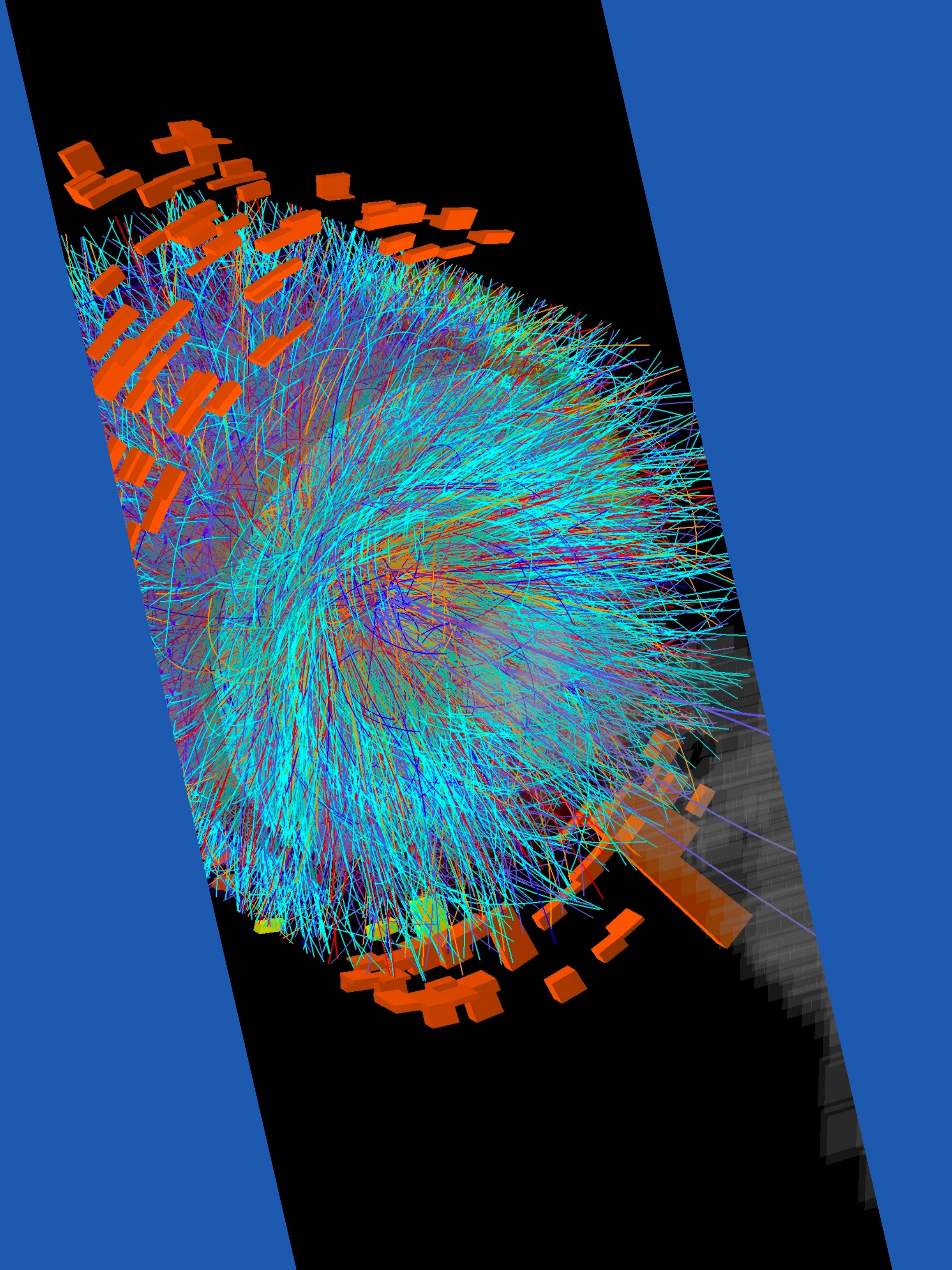
CERN Summer Student Lectures 2022

Heavy Ions 2/3

Francesca Bellini
University and INFN, Bologna, Italy
Contact: francesca.bellini@cern.ch



Production and characterization of the QGP at the LHC

Rapidity distributions in HI collisions

Before the collision: beams with given rapidity

E.g. at RHIC:

- p_{BEAM} = 100 GeV/c per nucleon
- $E_{BEAM} = \sqrt{(m_p^2+p_{BEAM}^2)}$ = 100.0044 per nucleon
- β = 0.999956, $\gamma_{BEAM} \approx 100$
- $y_{BEAM1} = -y_{BEAM2} = 5.36 \rightarrow \Delta y = 10.8$

After the collision, 2 possible scenarios

1. **Nuclei stopping**
   – For $\sqrt{s_{NN}}$ ~ 5 -10 GeV (AGS,…)

2. **Transparency**
   – For $\sqrt{s_{NN}}$ > 100 GeV (RHIC, **LHC**)
   – nuclei slow down to lower γ and y
   – particles are produced with a ‘’plateau’’ at midrapidity

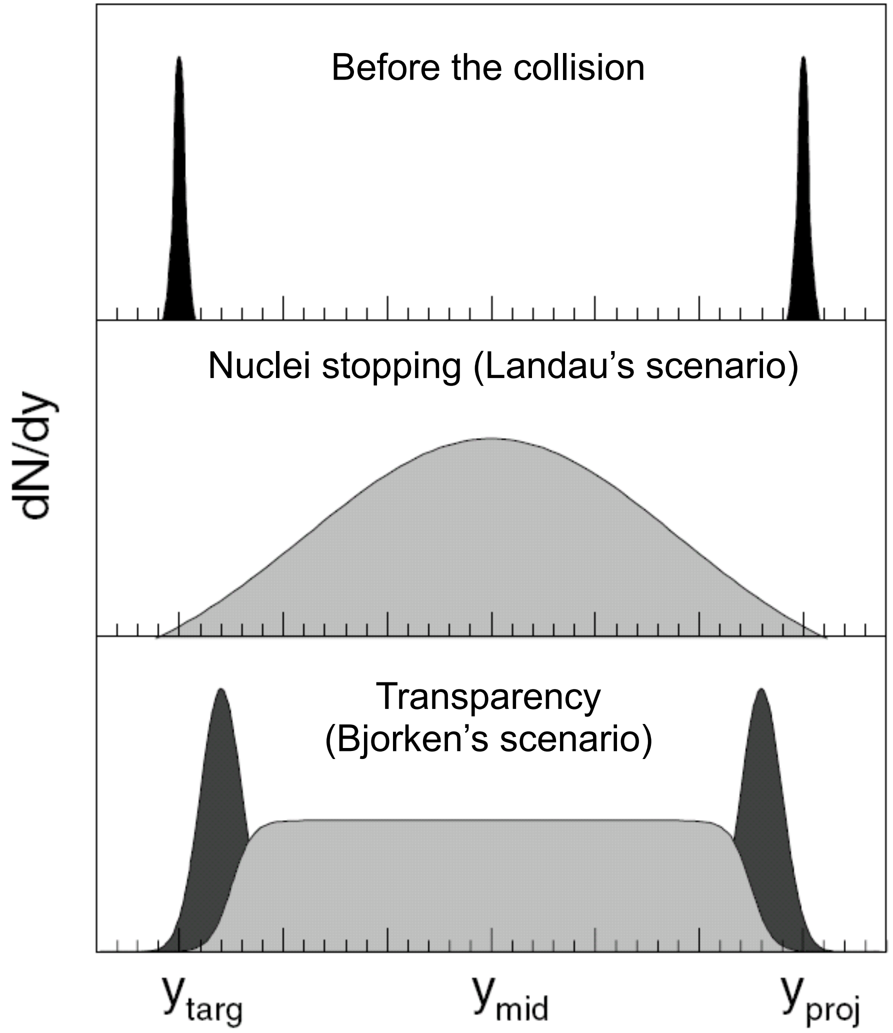
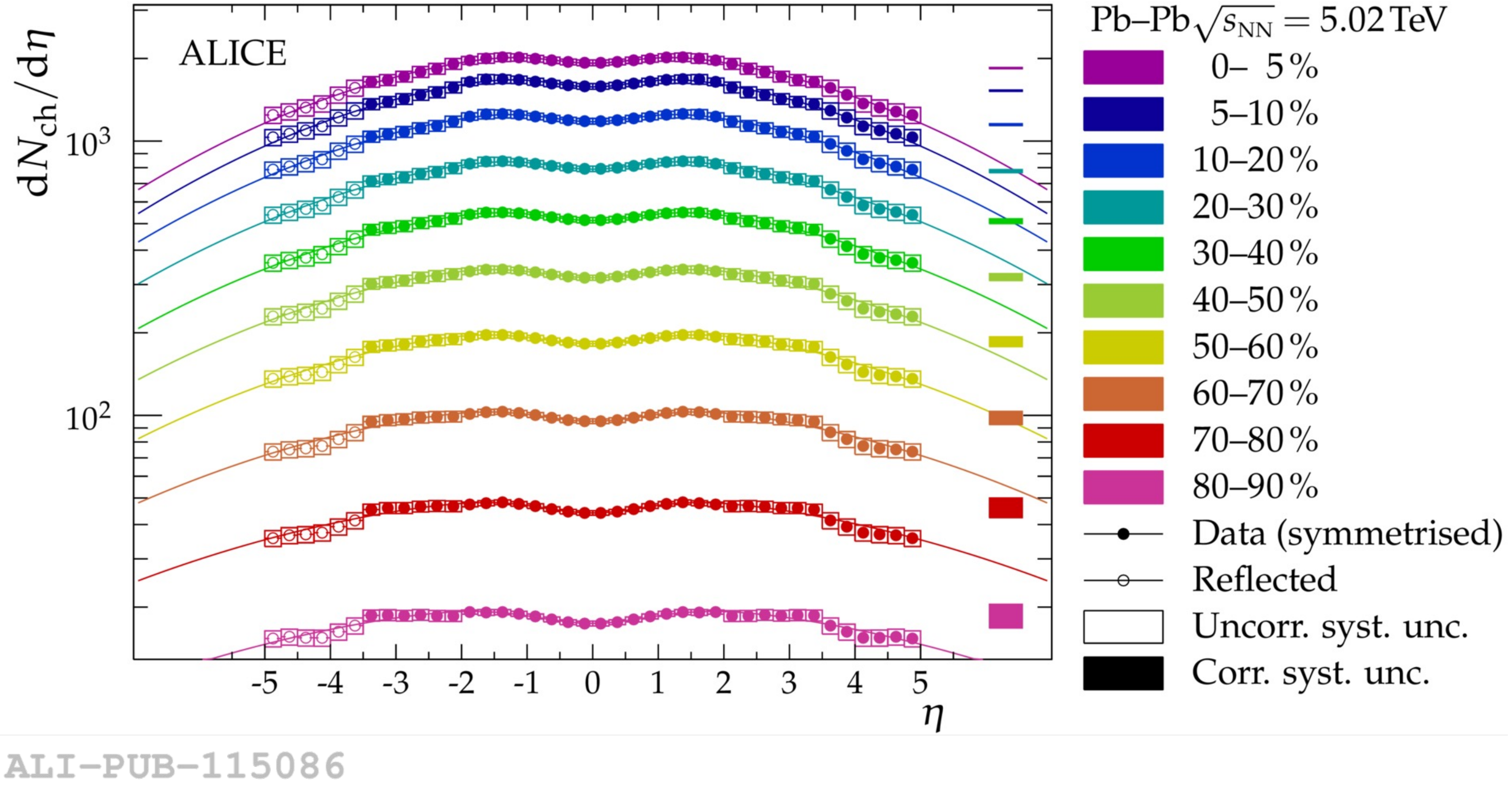


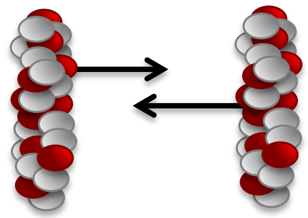
Figure from K. Reygers

Charged particle multiplicity vs centrality

Charged particle pseudorapidity density

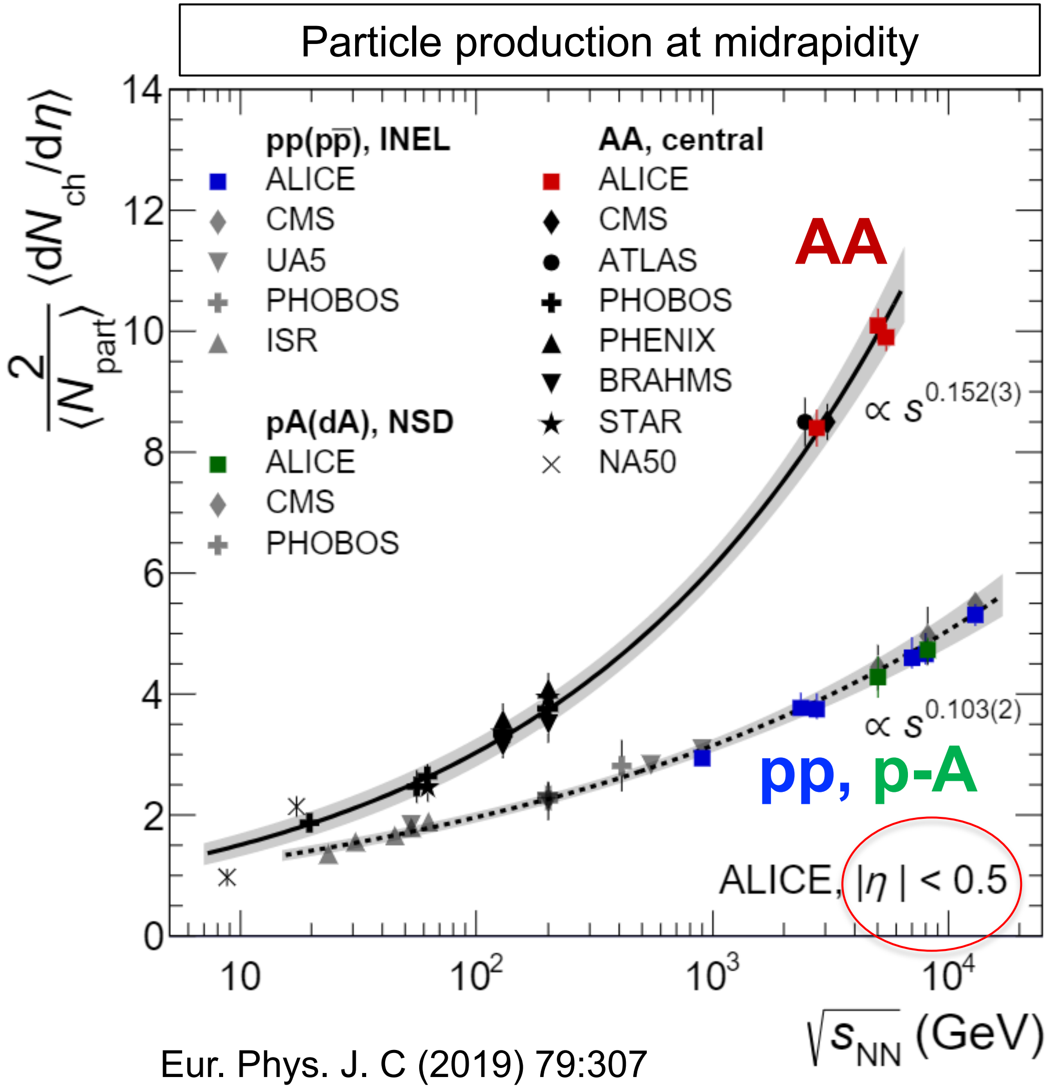


ALICE, Phys.Lett. B 772 (2017) 567-577



Pb-Pb

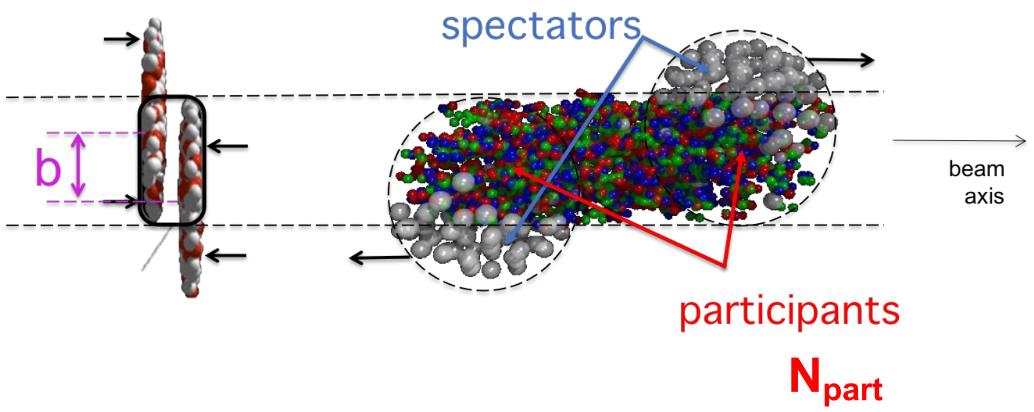
Charged particle production in central HI collisions



