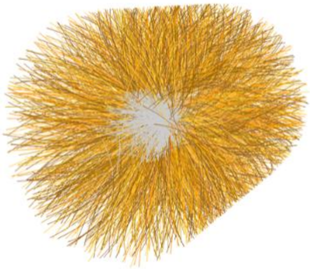


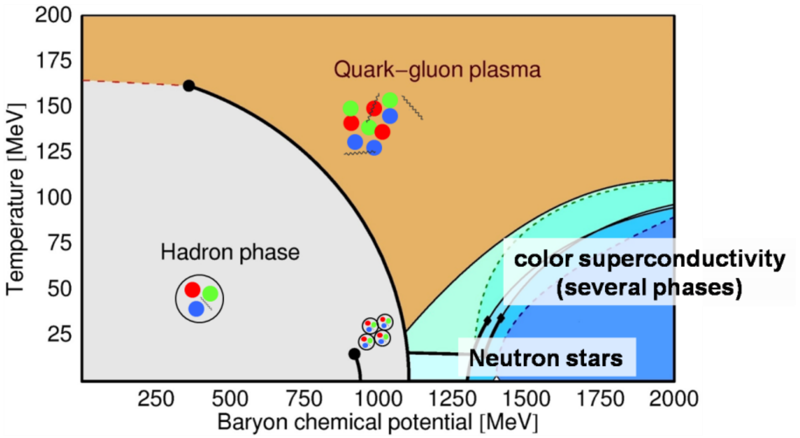
Introduction to Heavy-Ion Physics
Part II

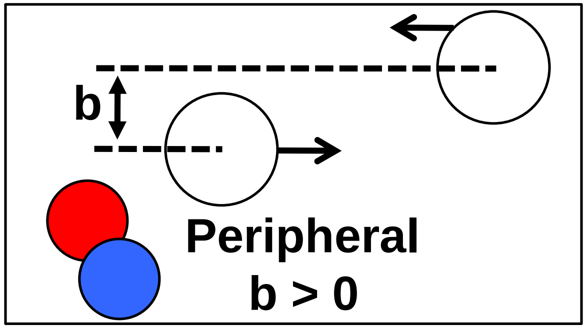
Jan Fiete Grosse-Oetringhaus, CERN

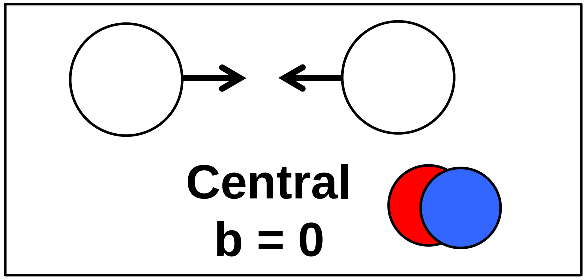
Summer Student Lectures 2017

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)





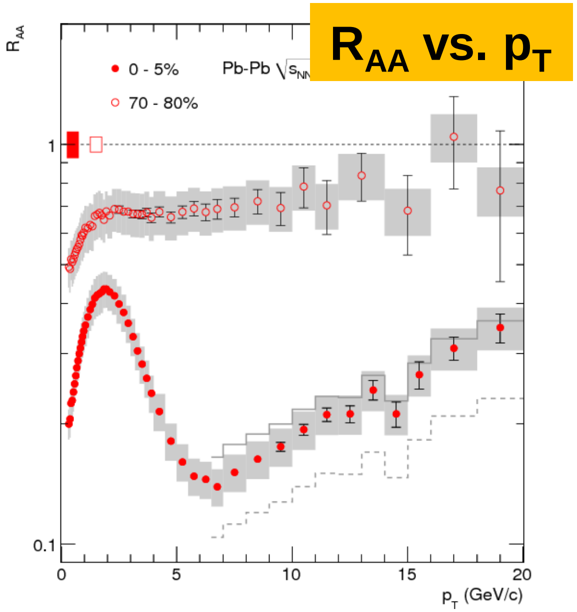


Recap Lecture 1

- 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

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

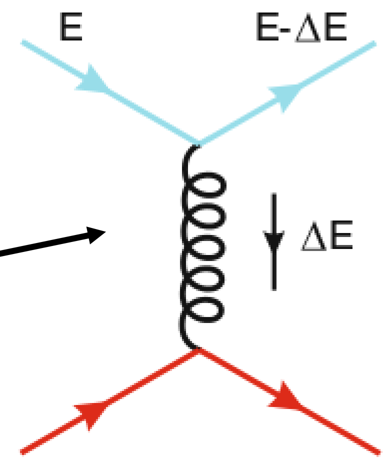
  - Significant suppression of hadron production in central collisions

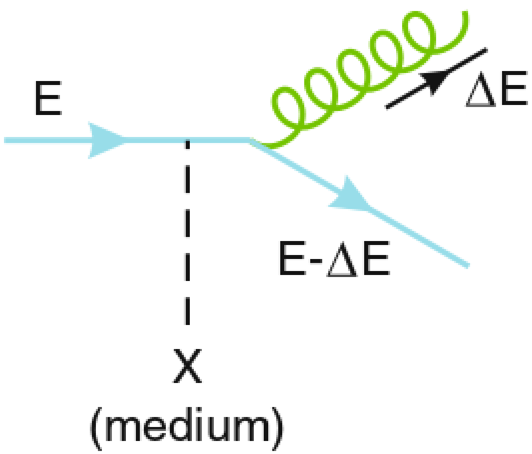


How does the medium achieve this suppression?

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





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

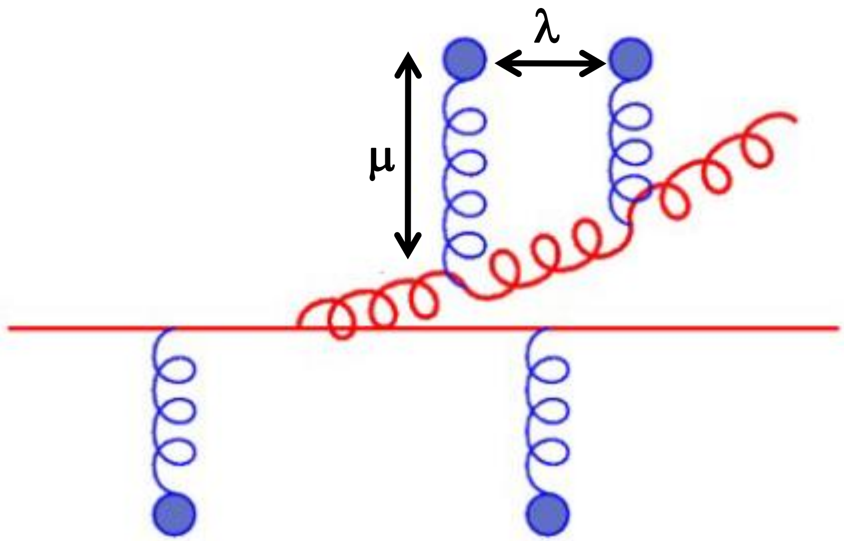
Lect. Notes Phys. 785,285 (2010)

Radiative Energy Loss

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

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

- 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**

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

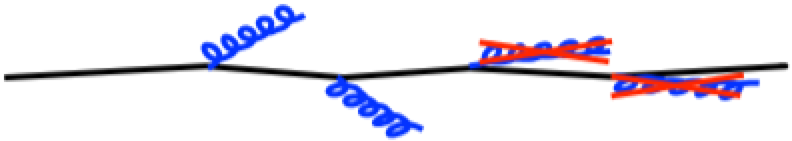
μ^2 ← **average transverse momentum transfer**

λ ← **mean free path**

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

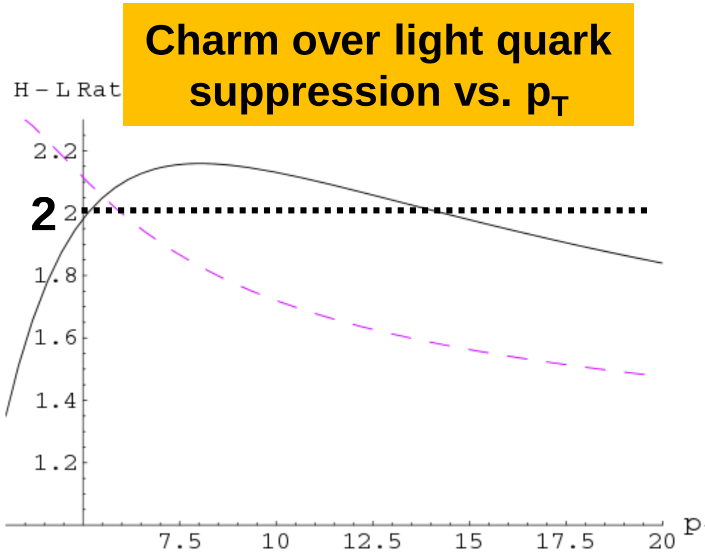
Dead Cone Effect

- Due to kinematical constraints, gluon radiation in vacuum suppressed for angles $\theta < m/E = 1/\gamma$ 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

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



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

Collisional Energy Loss

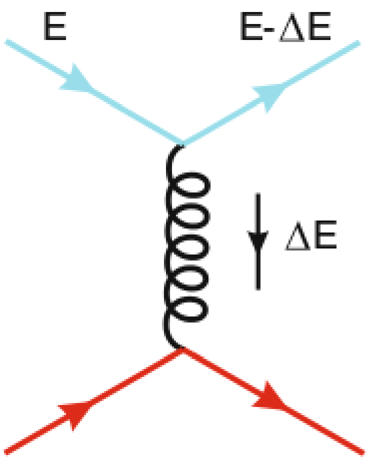
- For light quarks and gluons

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

- For heavy quarks additional term

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

- 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 !

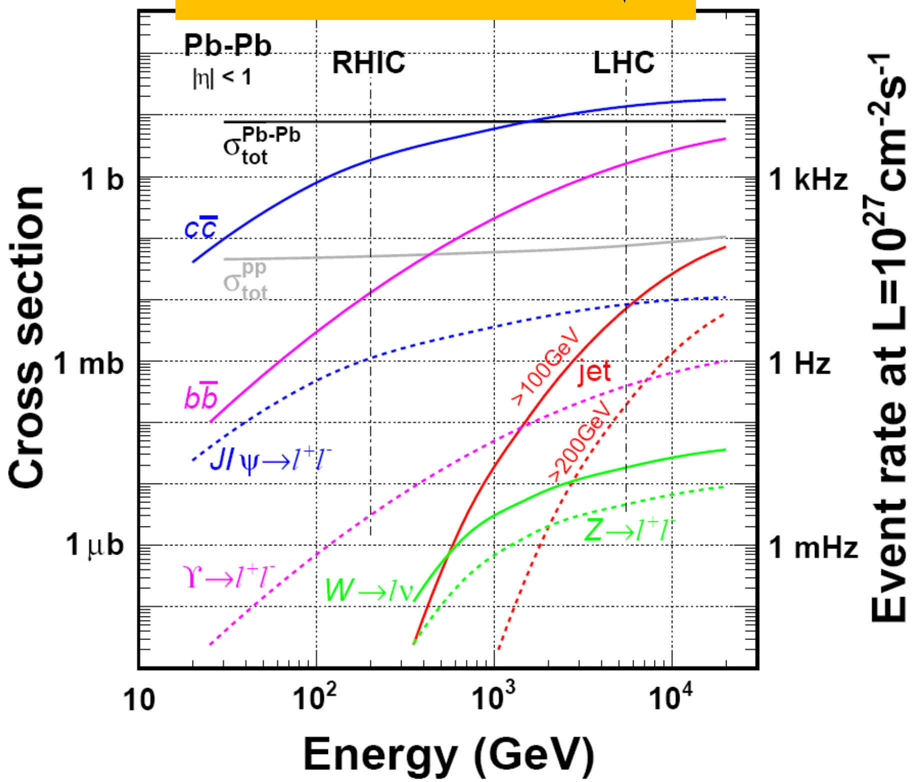
Heavy Quarks

- 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

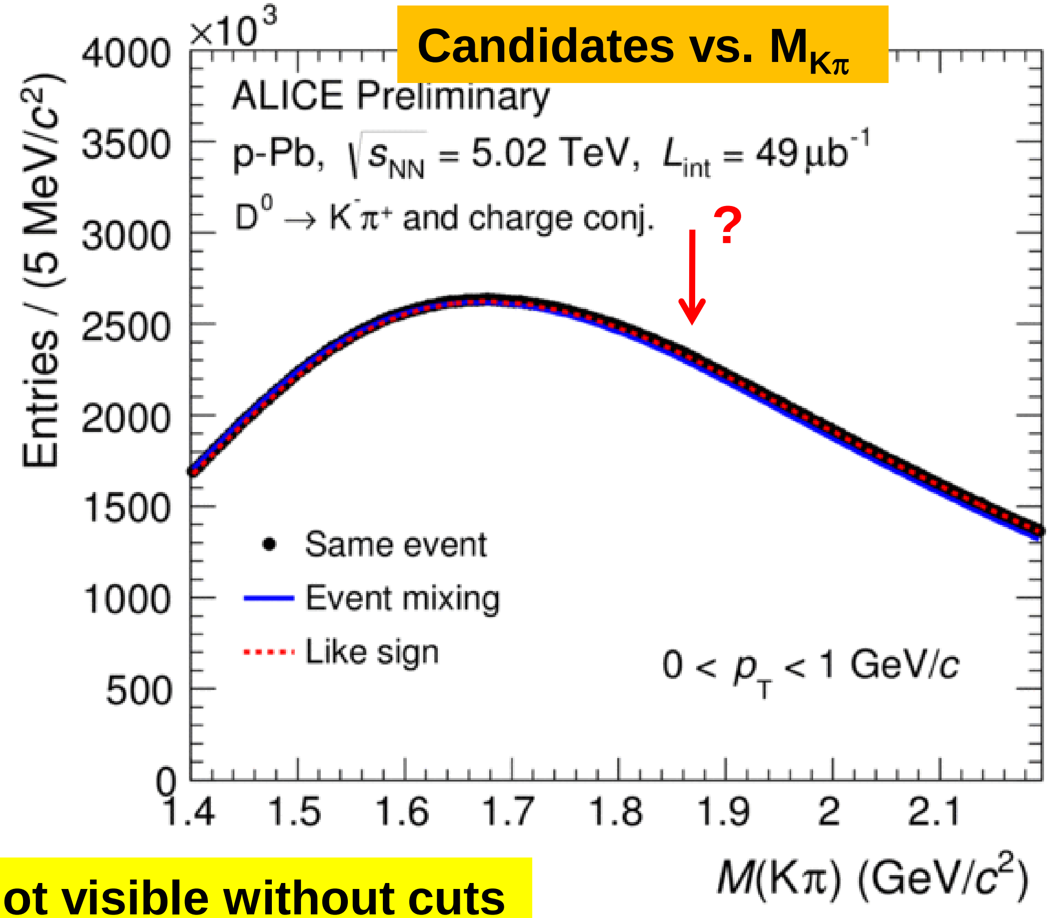


D^0 Reconstruction

- D^0 meson: m = 1.87 GeV/c^2 ; cτ = 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

