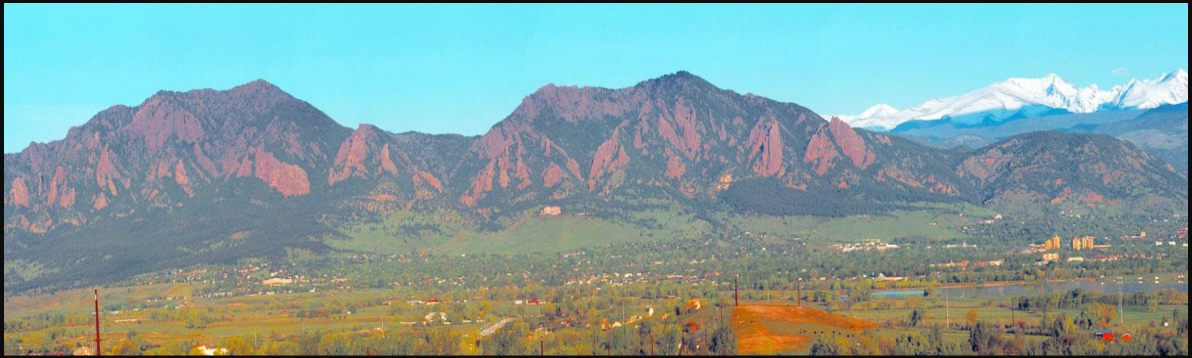
Geometry Rules:

Heavy Ion Physics of Heavy Quarkonia and Harmonic Flow

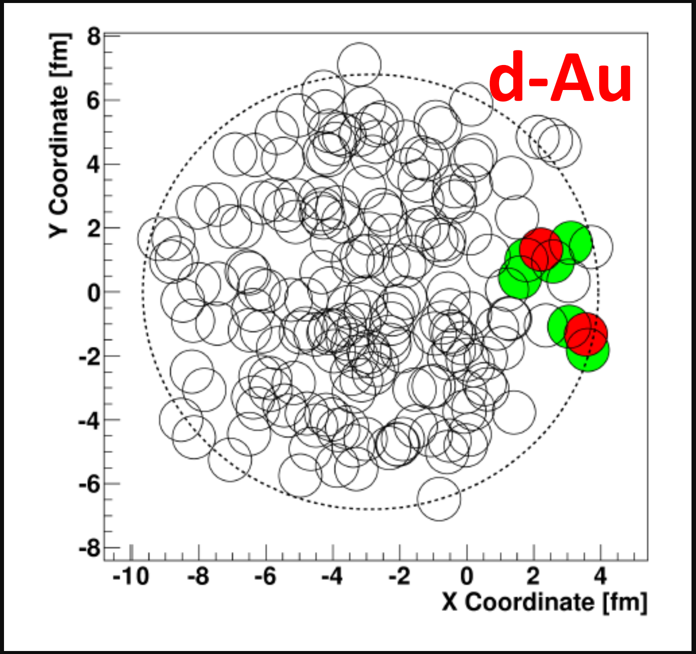


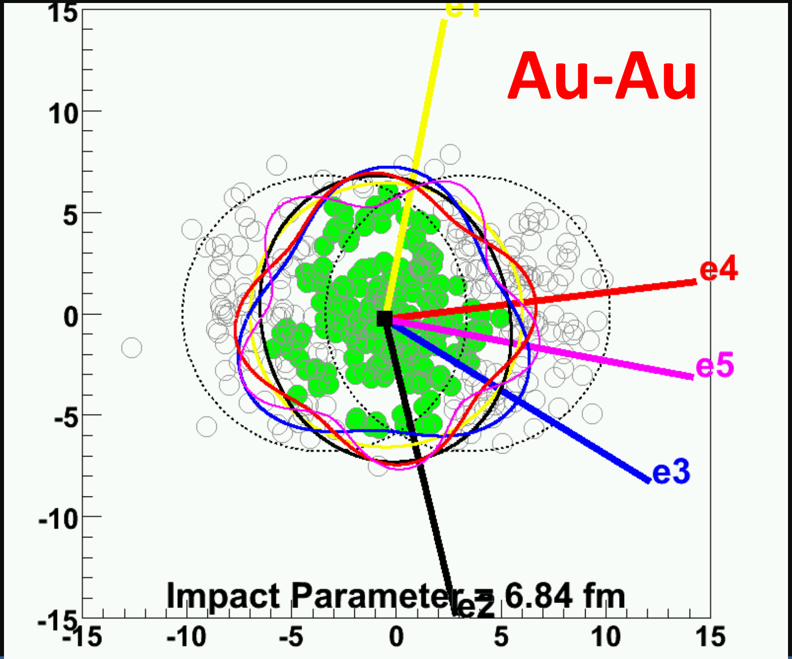
Jamie Nagle
Niels Bohr Institute, Copenhagen, Denmark
University of Colorado, Boulder, USA

Focus on two topics in today's talk…

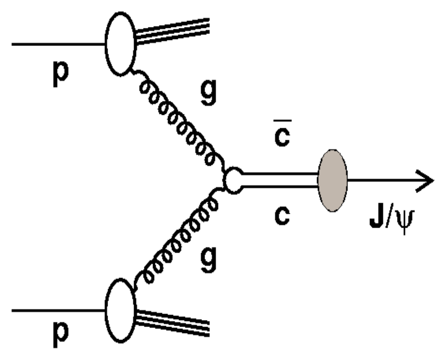
1. Heavy Quarkonia (J/ψ) in p-p, d-Au, Au-Au
2. Harmonic Flow of the bulk QGP

Highlight how geometric dependencies provide key insights…





Heavy Quarkonia

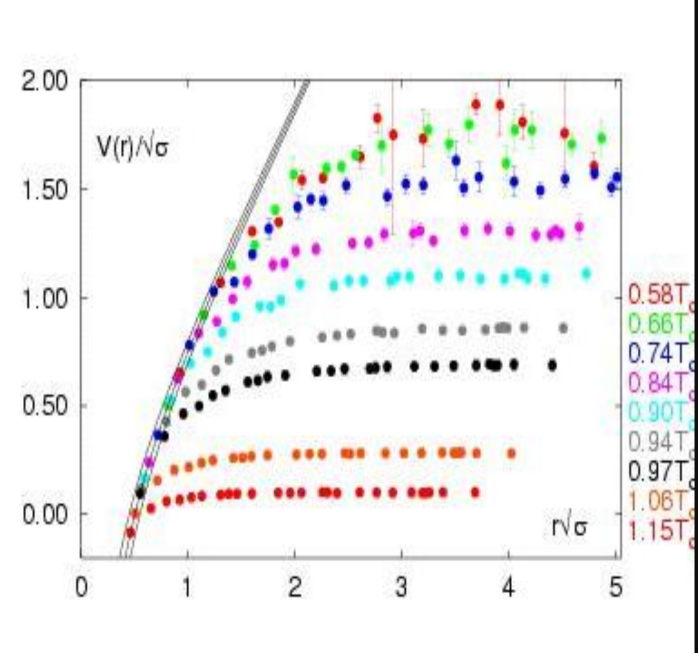


1. J/ψ Production Mechanisms

   Not understood and not addressed in this talk
   see excellent review in arXiv:1010.5827

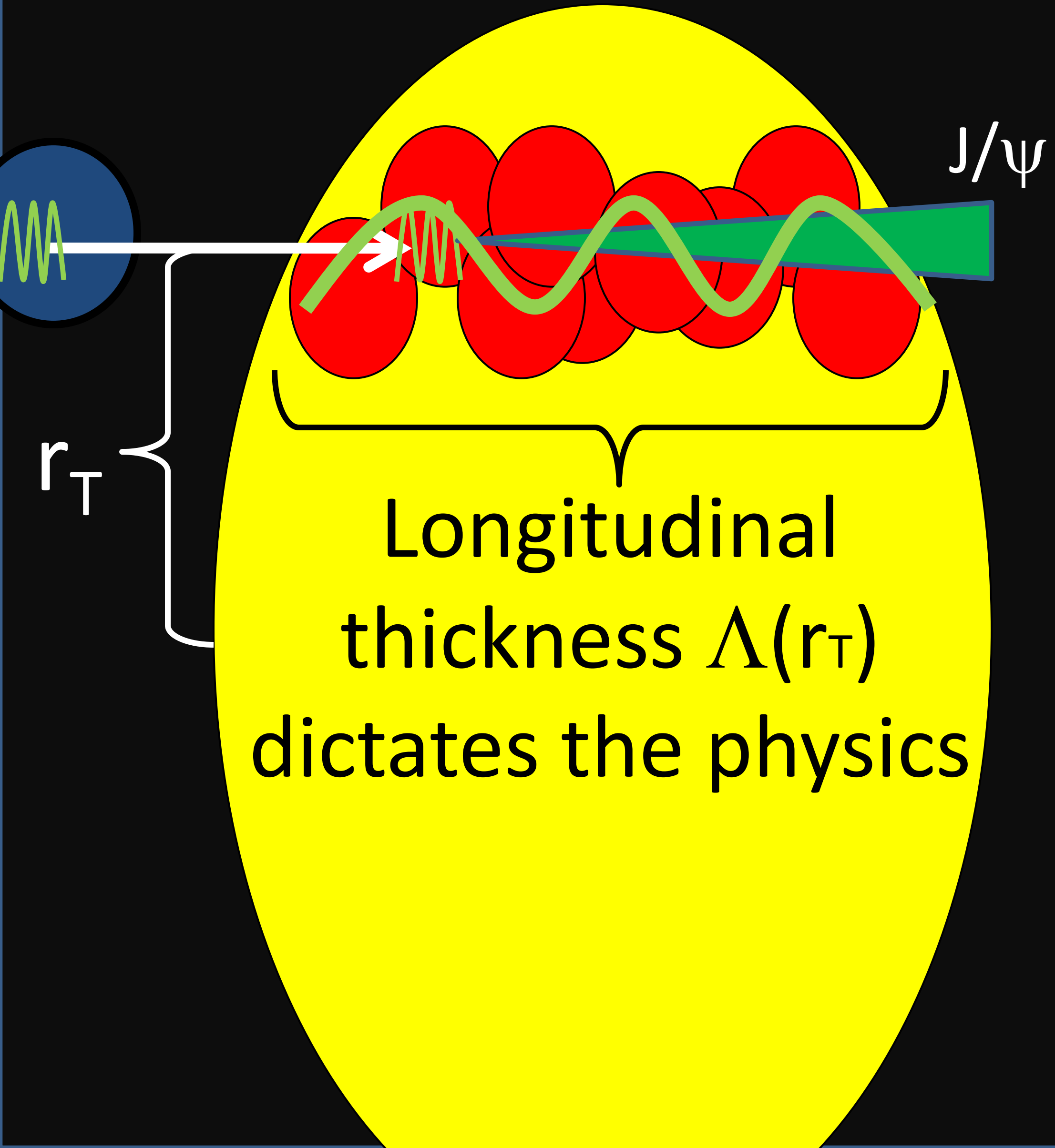
2. Time evolution into color neutral J/ψ state
   (d-Au reactions are an excellent test)

3. Color screening in QGP
   (Au-Au reactions are the test)



Highlight results from PHENIX Experiment
d-Au (Alex Linden-Levy) and
Au-Au (Matt Wysocki Ph.D. thesis) and
theory paper (JN, Frawley, Linden-Levy, Wysocki,
arXiv:1011.4534)

J/ψ Modifications in p-A Reactions



gluon-gluon → $c\,\bar{c}$

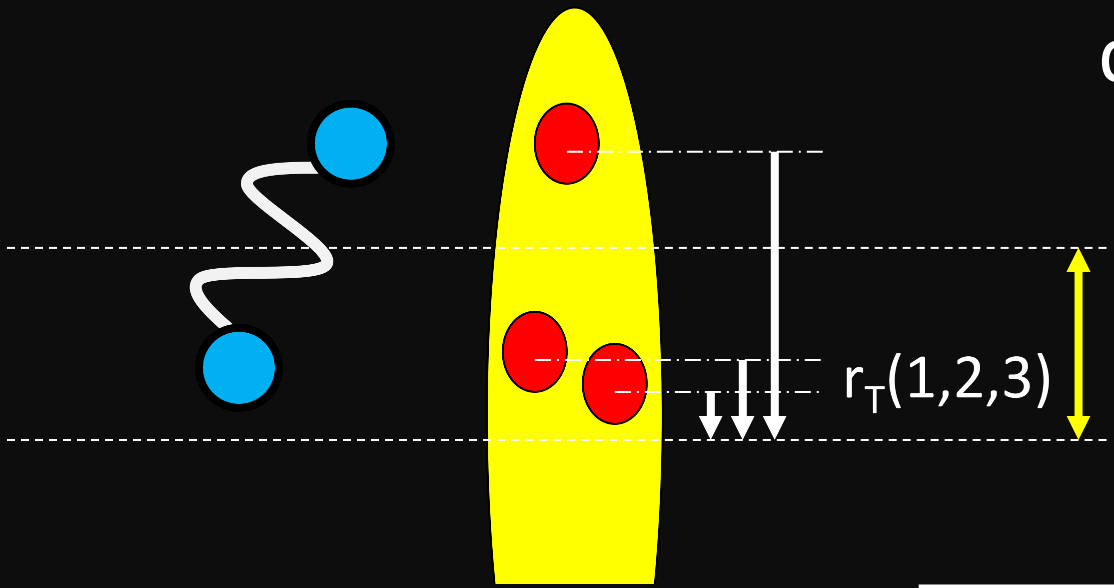
$c\,\bar{c}$ evolves to J/ψ on a timescale of 0.3 fm/c

