Heavy Ion Physics Lecture 2

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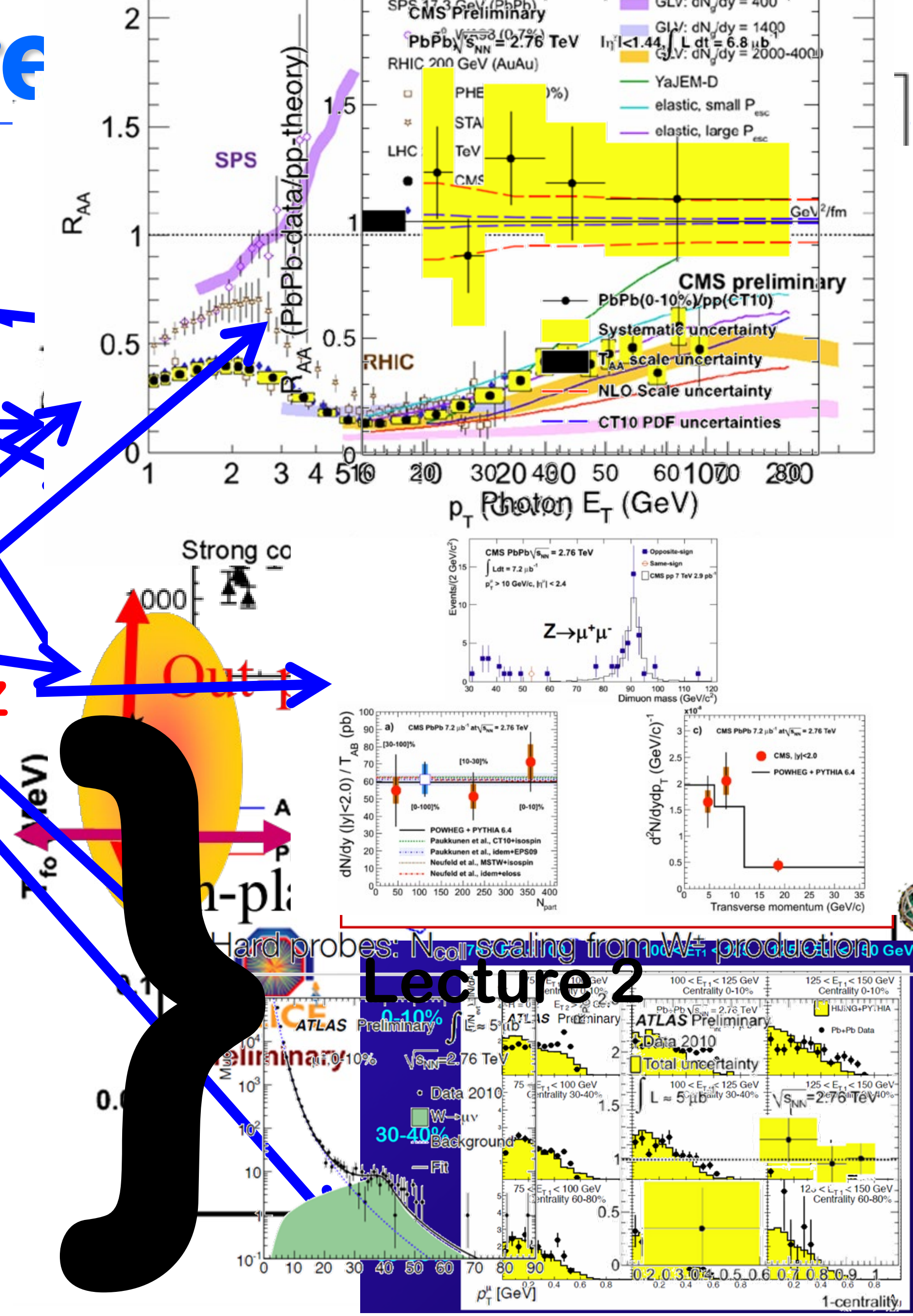
Outline of Lecture

- **What have we done?**
  - Energy Density
  - Initial Temperature
  - Chemical & Kinetic Equilibrium
  - System Size
- **Is There a There There?**
  - The Medium & The Probe
  - High Pt Suppression
  - Control Experiments: γ_{direct}, W, Z
- **What is It Like?**
  - Azimuthally Anisotropic Flow
  - Hydrodynamic Limit
  - Heavy Flavor Modification
  - Recombination Scaling
- **Is the matter exotic?**
  - Quarkonia, Jet Asymmetry, Color Glass Condensate
- **What does the Future Hold?**



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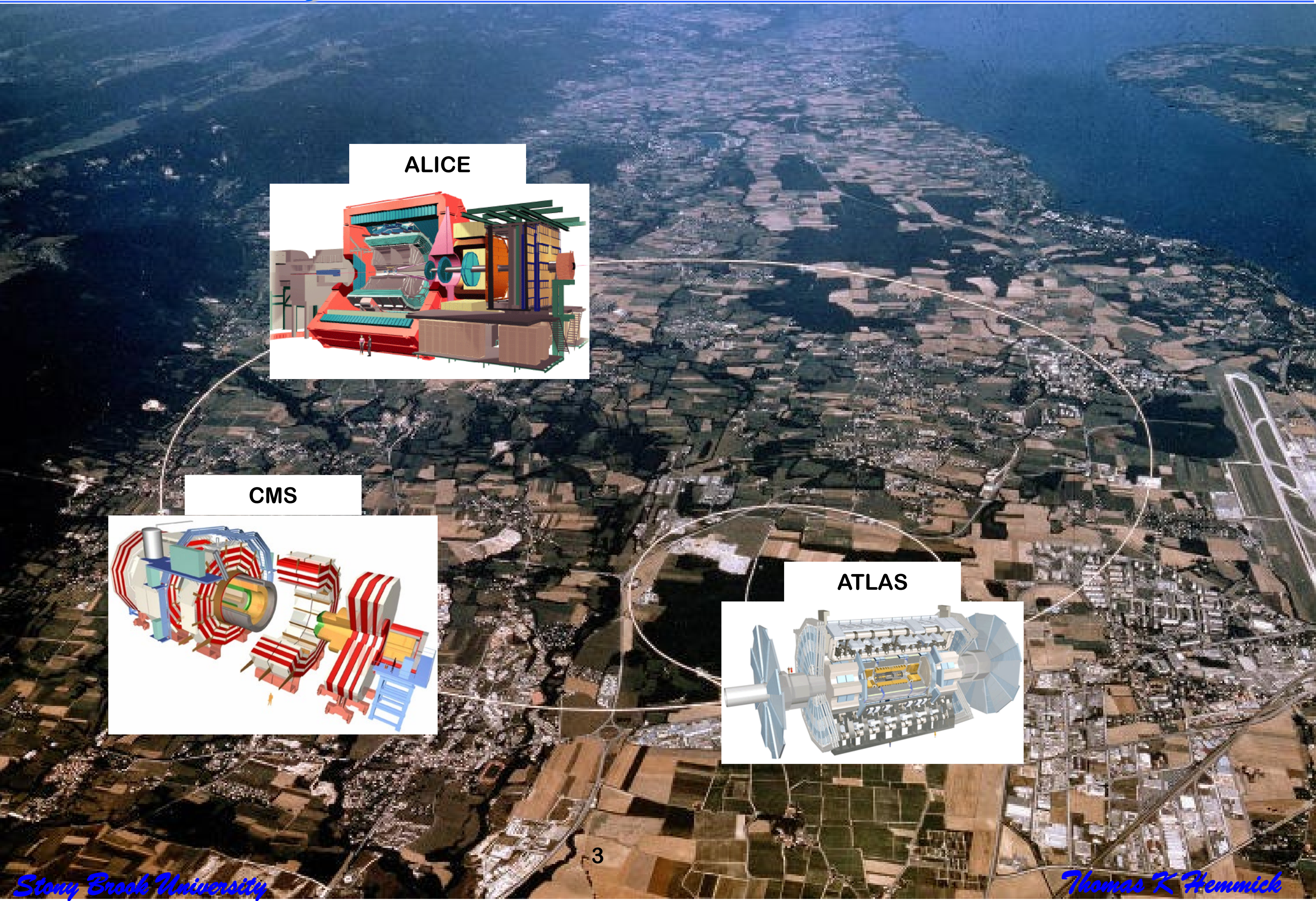
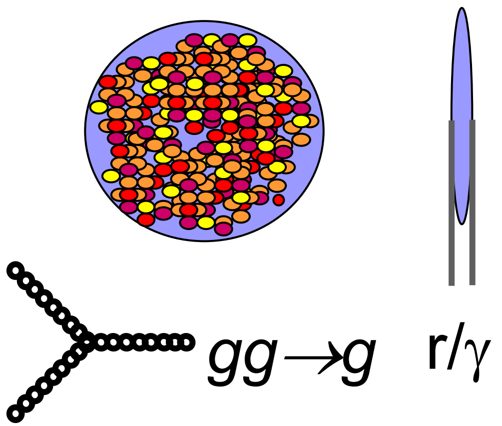
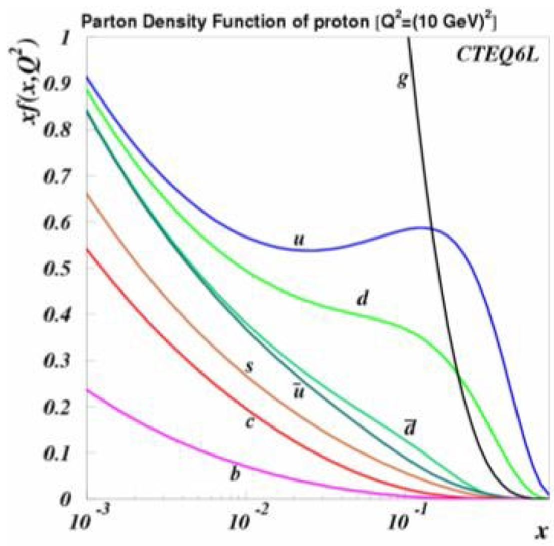
LHC Experiments

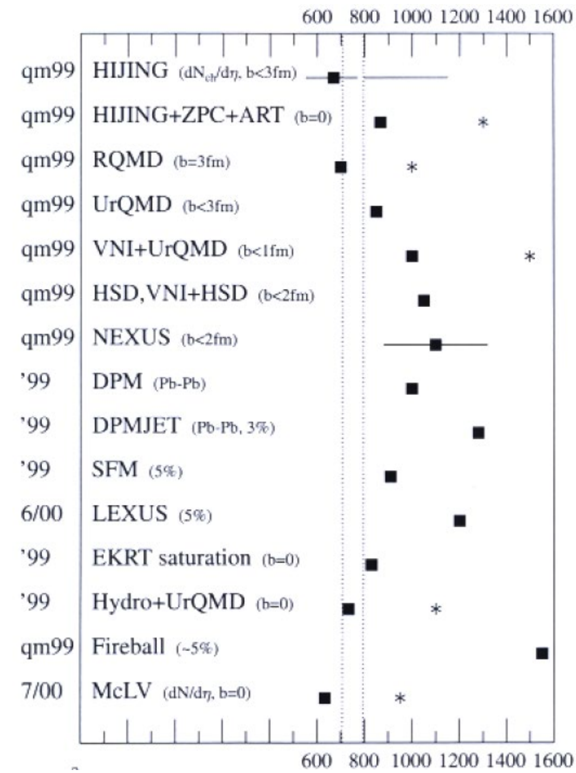


Could Suppression be Merely from the PDFs?

probe rest frame

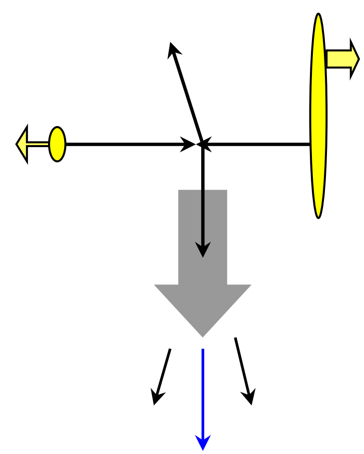


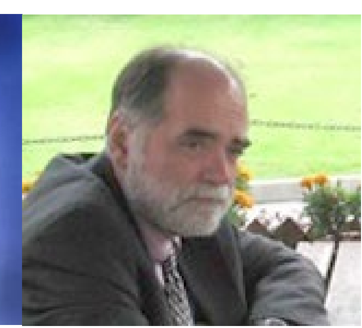




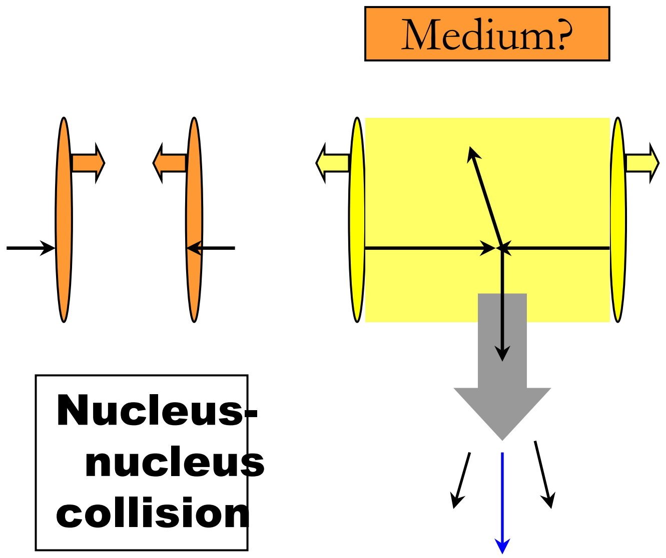
- **The lower in x one measures, the more gluons you find.**
- **At some low enough x, phase space saturates and gluons swallow one another.**
- **Another novel phase: Color Glass Condensate**

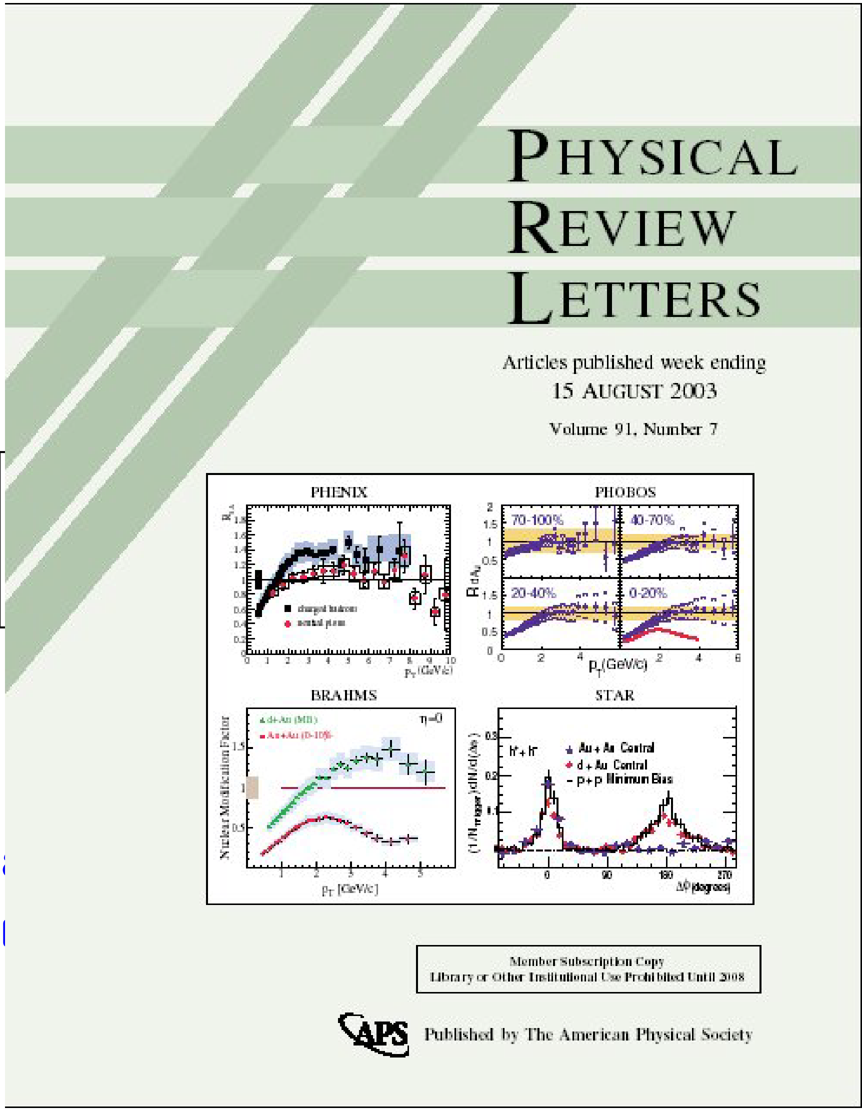
Control Experiment





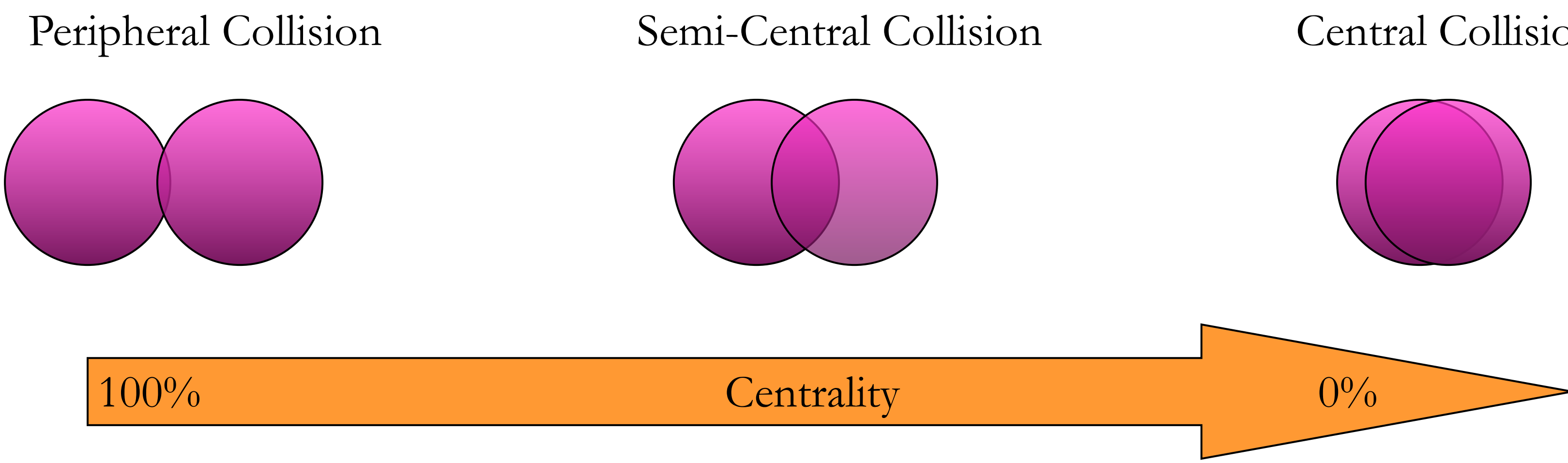
d+Au Control Experiment



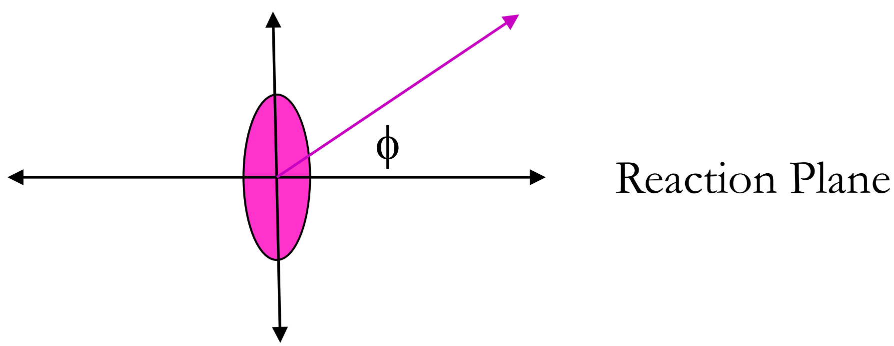


- Collisions of small with large nuclei qu
- Small + Large distinguishes **all** initial a

Terminology



- **Centrality and Reaction Plane determined on an Event-by-Event basis.**
- **N_{part}= Number of Participants**
  - **2 → 394**
- **N_{coll} = # Collisions**
  - **1→1000**



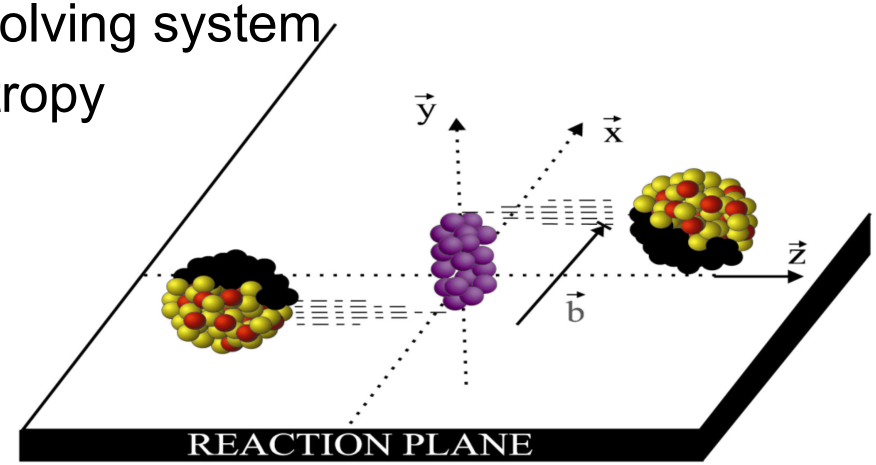
- **Fourier decompose azimuthal yield:**

$$\frac{d^3N}{d\phi\, dp_T\, dy} \propto \left[1 + 2v_1\cos(\phi) + 2v_2\cos(2\phi) + \ldots\right]$$

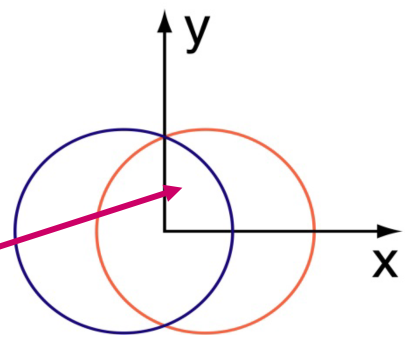
What is it Like? “elliptic flow”

Origin: spatial anisotropy of the system when created, followed by multiple scattering of particles in the evolving system

spatial anisotropy → momentum anisotropy

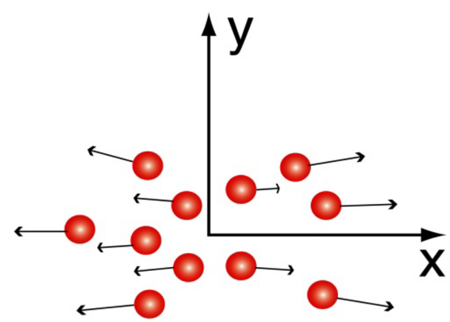


v_2: 2nd harmonic *Fourier coefficient* in azimuthal distribution of particles with respect to the reaction plane



Almond shape overlap region in coordinate space

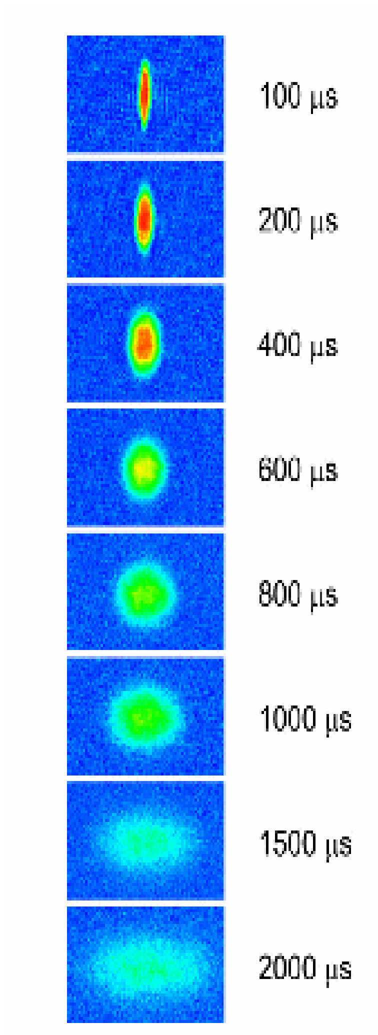
$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$



$$v_2 = \langle \cos 2\phi \rangle \qquad \phi = \mathrm{atan}\frac{p_y}{p_x}$$

Anisotropic Flow

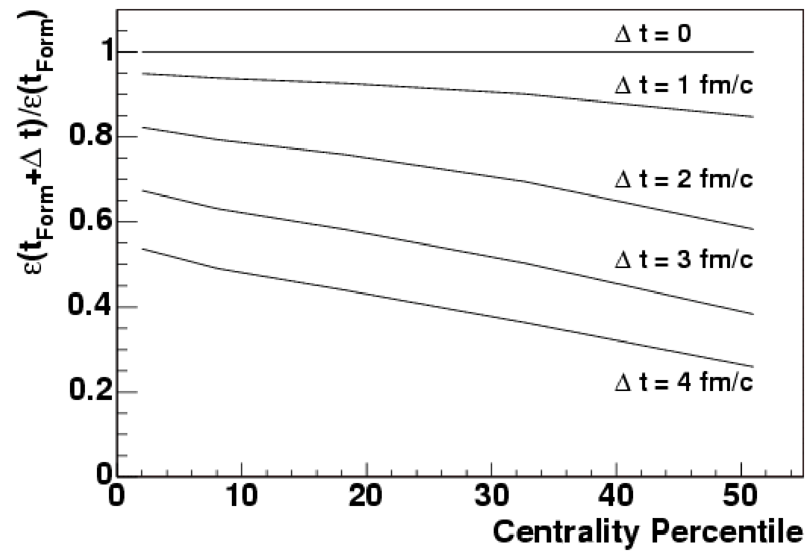
Liquid Li Explodes into Vacuum



Position Space anisotropy (eccentricity) is transferred to a momentum space anisotropy visible to experiment

- **Gases explode into vacuum uniformly in all directions.**
- **Liquids flow violently along the short axis and gently along the long axis.**
- **We can observe the RHIC medium and decide if it is more liquid-like or gas-like**

- **Process is SELF-LIMITING**
- **Sensitive to the initial time**



- **Delays in the initiation of anisotropic flow not only change the magnitude of the flow but also the centrality dependence increasing the sensitivity of the results to the initial time.**

Fourier Expansion

- Most general expression for ANY invariant cross section uses explicit Fourier-Series for explicit ϕ dependence:

$$\frac{1}{p_T}\frac{d^3N}{dp_T d\phi dy} = \frac{1}{2\pi p_T}\frac{d^2N}{dp_T dy}\left[1 + 2v_1(p_T, y)\cos(\phi) + 2v_2(p_T, y)\cos(2\phi) + \dots\right]$$

  here the sin terms are skipped by symmetry agruments.

- For a symmetric system (AuAu, CuCu) at y=0, v_{odd} vanishes

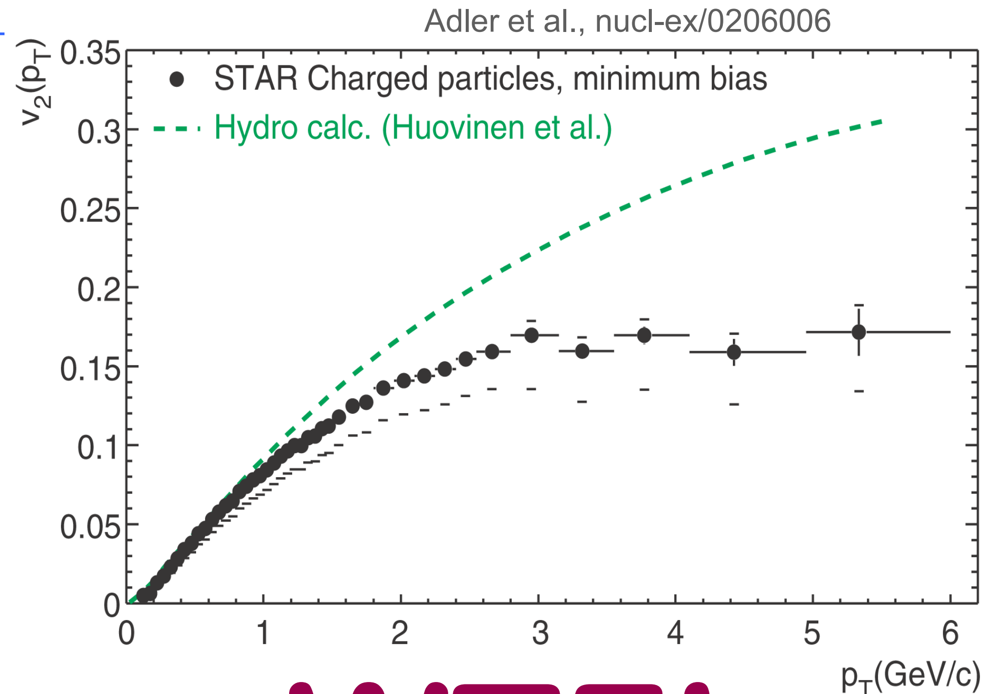
$$\frac{1}{p_T}\frac{d^3N}{dp_T d\phi dy} = \frac{1}{2\pi p_T}\frac{d^2N}{dp_T dy}\left[1 + 2v_2(p_T)\cos(2\phi) + 2v_4(p_T)\cos(4\phi) + \dots\right]$$

- v_4 and higher terms are non-zero and measured but will be neglected for this discussion.

$$\frac{1}{p_T}\frac{d^3N}{dp_T d\phi dy} = \frac{1}{2\pi p_T}\frac{d^2N}{dp_T dy}\left[1 + 2v_2(p_T)\cos(2\phi)\right]$$

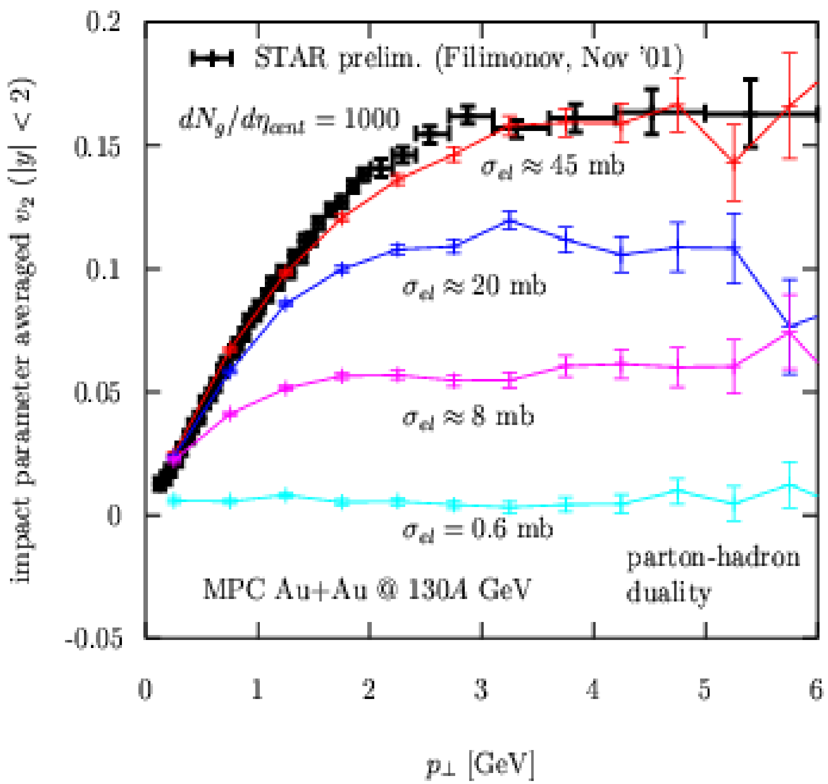
Huge v_2!