Eur. Phys. J. C (2019) 79:307

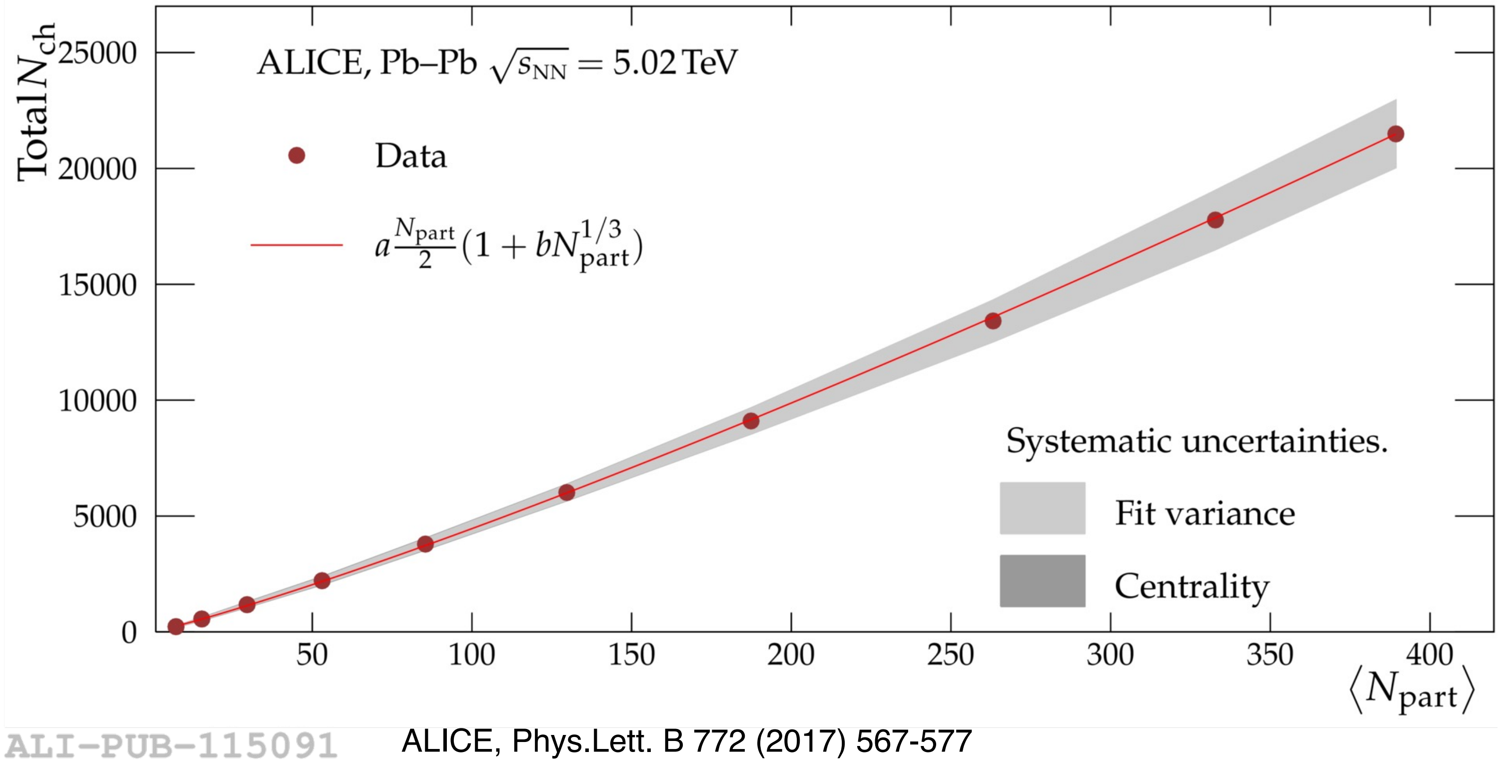
Particle production per participant in HI collisions follows a steeper power law than in pp, pA and increases by 2-3x from RHIC to the LHC

Heavy-ion collisions are more efficient in transferring energy from beam- to mid- rapidity than pp



How many particles are created in a collision?

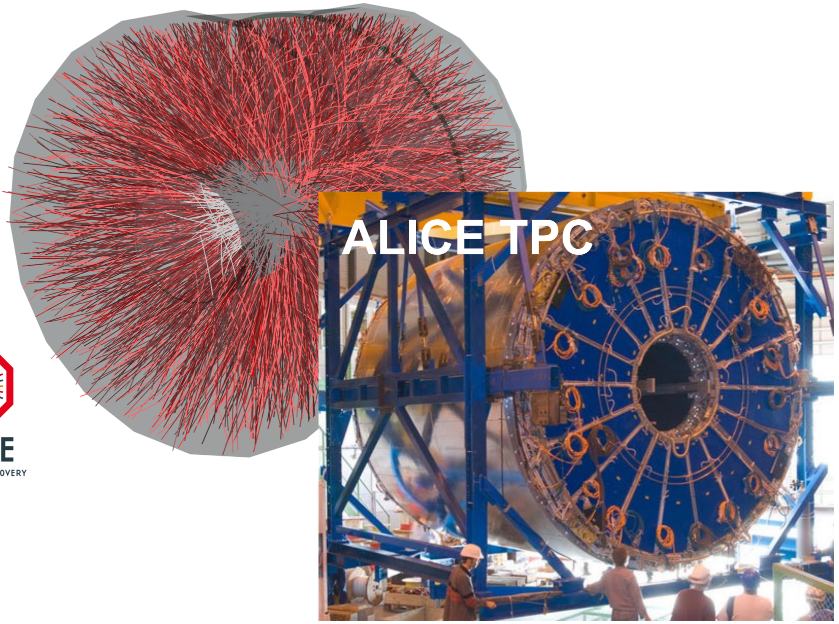
Total Charged particle multiplicity



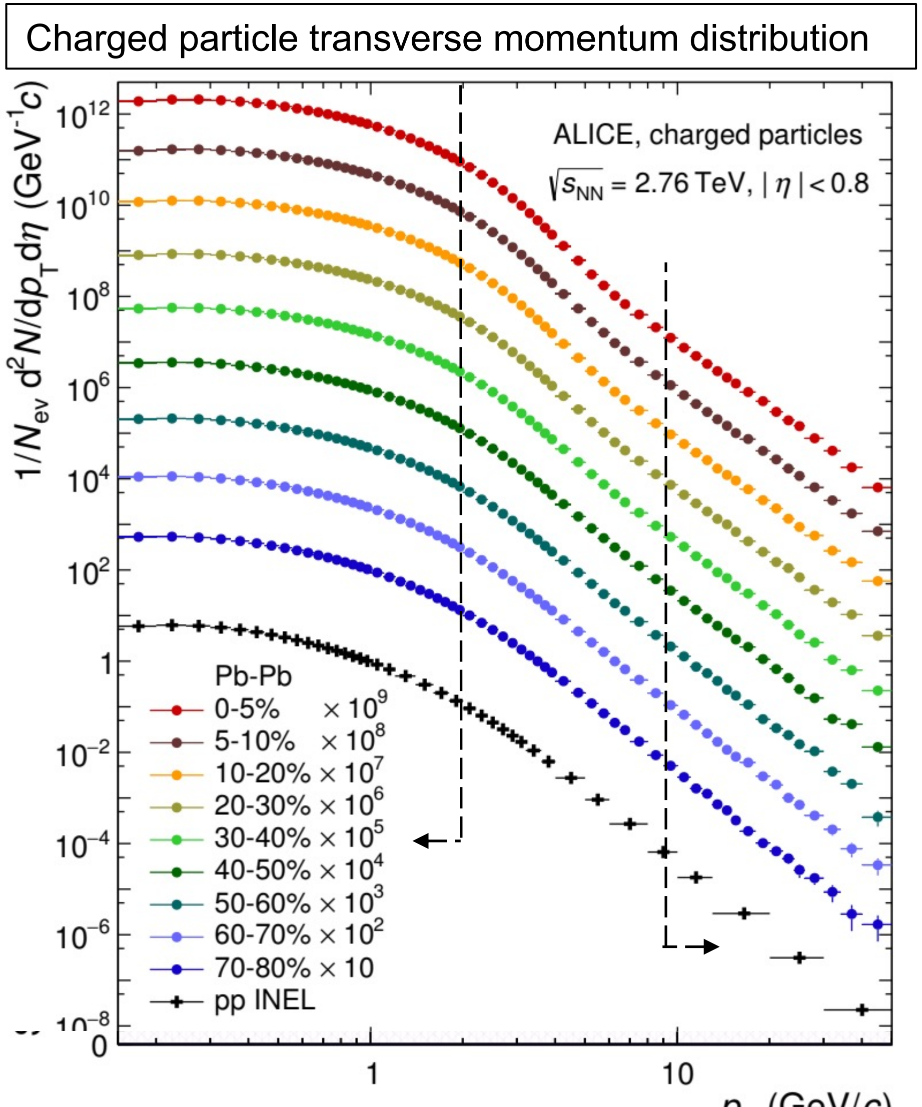
ALICE, Phys.Lett. B 772 (2017) 567-577

In a central Pb-Pb collision at the LHC, more than 20000 charged tracks must be reconstructed.

→ High granularity tracking systems, primary importance of tracking, vertexing calibration



Particle "spectra"



ALICE, JHEP 11 (2018) 013

Low p_T *(< 2 GeV/c)*
- Particle spectra are described by a Boltzmann distribution → "thermal", ~ $\exp(-1/k_B T)$
- "Bulk" dominated by light flavor particles
- Non-perturbative QCD regime

High p_T *(> 8-10 GeV/c)*
- Particle spectra described by a power law
- Dominated by parton fragmentation (jets)
- Perturbative QCD regime

Mid p_T *(2 to 8 GeV/c)*
- Interplay of parton fragmentation and recombination of partons from QGP

Heavy-ion and high-energy physics have different goals and thus different detector requirements.

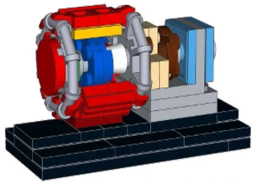
Observables:

- soft (low p_T) and hard (high p_T) probes
- hadron production rates (needs PID)
- flow (needs acceptance coverage)
- photon/W/Z (calorimetry)
- jets (coverage, high p_T)

In HI physics also emphasis on:

- **midrapidity** measurements
- **identification** of hadron species
- soft (non-perturbative) regime, i.e. **low p_T**
- **minimum bias** events

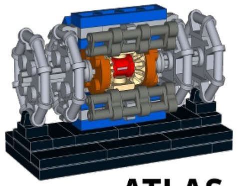
Complementarity of the LHC experiments



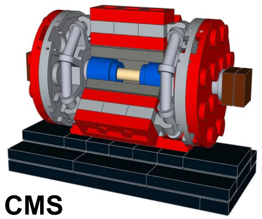
ALICE

ALICE

- Low p_T
- PID
- Low material budget next to IP



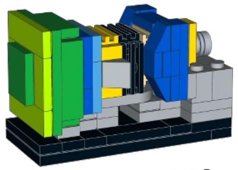
ATLAS



CMS

ATLAS/CMS

- Wide pseudorapidity coverage
- High $p_{T,}$ jets



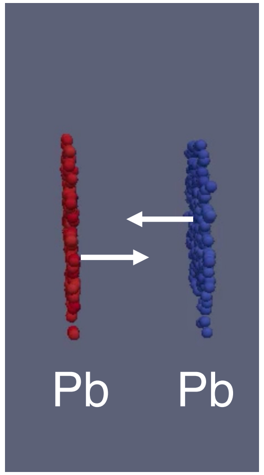
LHCb

LHCb

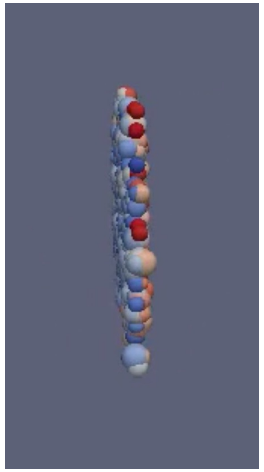
- Forward pseudorapidity
- PID
- Fixed target

The standard model of heavy-ion collisions

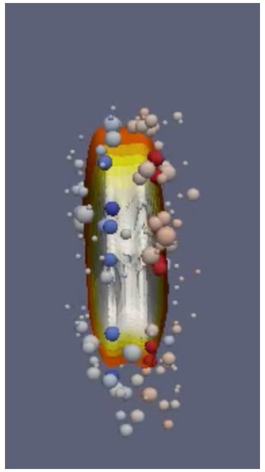
Initial state



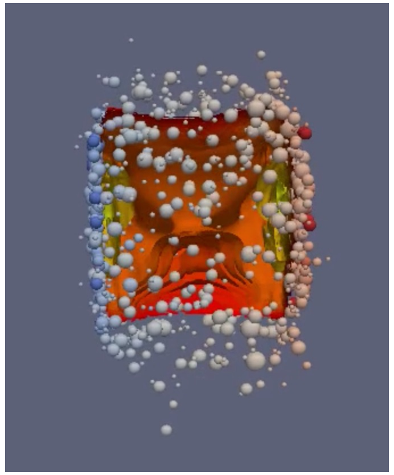
Hard scatterings



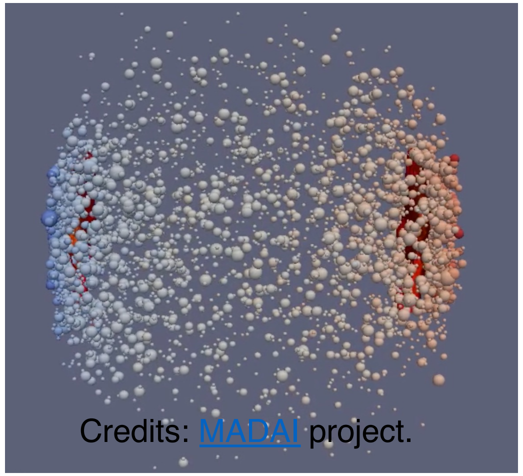
QGP formation



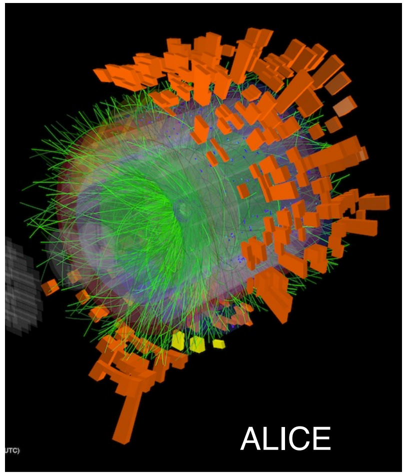
Hydrodynamic expansion



Hadronization and freeze-out



Detection



Time: $\tau = 0$ — $\tau \sim 1$ fm/c — $\tau \sim 10$ fm/c — $\tau > 10$ pm/c

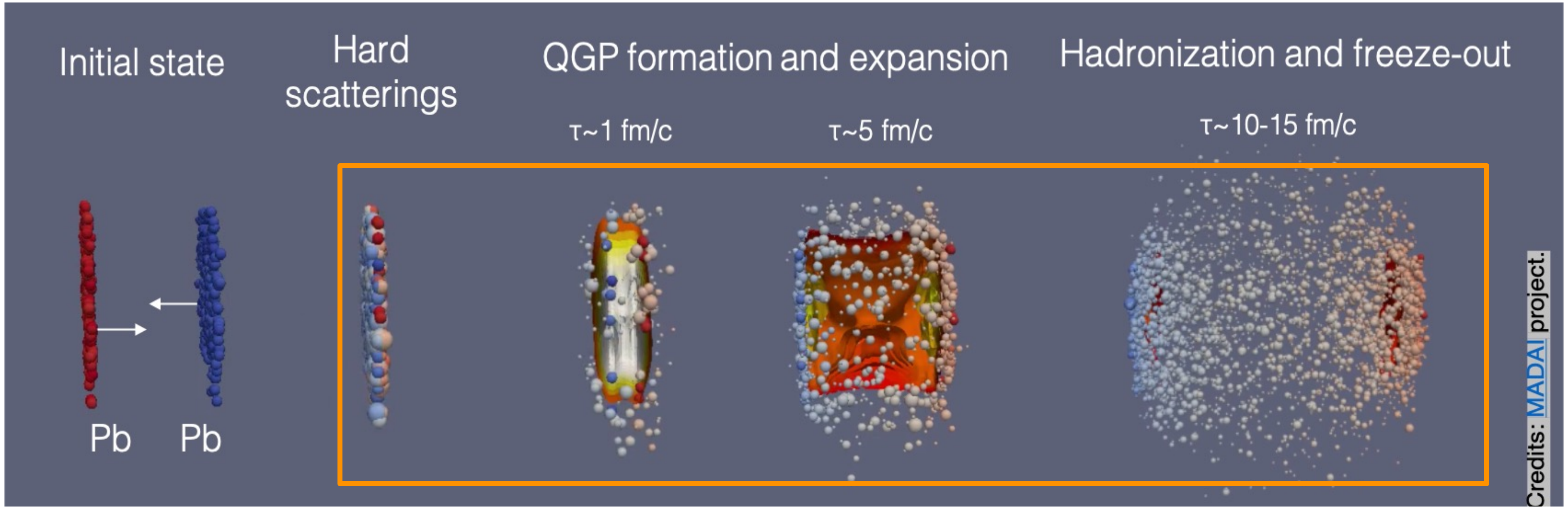
Temperature: T ~ 200-800 MeV [1] — T ~ 155-100 MeV [4]

