ALICE and the study of the Quark Gluon Plasma: status and future perspectives

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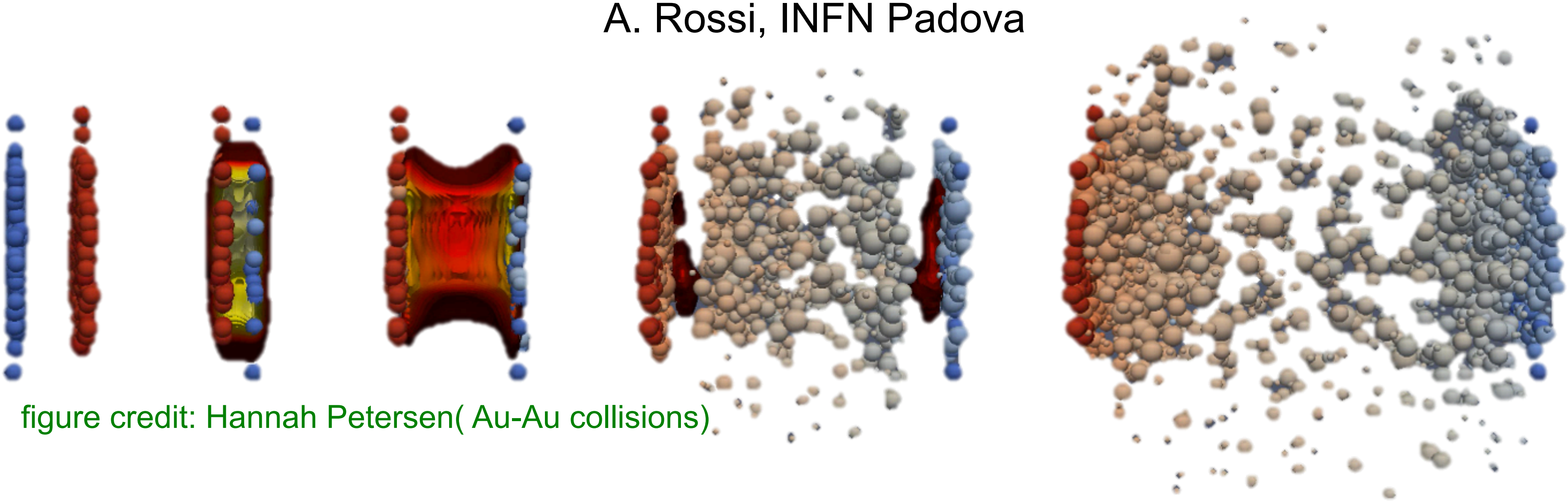


figure credit: Hannah Petersen(Au-Au collisions)

7^{th} IDPASC PhD School

Asiago, 21 June 2017

Elementary particles

Sensitive to strong interaction described by Quantum ChromoDynamics (QCD)

Strong-force charge: "colour" charge

Gluons, the strong-force "carriers" are coloured, differently from photon in QED

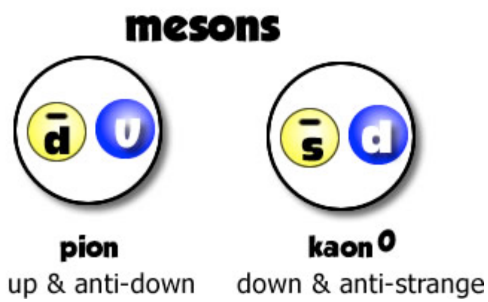
Lagrangian based on non-abelian symmetry group SU(3) → gluons interacts with gluons

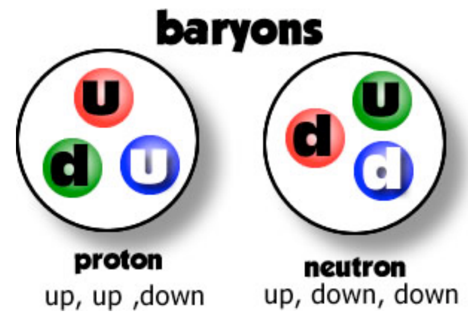
$$\mathcal{L}_{\mathrm{QCD}} = \bar{\psi}_i \left(i(\gamma^\mu D_\mu)_{ij} - m\,\delta_{ij} \right) \psi_j - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a$$

$$G^a_{\mu\nu} = \partial_\mu \mathcal{A}^a_\nu - \partial_\nu \mathcal{A}^a_\mu + g f^{abc} \mathcal{A}^b_\mu \mathcal{A}^c_\nu \,,$$

A hadronic world

Isolated quarks are never observed, only colourless bound states called hadrons are experimentally accessible: why?





Mesons $q\bar{q}$

Mesons are bosonic hadrons.
There are about 140 types of mesons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	−1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

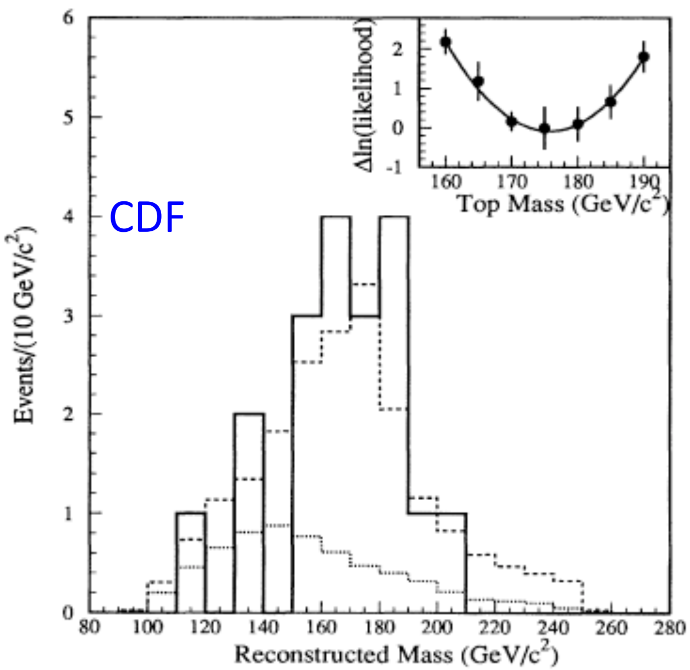
Baryons are fermionic hadrons.
There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	−1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	−1	1.672	3/2

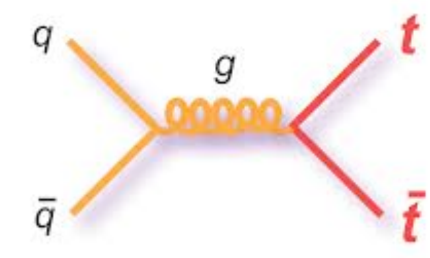
(parenthesis)… there's a quark we "see"

Quark top discovery at Fermilab

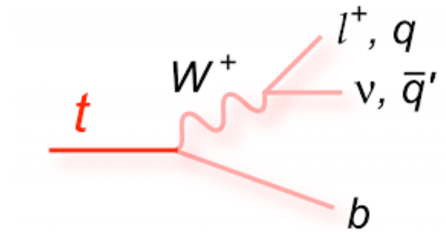
CDF: Phys. Rev. Lett. 74, 2626 (1995)
D0: Phys.Rev.Lett.74:2632-2637 (1995)



Production



Decay:
Γ~2 GeV → $\tau = \Gamma/h$~0.3,
$c\tau$ ~ 0.1 fm/c



Quark top decays before forming hadron

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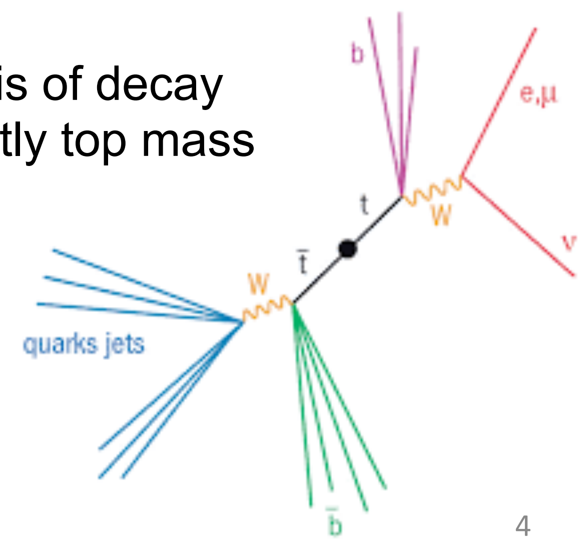
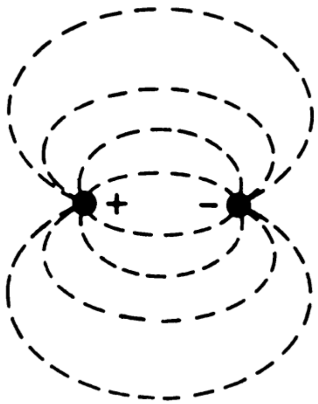
Invariant mass analysis of decay products reveals directly top mass



What does it mean that we "see" a particle?
Measure an identifying feature → mass

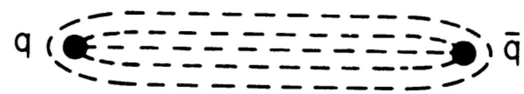
Confining potential in QCD

QED



(a)

QCD



(b)

- In QCD, the field lines are compressed into a “flux tube” (or “string”) of constant cross-section (~fm^2), leading to a long-distance potential which grows linearly with distance *r* :

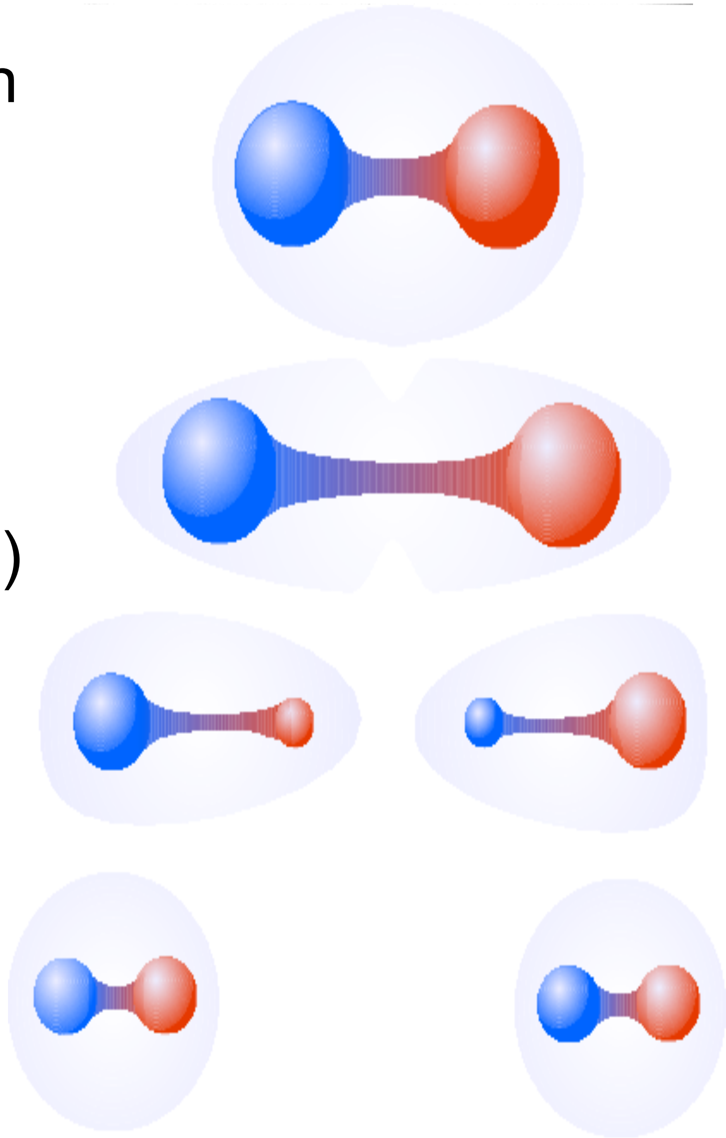
$$V(r) = -\frac{A}{r} + k \cdot r$$

(Cornell potential)

with k ~ 1 GeV/fm

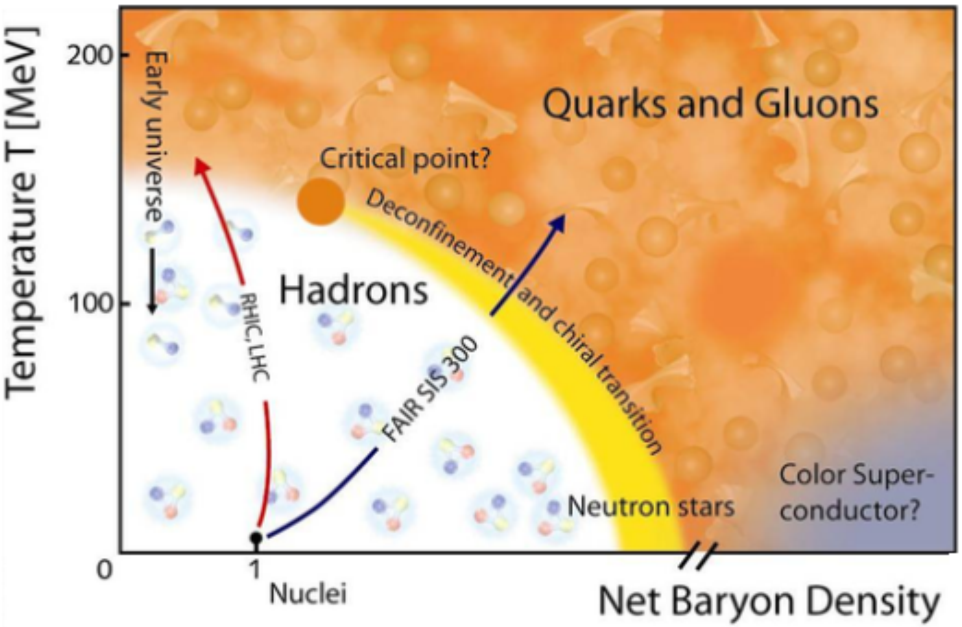
Confinement: string breaking

- If one tries to pull the string apart, when the energy stored in the string ($k \cdot r$) reaches the point where it is energetically favourable to create a $q\bar{q}$ pair, the string breaks…
- ...and one ends up with two colour-neutral strings (and eventually hadrons)
- The colour charge is confined into colourless hadrons



Is it possible to reach deconfinement?

Phase diagram of strongly-interacting (QCD) matter



At high energy density ε (high temperature and/or high density) hadronic matter undergoes a phase transition to the *Quark-Gluon Plasma (QGP): a state in which colour confinement is removed*

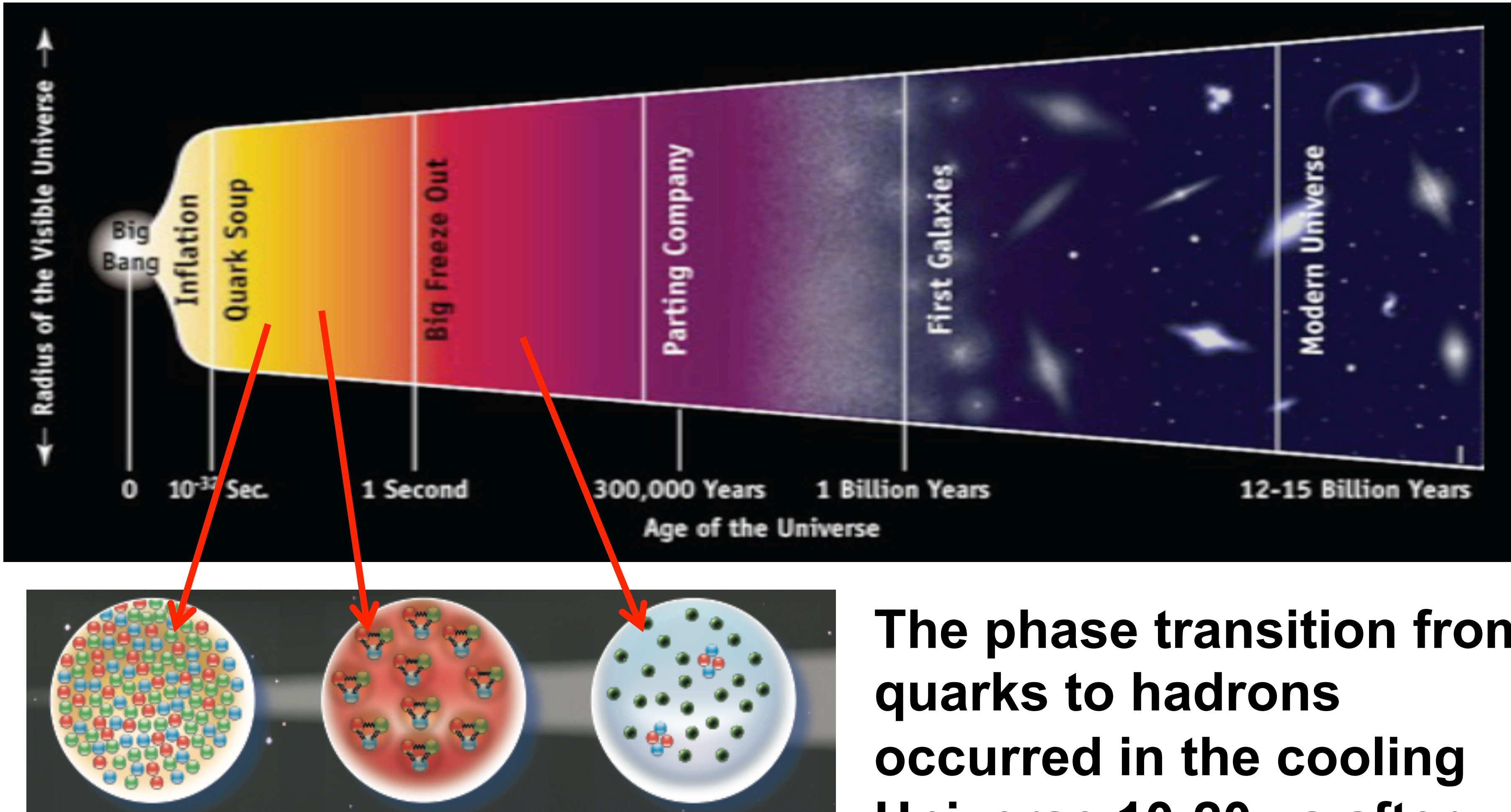
Phase transition: confined state → deconfined state

Lattice QCD calculations:

Critical temperature at 0 baryon density~ 155 MeV

Critical energy density ε_c ~ 1 GeV/fm^3 ~ 6-7 $\varepsilon_{nucleus}$

Quark-Gluon Plasma (QGP): the first "matter" in the primordial Universe



quark-gluon plasma

formation of protons/neutrons

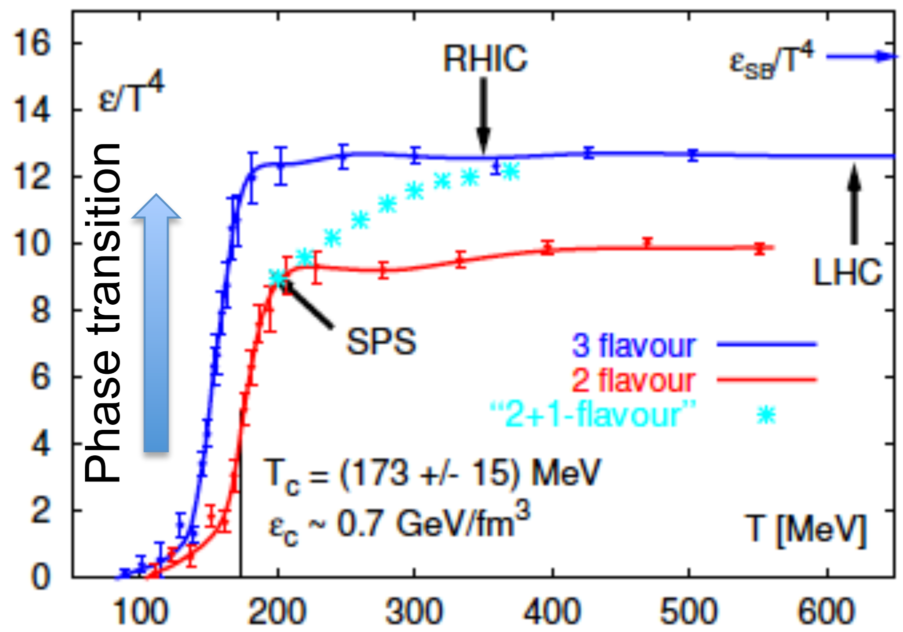
formation of atomic nuclei

The phase transition from quarks to hadrons occurred in the cooling Universe 10-20 μs after the Big Bang

Lattice QCD: Phase Transition

Lattice QCD is neither a calculation not a simulation: “realization” of QCD over a discretized space. It allows to compute thermodynamical properties of a system even in a non-perturbative regime of QCD

$$\frac{\varepsilon}{T^4} \;\; vs. \;\; T \longrightarrow$$ Proportional to number of degrees of freedom (ndof) (S. Boltzmann’s law)



- Zero baryon density, 2(u, d) or 3 (u, d, s) quark flavours
- **ε changes rapidly around T_c**
- **→ signal change in number of degrees of freedom**
- Most recent calculations:

  $T_c \sim 155$ MeV :

  $\rightarrow \varepsilon_c \sim 0.6$ GeV/fm^3

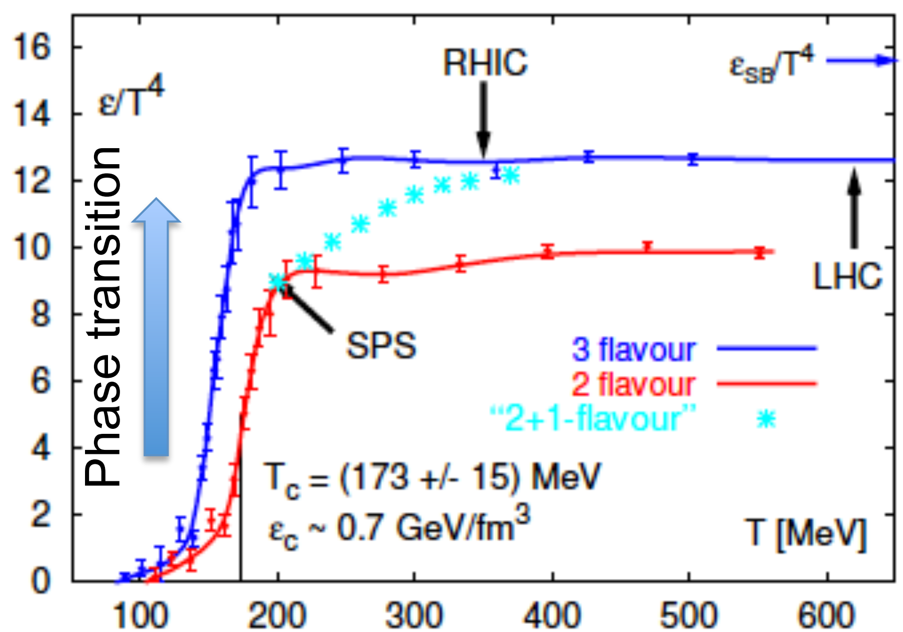
F. Karsch. Lattice QCD at High Temperature and Density. Lecture Notes of Physics, vol. 583, 2002. arXiv:hep-lat/0106019.

Lattice QCD: Phase Transition

Lattice QCD is neither a calculation not a simulation: "realization" of QCD over a discretized space. It allows to compute thermodynamical properties of a system even in a non-perturbative regime of QCD

$$\frac{\varepsilon}{T^4} \quad vs. \quad T \longrightarrow$$ Proportional to number of degrees of freedom (ndof) (S. Boltzmann's law)

$$n_{dof} = n_b + \frac{7}{8} n_f$$



Below T_c: gas of pions

$$n_b = 3(\text{isospin});\ n_f = 0 \quad \Rightarrow n_{dof} = 3$$

Above T_c: gas of g, u, d, (s) and anti-quarks

$$n_b = 8(\text{colors}) \times 2(\text{polar.})$$

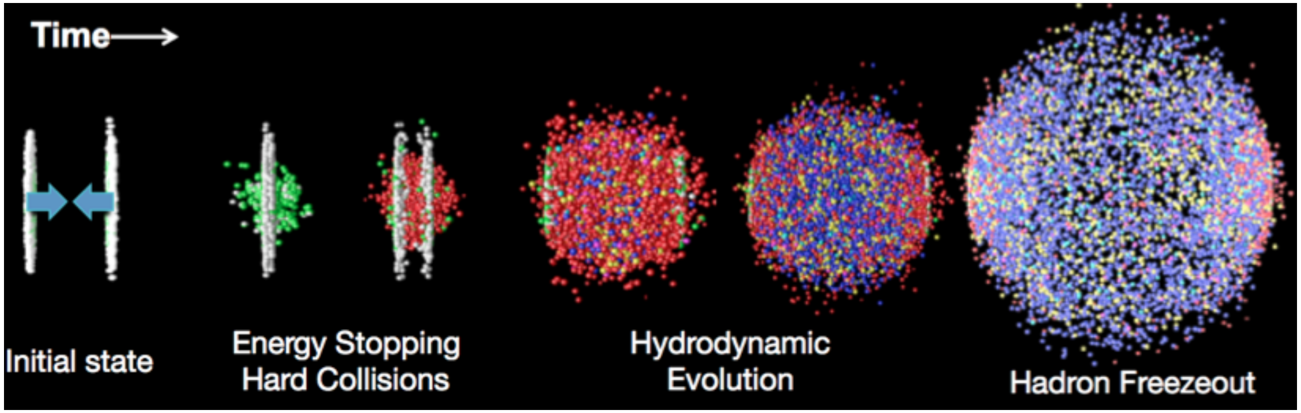
$$n_f = 3(\text{colors}) \times 2(\text{polar.}) \times 2(\text{flav.}) \times 2(\text{charg.})$$

$$\Rightarrow n_{dof} = 37(47.5)$$

F. Karsch. Lattice QCD at High Temperature and Density. Lecture Notes of Physics, vol. 583, 2002. arXiv:hep-lat/0106019.

QGP in laboratory: nucleus-nucleus collisions

- Can we form the QGP in laboratory? Need to compress/heat matter to very high energy densities.



- By colliding two heavy nuclei at ultra-relativistic energies we recreate, for a short time span (about 10^{-23} s, or a few fm/c) the conditions for deconfinement
- As the system expands and cools down it undergoes a phase transition from QGP to hadron again, like at the beginning of the life of the Universe: we end up with confined matter again
- **Chemical freeze out**: time at which inelastic interactions cease →abundances of particle species (π,K,p,.. yields, not resonance) are fixed
- Kinetic freeze out: all interactions cease → free streaming of particles to detector

Ultra-relativistic heavy-ion accelerators

-- only main collision systems are indicated --

- **BNL-AGS**, early '90s, Au-Au up to $\sqrt{s_{NN}} = 5 \text{ GeV}$
- **CERN-SPS**, from 1994, Pb-Pb up to $\sqrt{s_{NN}} = 17 \text{ GeV}$
- **BNL-RHIC**, from 2000, Au-Au $\sqrt{s_{NN}} = 8 - 200 \text{ GeV}$
- **CERN-LHC**, from 2010, Pb-Pb $\sqrt{s_{NN}} = 2.76 - 5.5 \text{ TeV}$

By increasing collision energy we produce a QGP

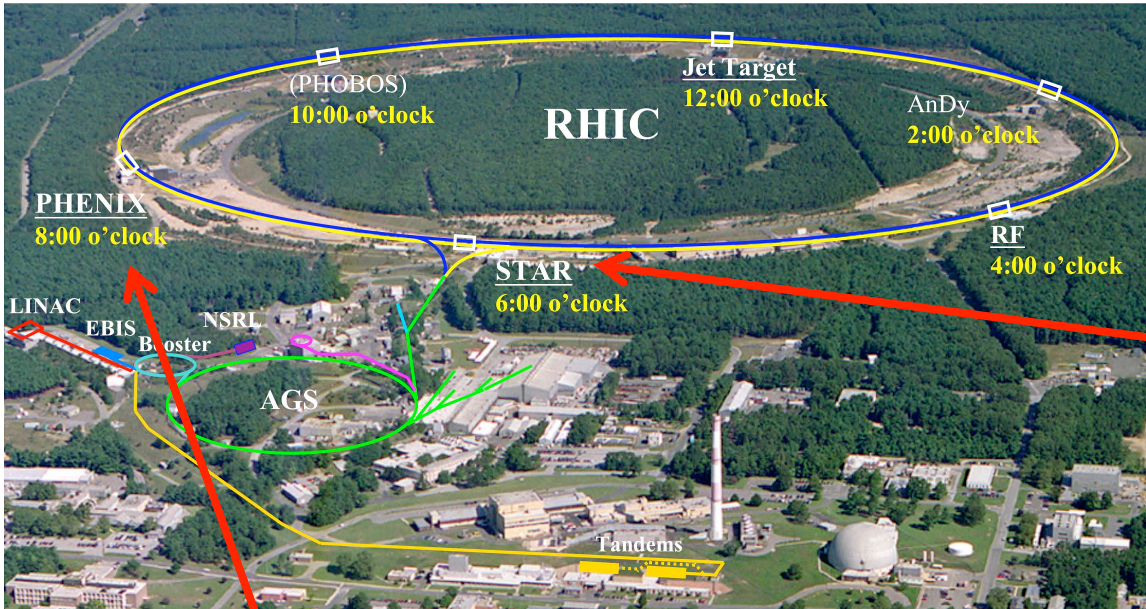
→ with higher initial energy density and temperature

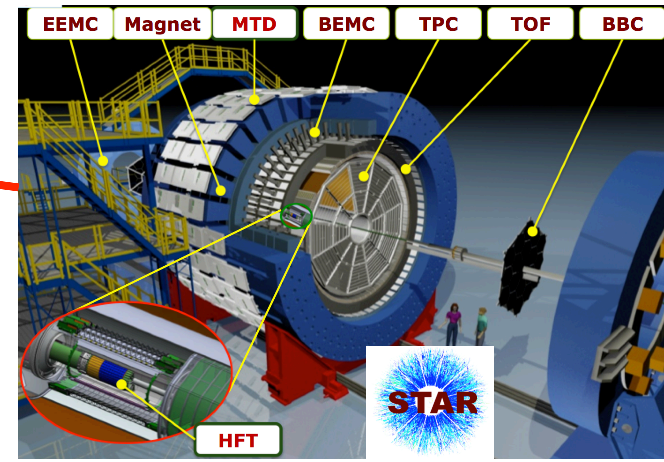
→ longer living

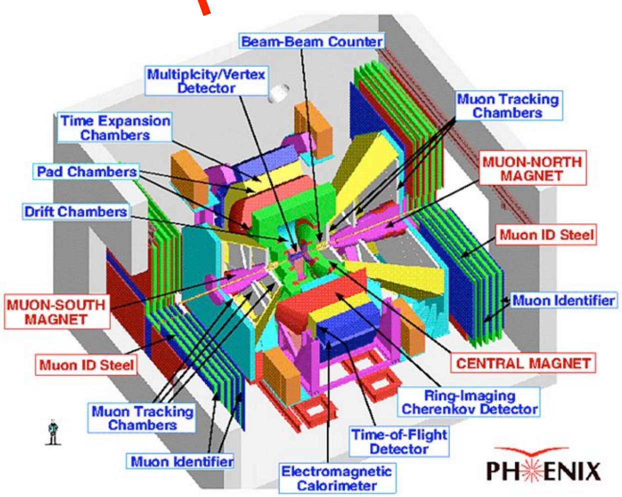
→ with reduced baryon density (number of baryons = anti-baryons), thus closer to early Universe conditions (and to available lQCD calculations)

+ larger cross section (→higher yield) for rare "energetic" probes (heavy quarks, jets, W/Z,…)

