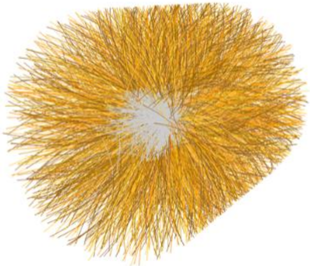


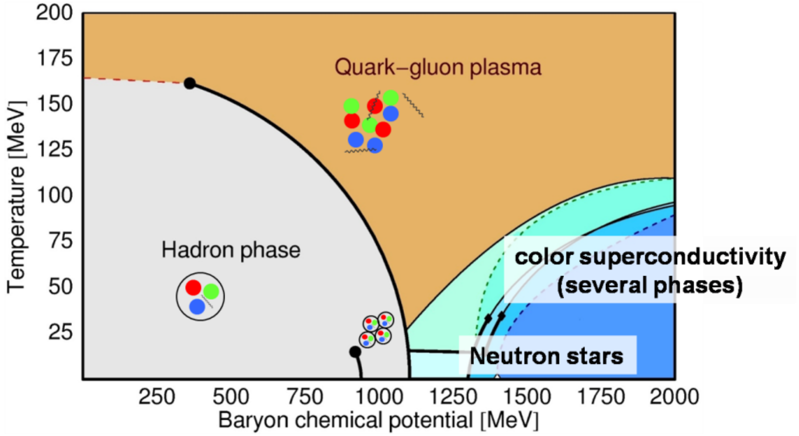
Introduction to Heavy-Ion Physics
Part II

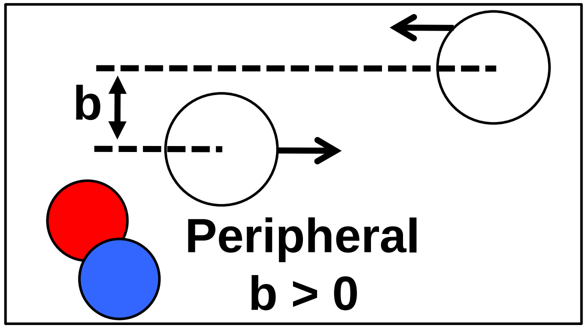
Jan Fiete Grosse-Oetringhaus, CERN

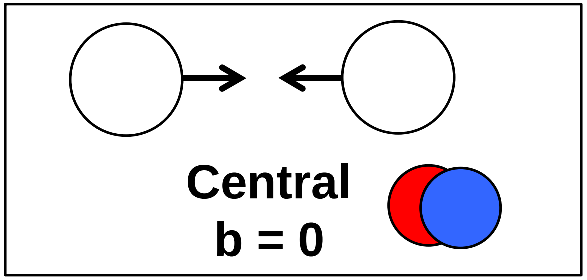
2015 CERN-Fermilab HCP Summer School

Recap Lecture 1

- Heavy-ion physics studies quark-gluon plasma (QGP)
    - Deconfined
    - Chiral symmetry restored
- Transition to QGP is expected at T ~ 150 – 170 MeV
- Event activity depends on impact parameter b
- Centrality estimated by multiplicity (ALICE) / energy (ATLAS/CMS)
- 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}





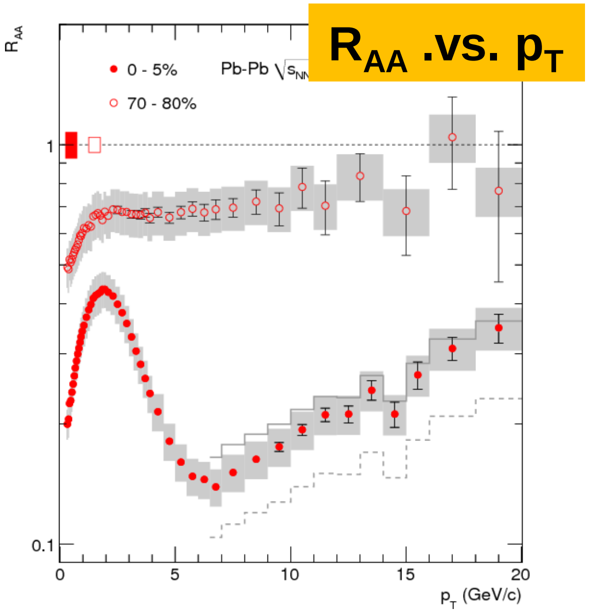


Recap Lecture 1

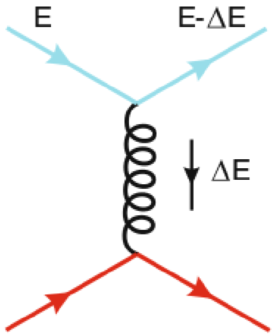
- Nuclear modification factor

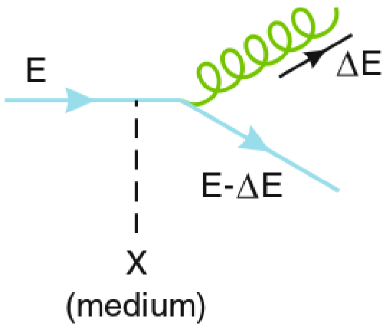
$$R_{AA} = \frac{dN_{AA}/dp_T}{\langle N_{coll} \rangle dN_{pp}/dp_T}$$

  - Significant suppression of hadron and jet production in central collisions


R_{AA} .vs. p_T

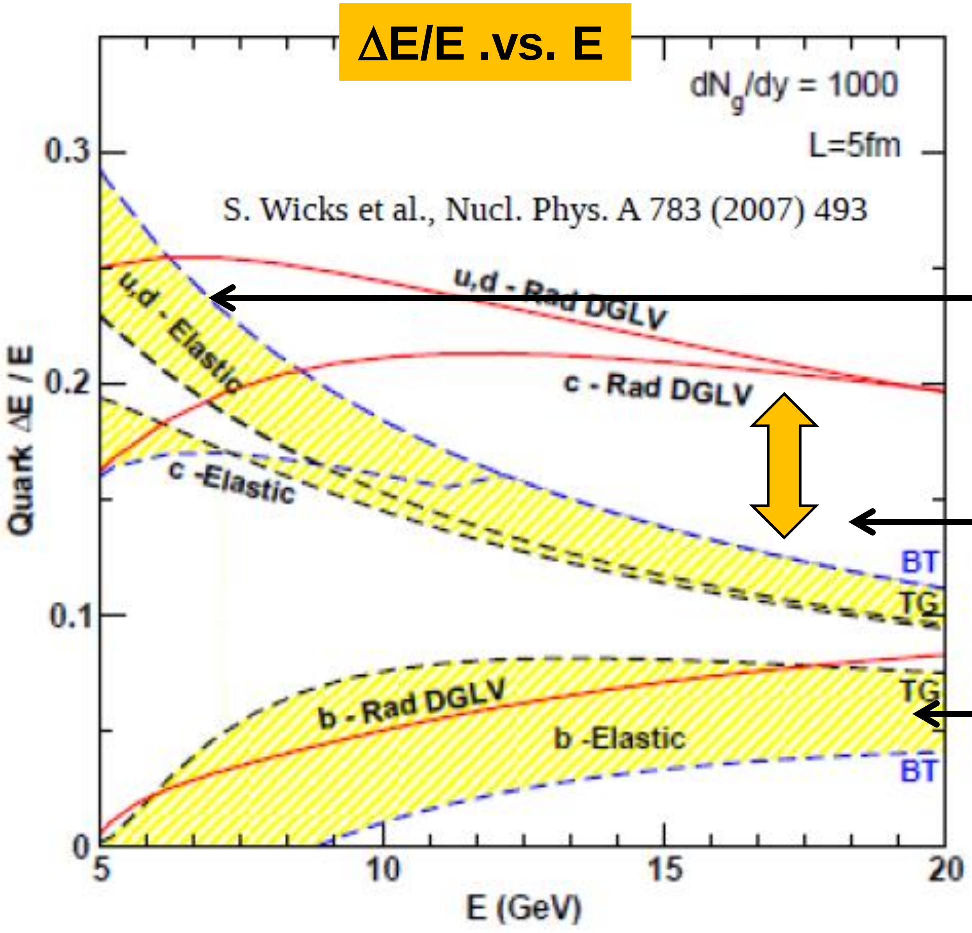
- Collisional energy loss
  - $\Delta E \sim L$ (path length)
  - Dominates at low momentum
- Radiative energy loss
  - $\Delta E \sim L^2$
  - Dominates at high momentum





Collisional .vs. Radiative E-Loss

ΔE/E .vs. E



Similar magnitude at low energies for u,d,c quarks

Radiative twice larger than collisional at high energies for u,d,c quarks

Similar magnitude for b quarks

— **Radiative energy loss**

🟨 **Collisional energy loss**

NPA 783 (2007) 493

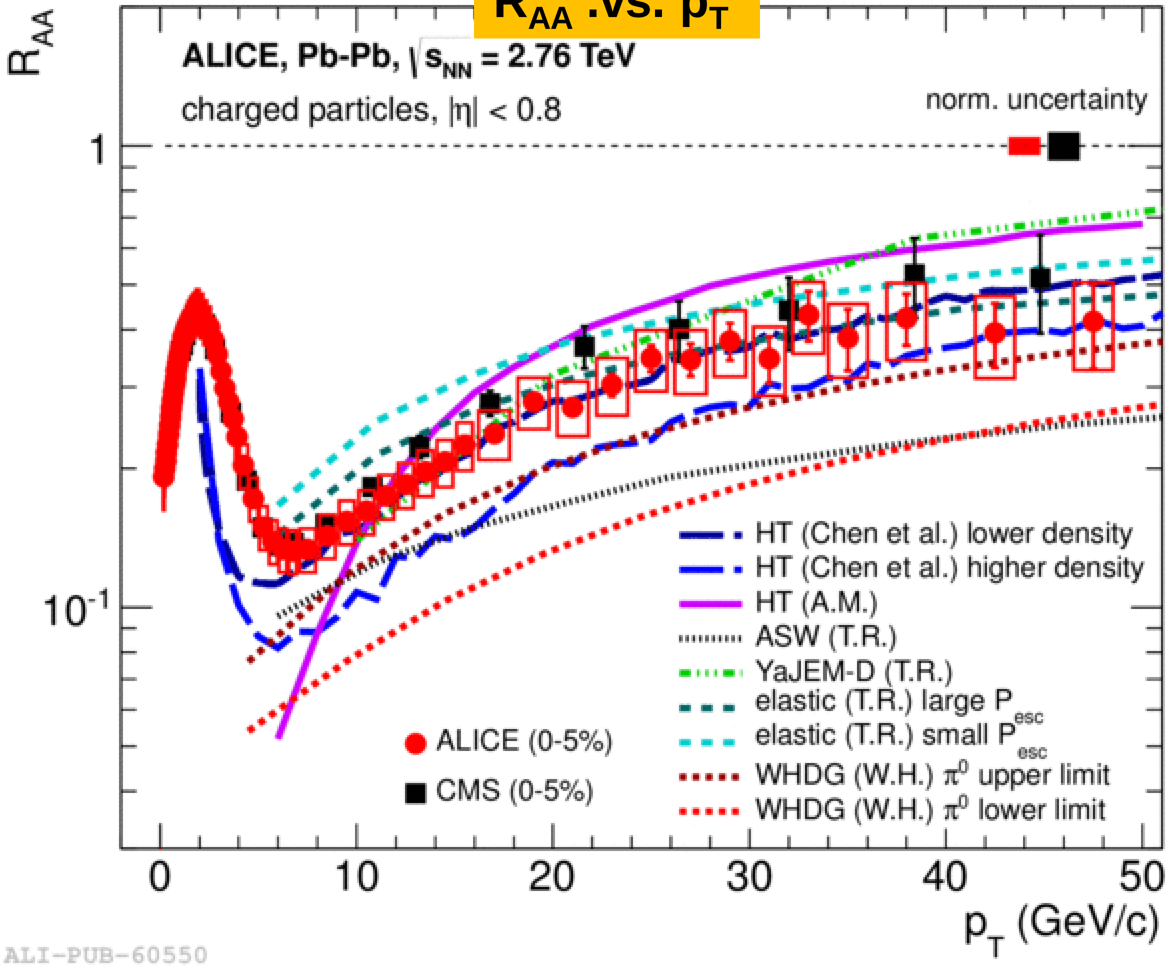
Energy Loss Models

- Presented formulas for infinite-energy parton traversing a static and uniform medium
- However
  - Medium expands rapidly, temperature and density change
  - Partons may be produced in the medium
  - Parton virtuality may change while traversing the medium
  - Eventually final-state hadron measured (not the parton)
- Phenomenological models try to include these effects
- Major directions
  - Calculations: BDMPS, GLV, HT, AMY
  - Monte Carlo: JEWEL, Martini, qPythia/qHerwig, YaJEM

see for example https://indico.cern.ch/event/30248/session/20/contribution/77/material/slides/1.pdf

Example: Comparison

R_{AA} .vs. p_T



Hadron R_{AA} not very constraining on its own

Observables beyond single hadron suppression to explore full parton shower:

- **Jet R_{AA}**
- **Di-jet correlations**
- **Jet shapes and fragmentation functions**
- **…**

PLB 720 (2013) 52

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 !