$T_{c,\,lQCD} \sim$ 155-159 MeV [2,3]

No direct observation of the QGP is possible
→ rely on emerging particles as "probes"

[1] F. Gardim et al. Nature Phys. 16 (2020) 6, 615-619
[2] A. Bazavov et al., Phys. Lett. B 795 (2019)
[3] Borsaniy et al. PRL 125 (2020) 5, 052001
[4] A. Andronic et al., Nature 561 (2018) 7723, 321-330

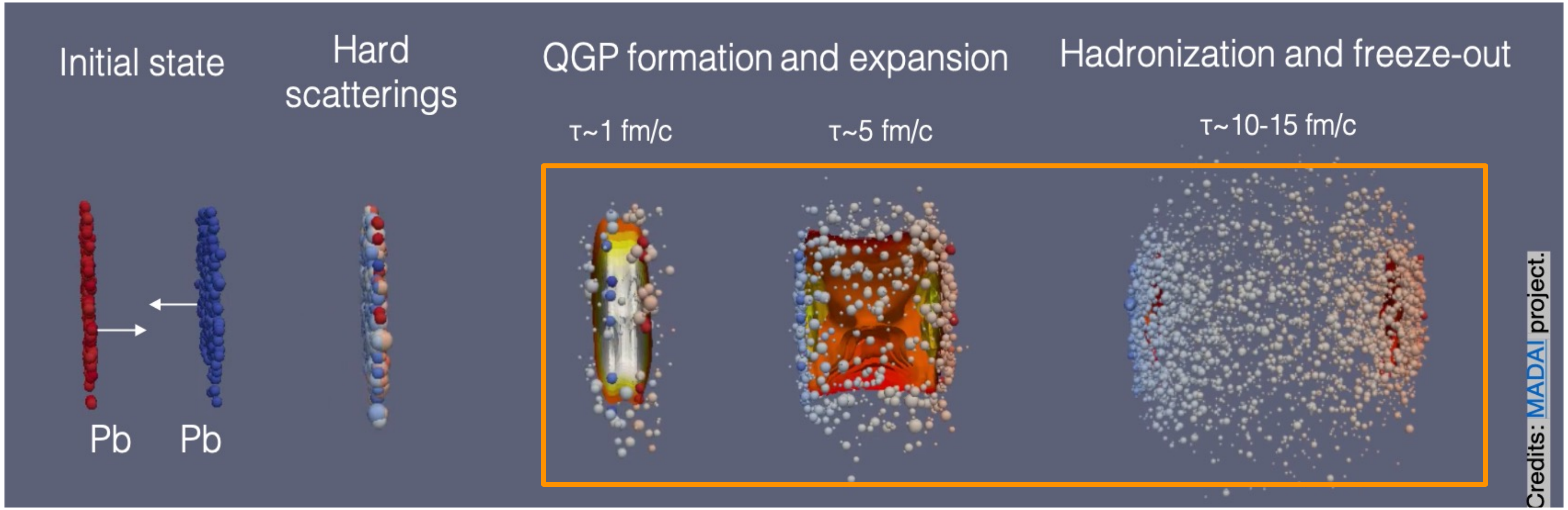
Probes 1/2



1 fm/c = 3×10^{-24} s, 1 MeV ~ 10^{10} K

High-p_T partons (→ jets), charm and beauty quarks (→ open HF, quarkonia)
produced in the early stages in hard processes,
traverse the QGP interacting with its constituents = colored probes in a colored medium
→ **rare, calibrated probes, perturbative QCD**
→ **in-medium interaction (energy loss) and transport properties**
→ **in-medium modification of the strong force and of fragmentation**

Probes 2/2



1 fm/c = 3x10^{-24} s, 1 MeV ~ 10^{10} K

Low-p_T particles, light flavour hadrons (u,d,s, +nuclei)
produced from hadronization of the strongly-interacting, thermalized QGP constitute the bulk of the system

→ **non-perturbative QCD regime**

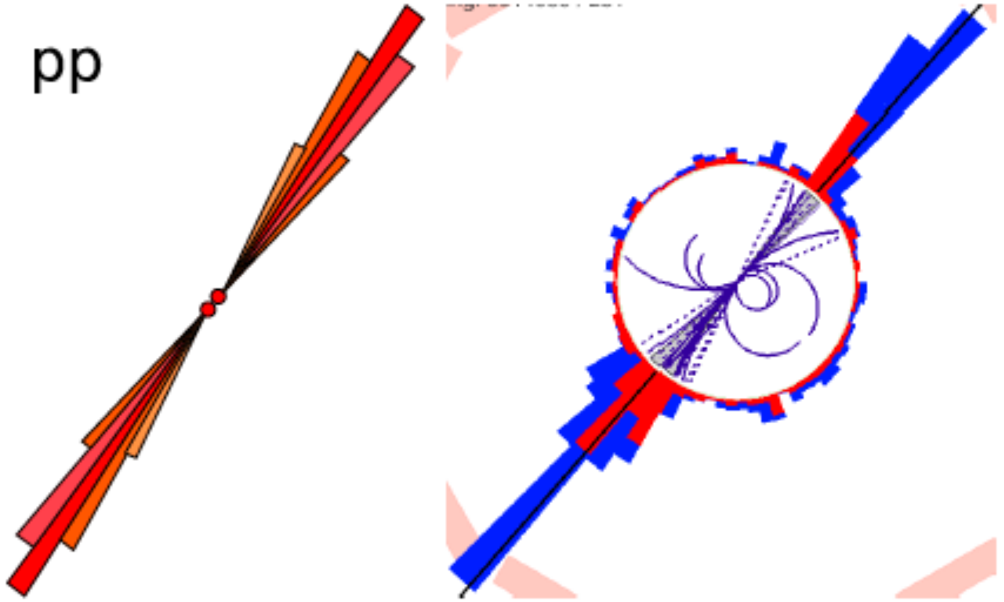
→ **thermodynamical, hydrodynamical and transport properties**

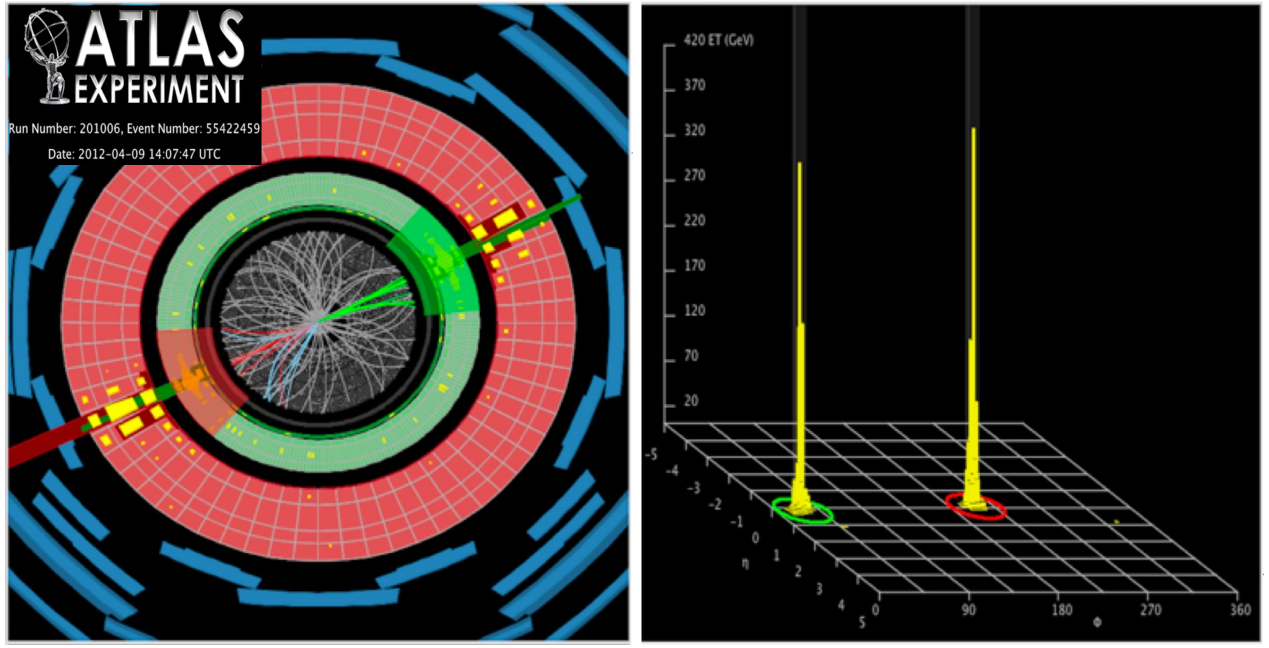
How does the presence of a colored QGP affect particle production?

Jets

In the early stages of the collision, hard scatterings produce back-to-back recoiling partons, which fragment into collimated ''sprays'' of hadrons.

→ **in-vacuum fragmentation**



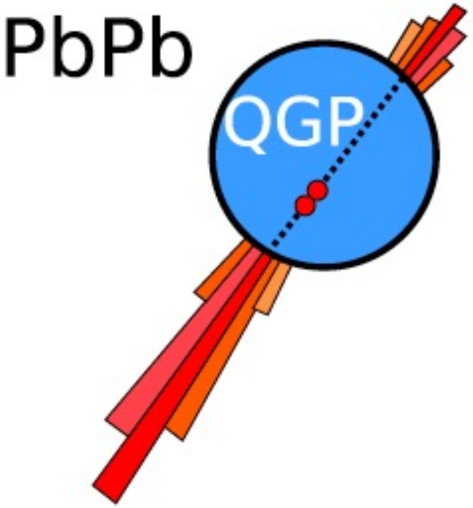


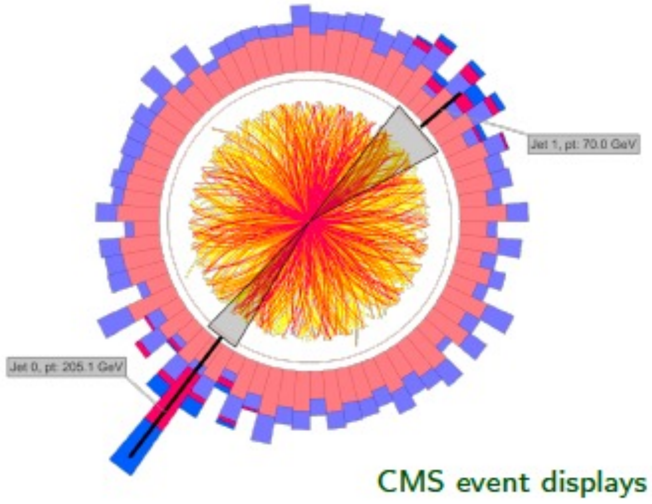
ATLAS, pp collision event display

Jets

In the early stages of the collision, hard scatterings produce back-to-back recoiling partons, which fragment into collimated ‘’sprays’’ of hadrons.

→ **in-vacuum fragmentation**

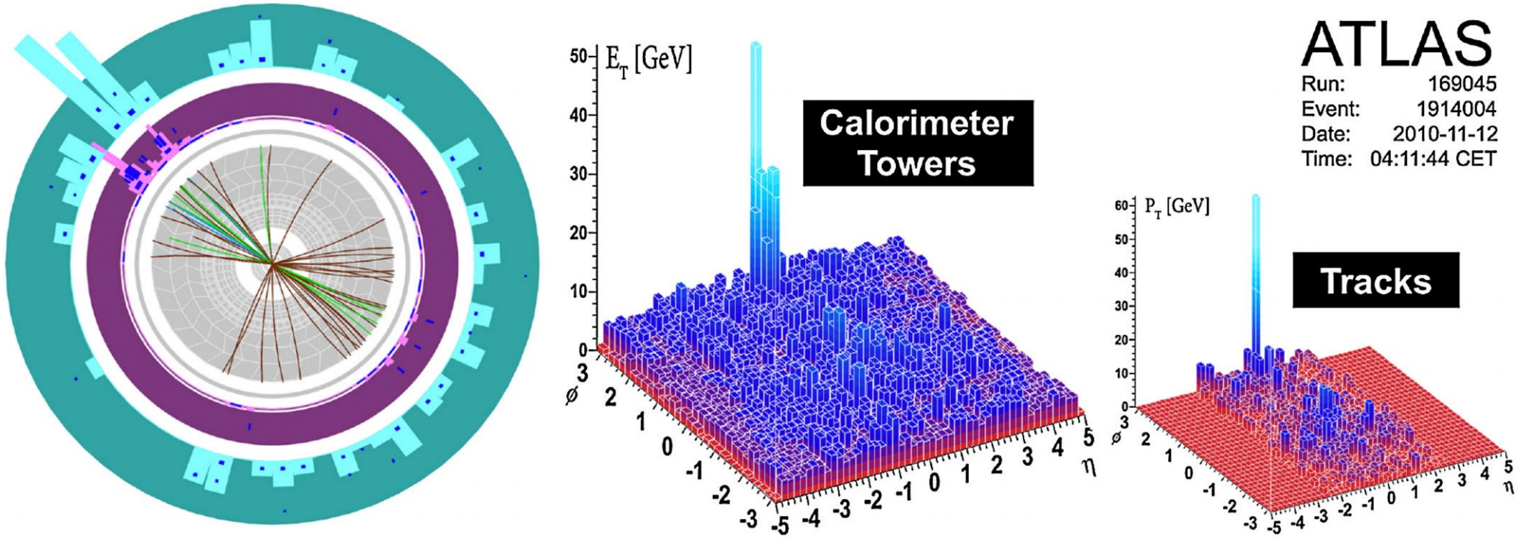




When a QGP is formed, the colored partons traverse and interact with a colored medium.