Heavy-ion experiments at RHIC

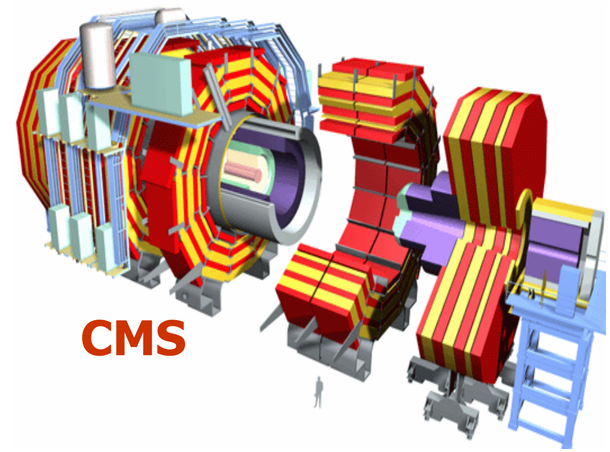


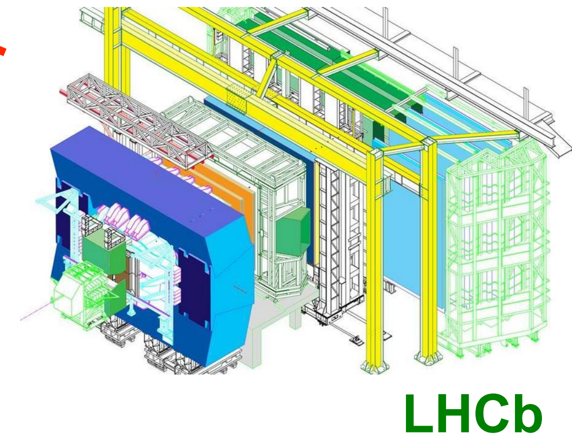


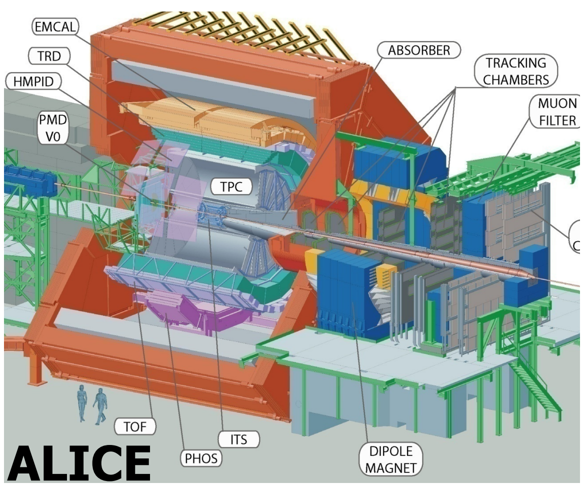


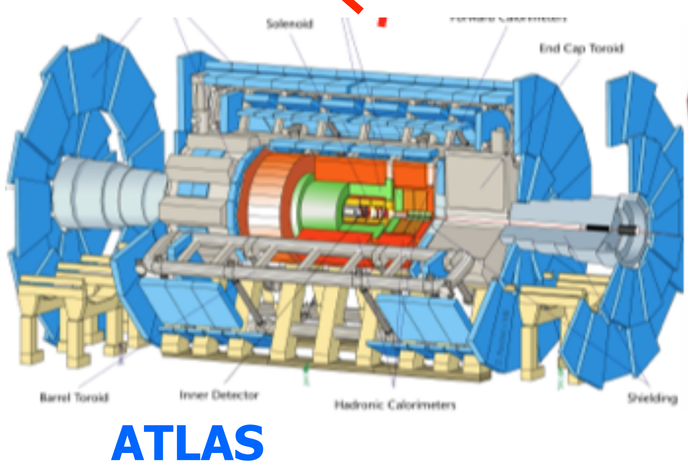
+ (completed) PHOBOS, BRAHMS

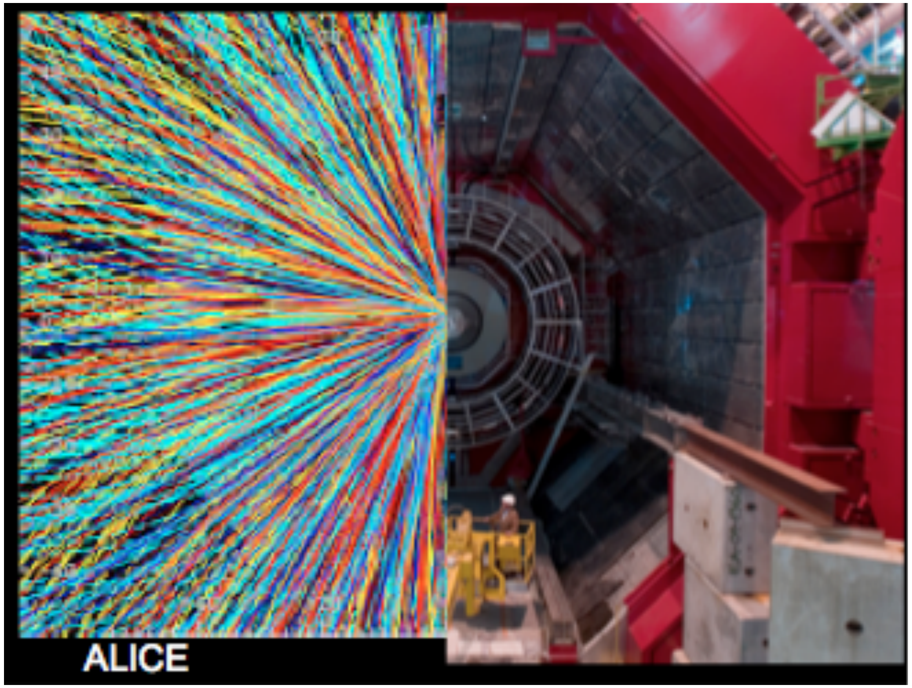
Heavy-ion experiments at the LHC







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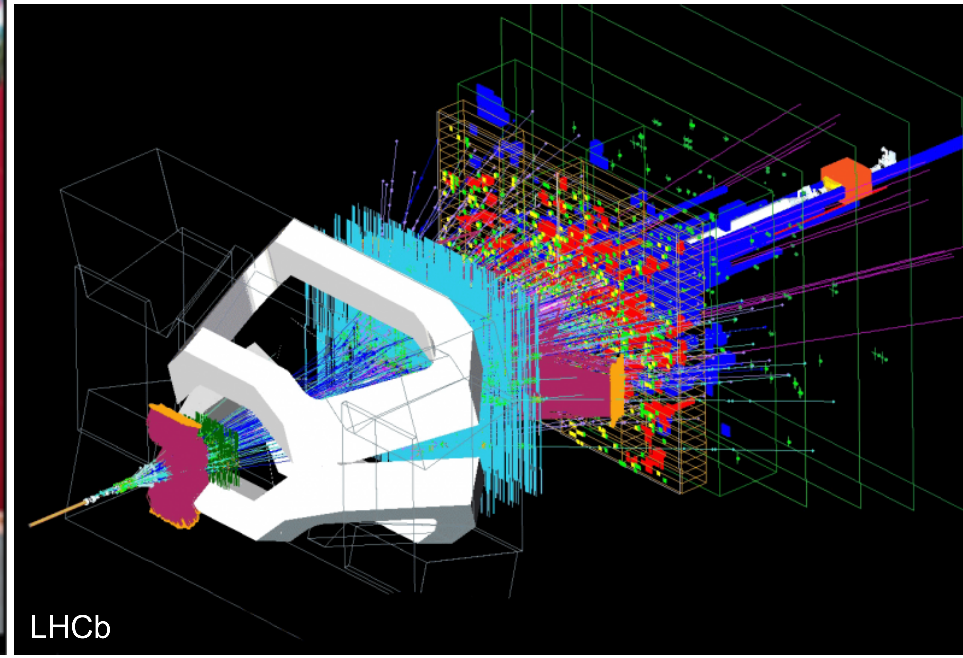
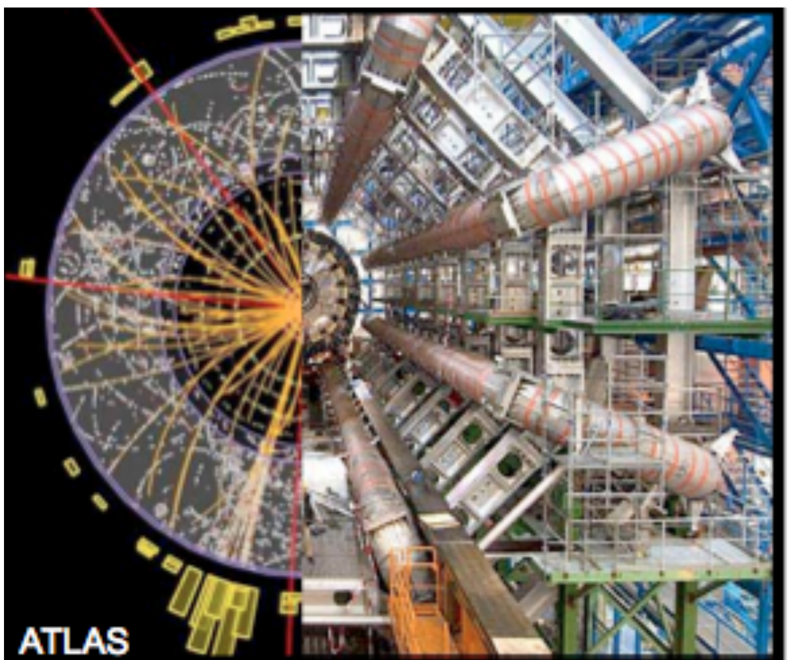
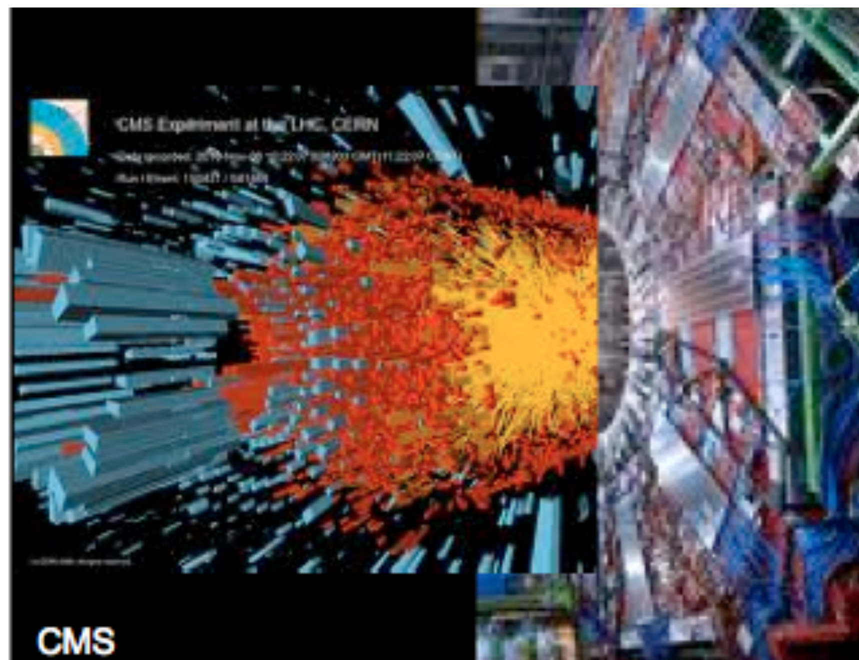
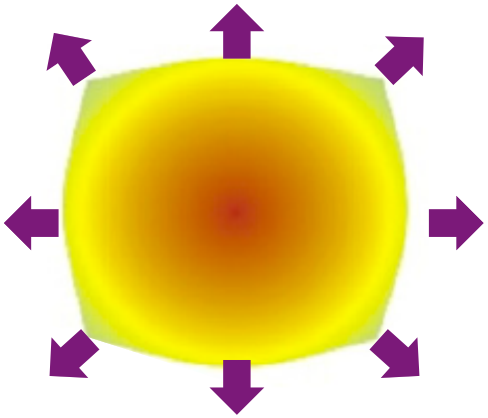

LHCb

ATLAS

CMS Experiment at the LHC, CERN
CMS

Outline

- How do we know that we that QGP is formed in heavy-ion collisions?
- What are its global properties (temperature, energy density, etc.) and how can we assess them?
- How can we access the local “partonic” interactions in the medium and obtain a microscopic picture of it?

Soft and hard probes

N.b. a simplistic and incomplete classification!

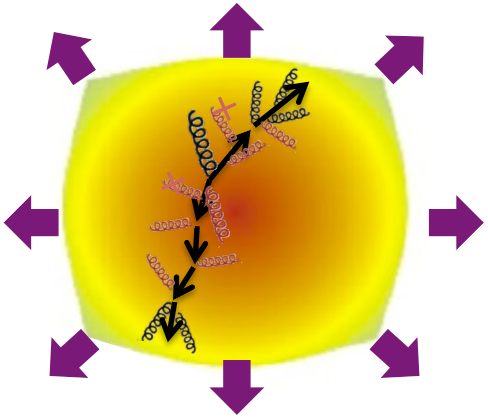


“Soft” probes

(e.g. light-flavour particle spectra and flow at low p_T)

Probe system as a whole

Test hydrodynamic description to extract global properties of the medium and of its evolution (e.g. temperature, density, viscosity, expansion velocity)



“Hard” probes

(e.g. high p_T particles, heavy flavours, quarkonia, jets)

Access **microscopic processes in the medium**

Resolve medium constituents (quarks and gluons)

Address transport coefficients, mean free path,…

⇩

Connection of global medium properties with “local” interactions

Microscopic description of the medium

Few introductory concepts

Transverse momentum (p_T): component of momentum transverse to the beam direction

Center-of-mass energy in nucleus-nucleus collisions

Accelerator exploits Lorentz force: $\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$

Electric field provides acceleration or rather energy gain

Magnetic field keeps particles on their path

q =|*e*| for protons, *Ze* for a nucleus with (*Z,A*)

→ With same E a nucleus gets Z times more energy, but its “inertia” is A times larger

→ Momentum “per nucleon” (=proton, neutron) = *p* x *Z/A* with *p* = momentum for beam of protons

Center-of-mass energy (collider at ultra-relativistic energies, E>>mass):

$$p_1^\mu = (p,0,0,p) \quad p_2^\mu = (p,0,0,-p) \rightarrow \sqrt{s} = \sqrt{(p_1^\mu + p_2^\mu)^2} = 2p$$

“Nucleon-nucleon” center-of-mass energy $\sqrt{s_{\mathrm{NN}}} = \sqrt{s_{\mathrm{pp}}} \sqrt{\dfrac{Z_1 Z_2}{A_1 A_2}}$

This is the relevant collision energy “scale” for ultra-relativistic heavy-ion collision

The mass number (A) influences the system size

Few introductory concepts: centrality, R_{AA}

Nuclear modification factor (R_{AA}): compare particle production in Pb-Pb with that in pp scaled by a "geometrical" factor (from Glauber model) to account for the larger number of nucleon-nucleon collisions

$$R_{AA}(p_T) = \frac{dN_{AA}/dp_T}{\langle N_{coll} \rangle \times dN_{pp}/dp_T}$$

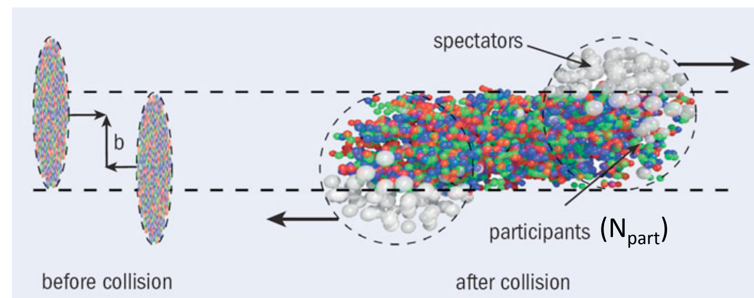
Pb-Pb

pp

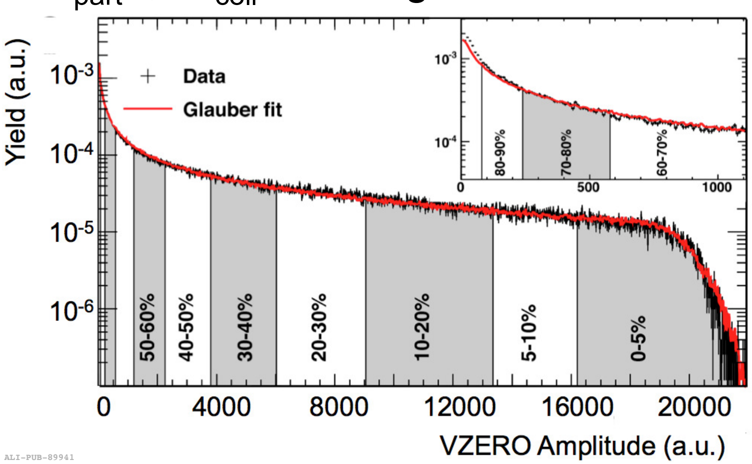
Binary nucleon-nucleon collisions, encodes collision geometry

If $R_{AA}=1$ → no nuclear effects

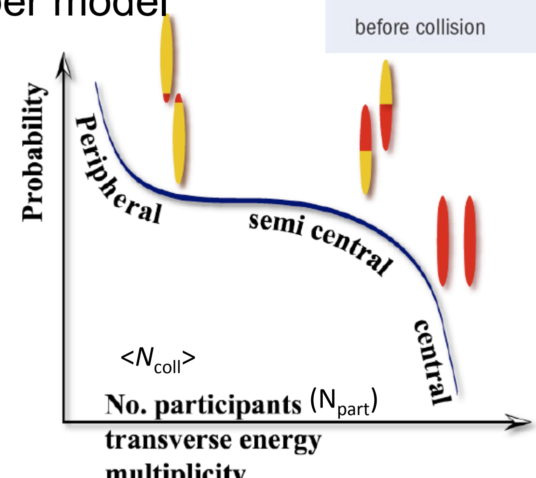
If $R_{AA}\neq 1$ → nuclear effects



$\langle N_{part} \rangle$, $\langle N_{coll} \rangle$ from "geometrical" Glauber model



~ particle multiplicity/deposited energy



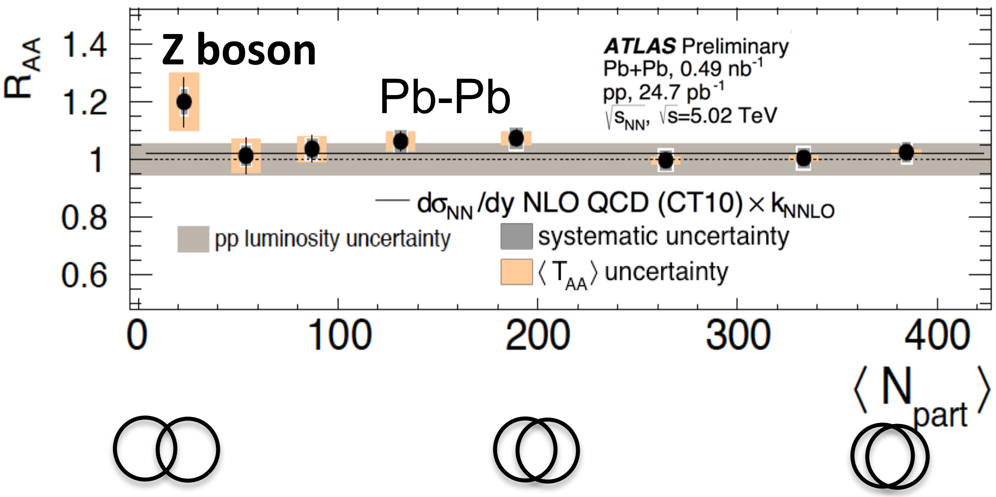
Note: N_{coll} scaling expected to hold only for hard (rare) processes

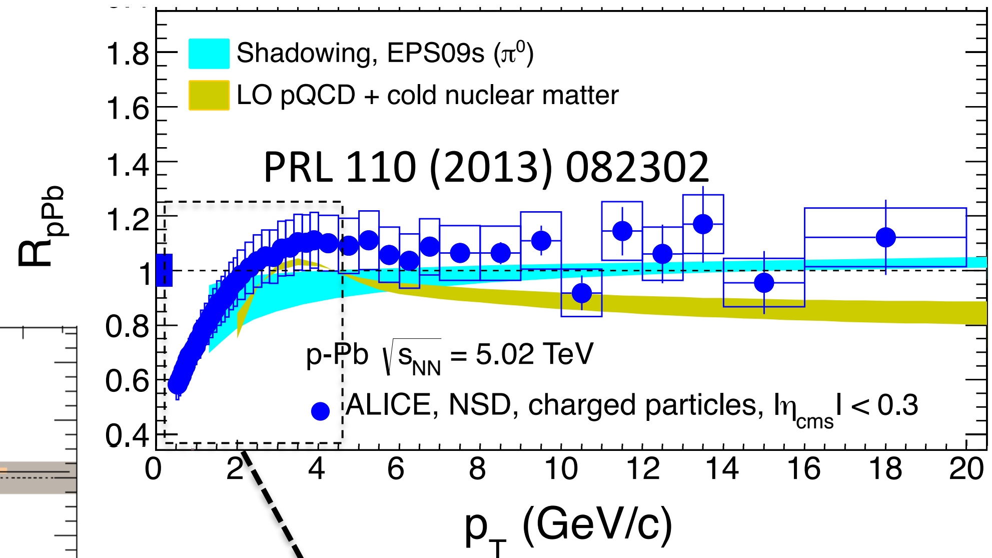
Geometry of heavy ion collisions

How can we be sure that we have the collision geometry under control?

→ Smaller/simpler collision systems (QGP not formed / not big impact on hard-probes production)

↓ Probes not sensitive to medium formation
→ electroweak signals (γ,W, Z bosons)





Caveats: breaking of N_{coll} scaling (soft processes) + initial state/ cold-nuclear matter effects at low p_T

CONF-2017-010

QGP discovery, two “historical” signatures: strangeness enhancement and J/ψ suppression

Quarkonium in the QGP

Bound quark-antiquark states: "charmonia" χ_c , J/ψ, ψ(2S),...
"bottomonia" Υ, Υ(2S), Υ(4S),..

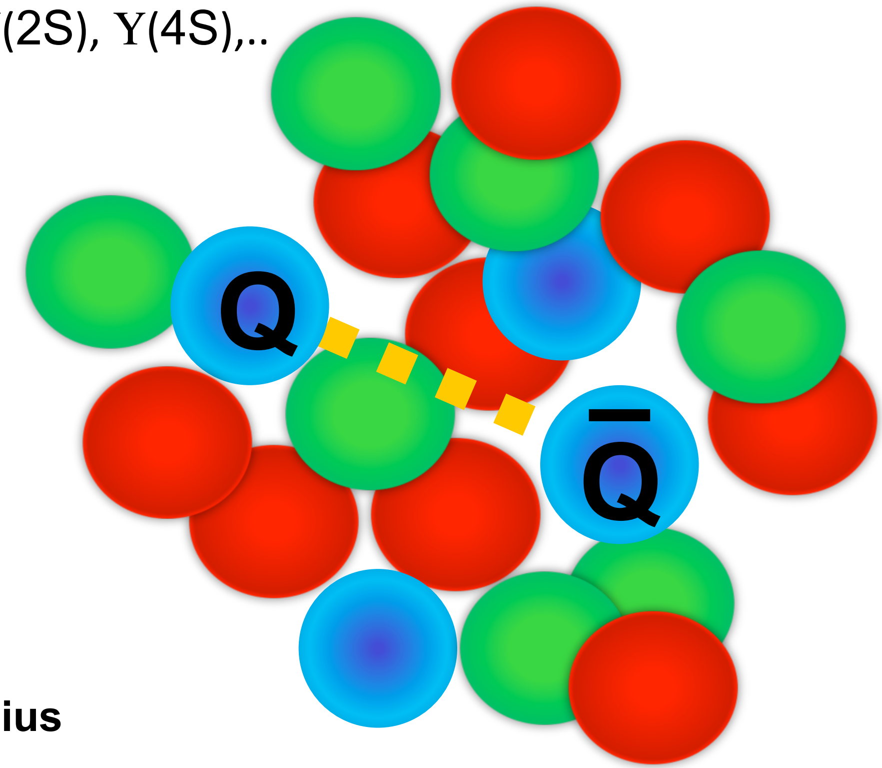
Recall: quant-antiquark QCD potential

$$V(r) = -\frac{\alpha}{r} + kr$$

The QGP consists of deconfined colour charges → screening effect

$$V(r) = -\frac{\alpha}{r} e^{-r/\lambda_D}$$

λ_D: screening radius

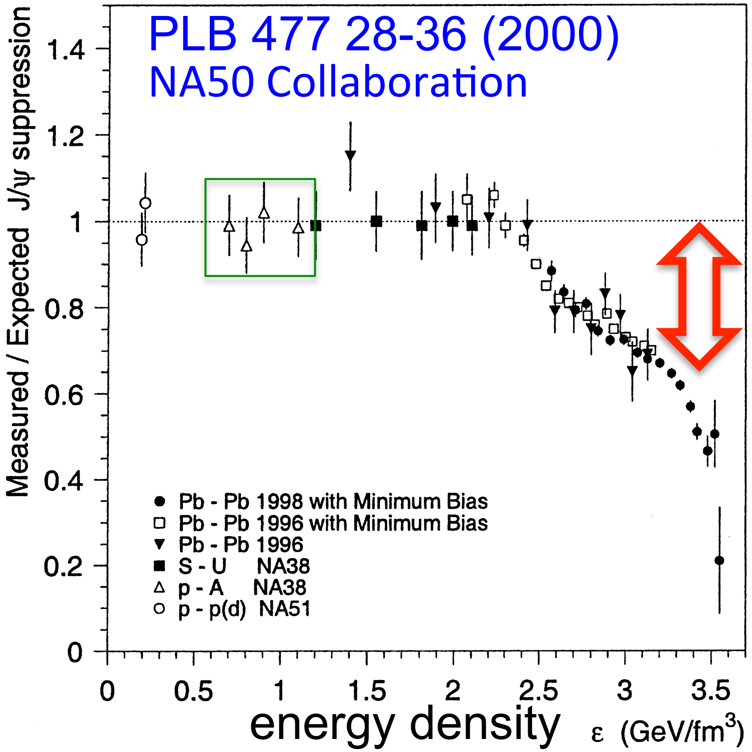


The binding of a $q\bar{q}$ pair is subject to the effects of colour screening:

- the "confinement" contribution disappears
- the coulumbian term of the potential is screened by the high color density

Matsui, Satz, PLB178 (1986) 416

J/ψ suppression
-- QGP discovery smoking gun --

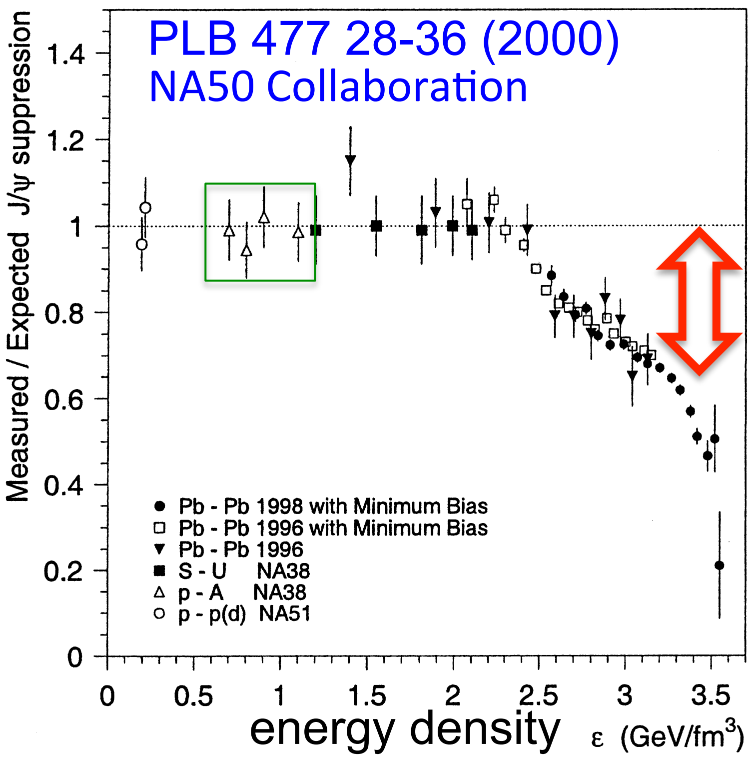


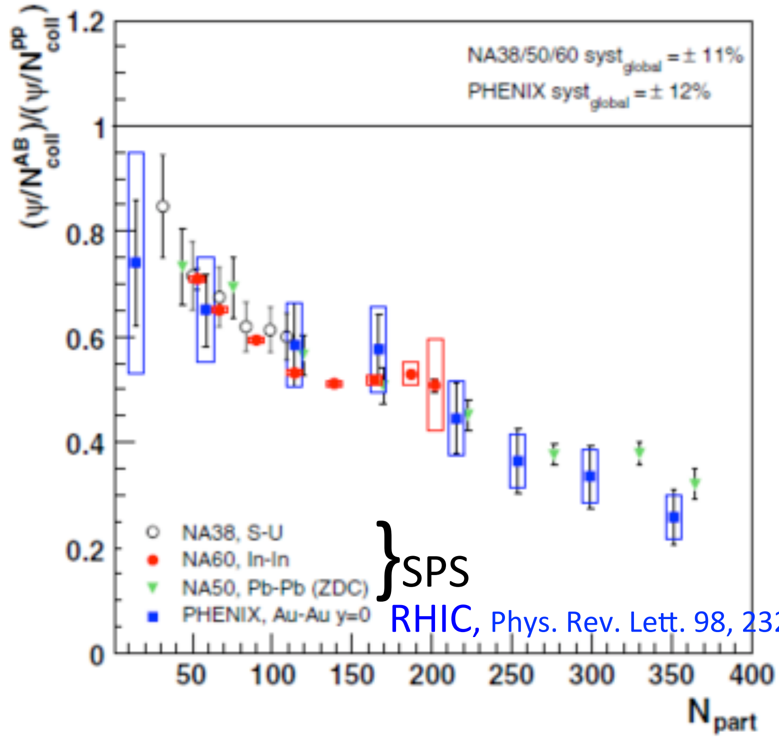
N.b. "expected suppression" = J/ψ absorption in "cold" nuclear matter (no QGP). Not discussed in the slides, but note: p-A needed as reference

Not first observation:
NA51 Collaboration, PLB 438 35 (1998)
NA38 Collaboration, PLB 444 516 (1998); PLB 449 128 (1999)

J/ψ suppression
-- QGP discovery smoking gun --

N.B. different quantities plotted on both x and y axes





Not first observation:
NA51 Collaboration, PLB 438 35 (1998)
NA38 Collaboration, PLB 444 516 (1998); PLB 449 128 (1999)

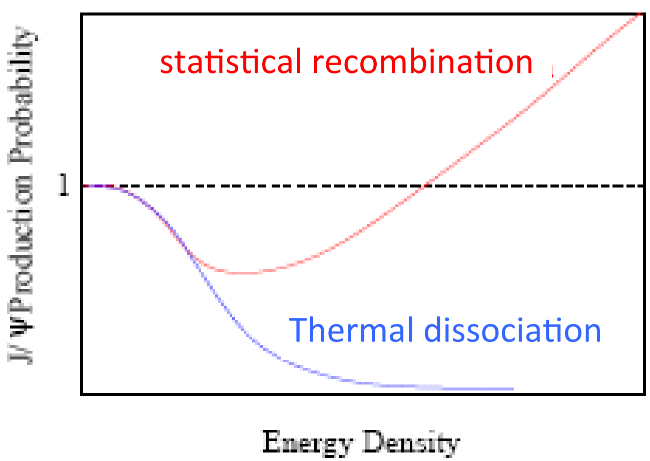
Adding RHIC data:
similar suppression than SPS,
despite the x12 larger collision energy (x2 ε)… unexpected!

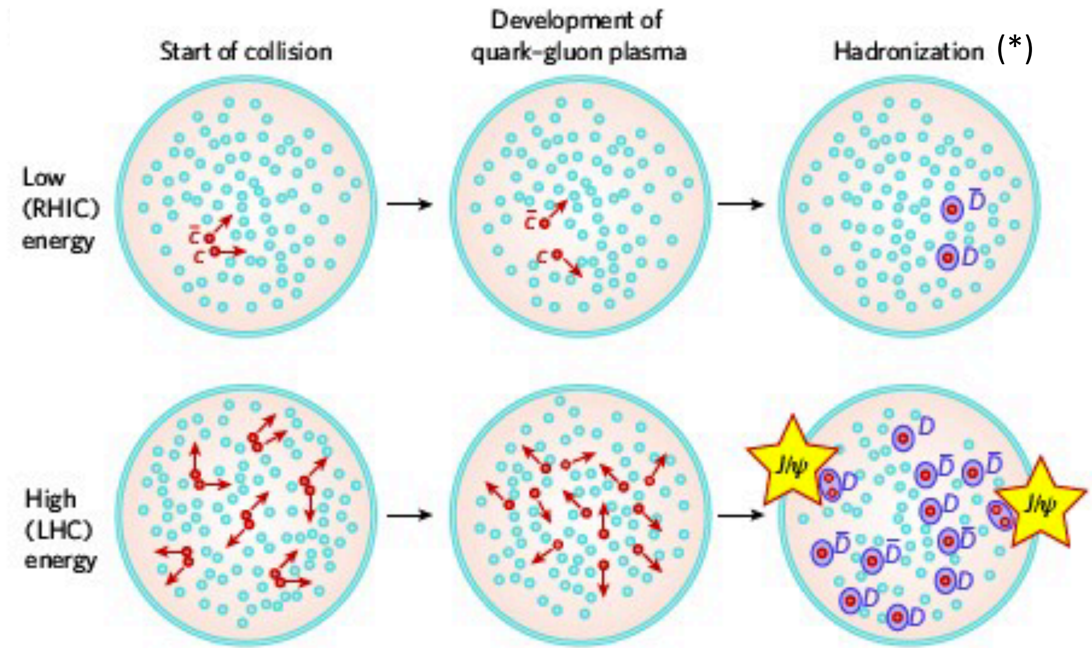
Quarkonium suppression & regeneration

Hot QGP→ **quarkonia suppression** due to Debye-like screening of QCD $Q\bar{Q}$ potential ("melting" of bound $Q\bar{Q}$ states) → **signature of deconfinement**
(T. Matsui and H. Satz, PLB 178 (1986) 416)

Surprisingly **similar J/ψ suppression at SPS and RHIC (εx2) energies**

→ Could quarkonia states be **(re)generated via recombination (coalescence) of deconfined quarks**? (P. Braun-Munzinger, J. Stachel, PLB 490 (2000) 196)



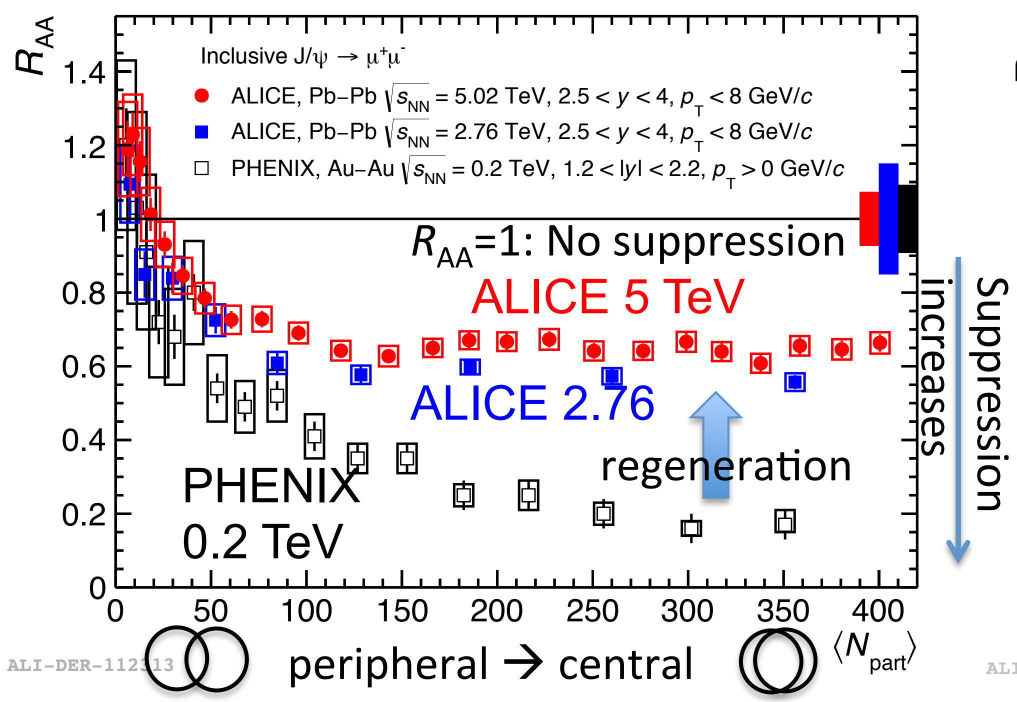


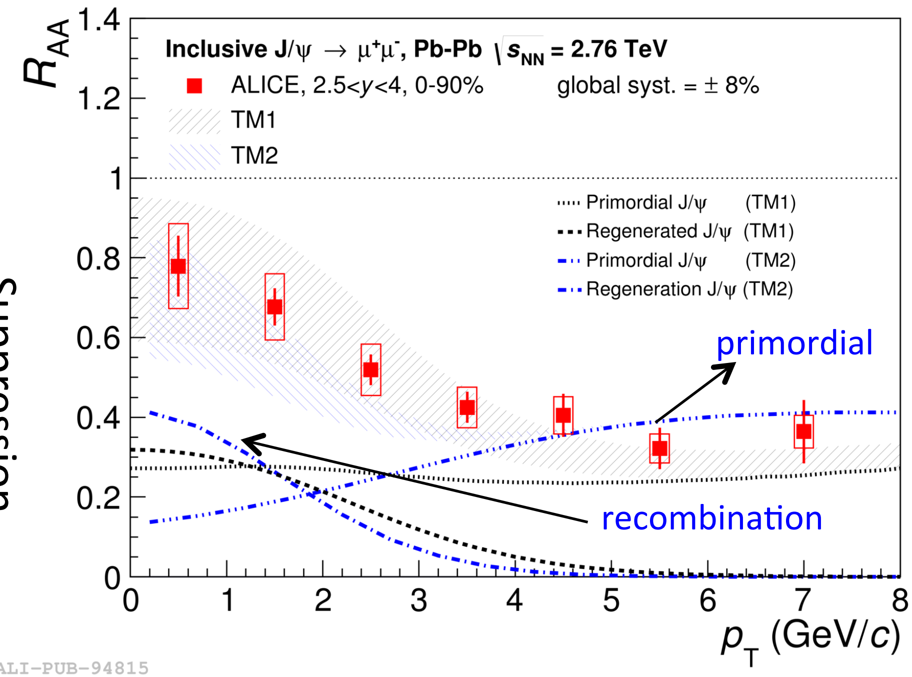
LHC vs. RHIC

Larger energy density → **stronger suppression**
Higher $c\bar{c}$ multiplicity → **larger recombination**

(*) Note that "in vacuum":
(ccbar →J/ψ) / (ccbar →DDbar) <<1 (~1-2%)

J/ψ suppression: LHC vs. RHIC

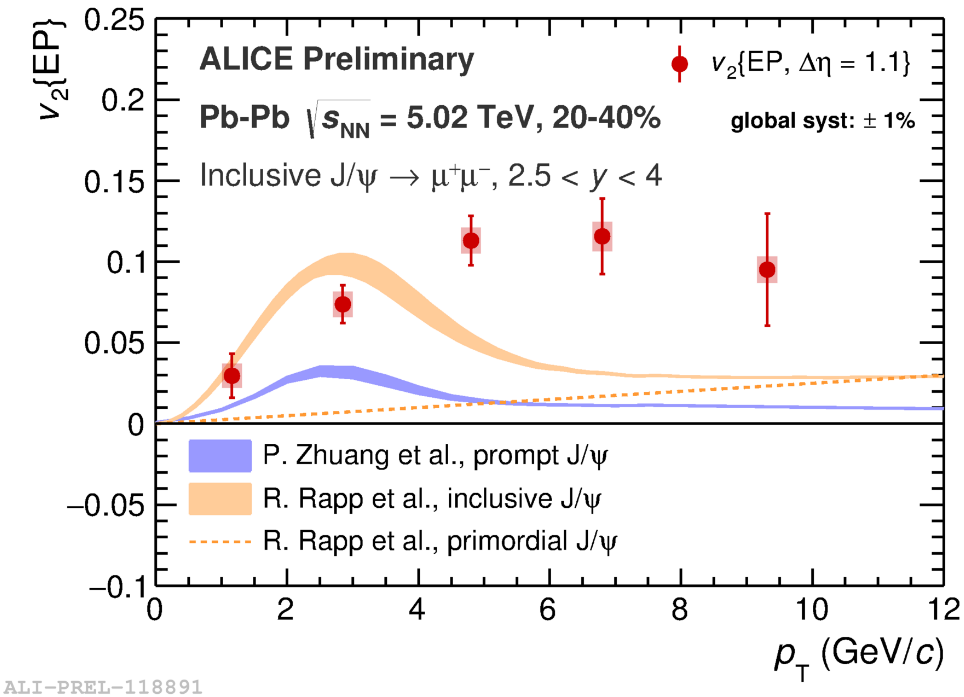


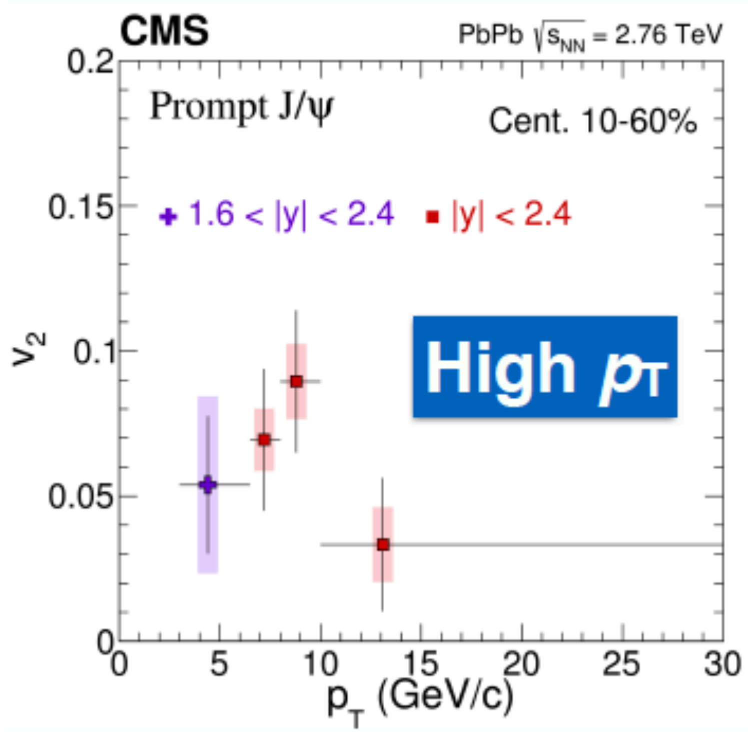


- J/ψ suppression stronger in central events than peripheral
- Smaller suppression at LHC than RHIC
- Analysis vs. transverse momentum: suppression stronger at higher momentum. In agreement with models expecting about 50% contribution of J/ψ from recombination at low p_T.

