Heavy Ion Physics Lecture 3

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Outline of Lectures

- 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

Lecture 1

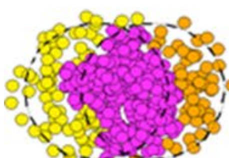
- What is It Like?
  - Azimuthally Anisotropic Flow
  - Hydrodynamic Limit
  - Heavy Flavor Modification
  - Recombination Scaling
- Is the matter exotic?
  - Quarkonia, Jet Asymmetry, Color Glass Condensate

Lecture 2

- What does the Future Hold? → Lecture 3

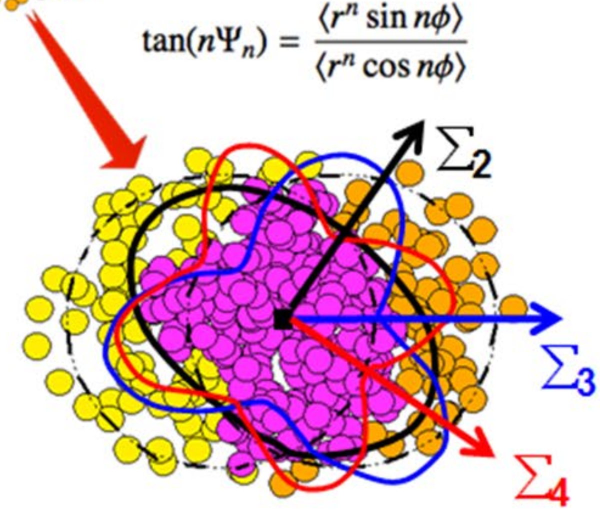
Ridge and Cone = v_3???

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

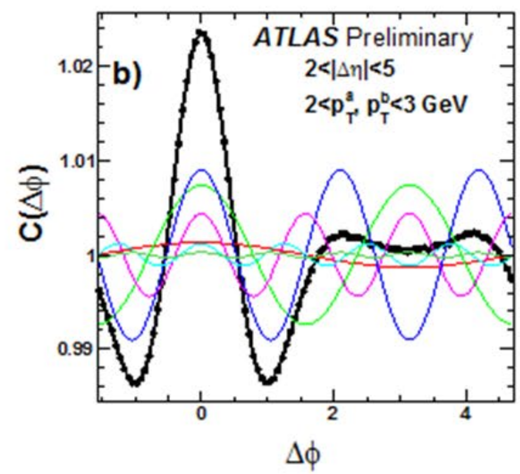


$$\epsilon_n = \sqrt{\frac{\langle r^n \cos n\phi\rangle + \langle r^n \sin n\phi\rangle}{\langle r^n\rangle}}$$

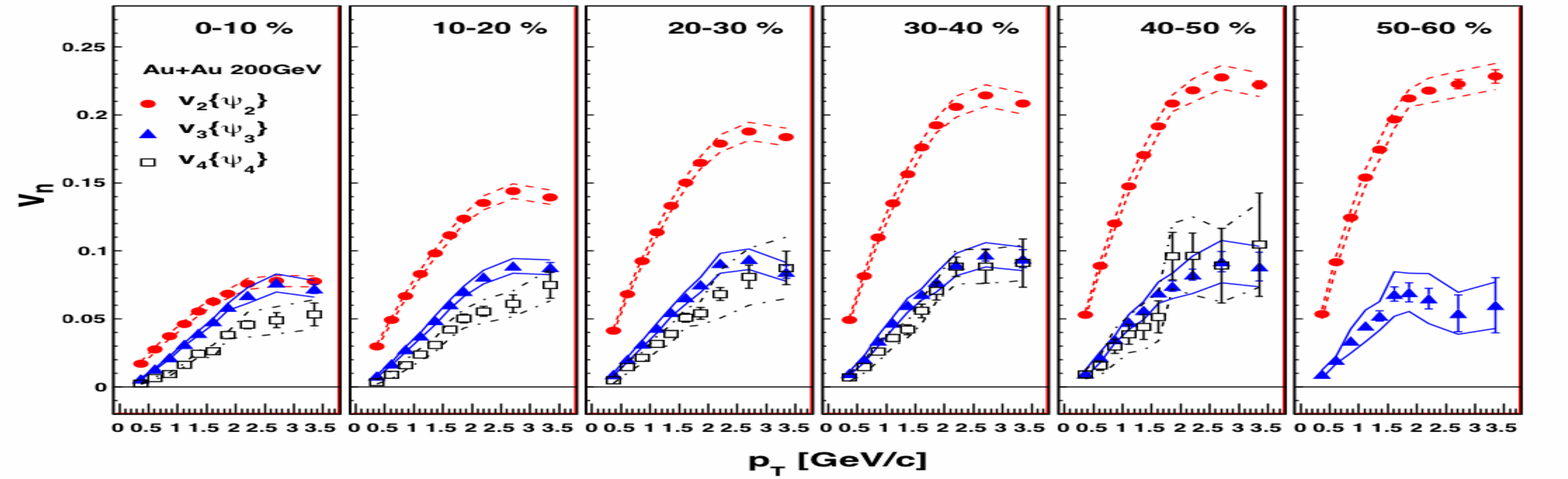
$$\tan(n\Psi_n) = \frac{\langle r^n \sin n\phi\rangle}{\langle r^n \cos n\phi\rangle}$$



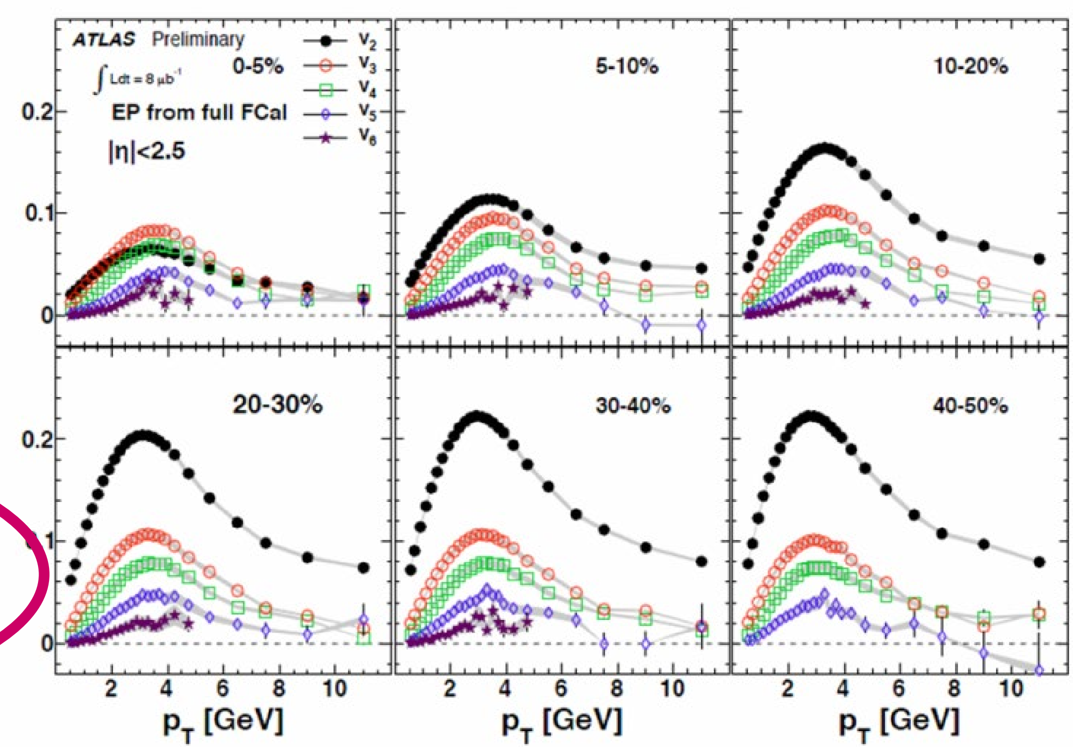
Singles:	$\frac{dN}{d\phi} \propto 1 + \sum_n 2v_n \cos n(\phi - \Psi_n)$	EP method
Pairs:	$\frac{dN}{d\Delta\phi} \propto 1 + \sum_n 2v_n^a v_n^b \cos(n\Delta\phi)$	2PC method



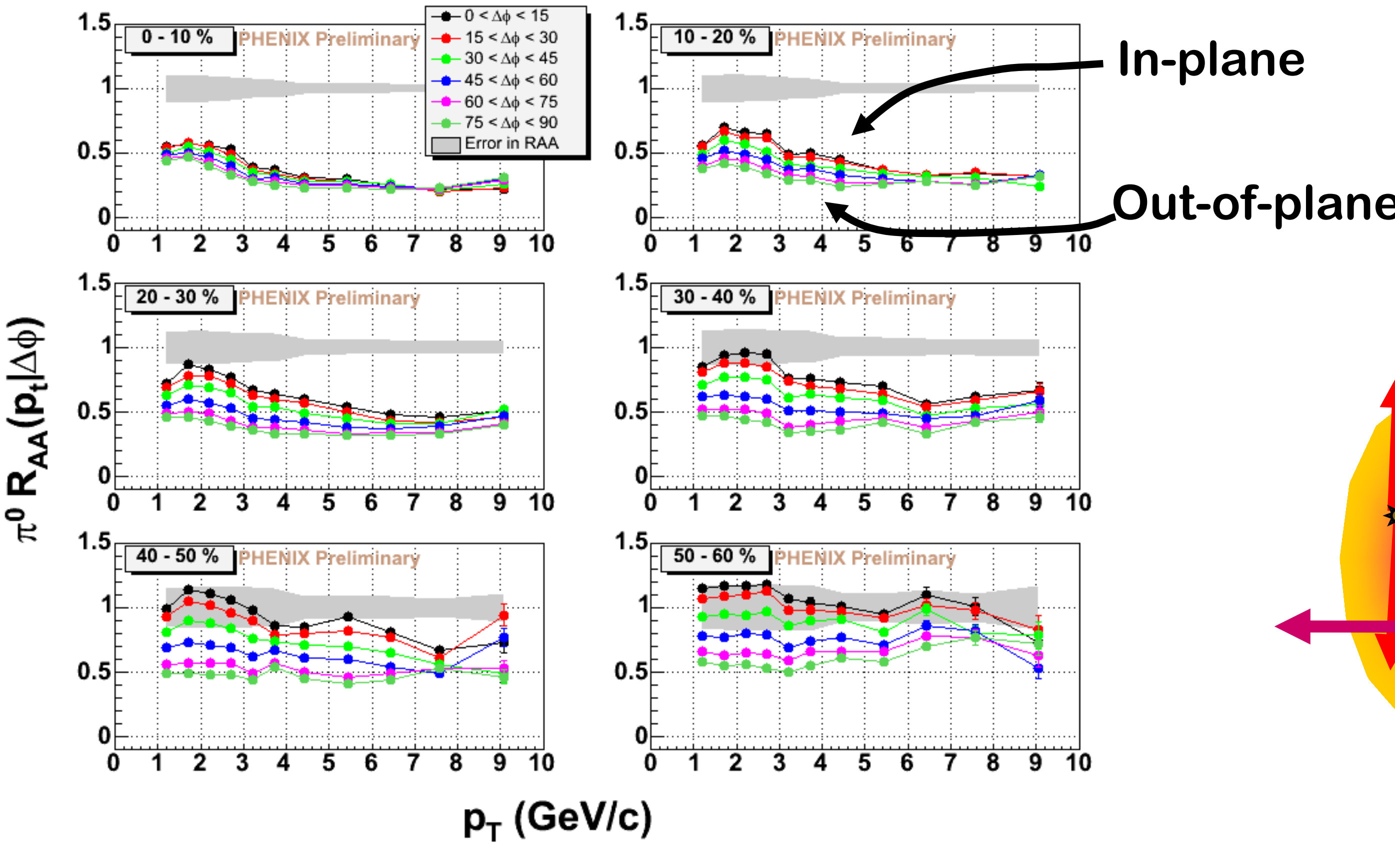
Reminder: Higher order moments

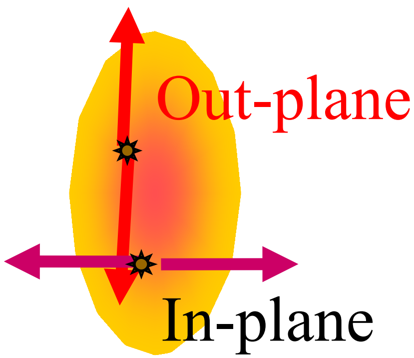


- Higher order moments can be measured WRT their own "reaction plane".
- Determines how initial state fluctuations are carried by fluid to final state.
- Higher order moments will serve to provide strong constraint on viscosity.



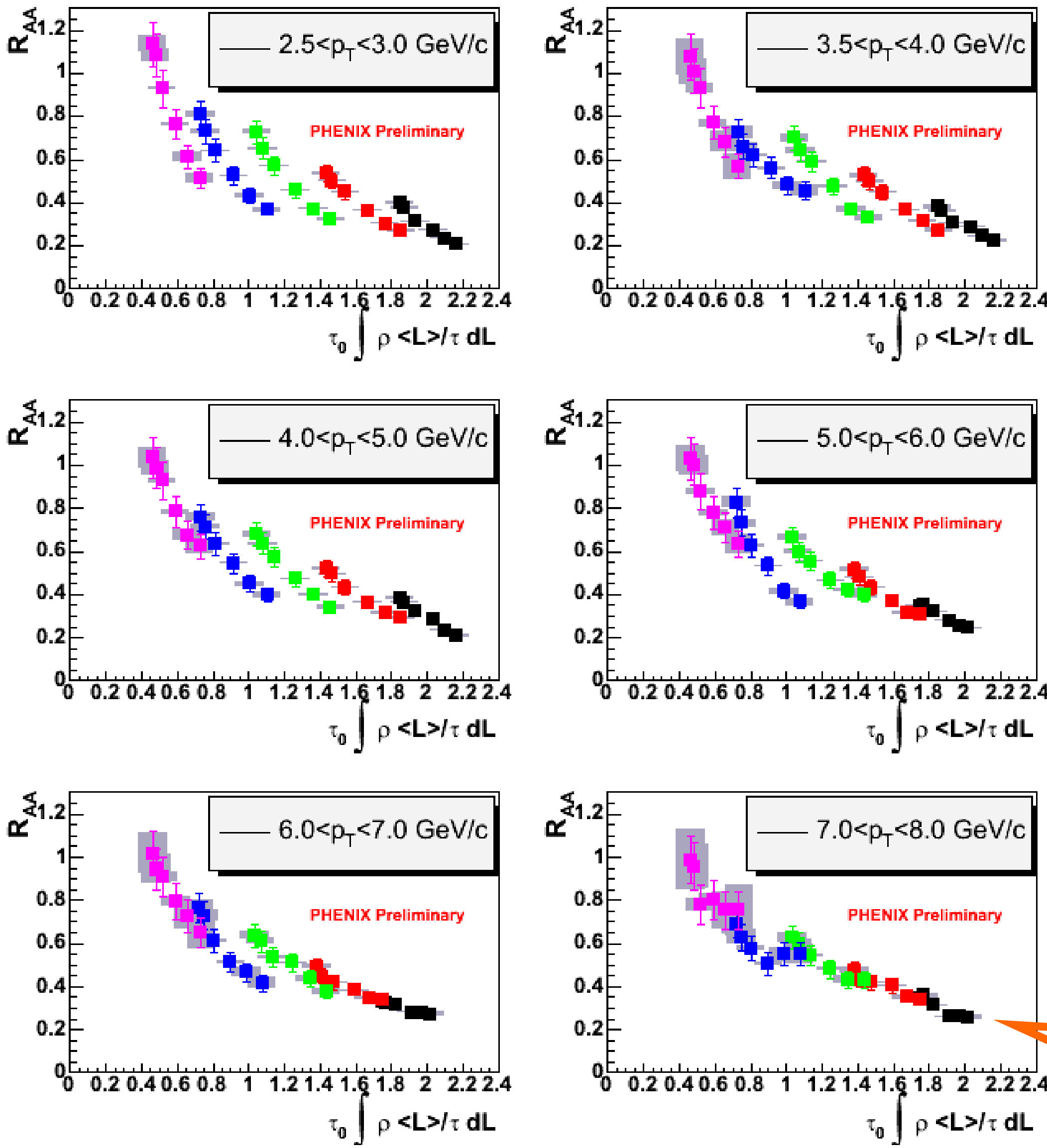
A closer look at R_{AA}

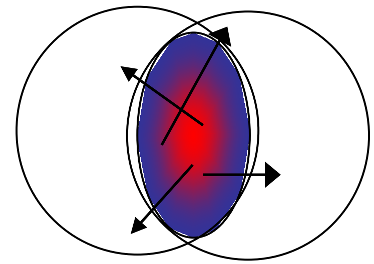




- R_{AA} is the ratio of what you observe/what you **naively** expect. (sensitive to e-hat…q-hat)
- Fourier-decomposed flow sensitive to pressures .
- Azimuthal R_{AA} plots both in a unique way.

R_{AA} vs. Angle+Centrality





Study RAA dependence on density-weighted average pathlength through collision region

10-20 % Centrality

20-30 % Centrality

40-50 % Centrality

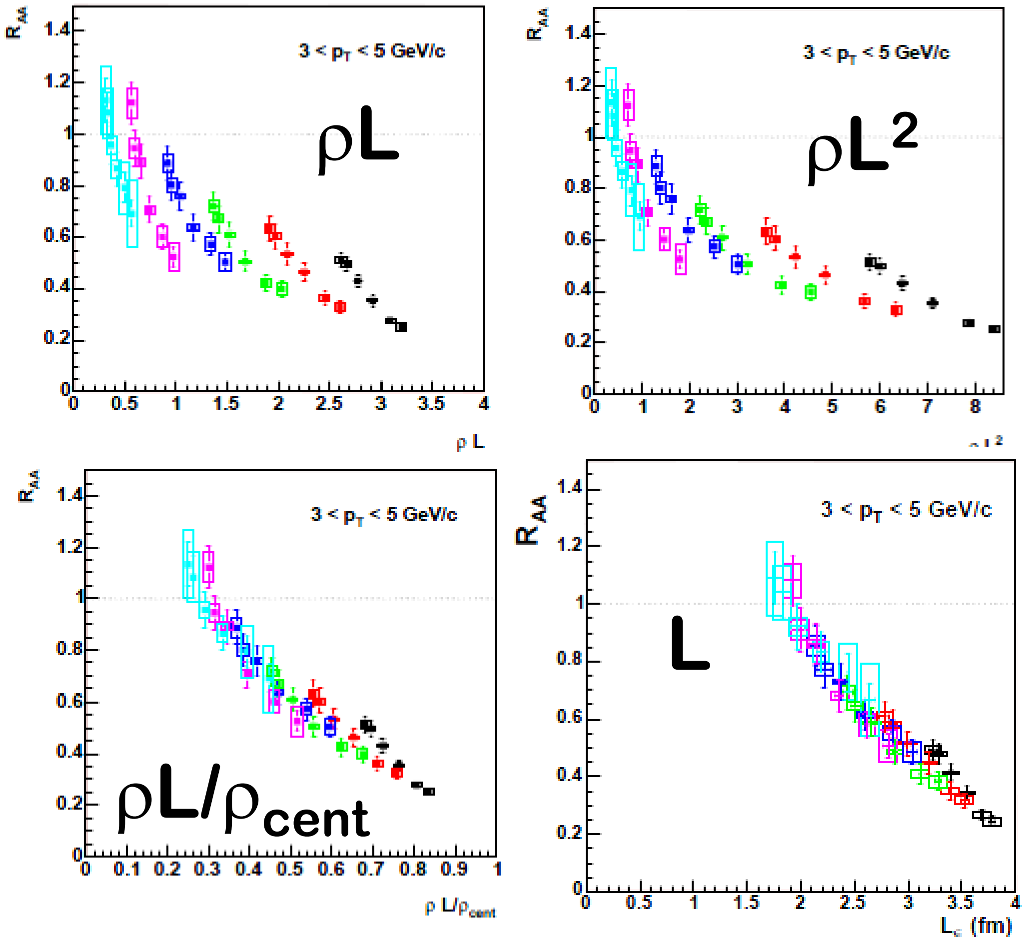
30-40 % Centrality

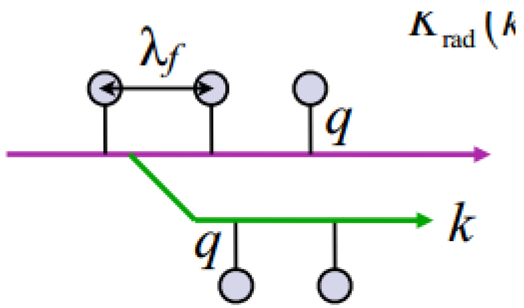
50-60 % Centrality

Angular and centrality dependence described by single curve only at high p_T

Thomas Hemmick

Try other powers of length…



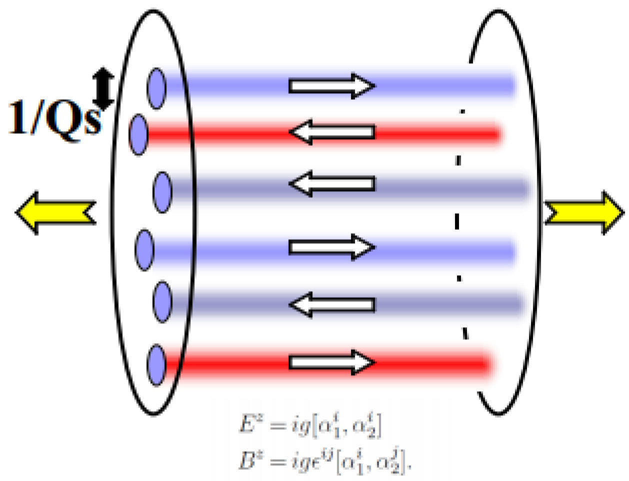


$$K_{LPM}(k,q;z) = 1 - \cos\left(\frac{(k-q)^2+\beta^2}{2xE}z\right)$$

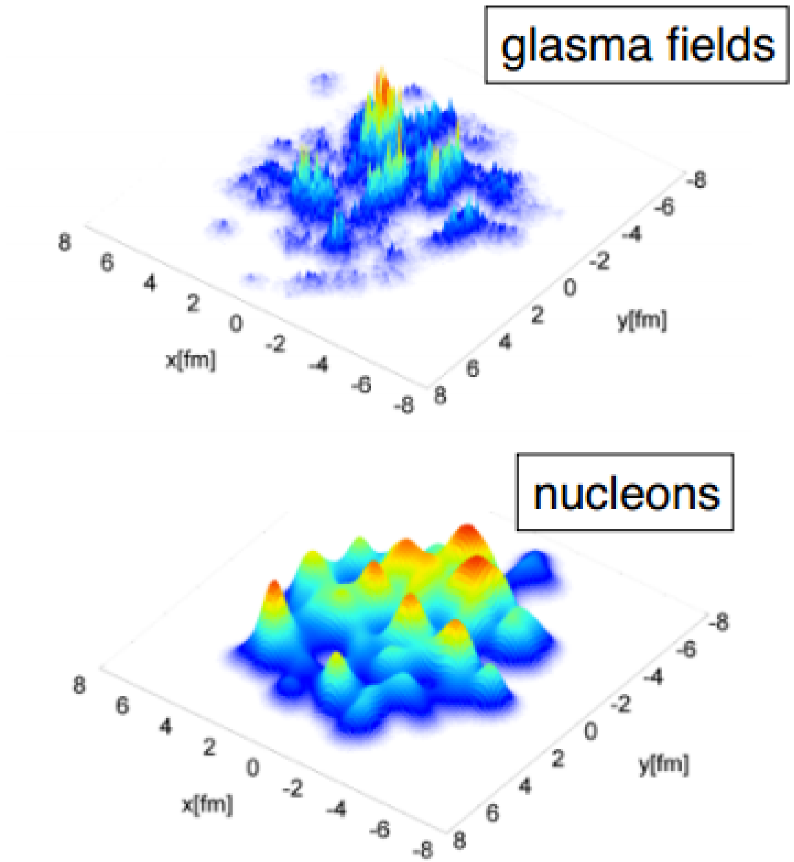
LPM coherence effect

- **LPM effect indices non-trivial dependence of E-loss on material thickness.**

The Limiting Factor



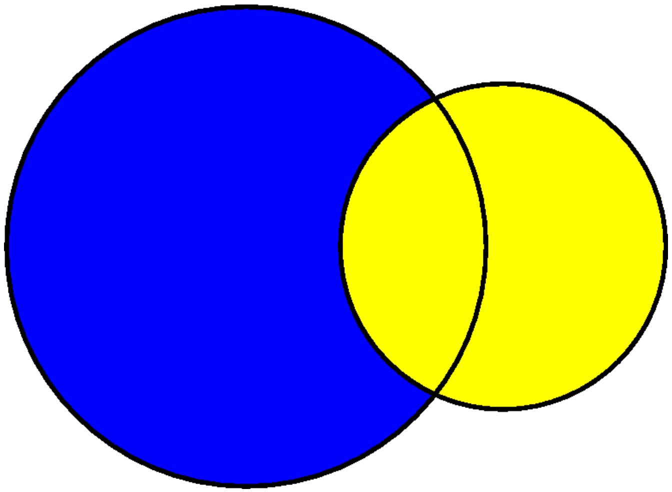
Transverse sections of the local energy density at τ = 0.4 fm/c



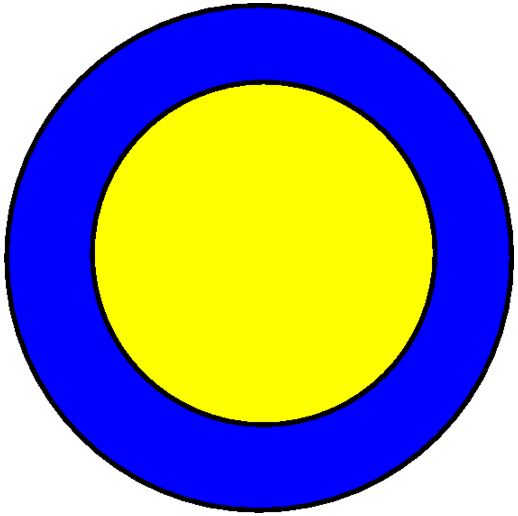
- **Initial State uncertainty!**
- **Further detailed study hampered by lack of understanding.**
- **Two choices:**
  - **Wait for theory.**
  - **Turn some knobs!**

CuAu Collisions!

Semi-Central:
Intrinsic odd harmonics



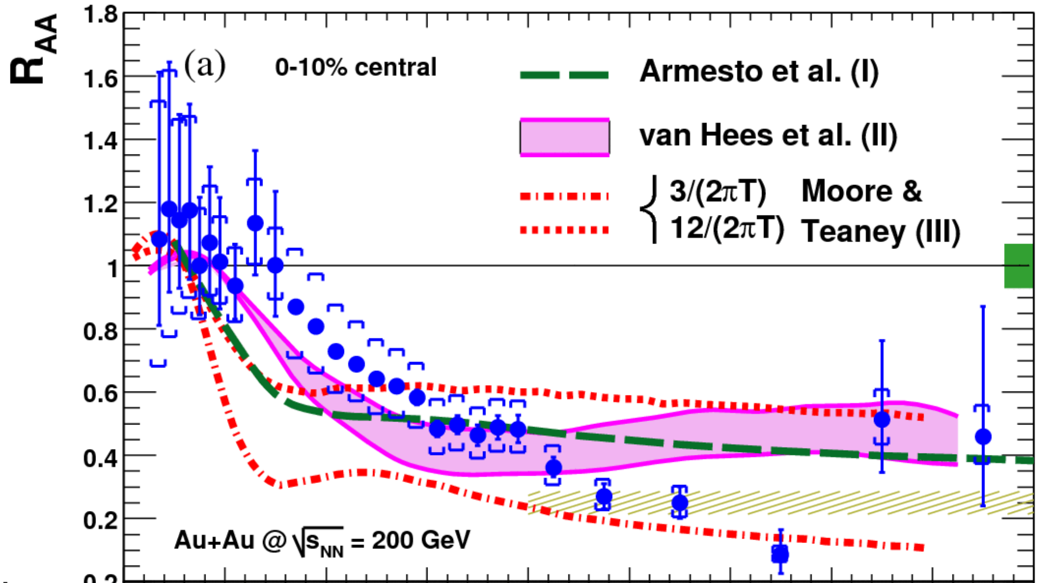
Central:
Uniform Density Profile

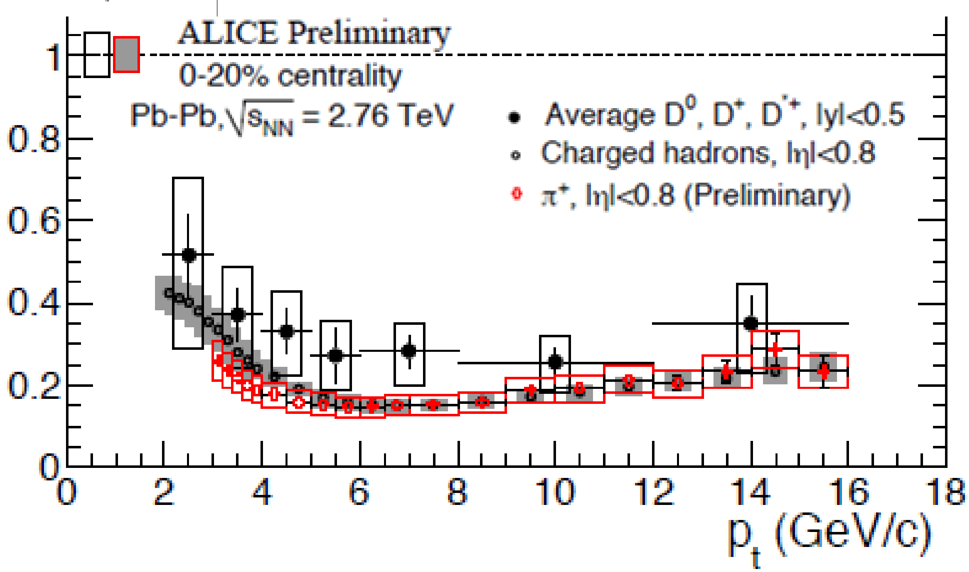


- We know that CuCu is sufficient to form plasma.
- CuAu forms unique geometry of initial state.
- Can guide/resolve initial state uncertainty.

Hard Probes: Open Heavy Flavor

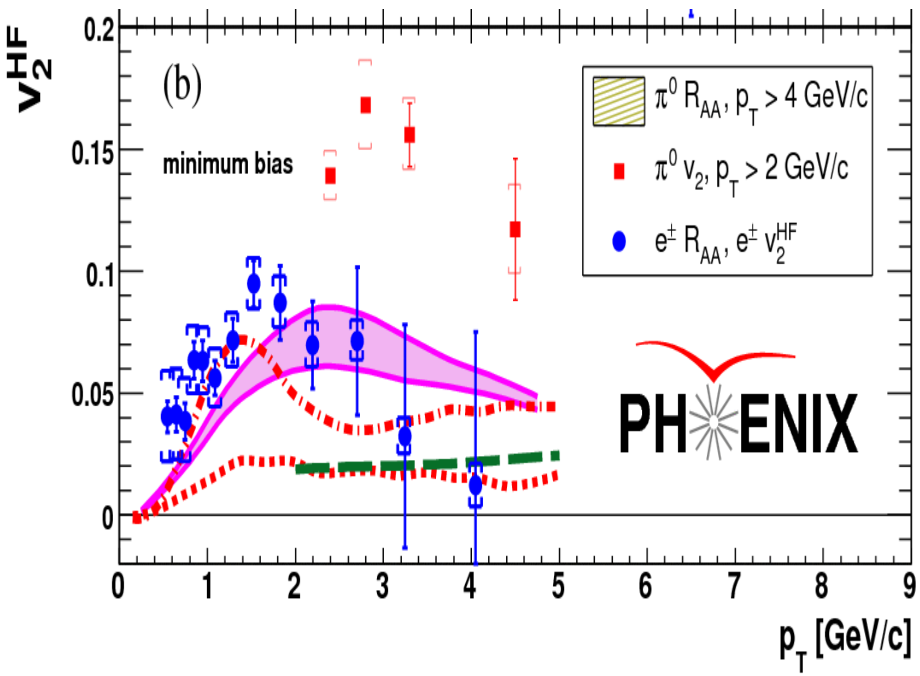
Electrons from c/b hadron decays

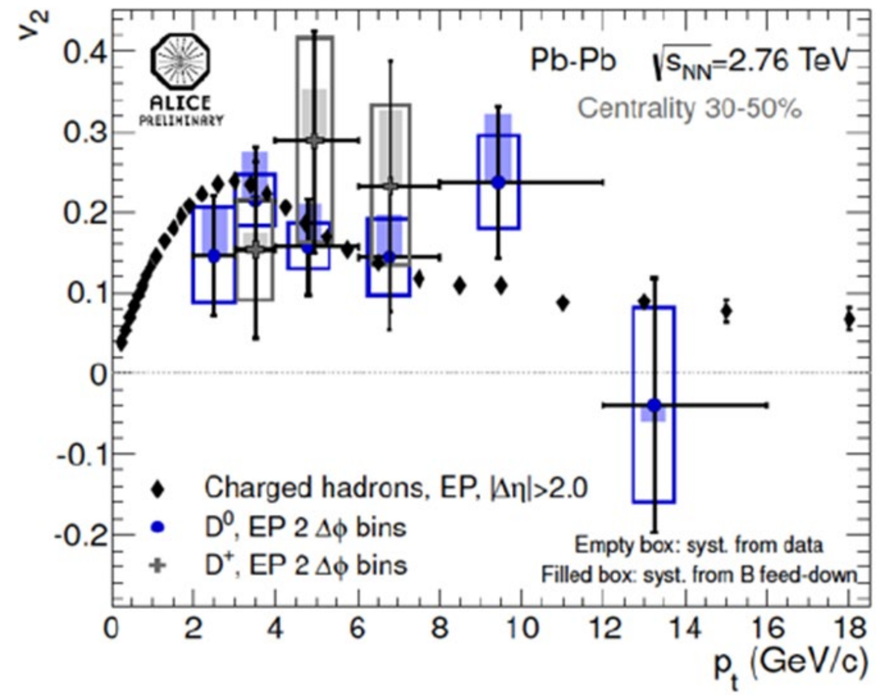




- **Calibrated probe?**
  - pQCD now predicts cross section well
  - Total charm follows binary scaling
- **Strong medium effects**
  - Significant suppression
  - Upper bound on viscosity!
  - Little room for bottom production
- **Limited agreement with energy loss calculations**

Heavy Flavor Quarks are Flowing!

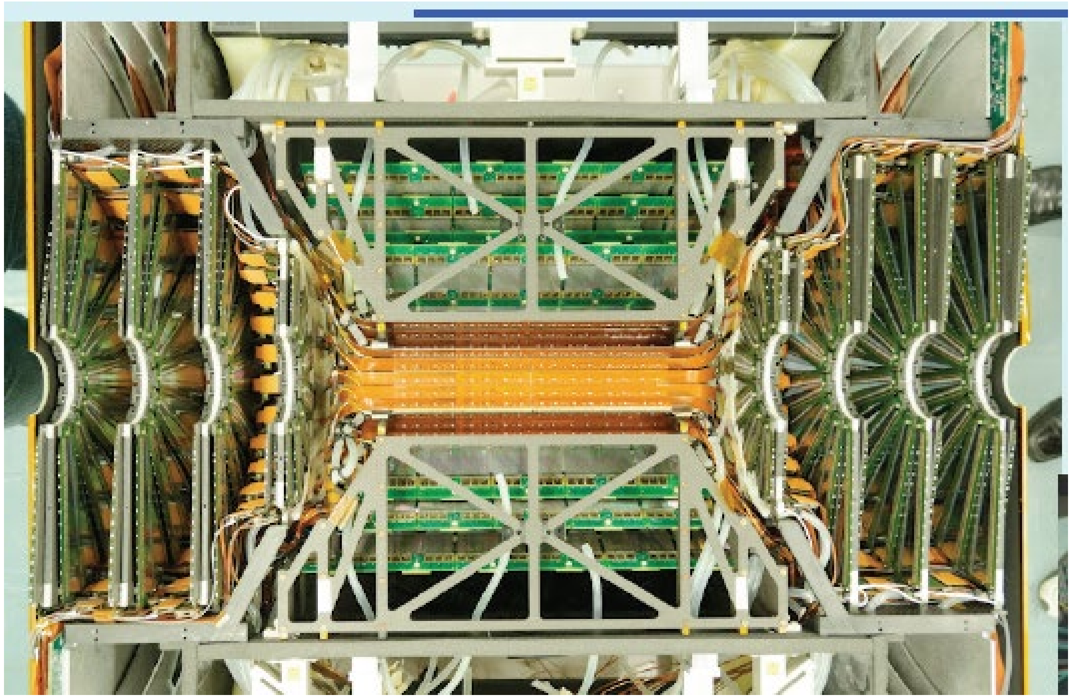


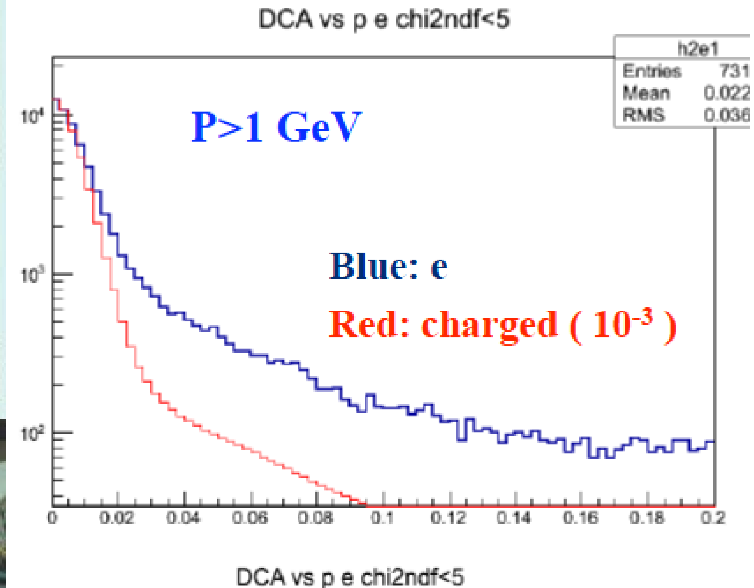


- We can imagine that the flowing QGP is a river that sweeps quarks.
- A “perfect fluid” is like a school of fish…all change direction at once.
- Our QGP river carries off heavy stones (not BOTTOM???)
- Requiring a model to SIMULTANEOUSLY fit R_{AA} and v_2 “measures” the η/s of the QGP fluid.