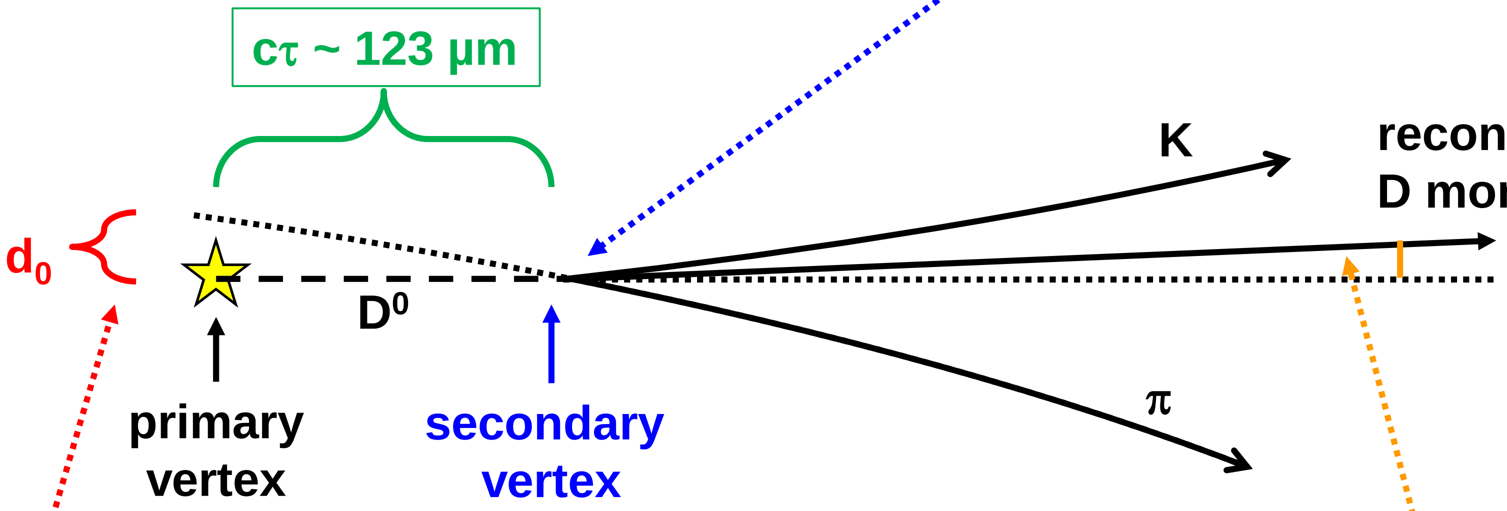


Peak not visible without cuts

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



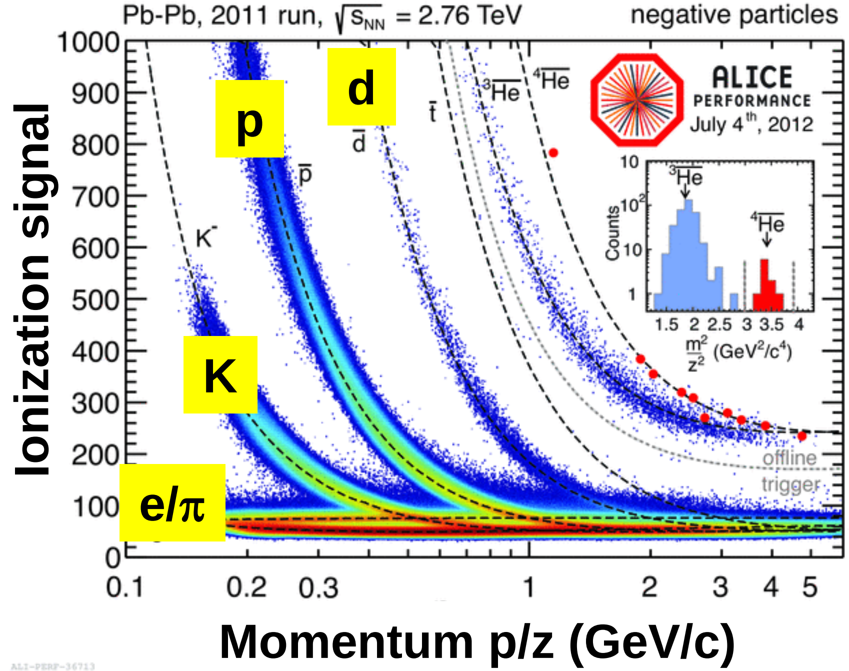
1) Require large impact parameter tracks

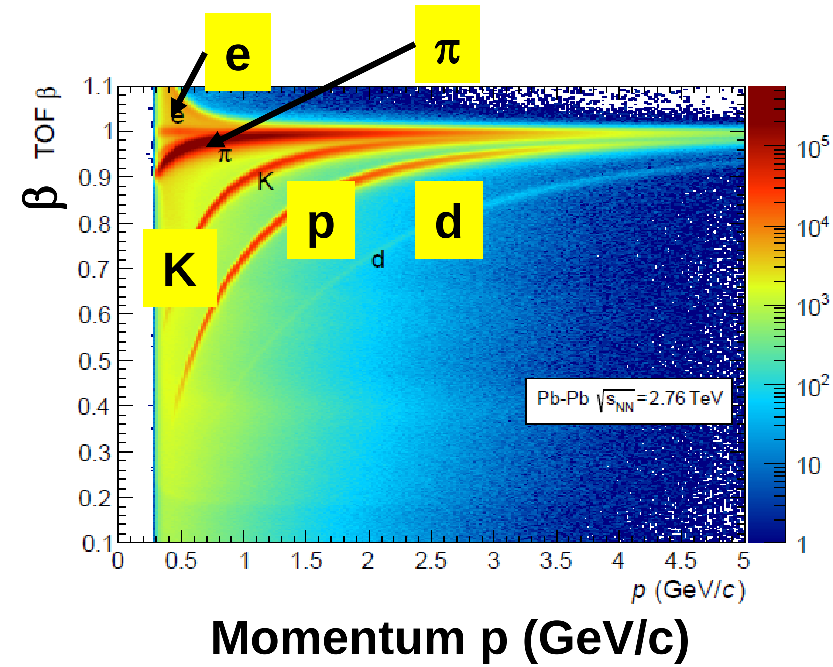
Plane transverse to beam

4) Require pointing angle θ to be small

PID

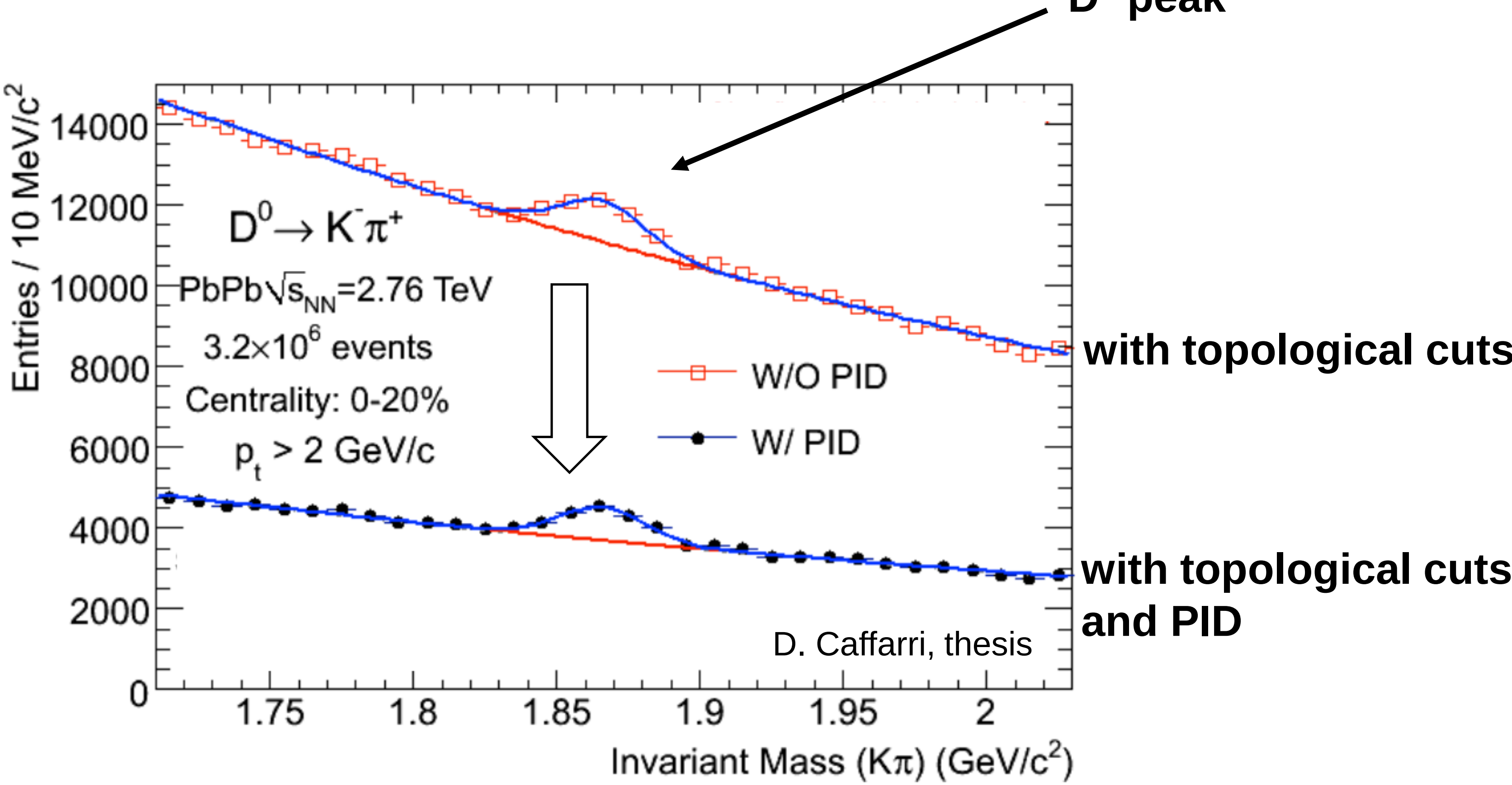
- Specific Energy Loss
  - Particles passing through matter loose energy mainly by ionization
  - Average energy loss calculated with Bethe-Bloch formula
  - Identify particle by measuring energy deposition and momentum
- Time Of Flight
  - Particles with the same momentum have slightly different speed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





