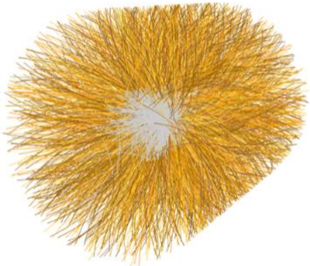


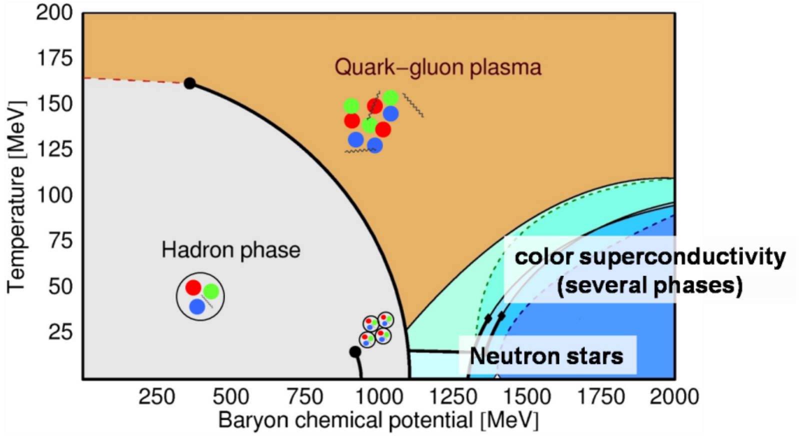
Introduction to Heavy-Ion Physics
Part II

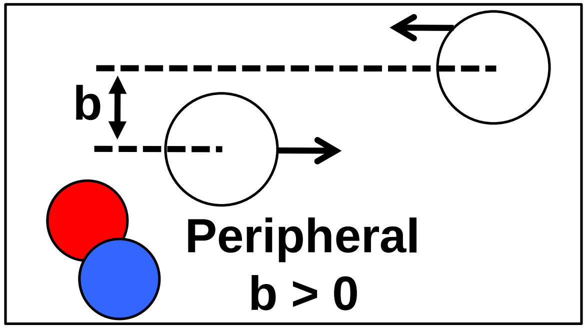
Jan Fiete Grosse-Oetringhaus, CERN

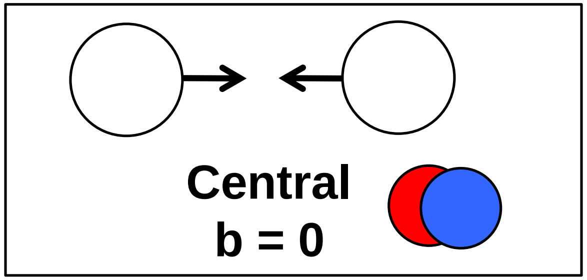
Summer Student Lectures 2018

Recap Lecture 1

- Heavy-ion physics studies quark-gluon plasma (QGP)
  - Deconfined
  - Chiral symmetry restored
- Transition to QGP is expected at T ~ 150 – 160 MeV
- Event activity depends on impact parameter b
- Centrality estimated by multiplicity (ALICE) / energy (ATLAS/CMS)





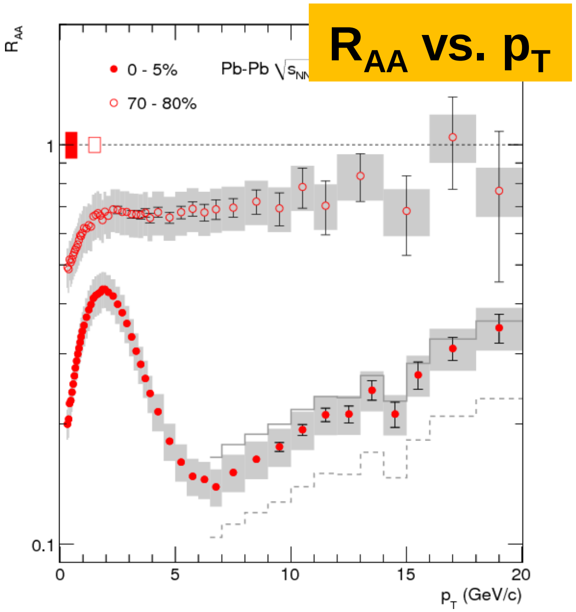


Recap Lecture 1

- Nucleon-nucleon collisions (N_{coll}) and participating nucleons (N_{part}) estimated with Glauber model
  - Hard processes scale with N_{coll}
  - Soft processes scale with N_{part}
- Nuclear modification factor

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

  - Significant suppression of hadron production in central collisions



R_{AA} vs. p_T

How does the medium achieve this suppression?

R_{AA} Interpretation

- p_T spectrum is power law

$$\frac{1}{p_T}\frac{dN}{dp_T} \sim p_T^{-n}$$

RHIC (200 GeV): n = 7.2
LHC (2.76 TeV): n = 5.4

- Constant energy loss

$$R_{AA} \approx \left(1 - \frac{\Delta E}{p_T}\right)^n$$

rising with p_T

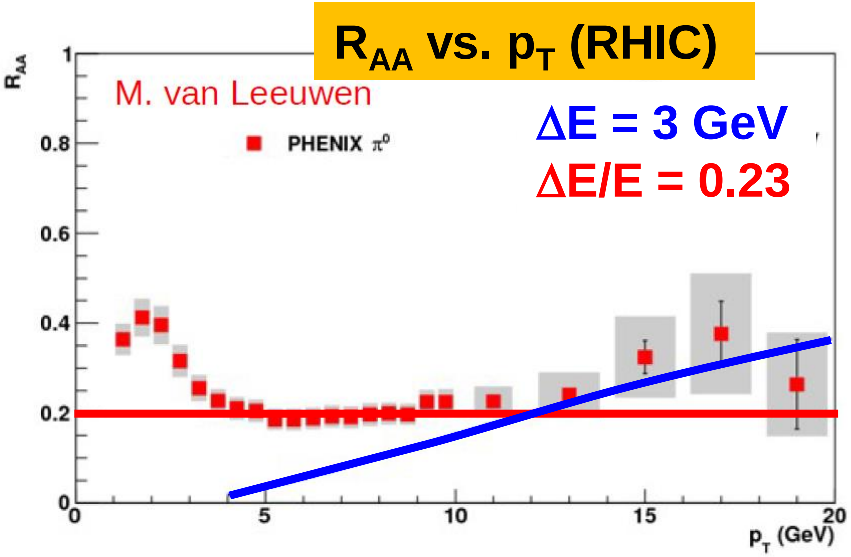
- Constant *fractional* energy loss ΔE/E

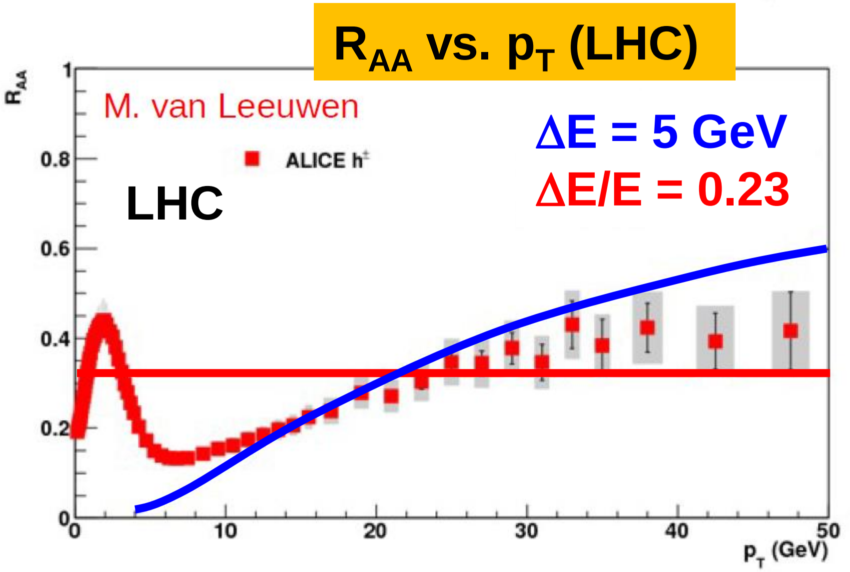
$$R_{AA} \approx \left(1 - \frac{\Delta E}{E}\right)^{n-1}$$

p_T independent

- Steepness of spectra influences R_{AA}
- Similar R_{AA} does not imply similar energy loss

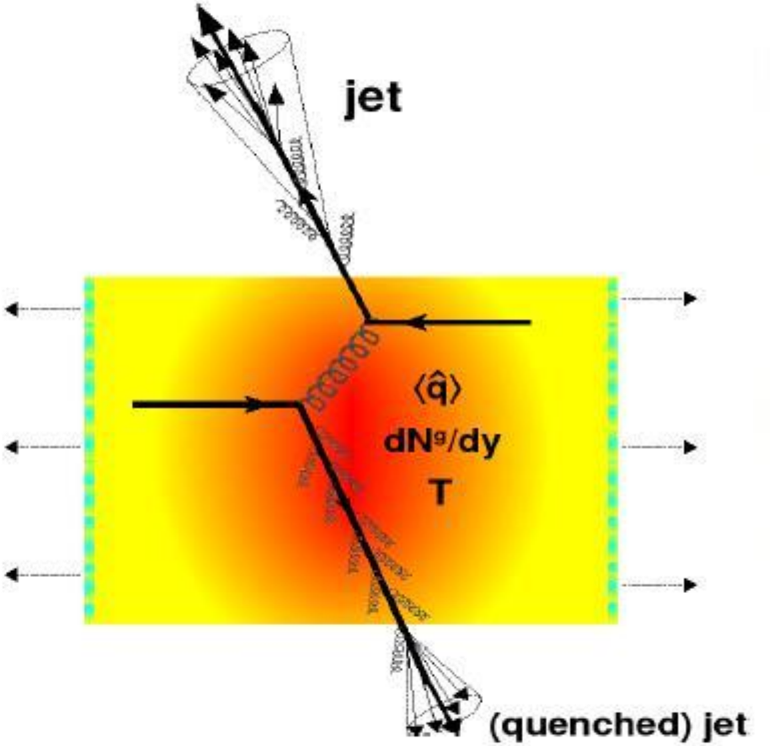
Medium energy loss : a few GeV


R_{AA} vs. p_T (RHIC)


R_{AA} vs. p_T (LHC)

Energy Loss

- Particle production in central collisions strongly suppressed

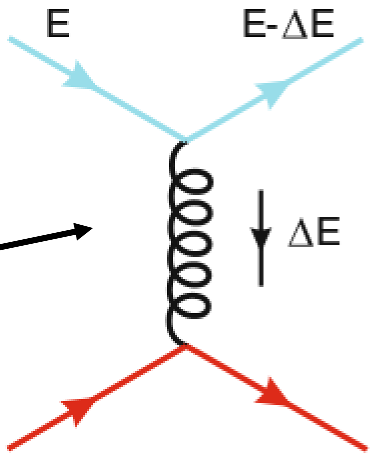


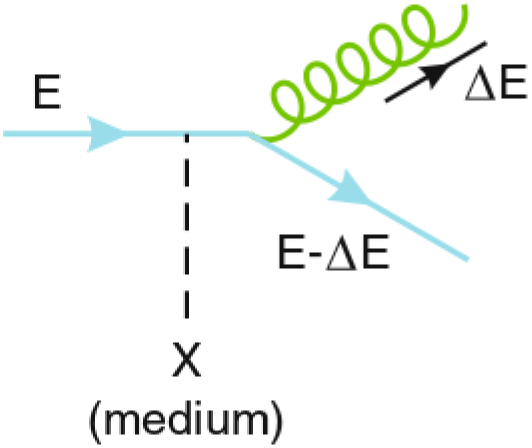
How does the medium achieve this suppression?

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

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





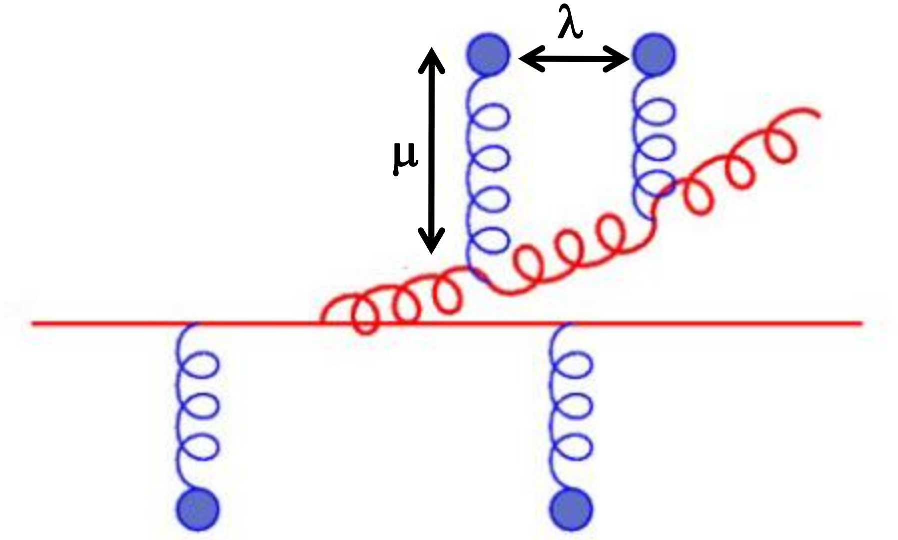
Lect. Notes Phys. 785,285 (2010)

Radiative Energy Loss

- BDPMS formalism
  - Baier, Dokshitzer, Mueller, Peigné, Schiff
  - Infinite energy limit
  - Static medium

$$\Delta E \sim \alpha_S \boxed{C_R} \hat{q} \boxed{L^2}$$

- Energy loss depends on
  - Path length through medium **squared**
  - Casimir factor
    - C_R = 4/3 (quarks)
    - C_R = 3 (gluons)
  - Medium parameter “q hat”



L path length, driven by:
- **gluon-gluon self interactions**
- **quantum interference**

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

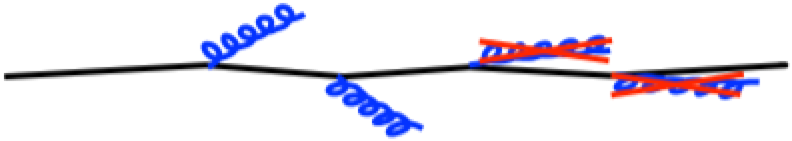
average transverse momentum transfer

mean free path

Baier, Dokshitzer, Mueller, Peigné, Schiff, NPB 483 (1997) 291

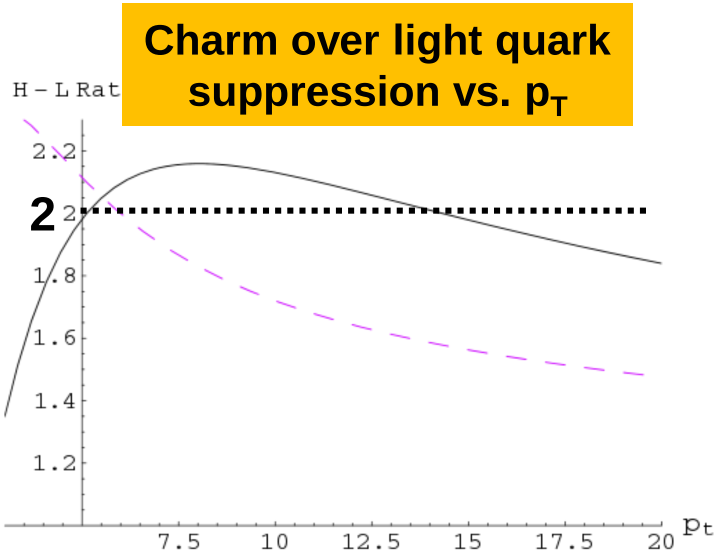
Dead Cone Effect

- Due to kinematical constraints, gluon radiation in vacuum suppressed for angles θ < m/E = 1/γ by $\left(1+\frac{m/E}{\theta}\right)^2$
  - Massless parton m = 0 → no suppression



