

Heavy ions at LHC

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Heavy Ions at LHC

- Introduction
- Observables
- Hard probes
- Prospects

- The idea behind the study of heavy ion collisions is to use the nucleus as a QCD laboratory
 - It has strong implications for cosmology and astrophysics since it represents the creation of a mini-Bang
 - Needs the understanding of collective effects in QCD matter
-

The Hagedorn argument

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- **Statistical bootstrap model:** As the collision energy increases the number of particles (states) increases. Hagedorn argued that the density of states goes as

$$\rho(m) = cm^a \exp(b.m)$$

- In a hadron gas the average energy is

$$\bar{E} = \frac{\int_0^\infty dE E \rho(E) e^{-E/T}}{\int_0^\infty dE \rho(E) e^{-E/T}} = \frac{\int_0^\infty dm m \rho(m) e^{-m/T}}{\int_0^\infty dm \rho(m) e^{-m/T}} \xrightarrow{\text{c.m.}} \int_0^\infty dm cm^{a+1} e^{-m(b-1/T)}$$

- **$T < b^{-1}$** that is, there **exists a limiting temperature** for the hadron gas! ($T_c = b^{-1} \sim 160$ MeV)
- This argument seems insensitive to the initial system type. So why should we use AA collisions? Simple exercises show why:

A simple exercise: p-p

Normal hadronic matter:

$$m_N = 0.94 \text{ GeV} ; 0.17 \text{ N.fm}^{-3}$$

$$\varepsilon = 0.94 \times 0.17 = 0.16 \text{ GeV.fm}^{-3}$$

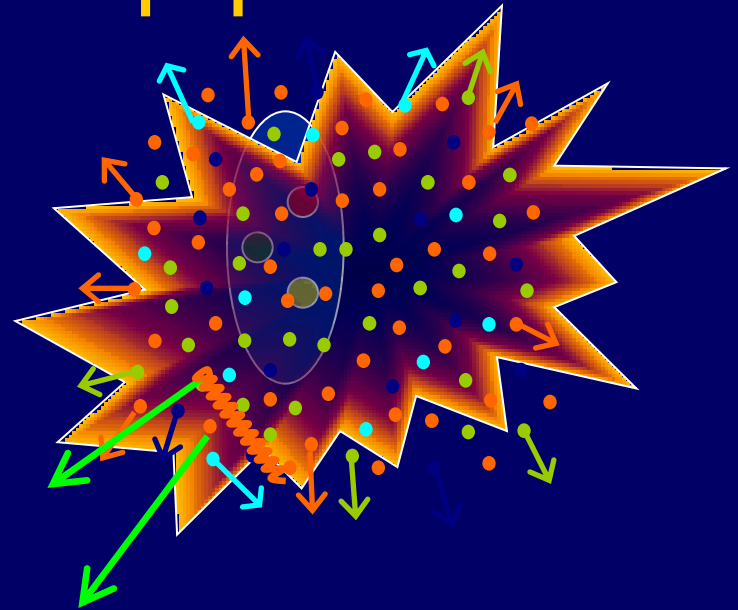
Case 1: **SPS (CERN)**

$$E_{\text{CM}} \sim 20 \text{ GeV}; \langle n_p \rangle \sim 3 \text{ com } \langle p \rangle \sim 0.5 \text{ GeV}/c$$

$$\varepsilon \cong \frac{3 \times (0.5 \text{ GeV})}{(\frac{4}{3}\pi)(1 \text{ fm})^3} = 0.4 \text{ GeV.fm}^{-3}$$

Case 2: **Tevatron (FNAL)**

$$E_{\text{CM}} \sim 1.8 \text{ GeV}; \langle n_p \rangle \sim 20 \rightarrow \varepsilon \sim 2 \text{ GeV.fm}^{-3}$$



A simple exercise: A-A

In each nucleus:

$$N_A = \frac{3}{4} \left[2\pi R_A (1 \text{ fm})^2 \right] \times n_0 \cong A^{1/3}$$

where

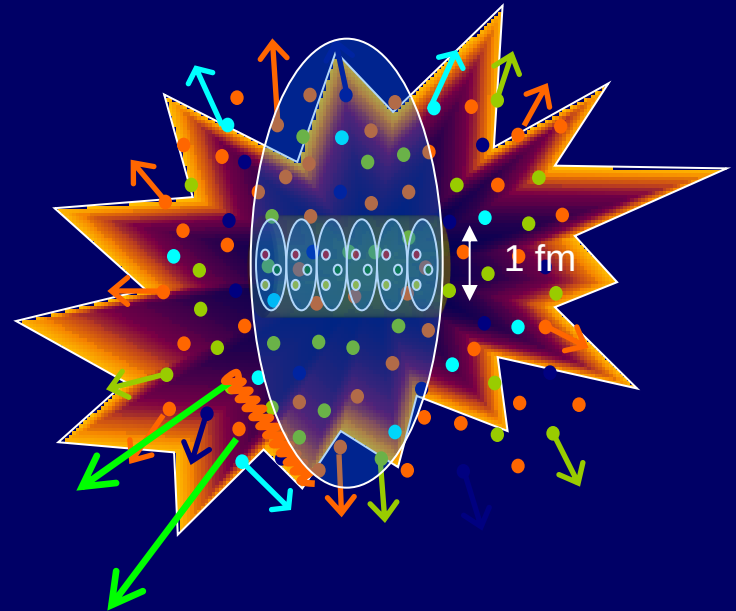
$$n_0 = 0.17 \text{ GeV.fm}^{-3}$$

$R_A = 1.14 A^{1/3}$ nuclear radius for mass number A

$\frac{3}{4}$ come from averaging over the tube length in a central collision

$$\epsilon_{AA} \sim A^{1/3} (0.4 \text{ GeV.fm}^{-3}) \sim 2 \text{ GeV. fm}^{-3}$$

Initial volume $\sim 170 \text{ fm}^3$



Check as an exercise

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- Choosing the correct observables is a major problem:
 - The complexity of the system is extremely high
 - If a dense and hot state is produced, its manifestation might be “hidden” during hadronization.
 - Collective x superposition effects
 - Collective effects: the role of thermodynamics
 - Control over background
-

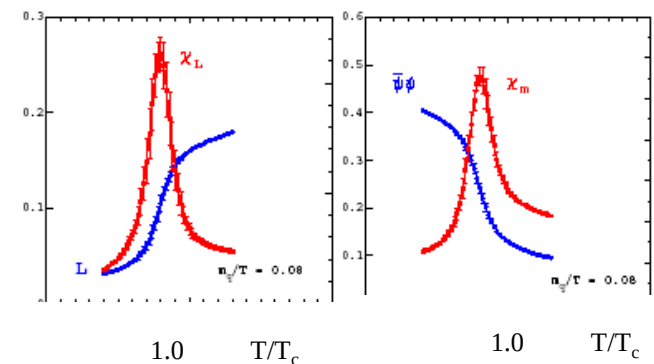
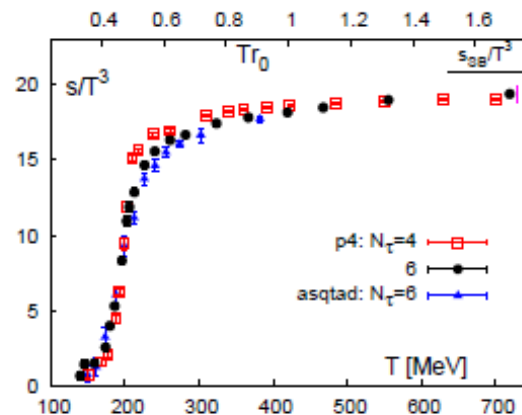
Facilities

Accelerator	Location	Ion beam	Momentum [A · GeV/c]	$\sqrt{s}$ [GeV]	Commissioning date
AGS	BNL	$^{16}\text{O}, ^{28}\text{Si}$	14.6	5.4	Oct.1986
		^{197}Au	11.4	4.8	Apr.1992
SPS	CERN	$^{16}\text{O}, ^{32}\text{S}$	200	19.4	Sep.1986
		^{208}Pb	158	17.4	Nov.1994
RHIC	BNL	$^{197}\text{Au} + ^{197}\text{Au}$	65	130	2000
		$^{197}\text{Au} + ^{197}\text{Au}$	100	200	2001
		$\text{d} + ^{197}\text{Au}$	100	200	2003
		$^{197}\text{Au} + ^{197}\text{Au}$	31.2	62.4	2004
		$^{63}\text{Cu} + ^{63}\text{Cu}$	100	200	2005
LHC	CERN	$^{208}\text{Pb} + ^{208}\text{Pb}$	2800	5600	2009

The QCD phase diagram

- Introduction
- Observables
- Hard probes
- Prospects

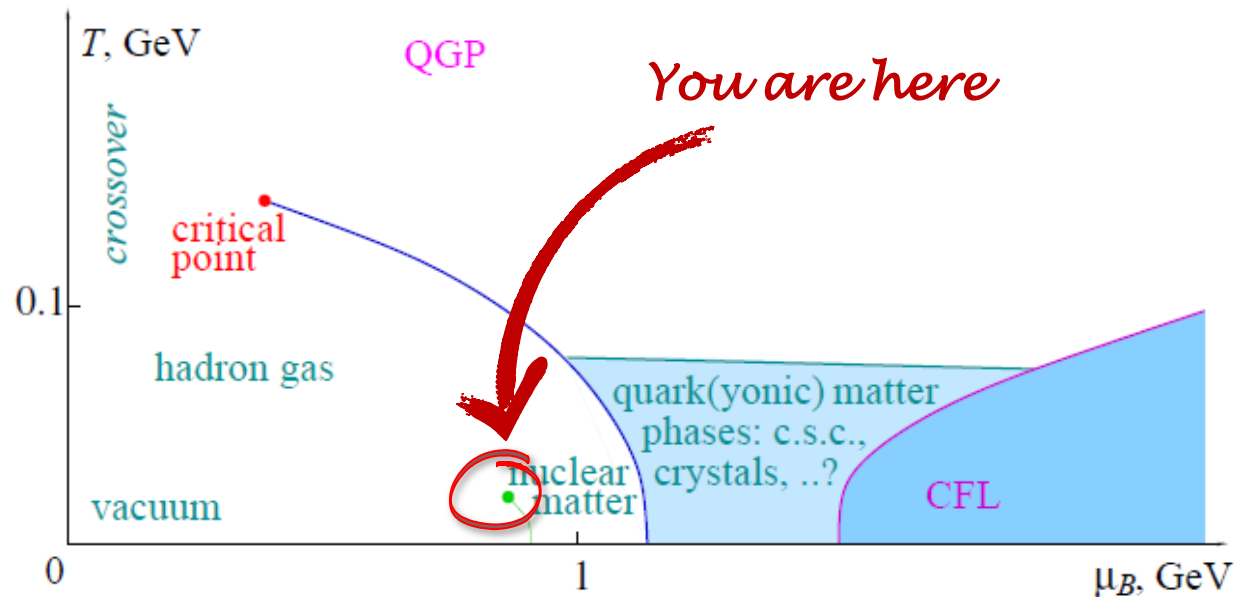
- Hagedorn: strong interacting matter should undergo a deconfining phase transition for large enough temperatures and densities.
- This fact was confirmed by LGT (**although not clear whether it is the same physics**).
- In fact LGT gave us first indication of the QCD phase diagram
- Unfortunately, LGT does not work everywhere.



The QCD phase diagram

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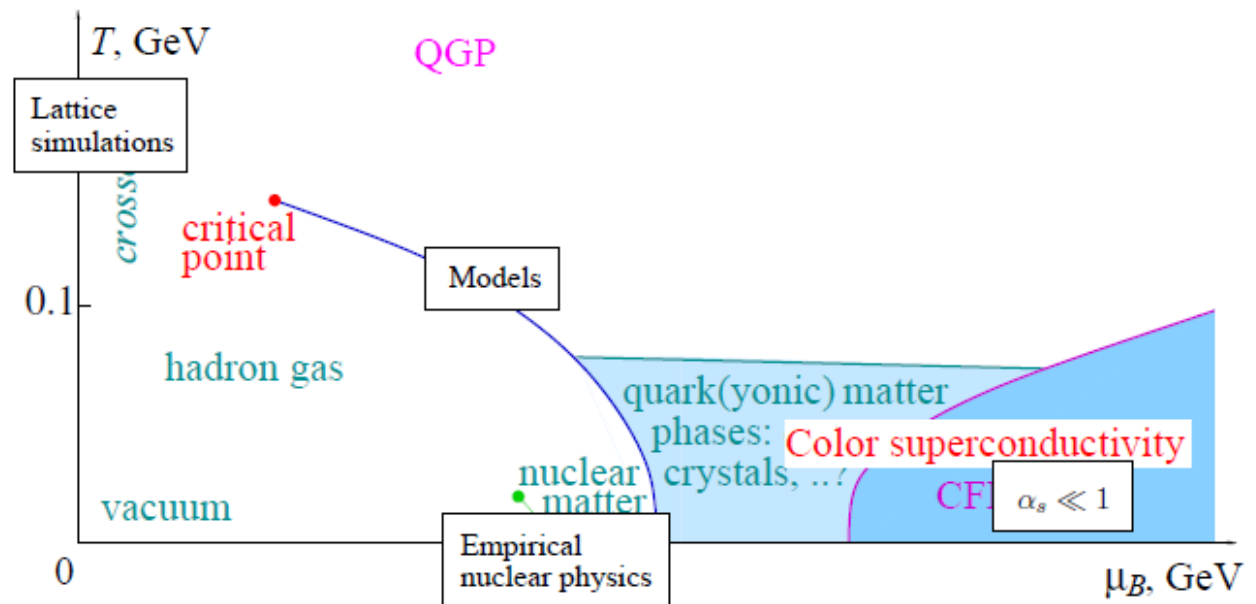
- The QCD phase diagram: models & LGT suggest that transition becomes 1st order for some μ_B



The QCD phase diagram

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- Observables
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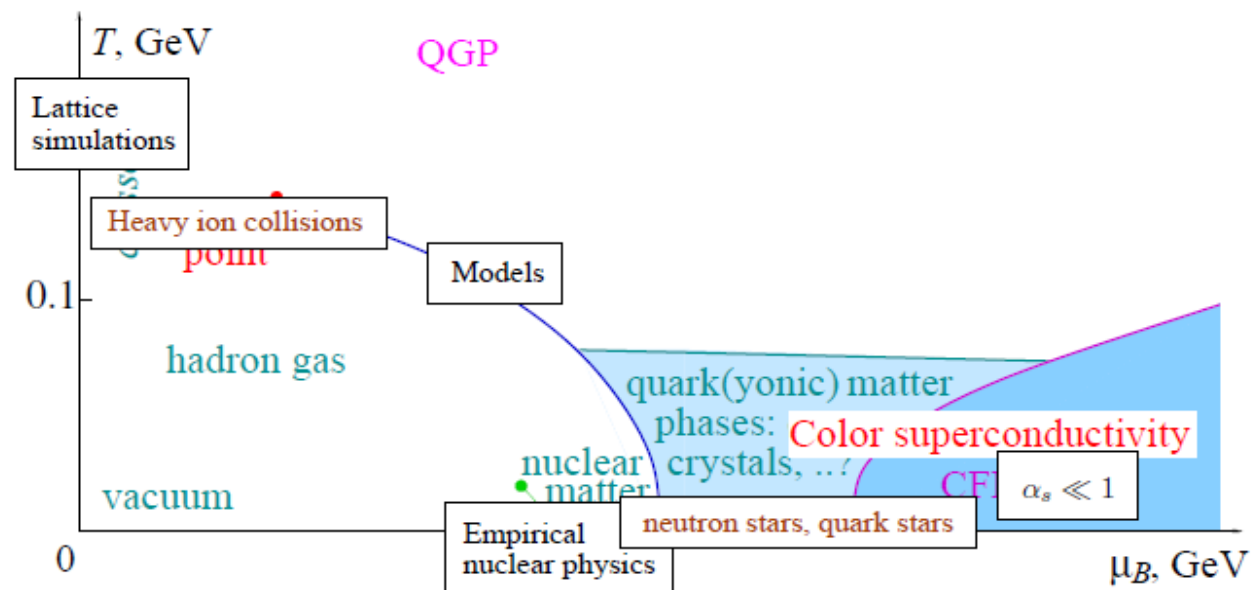
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The QCD phase diagram

- Introduction
- Observables
- SPS results
- RHIC results
- The LHC Era
- Prospects

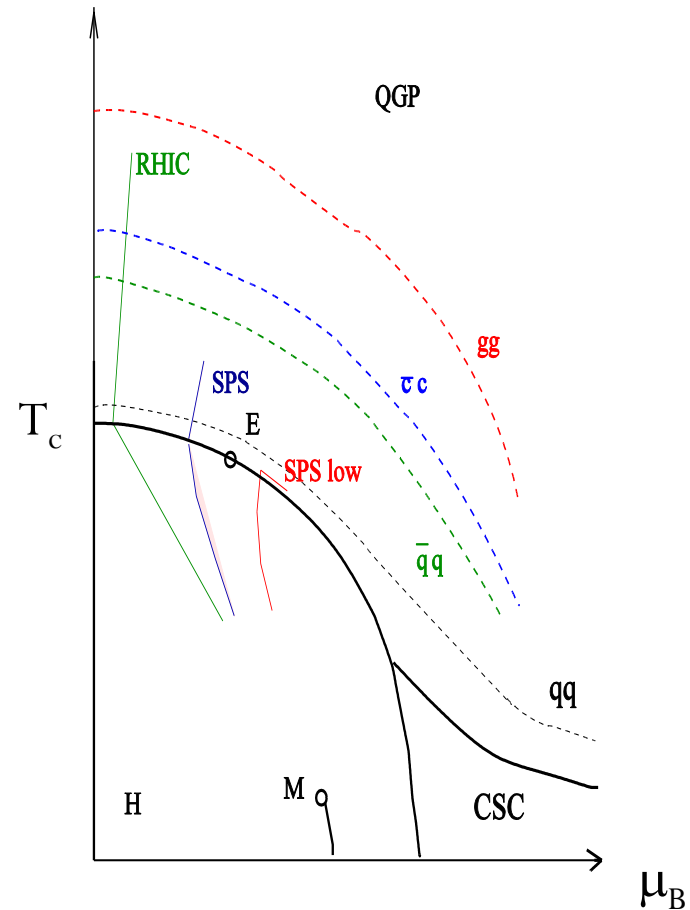
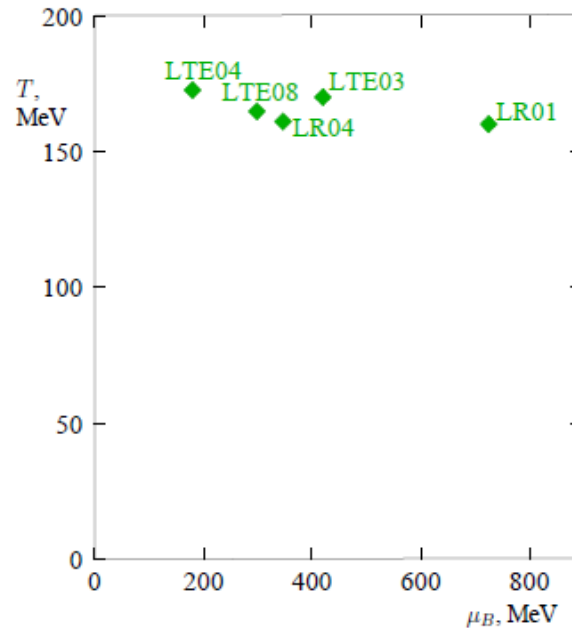
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The QCD phase diagram

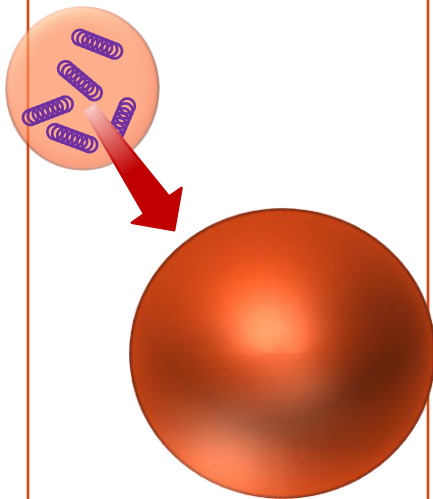
- Introduction
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- Where does it happen?



