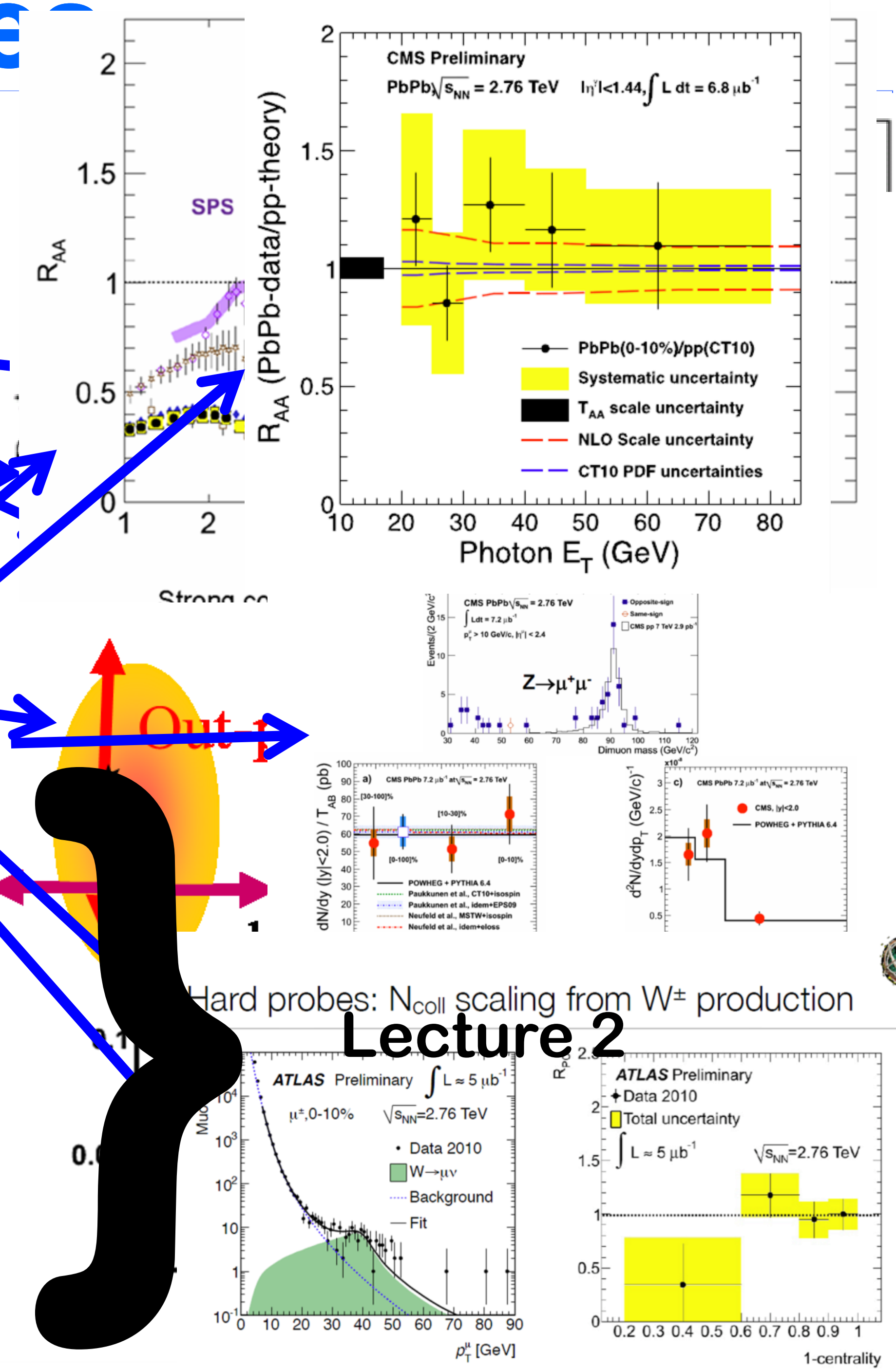
Heavy Ion Physics
Lecture 2

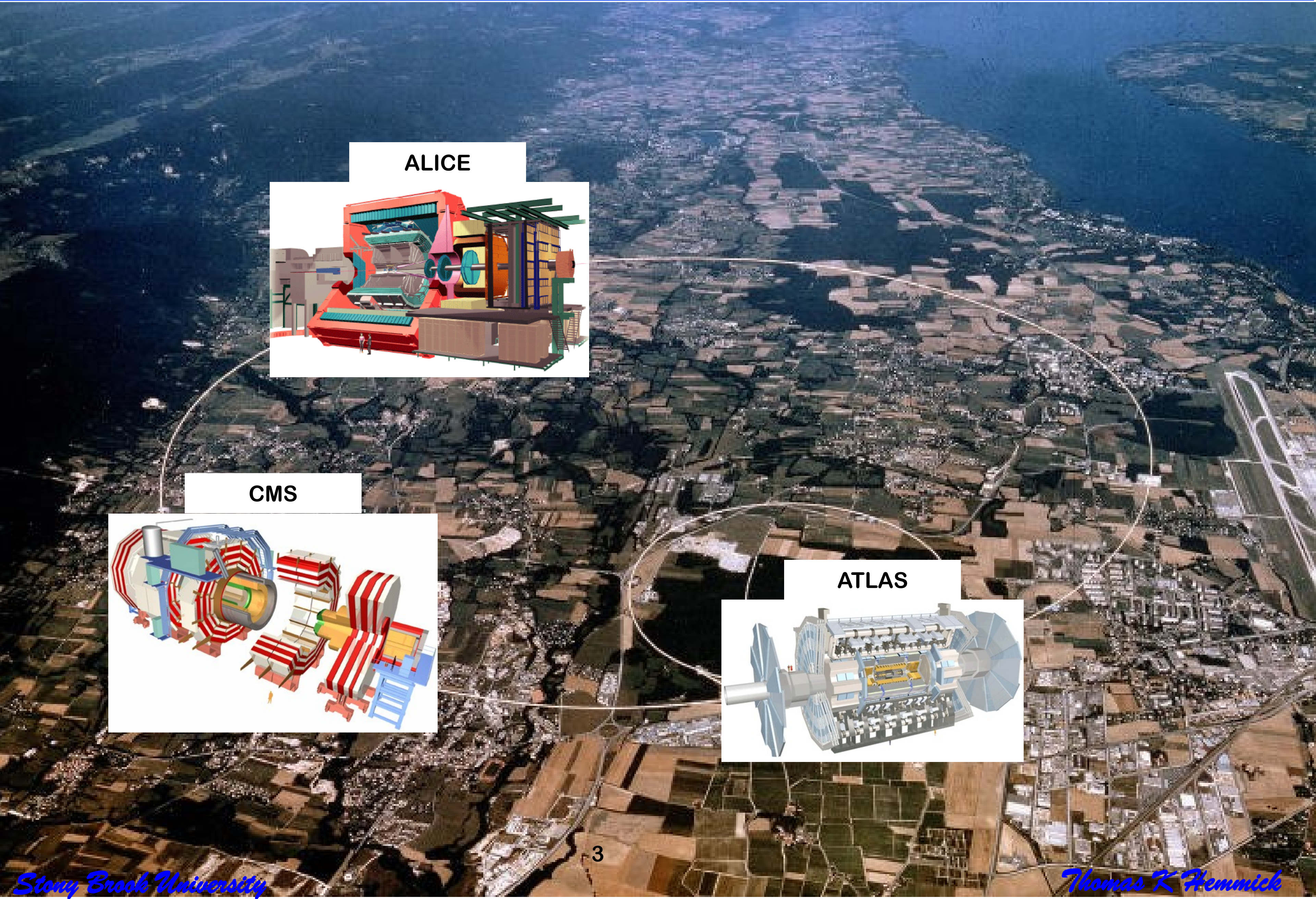
Thomas K Hemmick
Stony Brook University

Outline of Lecture

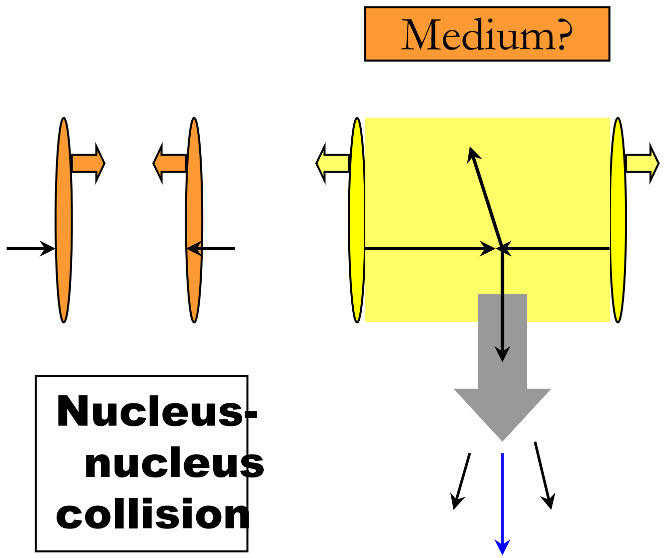
- **What have we done?**
  - ❑ **Energy Density**
  - ❑ **Initial Temperature**
  - ❑ **Chemical & Kinetic Equilibrium**
  - ❑ **System Size**
- **Is There a There There?**
  - ❑ **The Medium & The Probe**
  - ❑ **High Pt Suppression**
  - ❑ **Control Experiments: γ_{direct}, W,**
- **What is It Like?**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

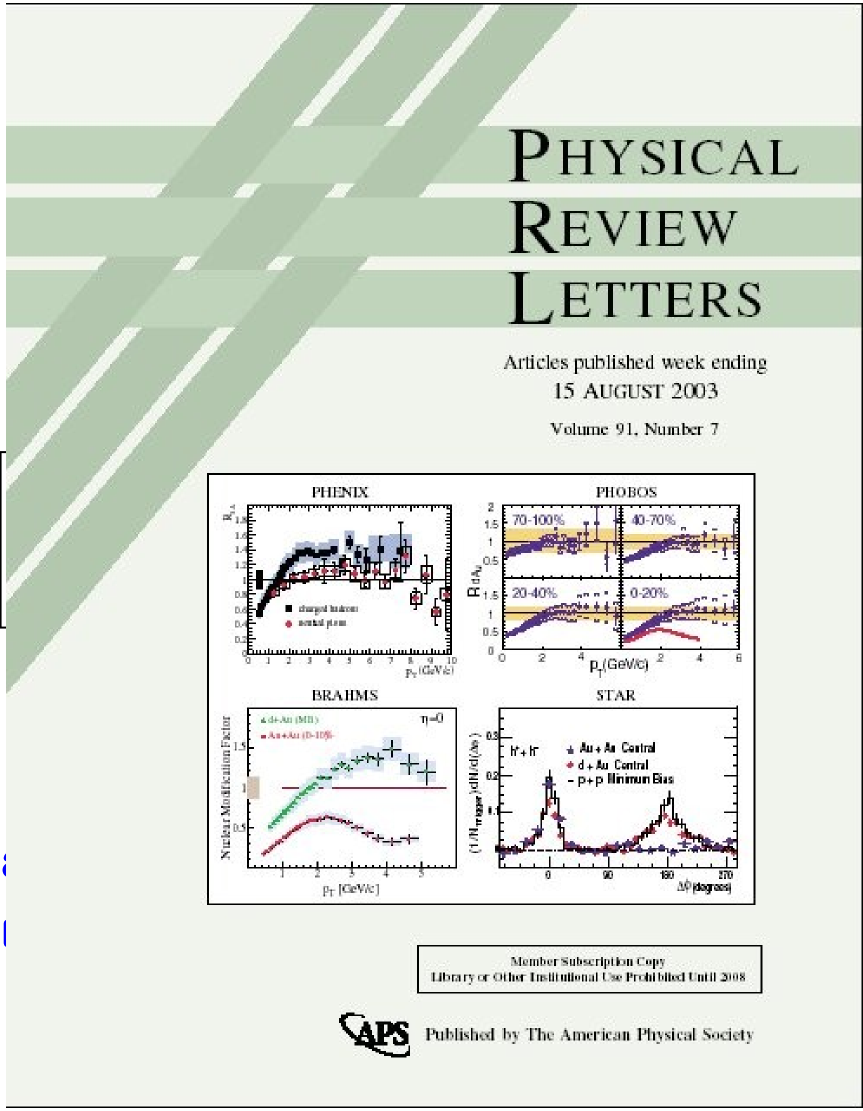


LHC Experiments



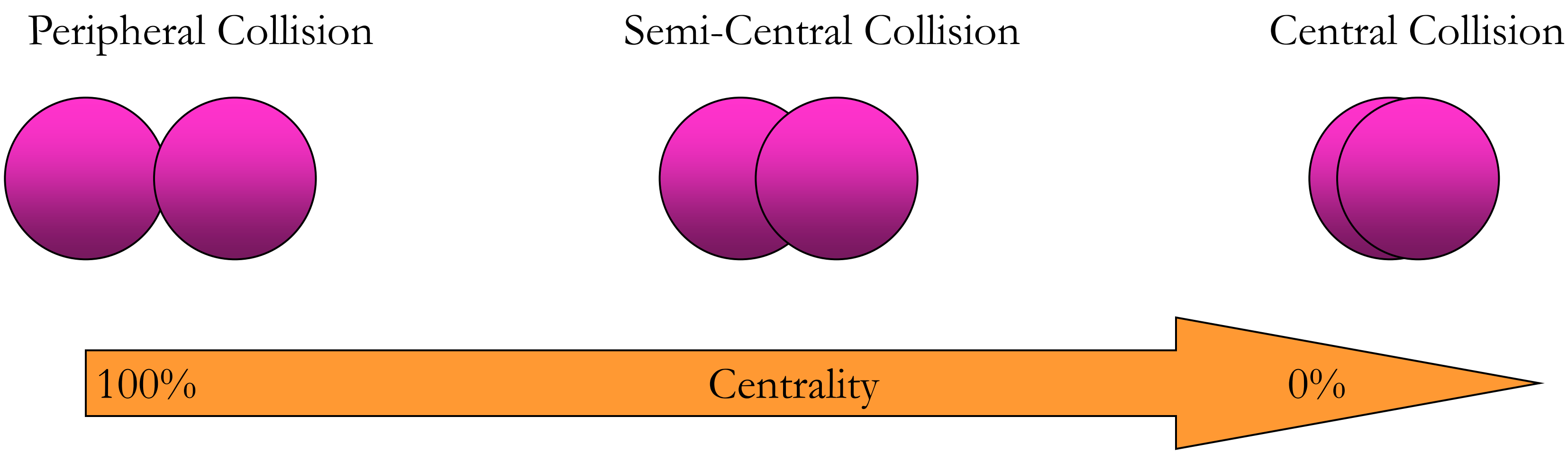
d+Au Control Experiment



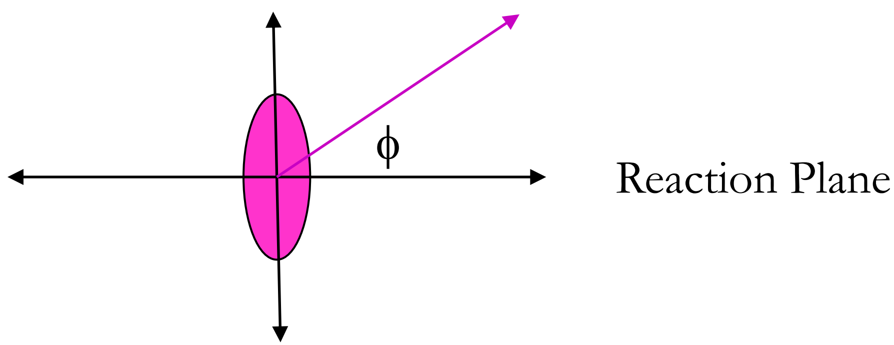


- Collisions of small with large nuclei qu
- Small + Large distinguishes all initial a

Terminology



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

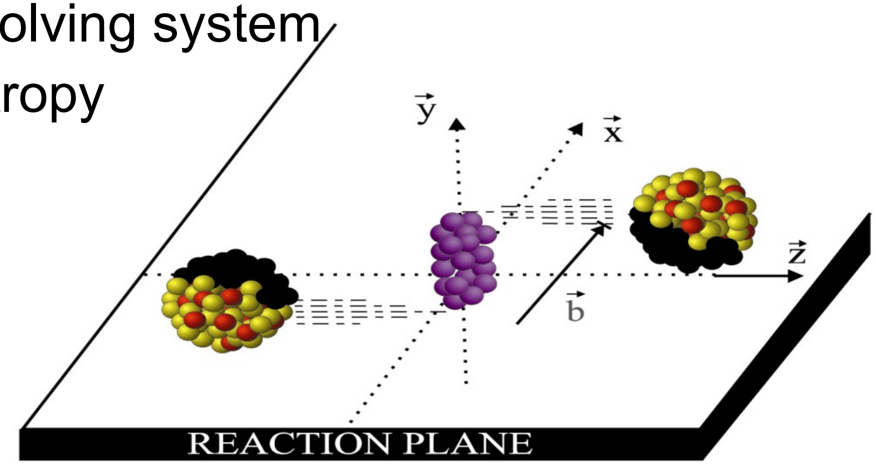


- **Fourier decompose azimuthal yield:**

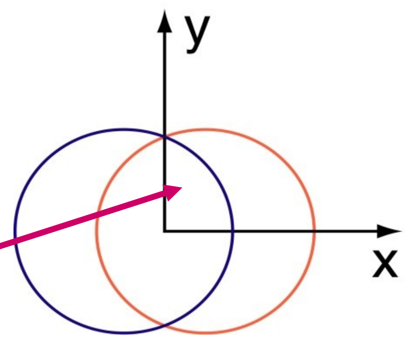
$$\frac{d^3N}{d\phi \, dp_T \, dy} \propto \left[1 + 2v_1 \cos(\phi) + 2v_2 \cos(2\phi) + \ldots\right]$$

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

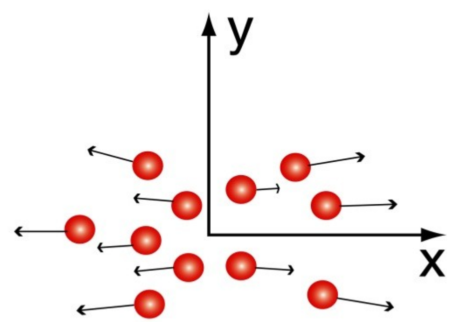


v_2: 2nd harmonic *Fourier coefficient* in azimuthal distribution of particles with respect to the reaction plane



Almond shape overlap region in coordinate space

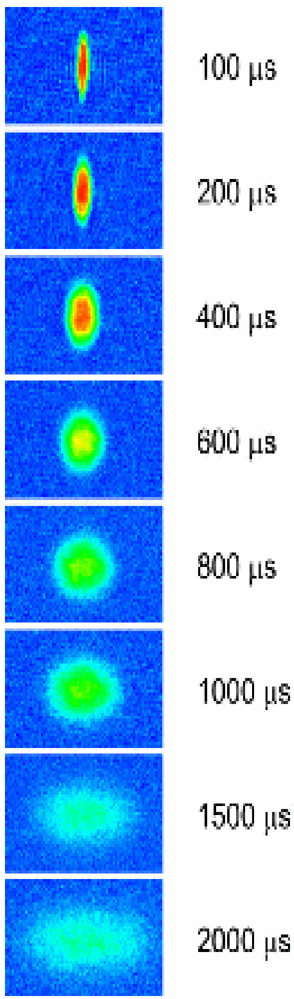
$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$



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

Anisotropic Flow

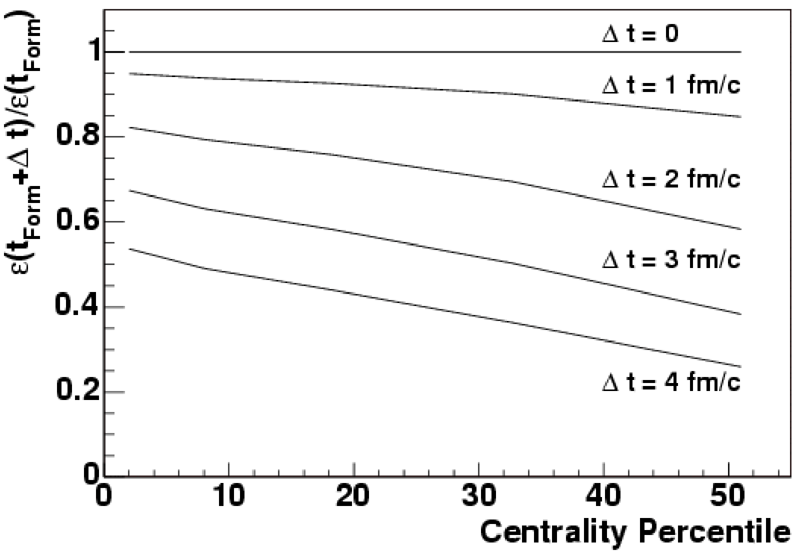
Liquid Li Explodes into Vacuum



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**

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

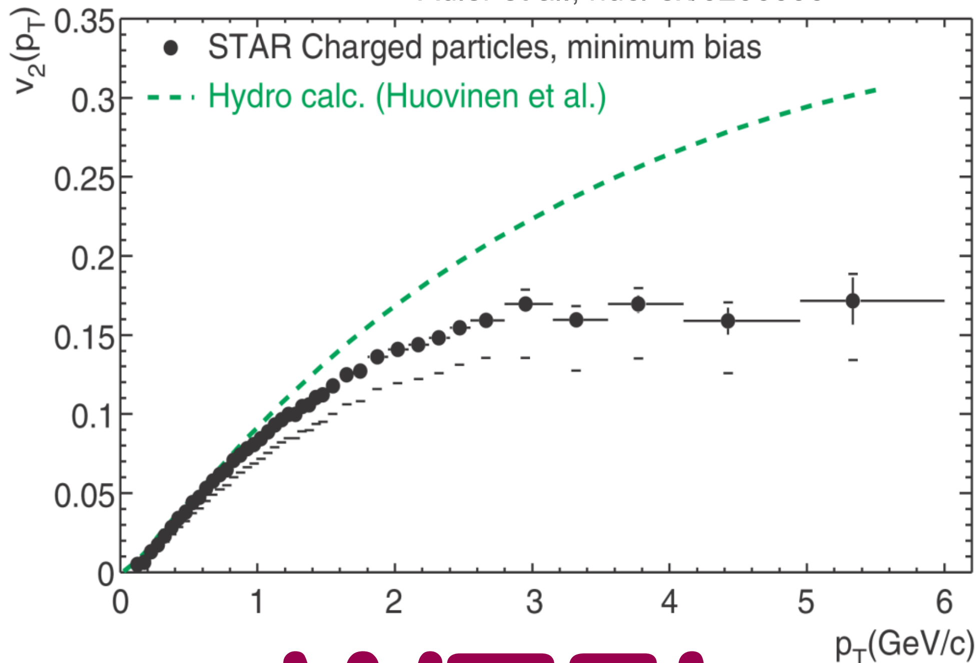
- **v_4 and higher terms are non-zero and measured but will be neglected for this discussion.**

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

Huge v_2!