"Twice a signature of QGP"

J/ψ elliptic flow





EPJC 77 (2017) 252

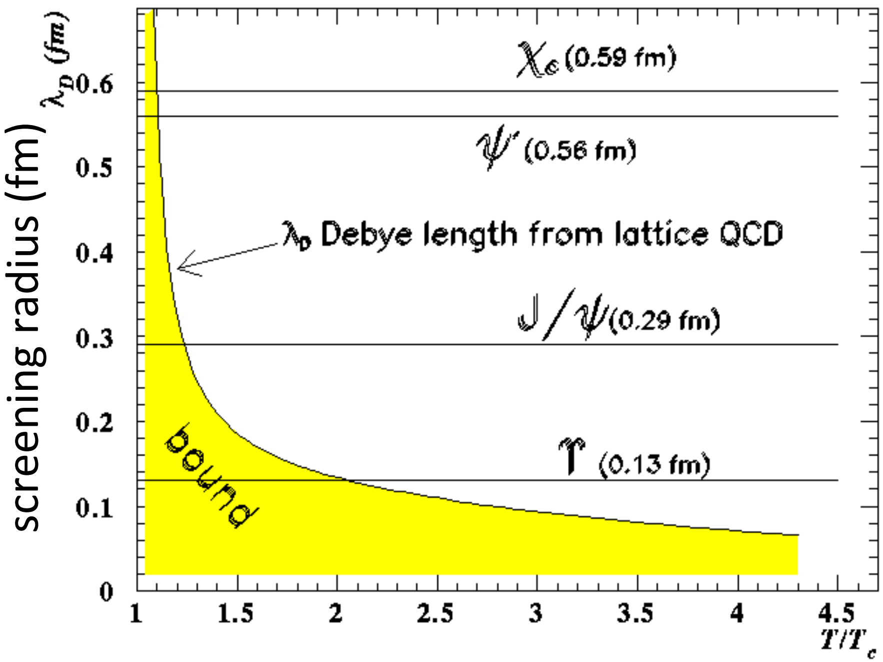
Positive J/ψ elliptic flow
Expected for J/ψ from recombination
Remains high at high p_T → not expected from models

Quarkonium suppression in the QGP

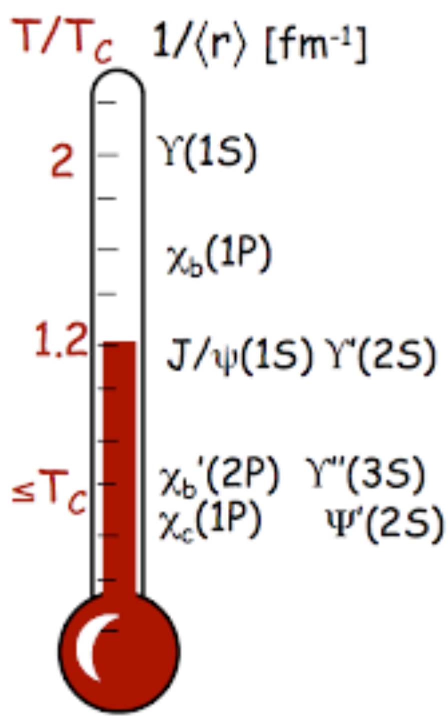
- The radius *r* of a quarkonium state is inversely proportional to its binding energy → different quarkonia have different radii
- In a QGP with Debye screening radius λ_D, the quarkonium states with radius $r > \lambda_D$ are not surviving, they "melt"
- The screening radius λ_D decreases with increasing temperature

→ "Sequential" suppression of quarkonia states

→ Quarkonium states as a "Thermometer of the QGP"

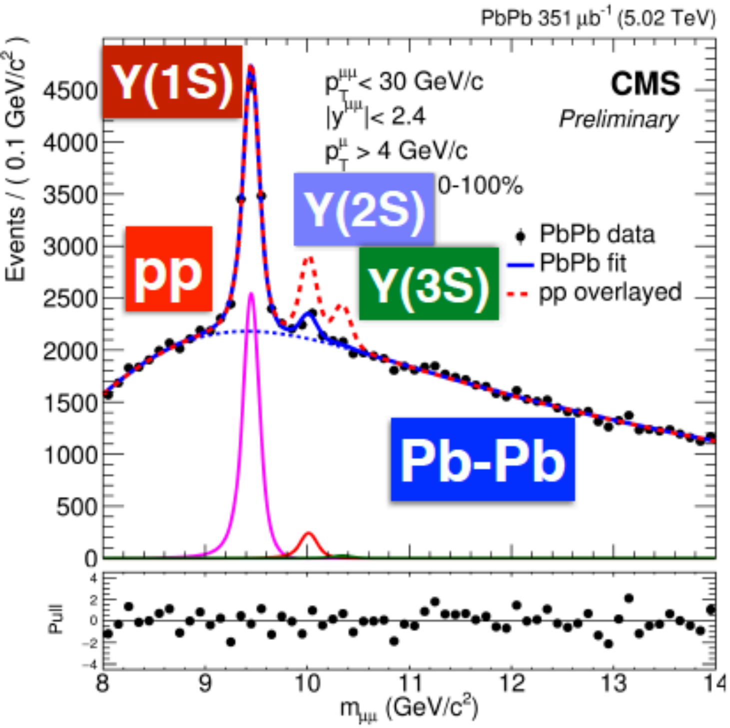


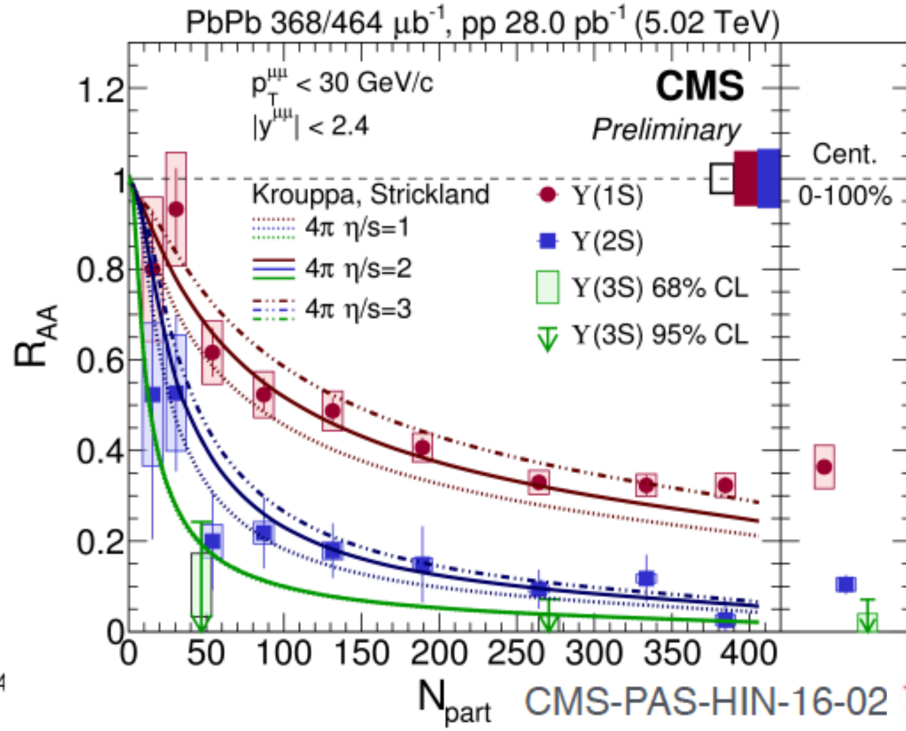
Digal,Petrecki,Satz PRD 64(2001) 0940150

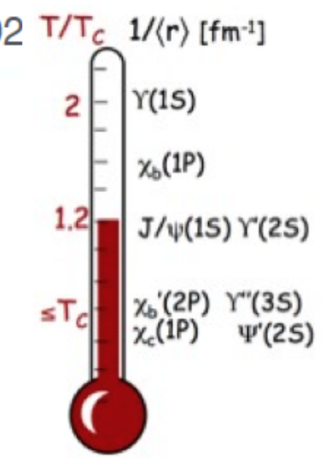


A. Mocsy, Eur.Phys.J. C61 (2009)

Bottomonium suppression







- Y(1s) ($E_{binding}$~1100 MeV), Y(2s) and Y(3s) (Eb~200 MeV) have different sensitivity to the medium
- Strong suppression of Y(2s,3s) with respect to Y(1s) increasing with centrality

→Trend expected from "sequential suppression"

QCD Lagrangian and spontaneous breaking of chiral symmetry

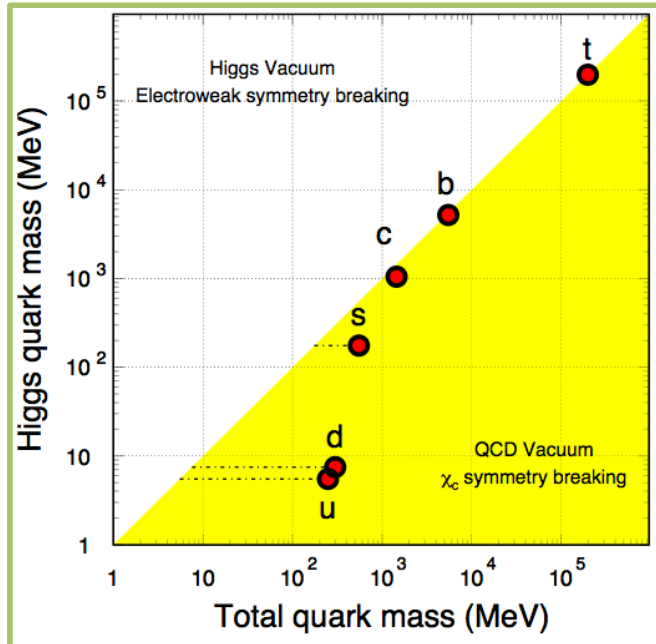
$$\mathcal{L}_{QCD} = \bar{\psi}_i \left(i(\gamma^\mu D_\mu)_{ij} - \cancel{m\,}\delta_{ij}\right)\psi_j - \frac{1}{4} G^a_{\mu\nu} G_a^{\mu\nu}$$

with m = "bare" mass

Strong interaction is insensitive to quark flavour: it "distinguishes" quarks only on the basis of their mass.

In the limit in which all quark masses are identical →Symmetry under the group SU(N_f) for rotating in quark fields in the flavour space → Isospin

In the limit of vanishing quark masses, the QCD Lagrangian becomes symmetric under transformations under the group SU(N_f)$_L$ × SU(N_f)$_R$: **chiral symmetry.**



X.Zhu et al., PLB 647 (2007) 366

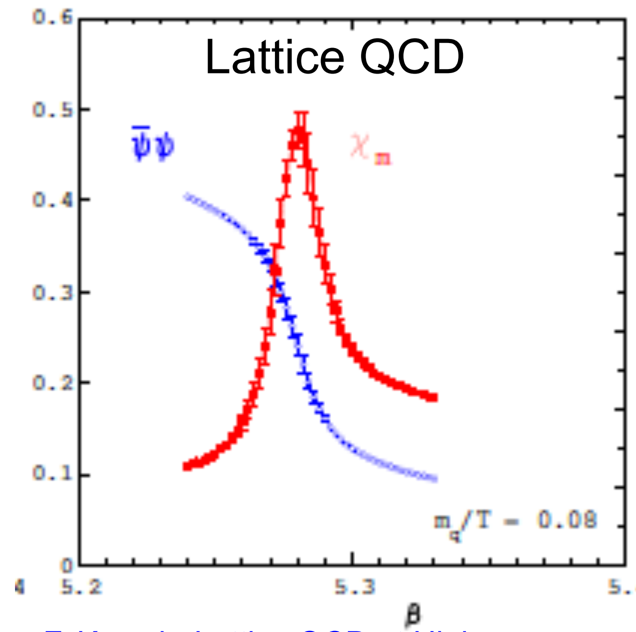
However, chiral symmetry is spontaneously broken by the non-zero expectation value of the chiral condensate $\langle \psi\bar{\psi} \rangle \neq 0$ in vacuum, which means that the QCD vacuum (at *T*=0) breaks the chiral symmetry. This mechanisms generates a "dynamical" mass for quarks, which is responsible for most of the matter mass.
This symmetry is approximately valid for u,d,(s) quarks (lightest).

Restoration of bare quark masses in the QGP (T>0)

Deconfinement is expected to be accompanied by a "Partial Restoration of Chiral Symmetry", due to the vanishing of the $\langle \psi\bar{\psi} \rangle$ expectation value. Quarks reacquire the "bare" mass values they have in the Lagrangian

– m(u,d): ~ 350 MeV $\rightarrow$ a few MeV
– m(s): ~ 500 MeV $\rightarrow$ ~ 150 MeV

Since the symmetry is exact only for massless particles, therefore its restoration here is only partial.



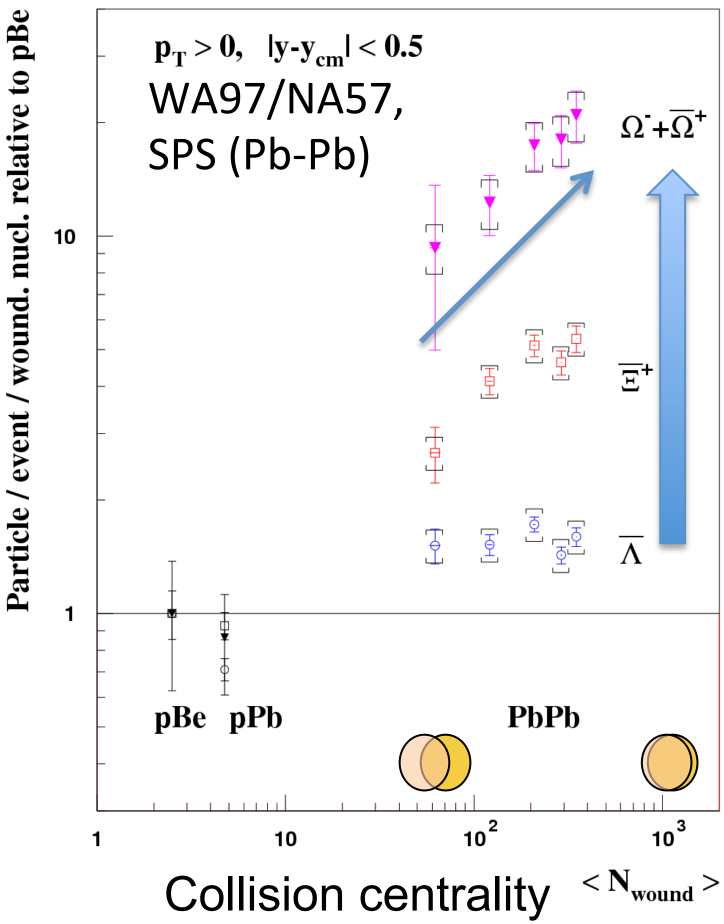
F. Karsch. Lattice QCD at High Temperature and Density. Lecture Notes of Physics, vol. 583, 2002. arXiv:hep-lat/0106019

Consequence:
it's easier to produce strange quarks!

Strangeness enhancement searched fot as a proof of chiral symmetry restoration (- - > deconfinement, with some caveats)

Strangeness enhancement at SPS

PLB449 (1999) 401



Ω=(sss), Ξ^-=(ssd) Λ=(uds)

Increased production of strange particles observed to w.r.t. to what measured in p-Be (no QGP)

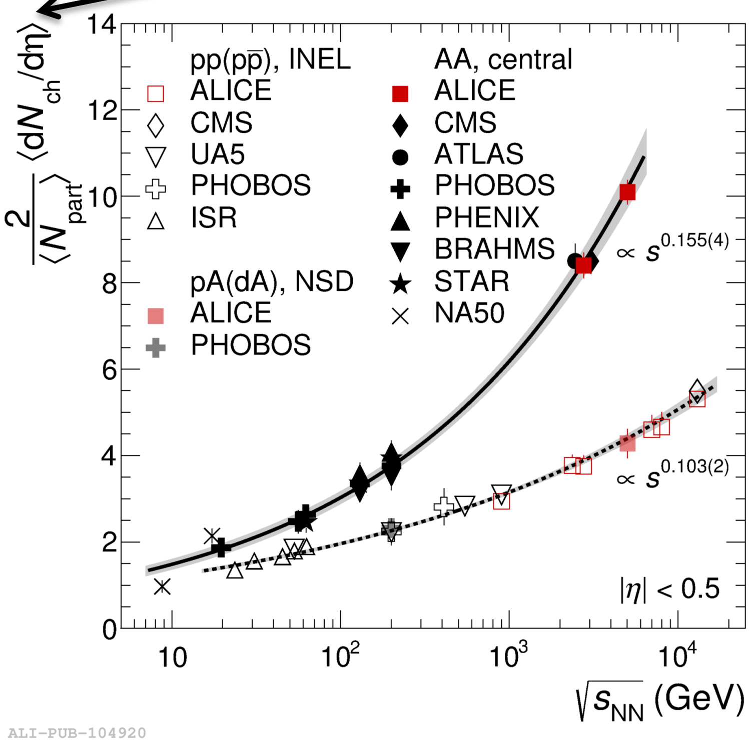
Effect larger for particles with higher strange content

Effect increasing towards more central events

Medium global properties

Energy density

- Particle multiplicity at mid-rapidity → transverse energy density



[Phys. Rev. Lett. 116 (2016) 222302]

Bjorken formula:

$$\varepsilon = \frac{E}{V} = \frac{1}{Sc\tau_0}\frac{dE_T}{dy}\bigg|_{y=0}$$

S = transverse dimension of nucleus

τ_0 = "formation time"~1 fm/c

	SPS	RHIC	LHC
$\frac{dE_T}{dy}\Big\|_{y=o}$ (GeV) *	400	800	2000
ε (GeV/fm^3) *	2.5	5	12

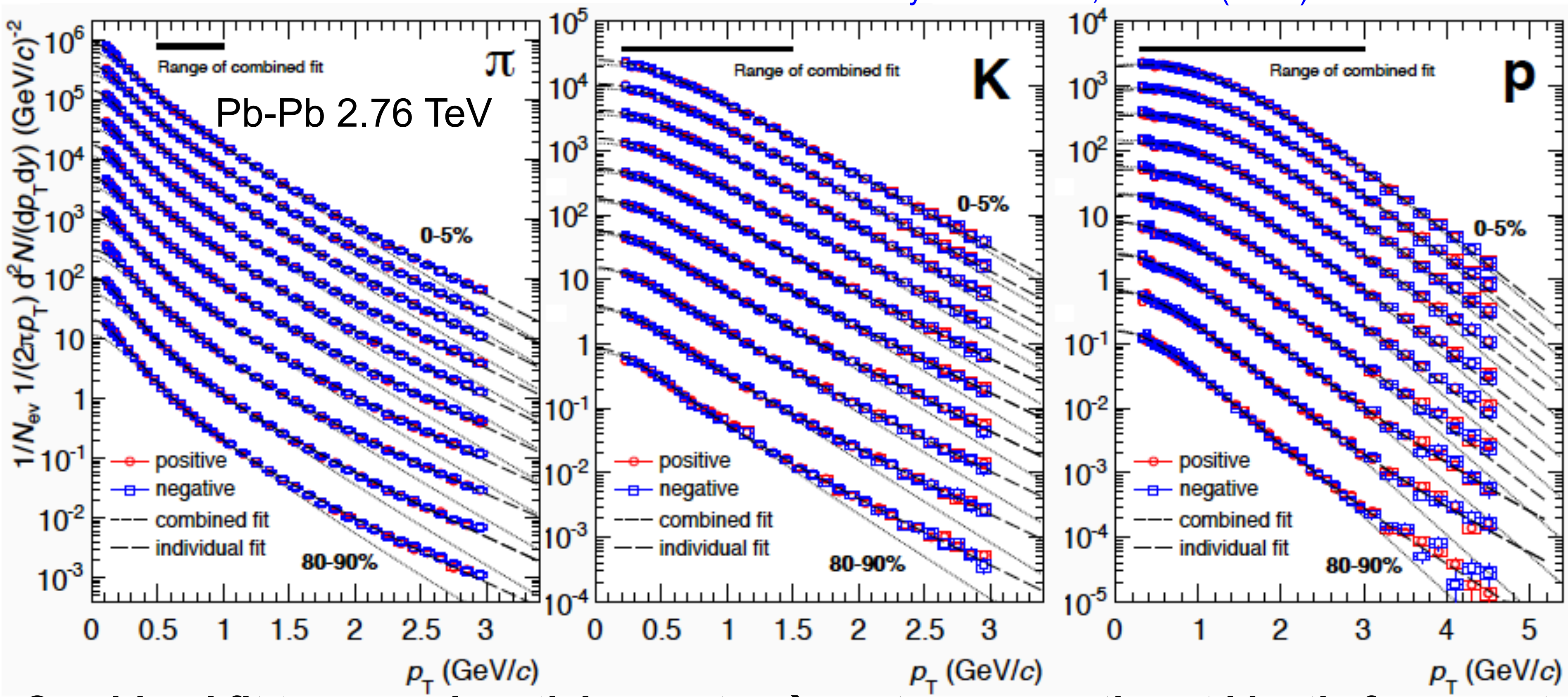
*Indicative numbers

More than enough for deconfinement!

ε_c ~ 0.6 GeV/fm^3

Kinetic freeze-out temperature

Phys. Rev. C 88, 044910 (2013)

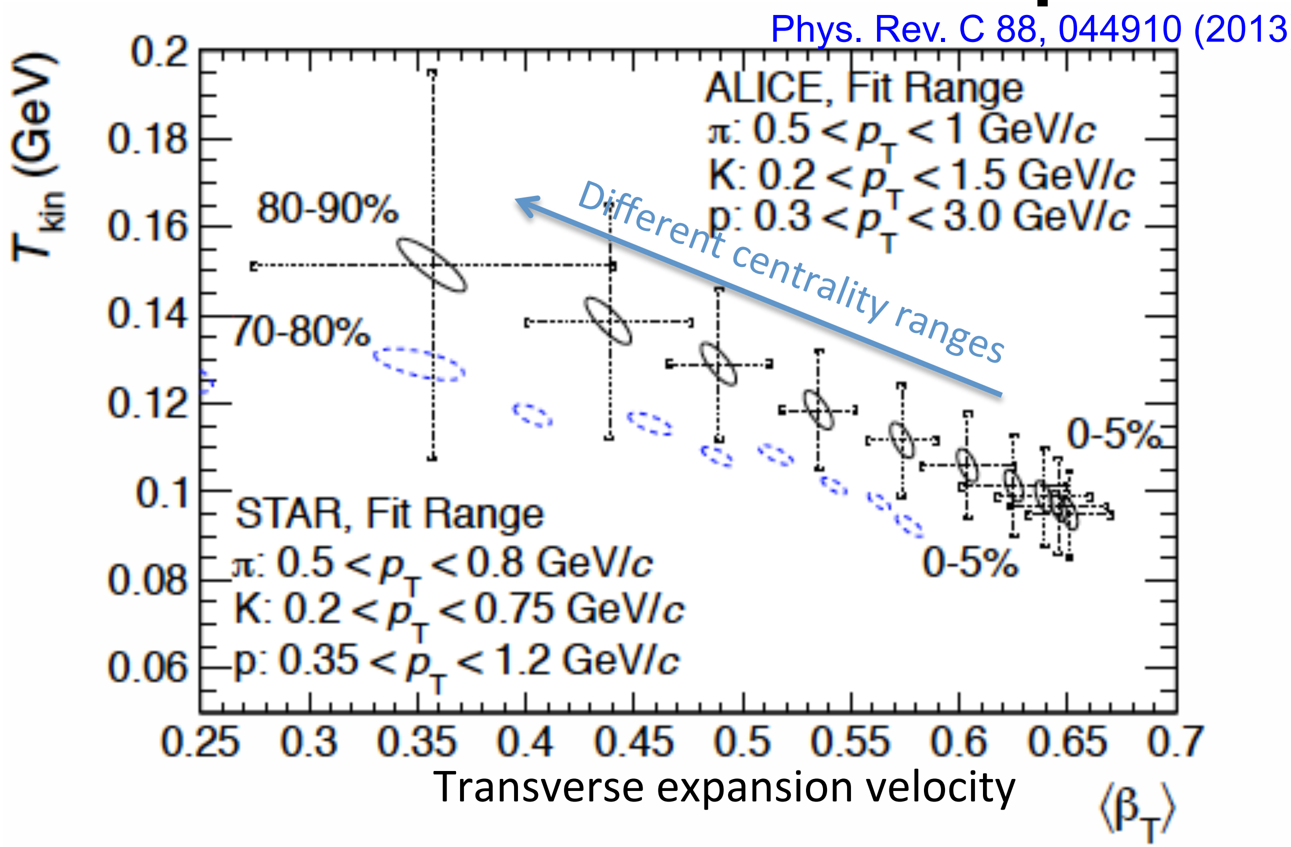


Combined fit to several particle spectra → system properties at kinetic freeze-out

"Blast-wave" model: thermalized volume elements expanding in a common velocity field (→ convolution of thermal velocity with expansion velocity)

- Goodness of the global fit → hydro-dynamical description holds

Kinetic freeze-out temperature

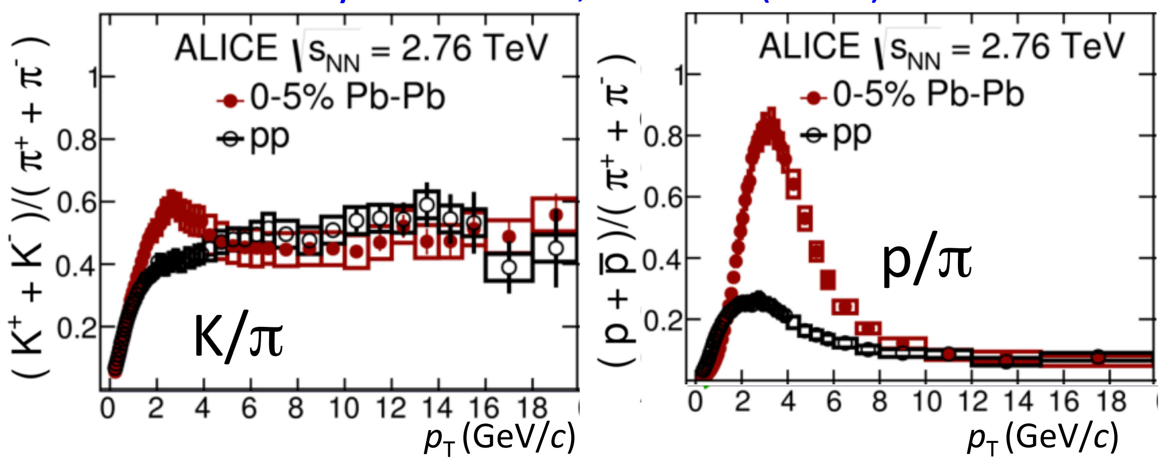


Combined fit to several particle spectra → system properties at kinetic freeze-out
"Blast-wave" model: thermalized volume elements expanding in a common velocity field (→ convolution of thermal velocity with expansion velocity)

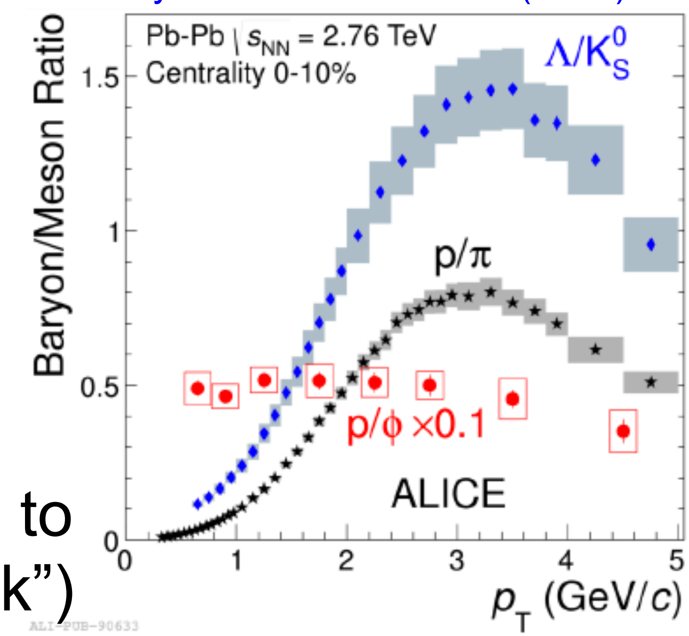
- Goodness of the global fit → hydro-dynamical description holds
- In central collisions at LHC: ***T_{kin}*~ 90 MeV, transverse expansion velocity ~0.65 *c***

Particle ratios

Phys. Rev. C 93, 034913 (2016)



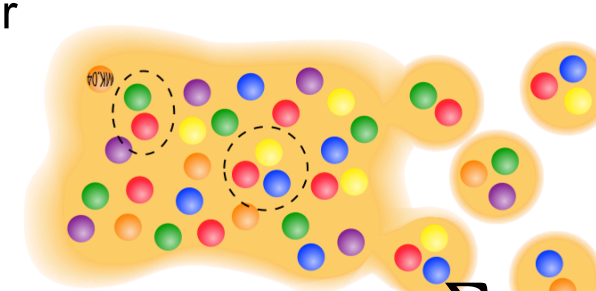
Phys. Rev. C 91 024609 (2015)



Strong modification of p/π vs. p_T from pp to central Pb-Pb collisions ("radial flow peak")

Indication of collective behaviour

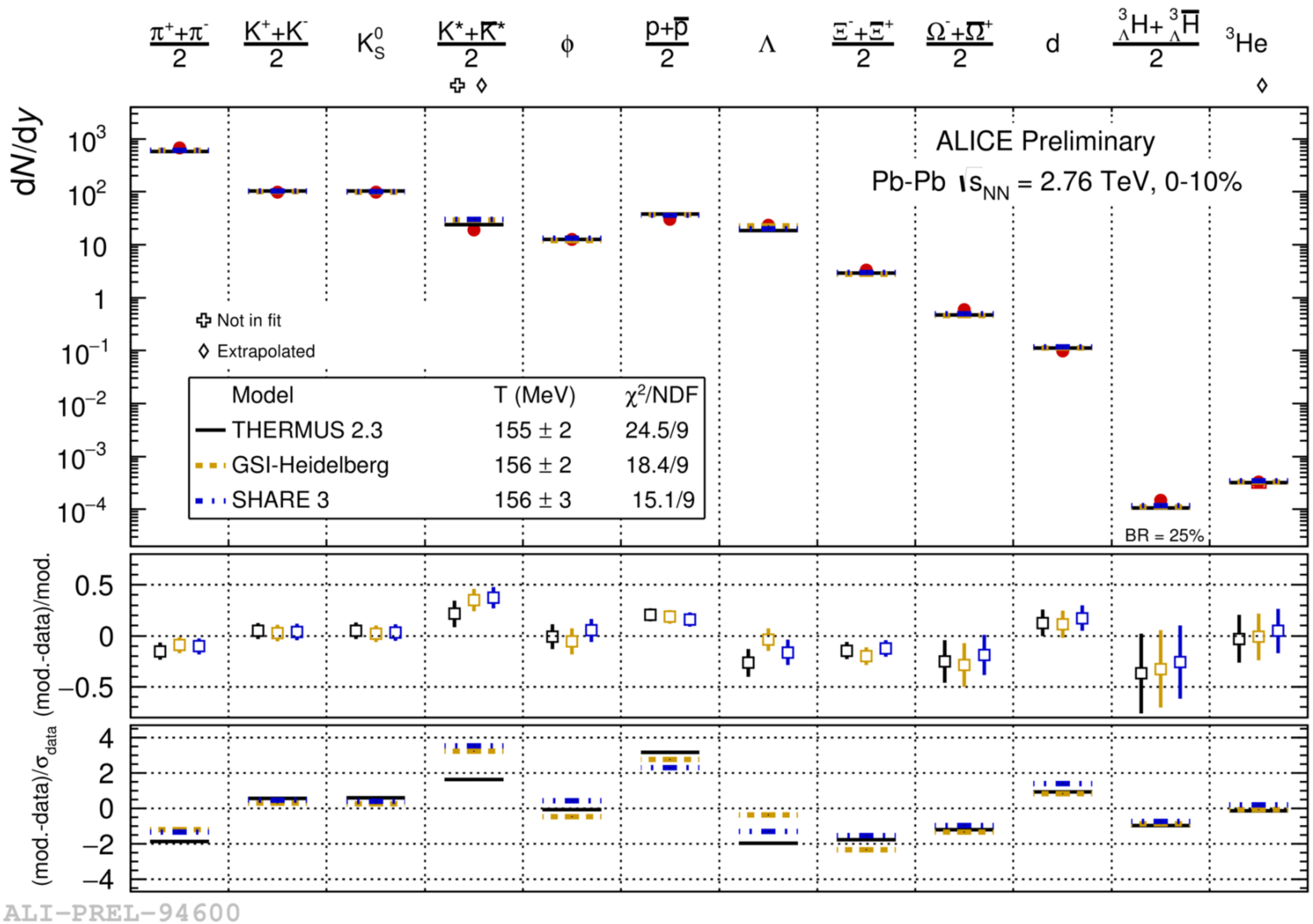
- Pressure gradients leads to radial flow
- Same "velocity" boost gives larger momentum to heavier particles
- Alternative/concurrent explanation: hadronisation via quark coalescence → higher momentum for baryons (3 quarks) than mesons (2 quarks): challenged by φ/p ratio



$p(qqq) > p(qq) \longleftarrow \vec{p} = \sum_{\text{quarks}} \vec{p}_i$

Thermal model and chemical freeze-out temperature

Chemical freeze-out temperature estimated from **relative particle abundances**
Model assuming statistical hadronization: particle abundances determined by their mass and quantum numbers (spin) at by system properties (T_{ch},u_B,..)