- Hydrodynamic limit exhausted at RHIC for low p_T particles.
- Can microscopic models work as well?
- Flow is sensitive to thermalization time since expanding system loses spatial asymmetry over time.
- Hydro models require thermalization in less than τ=1 fm/c



WTF!

What is needed, partonically for v_2?



parton transport solutions via **MPC 1.6.0** [D.M. & Gyulassy, NPA 697 ('02)]

$$p^\mu \partial_\mu f_i = S_i + C_i^{2\to2}[f] + \ldots$$

minijet initial conditions

$1g \to 1\pi$ hadronization

Huge cross sections!!

- **saturation pattern can be reproduced with elastic $2 \to 2$ interactions,**

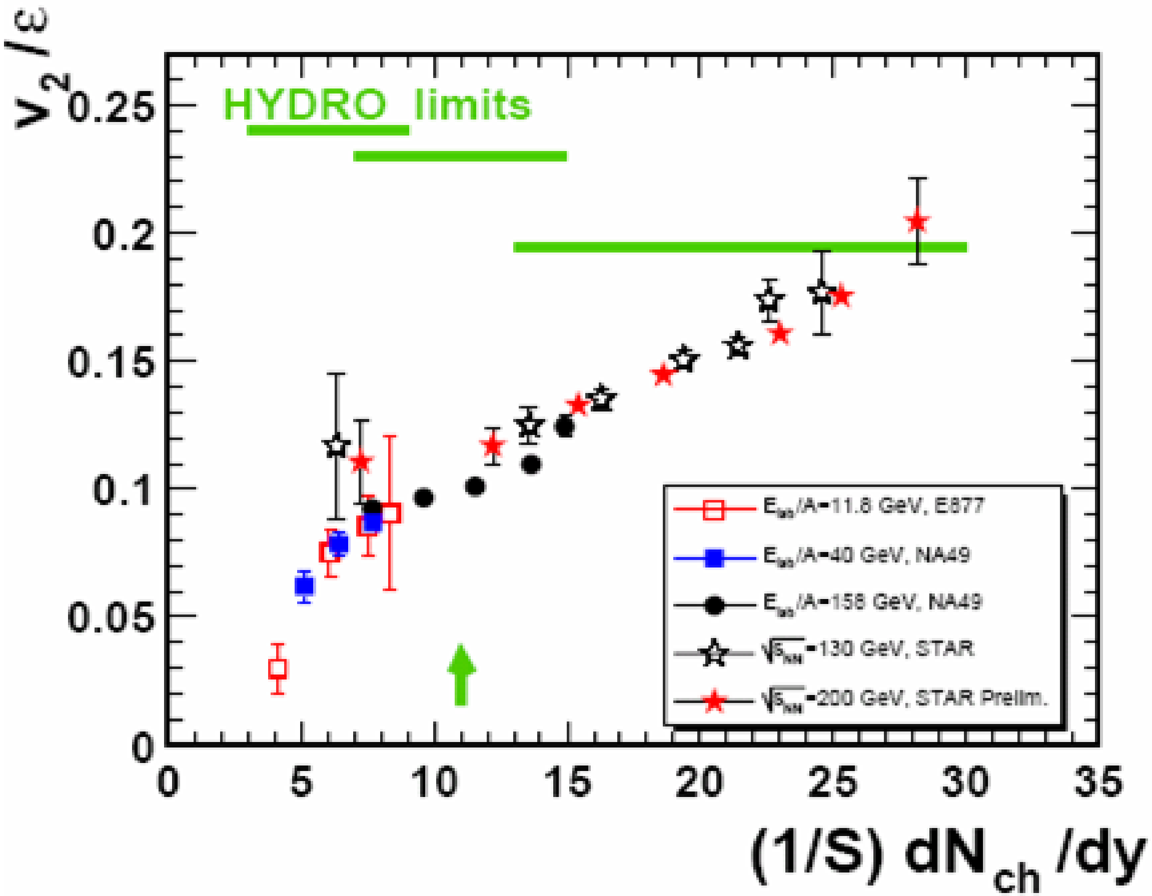
  requires large opacities $\sigma_{el} \times dN_g/d\eta \approx 45000$ mb $\gg$ pQCD (3 mb $\times 1000$)

  - large opacities also suggested by pion HBT data [D.M & Gyulassy, nucl-th/0211017]

if (πr^3==45 mb) {r=1.2 fm};

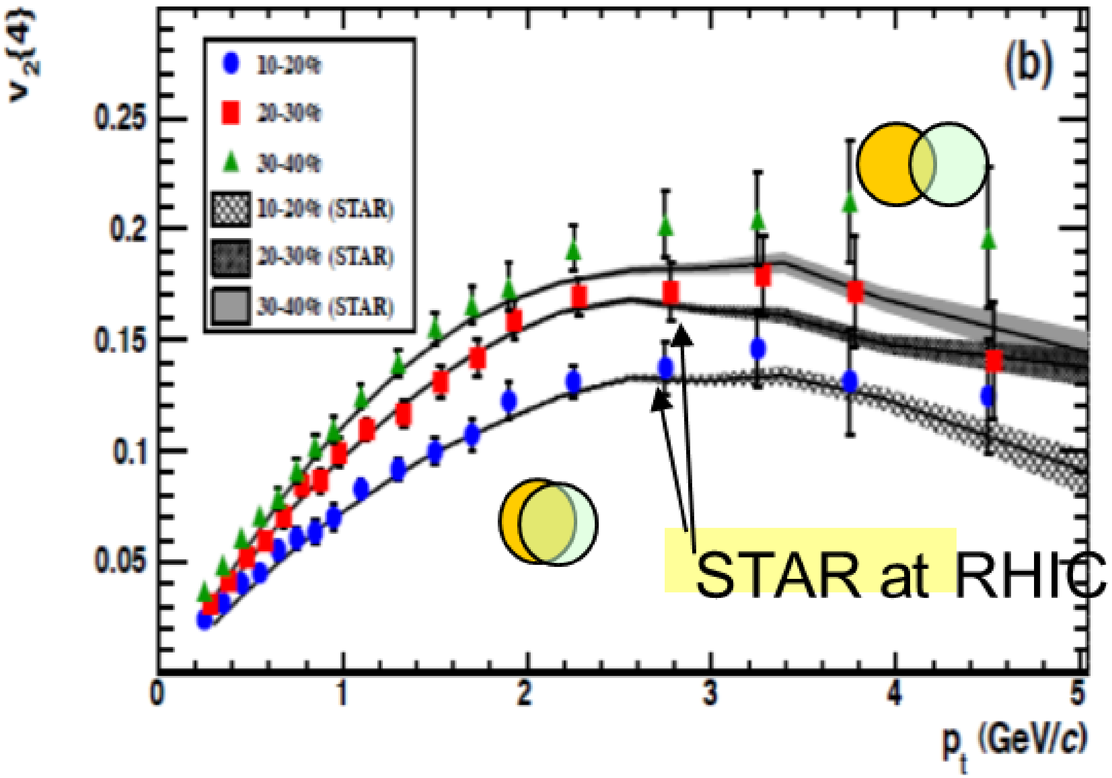
D. Molnár, SQM2003, Mar '02 – 4

Comparison to Hydro Limit



- Hydro limit drops with energy.
- RHIC "exhausts" hydro limit.
- Does the data flatten to LHC or rise?

LHC Flow results match RHIC

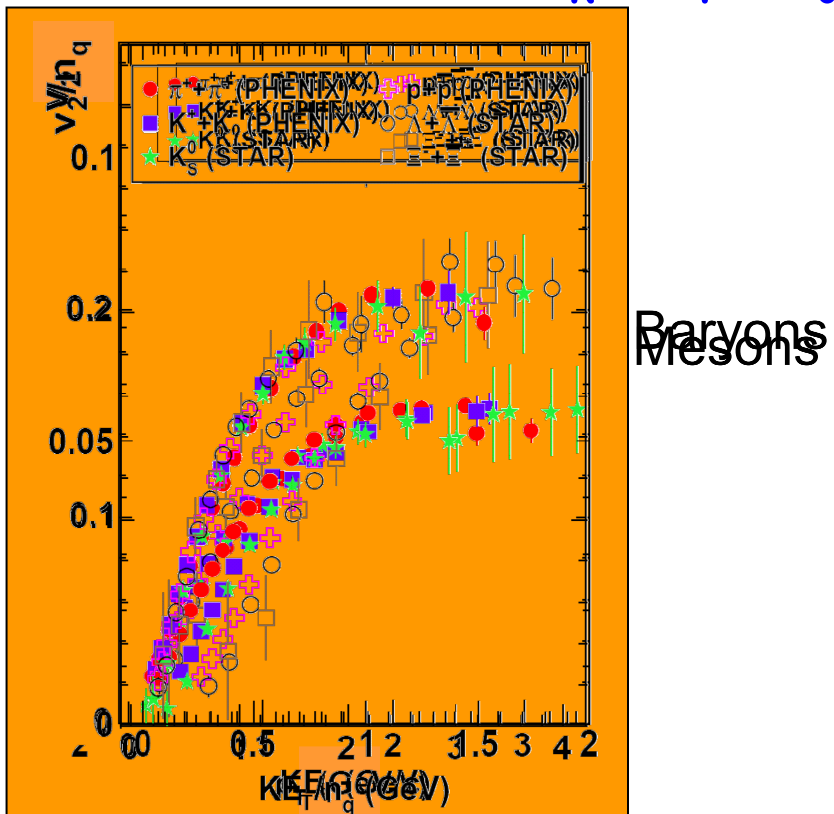


- Magnitude of flow as a FUNCTION of p_T is nearly exactly the same as at RHIC.
- LHC data reach to very high moments (v_6).

What else we can get from Hydro?

So far we have tracked the hydrodynamic evolution of the system back in time to the initial state. Let now Hydro do something good for us.

Approximately: $\partial_\nu T^{\mu\nu} = 0 \rightarrow \int \nabla P \, dV \;=\; \Delta E_K \cong m_T - m_0 \equiv \Delta KE_T \;= \sqrt{p_T^2 + m_0^2}$

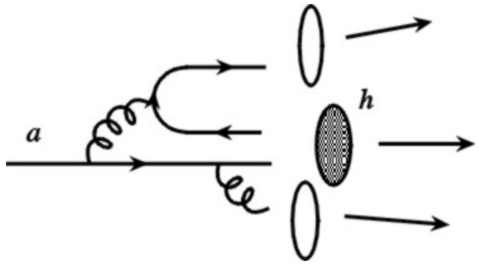


v_2 for different m_0 shows good agreement with “ideal fluid” hydrodynamics

An “ideal fluid” which knows about quarks!

Recombination Concept

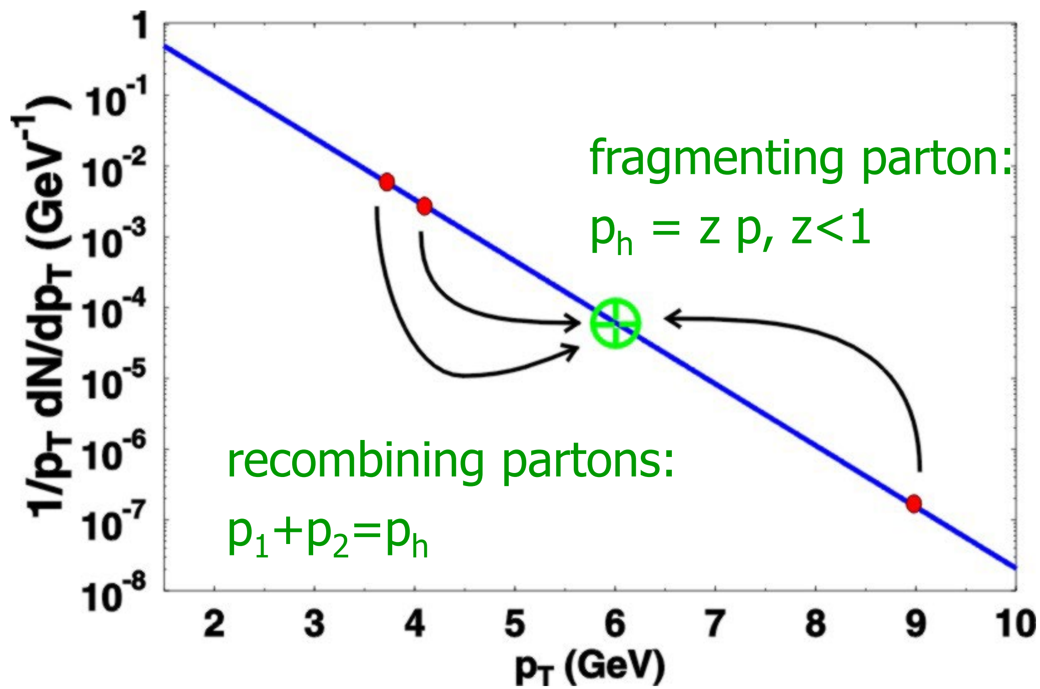
Fragmentation:



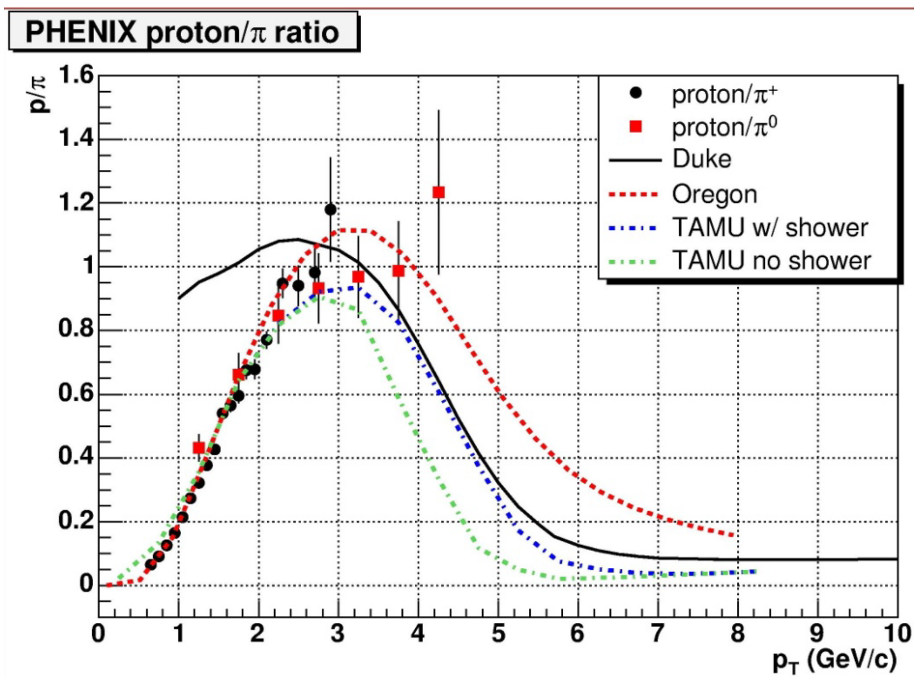
$$E\frac{dN_h}{d^3P} = \int_0^1 \frac{dz}{z^2}\,\frac{E}{z}\,\frac{dN_a}{d^3(P/z)}\,D_{\alpha\to h}(z)$$

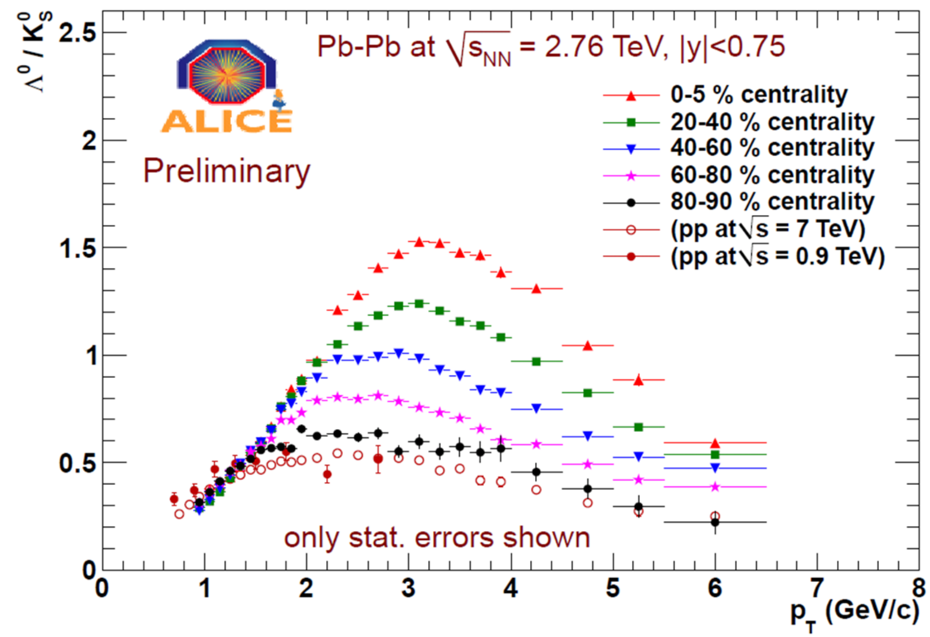
- for exponential parton spectrum, recombination is more effective than fragmentation
- baryons are shifted to higher p_t than mesons, for same quark distribution

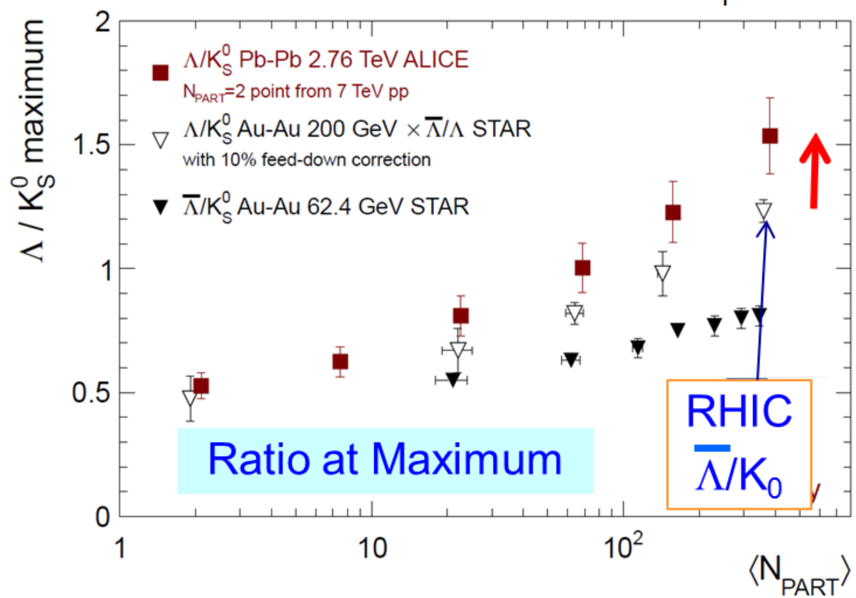
➢ understand behavior of protons!



Baryon Anomaly





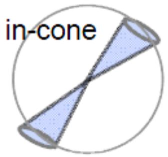


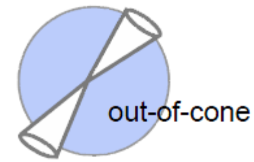
- Recombination models assume particles are formed by the coalescence of "constituent" quarks.
- Explain baryon excess by simple counting of valence quark content.

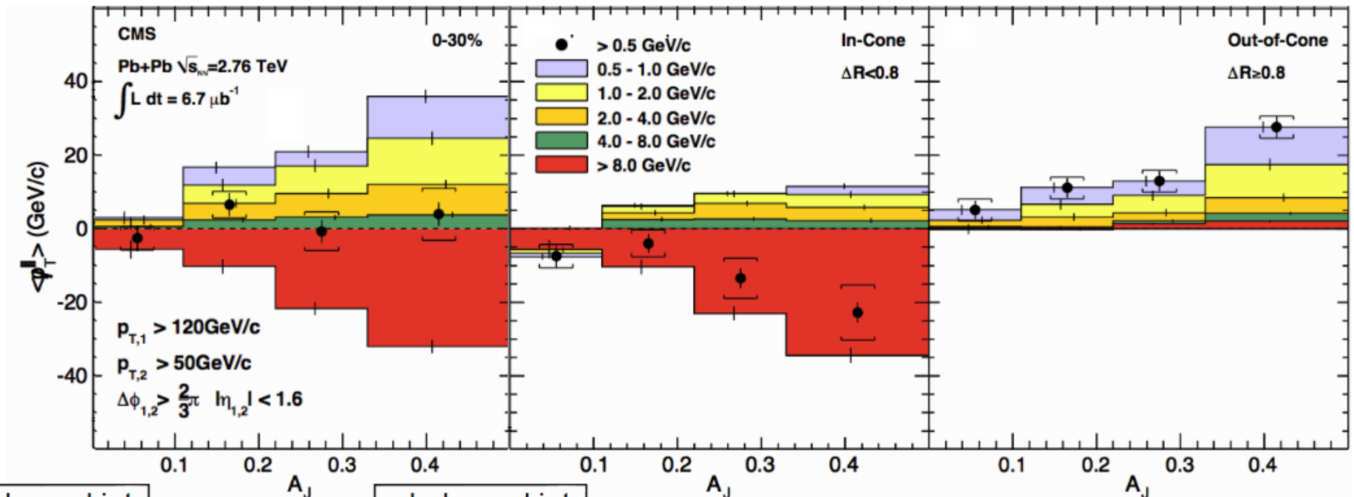
Where does the Energy: LHC

$$\not{p}_T^{\parallel} = \sum_{\text{Tracks}} -p_T^{\text{Track}} \cos\left(\phi_{\text{Track}} - \phi_{\text{Leading Jet}}\right)$$

0-30% Central PbPb







balanced jets　　unbalanced jets

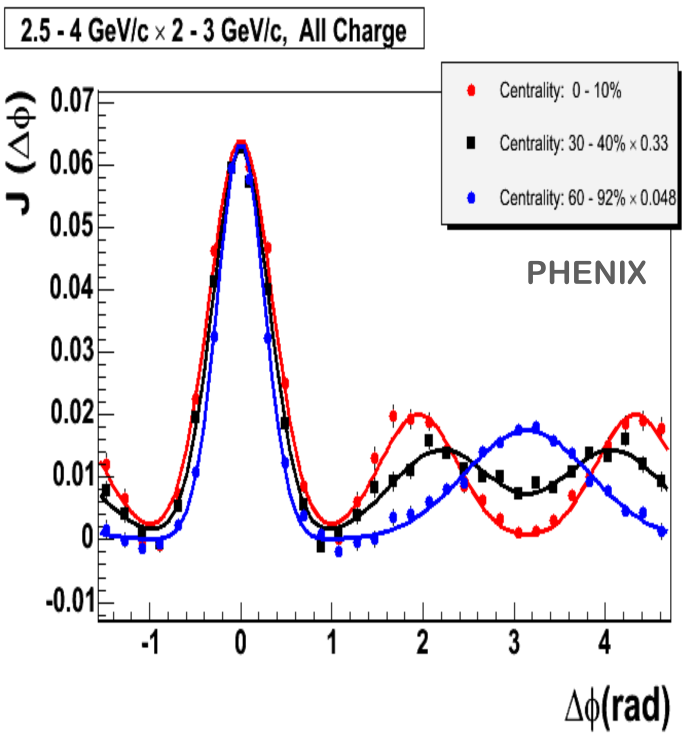
Low p_T, full acceptance
Momentum is balanced

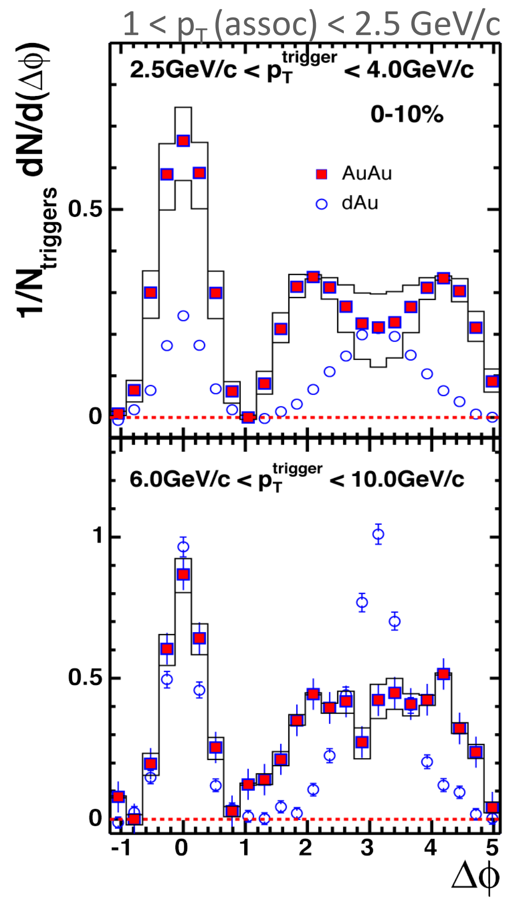
In-cone large momentum imbalance at high p_T
Consistent with calorimetry

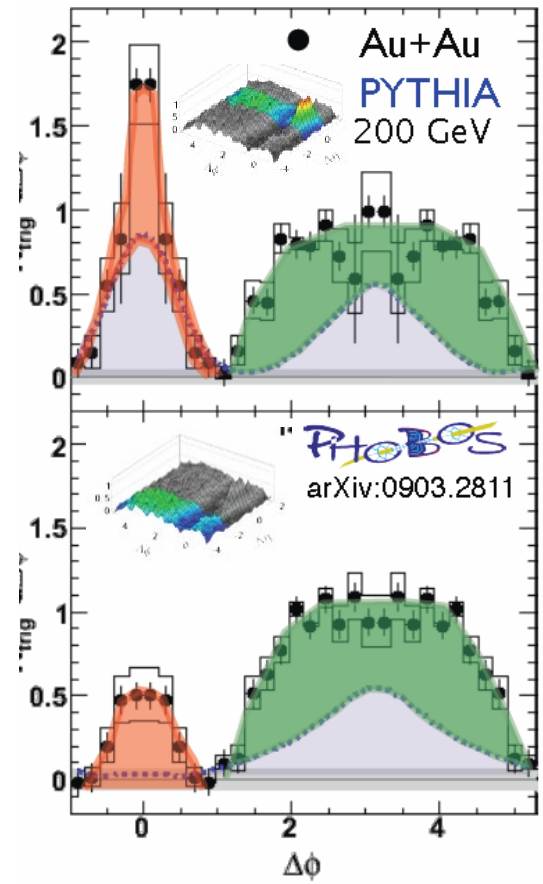
Out-off-cone low p_T particles balance the complete event

- **Outside of large cone (R=0.8)**
- **Carried by soft particles**

Away Jet cannot "Disappear"





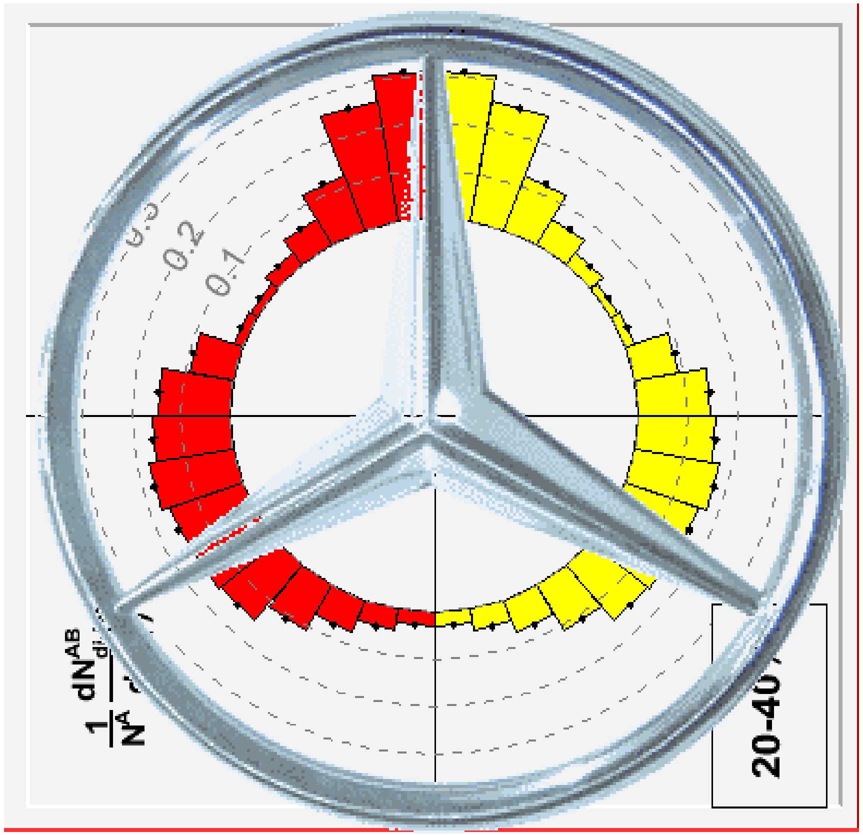


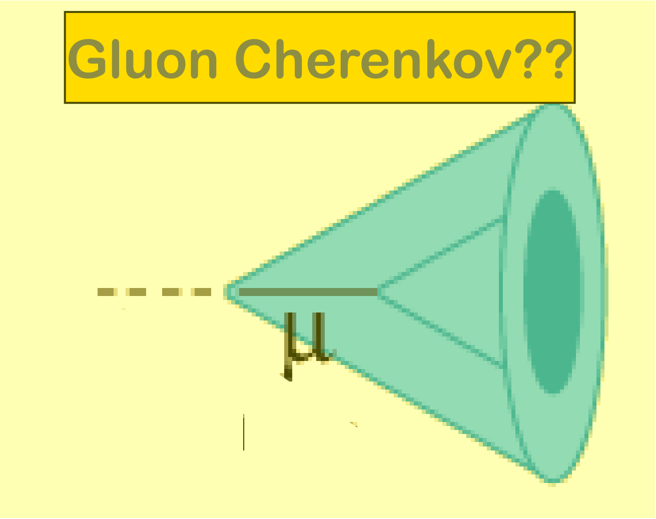
- Energy conservation says "lost" jet must be found.
- "Loss" was seen for partner momenta just below the trigger particle…Search low in momentum for the remnants.

Correlation of soft ~1-2 GeV/c jet partners

Emergence of a Volcano Shape

“split” of away side jet!

