Heavy-ion collisions: Hot QCD in the laboratory

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Contents

- High-energy nuclear collisions
  - properties of matter at high densities/temperatures (heavy-ion collisions!); matter and the control of high-energy strong interactions (colour glass condensate); study of structures of nucleons (proton spin!)
- HI collisions: experimental controls - calibration measurements
- Measurements the properties of quark-gluon plasma:
  - Collective effects: Particle correlations and flow
  - Probing the medium with quarks and jets

Thanks to all the authors/experiments for the graphics/slides shamelessly stolen for the purpose of this talk

SM and QCD... one minute reminder

FERMIONS
matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	−1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	−1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	−1

Quarks spin = 1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	−1/3
c charm	1.3	2/3
s strange	0.1	−1/3
t top	175	2/3
b bottom	4.3	−1/3

BOSONS
force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W$^-$	80.4	−1
W$^+$	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Strong interaction binds quarks into hadrons and nucleons into nuclei

QCD describes interaction between colour charges mediated by strong force carriers (gluons)

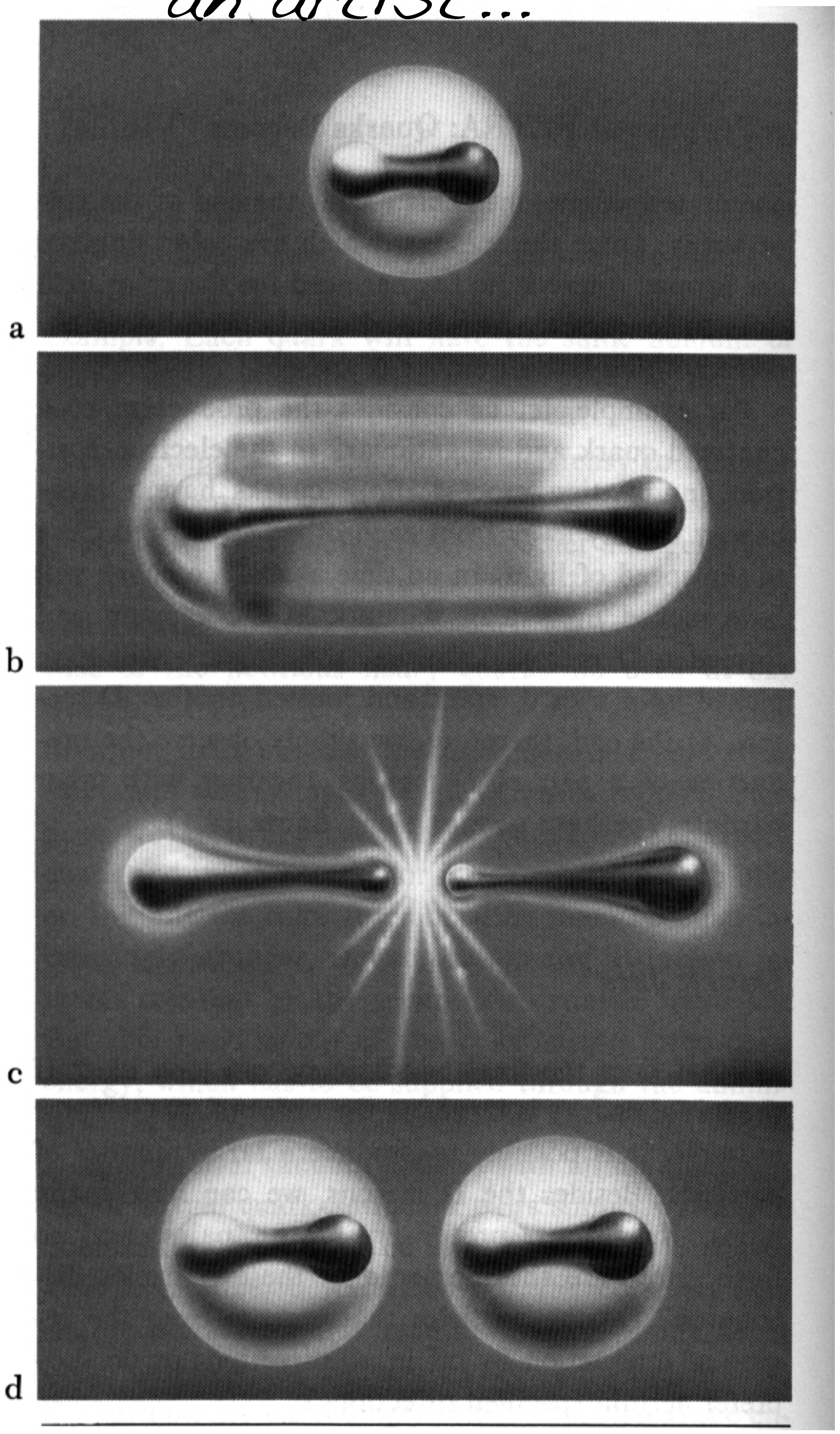
QCD is successful in describing many phenomena (experimental observations)

Puzzles:

- sum of masses of the constituent quarks (12 MeV) in a proton is much less than the mass of a proton (~1000 MeV)
- no free quarks detected (half of fundamental fermions!)

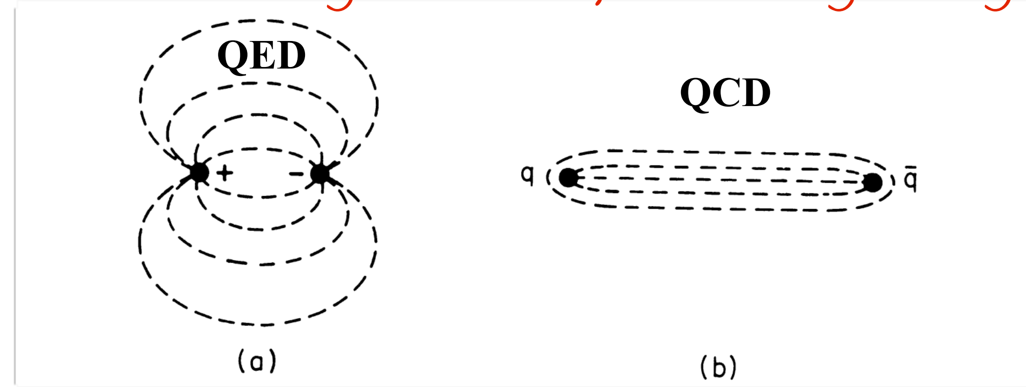
QCD Vacuum - example/reminder

String breaking by an artist...



[illustration from Fritzsch]

QCD: field lines compressed into a "flux tube" ("string") of constant cross-section (~fm²) => long-distance potential growing linearly with r:



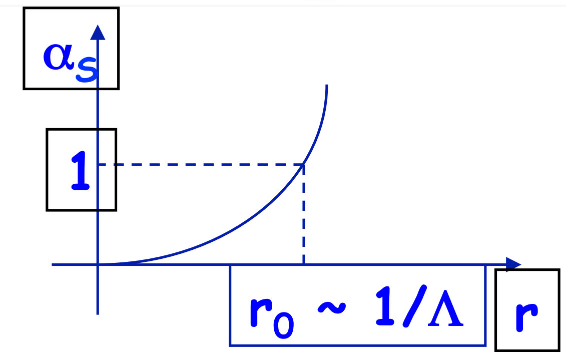
$$V_{long} = kr$$

k~1 GeV/fm

Two-gluon singlet at distance r

g ← r → g

$$\Delta p \Delta r \sim \hbar = 1$$



$$r \sim \frac{1}{p} \sim \frac{1}{E_{KIN}} \rightarrow E_{KIN} \sim \frac{1}{r}$$

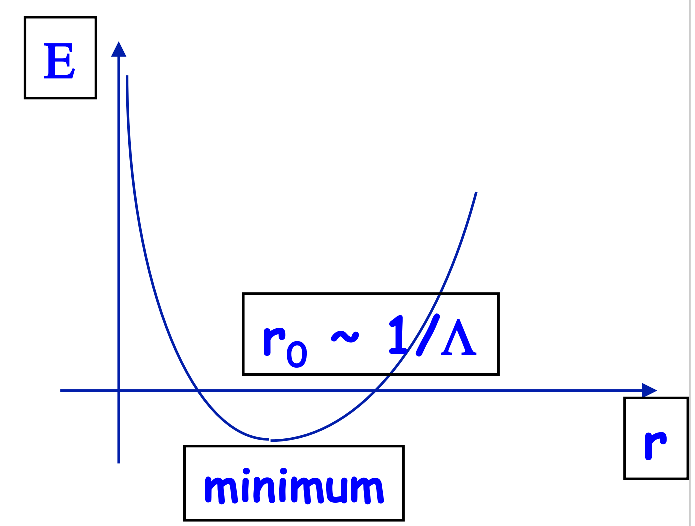
→

$$E = \frac{1}{r} - C\frac{\alpha_S}{r} = \frac{1 - C\alpha_S}{r}$$

$$r \rightarrow 0 \qquad E \sim \frac{1}{r}$$

$$r \sim r_0 \qquad E <\sim 0$$

$$r \rightarrow \infty \qquad E \sim kr$$



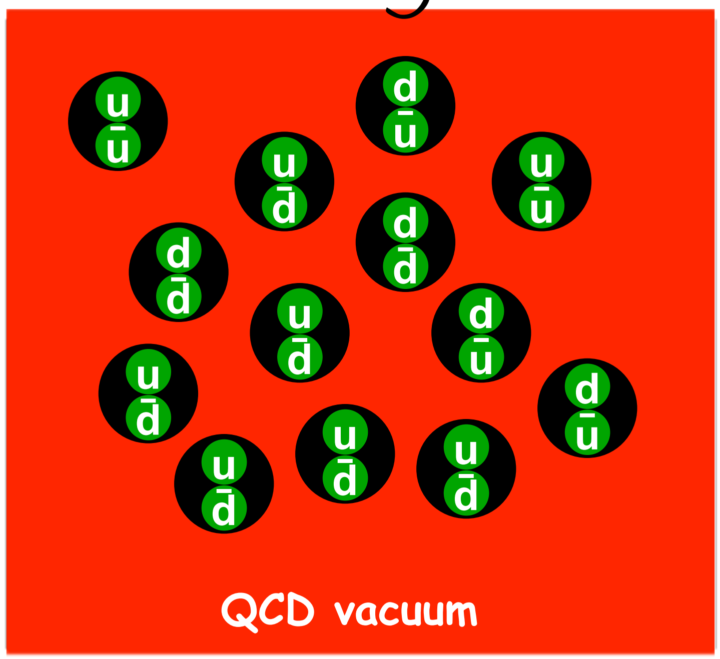
Pressure-temperature considerations

Gibbs' criterion: the stable phase is the one with the largest pressure

Statistical mechanics (ideal gas):

$$p = \frac{\varepsilon}{3} = \left(g_B + \frac{7}{8} g_F\right) \frac{\pi^2 T^4}{90}$$

Hadron gas

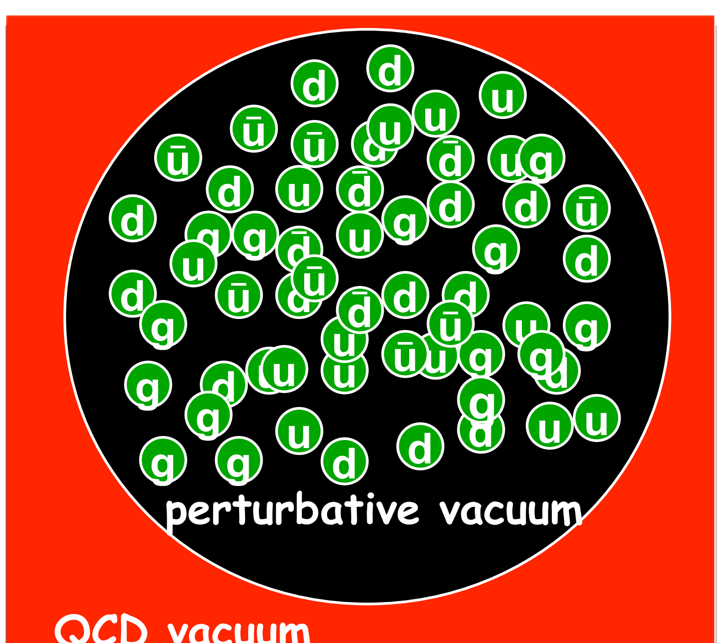


$g_B = 3 \quad g_F = 0$

$$p = \frac{3}{90}\pi^2 T^4 + B$$

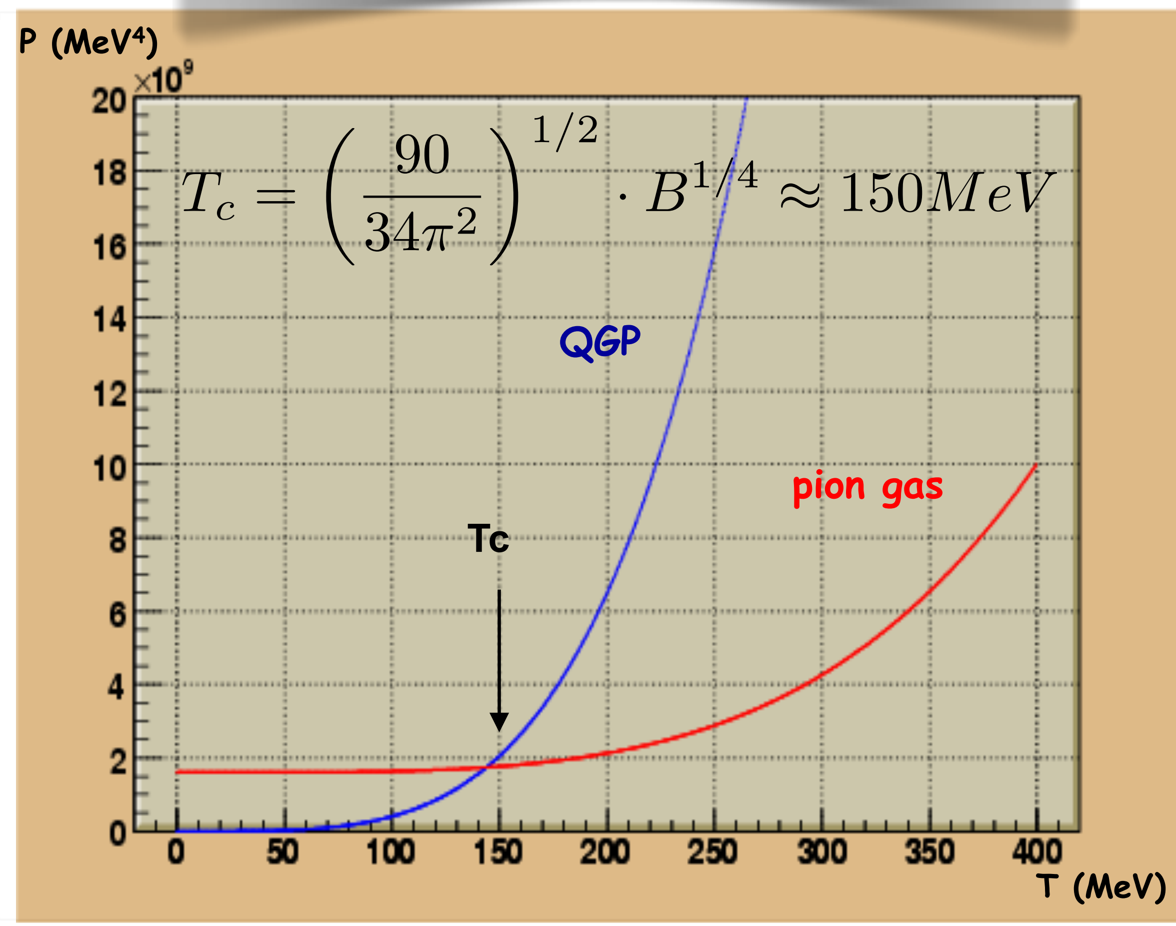
QCD vacuum pressure
$B \sim (200 MeV)^4$

Plasma



$g_B = 16 \quad g_F = 24$

$$p = \frac{37}{90}\pi^2 T^4$$



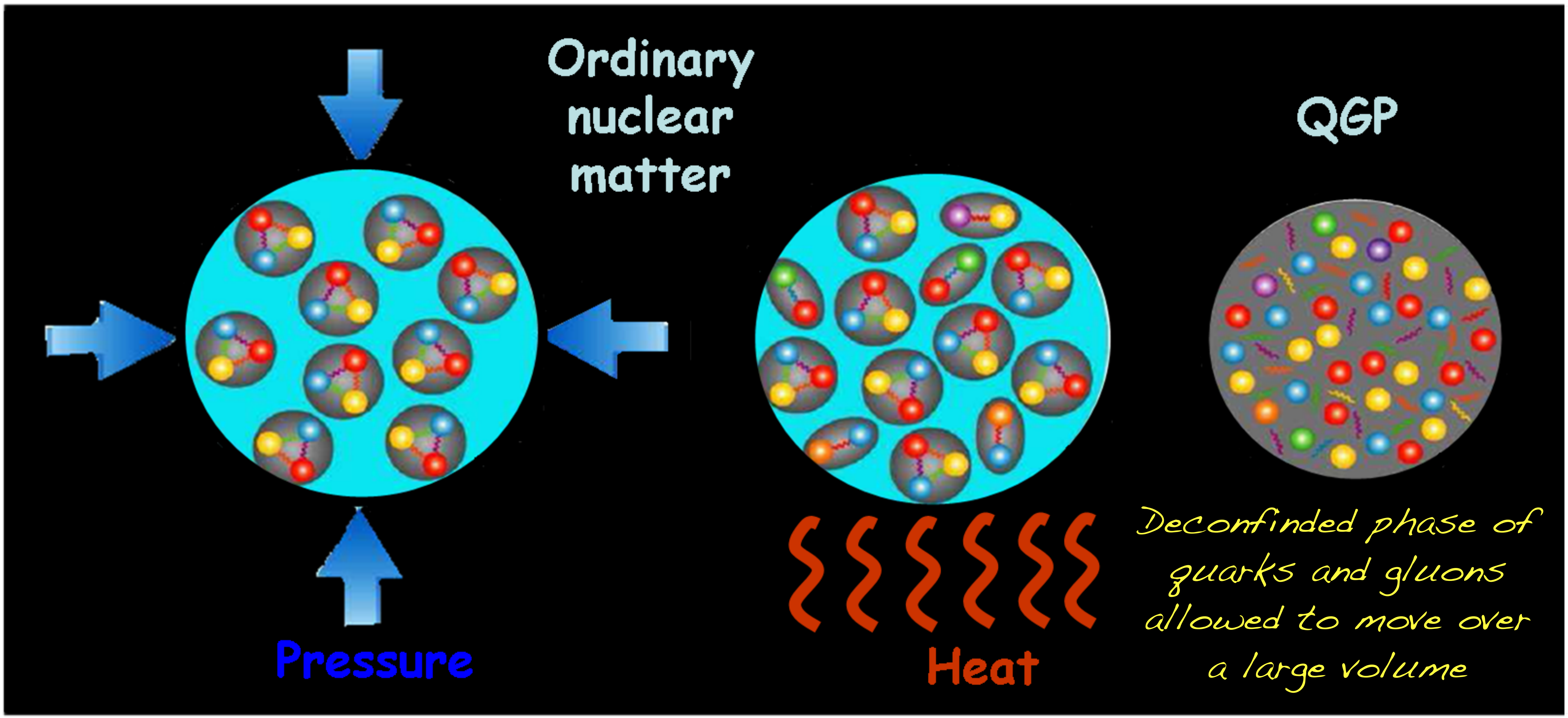
At low-T: hadron gas is the stable phase
At high-T: above T_c QGP is the stable phase

Refined calculations: Tc=170 MeV:
NOTE: T_{room} (300 K) ~ 25 meV (!lowercase m)
Tc ≈ 170 MeV ≈ 2000 billion K
(compare Sun core: 15 million K)

Create hot & colored medium

temperatures ~1.5 x 10^{12} K (~200 MeV)

far hotter than center of the sun (~1.5 x 10^{7}K)



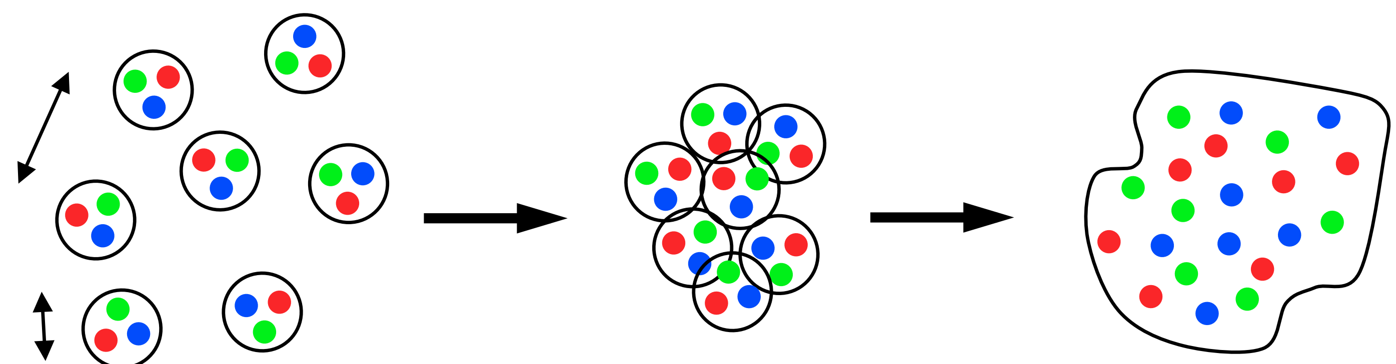
Heat and compress matter such that the individual nucleons start to "overlap"...

What it the critical energy-density?

Vacuum (quarks and gluons in bags (MIT bag model)) and nucleons

distance of two nucleons:
$2\ r_0 \sim 2.3$ fm

size of nucleon
$r_n \sim 0.8$ fm



- **normal nuclear matter ρ_0**

$$\rho_0 = \frac{A}{\frac{4\pi}{3} R^3} = \frac{3}{4\pi\, r_0^{\ 3}} : \ 0.16\ fm^{-3}$$

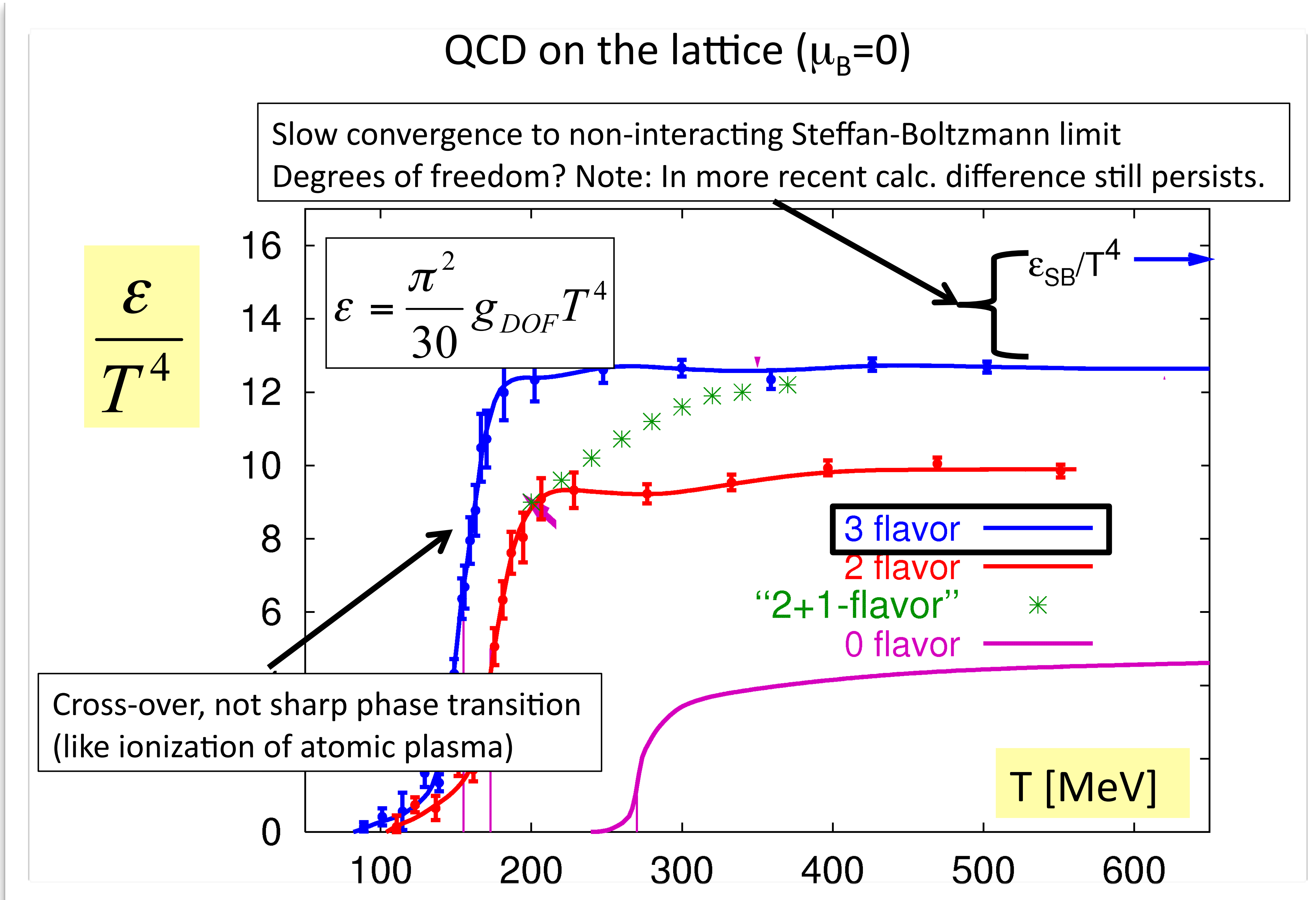
$$\varepsilon_0 : \ 0.15\ GeV / fm^3$$

- **critical density:**
  naïve estimation
  nucleons overlap $R \sim r_n$

$$\rho_c = \frac{3}{4\pi\, r_n^{\ 3}} : \ 0.5\ fm^{-3} \approx 3.1 \rho_0$$

$$\varepsilon_c : \ 0.5\ GeV / fm^3$$

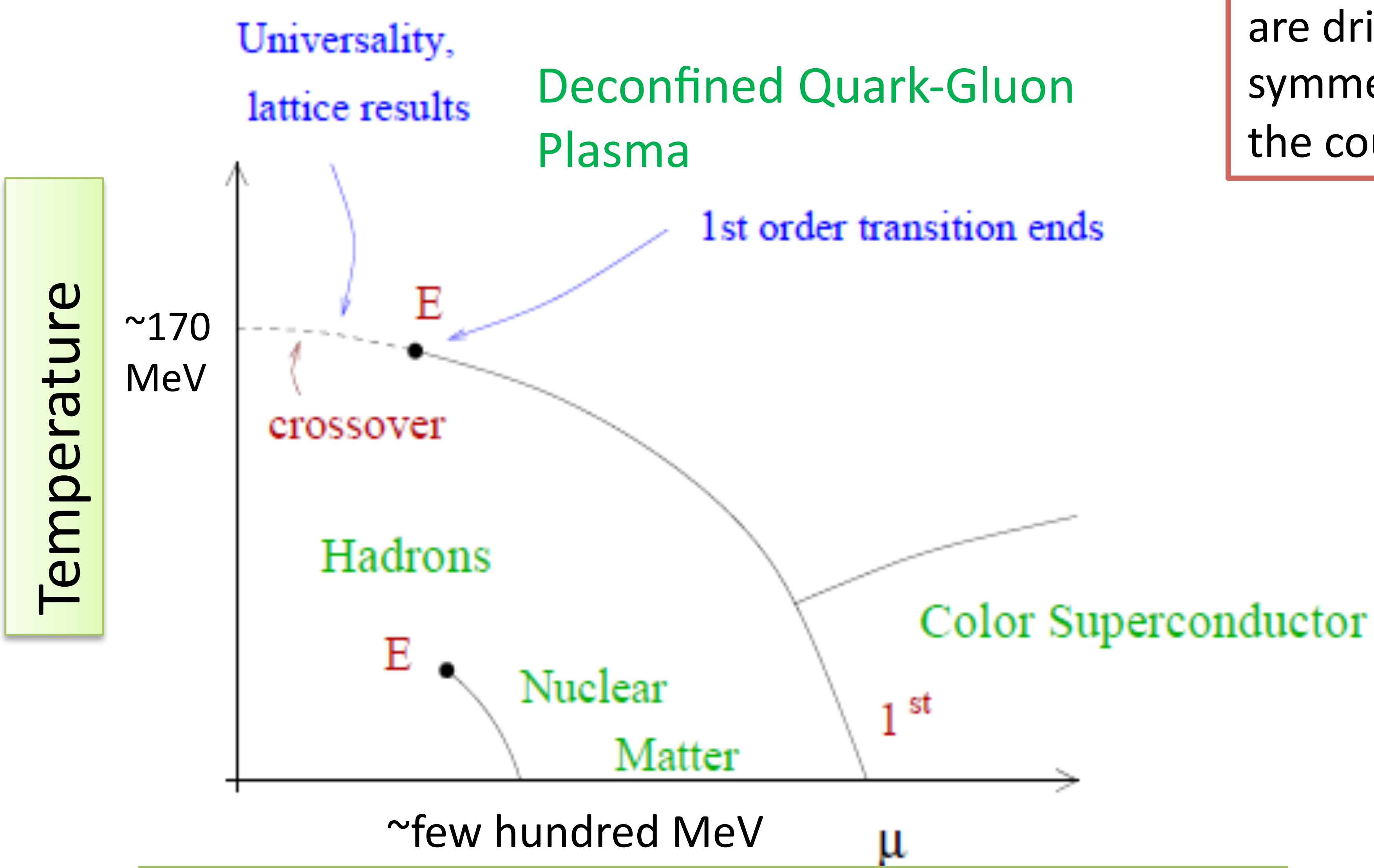
QCD Thermodynamics - calculation



"Lattice": rigorous calculations in non-perturbative regime of QCD - discretization on a space-time lattice ultraviolet (large momentum scale) divergencies avoidable

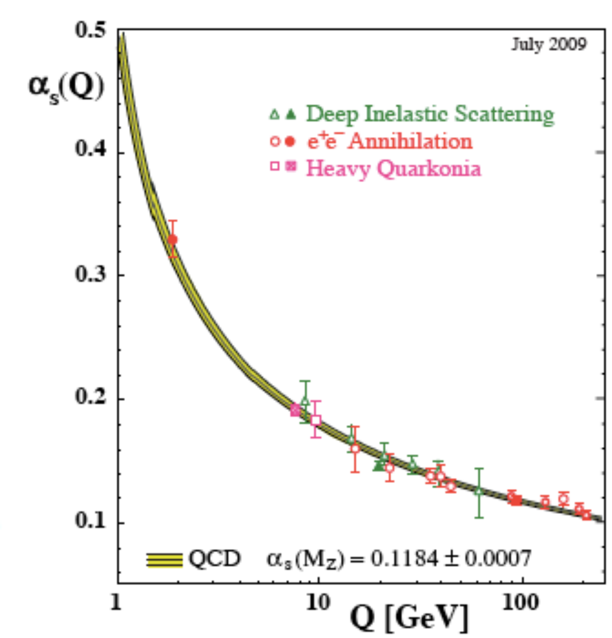
Zero baryon density, 3 flavours: ε changes rapidly around T_c = 170 MeV: ε_c = 0.6 GeV/fm^3 (at T~1.2 T_c: ε settles at about 80% of the Stefan-Boltzmann value for an ideal gas of q,q g (ε_{SB}))

QCD phase diagram – theoretical landscape



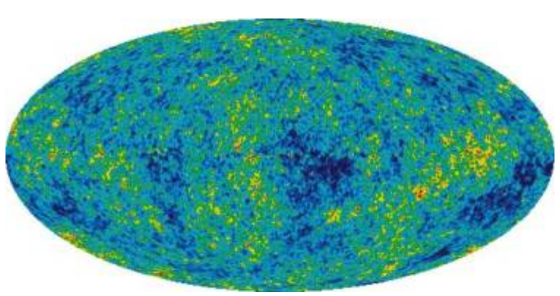
Baryon chemical potential μ_B ~ Density

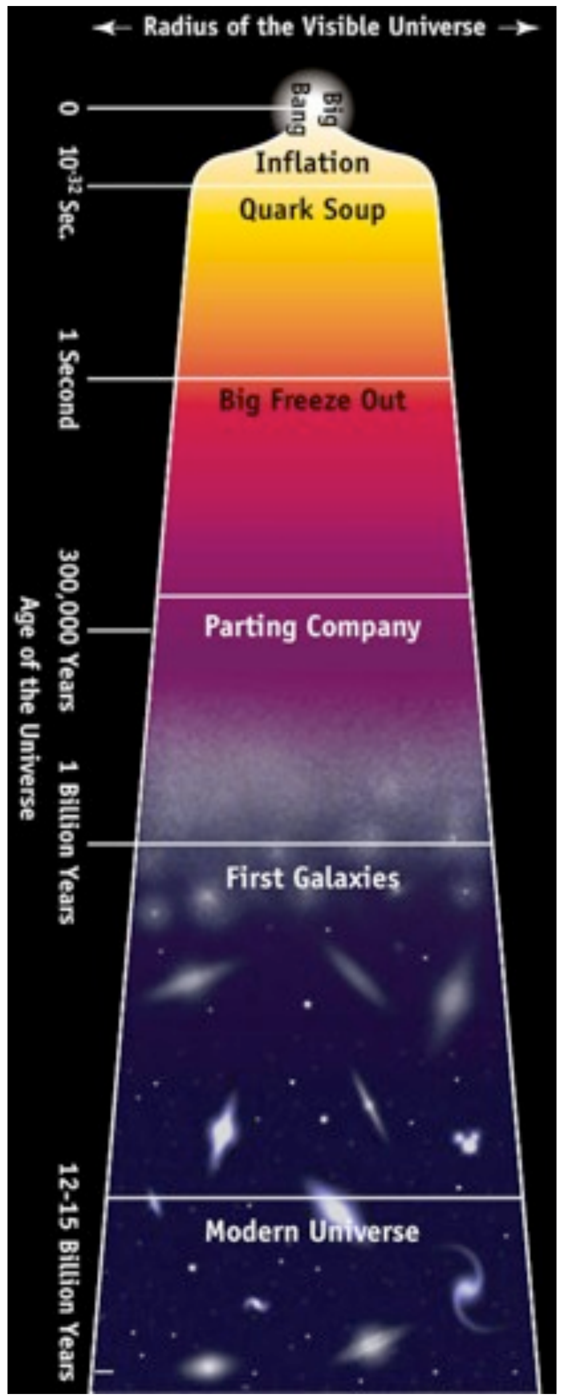
The features of this diagram are driven by QCD symmetries and running of the coupling constant



Some history...

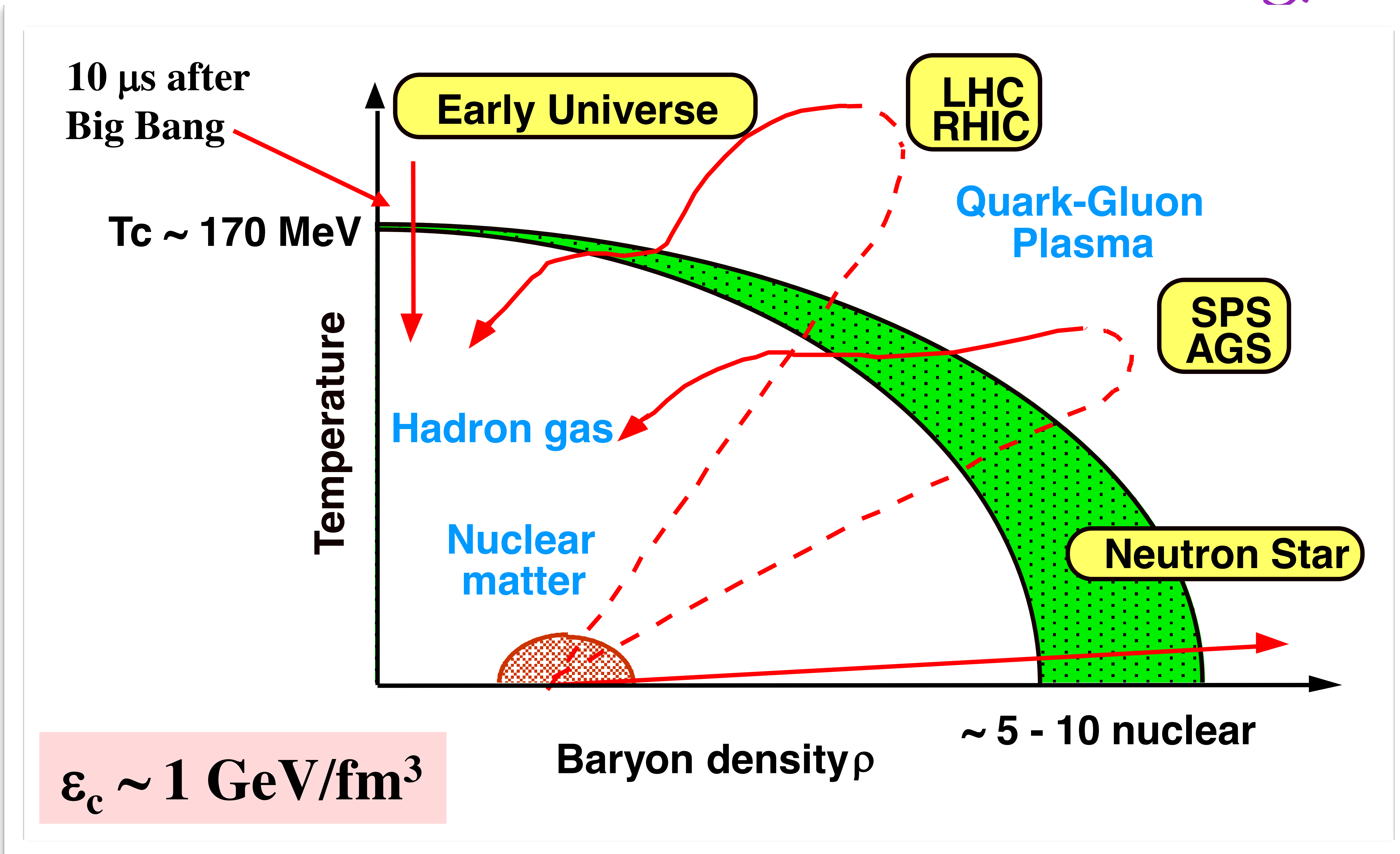
QCD Lab → "few" years later?





10^{-44} sec	Quantum Gravity	Unification of all 4 forces	10^{32} K
10^{-35} sec	Grand Unification	E-M/Weak = Strong forces	10^{27} K
10^{-35} sec?	Inflation	universe exponentially expands by 10^{26}	10^{27} K
$2\ 10^{-10}$ sec	Electroweak unification	E-M = weak force	10^{15} K
$2 \cdot 10^{-6}$ sec	Proton-Antiproton pairs	creation of nucleons	10^{13} K
6 sec	Electron-Positron pairs	creation of electrons	$6 \cdot 10^{9}$ K
3 min	Nucleosynthesis	light elements formed	10^{9} K
10^{6} yrs	Microwave Background	recombination - transparent to photons	3000 K
10^{9} yrs ?	Galaxy formation	bulges and halos of normal galaxies form	20 K

Another view - qualitative view of a H/I collision evolution (collision energy)

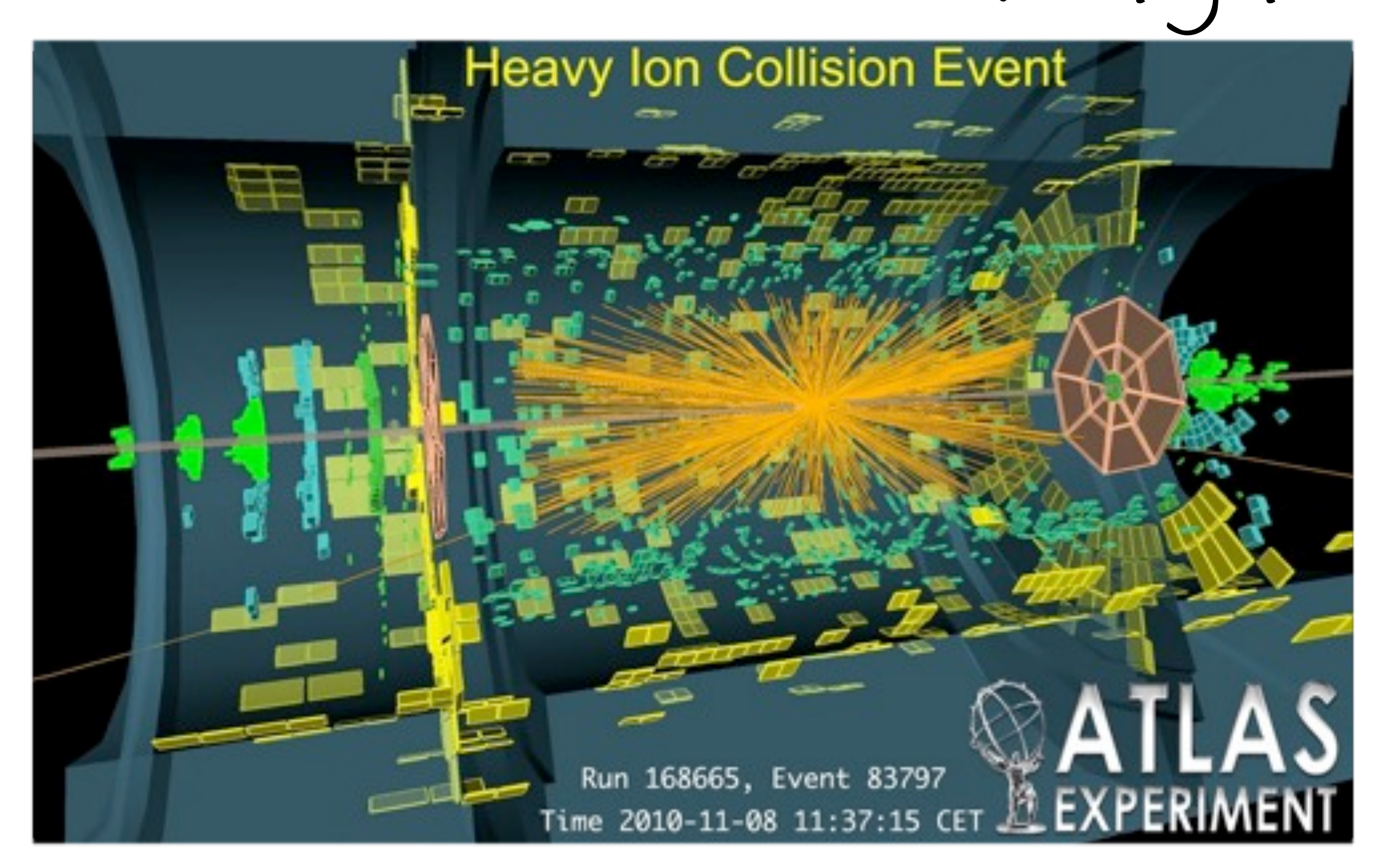


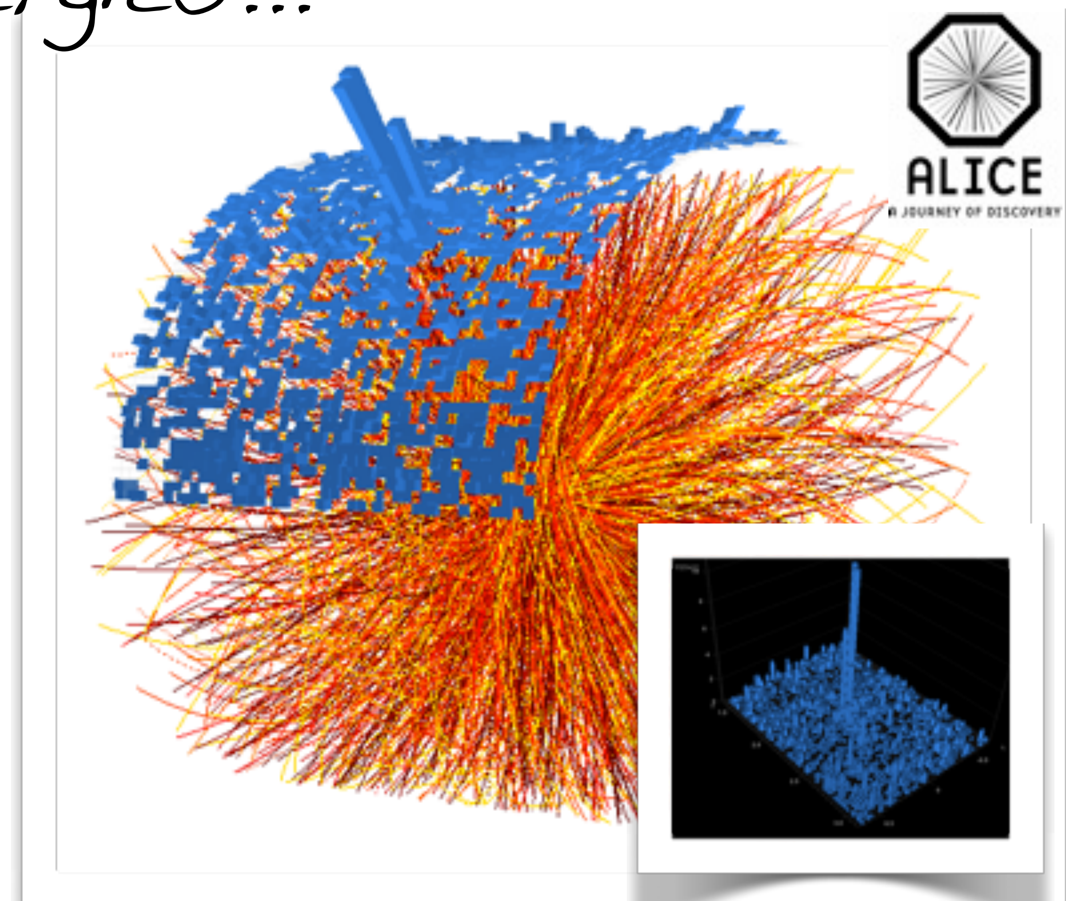
Strategy: how to study QCD matter experimentally?

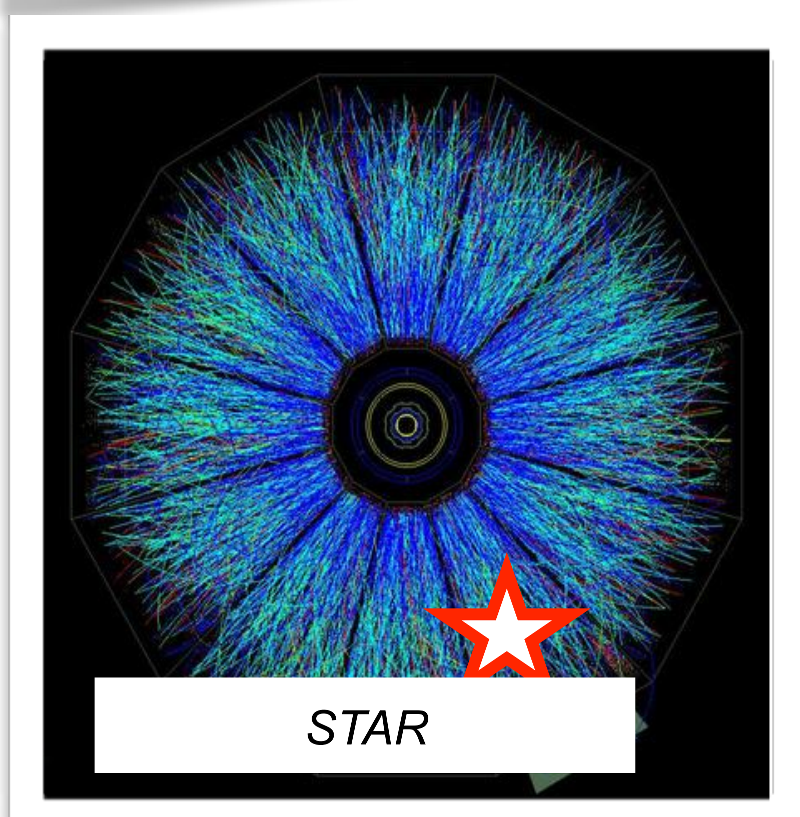
- **Need to find those observables that:**
  - Are sensitive to crucial parameters of hot QCD matter
  - **Can be modeled well – theoretical understanding**
  - **Can be measured well – experimental control**
  - **Can connect theory and data**
- **=> Inclusive measurements; correlations; compare with more elementary collisions (p-p, p-A); compare different energy regimes**

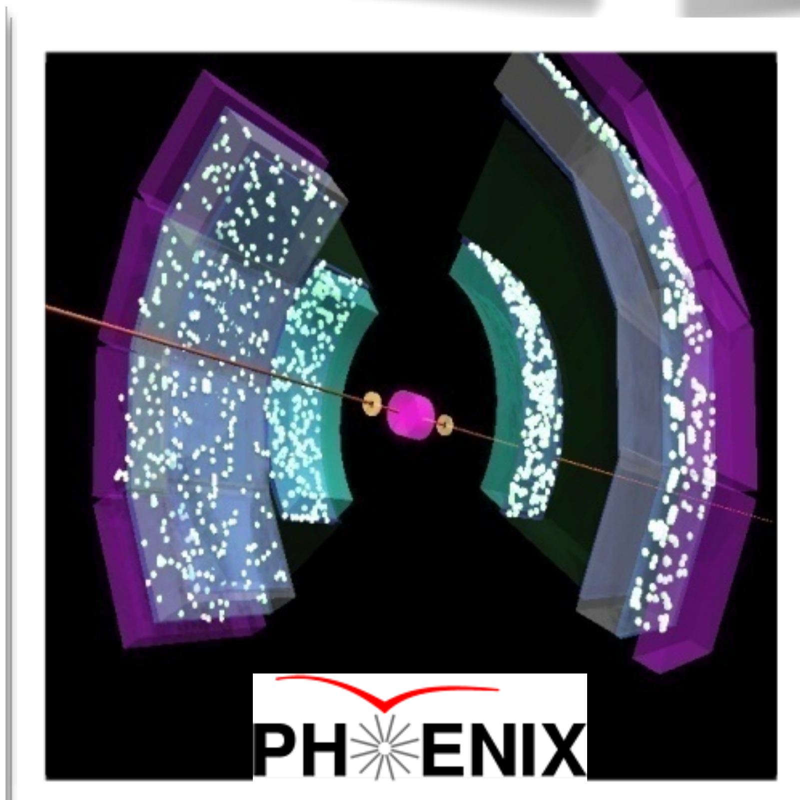
Heavy-ion collisions

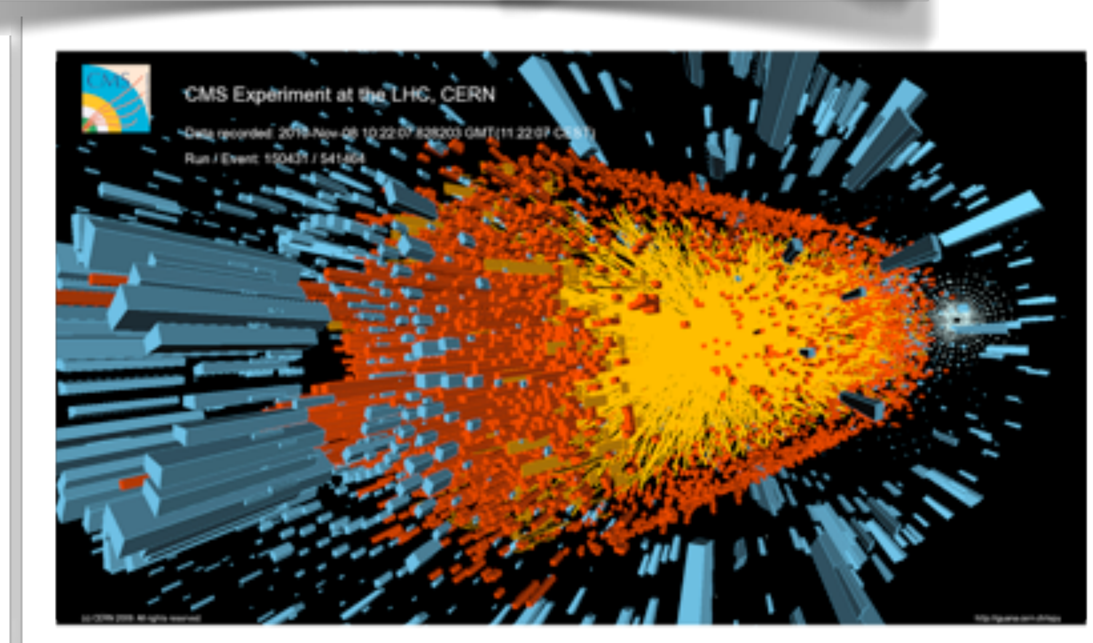
at high energies…







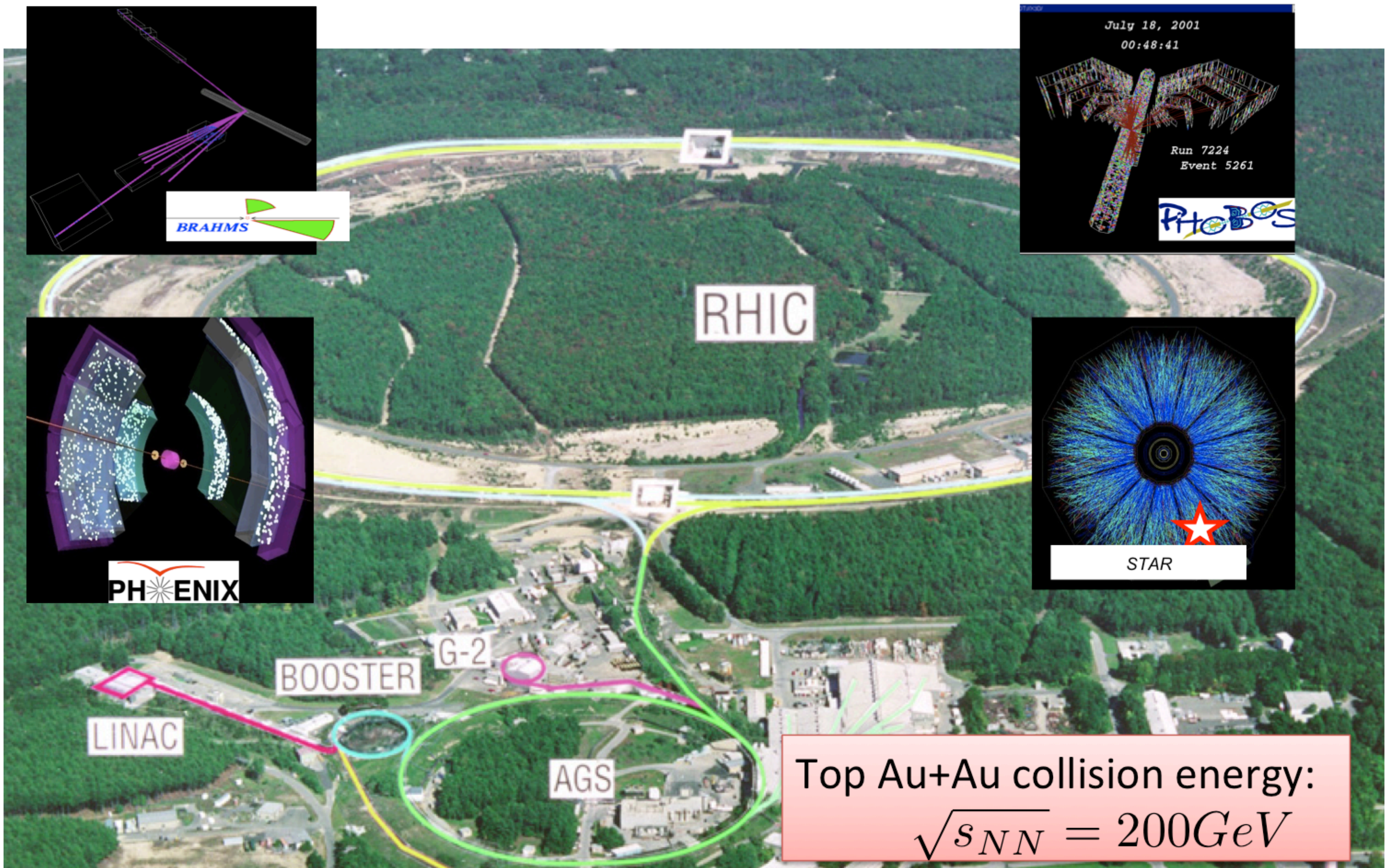




…RHIC to LHC

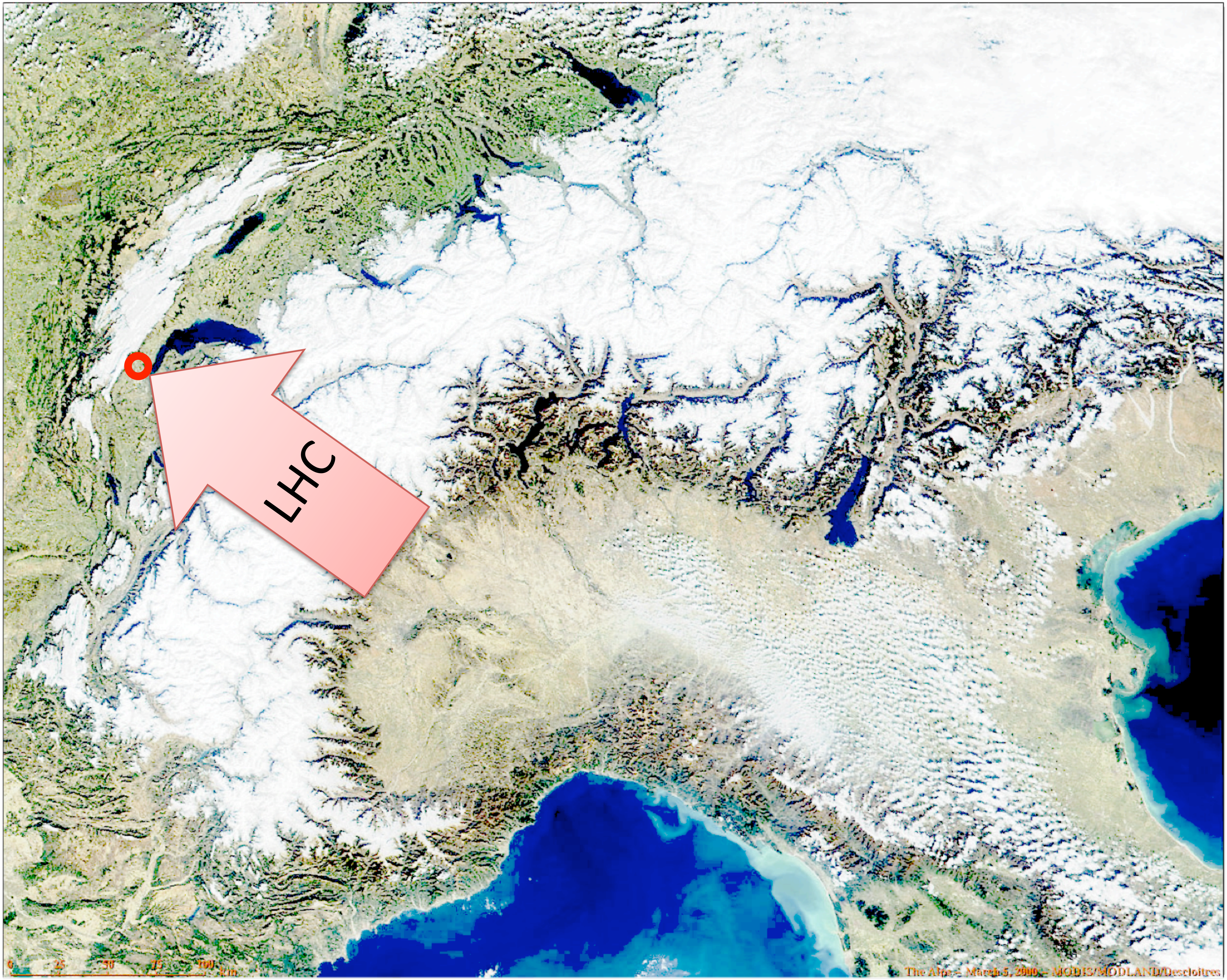
The hot-QCD laboratories

The Relativistic Heavy Ion Collider (BNL)

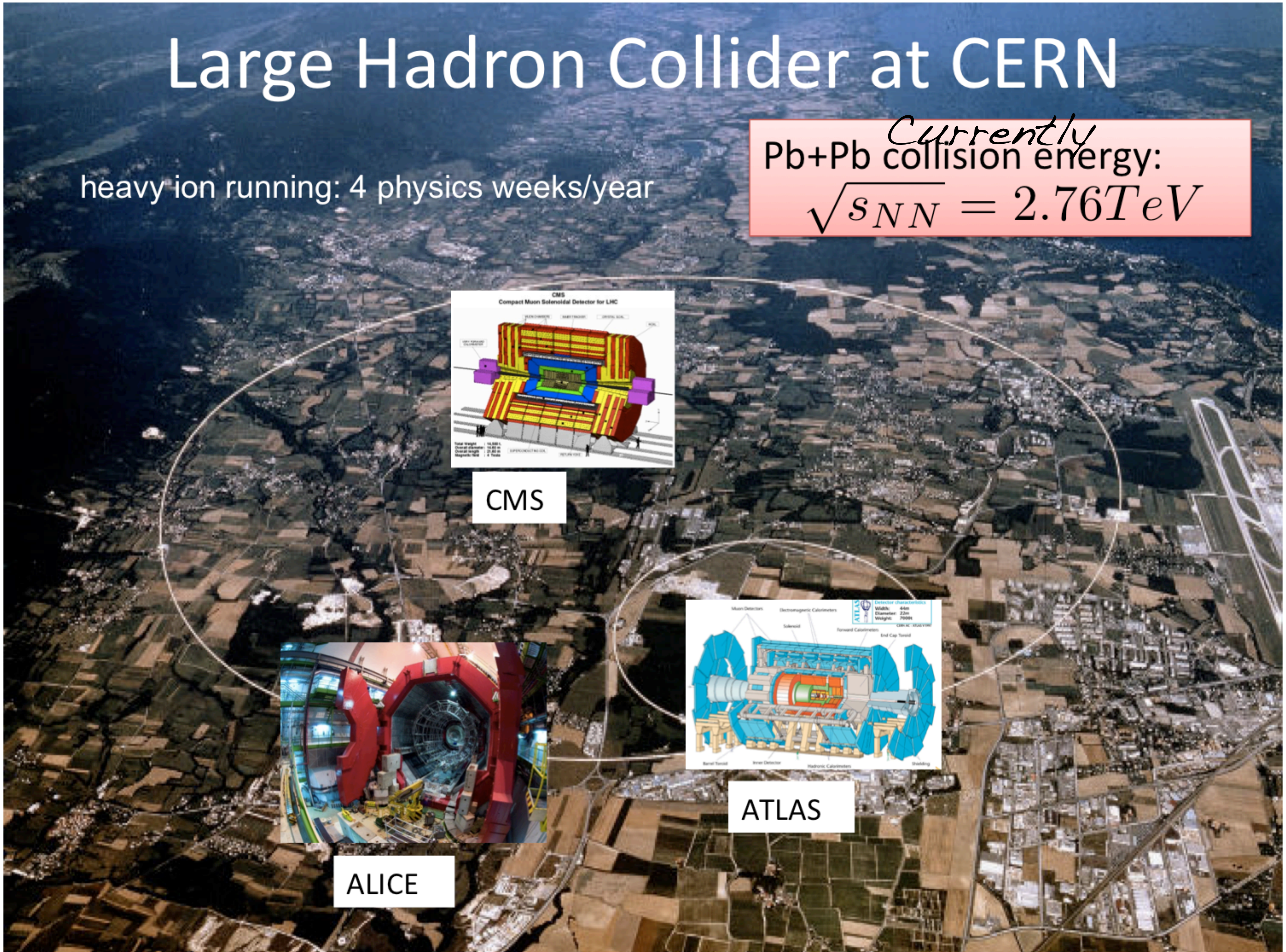


Top Au+Au collision energy:

$$\sqrt{s_{NN}} = 200GeV$$


LHC
0 25 50 75 100 km
The Alps – March 5, 2000 – MODIS/MODLAND/Descloitres

The hot-QCD laboratories



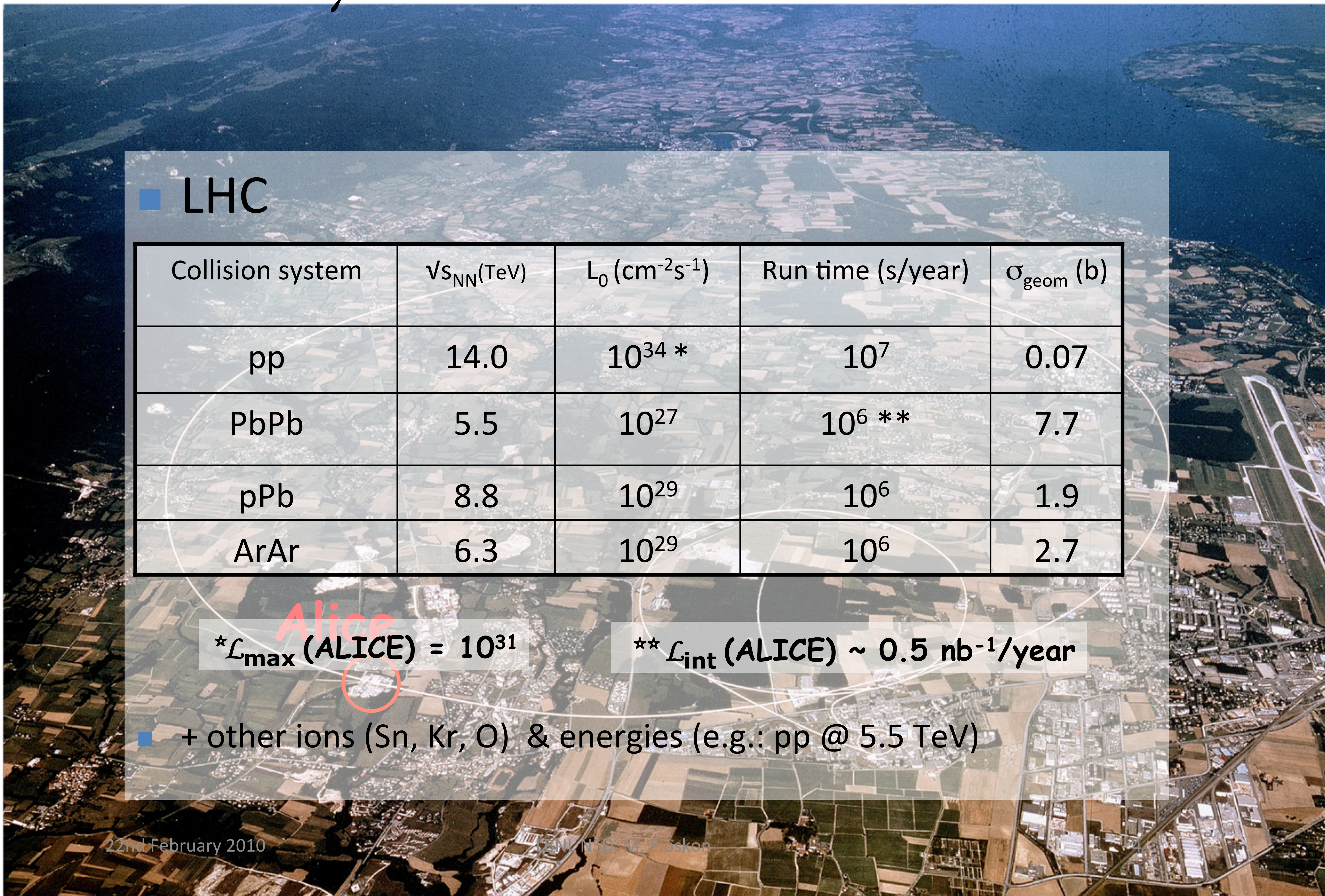
Design -> 5.5 TeV

2.76 at the moment.

Also: p-Pb and other ions plan

LHC and ion runs

Default plans... before the first runs...



- LHC

Collision system	$\sqrt{s_{NN}}$(TeV)	L_0 ($cm^{-2}s^{-1}$)	Run time (s/year)	σ_{geom} (b)
pp	14.0	10^{34} *	10^7	0.07
PbPb	5.5	10^{27}	10^6 **	7.7
pPb	8.8	10^{29}	10^6	1.9
ArAr	6.3	10^{29}	10^6	2.7

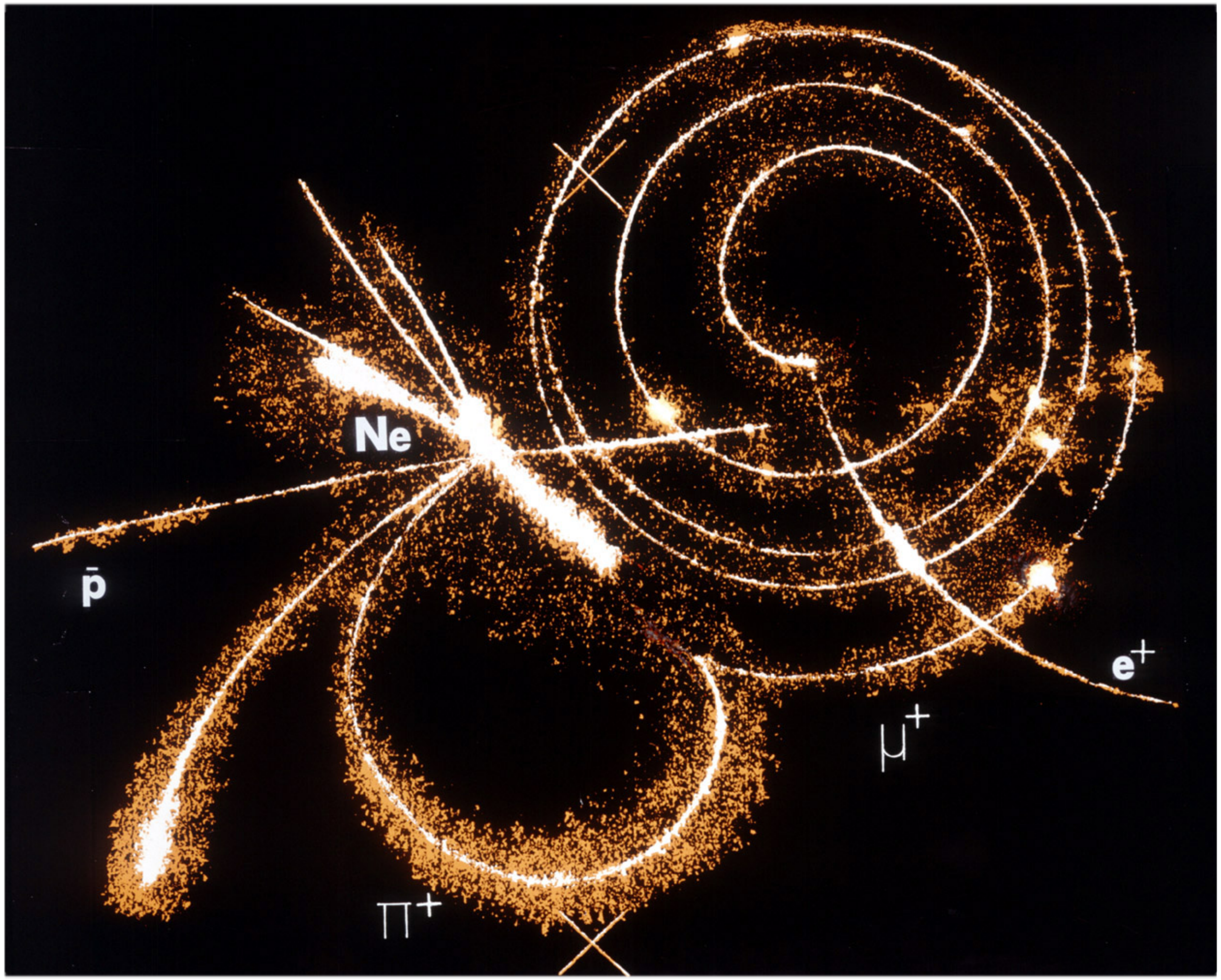
$^*\mathcal{L}_{max}$ (ALICE) = 10^{31}

$^{**}\mathcal{L}_{int}$ (ALICE) ~ 0.5 nb^{-1}/year

- + other ions (Sn, Kr, O) & energies (e.g.: pp @ 5.5 TeV)

Most advanced cameras...

$$\pi^+ \to \mu^+ \to e^+$$

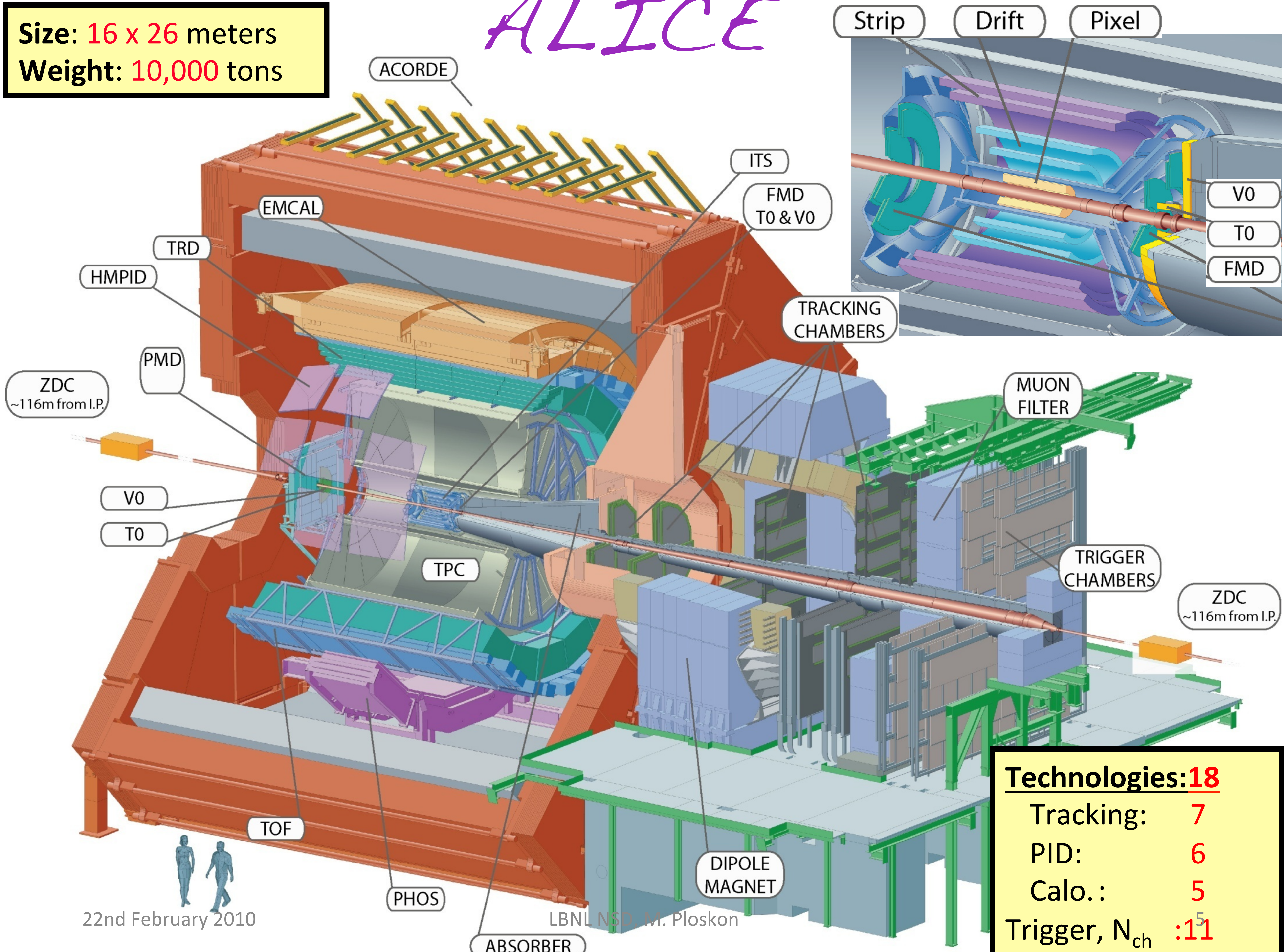


in streamer chamber (1984)

Dedicated HI experiment: ALICE

ALICE

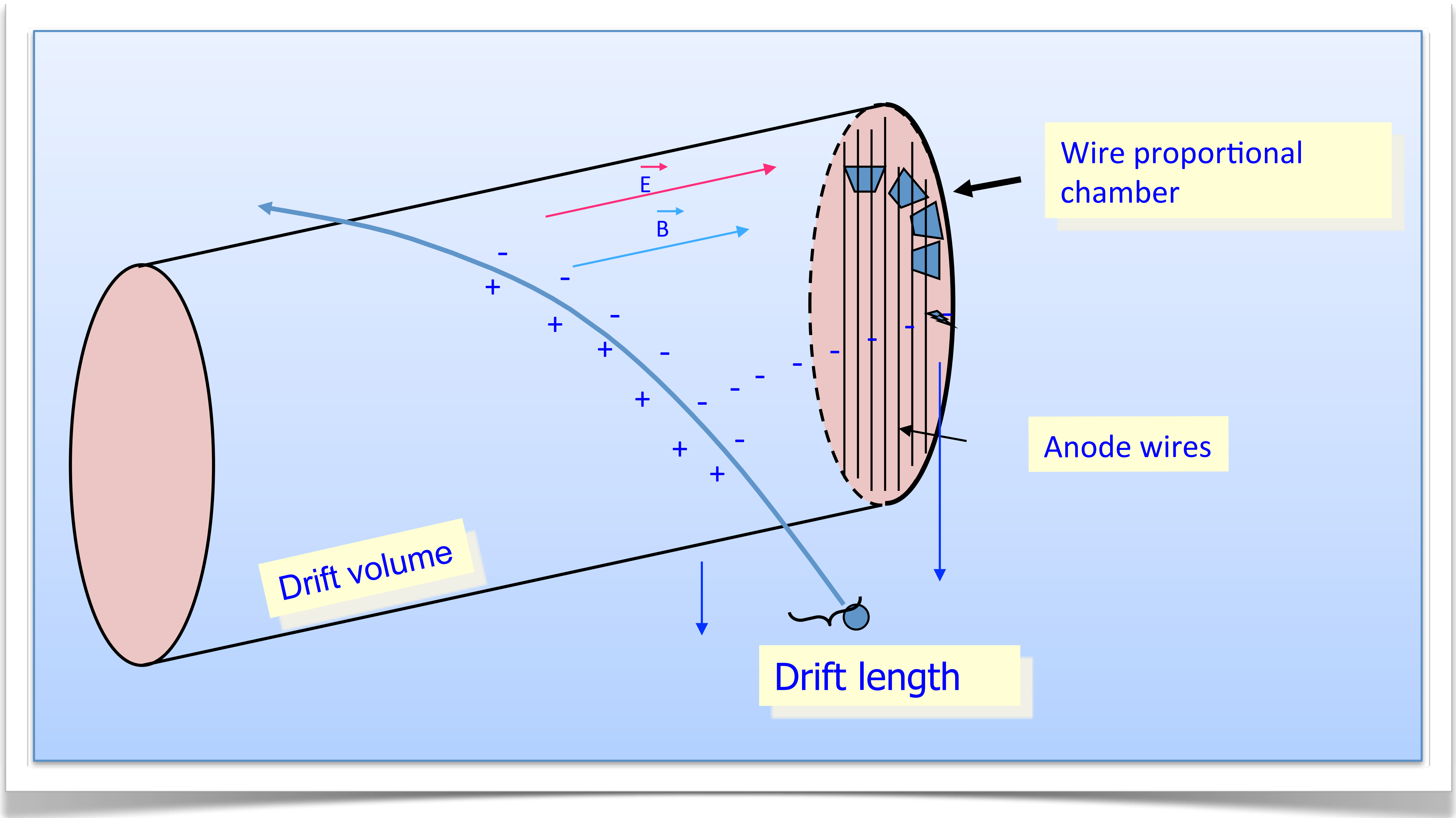
Size: 16 x 26 meters
Weight: 10,000 tons



Technologies:18

Tracking: 7
PID: 6
Calo. : 5
Trigger, N_{ch} :11

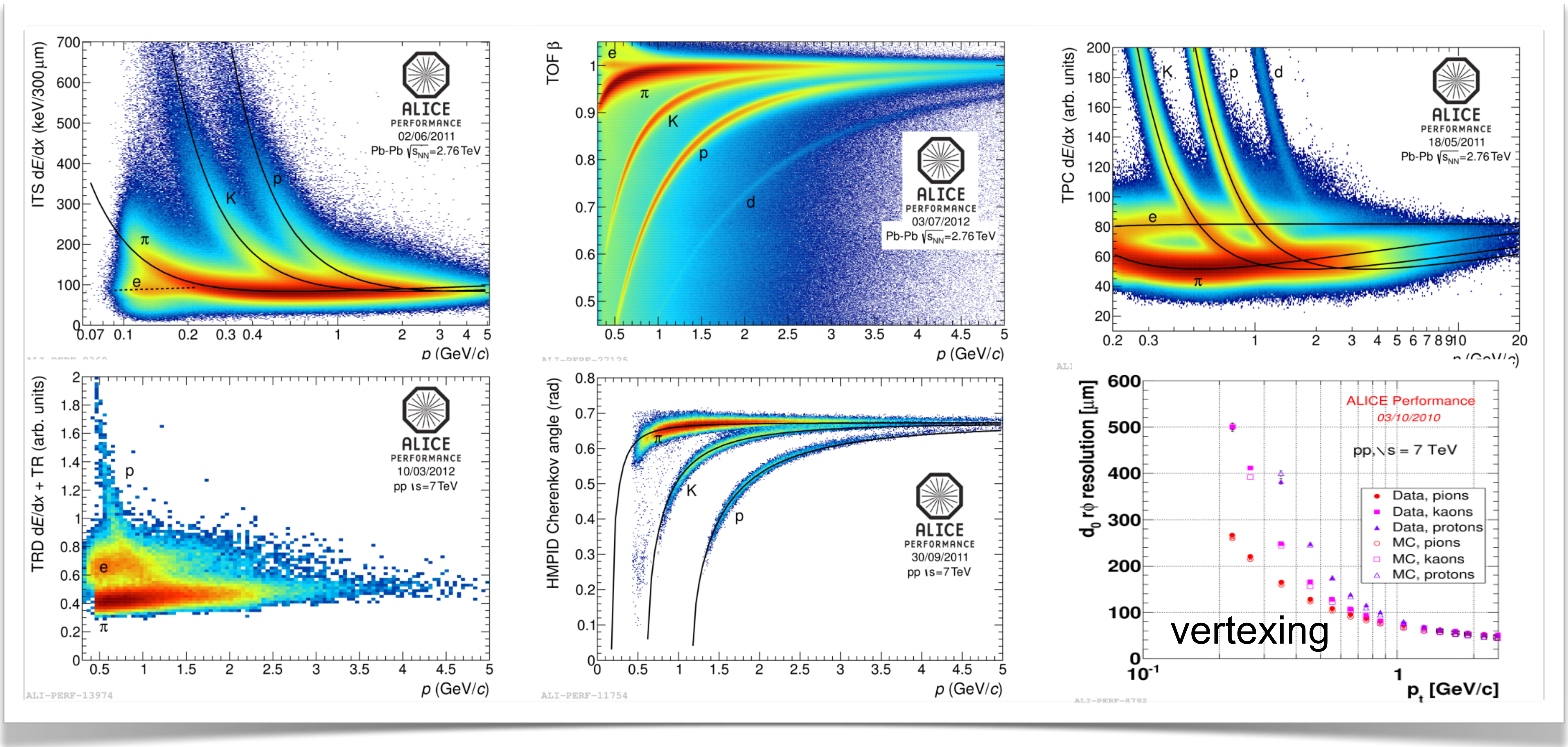
Time Projection Chamber



Spatial precision of track position is usually about 0.5 mm

Speed of TPC is given by drift time, typically 10 -- 100μs

ALICE - Particle identification



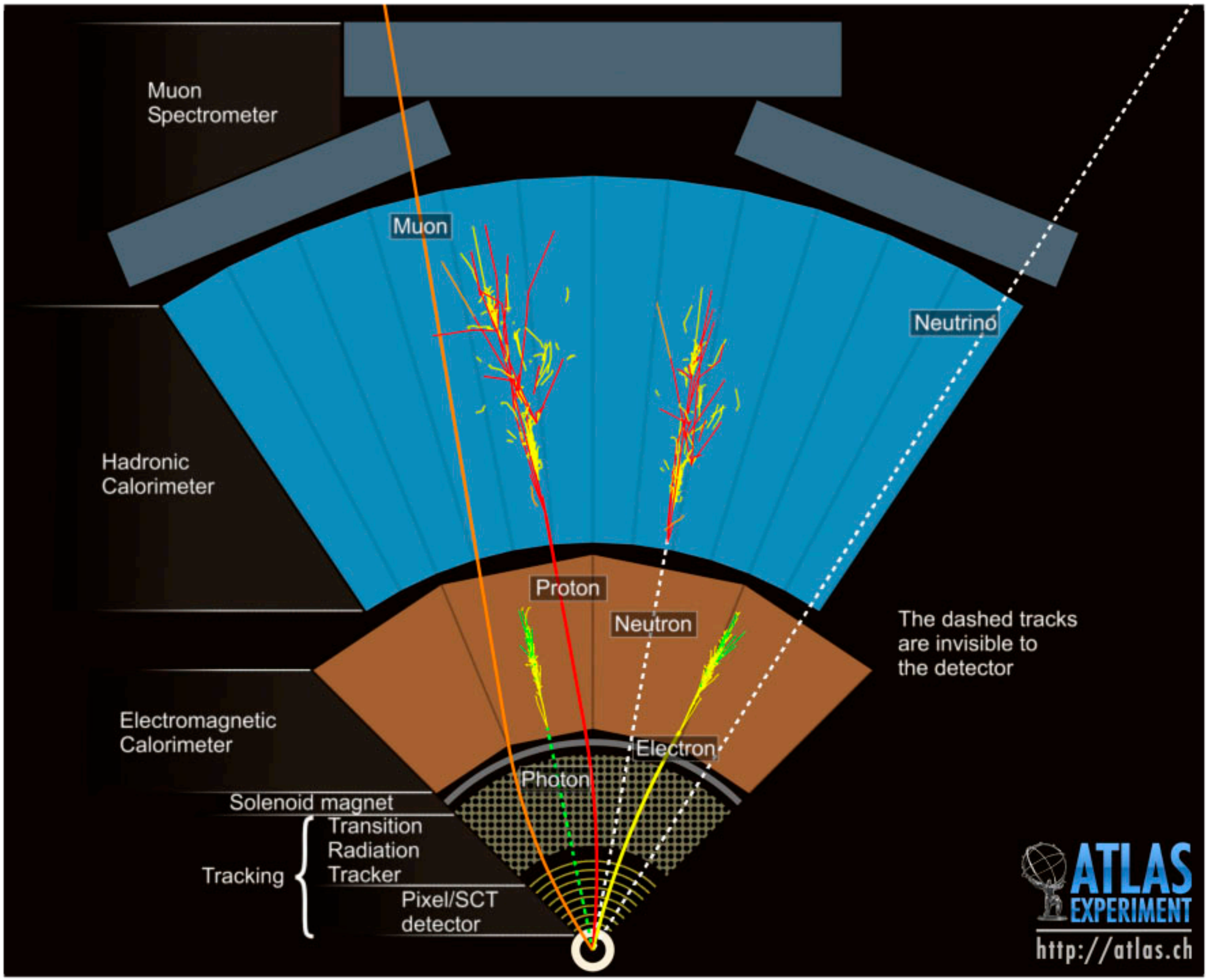
Particle identification (multiple techniques)

Extremely low-mass tracker ~ 10% of X_0

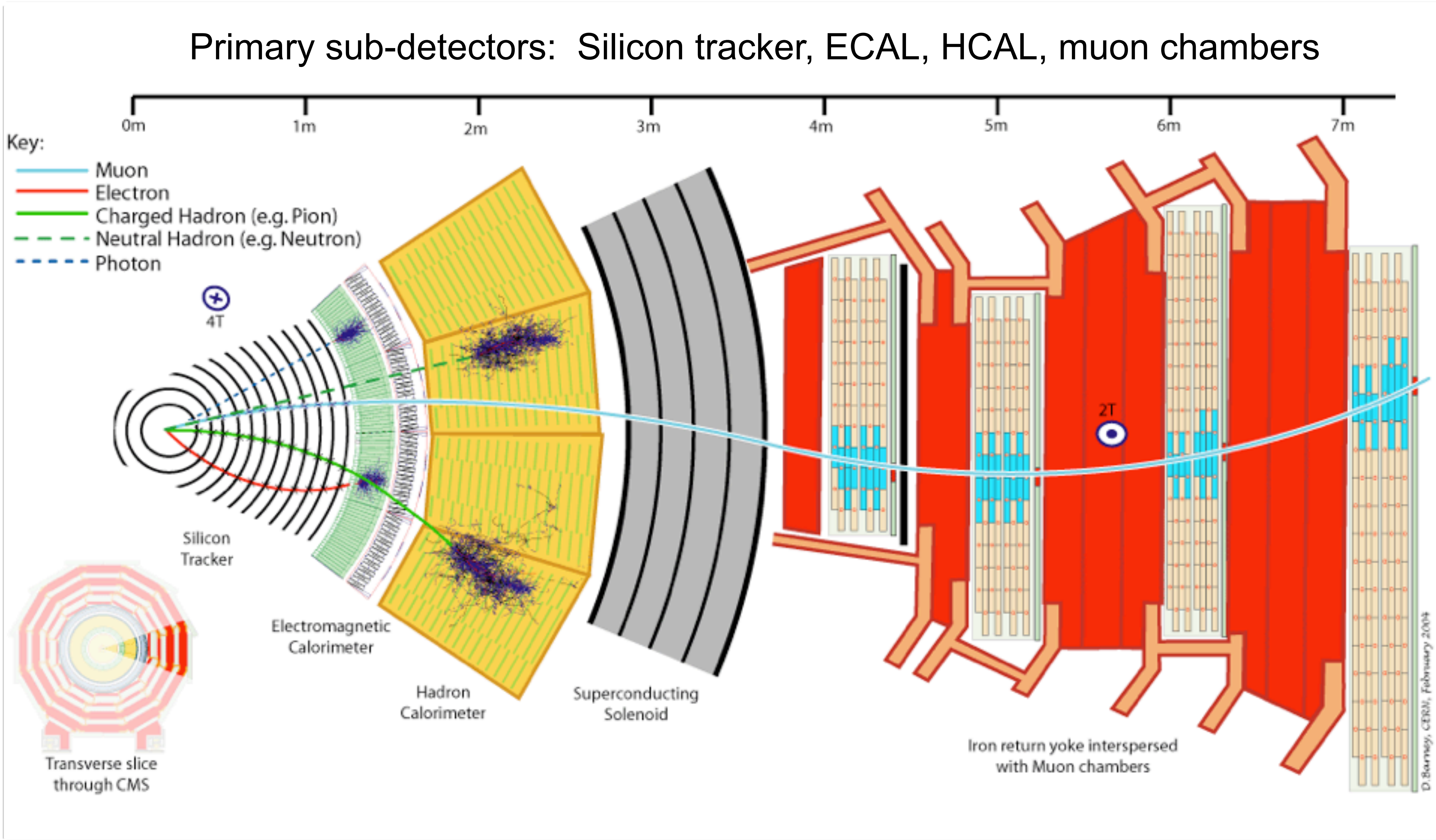
Excellent vertexing capability

Efficient low-momentum tracking - down to ~ 100 MeV/c

High energy particle detection - ATLAS

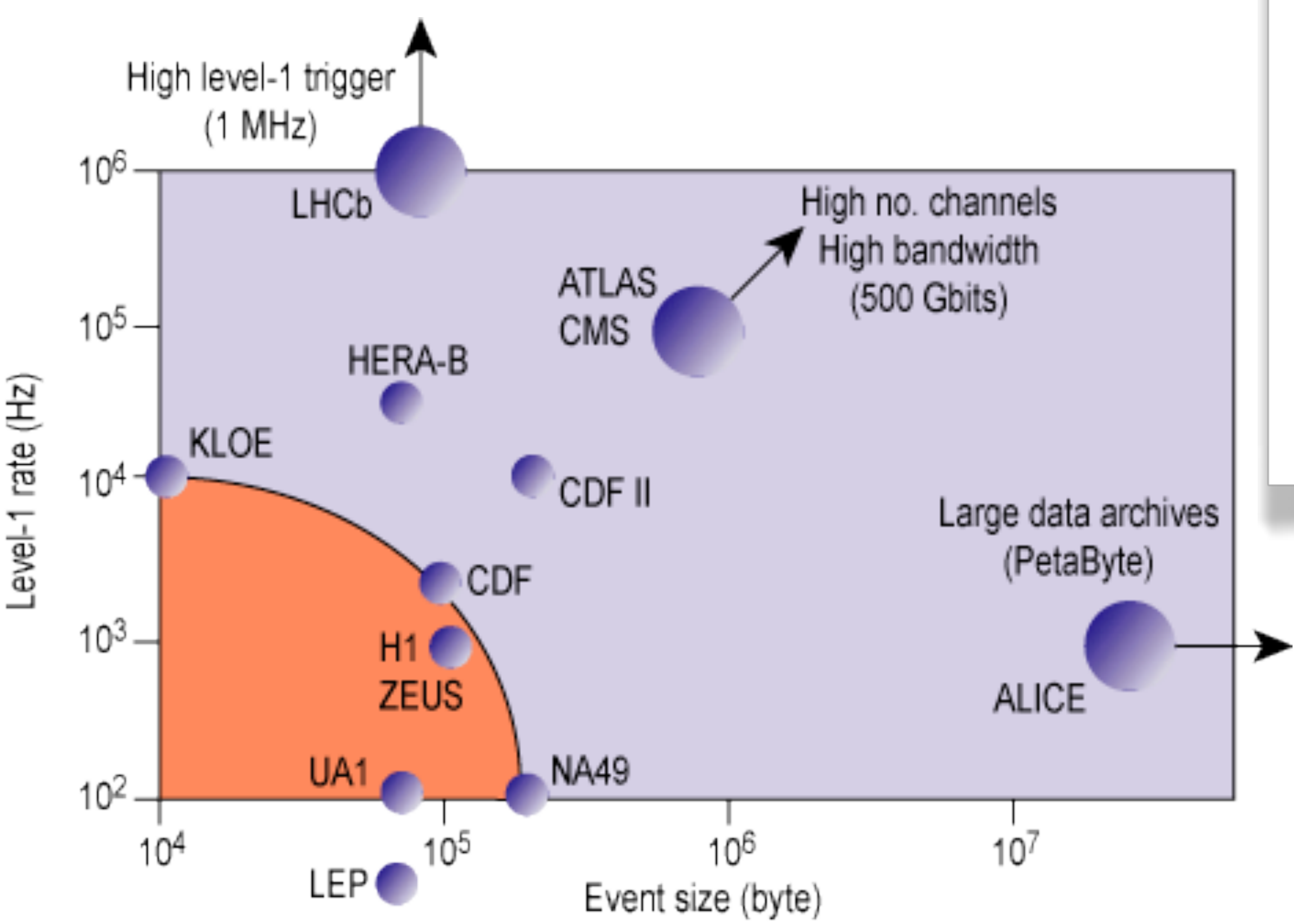


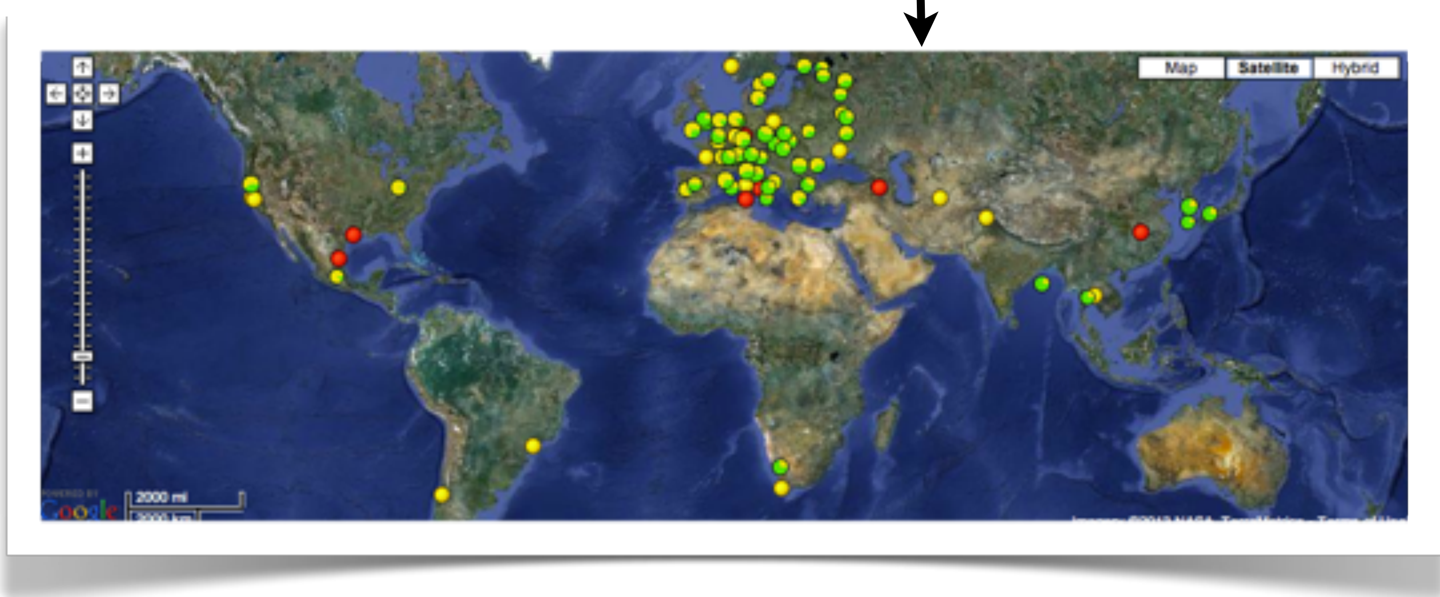
Compact Muon Spectrometer



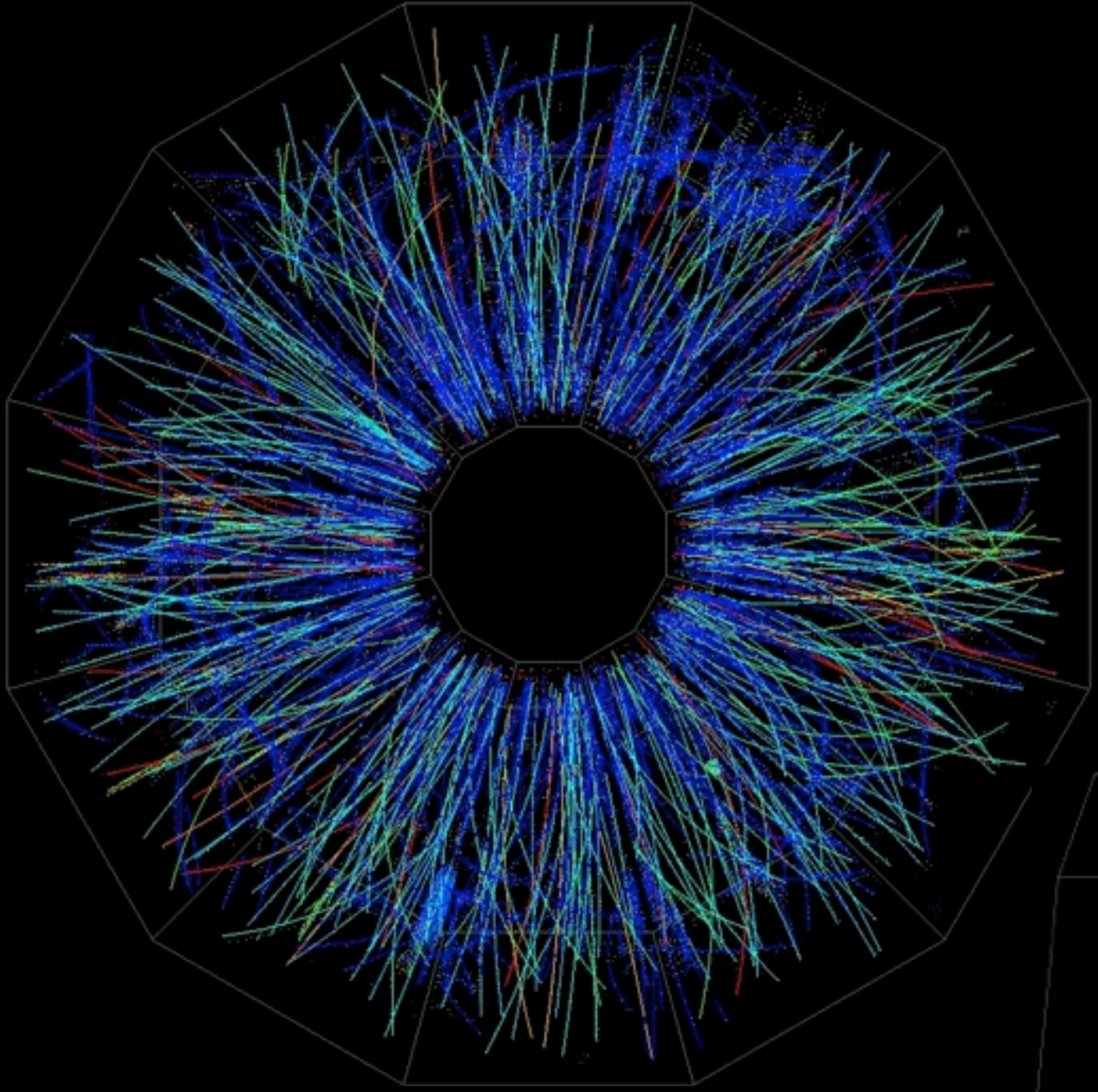
From trigger to data analysis...

Detector (front-end-electronics, digitalized information) → **Online systems** (Trigger: event rejection; online algorithms) → **Offline computing** (high capacity; offline reconstruction analysis; distributed computing - GRID)



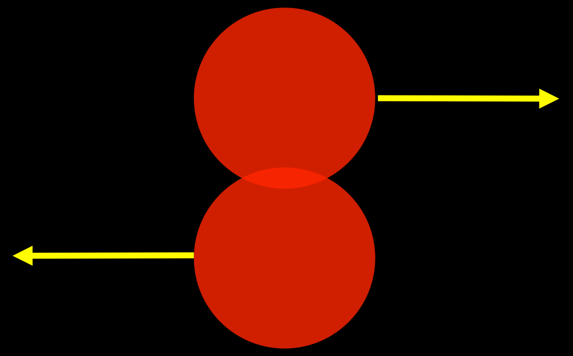


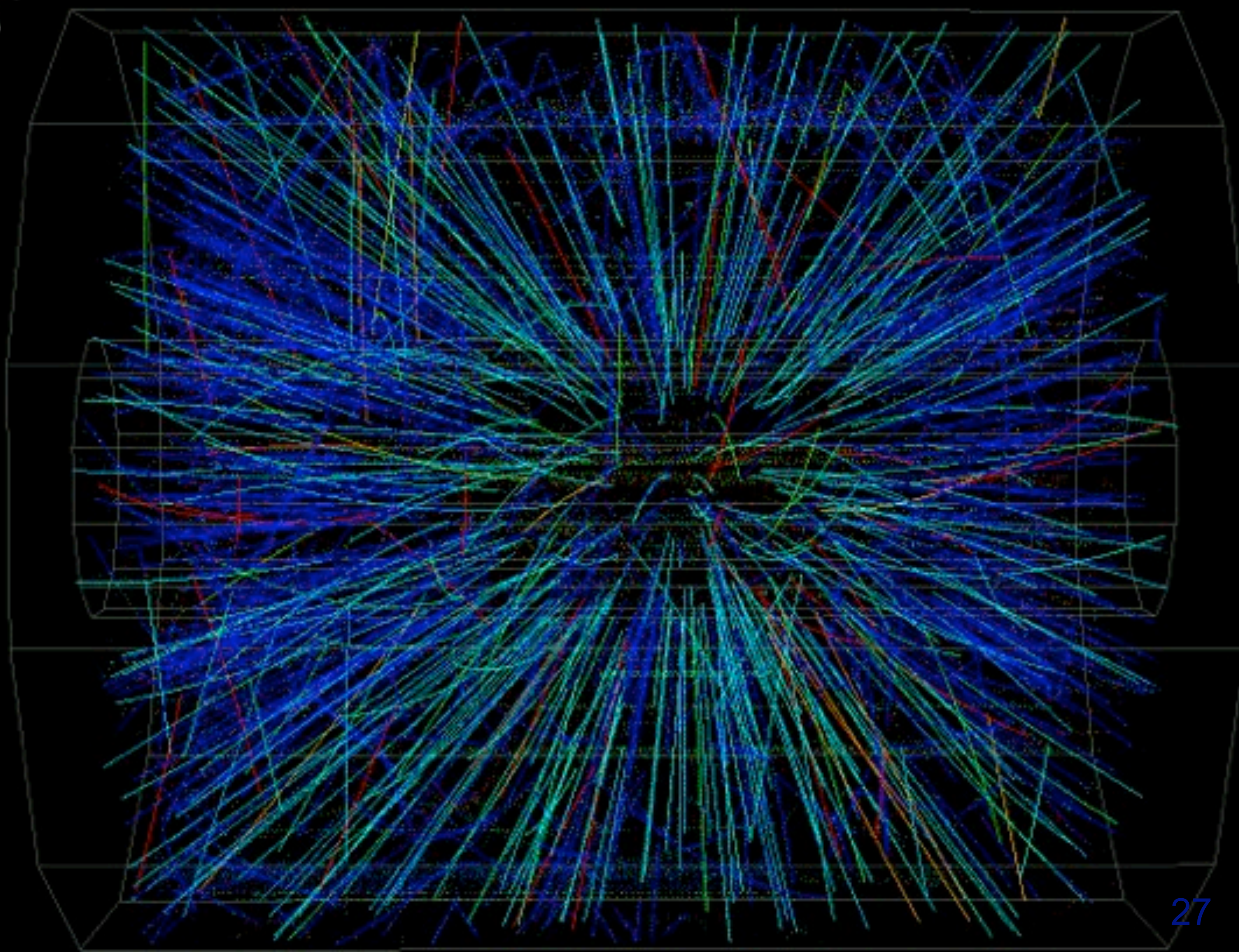
Onto heavy-ion collisions...



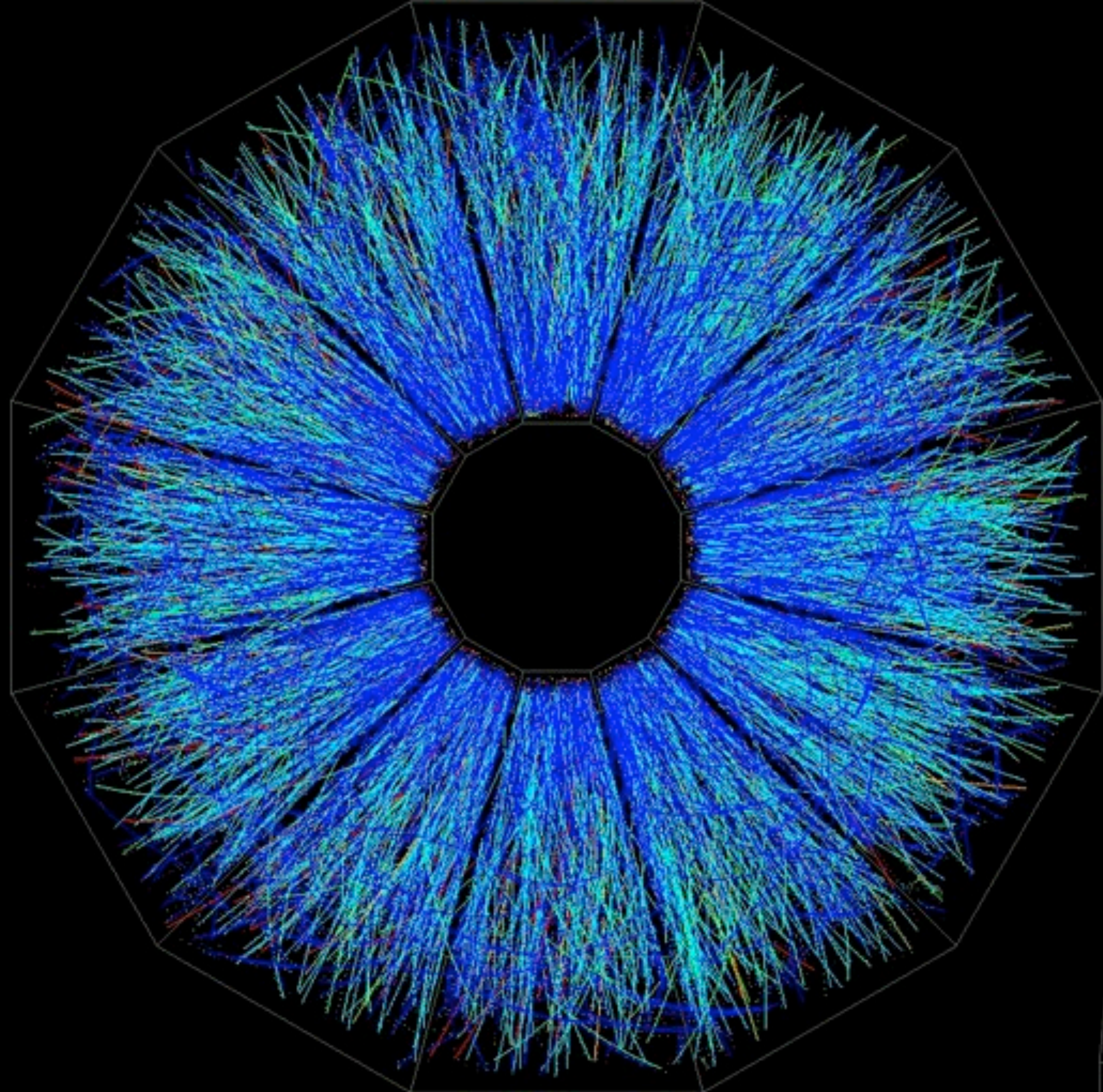
only charged particles visible

Peripheral Collision



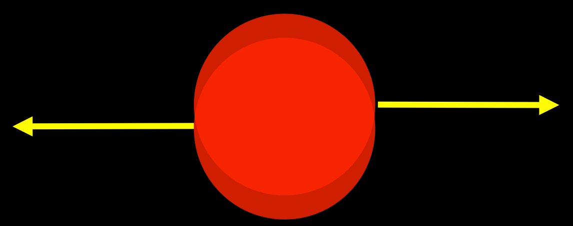


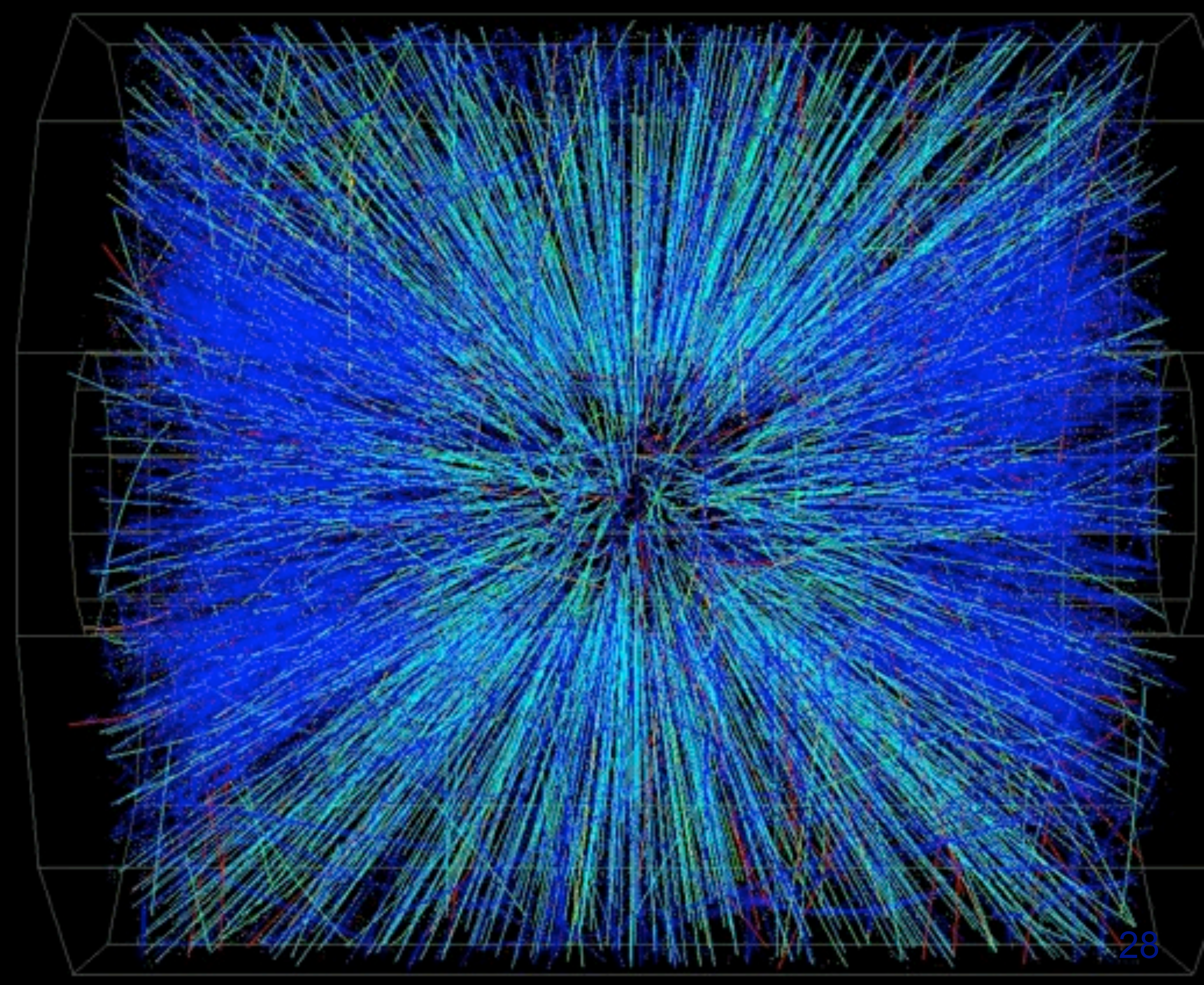
Color ⇒ Energy loss in TPC gas



only charged particles visible

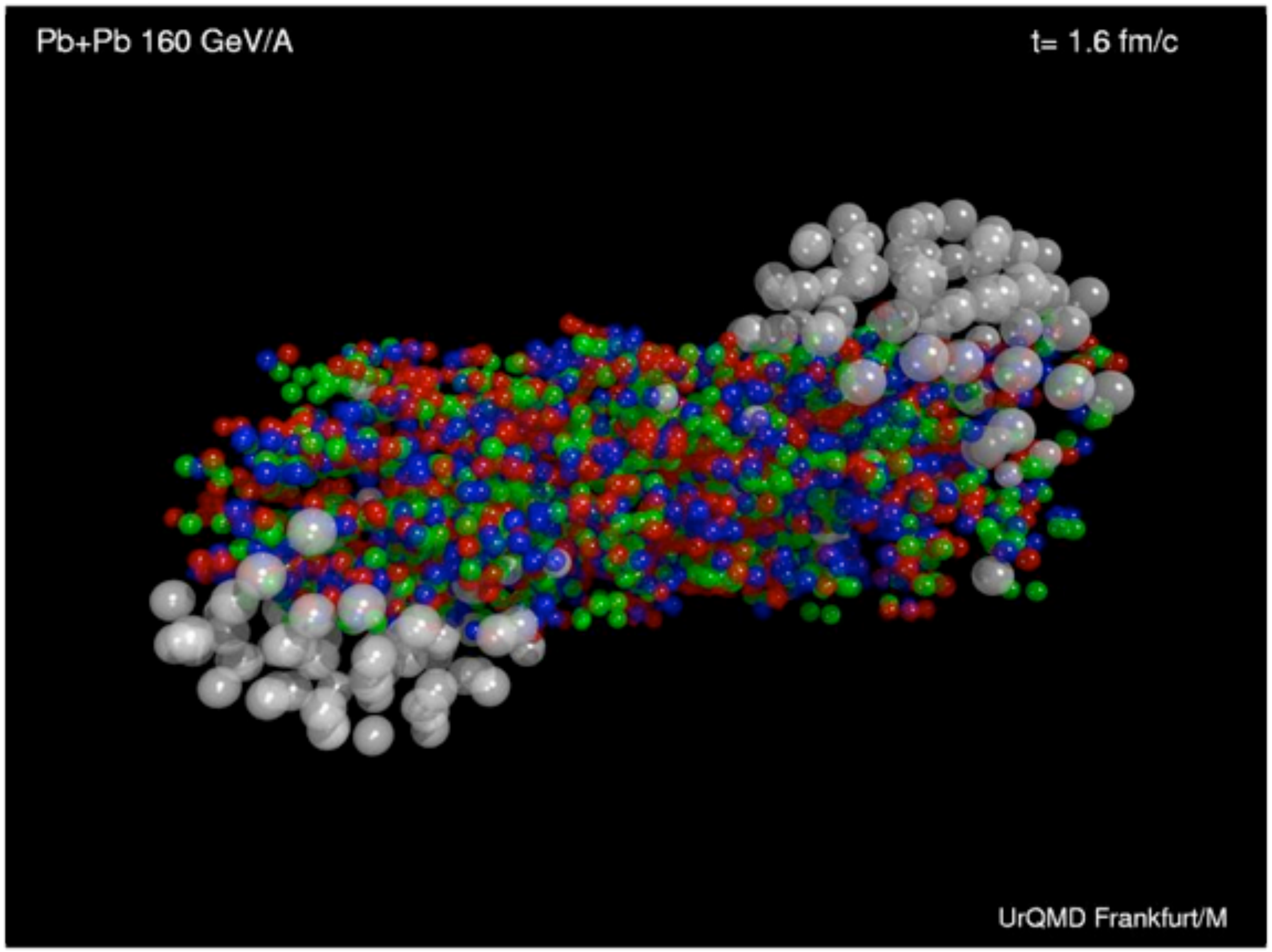
Central Collision





200 GeV Au+Au: $\mathbf{N_{ch} \sim 4800}$

Glauber model - a description of heavy-ion collisions



central collisions:

small impact parameter b

- high number of participants
- high energy density
- large volume

-> large number of produced particles

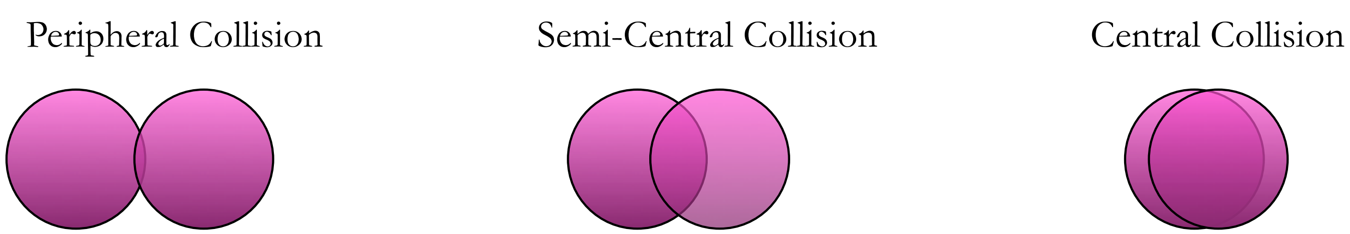
peripheral collisions:

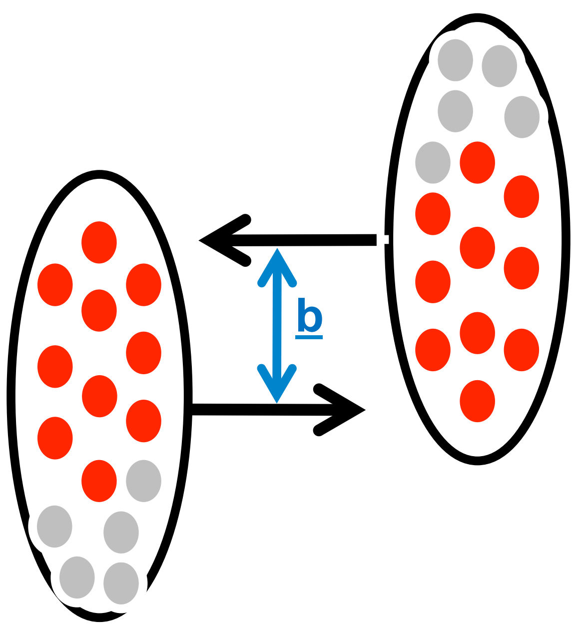
large impact parameter b

- low number of participants

-> low multiplicity

Glauber model - a description of heavy-ion collisions





Spectators

Participants
aka wounded nucleons

Impact parameter b is measured as:
- Fraction of cross section "centrality"
- Number of participants
- Number of nucleon-nucleon collisions

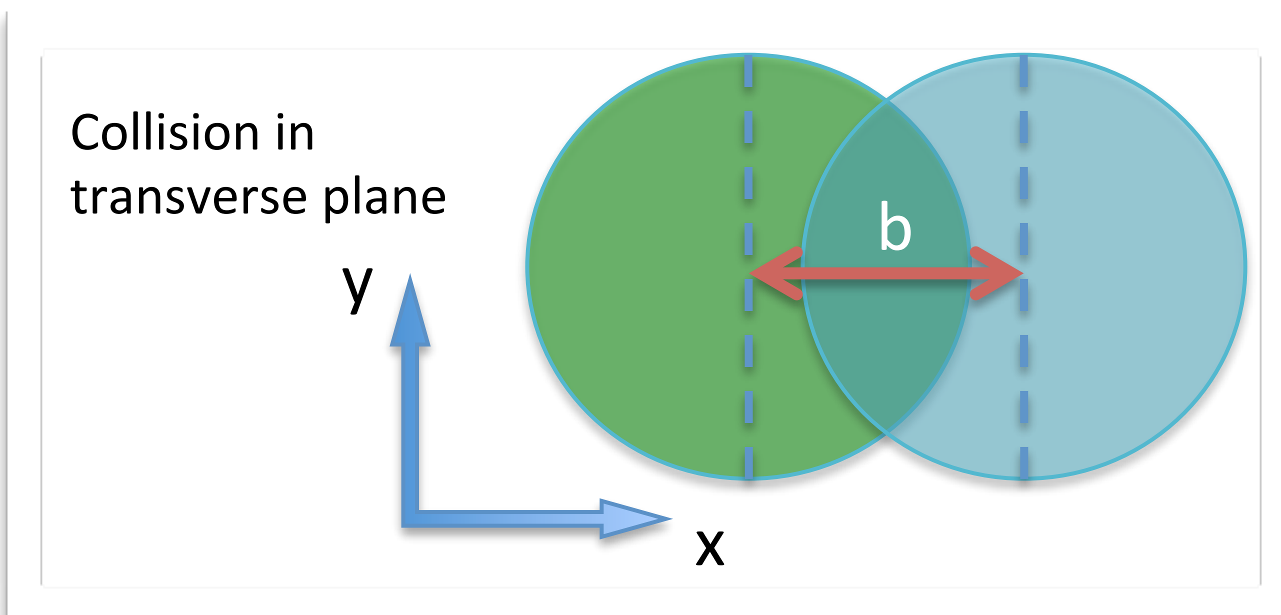
central collisions:
small impact parameter b
- high number of participants
- high energy density
- large volume
-> large number of produced particles

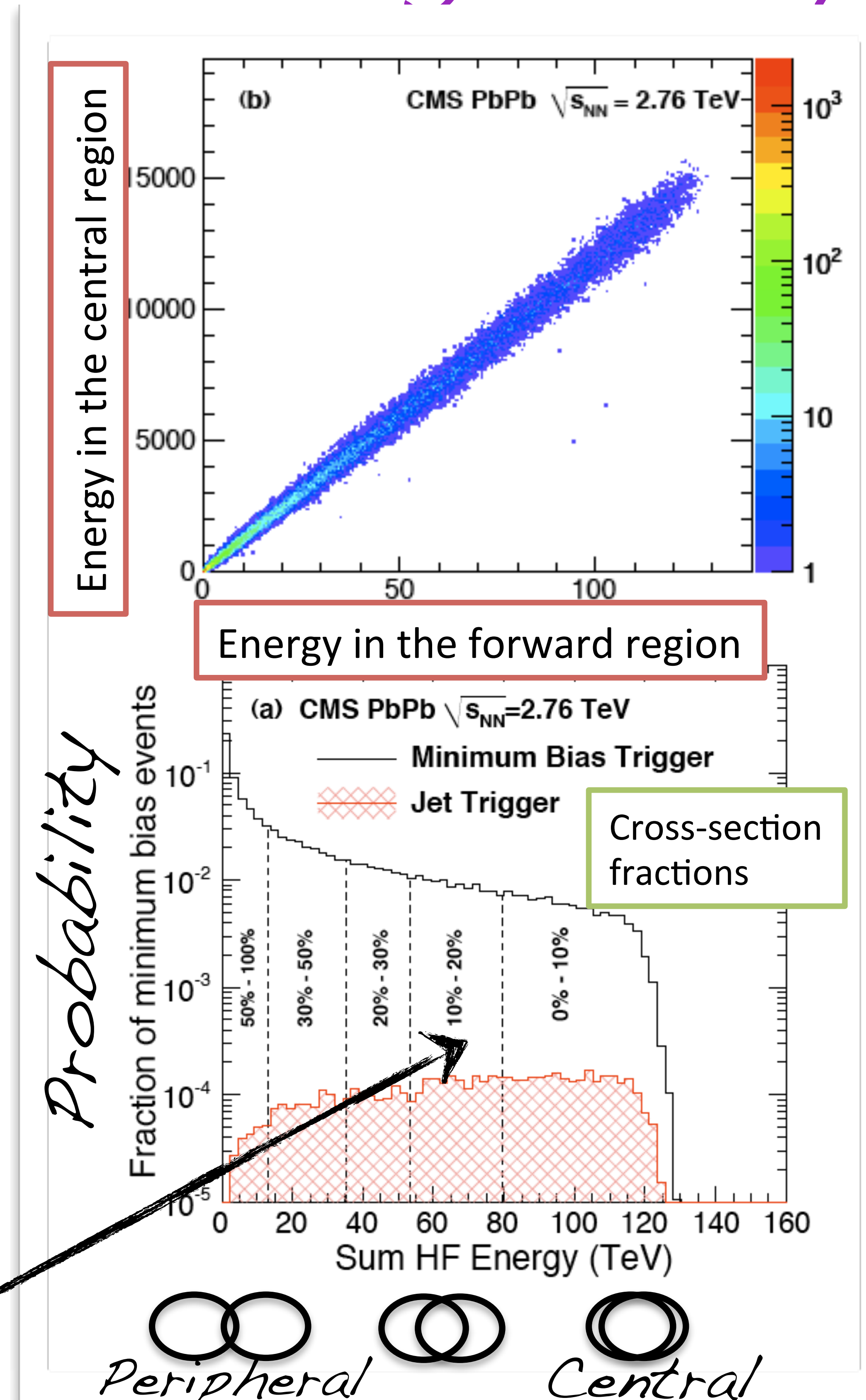
peripheral collisions:
large impact parameter b
- low number of participants
-> low multiplicity

Experimental control of collision geometry

How can we measure impact parameter in heavy-ion collisions?