→ **in-medium fragmentation**

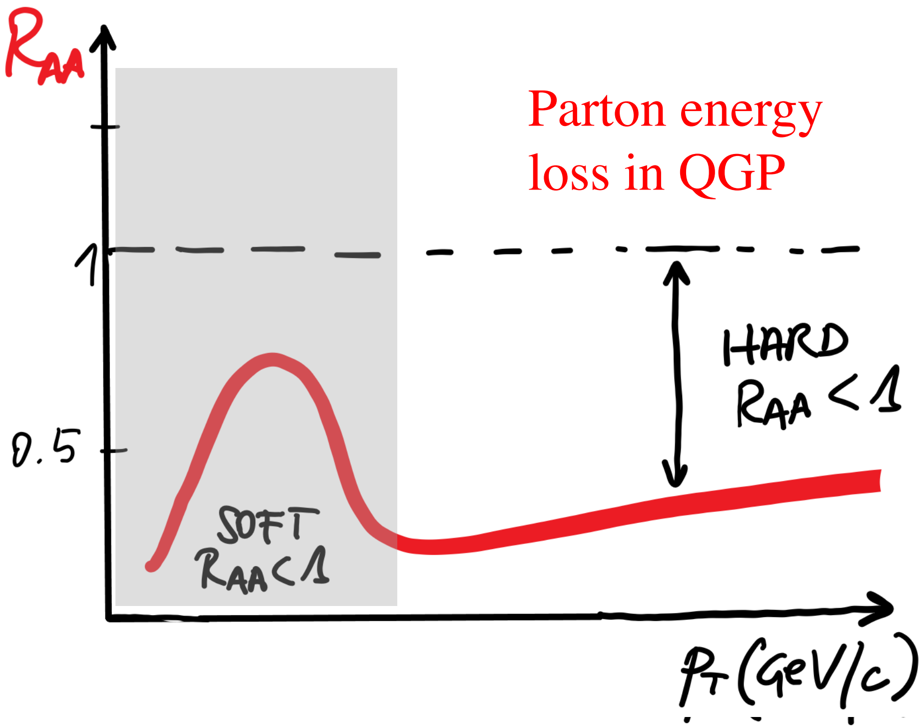
→ **jet ‘’quenching’’ (energy loss)**



Goal: understand the nature of this energy loss to characterize the strongly-interacting QGP

The nuclear modification factor, R_{AA}

$$R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$



If a AA collision is a incoherent superposition of independent pp collisions, the p_T spectra in AA collisions can be obtained by scaling the p_T spectra in pp collisions by the number of nucleon-nucleon collisions, N_{coll} :

$$dN_{AA}/dp_T = N_{coll} \times dN_{pp}/dp_T$$

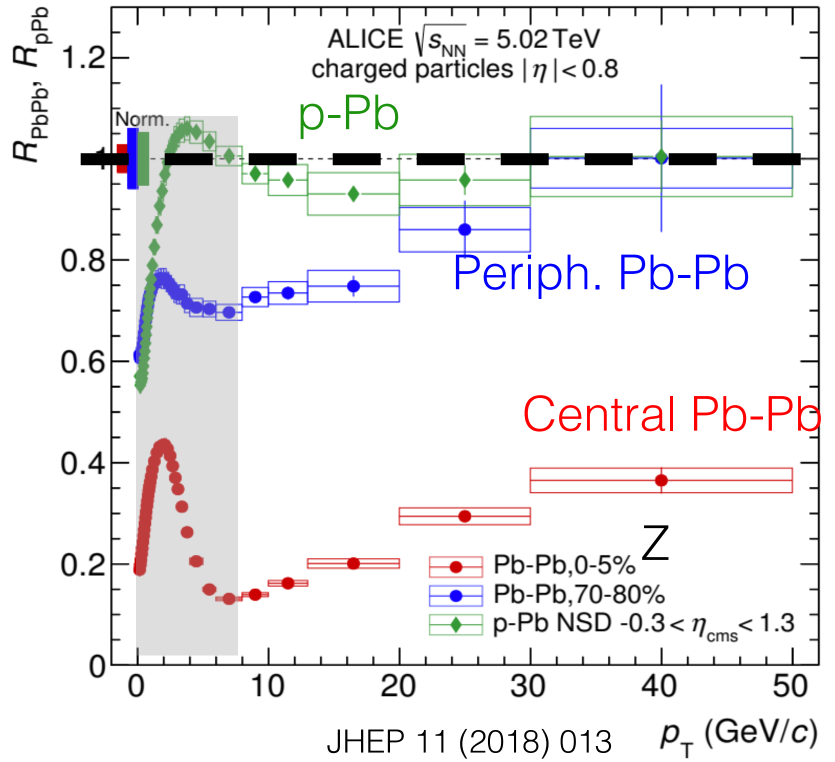
and $R_{AA} = 1$ at high p_T
→ the medium is transparent to the passage of partons

If $R_{AA} < 1$ at high p_T
→ the medium is opaque to the passage of partons
→ parton-medium final state interactions, energy loss, modification of fragmentation in the medium

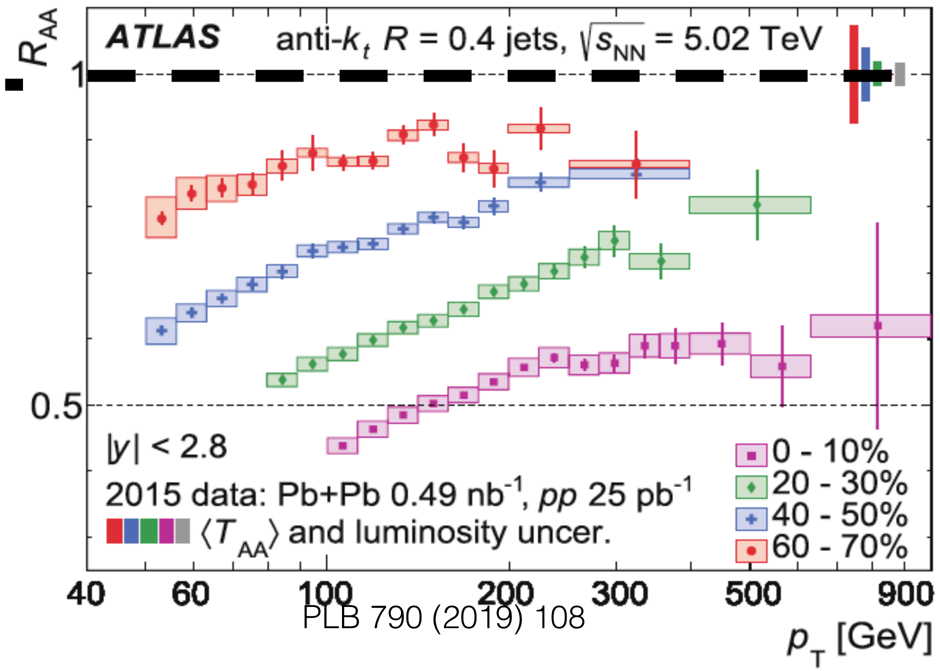
Evidence of parton energy loss in QGP

$$R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$

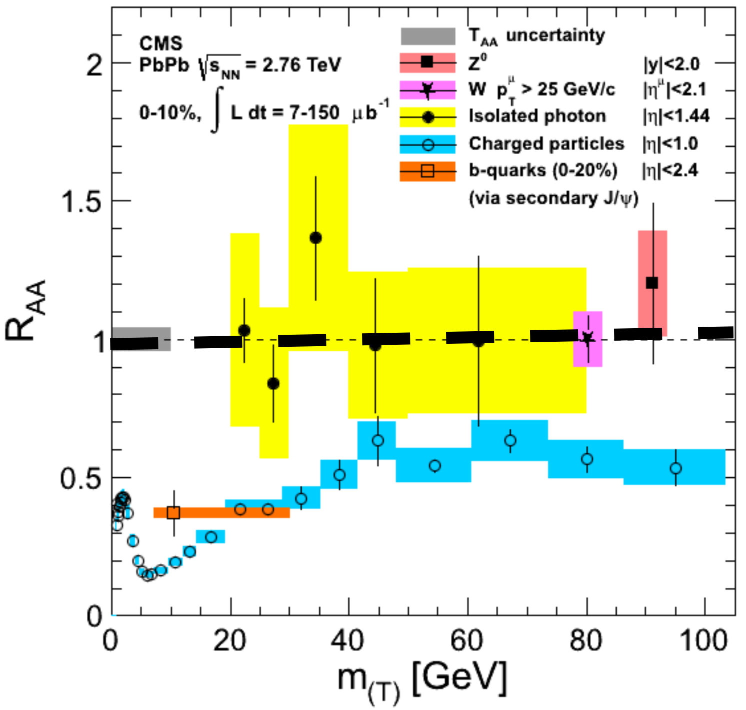
Charged particles



Inclusive jets



EW bosons



A strong suppression of high-p_T hadrons and jets is observed in central Pb-Pb collisions.

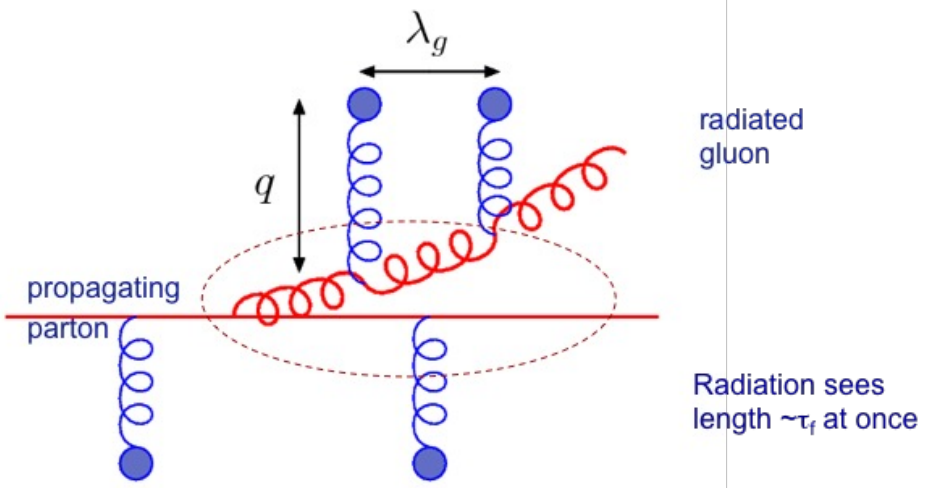
No suppression observed in p-Pb collisions, nor for the color-less Z bosons and photons.

→ Jet quenching is explained as **parton energy loss in a strongly interacting plasma**

Radiative energy loss

In the BDMPS (*Baier-Dokshitzer-Mueller-Peigné-Schiff*) approach, the energy loss depends on

- the **color-charge** via the Casimir factors C_r
  - $C_r = C_A = 3$ for g interactions
  - $C_r = C_F = 4/3$ for q,qbar interactions
- the **strong coupling**
- the **path length** L
- the **transport coefficient** $\hat{q}$ ("q-hat")
  - gives an estimate of the "strength" of the jet quenching
  - is <u>not directly measurable</u> → from data through model(s)



$$\frac{dE}{dx} = -C_r \alpha_s \hat{q} L$$

$$\hat{q} = \frac{\mu^2}{\lambda}$$

Average transverse momentum transfer

Mean free path

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

Density

Baier-Dokshitzer-Mueller-Peigné-Schiff, Nucl. Phys. B. 483 (1997) 291

How much energy is lost?

From the BDMPS formula :

$$\langle \Delta E \rangle = \frac{1}{4} \alpha_s \, C_R \, \hat{q} \, L^2 \xrightarrow{\text{Dimensional analysis}} \langle \Delta E \rangle = \frac{\alpha_s \, C_R \, \hat{q} \, L^2}{4 \hbar c}$$

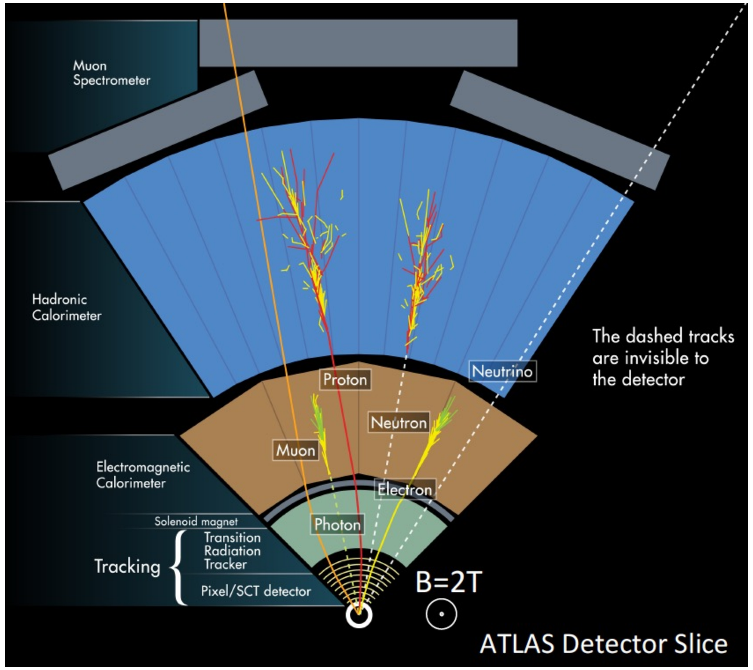
If we take

- $\hat{q}$ ~ 5 GeV^2/fm
- α_S = 0.2, strong coupling for Q^2 = 10 GeV
- C_R = 4/3
- L = 7.5 fm

we obtain <ΔE> ~ 95 GeV

Only partons with E $\gtrsim$ 105 GeV can traverse a 7.5 fm radius fireball and exit with $p_T \gtrsim$ 10 GeV/c

In other words, it takes a ~7.5 fm radius QGP droplet to stop a jet of ~ 100 GeV (or ~1.5m of hadronic calorimeter)



Jet transport coefficient $\hat{q}$

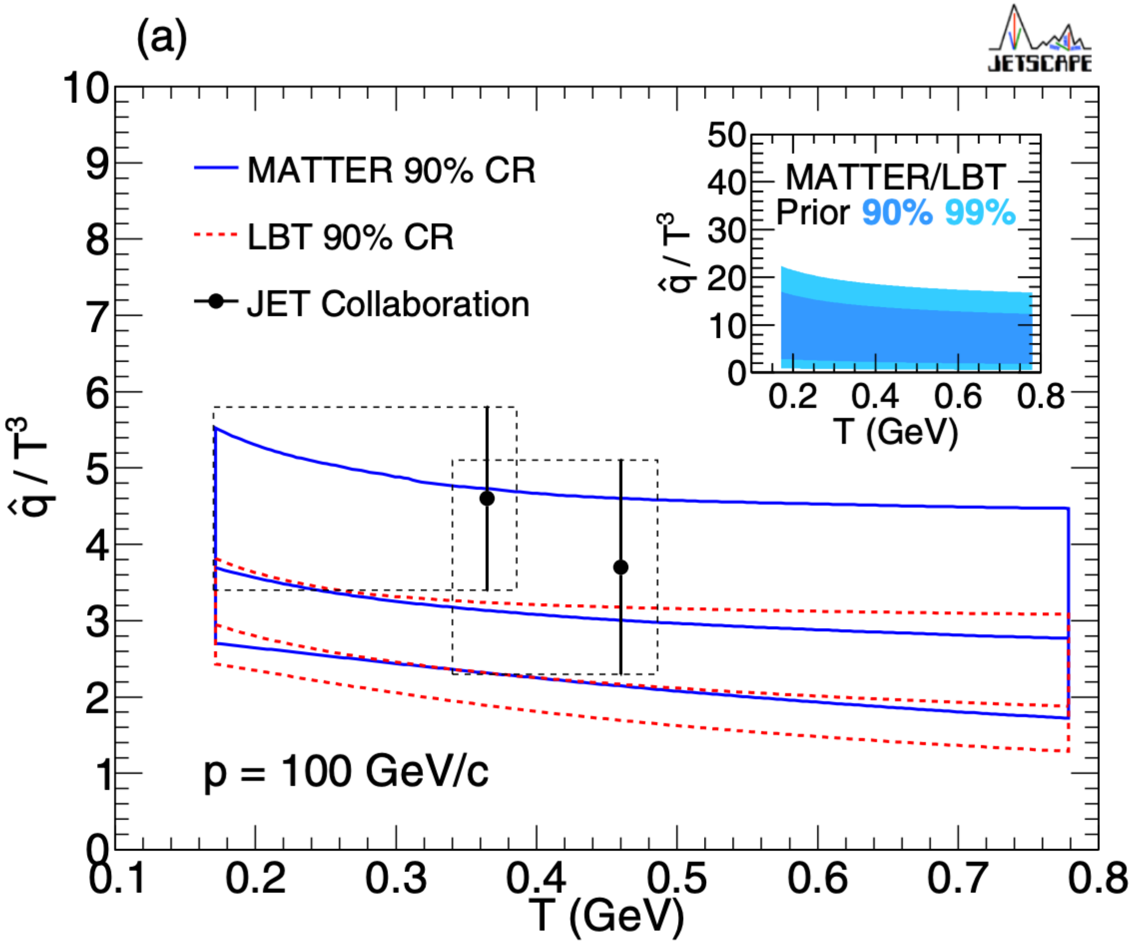
A recent combined analysis of the RHIC and the LHC data on jet quenching (inclusive hadron R_{AA}) allowed to extract a value for the $\hat{q}$ parameter

$$\frac{\hat{q}}{T^3} \approx \begin{cases} 4.6 \pm 1.2 & \text{at RHIC,} \\ 3.7 \pm 1.4 & \text{at LHC,} \end{cases}$$

For a quark jet with E = 10 GeV

$$\hat{q} \approx \begin{cases} 1.2 \pm 0.3 \\ 1.9 \pm 0.7 \end{cases} \mathrm{GeV}^2/\mathrm{fm} \;\; \text{at} \;\; \begin{matrix} \text{T=370 MeV} \\ \text{T=470 MeV} \end{matrix}$$

→ Still large uncertainties, but important step **towards a quantitative characterisation** of the QGP.