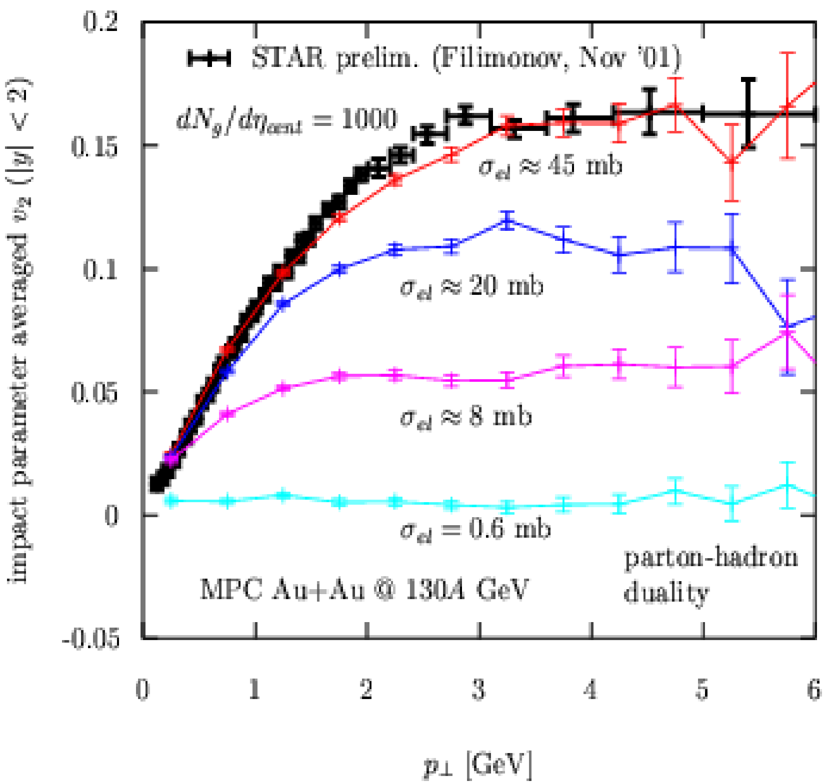
- Hydrodynamic limit exhausted at RHIC for low p_T particles.
- Can microscopic models work as well?
- Flow is sensitive to thermalization time since expanding system loses spatial asymmetry over time.
- Hydro models require thermalization in less than τ=1 fm/c

Adler et al., nucl-ex/0206006



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,**

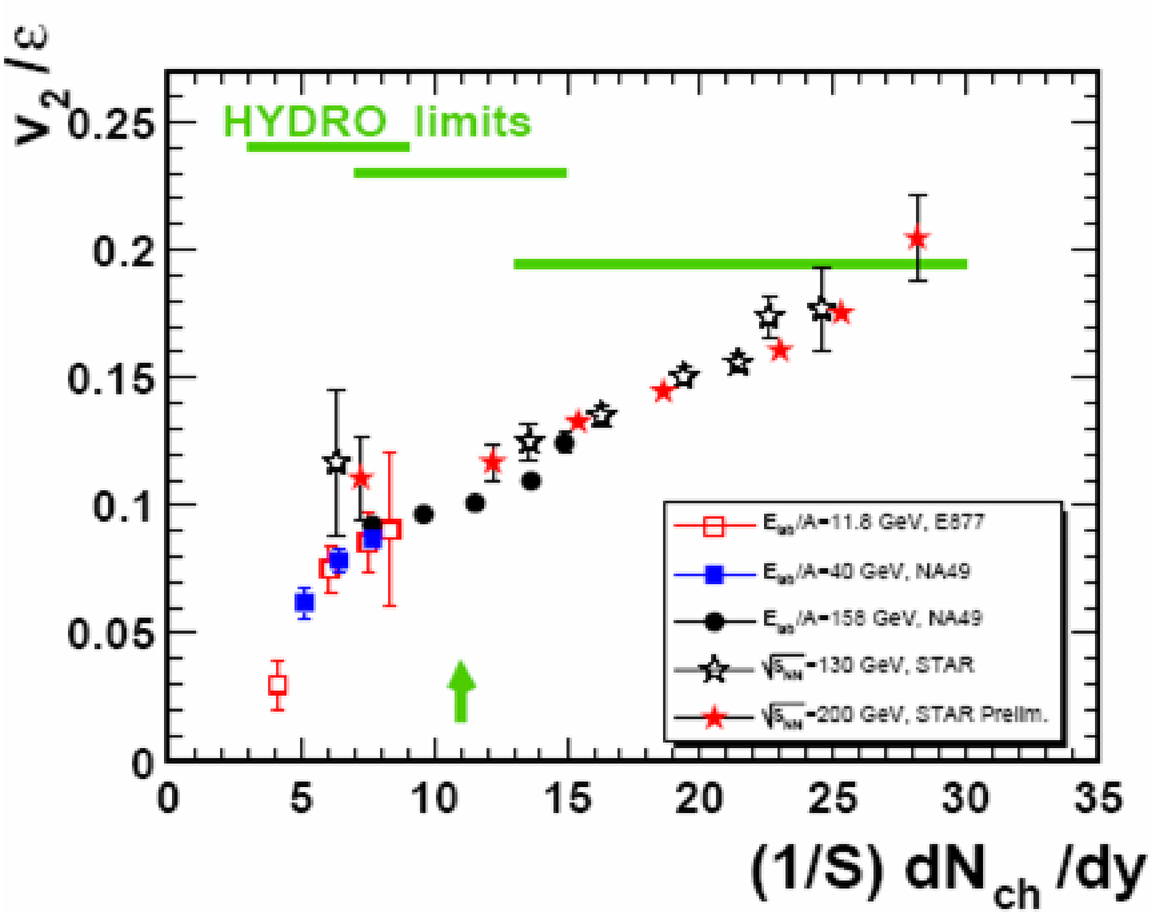
  requires large opacities $\sigma_{el} \times dN_g/d\eta \approx 45000$ mb $\gg$ pQCD (3 mb $\times 1000$)

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

if (πr^3==45 mb) {r=1.2 fm};

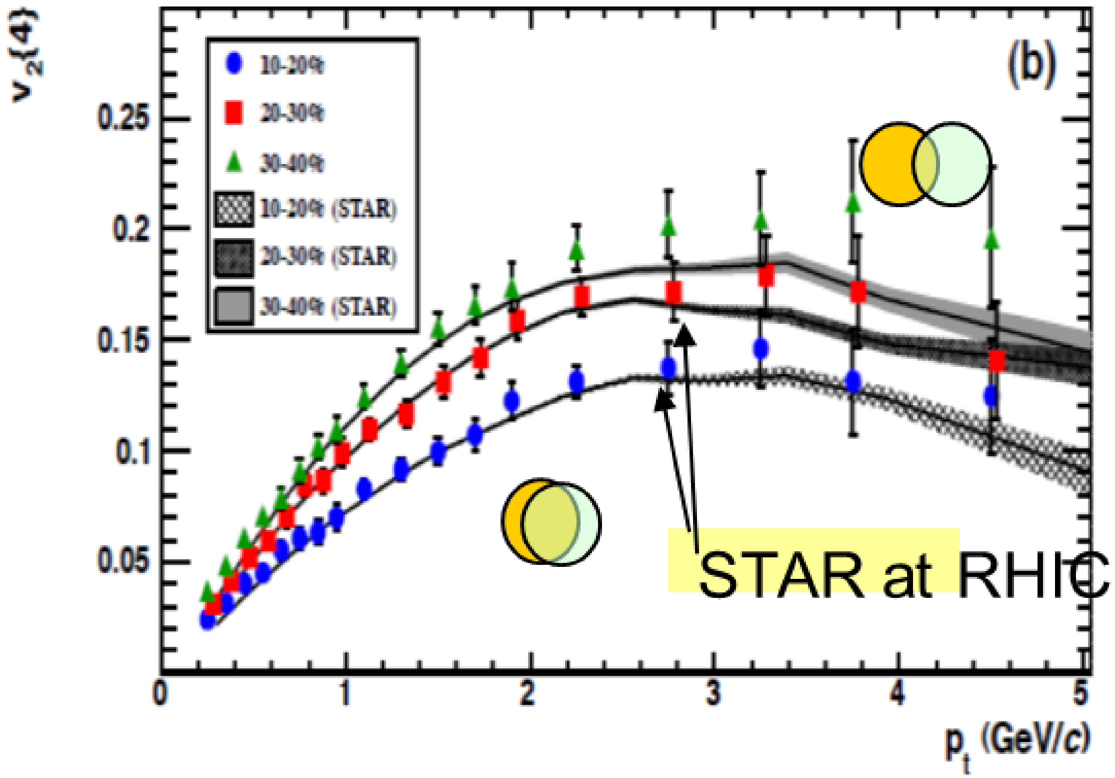
D. Molnár, SQM2003, Mar '02 – 4

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

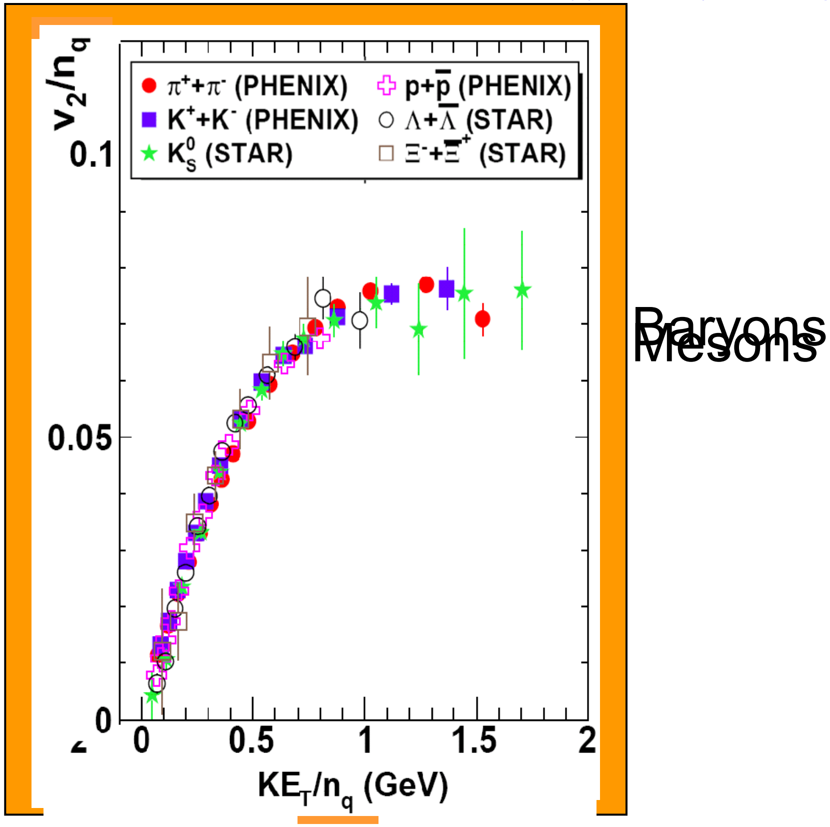


- **Magnitude of flow as a FUNCTION of p_T is nearly exactly the same as at RHIC.**
- **LHC data reach to very high moments (v_6).**

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

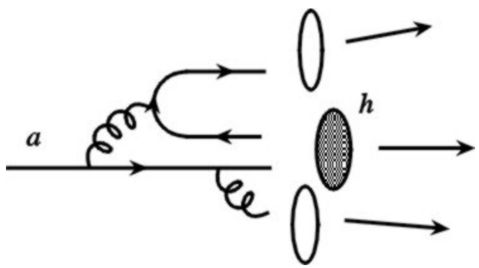


v_2 for different m_0 shows good agreement with “ideal fluid” hydrodynamics

An “ideal fluid” which knows about quarks!

Recombination Concept

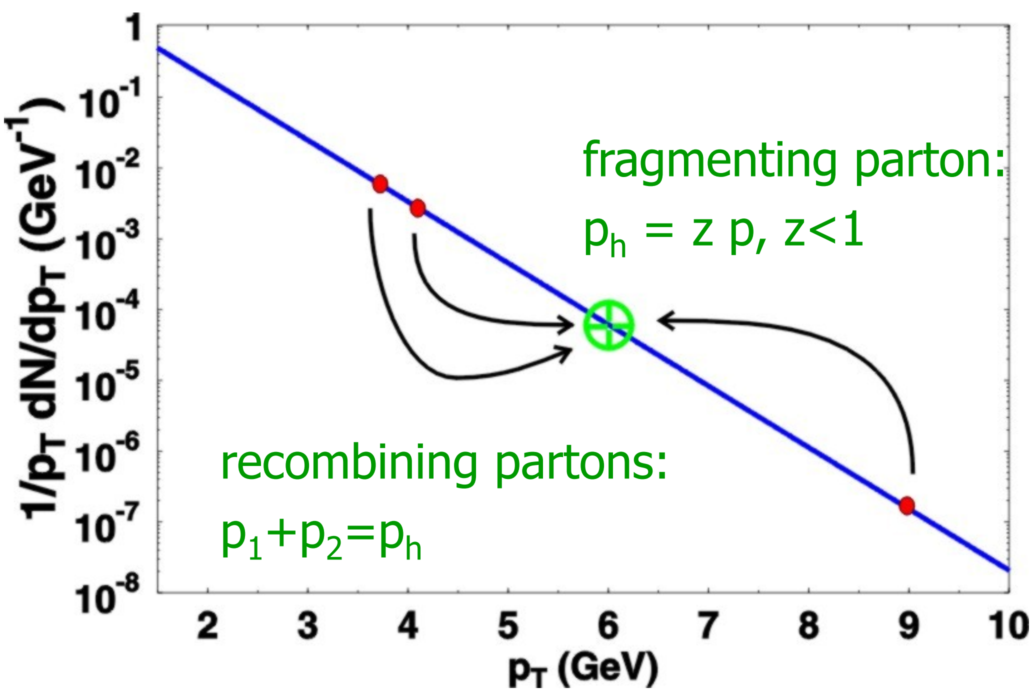
Fragmentation:



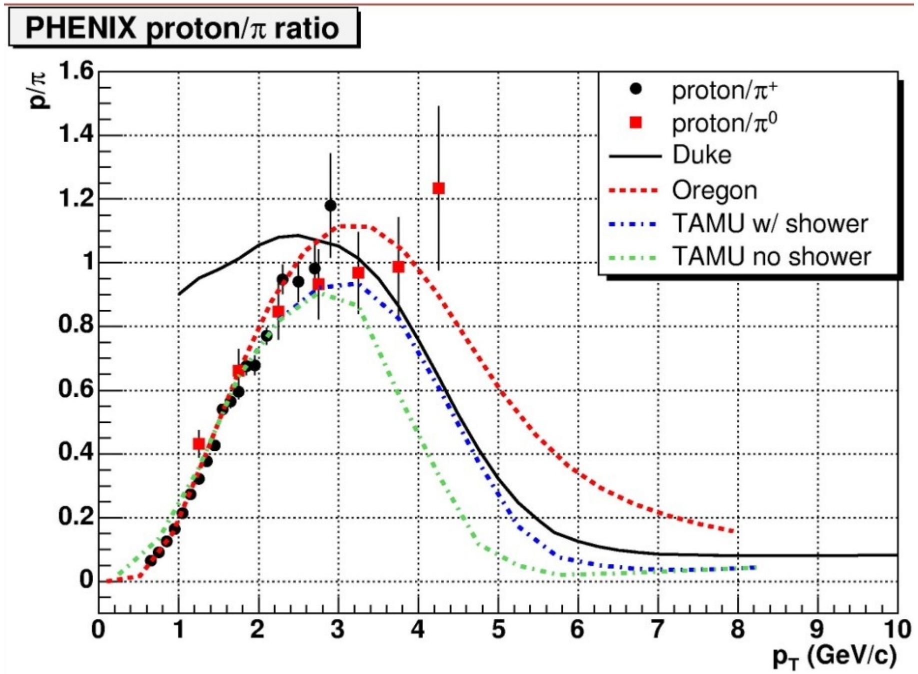
$$E\frac{dN_h}{d^3P}=\int_0^1\frac{dz}{z^2}\frac{E}{z}\frac{dN_a}{d^3(P/z)}D_{\alpha\to h}(z)$$

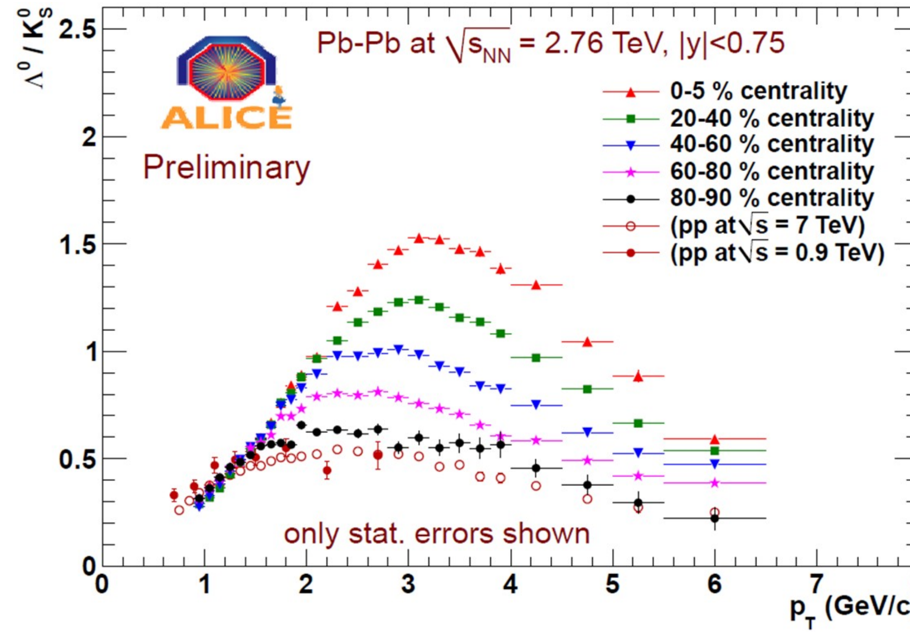
- for exponential parton spectrum, recombination is more effective than fragmentation
- baryons are shifted to higher p_t than mesons, for same quark distribution

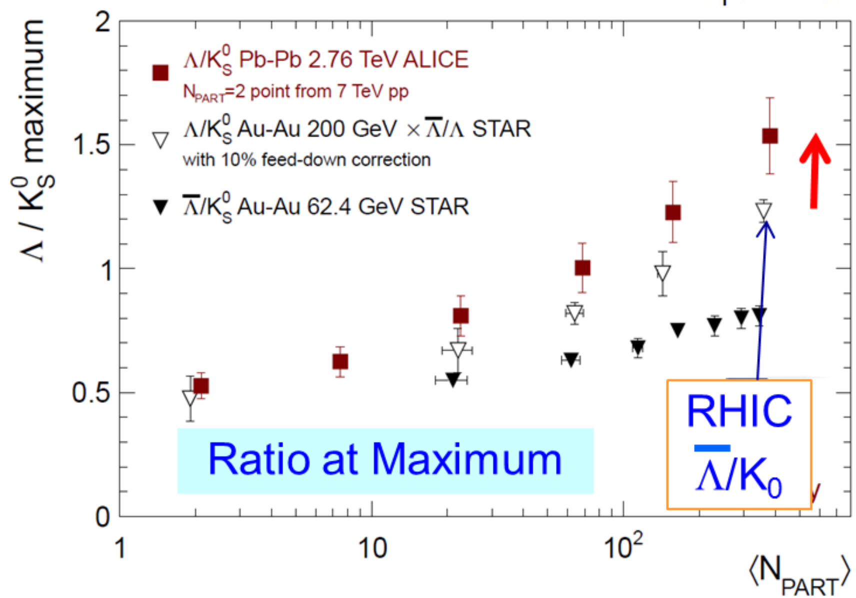
➢ understand behavior of protons!