Hadron yields described assuming chemical equilibrium and T_{ch}~156 MeV → close to lattice QCD

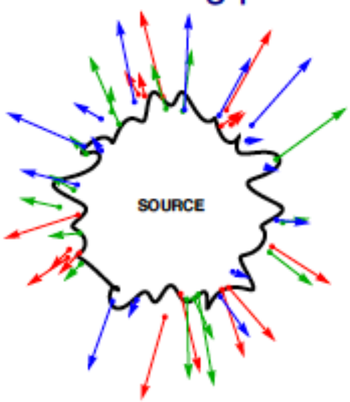
Some tension for protons and K*

System size: HBT interferometry

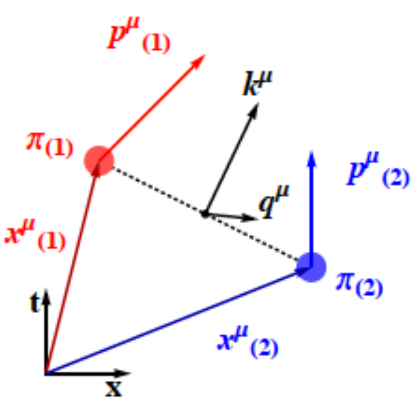
Hanbury-Brown and Twiss

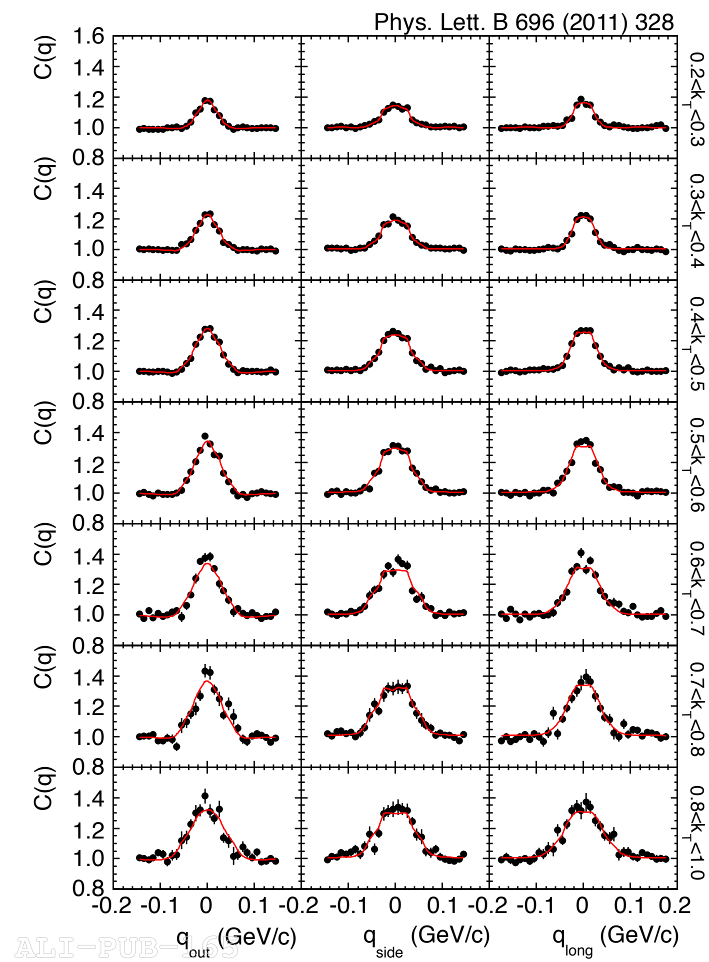
"Bose-Einstein" enhancement in the momentum correlation of identical bosons emitted close in phase ⟶ Probe "homogeneity emission region" and decoupling time

source emitting particles



two identical pions, $\pi^+\pi^+$, $\pi^-\pi^-$





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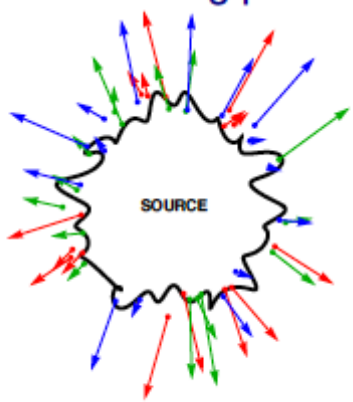

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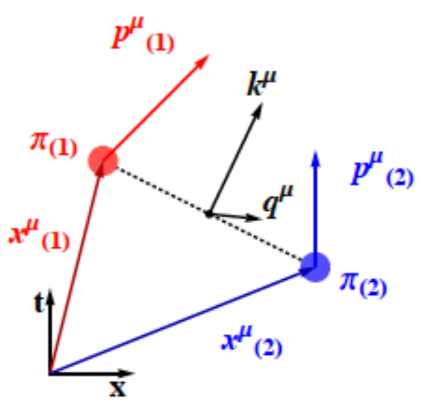
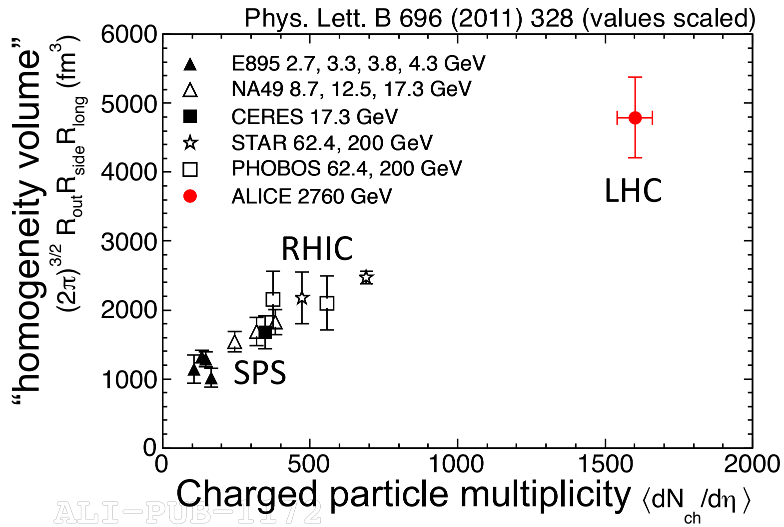
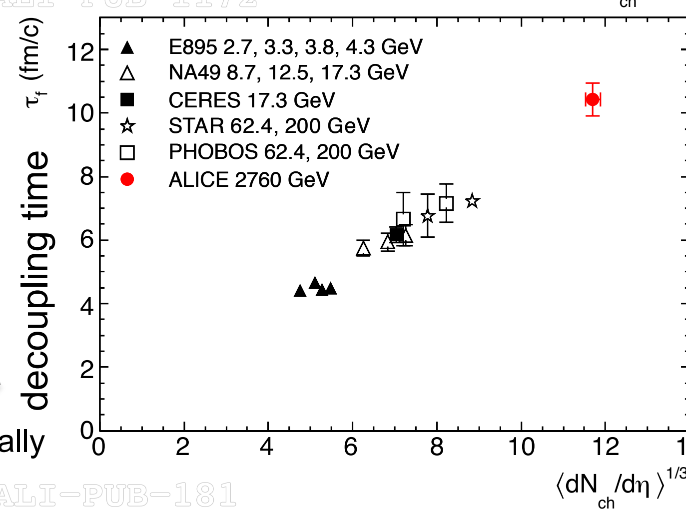






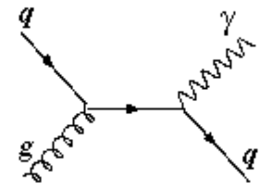
R_{out}~R_{side}~6 fm
R_{long}~8 fm

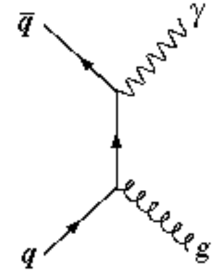
As expected, larger-size and longer living system produced at the LHC

From R_{long}, assuming longitudinally expanding emission source

Temperature from Photon spectrum

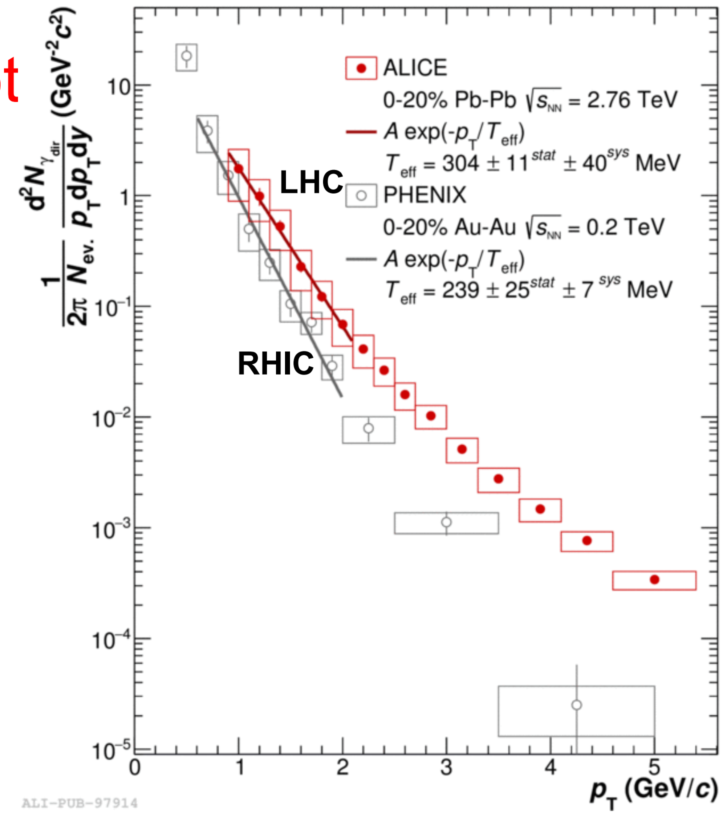
- Photons in heavy-ion collisions
  - Photons from QCD hard scattering: power law spectrum – dominant at high p_T
  - Thermal photons, emitted by the hot system (analogy with black body radiation): exponential spectrum – dominant at low p_T
    - From inverse slope:





T_{eff}^{*} = 304 ± 41 MeV
~ 2 T_c (T_c~160 MeV)
~ 1.25 x T_{eff}(RHIC)

* "Average" over whole medium evolution

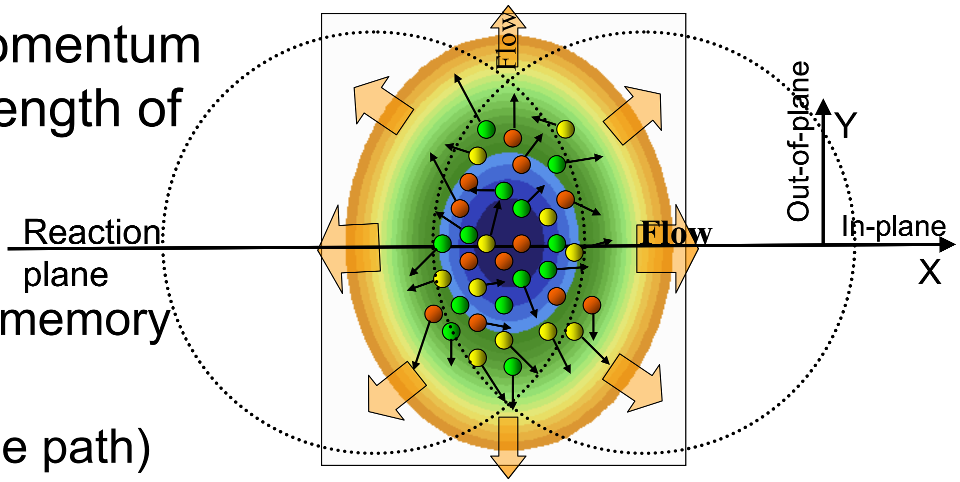


ALICE, Phys.Lett. B754 (2016) 235

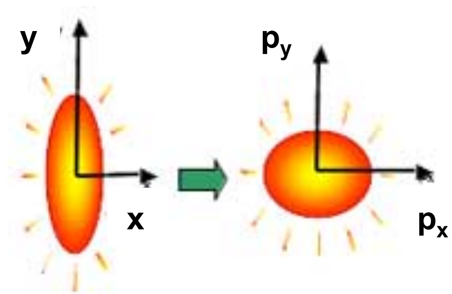
Anisotropic (Elliptic) flow

- Non-central collisions are azimuthally asymmetric

→ The transfer of this asymmetry to momentum space provides a measure of the strength of collective phenomena



- Large mean free path
  - particles stream out isotropically, no memory of the asymmetry
  - extreme: ideal gas (infinite mean free path)
- Small mean free path (← low viscosity)
  - larger density gradient → larger pressure gradient → larger momentum
  - extreme: ideal liquid (zero mean free path, hydrodynamic limit)



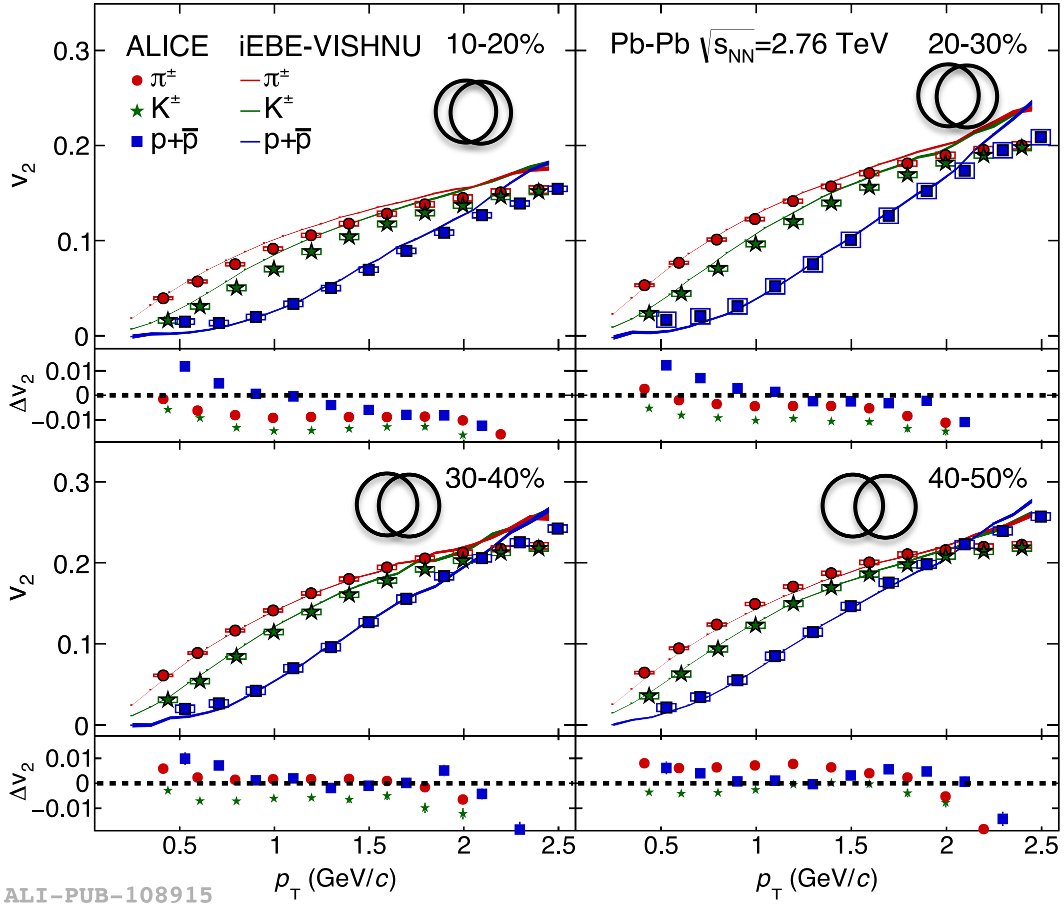
Effects addressed by measuring the azimuthal distribution of the particles with respect to the "Reaction Plane" → Fourier analysis

$$N(\varphi) \propto 1 + 2\sum v_n \cos(n(\varphi - \psi_{RP})) = 1 + 2v_1 \cos(\varphi - \psi_{RP}) + 2v_2 \cos(2(\varphi - \psi_{RP})) + \dots$$

v_2= Elliptic flow, main parameter

Anisotropic (Elliptic) flow

Points= data curves=model



JHEP 1609 (2016) 164

Elliptic flow (v_2) significantly>0

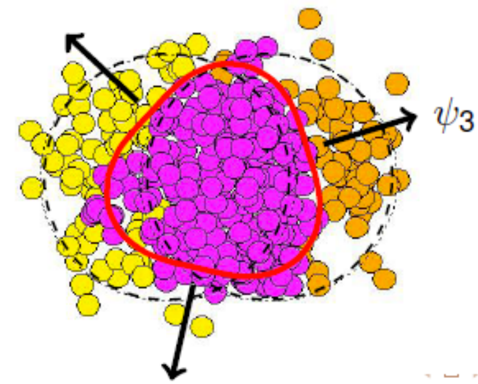
- Evidence of system collective motion
- "Early signal": develops in partonic phase
- Well described by hydrodinimical models
- Expected trends vs. particle mass

→ **Thermalized partonic system**

→ (via more detailed comparisons with models) **Data suggest very low viscosity (← small mean free path)**

System behaves as ~perfect liquid (the RHIC "paradigm")

Constraining further viscosity: higher harmonics



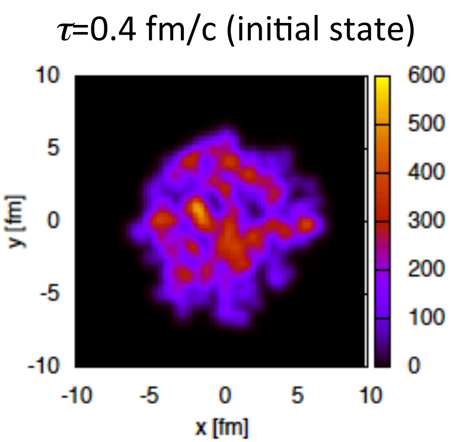
Initial geometry is not an ideal almond shape

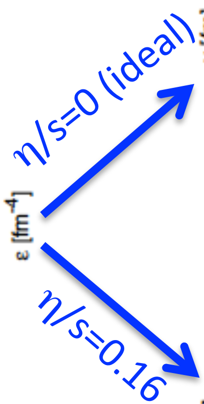
- Fluctuations of initial energy/pressure distributions lead to “irregular” shapes (→ need more harmonics to describe them) that fluctuate event-by-event

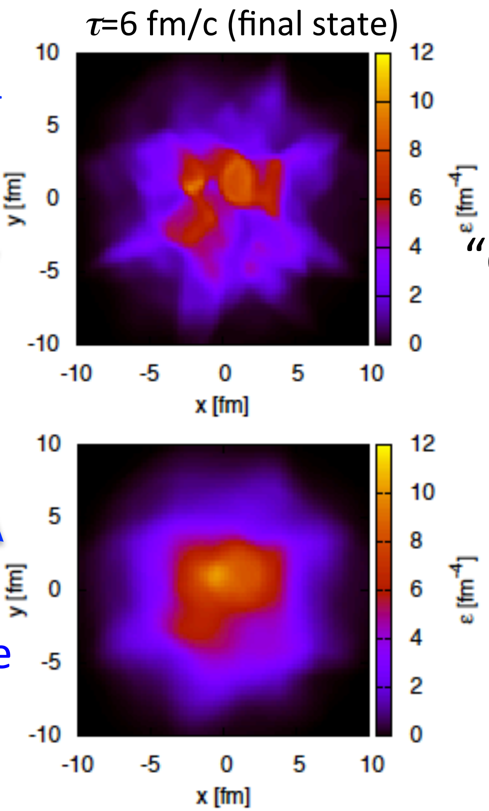
Simulation of energy density evolution

(ideal and viscous hydro)

Schenke, Jeon, Gale, PRL 106:042301,2011





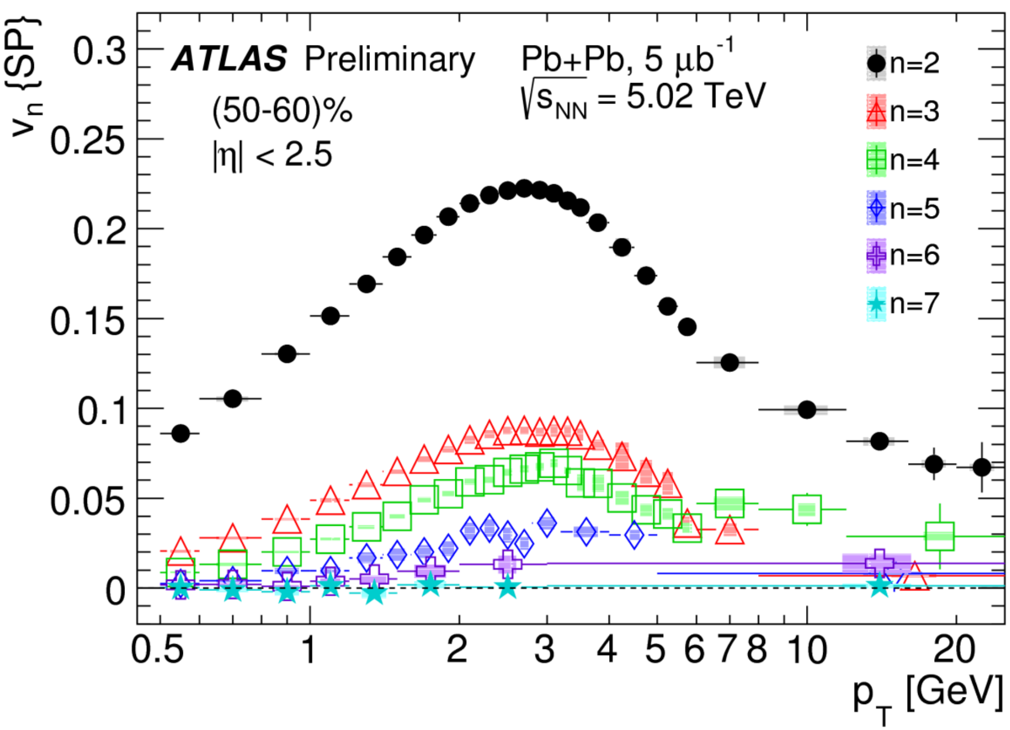


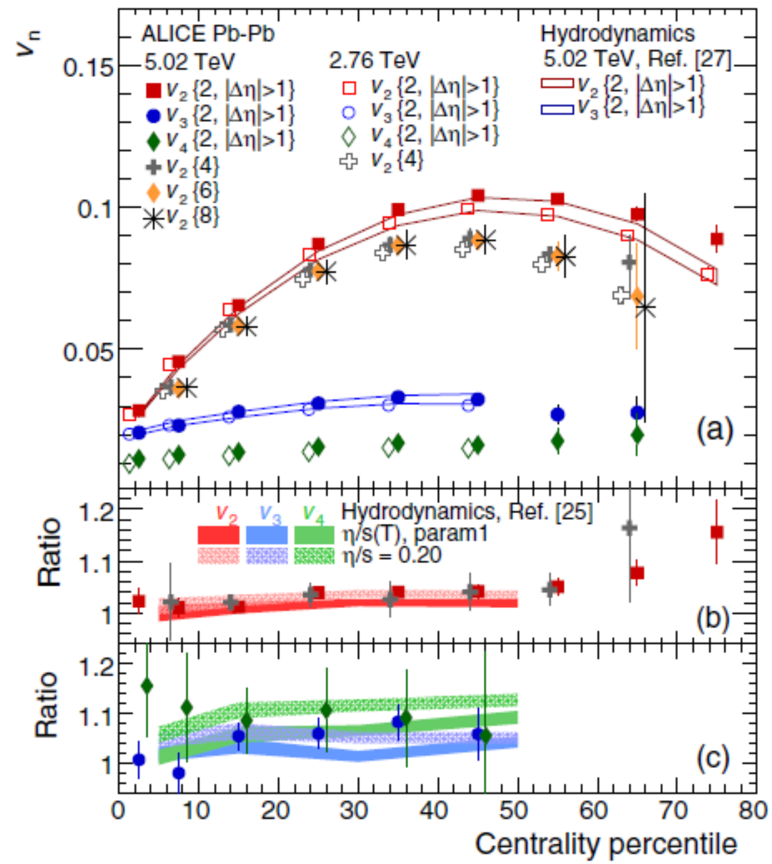
Fluctuations of initial state are damped by viscosity

Viscosity determines the “conversion efficiency” of the initial shape into final momentum azimuthal distribution

Higher harmonics add sensitivity to the value of shear viscosity

Constraining further viscosity: higher harmonics





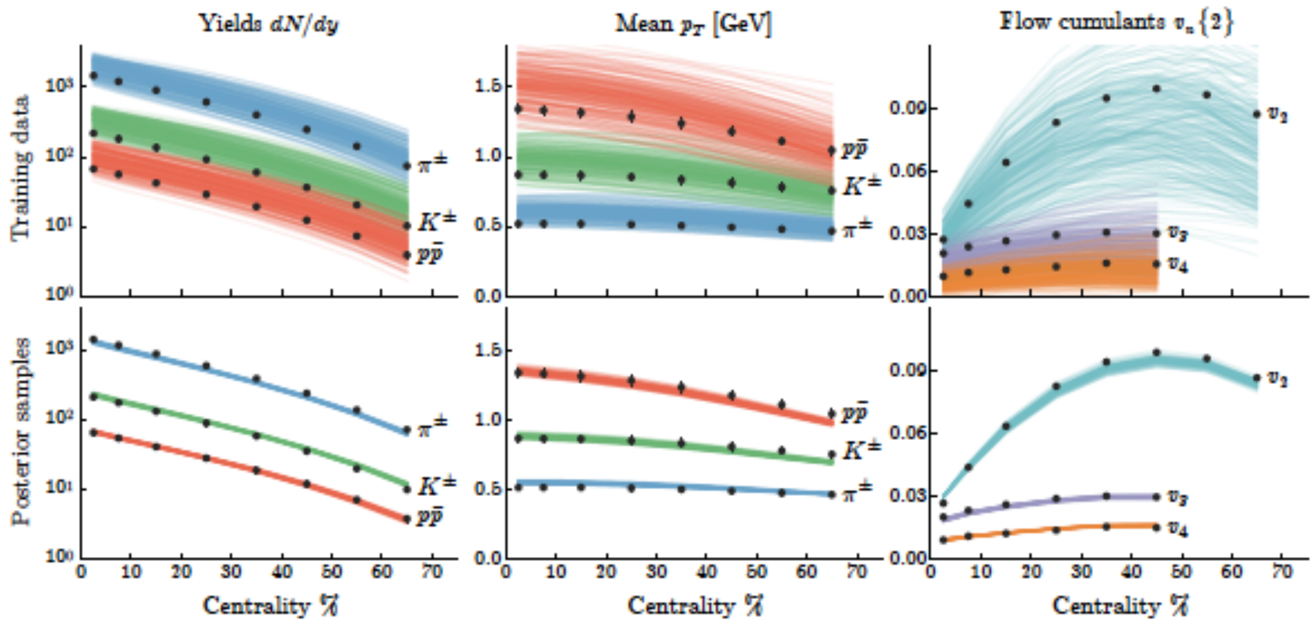
Higher-harmonic coefficients significantly non-zero
→ discriminate and constrain models

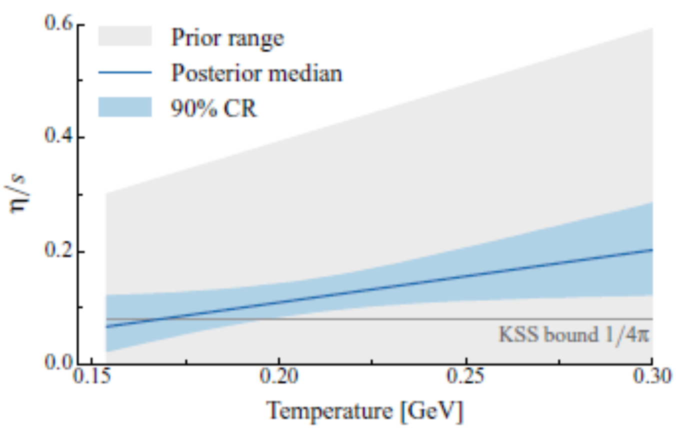
Constraining further viscosity: example with a model

J. E. Bernhard et al. Phys. Rev. C 94, 024907 (2016)

9 parameters: 3 initial state, 4 for QGP response, 2 model parameters

Particle yields, <p_T>, flow coefficients used to calibrate the model parameters to reproduce data





Bayes method used to extract probability distribution for the true values of the parameters

Main results: viscosity vs. temperature

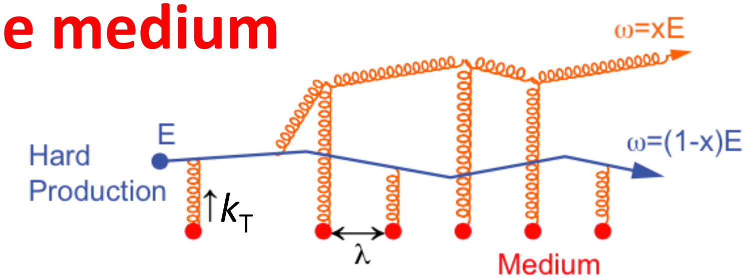
QGP viscosity very low (lower than any atomic matter)

High-energy probes → microscopic processes (local interactions) in the medium

QGP tomography with high-energy partons

- Early production in hard-scattering processes with high Q^2
- Production cross sections calculable with pQCD
- Strongly interacting with the medium

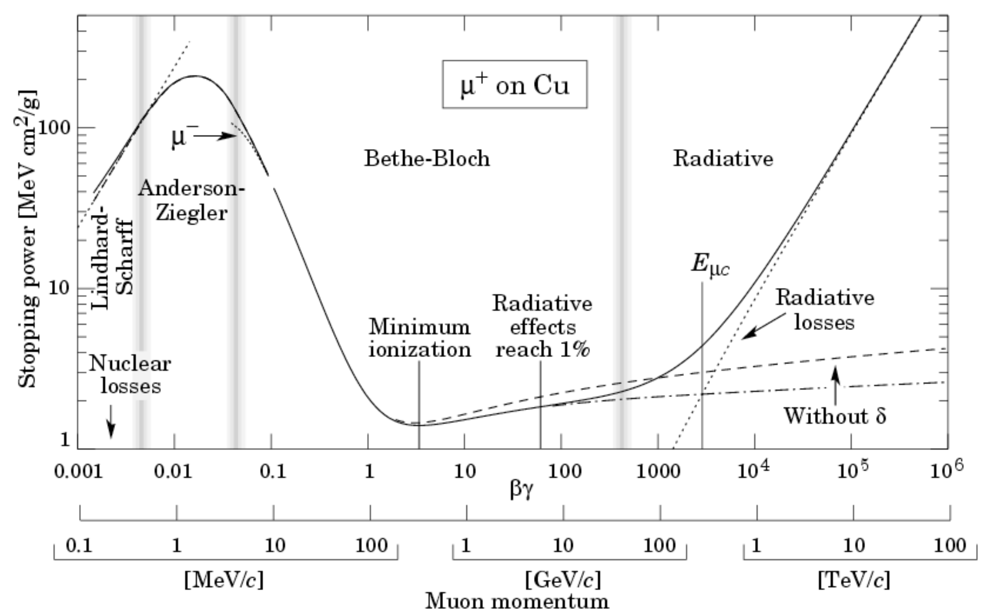
"Calibrated probes" of the medium



Study parton interaction with the medium

- **energy loss via radiative** ("gluon Bremsstrahlung")
  collisional processes

~ Study QCD "Bethe-Block" curve for partons in the QGP



Connection of "local" interactions with global medium properties → Microscopic description of the medium

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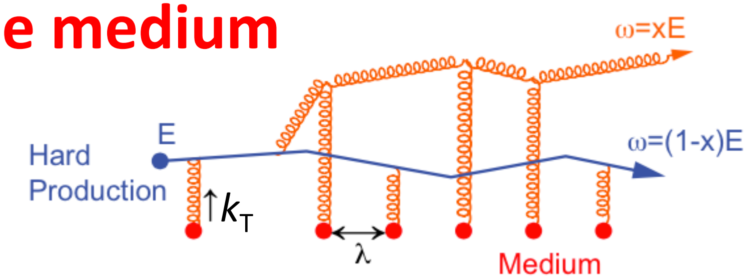
⇨ **"Calibrated probes" of the medium**



Study parton interaction with the medium

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~ Study QCD "Bethe-Block" curve for partons in the QGP

⇩

Connection of "local" interactions with global medium properties → Microscopic description of the medium

e.g. in BDMPS-Z formalism*

$$\langle \Delta E \rangle^{\mathrm{rad}} \propto \alpha_s C_R \hat{q} L^2$$

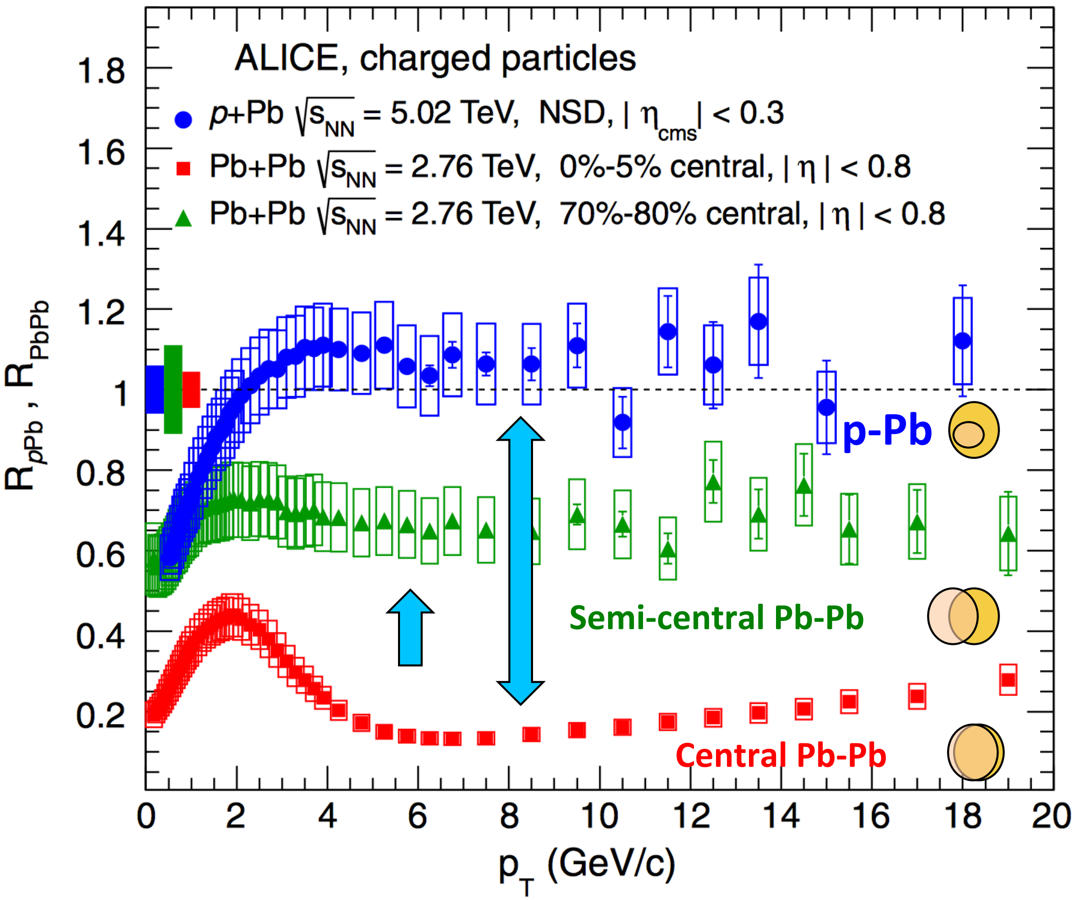
$$\hat{q} = \frac{\langle k_{\mathrm{T}}^2 \rangle}{\lambda} = \langle k_{\mathrm{T}}^2 \rangle \rho \sigma$$

Transport coefficient(s)

*Baier, Dokshitzer, Mueller, Peigné, Schiff, NPB 483 (1997) 29
Zakharov, JTEPL 63 (1996) 952.