At RHIC energies, the J/ψ forms outside the Lorentz contracted nucleus

Simplest modifications

1. Shadowing nPDF changes initial charm pair production.
2. Breakup of charm pair in nucleus

deuteron-Au collision

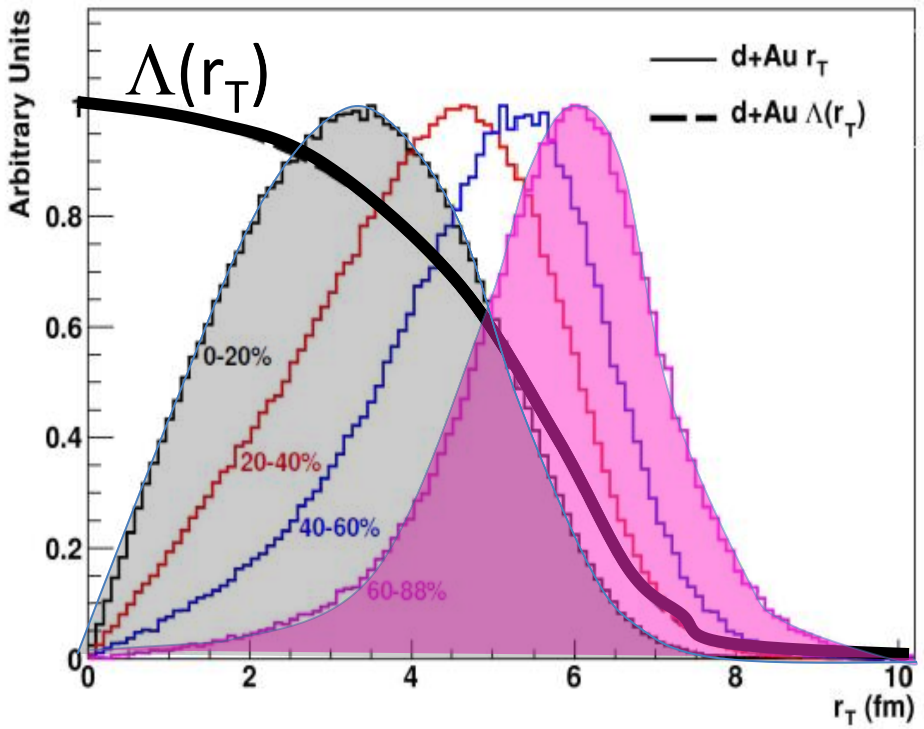


$r_T(1,2,3)$

b = event impact parameter

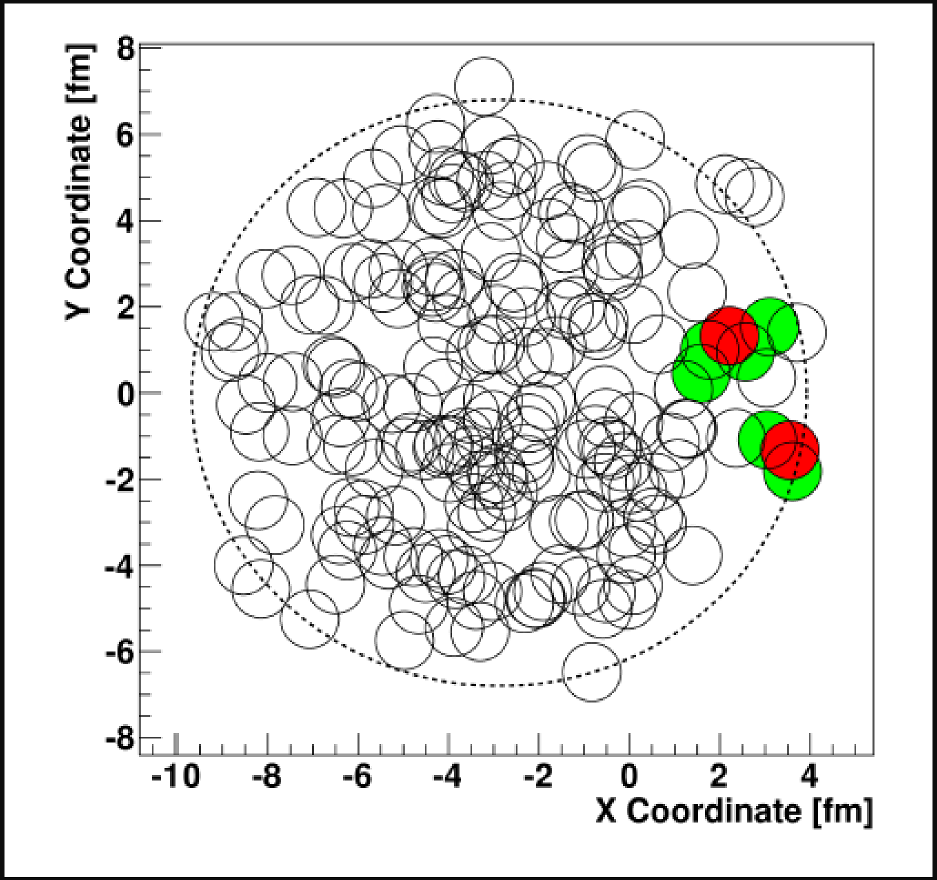
PHENIX collected a high statistics d-Au @ 200 GeV data set in 2008.

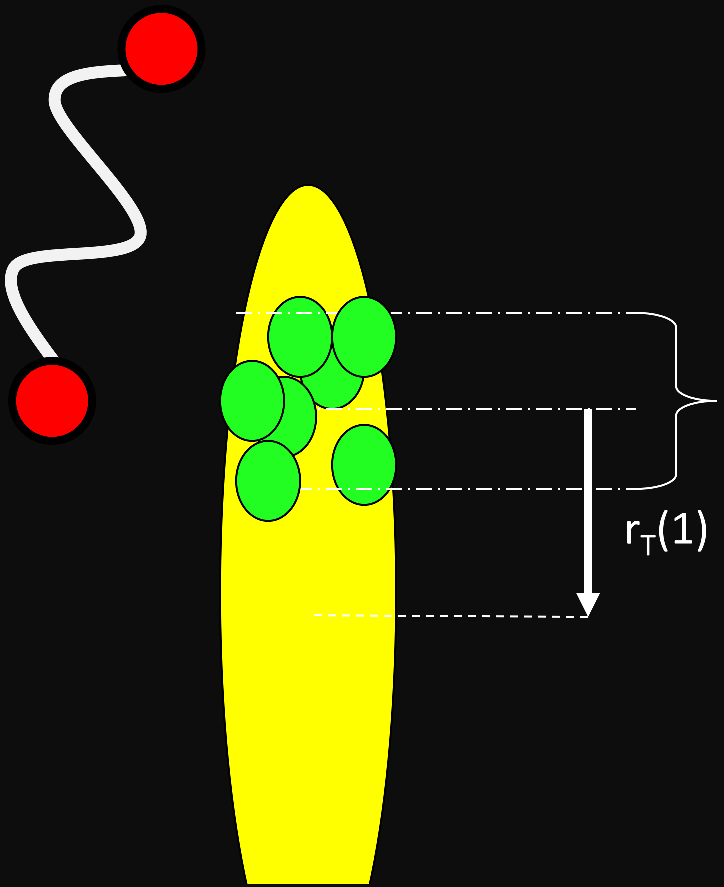
Using multiplicity in Beam-Beam Counter ($3.1 < \eta < 3.9$) we select on d-Au centrality, then use Glauber MC to determine r_T distributions.



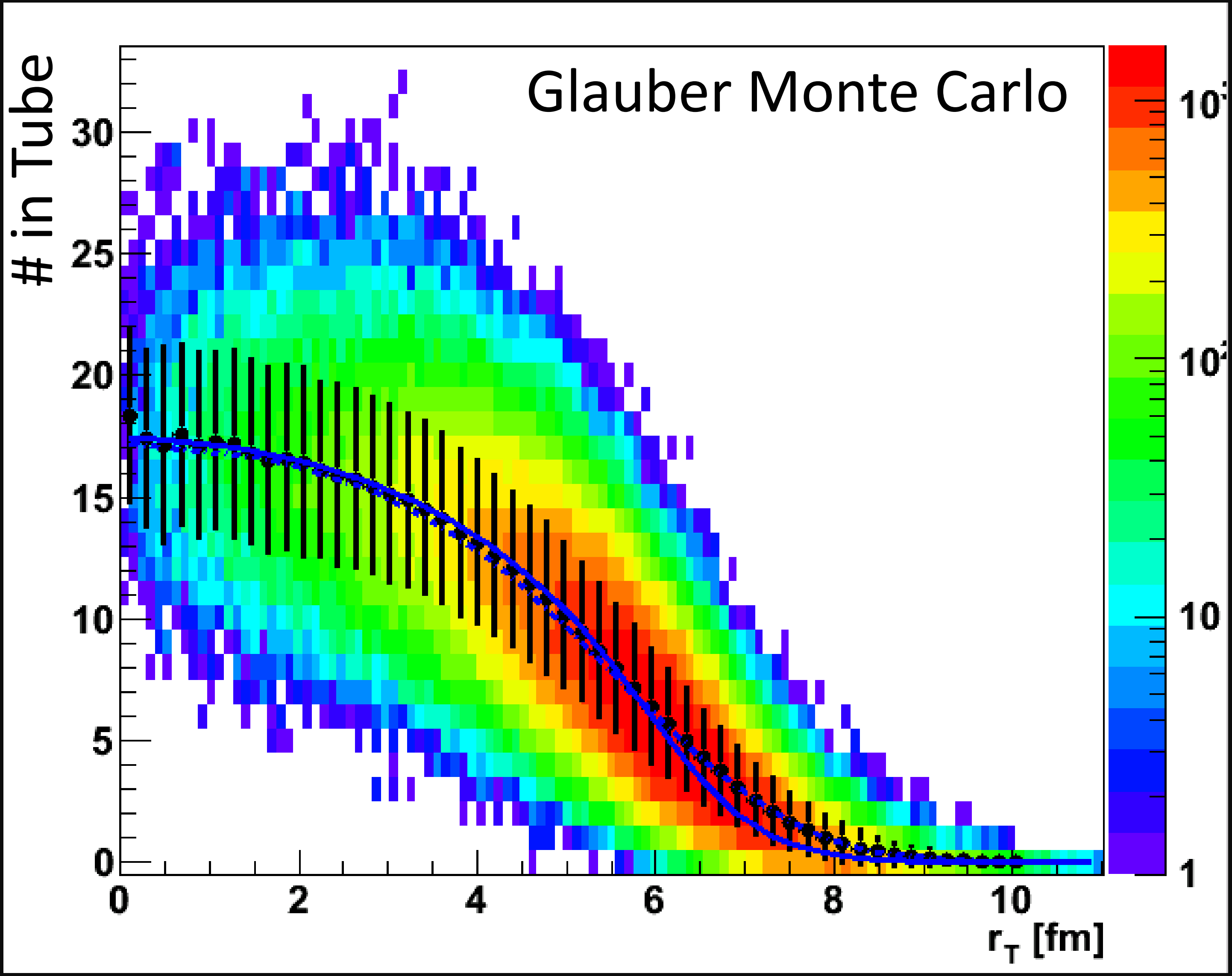
PHENIX arxiv:1010.1246v1

The nucleus is quite lumpy. Longitudinal thickness varies event-to-event.





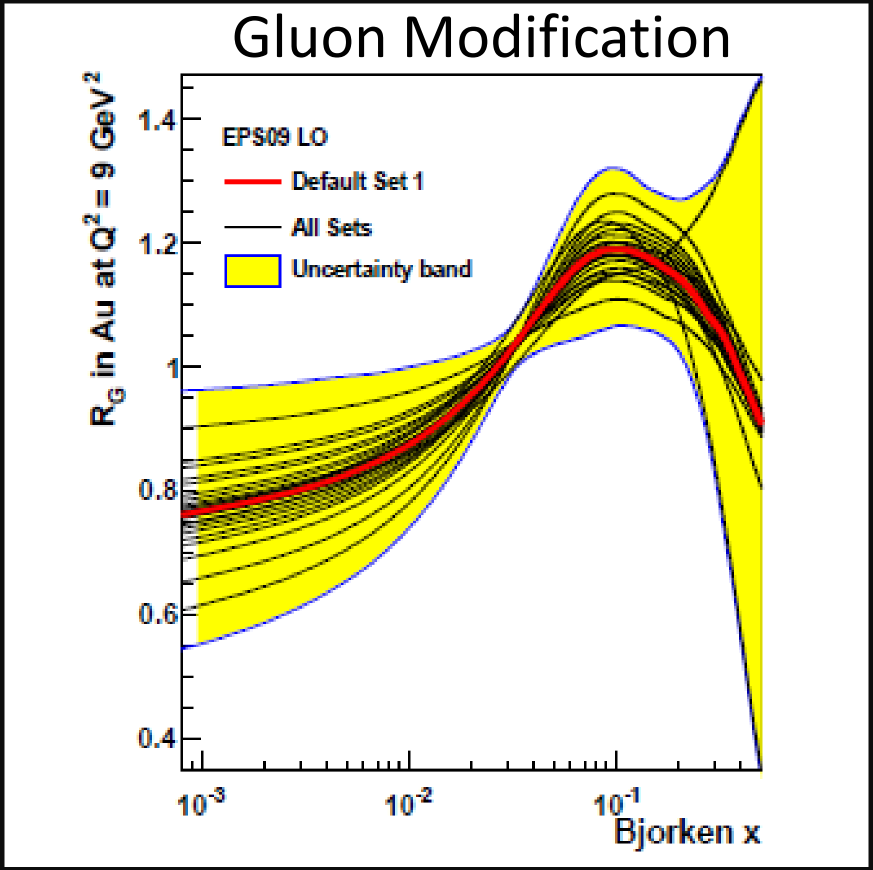
Thus, calculate the thickness $\Lambda(r_T)$ for each sampled charm pair production point by counting the number of nucleons in a tube (Ntube).



At the center of the nucleus, <N_{tube}> ≈ 18 and the rms ≈ 5.

Never believe any calculation with a smooth nucleus.

Nuclear Modified Parton Distribution Functions



EPS09 provides constrained nPDFs and with quantified uncertainties.