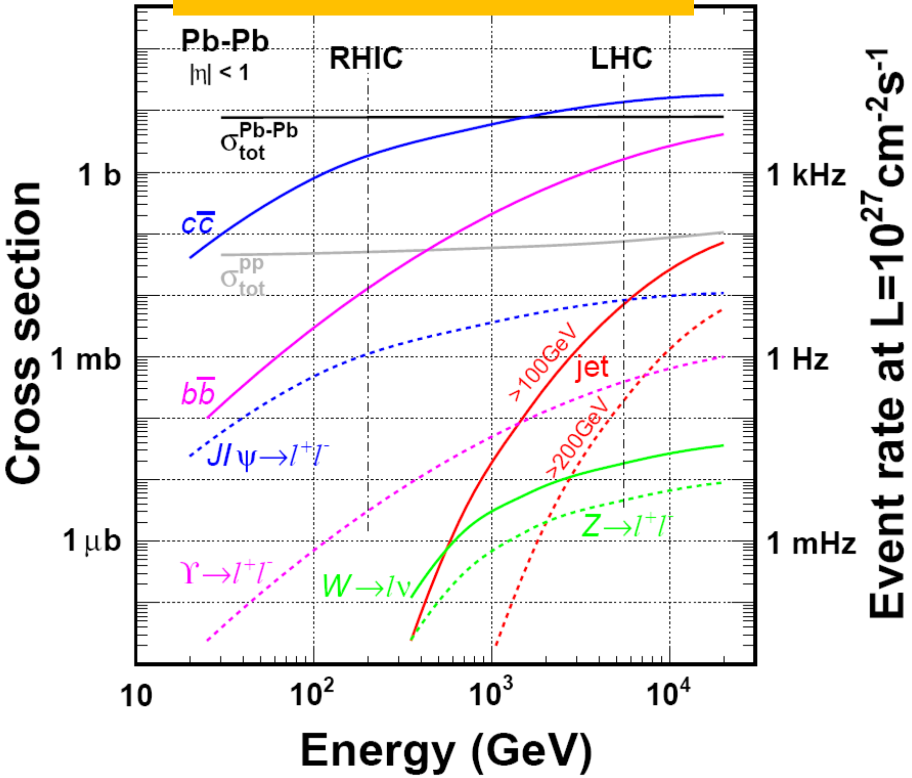
Heavy Quarks

- 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

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

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

Cross section .vs. √s

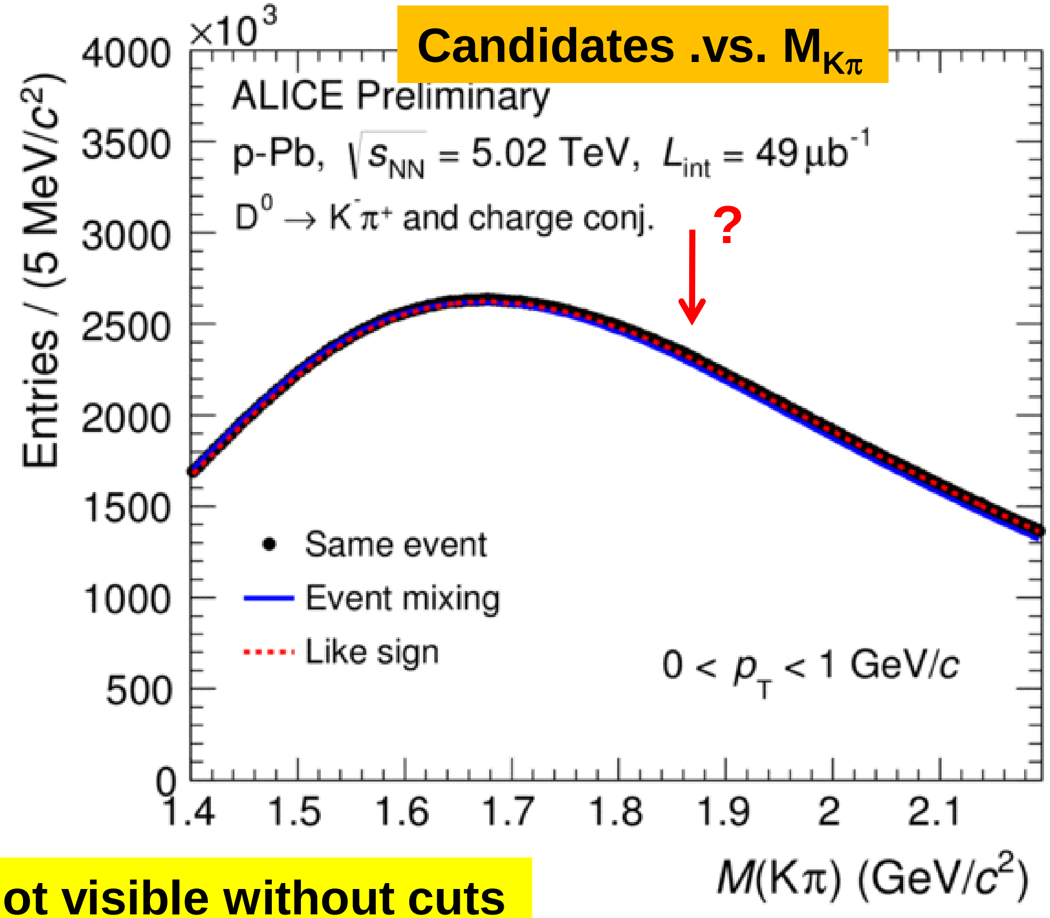


D^0 Reconstruction

- 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



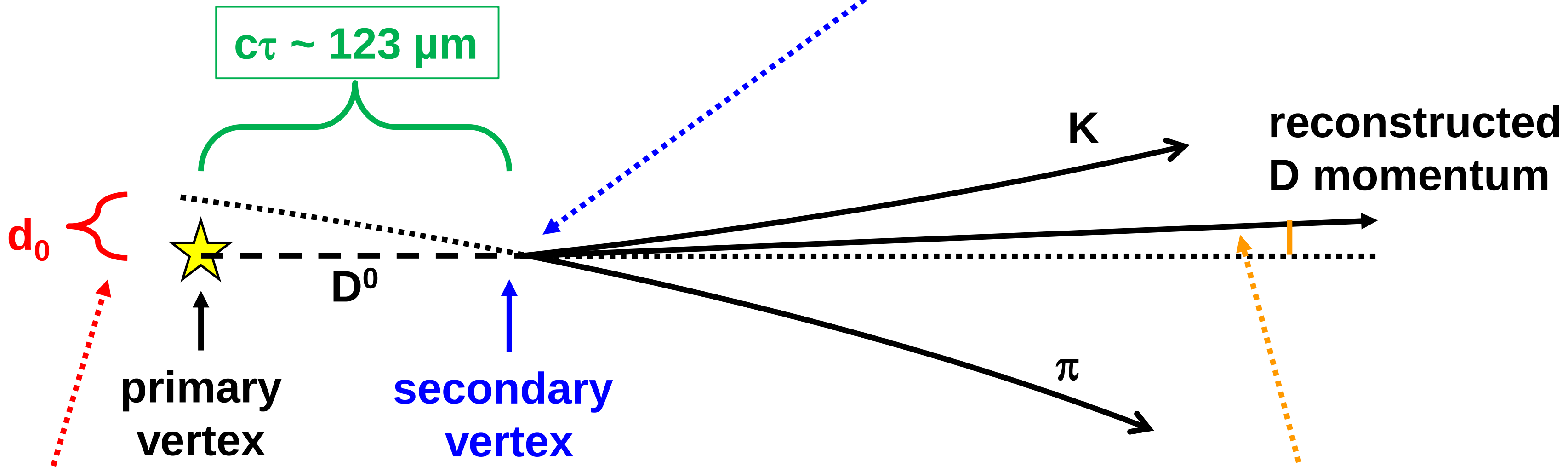
Candidates .vs. $M_{K\pi}$

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

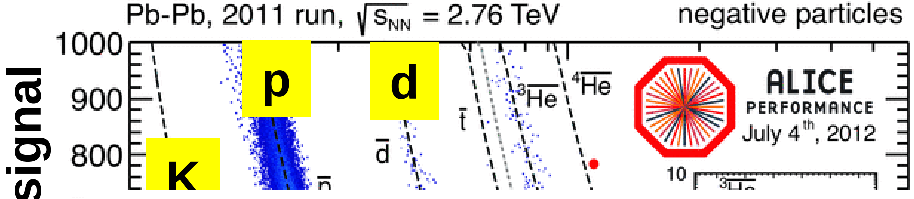
4) Require pointing angle θ to be small

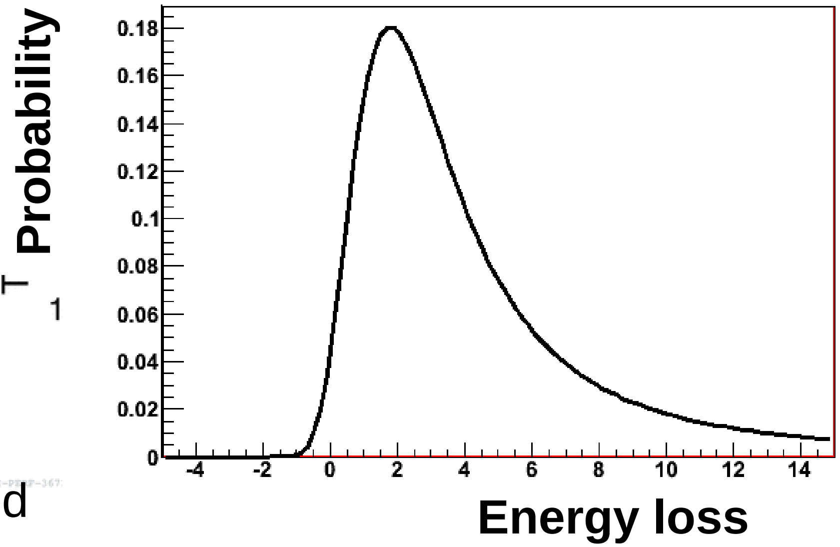
PID: Specific Energy Loss

- Particles passing through matter loose energy mainly by ionization
- Average energy loss can be calculated with the Bethe-Bloch formula

$$\langle \frac{dE}{dx} \rangle \propto \frac{1}{\beta^2}\left(\frac{1}{2}\log\frac{2m_e\boxed{\beta^2\gamma^2}T_0}{I^2} - \frac{\beta^2}{2}\left(1+\frac{T_0}{T_{max}}\right) - \frac{\delta}{2}\right)$$

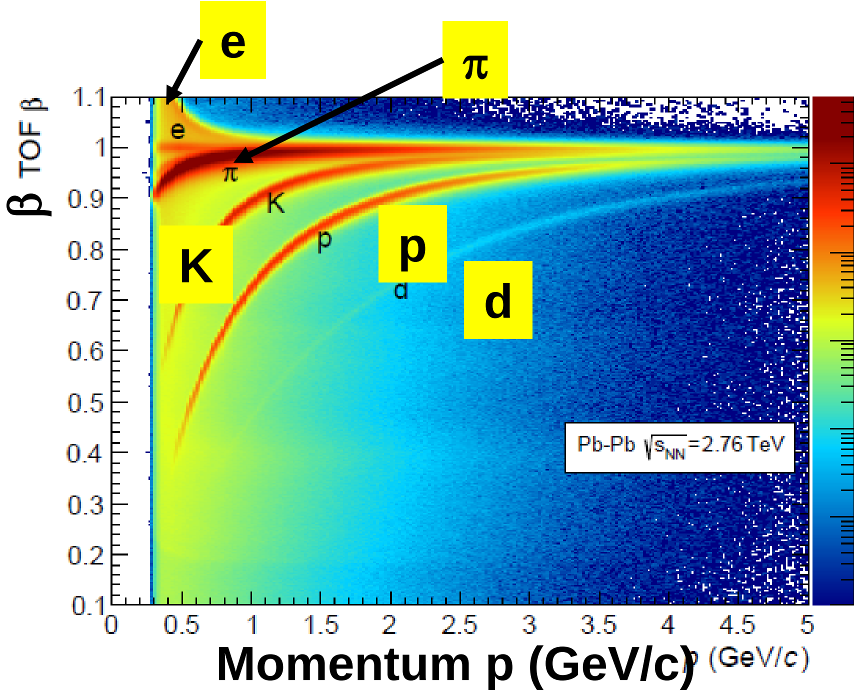
- Identify particle by measuring energy deposition and momentum
  - Not necessarily unique in all regions
- The single energy loss by (primary) ionization depends on E^{-2}
  - Most of the times the energy loss is small, but a small probability exists to have a large energy loss
  - Landau tail of the energy loss distribution → Truncated mean used





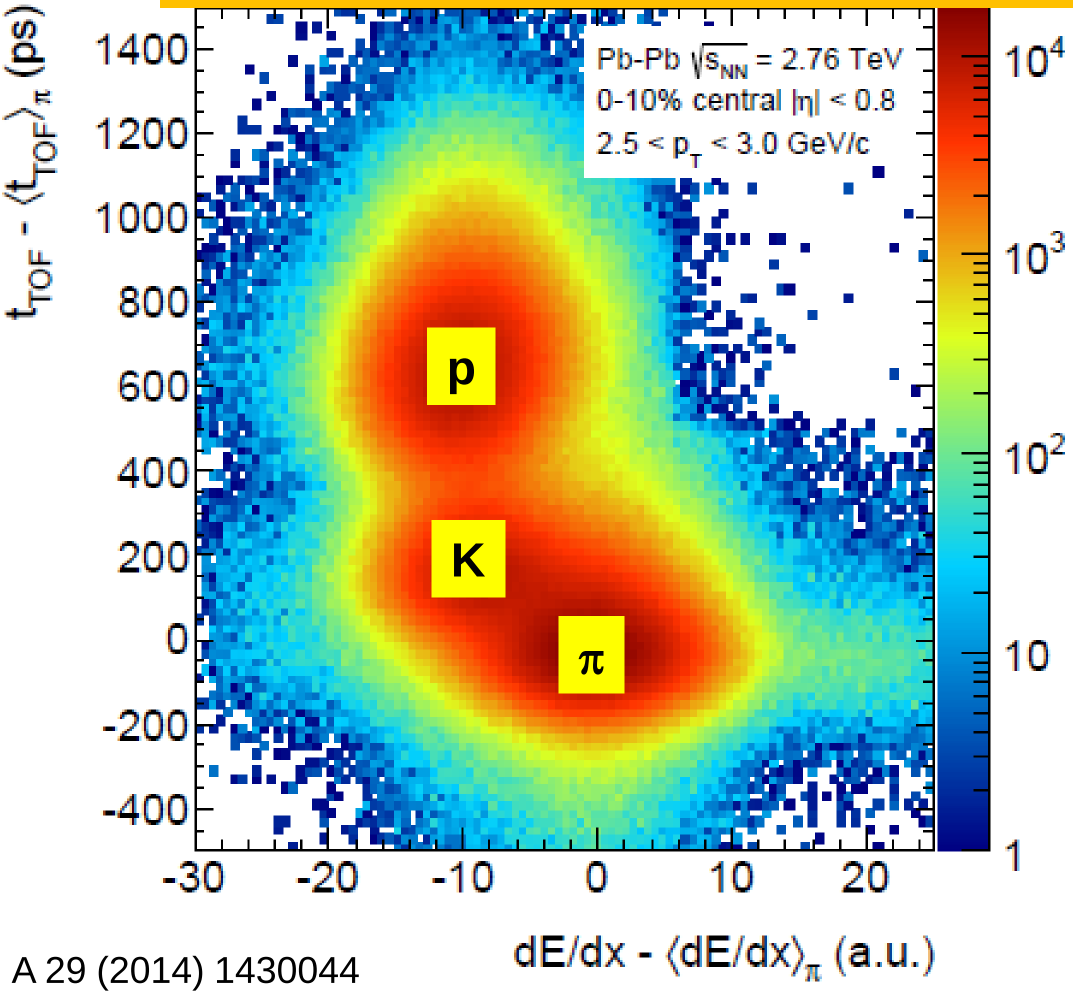
PID: Time Of Flight

- Although particles have practically speed of light, particles with the same momentum have slightly different speed due to their different mass
- Precise measurement of flight time between interaction and arrival in detector allows to determine mass, and thus the particle type
  - Needed 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
  - Detector without drift volume needed, dispersion usually spoils time resolution → MRPCs (multigap resistive plate chambers)