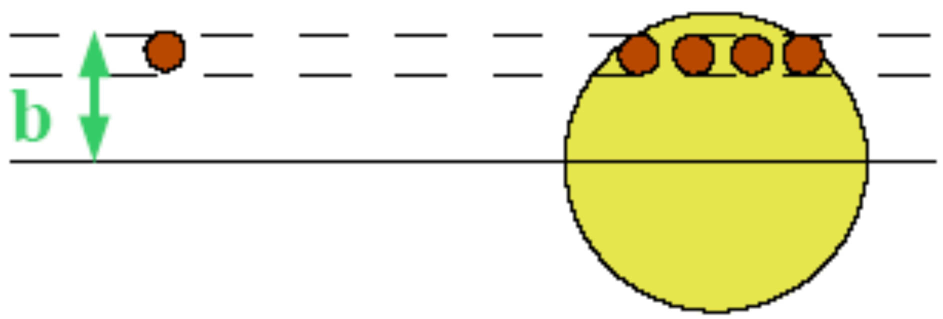
=> Correlate observables connected only by geometry





Characterize events via percentile (fraction) of inelastic cross section (jargon: "N% most central")

Nuclear geometry - Glauber model and hard (high-Q^2) processes



Normalized nuclear density r(*b*,*z*):

$$\int dz\, db\, \rho(b,z) = 1$$

Nuclear thickness function

$$T_A(b) = \int_{-\infty}^{\infty} dz\, \rho(b,z)$$

Inelastic cross section for p+A:

$$\sigma_{pA}^{inel} = \int d\vec{b} \left(1 - \left[1 - T_A(b)\sigma_{NN}^{inel}\right]^A\right)$$

Glauber scaling: hard processes with large momentum transfer

- short coherence length ⇒ successive NN collisions independent
- p+A is incoherent superposition of N+N collisions

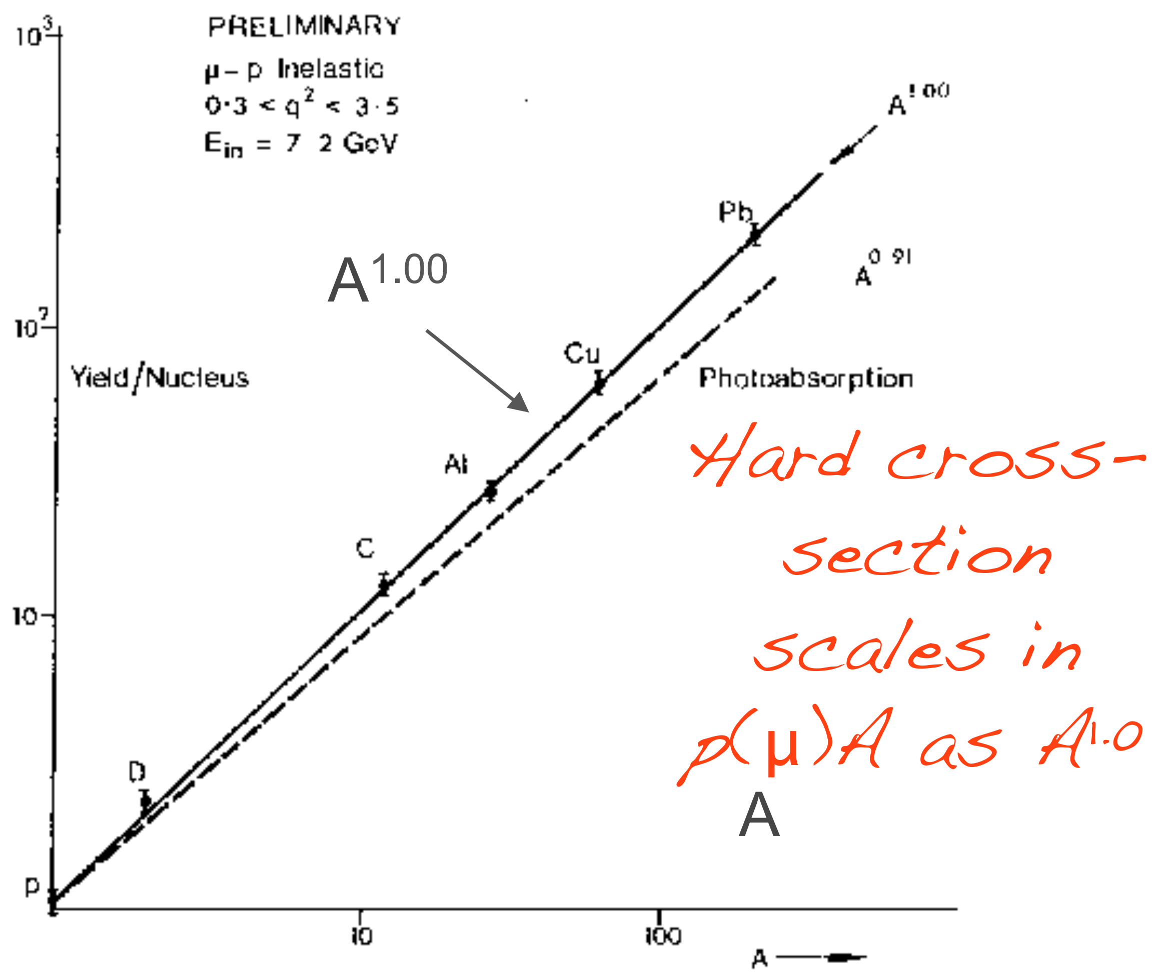
$$\sigma_{pA}^{hard} \approx A\sigma_{NN}^{hard} \int d\vec{b}\, T_A(\vec{b}) = A\sigma_{NN}^{hard}$$

Glauber scaling of hard processes

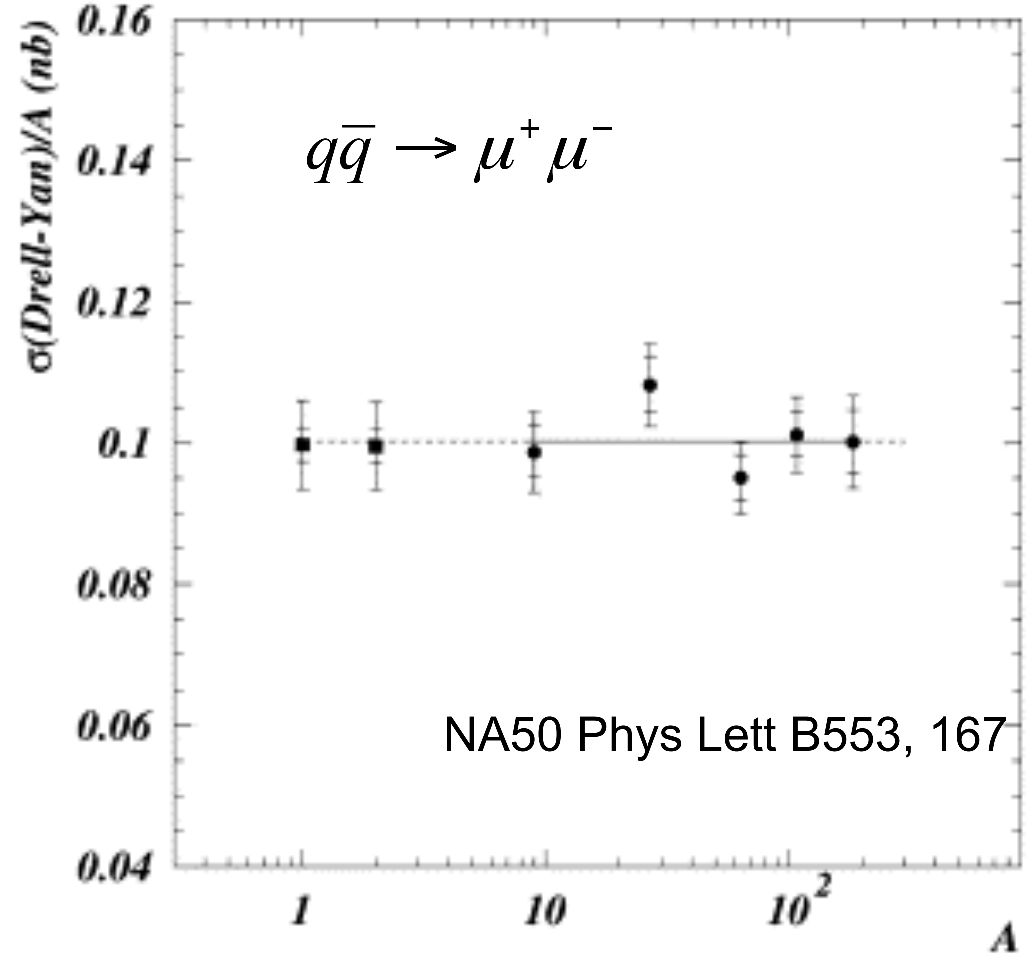
Glauber scaling: $\sigma_{pA}^{hard} = A\sigma_{NN}^{hard}$

σ_{inel} for 7 GeV muons on nuclei

M.May et al, Phys Rev Lett 35, 407 (1975)



$\sigma_{Drell\text{-}Yan}/A$ in p+A at SPS



Experimental control in heavy-ion collisions?

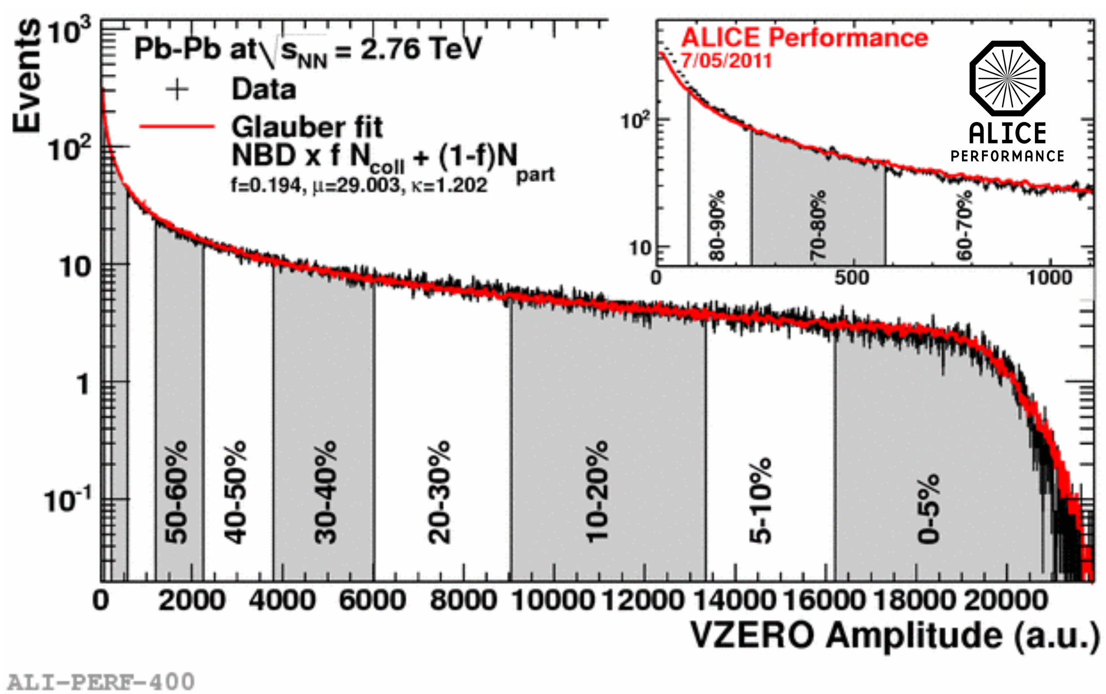
=> direct photons, Z's, measure pA collisions (discussed later...)

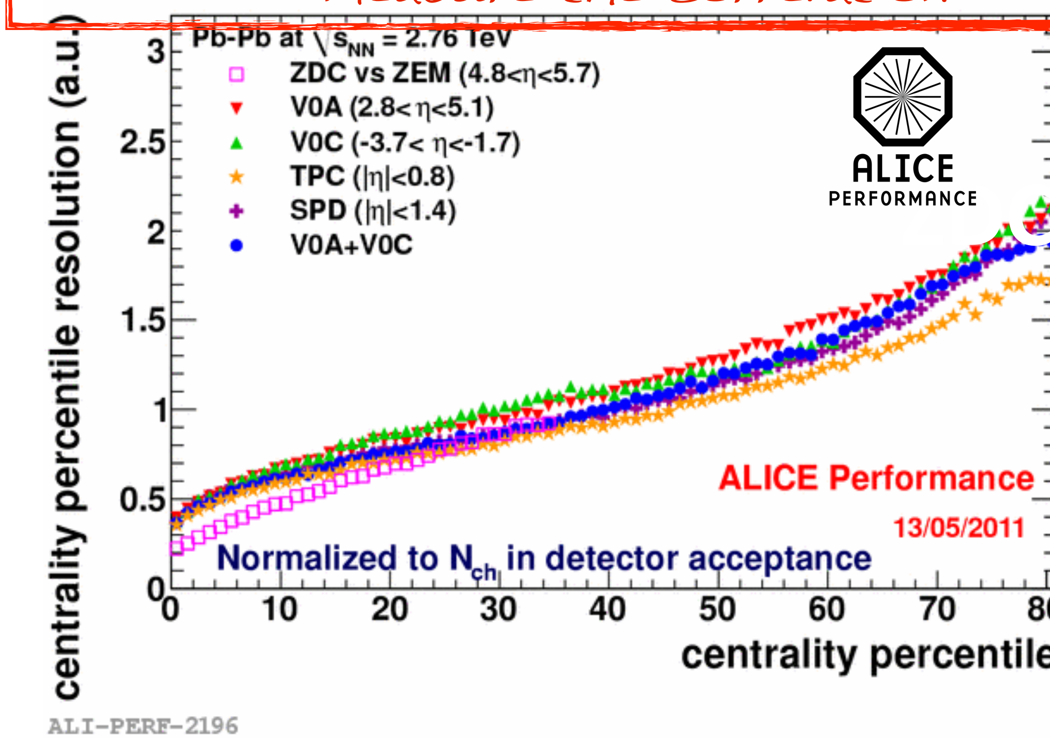
Centrality measurement: use of the Glauber model in an experiment

- Fraction of cross section, 2 approaches:
  - Fit with Glauber Monte Carlo
  - Correct: subtract BG, efficiency and integrate multiplicity distributions
- N_{part}, N_{coll}, N_{spect}: require Glauber fit (computed using cuts on impact parameter)
- Estimators:

  V0, SPD clusters, TPC tracks, ZDCs, …
- ZDC measures N_{spect}: test of Glauber picture

- Glauber fit ingredients
  - Woods-Saxon (constrained by low energy electron-nucleus scattering)
  - Inelastic pp cross section (measured by ALICE)
  - Nucleons follow straight line trajectories, interact based on their distance
  - Compute (fit) observables assuming:
    $$N_{ancestors} = \alpha \cdot N_{part} + (1-\alpha) \cdot N_{coll}$$
    Several detectors
    – measure the correlation





Energy density in AA collisions - RHIC example

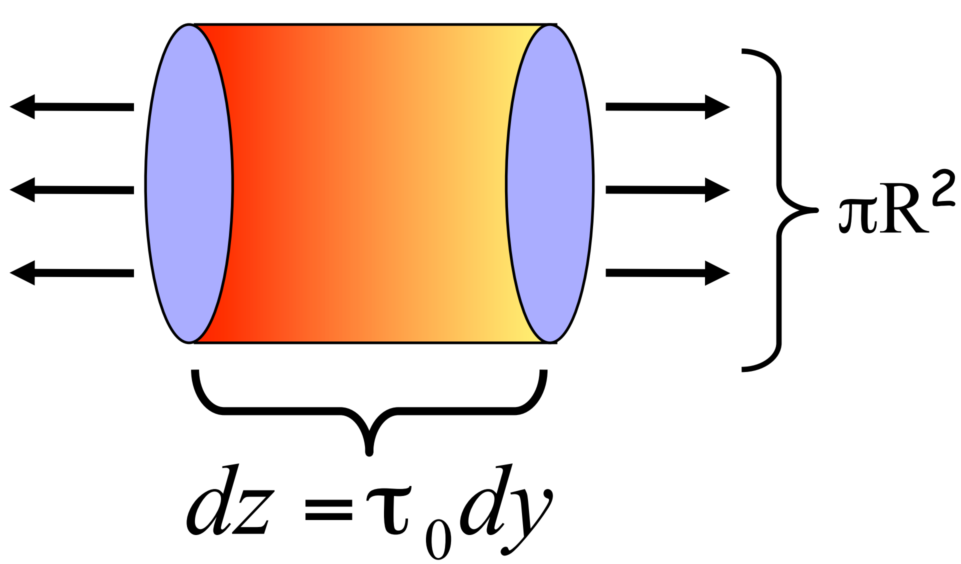
- (calorimeters) measure energy
- estimate volume of collision

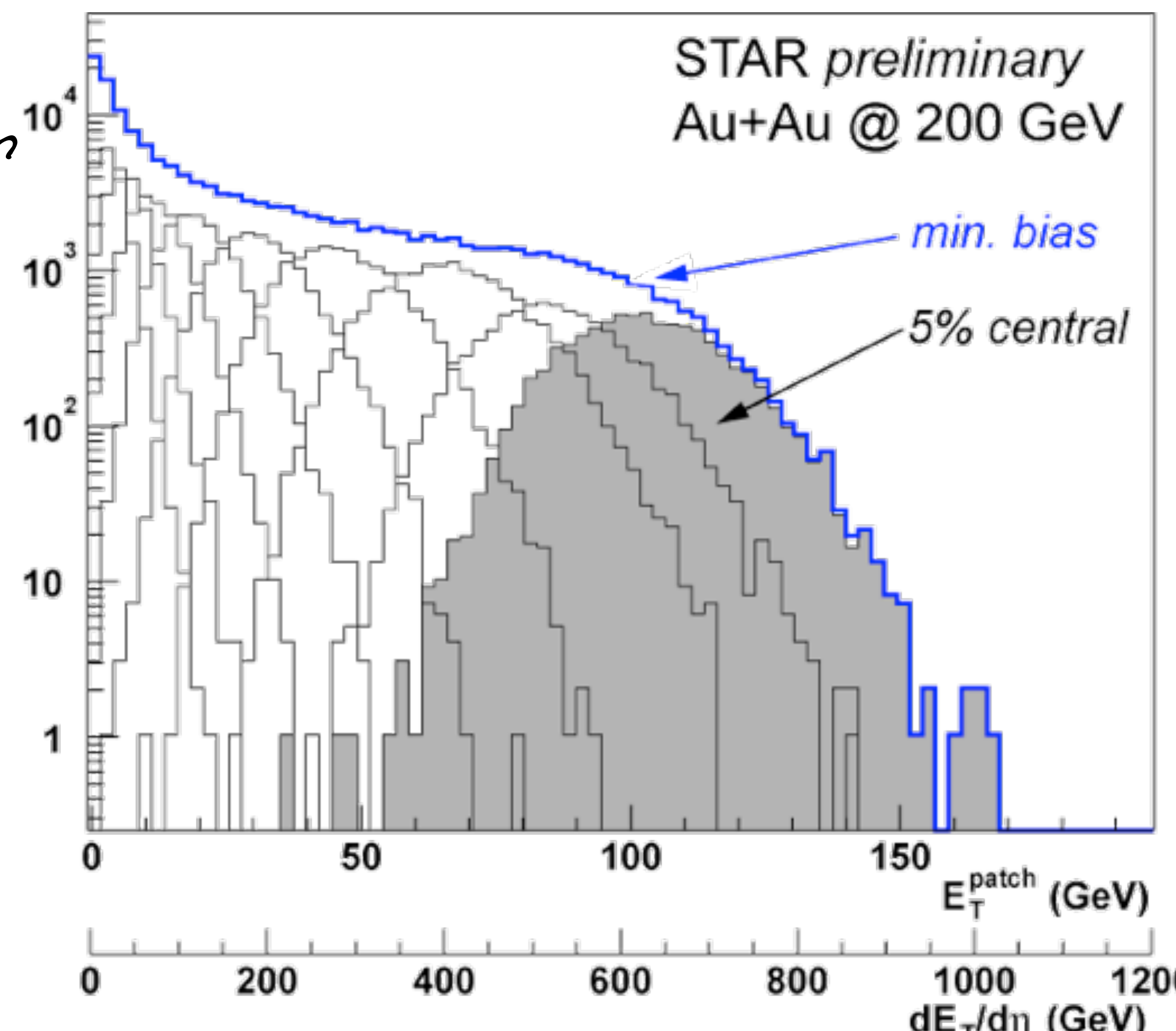
Bjorken energy density:

$$\varepsilon_{Bj} = \frac{\Delta E_T}{\Delta V} = \frac{1}{\pi R^2} \frac{1}{\tau_0} \frac{dE_T}{dy}$$

R~6.5 fm

Time it takes to thermalize system (t_0 ~ 1 fm/c)





RHIC:

$\varepsilon_{BJ} \approx 5.0$ GeV/fm³

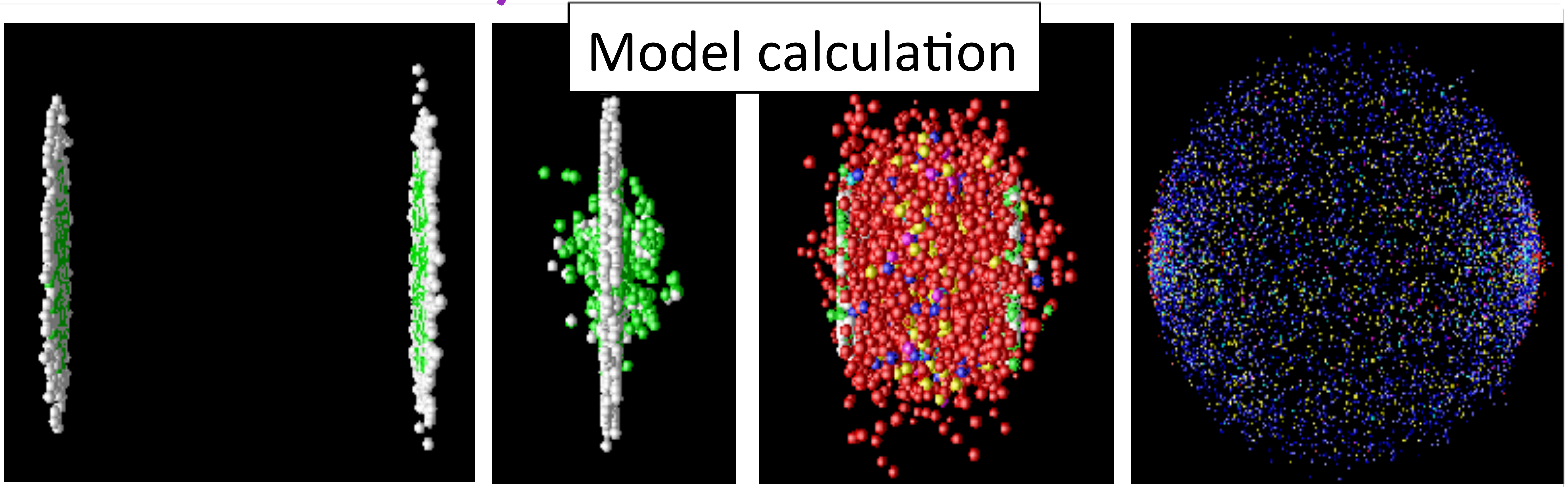
~30 times normal nuclear density

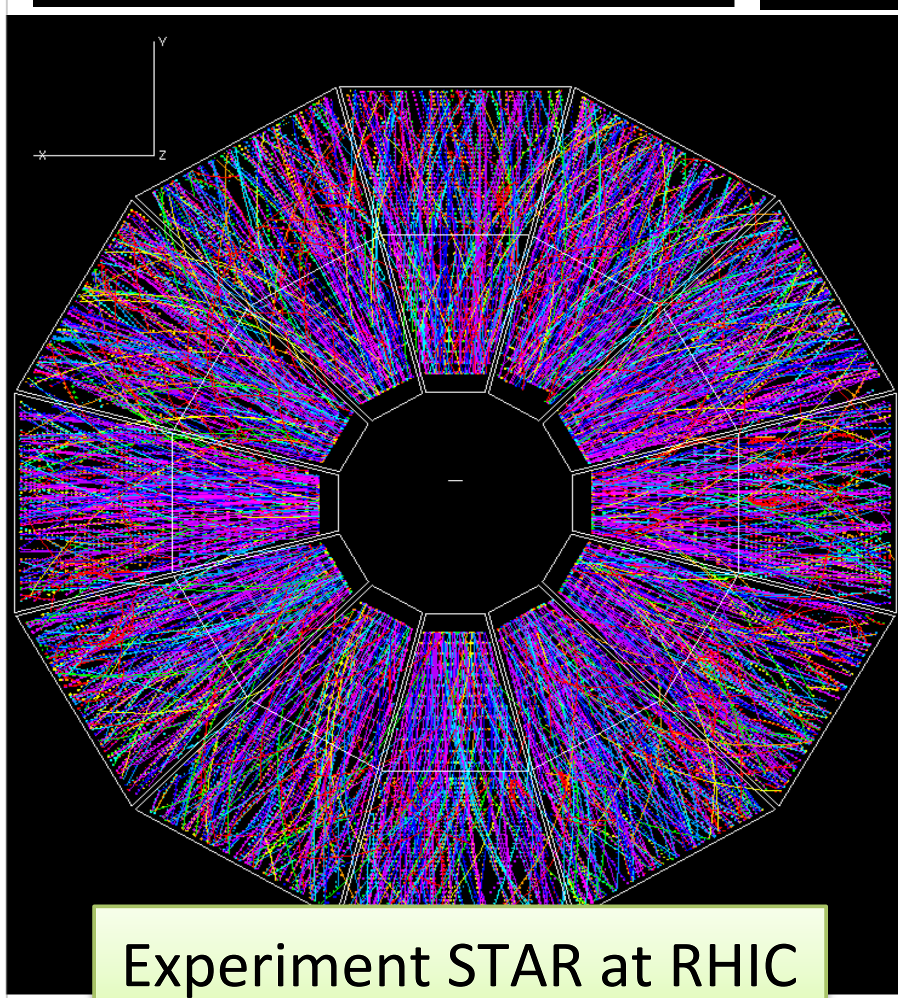
~ 5 times > $\varepsilon_{critical}$ (lattice QCD)

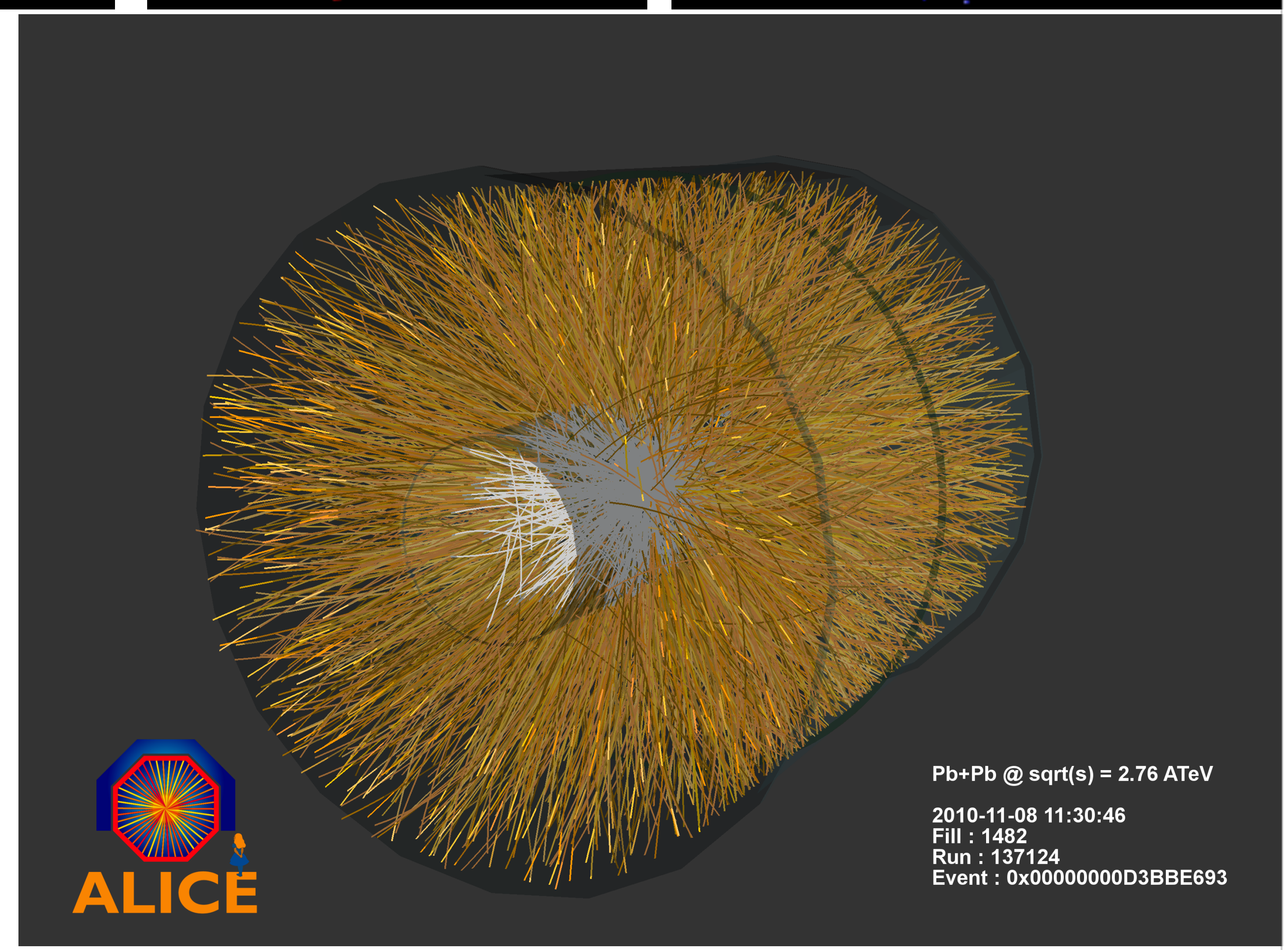
Will see later: LHC ~ 3 x RHIC

First: "control" understanding
- before measurements...

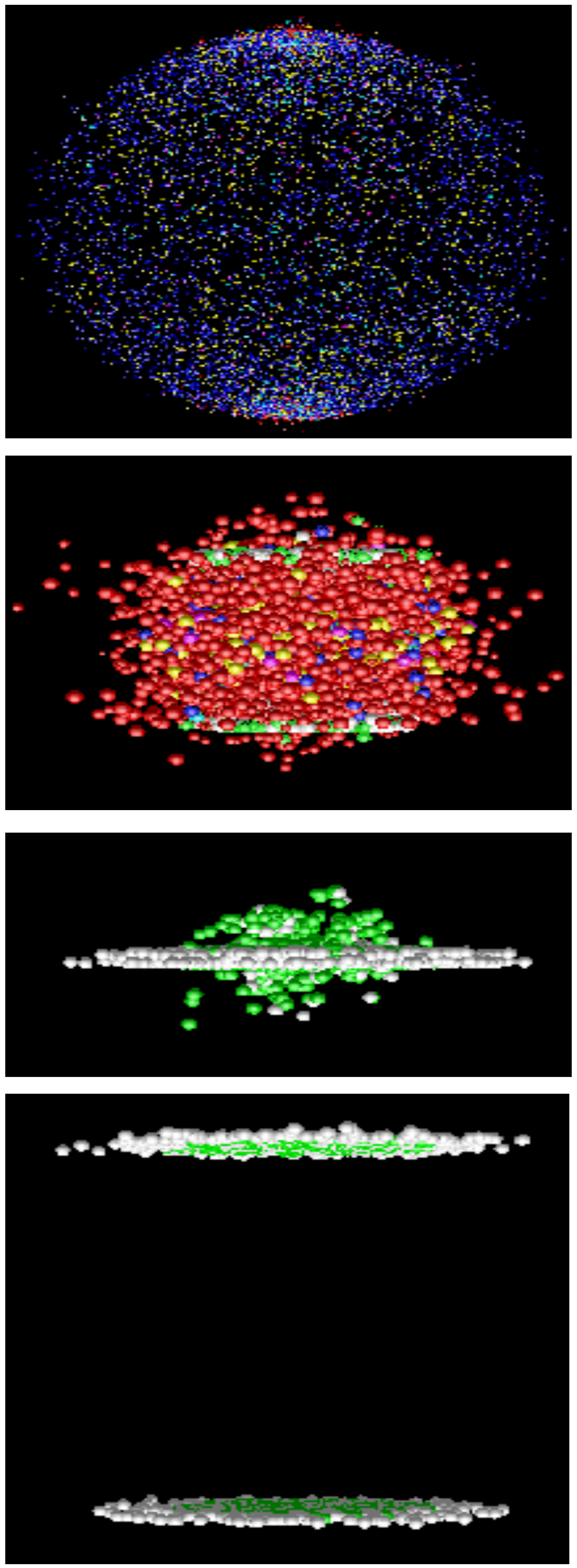
Heavy-ion collisions

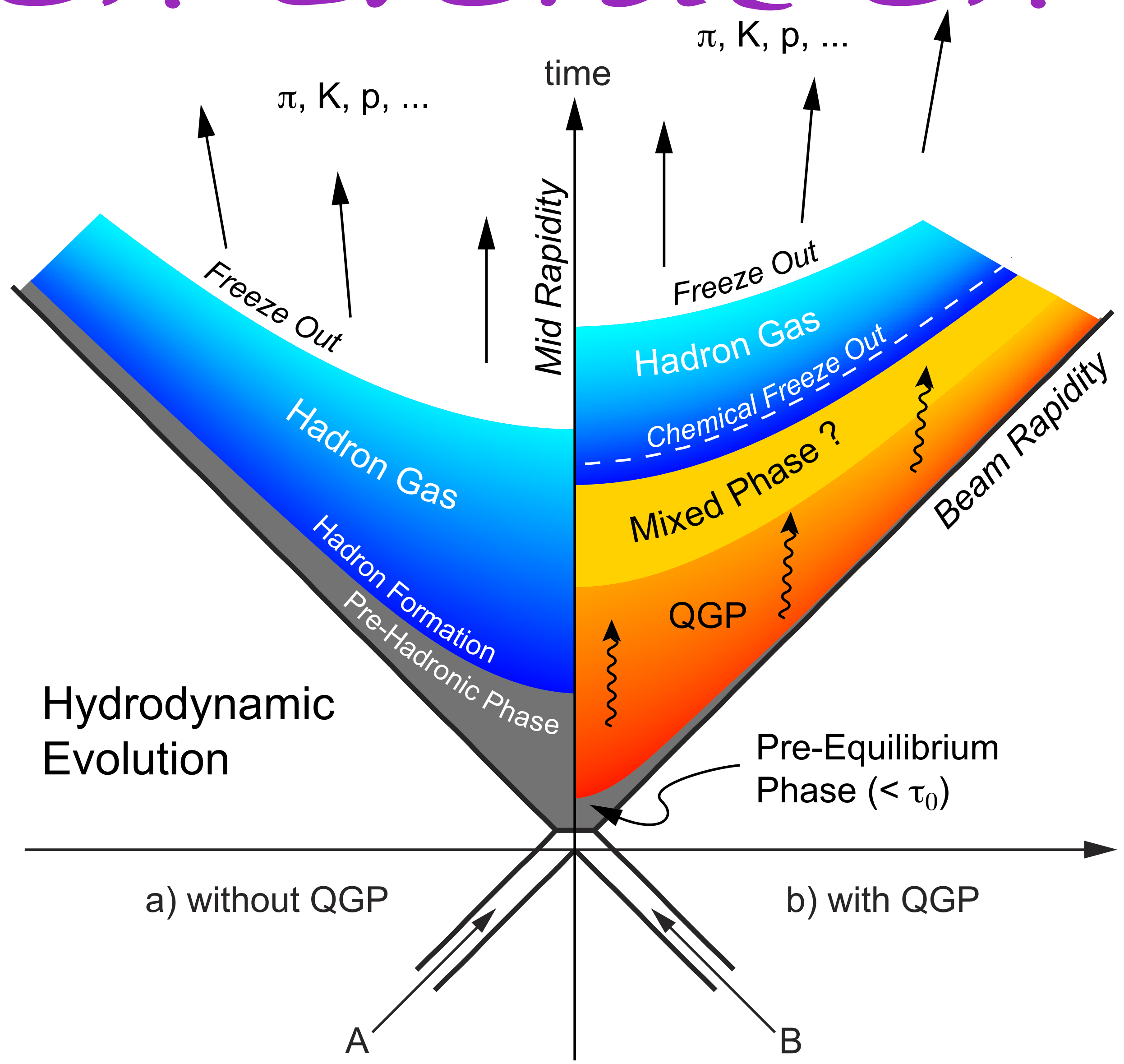






Collision evolution





Note: hard scatterings occur early (at t~0)!
High energy partons "witness" the evolution
and jets "testify" about their fate/CV

Two key things to follow-up: Chemical freeze-out
Kinetic freeze-out

Thermal equilibrium... Chemical and kinetic freeze-out

Chemical equilibrium:

- correct relative particle abundances?
- large system -> Grand Canonical ensemble: many particles; conservation laws on average - chemical potentials
- small system -> conservation laws E-by-E -> "canonical suppression" (strangeness)

$$n_i^0 = \frac{g_i}{2\pi^2}\int \frac{p^2 dp}{e^{\left(E-\mu_B B_i - \mu_s S_i - \mu_3 I^3\right)/T} \pm 1}$$

The ratios of produced particle yields between various species can be fitted to determine T, μ.

Kinetic equilibrium - radial flow:

- for any interacting system of particles expanding into vacuum, radial flow is a natural consequence.

During the cascade process, an ordering of particles with the highest common underlying velocity at the outer edge develops naturally

Hadrons are released in the final stage and therefore measure "FREEZE-OUT" Temp. - instructive simple parametrization - radially boosted source with velocity β and at y=0:

$$\frac{d^3N}{dp^3} \propto e^{-E/T}; E\frac{d^3N}{dp^3} = \frac{d^3N}{m_T dm_T d\phi dy} \propto Ee^{-E/T} = m_T \cosh(y) e^{-m_T\cosh(y)/T}$$

$$\frac{1}{m_T}\frac{dN}{dm_T} \propto m_T I_0\left(\frac{p_T\sinh(\rho)}{T}\right)K_1\left(\frac{m_T\cosh(\rho)}{T}\right)$$

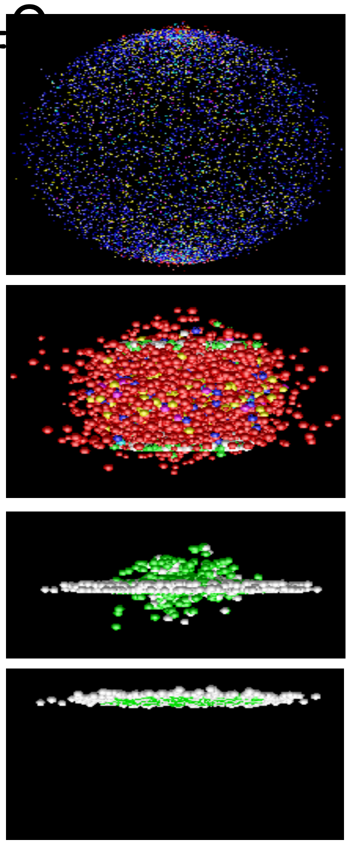
$$\rho = \tanh^{-1}\left(\beta_{boost}\right)$$

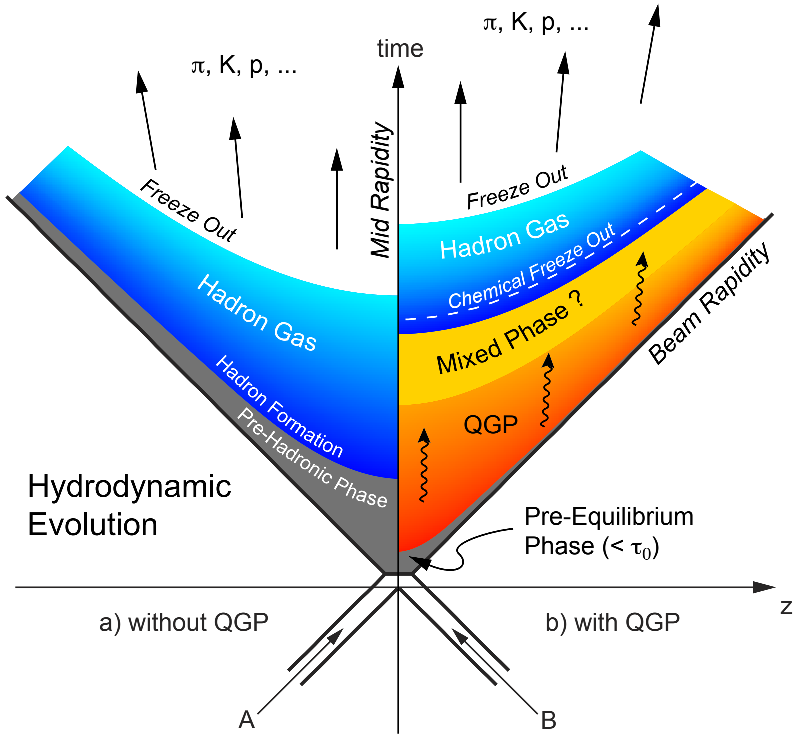
Simple assumption: uniform sphere of radius R and boost velocity varies linearly w/ r:

$$\frac{1}{m_T}\frac{dN}{dm_T} \propto \int_0^R r^2 dr\, m_T I_0\left(\frac{p_T\sinh(\rho)}{T}\right)K_1\left(\frac{m_T\cosh(\rho)}{T}\right)$$

$$\rho(r) = \tanh^{-1}\left(\beta_T^{MAX}\frac{r}{R}\right)$$

Blast Wave model => common T and β





Collision evolution

Few notes:

We are interested in properties of QGP (lifetimes ~ few fm/c !)

Need to disentangle effects from different phases

- not a simple problem by principle: detectors do NOT measure these time-periods/phases separately (detector: particles after hadronization!)

=> need for detail understanding of the physics processes, particle production, dynamics of the system in each phase(!), etc

=> modeling, various assumptions may play an important role in physics interpretation

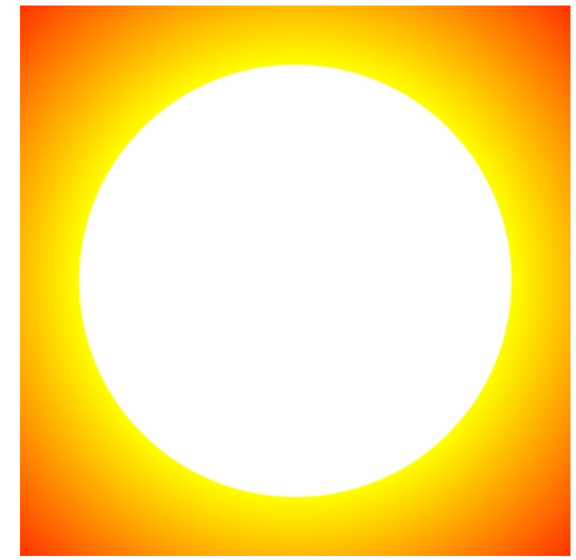
Need for control of the initial conditions, geometry of the collision, the incoming parton distributions (nuclear-PDF vs nucleon-PDF) ...

Measurements...

What is hot and what is not: Thermal radiation from a source

Remote Temperature Sensing

Red Hot



White Hot

- **Hot Objects produce thermal spectrum of EM radiation.**
- **Red clothes are NOT red hot, reflected light is not thermal.**

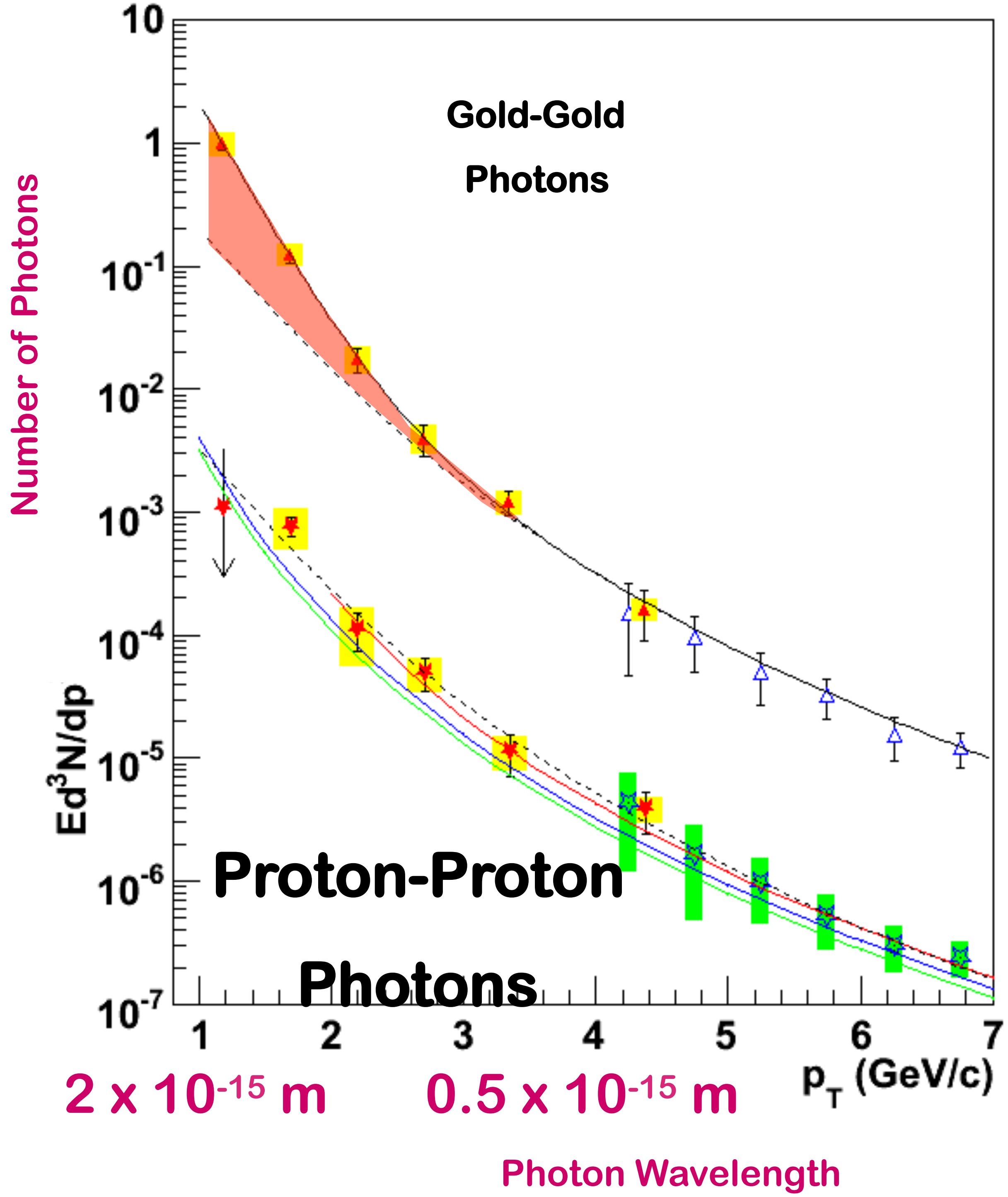
Photon measurements must distinguish thermal radiation from other sources: HADRONS!!!

Not Red Hot!

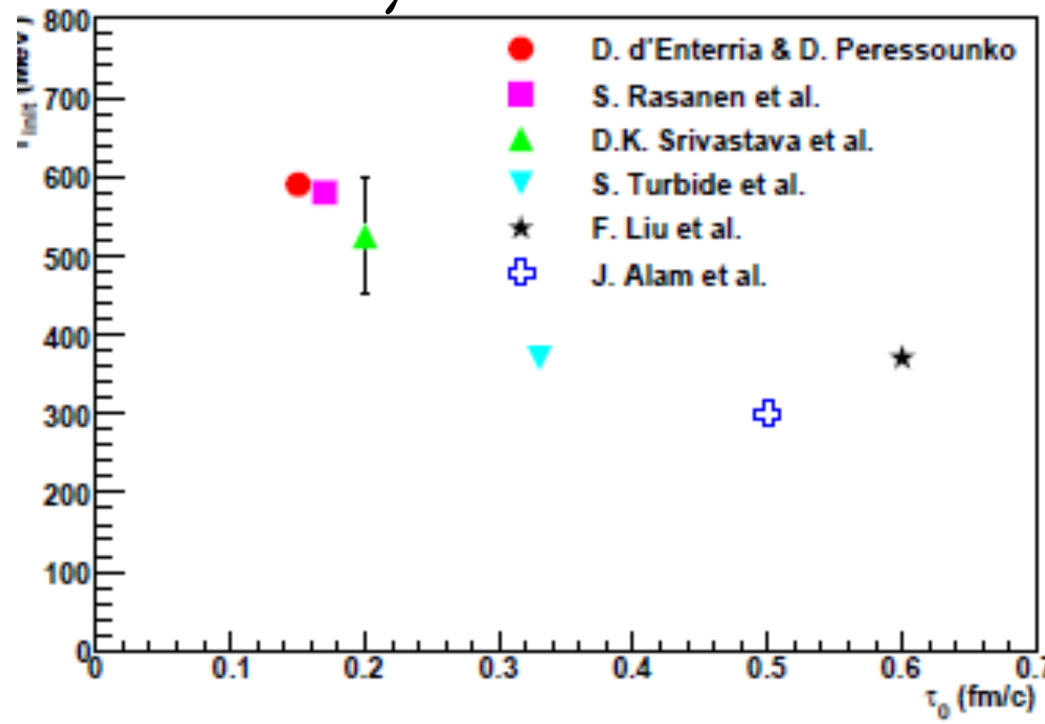
Thomas K Hemmick

Photons - RHIC

T_i = 4-8 trillion Kelvin



Initial Temp.

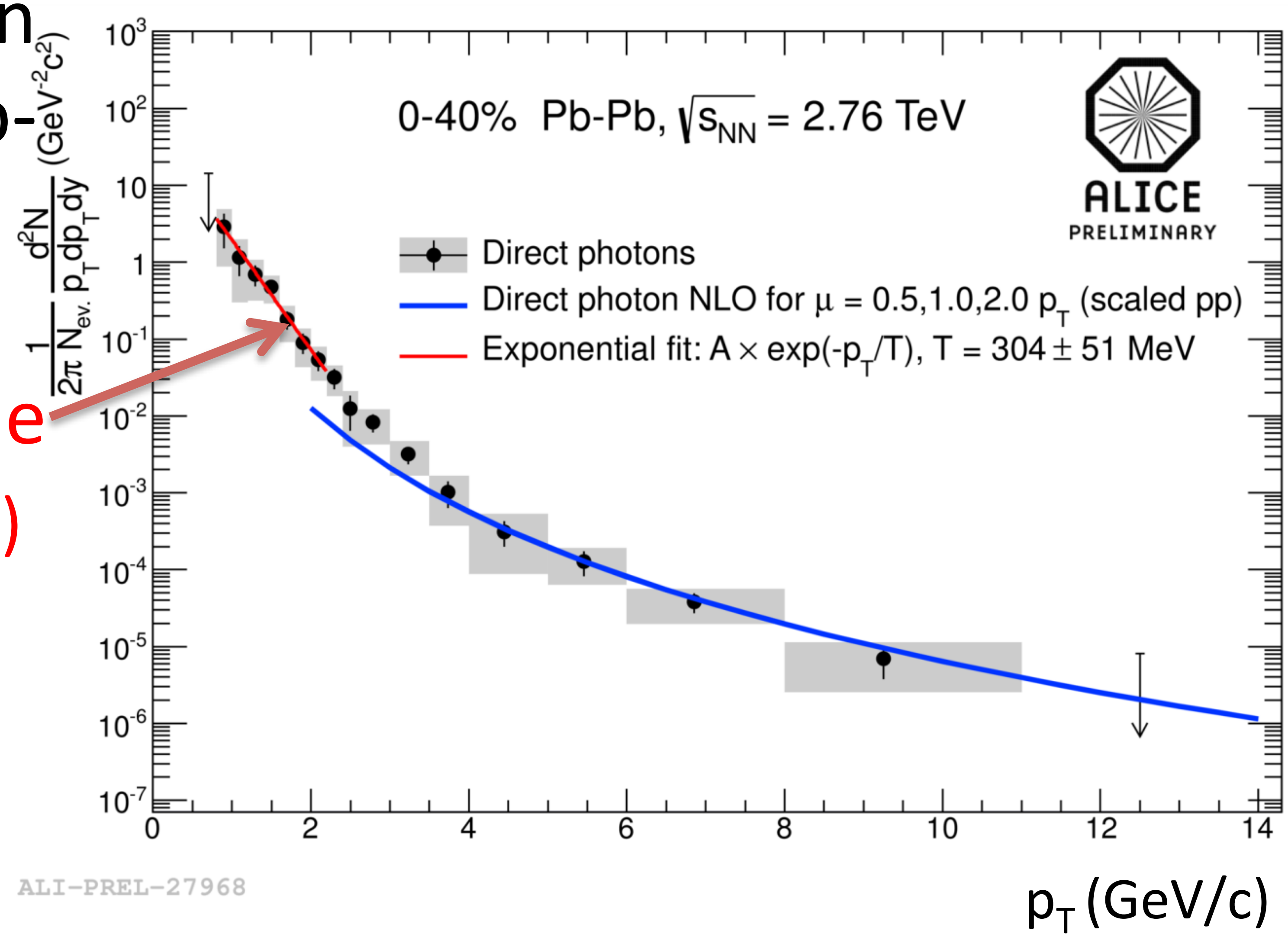


Emission rate and distribution consistent with equilibrated matter

T~300-600 MeV

LHC-QGP Shines bright - thermal photons

Production cross-section of photons in central Pb-Pb collisions



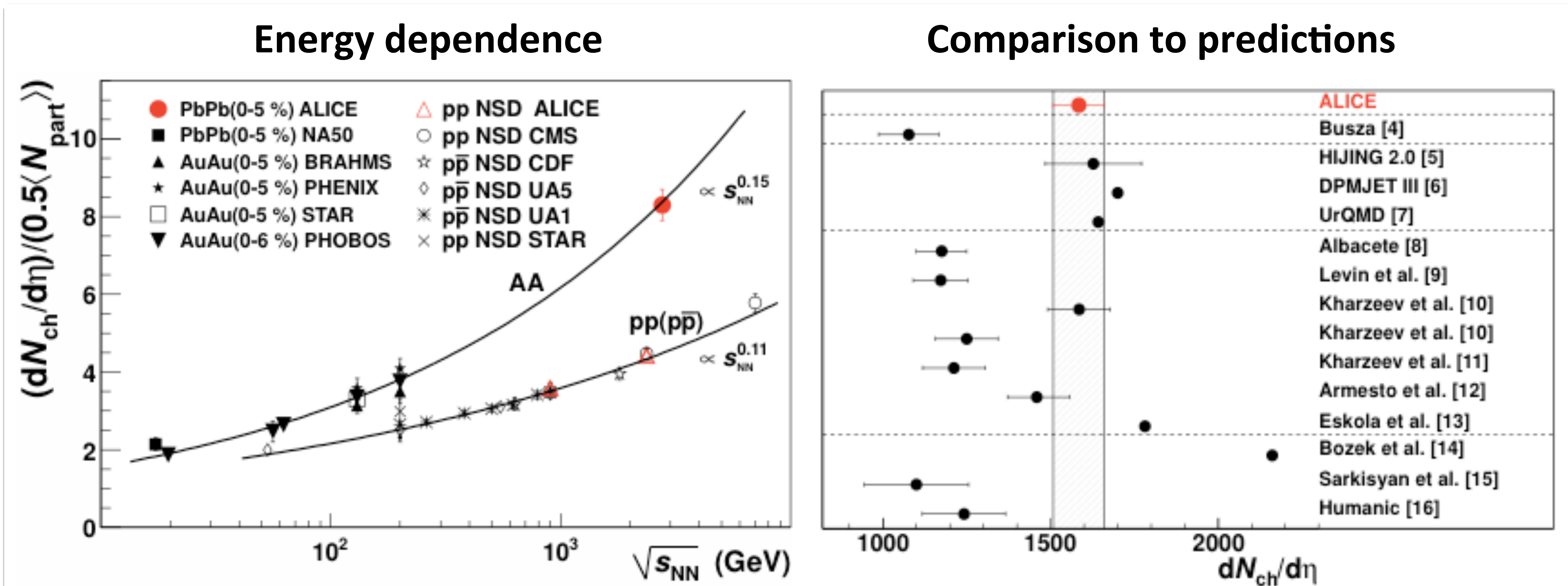
Photons shining from the plasma (thermal emission)

the LHC Quark-Gluon Plasma is the hottest man-made matter

Inverse slope of the exponential fit (p_T<2 GeV/c): 304 +/- 51 MeV

Calibration measurements...

HI collisions: Particle production

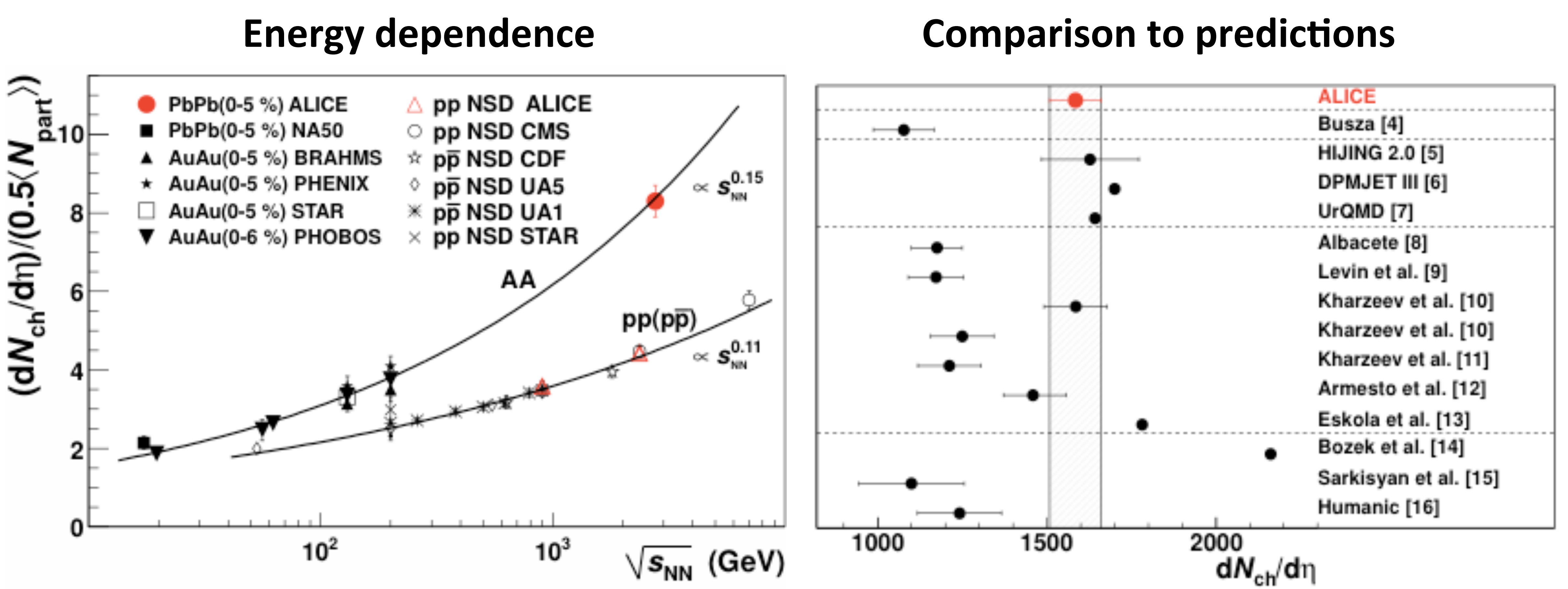


PRL 105, 252301 (2010)

Energy dependence

- p-p ~ $s_{NN}^{0.11}$
- A-A ~ $s_{NN}^{0.15}$ (most central - 2x RHIC)
  - – stronger rise than log extrapolation

HI collisions: Particle production

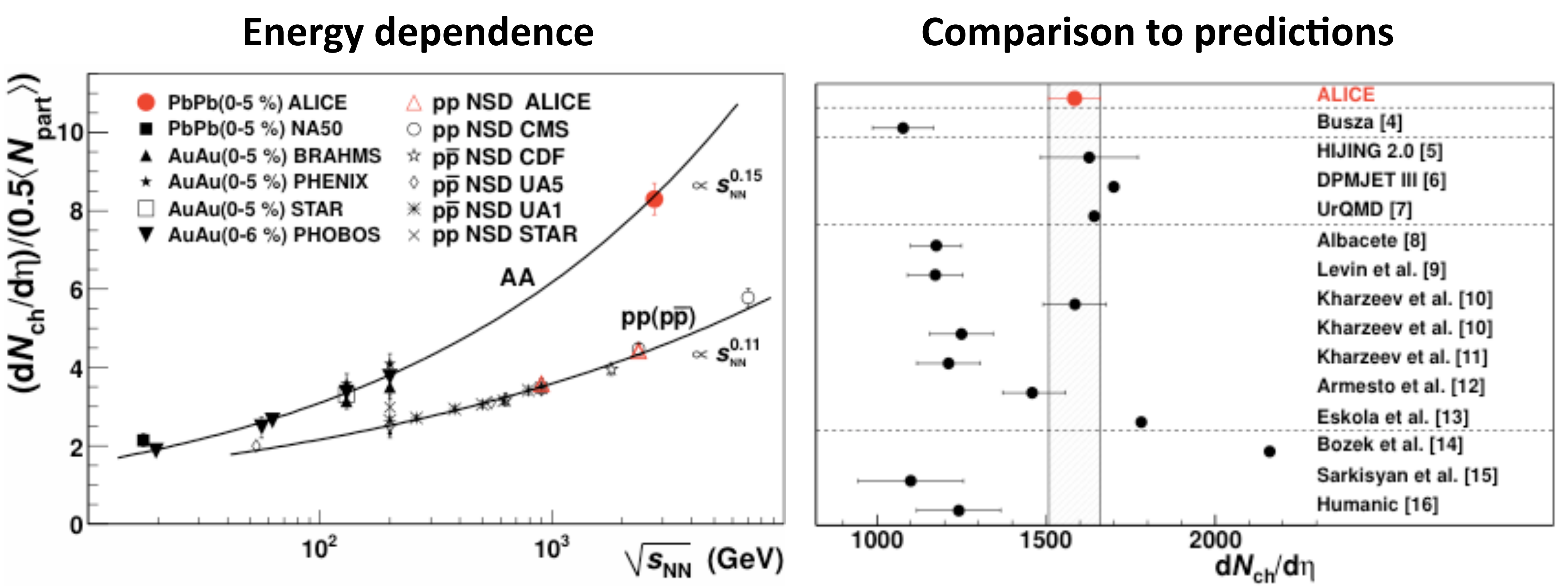


PRL 105, 252301 (2010)

Feedback within the heavy-ion community:

1. **Multiplicity is crucial [input] for modeling**
2. **Saturation models tend to predict lower multiplicity**
3. **Data driven extrapolations did not seem to anticipate the results**

HI collisions: Particle production



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Energy dependence

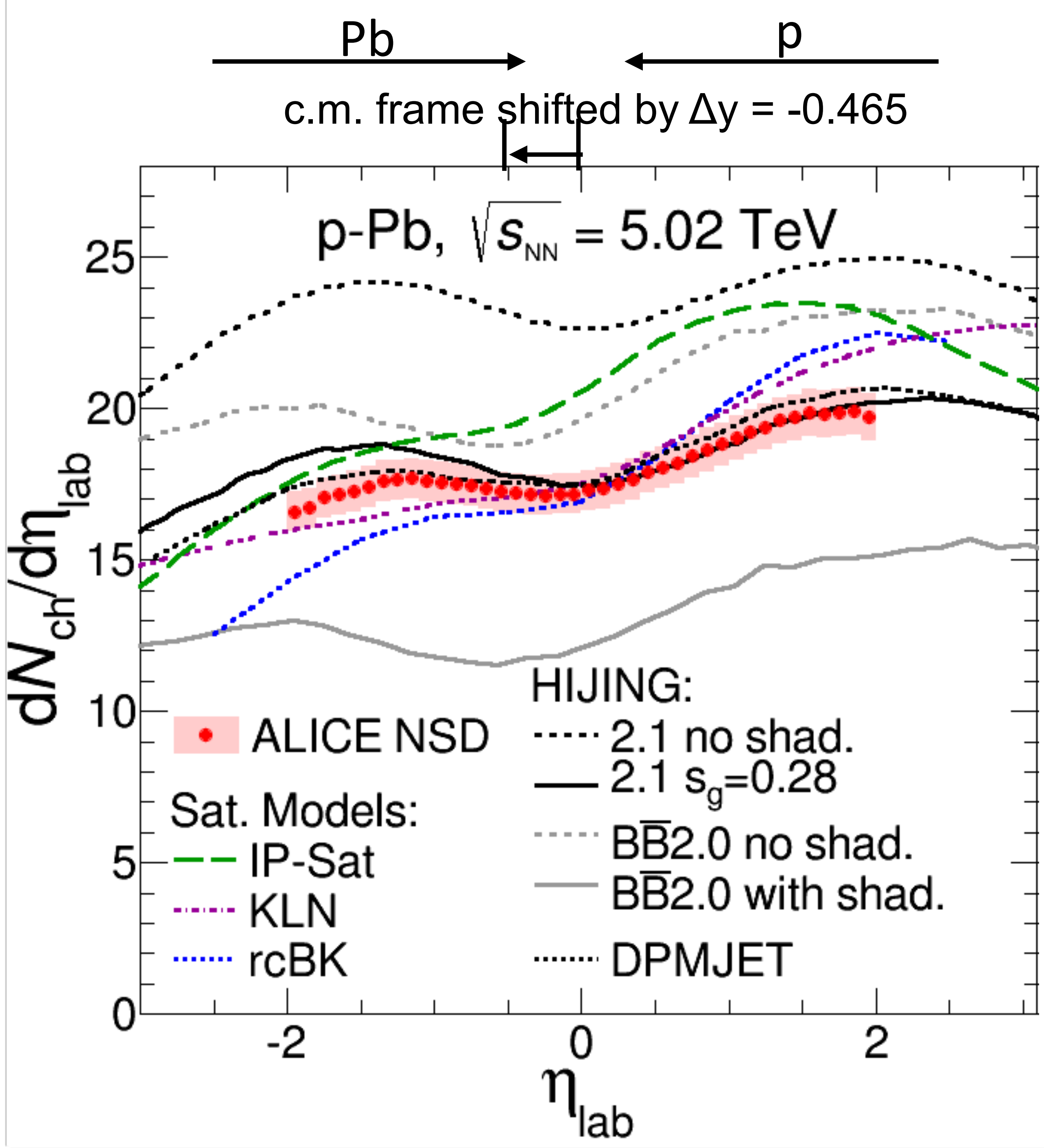
- **p-p ~ $s_{NN}^{0.11}$**
- **A-A ~ $s_{NN}^{0.15}$ (most central - 2x RHIC)**
  - **– stronger rise than log extrapolation**

Calibration: proton-A collisions

p-Pb run ongoing at this very moment!

More during the next lectures...

ALICE: arXiv: 1210.3615



Basic measurement allows to discriminate between models

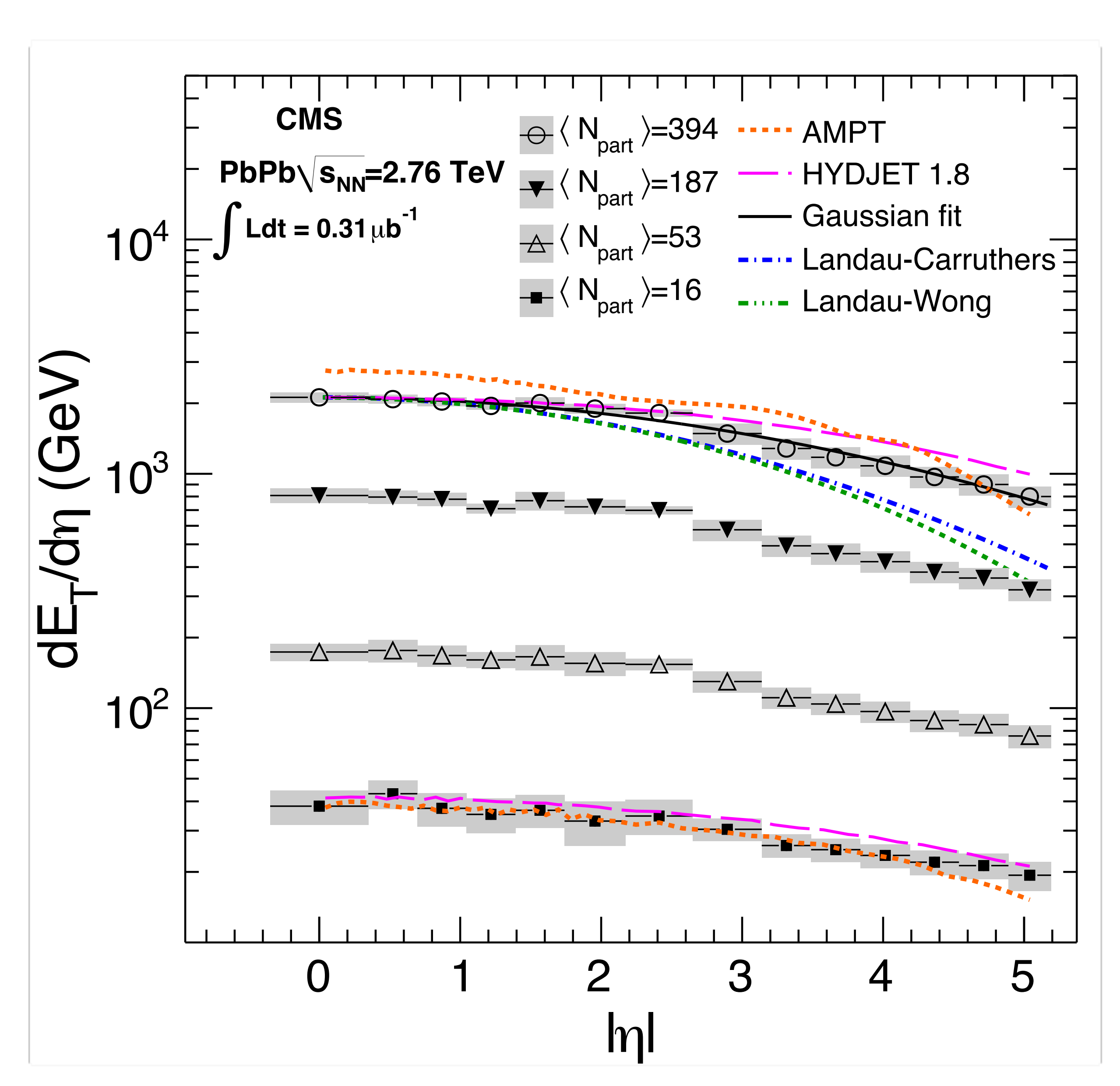
Data favors models that incorporate shadowing

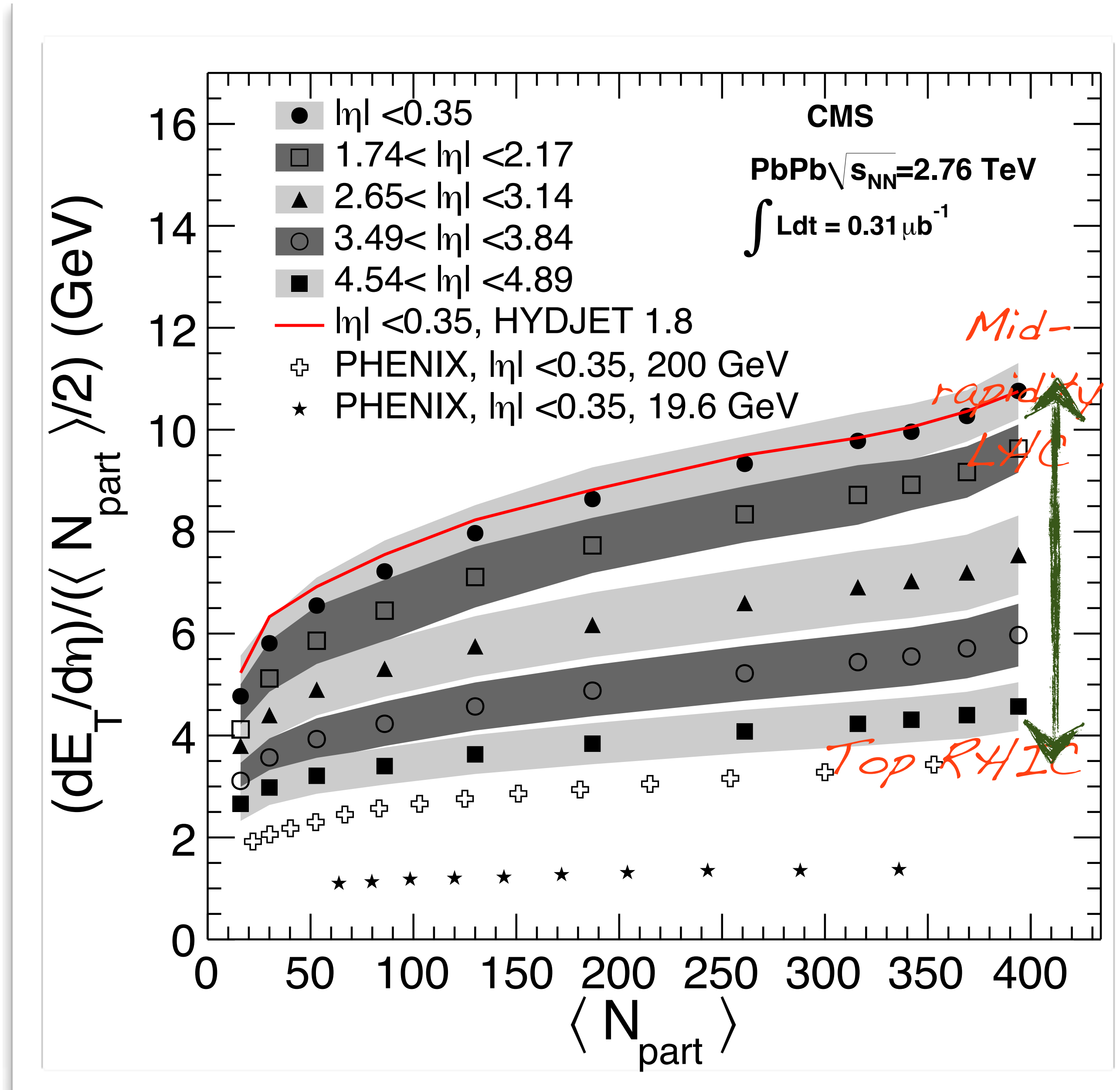
Saturation models predict much steeper η-dependence not seen in the data

Energy density: RHIC to LHC

LHC > 2.5 x RHIC

... within a volume (per nucleon)





Very hot, super dense? -> what are its "transport" properties... fundamental QCD questions

Systematic control: RHIC vs LHC

Centrality dependence of particle production

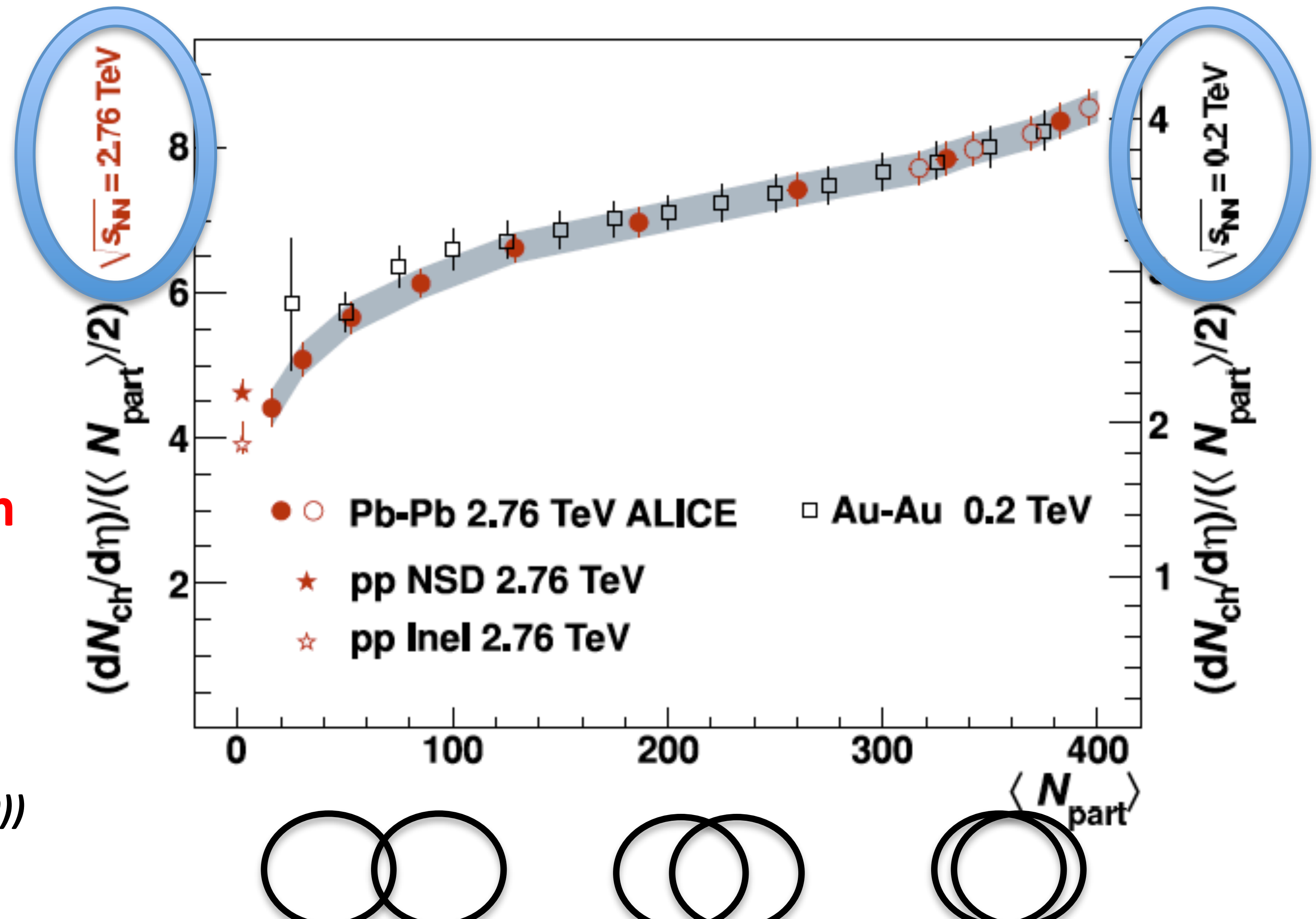
The same experiment under vastly different conditions!

- **Identical variation of particle production with centrality (volume) at RHIC and LHC!**

⇒ Global features of the system independent on energy

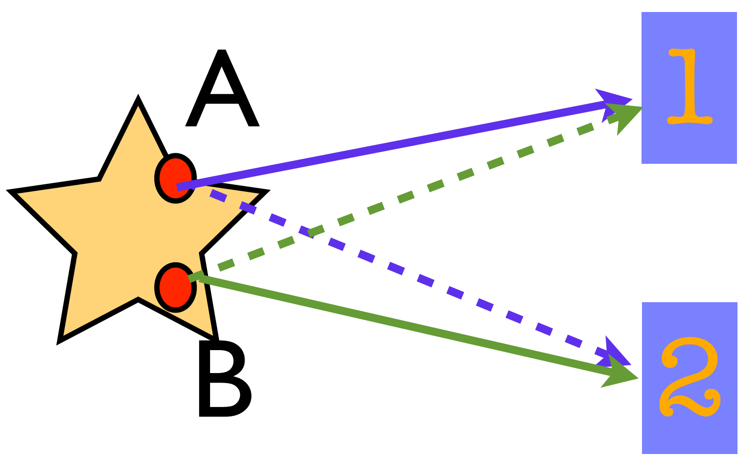
⇒ Initial conditions!

More on RHIC:
*Phobos (**Phys. Rev. Lett. 102, 142301 (2009)**)*



Centrality of the collisions: peripheral semi-central central

How to measure the dimensions of a source... - interferometry



quantum phenomenon: enhancement of correlation function for identical bosons from Heisenberg's uncertainty principle

Two particles emitted from two locations (A,B) within a single source.
These two are detected by detector elements (1,2).

$$A = \frac{1}{\sqrt{2}}\left(e^{ik_1^\mu (r_1-r_a)^\mu} e^{ik_2^\mu (r_2-r_b)^\mu} + e^{ik_1^\mu (r_1-r_b)^\mu} e^{ik_2^\mu (r_2-r_a)^\mu}\right)$$

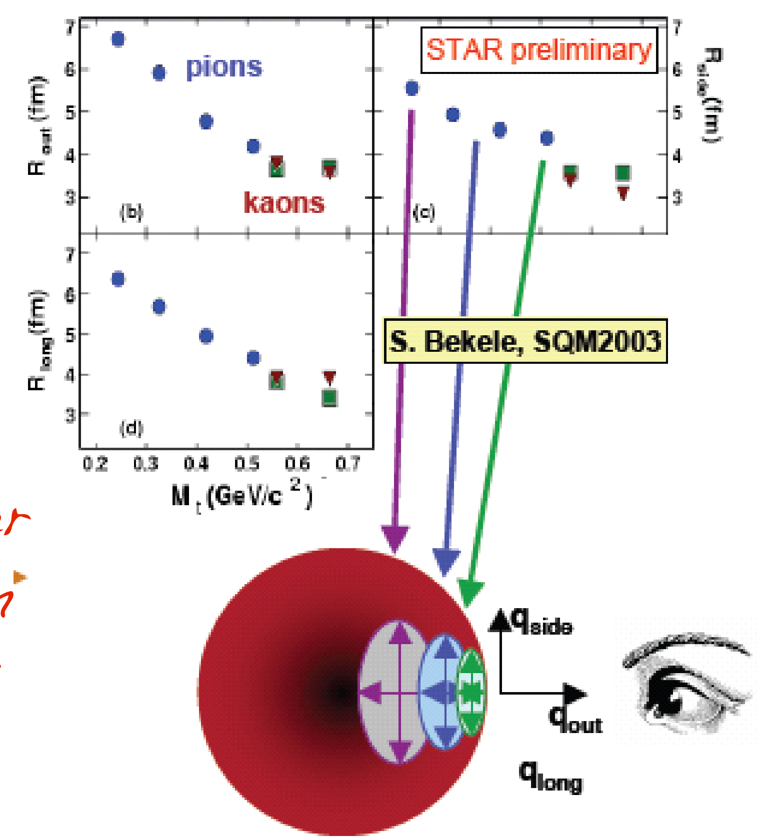
$$I = |A|^2 = 1 + \left\{e^{i(k_2-k_1)^\mu (r_a-r_b)^\mu} + c.c.\right\}$$

The intensity interference between the two point sources is an oscillator depending upon the relative momentum $q=k_2-k_1$, and the relative emission position!

$$C(p_1,p_2) = \frac{E_1E_2dN/(d^3p_1d^3p_2)}{(E_1dN/d^3p_1)(E_2dN/d^3p_2)} . \quad E_p\frac{dN}{d^3p} = \int d^4x\, S(x,p)$$

Correlation function summed incoherently (integration over all pairs of source points) in a function of 4-momentum sums and differences (q,K) - extract source dimensions:

$$C(q,K) = 1 \pm \lambda(K)\exp\left(-R_s^2(K)q_s^2 - R_o^2(K)q_o^2 - R_l^2(K)q_l^2\right)$$



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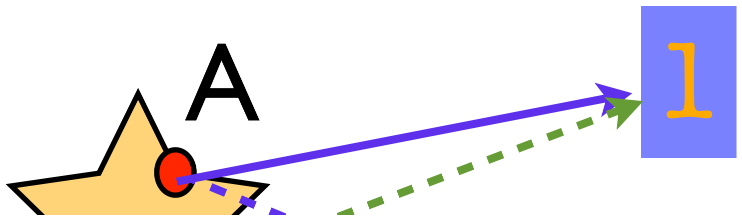


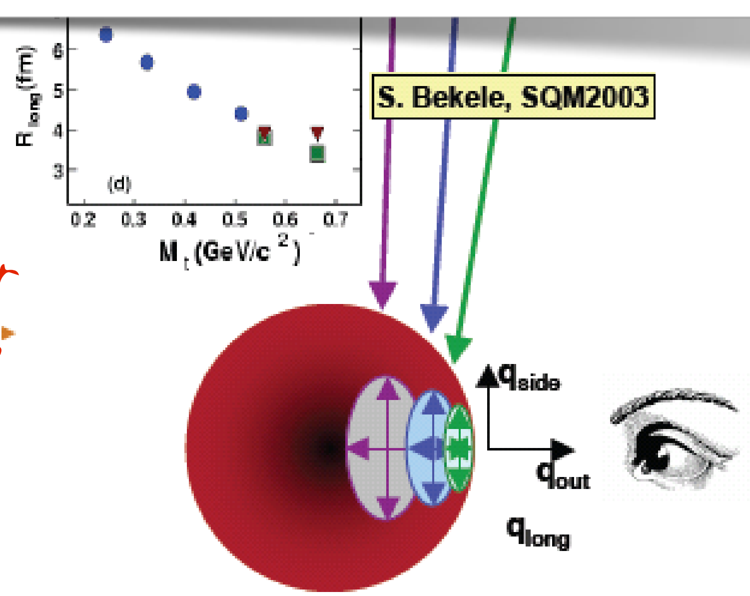
Two particles emitted from two locations (A,B) within a single source.

These two are detected by detector elements (1,2).

Th

First used with photons in the 1950s by astronomers Hanbury Brown and Twiss - hence HBT measurements in heavy-ion collisions...
=> measured size of star Sirius by aiming at it two photomultipliers separated by a few metres

$$C(\mathbf{p}_1, \mathbf{p}_2) = \frac{E_1 E_2 dN/(d^3p_1 d^3p_2)}{(E_1 dN/d^3p_1)(E_2 dN/d^3p_2)}. \qquad E_p \frac{dN}{d^3p} = \int d^4x\, S(x,p)$$



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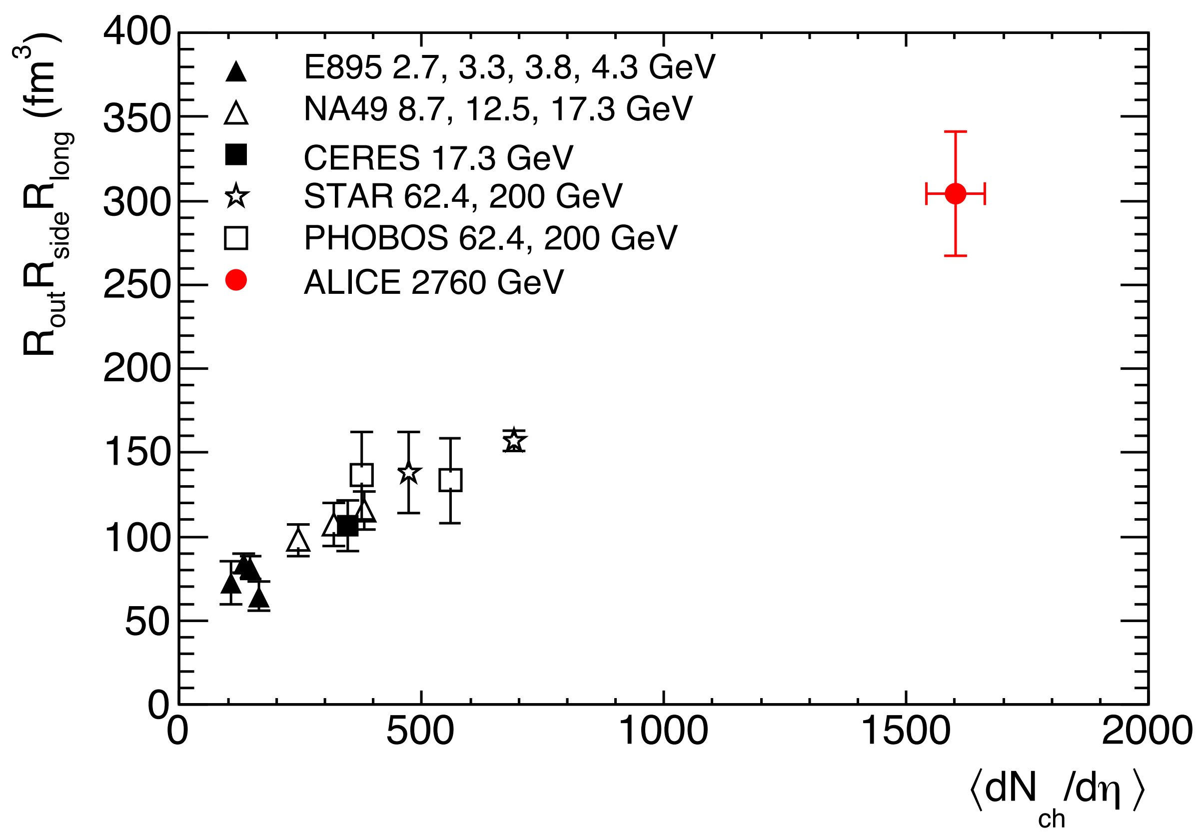
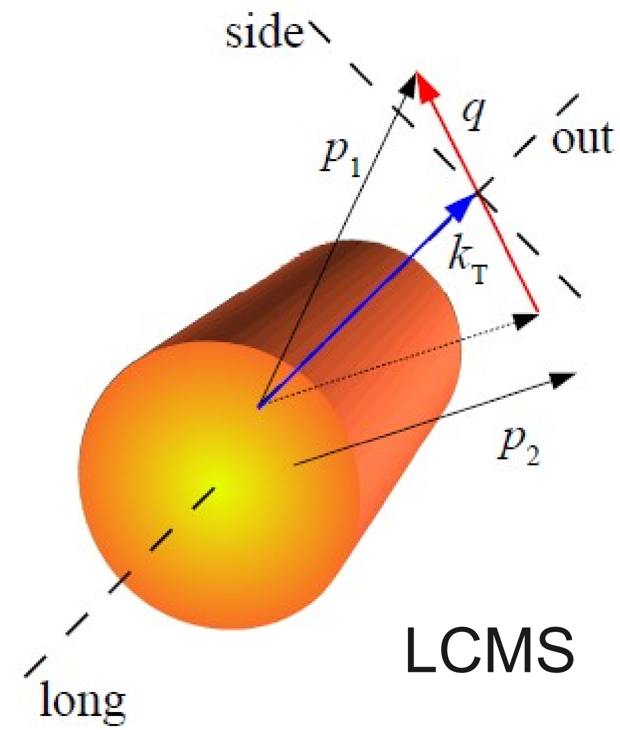
Particle production: source dimensions

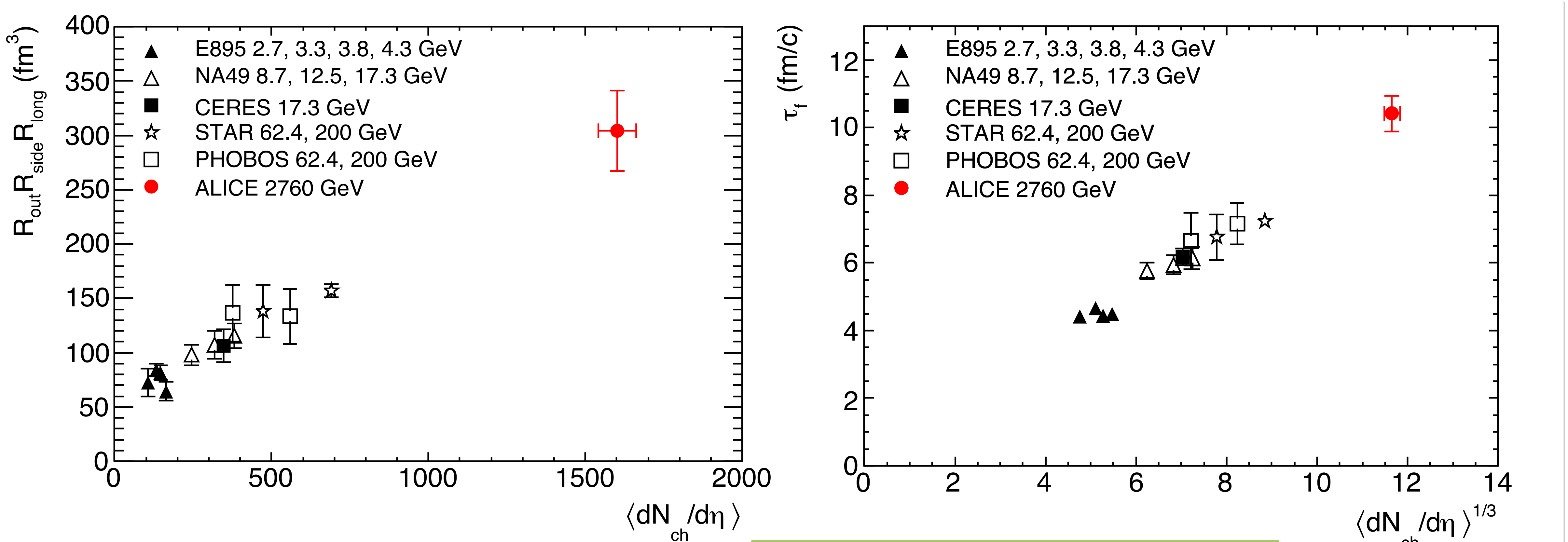




Phys.Lett.B 696:328-337,2011

1. **Energy dependence:**
   - **system with larger (2x) volume and (1.4x) lifetime (w.r.t RHIC); follows the trend of multiplicity; faster expansion <=> larger collective flow**
2. **Pair momentum dependence:**
   - **larger radii, strong dependence on kT; Rout/Rside smaller than at RHIC; overall agreement with extrapolations**
3. **Important constrains to [hydrodynamical] modelling**

Particle production: source dimensions



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3. Important constrains to [hydrodynamical] modelling

Thermal equilibrium...
Chemical and kinetic freeze-out

Chemical equilibrium:

- correct relative particle abundances?
- large system -> Grand Canonical ensemble: many particles; conservation laws on average - chemical potentials
- small system -> conservation laws E-by-E -> "canonical suppression" (strangeness)

$$n_i^0 = \frac{g_i}{2\pi^2}\int \frac{p^2 dp}{e^{\left(E-\mu_B B_i-\mu_s S_i-\mu_3 I^3\right)/T} \pm 1}$$

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$$\rho = \tanh^{-1}\left(\beta_{boost}\right)$$

Simple assumption: uniform sphere of radius R and boost velocity varies linearly w/ r:

$$\frac{1}{m_T}\frac{dN}{dm_T} \propto \int_0^R r^2 dr m_T I_0\left(\frac{p_T\sinh(\rho)}{T}\right)K_1\left(\frac{m_T\cosh(\rho)}{T}\right)$$

$$\rho(r) = \tanh^{-1}\left(\beta_T^{MAX}\frac{r}{R}\right)$$

Blast Wave model => common T and β

Statistical hadronization of the system (thermalized system?)

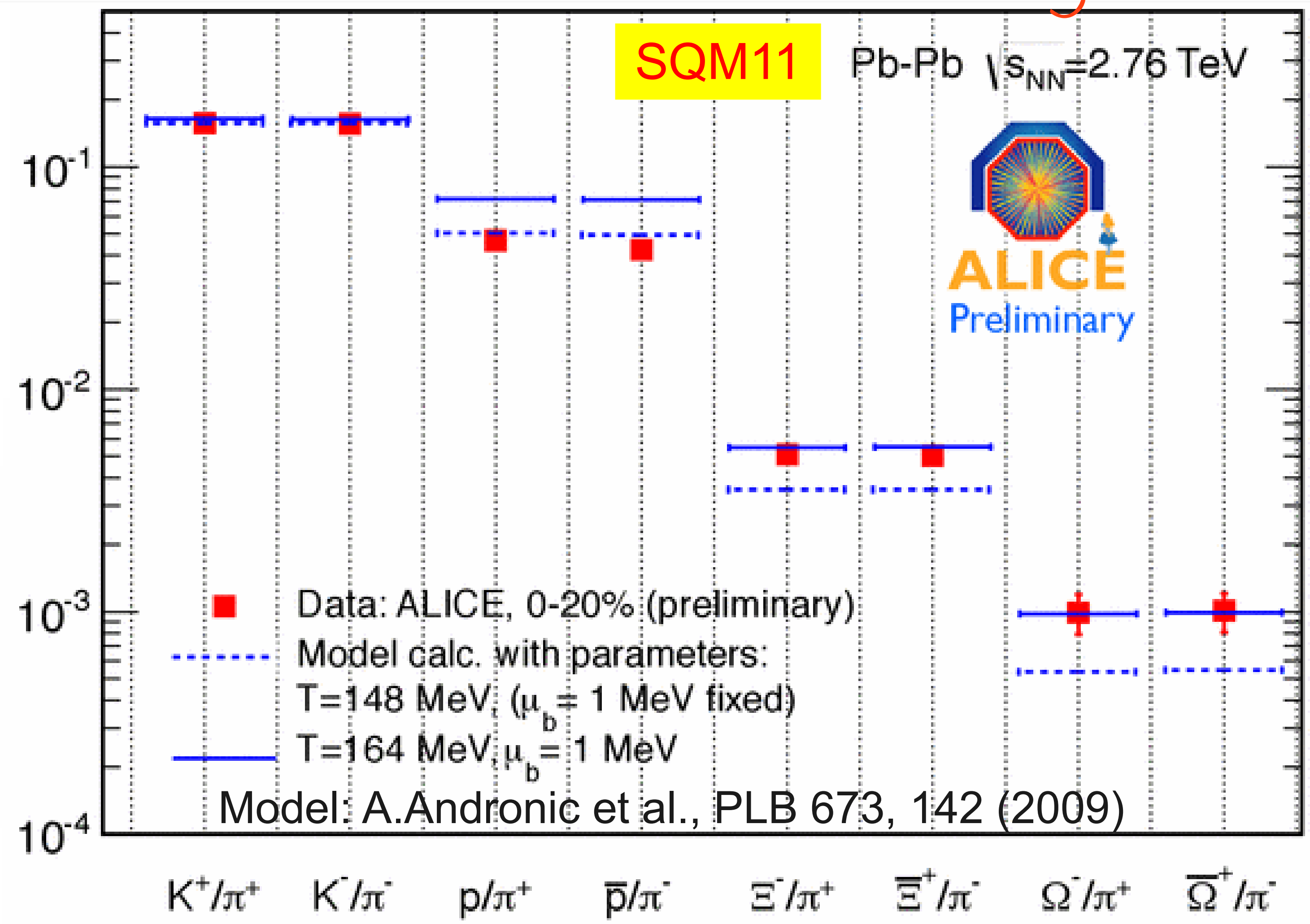
Data at RHIC - similar figure

Grand-canonical ensemble analysis

$$N_i \propto V \int \frac{d^3p}{2\pi^3} \frac{1}{e^{(E_i - \mu_B B_i)/Tch} \pm 1}$$

T_{ch} Chemical freeze-out temperature

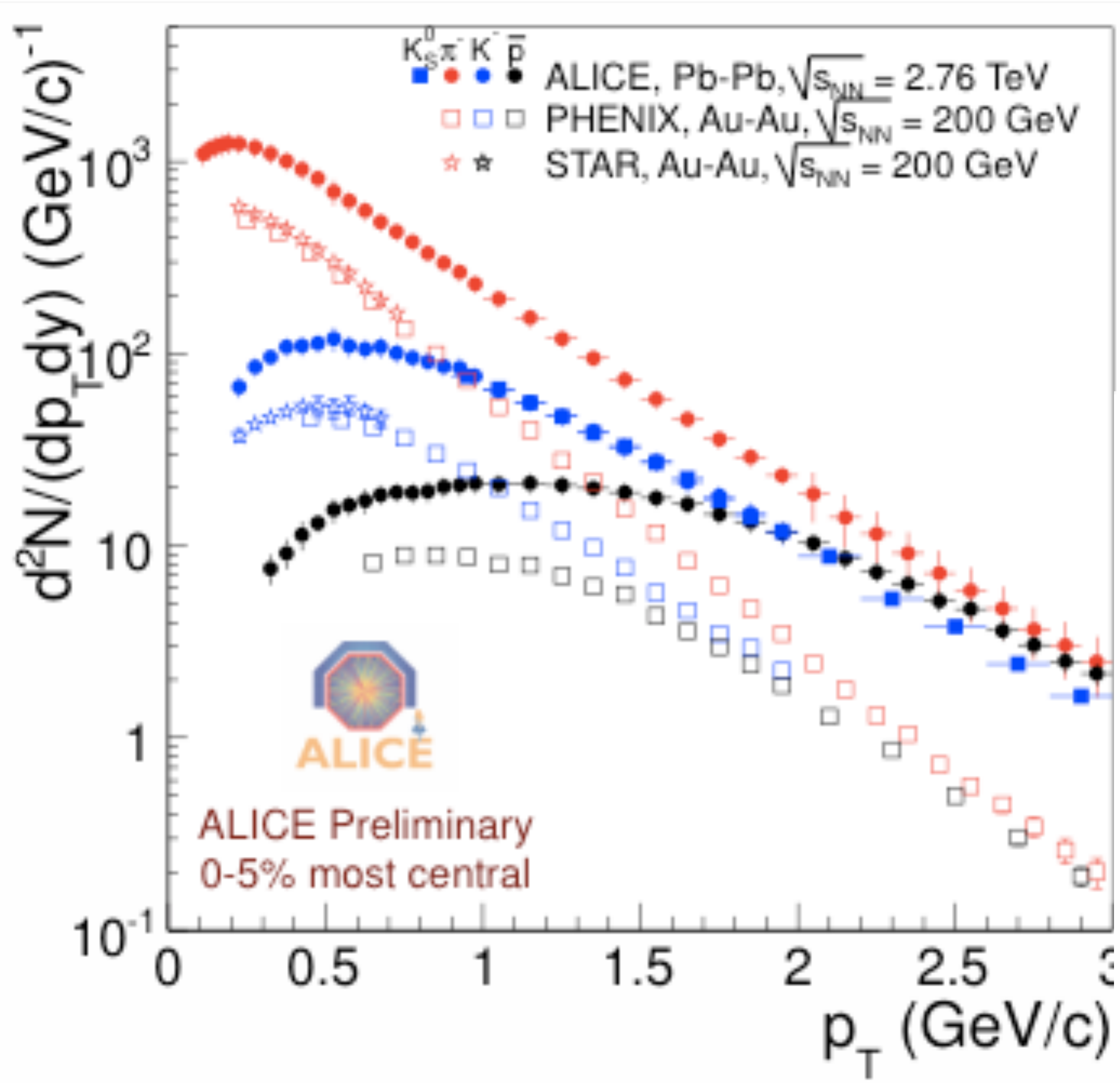
μ_B Baryochemical potential



All yields (but protons) described by thermal model with **T_{ch}=164 MeV (and μ_b=1 MeV)**

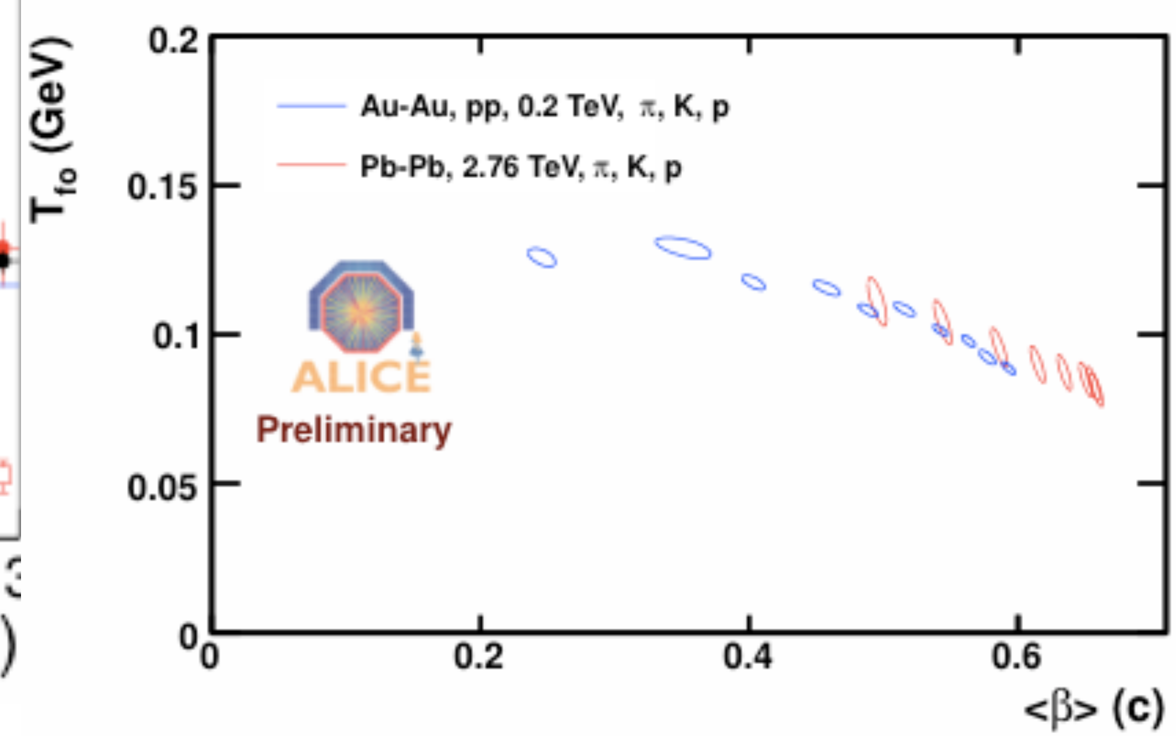
- Similar temperature as at RHIC, however proton/pion below the fit – the tension already present at RHIC
- Strange particles constrain fit
- Conclusions are model independent (confirmed with THERMUS)

Identified particles & expansion of the system



Stronger radial flow at the LHC.

"Blast wave" fits to spectra indicate an **increase of the average radial boost velocity** up to (2/3)c and a decrease in the kinetic freezeout temperature to just below 100 MeV relative to RHIC



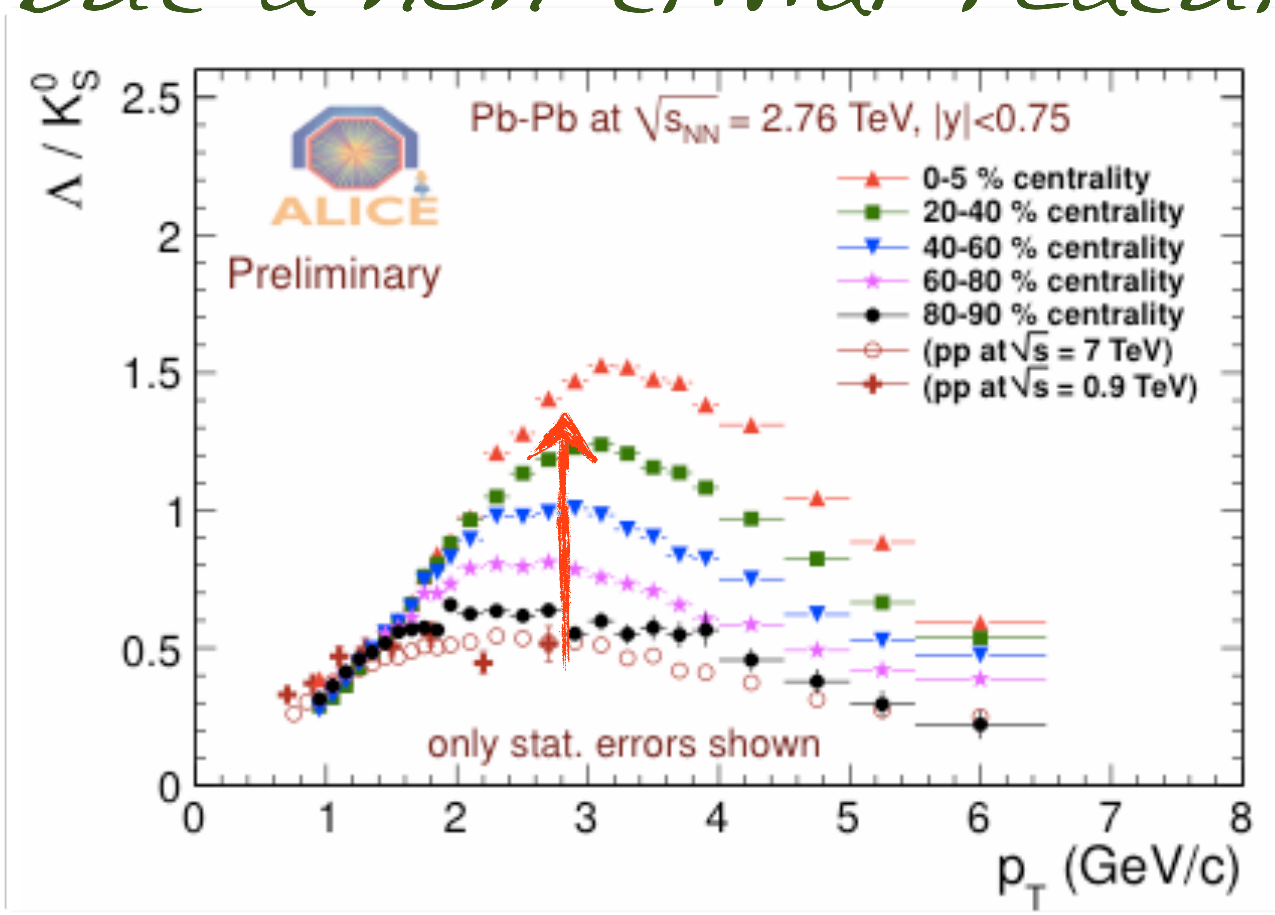
LHC: Large kinematic reach to explore

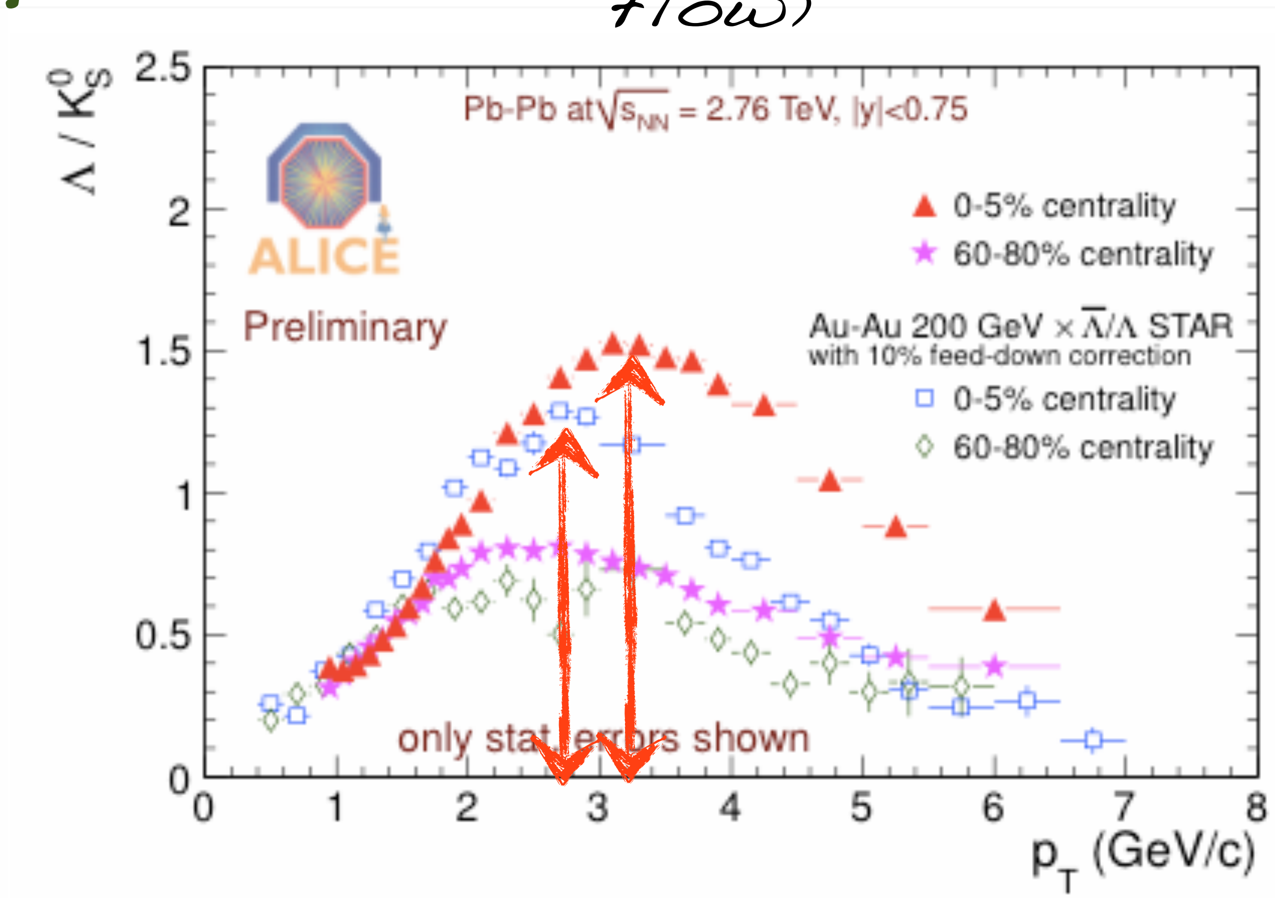
ALICE: excellent particle identification capabilities at the LHC

Hadron production in heavy-ion collisions

A slight digression...
but a non-trivial feature!

RHIC vs LHC
(LHC: higher mean pT - more flow)

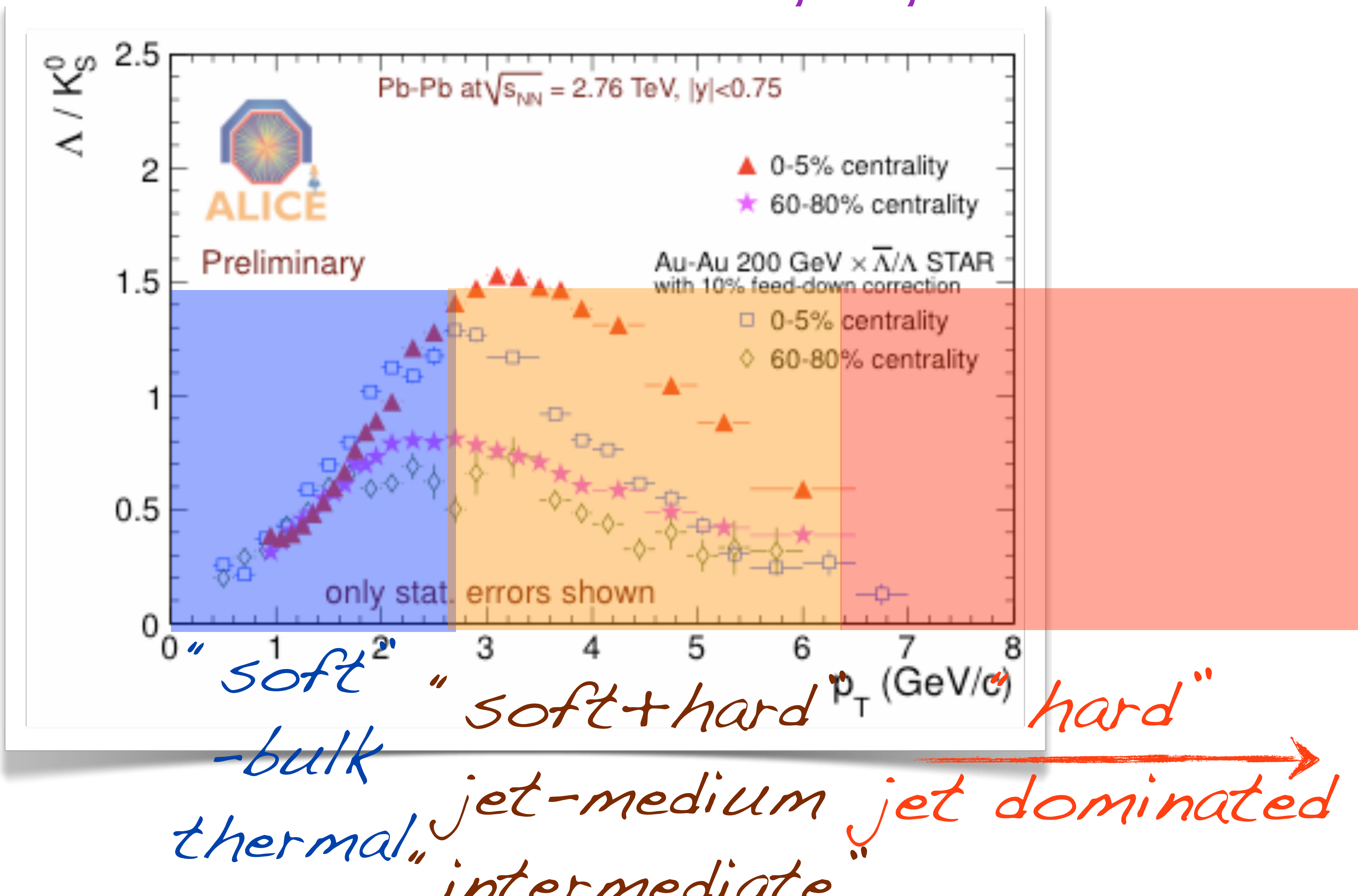




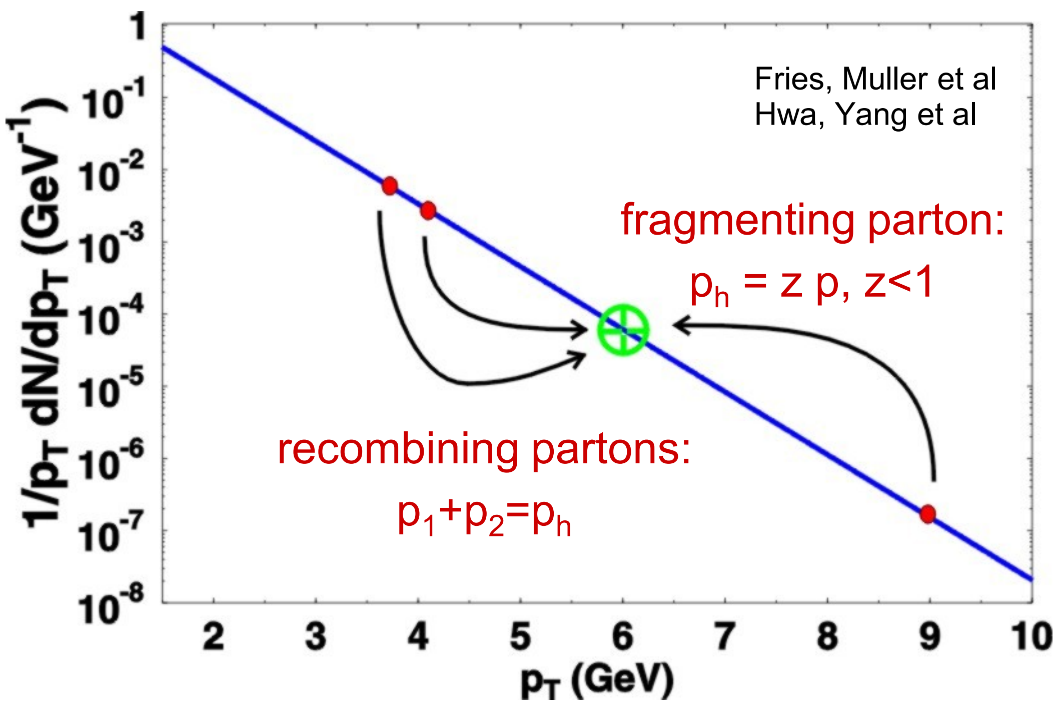
Much more baryons than mesons in central collisions as compared to proton-proton (coalescence/recombination? bulk+jet?)

LHC similar to RHIC
Maximum at slightly higher-pT

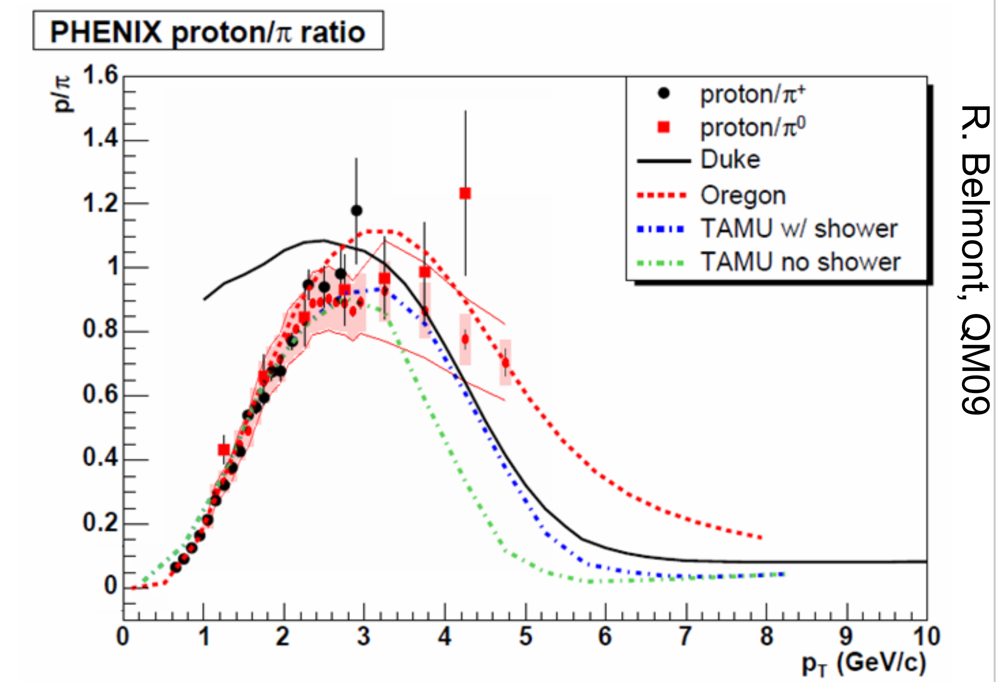
bulk, jets, medium and p_T:
arbitrary regions
and INFORMAL Language



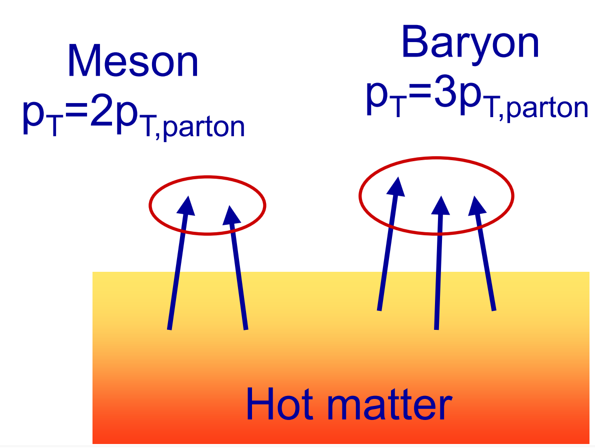
Hadronization of bulk+hard - parton coalescence



Recombination of thermal ('bulk') partons produces baryons at larger p_T

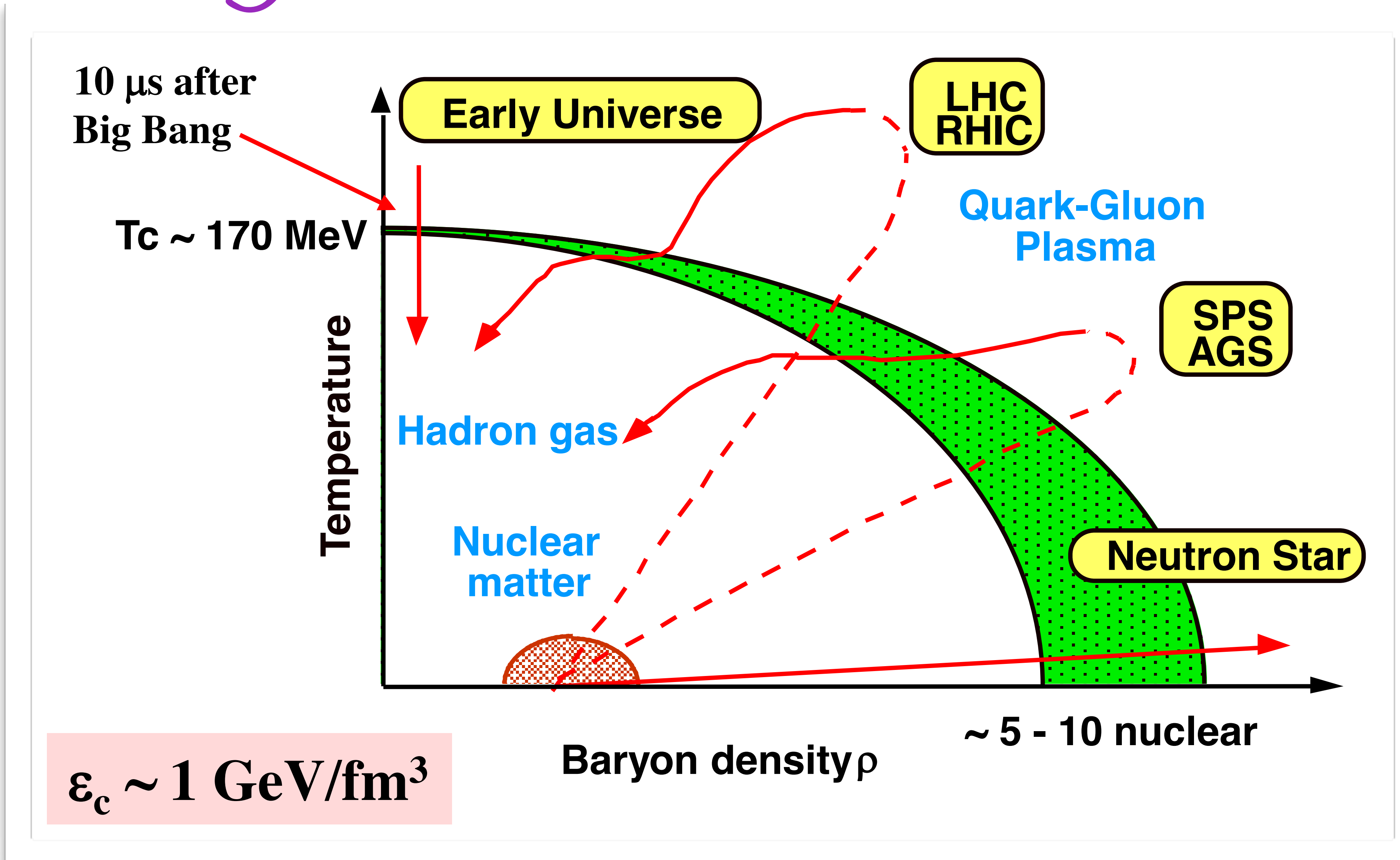


Recombination enhances baryon/meson ratio



Note also: v_2 scaling

Our progress... - next #2



A recipe:

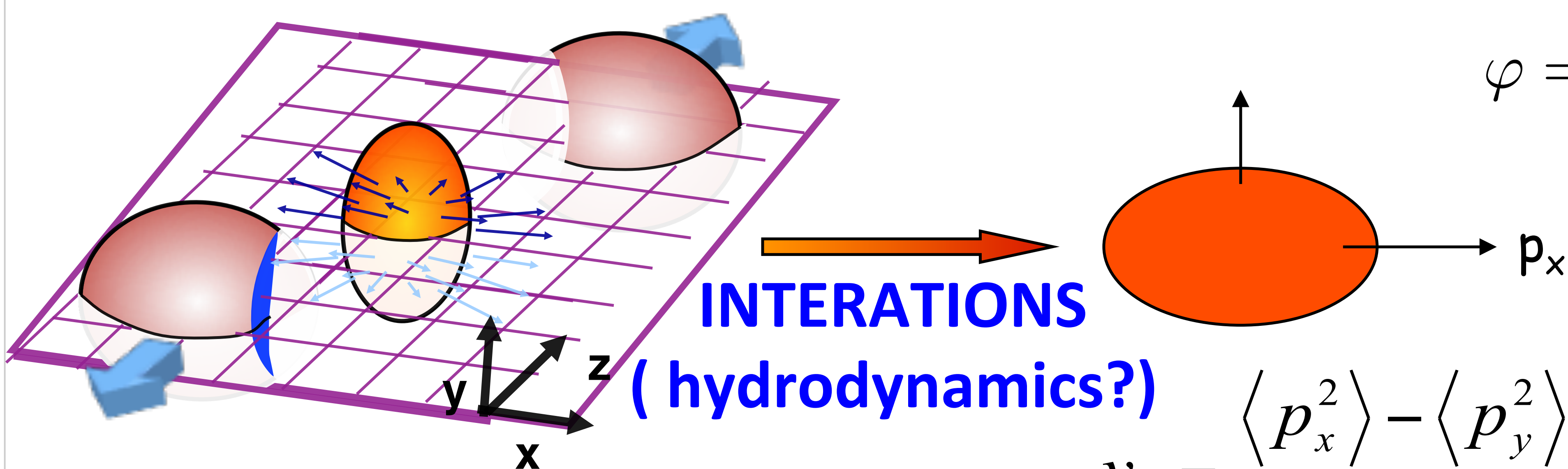
1. smash nuclei to drive the system to the new phase *medium* ...
2. Identify the *signatures* of the medium by *probing* its response / properties

Until now...

- Heavy-ion collisions at high-energies:
  - high-energy density
  - hot, deconfined matter with quark and gluon degrees of freedom (plasma -> QGP) - strongly coupled system
- Statistical description of relative particle multiplicities
- Common velocity - expansion of the system
- Particle production: baryon-to-meson anomaly (recombination / coalescence processes)
- Medium properties to be measured...