Baryon Anomaly





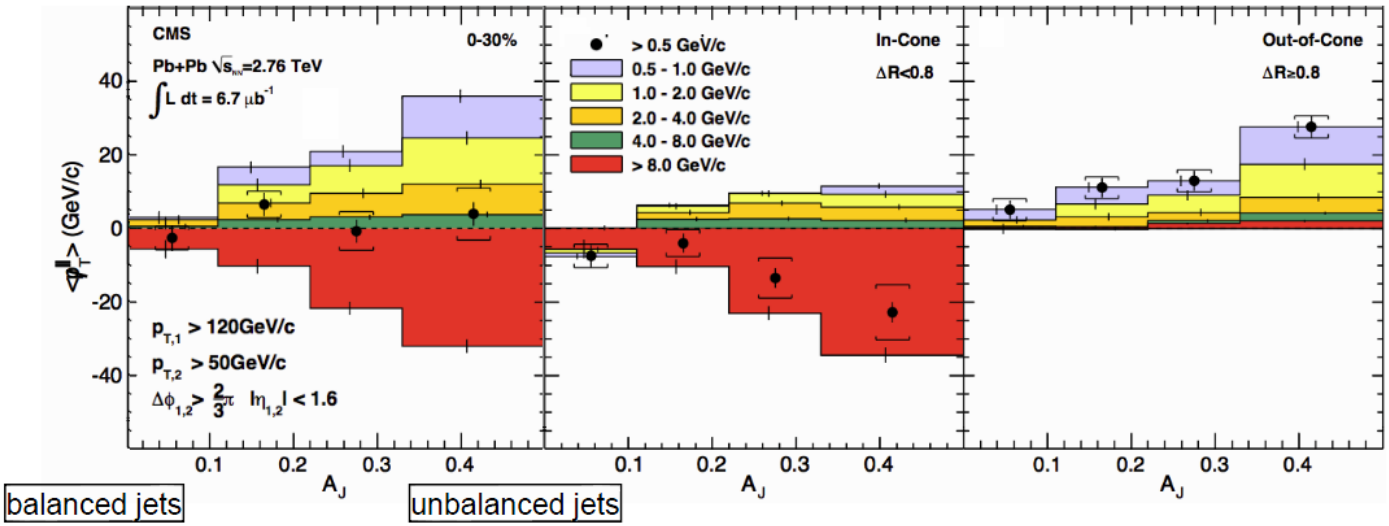


- Recombination models assume particles are formed by the coalescence of “constituent” quarks.
- Explain baryon excess by simple counting of valence quark content.

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



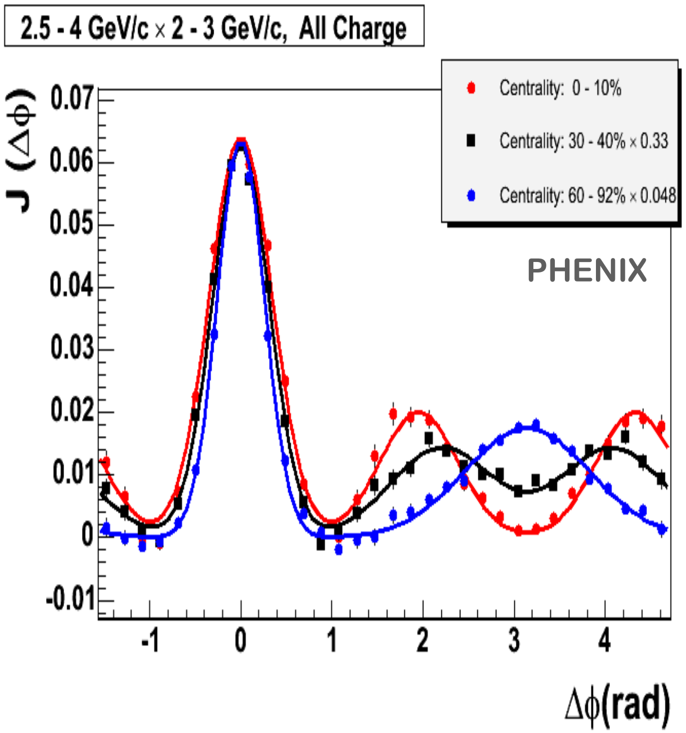
Low p_T, full acceptance
Momentum is balanced

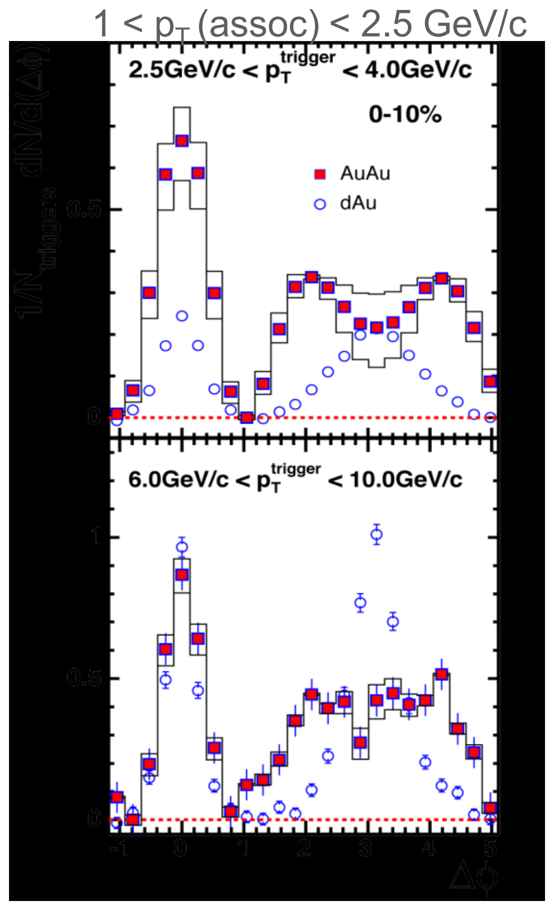
In-cone large momentum imbalance at high p_T
Consistent with calorimetry

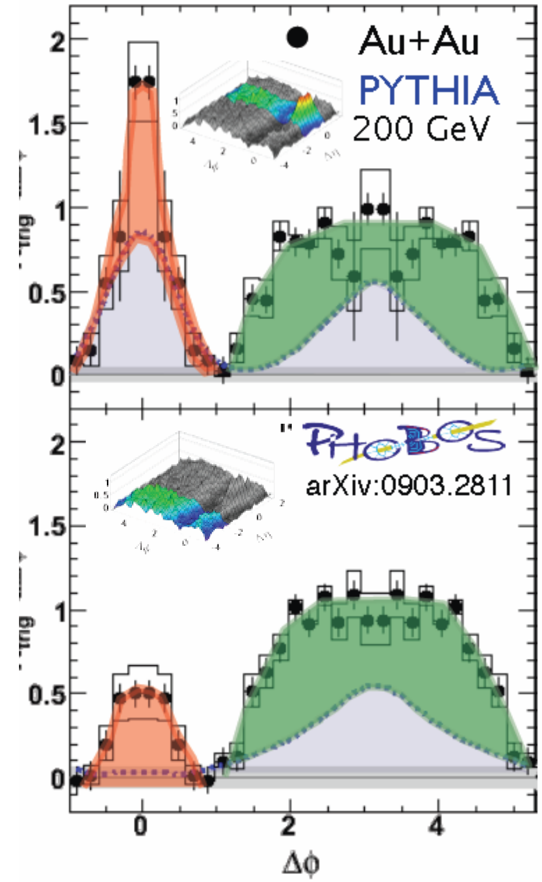
Out-off-cone low p_T particles balance the complete event

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

Away Jet cannot “Disappear”





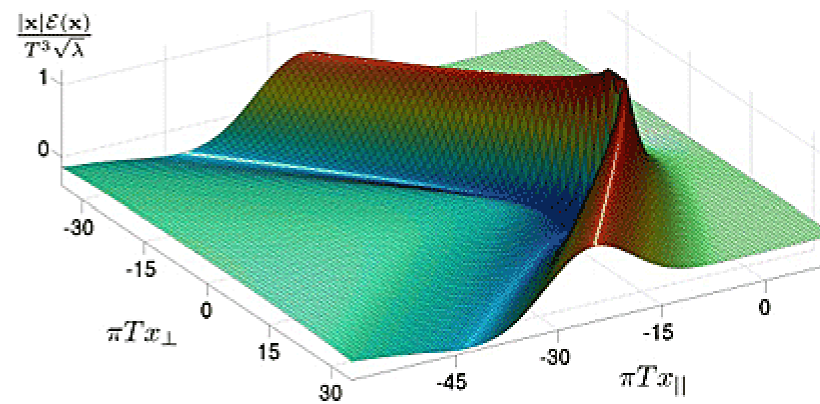


- **Energy conservation says “lost” jet must be found.**
- **“Loss” was seen for partner momenta just below the trigger particle…Search low in momentum for the remnants.**

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

Emergence of a Volcano Shape

"split" of away side jet!



Calculated from AdS/CFT Duality

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)**

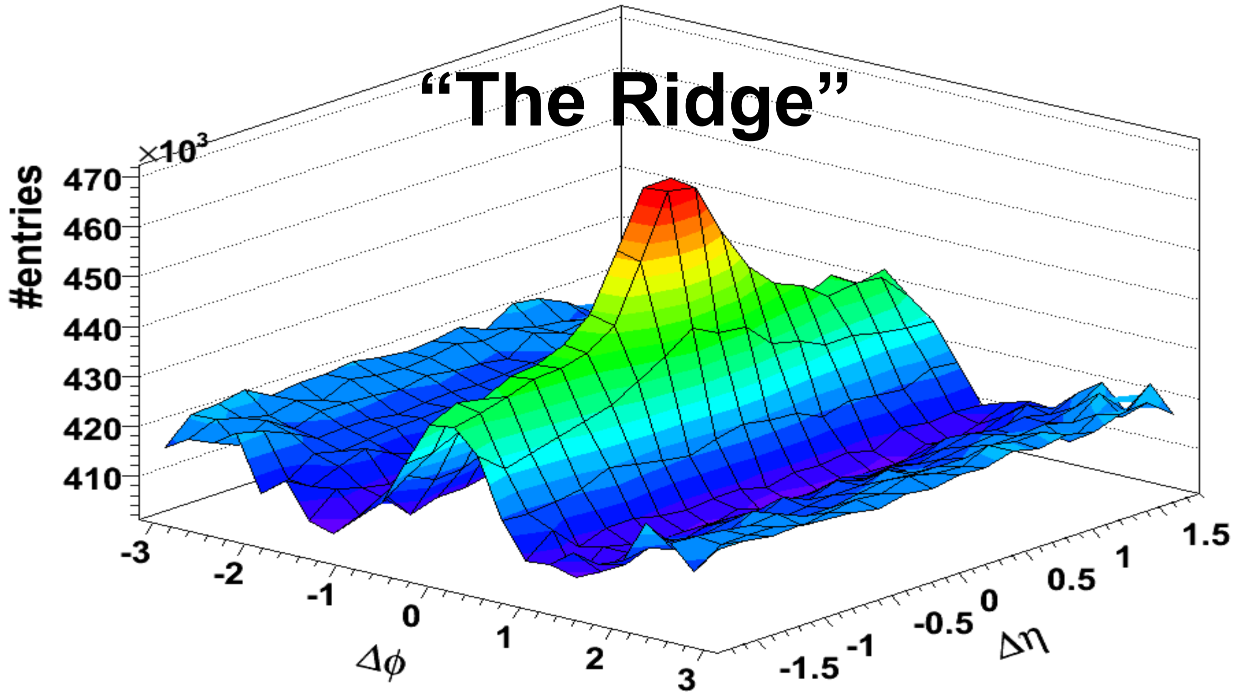
⇕

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

⇓ thermal

⇓ thermal due to the Hawking radiation

Another Exotic Structure: Ridge

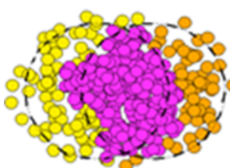


Is this bulk response to stimulus…long range flux tubes…v_3?

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

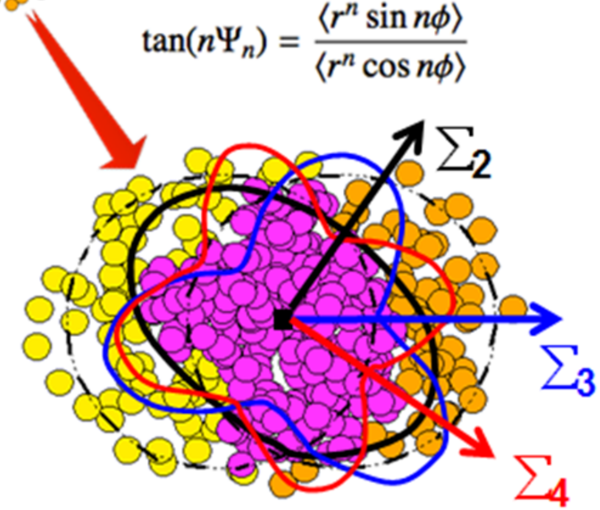
Ridge and Cone = v_3???

- 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.

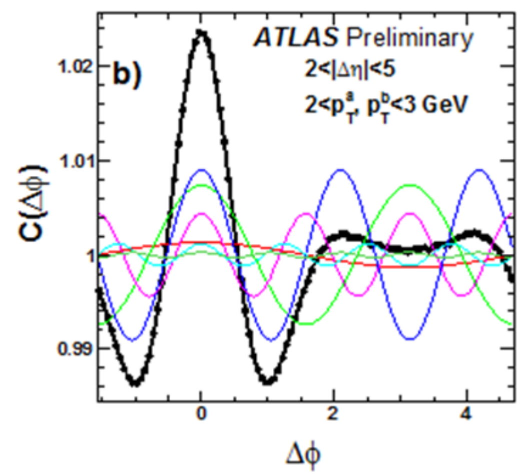


$$\epsilon_n = \sqrt{\frac{\langle r^n \cos n\phi \rangle + \langle r^n \sin n\phi \rangle}{\langle r^n \rangle}}$$

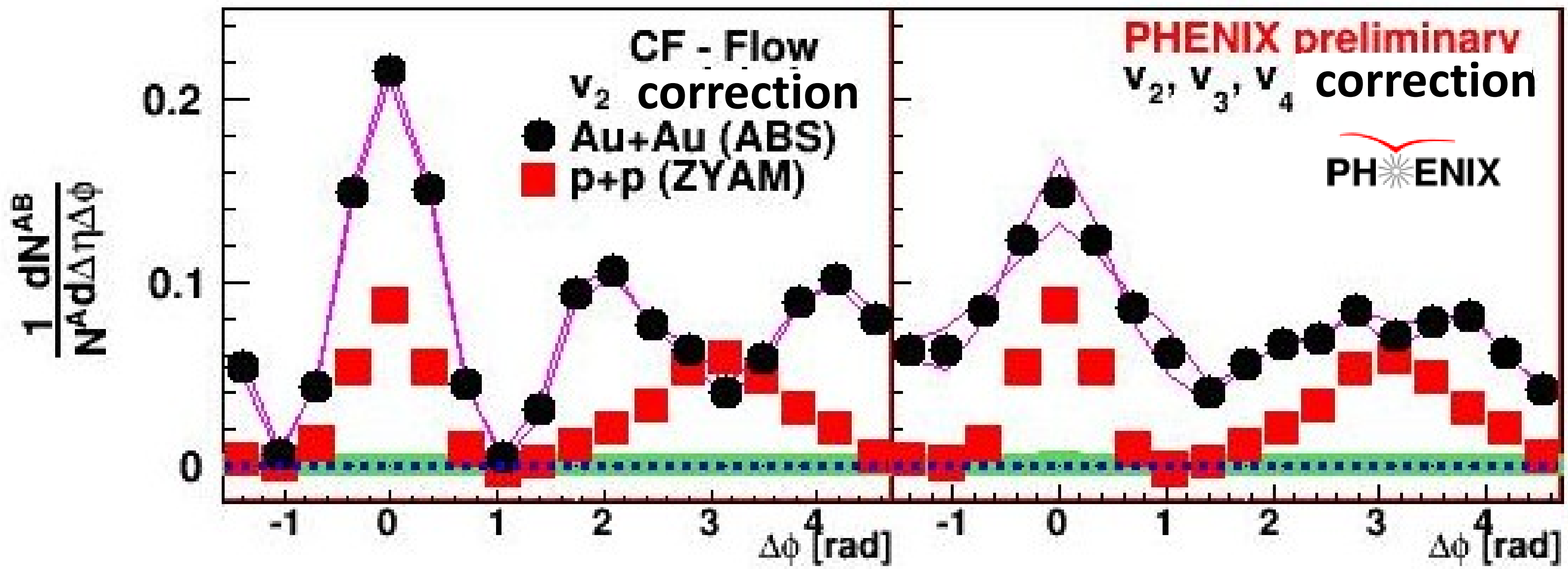
$$\tan(n\Psi_n) = \frac{\langle r^n \sin n\phi \rangle}{\langle r^n \cos n\phi \rangle}$$



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

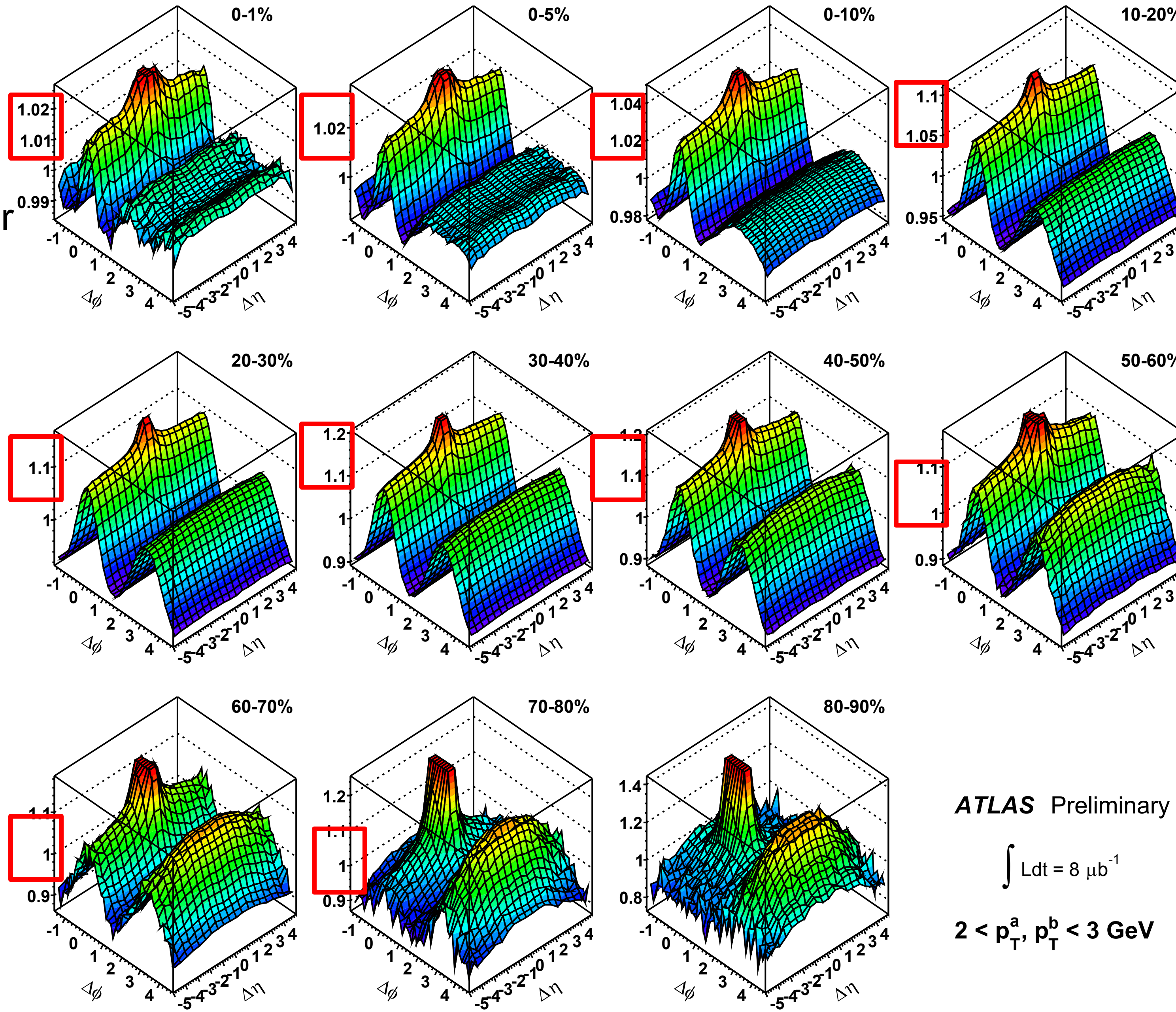


- v_2 correction only
  - double-hump
- v_2, v_3, v_4 correction
  - double-hump disappeared
  - Peak still broadened

