High Energy Density QCD
- experimental overview -

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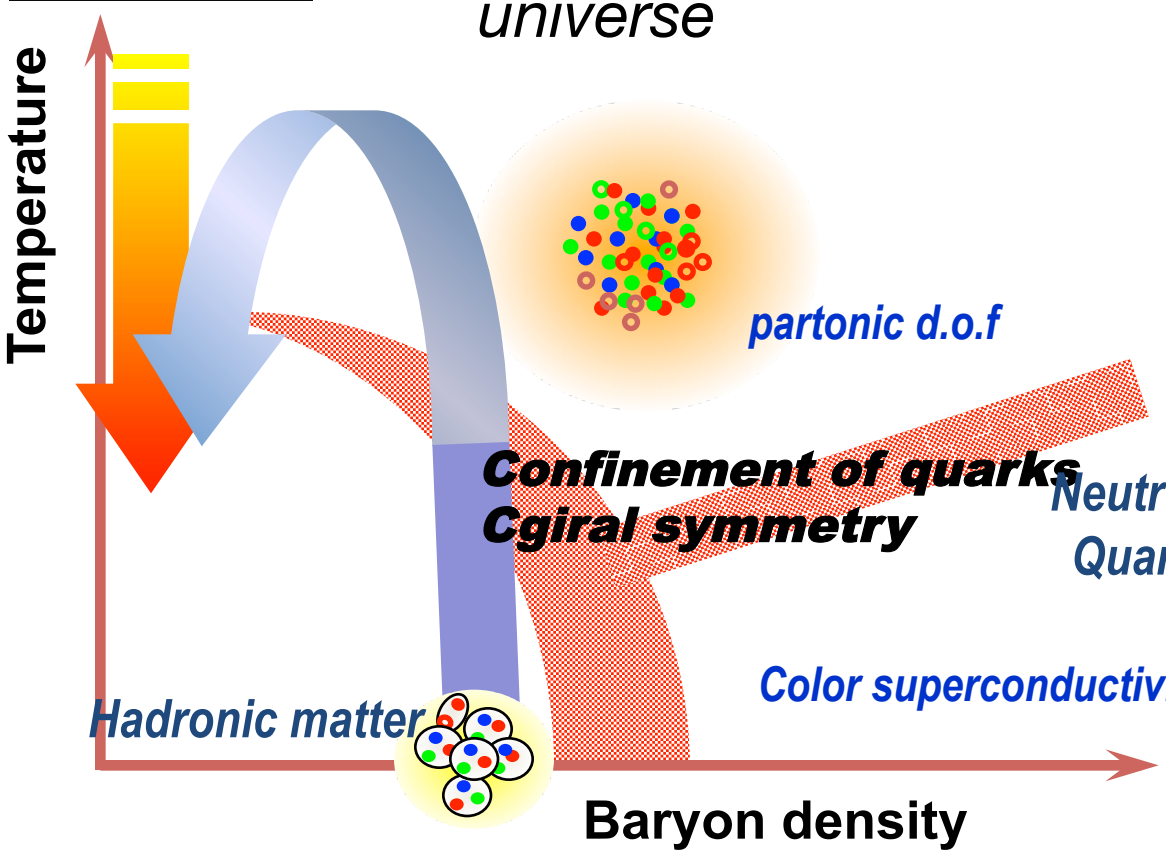
Outline

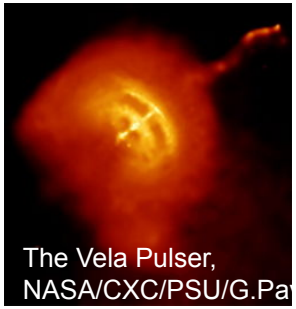
- Introduction
- Global Features
  - Multiplicity & transverse energy
  - Azimuthal anisotropy
- Hard Probes
  - Partonic energy loss
  - Heavy Flavor
  - Quarkonia
  - Thermal photons

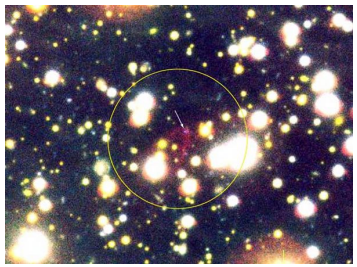
INTRODUCTION

High Energy Heavy Ion Collisions

- *To realize hot and dense QCD matter and to study its properties*
- *Similar matter existed in the early universe*

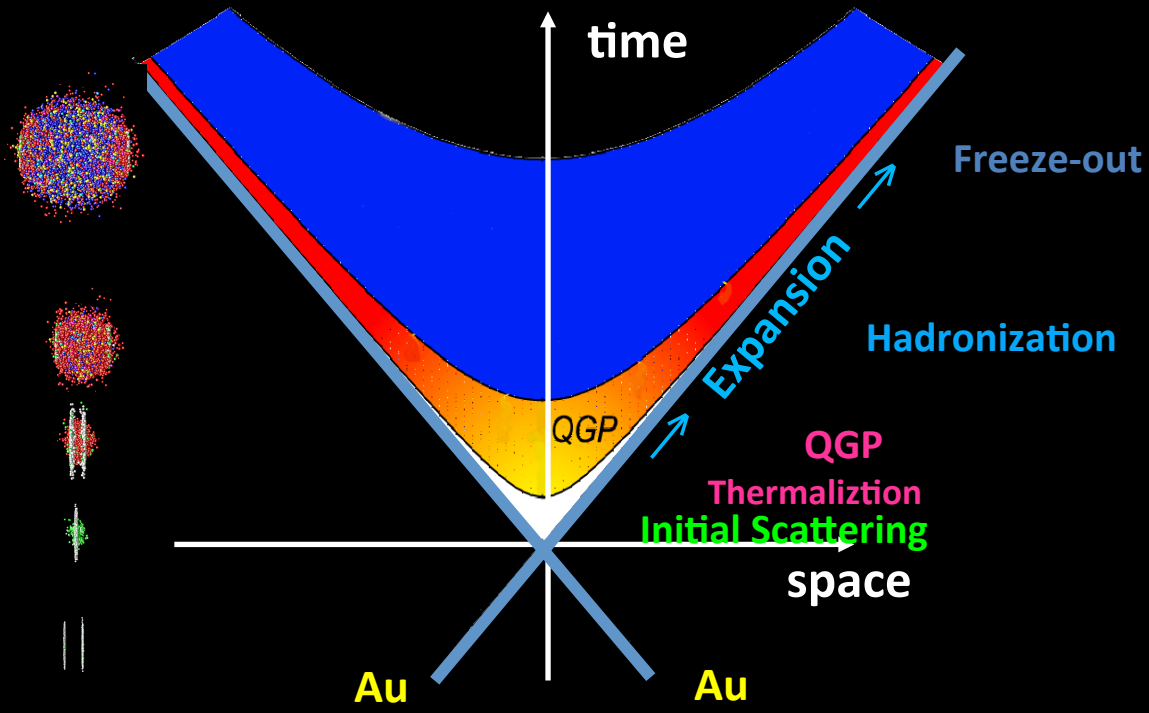






RX J1856.5-3754:
Credit: NASA/SAO/CXC/J.Drake et al.

Space-time Evolution of Collisions

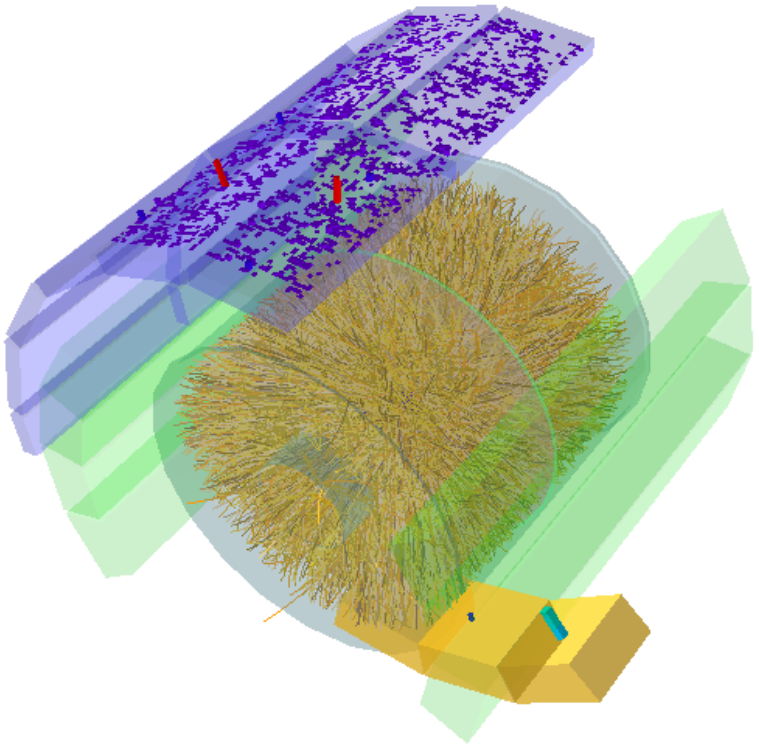


- Collision process is very dynamic and complex
  - Understanding dynamics is an essential part of investigations
- Reliable description of the space-time evolution is needed to deduce physics quantities from measurements
  - Good partnership with theories
- Observables as many as possible -> consistent description

A new era has just began

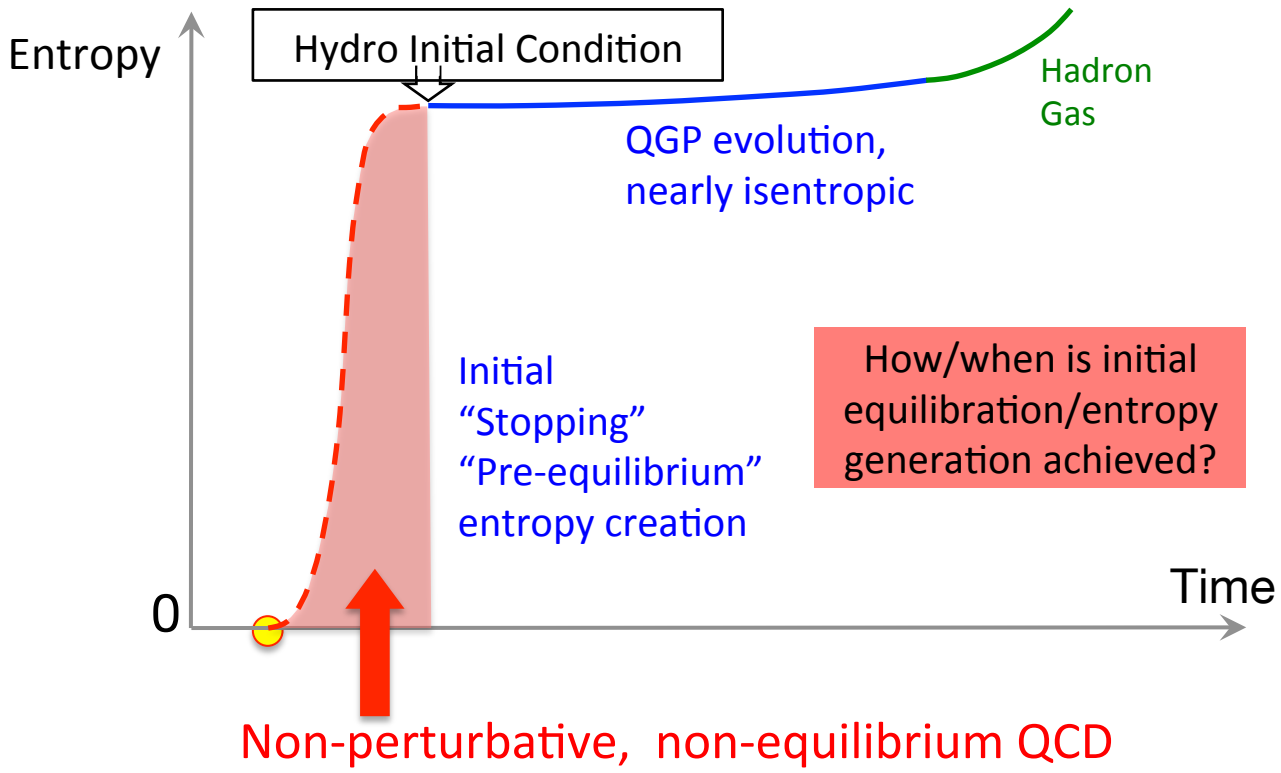
- With successful LHC operation for ion-ion collisions in November 2010, while RHIC has been steadily producing high-quality results

