Heavy-ion collision experiment
(Lecture2)

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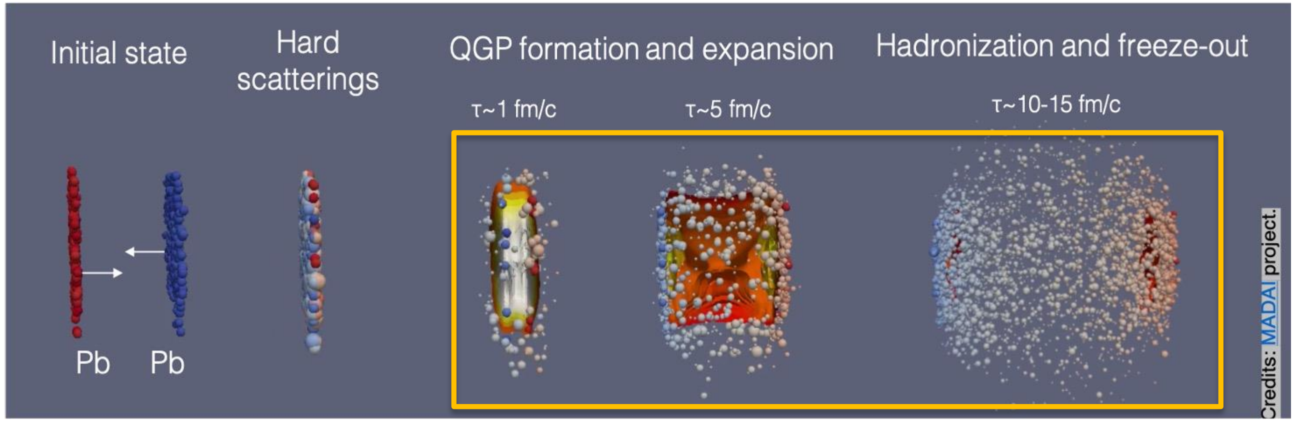
1. Why do we study relativistic heavy-ion collisions?
2. Experimental basis
3. Particle Yields and Statistical Model
4. Jet quenching and energy loss
5. Quarkonia
6. Highlights from small systems
7. Summary and outlook

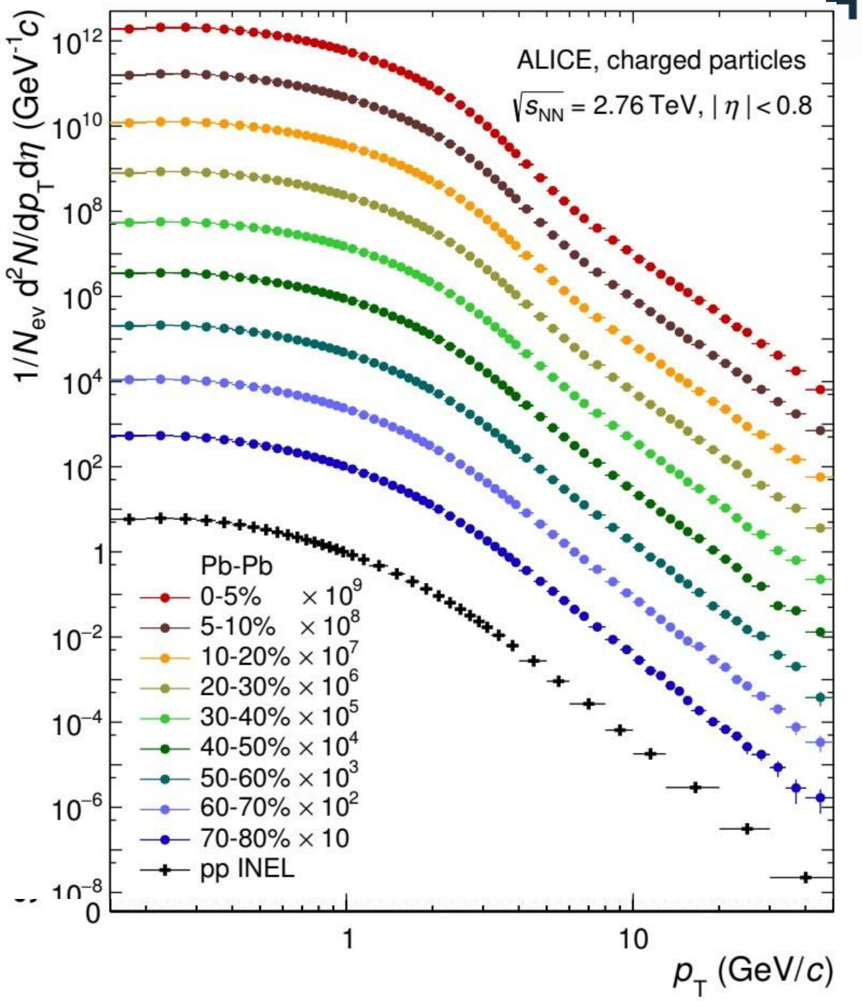
3. Particle Yields and Statistical Model

Bulk particle production



The bulk of particles is **soft** and composed by **light flavour** hadrons that are produced when the QGP hadronises.

The p_T and azimuthal distributions of hadrons carry information about the **collective evolution** of the system and its thermodynamical properties.



Goal: determine the thermodynamical and transport properties of the QGP

Particle spectra

Low p_T (< 2 GeV/c)

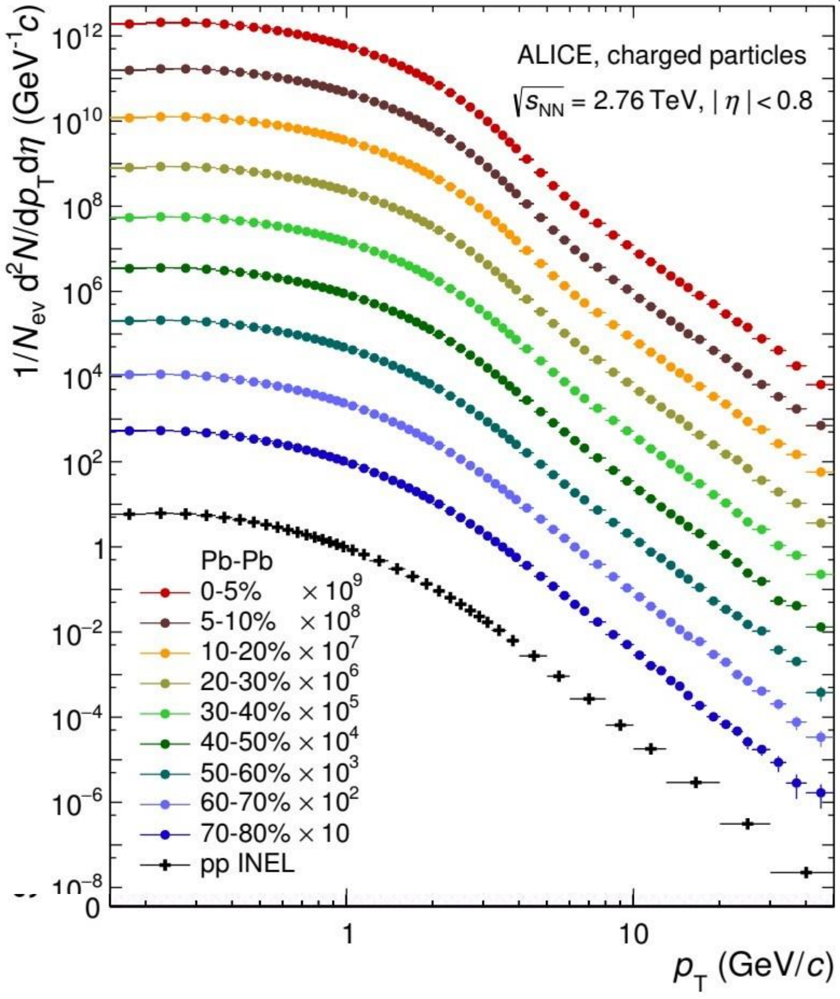
- Particle spectra are described by a Boltzmann distribution → "thermal", ~ $\exp(-1/k_B T)$
- "Bulk" dominated by light flavor particles
- Non-perturbative QCD regime

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



Chemical freez-out and Hadron-gas phase

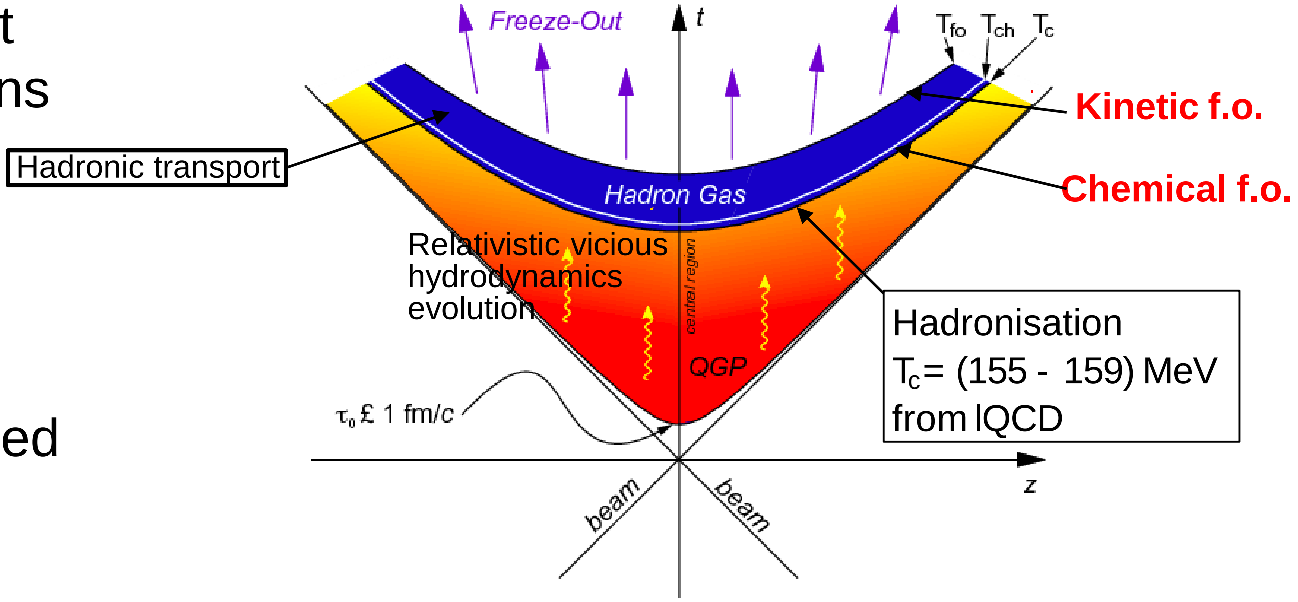
After hadronisation, the system is a hot (T< 155 MeV) and dense gas of hadrons and resonances.

Chemical freeze-out

- Inelastic collisions stop
- Relative particle abundances are fixed

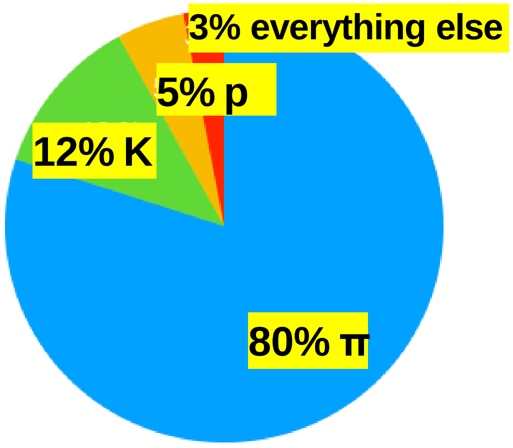
Kinetic freeze-out

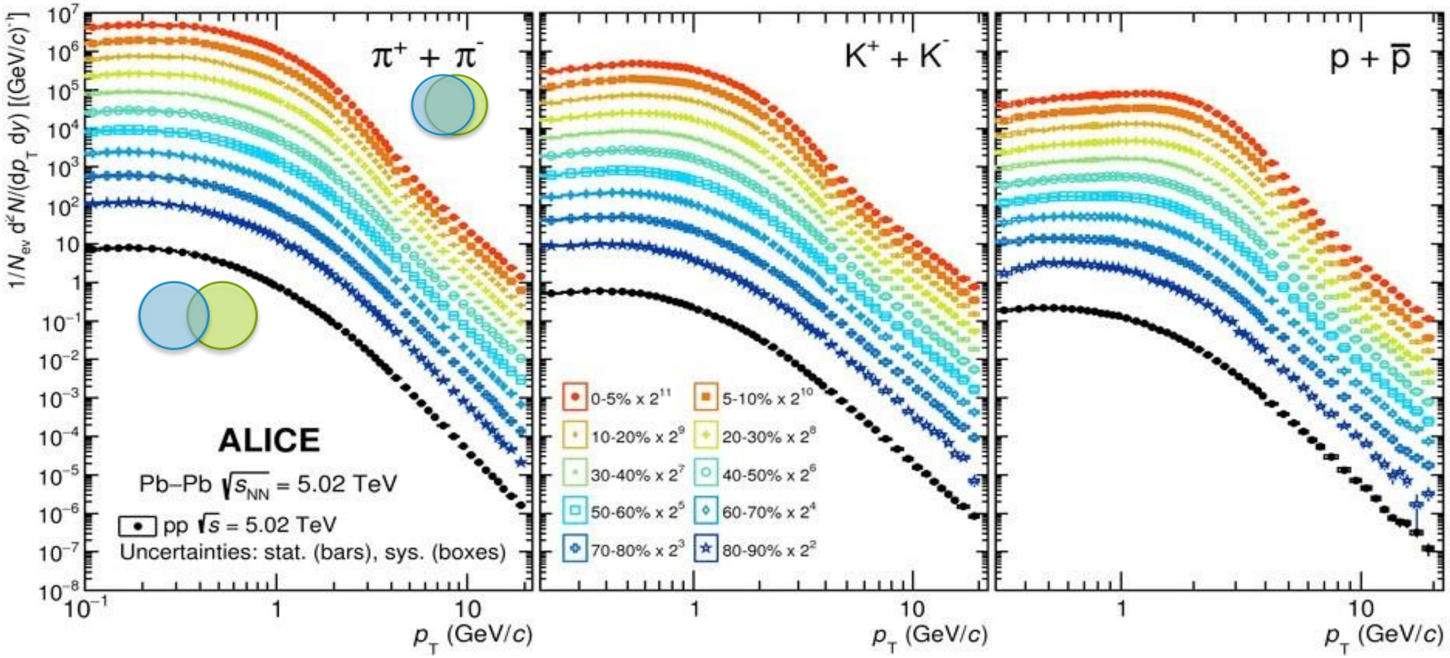
- (pseudo)elastic collisions stop
- Momentum distributions are fixed