Space-time picture

- Introduction
- Observables
- Hard probes
- Prospects

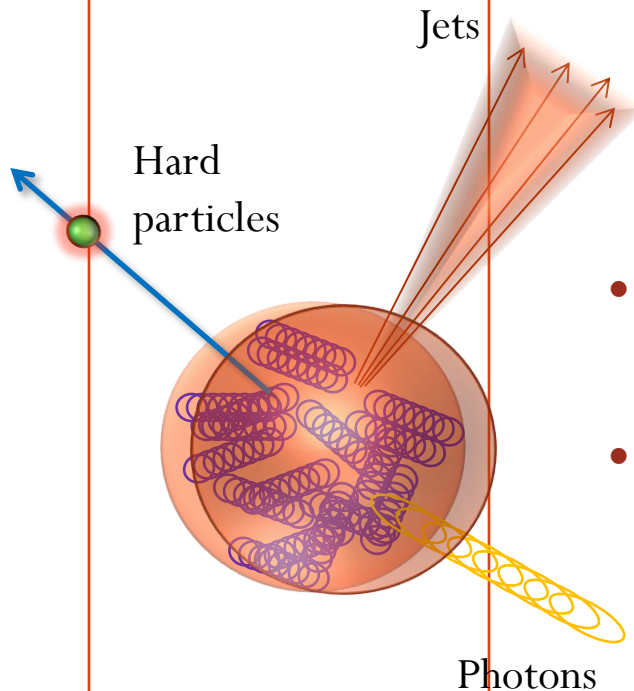


- **Stages of a heavy ion collision**

- Before the collision the nuclei resemble 2 pancakes, being affected along the direction of motion by a boost factor $\Upsilon \sim 100$
- These pancakes are mostly composed of gluons carrying a tiny fraction x of the parent nucleons longitudinal momenta. Their density decreases rapidly with $1/x$ which implies, by the uncertainty principle that they should have relatively large transverse momenta
- This initial gluonic form of matter has been dubbed ***Color Glass Condensate*** (CGC). It is weakly coupled and dense. Dominates the wavefunction of all hadrons

Space-time picture

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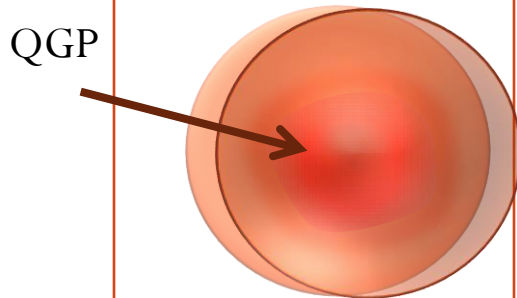


- **Stages of a heavy ion collision**

- At $\tau = 0$ fm/c the two nuclei hit each other and the interactions start developing.
- The hard processes occur faster (within a time $\sim 1/Q$, by the uncertainty principle). They are responsible for the production of *hard particles*, i.e. particles carrying transverse energies and momenta of the order of Q : (hadronic) jets, direct photons, dilepton pairs, heavy quarks, or vector bosons. They are often used to characterize the topology of the collision.
- At $\tau = 0.2$ fm/c the bulk of the partonic constituents of the colliding nuclei are liberated. This is when most of the final multiplicity is produced
- At the LHC Pb-Pb the density of the (non-equilibrium) medium at this stage is ~ 10 times the one of normal nuclear matter and the energy density $\epsilon > 15$ GeV/fm³: **Glasma**

Space-time picture

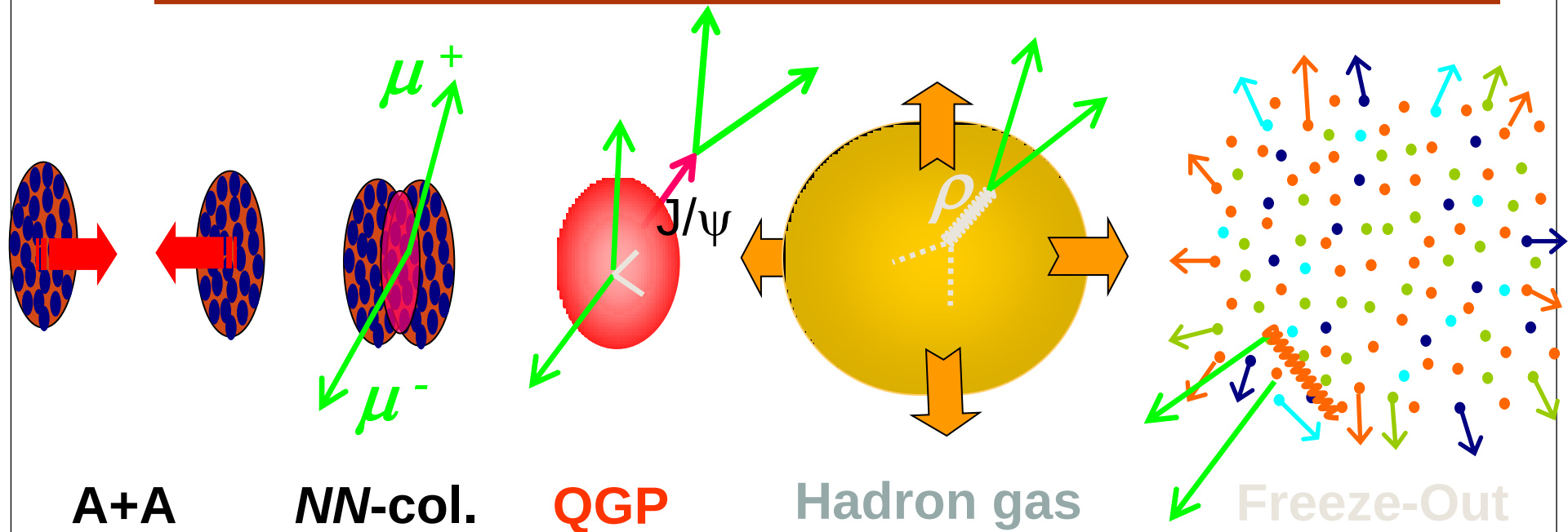
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- **Stages of a heavy ion collision**

- If the partons do not interact with each other (in pp collisions) they proceed to the final state. However in AA collisions they *do* interact strongly with each other. As a consequence of thermodynamics the medium equilibrates very rapidly (within ~ 1 fm/c). The dense partonic medium may be a strongly coupled *fluid* called the **Quark-Gluon Plasma** (QGP).
- At $\tau = 10$ fm/c (for Pb-Pb collisions at the LHC) the QGP hadronizes
- Between $10 \text{ fm/c} < \tau < 20 \text{ fm/c}$ the system is in equilibrium and forms a hot and dense **hadron gas** whose density and temperature decreases with time
- At $\tau \sim 20$ fm/c the density becomes so low that the hadrons do not interact any longer: This is the **freeze-out**. The outgoing particles have essentially the same thermal distribution as before in the fluid.

Space-time picture



Lepton pairs are emitted at all stages

NN collisions:

QGP:

Hot and dense hadron gas:

Freeze-out:

Drell-Yan

qq thermal annihilation

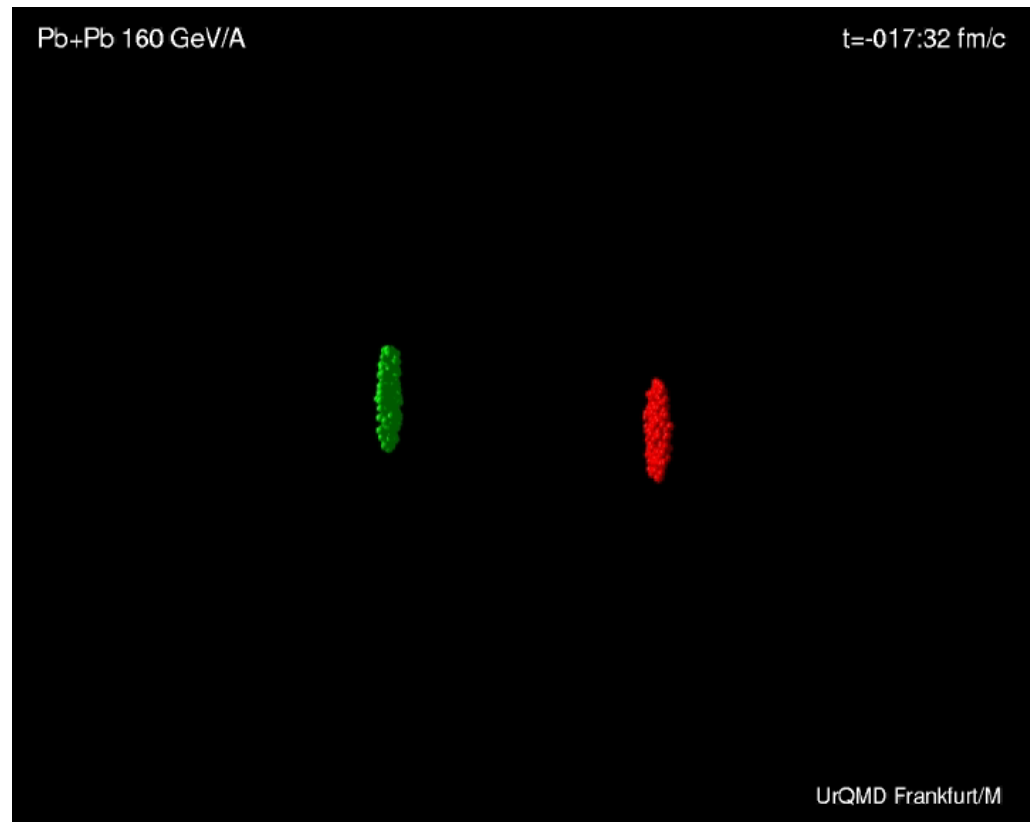
$\pi^+\pi^-$ thermal annihilation

free hadron decay (cocktail)

Space-time picture

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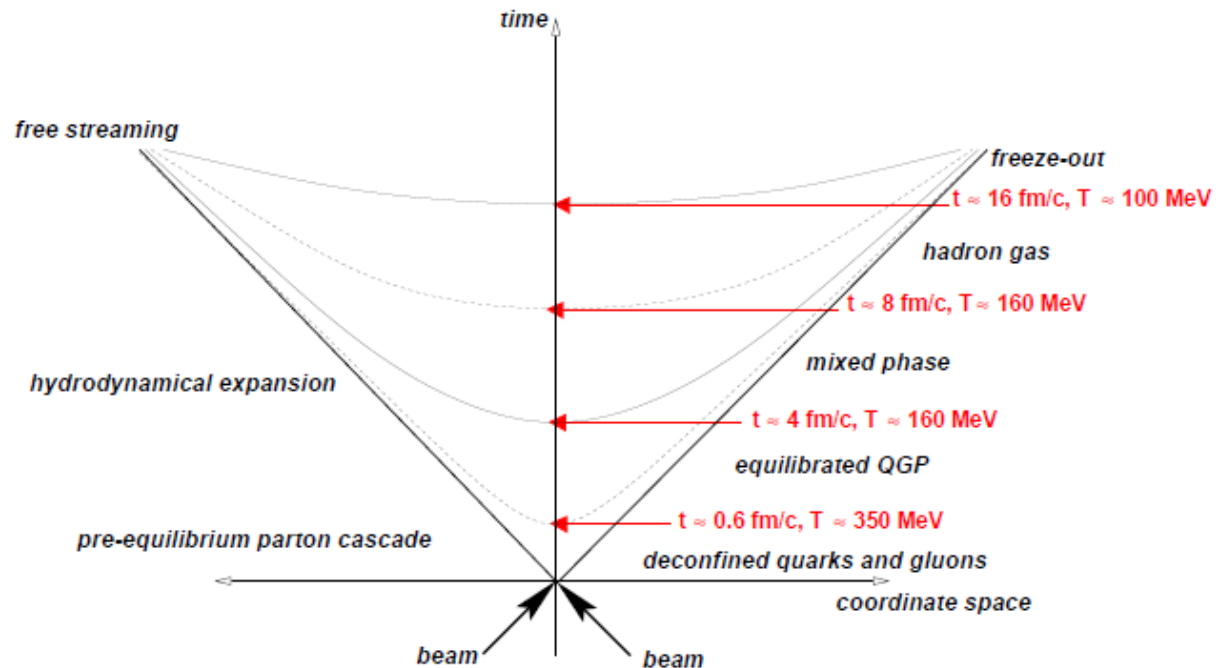
- To make thermodynamics one needs specific objects. How does one measure the initial energy in HIC?



Space-time picture

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Initial energy density (Bjorken)

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- Number of collisions can be very high (~ 800 in UU collision)
 - Energy is deposited in a small region $\sim z=0$ at $t=0$. Energy density is very high, but the baryon content is ~ 0 (QGP)
 - As the particles stream out of this region the volume they occupy depends on time.
 - We are going to observe these particles later, which implies that the initial energy density depends on proper time from our observational point of view.
 - The particles which stream out are mostly pions, having $p_T \sim 0.35$ GeV/c and $m_T \sim 0.38$ GeV/c. These particles are characterized by their rapidity distribution dN/dy .
-

Initial energy density (Bjorken)

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- **Bjorken estimation of initial energy density**

- To reconstruct the initial distribution we have to relate their space-time positions to rapidity

$$m_T = \sqrt{p_T^2 + m^2} ; \quad p_z = m_T \sinh y ; \quad p_0 = m_T \cosh y$$

The velocity is thus, for a particle streaming out of the origin

$$v_z = \frac{p_z}{p_0} = \tanh y = \frac{z}{t}$$

In terms of the proper time $\tau = \sqrt{t^2 - z^2}$

$$z = \tau \sinh y$$

$$t = \tau \cosh y$$

$$y = \frac{1}{2} \ln \frac{t+z}{t-z}$$

In the CMS the region around $y=0$ (central rapidity region) for a given τ corresponds to $z=0$.

Initial energy density (Bjorken)

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- A is the superposition region of the 2 nuclei. The volume is $A\Delta z$. Denote by τ_0 the proper time in which QGP is formed and equilibrated.