S. Cao et al., PRC 104, 024905 (2021)

In-medium jets: main questions

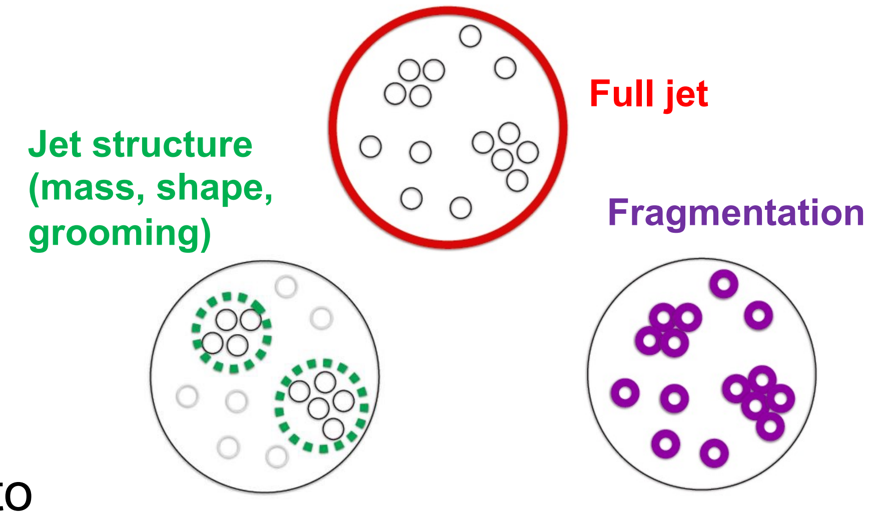
Related to the nature and properties of the medium

- Density of the medium and transport properties
- Nature of the scattering centers
- Distribution of the radiated energy
- …

Related to the nature of the energy loss mechanism

- Path length dependence
- Broadening effects
- Microscopic mechanism for energy loss
  → Study the **shape and structure of jets** for insight into the details of jet modification mechanisms due to interactions with the plasma

- Flavour dependence
  → **measure charm and beauty R_{AA}**

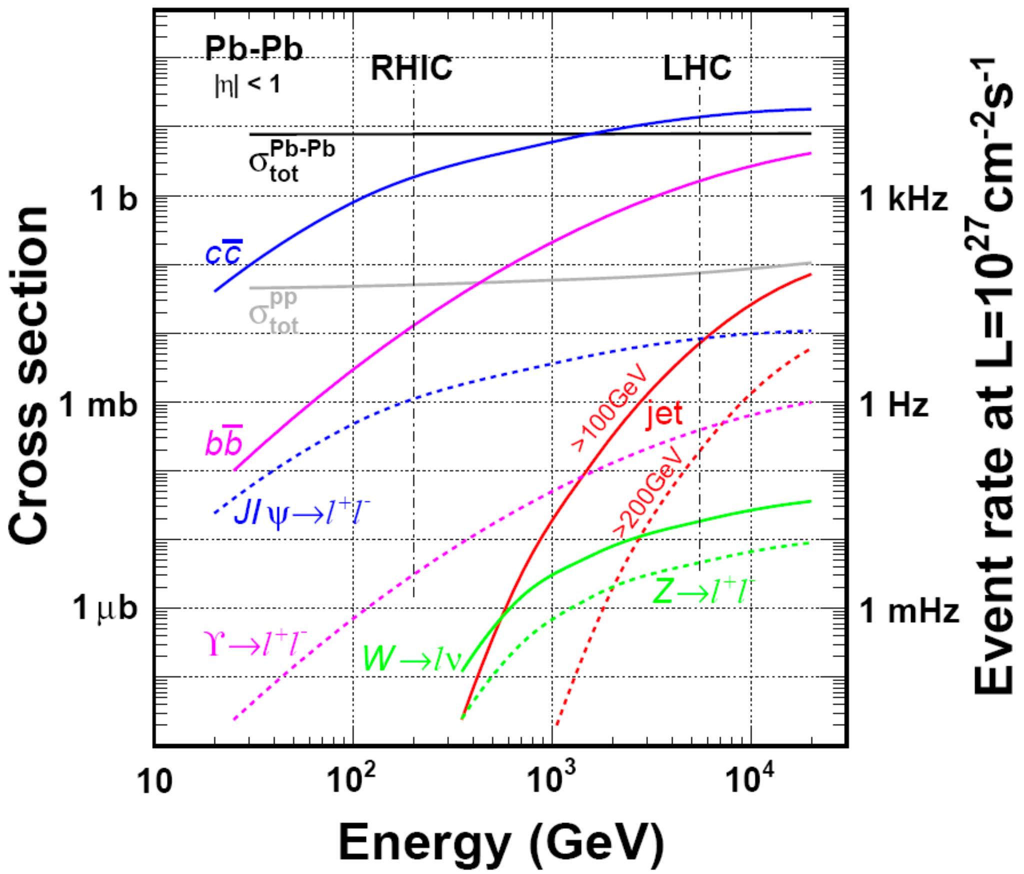


Charm and beauty

Heavy flavours:
m(charm) ~ 1.3 GeV/c^2
m(beauty) ~ 4.7 GeV/c^2

are ideal probes of the QGP at the LHC:

- **large production cross sections**
- Produced in **initial hard** parton scatterings
- **controlled** values of mass and colour charge of the propagating parton
- “brownian” motion through the medium, **diffusion**
- sensitive to QGP **hadronisation** (baryon/meson)



Energy loss of charm and beauty

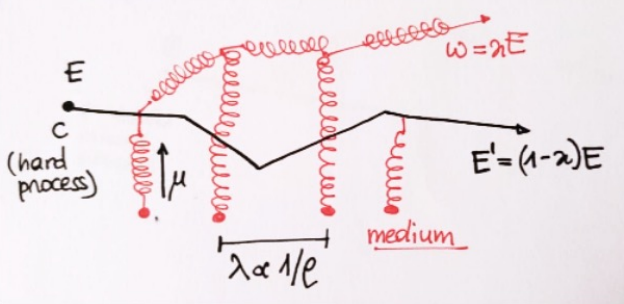
Charm and beauty loose energy via **gluon radiation** + **elastic collisions**

Due to the large masses, radiative energy loss is subject to the **dead cone effect** = suppression of the gluon radiation emitted by a (slow) heavy quark at small angles, $\vartheta < \vartheta_{DC} \sim m_q/E_q$

→ **hierarchy** in energy loss: $\Delta E_g > \Delta E_c > \Delta E_b$

→ radiative energy loss reduced by 25% (c) and 75% (b) [$\mu = 1$ GeV/c^2]

In-medium E_{loss}



Baier-Dokshitzer-Mueller-Peigné-Schiff, Nucl. Phys. B. 483 (1997) 291

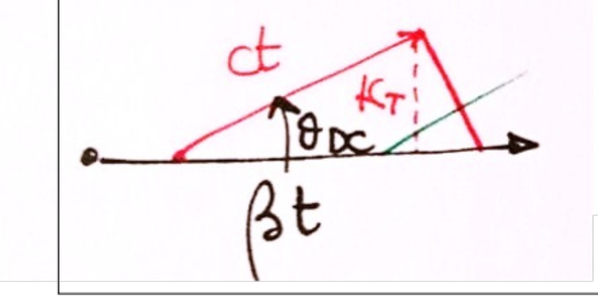
$$\langle \Delta E \rangle \propto \alpha_s C_r \hat{q} L^2$$

$$\hat{q} = \frac{\mu^2}{\lambda}$$

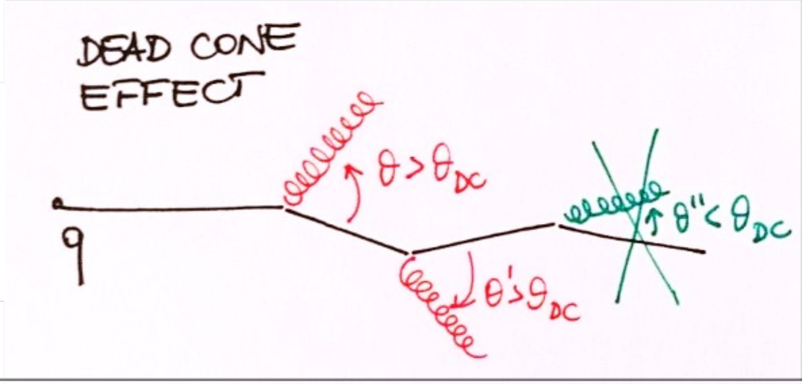
Average transverse momentum transfer

Mean free path ~1/density

Dead cone effect



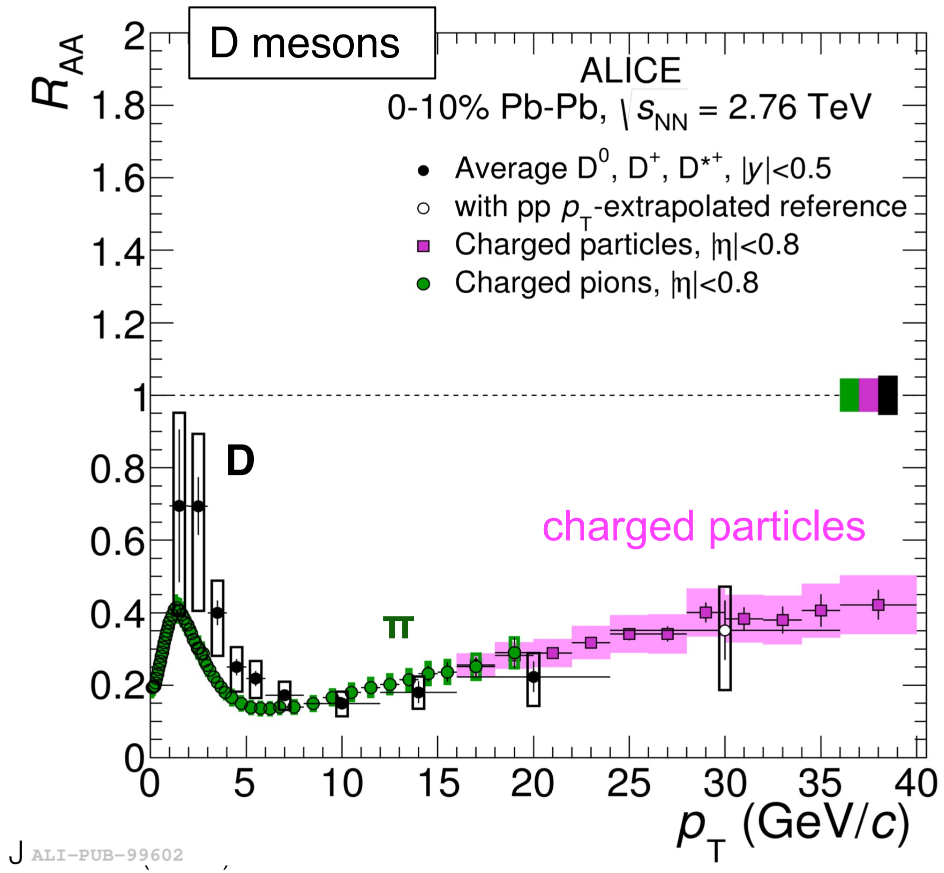
$$\sin \theta_{DC} = 1 - \beta^2 = \left(\frac{M}{E}\right)^2$$

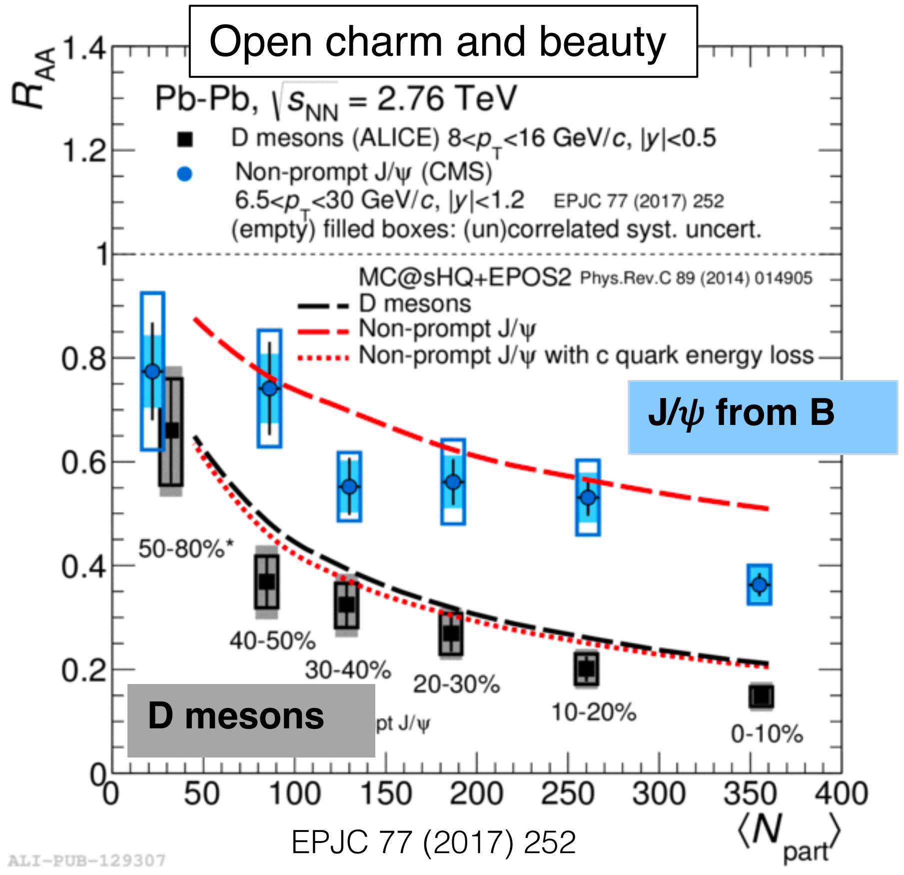


Nuclear modification of charm and beauty

A strong suppression is observed in the R_{AA} of D mesons J/psi from b decay.

