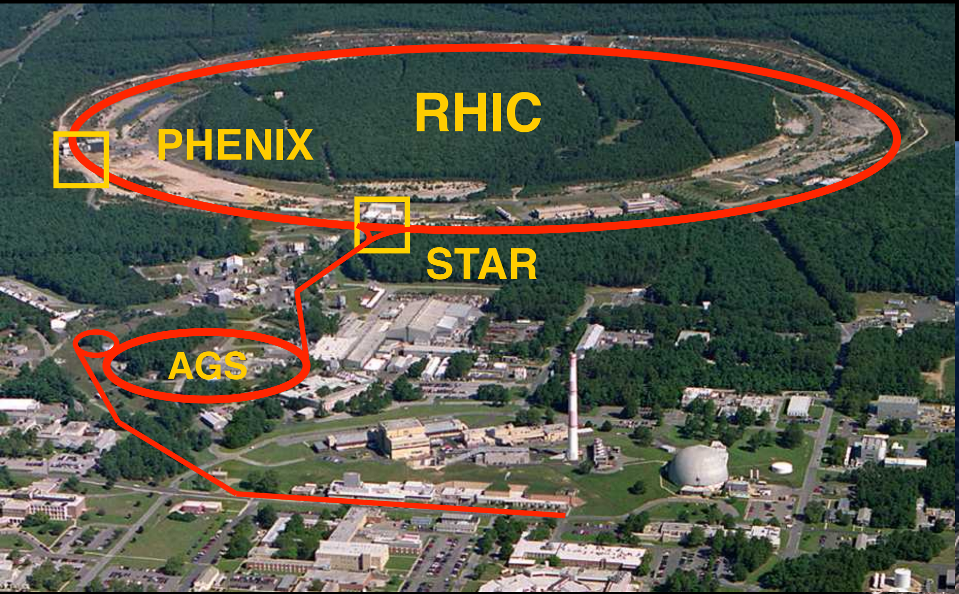
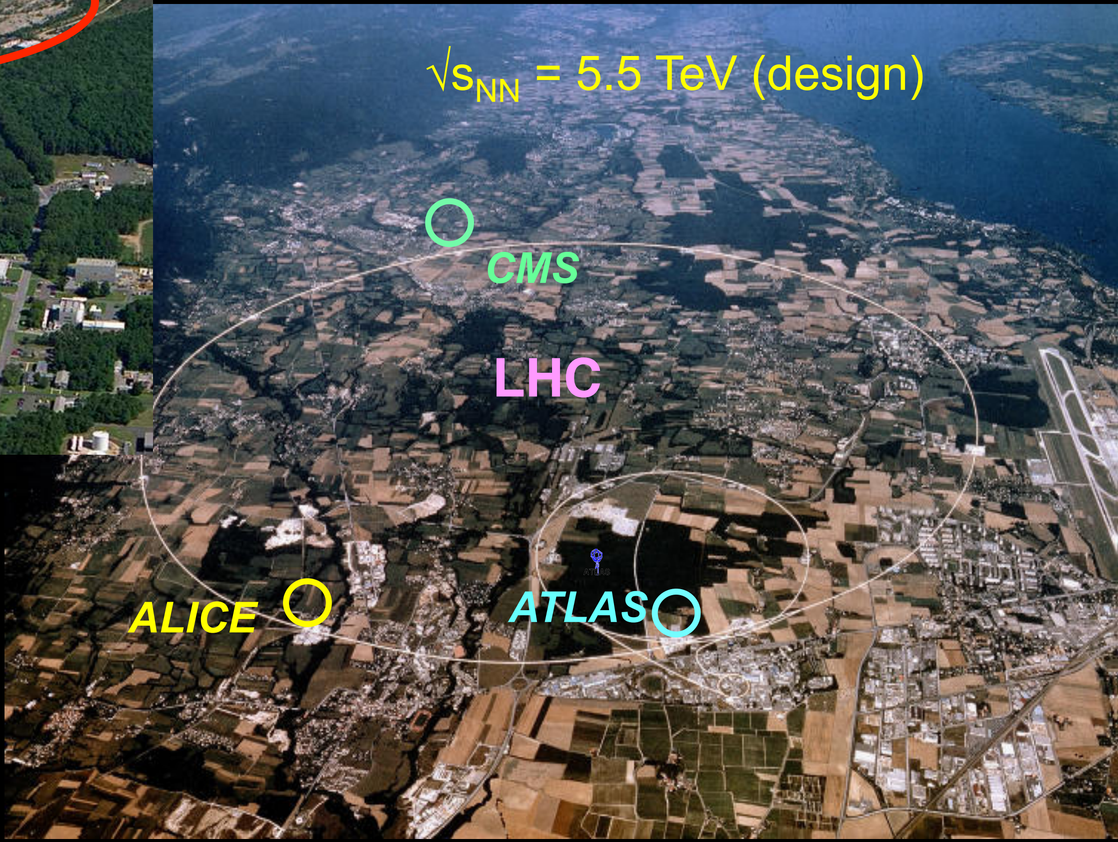
Review of Results with Heavy Ions at RHIC and LHC



Cover 3 decades of energy in center-of-mass



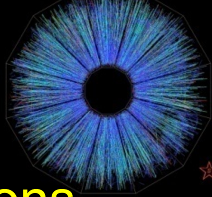
$\sqrt{s_{NN}}$ = 5 - 200 GeV

To investigate properties of hot QCD matter at T ~ 150 – 1000 MeV!

John Harris (Yale)

TURIC – 2012, Hersonissos, Crete, Greece, 28 June 2012

“What Do We Know” from RHIC & LHC

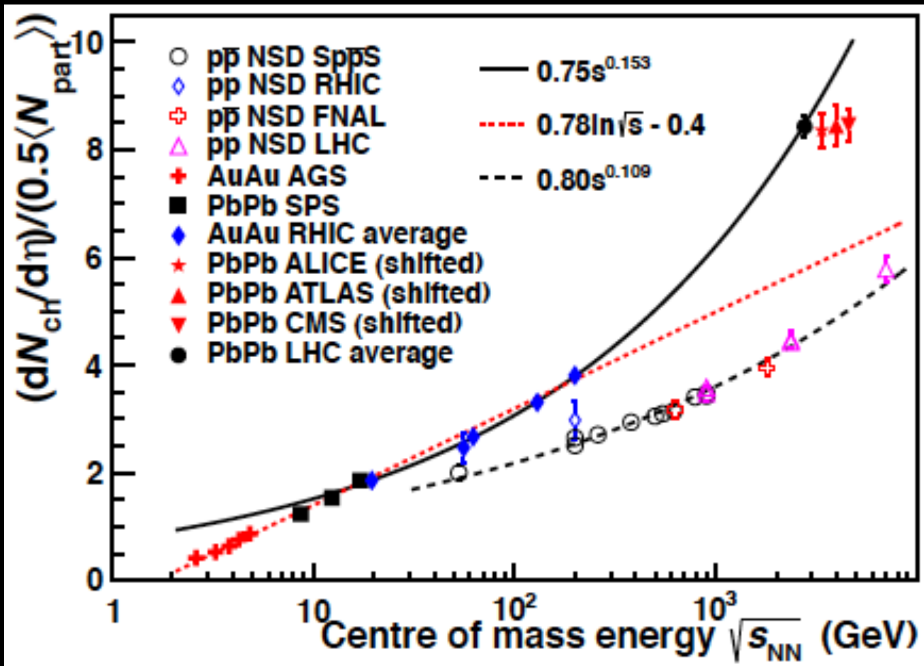


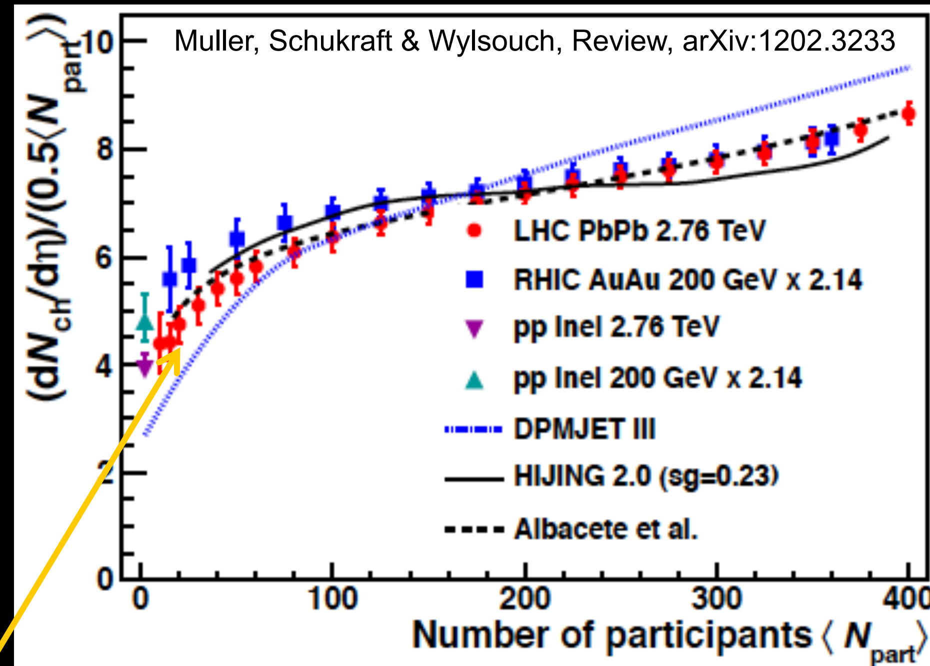
Consistent Picture of Geometry, Dynamics and Evolution of RHI Collisions

Dynamics & Evolution of RHI Collisions

"LHC & RHIC provide consistent picture" of dynamics & evolution of collisions

→ multiplicities, system size & lifetimes from RHIC to LHC





Small differences due to initial conditions (PDF shadowing vs geometry, hard processes ~ # binary collisions at LHC vs RHIC)?

Glauber vs CGC, Initial state fluctuations, Extent of shadowing
LHC pPb data later this year!

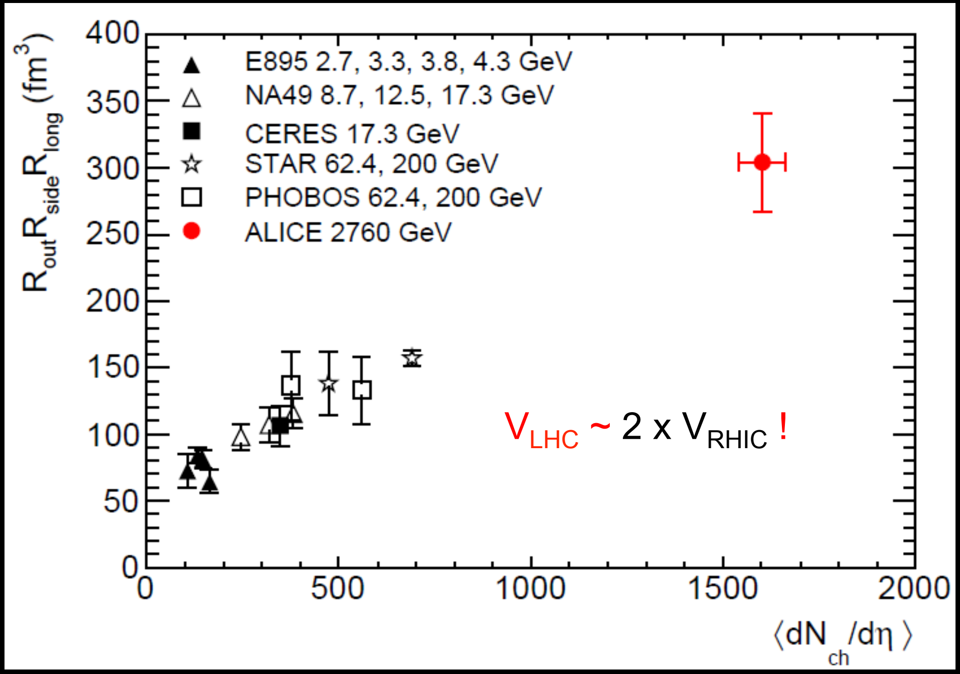
Dynamics & Evolution of RHI Collisions

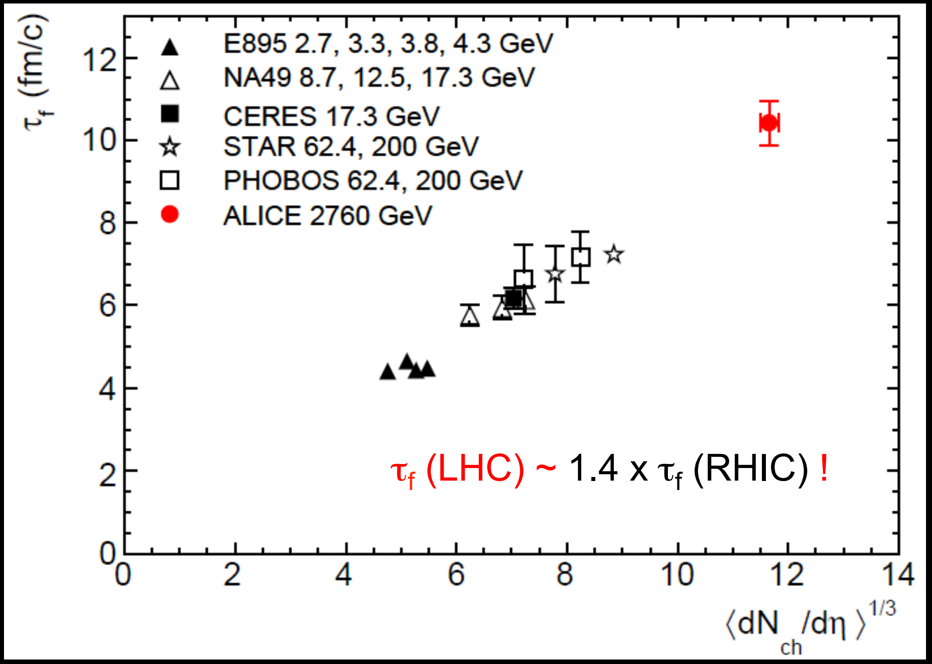
"LHC & RHIC provide consistent picture" of dynamics & evolution of collisions

→ multiplicities, system size & lifetimes from RHIC to LHC

→ properties of medium (ε, η/s, v_s, ...?)

ALICE, Phys.Lett. B696 (2011) 328





Size → Volume ~ dN/dη

$\tau_f \sim \langle dN_{ch}/d\eta \rangle^{1/3}$

τ_f (central PbPb) ~ 10 – 11 fm/c

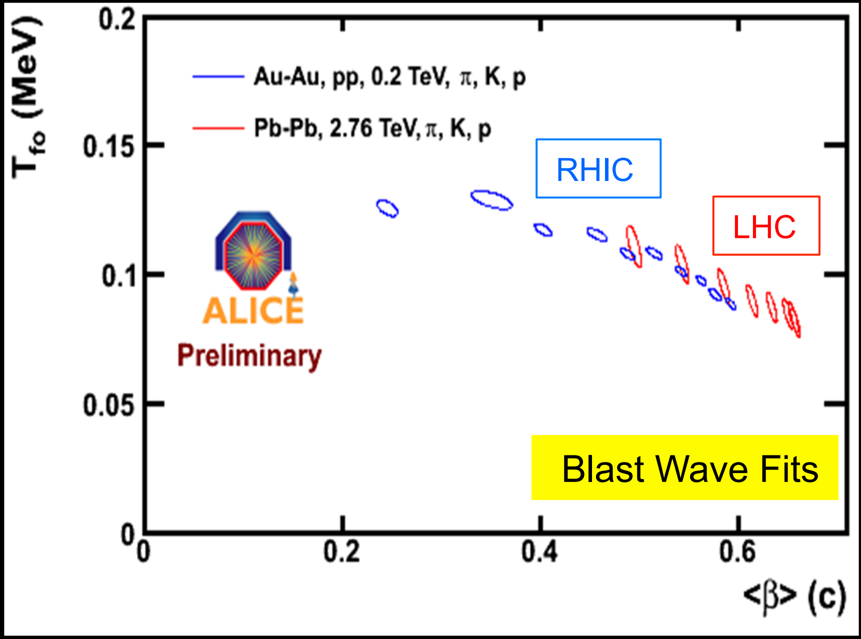
Lifetime → hydrodynamic expansion

Spectra & Radial Flow!

Slope changes at LHC vs RHIC

Smooth extrapolation?