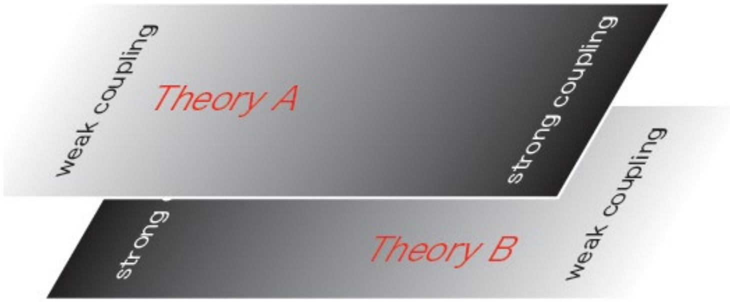




120°…is it just v_3???   Stay Tuned…

Strings: Duality of Theories that Look Different

- Tool in string theory for 10 years
- Strong coupling in one theory corresponds to weak coupling in other theory



- AdS/CFT duality
  (Anti deSitter Space/ Conformal field theory)

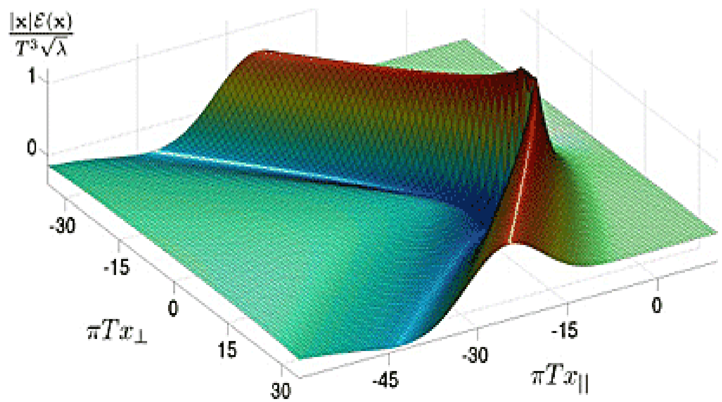
QGP (in QCD)

⇕

Finite temperature gauge theory ⇔ Black hole
at strong coupling (N=4 SYM) in AdS space

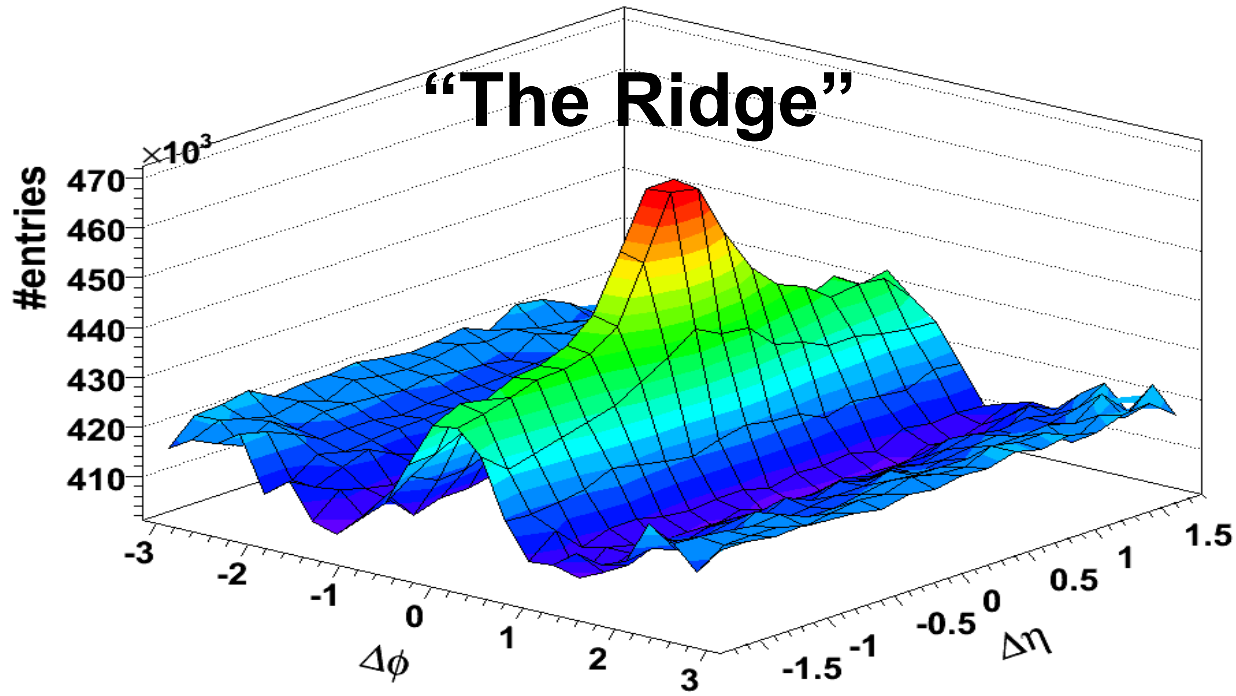
⇓ thermal

⇓ thermal due to the Hawking radiation



Calculated from AdS/CFT Duality

Another Exotic Structure: Ridge



Is this bulk response to stimulus…long range flux tubes…v_3?

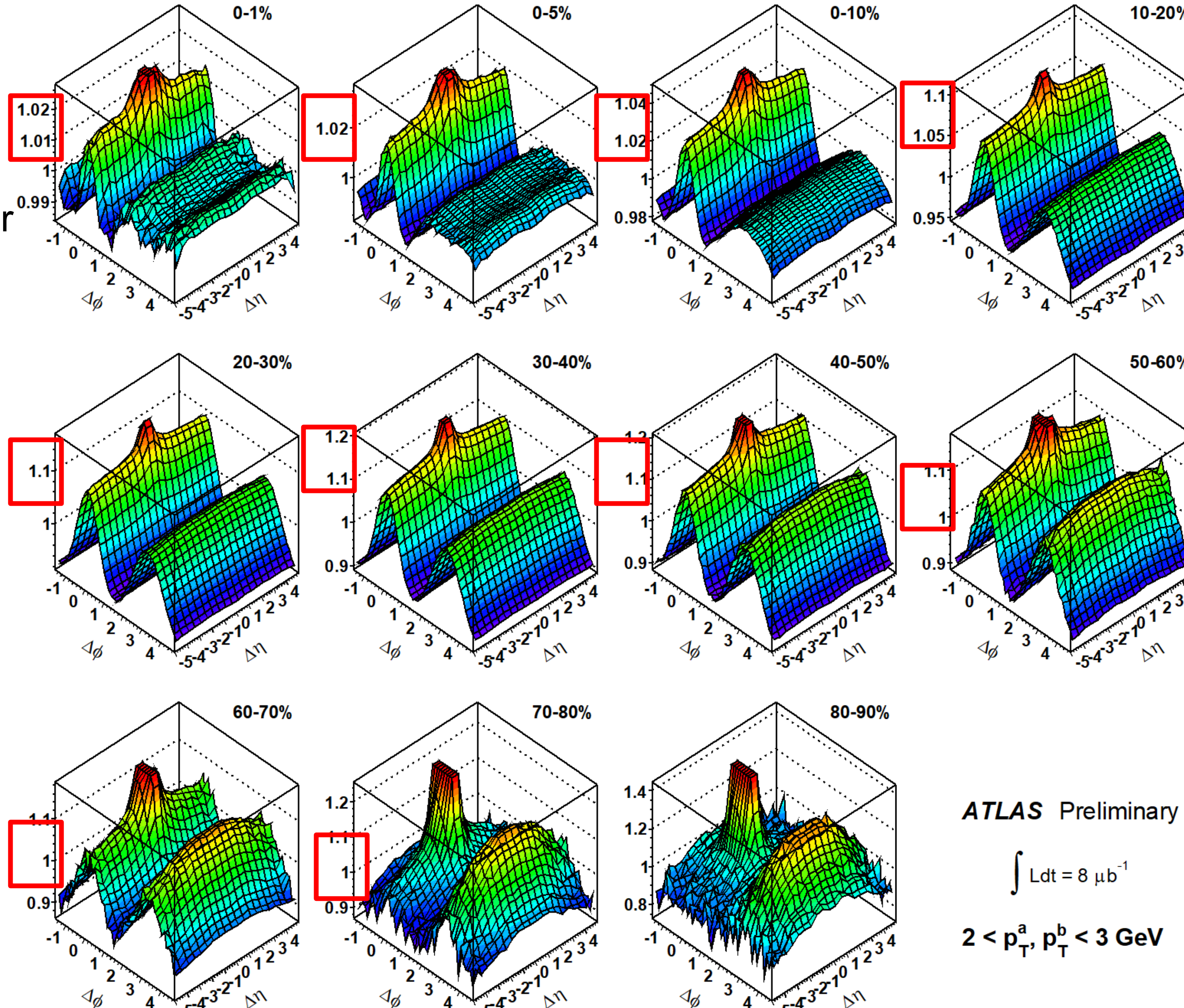
1. p_T spectra similar to bulk (or slightly harder)
2. baryon/meson enhancement similar to bulk
3. Scales per trigger like Npart similar to bulk

Rise and fall of "ridge/cone"—Centrality evolution

Pay attention to how long-range structures disappear and clear jet-related peaks emerge on the away-side

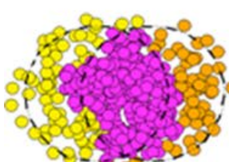
Strength of soft component increase and then decrease

Near-side jet peak is truncated from top to better reveal long range structure



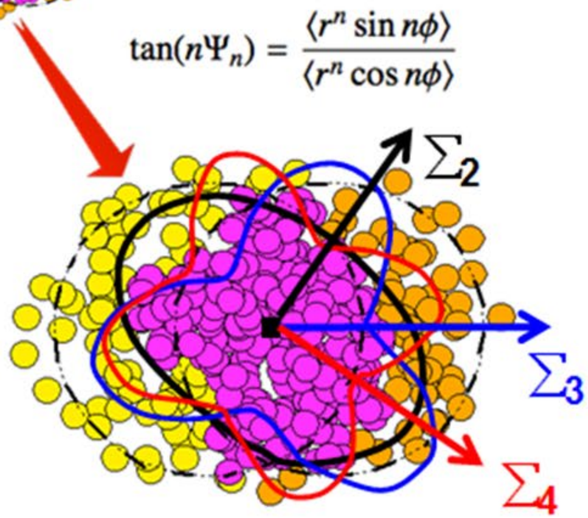
Ridge and Cone = v_3???

- **Event Plane method yields $\langle v_n \rangle$ ($v_{odd}=0$).**
- **2-particle yields SQRT($\langle v_n^2 \rangle$) ($v_{odd}>0$).**
- **How to disentangle:**
  - **PHENIX = EP method + factorization.**
  - **ATLAS = Rapidity OUTSIDE other Jet.**
  - **Everyone else = Factorization.**

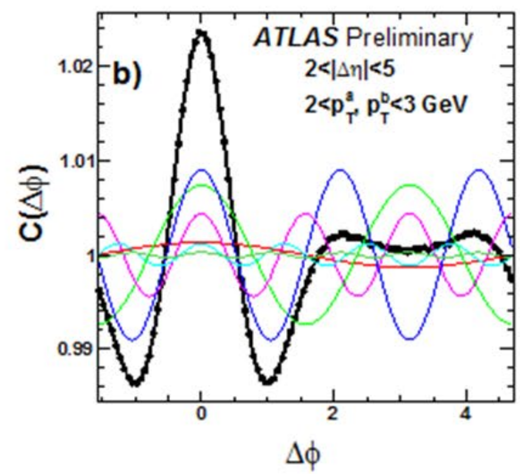


$$\epsilon_n = \sqrt{\frac{\langle r^n \cos n\phi \rangle + \langle r^n \sin n\phi \rangle}{\langle r^n \rangle}}$$

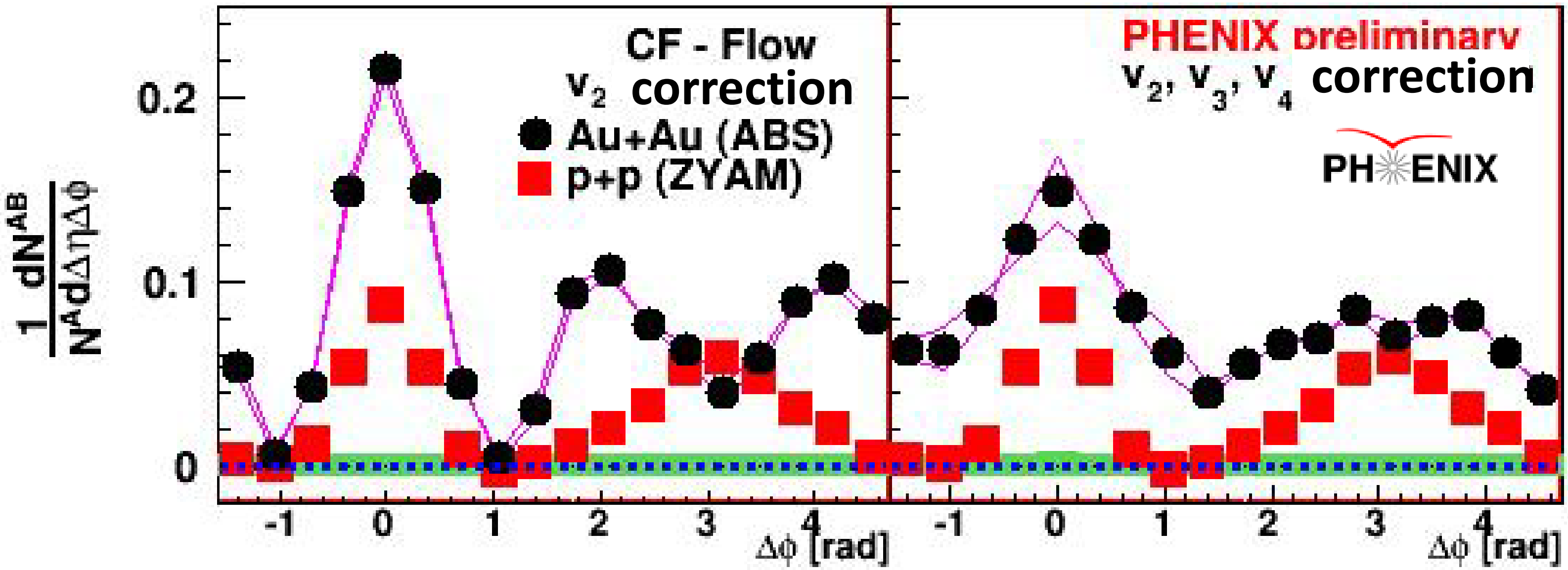
$$\tan(n\Psi_n) = \frac{\langle r^n \sin n\phi \rangle}{\langle r^n \cos n\phi \rangle}$$



Singles:	$\frac{dN}{d\phi} \propto 1 + \sum_n 2v_n \cos n(\phi - \Psi_n)$	**EP method**
Pairs:	$\frac{dN}{d\Delta\phi} \propto 1 + \sum_n 2v_n^a v_n^b \cos(n\Delta\phi)$	**2PC method**

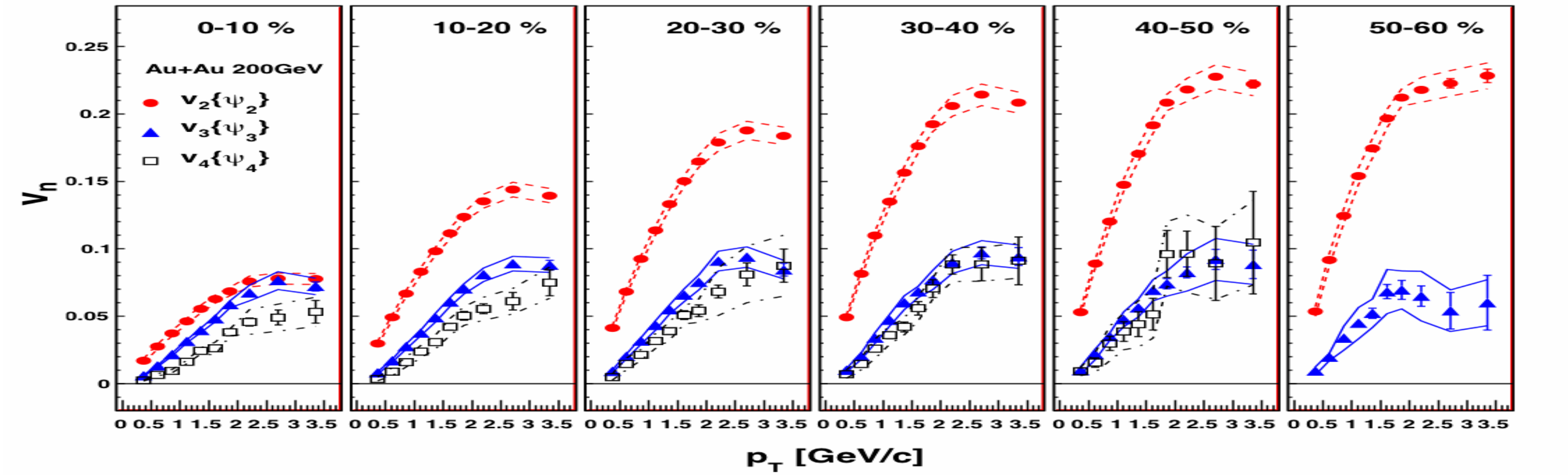


v_3 explains double-hump

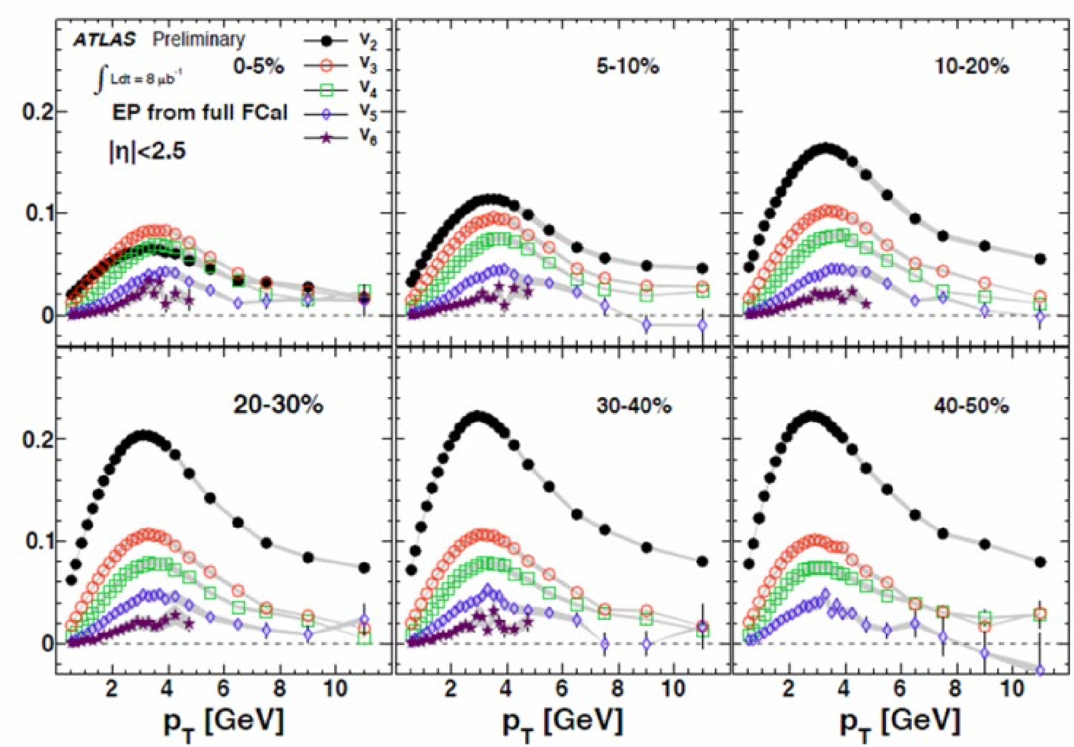


- v_2 correction only
  - double-hump
- v_2, v_3, v_4 correction
  - double-hump disappeared
  - Peak still broadened

Higher order moments

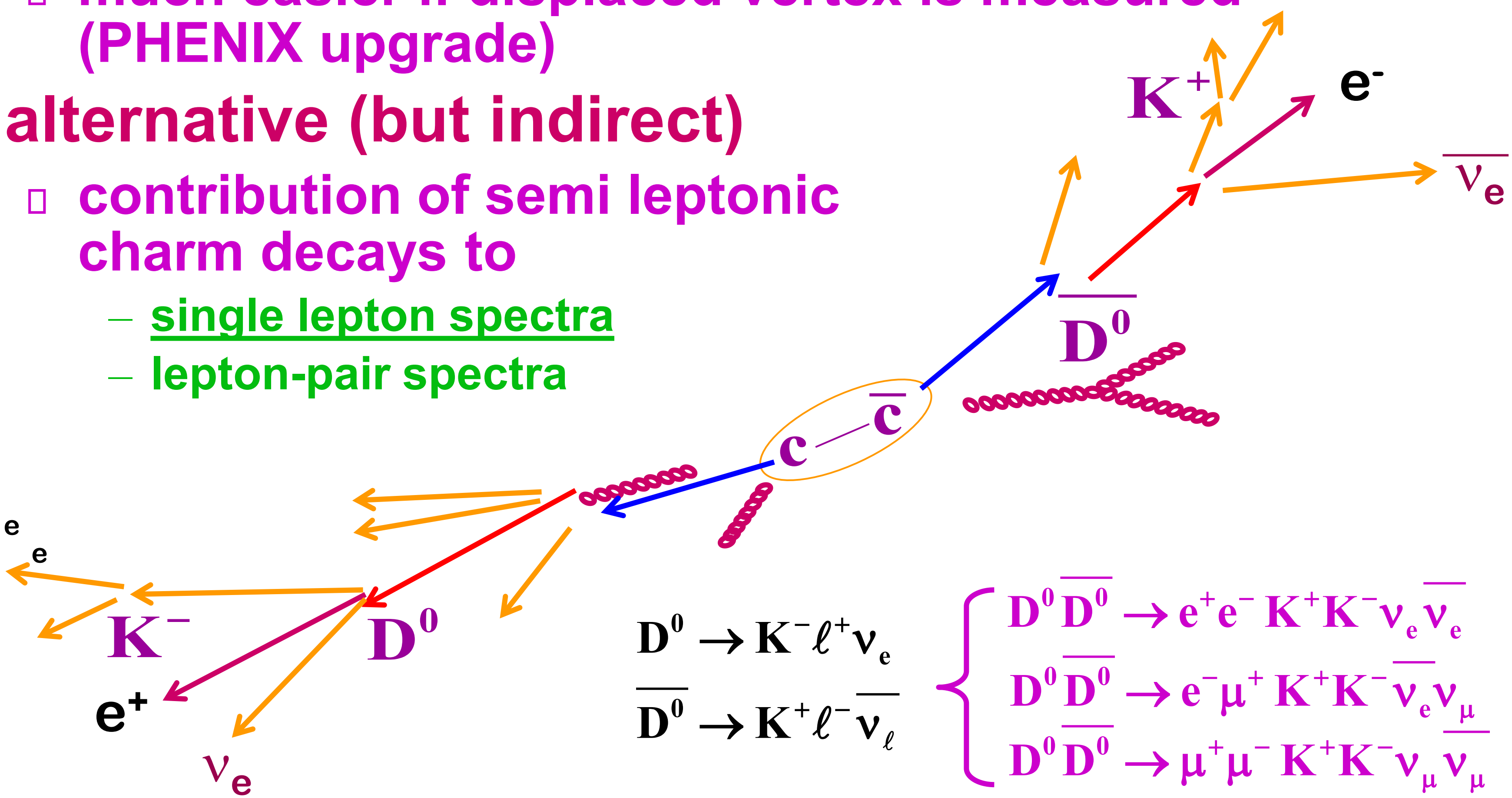


- Higher order moments can be measured WRT their own "reaction plane".
- Determines how initial state fluctuations are carried by fluid to final state.
- Higher order moments will serve to provide strong constraint on viscosity.



How can charm (bottom) be measured?

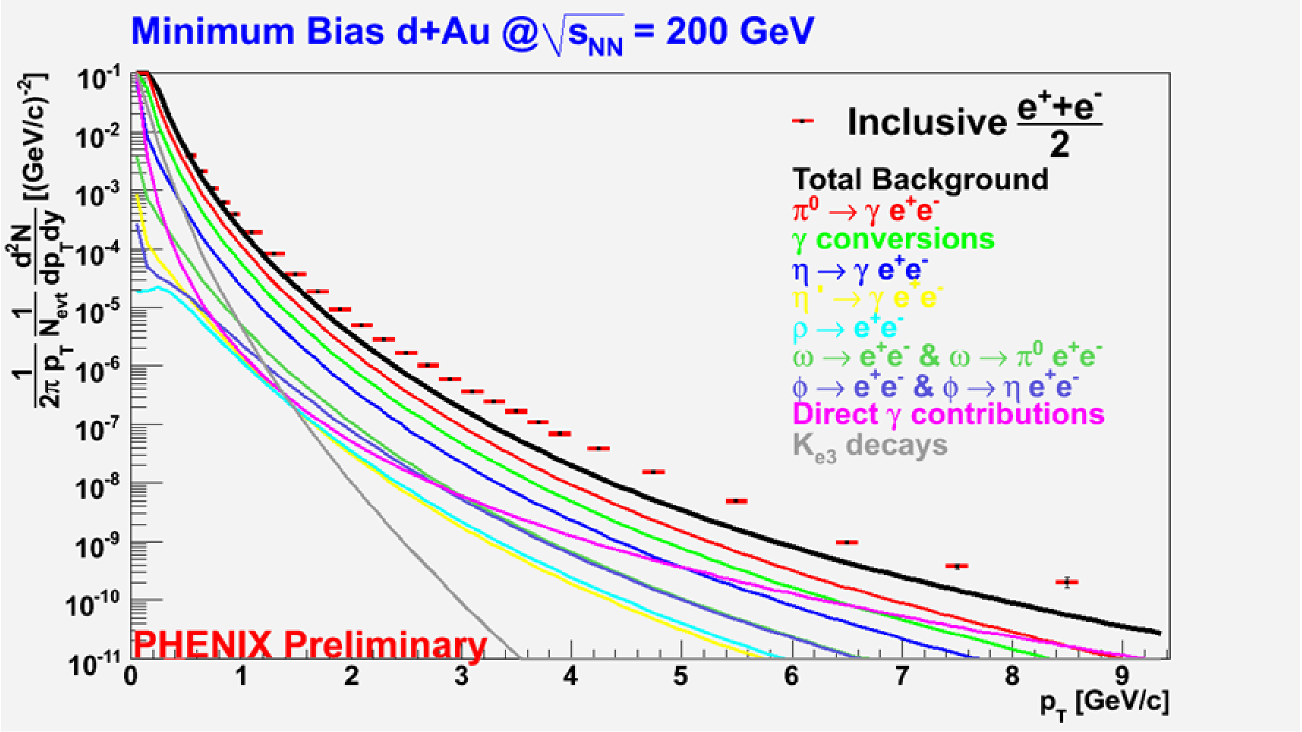
- ideal (but challenging)
  - direct reconstruction of charm decays (e.g. $D^0 \rightarrow K^- \pi^+$)
  - much easier if displaced vertex is measured (PHENIX upgrade)
- alternative (but indirect)
  - contribution of semi leptonic charm decays to
    - <u>single lepton spectra</u>
    - lepton-pair spectra



$$D^0 \rightarrow K^- \ell^+ \nu_e$$
$$\overline{D^0} \rightarrow K^+ \ell^- \overline{\nu}_\ell$$

$$\left\{ \begin{array}{l} D^0\overline{D^0} \rightarrow e^+ e^- K^+ K^- \nu_e \overline{\nu}_e \\ D^0\overline{D^0} \rightarrow e^- \mu^+ K^+ K^- \overline{\nu}_e \nu_\mu \\ D^0\overline{D^0} \rightarrow \mu^+ \mu^- K^+ K^- \nu_\mu \overline{\nu}_\mu \end{array} \right.$$

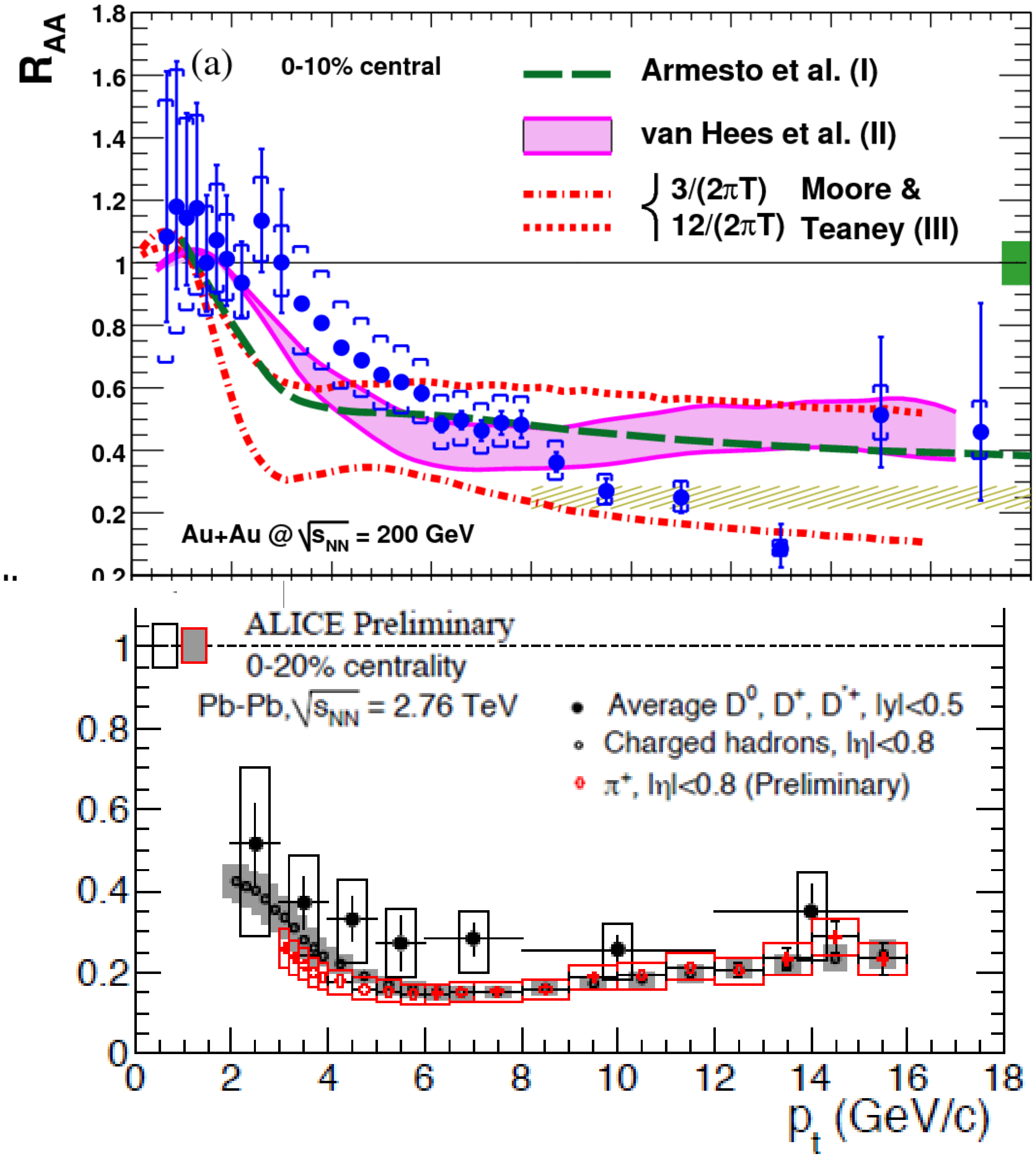
Inferred Heavy Flavor



- Measurement inclusive $e^{\pm}$.
- Measure π^0, η^0
- Construct "Cocktail" of electron sources other than c/b
  - light hadron decays
  - photon conversions
- Subtract $e^{\pm}$ "cocktail" leaves e from c/b.