Combine PID Methods

Time of flight .vs. specific energy loss

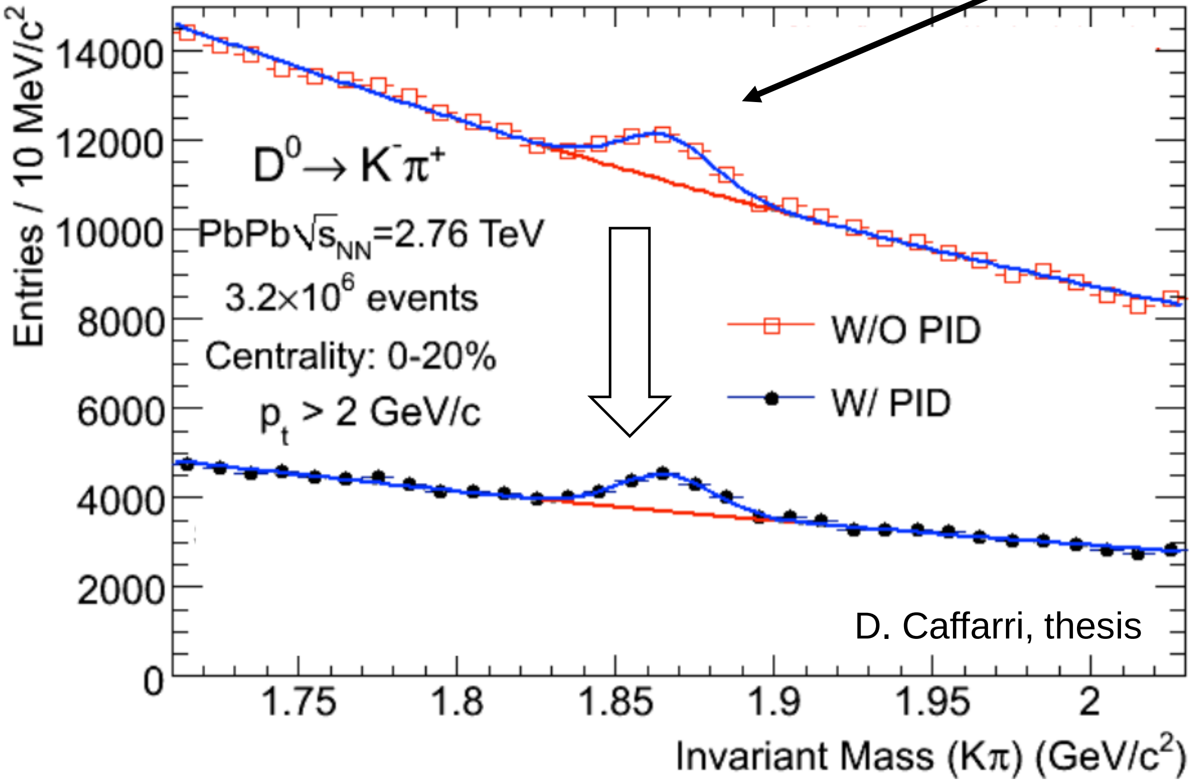


ALICE, Int. J. Mod. Phys. A 29 (2014) 1430044

Invariant Mass with Cuts

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

D^0 peak



D. Caffarri, thesis

with topological cuts

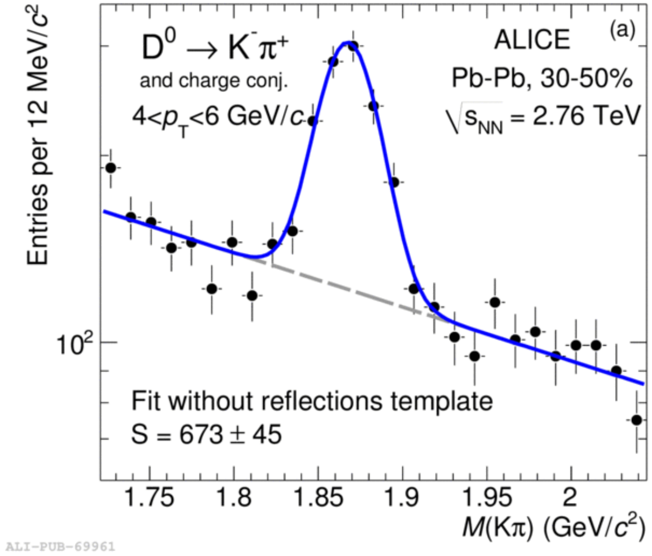
with topological cuts and PID

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

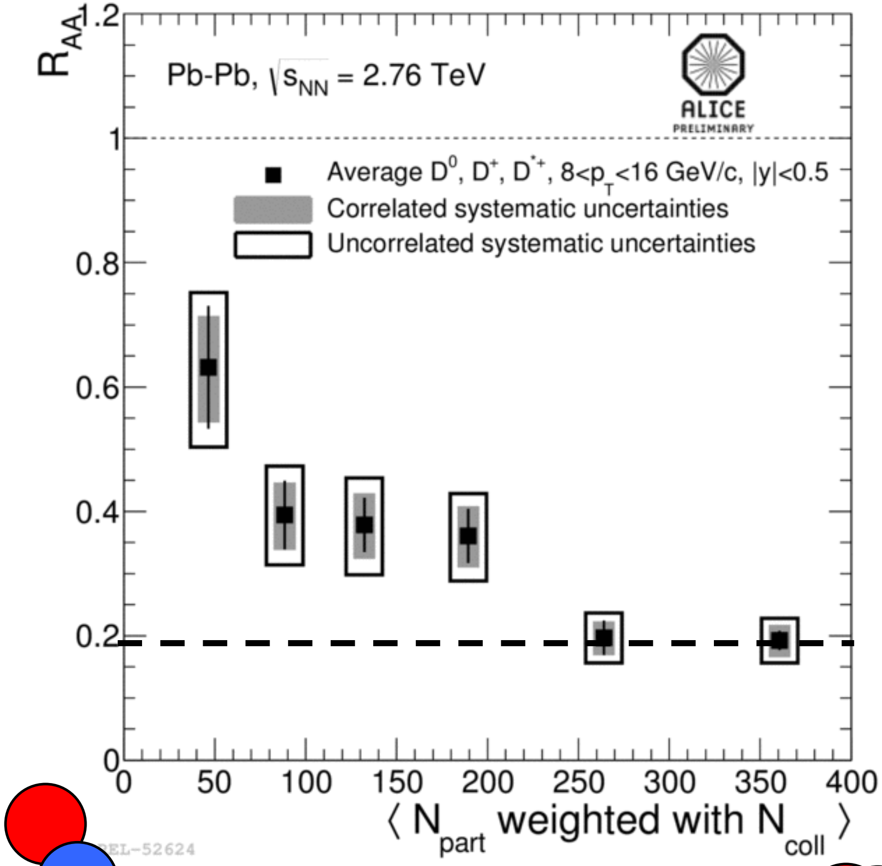
- Reconstruct D meson decay to K π
  - Rare signal
  - Combinatorial background reduced with particle identification and topological cuts
  - Invariant mass distribution
  - Background with like-sign combinations
  - Apply fit to extract yield



PRC 90 (2014) 034904

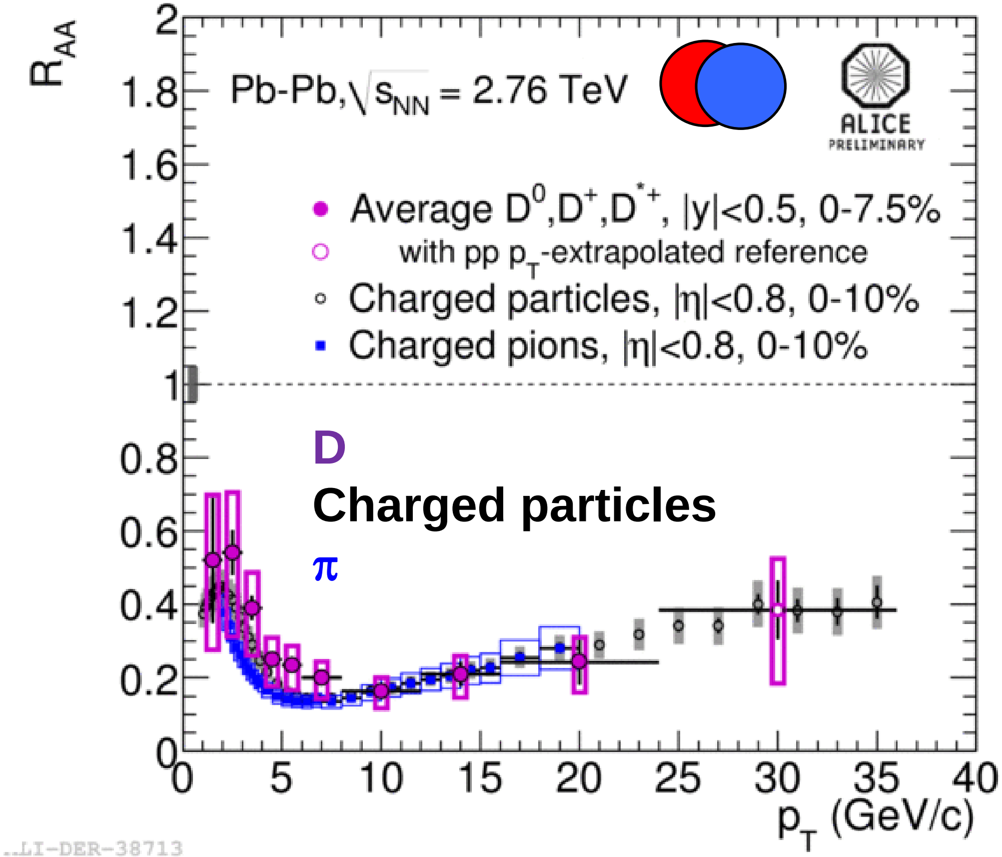
D R_{AA}

R_{AA} .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 → 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

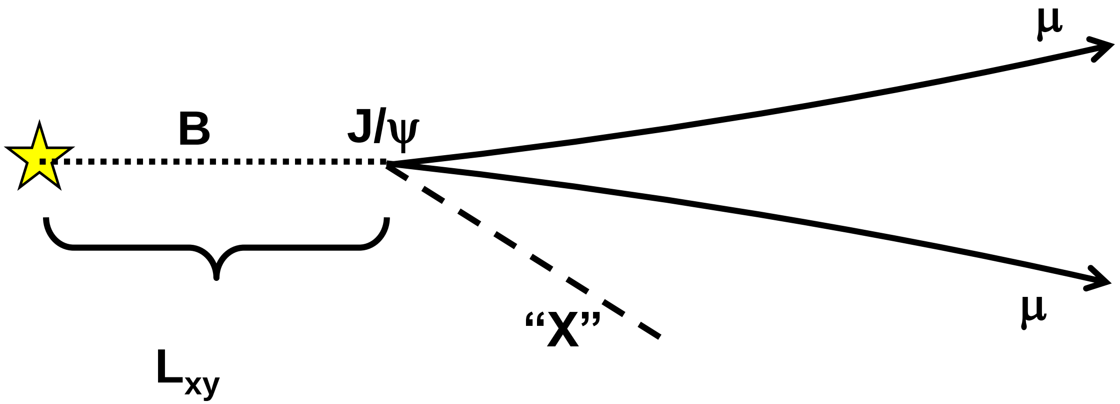
B Identification

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

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

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

Plane transverse to beam



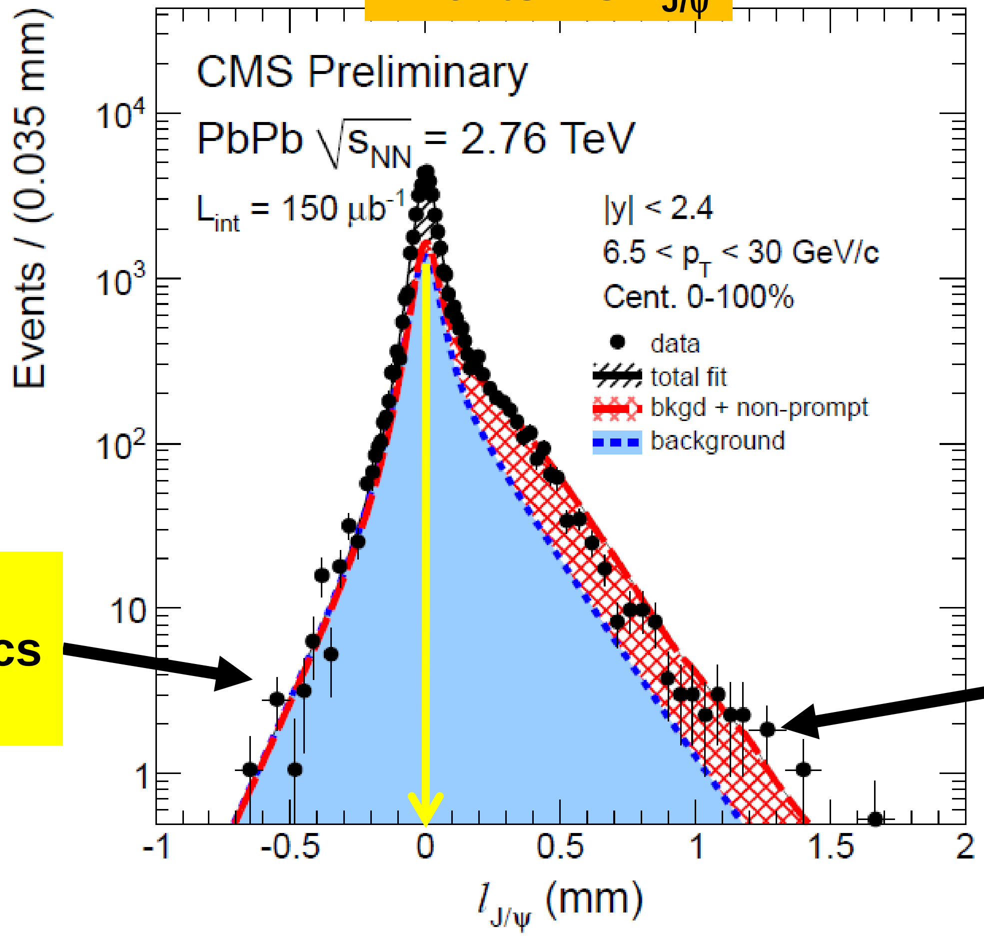
- Convert to pseudo-proper decay length as estimate of b-hadron decay length