Somewhat stronger radial flow, β ≈ 0.66, at LHC

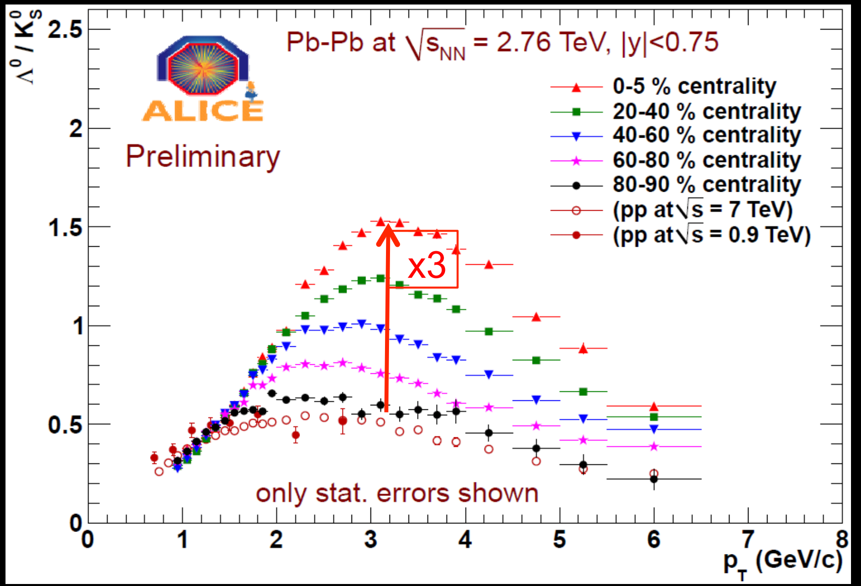


Enhanced baryon/meson ratio at LHC like RHIC

Increases with centrality

Peak central B/m ratio 3x pp value

Extends to higher p_T



“What Do We Know” from RHIC & LHC

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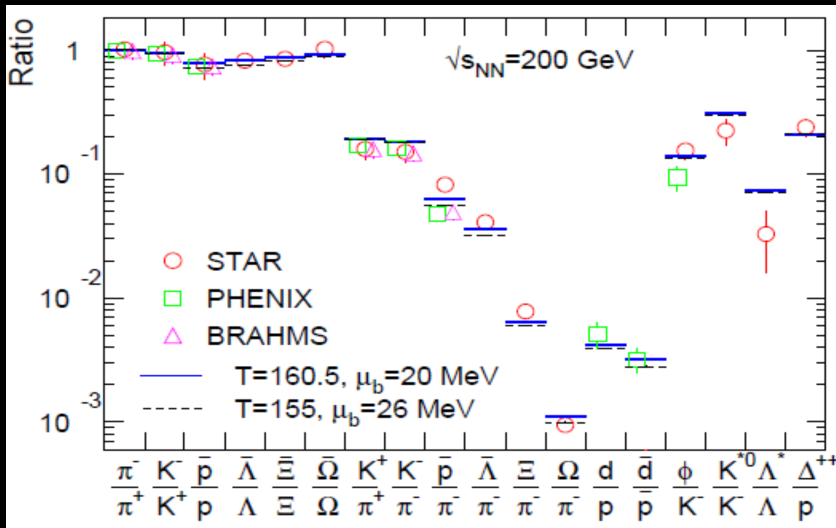
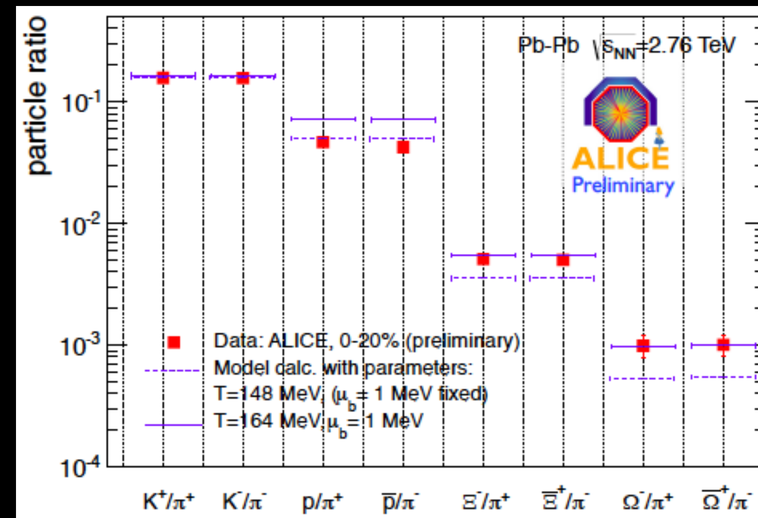
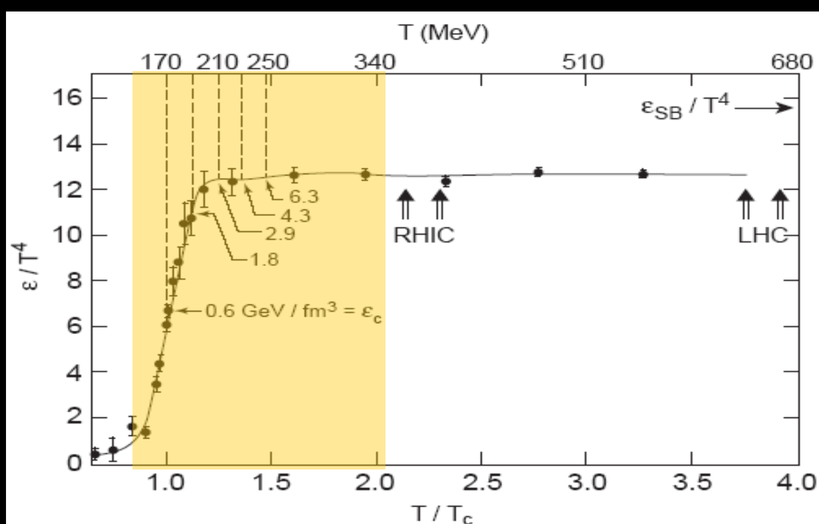
Confirm lattice predictions for $T_{critical}$, μ_B

Particles Formed at Universal Hadronization T

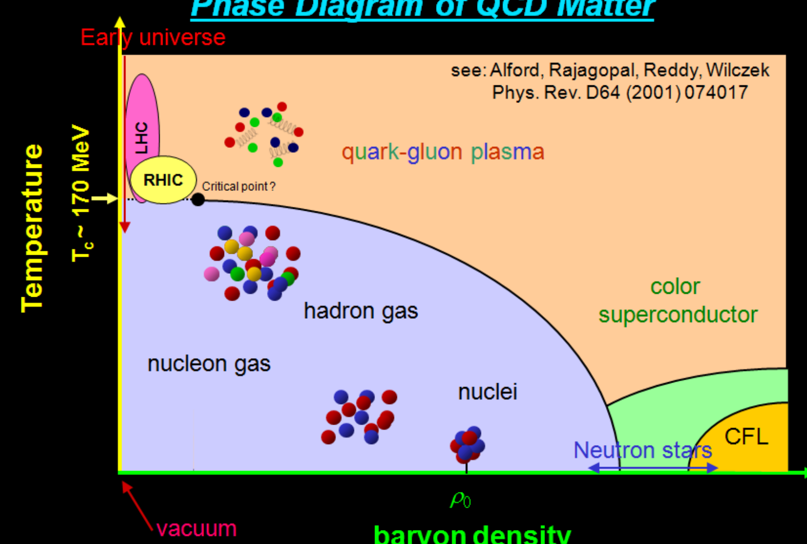




Particles yields → equilibrium abundances → universal hadronization $T_{critical}$



Phase Diagram of QCD Matter



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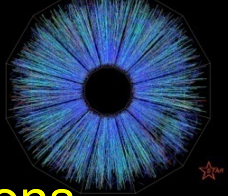

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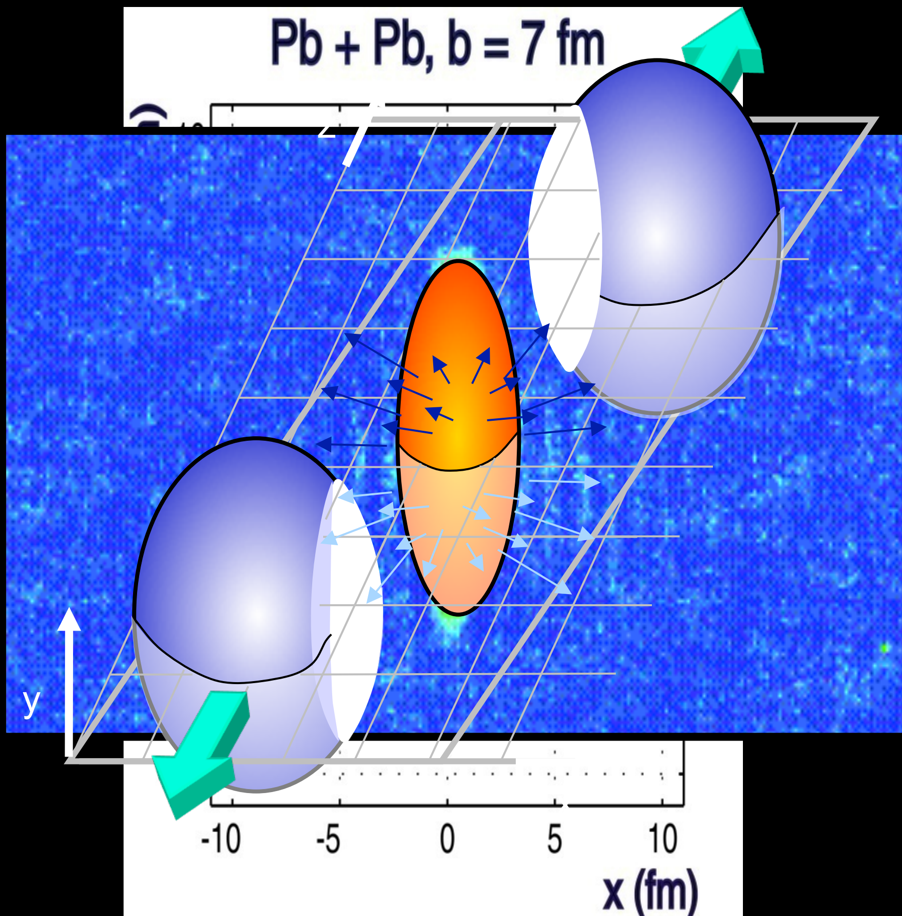
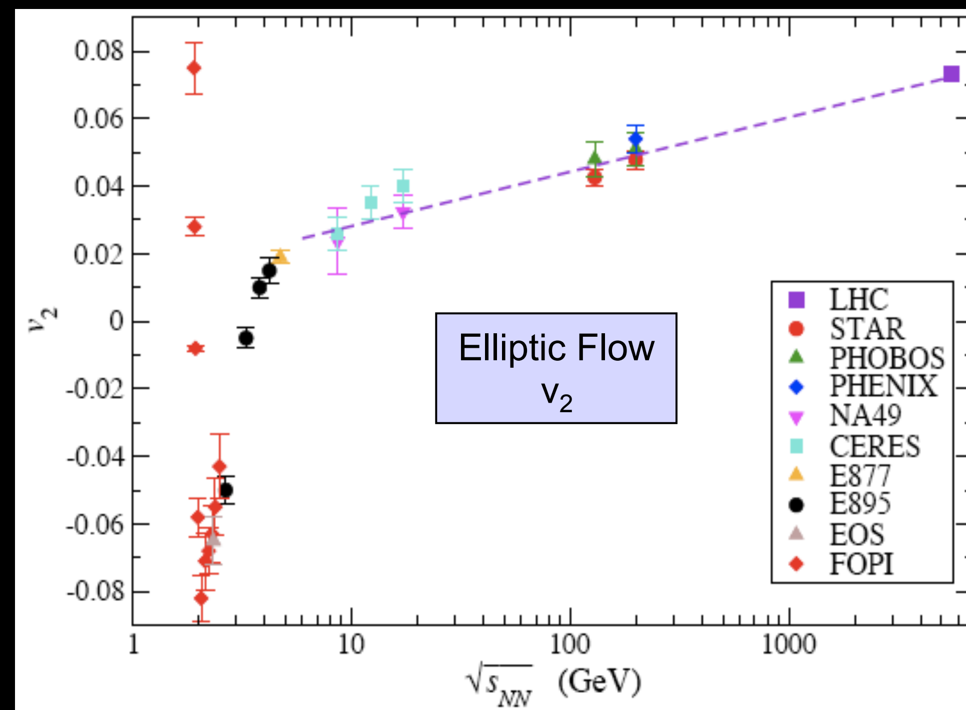
Strongly-coupled liquid

Flows with ultra-low shear viscosity

Large Elliptic Flow Observed – Implications?



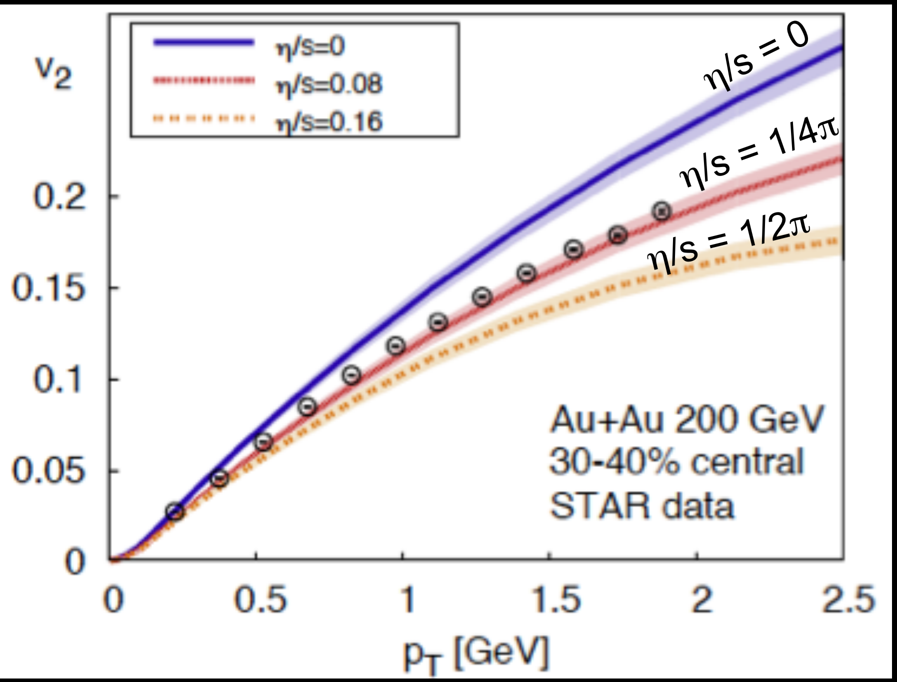
Azimuthal asymmetry of particles:
$dn/d\phi \sim 1 + 2\, v_2(p_T) \cos(2\phi) + \ldots$

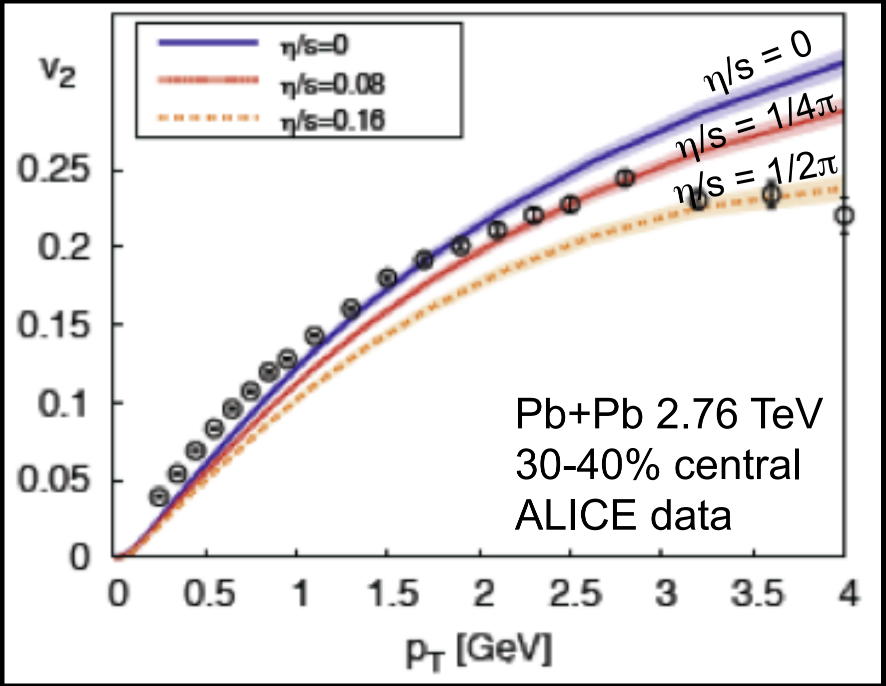


Predicted by hydrodynamics with very low shear viscosity

Increase in v_2 from RHIC to LHC

It's a Strongly-Coupled Medium with Ultra-Low Shear Viscosity





Viscous hydrodynamics calculations from Schenke, Jeon, Gale, PRL 106 (2011) 042301.