Hard Probes: Open Heavy Flavor

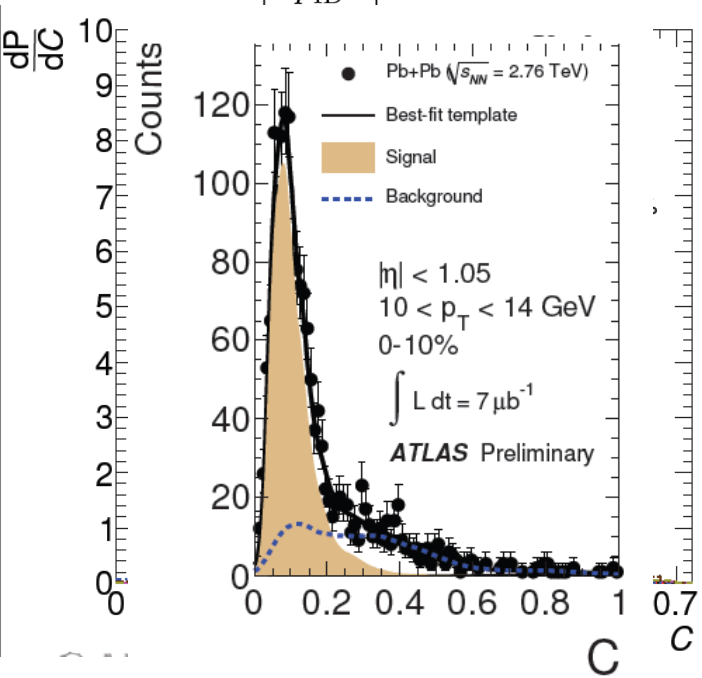
Electrons from c/b hadron decays

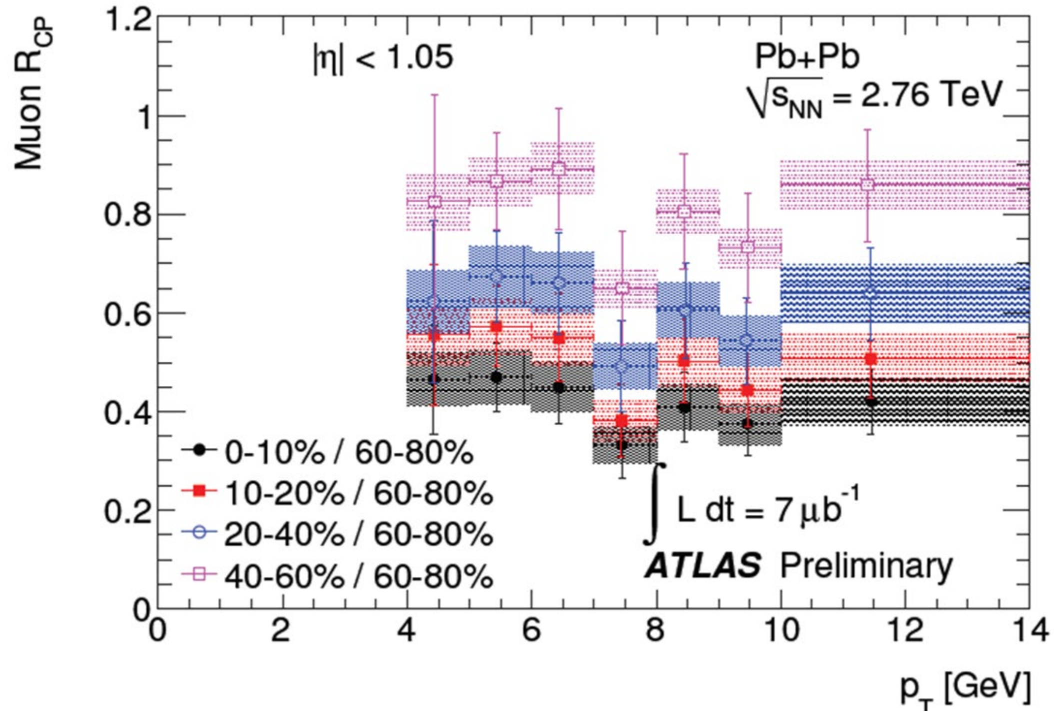


- **Calibrated probe?**
  - pQCD now predicts cross section well
  - Total charm follows binary scaling
- **Strong medium effects**
  - Significant suppression
  - Upper bound on viscosity!
  - Little room for bottom production
- **Limited agreement with energy loss calculations**

Single Muons from ATLAS

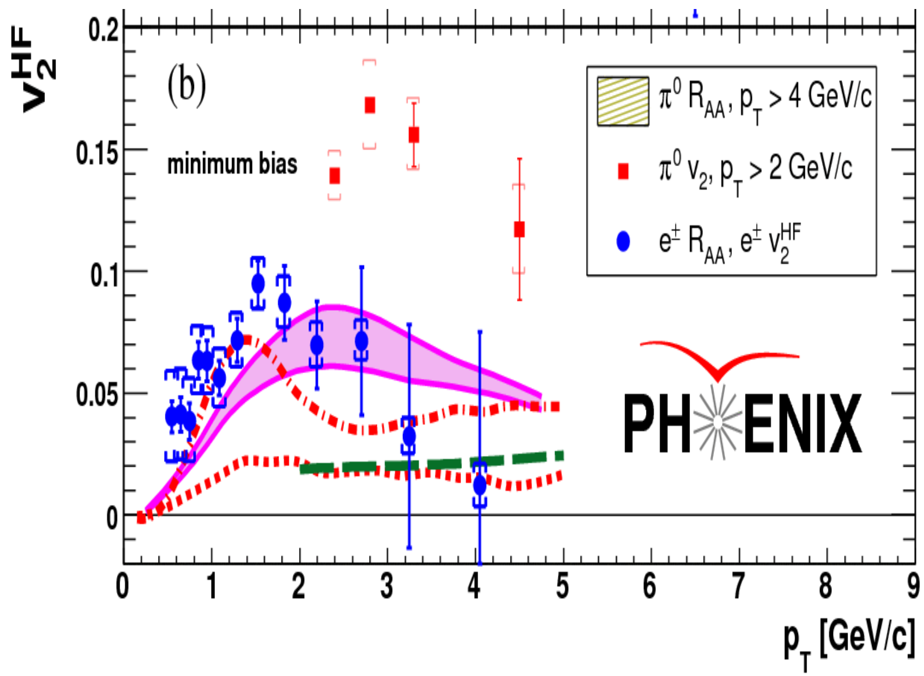
$$C = \left| \frac{\Delta p_{\mathrm{loss}}}{p_{\mathrm{ID}}} \right| + rS$$

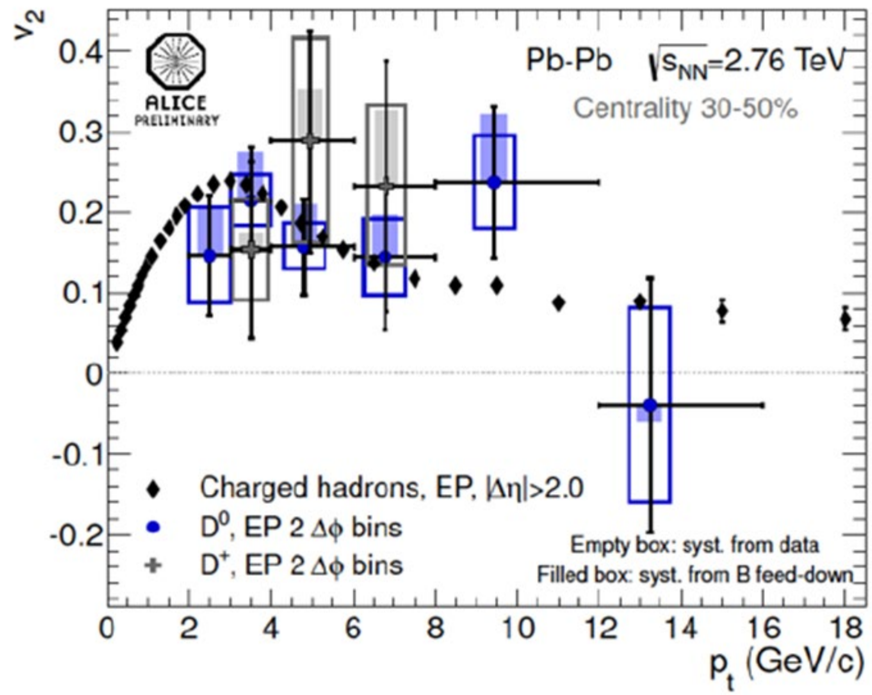




- High Momentum muons dominantly from heavy flavor.
- Eliminate unwanted background by statistical method.
- At these high momenta, the muons are likely dominated by bottom.
- Is there a limit to the power of the river?...Stay tuned.

Heavy Flavor Quarks are Flowing!

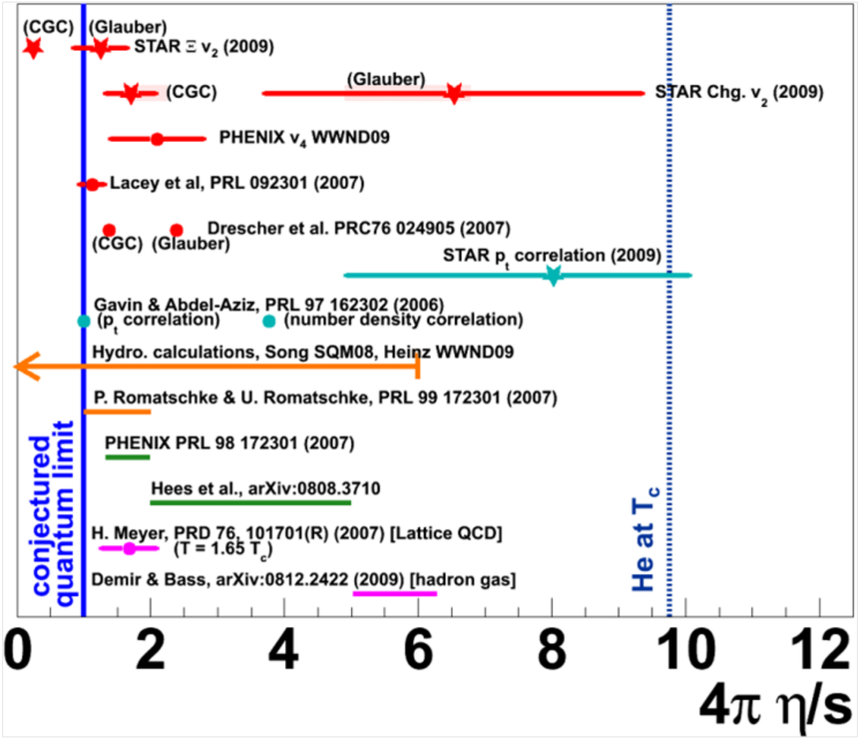




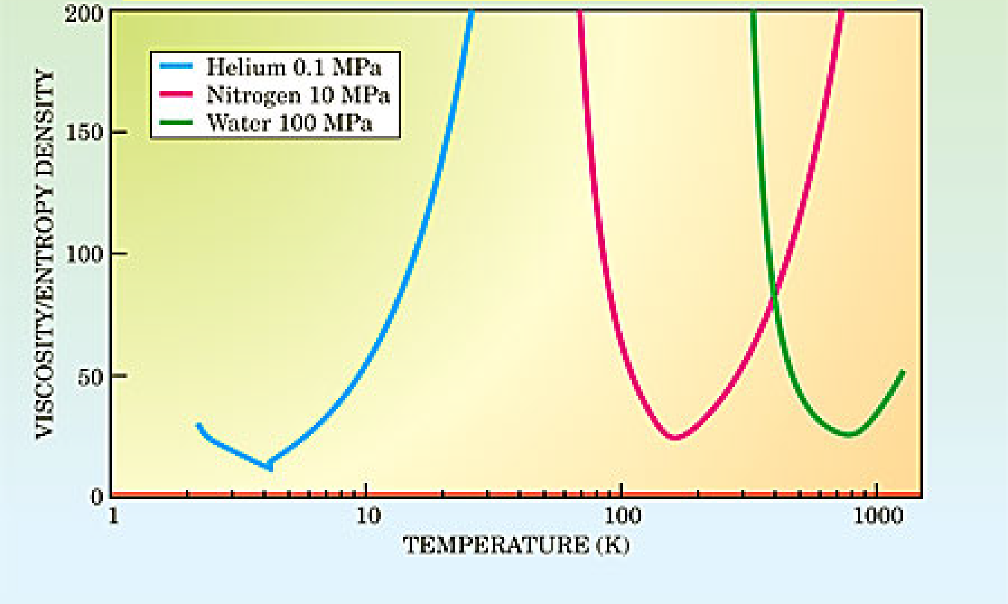
- We can imagine that the flowing QGP is a river that sweeps quarks.
- A "perfect fluid" is like a school of fish…all change direction at once.
- Our QGP river carries off heavy stones (not BOTTOM???)
- Requiring a model to SIMULTANEOUSLY fit R_{AA} and v_2 "measures" the η/s of the QGP fluid.

STONY BROOK

How Perfect is "Perfect" ?

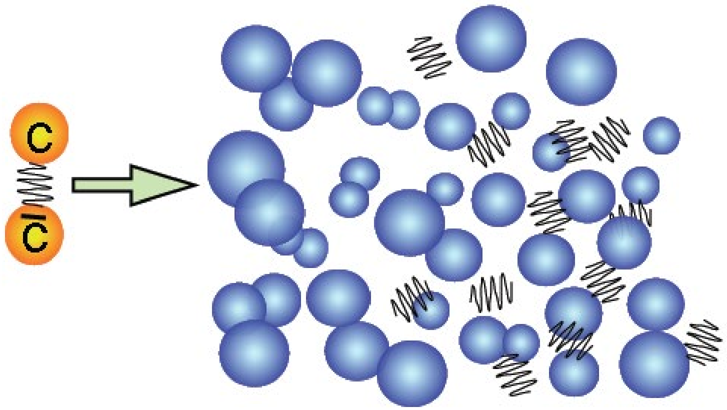


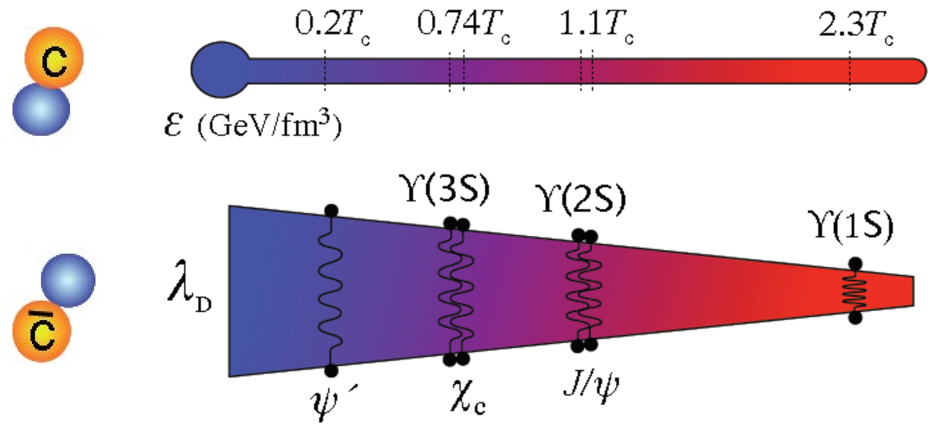
$$\eta \geq \frac{\hbar}{4\pi}(\ Entropy\ \ Density\ ) \equiv \frac{\hbar}{4\pi} s$$



- **RHIC "fluid" is at ~1-3 on this scale (!)**
- **The Quark-Gluon Plasma is, within preset error, the most perfect fluid possible in nature.**
- **High order v_n measurements to yield superb precision!**

Quarkonia Production

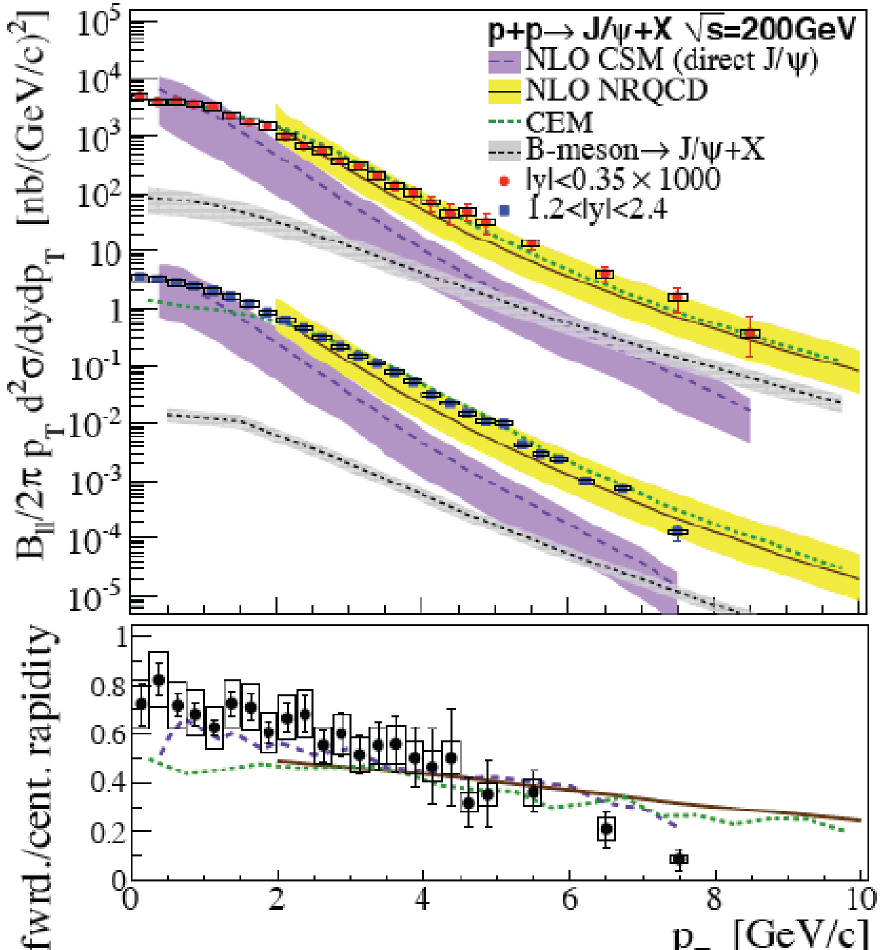




- ***J/psi Suppression by Quark-Gluon Plasma Formation,*** **T. Matsui and H. Satz, Phys.Lett.B178:416,1986.**
- **If cc dissolved, unlikely to pair with each other.**
- **Suppression of J/Ψ and Y.**
- **Suppression driven by size of the meson as compared to the Debye Radius (radius of color conductivity)**

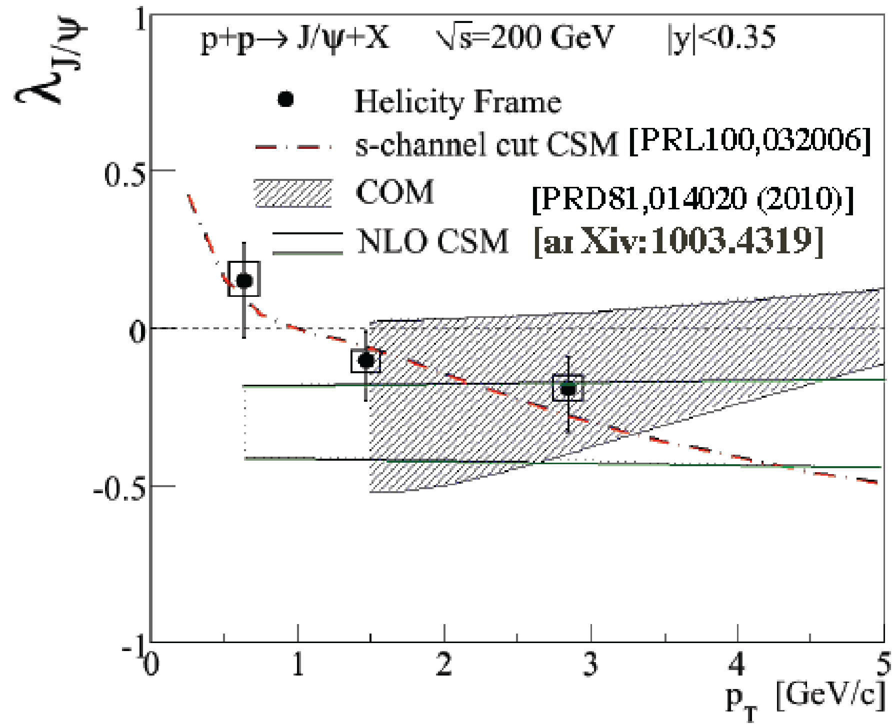
How is J/ψ formed in pp?

[arXiv:1105.1966]



- only models with color octet formation describe the data
- J/ψ polarization measured to be small

[PRD82,012001 (2010)]

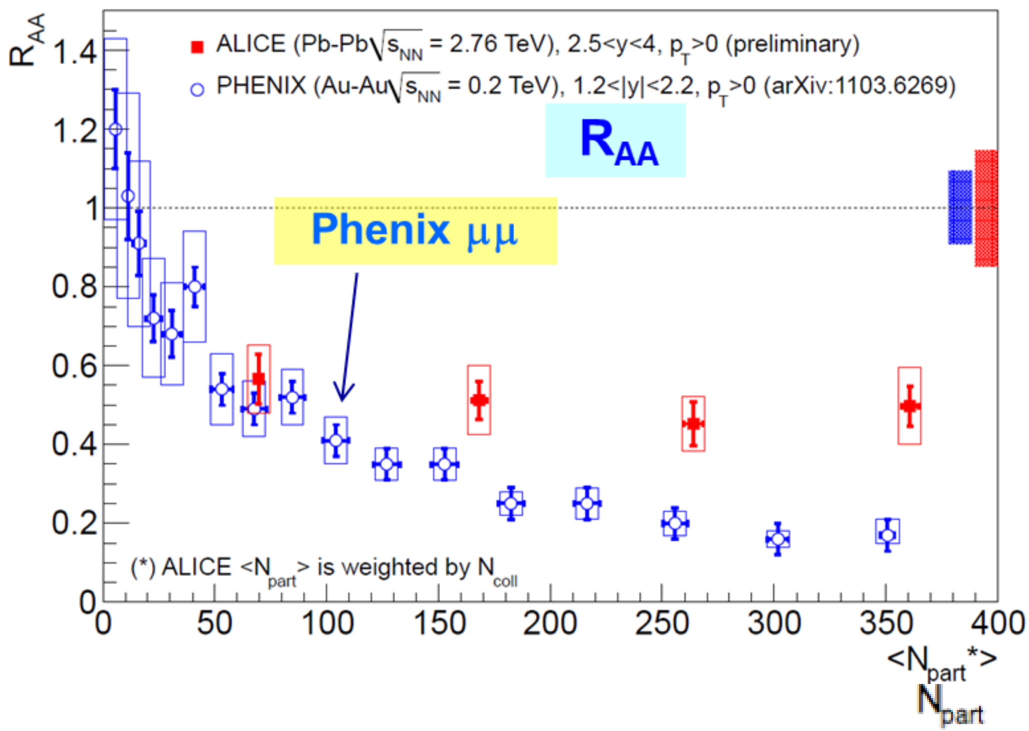


- new measurement of J/ψ yield in the mid and forward rapidities

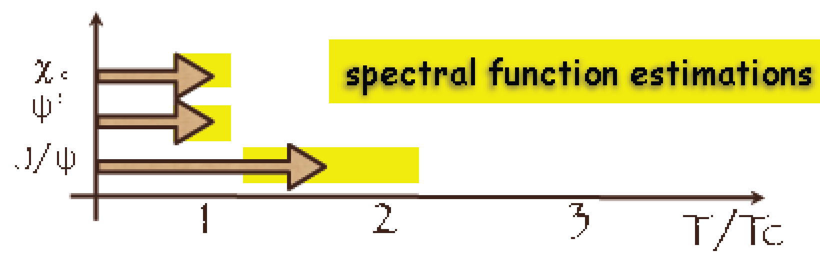
- color octet state may cross part of the nuclear matter as a pre-resonant state

J/ψ is suppressed (everywhere)

[arXiv:1103.6269v1]

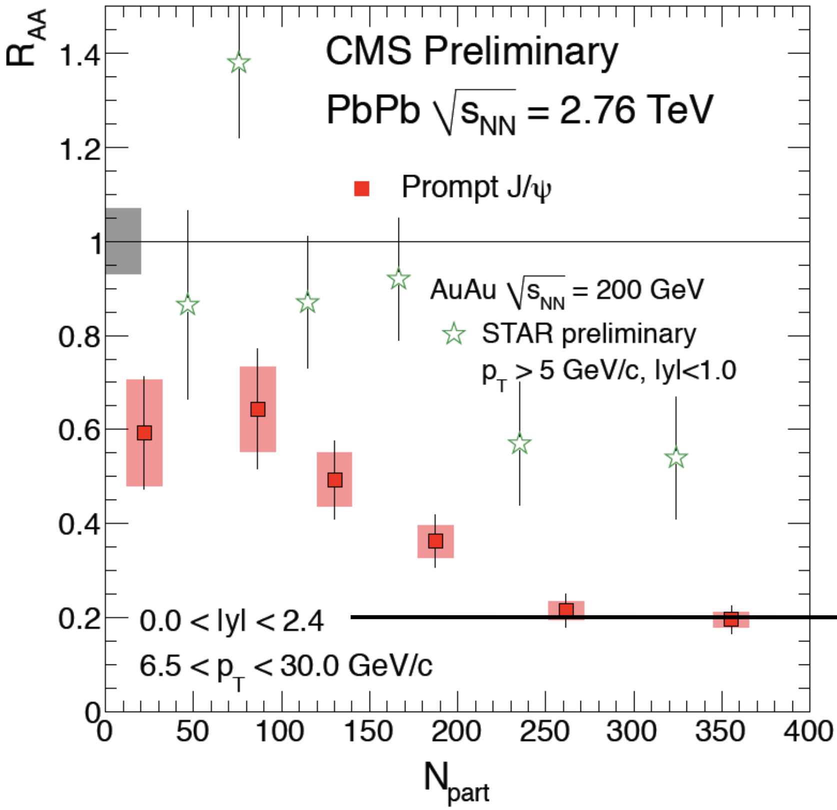


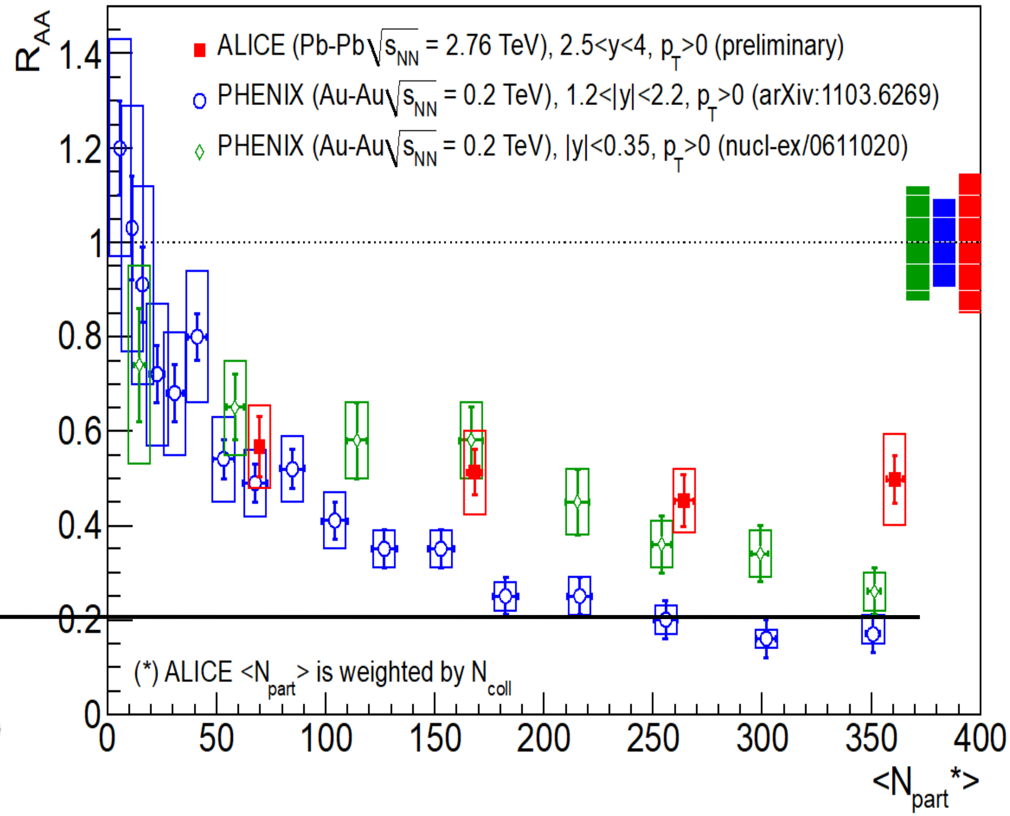
- Tc ~ 170 MeV
- inverse slope of thermal photons measured by PHENIX is 221±28MeV [PRL104, 132301 (2010)]
- hydro models fitted to the thermal photon data suggest T_{init} ~300-600 MeV
- who survives?



- if J/ψ from ψ' and χ_c fully suppressed R_{AA} drops to 0.6

LHC/RHIC comparison



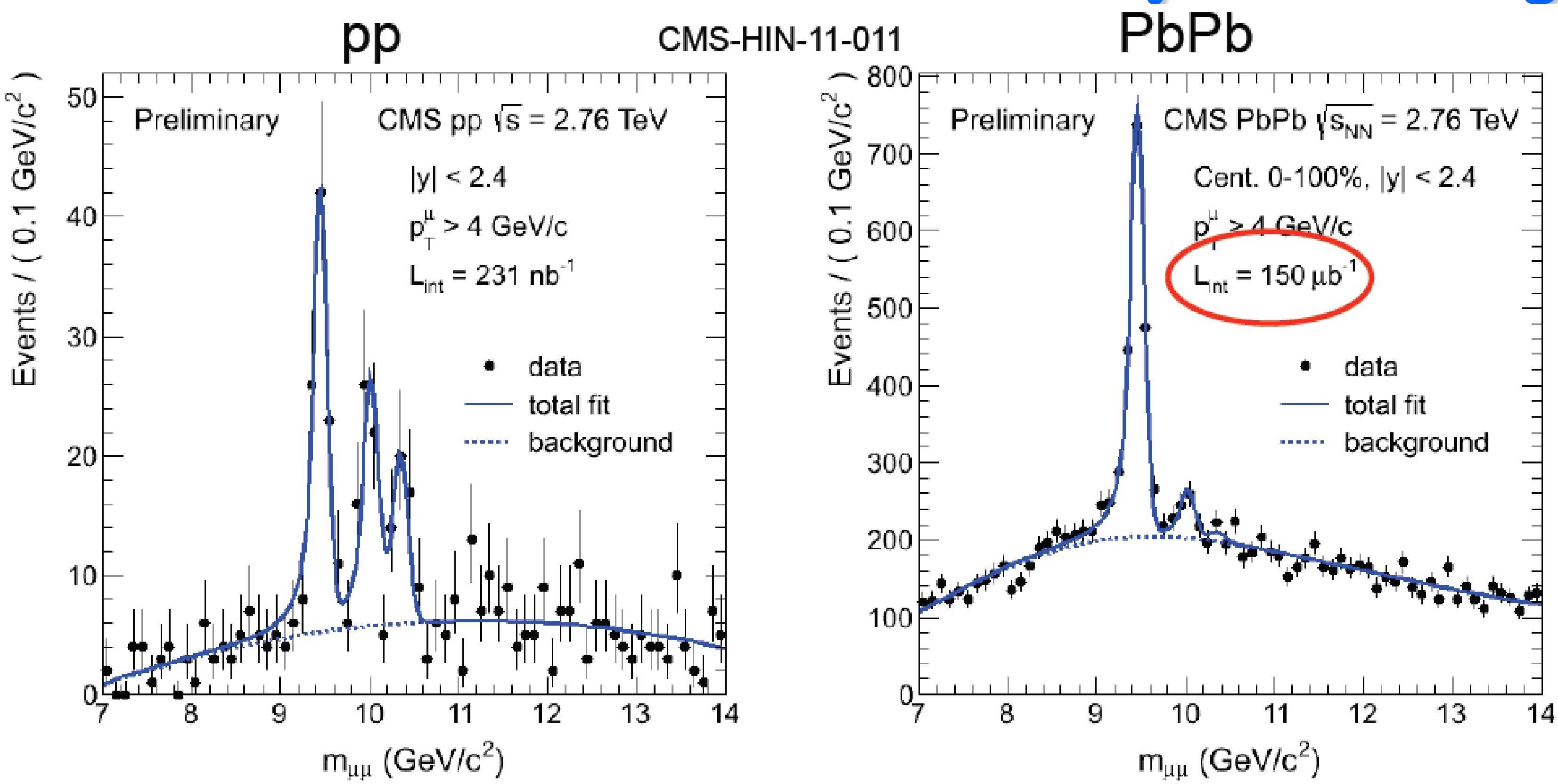


STAR (p_T>5 GeV) versus CMS (6.5<p_T<30 GeV)

PHENIX (p_T>0 GeV) versus ALICE (p_T>0 GeV)

Caveat: Different beam energy and rapidity coverage;
$dN_{ch}/d\eta(N_{part})^{LHC} \sim 2.1 \times dN_{ch}/d\eta(N_{part})^{RHIC}$

CMS: all the Υ states separately.