Plenary: S. Esumi, Tue
Parallel: R. Lacey (v3, jet shape) Mon

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

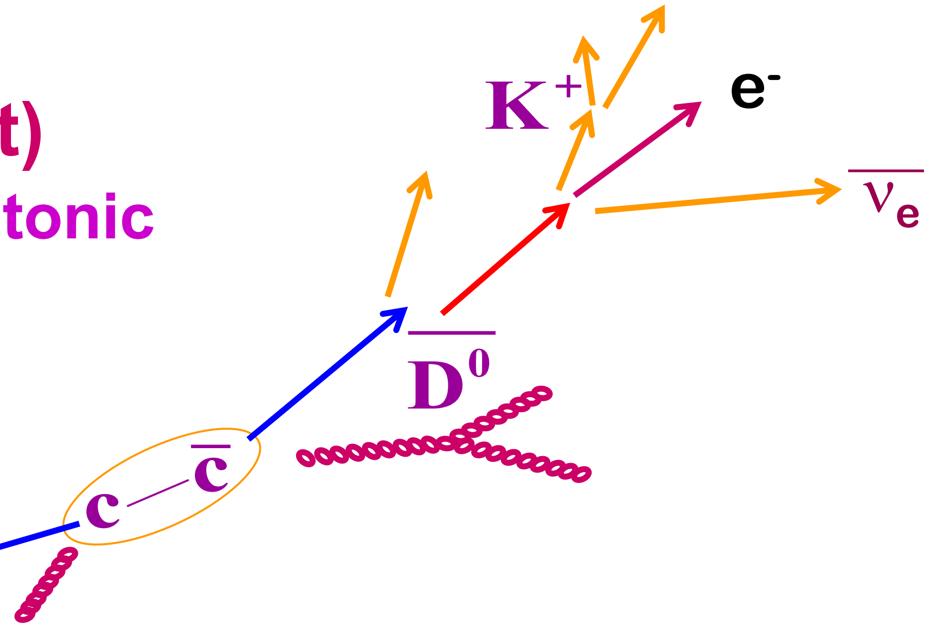


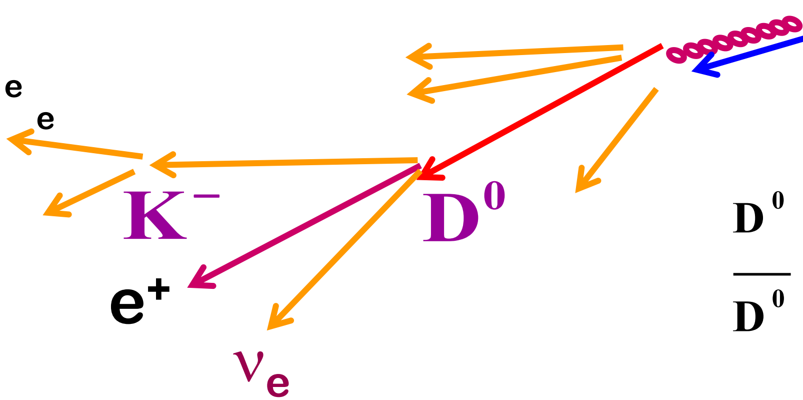
Strength of soft component increase and then decrease

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

How can charm (bottom) be measured?

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



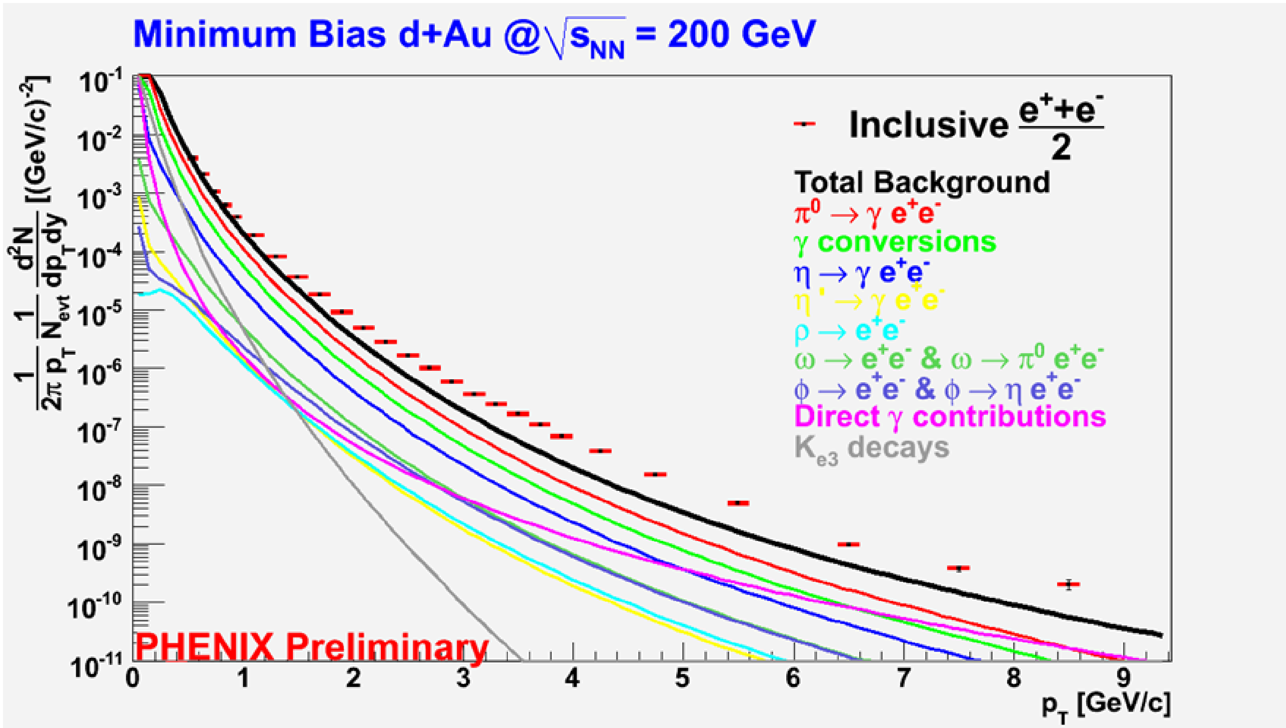


$D^0 \to K^- \ell$

$\bar{D}^0 \to K^+ \ell$

$$\begin{cases} D^0\bar{D}^0 \to e^+e^-K^+K^-\nu_e\bar{\nu}_e \\ D^0\bar{D}^0 \to e^-\mu^+K^+K^-\bar{\nu}_e\nu_\mu \\ D^0\bar{D}^0 \to \mu^+\mu^-K^+K^-\nu_\mu\bar{\nu}_\mu \end{cases}$$

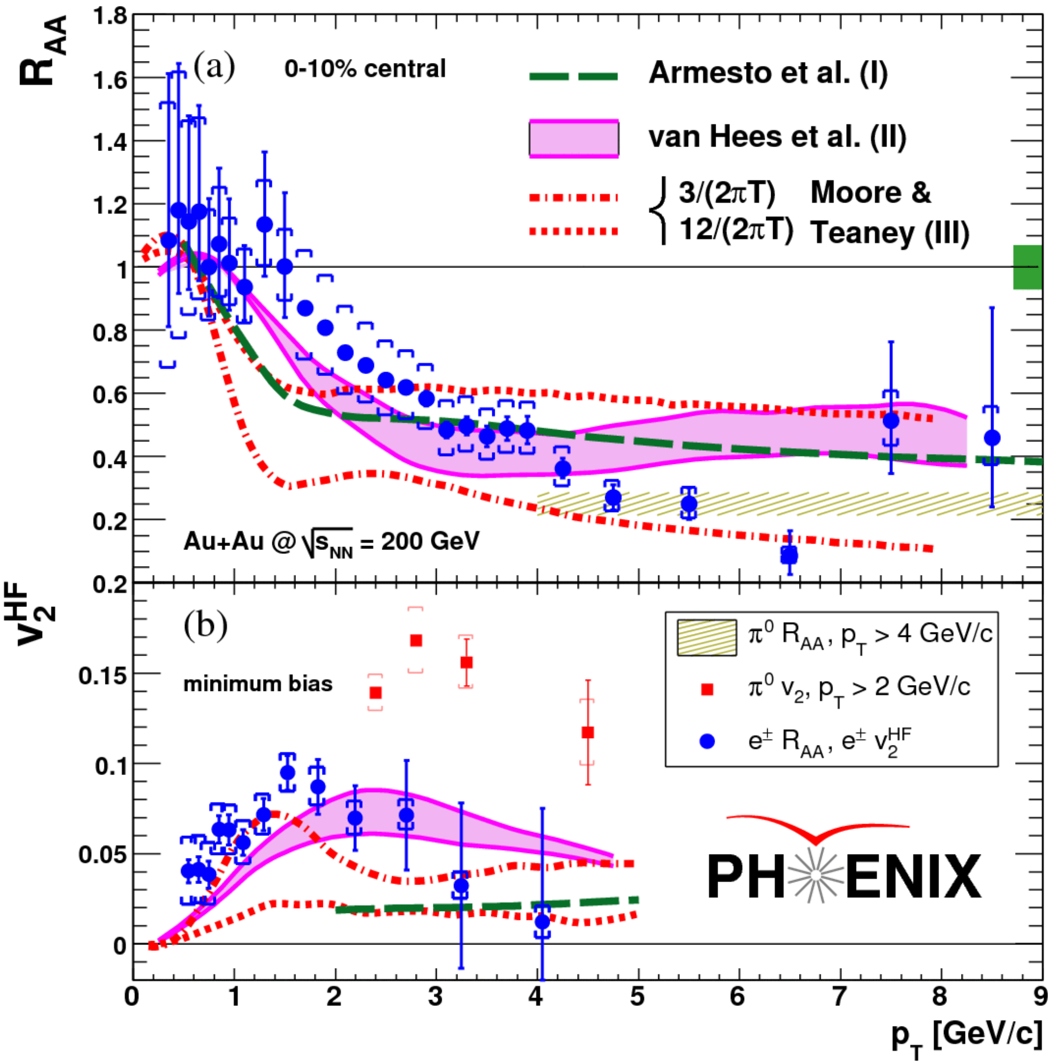
Inferred Heavy Flavor



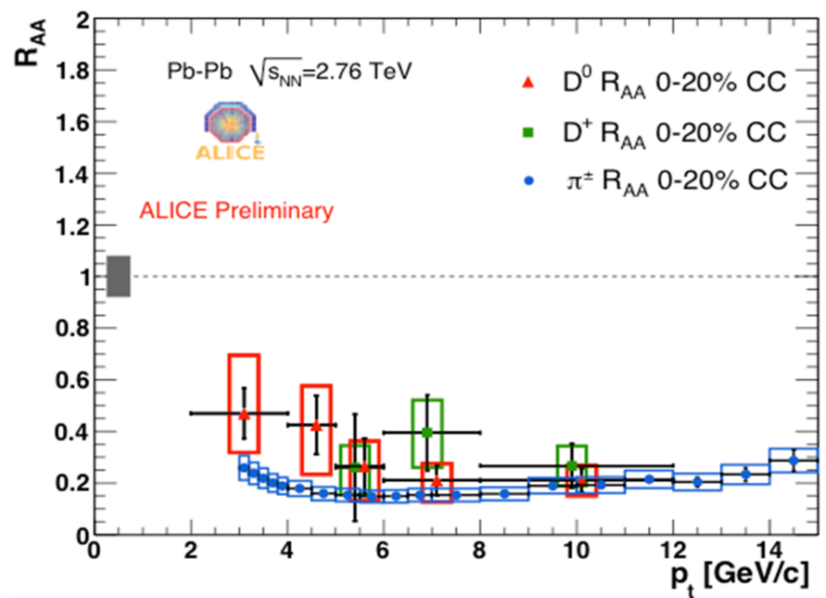
- **Measurement inclusive $e^{\pm}$.**
- **Measure π^0, η^0**
- **Construct "Cocktail" of electron sources other than c/b**
  - **light hadron decays**
  - **photon conversions**
- **Subtract $e^{\pm}$ "cocktail" leaves e from c/b.**

Hard Probes: Open Heavy Flavor

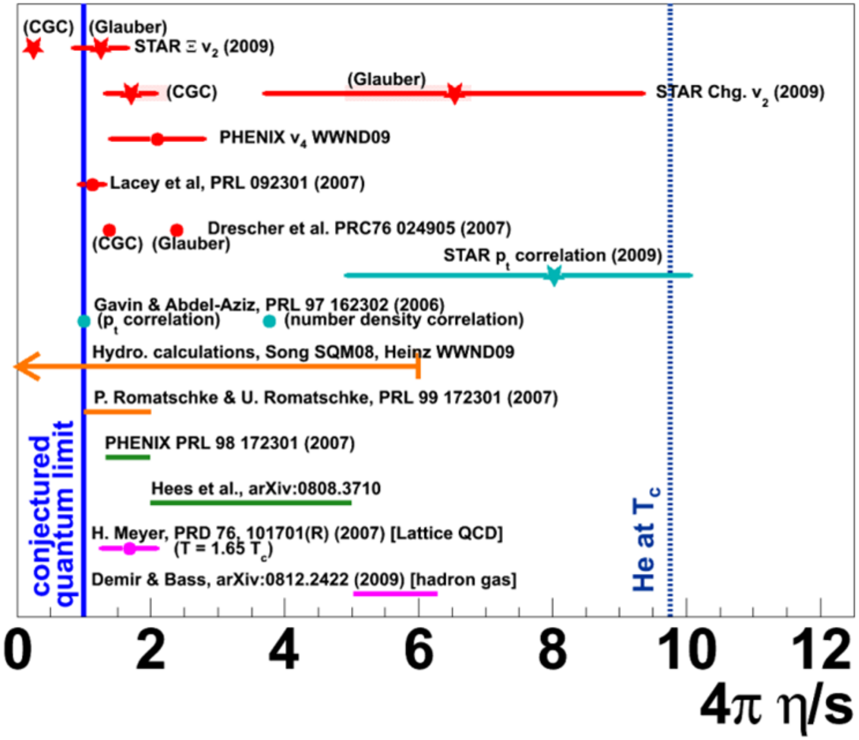
Electrons from c/b hadron decays



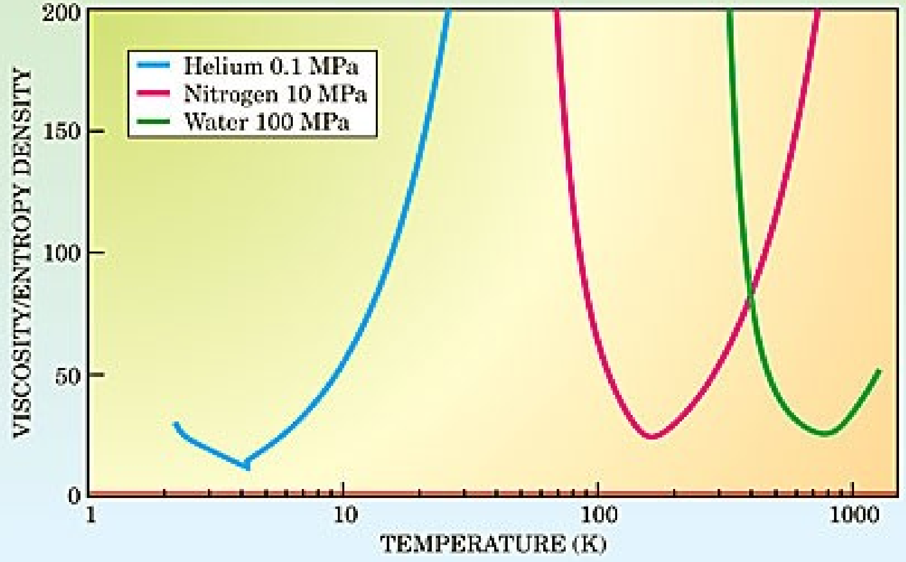
- **Status**
  - Calibrated probe?
    - pQCD now predicts cross section well
    - Total charm follows binary scaling
  - Strong medium effects
    - Significant suppression
    - Significant v2
    - Upper bound on viscosity!
    - Little room for bottom production
  - Limited agreement with energy loss calculations



How Perfect is “Perfect” ?

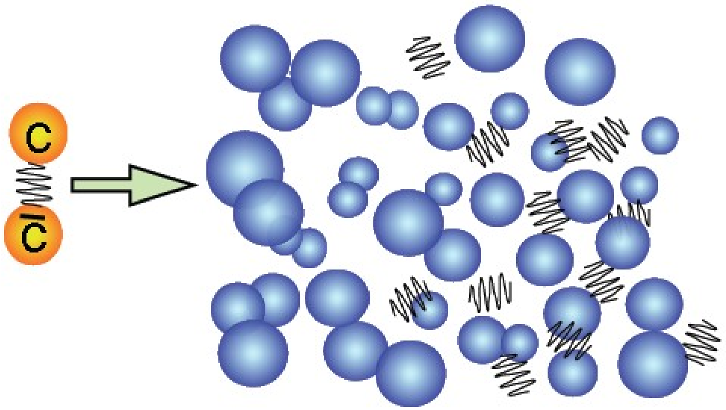


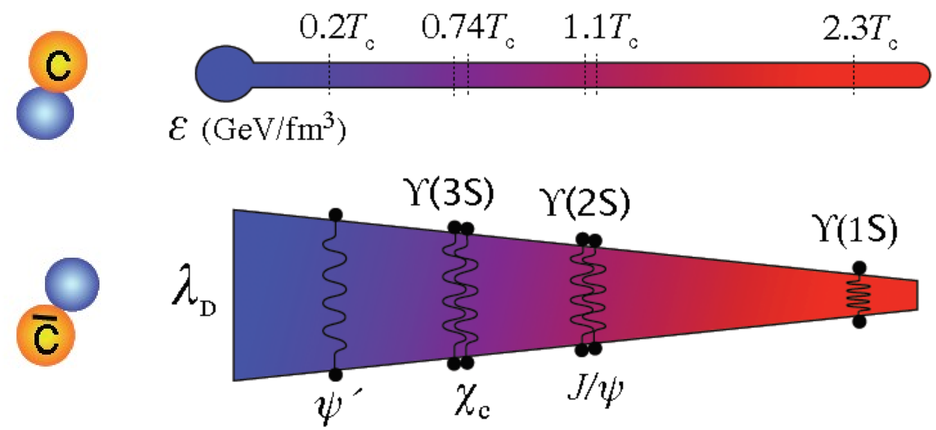
$$\eta \geq \frac{\hbar}{4\pi}(\,Entropy\,Density) \equiv \frac{\hbar}{4\pi}s$$



- 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

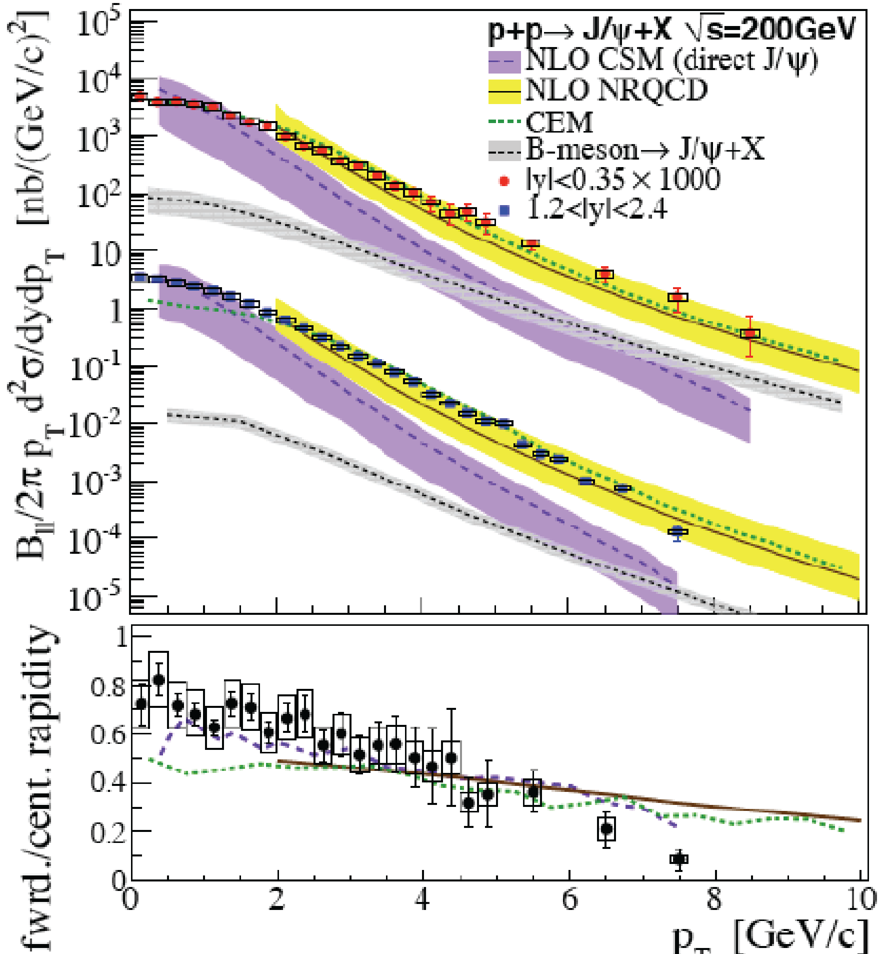




- *J/psi Suppression by Quark-Gluon Plasma Formation,* T. Matsui and H. Satz, Phys.Lett.B178:416,1986.
- If cc dissolved, unlikely to pair with each other.
- Suppression of J/Ψ and Y.
- Suppression driven by size of the meson as compared to the Debye Radius (radius of color conductivity)

How is J/ψ formed in pp?