$\rightarrow 1/4\pi < \eta/s < 1/2\pi$

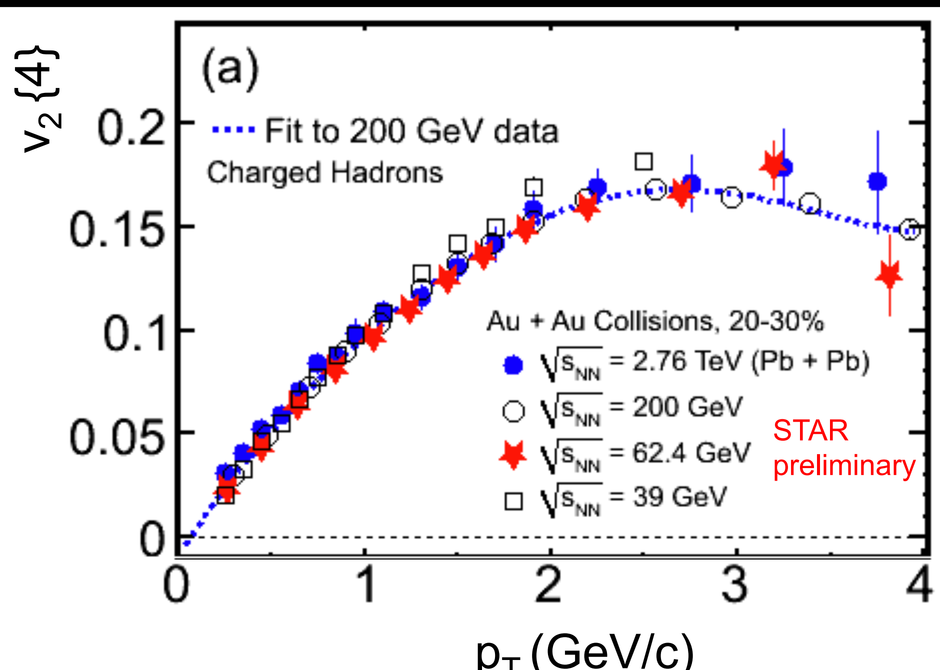
Universal lower bound on shear viscosity / entropy ratio (η/s):

Strong-coupling limit of non-Abelian gauge theories with a gravity dual:

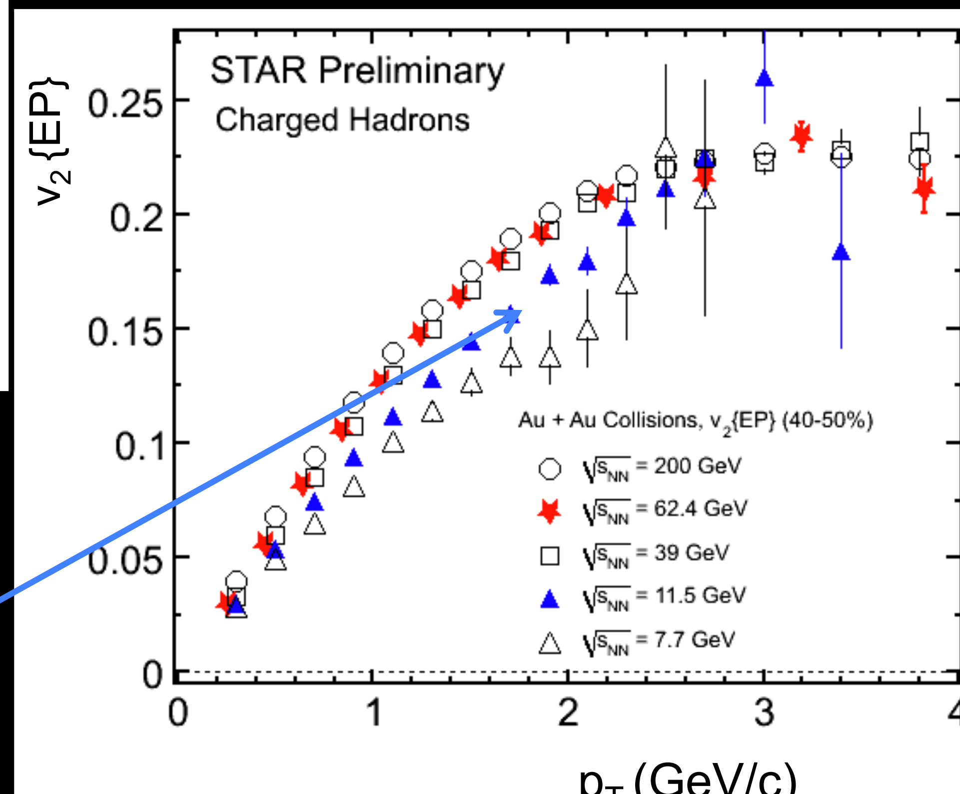
$\rightarrow \eta/s = 1 / 4\pi$ for the "perfect liquid"

Elliptic Flow – $\sqrt{s_{NN}}$ Dependence of $v_2(p_T)$

ALICE, Phys. Rev. Lett .105, 252302 (2010)
STAR: PRC 77 (2008) 054901; PRC 75 (2007) 054906



v_2 vs transverse momentum (p_T) same for 2.76 TeV down to 39 GeV!



Change in v_2 vs p_T below 39 GeV (at 7.7 & 11.5 GeV)!

What does this change imply?

(viscosity, QGP, other properties?)

Power Spectrum for Heavy Ions ↔ Analog WMAP!

An acoustic horizon in fluid dynamics (A Mocsy, P. Sorensen, arXiv:1101.1926)

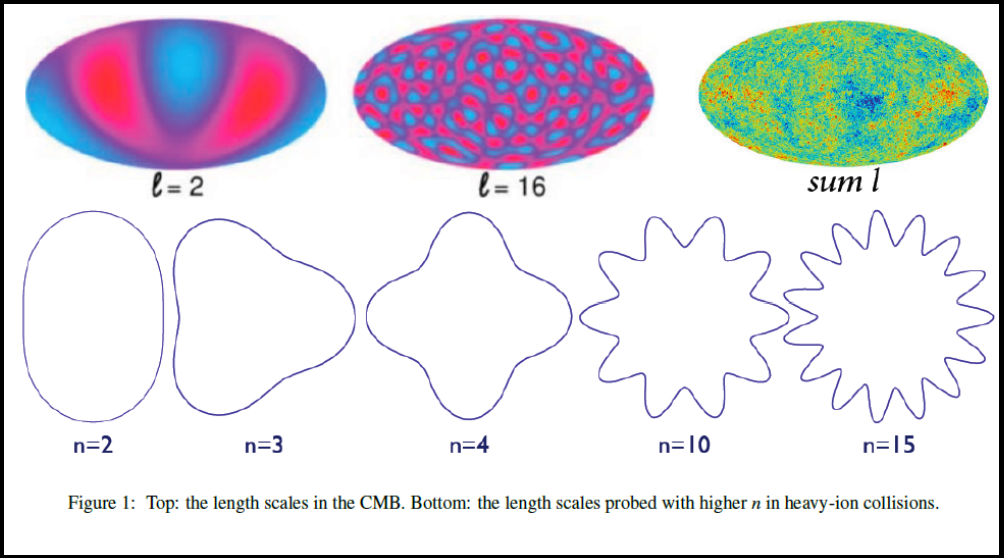
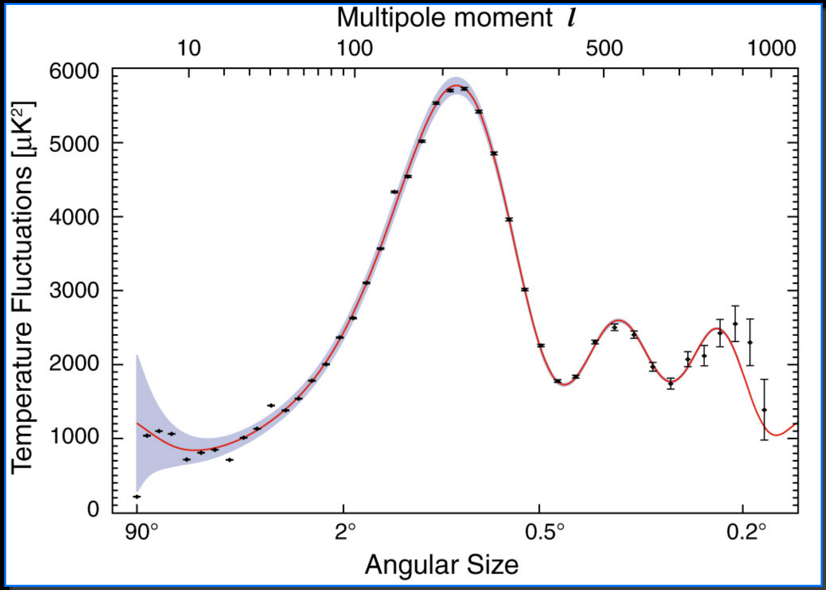
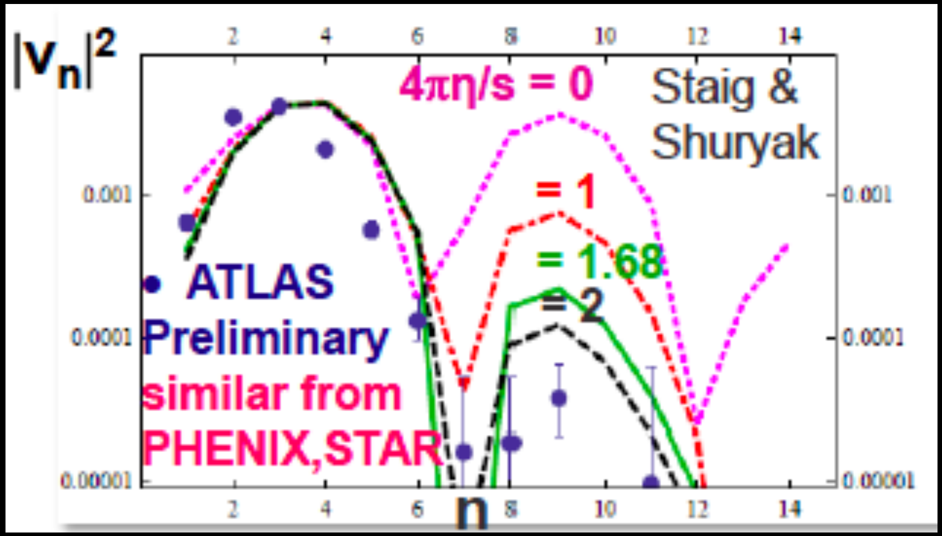


Figure 1: Top: the length scales in the CMB. Bottom: the length scales probed with higher n in heavy-ion collisions.





Gaussian width related to length scales

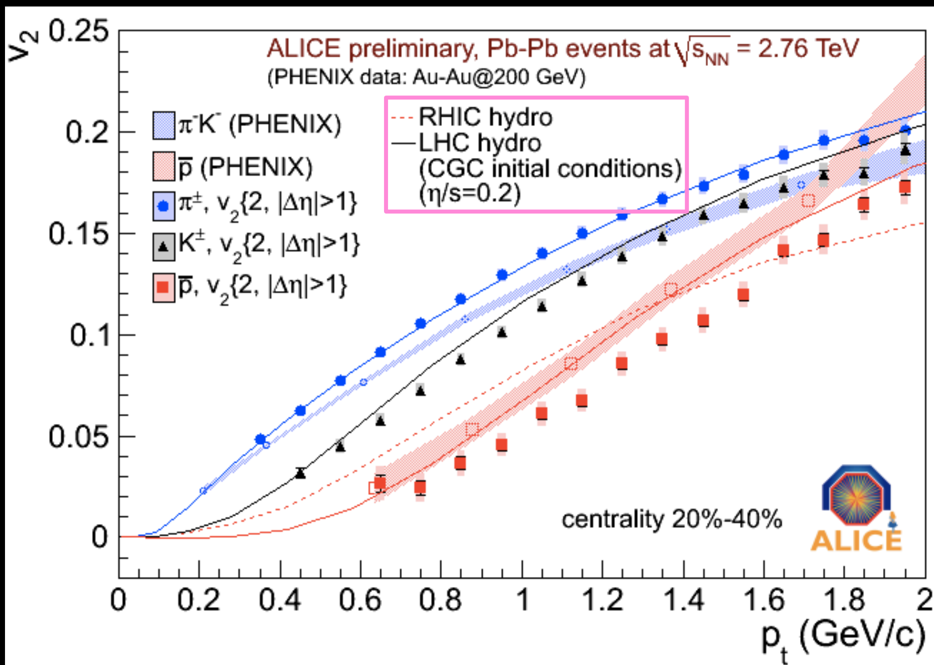
such as mean free path, acoustic horizon.

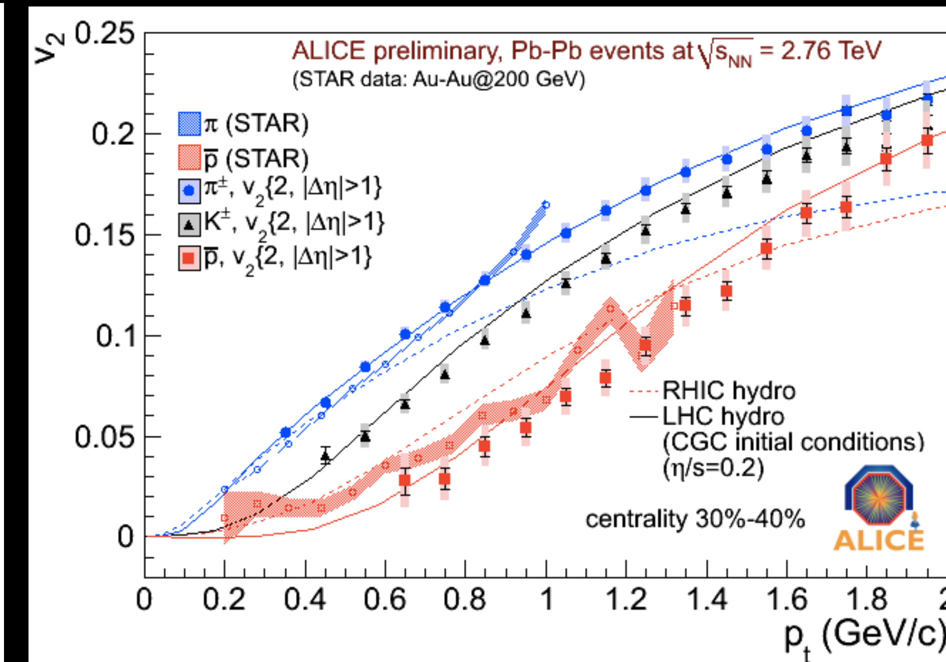
Like measurements of early universe sound harmonics…

Heavy Ion harmonics give key constraints on viscous damping & spatial correlations

LHC & RHIC Elliptic Flow – Identified Particles

ALICE, M. Krzewicki, R. Snellings, QM 2011





ALICE (π, K, $\bar{p}$) data points

PHENIX bands: Phys. Rev. Lett. 91, 182301 (2003)

STAR bands: Phys. Rev C 77, 054901 (2008)

Hydro curves: Shen, Heinz, Huovinen & Song, arXiv:1105.3226

Larger mass splitting at LHC than at RHIC

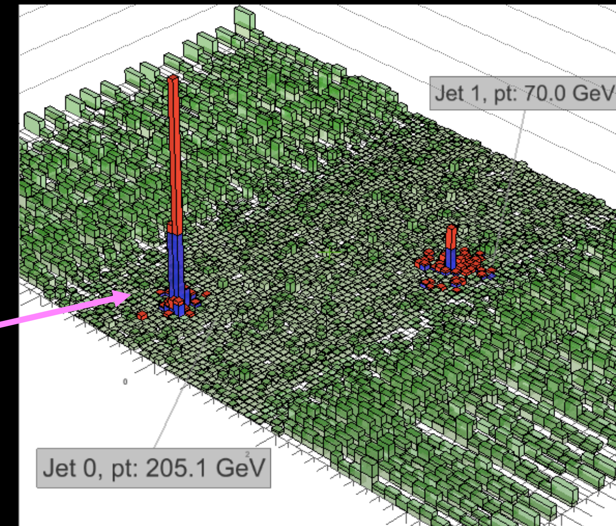
Hydro: CGC initial conditions, η/s = 0.2