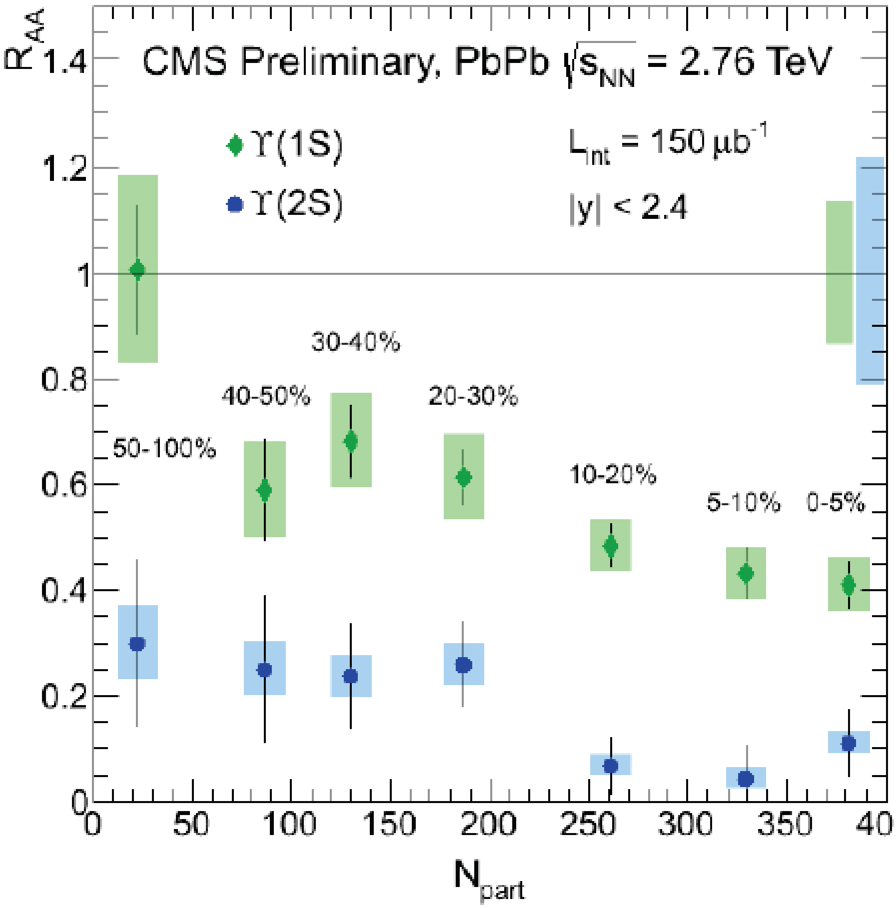


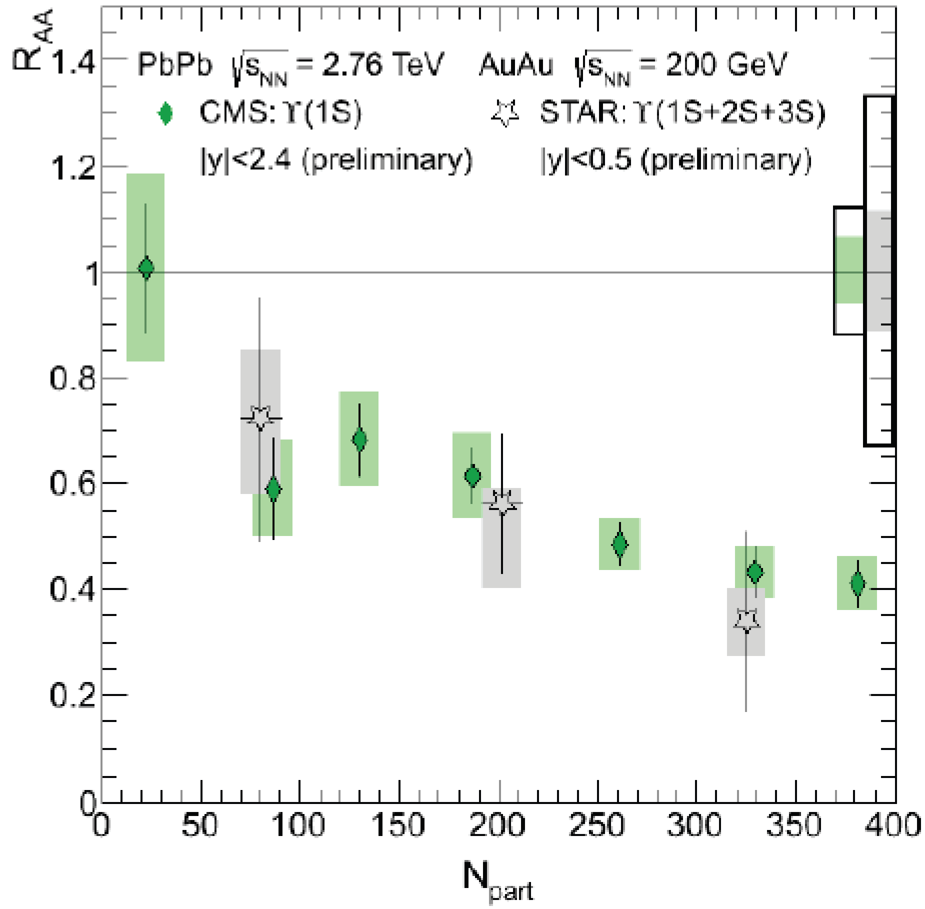
$$N_{\Upsilon(2S)}/N_{\Upsilon(1S)}|_{pp} = 0.56 \pm 0.13 \pm 0.01 \qquad N_{\Upsilon(2S)}/N_{\Upsilon(1S)}|_{PbPb} = 0.12 \pm 0.03 \pm 0.01$$

$$N_{\Upsilon(3S)}/N_{\Upsilon(1S)}|_{pp} = 0.21 \pm 0.11 \pm 0.02 \qquad N_{\Upsilon(3S)}/N_{\Upsilon(1S)}|_{PbPb} < 0.07$$

- **The data show that the 2s/3s are reduced compared to the 1s.**
- **This is first strong indication of sequential melting in QGP.**
- **Should yield screening length of our color conductor!**

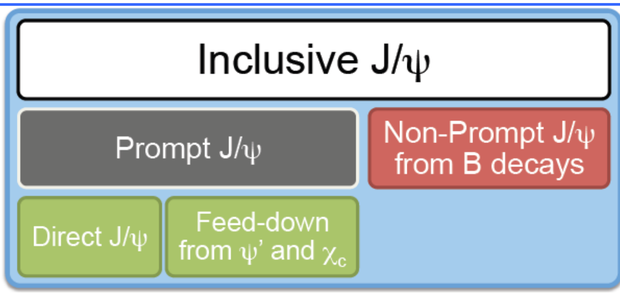
Upsilon Suppression



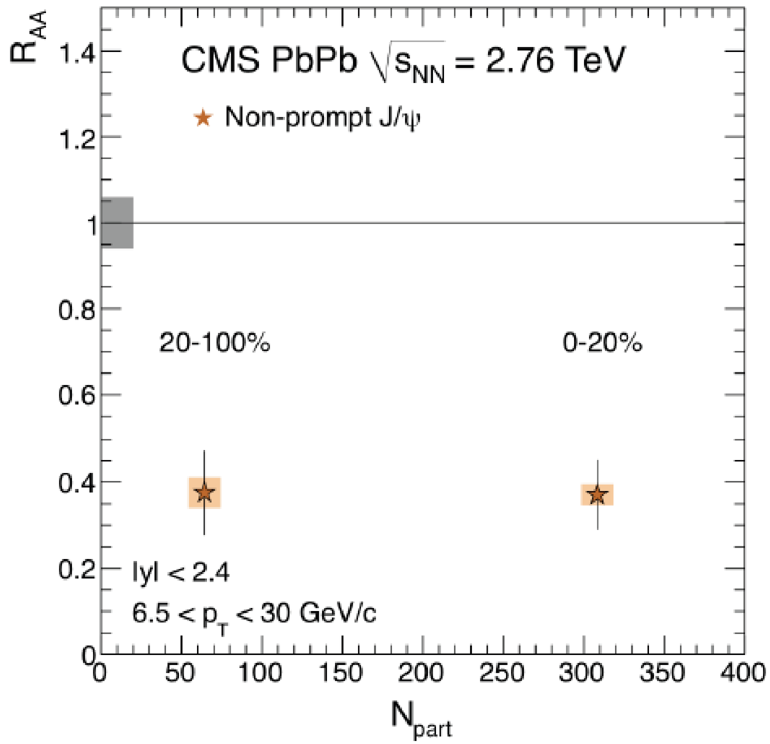


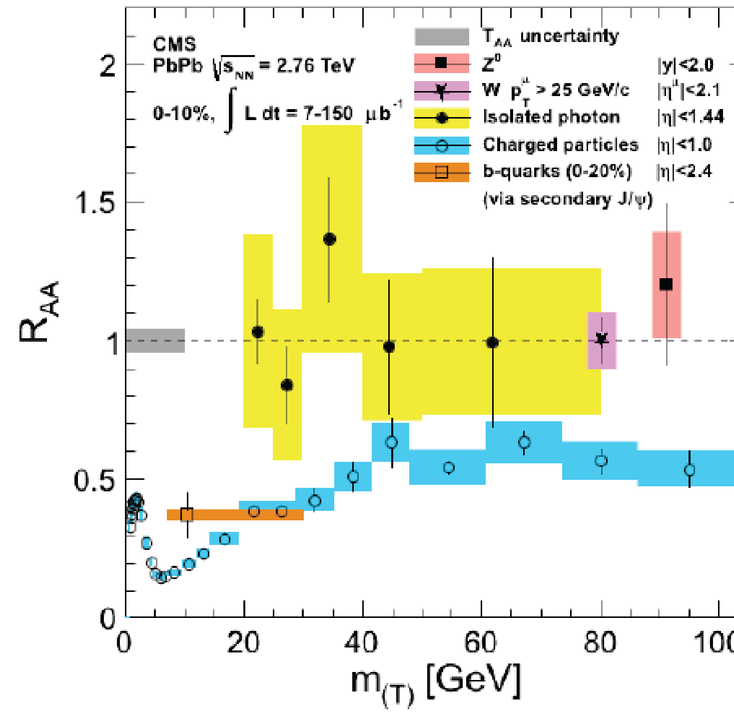
- Upsilon system is “cleaner” than the J/Psi.
- 1s state suffers from feed-down (~50%).
- Consistent with melting all Y except feeddown.

J/Psi as Bottom Suppression?



- **CMS can separate out J/Psi which are daughter states of decays from B mesons.**

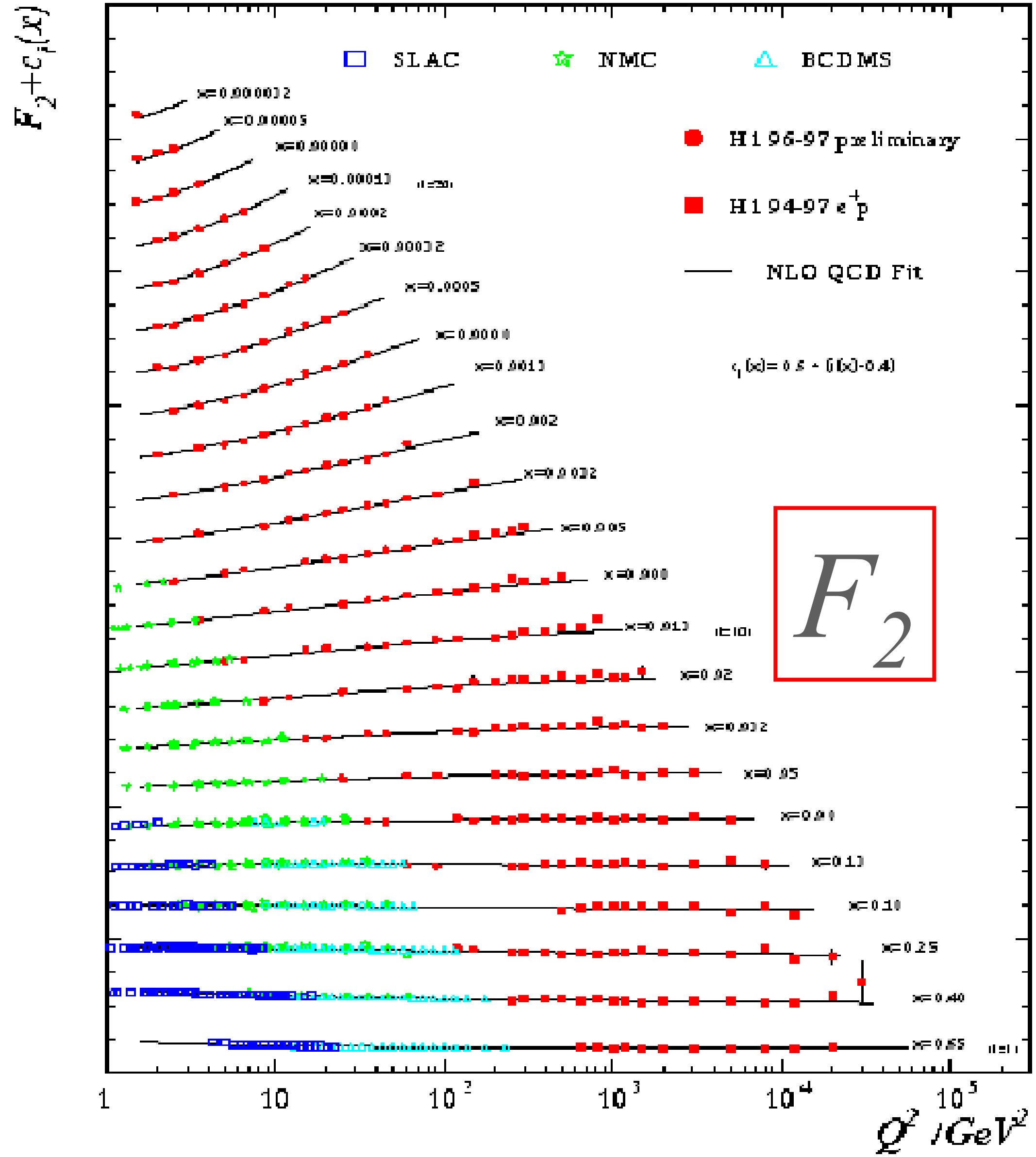




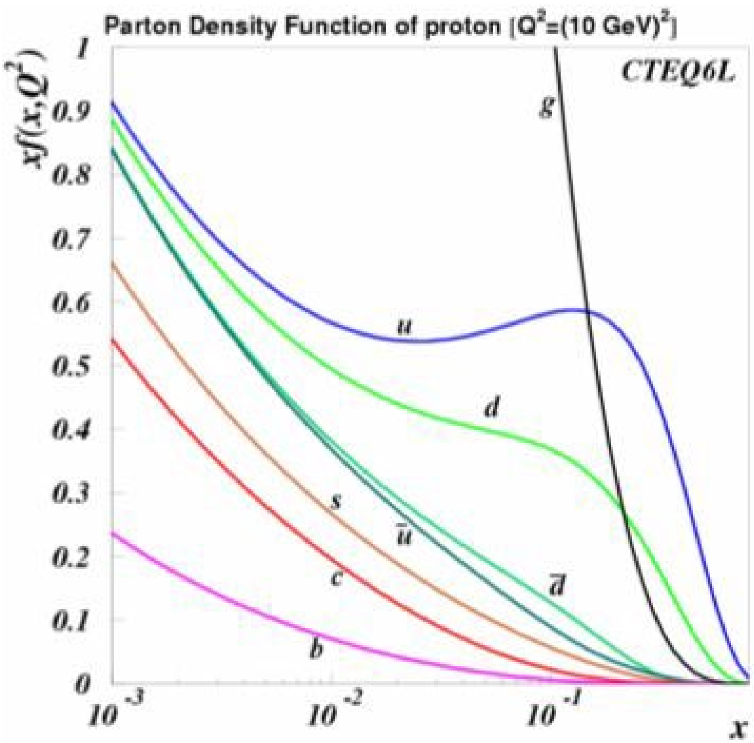
- **These are a surrogate for a bottom quark.**
- **Suppression same or less than π/charm?**

Parton Distribution Functions

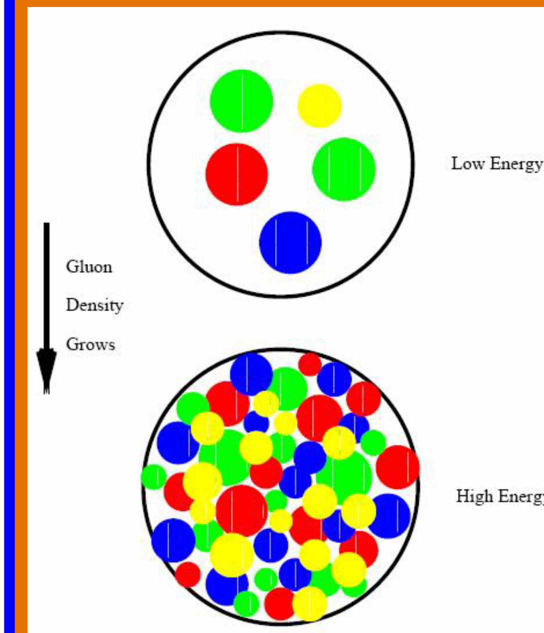
- PDFs are measured by e-p scattering.
- Calculations (PYTHIA) use theoretically inspired forms guided by the data:
  - CTEQ 5M
  - others…
- Unitarity requires that the integral under the PDF adds up to the full proton momentum.
- Dirty Little Secret: The sum of the parts exceeds the whole!

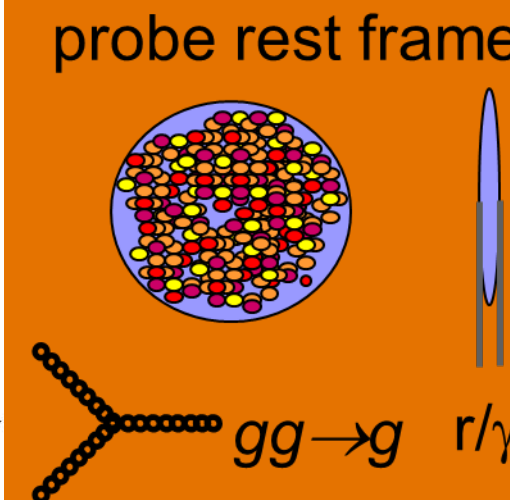


Crisis in Parton Distributions!



What happens if you pack too many gluons inside a box?

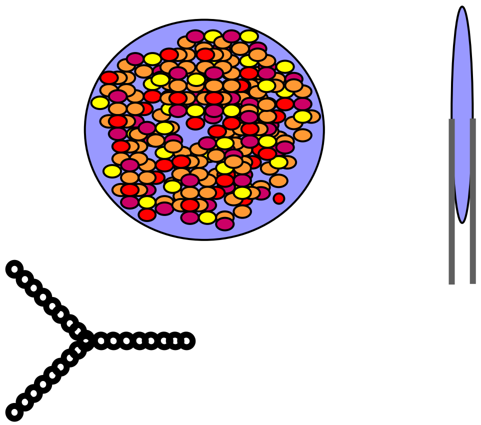




ANSWER: They eat each other.

- Parton Distributions explode at low x.
- The rise must be capped.

Glass at the Bottom of the Sea?



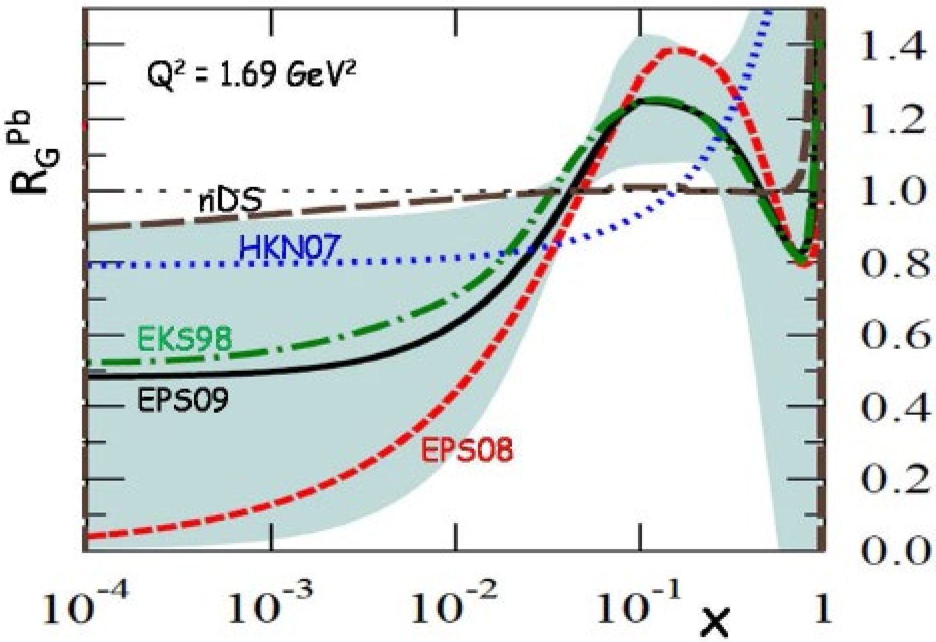
- Note that the gluon fusion reaction, $g+g \rightarrow g$, "eats gluons".
- Its kind of like a fish tank:
  - When the fish eat their young, the tank never overfills with fish.

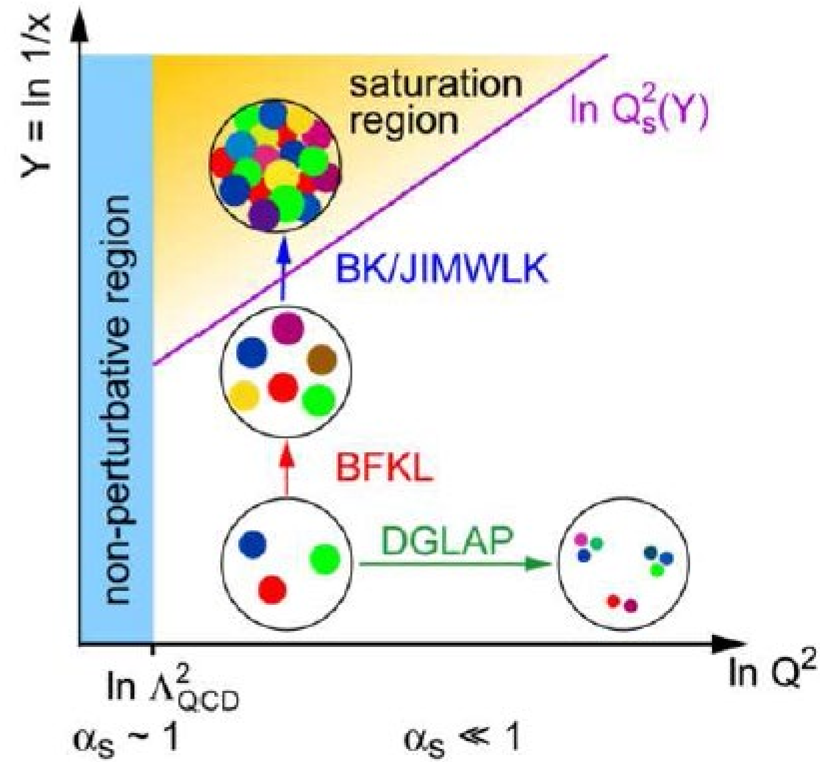
- This implies that

nature has a maximal gluon density.

- Material exhibiting nature's ultimate gluon density is called Color Glass Condensate.
- The existence of this material would cap the gluon growth at low x, restoring unitarity
- The Bottom of the Sea Fuses Into Color Glass.

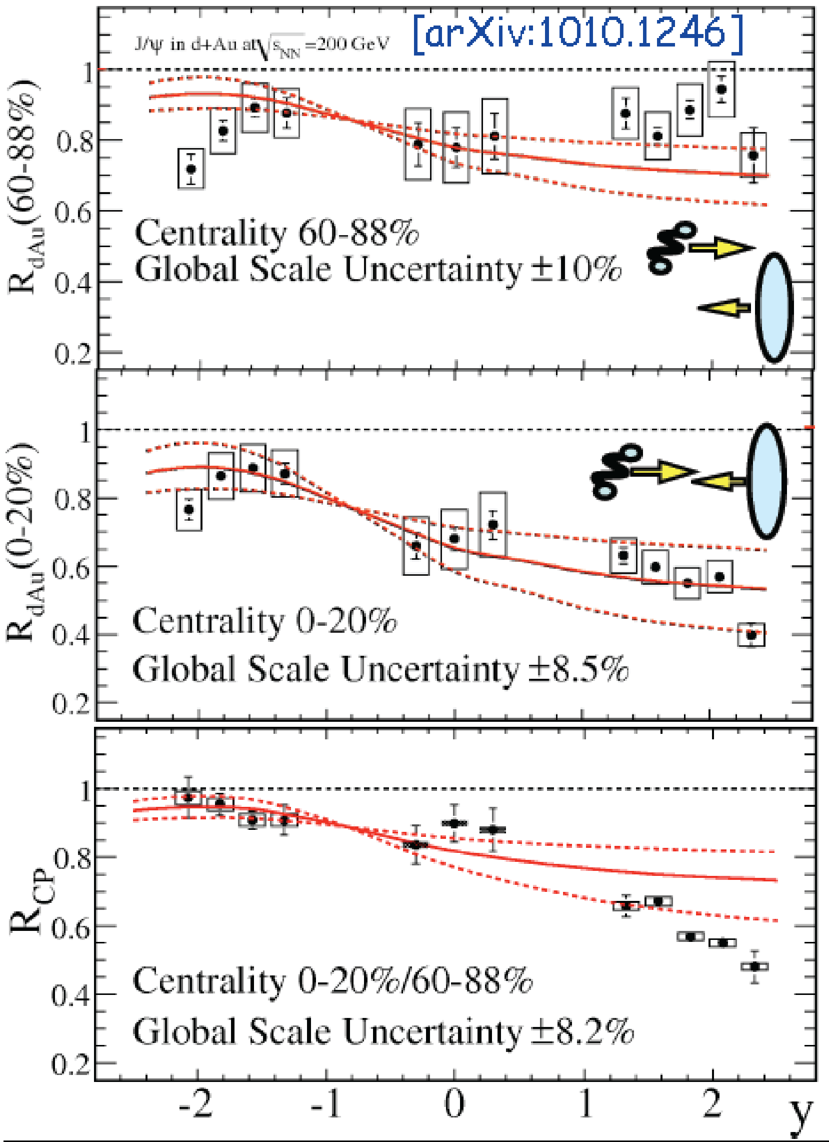
Nuclear Oomph…





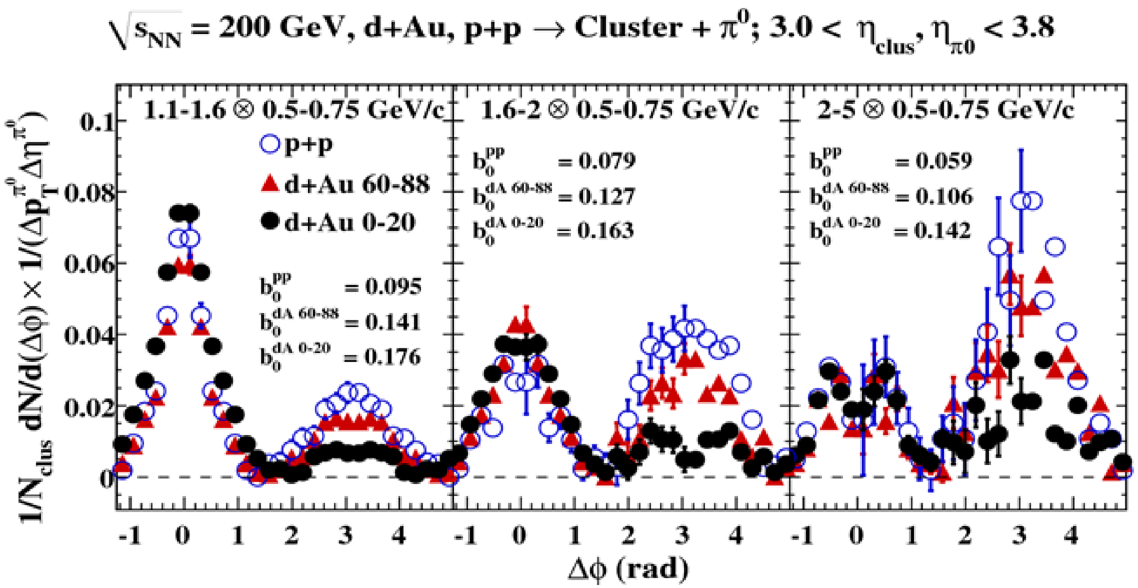
- **A nucleus compresses more matter and makes the CGC easily accessible.**
- **Shadowing competes with CGC.**
- **Many believe that shadowing is simply "parameterized" CGC.**

J/y complicated by CNM effects



- Electron-nucleus collisions are the most promising way to find CGC.
- Proton (deuteron) collisions are the best we have for now.
- A depletion in the low-x wave function of a Au nucleus decreases the number of scatterings in the deuteron direction.
- EPS09 shadowing fails.

Jets distinguish CGC from shadowing.