DISTINGUISH charm and bottom!

Solution: New Hardware!

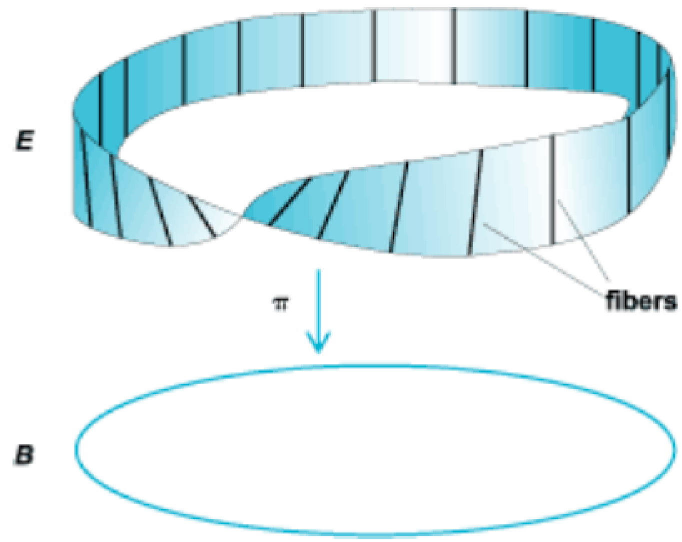


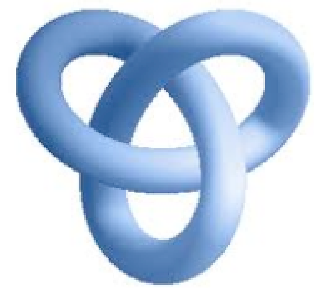


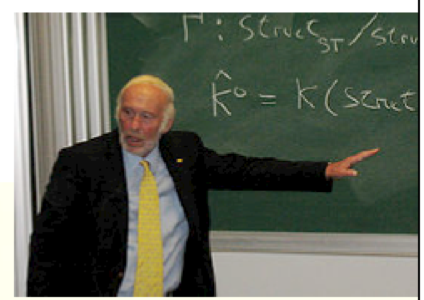
- Heavy quarks decay weakly.
- Macroscopic distance to collision point.
- Vertexing detectors identify displaced tracks.

Chiral Magnetic Effect

Gauge fields possess non-trivial topology







CHARACTERISTIC FORMS

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

.1)

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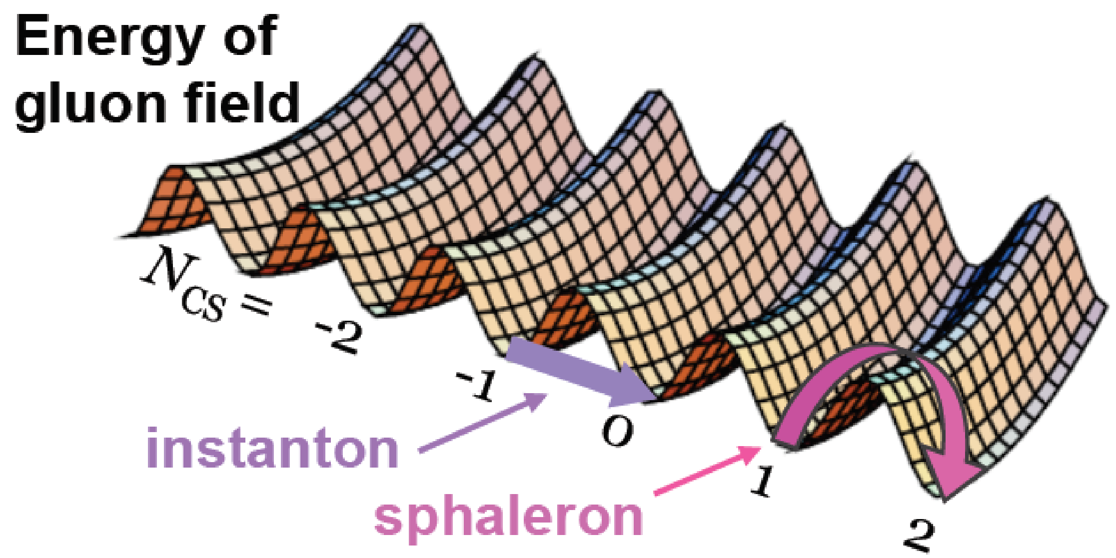
QCD vacuum is a superposition of states with different topology



Transitions between such states create the local imbalance of chirality

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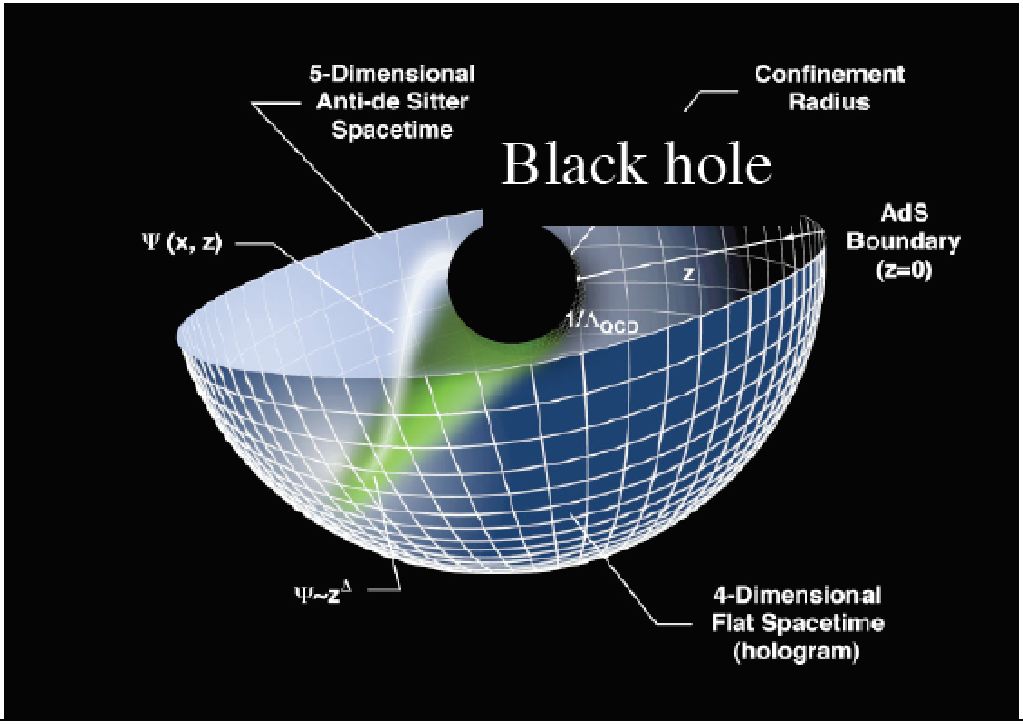
Topological transitions are frequent in sQGP

Chern-Simons number diffusion rate at strong coupling

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

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"

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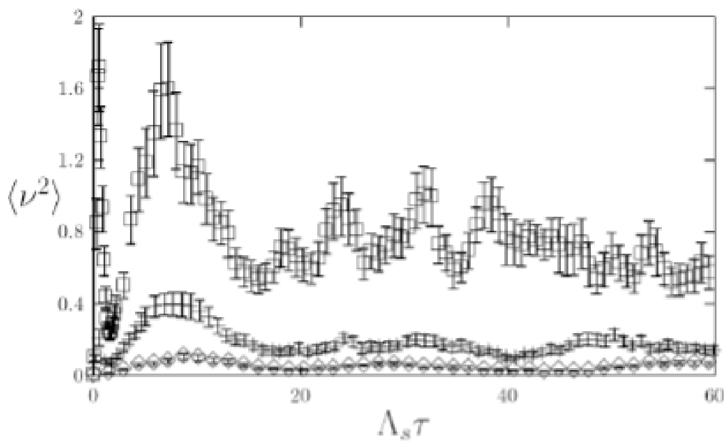
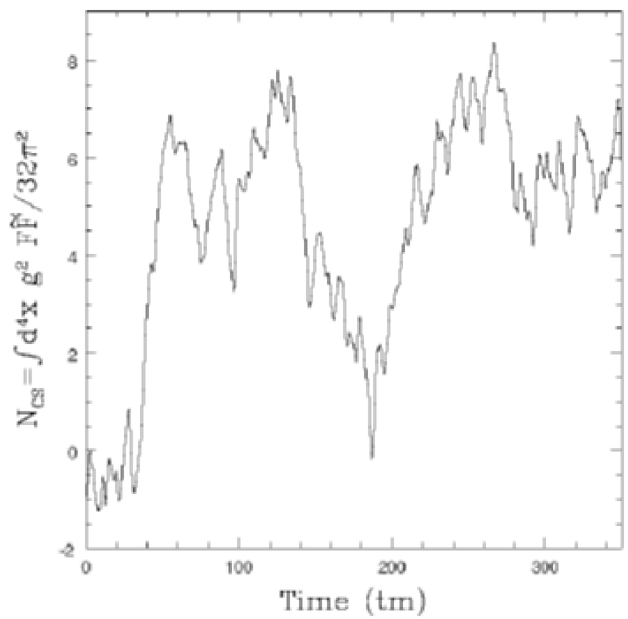
Topological transitions in QCD are seen in real-time lattice simulations



DK, A.Krasnitz and R.Venugopalan,
Phys.Lett.B545:298-306,2002



P.Arnold and G.Moore,
Phys.Rev.D73:025006,2006

Dima Kharzeev QM2011

Chiral Magnetic Effect in a chirally imbalanced plasma

Fukushima, DK, Warringa, PRD'08

Chiral chemical potential is formally equivalent to a background chiral gauge field: $\mu_5 = A_5^0$

In this background, vector e.m. current is not conserved:

$$\partial_\mu J^\mu = \frac{e^2}{16\pi^2} \left(F_L^{\mu\nu} \tilde{F}_{L,\mu\nu} - F_R^{\mu\nu} \tilde{F}_{R,\mu\nu} \right)$$

Compute the current through

$$J^\mu = \frac{\partial \log Z[A_\mu, A_\mu^5]}{\partial A_\mu(x)}$$

The result:

$$\boxed{\vec{J} = \frac{e^2}{2\pi^2}\, \mu_5\, \vec{B}}$$

Coefficient is fixed by the axial anomaly, no corrections

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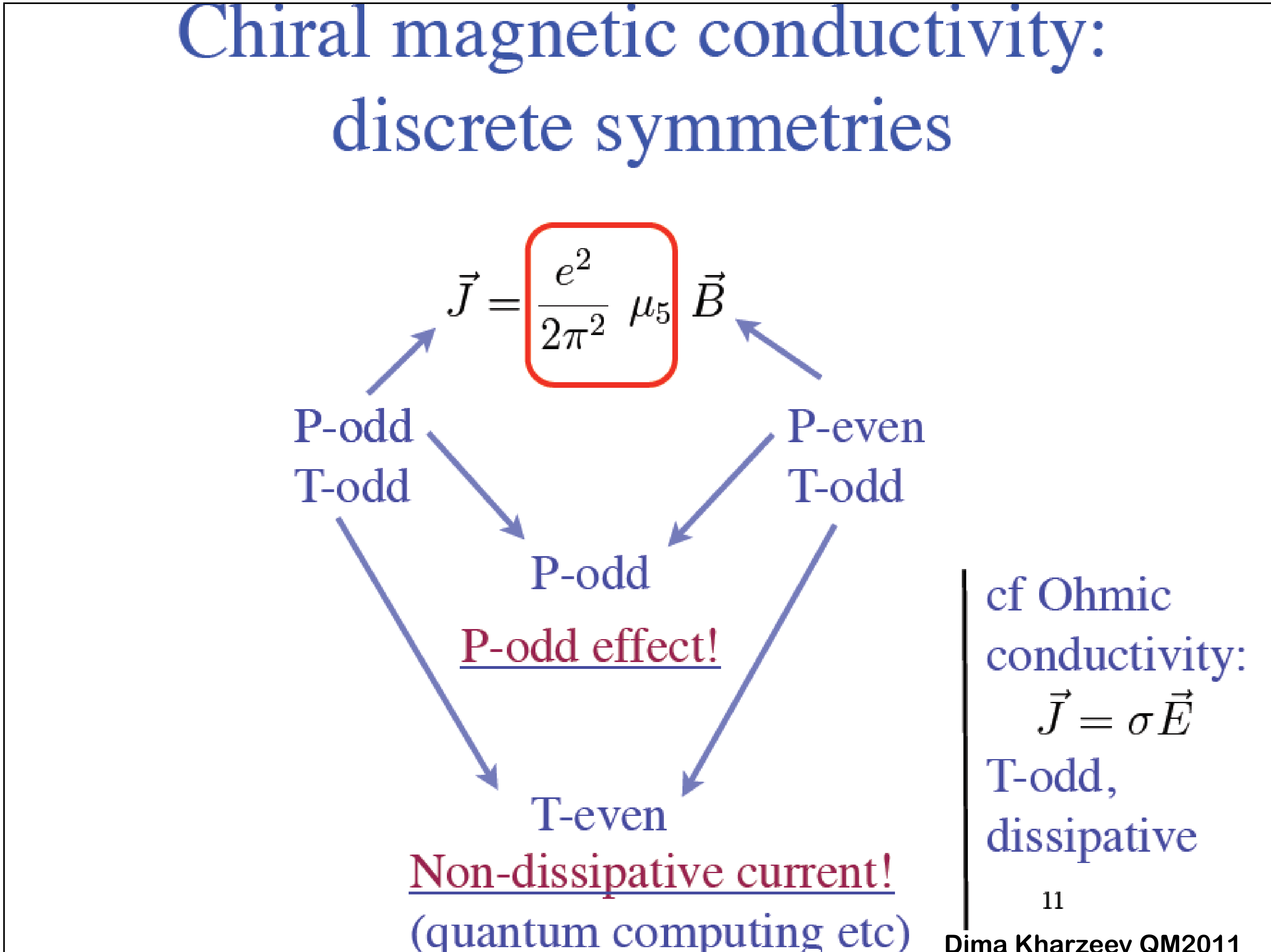
Chiral magnetic conductivity:
discrete symmetries
$\vec{J} = \boxed{\frac{e^2}{2\pi^2}\ \mu_5}\ \vec{B}$
P-odd
T-odd
P-even
T-odd
P-odd
P-odd effect!
T-even
Non-dissipative current!
(quantum computing etc)
cf Ohmic
conductivity:
$\vec{J} = \sigma \vec{E}$
T-odd,
dissipative
11
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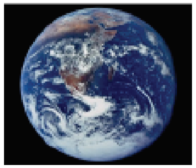
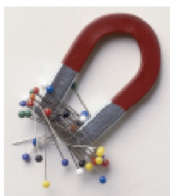
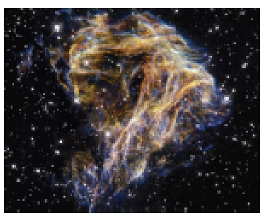
Comparison of magnetic fields

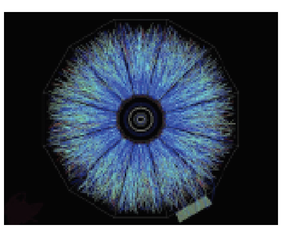






The Earths magnetic field	0.6 Gauss
A common, hand-held magnet	100 Gauss
The strongest steady magnetic fields achieved so far in the laboratory	4.5×10^5 Gauss
The strongest man-made fields ever achieved, if only briefly	10^7 Gauss
Typical surface, polar magnetic fields of radio pulsars	10^{13} Gauss
Surface field of Magnetars	10^{15} Gauss

http://solomon.as.utexas.edu/~duncan/magnetar.html



Heavy ion collisions: the strongest magnetic field ever achieved in the laboratory

Off central Gold-Gold Collisions at 100 GeV per nucleon

$$e\,B(\tau = 0.2\,\mathrm{fm}) \;=\; 10^3 \sim 10^4\ \mathrm{MeV}^2 \sim 10^{17}\,\mathrm{Gauss}$$

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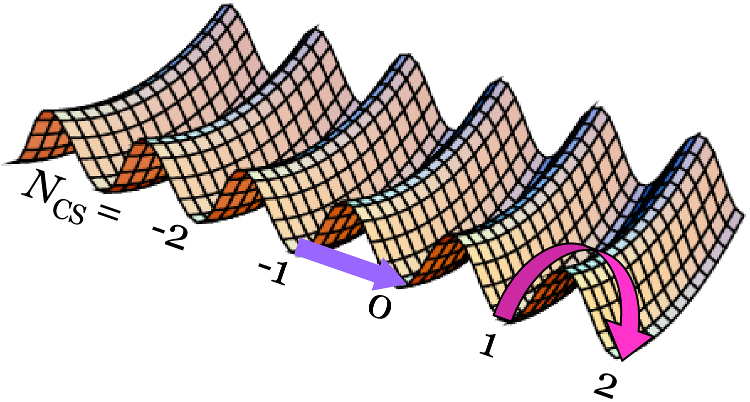
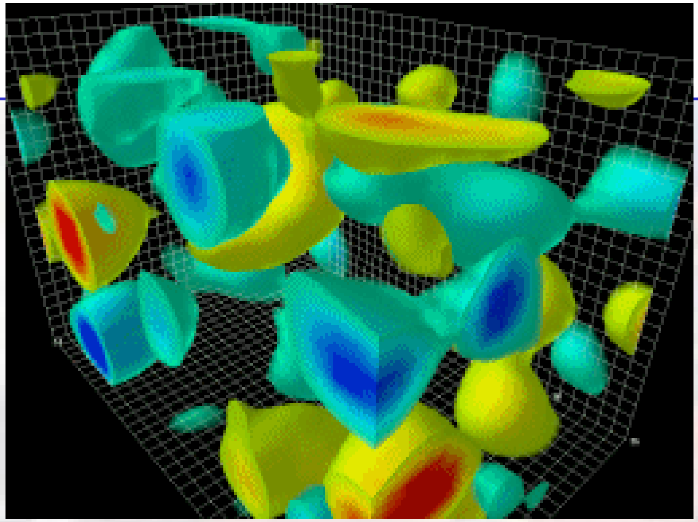
QCD vacuum topology

Energy of gluonic field is periodic in N_{cs} direction (~ a generalized coordinate)



Instantons and sphalerons are localized (in space and time) solutions describing transitions between different vacua



Chern-Simons number

$$N_{CS} = \frac{1}{16\pi^2}\int d^3\mathbf{x}\,\epsilon_{ijk}\left(A_i^a\partial_j A_k^a + \frac{1}{3}\epsilon^{abc}A_i^a A_j^b A_k^c\right)$$

winding number

$$A_i \to U^\dagger A_i U + iU^\dagger\partial_i U, \quad A_i \equiv A_i^a\frac{\tau^a}{2},$$

$$N_W = \frac{1}{24\pi^2}\int d^3\mathbf{x}\,\epsilon_{ijk}\left[(U^\dagger\partial_i U)(U^\dagger\partial_j U)(U^\dagger\partial_k U)\right].$$

$$N_{CS} \to N_{CS} + N_W$$

topological charge

$$Q_T = \frac{1}{32\pi^2}\int d^4x\, F_{\mu\nu}^a\tilde{F}_{\mu\nu}^a, \qquad \tilde{F}_{\mu\nu}^a \equiv \frac{1}{2}\epsilon_{\mu\nu\alpha\beta}F_{\alpha\beta}^a.$$

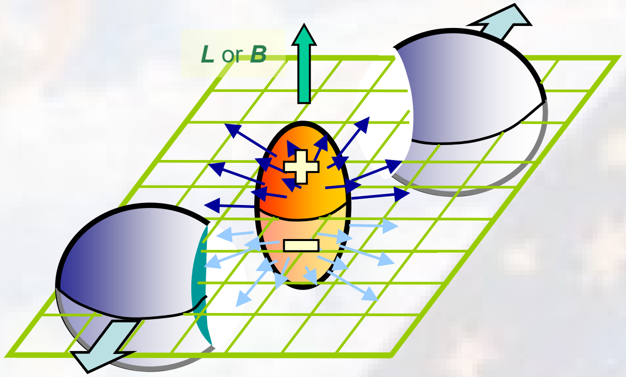
$$Q_T = N_{CS}(+\infty) - N_{CS}(-\infty).$$

The volume of the box is 2.4 by 2.4 by 3.6 fm.
The topological charge density
Animation by *Derek Leinweber*

Topological transitions have never been observed *directly* (e.g. at the level of quarks in DIS).
An observation of the *spontaneous strong* parity violation would be a clear proof for the existence of such physics.

EDM of QCD matter

D. Kharzeev / Physics Letters B 633 (2006) 260–264



Topologically non-trivial gluonic fields in HIC:
- sphalerons,
- glasma (McLerran, Venugopalan, Kharzeev)
- "turning points" (Shuryak)

Charge separation along the orbital momentum:
EDM of the QCD matter ~ the neutron EDM

Chiral magnetic effect:
$N_L \neq N_R$ ⊕ magnetic field   or
Induction of the electric field parallel to the (static) magnetic field

$$N_R - N_L = Q$$

$$A_u = \frac{N_R - N_L}{N_R + N_L}$$

$$A_{\pi^+} = -A_{\pi^-} \simeq \frac{Q}{N_{\pi^+}}$$

Theory: charge separation in HIC requires
- Deconfinement

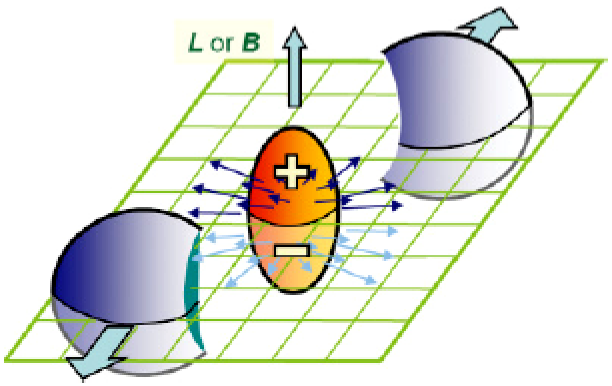
(needed for quarks to diffuse after initial "impulse" from interaction with gluonic configurations)
- Chiral symmetry restoration

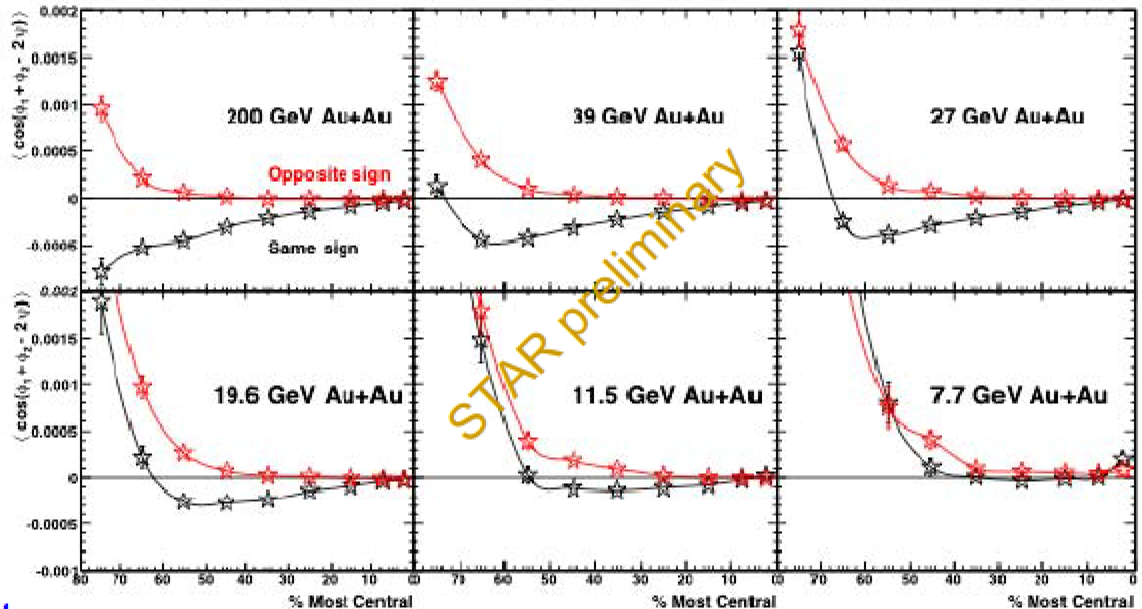
(propagation in a chirally broken phase kills the correlations)

The asymmetry is too small to observe in a single event but should be measurable by correlation techniques

Kharzeev, PLB 633 260 (2006) [hep-ph/0406125]
Kharzeev, Zhitnitsky, NPA 797 67 (2007)
Kharzeev, McLerran, Warringa, NPA 803 227 (2008)
Fukushima, Kharzeev, Waringa, PRD 78, 074033

Observation, but via P-even var.

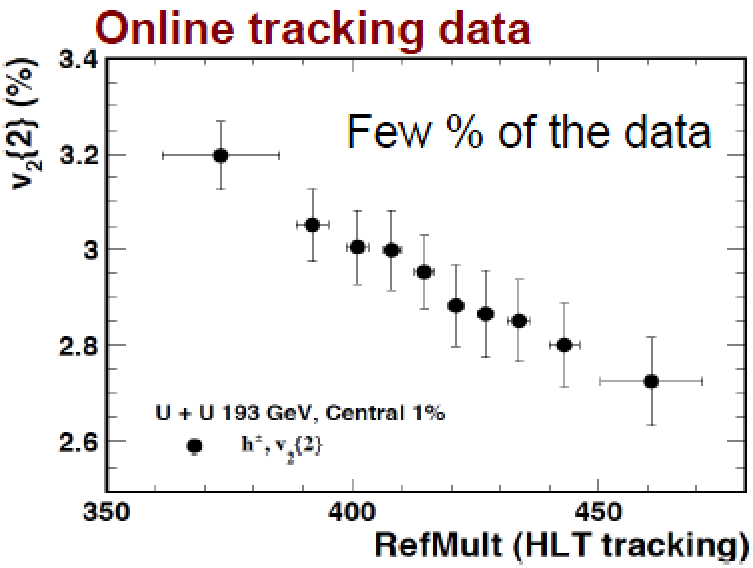


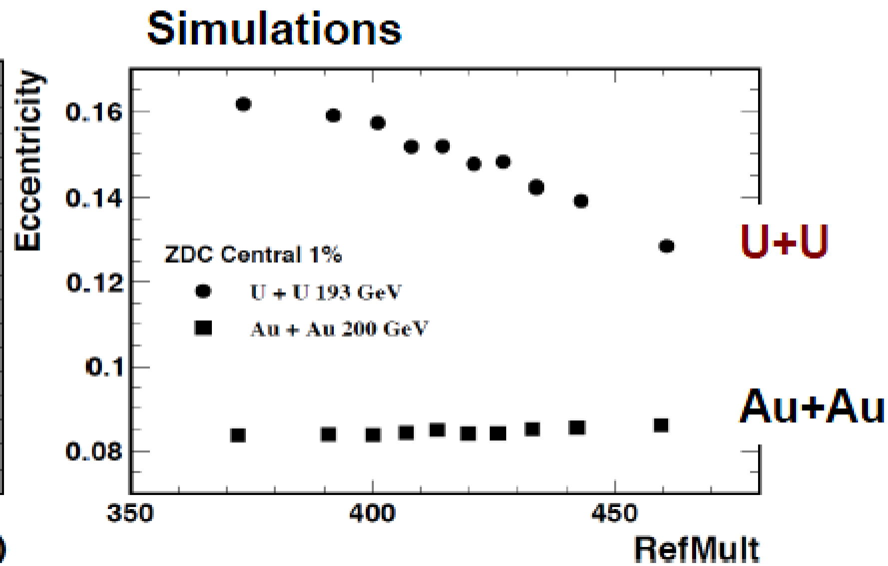


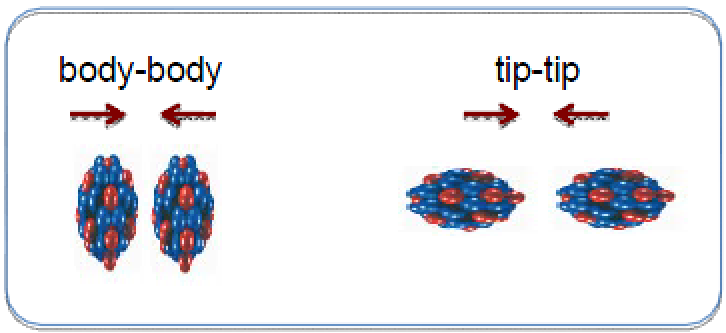
- Chiral magnetic effect:

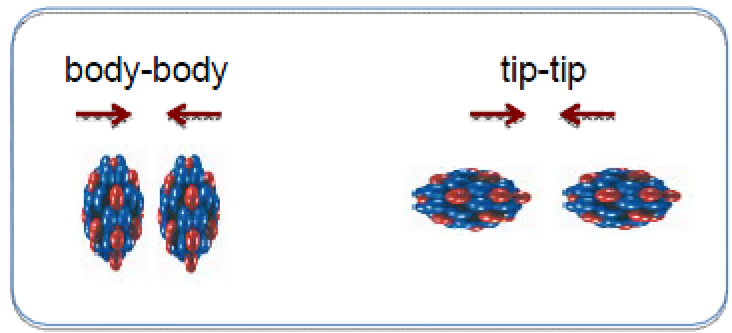
- **A qualitatively consistent result is seen in STAR, PHENIX, and ALICE.**
- **Is it CME or simpler physics (cons of momentum).**

Control Experiment: U+U



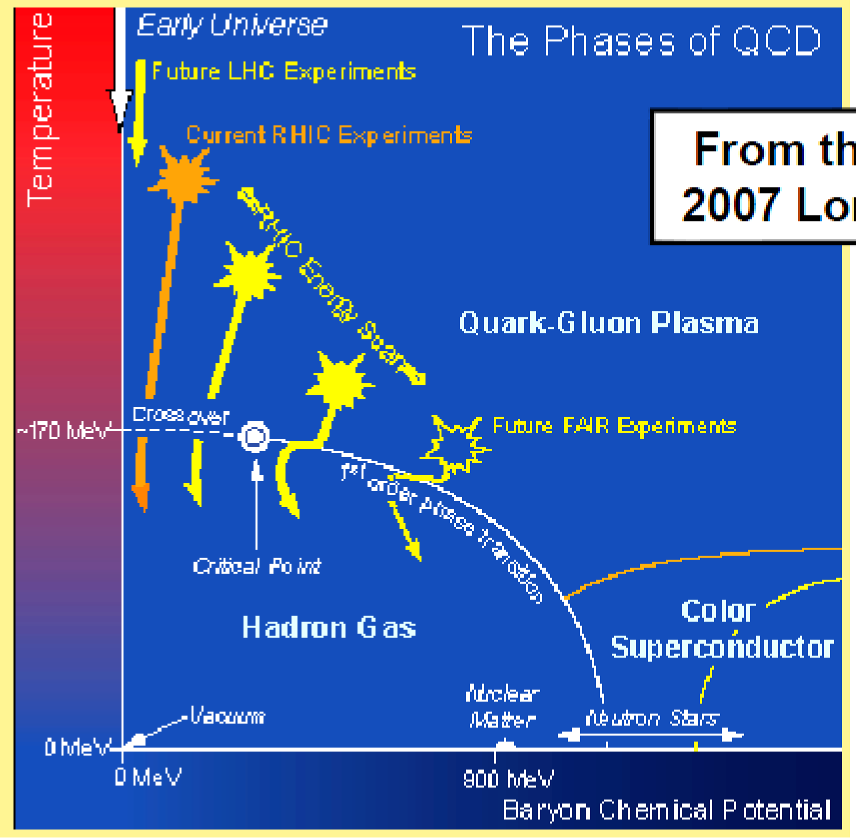






- In body-body collisions, there is a large v_2.
- However there is no magnetic field.
  - Effect stays: not CME.
  - Effect goes: could be…

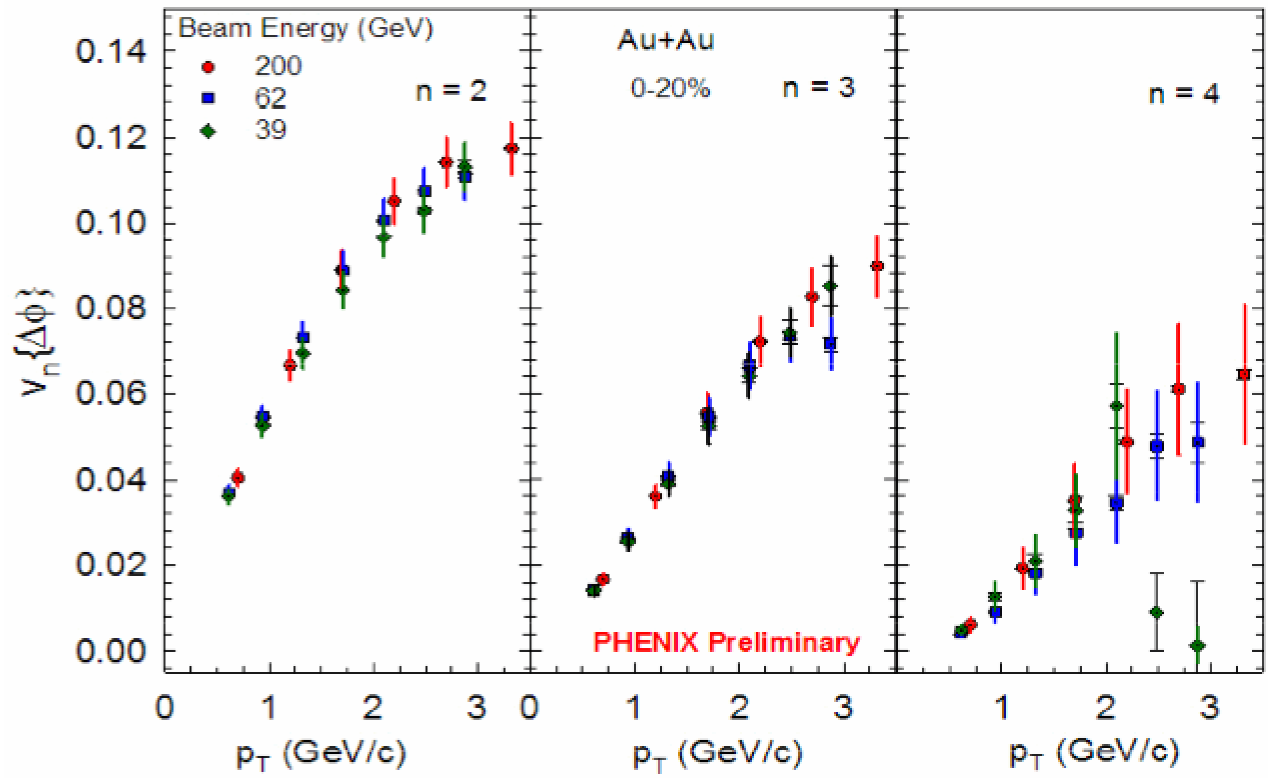
RHIC Beam Energy Scan



From the cover of the 2007 Long-Range Plan

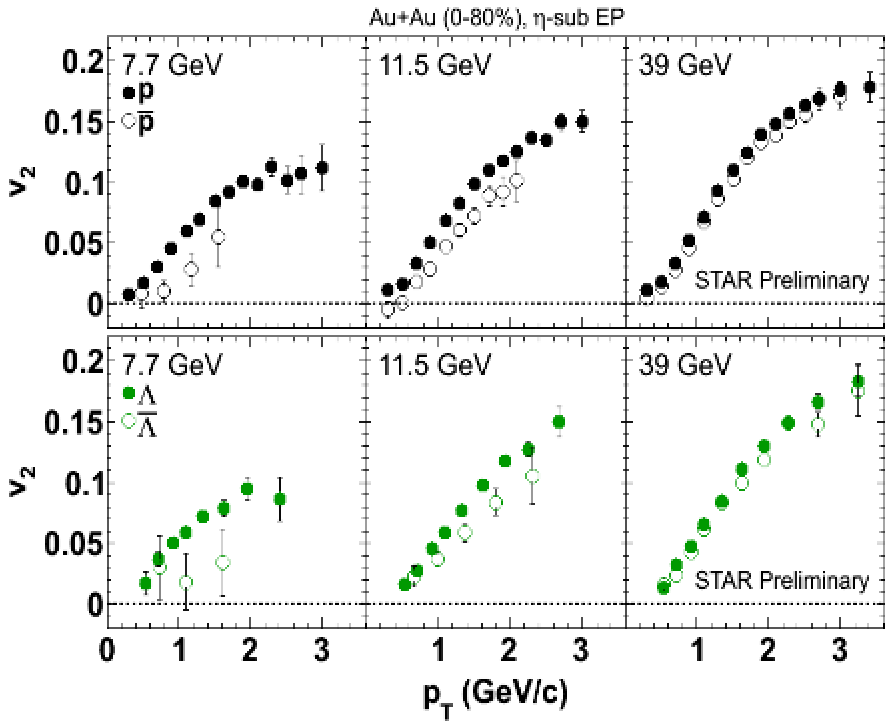
- The **QCD critical point** and the **1st order phase transition line** represent **landmarks on the QCD phase diagram**

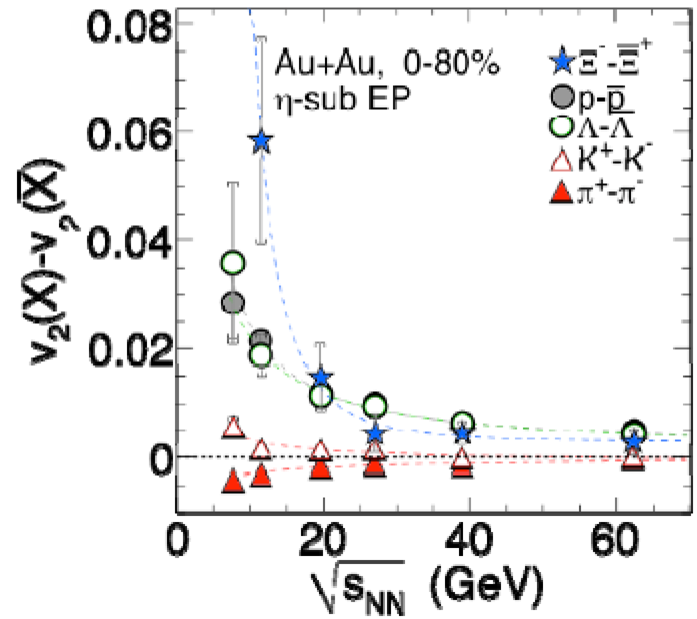
Valence Quark Flow Scaling



- v_2, v_3, and v_4 independent of energy from 39 to 200 GeV
- Also similar at LHC energies
- Partonic medium persists at least down to 39 GeV

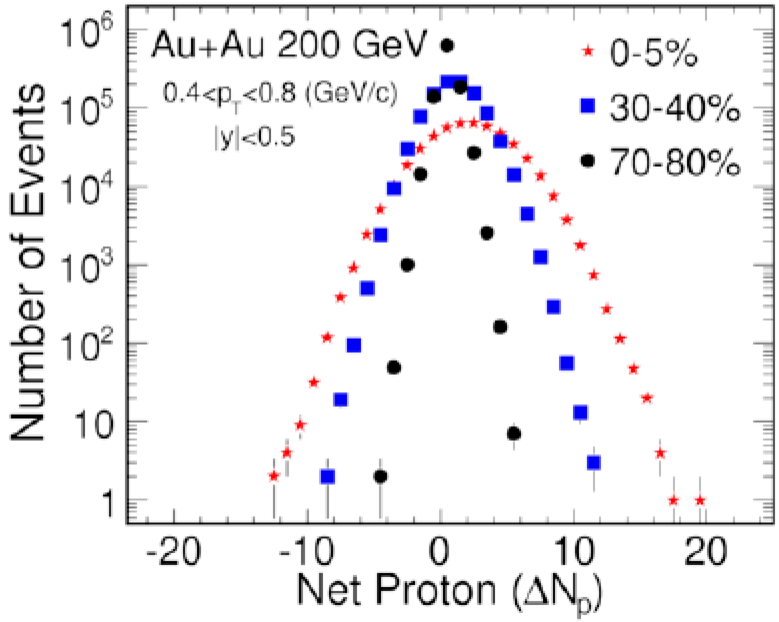
Scaling broken!