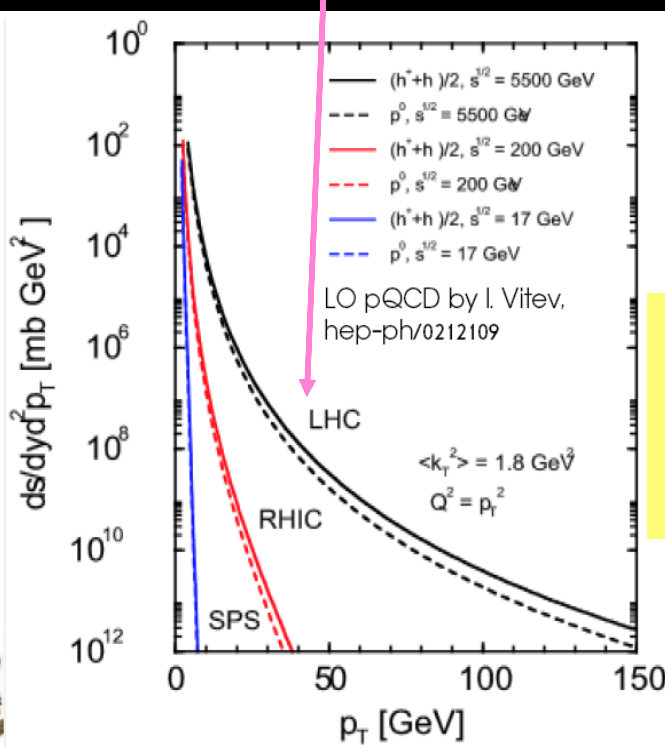
Hard Probes – RHIC & LHC Heavy Ions

Significant increase in hard cross sections (p_T or mass > 2 GeV/c) at LHC –

$\rightarrow \sigma_{\text{large } p_T} / \sigma_{\text{total}} \sim$ 2% at SPS
50% at RHIC
98% at LHC

- "real" jets, large p_T processes
- abundance of heavy flavors
- probe early times, calculable

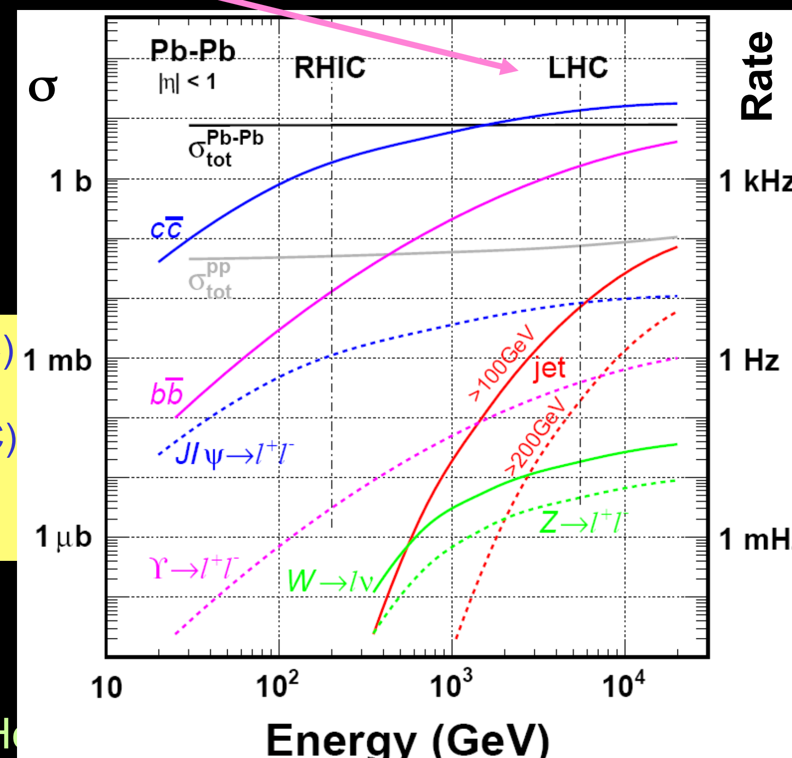




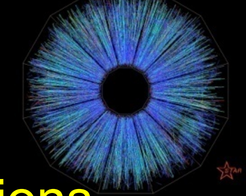
σ_{jet} (LHC) > 100 σ_{jet} (RHIC)

σ_{bb} (LHC) ~ 100 σ_{bb} (RHIC)

σ_{cc} (LHC) ~ 10 σ_{cc} (RHIC)



"What Do We Know" from RHIC & LHC



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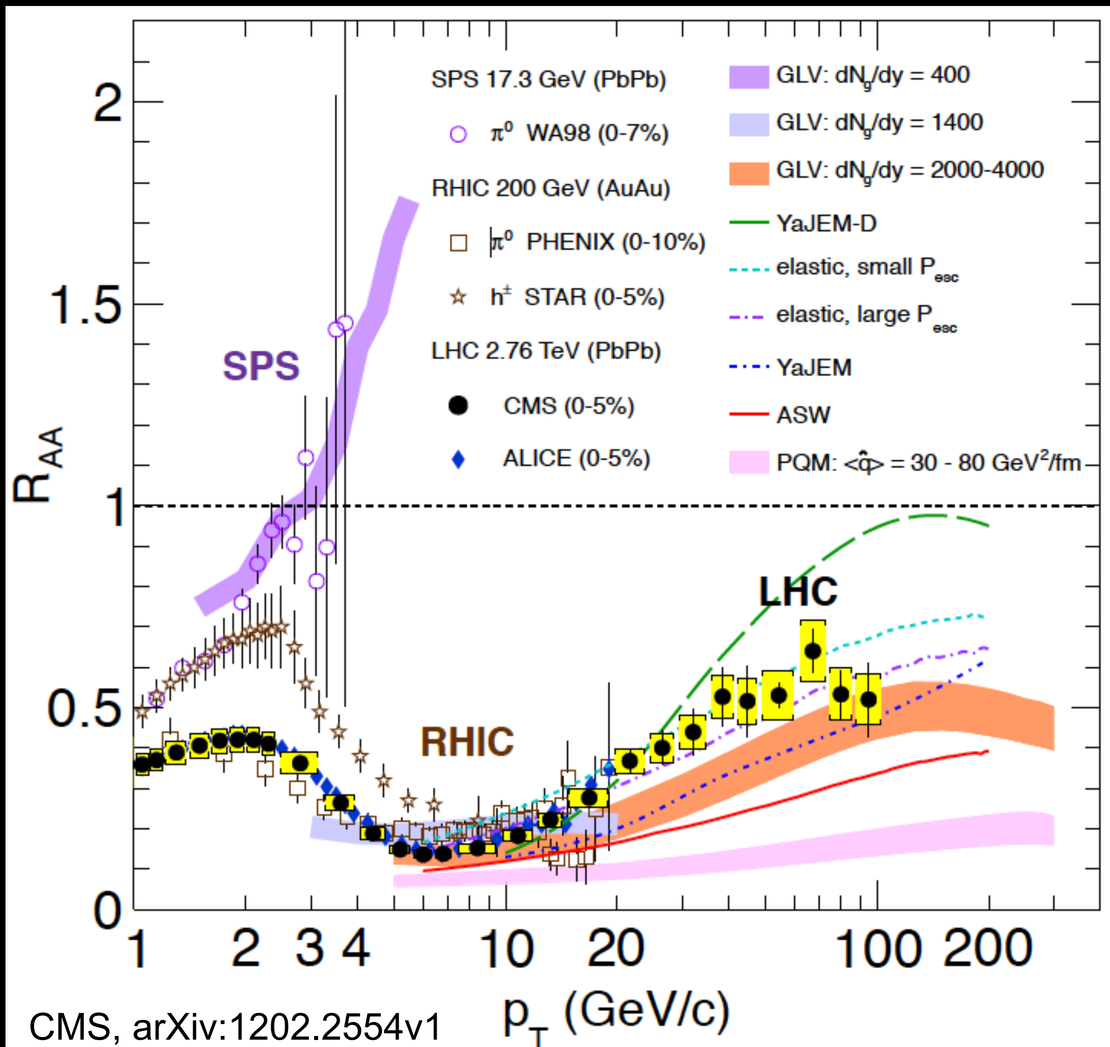
Large Transverse Momentum (p_T) Particles Are Suppressed

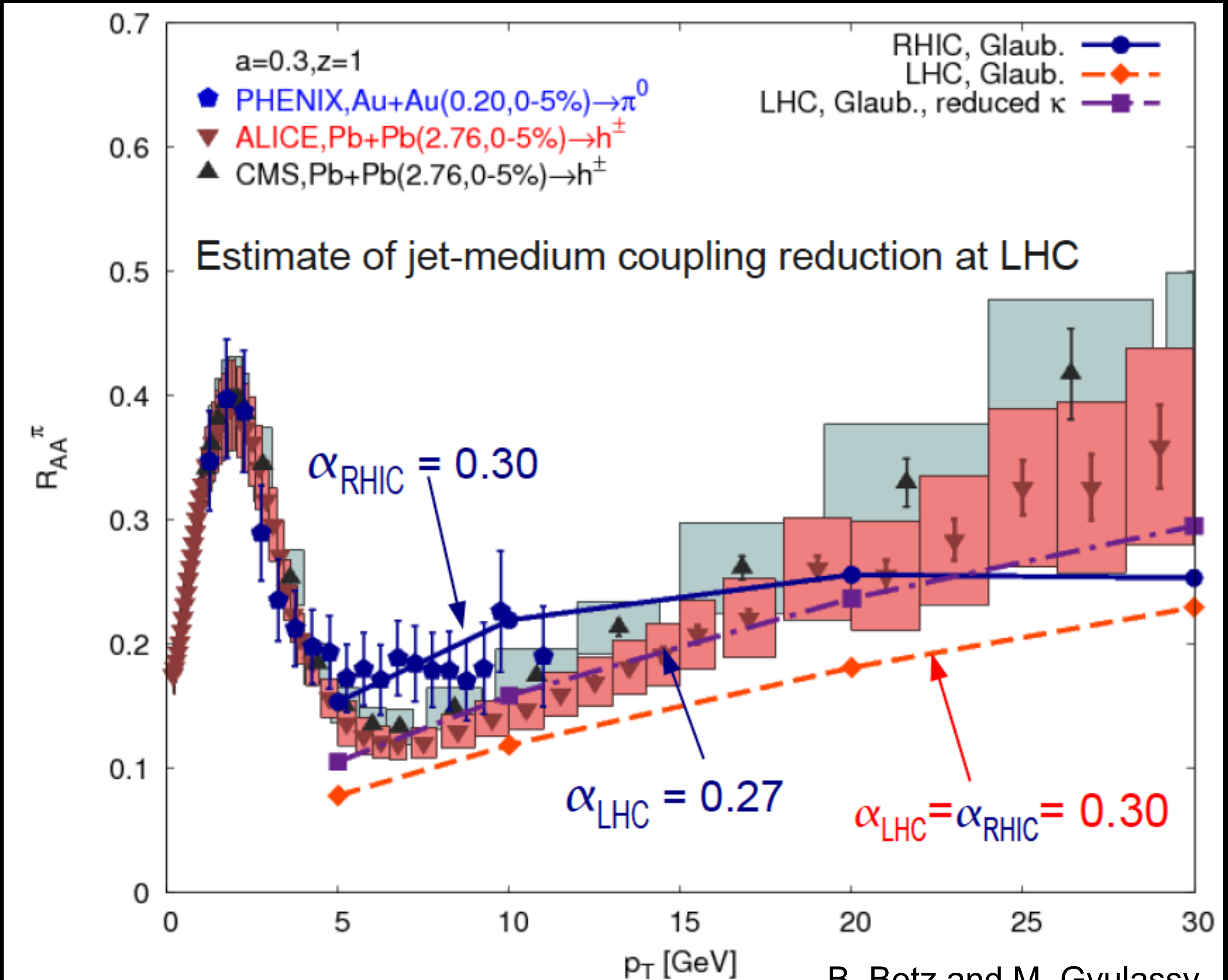


$$R_{AA} = \frac{N_{AA}^{\pi/\gamma}}{N_{coll} N_{pp}^{\pi/\gamma}}$$

$R_{AA} = 1$

Suppression

Suppression of "Intermediate p_T" Particles



B. Betz and M. Gyulassy, arXiv:1201.0281

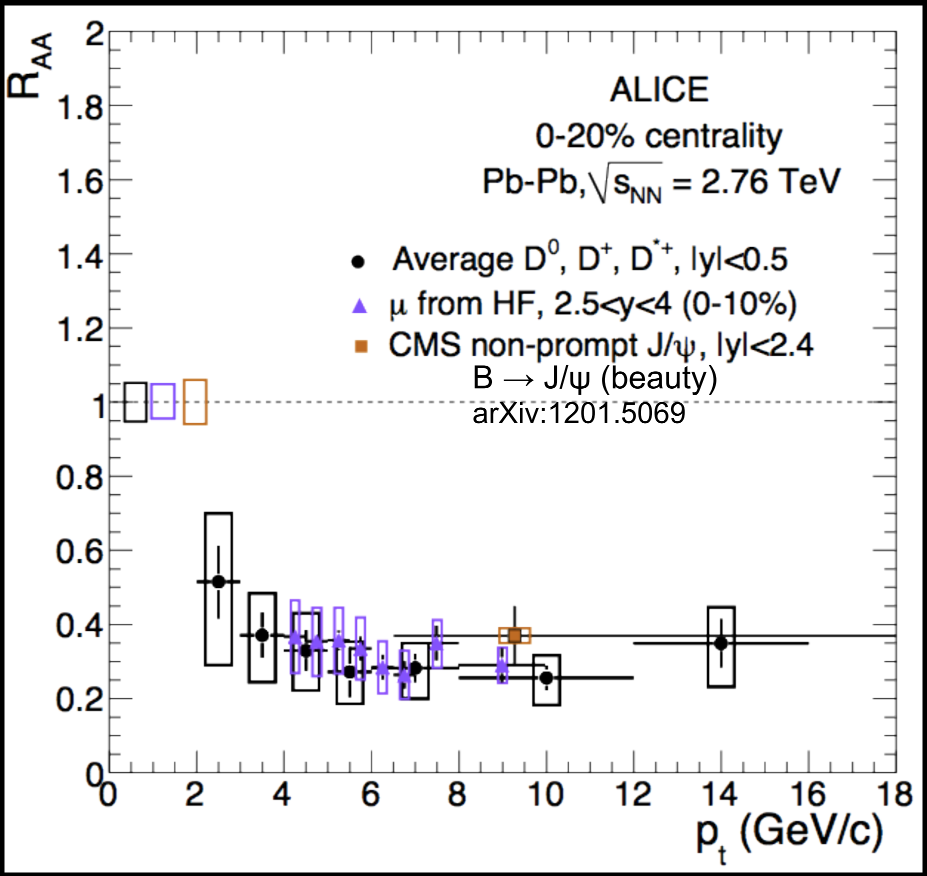
$$R_{AA} = \frac{N_{AA}^{\pi/\gamma}}{N_{coll} N_{pp}^{\pi/\gamma}}$$

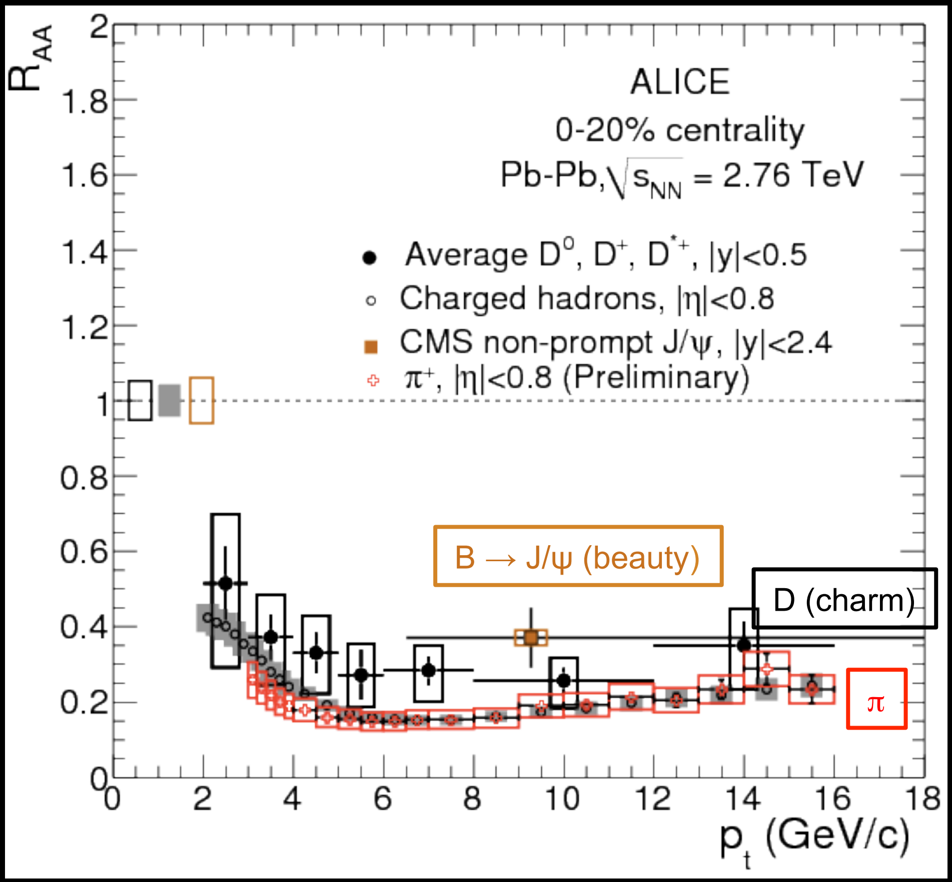
R_{AA} at LHC theory:

pQCD behavior!