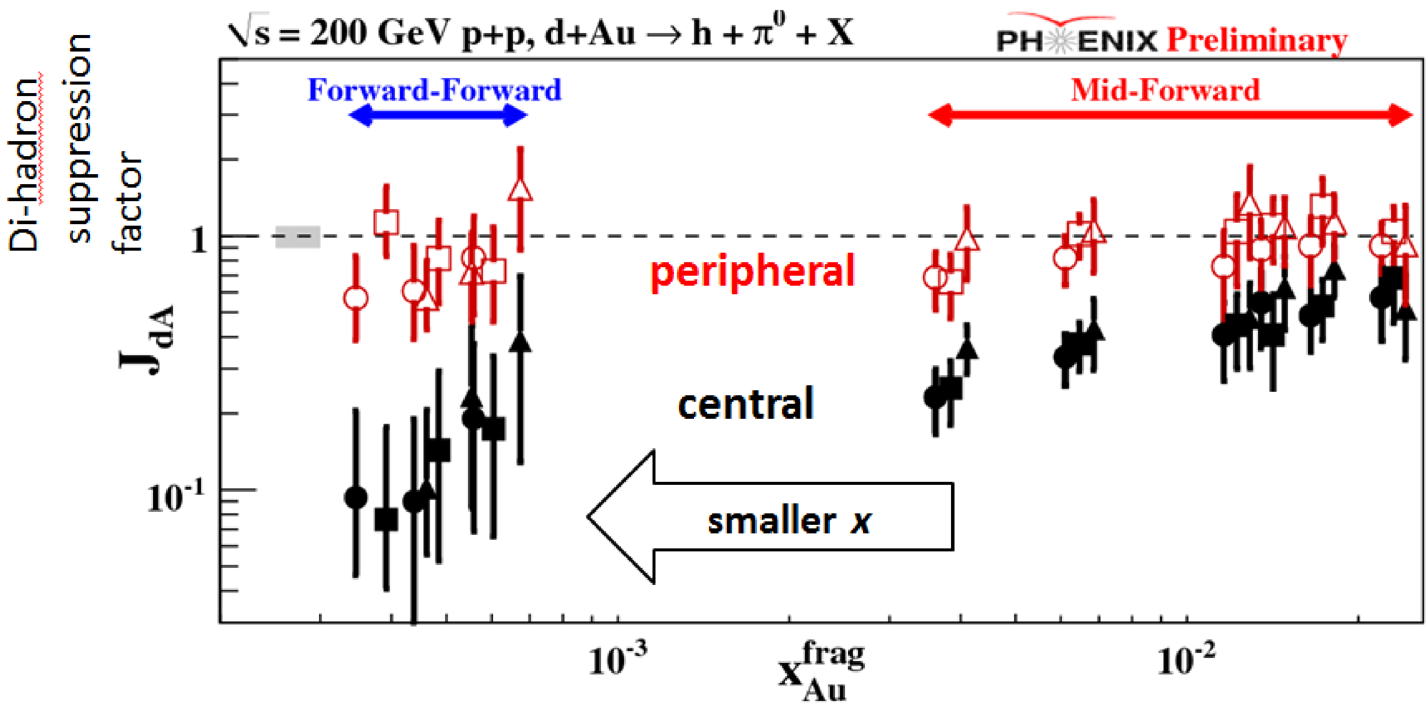


Color Glass Condensate?

new forward
EM calorimeter
|η| = 3.0-3.8

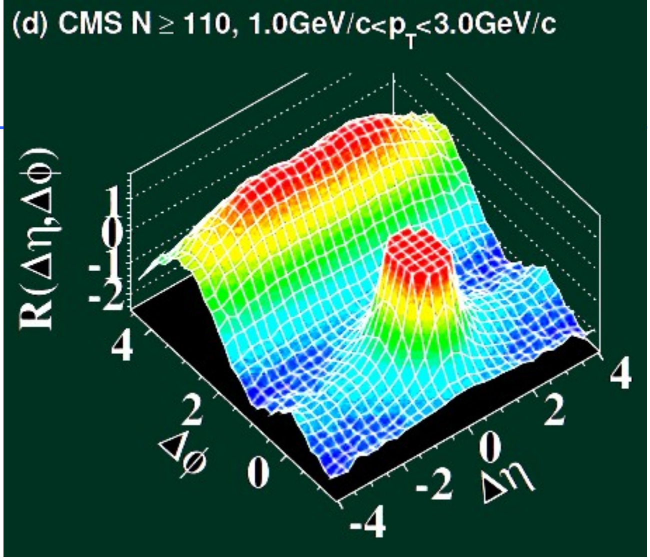
- The fundamental difference between the CGC model of cold nuclear matter and the shadowing model is the number of partons that scatter.
- Shadowing changes the PDF, but still does all physics as 1-on-1 parton scatterings.
- CGC allows one (from deuteron) against many (from glass), and thereby splits away-side jet into many small pieces.

HUGE suppression in low X.



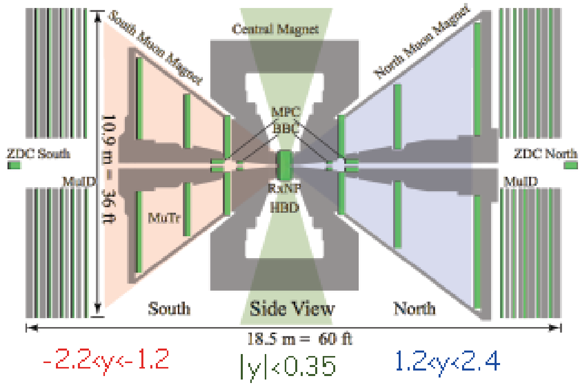
- The suppression factor from cold nuclear matter is a factor of ~10!
- The away-side jet "decorrelates".
- Jury still out:
  - Nearly all measurements follow CGC predictions.
  - Predictions are often qualitative.
- Electron-ion collisions will find the truth.

Summary



- Nuclear Collisions provide access to the collective color interaction.
- These provide a glimpse at aspects of the color force inaccessible through elementary collisions.
- Partonic matter just beyond the phase transition is a strongly-coupled plasma exhibiting explosive flow into the vacuum.
- String-theory has provided “Nature’s lower bound” on η/s…a limit realized within error by sQGP.
- Nuclear collisions can provide access to dense color fields in cold nuclear matter that may exhibit CGC.
- Short time scales for thermalization challenge theory.

Length dependence of J/ψ



scan different values for the strength "a" in R_{dAu} formula

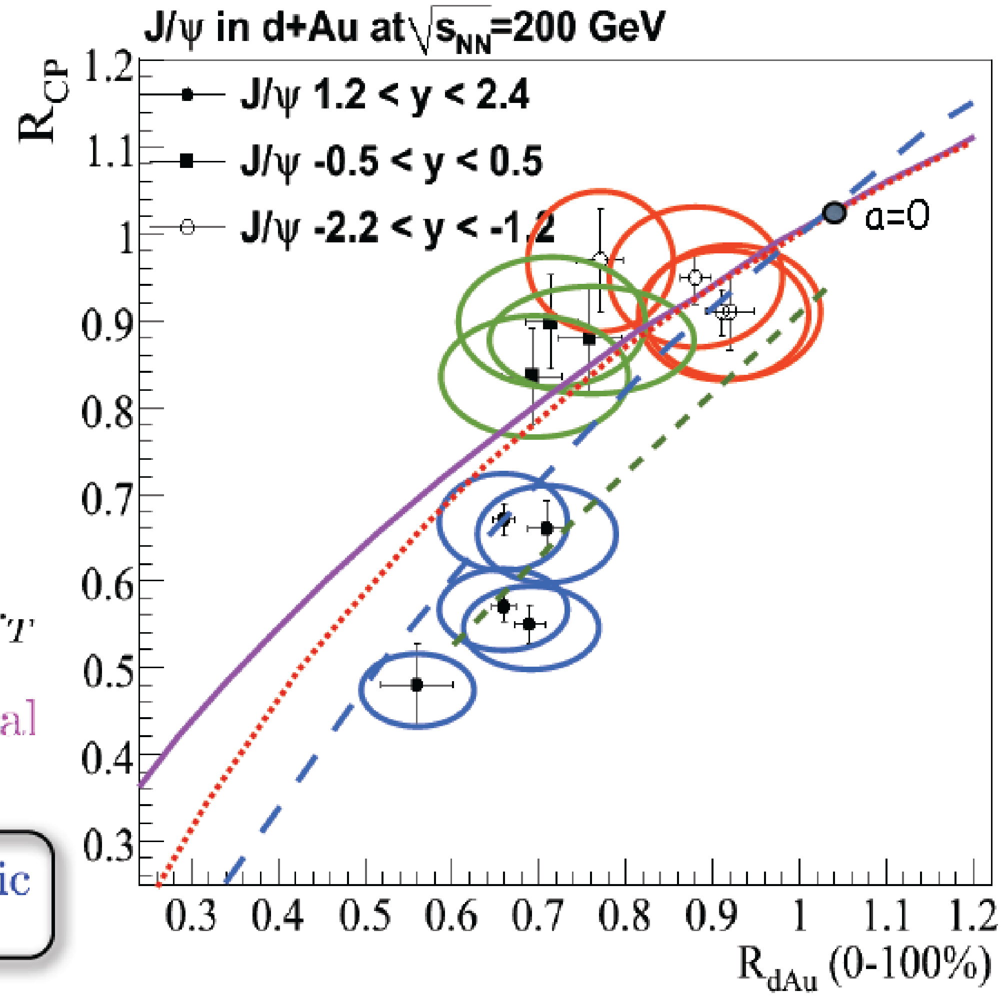
$$R_{dAu,i}(a) = \int f_i(r_T)\, M(r_T;a)\, dr_T$$

$M(r_T;a) = e^{-a\Lambda(r_T)}$ exponential

$M(r_T;a) = 1 - a\Lambda(r_T)$ linear

$M(r_T;a) = 1 - a\Lambda(r_T)^2$ quadratic

nuclear modification requires a quadratic or higher order dependence

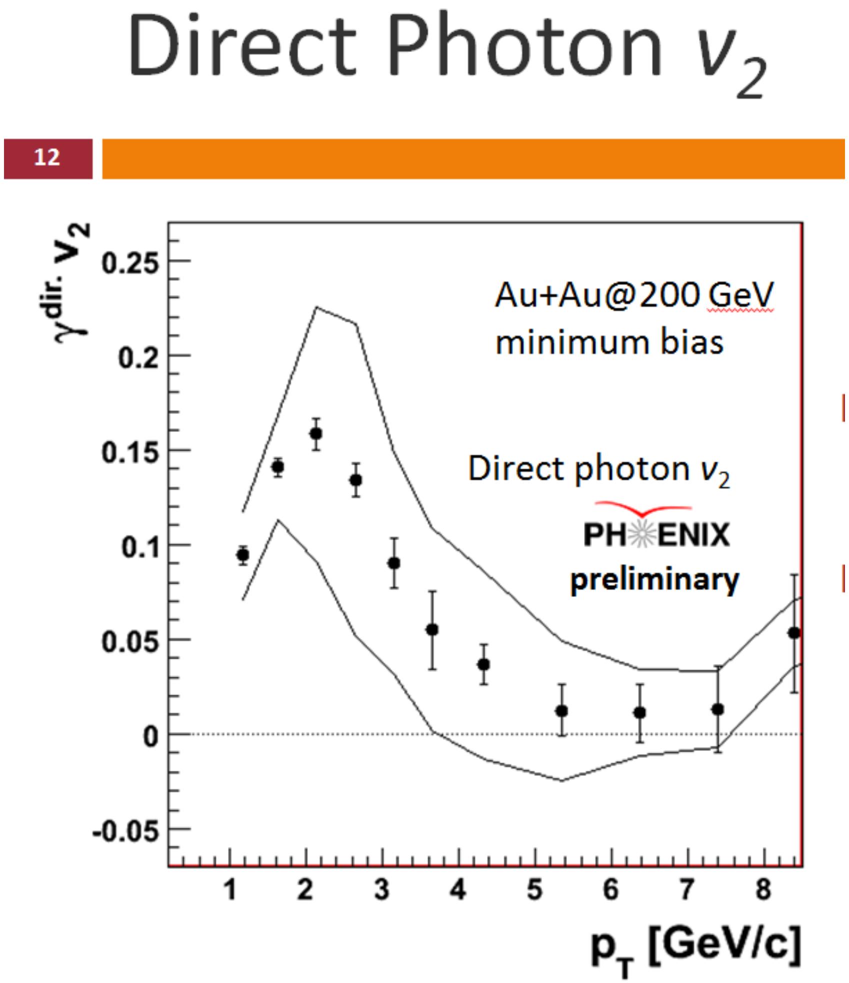


- by the way, reasonable agreement with *CGC* model as well

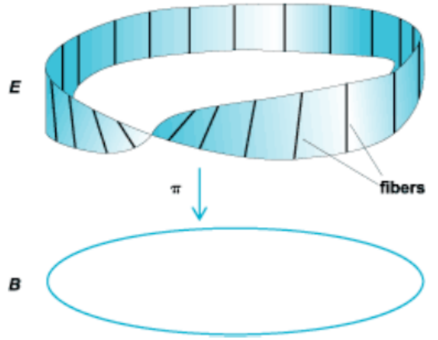
[Kharzeev and Tuchin, Nucl. Phys. A770, 40 (2006)]

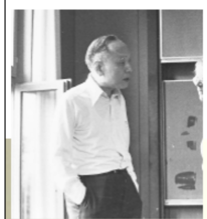
SURPRISE!

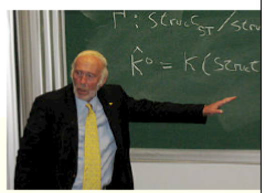
- The direct virtual photons measured by PHENIX have been associated with early stage thermal radiation.
- If true, they should show little flow.
- Surprise…they flow.
- We must take care in interpreting these photons…



Gauge fields possess non-trivial topology





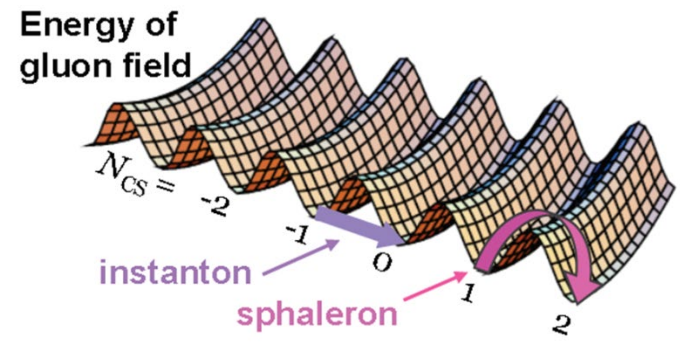


CHARACTERISTIC FORMS

$$TP_1(\theta) = \frac{1}{4\pi^2}\{\theta_{12} \wedge \theta_{13} \wedge \theta_{23} + \theta_{12} \wedge \Omega_{12} + \theta_{13} \wedge \Omega_{13} + \theta_{23} \wedge \Omega_{23}\} \ . \quad (6.1)$$

Dima Kharzeev. QM2011

QCD vacuum is a superposition of states with different topology



Transitions between such states create the local imbalance of chirality

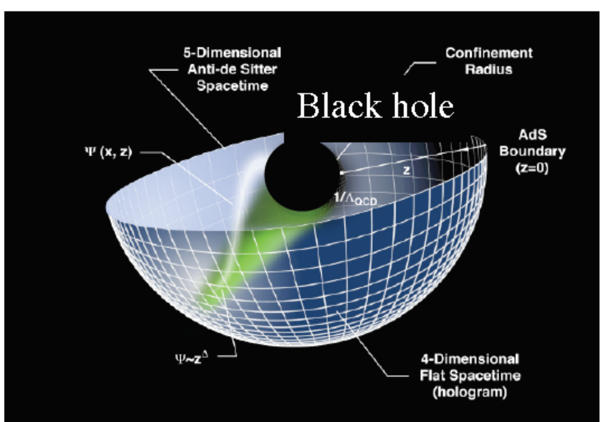
4

Topological transitions are frequent in sQGP

Chern-Simons number diffusion rate at strong coupling

$$\Gamma = \frac{(g_{YM}^2 N)^2}{256\pi^3} T^4$$

D.Son, A.Starinets hep-th/ 020505



NB: This calculation is completely analogous to the calculation of shear viscosity that led to the "perfect liquid"

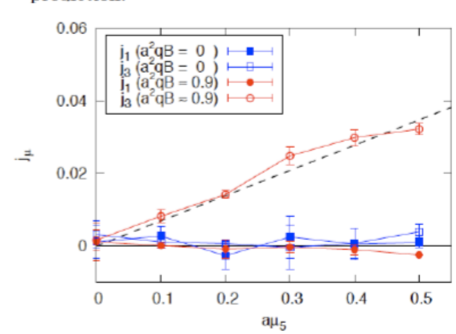
arXiv:1105.0385, May 3, 2011

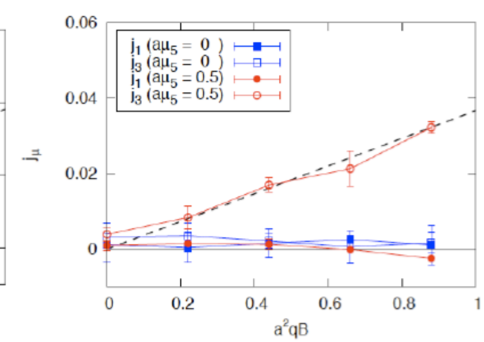
Chiral magnetic effect in lattice QCD with chiral chemical potential

Arata Yamamoto
Department of Physics, The University of Tokyo, Tokyo 113-0033, Japan

(Dated: May 3, 2011)

We perform a first lattice QCD simulation including two-flavor dynamical fermion with chiral chemical potential. Because the chiral chemical potential gives rise to no sign problem, we can exactly analyze a chirally asymmetric QCD matter by the Monte Carlo simulation. By applying an external magnetic field to this system, we obtain a finite induced current along the magnetic field, which corresponds to the chiral magnetic effect. The obtained induced current is proportional to the magnetic field and to the chiral chemical potential, which is consistent with an analytical prediction.

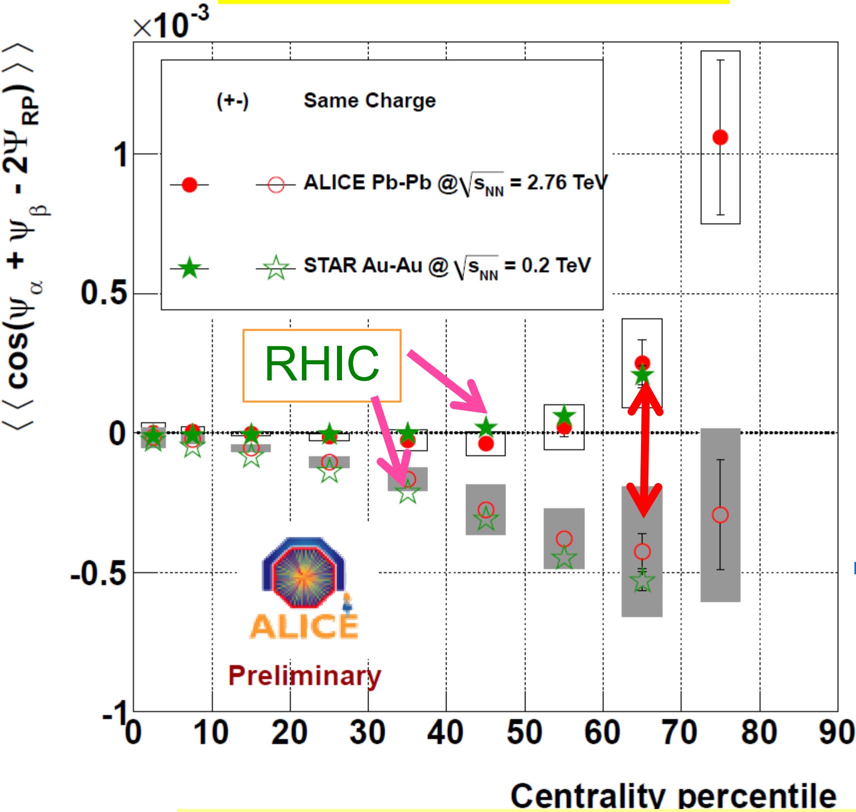


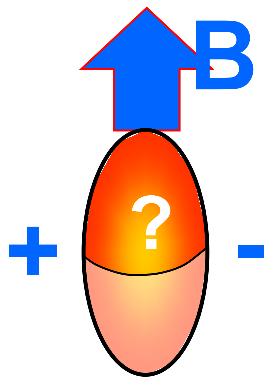


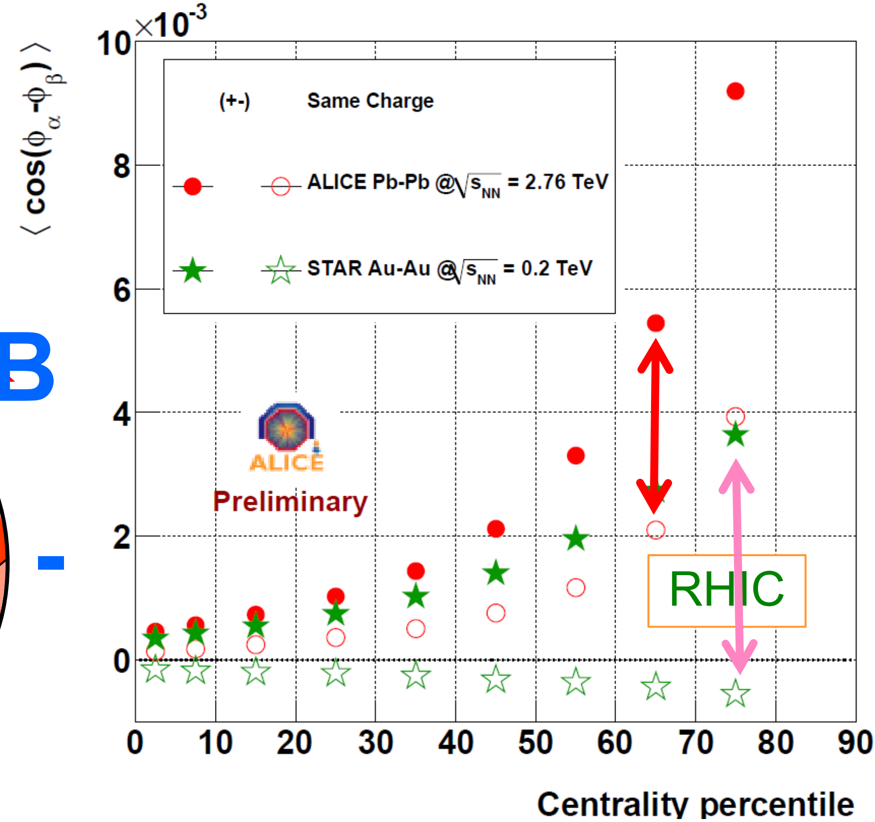
Chiral Magnetic Effect ('strong parity violation')

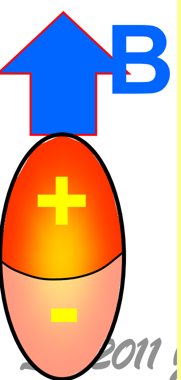
$\langle \cos(\varphi_\alpha + \varphi_\beta - 2\Psi_{RP}) \rangle$

$\langle \cos(\varphi_\alpha - \varphi_\beta) \rangle$









Same charge correlations **positive**

Opposite charge correlations **negative**

RHIC ≈ LHC

RHIC : (++), (+-) **different sign** and magnitude

LHC: (++),(+-) **same sign**, similar magnitude

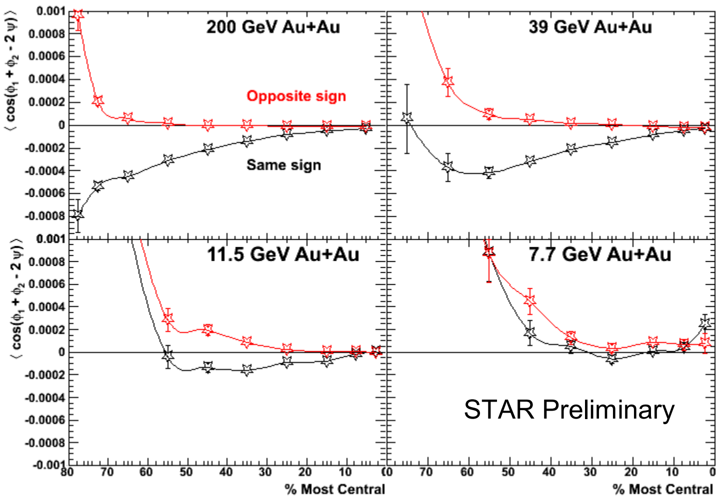
Local Parity Violation
in 10^{17} Gauss magnetic Field ?

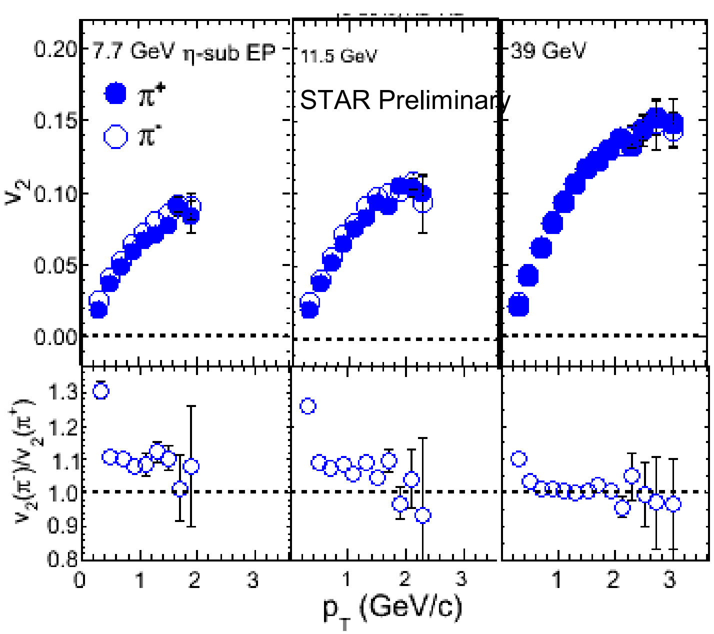
may decrease with √s

Backup Slides

Dynamical Charge Correlations

Possible interpretations:





(A) If linked to LPV effect - de-confinement and chiral symmetry restoration. Absence of difference in correlations means absence of phase transition.

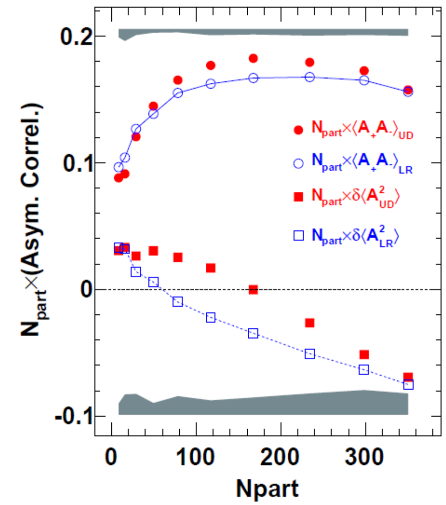
K. Fukushima et al, PRD 78, 074033 (2008)

Alternate Observables

(B) Charge asymmetry

QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.

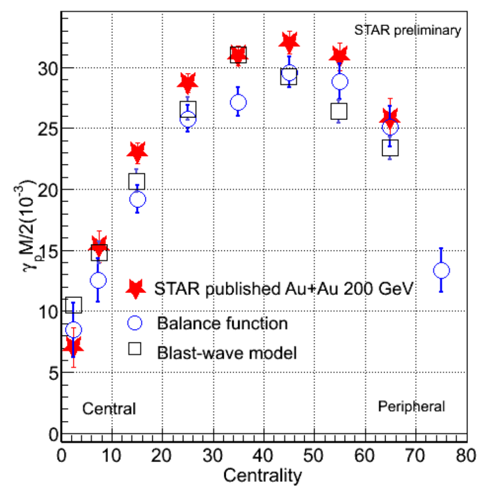
LPV: $\langle A_+A_-\rangle_{UD} < \langle A_+A_-\rangle_{LR}$



(C) Conservation effects: momentum & Local charge and flow.

Reaction plane dependence balance function ~ difference between opposite and same charge correlations.

A. Bzdak, et al., PRC 83 (2011) 014905
S. Schlichting et al., PRC 83 (2011) 014913
Y. Burnier et al., arXiv:1103.1307

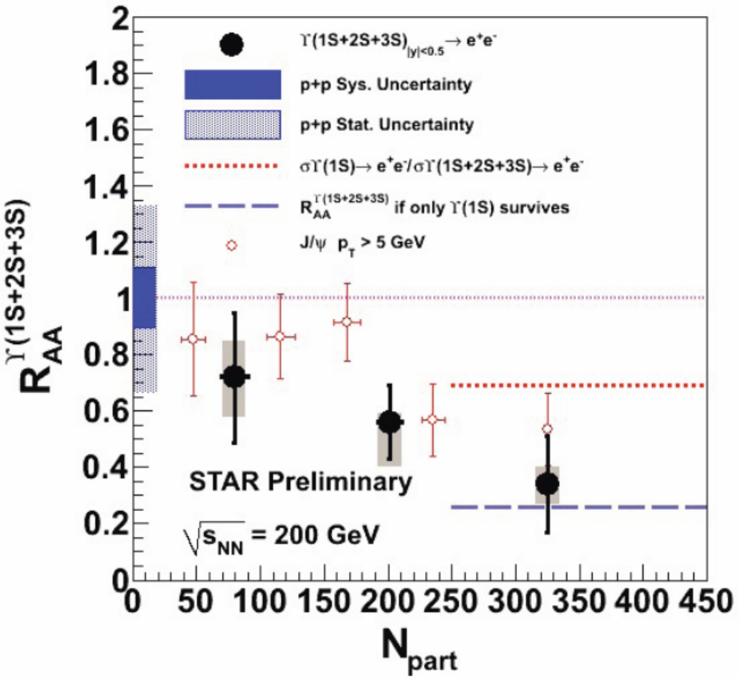


How to reconcile (A) with the fact $v_2(\pi^+) < v_2(\pi^-)$ at 7.7 GeV

Suppression.

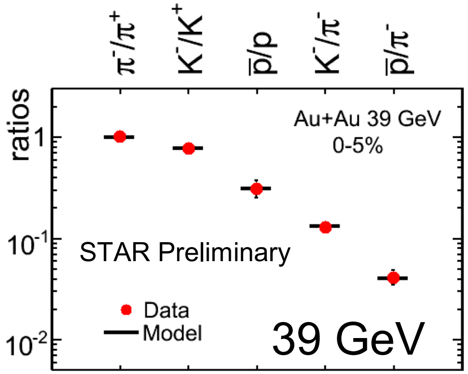
- 1s state should be too large to melt in the plasma.
- 2s/3s could be melted.
- Data are above blue-dashed which would be consistent with only 1s survival and removal of nearly all 2s/3s.

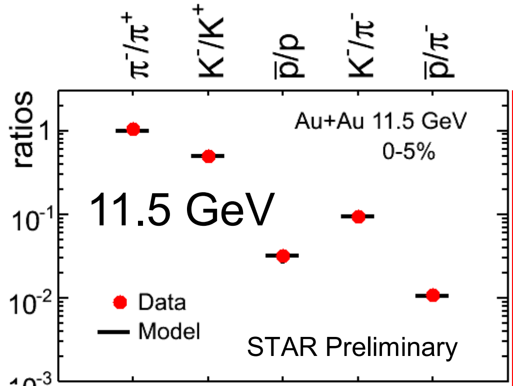
ϒ R_{AA}

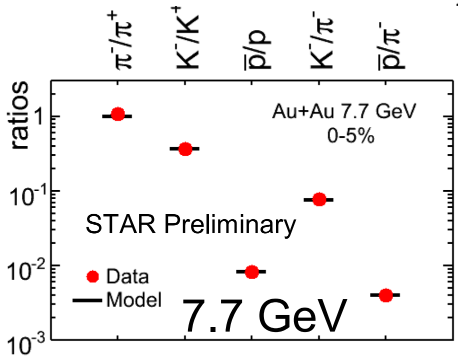


Freeze-out Conditions

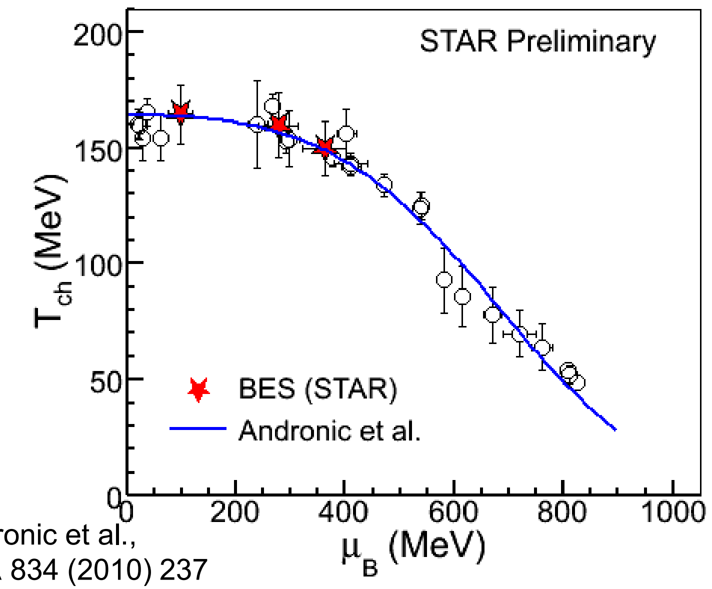
QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.