- Difference in v_2 between particles and anti-particles at lower energies
  - Difference increases with decreasing energy
  - Difference is much larger for baryons than mesons
    - Baryon transport to mid-rapidity?
- Requires significant fraction of the flow to build up during the hadronic phase

Fluctuations in Net Protons.

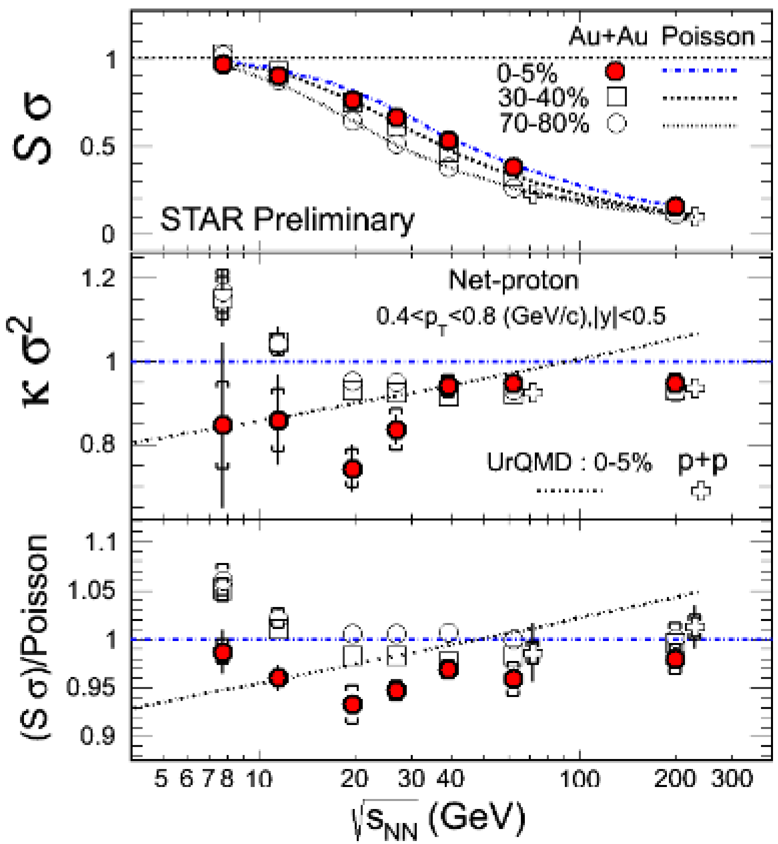


$$\chi_B^{(n)} = \left.\frac{\partial^n (P/T^4)}{\partial(\mu_B/T)^n}\right|_T$$

$$\chi_B^4 / \chi_B^2 = (\kappa\sigma^2)_B$$
$$\chi_B^3 / \chi_B^2 = (S\sigma)_B$$

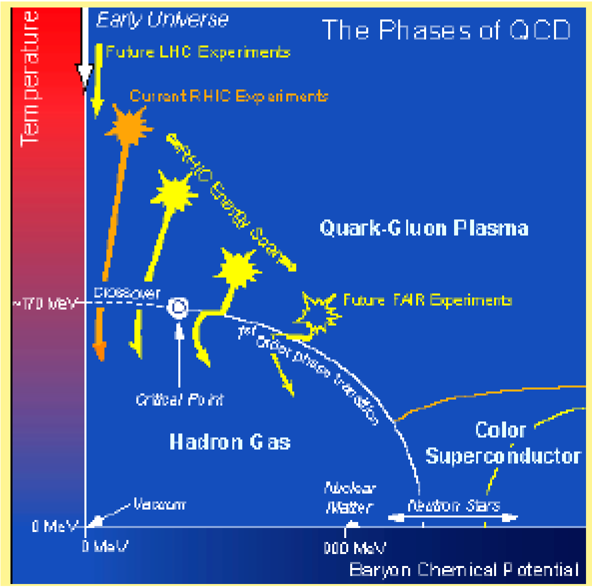
- Link between susceptibilities (e.g., from lattice QCD) and products of higher moments for conserved quantities
- Large fluctuations predicted near the critical point
  - Skewness is proportional to $\xi^{4.5}$
  - Kurtosis is proportional to ξ^7
- Measure net-proton number fluctuations as surrogate for baryon number fluctuations

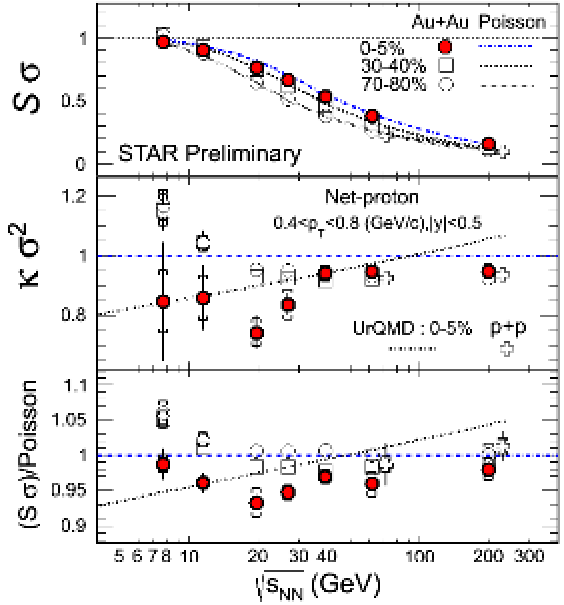
Hint of a signal…



- Possible minimum for skewness and kurtosis in central events around $\sqrt{s_{NN}} \sim 20$ GeV
- Not seen for 30-40% and 70-80% centralities

Phase II of the Beam Energy Scan





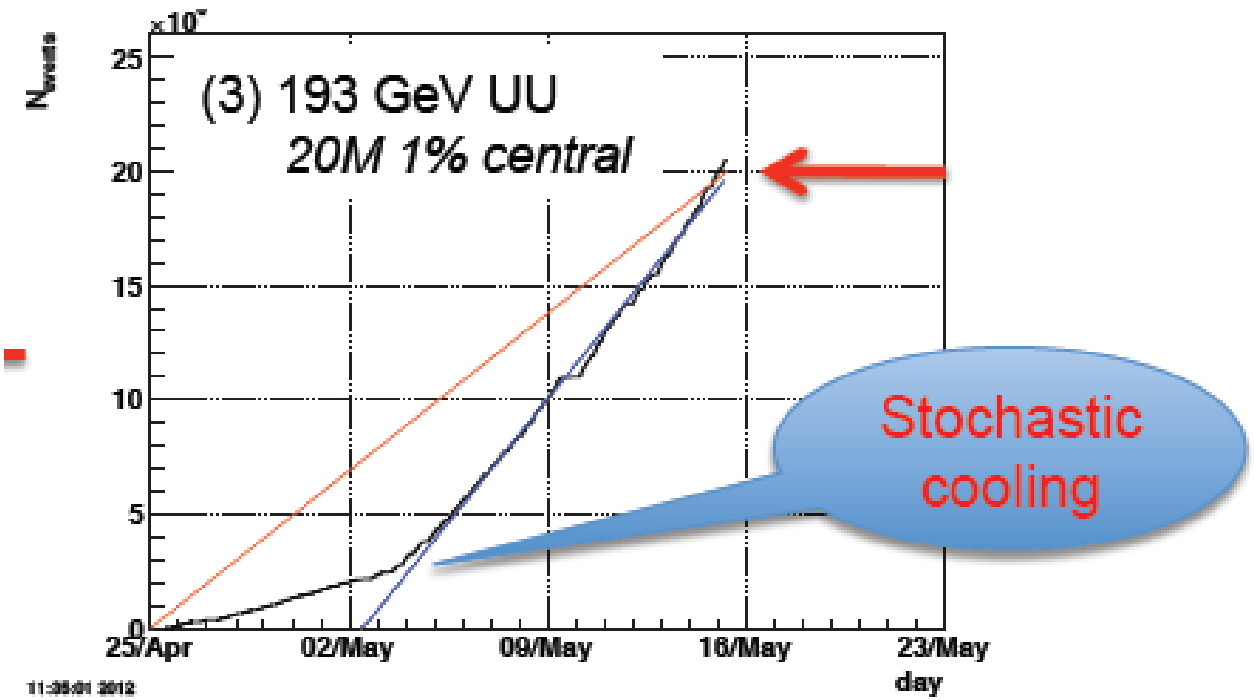
Unique opportunity for RHIC!

- Results to date **demand much higher statistics** (x10 or more) for the points below $\sqrt{s_{NN}} < 20$ GeV, another energy point around 15 GeV, and ideally at least one point below 7.7 GeV
- Can't get there from here under the status quo with any realistic beam time scenario
- **Need electron cooling** of the low-energy Au beams in RHIC

A new RHIC detector?

- **RHIC early days:**
  - **PHENIX:** small aperture high rate.
  - **STAR:** large aperture low rate
- **Modern Era:**
  - **New STAR DAQ**
  - **New PHENIX Aperture**

RHIC II Luminosity Achieved this year



- **sPHENIX: Physically compact via new technology.**
- **Brings RHIC Jet capabilities comparable to LHC.**
- **Why is this needed?**

Farther future & Broader Issues

- The textbook (or Wiki entry) on the Quark-Gluon Plasma will be incomplete without

  a fundamental explanation for how the perfect fluid emerges at strong coupling near Tc from an asymptotically free theory of quarks and gluons.

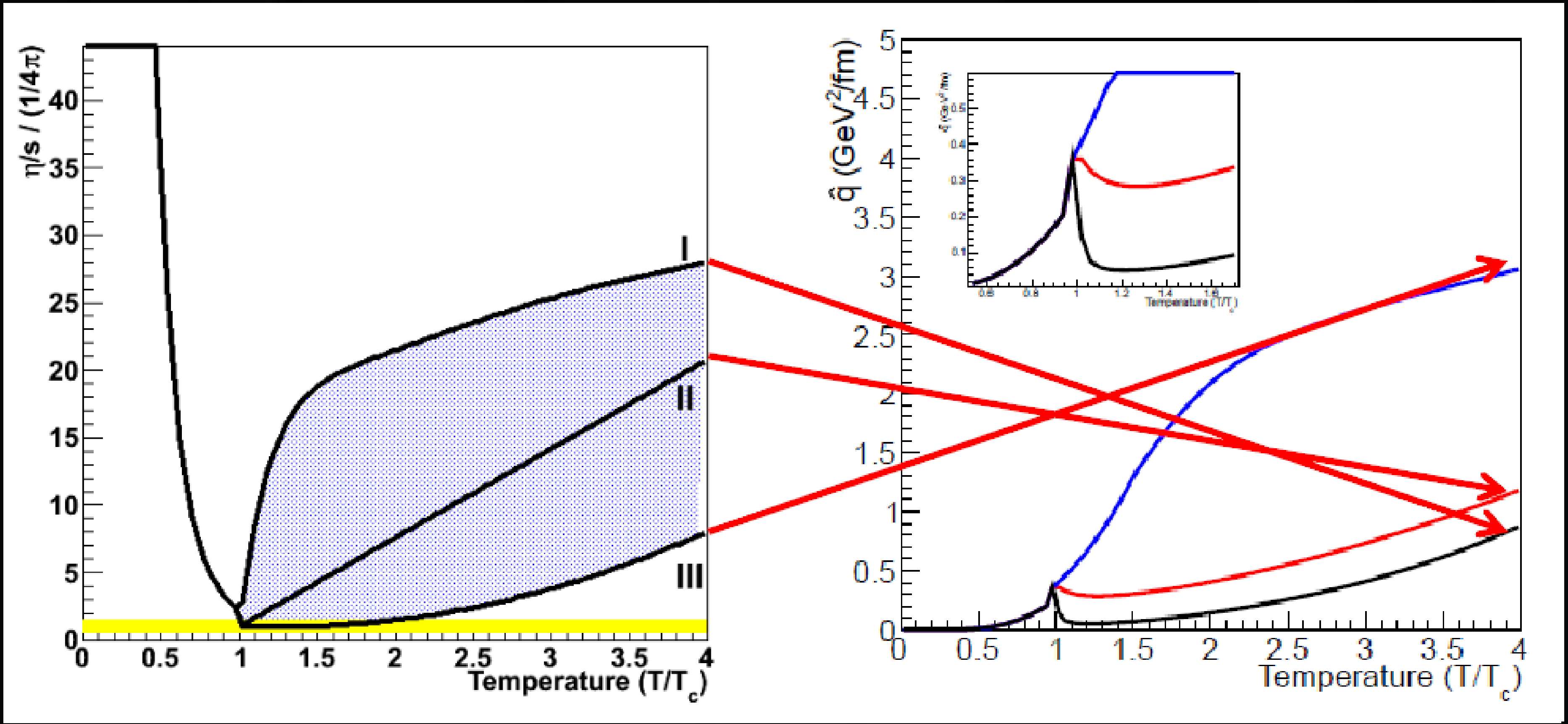
- Jet observables at RHIC enabled by an sPHENIX upgrade are critical to providing this explanation by probing the QGP near 1-2 Tc and at distances comparable to the thermal scale.
- Measurements of jets only at the LHC will leave these questions with an incomplete answer (particularly right where the coupling may be strongest).

Mapping Out Strong Coupling with Jet Probes

"Small Shear Viscosity Implies Strong Jet Quenching"
A. Majumder, B. Muller, X.N. Wang, PRL (2007).

Jamie Nagle, BNL PAC

$$\hat{q} = \frac{1.25T^3}{\eta / s}$$

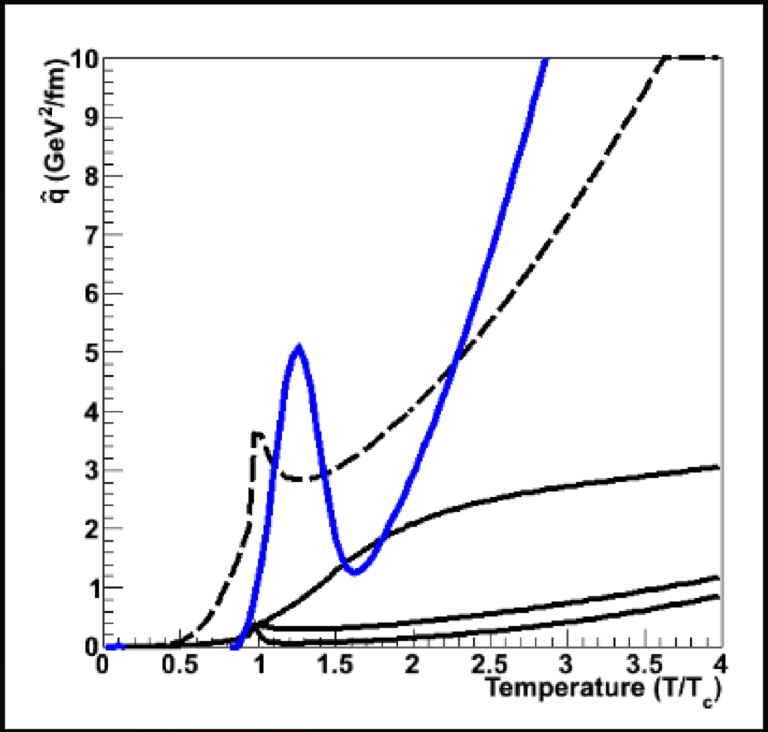


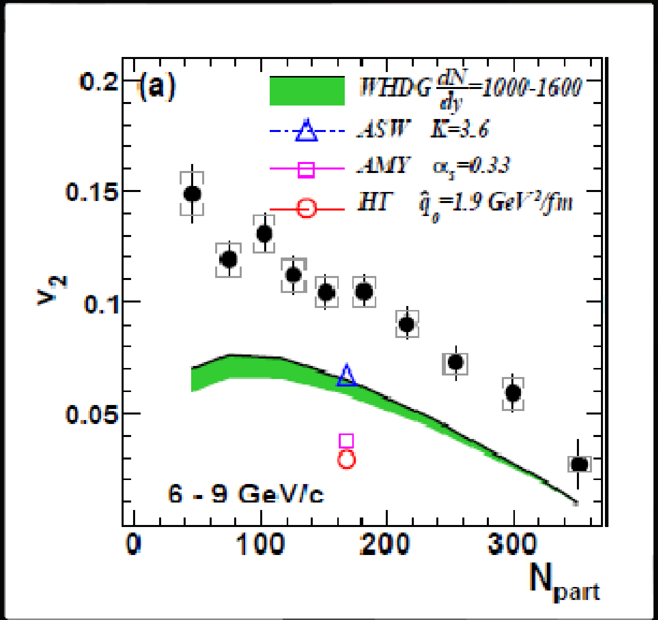
Key is independently measuring both sides of this equation!

Super-Strong Coupling near Transition Temperature?

"Jet Quenching is a few times <u>stronger</u> near T_c relative to the QGP at $T > T_c$."
Liao and Shuryak, PRL (2009)

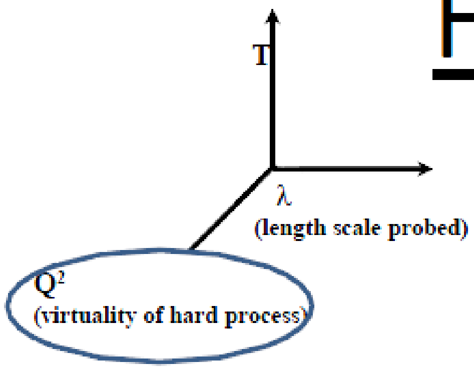
"The surprisingly transparent sQGP at the LHC [compared to RHIC]"
Horowitz and Gyulassy, NPA (2011)





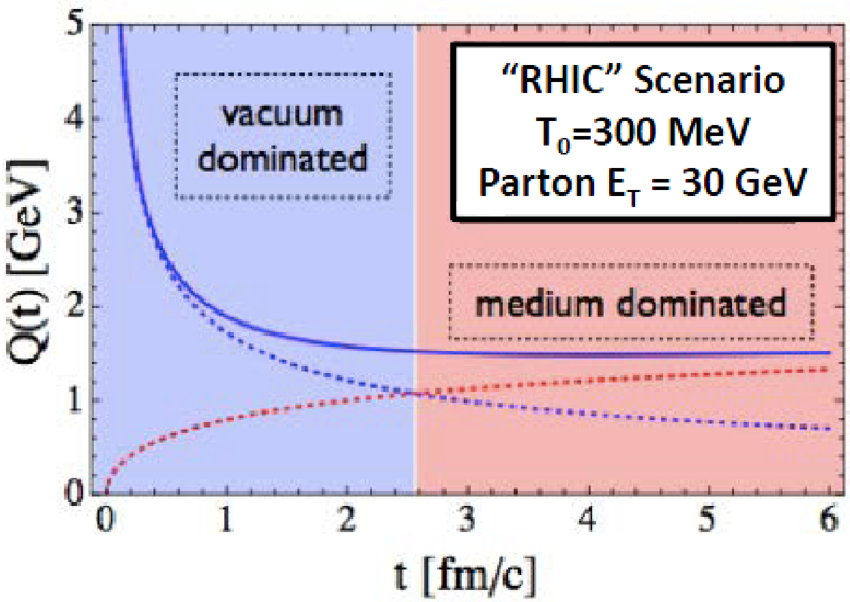
"Large v_2 is striking in that it exceeds expectations of pQCD models even at 10 GeV/c."
PHENIX, PRL (2010)

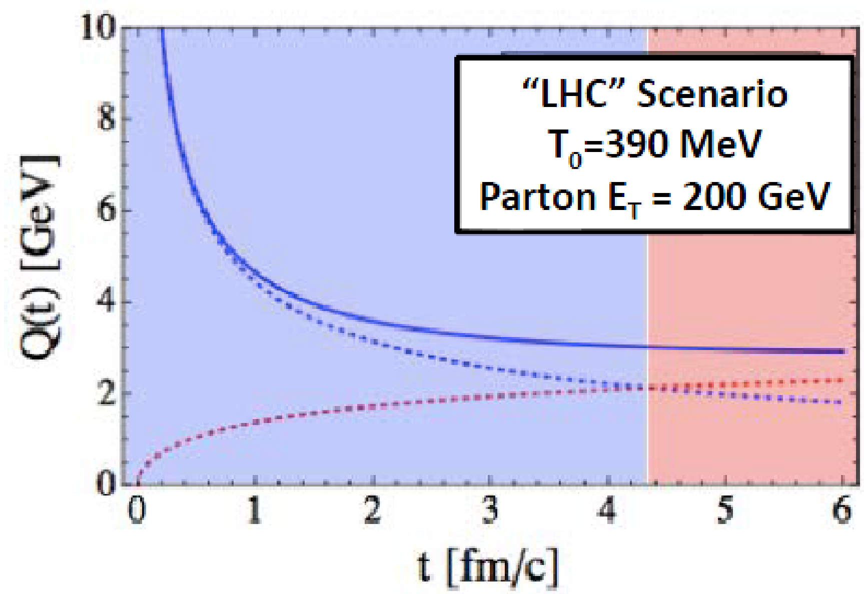
Hard Parton Virtuality



$$Q^2_{vac}(t) = \frac{E}{2t} \qquad Q^2_{med}(t) = \int \hat{q}(t)\,dt$$

$$Q^2(t) = Q^2_{vac}(t) + Q^2_{med}(t)$$



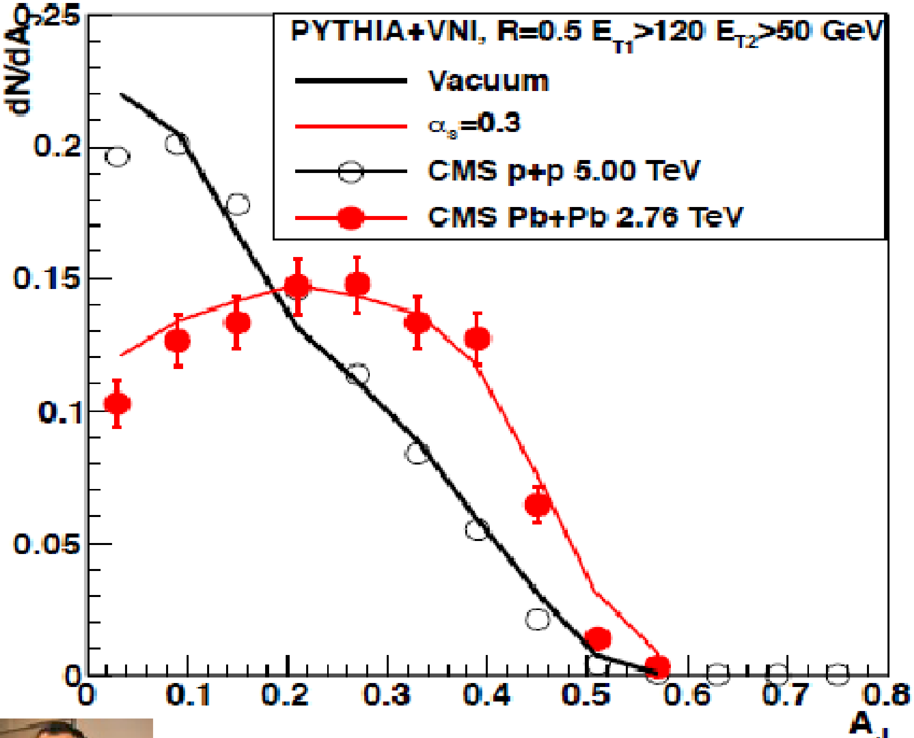


LHC Scenario

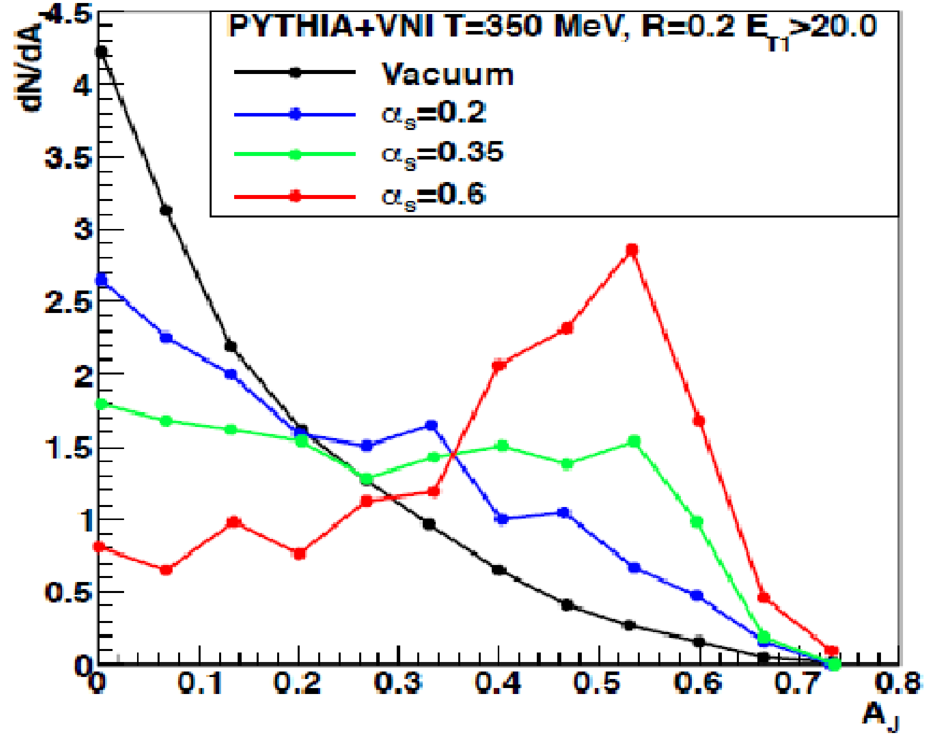
the vacuum contribution to the parton virtuality to fall below the in-medium contribution in the pQCD scenario. This effect is due to the collinear splitting in pQCD, which reduces the parton energy only gradually and thus leads to an increase in time dilation as the virtuality drops. This means that the very energetic parton hardly notices the medium for the first 3 – 4 fm of its path length. On the other hand, in the AdS/CFT scenario, parton energy and virtuality

B. Muller. Nucl.Phys., A855:74–82, 2011, RHIC/AGS Users Meeting 2011

Comparison to LHC data



Sensitivity to α_s at RHIC energies



symmetric ⟷ asymmetric

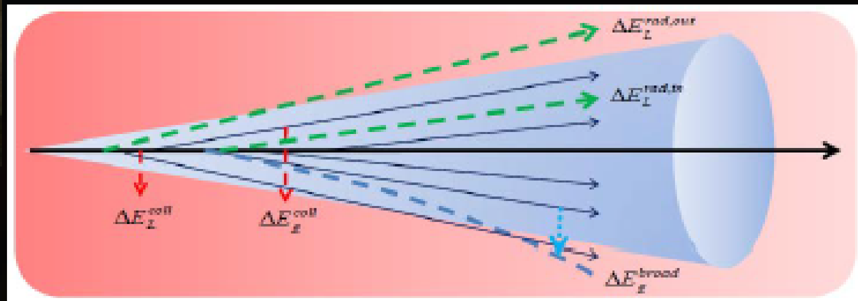
Chris Coleman-Smith (Duke)

Dijets at RHIC scales are likely to be strongly modified by the presence of the deconfined QGP medium. The observables we have discussed are sensitive to many aspects of this modification and suggest that further jet measurements at RHIC will provide valuable insights into the nature of the QGP and into the applicability of pQCD jet suppression models .

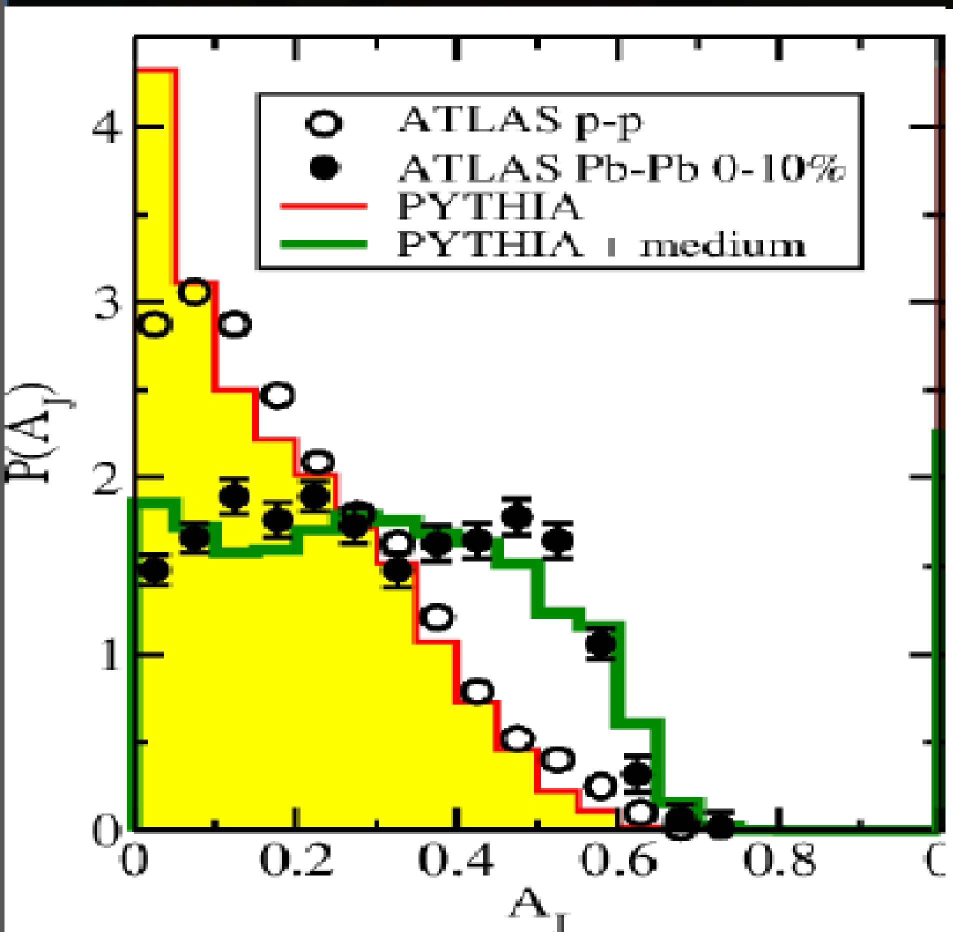
Jamie Nagle, BNL PAC

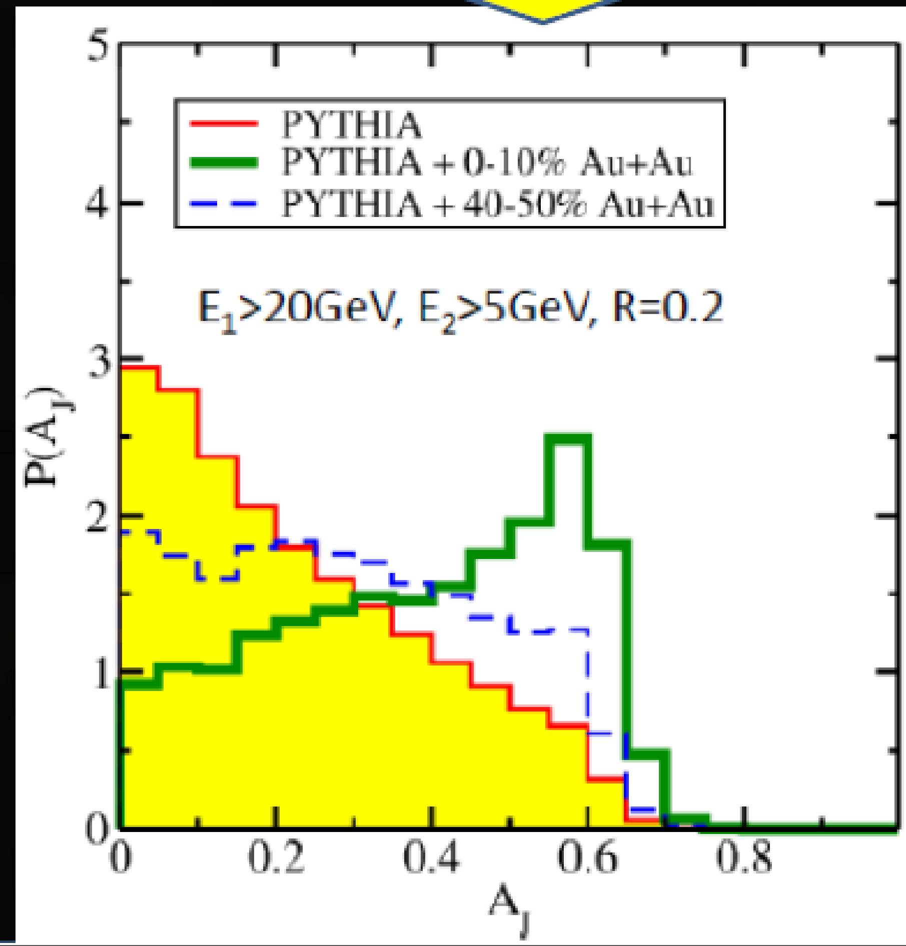
PRL 2011

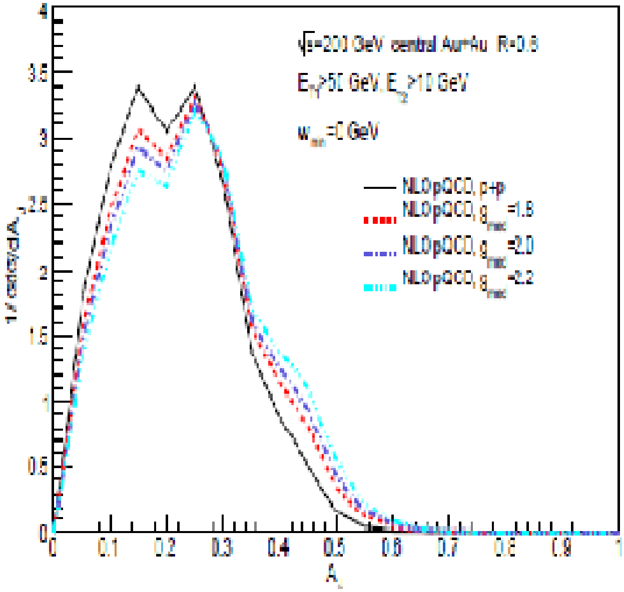
Guangyou Qin, Berndt Muller



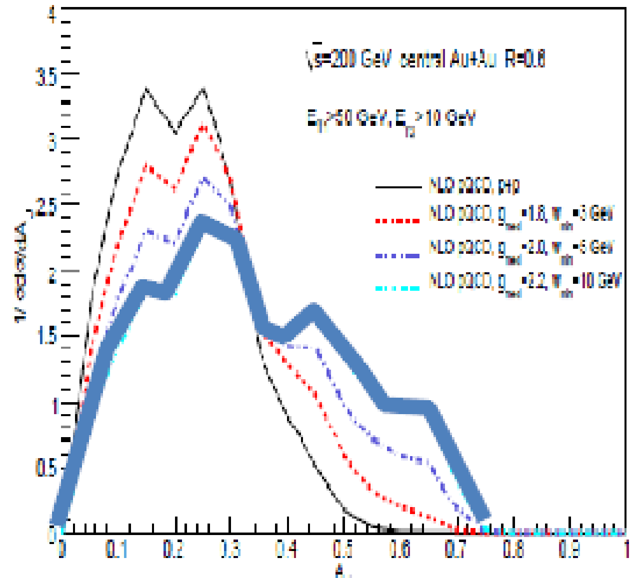
Larger modification at RHIC
More of parton shower equilibrated into medium.