Properties of QGP with particle correlations

Azimuthal angular asymmetry in particle production



$$\varphi = \arctan \frac{p_y}{px}$$

$$\varepsilon = \frac{\langle y^2 \rangle - \langle x^2 \rangle}{\langle y^2 \rangle + \langle x^2 \rangle}$$

Initial spatial anisotropy

$$v_2 = \frac{\langle p_x^2 \rangle - \langle p_y^2 \rangle}{\langle p_x^2 \rangle + \langle p_y^2 \rangle}$$

Final momentum anisotropy

Reaction plane defined by "soft" (low p_T) particles

$$\Delta\varphi = \varphi - \varphi^{Reaction\ \ Plane}$$

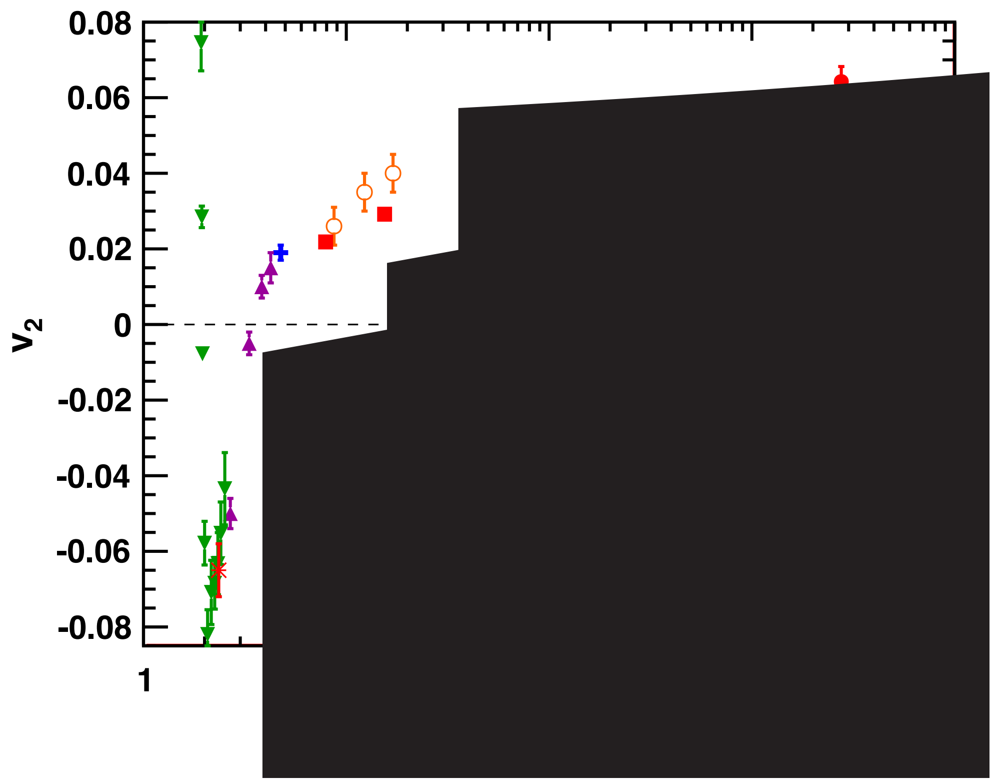
Elliptic flow

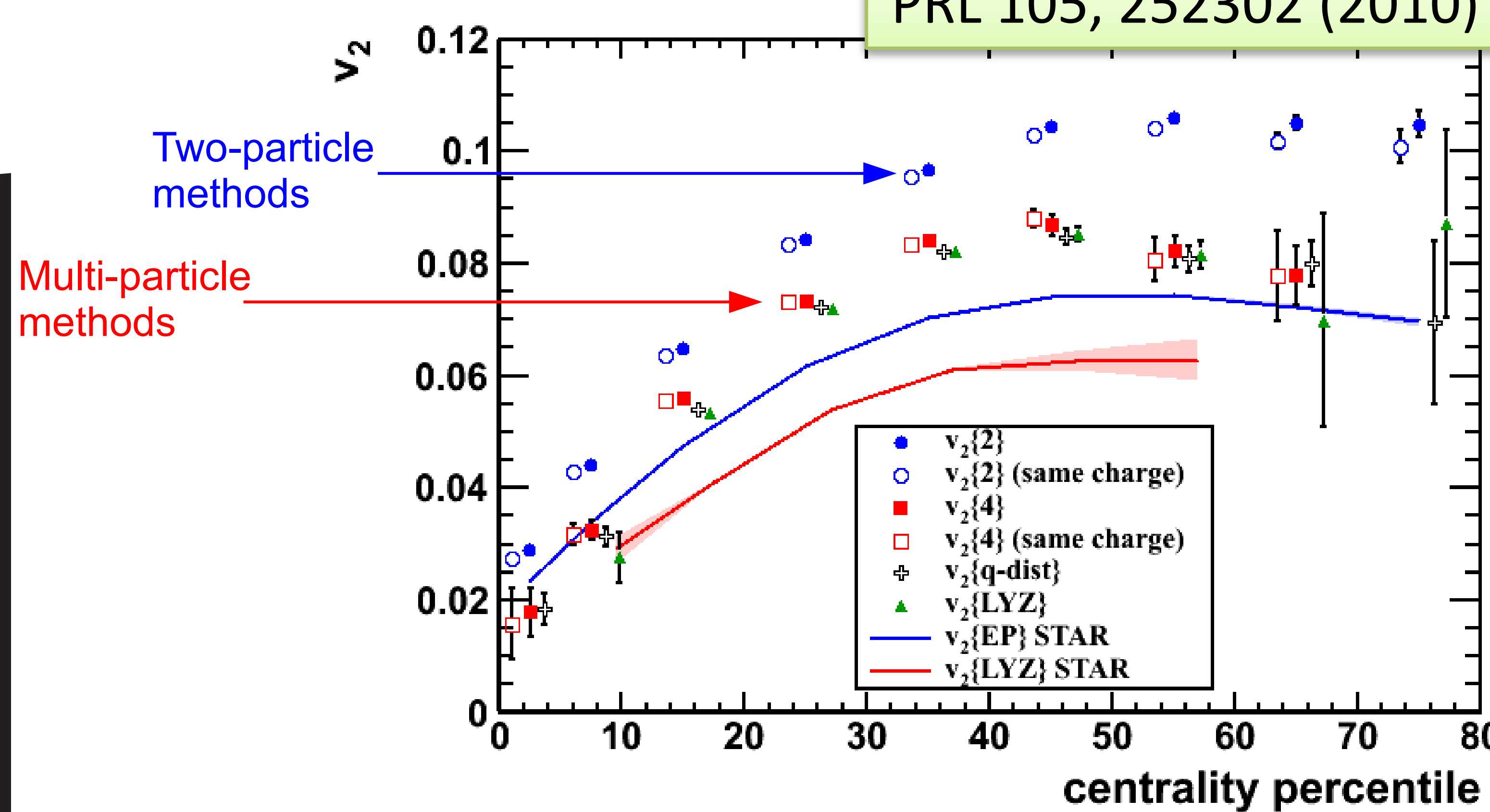
$$\frac{dN}{d\Delta\varphi} \propto 1 + 2v_2 \cos(2\Delta\varphi)$$

Azimuthal anisotropy

PRL 105, 252302 (2010)

Energy dependence of v2



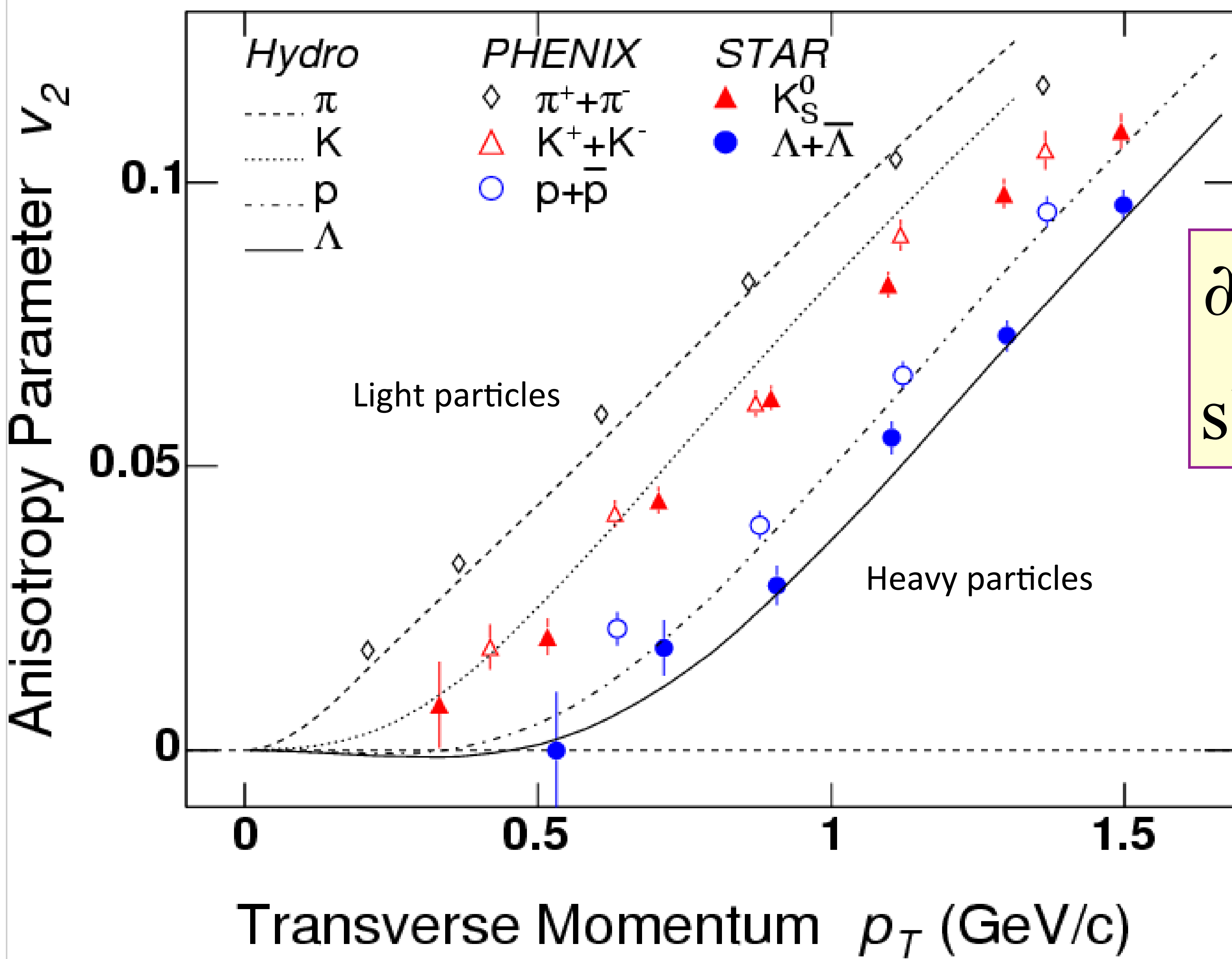


APS Viewpoint: A "Little Bang" arrives at the LHC (E. Shuryak)

1. **Collective behavior observed in Pb-Pb collisions at LHC (integrated: +0.3 v_2^{RHIC} – consequence of larger <p_T>) -> $v_2(p_T)$ similar to RHIC – almost ideal fluid at LHC ? Similar observation down to 39GeV!**
2. **New input to the energy dependence of collective flow**
3. **Additional constraints on Eq-Of-State and transport properties**

Relativistic (ideal) hydrodunamics

Heinz '04



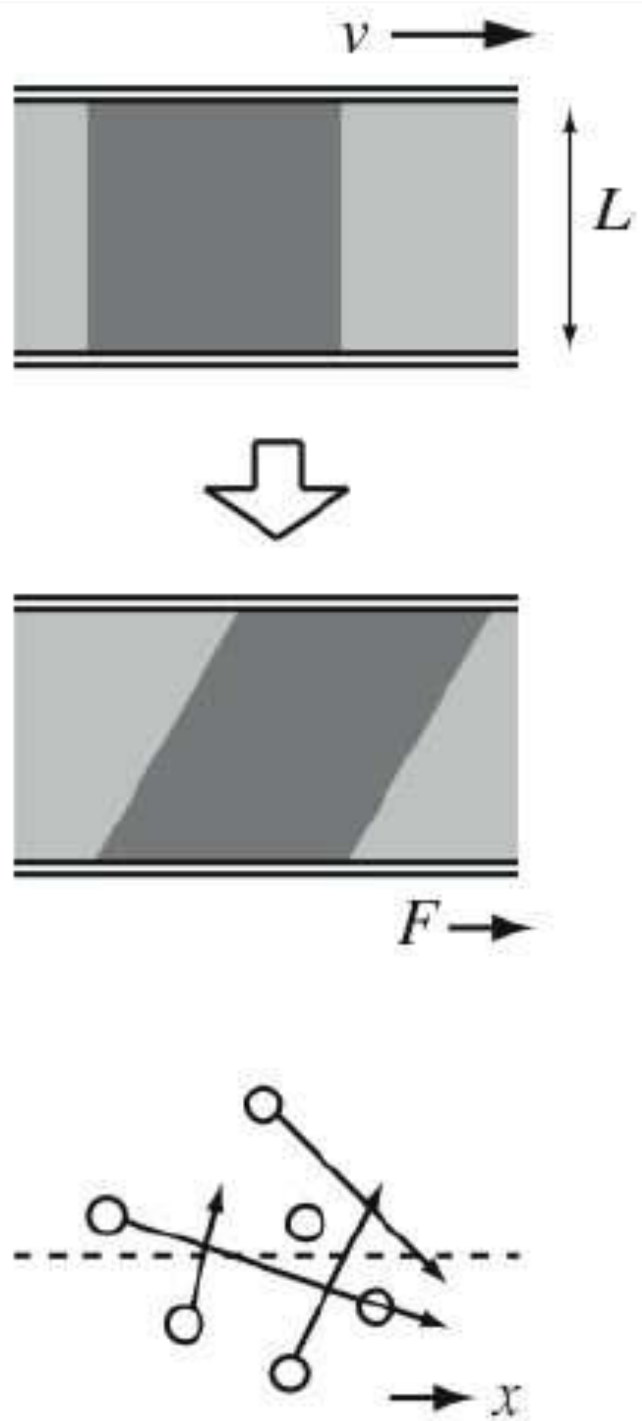
$$\partial_\mu T^{\mu\nu} = 0$$

shear viscosity $\eta = 0$

Mass hierarchy vs *momentum* is characteristic of common *velocity* distribution

Ideal hydro: qualitative agreement but missing the details

Shear viscosity in fluids...



$$\frac{F}{A} = \eta \frac{\mathrm{v}}{L}; \quad \eta \sim \rho \langle \mathrm{v} \rangle \lambda_{mfp}$$

Properties are counter-intuitive:

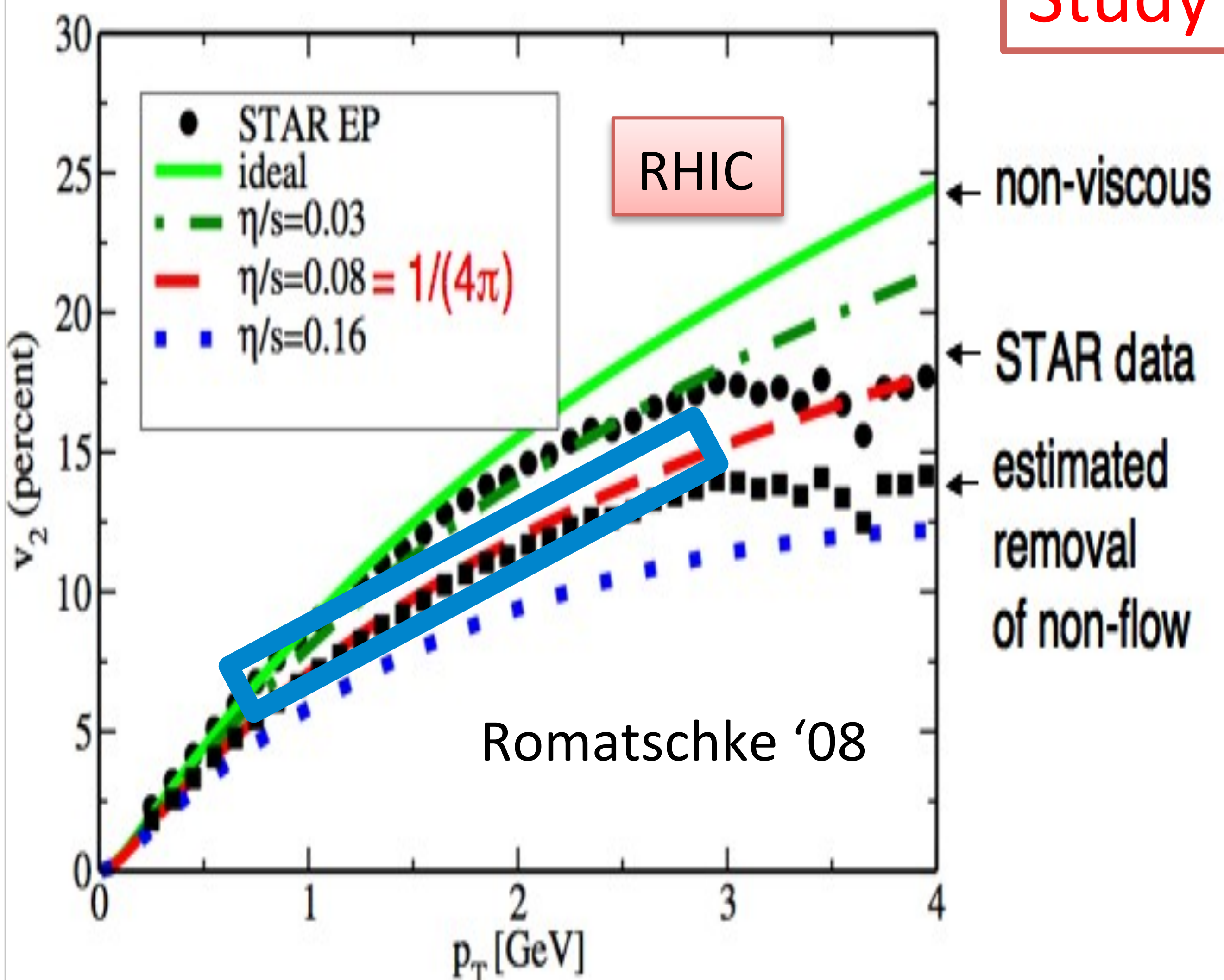
Weak coupling
• small cross section, long mean free path
⇒ large viscosity

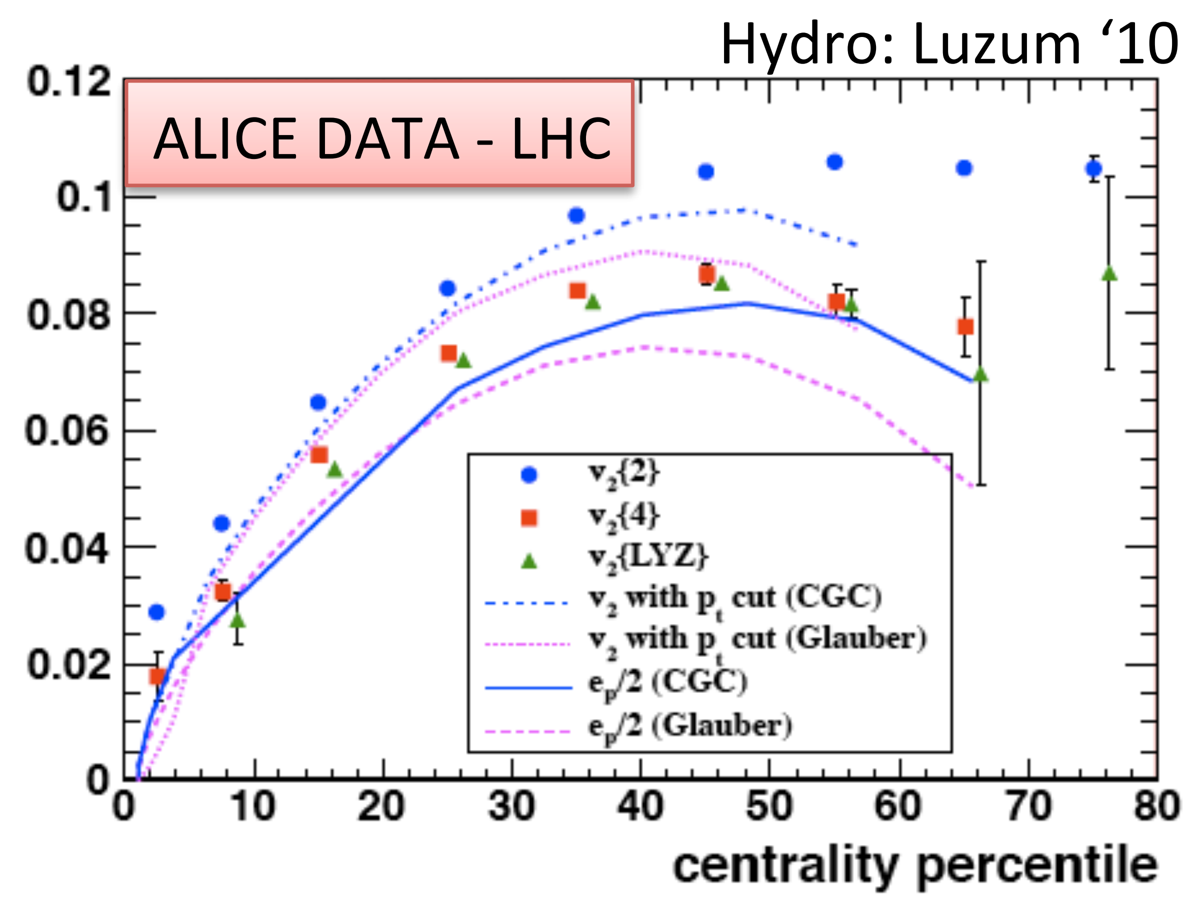
Strong coupling
• large cross section, small mean free path
⇒ small viscosity

η→0: strongly coupled (perfect) fluid
η→∞: weakly coupled (ideal) gas

QGP liquid- how perfect is perfect?

Study elliptic flow of matter





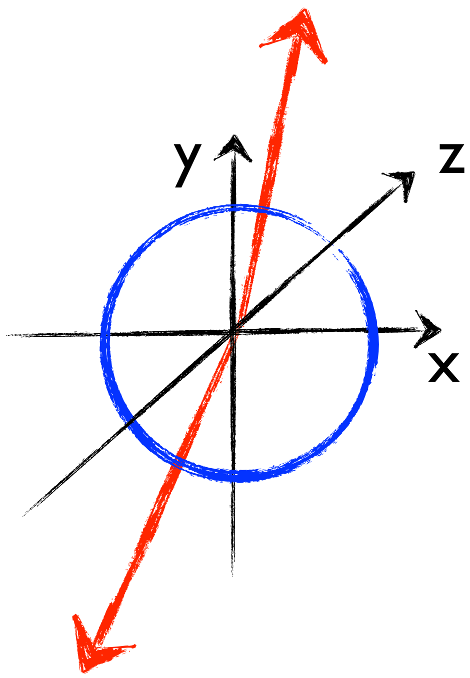
Shear viscosity – lower limit: $$\frac{\eta}{s} > \frac{1}{4\pi}$$

KSS (string theory); Gyullassy-Danielewicz
(quantum mechanics + ballistic theory)

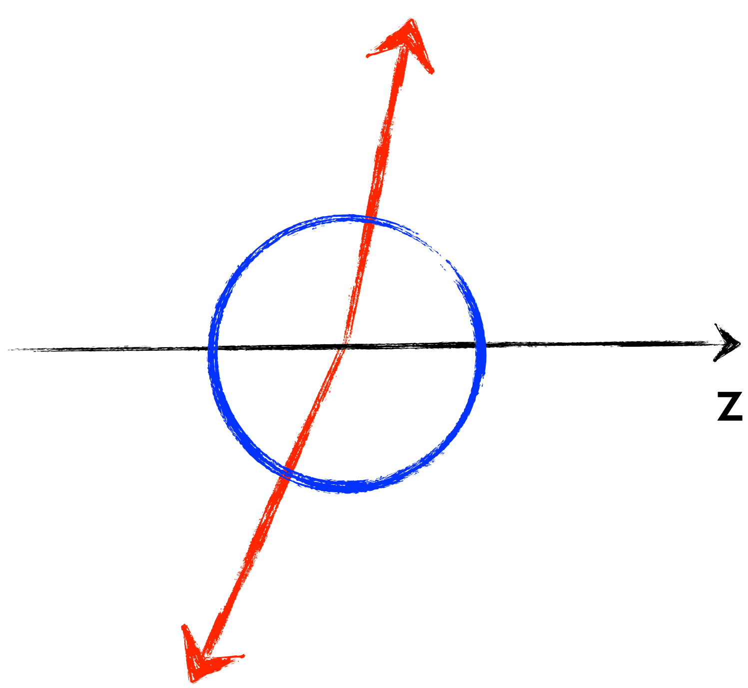
Alfonso! Yesterday…

Hot, deconfined QCD matter flows as an almost perfect fluid

Two particle correlations



Δφ - azimuthal angle difference
angle in the transverse plane



Δη - longitudinal - pseudo-rapidity distance

Sensitivity of particle correlations to different underlying physics

Two-particle correlations

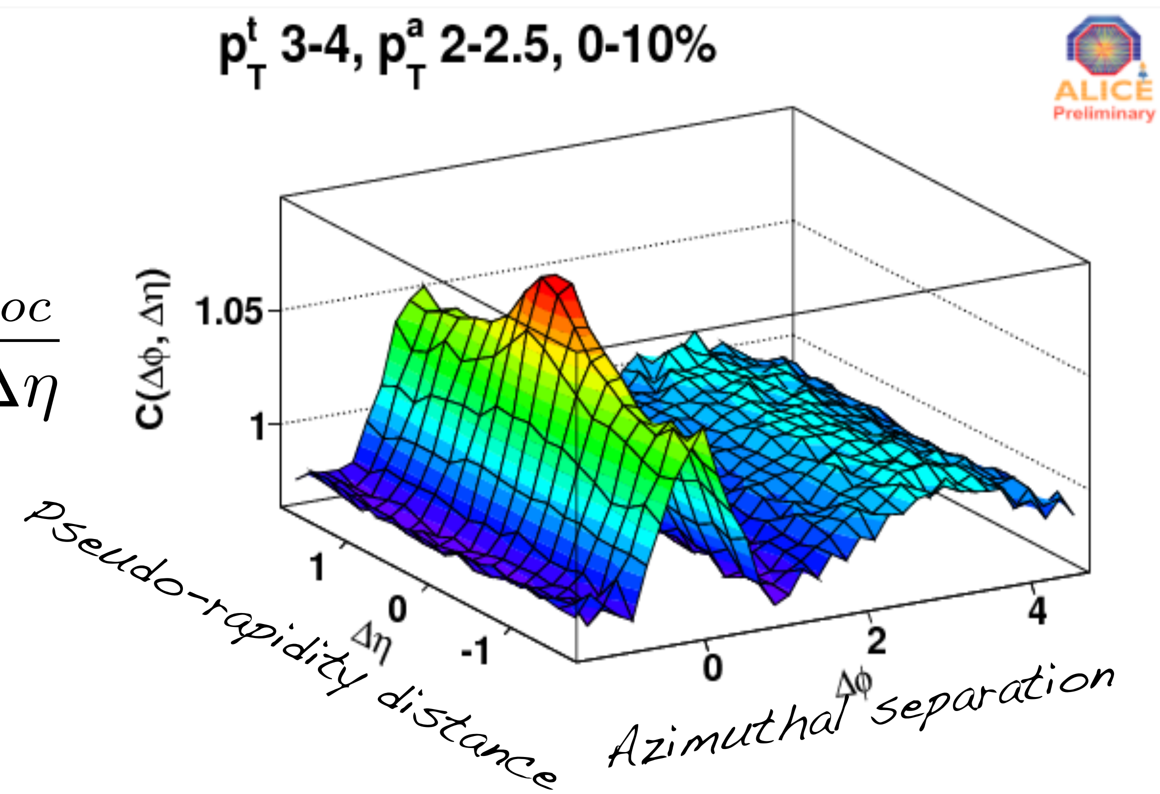
- conditional [per-trigger] yields

$$\frac{1}{N_{trig}}\frac{dN_{assoc}}{d\Delta\varphi} \quad \text{and} \quad \frac{1}{N_{trig}}\frac{d^2N_{assoc}}{d\Delta\varphi d\Delta\eta}$$

At Low-p_T :

Ridge

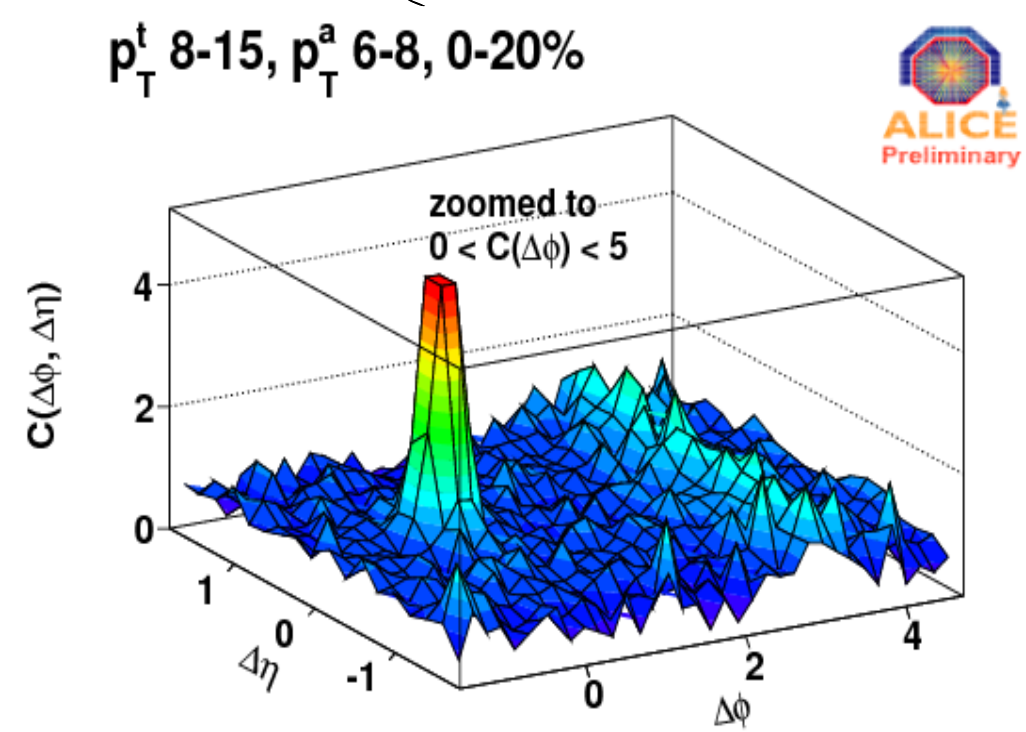
Hydrodynamics, flow



At High-p_T :

Discussed later…

Quenching/suppression, broadening

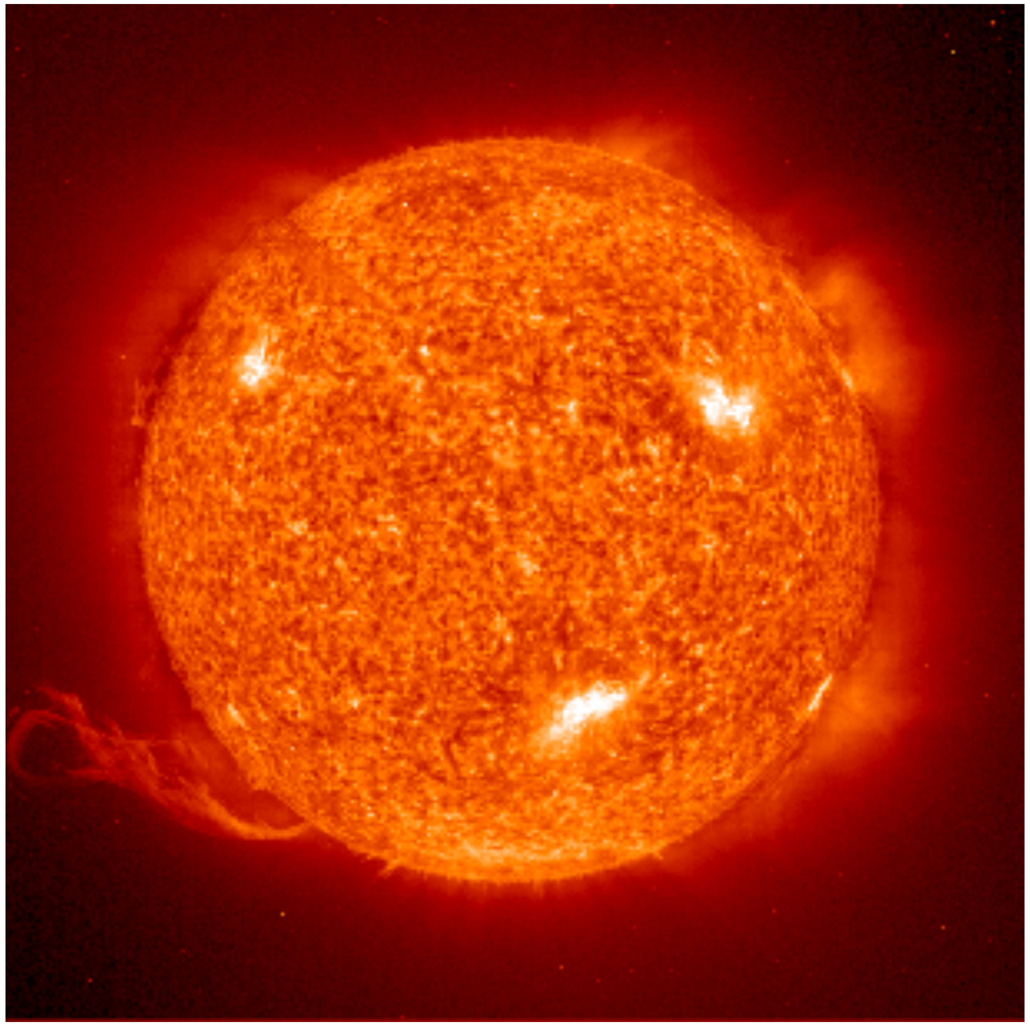


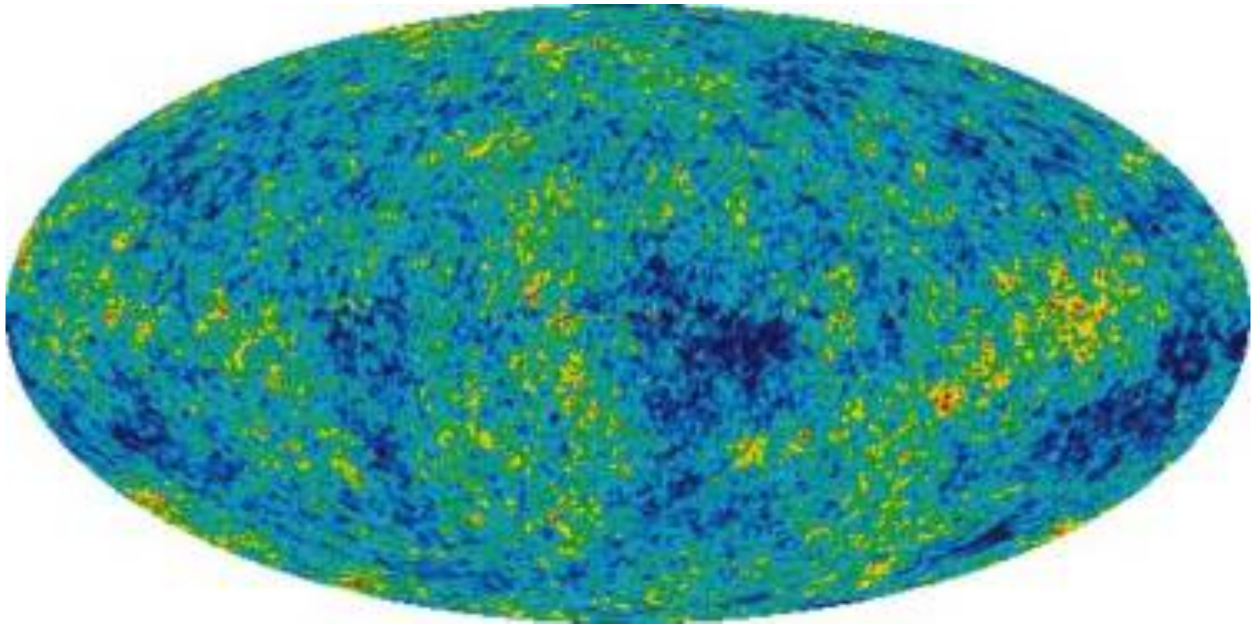
I_{CP}: Yields in central v.s. peripheral collisions

I_{AA}: Yields in A-A compared to p-p

"Beyond" v2

higher moments -> fluctuations / hotspots



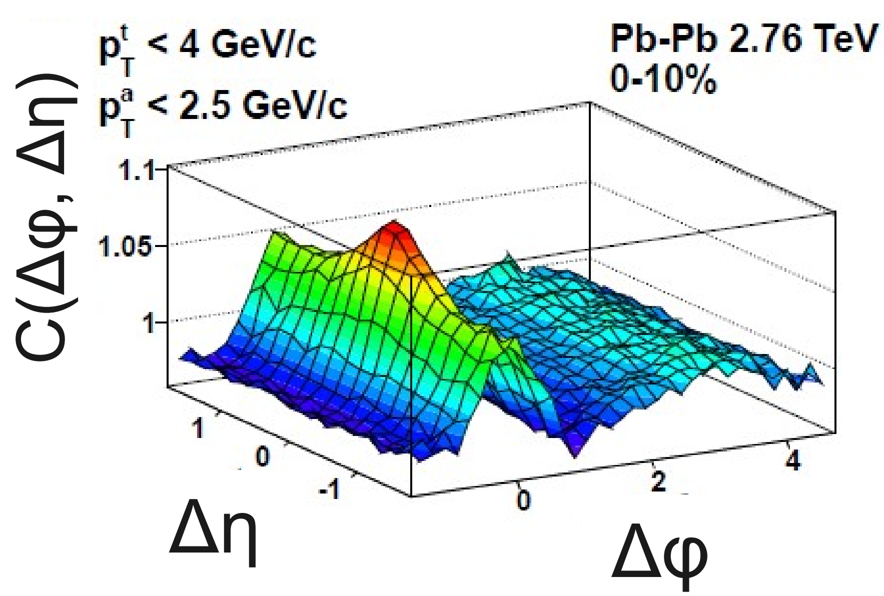


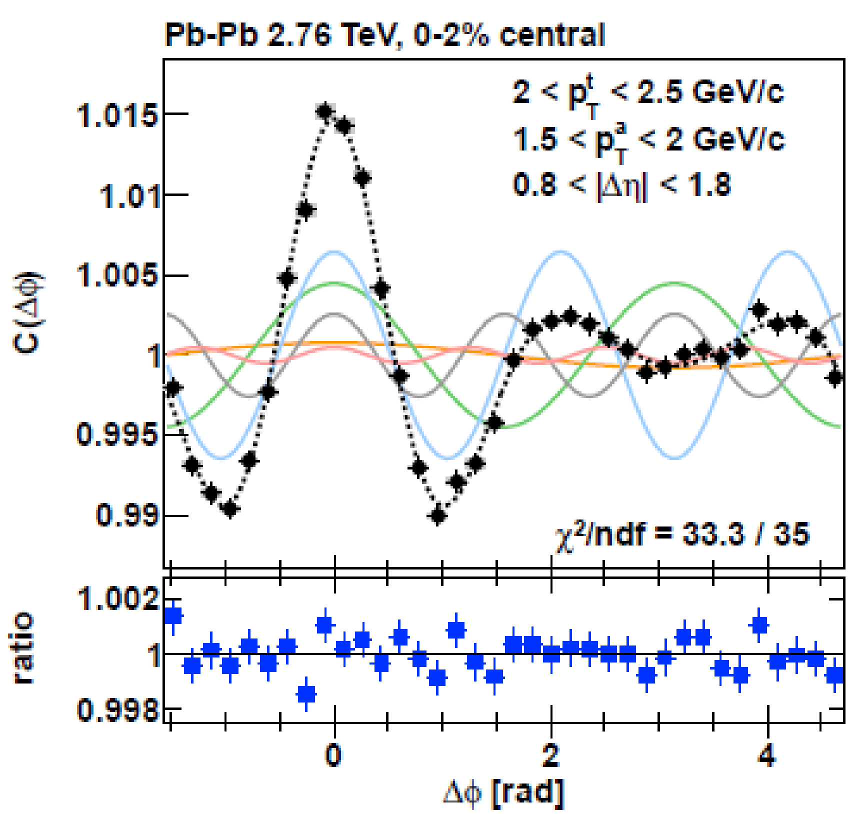
Single event!

$$\frac{dN}{d\varphi} \sim 1 + 2v_2 \cos(2\Delta\varphi) + \ldots$$

Non-zero!

Two-particle correlations - Fourier decomposition



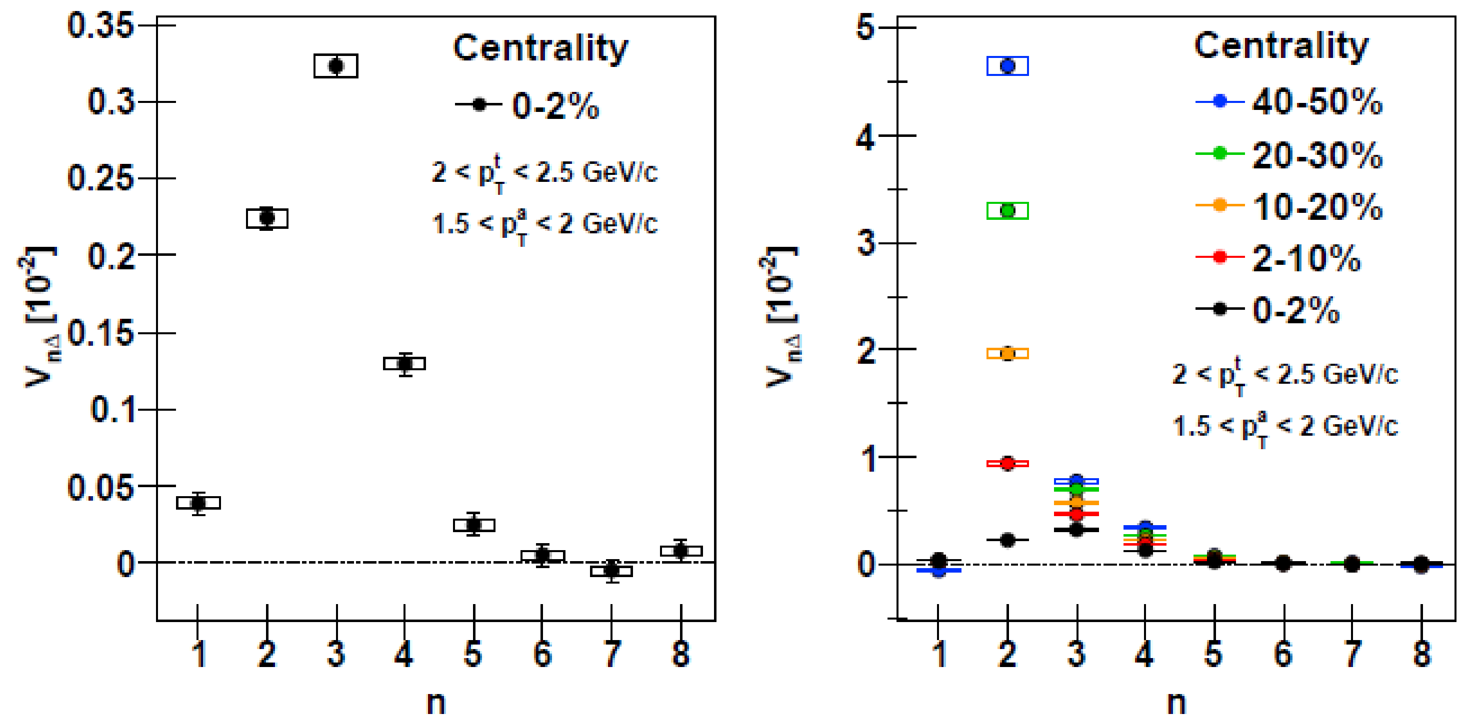


Integration of the correlation function in 0.8 < |Δη| < 1.8 (long) and Fourier decomposition

Collective flow: the coefficients factorize $V_{n\Delta}=v_n(p_T^T)v_n(p_T^A)$

$$C(\Delta\phi)=\frac{1}{\Delta\eta_{max}-\Delta\eta_{min}}\int_{\Delta\eta_{min}}^{\Delta\eta_{max}} C(\Delta\eta,\Delta\phi) \sim 1+2\sum_{n=1} V_{n\Delta}\cos(n\Delta\phi)$$

Pair-wise coefficients



Few components describe the low-pT correlations

⇔ Strong near side ridge and double-peak on the away

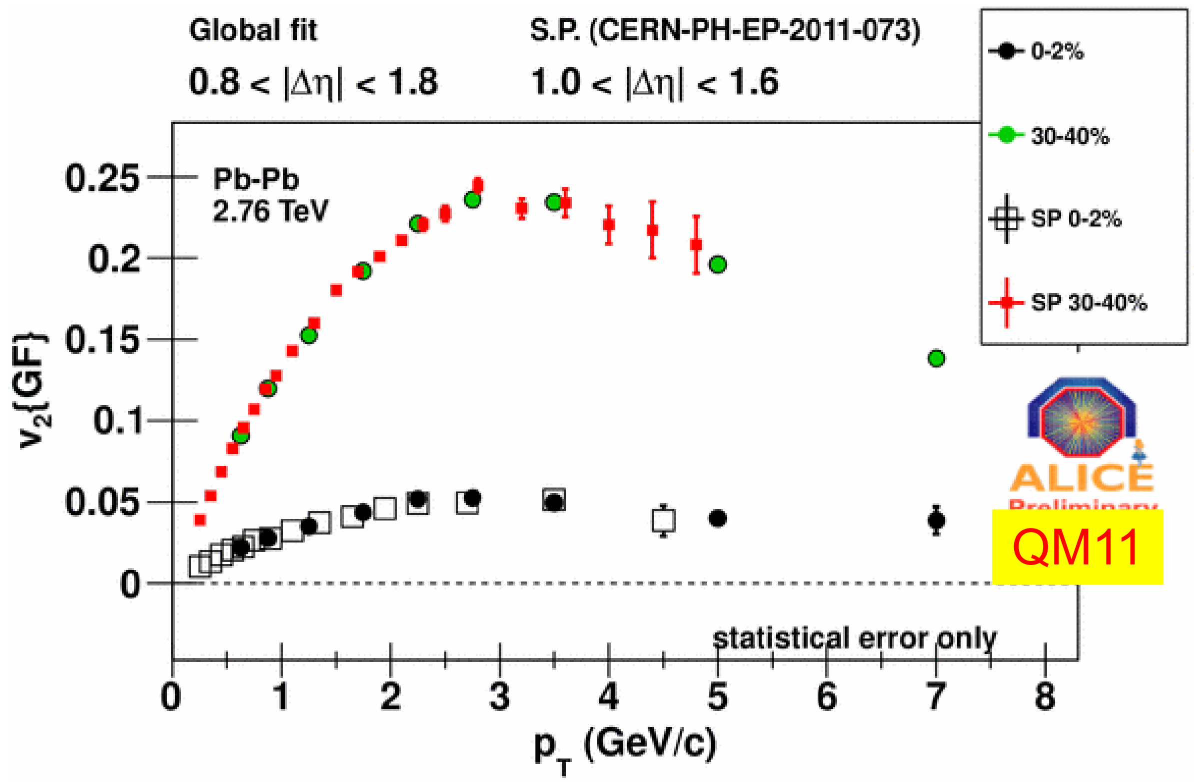
⇔ Also recoil jet up to p_T^{trig}>8 & p_T^{assoc} 6-8 in central

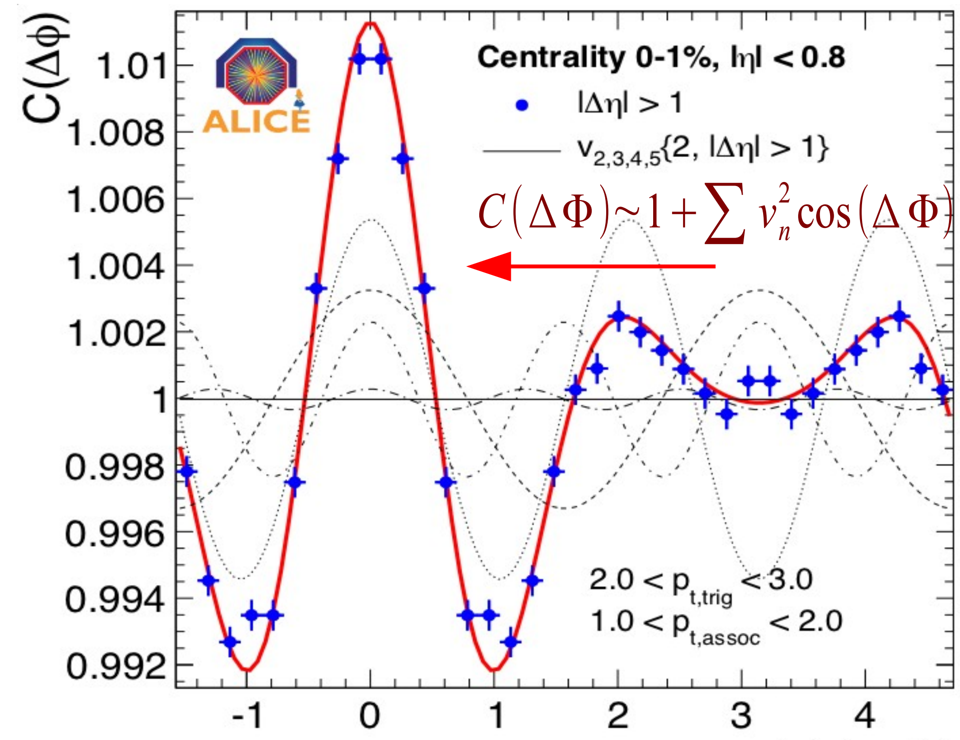
Correlations & hydrodynamics...

Long range correlations – collective flow: the coefficients must factorize such that:

$$V_{n\Delta}=\langle\cos\left[n\left(\phi_{trig}-\phi_{assoc}\right)\right]\rangle=\langle\cos\left[n\left(\phi_{trig}-\Psi_{n}\right)\right]\rangle\langle\cos\left[n\left(\phi_{assoc}-\Psi_{n}\right)\right]\rangle=v_{n}\left(p_{t}^{trig}\right)\cdot v_{n}\left(p_{t}^{assoc}\right)$$

arXiv:1109.2501



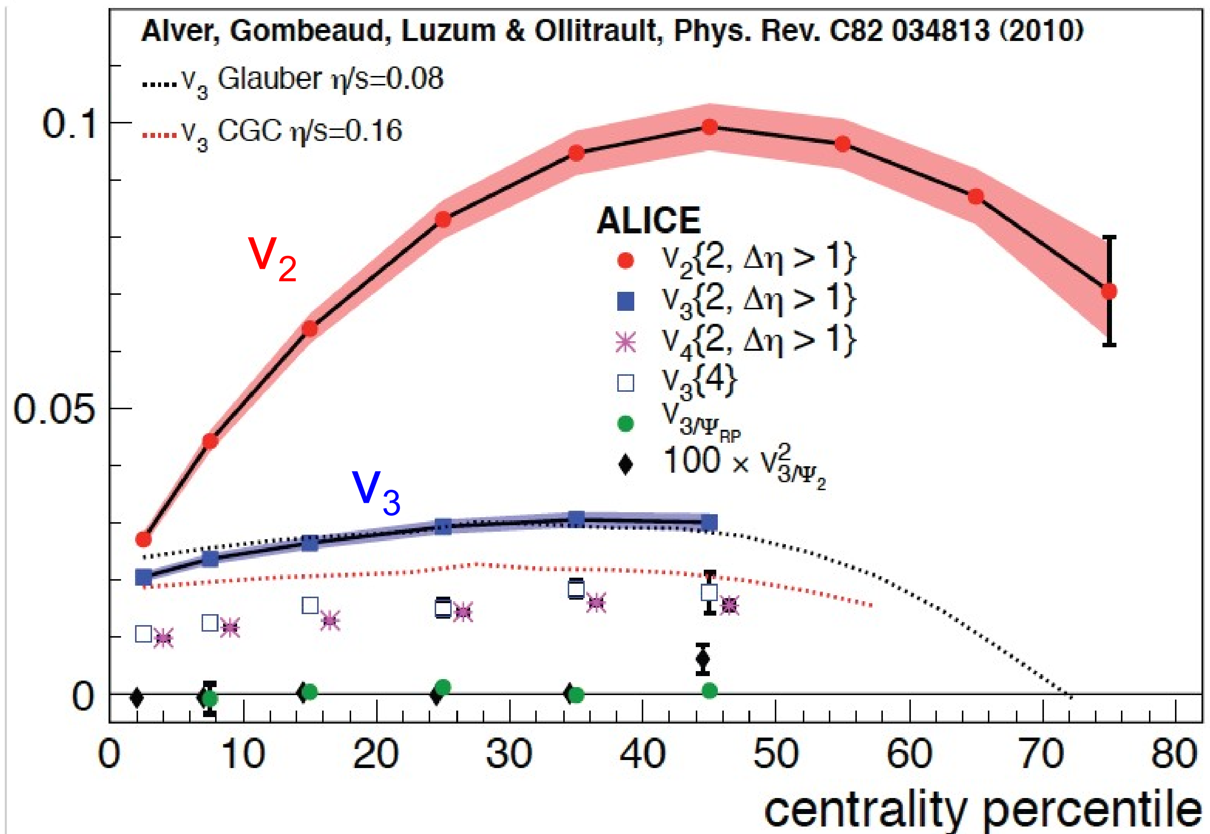


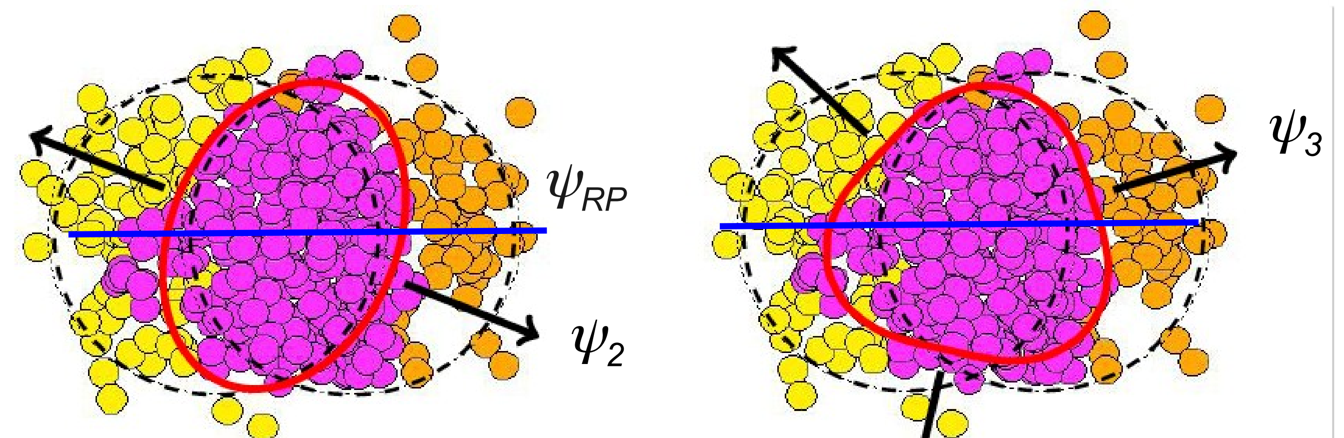
PRL, 107, 032301 (2011)

Global fits show:

- Collective flow dominates to about 3-4 GeV/c for all n>1
- Description breaks for high pT or peripheral collisions
- For low pT: double peak and ridge structures seen in two particle correlations are naturally explained by measured anisotropic flow coefficients

Higher harmonics w.r.t. to event plane

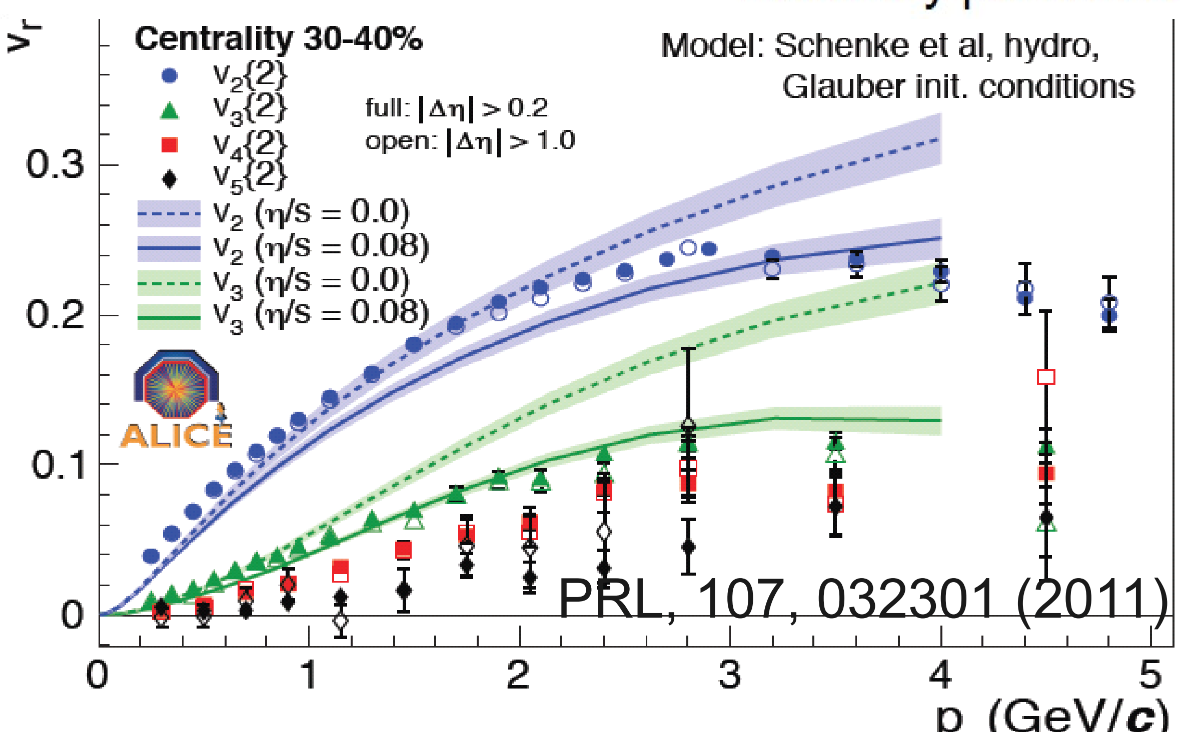




Alver, Roland, 2010

v_3 - triangular flow :

- weak centrality dependence
- vanishes as expected when measured w.r.t. reaction plane

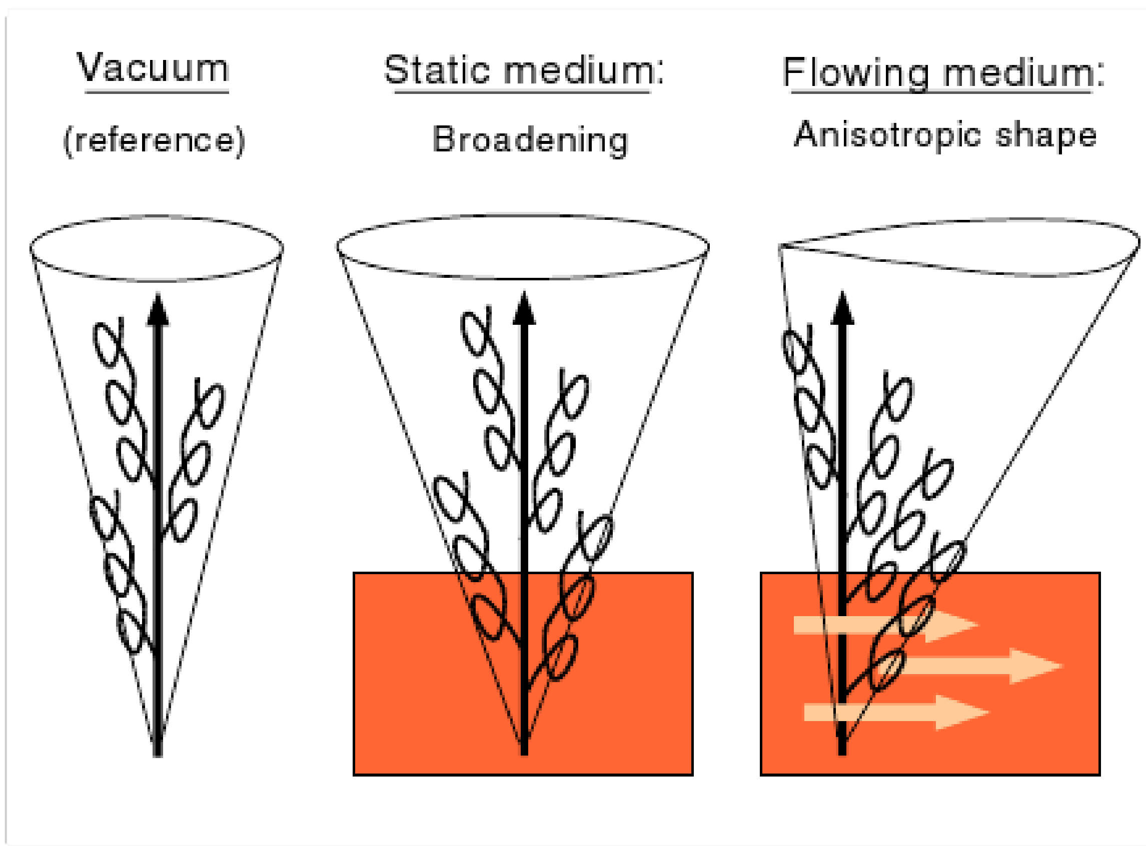


Similar pT dependence for all v_n

Higher harmonics - additional constraints on η/s !!!

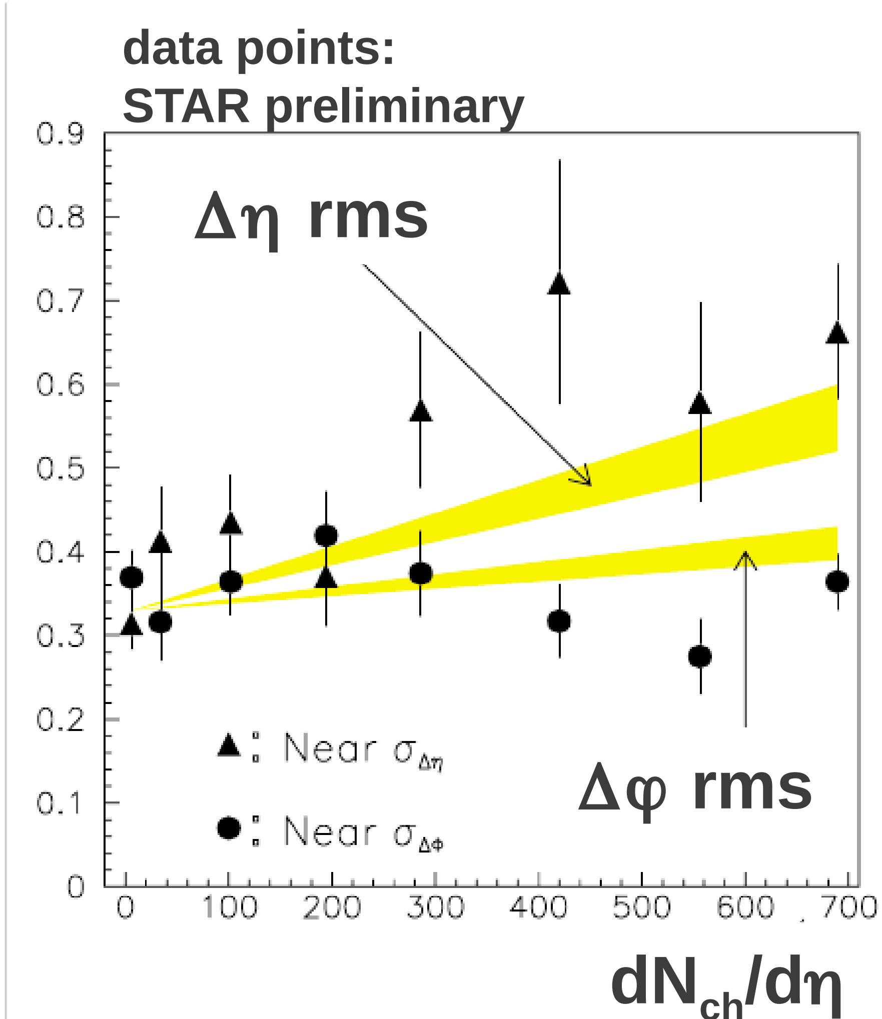
η/s small, similar as at RHIC

Jet-medium-flow coupling via two particle correlations?



N. Armesto, C. Salgado, U. Wiedemann:
Measuring the Collective Flow with Jets

[PRL 93,242301 (2004)]

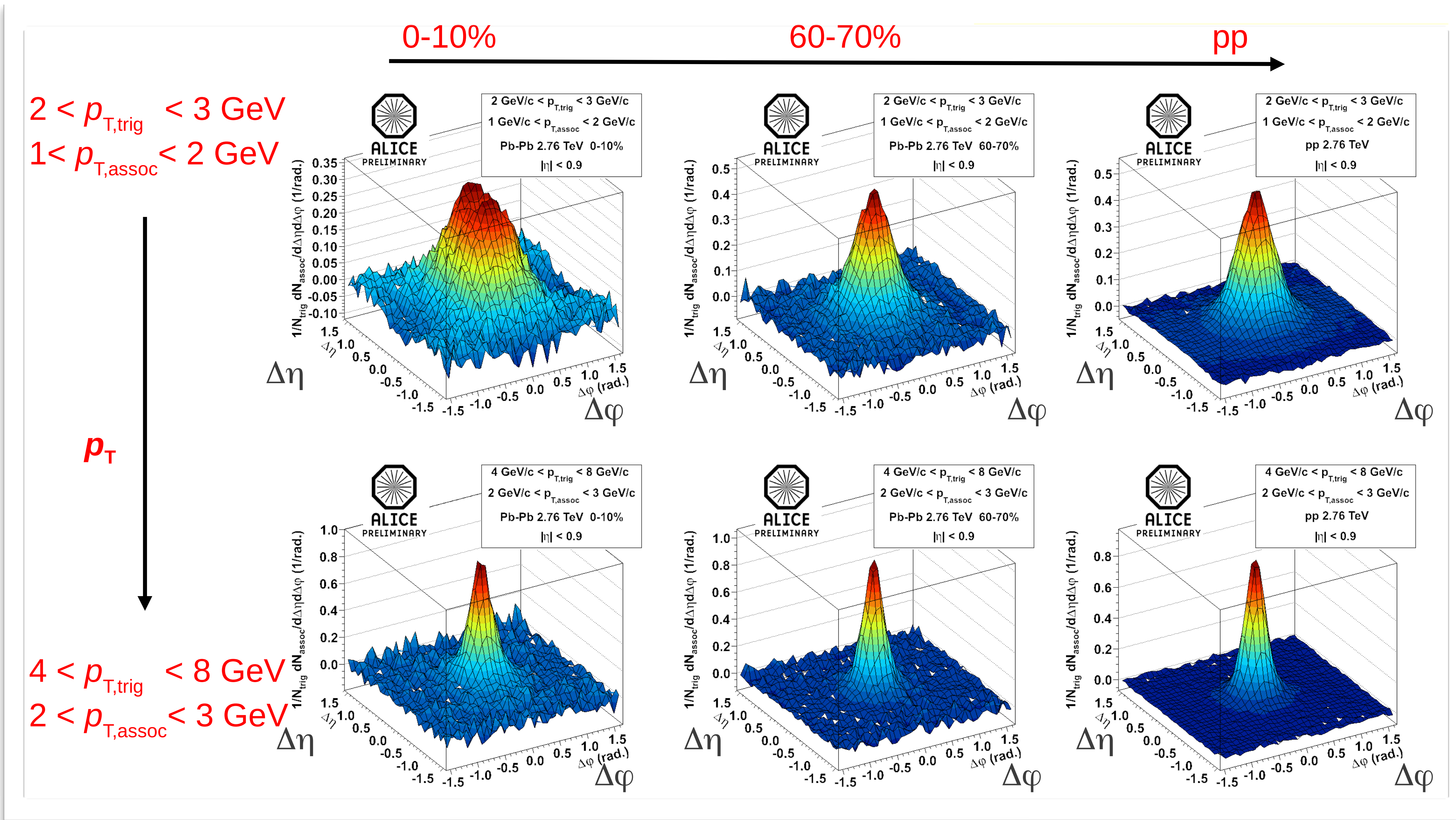


PRL 93,242301 (2004)

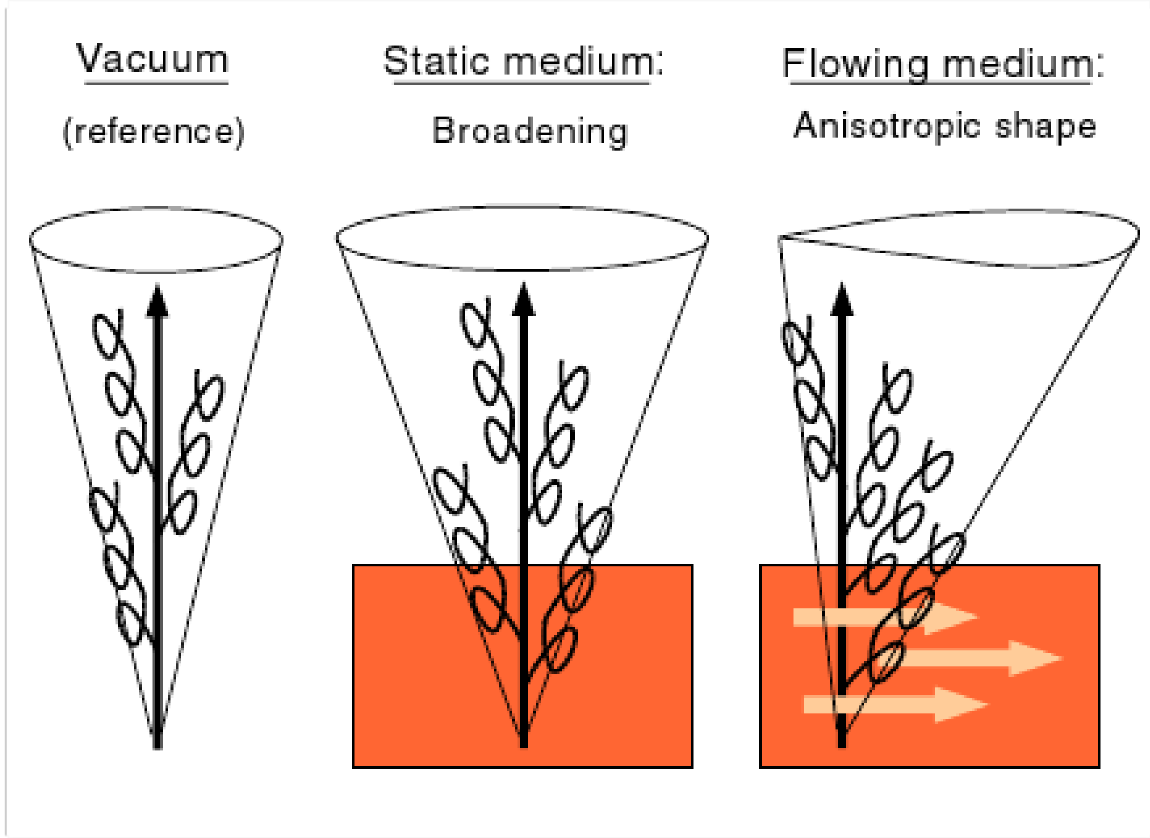
=> LHC? - more jets + somewhat more flow...

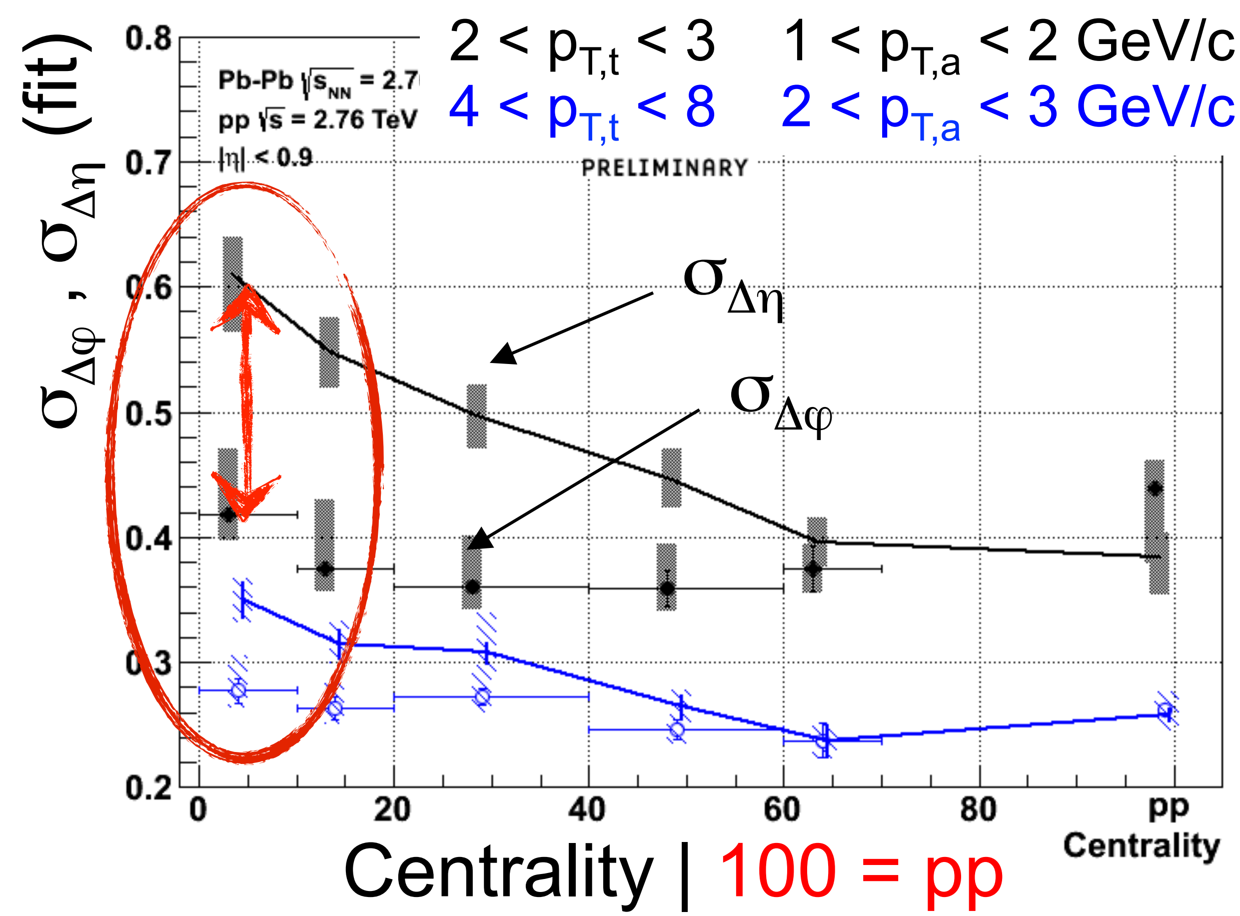
Jet-peak shape olution - intermediate pT

Wider peak in central collisions
Peripheral and p-p similar shape
Strong pT dependence
=> Characterize the peak



Measuring widths of the correlations in azimuth and pseudo-rapidity





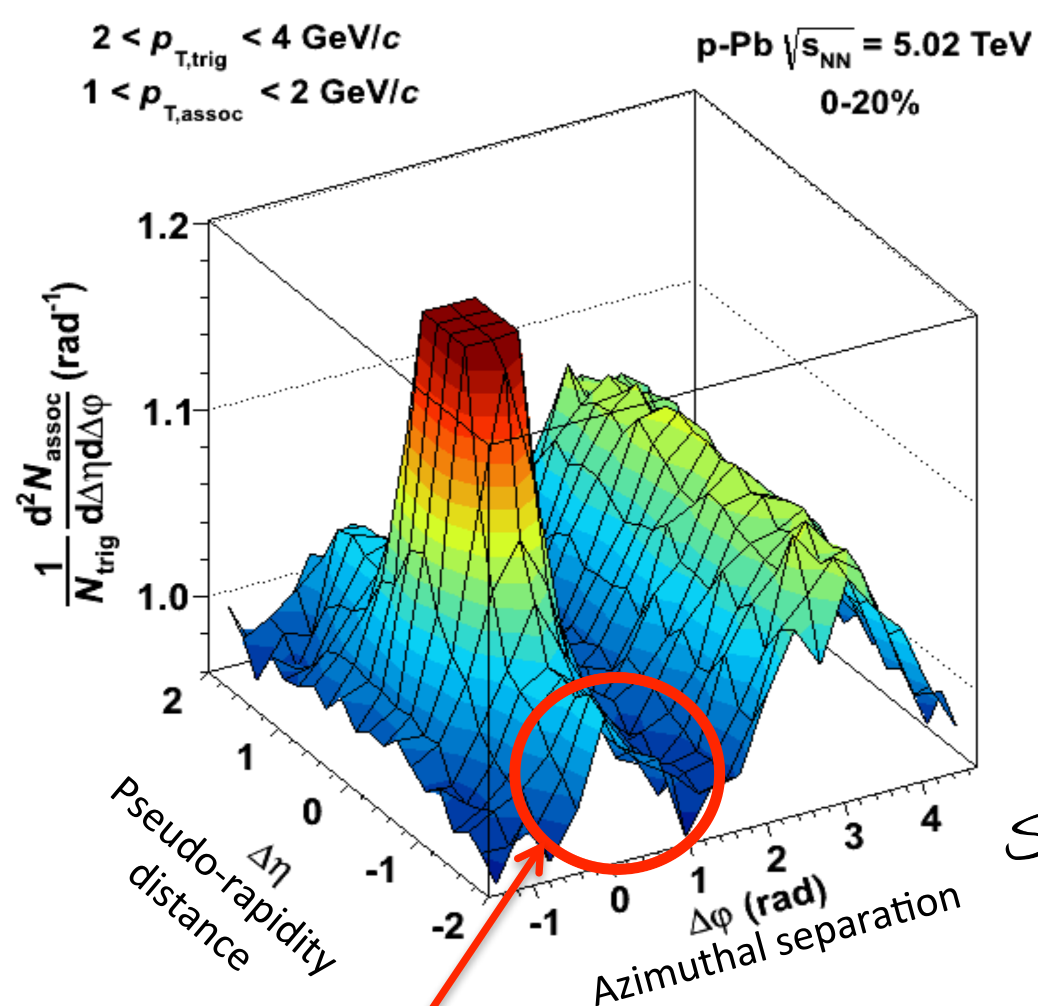
Measure of jets interactions with longitudinal flow (?)

- AMPT (**A** **M**ulti**P**hase **T**ransport Code)
  - Initial conditions simulated using HIJING
  - Parton scattering
  - Hadronization: Lund model + coalescence
  - Hadron scattering
- AMPT describes the main features of the near-side shape evolution observed in data

p-Pb collisions - new feature!

Correlations for pairs of trigger and associated particles, $p_{T,trig} > p_{T,assoc}$, as $f(\Delta\varphi, \Delta\eta)$, defined as associated yield per trigger particle

ALICE p-Pb **arXiv:1212.2001**



Long range correlation qualitatively similar to CMS

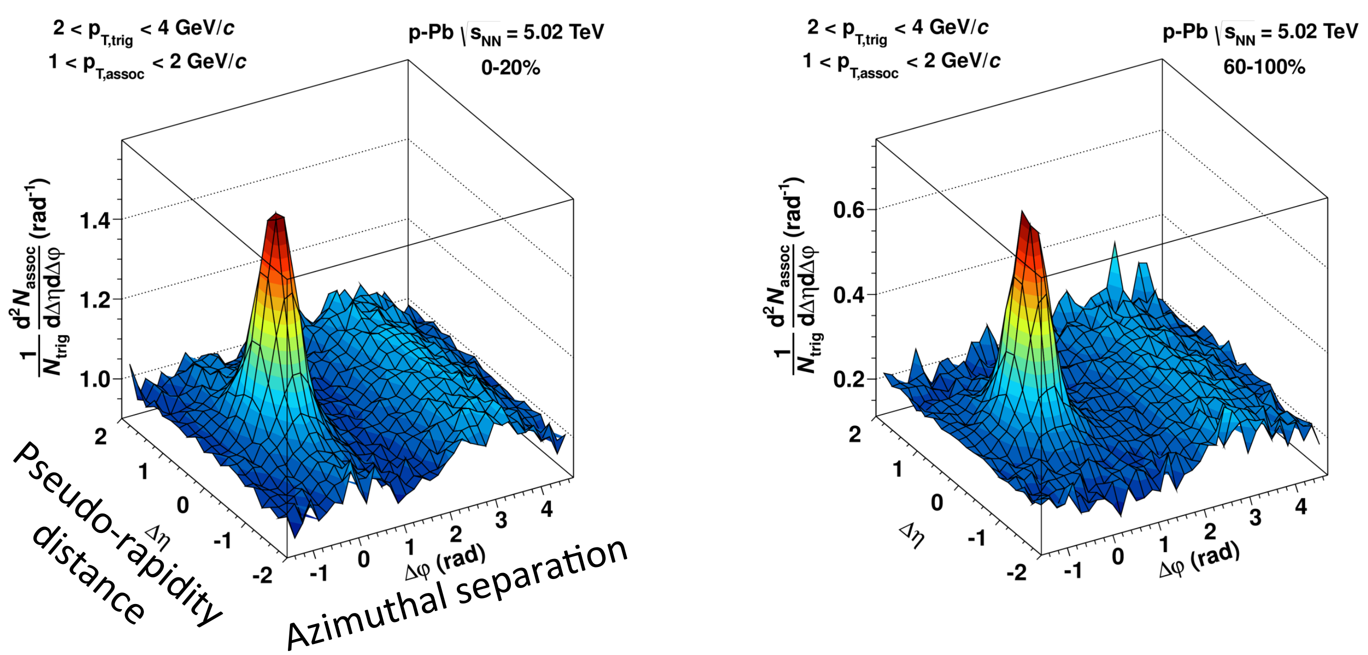
ALICE and CMS observe an elongated structure in high-multiplicity events!

Similar as CMS in even in p-p events...

¿ Who ordered that?

Extraction of the ridge properties

Method: from the high-multiplicity yield subtract the jet yield in low-multiplicity events (no ridge)



High multiplicity event class

$\langle dN_{ch}/d\eta \rangle \sim 35$

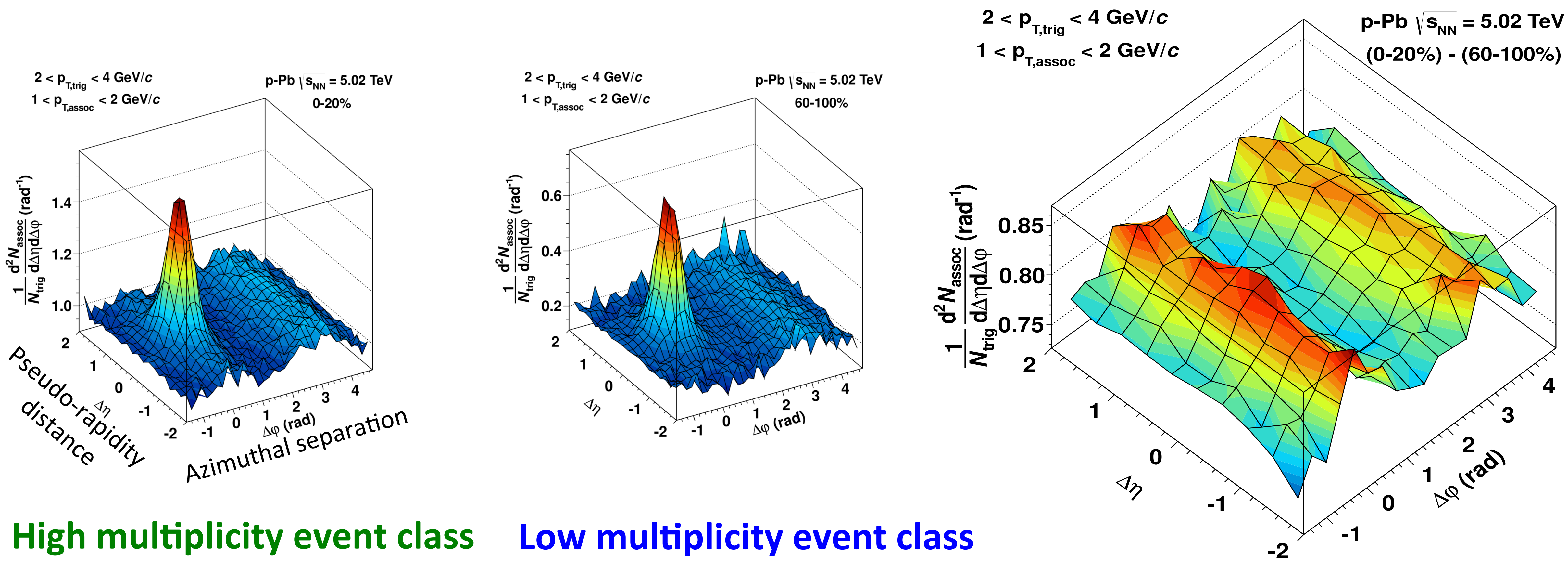
Low multiplicity event class

$\langle dN_{ch}/d\eta \rangle \sim 7$

Analysis in multiplicity classes defined by the total charge in VZERO detector (away from the central region)

Extraction of the ridge properties

The method: from the high-multiplicity yield subtract the jet yield in low-multiplicity events (no ridge)



High multiplicity event class

$\langle dN_{ch}/d\eta \rangle \sim 35$

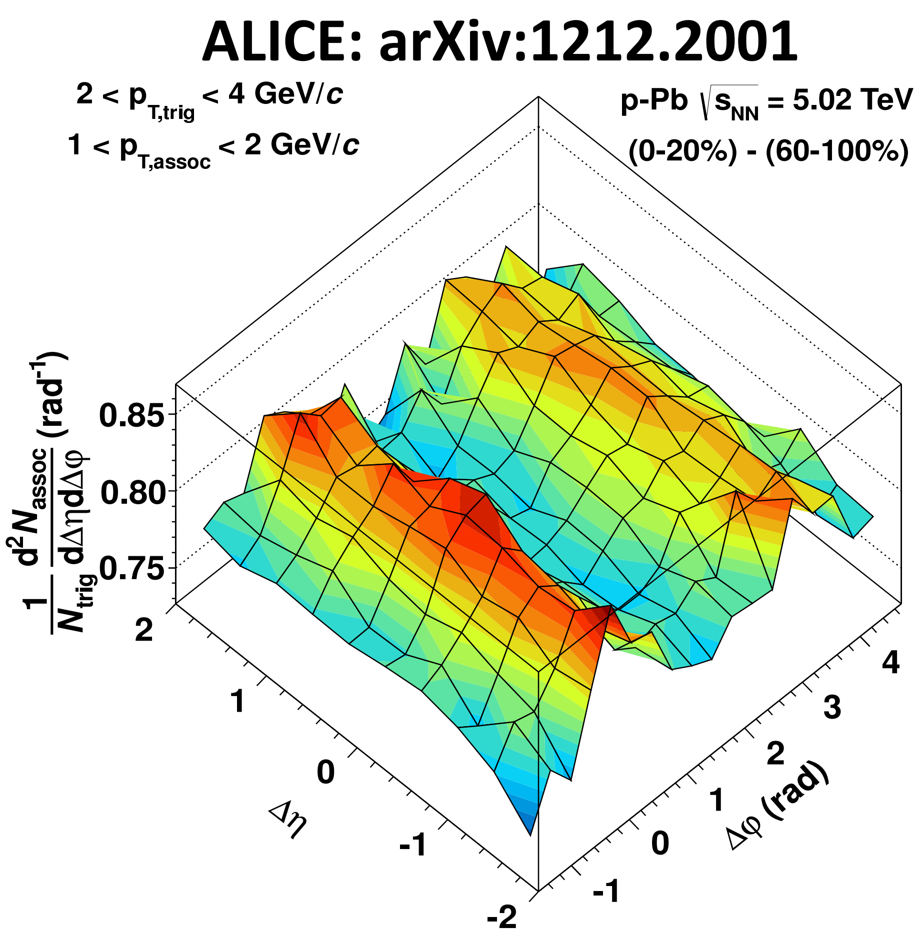
Low multiplicity event class

$\langle dN_{ch}/d\eta \rangle \sim 7$

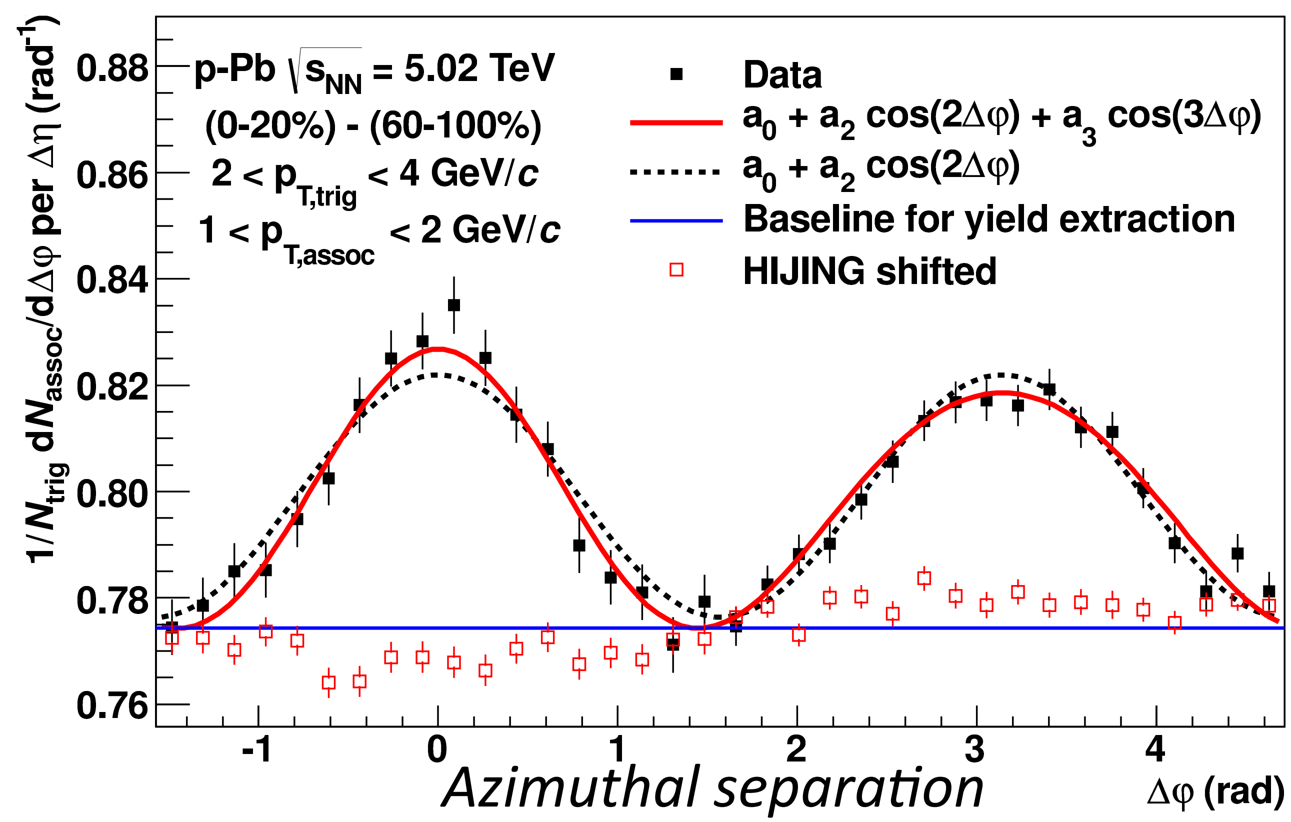
Remaining correlation: two twin long range structures

Analysis in multiplicity classes defined by the total charge in VZERO detector (away from the central region)

Twin ridge structure uncovered – also in pA collisions



Remaining correlation described by finite amplitudes of Fourier terms



Further investigations reveal:

- **the full modulation is (1) di-jets and (2) the double-ridge structure – nothing more**
- **Same yield near and away side for all classes of p_T and multiplicity suggest a common underlying process**

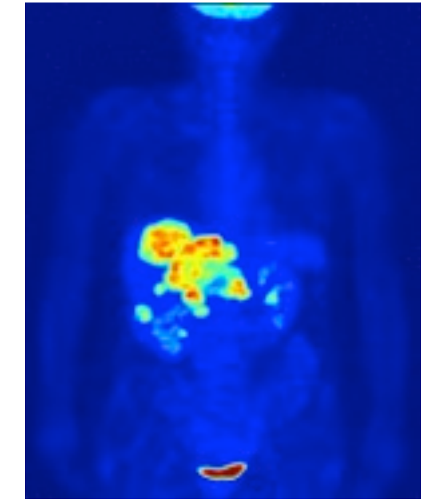
Similar observations in Pb-Pb are ascribed to collective effects!

First explanations are being put forward:

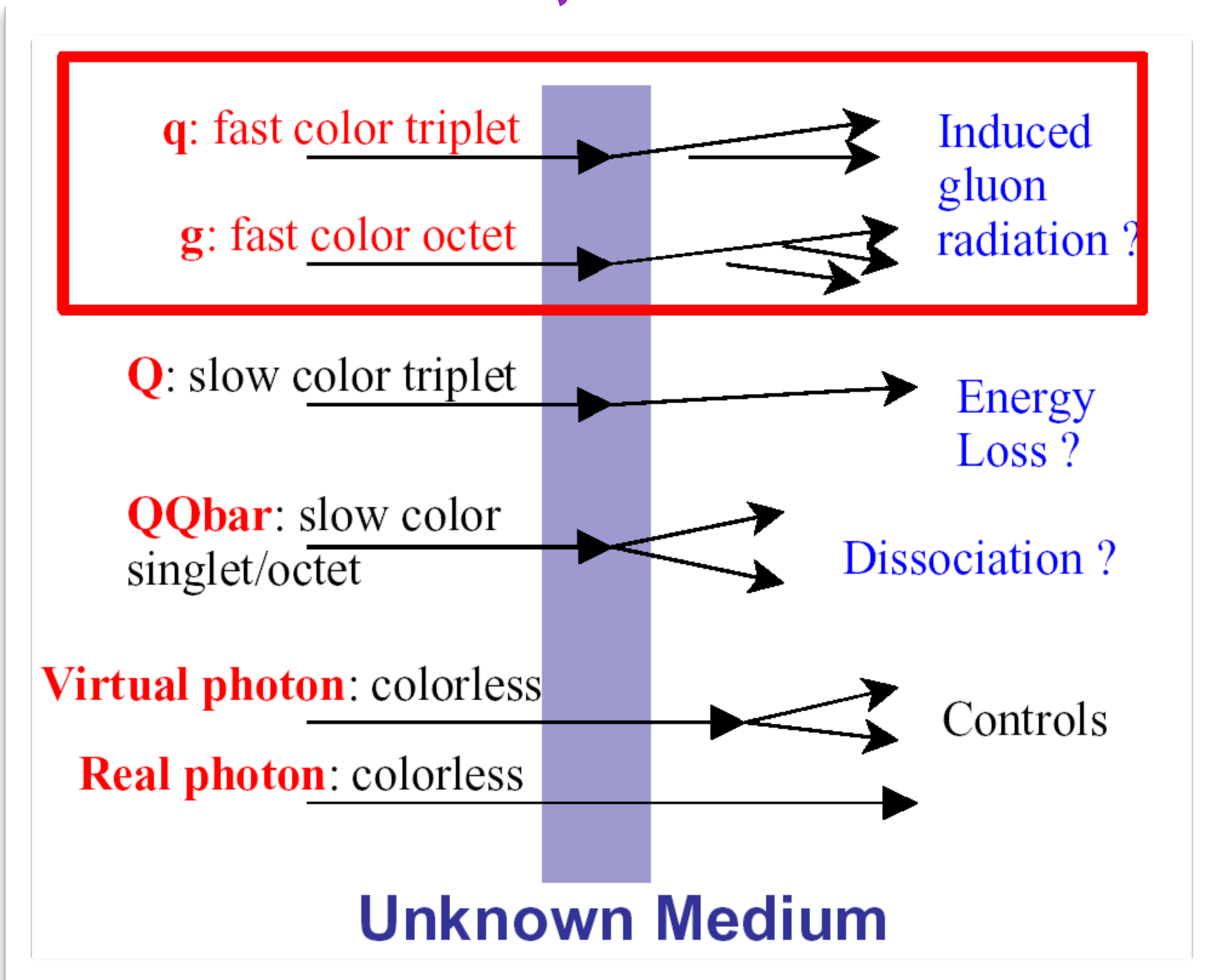
- Hydrodynamics – arXiv: 1112.0915
- Colour Glass Condensate – arXiv:1211.3701

Probing an unknown medium...

Probing the unknown medium...



Human



jet suppression (quenching)

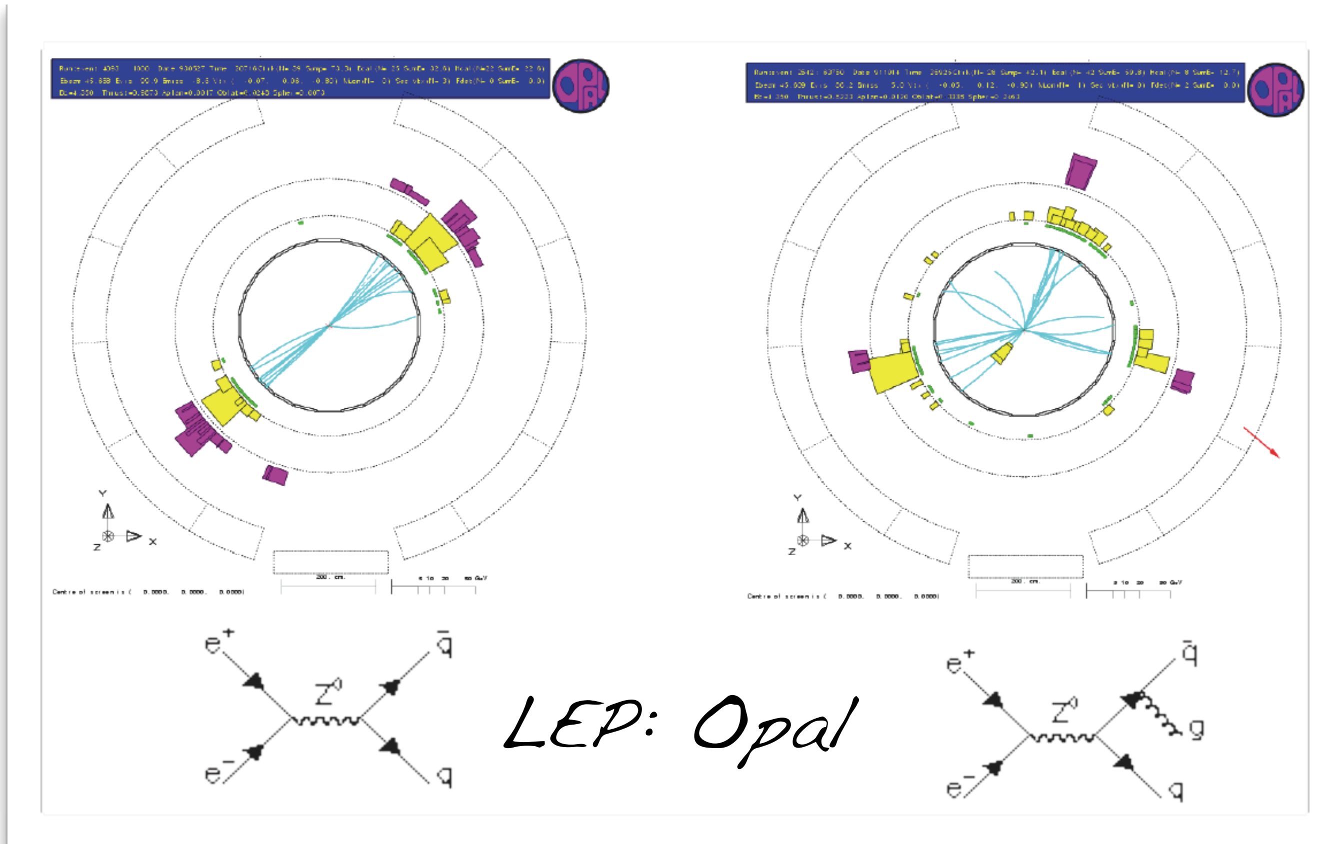
charm/bottom dynamics

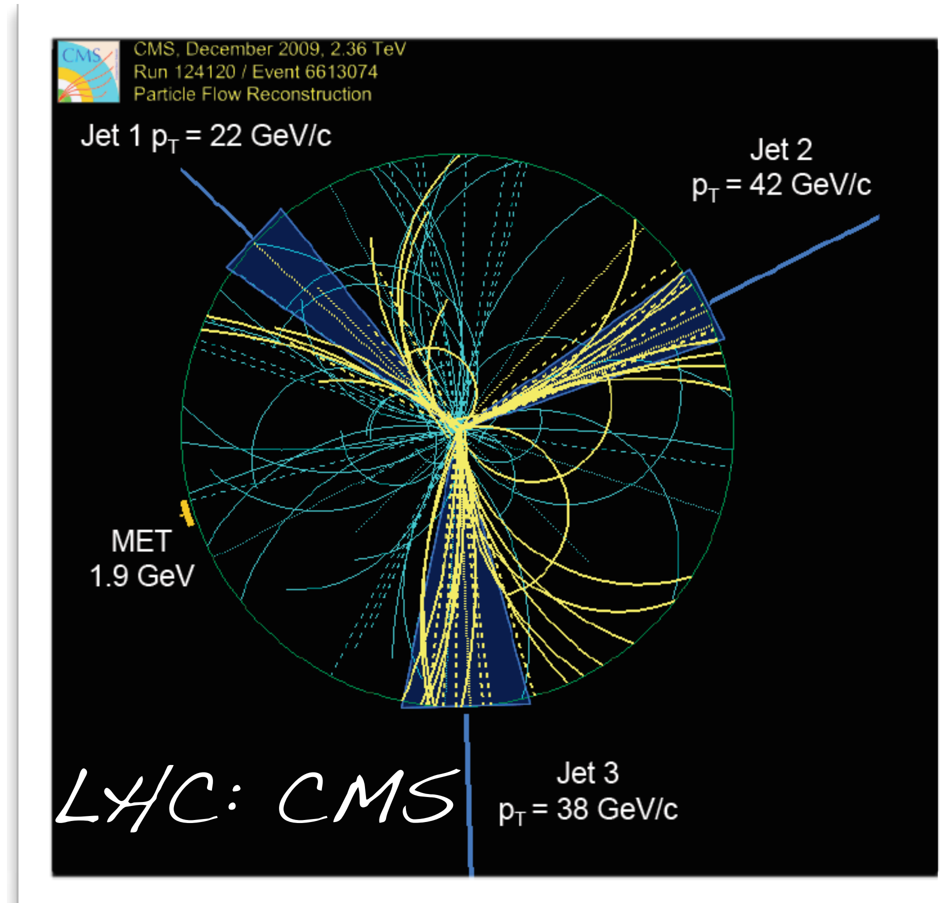
J/ψ & Υ

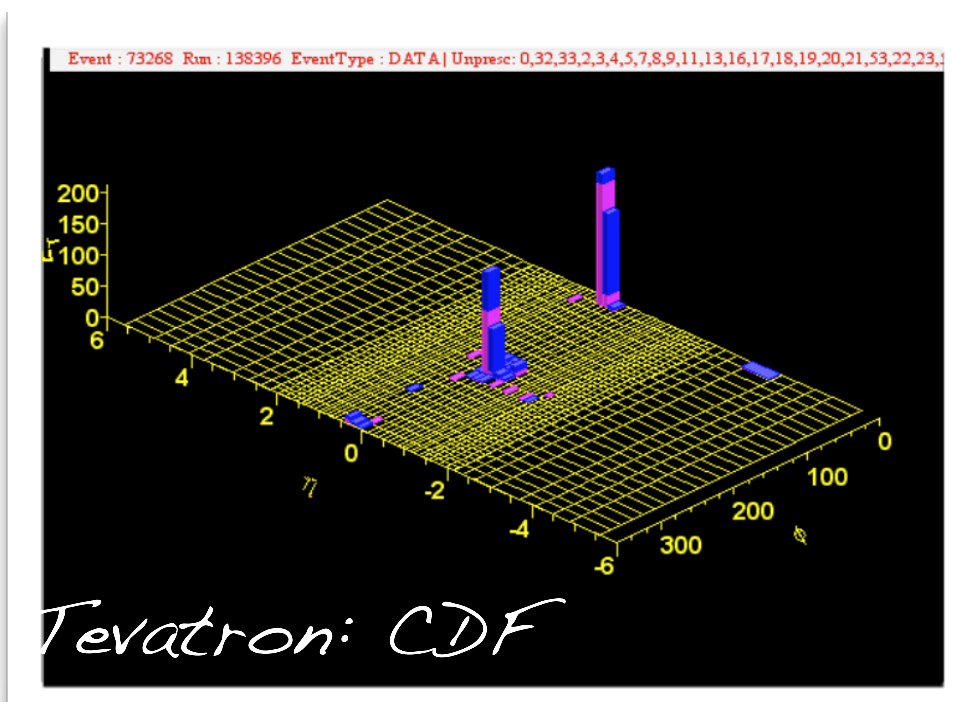
color-less particles

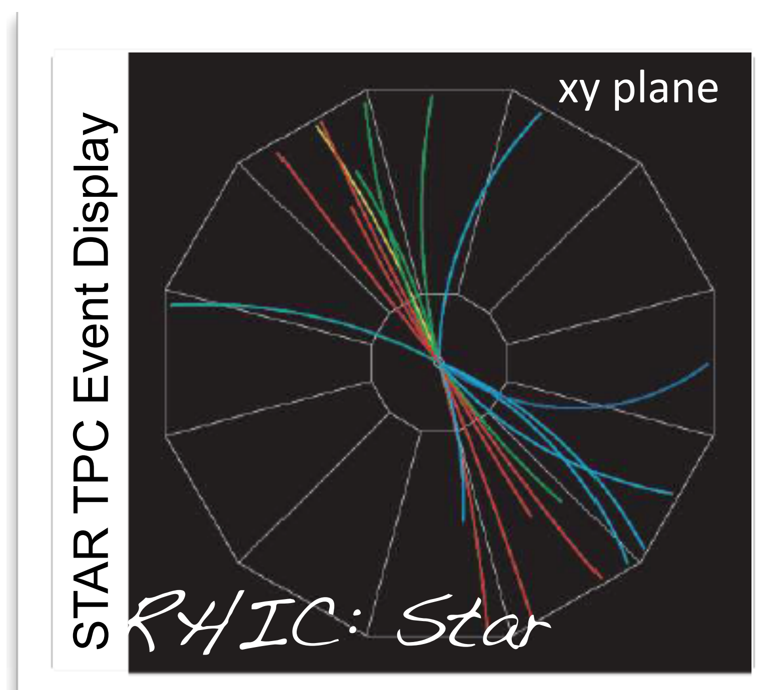
Note: these probes are auto-generated within heavy-ion collisions - need to know "input" intensity (p-p collisions)

Jets in collider experiments









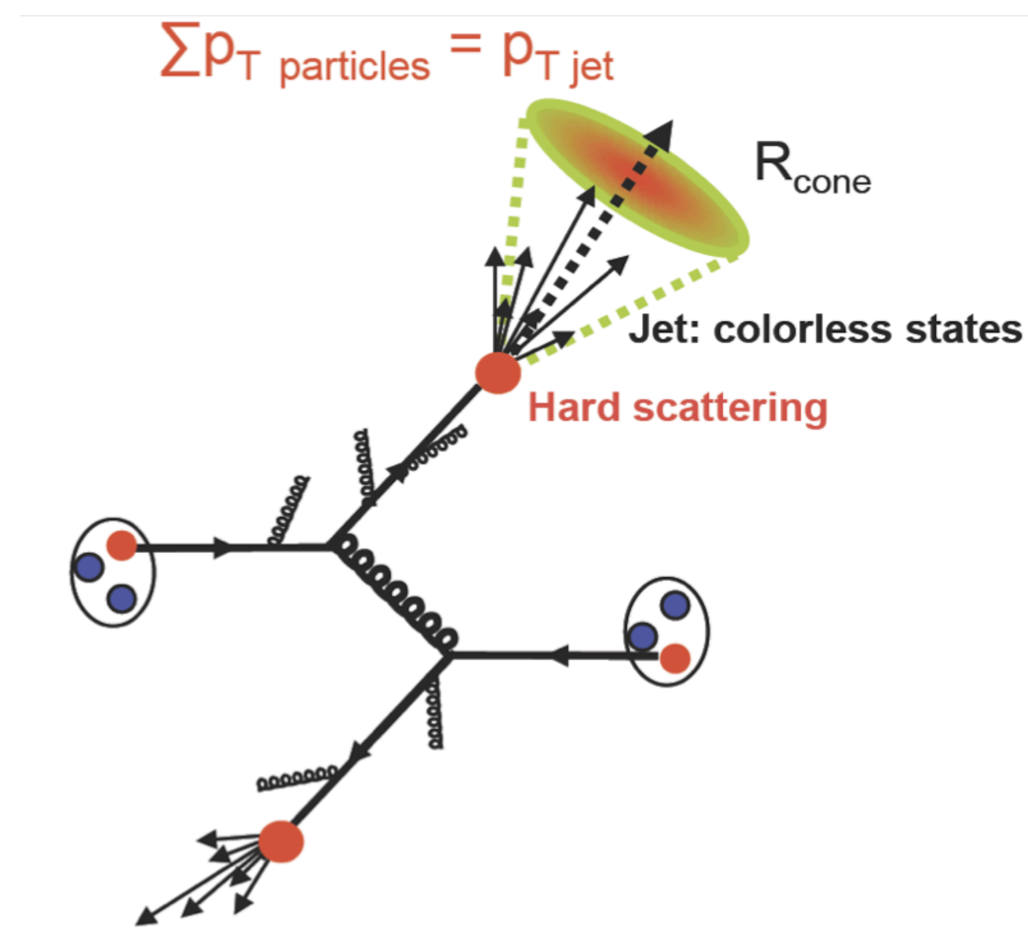
What is a jet?

A spray of collimated showers/particles
- Hardly ever better defined...

Jet = Parton AND its radiation

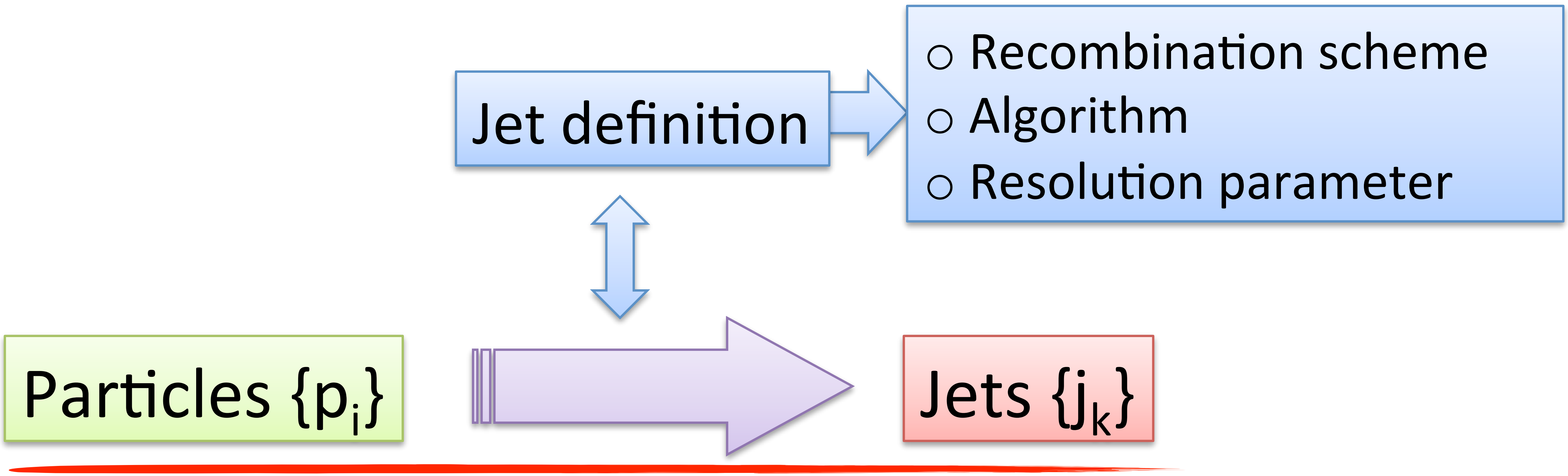
Note: experiment measures spray of particles (~hadrons)

Jets (unlike single hadrons) are objects which are "better" understood/ calculable within pQCD



S.D Drell, D.J.Levy and T.M. Yan, Phys. Rev. **187**, 2159 (1969)
N. Cabibbo, G. Parisi and M. Testa, Lett. Nuovo Cimento **4**,35 (1970)
J.D. Bjorken and S.D. Brodsky, Phys. Rev. D 1, 1416 (1970)
Sterman and Weinberg, Phys. Rev. Lett. 39, 1436 (1977) ...

Jet finding



Note: jets originate from hard partons, however definition of a parton in terms of a jet is ambiguous -> multiple jet definitions.

Optimum jet finder algorithm

Several important properties that should be met by a jet definition are [3]:

1. Simple to implement in an experimental analysis;
2. Simple to implement in the theoretical calculation;
3. Defined at any order of perturbation theory;
4. Yields finite cross section at any order of perturbation theory;
5. Yields a cross section that is relatively insensitive to hadronization.

Tevatron 1990

... and infrared safe and colinear safe

(~2000)

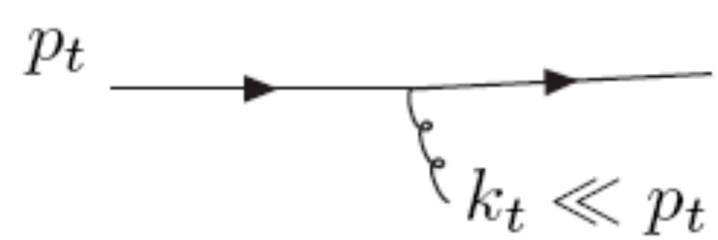
QCD divergencies and jet finders

QCD probability for gluon bremsstrahlung at angle θ and $\perp$-mom. k_t:

$$dP \propto \alpha_s \frac{d\theta}{\theta} \frac{dk_t}{k_t}$$

Two divergences:

Collinear

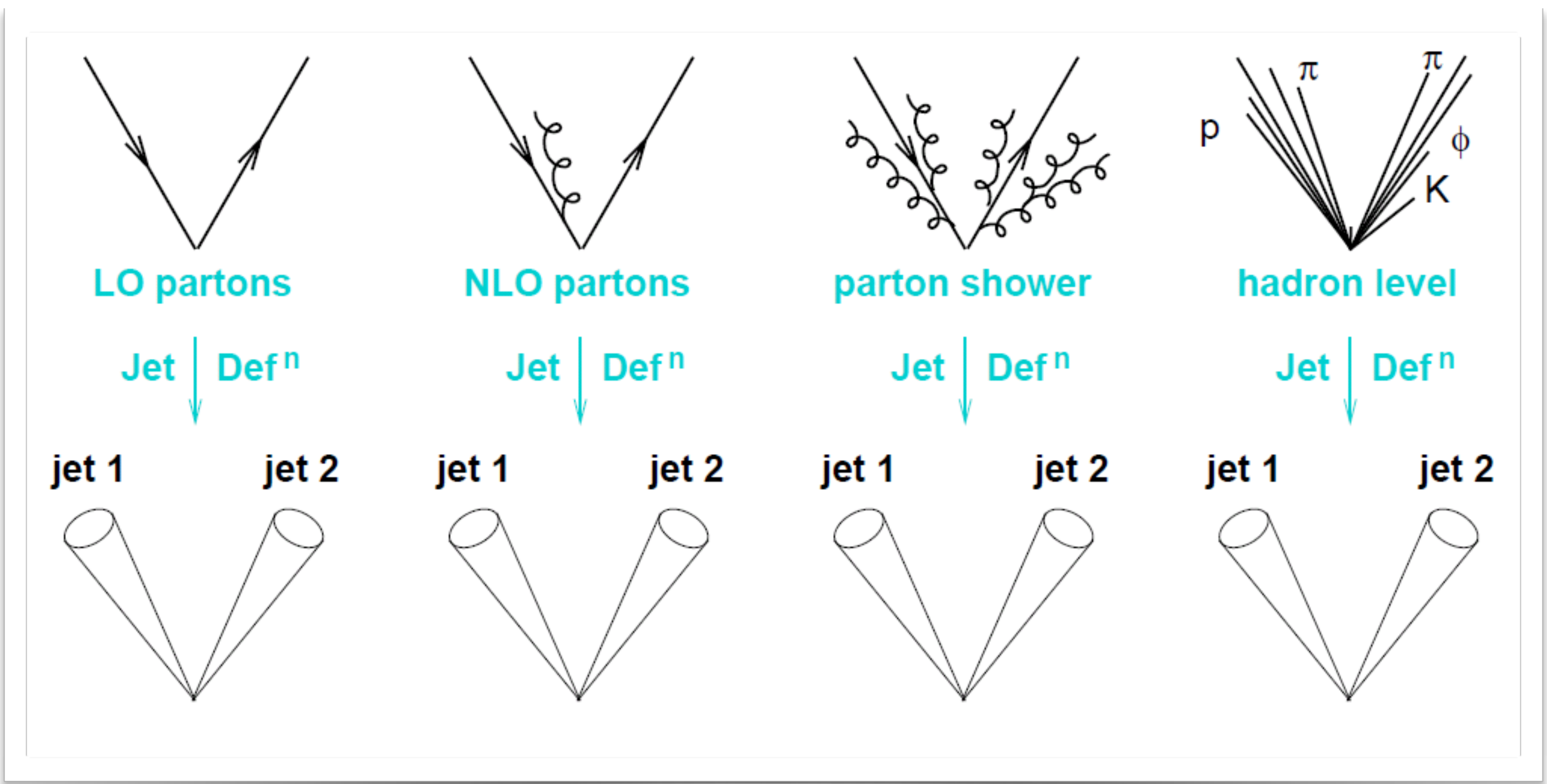


Soft

For pQCD to make sense, the (hard) jets should not change when

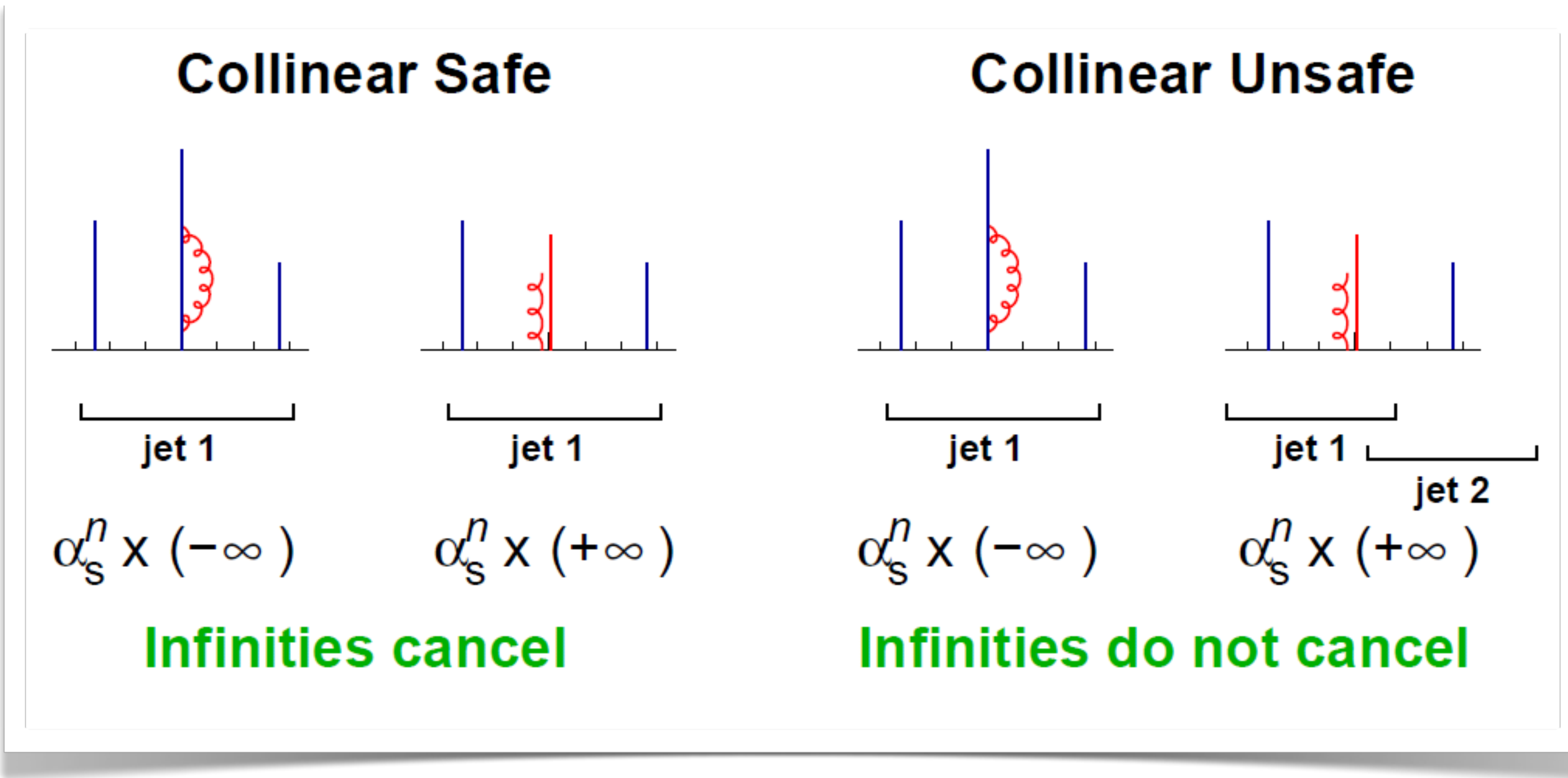
- one has a collinear splitting
  i.e. replaces one parton by two at the same place (η, ϕ)
- one has a soft emission *i.e.* adds a very soft gluon

Jet algorithms: Colinear & infra-red safety



Safety: Results = jets = reconstructed objects - insensitive to modifications at the soft scale of radiation (hadronization, soft colin. radiation)

Collinear safety

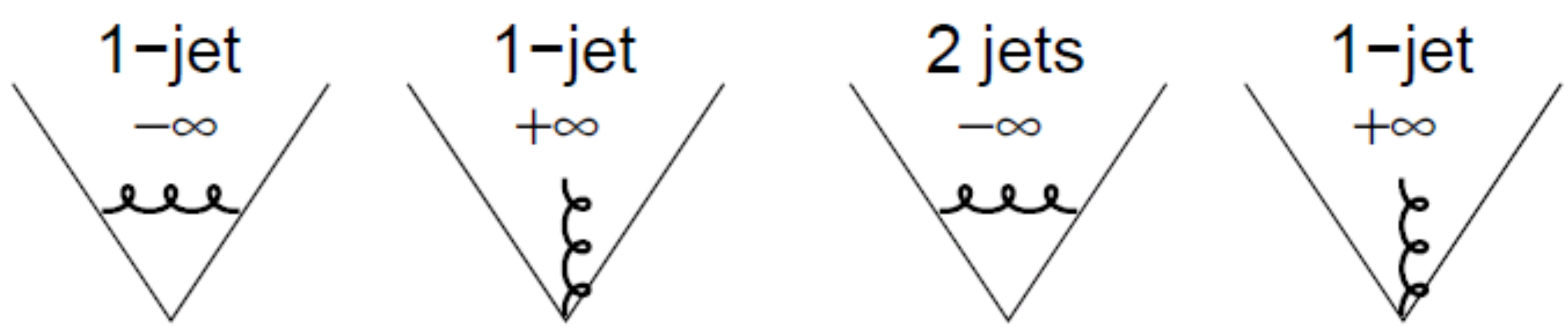


Infrared safety

Soft emission, collinear splitting are both **infinite** in pert. QCD.

Infinities **cancel** with loop diagrams if jet-alg IRC safe

IRC safe | **IRC unsafe**



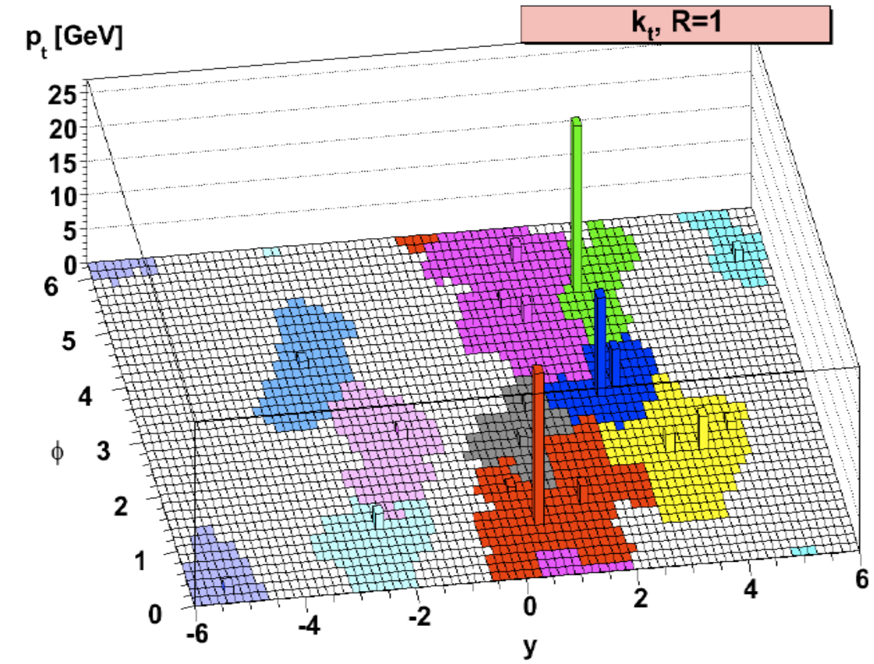
sum is finite | sum is infinite

Some calculations simply become **meaningless**

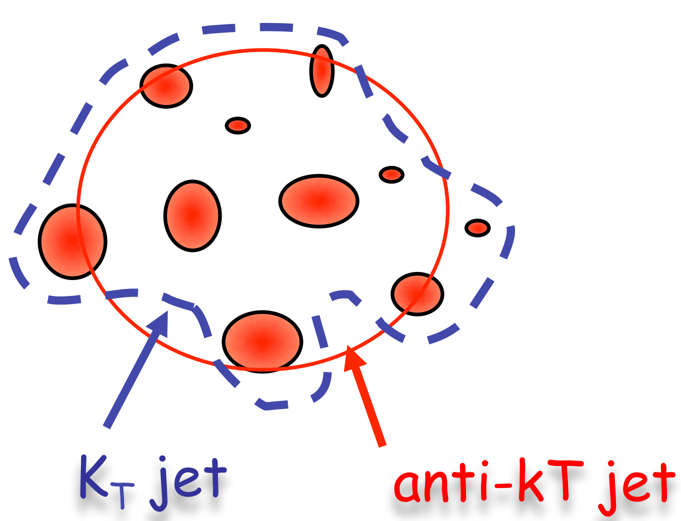
Infrared safety also implies robustness against soft background in heavy ion collisions

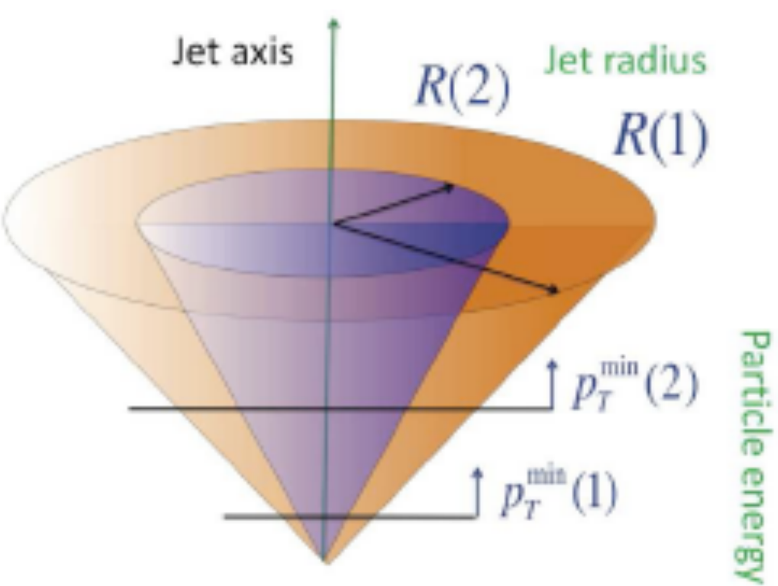
Modern jet algorithms

- Colinear and infrared safe
- Improved performance
- Rigorous definition of jet area
- Different algorithms -> different response to the underlying event
  - Developed for uniform bg subtraction (pile-up) at LHC



Two main classes of algorithms:
recombination (kt, Cambridge/Aachen, anti-kt) and cone (Mid point cone, CDF, SIScone)





Sequential recombination (clustering) algorithms

Majority of QCD branching is soft & collinear, with following divergences:

$$[dk_j]|M^2_{g\to g_i g_j}(k_j)| \simeq \frac{2\alpha_s C_A}{\pi} \frac{dE_j}{\min(E_i, E_j)} \frac{d\theta_{ij}}{\theta_{ij}}, \qquad (E_j \ll E_i\,, \;\; \theta_{ij} \ll 1)\,.$$

To invert branching process, take pair with strongest divergence between them — they're the most *likely* to belong together.