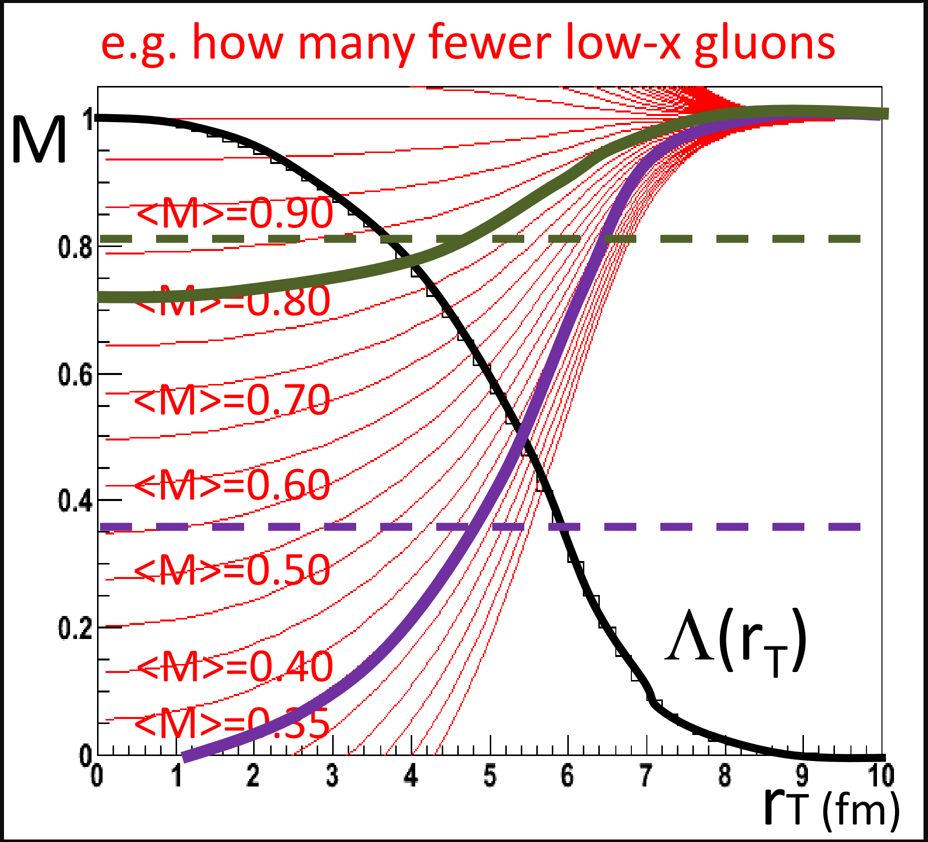
However, there is <u>no $\Lambda(r_T)$ dependence</u> (only average modification)

Many calculations in the literature assume that the modification is linear in the thickness

What does that look like?

Geometric Mapping

Modification (M) linear in $\Lambda(r_T)$ for different average <M>


e.g. how many fewer low-x gluons

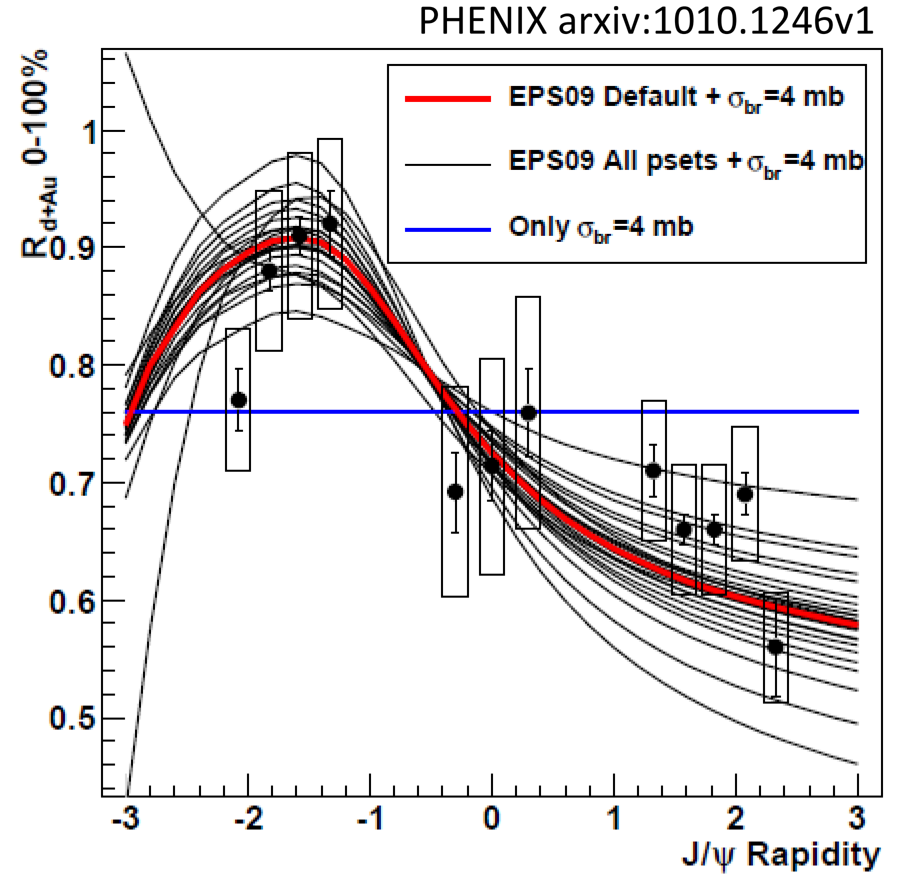
$$\text{Linear}: M(r_T) = 1.0 - a\Lambda(r_T)$$

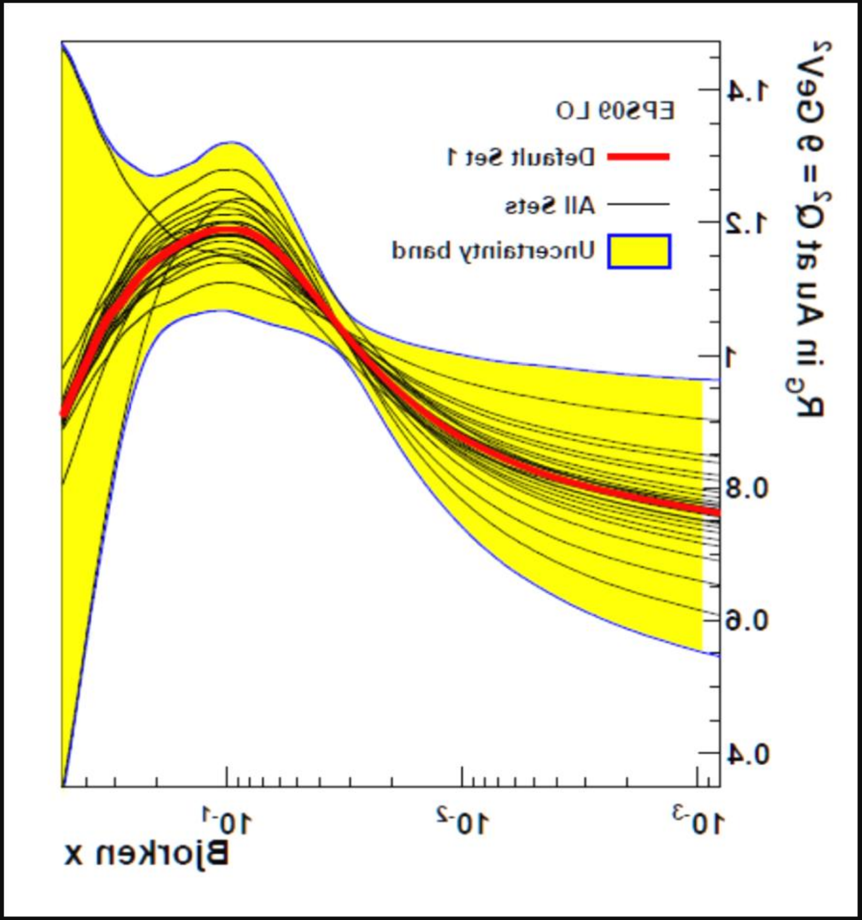
For <M> ≈ 0.35, one is forced to have a negative value at small r_T.

This is unphysical.

Also try other forms…

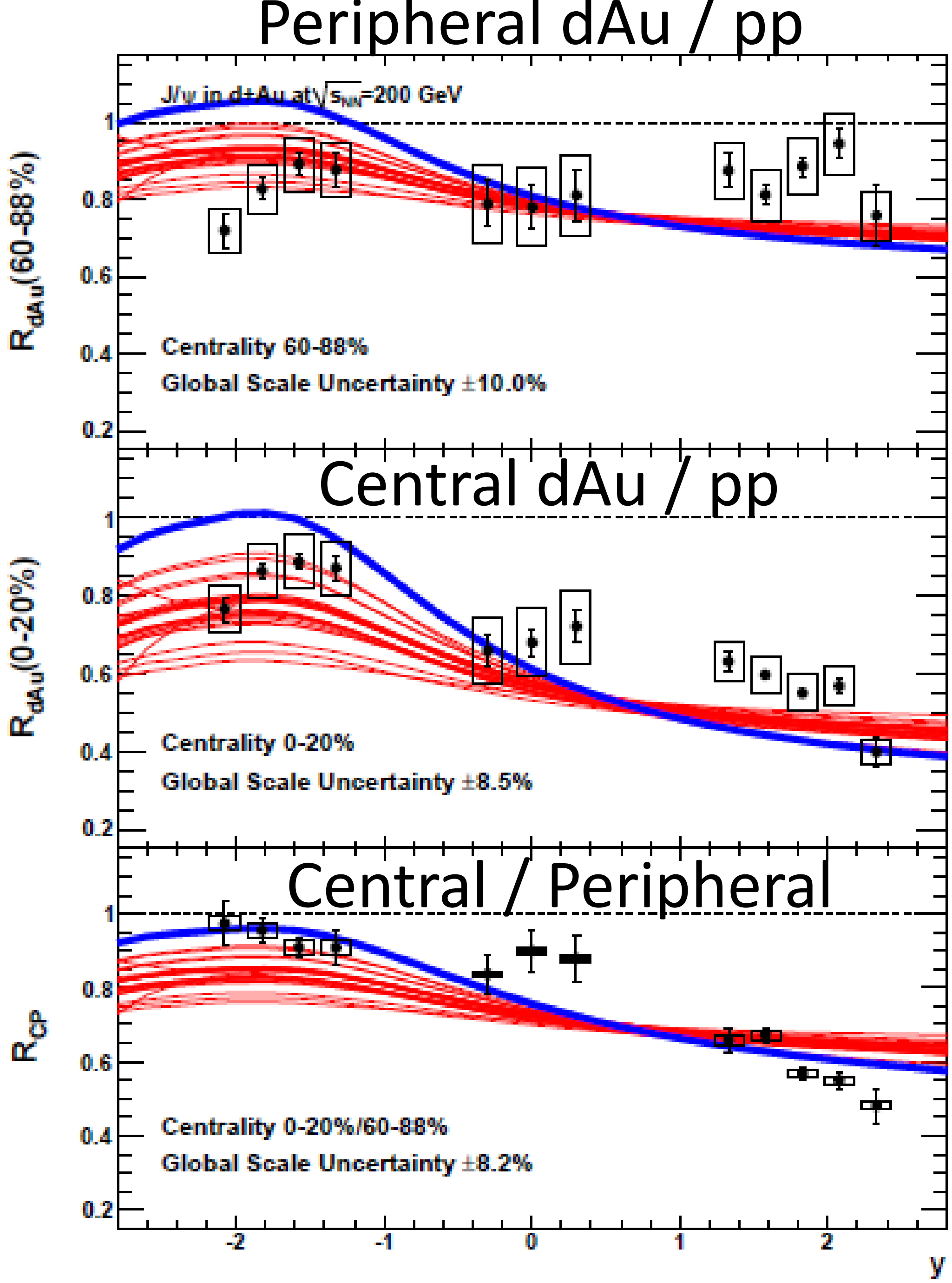
J/ψ Data Averaged Over All Geometries





We test all EPS09 nPDF variations and find reasonable agreement within uncertainties by including σ_{br}= 4 mb.

Rapidity dependence comes entirely from nPDF.



For each EPS09 nPDF set, fit the data including statistical and systematic uncertainties to find the best σ_{br}.

Best fit EPS09 pset = 17 and σ_{br} = 3.2 mb. However, the fit is very poor (pvalue < 0.0001).

Data cannot be described by **<u>any</u>** combination of EPS09 nPDF and σ_{br}!

Geometry Test

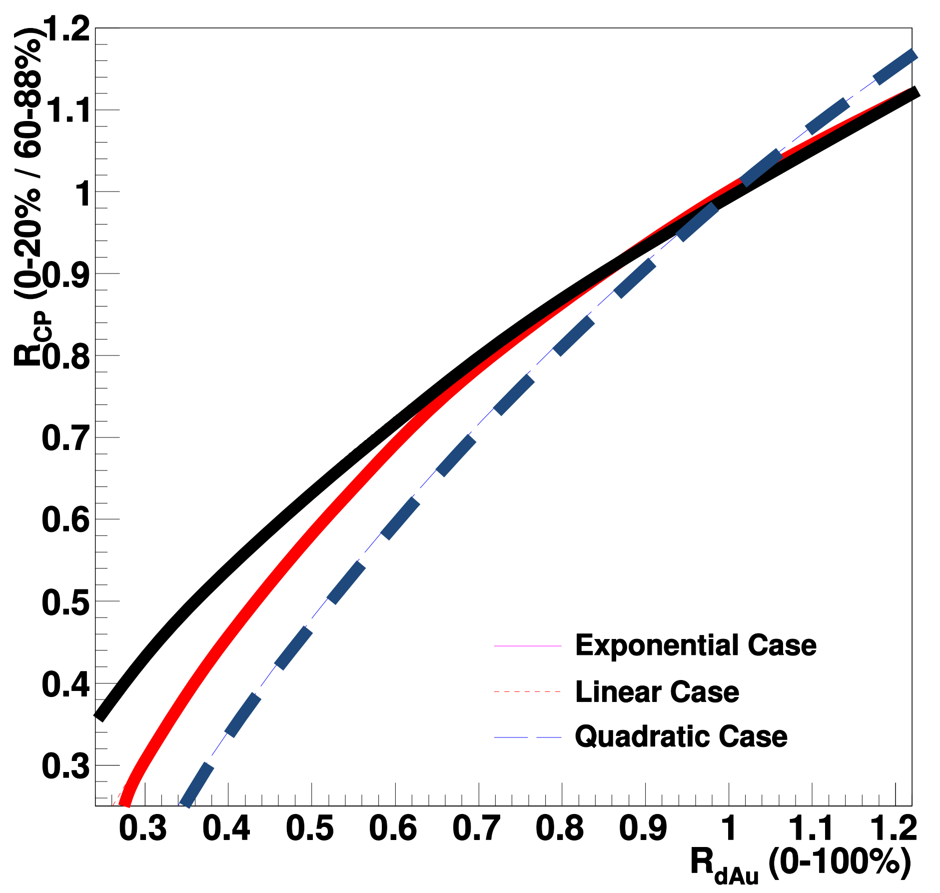
$$\text{Linear}: M(r_T) = 1.0 - a\Lambda(r_T)$$