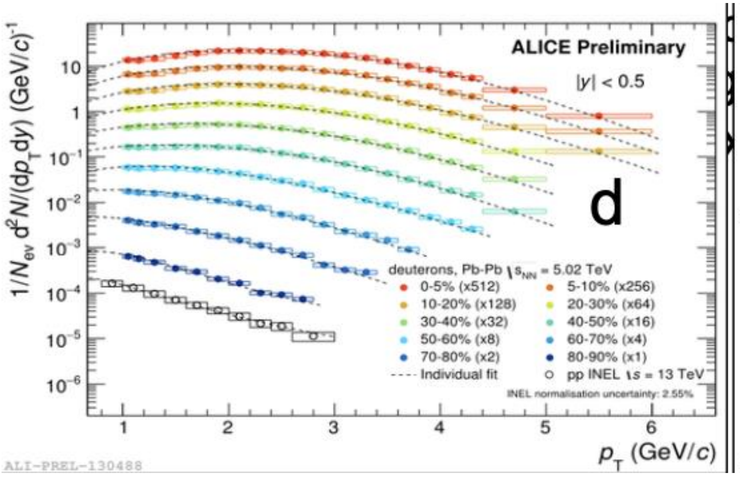


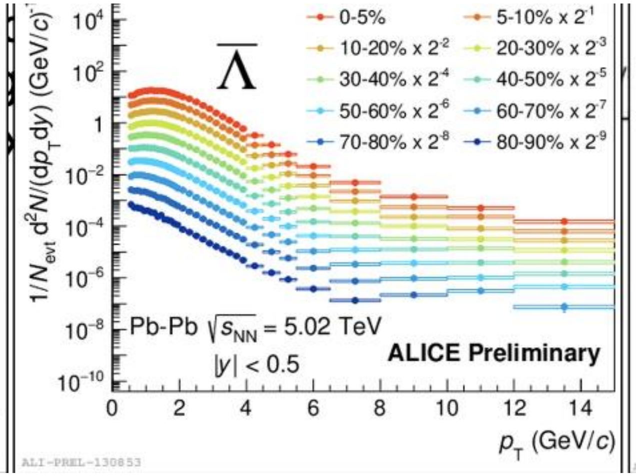
→ Fit abundance of identified hadrons: probe chemical equilibrium at **chemical freeze-out**
→ Fit shape of p_T spectra: probe final hadron kinematics at **kinetic freeze-out**

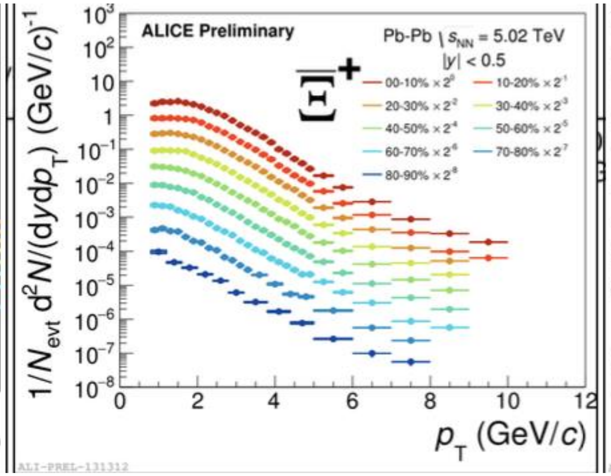
Identified particle production

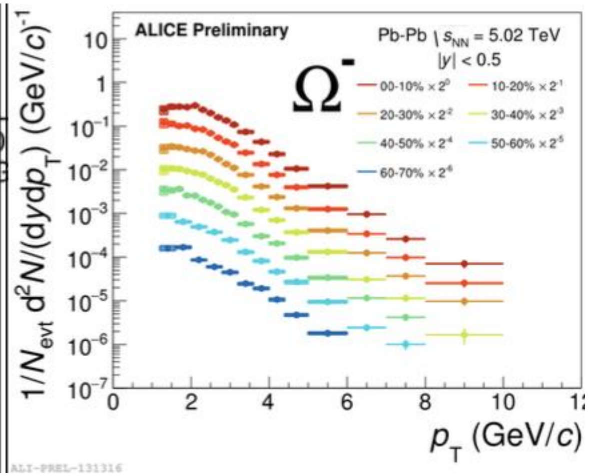












Statistical hadronisation model

It models an ideal relativistic gas of hadrons and resonances in **chemical equilibrium** (as the result of the hadronization of a QGP in thermodynamical equilibrium)

Particle abundances are obtained from the partition function of a Grand Canonical (GC) ensemble

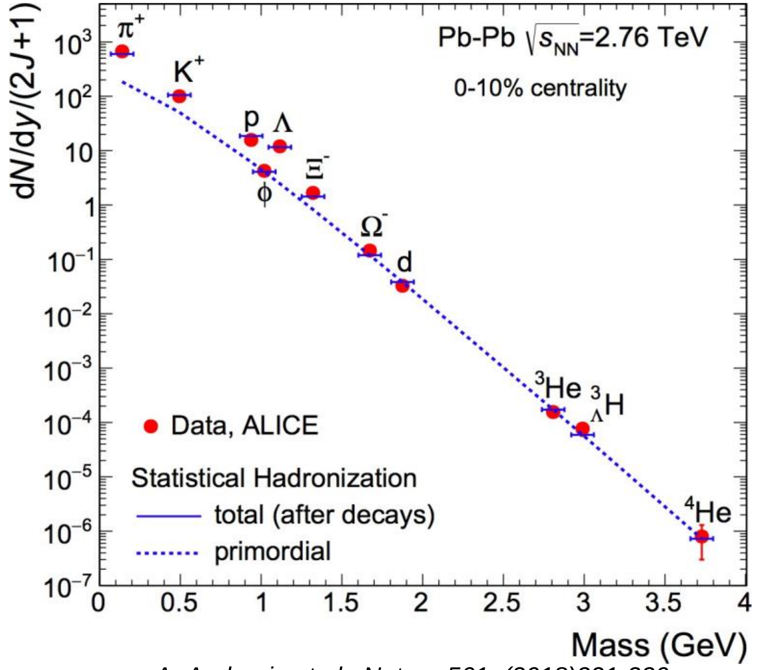
$$n_i = N_i/V = -\frac{T}{V}\frac{\partial \ln Z_i}{\partial \mu} = \frac{g_i}{2\pi^2}\int_0^\infty \frac{p^2 \mathrm{d}p}{\exp[(E_i-\mu_i)/T]\pm 1}$$

where chemical potential for quantum numbers are constrained with conservation laws.

$$\mu_i = \mu_B B_i + \mu_S S_i + \mu_{I_3} I_{3,i} + \mu_C C_i$$

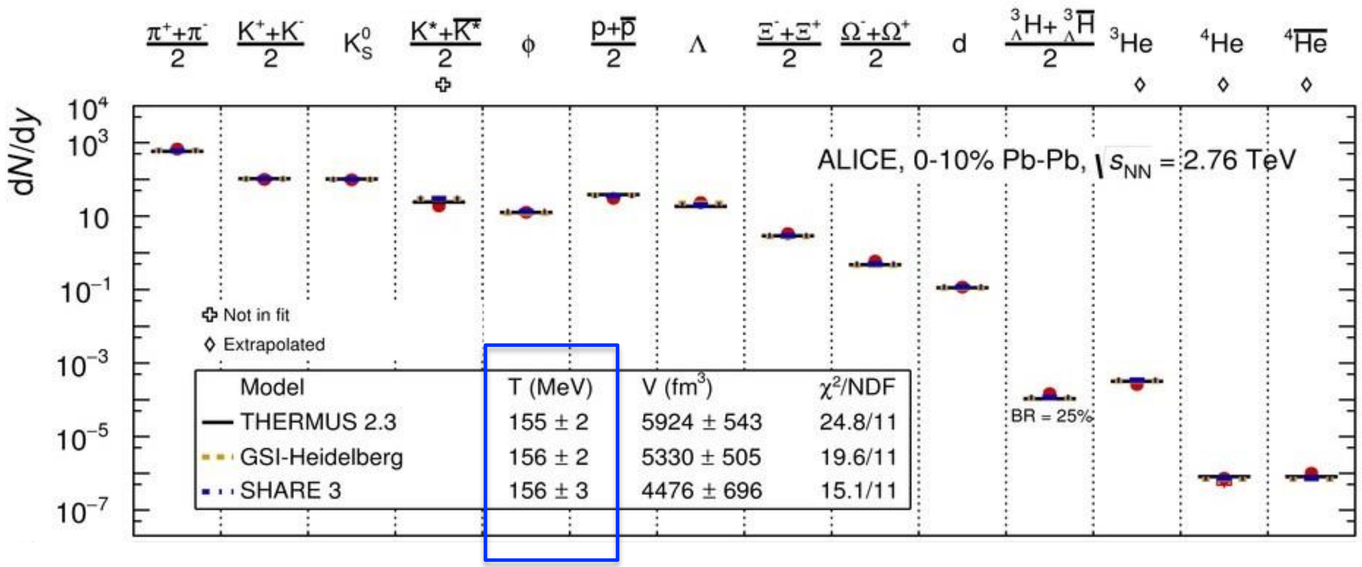
- ❑ Predict yields (see right figure) at a given temperature
- ❑ Fit measured particle yields (or ratios) to extract μ_B, T_{ch}, V.

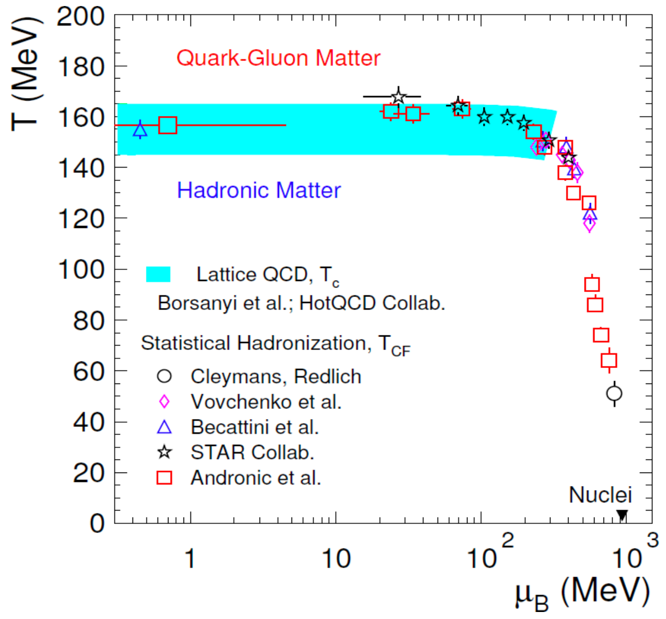
(2J+1)-spin degeneracy factor



A. Andronic et al., Nature 561, (2018)321-330

Chemical freeze-out temperature





Production of (most) light-flavour hadrons (and anti-nuclei) is described (χ^2/ndf ~ 2) by thermal models with a **single chemical freeze-out** temperature, **T_{ch} ≈ 156 MeV**

→ Approaches the critical temperature roof from lattice QCD: **limiting temperature** for hadrons!

→ the success of the model in fitting yields over 10 orders of magnitude supports the picture of a system in **local thermodynamical equilibrium**

Summary (Particle Yields & Statistical Model)

- After chemical freeze-out particle composition is fixed
- More than 10 species of hadrons measured at LHC
- Statistical model allows extraction of freeze-out temperature and baryochemical potential
- At high $\sqrt{s_{NN}}$ chemical freeze-out temperature close to phase transition temperature

Statistical models describe hadron production from $\sqrt{s_{NN}}$ = 2 to 5040 GeV

→

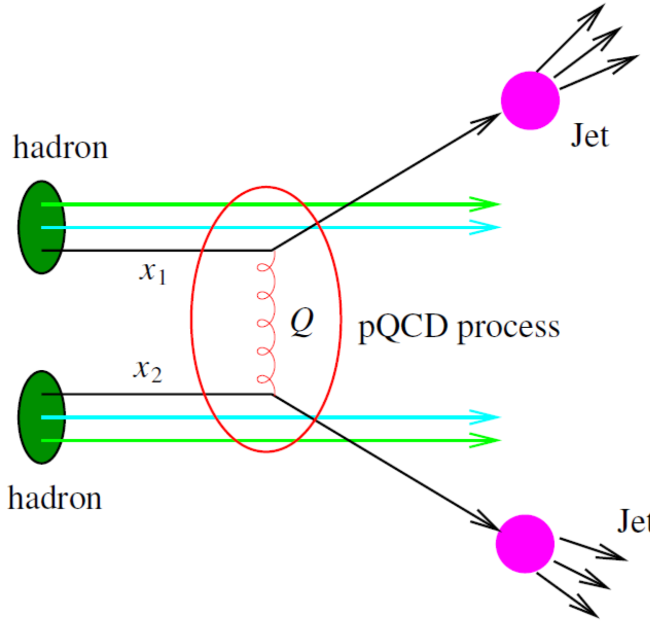
Matter created in HI collisions is in local thermal equilibrium

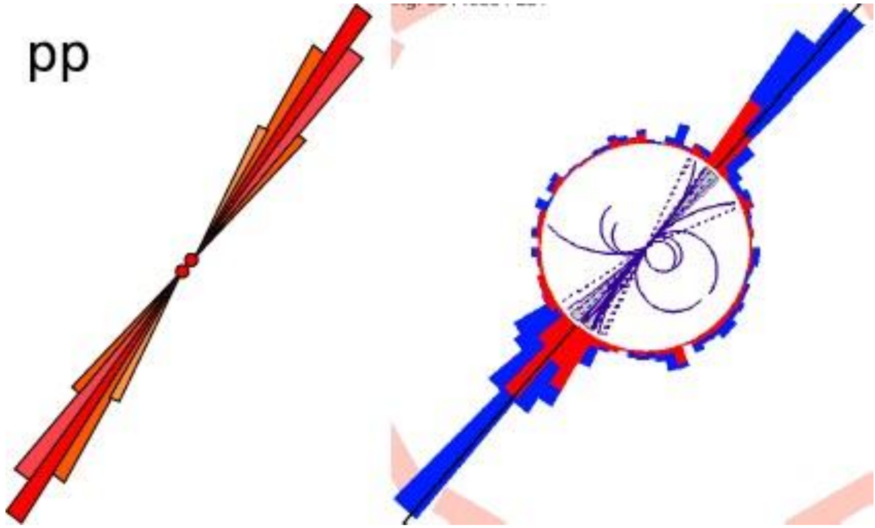
4. Jet quenching and energy loss

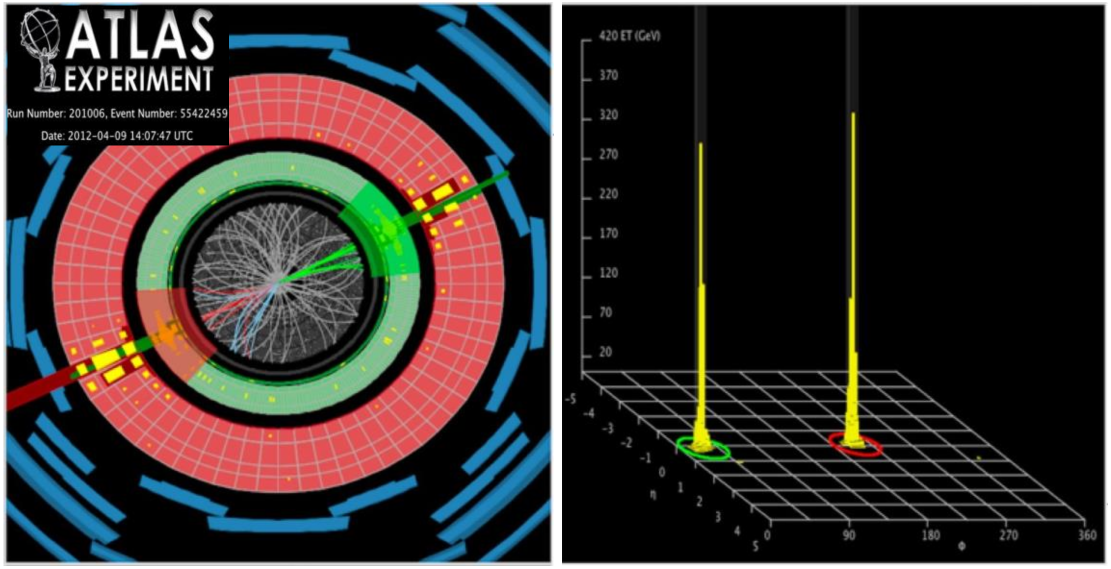
Jets

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.