This is basis of **k_t/Durham algorithm** (e^+e^-):

1. Calculate (or update) distances between all particles i and j:

$$y_{ij} = \frac{2\min(E_i^2, E_j^2)(1-\cos\theta_{ij})}{Q^2}$$

NB: relative k_t between particles

2. Find smallest of y_{ij}
   - If $> y_{cut}$, stop clustering
   - Otherwise recombine i and j, and repeat from step 1

Catani, Dokshitzer, Olsson, Turnock & Webber '91

Example: k_T algorithm

1.1 k_t jet algorithm

The definition of the inclusive k_t jet algorithm that is coded is as follows:

1. For each pair of particles i, j work out the k_t distance

$$d_{ij} = \min(k_{ti}^2, k_{tj}^2)\, \Delta R_{ij}^2 / R^2 \tag{1}$$

   with $\Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$, where k_{ti}, y_i and ϕ_i are the transverse momentum, rapidity and azimuth of particle i and R is a jet-radius parameter usually taken of order 1; for each parton i also work out the beam distance $d_{iB} = k_{ti}^2$.

2. Find the minimum $d_{\min}$ of all the d_{ij}, d_{iB}. If $d_{\min}$ is a d_{ij} merge particles i and j into a single particle, summing their four-momenta (this is E-scheme recombination); if it is a d_{iB} then declare particle i to be a final jet and remove it from the list.

3. Repeat from step 1 until no particles are left.

Anti-kt: k_t^2 is replaced by k_t^{-1}

M. Cacciari, G. P. Salam, G. Soyez JHEP 0804:063,2008. e-Print: arXiv:0802.1189 [hep-ph]

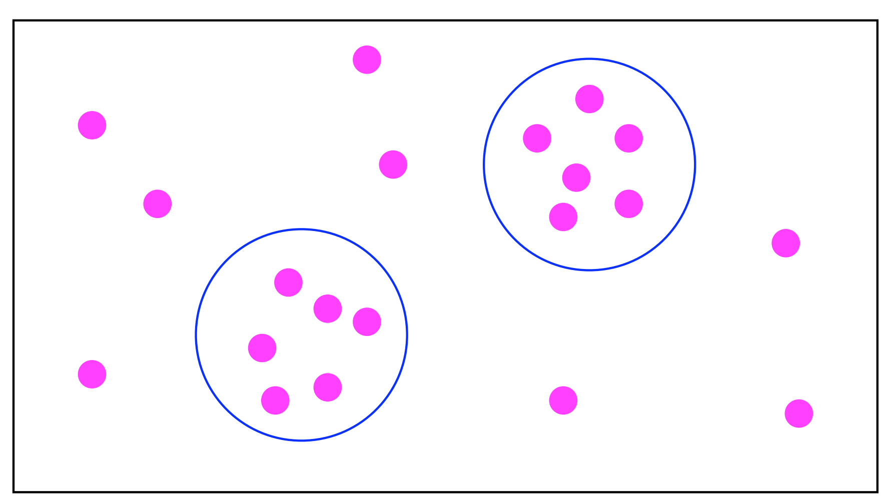
Cone algorithms

Jet Cones

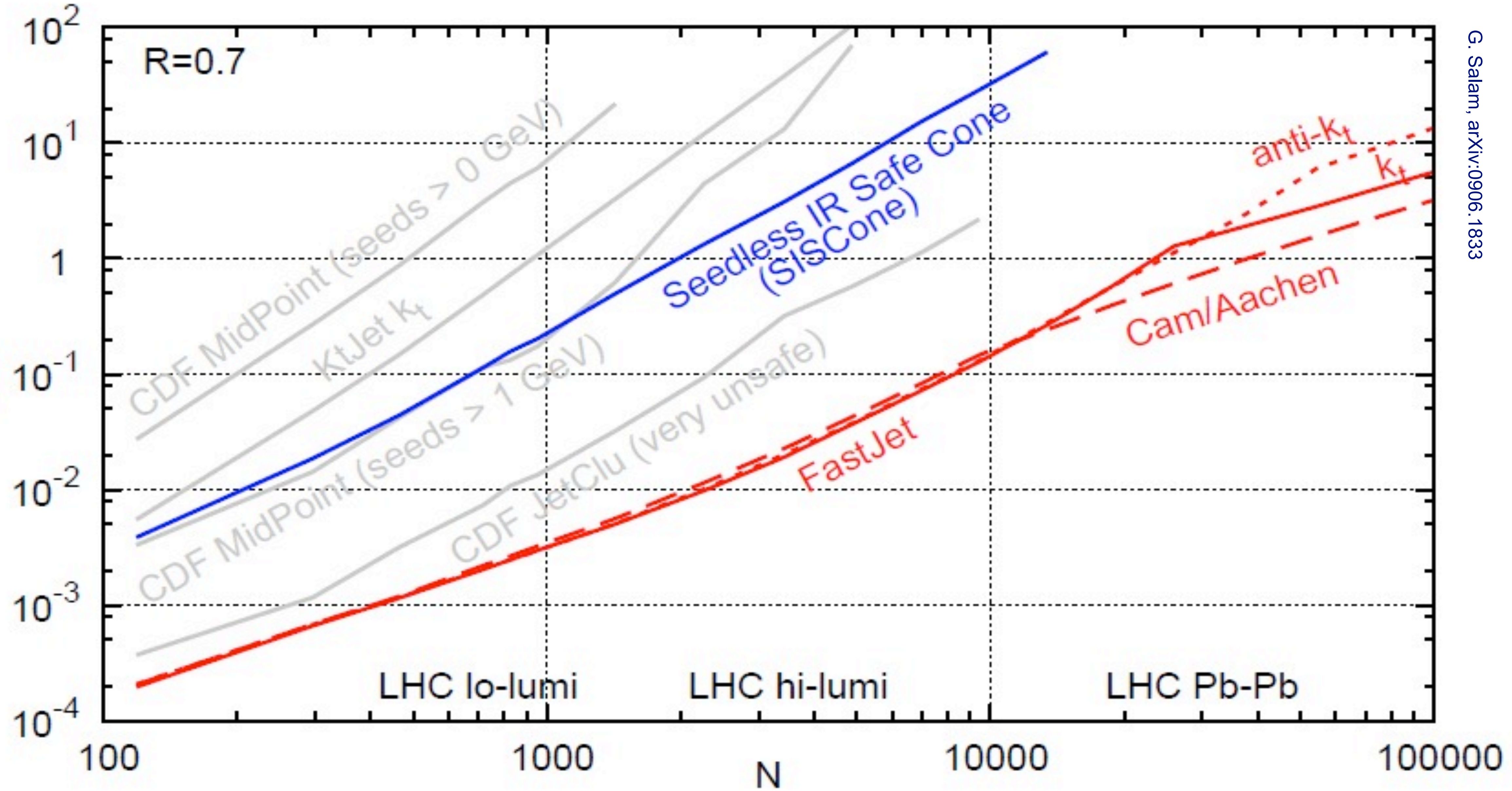
- Cones are always understood as circles in rapidity (y) and azimuth ϕ.
- A particle i is within the cone of radius R around the axis a if
  - $\Delta R^2_{ia} = (y_i - y_a)^2 + (\phi_i - \phi_a)^2 < R^2$
  - ... usual hadron collider variables
- Typical: R = 0.4 - 0.7

Basic Idea:

- Find directions of dominant energy flow " find ALL stable cones
- center of the cone ≡ direction of the total momentum of its particle contents



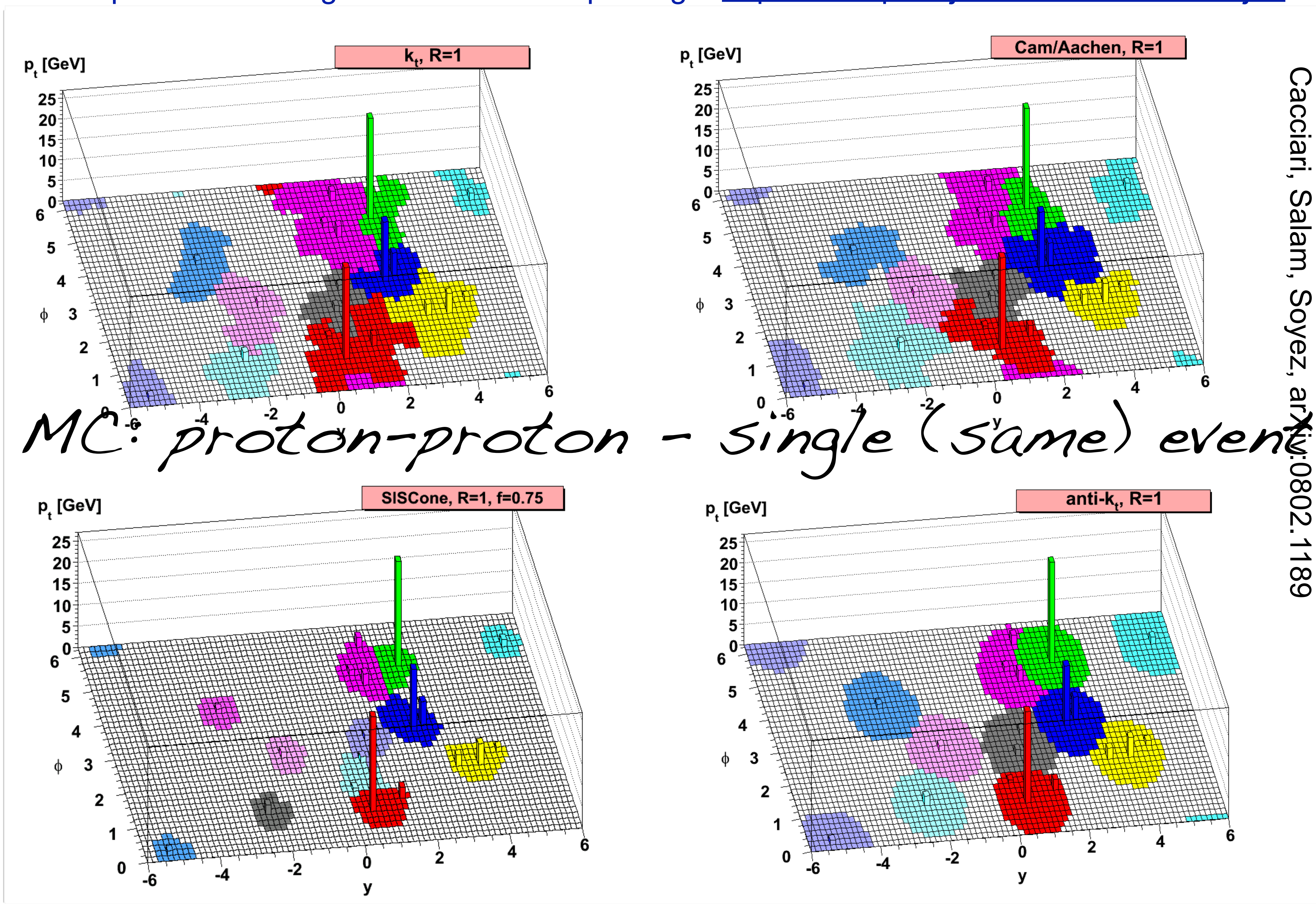
Speed matters!



FJ: Significant gain for high-multiplicities

Jet finding - jet finders

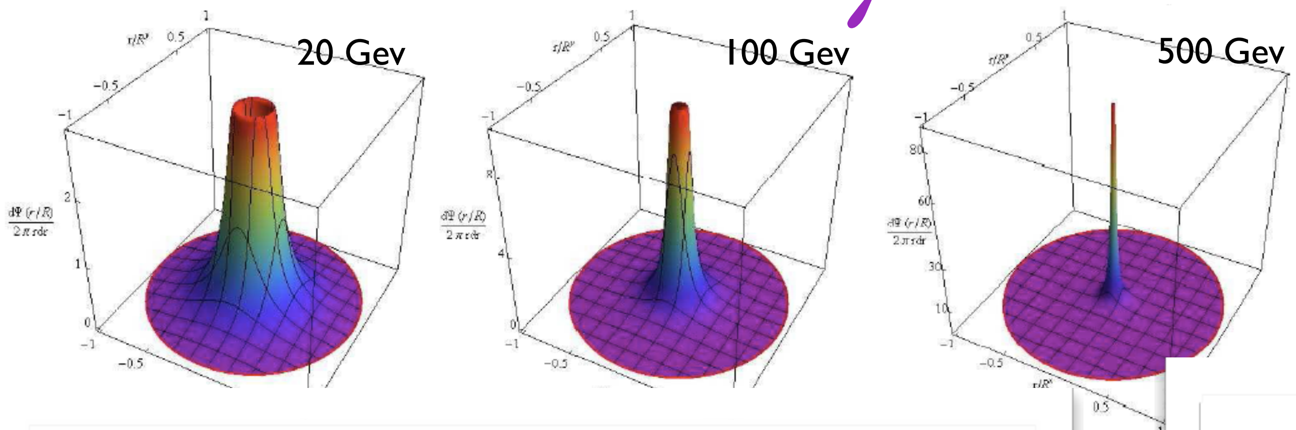
Complete suite of algorithms - FastJet package: http://www.lpthe.jussieu.fr/~salam/fastjet/

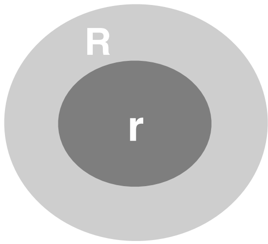


MC: proton-proton - single (same) event

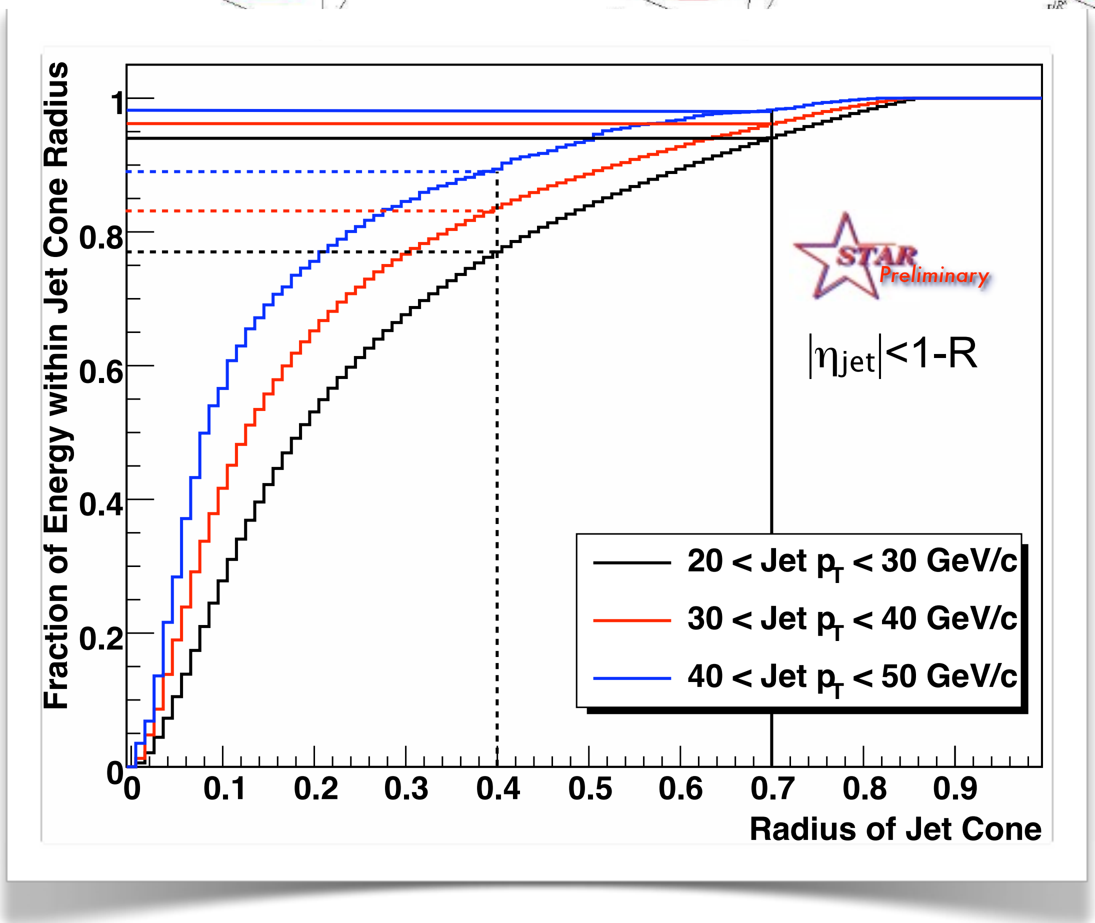
Cacciari, Salam, Soyez, arXiv:0802.1189

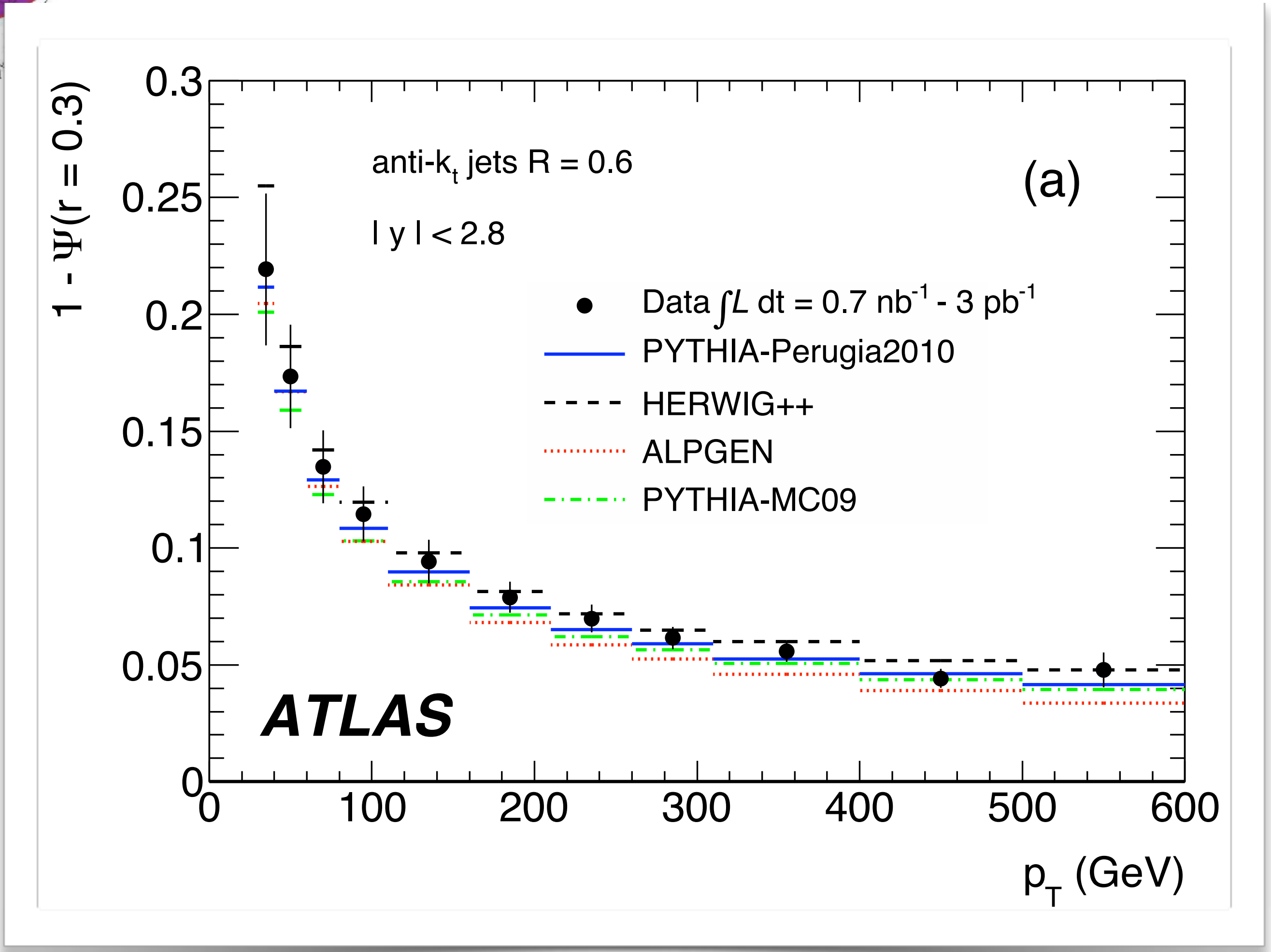
Jet shape - R-dependence





$$\Psi(r) = \frac{1}{N^{\text{jet}}} \sum_{\text{jets}} \frac{p_T(0,r)}{p_T(0,R)}$$





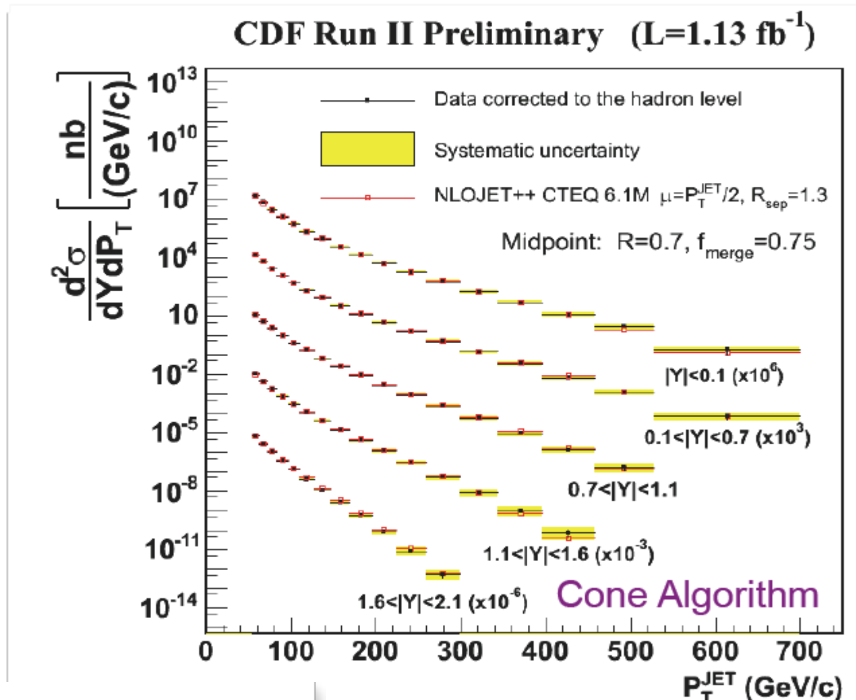
Jets get more collimated/narrower with increasing jet energy

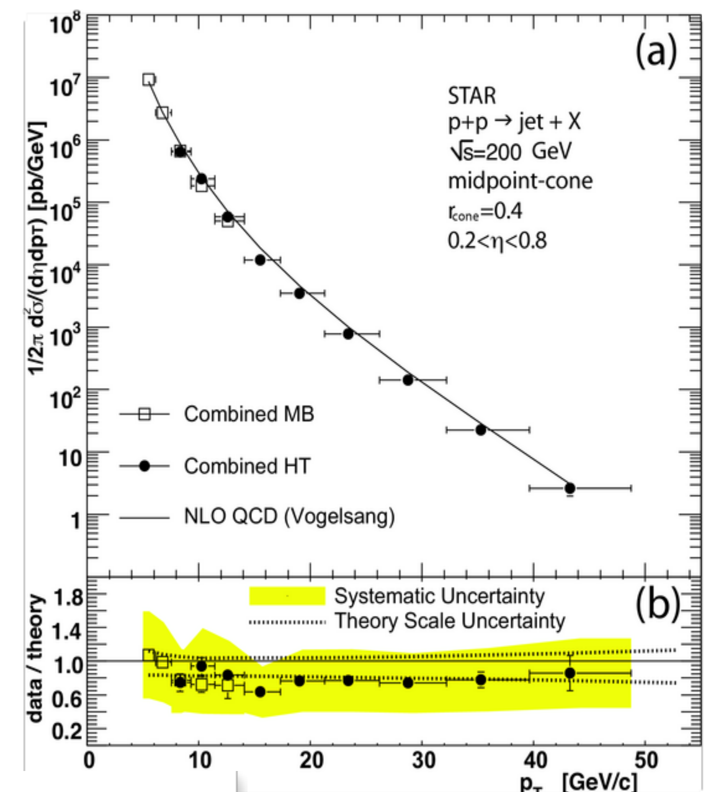
Energy - integrated within a smaller R - depends on R!
=> importance of the jet definition

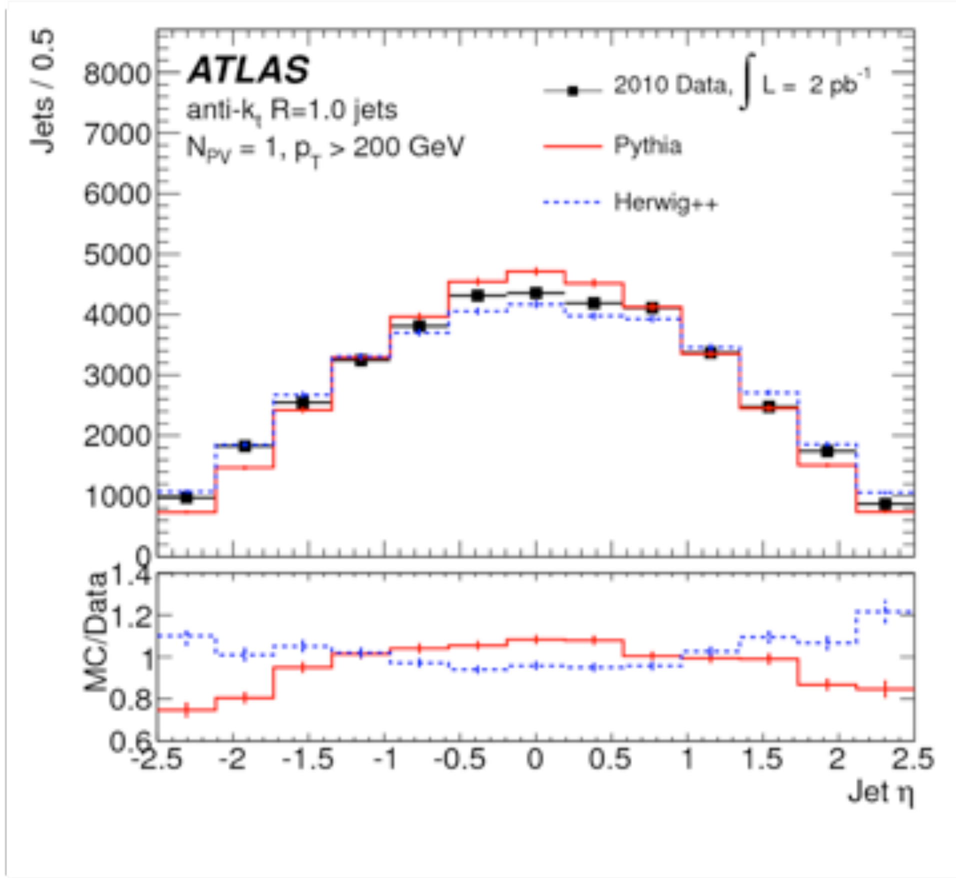
Jets in collider experiments

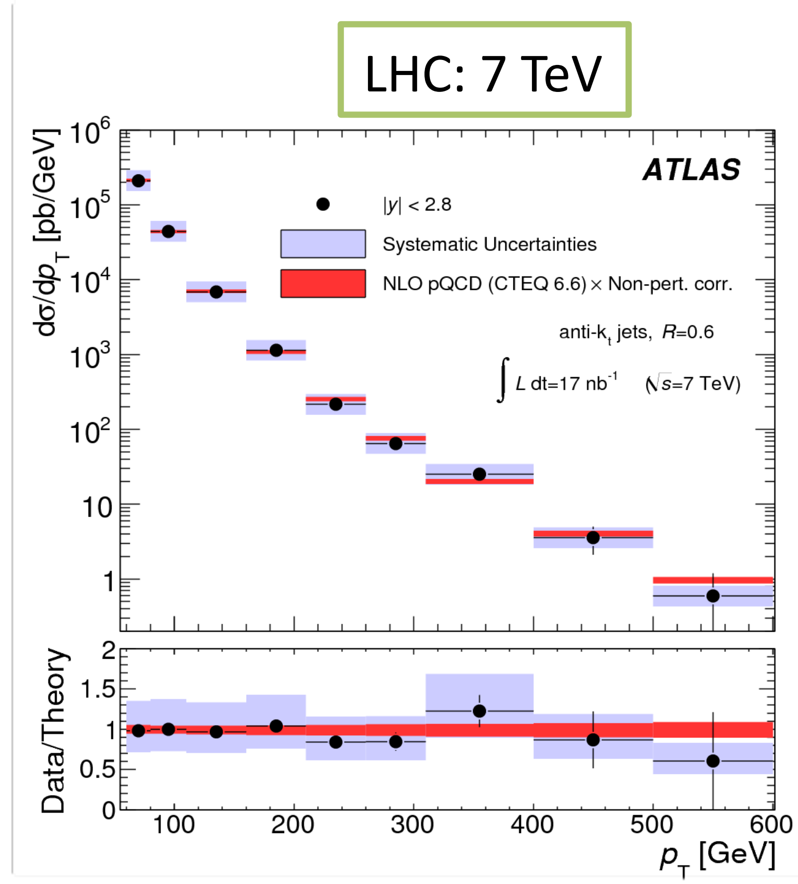
Jets are fairly well known by now… and well described by theory and MC

=> attractive tool for heavy-ions









Hadronic collisions: pQCD and jets

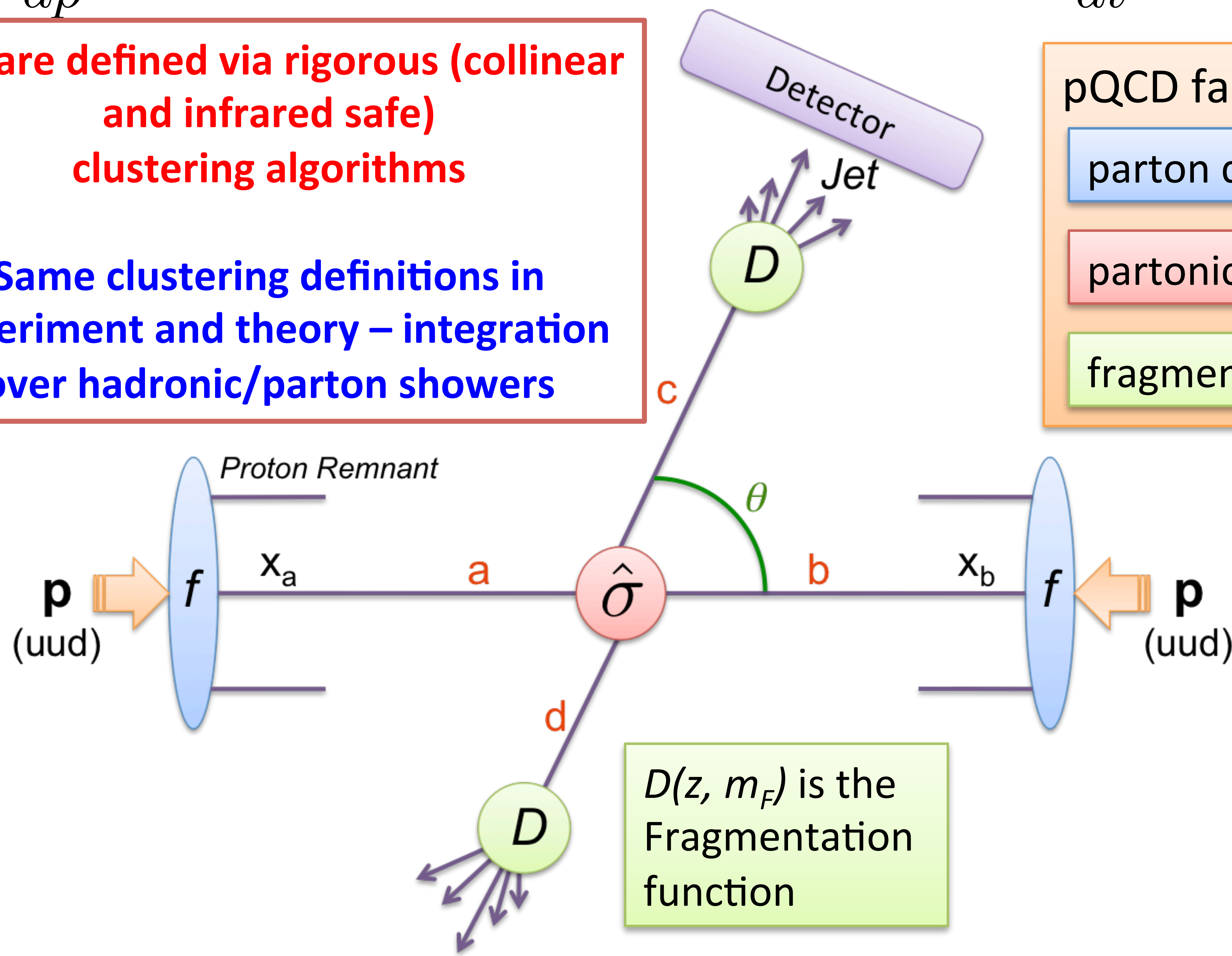
$$E\frac{d^3\sigma}{dp^3} \propto f_{a/A}(x_a, Q^2) \otimes f_{b/B}(x_b, Q^2) \otimes \frac{d\hat{\sigma}^{ab\to cd}}{dt} \otimes D_{h/c}(z_c, Q^2)$$

Jets are defined via rigorous (collinear and infrared safe) clustering algorithms

Same clustering definitions in experiment and theory – integration over hadronic/parton showers

pQCD factorization:

- parton distribution fn $f_{a/A}$
- partonic cross section
- fragmentation fn $D_{h/c}$

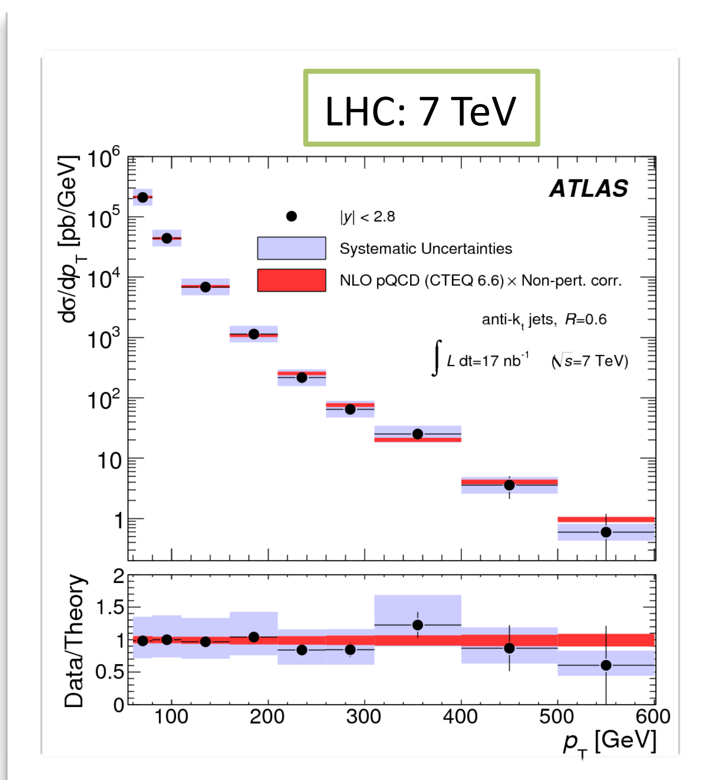


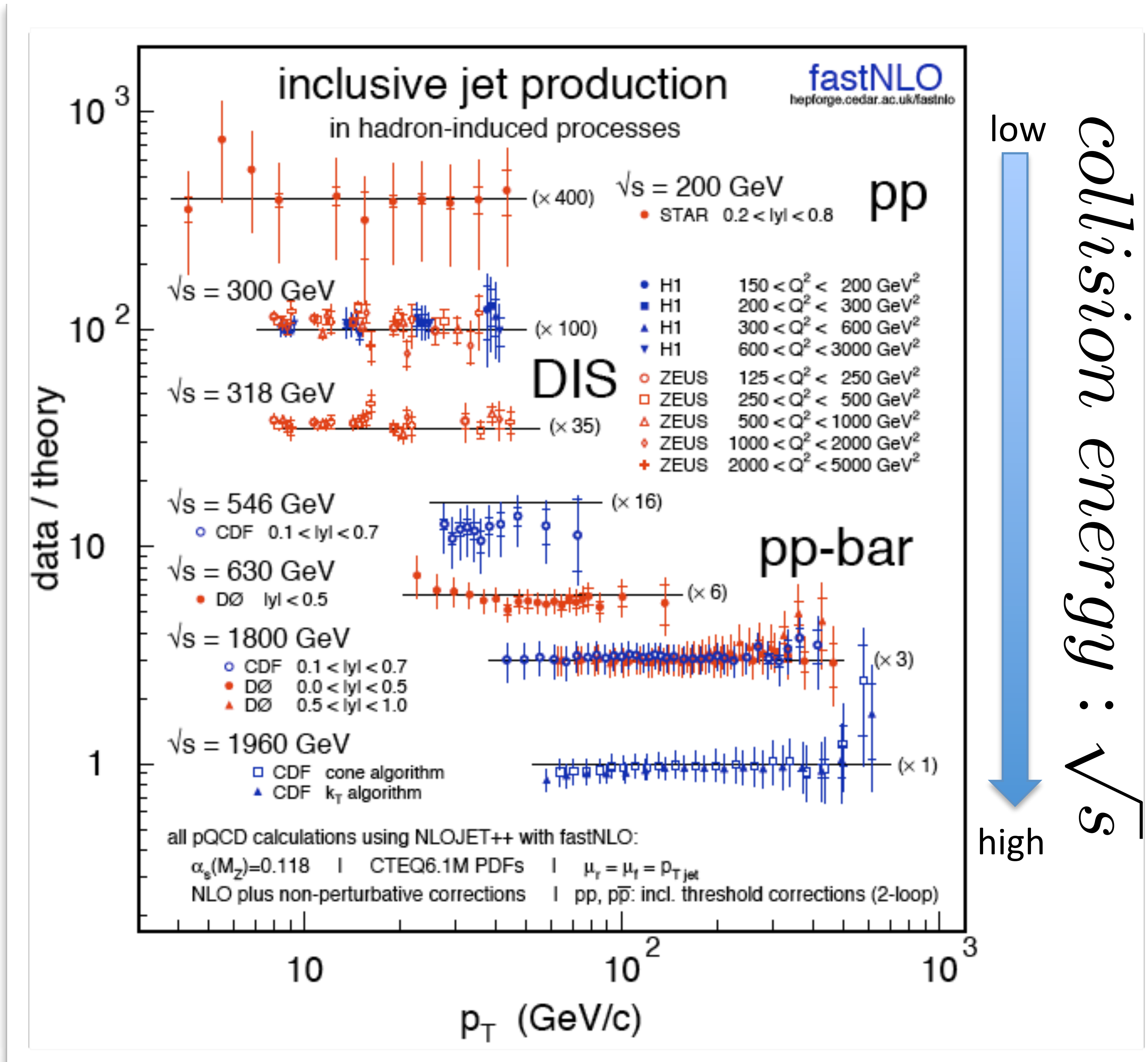
$D(z, m_F)$ is the Fragmentation function

Inclusive jet production: pQCD & data

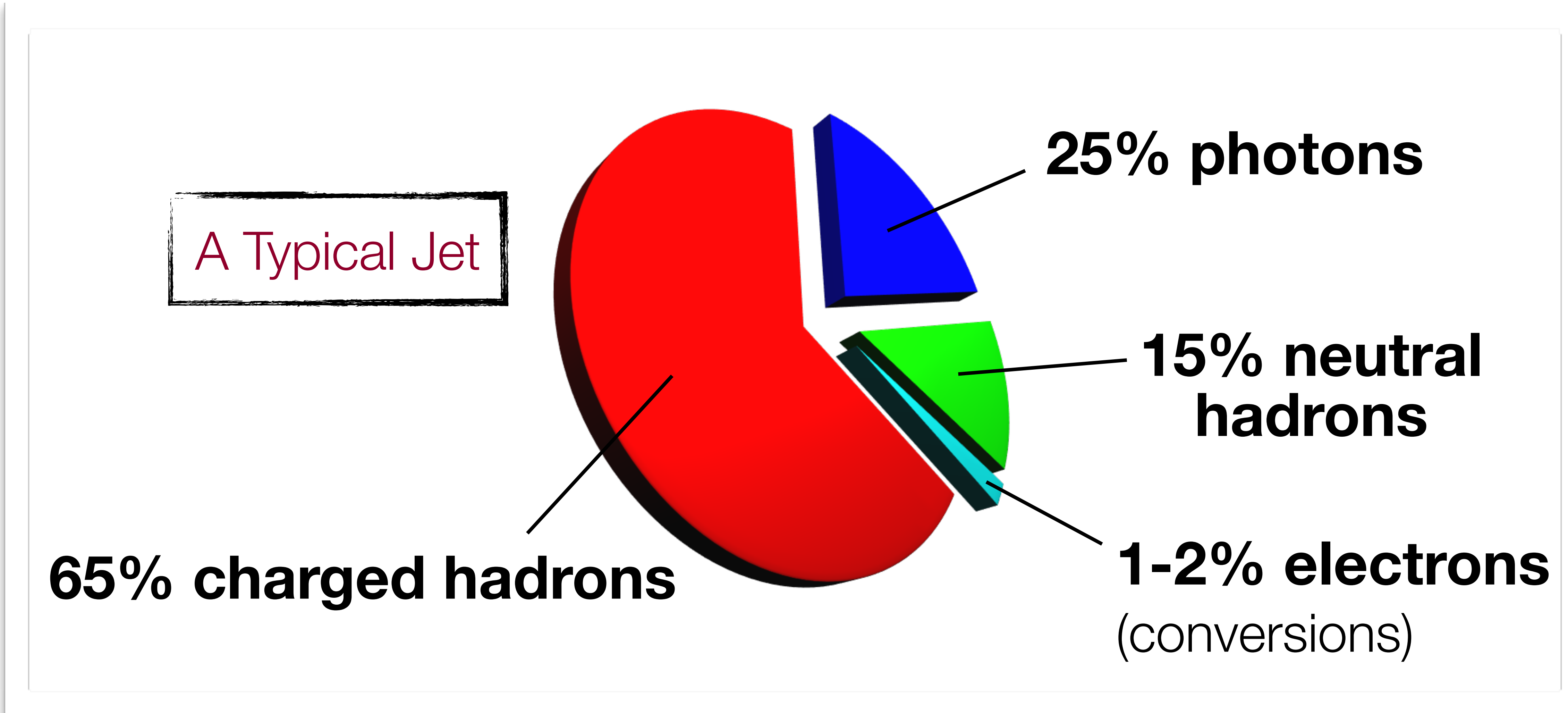
Jets are fairly well known by now... and well described by theory and MC

=> attractive tool for heavy-ions





JET composition



Measure a jet?

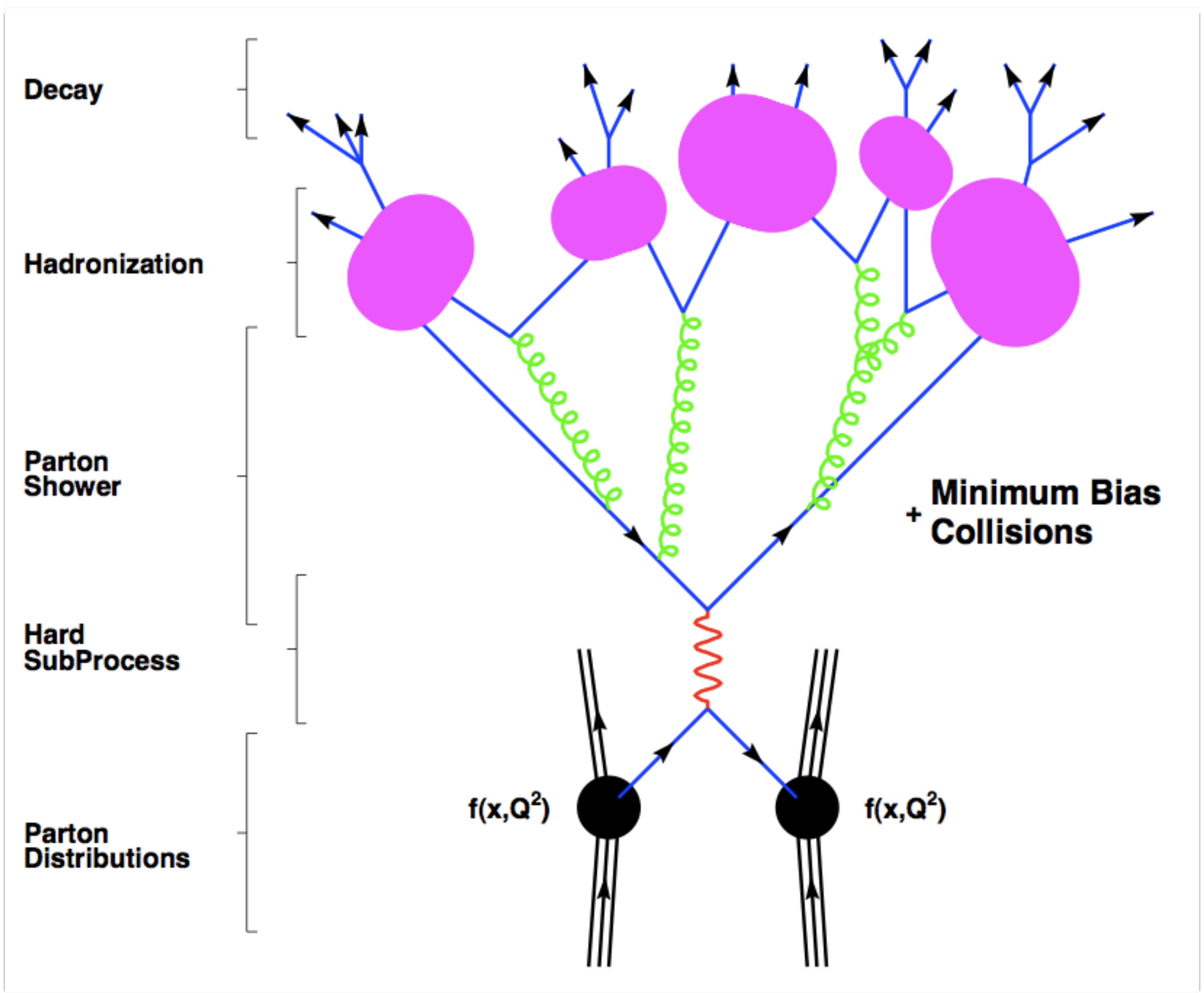
Need to have control over all components...

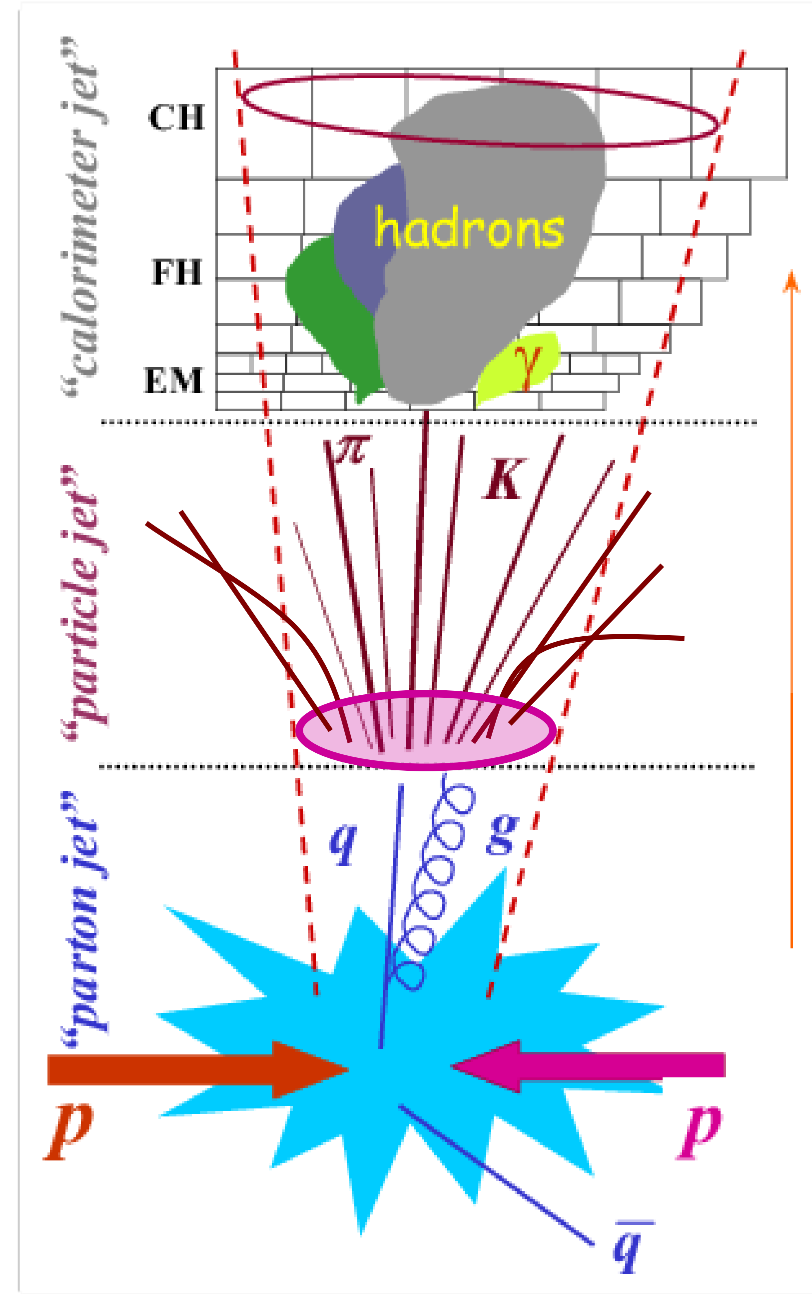
Measure or "know"

the [unknown] rest from DATA + MC

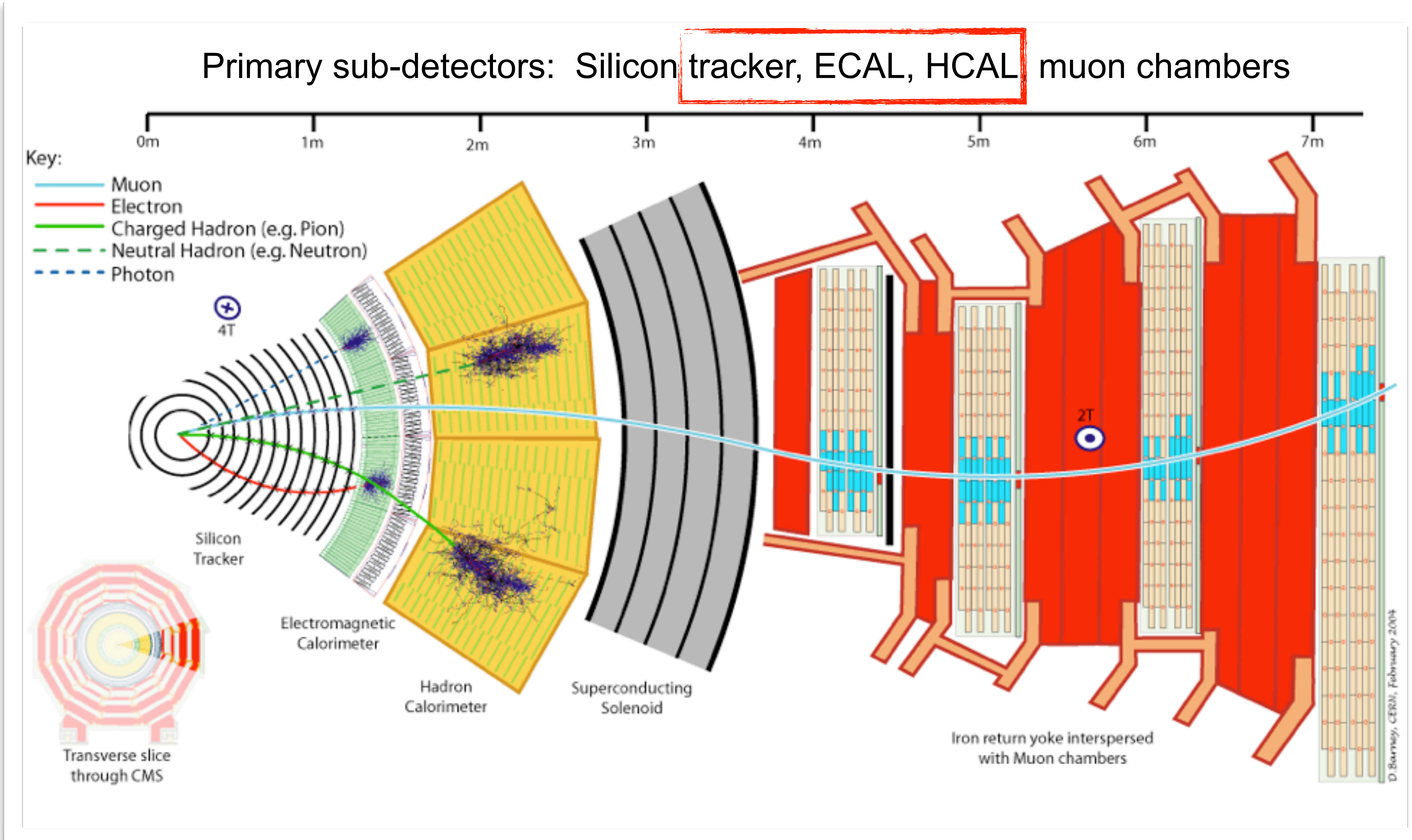
$$J(\vec{p}_{partons}) \approx J(\vec{p}_{shower}) \approx J(\vec{p}_{hadrons}) \approx J(\vec{p}_{cells/tracks})$$

Jet: from parton to detector

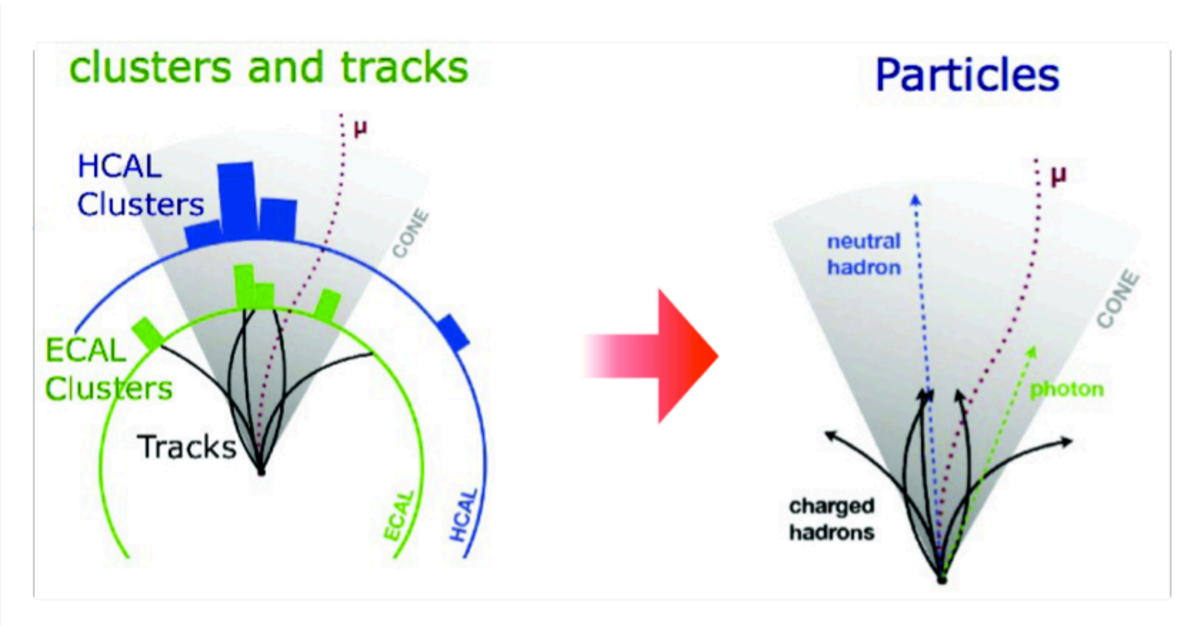




A Jet Detector

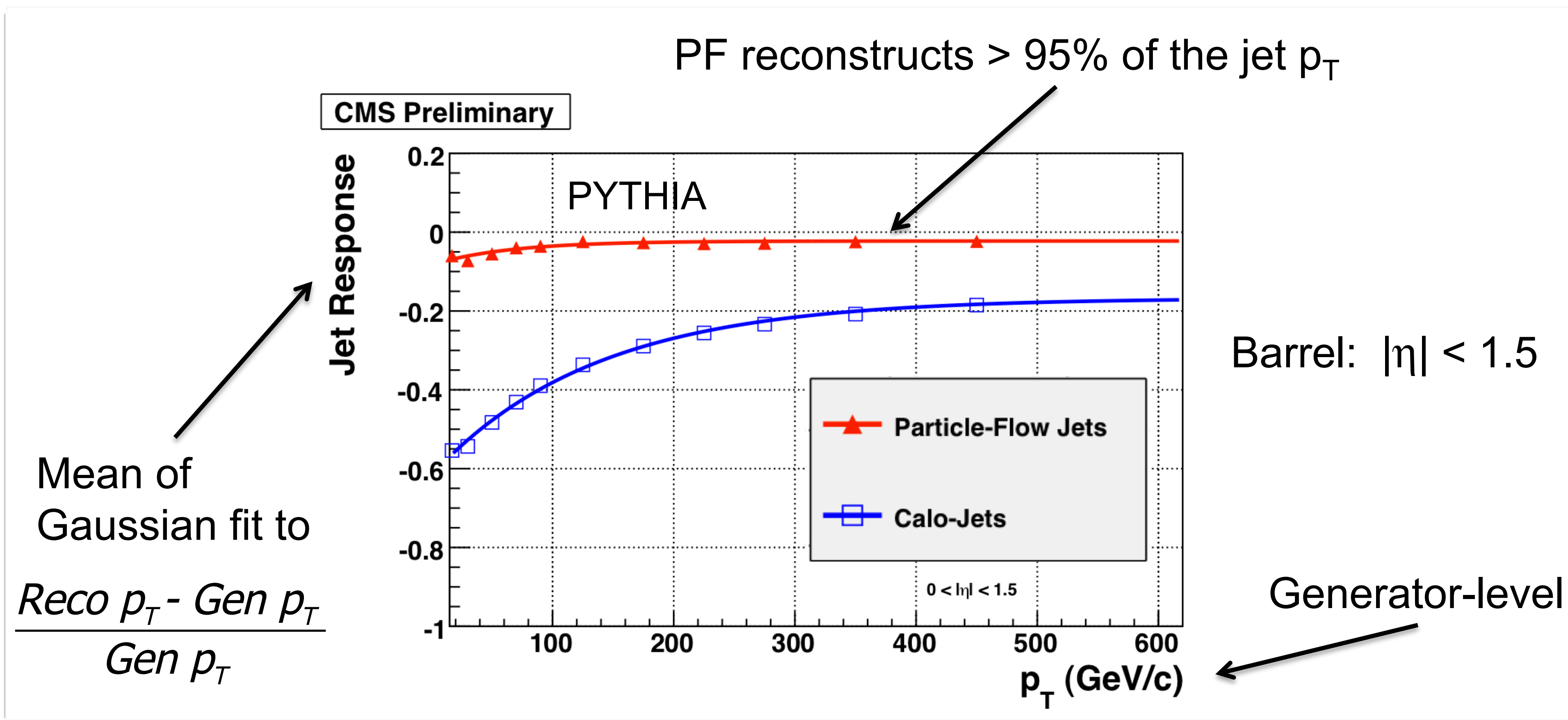


Improvements in jet reconstruction on detector level => Particle flow

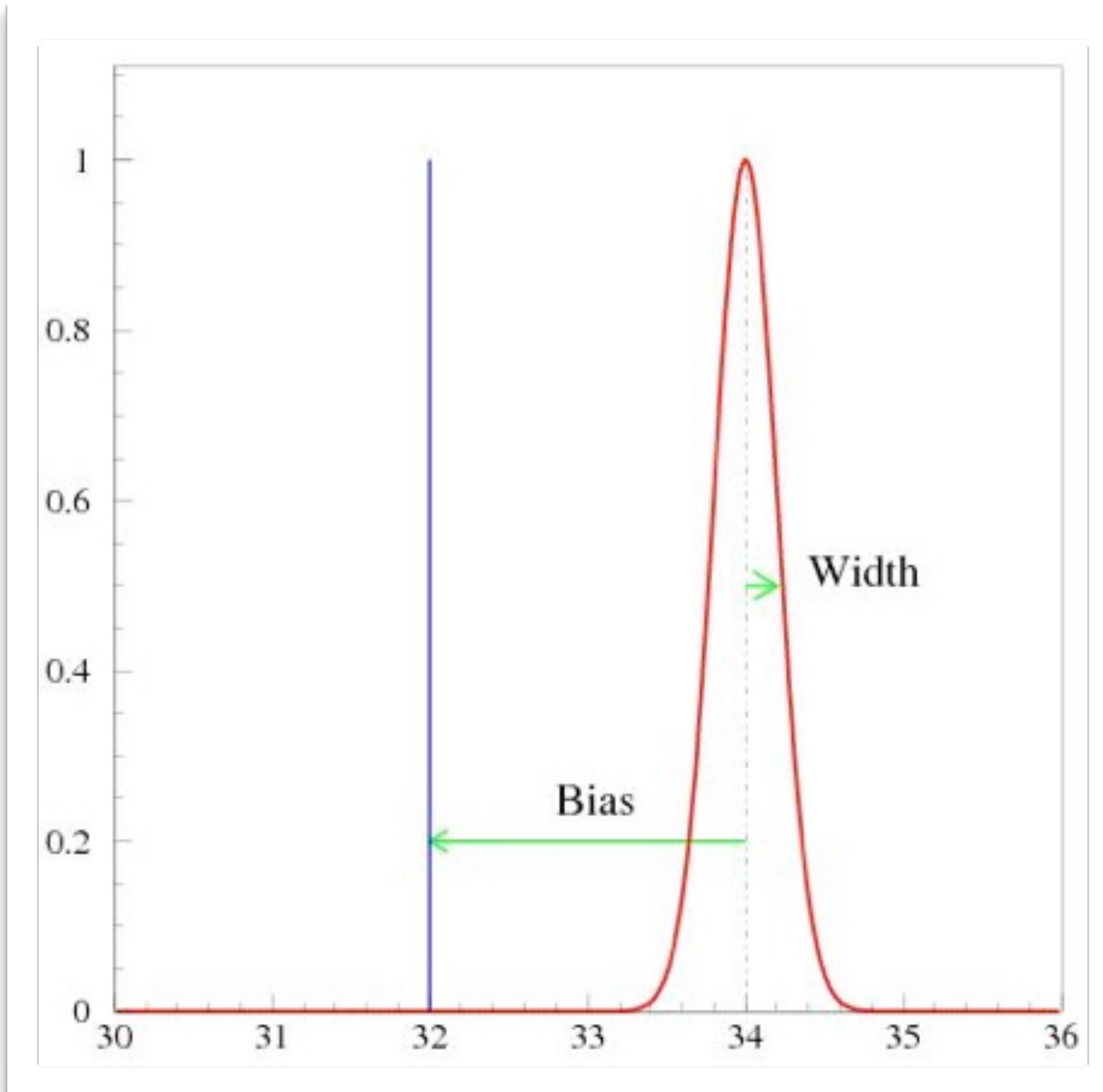


Purely calorimeter jet vs. Particle Flow jet

Better response w.r.t. calorimeter measurement => smaller jet-energy corrections



Jet: energy scale & resolution

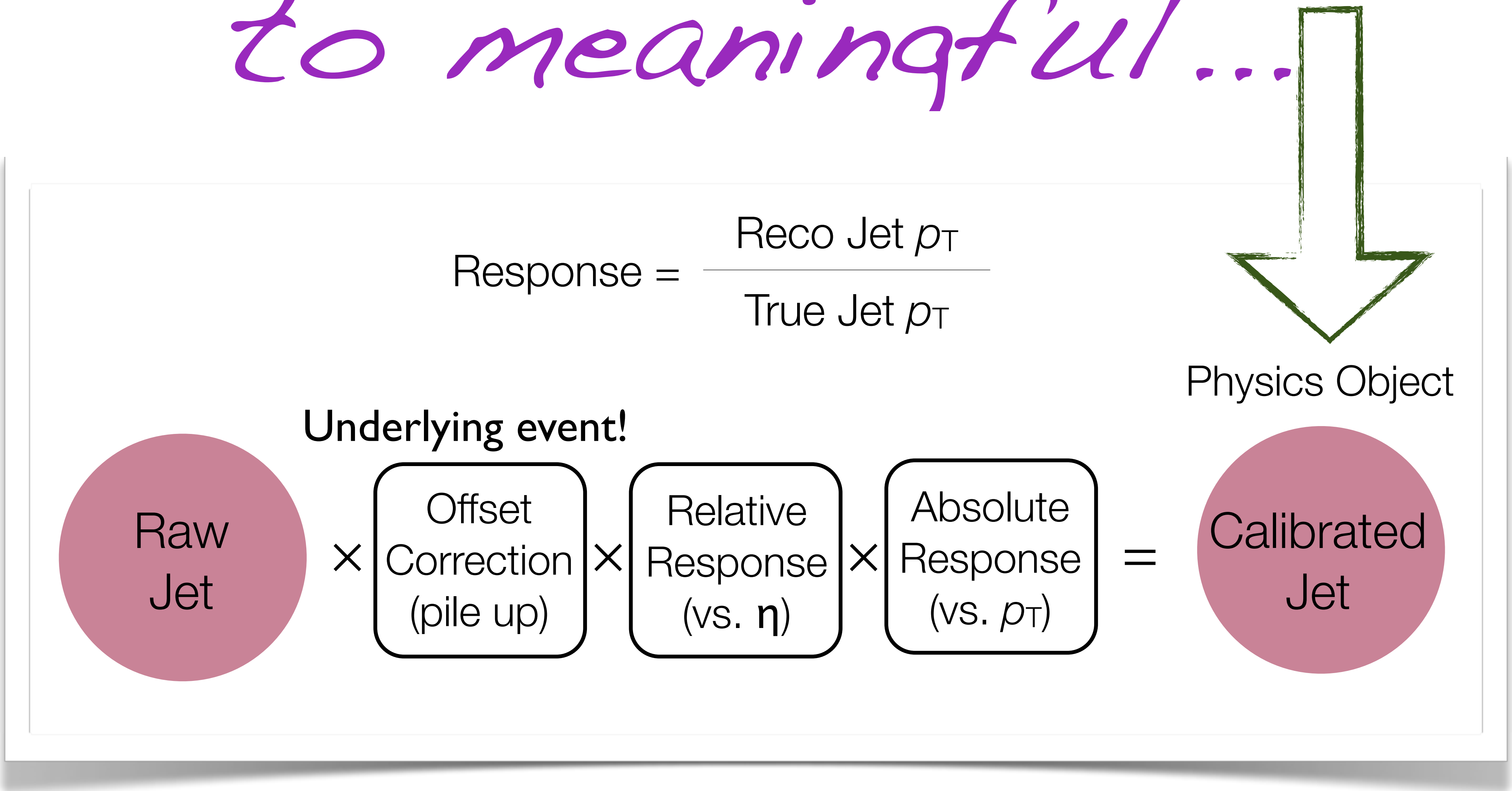


Control over the two crucial in p-p and AA collisions

Bias == Scale

Width == Resolution

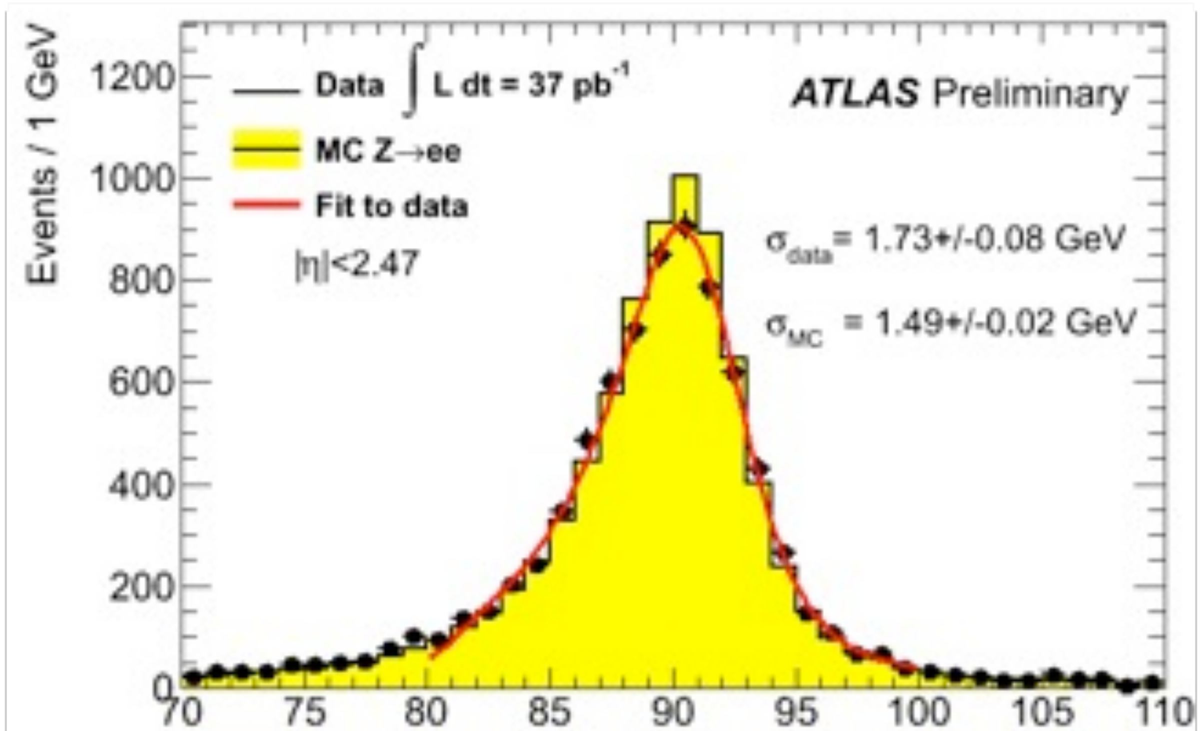
JET: From Measured to meaningful…

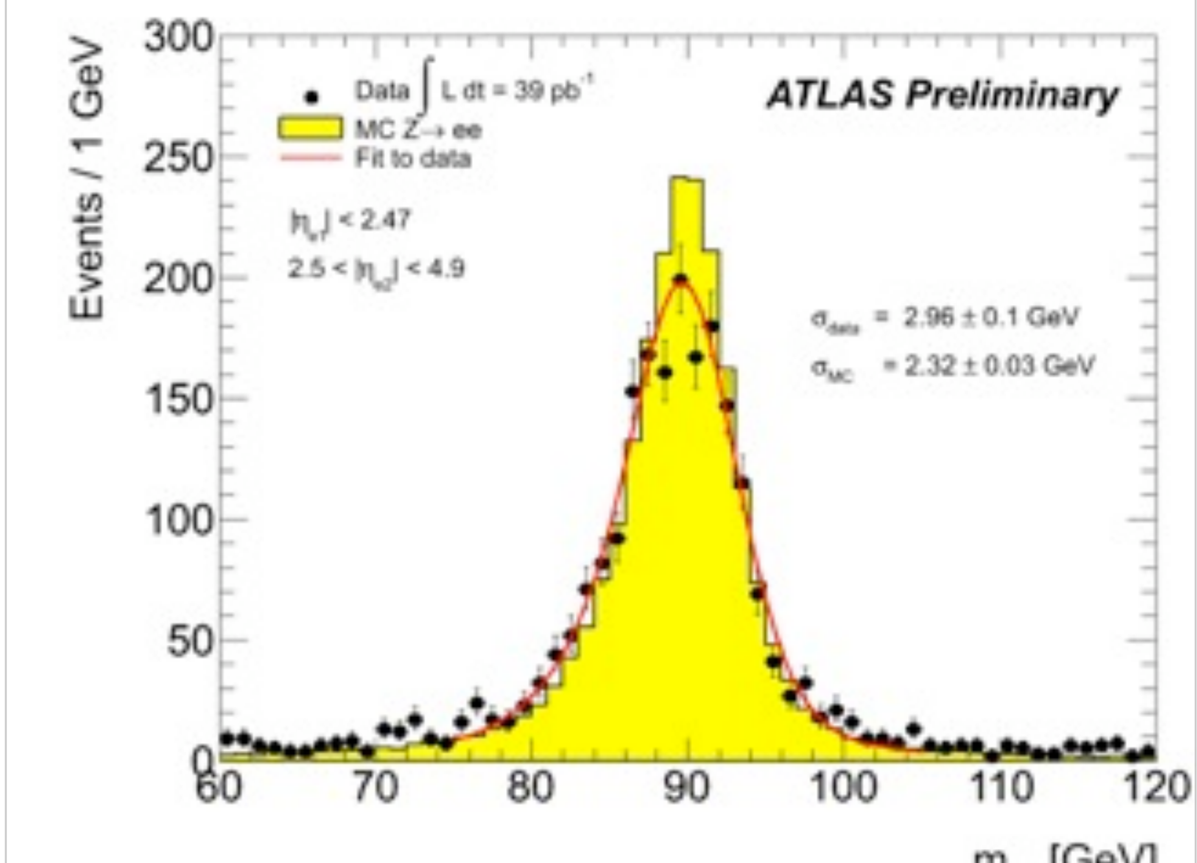


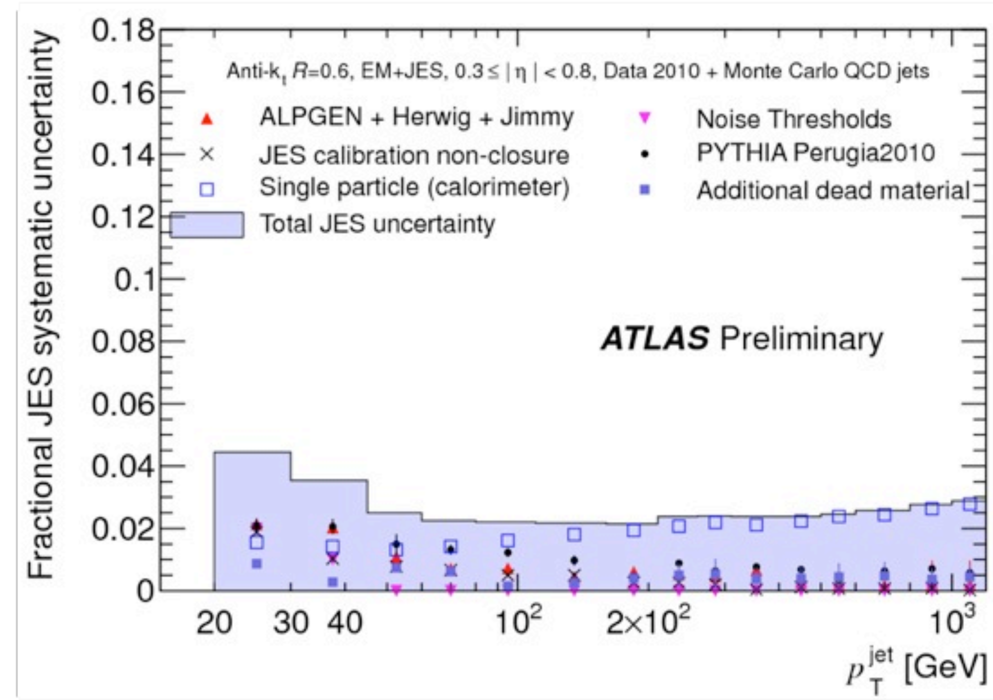
This is an experimental enterprise!

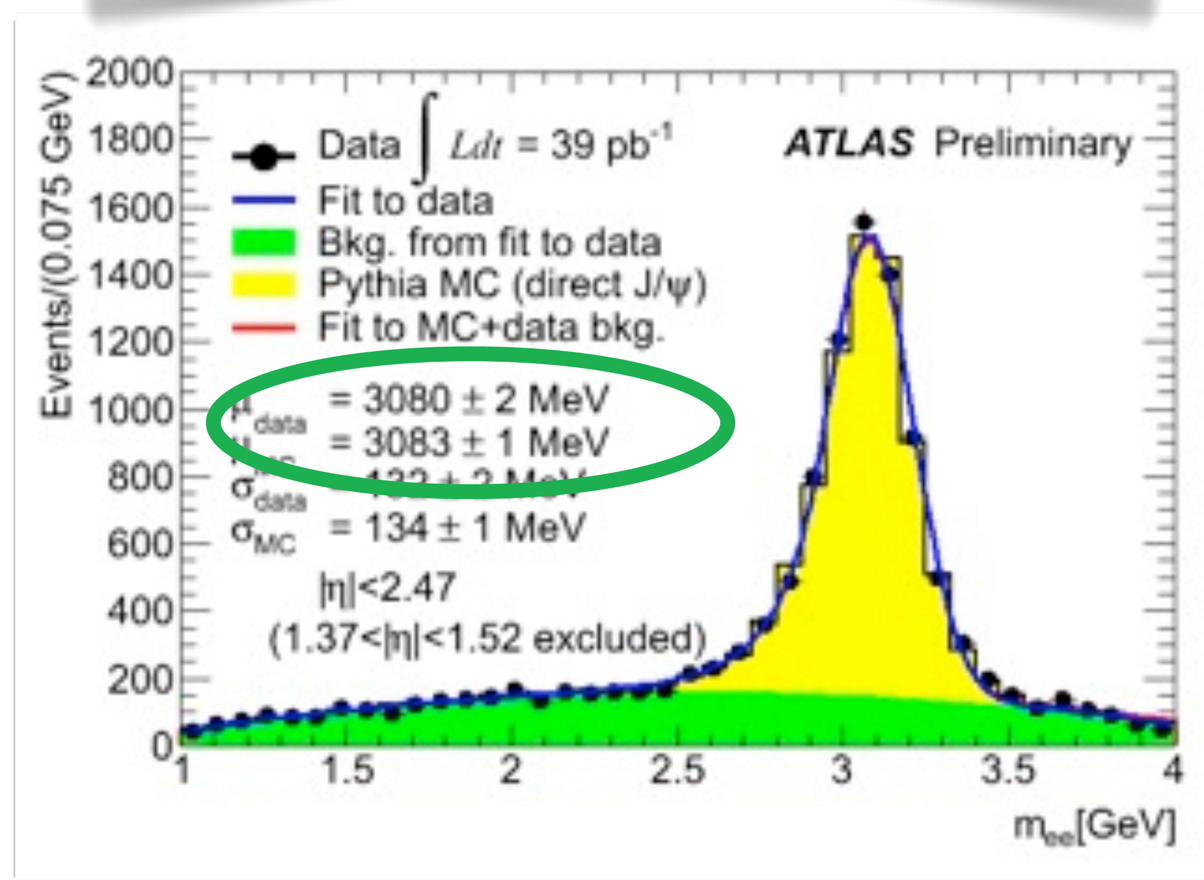
It is a substantial effort…

Control of the energy scale - ATLAS - linearity





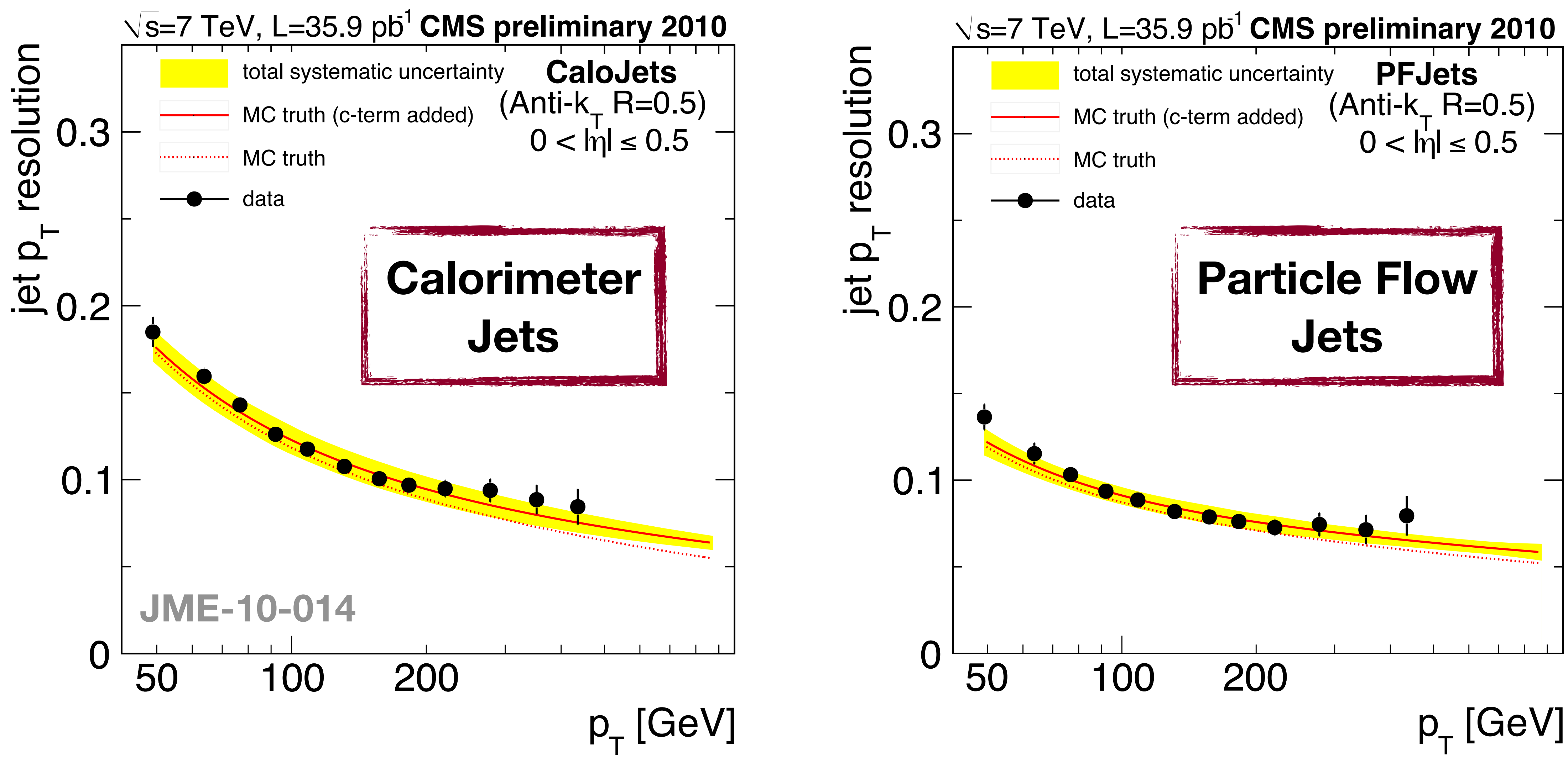




Jet energy resolution

An example: proton-proton collisions

$$\mathcal{A} = \frac{p_{\mathrm{T}}^{\mathrm{Jet1}} - p_{\mathrm{T}}^{\mathrm{Jet2}}}{p_{\mathrm{T}}^{\mathrm{Jet1}} + p_{\mathrm{T}}^{\mathrm{Jet2}}} \longrightarrow \frac{\sigma(p_{\mathrm{T}})}{p_{\mathrm{T}}} = \sqrt{2}\,\sigma_{\mathcal{A}}$$



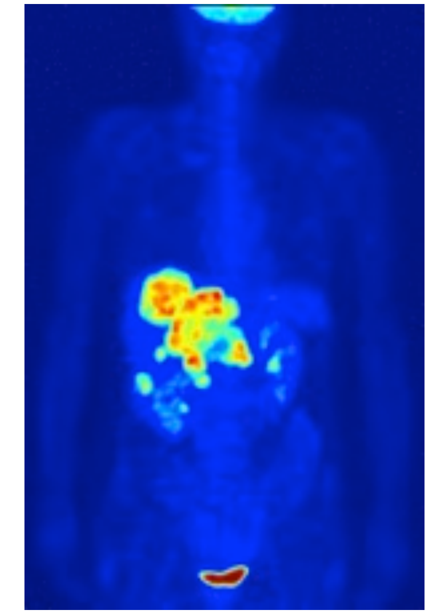
Until now...

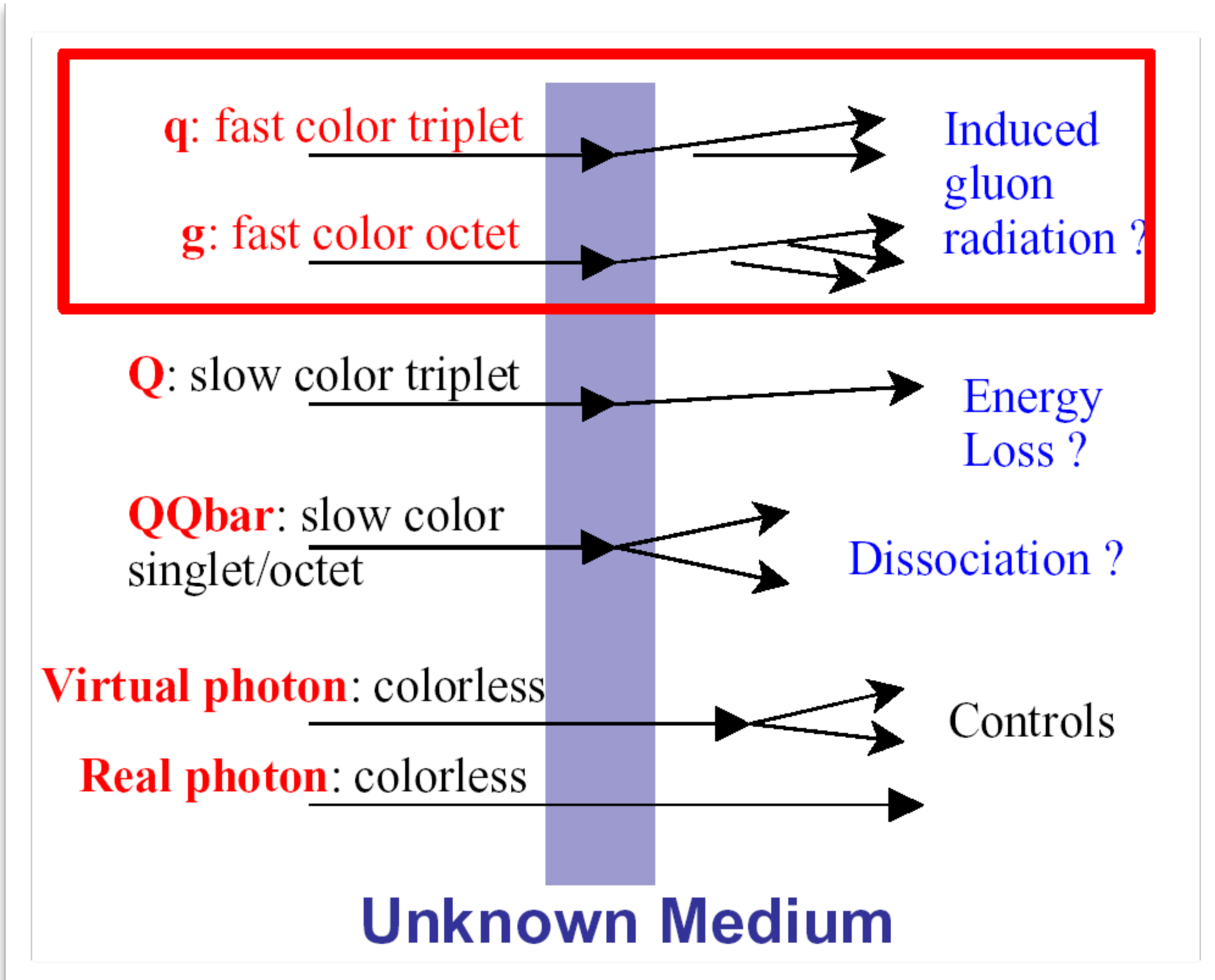
- Jets in elementary collisions: must specify an operational definition (algorithm, R, recombination scheme); variety of infrared and collinear safe algorithms

- Jet measurements in e-e and p-p collisions under control - experimental and theoretical understanding - although proper jet reconstruction is an effort even in the "simple" case (vacuum)

- HI collisions: hot QCD matter; large particle (production) densities as compared to vacuum - evolving with centrality

Probing the unknown medium...





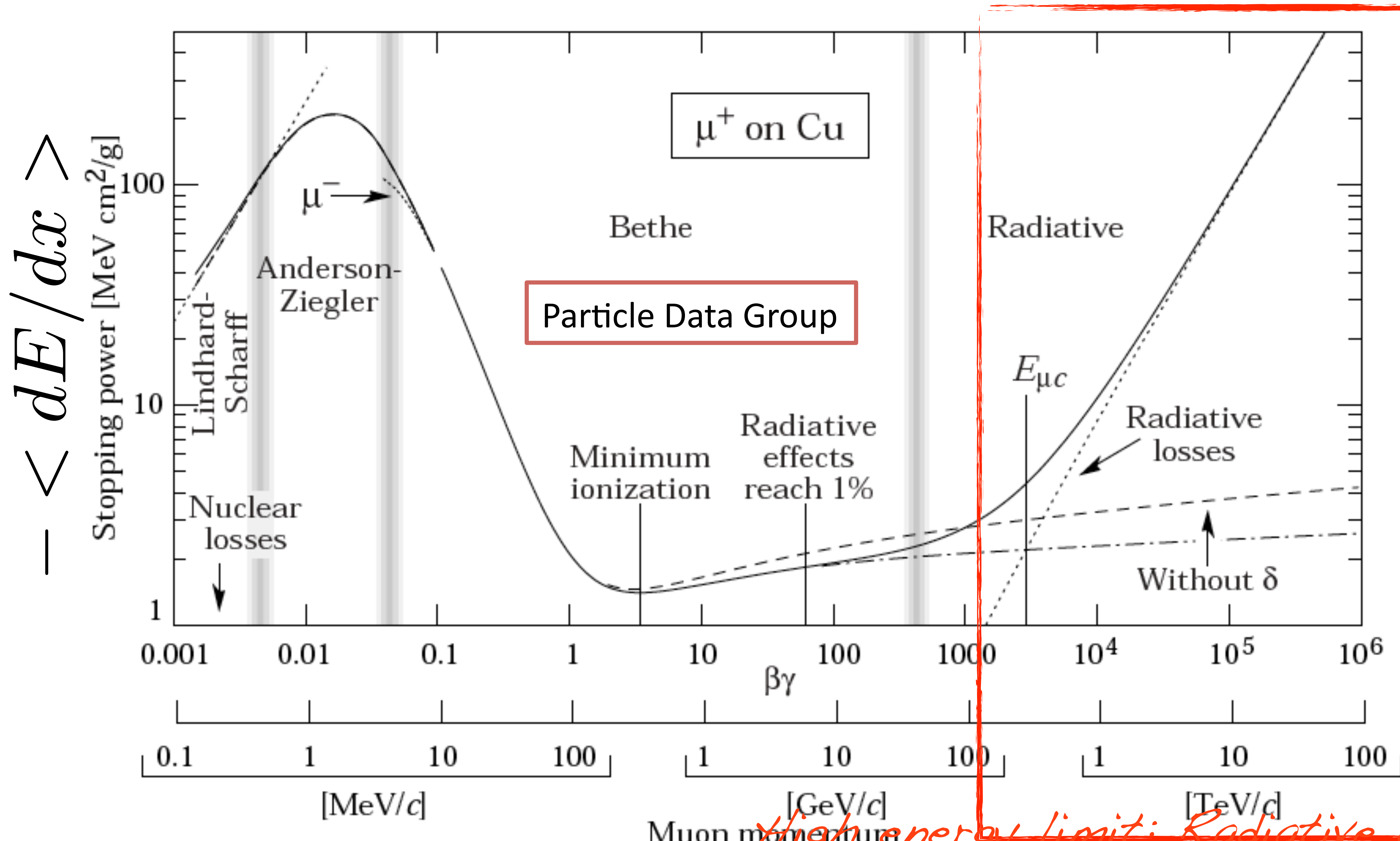
jet suppression (quenching)

charm/bottom dynamics

J/ψ & Υ

color-less particles

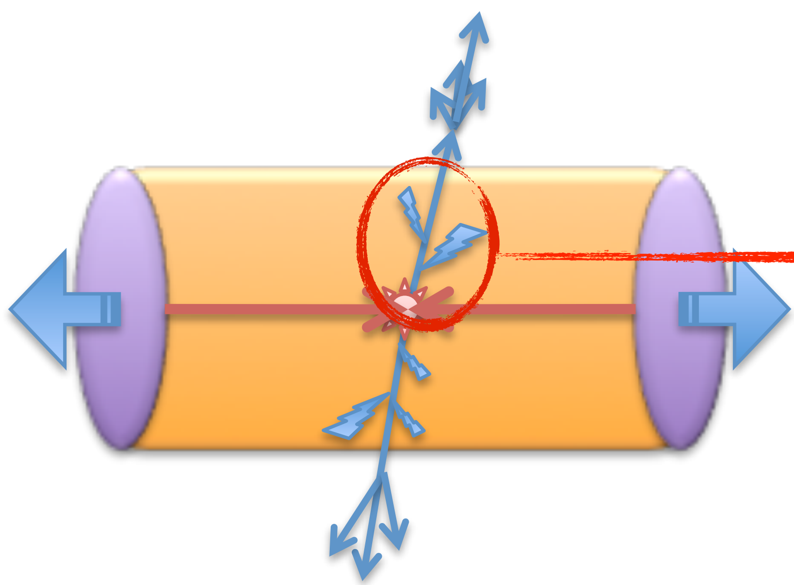
QED: Passage of electrically charged particle through

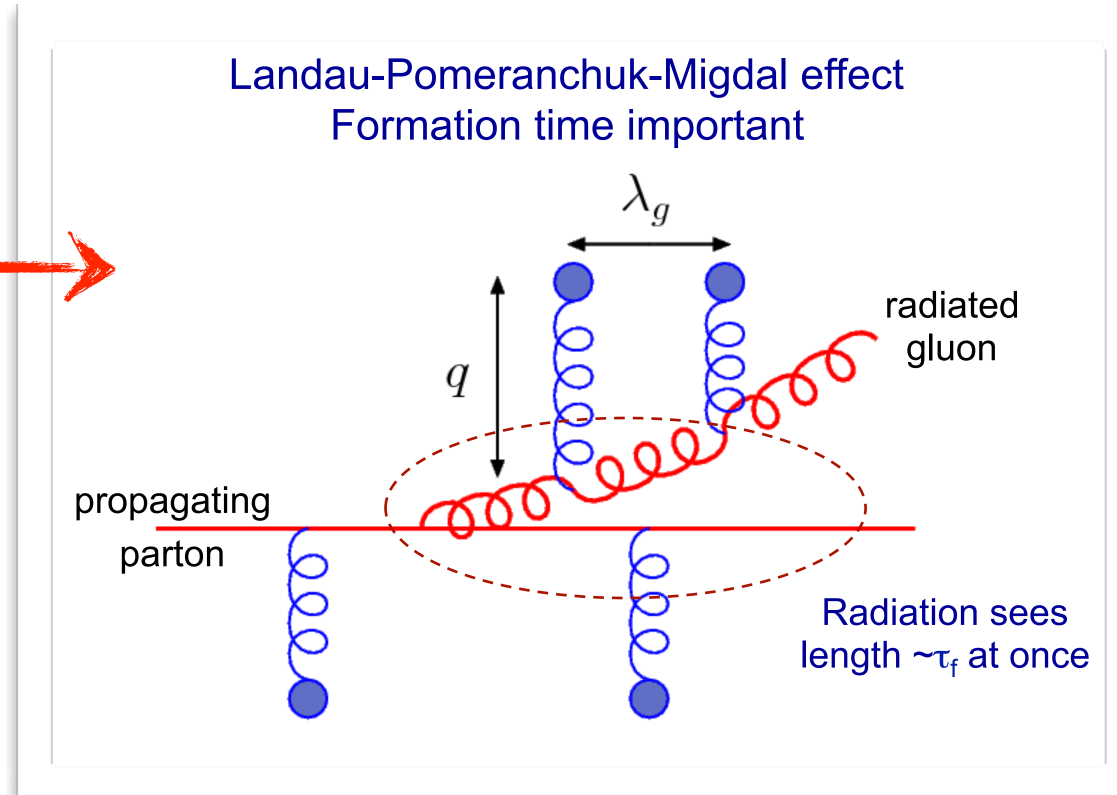


High energy limit: Radiative energy loss

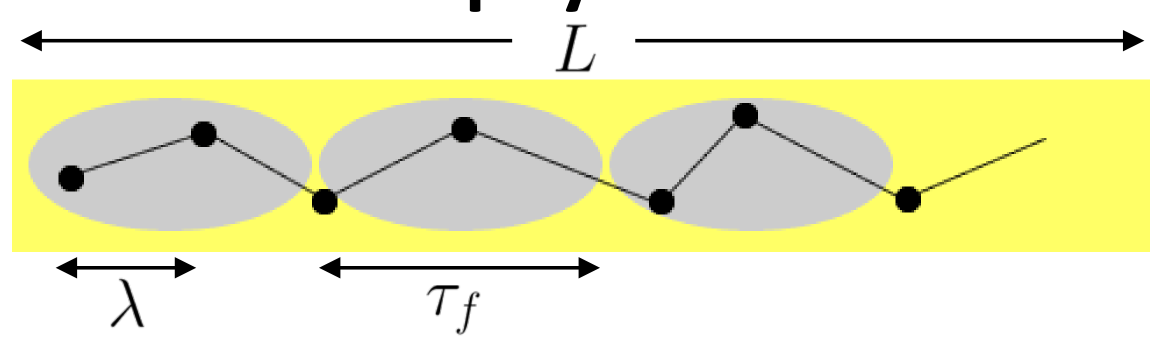
What is the equivalent in QCD?

Bremsstrahlung in QCD: Formation time -> coherence effects





Formation time physics

- 

$\tau_f \sim \frac{2\omega}{k_\perp^2}$

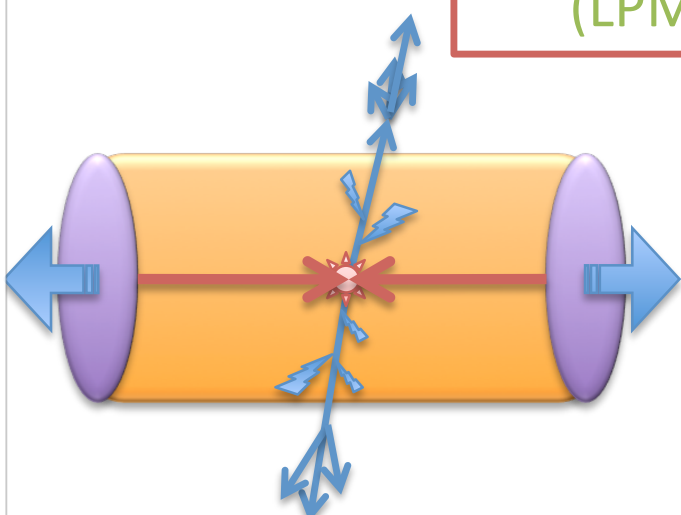
  - $\tau_f < \lambda < L$ Incoherent multiple collisions
  - $\lambda < \tau_f < L$ LPM effect (radiation suppressed by multiple scatterings within one coherence length)
  - $\lambda < L < \tau_f$ Factorization limit (acts as one single scatterer)

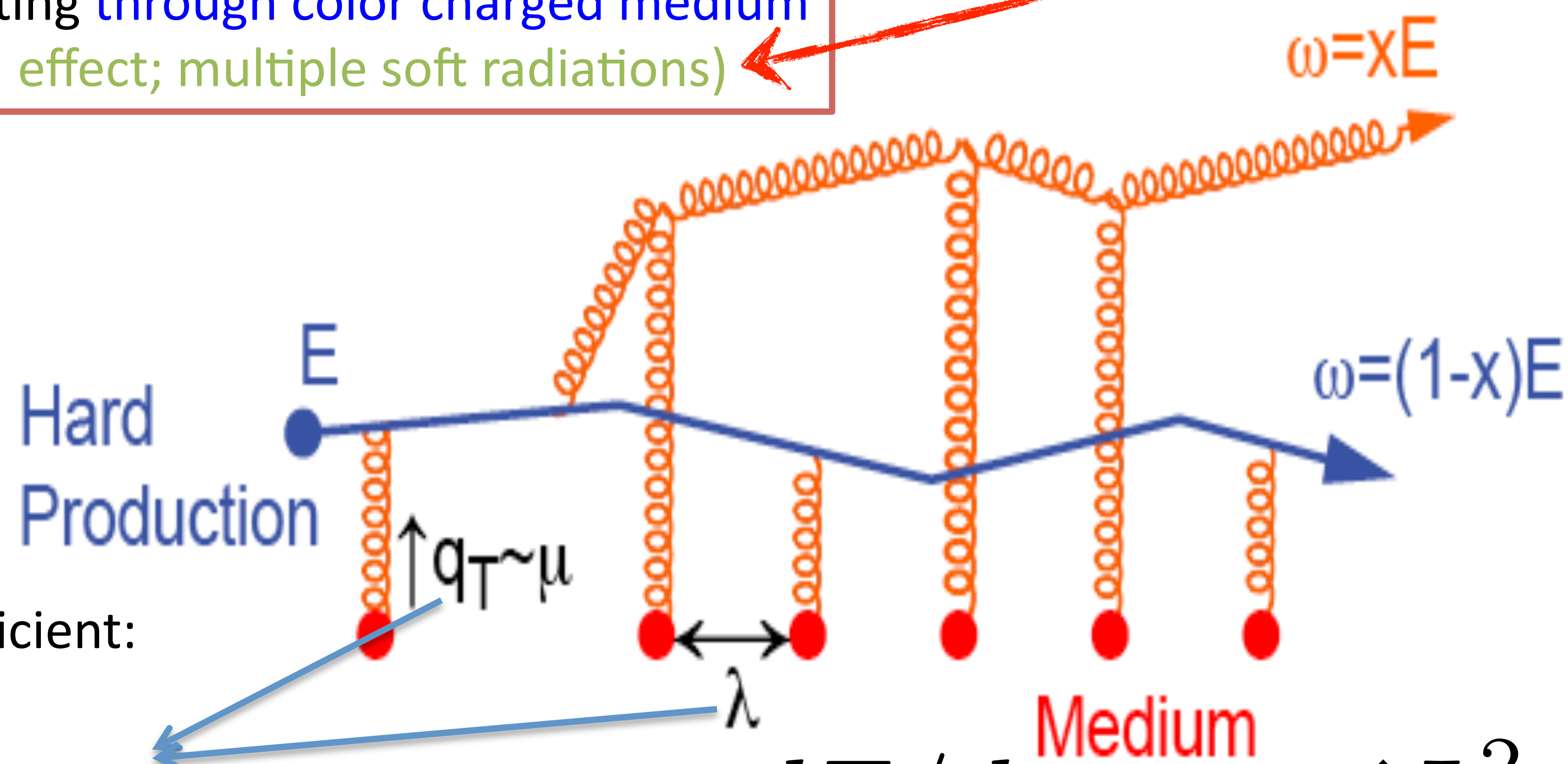
Bremsstrahlung in QCD

$\lambda < \tau \Rightarrow$ *Multiple scatterings add coherently*

$t_{formation} < L \Leftrightarrow \omega < \omega_c$

High energy **color charged probe**
propagating through color charged medium
(LPM effect; multiple soft radiations)





Define a transport coefficient:

$$\hat{q} \sim \mu^2/\lambda$$

$$-dE/dx \sim \alpha_s \hat{q} L^2$$

Partonic energy loss in QCD medium is proportional:

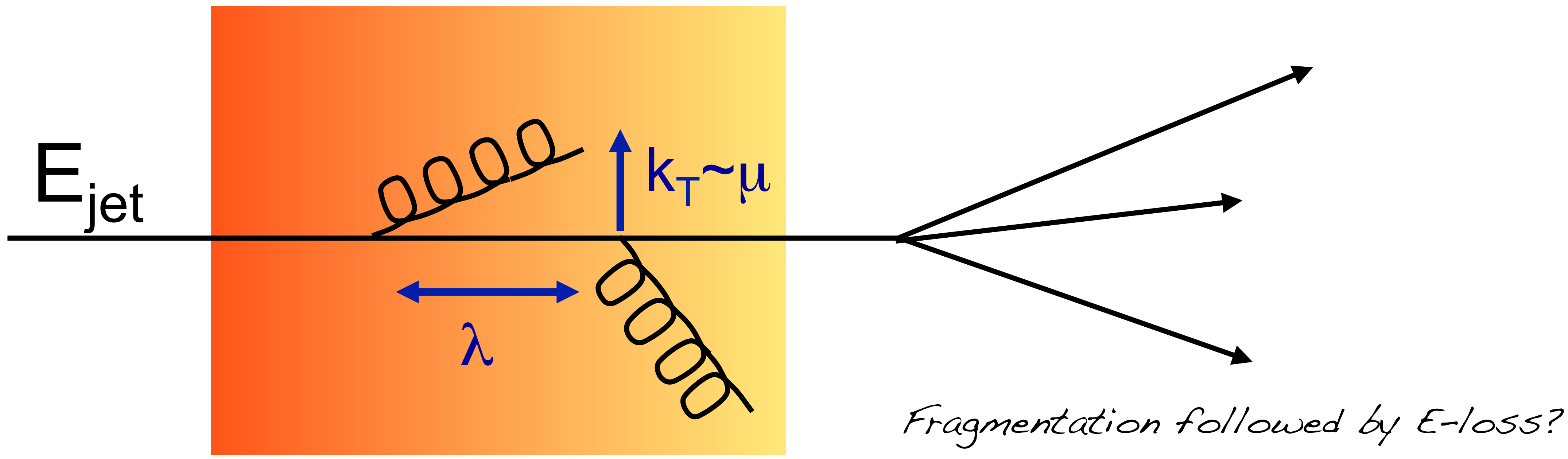
- to squared average path length (Note: QED ~ linear)
- to density of the medium

$$\lambda \propto \frac{1}{\rho}$$

⇒ energy flow (parton+radiation) modified as compared to jet in vacuum

⇒ jet “quenched” (“softened” fragmentation)

Generic expectations from energy loss



Longitudinal modification:

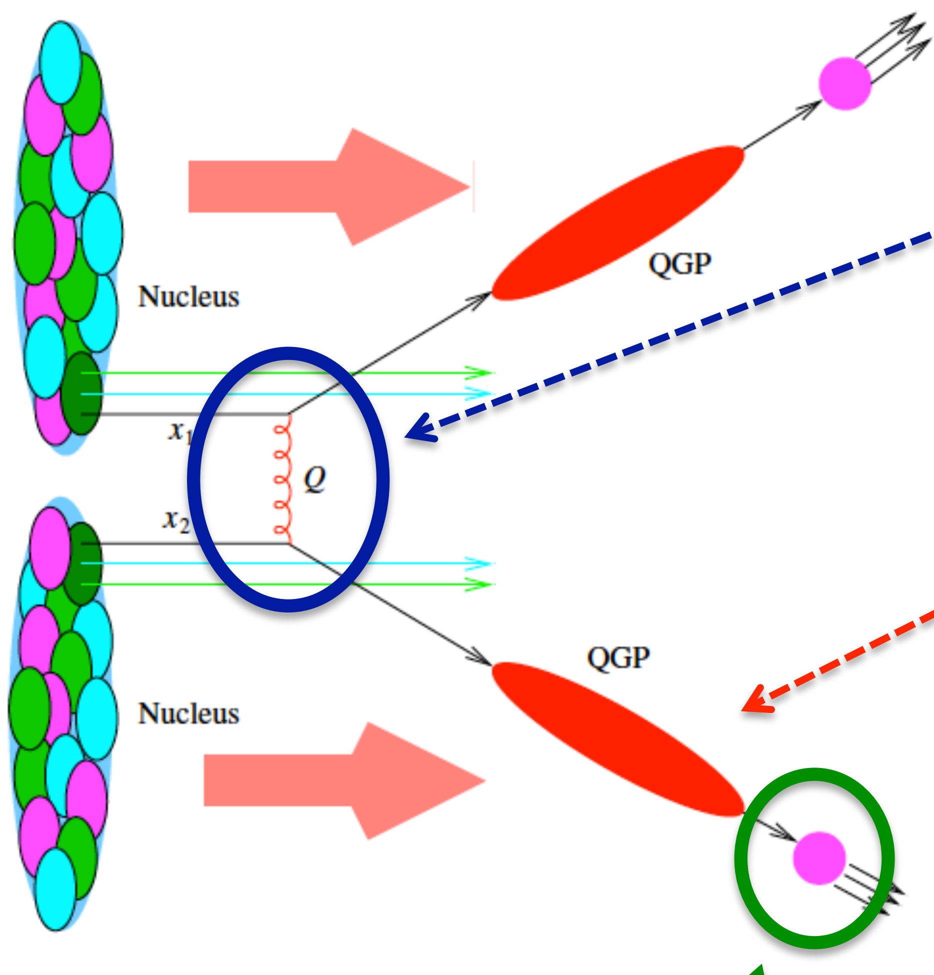
- out-of-cone: energy lost, loss of yield, di-jet energy imbalance
- in-cone: softening of fragmentation

Transverse modification

- out-of-cone: increase acoplanarity k_T
- in-cone: broadening of jet-profile

Jets in heavy-ion collisions - an idealization

=> Factorized picture. $\sigma \propto f_a^{PDF} \otimes f_b^{PDF} \otimes \sigma^{hard}$



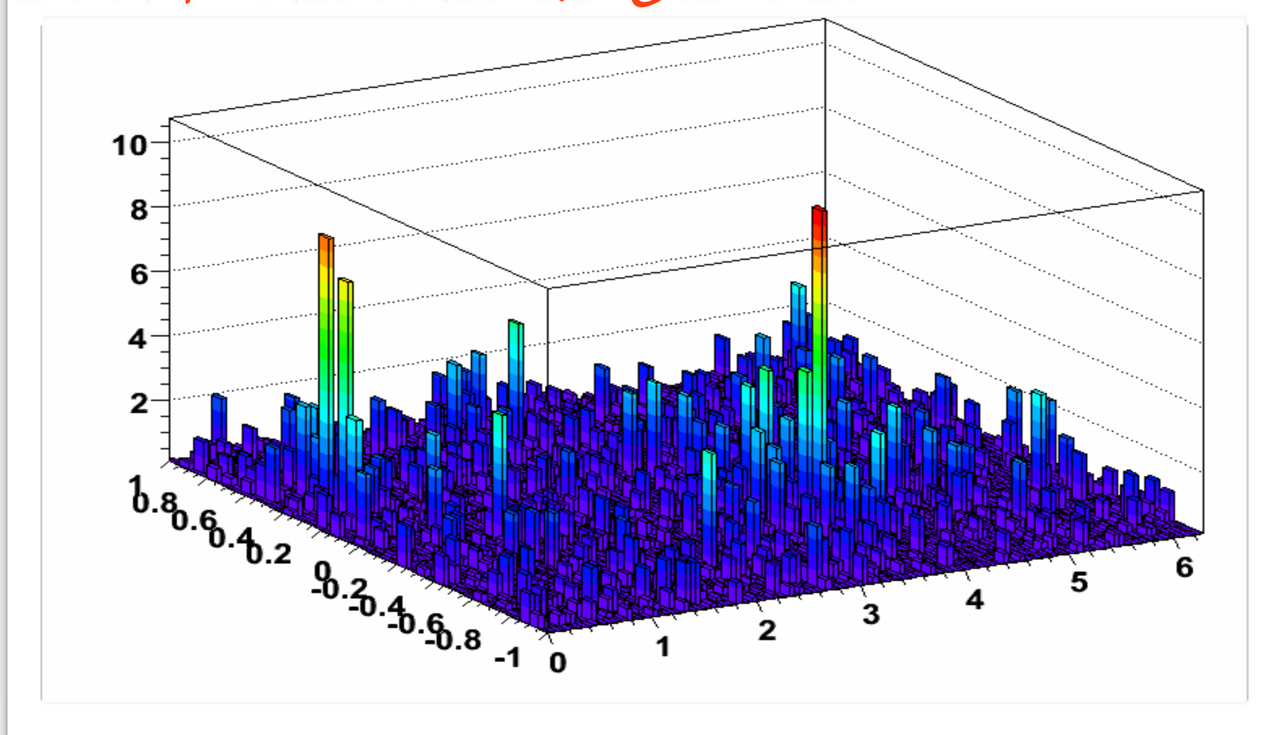
production vertex: high Q^2
→ pQCD

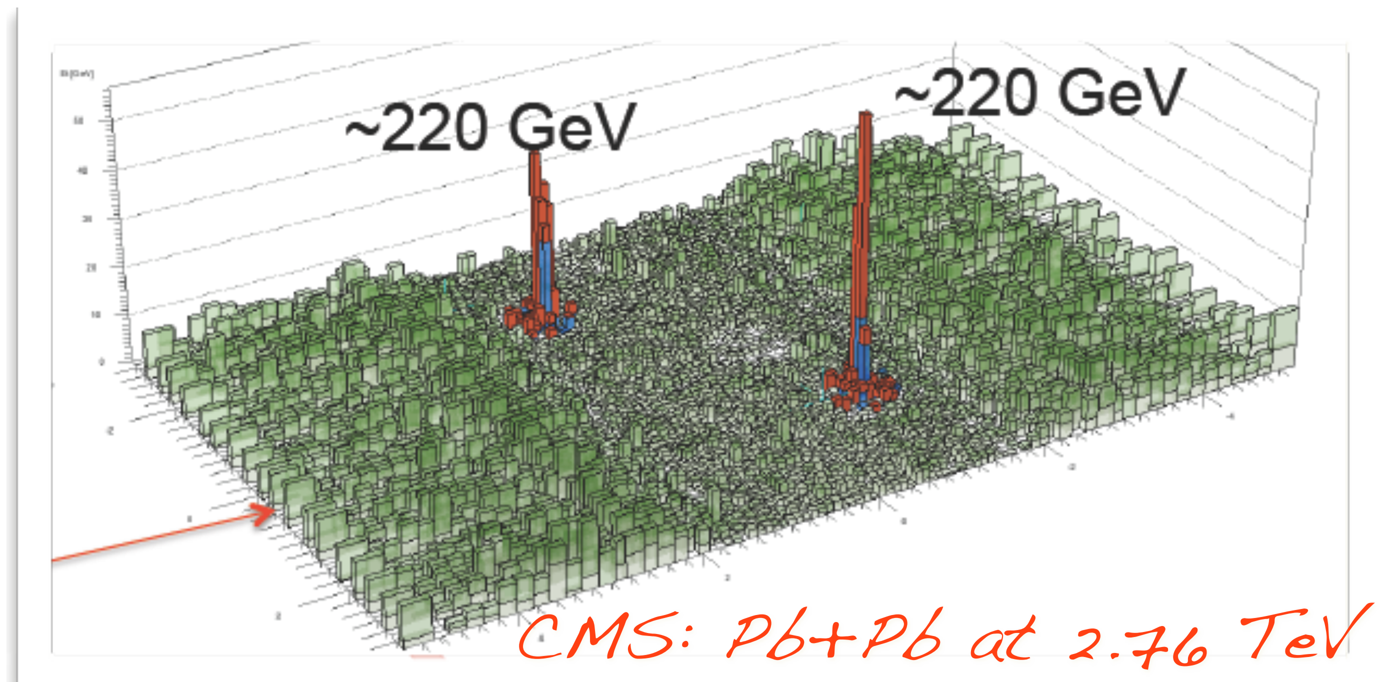
Propagation in strongly coupled Quark Gluon Plasma
→ pQCD-based jet quenching
→ hydrodynamics
→ AdS/CFT
→ ...

Vacuum fragmentation into hadrons
→ non-pert. QCD

Jets in heavy-ion collisions RHIC & LHC

STAR: Au+Au at 0.2 TeV





CMS: Pb+Pb at 2.76 TeV

LHC + RHIC: QCD evolution of jet quenching ?

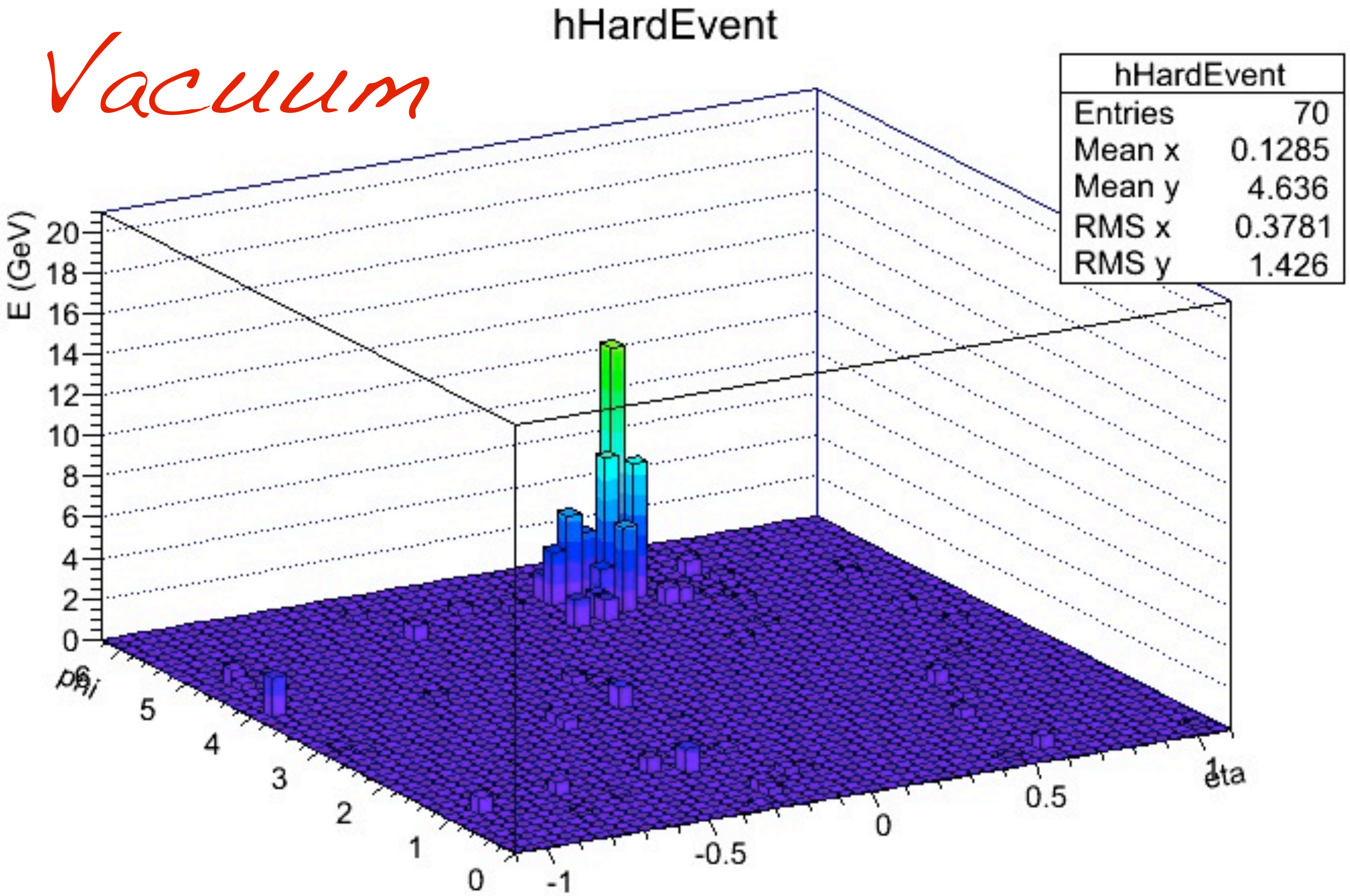
Vary energy of the jet:

LHC: Vary the scale with which QGP is probed (a la DIS)

Compare and contrast RHIC and LHC

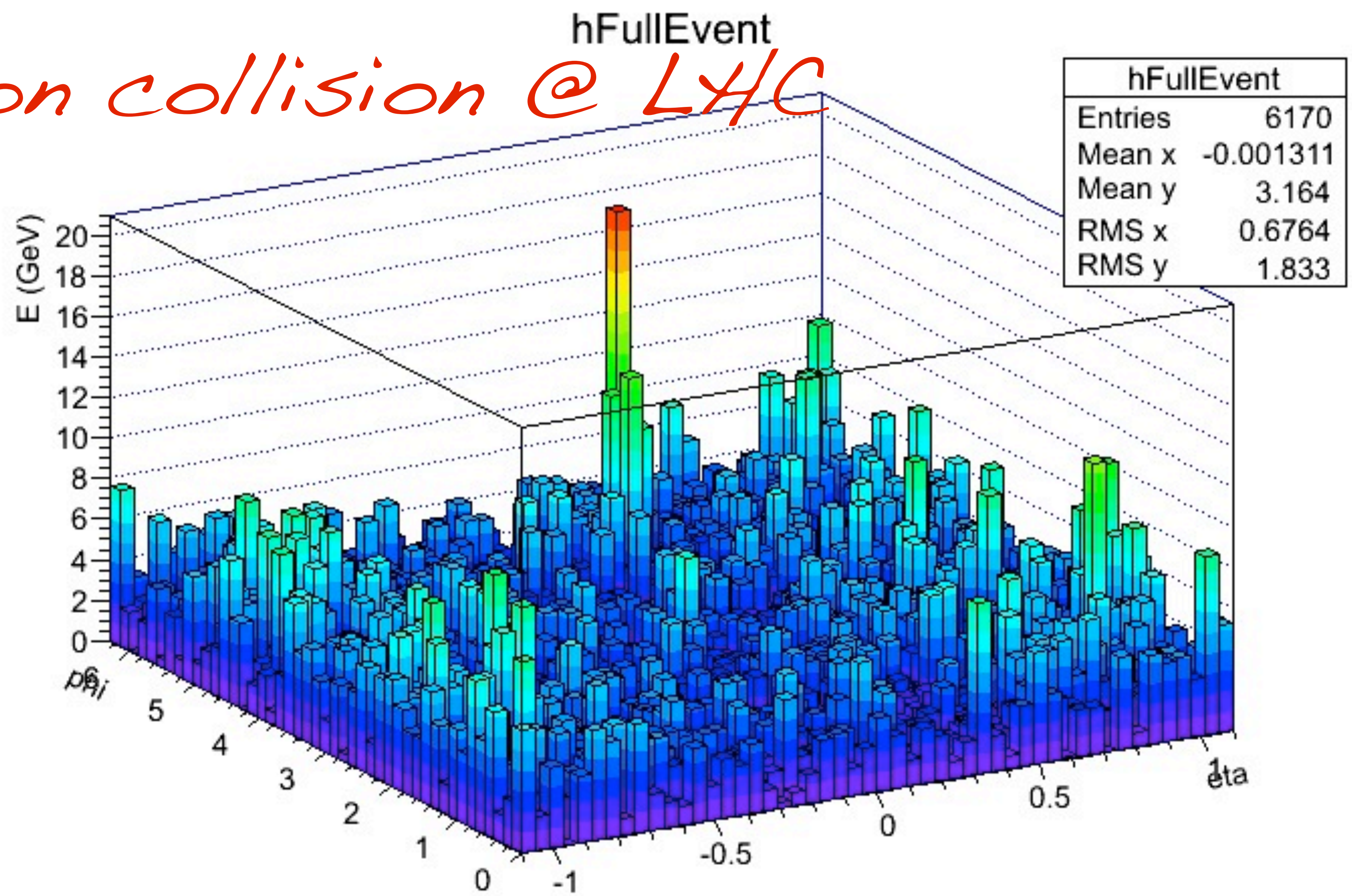
Jets in HI collisions & Experimental difficulties: Vacuum jet vs jet on top of the HI background...

Vacuum

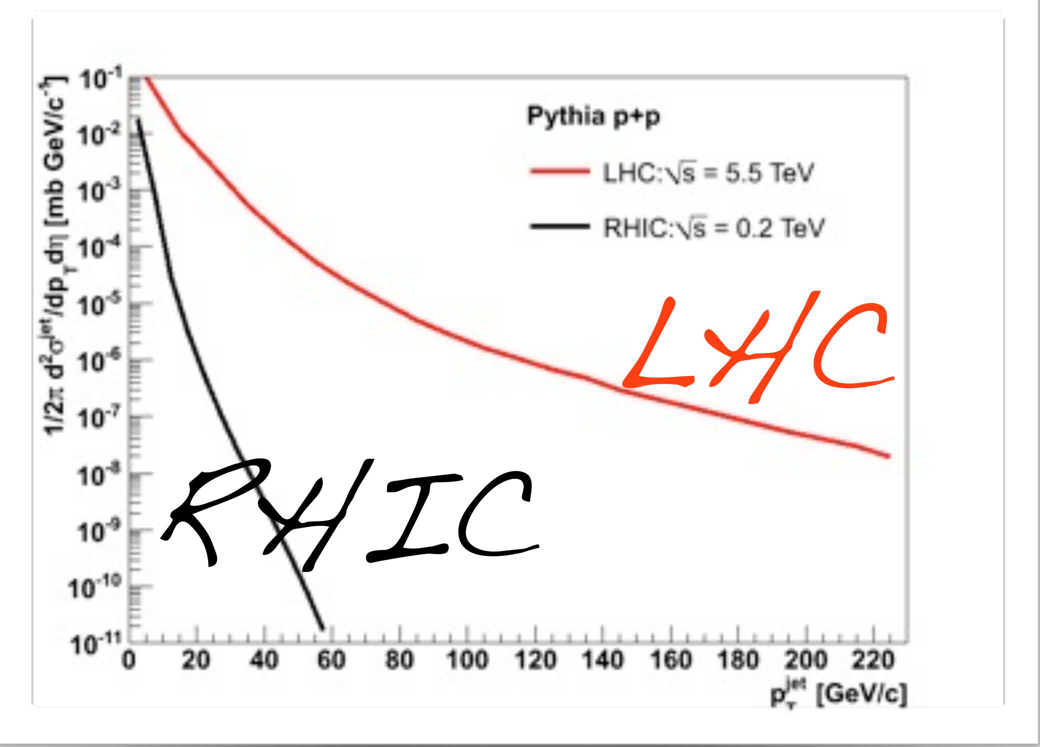


Jets in HI collisions & Experimental difficulties: Vacuum jet vs jet on top of the HI background...

Heavy-ion collision @ LHC



Jets in heavy-ion collisions RHIC & LHC



Jets in heavy-ion environment - few experimental notes:

- large combinatorial backgrounds (especially at RHIC)
- energy within an event varies from point to point ("fluctuations")
- a plus for LHC is larger kinematic reach - abundance of high-energy jets (higher-pT measurements less affected by backgrounds)

=> various approaches among experiments for background suppression AND/OR jet energy-resolution corrections

- is there an optimal jet definition for heavy-ion collisions (?)

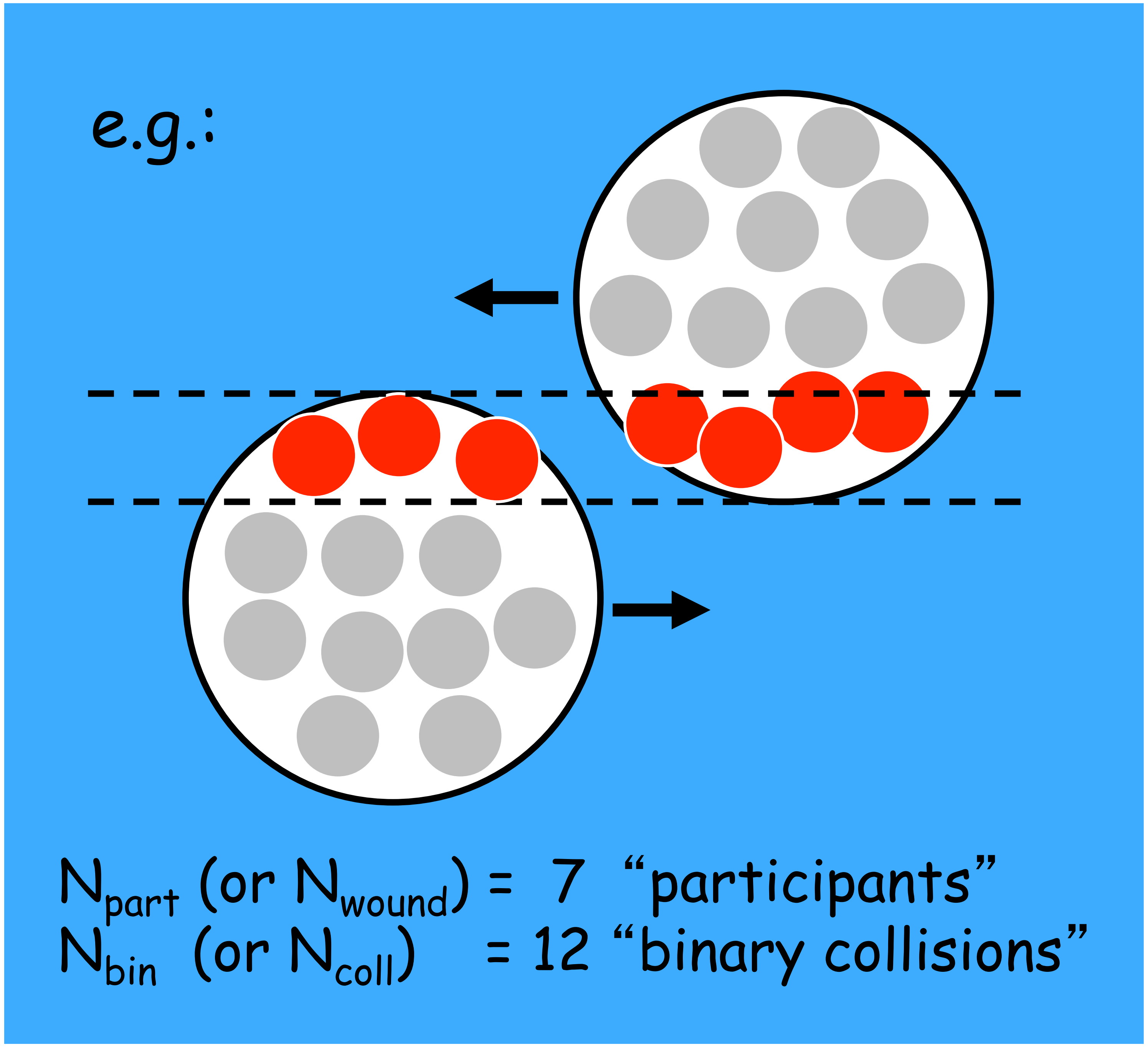
=> use multiple jet algorithms (?); sub-jets (?); filtering (?)