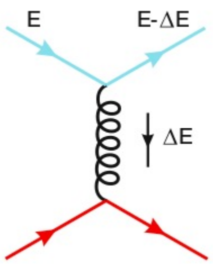
J/ψ from beauty is less suppressed than D mesons from charm → $\Delta E_c > \Delta E_b$





EPJC 77 (2017) 252

Collisional energy loss



It depends on

- **path length** through the medium, L (linearly)
- **parton type**
  - For light quarks

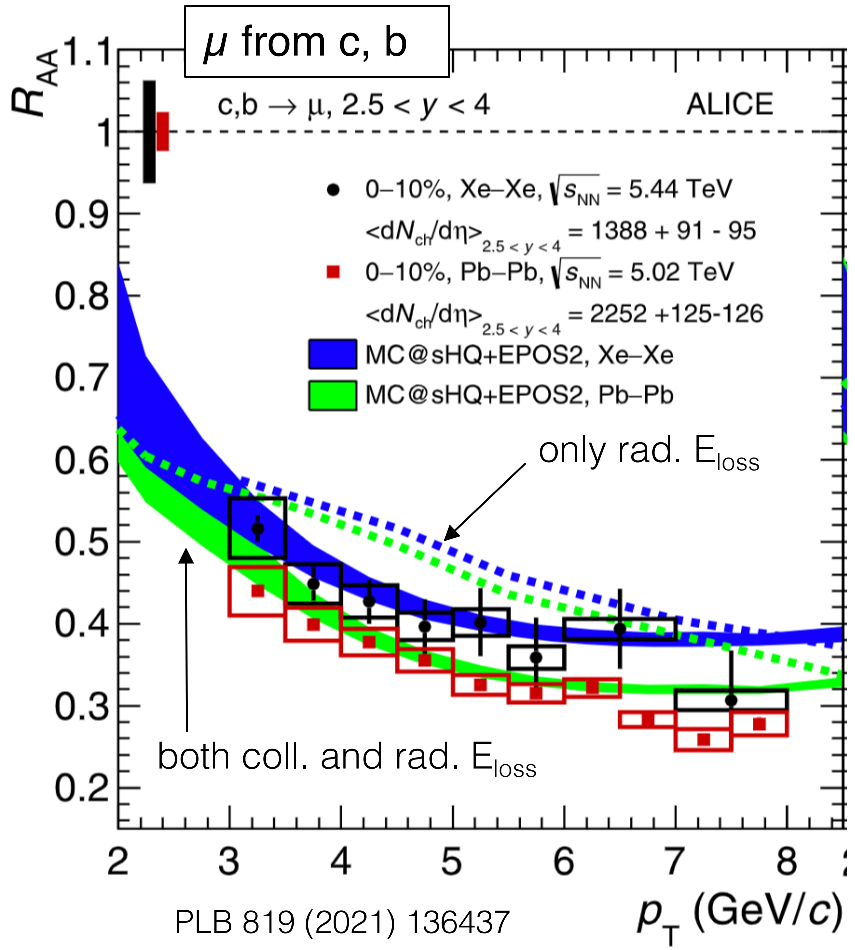
$$\Delta E_{q,g} \sim \alpha_S\, C_R\, \mu^2 L \ln \frac{ET}{\mu^2}$$

  - For heavy quarks

$$+\ \alpha_s^2 T^2\, C_R\, \mu^2 L \ln \frac{ET}{M^2}$$

- **temperature** of the medium, T
- **mass** of the heavy quark M
- average transverse momentum transfer **μ** in the medium

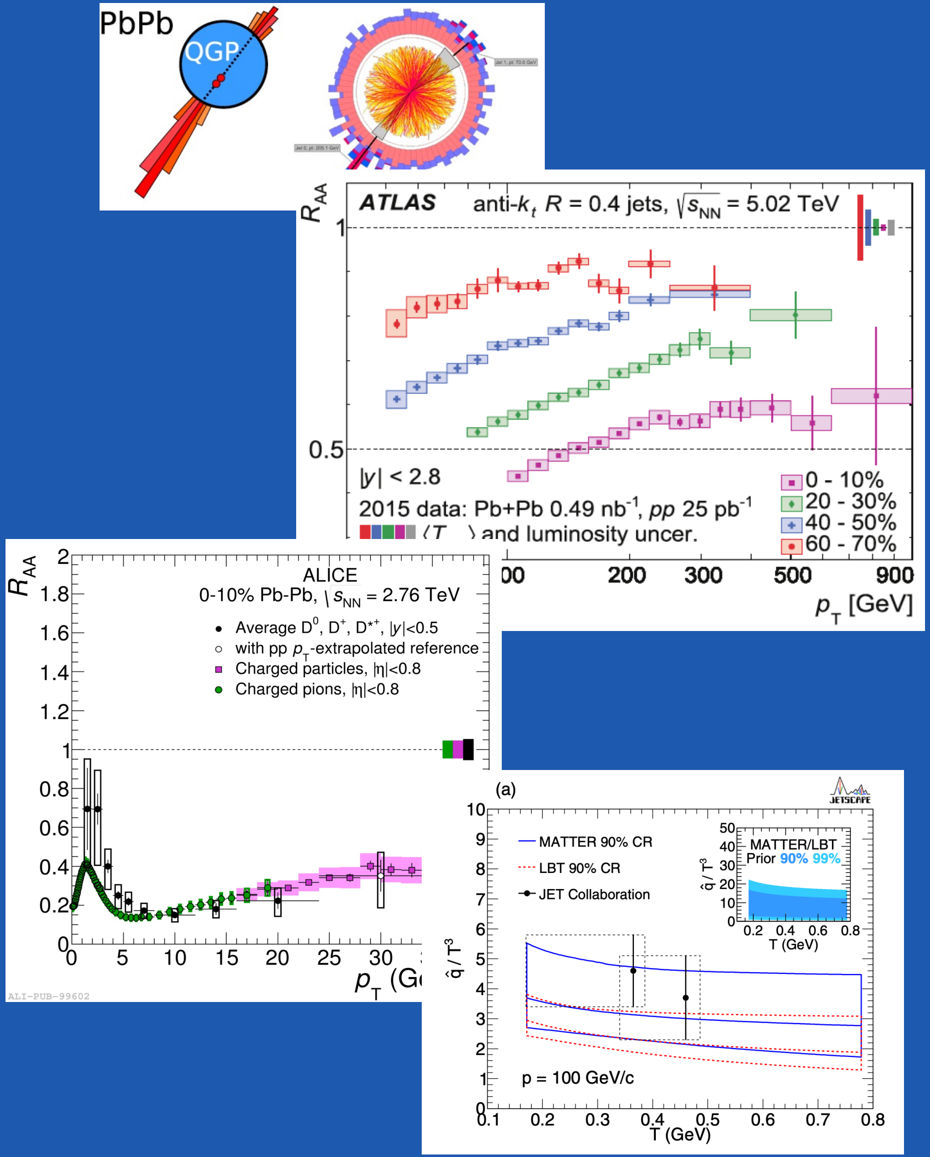
→ Data are well described by models that include both collisional and radiative E_{loss}



Summary 1/2

Evidence of the creation of a strongly-interacting medium in central heavy ion collisions comes from the observed strong suppression of particle production, explained by the energy loss of colored partons in the colored QGP.

- Radiative energy loss dominates at high p_T for light flavours, gluons and charm
- Collisional and radiative energy loss play similar role for beauty



A **quantitative characterization** of the properties of the medium (e.g. transport coefficient, …) requires **models**.

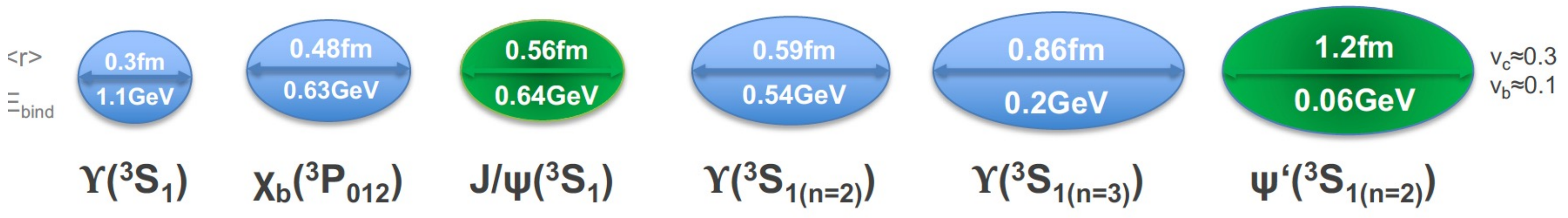
How does the presence of a colored QGP affect hadron formation?

Quarkonia

c-cbar (J/Ψ, Ψ',..) and b-bar (Υ', Υ'',Υ''') pairs are a laboratory for QCD:

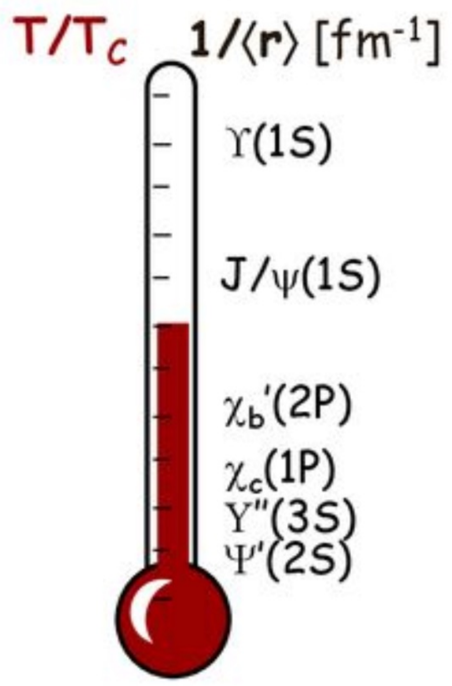
- Small decay width (~keV), significant BR into dileptons
- Intrinsic separation of energy scales: $m_Q >> \Lambda_{QCD}$ and $m_Q >> B_E$
- A variety of states characterized by different binding energies

→ Goal: understand mechanisms of **dissociation and regeneration** in QGP



To larger radius →

To lower binding energy →



Quarkonium as a thermometer for QGP

Charmonium suppression (J/ψ, ψ',…) suggested as ''smoking gun'' signatures for the QGP back in the 1980's.

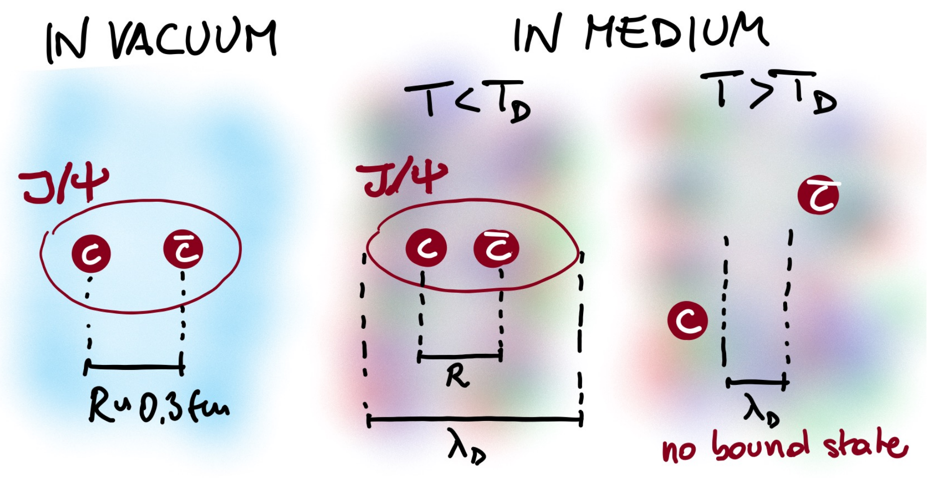
In vacuum (T=0), qqbar is bound by the Cornell potential.

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

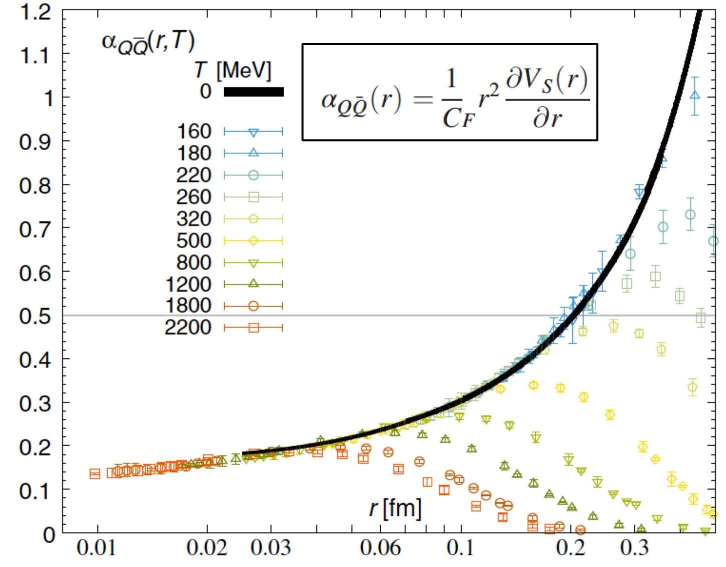
When the qqbar is immersed in the dense and hot QGP (**T>0**), the surrounding color charges screen the binding potentials (color Debye screening), resulting in

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

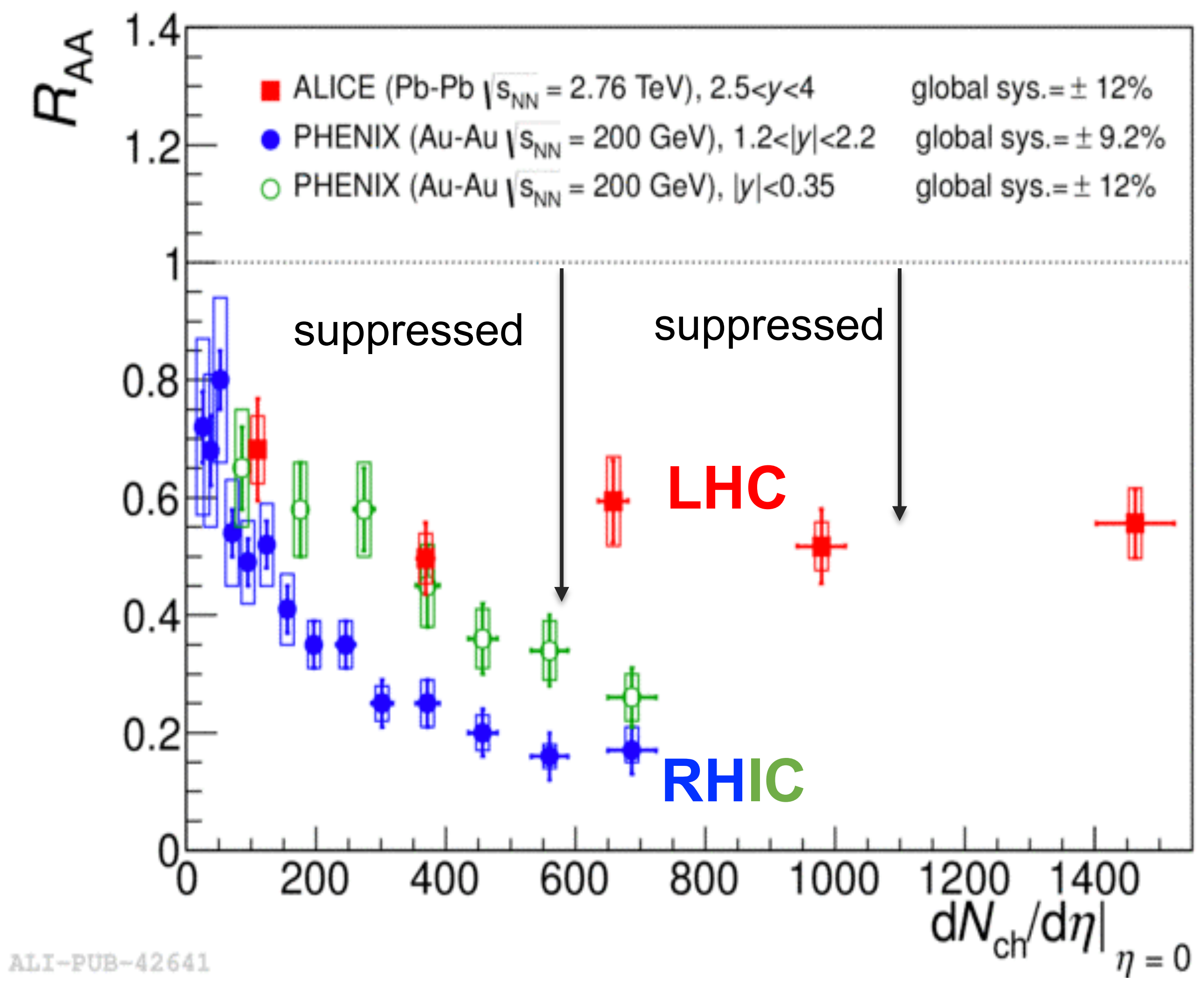
The effective coupling between q and qbar at large distances gets reduced → **q-qbar melting**