The particle number density at $z=0$ is

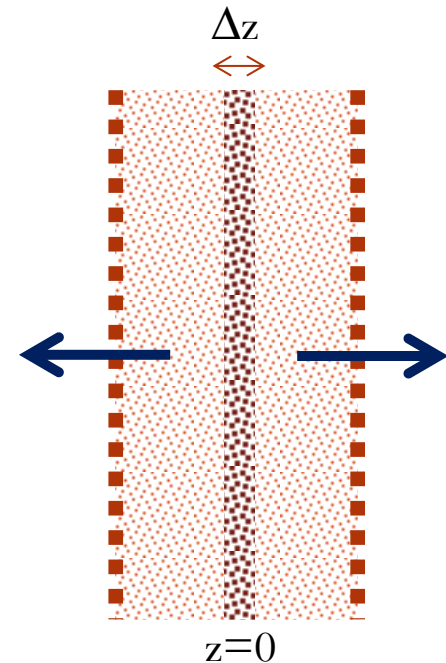
$$\begin{aligned}\frac{\Delta N}{A\Delta z} &= \frac{1}{A} \frac{dN}{dy} \frac{dy}{dz} \Big|_{y=0} \\ &= \frac{1}{A} \frac{dN}{dy} \frac{1}{\tau_0 \cosh y} \Big|_{y=0}\end{aligned}$$

The energy of a particle with rapidity y is $m_T \cosh y$. Therefore the initial energy density is

$$\epsilon_0 = m_T \cosh y \frac{\Delta N}{A\Delta z}$$

$$\epsilon_0 = \frac{m_T}{A\tau_0} \frac{dN}{dy} \Big|_{y=0}$$

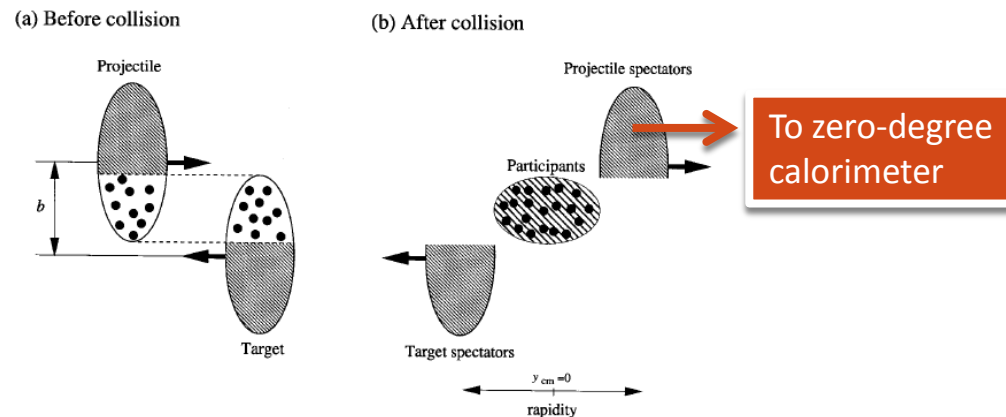
$$\tau_0 \sim 1 \text{ fm}/c$$



Initial energy density (Bjorken)

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- **Bjorken estimation of initial energy density**
 - We are thus left with problems:
 1. Measure (or calculate) the rapidity distribution
 2. Determine the overlapping region
 - This must be complemented by a knowledge of collective x superposition processes. The **Glauber model** gives the number of collisions as a function of the impact parameter of the collision. Allows centrality estimation



Glauber model

- Introduction
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- A simple geometrical picture of a AA collision.
- Semi-classical model treating the nucleus-nucleus collisions as multiple NN interactions: a nucleon of incident nucleus interacts with target nucleons with a given density distribution.
- Nucleons are assumed to travel on straight line trajectories and are not deflected even after the collisions, which should hold as a good approximation at very high energies.
- NN inelastic cross section σ_{NN}^{in} is assumed to be the same as in the vacuum.
- The nucleons are assumed to be randomly distributed according to a Woods-Saxon distribution corresponding to the density profile

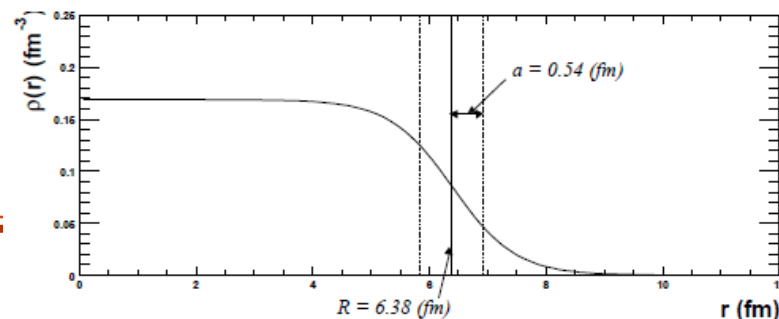
$$\rho(r) = \rho_0 \frac{1}{1 + \exp\left(\frac{r - R}{a}\right)}$$

Au: $R = 6.38 \text{ fm}$
 $a = 0.54 \text{ fm}$
 $\rho_0 = 0.169 \text{ fm}^{-3}$
 $\sigma_{NN}^{in} = 42 \text{ mb}$
 $@\sqrt{s_{NN}} = 200 \text{ GeV}$

Glauber model

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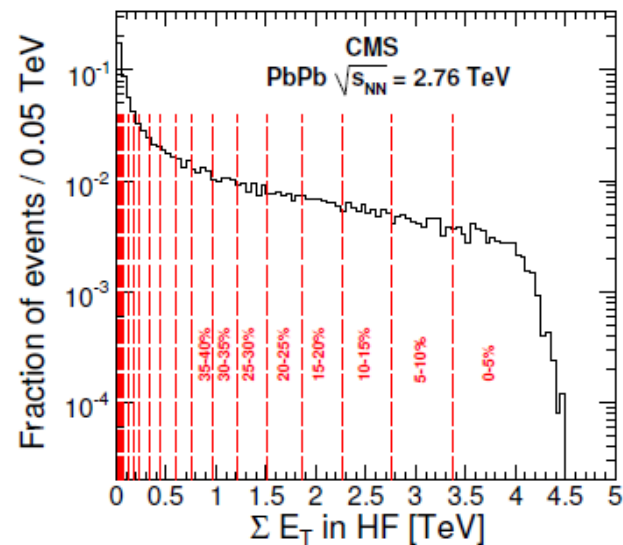


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@ $\sqrt{s_{NN}} = 200$ GeV

Glauber model

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- A CMS example



Centrality	0-5%	5-10%	10-15%	15-20%	20-25%	25-30%
N_{part}	381 ± 2	329 ± 3	283 ± 3	240 ± 3	203 ± 3	171 ± 3
Centrality	30-35%	35-40%	40-45%	45-50%	50-55%	55-60%
N_{part}	142 ± 3	117 ± 3	95.8 ± 3.0	76.8 ± 2.7	60.4 ± 2.7	46.7 ± 2.3
Centrality	60-65%	65-70%	70-75%	75-80%	80-85%	85-90%
N_{part}	35.3 ± 2.0	25.8 ± 1.6	18.5 ± 1.2	12.8 ± 0.9	8.64 ± 0.56	5.71 ± 0.24

Table 1. Average N_{part} values and their uncertainties for each PbPb centrality range defined in 5 percentile segments of the total inelastic cross section. The values were obtained using a Glauber MC simulation with the same parameters as in ref. [14].

Particle production

- Introduction
- Observables
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- **Fermi:** Because of saturation of the phase space, the multi particle production resulting from the high energy elementary collisions is consistent with a thermal description.
- In heavy-ion collisions, hydrodynamical behavior, that is, local thermal equilibrium and collective motion, may be expected because of the large number of secondary scatterings.
- In the case of pure thermal motion $\langle E_{\text{kin}} \rangle \sim T$; thermodynamical “blast-wave” model of Schnedermann et al.

$$\frac{d\sigma}{m_T dm_T} \propto \int_0^R r dr m_T I_0\left(\frac{p_T \sinh \rho}{T_{\text{fo}}}\right) K_1\left(\frac{m_T \cosh \rho}{T_{\text{fo}}}\right),$$

Freeze-out temperature

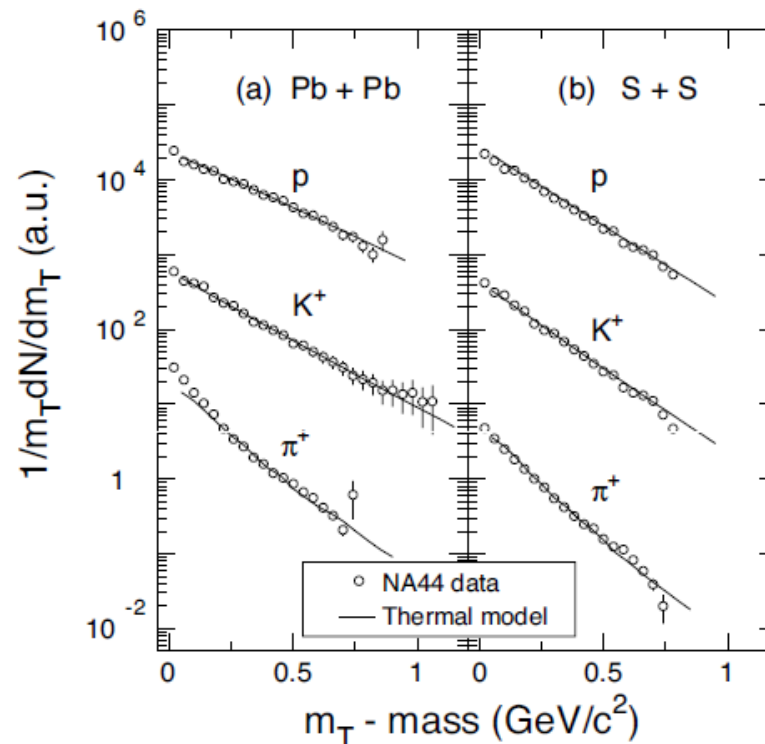
Mod. Bessel func.

Particle production

- Introduction
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- This model can be approximated by

$$\frac{1}{m_T} \frac{dN}{dm_T} = A \exp\left(-\frac{m_T}{T}\right)$$



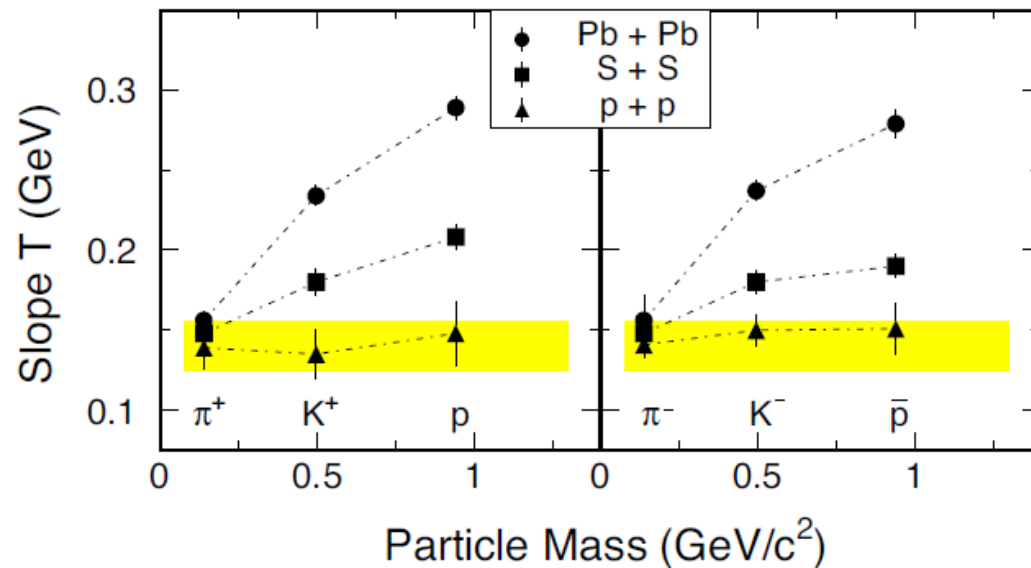
Because of decay products from the resonances, a steeper component exist in low- m_T region for pions. Proton and anti-proton distributions look flatter than those for pions and kaons.

Particle production

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- This model can be approximated by

$$\frac{1}{m_T} \frac{dN}{dm_T} = A \exp\left(-\frac{m_T}{T}\right)$$



Hadron multiplicities

- Introduction
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- Particle abundances can be evaluated by integrating particle yields over the complete phase space
- Unlike the momentum distributions, particle ratios are expected to be insensitive to the underlying processes.
- It is found that the ratios of produced hadrons are well described by a simple statistical model based on the grand-canonical ensemble: particle density of species i is given by

$$n_i = \frac{g_i}{2\pi^2} \int_0^\infty \frac{p^2 dp}{\exp[(E_i - \mu_i)/T_{\text{ch}}] \pm 1}$$

g_i - spin degeneracy

$$\mu_i = \mu_B B_i - \mu_S S_i - \mu_{I_3} I_i^3 - \text{chemical potential}$$

Baryon quant. number

Strangeness quant. number

Isospin “z-component”
quant. number

- Introduction
- **Observables**
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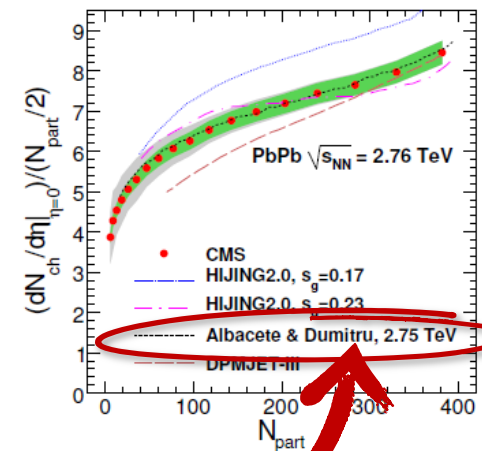
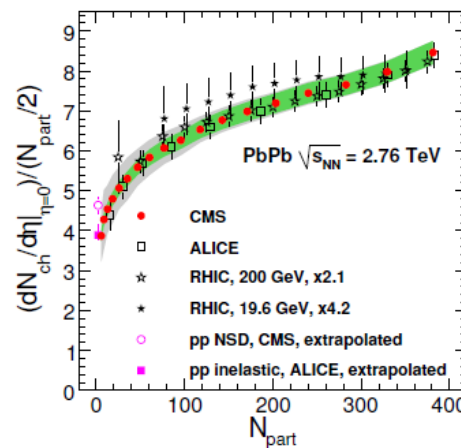
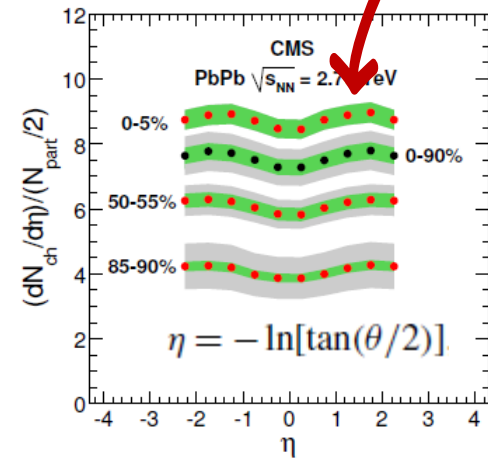
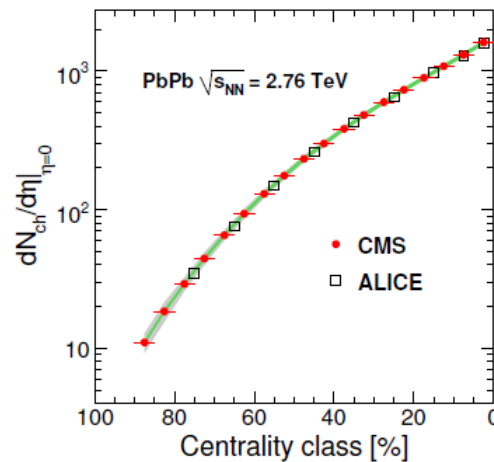
- **Intriguing fact:** abundances of multi-strange particles *also* show chemical equilibrium. They are supposed to decouple early from the fireball → do not have enough time to reach the chemical equilibrium if they are produced in hadronic interactions. Early thermalization?

Hadron multiplicities

Bjorken

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• Particle distributions at LHC: the CMS case



CGC

Hadron multiplicities

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- Particle distributions at LHC: the CMS case

$$\frac{dN^{AA}}{dyd^2p_T} = \langle N_{\text{coll}} \rangle \frac{dN^{NN}}{dyd^2p_T}$$

$$\frac{1}{\sigma_{\text{inel}}^{AA}} \frac{d\sigma^{AA}}{dyd^2p_T} = \frac{\langle N_{\text{coll}} \rangle}{\sigma_{\text{inel}}^{NN}} \frac{d\sigma^{NN}}{dyd^2p_T}$$



$$R_{AA}(p_T) = \frac{d^2 N_{\text{ch}}^{AA} / dp_T d\eta}{\langle T_{AA} \rangle d^2 \sigma_{\text{ch}}^{pp} / dp_T d\eta},$$

Departure from 1 indicates medium effects

$$R_{CP}(p_T) = \frac{(d^2 N_{\text{ch}}^{AA} / dp_T d\eta) / \langle T_{AA} \rangle [\text{central}]}{(d^2 N_{\text{ch}}^{AA} / dp_T d\eta) / \langle T_{AA} \rangle [\text{peripheral}]}$$

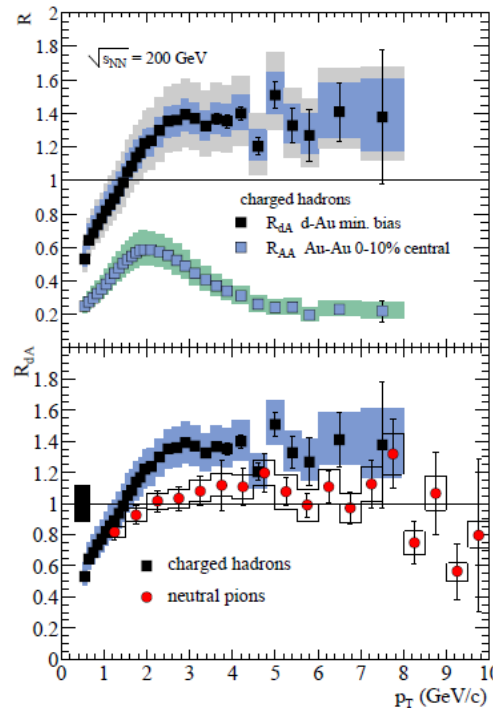
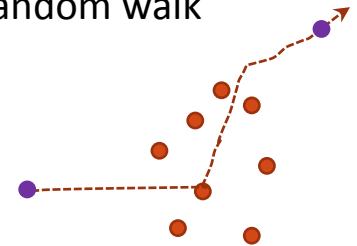
Centrality bin	$\langle N_{\text{part}} \rangle$	r.m.s.	$\langle N_{\text{coll}} \rangle$	r.m.s.	$\langle T_{AA} \rangle$ (mb ⁻¹)	r.m.s.
0–5 %	381 ± 2	19.2	1660 ± 130	166	25.9 ± 1.06	2.60
5–10 %	329 ± 3	22.5	1310 ± 110	168	20.5 ± 0.94	2.62
10–30 %	224 ± 4	45.9	745 ± 67	240	11.6 ± 0.67	3.75
30–50 %	108 ± 4	27.1	251 ± 28	101	3.92 ± 0.37	1.58
50–70 %	42.0 ± 3.5	14.4	62.8 ± 9.4	33.4	0.98 ± 0.14	0.52
70–90 %	11.4 ± 1.5	5.73	10.8 ± 2.0	7.29	0.17 ± 0.03	0.11
50–90 %	26.7 ± 2.5	18.84	36.9 ± 5.7	35.5	0.58 ± 0.09	0.56

Hadron multiplicities

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- **Particle distributions at LHC: the CMS case**

- Expectations: in a very dense medium the random walk of partons should increase the production of high p_T hadrons (Cronin effect)