QGP tomography with high-energy partons

ALICE, PRL 110 (2013) 082302



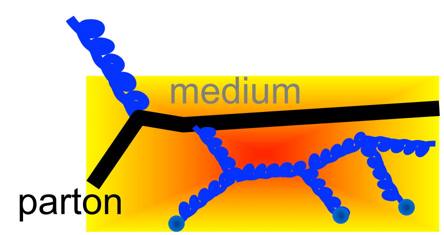
$$R_{AA}(p_{\mathrm{T}}) = \frac{dN_{AA} / dp_{\mathrm{T}}}{\langle N_{coll} \rangle \times dN_{pp} / dp_{\mathrm{T}}}$$

Strong suppression of intermediate/ high p_{T} particles in central Pb-Pb collisions

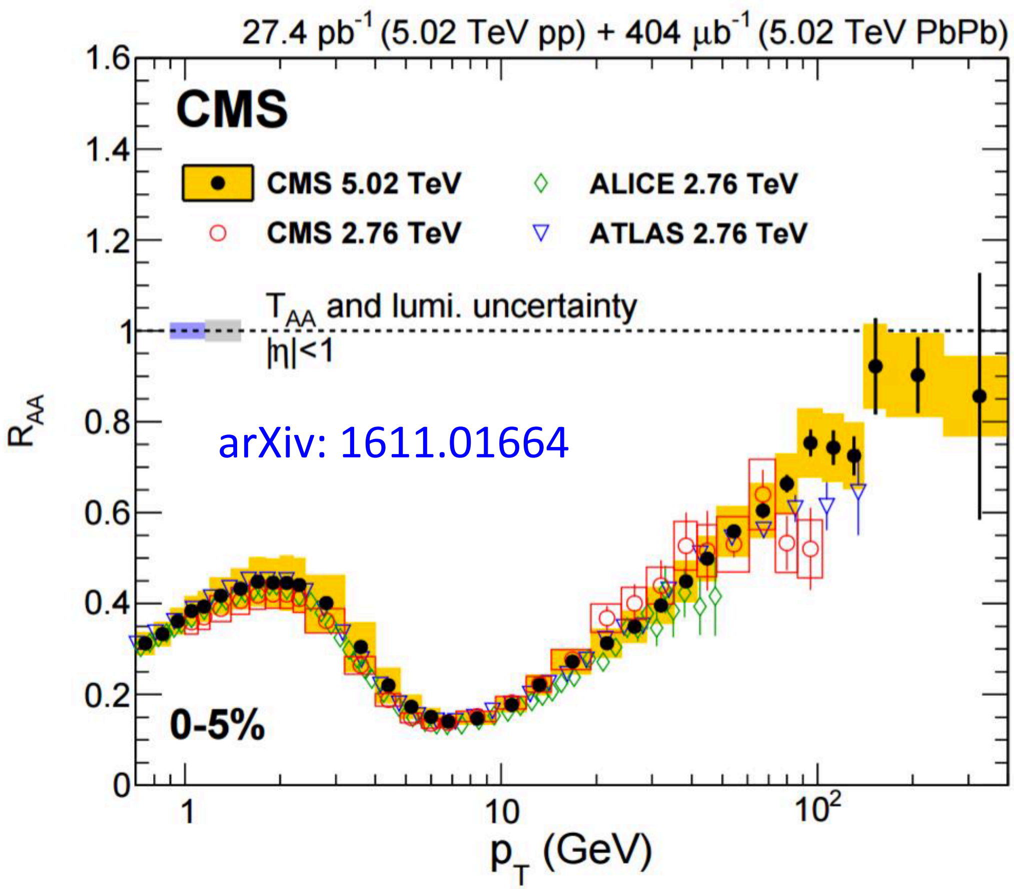
Absent in p-Pb collisions (no QGP expected)

→ final-state effect

→ Evidence of in-medium partonic energy loss



QGP tomography with high-energy partons



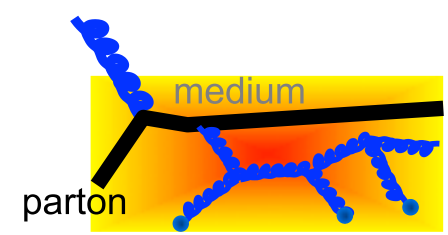
Suppression up to very high p_T

Strong suppression of intermediate/ high p_T particles in central Pb-Pb collisions

Absent in p-Pb collisions (no QGP expected)

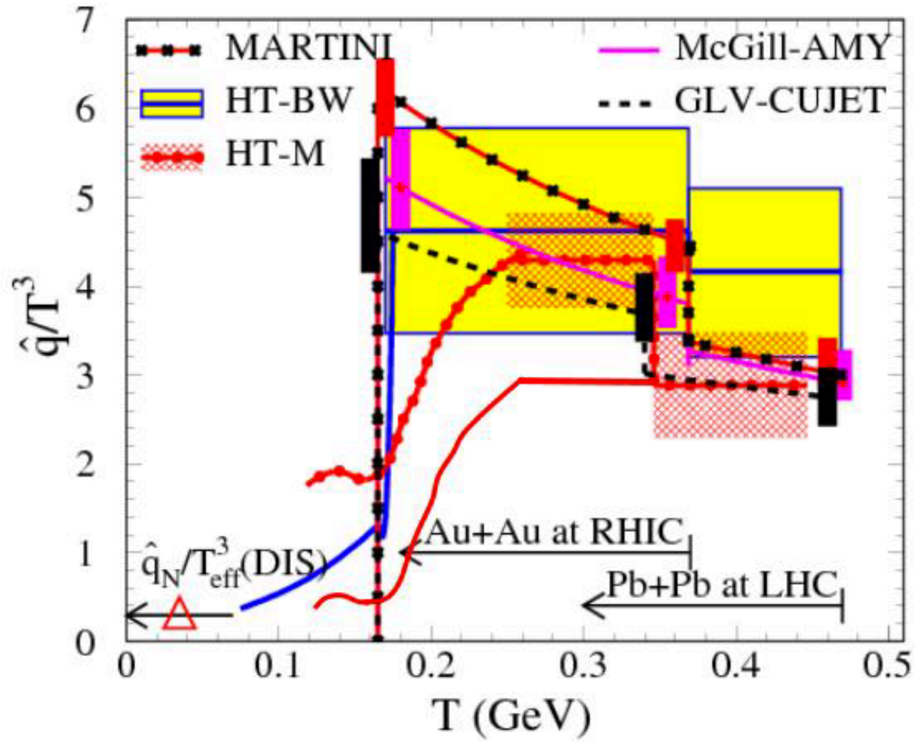
→ final-state effect

→ Evidence of in-medium partonic energy loss



Started to extract information from data

From analysis of inclusive charged particle spectra at RHIC and LHC and considering many models

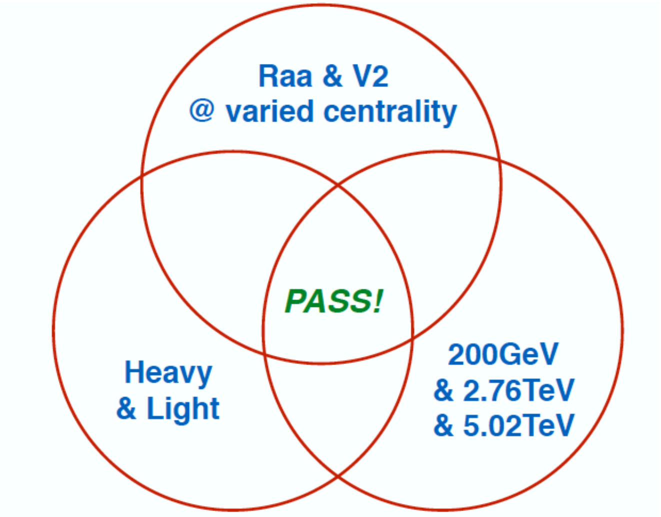


Nucl.Phys. A931 (2014) 404-409

$$\hat{q} = 1.2 \pm 0.3 \text{ GeV}^2/\text{fm (central Au-Au } \sqrt{s_{NN}} = 200 \text{ GeV)}$$

$$\hat{q} = 1.9 \pm 0.7 \text{ GeV}^2/\text{fm (central Pb-Pb } \sqrt{s_{NN}} = 2.76 \text{ TeV)}$$

Only a starting point!

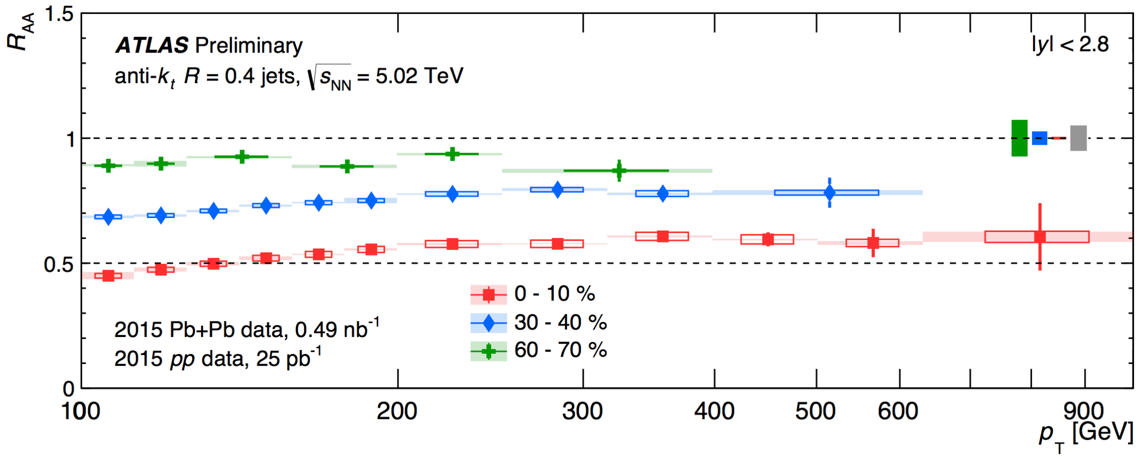


from J. Liao, QM2017

Jet quenching

Jets are “extended” objects → provide complementary information to single particle observables

- Address spatial distribution and kinetic properties of radiated energy
  - **Out-of-cone radiation → jet suppression**

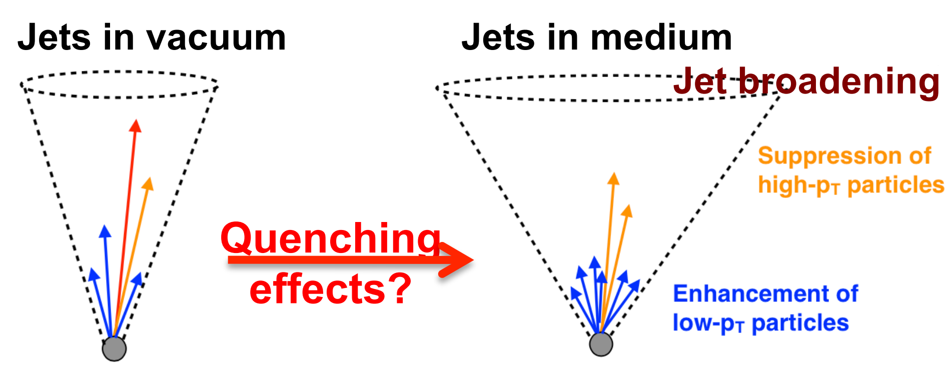


Jet suppression up to ~1 TeV!

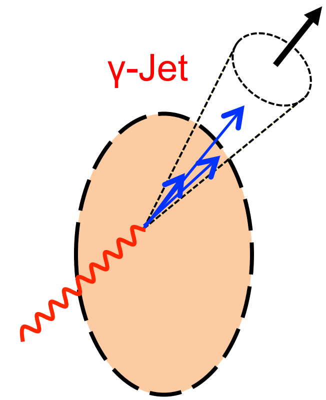
Is the jet internal structure modified?

- Kinetic properties
- Spatial distribution of jet constituents
- Particle specie composition

Many studies performed

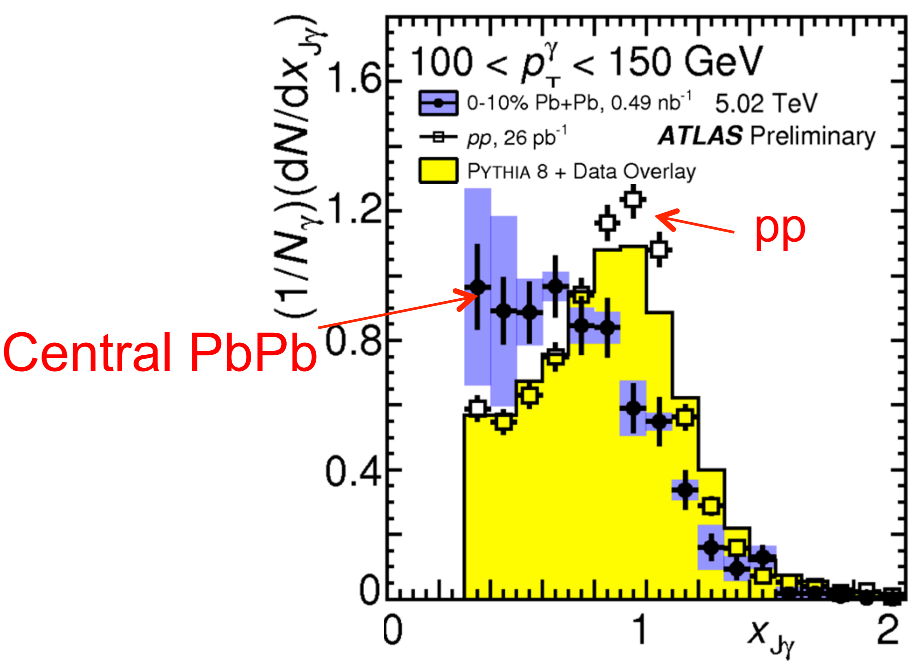


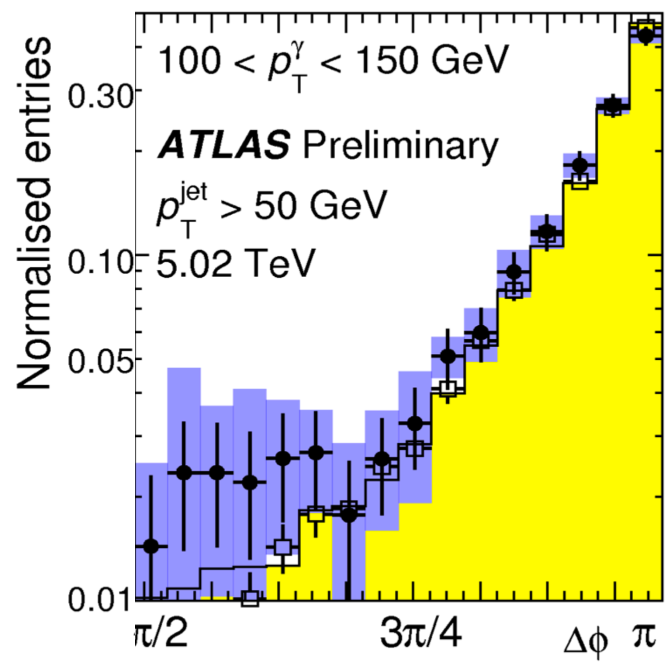
Jet quenching with γ-jet



- γ provides calibration of jet energy before quenching
  - medium effects via $\mathbf{x_{J\gamma} = p_{T,jet}/p_{T,\gamma}}$ and $\Delta\phi$ decorrelation
- Central 0-10% PbPb compare to pp
  - $\langle x_{J\gamma} \rangle$ shifted towards lower value
    ➔ Strong energy loss for associated jet.
  - $\Delta\phi$ distribution consistent with pp data
    ➔ Little modification of the jet direction.

CONF-2016-110





Summary (part 1)

… only a snapshot of the main results presented
... addressing even a smaller questions of open questions in the field

After 30 years of studies QGP formation in heavy-ion collisions quite established

The experimental goal is now to measure precisely its properties and achieve a comprehensive microscopic description of the medium

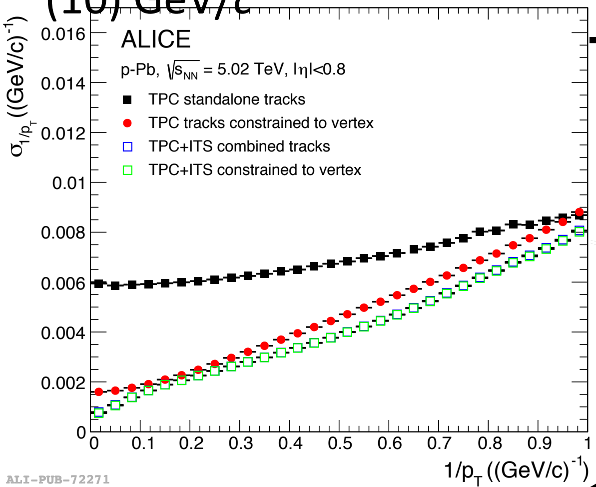
- Event-by-event studies and fluctuations
- Push precision for particle chemistry (baryon/mesons, resonances,…)
- Hard-probes: still much room for improving precision and for more differential measurements → still a lot to learn!

Second part

- The ALICE detector
- Open charm and beauty results
- Prospects for the future

The ALICE detector: central barrel

Transverse momentum (p_T) resolution: 0.8% (2%) at 1 (10) GeV/c

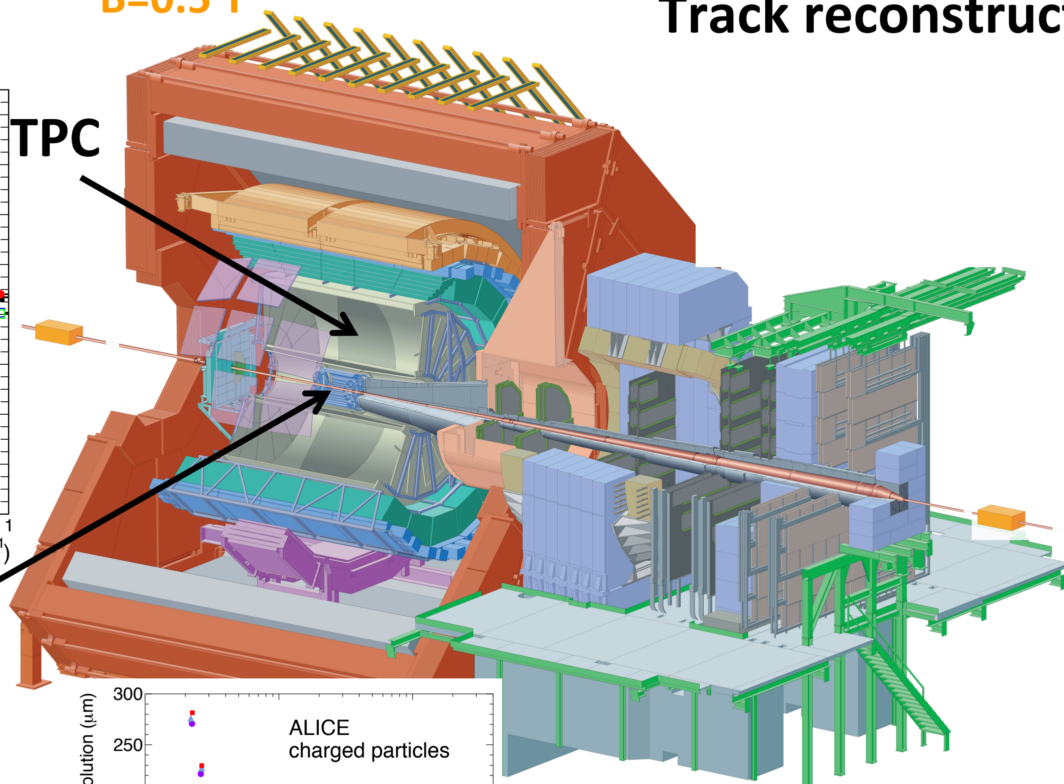


|η|<0.9

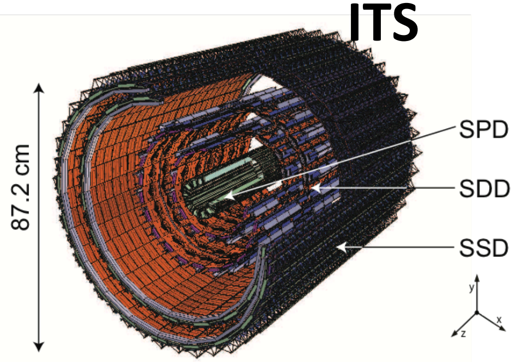
B=0.5 T

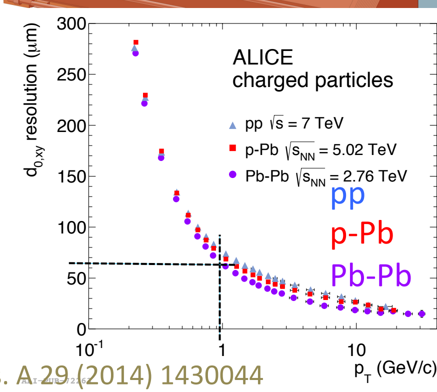
Track reconstruction

TPC



ITS





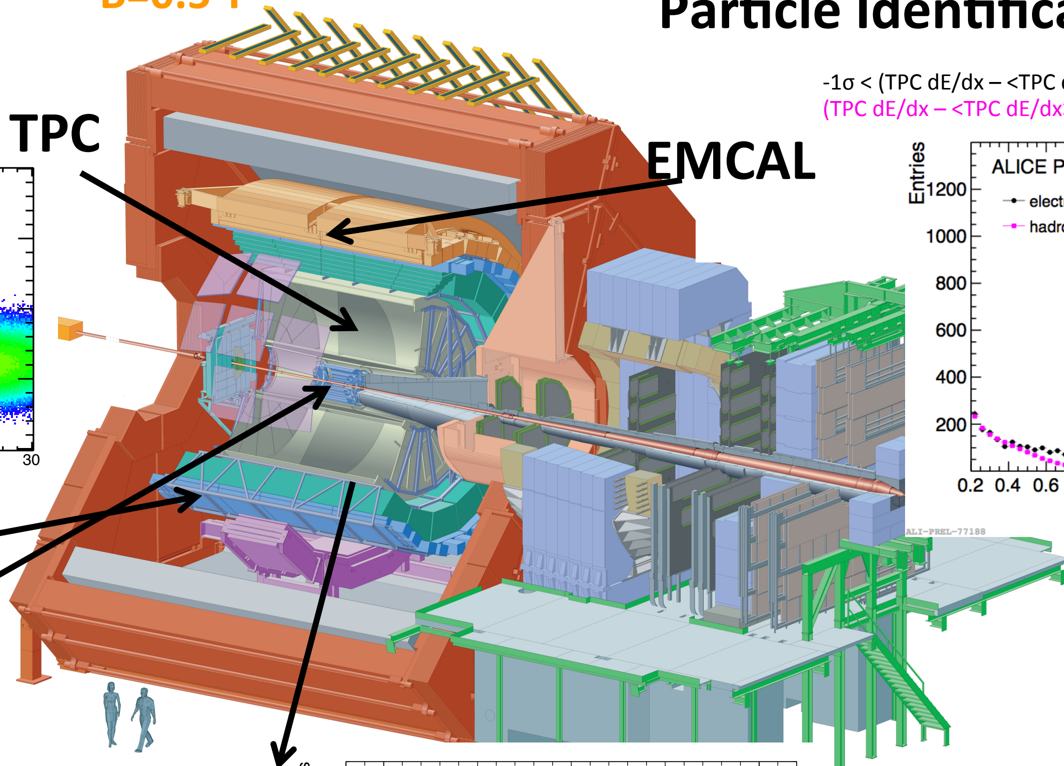
Int. J. Mod. Phys. A 29 (2014) 1430044

Resolution on track position at the primary vertex better than 70 micron for p_T>1 GeV/c (crucial for D-meson reconstruction)

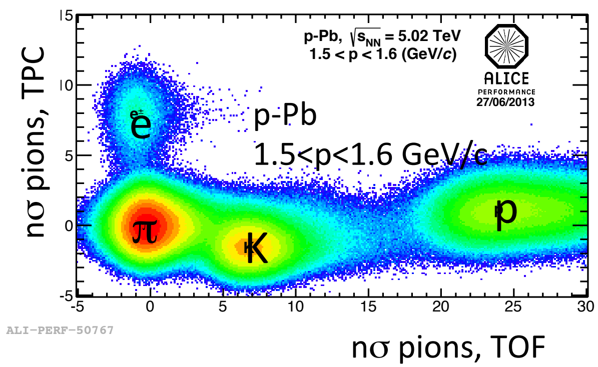
The ALICE detector: central barrel

|η|<0.9

B=0.5 T

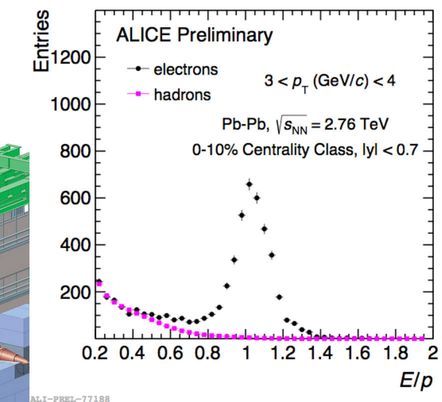


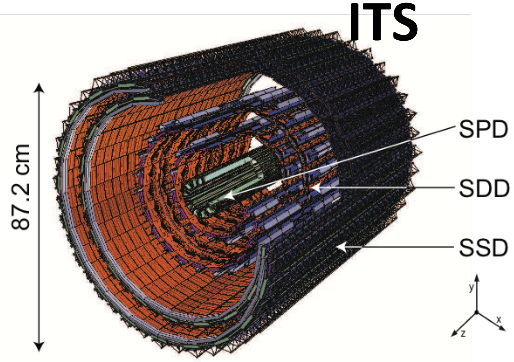
Particle Identification

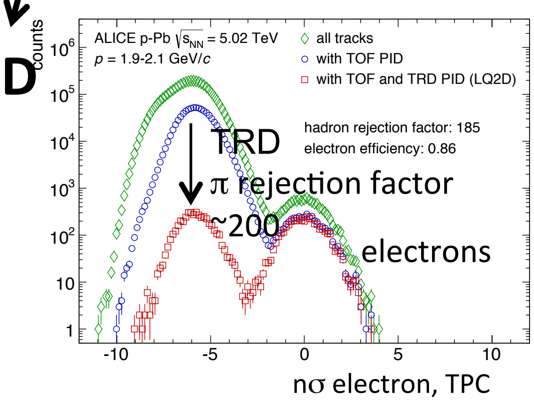


-1σ < (TPC dE/dx – <TPC dE/dx>e)TPC < 3σ

(TPC dE/dx – <TPC dE/dx>e)TPC < -4σ



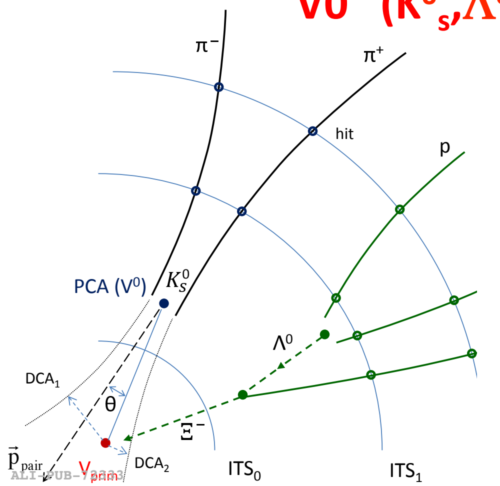


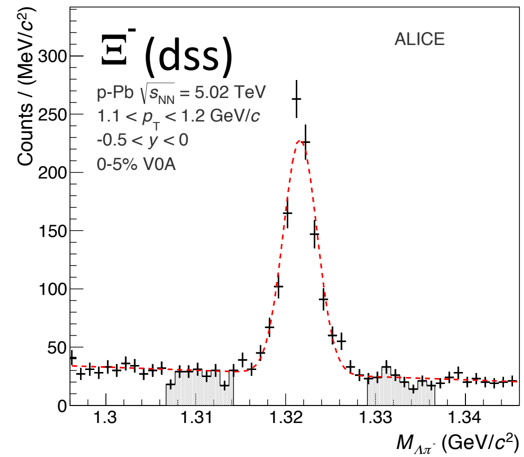


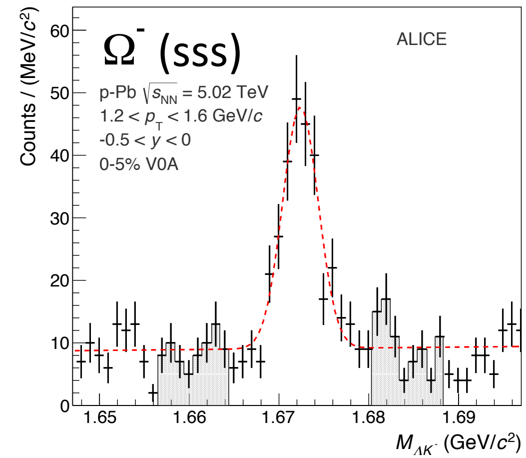
N.B. only detectors used for the measurements that are shown

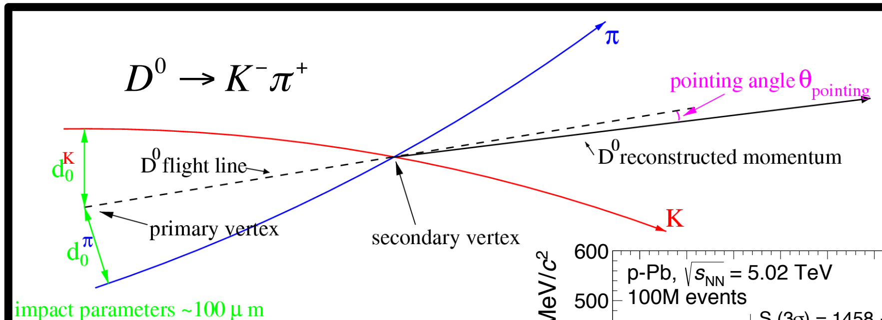
Signals reconstructed with central barrel

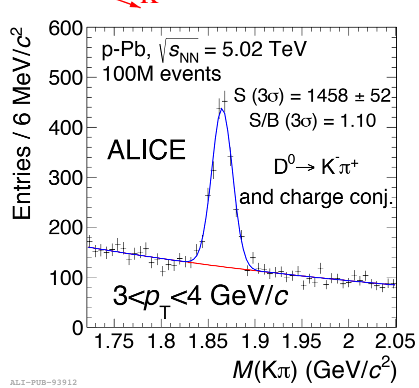
“V0” (K^0_s,Λ^0) and “Cascades” (Ξ,Ω)





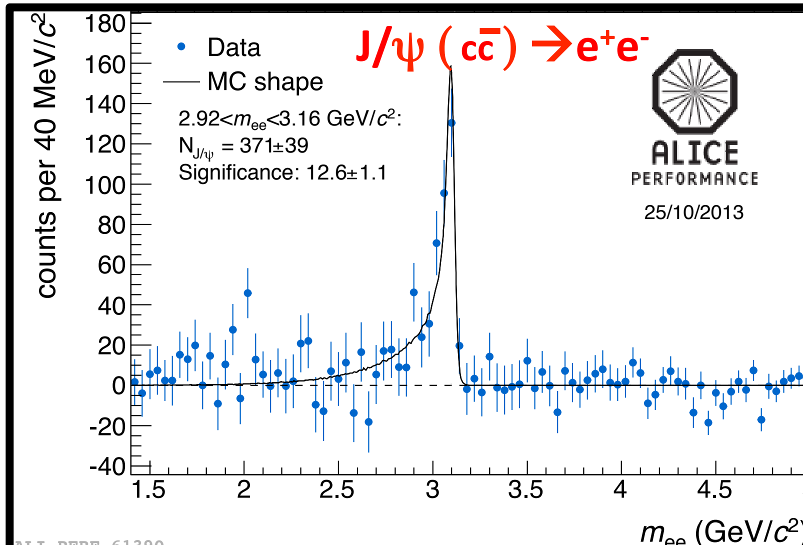






D mesons (e.g. $D^0(c\bar{u})$)