Effective coupling from (2+1) QCD at various T



J/ψ suppression



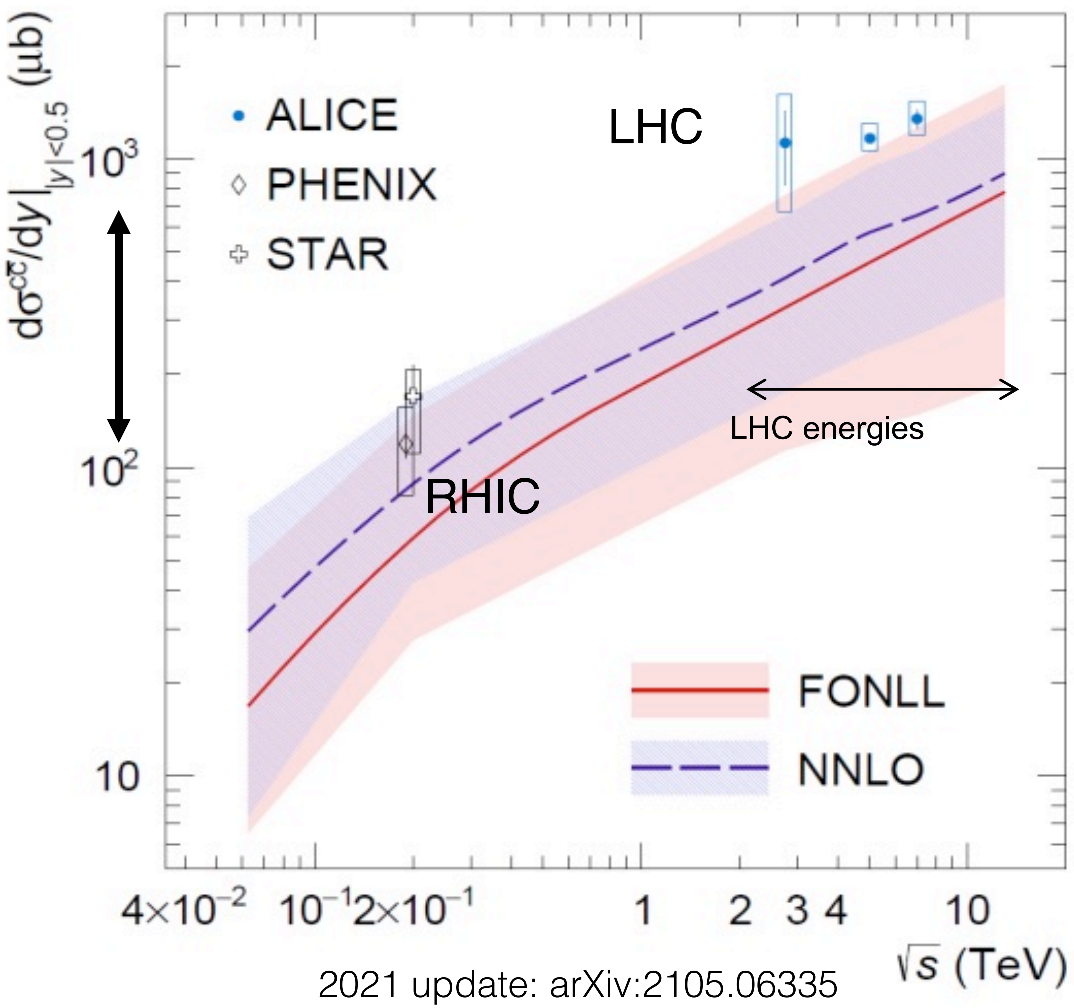
- observed at the SPS ($\sqrt{s_{NN}}$ = 17 GeV)
- later measured at RHIC ($\sqrt{s_{NN}}$=200 GeV) up to very high multiplicities

For similar multiplicities the suppression at SPS is similar to that at RHIC despite the energy difference

At the LHC, $\sqrt{s_{NN}}$ = 2.76 TeV, yet J/ψ is less suppressed, due to the larger charm cross section.

J/ψ production vs √s

c-cbar production cross section



2021 update: arXiv:2105.06335

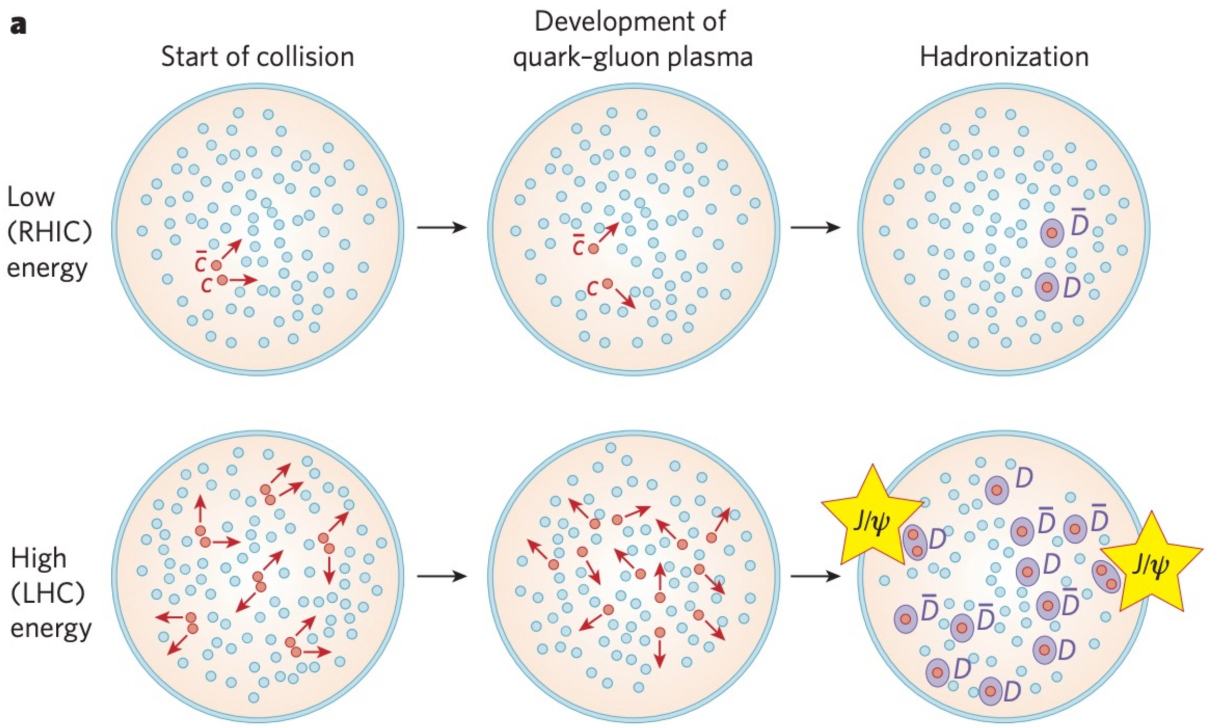
The cross section for producing a c-cbar pair increases with √s

In a central event
At SPS ~0.1 c-cbar
At RHIC ~10 c-cbar
At LHC ~100 c-cbar

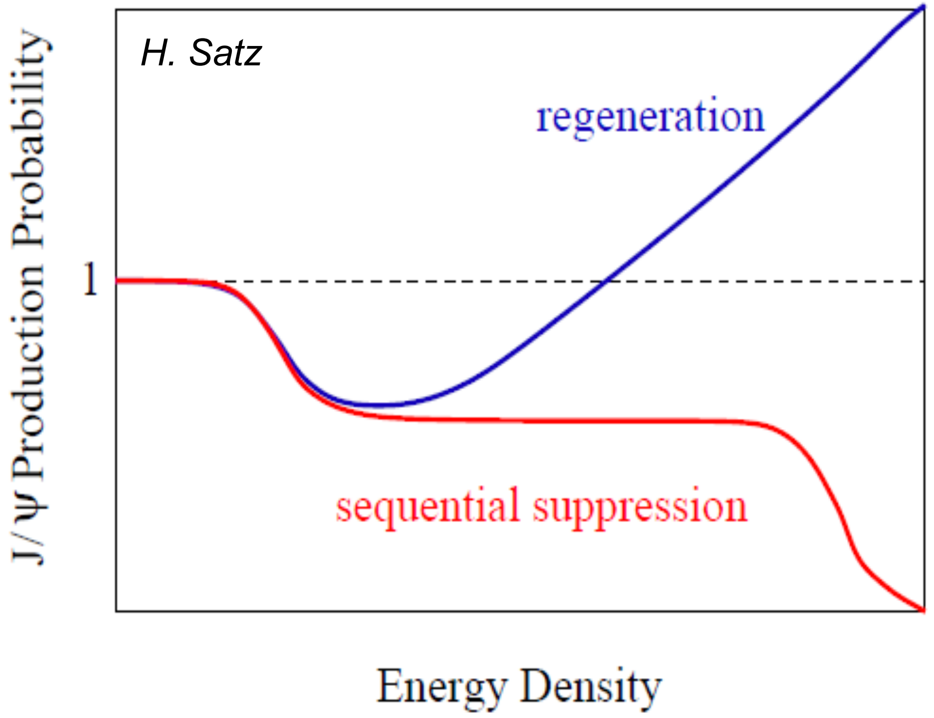
c from one c-cbar pair may combine with cbar from another c-cbar pair at hadronization to form a J/ψ
→ **regeneration!**

J/ψ suppression vs regeneration 1/2

(Re)generation of charmonium and charmed hadron production take place at the phase boundary or in QGP.
Dissociation and regeneration work in opposite directions vs energy density.



P. Braun-Munzinger, J. Stachel., Nature 448, 302–309 (2007)

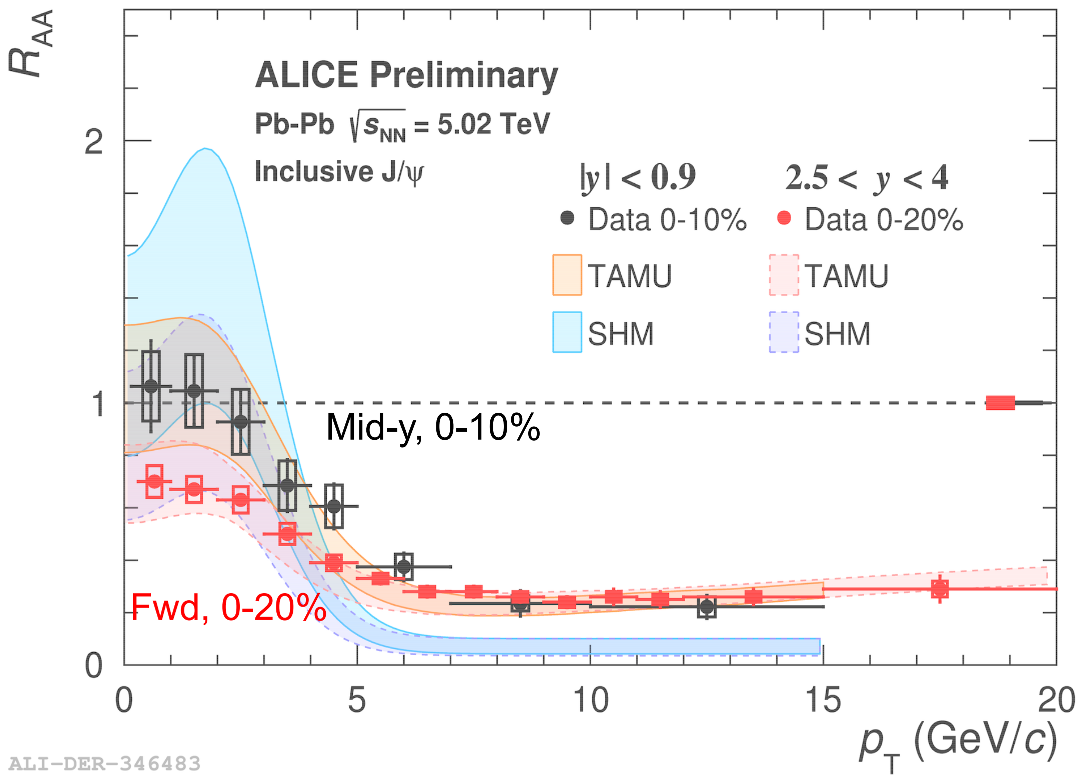


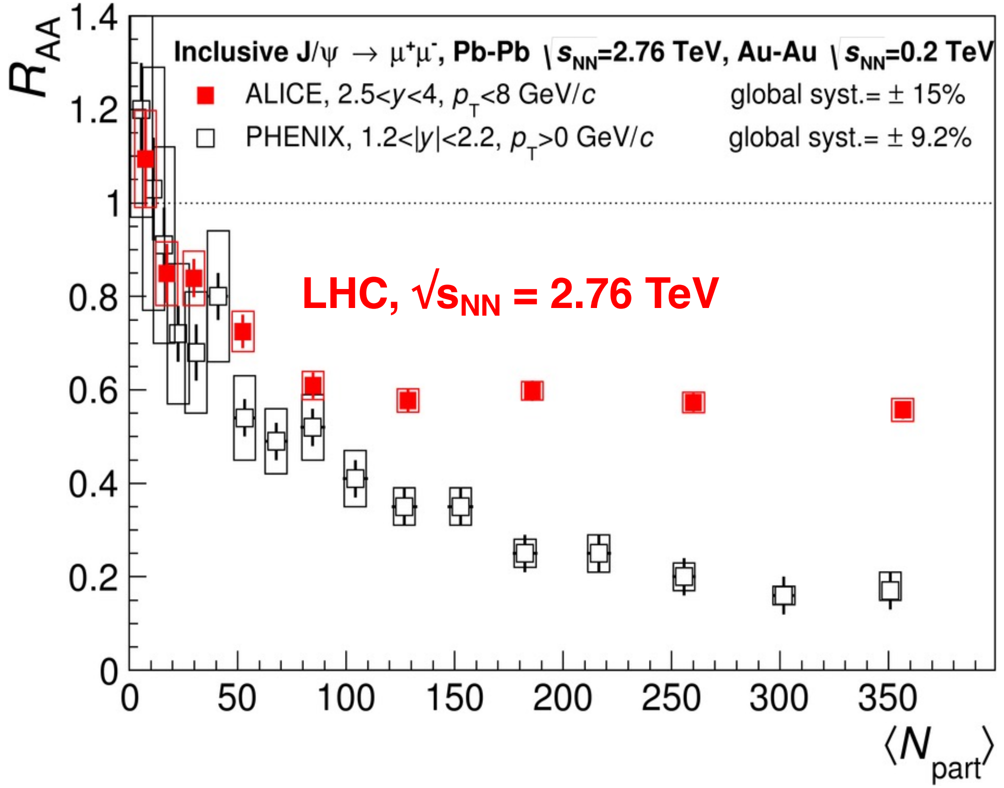
J/ψ suppression vs regeneration 2/2

ALICE data from 5.02 TeV Pb-Pb collisions confirm the J/ψ recombination picture:

