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 is 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

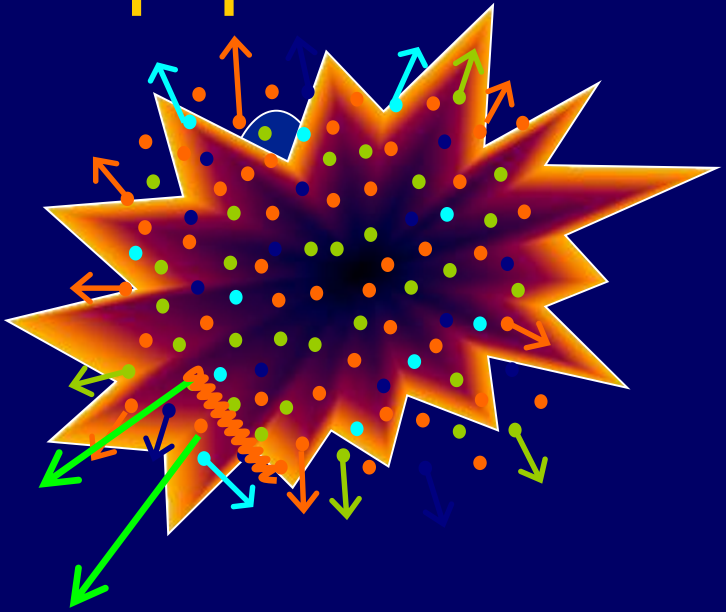
$$\rho(m) = cm^{a}\exp(b.m)$$

- In a hadron gas the average energy is

$$\overline{E} = \frac{\int_0^\infty dE\, E\rho(E)e^{-E/T}}{\int_0^\infty dE\, \rho(E)e^{-E/T}} \overset{c.m.}{=} \frac{\int_0^\infty dm\, m\rho(m)e^{-m/T}}{\int_0^\infty dm\, \rho(m)e^{-m/T}} \rightarrow \int_0^\infty dm\, cm^{a+1}e^{-m(b-1/T)}$$

- ***$T < b^{-1}$*** that is, there ***exists a limiting temperature*** for the hadron gas! ($T_c = b^{-1}$ ~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:

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

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

Case 1: SPS (CERN)

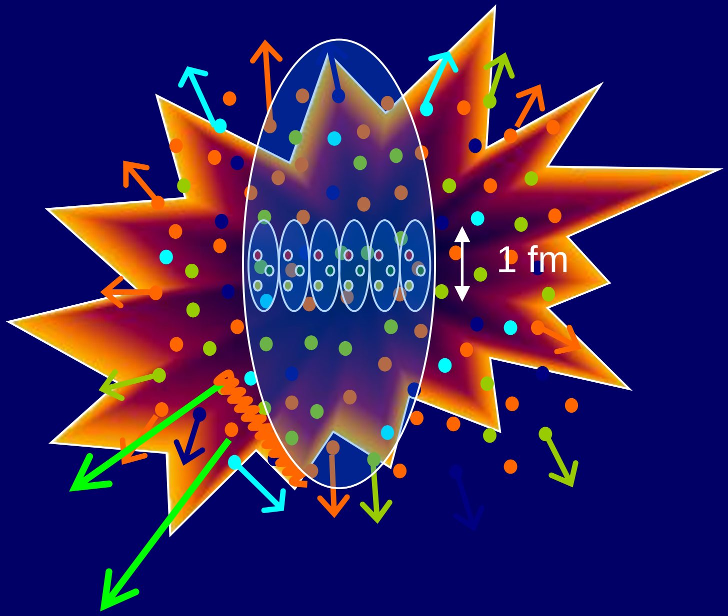
$E_{CM} \sim 20$ GeV; $\langle n_p \rangle \sim 3$ com $\langle p \rangle \sim 0.5$ GeV/c

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

Case 2: Tevatron (FNAL)

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

A simple exercise: A-A



In each nucleus:

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

where

n_0=0.17 GeV.fm^{-3}

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

¾ come from averaging over the tube length in a central collision ← Check as an exercise

ε_{AA}~$A^{1/3}$(0.4 GeV.fm^{-3})~2 GeV. fm^{-3}

Initial volume ~170 fm^3

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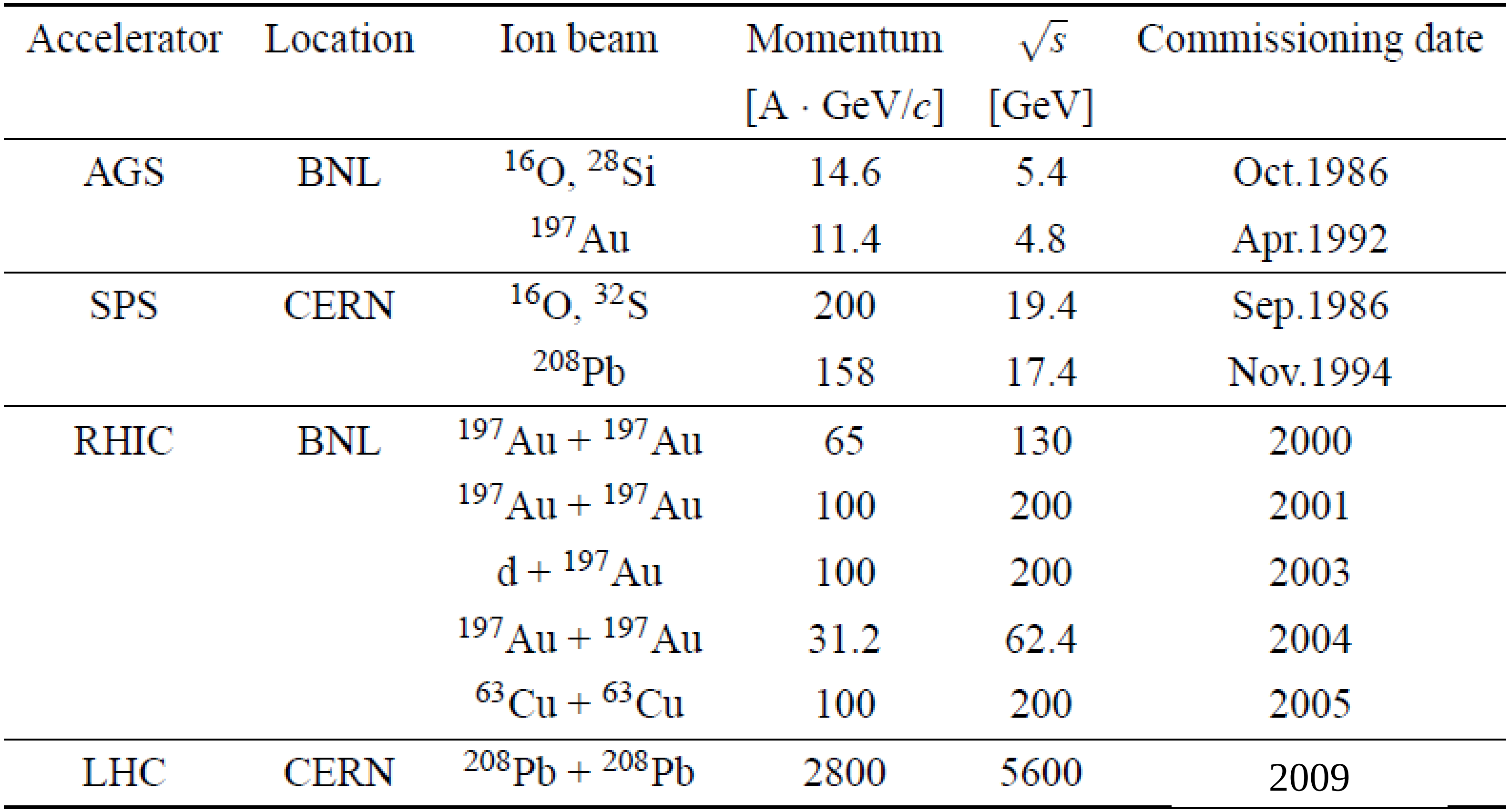
- Chosing the correct observables is a major problem:
  - The complexity of the system is extremely high
  - If a dense and hot state is produced, its manifestation might be “hidden” during hadronization.
  - Collective x superposition effects
  - Colective effects: the role of thermodynamics
  - Control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

Facilities



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

The QCD phase diagram

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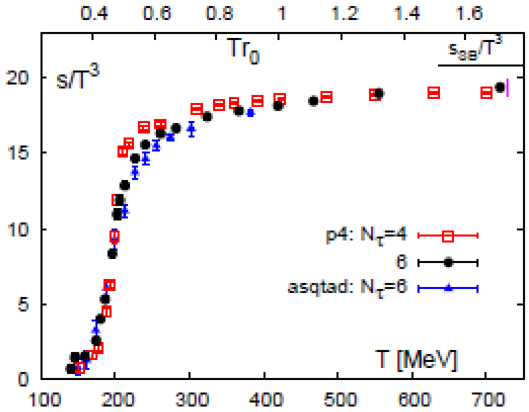
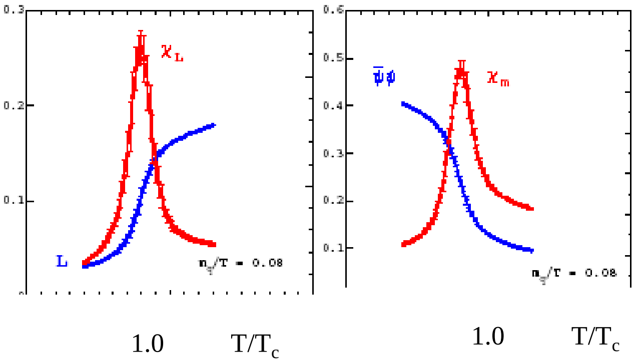
- Hagedorn: strong interacting matter should undergo a deconfining phase transition for large enough temperatures and densities.
- This fact was confirmed by LGT (although not clear whether it is the same physics).
- In fact LGT gave us first indication of the QCD phase diagram
- Unfortunately, LGT does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





The QCD phase diagram

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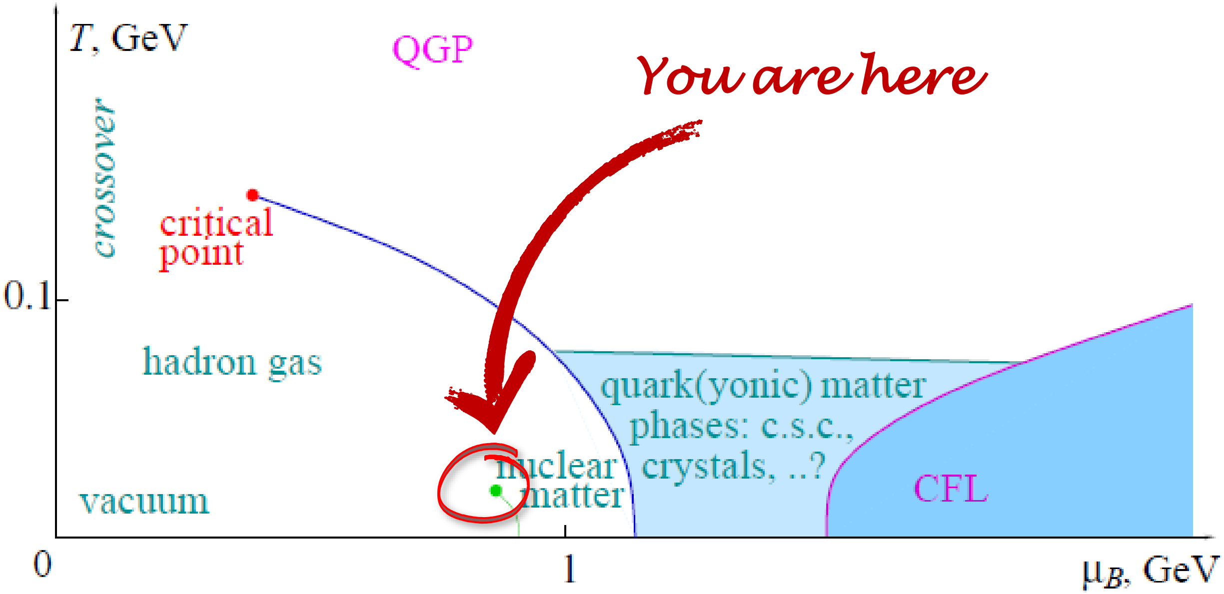
- The QCD phase diagram: models & LGT suggest that transition becomes 1st order for some μ_B



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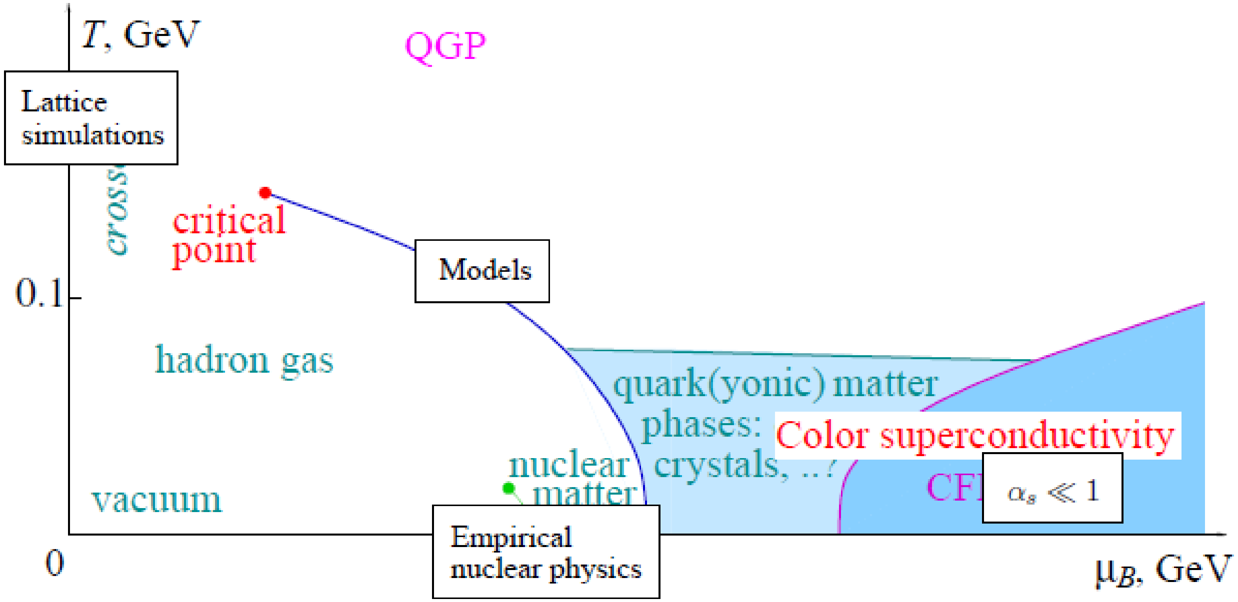
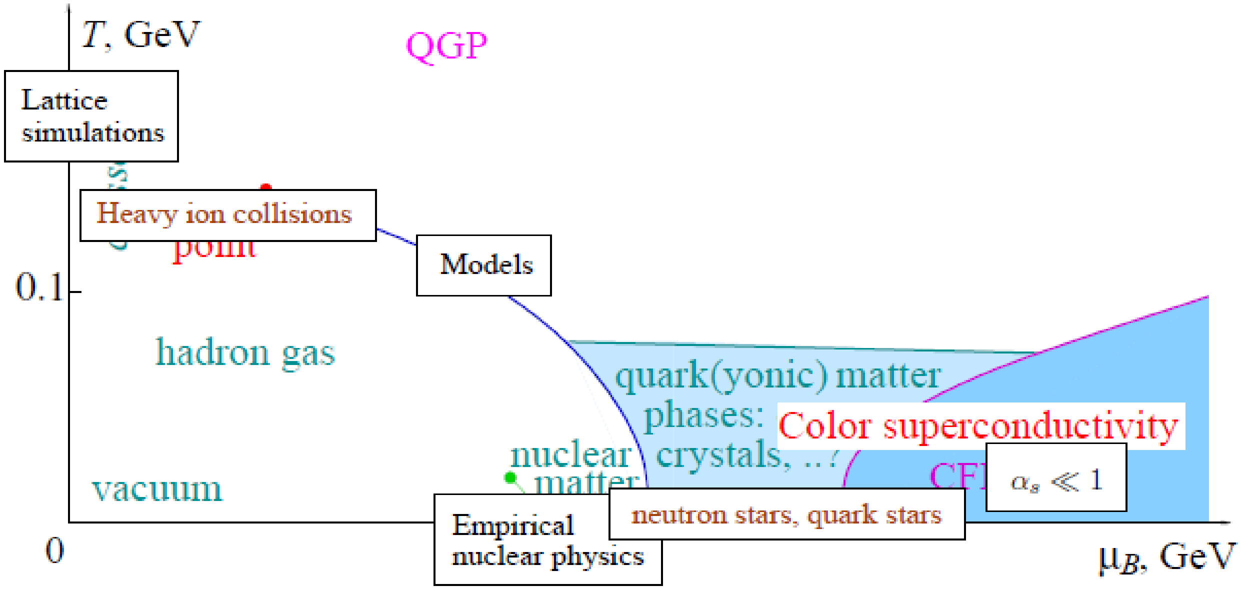