Radiative E-loss only



Radiative + Collisional E-loss

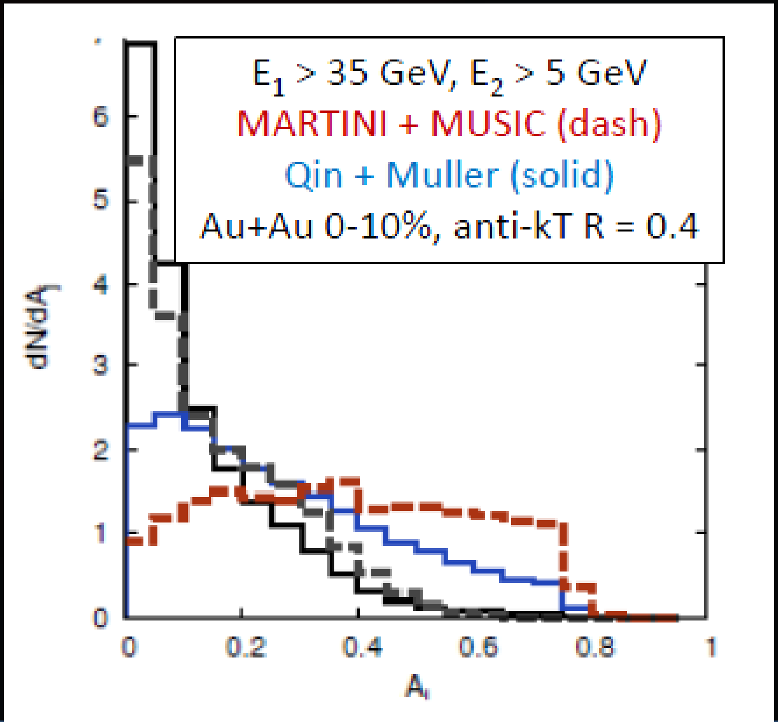
±10% changes in coupling strength

Ivan Vitev et al.

Jamie Nagle, BNL PAC

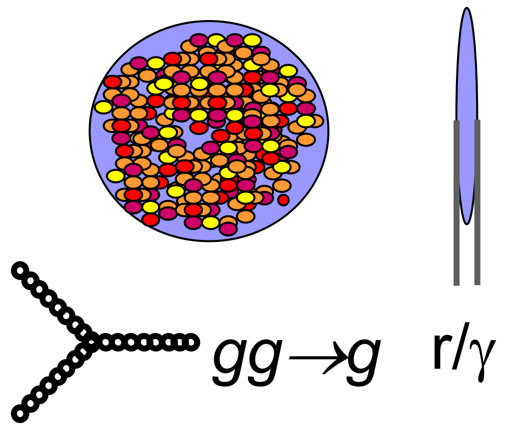
Bjorn Schenke, Clint Young et al.

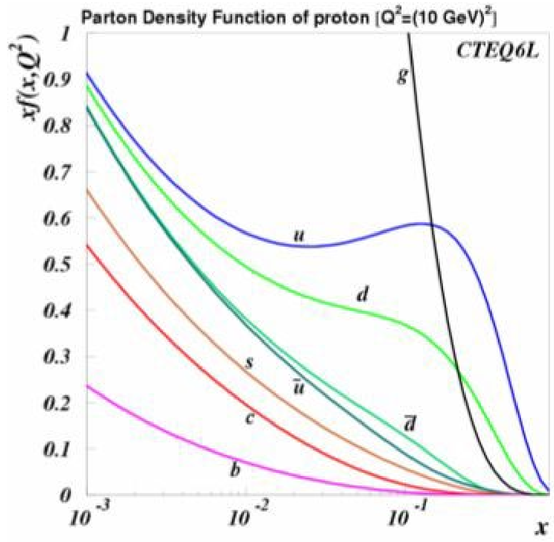
Large effects!
Different models
matching LHC
data disagree on
RHIC predictions.

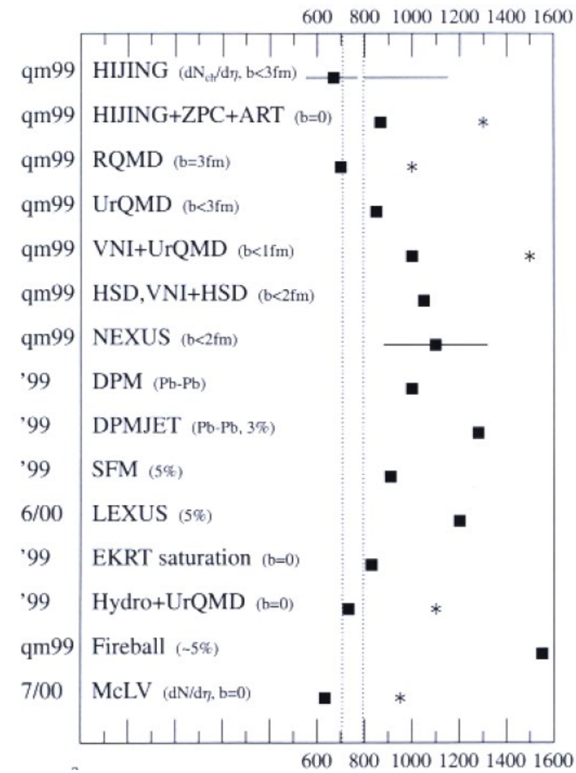


Could Suppression be Merely from the PDFs?

probe rest frame

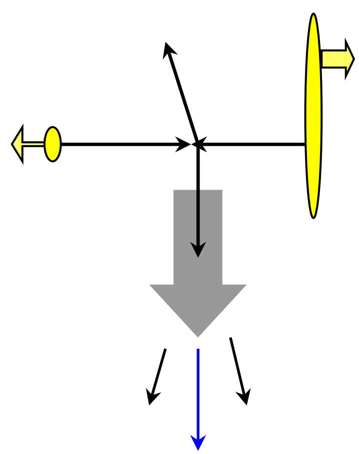


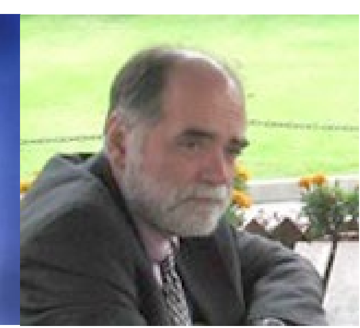




- **The lower in x one measures, the more gluons you find.**
- **At some low enough x, phase space saturates and gluons swallow one another.**
- **Another novel phase: Color Glass Condensate**

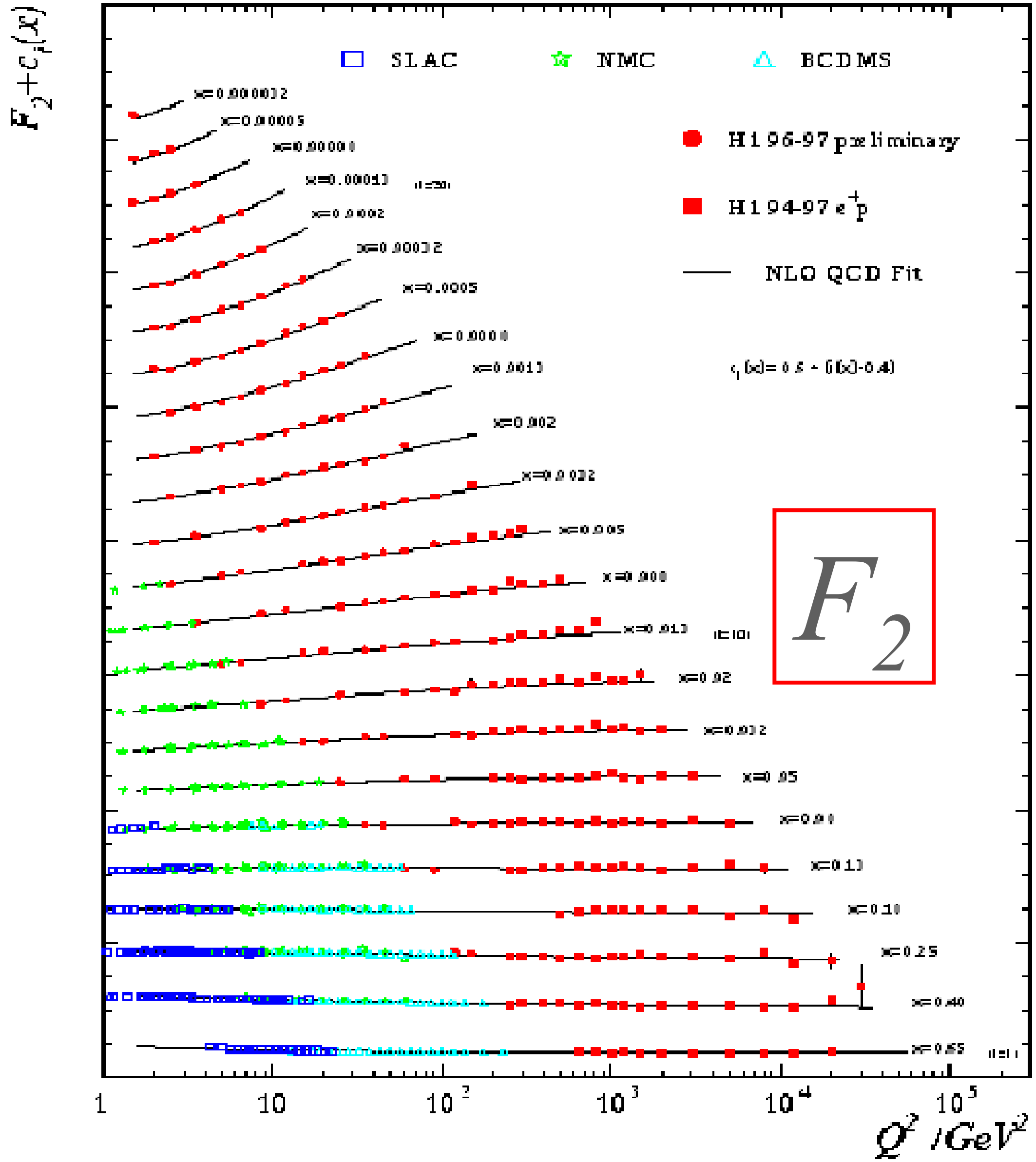
Control Experiment



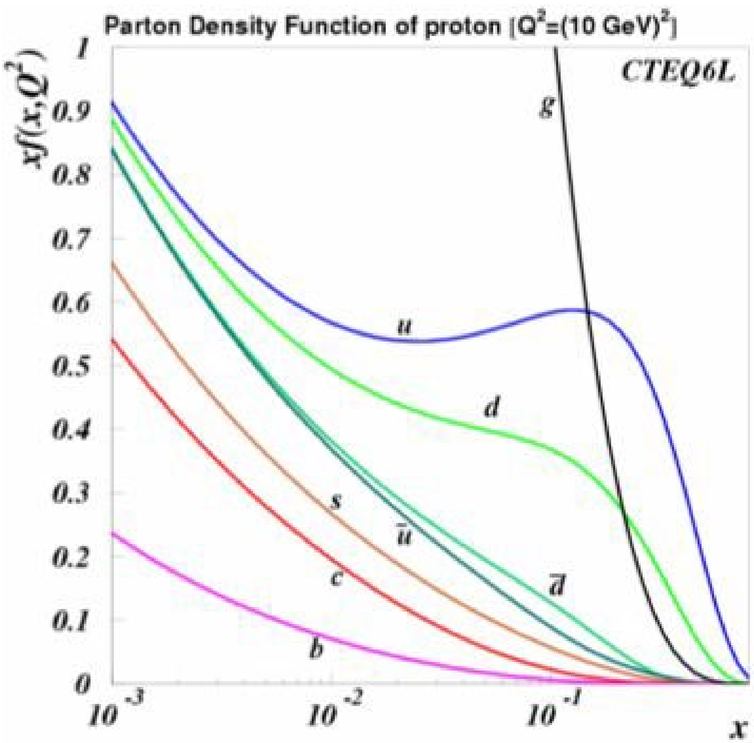


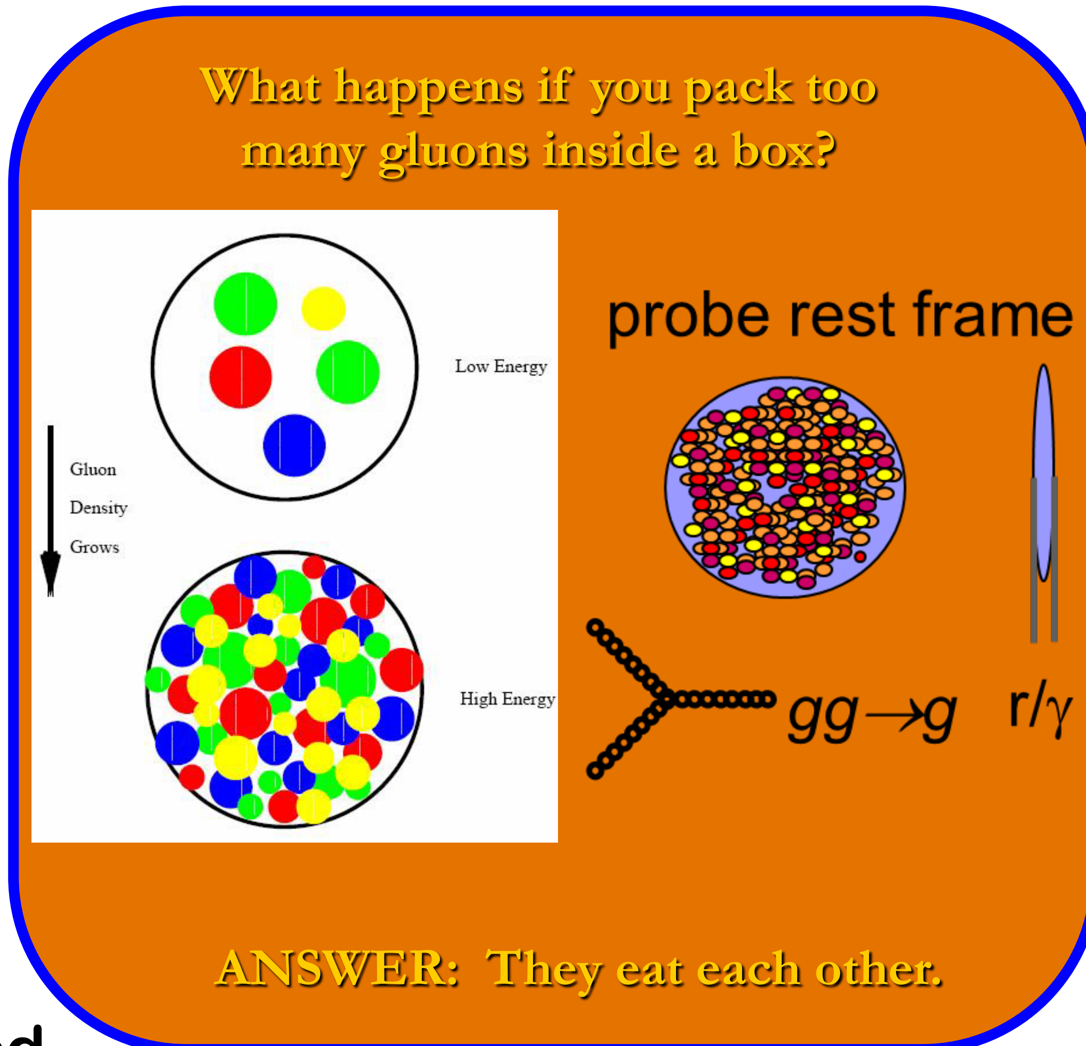
Parton Distribution Functions

- **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!**



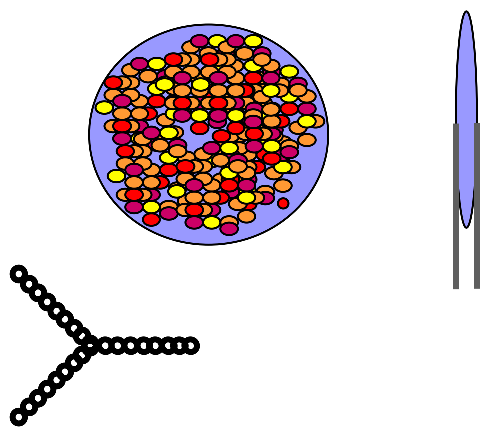
Crisis in Parton Distributions!





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

Glass at the Bottom of the Sea?

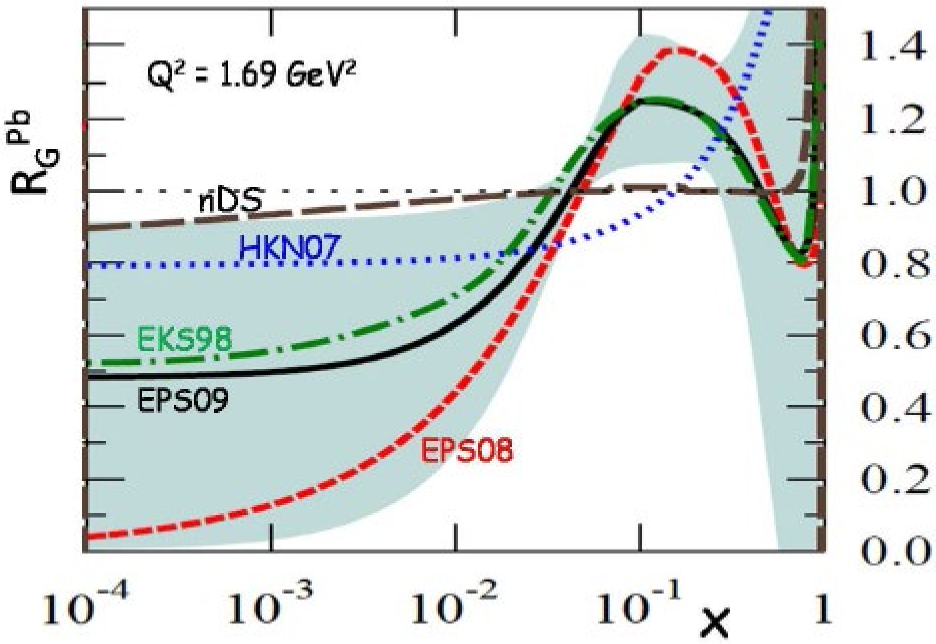


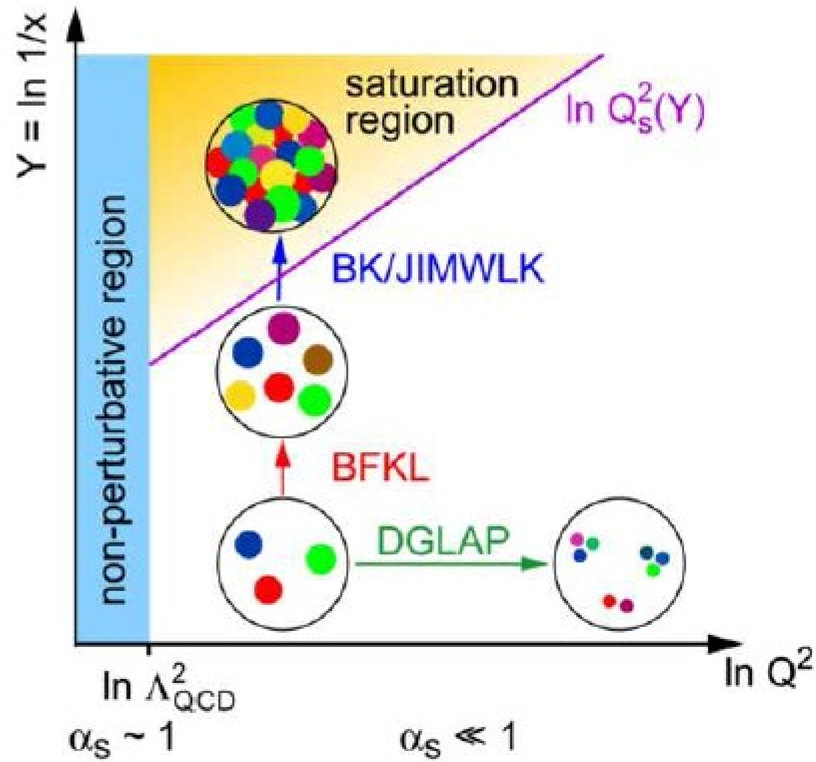
- Note that the gluon fusion reaction, g+g→g, "eats gluons".
- Its kind of like a fish tank:
  - When the fish eat their young, the tank never overfills with fish.
- This implies that

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.

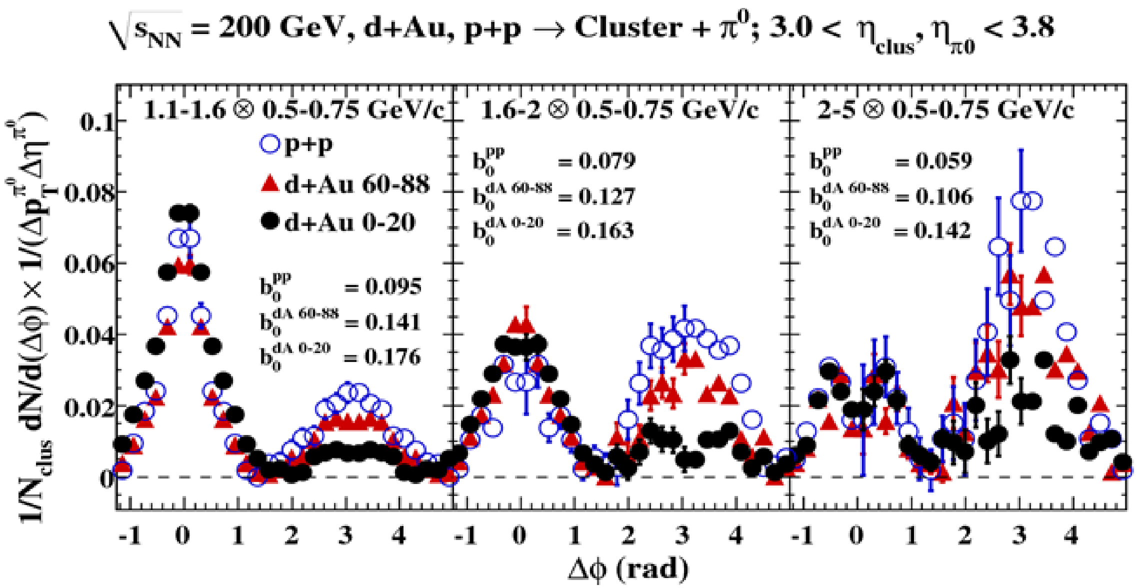
Nuclear Oomph…





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

Jets distinguish CGC from shadowing.

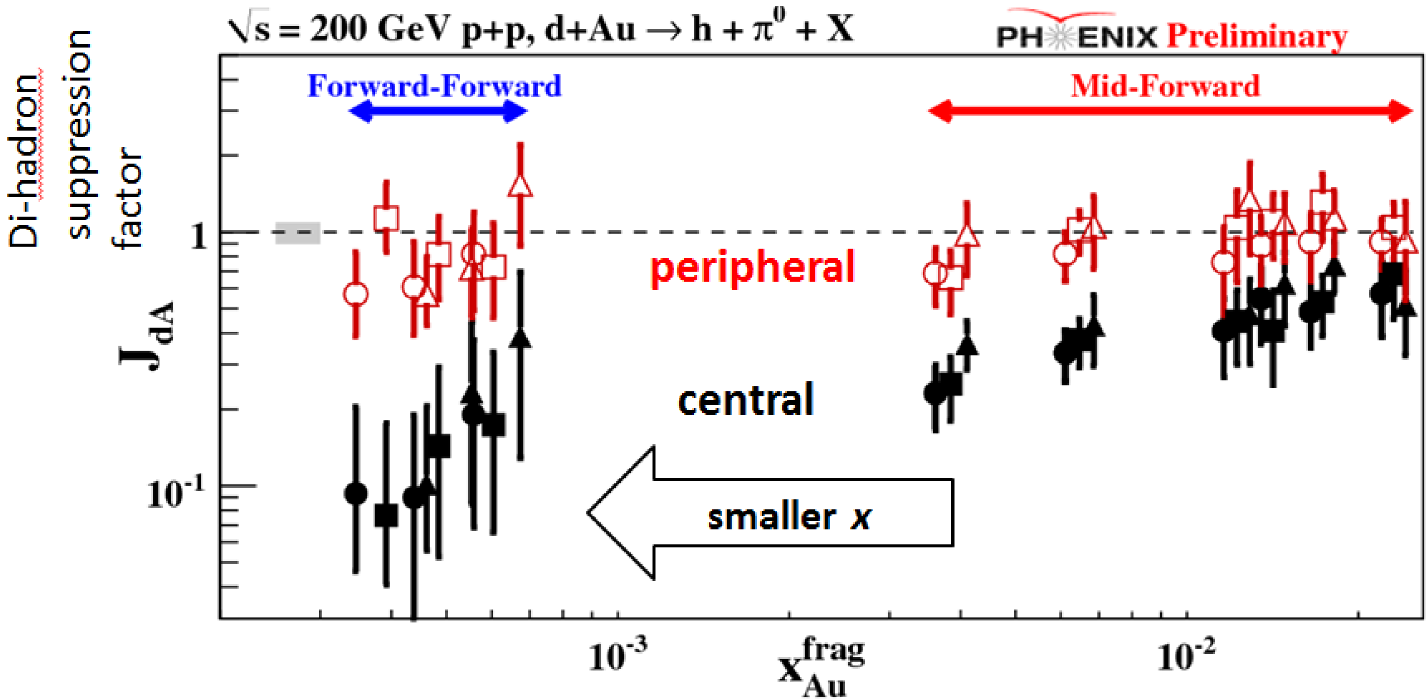


Color Glass Condensate?

new forward
EM calorimeter
$|\eta|$ = 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.

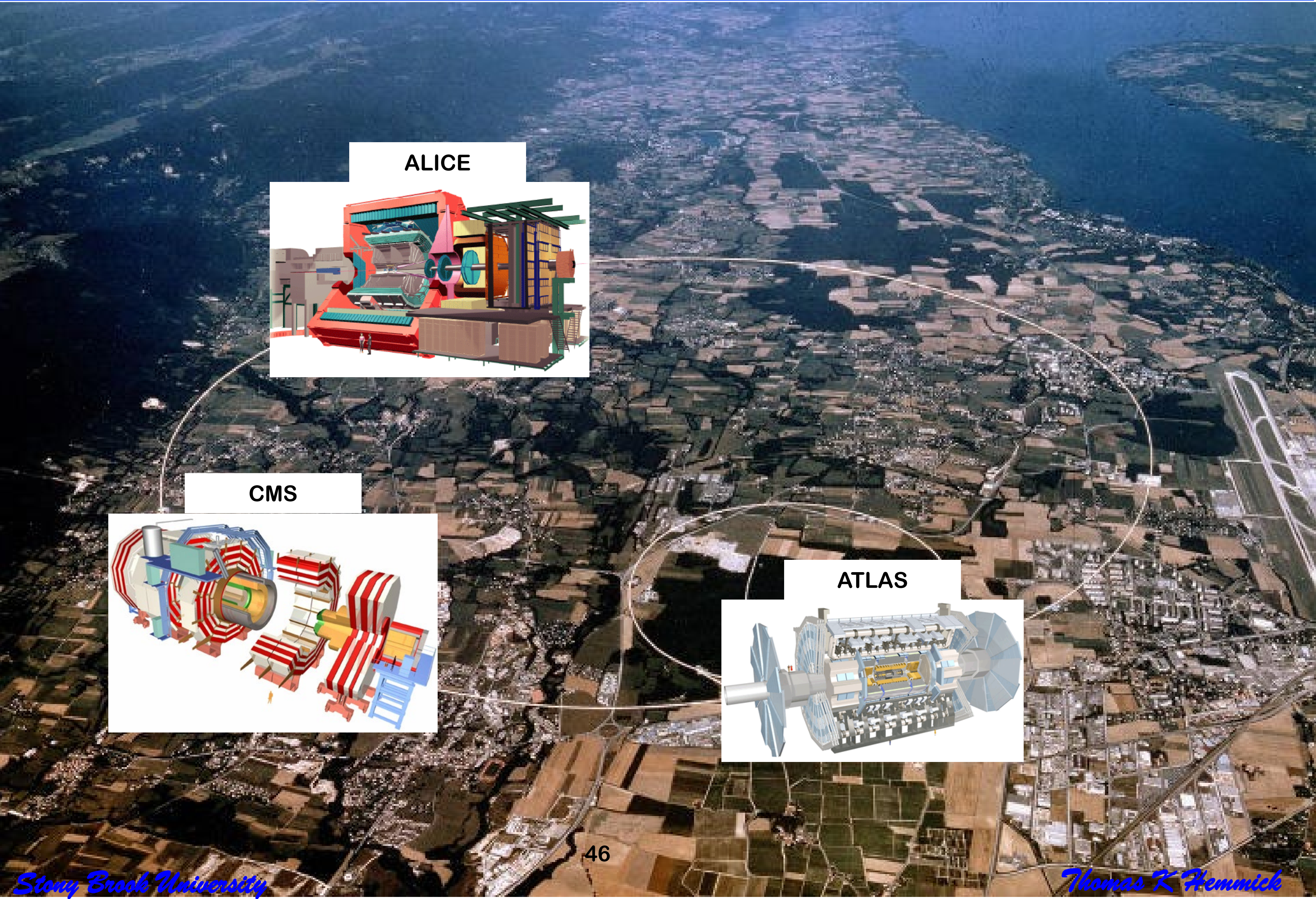


- **The suppression factor from cold nuclear matter is a factor of ~10!**
- **The away-side jet "decorrelates".**
- **Jury still out:**
  - **Nearly all measurements follow CGC predictions.**
  - **Predictions are often qualitative.**
- **Electron-ion collisions will find the truth.**

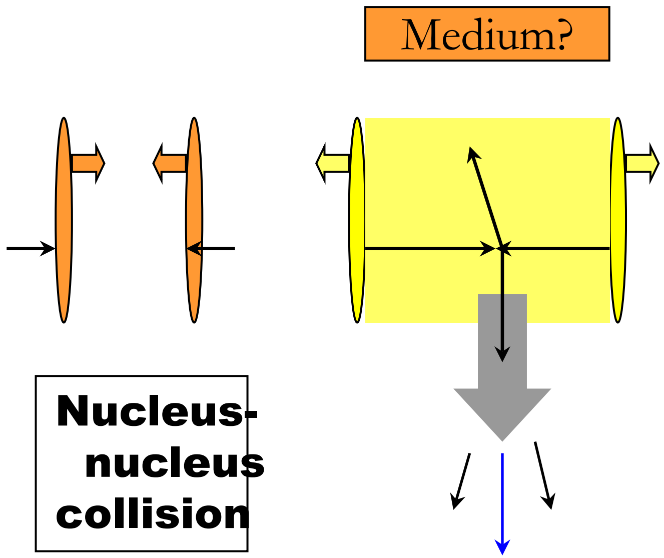
I'm a Believer

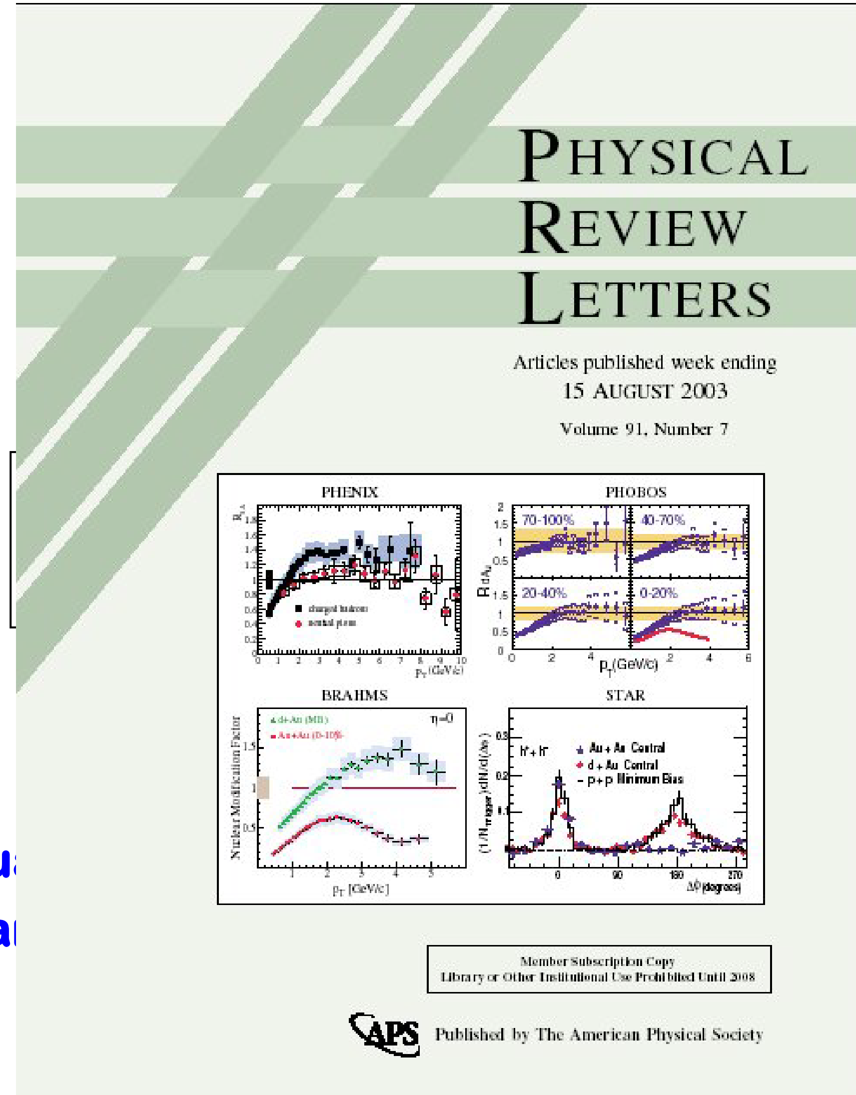
- I believe that QCD is among the most fascinating arena of physics and that the pQCD diagram only scratches the surface of this rich physics.
- I believe that nature provides us with two principle arenas within which to study this beautiful physics:
  - The QCD vacuum structure released into the lab via the QGP.
  - The deep interior of the nucleon.
- I believe that these two communities that study QCD from these different vantage points will eventually recognize their common interests and realize the next phase at the Electron-Ion Collider.
- I believe that the long term future of all significant human endeavors lies with the next generation.
- I BELIEVE IN YOU!