- Similar effect in the medium
  - Significant for charm and beauty
  - Radiative energy loss reduced by 25% (c) and 75% (b) [μ = 1 GeV/c^2]
- Implies quark mass dependence

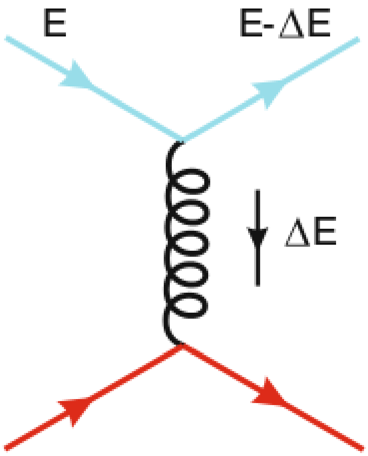
$$R_{AA}^{\pi} < R_{AA}^{D} < R_{AA}^{B}$$



Charm over light quark suppression vs. p_T

PLB519:199-206,2001
Lect. Notes Phys. 785,285 (2010)

Collisional Energy Loss



- For light quarks and gluons

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

- For heavy quarks additional term

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

- Energy loss depends on
  - Path length through medium **linear**
  - Parton type (light or heavy)
  - Temperature T
  - Mass of heavy quark M
  - Medium parameter μ (average transverse momentum transfer)

PRD 77, 114017 (2008) 291

Recap

- We have seen significantly suppression of charged hadron spectra
  - Dominated by light quarks / gluons…
  - … which at low p_T are also produced within the medium

- Energy loss occurs by radiative and collisional processes
- Theoretical calculations extract medium properties like density, average momentum transfer, mean free path, $\hat{q}$

- Calculations more accurate for heavy quarks
- Dependence of energy loss on quark mass expected

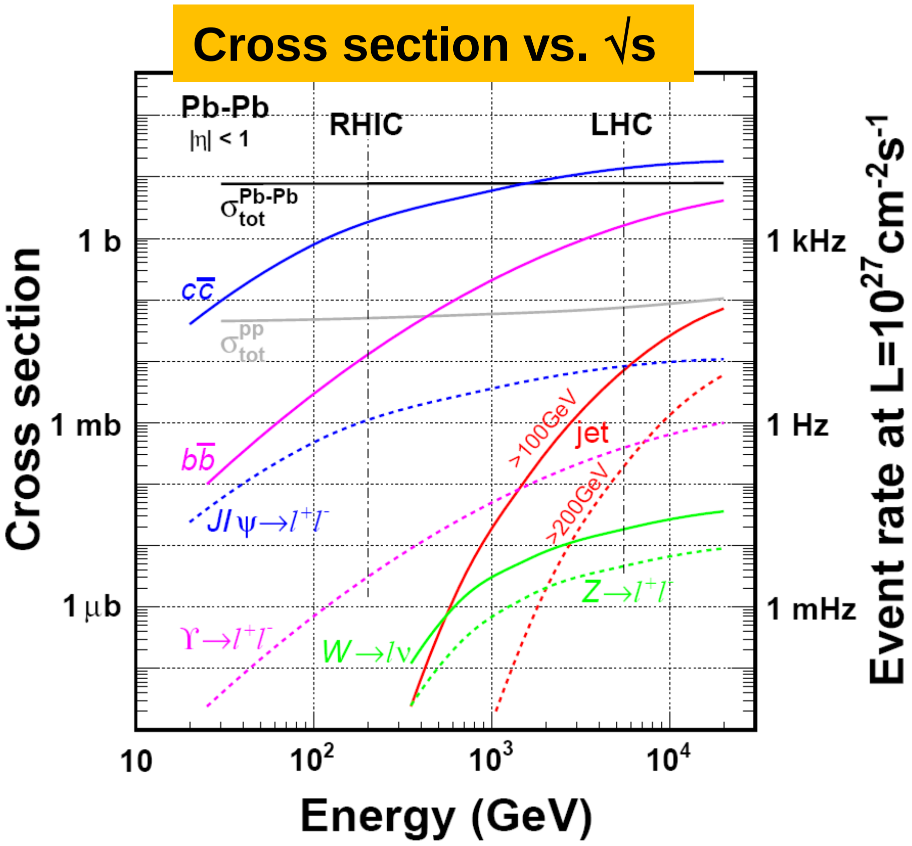
Let's measure energy loss with heavy quarks !

Heavy Quarks

- Charm (m ~ 1.3 GeV/c^2)
- Beauty (m ~ 4.7 GeV/c^2)
- Produced in hard scattering
- Essentially not produced in the QGP
- Expectation

$$R_{AA}^{\pi} < R_{AA}^{D} < R_{AA}^{B}$$

- LHC: ~7 D > 2 GeV/c per central event



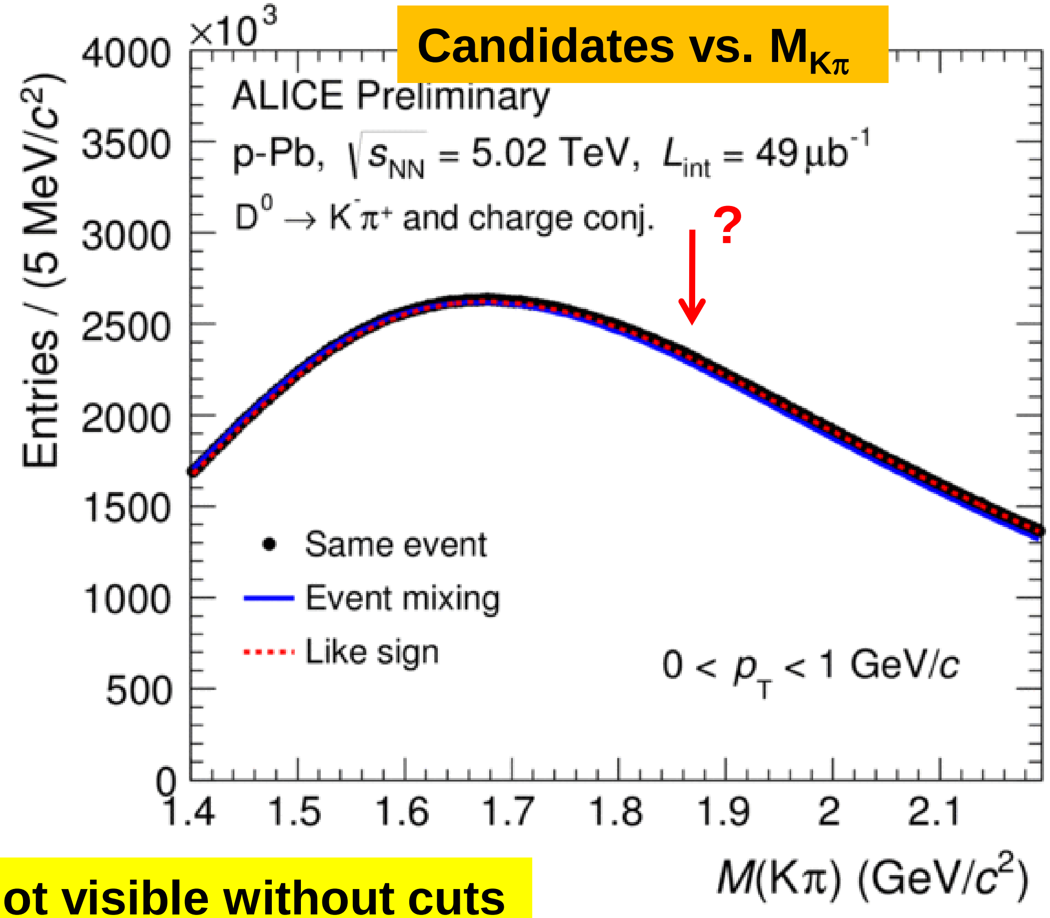
Cross section vs. √s

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

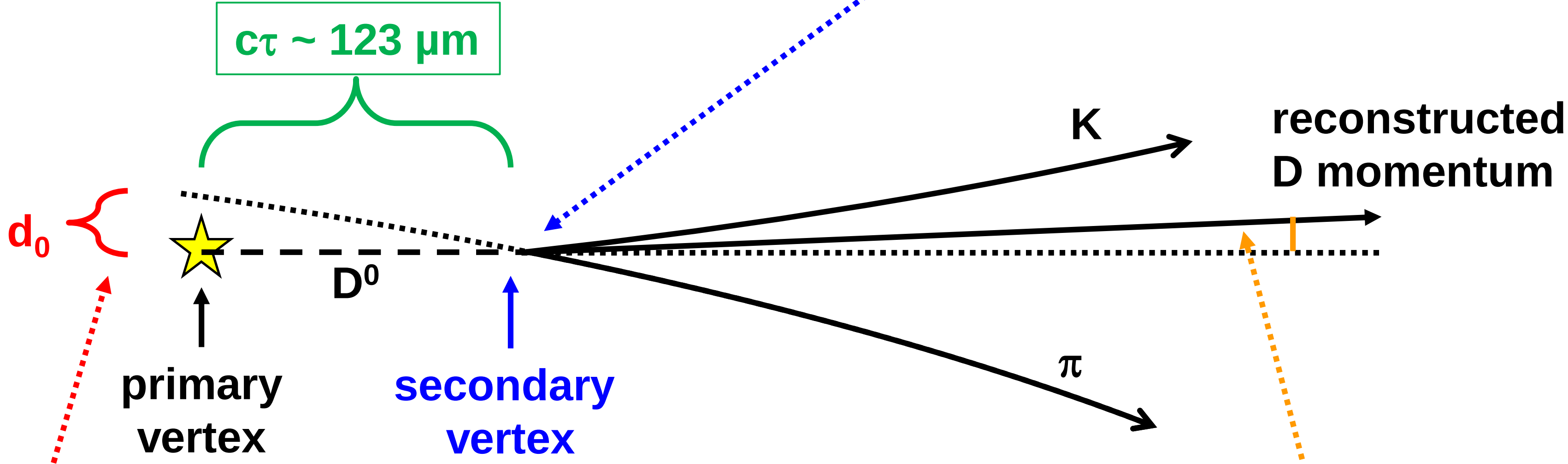


Peak not visible without cuts

Topological Cuts

3) Require distance of primary and secondary vertex (impact parameter) [~100 μm challenging for pixel detectors!]

2) Require that K and π share a secondary vertex



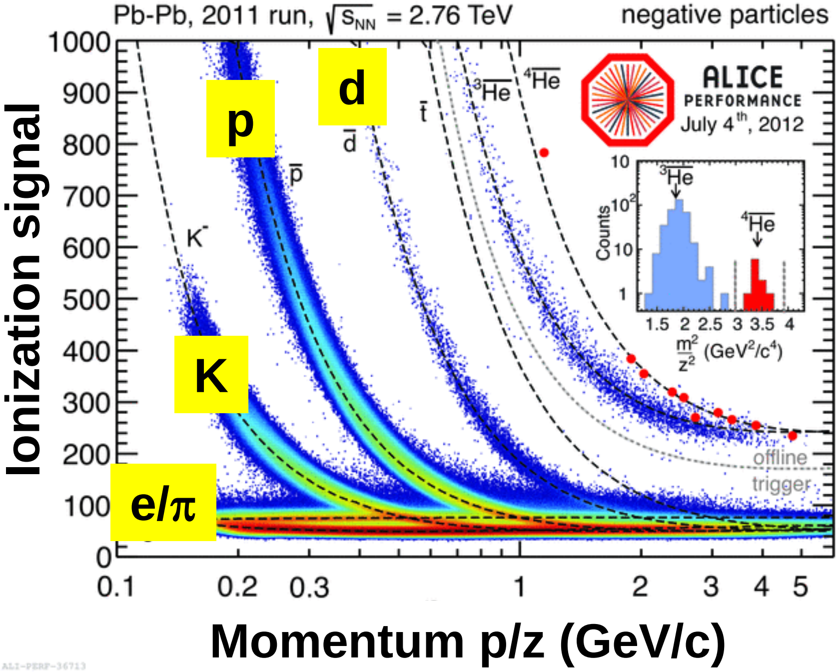
1) Require large impact parameter tracks

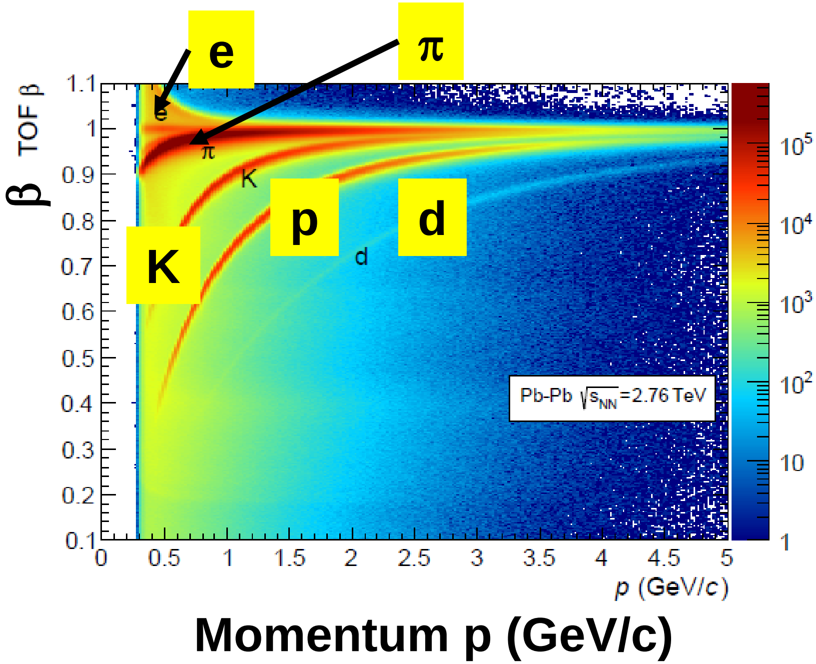
Plane transverse to beam

4) Require pointing angle θ to be small

PID

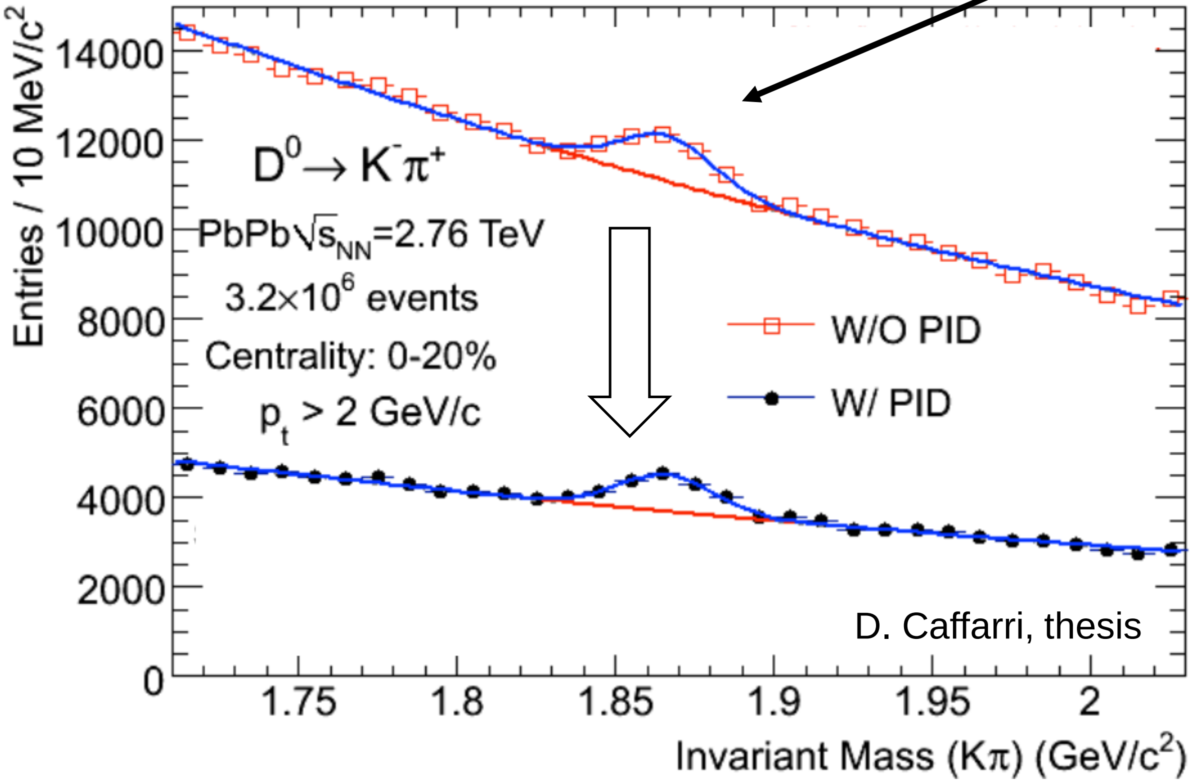
- Specific Energy Loss
  - Particles passing through matter loose energy mainly by ionization
  - Average energy loss calculated with Bethe-Bloch formula
  - Identify particle by measuring energy deposition and momentum
- Time Of Flight
  - Particles with the same momentum have slightly different speed 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 with Cuts