The QCD phase diagram

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

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



The QCD phase diagram

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- RHIC results
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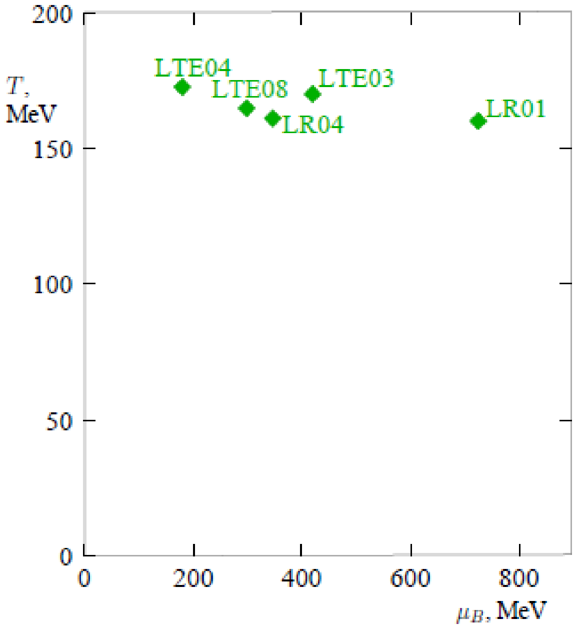
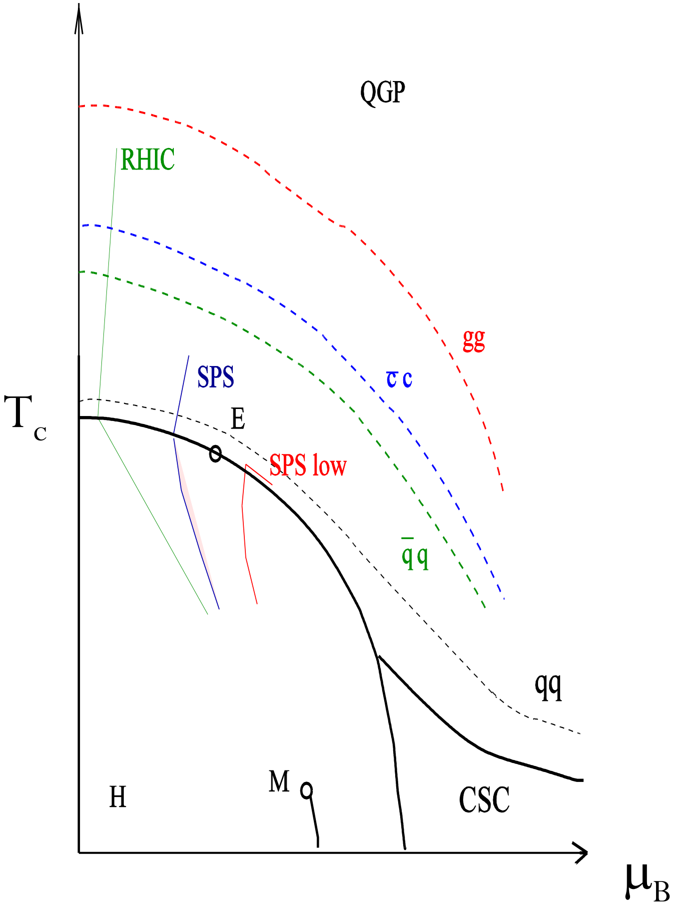
- Where does it happen?





Space-time picture

- Introduction
- Observables
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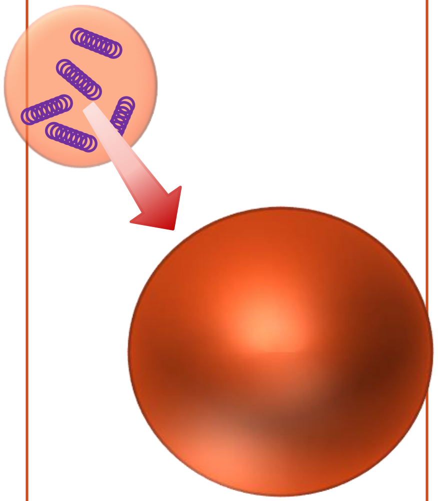

- **Stages of a heavy ion collision**
  - Before the collision the nuclei resemble 2 pancakes, being affected along the direction of motion by a boost factor ϒ~100
  - These pancakes are mostly composed of gluons carrying a tiny fraction x of the parent nucleons longitudinal momenta. Their density decreases 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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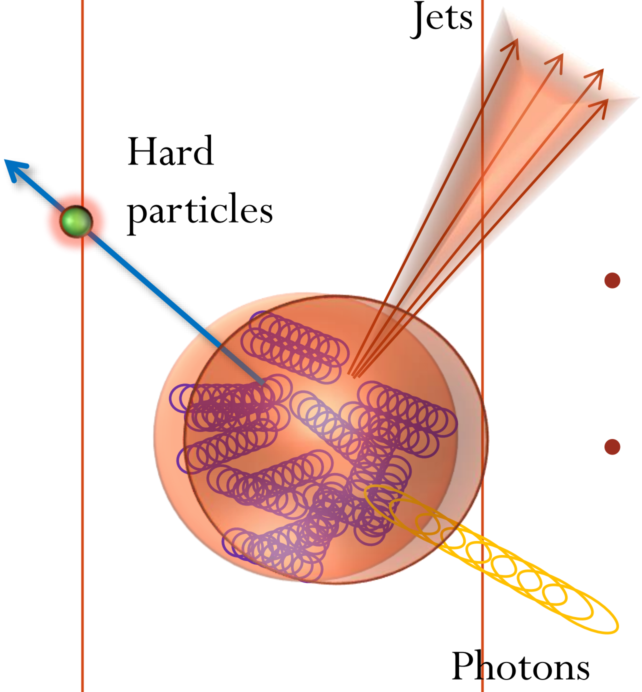
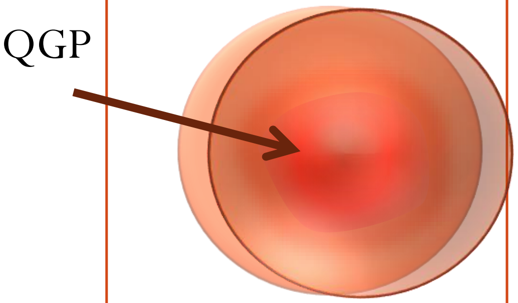


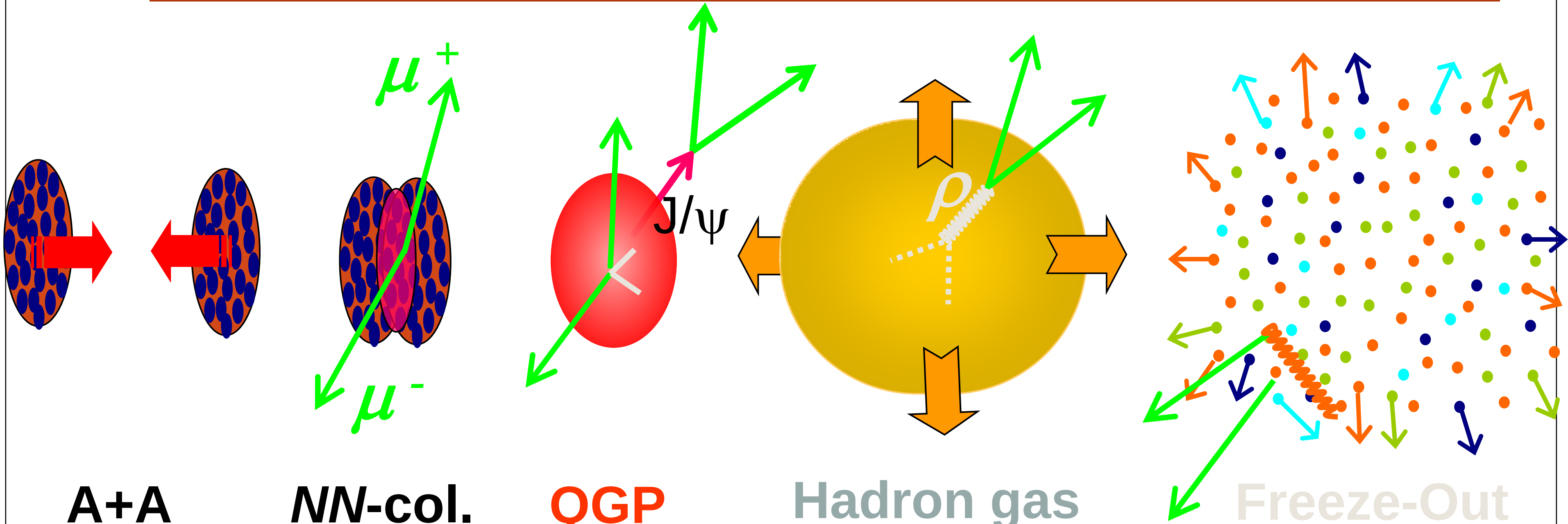
- **Stages of a heavy ion collision**
  - At τ= 0 fm/c the two nuclei hit each other and the interactions start developing.
  - The hard processes occur faster (within a time ~1/Q, by the uncertainty principle). They are responsible for the production of *hard particles*, i.e. particles carrying transverse 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 τ= 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 ε> 15 GeV/fm^3: ***Glasma***

Space-time picture



- **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



A+A ***NN*-col.** **QGP** **Hadron gas** **Freeze-Out**

Lepton pairs are emitted at all stages

NN collisions:	Drell-Yan
QGP:	*qq* thermal annihilation
Hot and dense hadron gas:	$\pi^+\pi^-$ thermal annihilation
Freeze-out:	free hadron decay (cocktail)

Space-time picture

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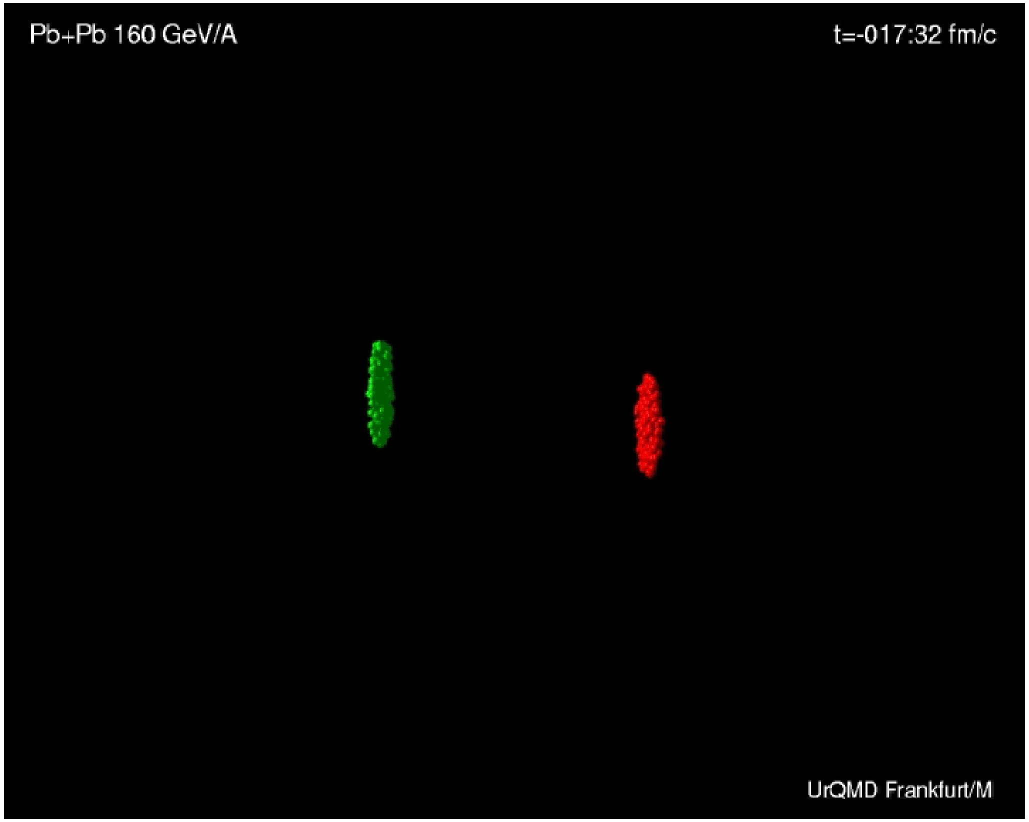
- To make thermodynamics one needs specific objects. How does one measure the initial energy in HIC?