LHC Experiments



d+Au Control Experiment





PHYSICAL REVIEW LETTERS

Articles published week ending
15 AUGUST 2003

Volume 91, Number 7

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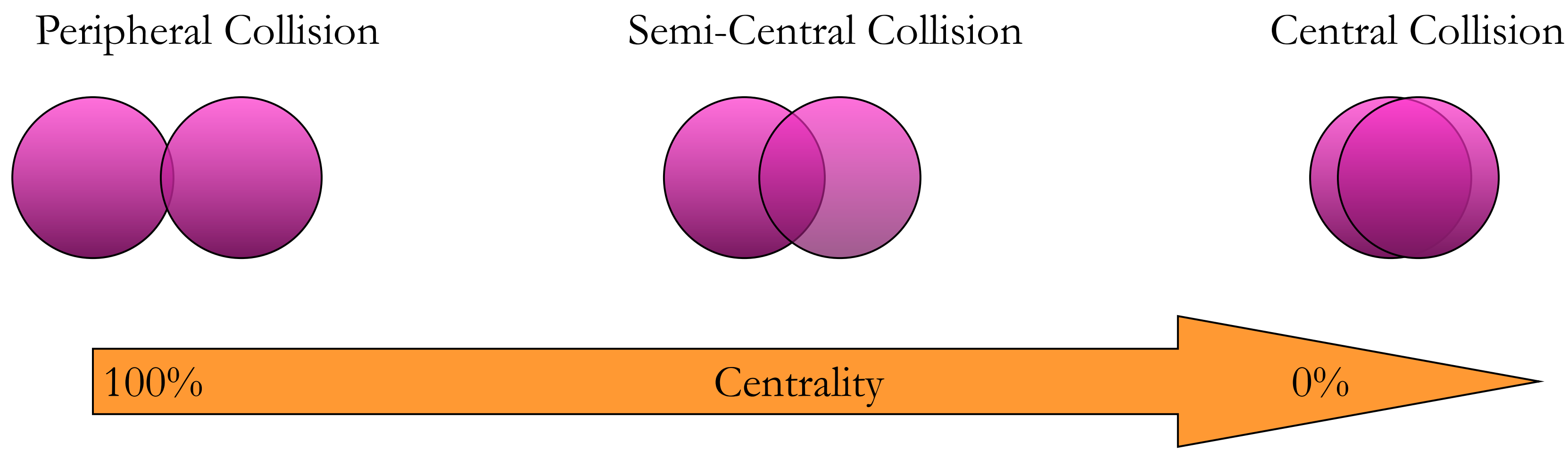
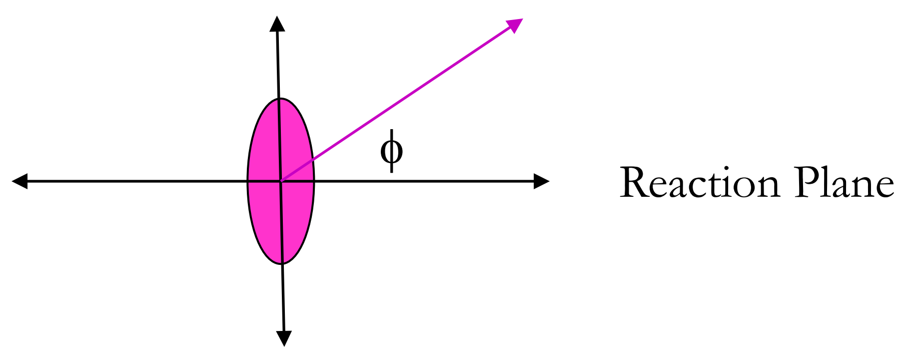
APS Published by The American Physical Society

- 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**

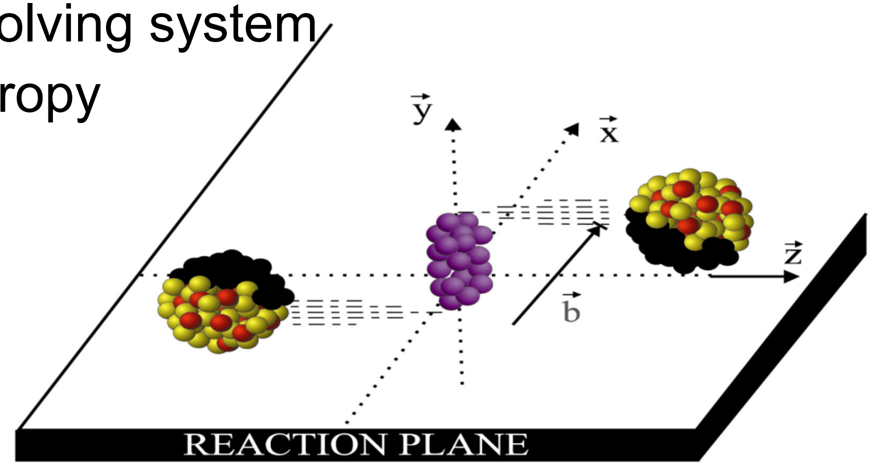


- **Fourier decompose azimuthal yield:**

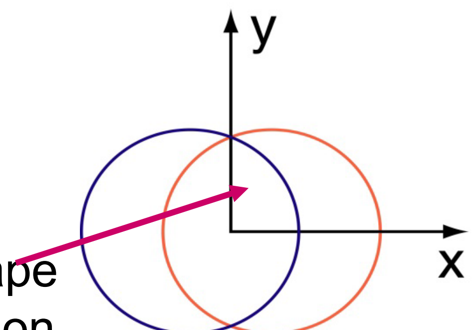
$$\frac{d^3N}{d\phi dp_T dy} \propto \left[1 + 2v_1 \cos(\phi) + 2v_2 \cos(2\phi) + \ldots\right]$$

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

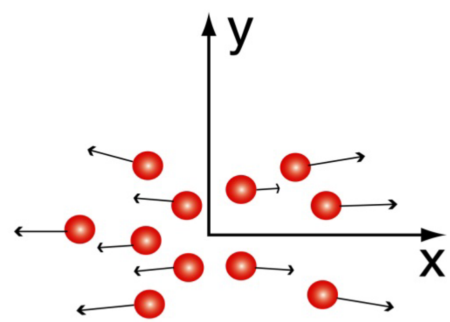


v_2: 2^{nd} harmonic *Fourier coefficient* in azimuthal distribution of particles with respect to the reaction plane



Almond shape overlap region in coordinate space

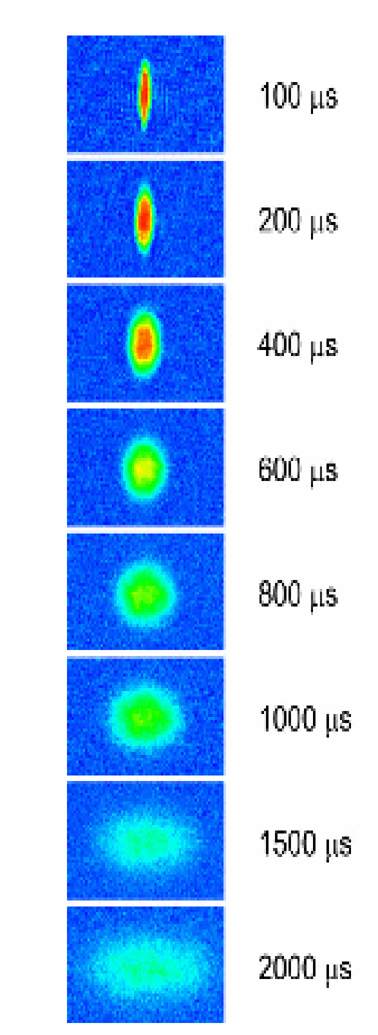
$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$



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

Anisotropic Flow

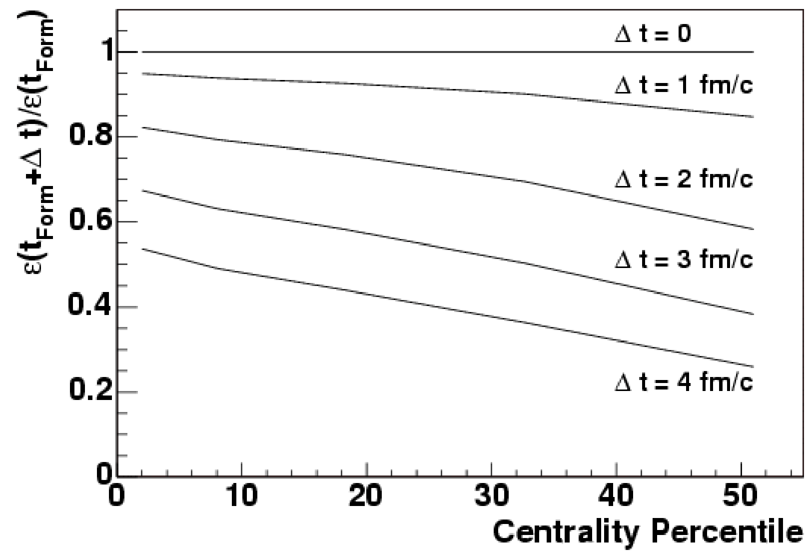
Liquid Li Explodes into Vacuum



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:**

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

here the sin terms are skipped by symmetry agruments.

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

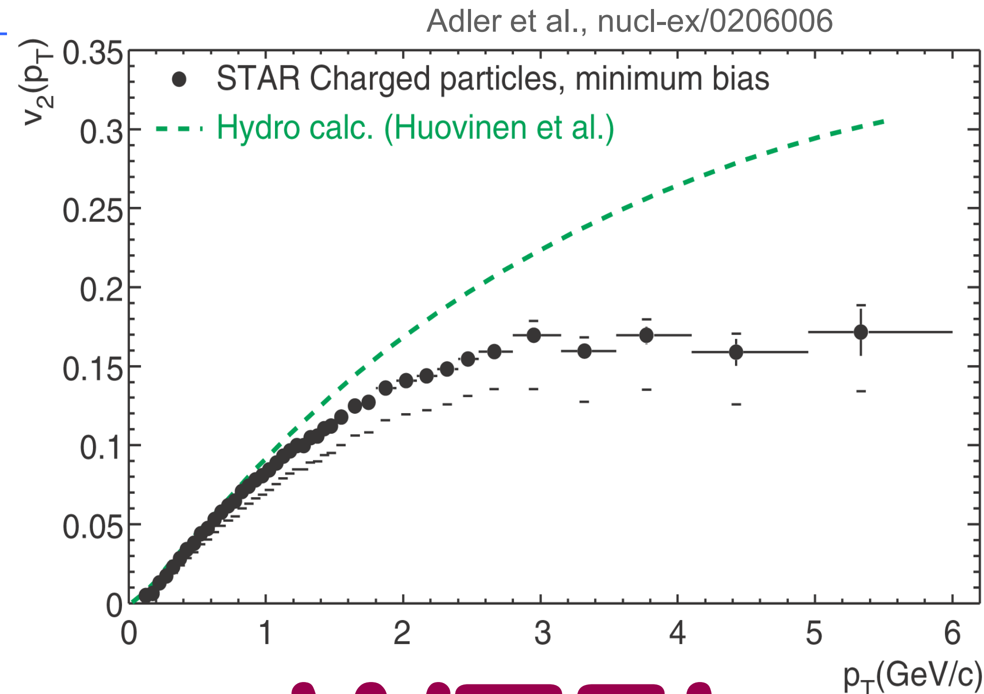
$$\frac{1}{p_T}\frac{d^3N}{dp_T d\phi dy} = \frac{1}{2\pi p_T}\frac{d^2N}{dp_T dy}\left[1 + 2v_2(p_T)\cos(2\phi) + 2v_4(p_T)\cos(4\phi) + \ldots\right]$$

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

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

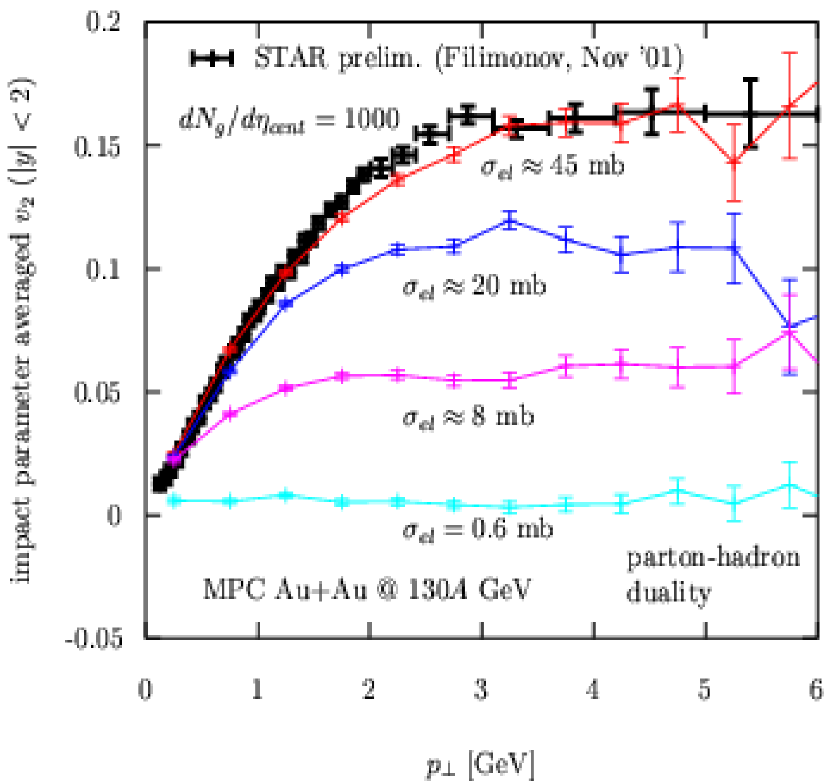
Huge v_2!

- 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)]

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

minijet initial conditions

$1g \to 1\pi$ hadronization

Huge cross sections!!

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

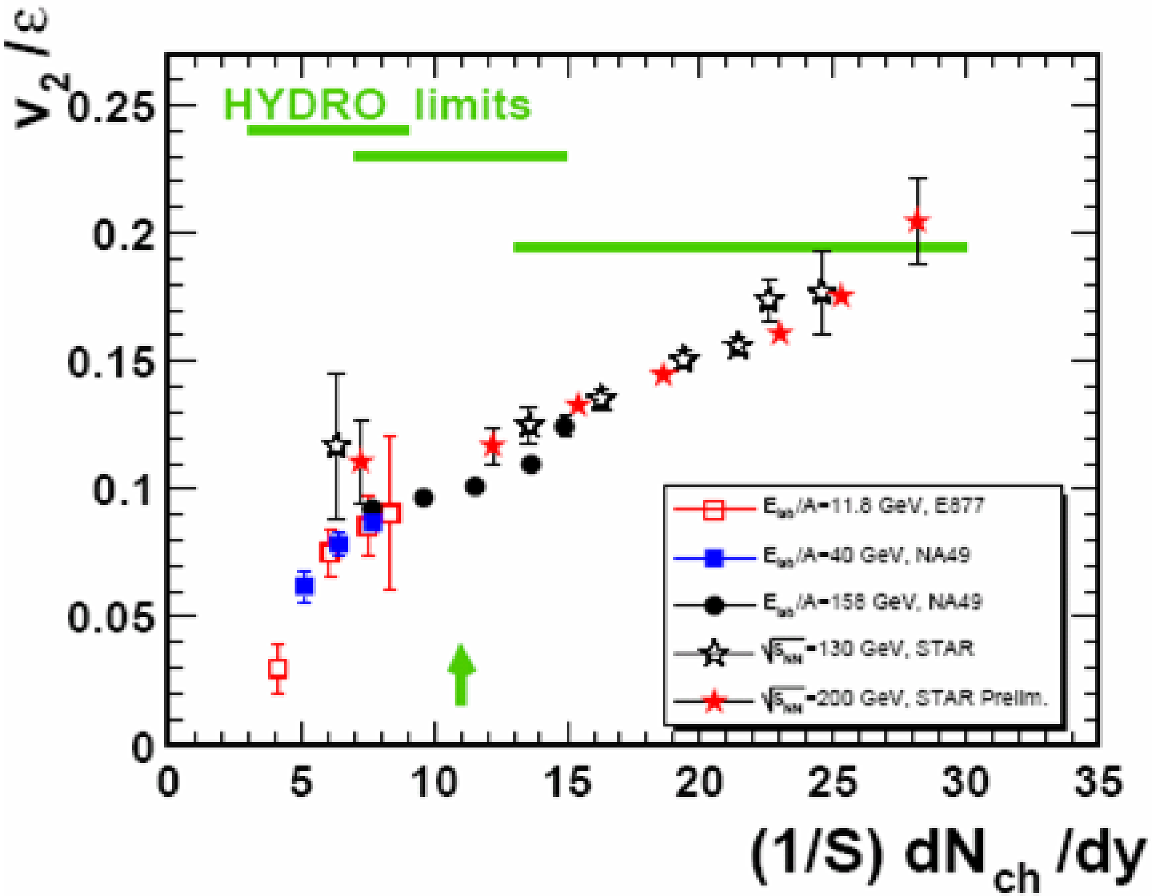
  requires large opacities $\sigma_{el} \times dN_g/d\eta \approx 45000$ mb $\gg$ pQCD (3 mb $\times 1000$)

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

if (πr^3==45 mb) {r=1.2 fm};

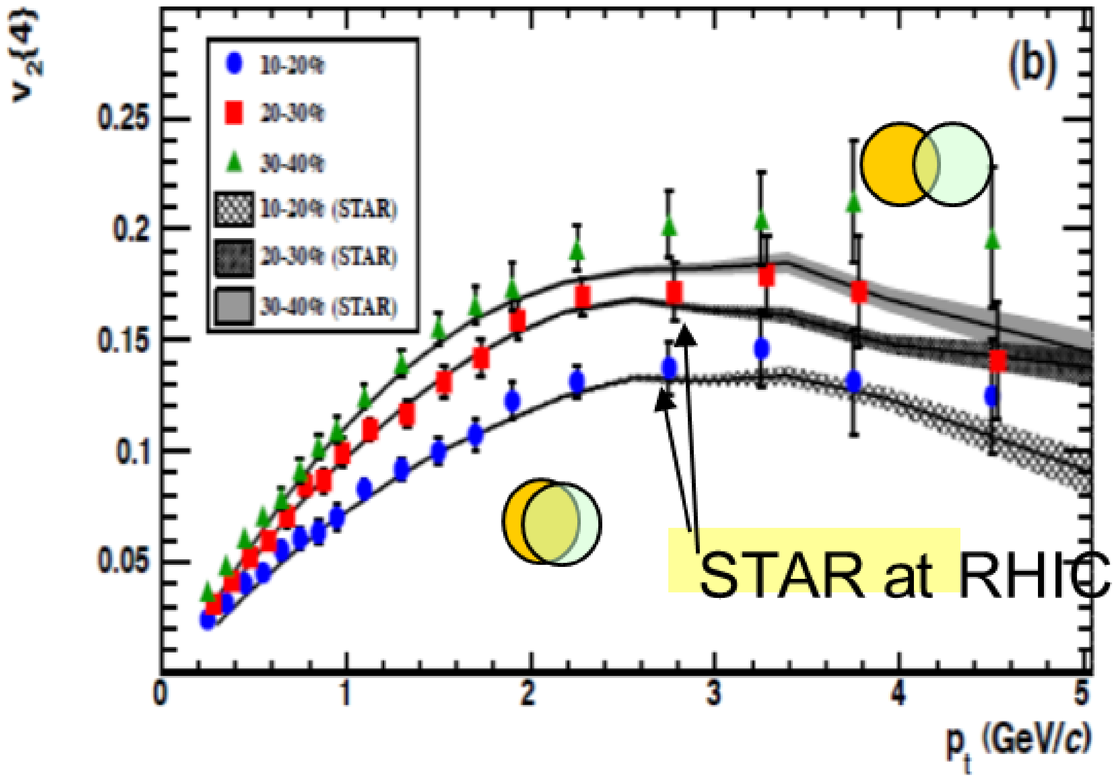
D. Molnár, SQM2003, Mar '02 – 4

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

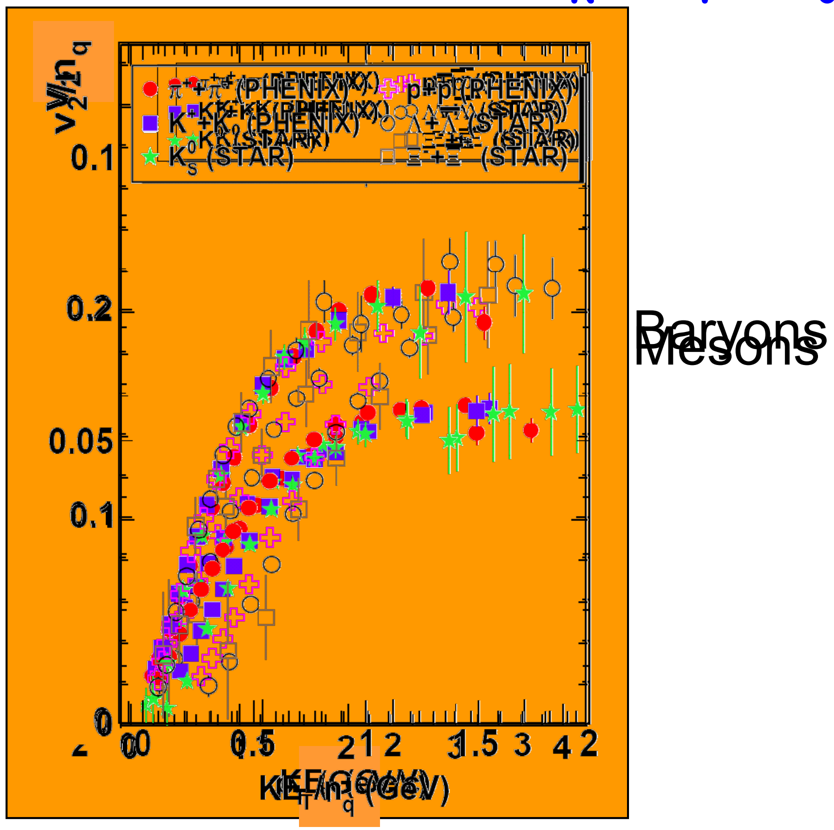


- Magnitude of flow as a FUNCTION of p_T is nearly exactly the same as at RHIC.
- LHC data reach to very high moments (v_6).

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

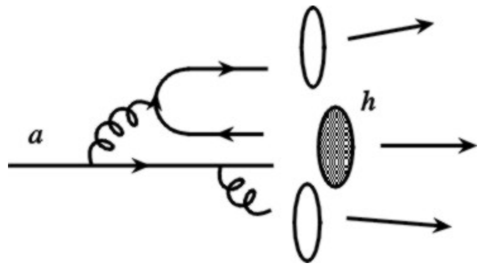


v_2 for different m_0 shows good agreement with "ideal fluid" hydrodynamics

An "ideal fluid" which knows about quarks!

Recombination Concept

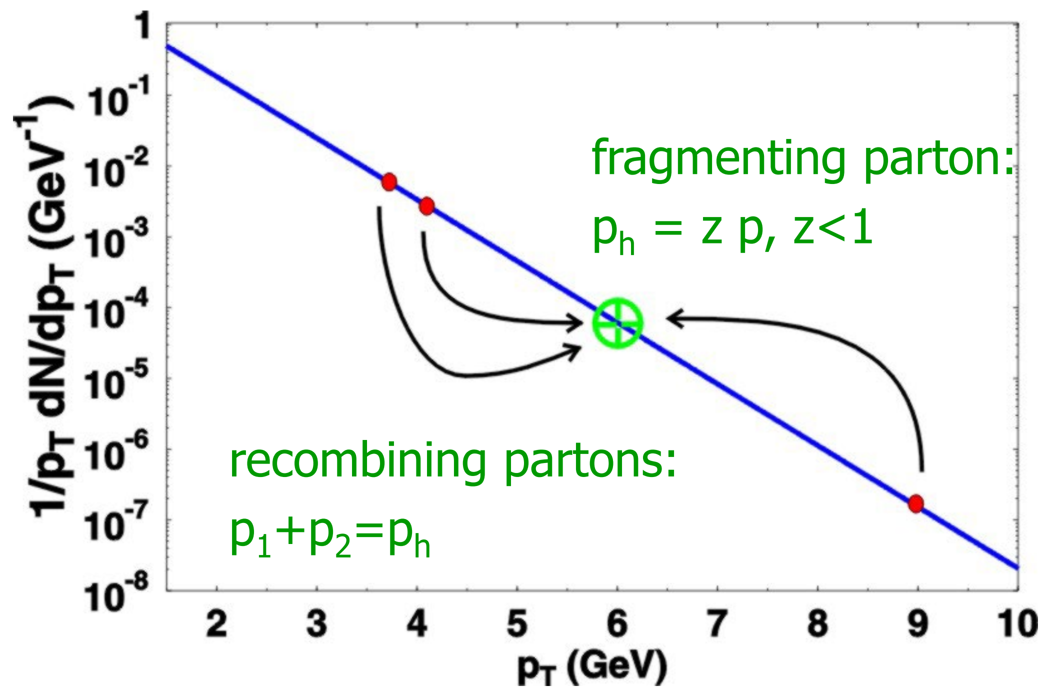
Fragmentation:



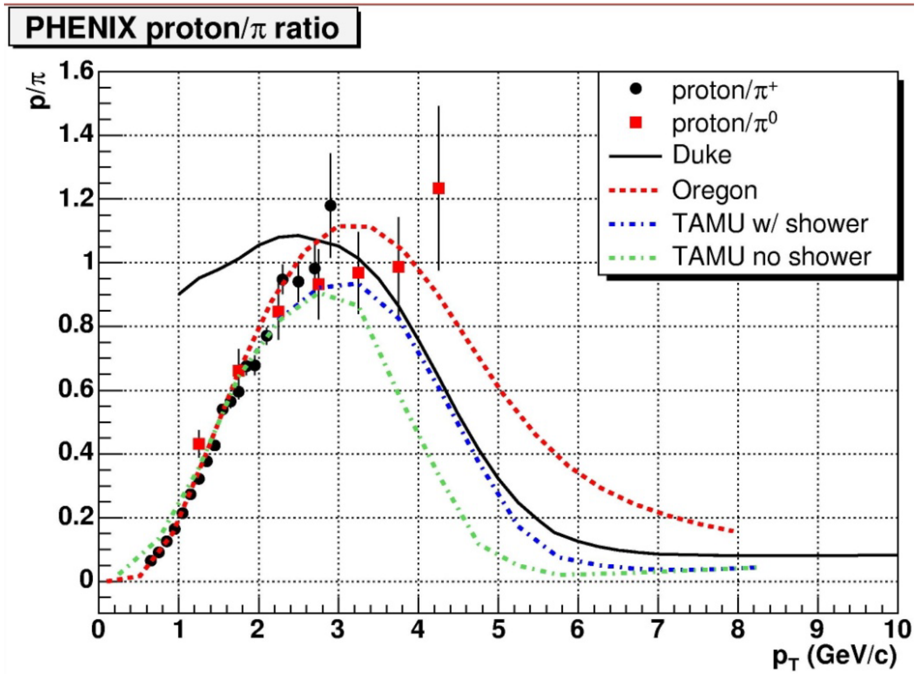
$$E\frac{dN_h}{d^3P}=\int_0^1 \frac{dz}{z^2}\frac{E}{z}\frac{dN_a}{d^3(P/z)}D_{\alpha\to h}(z)$$

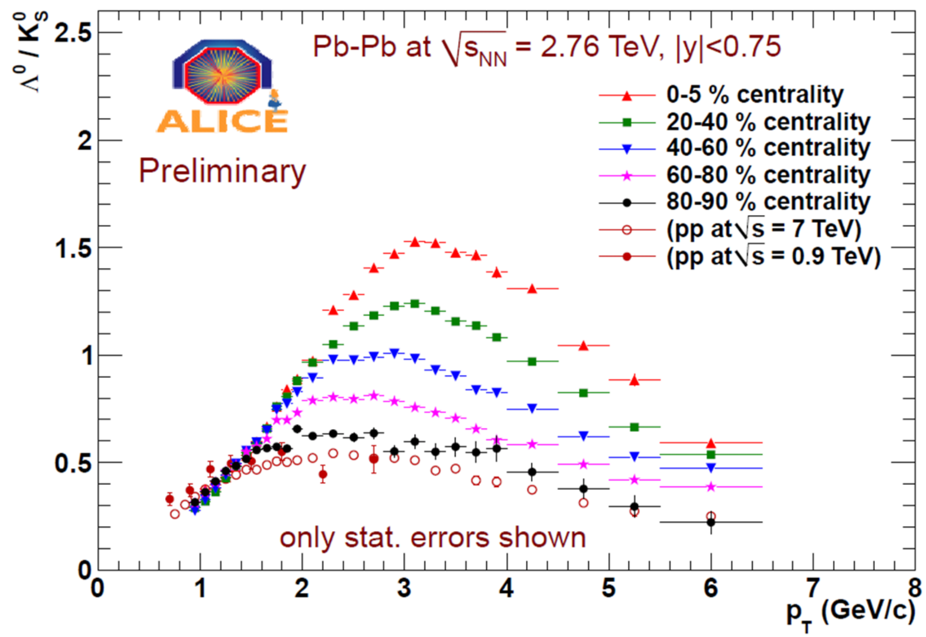
- for exponential parton spectrum, recombination is more effective than fragmentation
- baryons are shifted to higher p_t than mesons, for same quark distribution

➢ understand behavior of protons!

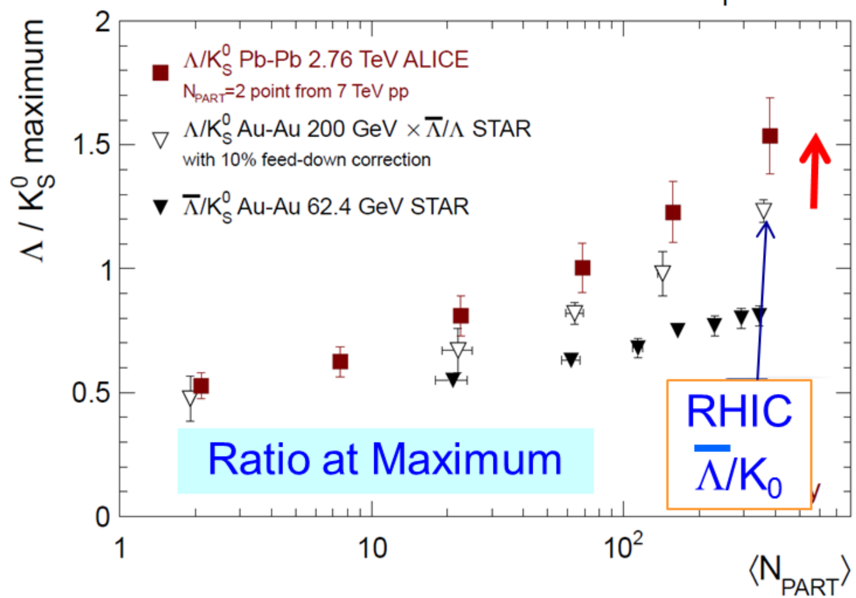


Baryon Anomaly



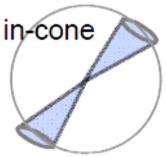


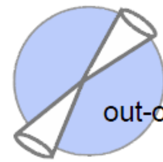
- Recombination models assume particles are formed by the coalescence of "constituent" quarks.
- Explain baryon excess by simple counting of valence quark content.



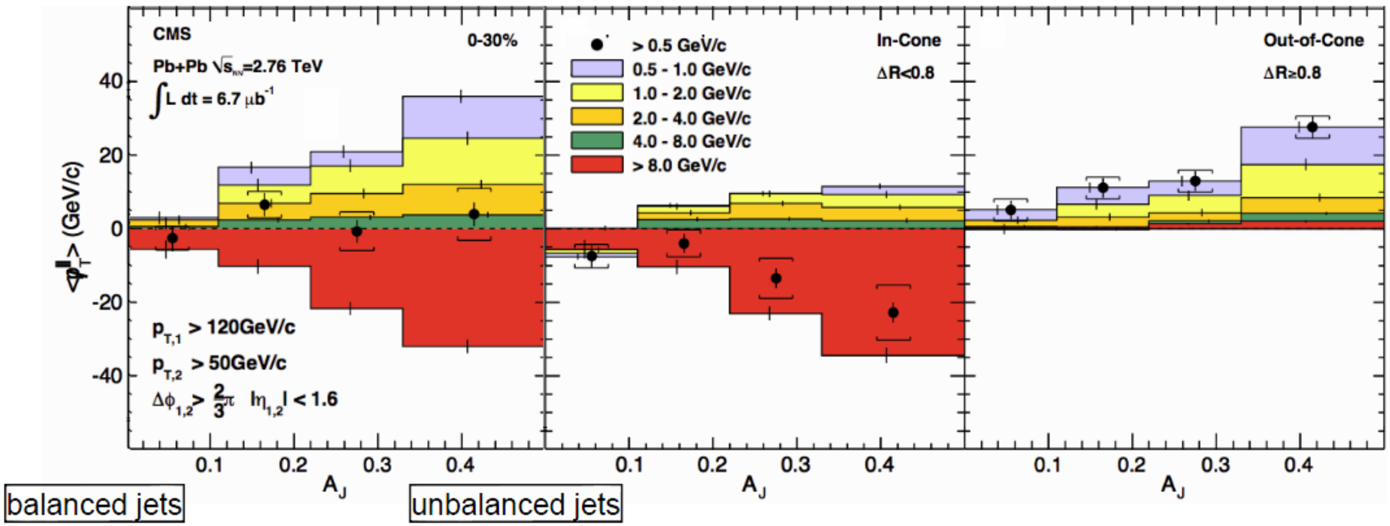
Where does the Energy: LHC

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





0-30% Central PbPb



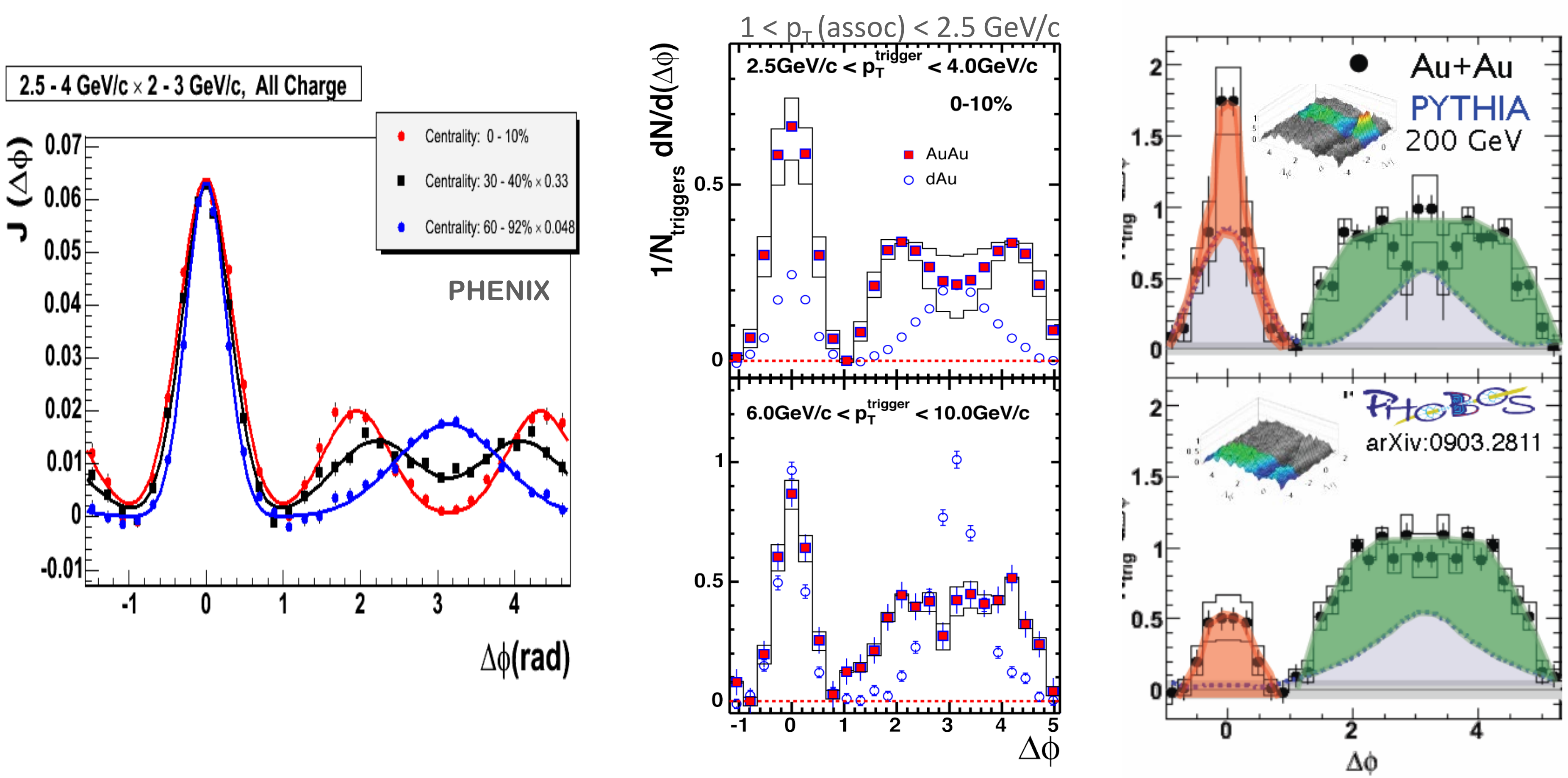
Low p_T, full acceptance
Momentum is balanced

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"

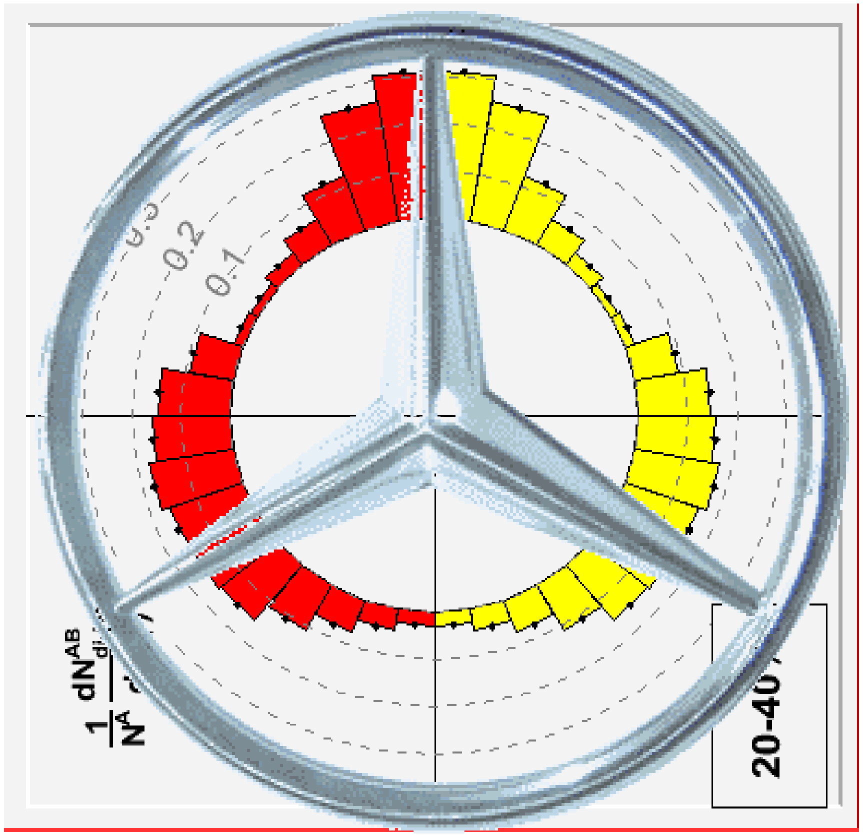


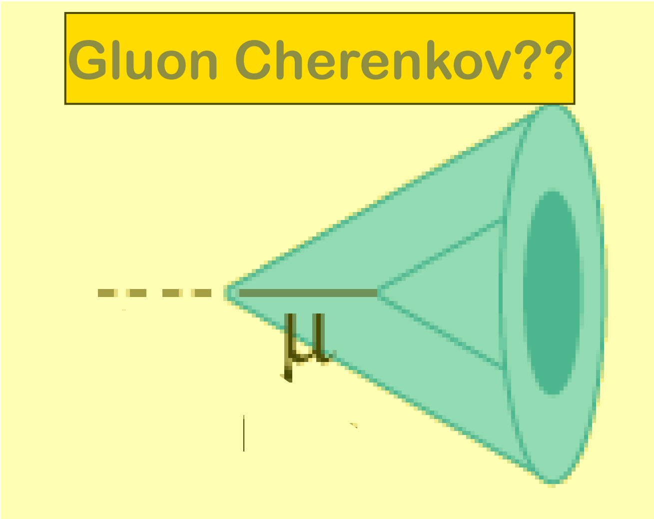
- Energy conservation says "lost" jet must be found.
- "Loss" was seen for partner momenta just below the trigger particle…Search low in momentum for the remnants.