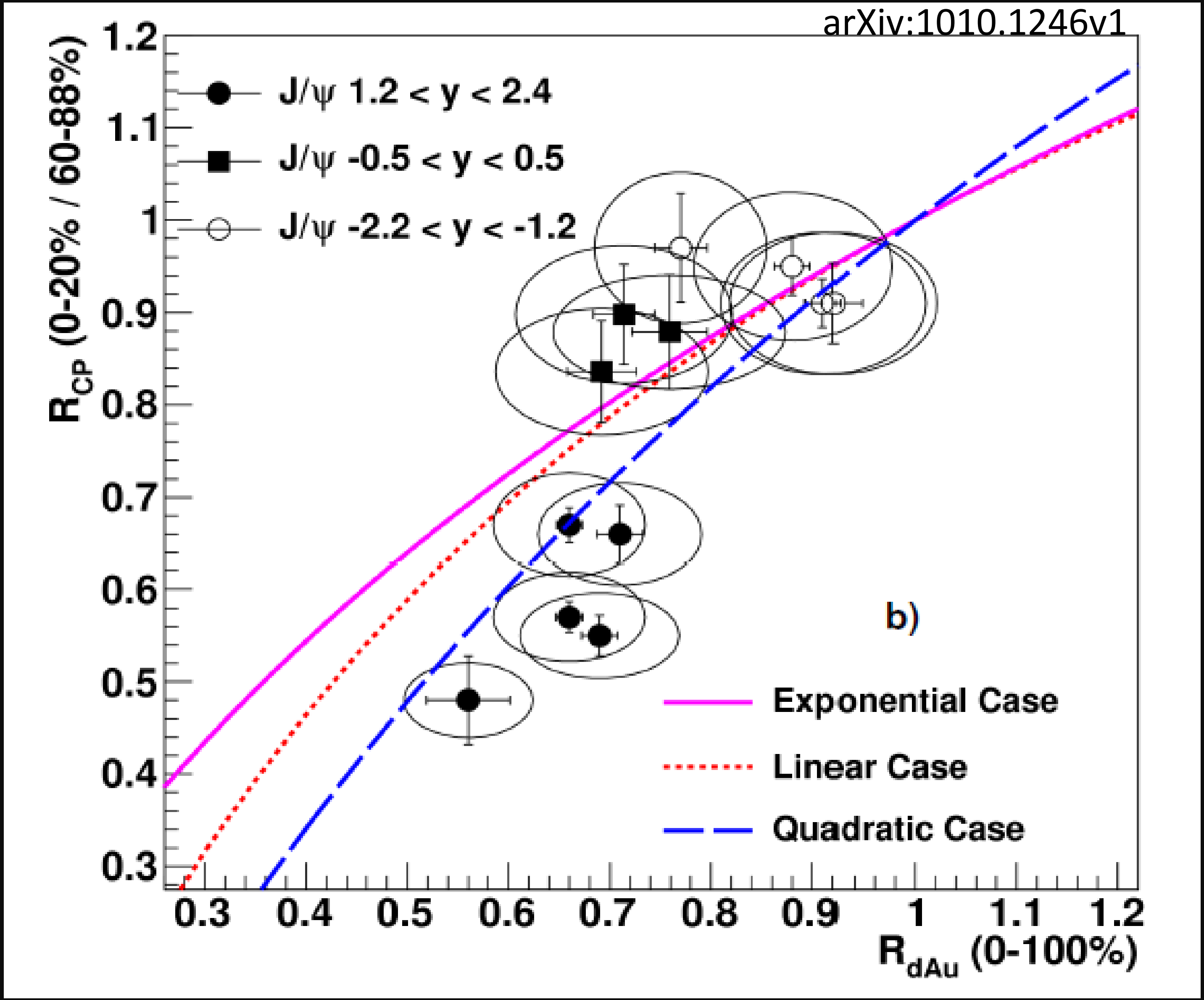
$$\text{Quadratic}: M(r_T) = 1.0 - a\Lambda(r_T)^2$$

$$\text{Exponential}: M(r_T) = e^{-a\Lambda(r_T)}$$

For each value of **a** and the distribution for $\Lambda(r_T)$ one can calculate R_{dAu} for every centrality case.

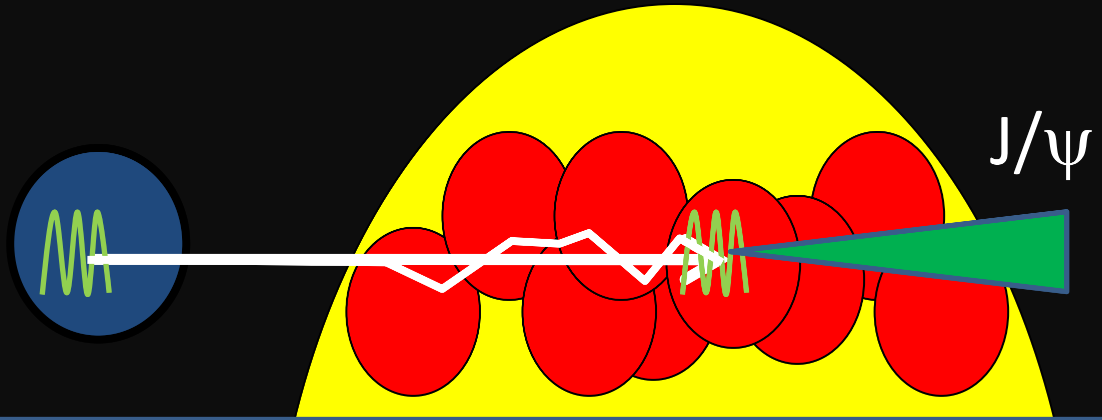
For the Linear Case, for any values of **a**, there is a unique relationship between the average suppression (R_{dAu}) and the steepness versus centrality (R_{CP}).



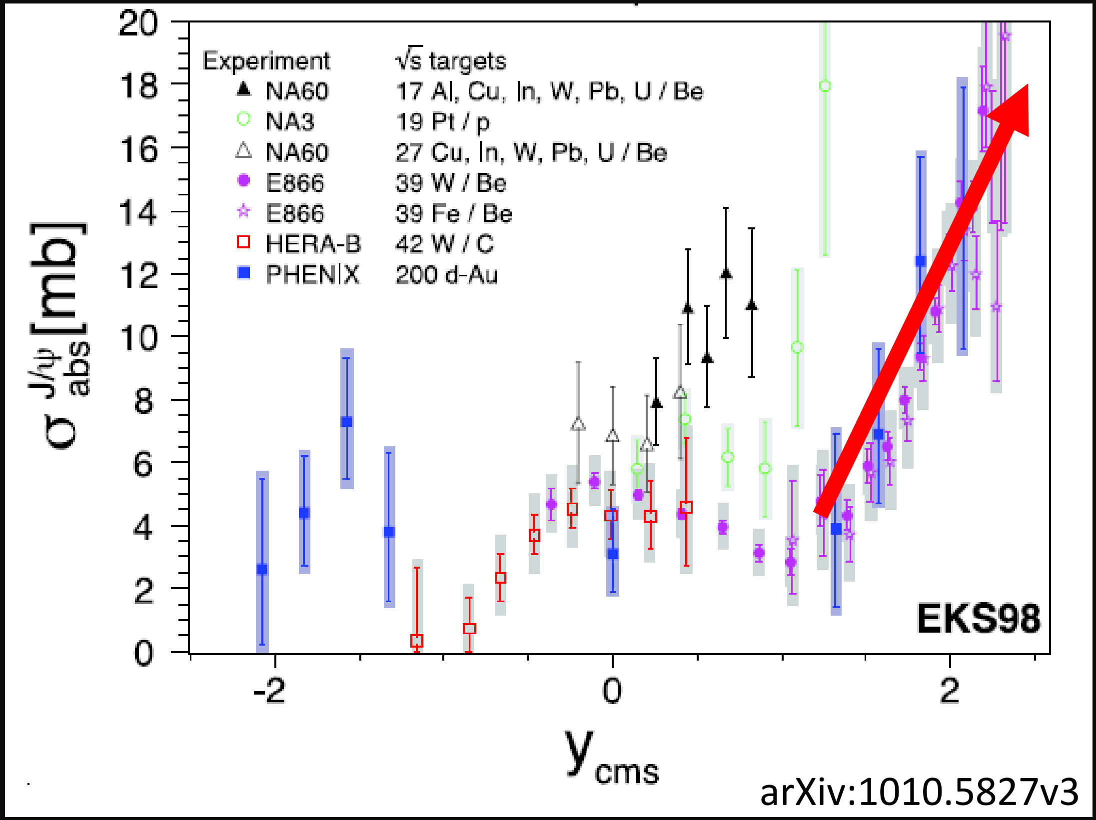


Data driven proof that non-linear (in the thickness) physics effects must contribution to J/ψ modification.

Initial State Parton Energy Loss



Energy loss of incoming gluon prior to hard scatter creating charm pair



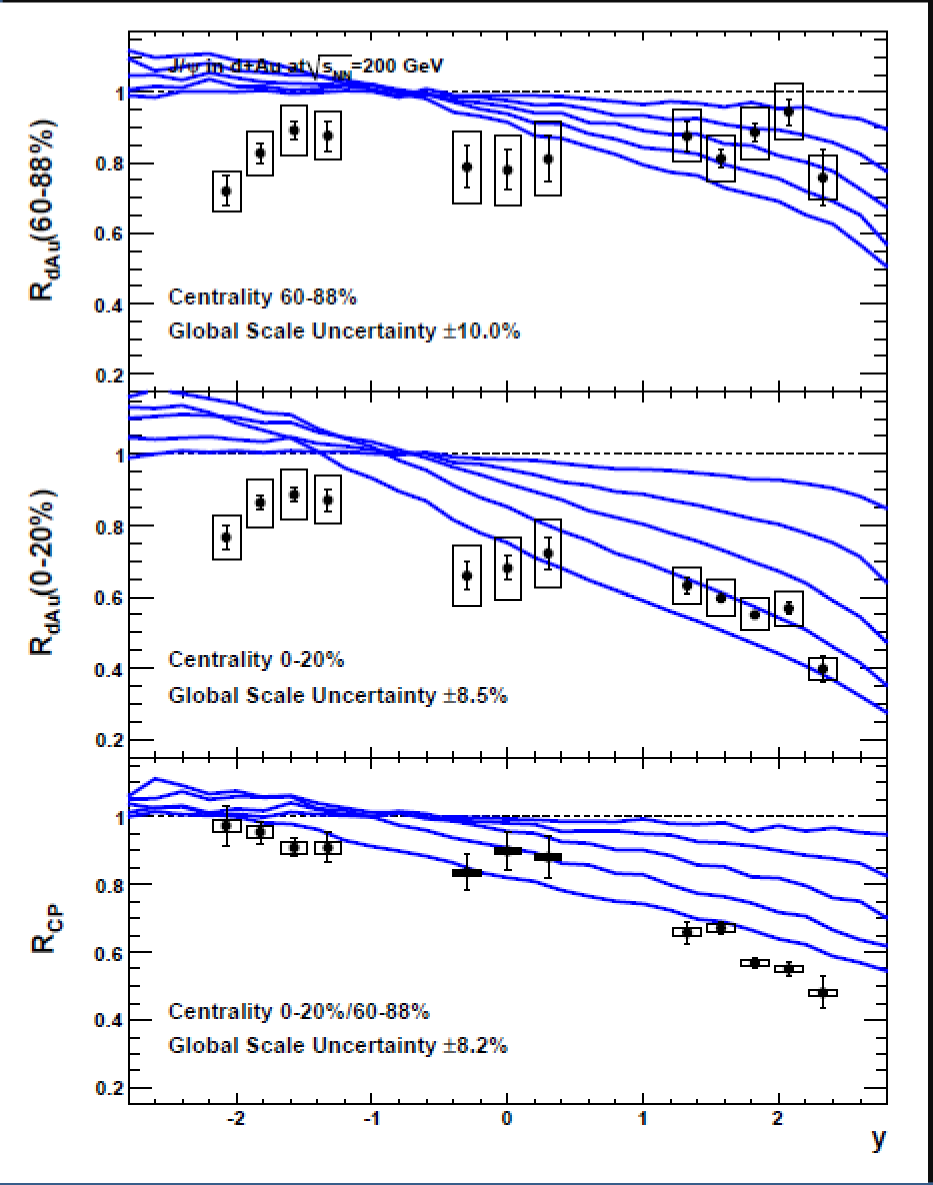
arXiv:1010.5827v3

Fit each rapidity point to a separate σ_{br}, yields rapid increase of σ_{br} at forward rapidity.

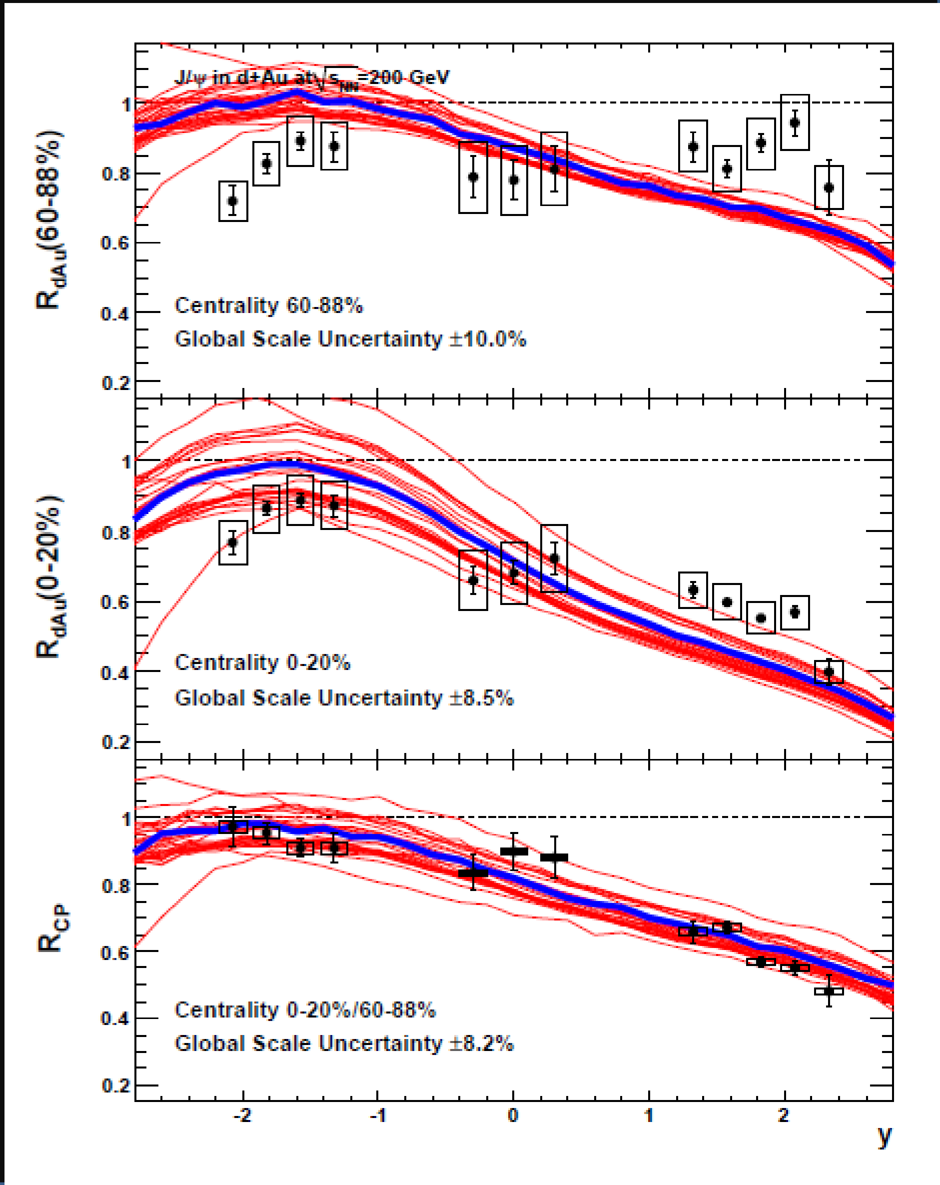
Initial state energy loss of high x partons?