- Collisions at LHC
  - 2009/11/23: First p+p collisions at 900 GeV
  - 2010/3/31: p+p collisions at 7 TeV
  - 2010/11/8: Pb+Pb collisions at 2.76 TeV/A



GLOBAL FEATURES

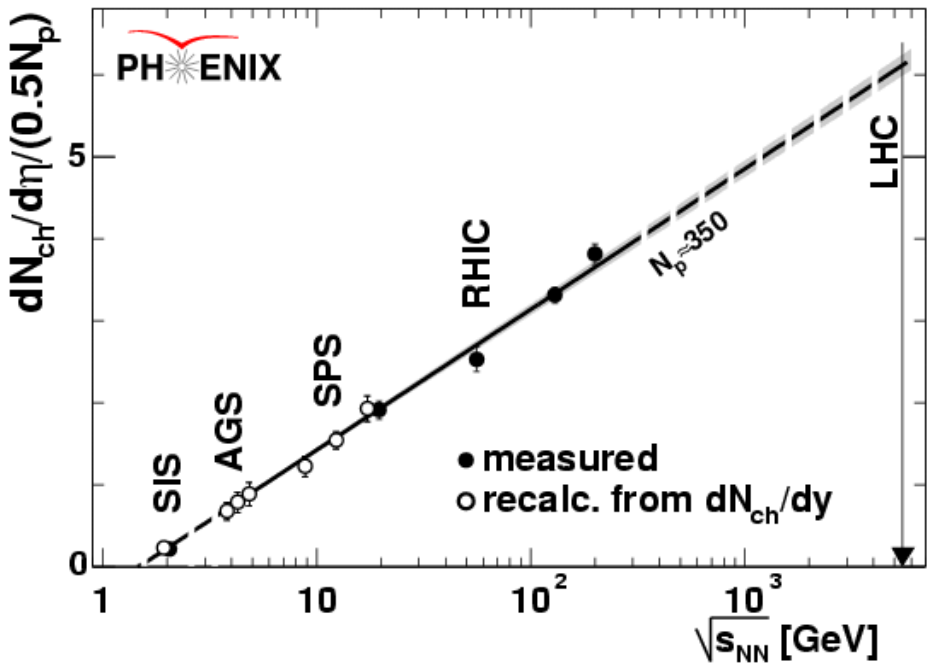
Toward Local Equilibration

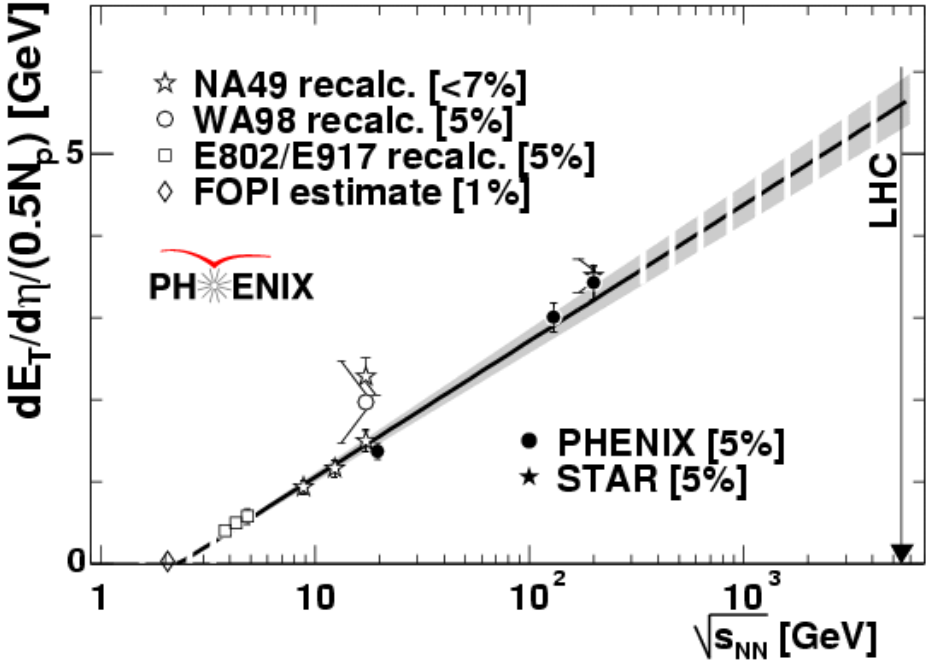


- Initial collision process: comfortable description of is still not available
- Pre-equilibration stage: no reliable description available

Ambiguity in the initial condition prevents from deducing physics quantities

Multiplicity and Transverse Energy

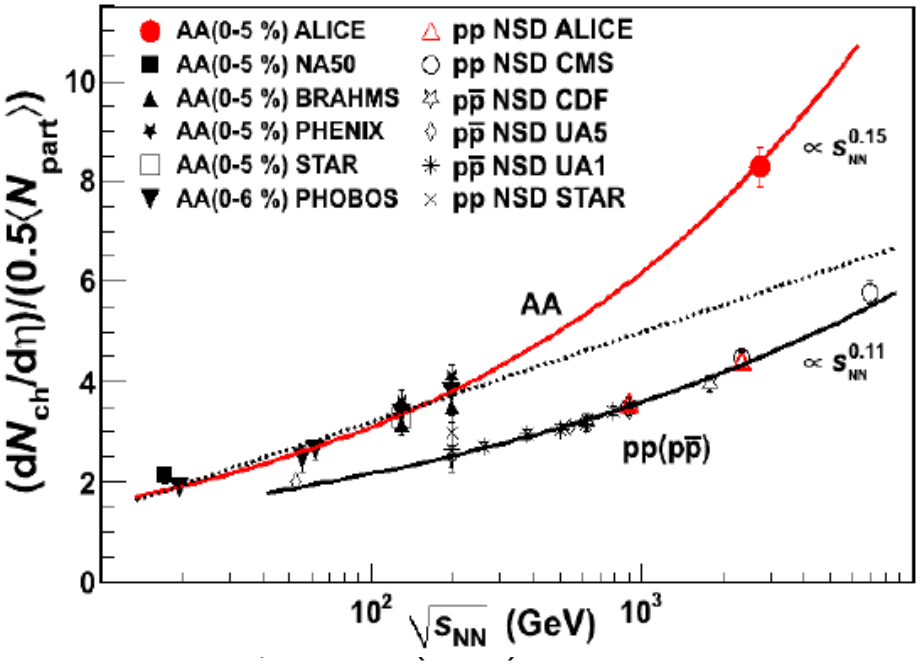


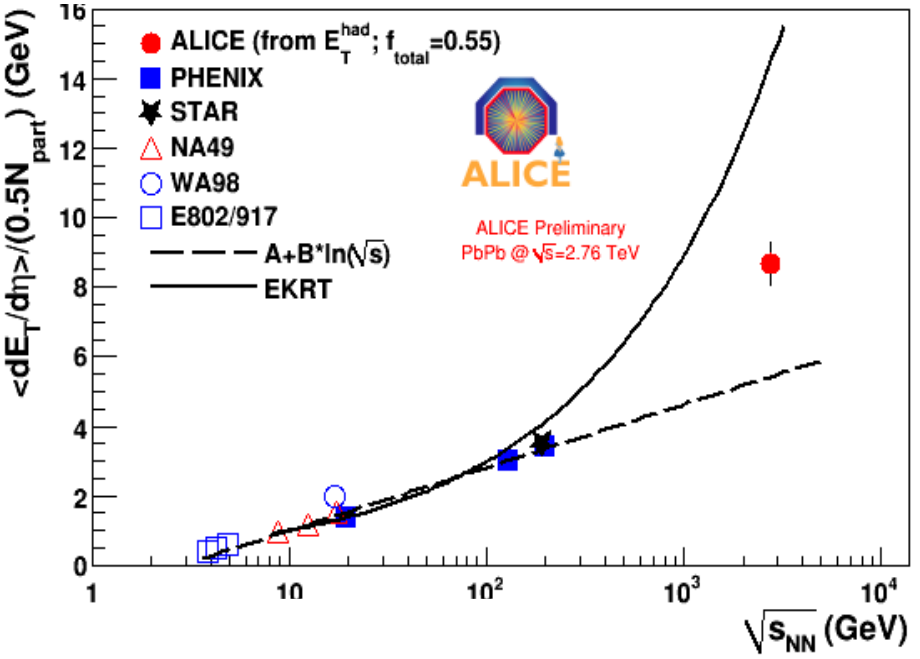


- Very basic quantities
- Before LHC: Both $dN_{ch}/d\eta$ and $dE_T/d\eta$ seems to increase almost linearly with $\ln(s_{NN})$

Multiplicity and Transverse Energy

- At LHC, large increase seen in $dN_{ch}/d\eta$ and $dE_T/d\eta$





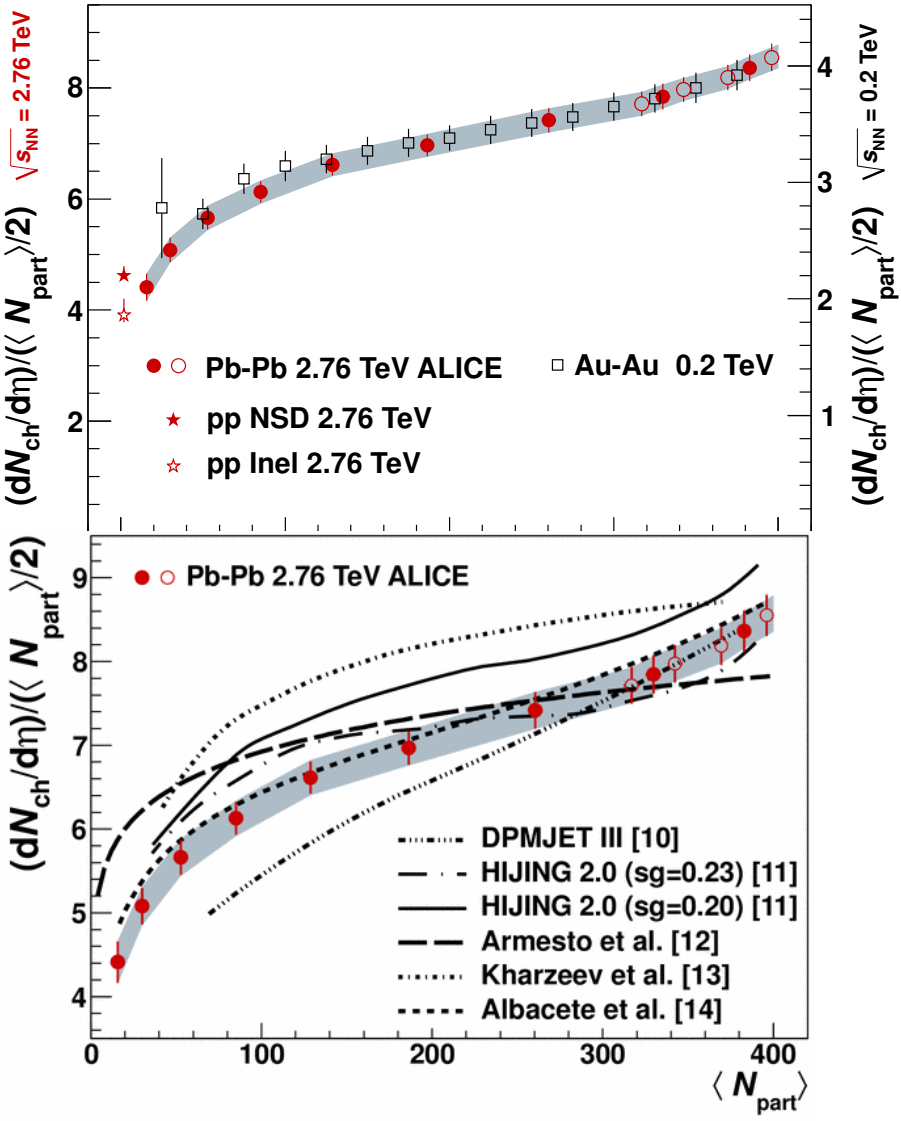
- $(dN_{ch}/d\eta)/(0.5\langle N_{par}\rangle) \sim 8$
  - 2.1 times RHIC
  - faster increase than p+p