Invariant Mass with Cuts

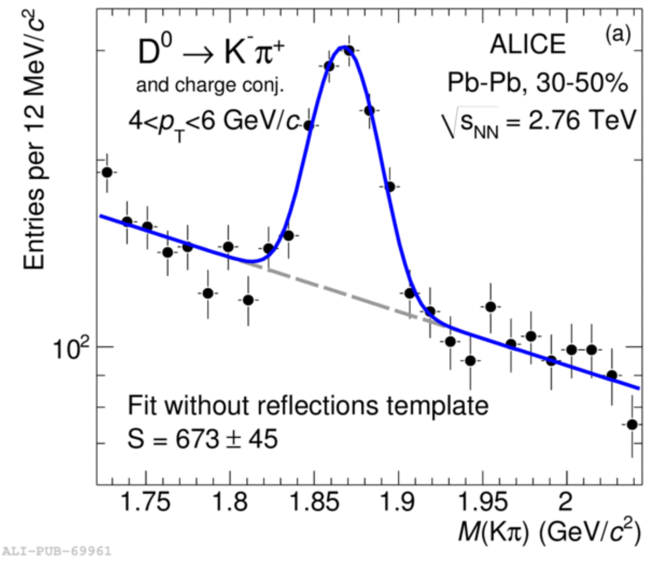
- $D^0 \rightarrow K\ \pi$



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

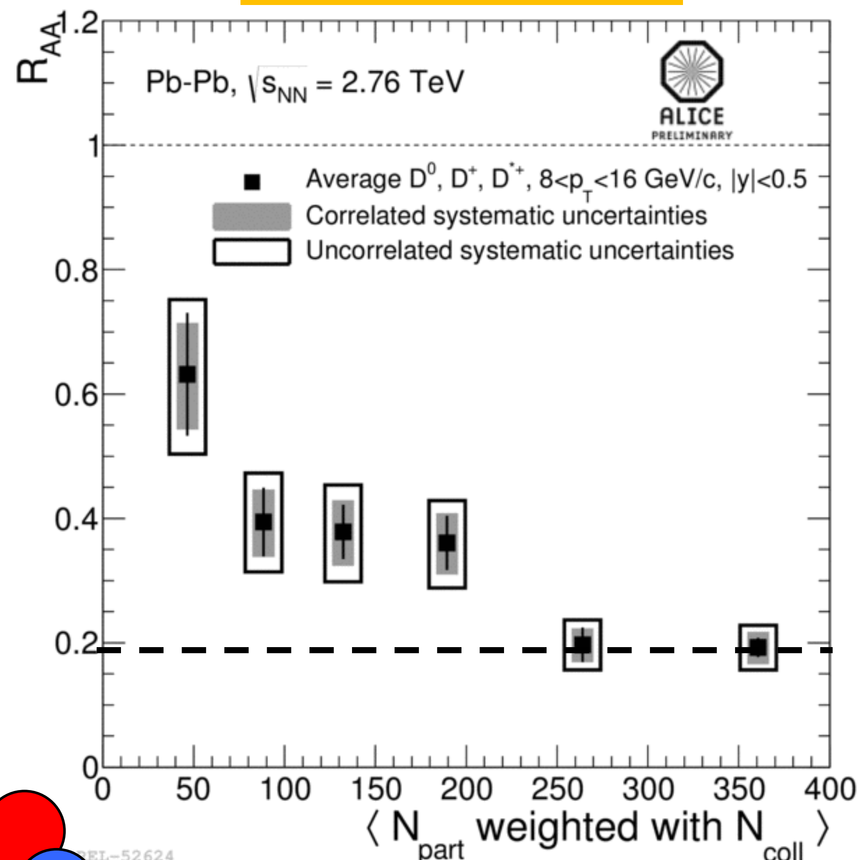


PRC 90 (2014) 034904

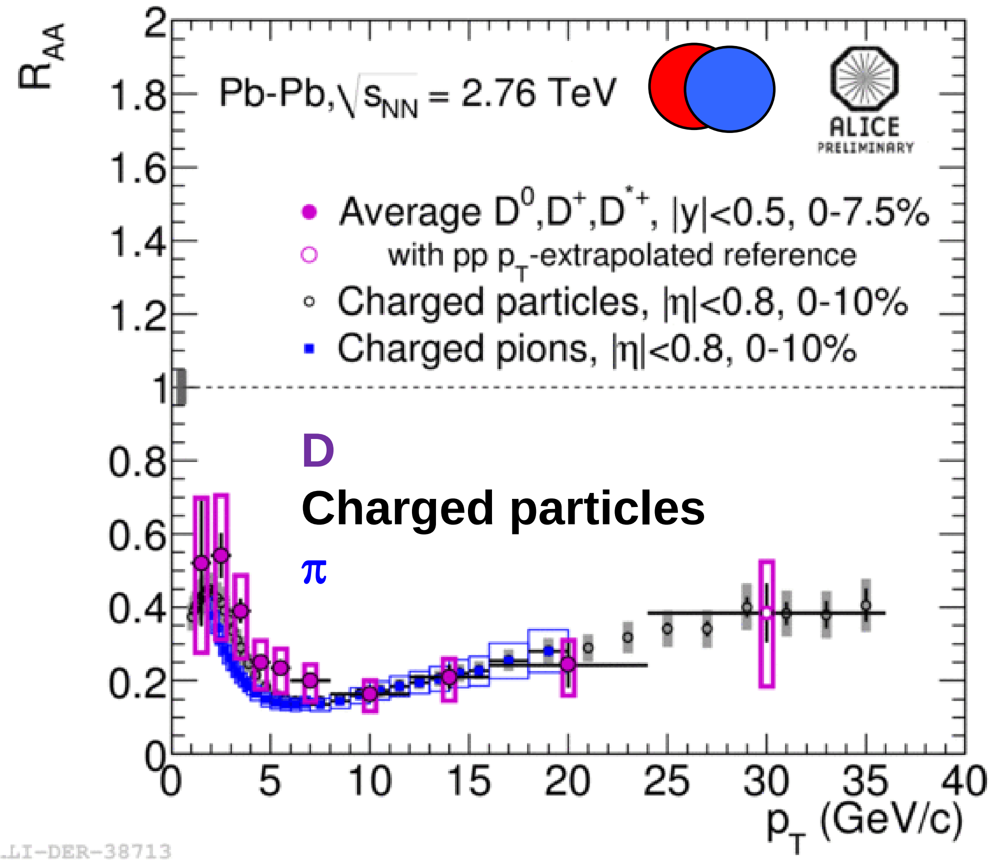
D R_{AA}

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

R_{AA} vs. centrality



R_{AA} vs. p_T



strong suppression ~ 0.2

D and π R_{AA} compatible

arXiv:1506.06604

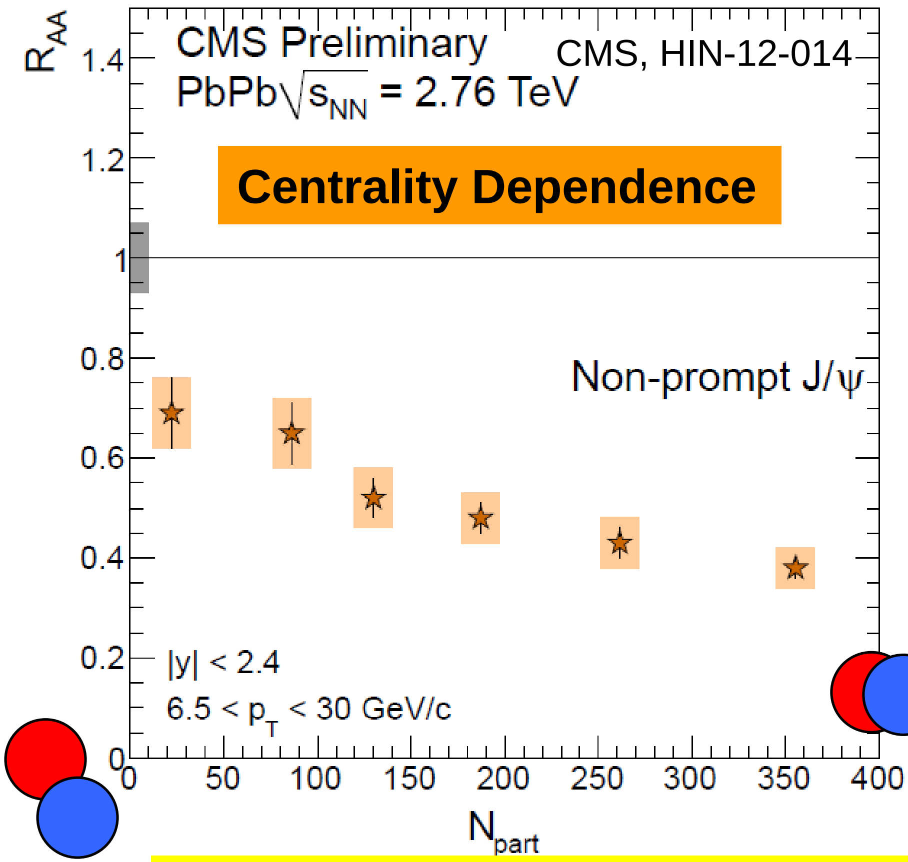
π R_{AA} vs. D R_{AA}

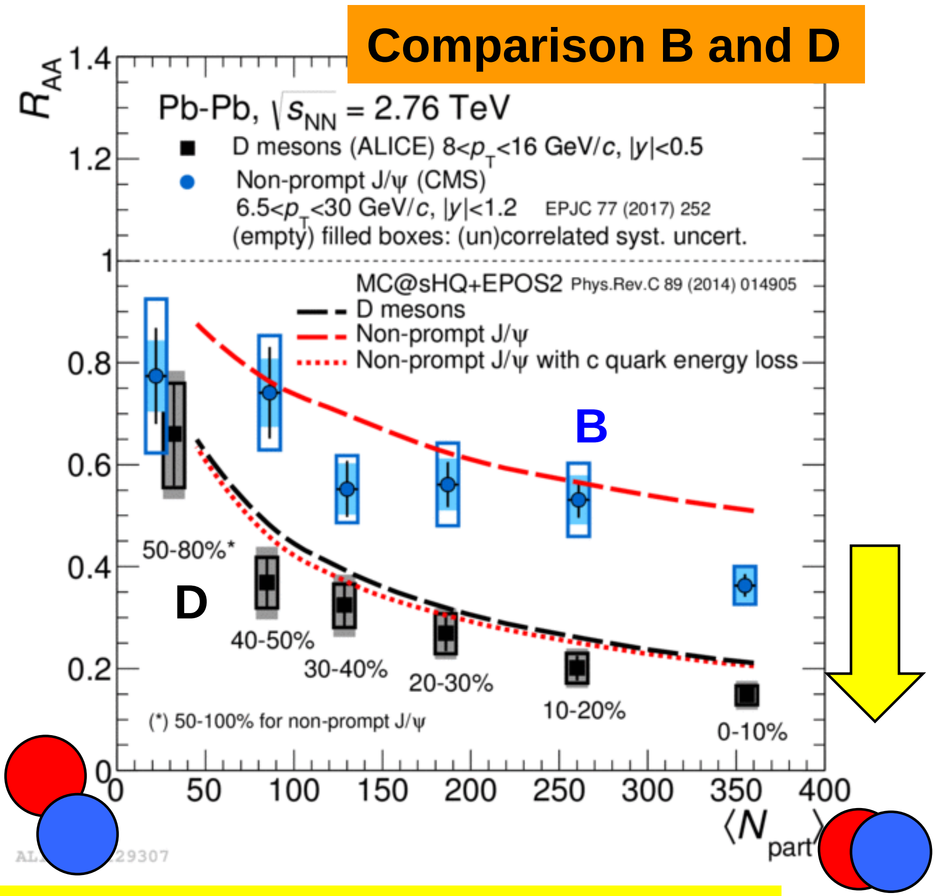
- Expectation $R_{AA}^{\pi} < R_{AA}^{D} < R_{AA}^{B}$
- However $R_{AA}^{\pi} \approx R_{AA}^{D}$
- Are the energy loss models wrong?
- Not necessarily
  - Effect expected for p_T close to charm mass (~1.3 GeV/c^2)
  - Uncertainties on D R_{AA} large for p_T < 5 GeV/c
  - Fragmentation (→ hadron) different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

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

B R_{AA}

B± → (J/ψ → μμ) + X identified by displaced secondary vertices (see backup)





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

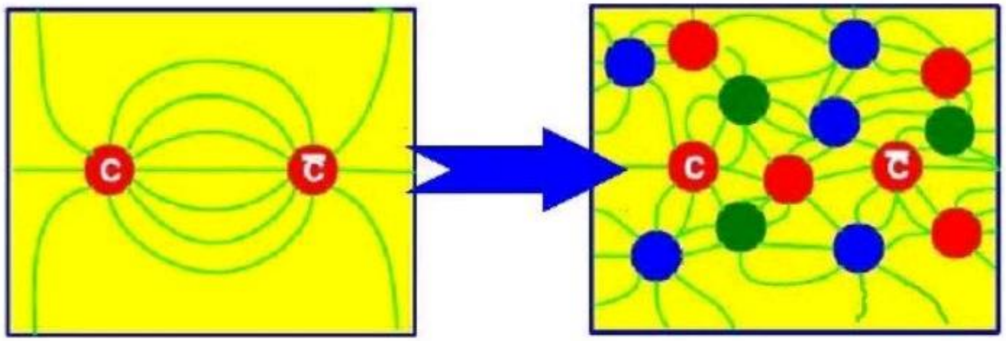
Measurement of b → J/ψ requires displaced vertices. What about J/ψ stemming directly from the interaction?

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

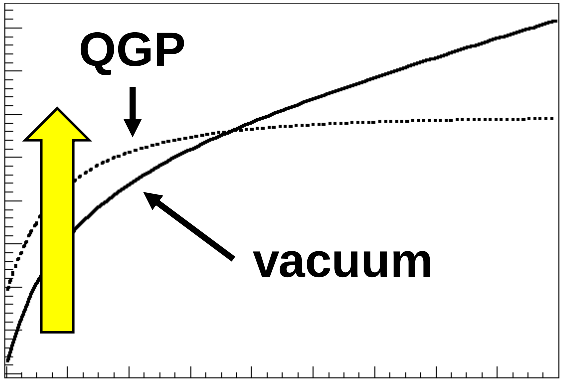
α gauge coupling
σ string tension
μ screening mass

- Changes (binding) potential

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

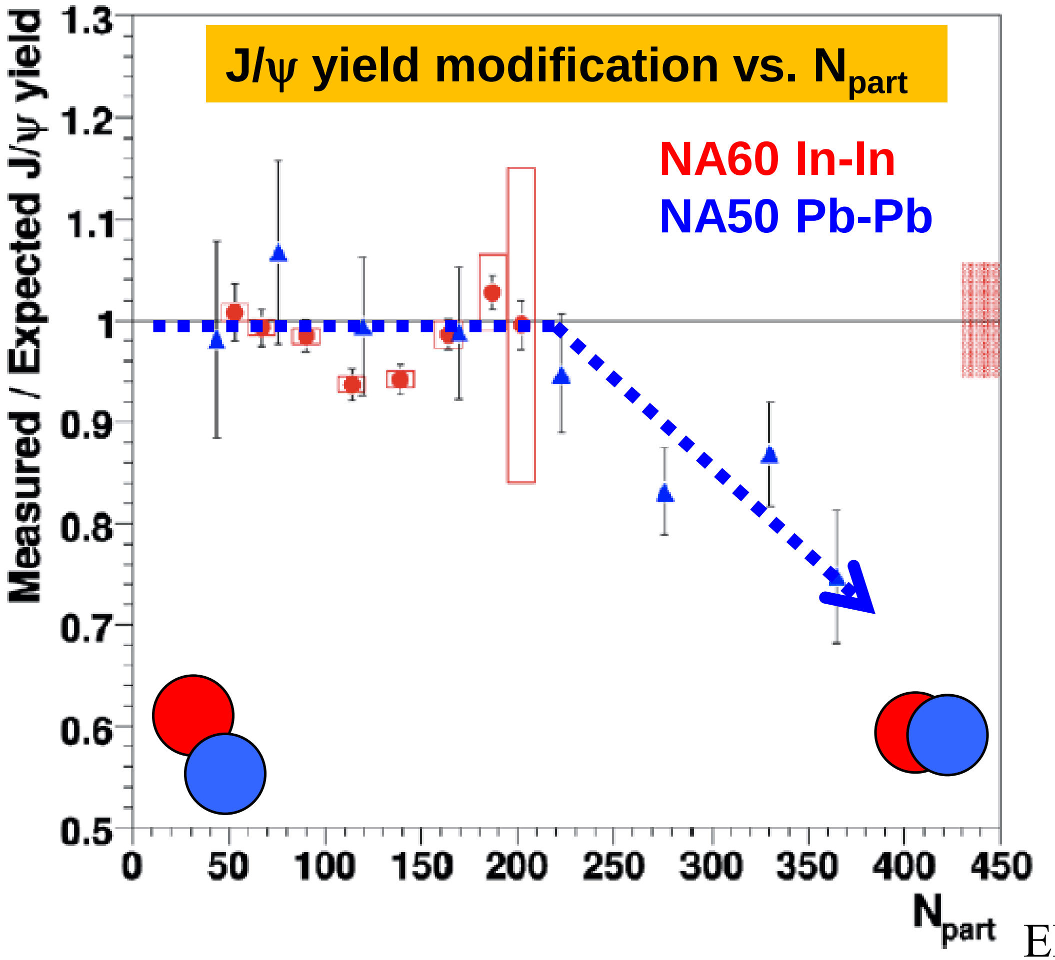
- Quarks with distance larger than 1/μ do not see each other
  - → Dissociation of q-qbar pair !
  - → Quarkonia "melt"

Potential vs. r



J/ψ Suppression

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

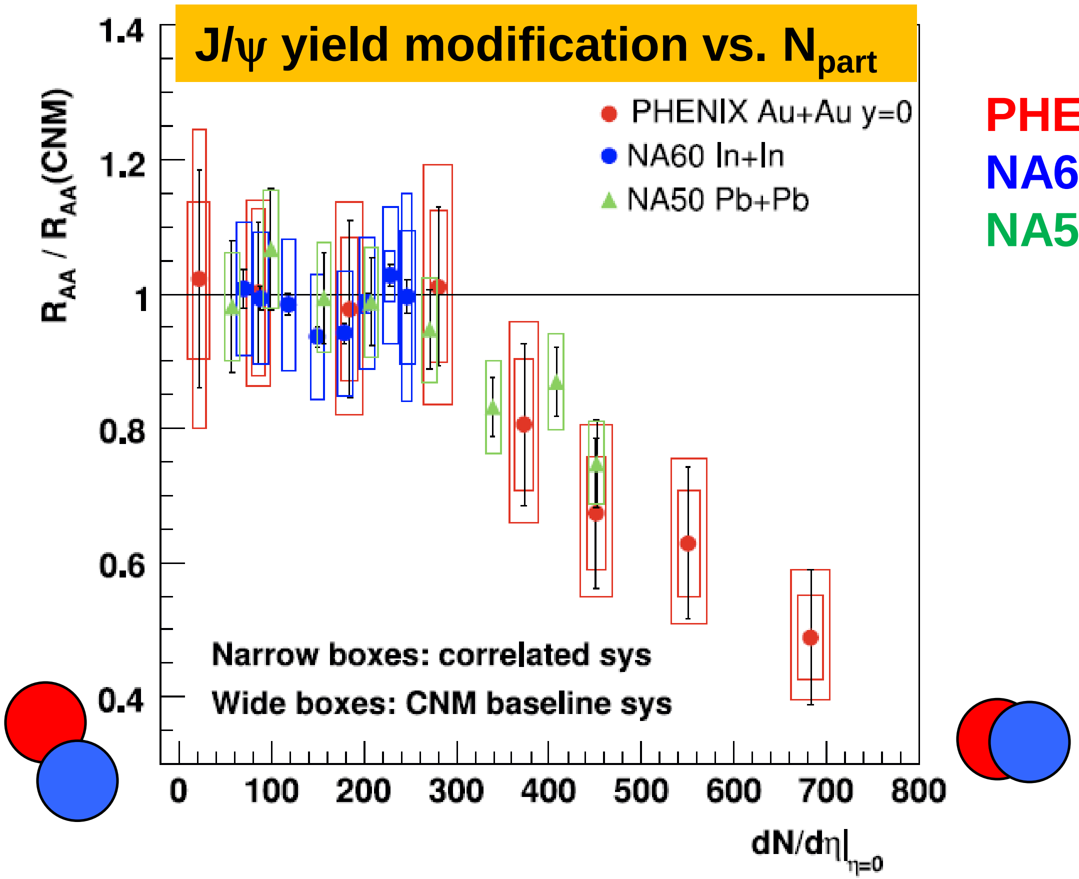


In: A = 105
Pb: A = 208

EPJC (2011) 71:1534

J/ψ Suppression (2)