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

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 $l_{J/\psi}$

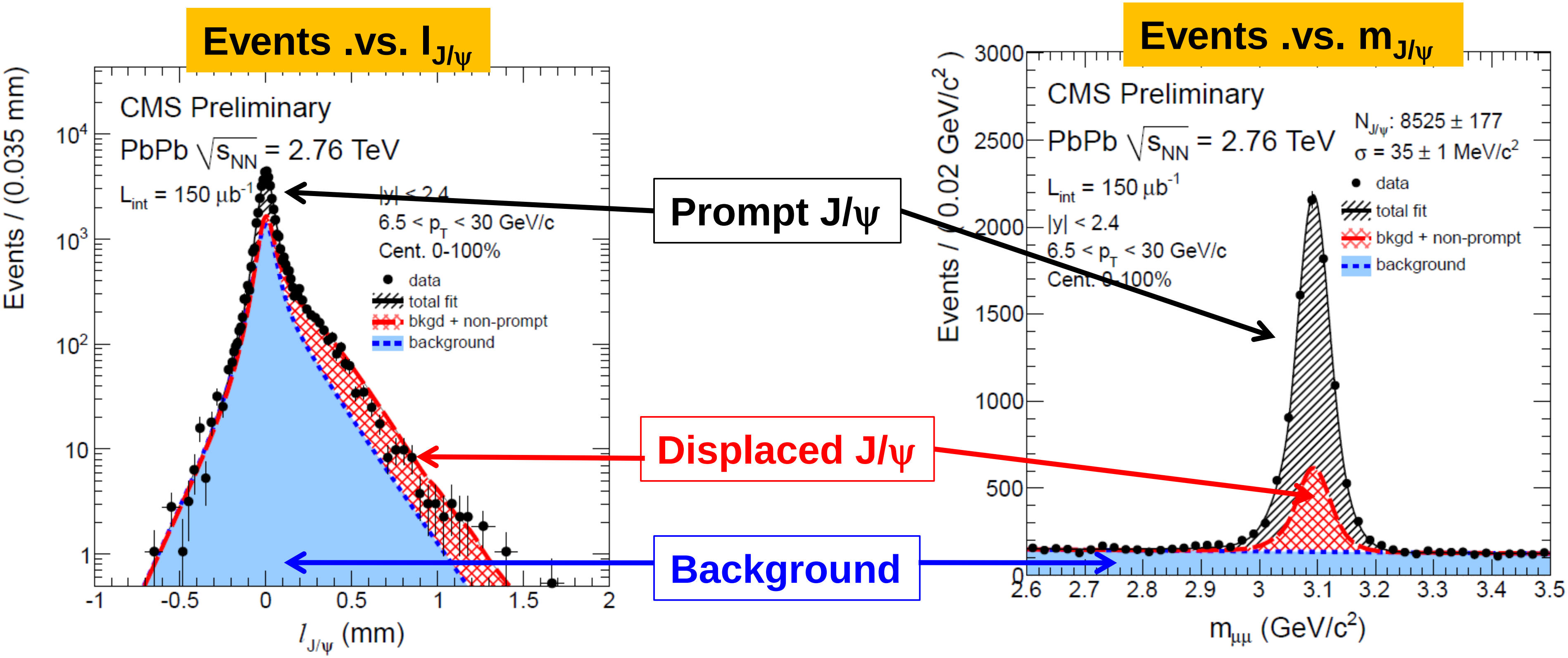
CMS, HIN-12-014

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

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

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



Prompt J/ψ

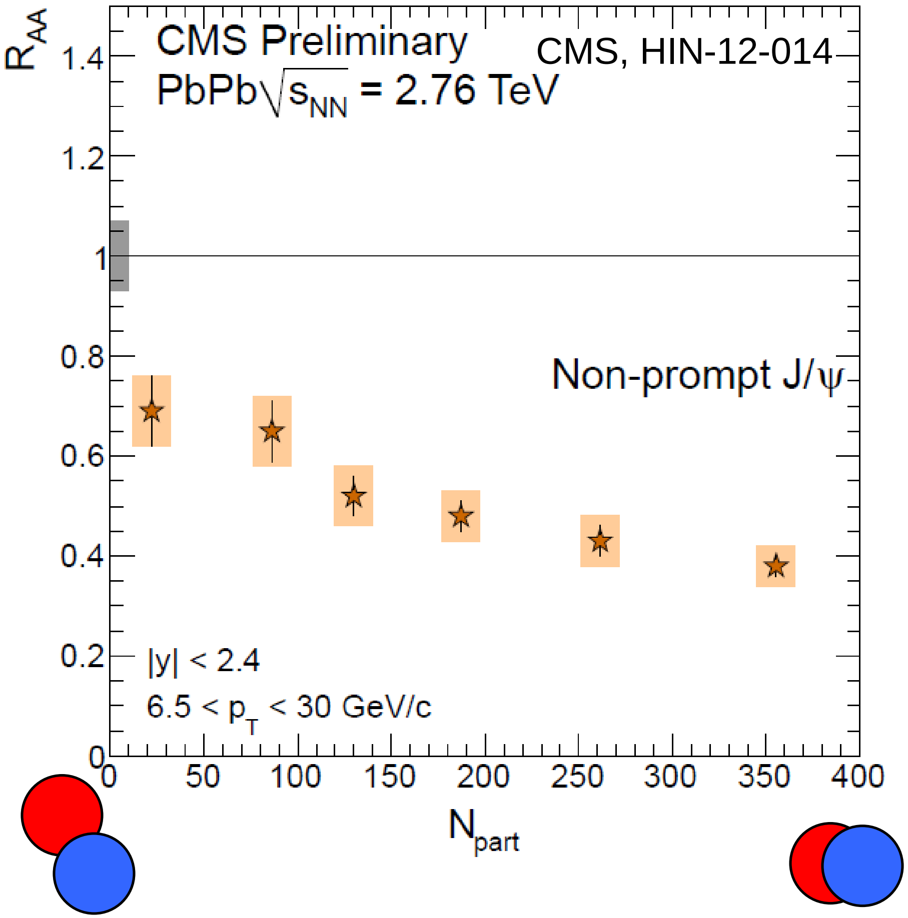
Displaced J/ψ

Background

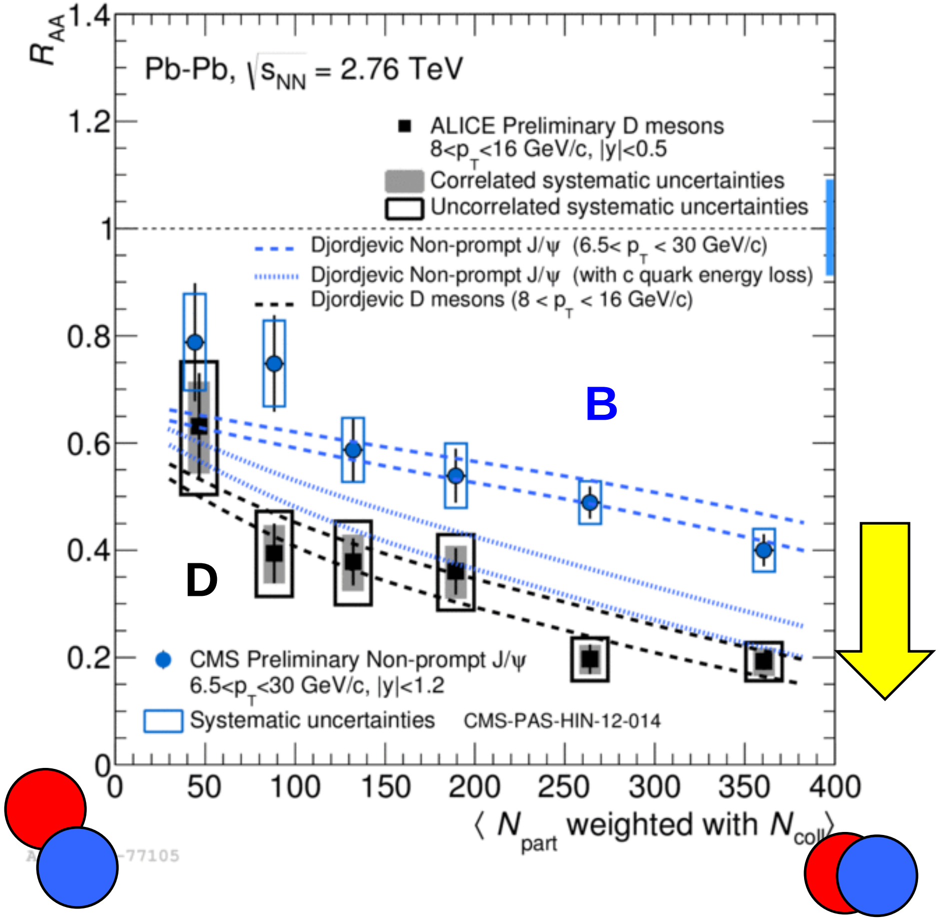
CMS, HIN-12-014

B R_{AA}

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

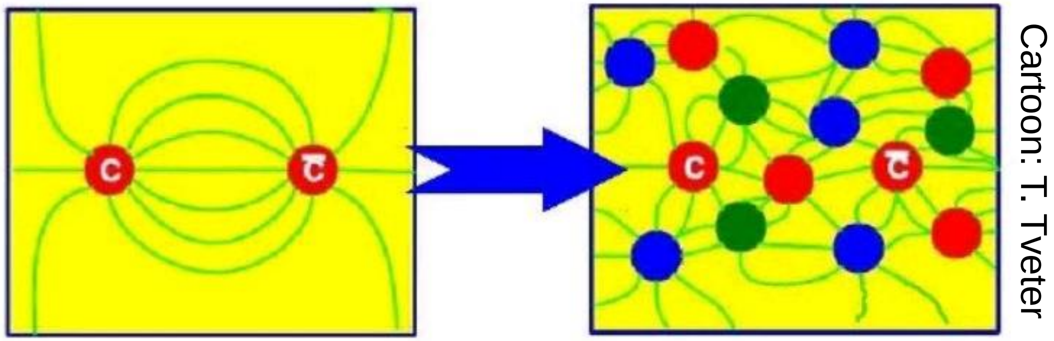
Measurement of b → J/ψ requires displaced vertices.
What about J/ψ stemming directly from the interaction?

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

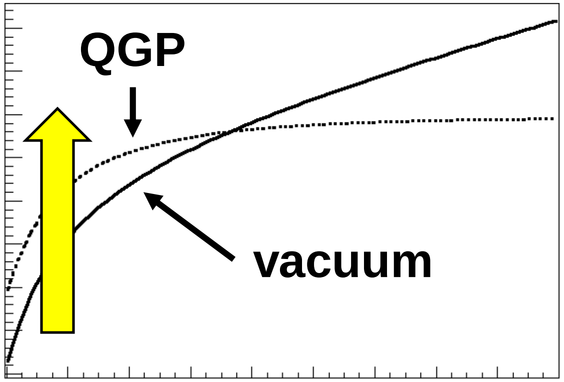
α gauge coupling
σ string tension
μ screening mass

- Changes (binding) potential

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

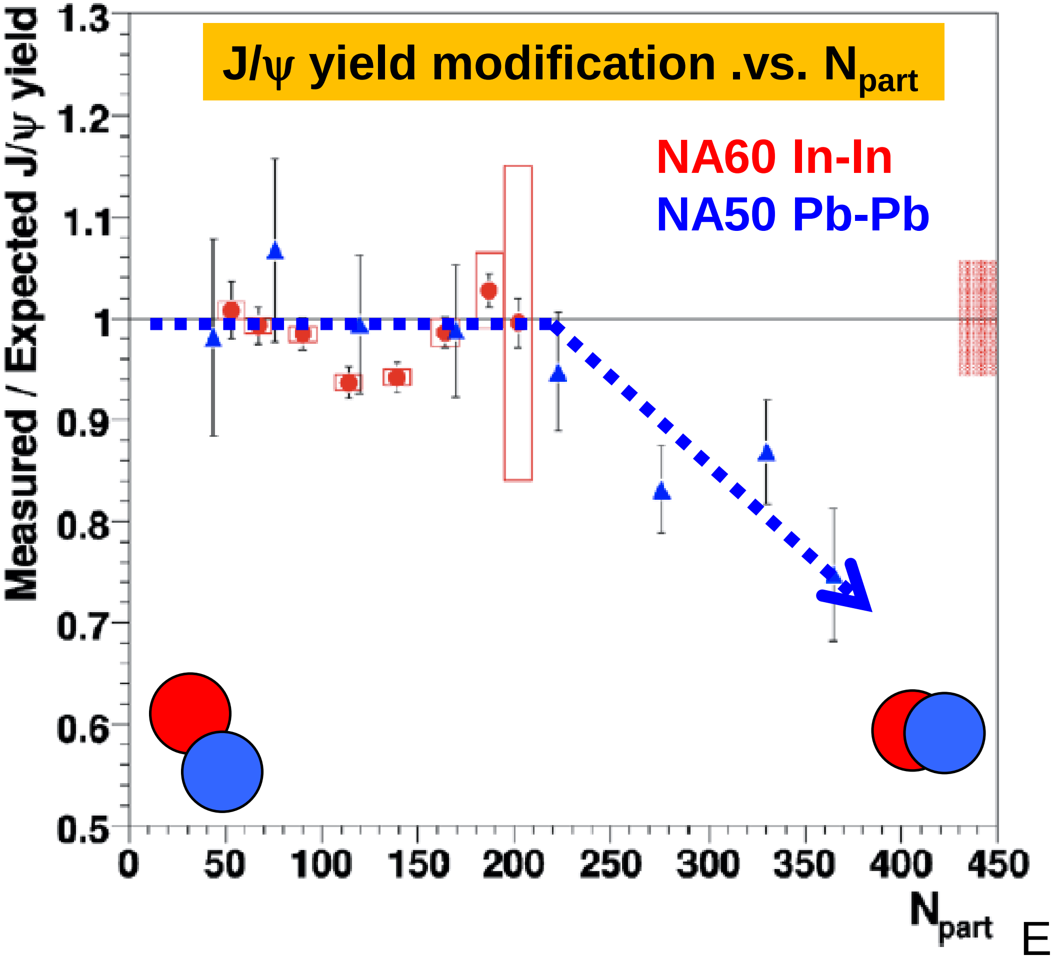
- Quarks with distance larger than 1/μ do not see each other
  - → Dissociation of q-qbar pair !
  - → Quarkonia "melt"

Potential .vs. r



J/ψ Suppression

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

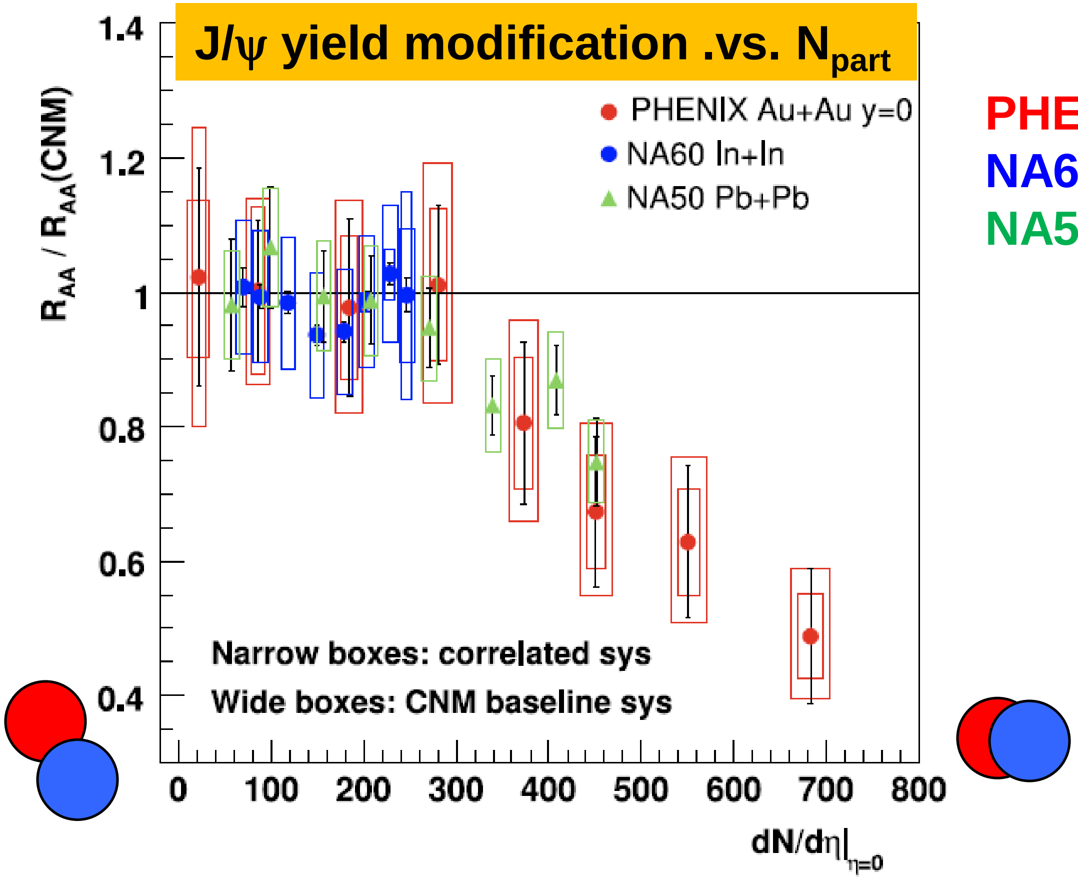


In: A = 105
Pb: A = 208

EPJC (2011) 71:1534

J/ψ Suppression (2)