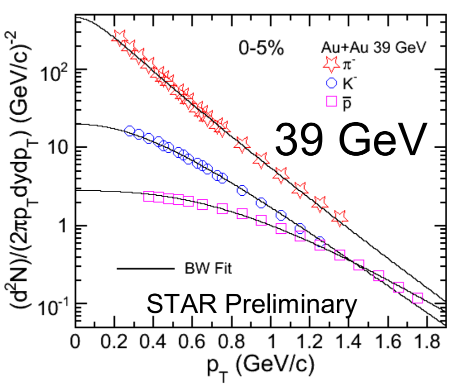


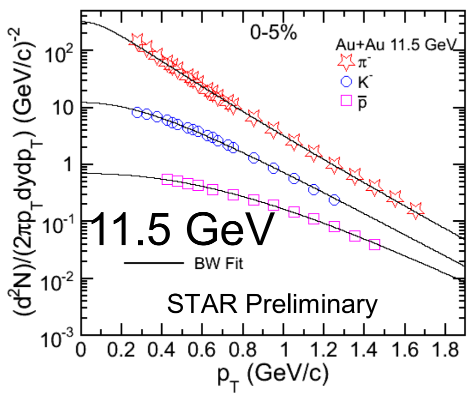
Chemical freeze-out:
Particle ratios

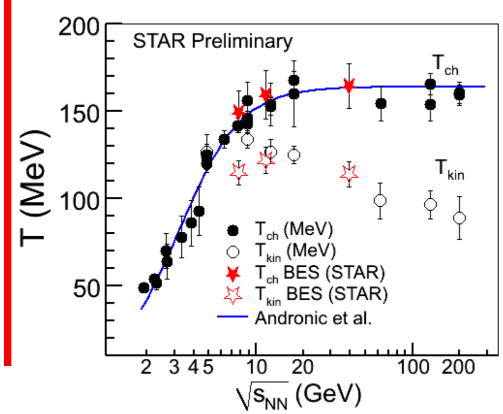


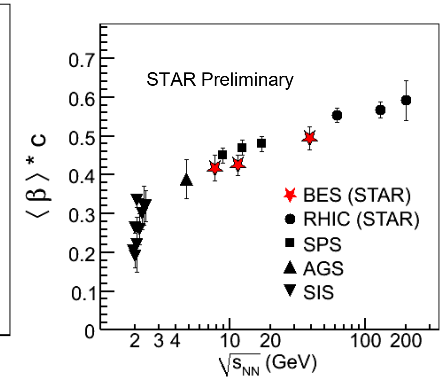
Andronic et al.,
NPA 834 (2010) 237

QuickTime™ and a
TIFF (Uncompressed) decompress
are needed to see this picture.







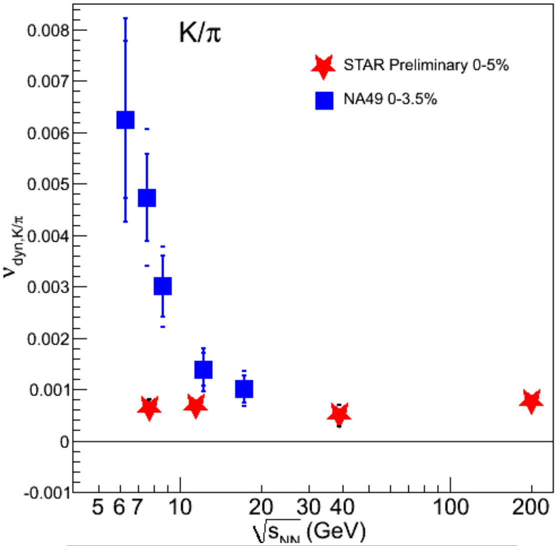


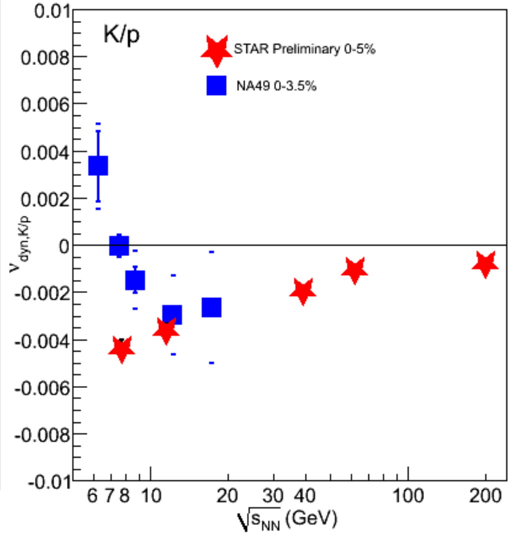
Kinetic freeze-out : Momentum distributions

L. Kumar, Energy scan, 27th May

Particle Ratio Fluctuations

Observations:



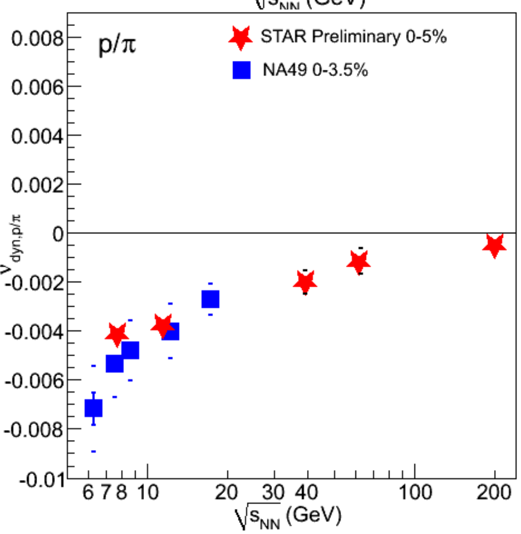


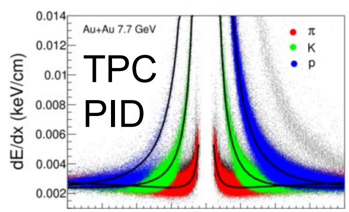
Fluctuations in particle ratios

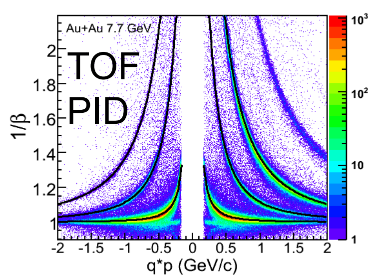
-- Sensitive to particle numbers at chemical FO not kinetic FO

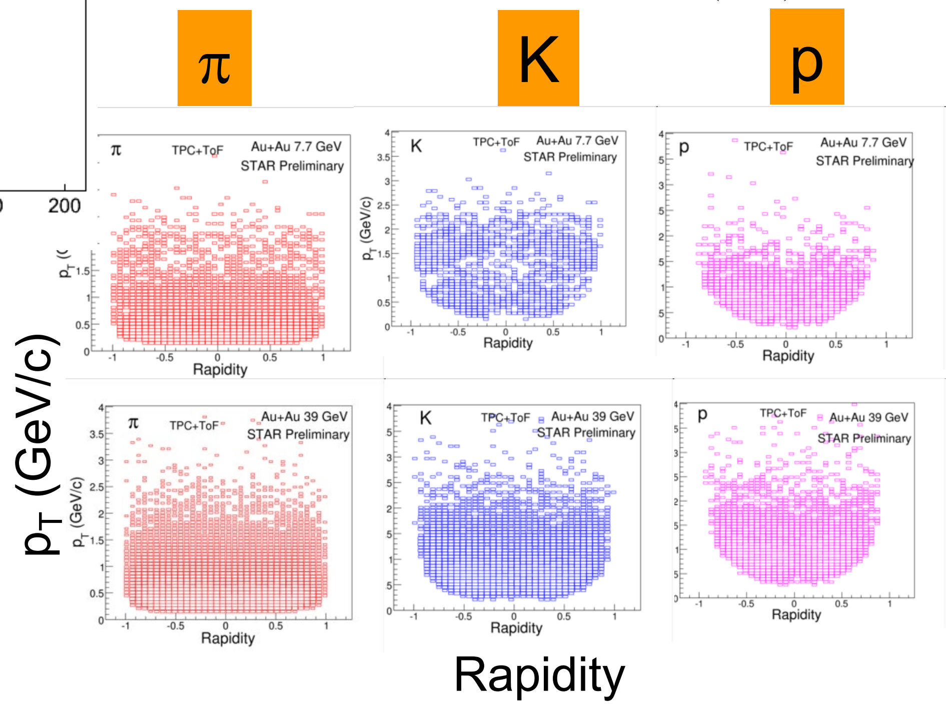
-- Volume effects may cancel

S. Jeon, V. Koch, PRL 83, 5435 (1999)









Constant or monotonic trends observed

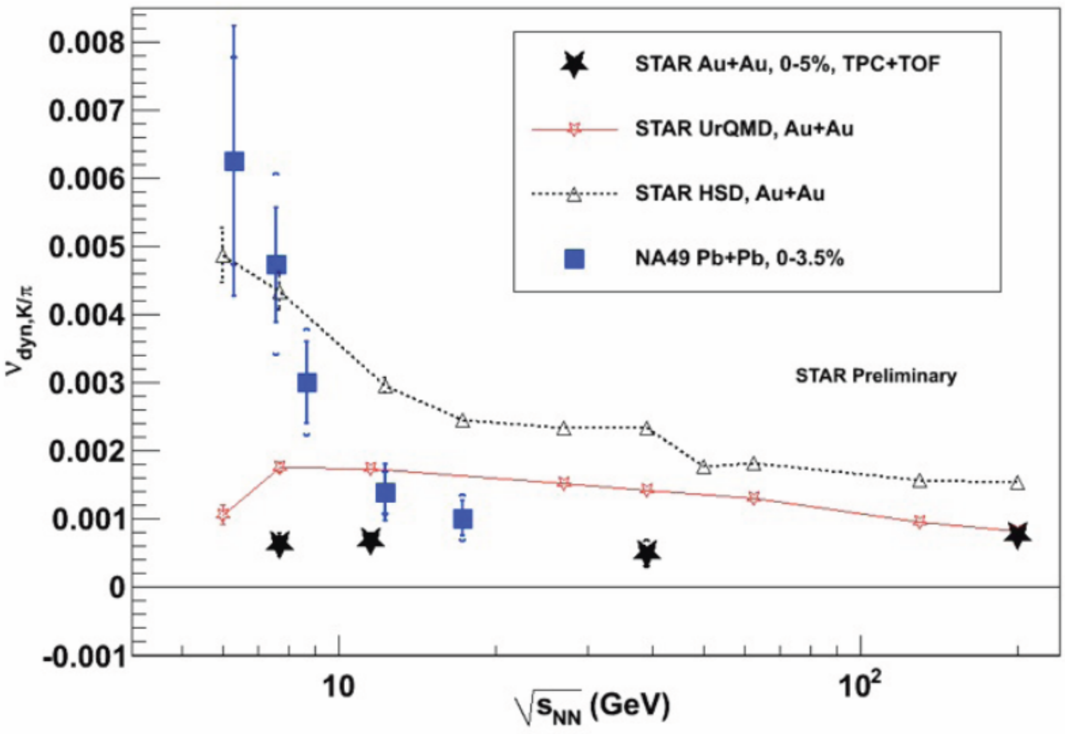
Apparent differences (results with Kaons) with SPS

Differences could be due to difference in acceptance and/or PID selections --- under discussion

fluct.

Particle ratio fluctuations

Terence Tarnowsky,
Mon/23 16:00



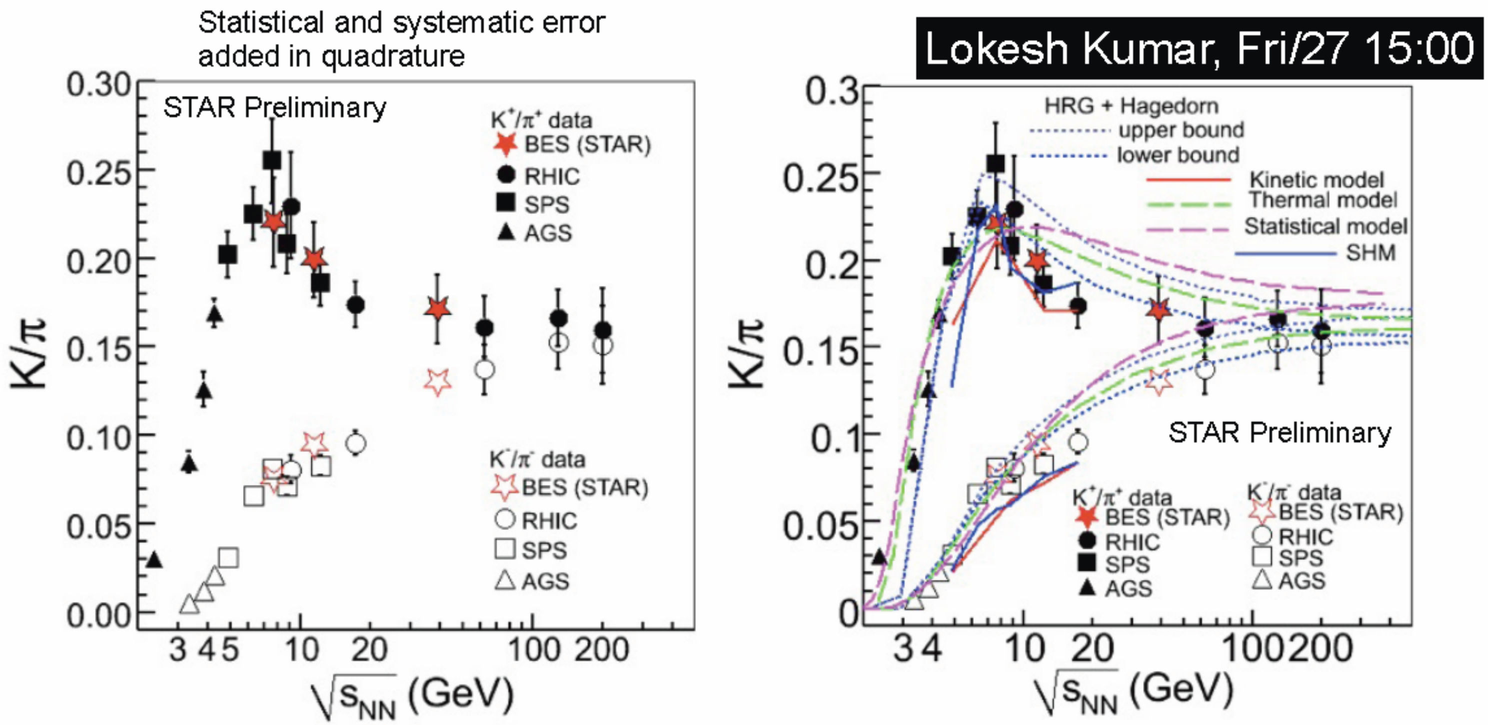
STAR TPC+TOF

π: 0.2 < p_T < 1.4 GeV/c

K; 0.2 < p_T < 1.4 GeV/c

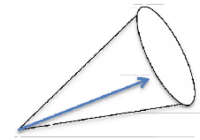
Data are still "horny"

K/π ratio

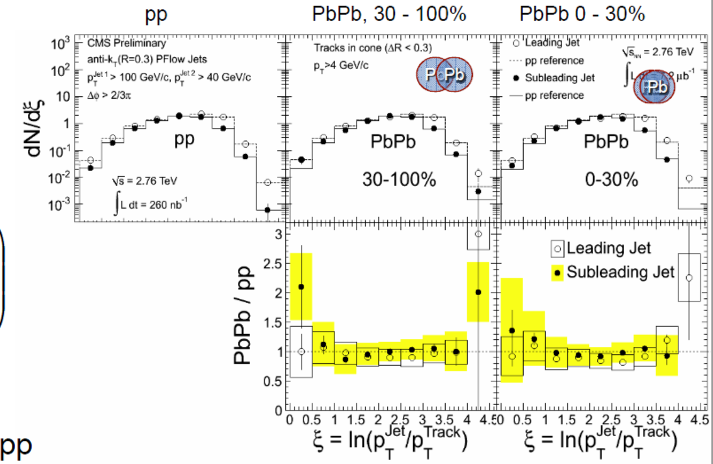


- **Can be naturally explained by change of strangeness production from ΛK to KK…**

Fragmentation Function at LHC

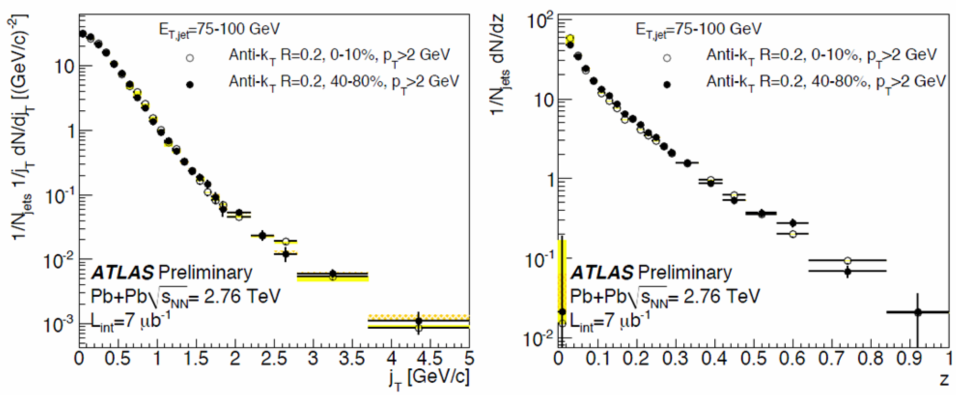


$$\xi = \ln\left(\frac{p_T^{Jet}}{p_T^{Track}}\right)$$



Fragmentation Functions

- Compare PbPb to pp



p_T cut to suppress underlying event, and background subtracted using region outside jet cone

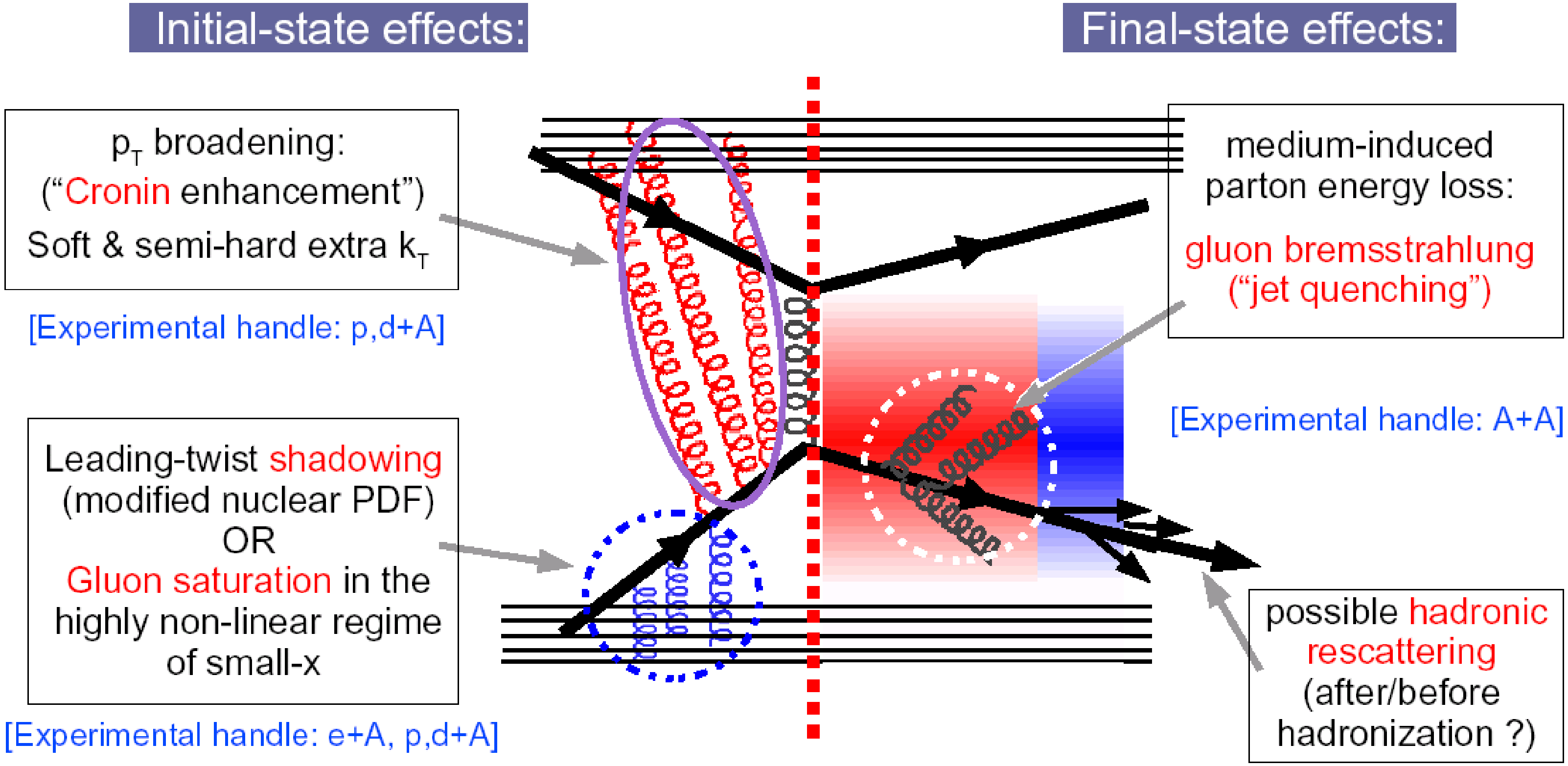
Yellow bands represent uncertainties from background subtraction

No strong modification of fragmentation functions between peripheral and central: surprising in a radiative energy loss scenario?

26

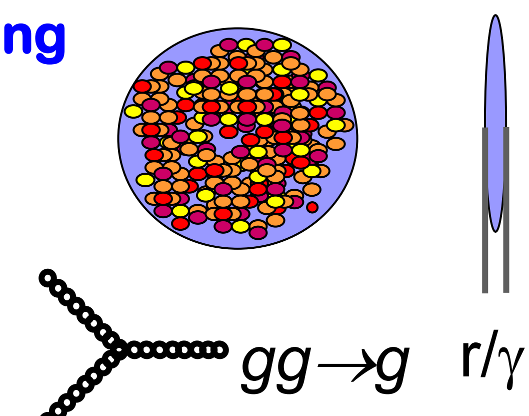
- Not modified!
- Need to be more quantitative to really understand differences from RHIC.

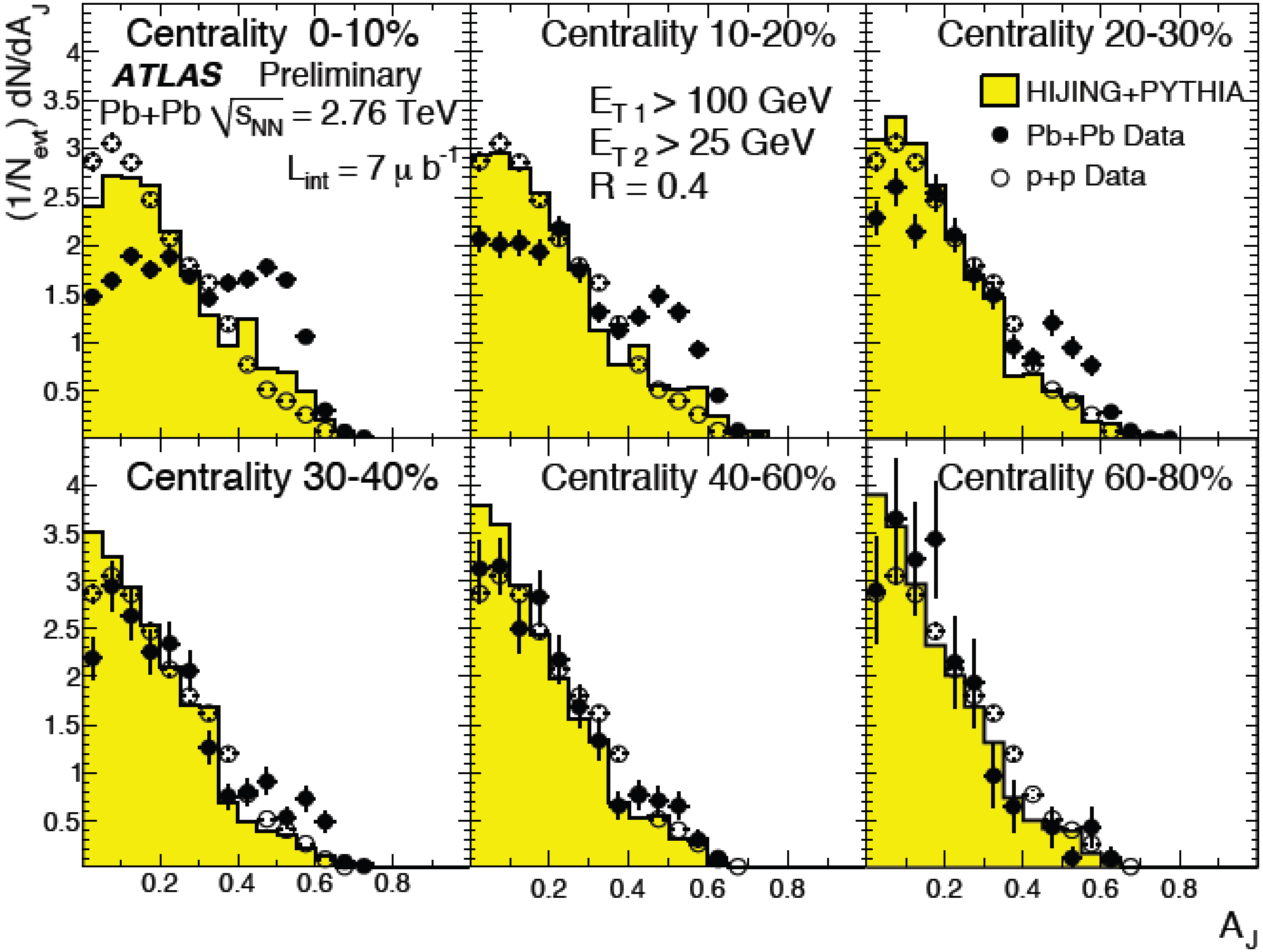
STONY BROOK
STATE UNIVERSITY OF NEW YORK



- **Color Glass Condensate**
- **Gluon fusion reduces number of scattering centers in initial state.**
- **Theoretically attractive; limits DGLAP evolution/restores unitarity**

probe rest frame



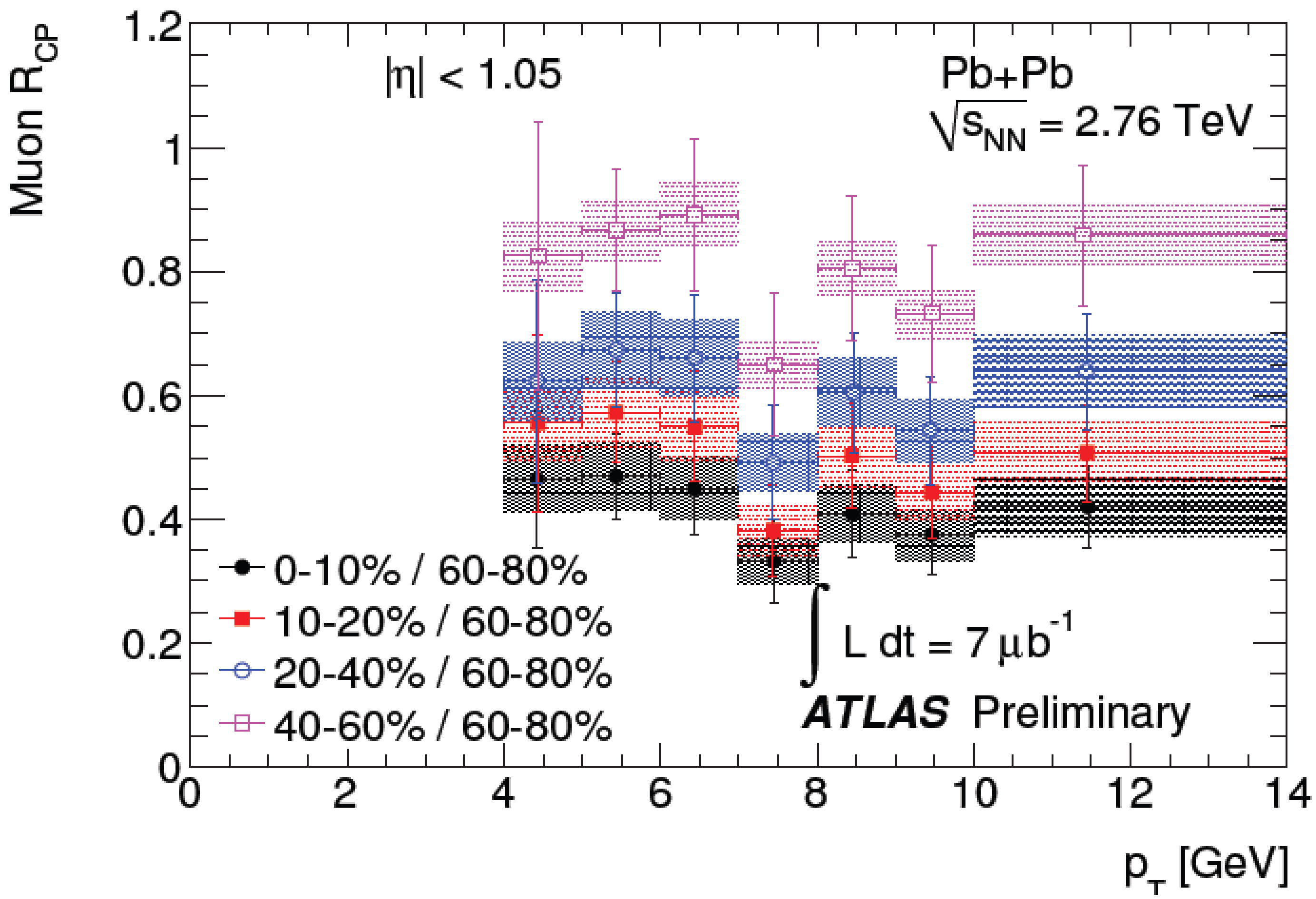


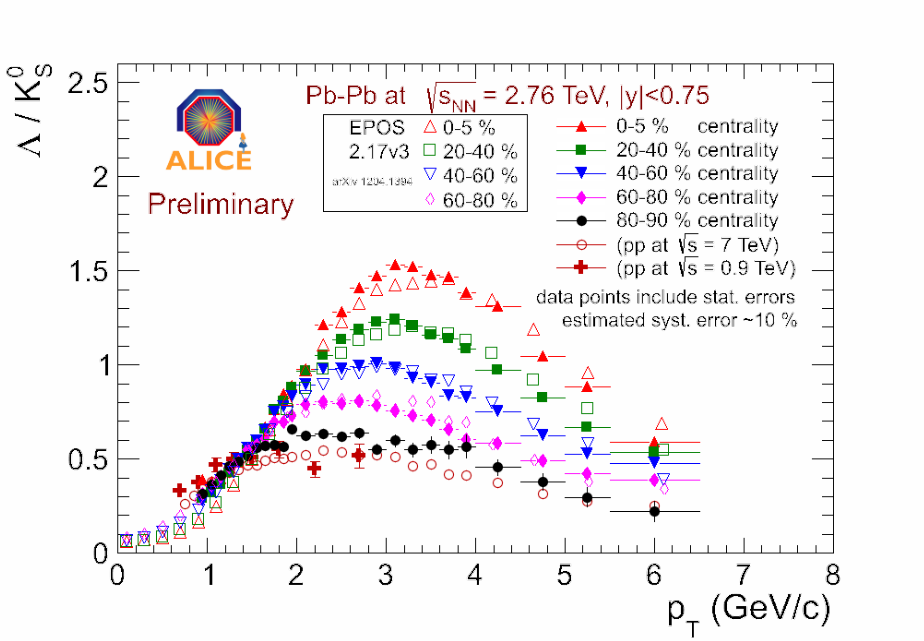
$$A_J = \frac{E_T^1 - E_T^2}{E_T^1 + E_T^2}$$