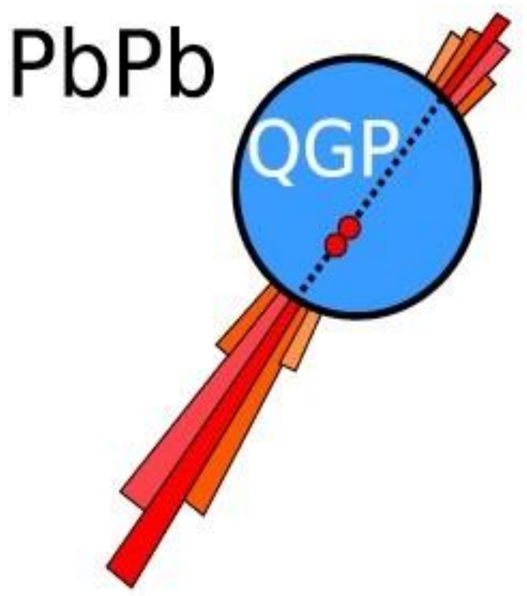
→ **in-vacuum fragmentation**

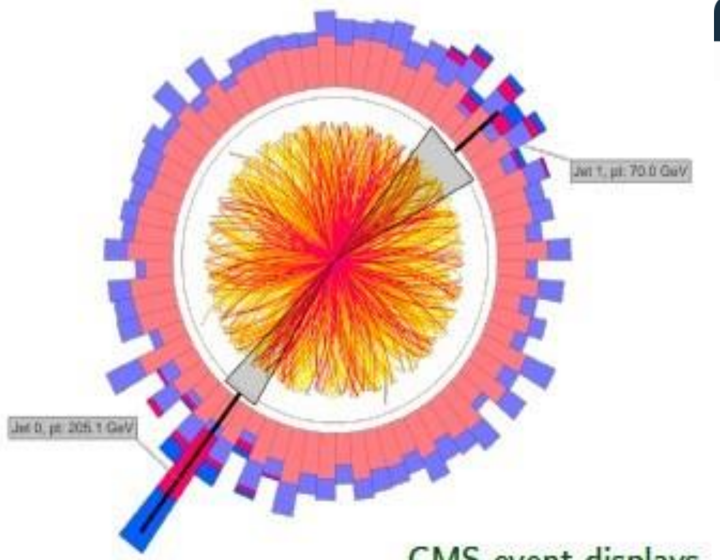
When a QGP is formed, the colored partons traverse and interact with a colored medium.

→ **in-medium fragmentation**

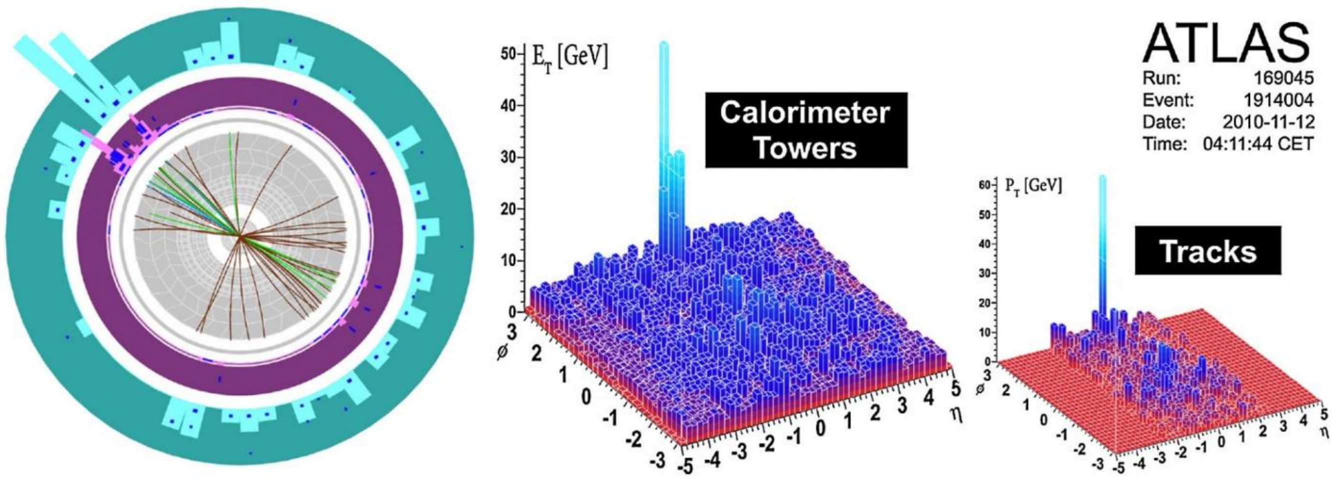
→ **jet ''quenching'' (energy loss)**

Goal: study and understand the nature of parton energy loss induced by the QGP



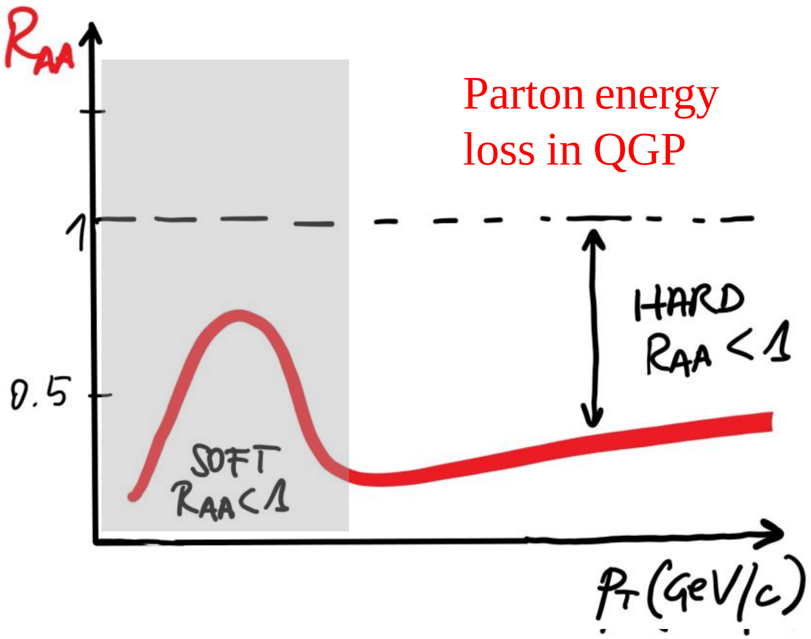


CMS event displays



The nuclear modification factor, R_{AA}

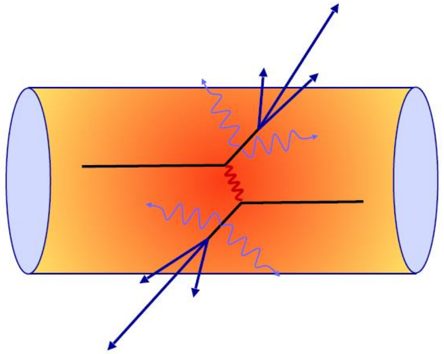
$$R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$



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

$$\mathrm{d}N_{AA}/\mathrm{d}p_T = N_{coll} \times \mathrm{d}N_{pp}/\mathrm{d}p_T$$

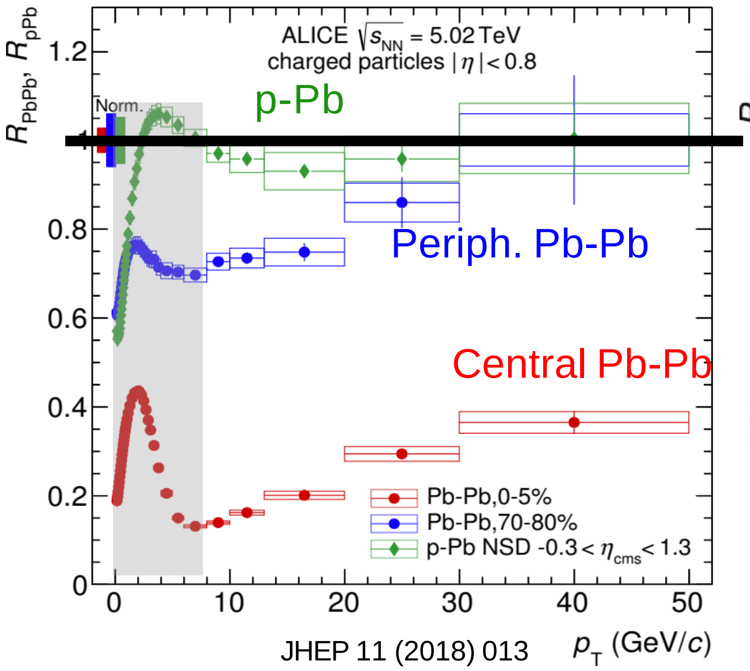
and $R_{AA} = 1$ at high p_T
→ the medium is transparent to the passage of partons



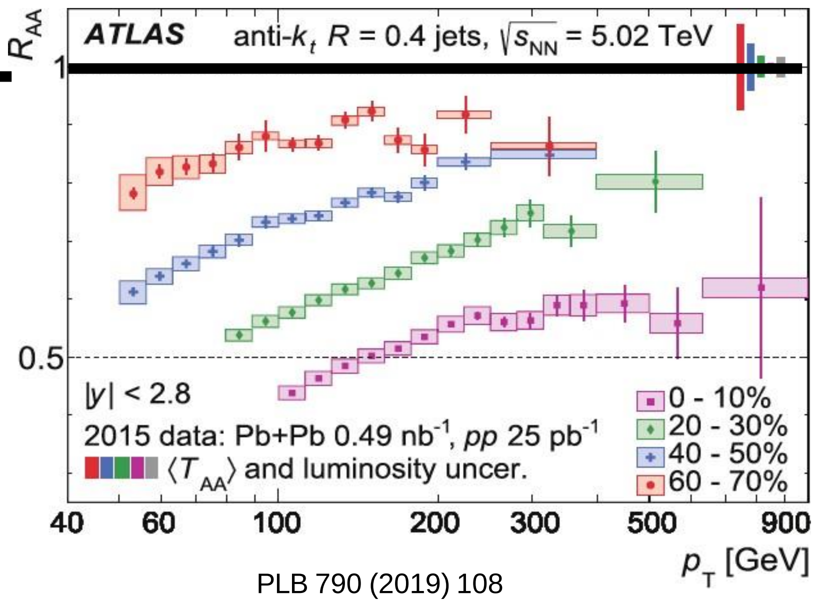
If $R_{AA} < 1$ at high p_T
→ the medium is opaque to the passage of partons
→ **parton-medium final state interactions, energy loss, modification of fragmentation in the medium**

Evidence of parton energy loss in QGP

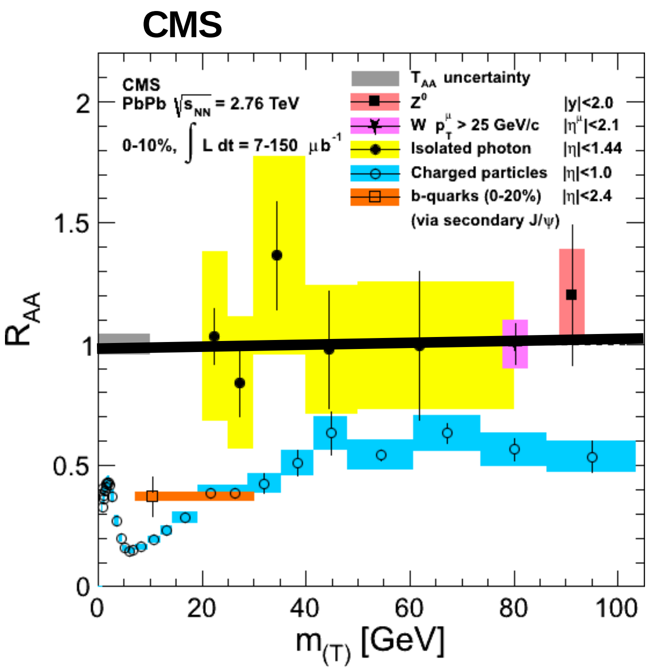
Charged particles



Inclusive jets



EW bosons



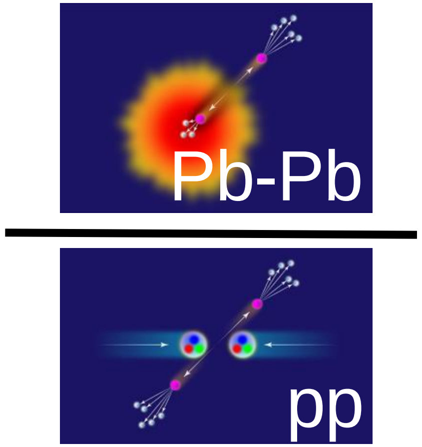
- A strong suppression of high-p_T hadrons and jets is observed in central Pb-Pb collisions.
- No suppression observed in p-Pb collisions, nor for the color-less Z bosons and photons.