Naïve interpretation: larger contribution from hard process

- $(dE_T/d\eta)/(0.5\langle N_{par}\rangle) \sim 9$
  - ~2.6 times RHIC
  - Consistent with ~20% increase of $\langle p_T\rangle$; stiffer momentum spectra

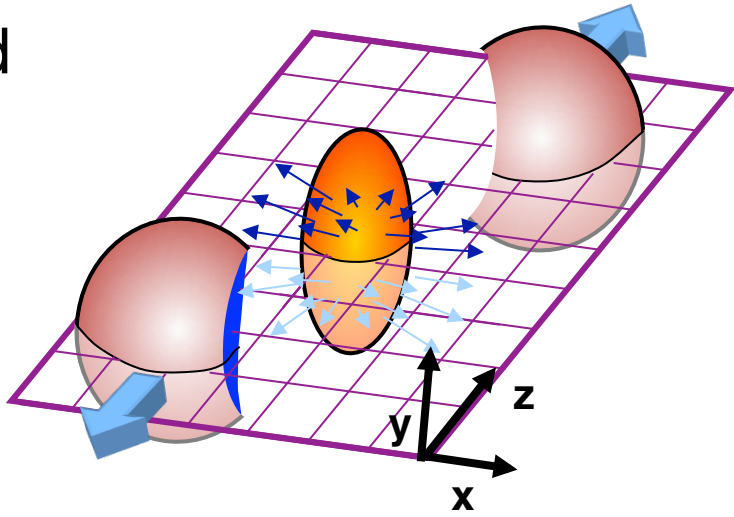
Puzzling (?) $dN_{ch}/d\eta$ Behavior

- $dN_{ch}/d\eta/(N_{part}/2)$ vs N_{part} at LHC and RHIC behaves very similarly
- Glauber model -> N_{coll}/N_{part} increases with N_{part}
  - Fraction of hard process is larger in central AA collisions than pp collisions
- Hard process is dominant at LHC -> larger increase in $dN_{ch}/d\eta/(N_{part}/2)$ with N_{part} is to be seen
- *Semi-hard process seems to be significantly hindered at LHC -- significant modification of gluon PDF at small x,* which is relevant to *min-jet process*

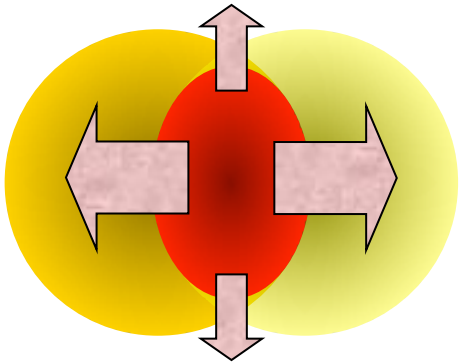


Azimuthal Angular Distribution

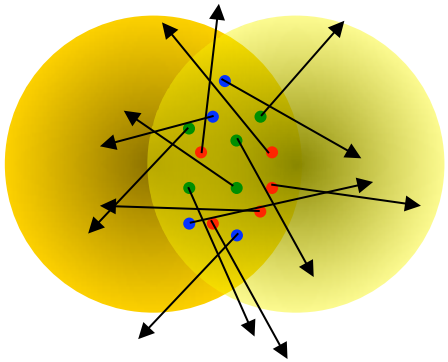
- Geometrical anisotropy is converted to azimuthal anisotropy in particle emission
- Magnitude of elliptic component v_2 depends on the property of created medium, and space-time evolution



Short *mfp* → hydrodynamic



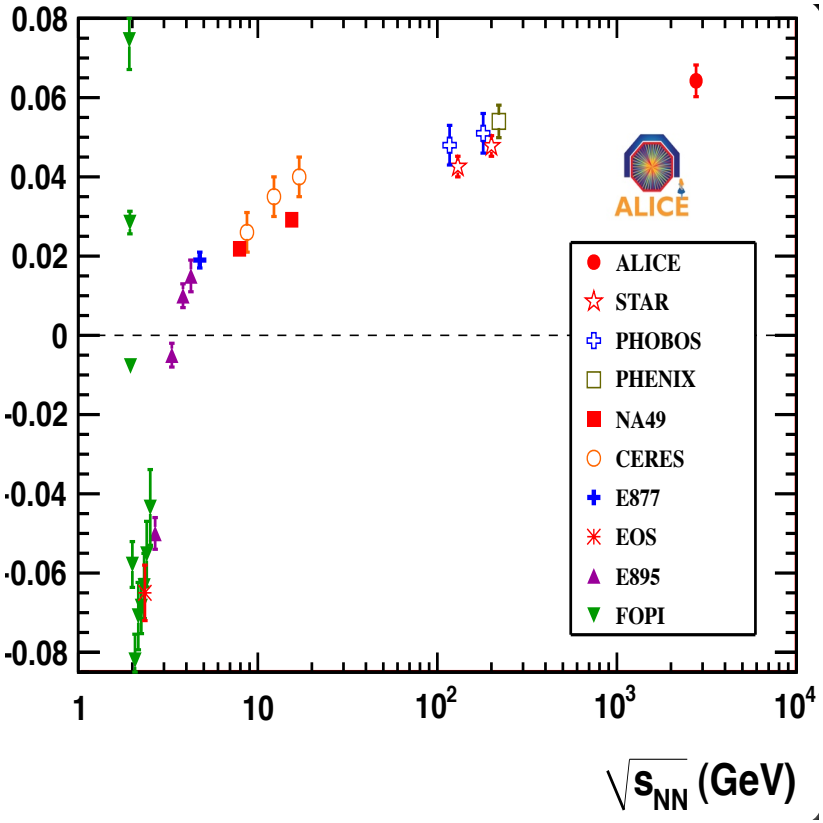
Long *mfp* → weakly interacting gas

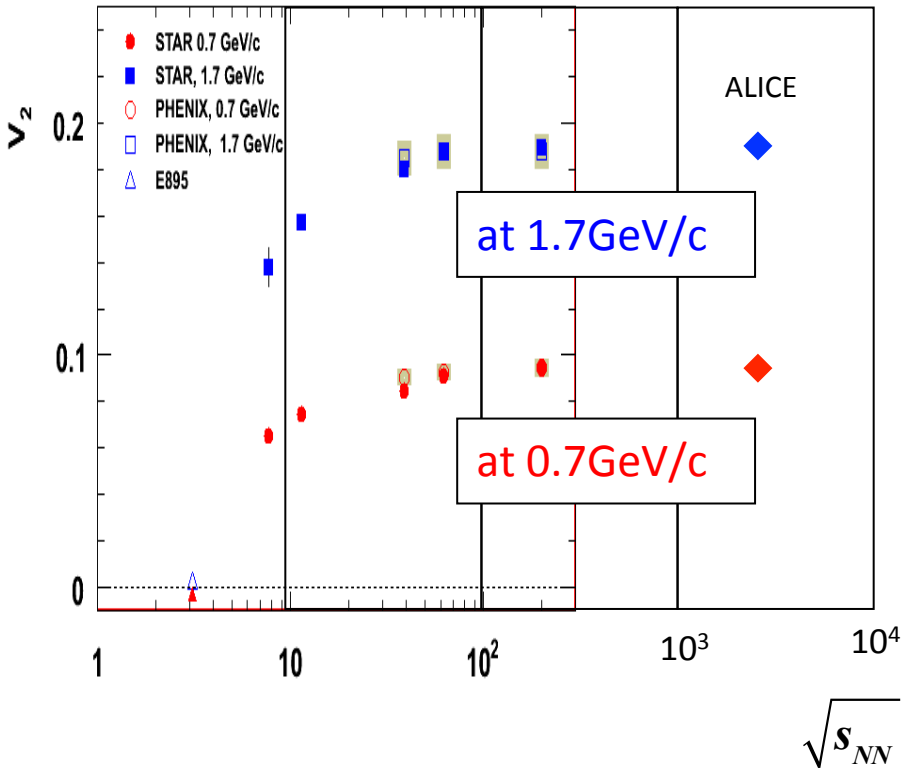


- *Large anisotropy found at RHIC; realization of matter with small viscosity => strongly interacting QGP*

Azimuthal Angular Distribution

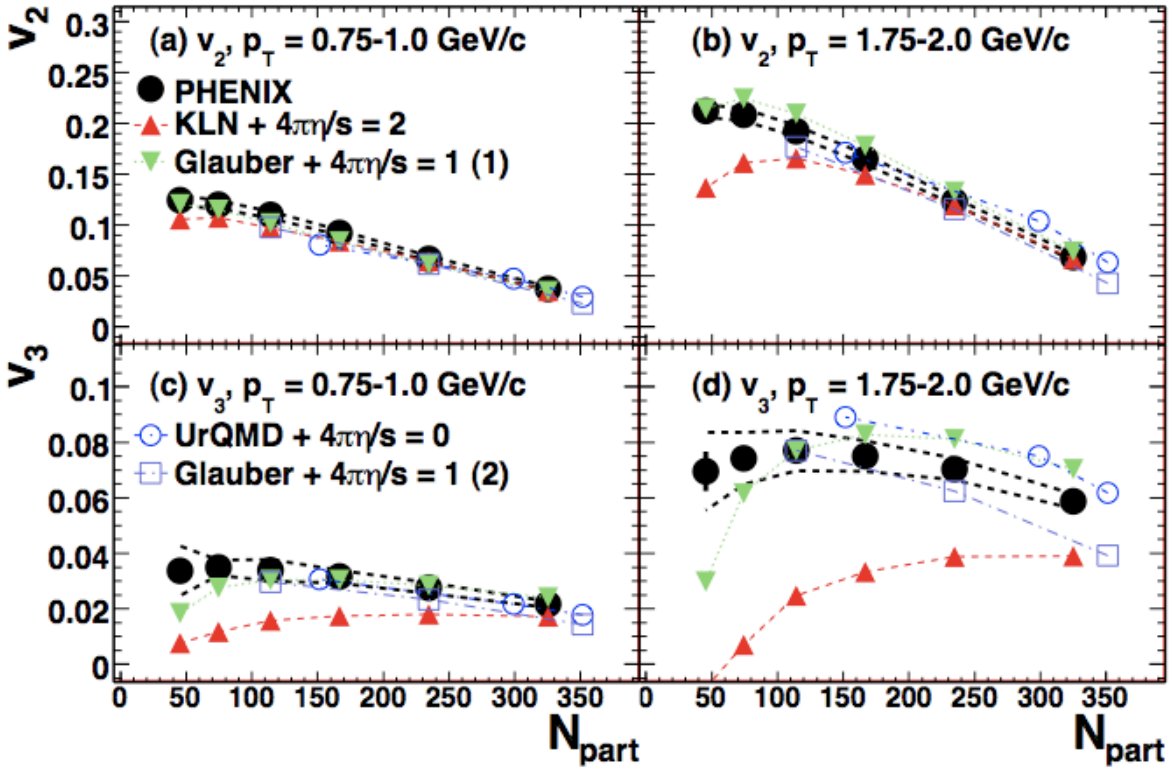
- Integrated v_2 increases with colliding energy, while differential $v_2(p_T)$ stays almost same *from 39GeV to 2.76TeV*
- Does created fluid have a similar property *from 39GeV to 2.76TeV*?