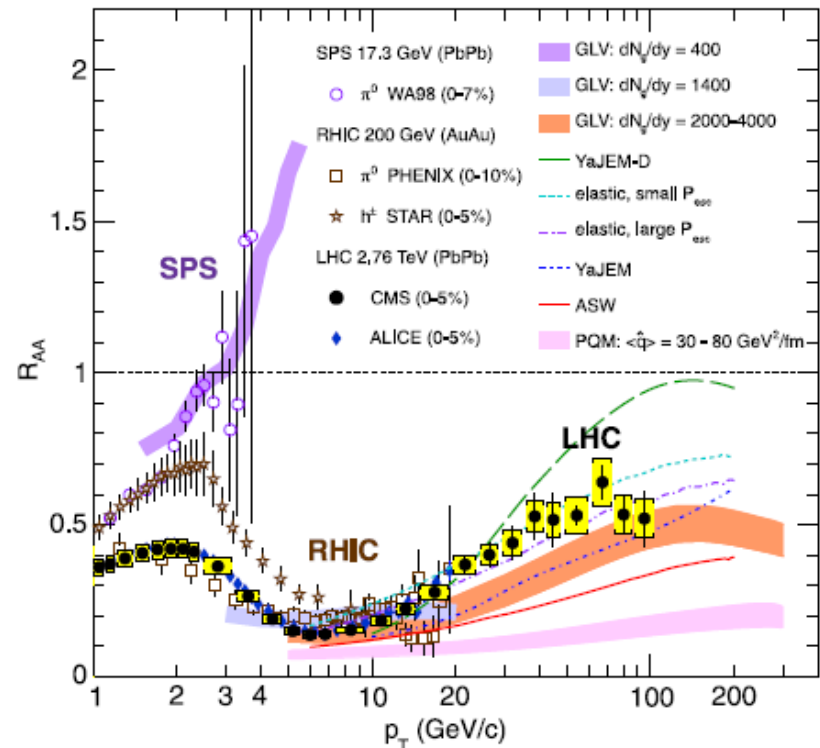
For $p_T > 2$ GeV one observes a suppression in R_{AA} consistent with energy loss of partons in the medium

Hadron multiplicities

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- Particle distributions at LHC: the CMS case

Fig. 7 Measurements of the nuclear modification factor R_{AA} in central heavy-ion collisions at three different center-of-mass energies, as a function of p_T , for neutral pions (π^0), charged hadrons ($h^\pm$), and charged particles [12, 27–30], compared to several theoretical predictions [32–37] (see text). The *error bars* on the points are the statistical uncertainties, and the *yellow boxes* around the CMS points are the systematic uncertainties. Additional absolute T_{AA} uncertainties of order $\pm 5\%$ are not plotted. The *bands* for several of the theoretical calculations represent their uncertainties

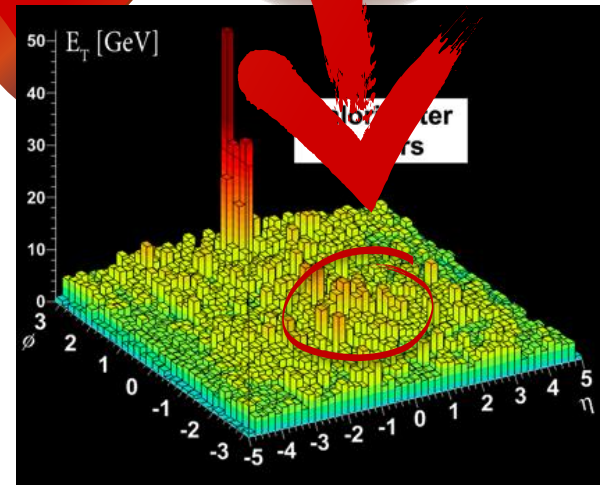
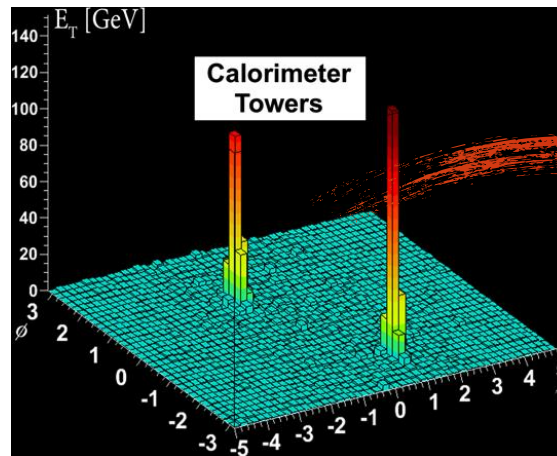


Jet quenching (again)

- Introduction
- Observables
- Hard probes
- Prospects

- The expectation: jet quenching (ATLAS & CMS)

Peripheral



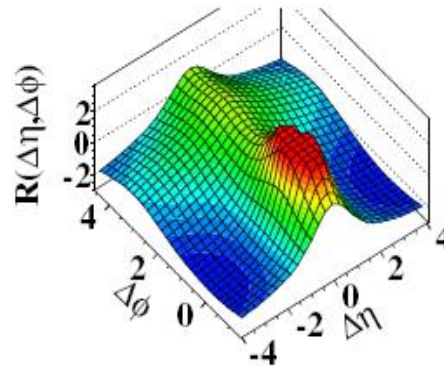
Central

2-particle correlations

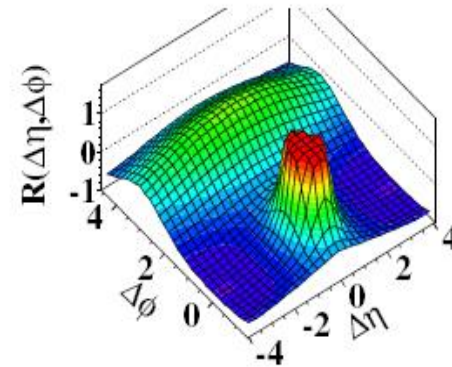
- Introduction
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- **The surprise: 2 particle correlations**

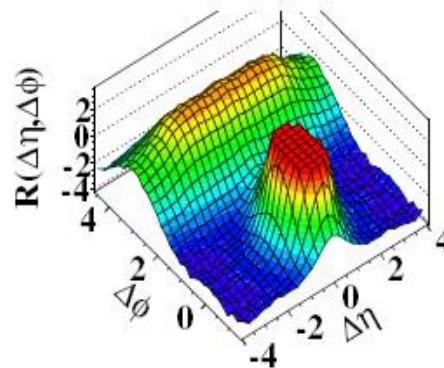
(a) CMS MinBias, $p_T > 0.1 \text{ GeV}/c$



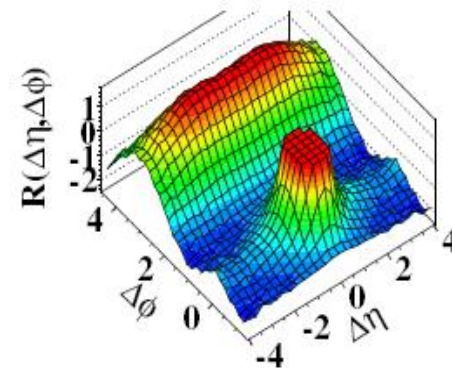
(b) CMS MinBias, $1.0 \text{ GeV}/c < p_T < 3.0 \text{ GeV}/c$



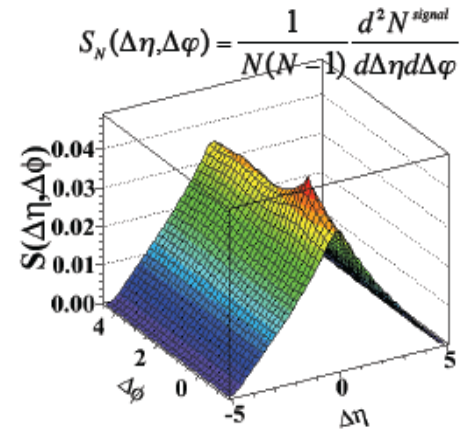
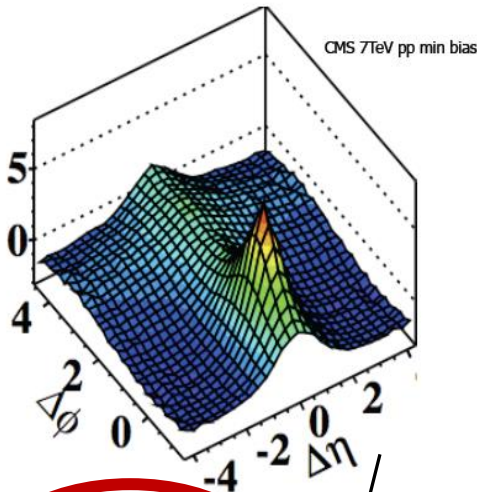
(c) CMS $N \geq 110$, $p_T > 0.1 \text{ GeV}/c$



(d) CMS $N \geq 110$, $1.0 \text{ GeV}/c < p_T < 3.0 \text{ GeV}/c$



2-particle correlation function



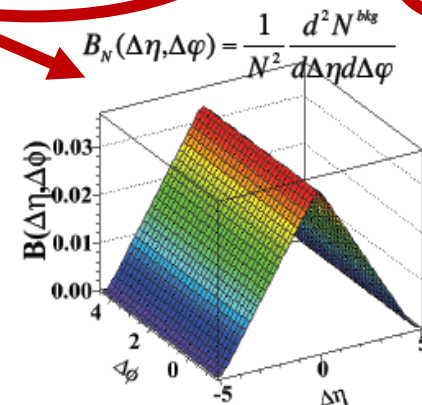
$$R(\Delta\eta, \Delta\phi) = \left\langle \left(\frac{S_N(\Delta\eta, \Delta\phi)}{B_N(\Delta\eta, \Delta\phi)} - 1 \right) \right\rangle_{bins}$$

Same event pairs

$$\Delta\eta = \eta_1 - \eta_2$$

$$\Delta\phi = \phi_1 - \phi_2$$

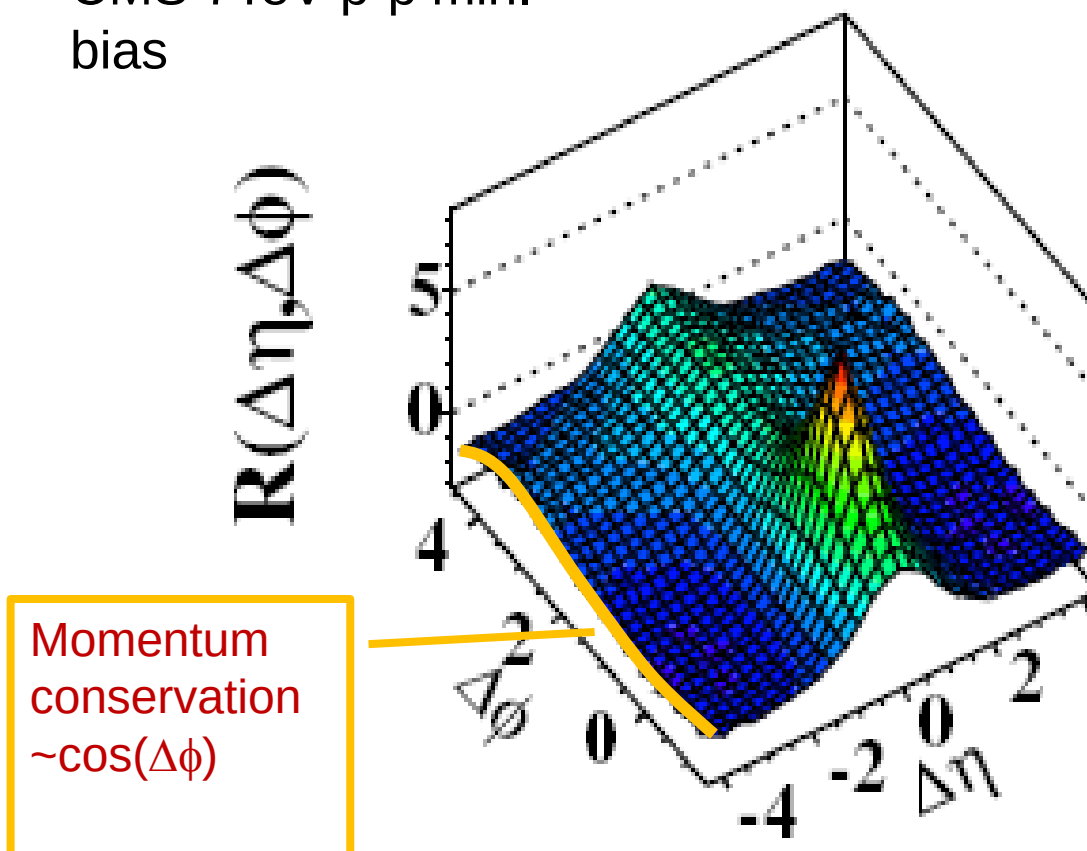
tracks/event
averaged over
the multiplicity
bin



Mixed event pairs

Anatomy of 2-particle correlations

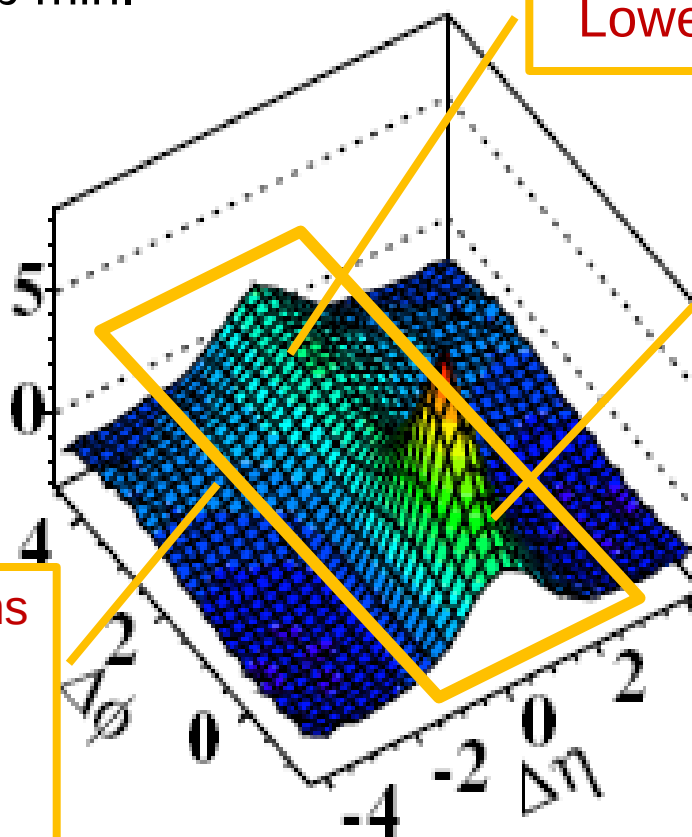
CMS 7TeV p-p min.
bias



Anatomy of 2-particle correlations

CMS 7TeV p-p min.
bias

$R(\Delta\eta, \Delta\phi)$



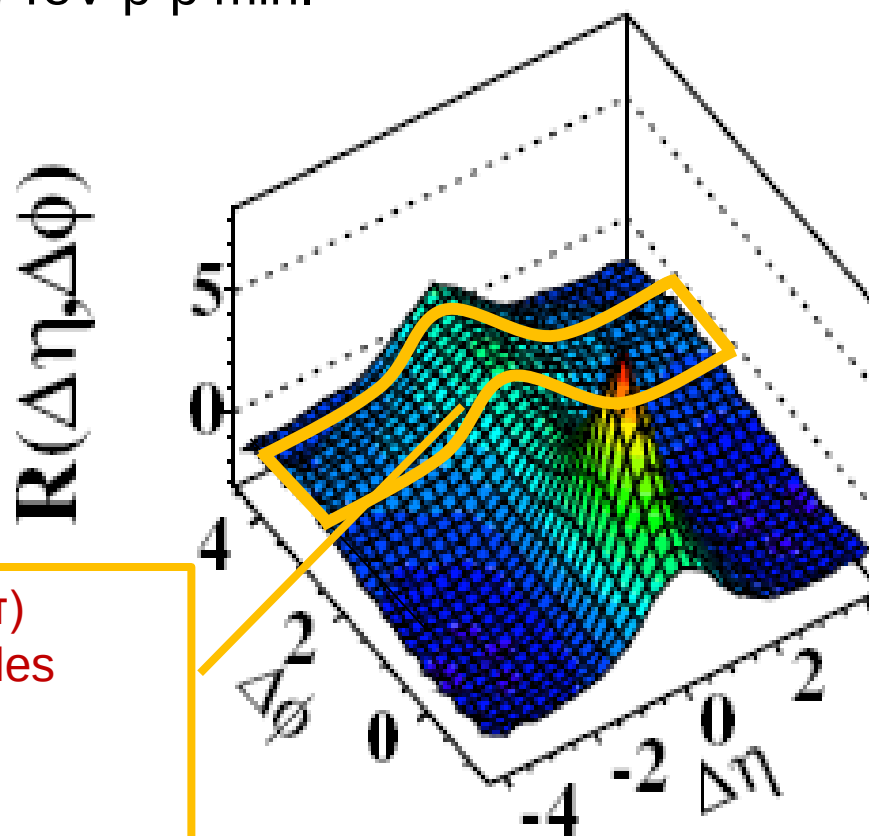
Lower p_T clusters

Higher p_T
clusters

Short-range correlations
($\Delta\eta < 2$):
Resonances, string
fragmentation,
“clusters”