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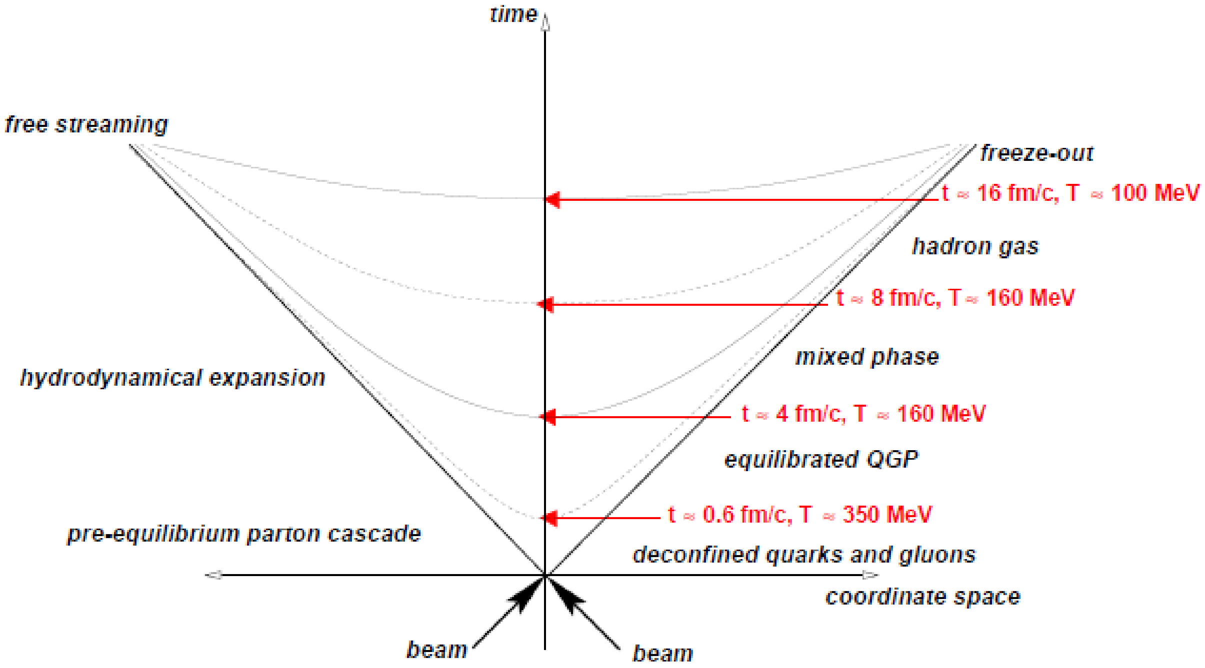

Initial energy density (Bjorken)

- Number of collisions can be very high (~800 in UU collision)
- Energy is deposited in a small region ~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~0.35 GeV/c and m_T~0.38 GeV/c. These particles are characterized by their rapidity distribution dN/dy.

Initial energy density (Bjorken)

- **Bjorken estimation of initial energy density**
  - To reconstruct the inital distribution we have to relate their space-time positions to rapidity

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

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*Δ*z*. Denote by τ_0 the proper time in which QGP is formed and equilibrated.

The particle number density at *z*=0 is

$$\frac{\Delta N}{A\Delta z} = \frac{1}{A}\frac{dN}{dy}\frac{dy}{dz}\bigg|_{y=0}$$

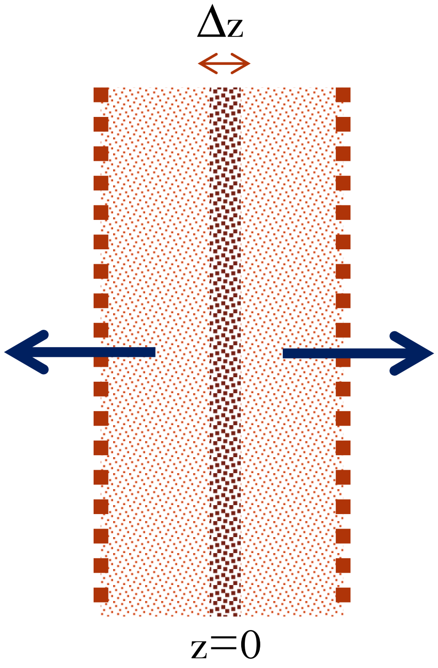
$$= \frac{1}{A}\frac{dN}{dy}\frac{1}{\tau_0 \cosh y}\bigg|_{y=0}$$

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

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

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

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



Initial energy density (Bjorken)

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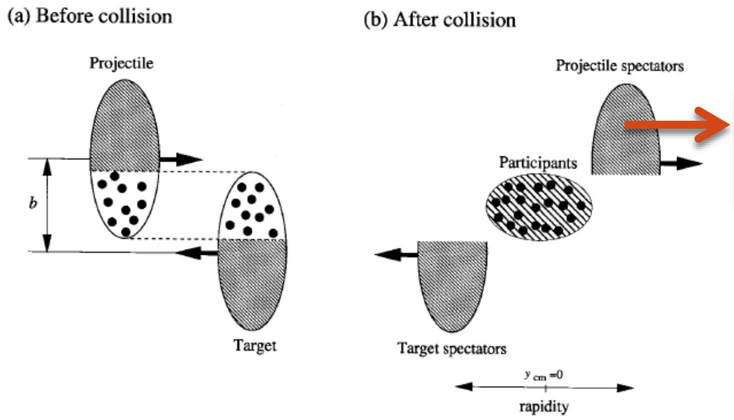
- **Bjorken estimation of initial energy density**
  - We are thus left with problems:
    1. Measure (or calculate) the rapidity distribution
    2. Determine the overlapping region
  - This must be complemented by a knowledge of collective x superposition processes. The **Glauber model** gives the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



To zero-degree calorimeter

Glauber model

- 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 fm
a= 0.54 fm
ρ_0=0.169 fm^{-3}
σ_{NN}^{in}=42mb
$@\sqrt{s_{NN}} = 200\ GeV$

Glauber model

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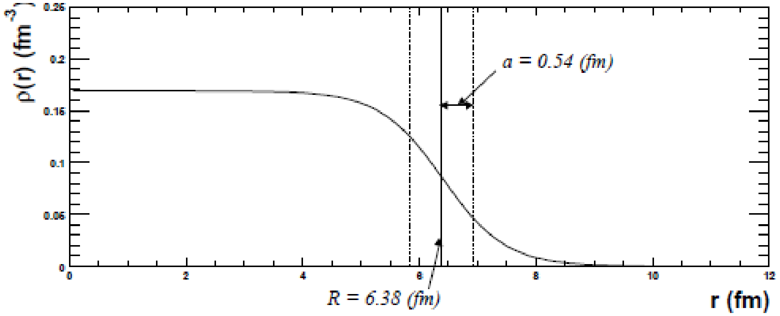

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Glauber model

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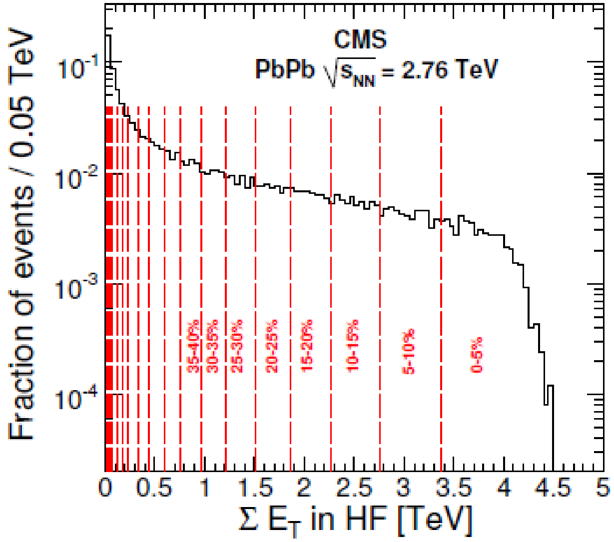
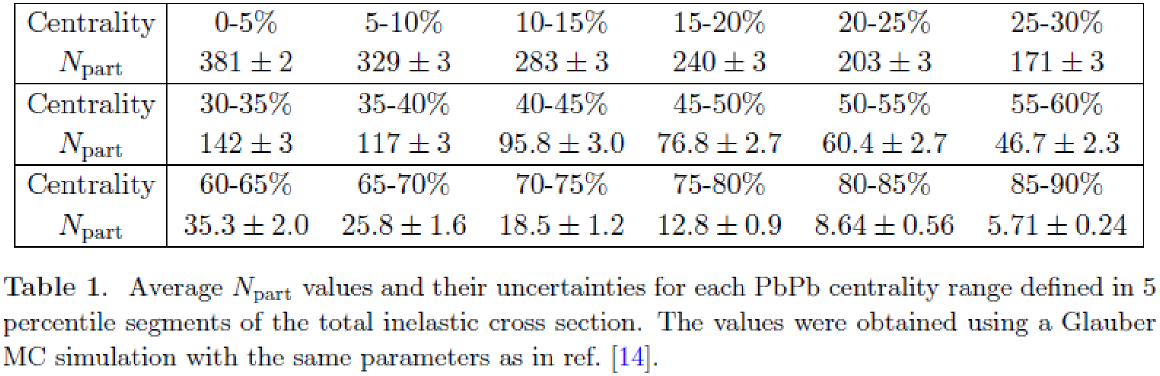
- A CMS example





Centrality	0-5%	5-10%	10-15%	15-20%	20-25%	25-30%
$N_{\rm part}$	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%
$N_{\rm part}$	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%
$N_{\rm part}$	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 $N_{\rm part}$ 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

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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 $<E_{kin}>\sim T$; thermodynamical “blast-wave” model of Schnedermann et al.

$$\frac{d\sigma}{m_{\mathrm{T}}\,dm_{\mathrm{T}}} \propto \int_0^R r\,dr\,m_{\mathrm{T}} I_0\left(\frac{p_{\mathrm{T}}\sinh\rho}{T_{\mathrm{fo}}}\right) K_1\left(\frac{m_{\mathrm{T}}\cosh\rho}{T_{\mathrm{fo}}}\right),$$

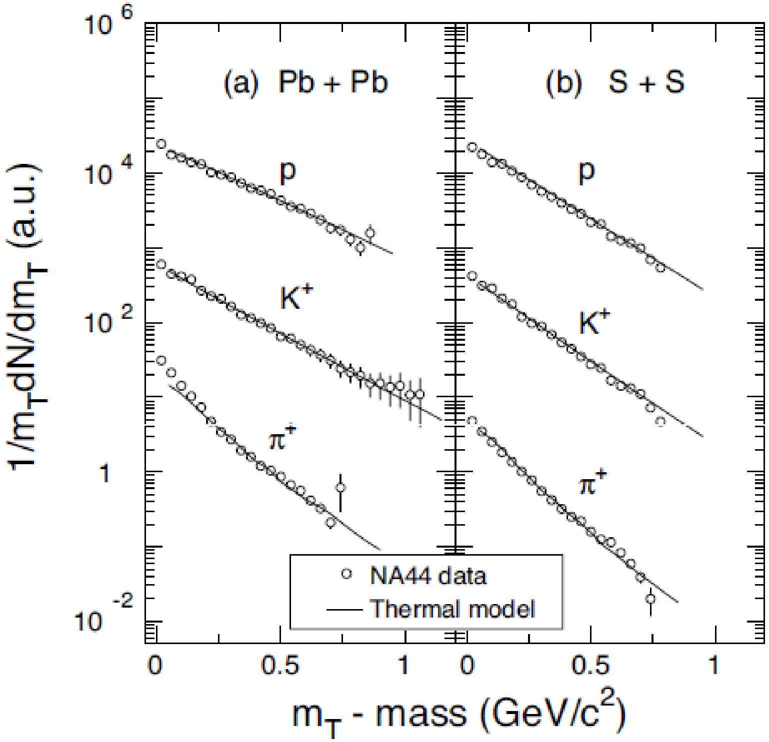
Freeze-out temperature

Mod. Bessel func.

Particle production

- 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.

Hadron multiplicities

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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

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

g_i - spin degeneracy

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

Baryon quant. number

Strangeness quant. number

Isospin "z-component" quant. number

Hadron multiplicities

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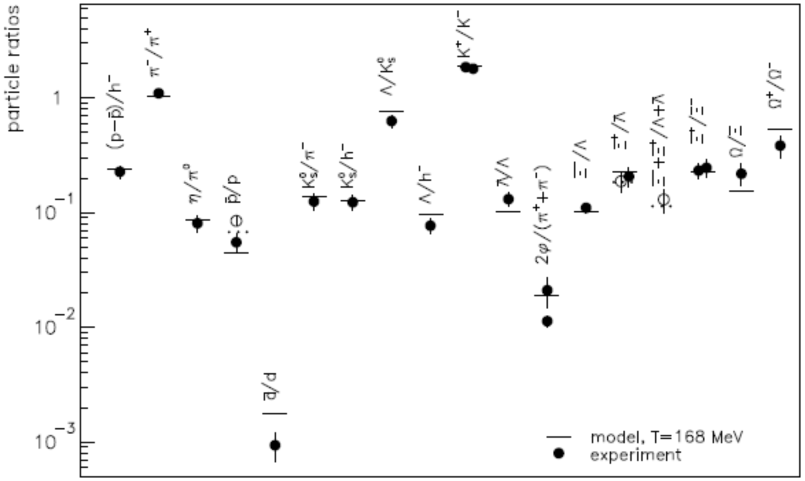
- With this model only two parameters are independent: the temperature T_{ch} and the baryon chemical potential μ_B . Data gives $T_{ch} \sim 170\ MeV \quad \mu_B \sim 270\ MeV$
- Chemical equilibrium seems to hold. Particle yield ratios are well described:



- **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

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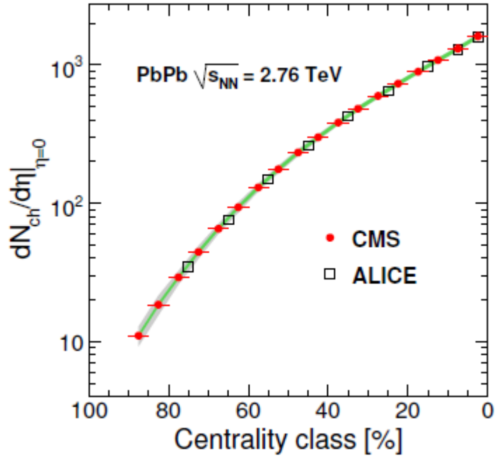
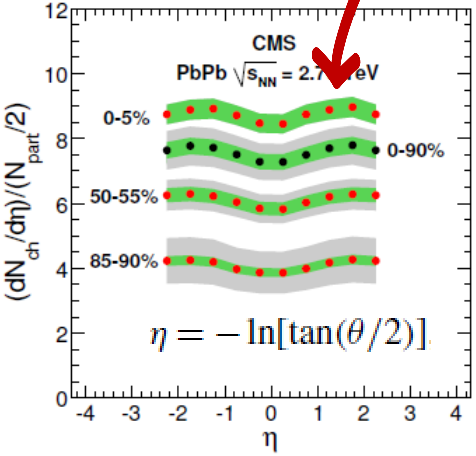
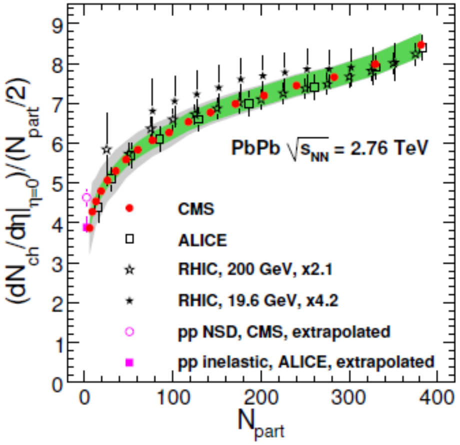
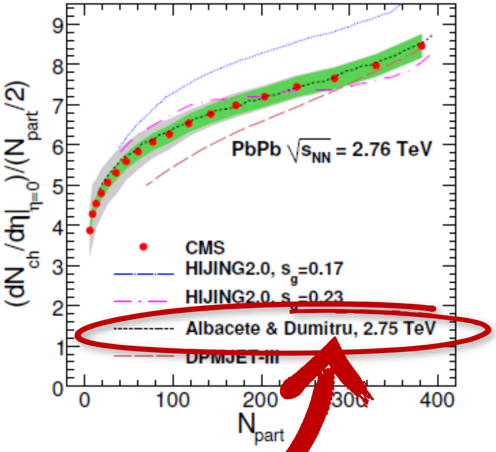
- **Particle distributions at LHC: the CMS case**