Higher Order Anisotropy

- Study of higher order anisotropy becomes popular
- v_3 does not have direct connection to collision geometry like v_2, and is originated from initial fluctuations

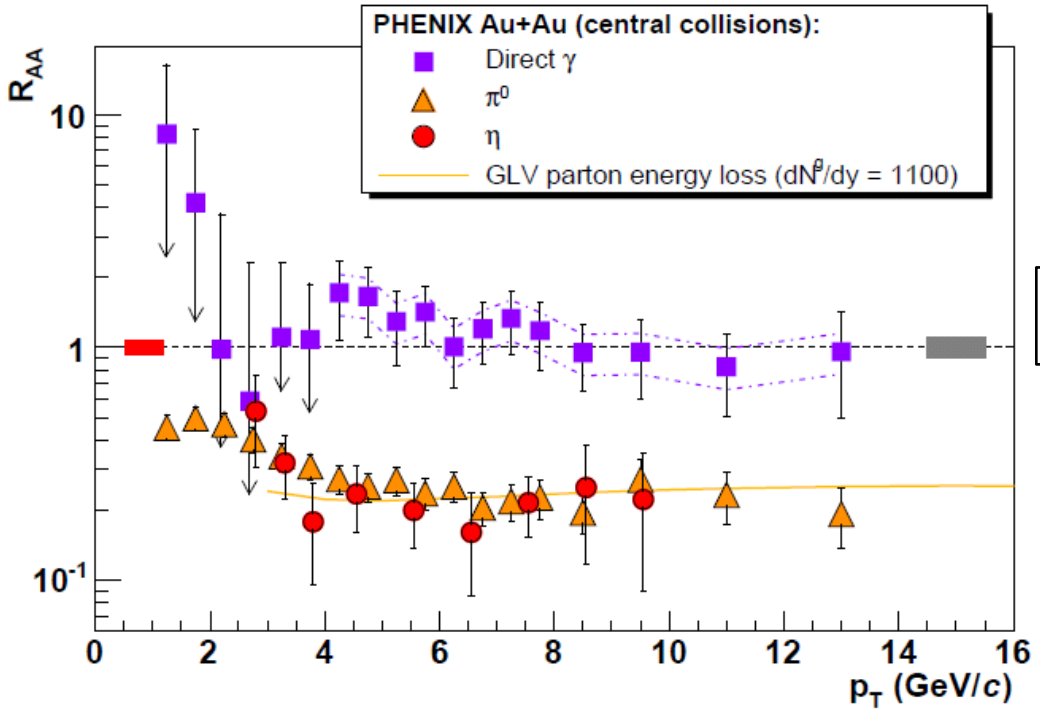


KLN + ($4\pi\eta/s = 2$)
Glauber + ($4\pi\eta/s = 1$)
UrQMD + ($4\pi\eta/s = 0$)

- *Ambiguous initial condition makes effect*
- v_3 seems to favor small η/s

HARD PROBES

Partonic Energy Loss

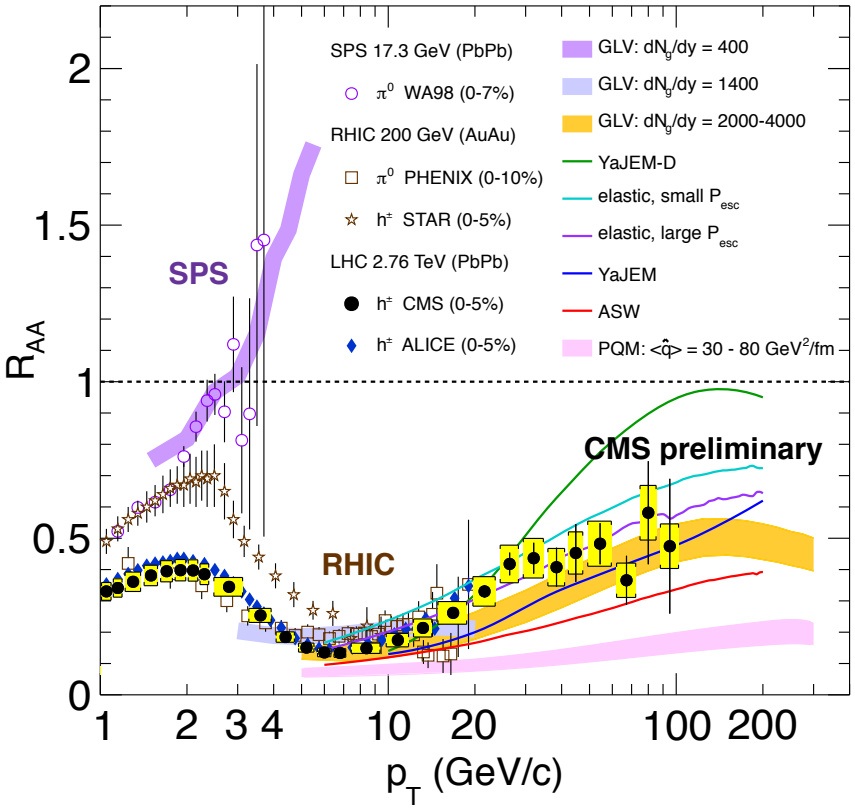


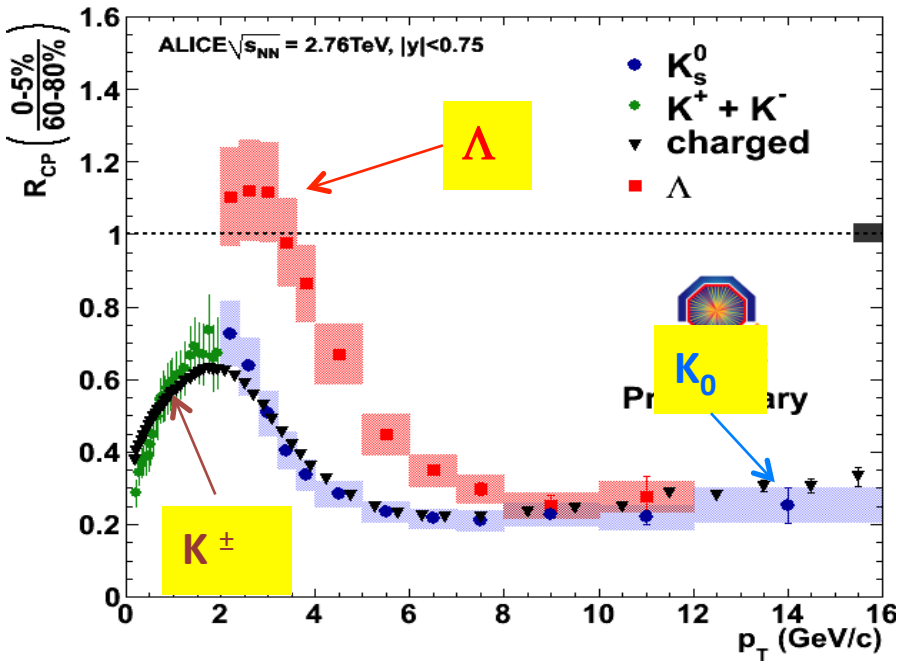
$$R_{AA} = \frac{1}{N_{coll}} \frac{N_{AA}(\mathbf{p};\mathbf{b})}{N_{pp}(\mathbf{p})}$$

Nuclear modification factor

- Strong yield suppression observed for pions in Au+Au central collisions at RHIC
  - No suppression for photons -> suppression for pions is ascribed to partonic energy loss; jet quenching
  - *Direct evidence of realization of matter with high density*

Partonic Energy Loss at LHC





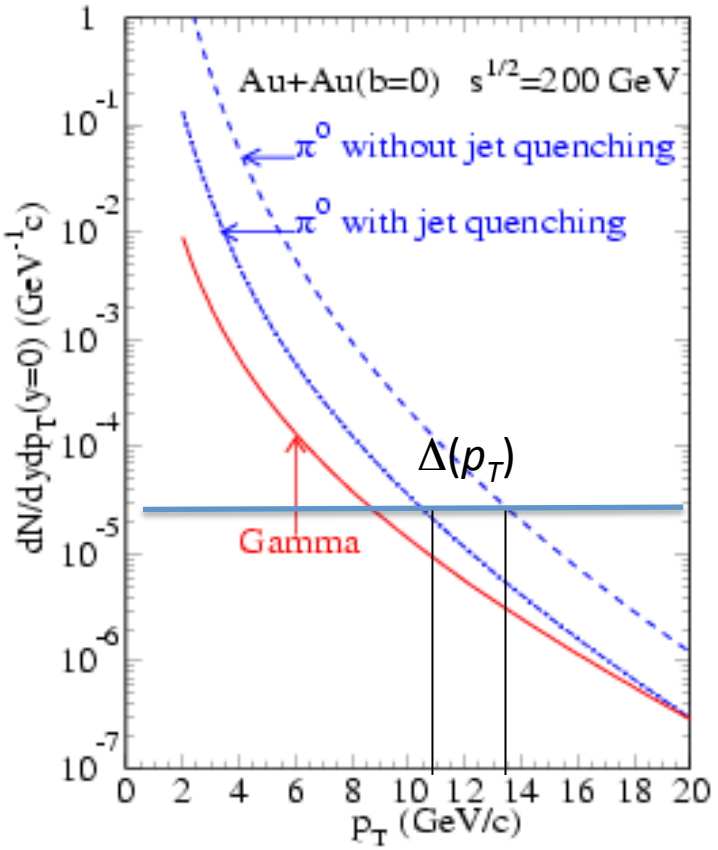
- Large suppression for *h* comparable to RHIC
- R_{AA} hit minimum at 6 - 8 GeV/c, and rises with p_T
- Baryon and meson behave differently below p_T ~ 6 GeV/c, but seem to merge at p_T ~ 8 GeV/c

Naive Consideration on R_{AA}

$$\frac{d^3N_{pp}}{p_T dp_T dy d\phi} \approx Ap_T^{-n}$$

$$\frac{d^3N_{AA}}{p_T dp_T dy d\phi} \approx B\left(p_T + \Delta\left(p_T\right)\right)^{-n} \qquad R_{AA} = \left(1 + \frac{\Delta\left(p_T\right)}{p_T}\right)^{-n}$$