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

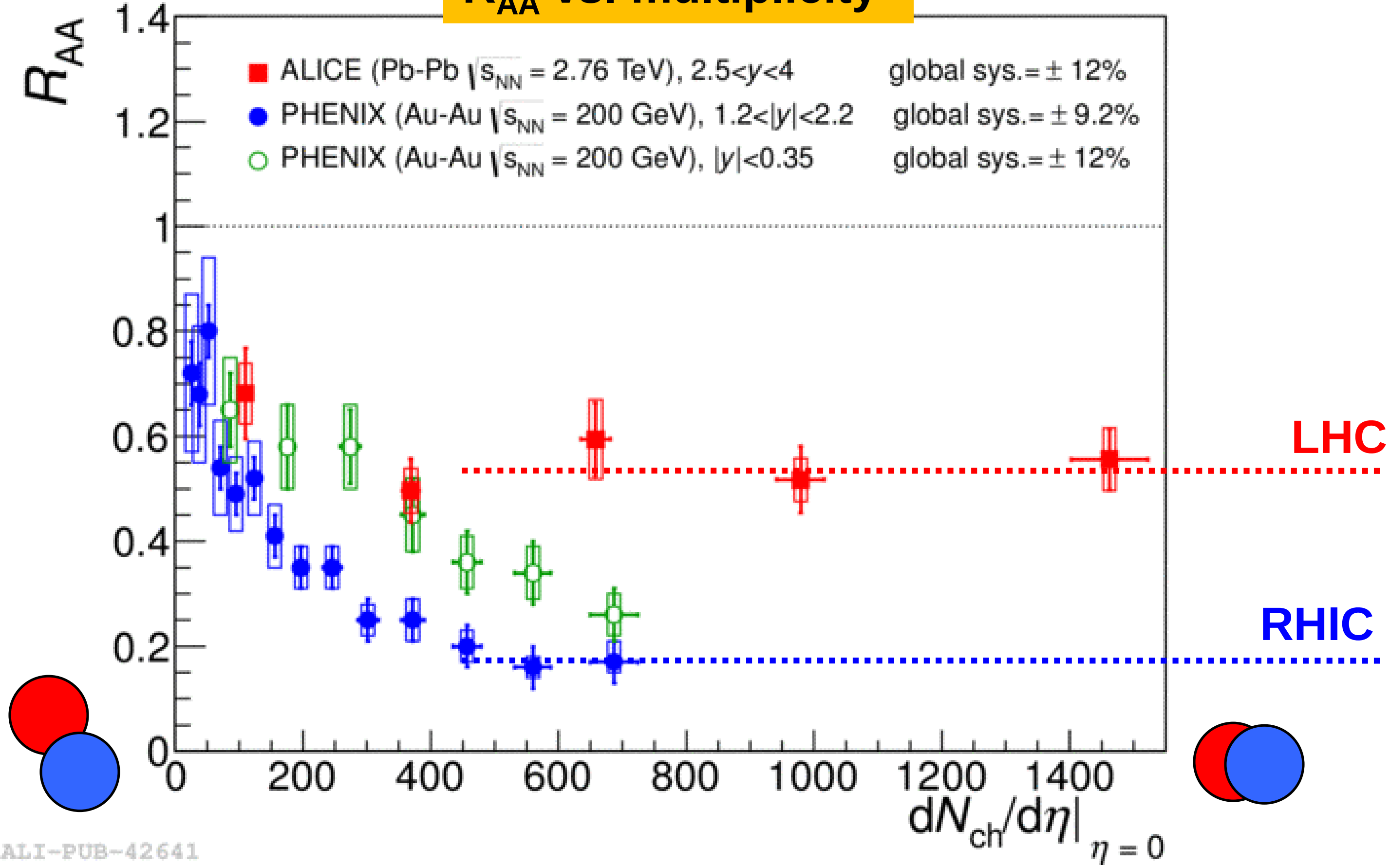


PHENIX Au-Au
NA60 In-In
NA50 Pb-Pb

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

J/ψ Suppression (3)

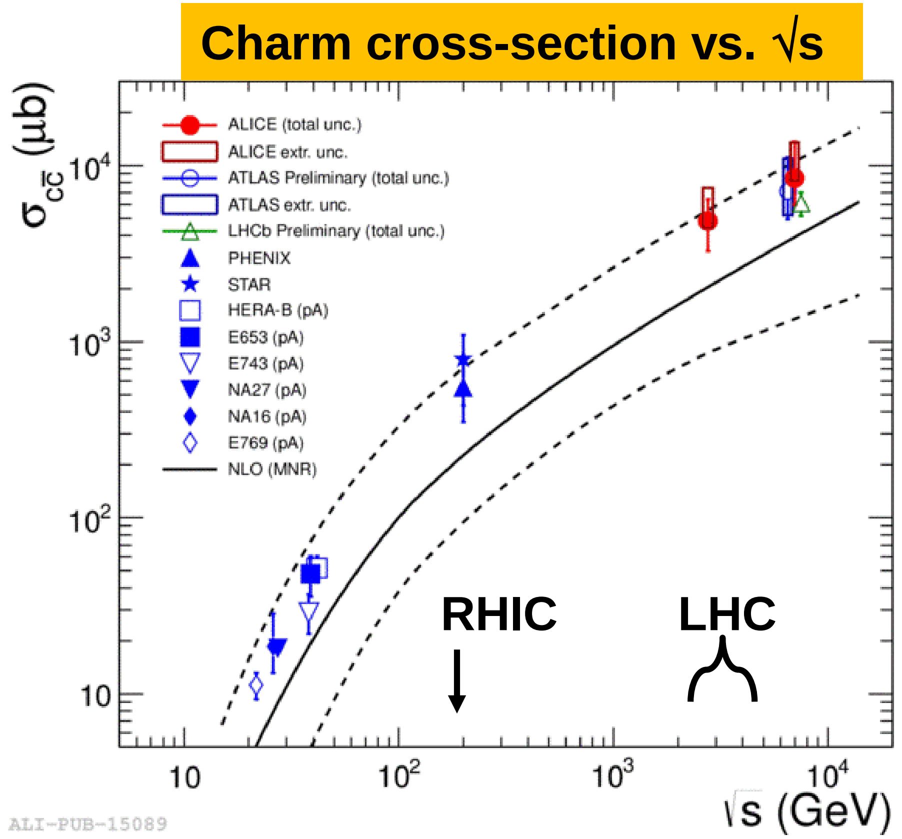
R_{AA} vs. multiplicity



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

Charm Abundances

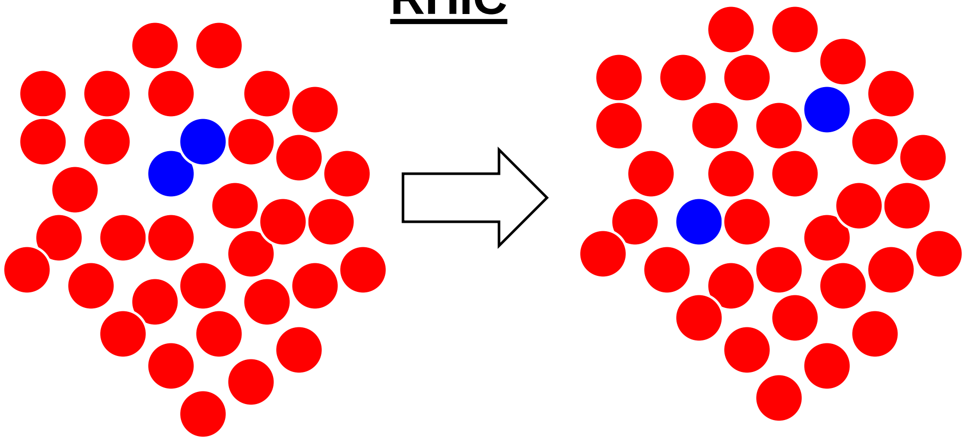
- Number of c-cbar pairs increase with cms energy
- In a central event
  - SPS ~0.1 c-cbar
  - RHIC ~10 c-cbar
  - LHC ~100 c-cbar
- c from one c-cbar may combine with cbar from another c-cbar at hadronization to form a J/ψ



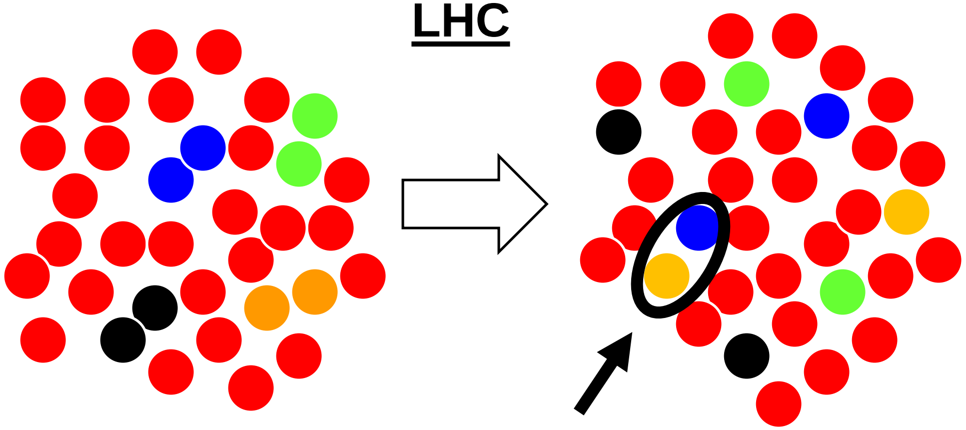
JHEP 1207 (2012) 191

J/ψ Regeneration

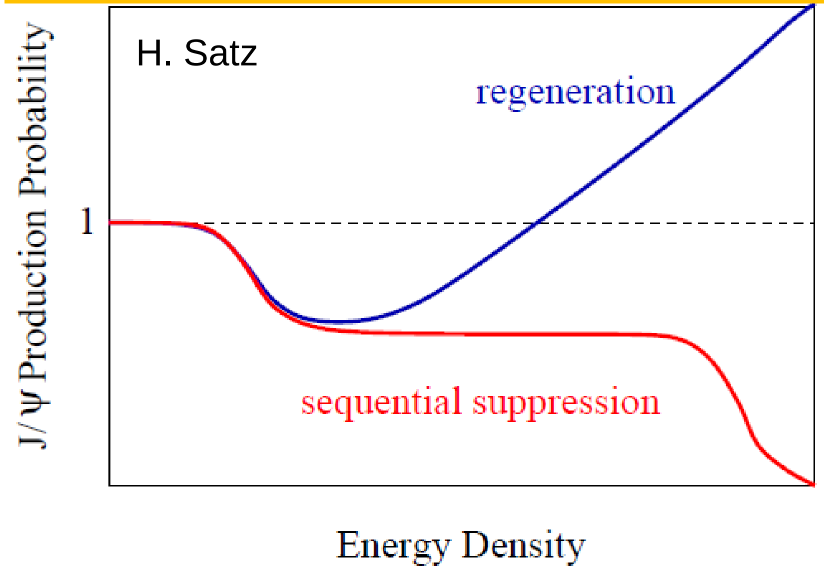
RHIC



LHC



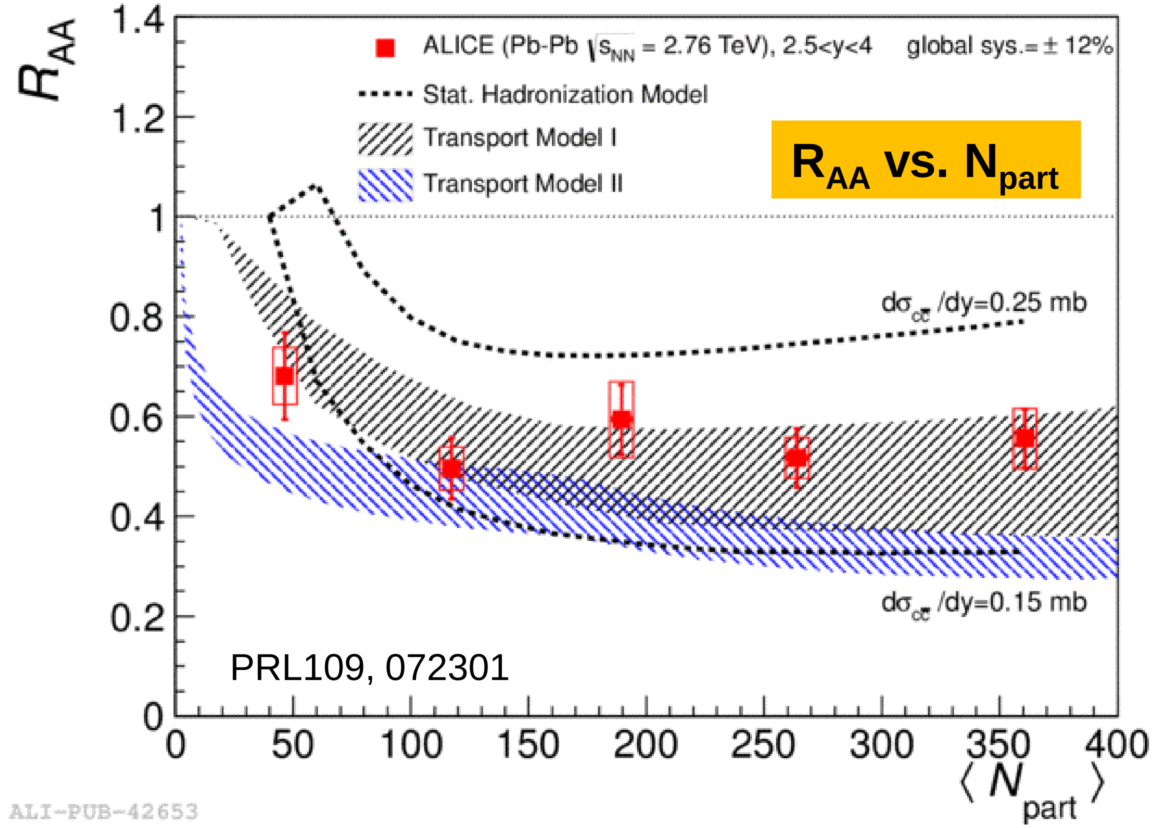
J/ψ modification vs. energy density



Dissociation and regeneration work in opposite directions

J/ψ Regeneration (2)

- J/ψ regeneration / statistical hadronization models



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”)

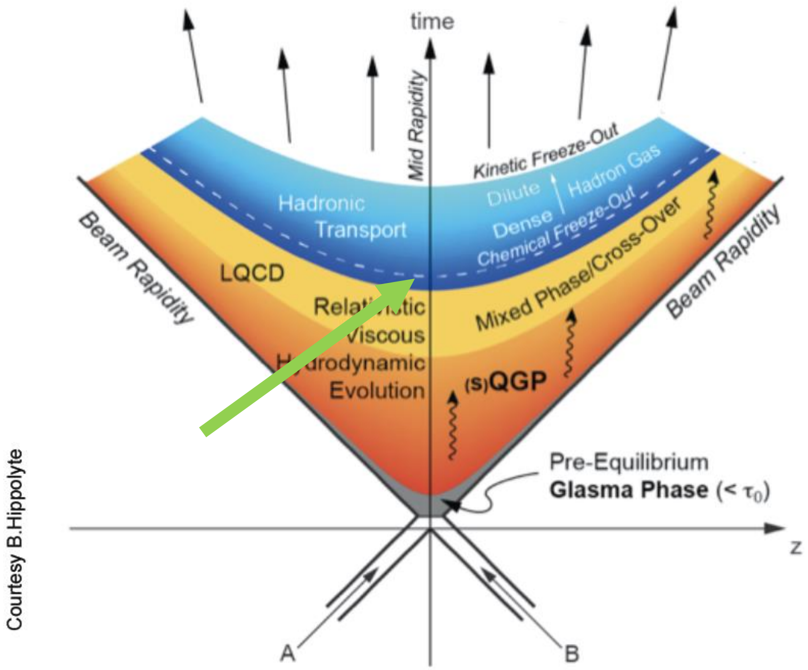
Particle Yields
&
Statistical Model

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



- 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)

$$\ln Z_i(T,V,\mu) = \pm g_i V \int \frac{d^3p}{(2\pi\hbar)^3} \ln\left(1 \pm \exp\left(-(E_i(p)-\mu_i)/T\right)\right)$$

$$E_i = \sqrt{p^2 + m_i^2}$$

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

volume

spin degeneracy

Temperature

chemical potential (conserved quantities)

baryon number

strangeness

isospin

charm

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

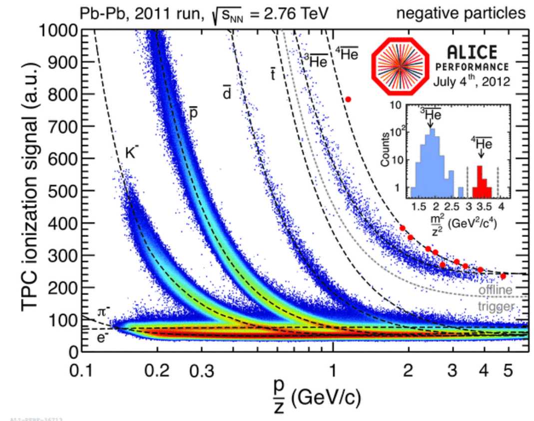
$$s = \frac{1}{V}\frac{\partial(T \ln Z)}{\partial T}$$