Anatomy of 2-particle correlations

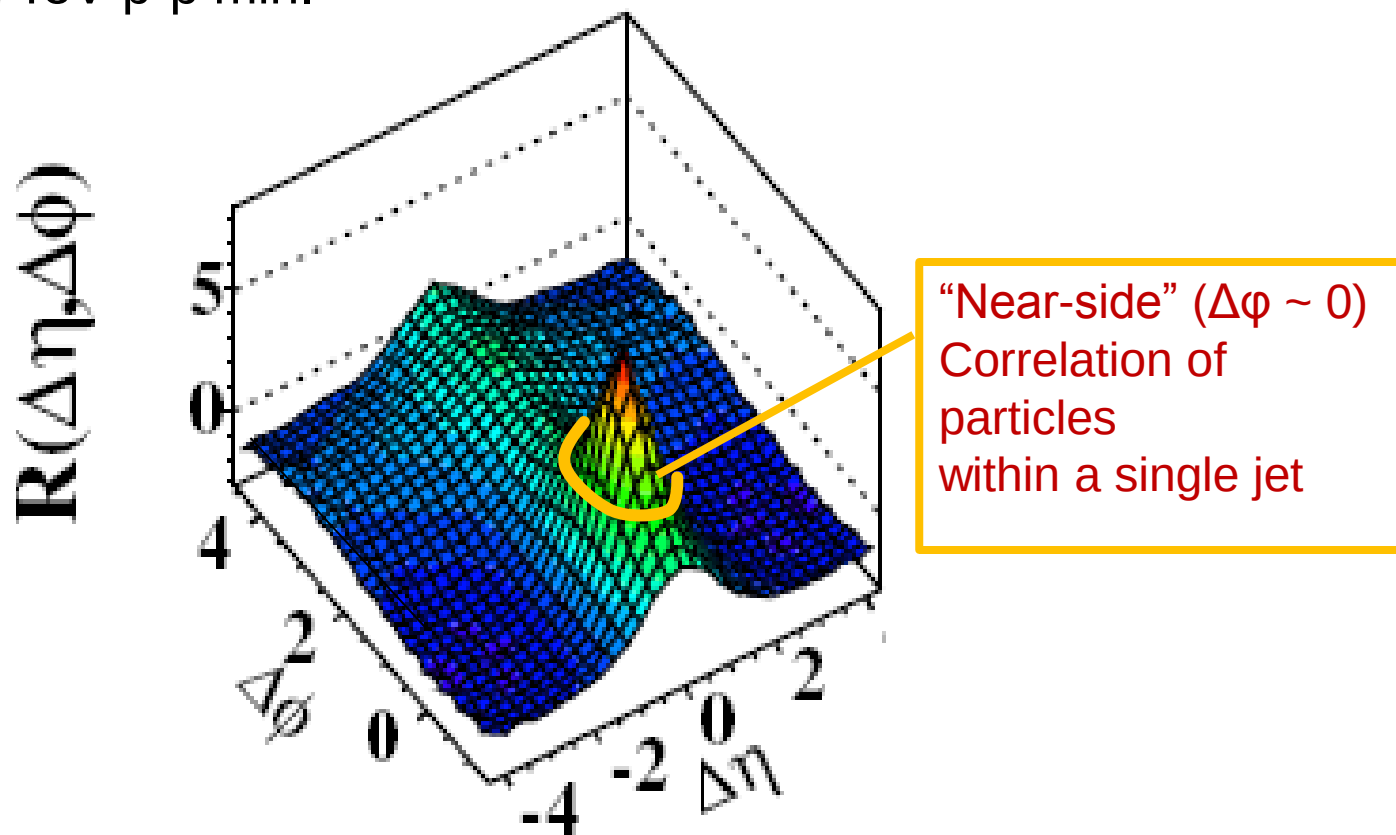
CMS 7TeV p-p min.
bias



“Away-side” ($\Delta\phi \sim \pi$)
Correlation of particles
between back-to-
back jets

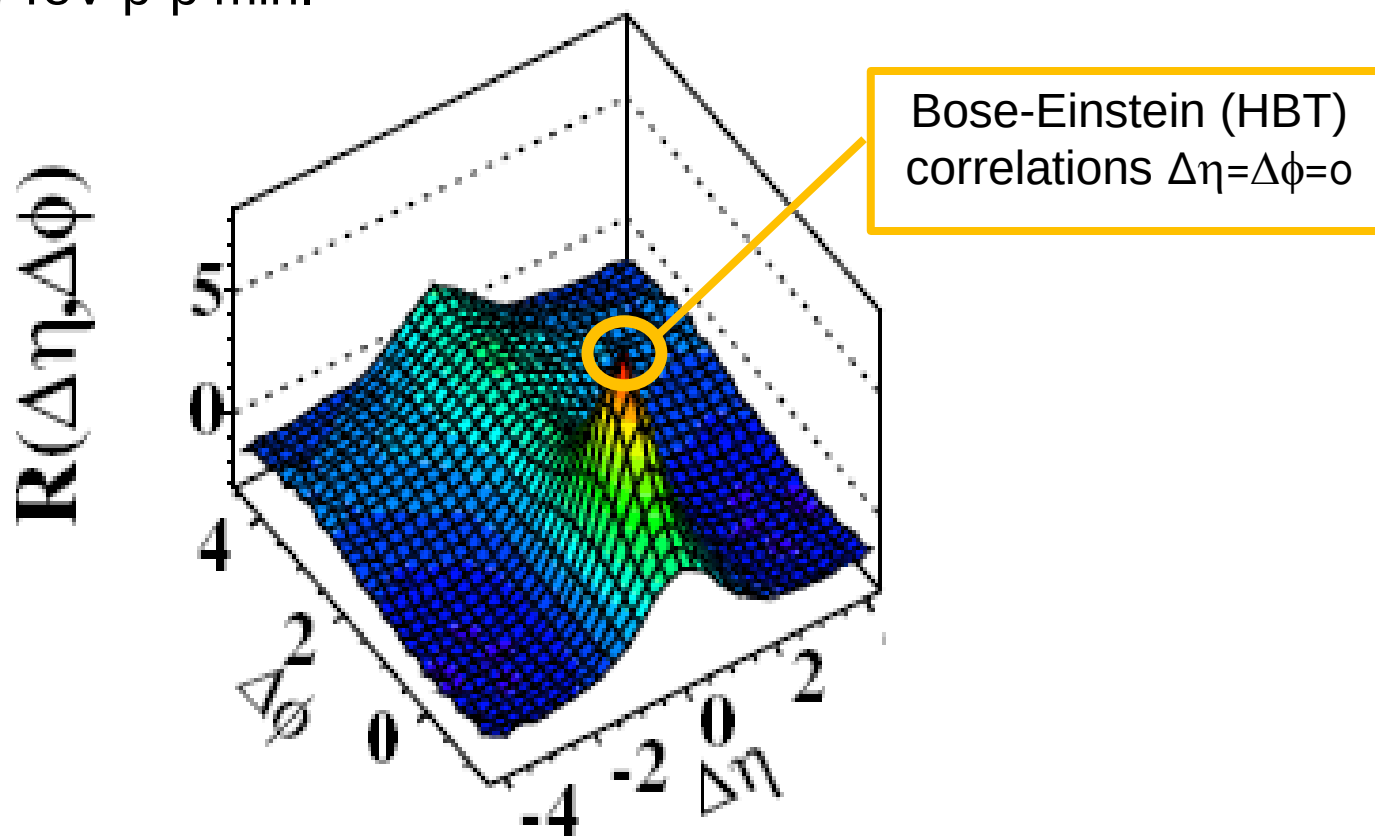
Anatomy of 2-particle correlations

CMS 7TeV p-p min.
bias



Anatomy of 2-particle correlations

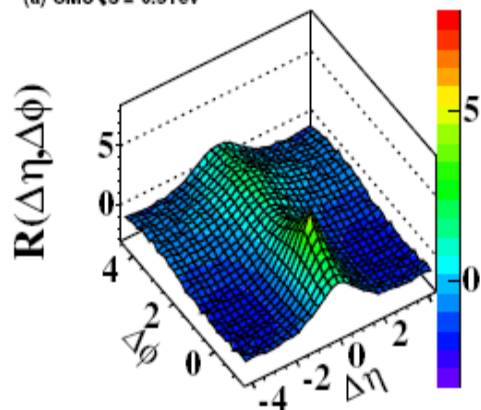
CMS 7TeV p-p min.
bias



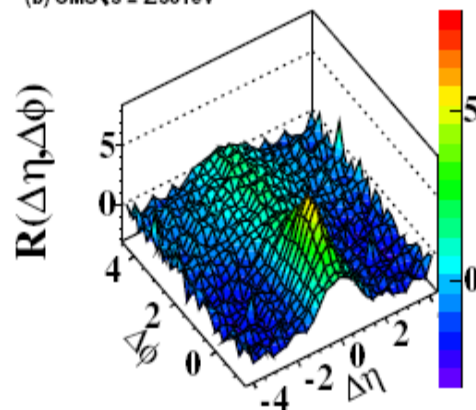
Minimum bias results

p_T inclusive distributions

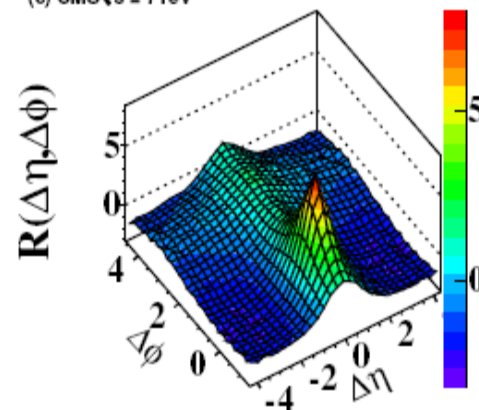
(a) CMS $\sqrt{s} = 0.9\text{TeV}$



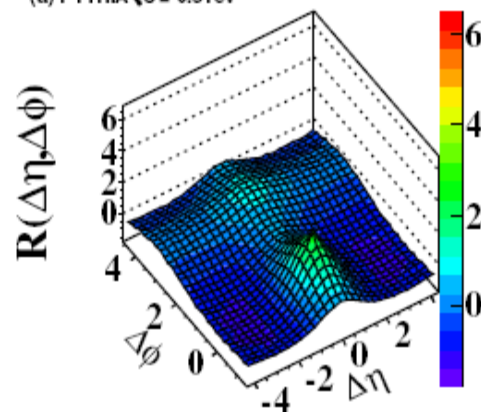
(b) CMS $\sqrt{s} = 2.36\text{TeV}$



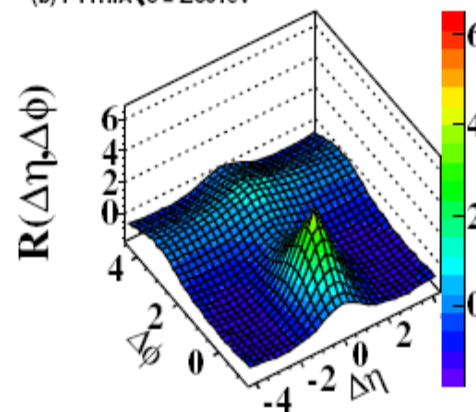
(c) CMS $\sqrt{s} = 7\text{TeV}$



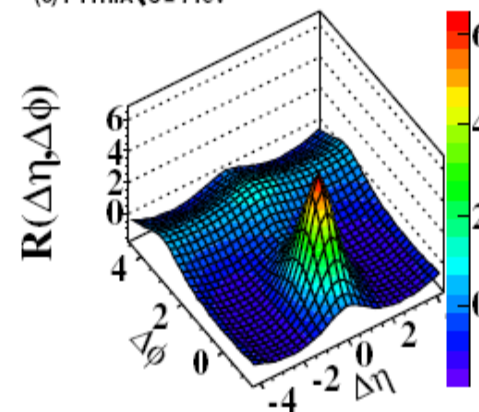
(a) PYTHIA $\sqrt{s} = 0.9\text{TeV}$



(b) PYTHIA $\sqrt{s} = 2.36\text{TeV}$



(c) PYTHIA $\sqrt{s} = 7\text{TeV}$



High multiplicity results

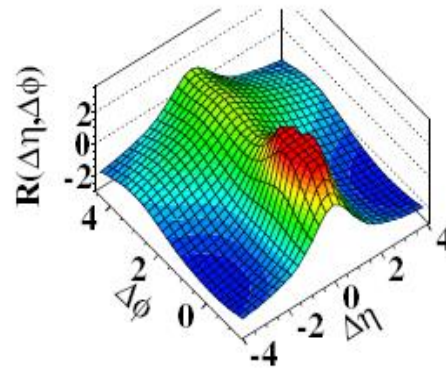


- Analysis performed along the same lines as for minimum bias data
- To reach good statistics only data at 7 TeV were used

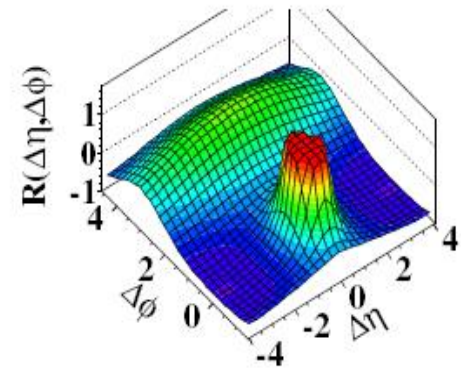
High multiplicity data
integrated over p_T $\Delta\phi \approx 0$ and
 $|\Delta\eta| > 2$ minimum less
pronounced

Ridge structure reappears for
high multiplicity events and
intermediate p_T

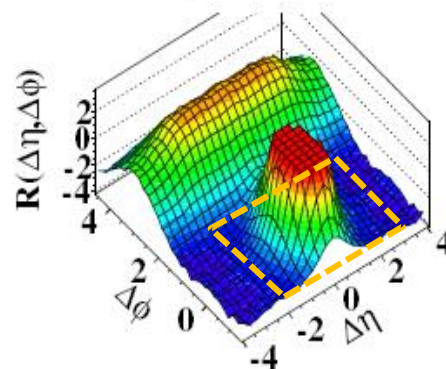
(a) CMS MinBias, $p_T > 0.1 \text{ GeV}/c$



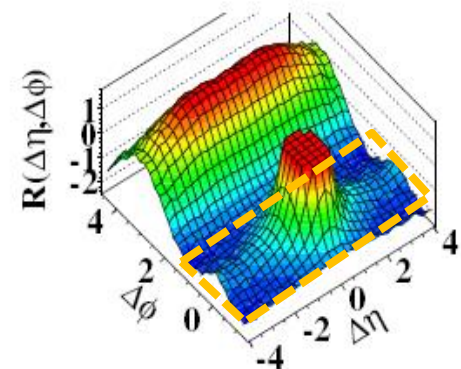
(b) CMS MinBias, $1.0 \text{ GeV}/c < p_T < 3.0 \text{ GeV}/c$



(c) CMS $N \geq 110$, $p_T > 0.1 \text{ GeV}/c$



(d) CMS $N \geq 110$, $1.0 \text{ GeV}/c < p_T < 3.0 \text{ GeV}/c$



Hard probes

- Introduction
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- LGT shows that the interquark potential is screened. At $T=0$ the hamiltonian for the $q\bar{q}$ system is

$$H = \frac{p^2}{2\mu} - \frac{\alpha_{eff}}{r} + kr$$

Cornell potential

- However, in a QGP the hamiltonian should be

$$H = \frac{p^2}{2\mu} - \frac{\alpha_{eff} e^{-\frac{r}{\lambda_D}}}{r}$$

Debye screening length

- To study the stability of the system one can use the uncertainty relations

$$E(r) = \frac{1}{2\mu r^2} - \frac{\alpha_{eff} e^{-\frac{r}{\lambda_D}}}{r}$$

- A bound state exists if the energy has a minimum

$$-\frac{1}{2\mu r^3} + \frac{\alpha_{eff} \left(1 + \frac{r}{\lambda_D}\right) e^{-\frac{r}{\lambda_D}}}{r^2} = 0$$

Hard probes

- Introduction
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- This can be written in the form

$$x(1+x)e^{-x} = \frac{1}{\alpha_{eff}\mu\lambda_D} \quad x = \frac{r}{\lambda_D}$$

- The function is 0 at $x=0$, increases to a maximum value of 0.840 at $x=1.62$ and decreases to 0 as $x \rightarrow \infty$. Therefore a solution exists only if the rhs < 0.84 . In other words

The system will not be bound if

$$\frac{1}{0.84 \alpha_{eff}\mu} > \lambda_D$$

Bohr radius

- The Debye screening length depends on the temperature. From lowest order perturbative QCD

$$\lambda_D(PQCD) = \sqrt{\frac{2}{3g^2}} \frac{1}{T} = 0.36 \text{ fm @ } T = 200 \text{ GeV}$$