- jets are reported on the particle (generator) level - hadronization corrections (to the "parton" jet) in HI collisions impossible

Reminder...

"Soft", large cross-section processes expected to scale with N_{part}

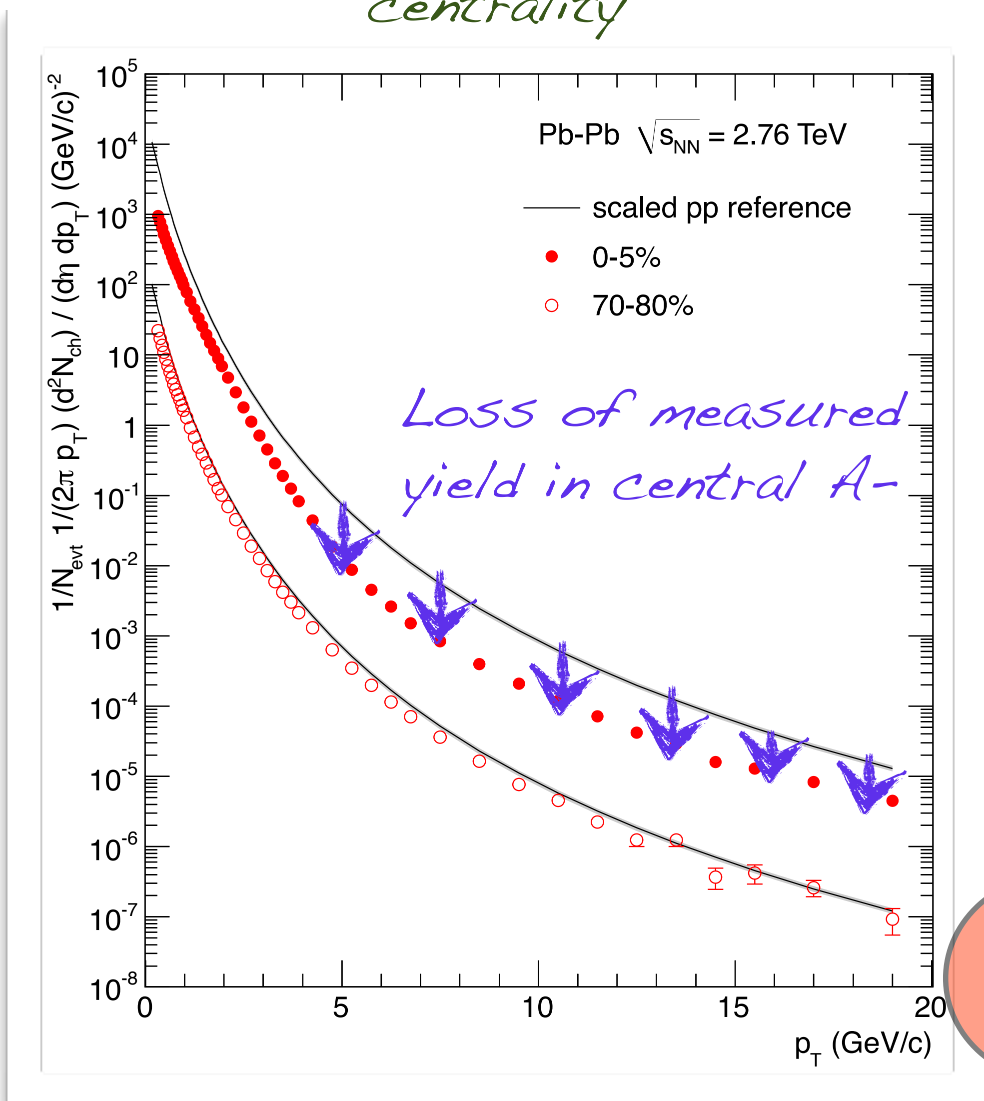
"Hard", low cross-section processes expected to scale with N_{bin}

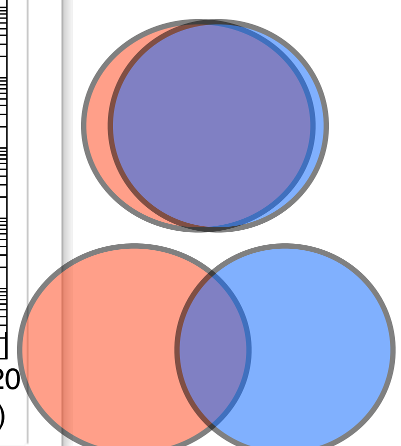


"Easier" (than full jet reconstruction) exercise: Jet-quenching via leading hadrons

Inclusive hadron production

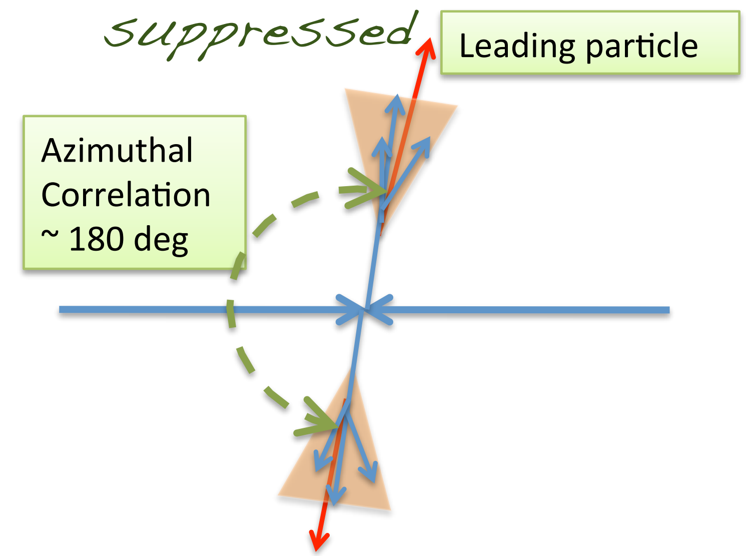
Measured as a function of collision centrality

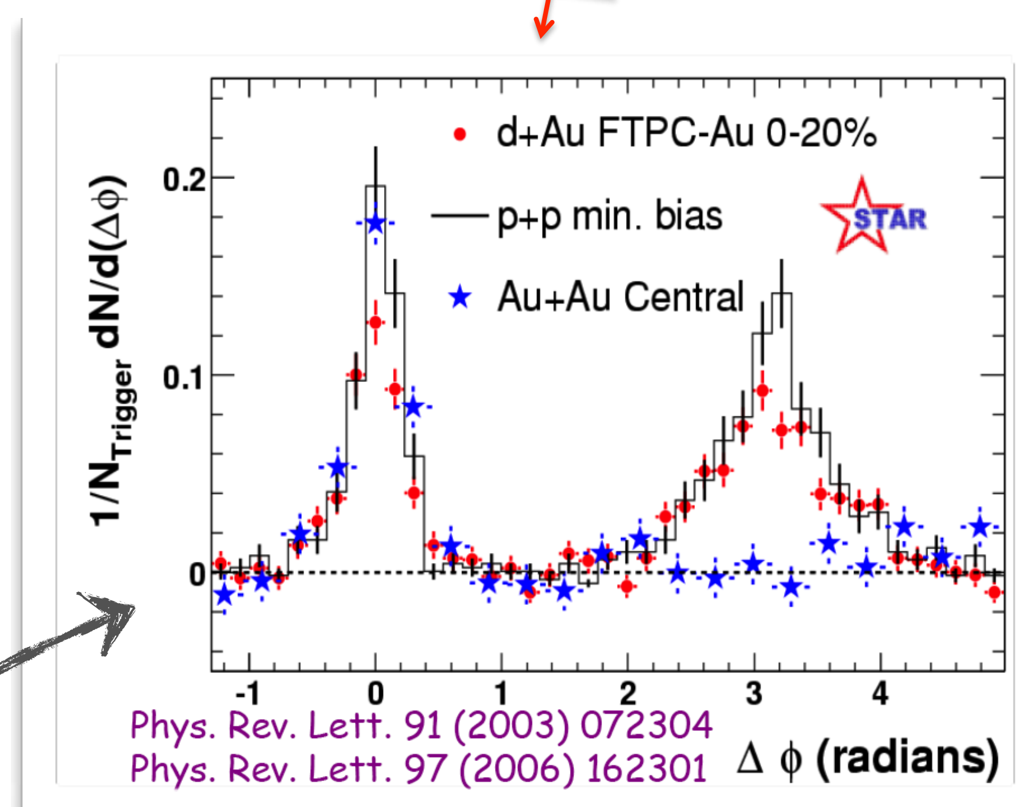




Di-hadron correlations

Rates of recoil ("away-side") hadrons suppressed





Phys. Rev. Lett. 91 (2003) 072304
Phys. Rev. Lett. 97 (2006) 162301

Note on correlations: interesting tool to study the "intermediate"-p_T region - jets vs flow and recombination

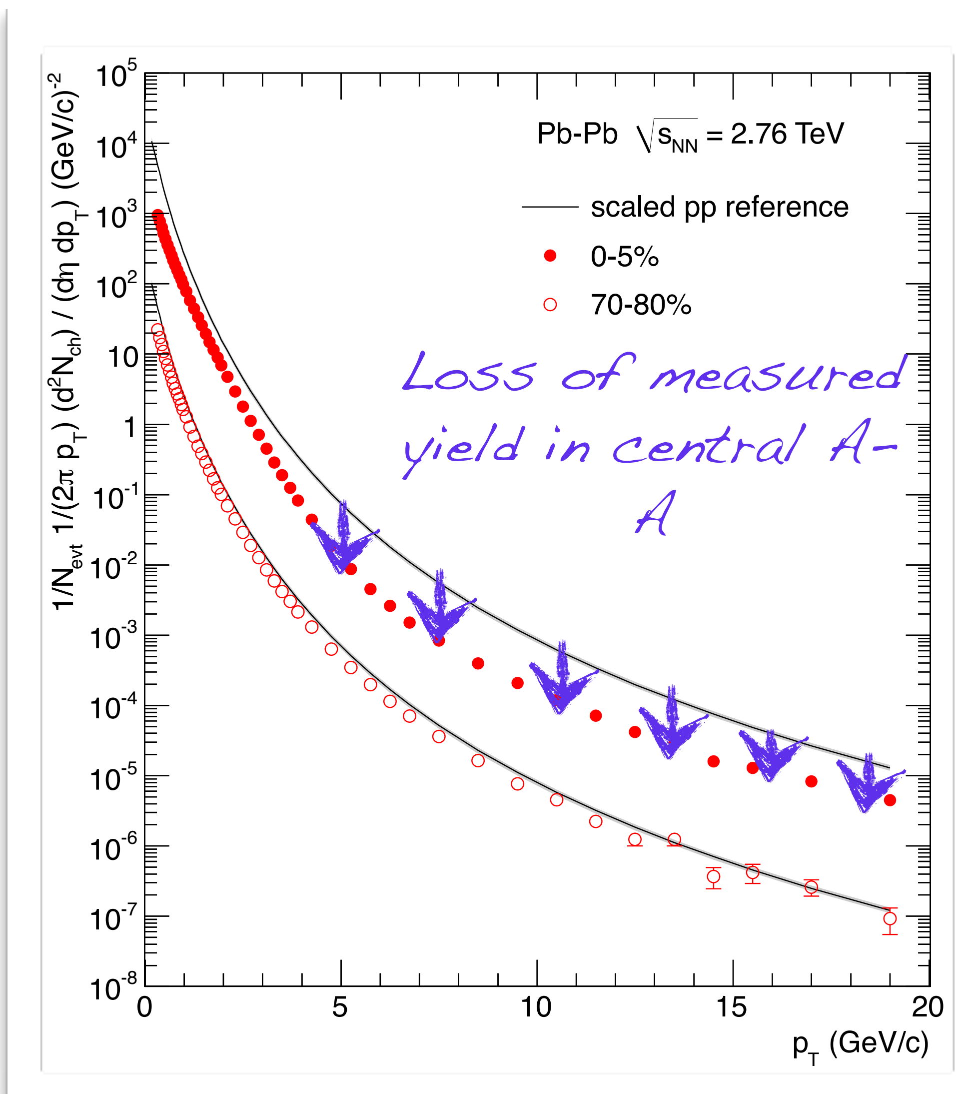
Hadron suppression

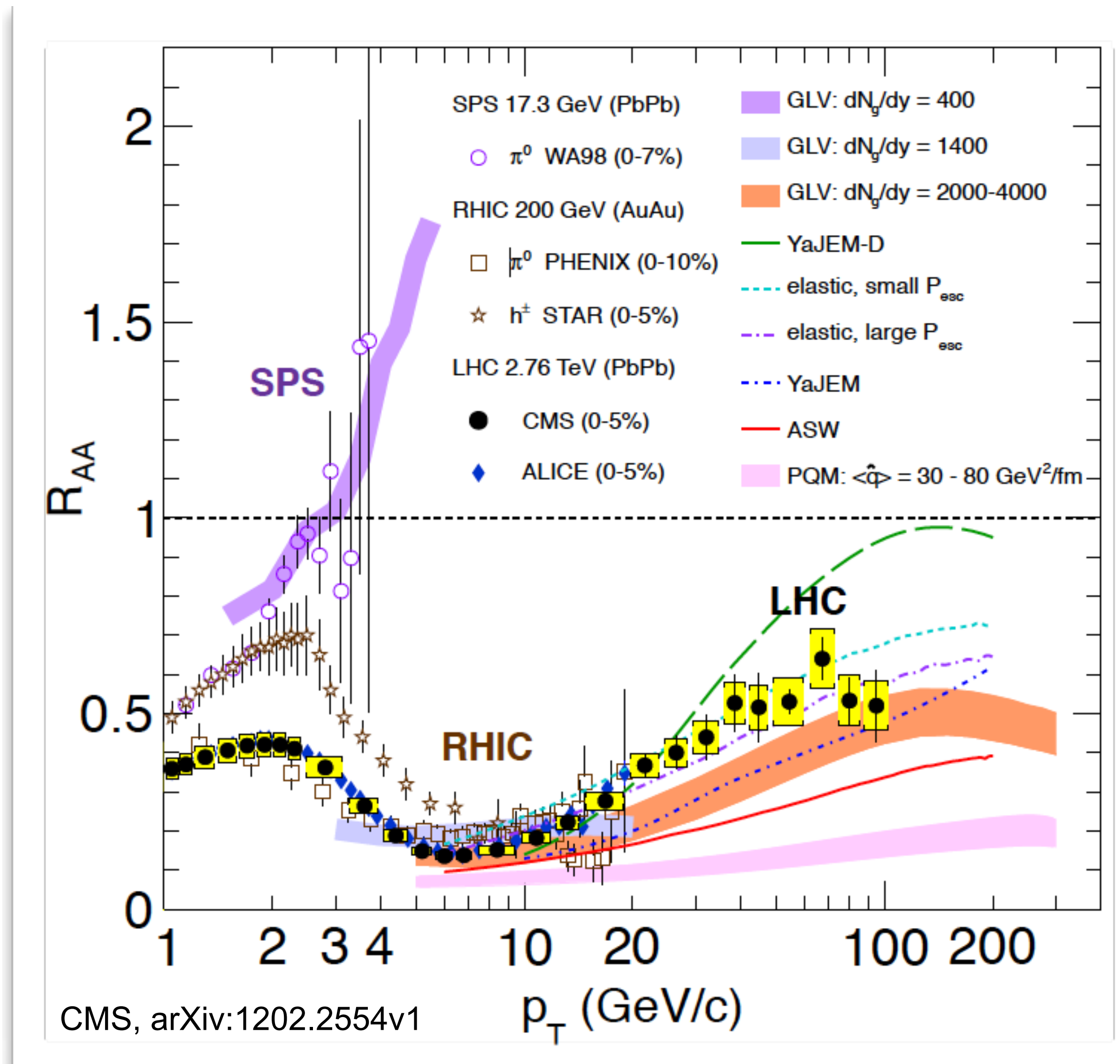
$$R_{AB} = \frac{d^2N/dp_t d\eta}{T_{AB} d^2\sigma^{pp}/dp_t d_\eta}$$

$$T_{AB} = < N_{bin} > / \sigma^{pp}_{inel}$$

Nuclear modification factor:

$$R_{AA} = \frac{\#(\text{particles observed in AA collision per N-N (binary) collision})}{\#(\text{particles observed per p-p collision})}$$



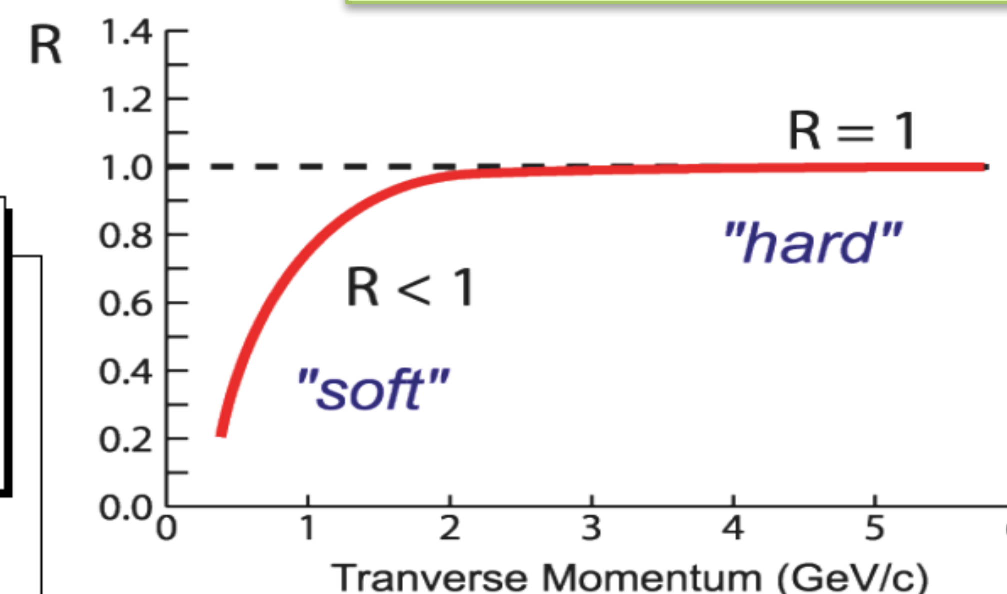


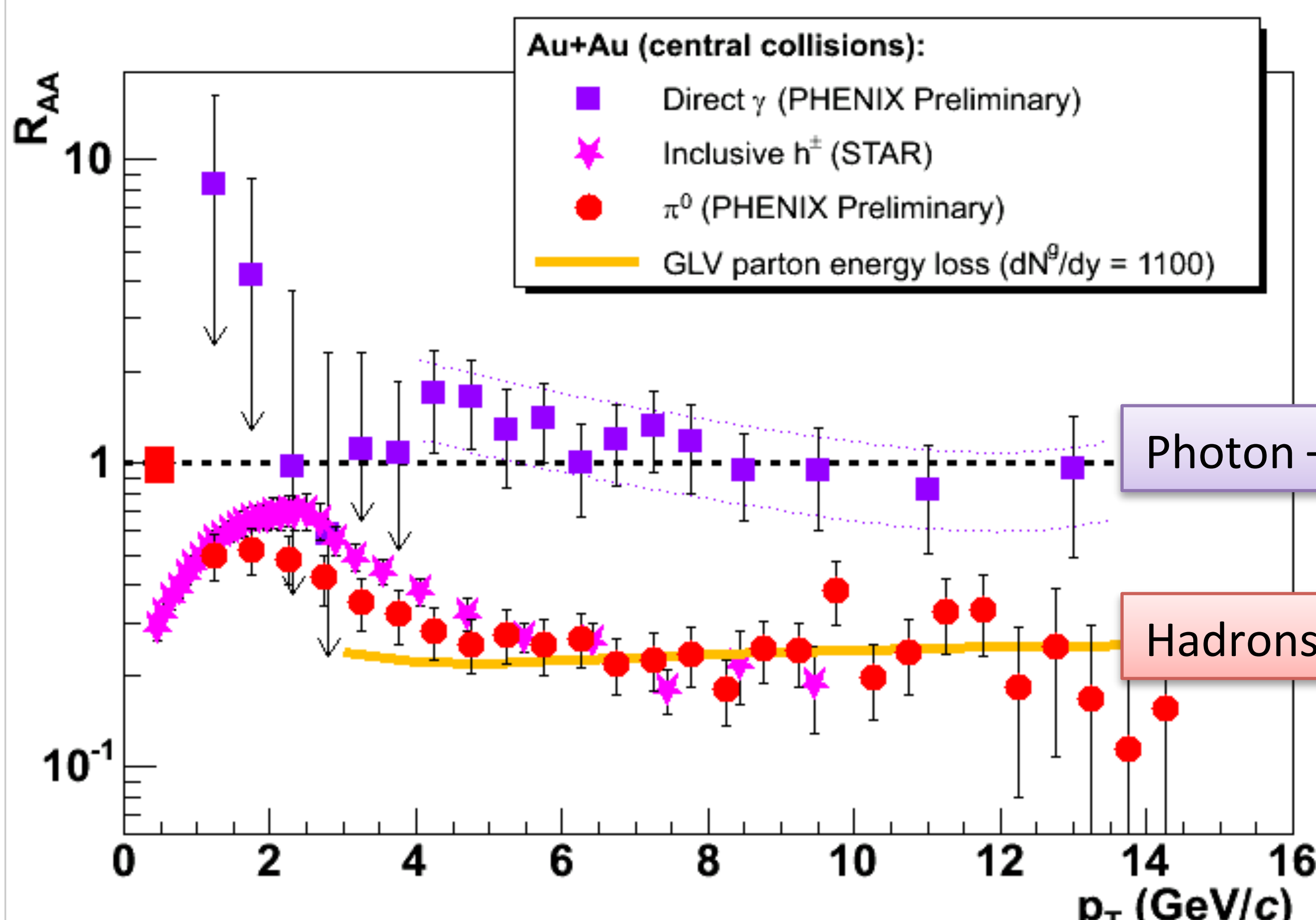
"No effect" case is for RAA = 1 at high pT where hard processes

Jet quenching - RHIC

$$\text{Ratio} = \frac{\#(\text{particles observed in AA collision per binary collision})}{\#(\text{particles observed per p-p collision})}$$

No "effect":
R < 1 at small momenta
R = 1 at higher momenta where hard processes dominate





Photon – color neutral probe => No suppresion

Hadrons from color charged jets => Suppression

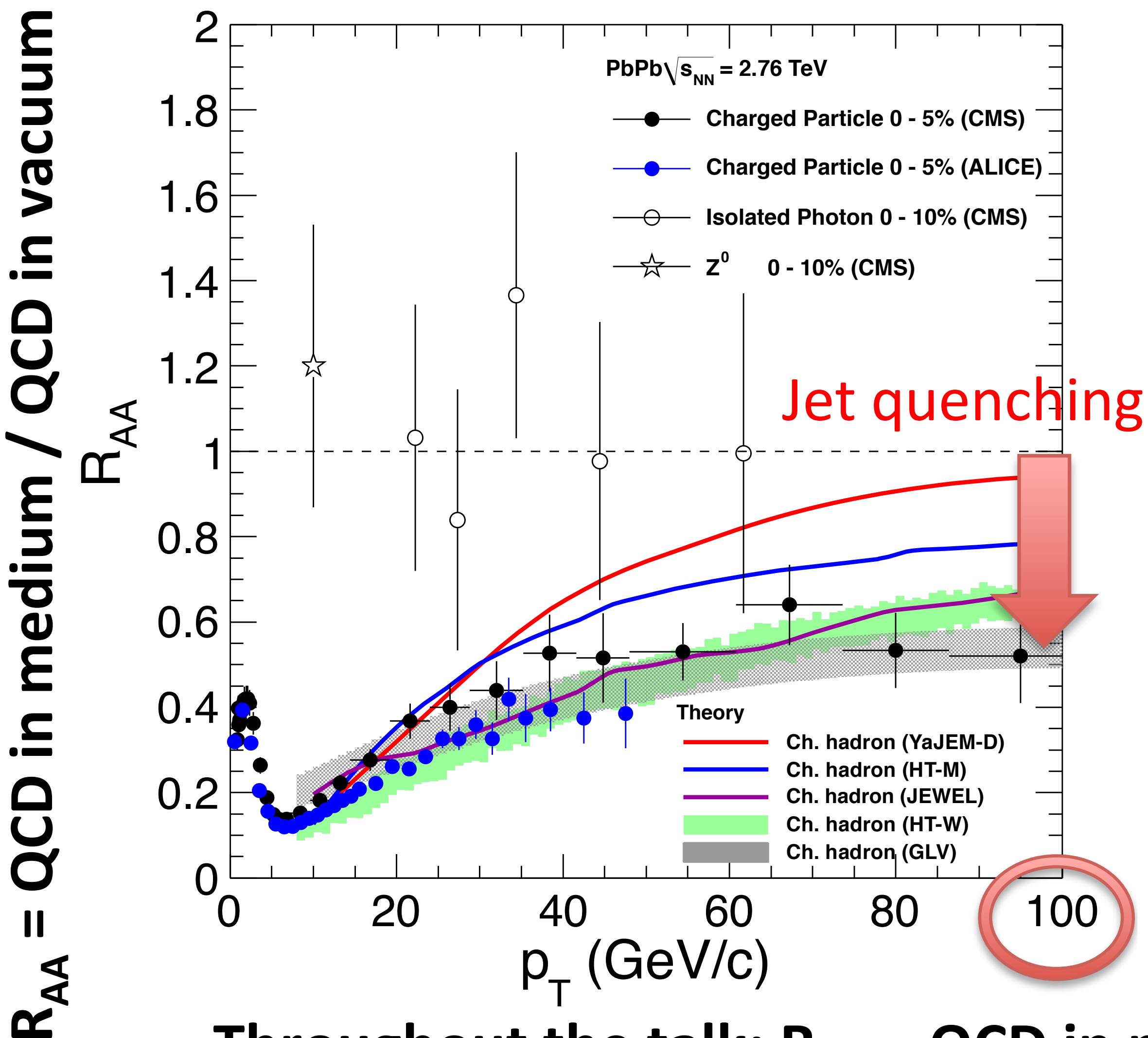
Energy-loss - QGP state effect!

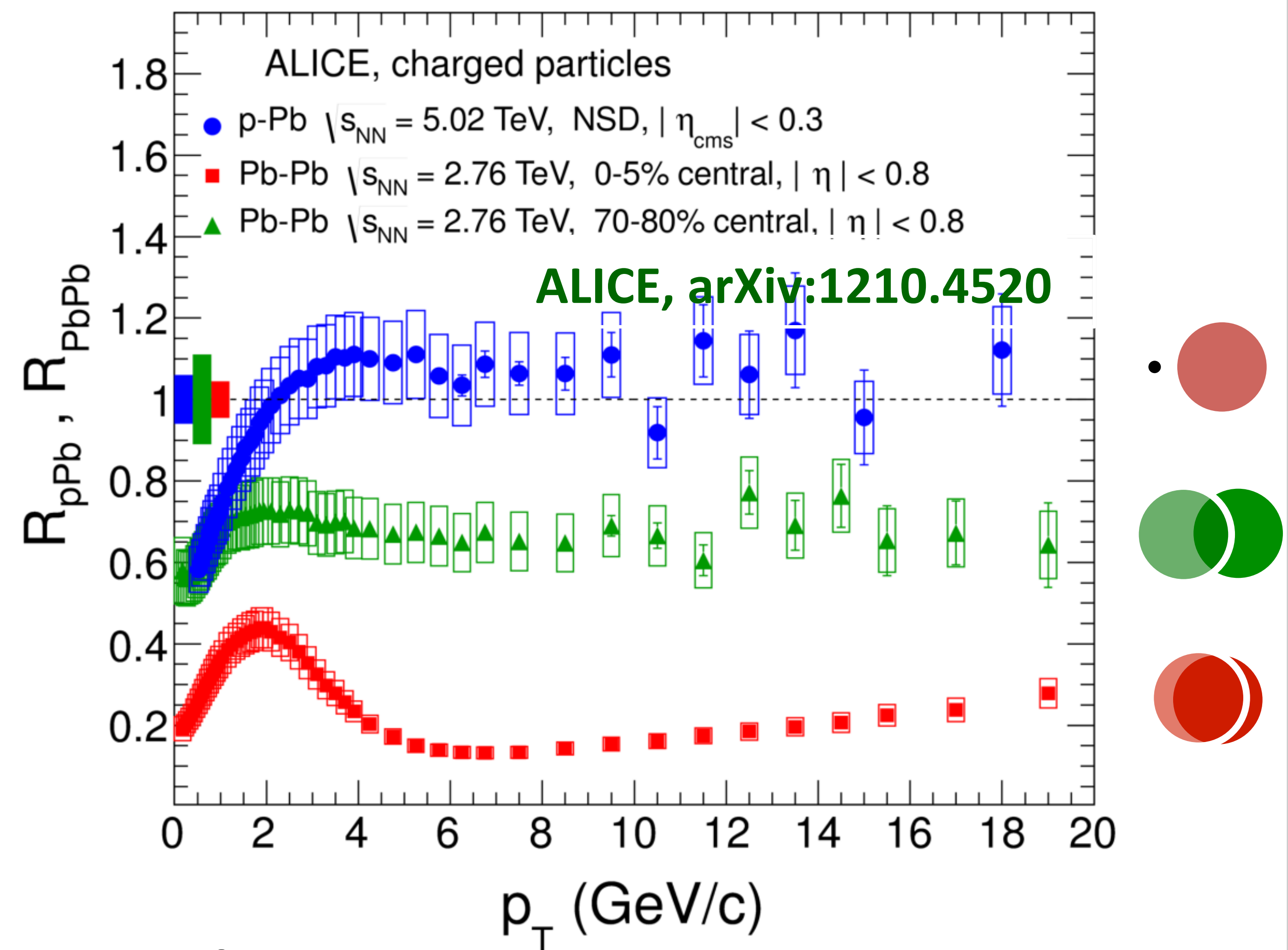
Color charged probes suppressed

Color neutral probe production scales with Nbin collisions

pA collisions: suppression is an effect of QGP

$$R_{AA} = \frac{1}{< N_{\rm coll} >} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$





Throughout the talk: R_{AA} = QCD in medium / QCD in vacuum

Note: only colored probes quenched; pA: jet quenching is a in-medium effect

RAA: extreme scenarios

Note: I am not showing you the P(ΔE)

P(ΔE) - probability for parton to loose ΔE

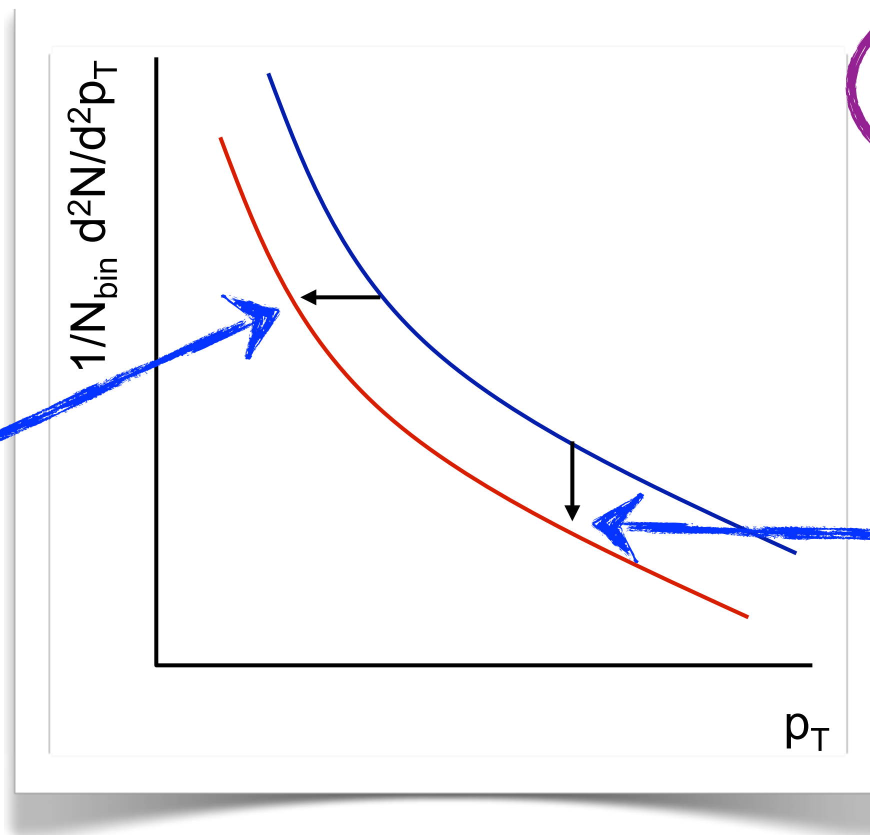
Scenario I
$P(\Delta E) = \delta(\Delta E_0)$

"Energy loss"

Scenario II
$P(\Delta E) = a\,\delta(0) + b\,\delta(E)$

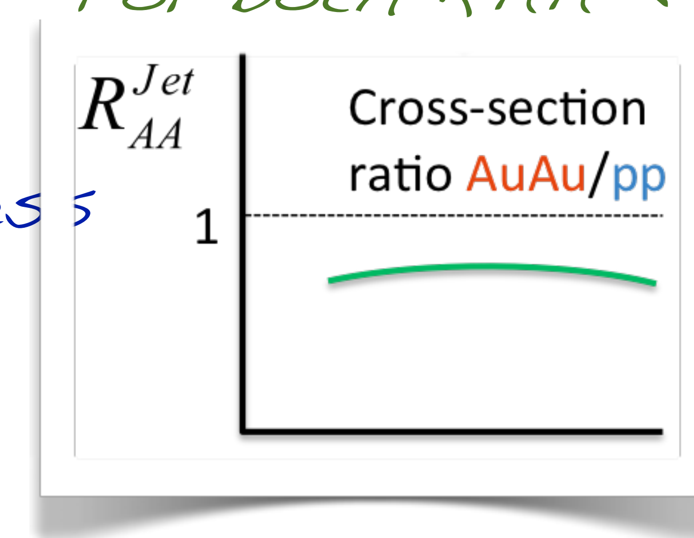
"Absorption"

"Shift" to lower pT



"Shift" in yield

For both RAA < 1



P(ΔE) encodes the full energy loss process

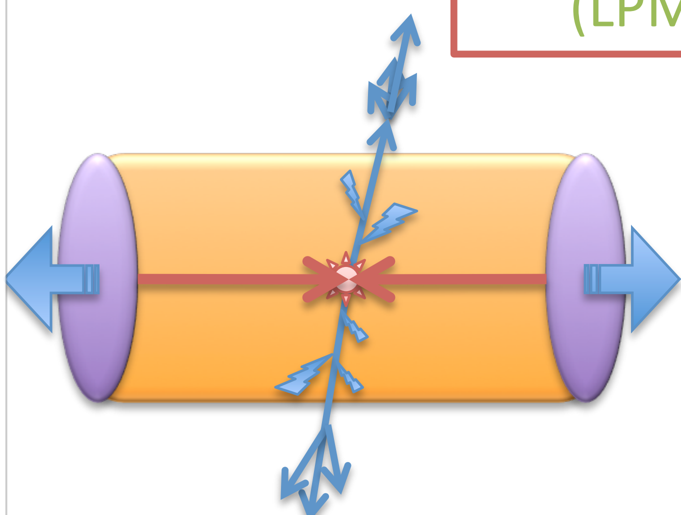
R_{AA} not sensitive to energy loss distribution, details of mechanism...

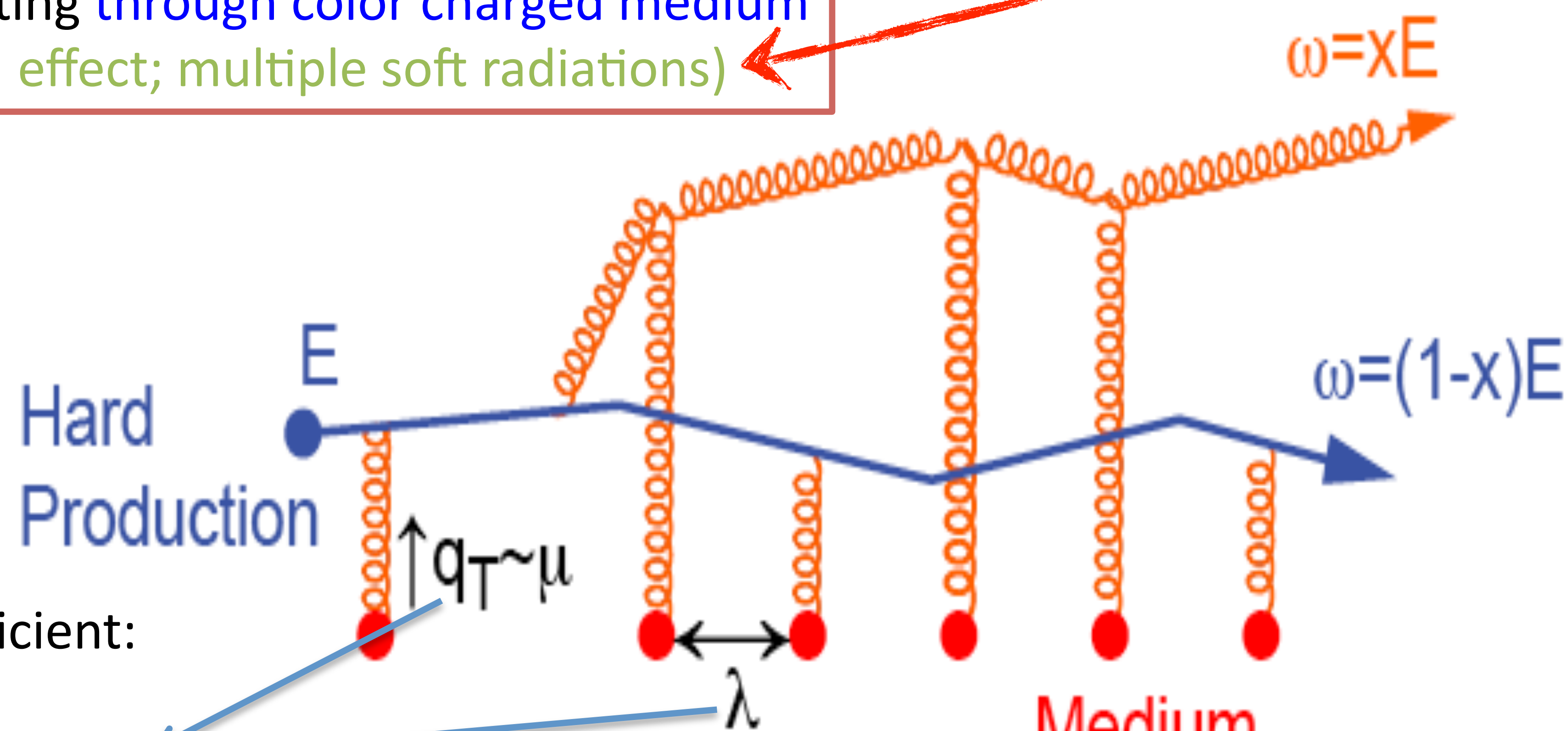
Brehmsstrahlung in QCD

λ<τ=> Multiple scatterings add coherently

$$t_{formation} < L \Leftrightarrow \omega < \omega_c$$

High energy **color charged probe** propagating **through color charged medium** (LPM effect; multiple soft radiations)





Define a transport coefficient:

$$\hat{q} \sim \mu^2/\lambda$$

$$-dE/dx \sim \alpha_s \hat{q} L^2$$

Partonic energy loss in QCD medium is proportional:
- to squared average path length (Note: QED ~ linear)
- to density of the medium

$$\lambda \propto \frac{1}{\rho}$$

⇒ **energy flow (parton+radiation) modified as compared to jet in vacuum**

⇒ **jet "quenched" ("softened" fragmentation)**

Bremsstrahlung in QCD

λ<τ=> Multiple scatterings add coherently

$t_{formation} < L \Leftrightarrow \omega < \omega_c$

ω=xE

High energy color charged probe
propagating through color charged medium
(LPM effect; multiple soft radiations)

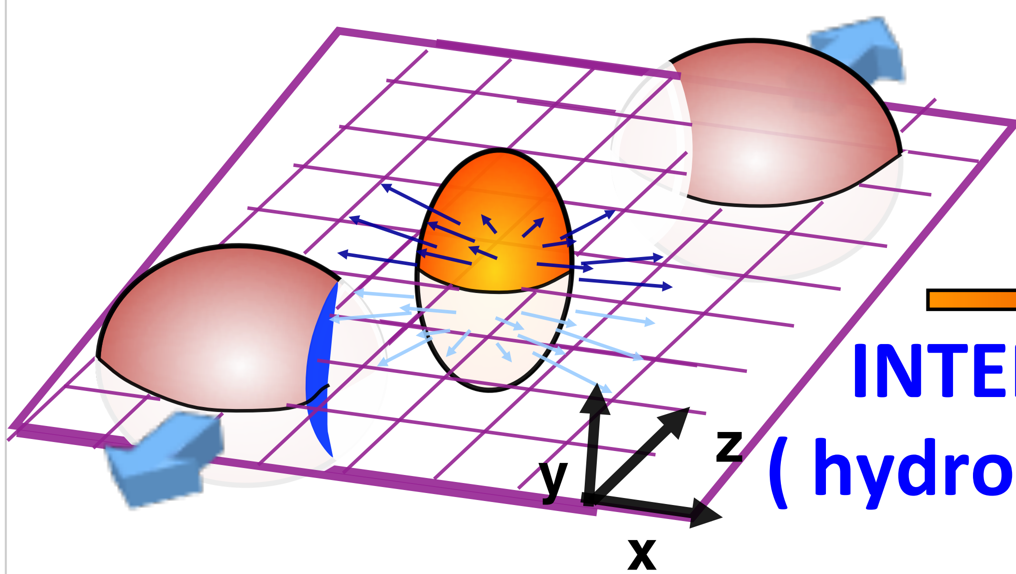
An idea: vary the path length experimentally?
-> sensitivity to the collision profile
-> different collisions systems?

Partonic energy loss in QCD medium is proportional:
- to squared average path length (Note: QED ~ linear)
- to density of the medium

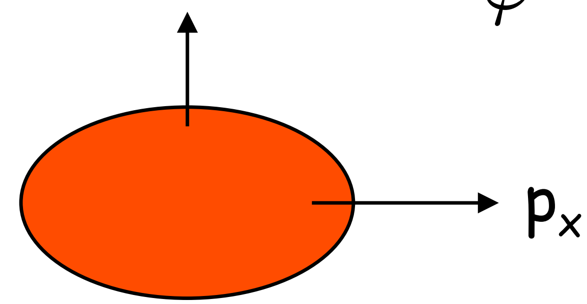
$$\lambda \propto \frac{1}{\rho}$$

⇒ energy flow (parton+radiation) modified as compared to jet in vacuum
⇒ jet "quenched" ("softened" fragmentation)

Azimuthal angular asymmetry in particle production



INTERATIONS
(hydrodynamics?)



$$\varphi = \arctan \frac{p_y}{px}$$

$$\varepsilon = \frac{\langle y^2 \rangle - \langle x^2 \rangle}{\langle y^2 \rangle + \langle x^2 \rangle}$$

Initial spatial anisotropy

$$v_2 = \frac{\langle p_x^2 \rangle - \langle p_y^2 \rangle}{\langle p_x^2 \rangle + \langle p_y^2 \rangle}$$

Final momentum anisotropy

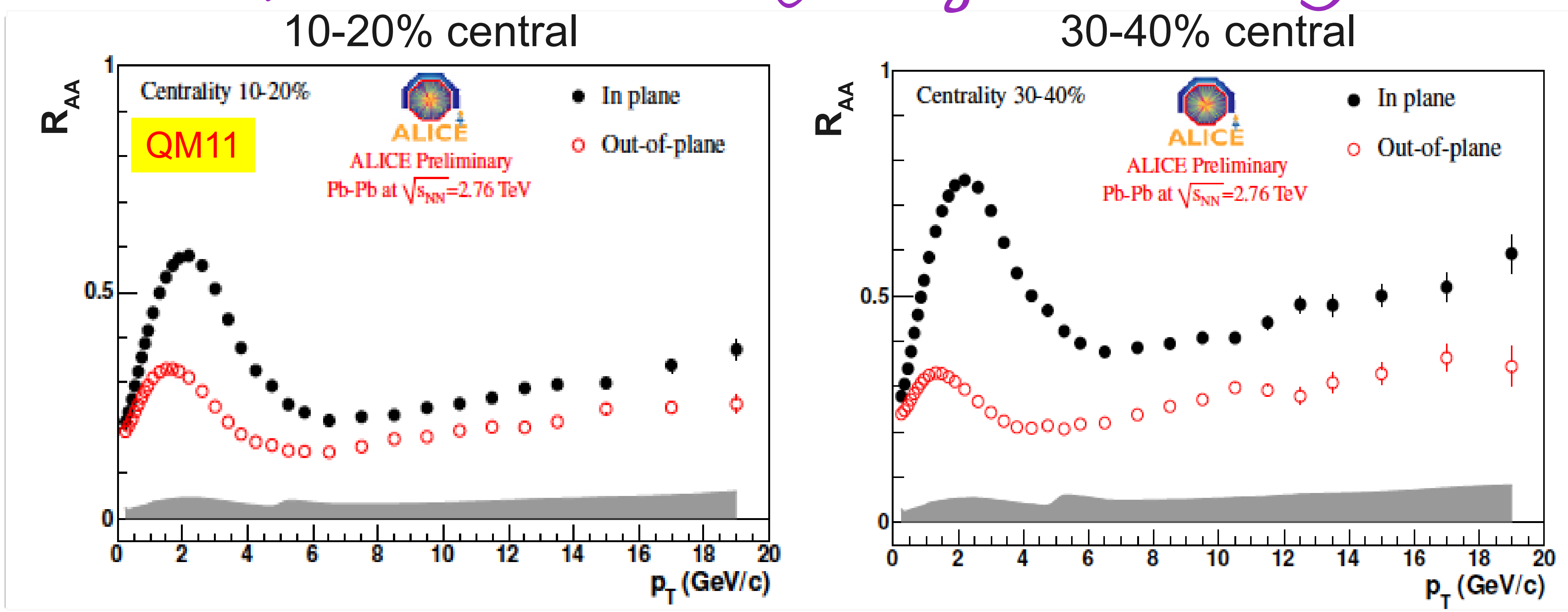
Reaction plane defined by "soft" (low p_T) particles

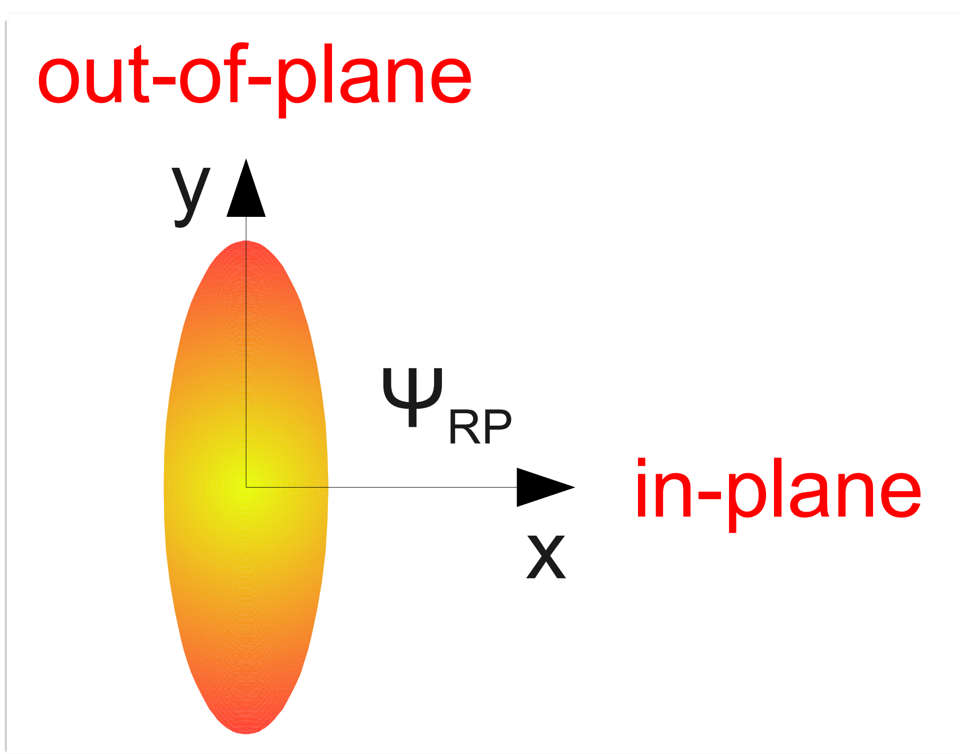
$$\Delta\varphi = \varphi - \varphi^{Reaction\ Plane}$$

Elliptic flow

$$\frac{dN}{d\Delta\varphi} \propto 1 + 2v_2 \cos(2\Delta\varphi)$$

RAA wrt reaction plane - path length dependence of jet quenching?





Suppression out-of-plane stronger <= longer in-medium path length - significant effect even at 20 GeV/c

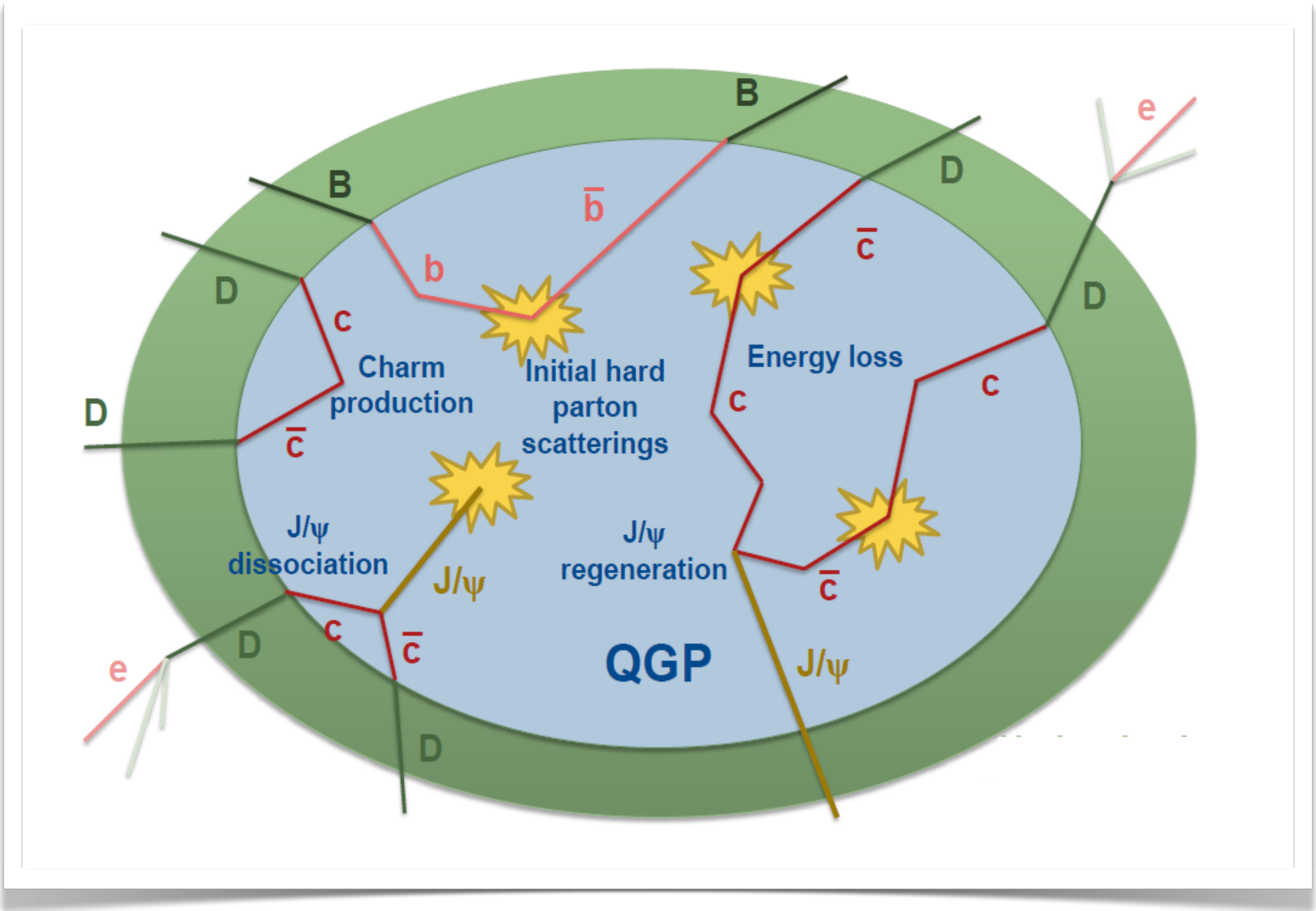
=> Path length dependence of energy loss ?

Additional constraints to energy loss models (?)

- **similar** information from v2 at high p_T

$$R_{AA}(\varphi) = R_{AA}(1 + 2v_2 \cos 2(\varphi - \psi))$$

Heavy-flavor in medium



R_{AA} for different particle type

Is parton energy loss different
for gluons, light-quarks and heavy-quarks?

Expectation: $\Delta E_g > \Delta E_{light-q} > \Delta E_{heavy-q}$

$\Delta E \propto \alpha_S C_R q L^2$
CR = 4/3 for quarks, 3 for gluons

Casimir (color factor)
- gluons "glue" better to the medium than quarks

"Dead-cone" effect:
mass of the parent quark
=> radiation for angles $\theta < m/E$ is suppressed

=> $R_{AA}^{pions} < R_{AA}^{D-mesons} < R_{AA}^{B-mesons}$

Parton energy-loss: gluons vs. quarks

$$\Delta E \propto \alpha_s C_R \hat{q} L^2$$

- Energy loss depends on parton:
  - Casimir factor (C_R=3 for gluons and 4/3 for quarks)
  - Mass of the quark (**dead cone** effect): radiation suppressed for angles $\theta < m/E$

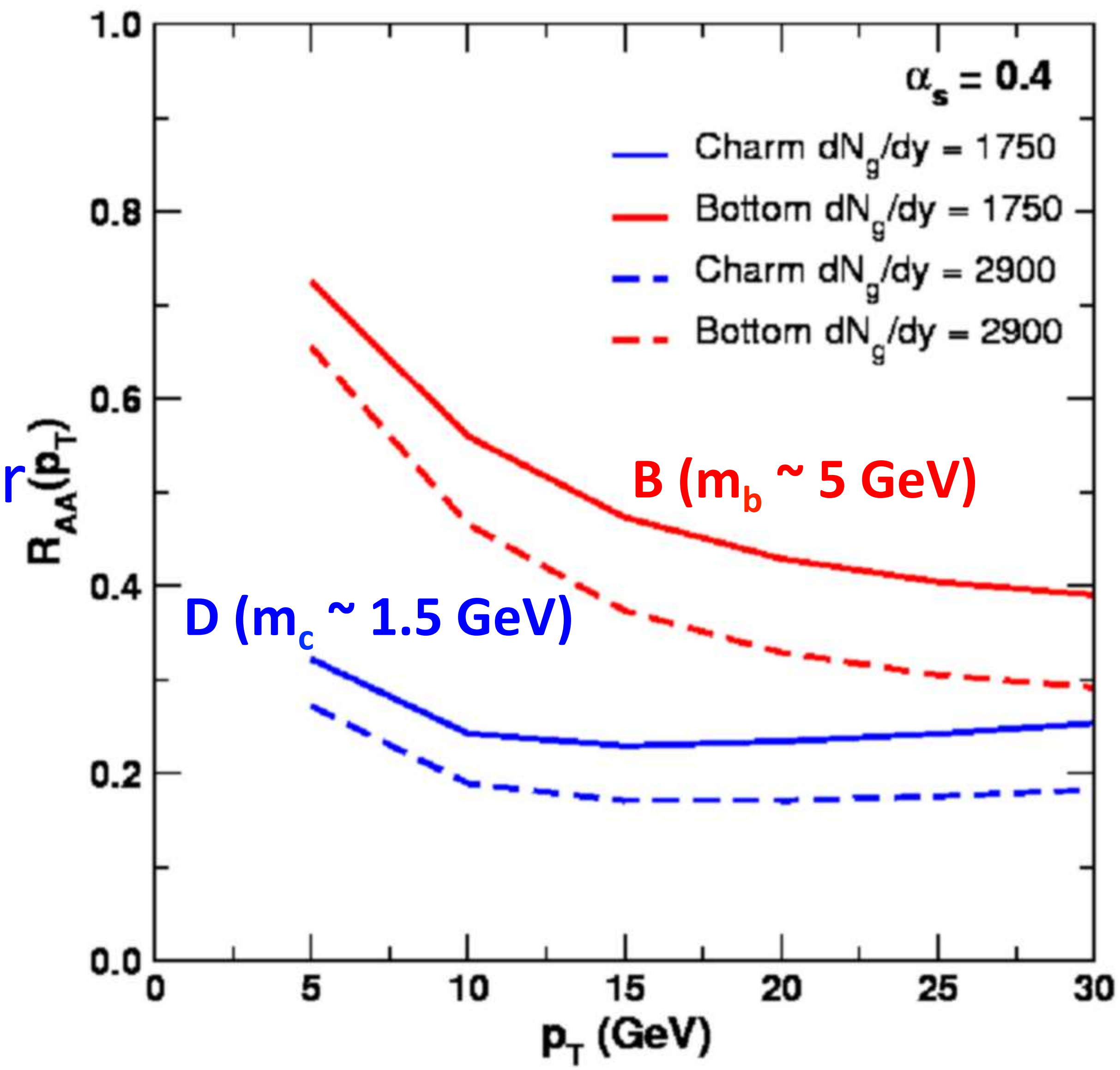
$$\Delta E_{gluon} > \Delta E_{quark}$$
$$\Delta E_{light-q} > \Delta E_{heavy-q}$$

- Does it persist at low-p_T as:

$$R^{\pi}_{AA} < R^{D}_{AA} < R^{B}_{AA}$$

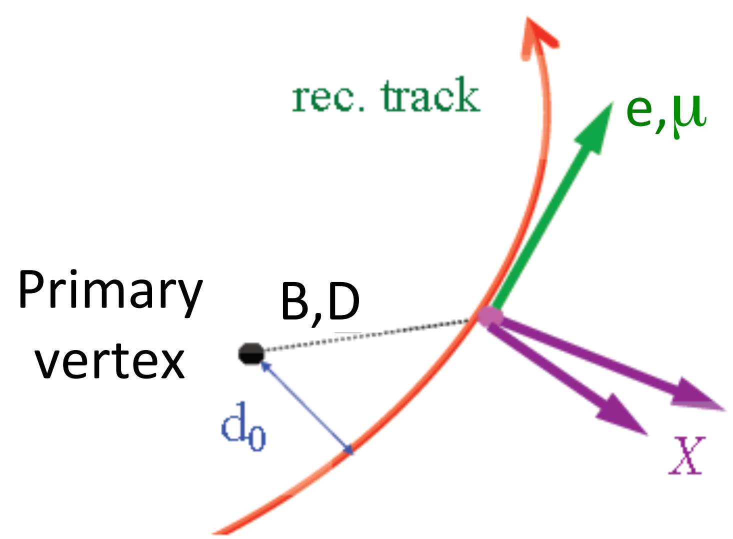
Prediction!

Wicks, Gyulassy, Last Call for LHC predictions

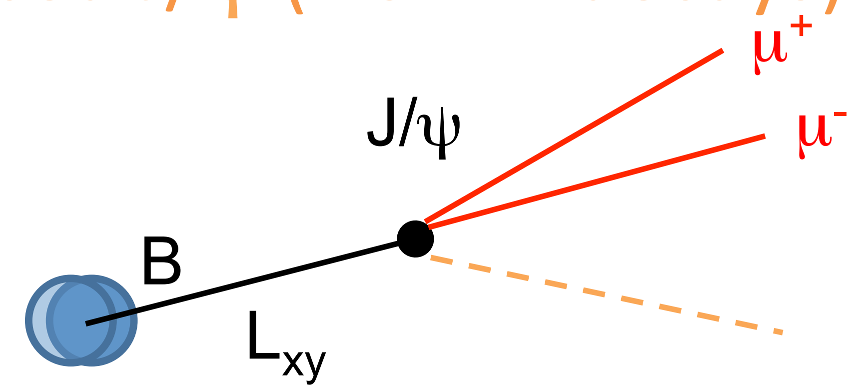


Heavy-flavor reconstruction

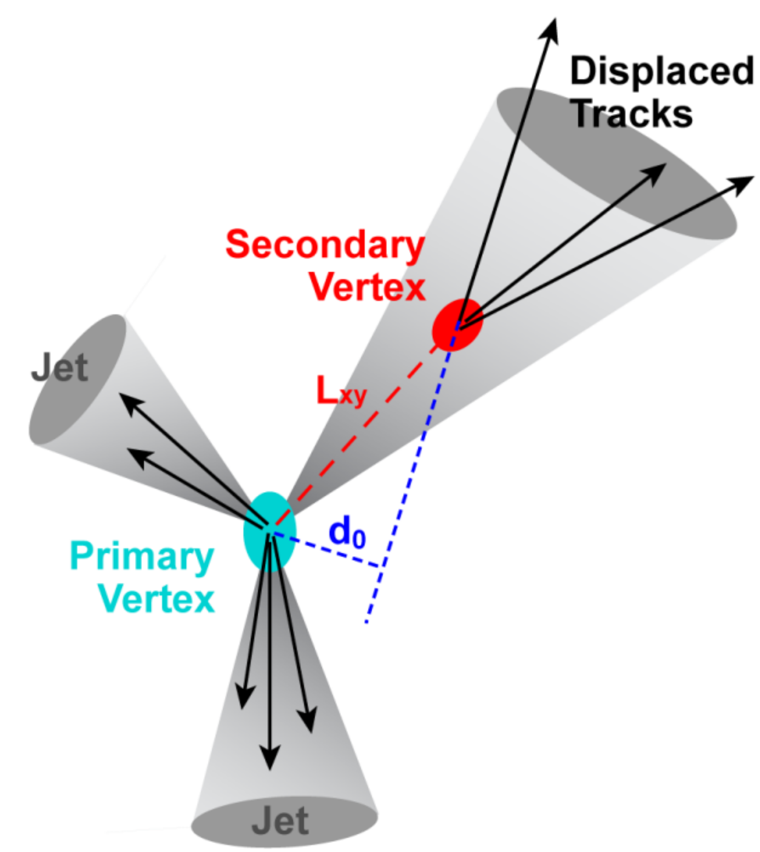
Semi-leptonic decays (c,b)



Displaced J/ψ (from B decays)



jet b-tagging



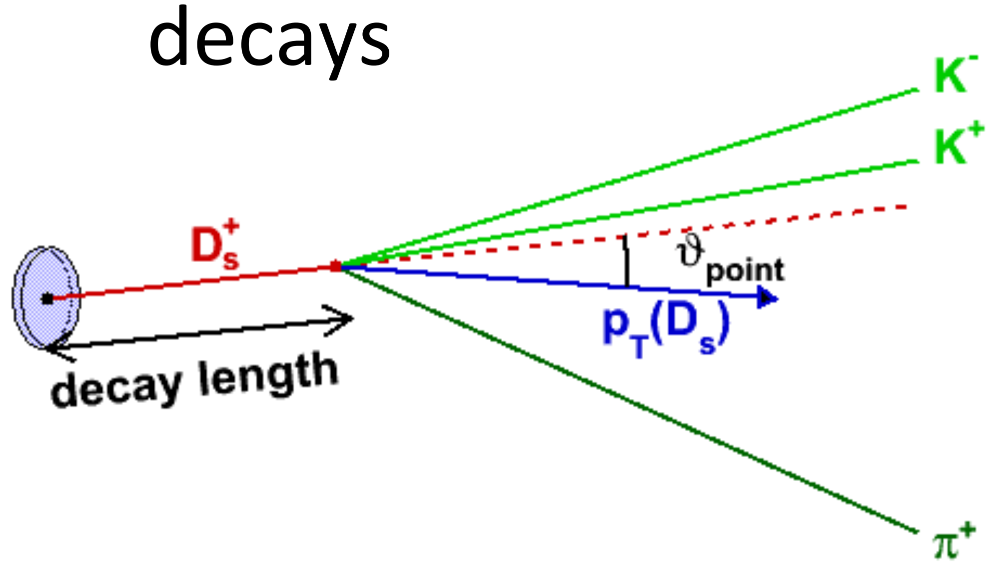
Full reconstruction of D meson hadronic decays

$D^0 \rightarrow K^- \pi^+$

$D^+ \rightarrow K^- \pi^+ \pi^+$

$D^{*+} \rightarrow D^0 \pi^+$

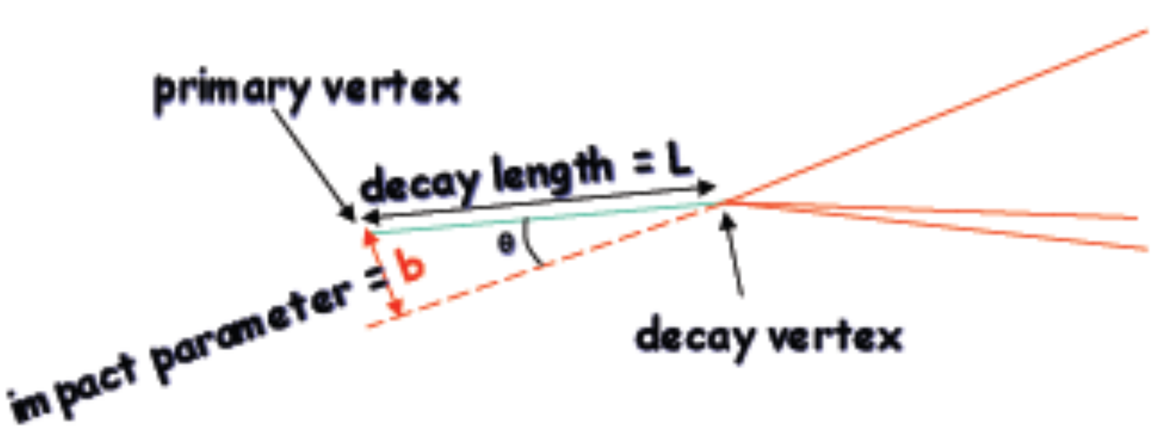
$D_s^+ \rightarrow K^- K^+ \pi^+$

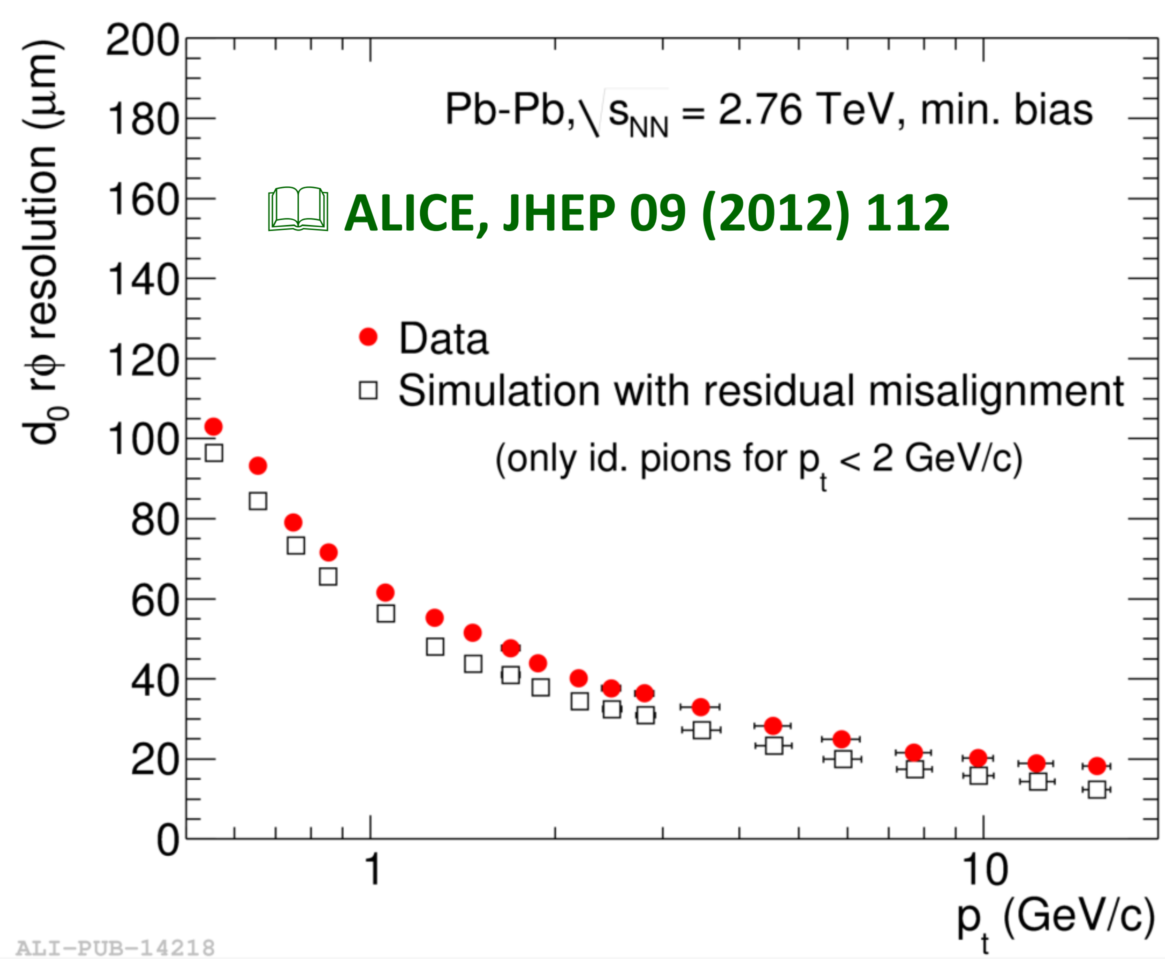


Experimental How-to: Displaced tracks

- Lower mass heavy flavour hadrons decay weakly:
  - Lifetimes: ≈0.5-1 ps for D and ≈1.5 ps for B
  - cτ: ≈100-300 μm for D and ≈ 500 μm for B
- Possibility to detect decay vertices/displaced tracks
  - Tracking precision plays a crucial role

- Track impact parameter: distance of closest approach of a track to the interaction vertex

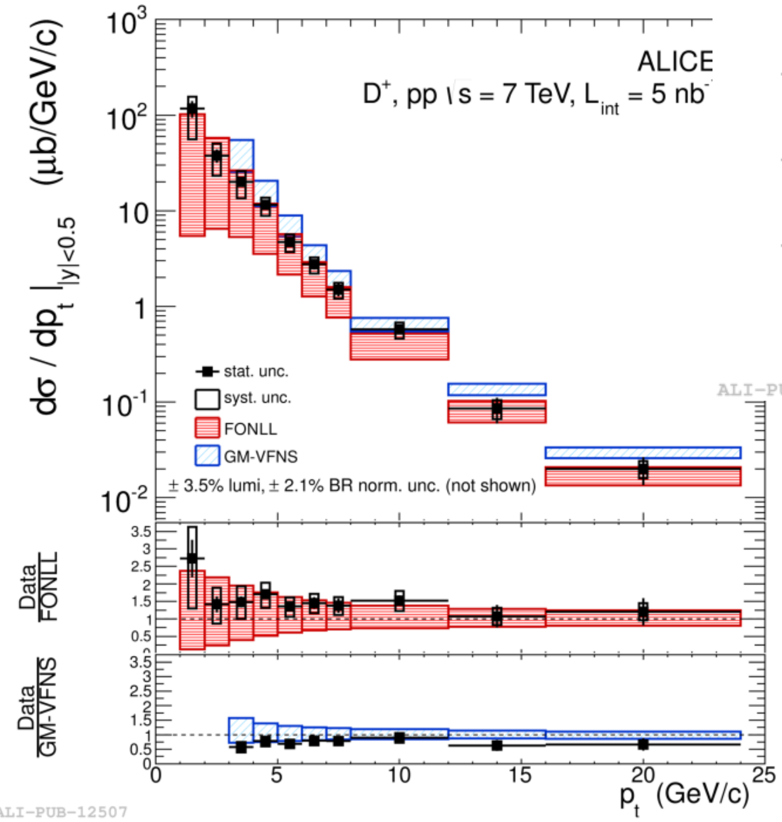




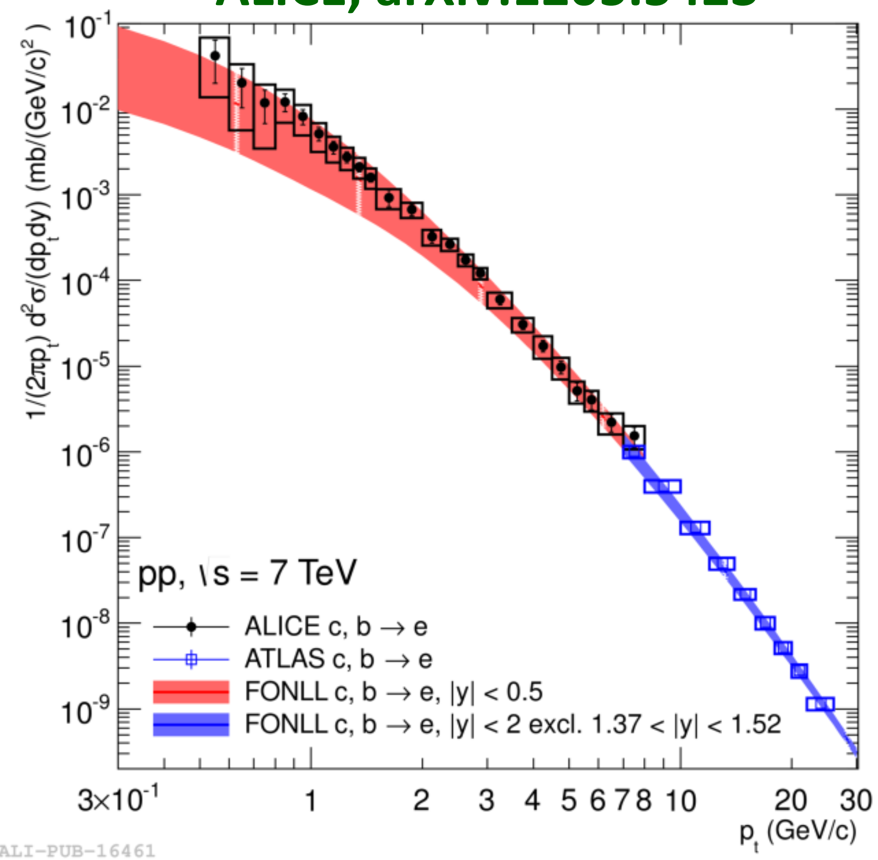
Heavy-flavor - calibrated probes?

Production in p-p

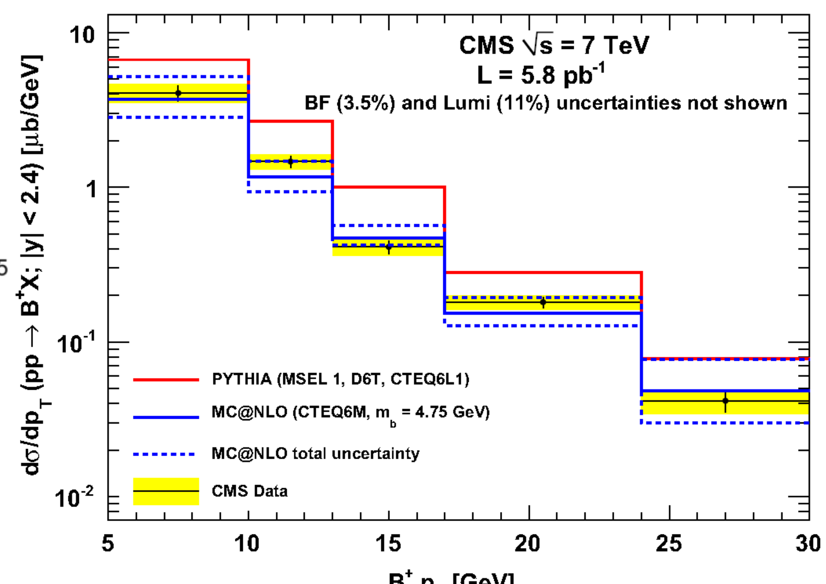
ALICE, JHEP 1201 (2012)



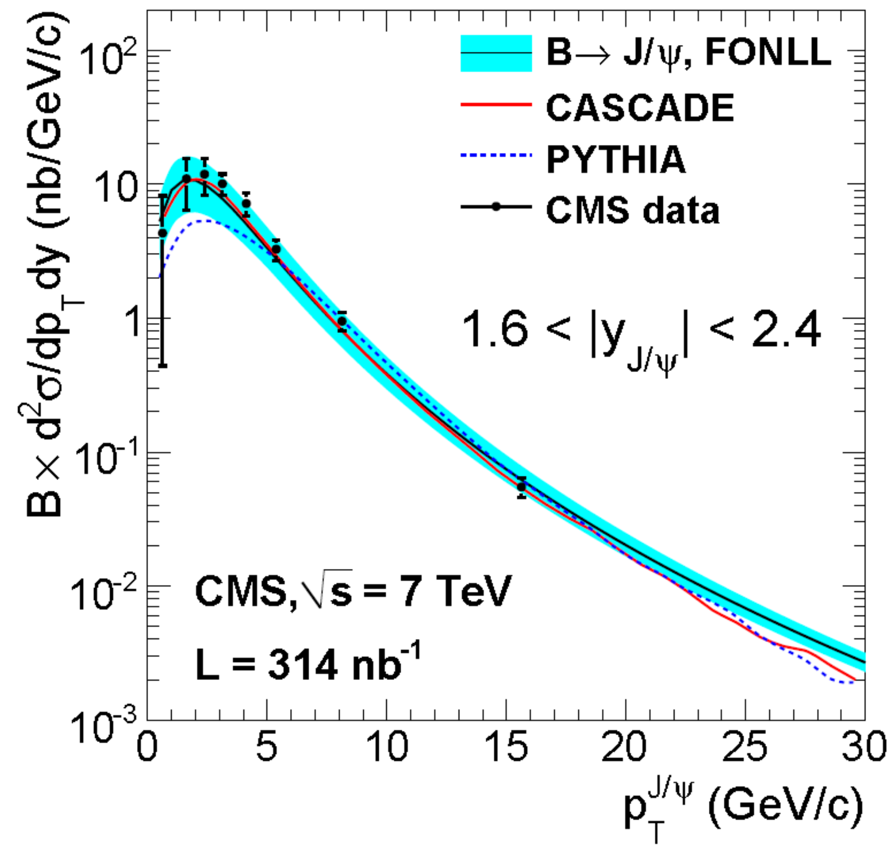
ALICE, arXiv:1205.5423



CMS, PRL 106 (2011) 112001

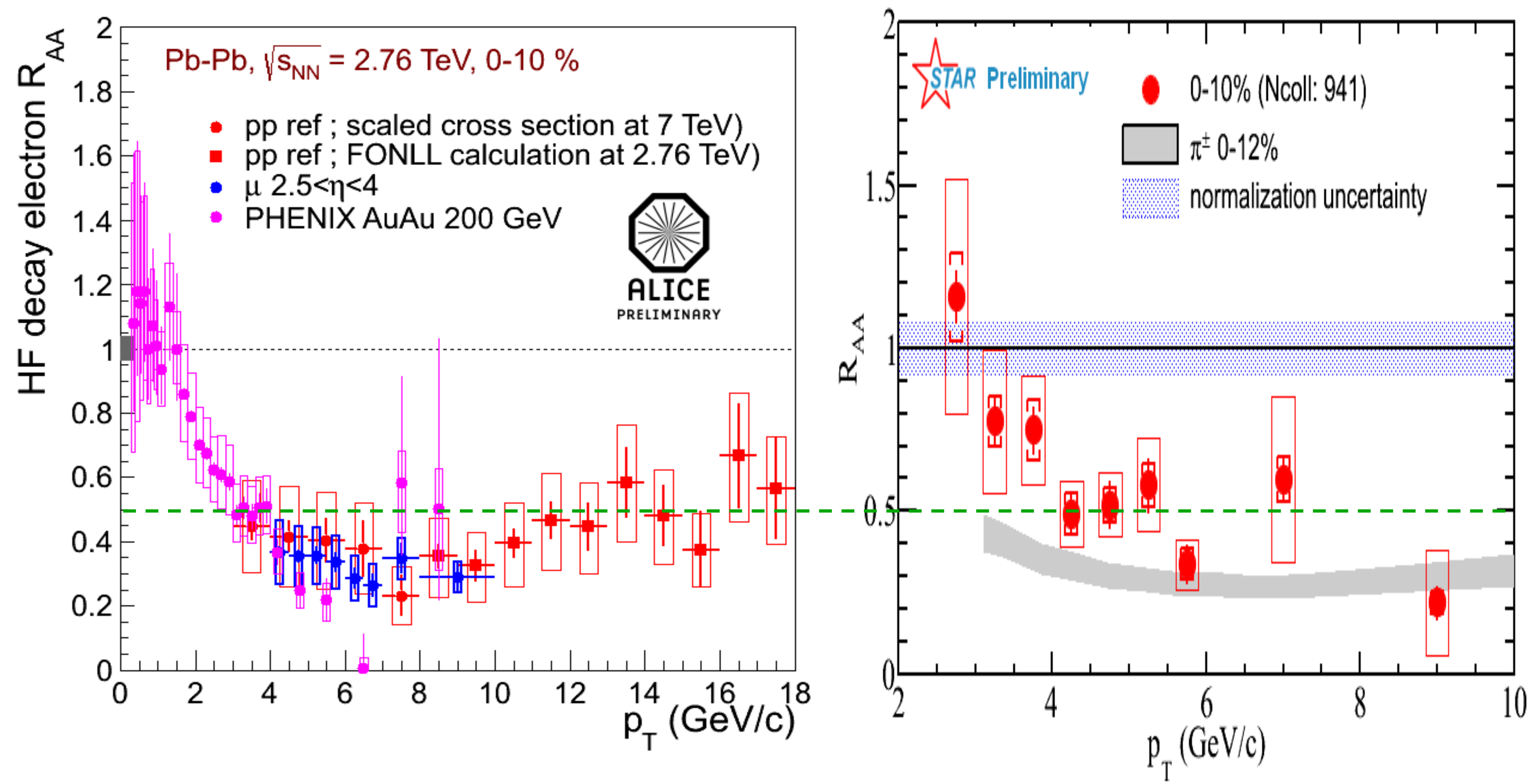


CMS, EPJC 71 (2011) 1575



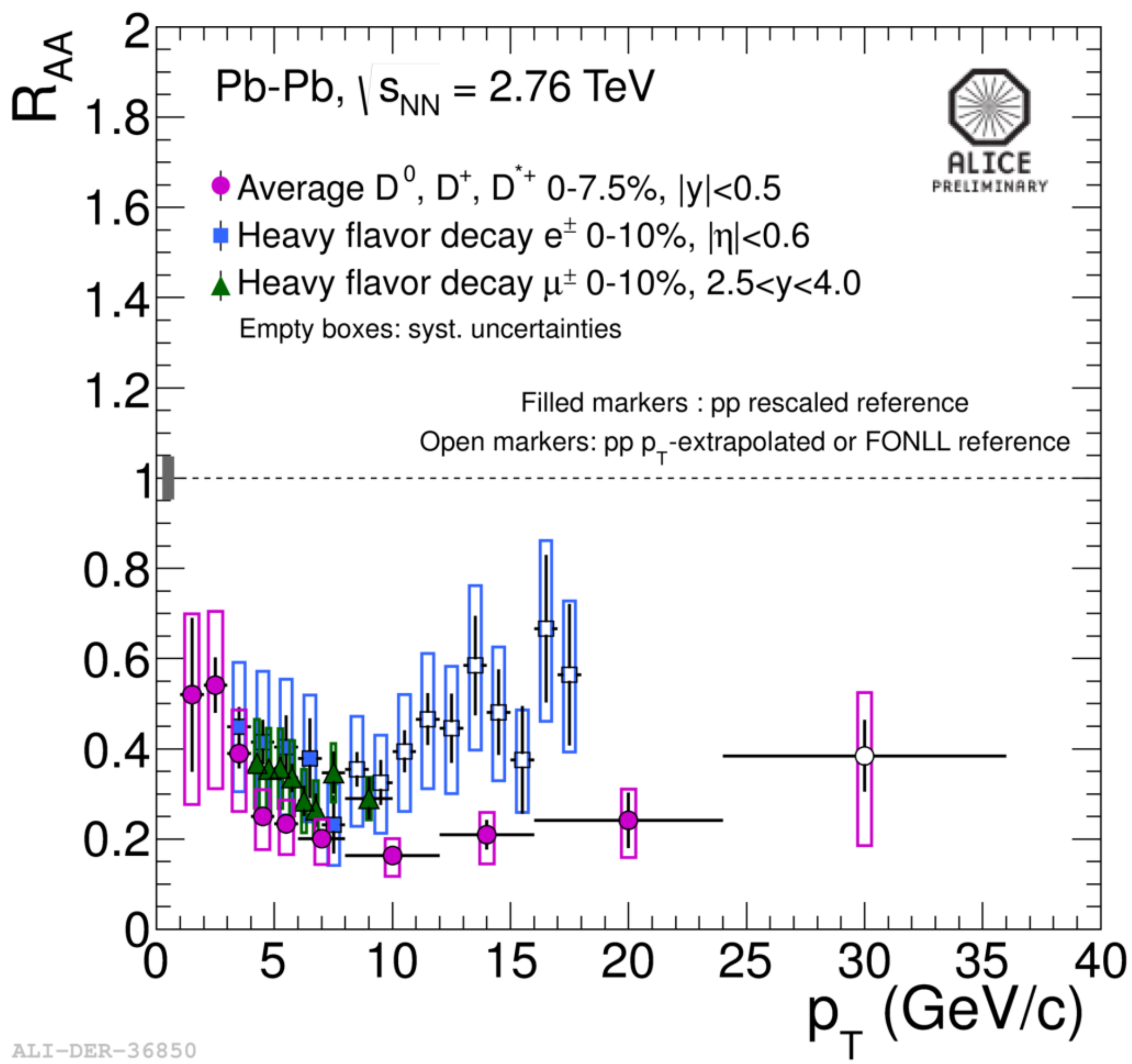
pQCD agree with data within uncertainties

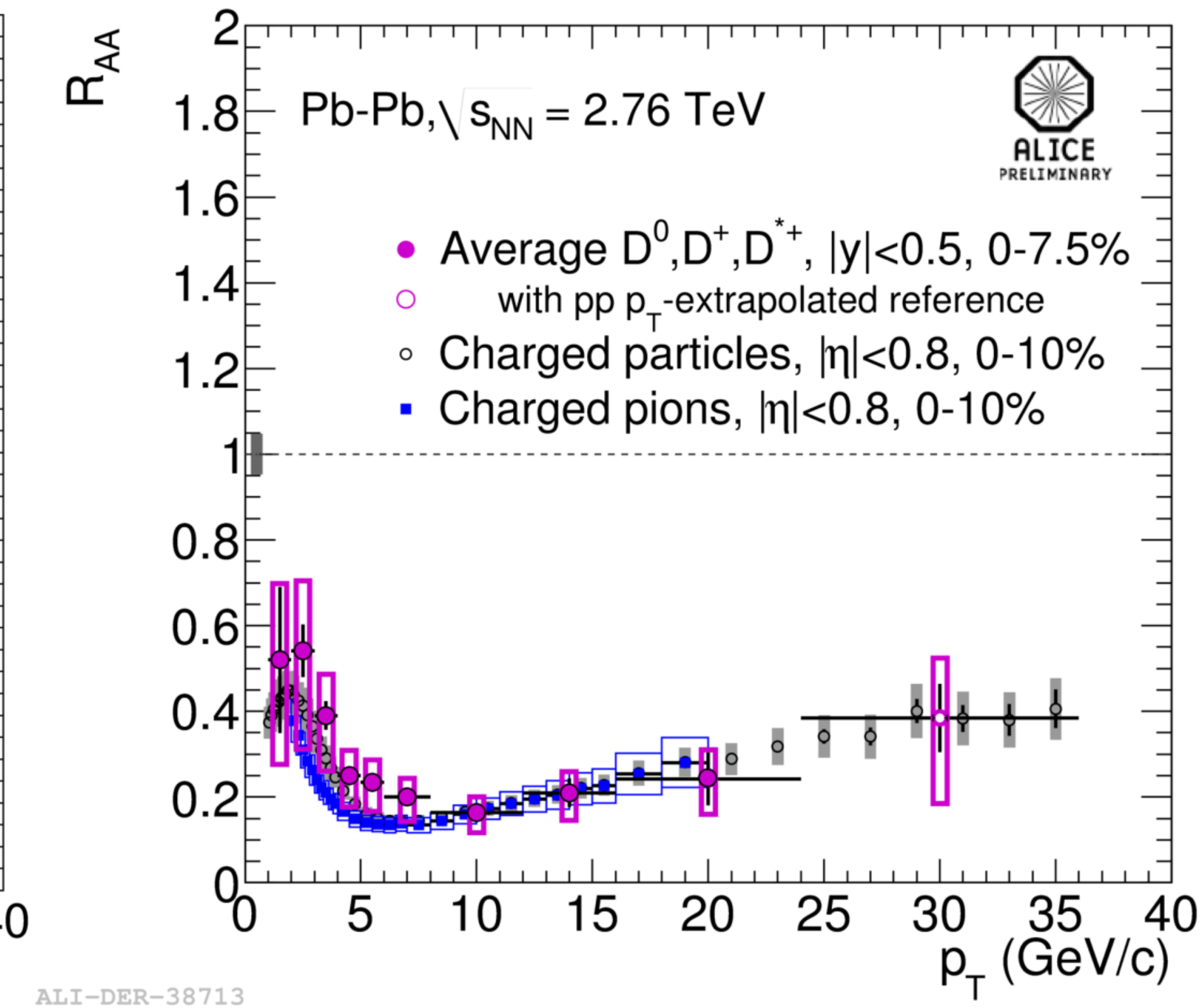
Electrons from heavy-flavor: R_{AA} at the LHC and RHIC



- Consistent with HF-Muon R_{AA} (2.5<y<4) @ 2.76 TeV PbPb collisions
- Consistent with HFE R_{AA} @ 200 GeV AuAu collisions

D vs heavy flavor leptons and the light flavor

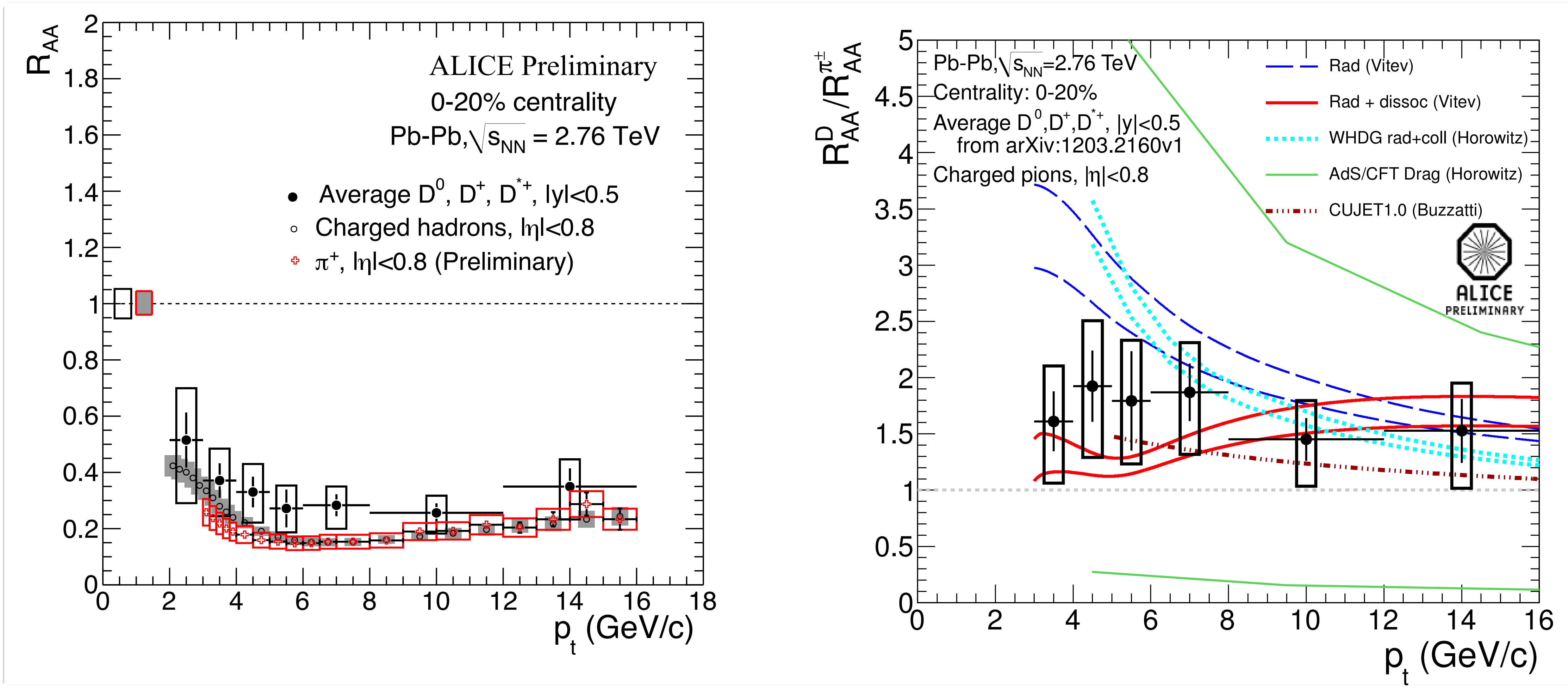




- Proper comparison of Ds and leptons only with decay kinematics:
  - $p_T^e \approx 0.5 \cdot p_T^B$ at high p_T^e

- Similar trend vs. p_T for D, charged particles and $\pi^{\pm}$
  - hint of $R_{AA}^D > R_{AA}^{\pi}$ at low p_T ?

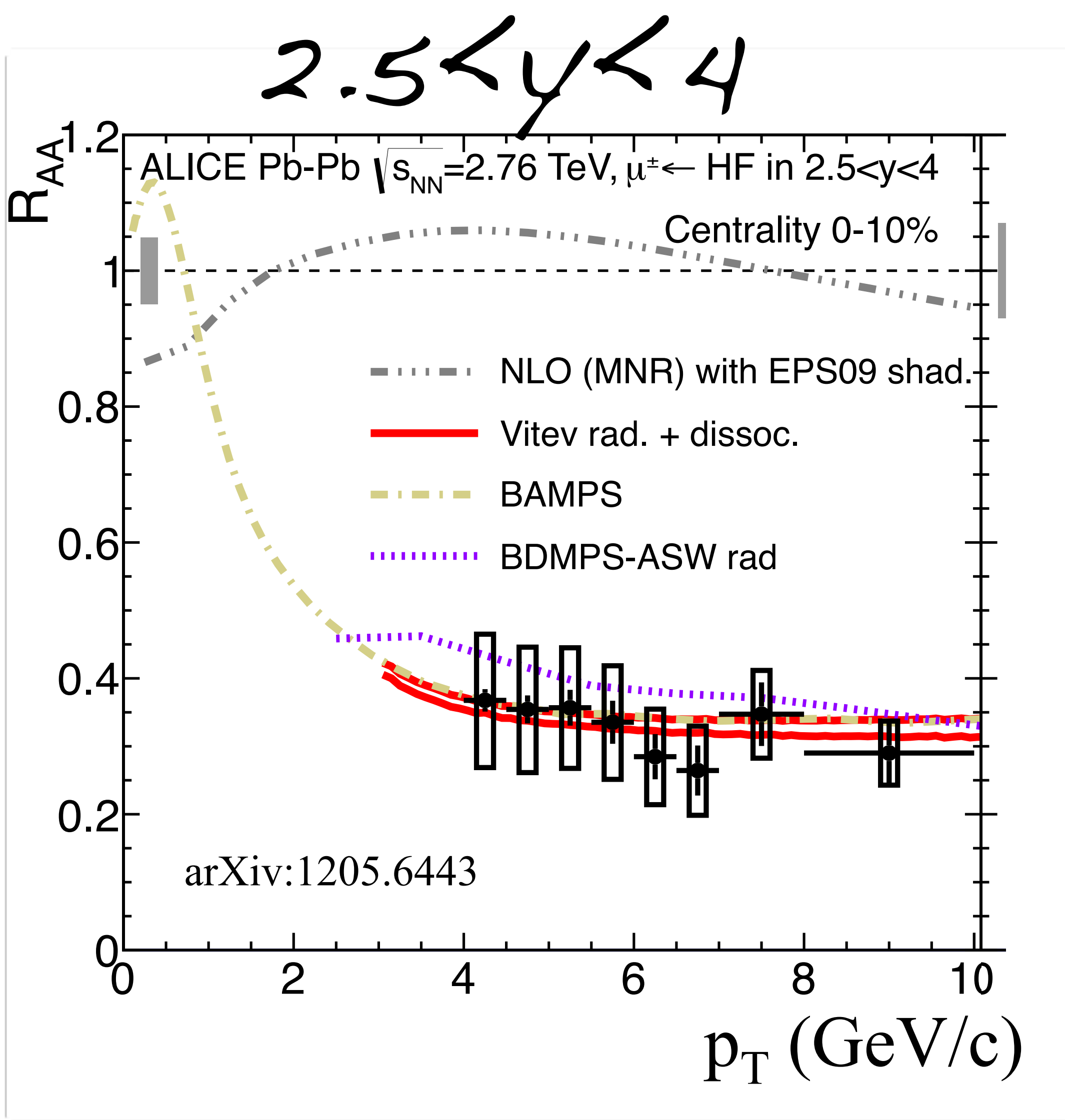
Charm-q energy loss via D-mesons RAA

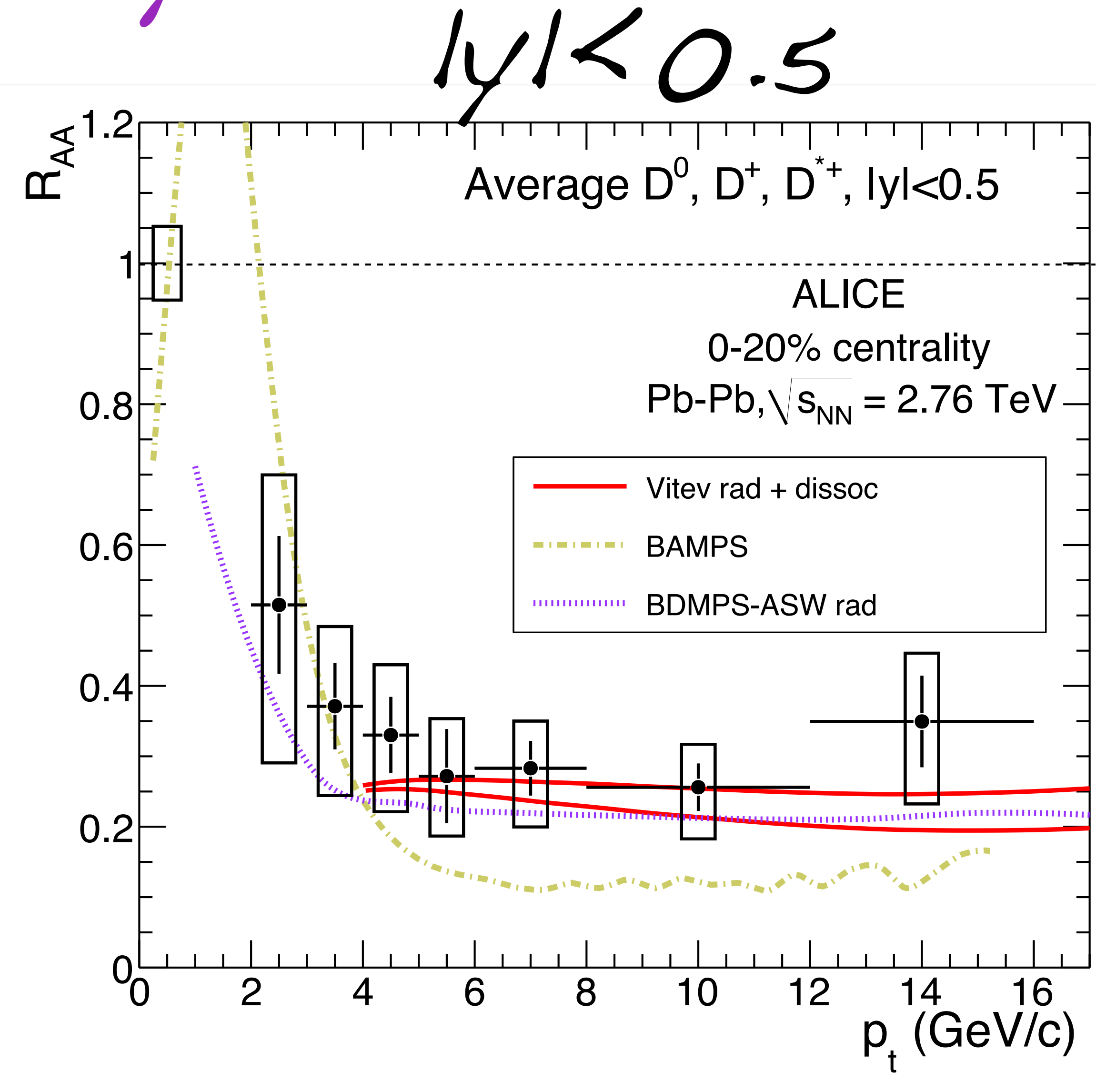


Hint of larger R_{AA} for D than π

- Color-charge effect?
- No evidence for dead cone effect (p_T dependence)
- Higher precision in progress (Alice)

Heavy-flavor suppression - rapidity dependence

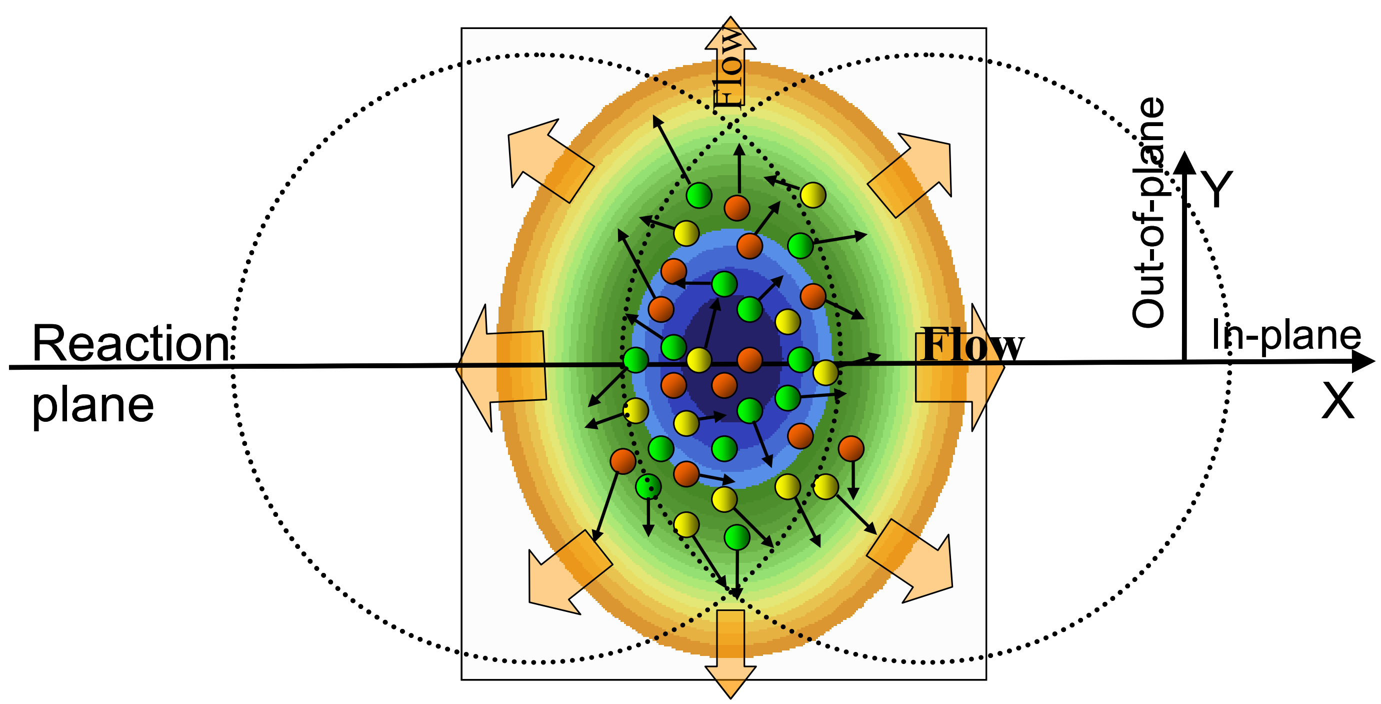




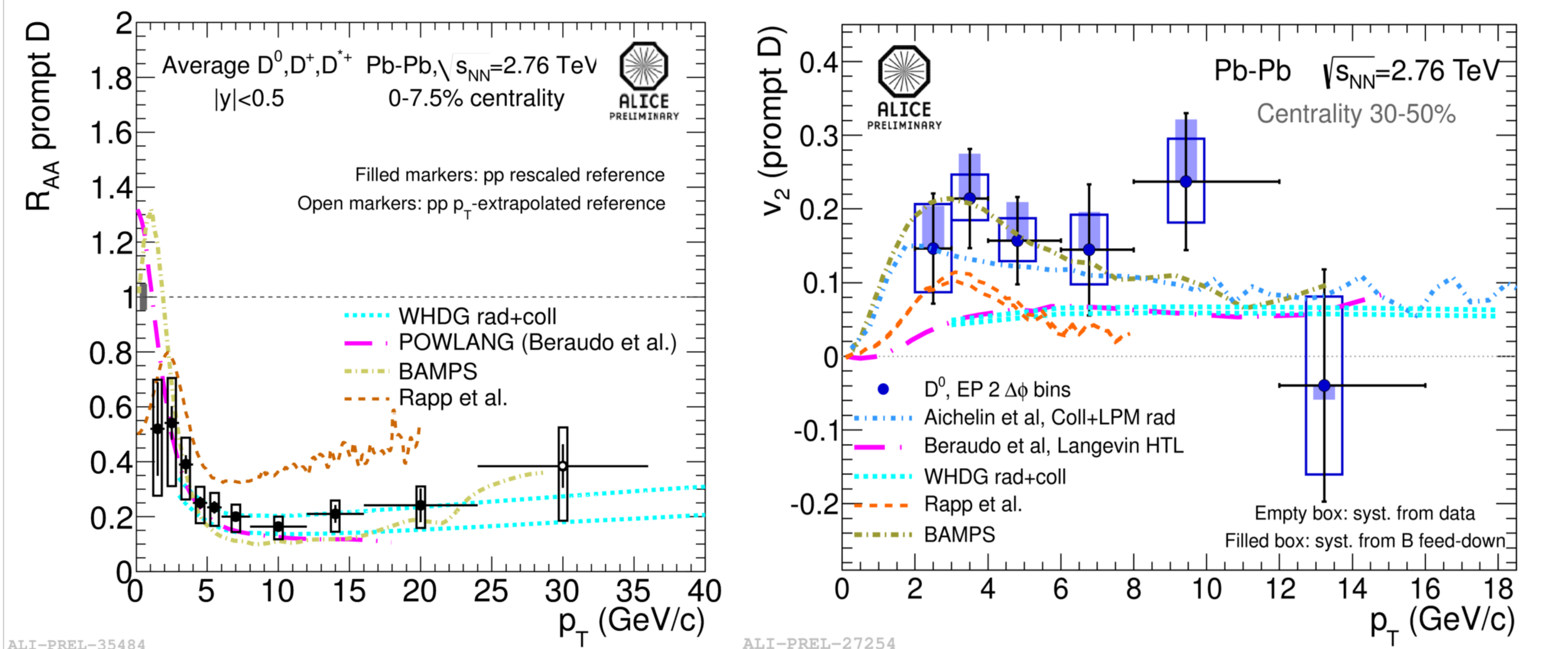
Variants of radiative++ energy loss agree with data

Heavy-flavor - azimuthal anisotropy

- Due to their large mass, c and b quarks should take longer time (= more re-scatterings) to be influenced by the collective expansion of the medium
  - $v_2(b) < v_2(c)$
- Uniqueness of heavy quarks: cannot be destroyed and/or created in the medium
  - Transported through the full system evolution

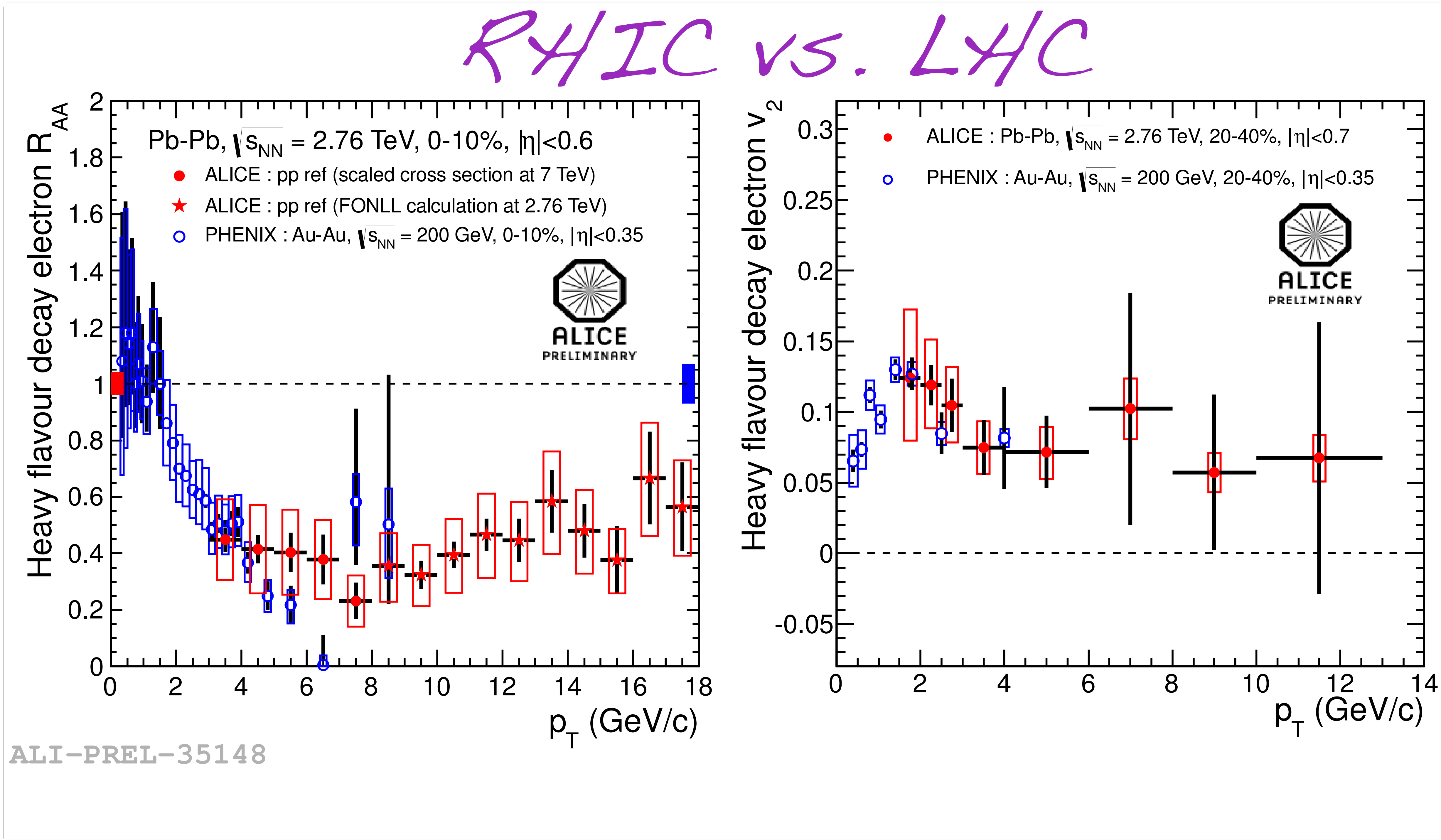


Challenge for theory – consistent description of charm production and its v_2



- **The simultaneous description of D meson R_{AA} and v_2 is a challenge to theoretical models**

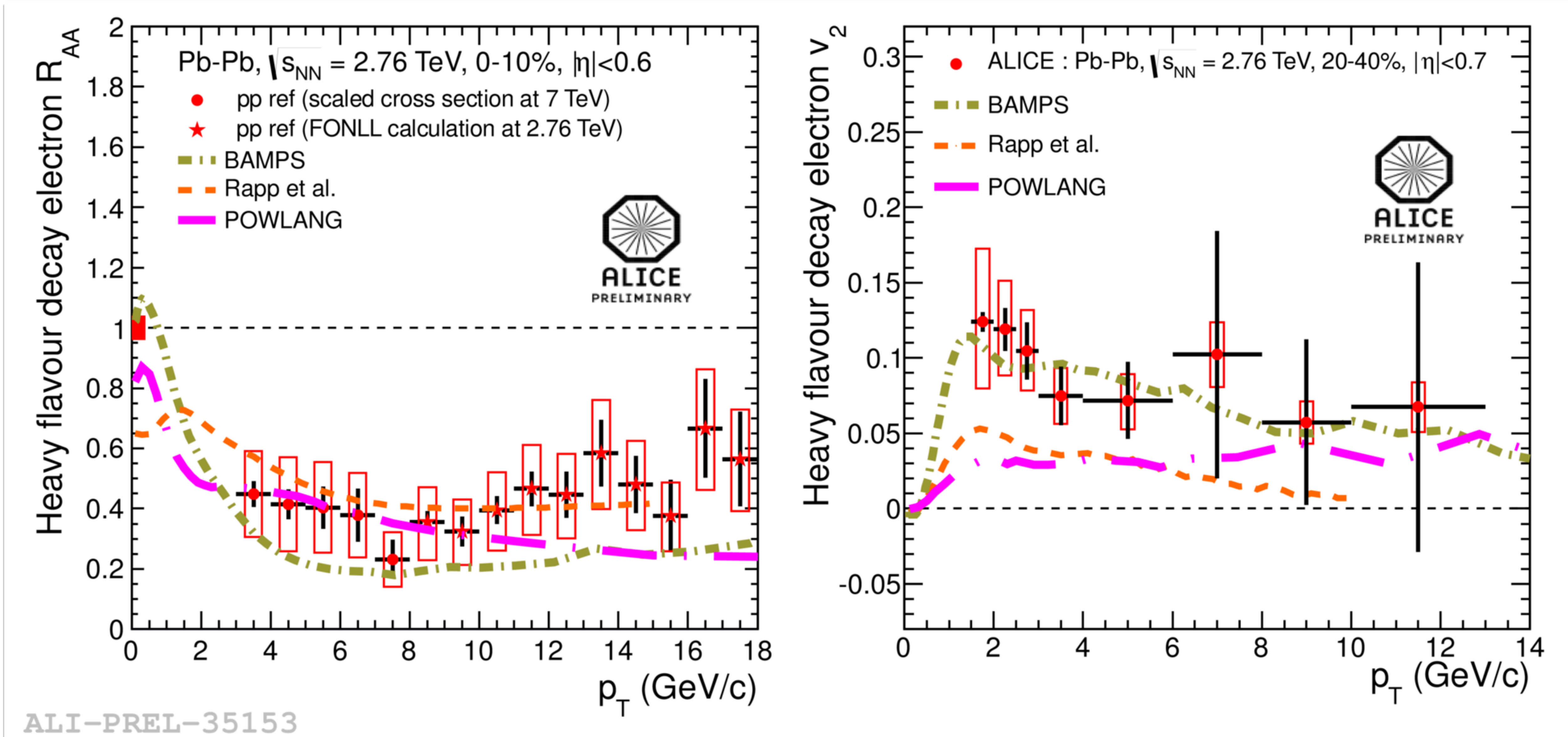
Heavy-flavor electrons: RHIC vs. LHC



Vast difference in energy of the collisions; however the properties of the medium are not so different

LHC bonus for the kinematic reach (energy dependence)

Challenge for theory – consistent description of HFE and its v_2

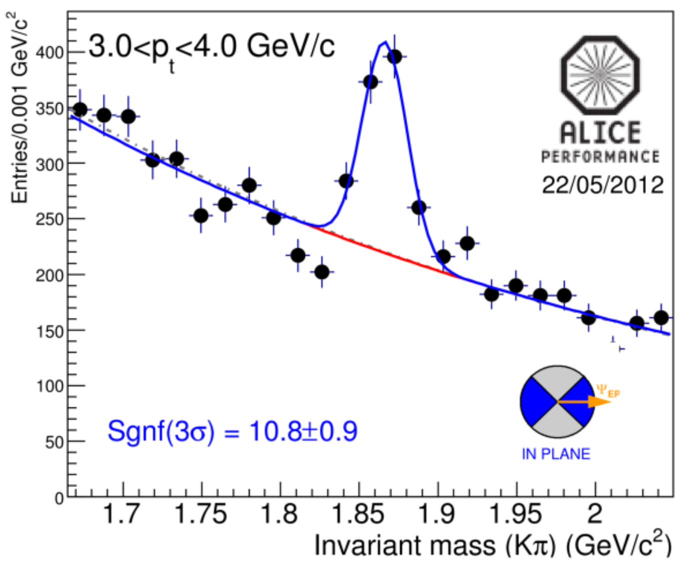


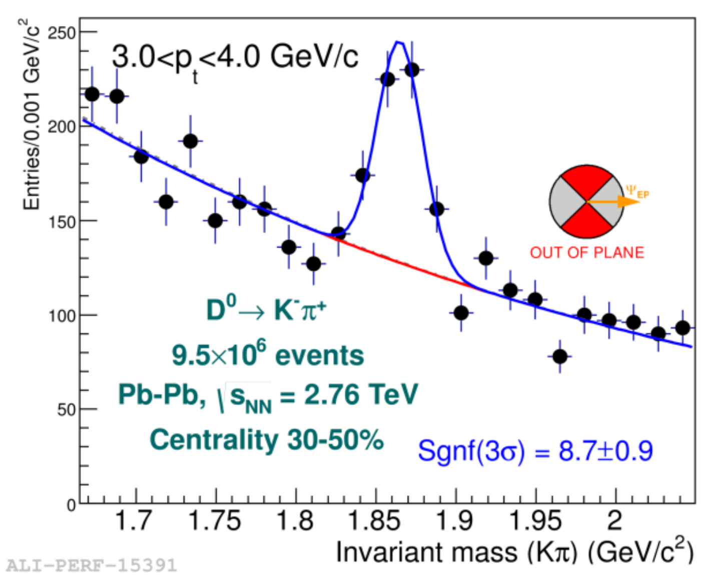
- **The simultaneous description of heavy flavor decay electrons R_{AA} and v_2 is a challenge to theoretical models**

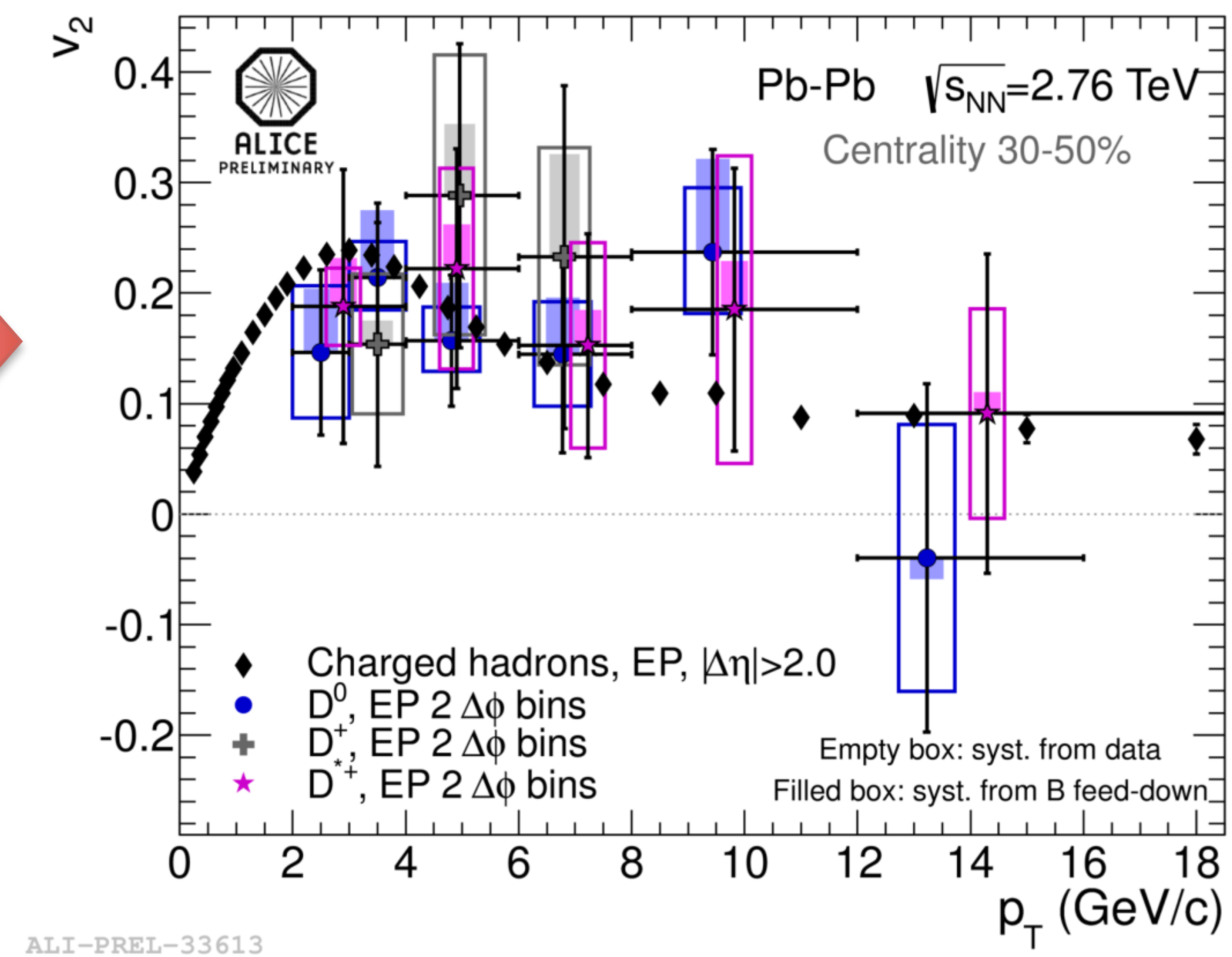
D-meson v_2

- **First direct measurement of D anisotropy in heavy-ion collisions**
- Yield extracted from invariant mass spectra of Kπ candidates in 2 bins of azimuthal angle relative to the event plane

$$v_2 = \frac{1}{R_2}\frac{\pi}{4}\frac{N_{IN} - N_{OUT}}{N_{IN} + N_{OUT}}$$



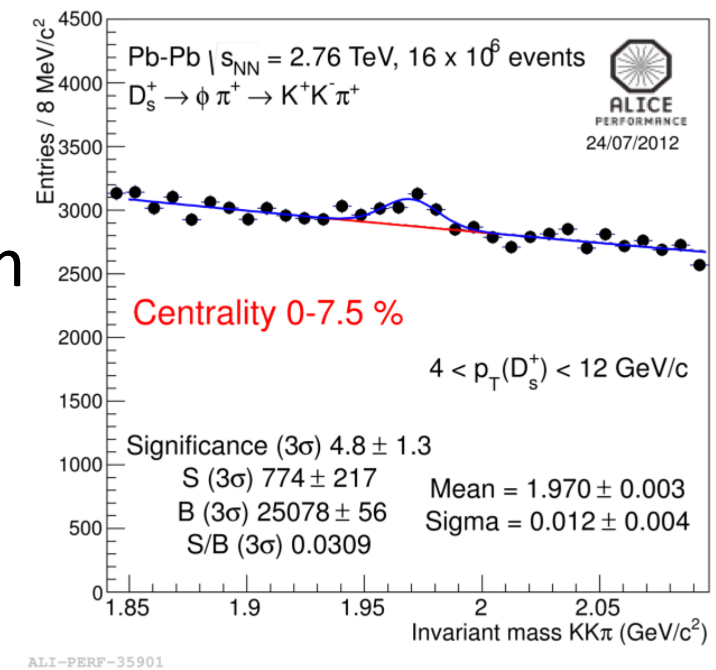


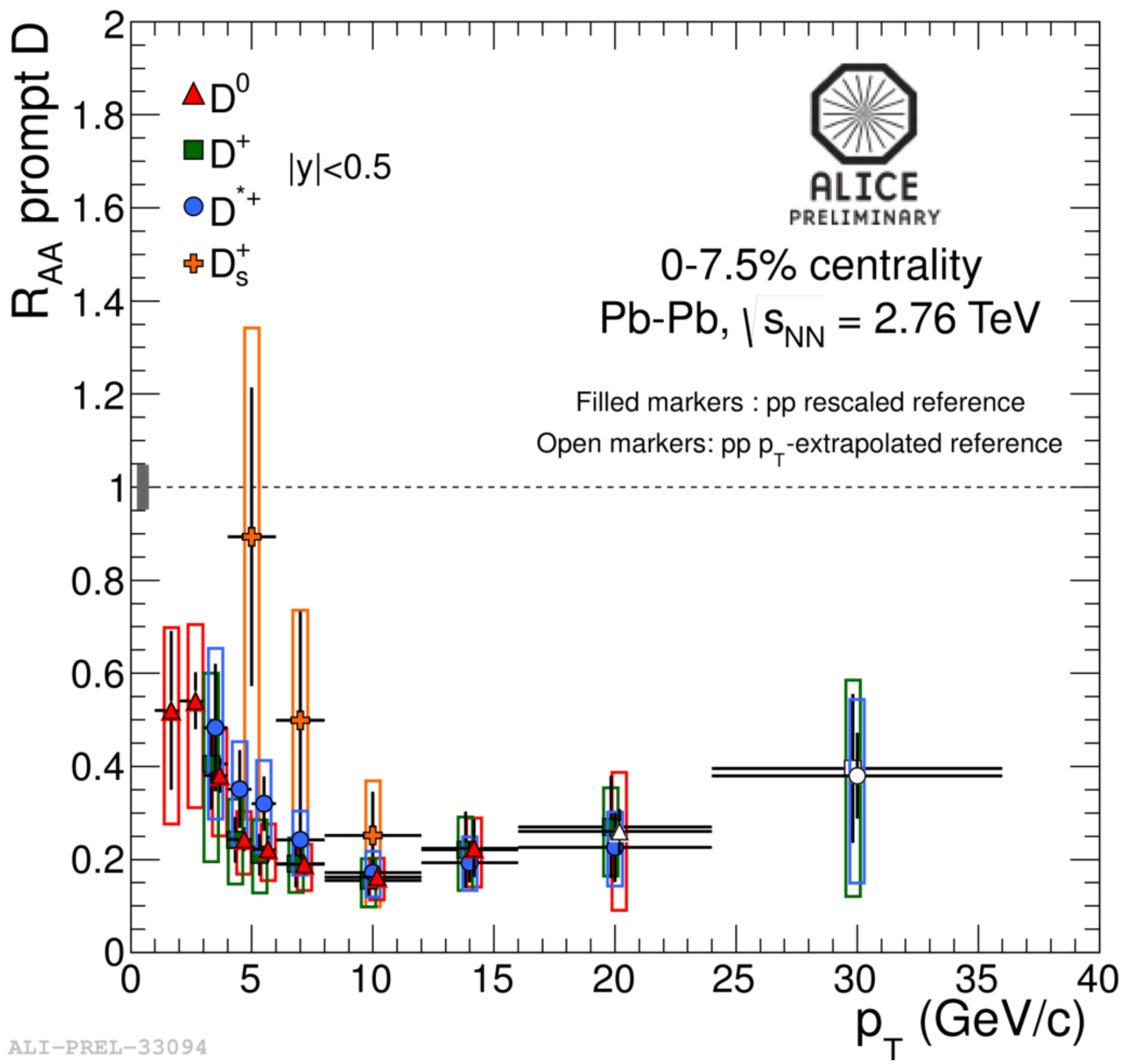


-> indication of non-zero D meson v_2 (3σ effect) in $2<p_T<6$ GeV/c

Charm + strange: D_s^+

- First measurement of D_s^+ in AA collisions
- Expectation: enhancement of the strange/non-strange D meson yield at intermediate p_T if charm hadronizes via recombination in the medium





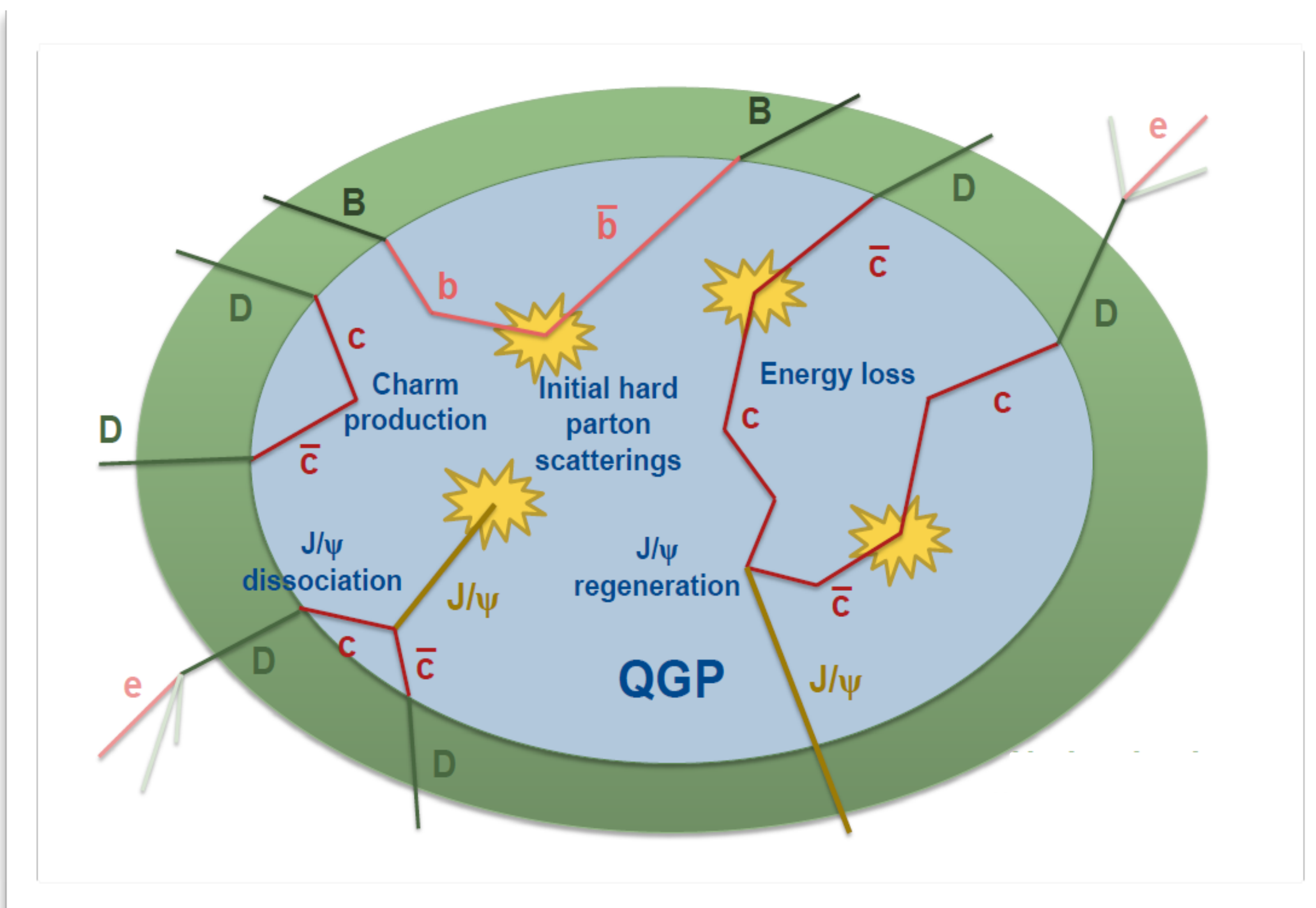
- Strong D_s^+ suppression (similar as D^0, D^+ and D^{*+}) for 8< p_T <12 GeV/C
- R_{AA} seems to increase (=less suppression) at low p_T
  - Current data do not allow a conclusive comparison to other D mesons within uncertainties

Kuznetsova, Rafelski, EPJ C 51 (2007) 113
He, Fries, Rapp, arXiv:1204.4442

Until now...