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)

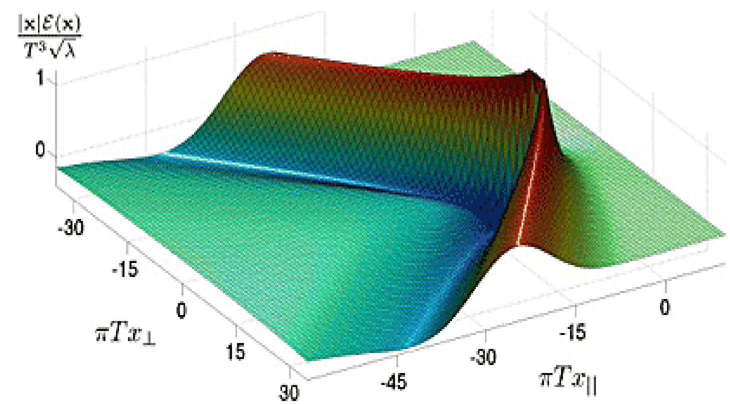
QGP (in QCD)

⇕

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

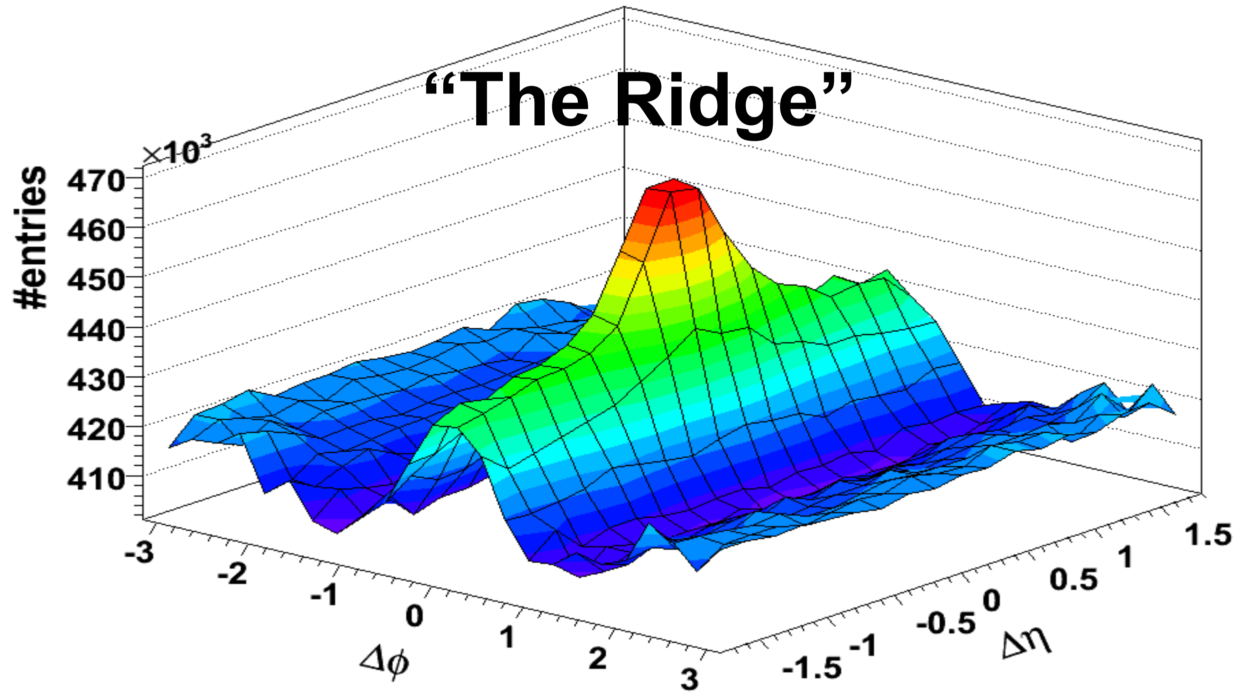
⇓ thermal

⇓ 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?

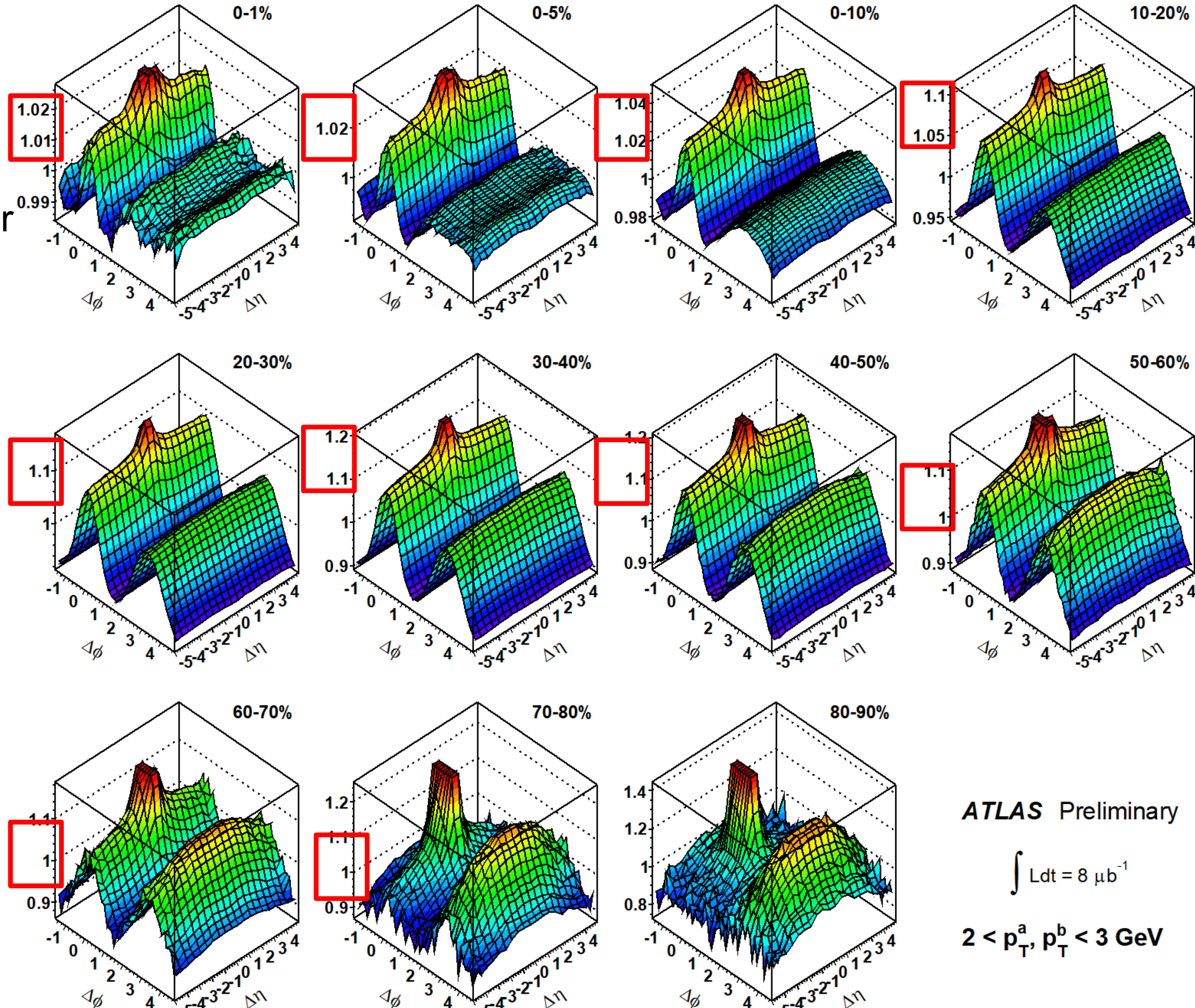
1. p_T spectra similar to bulk (or slightly harder)
2. baryon/meson enhancement similar to bulk
3. Scales per trigger like Npart similar to bulk

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

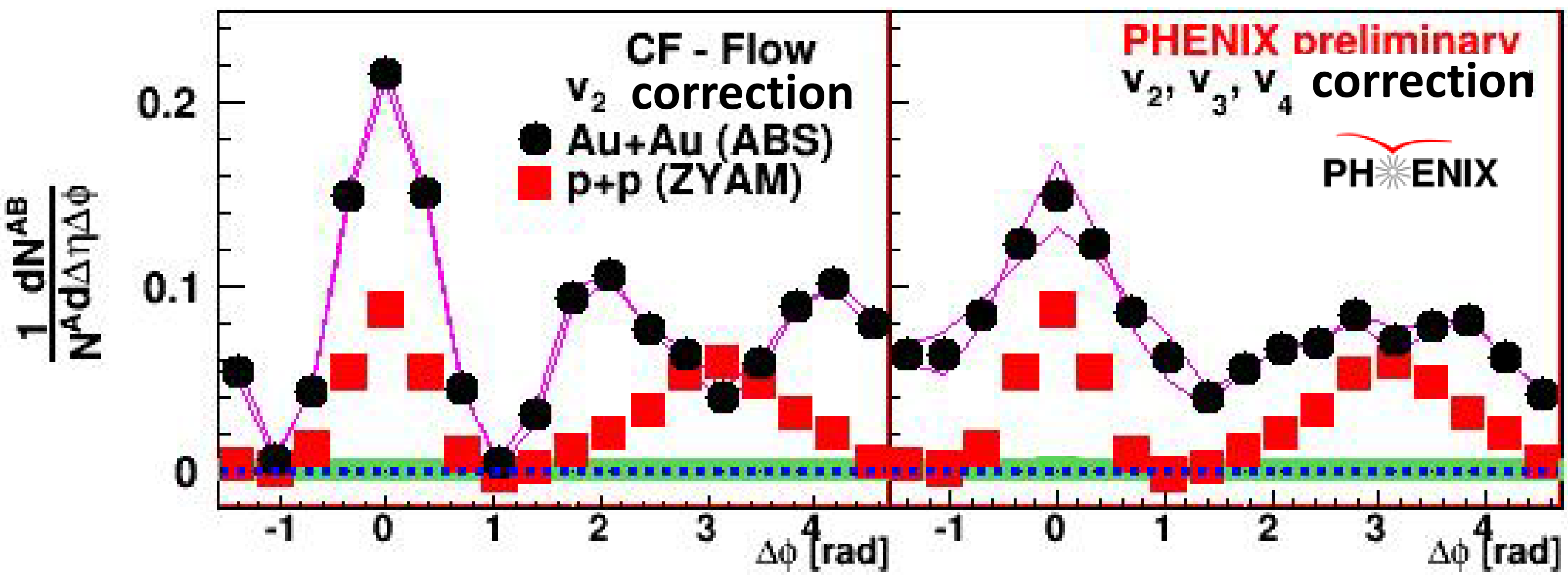


ATLAS Preliminary

$\int Ldt = 8\ \mu b^{-1}$

$2 < p_T^a, p_T^b < 3$ GeV

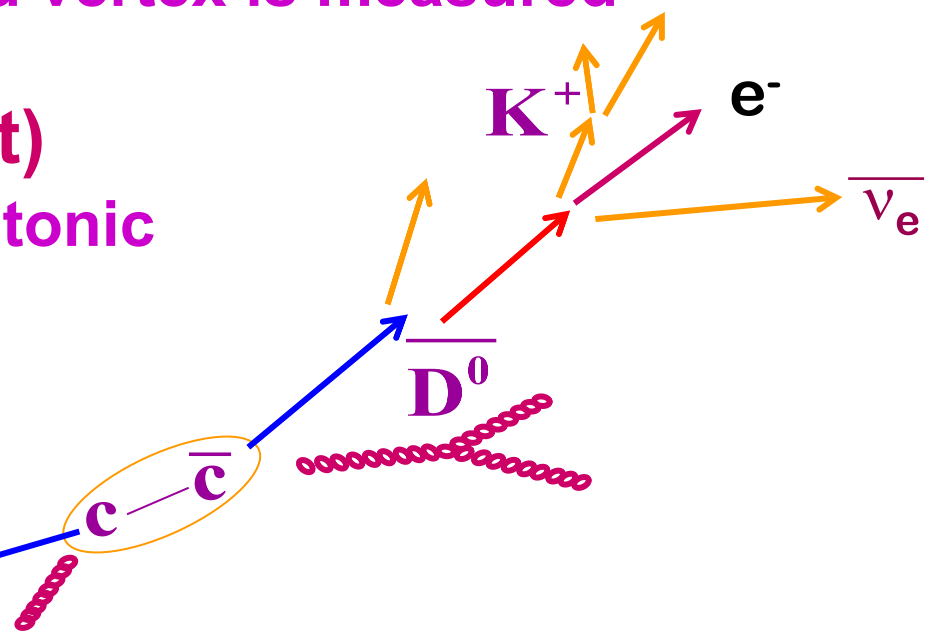
v_3 explains double-hump

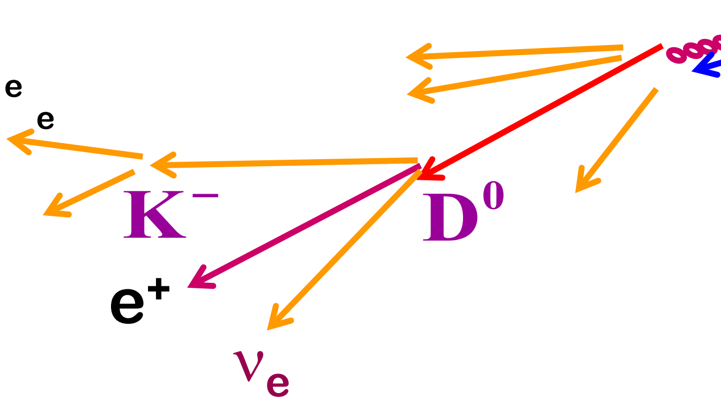


- v_2 correction only
  - double-hump
- v_2, v_3, v_4 correction
  - double-hump disappeared
  - Peak still broadened

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

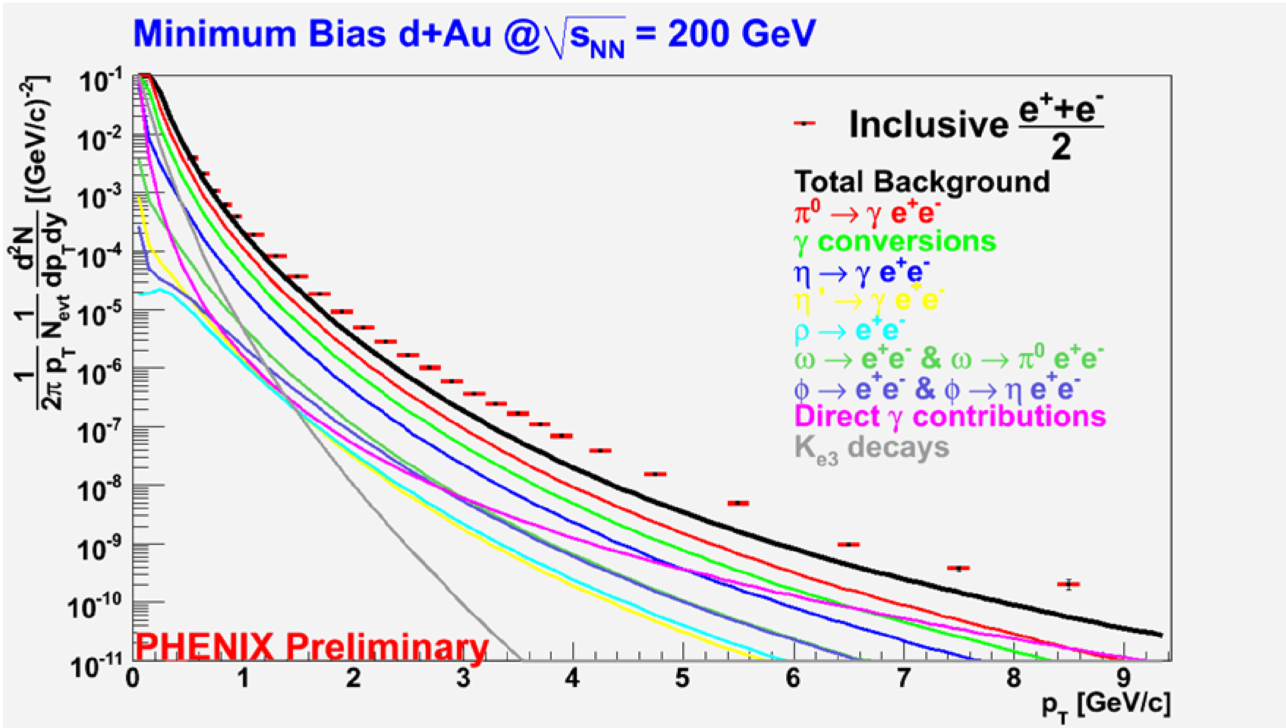




$$D^0 \rightarrow K^- \ell^+ \nu_e$$
$$\overline{D}^0 \rightarrow K^+ \ell^- \overline{\nu}_\ell$$

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

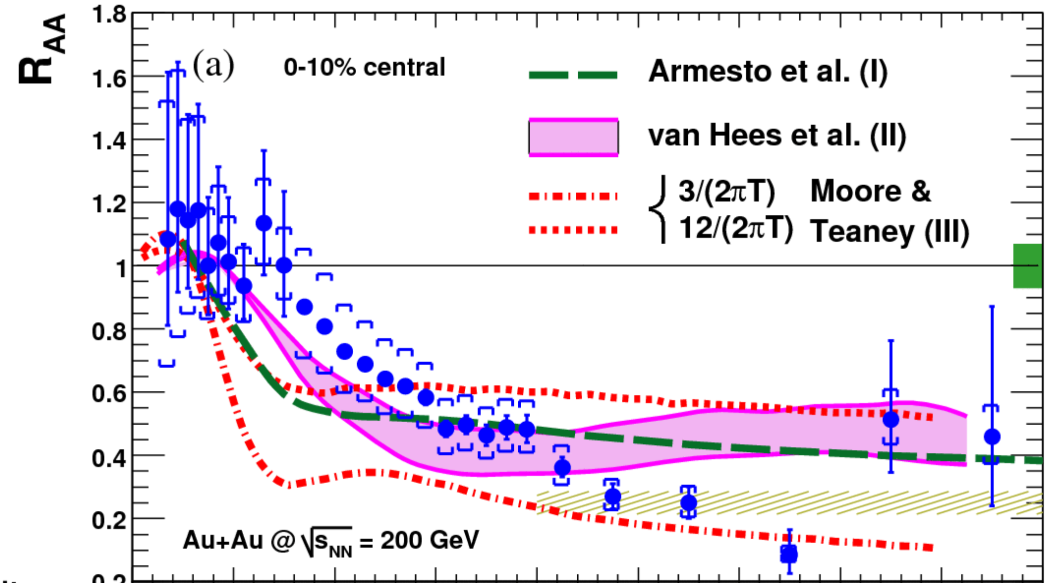
Inferred Heavy Flavor

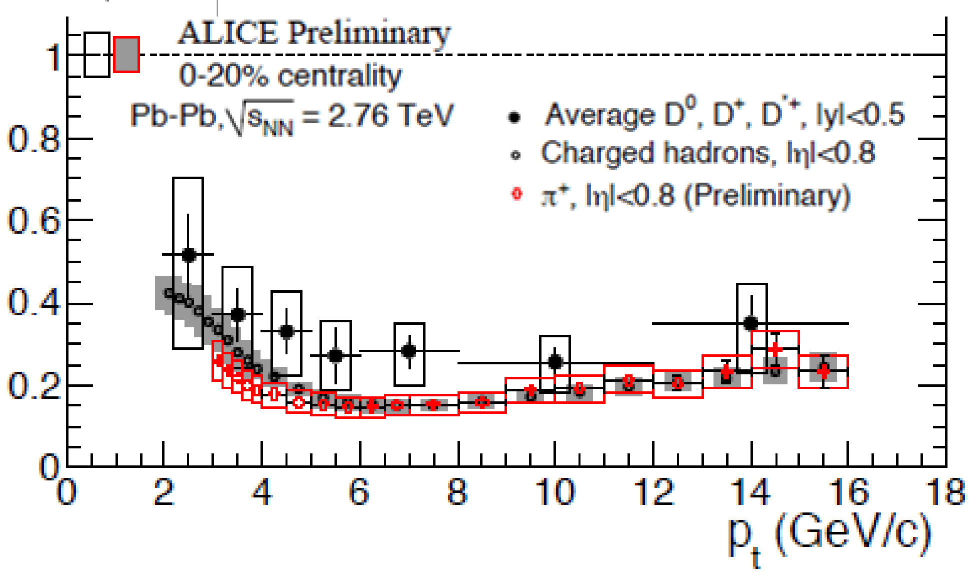


- Measurement inclusive $e^{\pm}$.
- Measure π^0, η^0
- Construct "Cocktail" of electron sources other than c/b
  - light hadron decays
  - photon conversions
- Subtract $e^{\pm}$ "cocktail" leaves e from c/b.

Hard Probes: Open Heavy Flavor

Electrons from c/b hadron decays

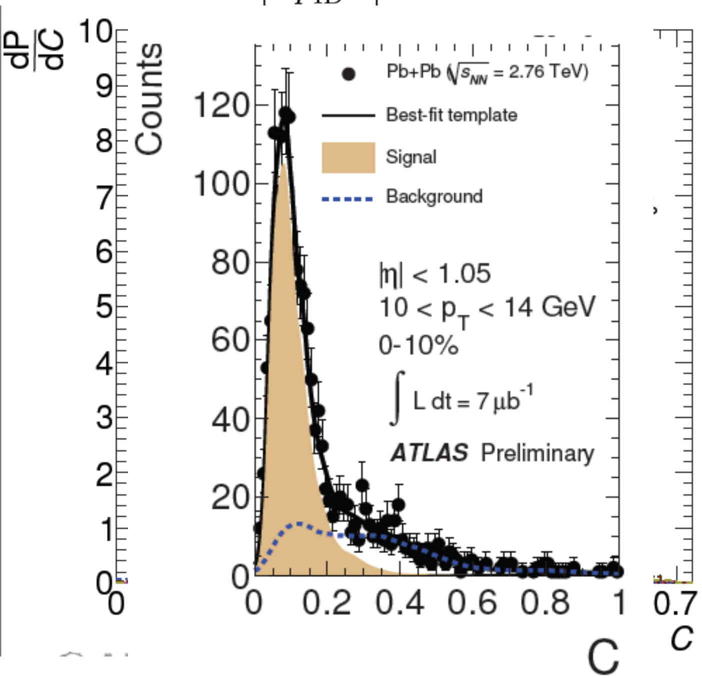


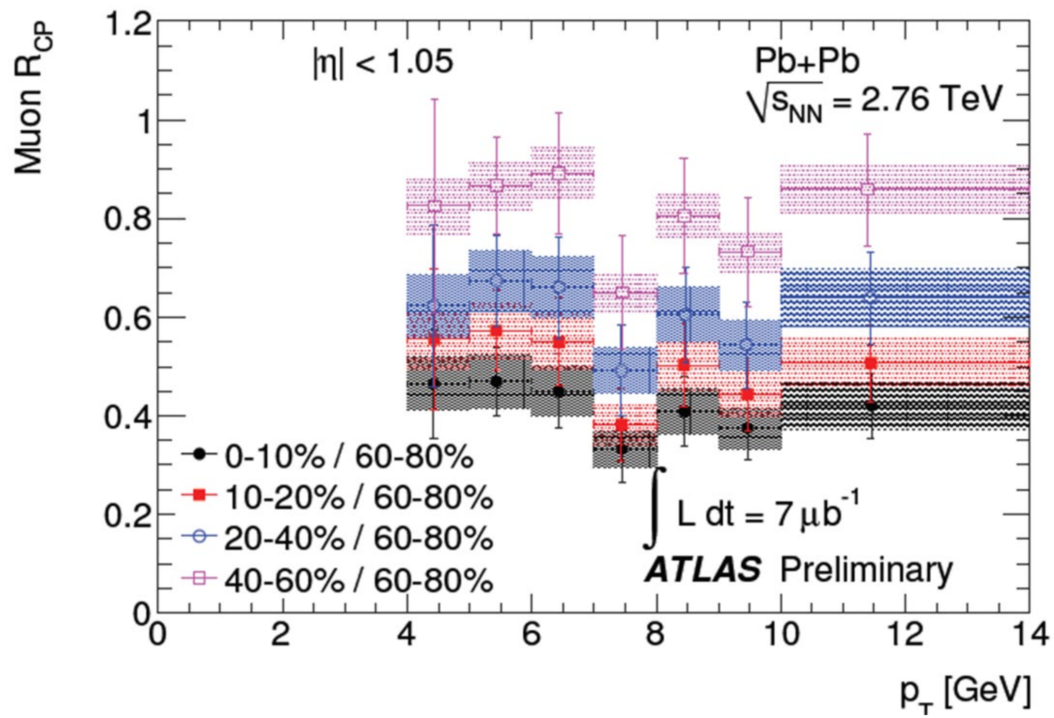


- **Calibrated probe?**
  - pQCD now predicts cross section well
  - Total charm follows binary scaling
- **Strong medium effects**
  - Significant suppression
  - Upper bound on viscosity!
  - Little room for bottom production
- **Limited agreement with energy loss calculations**

Single Muons from ATLAS

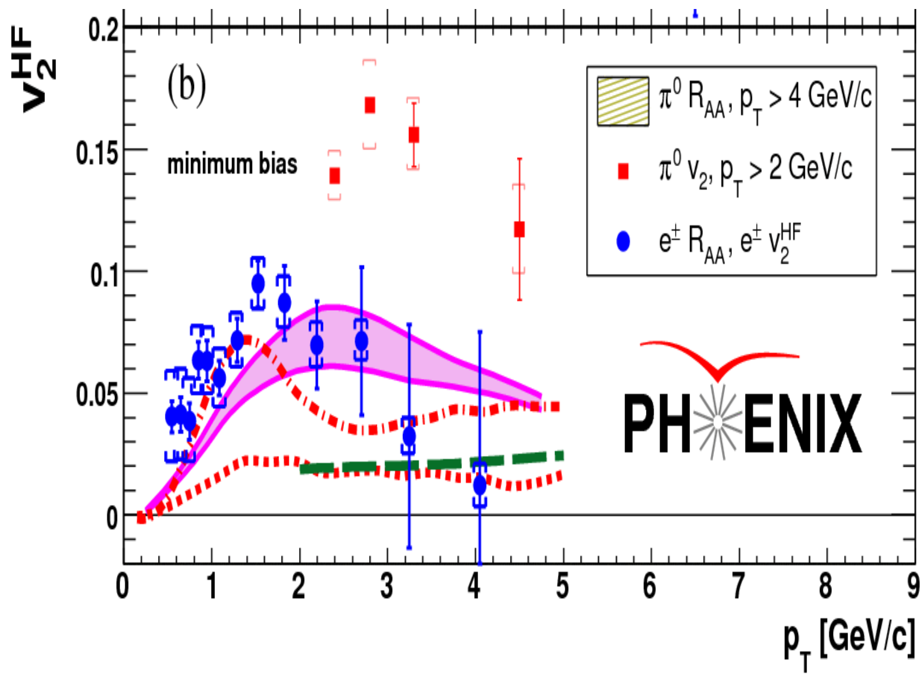
$$C = \left|\frac{\Delta p_{\mathrm{loss}}}{p_{\mathrm{ID}}}\right| + rS$$

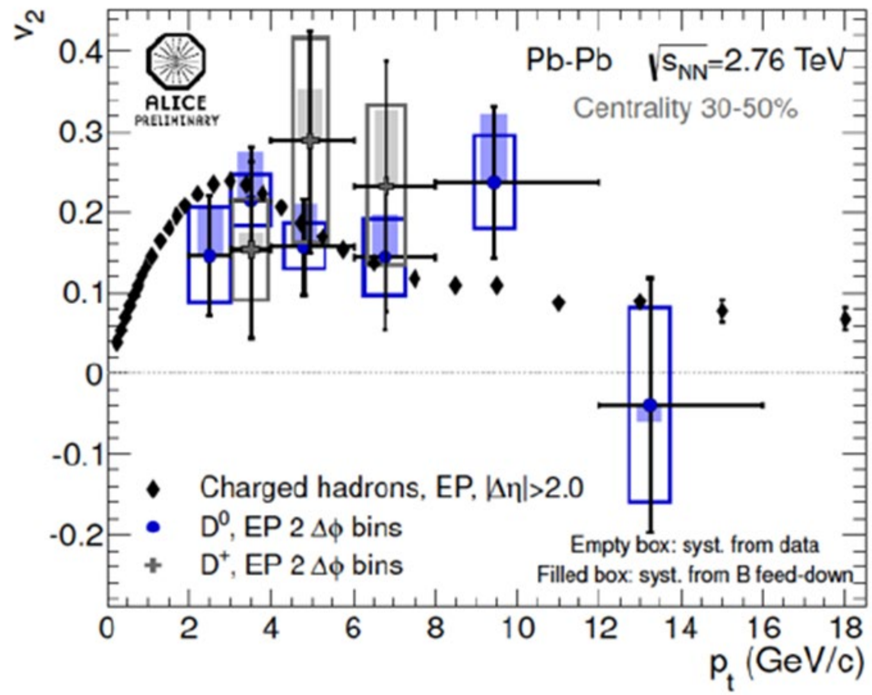




- High Momentum muons dominantly from heavy flavor.
- Eliminate unwanted background by statistical method.
- At these high momenta, the muons are likely dominated by bottom.
- Is there a limit to the power of the river?...Stay tuned.

Heavy Flavor Quarks are Flowing!

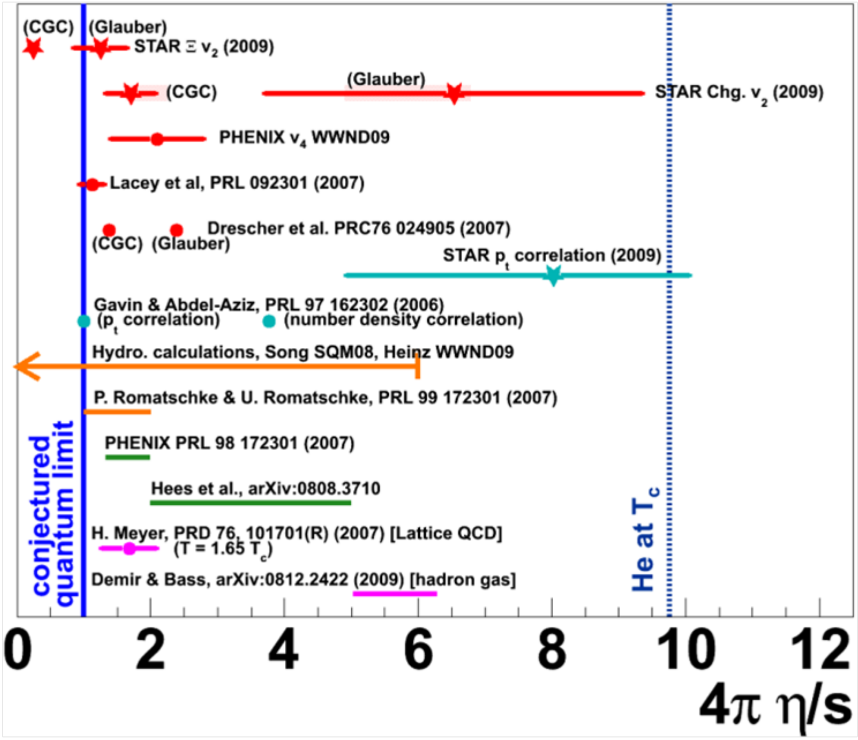




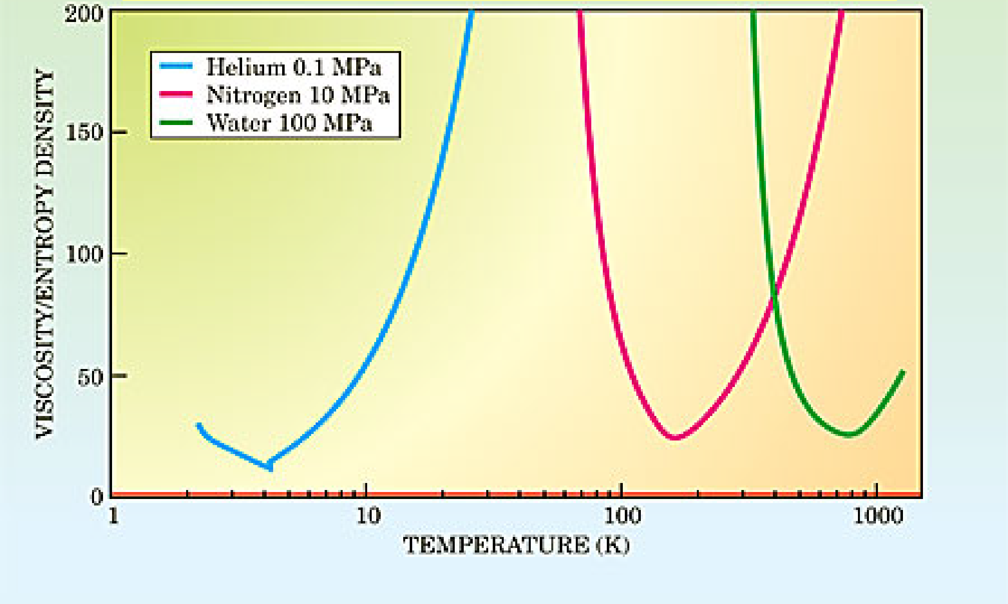
- **We can imagine that the flowing QGP is a river that sweeps quarks.**
- **A "perfect fluid" is like a school of fish…all change direction at once.**
- **Our QGP river carries off heavy stones (not BOTTOM???)**
- **Requiring a model to SIMULTANEOUSLY fit R_{AA} and v_2 "measures" the η/s of the QGP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

STONY BROOK

How Perfect is “Perfect” ?