LGT gives $\lambda_D \sim 0.18 \text{ fm}$

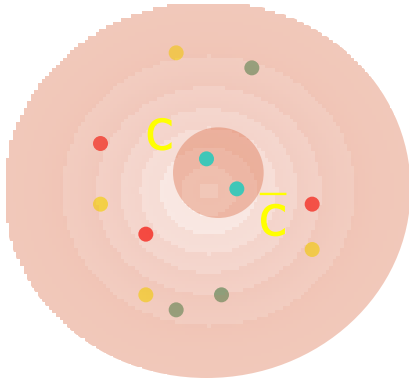
The Satz-Matsui argument

- Introduction
- Observables
- Hard probes
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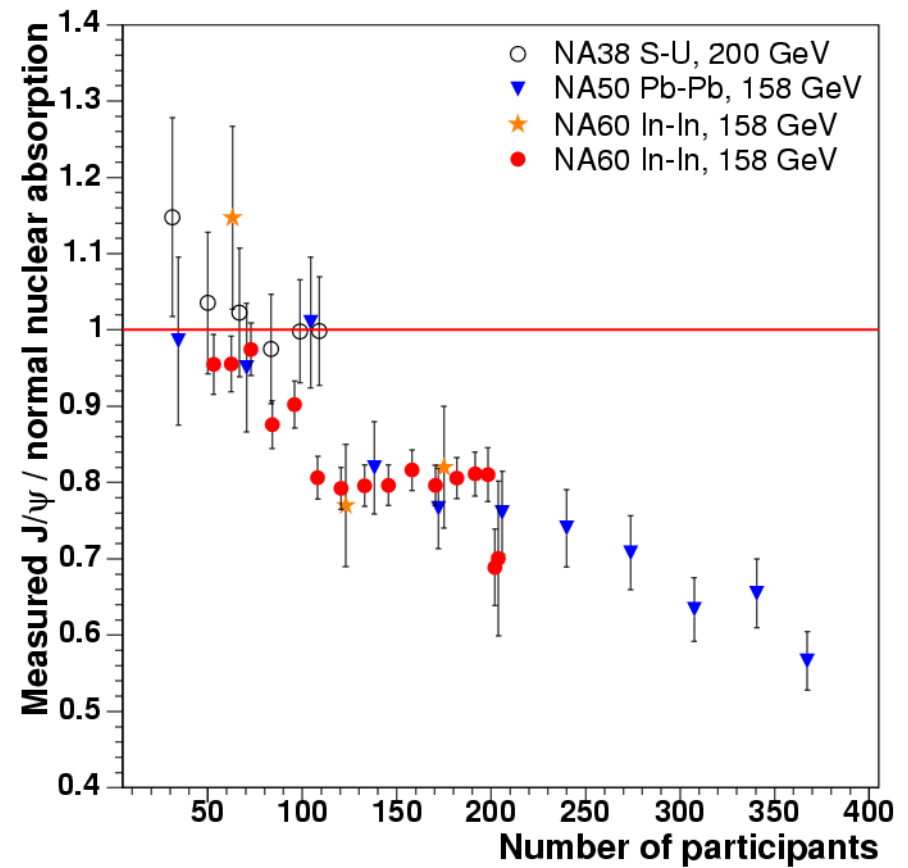
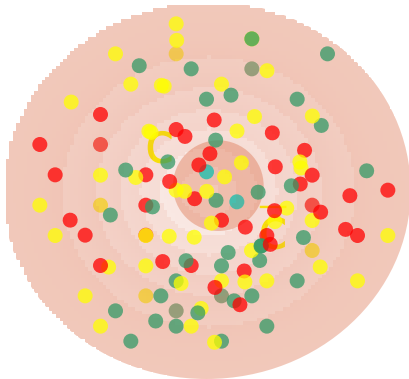
- For a $c\bar{c}$ system $\mu = 1.84 \text{ GeV}/2$ and $\alpha_{eff} = 0.52$; the Bohr radius is 0.41 fm and thus this system **can not be bound** for $T=200 \text{ MeV}$
- For a QGP α_{eff} decreases with T ; at $T=1.5T_c$ $\alpha_{eff} = 0.2$ which implies that the critical temperature $\sim 130 \text{ MeV}$
- By the way, for a $s\bar{s}$ system the Bohr radius is 3.8 fm. Therefore this system cannot be bound in a QGP@ $T=200 \text{ MeV}$
- The J/Ψ or Y are not suppressed at hadronization, which makes them excellent probes. What to expect:
 - At $T=0$ (no QGP) the J/Ψ or Y should be normally produced
 - At $T>T_c$ (QGP) these states should be **suppressed**
- This should affect also (and probably mostly) the excited states

Hard probes

- At SPS:



J/Ψ



Hard probes

- Introduction
- Observables
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- At LHC: the J/ψ CMS example. The baseline

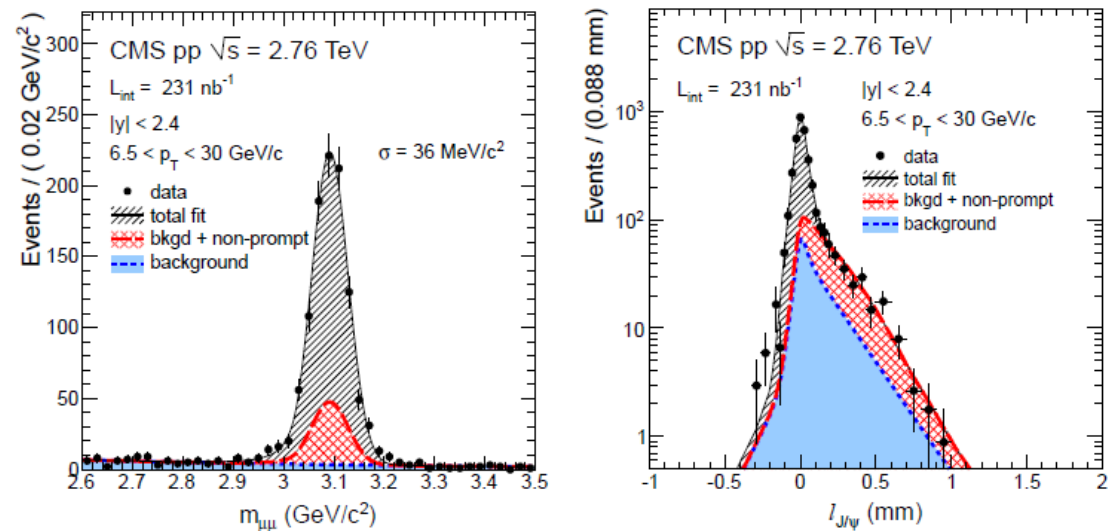
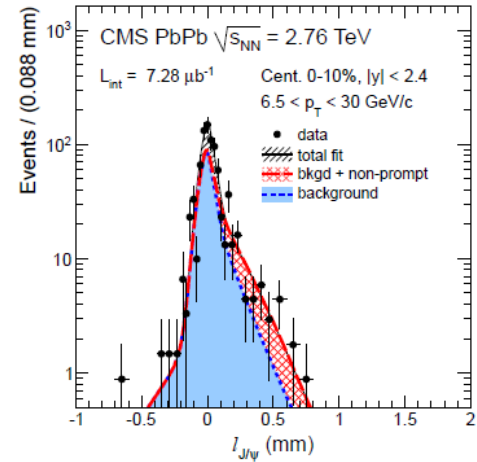
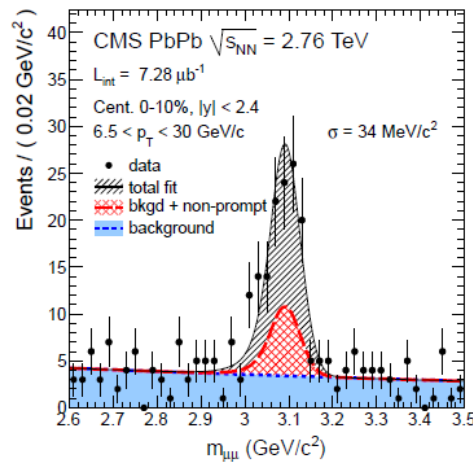
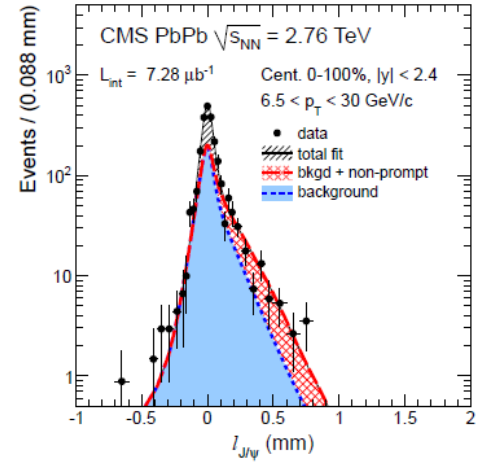
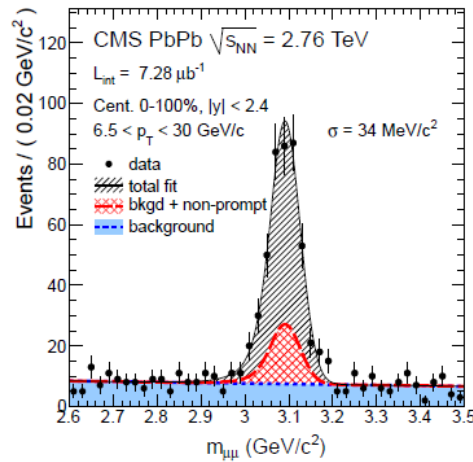


Figure 8: Non-prompt J/ψ signal extraction for pp collisions at $\sqrt{s} = 2.76$ TeV: dimuon invariant mass fit (left) and pseudo-proper decay length fit (right).

Hard probes

- Introduction
- Observables
- Hard probes
- Prospects

- At LHC: the J/ψ CMS example



Hard probes

- Introduction
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- At LHC: the J/ψ CMS example

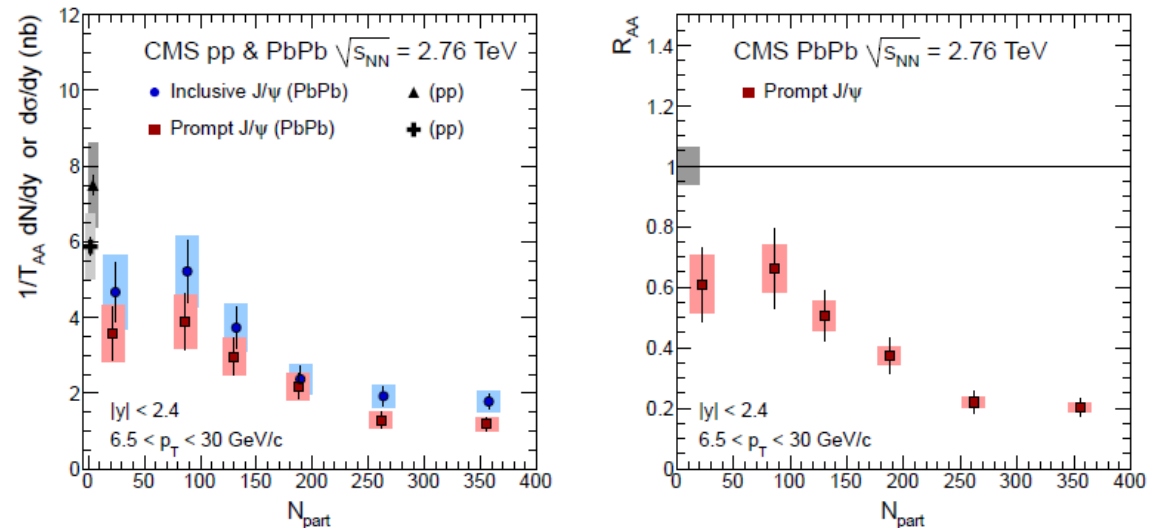


Figure 12: Left: yield of inclusive J/ψ (blue circles) and prompt J/ψ (red squares) divided by T_{AA} as a function of N_{part} . The results are compared to the cross sections of inclusive J/ψ (black triangle) and prompt J/ψ (black cross) measured in pp. The inclusive J/ψ points are shifted by $\Delta N_{part} = 2$ for better visibility. Right: nuclear modification factor R_{AA} of prompt J/ψ as a function of N_{part} . A global uncertainty of 6%, from the integrated luminosity of the pp data sample, is shown as a grey box at $R_{AA} = 1$. Statistical (systematic) uncertainties are shown as bars (boxes).

Hard probes

- Introduction
- Observables
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- At LHC: the Y CMS example

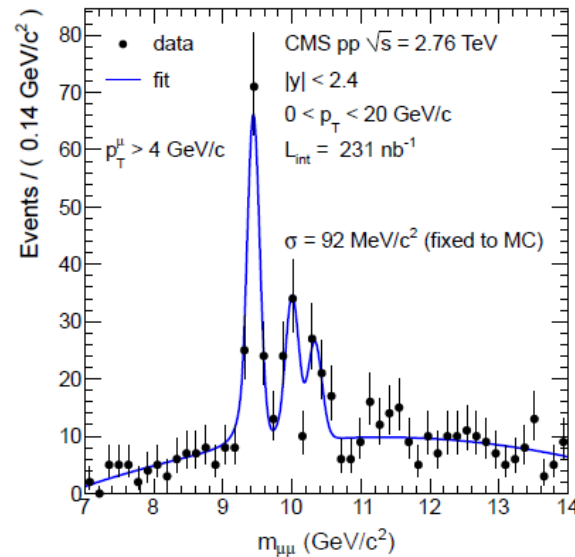
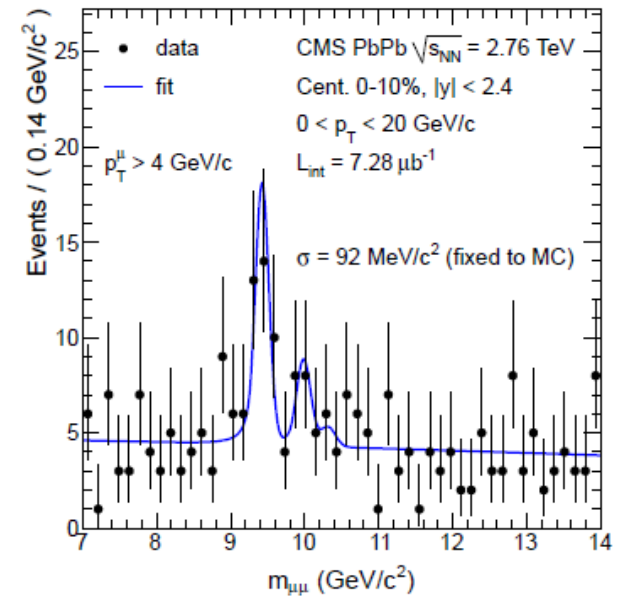
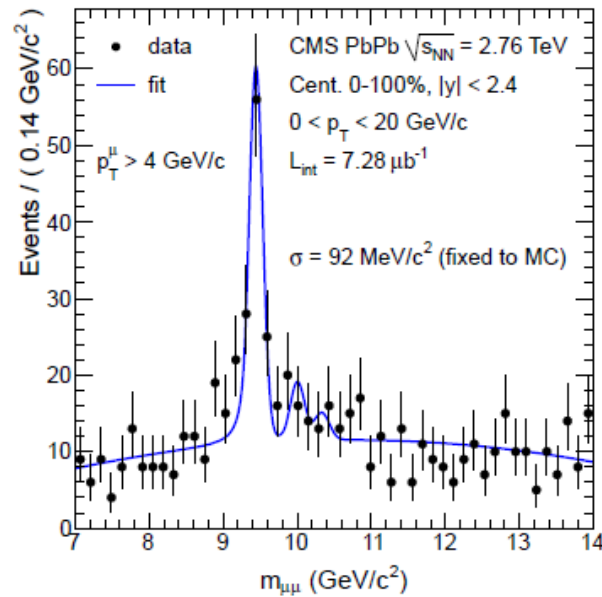


Figure 9: The pp dimuon invariant-mass distribution in the range $p_T < 20 \text{ GeV}/c$ for $|y| < 2.4$ and the result of the fit to the Y resonances.

Hard probes

- Introduction
- Observables
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- At LHC: The Y CMS example



Hard probes

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- Hard probes
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- At LHC: The Y CMS example

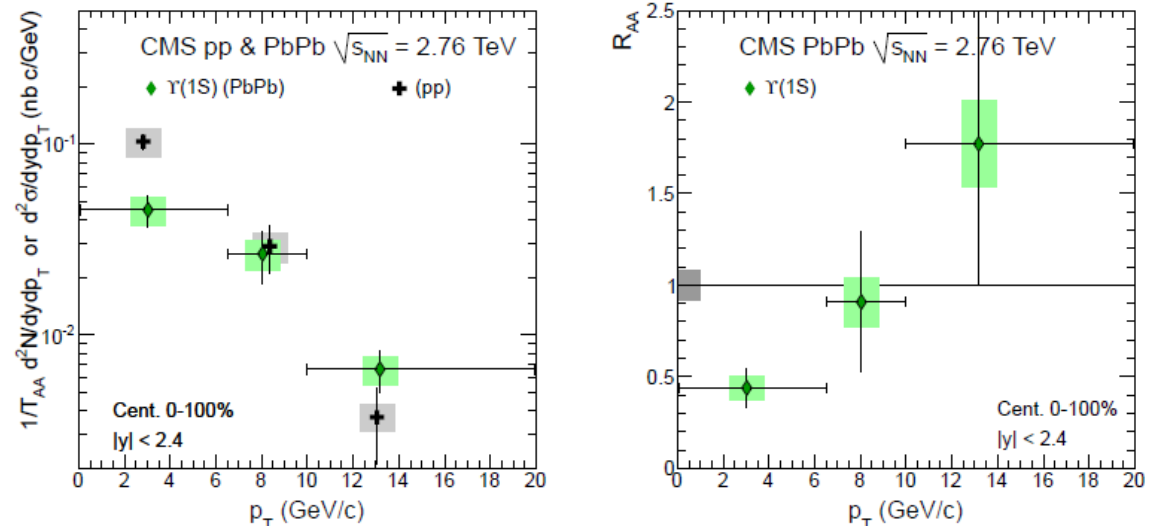


Figure 15: Left: Y(1S) yield divided by T_{AA} in PbPb collisions (green diamonds) as a function of p_T . The result is compared to the cross section measured in pp collisions (black crosses). The global scale uncertainties on the PbPb data due to T_{AA} (5.7%) and the pp integrated luminosity (6.0%) are not shown. Right: nuclear modification factor R_{AA} of Y(1S) as a function of p_T . A global uncertainty of 8.3%, from T_{AA} and the integrated luminosity of the pp data sample, is shown as a grey box at $R_{AA} = 1$. Points are plotted at their measured average p_T . Statistical (systematic) uncertainties are shown as bars (boxes). Horizontal bars indicate the bin width.

Hard probes

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- At LHC: The Υ CMS example

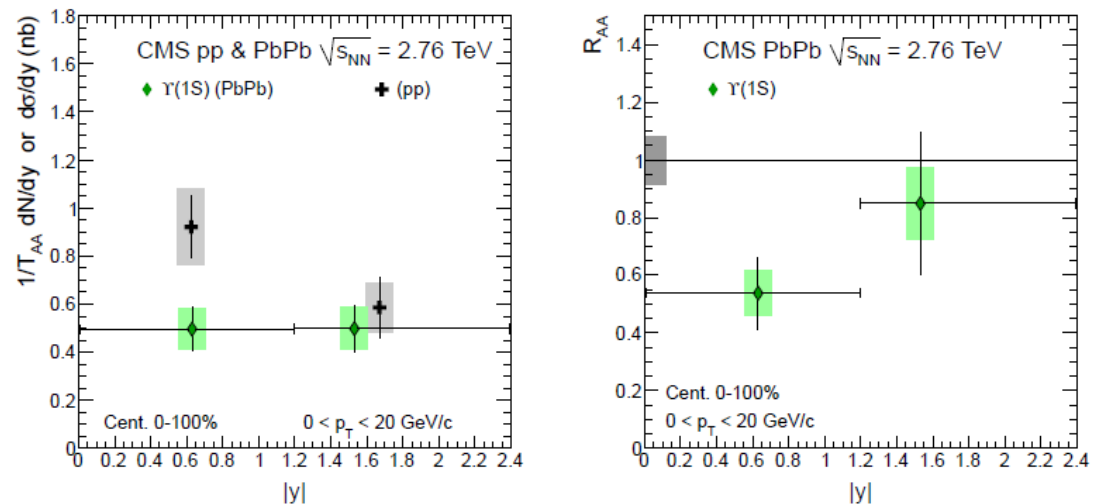


Figure 16: Left: $\Upsilon(1S)$ yield divided by T_{AA} in PbPb collisions (green diamonds) as a function of rapidity. The result is compared to the cross section measured in pp collisions (black crosses). The global scale uncertainties on the PbPb data due to T_{AA} (5.7%) and the pp integrated luminosity (6.0%) are not shown. Right: nuclear modification factor R_{AA} of $\Upsilon(1S)$ as a function of rapidity. A global uncertainty of 8.3%, from T_{AA} and the integrated luminosity of the pp data sample, is shown as a grey box at $R_{AA} = 1$. Points are plotted at their measured average $|y|$. Statistical (systematic) uncertainties are shown as bars (boxes). Horizontal bars indicate the bin width.