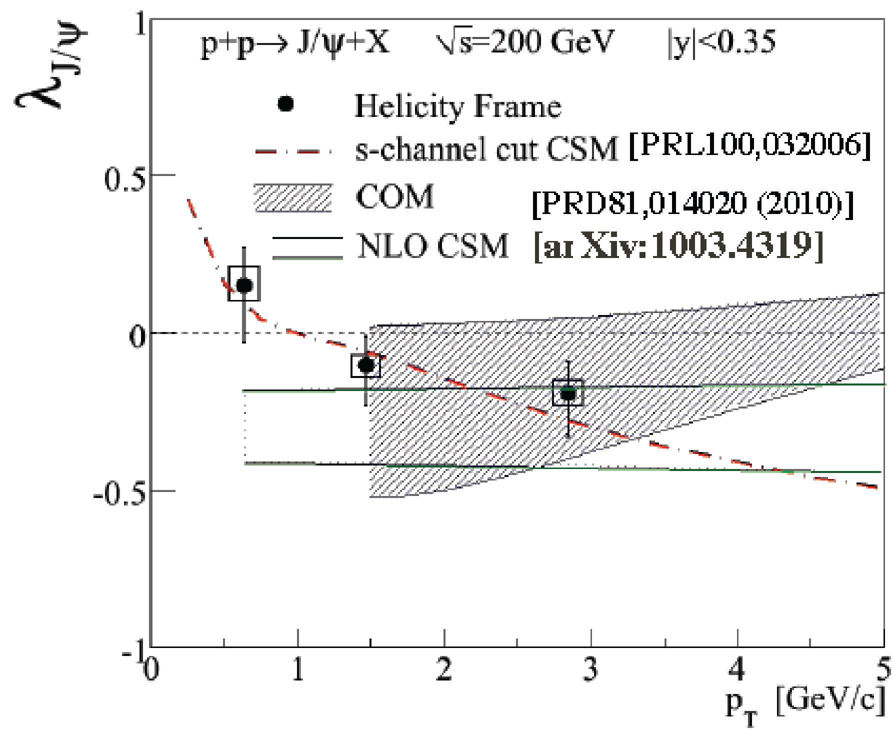
[arXiv:1105.1966]



- 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

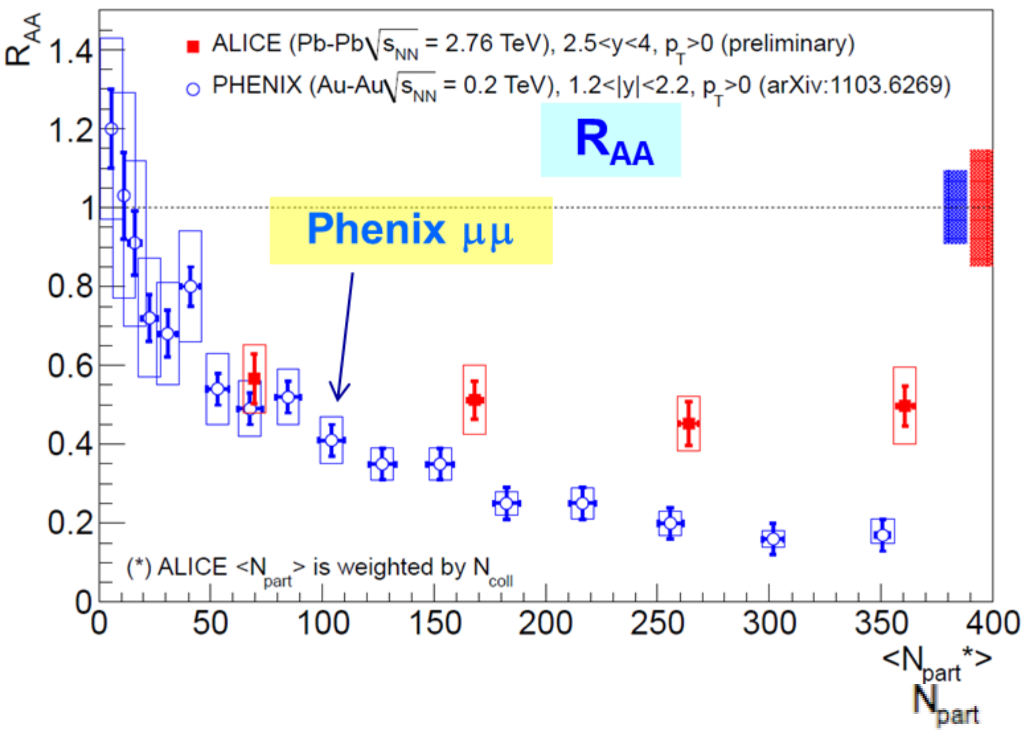
[PRD82,012001 (2010)]



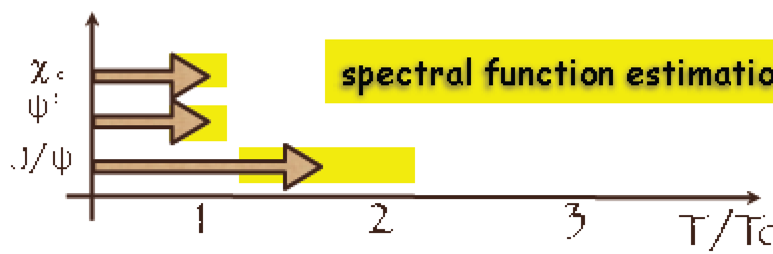
- color octet state may cross part of the nuclear matter as a pre-resonant state

J/ψ is suppressed (everywhere)

[arXiv:1103.6269v1]

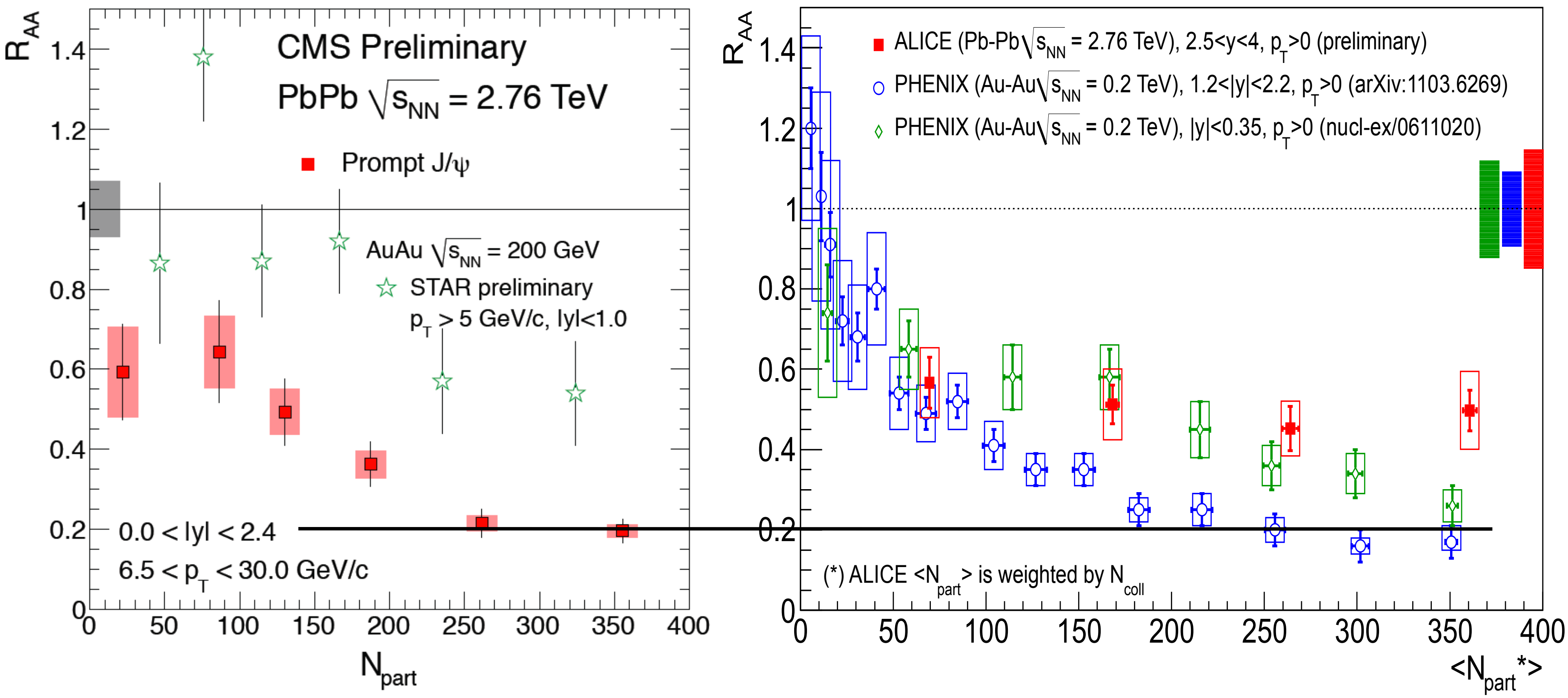


- Tc ~ 170 MeV
- inverse slope of thermal photons measured by PHENIX is 221±28MeV [PRL104, 132301 (2010)]
- hydro models fitted to the thermal photon data suggest T_{init} ~300-600 MeV
- who survives?



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

LHC/RHIC comparison

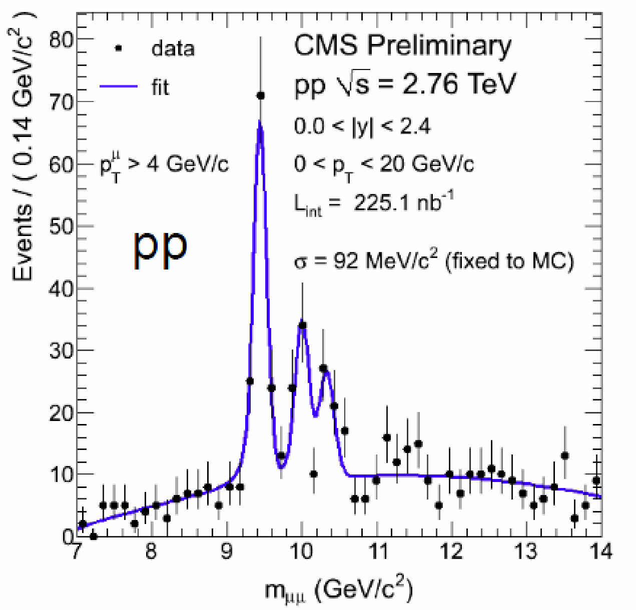


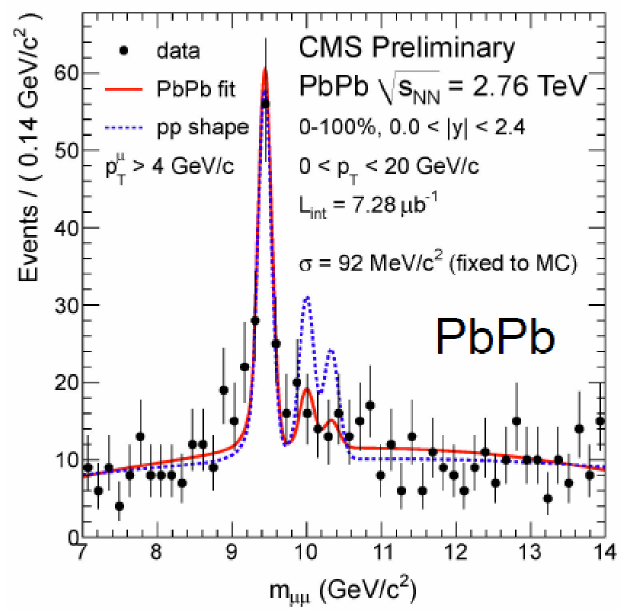
STAR (p_T>5 GeV) versus CMS (6.5<p_T<30 GeV)

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.





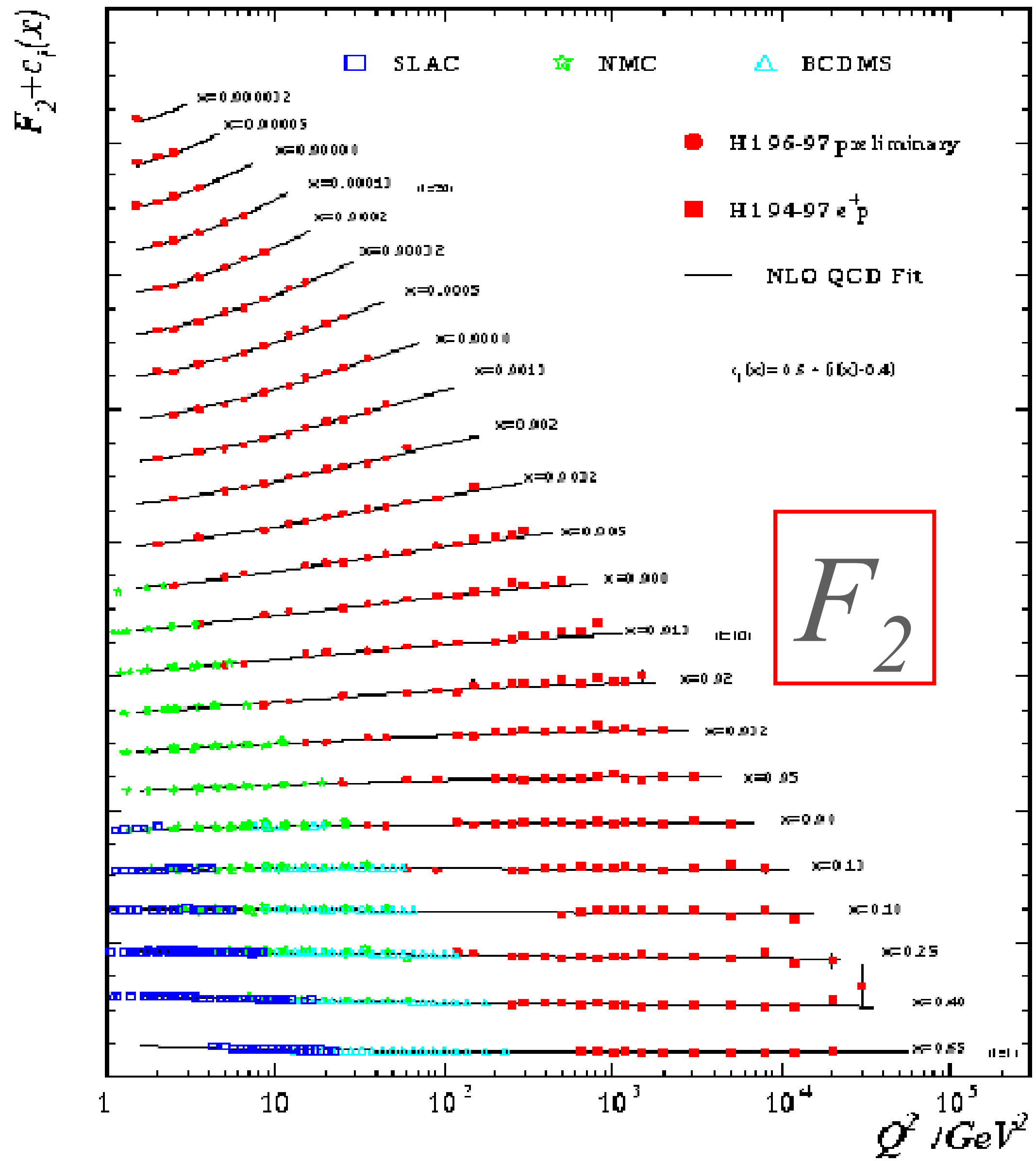
$$\Upsilon(2S+3S)/\Upsilon(1S)\big|_{pp} = 0.78^{+0.16}_{-0.14} \pm 0.02 \qquad \Upsilon(2S+3S)/\Upsilon(1S)\big|_{PbPb} = 0.24^{+0.13}_{-0.12} \pm 0.02$$

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

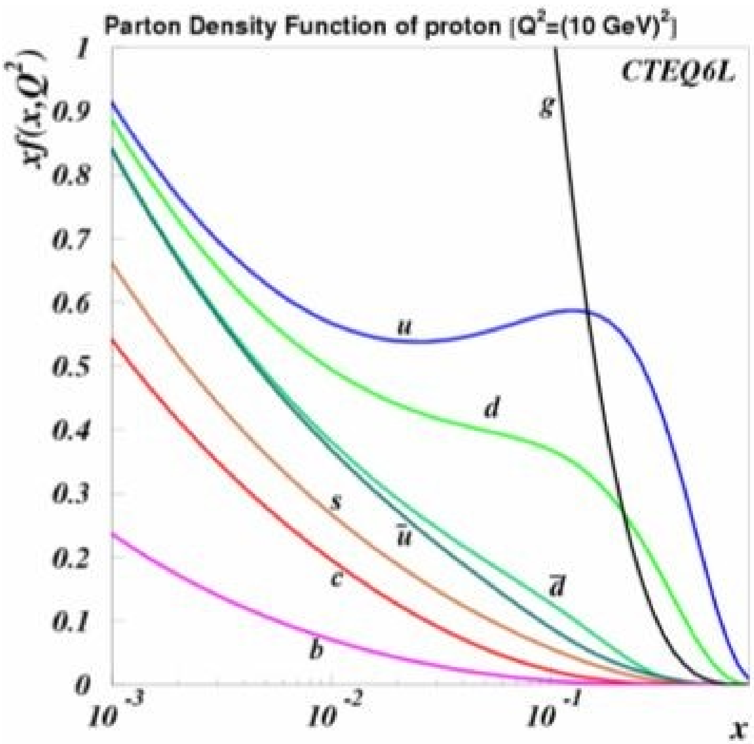
- **The data show that the 2s/3s are reduced compared to the 1s.**
- **This is first strong indication of sequential melting in QGP.**
- **Should yield screening length of our color conductor!**

Parton Distribution Functions

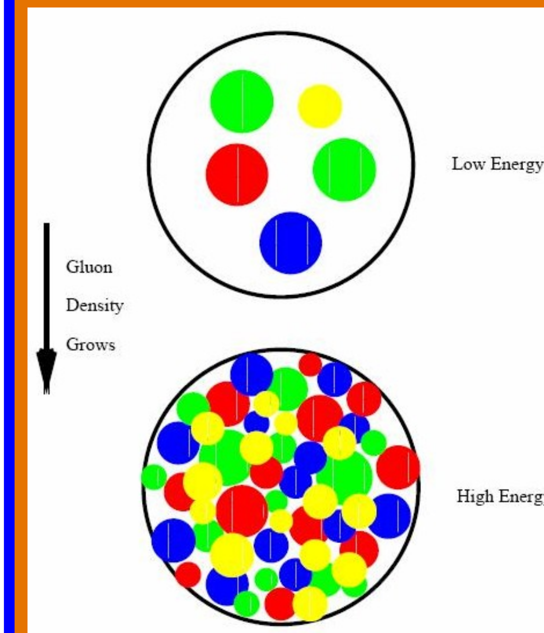
- **PDFs are measured by e-p scattering.**
- **Calculations (PYTHIA) use theoretically inspired forms guided by the data:**
  - **CTEQ 5M**
  - **others…**
- **Unitarity requires that the integral under the PDF adds up to the full proton momentum.**
- **Dirty Little Secret: The sum of the parts exceeds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

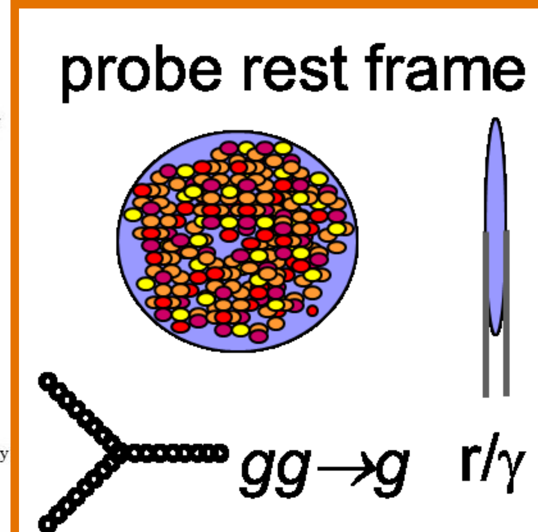


Crisis in Parton Distributions!