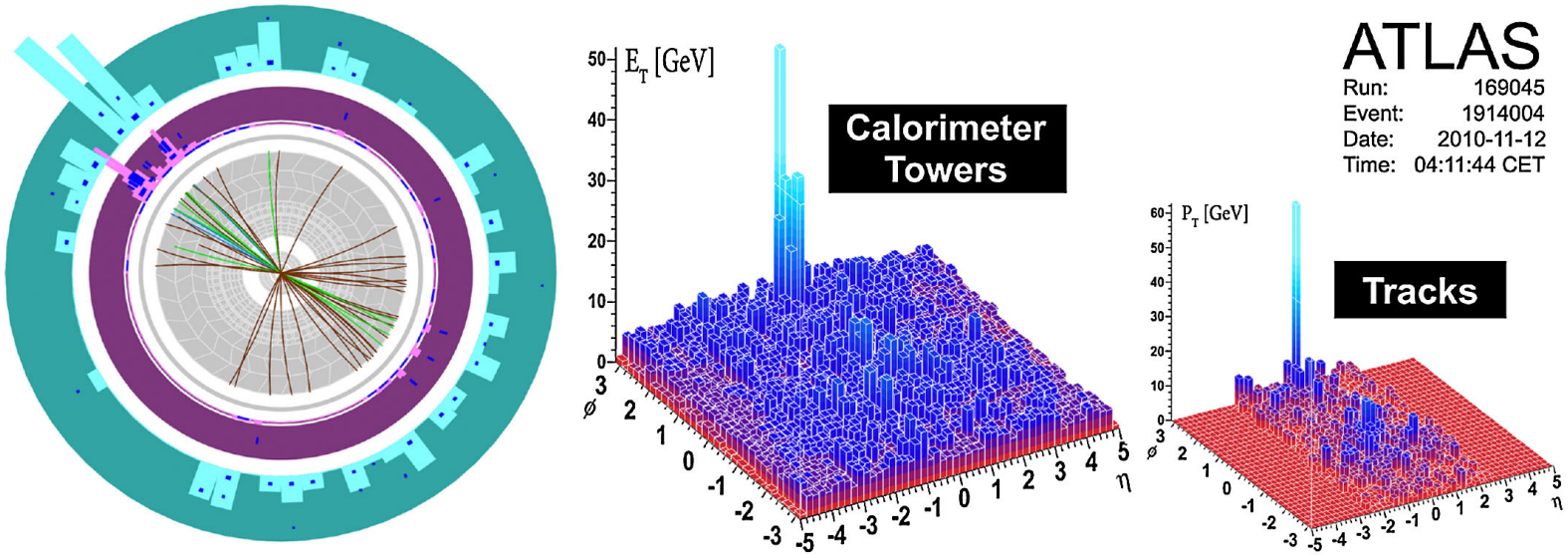
$$R_{AA} = \left(1 + \frac{\Delta\left(p_T\right)}{p_T}\right)^{-n}$$



- Assume $\Delta(p_T) = cp_T^k$
  - k = 1 → $R_{AA}(p_T)$ = constant
  - k > 1 → $R_{AA}(p_T)$ decreases with p_T
  - k < 1 → $R_{AA}(p_T)$ increases with p_T
- For 0 < k < 1, R_{AA} increases with p_T, while *energy loss itself also increases with p_T*

Partonic Energy Loss

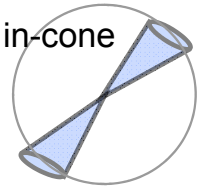
- Event-by-event dijet reconstruction by ATLAS & CMS
- A highly asymmetric dijet event
  - No high-energy calorimeter cells in the opposite side
  - Tracks dispersed widely over the azimuth

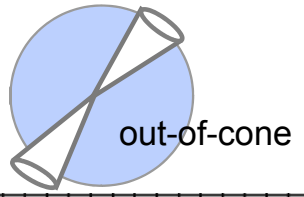


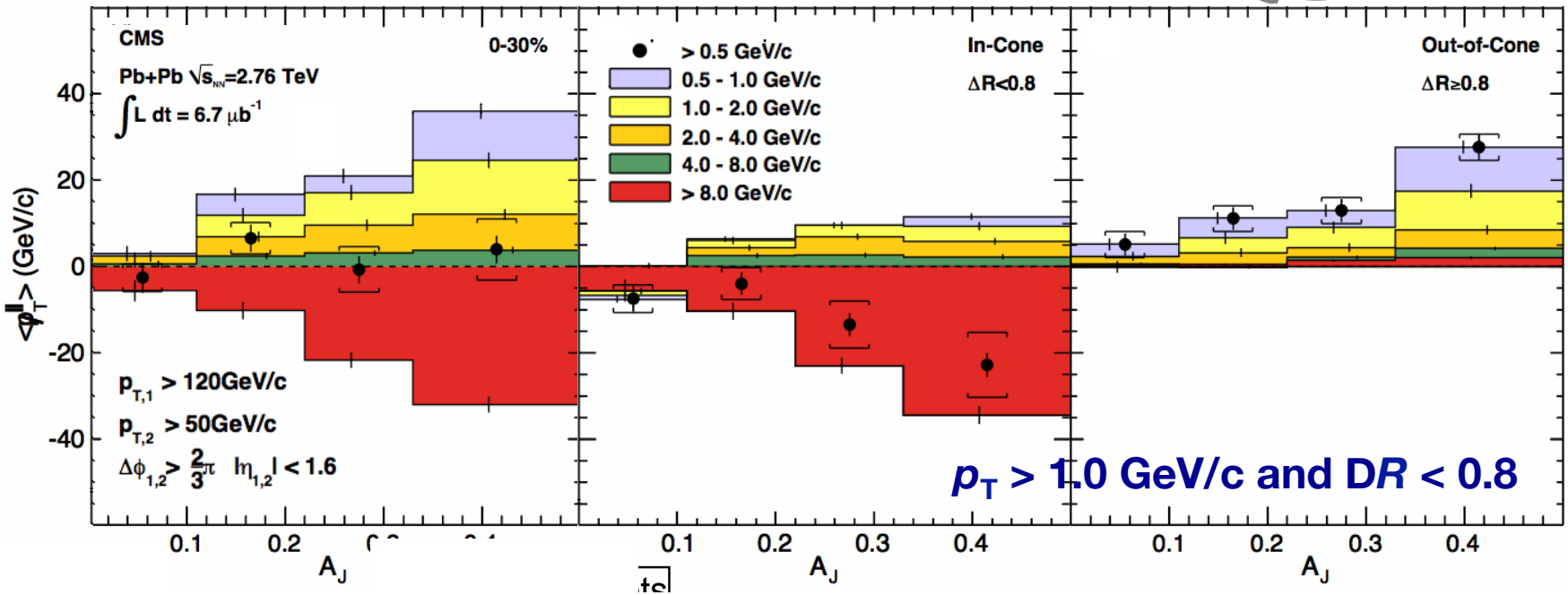
Partonic Energy Loss

Fate of the lost energy: shared by particles with small energy distributed at large angles

calorimeter + tracking





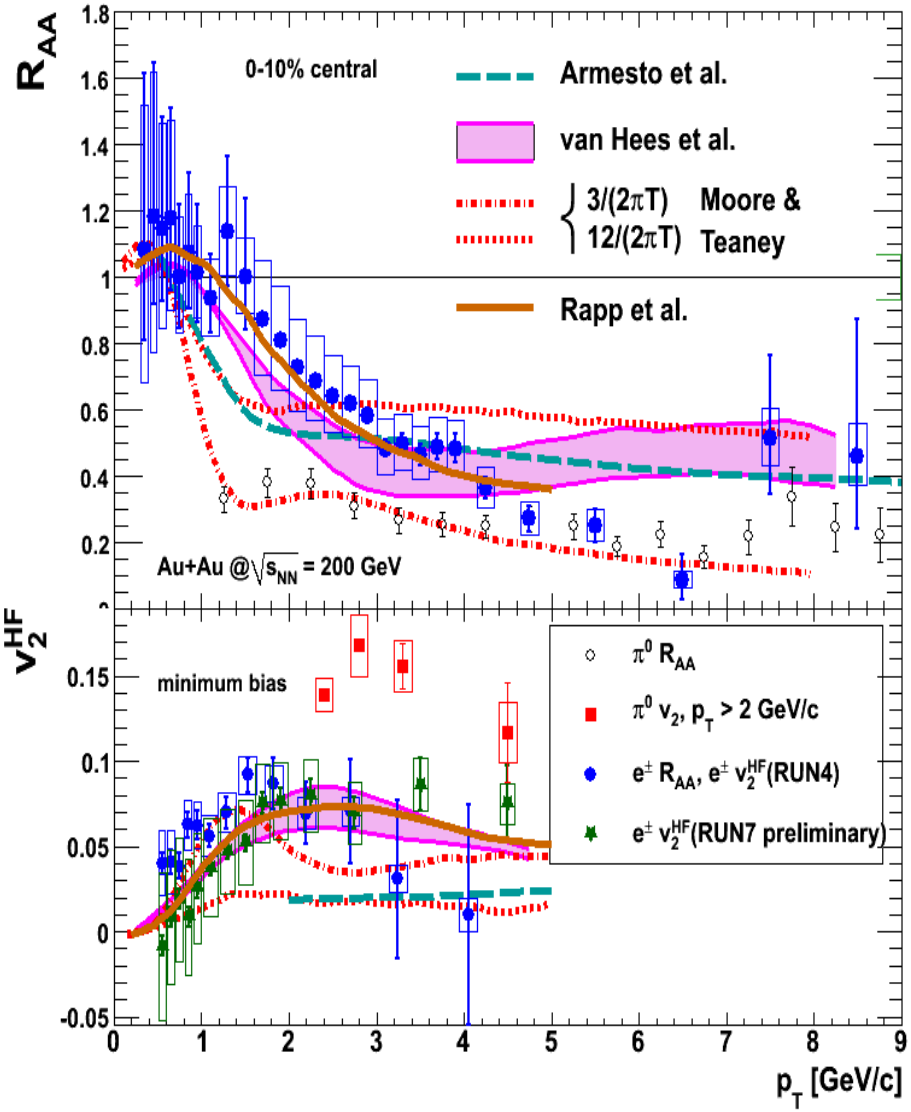


Low p_T, full acceptance
Momentum is balanced

In-cone; large momentum imbalance at high p_T
Consistent with calorimetry

Out-off-cone; excess of momentum balance due to low p_T particles

Heavy Flavor



Heavy flavor = a good probe of matter property at the early stage of collisions

- Heavy impurity doing Brownian motion in QGP ; Langevin equation
- Discovery of large energy loss and sizable v_2, which implies high density & small diffusion coefficient => **$4\pi\eta/s$ = 1.3 ~ 2.0 was deduced**

$D\,T = (4 \sim 6)/2\pi$

- by Rapp & van Hees (PRC 71, 034907 (2005))