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

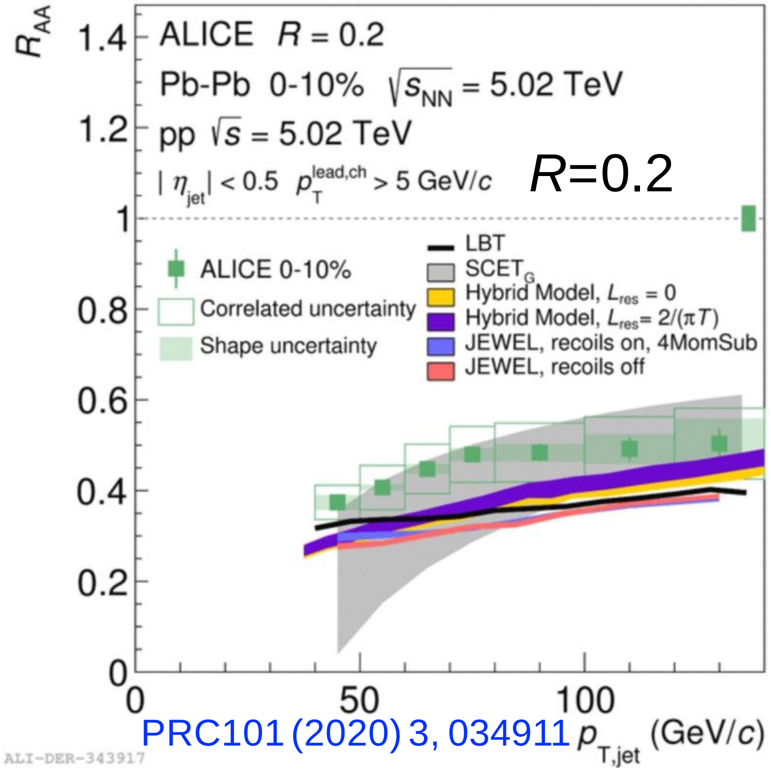
$$R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$

Probing Jet quenching in Pb-Pb collisions

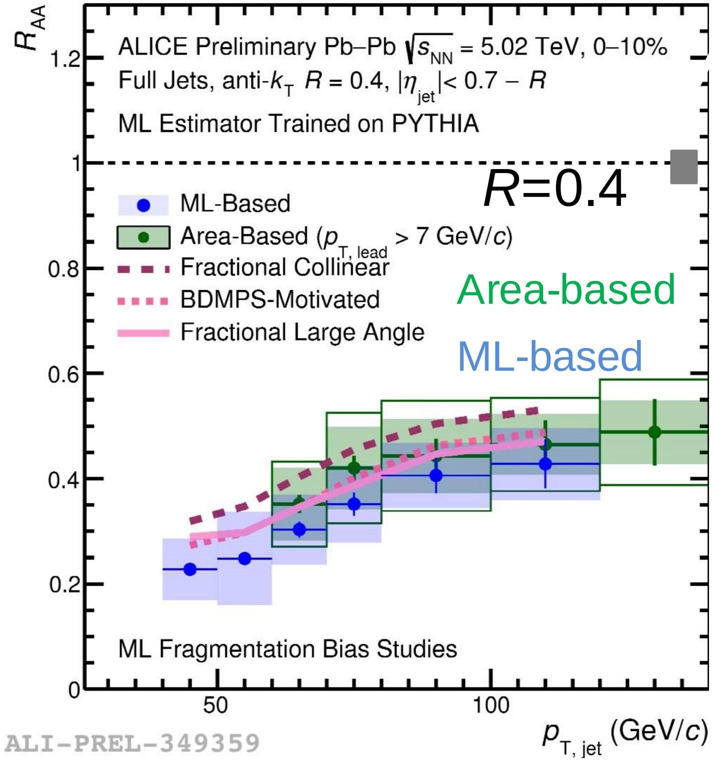
$$R_{AA} = \frac{1}{\langle N_{coll}\rangle}\frac{dN/dp_T|_{PbPb}}{dN/dp_T|_{pp}}$$



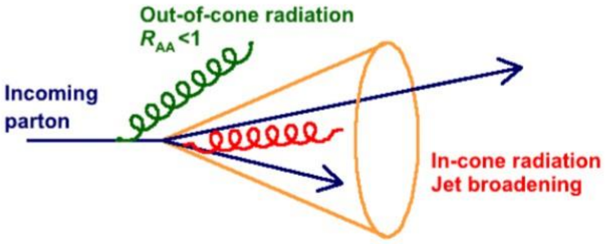
with area-based background subtraction



Exploring ML background subtraction



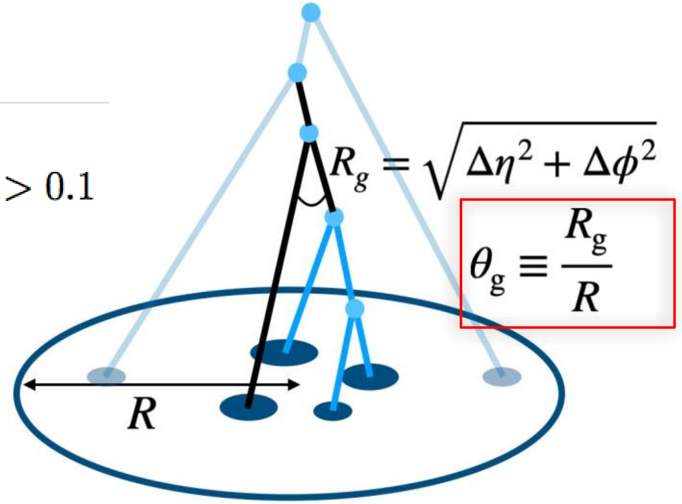
- ➢ Large reduction (factor 3-4) of jet yields, down to 40 GeV/*c*
- ➢ Lost energy is not recovered within the jet "cone" up to R= 0.4→ large angle QGP-induced gluon emission

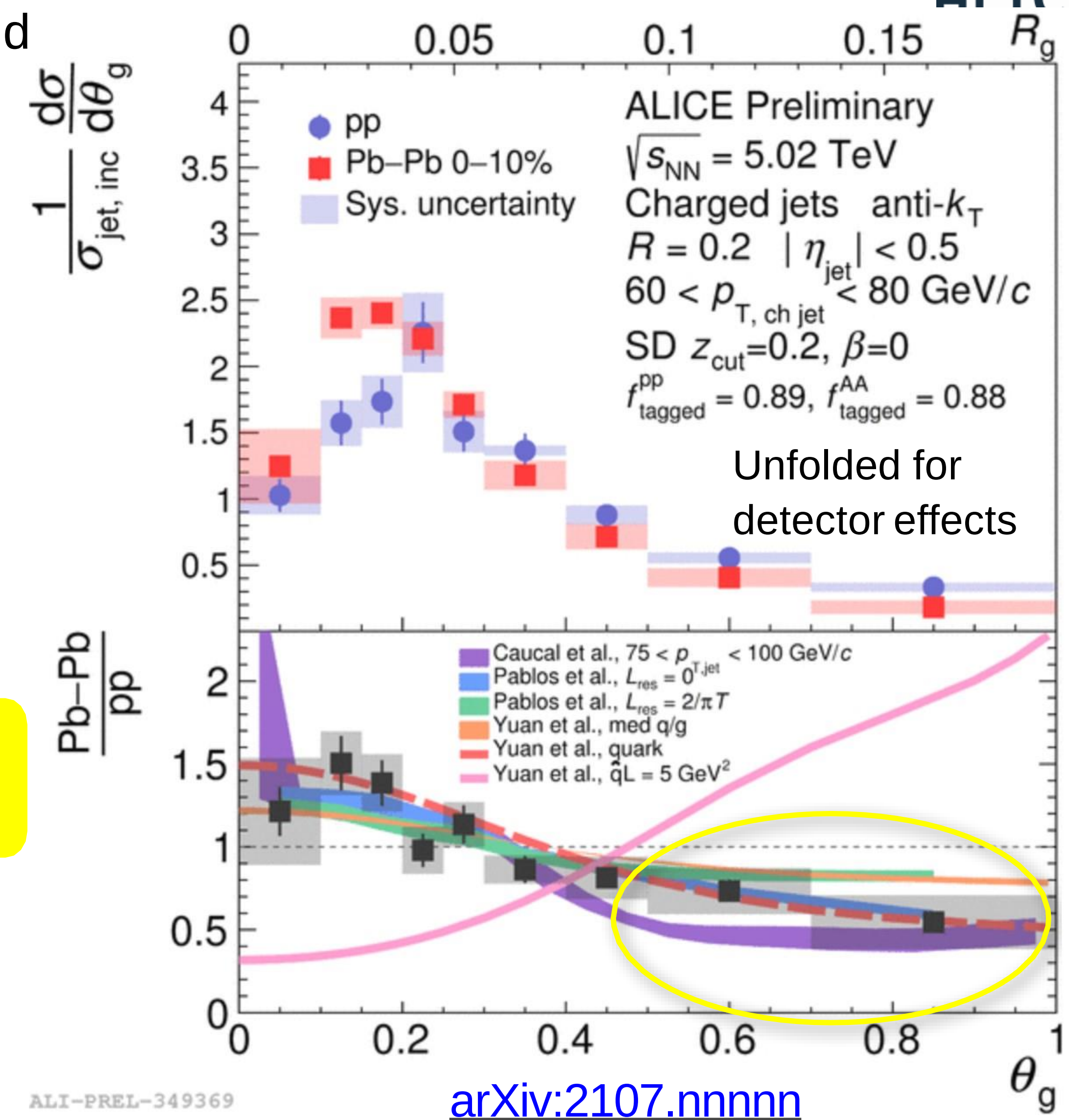


Jet substructure in Pb-Pb collisions

- Understand evolution of parton-medium interactions and energy redistribution by exploring substructure of jet
  - —By soft drop (SD) grooming to find first hard splitting

$$z_g = \frac{\min(p_{\perp,1}, p_{\perp,2})}{p_{\perp,1} + p_{\perp,2}} \qquad z_g > 0.1$$

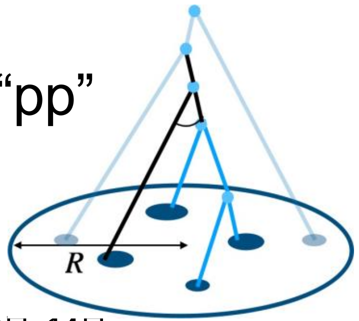




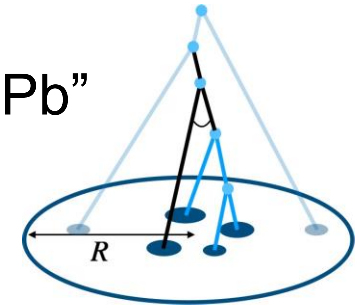
arXiv:2107.nnnnn

➢ First evidence: Jet core is more collimated in Pb-Pb than in pp

Cartoon: "pp"

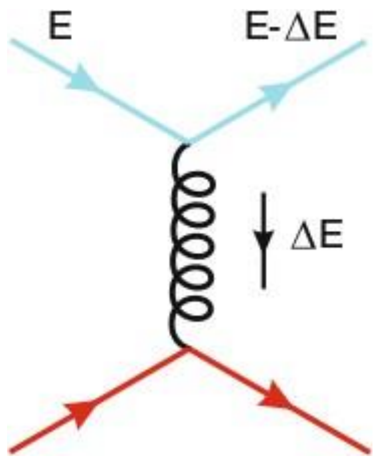


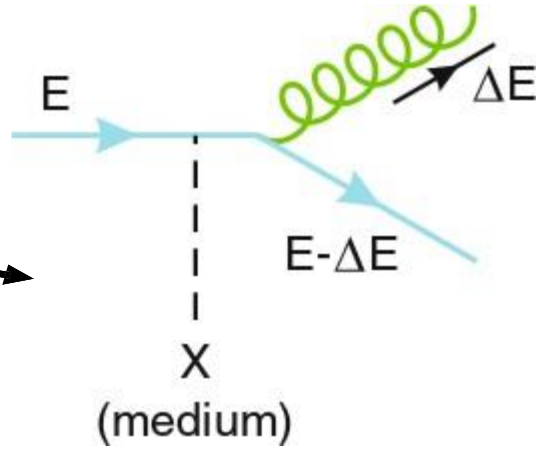
"Pb-Pb"



Energy Loss in the QGP

- QGP: high density of quarks and gluons / color sources
- Traversing quark / gluon feels color fields
- Collisional energy loss
  - Elastic scatterings
  - Dominates at low momentum
- Radiative energy loss
  - Inelastic scatterings
  - Dominates at high momentum
  - Gluon bremsstrahlung





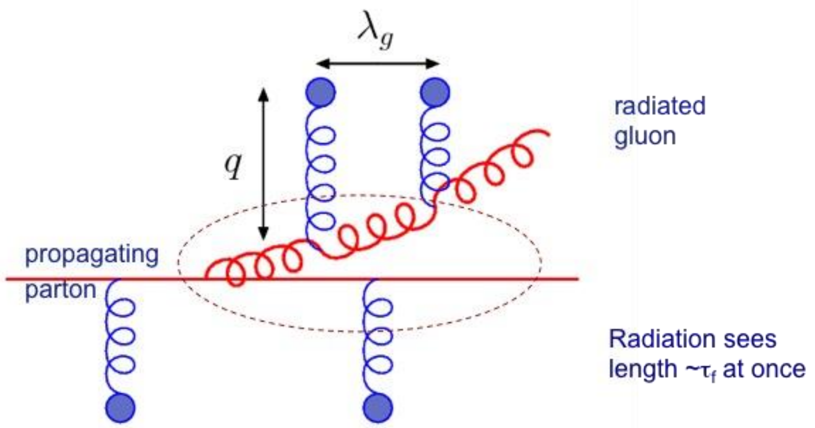
$\Delta E = \Delta E_{coll} + \Delta E_{rad}$

Lect. Notes Phys. 785,285 (2010)

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 =3 for gluon interactions
  - C_r =4/3 for quark 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)



$$\frac{dE}{dx} = -C_r \alpha_s \hat{q} L^2$$

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

Average transverse momentum transfer

Mean free path

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

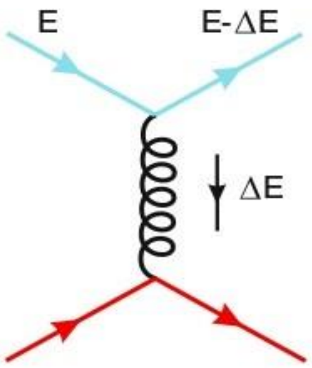
Density

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

Collisional energy loss

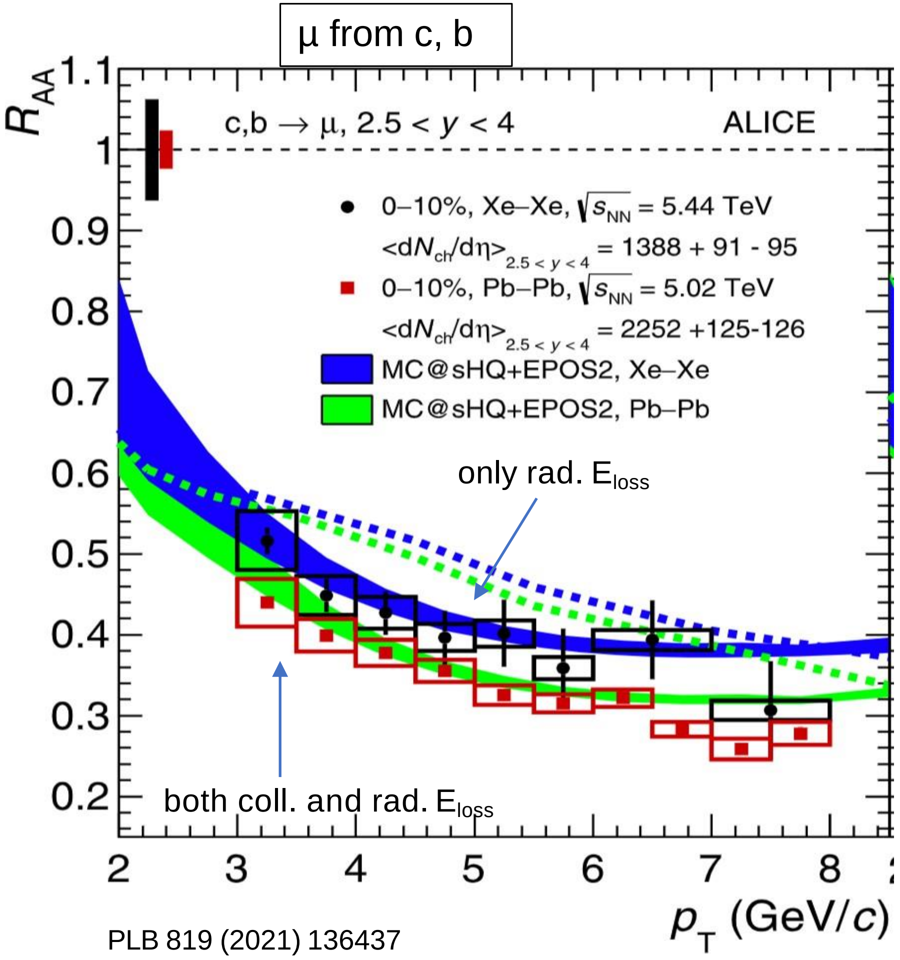
It depends on

- **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 （MC@sHQ+EPOS2） that include both collisional and radiative E_{loss} ,
but PHSD model including nuclear PDF modification and collisional energy loss cann't (see dot lines).