Bjorken









CGC

Hadron multiplicities

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

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

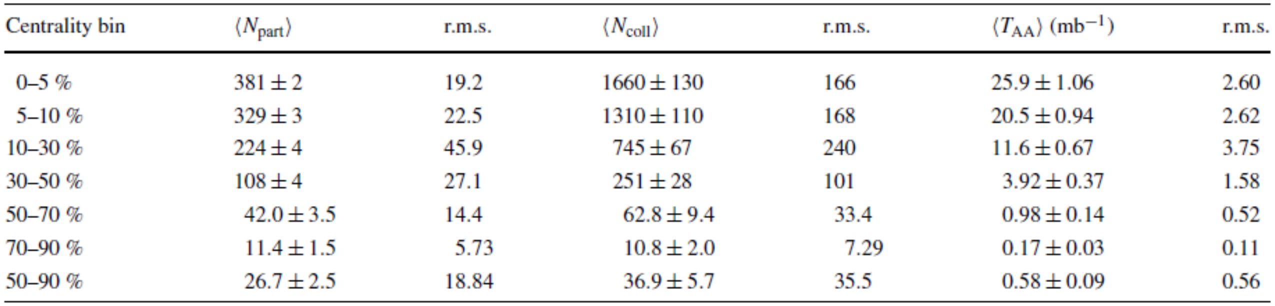
$$\frac{1}{\sigma^{AA}_{inel}}\frac{d\sigma^{AA}}{dyd^2p_T} = \frac{\langle N_{\rm coll}\rangle}{\sigma^{NN}_{inel}}\frac{d\sigma^{NN}}{dyd^2p_T}$$

$\Rightarrow$

$$R_{\rm AA}(p_{\rm T}) = \frac{{\rm d}^2N^{\rm AA}_{\rm ch}/{\rm d}p_{\rm T}\,{\rm d}\eta}{\langle T_{\rm AA}\rangle {\rm d}^2\sigma^{\rm pp}_{\rm ch}/{\rm d}p_{\rm T}\,{\rm d}\eta},$$

Departure from 1 indicates medium effects

$$R_{\rm CP}(p_{\rm T}) = \frac{({\rm d}^2N^{\rm AA}_{\rm ch}/{\rm d}p_{\rm T}\,{\rm d}\eta)/\langle T_{\rm AA}\rangle\ [\text{central}]}{({\rm d}^2N^{\rm AA}_{\rm ch}/{\rm d}p_{\rm T}\,{\rm d}\eta)/\langle T_{\rm AA}\rangle\ [\text{peripheral}]}.$$

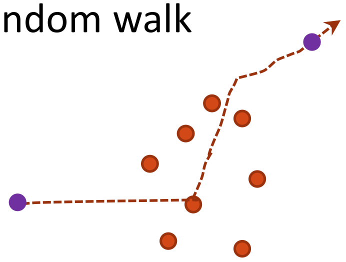


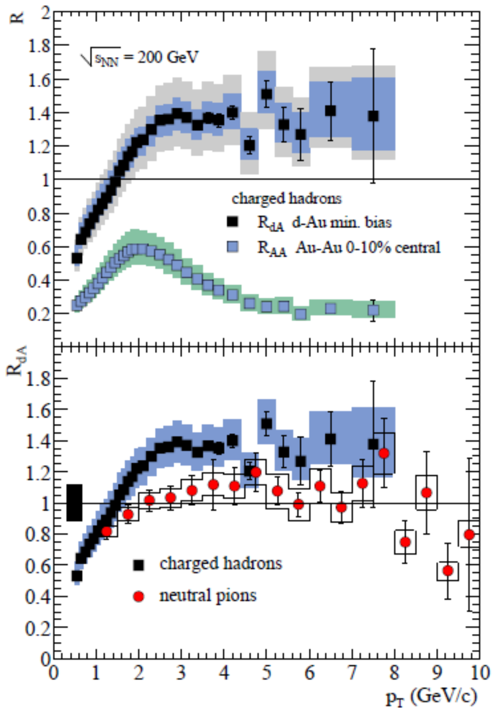
Centrality bin	$\langle N_{\rm part}\rangle$	r.m.s.	$\langle N_{\rm coll}\rangle$	r.m.s.	$\langle T_{\rm AA}\rangle$ (mb^{-1})	r.m.s.
0–5 %	381 ± 2	19.2	1660 ± 130	166	25.9 ± 1.06	2.60
5–10 %	329 ± 3	22.5	1310 ± 110	168	20.5 ± 0.94	2.62
10–30 %	224 ± 4	45.9	745 ± 67	240	11.6 ± 0.67	3.75
30–50 %	108 ± 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

- Introduction
- Observables
- Hard probes
- Prospects

- **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

- Introduction
- Observables
- Hard probes
- Prospects

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

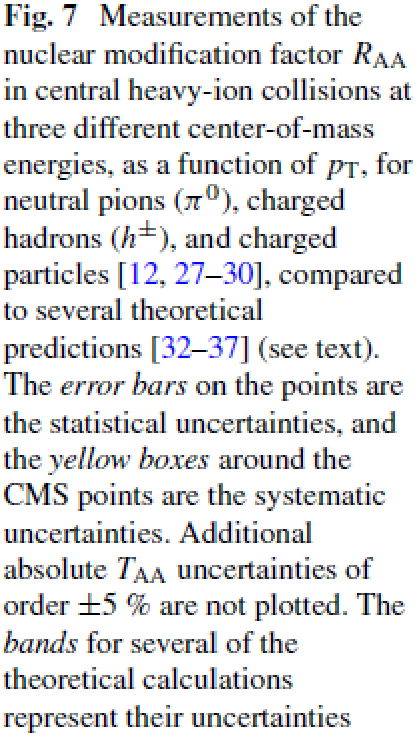
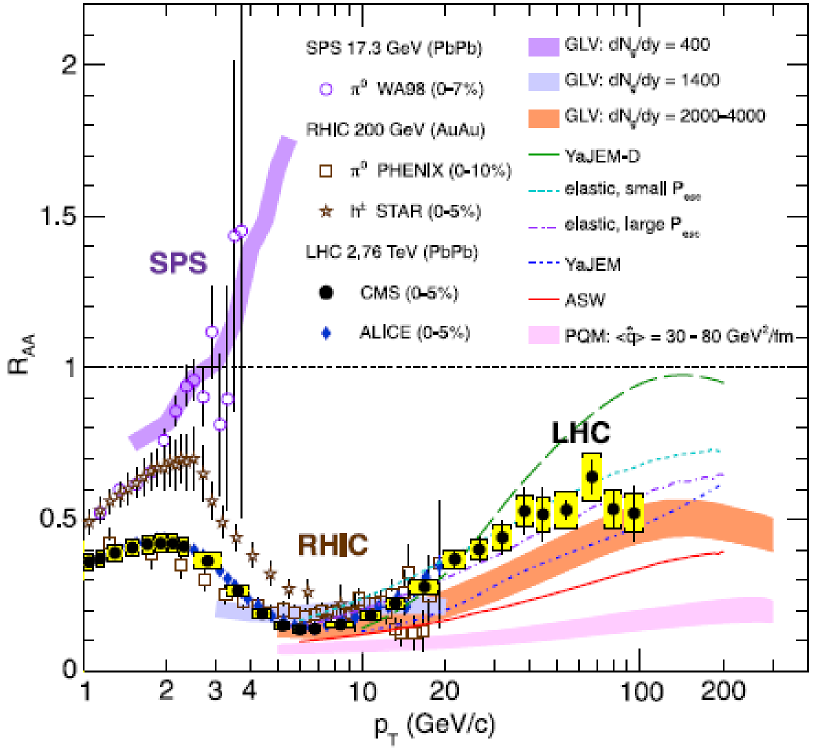


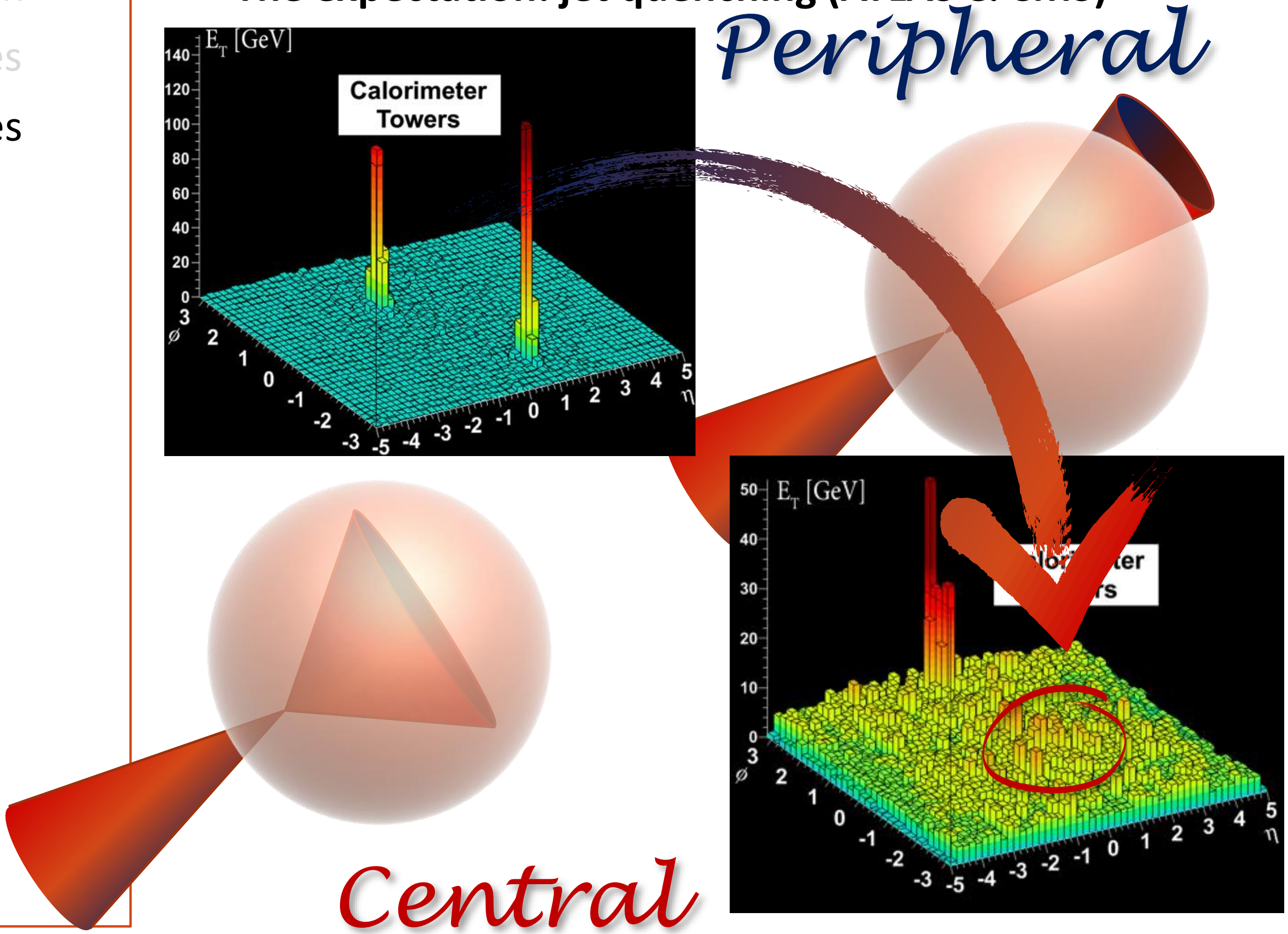
Fig. 7 Measurements of the nuclear modification factor R_{AA} in central heavy-ion collisions at three different center-of-mass energies, as a function of p_T, for neutral pions (π^0), charged hadrons ($h^{\pm}$), and charged particles [12, 27–30], compared to several theoretical predictions [32–37] (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 ±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)**



Hard probes

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

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

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
- Observables
- Hard probes
- Prospects

- This can be written in the form

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

- 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*→∞. 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 $\lambda_D \sim 0.18$ fm

The Satz-Matsui argument

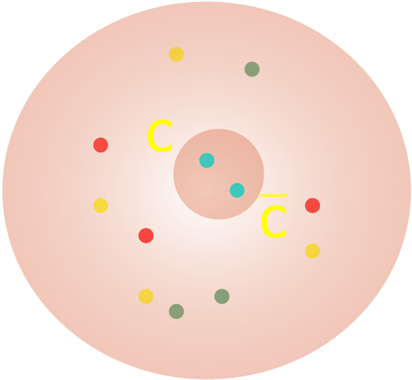
- For a $c\bar{c}$ system $\mu = 1.84$ GeV/2 and $\alpha_{eff} = 0.52$; the Bohr radius is 0.41 fm and thus this system ***can not be bound*** for *T*=200 MeV
- For a QGP α_{eff} decreases with *T*; at T=1.5T_c $\alpha_{eff} = 0.2$ which implies that the critical temperature ~130 MeV
- By the way, for a $s\bar{s}$ system the Bohr radius is 3.8 fm. Therefore this system cannot be bound in a QGP@*T*=200 MeV
- The J/Ψ or Υ are not suppressed at hadronization, which makes them excellent probes. What to expect:

- At *T=0 (no QGP)* the J/Ψ or Υ should be normally produced
- At $T>T_c$ *(QGP)* these states should be **suppressed**

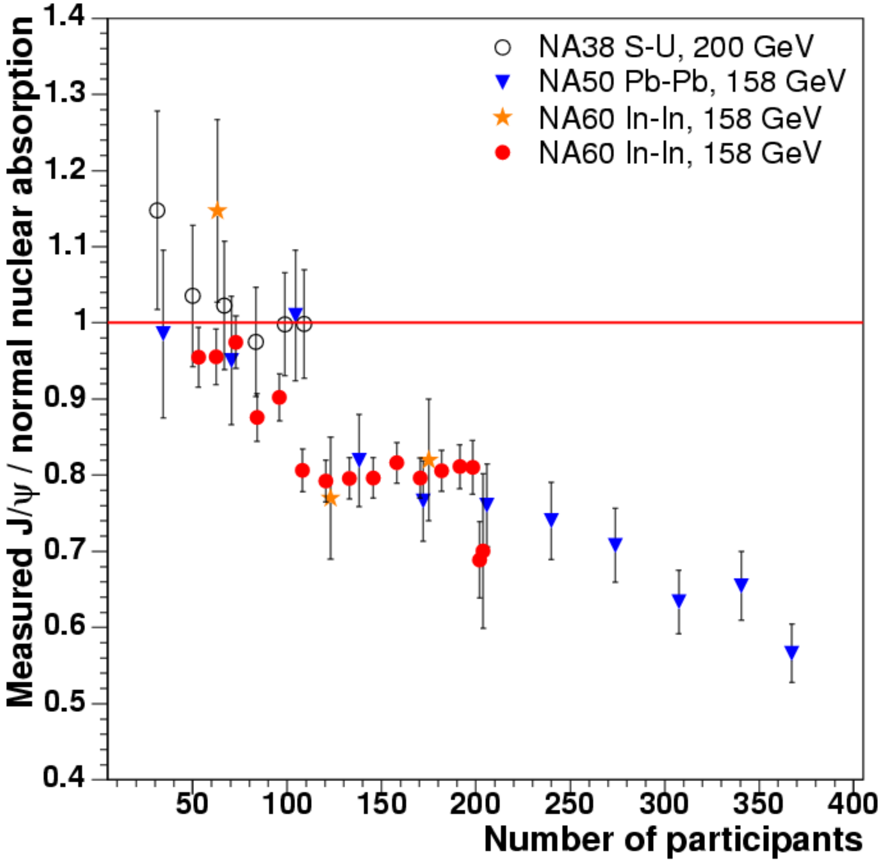
- This should affect also (and probably mostly) the excited states