A few more details left.

Suppression of Heavy Flavors



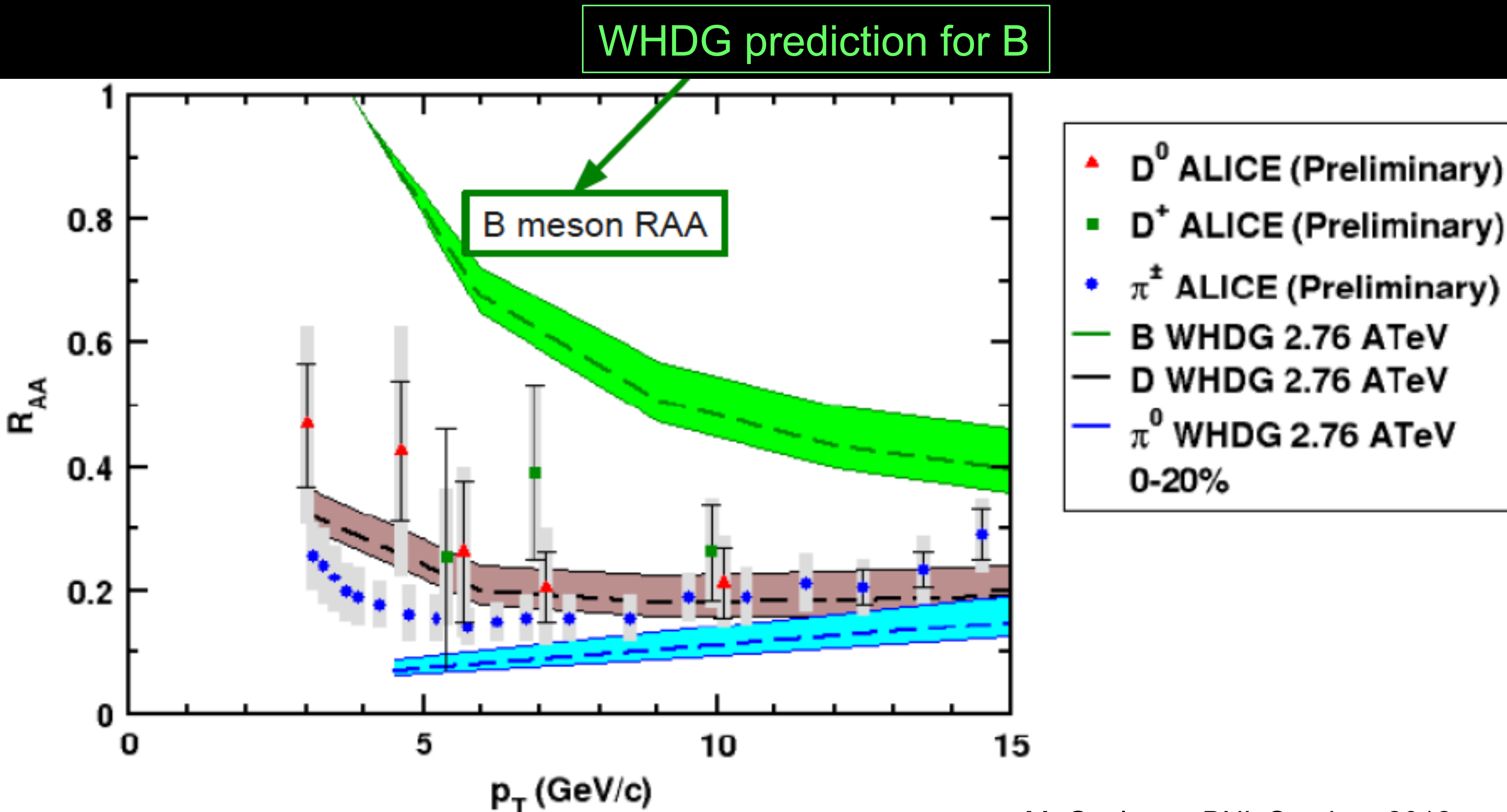


Charm and beauty:
No evidence of mass effects yet!

Pions, charm and beauty:
Suggestion of a hierarchy!

Requires better statistics, esp. for beauty and path-length dependence!

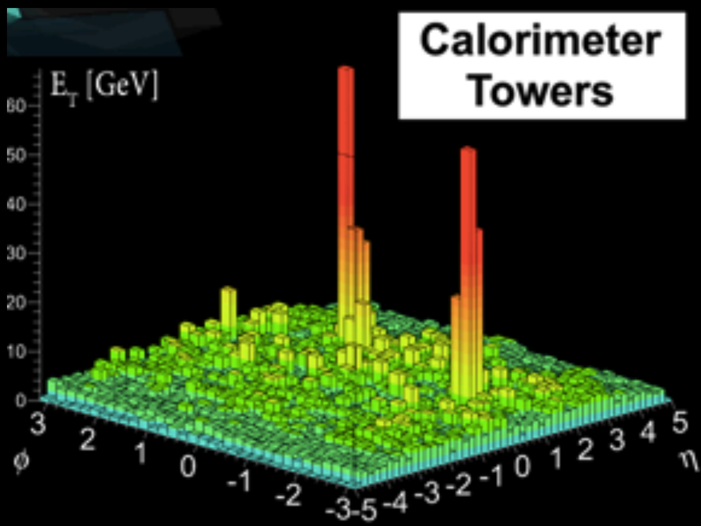
Heavy Quark Energy Loss in the Medium

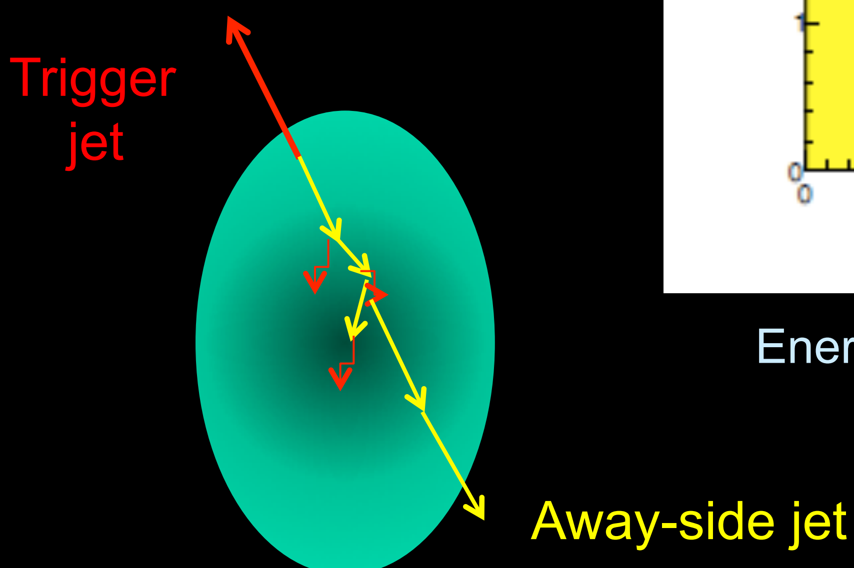


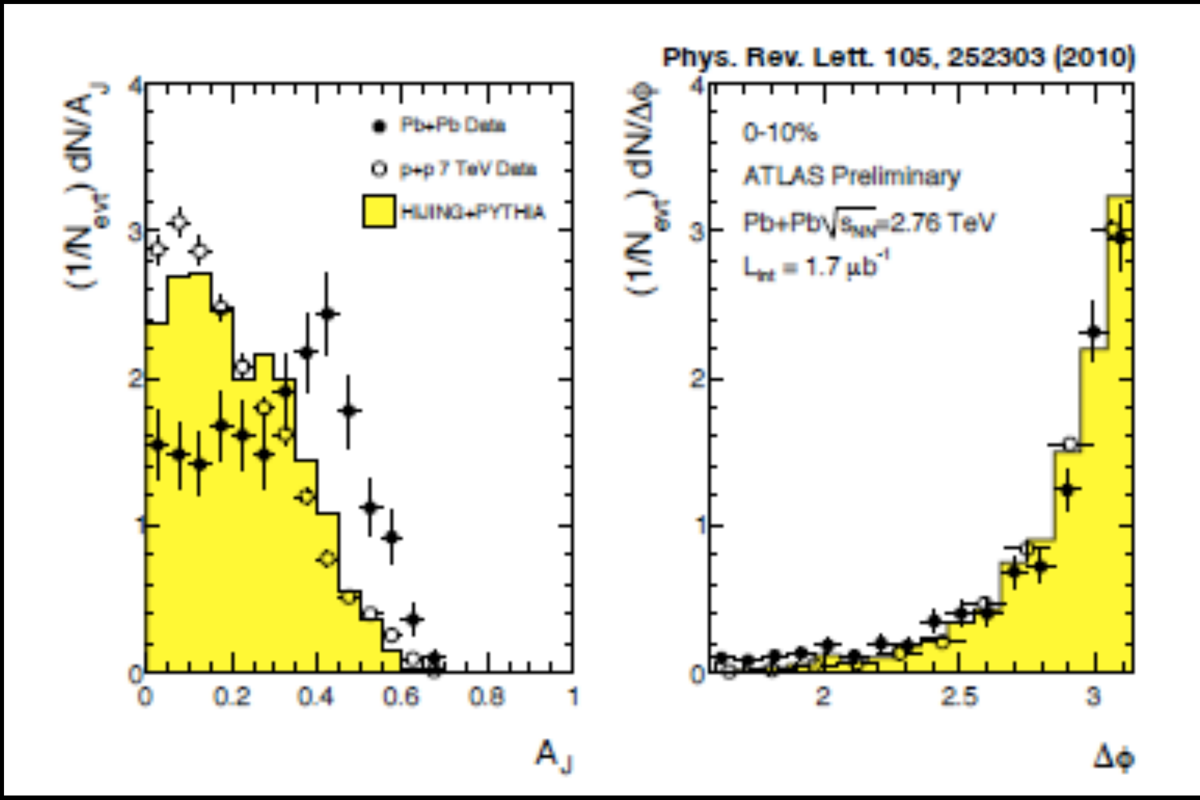
M. Gyulassy, BNL Seminar 2012

Will b-quarks behave as pQCD predicts (Dead-cone Effect→less suppressed)?

Jets at the LHC – Di-Jet Energy Imbalance!







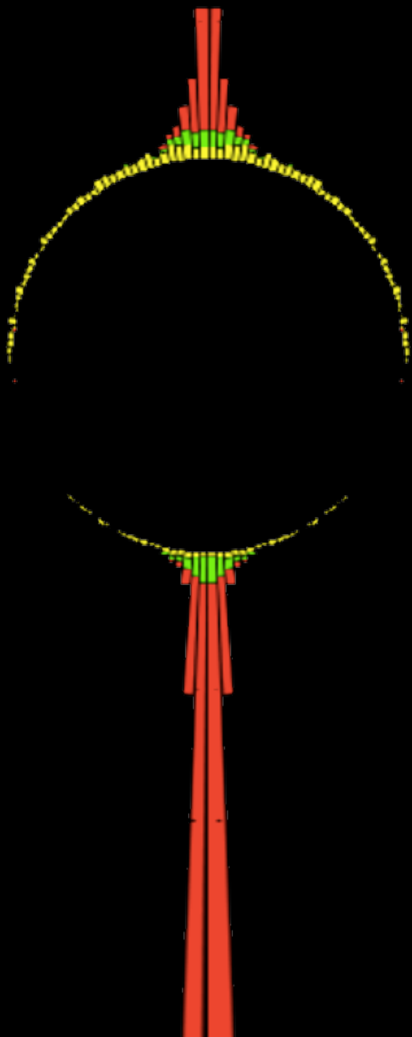
Energy Asymmetry: $A_J = E_{T1} – E_{T2} \;/\; E_{T1} + E_{T2}$

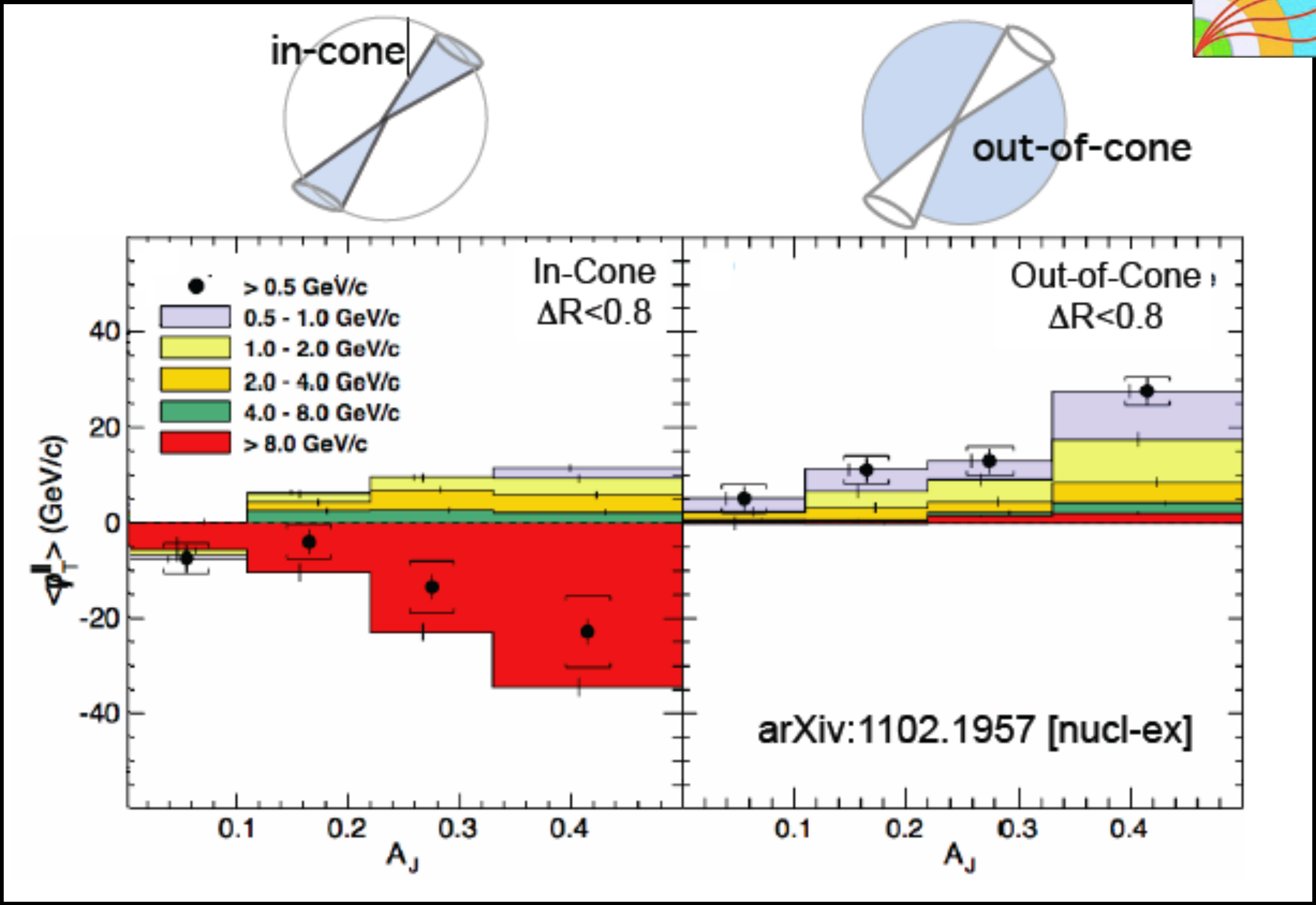
for $\Delta\phi > \pi/2$

$E_{T1} > 100$ GeV $\quad E_{T2} > 25$ GeV

Where does the Energy Go? – CMS

PRC 84 (2011) 024906

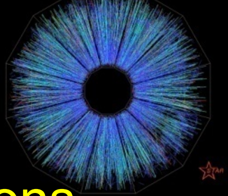




Energy/momentum balance in event is carried by low momentum particles at large angles to jets!

pQCD, vacuum fragmentation, thermalization of lost energy?