PLB 819 (2021) 136437

Jet transport coefficient $\hat{q}$

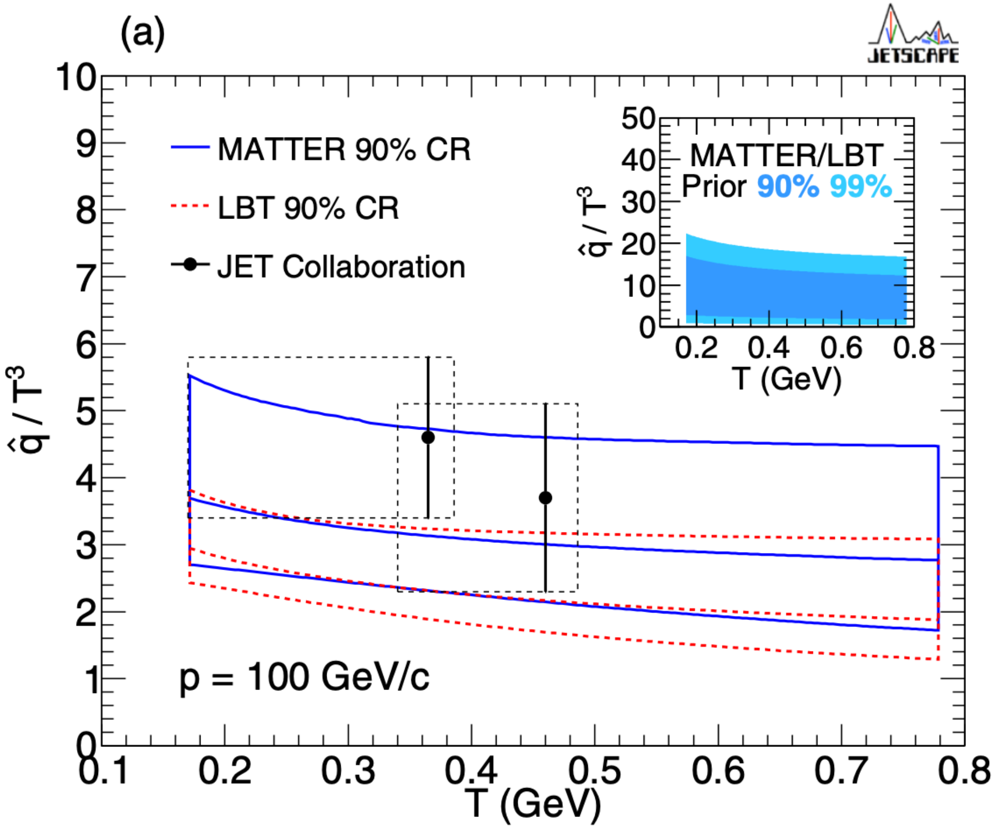
A recent combined analysis of the RHIC and the LHC data on jet quenching (inclusive hadron R_{AA}) allowed to extract a value for the $\hat{q}$ parameter

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

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

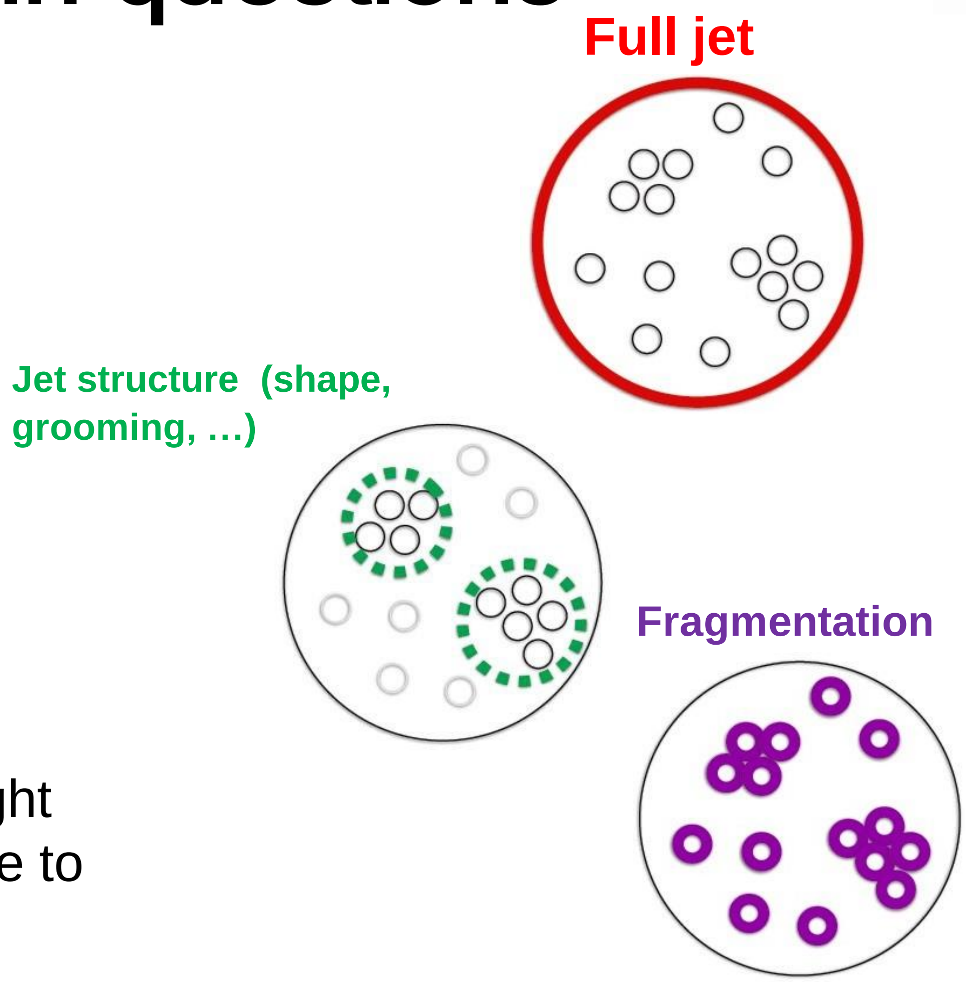
Related to the properties of the medium

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

Related to 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}**



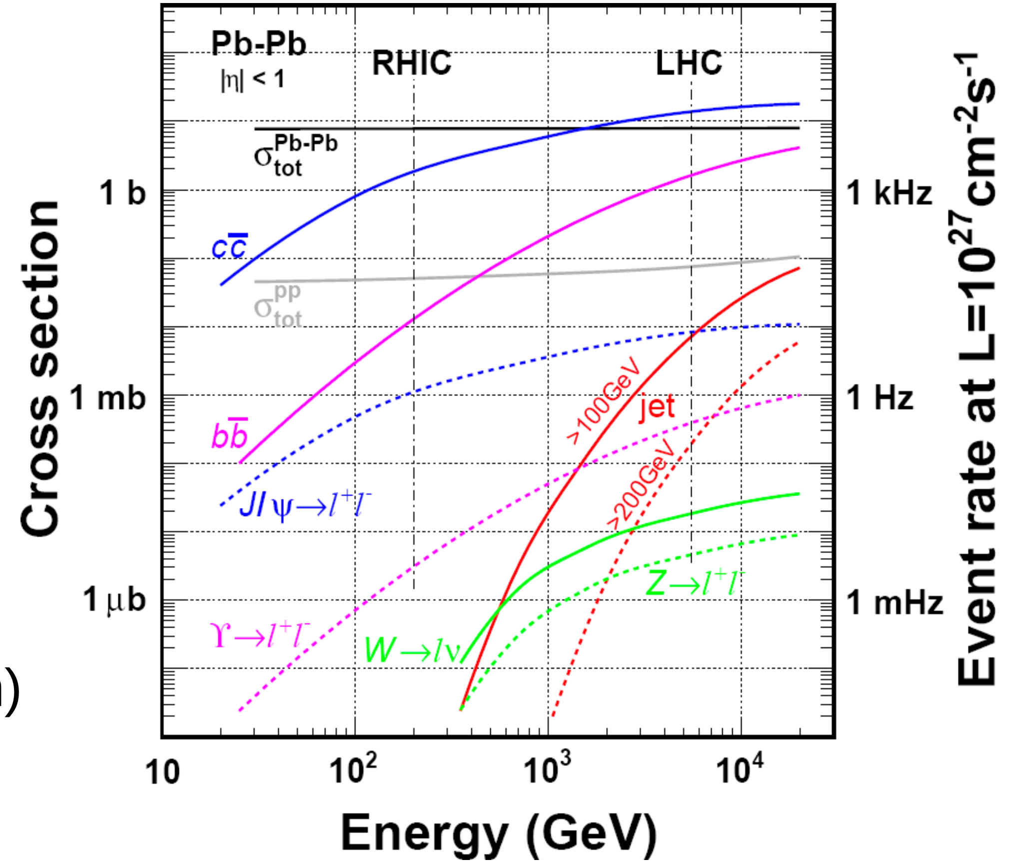
Heavy Quarks: charm and beauty

Charm (m ~ 1.3 GeV/c^2)) and Beauty (m ~ 4.7 GeV/c^2)

- produced in **initial hard** parton scatterings
  τ_b ~ 0.02<τ_c ~0.07<τ_QGP ~ 0.1-1 fm/c
- **large production cross sections**
  (~7 D > 2 GeV/c per central event)
- Essentially not produced in the QGP

➡ ideal probes of the QGP at the LHC

- "brownian" motion through the medium, **diffusion**
- sensitive to QGP **hadronisation** (into baryon/meson)
- Expectation $R^{\pi}_{AA} < R^{D}_{AA} < R^{B}_{AA}$



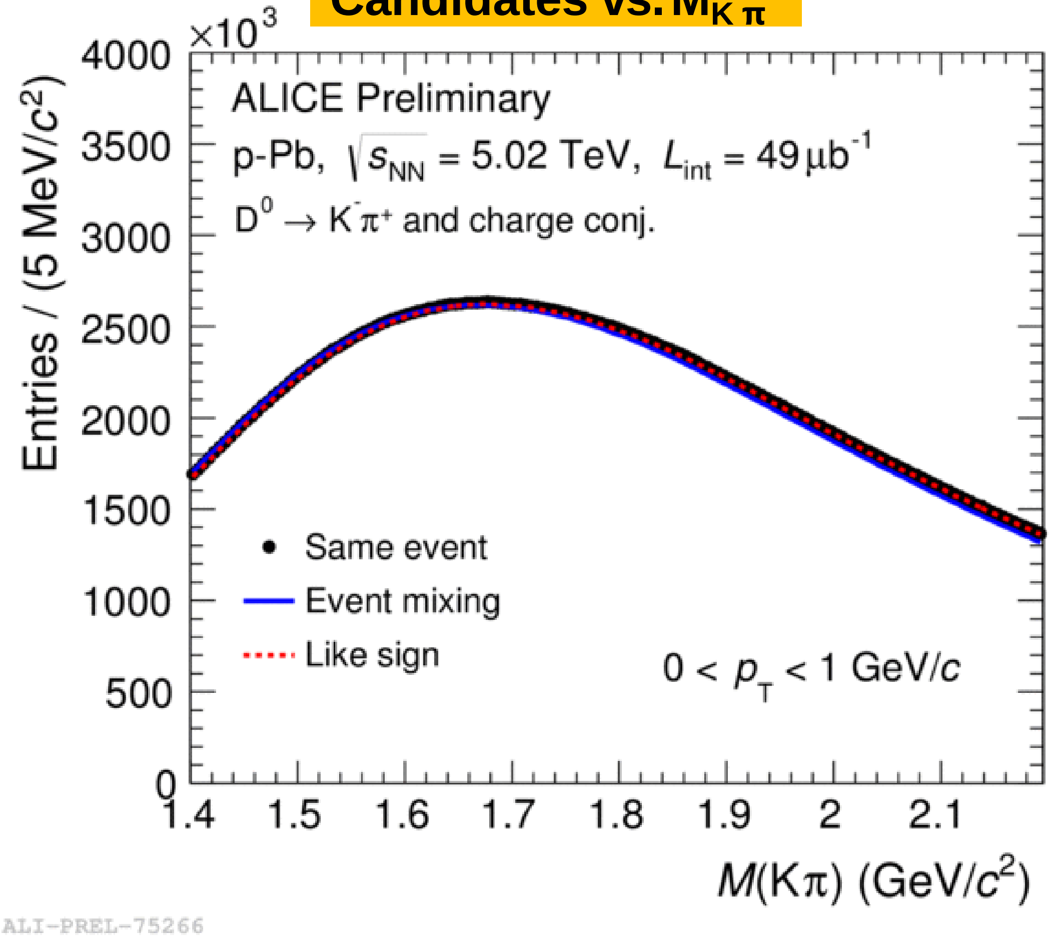
D^0 Reconstruction

- D^0 meson: m = 1.87 GeV/c^2 ; $c\tau$ = 123 μm
  - Rather short lived
  - Many decay modes
  - $D^0 \rightarrow K\,\pi$ (branching ratio 3.9%)
- Standard method: invariant mass of opposite charge pairs
  - Per central event ($D^0 \rightarrow K\,\pi$, > 2 GeV/c, incl. efficiencies): 0.001 compared to ~700 K and up to ~2500 π
  - Signal over background far too small to extract a peak
- Reduce combinatorial background (see next slides)
  - Topological cuts
  - Particle identification (PID) of K and π