- $D^0 \rightarrow K\,\pi$



D. Caffarri, thesis

D^0 peak

with topological cuts

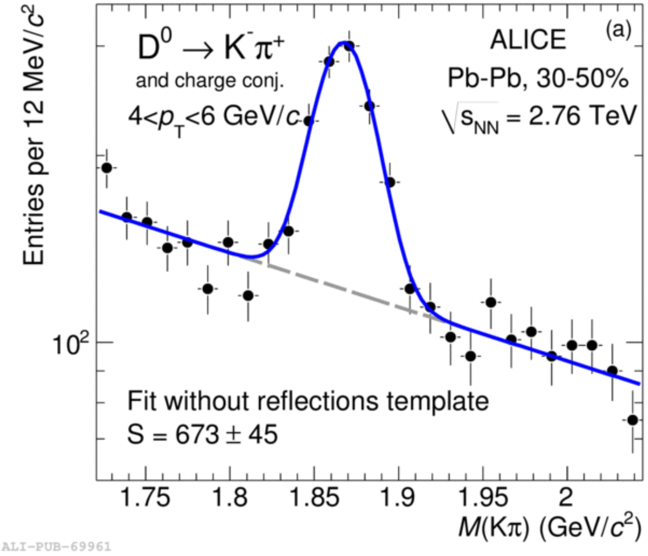
with topological cuts and PID

PID reduces background, but signal peak stays of same magnitude

Recap: D Meson Yield

- We would like to learn about the energy loss of charm

- Reconstruct D meson decay to K π
  - Rare signal
  - Combinatorial background reduced with particle identification and topological cuts
  - Invariant mass distribution
  - Background with like-sign combinations
  - Apply fit to extract yield

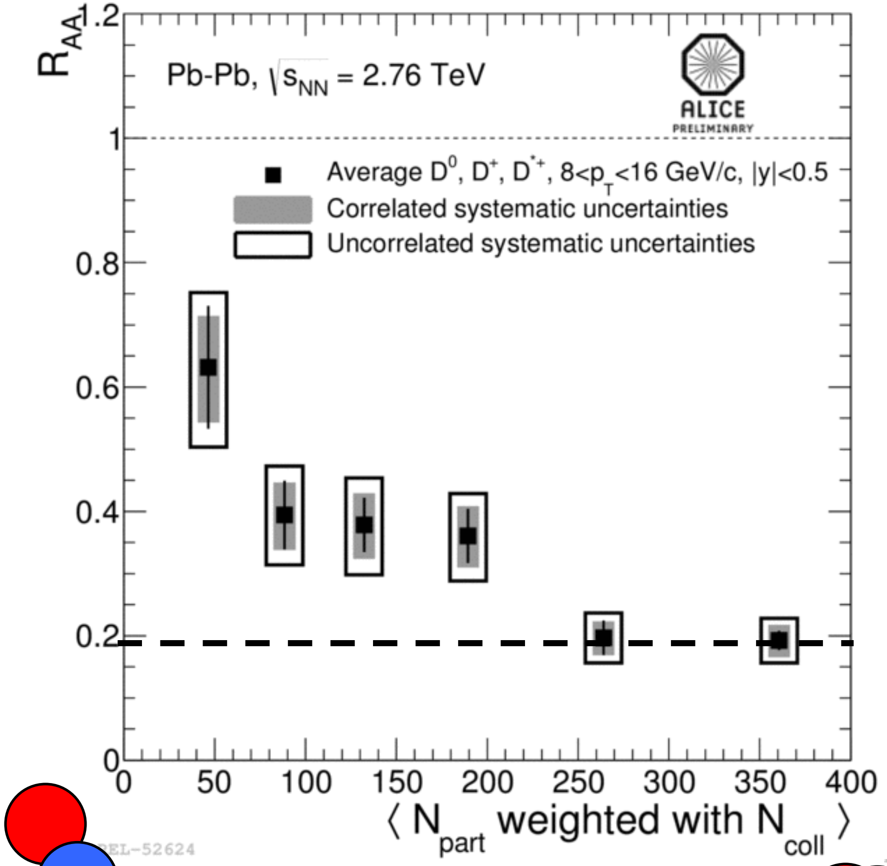


PRC 90 (2014) 034904

D R_{AA}

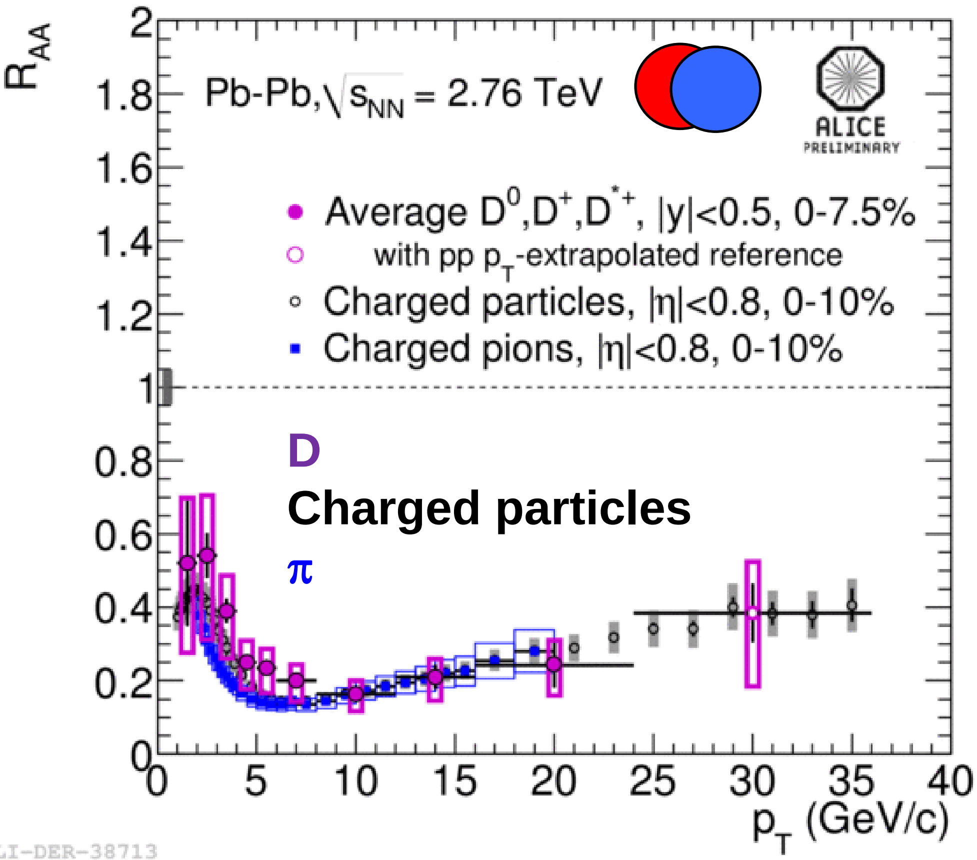
$$R_{AA} = \frac{dN_{AA}/dp_T}{\langle N_{coll} \rangle dN_{pp}/dp_T}$$

R_{AA} vs. centrality



strong suppression ~ 0.2

R_{AA} vs. p_T



D and π R_{AA} compatible

arXiv:1506.06604

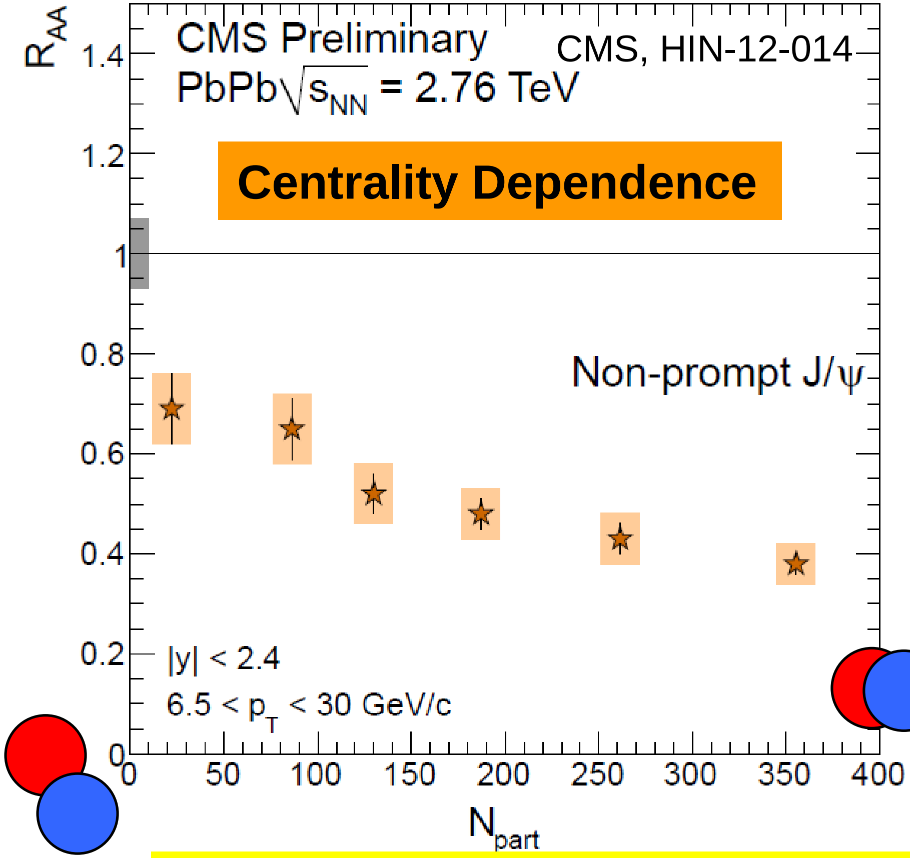
π R_{AA} vs. D R_{AA}

- Expectation $R_{AA}^{\pi} < R_{AA}^{D} < R_{AA}^{B}$
- However $R_{AA}^{\pi} \approx R_{AA}^{D}$
- Are the energy loss models wrong?
- Not necessarily
  - Effect expected for p_T close to charm mass (~1.3 GeV/c^2)
  - Uncertainties on D R_{AA} large for p_T < 5 GeV/c
  - Fragmentation (→ hadron) different for gluons and quarks

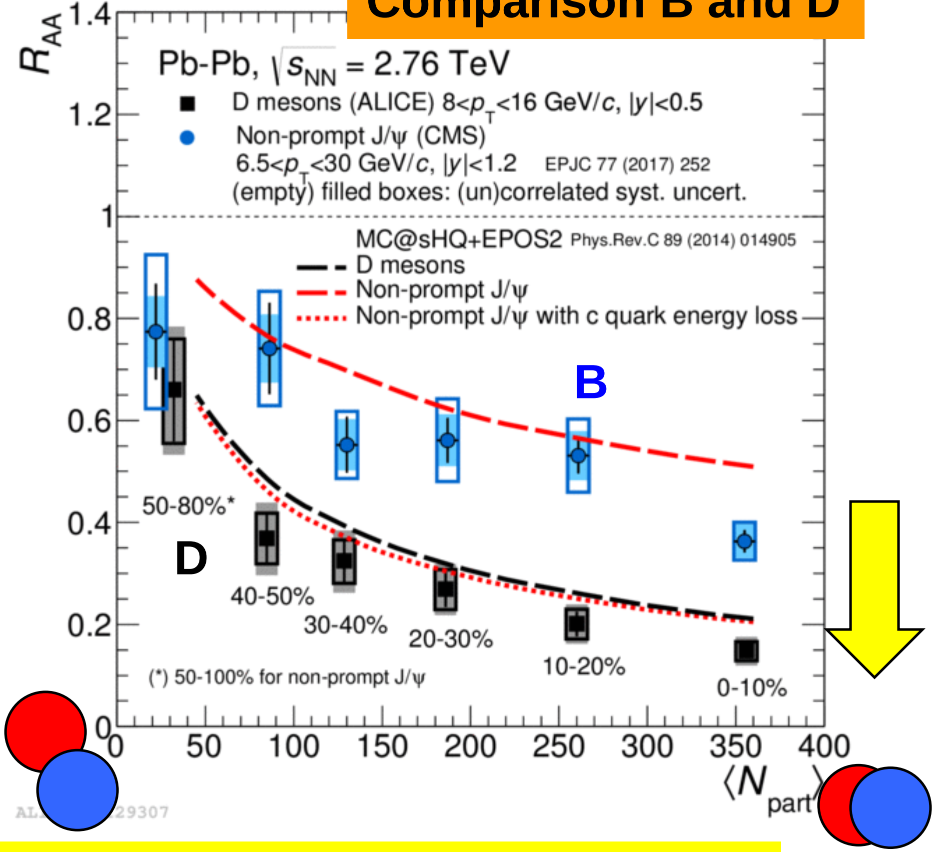
Let's have a look at particles containing a heavier b…

B R_{AA}

$B^{\pm}$ → (J/ψ → μμ) + X identified by displaced secondary vertices (see backup)



Centrality Dependence



Comparison B and D

D is stronger suppressed than B ! → hint of quark mass dependence

Summary
Jet Quenching & Energy Loss

- Particle production strongly suppressed in central heavy-ion collisions
  - Mass dependence observed

$$R_{AA}^{\pi} \approx R_{AA}^{D} < R_{AA}^{B}$$

- Radiative and collisional energy loss
  - Radiative energy loss dominates at high p_T for u, d, c, g
  - Radiative and collisional e-loss play similar role for b quarks
- Theoretical models used to constrain medium properties like density, average momentum transfer, mean free path

A dense strongly coupling medium is produced in HI collisions

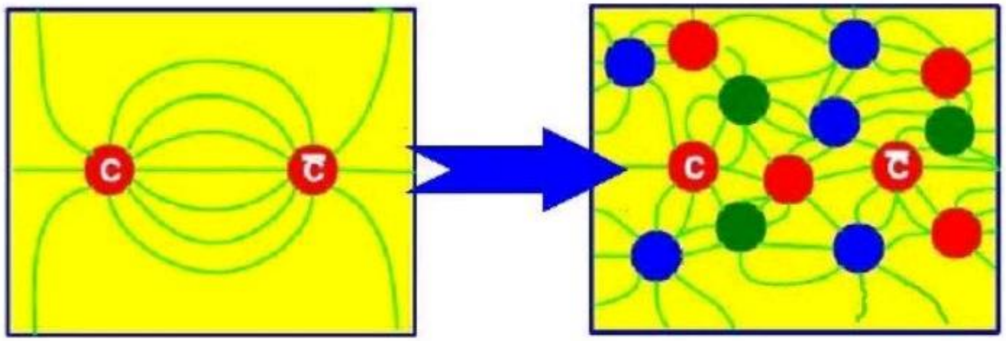
**Measurement of b → J/ψ requires displaced vertices.
What about J/ψ stemming directly from the interaction?**

Quarkonia

How does a quark-gluon plasma affect c-cbar and b-bbar states?