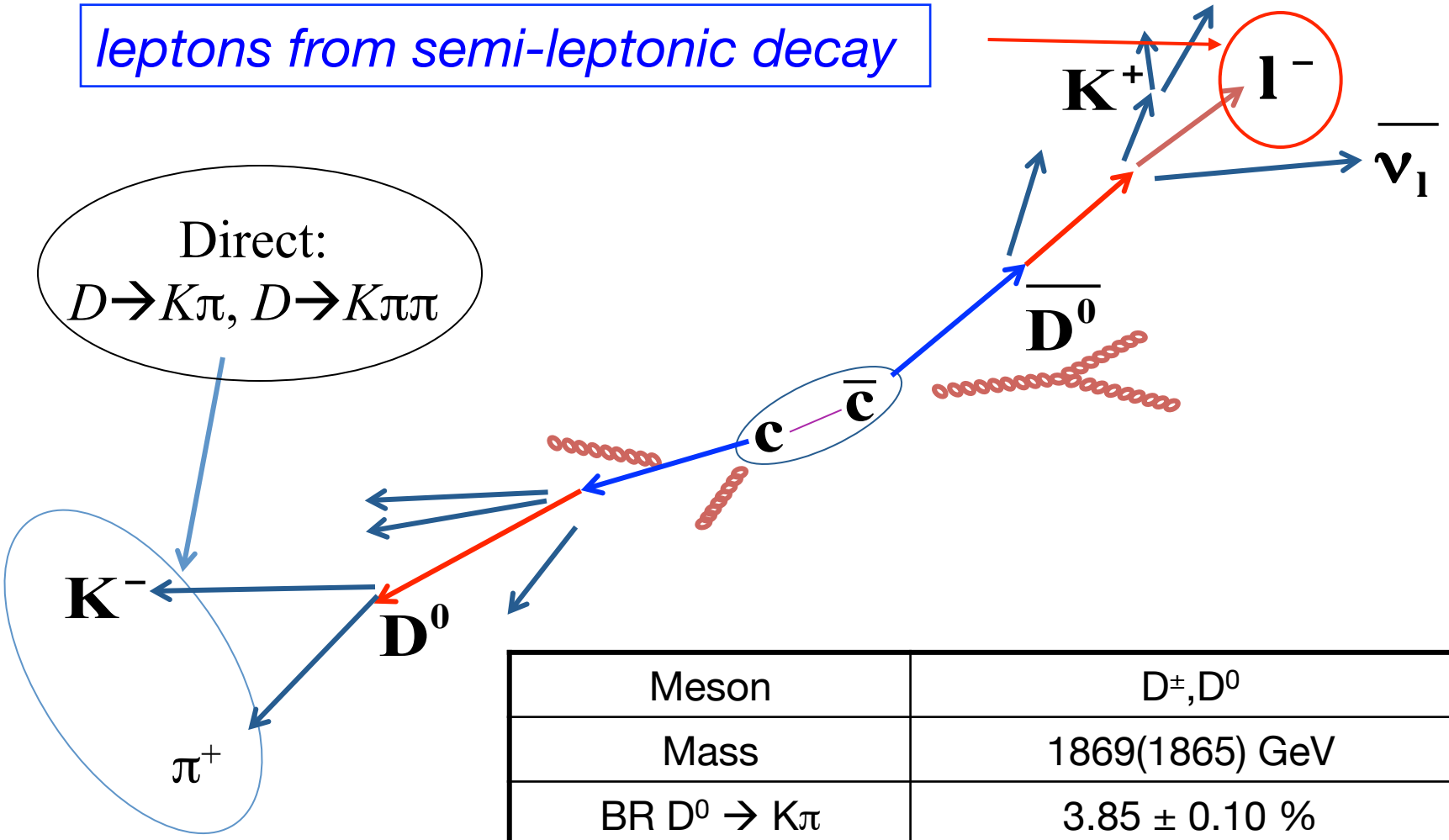
$2DT \sim 4\pi T \times \eta/(e+P) = 4\pi\eta/s$

- by Moore & Teaney (PRC 71, 064904 (2005))

-> **$4\pi\eta/s$ = 1.3 ~ 2.0**

Two ways to Measure Heavy Quarks

leptons from semi-leptonic decay

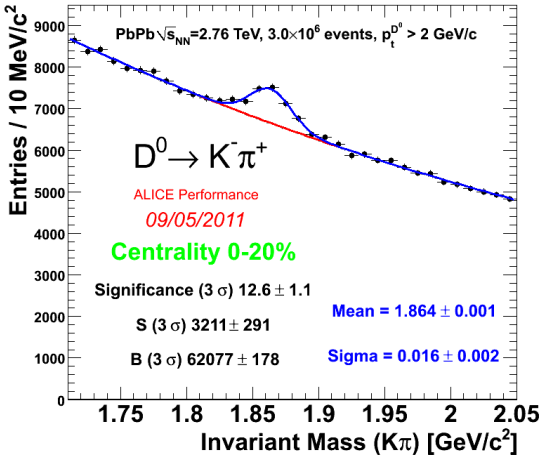


Meson	$D^{\pm}$,D^0
Mass	1869(1865) GeV
BR $D^0 \rightarrow K\pi$	3.85 ± 0.10 %
BR $D \rightarrow e + X$	$D^{\pm}$: 17.2, D^0: 6.7 %

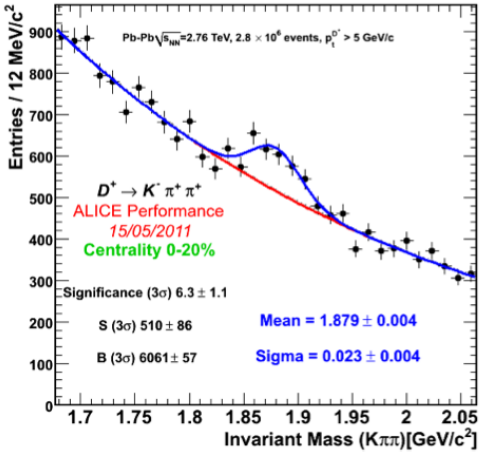
Heavy Flavor

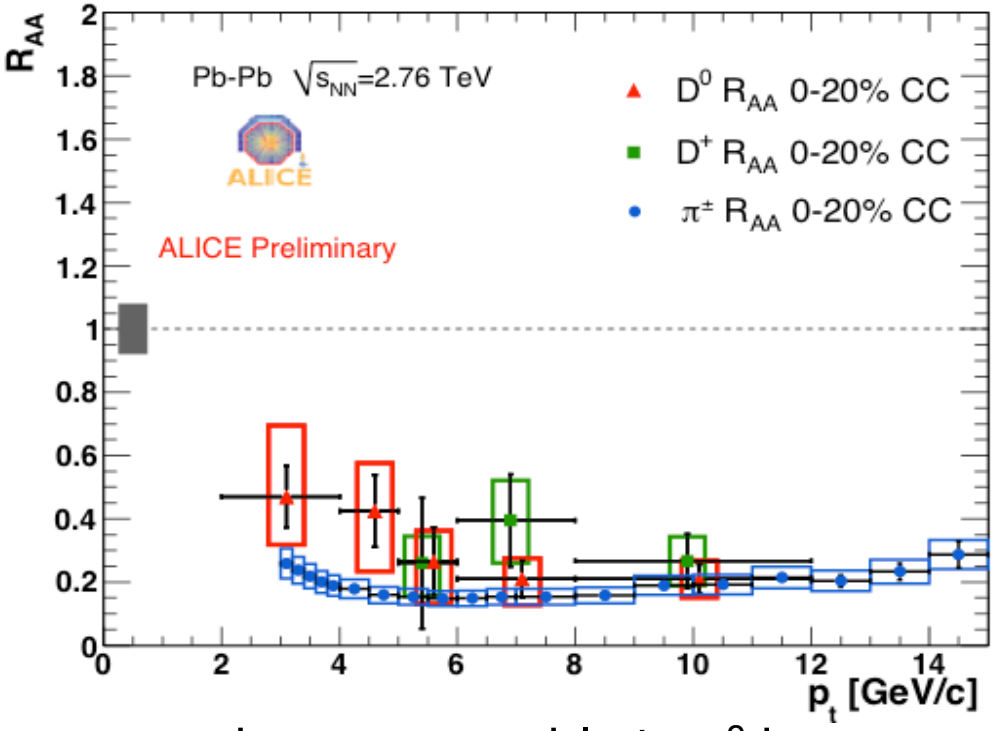
Measurement of D mesons at LHC

$D^0 \rightarrow K\pi$



$D^+ \rightarrow K\pi\pi$





- Large suppression, comparable to π^0 in p_T > 6 GeV/c
- Less suppression in p_T < 6 GeV/c
  - Dead cone effect?

Heavy Flavor

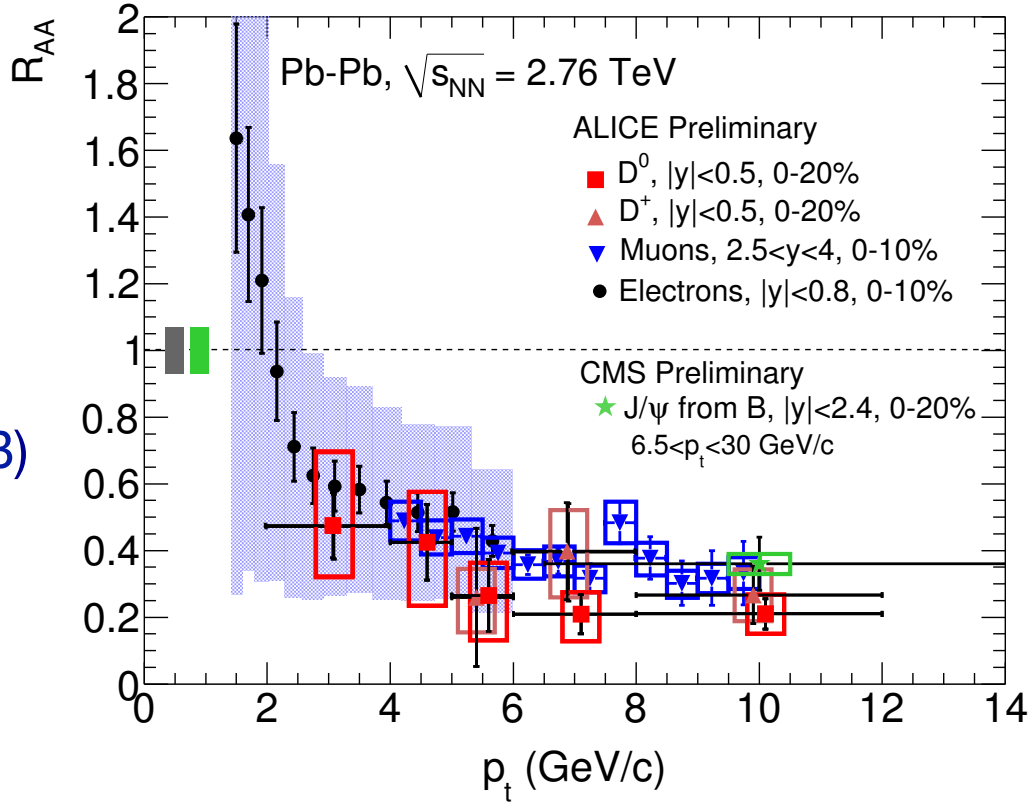
Compare R_{AA} for charm and e & μ

- Single e and μ ; majority are from c and b decay
  - For pT > 5 – 6 GeV/c, fraction of b becomes larger

- *J/ψ* from *B* decay
  - select off-vertex *J/ψ*

- In p_T > 6 GeV/c
  - R_{AA}(charm) < R_{AA}(e, μ)
  - R_{AA}(charm) < R_{AA}(*J/ψ* from B)