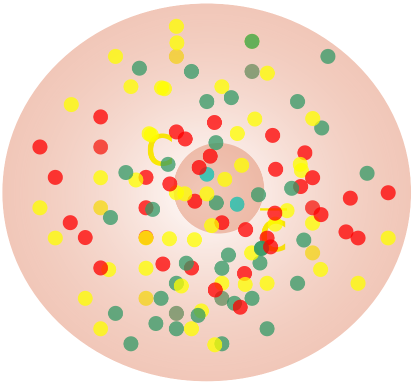
Hard probes

- At SPS:



J/Ψ





Hard probes

- Introduction
- Observables
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- Prospects

- At LHC: the J/Ψ CMS example. The baseline

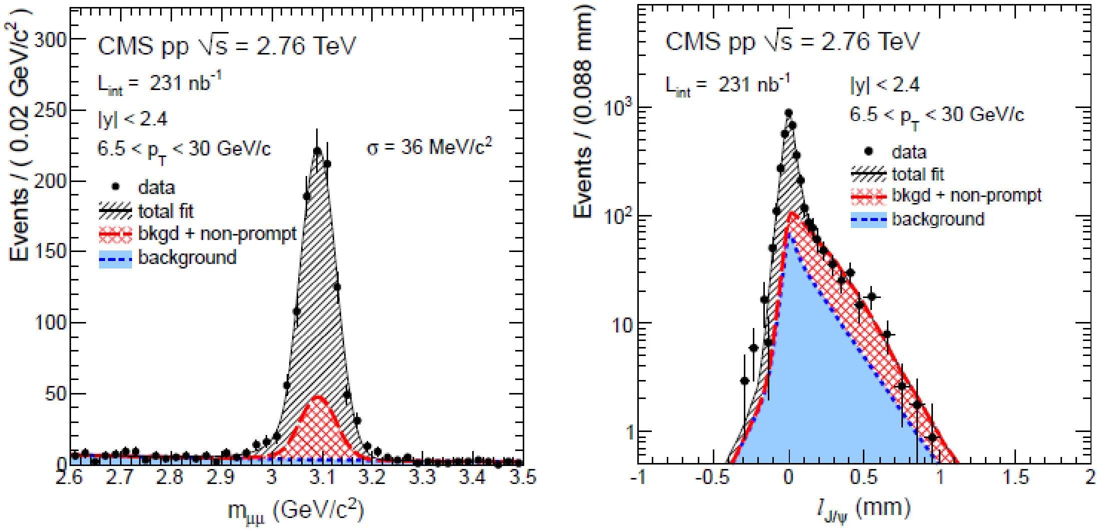
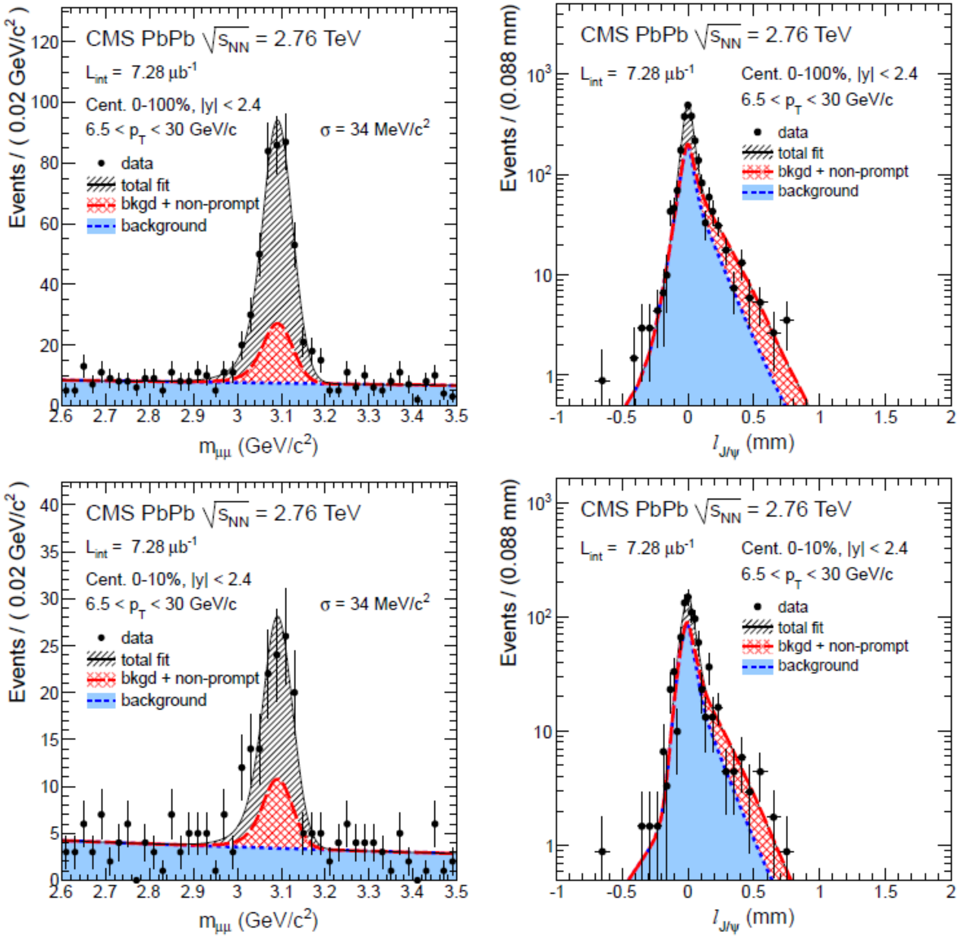


Figure 8: Non-prompt J/ψ signal extraction for pp collisions at $\sqrt{s} = 2.76$ TeV: dimuon invariant mass fit (left) and pseudo-proper decay length fit (right).

Hard probes

- Introduction
- Observables
- Hard probes
- Prospects

- At LHC: the J/Ψ CMS example



Hard probes

- Introduction
- Observables
- Hard probes
- Prospects

- At LHC: the J/Ψ CMS example

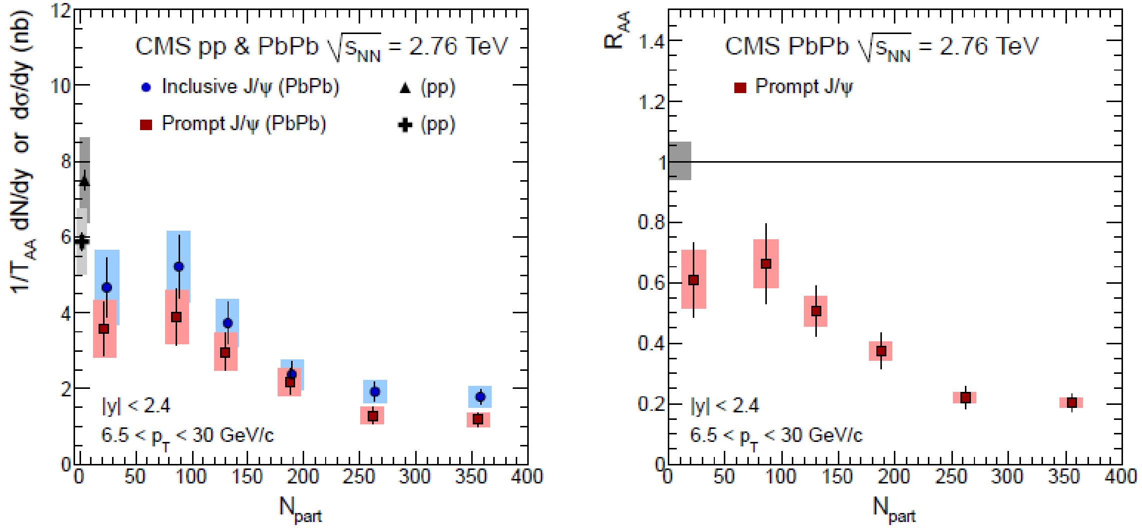


Figure 12: Left: yield of inclusive J/ψ (blue circles) and prompt J/ψ (red squares) divided by T_{AA} as a function of N_{part}. The results are compared to the cross sections of inclusive J/ψ (black triangle) and prompt J/ψ (black cross) measured in pp. The inclusive J/ψ points are shifted by $\Delta N_{\text{part}} = 2$ 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
- Hard probes
- Prospects

- At LHC: the Y CMS example

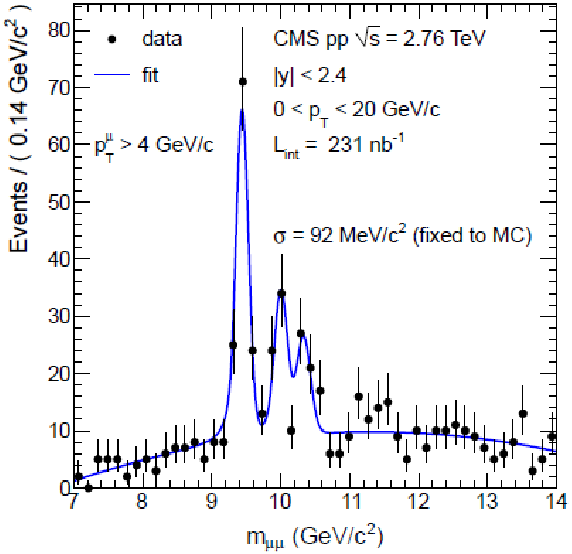
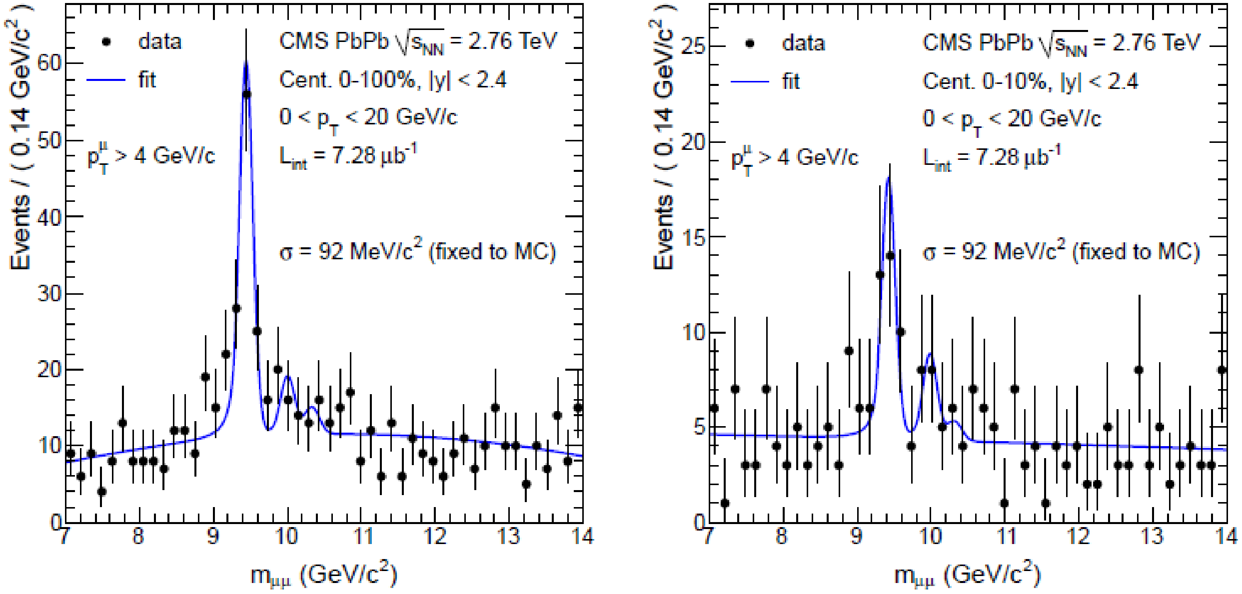


Figure 9: The pp dimuon invariant-mass distribution in the range $p_T < 20\,\mathrm{GeV}/c$ for $|y| < 2.4$ and the result of the fit to the Υ resonances.

Hard probes

- Introduction
- Observables
- Hard probes
- Prospects

- At LHC: The Υ CMS example



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/*y* 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/*y* 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/*y* 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 ~50% for Y(1S) with pT > 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.

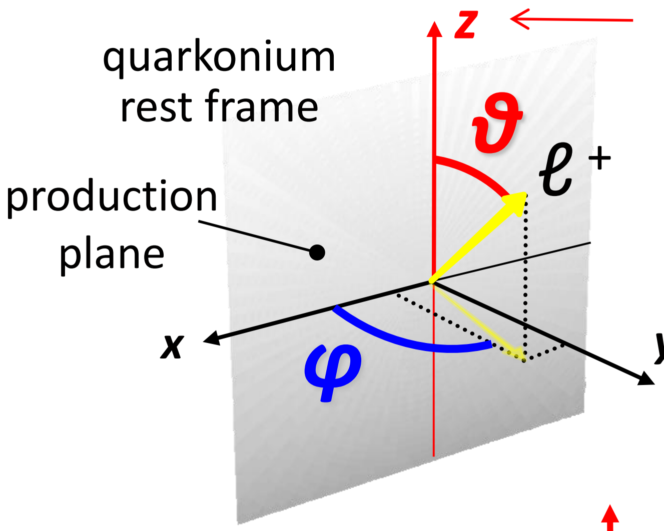
What about feed-down?

- 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

- 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): ≈ dir. of colliding partons

Helicity axis (HX): dir. of quarkonium momentum

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

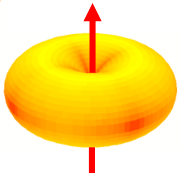
$\lambda_\vartheta = +1$

$\lambda_\varphi = \lambda_{\vartheta\varphi} = 0$

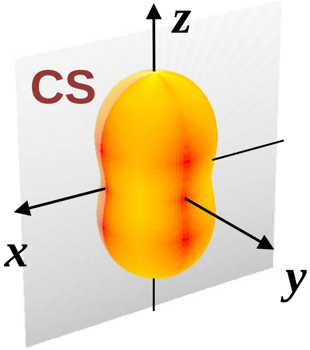
$J_z = \pm 1$ → $\lambda_\vartheta = +1$: **"transverse"** (= photon-like) pol.

$\lambda_\vartheta = -1$

$\lambda_\varphi = \lambda_{\vartheta\varphi} = 0$



$J_z = 0$ → $\lambda_\vartheta = -1$: **"longitudinal"** pol.