Quarkonia

- c-cbar (J/ψ, ψ’) and b-bbar (ϒ, ϒ’, ϒ’’) from hard process
- High density of quarks and gluons causes screening



Cartoon: T. Tveter

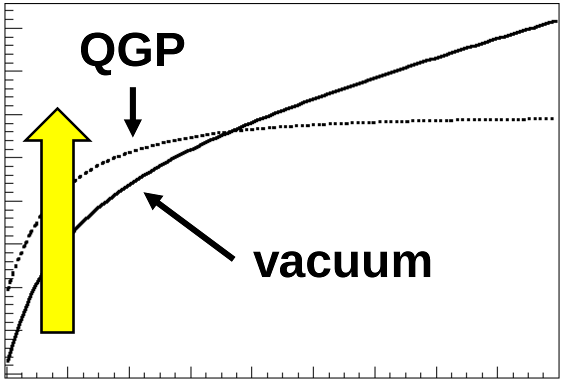
α **gauge coupling**
σ **string tension**
μ **screening mass**

- Changes (binding) potential

$$V(r) = -\frac{\alpha}{r} + \sigma r \longrightarrow V(r) = -\frac{\alpha}{r} e^{-\mu r} + \sigma r \left[\frac{1 - e^{-\mu r}}{\mu r} \right]$$

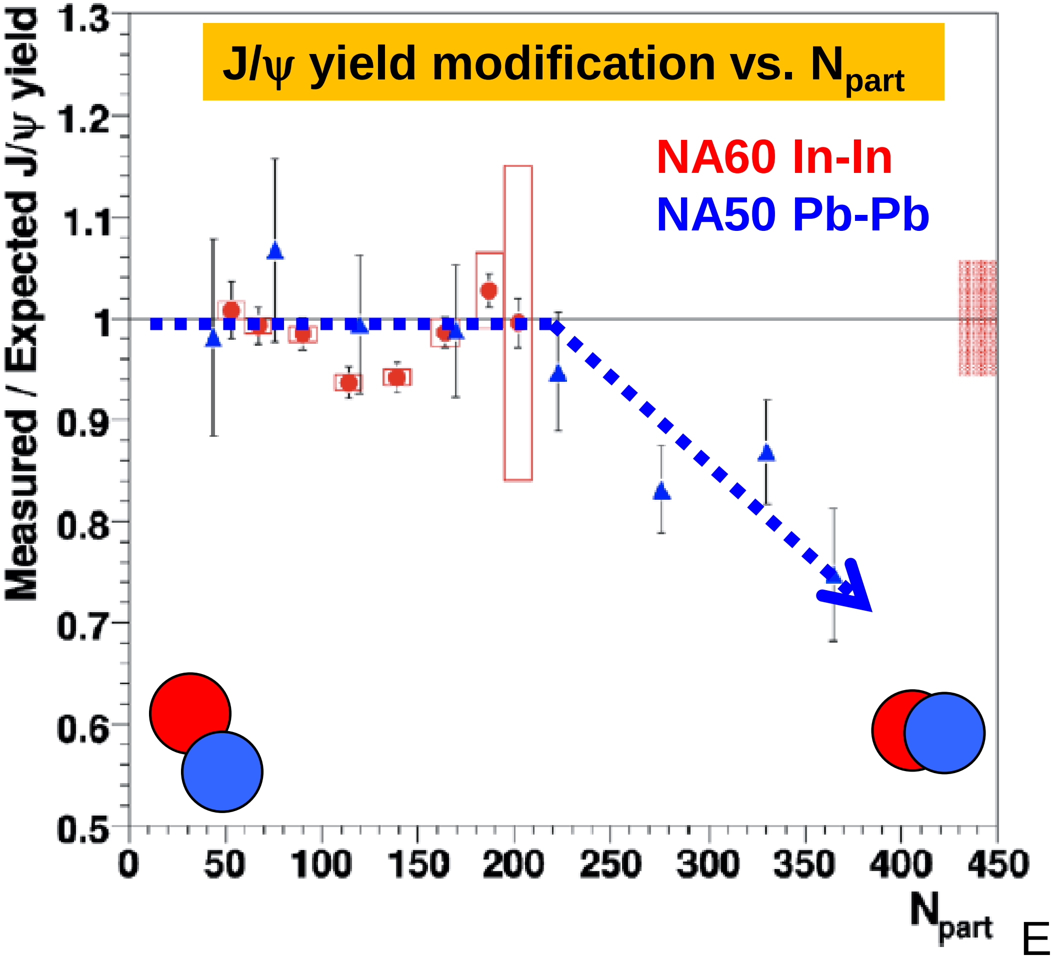
- Quarks with distance larger than 1/μ do not see each other
  - → Dissociation of q-qbar pair !
  - → Quarkonia “melt”

Potential vs. r



J/ψ Suppression

- Observed at SPS in Pb-Pb collisions ($\sqrt{s_{NN}}$ = 17 GeV)

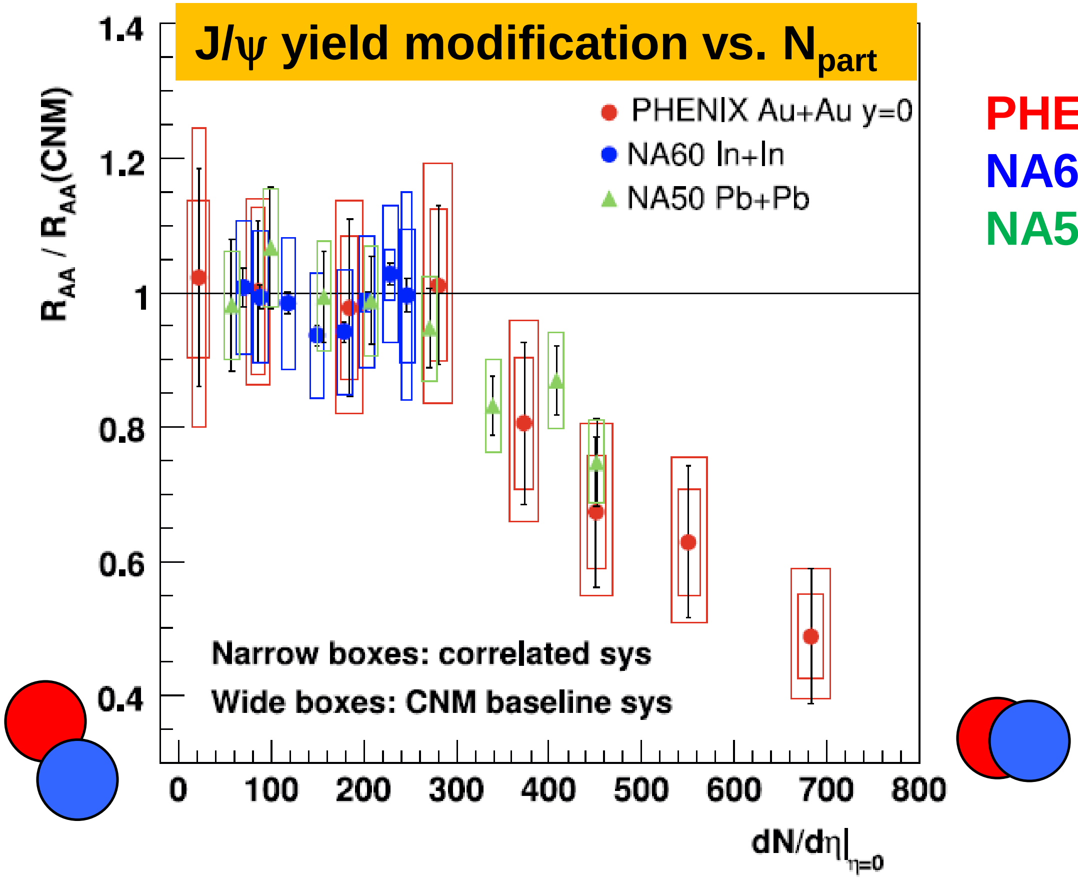


In: A = 105
Pb: A = 208

EPJC (2011) 71:1534

J/ψ Suppression (2)

- … and at RHIC ($\sqrt{s_{NN}}$ = 200 GeV)



PHENIX Au-Au

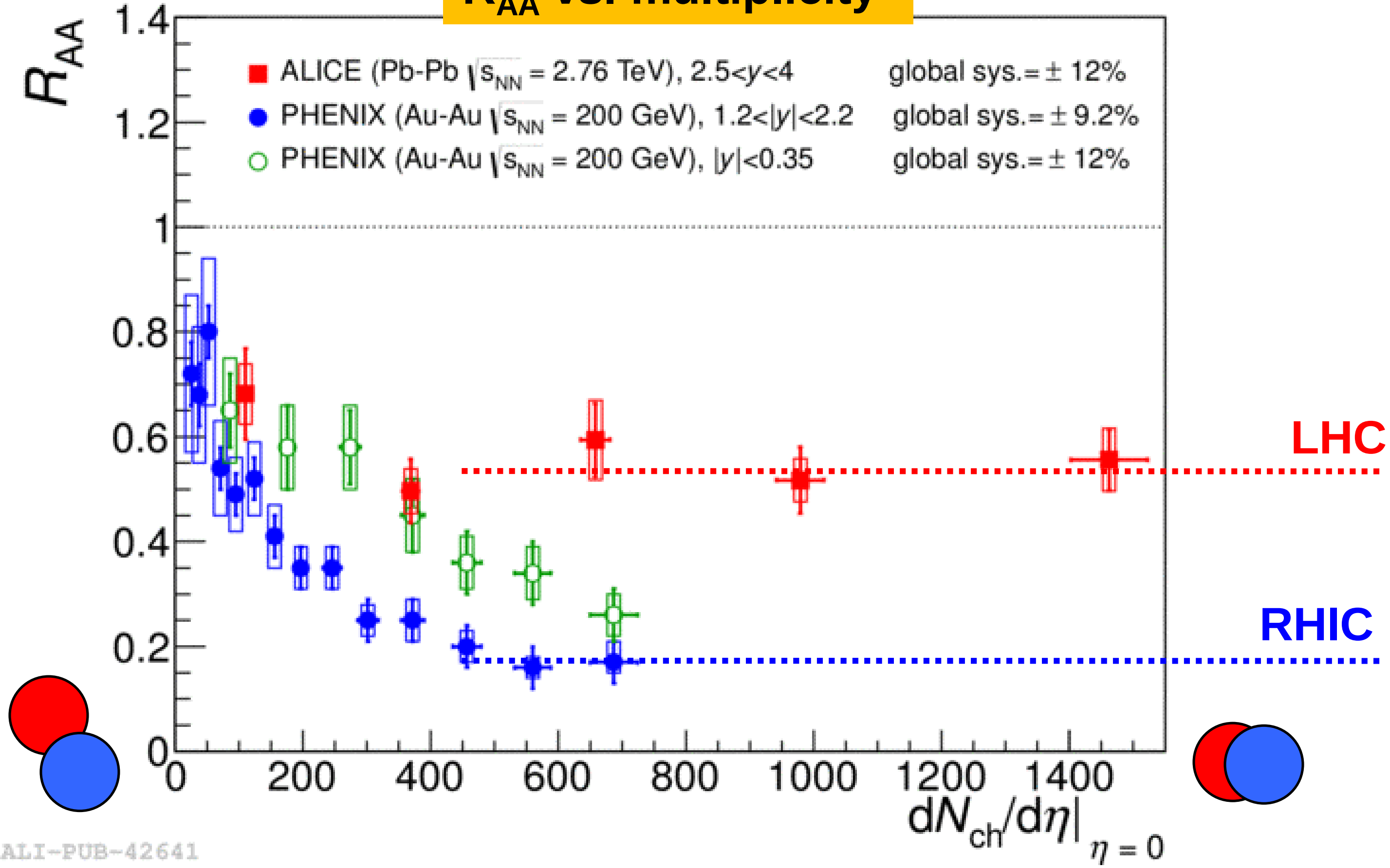
NA60 In-In

NA50 Pb-Pb

Wouldn't we expect a stronger suppression at larger $\sqrt{s_{NN}}$?

J/ψ Suppression (3)

R_{AA} vs. multiplicity

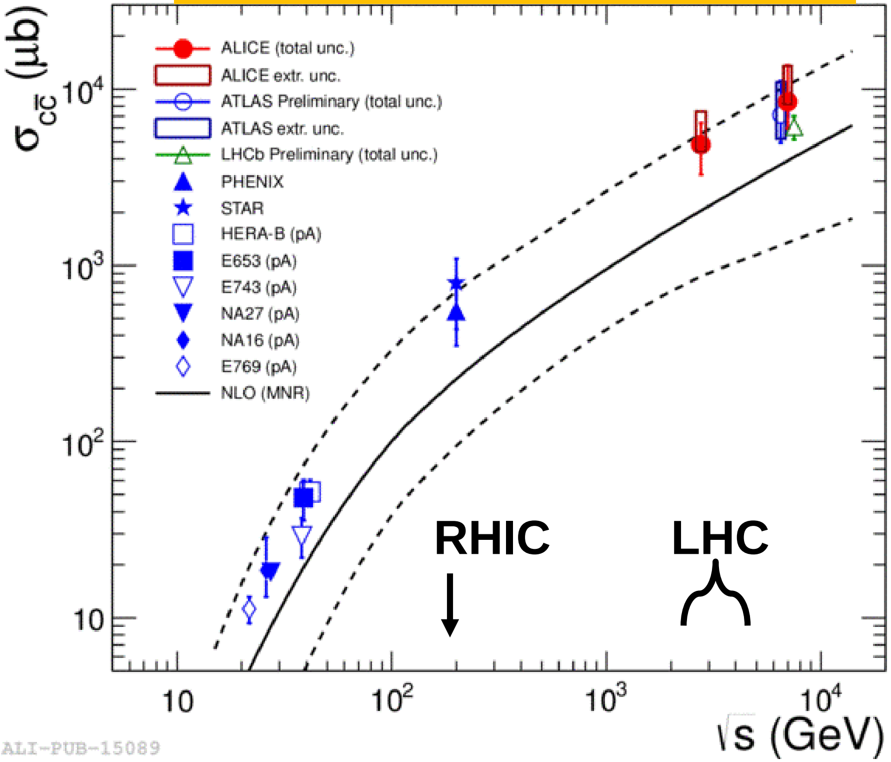


LHC → RHIC : $\sqrt{s_{NN}}$ 14 times larger … but the suppression is smaller !