“What Do We Know” from RHIC & LHC



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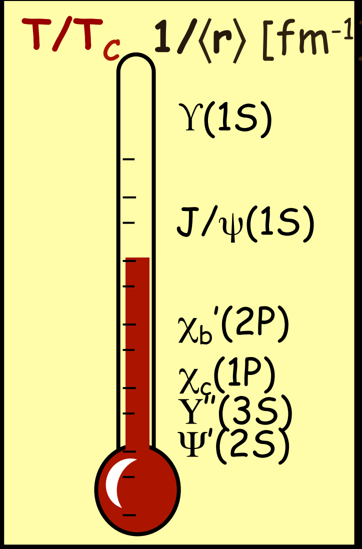
Suppression of quarkonia (J/ψ and Υ states)

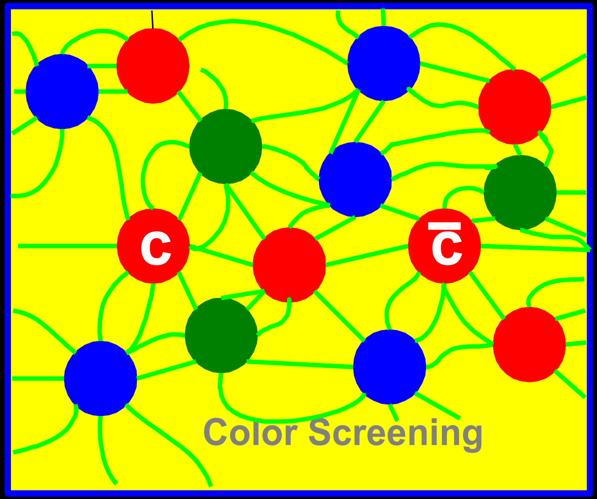
Quarkonia in the QGP

Quarkonia: $c\bar{c}$: Ψ', χ_c, J/ψ $b\bar{b}$: Y", Y', Y

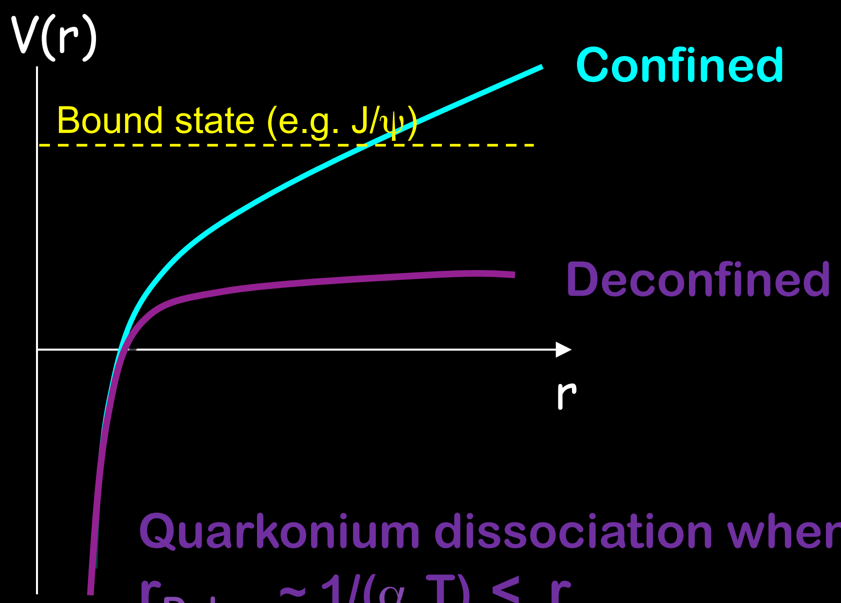
(Debye color screening, recombination)

Measure melting order of $c\bar{c}$: Ψ', χ_c, J/ψ $b\bar{b}$: Y", Y', Y



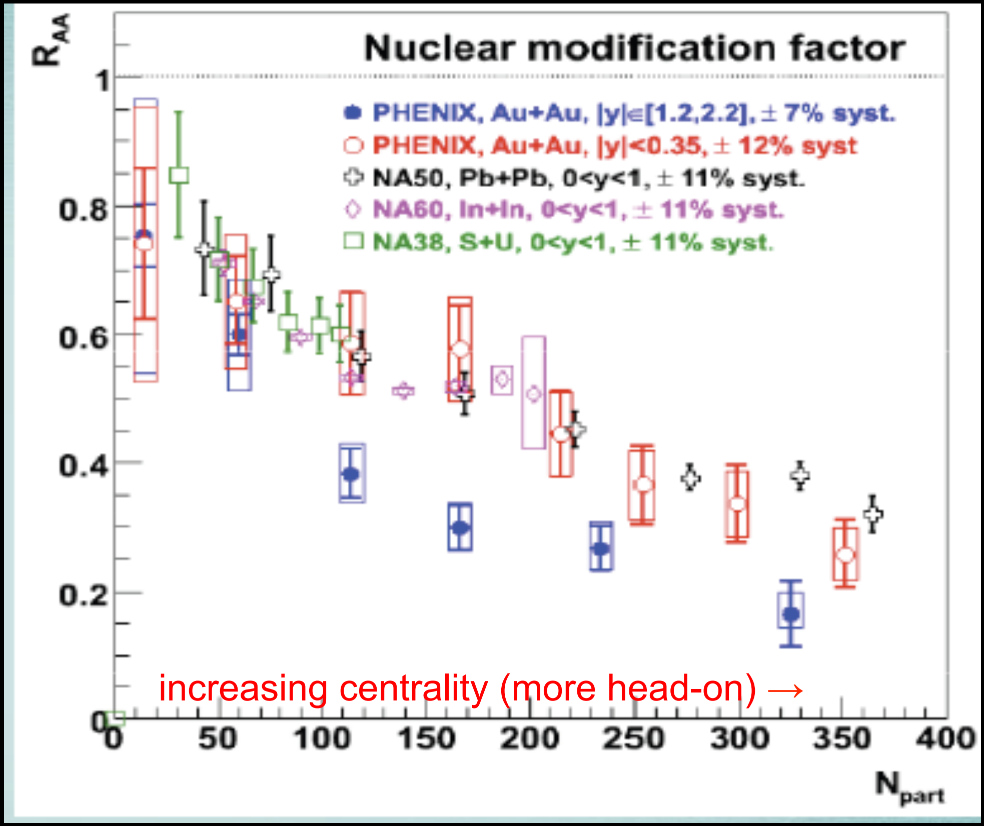


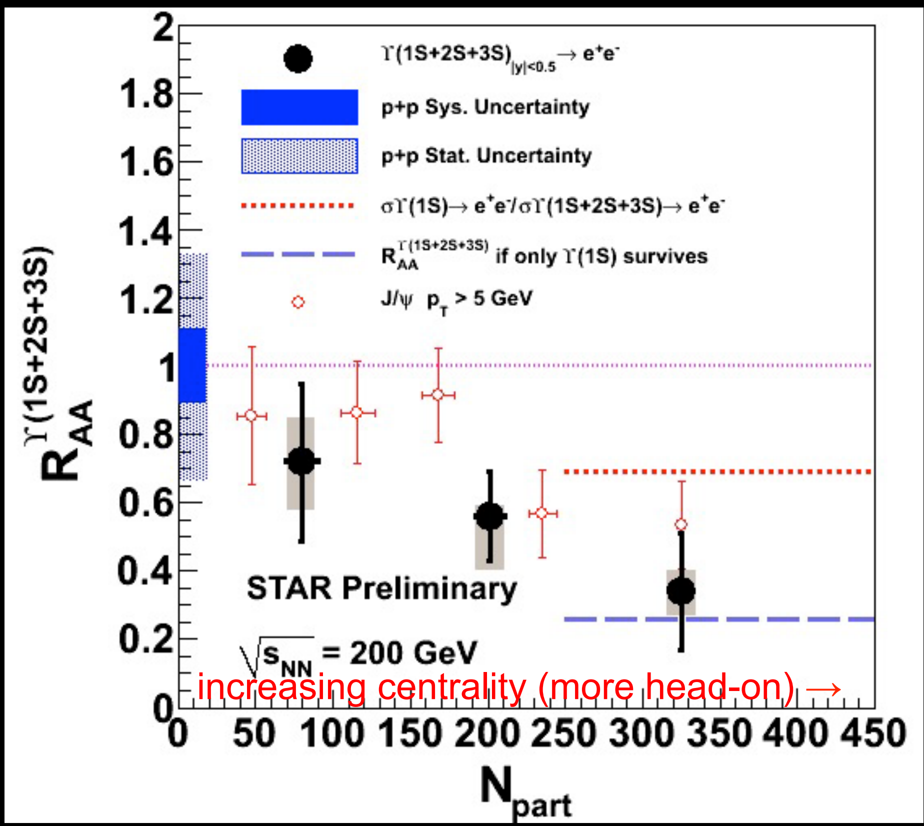
Color screening of $c\bar{c}$ pair results in J/ψ ($c\bar{c}$) suppression!



Quarkonium dissociation when $r_{Debye} \sim 1/(\alpha_s T) < r_{qq}$

J/Ψ and ϒ Suppression at RHIC





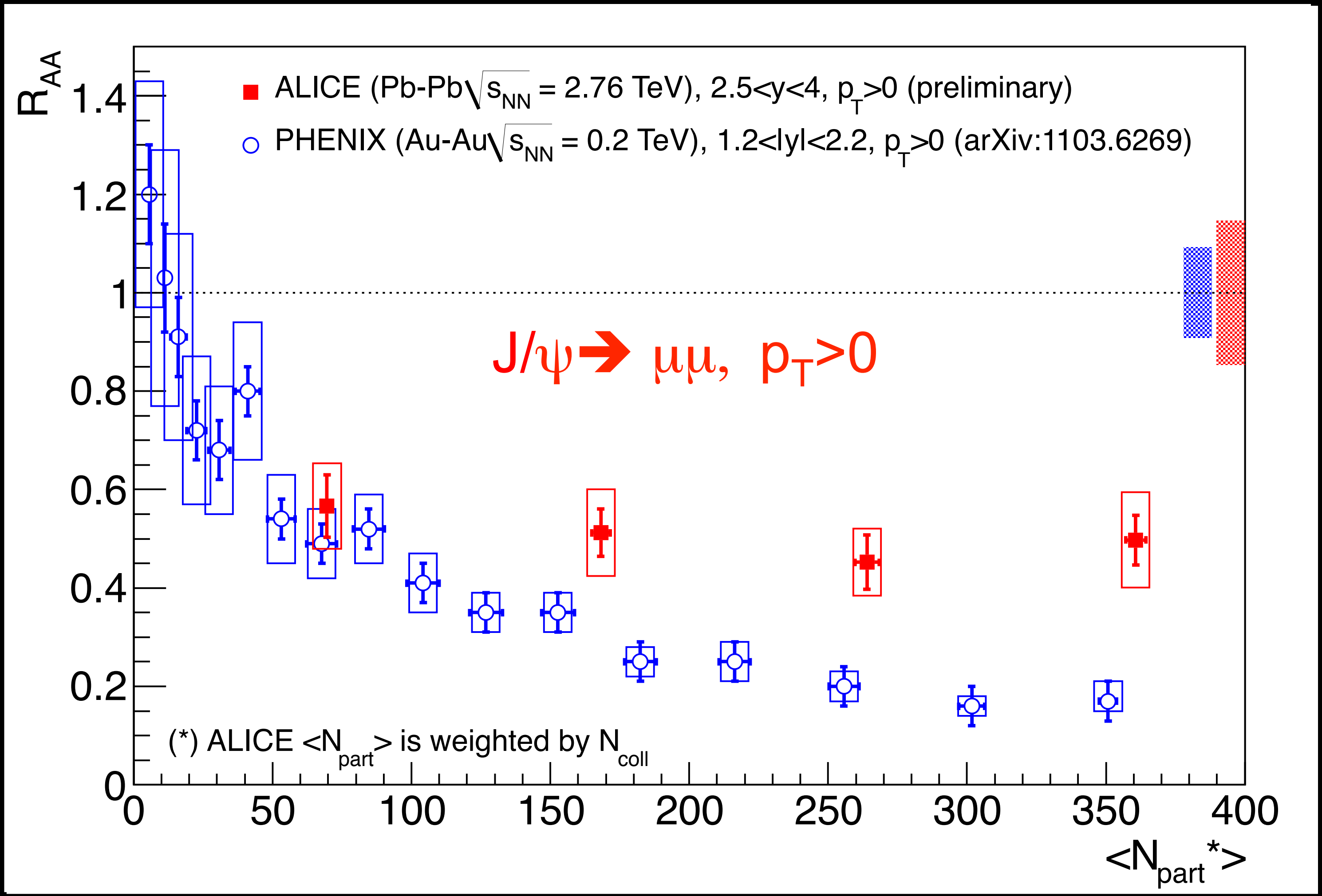
J/ψ and ϒ(1s+2s+3s) suppressed at RHIC
Increases with centrality.

J/ψ – more suppressed forward.
Partly due to cold nuclear matter!

ϒ consistent with 1s survival & 2s+3s suppression!