- Heavy-ion collisions at high-energies: high-energy density; hot, deconfined matter with quark and gluon degrees of freedom (plasma -> QGP) - strongly coupled system
- Statistical description of relative particle multiplicities; common velocity - expansion of the system
- Medium properties: nearly perfect liquid; opague to high-energy partons (including heavy-quarks - hints for flavor dependence of the parton energy loss - fundamental QCD); some signals of jet modifications;
- Jets and heavy-quarks are well calibrated probes! Let`s use these...
- TODAY: quarkonia, particle correlations at high-pT, full jet reconstruction in HI collisions and jet quenchig at the LHC - experimental summary...

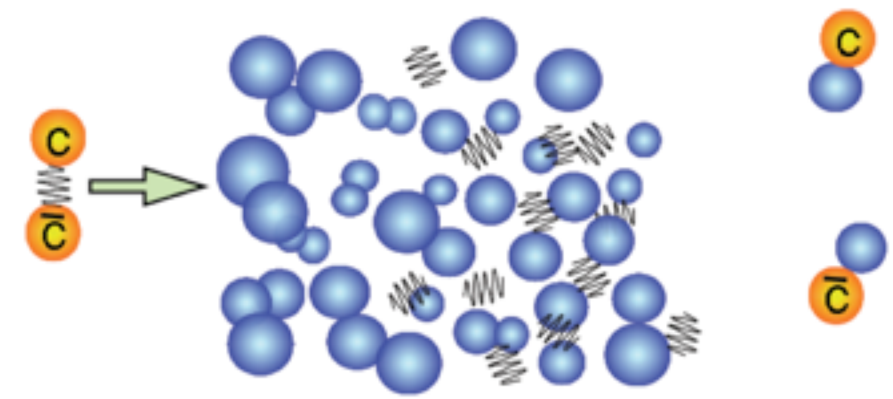
Quarkonia: q-qbar in medium



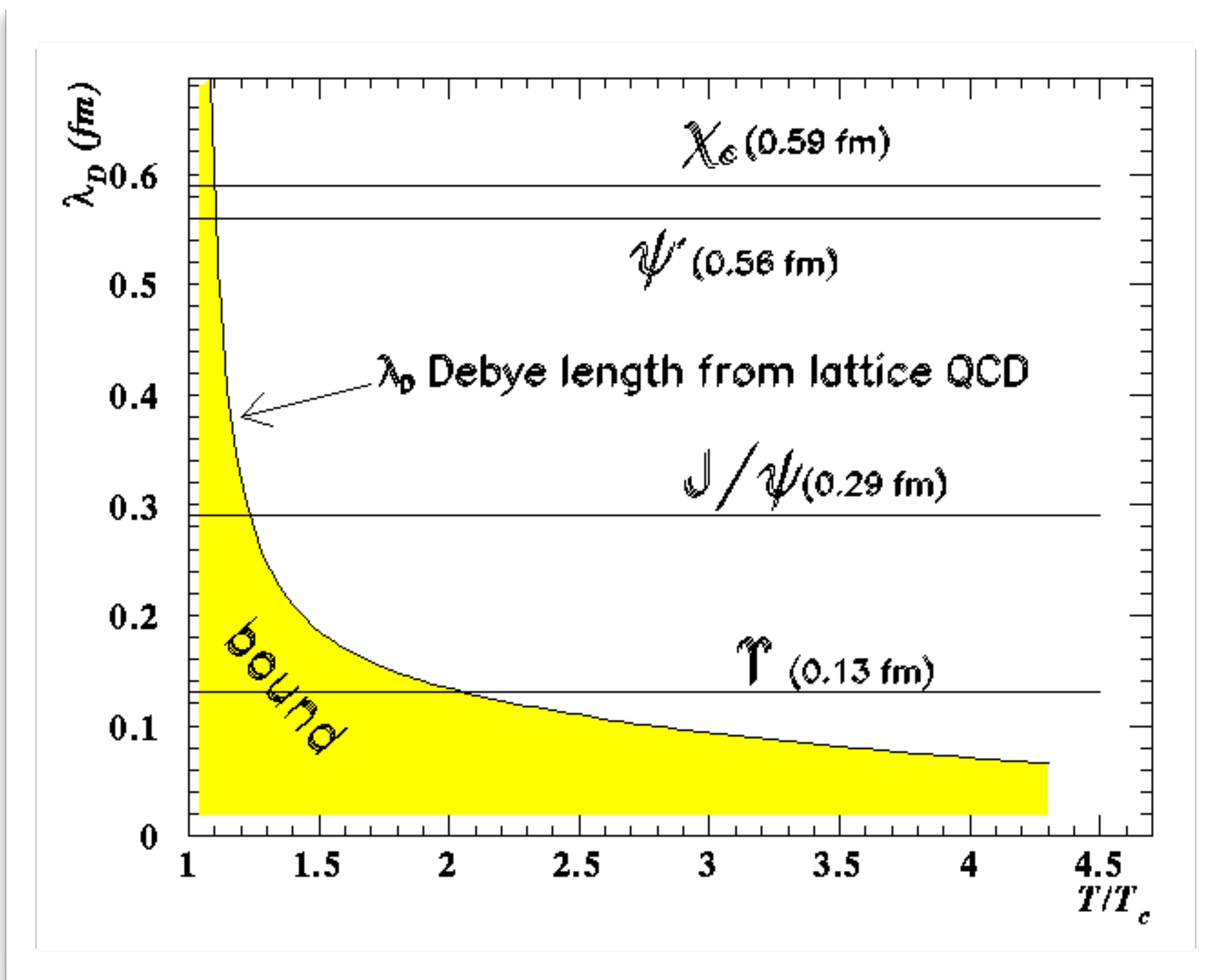
Charmonium suppression

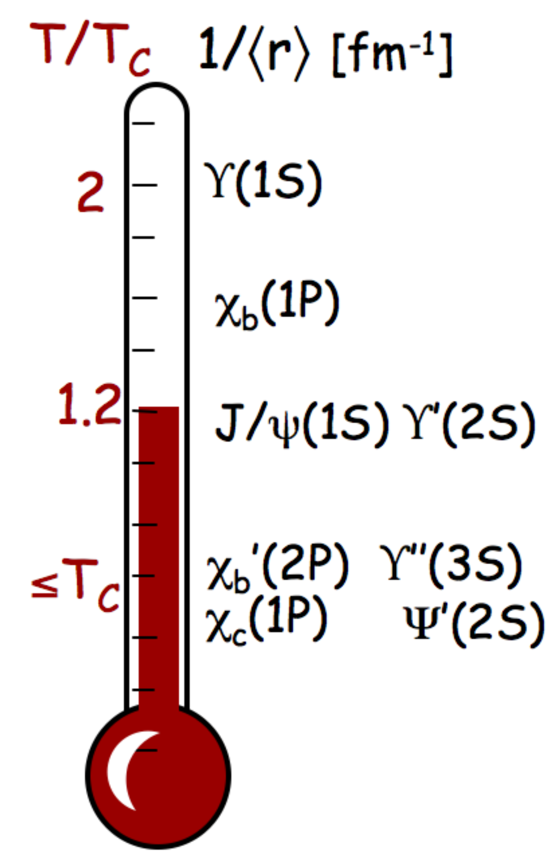
QGP signature proposed by Matsui and Satz, 1986

In the plasma phase the interaction potential is expected to be screened beyond the Debye length λ_D (analogous to e.m. Debye screening):



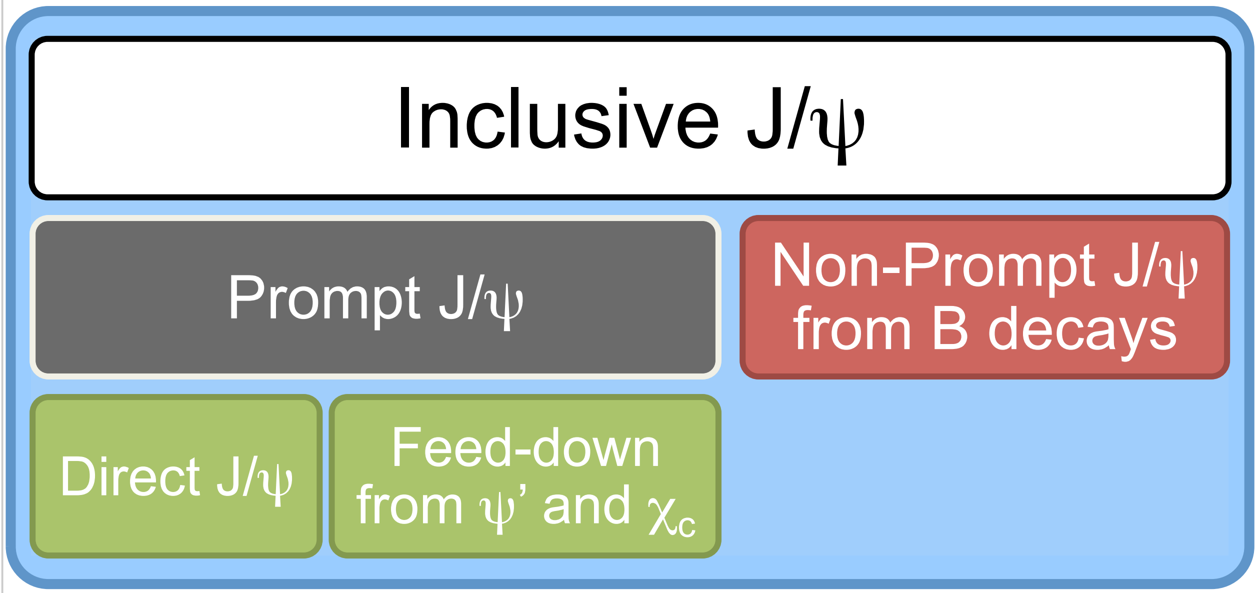
Charmonium ($c\bar{c}$) and bottonium ($b\bar{b}$) states with $r > \lambda_D$ will not bind; their production will be suppressed (qqbar states will "melt")





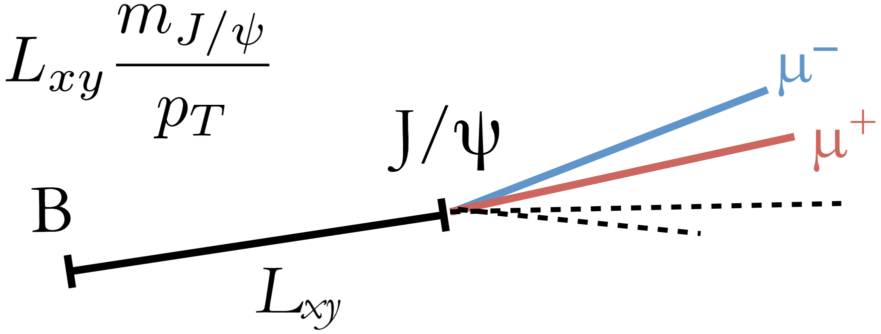
Mocsy, EPJ C 61 (2009) 705

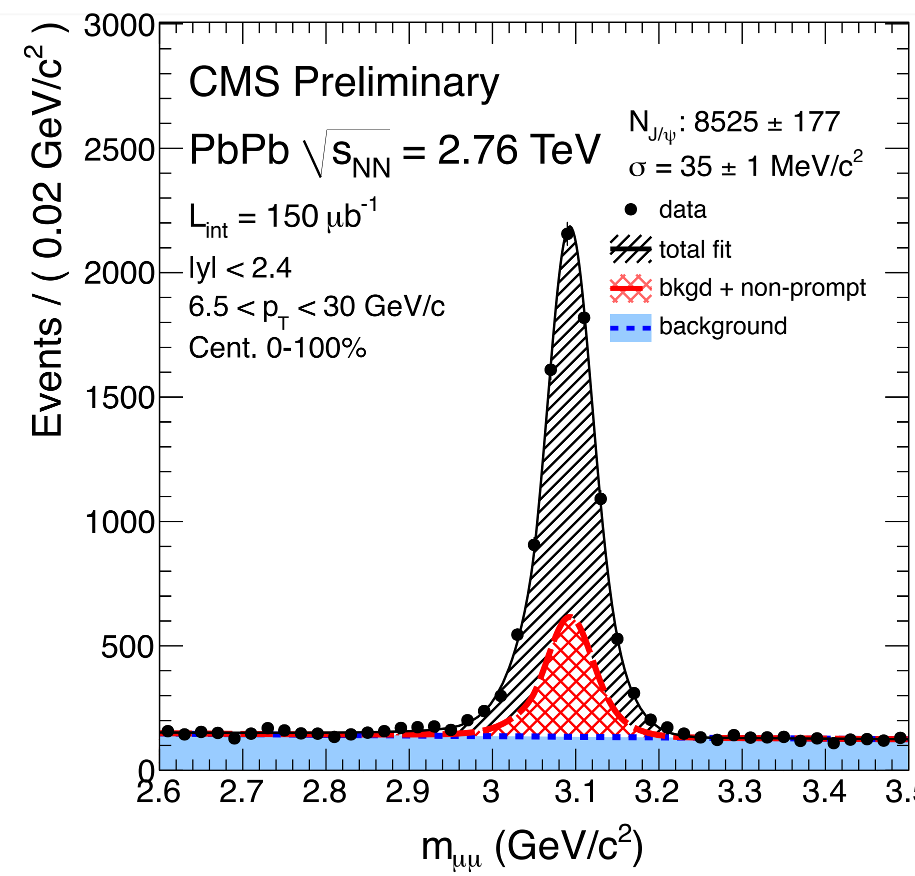
J/ψ in heavy-ion collisions

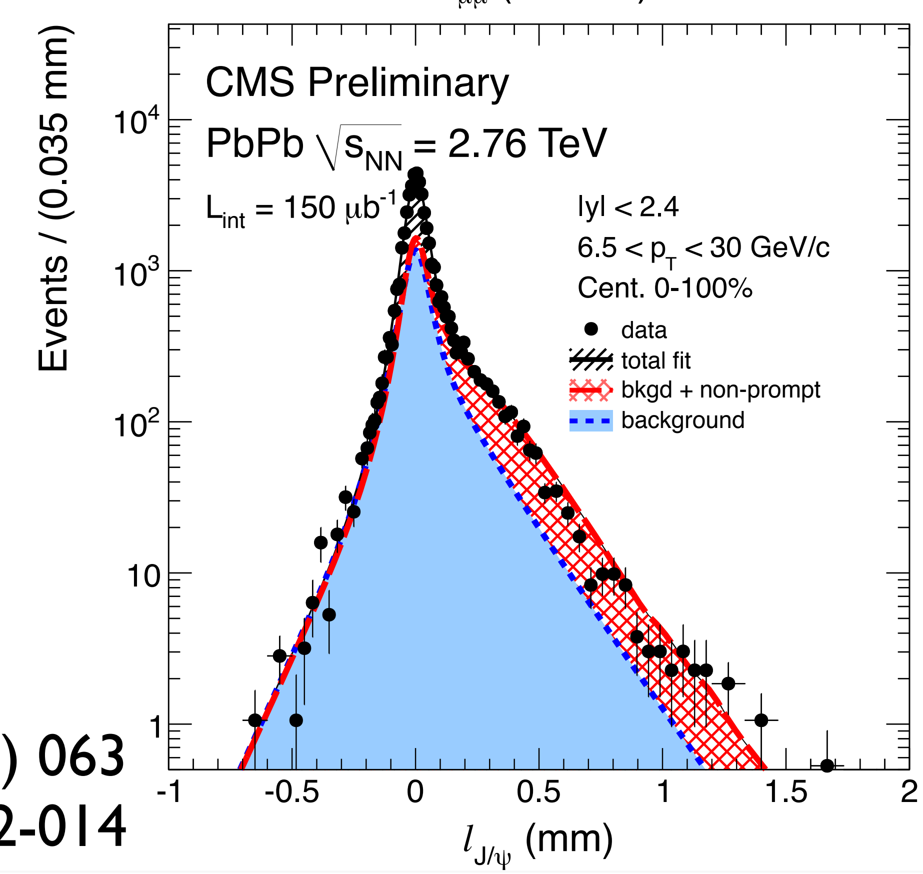


- Non-prompt J/ψ become significant towards higher p_T (20–30%)!
- Reconstruct $\mu^+\mu^-$ vertex
- Simultaneous fit of $\mu^+\mu^-$ mass and pseudo-proper decay length

$$\ell_{J/\psi} = L_{xy}\frac{m_{J/\psi}}{p_T}$$







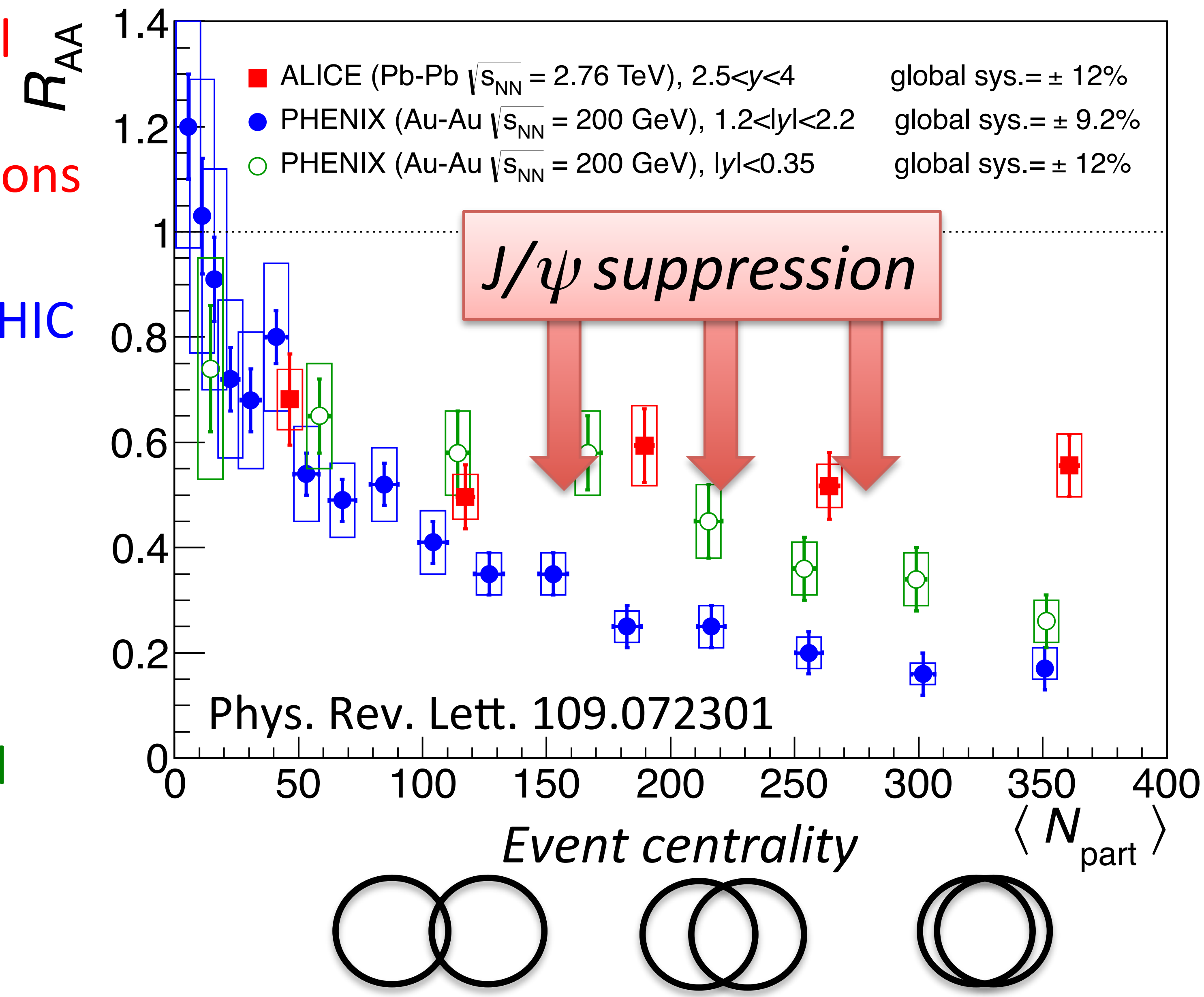
2010 data: JHEP 1205 (2012) 063
2011 data: CMS PAS HIN-12-014

J/ψ suppression - RHIC vs LHC

- Inclusive J/ψ yield lost in central Pb-Pb collisions as compared to equivalent number of p-p collisions
  - Quarkonia “melts” within QGP
- LHC: Less suppression than at RHIC and flat centrality dependence
- => in-medium ccbar
  recombination?
- Important: better knowledge of initial state effects crucial – cold nuclear matter / shadowing / saturation

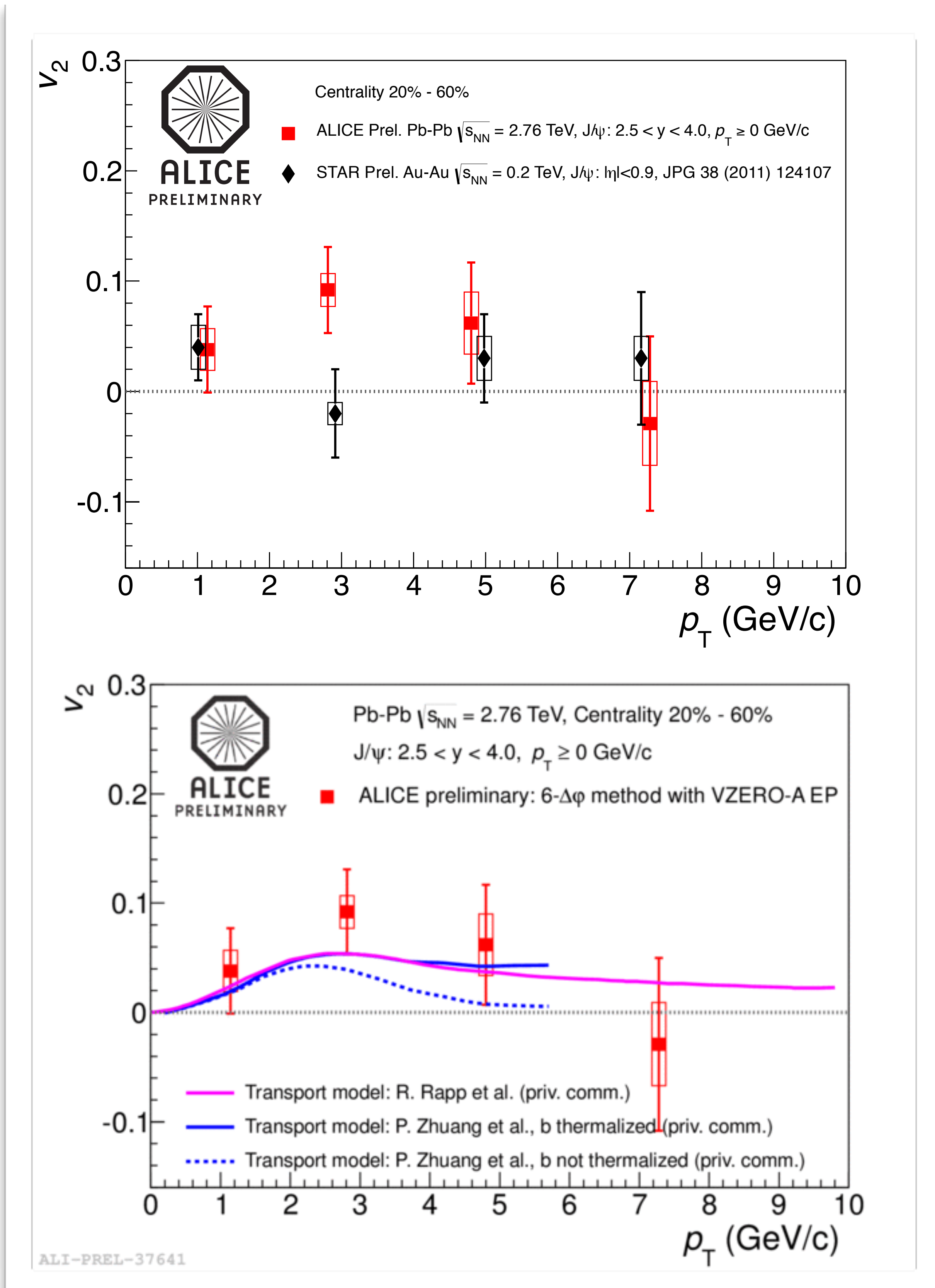
J/ψ measured with forward muon arm

$J/\psi \rightarrow \mu^+\mu^-$



Cold nuclear matter? => Measure p-Pb collisions!

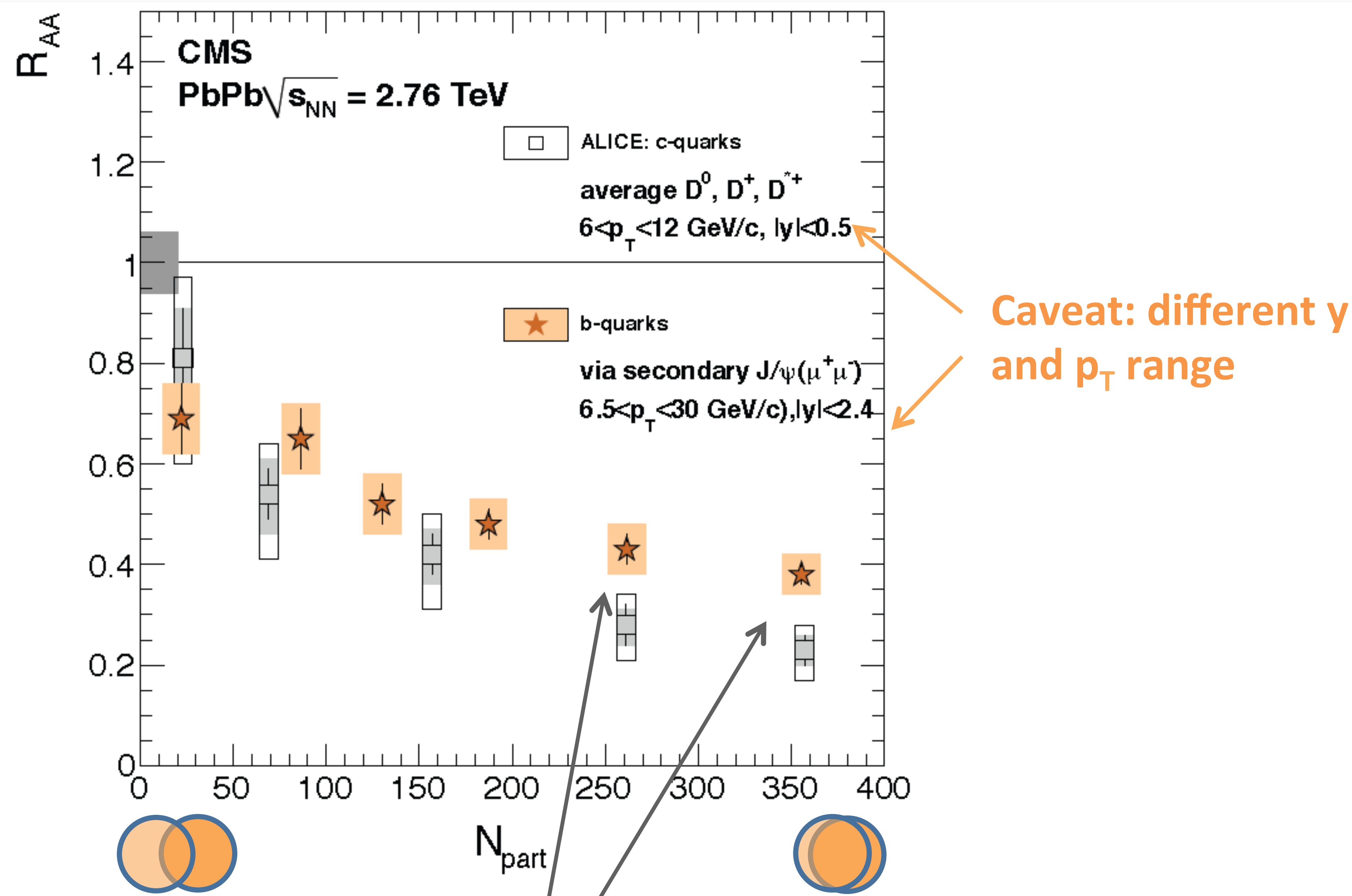
Regeneration – J/ψ flow?



- Expect J/ψ from regeneration to exhibit similar elliptic flow as D mesons
- STAR at RHIC:
  - no significant elliptic flow
- ALICE at LHC:
  - hint at 3 GeV/c
  - local significance 2.2 σ
- Does one point really make the difference?
  - More data will bring the answer

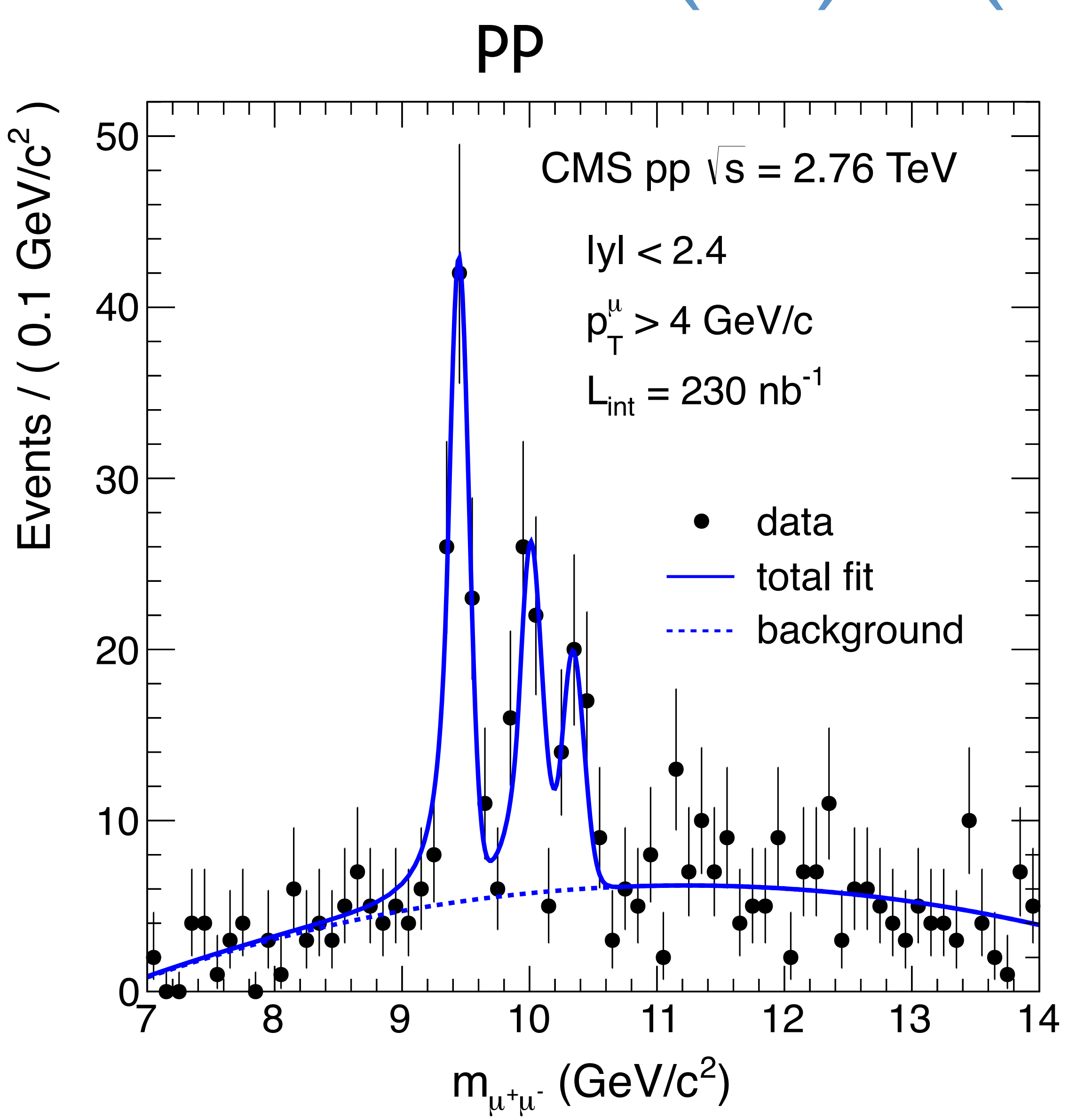
sqrt(s) grows

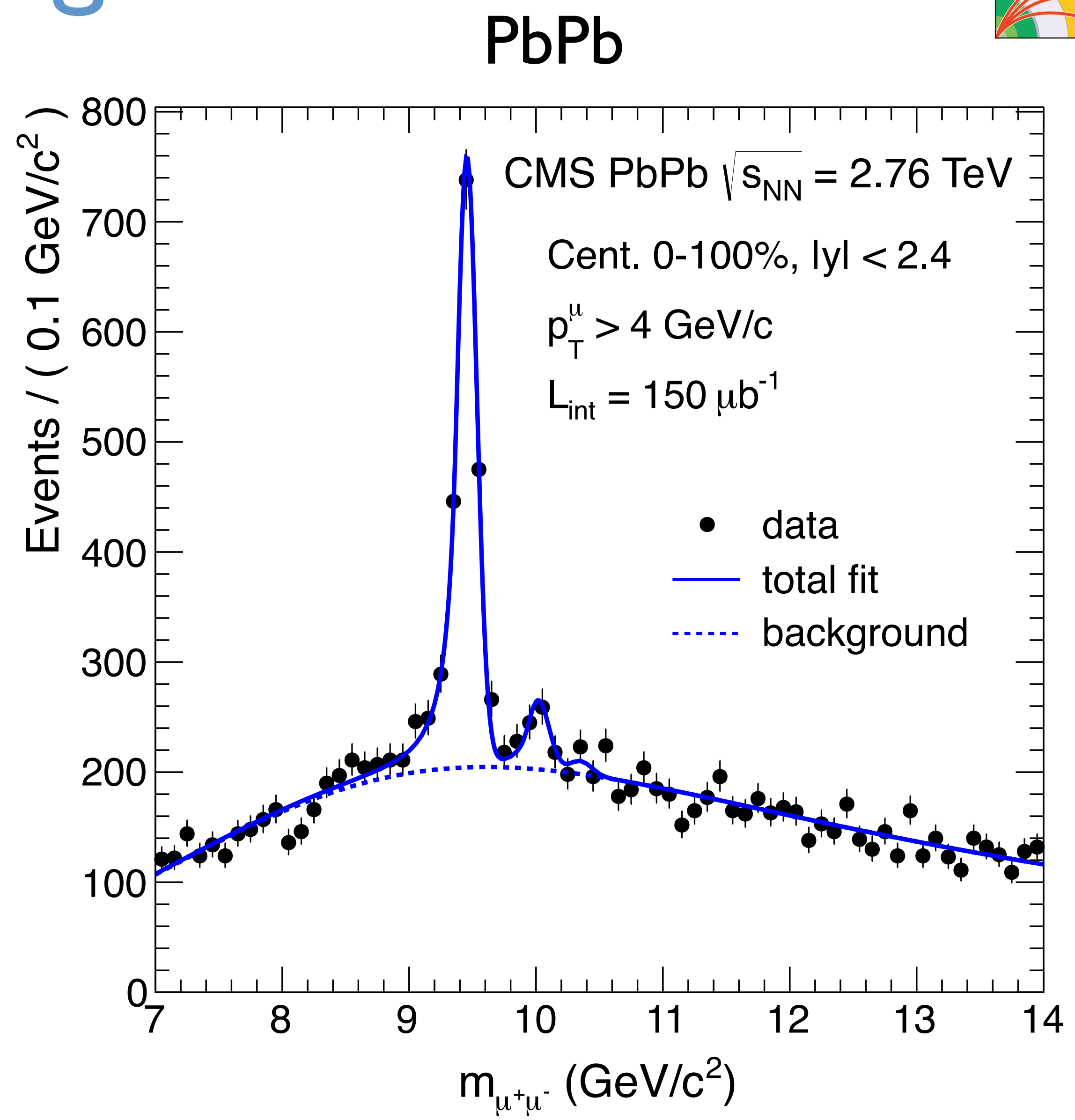
Beauty vs. charm



In central collisions, the expected R_{AA} hierarchy is observed: $R_{AA}^{charm} < R_{AA}^{beauty}$

Υ(nS)/Υ(1S) Single Ratios

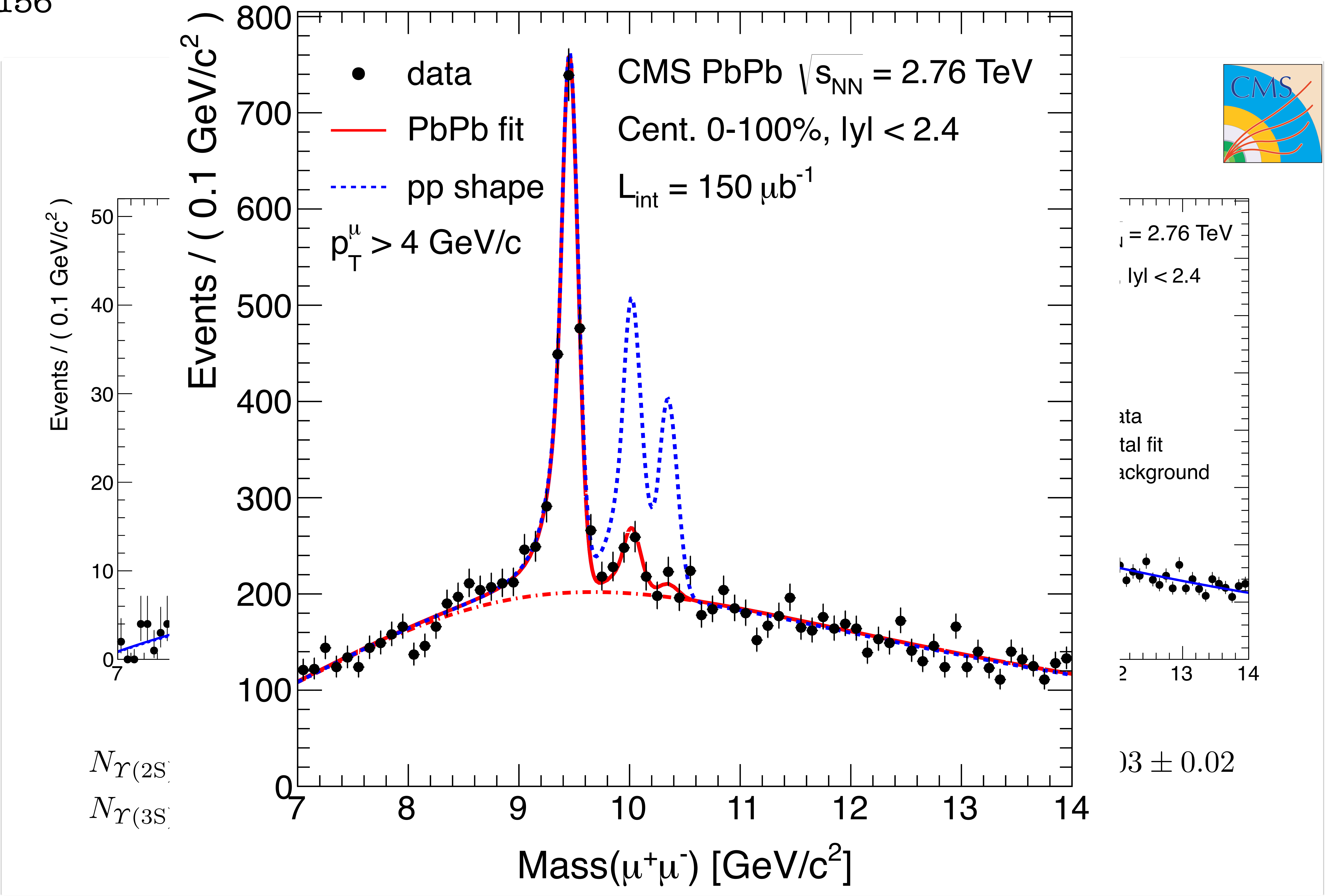




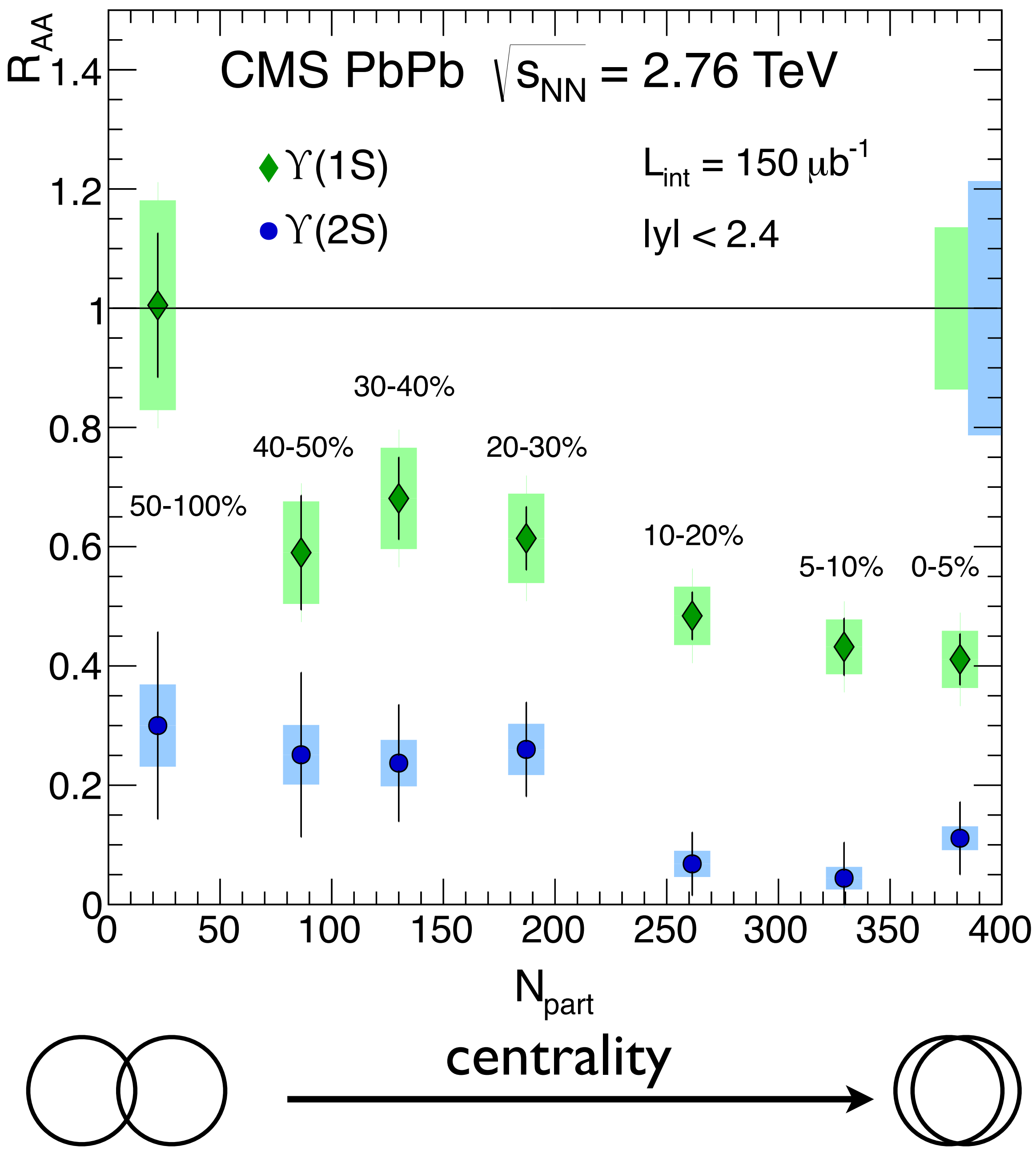
$$N_{\Upsilon(2S)}/N_{\Upsilon(1S)}|_{pp} = 0.56 \pm 0.13 \pm 0.02$$
$$N_{\Upsilon(3S)}/N_{\Upsilon(1S)}|_{pp} = 0.41 \pm 0.11 \pm 0.04$$

$$N_{\Upsilon(2S)}/N_{\Upsilon(1S)}|_{PbPb} = 0.12 \pm 0.03 \pm 0.02$$
$$N_{\Upsilon(3S)}/N_{\Upsilon(1S)}|_{PbPb} < 0.07$$

Ratios not corrected for acceptance and efficiency


data
PbPb fit
pp shape
p_T^μ > 4 GeV/c
CMS PbPb √s_NN = 2.76 TeV
Cent. 0-100%, |y| < 2.4
L_int = 150 μb^-1
Events / (0.1 GeV/c^2)
Mass(μ+μ-) [GeV/c^2]

$\Upsilon(nS)$ R_{AA}



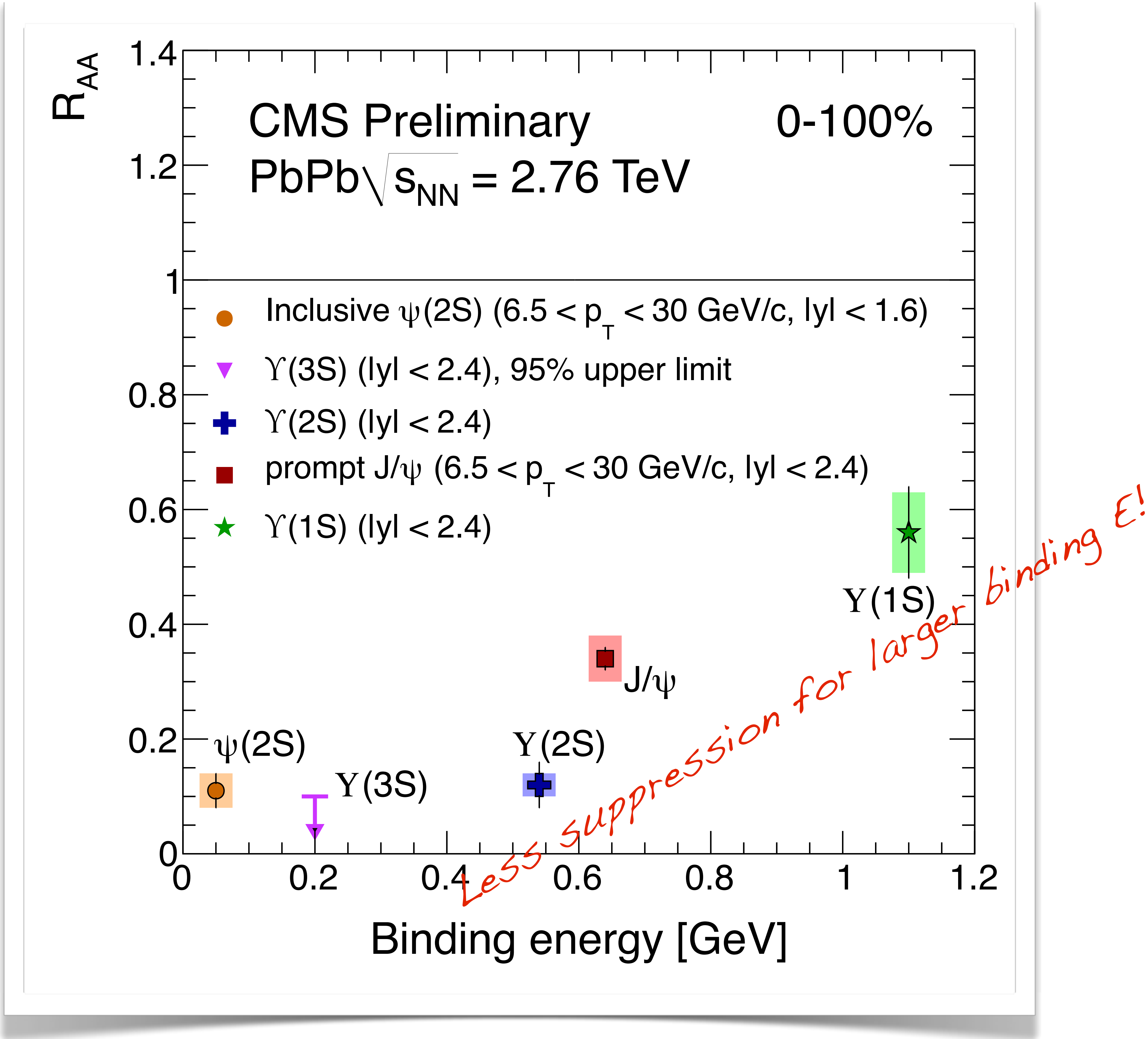
- In 2010 (7.28 μb^{-1}):
  - only Υ(1S) R_{AA} in 3 centrality bins
  - JHEP 1205 (2012) 063
- In 2011 (150 μb^{-1}):
  - Υ(1S) R_{AA} in 7 centrality bins
  - clear suppression of Υ(2S)
  - Υ(1S) suppression consistent with excited state suppression (~50% feed down)
  - centrality integrated:

$$R_{AA}(\Upsilon(1S)) = 0.56 \pm 0.08\,(\text{stat.}) \pm 0.07\,(\text{syst.})$$
$$R_{AA}(\Upsilon(2S)) = 0.12 \pm 0.04\,(\text{stat.}) \pm 0.02\,(\text{syst.})$$
$$R_{AA}(\Upsilon(3S)) < 0.1\ (\text{at } 95\%\ \text{C.L.})$$

- Sequential suppression of the three states in order of their binding energy

CMS HIN-11-011
arXiv:1208.2826
(accepted by PRL)

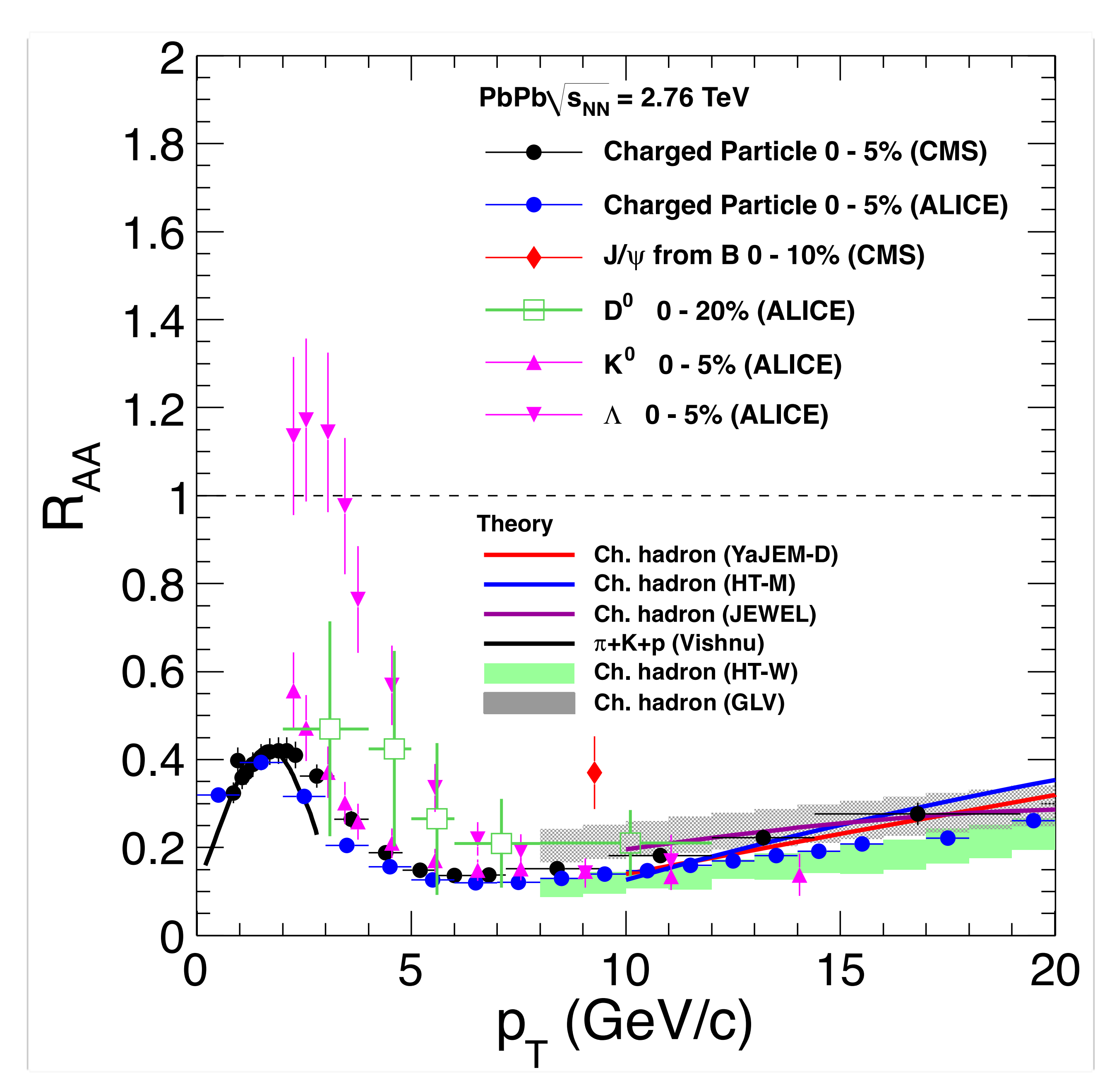
Quarkonia suppression at the LHC



So, what about jet quenching...?

RAA for different particle type

Discussion based on LHC results



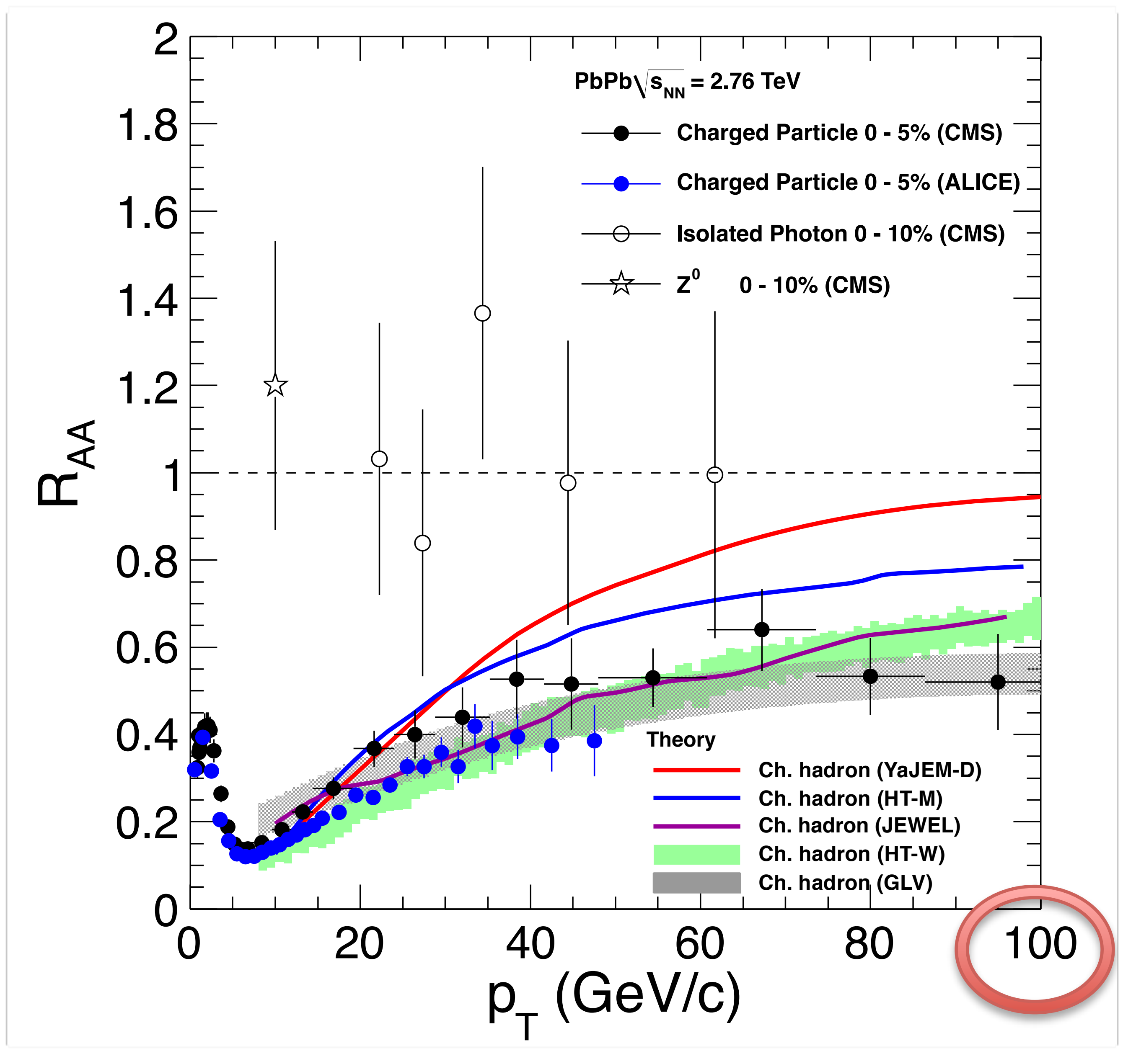
Similar suppression for heavier-q (strange, charm) and gluons (large elastic e-loss; less dep. on mass?; color factor? - small effect?)
J/ψ from B-decays - dead cone effect?

Lambda vs K0 R_{AA} below 7 GeV - manifestation of flow (?)

Rise towards higher pT's:
1) Harder partonic spectrum (as compared to RHIC)
2) Weak dependence of [pQCD] e-loss on parton energy

RAA for different particle type

Discussion based on LHC results



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Lambda vs K0 R_{AA} below 7 GeV - manifestation of flow (?)

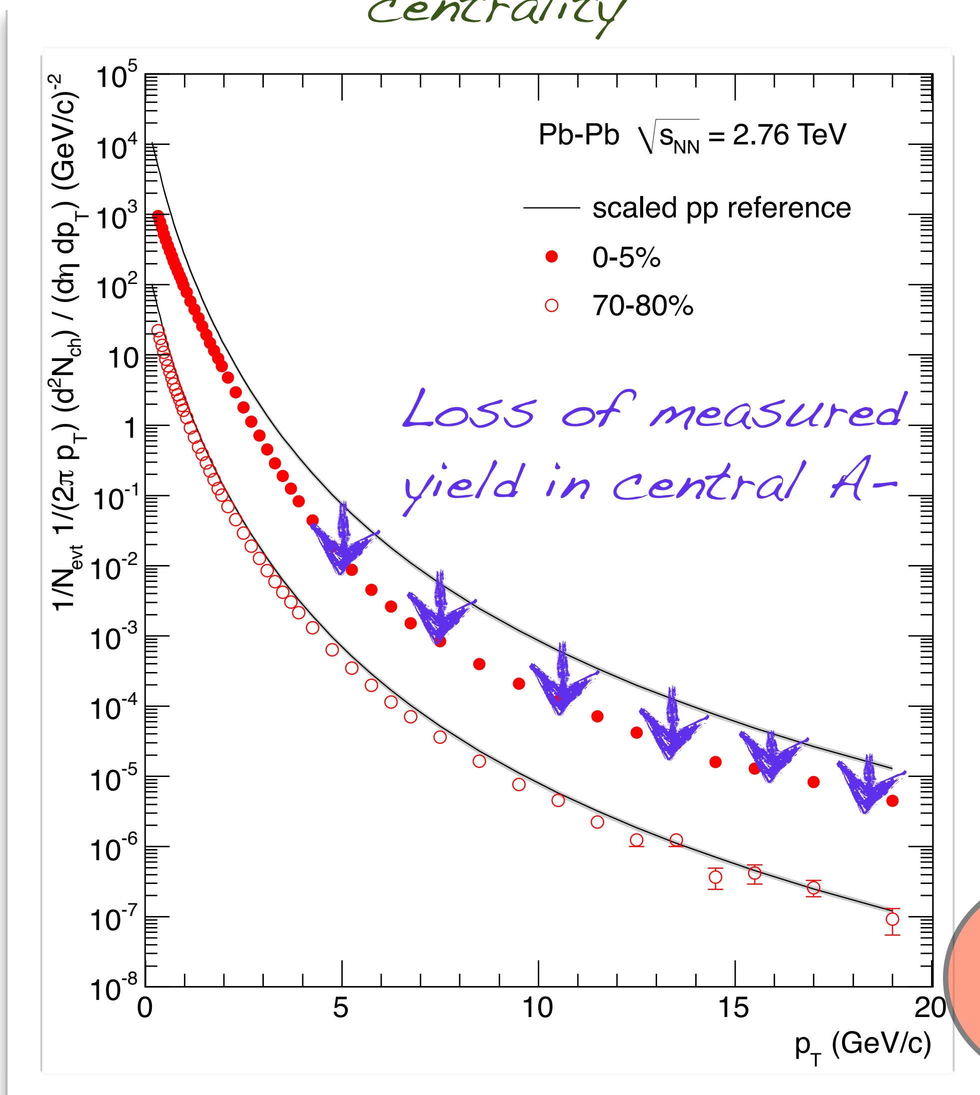
Rise towards higher pT's:
1) Harder partonic spectrum (as compared to RHIC)
2) Weak dependence of [pQCD] e-loss on parton energy

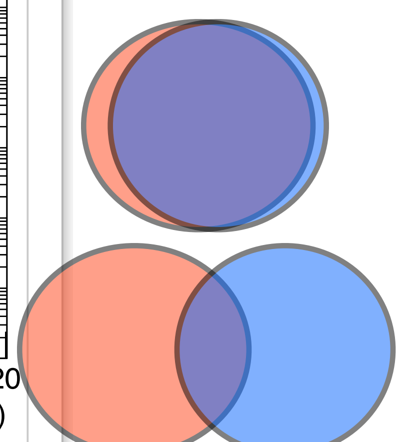
Photons and Z's not suppressed -> quenching is a final state effect

"Easier" (than full jet reconstruction) exercise: Jet-quenching via leading hadrons

Inclusive hadron production

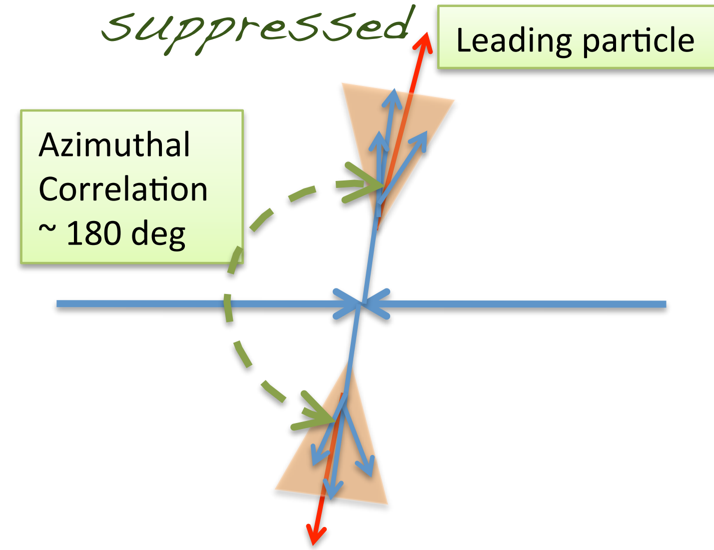
Measured as a function of collision centrality

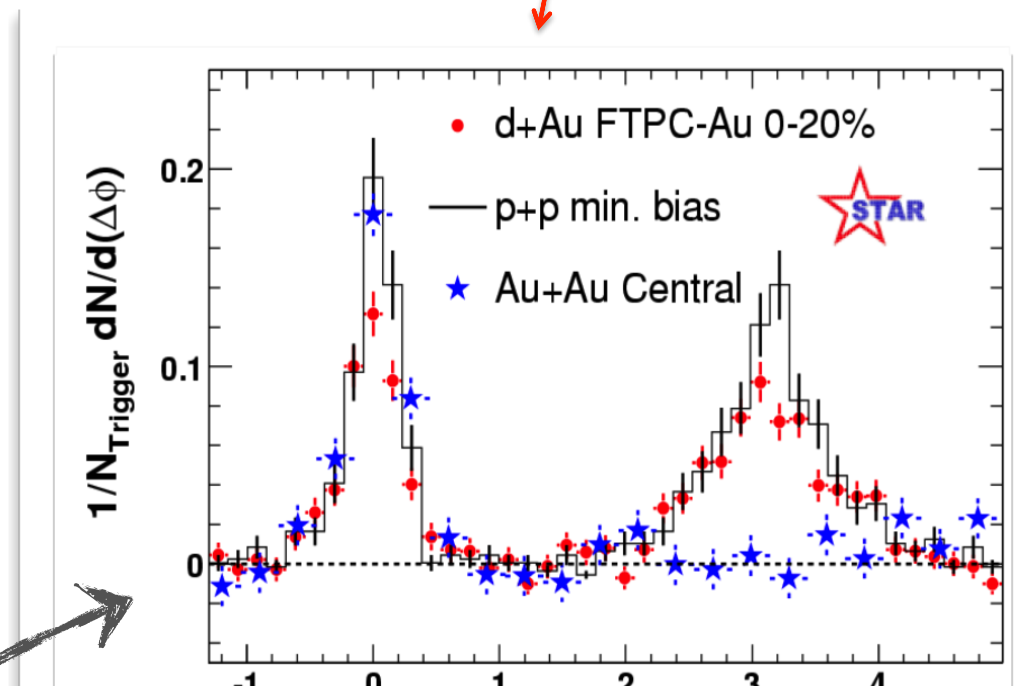




Di-hadron correlations

Rates of recoil ("away-side") hadrons suppressed





Phys. Rev. Lett. 91 (2003) 072304
Phys. Rev. Lett. 97 (2006) 162301

Note on correlations: interesting tool to study the "intermediate"-p_T region - jets vs flow and recombination

Sensitivity of particle correlations to different underlying physics

Two-particle correlations

- **conditional [per-trigger] yields**

$$\frac{1}{N_{trig}}\frac{dN_{assoc}}{d\Delta\varphi} \quad \text{and} \quad \frac{1}{N_{trig}}\frac{d^2N_{assoc}}{d\Delta\varphi d\Delta\eta}$$

At Low-p_T :

Ridge

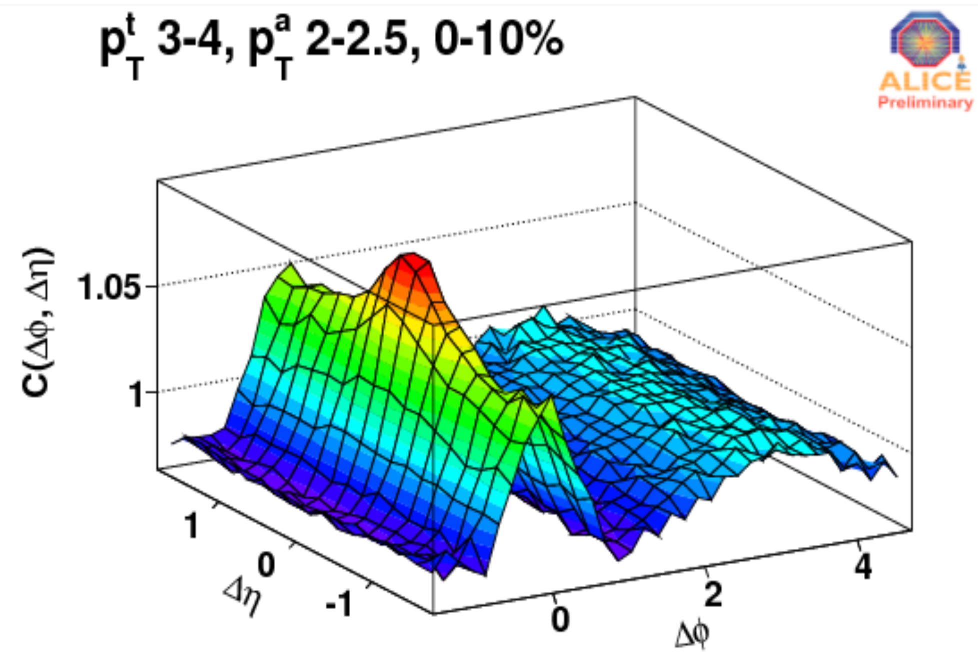
Hydrodynamics, flow

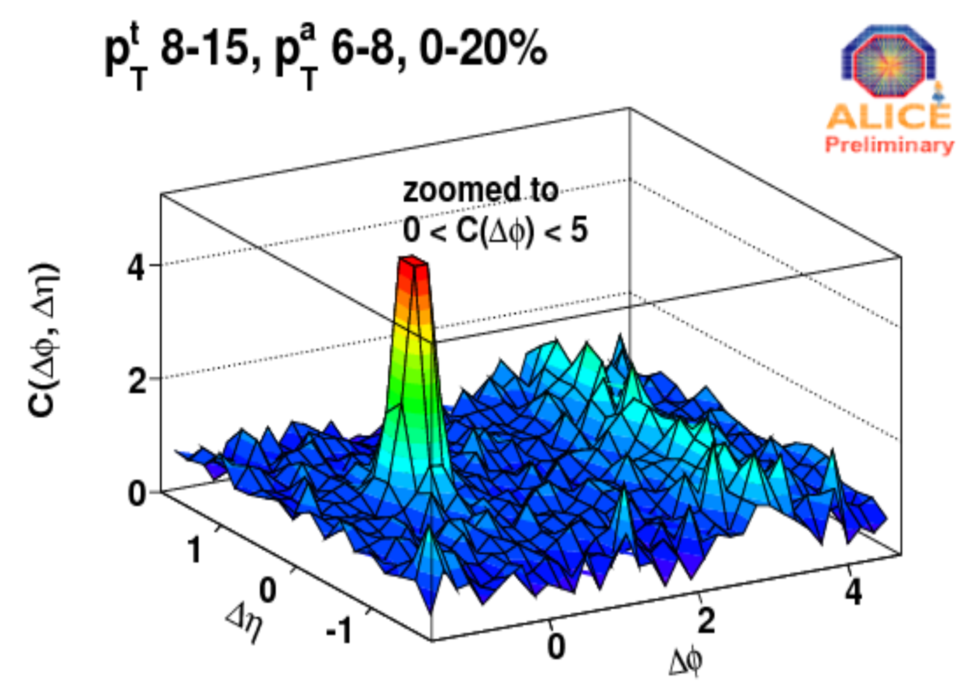
At High-p_T :

Quenching/suppression, broadening

I_{CP}: Yields in central v.s. peripheral collisions

I_{AA}: Yields in A-A compared to p-p

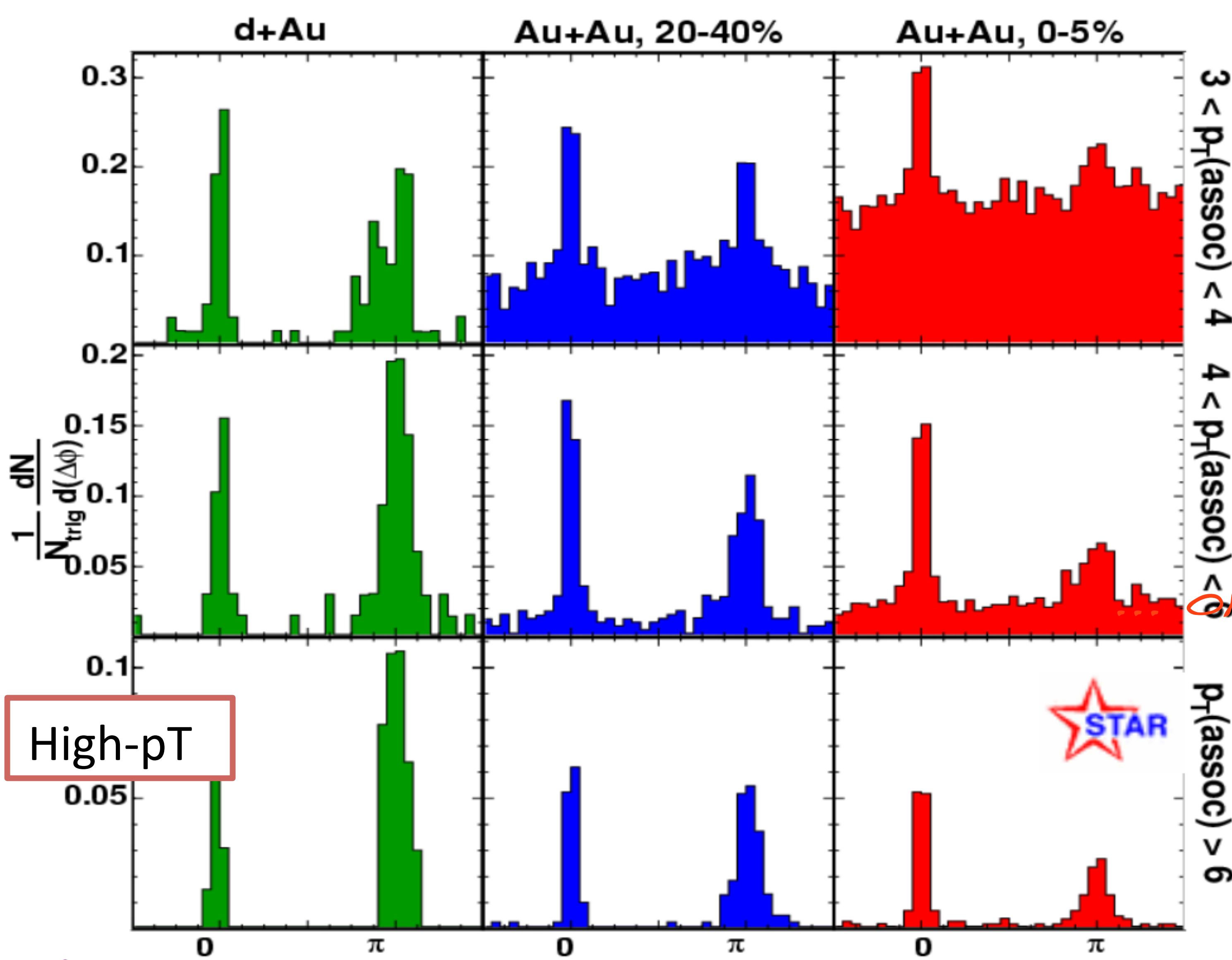




Two-particle correlations

RHIC @ 0.2 TeV

Most central



High-pT

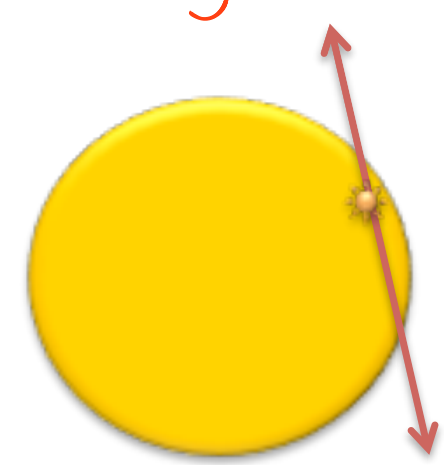
Phys.Rev.Lett.97:162301,2006

Reaperance of the away side peak at high-assoc.-pT:

- similar suppression as in the inclusive spectra
- unmodified shape

Differential measurement of jets w/o interaction

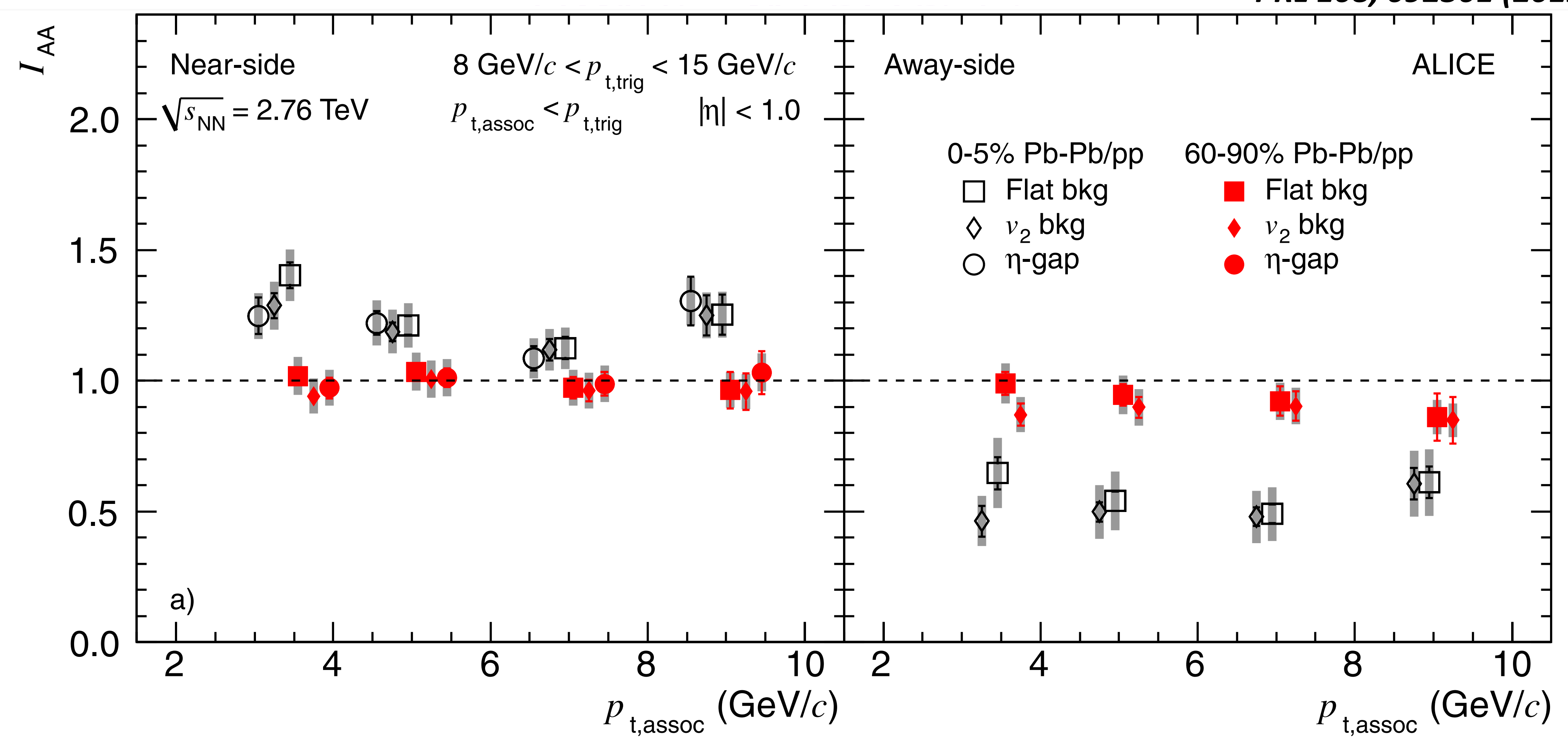
or jets fragment as in vacuum



Conditional yields - LHC

Yield per trigger particle AA/pp -> I_{AA}

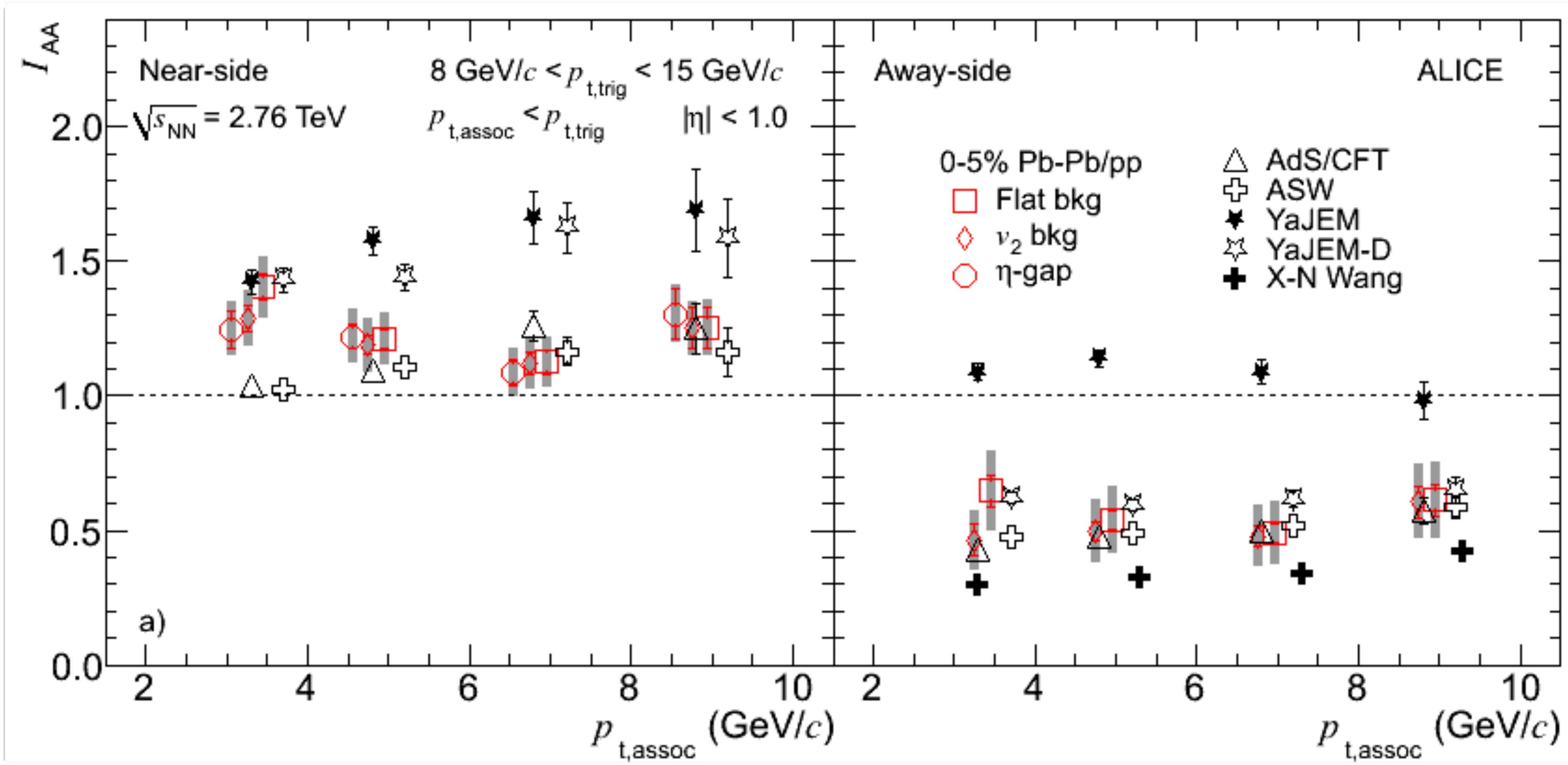
PRL 108, 092301 (2012)



Compare pp and Pb-Pb → $I_{AA} = Y_{AA}/Y_{pp}$

- Central events:
  - near-side enhancement (>1: change in FF? bias on parton spectrum?; q/g-mix different in PbPb as compared to p-p?) - consistent with jet quenching...
  - recoil: suppressed - consistent with quenching

IAA: data & theory description



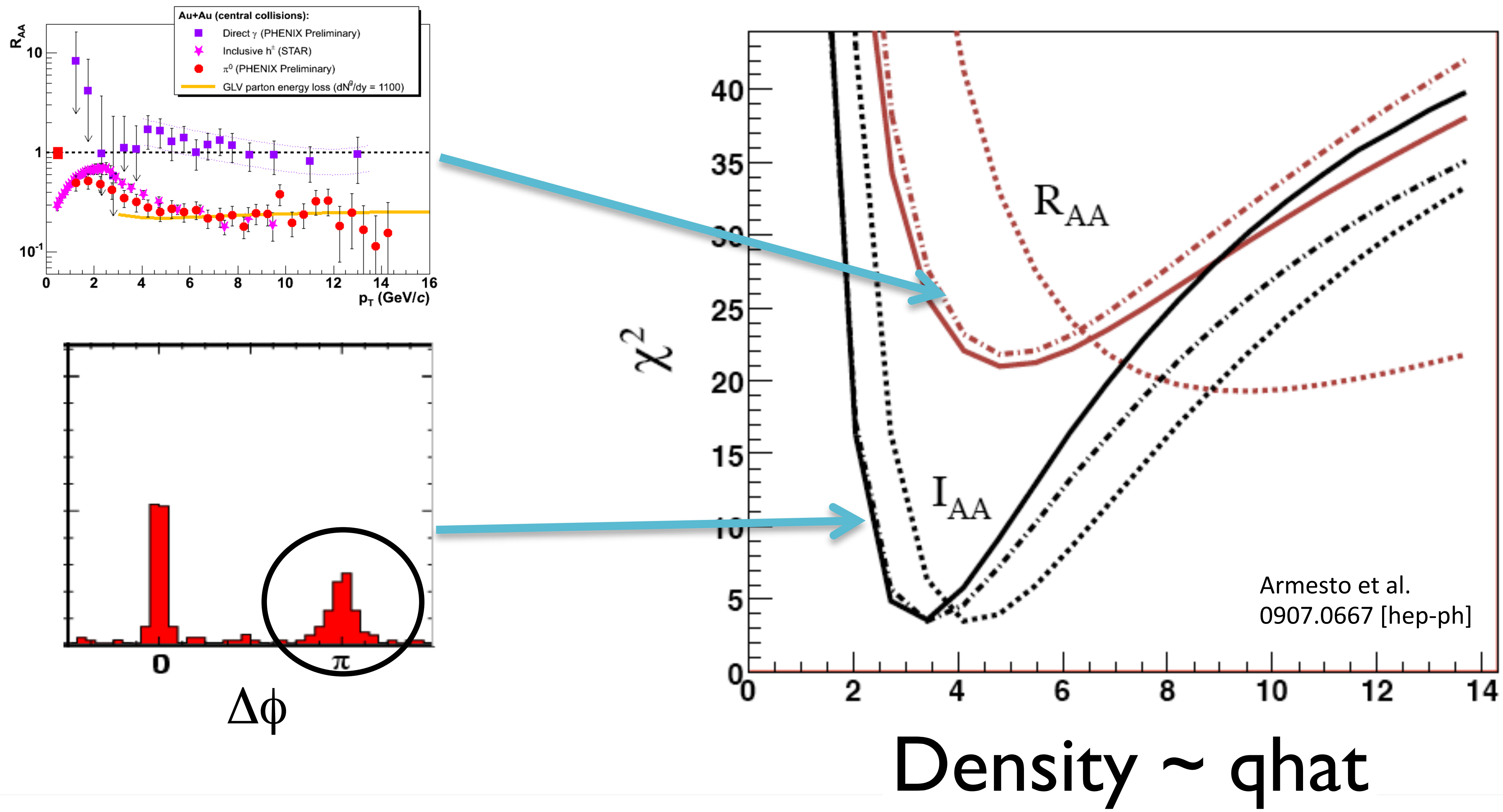
Near-side enhancement:

- Reproduced by AdS/CFT - inspired (L^3 path length dependence) and ASW - inspired (L^2) models
- YaJEM too high (L dependence)

ok, so... compatible with jet quenching...

RHIC Example: High-p_T hadrons - quantitative analysis

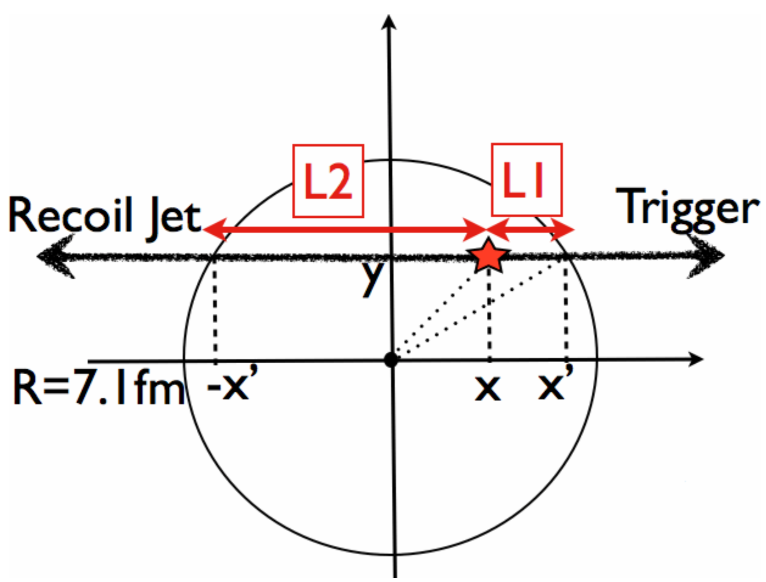
Model calculation: ASW quenching weights, detailed geometry
Simultaneous fit to data.

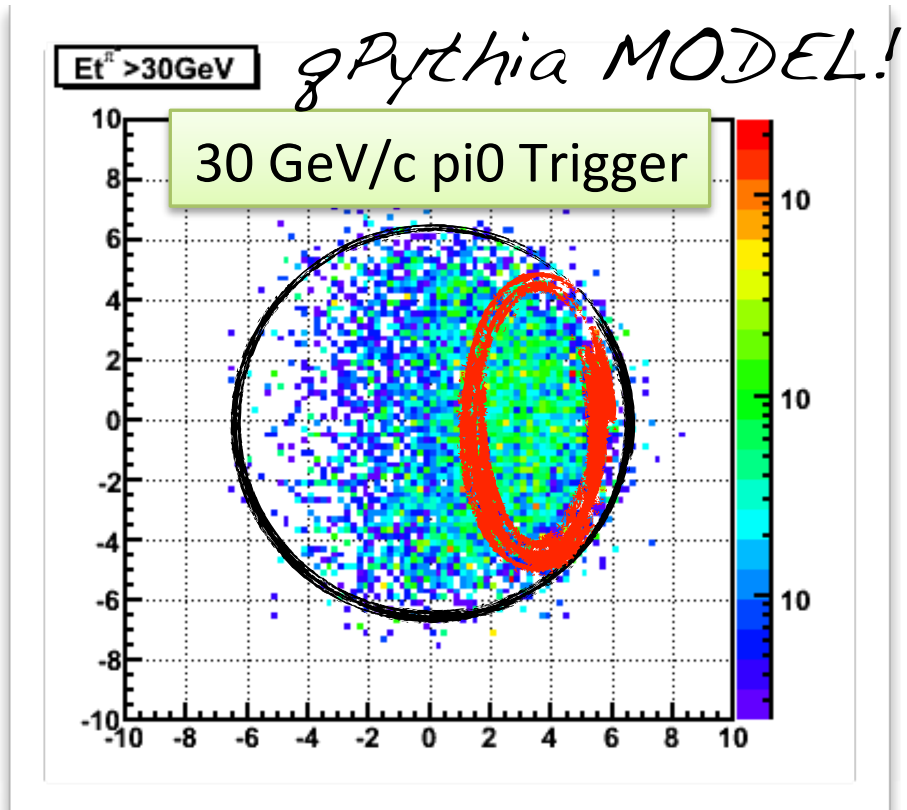


Reasonably self-consistent fit of independent observables
Main limitation was/is the accuracy of the theory...

So, why bother with full jet reconstruction in heavy-ion collisions?

R_{AA} and correlations of leading hadrons provide constraints on density of the medium (qhat), however do not tell us about the *parton* energy loss and its dynamics; leading hadrons are biased towards jets that interact little or not at all with the medium



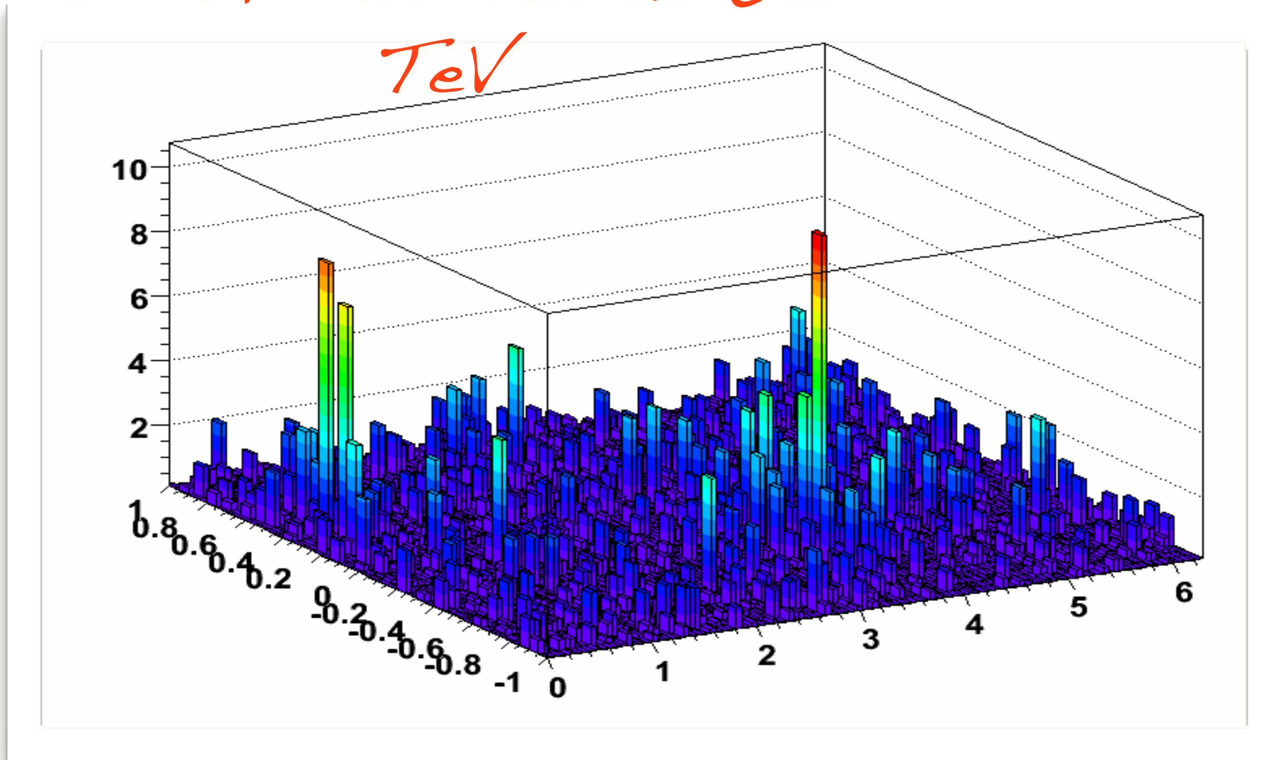


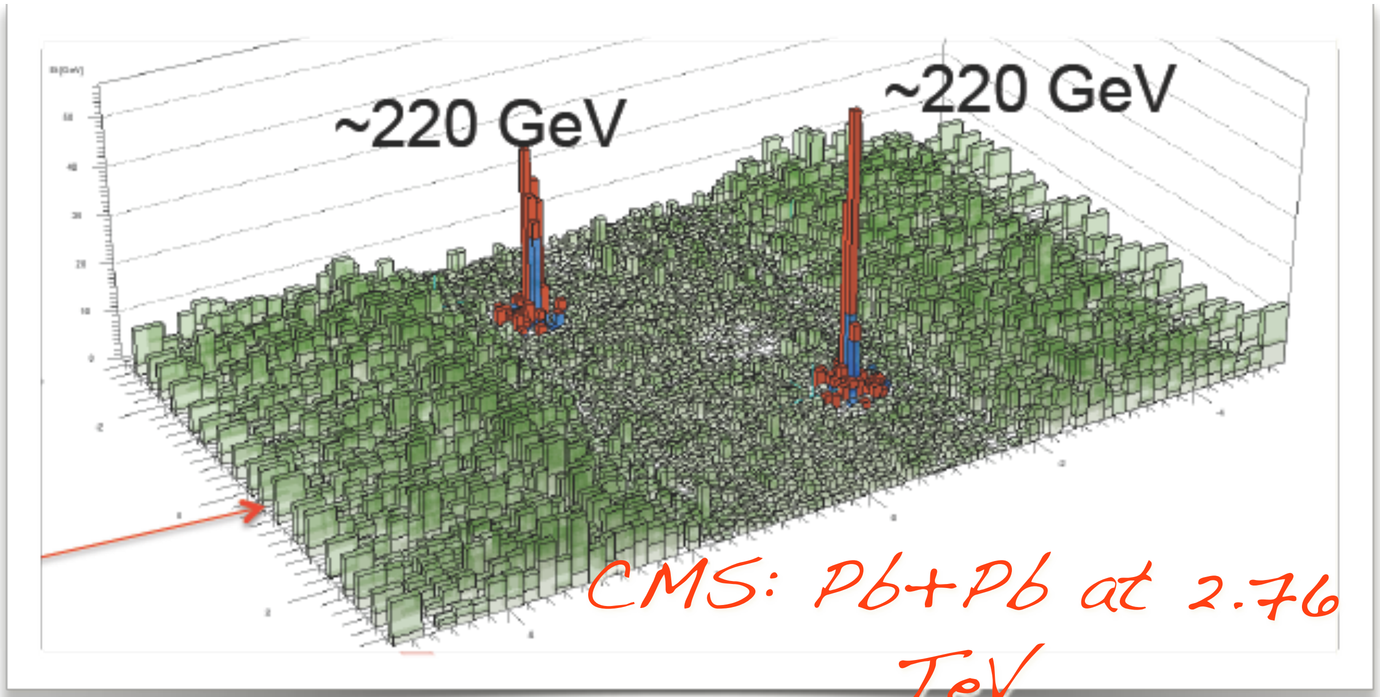
So called surface bias: requesting a high-pT particle selects a population of jets close to surface of the medium - these jets interact only little (or not at all) with the medium

=> full jet reconstruction premise: integrate over the hadronic degrees of freedom; better access to the parton energy scale; dynamics of the jet quenching (?); other promising observables: gamma-jet correlations

Jets in heavy-ion collisions

STAR: Au+Au at 0.2 TeV





CMS: Pb+Pb at 2.76 TeV

LHC + RHIC: QCD evolution of jet quenching ?

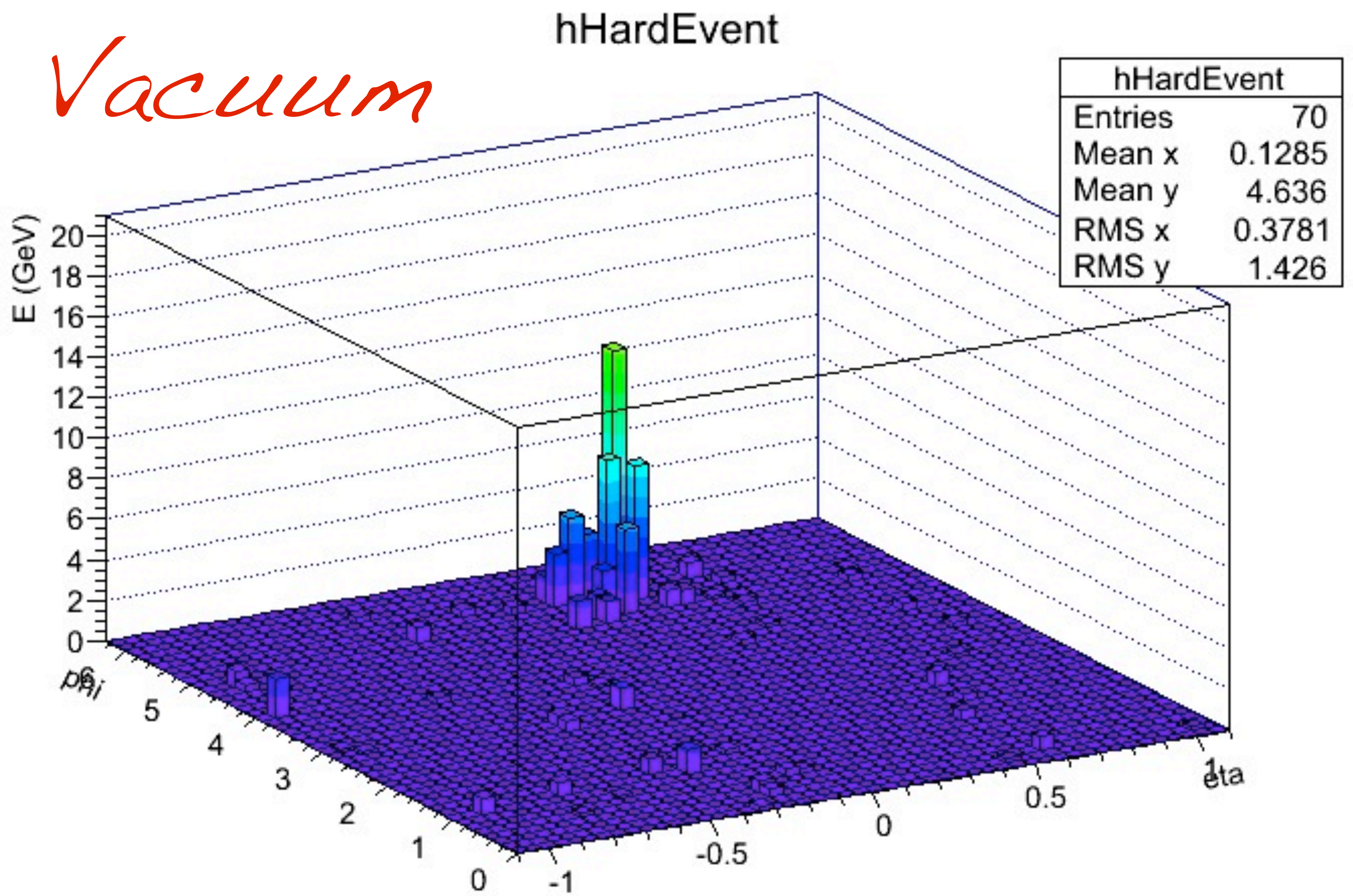
Vary energy of the jet:

LHC: Vary the scale with which QGP is probed (a la DIS)

Compare and contrast RHIC and LHC

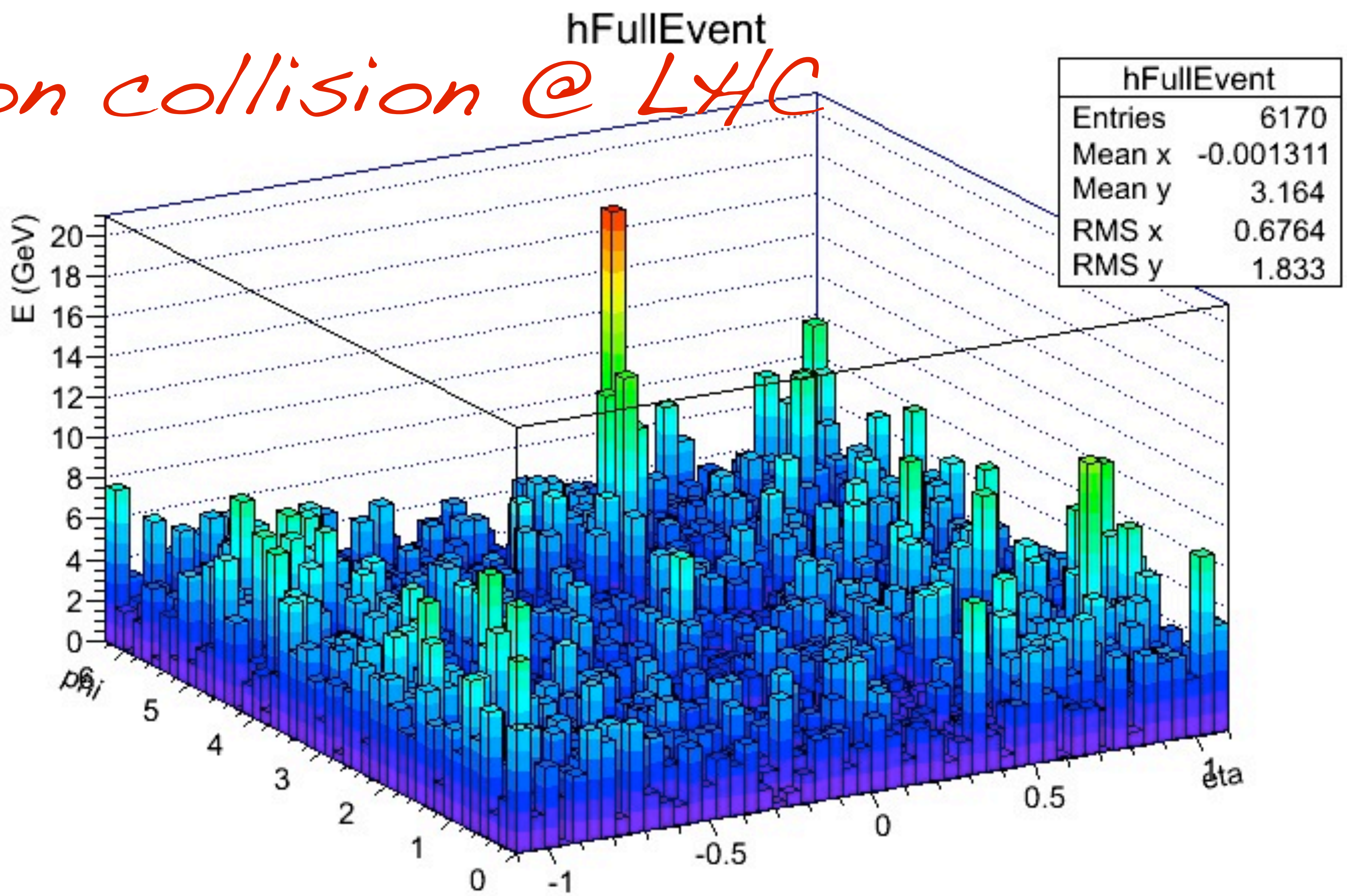
Jets in HI collisions & Experimental difficulties: Vacuum jet vs jet on top of the HI background...

Vacuum

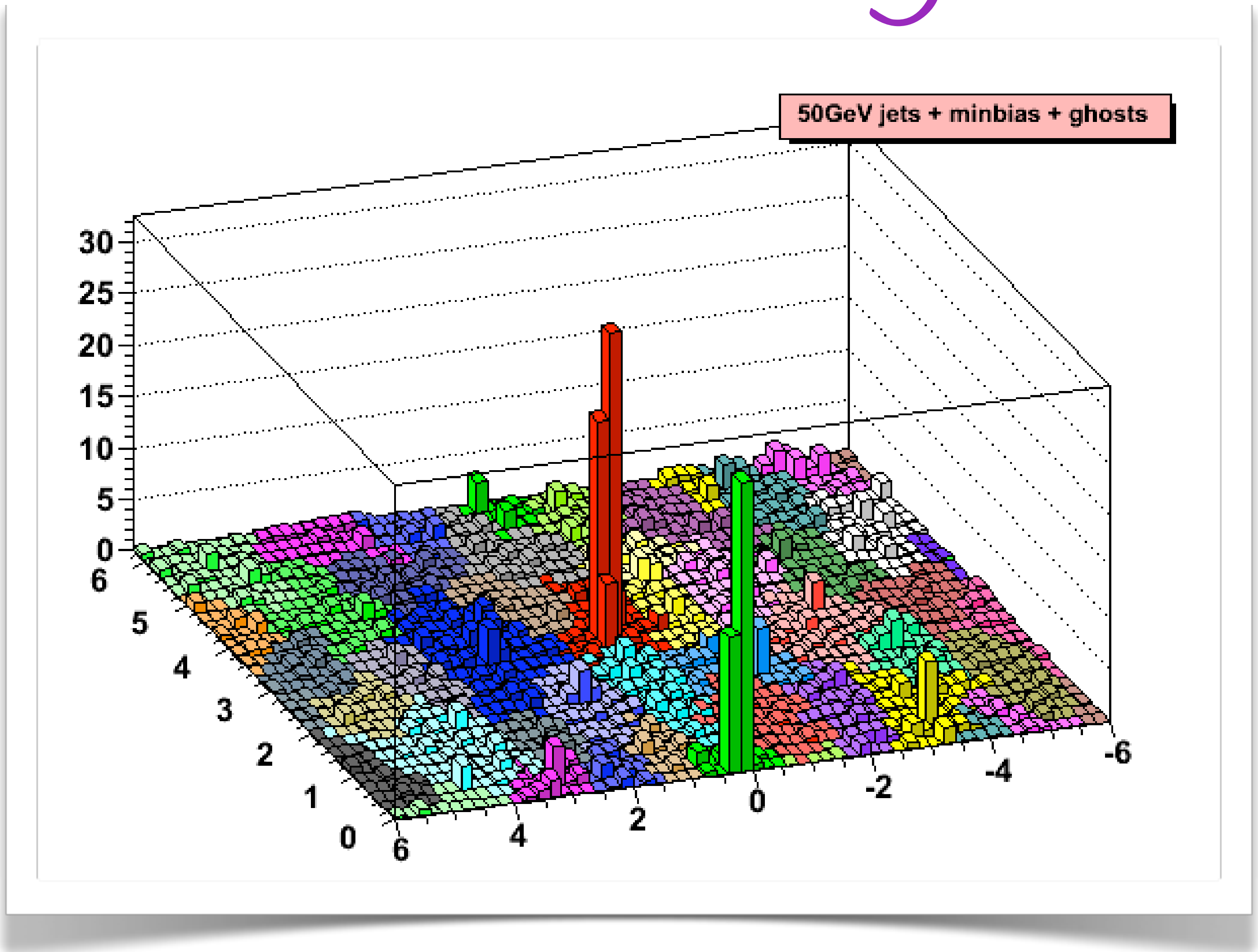


Jets in HI collisions & Experimental difficulties: Vacuum jet vs jet on top of the HI background...

Heavy-ion collision @ LHC



HI jet finding: dealing with the background energy



A single event: all particles clustered ("assigned") to a jet

Many of these objects are simply background

Energy of the signal jets overestimated due to background energy

=> several possibilities to subtract the average background and/or suppress the background particles [and background jets]

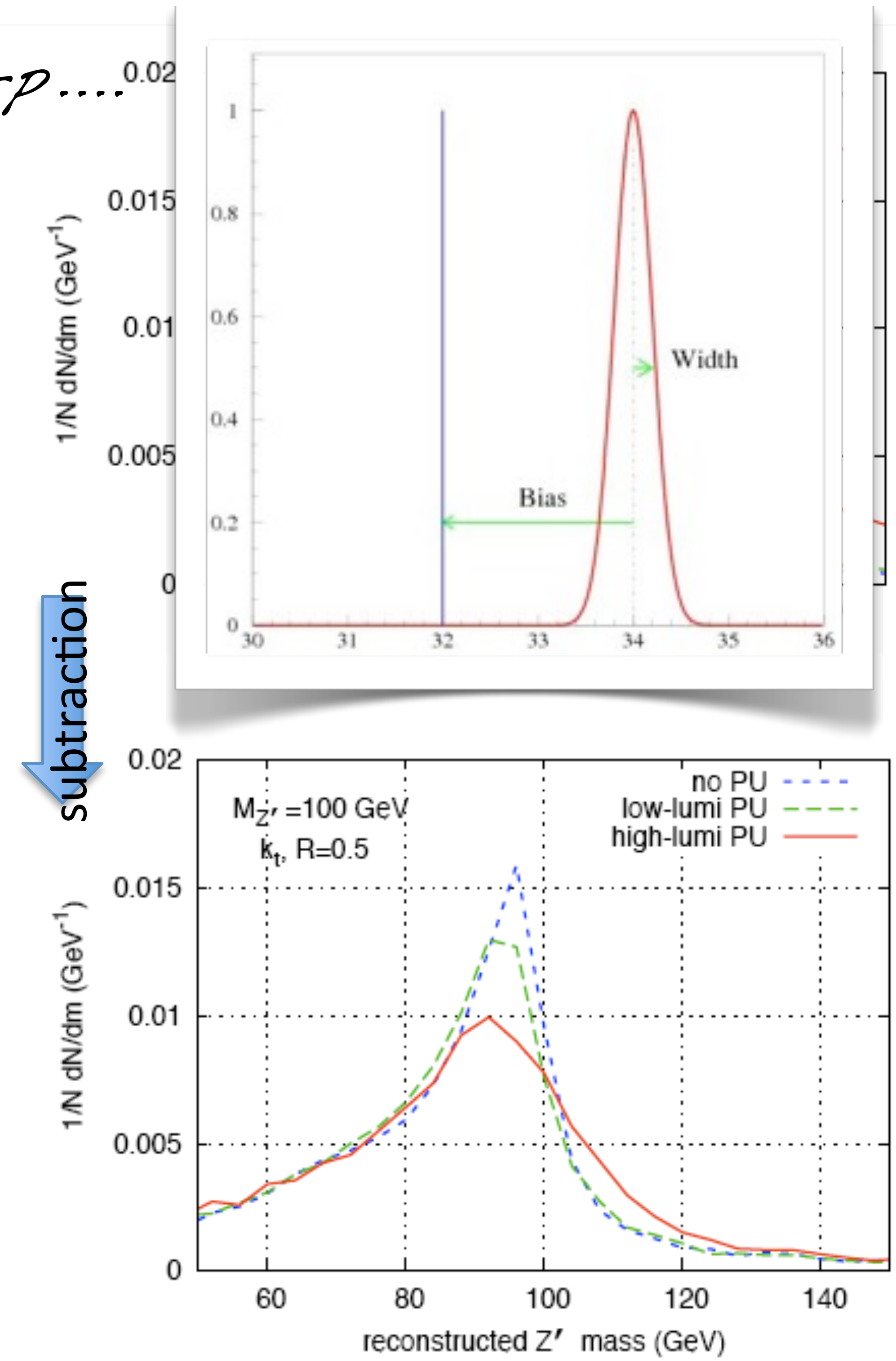
Background subtraction

Developed for pile-up rejection in p-p....

$$p_T^{jet} = p_T^{cluster} - \rho \times Area$$

$$p_T^{jet} = p_T^{true} \otimes \delta\rho$$

- ρ: median pT per unit area of the diffuse background in an event – measured using background *"jets"* as found by kT algorithm
- A: area of the jet – measured using number of artificially injected infinitely soft particles of finite *"size"* into an event that are clustered into the jet
- δρ: uncertainty due to noise fluctuations – non-uniformity of the event background



M. Cacciari, G. Salam, G. Soyez JHEP 0804:063,2008. e-Print: arXiv:0802.1189 [hep-ph]
M. Cacciari, G.Salam Phys.Lett.B659:119-126,2008. e-Print: arXiv:0707.1378 [hep-ph]

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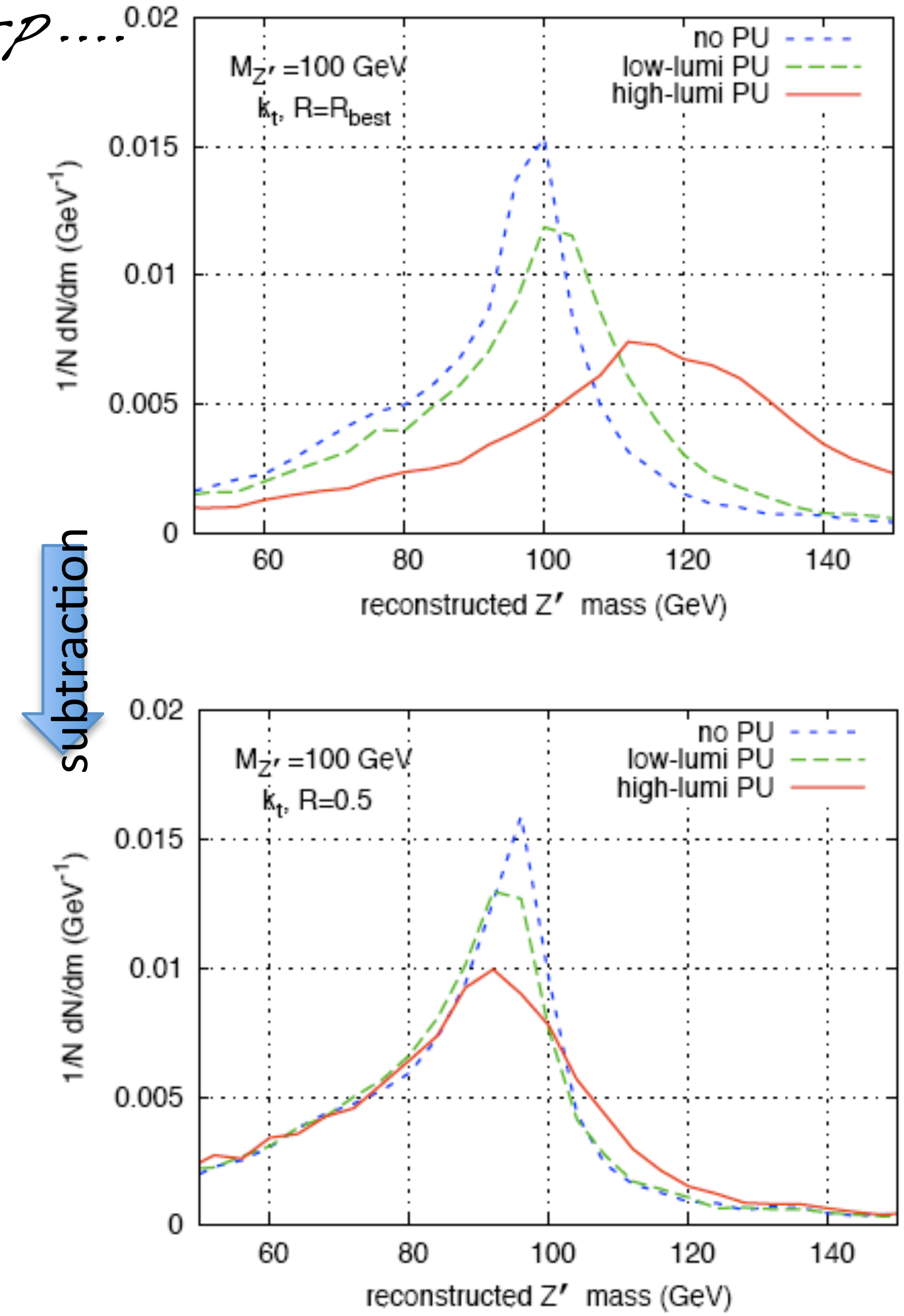
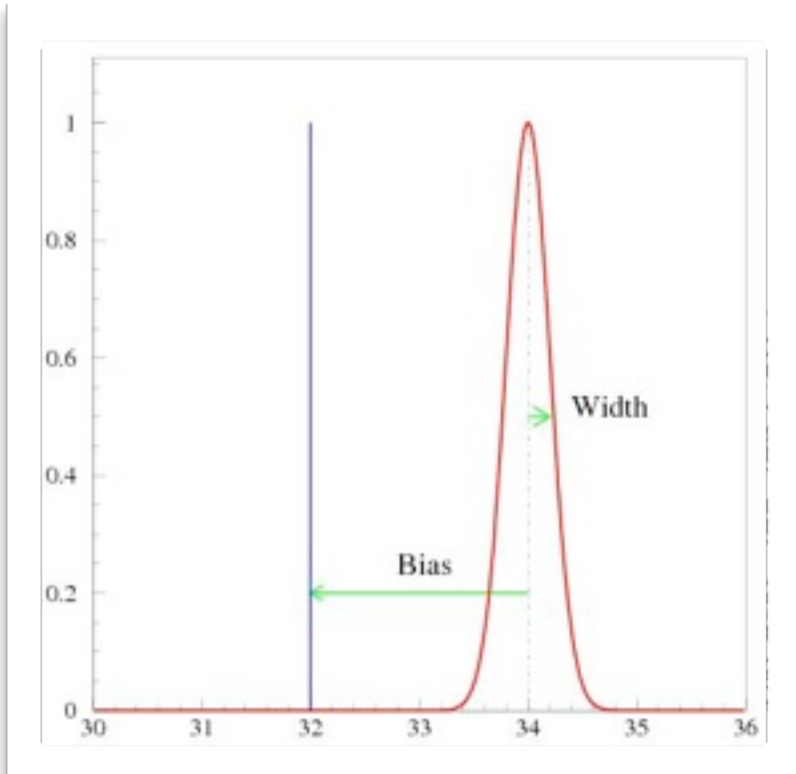
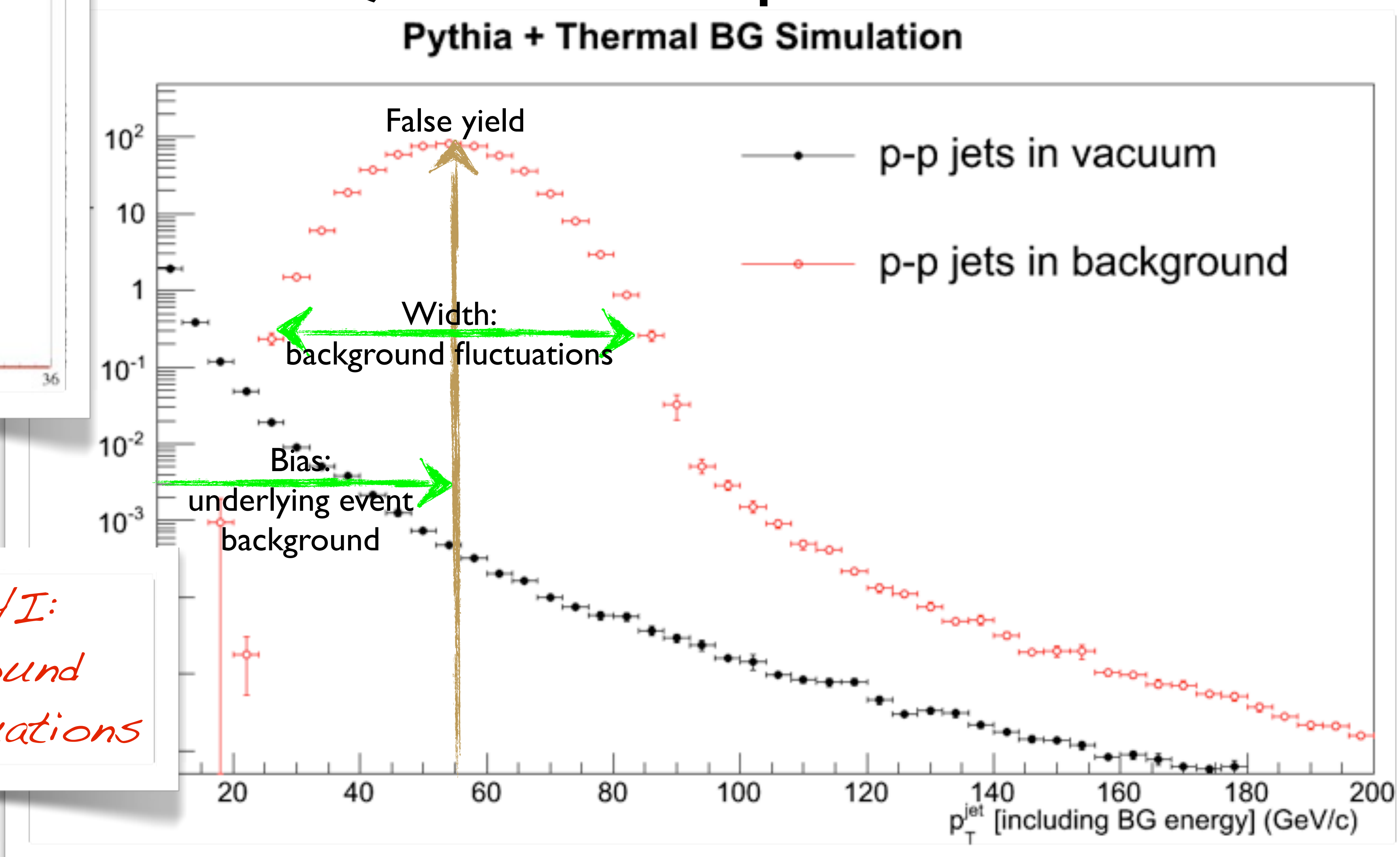


M. Cacciari, G. Salam, G. Soyez JHEP 0804:063,2008. e-Print: arXiv:0802.1189 [hep-ph]
M. Cacciari, G.Salam Phys.Lett.B659:119-126,2008. e-Print: arXiv:0707.1378 [hep-ph]

Jets in heavy-ion collisions – main difficulties



Qualitative picture

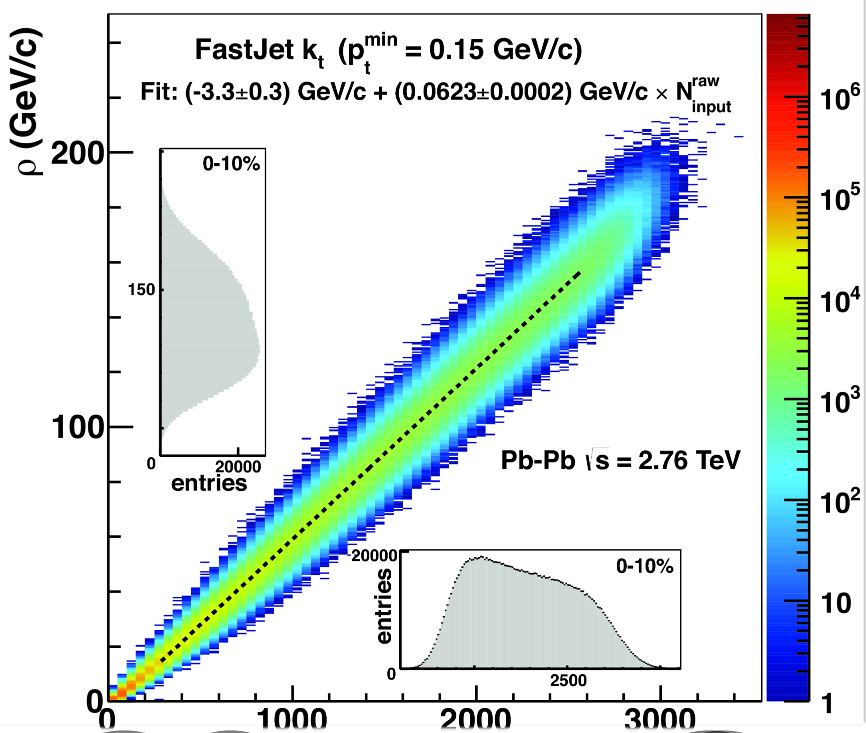


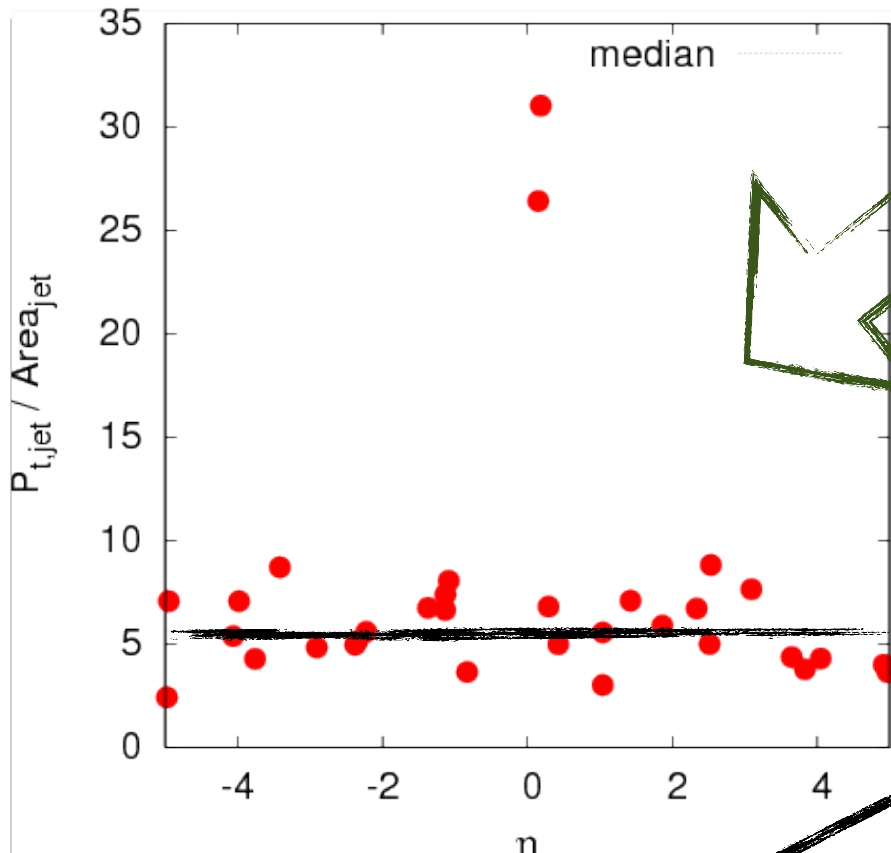
=> Procedure in HI:
1) subtract background
2) correct for fluctuations

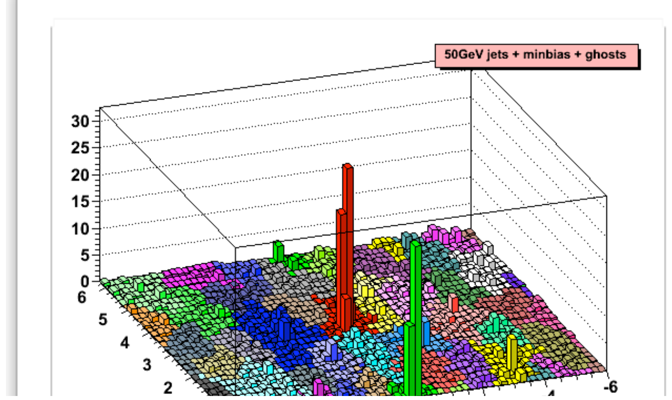
HI jet finding: treatment of the background

Method 1

$$\rho = median\left(\frac{p_T^{jet,i}}{A_i^{jet}}\right)$$







NOT all of the objects returned by jet finder are TRUE jets! (aka - fake/ false jets!)