Charm Abundances

- Number of c-cbar pairs increase with cms energy
- In a central event
  - SPS ~0.1 c-cbar
  - RHIC ~10 c-cbar
  - LHC ~100 c-cbar
- c from one c-cbar may combine with cbar from another c-cbar at hadronization to form a J/ψ

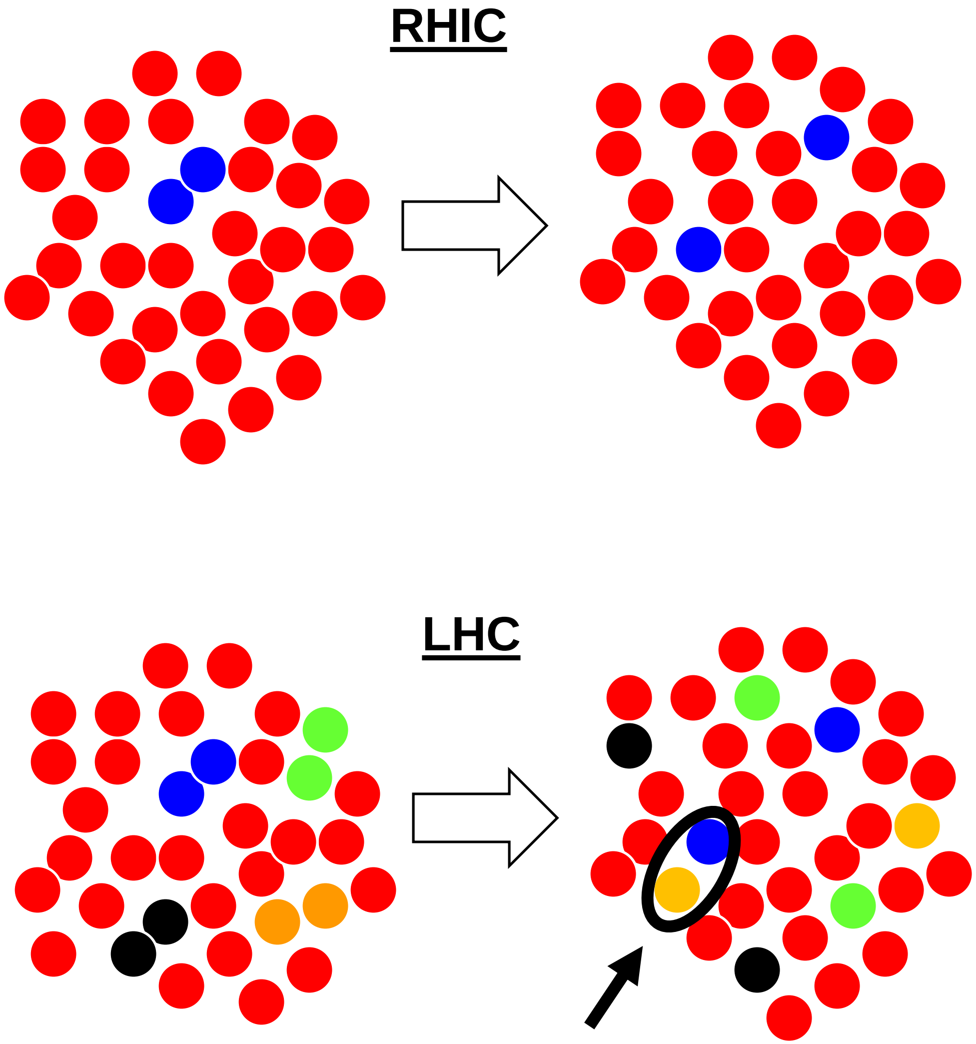
Charm cross-section vs. √s



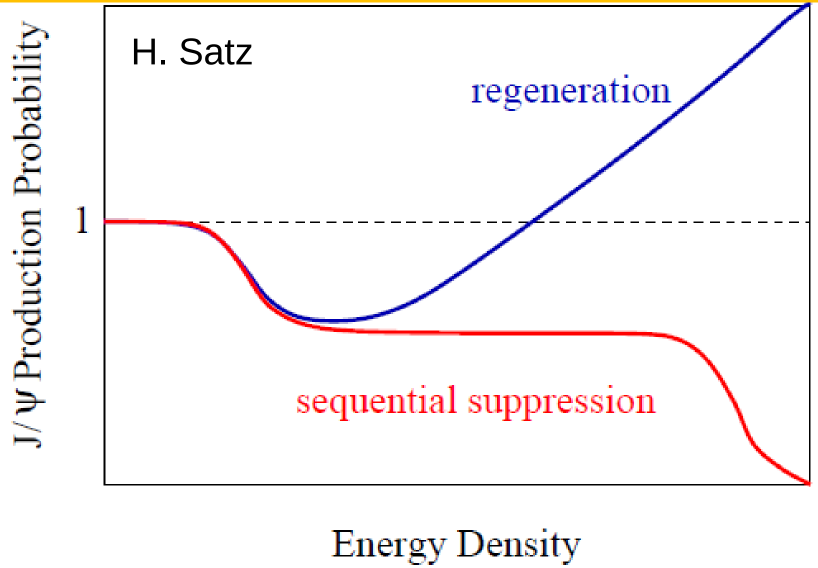
ALI-PUB-15089

JHEP 1207 (2012) 191

J/ψ Regeneration



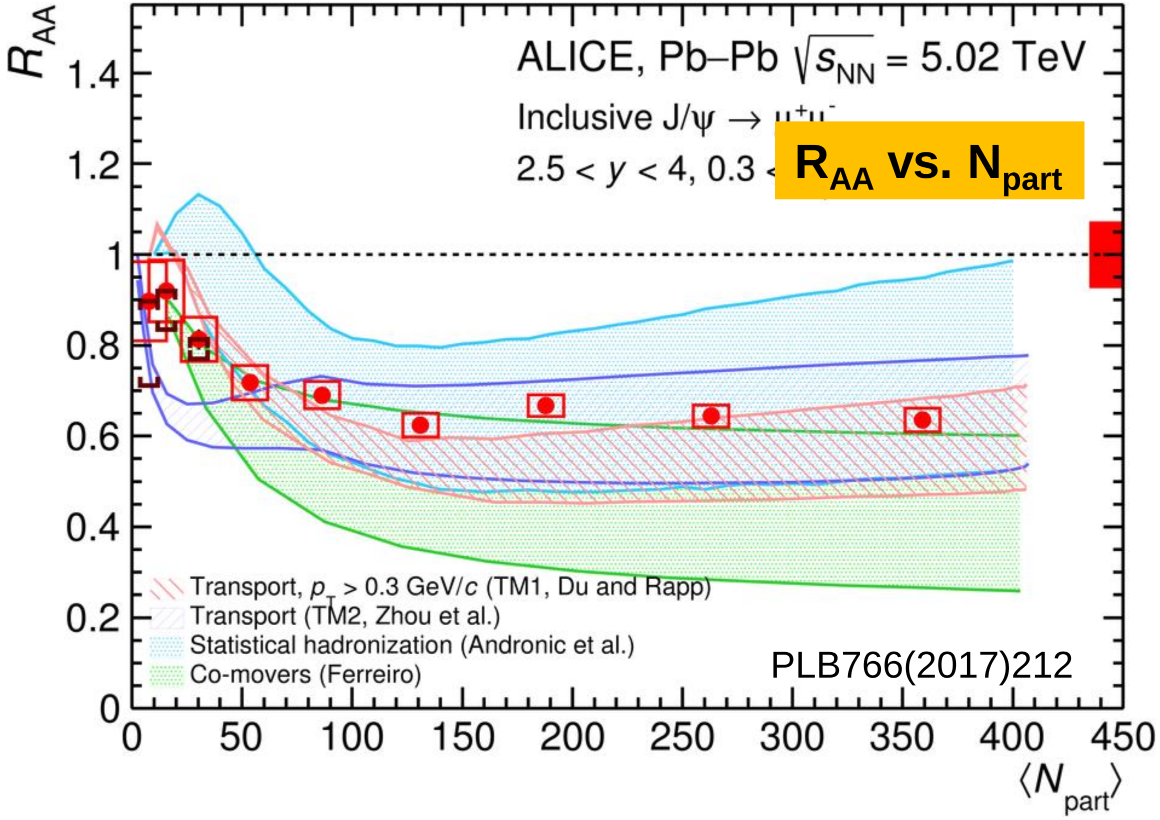
J/ψ modification vs. energy density



Dissociation and regeneration work in opposite directions

J/ψ Regeneration (2)

- J/ψ regeneration / statistical hadronization models



PLB766(2017)212

P. Braun-Munzinger and J. Stachel, PLB490(2000) 196
R. Thews et al, PRC63:054905(2001)

Other quarkonia states melt at different temperatures
→ QGP thermometer (see backup)

Summary
Quarkonia

- High density of color charges in QGP leads to melting of quarkonia (c-cbar and b-bar)

- 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”)

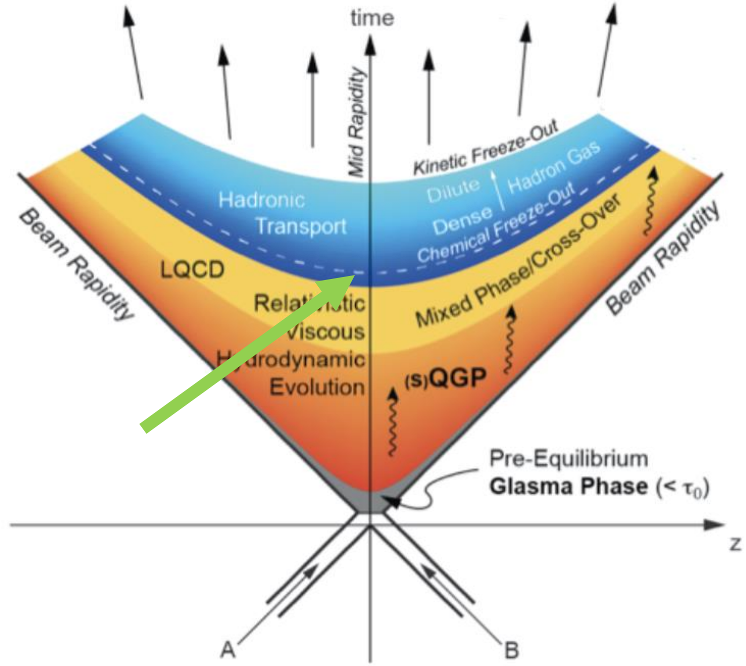
Particle Yields
&
Statistical Model

What can particle abundances tell about the transition between QGP and hadrons?

Chemical Freeze-Out

- Hadronization has occurred
- Inelastic collisions stop
- Particle yields fixed

- Elastic collisions may still occur until kinetic freeze-out



Courtesy B.Hippolyte

- Assume system to be in *chemical equilibrium*
- Particle yields can be calculated with *statistical models*
- Calculated in framework of statistical thermodynamics

Statistical Model

- Relativistic ideal quantum gas of hadrons
- Partition function *Z* for grand-canonical ensemble
  - How is probability distributed between available states?
  - For particle *i* (out of π, K, p, …, all known particles)

$$\ln Z_i(T,\underset{\text{volume}}{V},\mu) = \pm \underset{\text{spin degeneracy}}{g_i} V \int \frac{d^3p}{(2\pi\eta)^3} \ln\left(1 \pm \exp\left(-(\underset{E_i=\sqrt{p^2+m_i^2}}{E_i(p)} - \underset{\text{chemical potential (conserved quantities)}}{\mu_i})/\underset{\text{Temperature}}{T}\right)\right)$$

$$\mu_i = \underset{\text{baryon number}}{\mu_B} B_i + \underset{\text{strangeness}}{\mu_S} S_i + \underset{\text{isospin}}{\mu_{I_3}} I_{3,i} + \underset{\text{charm}}{\mu_C} C_i$$

E.g. NPA722(2006)167

Statistical Model (2)

- Chemical potential constrained with conservation laws

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

  - Sum over considered particles (results depends on particle list)
- 3 free parameters remain (V, T, μ_B)
- Thermodynamic quantities can be calculated from *Z*

$$n = \frac{N}{V} = -\frac{1}{V}\frac{\partial(T\ln Z)}{\partial\mu}$$

Particle densities

$$P = \frac{\partial(T\ln Z)}{\partial V}$$

Pressure

$$s = \frac{1}{V}\frac{\partial(T\ln Z)}{\partial T}$$

Entropy

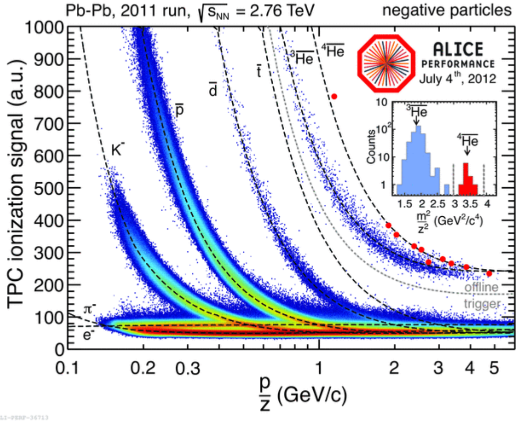
- In particle ratios V cancels → two free parameters (T, μ_B)

Let’s have a look at the data…

Particle Identification

Direct particle identification

π K p d ^{3}He ^{3}H



Large impact parameter

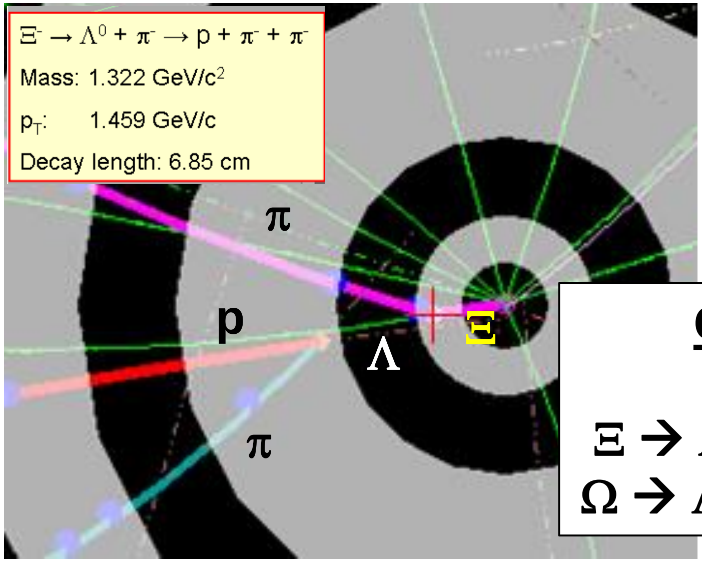
K^0_S → π π (cτ = 2.7 cm)
Λ →p π (cτ = 7.9 cm)

"Kink" in detector volume

K → μ ν (cτ = 3.7 m)