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

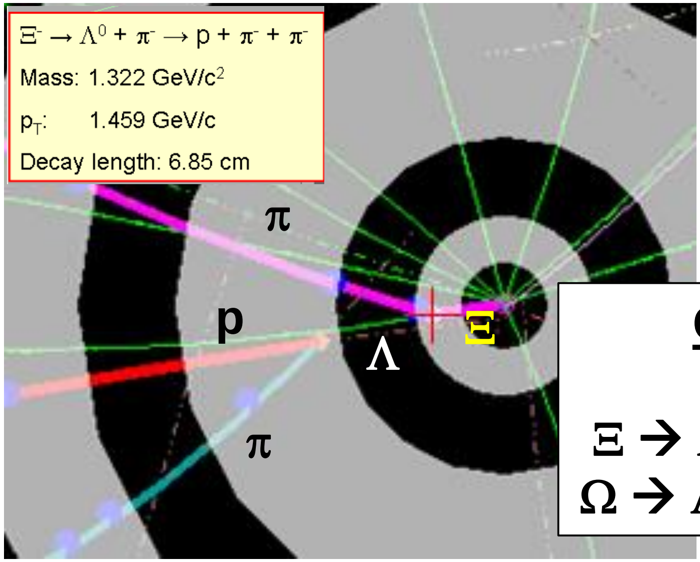
K^0_S → π π (cτ = 2.7 cm)
Λ → p π (cτ = 7.9 cm)

"Kink" in detector volume

K → μ ν (cτ = 3.7 m)

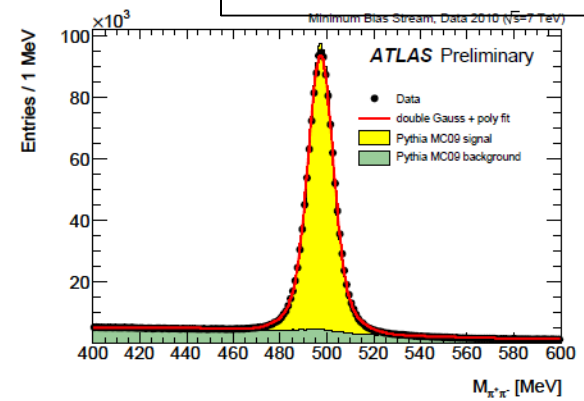
Invariant mass

ϕ → K K
K^* → K π

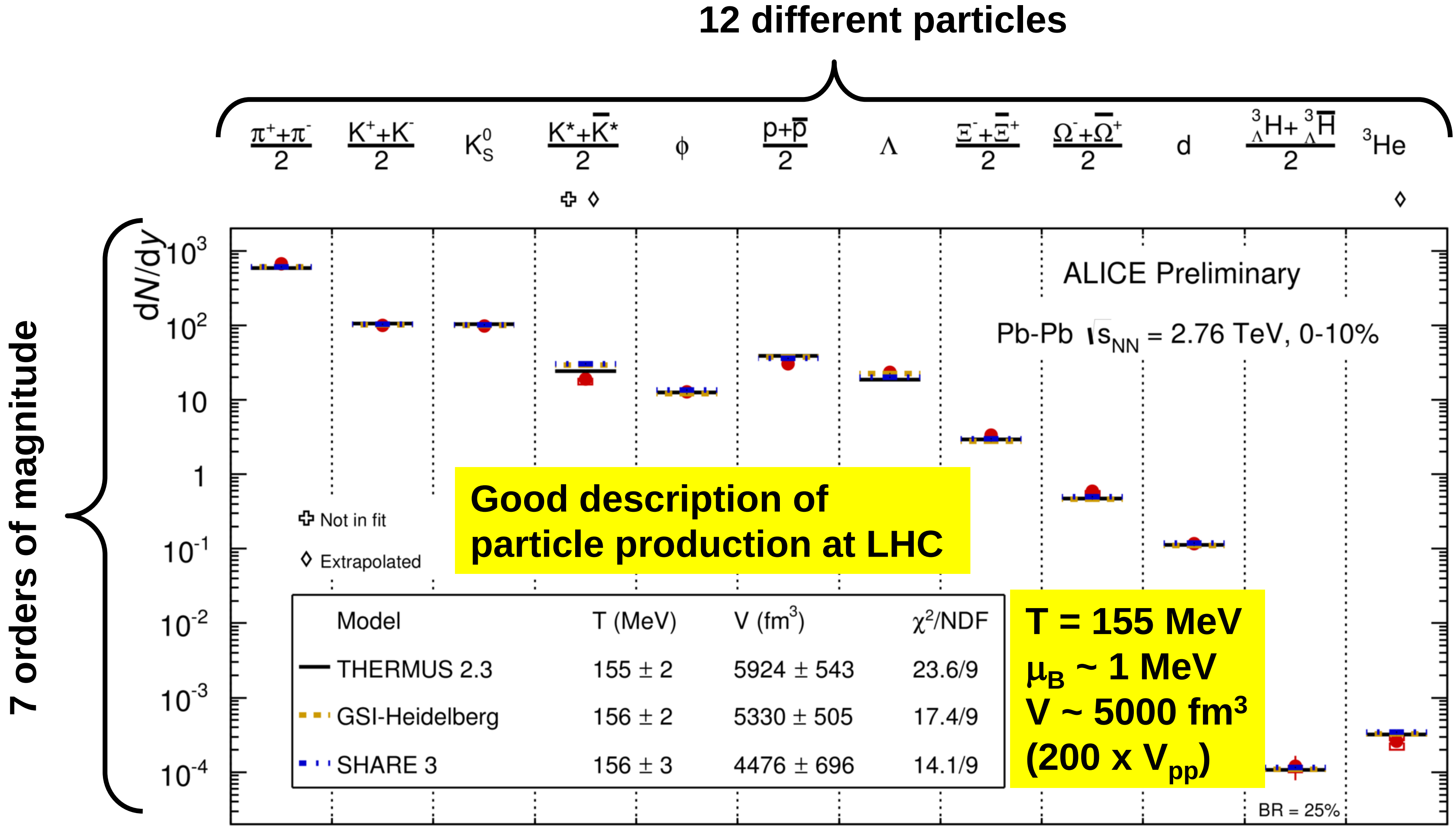


Cascade

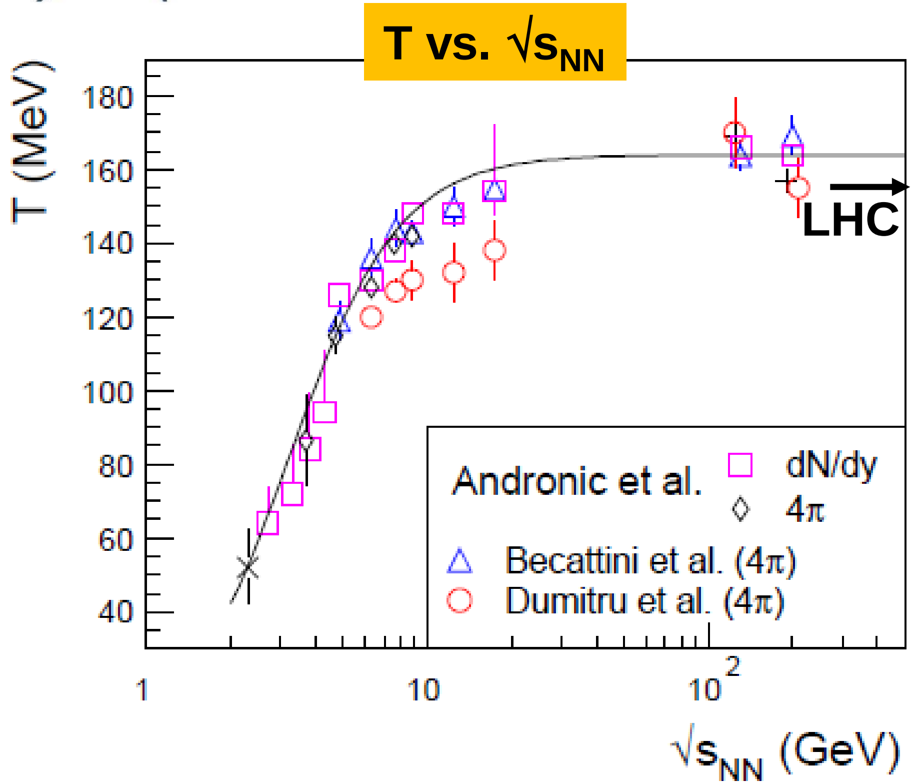
Ξ → Λ + π → p π π
Ω → Λ + K → p π K

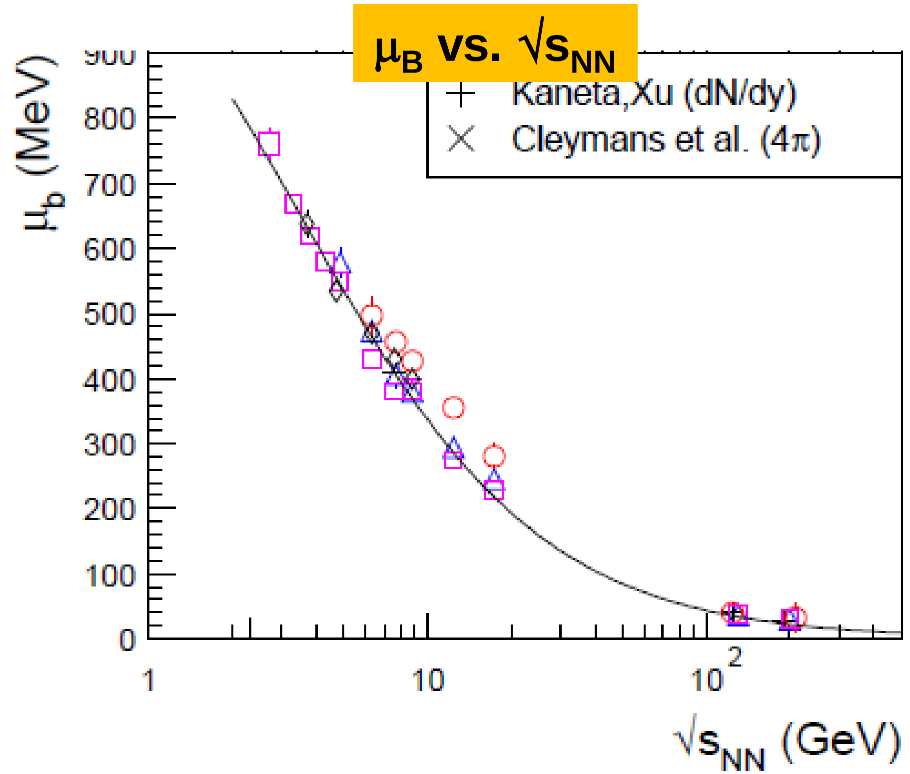


Statistical Model at LHC



√s Dependence



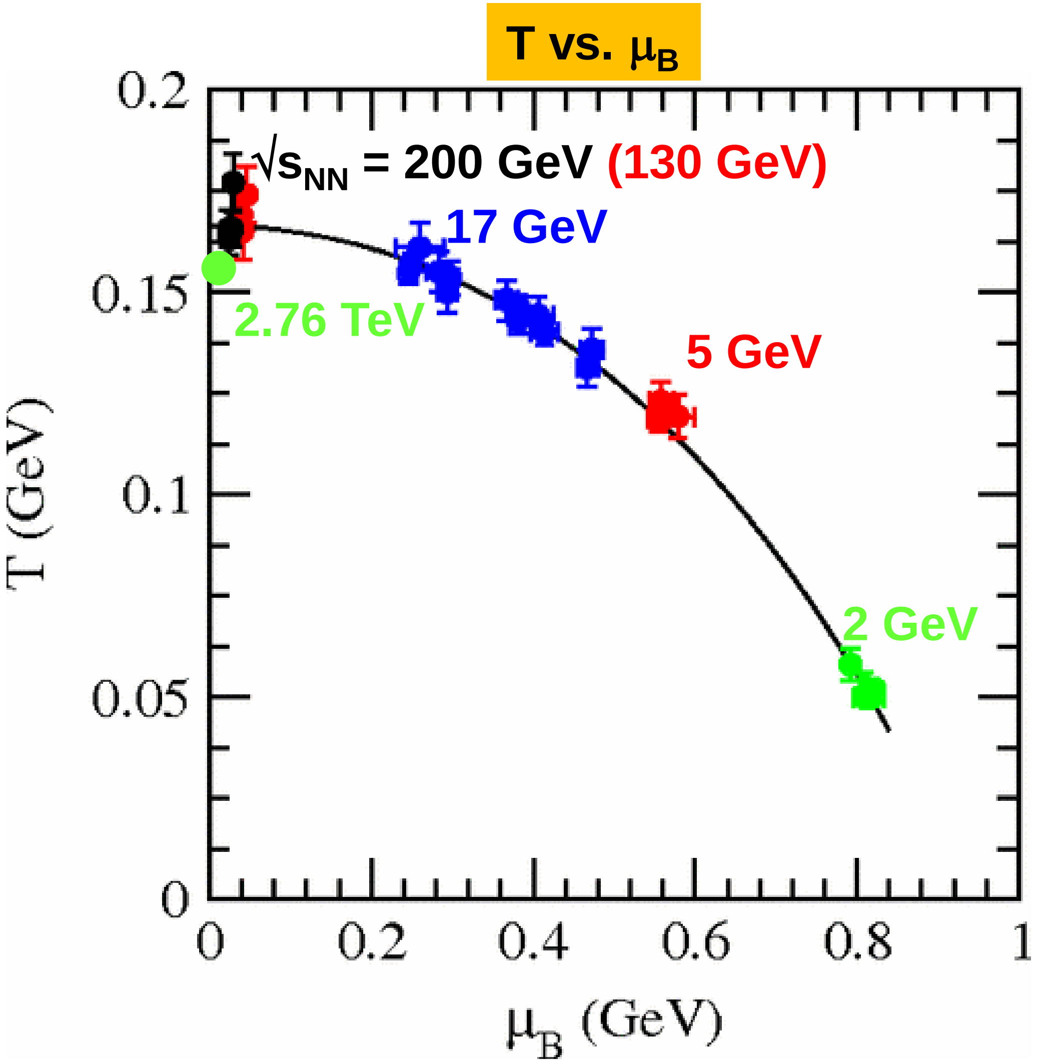


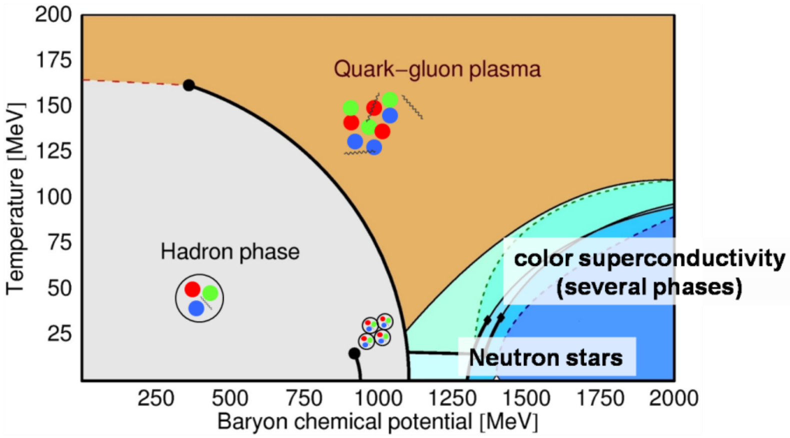
Temperature increases with √s and reaches plateau of about 160 MeV at $\sqrt{s_{NN}}$ > 20 GeV

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

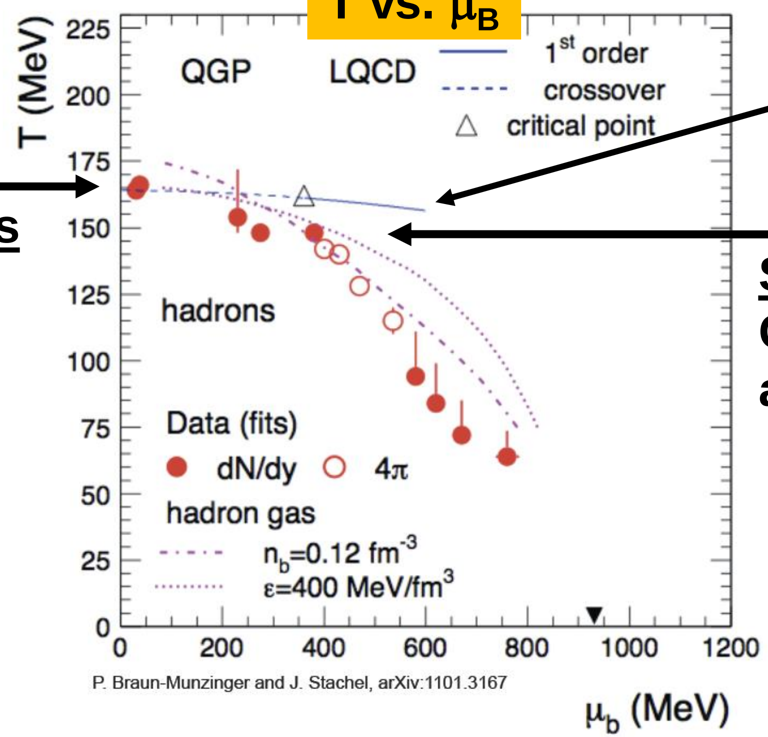
adapted from
PRC 73, 034905 (2006)