CS ⊥ HX for mid rap. / high p_T

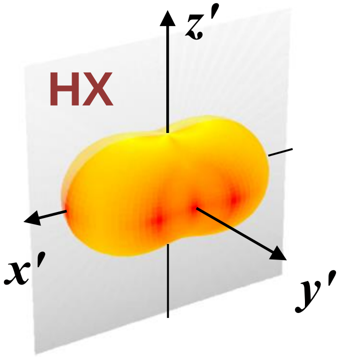
$\lambda_\vartheta = +1$

$\lambda_\varphi = 0$

90º

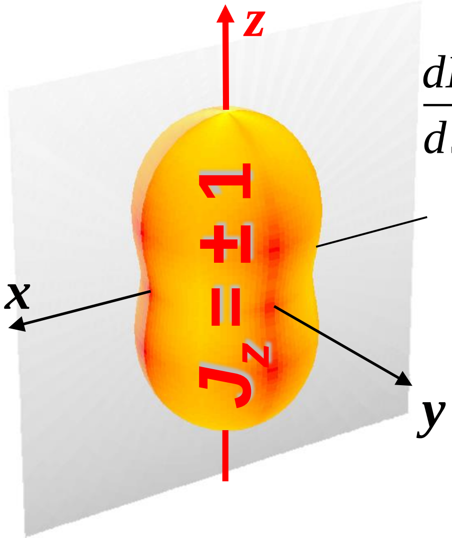
$\lambda_\vartheta = -1/3$

$\lambda_\varphi = +1/3$



The azimuthal anisotropy is not a detail

Case 1: natural transverse polarization

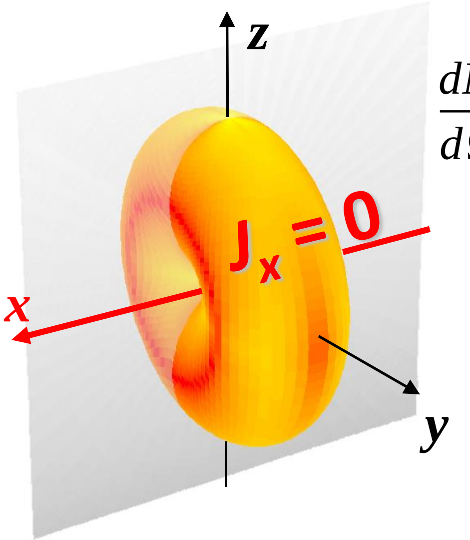


$$\frac{dN}{d\Omega} \propto 1 + \cos^2\theta$$

$\lambda_\vartheta = +1$

$\lambda_\varphi = 0$

Case 2: natural longitudinal polarization, observation frame ⊥ to the natural one



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

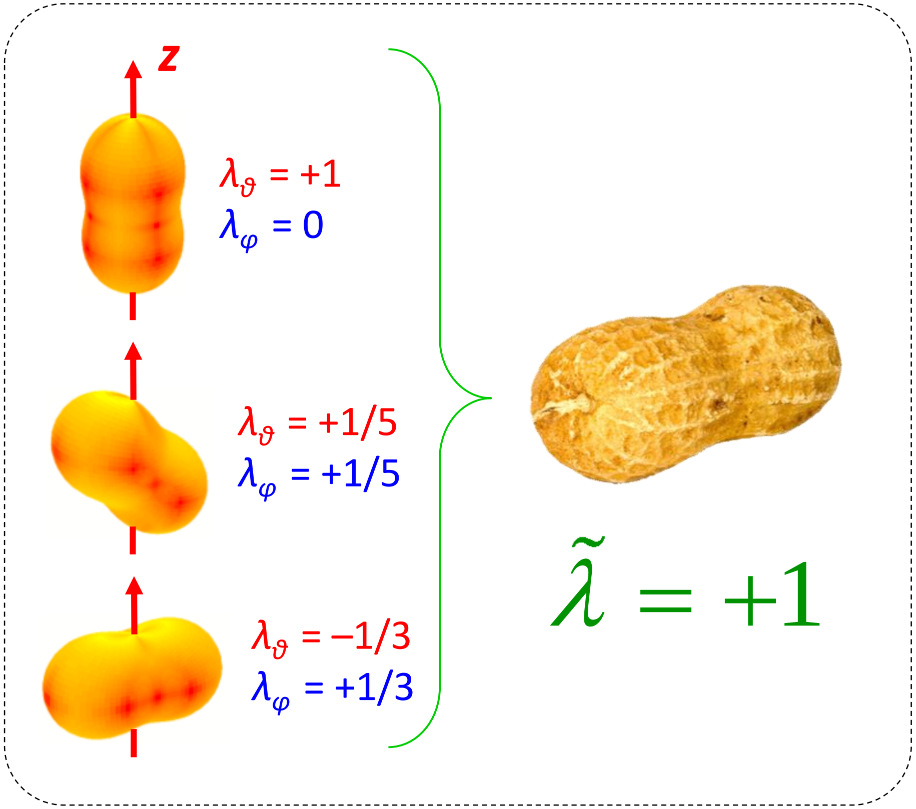
$\lambda_\vartheta = +1$

$\lambda_\varphi = -1$

- 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. $\tilde{\lambda} = \frac{\lambda_\vartheta + 3\lambda_\varphi}{1 - \lambda_\varphi}$

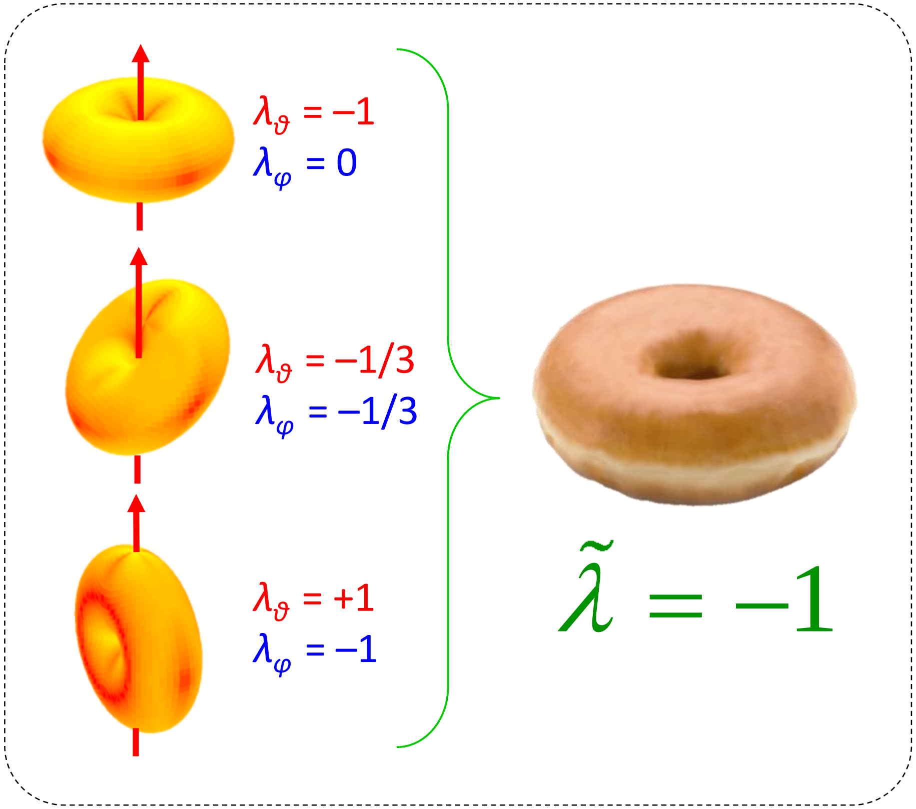


$\lambda_\vartheta = +1$
$\lambda_\varphi = 0$

$\lambda_\vartheta = +1/5$
$\lambda_\varphi = +1/5$

$\lambda_\vartheta = -1/3$
$\lambda_\varphi = +1/3$

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



$\lambda_\vartheta = -1$
$\lambda_\varphi = 0$

$\lambda_\vartheta = -1/3$
$\lambda_\varphi = -1/3$

$\lambda_\vartheta = +1$
$\lambda_\varphi = -1$

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

FLSW, PRL 105, 061601; PRD 82, 096002; PRD 83, 056008

…and a series of questions to answer

- Is there a simple composition of processes, probably dominated by one single mechanism, that is responsible for the production of all quarkonia?

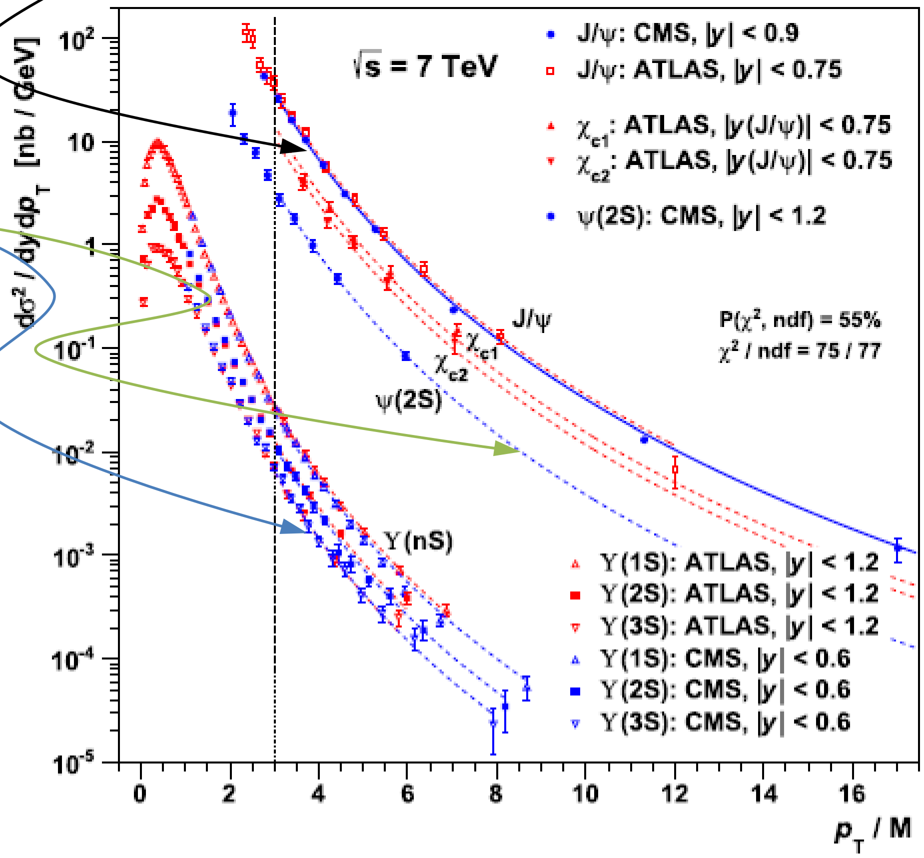
Solid curve is a fit to the *J/ψ* CMS data ($p_T/M>3$)

Remaining curves are replicas with normalizations adjusted to the individual datasets

$$f\left(\frac{p_T}{M}\right) = \left(1 + \frac{1}{\beta - 2} \cdot \frac{\left(\frac{p_T}{M}\right)^2}{\gamma}\right)^{-\beta}$$

$$\beta = 3.62 \pm 0.07$$
$$\gamma = 1.29 \pm 0.32$$

P. Faccioli *et al, PLB 736(2014) 98*



…and a series of questions to answer

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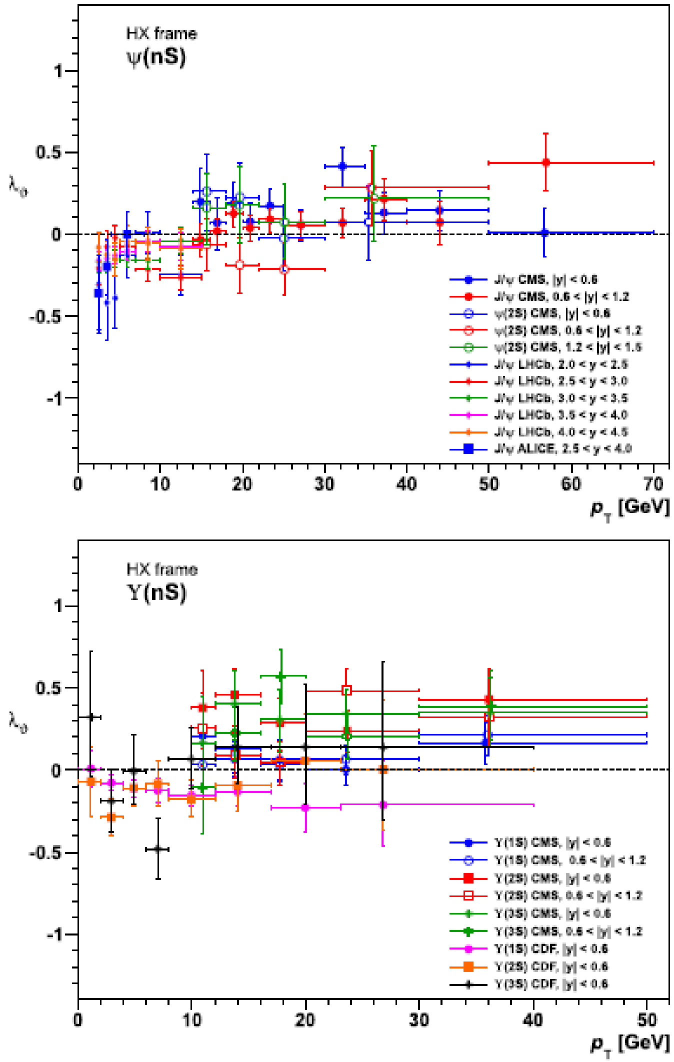
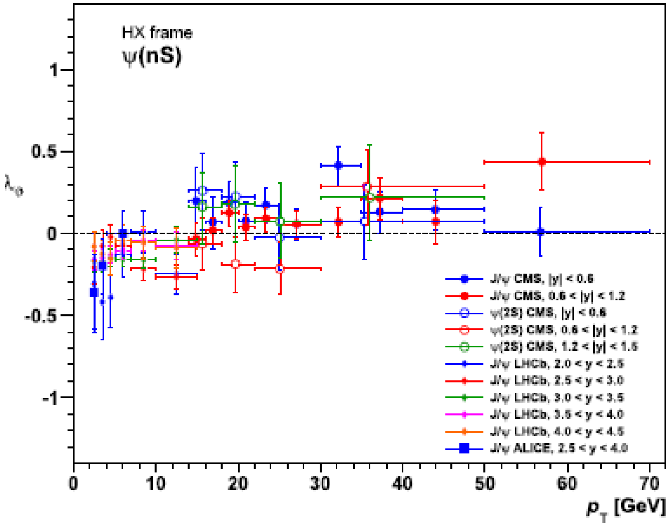
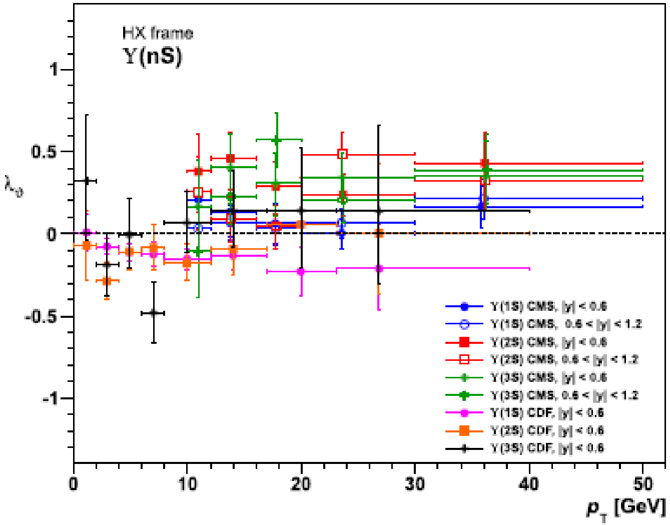