Low p_T J/ψ R_{AA} Centrality Dependence – LHC & RHIC

ALICE, G. Martinez-Garcia QM 2011

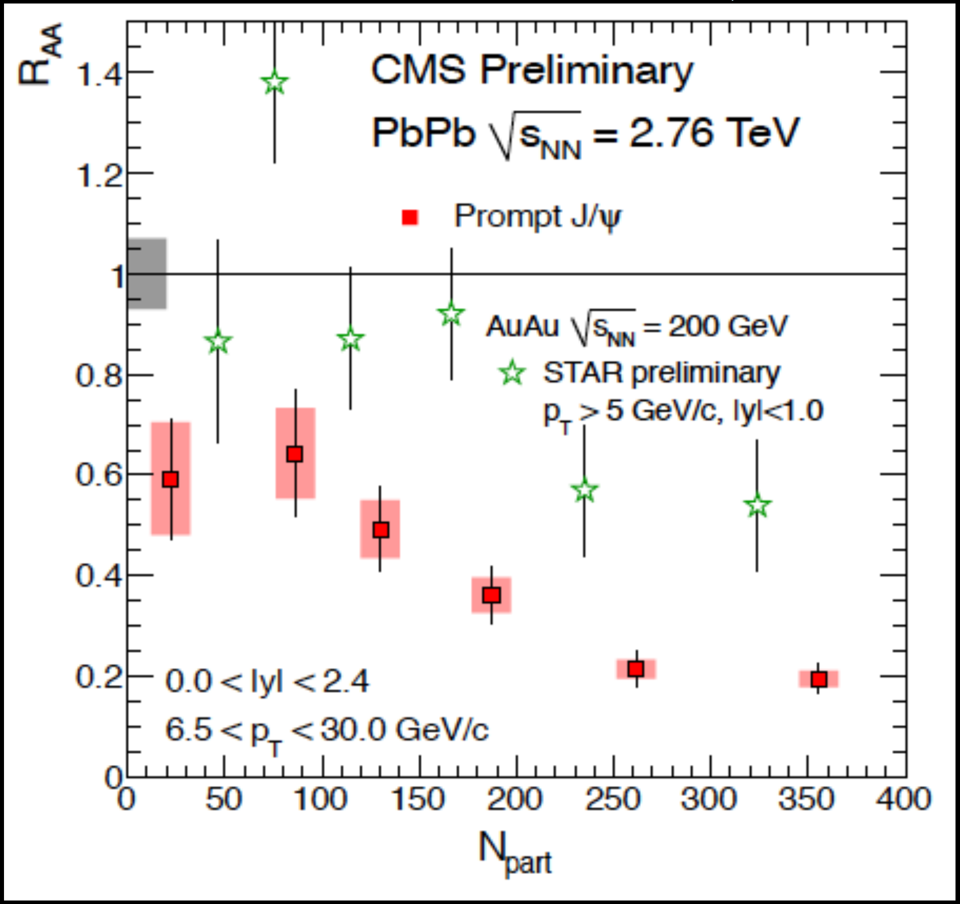


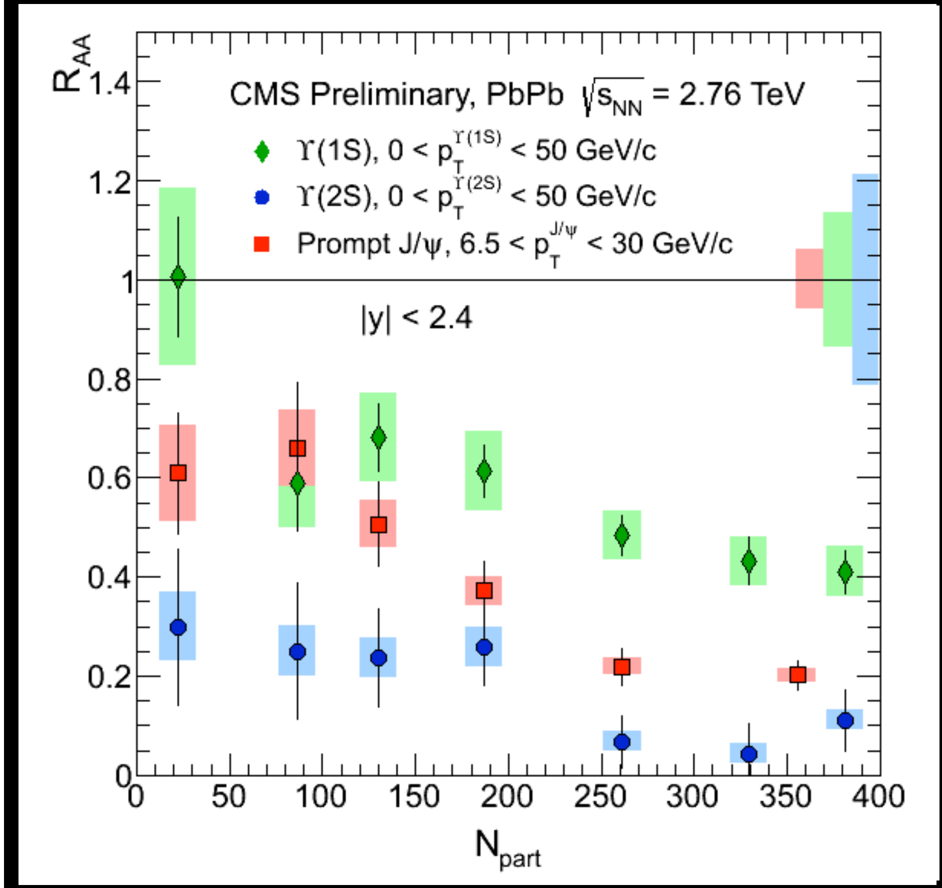
J/ψ R_{AA} larger at LHC (2.5<y<4) than at RHIC (1.2<|y|<2.2)

Similar to RHIC (|y|<0.35), except most central bin, Note: $dN_{ch}/d\eta(N_{part})^{LHC} \sim 2.1 \times dN_{ch}/d\eta(N_{part})^{RHIC}$

J/Ψ and ϒ Suppression at the LHC

CMS, PRL 107 (2011) 052302

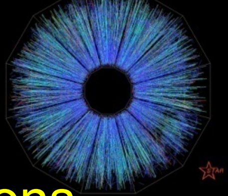




High p_T J/ψ more suppressed than at RHIC
→ energy loss of charm quark

ϒ(2s), ϒ(3s) suppressed wr to ϒ(1s), & relative to p+p collisions

"What Do We Know" from RHIC & LHC



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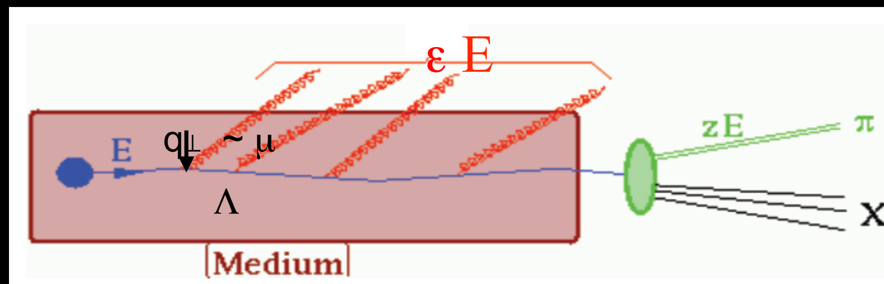
Still much to be done experimentally and theoretically………for example…

Still to Do to Address Parton Energy Loss

Determine Parton Energy Loss & Disentangle effects!

- Mass and color effects $\Delta E_{gluon} > \Delta E_{quark,\ m=0} > \Delta E_{quark,\ m>0}$

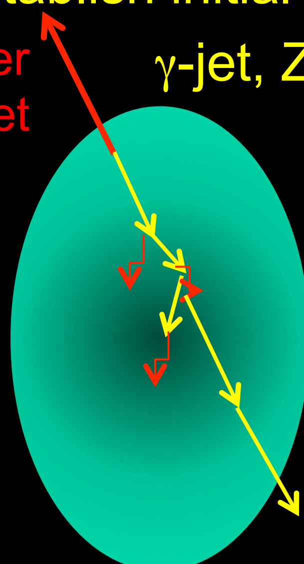
  b-quark vs c-quark vs light-quark suppression!



- Establish initial parton kinematics for jets (before parton energy loss!)

Trigger
γ, Z, jet

γ-jet, Z-jet, di-jets – γ and Z non-interacting in QGP!



Gluon vs quark suppression (color factor)

Measure dE/dx (color charge in QCD ala QED!)

Virtuality of partons different at RHIC & LHC?

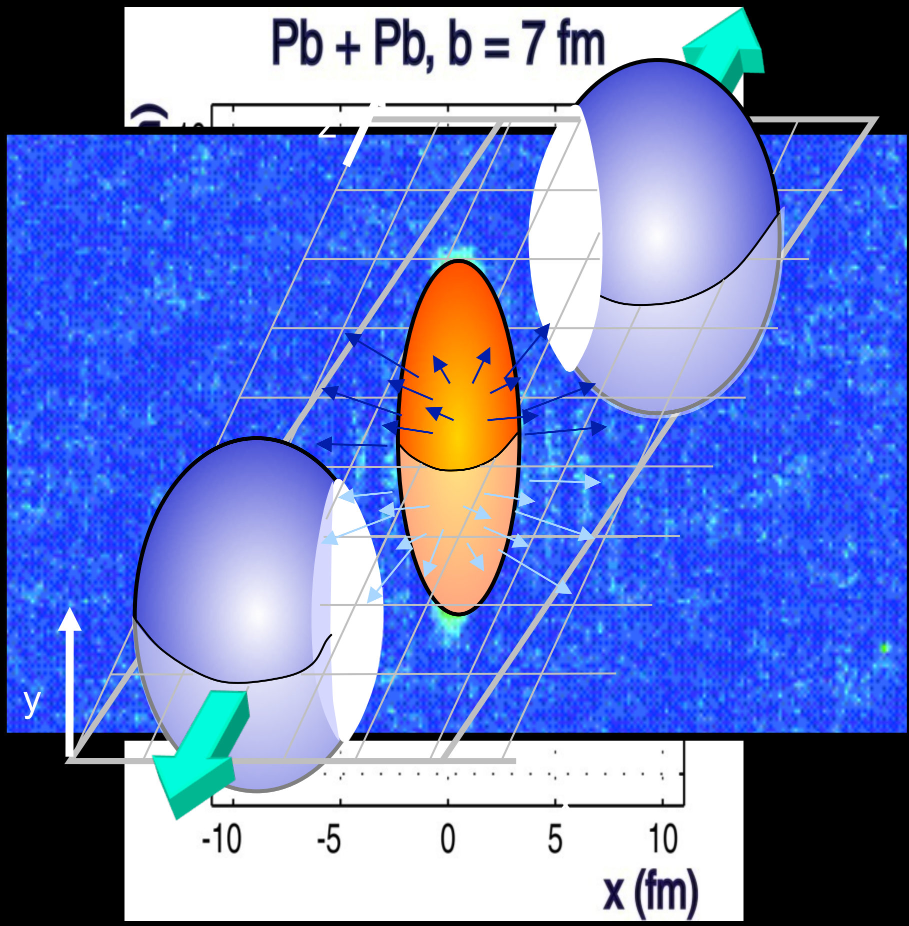
Away-side jet

Measure pathlength L dependence

Need to Measure Differential Quantities!

Detailed investigation of variables (parton attenuation & QGP transport properties) as function of:

- Centrality (impact parameter/shape) & Event Plane (Directionality)
  (Pressure gradients and pathlength dependence)



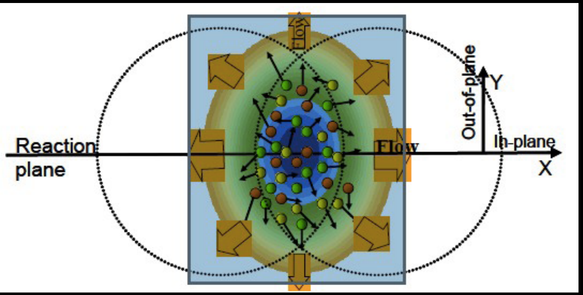
Measure & correlate differences in:

Parton propagation
Transport properties

Also dependence on:

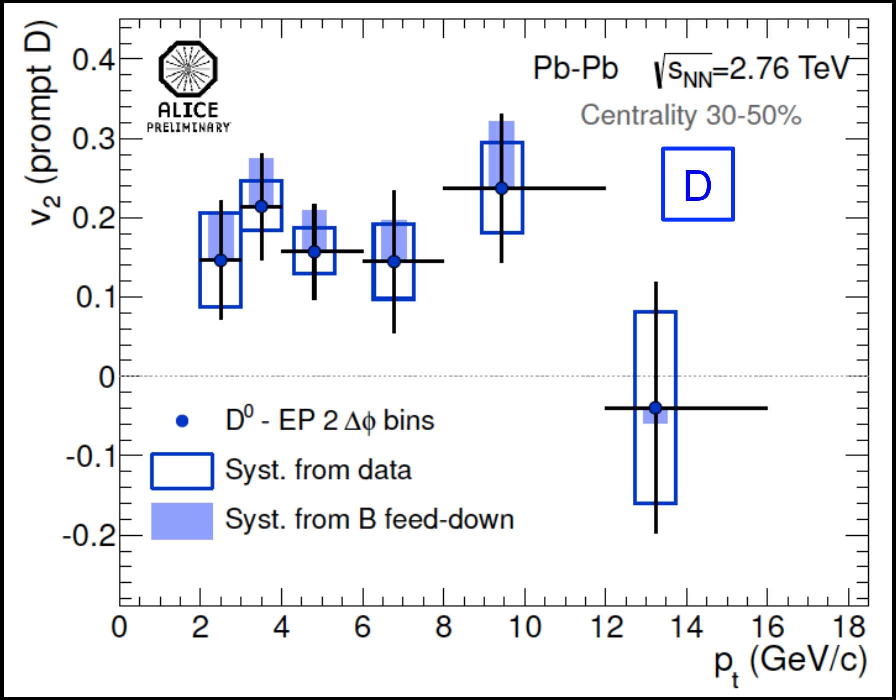
Momentum
Flavor

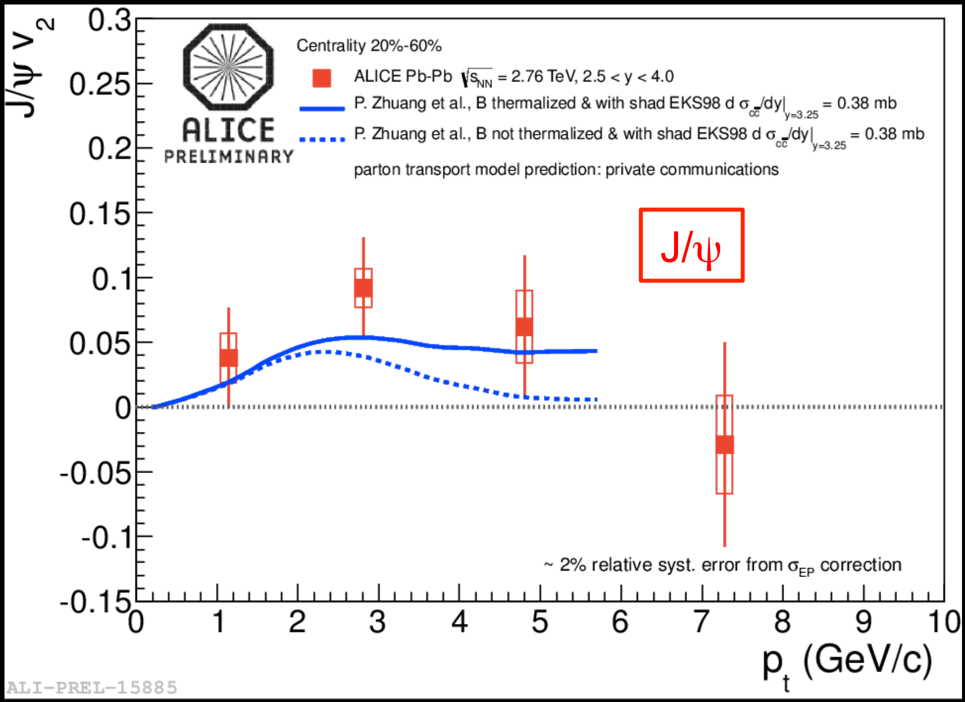
Note – Flow of Heavy Flavors



Detailed investigation of flow as function of:

- Particle type (quark content):
- Centrality (impact parameter/shape)
- Event Plane (Directionality)
  (Pressure gradients and pathlength dependence)





Requires much better statistics, esp. for path-length dependence!

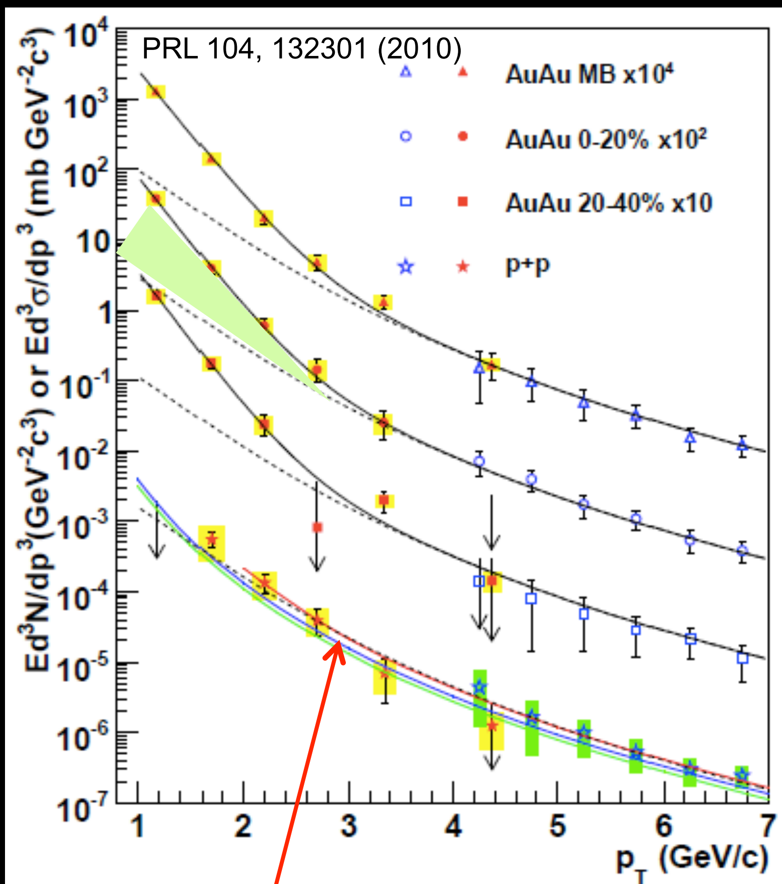
Real and Virtual Photons at RHIC

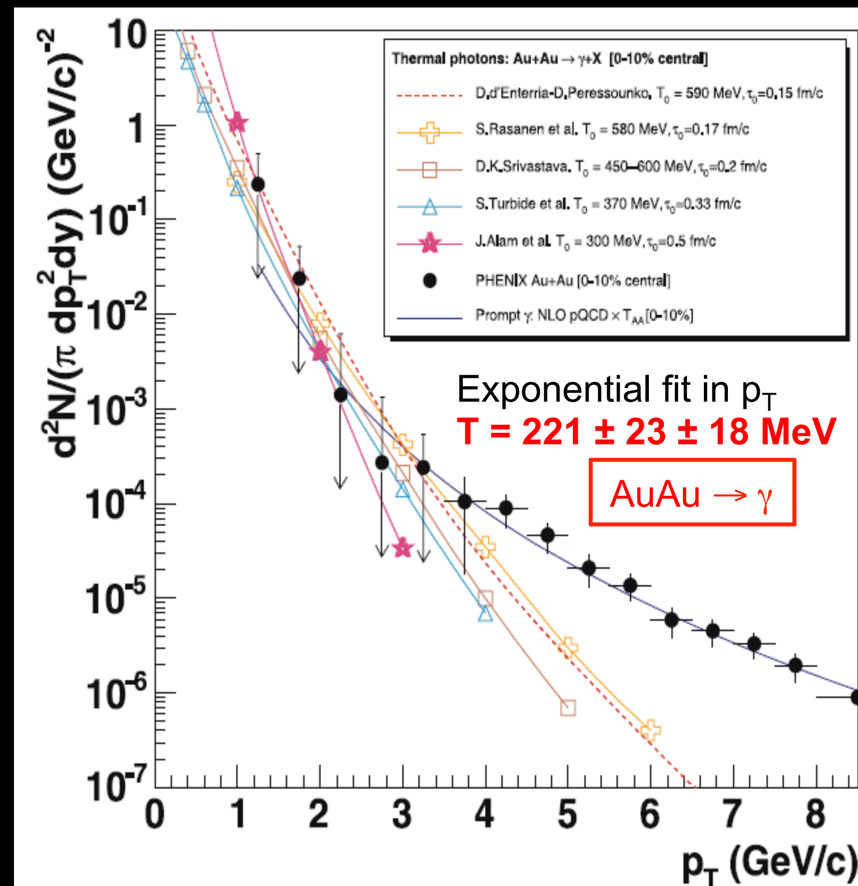
In progress at LHC…?