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

⇒

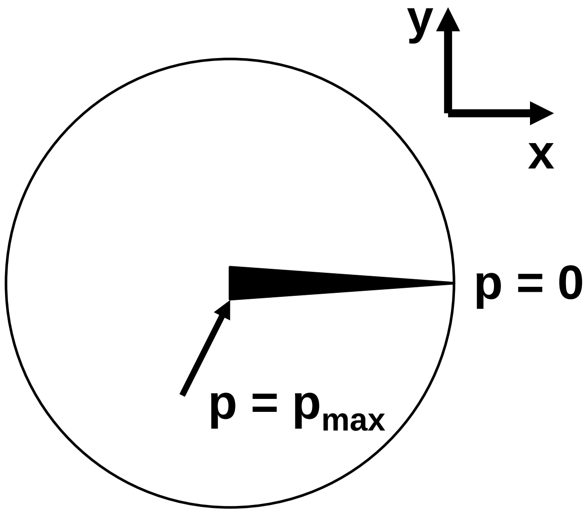
Matter created in HI collisions is in local thermal equilibrium

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

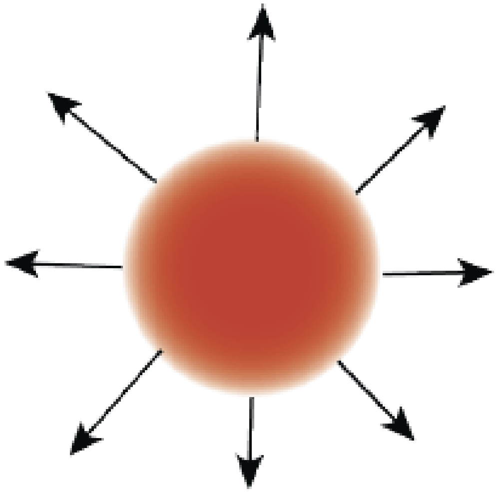
Expansion



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

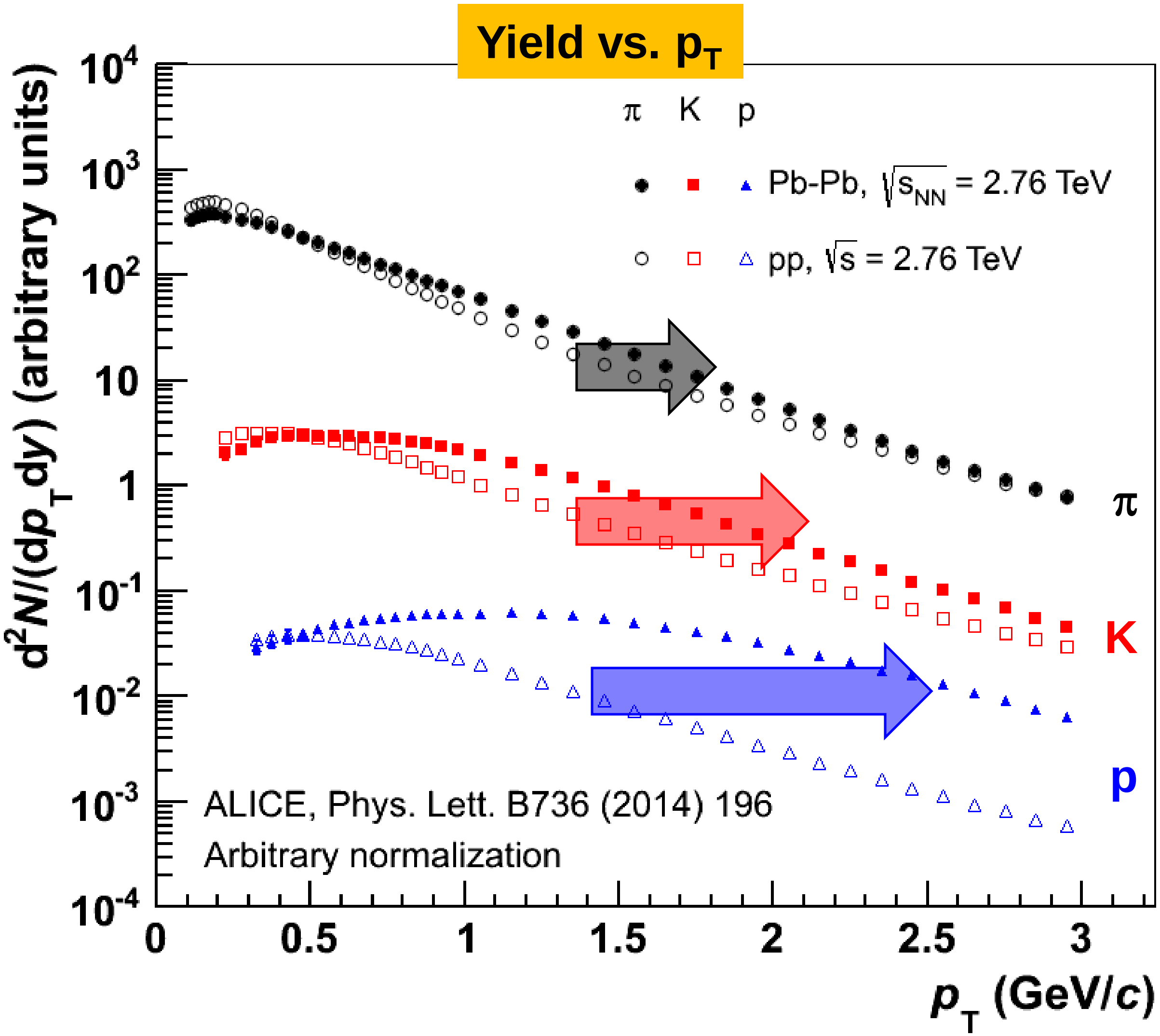
view in beam direction

- 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



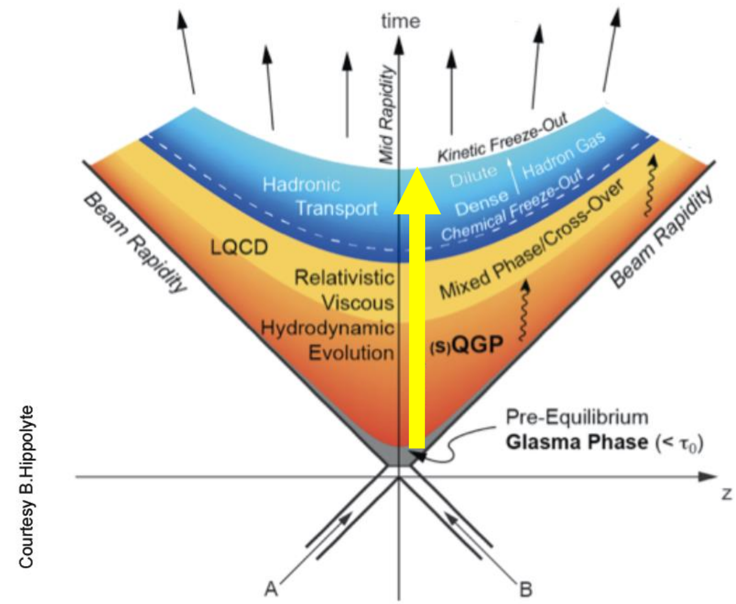
Particle p_T increases
Spectra pushed outwards

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 hydro-dynamic modeling (discussed later)
- Locally thermalized medium
- Common velocity field
- Instantaneous freeze-out
- All particle species described with three parameters



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

Bessel functions I_0 K_1

kinetic freeze-out temperature

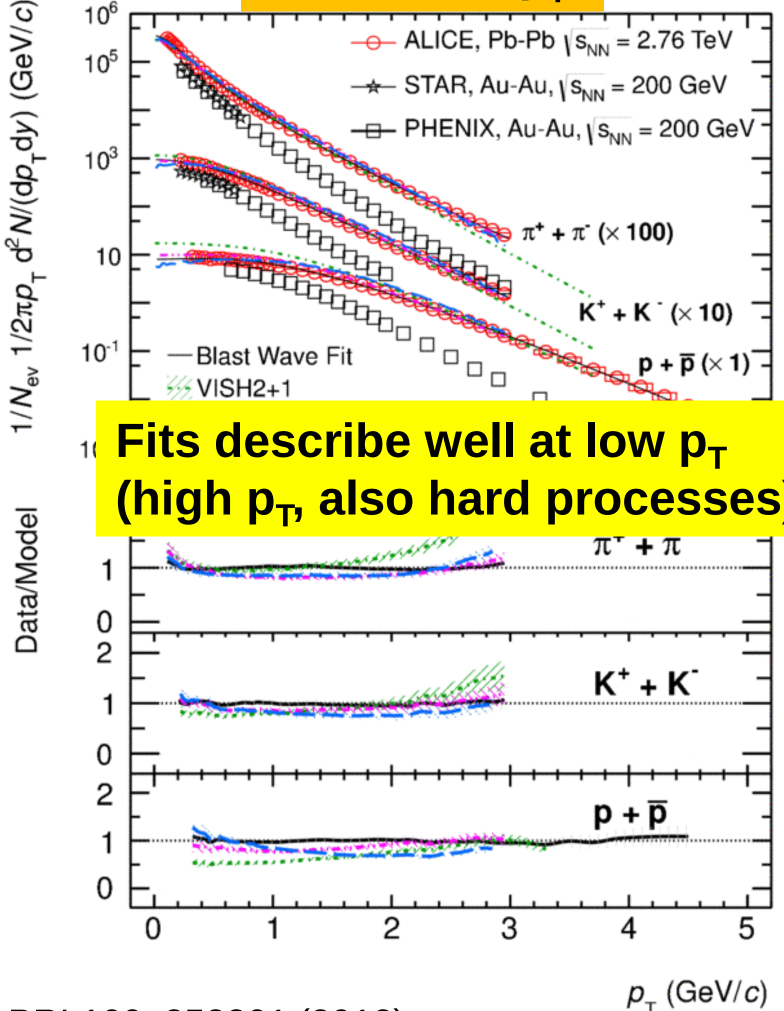
radial flow velocity

velocity profile

PRC 48, 2462 (1993)

Blast-Wave Fits (2)

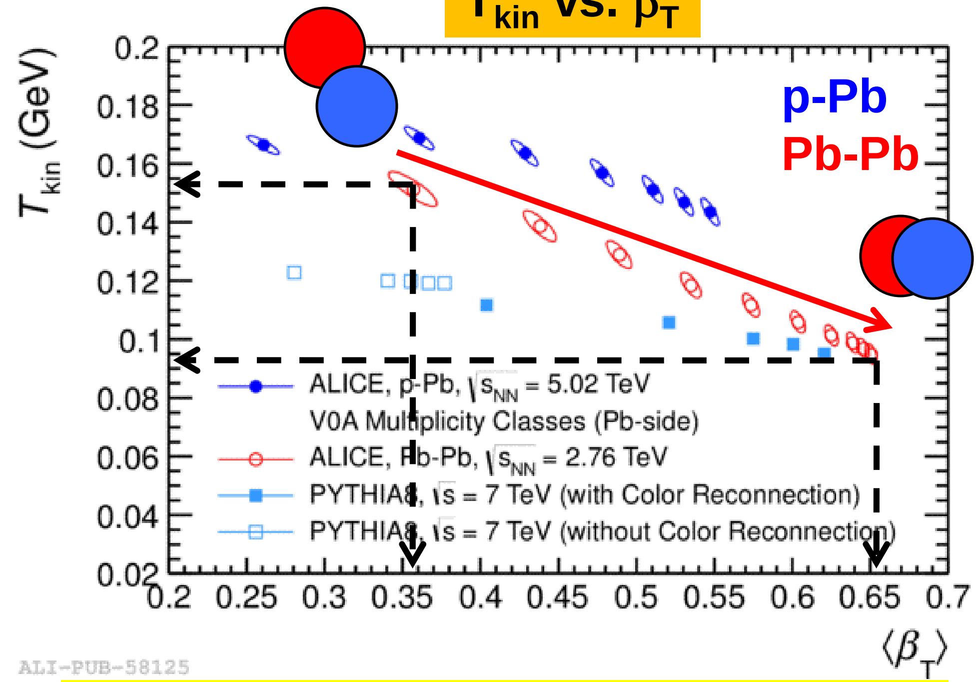
BW fits vs. p_T



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

PRL109, 252301 (2012)

T_{kin} vs. β_T



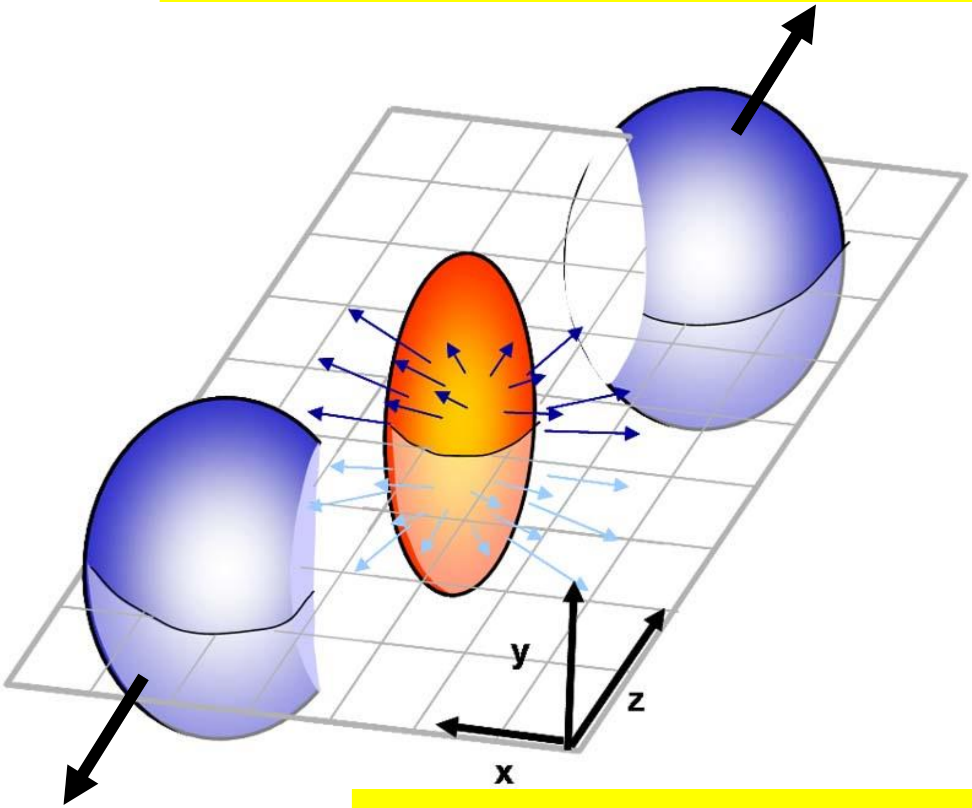
	Peripheral	→	Central
Expansion	**0.35 c**	**–**	**0.65 c**
T_{kin}	**150 MeV**	**–**	**90 MeV**