Initial parton energy loss in our calculation (ΔE α L or L^2)

Only e-loss (ΔE α L)

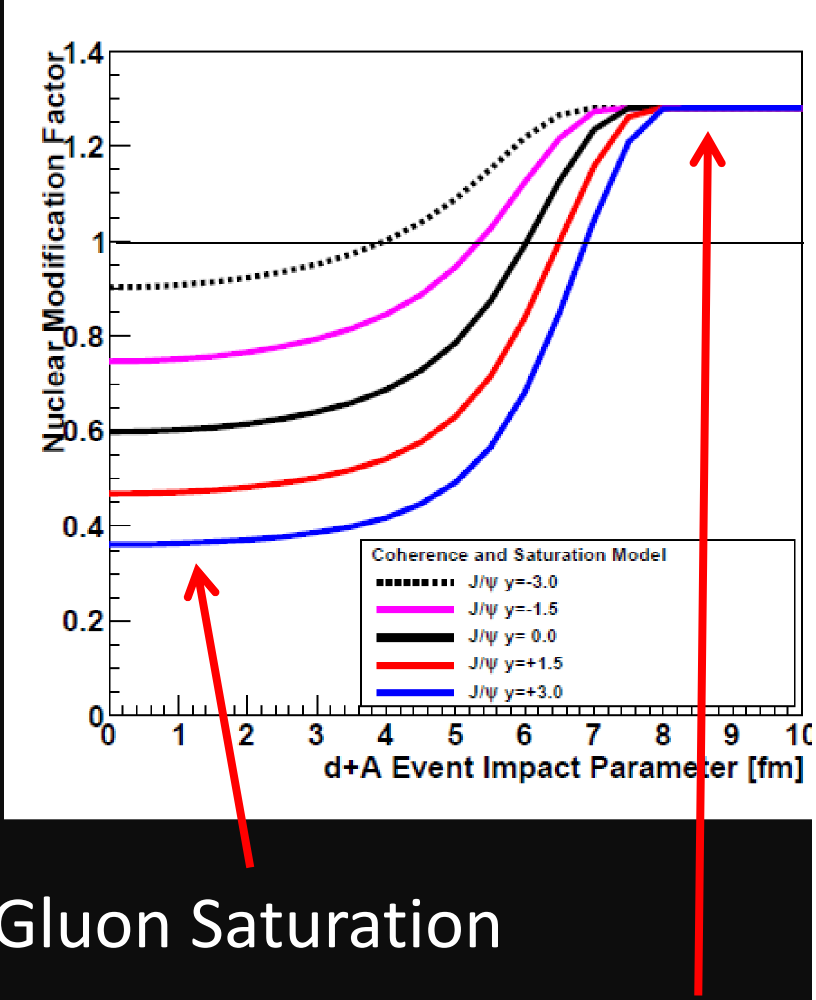


Best fit e-loss, nPDF, σ_{br}



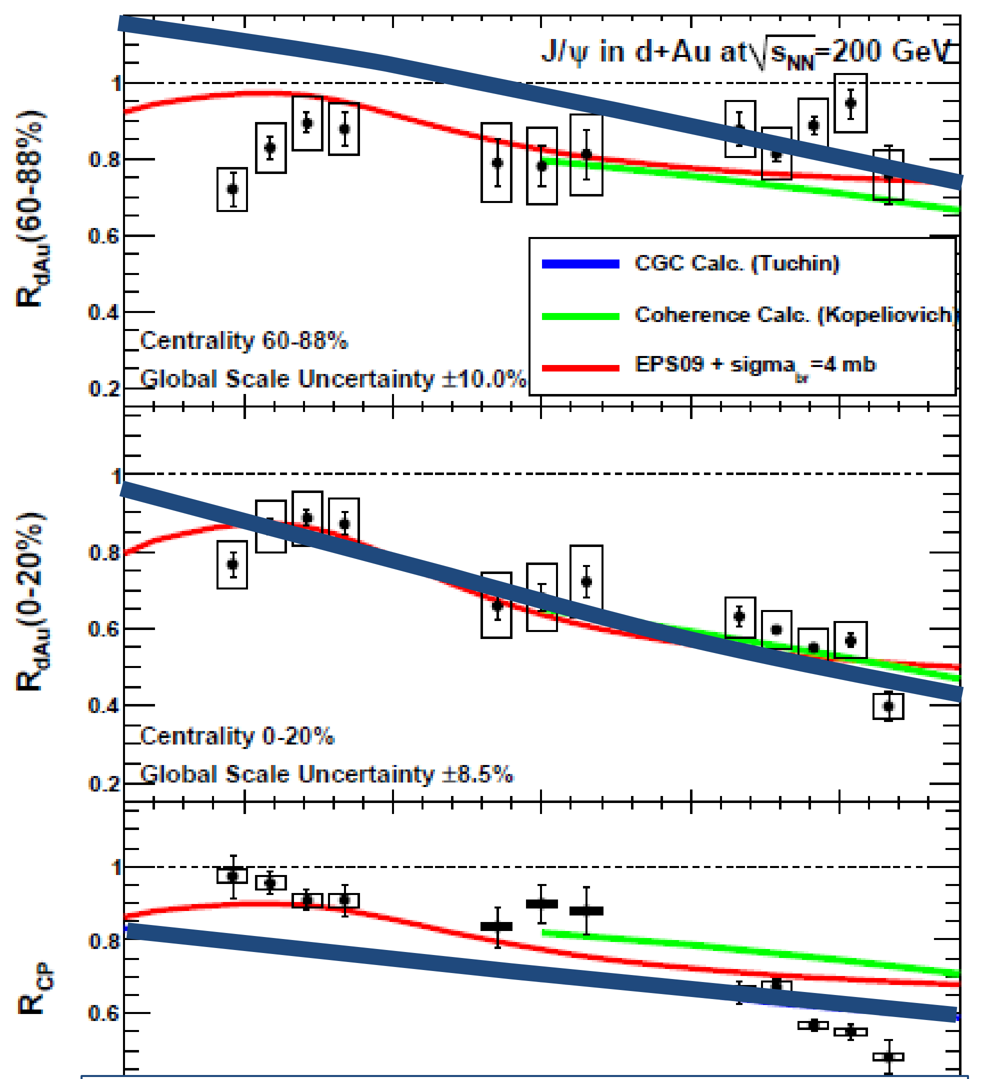
Coherence Calculations

Color Glass Condensate
K. Tuchin



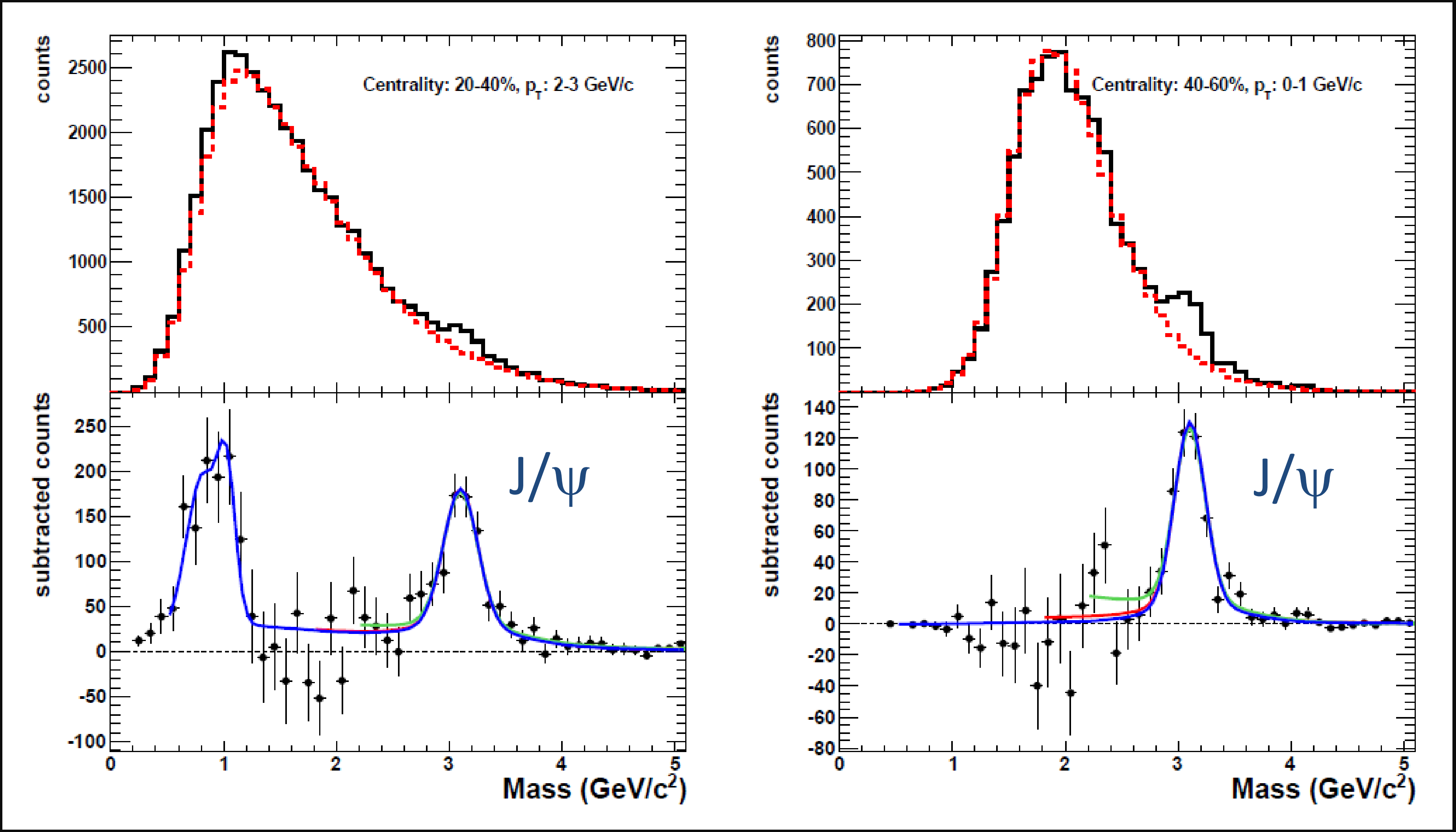
Gluon Saturation

Double gluon exchange



But peripheral makes no physics sense.

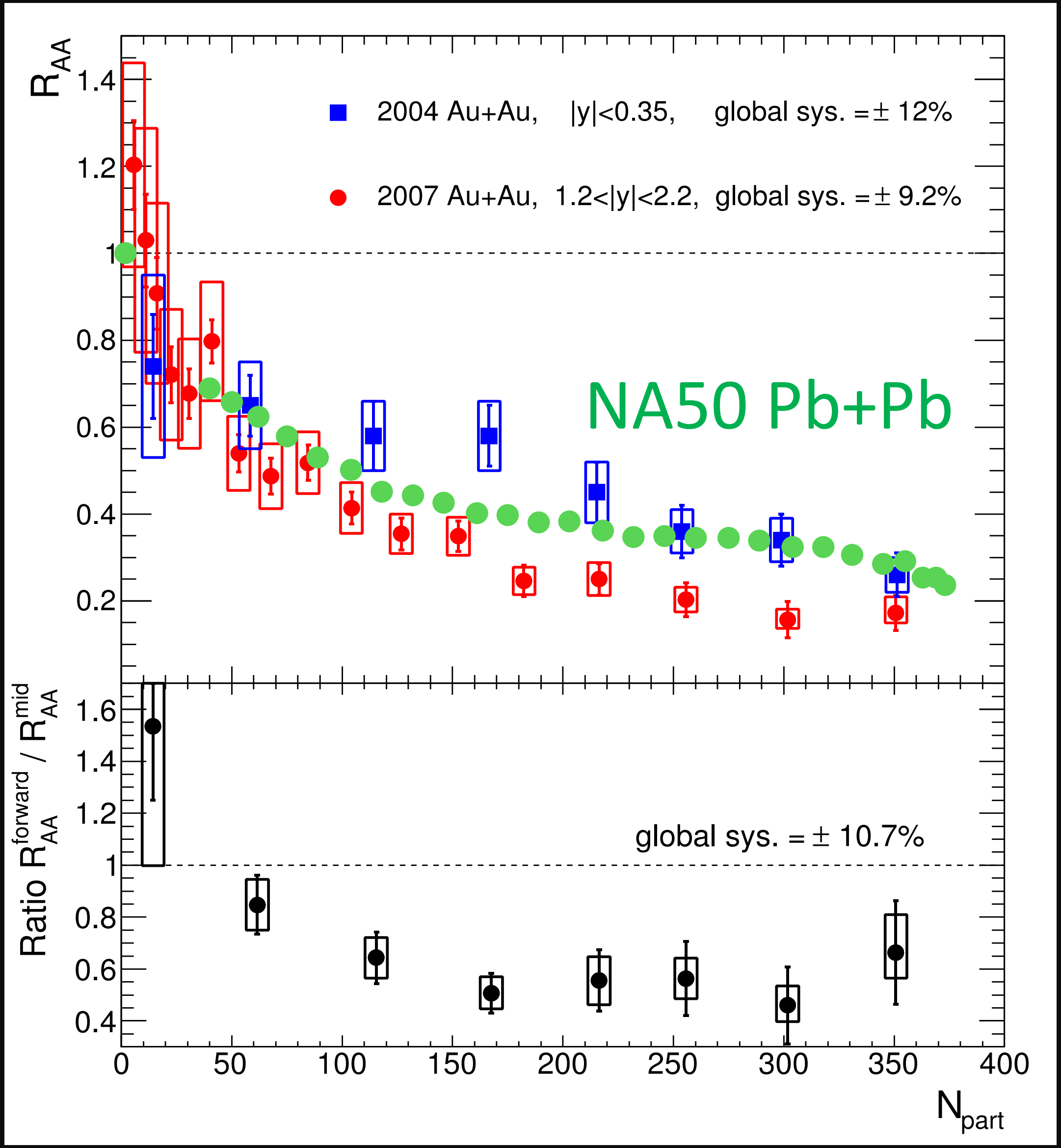
Gold-Gold Data (arXiv:1103.6269 and Wysocki Ph.D.)