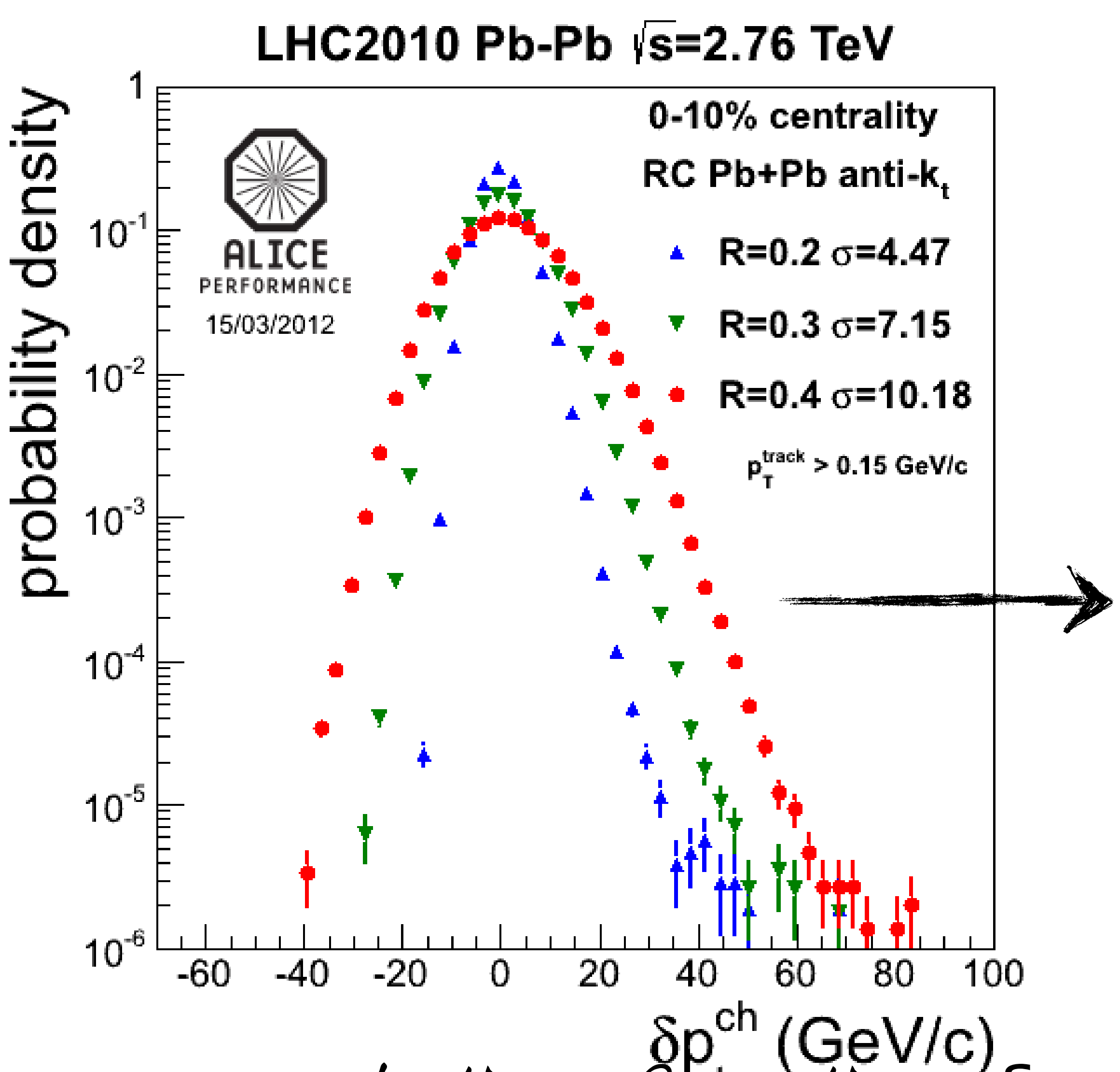
average background energy density

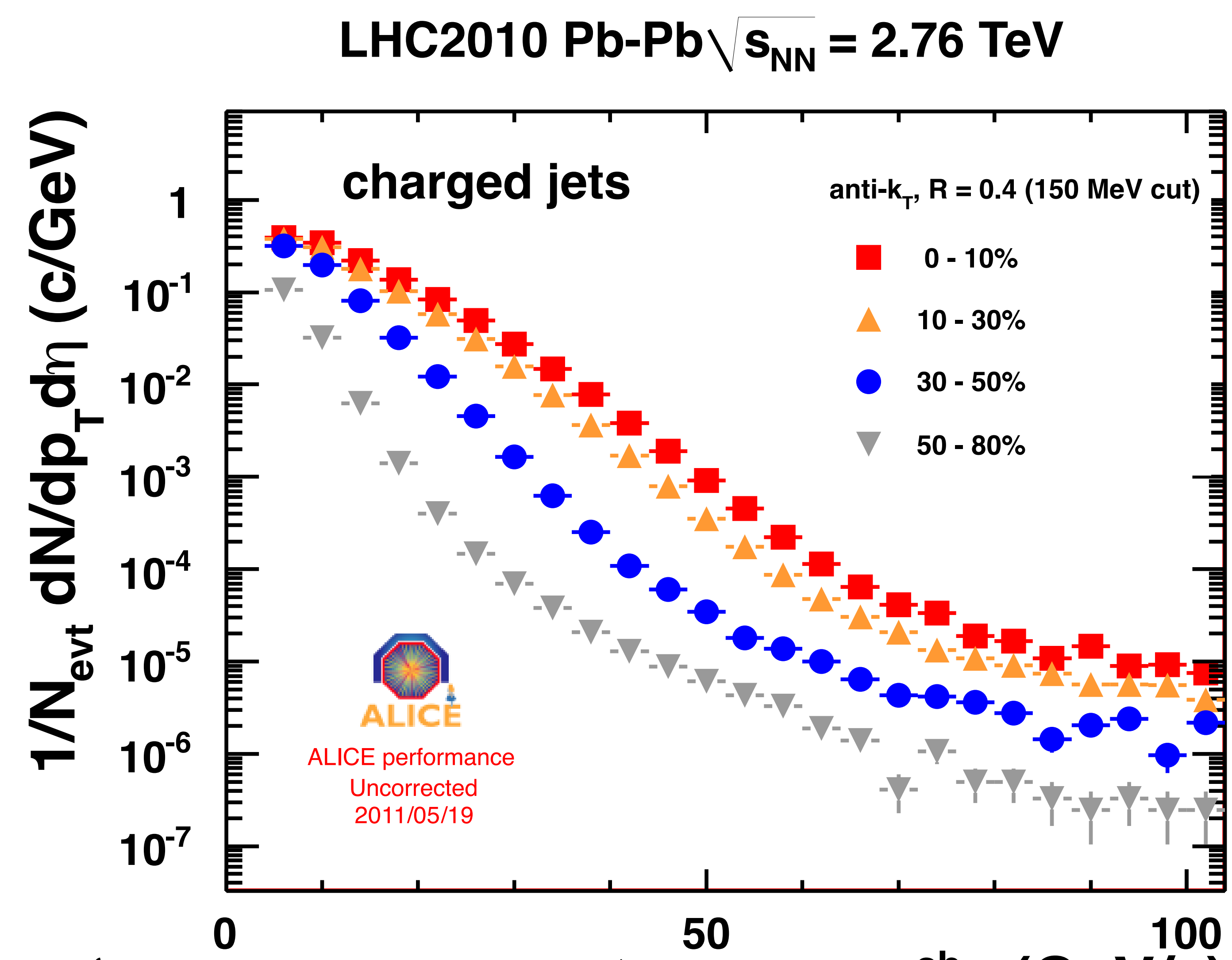
$$p_T = p_T^{raw} - \rho \times Area_{jet}$$

Must correct for remaining residual energy resolution

- magnitude of the correction is related to the background fluctuations
- jet Area : small R (area) - smaller correction

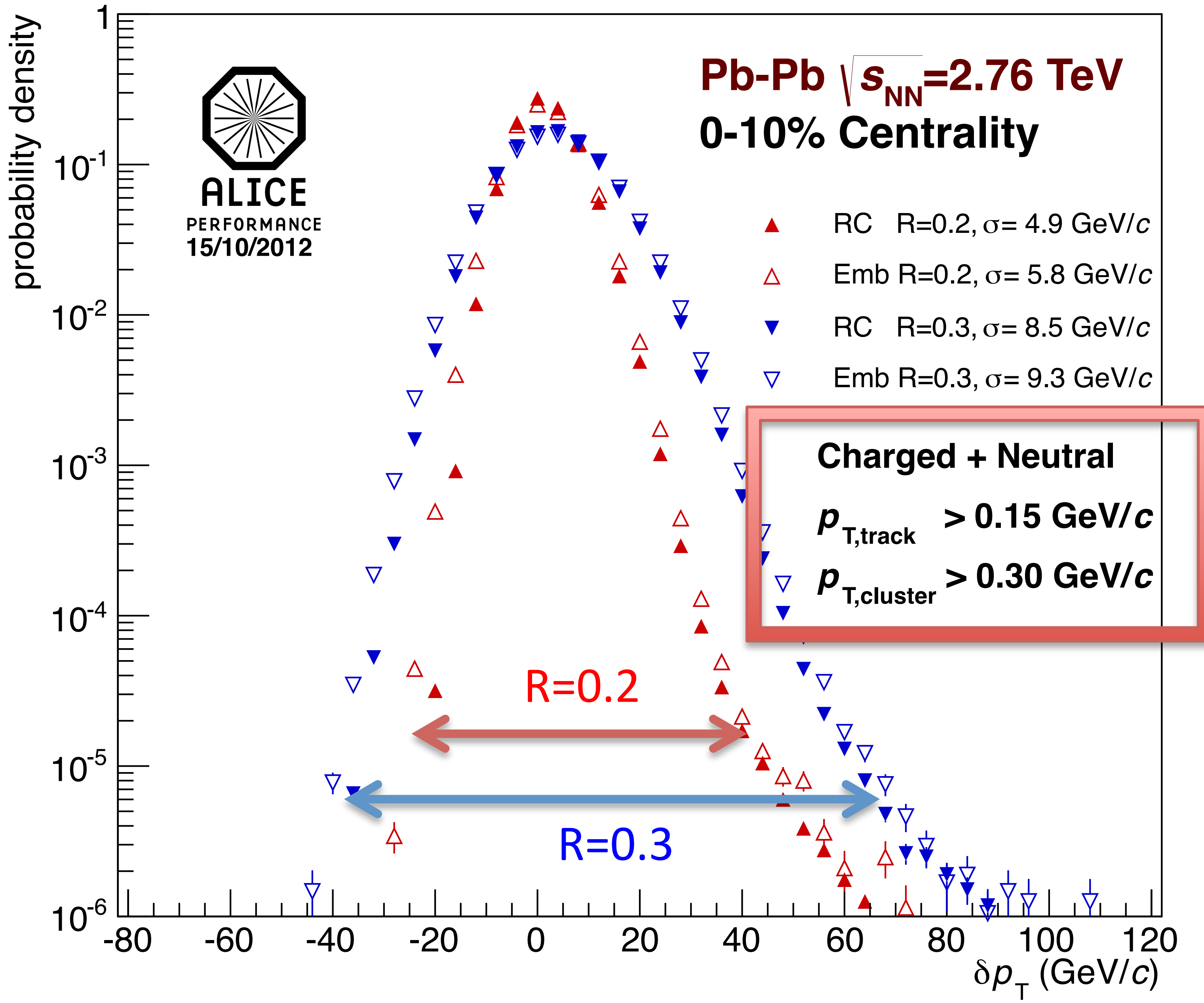
Jet reconstruction in HI collisions: Background fluctuations: characterized by δpT; spectrum before corrections





NOT all of the objects returned by jet finder are TRUE jets! (aka - fake/false jets!) - even after background subtraction! <-> fluctuations

Measuring background (fluctuations)



σ ≈ 5.5 GeV/c for R=0.2

σ ≈ 9.0 GeV/c for R=0.3

Note: the correction for the background energy does not correct for energy resolution due to background fluctuations

Single particle embedding

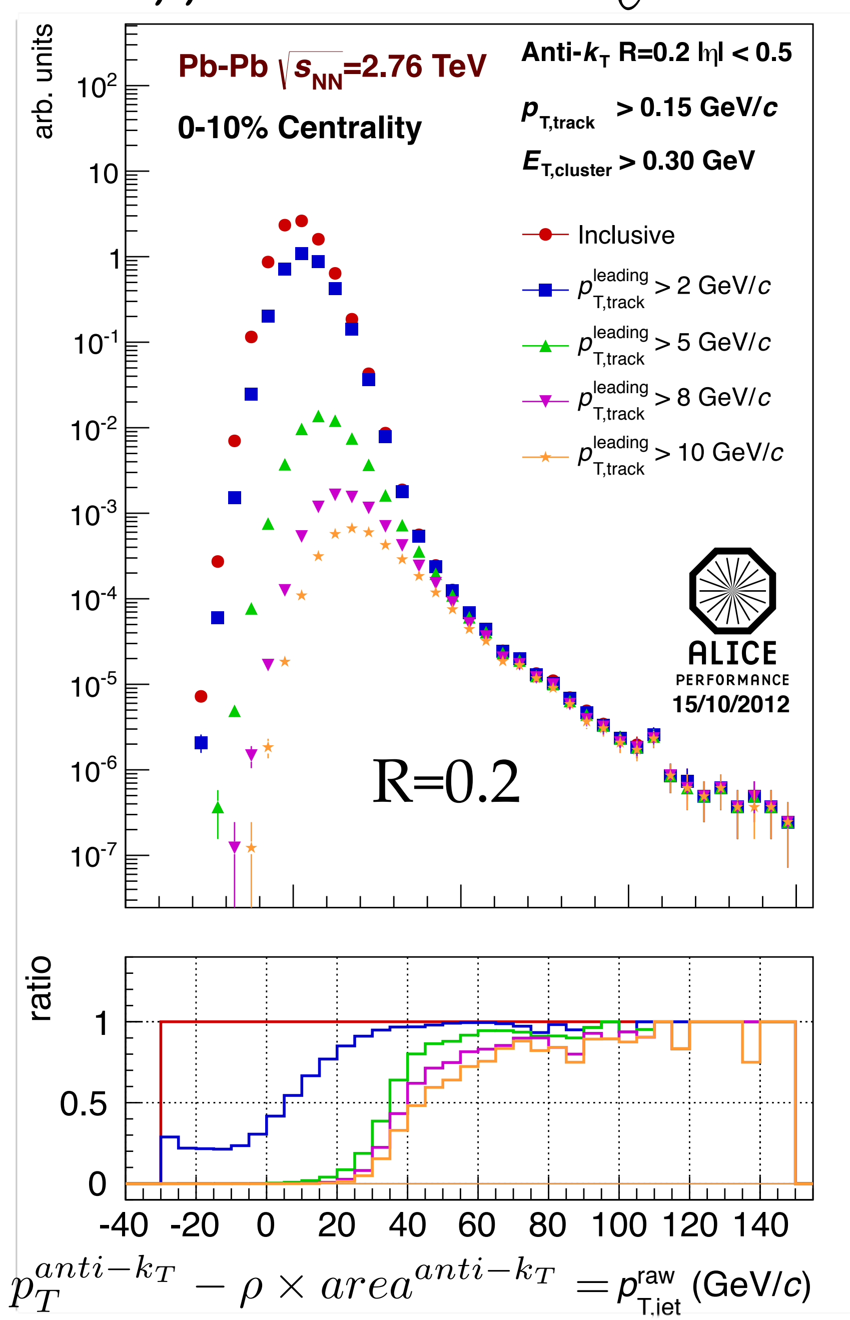
1. Embed a high p_T particle
2. Run the Anti-k_T jet finder
3. Pick up the jet which contain the embedded particle and calculate

$$\delta p_T^{emb} = p_T^{jet} - p_T^{probe} - A^{jet}\rho$$

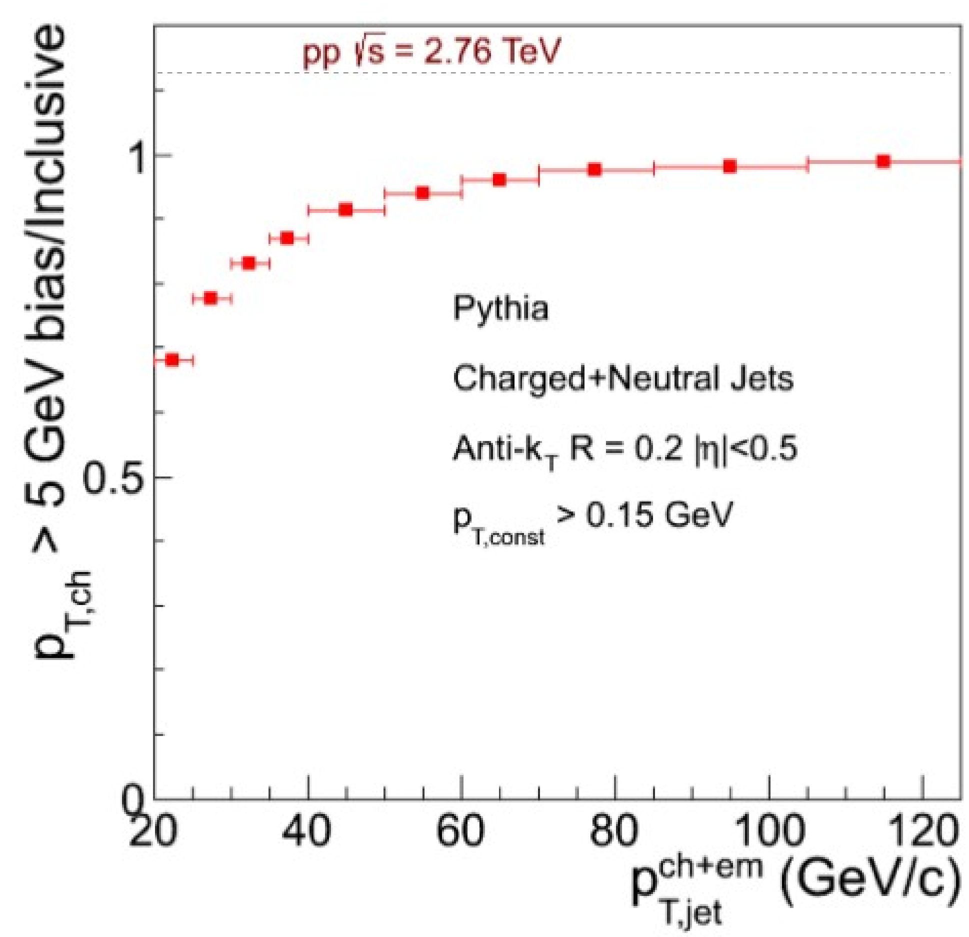
Measured resolution function – directly applicable for unfolding procedure

Suppression of the background - false jet yield

Leading track bias to suppress the false jets



- False jets in heavy-ion collisions can be suppressed via a leading track (particle) requirement
- Warning: trade-off/bias against possible fragmentation modifications (quenching) in HI collisions
- Effect of the bias persists up to high-pT jets - illustrated on vacuum jets



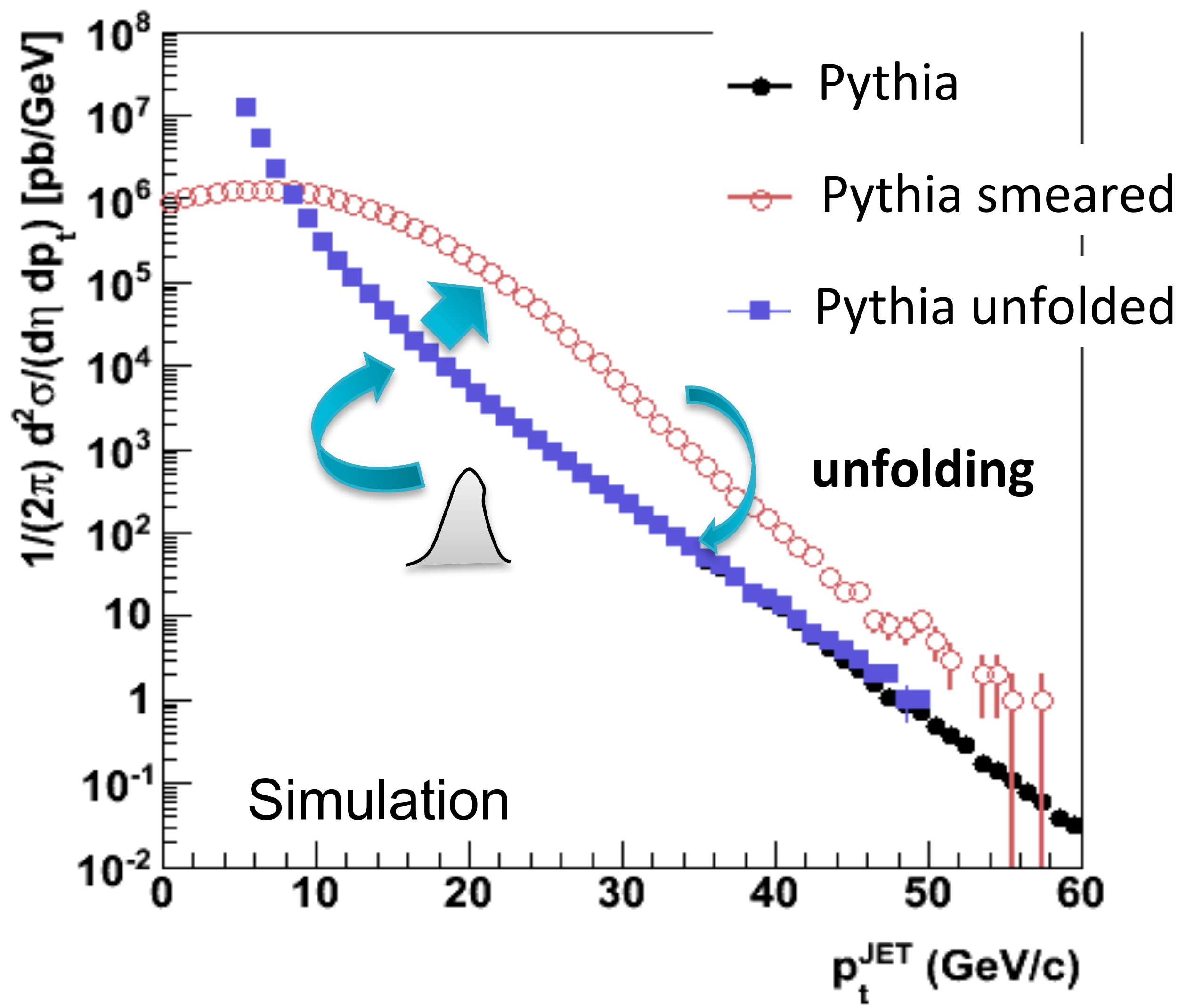
Energy resolution deteriorated due to background energy fluctuations

Model demonstration

$$\frac{dN^{\text{Meas}}}{dp_T} = \frac{dN^{\text{True}}}{dp_T} \otimes f^{\text{Resol}}(\delta\rho)$$

δP_T distribution:
'smearing' of jet spectrum
due to background fluctuations

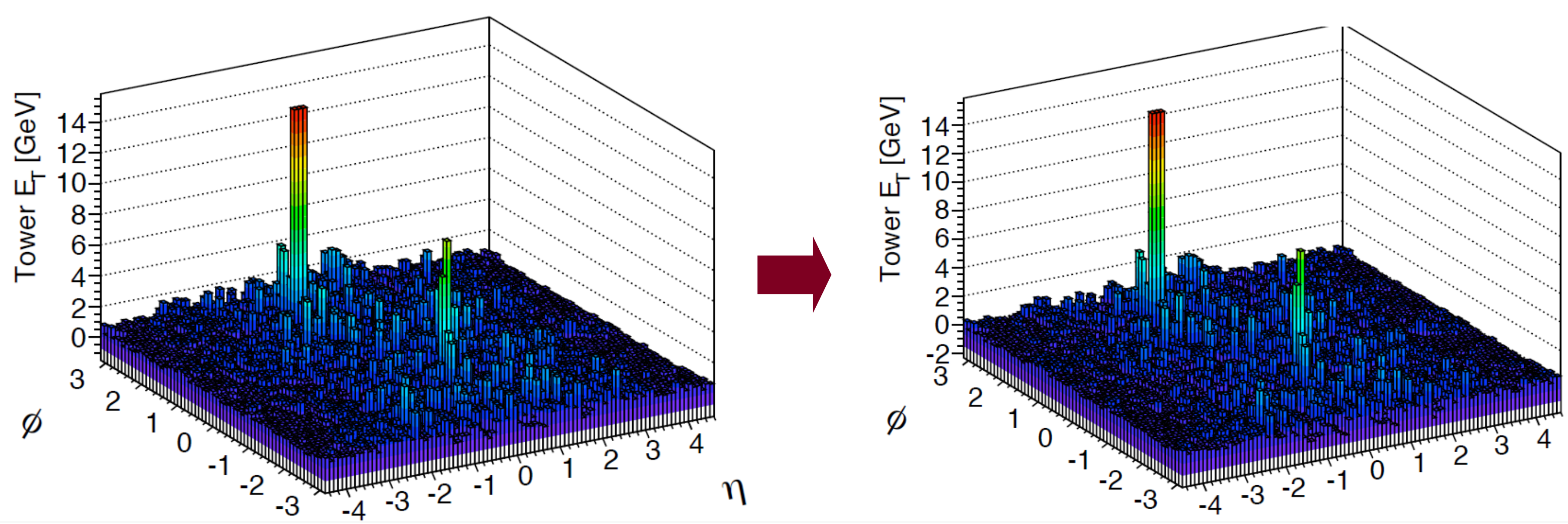
Large effect on yields
Need to unfold



Background corrections in Atlas

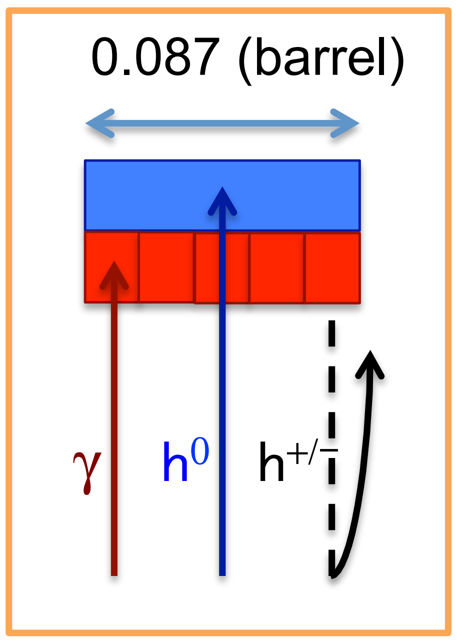
- UE fluctuations from soft particles can be reconstructed as jets (fakes)
  - Worse for larger *R*, contribute up to ~80 GeV
  - Require additional signal of **hard particle** production
    - Reject fakes by requiring jet to match:
      - Track jets or EM clusters with p_T > 7 GeV
    - Residual fake rate estimated to be ~3% at 50 GeV

- Reconstruction algorithm anti-k_t (0.2, 0.4).
- Input: calorimeter towers 0.1 x 0.1 (Δη x Δφ).
- Event-by-event background subtraction: $E_{Tsub}^{cell} = E_T^{cell} - \rho^{layer}(\eta) \times A^{cell}$
- → Anti-k_t reconstruction prior to a background subtraction.
- → Underlying event estimated for each longitudinal layer and η slice separately.
- We exclude jets with $D = E_{T\,tower}^{max} / \langle E_{T\,tower} \rangle > 4$ to avoid biasing subtraction from jets but no jet rejection based on *D*.
- Iteration step to exclude jets with E_T > 50 GeV from background estimation. Jets corrected for flow contribution.

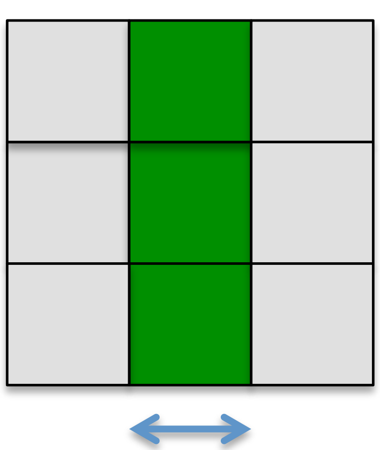


Background subtraction / jet energy corrections (CMS)

PF pseudo-tower



η strip



0.087 (barrel)

a) Event-by-event subtraction of the heavy-ion background

- Reconstructed particles towered into an (η,φ) grid according to HCAL cell dimensions

- Mean tower energy and dispersion are calculated for each η strip
- Same iterative background subtraction applied in [0], described in [1]
- Random cone studies: good agreement between background fluctuations in data and HYDJET simulations
- The effect of quenching on the energy scale is constrained using the jet associated charged particle spectra

b) Jet energy corrections (JEC) based on GEANT simulation of PYTHIA jets

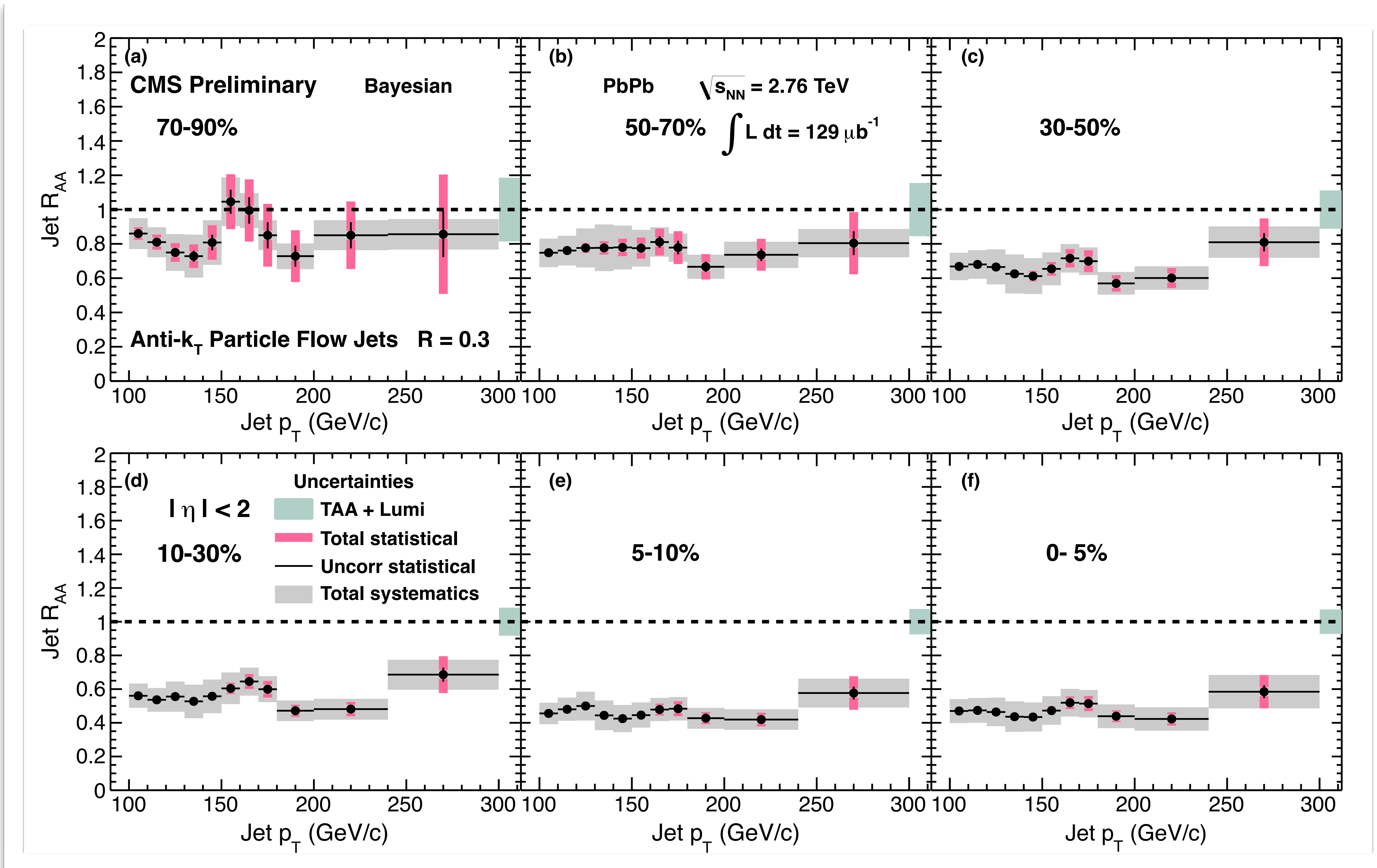
c) Validation of the BG subtraction + JEC for PYTHIA jets embedded in HYDJET

[0] CMS, arXiv:1102.1957
[1] Kodolova et al., EPJC 50 (2007) 117

Jet quenching measurements with fully reconstructed jets

Jet R_{AA}

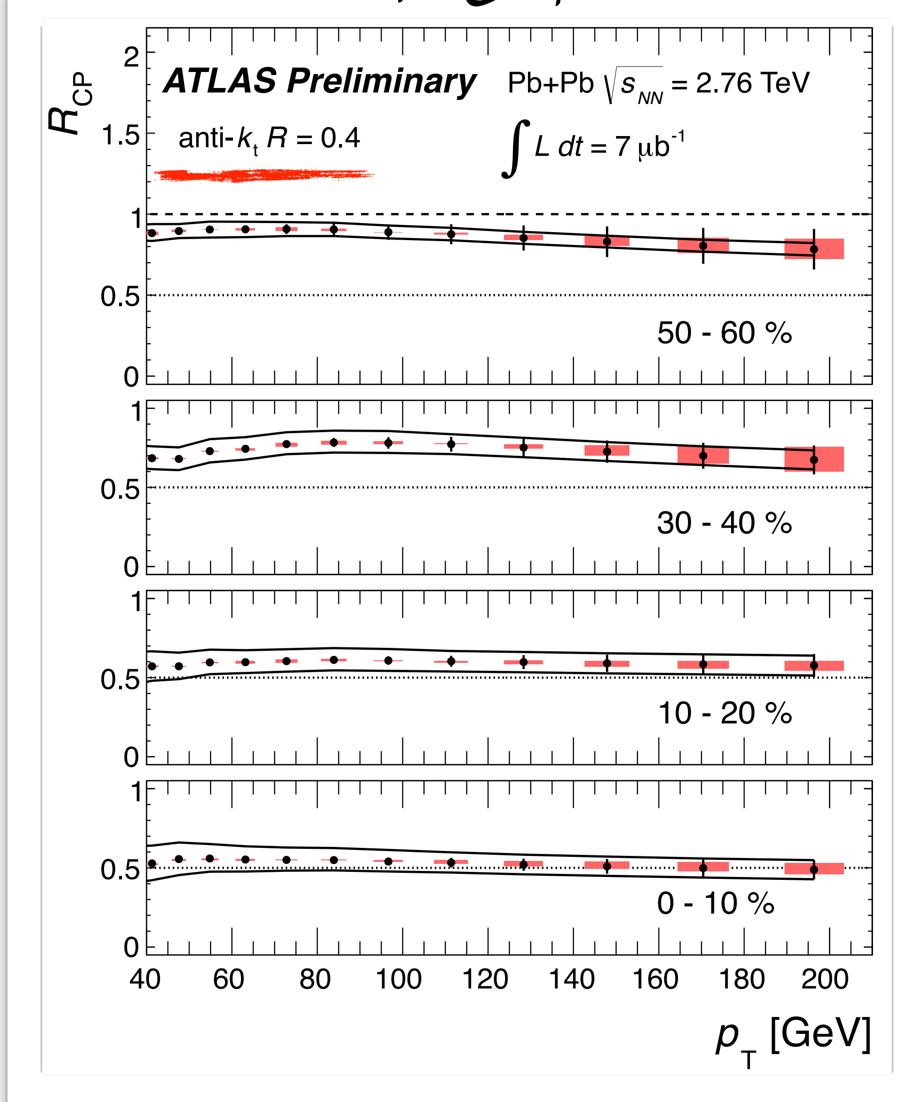
$$R_{AA} = \frac{\#(\text{jets observed in AA collision per N-N (binary) collision})}{\#(\text{jets observed per p-p collision})}$$



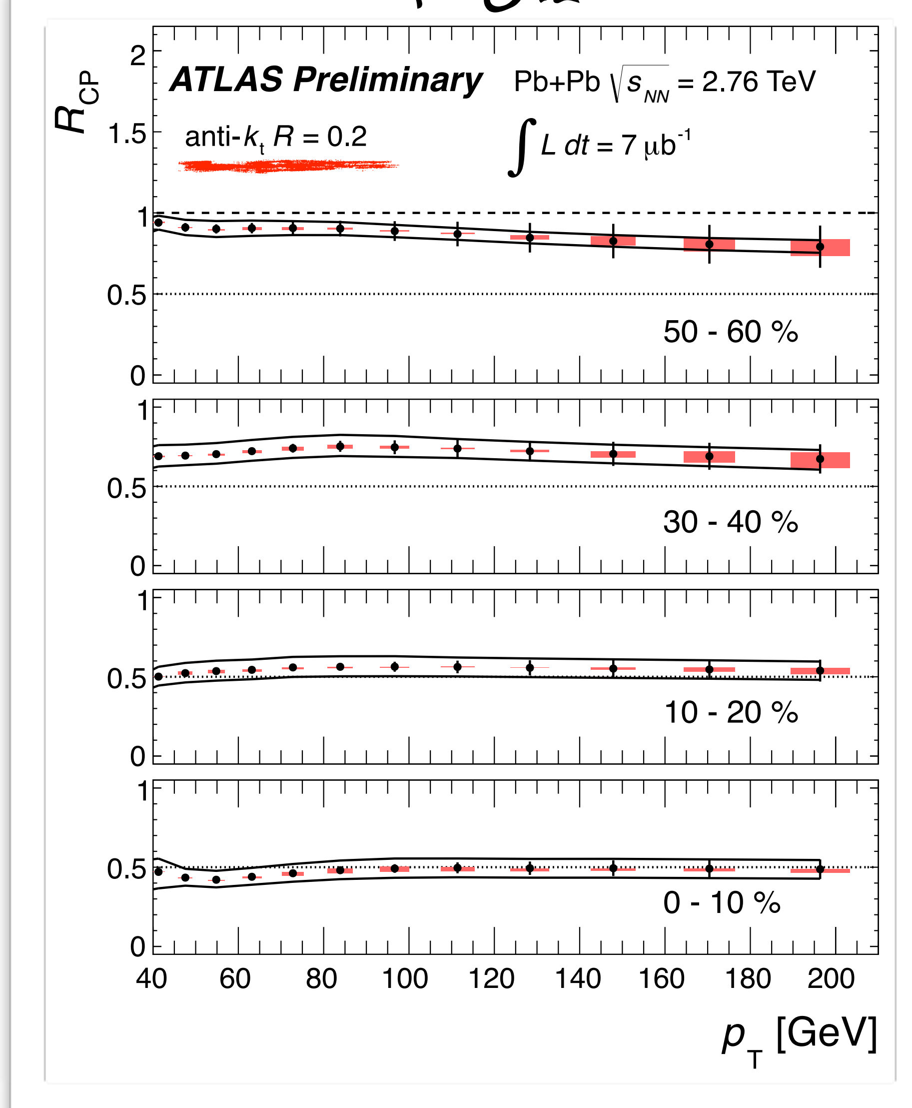
Jet $R_{Central-Peripheral(60-80\%)}$

R_{CP} : similar as R_{AA}, but denominator are not yields from proton-proton but from peripheral heavy-ion collisions

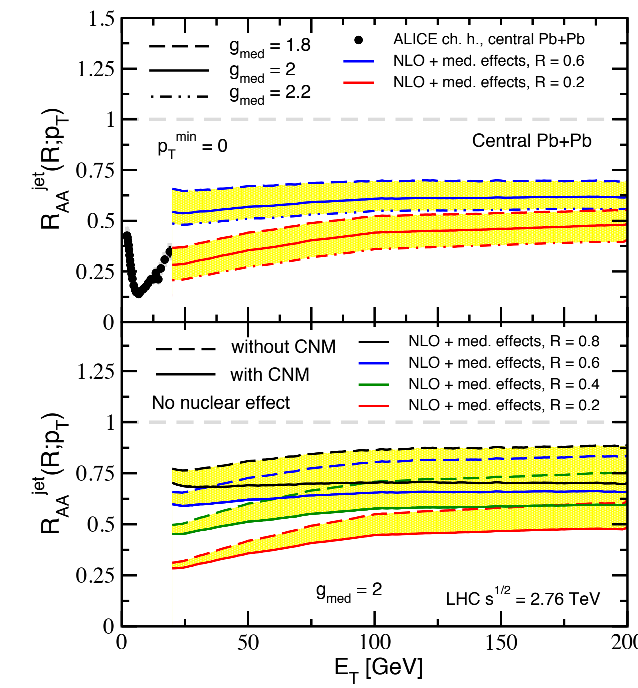
R=0.4



R=0.2



Measure single jet suppression with multiple jet sizes



He, Vitev, and Zhang hep-ph/1105.2566

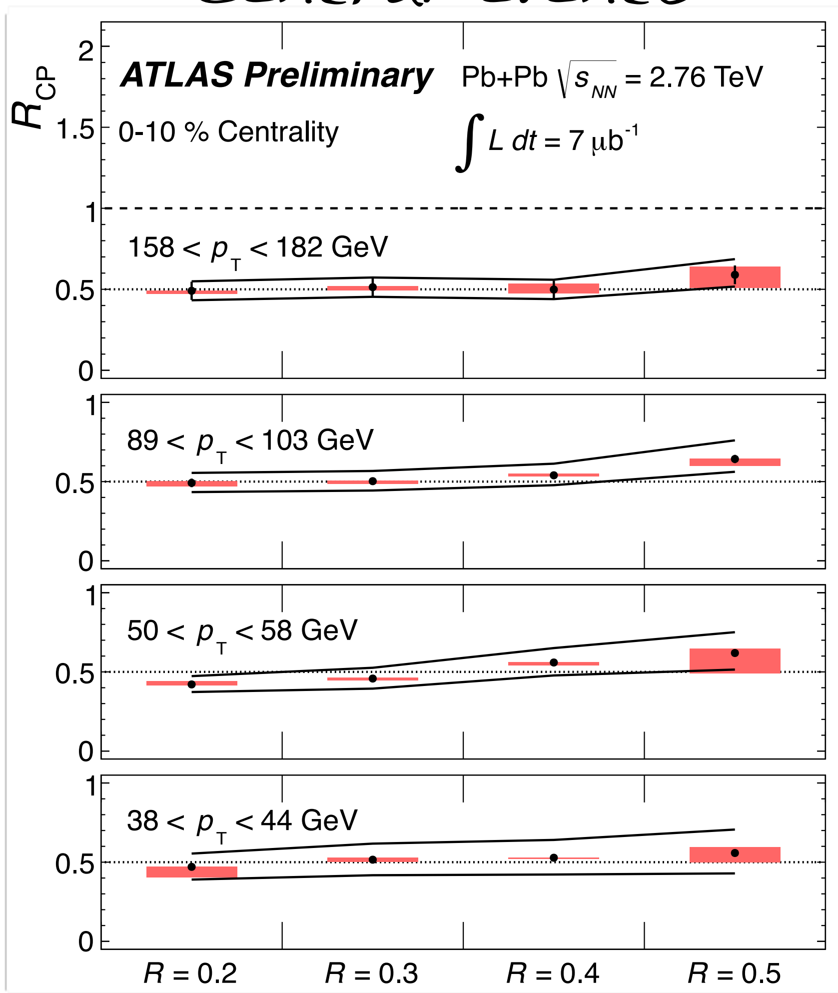
Note: Flat! – in contrast to R_{AA} of hadrons

R_{CP} ~ 0.5 => suppression – jets loose energy in most central events – the radiation is not captured within the jet cone (R)

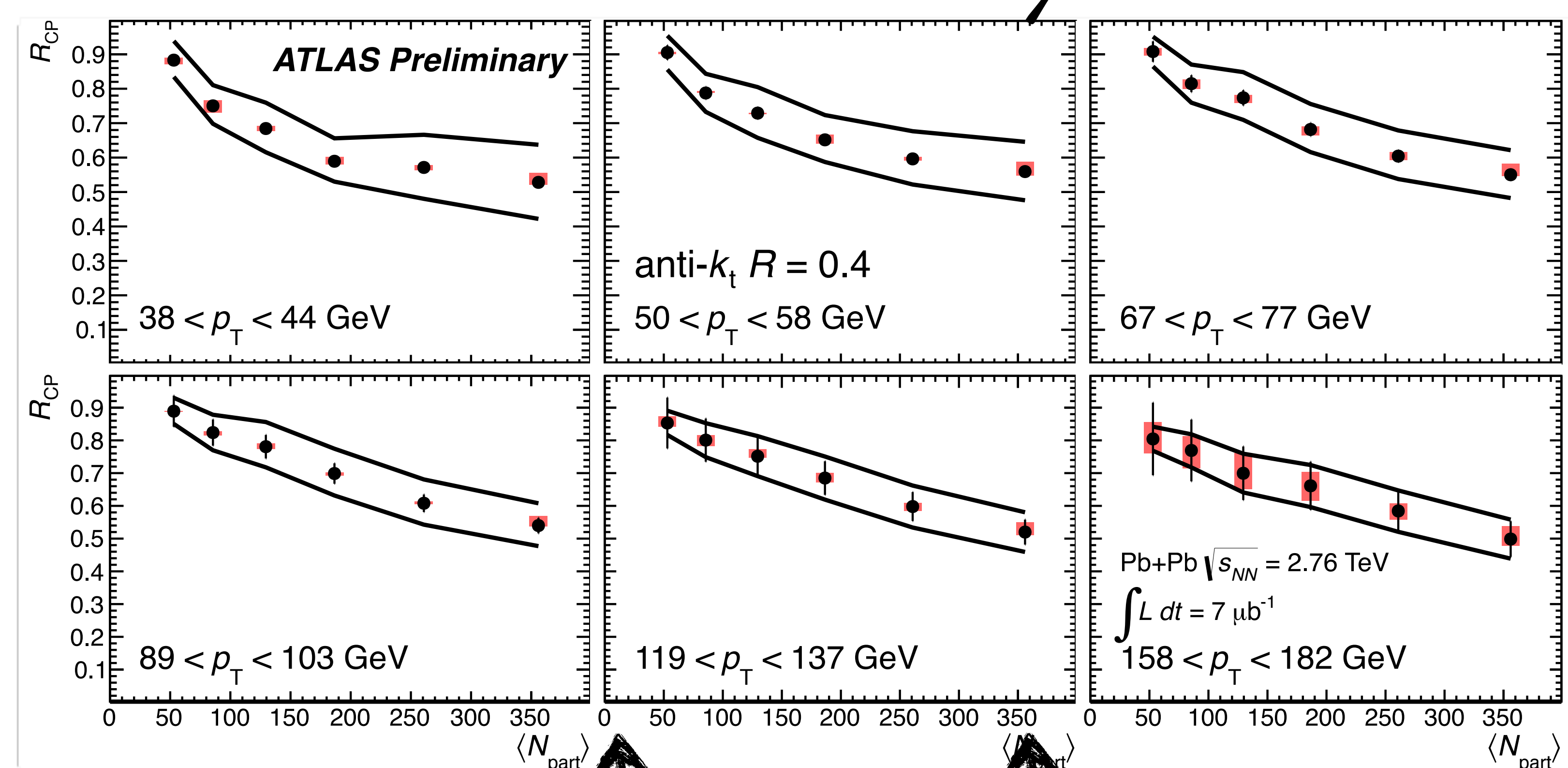
RCP of Jets

Measure single jet suppression with multiple jet sizes

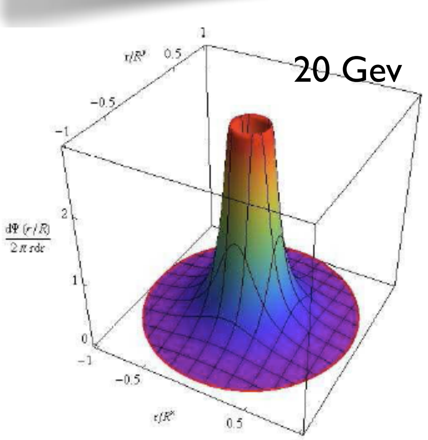
Central events

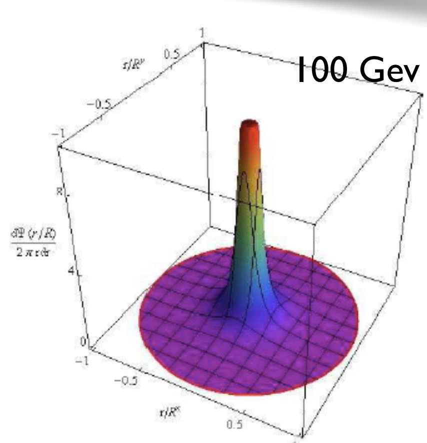


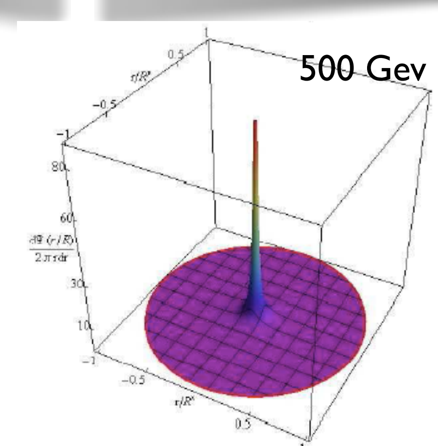
Suppression pattern as a function of centrality



Peripheral Central

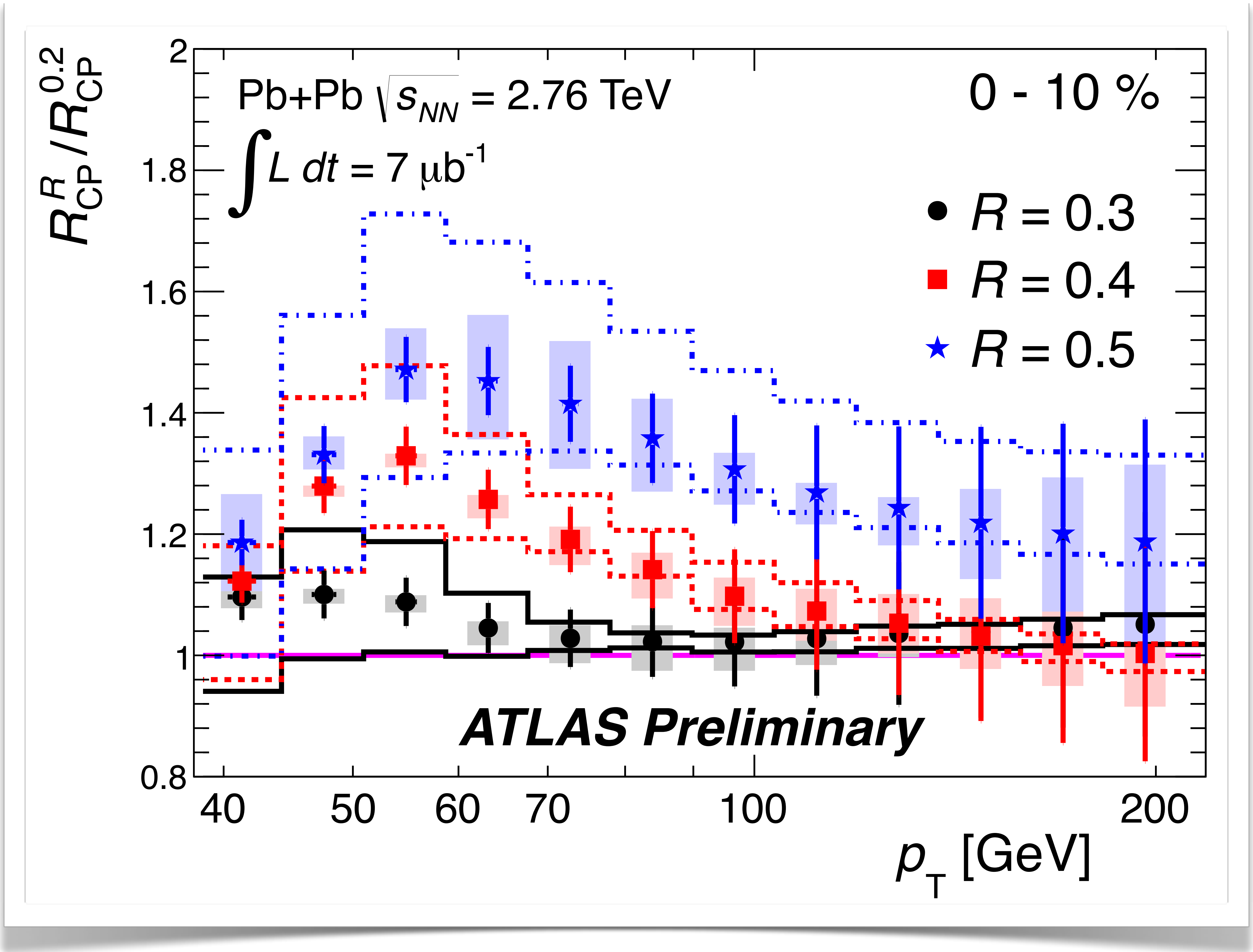




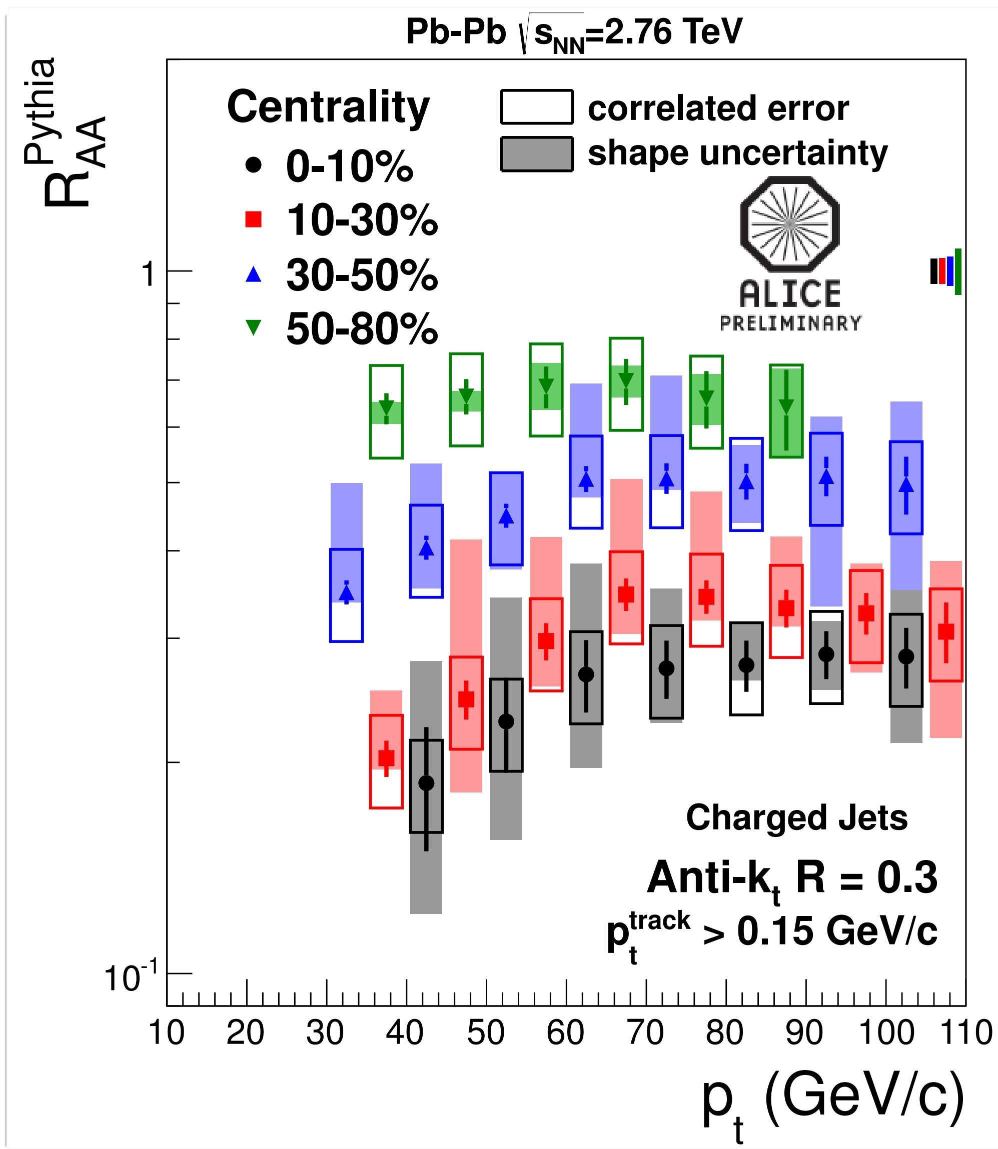


Note: RAA at RHIC also largely below unity...
(see backup)

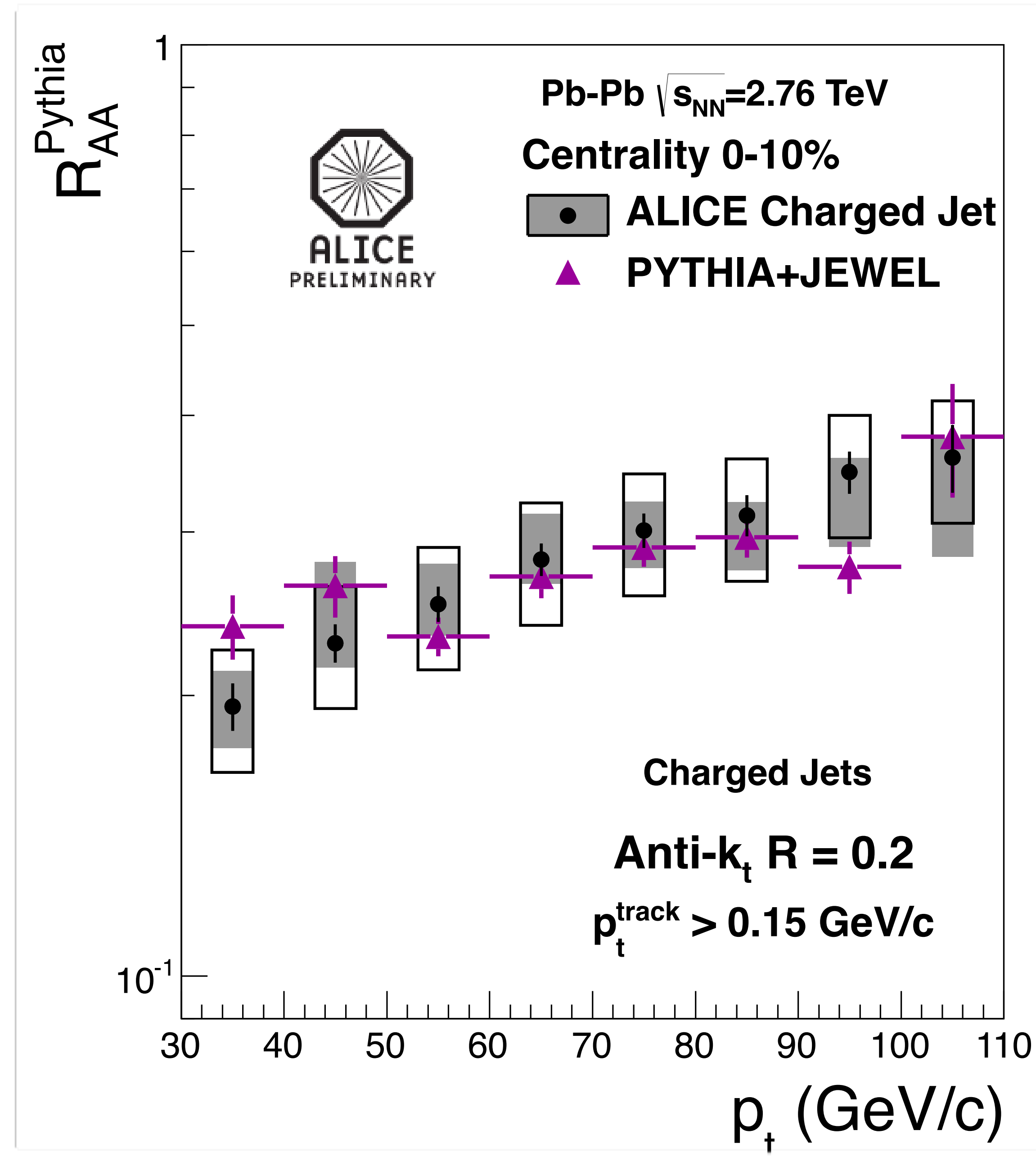
Suppression as a function of R



Jet quenching with charged jets - ALICE

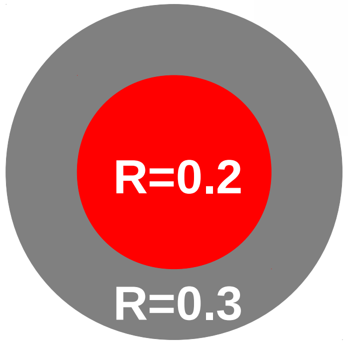


NOTE: Systematically different measurement - same effect found!



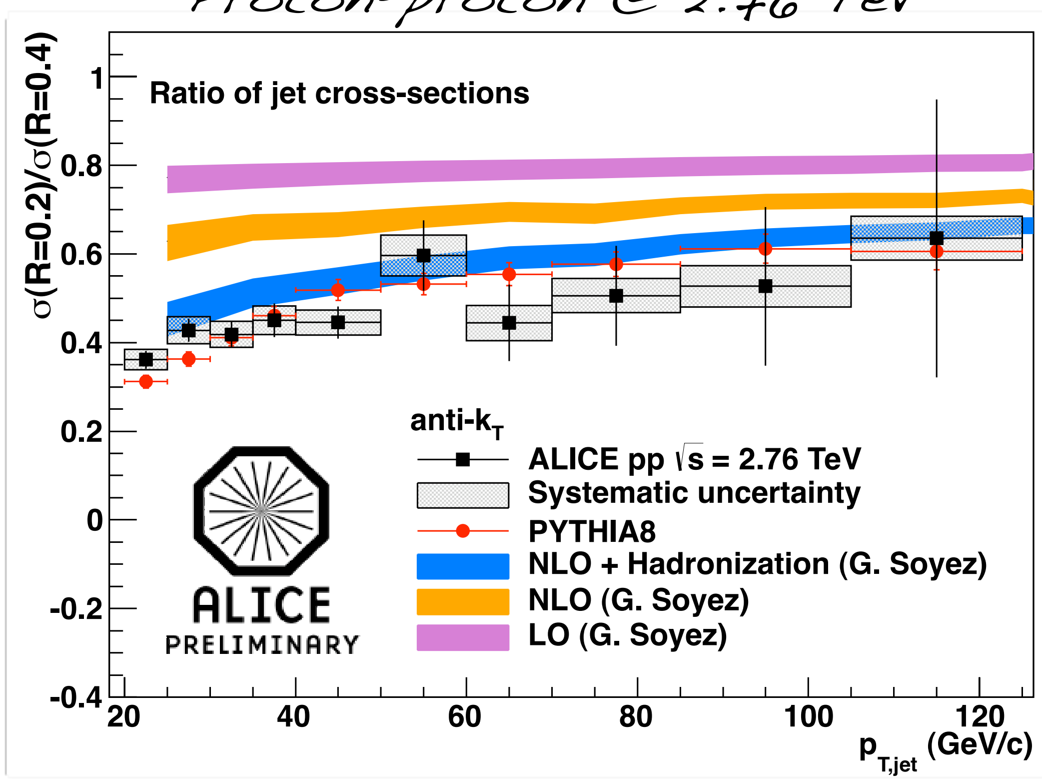
Model tuned on hadron RAA -> reproduces jet RAA

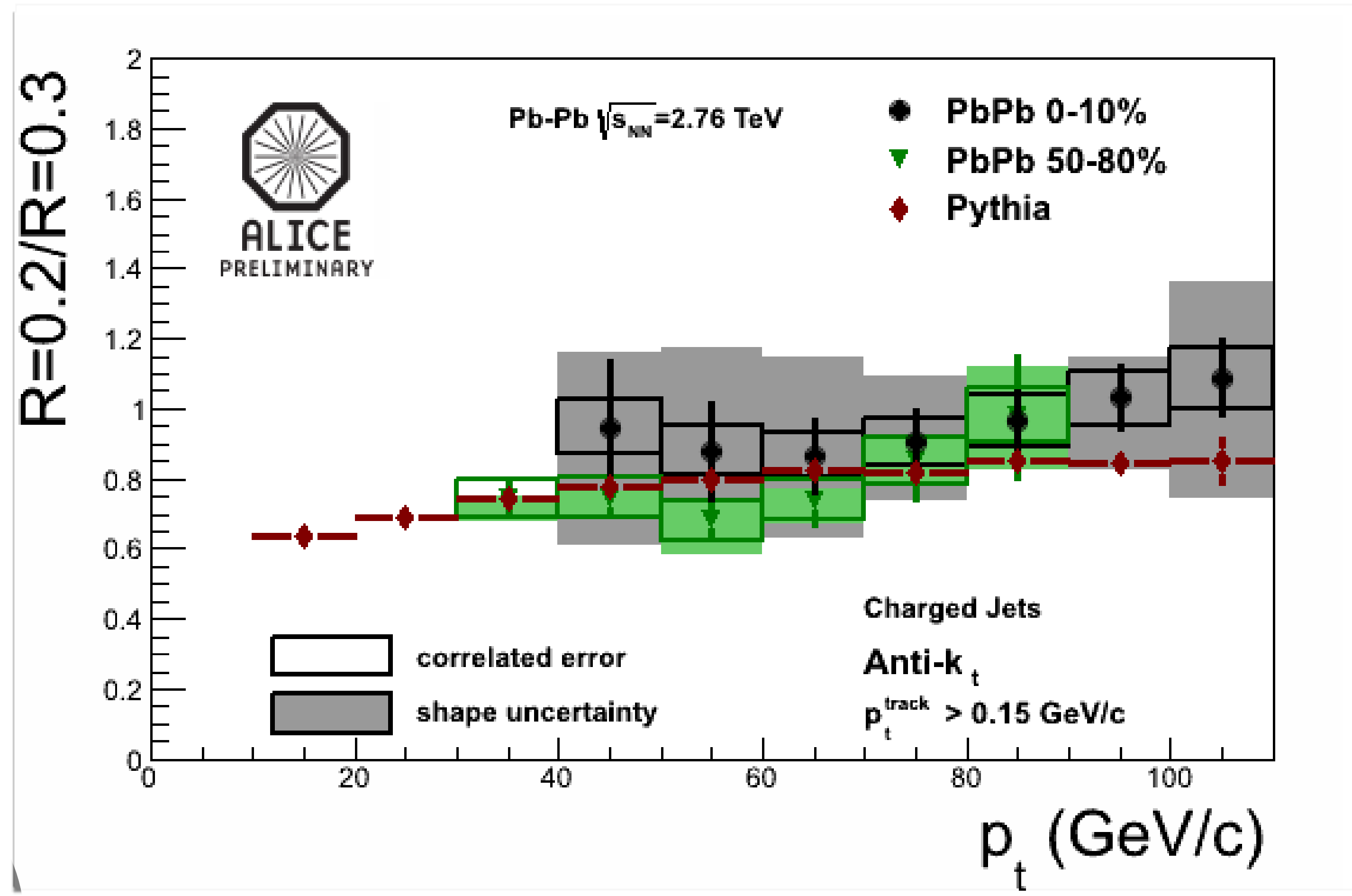
Jet quenching with charged jets - ALICE



Another observable: Ratio of x-sections: R1/R2 where R1<R2

Proton-proton @ 2.76 TeV

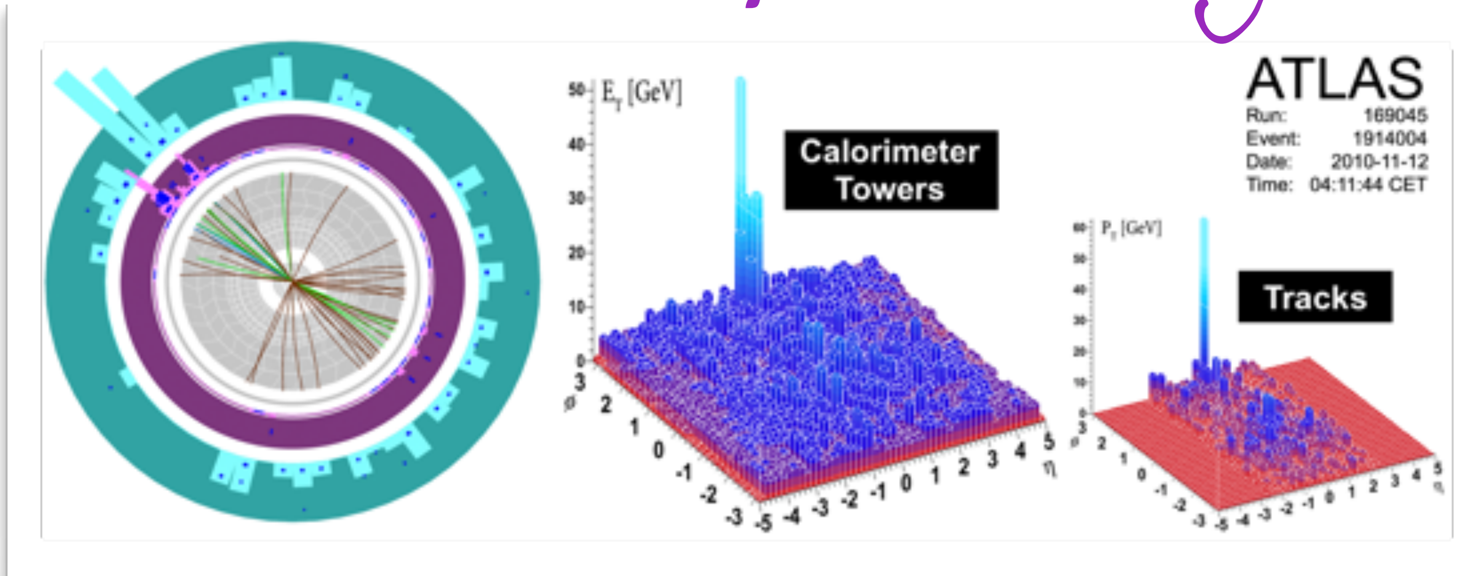




NOTE: Systematically different measurement - same effect found!

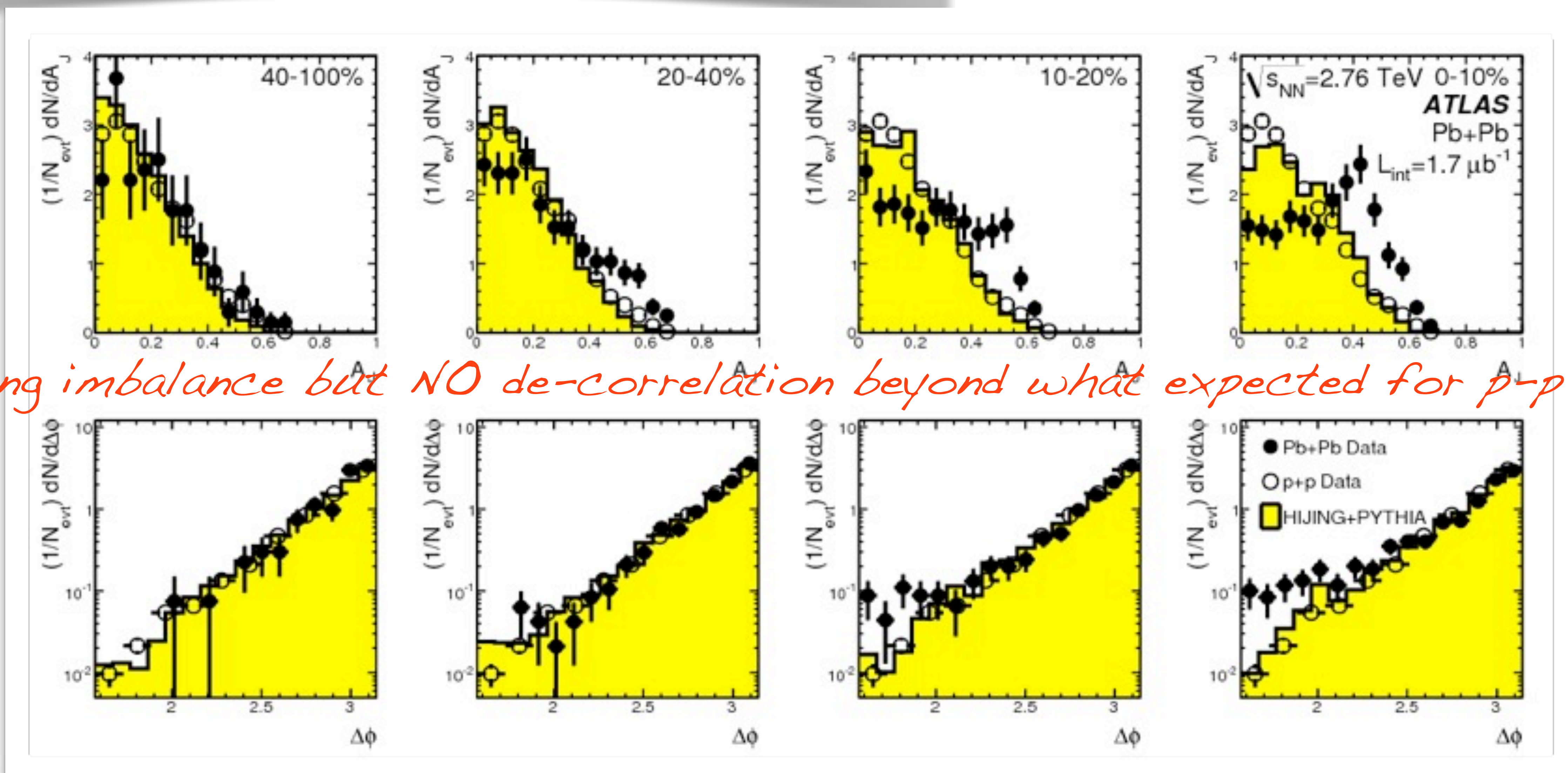
Ratio R=0.2/R=0.3 consistent with vacuum jets for peripheral and central collisions

LHC: Di-jet asymmetry



$$A_J \equiv \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}$$

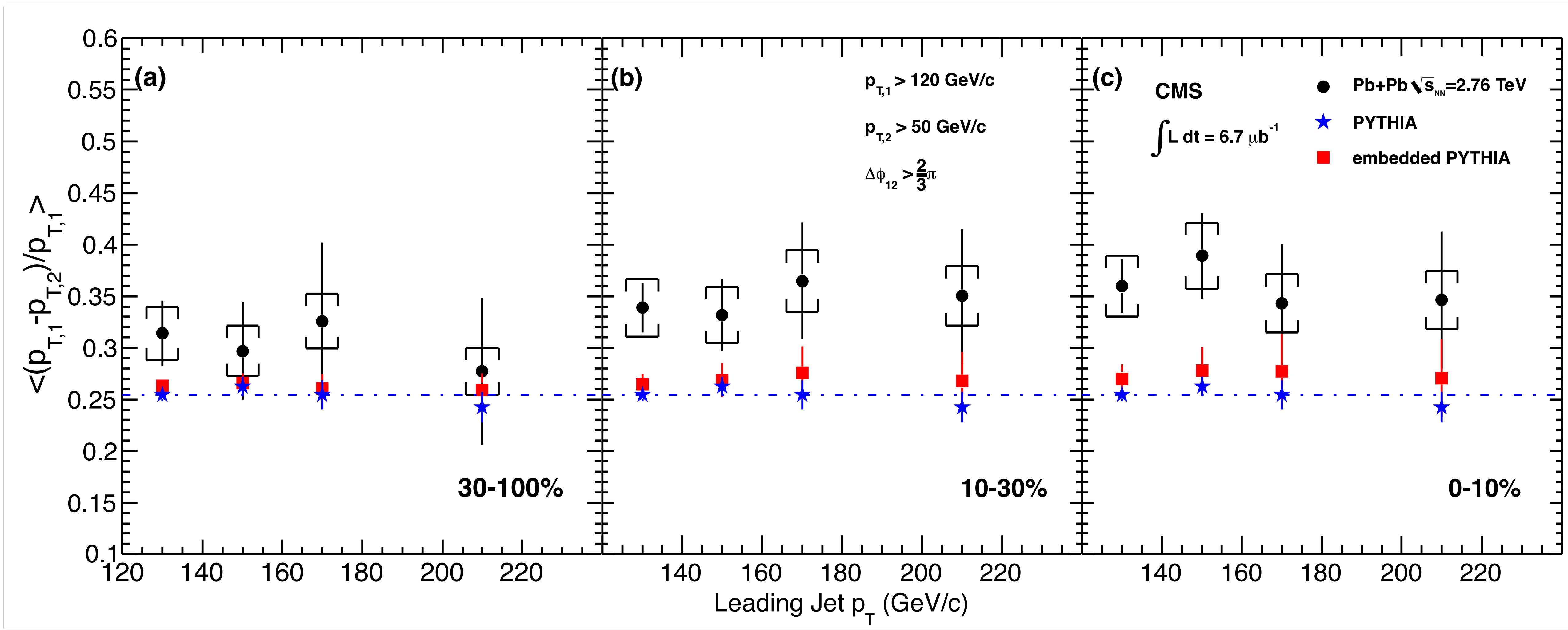
Warning: Aj is sensitive to background fluctuations! Need proper treatment in the data.



Strong imbalance but NO de-correlation beyond what expected for p-p case(!)

Note (backup): No de-correlation also seen at RHIC: PHENIX in Cu+Cu; also remember the 2-hadron correlations...

CMS - quantifying the di-jet asymmetry



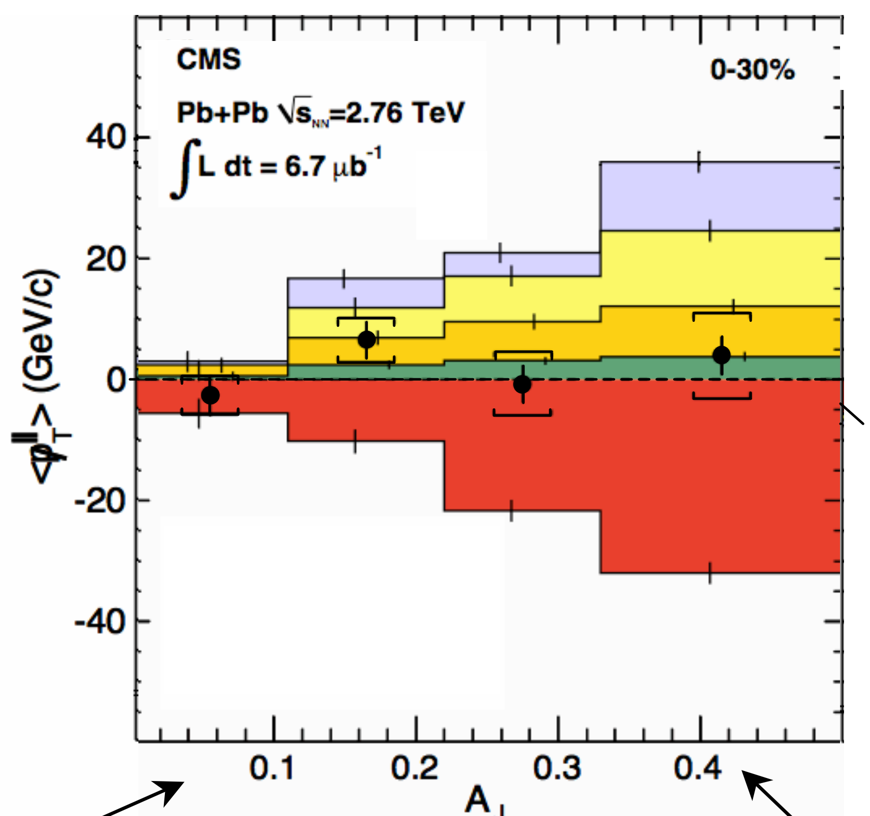
The fractional imbalance:

- grows with collision centrality and reaches a much larger value than in PYTHIA or PYTHIA+DATA
- clearly visible even for the highest-p_T jets observed in the data set
- the $p_{T,1}$ dependence of the excess imbalance is compatible with either a constant difference or a constant fraction of $p_{T,1}$.

di-jet asymmetry: where does the energy go?

Missing $p_T^{||}$: $\not{p}_T^{||} = \sum_{\text{Tracks}} -p_T^{\text{Track}} \cos\left(\phi_{\text{Track}} - \phi_{\text{Leading Jet}}\right)$

0-30% Central PbPb



balanced jets

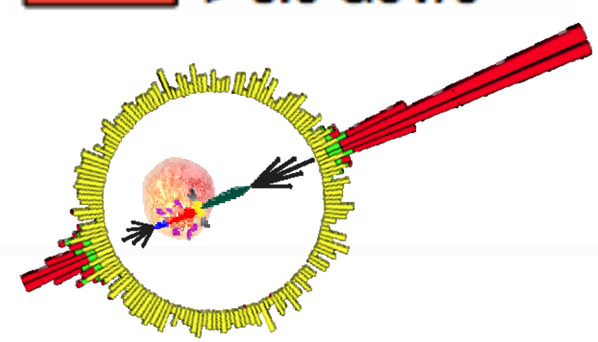
unbalanced jets

excess away from leading jet

excess towards leading jet

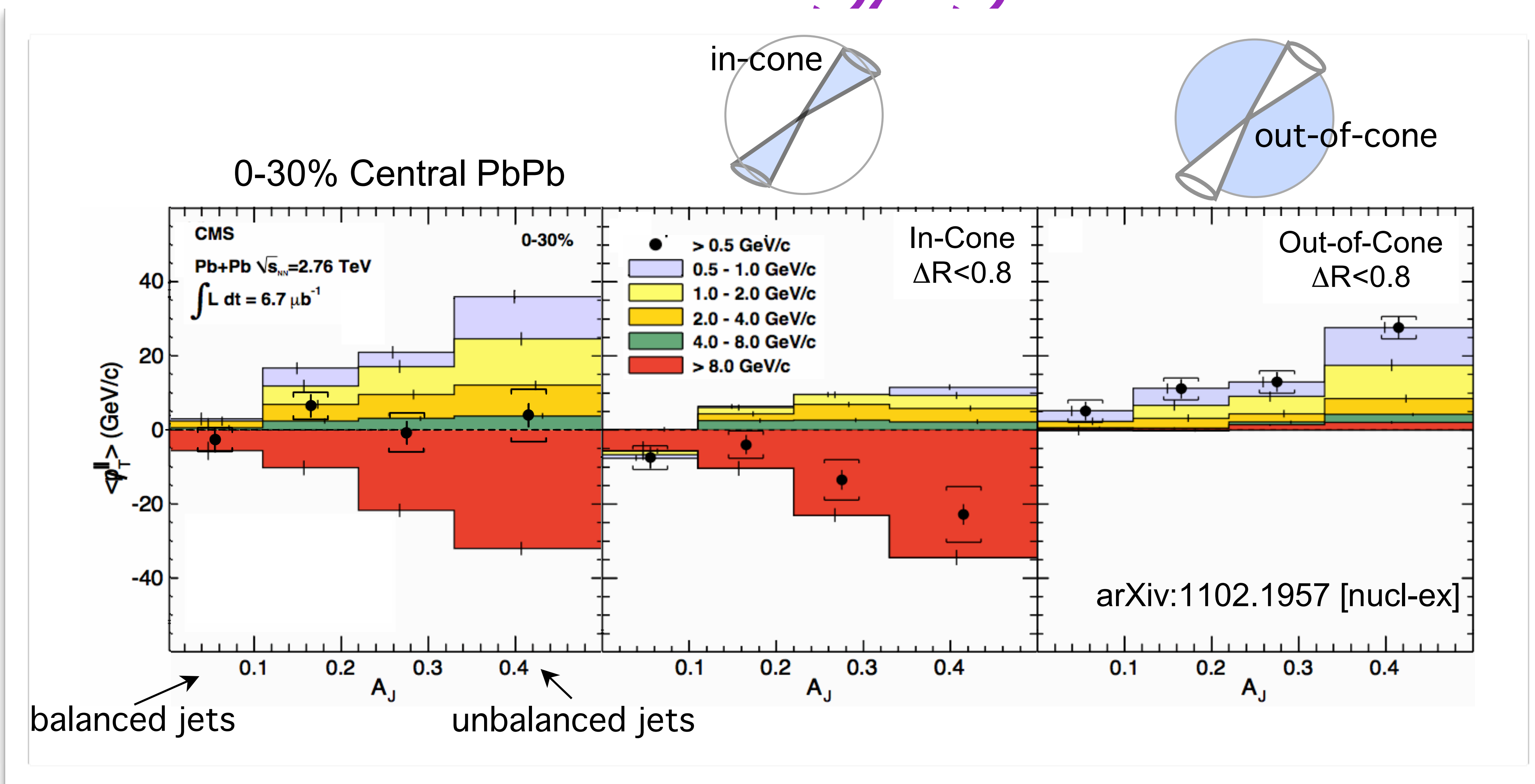
Calculate missing p_T in ranges of track p_T:

- ● > 0.5 GeV/c
- 0.5 - 1.0 GeV/c
- 1.0 - 2.0 GeV/c
- 2.0 - 4.0 GeV/c
- 4.0 - 8.0 GeV/c
- > 8.0 GeV/c

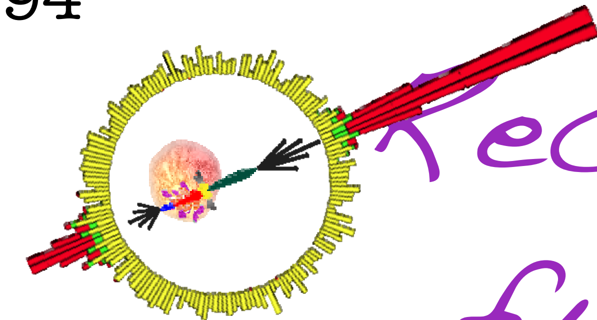


The momentum difference balanced by low-pT particles

di-jet asymmetry: where does the energy go?

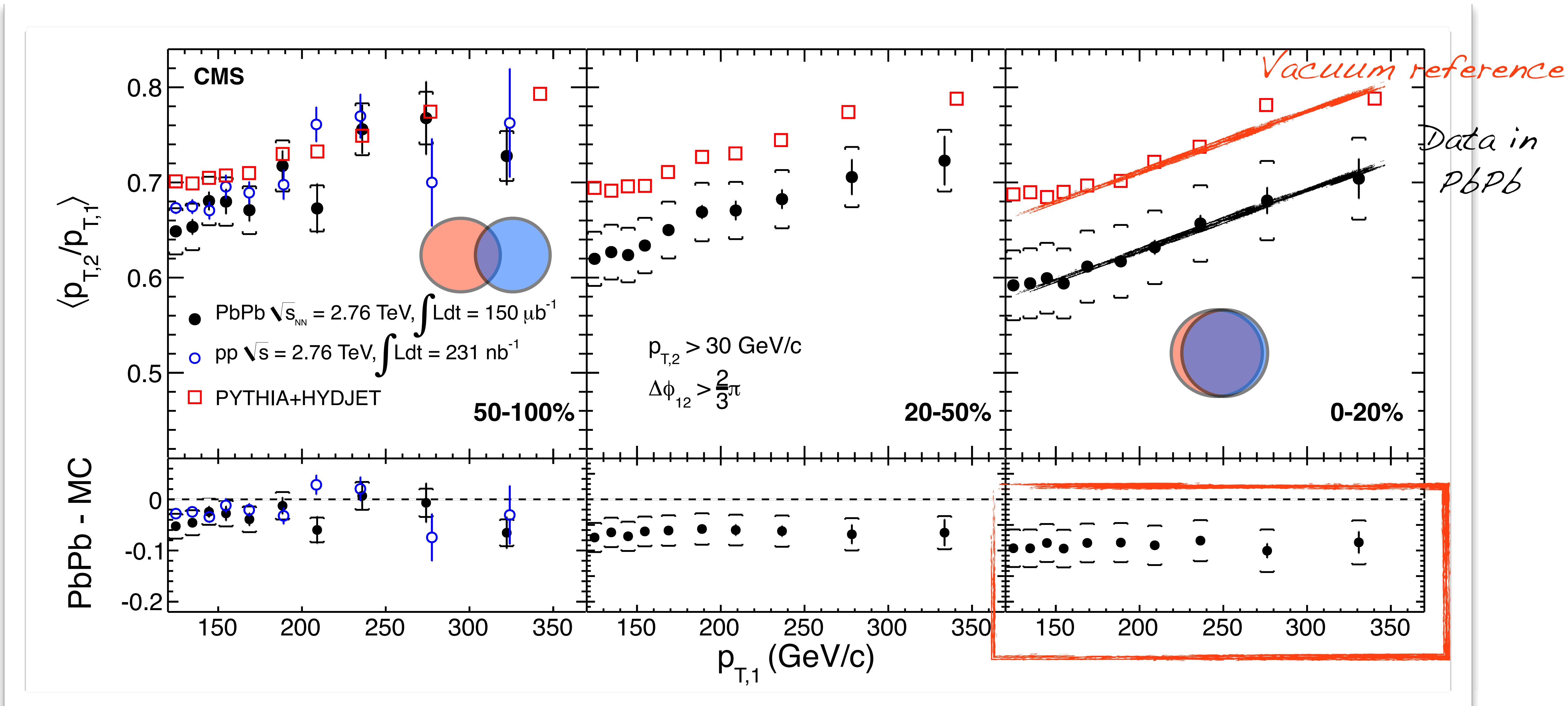


The low-pT particles "balancing" the lost energy appear at large angles wrt recoil jet



$p_{T,2}$ > 30 GeV/c

Recoil jet (2) energy-loss as a function of trigger jet (1) p_T

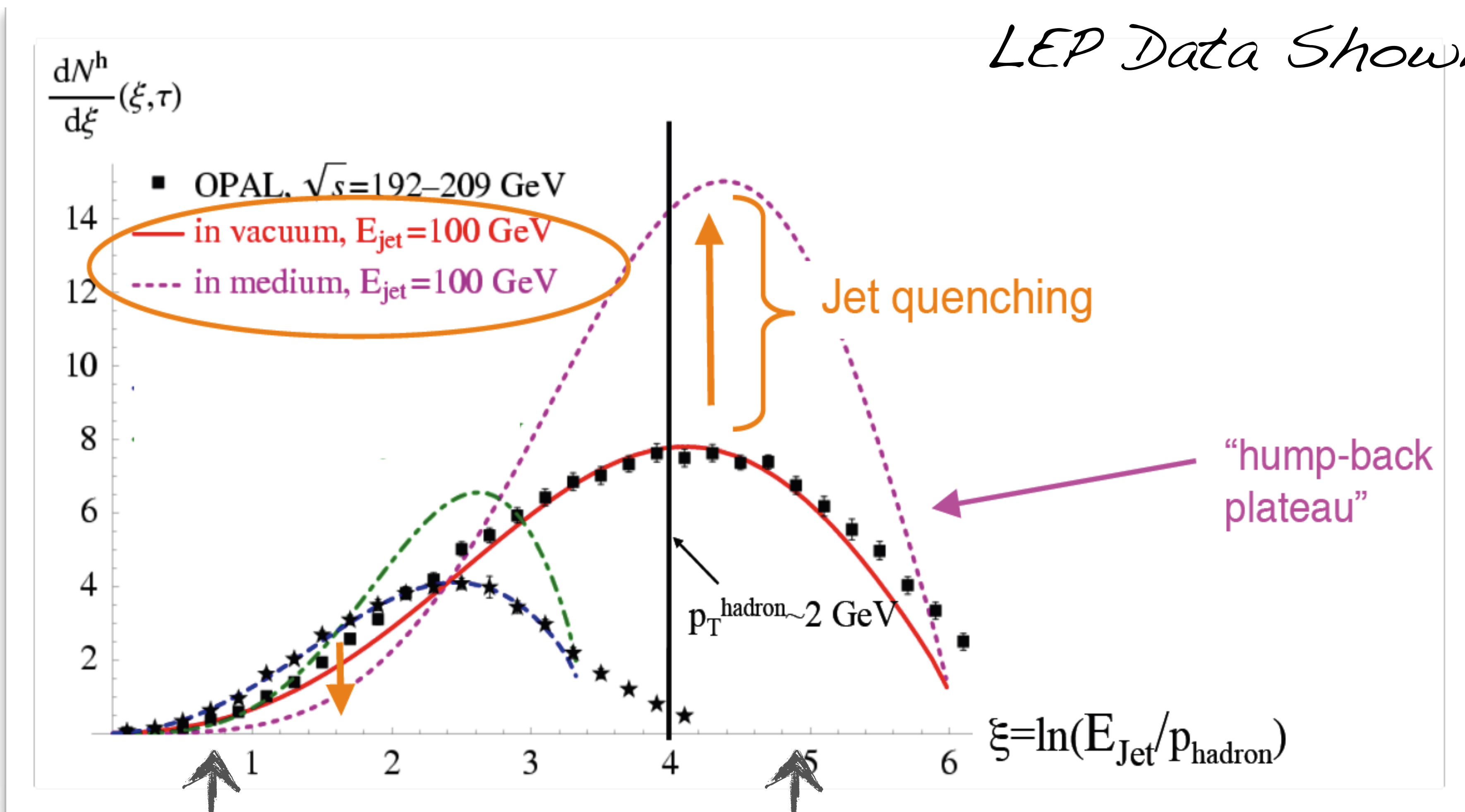


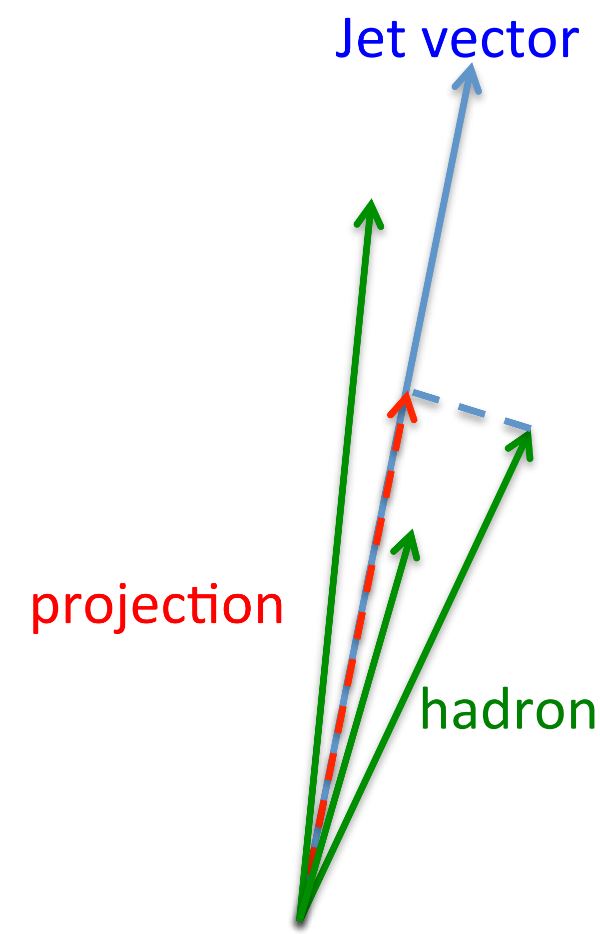
Ratio follows the PYTHIA+HYDJET reference with the same rate - constant offset over 200 GeV in p_T

Modified jet fragmentation – an expectation from jet quenching

$$\xi = ln(E_{jet}/p_{hadron})$$

LEP Data Shown



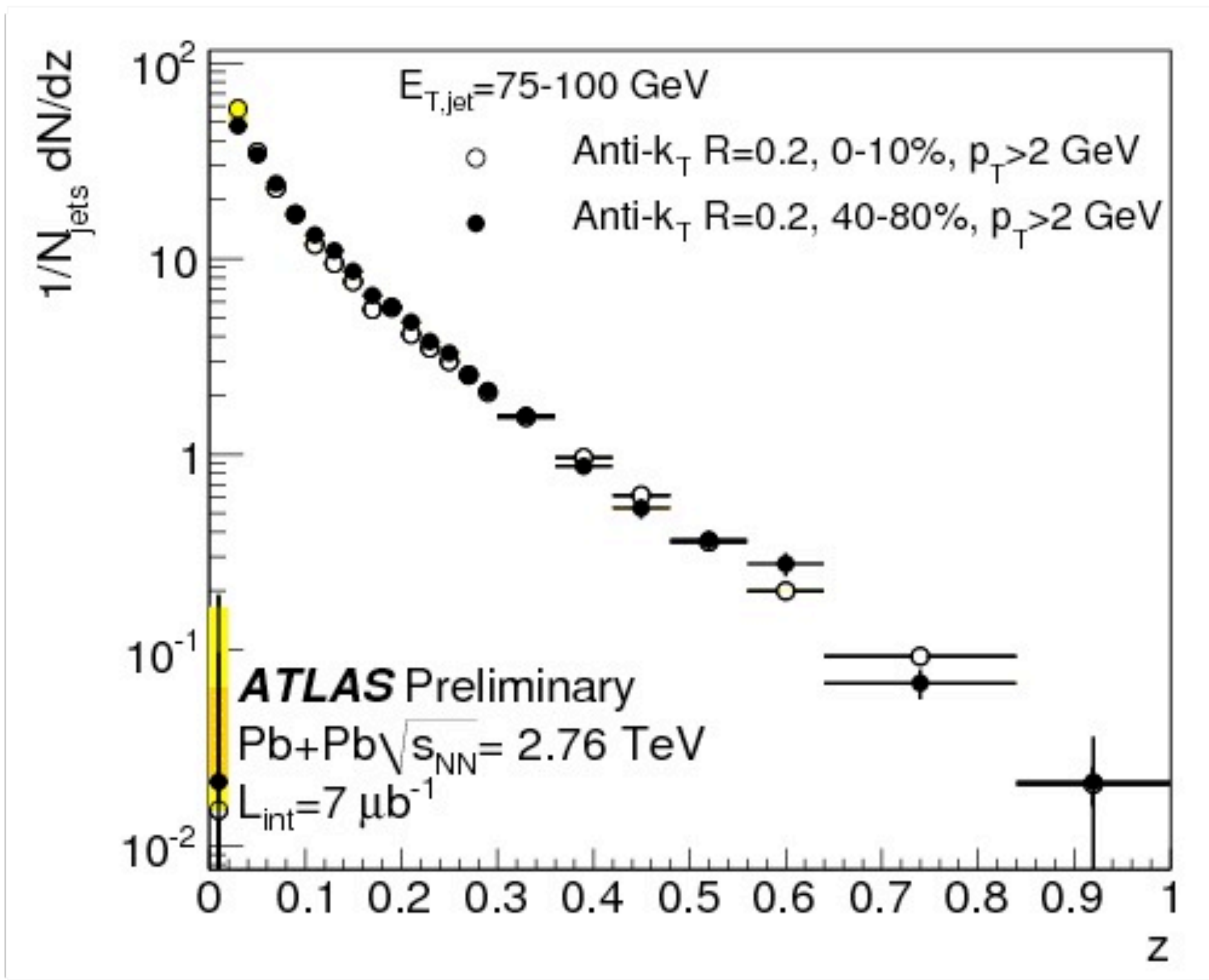


High momentum hadrons

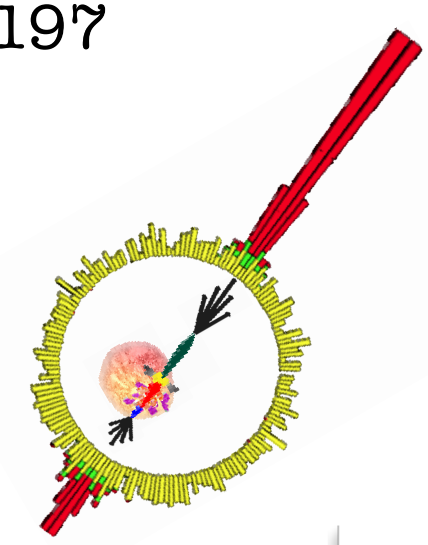
Low momentum hadrons

Measurements: Modification of the jet fragmentation

$z = p_T^{hadron} / p_T^{jet} = 1/\zeta$



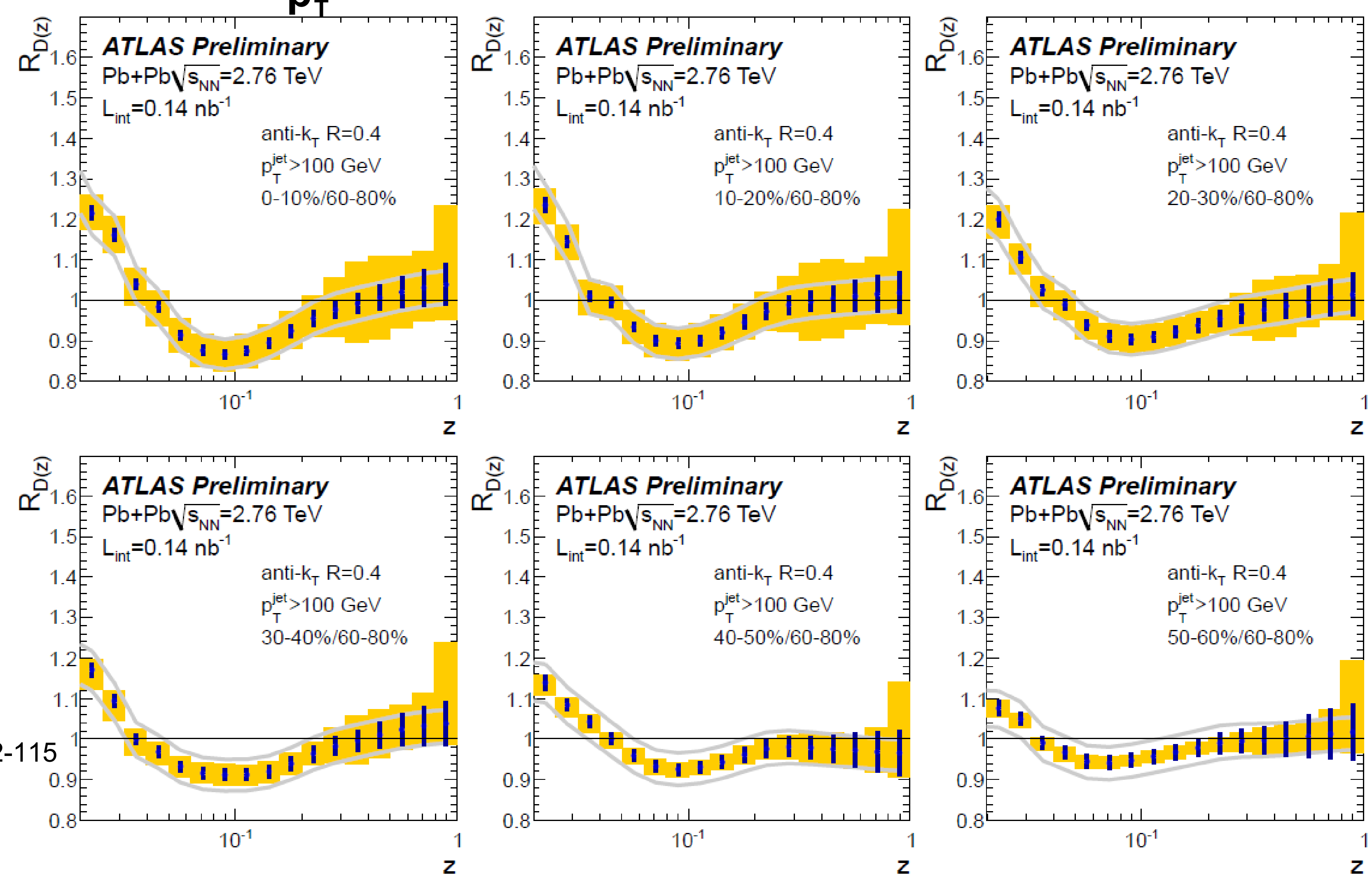
Measure in A-A and compare to proton-proton collisions or peripheral A-A (where no medium effects present)



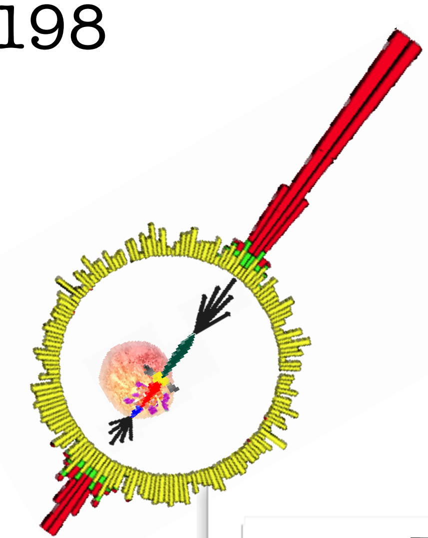
Jet fragmentation in Heavy-ion collisions

$p_T^{had} > 2\,\mathrm{GeV}$ $\quad z \equiv \frac{p_T^{had}}{p_T^{jet}} \cos \Delta R$

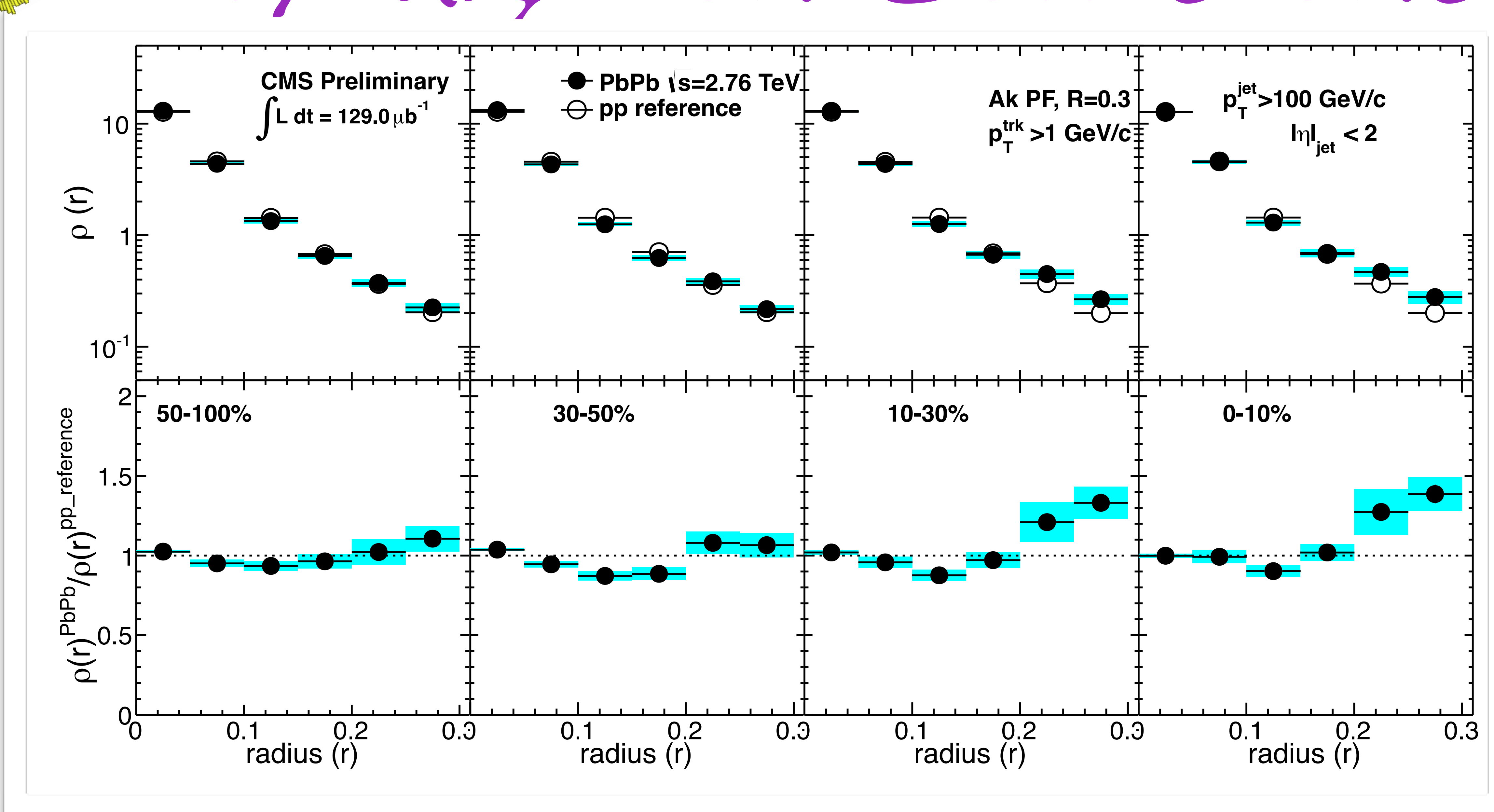
$$R_{D(z)} \equiv D(z)_{cent} / D(z)_{60-80\%}$$



- Enhancement at low z, suppression at z≈0.1
- No modification at high z
- Similar results found for R=0.2 and 0.3 jets



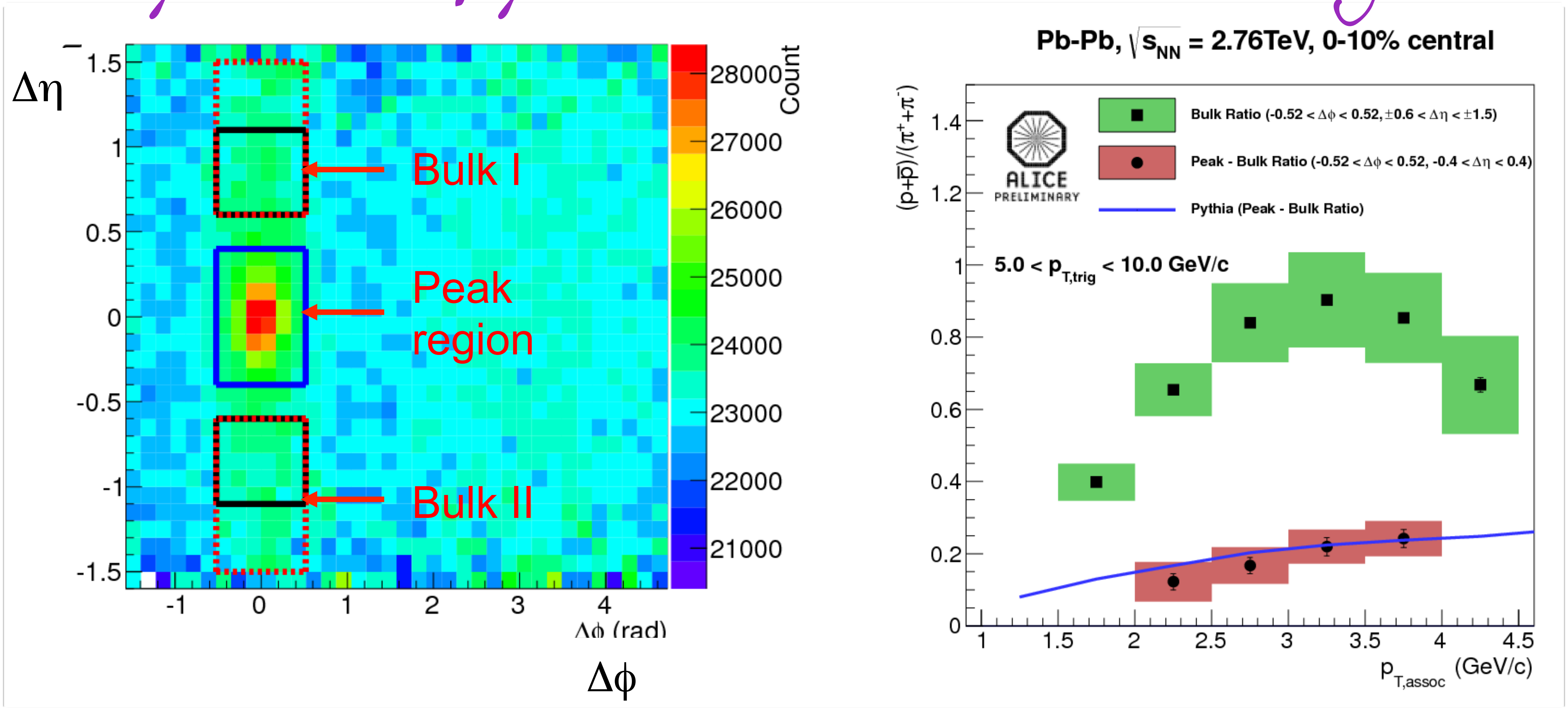
Jet fragmentation in Heavy-ion collisions



CMS jet shape: rho - differential energy density within the jet - here shown as a function of r - distance to the jet axis

Non trivial (monotonous) energy redistribution due to quenching; rigid core

Internal composition of HI jets: proton/pion ratio within a jet



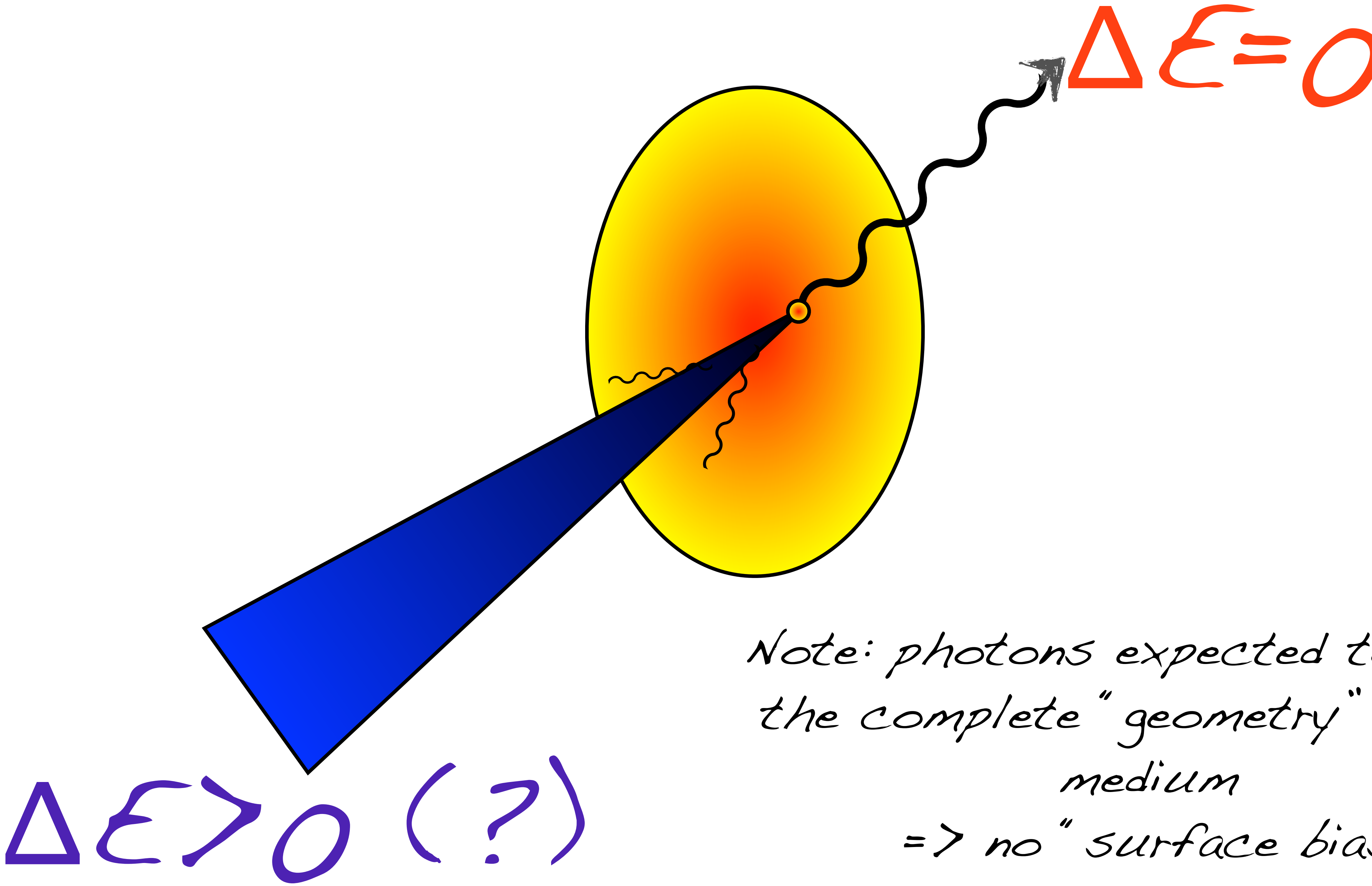
p/π in jet peak (fragmentation) consistent with PYTHIA

- No evidence of medium-induced modification
- Caution: physics evolves rapidly with pT in this region

p_{Ttrig} :=> fragmentation bias

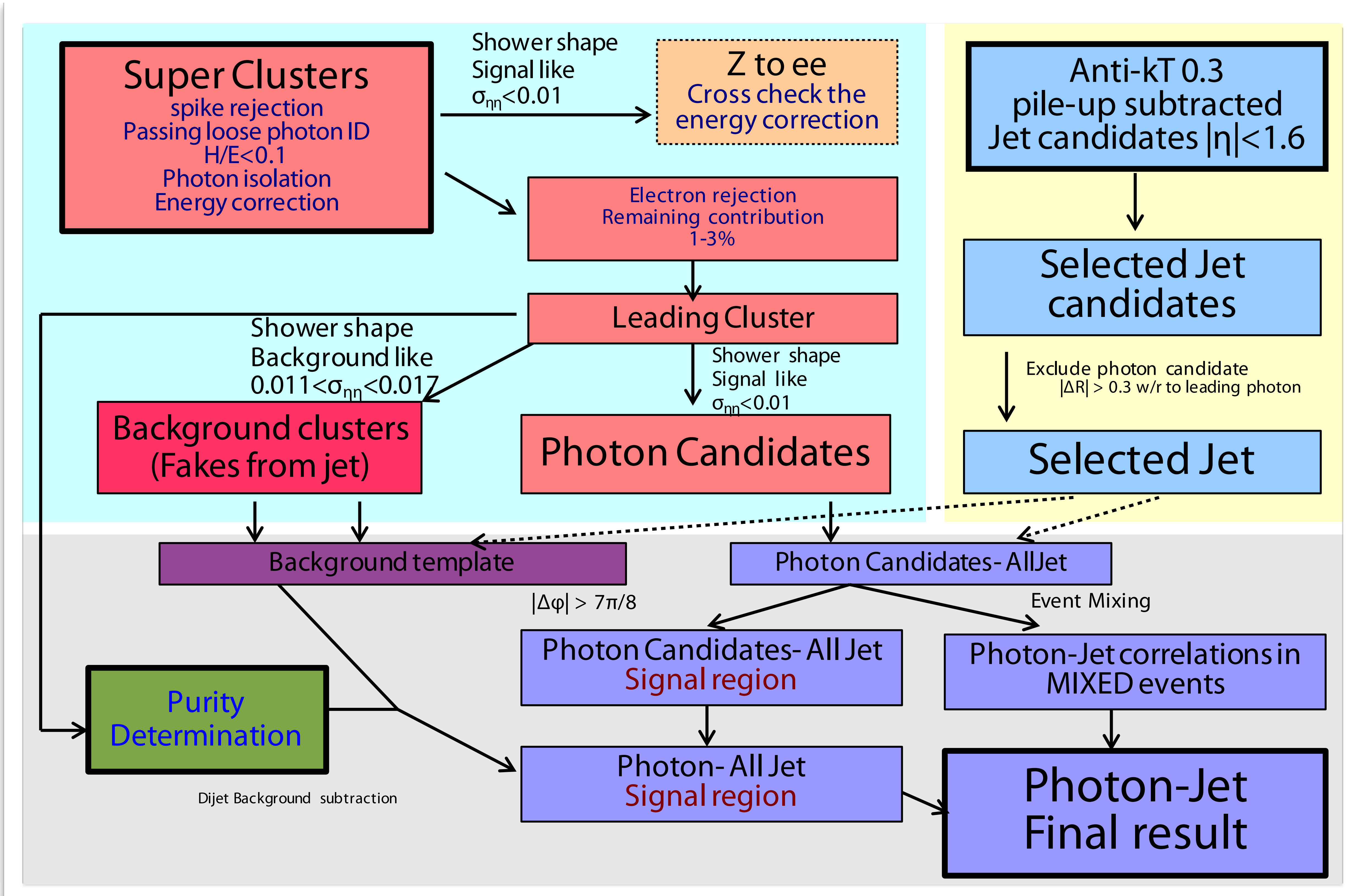
Note: consistent with RAA at high-pT - similar to all species (RHIC&LHC)

Photon-jet



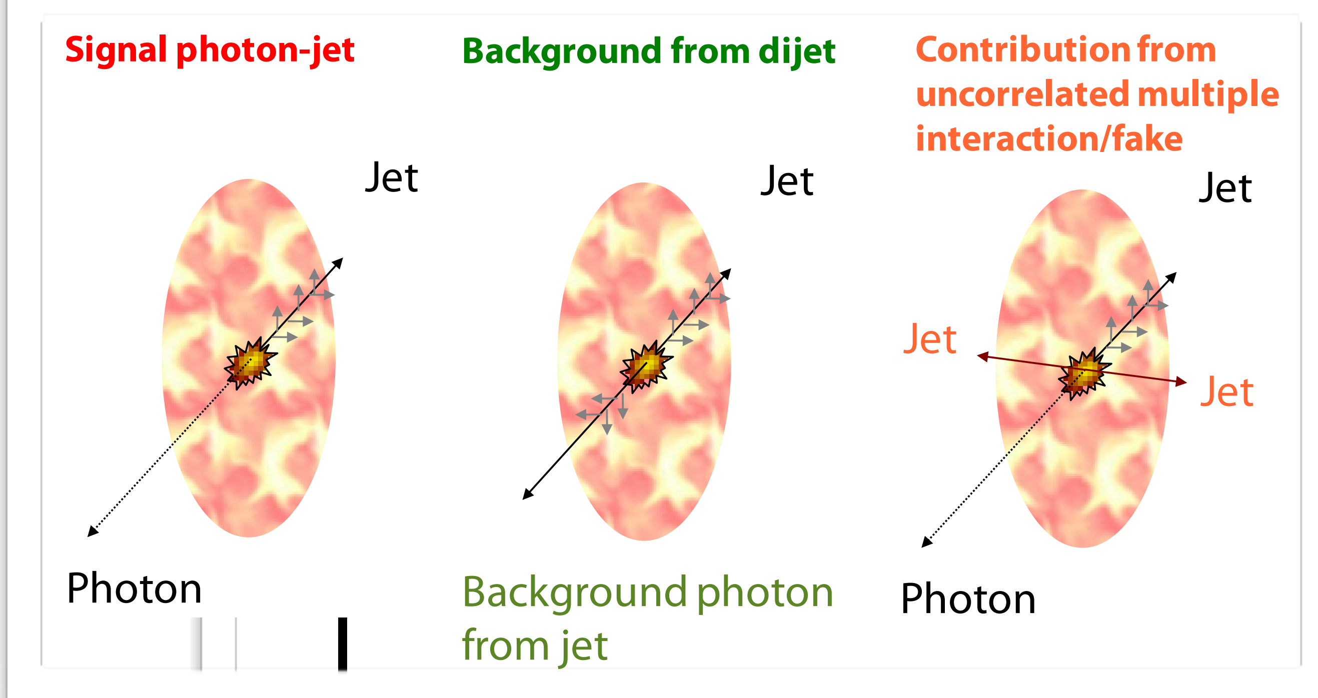
Note: photons expected to probe the complete "geometry" of the medium
=> no "surface bias"

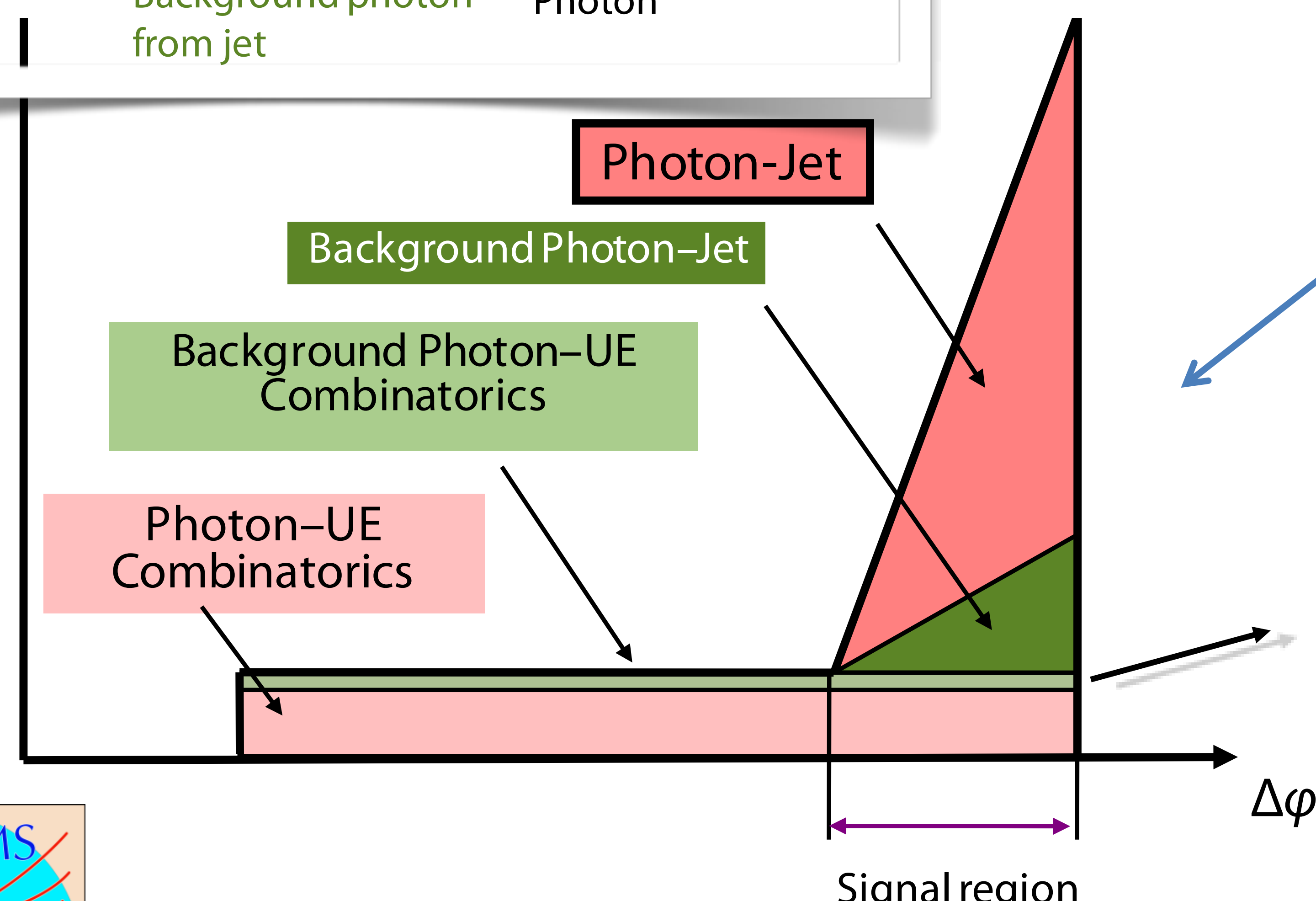
Direct photon(-jet) measurement

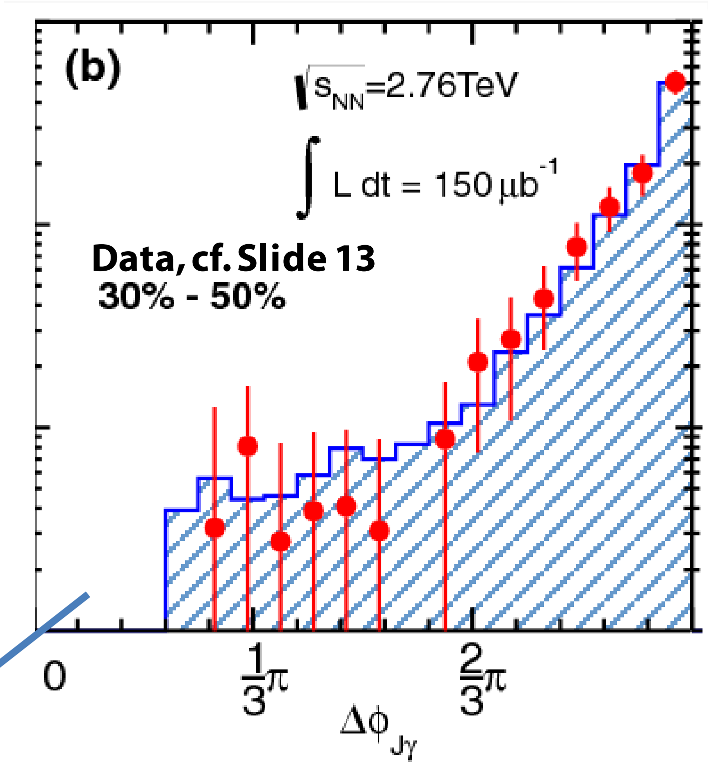


An experimental chart... of the effort(!)