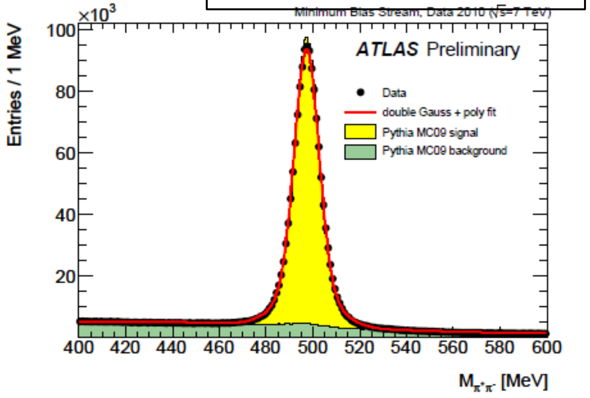
Invariant mass

ϕ → K K
K* → K π



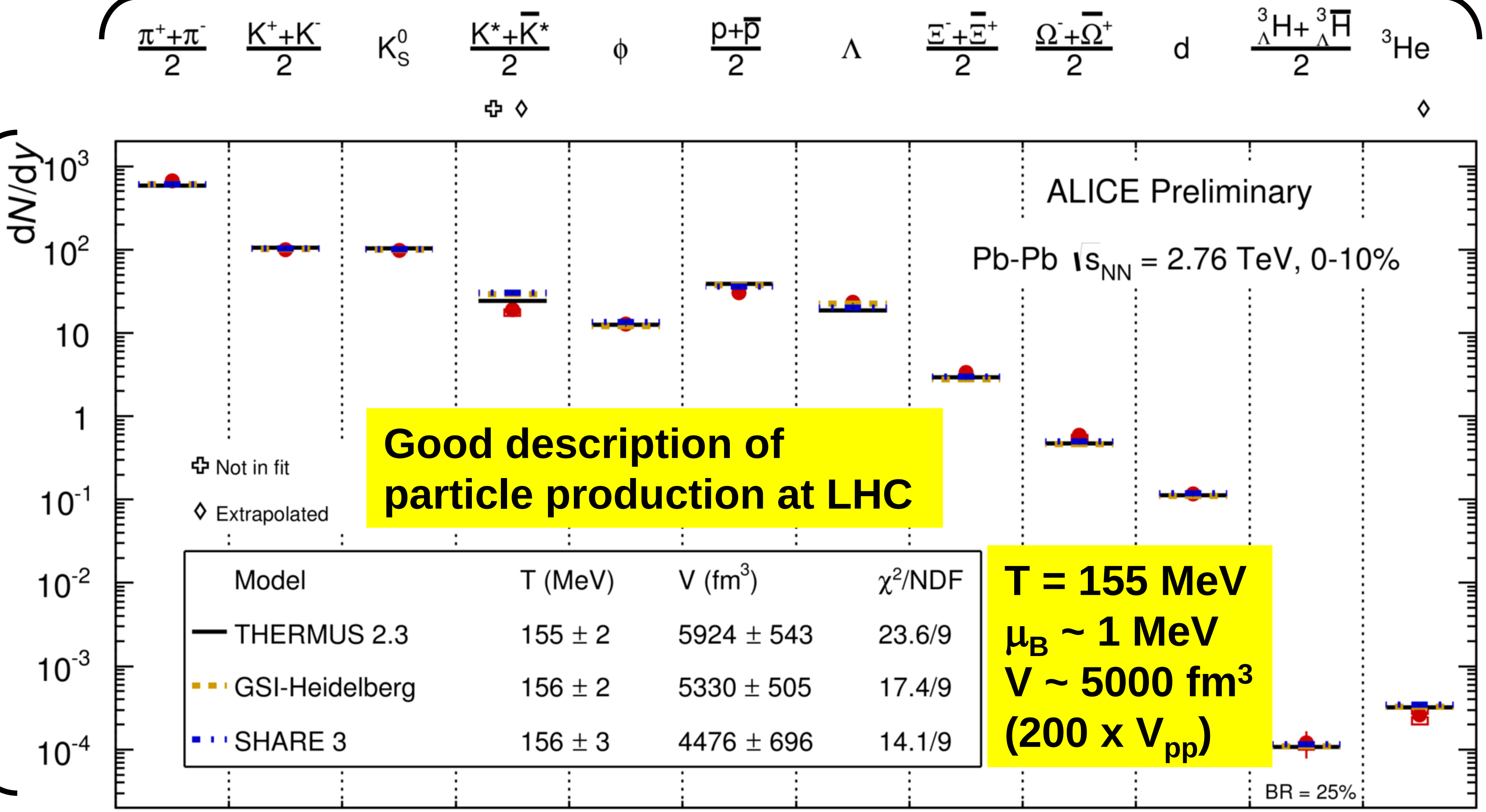
Cascade

Ξ → Λ + π → p π π
Ω → Λ + K → p π K



Statistical Model at LHC

12 different particles



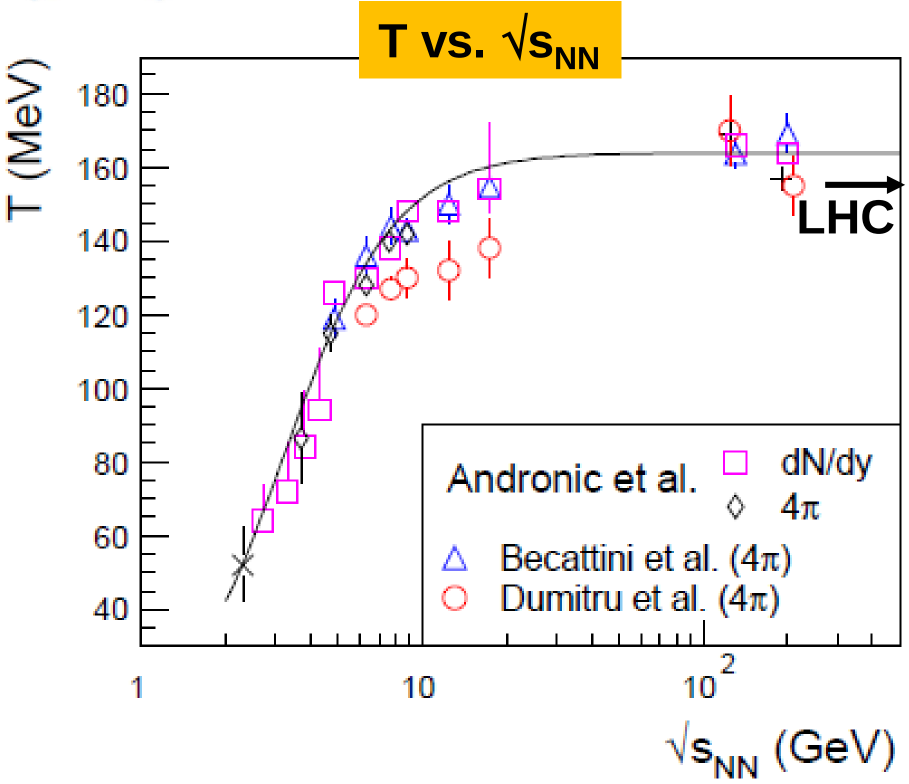
Model	T (MeV)	V (fm^3)	χ^2/NDF
— THERMUS 2.3	155 ± 2	5924 ± 543	23.6/9
- - GSI-Heidelberg	156 ± 2	5330 ± 505	17.4/9
- · SHARE 3	156 ± 3	4476 ± 696	14.1/9

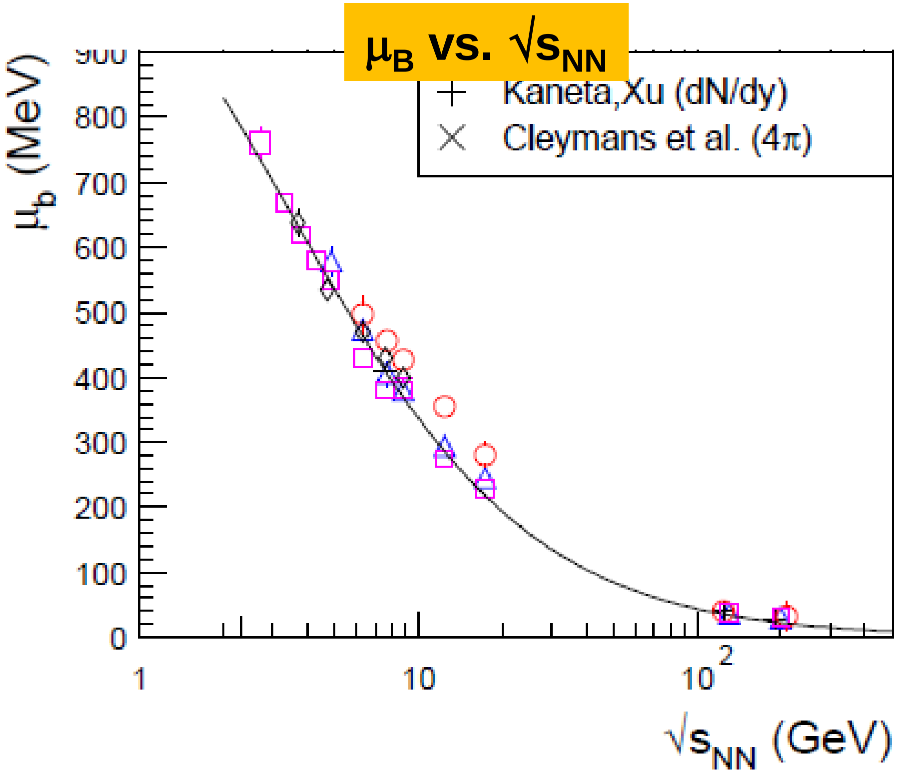
Good description of particle production at LHC

T = 155 MeV
μ_B ~ 1 MeV
V ~ 5000 fm^3
(200 x V_{pp})

7 orders of magnitude

$\sqrt{s}$ Dependence



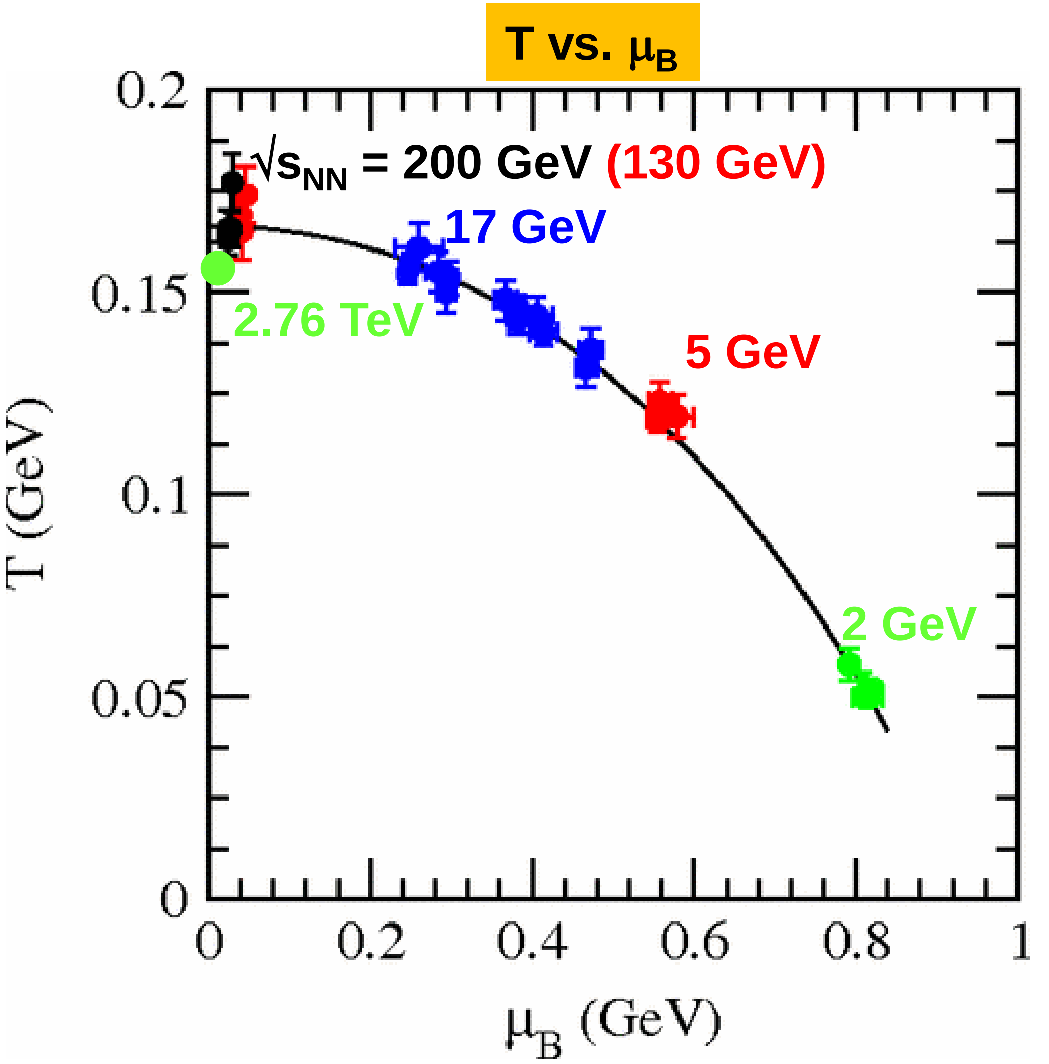


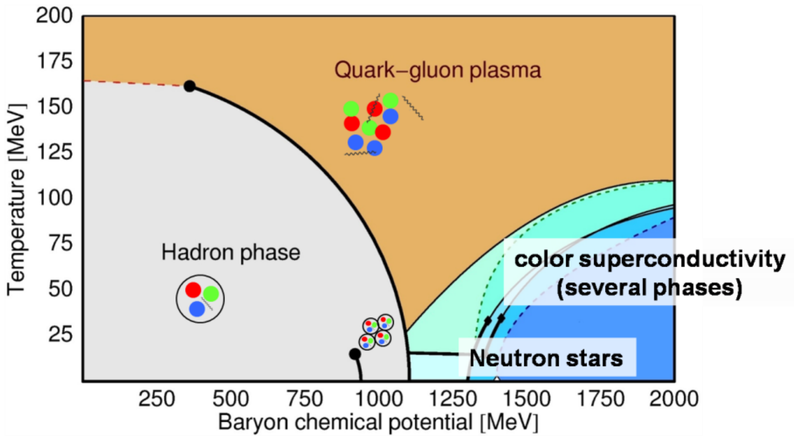
Temperature increases with $\sqrt{s}$ and reaches plateau of about 160 MeV at $\sqrt{s_{NN}}$ > 20 GeV

Baryochemical potential drops with $\sqrt{s_{NN}}$
→ transport of baryon number from nuclei to mid-rapidity is more and more difficult

arXiv:0911.4931

QCD Phase Diagram





- Fit results from $\sqrt{s_{NN}}$ = 2 to 2760 GeV
- Defines chemical freeze-out line in QCD phase diagram

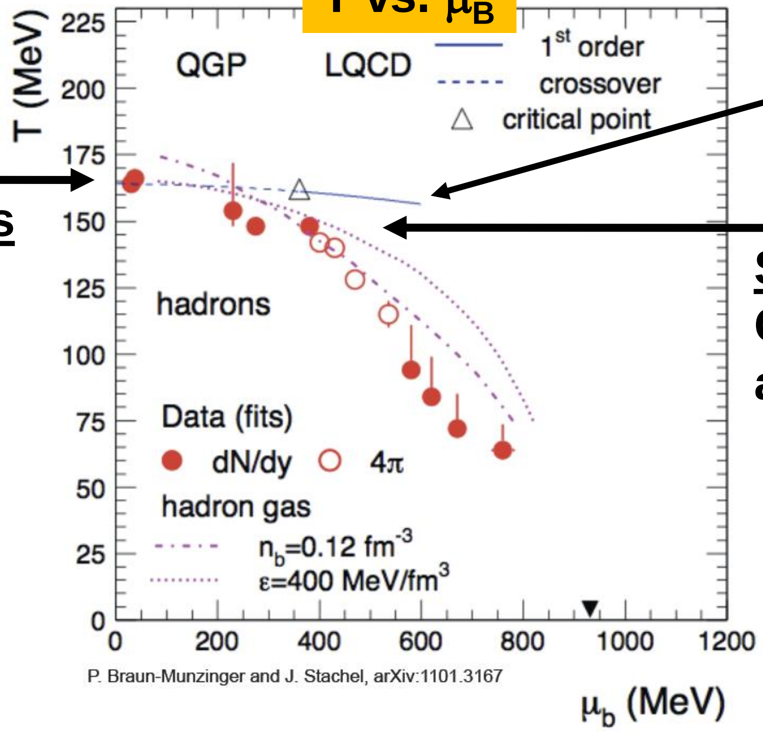
adapted from
PRC 73, 034905 (2006)

QCD Phase Diagram (2)

- Statistical model provides T where inelastic collisions stop

Chemical freeze-out temperature != phase transition temperature

T vs. μ_B



P. Braun-Munzinger and J. Stachel, arXiv:1101.3167

Phase transition from lattice QCD

<u>LHC,RHIC,top SPS energies</u>
Chemical freeze-out close to phase transition

<u>SPS and below</u>
Chemical freeze-out at lower T

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 2760 GeV

→

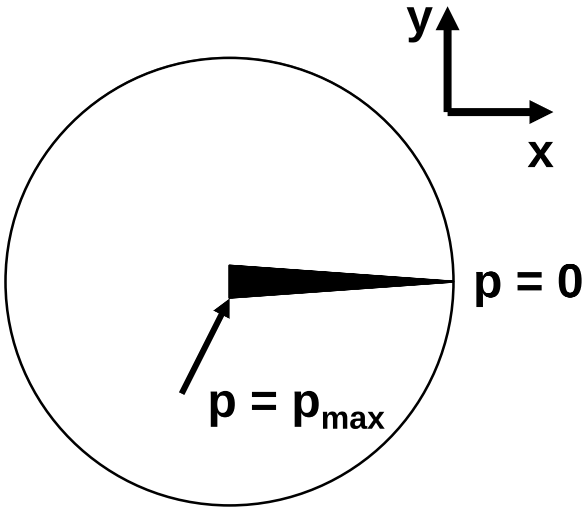
Matter created in HI collisions is in local thermal equilibrium

Collective Flow
&
Hydrodynamics

How does a strongly coupled pressurized system affect particle production?