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



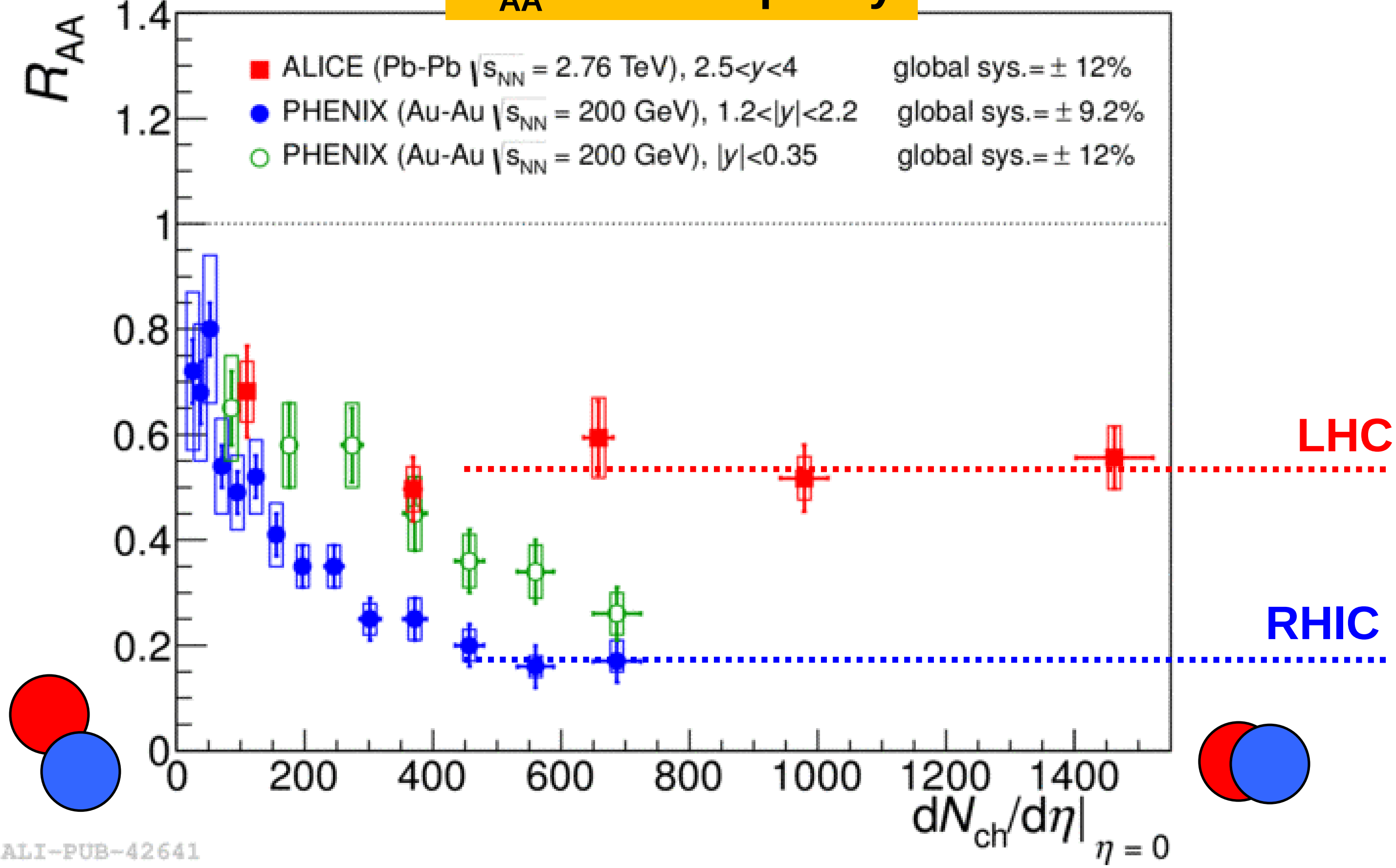
J/ψ yield modification .vs. N_{part}

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

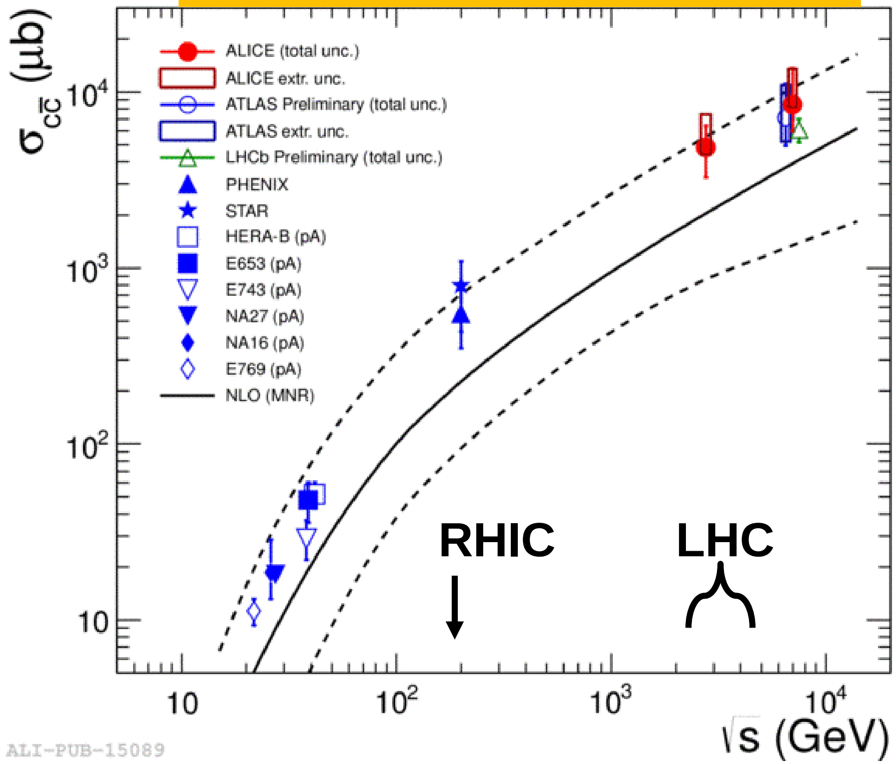


LHC → RHIC : $\sqrt{s_{NN}}$ 14 times larger … but the suppression is smaller !

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

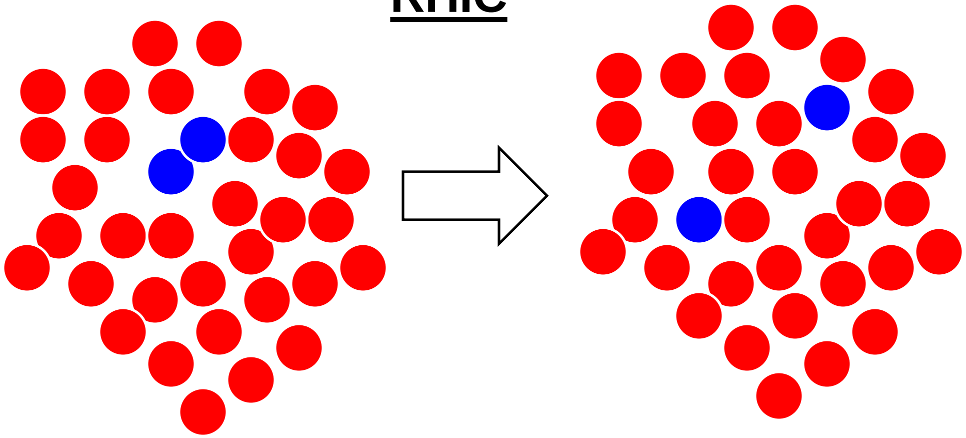
Charm cross-section .vs. √s



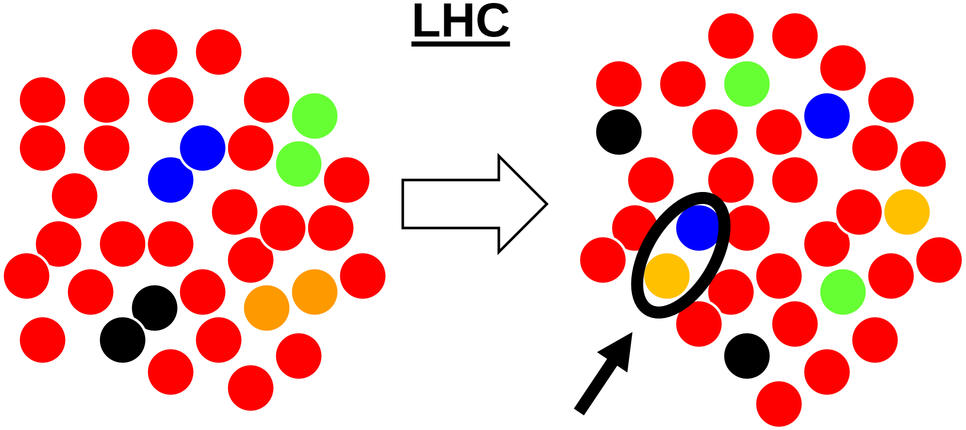
JHEP 1207 (2012) 191

J/ψ Regeneration

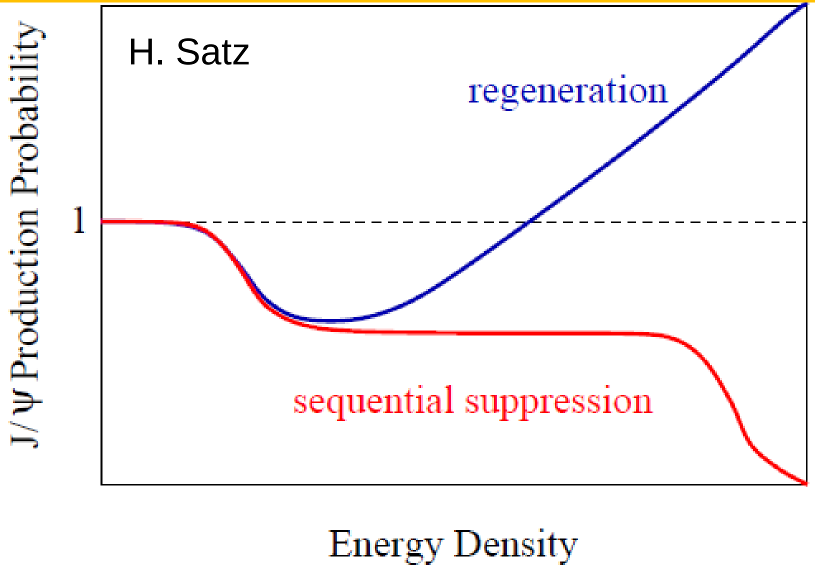
RHIC



LHC



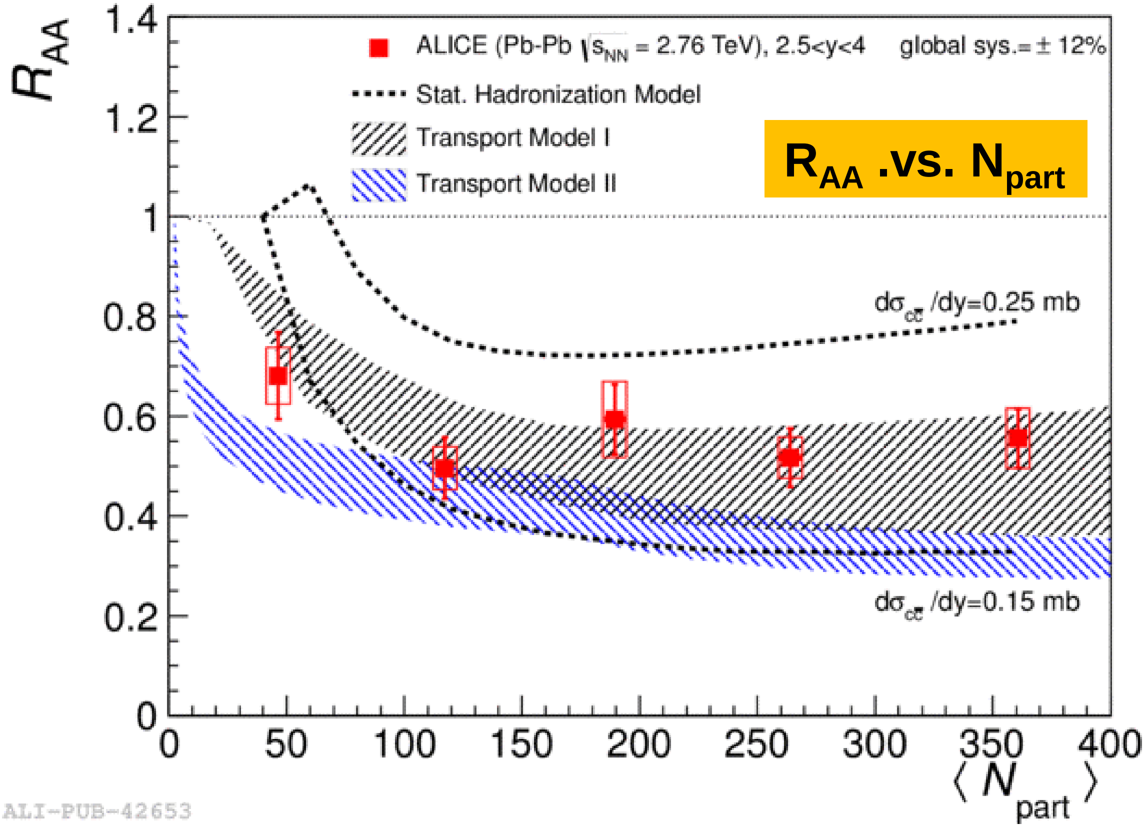
J/ψ modification .vs. energy density



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)