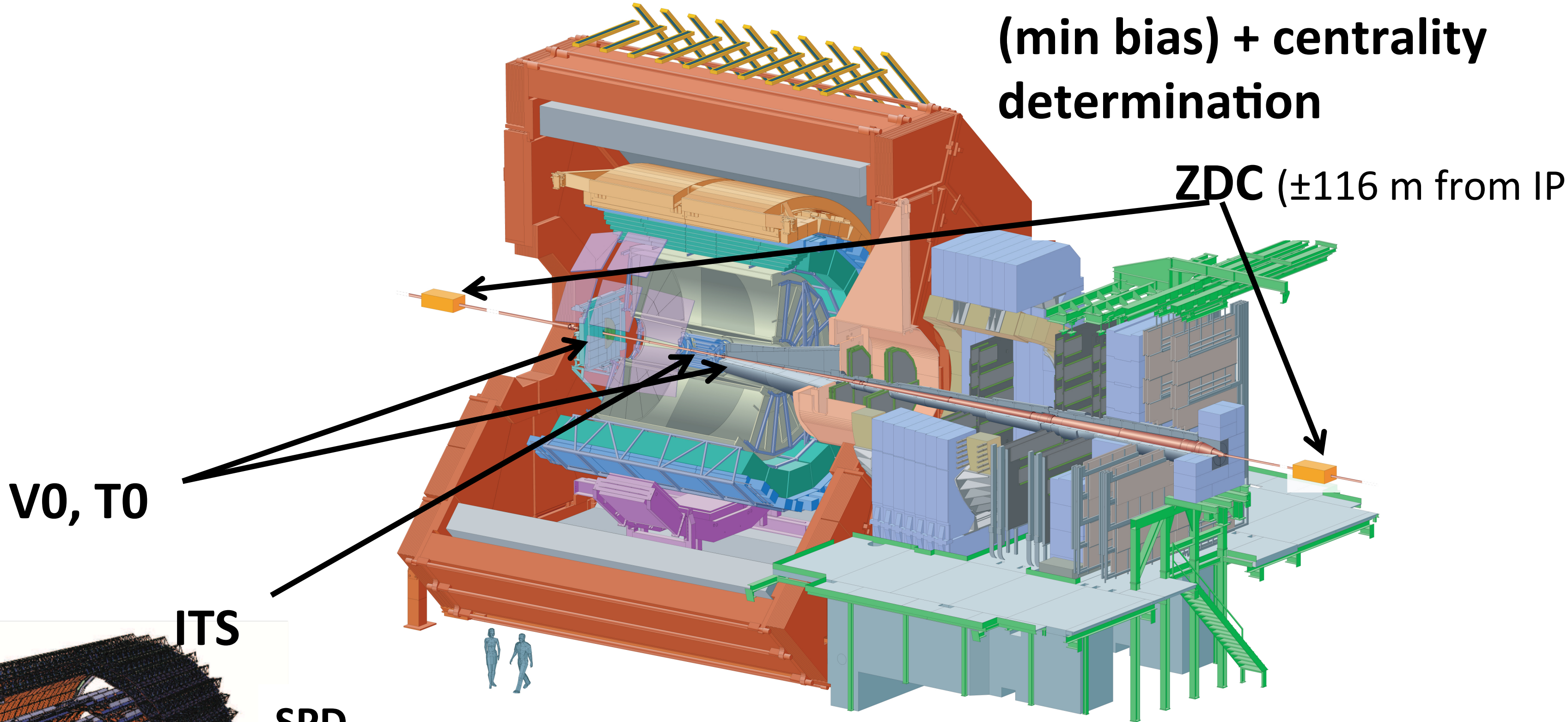
J/ψ ($c\bar{c}$) $\rightarrow e^+e^-$

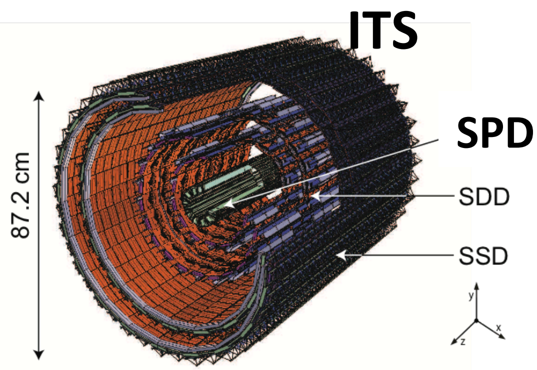


+ spectra of identified particles

The ALICE detector: “small-angle” detectors

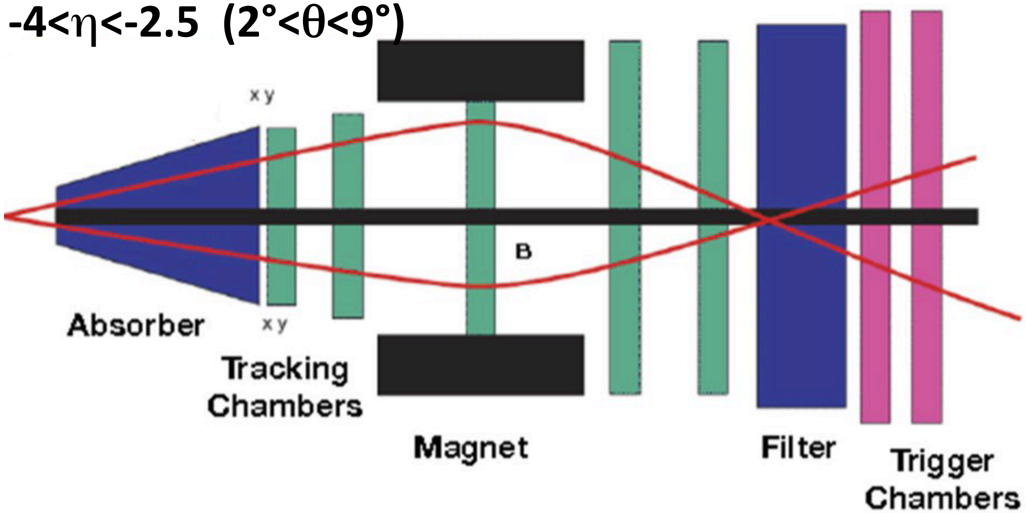
Event selection (min bias) + centrality determination



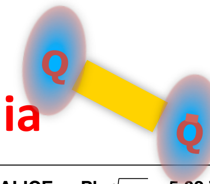


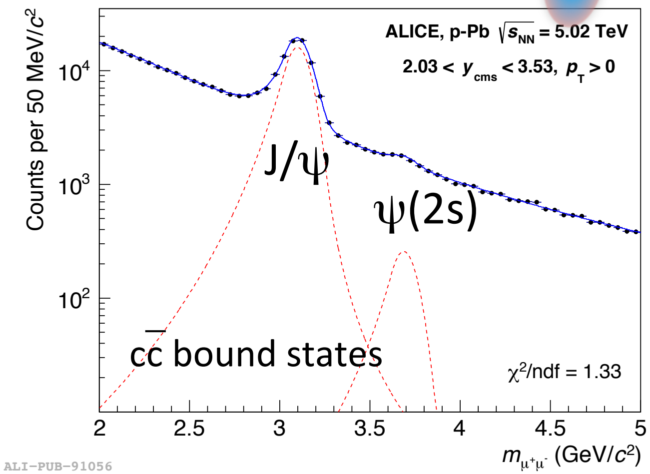
The ALICE detector: forward muon spectrometer

MUON SPECTROMETER
$-4<\eta<-2.5$ ($2°<\theta<9°$)



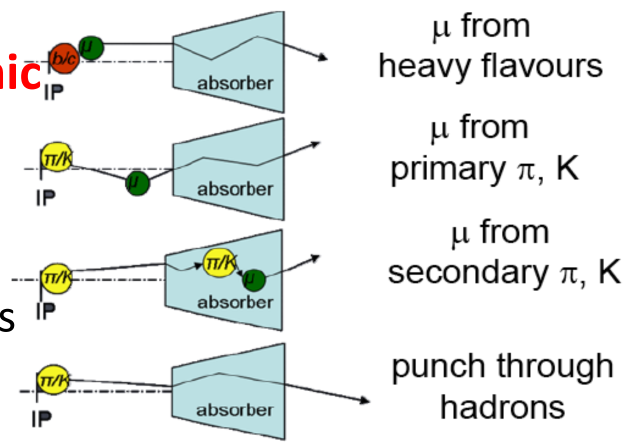
Quarkonia

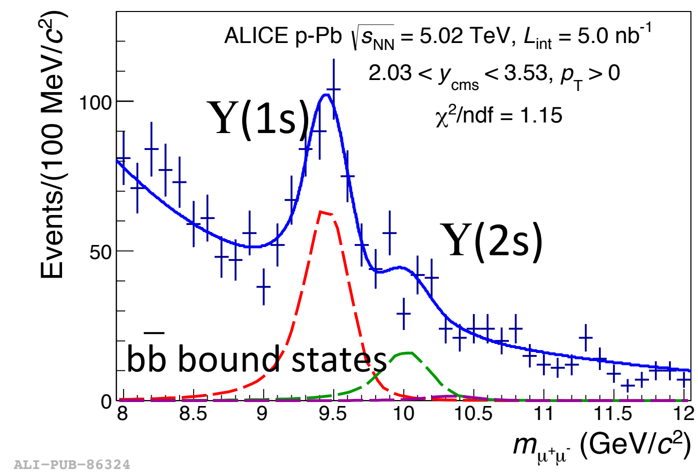




Muons from semi-leptonic heavy-flavour hadron decays

D,B, Λ_c,..→ μ X
(after subtraction of muons from non-HF sources)



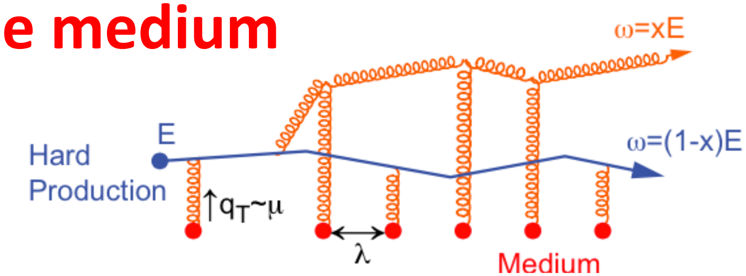


QGP tomography with heavy quarks

- Early production in hard-scattering processes with high Q^2
- Production cross sections calculable with pQCD
- Strongly interacting with the medium
- Hard fragmentation ➜ measured meson properties closer to parton ones

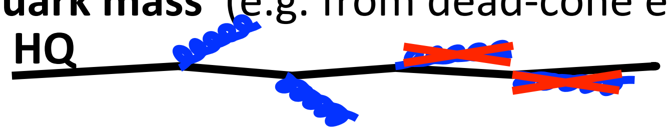
at all p_T for charm and beauty (large masses >> Λ_{QCD})

"Calibrated probes" of the medium

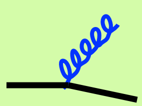


Study parton interaction with the medium

- **energy loss via radiative** ("gluon Bremsstrahlung")
  collisional processes
  - path length and medium density
  - **color charge** (Casimir factor)
  - **quark mass** (e.g. from dead-cone effect)



Gluonsstrahlung probability



$$\propto \frac{1}{[\theta^2 + (m_Q / E_Q)^2]^2}$$

Dokshitzer, Khoze, Troyan, JPG 17 (1991) 1602.
Dokshitzer and Kharzeev, PLB 519 (2001) 199.

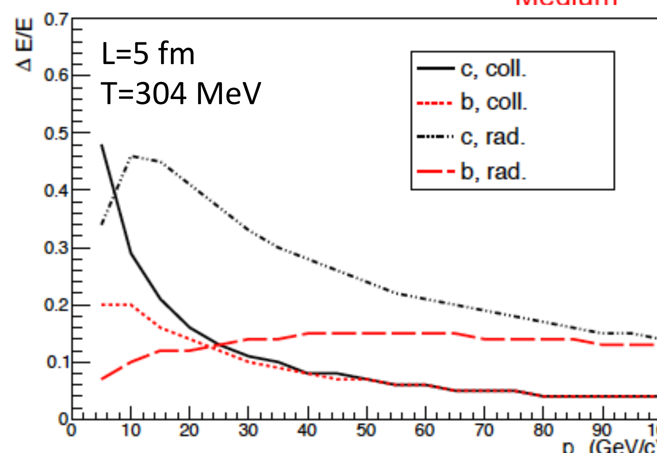
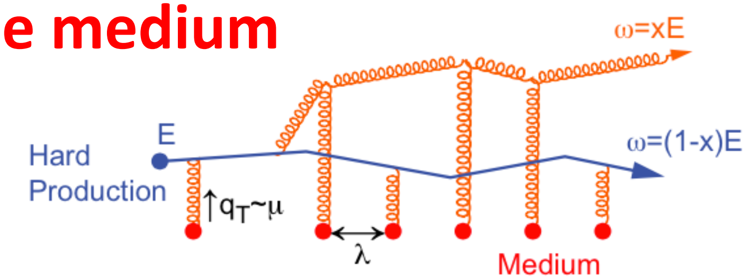


Figure from A. Andronic *et al.*, EPJC C76 (2016)
M. Djordjevic, Phys. Rev. C80 064909 (2009), Phys. Rev. C74 064907 (2006).

QGP tomography with heavy quarks

- Early production in hard-scattering processes with high Q^2 ← at all p_T for charm and beauty
- Production cross sections calculable with pQCD ← (large masses >> Λ_{QCD})
- Strongly interacting with the medium
- Hard fragmentation ➜ measured meson properties closer to parton ones

⇒ **"Calibrated probes" of the medium**



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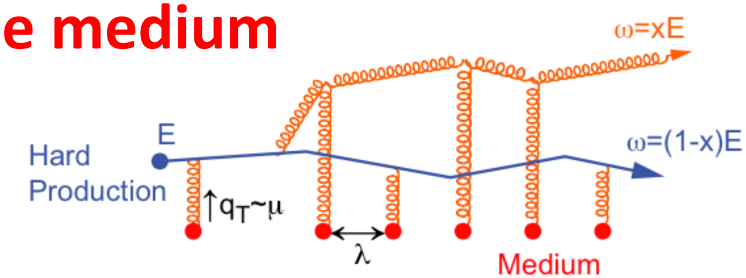

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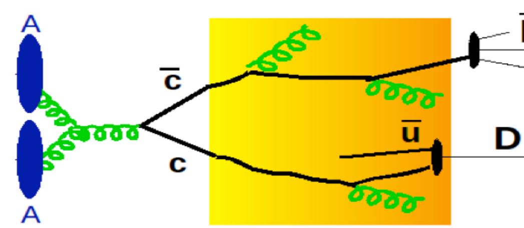
- medium **modification to HF hadron formation**
  - hadronization via quark coalescence



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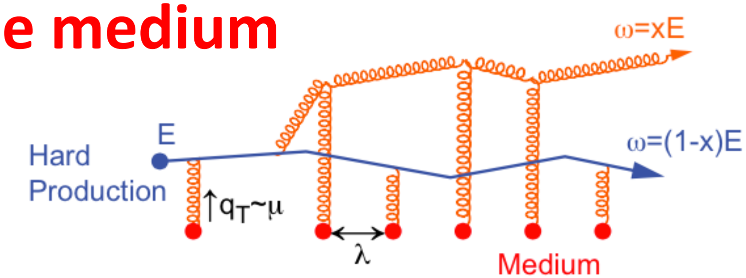

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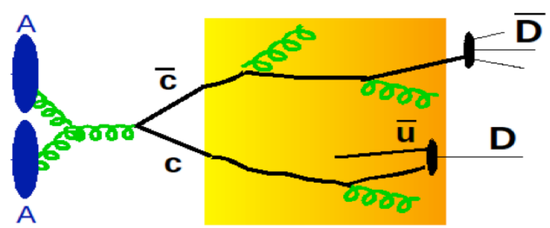
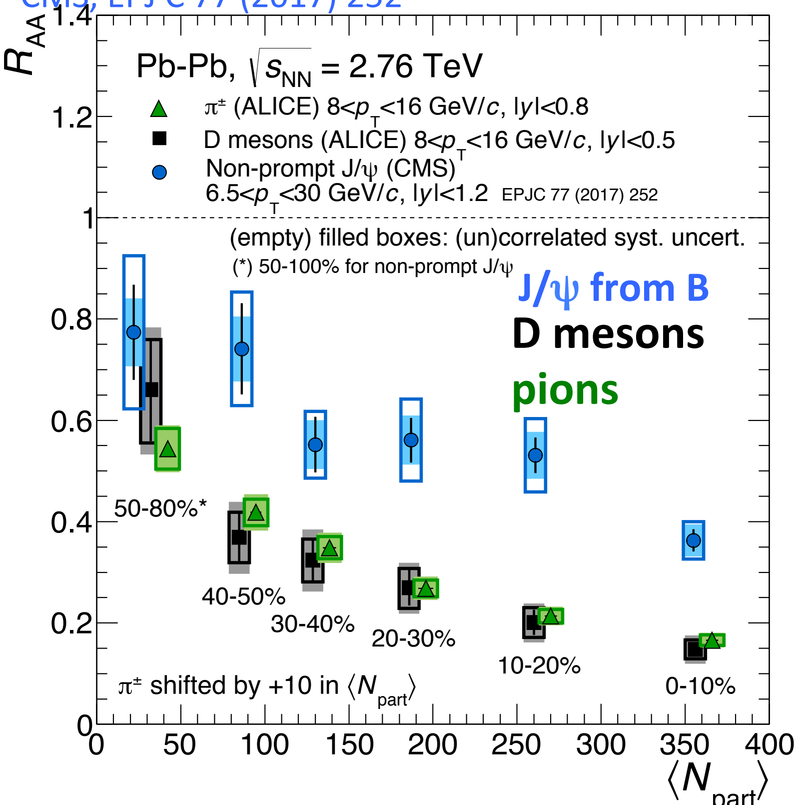


- participation in collective motion ➜ azimuthal anisotropy of produced particle

Open charm and beauty

ALICE, JHEP 1511 (2015) 205
CMS, EPJ C 77 (2017) 252



Similar D meson and pion R_{AA}

Expected from small charm-quark mass + differences between charm and gluon/LF spectra slope and fragmentation

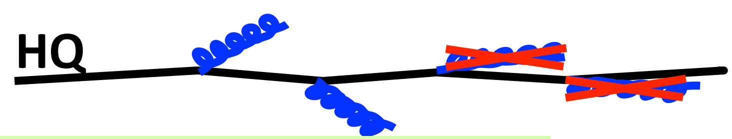
R_{AA} (J/ψ from B) > **R_{AA}(D)** in central collisions

⇩

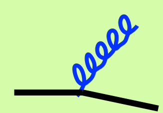
Indication of R_{AA} (B) > R_{AA}(D)

The different suppression and the centrality dependence as expected from **models with quark-mass dependent energy loss ($\Delta E_g > \Delta E_{lq} \geq \Delta E_c > \Delta E_b$)**

Expected from dead cone effect:



Gluonsstrahlung probability



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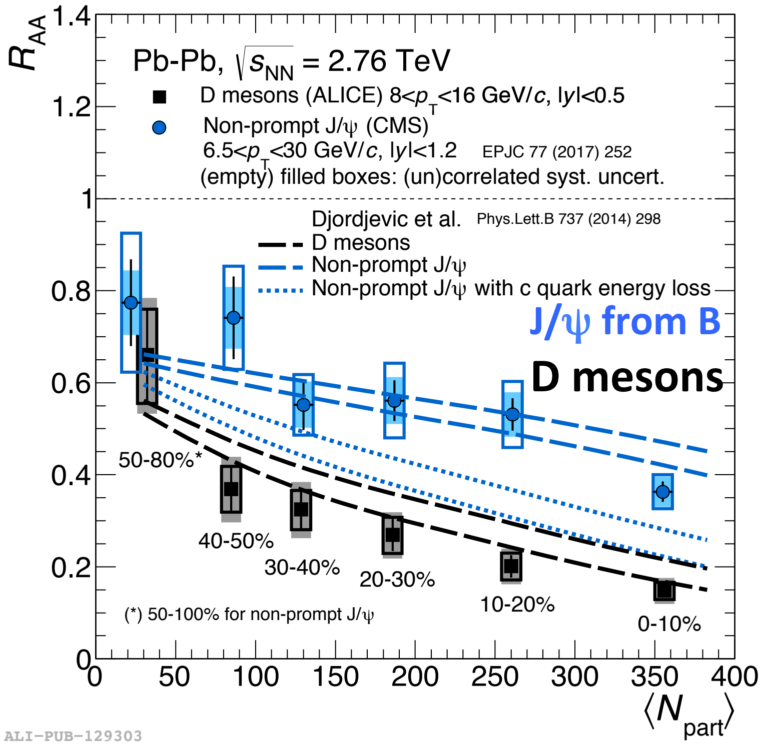
CMS, EPJ C 77 (2017) 252



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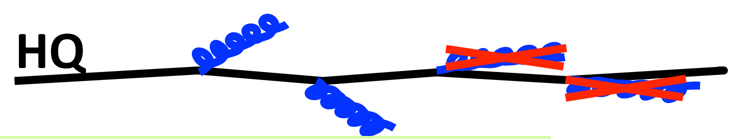

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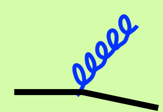

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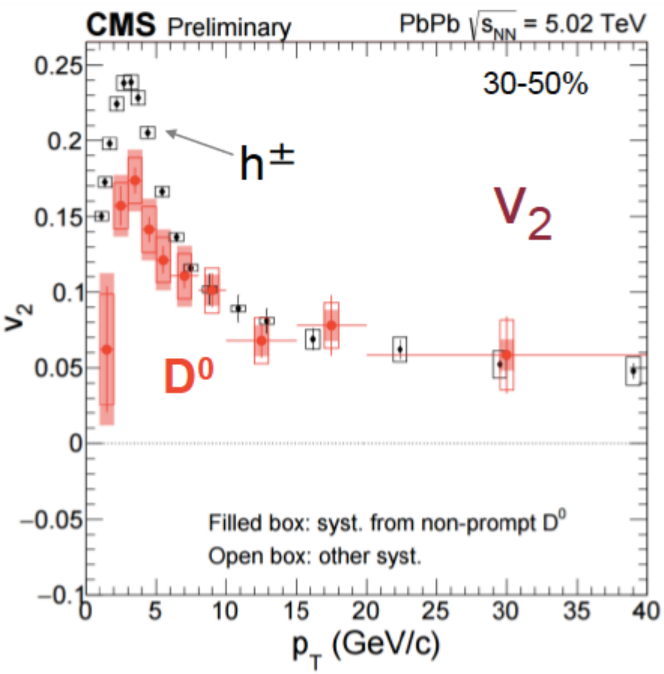
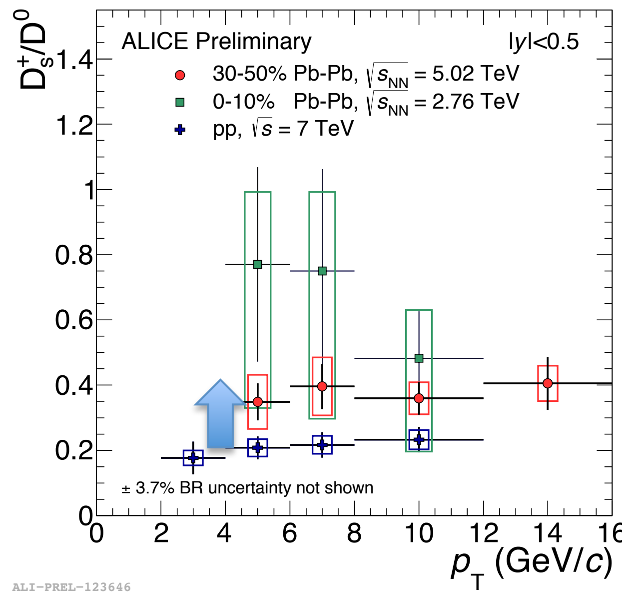
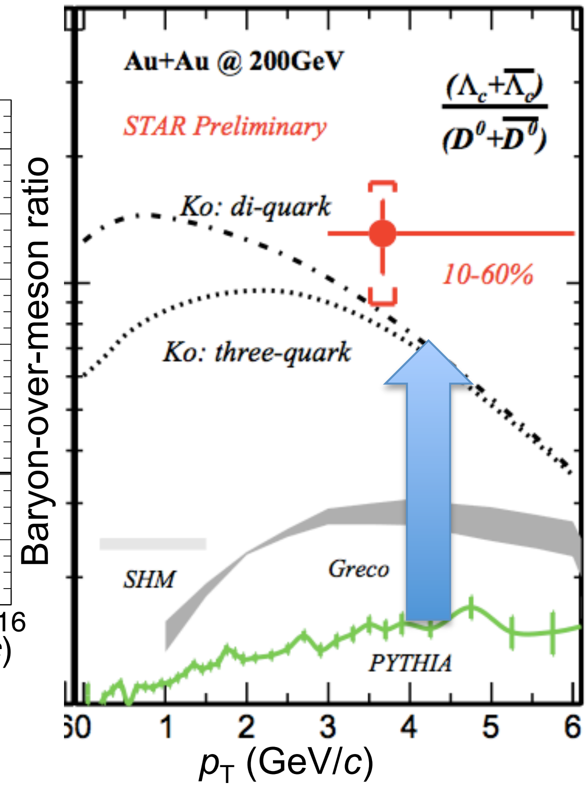
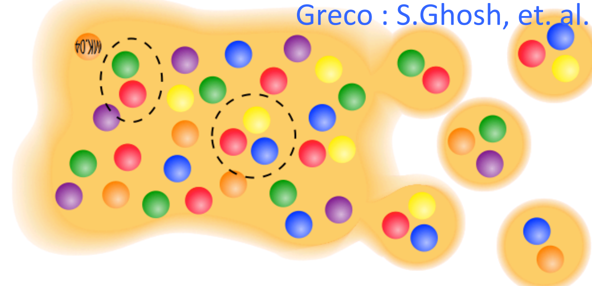






Ko : Y. Oh, et.al. PRC 79 (2009) 044905;
Greco : S.Ghosh, et. al. PRD 90 (2014) 054018

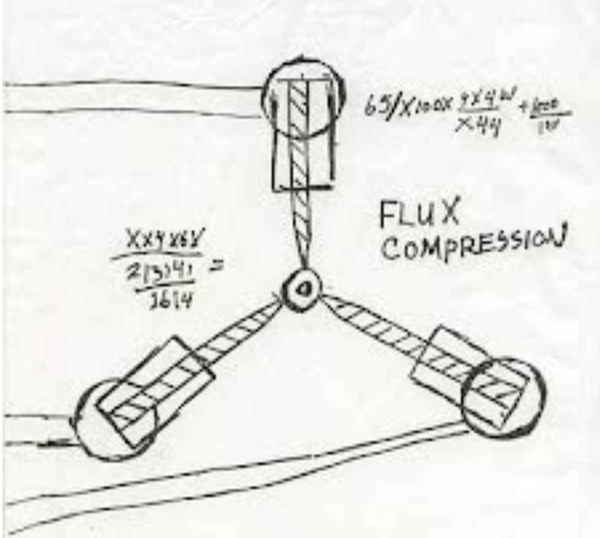
Charm flows
Modification of particle species abundances
→hadronisation via coalescence?



→ Charm participates to system collective motion
→ Possible thermalisation?

Prospects for the future

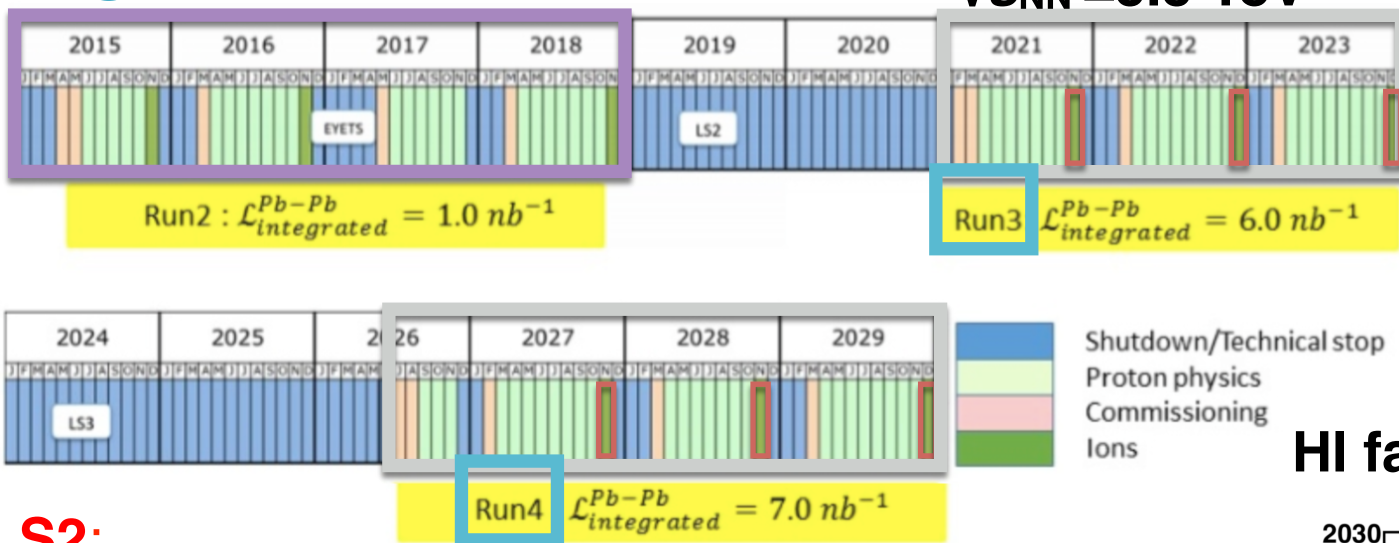
HL-LHC and ALICE upgrade
- entering into a high-precision era of QGP investigation-



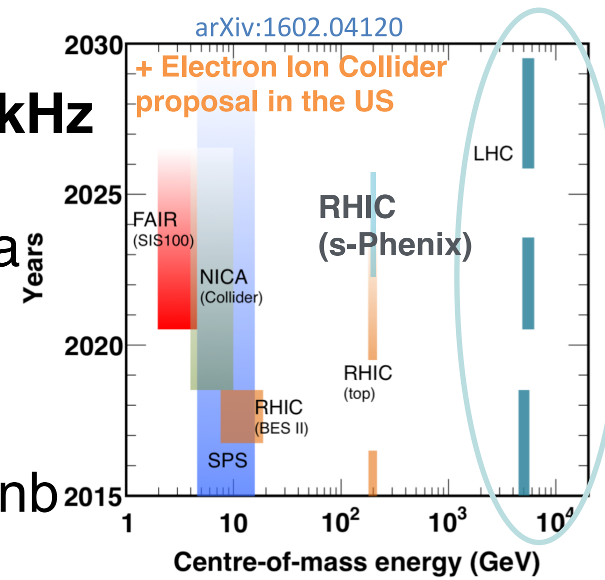
High Luminosity (HL)-LHC era

RUN2 $\sqrt{s_{NN}}$ =5.02 TeV

$\sqrt{s_{NN}}$ =5.5 TeV



HI facilities up to 2030



LS2:

- LHC **injector upgrades**: interaction rate **up to 50kHz** (now <10 kHz)

→x10 more statistics w.r.t. the current available data

- Experiments upgrade LS2 and LS3

Run 3+4: "HL-HI-LHC"

- All the four LHC experiments will participate to HI program
  - request: 1 month of Pb-Pb collisions/year > 10/nb
    - corresponds to x100 more statistics for min. bias for ALICE

- Possible interest by experiment for lighter ion run (Ar or Xe)

ALICE upgrade: New ITS

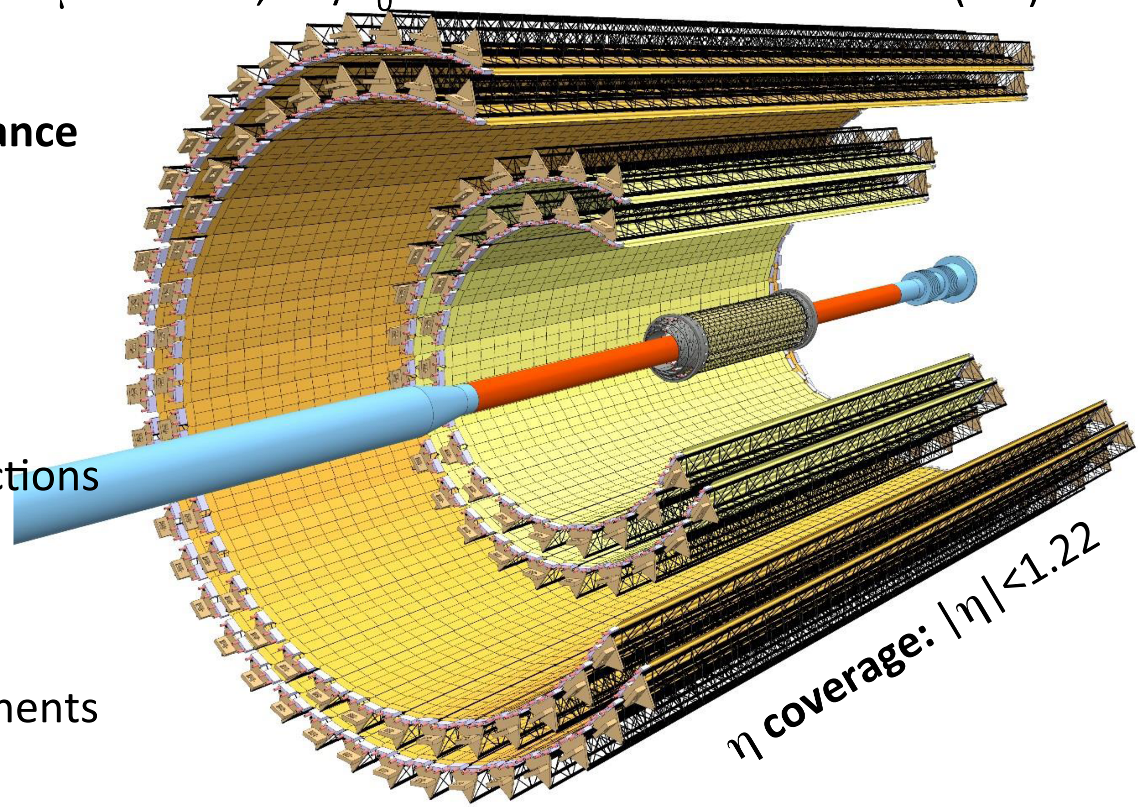
Design requirements:

1. **Improve impact parameter resolution by a factor ~3 (5) in rφ (z)**
   - ➜ Reduce pixel size (currently 50 μm x 425 μm)
     - monolithic (MAPS) with size ~ 28 μm x 28 μm
   - ➜ Go closer to interaction point:
     - ➜ new smaller beam pipe: 2.9 cm ➜ 1.9 cm
     - ➜ first layer with smaller radius (2.3 cm, currently 3.9 cm)
   - ➜ Reduce material thickness: 50 μm silicon, X/X_0 from current ~1.13% to ~0.3(0.8)% per layer

2. **High standalone tracking performance** (efficiency, spatial and momentum resolutions)
   - ➜ Increase granularity
   - ➜ Add 1 layer (from 6 to 7)

3. **Faster (x50) readout**: Pb-Pb interactions up to 100 kHz

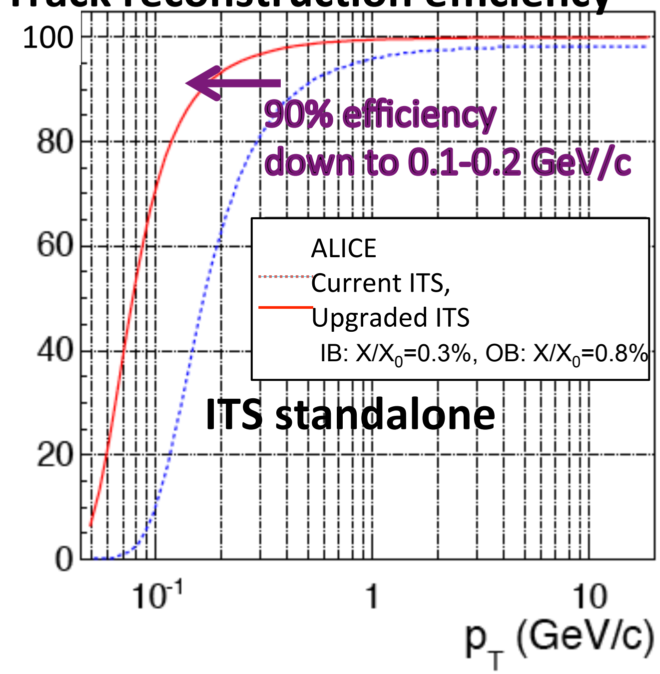
4. **Maintenance:** allow for removal/ insertion of faulty detector components during annual winter shutdown



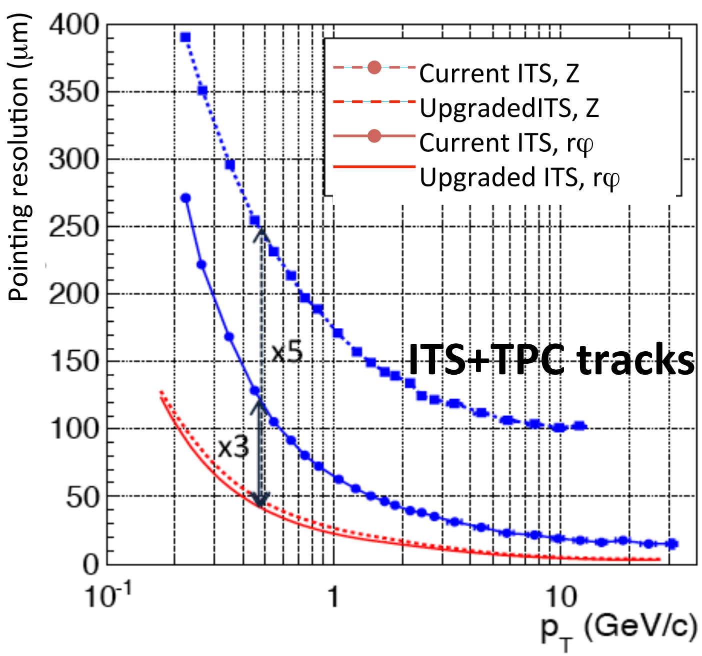
New ITS: performance

Studies done with simulations with realistic and complete detector geometry and material budget description.