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

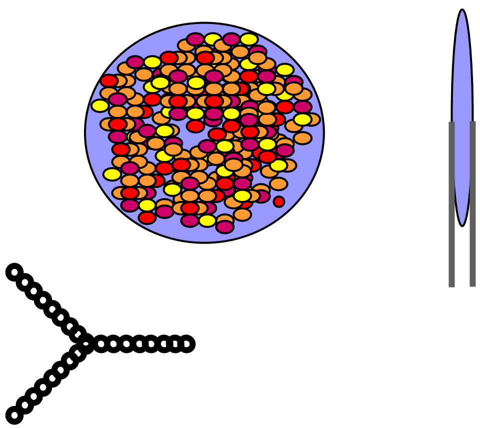




ANSWER: They eat each other.

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

Glass at the Bottom of the Sea?



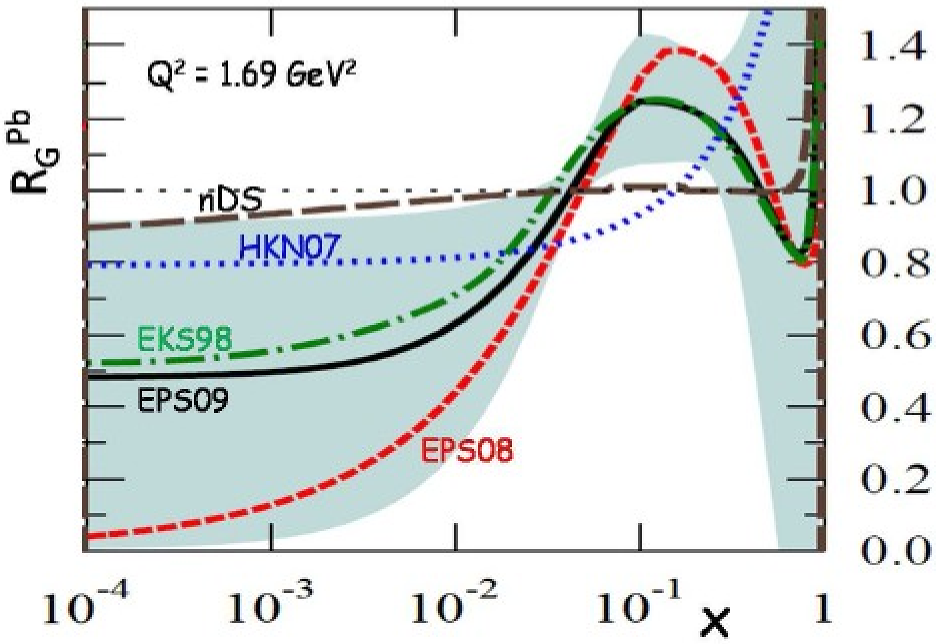
- Note that the gluon fusion reaction, g+g→g, "eats gluons".
- Its kind of like a fish tank:
  - When the fish eat their young, the tank never overfills with fish.

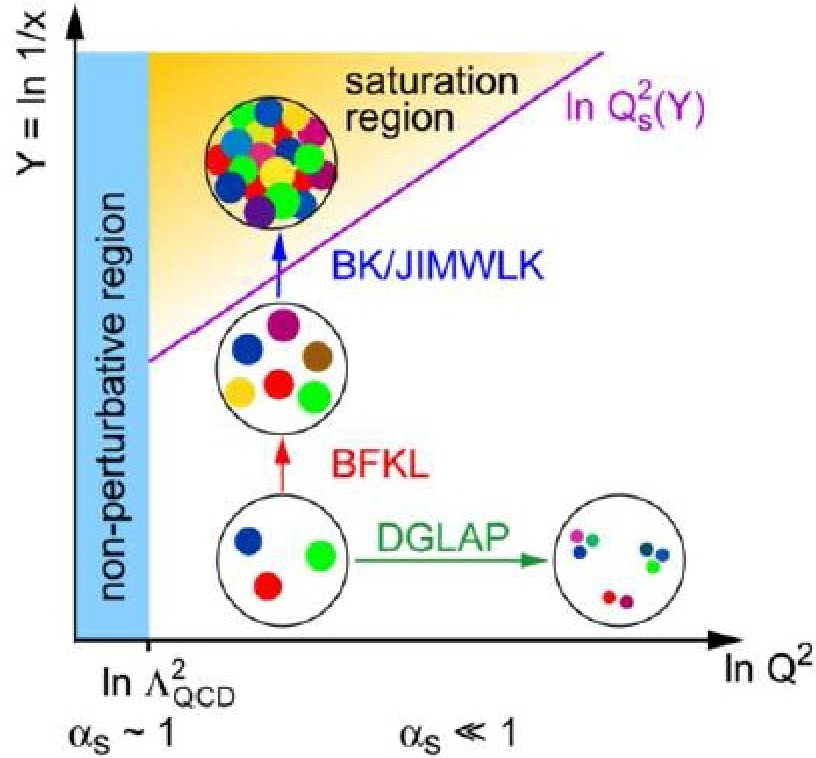
- This implies that

  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.

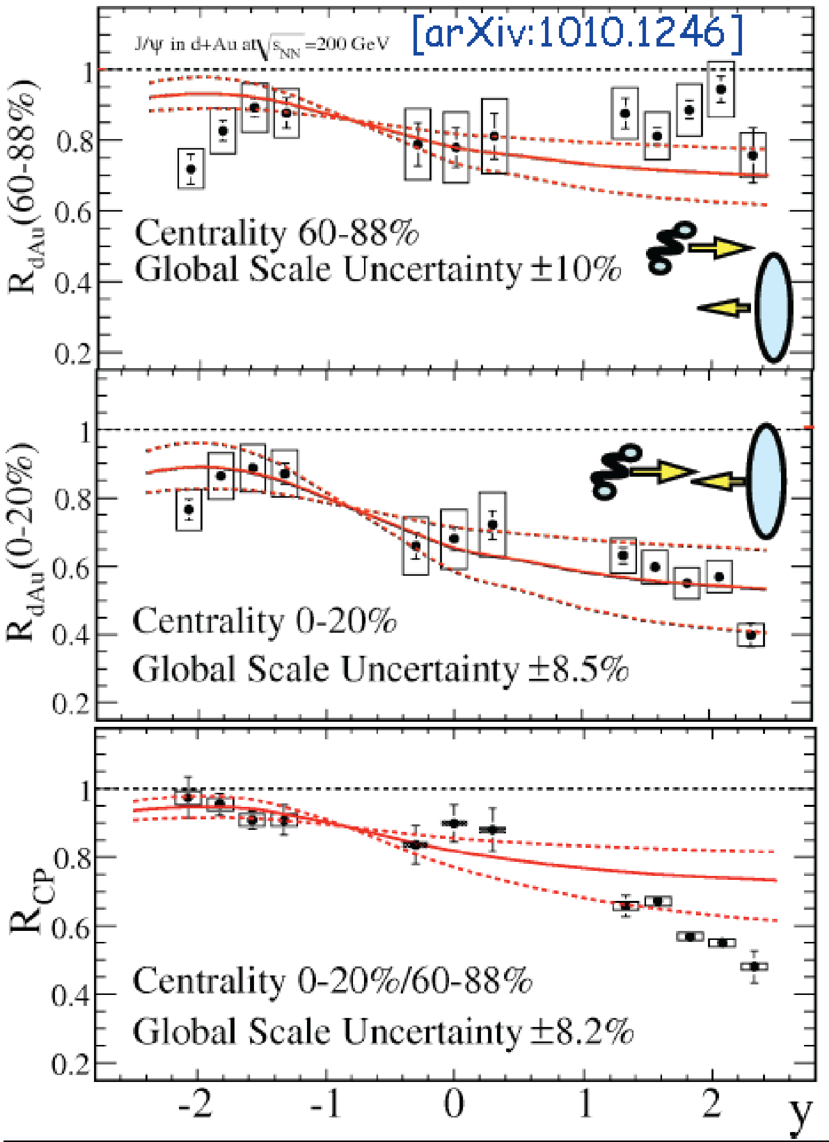
Nuclear Oomph…





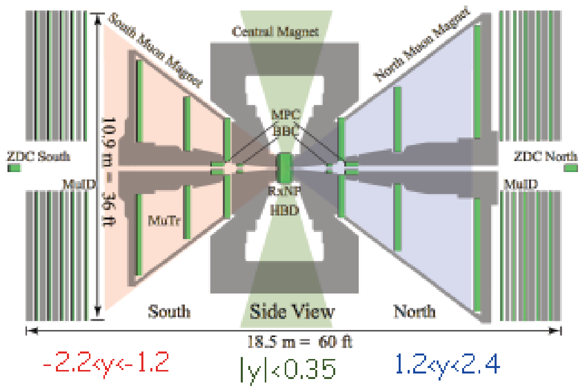
- **A nucleus compresses more matter and makes the CGC easily accessible.**
- **Shadowing competes with CGC.**
- **Many believe that shadowing is simply "parameterized" CGC.**

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.**

Length dependence of J/ψ



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

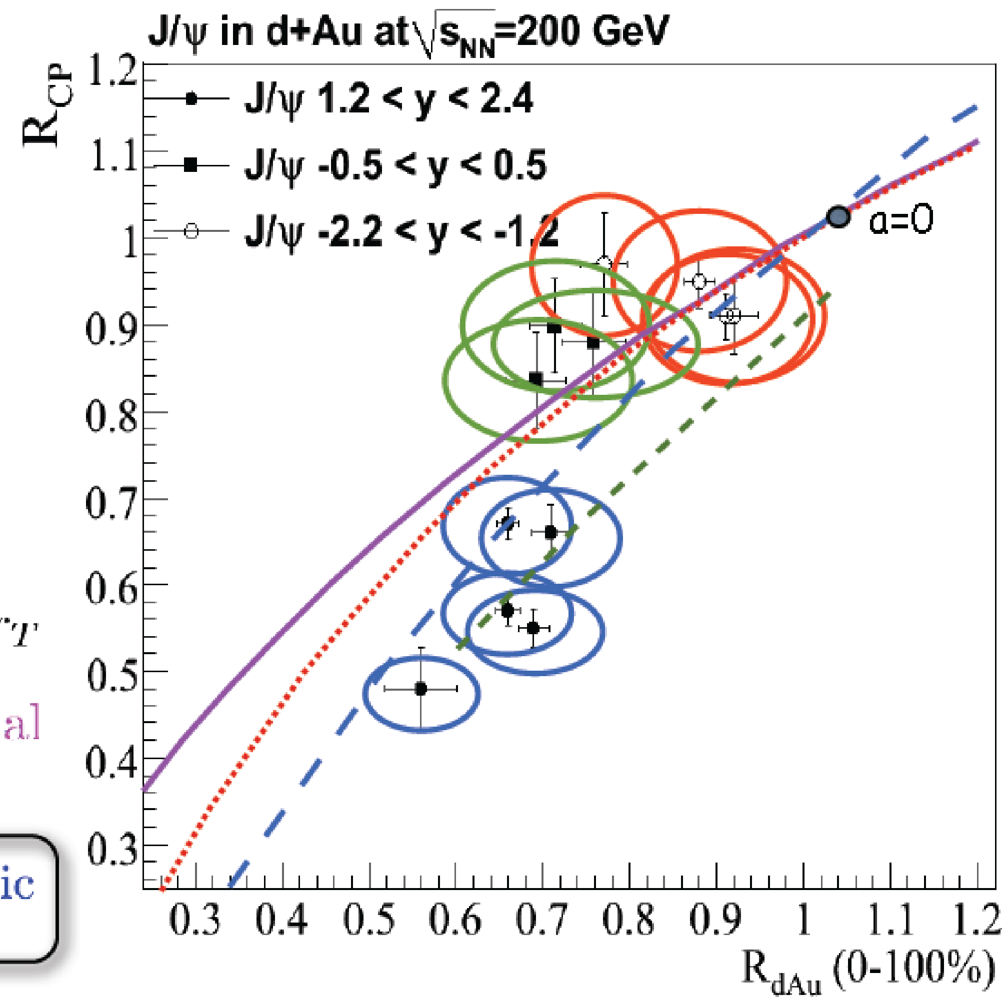
$$R_{dAu,i}(a) = \int f_i(r_T)\, M(r_T; a)\, dr_T$$

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

$$M(r_T; a) = 1 - a\Lambda(r_T) \quad \text{linear}$$

$$M(r_T; a) = 1 - a\Lambda(r_T)^2 \quad \text{quadratic}$$

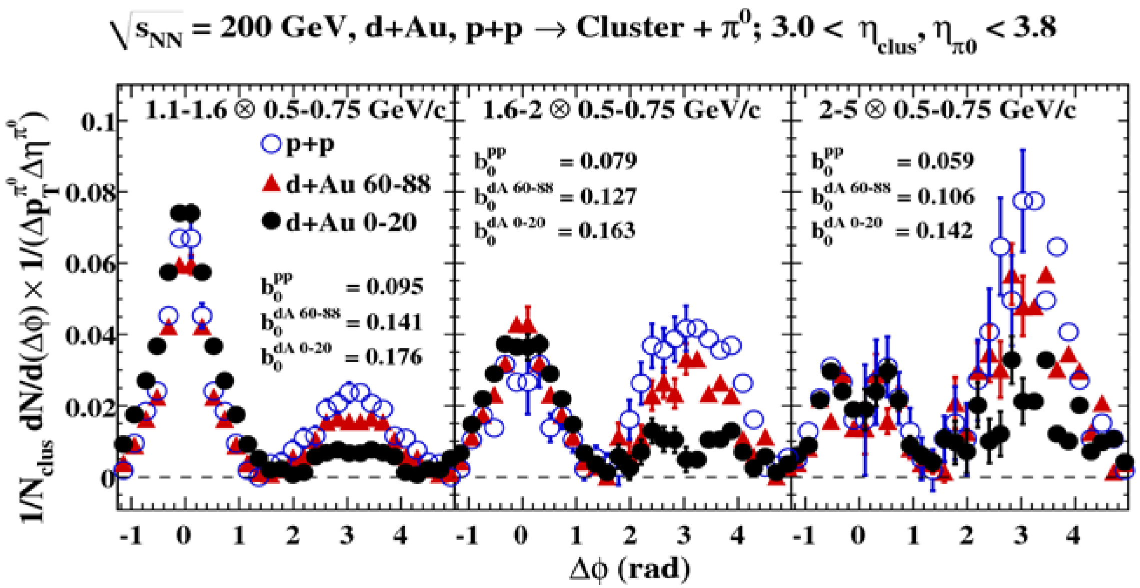
nuclear modification requires a quadratic or higher order dependence



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

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

Jets distinguish CGC from shadowing.

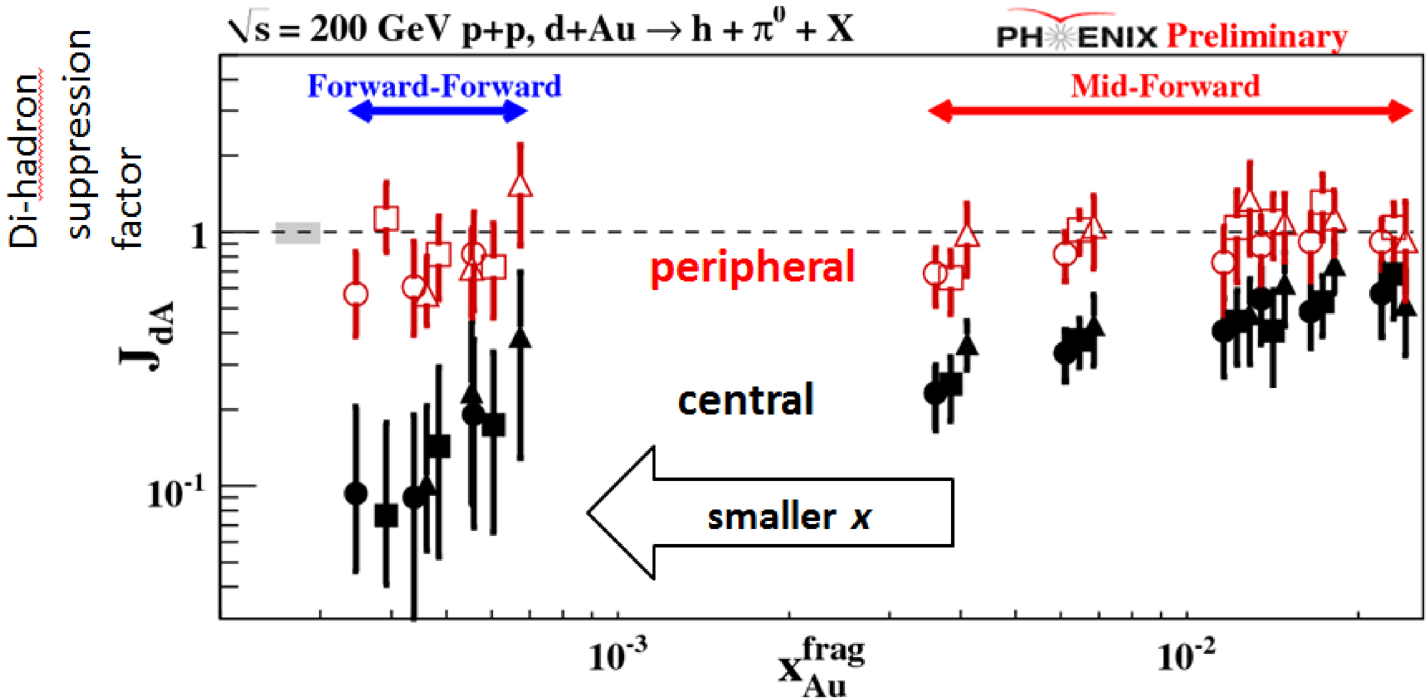


Color Glass Condensate?

new forward
EM calorimeter
$|\eta| = 3.0\text{-}3.8$

- **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.**

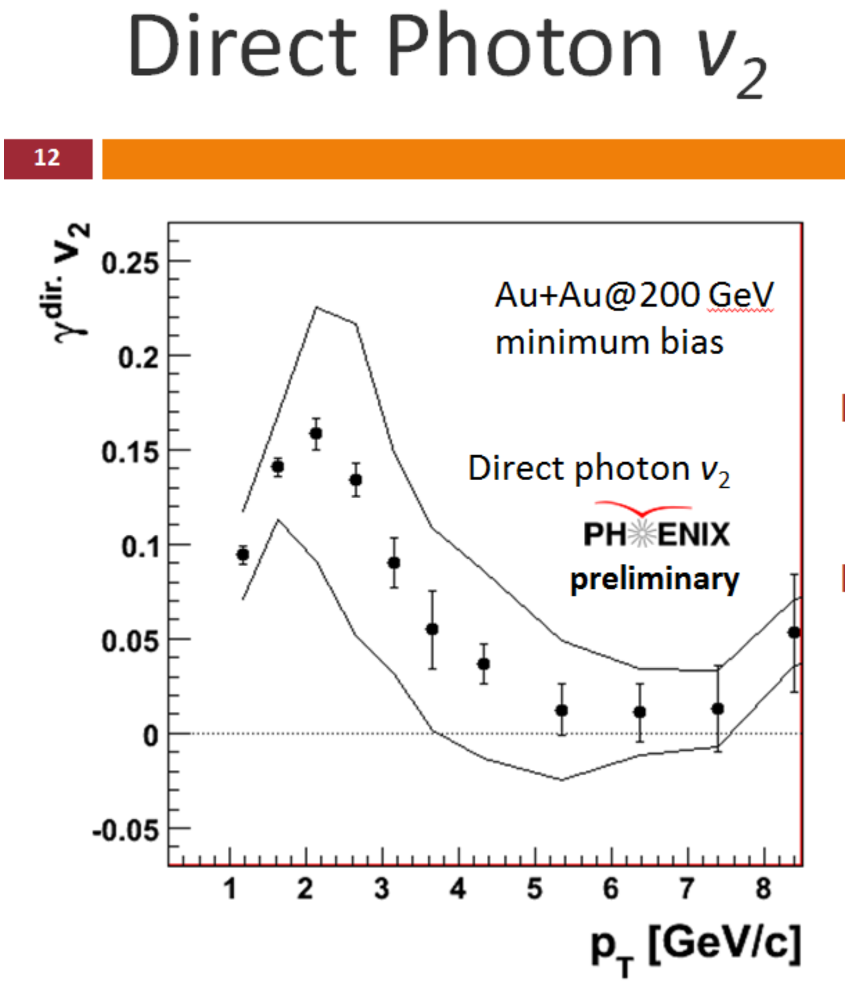
HUGE suppression in low X.



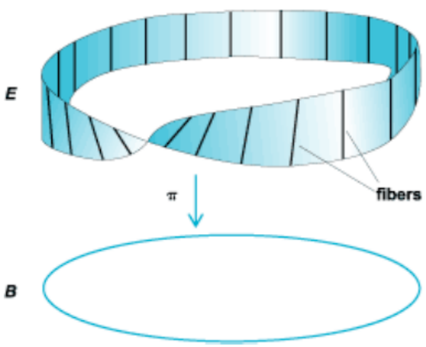
- **The suppression factor from cold nuclear matter is a factor of ~10!**
- **The away-side jet "decorrelates".**
- **Jury still out:**
  - **Nearly all measurements follow CGC predictions.**
  - **Predictions are often qualitative.**
- **Electron-ion collisions will find the truth.**

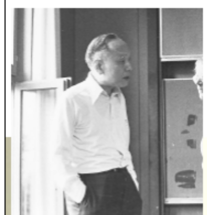
SURPRISE!