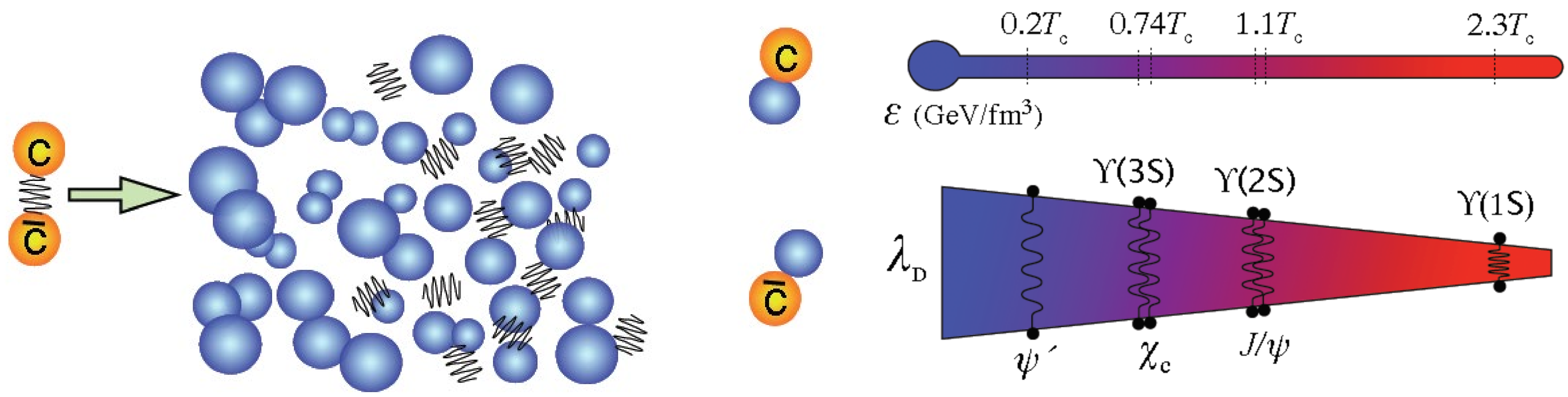


$$\eta \geq \frac{\hbar}{4\pi}(\ Entropy\ \ Density\ ) \equiv \frac{\hbar}{4\pi}s$$



- 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!

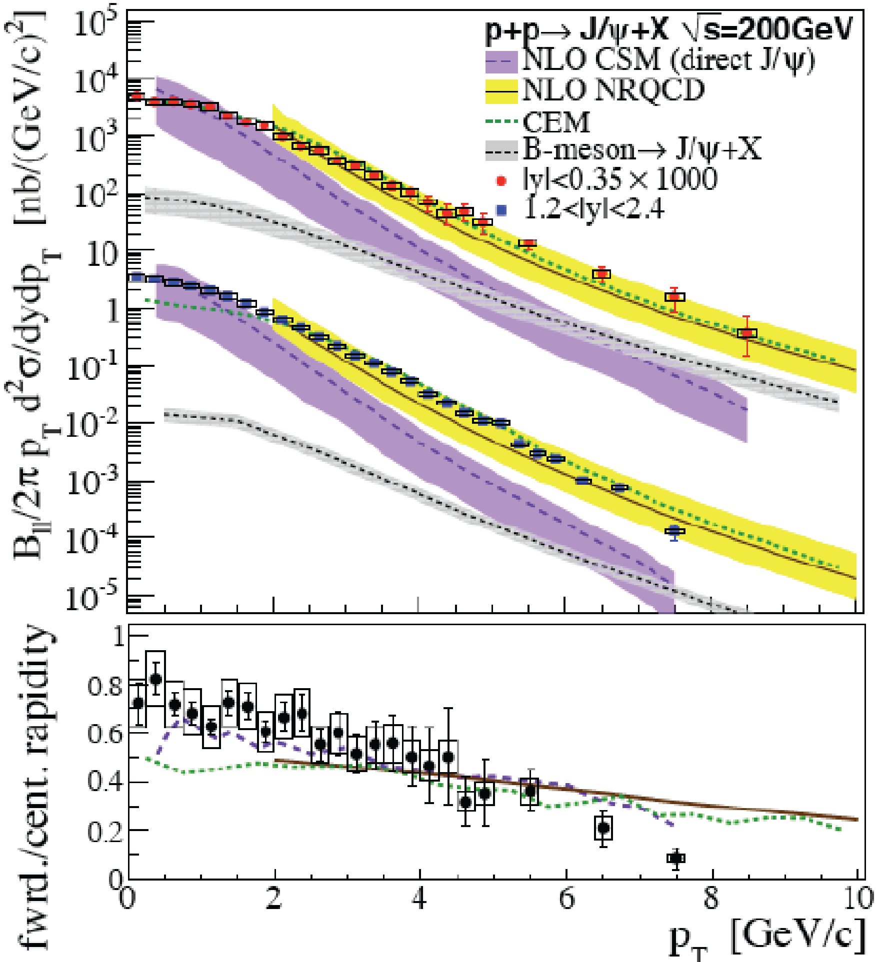
Quarkonia Production



- *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 Υ.**
- **Suppression driven by size of the meson as compared to the Debye Radius (radius of color conductivity)**

How is J/ψ formed in pp?

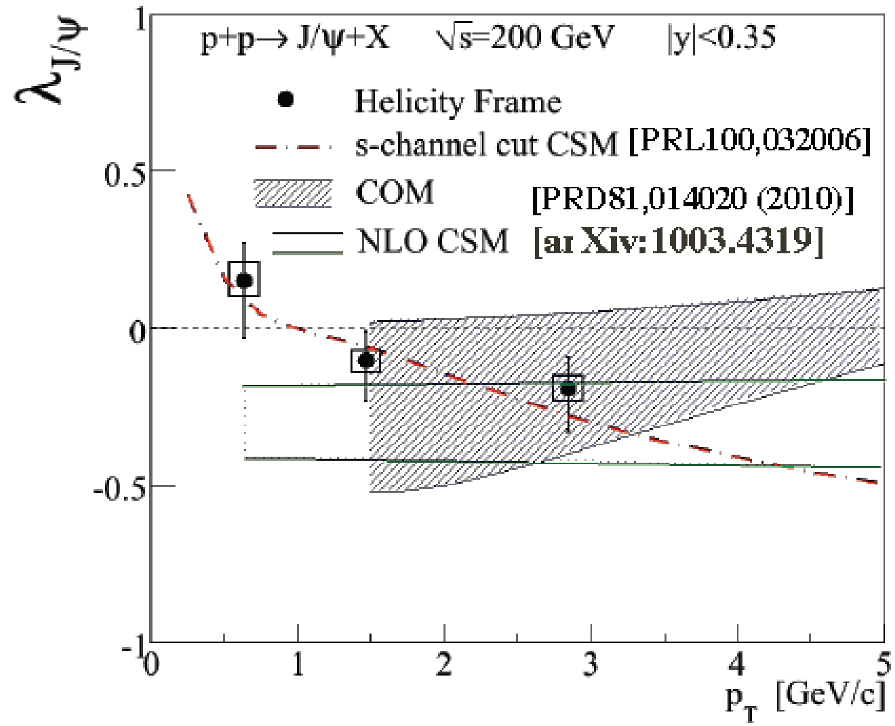
[arXiv:1105.1966]



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

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

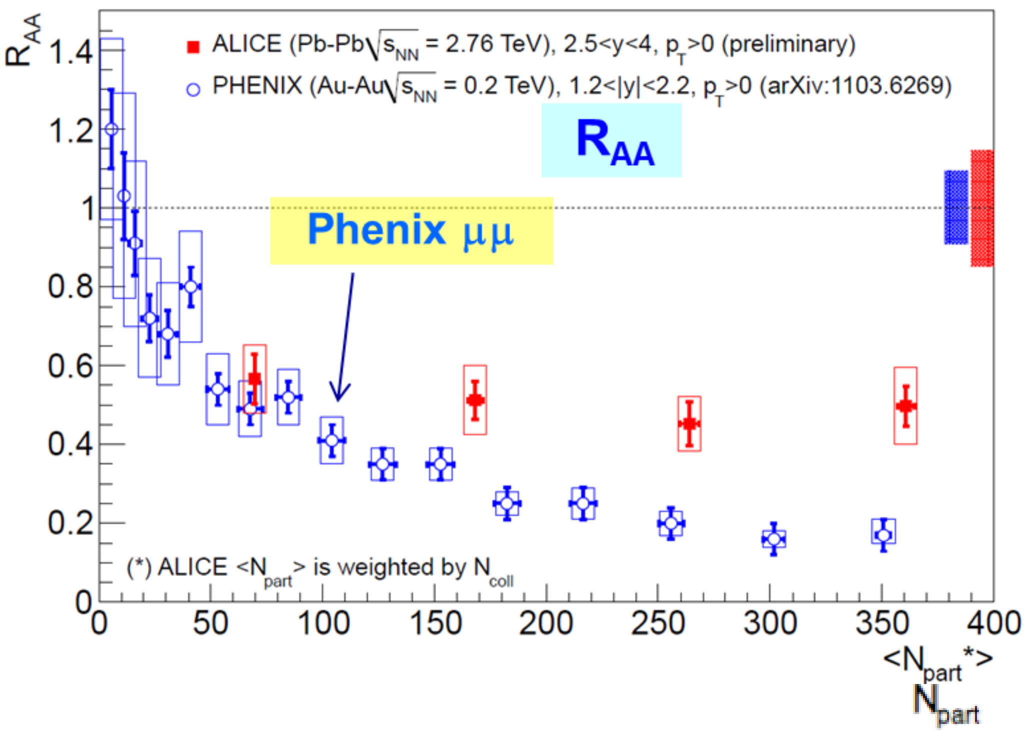
[PRD82,012001 (2010)]



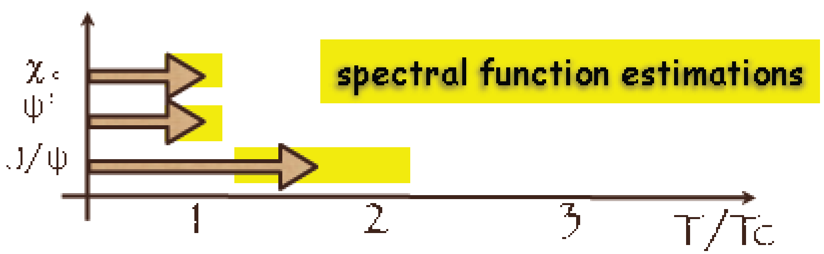
- color octet state may cross part of the nuclear matter as a pre-resonant state

J/ψ is suppressed (everywhere)

[arXiv:1103.6269v1]

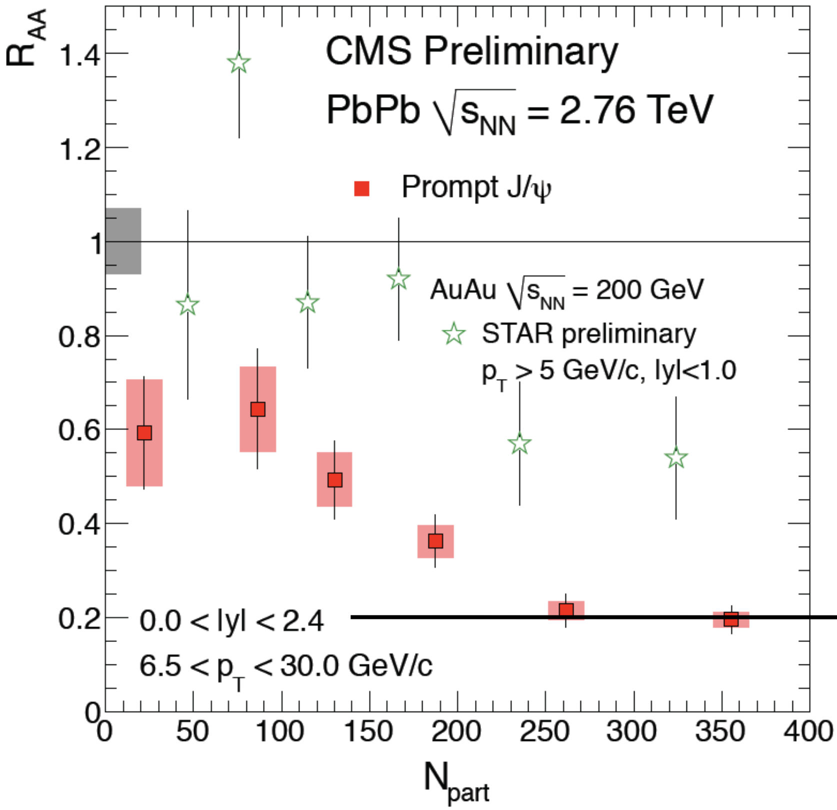


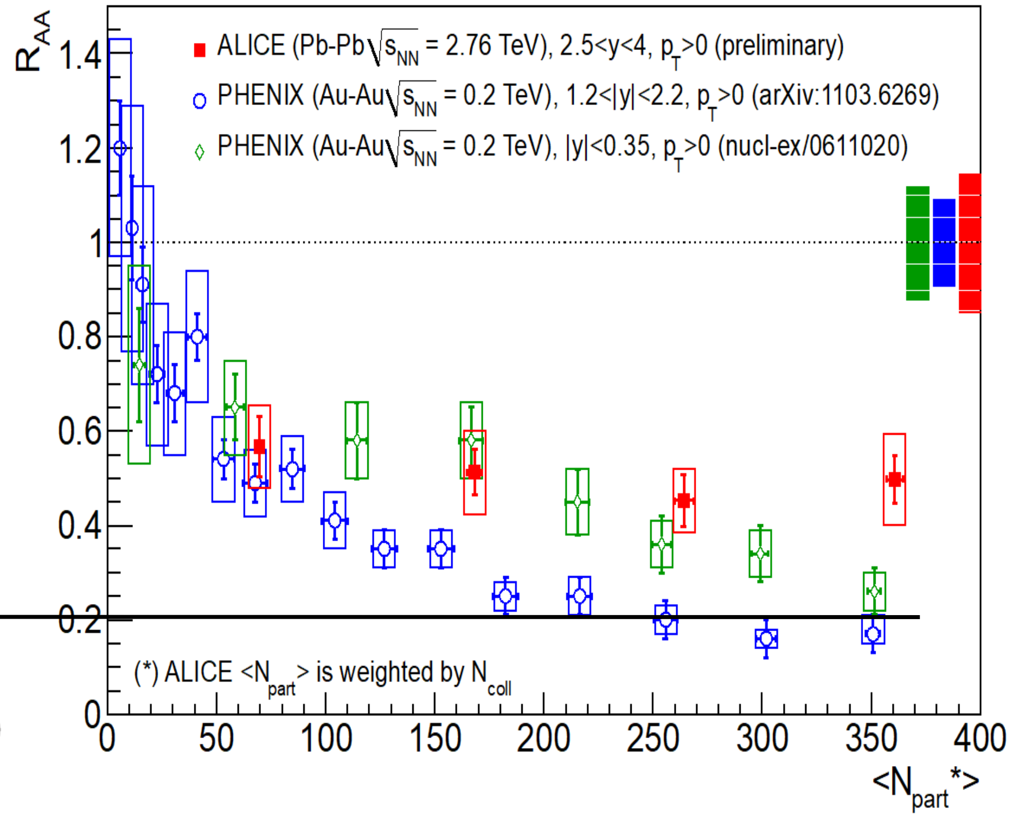
- Tc ~ 170 MeV
- inverse slope of thermal photons measured by PHENIX is 221±28MeV [PRL104, 132301 (2010)]
- hydro models fitted to the thermal photon data suggest T_{init} ~300-600 MeV
- who survives?



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

LHC/RHIC comparison



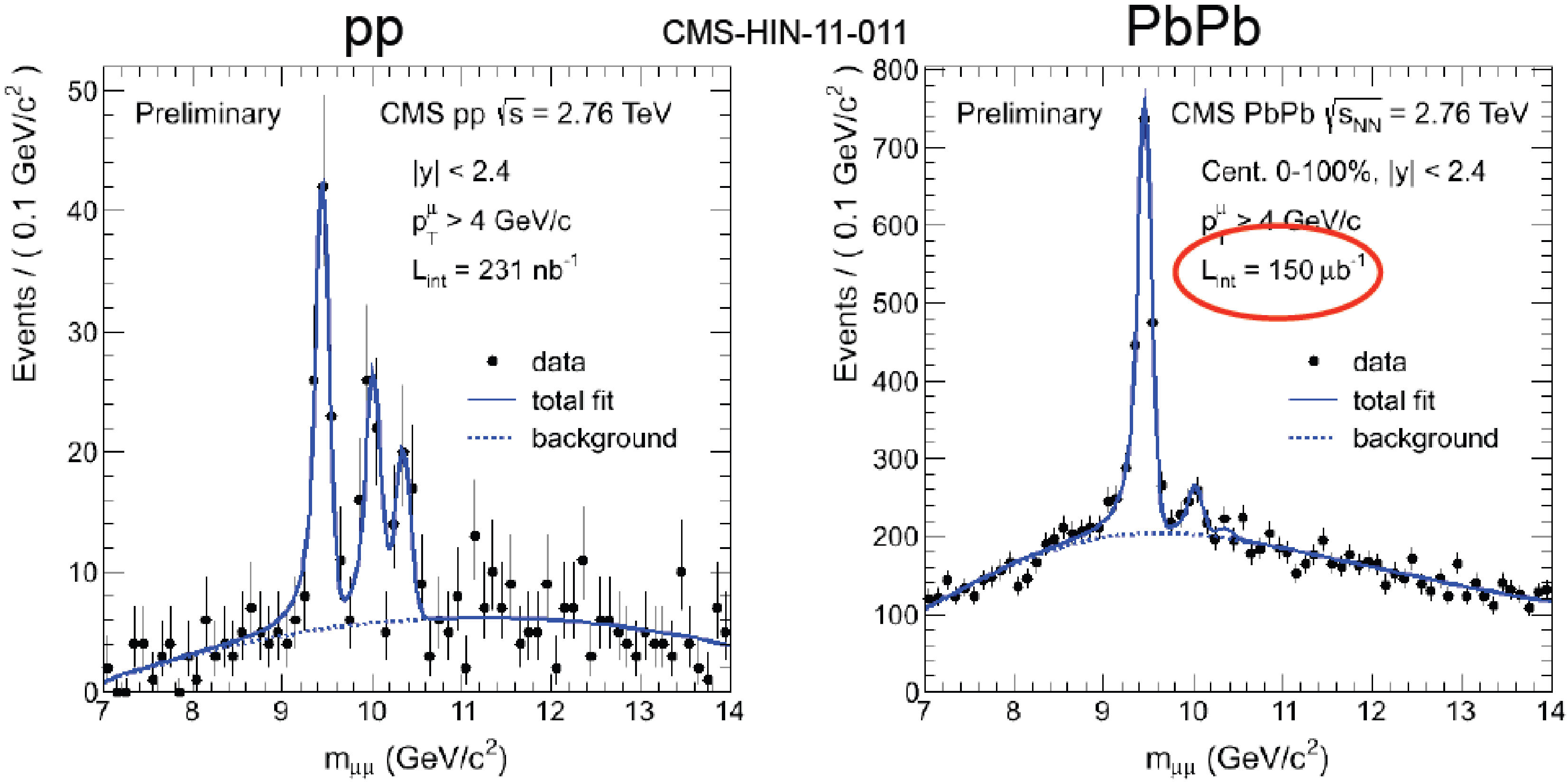


STAR (p_T>5 GeV) versus CMS (6.5<p_T<30 GeV)

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.



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

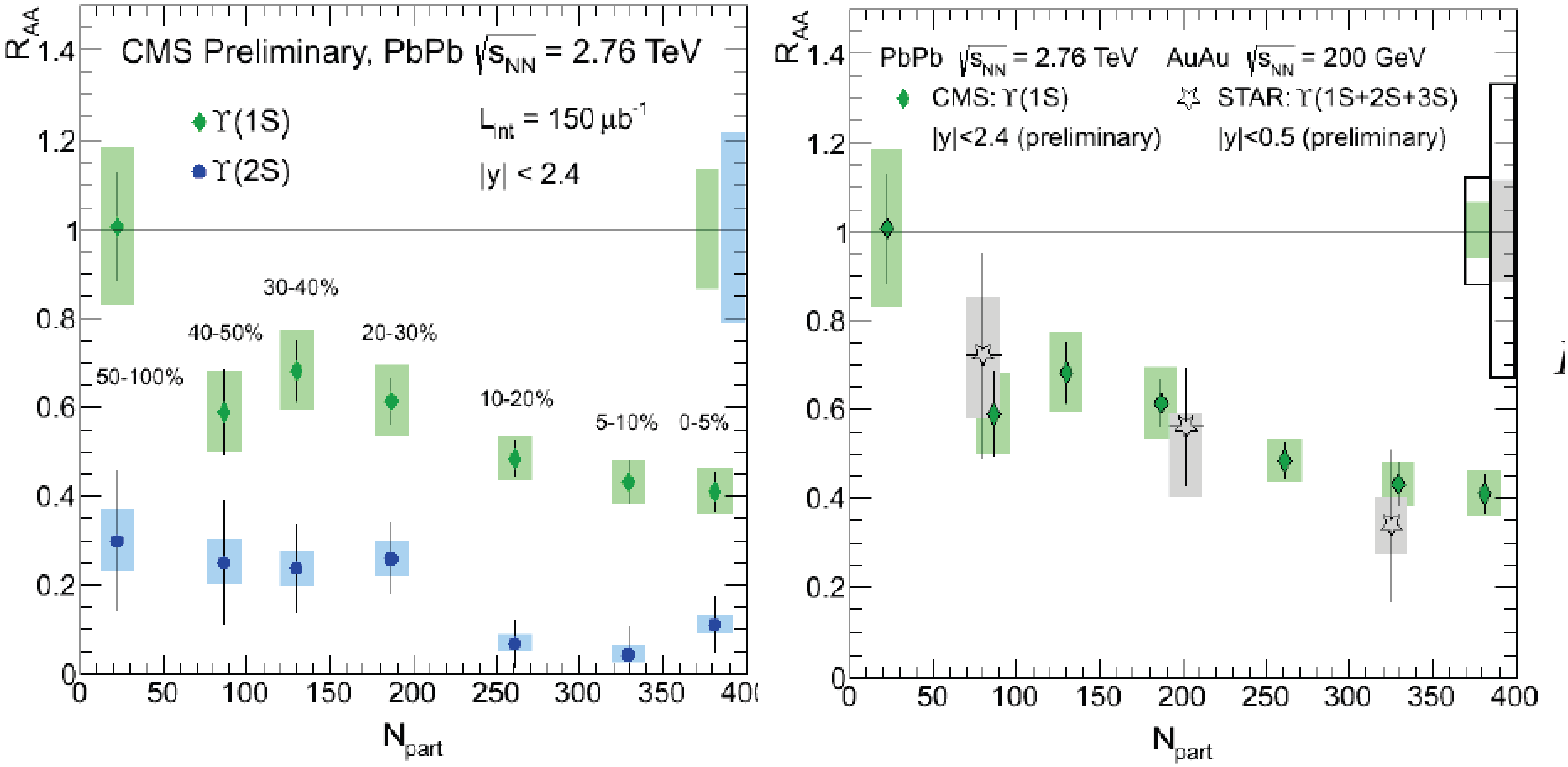
$$N_{\Upsilon(3S)}/N_{\Upsilon(1S)}|_{pp} = 0.21 \pm 0.11 \pm 0.02$$

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

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

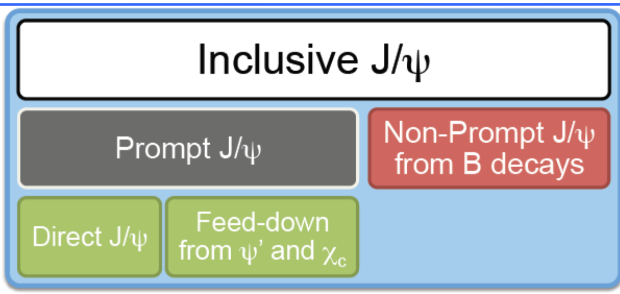
- **The data show that the 2s/3s are reduced compared to the 1s.**
- **This is first strong indication of sequential melting in QGP.**
- **Should yield screening length of our color conductor!**

Upsilon Suppression

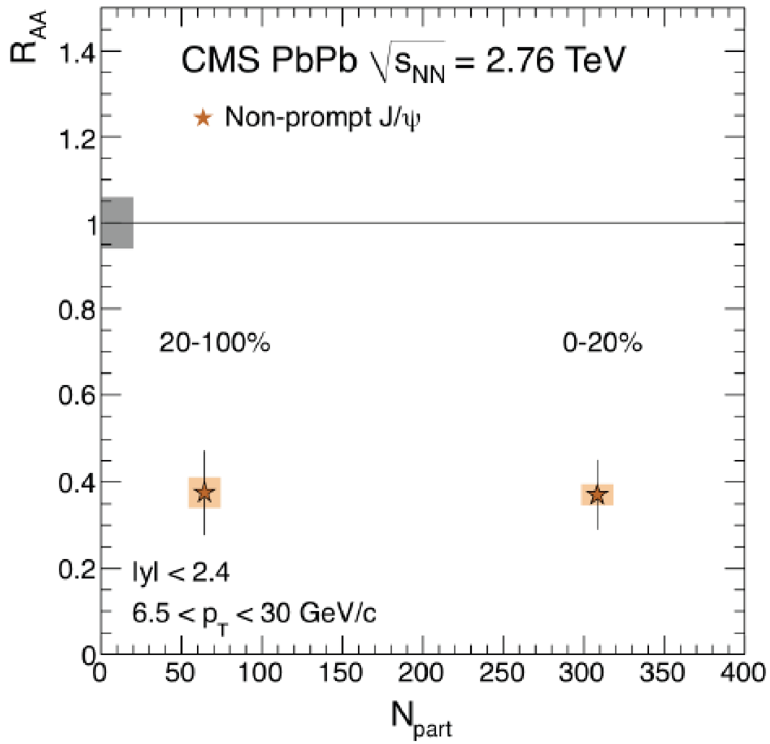


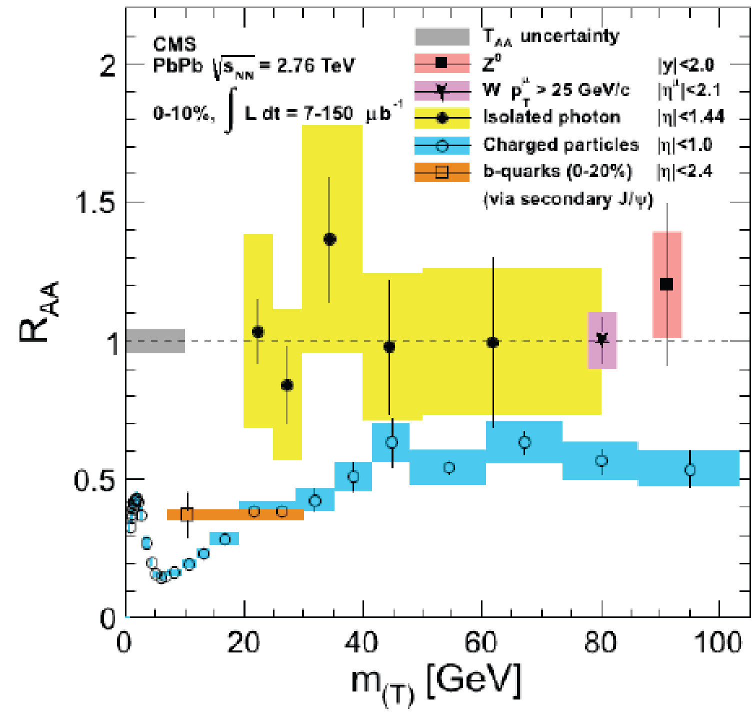
- **Upsilon system is "cleaner" than the J/Psi.**
- **1s state suffers from feed-down (~50%).**
- **Consistent with melting all Y except feeddown.**

J/Psi as Bottom Suppression?



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



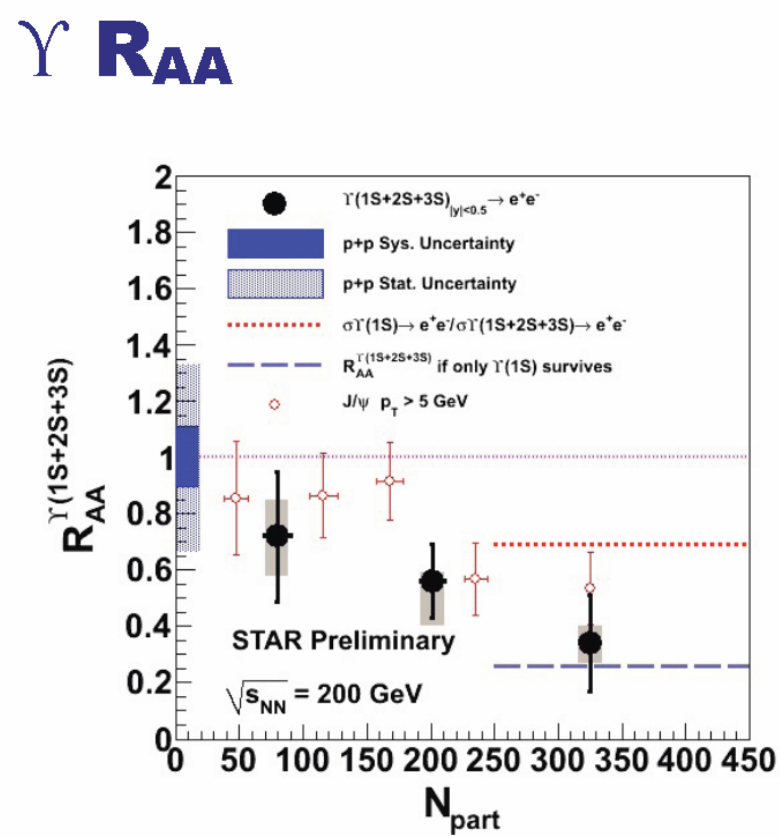


- **These are a surrogate for a bottom quark.**
- **Suppression same or less than π/charm?**

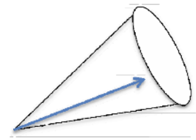
Backup Slides

Suppression.

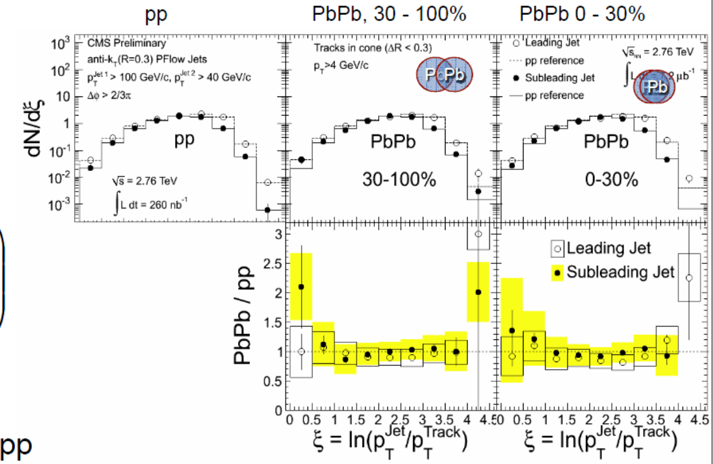
- 1s state should be too large to melt in the plasma.
- 2s/3s could be melted.
- Data are above blue-dashed which would be consistent with only 1s survival and removal of nearly all 2s/3s.



Fragmentation Function at LHC

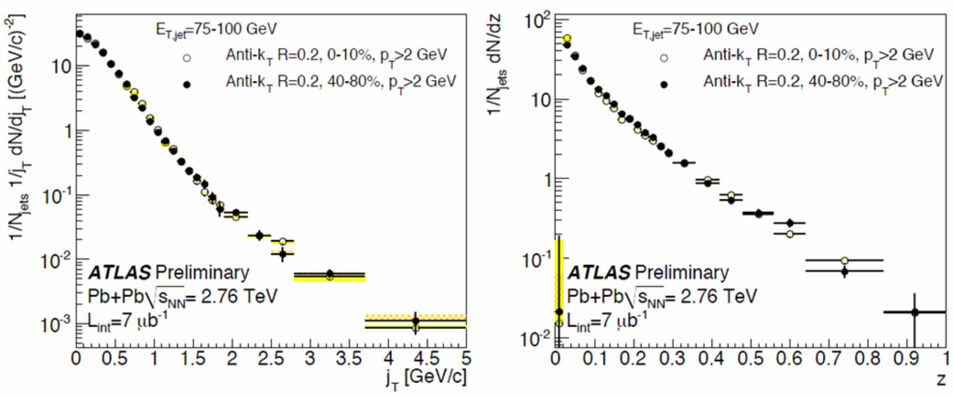


$$\xi = \ln\left(\frac{p_T^{Jet}}{p_T^{Track}}\right)$$



Fragmentation Functions

- Compare PbPb to pp



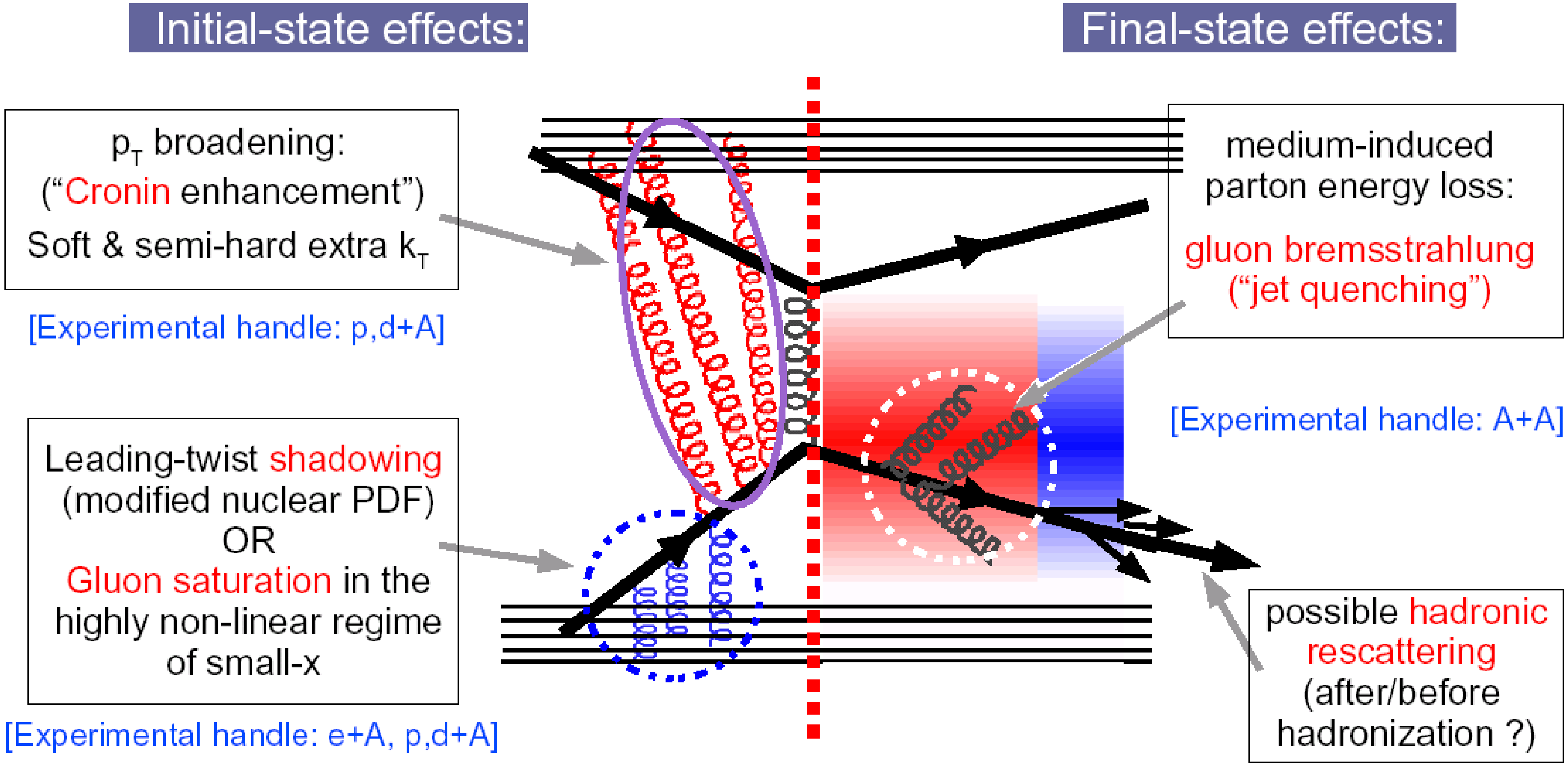
p_T cut to suppress underlying event, and background subtracted using region outside jet cone

Yellow bands represent uncertainties from background subtraction

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

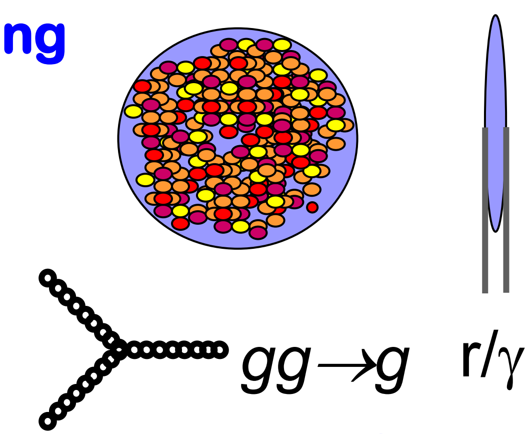
26

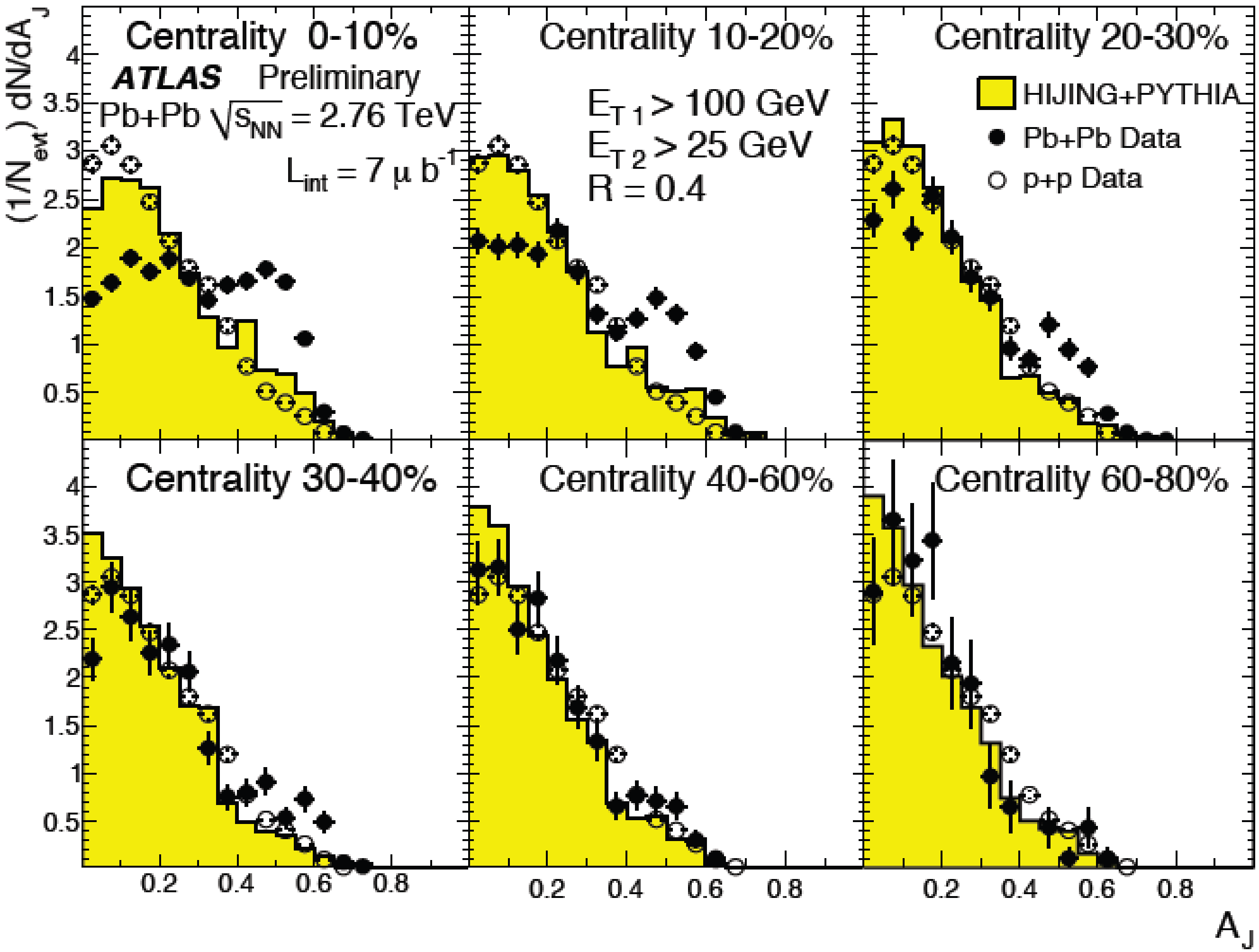
- Not modified!
- Need to be more quantitative to really understand differences from RHIC.