Track reconstruction efficiency

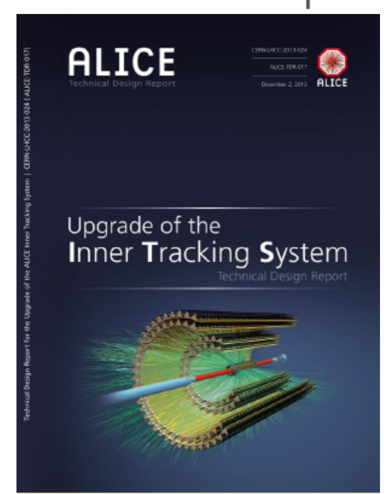


Track spatial resolution at the primary vertex

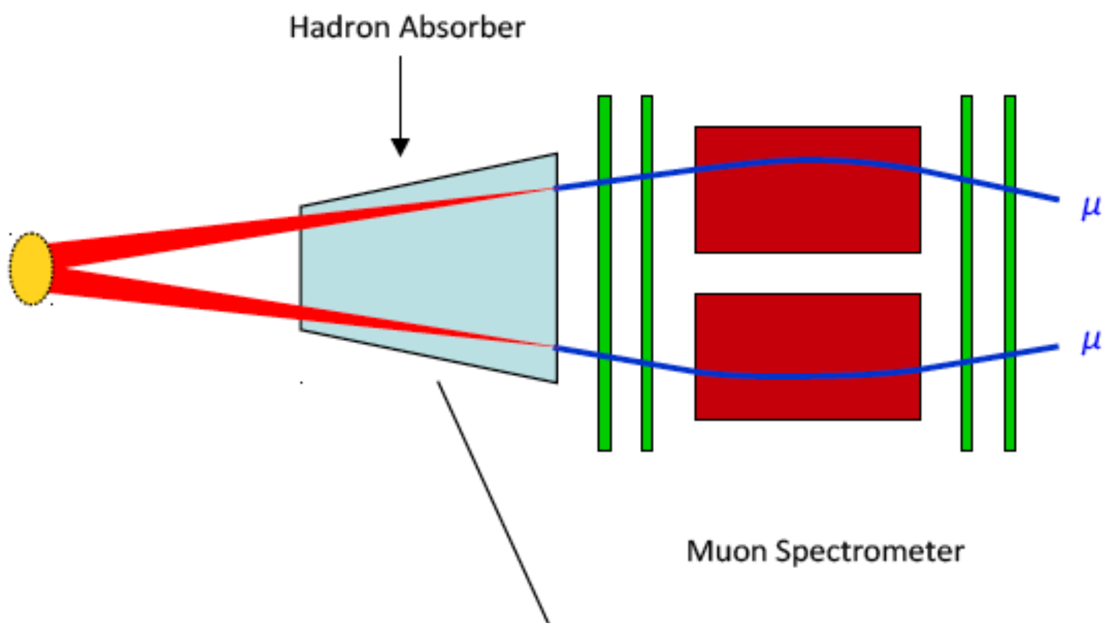


Find more in ALICE ITS TDR:

CERN-LHCC-2013-024 ; ALICE-TDR-017



Muon Forward Tracker

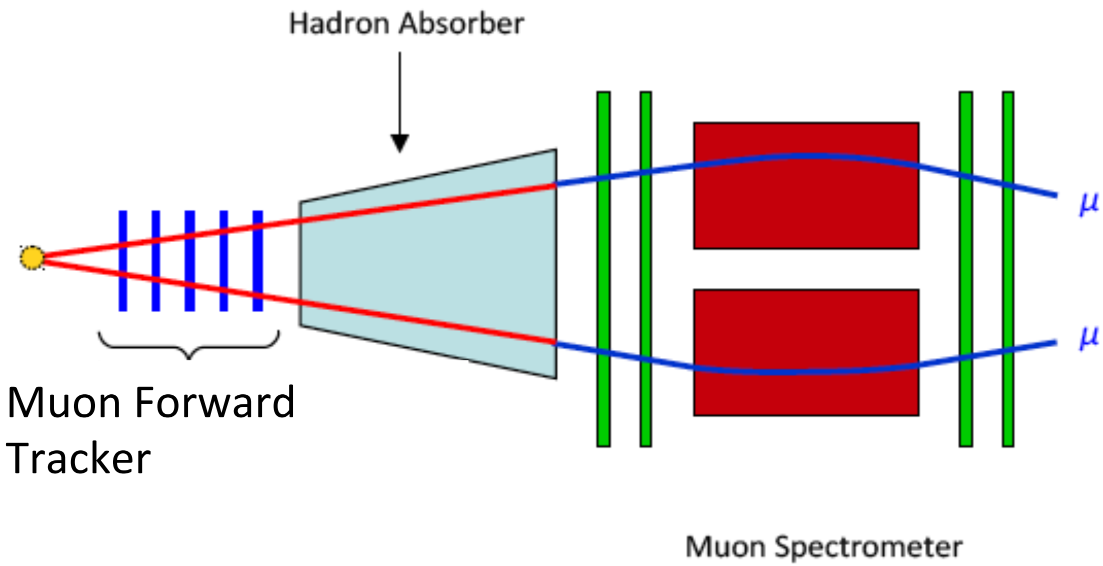


Complementing muon spectrometer at forward rapidity

Extrapolating back to the vertex region degrades the information on the kinematics and trajectory

➔ Cannot separate prompt and displaced muons

Muon Forward Tracker



Complementing muon spectrometer at forward rapidity

Muon tracks are extrapolated and matched to the MFT clusters before the absorber

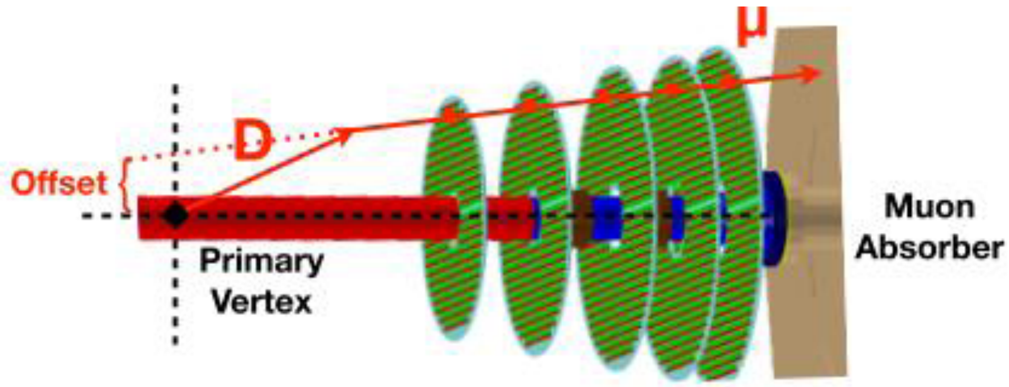
↓

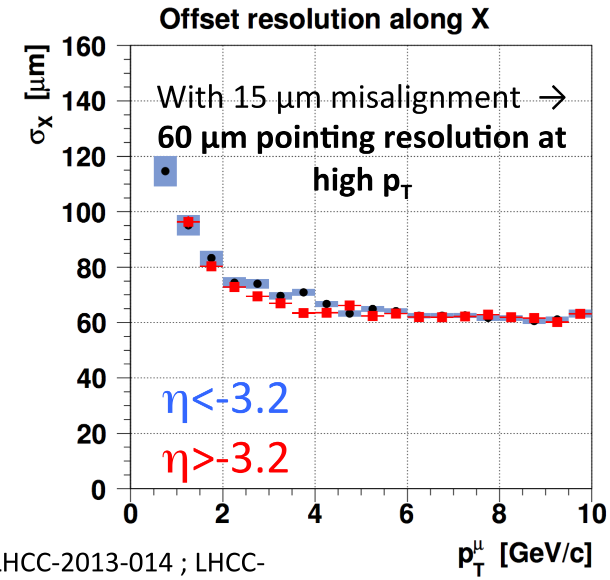
High pointing accuracy

↓

Separation of charm and beauty signals (single μ, J/ψ)

Muon Forward Tracker



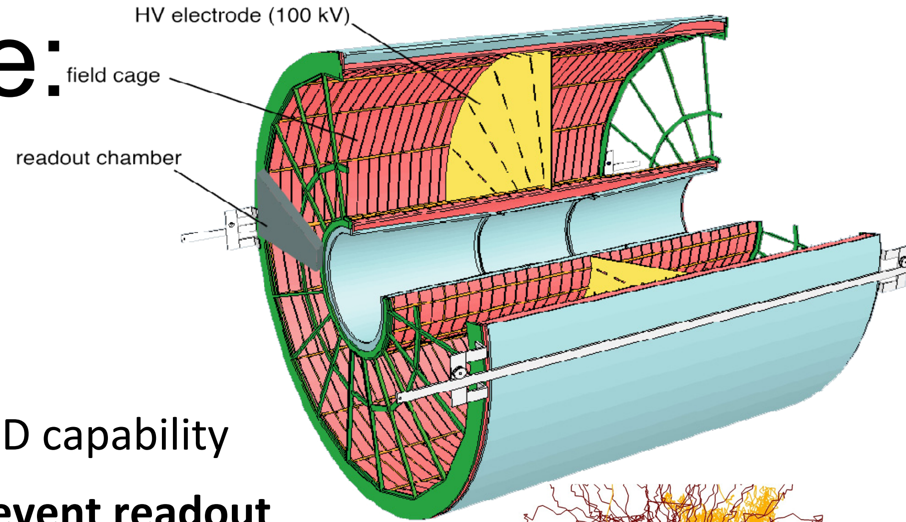


CERN-LHCC-2013-014 ; LHCC-I-022-ADD-1

5-6 planes of CMOS silicon pixel sensors (same technology as ITS):

- $50 < z < 80$ cm
- $R_{min} \approx 2.5$ cm (beam pipe constraint)
- $11 < R_{max} < 16$ cm
- Area ≈ 2700 cm^2
- $X/X_0 = 0.4\%$ per plane
- Current pixel size scenario: ~28 x 28 μm^2

ALICE at high rate: TPC Upgrade



Goals

- Operate TPC at 50 kHz
- Preserving current momentum resolution and PID capability

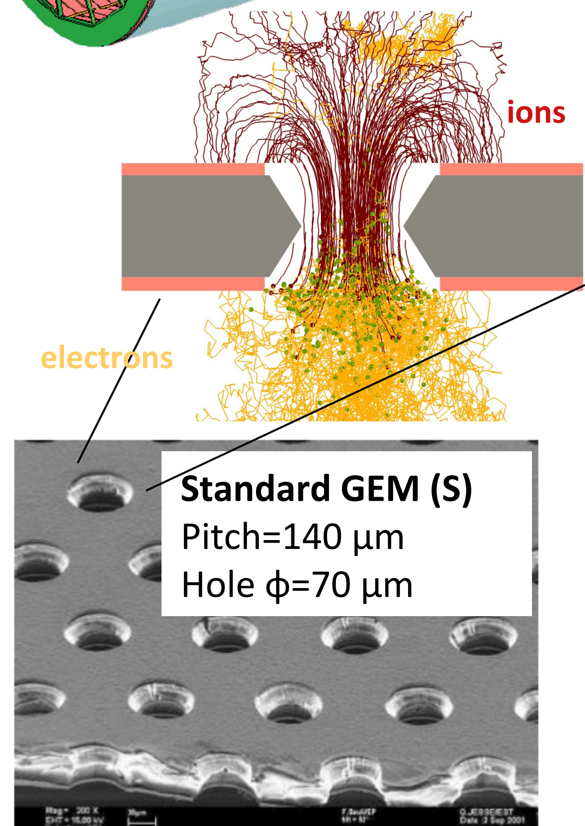
Current TPC readout based on MWPC limits the event readout rate to 3.5 kHz

➜ Upgrade TPC strategy

- **New readout chambers:** MWPC replaced with micropattern gaseous detectors, including **GEM (Gas Electron Multiplier)**
  - No gating, small ion backflow

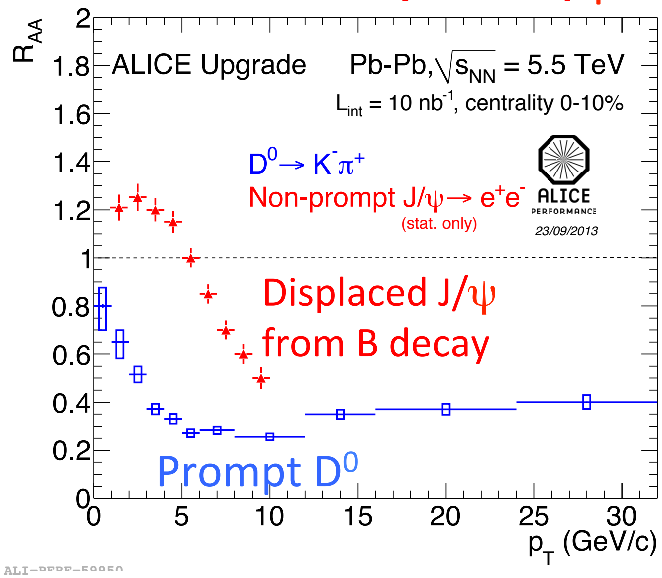
- Redesign TPC front-end and readout electronic systems to allow for continuous readout

- Significant online data reduction to comply with the limited bandwidth
  - Online cluster finding and cluster-track association

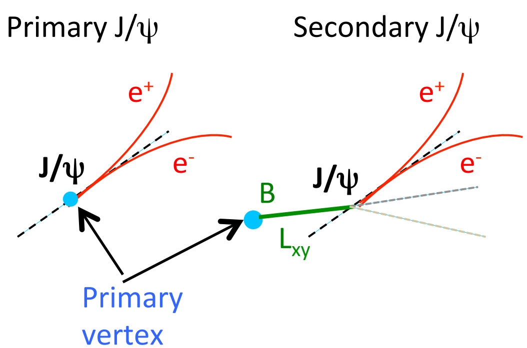


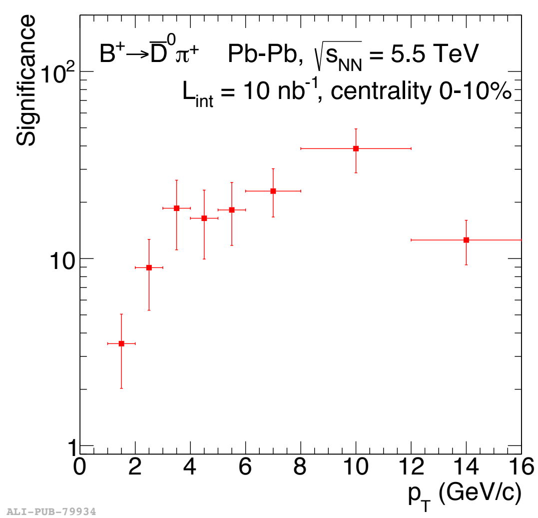
Example of performance for HF signals

Access to beauty at low p_T via:



Displaced $J/\psi \rightarrow e^+e^-$
at midrapitity down to 1 GeV/c

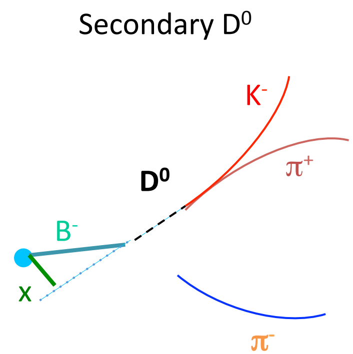




Full B meson reconstruction in central Pb-Pb collisions

Down to p_T=2 GeV/c

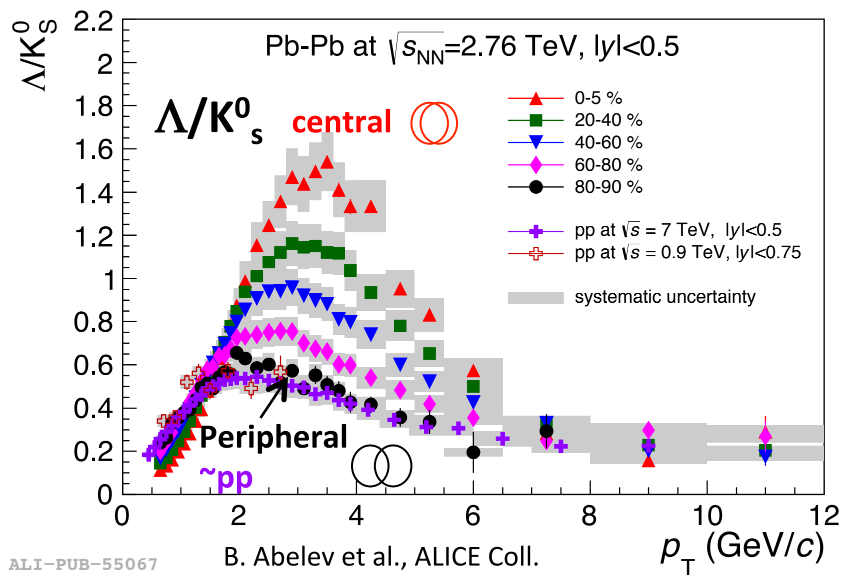
Closer to b-quark momentum



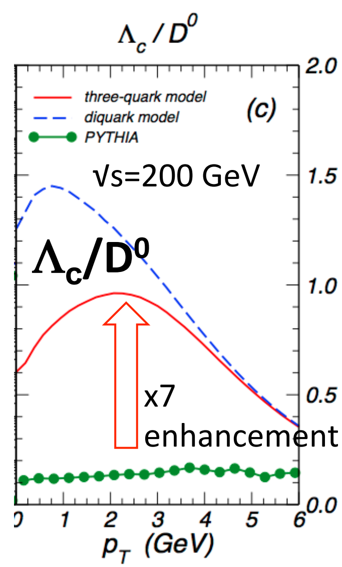
Heavy Flavour: hadronization

- Investigate possible baryon/meson enhancement and strangeness enhancement in charm sector
  - Radial flow effect? (velocity field → larger momentum for heavier particles)
  - Hadronization via coalescence?

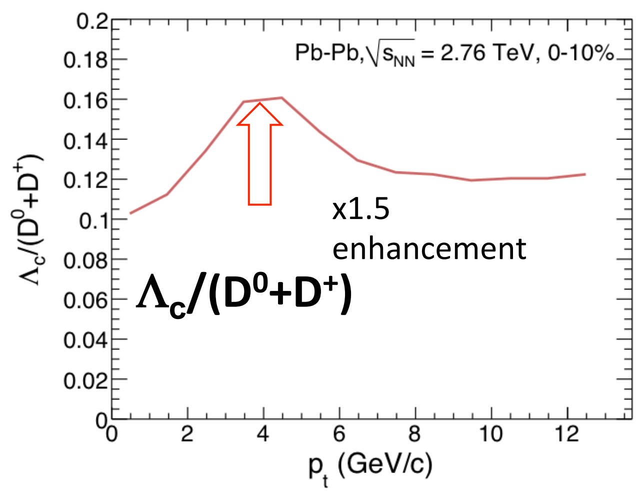
⇒ **Heavy Flavour Baryon (Λ_c, Λ_b)? ← degree of thermalization of HF quarks**



B. Abelev et al., ALICE Coll. PRL **111**, 222301 (2013).



C.M.Ko et al. PRC79



R. Rapp et al. PRC86

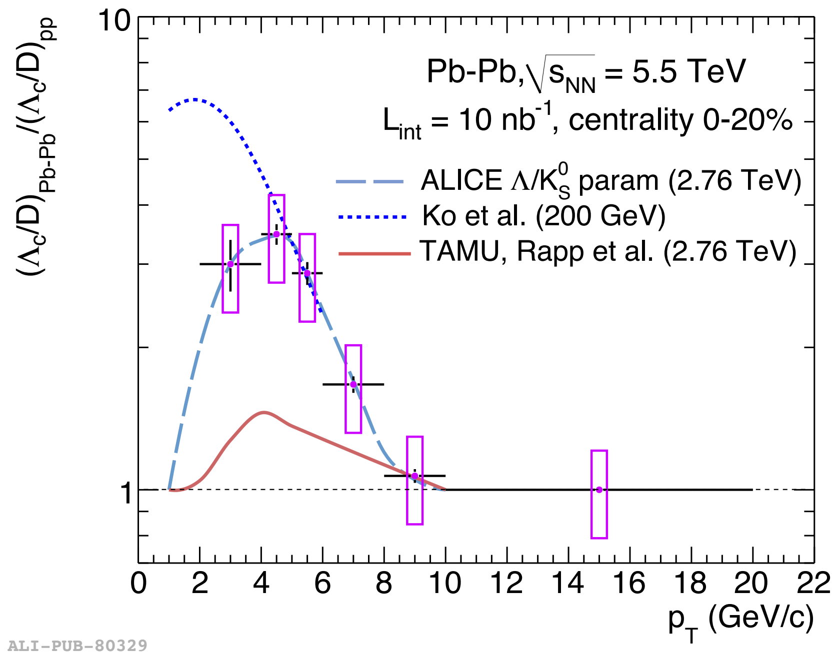
Heavy Flavour: hadronization

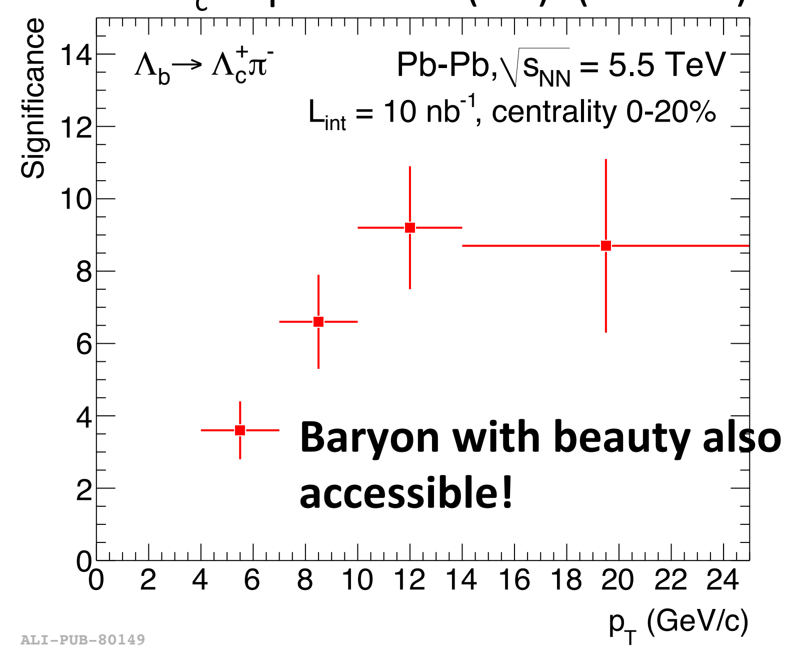
- Investigate possible baryon/meson enhancement and strangeness enhancement in charm sector
  - Radial flow effect? (velocity field → larger momentum for heavier particles)
  - Hadronization via coalescence?

⇨ **Heavy Flavour Baryon (Λ_c, Λ_b)? ← degree of thermalization of HF quarks**

$\Lambda_c \rightarrow pK^-\pi^+$, $c\tau$~60 μm BR: 5.0±1.3 %

$\Lambda_b \rightarrow \Lambda_c\pi^+$, $c\tau$~419 μm
↳ $\Lambda_c \rightarrow pK^-\pi^+$ BR(tot): (4.5±1.9)×10^{-4}



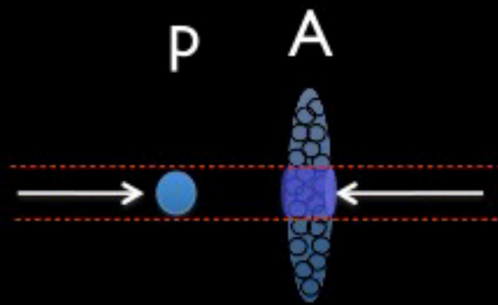


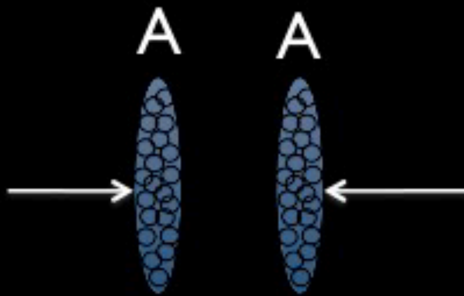
Baryon with beauty also accessible!

QGP in small systems?

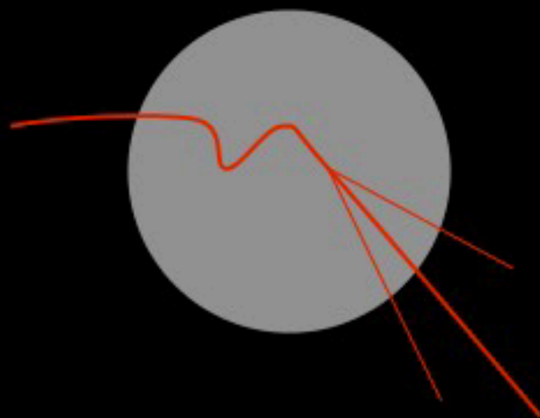
The feature has already started!!

The multi collision-system experimental approach: the initial design

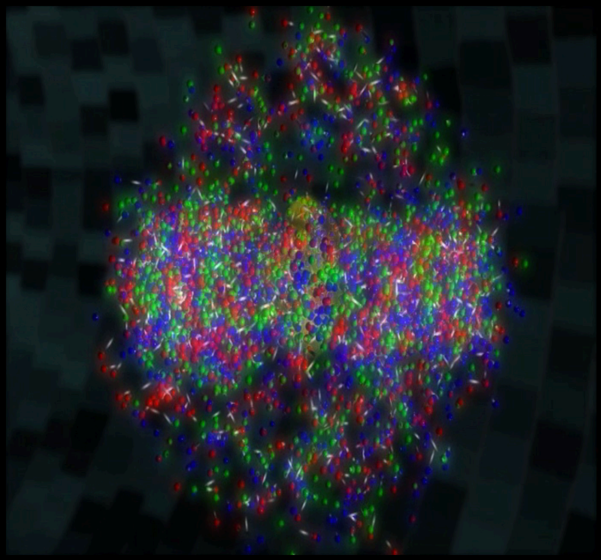




Local structure of QCD vacuum



Local QCD
+
initial state/cold nuclear matter



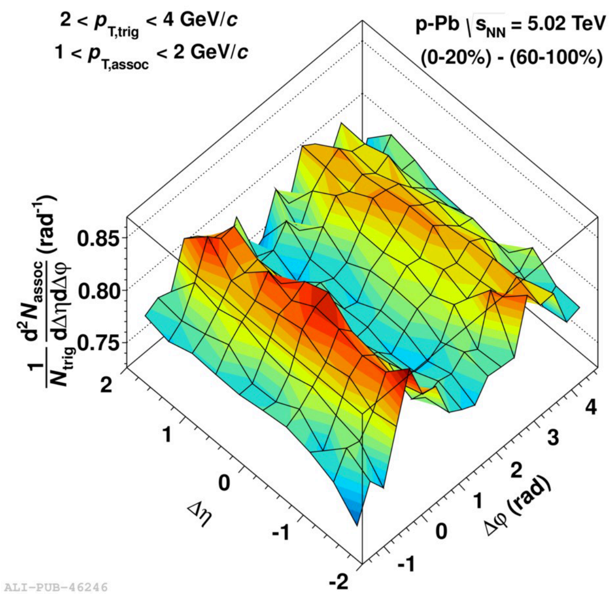
Local QCD
+
initial state/cold nuclear matter
+
Quark-Gluon Plasma

Copied by. C. Loizides who adapted it from G. Roland

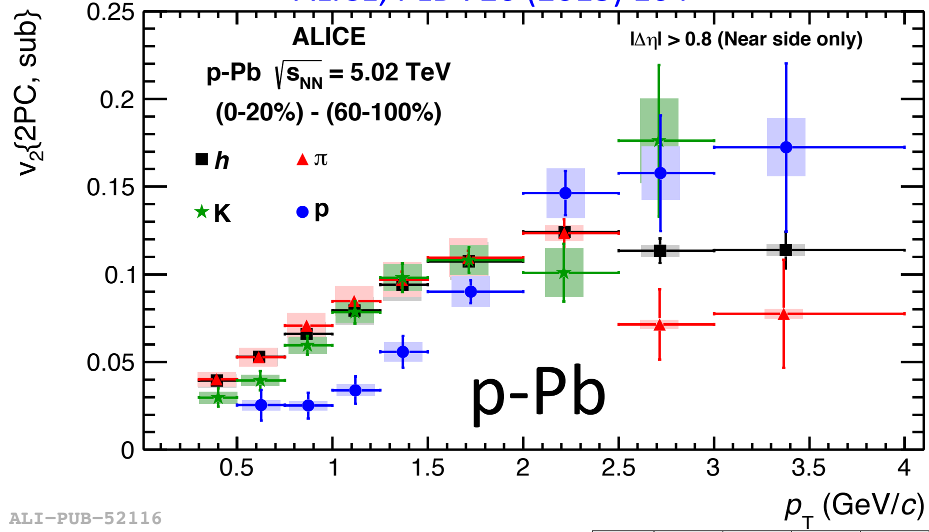
More in P. Bartalini's talk

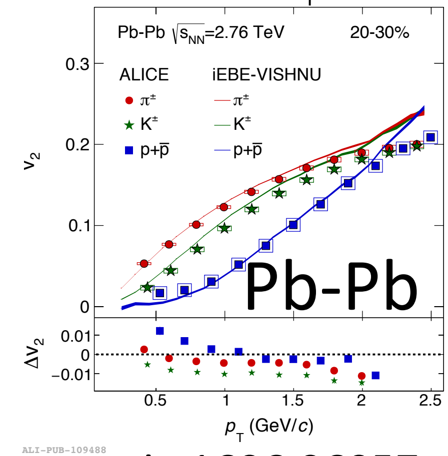
Long range correlations and flow in p-Pb

ALICE, PLB 719 (2013) 29



ALICE, PLB 726 (2013) 164





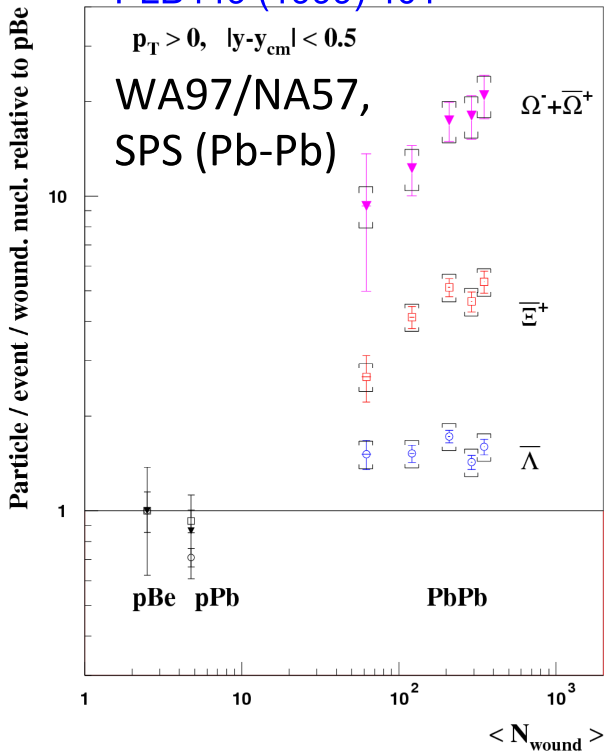
arxiv:1606.06057

Large v_2 (elliptic flow) values!