PRL109, 072301

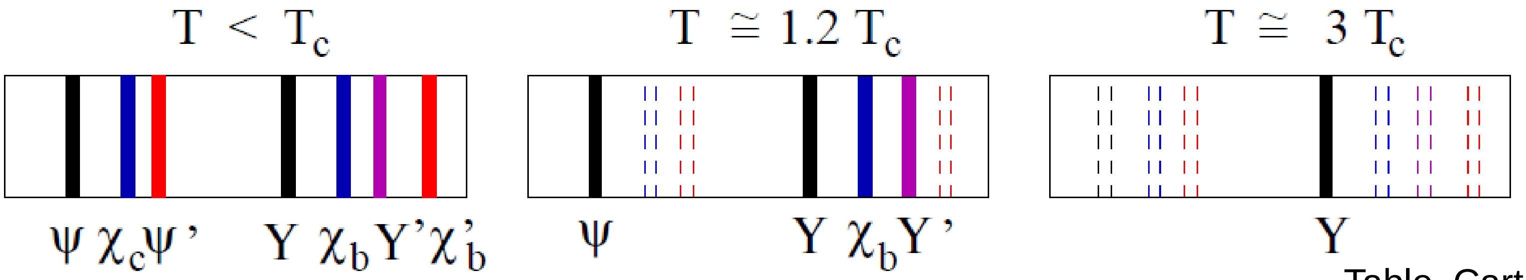
Other Quarkonia

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

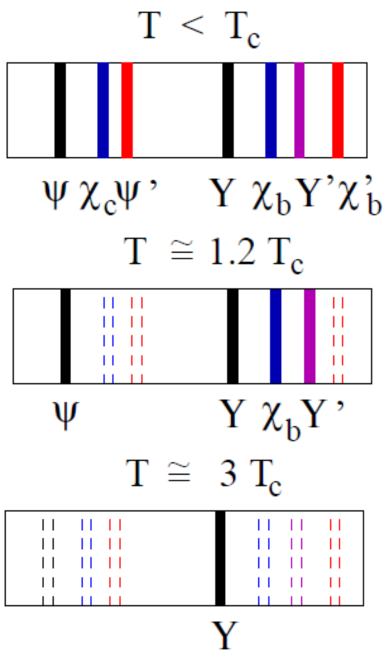
dissociates last

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

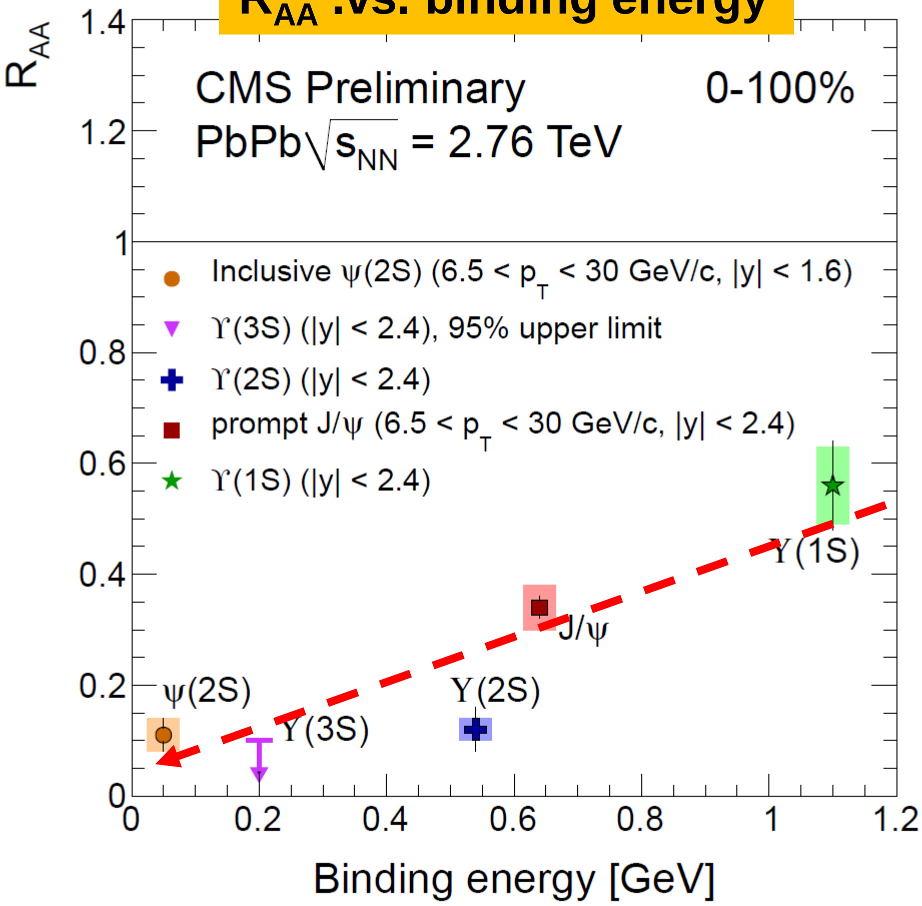


Table, Cartoon: H. Satz

QGP Thermometer



R_{AA} .vs. binding energy



States with lower binding energies more suppressed !

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

&

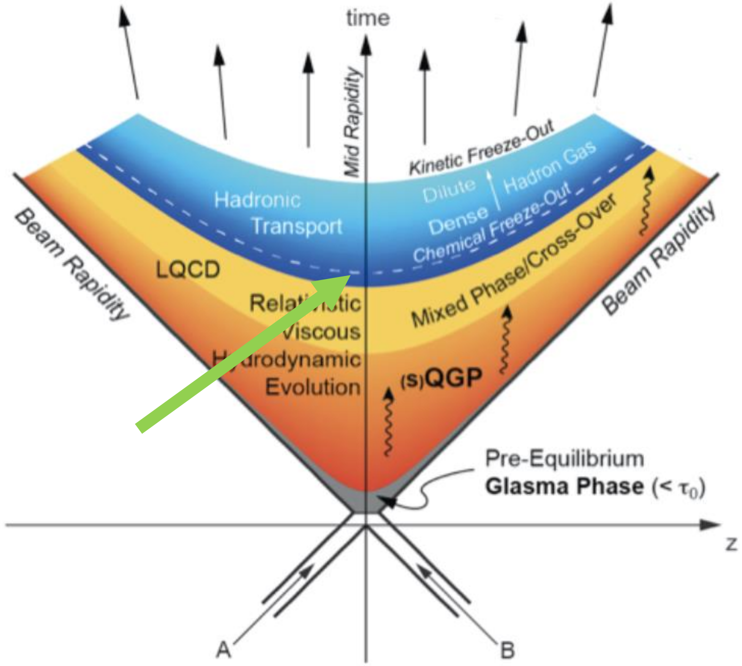
Statistical Model

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)

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

spin degeneracy

Temperature

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

volume

chemical potential
(conserved quantities)

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

baryon number

strangeness

charm

isospin

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*

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

Particle densities **Pressure** **Entropy**

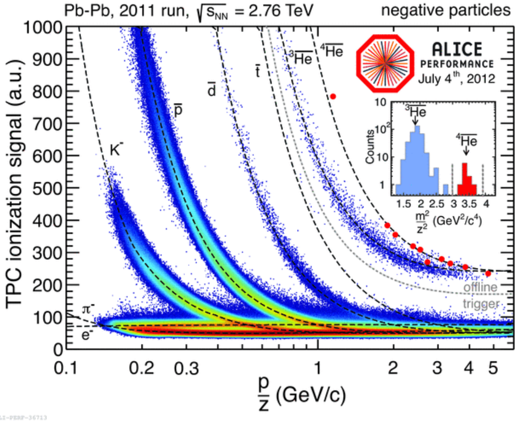
- In particle ratios V cancels → two free parameters (T, μ_B)

Let's have a look at the data…

Particle Identification

Direct particle identification

π K p d ^{3}He ^{3}H



Large impact parameter

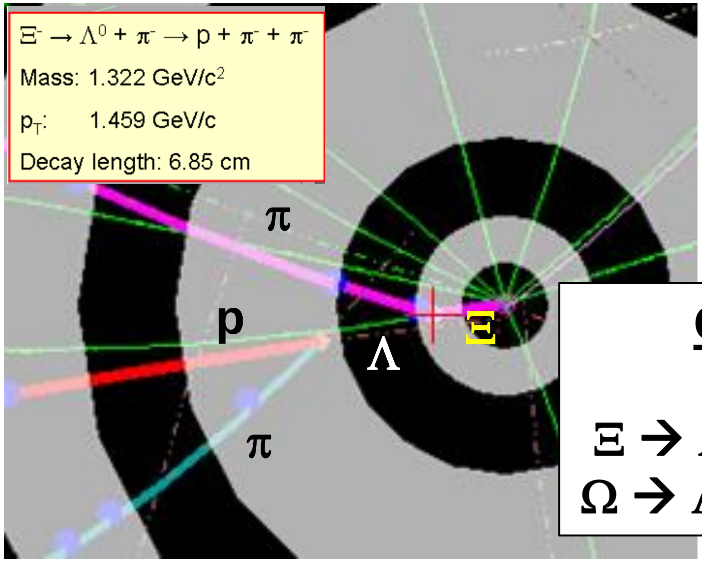
$K^0_S \rightarrow \pi\ \pi$ ($c\tau$ = 2.7 cm)
$\Lambda \rightarrow p\ \pi$ ($c\tau$ = 7.9 cm)

"Kink" in detector volume

$K \rightarrow \mu\ \nu$ ($c\tau$ = 3.7 m)

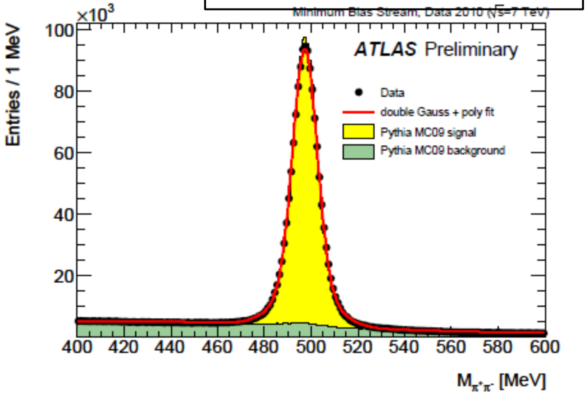
Invariant mass

$\phi \rightarrow K\ K$
$K^* \rightarrow K\ \pi$



Cascade

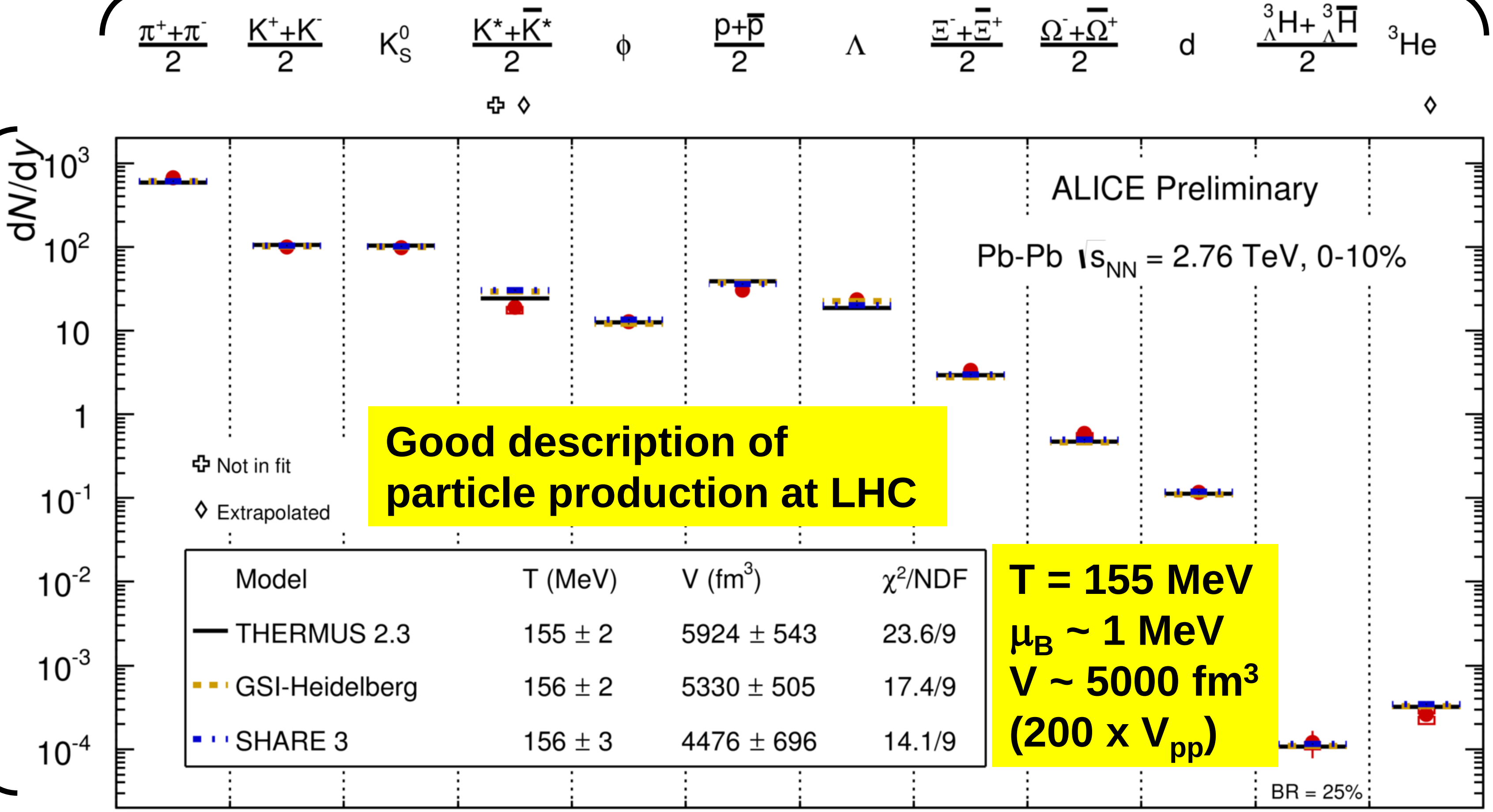
$\Xi \rightarrow \Lambda + \pi \rightarrow p\ \pi\ \pi$
$\Omega \rightarrow \Lambda + K \rightarrow p\ \pi\ K$



Statistical Model at LHC

12 different particles

7 orders of magnitude

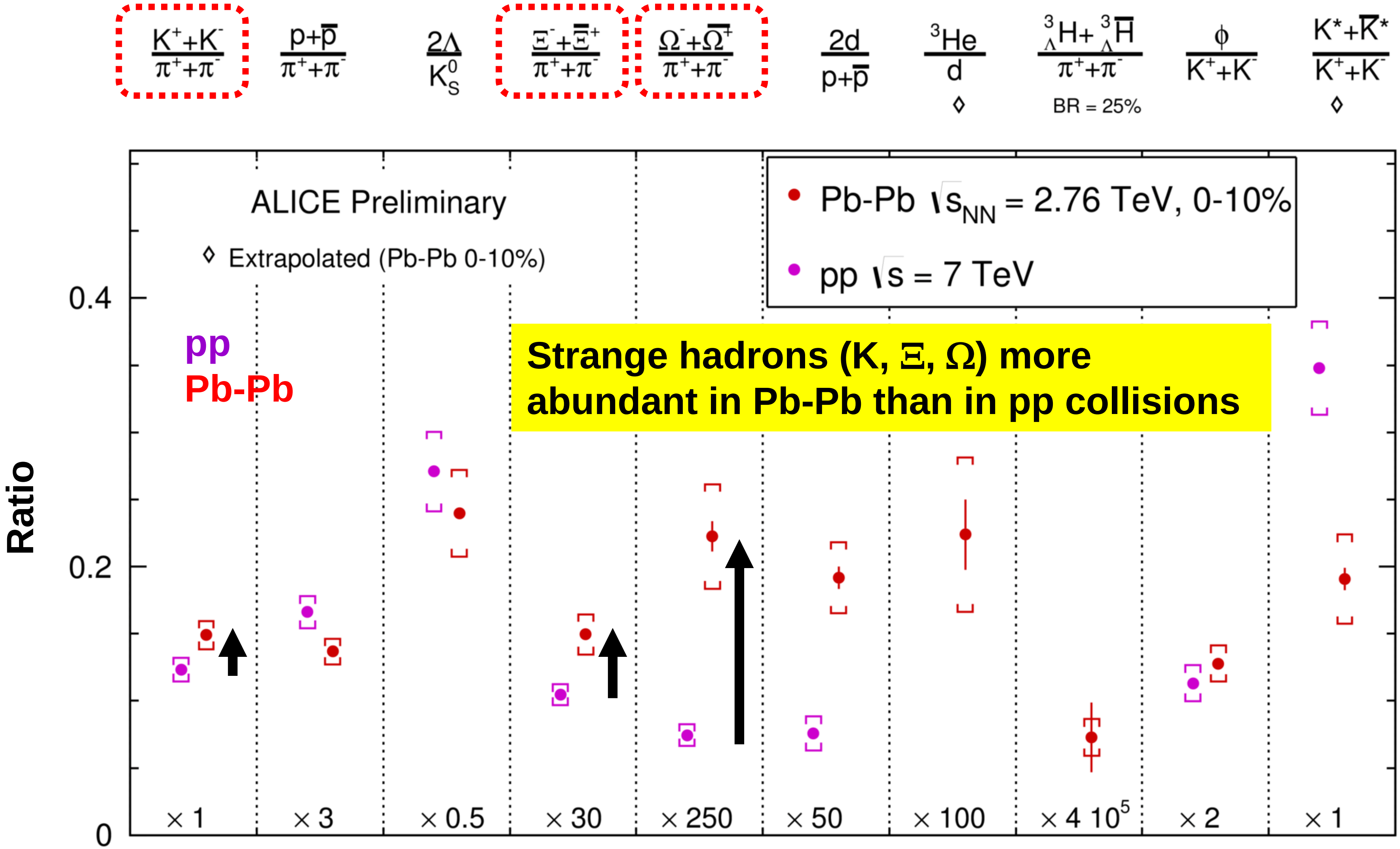


Model	T (MeV)	V (fm^{3})	χ^{2}/NDF
THERMUS 2.3	155 ± 2	5924 ± 543	23.6/9
GSI-Heidelberg	156 ± 2	5330 ± 505	17.4/9
SHARE 3	156 ± 3	4476 ± 696	14.1/9