Challenging analysis with low signal to background.

Over 3 billion Au+Au events recorded for analysis.

PHENIX Data



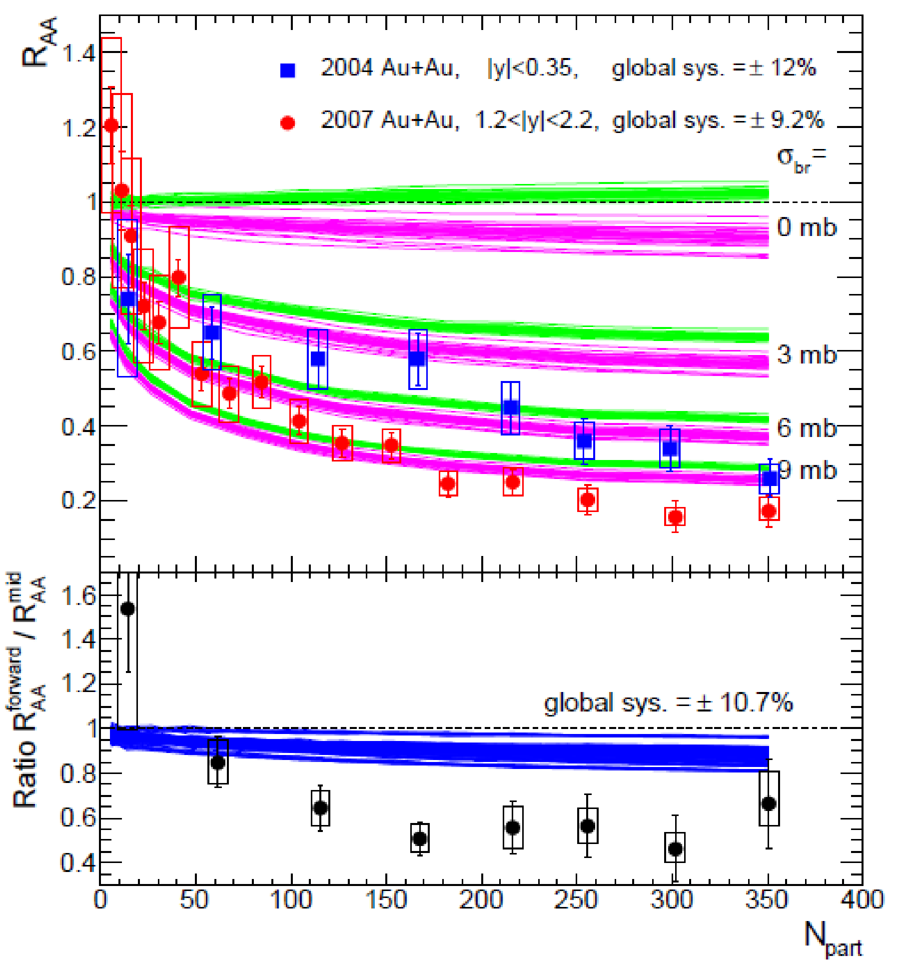
Very similar suppression at CERN-SPS and RHIC at mid-rapidity.

New data confirms with precision the larger suppression at forward rapidity.

Is this just a cold nuclear matter effect?

Extrapolate Cold Nuclear Matter Effects

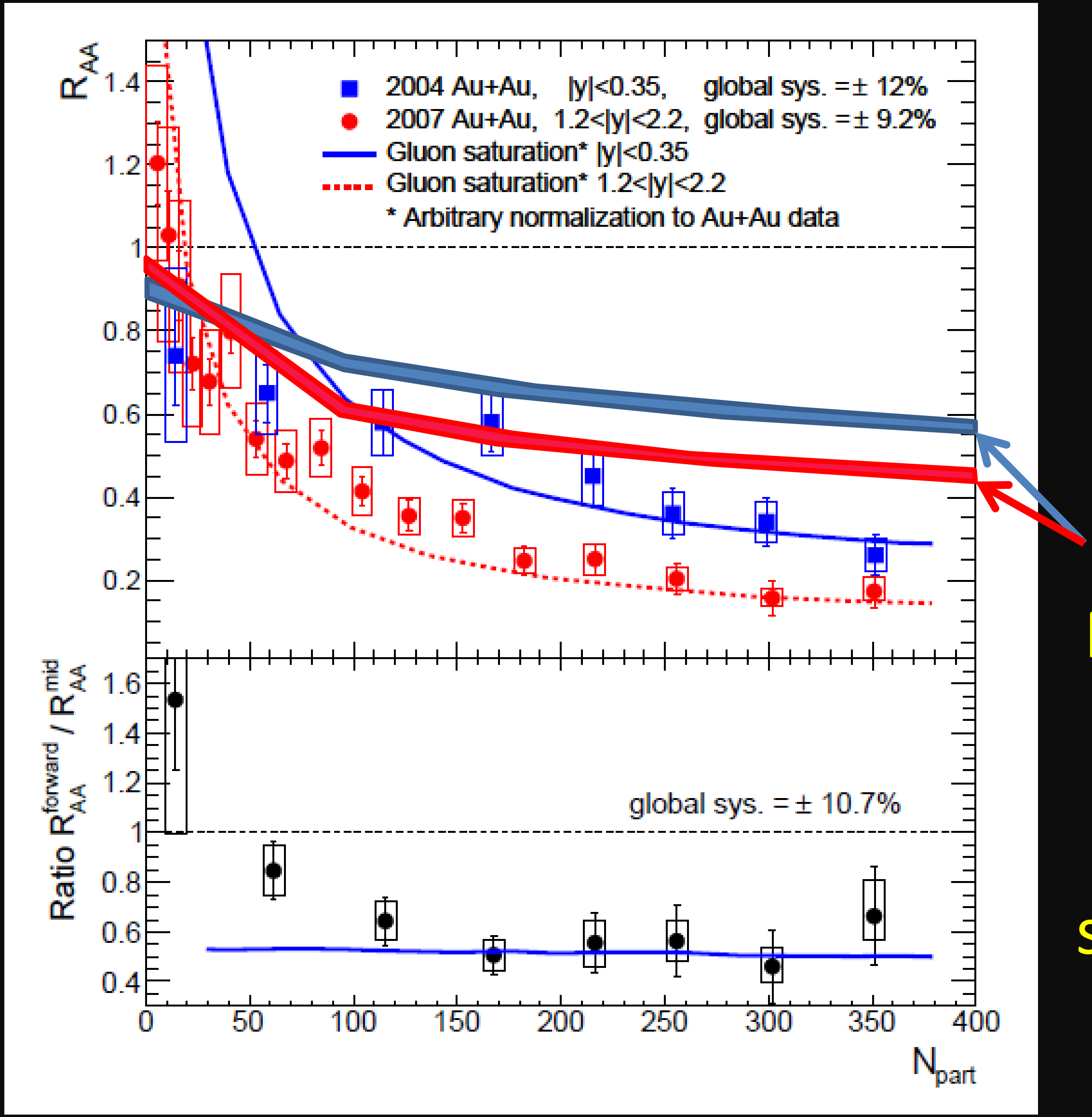
We calculate with all EPS09 parameterizations and σ_{br}.
Almost no additional forward suppression – cancellation of low-x gluon (↓) and high-x gluon (↑).



Including energy loss matched to d-Au data does very little to change the picture.

Hot nuclear matters (perhaps screening) effects are definitely important.

Gluon Saturation (Color Glass Condensate)



Appears to describe data and forward suppression.

However, arbitrary normalization to data.

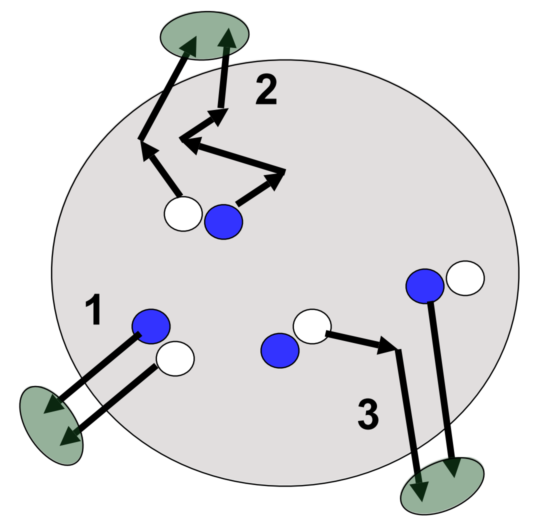
New calculation from M. Nardi et al. indicate much smaller effect.

At Hard Probes 2010, she declared that there are definitely final state effects.

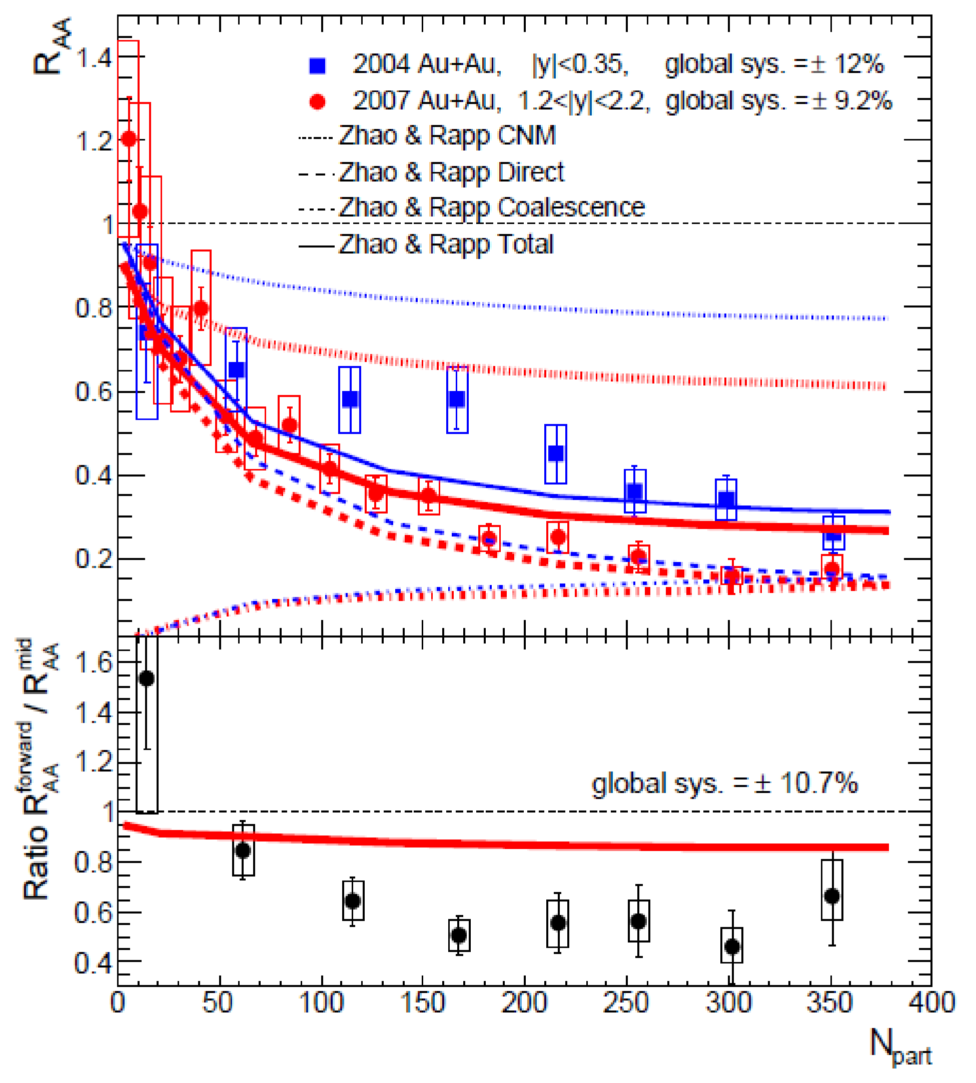
Charm Recombination

Similar R_{AA} as lower energies due to larger screening loss compensated by later recombination (?)

Less recombination at forward rapidity since lower ccbar density.