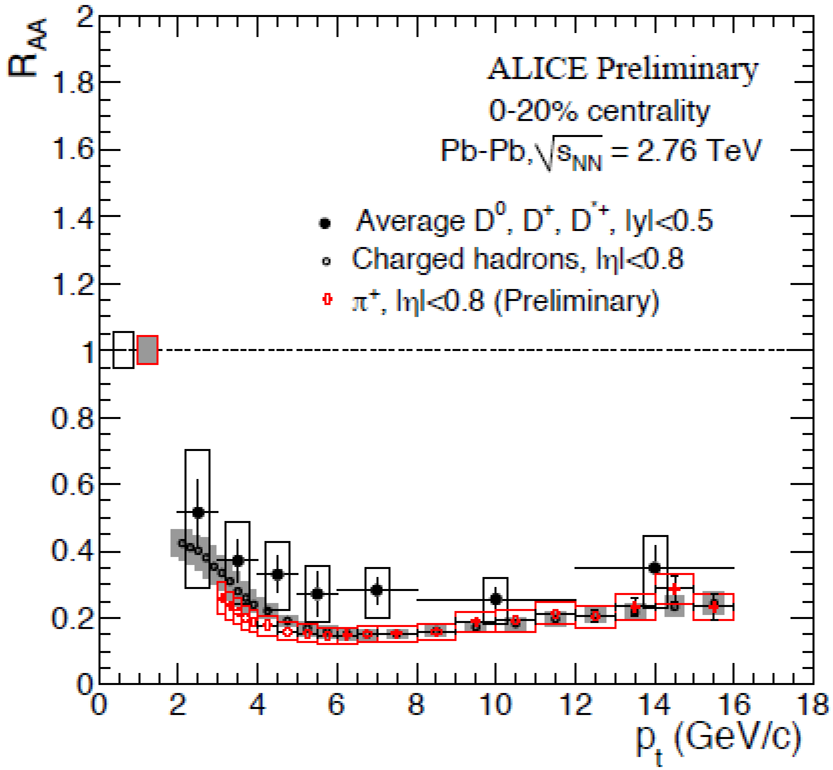
$$E_{T\,1} > 100\ GeV$$

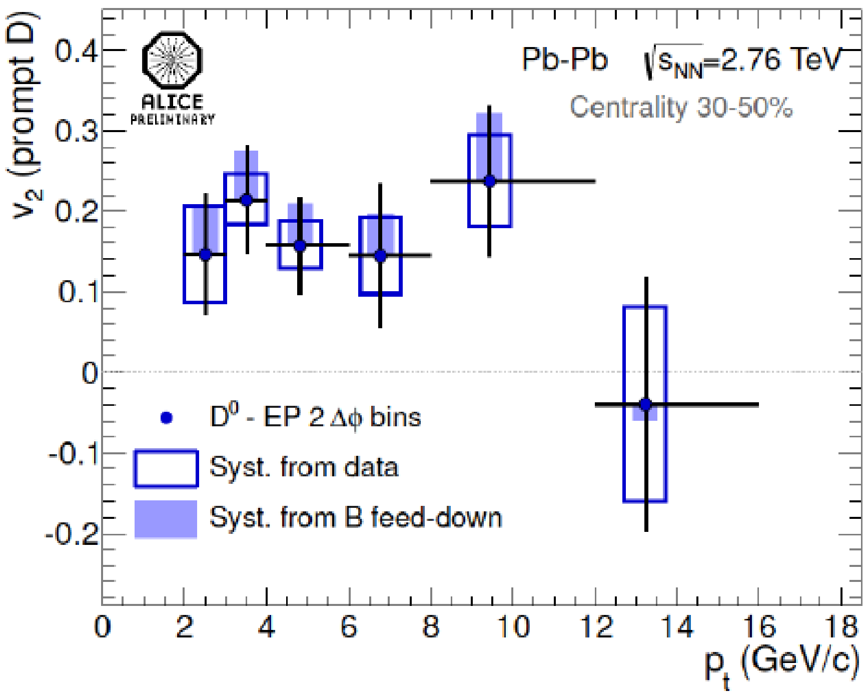
$$E_{T\,2} > 25\ GeV$$

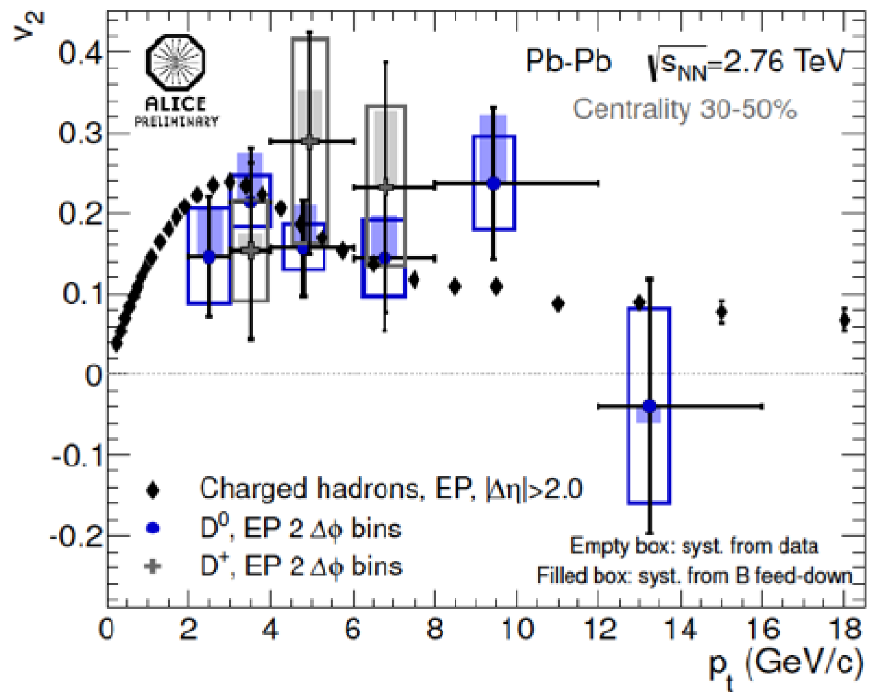
Updated from published result

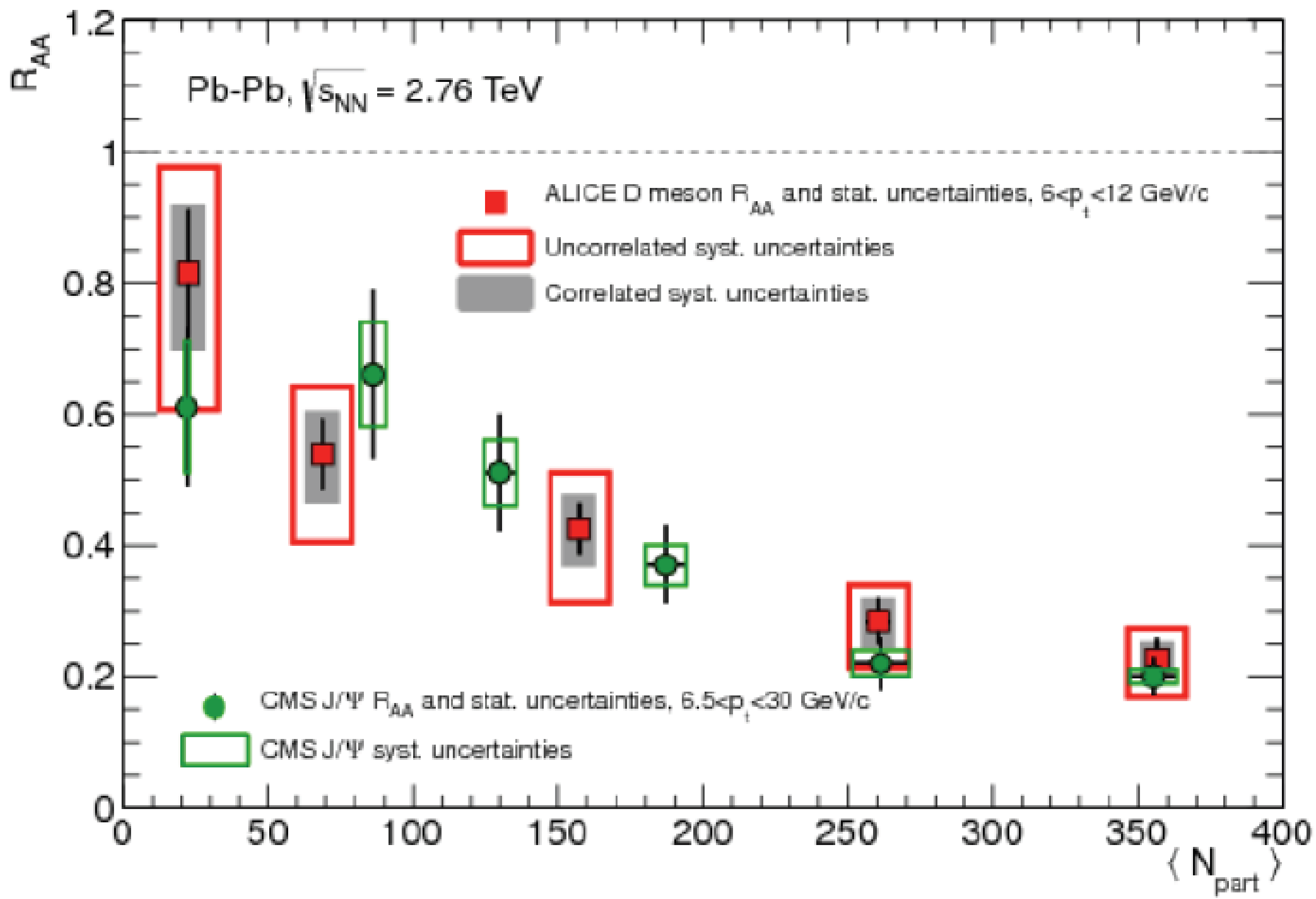

Muon R_{CP}
$|\eta| < 1.05$
Pb+Pb
$\sqrt{s_{NN}} = 2.76$ TeV
0-10% / 60-80%
10-20% / 60-80%
20-40% / 60-80%
40-60% / 60-80%
$\int L\,dt = 7\,\mu b^{-1}$
ATLAS Preliminary
p_T [GeV]
0
0.2
0.4
0.6
0.8
1
1.2
2
4
6
8
10
12
14

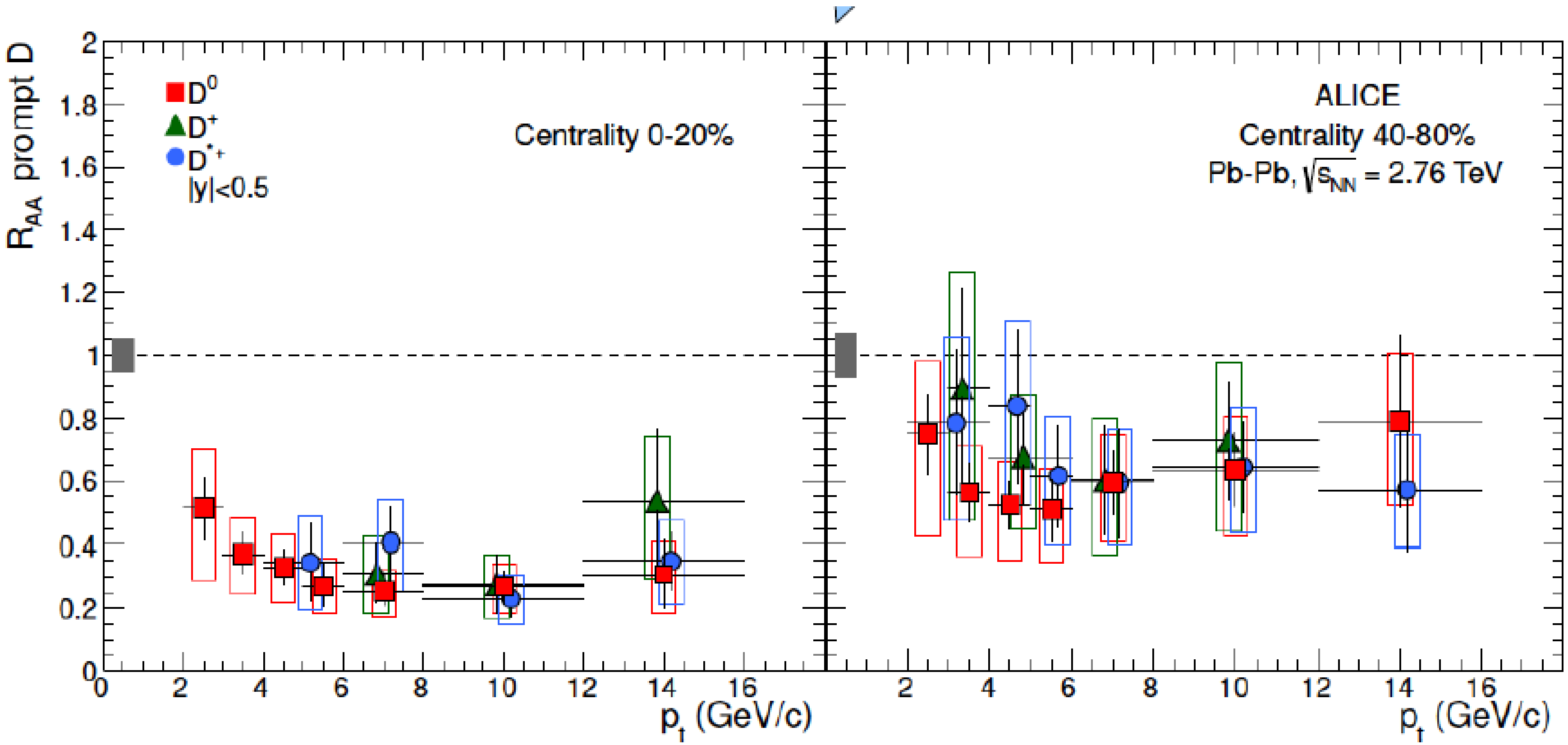

Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 TeV, |y|<0.75
ALICE
Preliminary
EPOS 2.17v3
0-5 %
20-40 %
40-60 %
60-80 %
0-5 % centrality
20-40 % centrality
40-60 % centrality
60-80 % centrality
80-90 % centrality
(pp at $\sqrt{s}$ = 7 TeV)
(pp at $\sqrt{s}$ = 0.9 TeV)
data points include stat. errors
estimated syst. error ~10 %
Λ / K^0_S
p_T (GeV/c)


ALICE Preliminary
0-20% centrality
Pb-Pb, $\sqrt{s_{NN}}$ = 2.76 TeV
Average D^0, D^+, D^{*+}, |y|<0.5
Charged hadrons, |η|<0.8
π^+, |η|<0.8 (Preliminary)
R_{AA}
p_t (GeV/c)

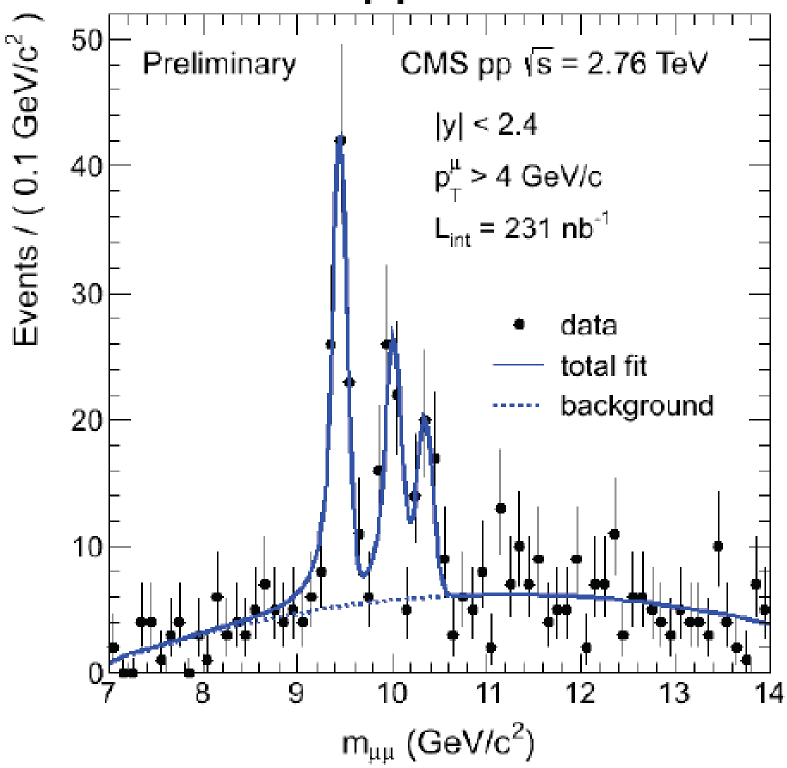

v2 (prompt D)
ALICE PRELIMINARY
Pb-Pb √sNN=2.76 TeV
Centrality 30-50%
D0 - EP 2 Δφ bins
Syst. from data
Syst. from B feed-down
pt (GeV/c)

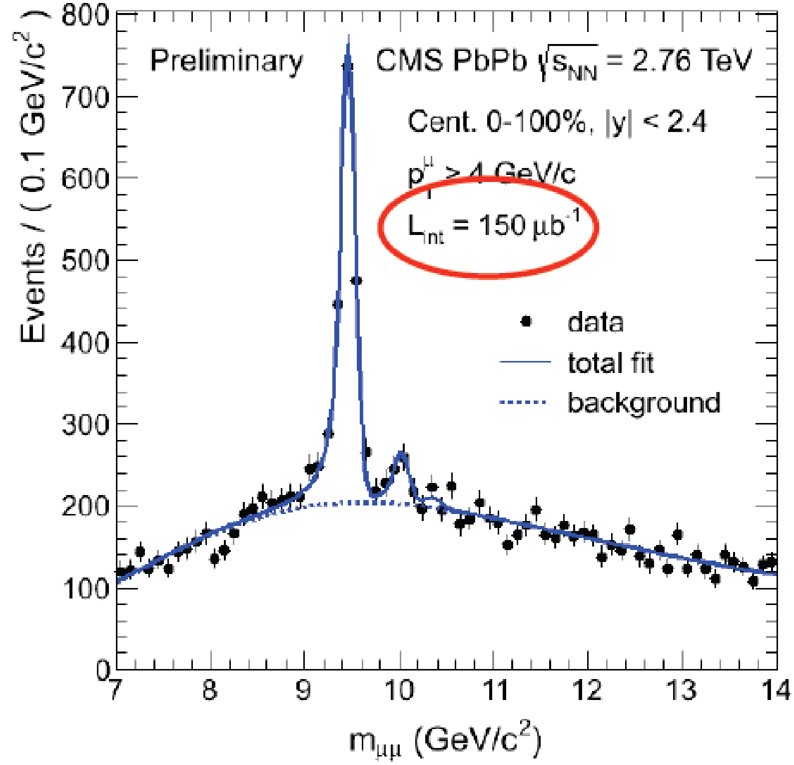

v2
ALICE PRELIMINARY
Pb-Pb √sNN=2.76 TeV
Centrality 30-50%
Charged hadrons, EP, |Δη|>2.0
D0, EP 2 Δφ bins
D+, EP 2 Δφ bins
Empty box: syst. from data
Filled box: syst. from B feed-down
pt (GeV/c)


Pb-Pb, $\sqrt{s_{NN}}$ = 2.76 TeV
ALICE D meson R_{AA} and stat. uncertainties, 6<p_t<12 GeV/c
Uncorrelated syst. uncertainties
Correlated syst. uncertainties
CMS J/Ψ R_{AA} and stat. uncertainties, 6.5<p_t<30 GeV/c
CMS J/Ψ syst. uncertainties
R_{AA}
⟨N_{part}⟩
0
50
100
150
200
250
300
350
400
0.2
0.4
0.6
0.8
1
1.2


R_{AA} prompt D
D^0
D^+
D^{*+}
|y|<0.5
Centrality 0-20%
ALICE
Centrality 40-80%
Pb-Pb, $\sqrt{s_{NN}}$ = 2.76 TeV
p_t (GeV/c)
p_t (GeV/c)

pp CMS-HIN-11-011 PbPb



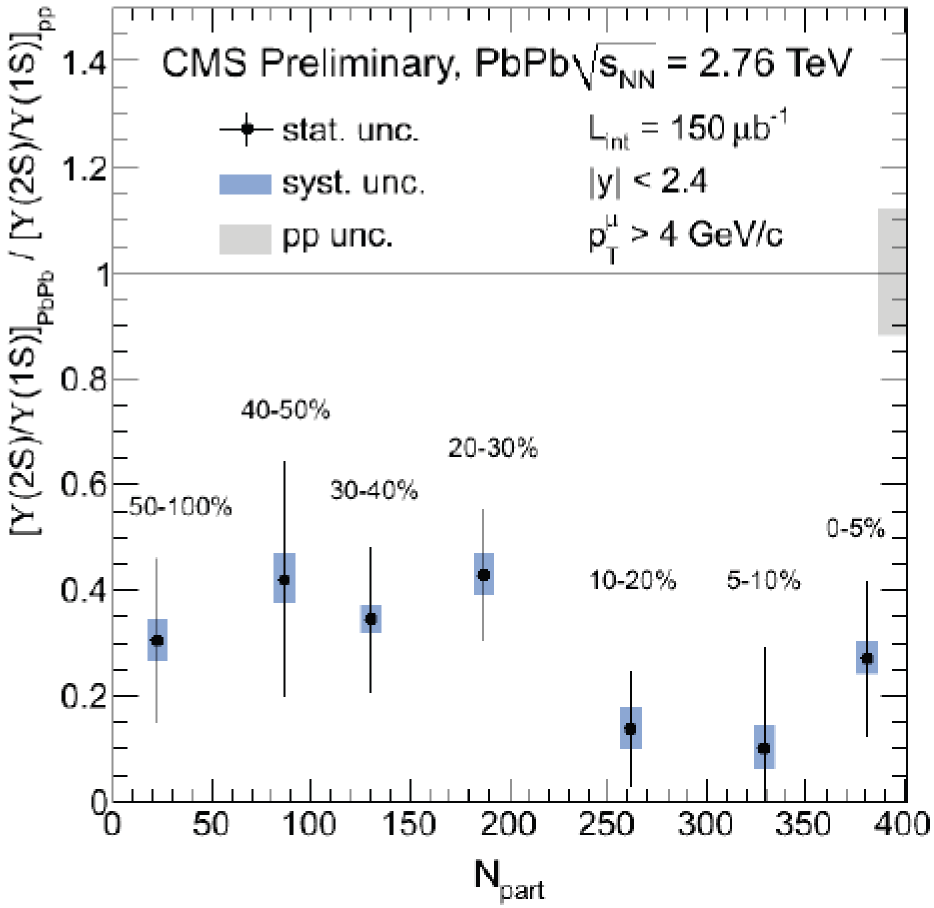


$$N_{\Upsilon(2S)}/N_{\Upsilon(1S)}|_{pp} = 0.56 \pm 0.13 \pm 0.01$$

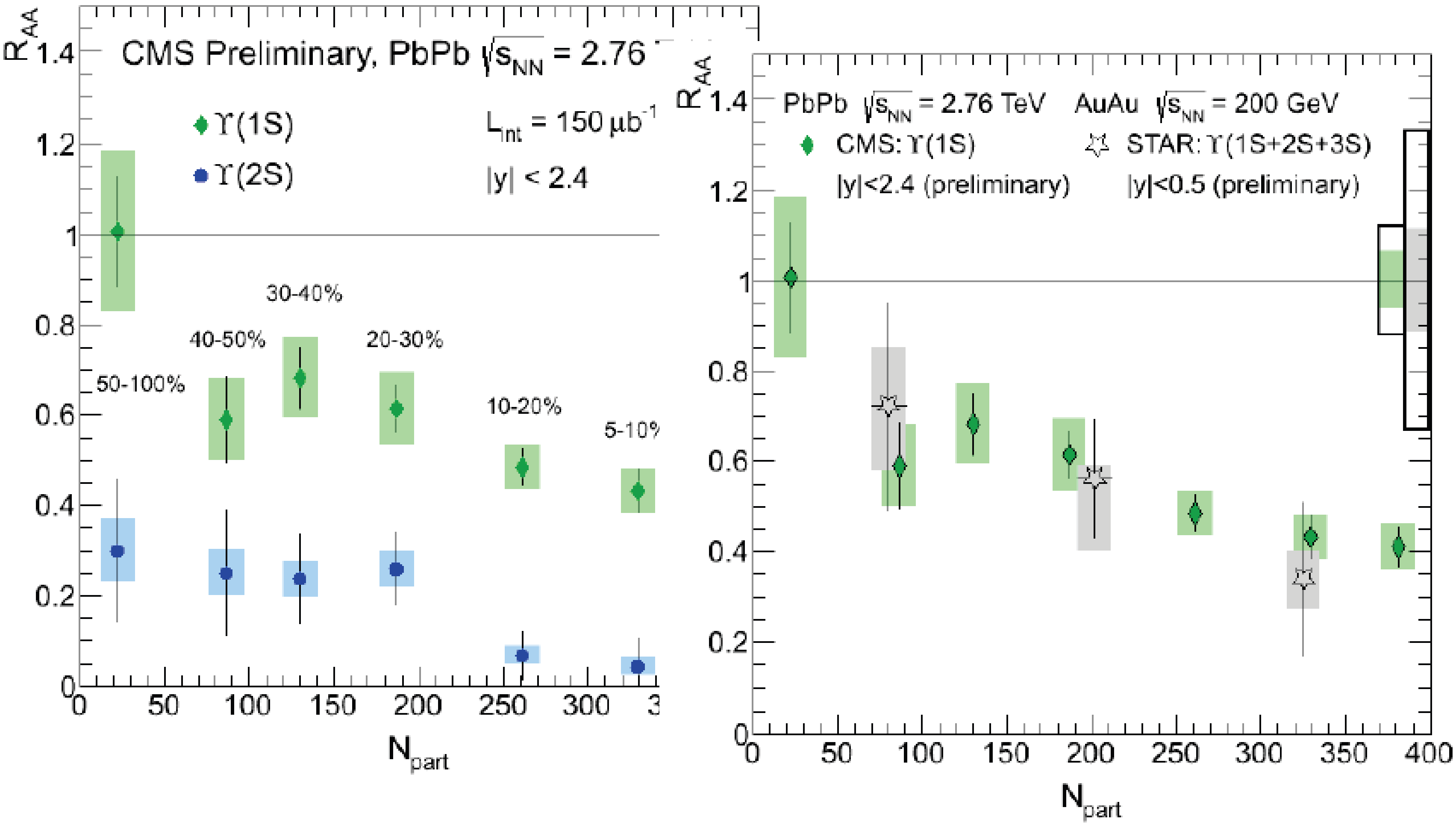
$$N_{\Upsilon(3S)}/N_{\Upsilon(1S)}|_{pp} = 0.21 \pm 0.11 \pm 0.02$$

$$N_{\Upsilon(2S)}/N_{\Upsilon(1S)}|_{\mathrm{PbPb}} = 0.12 \pm 0.03 \pm 0.01$$

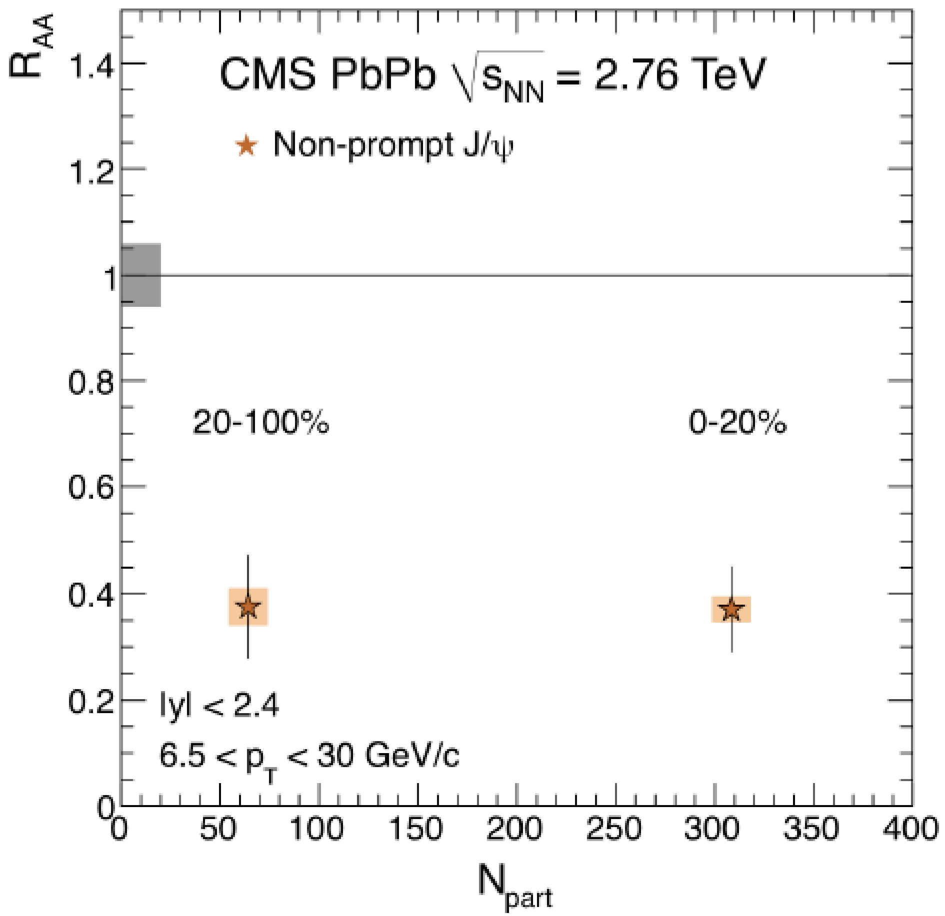
$$N_{\Upsilon(3S)}/N_{\Upsilon(1S)}|_{\mathrm{PbPb}} < 0.07$$



$$\frac{N_{\Upsilon(2S)}/N_{\Upsilon(1S)}|_{\mathrm{PbPb}}}{N_{\Upsilon(2S)}/N_{\Upsilon(1S)}|_{\mathrm{pp}}} = 0.21 \pm 0.07 \pm 0.02$$



CMS Preliminary, PbPb $\sqrt{s_{NN}}$ = 2.76
Υ(1S)
Υ(2S)
L_{int} = 150 μb^{-1}
|y| < 2.4
50-100%
40-50%
30-40%
20-30%
10-20%
5-10%
R_{AA}
N_{part}
PbPb $\sqrt{s_{NN}}$ = 2.76 TeV
AuAu $\sqrt{s_{NN}}$ = 200 GeV
CMS: Υ(1S)
|y|<2.4 (preliminary)
STAR: Υ(1S+2S+3S)
|y|<0.5 (preliminary)
R_{AA}
N_{part}


CMS PbPb $\sqrt{s_{NN}}$ = 2.76 TeV
Non-prompt J/ψ
20-100%
0-20%
|y| < 2.4
6.5 < p_T < 30 GeV/c
R_{AA}
N_{part}