Hard probes

- Introduction
- Observables
- **Hard probes**
- Prospects

- **At LHC:**

- The non-prompt J/Ψ produced in AA is strongly suppressed when compared to pp collisions (problem with pp...)
- The suppression of non-prompt J/ψ is of a comparable magnitude to the charged hadron R_{AA} measured by ALICE, which reflects the in-medium energy loss of light quarks.
- The non-prompt J/ψ yield though strongly suppressed in the 20% most central collisions, shows no strong centrality dependence, within uncertainties, when compared to a broad peripheral region (20–100%).
- Furthermore, this suppression of non-prompt J/ψ is comparable in size to that observed for high- p_T single electrons from semileptonic heavy-flavour decays at RHIC in which charm and bottom decays were not separated.
- The $Y(1S)$ yield divided by T_{AA} as a function of p_T , rapidity, and centrality has been measured in PbPb collisions.
- No strong centrality dependence is observed within the uncertainties. The suppression is observed predominantly at low p_T .
- CDF measured the fraction of directly produced $Y(1S)$ as $\sim 50\%$ for $Y(1S)$ with $p_T > 8$ GeV/c. Therefore, the $Y(1S)$ suppression could be indirectly caused by the suppression of excited Y states, as indicated by earlier results from CMS.

What about feed-down?

- Introduction
- Observables
- Hard probes
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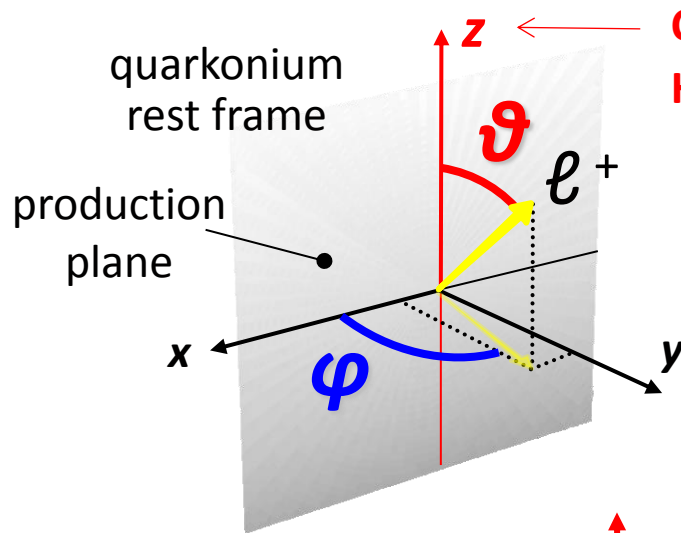
- The Satz-Masui argument affects all quarkonia states, including the ones which decay to J/ψ and Υ , such as the χ states.
 - In the Satz-Matsui picture these states are not supposed to melt at the same temperature.
 - LGT support this view
 - A sequential suppression scenario is thus quite probable in which the χ states melt first and at higher temperatures the J/ψ and Υ states melt.
 - How is it possible to test this scenario?
 - The answer is in the polarization of these states.
-

Prospects

- Introduction
- SPS results
- RHIC results
- The LHC Era
- Prospects

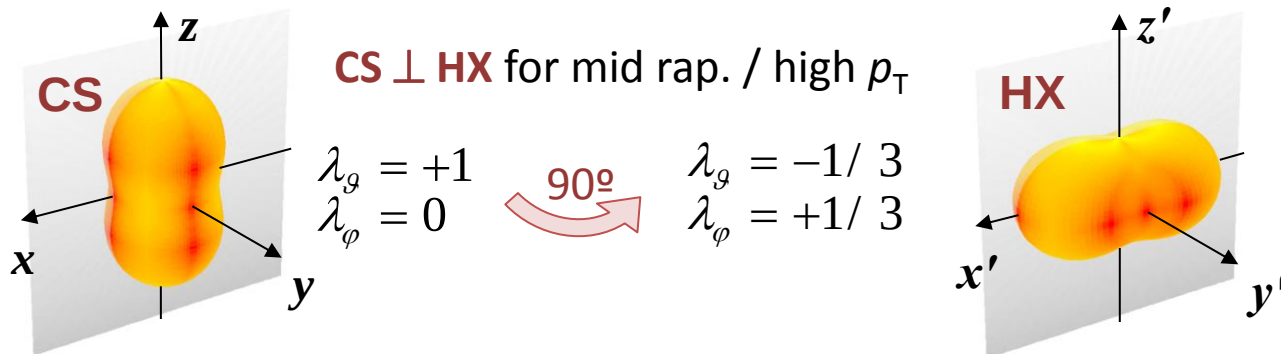
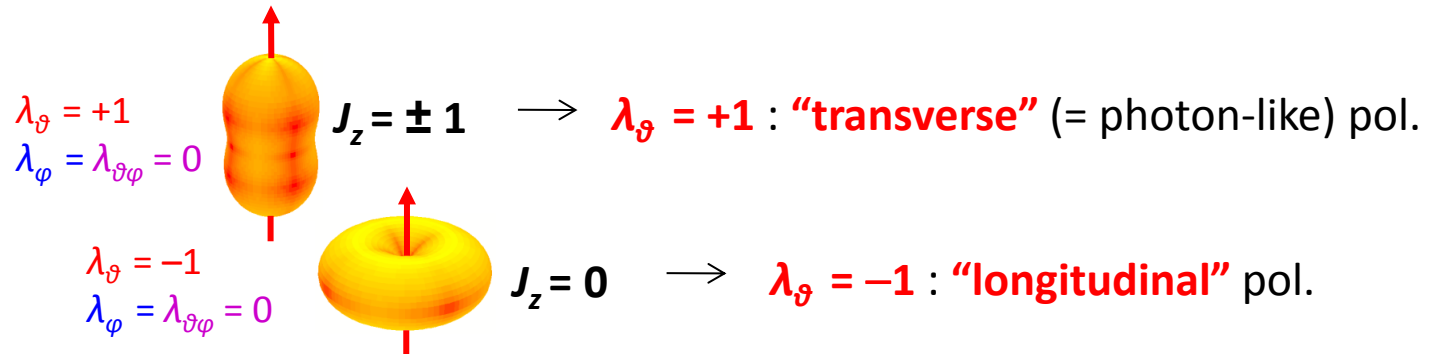
- Heavy ion collisions at high energies have provided a wealth of information concerning the phase structure of QCD
 - However, the accelerator information must be complemented by other (astrophysical?) information. Extreme densities at $T=0$ not accessible
 - Properties of matter at extreme conditions are surprisingly different from expected
 - QGP thermodynamics is starting now
 - What about pp?
-

Frames and parameters



Collins-Soper axis (CS): $\approx$ dir. of colliding partons
Helicity axis (HX): dir. of quarkonium momentum

$$\frac{dN}{d\Omega} \propto 1 + \lambda_\theta \cos^2 \theta + \lambda_\varphi \sin^2 \theta \cos 2\varphi + \lambda_{\theta\varphi} \sin 2\theta \cos \varphi$$



J=1 states are intrinsically polarized

Single elementary subprocess: $|\psi\rangle = a_{-1} |1, -1\rangle + a_0 |1, 0\rangle + a_{+1} |1, +1\rangle$

$$\frac{dN}{d\Omega} \propto 1 + \lambda_{\theta} \cos^2 \theta + \lambda_{\phi} \sin^2 \theta \cos 2\phi + \lambda_{\theta\phi} \sin 2\theta \cos \phi + \dots$$

$$\frac{1 - 3|a_0|^2}{1 + |a_0|^2} \quad \frac{2 \operatorname{Re} a_{+1}^* a_{-1}}{1 + |a_0|^2} \quad \frac{\sqrt{2} \operatorname{Re}[a_0^* (a_{+1} - a_{-1})]}{1 + |a_0|^2}$$

There is no combination of a_0 , a_{+1} and a_{-1} such that $\lambda_{\theta} = \lambda_{\phi} = \lambda_{\theta\phi} = 0$
 The angular distribution is never intrinsically isotropic

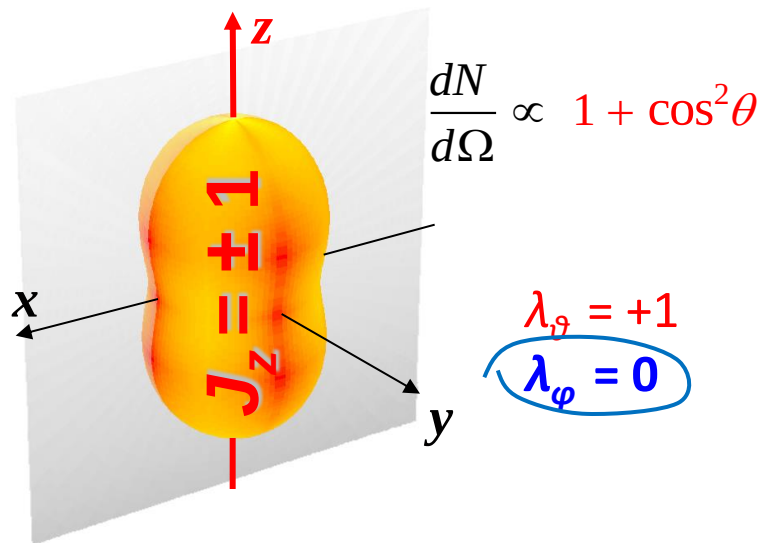
Only a “fortunate” **mixture of subprocesses**
 (or randomization effects)
 can lead to a cancellation of **all three** observed
 anisotropy parameters

To measure zero polarization
 would be an exceptionally interesting result...

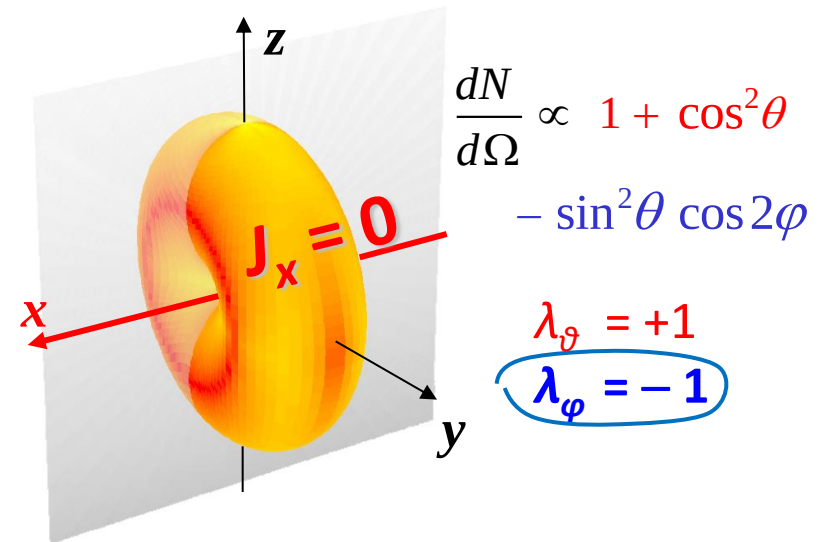


The azimuthal anisotropy is not a detail

Case 1: natural **transverse** polarization



Case 2: natural **longitudinal** polarization, observation frame $\perp$ to the natural one

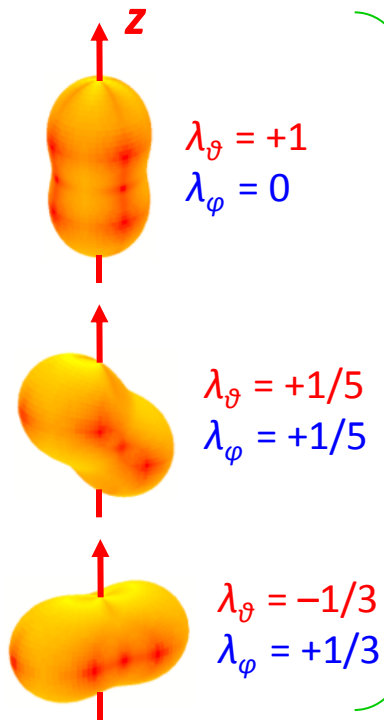


- Two very different physical cases
- Indistinguishable if λ_ϕ is not measured (integration over ϕ)

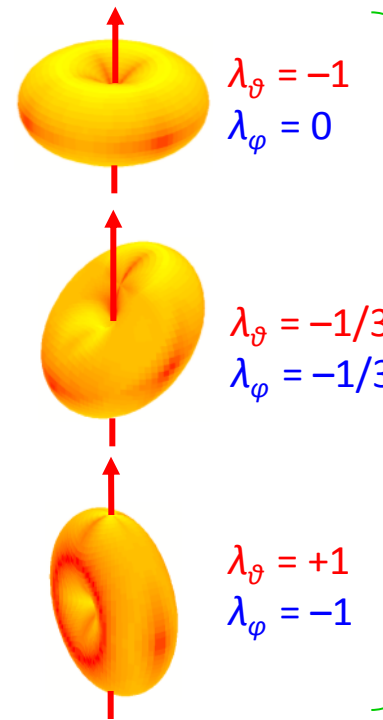
Frame-independent polarization

The **shape** of the distribution is obviously frame-invariant.

→ it can be characterized by a frame-independent parameter, e.g. $\tilde{\lambda} = \frac{\lambda_g + 3\lambda_\phi}{1 - \lambda_\phi}$



$$\tilde{\lambda} = +1$$

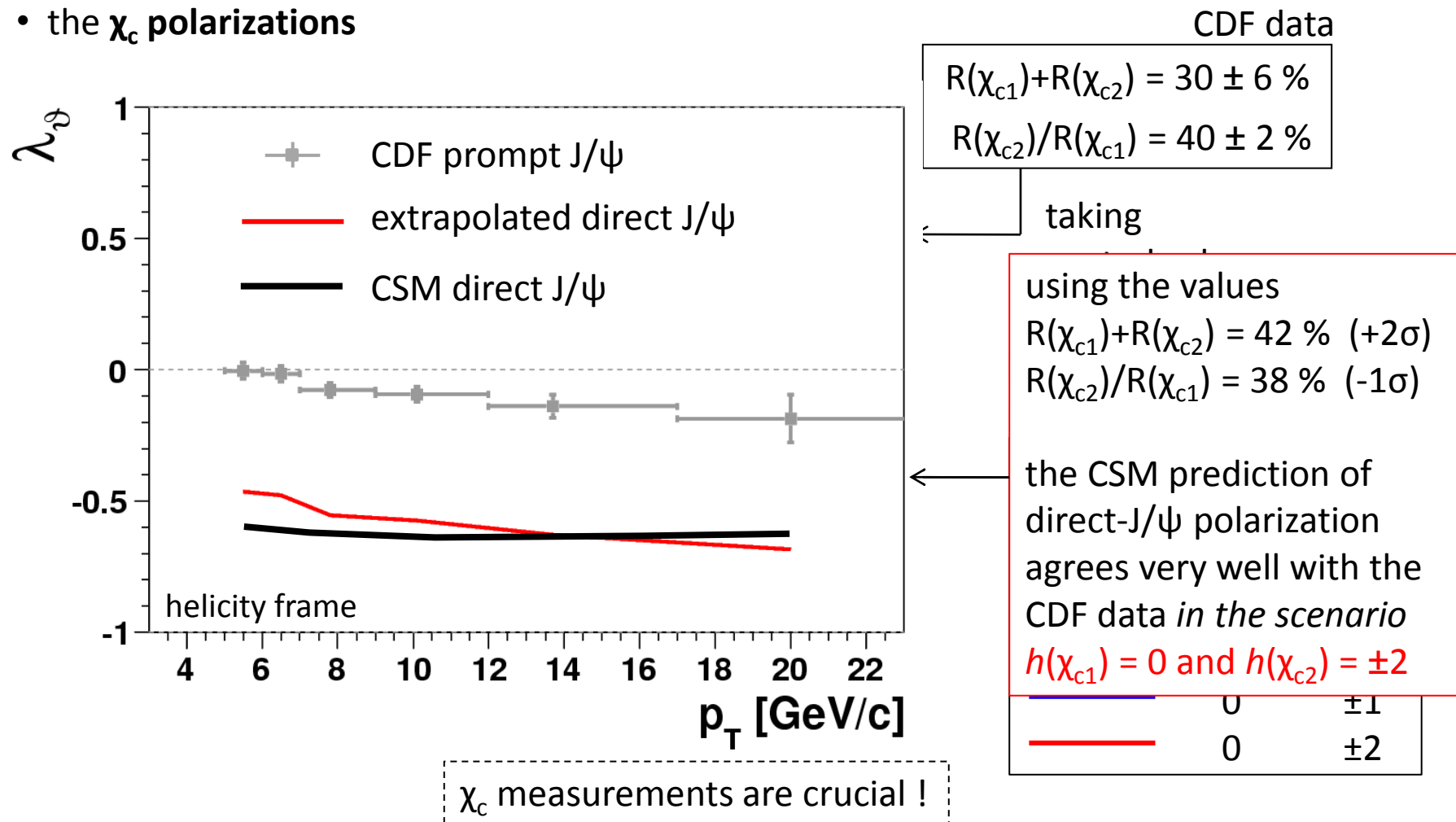


$$\tilde{\lambda} = -1$$

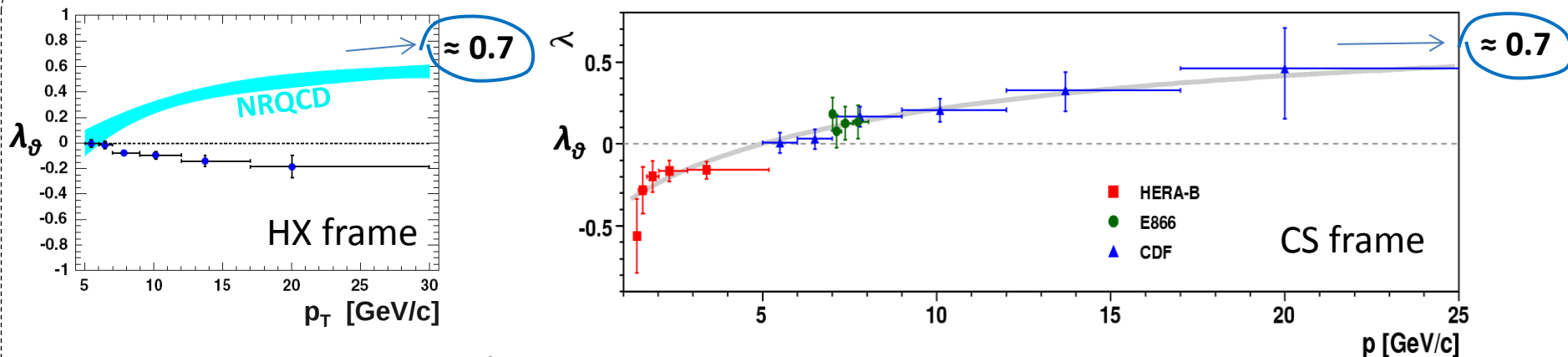
Direct vs prompt J/ψ

The direct-J/ψ polarization (cleanest theory prediction) can be derived from the prompt-J/ψ polarization measurement of CDF knowing