No effect, recombination of "diagonal pairs" dominates



Quarkonia Summary

Precision d-Au and Au-Au data sets

Non-linear physics is needed, perhaps e-loss or saturation

No complete description of d-Au data set

Au-Au indicates hot nuclear matter effect, and exact quantification remains elusive

206 citations for PHENIX PRL (2007), but no breakthrough

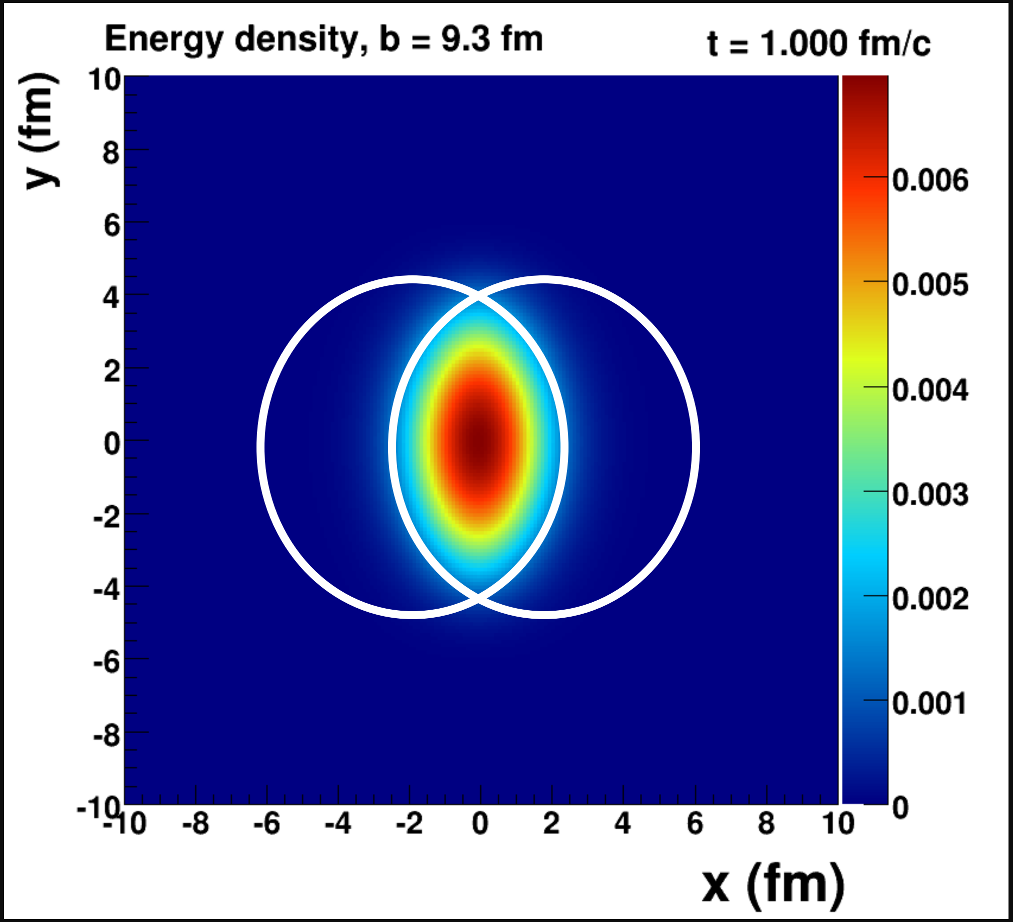
Near future data from lower energies 39 GeV, 62 GeV from PHENIX and LHC data may shed light…

Upgrades to push for even more forward measurements including Drell-Yan to disentangle effects.

Harmonic Flow and Constraining QGP Properties

Our mental picture of heavy ion collisions has evolved…

Smooth initial conditions

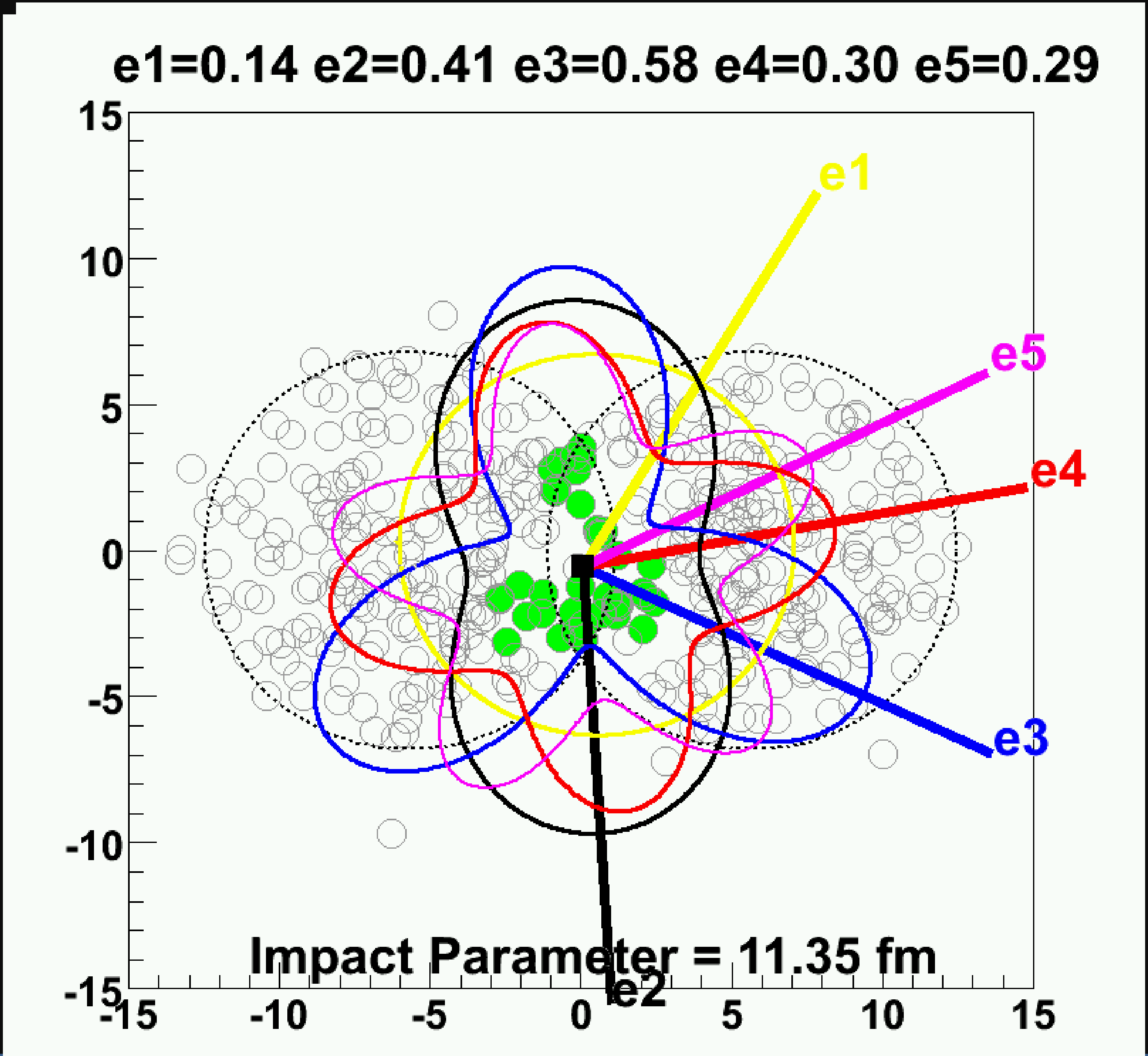


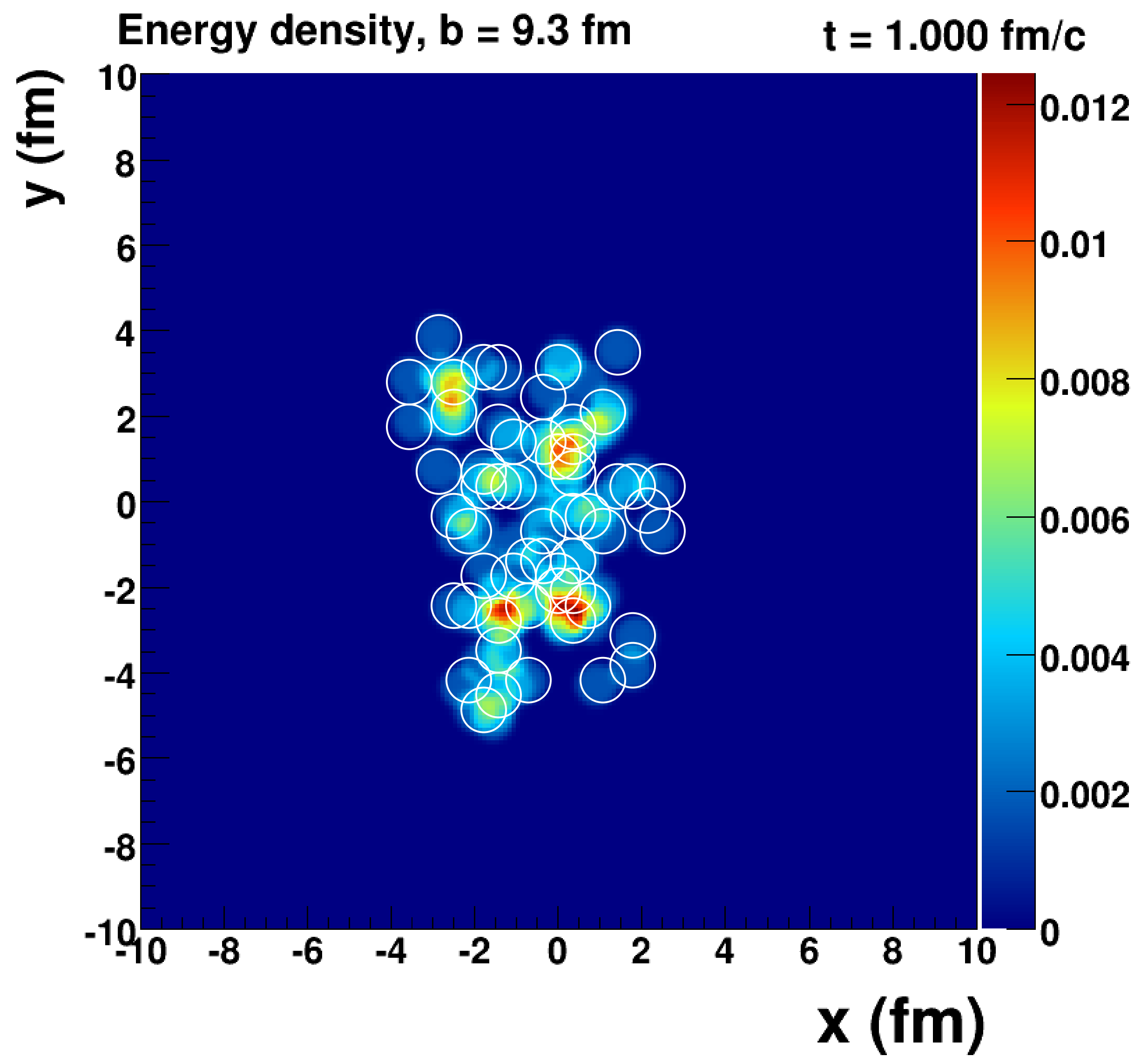
Need to know initial geometric shape.

Initial Eccentricity ε_2 results in cos(2ϕ) flow called v_2.

Measured v_2 is sensitive to key QGP properties like the shear viscosity η/s.

Reality = Lumpy Initial Conditions



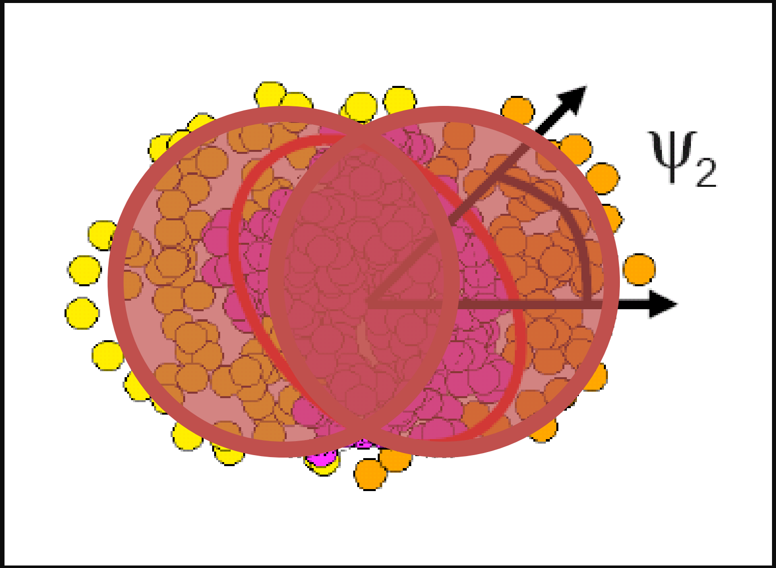


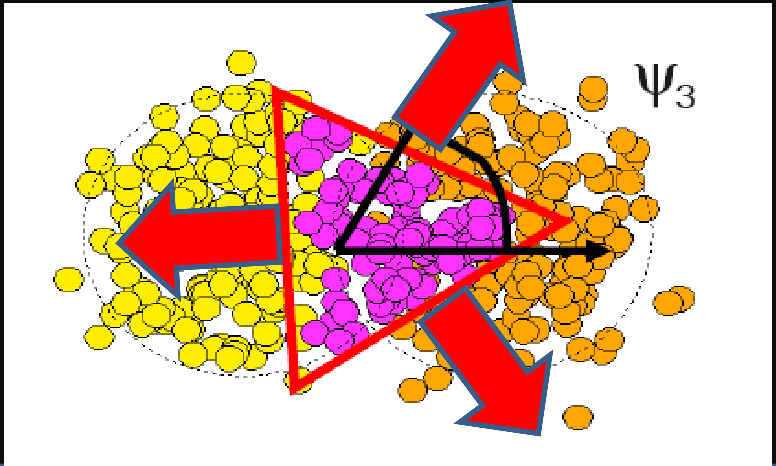
Romatschke=viscous hydrodynamics, McCumber=lumpy conditions + animation