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

probe rest frame



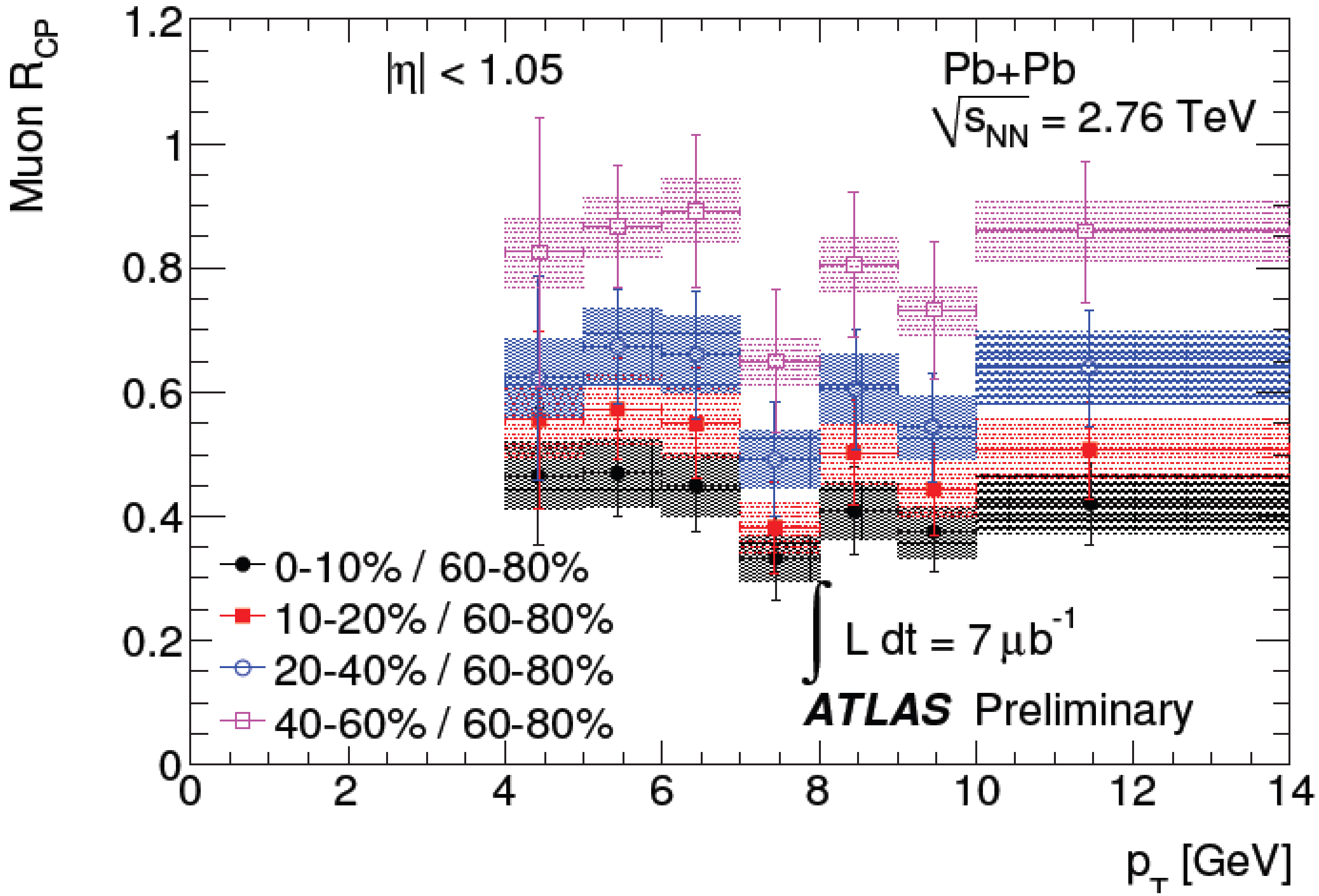


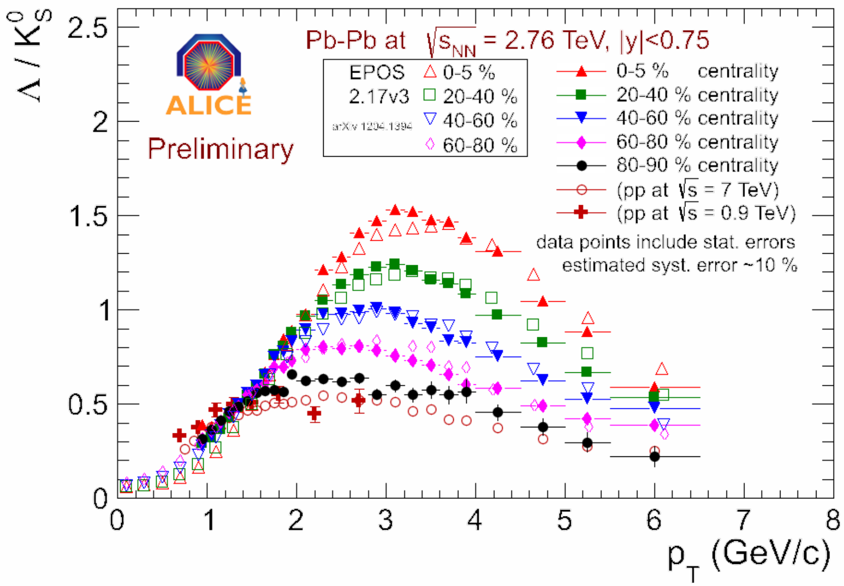
$$A_J = \frac{E_T^1 - E_T^2}{E_T^1 + E_T^2}$$

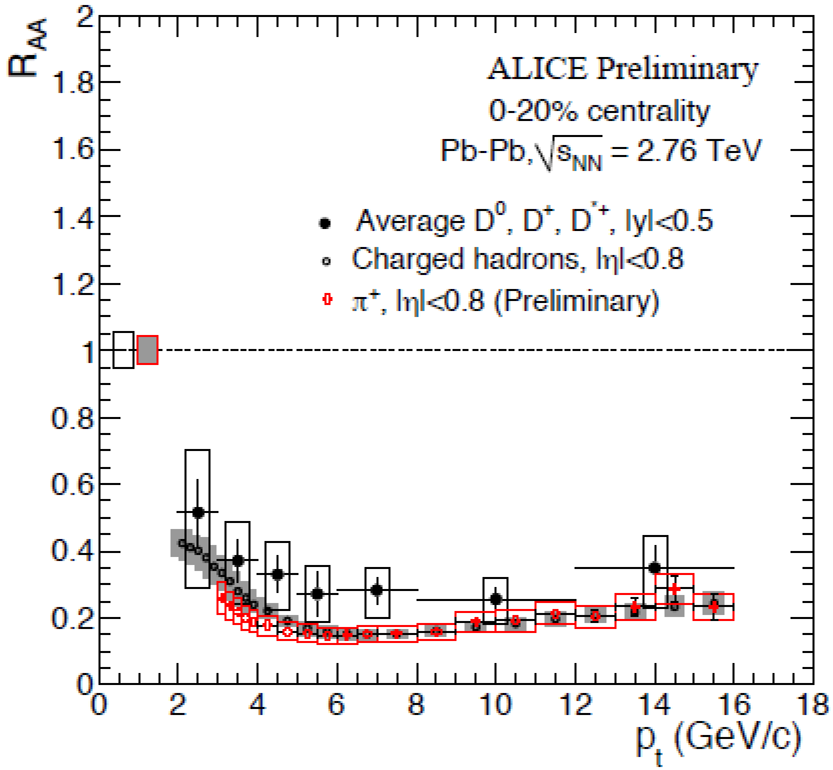
$$E_{T\,1} > 100\ GeV$$

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

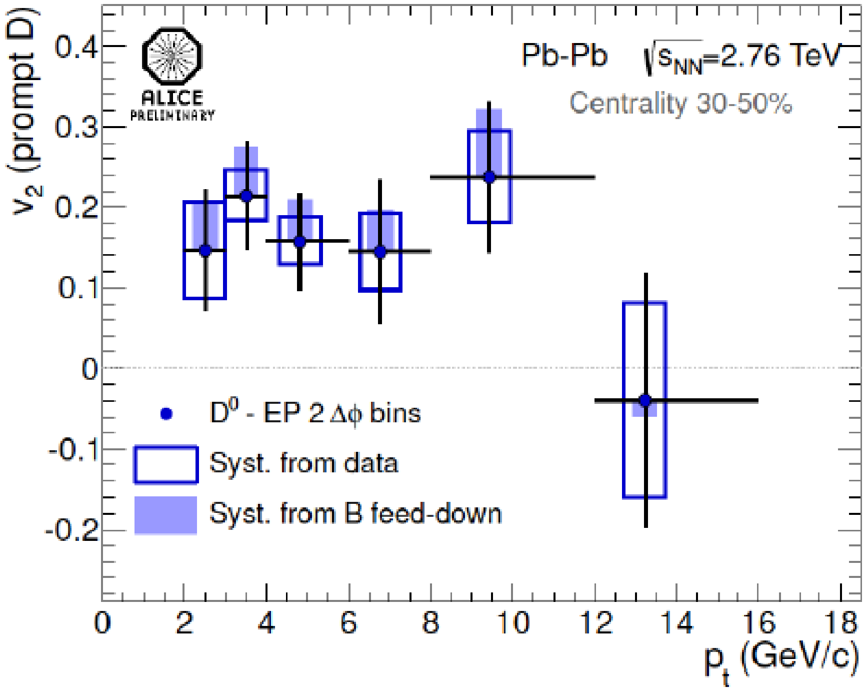
Updated from published result


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
0
2
4
6
8
10
12
14

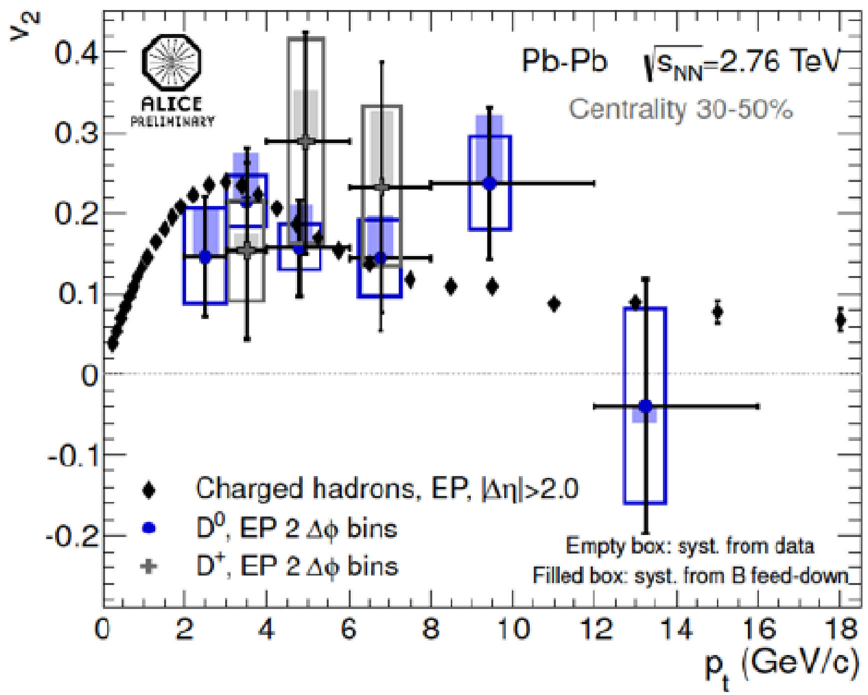

Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 TeV, |y|<0.75
ALICE
Preliminary
EPOS 2.17v3
arXiv:1204.1394
0-5 %
20-40 %
40-60 %
60-80 %
0-5 % centrality
20-40 % centrality
40-60 % centrality
60-80 % centrality
80-90 % centrality
(pp at $\sqrt{s}$ = 7 TeV)
(pp at $\sqrt{s}$ = 0.9 TeV)
data points include stat. errors
estimated syst. error ~10 %
Λ / K^0_S
p_T (GeV/c)



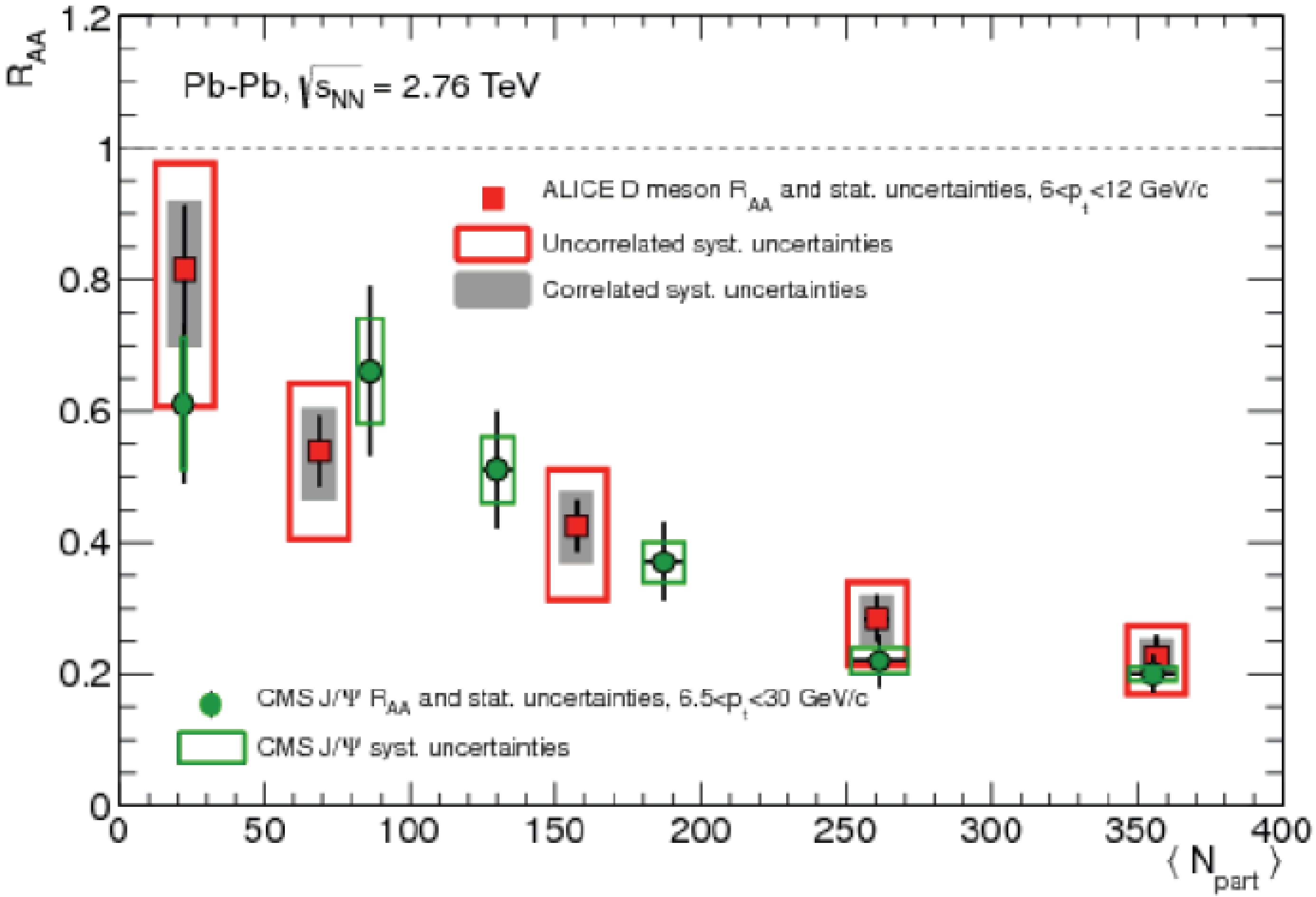
ALICE Preliminary
0-20% centrality
Pb-Pb,$\sqrt{s_{NN}}$ = 2.76 TeV
Average D^0, D^+, D^{*+}, |y|<0.5
Charged hadrons, |η|<0.8
π^+, |η|<0.8 (Preliminary)
R_{AA}
p_t (GeV/c)

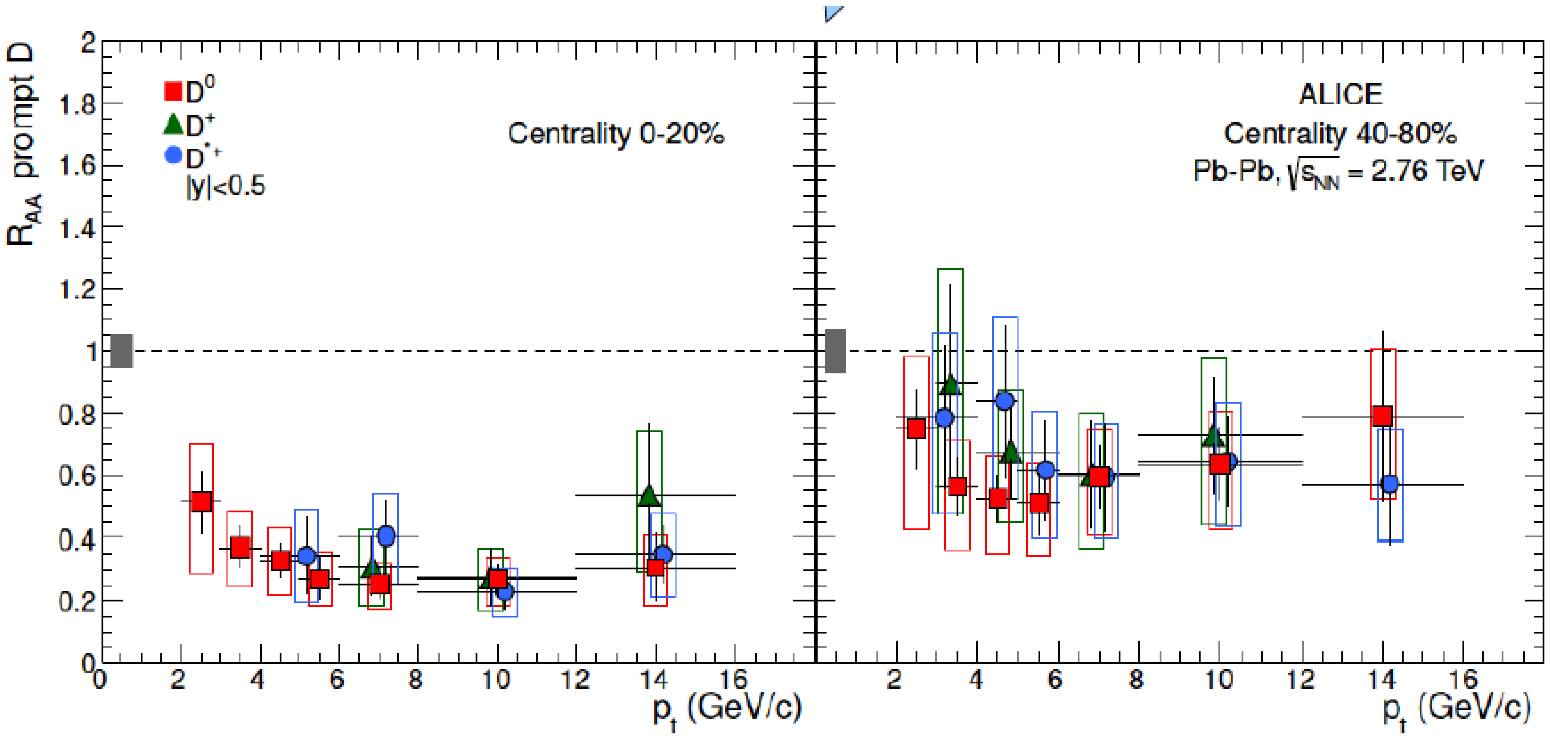


ALICE PRELIMINARY
Pb-Pb $\sqrt{s_{NN}}$=2.76 TeV
Centrality 30-50%
v_2 (prompt D)
D^0 - EP 2 $\Delta\phi$ bins
Syst. from data
Syst. from B feed-down
p_t (GeV/c)



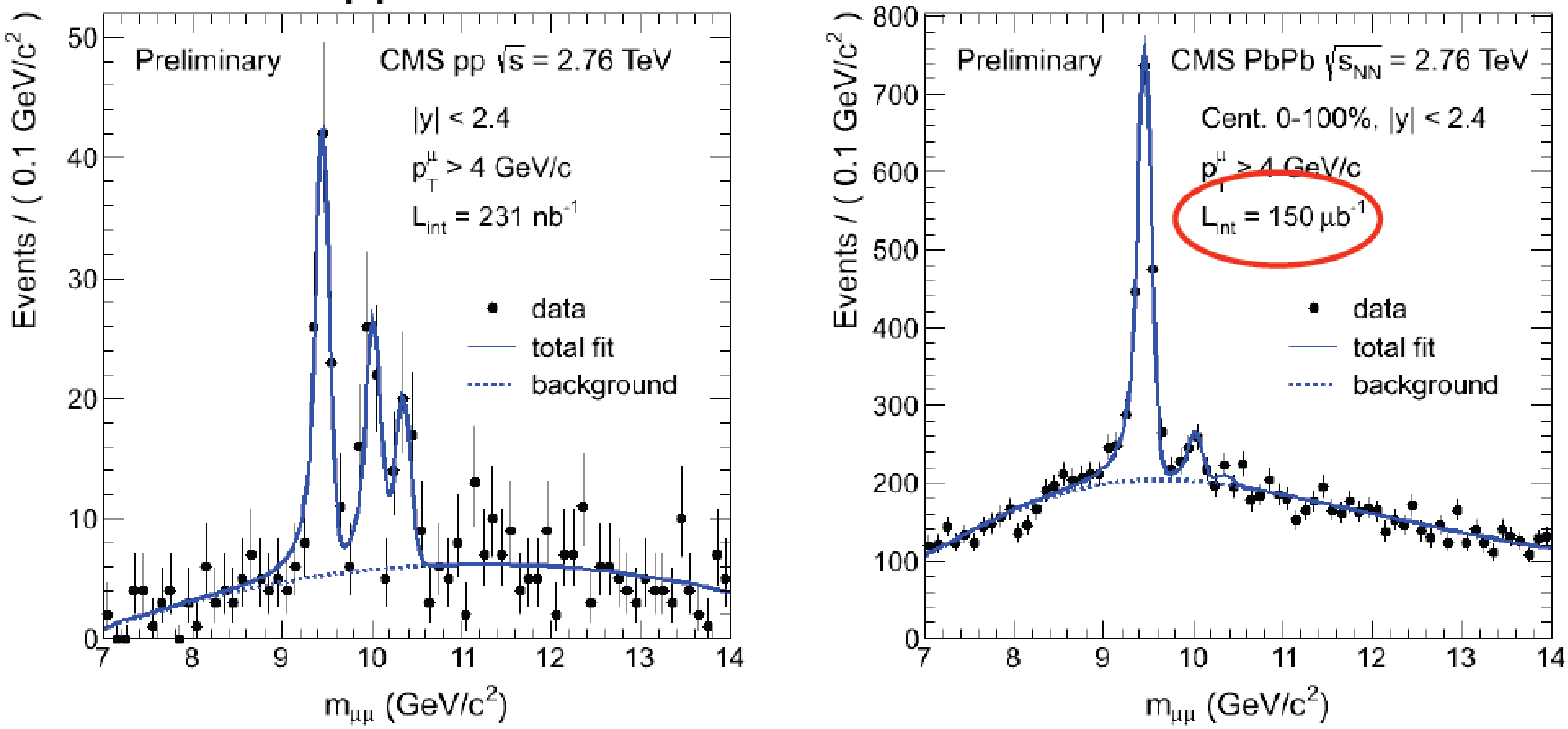
ALICE PRELIMINARY
Pb-Pb $\sqrt{s_{NN}}$=2.76 TeV
Centrality 30-50%
v_2
Charged hadrons, EP, $|\Delta\eta|$>2.0
D^0, EP 2 $\Delta\phi$ bins
D^+, EP 2 $\Delta\phi$ bins
Empty box: syst. from data
Filled box: syst. from B feed-down
p_t (GeV/c)


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

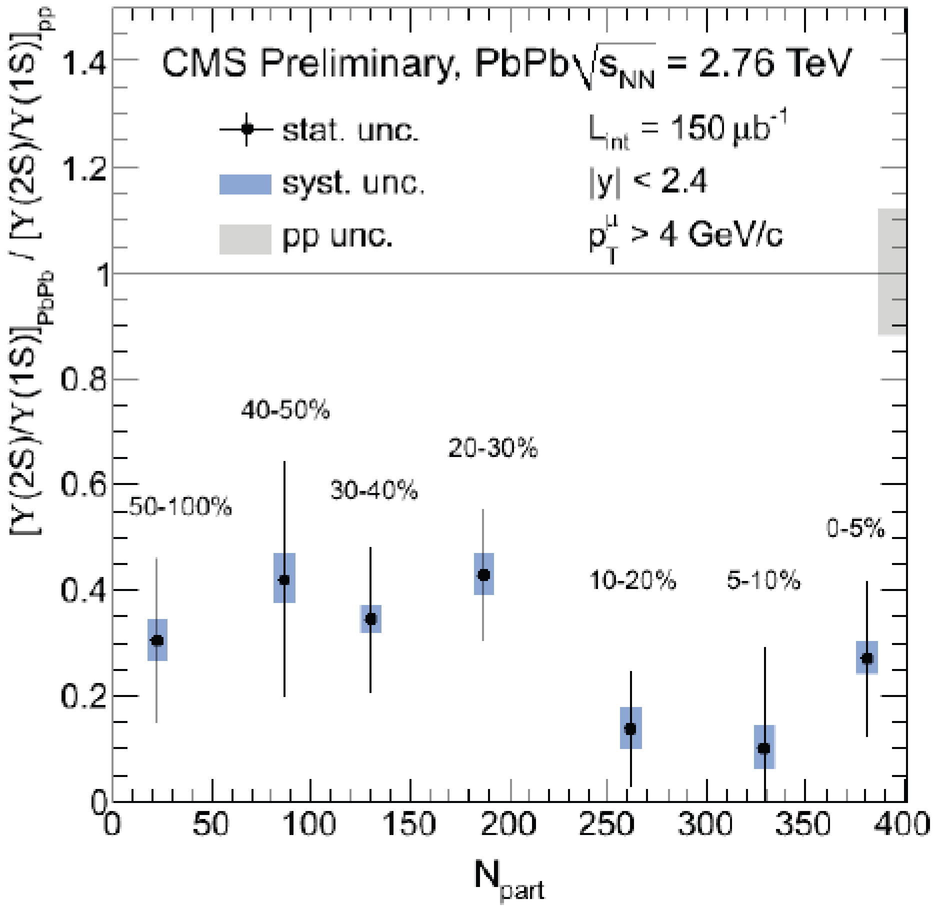


$N_{\Upsilon(2S)}/N_{\Upsilon(1S)}|_{pp} = 0.56 \pm 0.13 \pm 0.01$

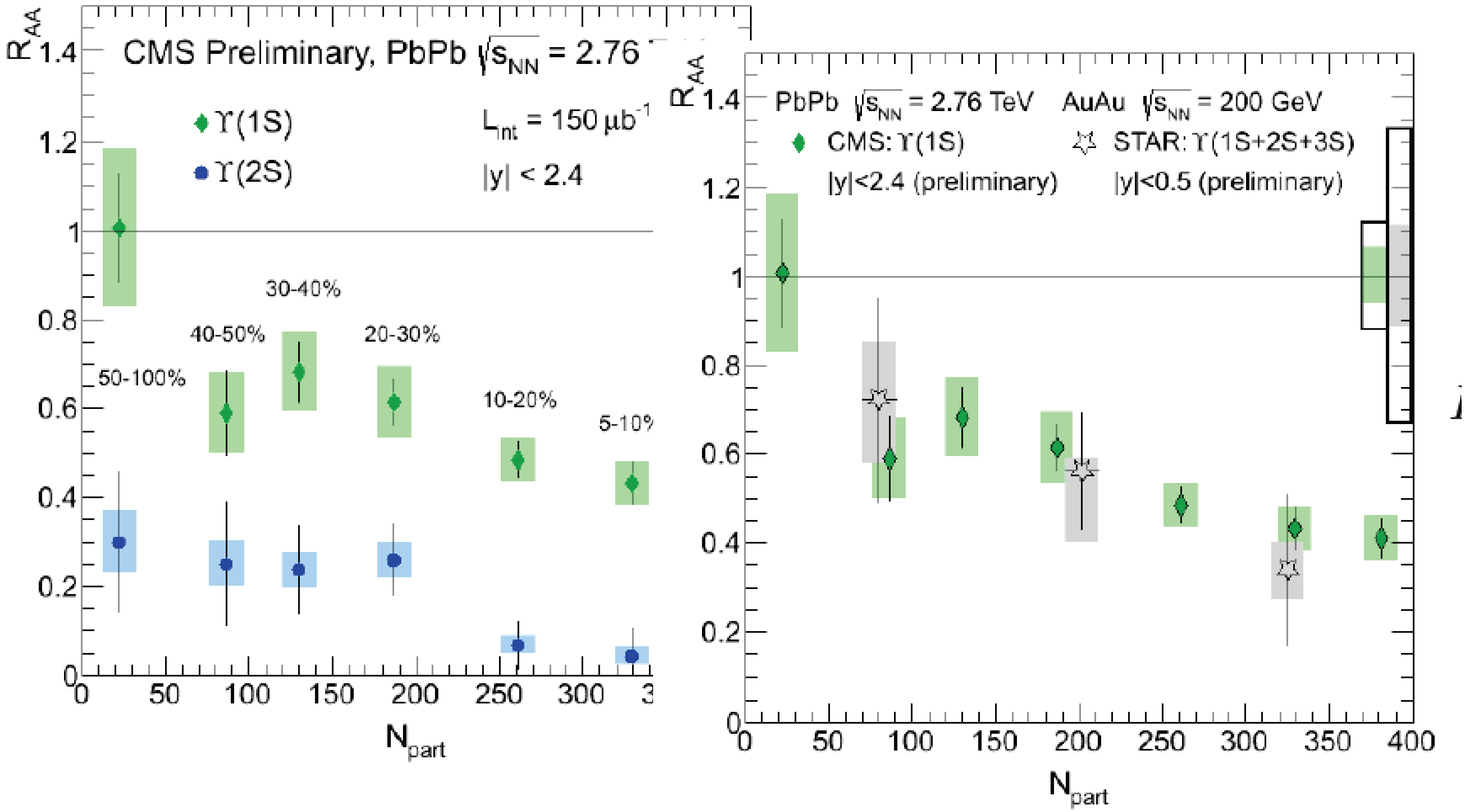
$N_{\Upsilon(3S)}/N_{\Upsilon(1S)}|_{pp} = 0.21 \pm 0.11 \pm 0.02$

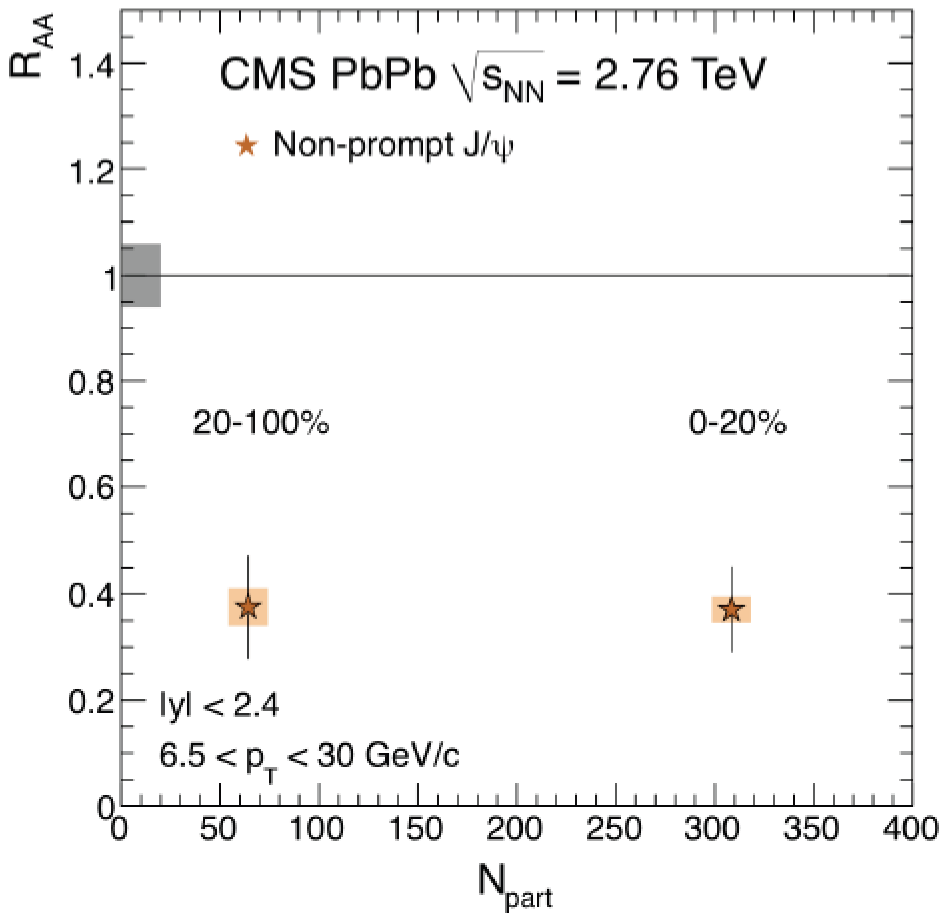
$N_{\Upsilon(2S)}/N_{\Upsilon(1S)}|_{PbPb} = 0.12 \pm 0.03 \pm 0.01$

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



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


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%
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)


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}
0
0.2
0.4
0.6
0.8
1
1.2
1.4
50
100
150
200
250
300
350
400