- R_{AA}(LHC) > R_{AA}(RHIC)
- R_{AA} midrapidity > R_{AA} forward rapidity

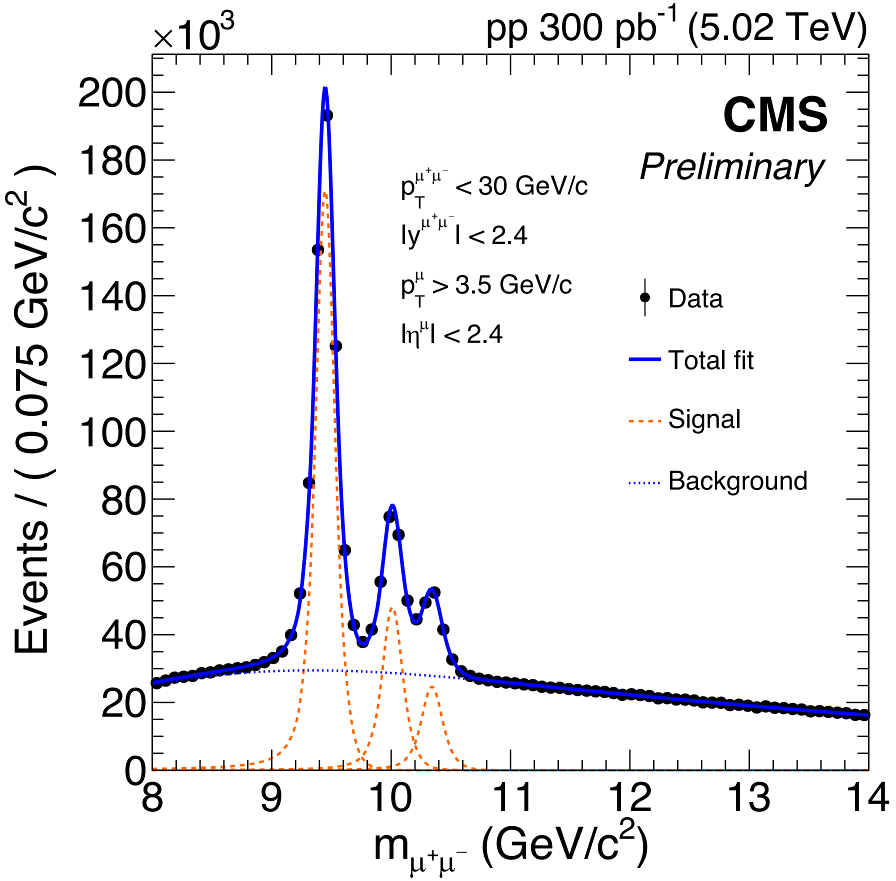
→ **Signature of de-confinement.**

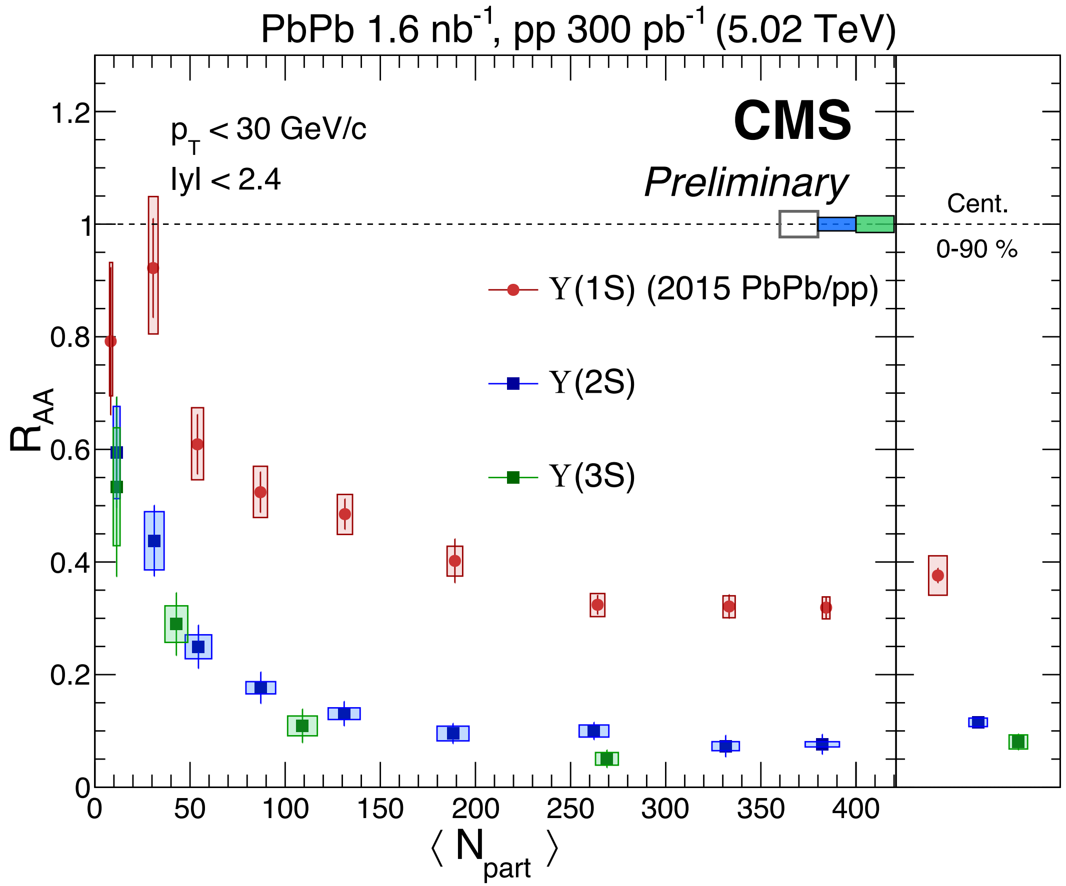




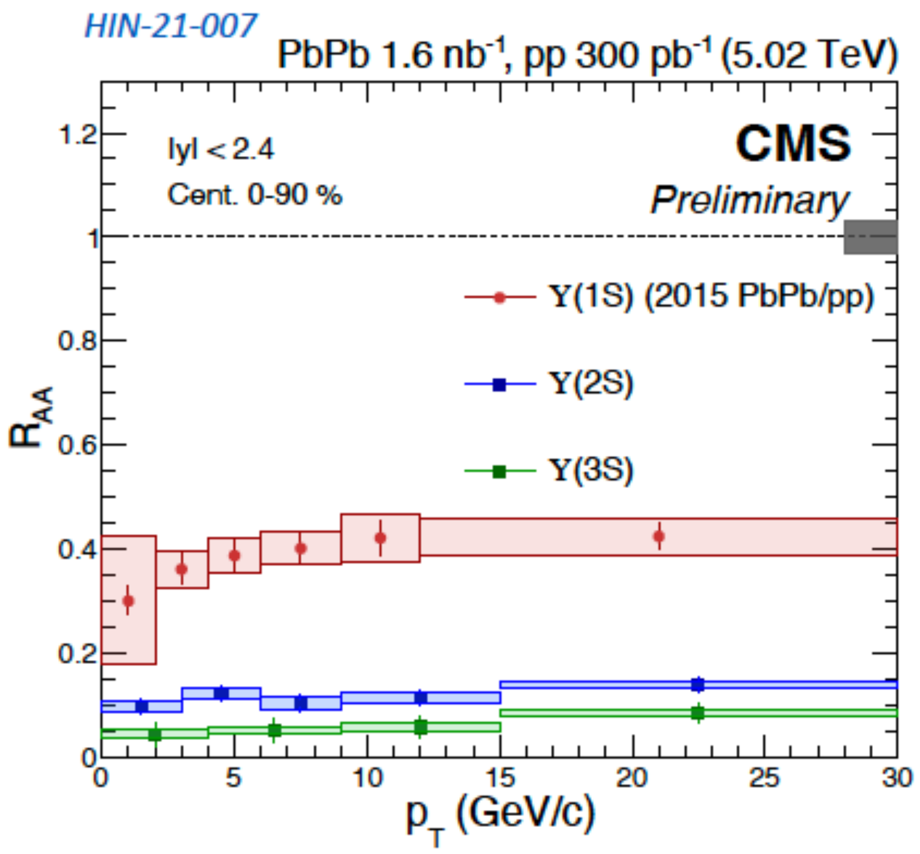
Sequential melting of quarkonia

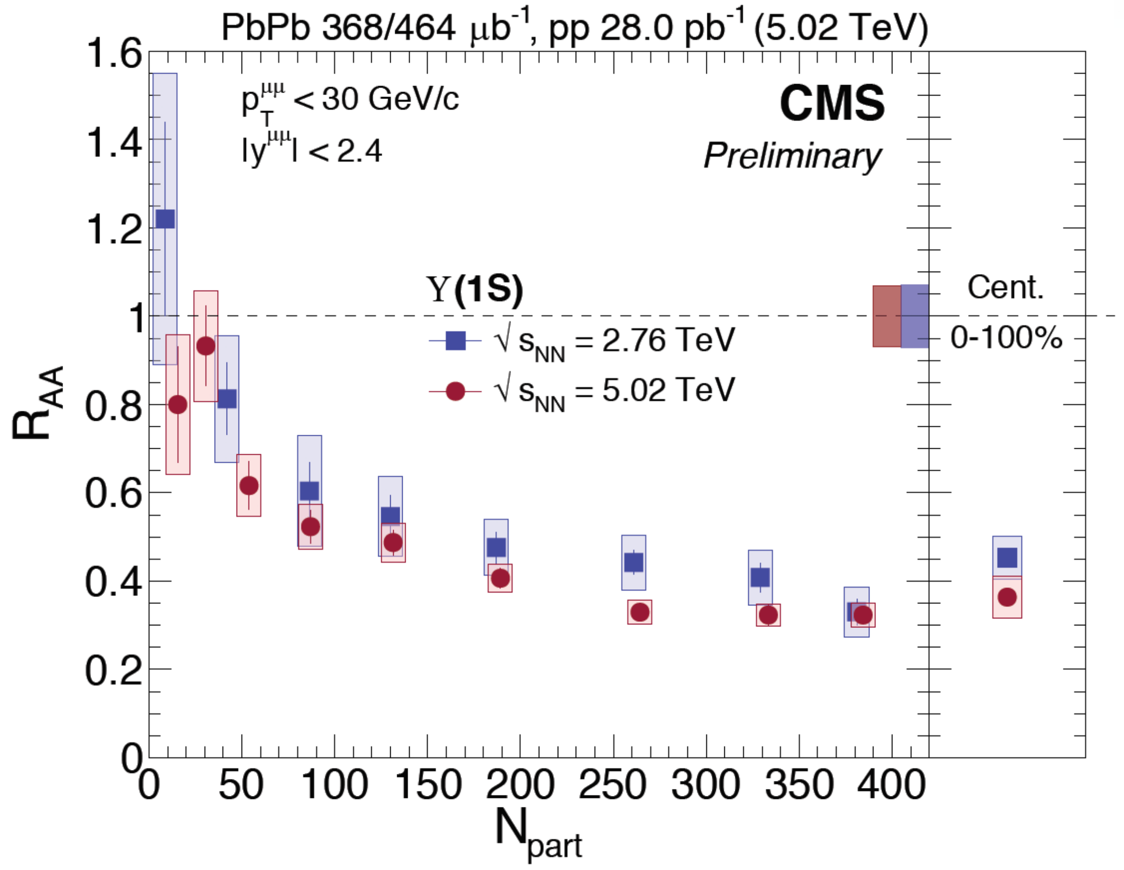
Measurements reveal a sequential suppression of high mass bottomonium states.
The centrality dependence of the suppression is consistent with progressive suppression in a hotter medium.





Sequential melting of quarkonia



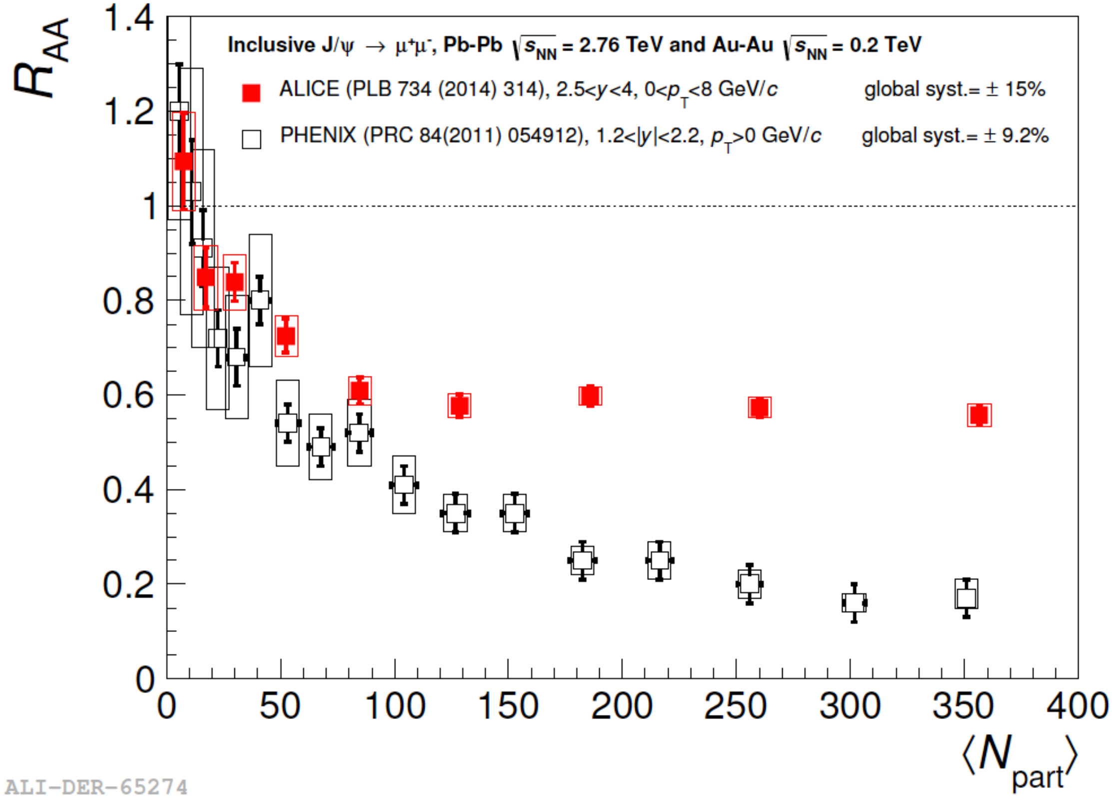


$R_{AA}(Y(3S) \sim 0.5\ R_{AA}(Y(2S))$
→ Can be used to constrain models!

Increased suppression with increased collision energy
→ no recombination at hadronisation

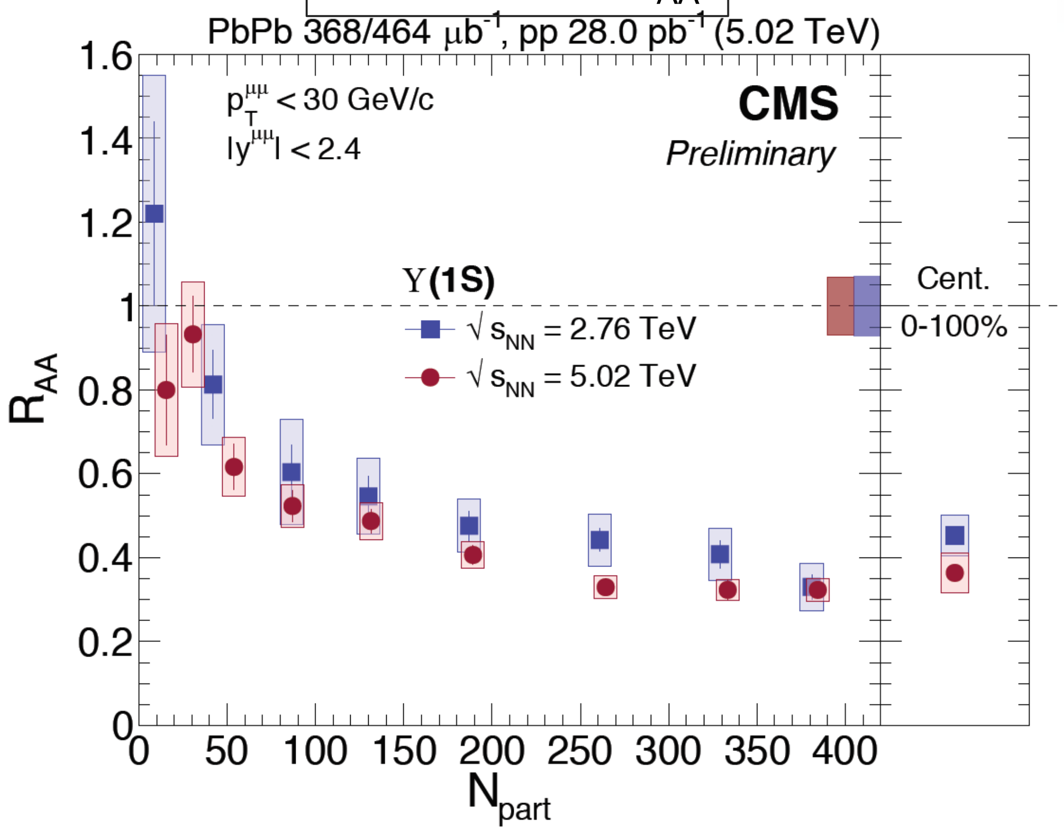
Quarkonia as probes

Charmonium R_{AA}



Charm is partially equilibrated (thermalised) with the medium
→ a partially-equilibrated probe of the late hadronization stages

Bottomonium R_{AA}



Beauty/bottomonia: no evidence that beauty is even partially equilibrated with the medium **→ non-equilibrium probe**

Summary 2/2

The study of quarkonium (ccbar, bbar) states provides information on the mechanisms of **dissociation and regeneration** of strongly-bound state in a medium (T>0).

- The high density of color charges in the QGP leads to melting of quarkonia
- The large abundance of charm quarks at LHC results in regeneration of the amount of J/ψ
- States with smaller binding energies are more suppressed