P. Faccioli *et al, PLB 736(2014) 98*

…and a series of questions to answer

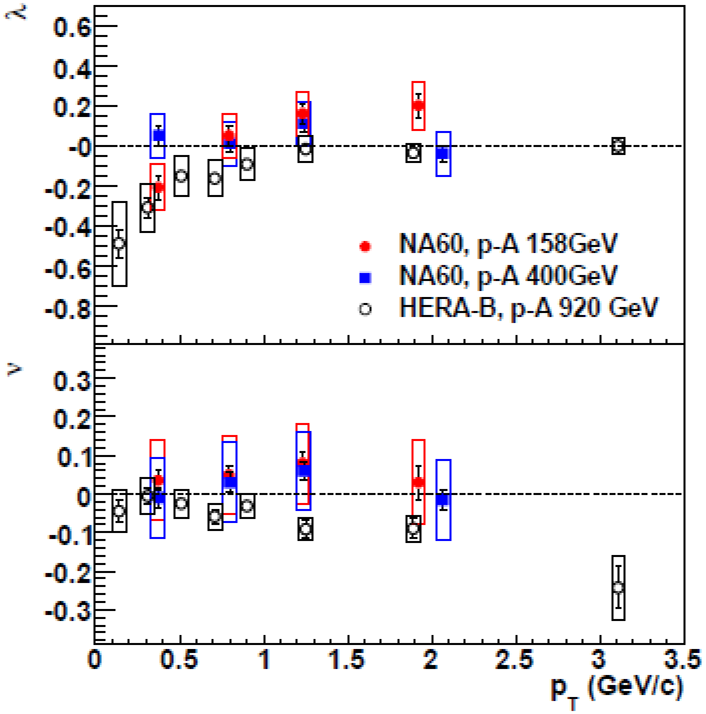
- **Is this mechanism perturbed in the presence of matter at high density and high temperature?**

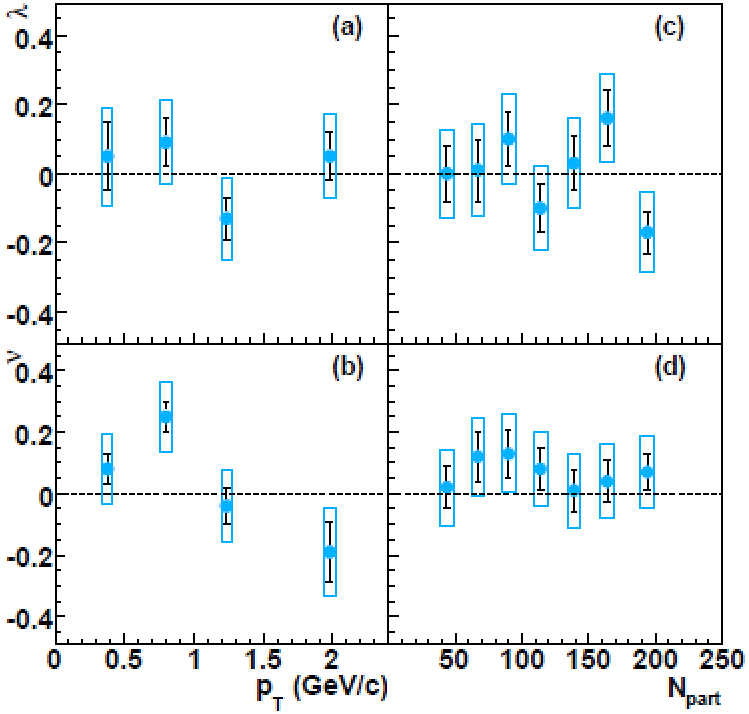




Pioneering measurements at SPS: NA60

- λ_θ and λ_φ measured (p-A); HX and CS frames used.

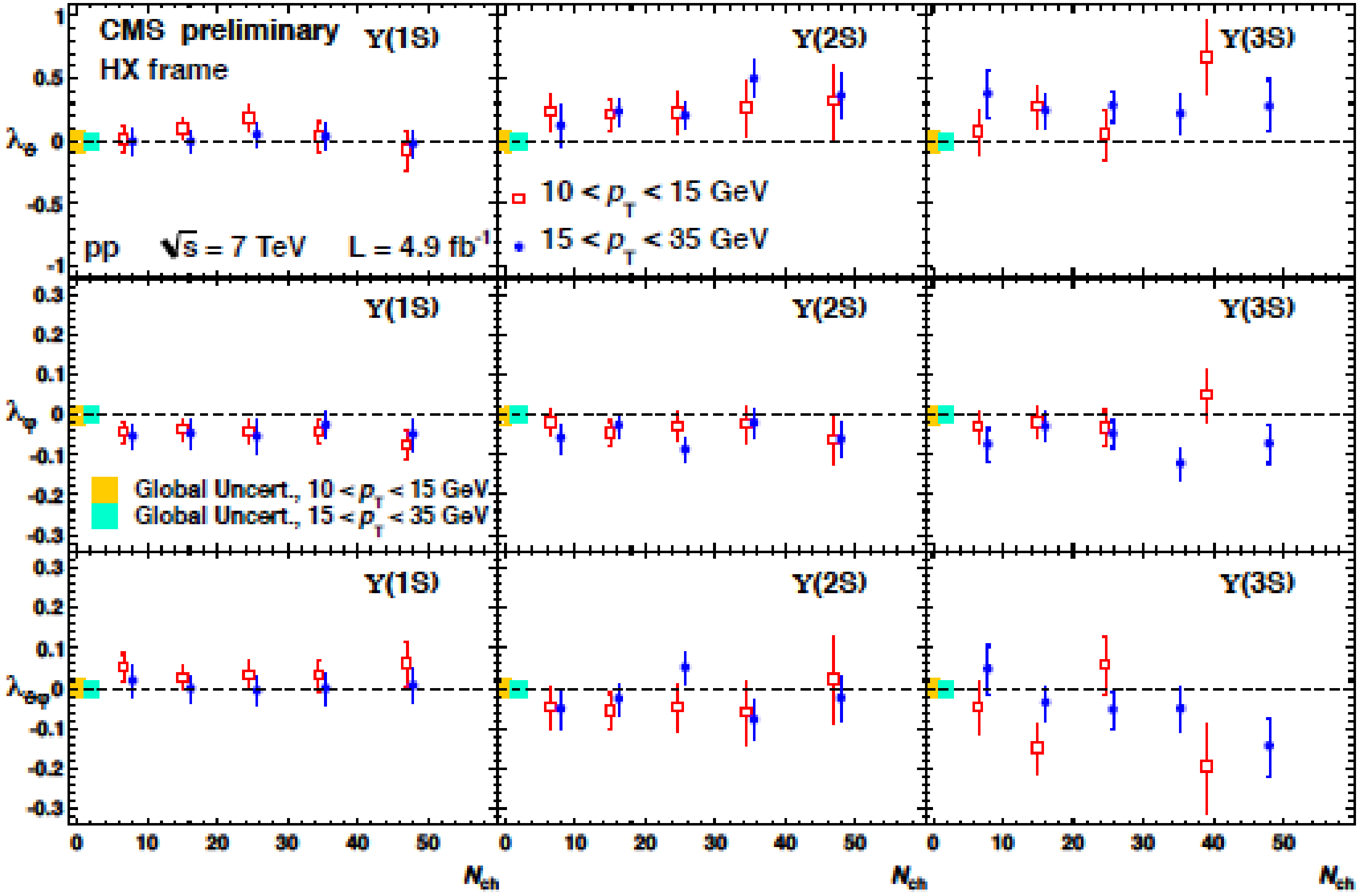




http://arxiv.org/abs/0907.5004
http://arxiv.org/abs/0907.3682

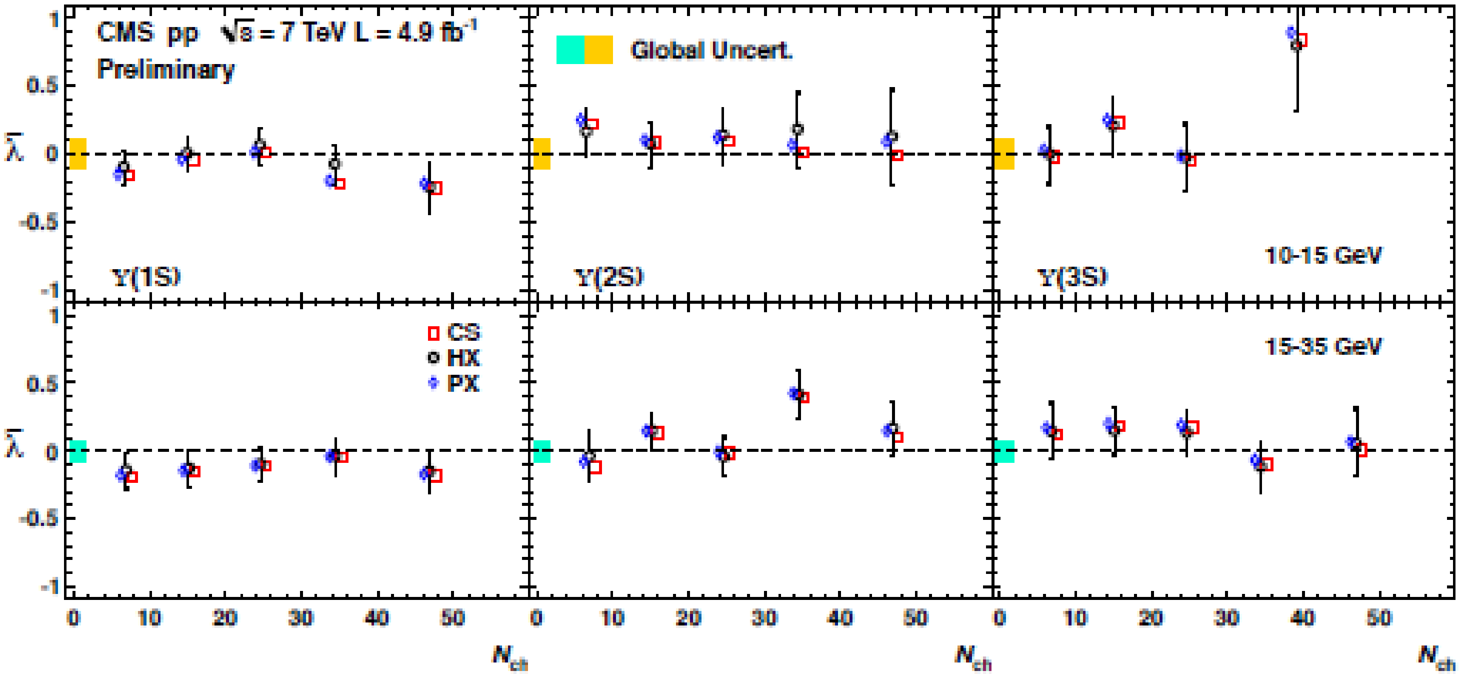
A first step in this program at LHC: polarization as a function of multiplicity

CMS p-p



A first step in this program: polarization as a function of multiplicity

CMS p-p



Summary

- The new quarkonium polarization measurements have many improvements with respect to previous analyses and shed, when combined with cross-section data, a new light on quarkonium production

  Will we (finally) manage to solve an old puzzle?

- General advice: do not throw away physical information!
  (azimuthal-angle distribution, rapidity dependence, ...)

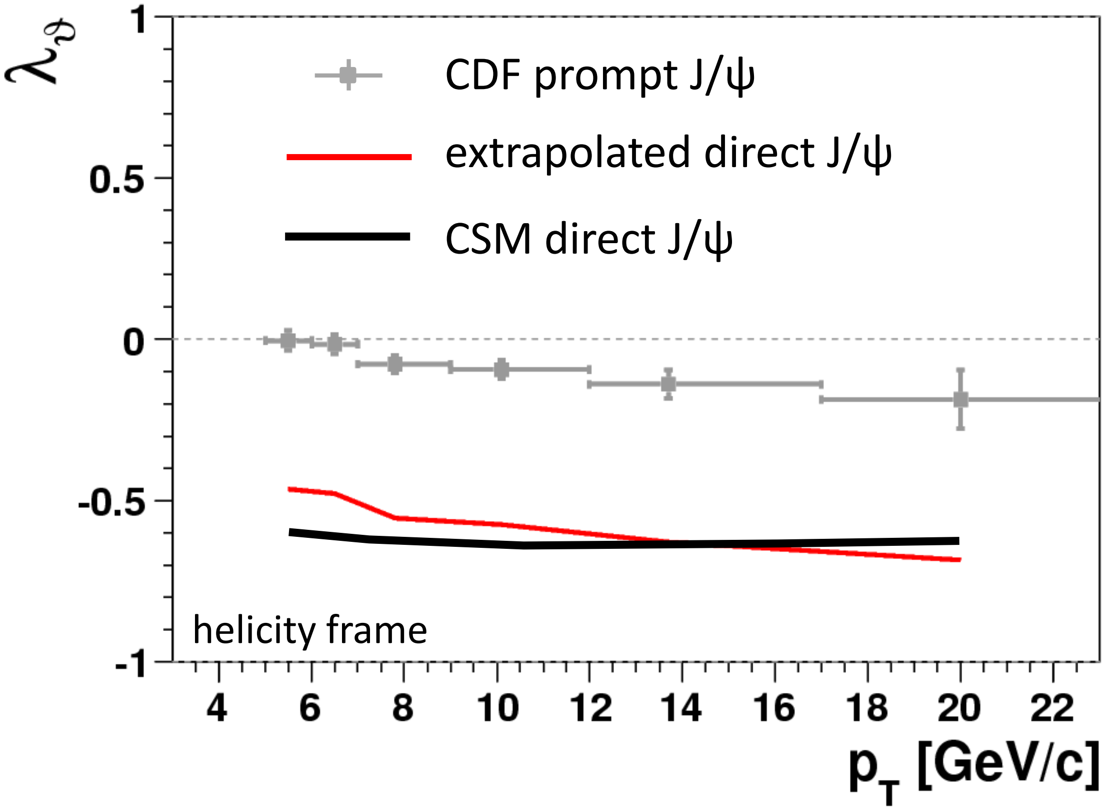
- A new method based on rotation-invariant observables gives several advantages in the measurement of decay distributions and in the use of polarization information

- Quarkonium polarization could be used to probe hot and dense matter. A complete program is under way.