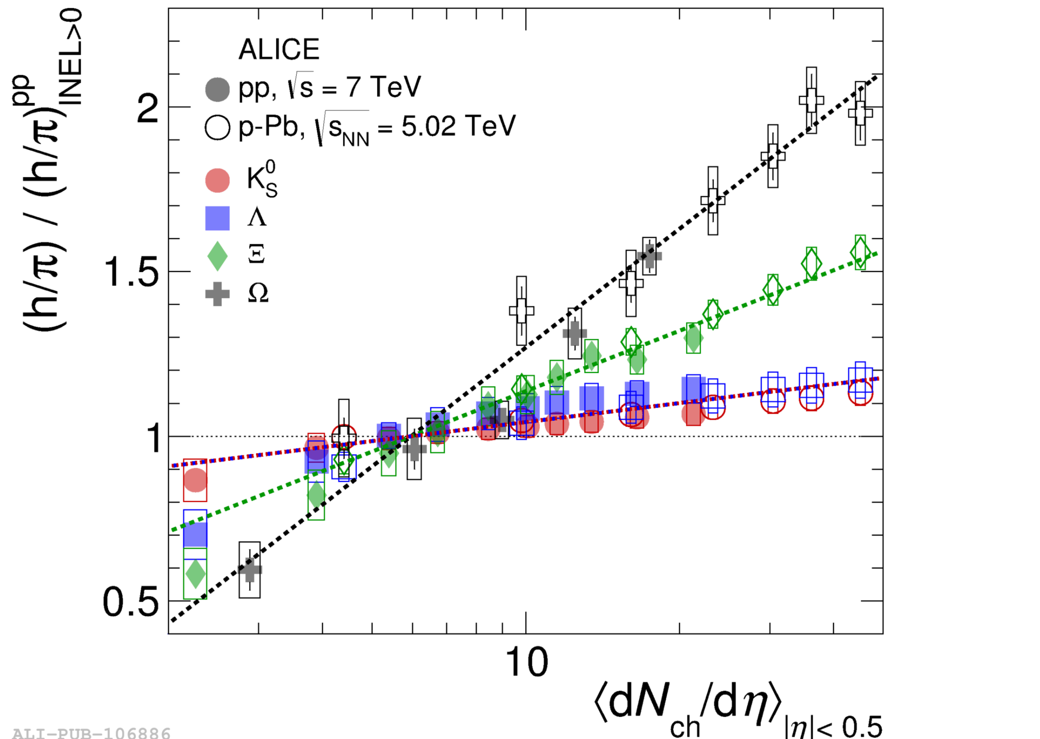
Mass ordering and "crossing" similar to Pb-Pb, where data are reproduced by hydrodynimical models

Strangeness enhancement

PLB449 (1999) 401



Nature Physics (2017) doi:10.1038/nphys4111



- Increase of strange particle yield with collision centrality
- Stronger effect for particles with larger strangeness content
- Historical QGP “smoking gun” (Rafelski, Müller, PRL48(1982)1066), associated with chiral symmetry restoration and removal of canonical suppression

Now observed also in pp collisions at high multiplicity

→ New research direction

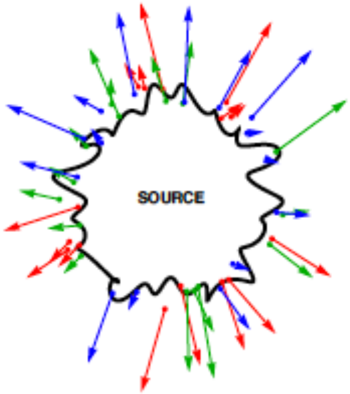
Extra

System size: HBT interferometry

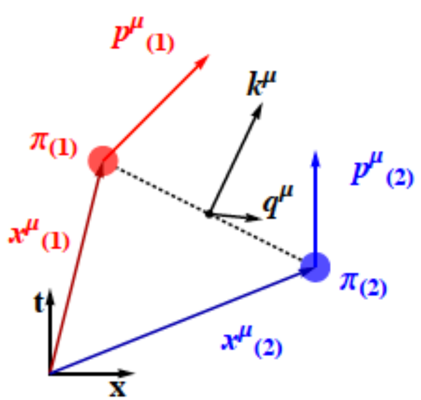
Hanbury-Brown and Twiss

"Bose-Einstein" enhancement in the momentum correlation of identical bosons emitted close in phase ⟶ Probe "homogeneity emission region" and decoupling time

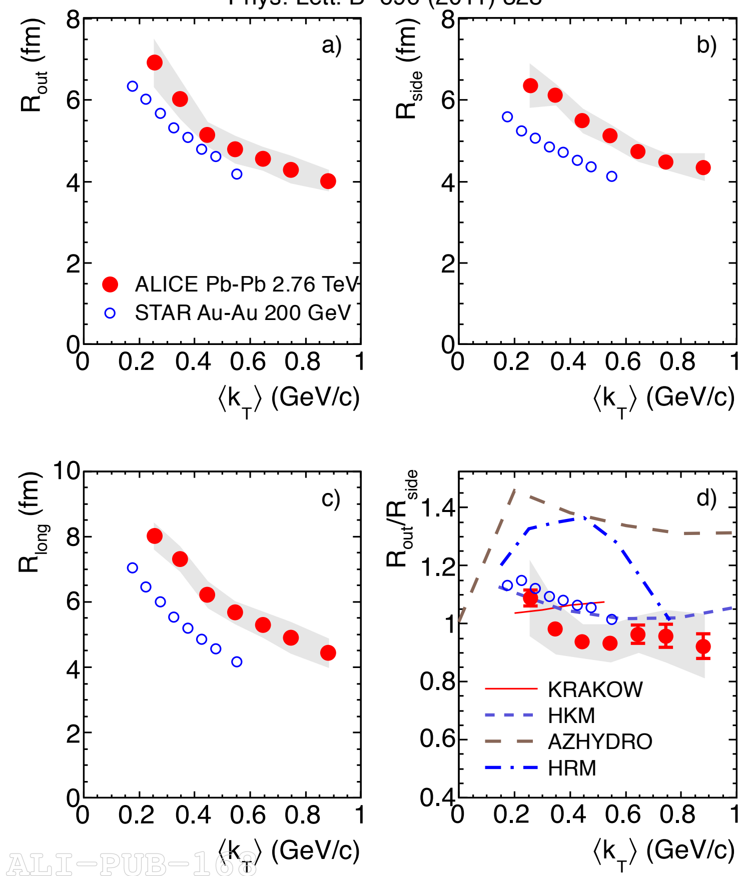
source emitting particles

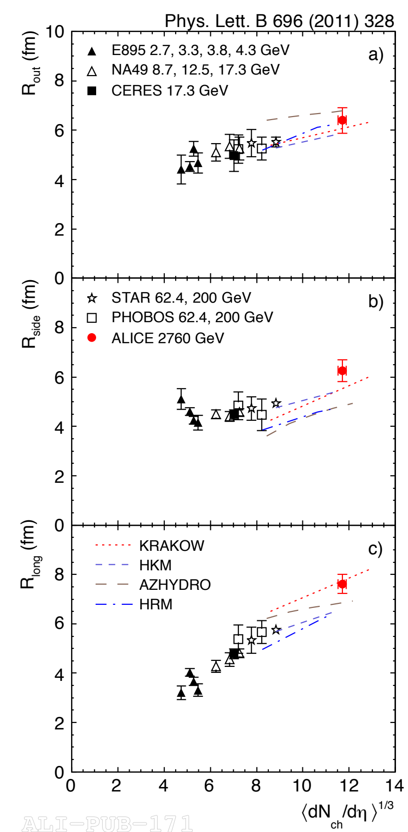


two identical pions, $\pi^+\pi^+$, $\pi^-\pi^-$

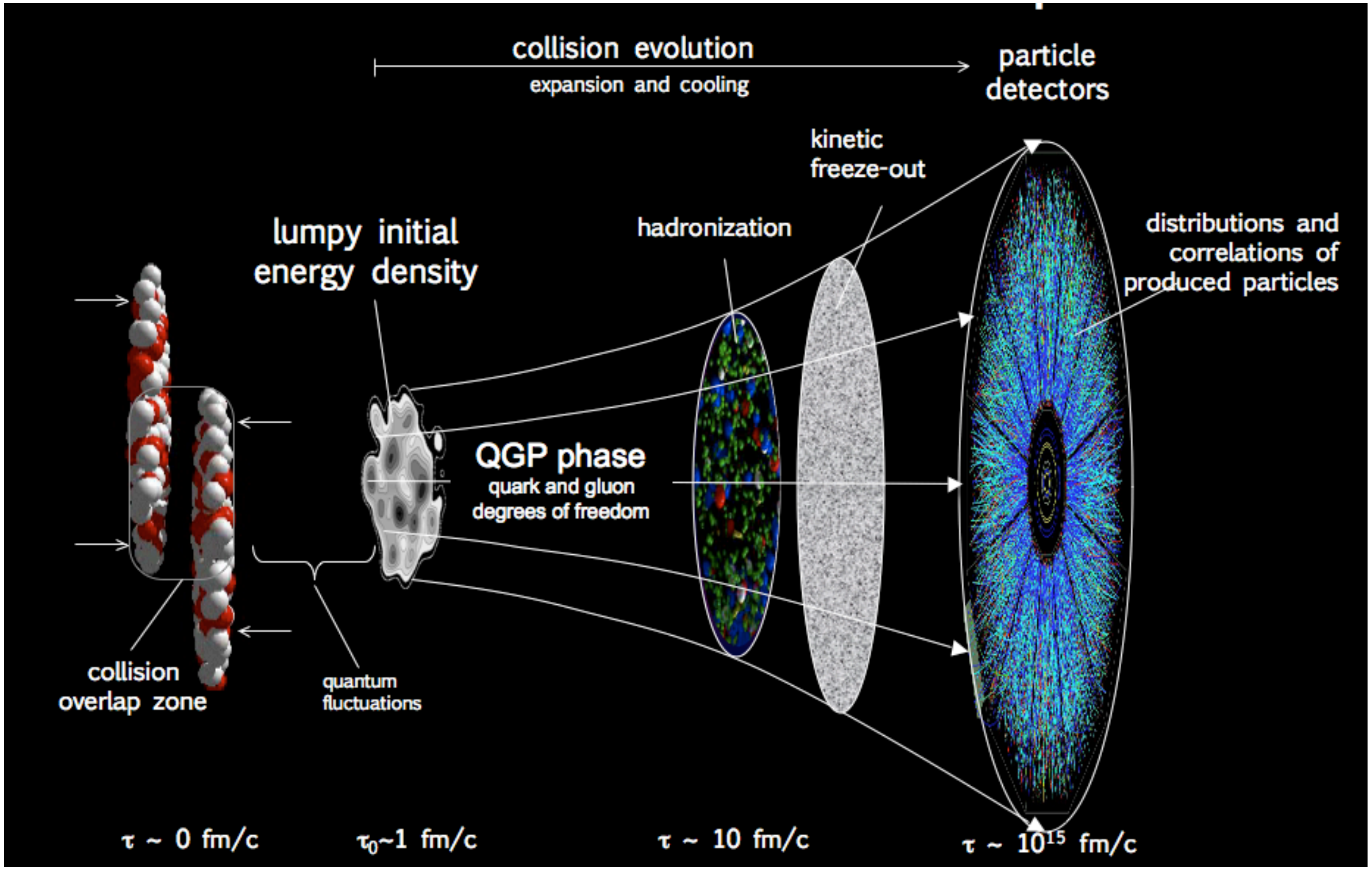


Phys. Lett. B 696 (2011) 328





The medium evolution

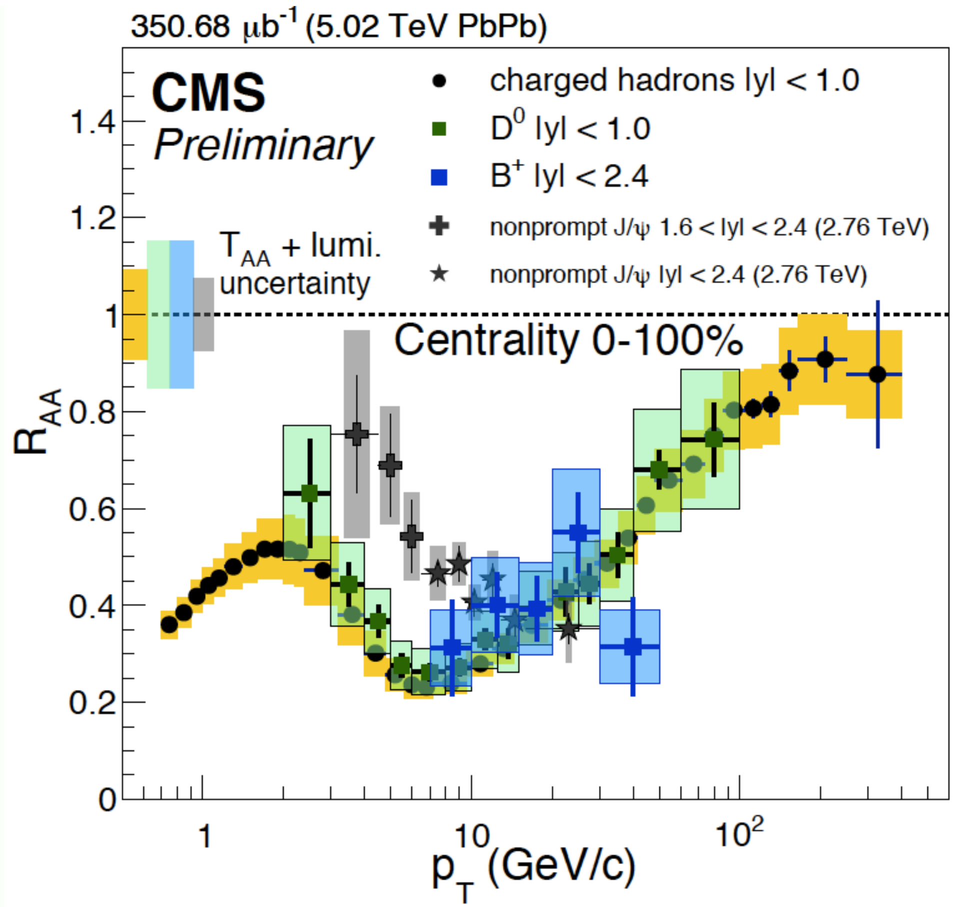


After hadronization: "**hadronic phase**"

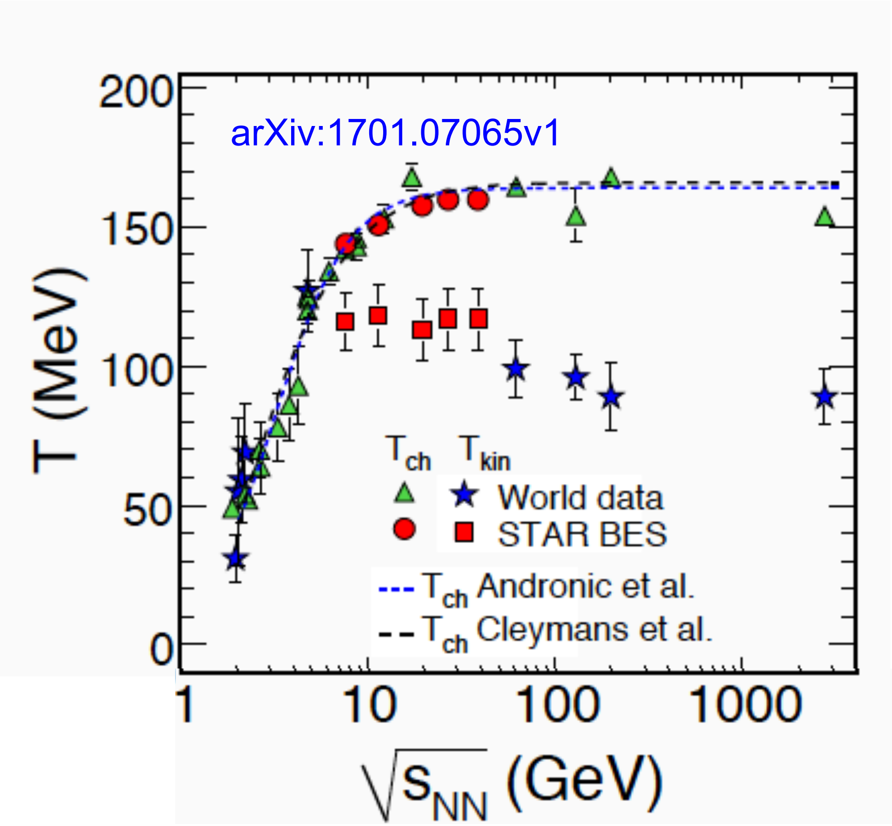
Chemical freeze out: time at which inelastic interactions cease →abundances of particle species (π,K,p,.. yields) are fixed (not resonance ones)

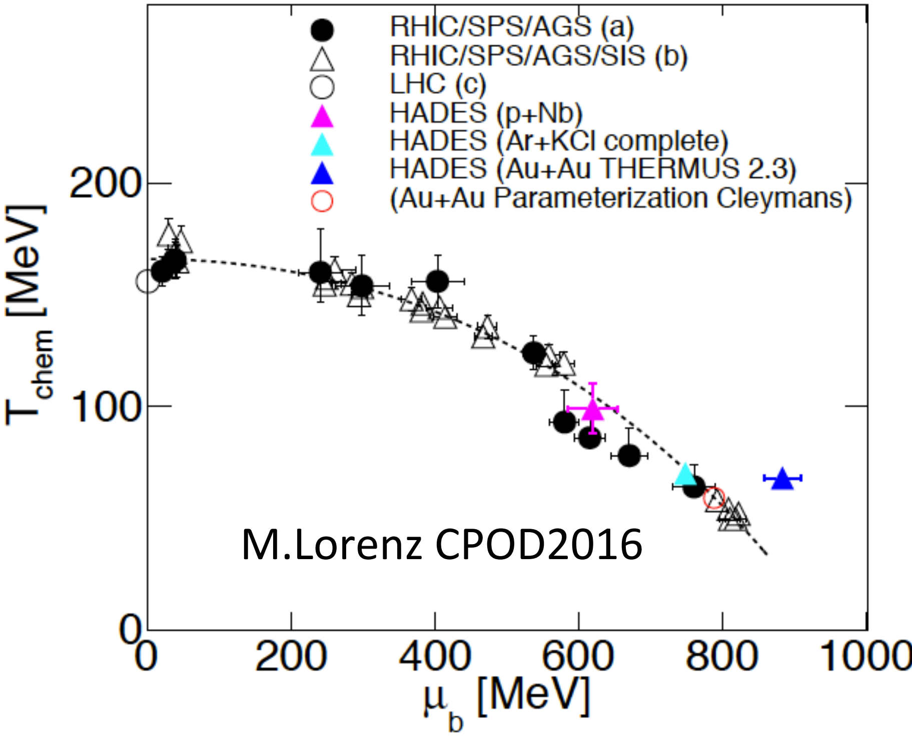
Kinetic freeze out: all interactions cease → free streaming of particles to detector

Beauty nuclear modification factor



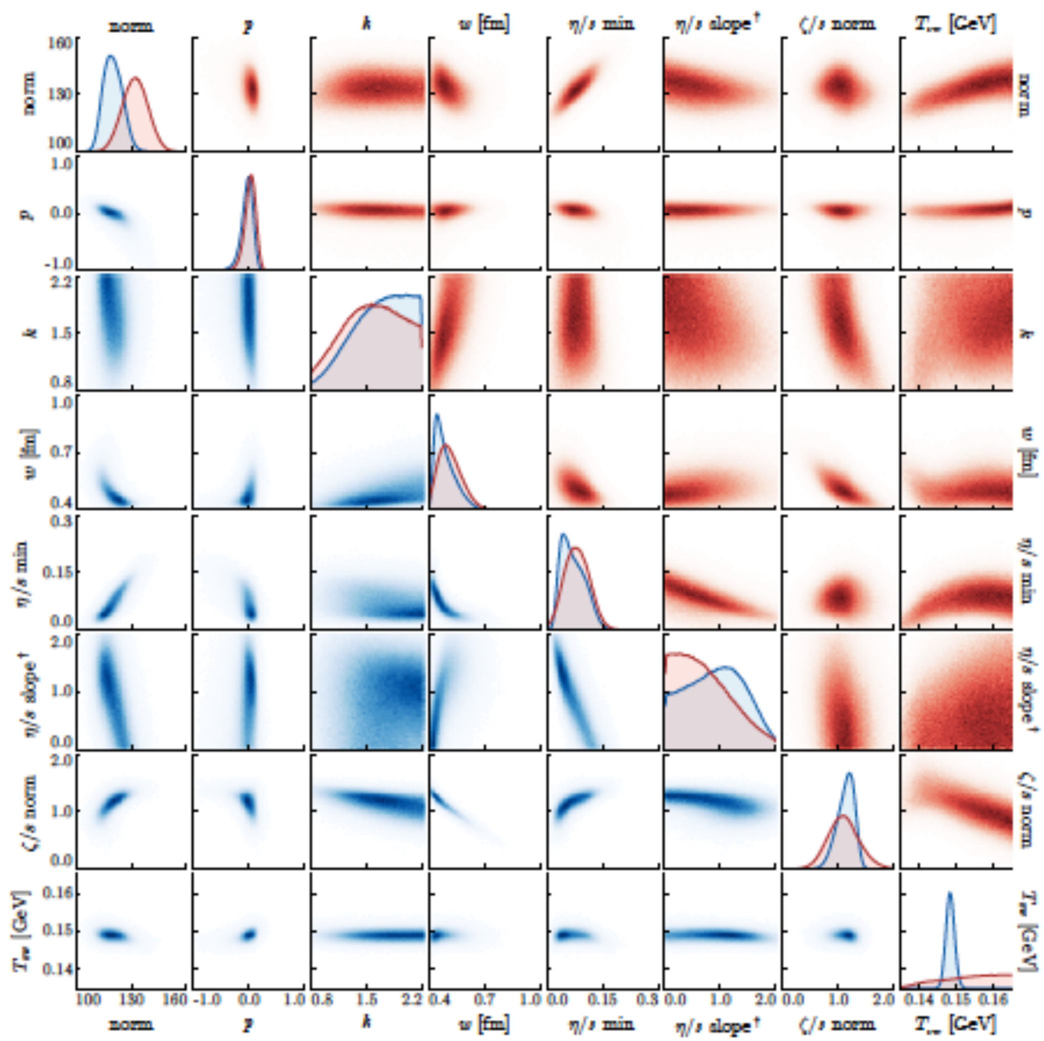
Beam-energy scan at RHIC





Constraining further viscosity: example with a model

J. E. Bernhard et al. Phys. Rev. C 94, 024907 (2016)

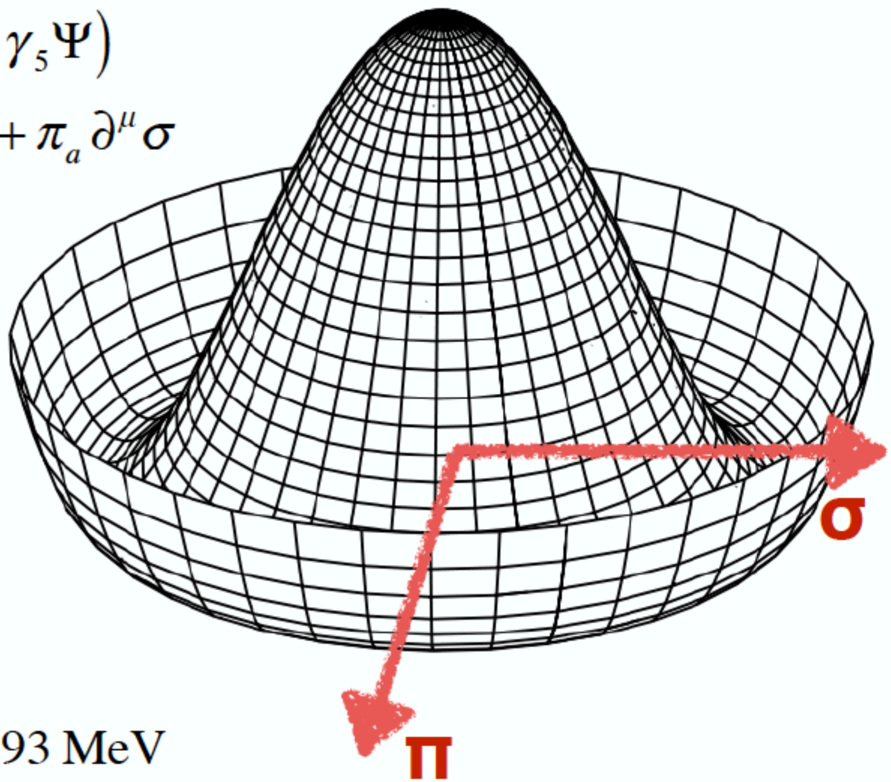


More on chiral symmetry breaking

$$\mathcal{L} = \frac{-1}{2}\left\{\sigma\,\partial^2\sigma + \vec{\pi}\,\partial^2\cdot\vec{\pi}\right\} + \frac{1}{2}M_0^2\left\{\sigma^2 + |\vec{\pi}|^2\right\} - \frac{\lambda}{4}\left\{\sigma^2 + |\vec{\pi}|^2\right\}^2$$

$$+ g_{\pi N}\left(\sigma\bar{\Psi}\Psi + i\vec{\pi}\cdot\bar{\Psi}\vec{\tau}\gamma_5\Psi\right)$$

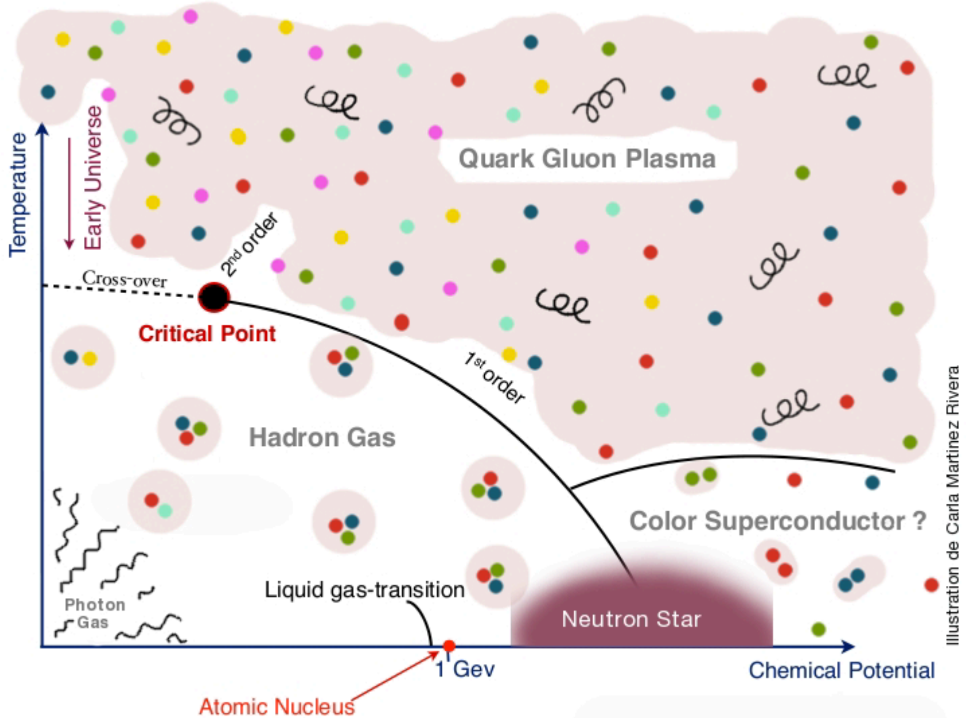
$$j_a^\mu = \bar{\Psi}\gamma_5\gamma^\mu\tau_a\Psi + \sigma\,\partial^\mu\pi_a + \pi_a\,\partial^\mu\sigma$$



$$M_N \approx g_{\pi N}\langle\sigma\rangle,\ \langle\sigma\rangle = f_\pi = 93\,\text{MeV}$$

More on phase transition

With realistic (i.e. non-zero) quark masses the phase transition at small μ_B is predicted to be a crossover

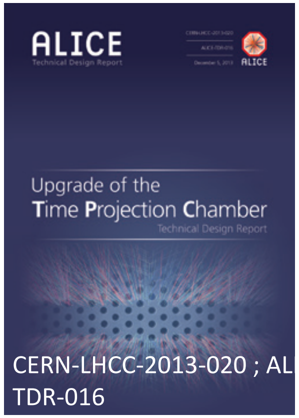


See arXiv:hep-lat/0701002 for a clear overview (though old)

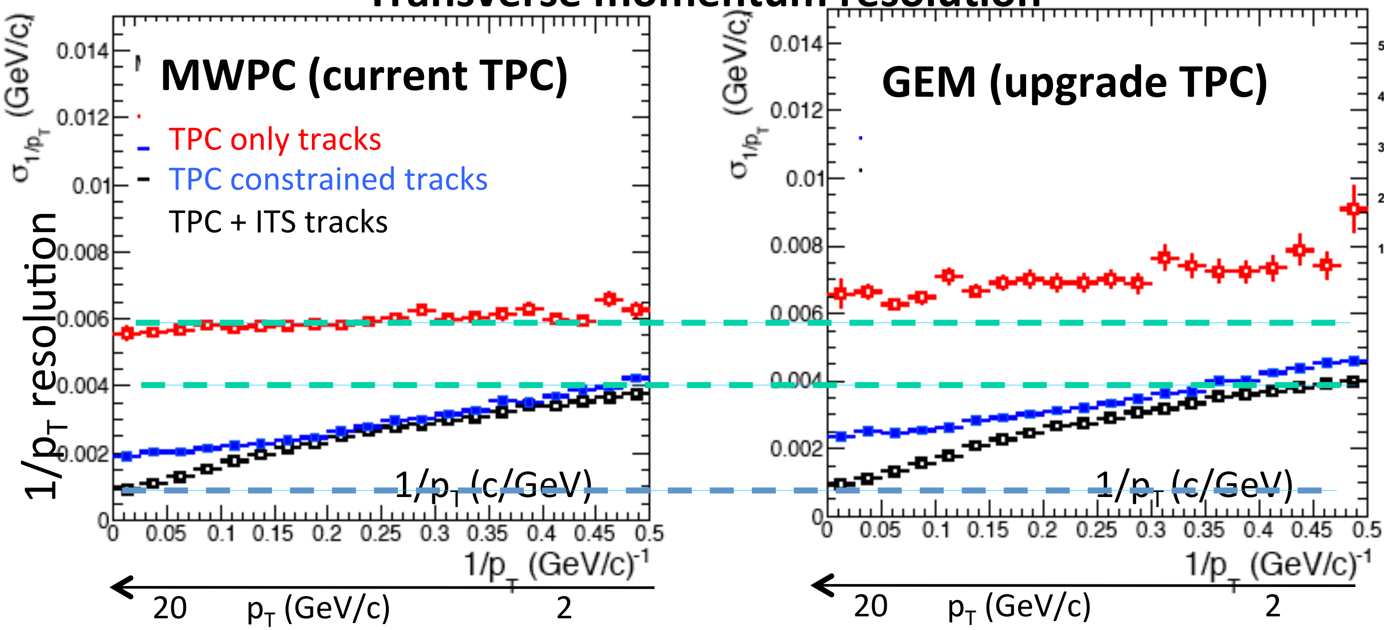
ALICE at high rate: TPC Upgrade

Expected performance:

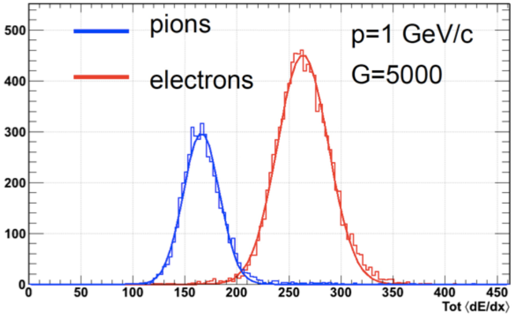
- p_T resolution practically unchanged for TPC+ITS tracks (simulations)
- dE/dx resolution comparable to current performance (beam tests at PS)



Transverse momentum resolution



PID



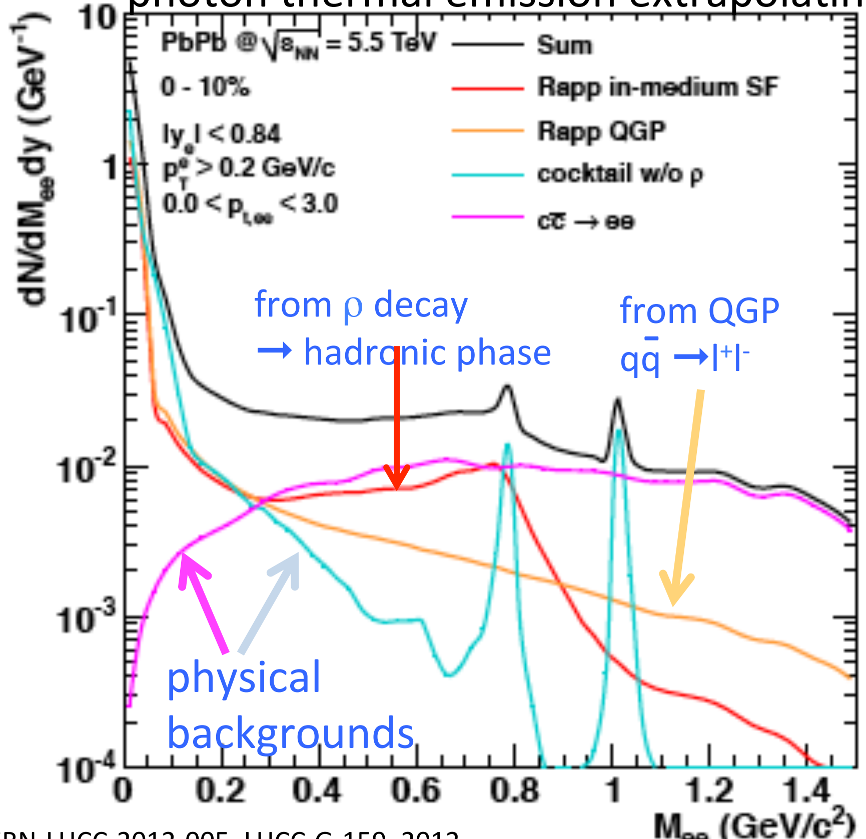
Beam test at PS

- Good e/π separation

Di-electron production

One of the most fundamental measurements, sensitive to:

- chiral-symmetry restoration by modification of ρ-meson spectral function
- partonic equation of state studying space–time evolution with invariant-mass and p_T distributions of dileptons
- photon thermal emission extrapolating to zero dilepton mass



CERN-LHCC-2012-005, LHCC-G-159, 2012.

Target measurements:

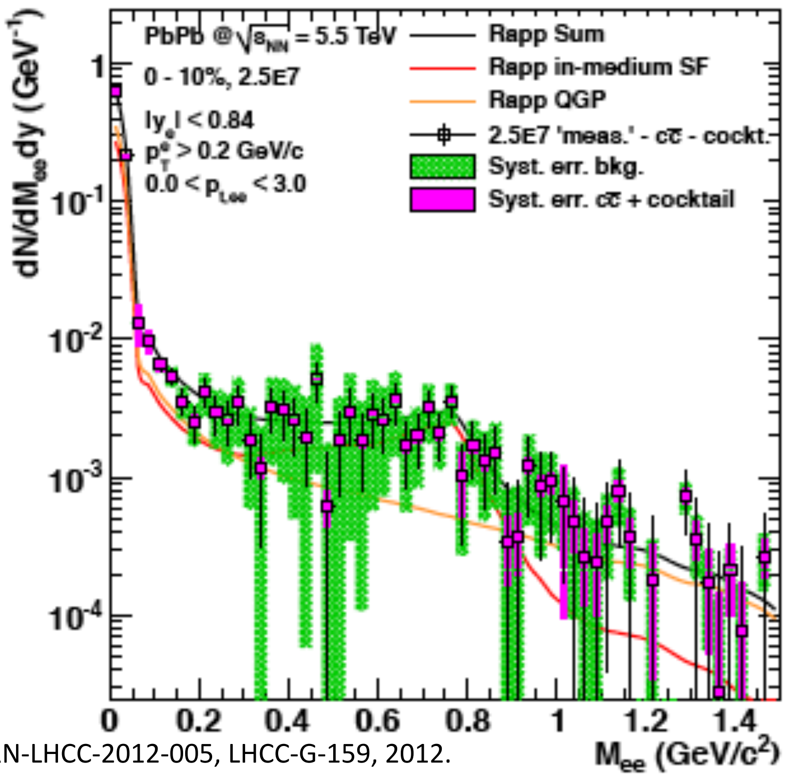
- di-electron yield vs. mass and p_T (require background subtraction)
- di-electron elliptic flow

New ITS

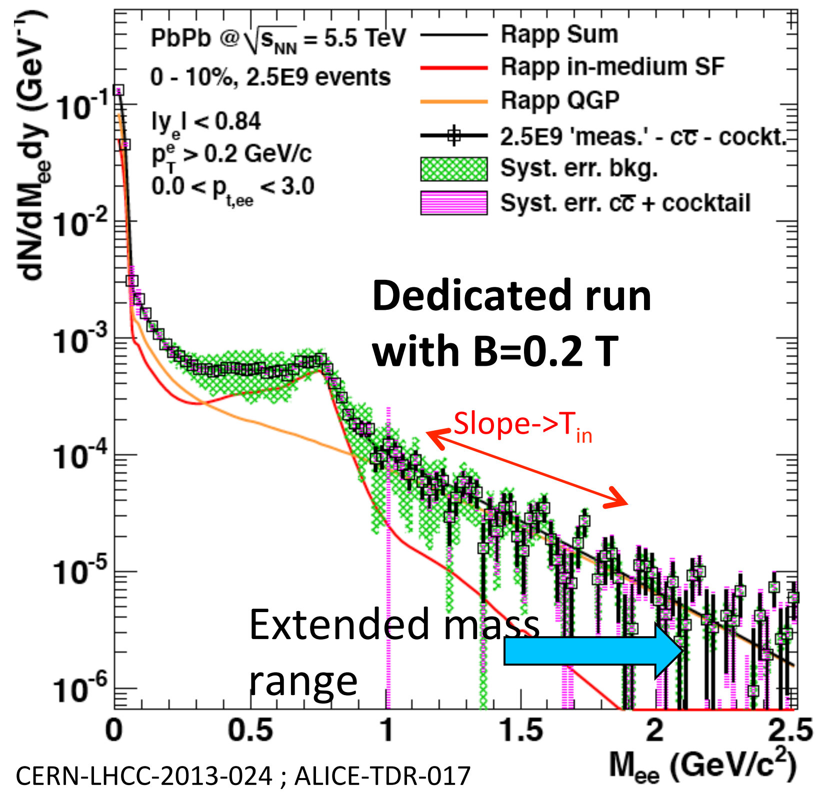
- Reduced combinatorial background (reduce impact of γ-conversions)
- Charm rejection

Di-electron production

Excess after background subtraction



CERN-LHCC-2012-005, LHCC-G-159, 2012.



CERN-LHCC-2013-024 ; ALICE-TDR-017

current ITS and event rate:
large statistical and systematic uncertainties

new ITS and high-rate:
precise measurement

Allows for an estimation of the **temperature at various phases of system expansion** with 10-20% precision (stat.+syst.)