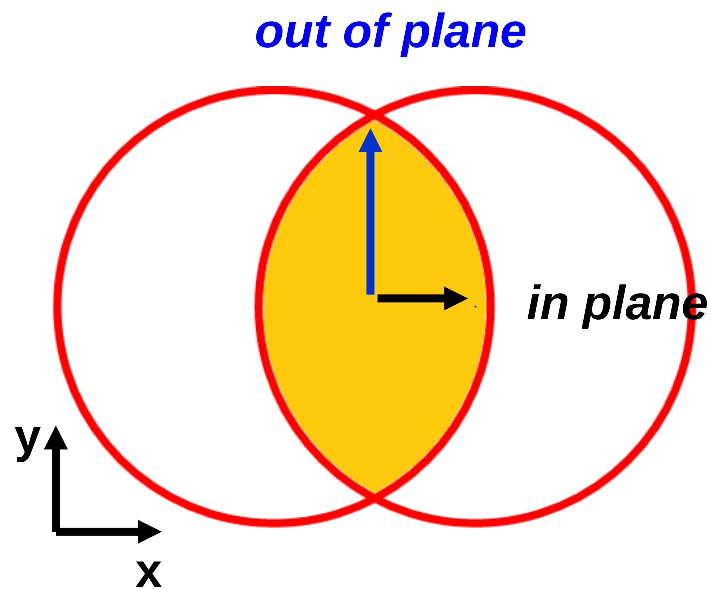
Denser system in central collisions decouples at lower T

PLB 728 (2014) 25

Elliptic Flow

Overlap of colliding nuclei not isotropic in non-central collisions





Defines *reaction plane* Ψ_{RP}
(spanned by beam axis
and impact parameter vector)

→ Pressure gradients dependent on direction

here: $\frac{dp_x}{dL} > \frac{dp_y}{dL}$

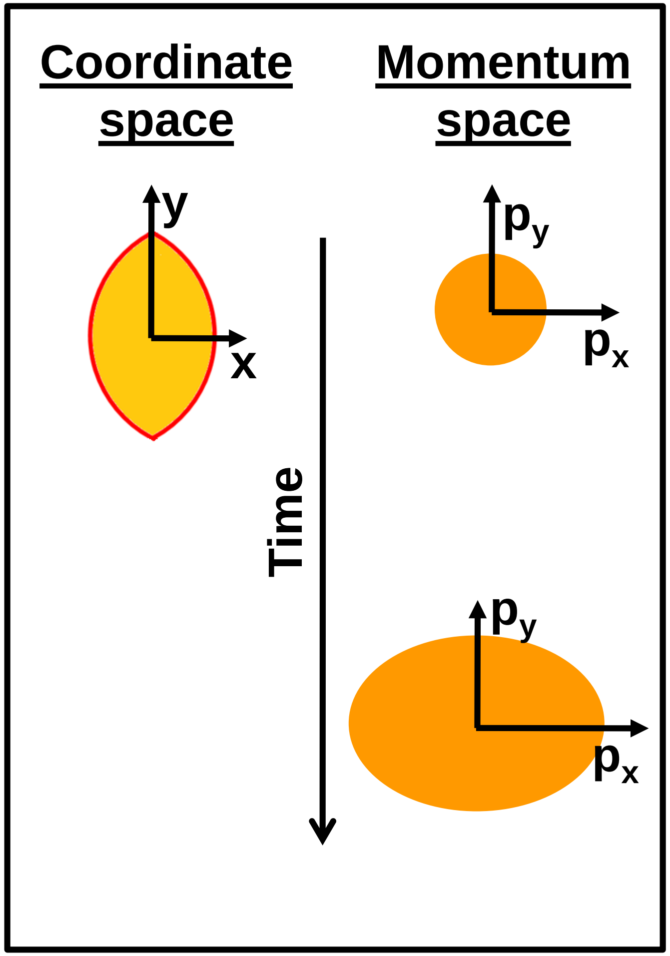
Elliptic Flow (2)

- Spatial anisotropy (almond shape)
  - Quantified by eccentricity ε

$$\varepsilon = \frac{y^2 - x^2}{y^2 + x^2}$$

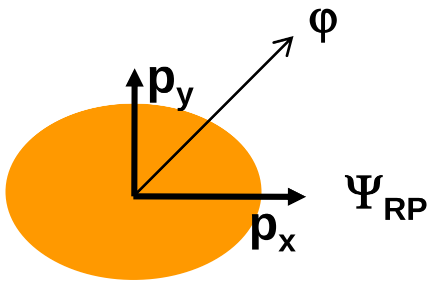
- Pressure gradient larger in-plane
- Pressure pushes partons
  - More in in-plane than out-of-plane

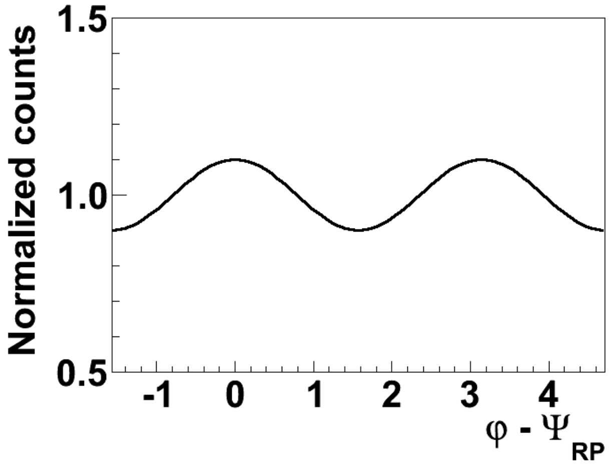
- Spatial anisotropy converts into momentum-space anisotropy
  - "Faster" particles in-plane
  - Measurable in the final state!



Elliptic Flow (3)

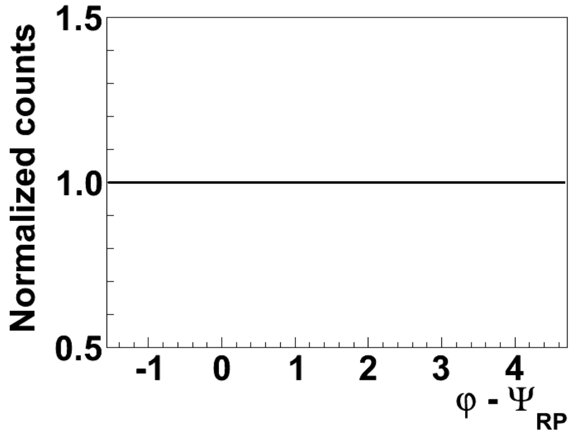
- Particles as a function of $\varphi - \Psi_{RP}$





$$\frac{dN}{d\varphi} = A\left(1 + 2v_2 \cos 2(\varphi - \Psi_{RP})\right)$$

- Define $v_2 = \langle \cos 2(\varphi - \Psi_{RP}) \rangle$
  - Second coefficient of Fourier expansion
- Ψ_{RP} common *symmetry plane* (for all particles)
- What if there were no correlations with Ψ_{RP}?



Measuring Elliptic Flow

$v_2 = \langle \cos 2 (\varphi - \Psi_{RP}) \rangle$

Measure tracks

Measure reaction-plane angle

- Reaction plane angle
  - From the particles themselves

$$Q_x = \sum_i w_i \cos 2\varphi_i \qquad Q_y = \sum_i w_i \sin 2\varphi_i \qquad \Psi_{\mathrm{RP}} = \tan^{-1}(Q_x, Q_y)/2$$

weight w

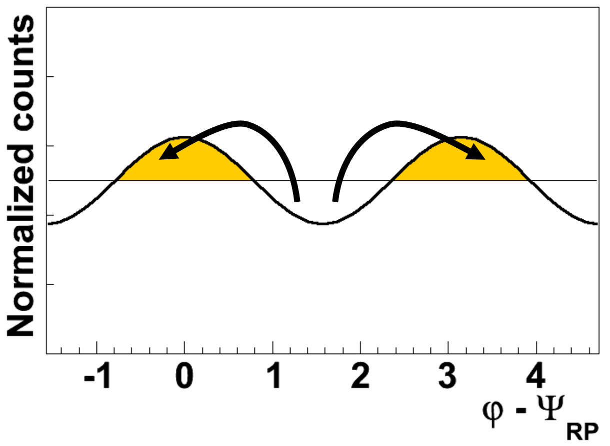
  - Ψ_{RP} approximates true reaction-plane angle (called *event plane*)
- Calculation of *integrated* $v_2 = \langle \cos 2 (\varphi - \Psi_{RP}) \rangle$
- $v_2(p_T)$ by considering only particles at given p_T
- Called *event plane method*, denoted $v_2\{EP\}$

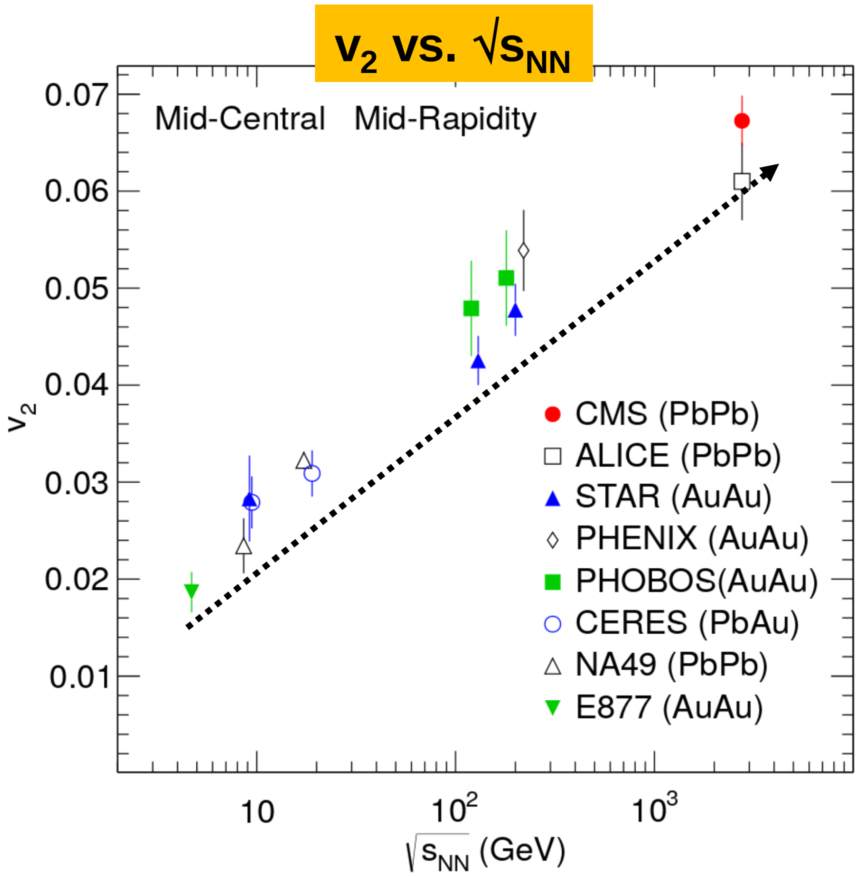
$\sqrt{s_{NN}}$ Dependence

- Increases with $\sqrt{s_{NN}}$
- At LHC v_2 ~ 0.06
  - What does that mean?

$$\frac{dN}{d\varphi} = A\left(1 + 2v_2 \cos 2(\varphi - \Psi_{RP})\right)$$

  - $2v_2$ = 12% of particles "move" from out-of-plane to in-plane

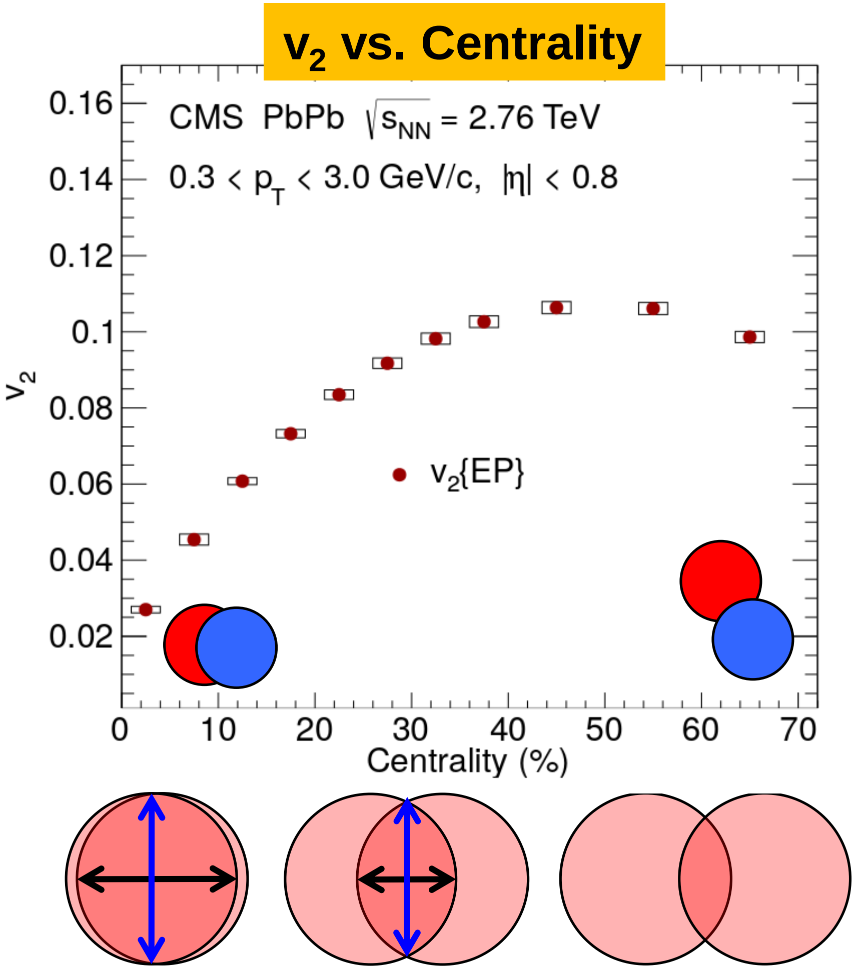




CMS, PRC 87(2013) 014902

Centrality Dependence

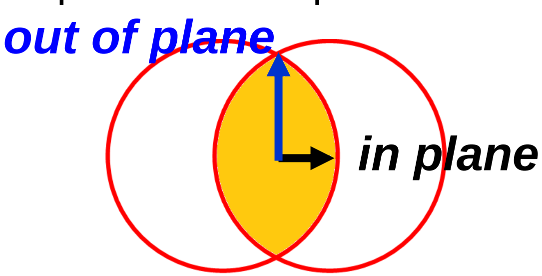
- Strong centrality dependence
- v_2 largest for 40-50%
- Spatial anisotropy very small in central collisions
- Largest anisotropy in mid-central collisions
- Small overlap region in peripheral collisions