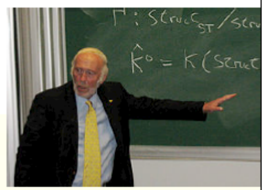
- The direct virtual photons measured by PHENIX have been associated with early stage thermal radiation.
- If true, they should show little flow.
- Surprise…they flow.
- We must take care in interpreting these photons…



Gauge fields possess non-trivial topology





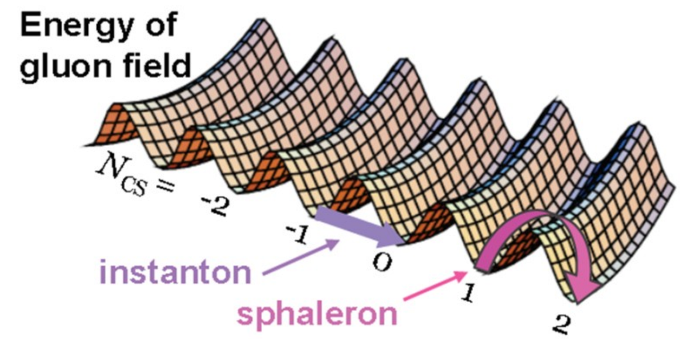


CHARACTERISTIC FORMS

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

Dima Kharzeev. QM2011

QCD vacuum is a superposition of states with different topology



Transitions between such states create the local imbalance of chirality

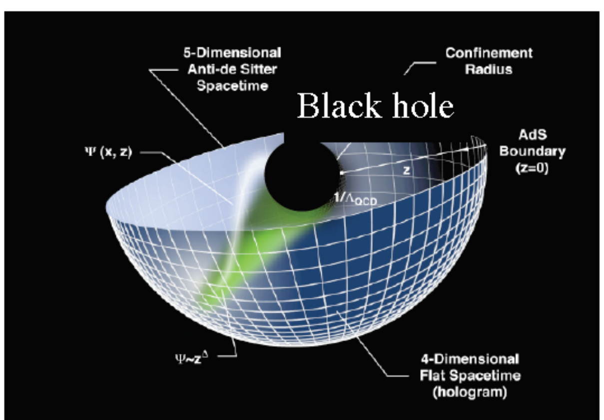
4

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

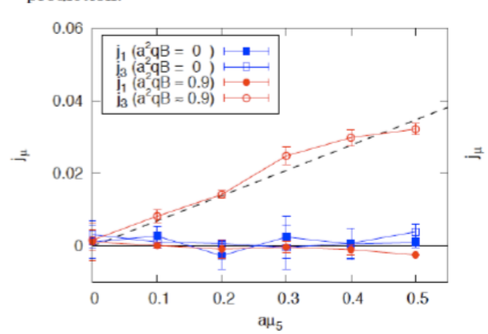
Chiral magnetic effect in lattice QCD with chiral chemical potential

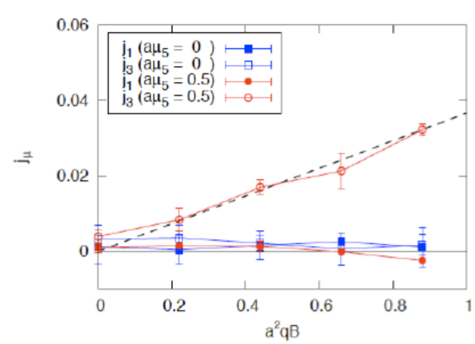
Arata Yamamoto

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.

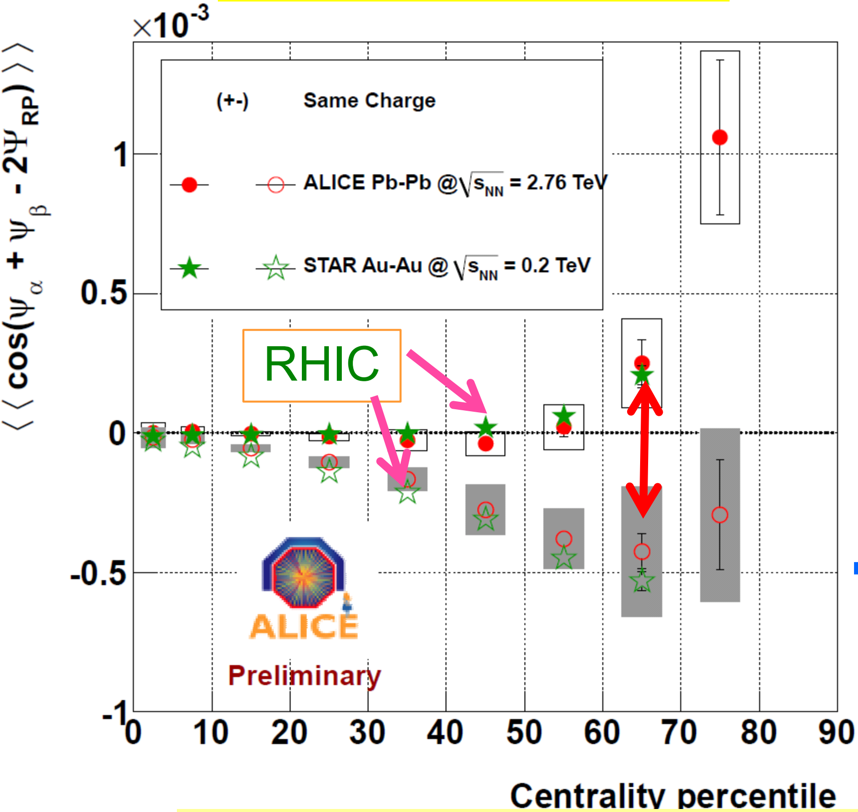


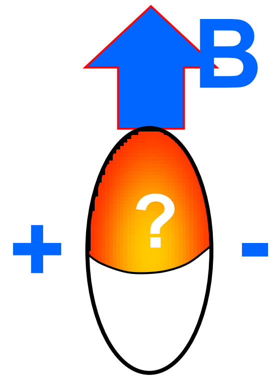


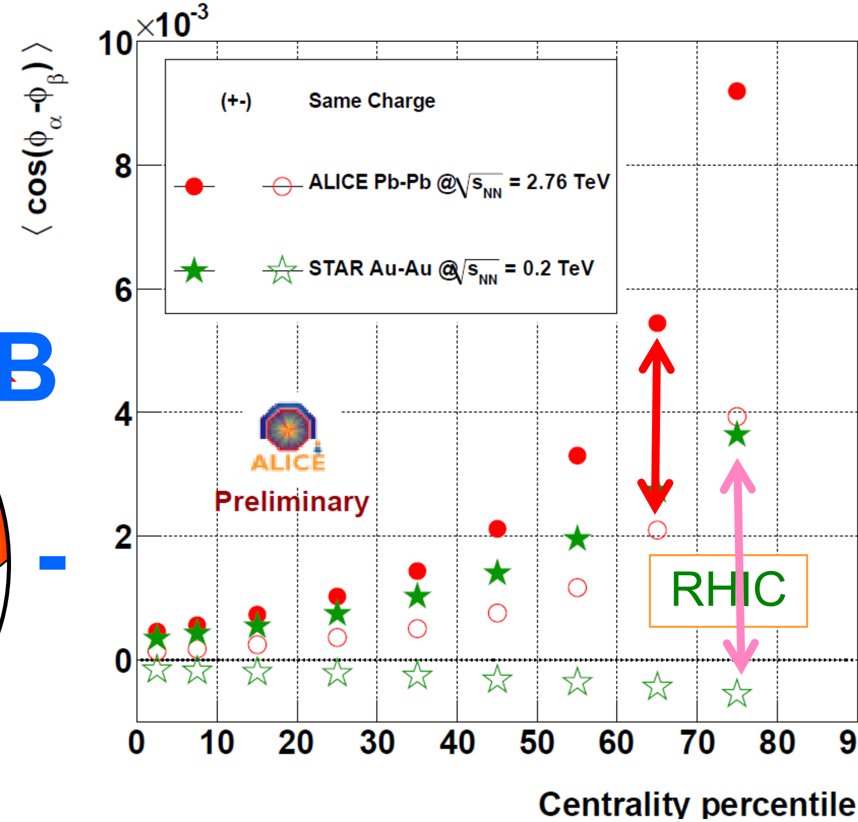
Chiral Magnetic Effect ('strong parity violation')

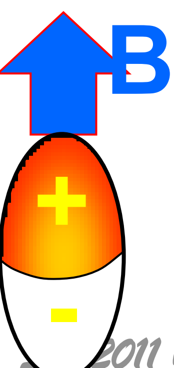
$$\left\langle \cos\left(\varphi_{\alpha} + \varphi_{\beta} - 2\Psi_{RP}\right)\right\rangle$$

$$\left\langle \cos\left(\varphi_{\alpha} - \varphi_{\beta}\right)\right\rangle$$









Same charge correlations **positive**

Opposite charge correlations **negative**

RHIC ≈ LHC

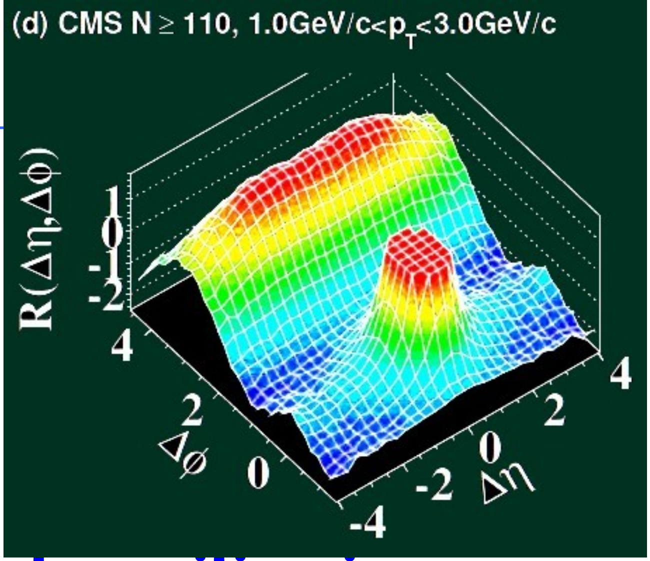
Local Parity Violation
in 10^{17} Gauss magnetic Field ?

may decrease with √s

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

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

Summary



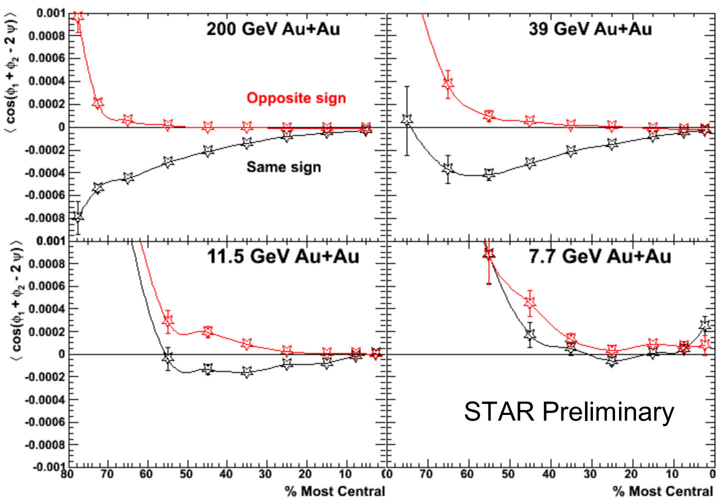
- Nuclear Collisions provide access to the collective color interaction.
- These provide a glimpse at aspects of the color force inaccessible through elementary collisions.
- Partonic matter just beyond the phase transition is a strongly-coupled plasma exhibiting explosive flow into the vacuum.
- String-theory 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.
- Deconfinement coupled with strong magnetic fields may reveal the parity-odd aspects of the color force.

CONGRATULATIONS on being a student in this field at these exciting times.

Backup Slides

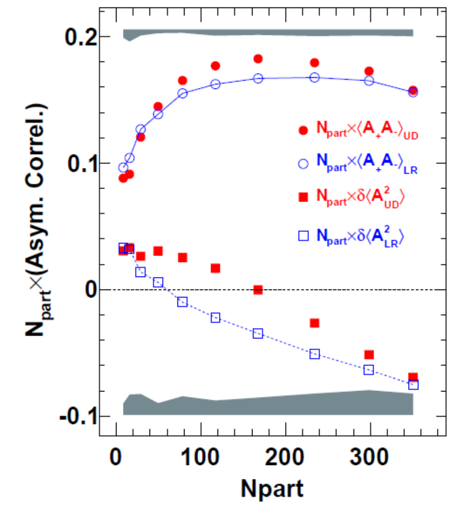
Dynamical Charge Correlations

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)

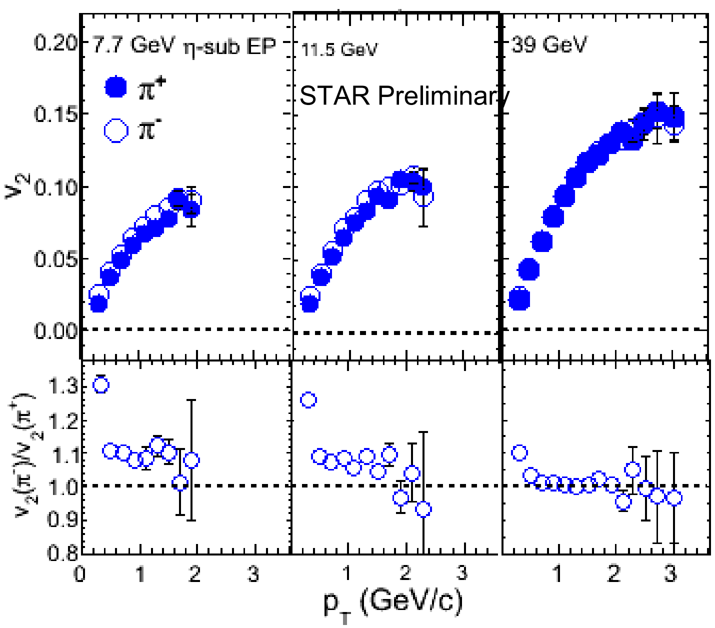


Alternate Observables

(B) Charge asymmetry

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

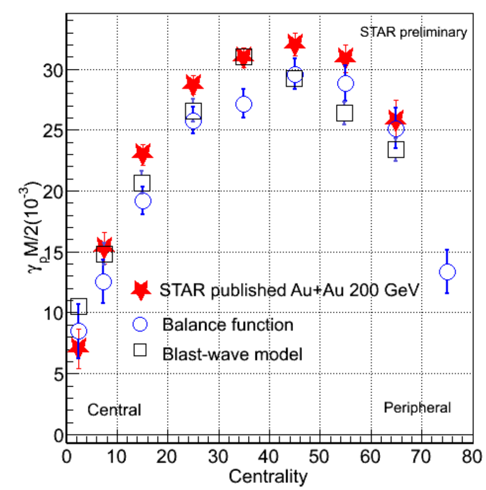
LPV: $\langle A_+A_-\rangle_{UD} < \langle A_+A_-\rangle_{LR}$



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

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

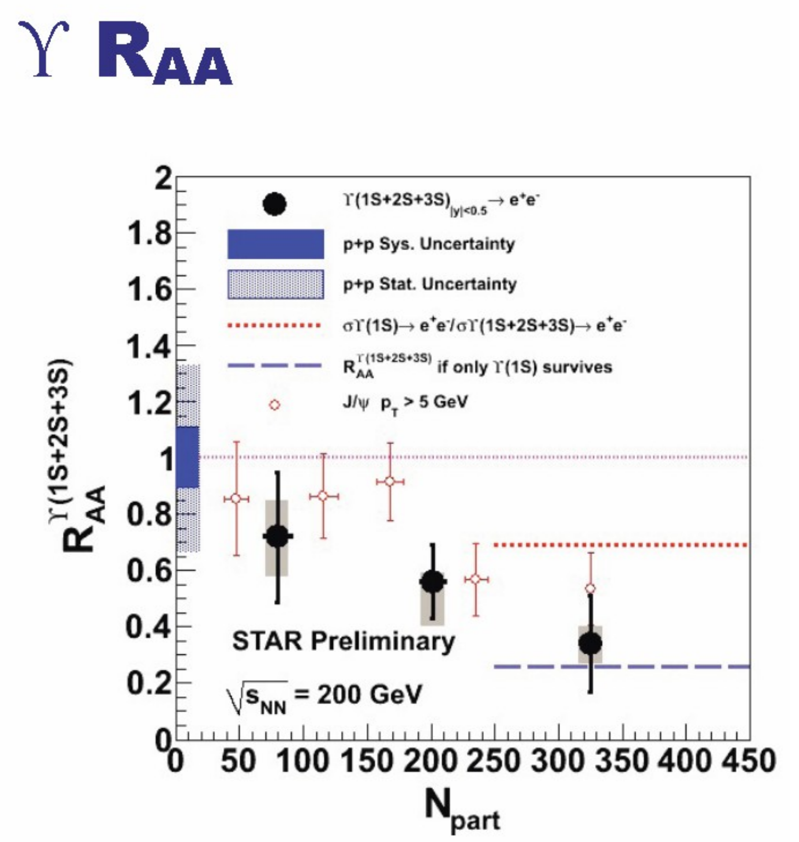
A. Bzdak, et al., PRC 83 (2011) 014905
S. Schlichting et al., PRC 83 (2011) 014913
Y. Burnier et al., arXiv:1103.1307



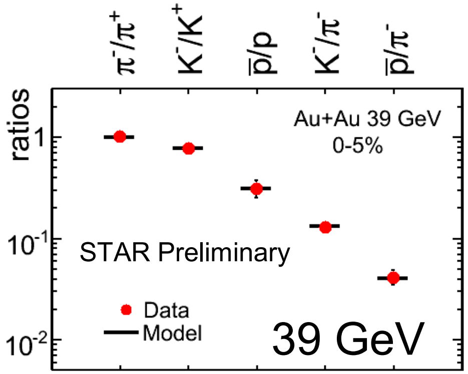
How to reconcile (A) with the fact $v_2(\pi^+) < v_2(\pi^-)$ at 7.7 GeV

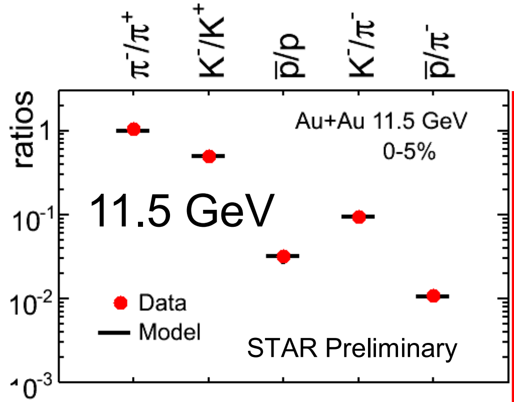
Suppression.

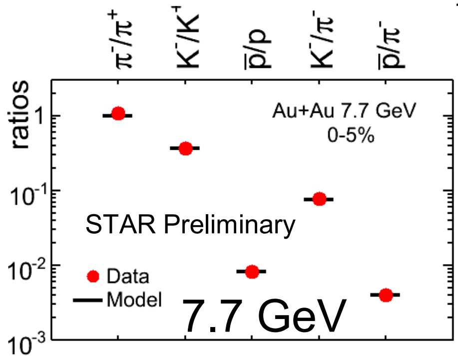
- 1s state should be too large to melt in the plasma.
- 2s/3s could be melted.
- Data are above blue-dashed which would be consistent with only 1s survival and removal of nearly all 2s/3s.