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**



CDF data

$R(\chi_{c1})+R(\chi_{c2})$ = 30 ± 6 %

$R(\chi_{c2})/R(\chi_{c1})$ = 40 ± 2 %

taking

using the values

$R(\chi_{c1})+R(\chi_{c2})$ = 42 % (+2σ)

$R(\chi_{c2})/R(\chi_{c1})$ = 38 % (-1σ)

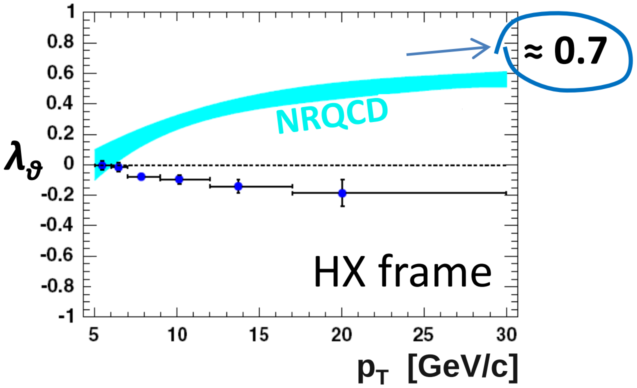
the CSM prediction of direct-J/ψ polarization agrees very well with the CDF data *in the scenario* *h*(χ_{c1}) = 0 and *h*(χ_{c2}) = ±2

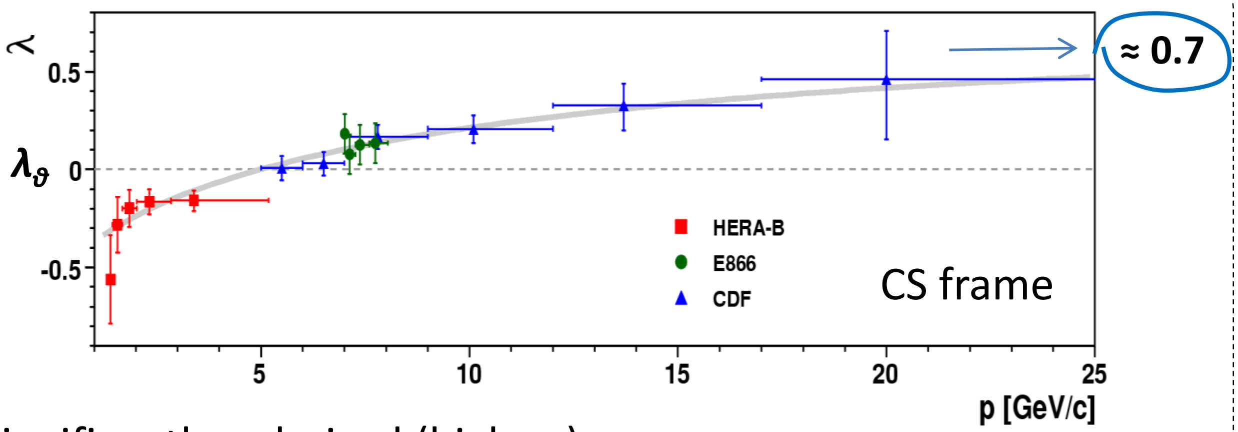
0 ±1

0 ±2

χ_c measurements are crucial !

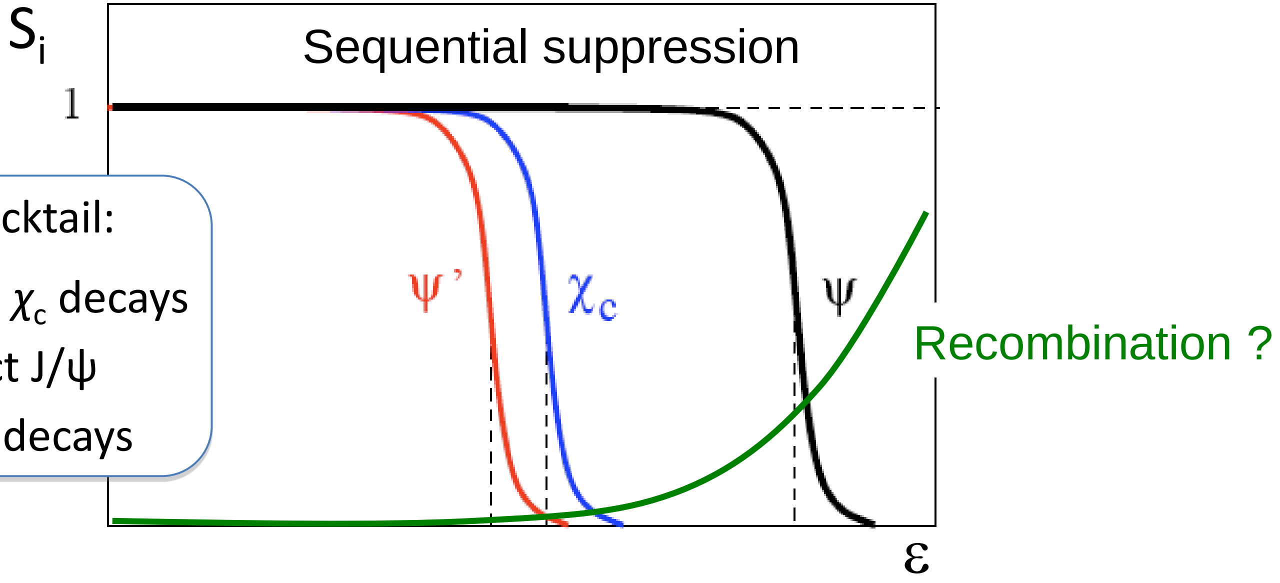
J/ψ polarization as a signal of colour deconfinement?





Starting "pp" scenario:

- J/ψ significantly polarized (high p_T)
- feeddown from χ_c states (≈ 30%) smears the polarizations



J/ψ cocktail:

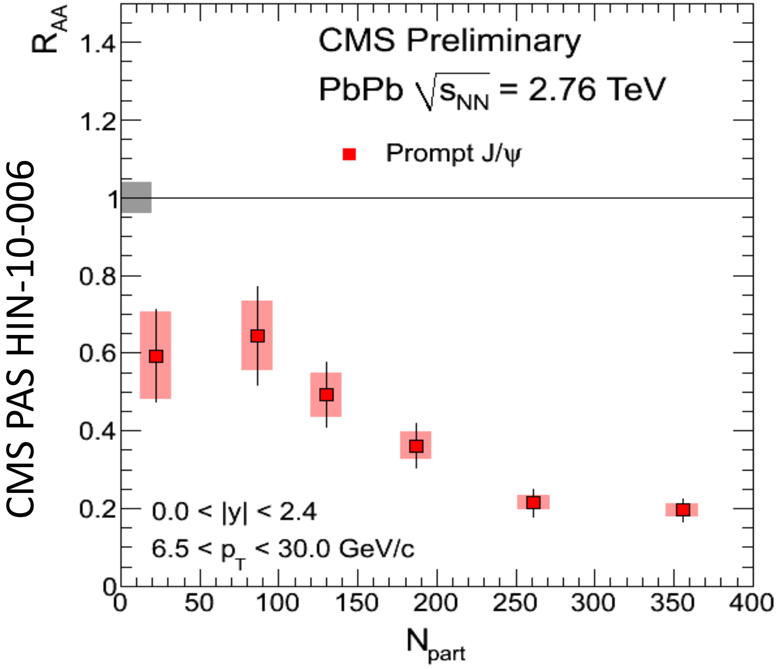
≈ 30% from χ_c decays

≈ 70% direct J/ψ

+ ψ' decays

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

J/ψ polarization as a signal of sequential suppression?



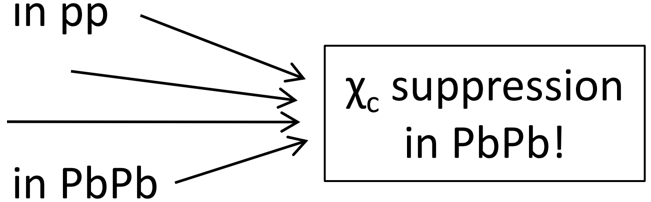
CMS data:

- 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!



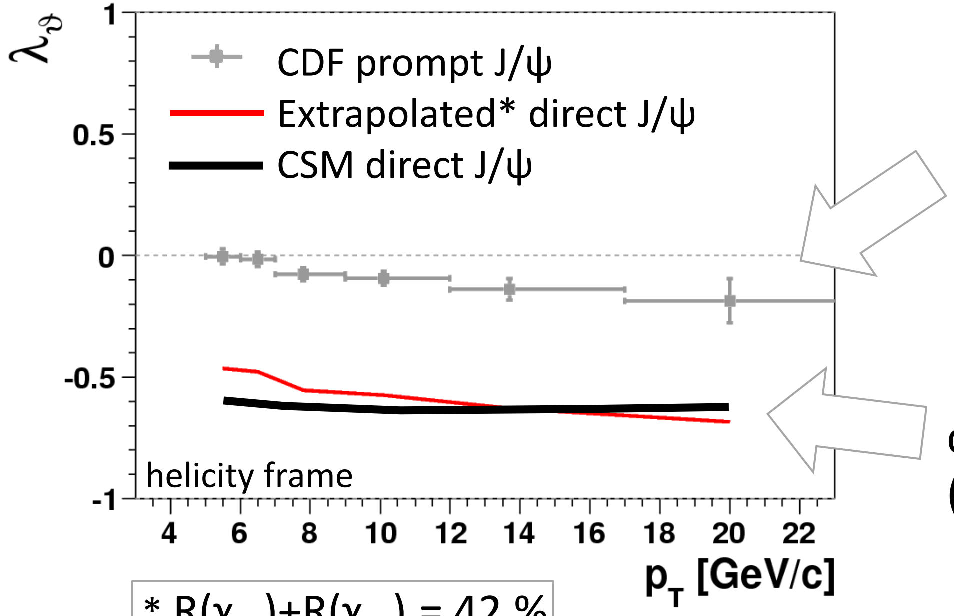
Reasonable timeline of measurements:

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:



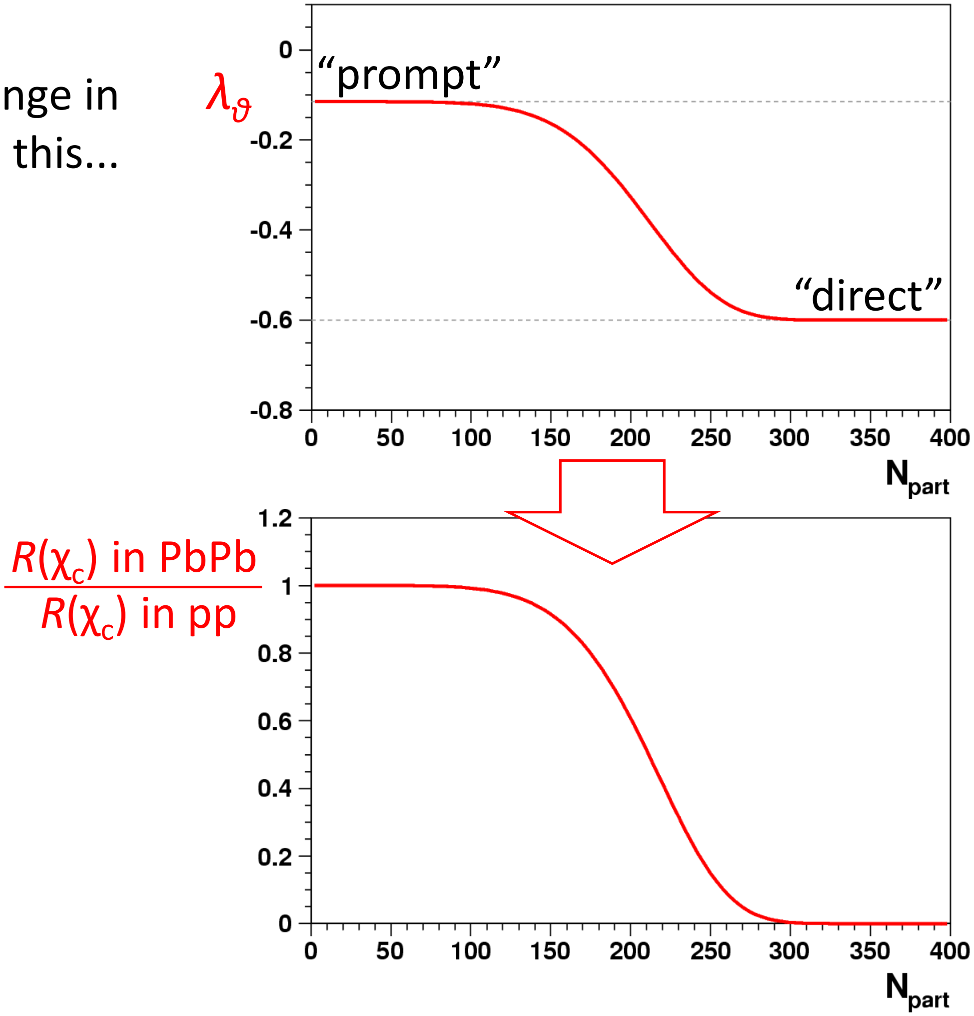
prompt-J/ψ polarization in pp: $\lambda_\vartheta \cong -0.15$

direct-J/ψ polarization: $\lambda_\vartheta \cong -0.6$
(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

Simplifying assumptions:

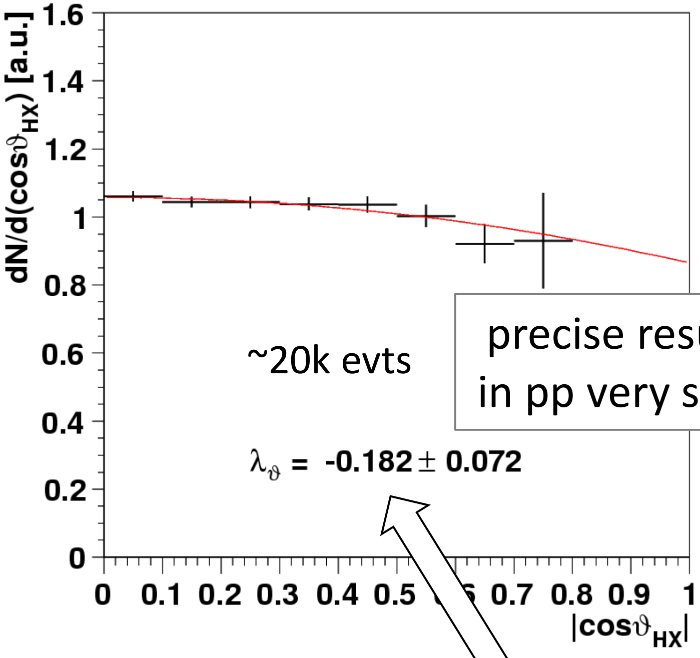
- direct-J/ψ polarization is the same in pp and PbPb
- *normal* nuclear effects affect J/ψ and χ_c in similar ways
- χ_{c1} and χ_{c2} are equally suppressed in PbPb

J/ψ polarization as a signal of sequential suppression?

When will we be sensitive to an effect like this?

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

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



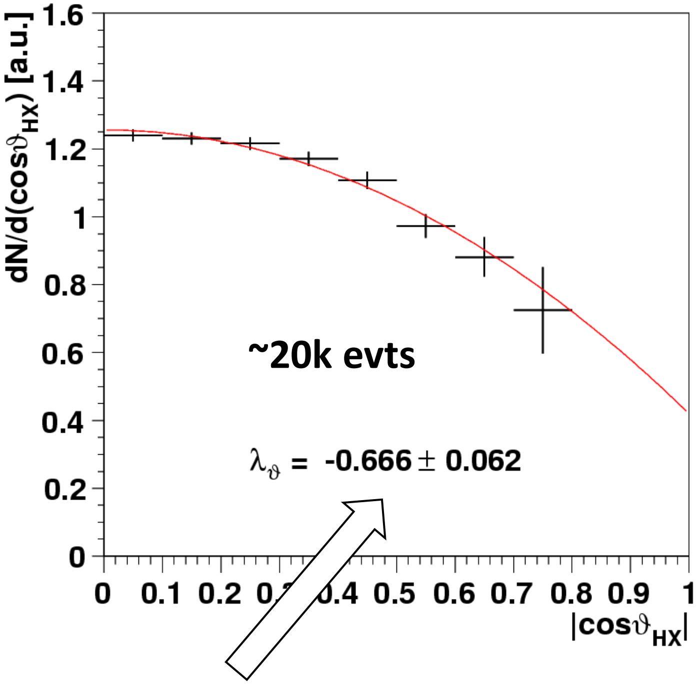
~20k evts

λ_ϑ = -0.182 ± 0.072

precise results
in pp very soon

efficiency-
corrected
|cosϑ_{HX}|
distribution

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



~20k evts

λ_ϑ = -0.666 ± 0.062

In this scenario, the χ_c disappearance is measurable at ~5σ level with ~20k J/ψ's in central Pb-Pb collisions

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**