⚠ **Collective flow has nothing to do with the particle flow method to reconstruct tracks and jets in ATLAS/CMS**

Expansion

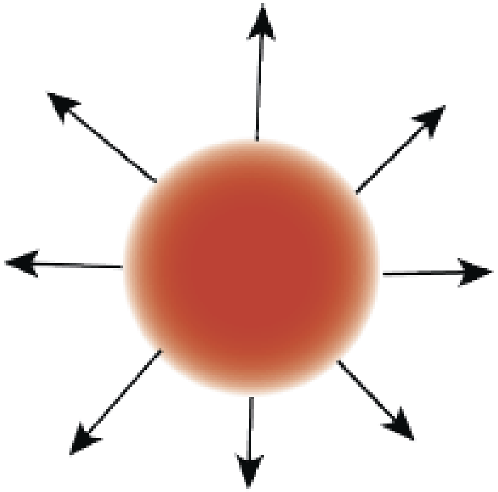


view in beam direction

- After collision, QGP droplet in vacuum
- Energy density very high
- Strong pressure gradient from center to boundary

- Consequence: rapid expansion ("little bang")
- Partons get pushed by expansion
  → Momentum increases

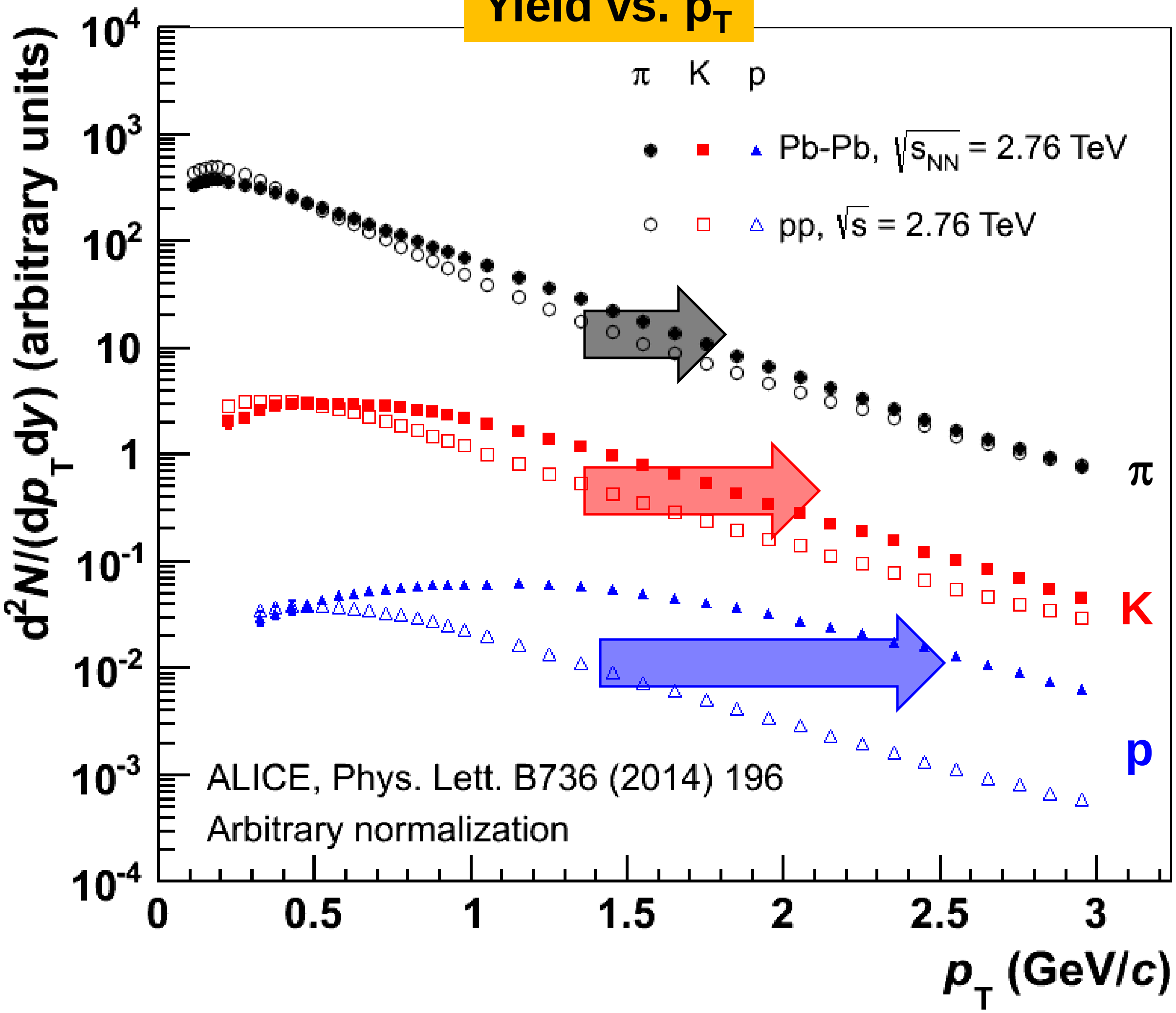
- Measurable in the transverse plane (p_T)
  - Called *radial flow*



Longitudinal expansion (in beam direction) not discussed here.
Have a look at for example: http://www.physi.uni-heidelberg.de/~reygers/lectures/2015/qgp/qgp2015_06_space_time_evo.pdf

Radial Flow

Yield vs. p_T



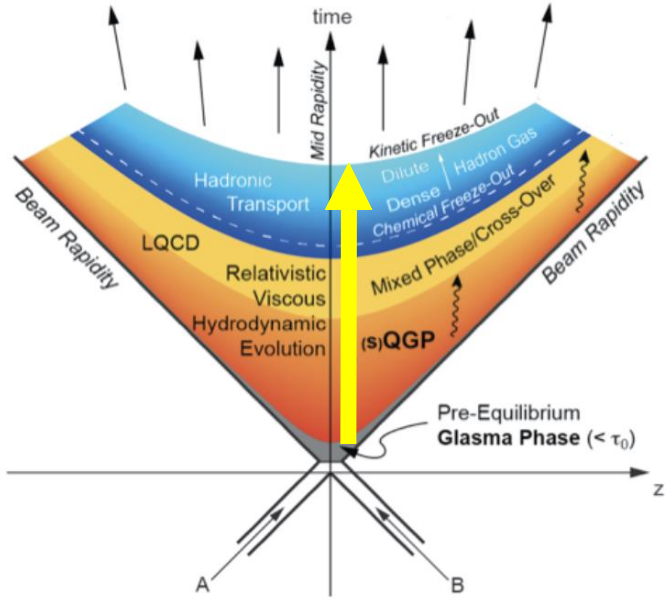
Particle p_T increases
Spectra pushed outwards

Effect larger for
p >> K >> π
→ mass dependence

p = mβγ
common velocity field
(βγ fixed)
→ mass dependence

Blast-Wave Fits

- Quantification of radial flow
  - Reproduce basic features of hydrodynamic modeling (discussed later)
- Locally thermalized medium
- Common velocity field
- Instantaneous freeze-out
- All particle species described with three parameters



Courtesy B.Hippolyte

$$\frac{1}{m_T}\frac{dN}{dm_T} = \int r\,dr\,m_T\,I_0\left(\frac{p_T \sinh\rho}{T_{kin}}\right)K_1\left(\frac{m_T \cosh\rho}{T_{kin}}\right) \longleftarrow \rho = \tanh^{-1}\beta_T\left(\frac{r}{R}\right)^n$$

Bessel functions I_0 K_1

kinetic freeze-out temperature

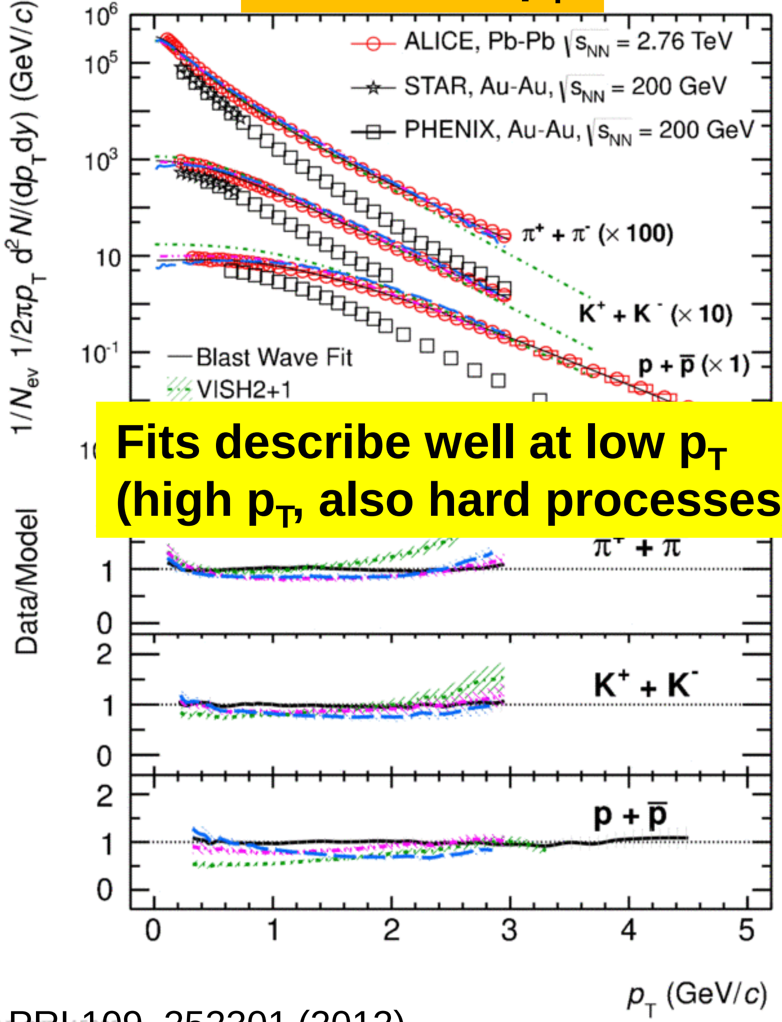
radial flow velocity

velocity profile

PRC 48, 2462 (1993)

Blast-Wave Fits (2)

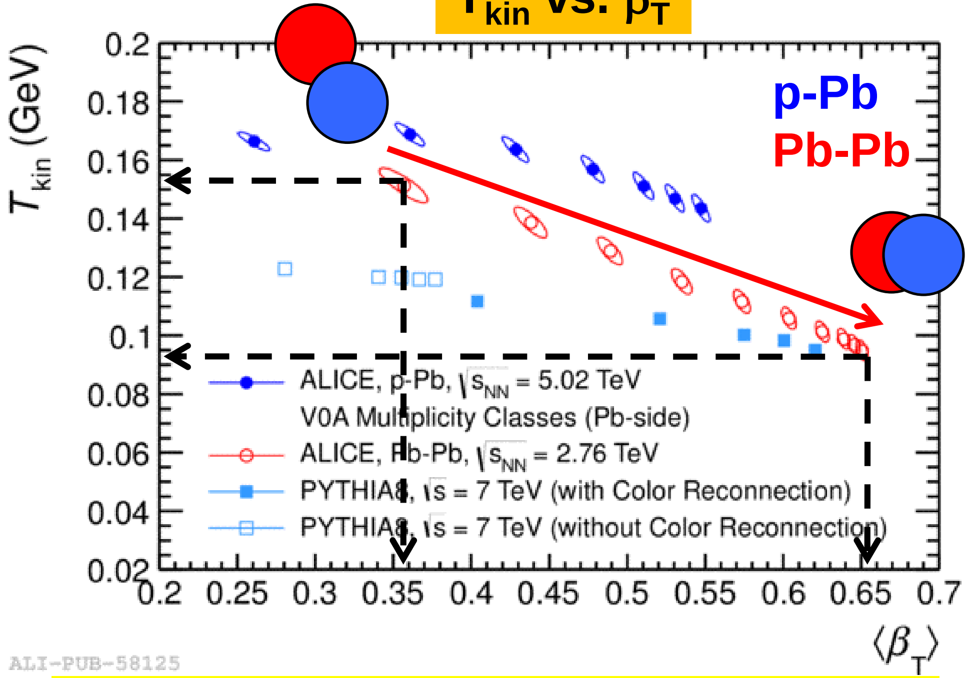
BW fits vs. p_T



Fits describe well at low p_T (high p_T, also hard processes)

PRL109, 252301 (2012)

T_{kin} vs. β_T



	Peripheral	→	Central
Expansion	**0.35 c**	**–**	**0.65 c**
T_{kin}	**150 MeV**	**–**	**90 MeV**

Denser system in central collisions decouples at lower T

PLB 728 (2014) 25

Backup

B → J/ψ

- $B^{\pm}$; m = 5.28 GeV ; cτ = 492 µm (4 times larger than D)
- B^{0} ; m = 5.28 GeV ; cτ = 455 µm

- $B^{\pm}$ → J/ψ + X (branching ratio ~ 0.5%)
- B^{0} → J/ψ + X (branching ratio ~ 0.5%)
- J/ψ → µµ (branching ratio ~ 6%)

- Identification by displaced secondary vertex
  - No reconstruction of full decay chain