Freeze-out Conditions

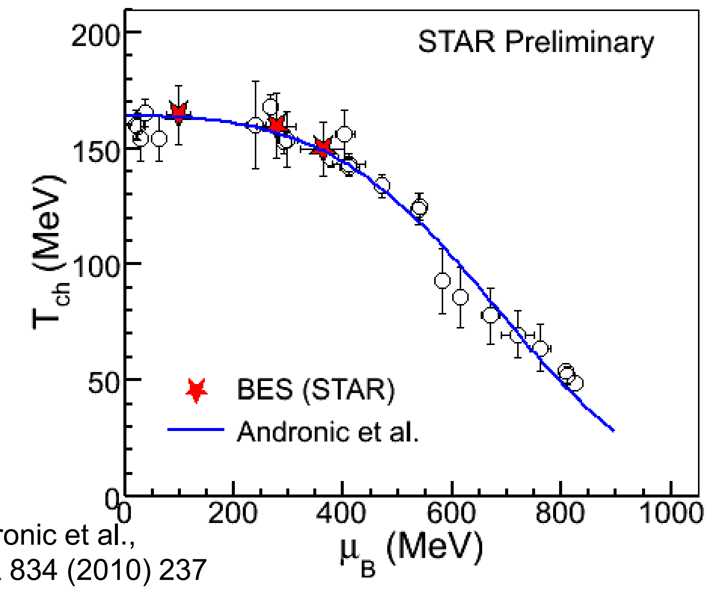






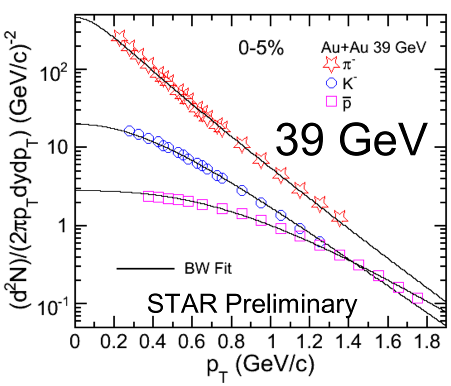
Chemical freeze-out: Particle ratios

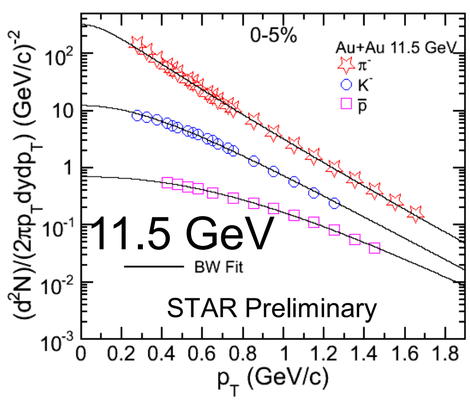
QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.

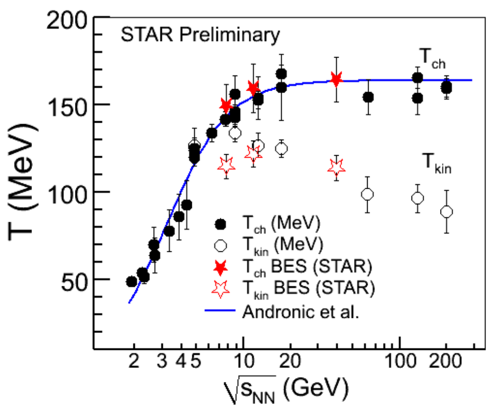


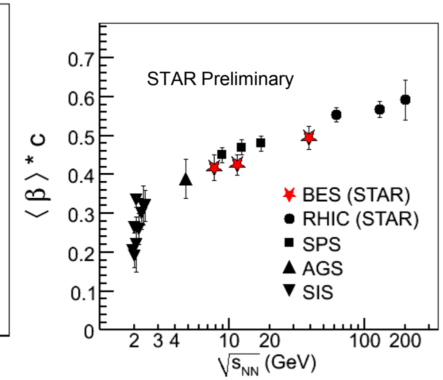
Andronic et al., NPA 834 (2010) 237

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







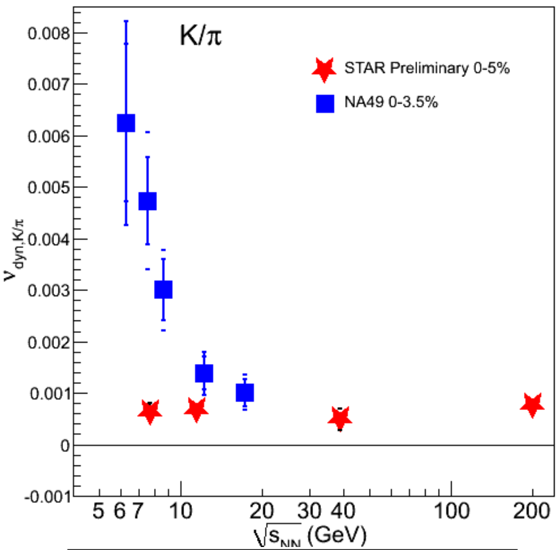


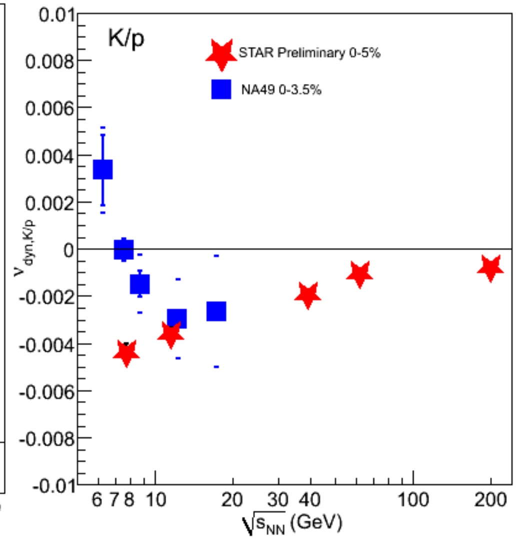
Kinetic freeze-out : Momentum distributions

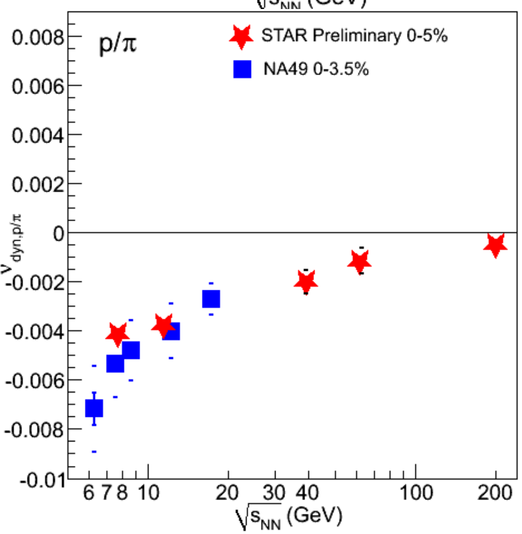
L. Kumar, Energy scan, 27th May

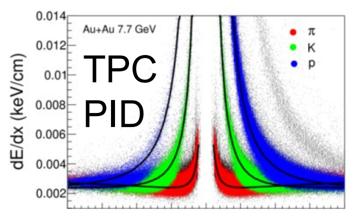
Particle Ratio Fluctuations

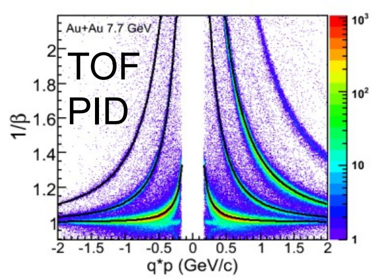
Observations:





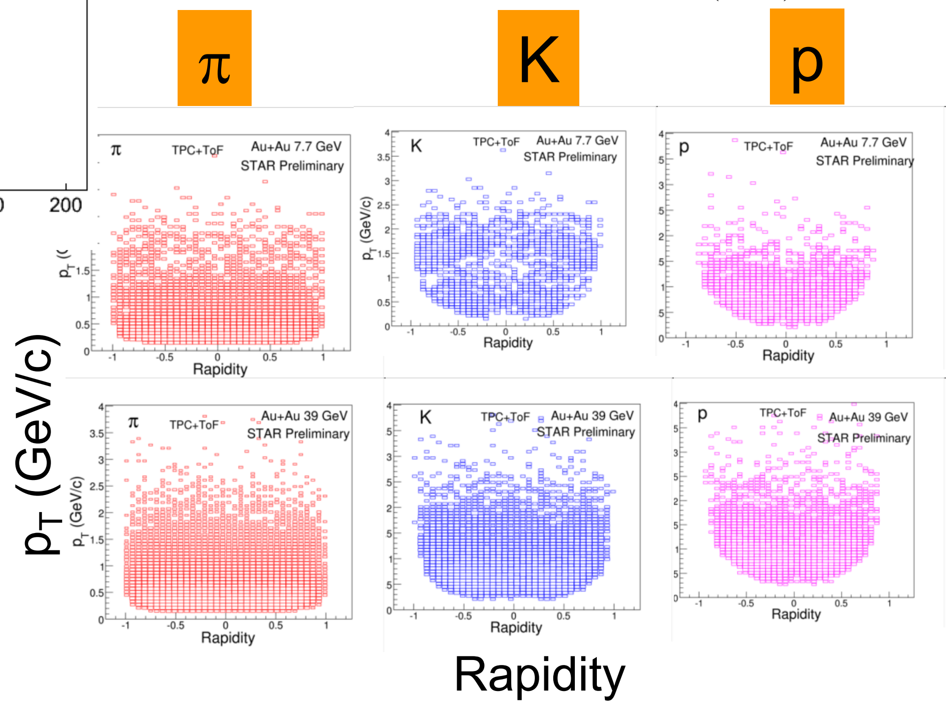






Fluctuations in particle ratios
-- Sensitive to particle numbers at chemical FO not kinetic FO
-- Volume effects may cancel

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



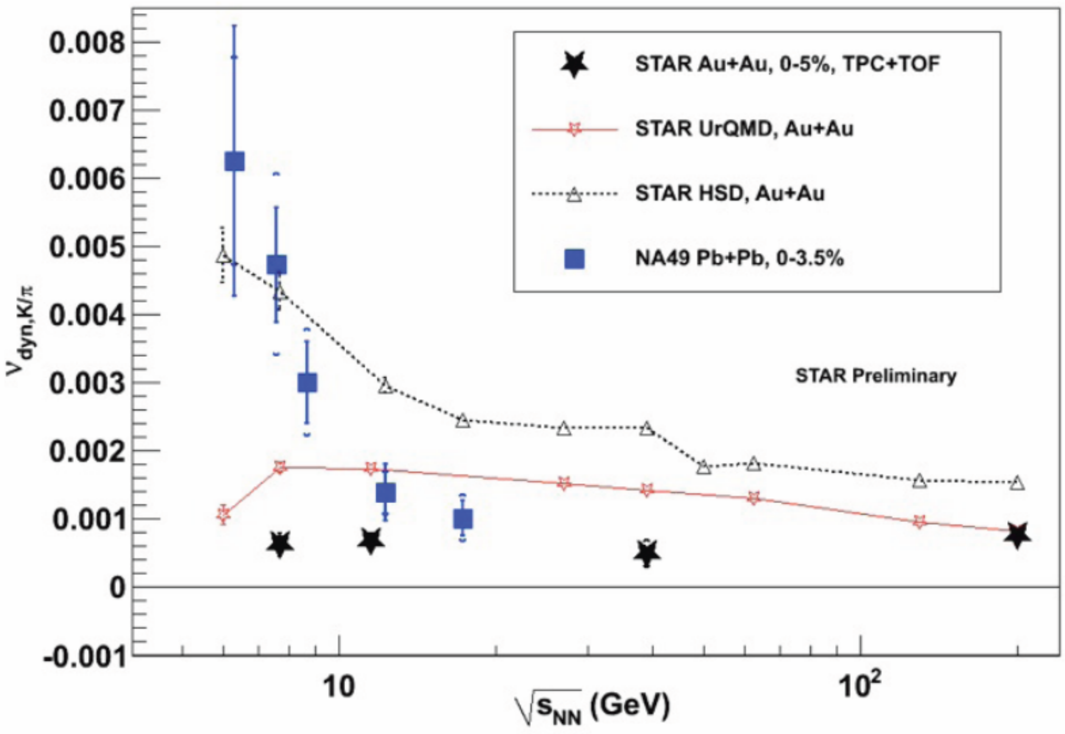
Constant or monotonic trends observed
Apparent differences (results with Kaons) with SPS

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

fluct.

Particle ratio fluctuations

Terence Tarnowsky,
Mon/23 16:00



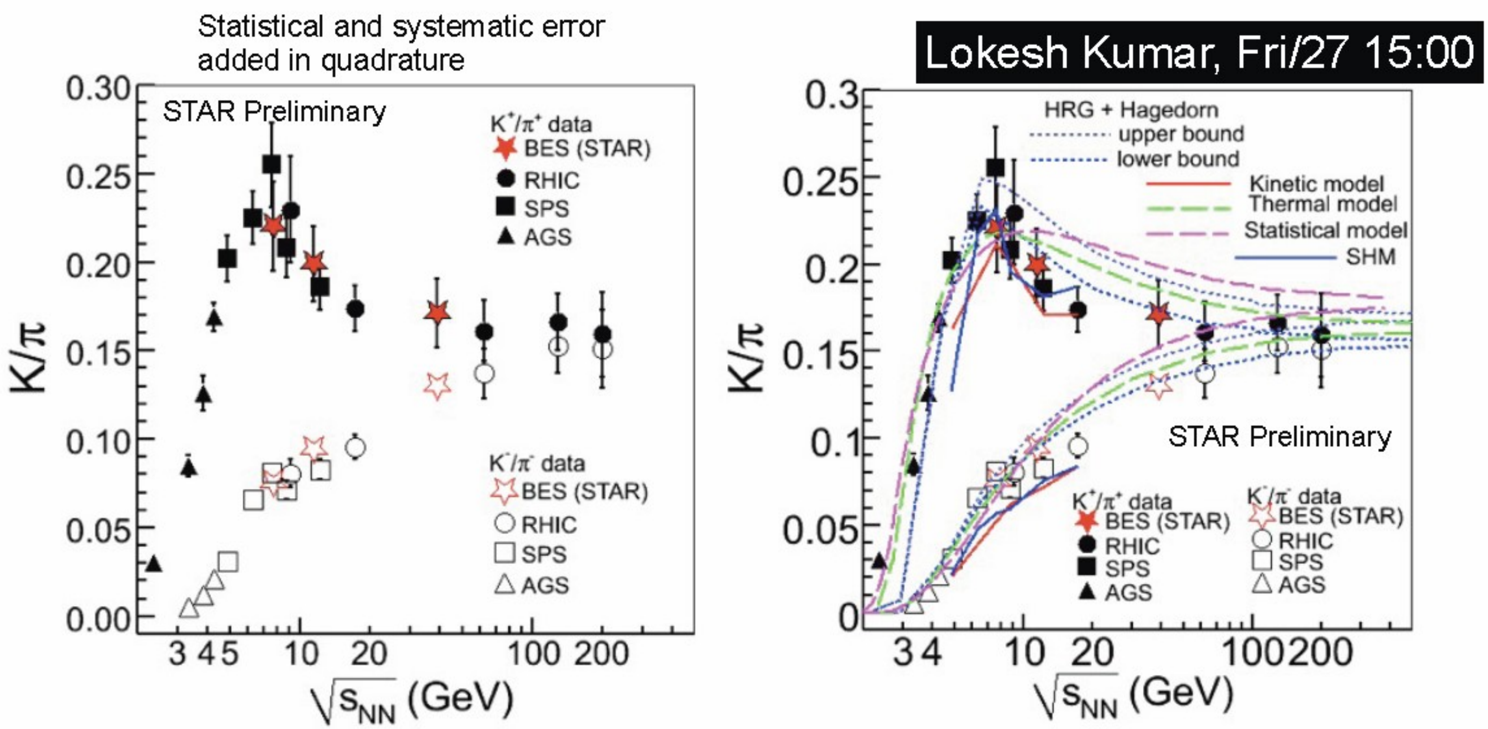
STAR TPC+TOF

π: 0.2 < p_T < 1.4 GeV/c

K; 0.2 < p_T < 1.4 GeV/c

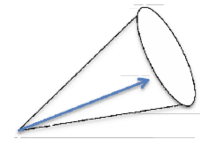
Data are still "horny"

K/π ratio

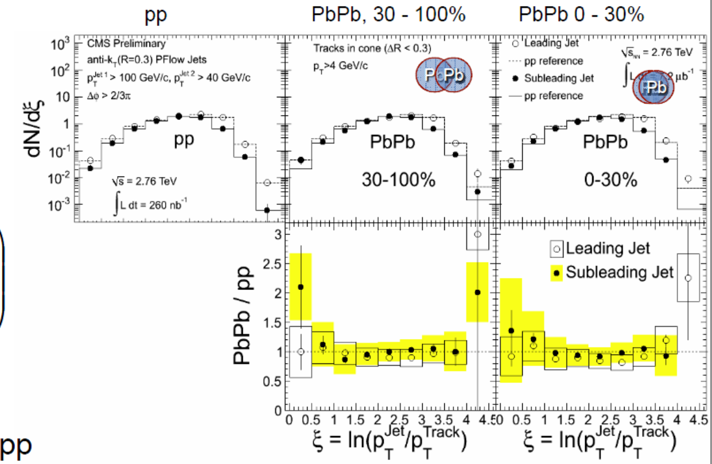


- **Can be naturally explained by change of strangeness production from ΛK to KK…**

Fragmentation Function at LHC

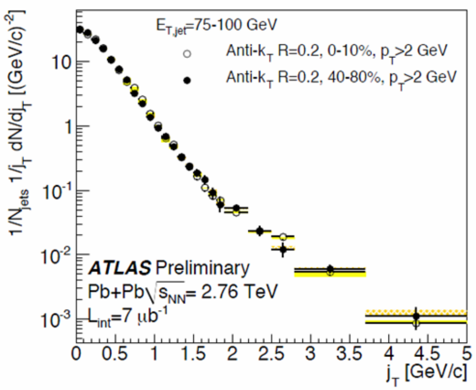


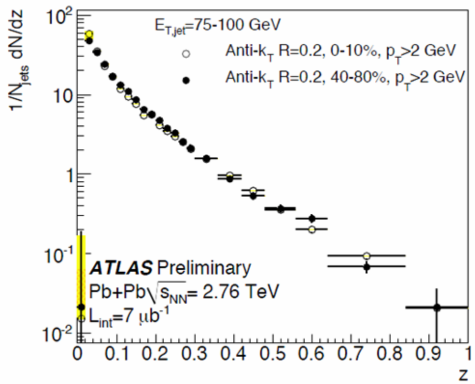
$$\xi = \ln\left(\frac{p_T^{Jet}}{p_T^{Track}}\right)$$



Fragmentation Functions

- Compare PbPb to pp





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

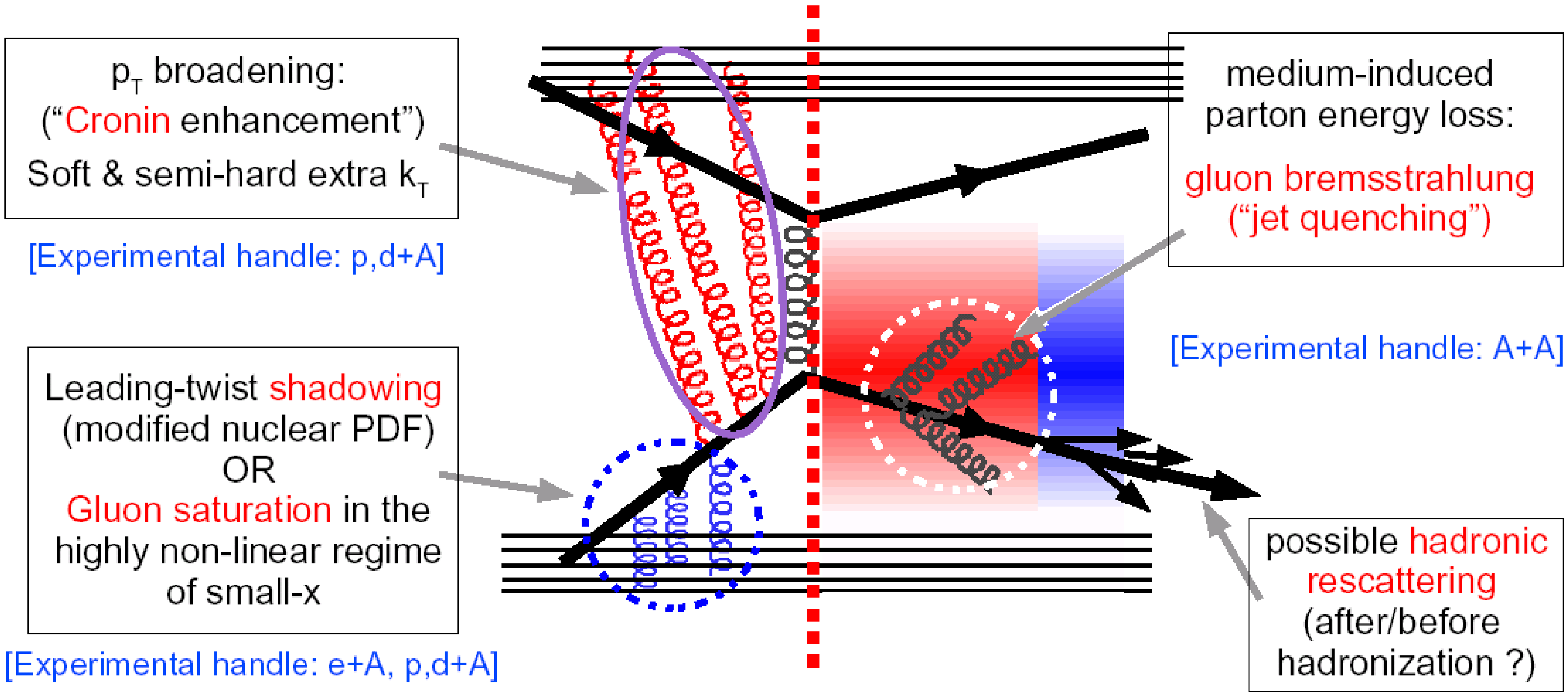
Yellow bands represent uncertainties from background subtraction

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.

Initial-state effects: Final-state effects:



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