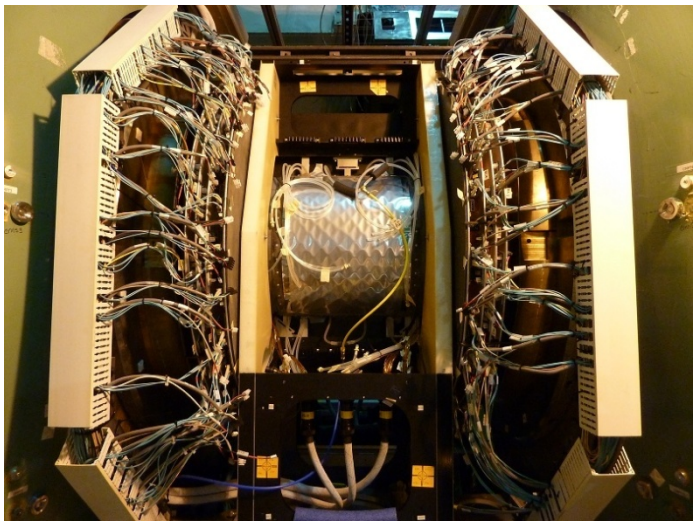
- *Mass dependent energy loss?*

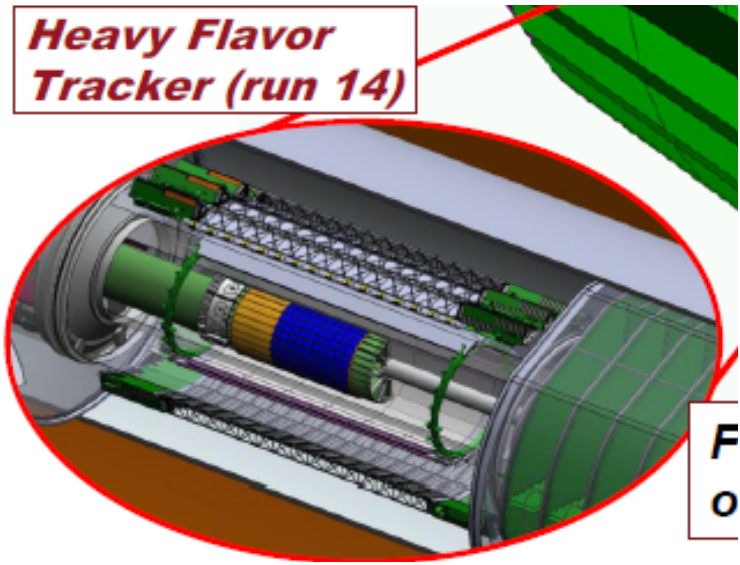


Heavy Flavor

- PHENIX: Silicon Vertex Detector
  - VTX successfully commissioned in 2011 p+p run
  - VTX taking data in 2011 Au+Au run
- STAR: Heavy Flavor Tracker
  - Will be ready in 2014 run

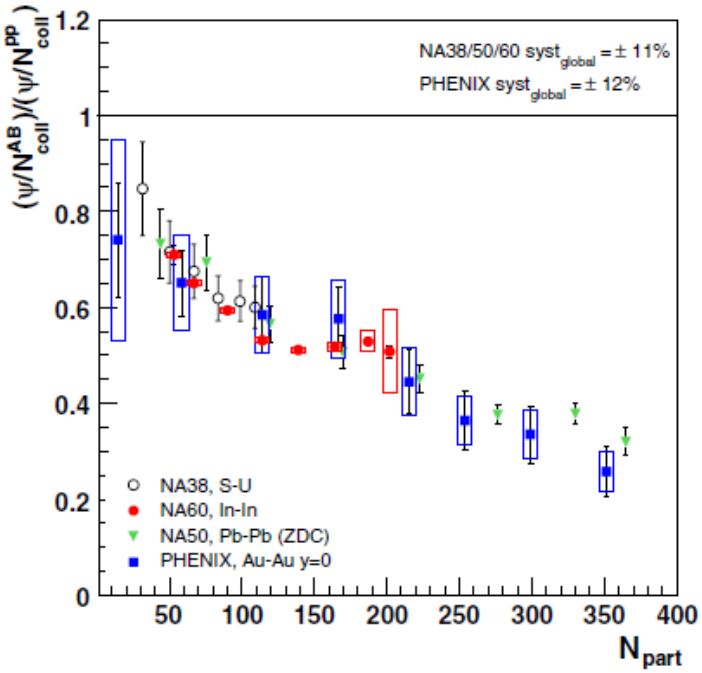
- Extensive studies expected at both LHC and RHIC in the coming years
  - R_{AA} of c, b separately
  - v_2 of c, b separately
  - Jet tomography

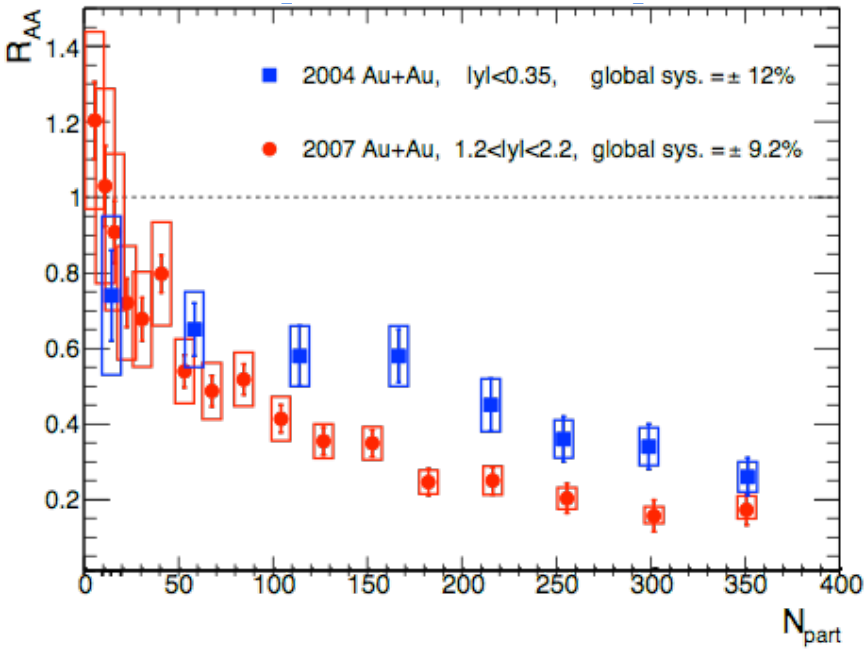




Quarkonia

- J/ψ suppression was proposed as a probe of deconfinement by T. Matsui and H. Satz (1985)
- Anomalous suppression over *Nuclear Absorption* was observed in Pb +Pb collisions at SPS → *Survived till now*
- R_{AA} (RHIC: 1.2<|y|<2.2) < R_{AA} (RHIC: |y|<0.35)
- R_{AA} (RHIC: |y|<0.35) ~ R_{AA}(SPS: 0<y<1)



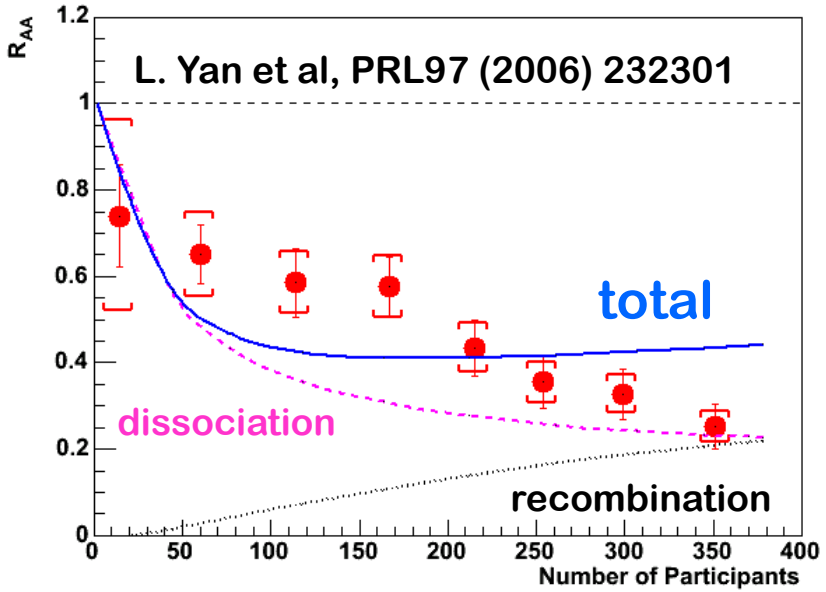


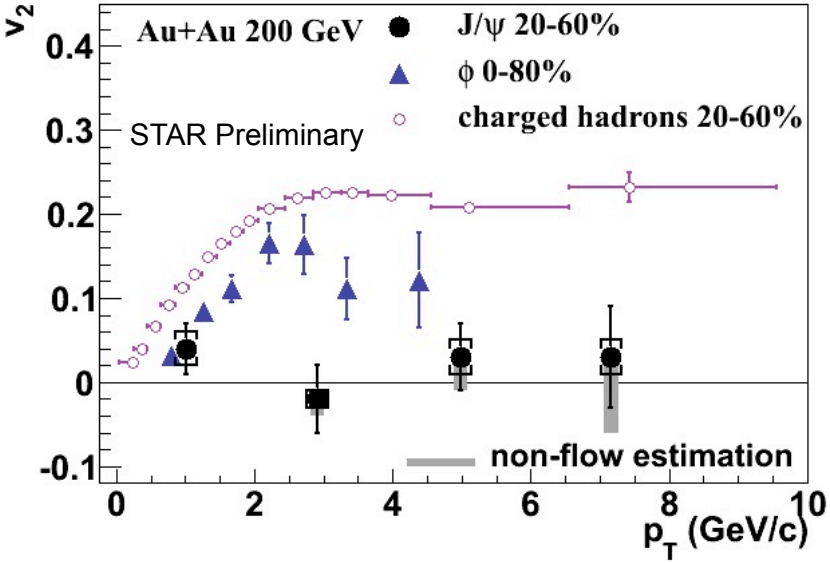
Quarkonia

Relevant Processes

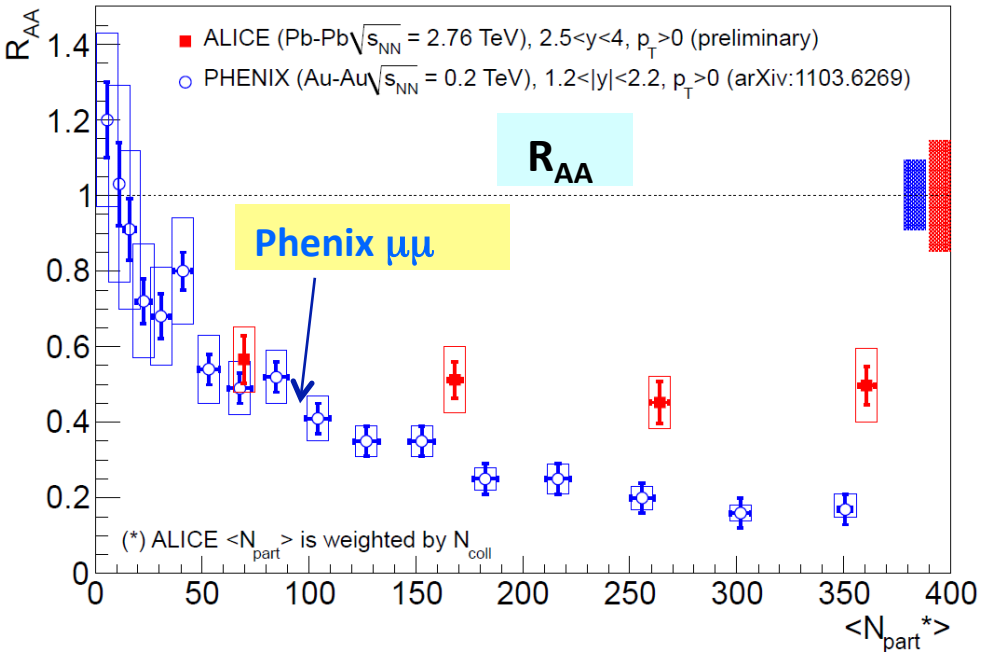
- Debye screening
  - different states melt at different temperature
- Dynamical dissociation
- Quark recombination
  - Recombination of c-cbar pairs
  - Finite v2 may be expected