Good description of particle production at LHC

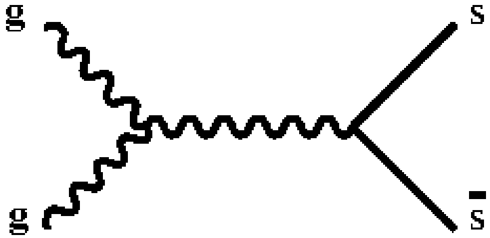
T = 155 MeV
μ_B ~ 1 MeV
V ~ 5000 fm^3
(200 x V_{pp})

Pb-Pb .vs. pp



Strange hadrons (K, Ξ, Ω) more abundant in Pb-Pb than in pp collisions

Strangeness Enhancement



- Threshold for strange production
  - Hadronic matter: production of 2K (~1 GeV)
  - QGP: gluon fusion to s-sbar pair (~0.3 GeV)
- T ~ 170 MeV in the QGP
- Production more abundant in the QGP
- Proposed as one of the first QGP signatures (1982)
  - and observed at SPS
- Statistical models suppress strangeness production by additional parameter (γ_S)
  - γ_S ~ 1 in central HI collisions; smaller in pp collisions

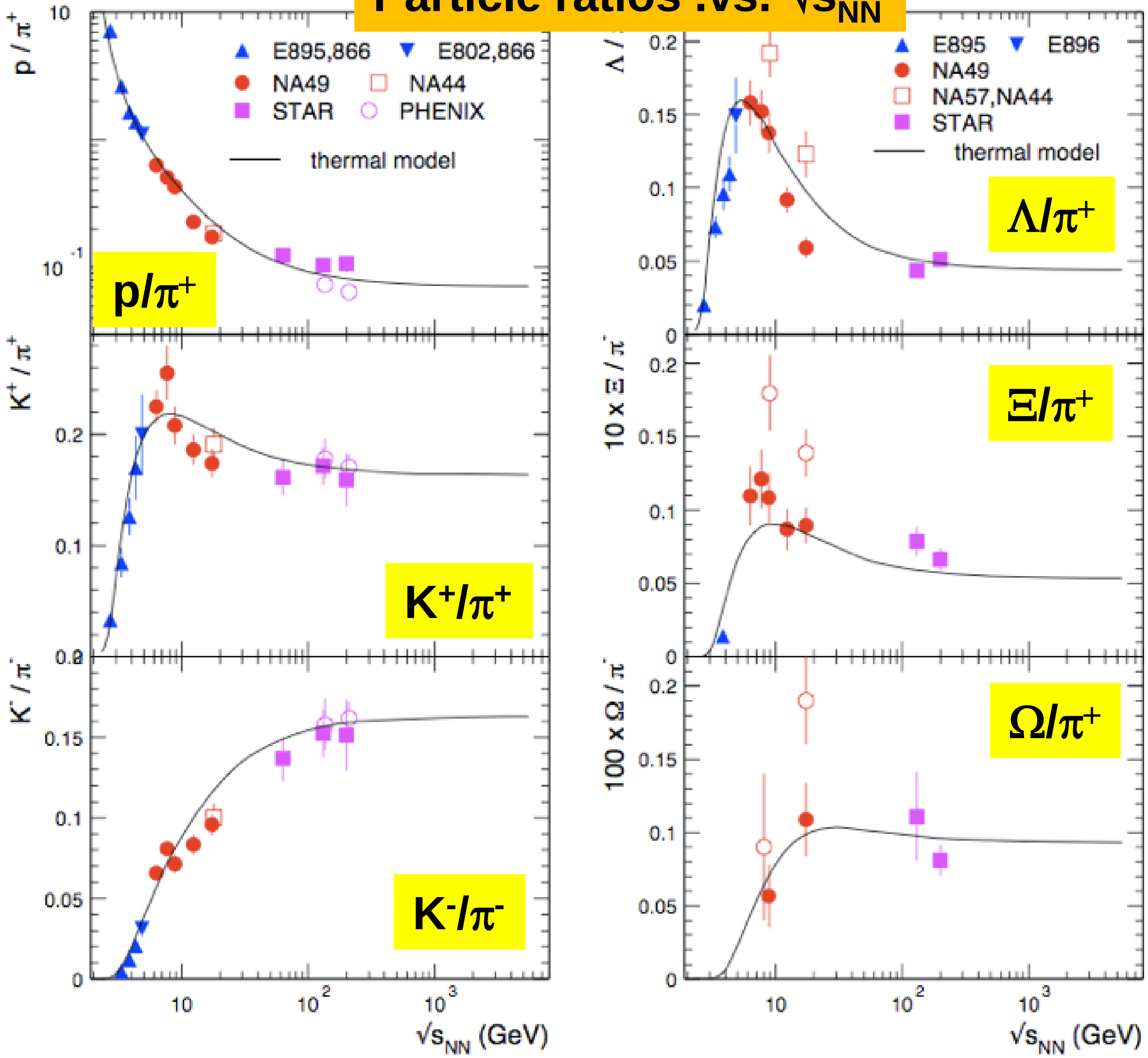
In small systems strangeness conservation reduces the available phase space (*canonical suppression*)

- Suppression without QGP → Power as QGP signature limited

Thermal Model: Very Successful

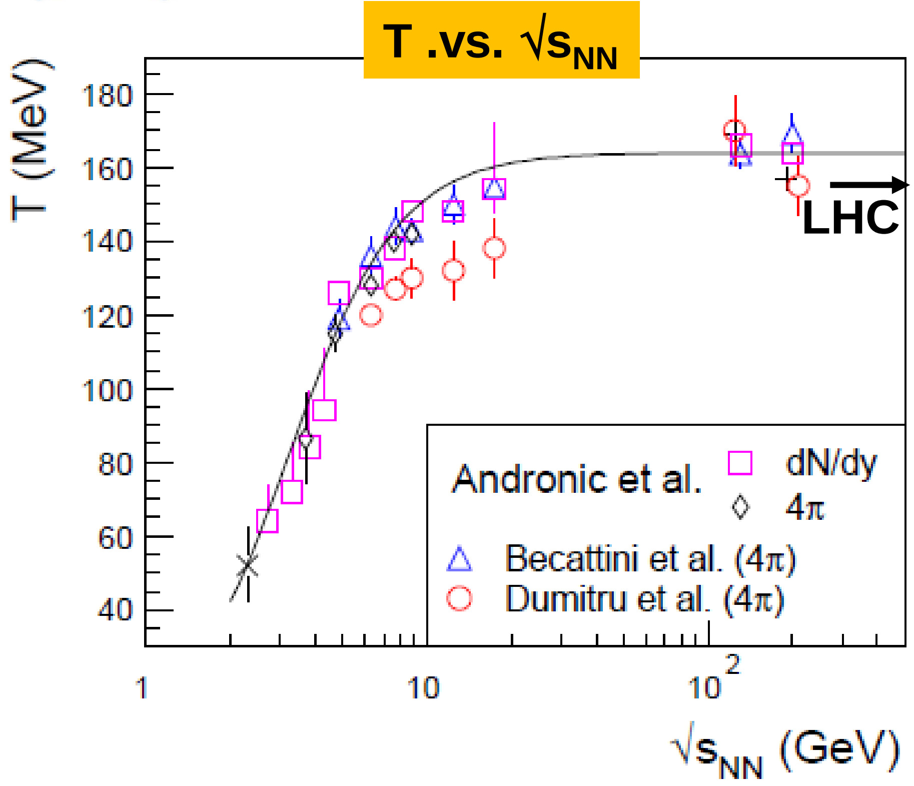
Particle ratios described well from 2 to 200 GeV

Particle ratios .vs. $\sqrt{s_{NN}}$

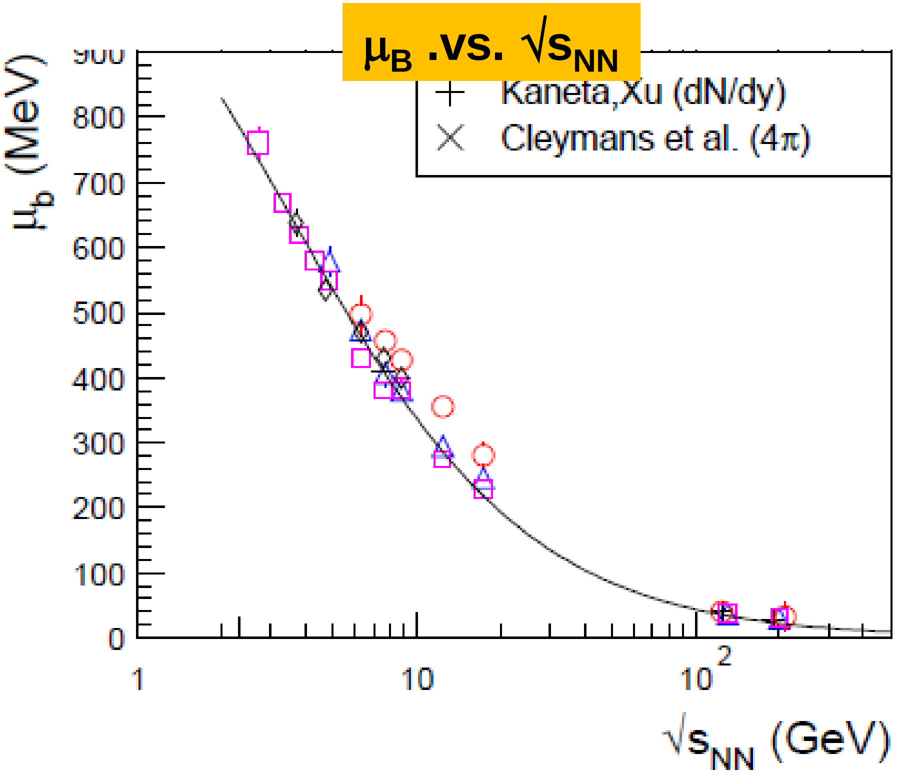


arXiv:1101.3167

√s Dependence



T .vs. $\sqrt{s_{NN}}$



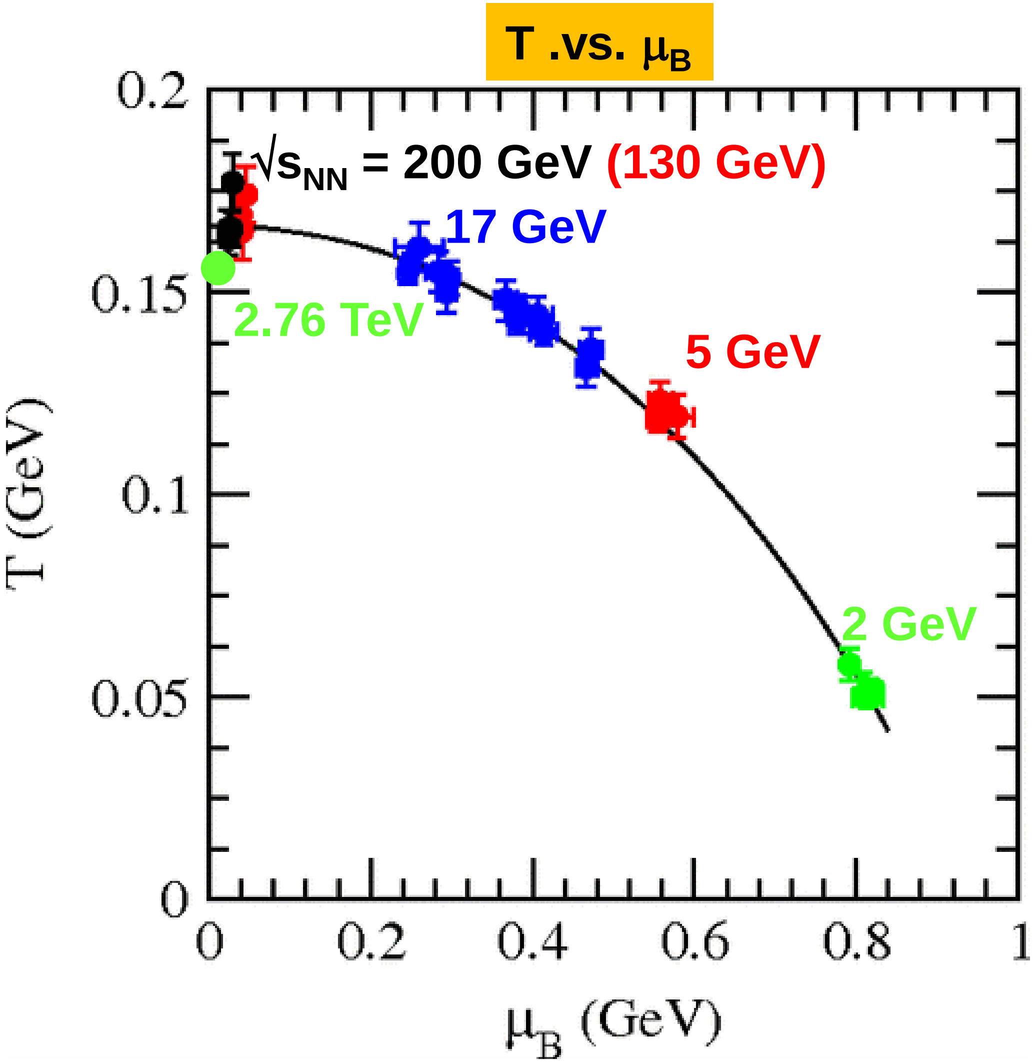
μ_B .vs. $\sqrt{s_{NN}}$

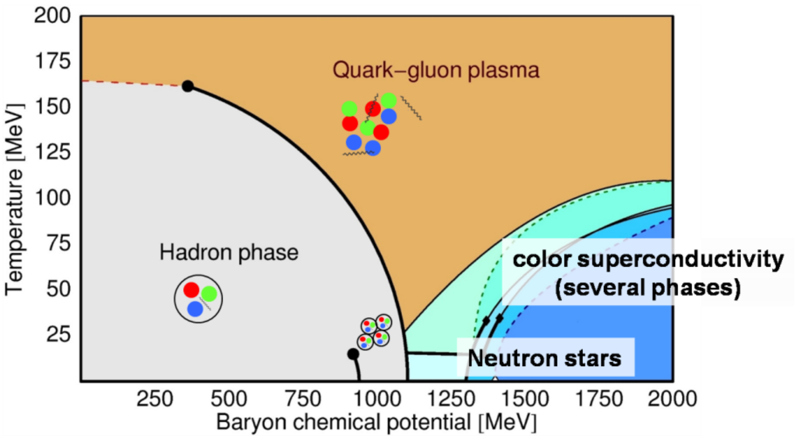
Temperature increases with √s and reaches plateau of about 160 MeV at $\sqrt{s_{NN}}$ > 20 GeV