Invariant Mass

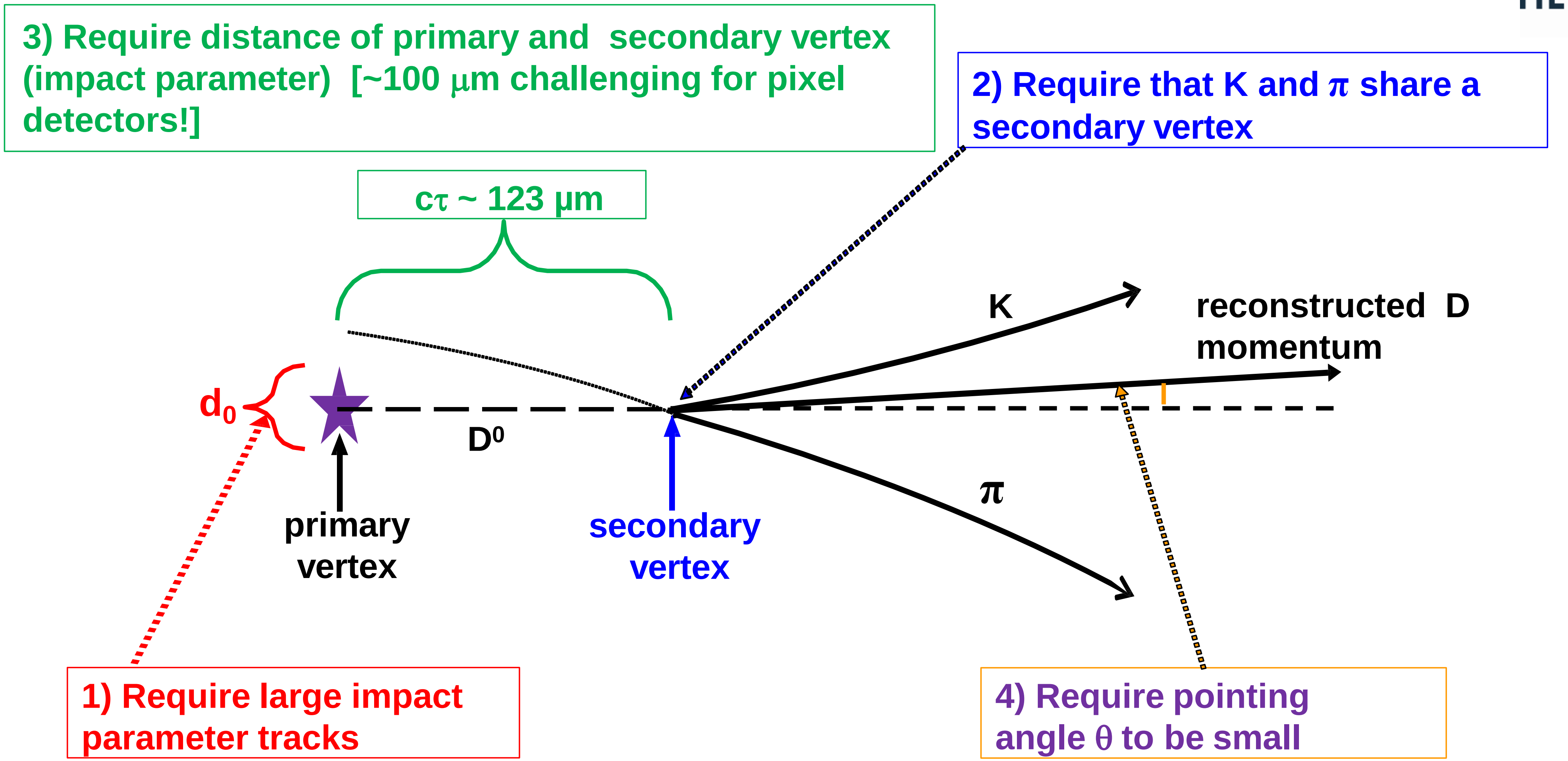
- $D^0 \rightarrow K\,\pi$ without PID and without topological cuts

Candidates vs. $M_{K\,\pi}$



Peak not visible without cuts

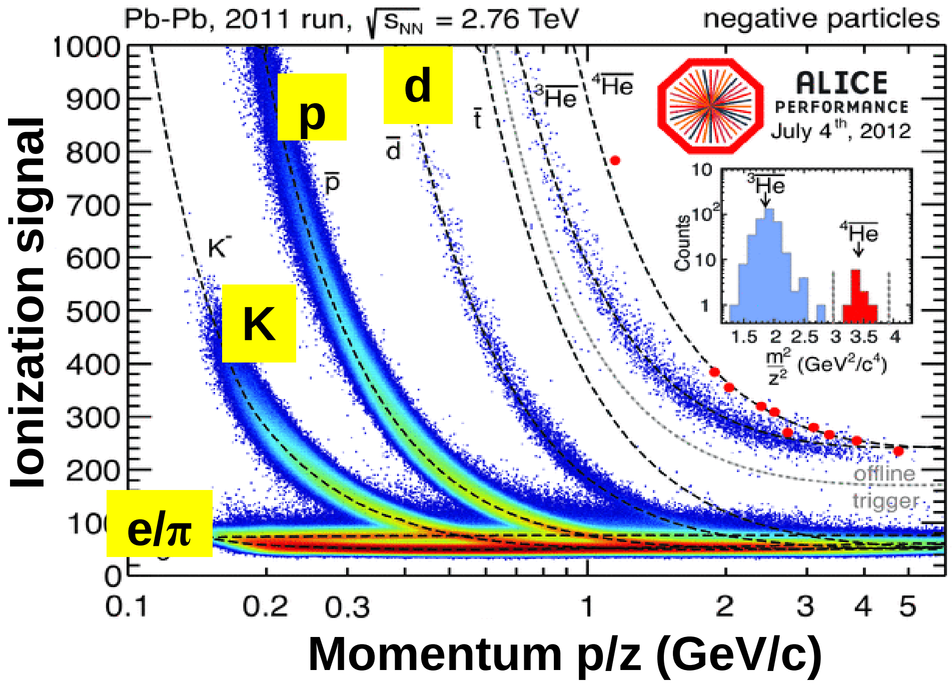
Topological Cuts

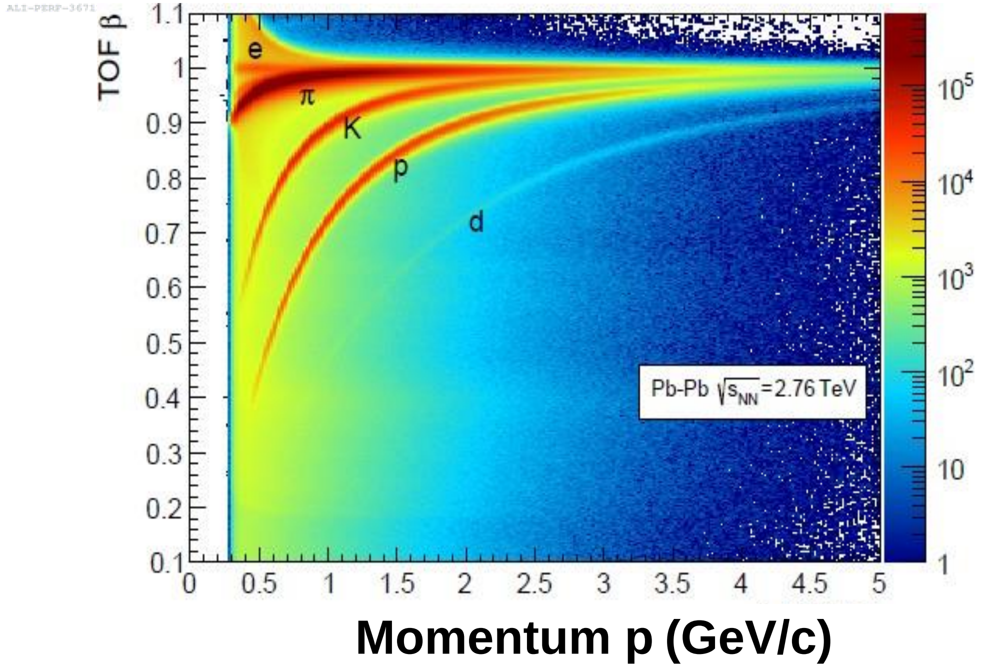


Plane transverse to beam

PID

- **Specific Energy Loss**
  - Particles passing through matter loose energy mainly by ionization
  - Average energy loss calculated with Bethe-Bloch formula
  - Identify particle by measuring energy deposition and momentum
- **Time Of Flight**
  - Particles with the same momentum have slightly different speed due to their different mass
  - Needed flight time precision, e.g. for a particle with p = 3 GeV/c, flying length 3.5 m:
    t(π) ~ 12 ns | t(K) – t(π) ~ 140 ps
- **Methods can be combined**

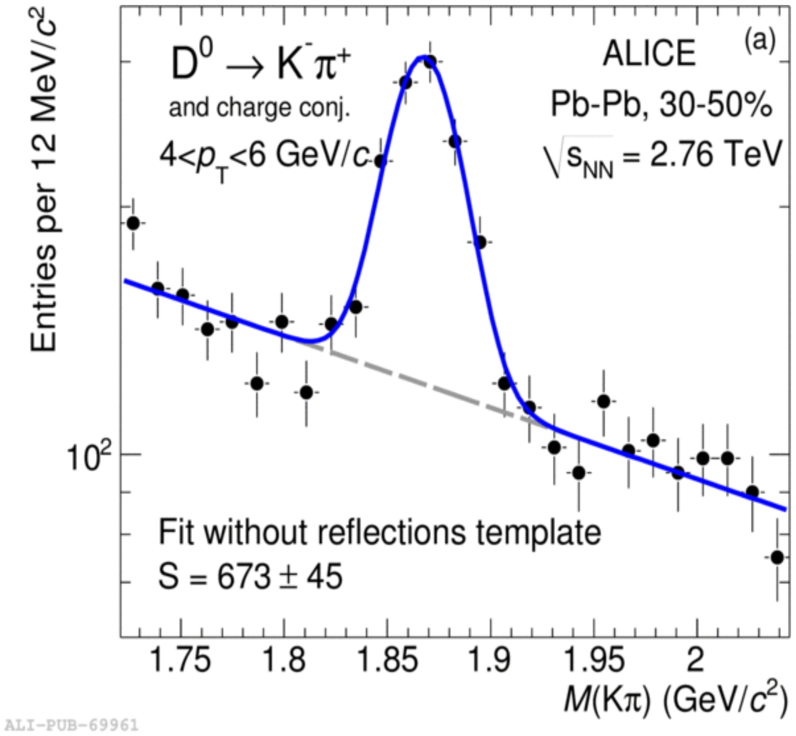




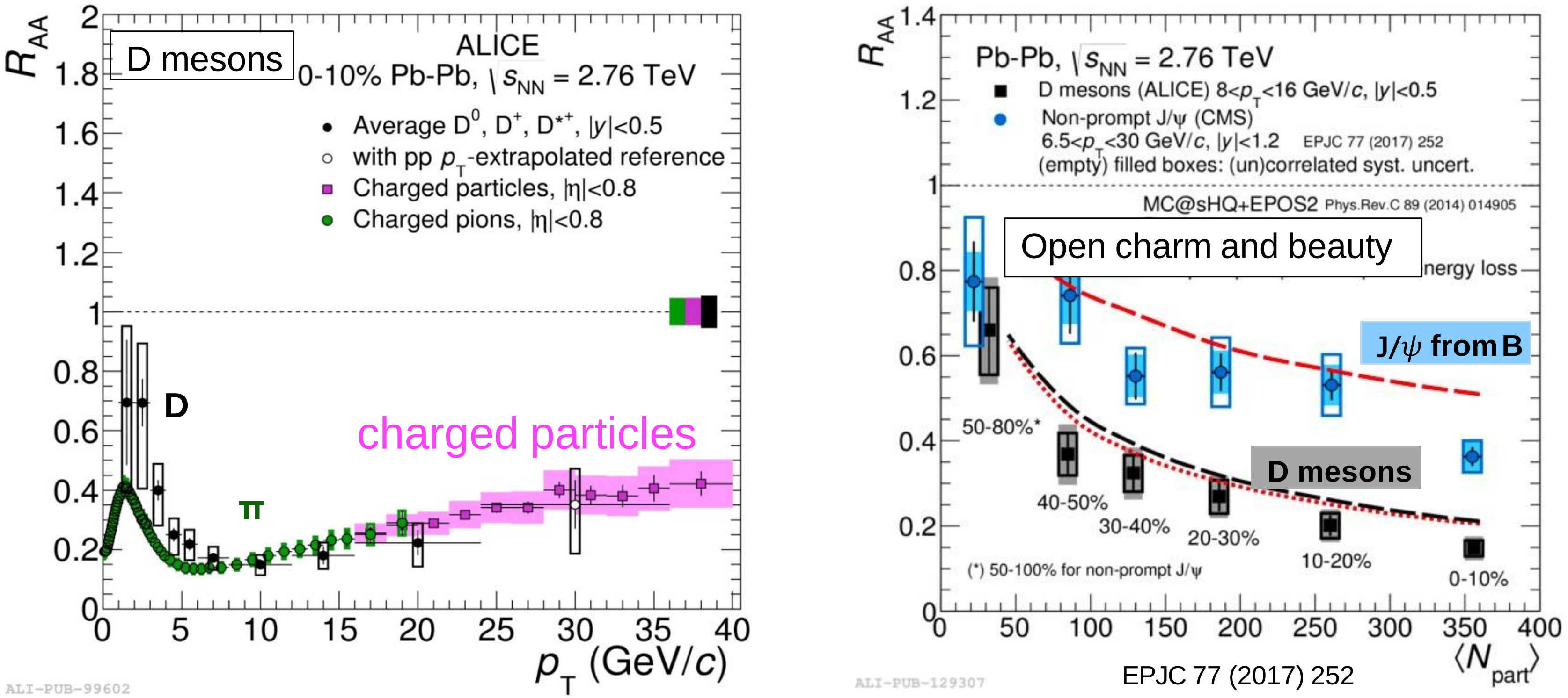
Invariant Mass

- Reconstruct D meson decay to K π based on the following methods
  - Combinatorial pairs
  - background reduced
    with particle identification
    and topological cuts
  - Invariant mass distribution
  - Background with like-sign combinations
  - Apply fit to extract yield

(Details seen in backup)



Nuclear modification of charm and beauty



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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 → $\Delta E_c > \Delta E_b$

Summary

- Strong nuclear suppression of particle production observed in central heavy ion collisions, which provides the **evidence that a dense strongly coupling medium is produced in HI collisions**
- Mass dependence of energy loss of colored partons in the QGP is observed:

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

- Radiative energy loss dominates at high p_T for light flavors u, d, gluons and charm

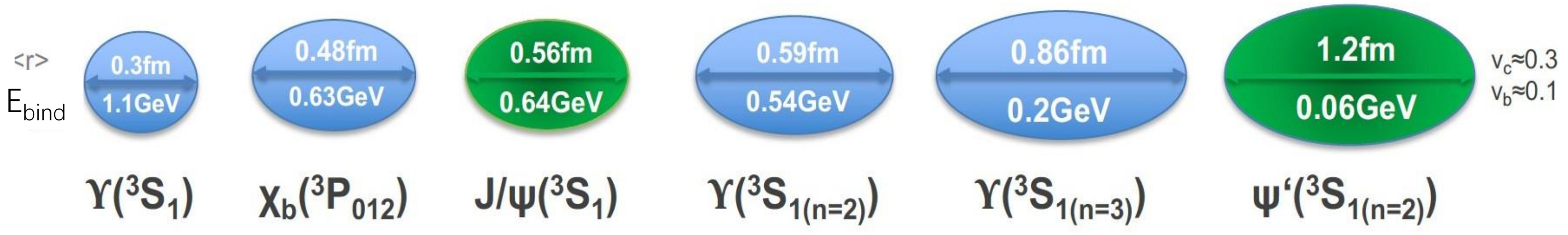
5. Quarkonia

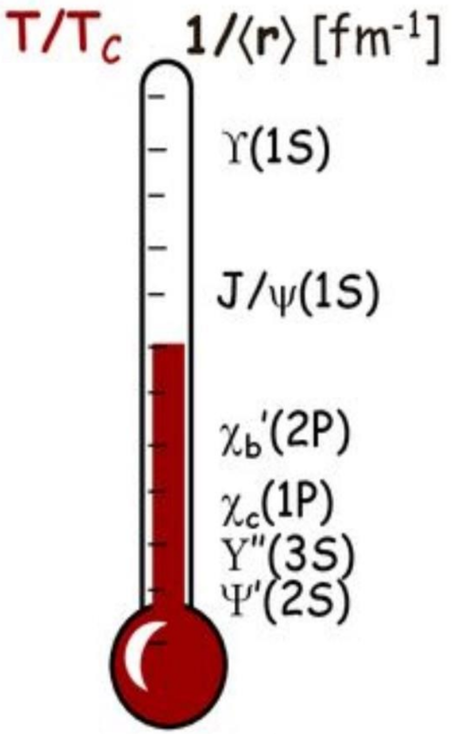
Quarkonia

c-cbar (J/Ψ, Ψ’,..) and b-bar (Υ’, Υ”,Υ’”) pairs from hard process

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

→ 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.

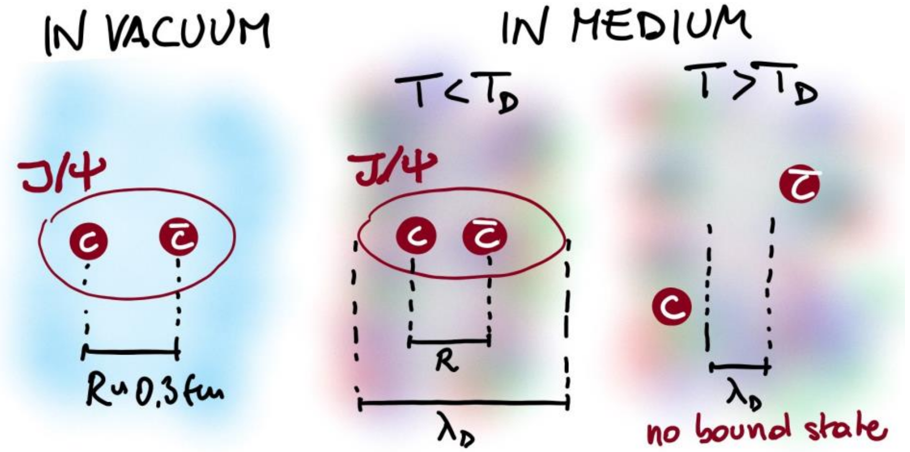
In vacuum (T=0), qqbar is bound by the Cornell potential

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

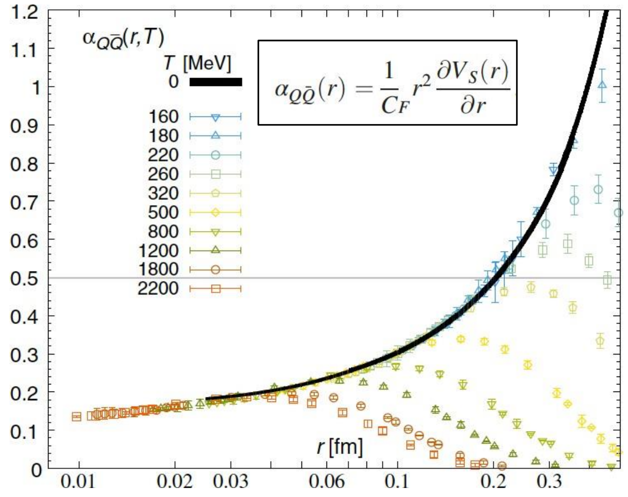
When the qqbar is immersed in the high density of quarks and gluons (QGP) **(T>0)**, the surrounding color charges screen the binding potentials (color Debye screening), resulting in

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

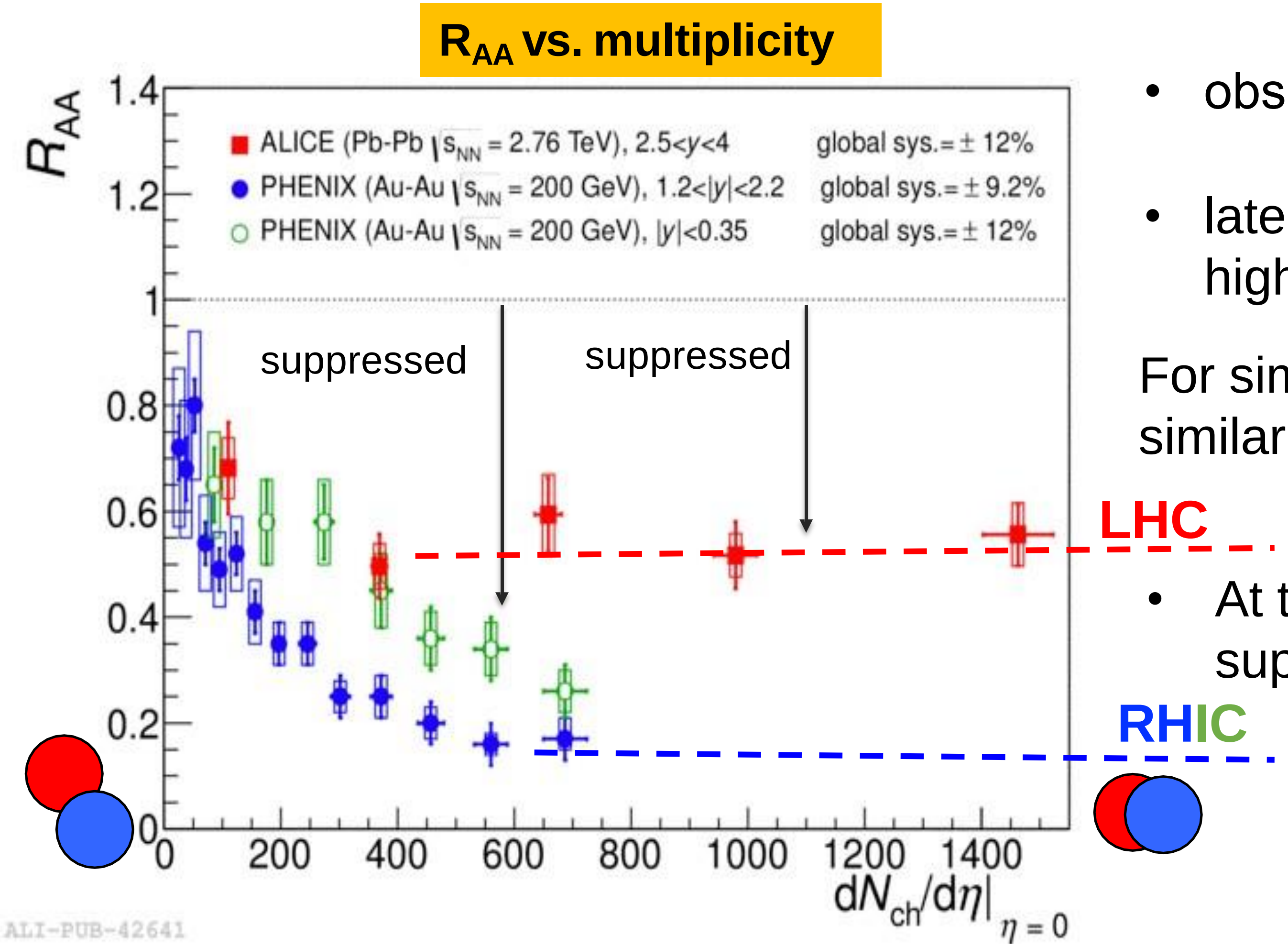
The effective coupling between q and qbar at large distances gets reduced → **q-qbar melting**



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



J/ψ suppression



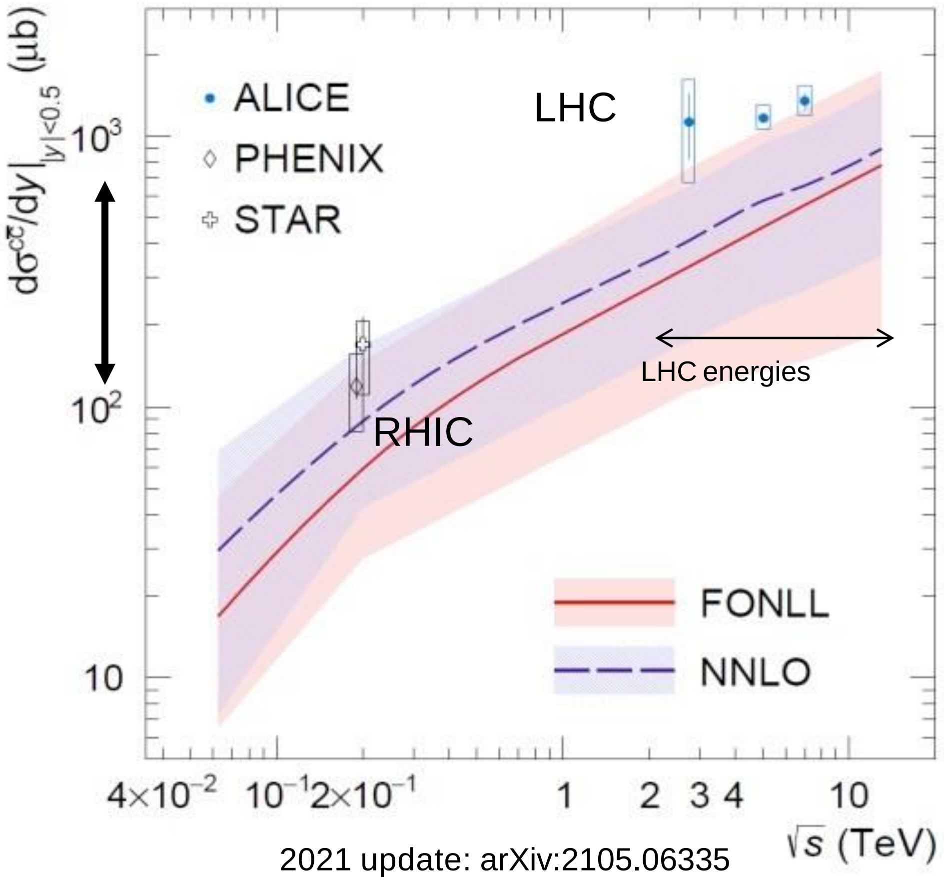
- observed at the SPS ($\sqrt{s_{NN}}$ = 17 GeV)
- later measured at RHIC ($\sqrt{s_{NN}}$=200 GeV) up to very high multiplicities

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.

c-cbar production vs Collision energy

c-cbar production cross section



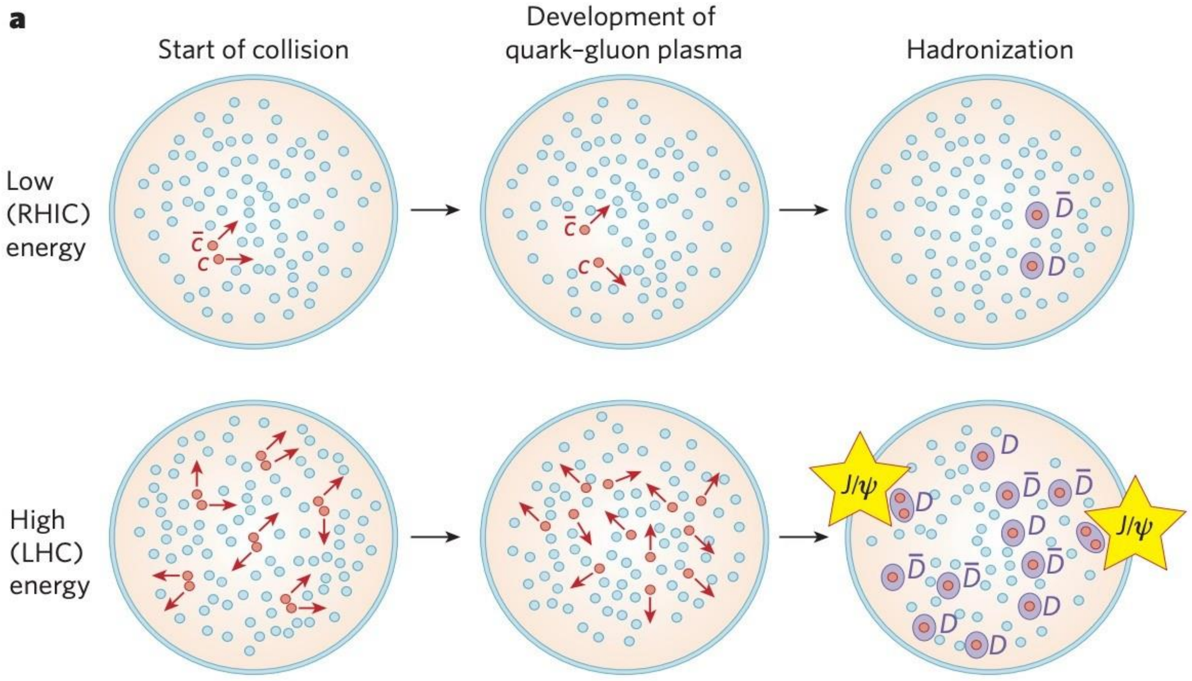
2021 update: arXiv:2105.06335

The cross section for producing a c-cbar pair increases with collision energy

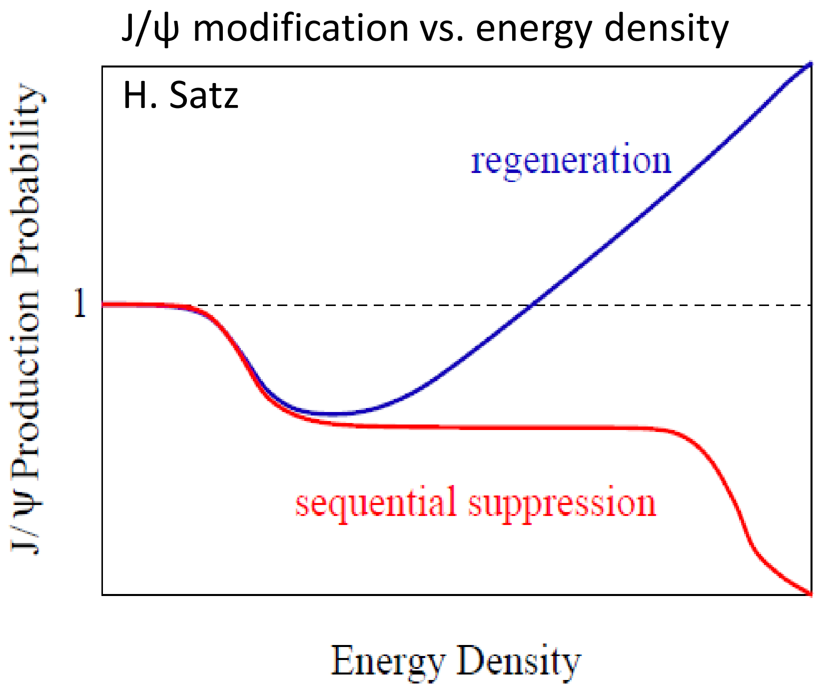
In a central event
At SPS ~0.1 c-cbar At
RHIC ~10 c-cbar At
LHC ~100 c-cbar