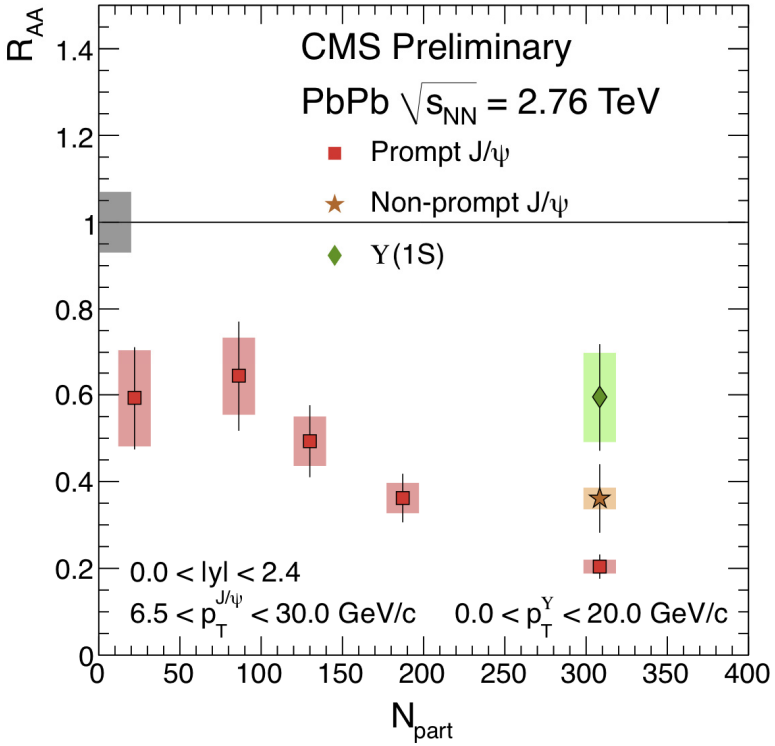
- v2 result = consistent with zero over wide p_T range
  - contribution from charm recombination is small
  - charm does not flow





Quarkonia at LHC



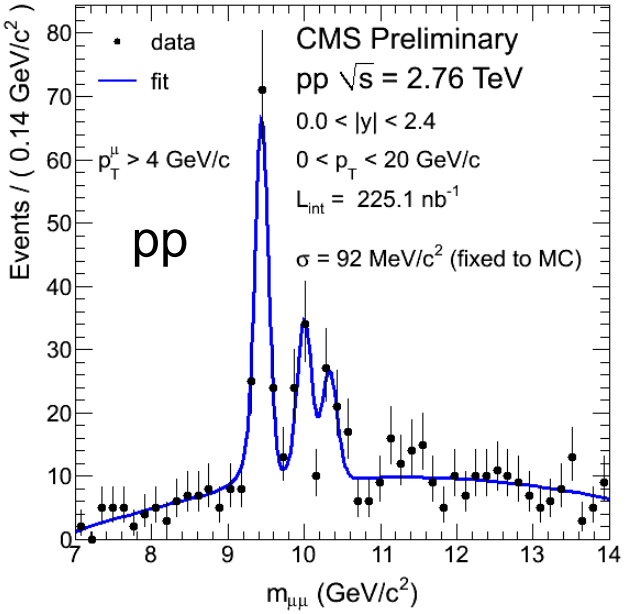


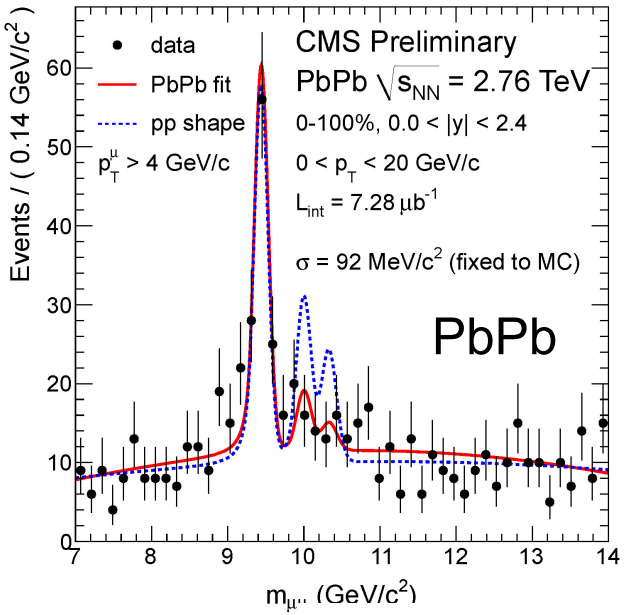
- Suppression of low p_T J/ψ is weak
  of high p_T J/ψ is strong

=> *recombination?*

- Non-prompt high p_T J/ψ
  - originated from b decay, and is a measure of b-quark energy loss
- Υ(1S) suppression is not strong => *next slide*

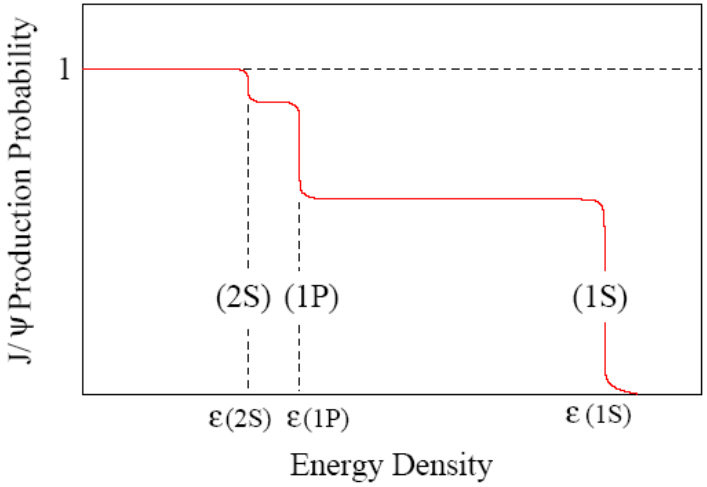
Suppression of Excited States of Υ



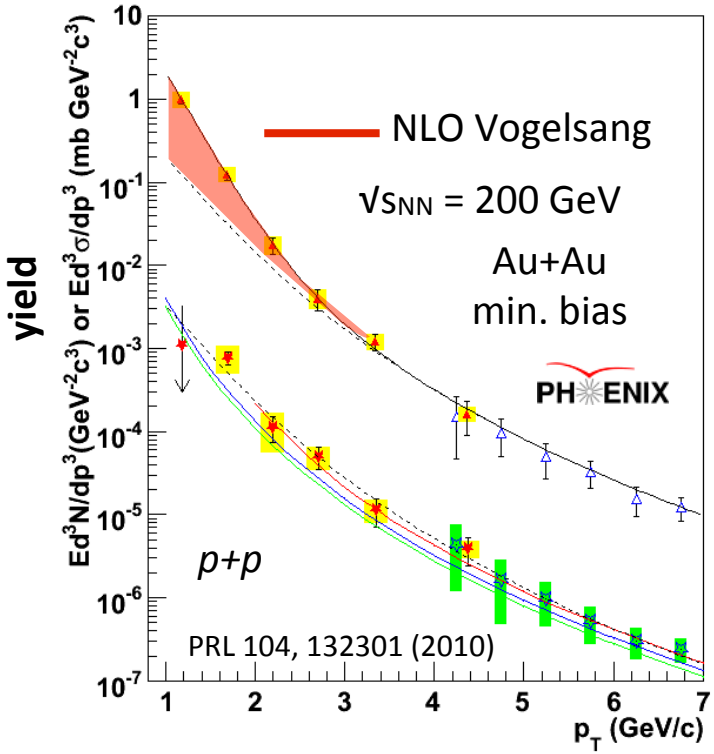


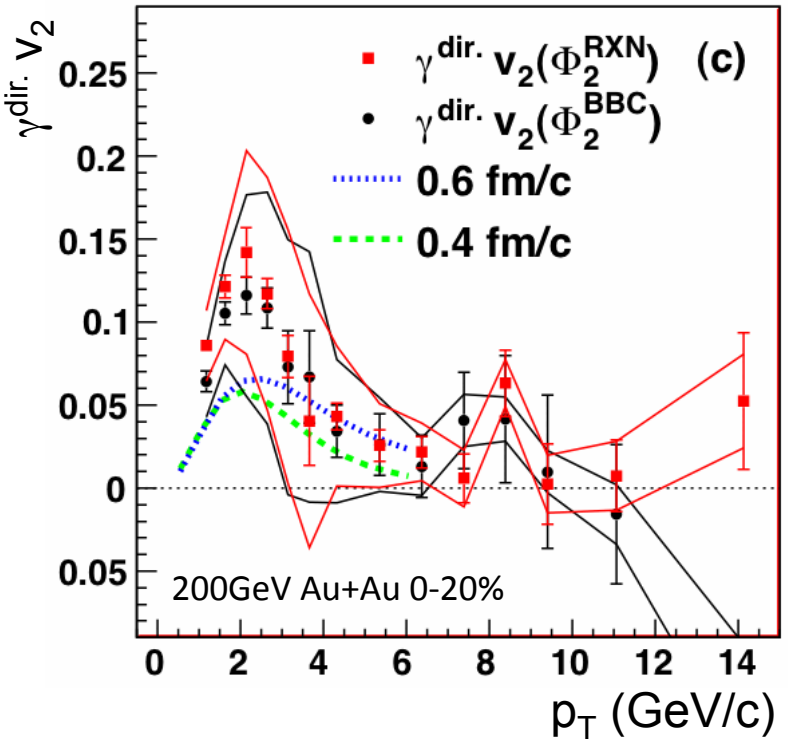
$$\frac{\Upsilon(2S+3S)/\Upsilon(1S)\big|_{PbPb}}{\Upsilon(2S+3S)/\Upsilon(1S)\big|_{pp}} = 0.31^{+0.19}_{-0.15} \pm 0.03$$

- Recall the sequential meting scenario; excited states dissolve at lower *T*



Excessive Photons with Low p_T





- Excess of low p_T photons in Au+ Au collisions at RHIC
  - Natural interpretation = thermal emission from QGP
- Large v_2 in the low p_T region
  - Too large to explain => challenge to theorists

Summary of Global Measurements

- Large energy & particle density with long duration time over large volume seems to be realized at LHC
  - $dN_{ch}/d\eta$ and $dE_T/d\eta$
  - *Behavior of $dN_{ch}/d\eta$ vs Npart seems to suggest strong hindrance of semi-hard (mini-jet) process*
  - Stiffer hadron spectra at low pT region
  - Homogeneity volume at LHC: ~2 times larger compared at RHIC
- Azimuthal anisotropy
  - Integrated v2 is larger at LHC, while differential v2 is very similar in a wide range of collision energy
  - v3, of fluctuation origin, is sensitive to initial condition and η/s
  - Relation of higher harmonics with ridge and Mach-cone structure
- Initial condition is the least known item
  - the reliable description of initial collision stage & equilibration stage is needed

Summary of Hard Probes

- Parton energy loss
  - R_{AA} of single particles in a wide p_T range at LHC
  - Successful event-by-event dijet reconstruction
  - Lost energy is shared by particles with small energy distributed at large angles *-> a key item of investigation in the coming years*
  - Azimuthal anisotropy -> path length dependence of energy loss *-> a key item of investigation in the coming years*
- Heavy flavor
  - Charmed meson measurement & single lepton measurement
  - *Active topic both at LHC and RHIC in the coming years*
- Quarkonia
  - Conclusive interpretation is not possible for RHIC results
  - *New results from LHC, including Υ -> very promising*
- Thermal photons?
  - Large v2 seems to be difficult to reproduce via conventional models
  - Other possible sources are currently being discussed