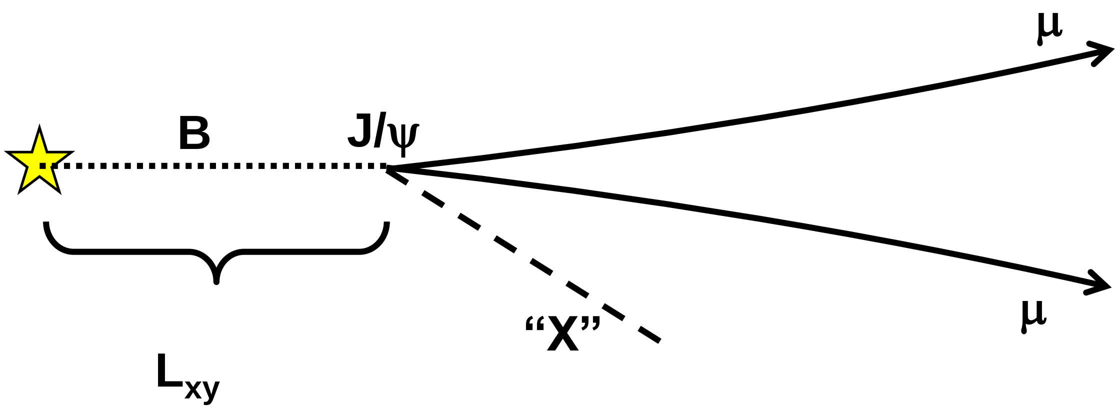
B Identification

- Most probably transverse b-hadron decay length
  - Transverse because vertex is better known in this direction

$$L_{xy} = \frac{\hat{u}^T S^{-1} \overset{\rho}{r}}{\hat{u}^T S^{-1} \hat{u}}$$

u J/ψ vector
r primary vertex
S cov. matrices

Plane transverse to beam



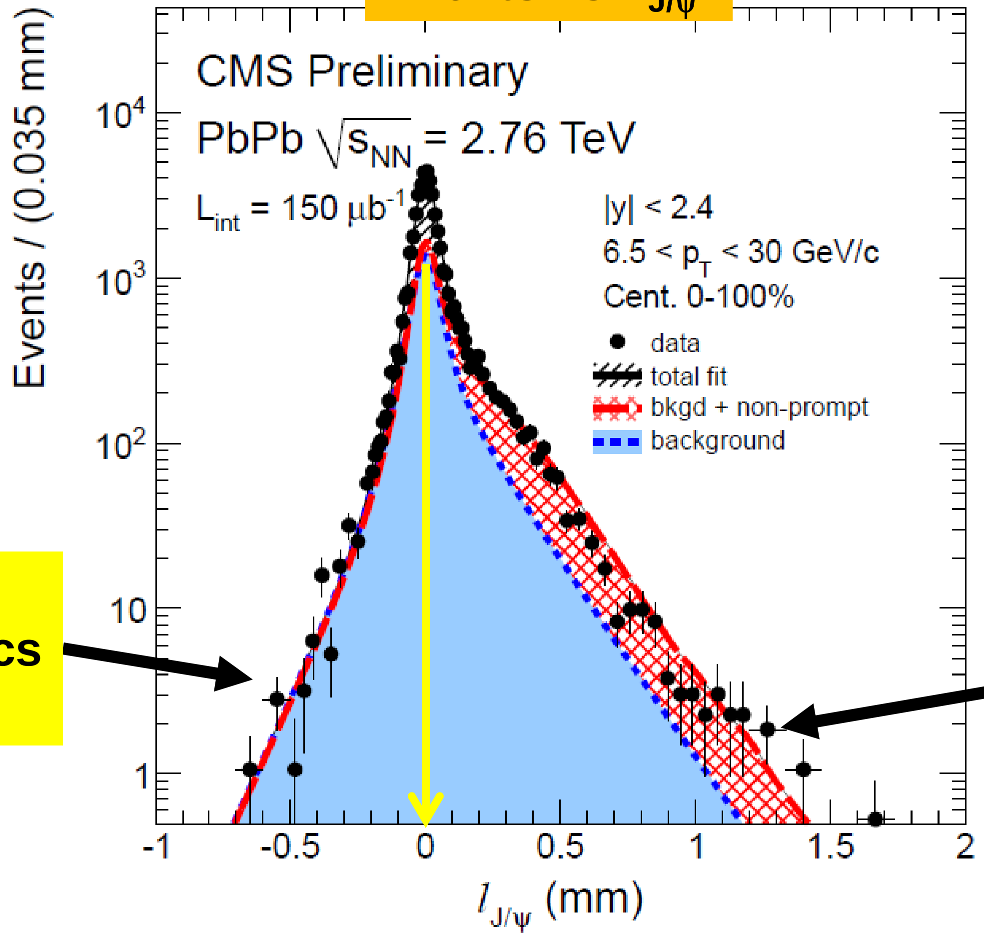
- Convert to pseudo-proper decay length as estimate of b-hadron decay length (time dilatation)

$$l_{J/\psi} = L_{xy} m_{J/\psi} / p_T$$

J/ψ candidate mass and p_T

Decay Length Distribution

Events vs. $l_{J/\psi}$



$\underline{l_{J/\psi} < 0}$
combinatorics
resolution

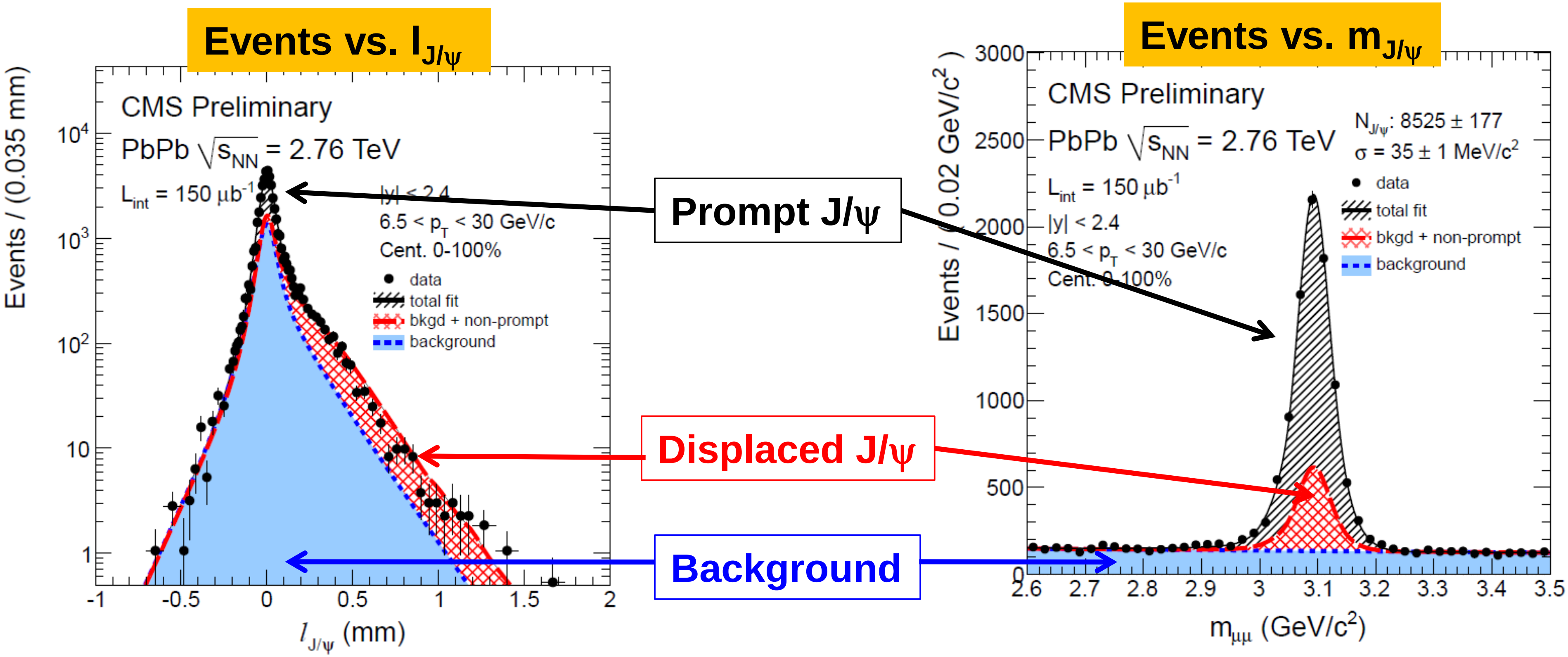
$\underline{l_{J/\psi} > 0}$
combinatorics
resolution
b decays

→ Experimental handle on resolution of $l_{J/\psi}$

CMS, HIN-12-014

Yield Extraction

- (Multi-dimensional) fit to $l_{J/\psi}$ and invariant mass $m_{\mu\mu}$
  - Total number of J/ψ and fraction of displaced J/ψ



Events vs. $l_{J/\psi}$

Events vs. $m_{J/\psi}$

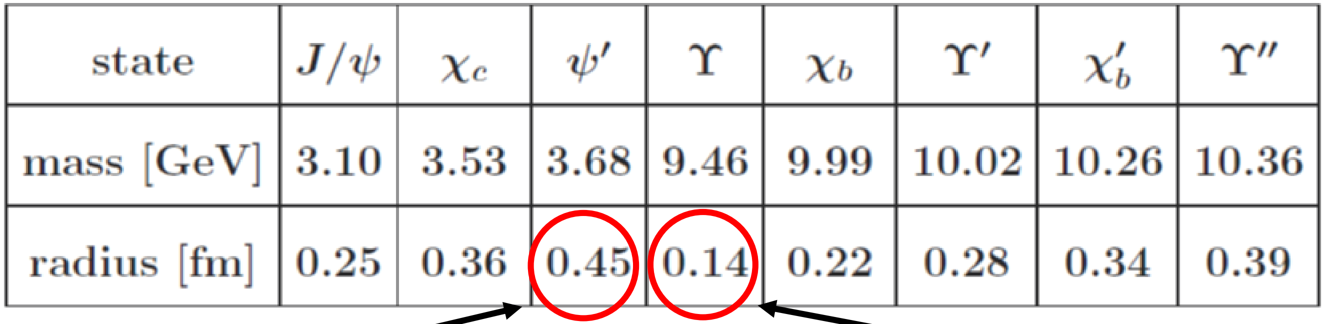
Prompt J/ψ

Displaced J/ψ

Background

CMS, HIN-12-014

Other Quarkonia

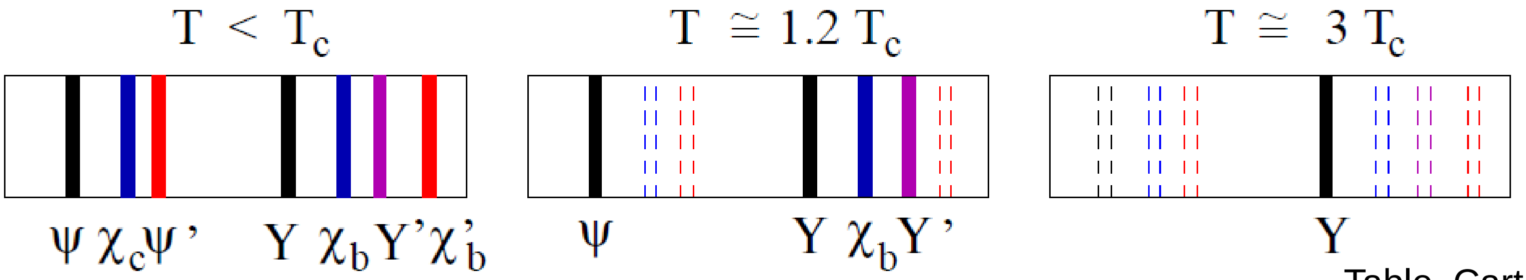


state	J/ψ	χ_c	ψ'	Υ	χ_b	Υ'	χ'_b	Υ''
mass [GeV]	3.10	3.53	3.68	9.46	9.99	10.02	10.26	10.36
radius [fm]	0.25	0.36	0.45	0.14	0.22	0.28	0.34	0.39

dissociates first

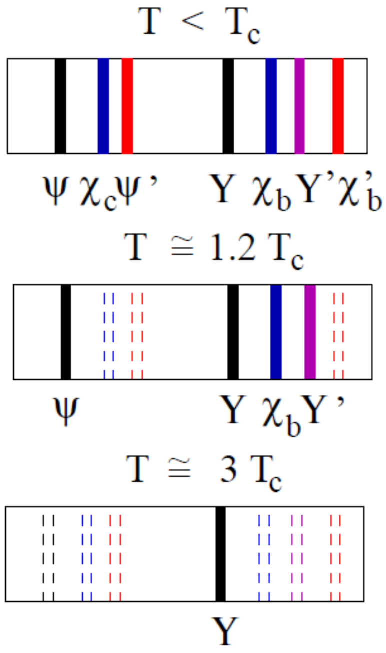
dissociates last

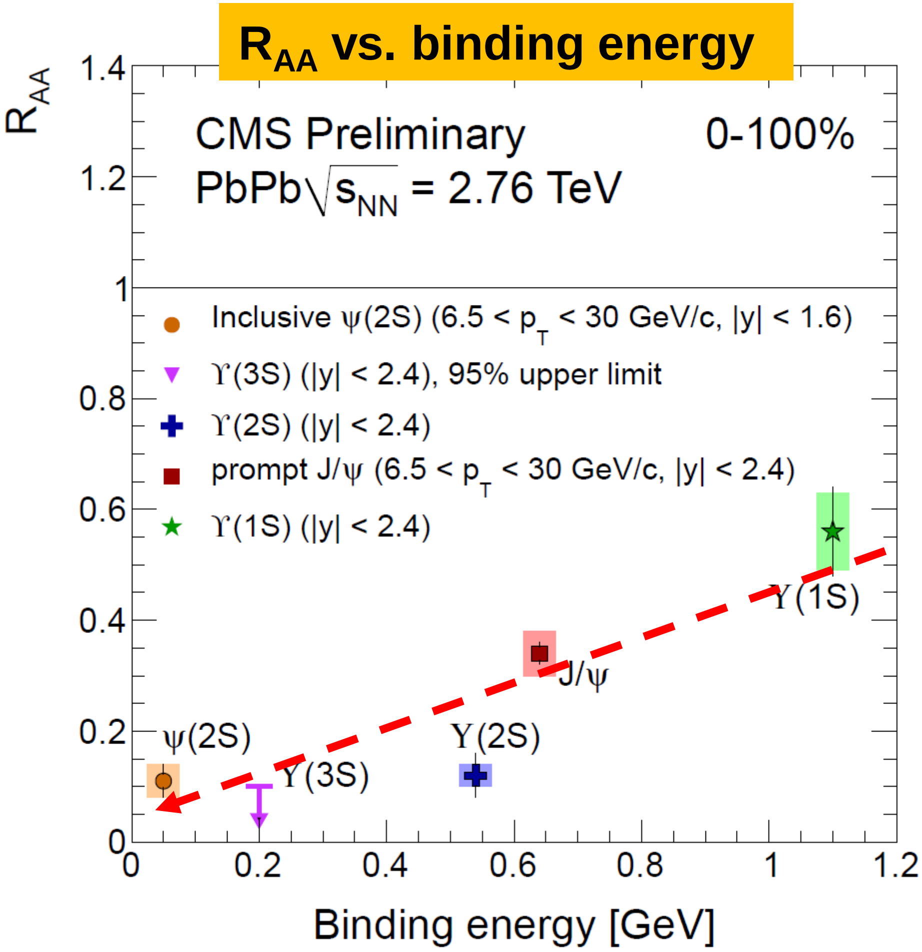
- $\mu = 1/r_D$ increases with T of QGP
  - Lattice estimate: $\mu(T) \cong 4T$
- T controlled by centrality and center of mass energy
- “Spectroscopy” / “Thermometer” of QGP



Table, Cartoon: H. Satz

QGP Thermometer




R_{AA} vs. binding energy

States with lower binding energies more suppressed !