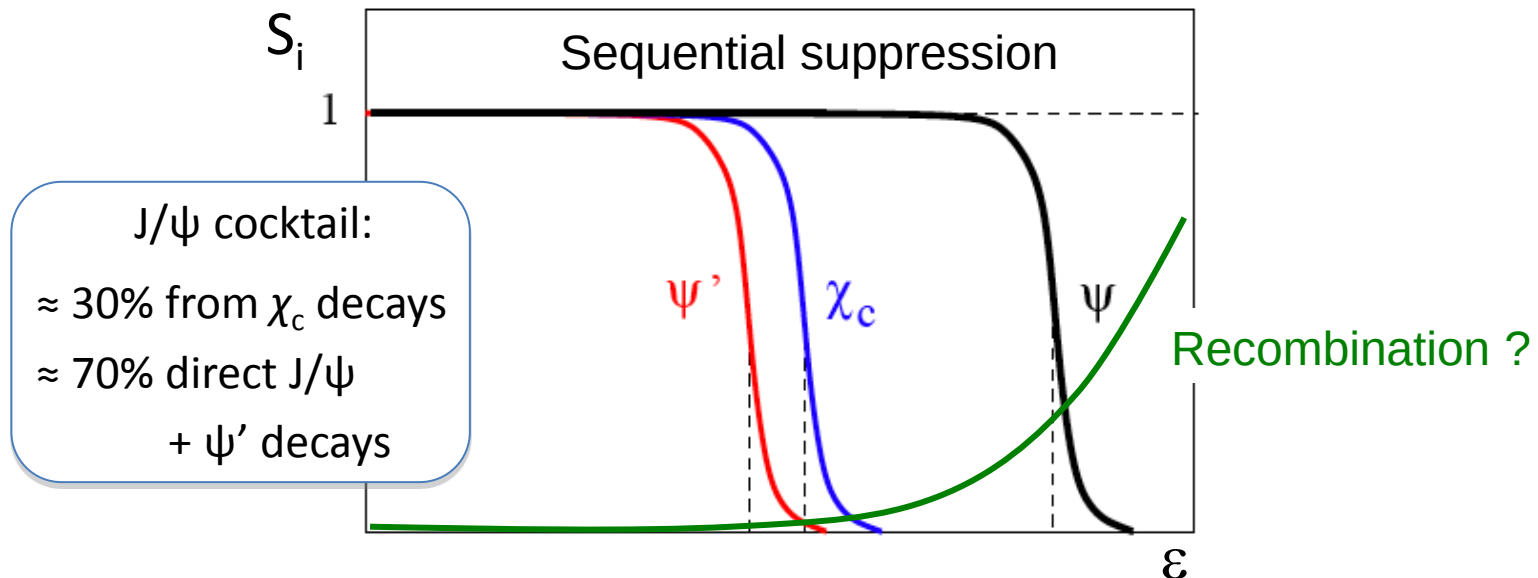
- the χ_c -to-J/ψ feed-down fractions
- the χ_c polarizations



J/ψ polarization as a signal of colour deconfinement?

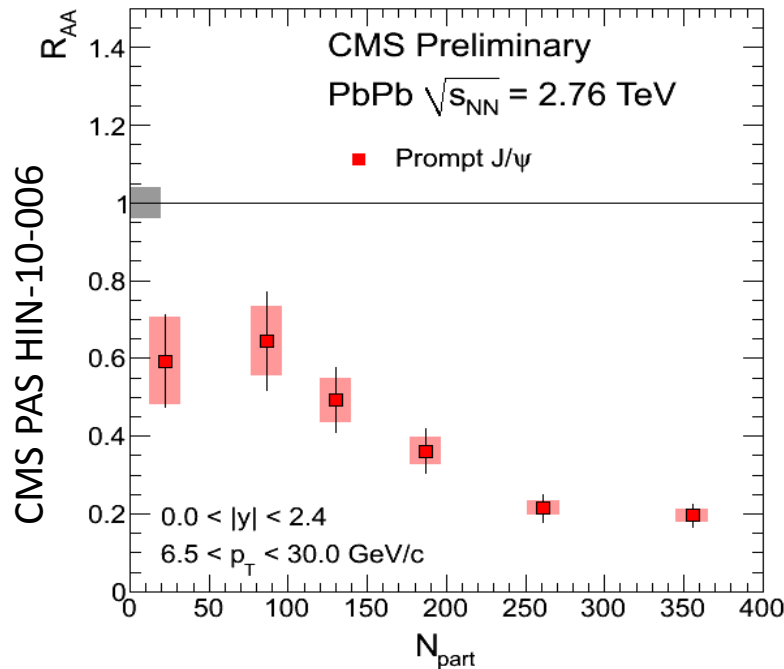


- Starting “pp” scenario:
- J/ψ significantly polarized (high p_T)
 - feeddown from χ_c states ($\approx 30\%$) smears the polarizations



- As the χ_c (and ψ') mesons get dissolved by the QGP, λ_θ should *increase* from $\approx \mathbf{0.7}$ to $\approx \mathbf{1}$ [values for high p_T ; cf. NRQCD]

J/ψ polarization as a signal of sequential suppression?



CMS data:

- up to 80% of J/ψ's disappear from pp to Pb-Pb
- more than 50% ($\gtrsim$ fraction of J/ψ's from ψ' and χ_c) disappear from peripheral to central collisions

→ **sequential suppression** gedankenscenario:
in central events **ψ' and χ_c are fully suppressed**
and all J/ψ's are *direct*

It may be impossible to test this directly:

measuring the χ_c yield (reconstructing χ_c radiative decays) in PbPb collisions is prohibitively difficult due to the huge number of photons

However, a **change of prompt-J/ψ polarization** must occur from pp to central Pb-Pb!

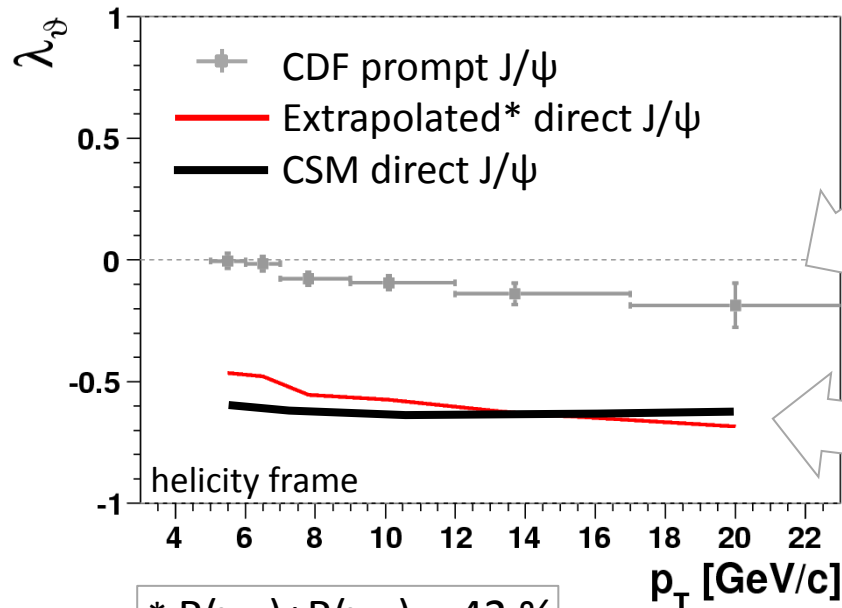
Reasonable timeline
of measurements:

- 1) prompt J/ψ polarization in pp
- 2) χ_c -to-J/ψ fractions in pp
- 3) χ_c polarizations in pp
- 4) prompt J/ψ polarization in PbPb

χ_c suppression
in PbPb!

J/ψ polarization as a signal of sequential suppression?

Example scenario:



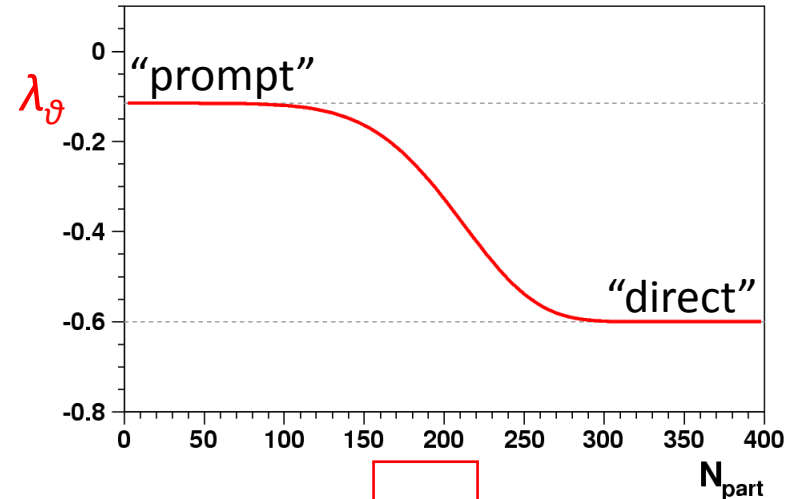
prompt-J/ψ polarization in pp: $\lambda_\theta \cong -0.15$

direct-J/ψ polarization: $\lambda_\theta \cong -0.6$
(assumed to be the same in pp and PbPb)

* $R(\chi_{c1}) + R(\chi_{c2}) = 42\%$
 $R(\chi_{c2})/R(\chi_{c1}) = 38\%$
 $h(\chi_{c1}) = 0$
 $h(\chi_{c2}) = \pm 2$

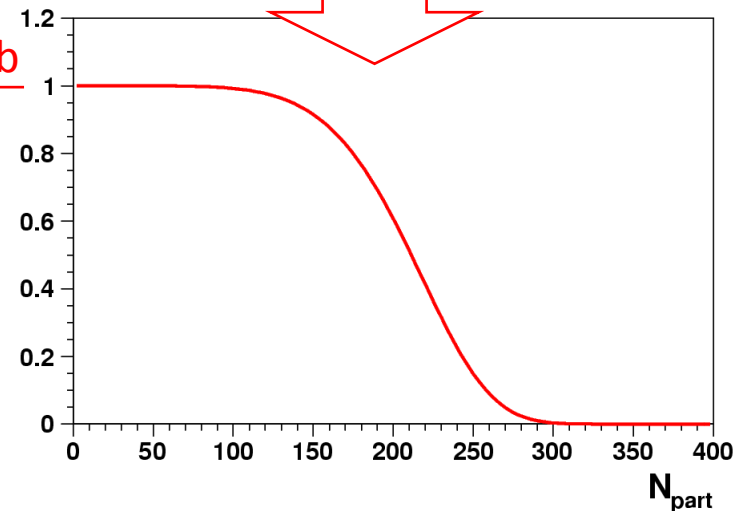
J/ ψ polarization as a signal of sequential suppression?

If we measure a change in prompt polarization like this...



... we are observing the disappearance of the χ_c relative to the J/ ψ

$$\frac{R(\chi_c) \text{ in PbPb}}{R(\chi_c) \text{ in pp}}$$



Simplifying assumptions:

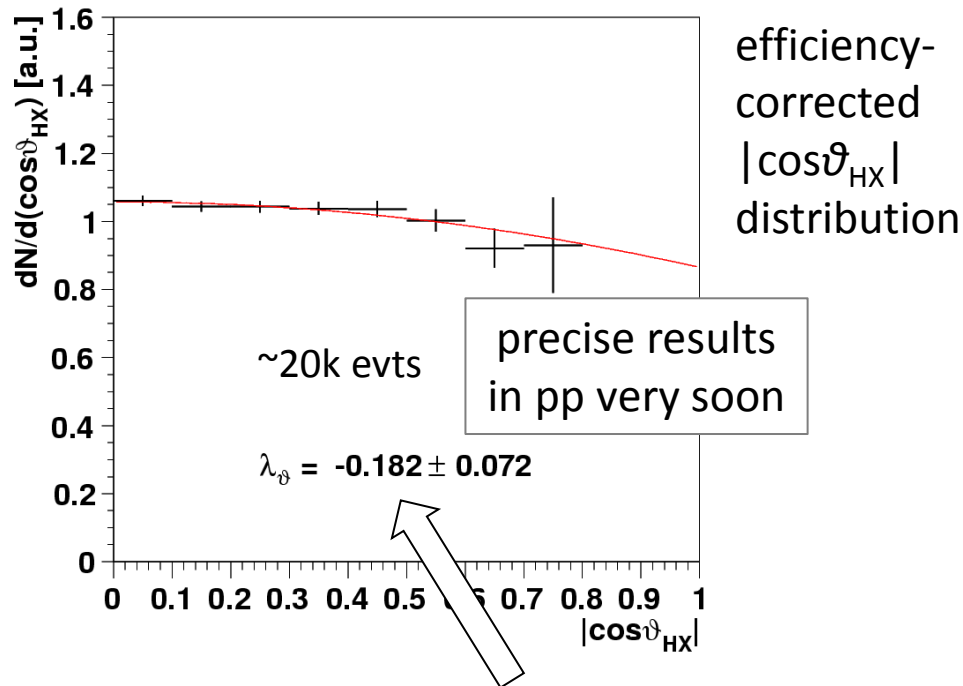
- direct-J/ ψ polarization is the same in pp and PbPb
- *normal* nuclear effects affect J/ ψ and χ_c in similar ways
- χ_{c1} and χ_{c2} are equally suppressed in PbPb

J/ψ polarization as a signal of sequential suppression?

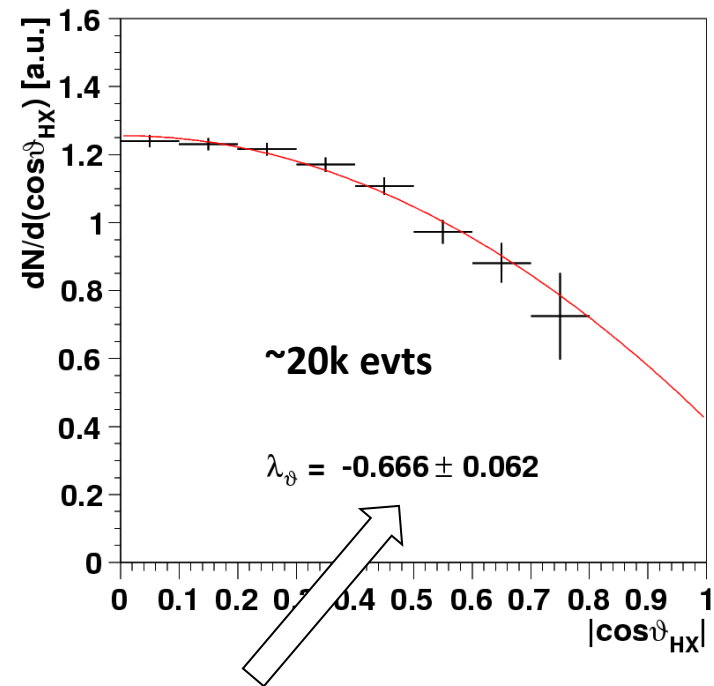
When will we be sensitive to an effect like this?

CMS-like toy MC with $p_T(\mu) > 3 \text{ GeV}/c$,
 $6.5 < p_T < 30 \text{ GeV}/c$, $0 < |y| < 2.4$

prompt-J/ψ polarization
as observed in **pp** (and peripheral PbPb)



prompt-J/ψ polarization
as observed in **central PbPb**



In this scenario, the χ_c disappearance is measurable at $\sim 5\sigma$ level with $\sim 20\text{k J}/\psi$'s in central Pb-Pb collisions

Prospects

- Introduction
- SPS results
- RHIC results
- The LHC Era
- Prospects

- Heavy ion collisions at high energies have provided a wealth of information concerning the phase structure of QCD
 - However, the accelerator information must be complemented by other (astrophysical?) information. Extreme densities at $T=0$ not accessible
 - Properties of matter at extreme conditions are surprisingly different from expected
 - QGP thermodynamics is starting now
 - What about pp?
-

-
- Backup
-

Cronin x Nuclear matter effects

- Introduction
- Observables
- Hard probes
- Prospects

- **Particle distributions at LHC: the CMS case**