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 & regeneration



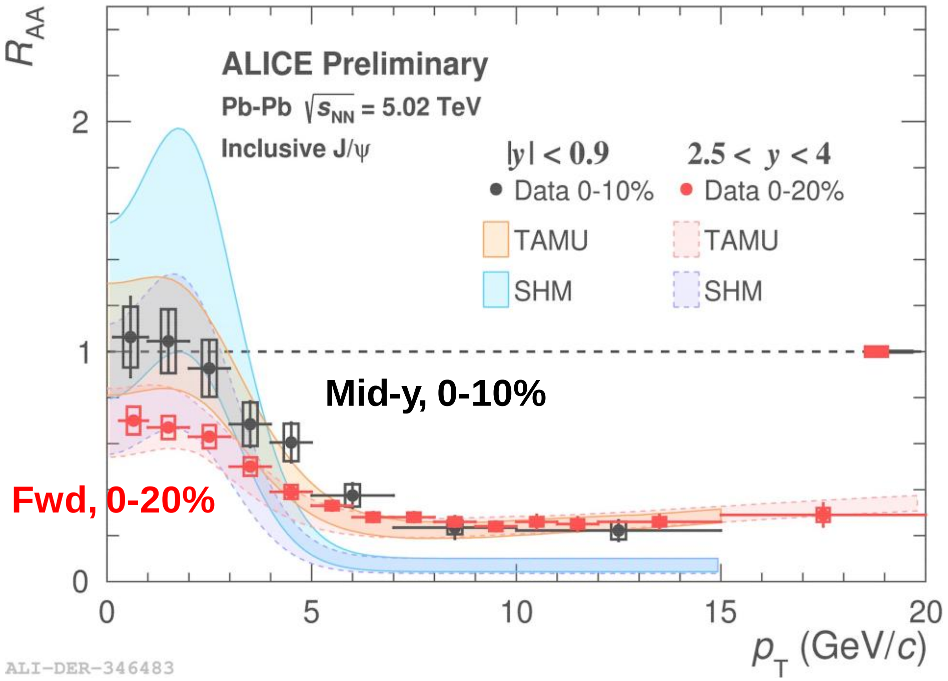
P. Braun-Munzinger, J. Stachel., Nature 448, 302–309 (2007)

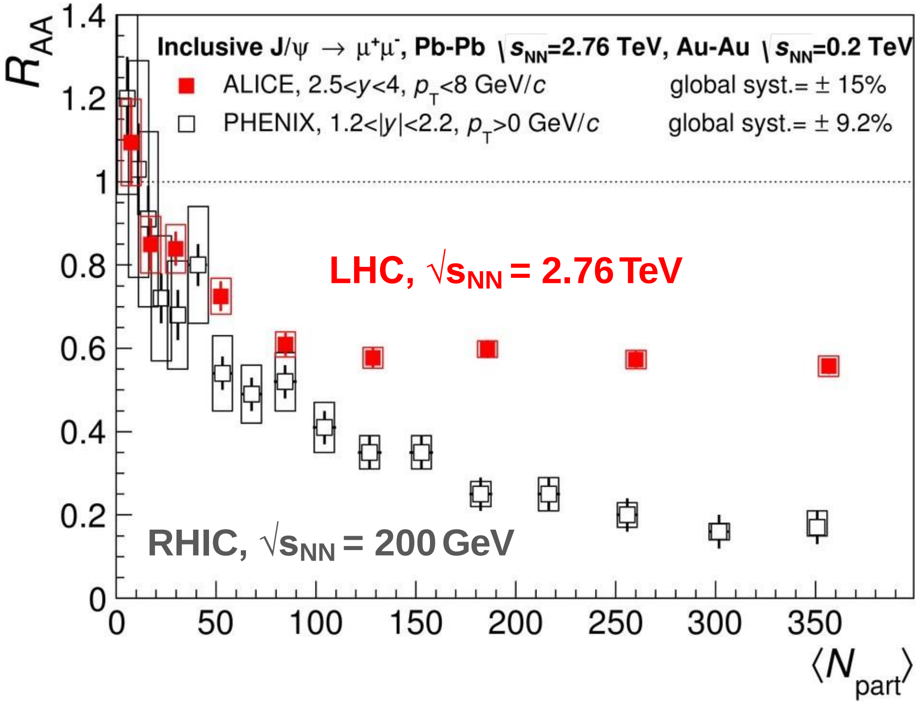


Regeneration of charmonium and **charmed hadron production** take place at the phase boundary or in QGP.

Dissociation and **regeneration** take place in opposite directions vs energy density.

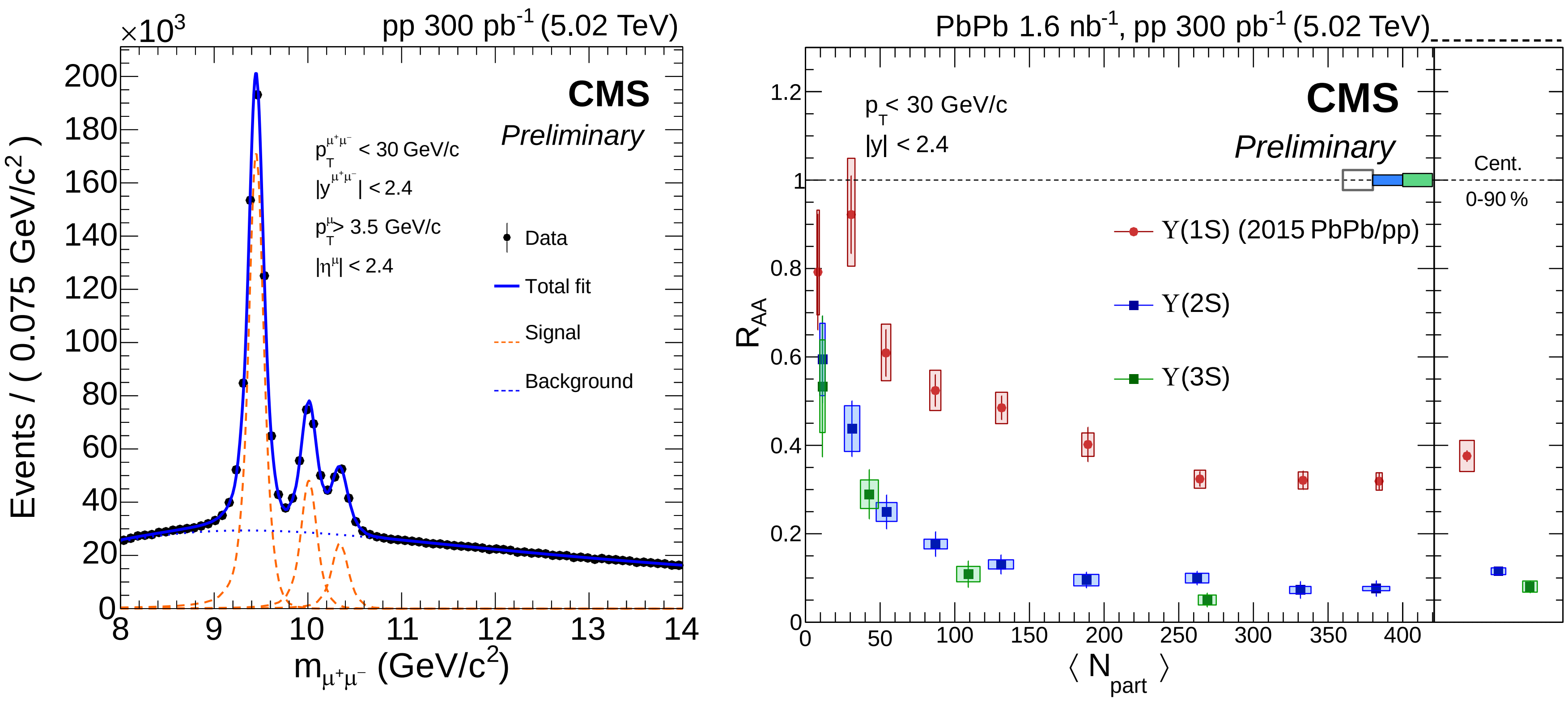
J/ψ suppression vs regeneration





- 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.

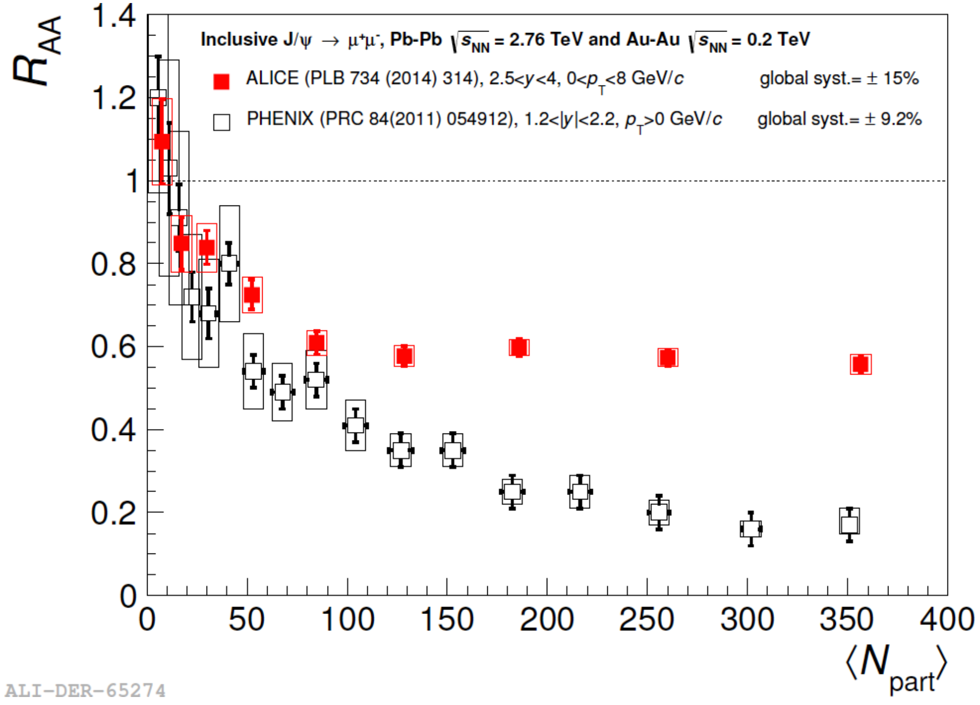
Sequential melting of quarkonia



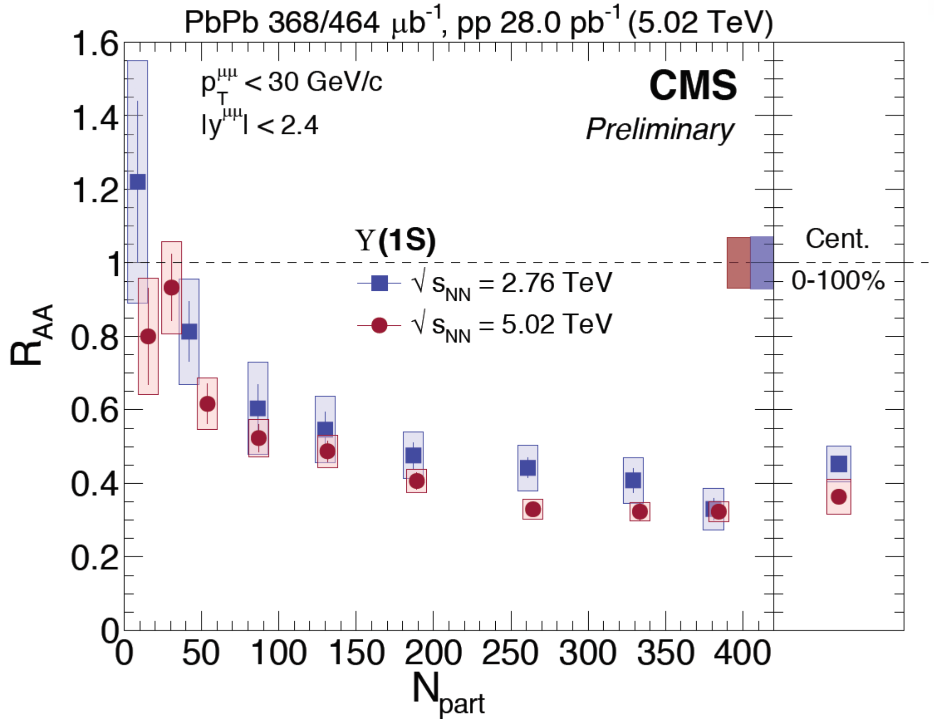
- Measurements reveal a sequential suppression of high mass bottomonium states.
- The centrality dependence of the asymptotical suppression in a hotter medium is observed.

Quarkonia as probes

Charmonium R_{AA}



Bottomonium R_{AA}



Charm is partially equilibrated (thermalized) with the medium

- ➢ A partially-equilibrated probe of the late hadronization stages

Beauty/bottomonia: no evidence that beauty is even partially equilibrated with the medium

- ➢ Non-equilibrium probe

Summary(Quarkonia)

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 ("QGP thermometer")