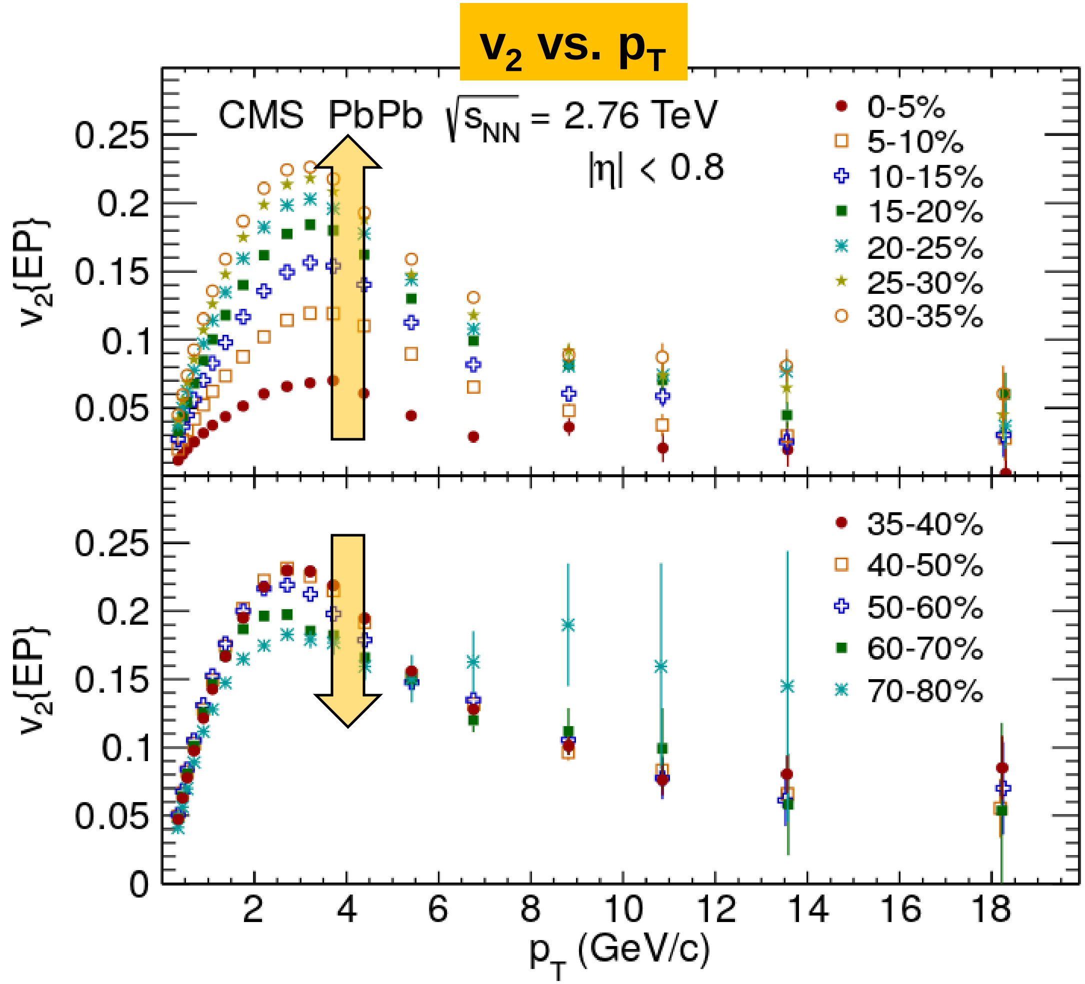


CMS, PRC 87(2013) 014902

p_T Dependence

- Centrality dependence independent of p_T
- Largest v_2 for p_T ~ 3 GeV/c
- Low and intermediate p_T, v_2 caused by collective expansion
- Large p_T, v_2 caused by *length-dependent jet quenching*
  - Longer path length out of plane than in plane





CMS, PRC 87(2013) 014902

Recap

- Pressure in dense medium affects momenta
- Isotropic expansion effect called *radial flow*

- Overlap of colliding nuclei causes spatial anisotropy
- Converted into momentum-space anisotropy in medium evolution
- Modulation of observed particles
- Quantified by $v_2 = \langle \cos 2 (\varphi - \Psi_{RP}) \rangle$

What other methods exist to measure v_2?

What effect do jet-related particles have on v_2?

Backup

$B \rightarrow J/\psi$

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

- $B^{\pm} \rightarrow J/\psi + X$ (branching ratio ~ 0.5%)
- $B^0 \rightarrow J/\psi + X$ (branching ratio ~ 0.5%)
- $J/\psi \rightarrow \mu\mu$ (branching ratio ~ 6%)

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

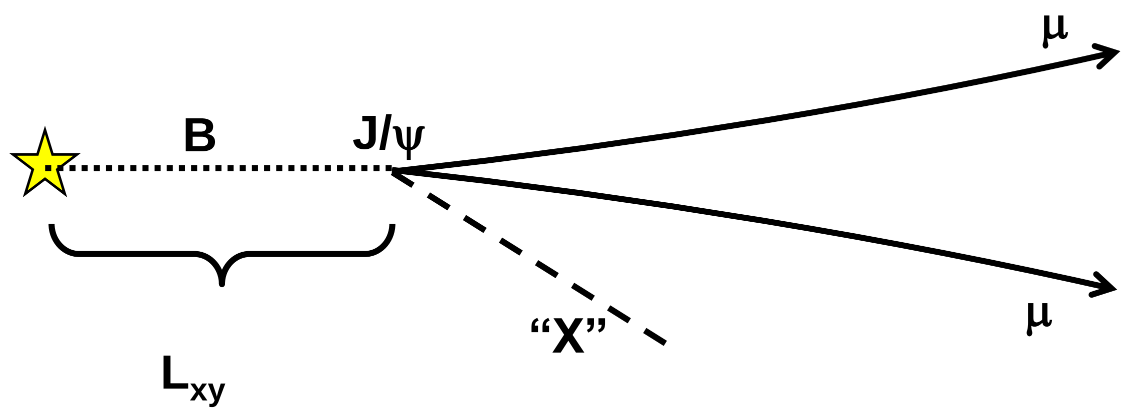
B Identification

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

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

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

Plane transverse to beam



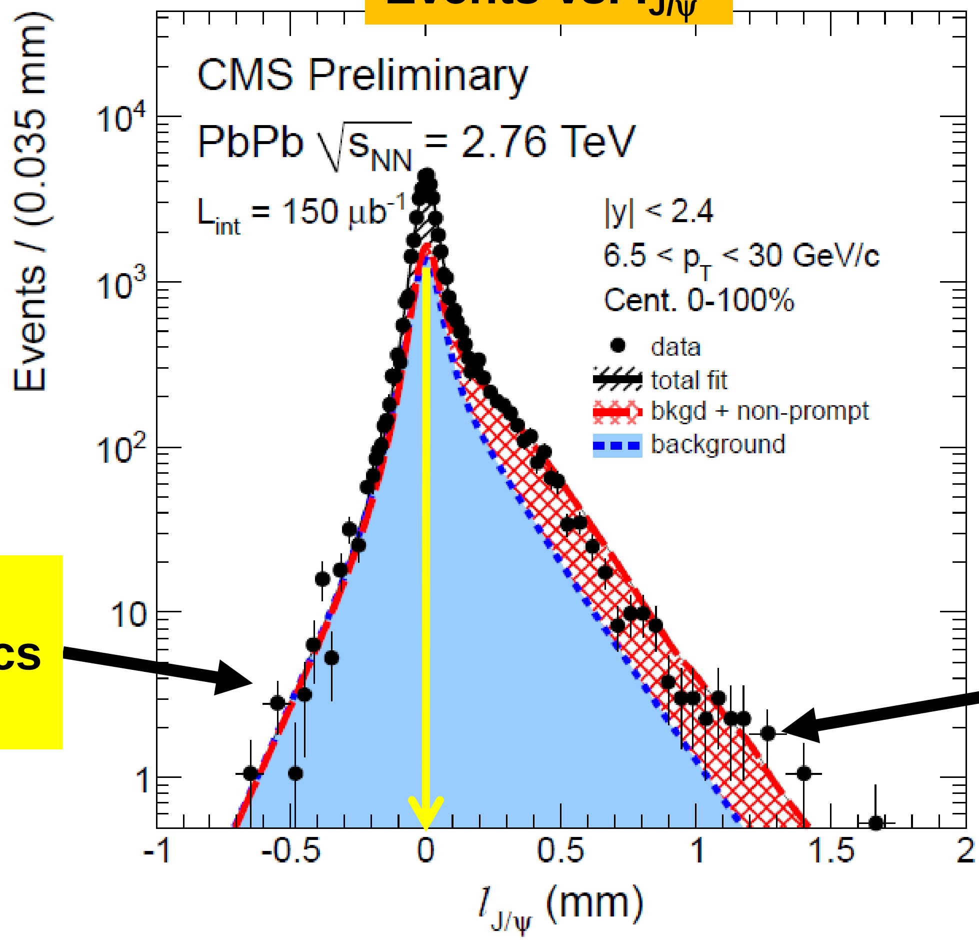
- Convert to pseudo-proper decay length as estimate of b-hadron decay length (time dilatation)

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

J/ψ candidate mass and p_T

Decay Length Distribution

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



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

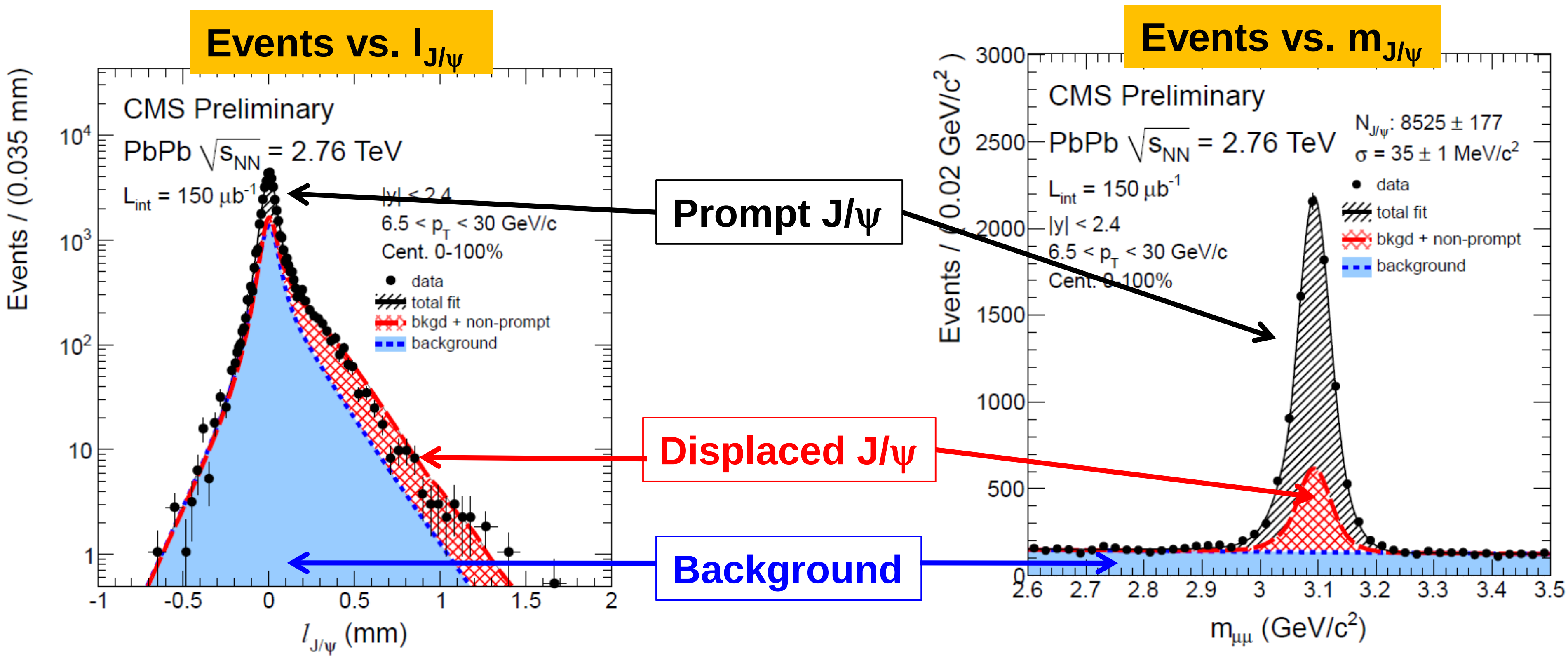
$l_{J/\psi}$ > 0
combinatorics
resolution
b decays

→ 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



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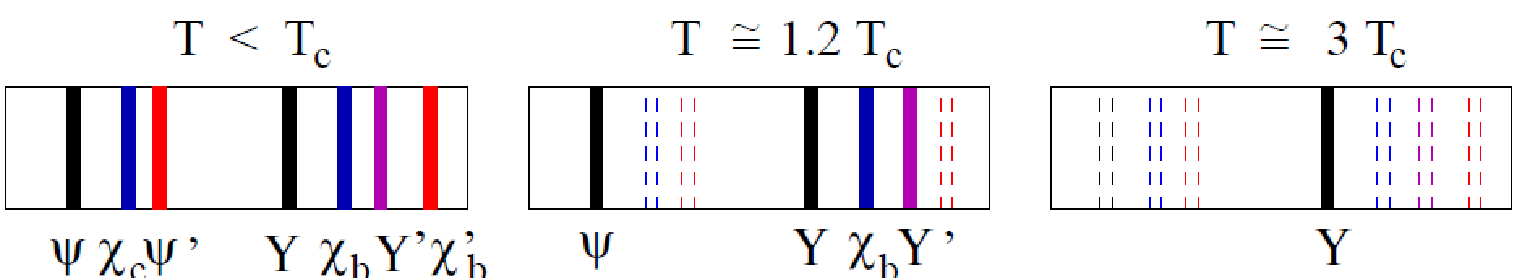
Other Quarkonia

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 → 0.45 (ψ')

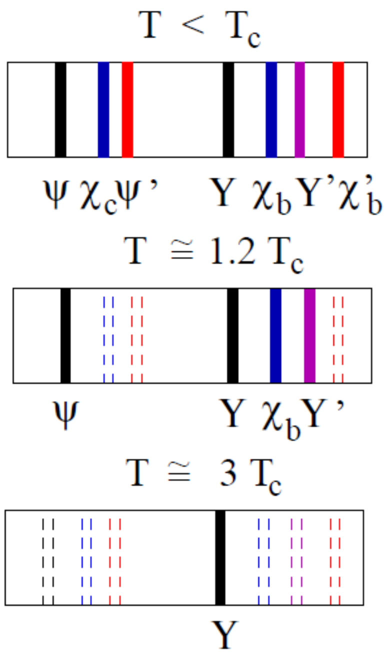
dissociates last → 0.14 (Υ)

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

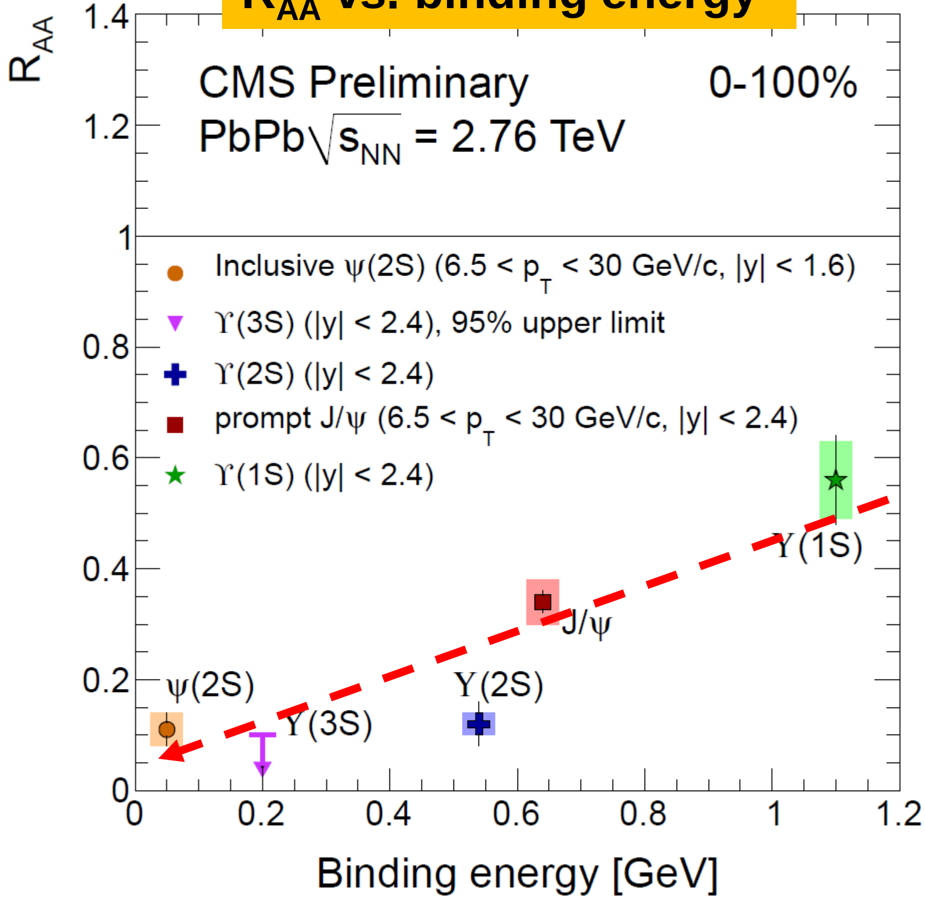


Table, Cartoon: H. Satz

QGP Thermometer



R_{AA} vs. binding energy



States with lower binding energies more suppressed !