Thermal photons – shining of the QGP (at RHIC)

Must understand the other contributions

Spectrum integrates over space-time evolution





pp→ γ, good agreement with pQCD

Real and Virtual Photons

LHC…?

Virtual photons – Di-leptons

Medium modification of resonance & hadron masses

Chiral symmetry restoration?

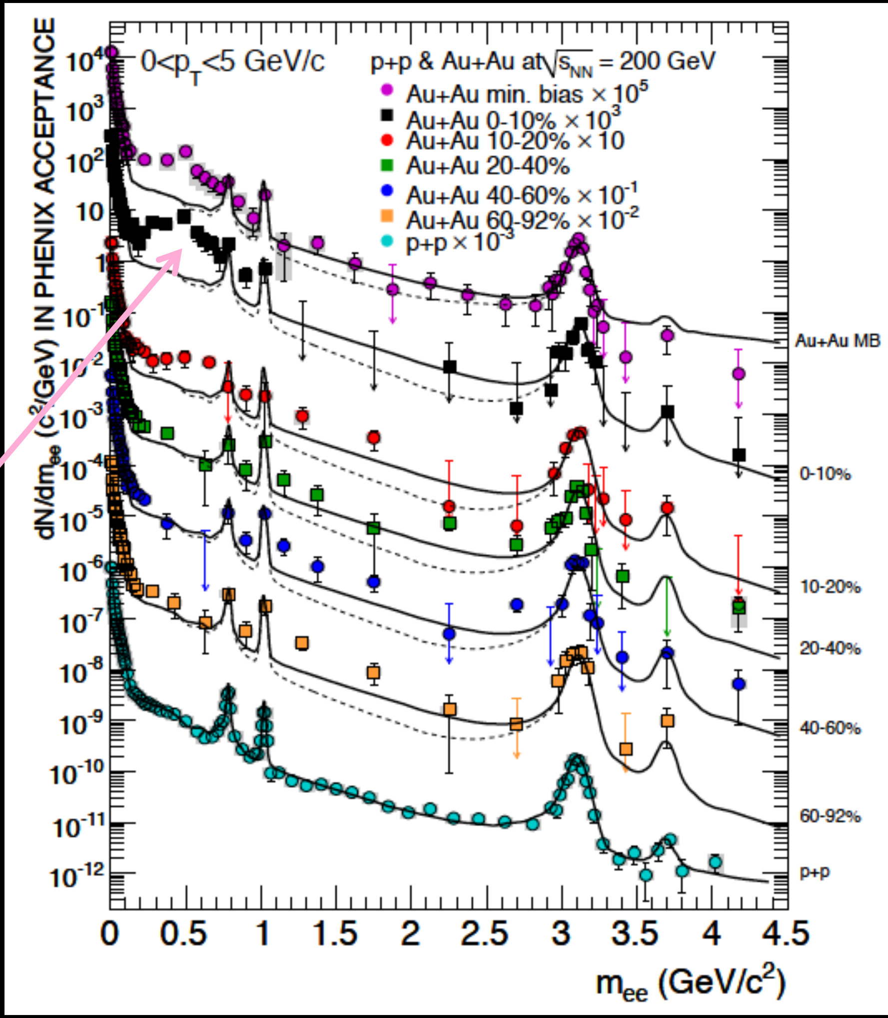
Centrality dependence:
PHENIX, PRC81, 034911(2010), arXiv:0912.0244

Virtual photons from decays in QGP

Must subtract all hadronic decays outside medium (scale pp data)

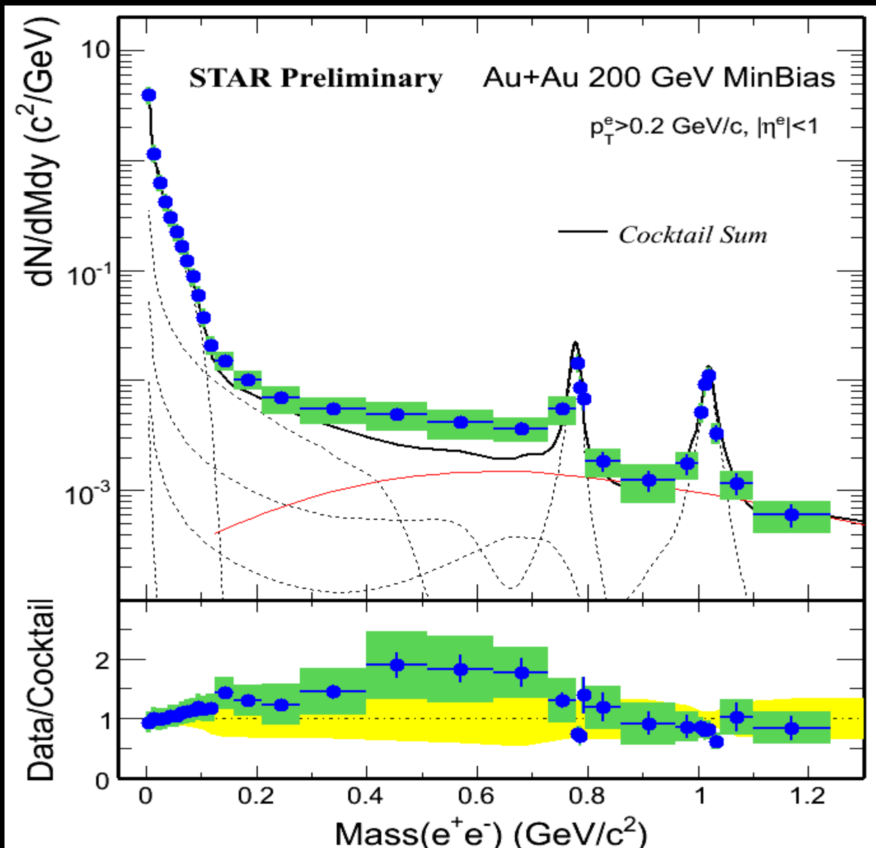
Low mass di-lepton Enhancement!

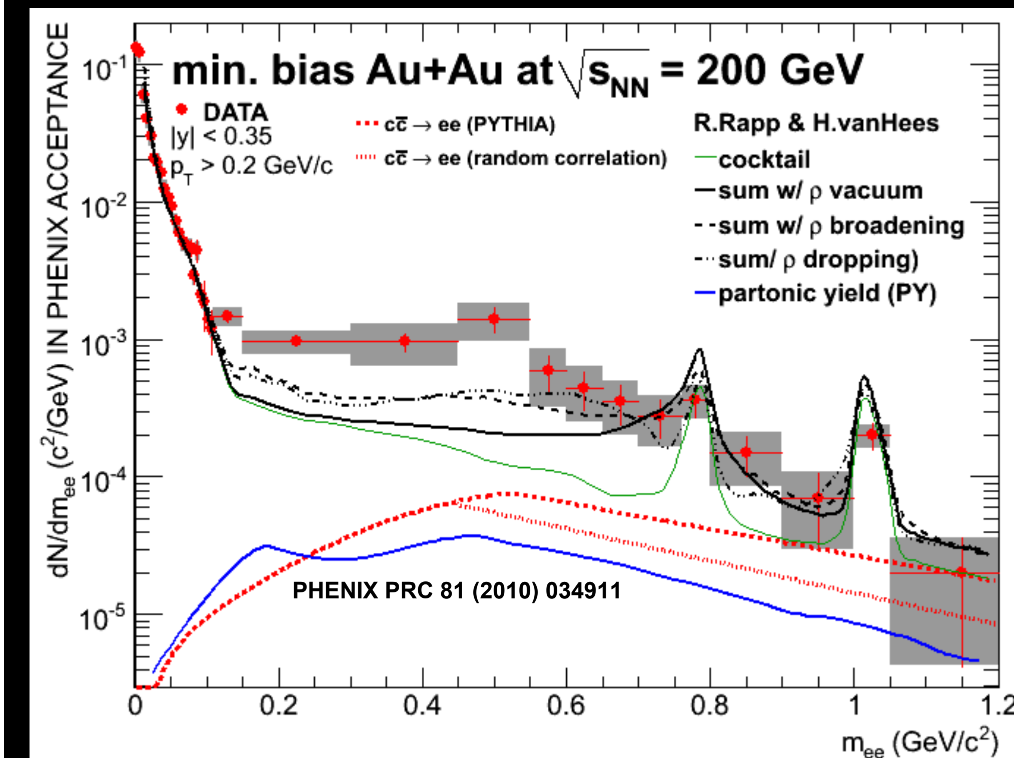
Increases with centrality.



Low Mass Di-Leptons at RHIC

LHC…?





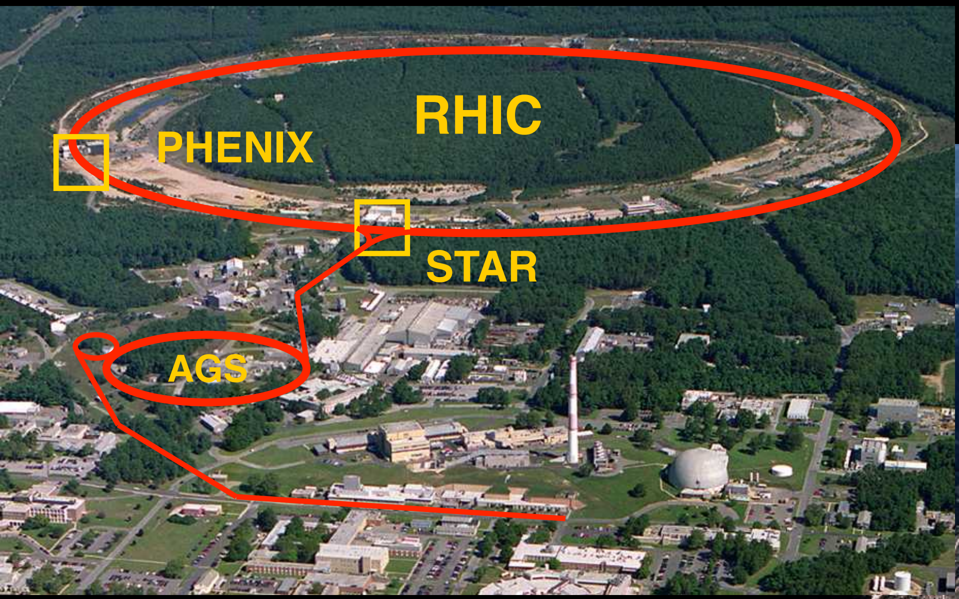
Enhancement factor in 0.15<M_{ee}<0.75 Gev/c2

	Minbias (value ± stat ± sys)	Central (value ± stat ± sys)
STAR	1.53 ± 0.07 ± 0.41 (w/o ρ) 1.40 ± 0.06 ± 0.38 (w/ ρ)	1.72 ± 0.10 ± 0.50 (w/o ρ) 1.54 ± 0.09 ± 0.45 (w/ ρ)
PHENIX	4.7 ± 0.4 ± 1.5	7.6 ± 0.5 ± 1.3
Difference	2.0 σ	4.2 σ

Disagreement & very difficult "task"!

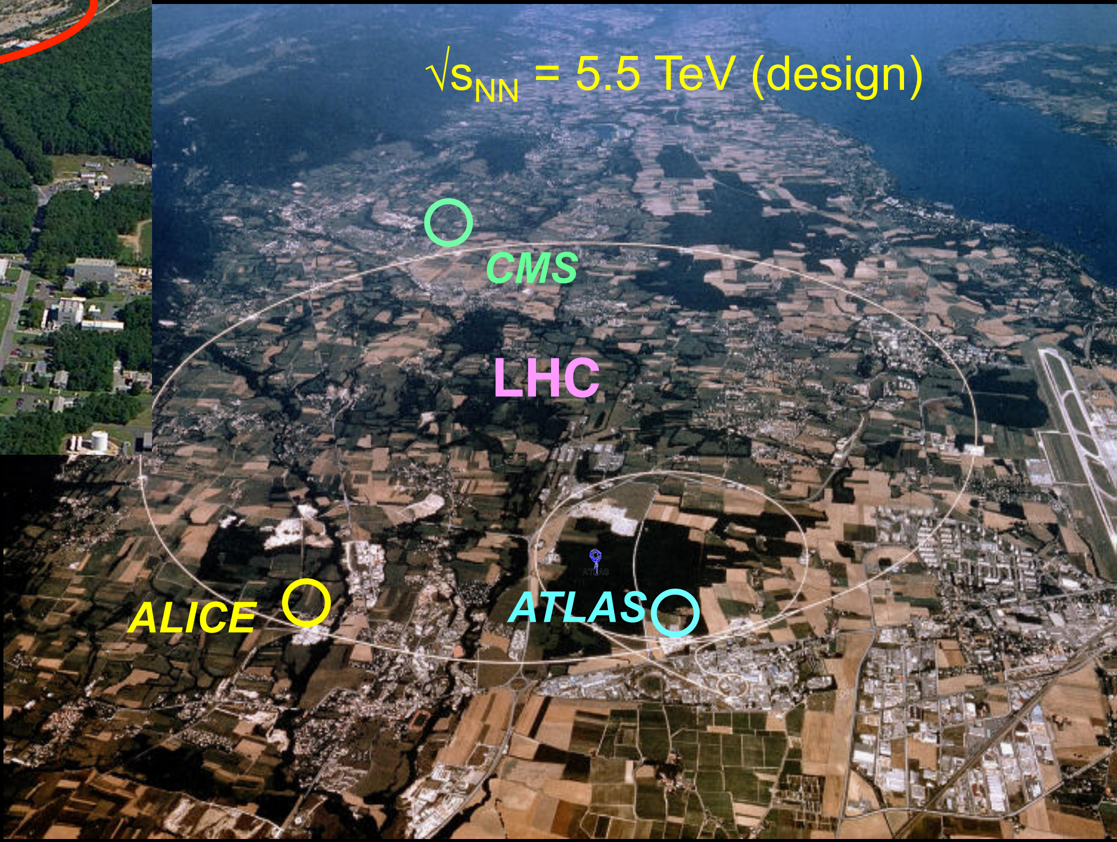
Note: Acceptance differences etc.

Heavy Ions at RHIC and LHC



$\sqrt{s_{NN}}$ = 5 - 200 GeV

Cover 3 decades of energy in center-of-mass



To investigate properties of hot QCD matter at T ~ 150 – 1000 MeV!

In Summary – What Are the Remaining BIG Questions for the Field at RHIC & LHC?

- How does the system evolve and thermalize from its initial state?
  - What is the initial state (Color-Glass Condensate?)→ pPb run in November 2012
- What are the properties & constituents (vs. T) of the QGP?
- Can we understand parton propagation & energy loss at a fundamental level?
  - What can we learn about the response of the QGP?
  - How does hadronization take place as the parton propagates?
- Can we understand & quarkonium melting (suppression) at the basic level?
  - What does it tell us? Is the melting vs T consistent with LQCD?
- Is the QCD Phase Diagram featureless above Tc?
  - What is the coupling strength vs T….
- Are there new phenomena? Can we say something about χ-symmetry restoration?....
- Can there be new developments in theory (lattice, hydro, parton E-loss, string theory…) and understanding……across fields……?

Thanks