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

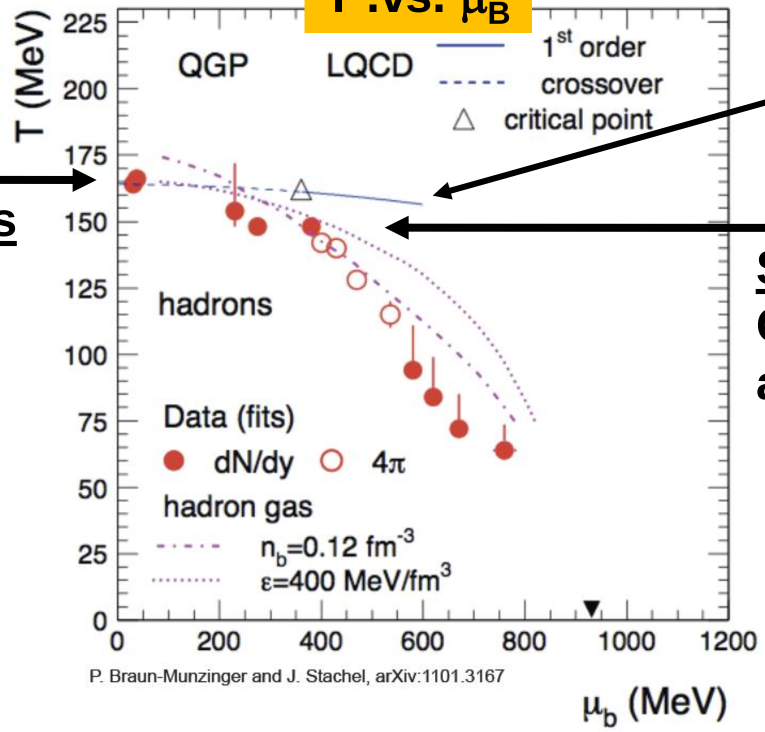
adapted from
PRC 73, 034905 (2006)

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

→

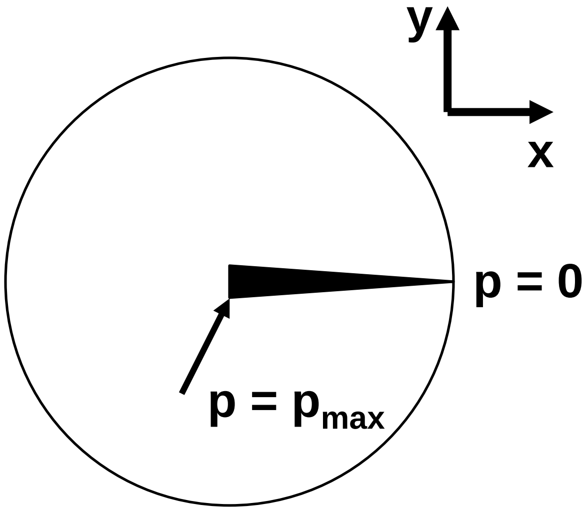
Matter created in HI collisions is in local thermal equilibrium

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

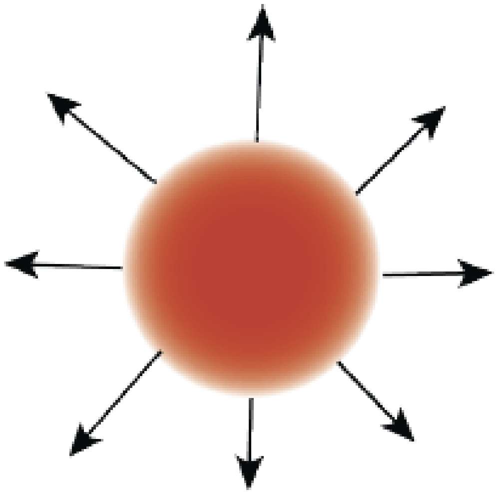


view in beam direction

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

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

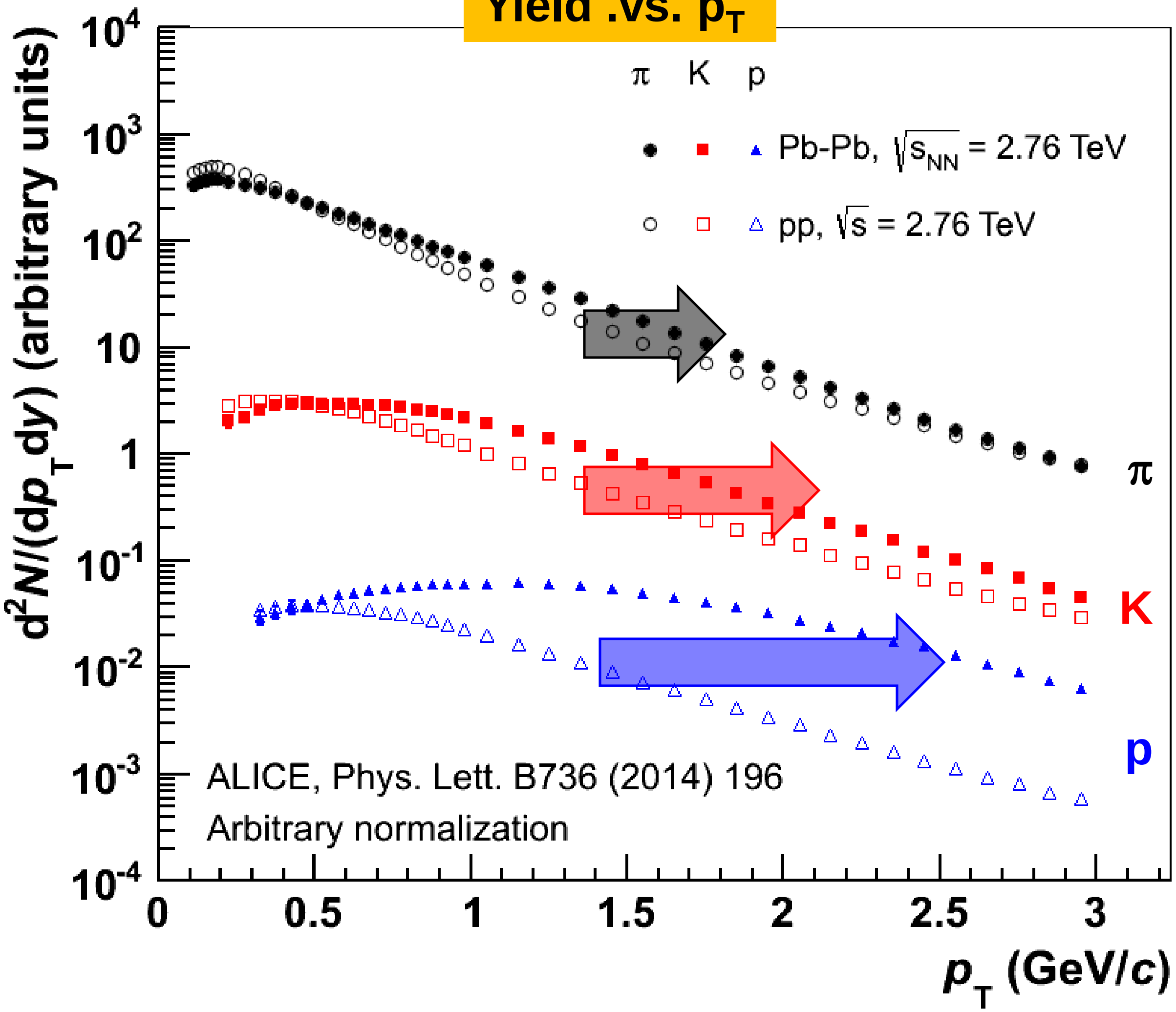
- Measurable in the transverse plane (p_T)
  - Called *radial flow*



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



ALICE, Phys. Lett. B736 (2014) 196
Arbitrary normalization

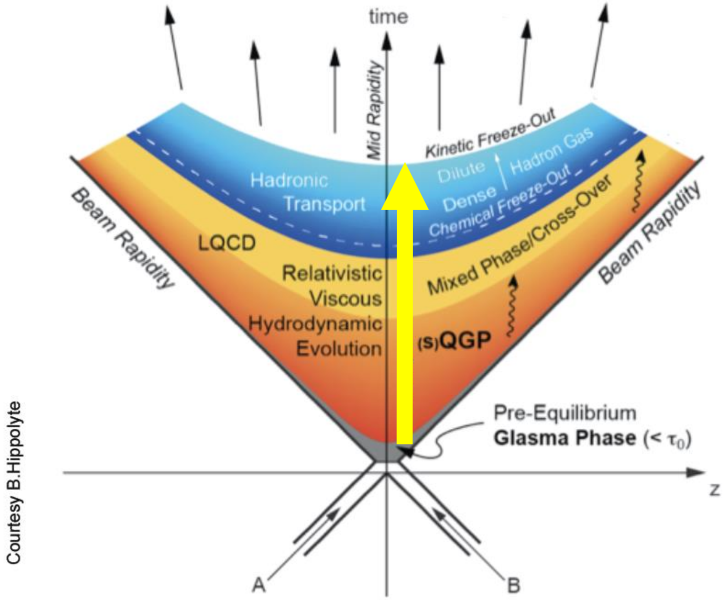
Particle p_T increases
Spectra pushed outwards

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

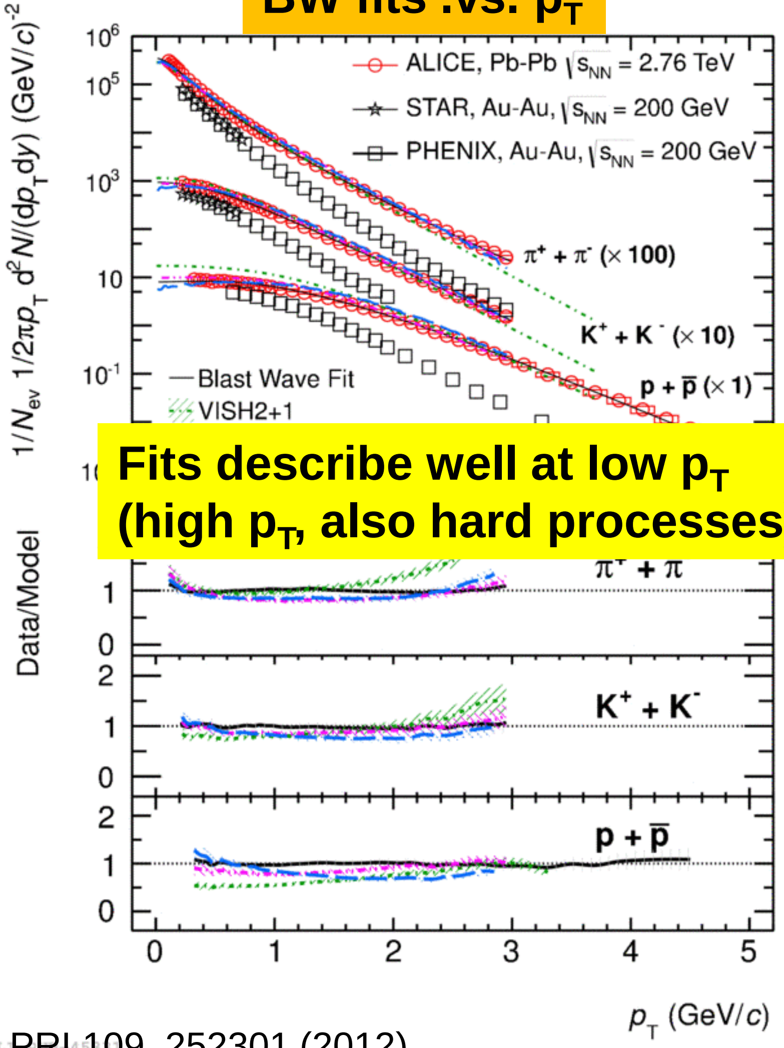
radial flow velocity

velocity profile

PRC 48, 2462 (1993)

Blast-Wave Fits (2)

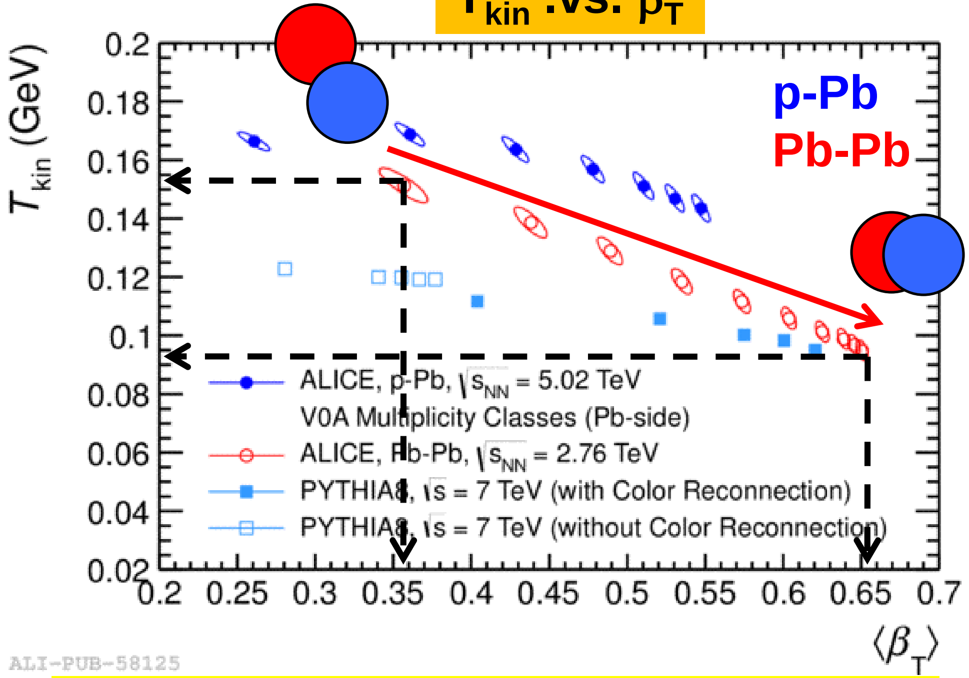
BW fits .vs. p_T



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