Direct photon(-jet) measurement

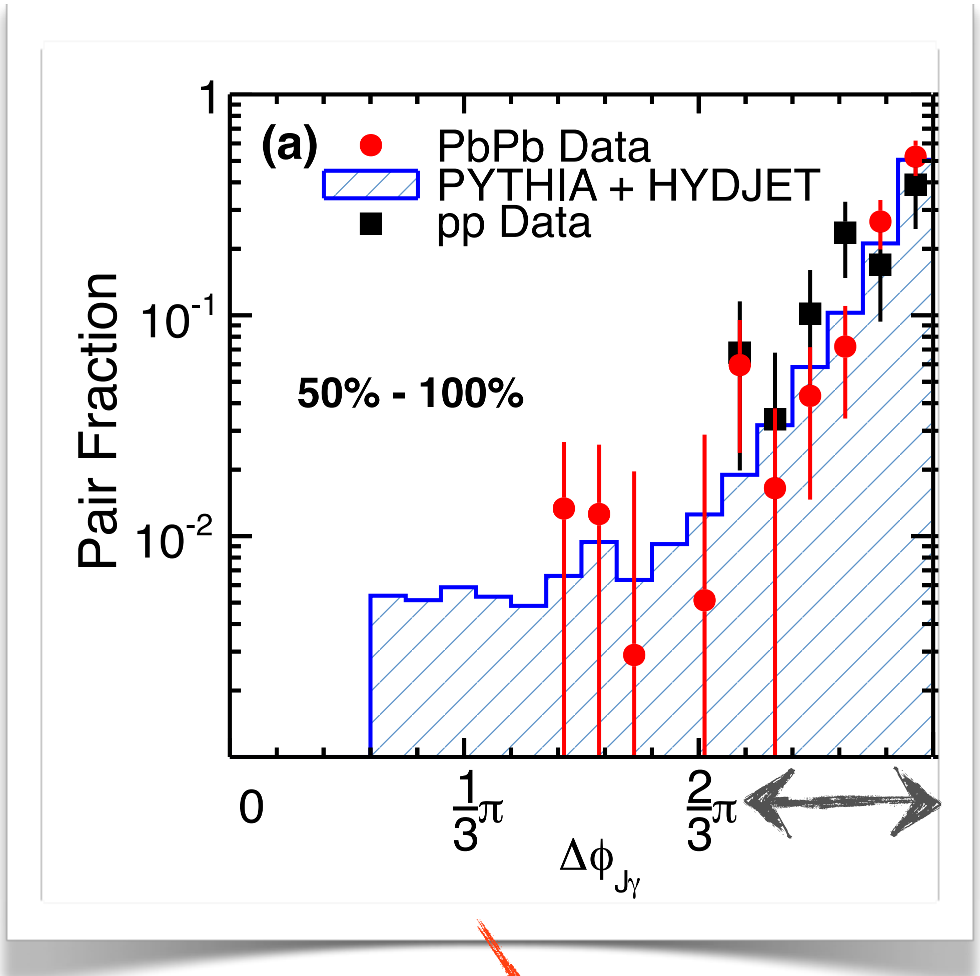


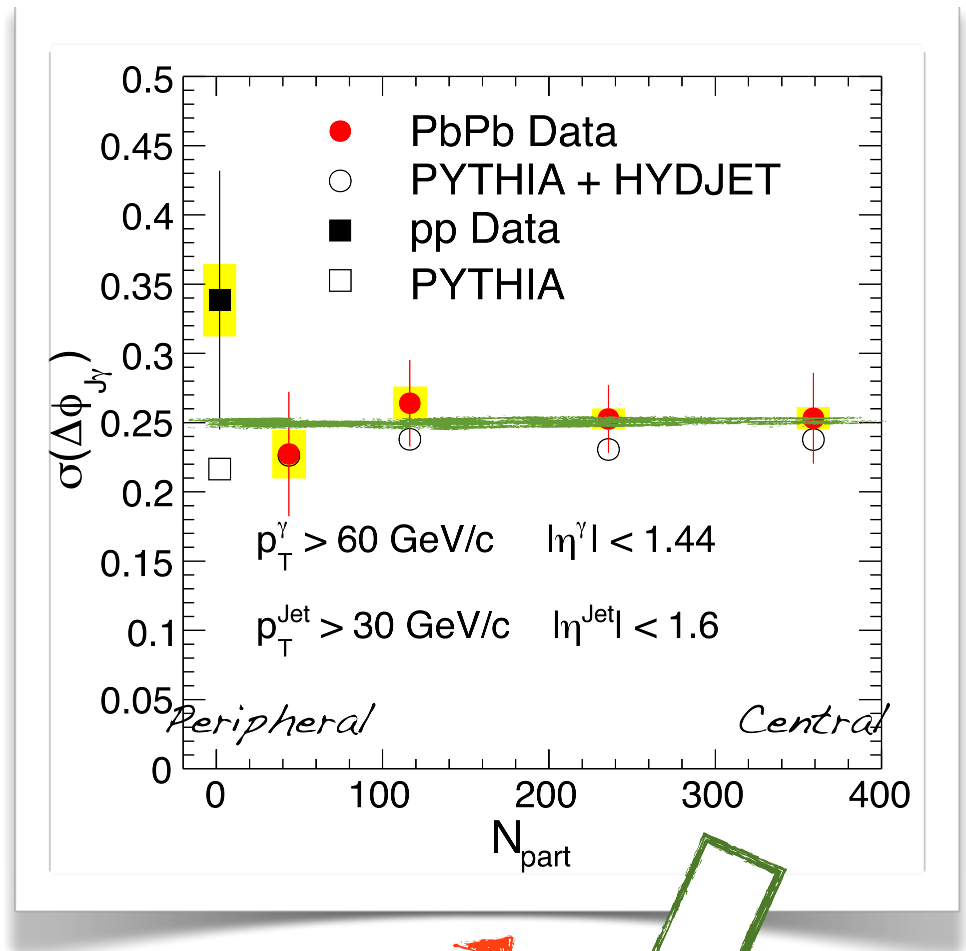




Estimated from event mixing method using minimum-bias data

Result: Photon(ΔE=0)-jet(ΔE>0)





Fit $\frac{1}{N_{J\gamma}}\frac{dN_{J\gamma}}{d\Delta\phi_{J\gamma}} = \frac{e^{(\Delta\phi-\pi)/\sigma}}{(1-e^{-\pi/\sigma})\,\sigma}$

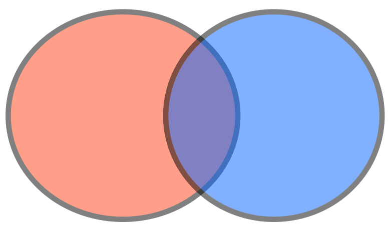
Range: $\Delta\phi > 2\pi/3$

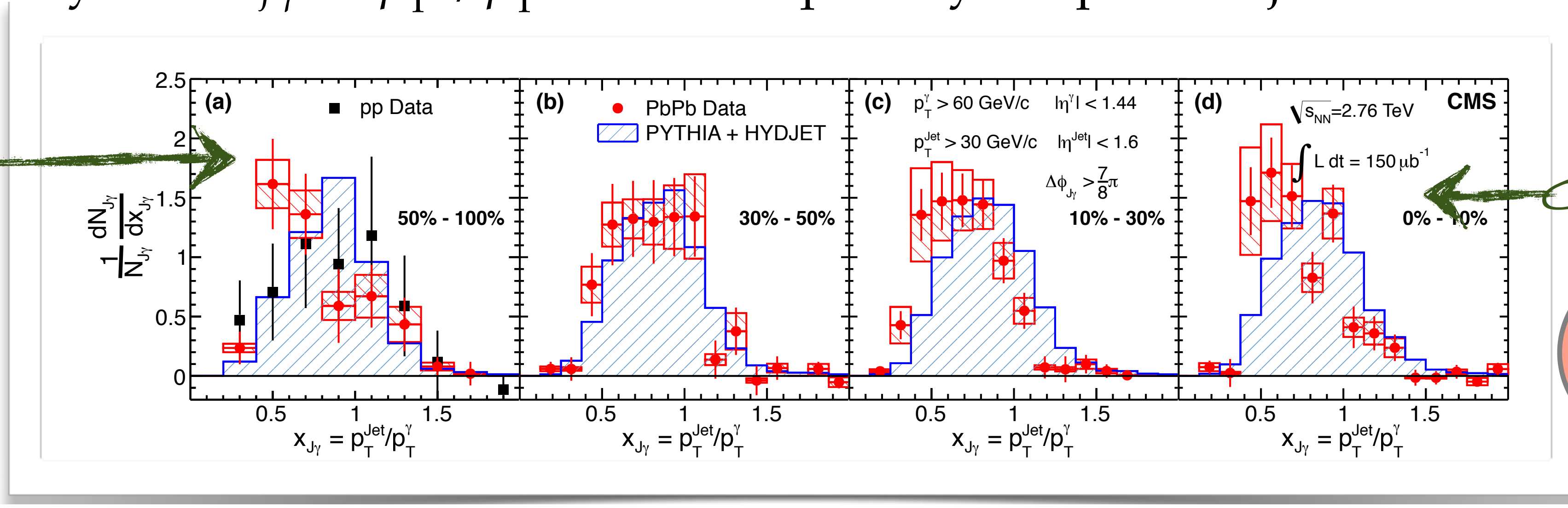
"Width" consistent with vacuum

Photon$_{(\Delta E=0)}$-jet$_{(\Delta E>0)}$

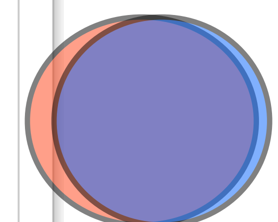
The asymmetry ratio $x_{J\gamma} = p_T^{\text{Jet}} / p_T^{\gamma}$ is used to quantify the photon+jet momentum imbalance.

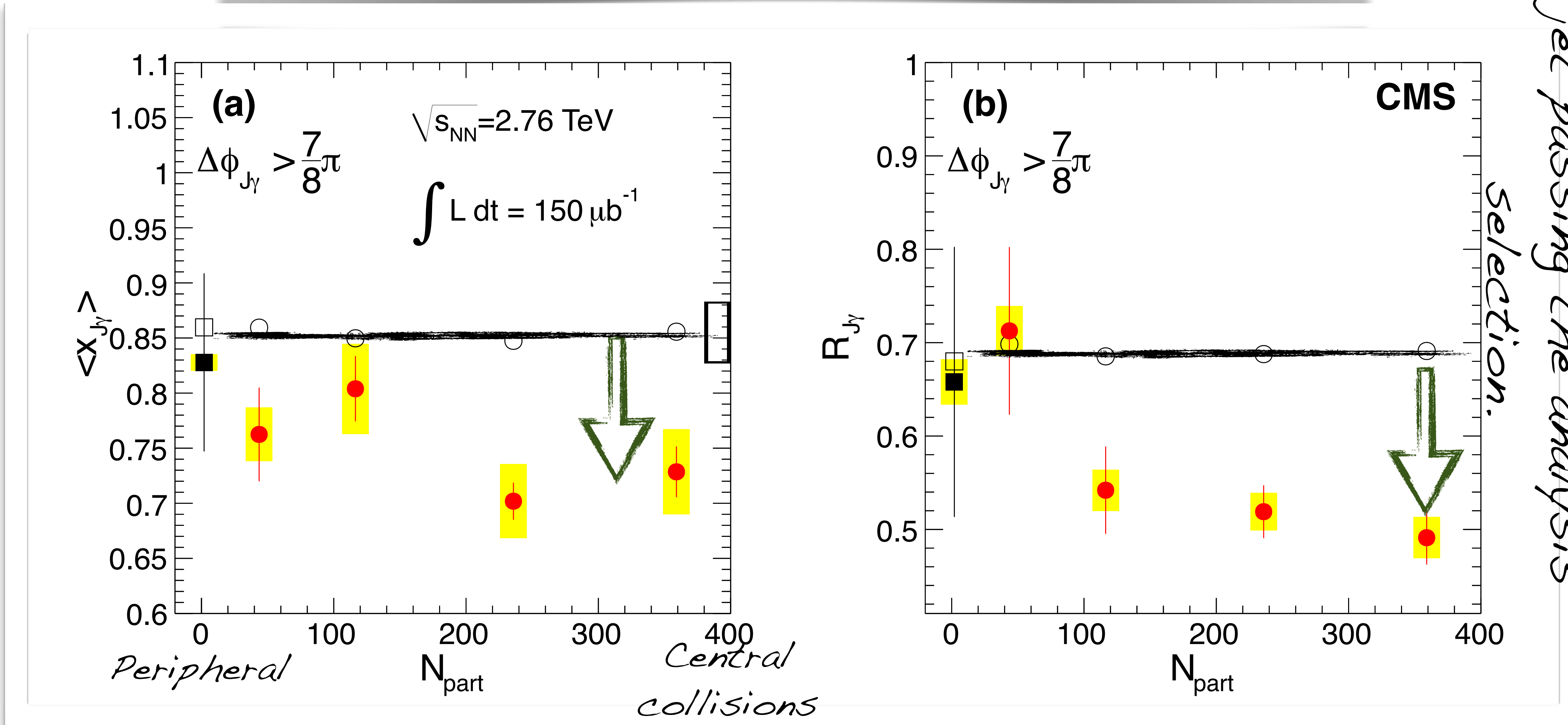
peripheral events





central events



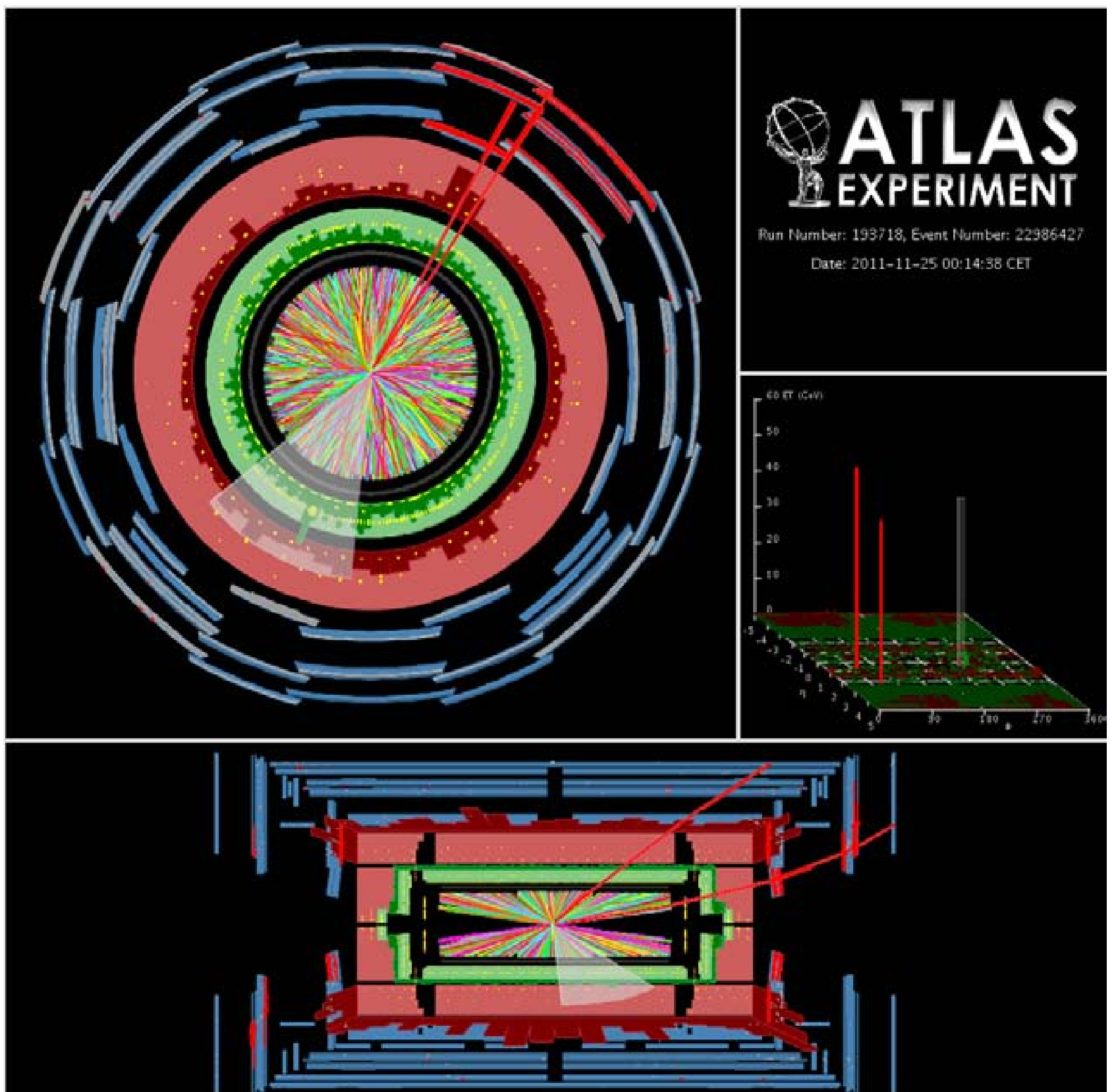


$R_{J\gamma}$ - the fraction of isolated photons that have an associated jet passing the analysis selection.

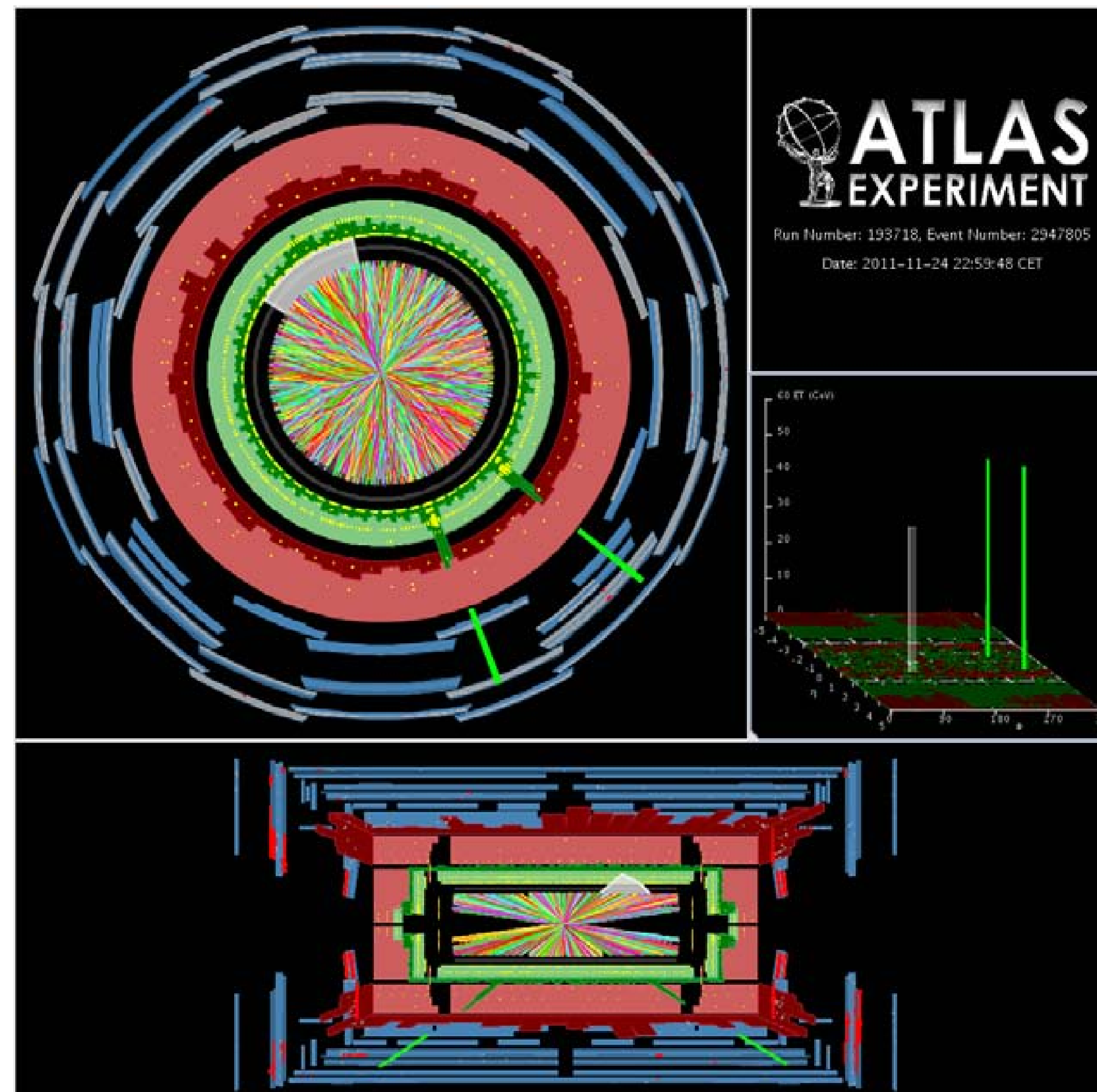
Even better? z-jet!

LHC... yet again: an amazing machine...

$Z(\to \mu^+\mu^-)$ - jet



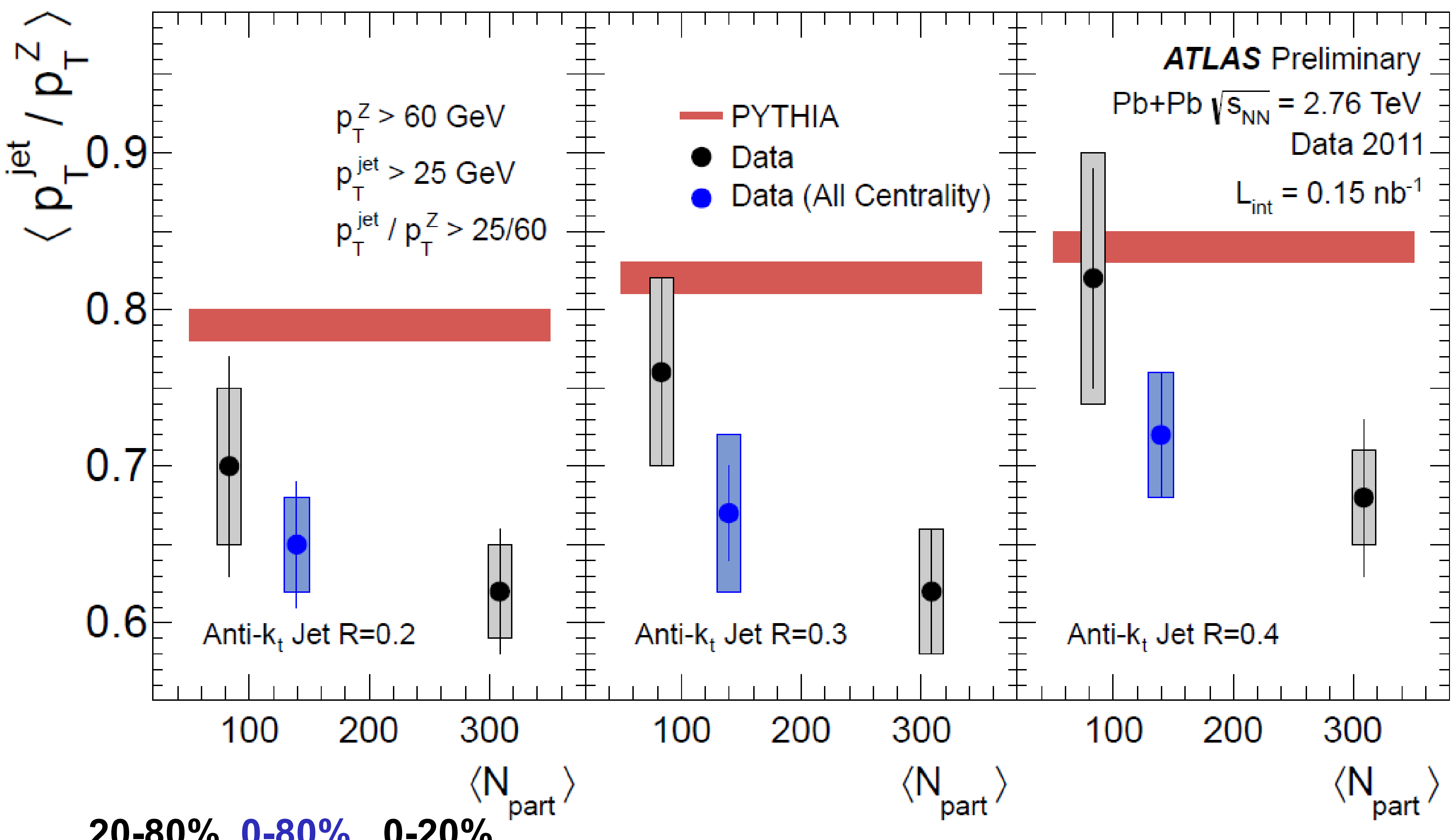
$Z(\to e^+e^-)$ - jet



Even better? z-jet!

LHC... yet again: an amazing machine...

- $Z \to e^+e^-, \mu^+\mu^-$ $p_T > 60$ GeV
- Jet: anti-kT, R=0.2, 0.3, 0.4, p_T>25 GeV, $|\eta|$<2.1
- Z-jet separation > $\pi/2$ $\to$ 37 events for L_{int}=0.15 nb^{-1}



$\langle p_T^{jet} / p_T^Z \rangle$

- Suppression of the $\langle p_T^{jet} / p_T^Z \rangle$ relative to MC simulations with no energy loss (PYTHIA: Z+jet events)
- Stronger suppression for more central collisions

Summa summarum

- High energy heavy-ion collisions: Hot and dense (opaque to high-energy partons) quark-gluon plasma
- Hadron spectra suppressed (both at RHIC and LHC); Correlations of hadrons (proxies for 2->2 jet process) consistent with jet quenching
- Fully reconstructed jets suppressed (pT dependence of the suppression pattern different than for hadrons) -> constant fractional energy loss (?) -> up to highest jet energies measured (RHIC & LHC)
- The observed jets consistent modified fragmentation (subtle effect!); The radiated energy "recovered" at large angles wrt jet axis
  - At high-pT: No indication for particle type composition (p/pion etc) modifications of high-pT jets
  - Similar to jet-jet, the photon-jet correlations do NOT show de-correlation beyond p-p case (recoil jet also with unmodified fragmentation)
- Models explaining the phenomena being put forward.

Check the extra slides for more... RHIC jet results and examples of other observables (correlations) from LHC...

Do we understand everything about jet quenching and what fully reconstructed jet observables tell us?
NO! But we learned already a lot... and this is just a good beginning!

Instead of of a summary...

- HI collisions at high-energies allow to study hot and dense, [nearly] perfect liquid plasma of quarks and gluons - opaque, attenuating high-energy partons - inducing jet modifications
- Unique studies of fundamental properties of QCD!

Always good to ask: What is next?

- Improved control of the jet reconstruction in HIC - still improvements possible (less biases, other observables) - conceptually different approaches in making...
    - New observables? Hadron-jet etc; Rates for 2+1+1 events? Structure of the jet with improved low-pT resolution? (sub-jets ?)
    - Correlation of jets with the "soft" background and other observables? (low/intermediate-pT hadron correlations - take a look at the extra slides...)
    - Heavy-flavor jets? and their correlations?

Extra slides!

- Experiment:Energy-evolution of jet quenching - more to learn? Higher energy (LHC)... RHIC still working on jets! Various collision systems...
- Theory: Progress in theoretical description crucial and ongoing...; improved modeling and Monte Carlo strongly desired (looking forward to qPythia++; Next-gen. JEWEL model and others...)

...worth to look forward to...

Your ideas can make a difference!

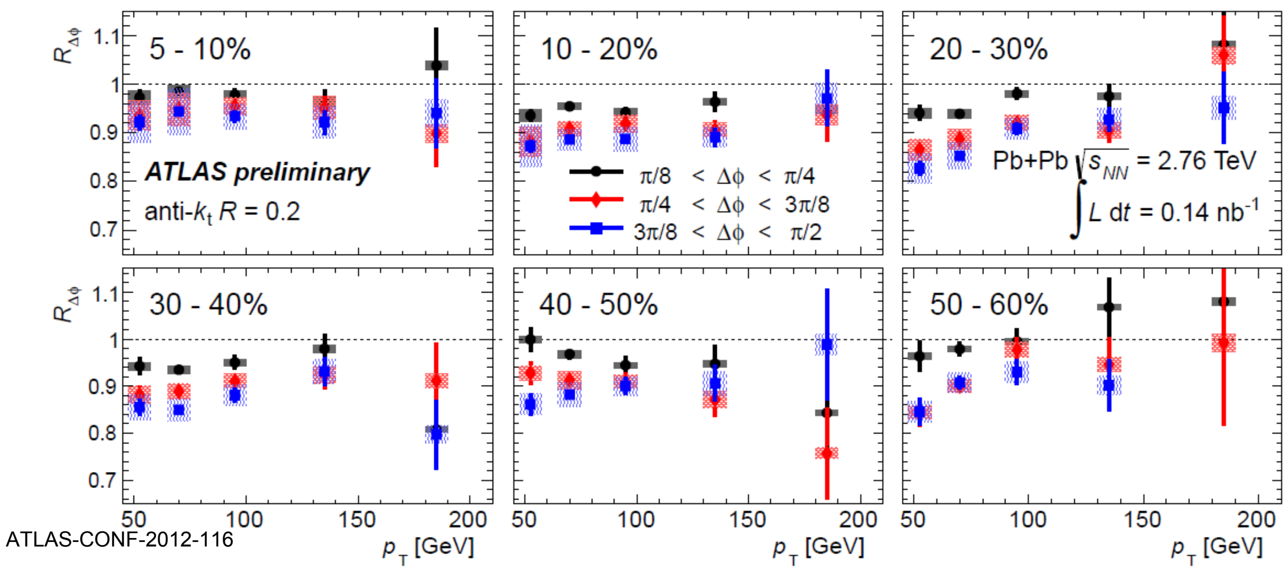
Thank you for your attention!

Azimuthal dependence of jet yields

Path length dependence of jet suppression

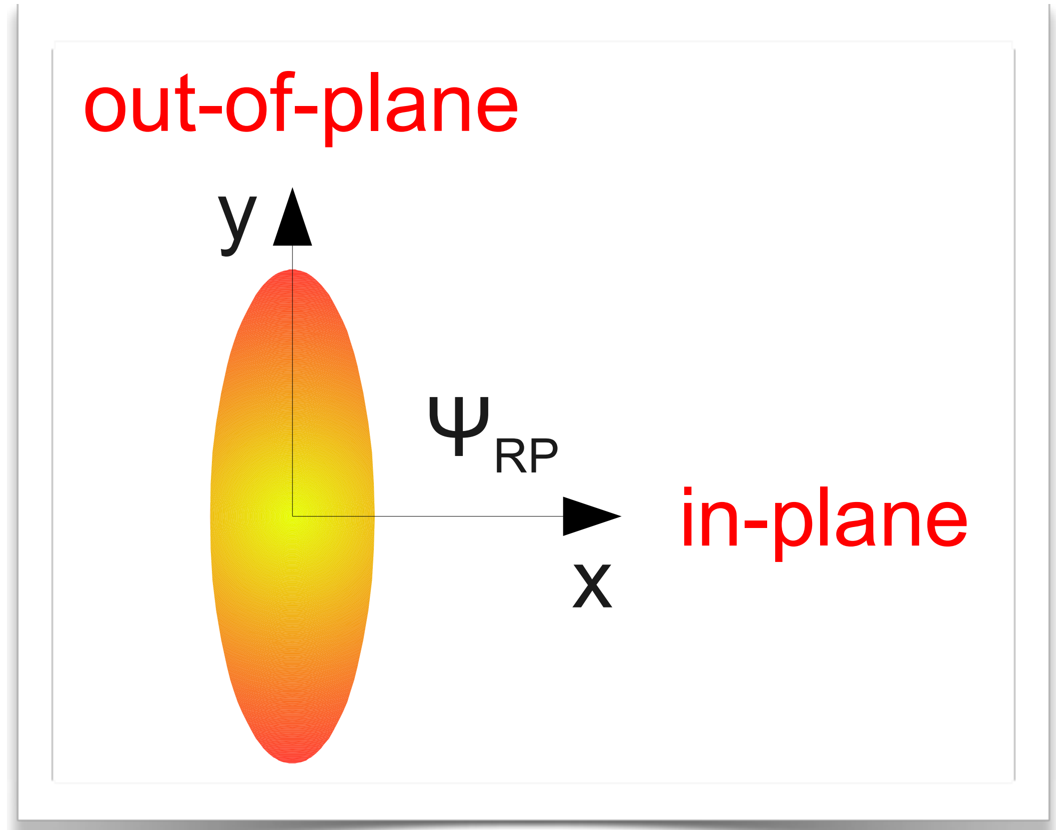
- **Ratios of yields in different slices of $\Delta\phi = \phi^{jet} - \Psi_2$**

$$R_{\Delta\phi} = \frac{\left.\frac{d^2N_{jet}}{dp_T d\Delta\phi}\right|_{\Delta\phi=\Delta\phi_i}}{\left.\frac{d^2N_{jet}}{dp_T d\Delta\phi}\right|_{\Delta\phi=0-\pi/8}}$$

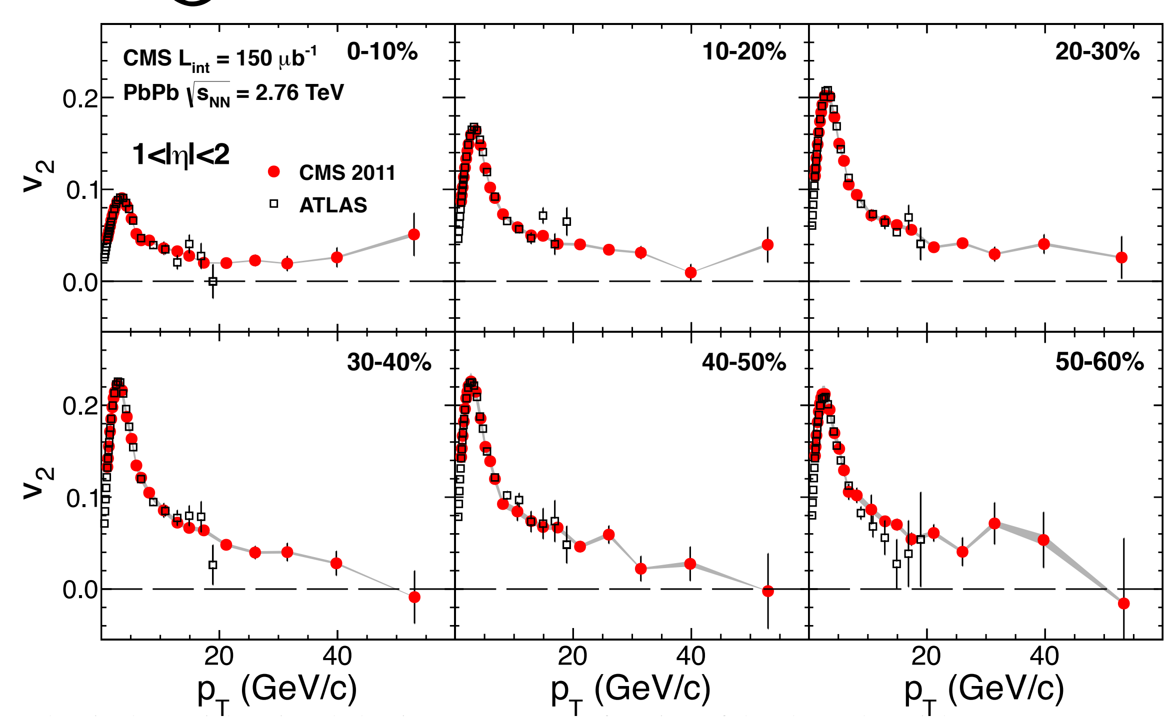


- Yields are reduced by about 15% for $3\pi/8<\Delta\phi<\pi/2$ relative to $0<\Delta\phi<\pi/8$

$$R_{AA}(\varphi) = R_{AA}\left(1 + 2v_2 \cos 2(\varphi - \psi)\right)$$

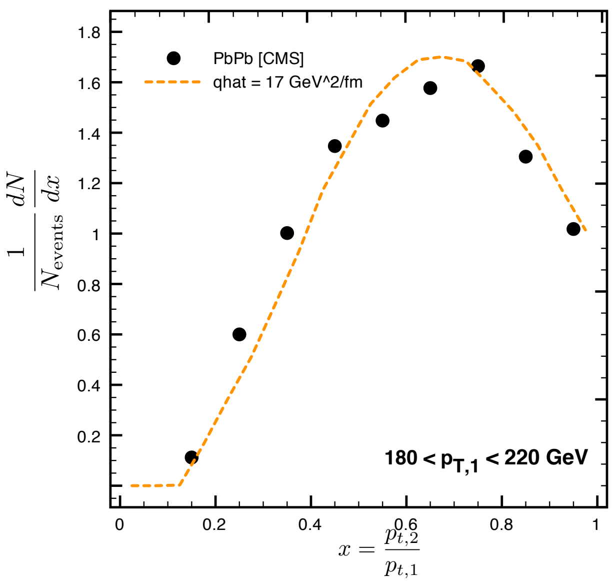


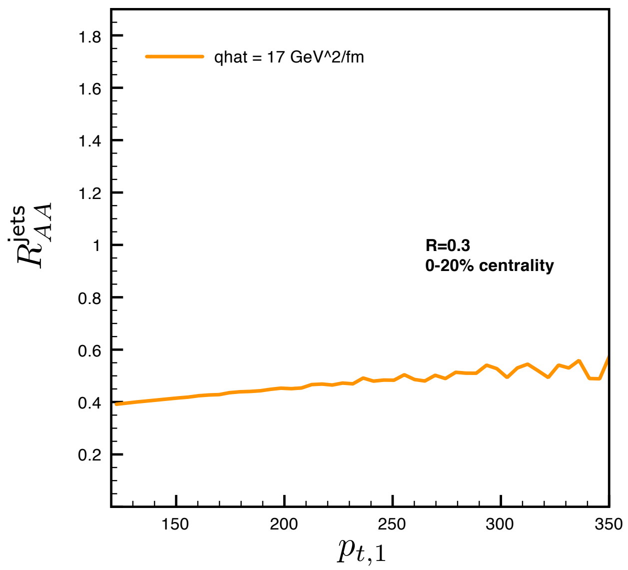
Single particle v2 - CMS

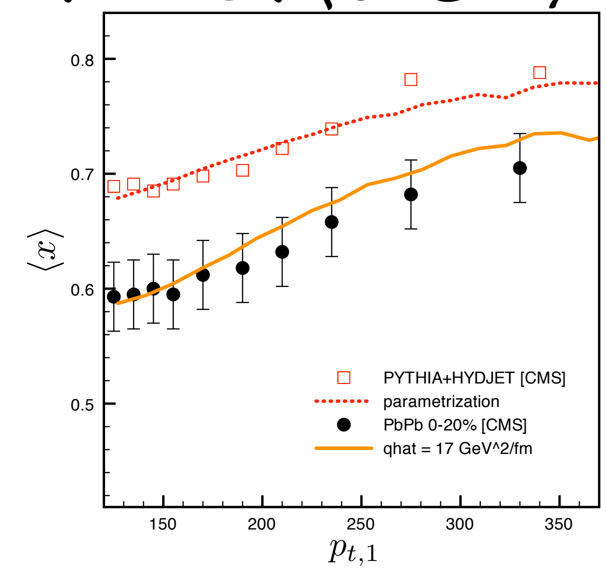


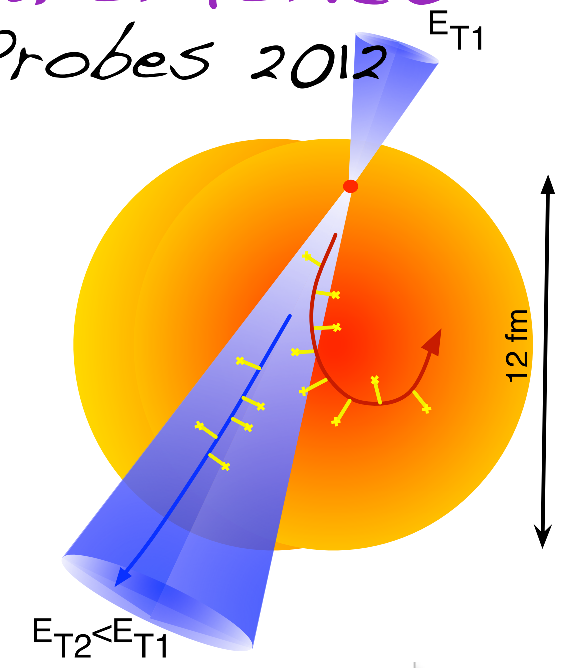
A model describing the first measurements

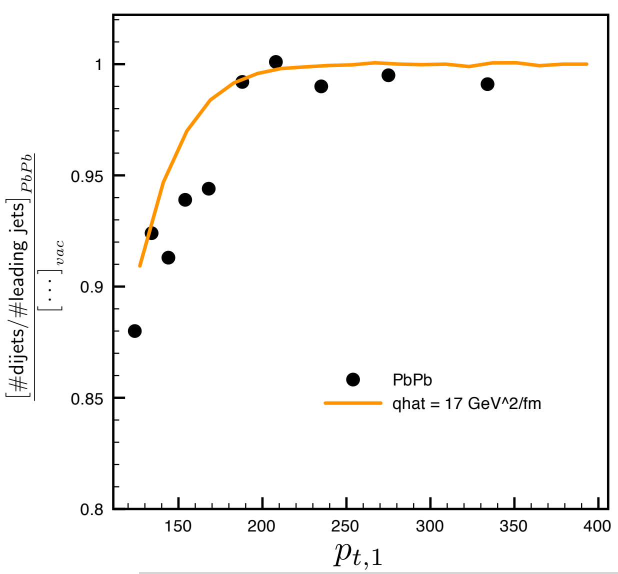
Solana+Milano: talks @ Hard Probes 2012

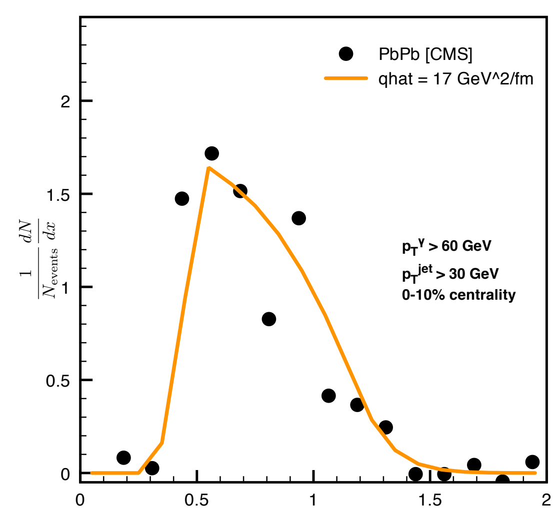






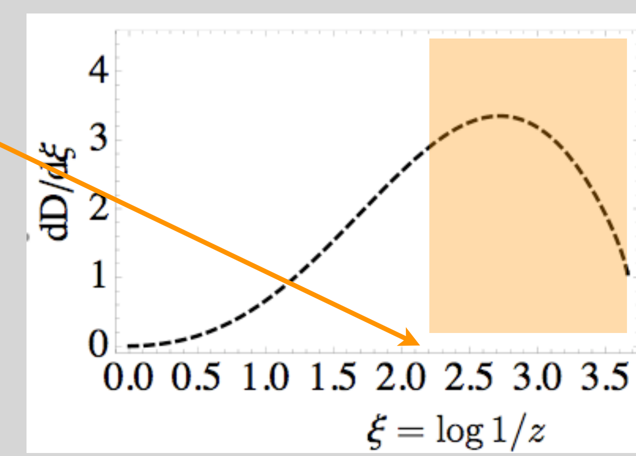


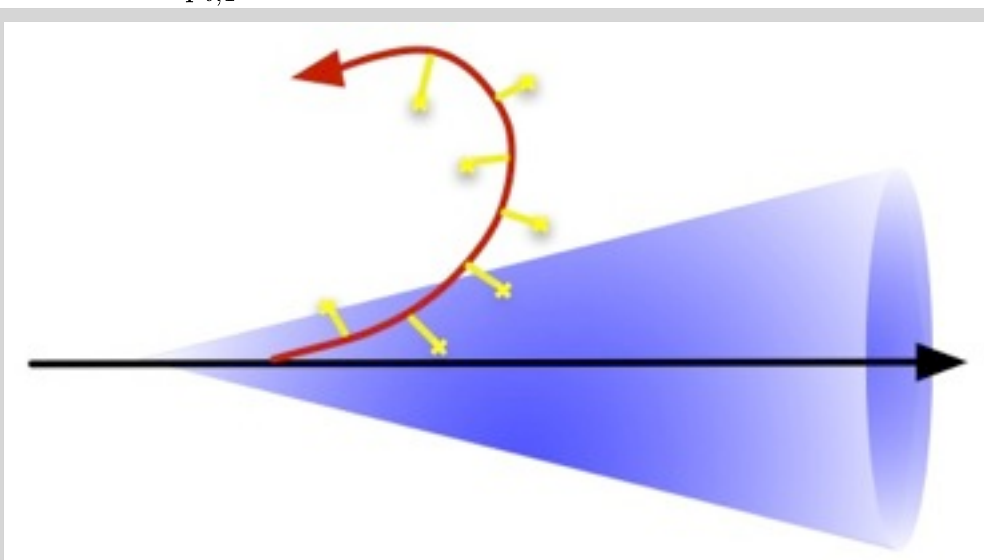




sufficiently soft modes decorrelated [lost] from jet

$\omega \leq \sqrt{\hat{q} L}$





all jet components accumulate transverse momentum

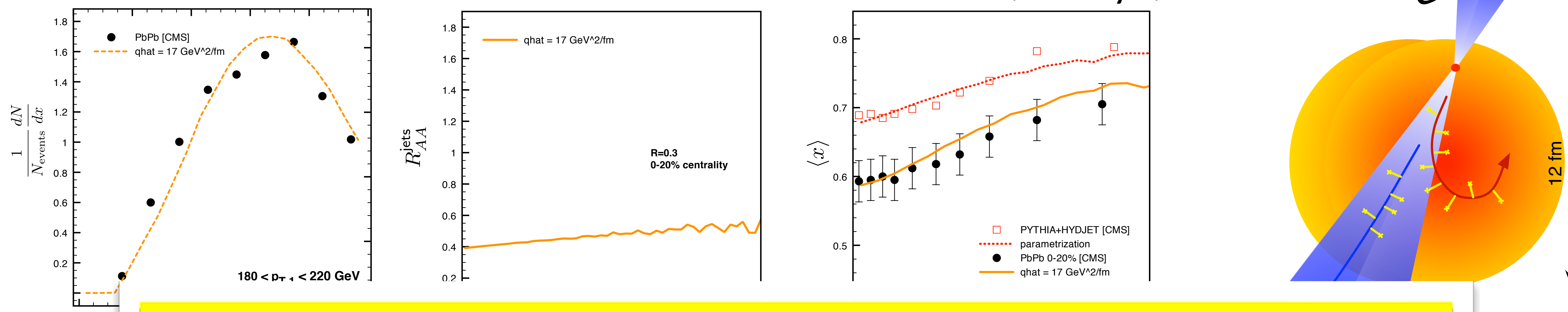
$$\langle k_\perp \rangle \sim \sqrt{\hat{q} L}$$

early availability of soft modes

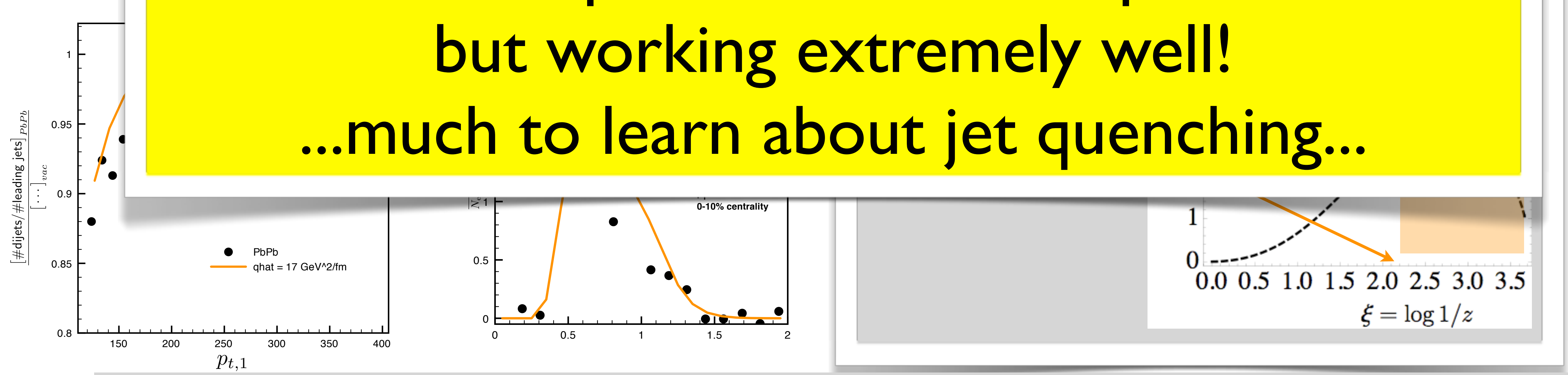
$$\tau \sim \frac{\omega}{k_\perp^2} \xrightarrow[\langle k_\perp^2 \rangle \sim \hat{q}\tau]{} \langle \tau \rangle \sim \sqrt{\frac{\omega}{\hat{q}}}$$

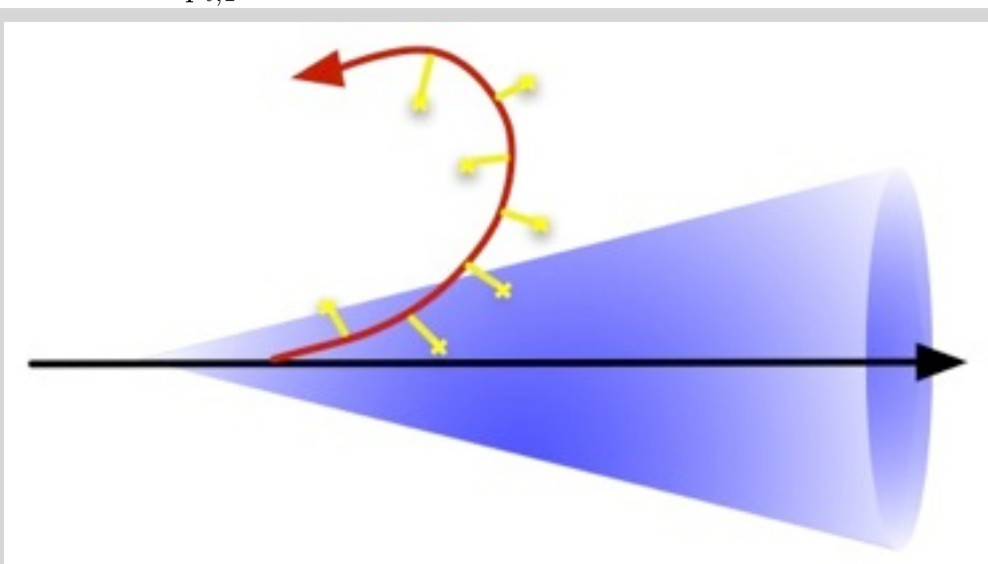
A model describing the first measurements

Milano: Hard Probes 2012



More in development - this is a representative...
but working extremely well!
...much to learn about jet quenching...





all jet components accumulate transverse momentum

$$\langle k_\perp \rangle \sim \sqrt{\hat{q}L}$$

early availability of soft modes

$$\tau \sim \frac{\omega}{k_\perp^2} \xrightarrow[\langle k_\perp^2 \rangle \sim \hat{q}\tau]{} \langle \tau \rangle \sim \sqrt{\frac{\omega}{\hat{q}}}$$

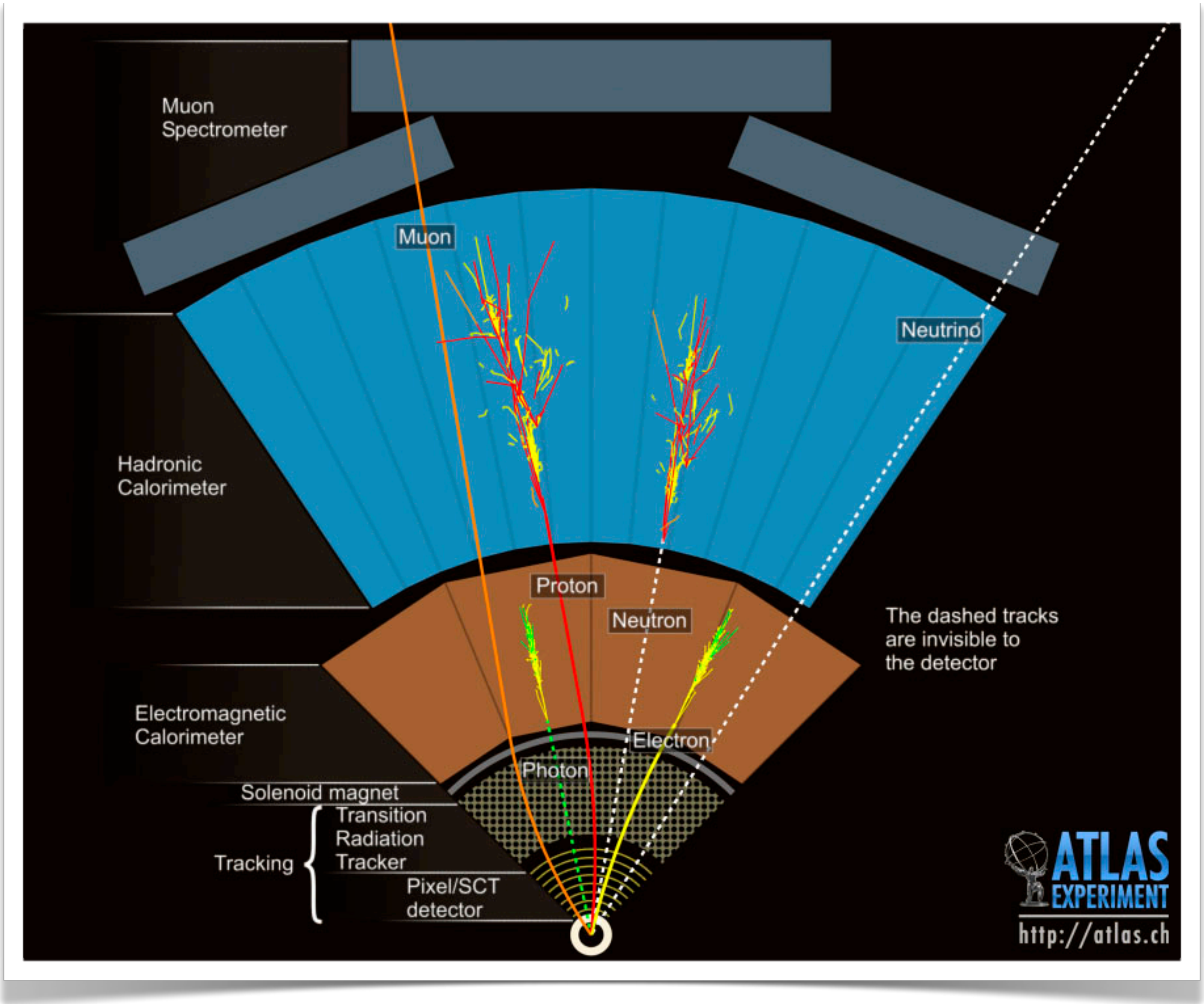
References (and refs therein!)

- Jet reconstruction (p-p and HIC), algorithms etc - FastJet : http://fastjet.fr/about.html
- PHENIX results: http://www.phenix.bnl.gov/results.html
- STAR results: http://drupal.star.bnl.gov/STAR/publications
- ALICE results: http://aliceinfo.cern.ch/ArtSubmission/publications
- ATLAS HI results: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavyIonsPublicResults
- CMS HI results: http://cms.web.cern.ch/org/cms-papers-and-results
- Overview of first LHC results: Mueller, Wysloluch, Schuckraft: http://arxiv.org/abs/1202.3233
- Hard Probes 2012 conference:
    - http://agenda.infn.it/conferenceOtherViews.py?view=standard&confId=4157

Extra slides

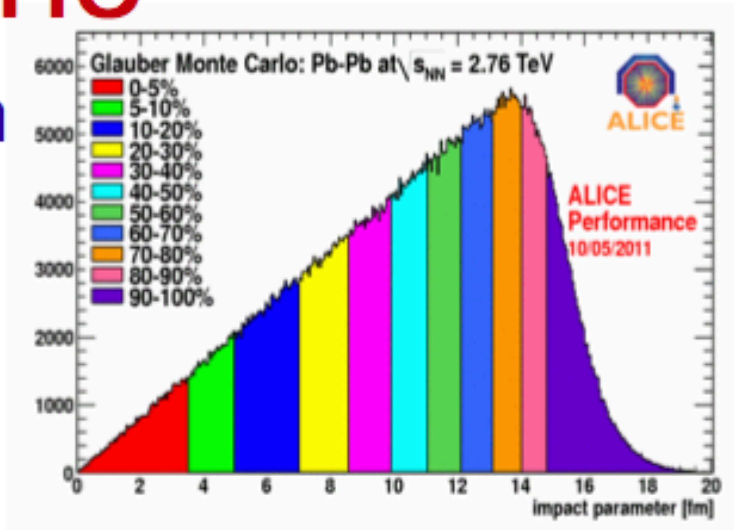
- Did not fit for time reasons but also relevant(!)... make sure you go through these as well.

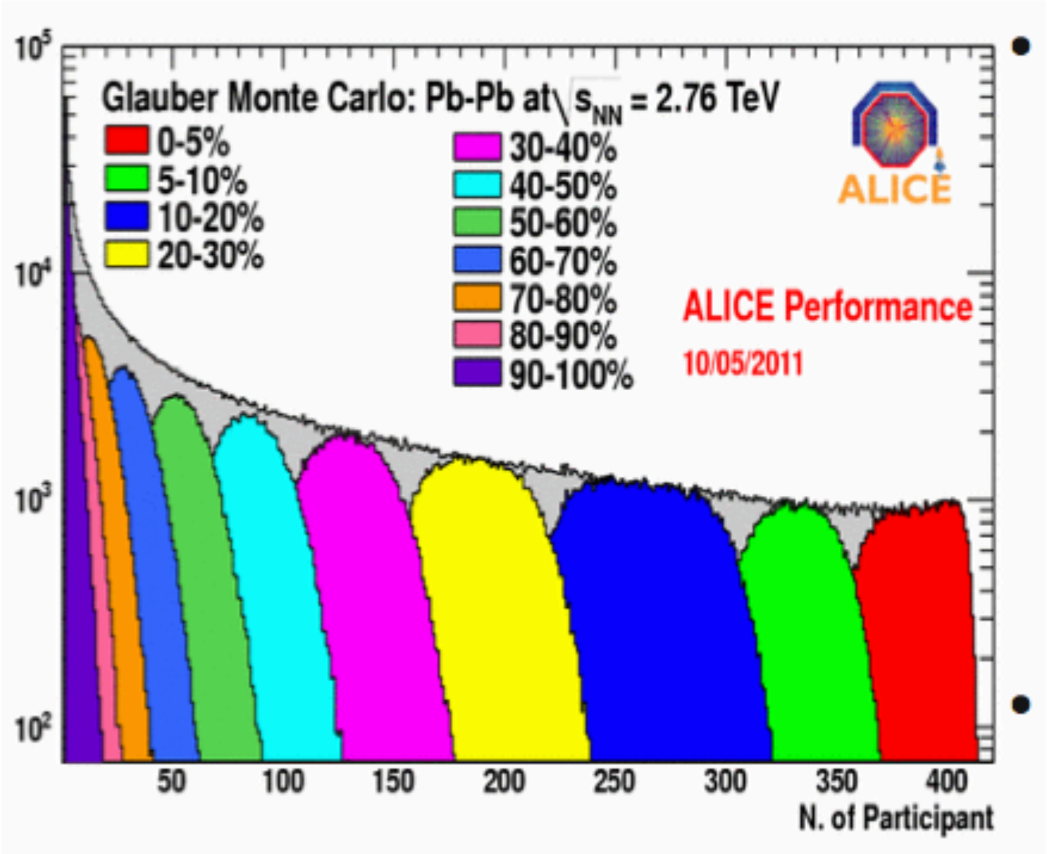
Particle detection



Glauber Monte Carlo

- Glauber model: geometrical picture of AA collision
  - Straight−line nucleon trajectories
  - N-N cross−section independent of the number of collisions the nucleons have undergone before



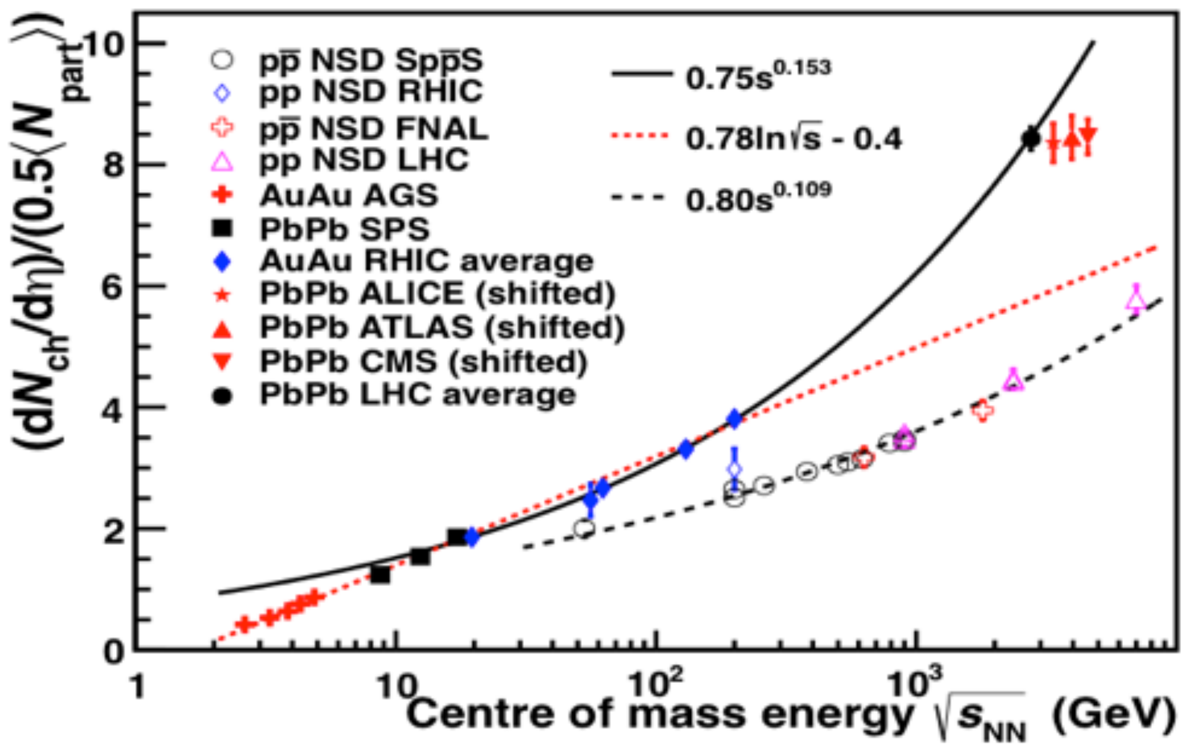


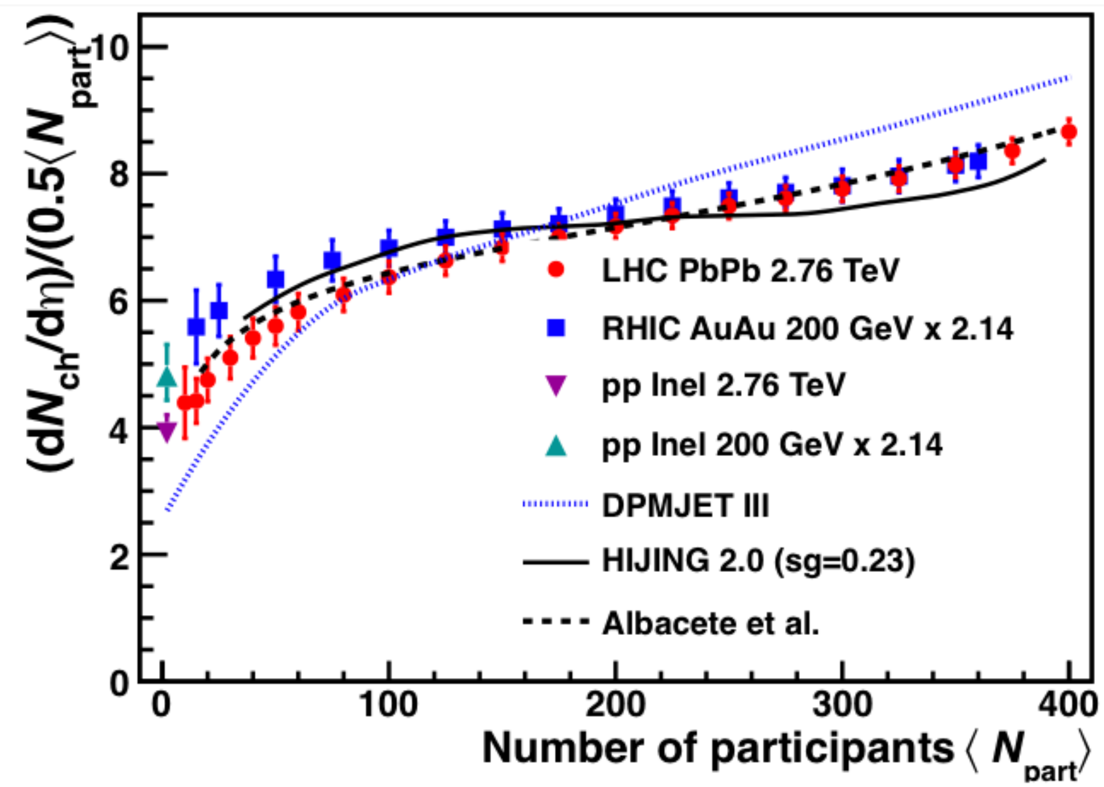
- Nuclear density profile: Woods−Saxon (2pF)

$$\rho(r) = \rho_o \cdot \frac{1}{1 + \exp\left(\frac{r - R}{d}\right)}$$

  - Radius=6.62±0.06fm
  - skin depth=0.546±0.01fm
  - Intra-nucleon distance=0.4±0.4fm
- Nucleon-Nucleon inelastic cross section σ_{NN}=64±5 mb at 2.76 TeV
- Estimate uncertainty by varying model assumptions

Particle multiplicity & centrality





dN/dη scales faster than pp

- Trend predicted by some saturation model
- Excellent agreement with LHC experiments
- Energy density × τ_0 ≈ 3 × RHIC

$$\varepsilon \geq \frac{dE_T/d\eta}{\tau_0 \pi R^2} = \frac{3}{2}\langle E_T/N\rangle \frac{dN_{ch}/d\eta}{\tau_0 \pi R^2}$$

Scaling similar to RHIC:

- Contribution of hard processes (N_{coll} scaling)?

Classes of models

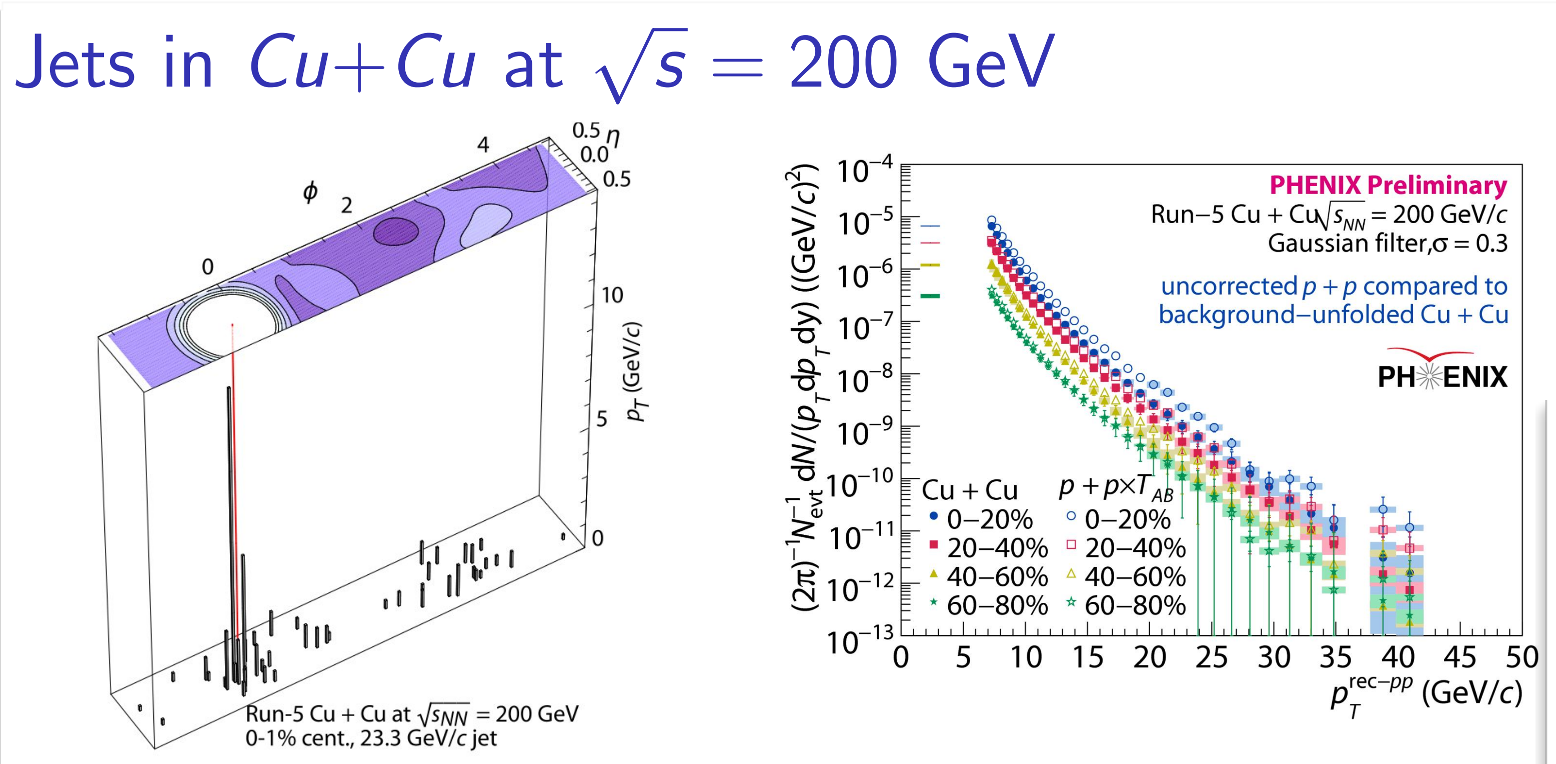
- Saturation
- 2 components (hard/soft)

➔models incorporating moderation of multiplicity (shadowing/saturation) favoured

- More on two-particle correlations

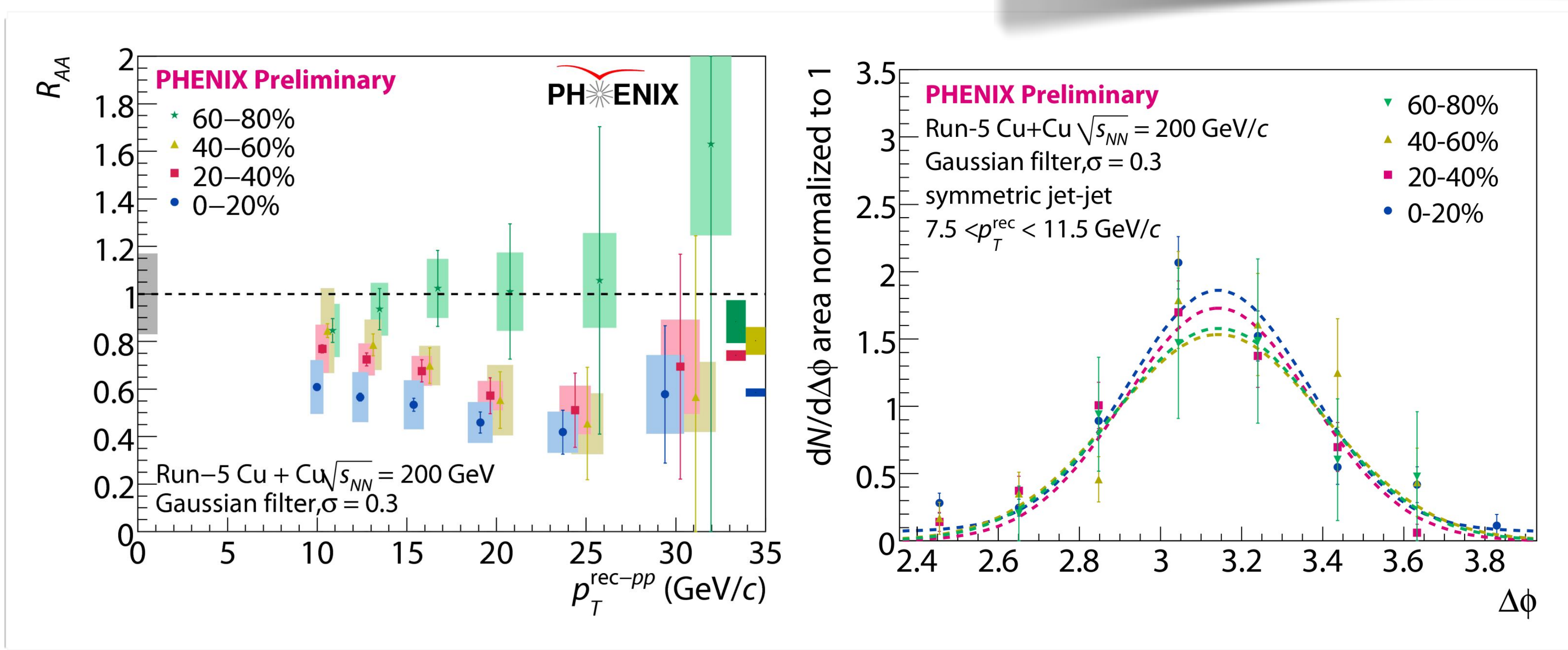
- Jets at RHIC...

Jets at RHIC in HIC



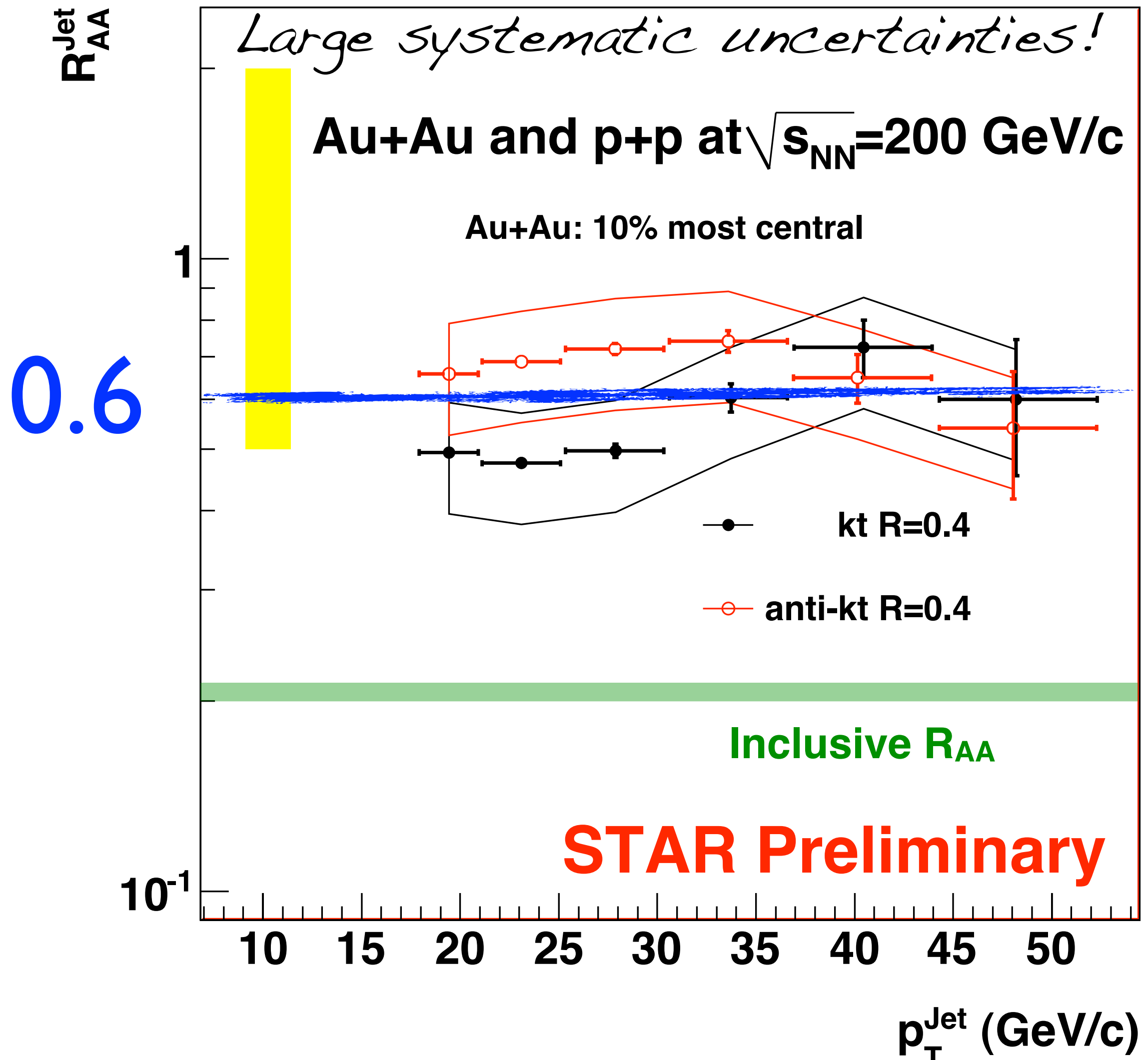
Custom jet finder (Gaussian Filtering) tunned to reject combinatorial jets
- tune based on vacuum fragmentation

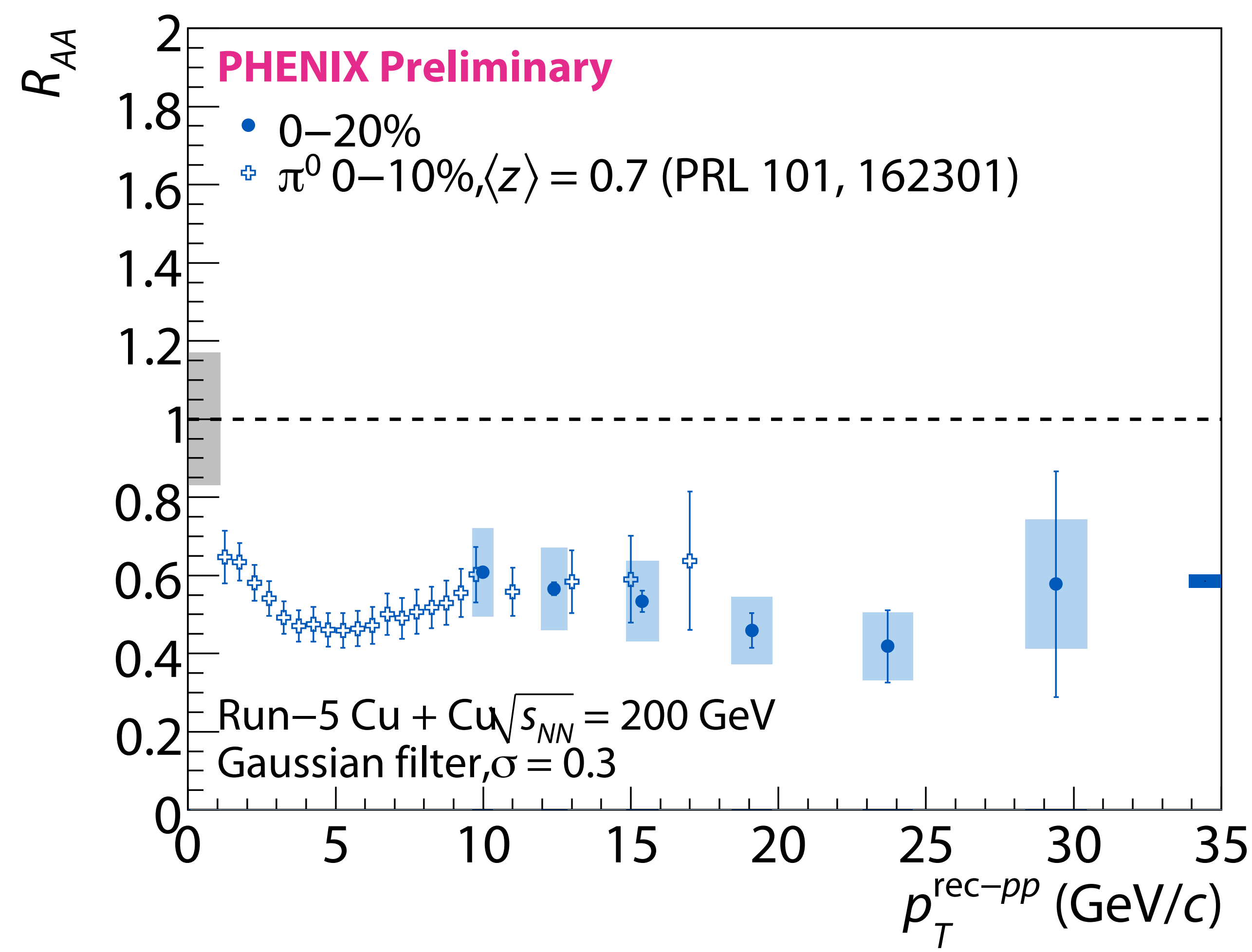
- Suppression of reconstructed jet R_{AA}:
  - ⇒ over a wide p_T range
  - ⇒ increasing suppression in more central collisions
- Reconstructed di-jet $\Delta\phi$ distributions unmodified:
  - ⇒ no angular de-correlation in central collisions!



Jets at RHIC in HIC

Work on final results in progress...





STAR Au+Au: R_{AA}^{JETS} > R_{AA} single particle

=> part of the parton energy recovered

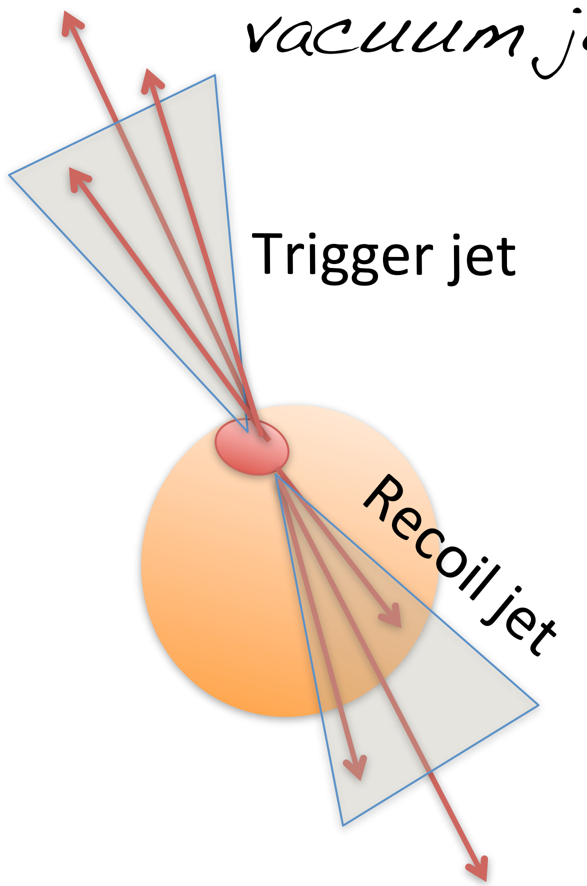
PHENIX Cu+Cu: R_{AA}^{JETS} ~ R_{AA} hadrons

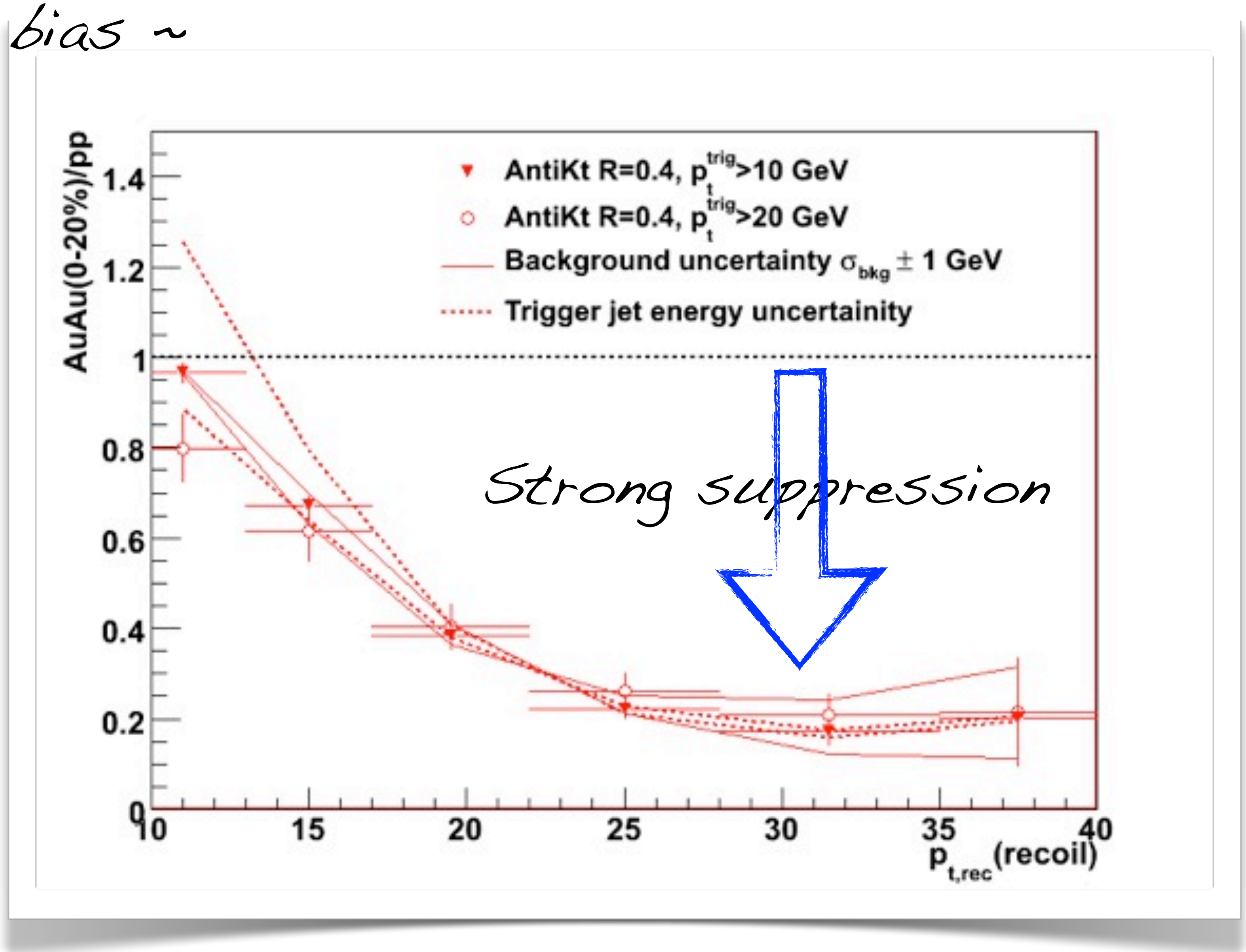
=> measure of vacuum fragmentation

Recoil jet spectrum at RHIC

Trigger-jet: biased towards surface

- strong fragmentation bias ~ vacuum jet





- Selecting biased trigger jet maximizes path length for the
recoil (b-2-b) jets: extreme selection of jet population

RHIC: Jet-hadron

Broadening & softening of the recoil jet at RHIC? -> but v3 component NOT negligible

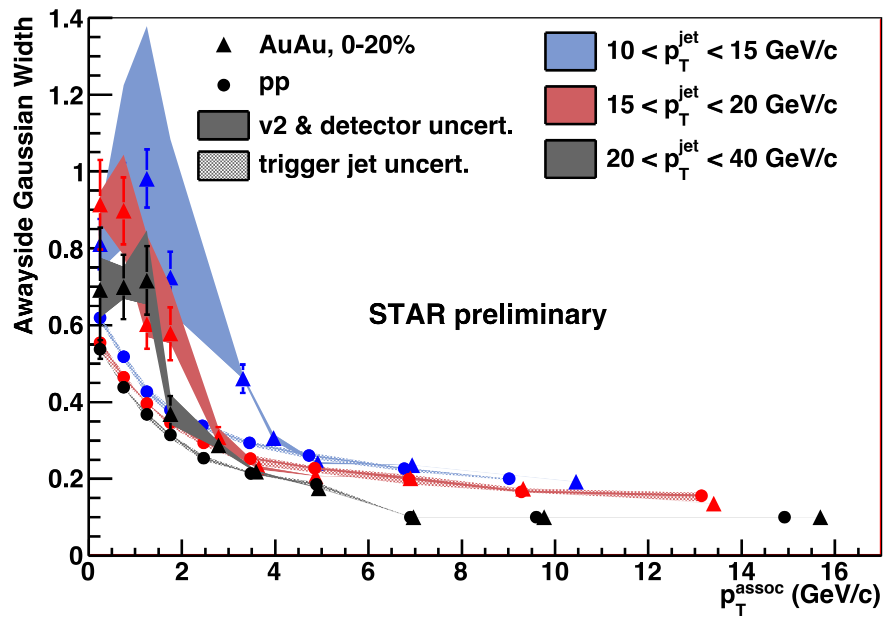
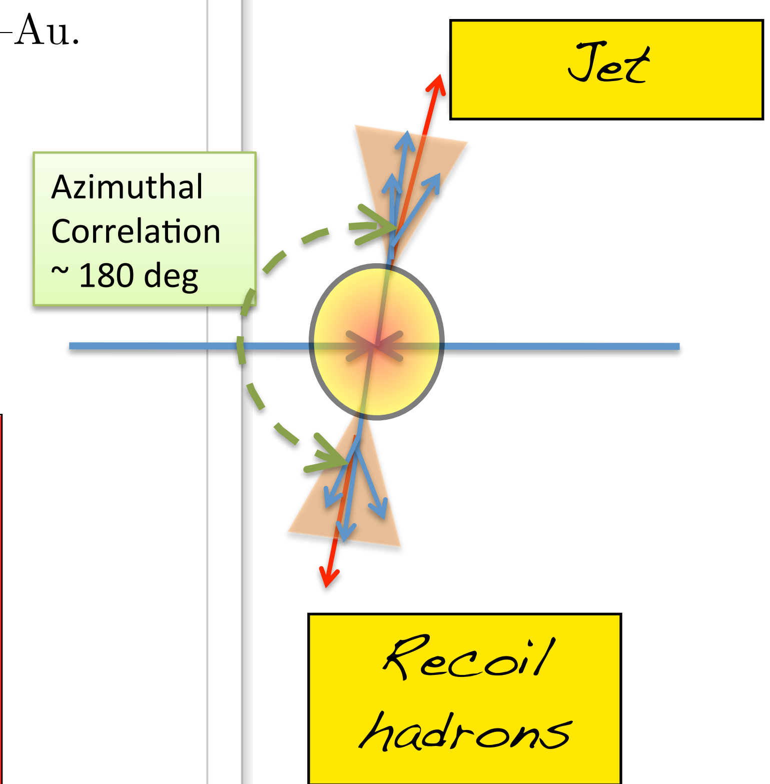


Figure 1. The Gaussian widths of the awayside jet peaks in Au–Au (triangles) and p–p (circles) indicate broadening of the awayside jet in Au–Au.

STAR @ RHIC



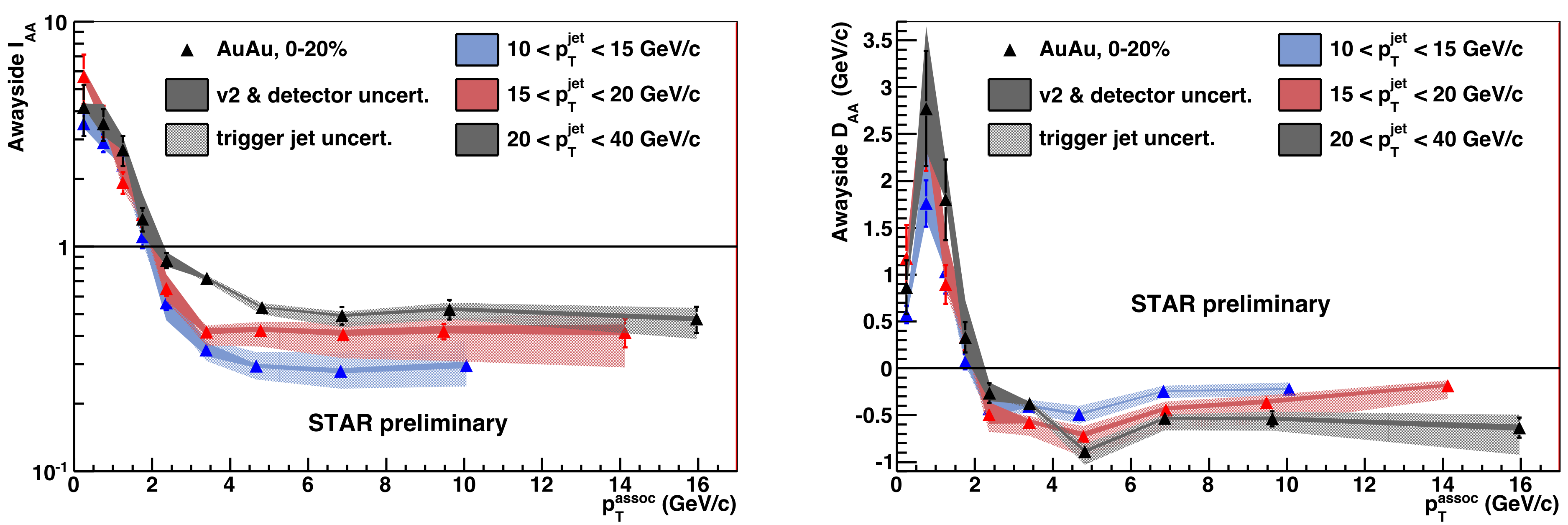


Figure 2. The awayside I_{AA} (left) and D_{AA} (right) indicate a softening of the awayside jet for three reconstructed jet energy ranges. The awayside D_{AA} shows that high-p_T^{assoc} suppression is compensated for by low-p_T^{assoc} enhancement.

Reminder on fragmentation bias...

- Fragmentation bias! - nature is kind and (in most cases) will give you what you ask for - perhaps NOT what you WANT

Thank you!

Thanks to all the authors/experiments for the graphics/slides shamelessly stolen for the purpose of this talk

- For graphics/slides from: F. Antinori, B. Cole, T. Dahms, P. Govoni, M. Nguyen, T. Hemmick, P. Jacobs, M. Floris, M. van Leeuwen, C. Loizides, A. Morsch, J. Putschke, C. Roland, M. Rybár , G. Salam, Y. Shi Lai, G. Soyez, I. Wingerter
- For the material by collaborations: ALICE, ATLAS, CMS, PHENIX, STAR

Energy density estimation...

What have we done? Energy Density

Overly Simplified: Particles don't even have to interact!

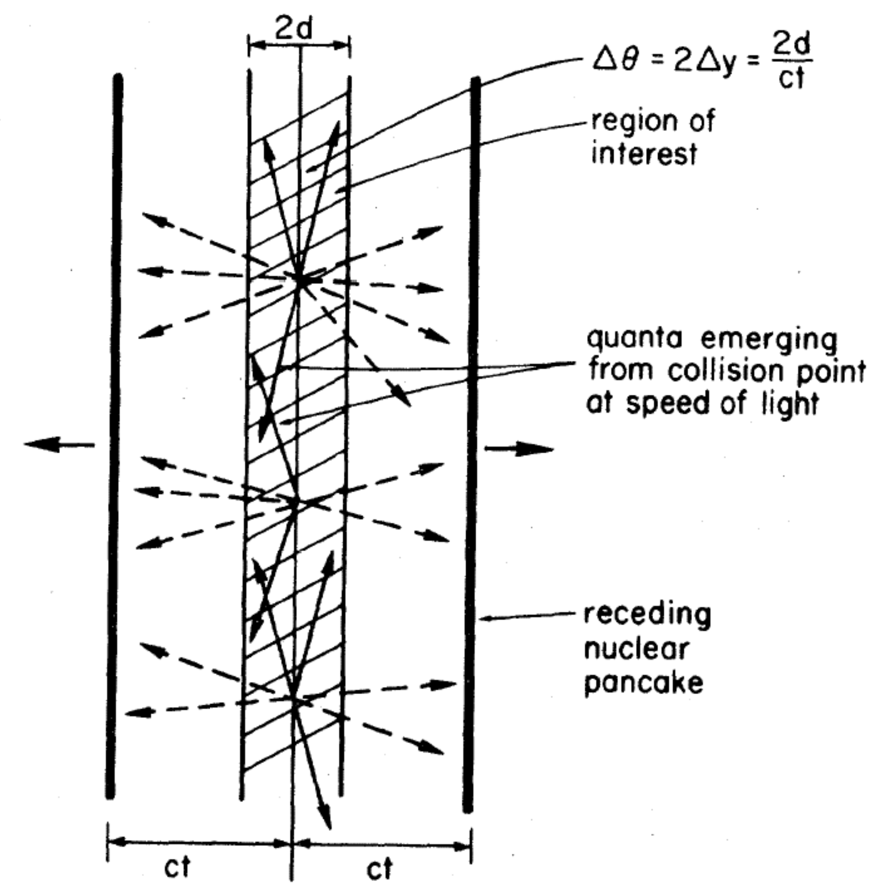
- **Let's calculate the Mass overlap Energy:**

$$\langle \varepsilon \rangle = 2\rho_0 \gamma^2 = 3150 \frac{GeV}{fm^3} \qquad \rho_0 = 0.14 \frac{GeV}{fm^3}; \gamma_{RHIC} = 106$$

- **Bjorken Energy Density Formula:**

$$\langle \varepsilon_{BJ}(t_{form}) \rangle = \frac{1}{t_{form} \cdot A} \frac{dE_T(t_{form})}{dy}$$

Assumed (t_{form}) Measured ($\frac{dE_T(t_{form})}{dy}$)

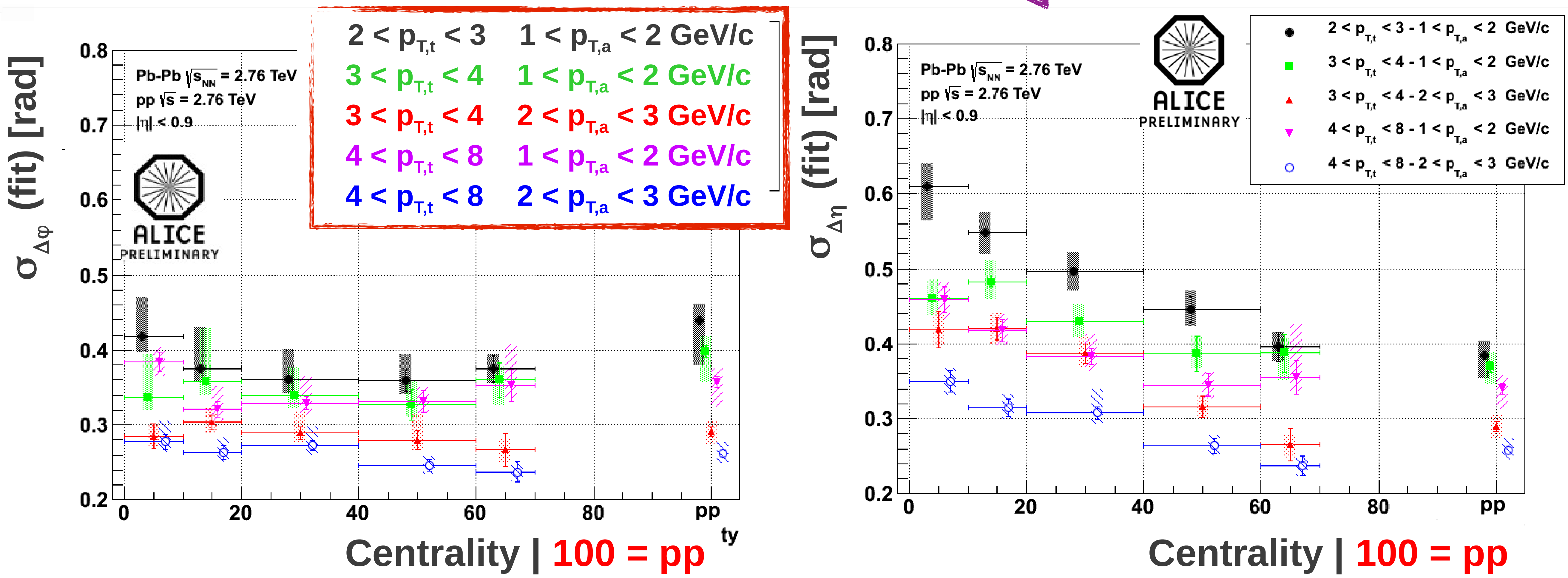


- **RHIC: $\varepsilon\tau$ = 5.4 +/- 0.6 GeV/fm^{2}c**
  LHC: $\varepsilon\tau$ = 16 GeV/fm^{2}c

Measuring widths of the correlations in azimuth and pseudo-rapidity

$\sigma_{\Delta\phi}, \sigma_{\Delta\eta}$ from Fit

Scan in kinematics



Note: Higher trigger pT -> higher av. parton pT

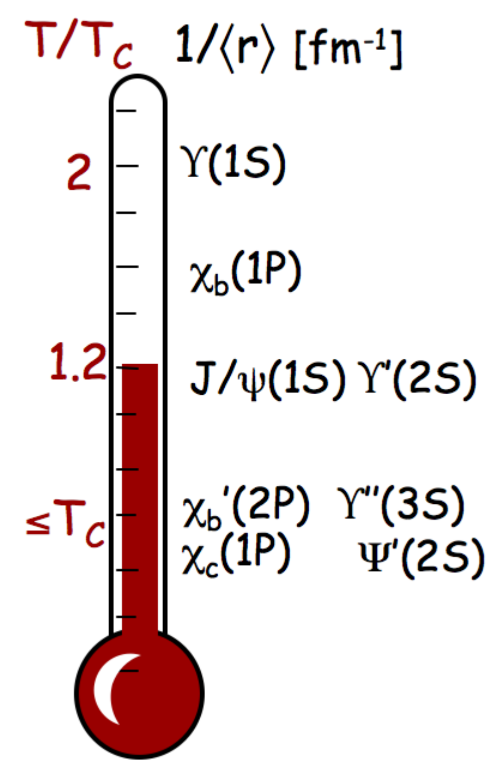
- No centrality dependence of σ_ϕ
  - $p_{T,assoc}$ dependence governed by $j_T \sim p_{T,assoc}\, \sigma_\phi$ = const.
  - Same for σ_η in peripheral collisions
- Significant increase of σ_η towards central events
  - For the lowest p_T bin, eccentricity $(\sigma_\eta - \sigma_\phi) / (\sigma_\eta + \sigma_\phi)$ increases from 0 to 0.2
- Smooth continuation from peripheral to pp

Quarkonia and QGP

- Heavy quarks
  - produced in the initial hard-scattering process
  - Debye screening in QGP leads to melting of quarkonia
- Different binding energy of bound states lead to sequential melting of the states with increasing temperature
  - also observable in the rates of the ground state due to suppression of feed down contribution

State	J/ψ (1S)	χ_c (1P)	ψ' (2S)
m (GeV/c^2)	3.10	3.53	3.68
r_0 (fm)	0.50	0.72	0.90

Υ (1S)	χ_b (1P)	Υ' (2S)	χ_b' (2P)	Υ'' (3S)
9.46	9.99	10.02	10.26	10.36
0.28	0.44	0.56	0.68	0.78

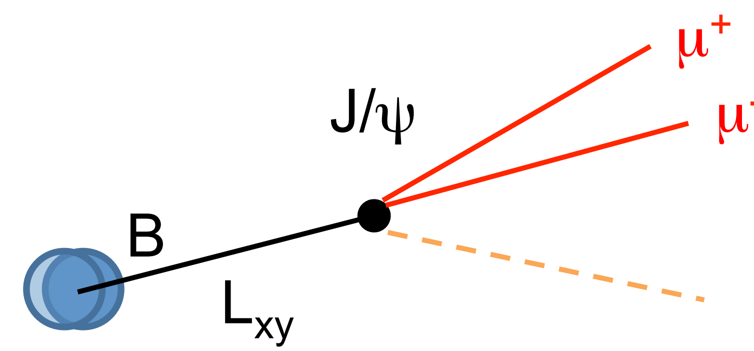


- The beginning: Matsui & Satz, PLB 178 (1986) 416

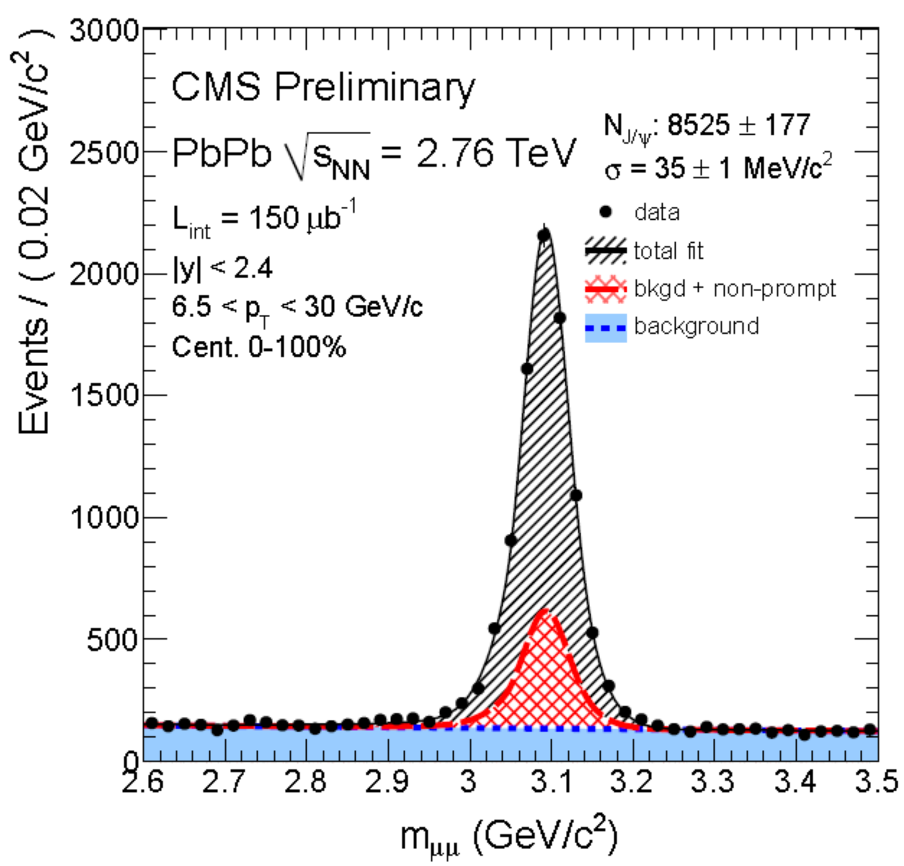
Mocsy, EPJ C 61 (2009) 705

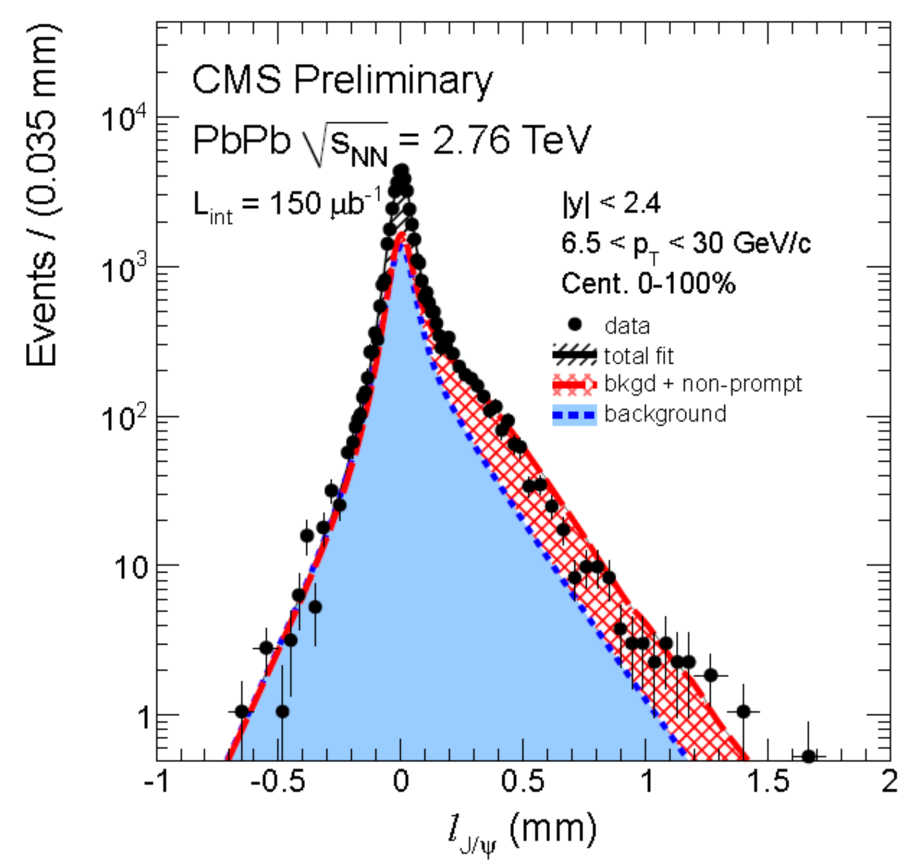
J/ψ from B-decays

- J/ψ from B decays to access beauty in-medium energy loss
  - Long B-meson lifetime -> secondary J/ψ's from B feed-down feature decay vertices displaced from the primary collision vertex
  - Fraction of non-prompt J/ψ from simultaneous fit to $\mu^+\mu^-$ invariant mass spectrum and pseudo-proper decay length distributions

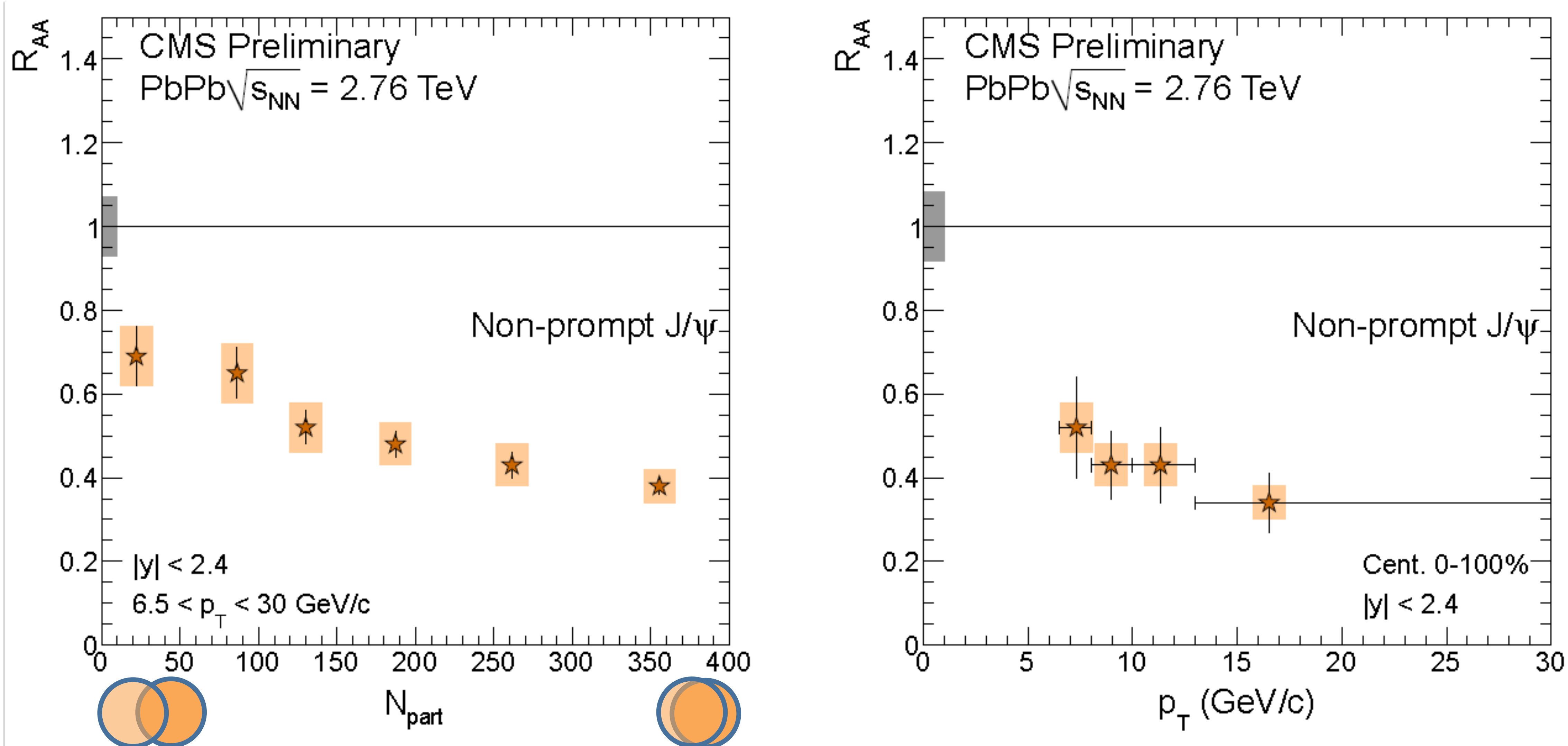


$$\ell_{J/\psi} = L_{xy}(J/\psi) \cdot \frac{M_{J/\psi}}{p_T(J/\psi)}$$





R_{AA} of non-prompt J/ψ



- Slow decrease of R_{AA} with increasing centrality
- Hint for increasing suppression (-> smaller R_{AA}) with increasing p_T

CMS, PAS HIN-12-014

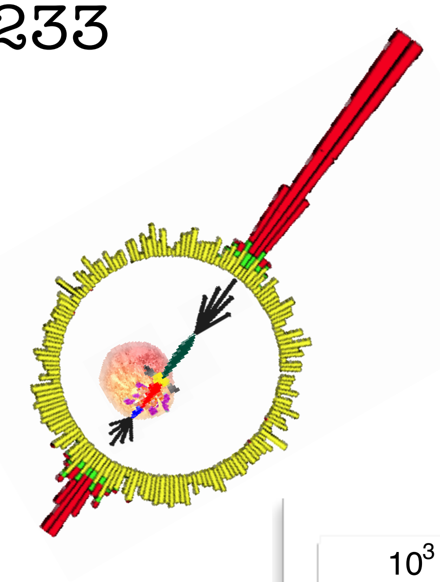
Until now...

- Jets in elementary collisions: must specify an operational definition (algorithm, R, recombination scheme); variety of infrared and collinear safe algorithms; under control theory/experiment;

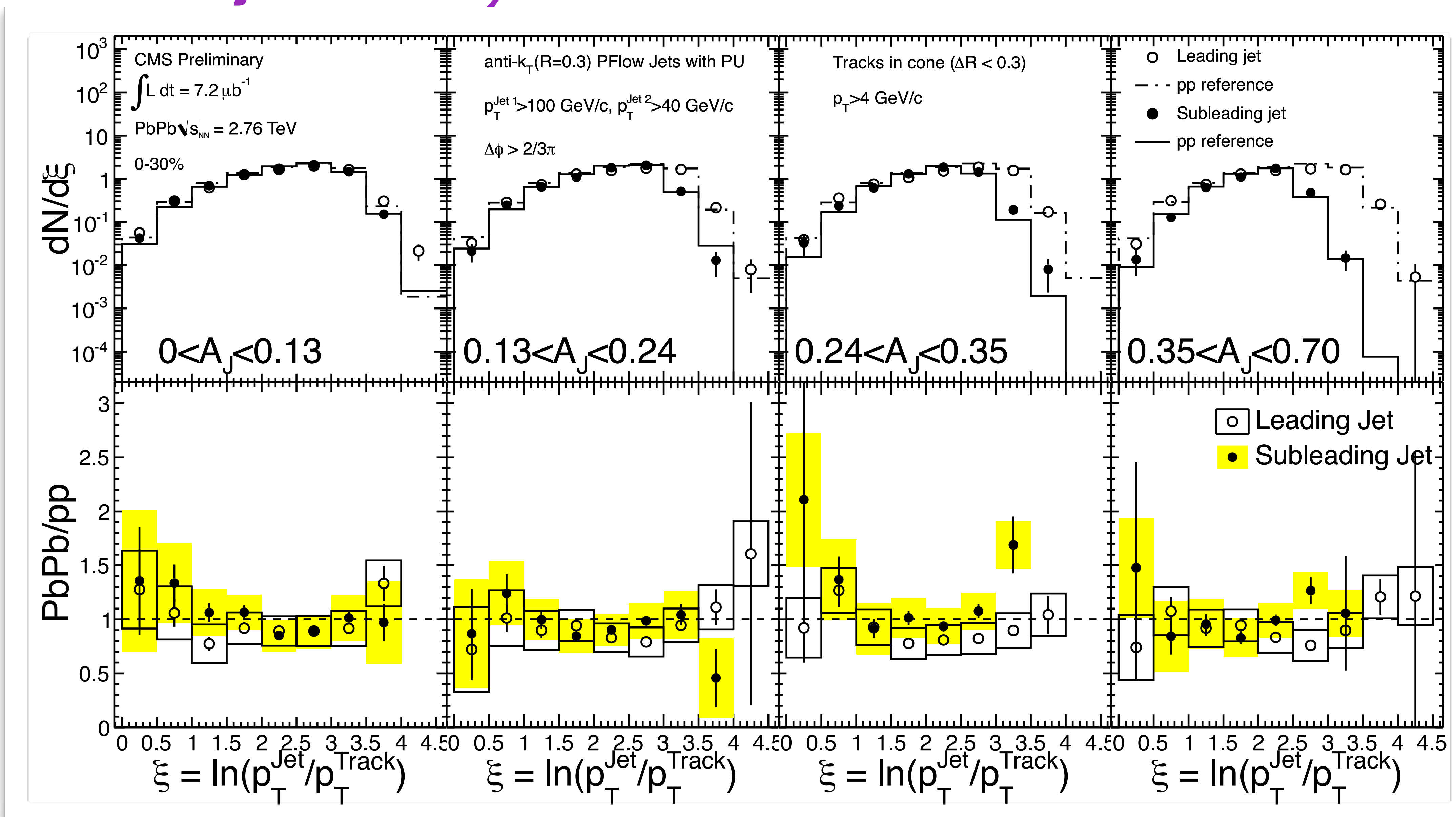
- HI collisions: hot QCD matter; large particle (production) densities as compared to vacuum - evolving with centrality; Jet measurements difficult (Today you will see that possible nevertheless)

- Leading hadrons suppressed <-> parton energy loss (jet quenching); Hadrons select particular ensemble of jets(!) - fragmentation bias (more Today) - relation of parton vs hadron energy (?)

... back to jet quenching measurements



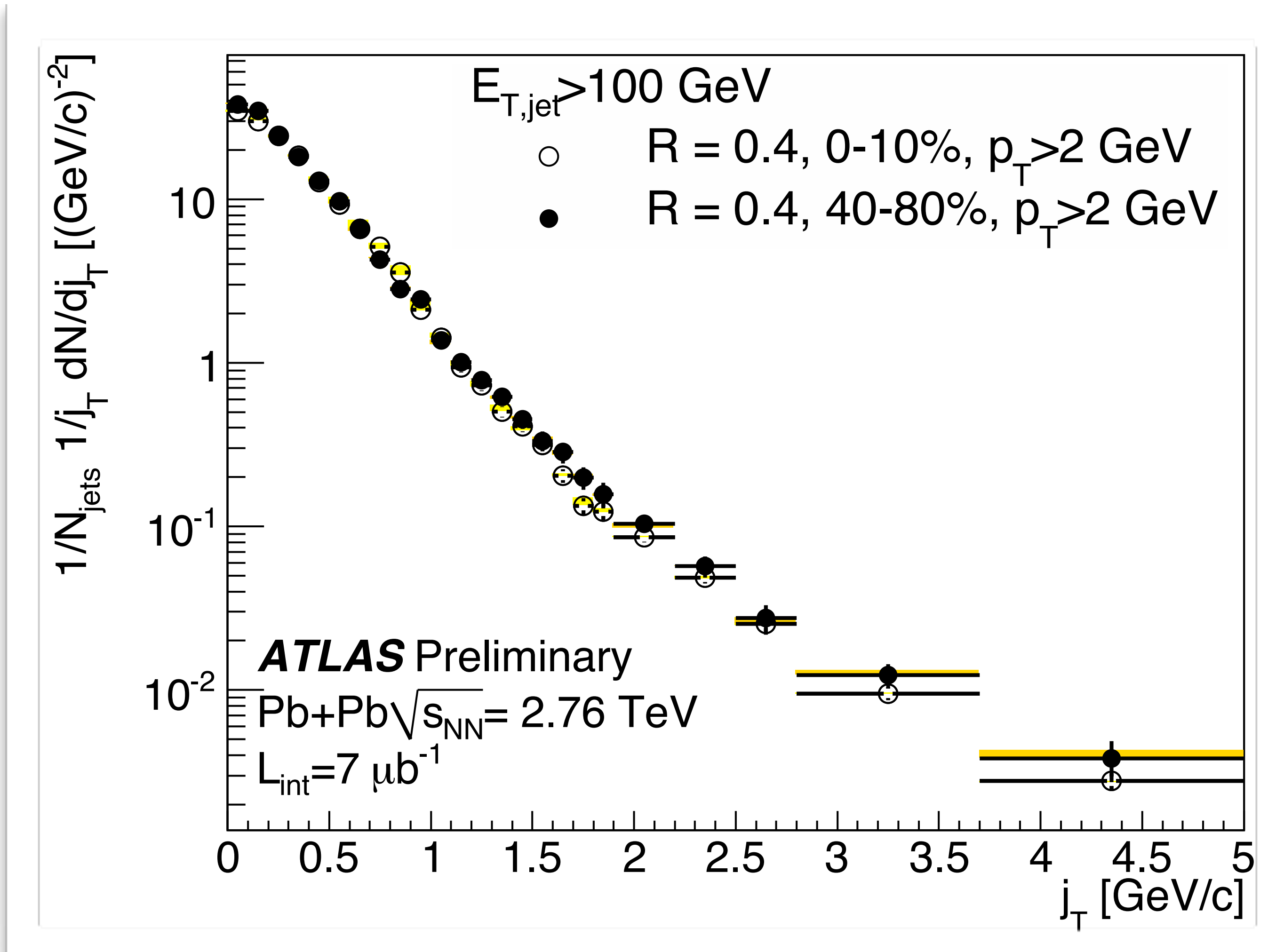
Jet fragmentation in Heavy-ion collisions

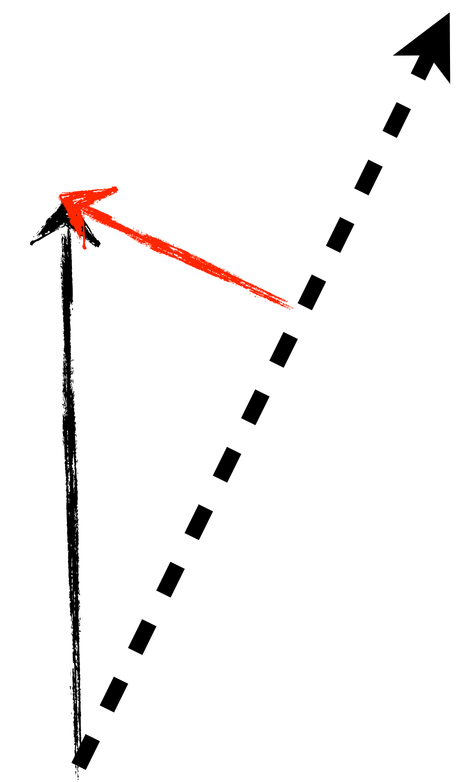


CMS observation: Fragmentation of jets that lost energy consistent with jet fragmentation in proton-proton (vacuum) - similar observations by ATLAS

- a good question: is the particle composition of the jet modified?

Transverse jet structure: j_T measurements from Atlas





- Measure distribution of fragment p_T normal to jet axis: $j_T \equiv p_T^{\mathrm{had}} \sin \Delta R = p_T^{\mathrm{had}} \sin\left(\sqrt{\Delta\eta^2 + \Delta\phi^2}\right)$
  - Compare central (0-10%) to peripheral (60-80%)
    - ⇒No substantial broadening observed.