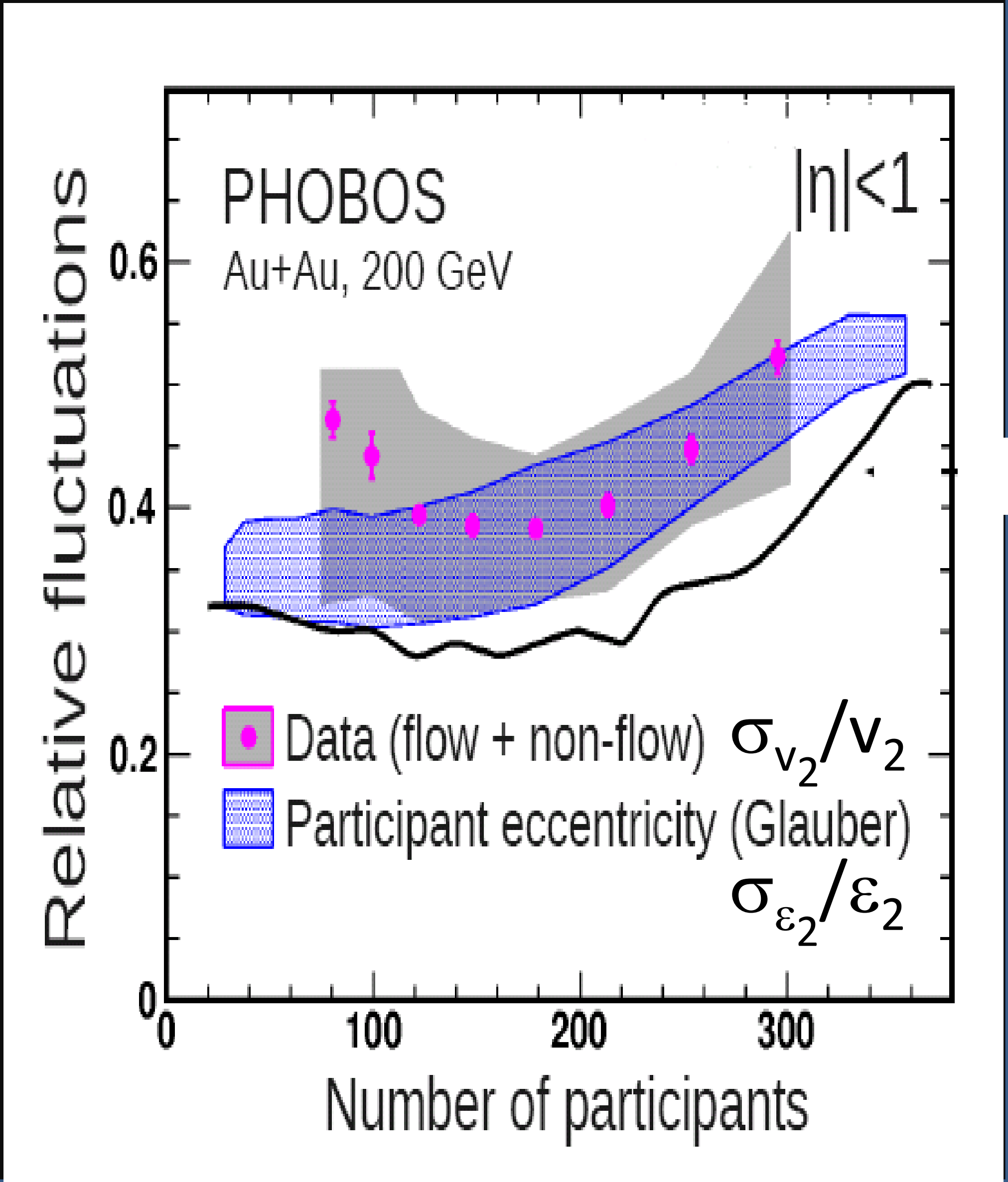
Fluctuations Dominate

$\sigma(v_2)/v_2$

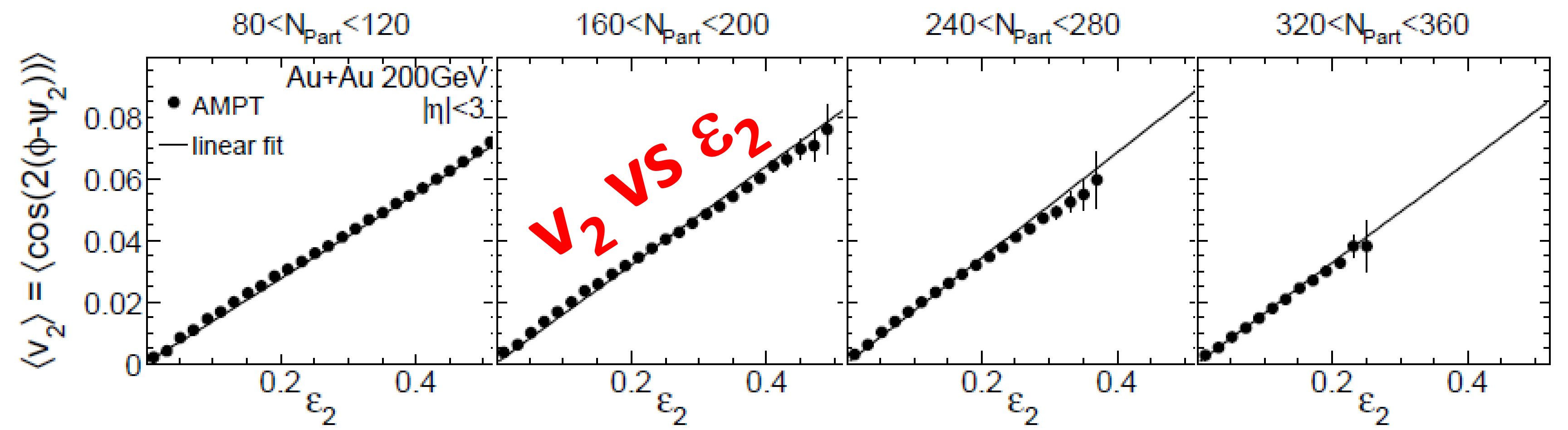
Flow dictated by participating nucleon geometry







Spatial moments translate into momentum anisotropy moments

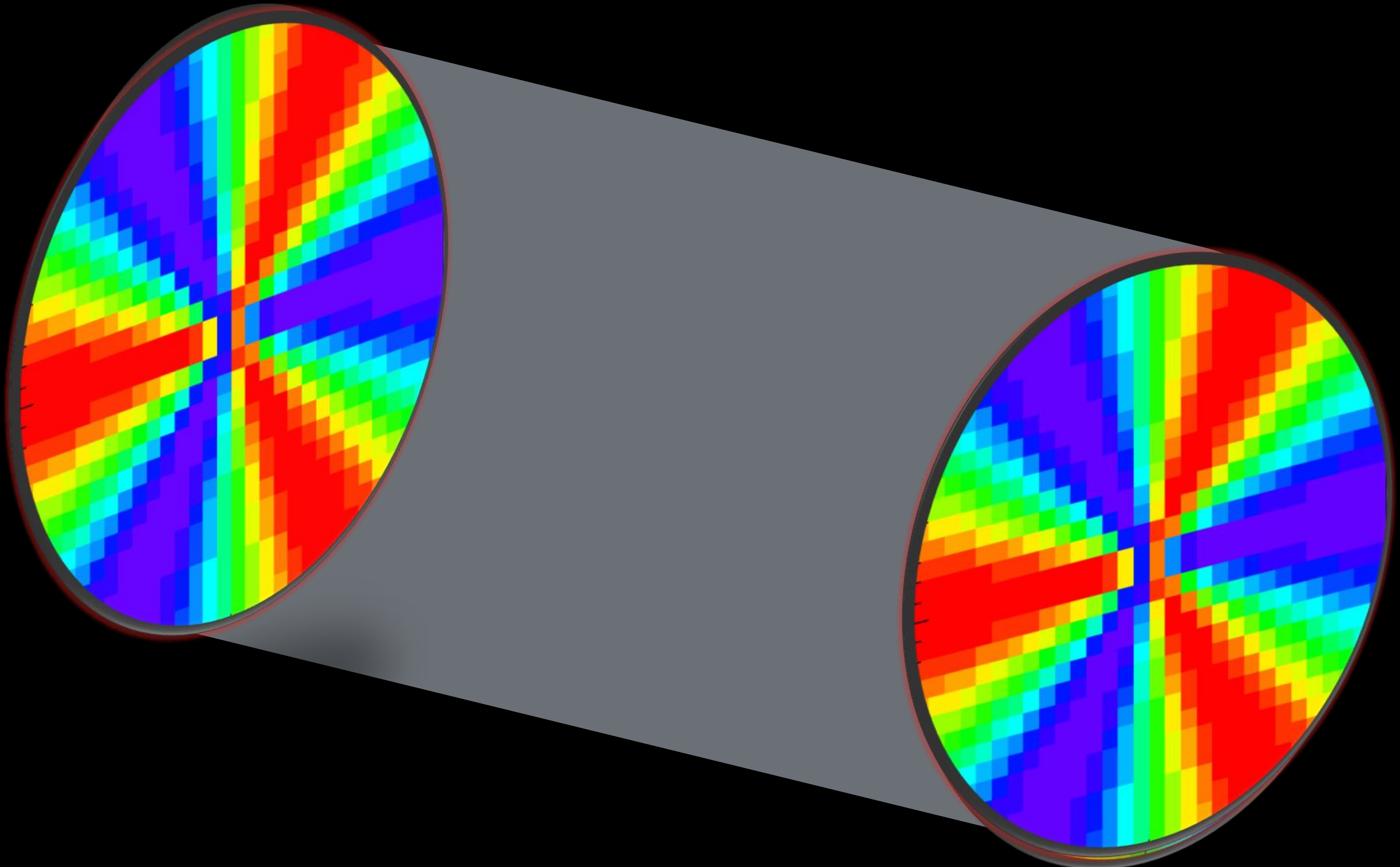


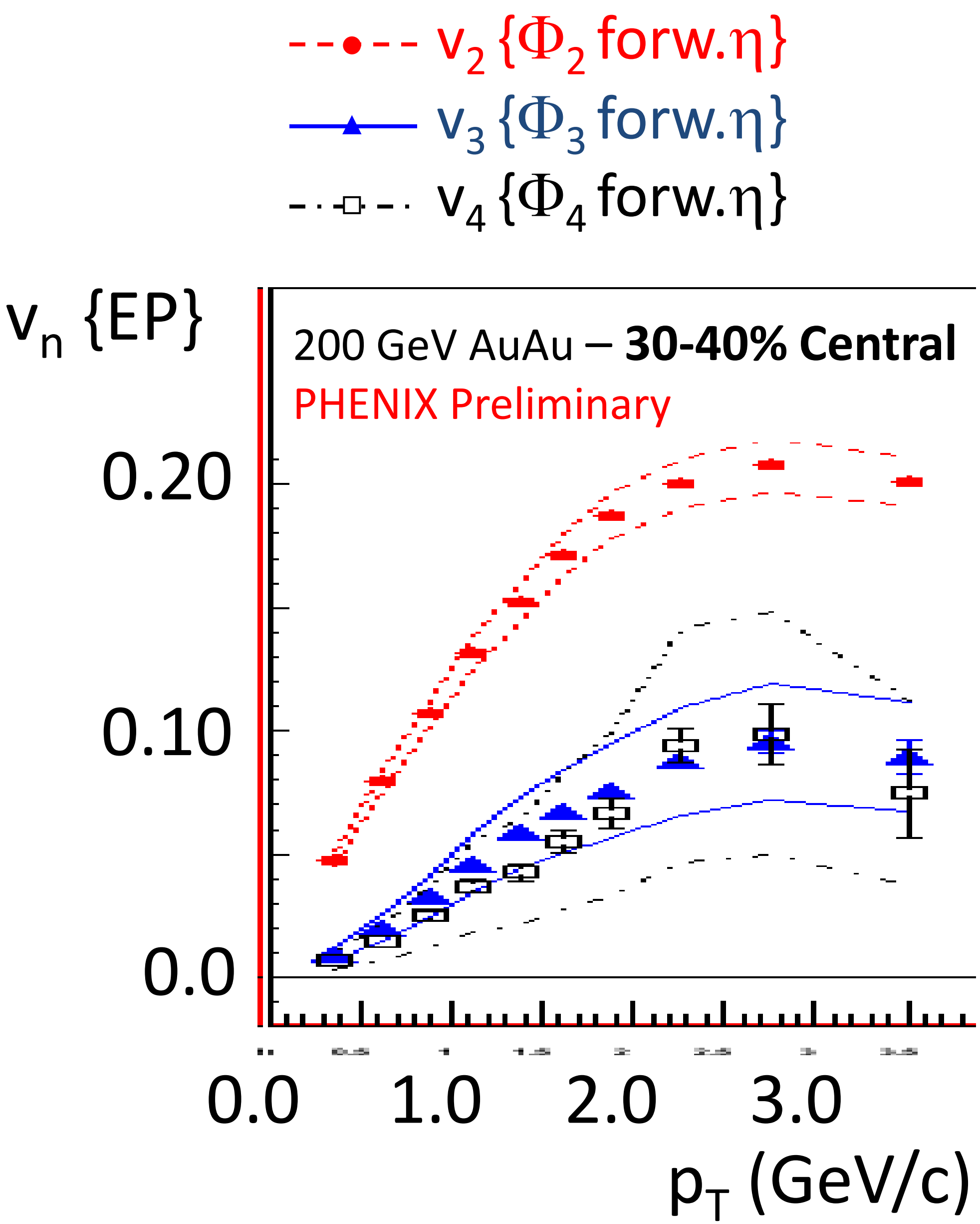
v_3 is as irrefutable as v_2 from ε_2.
Now we must quantify the effects and implications.

Alver, Roland, arXiv:1003.0194v3

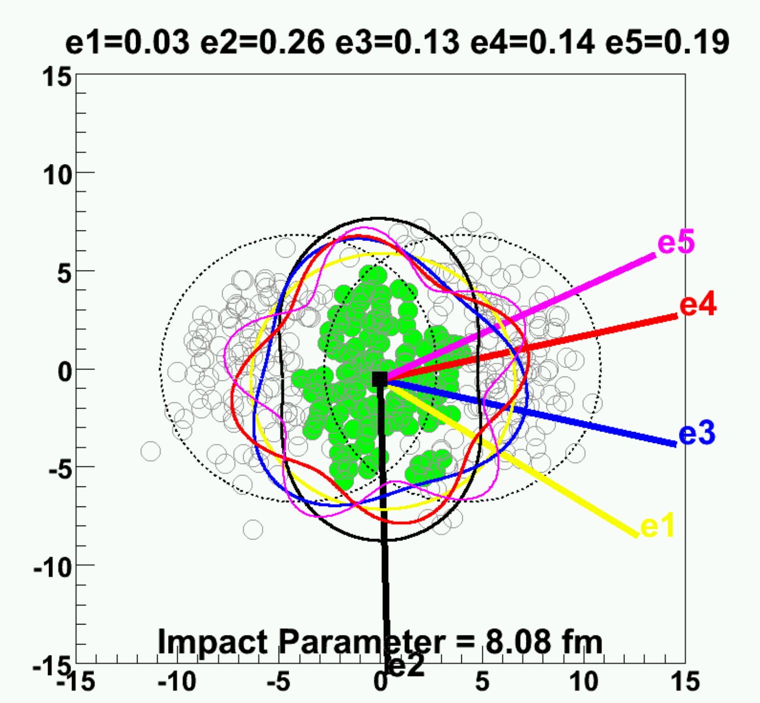
Measuring v_3

First, can detectors separated by $\Delta\eta = 2$ or even $\Delta\eta = 6$ measure event-by-event the 3rd order participant plane?

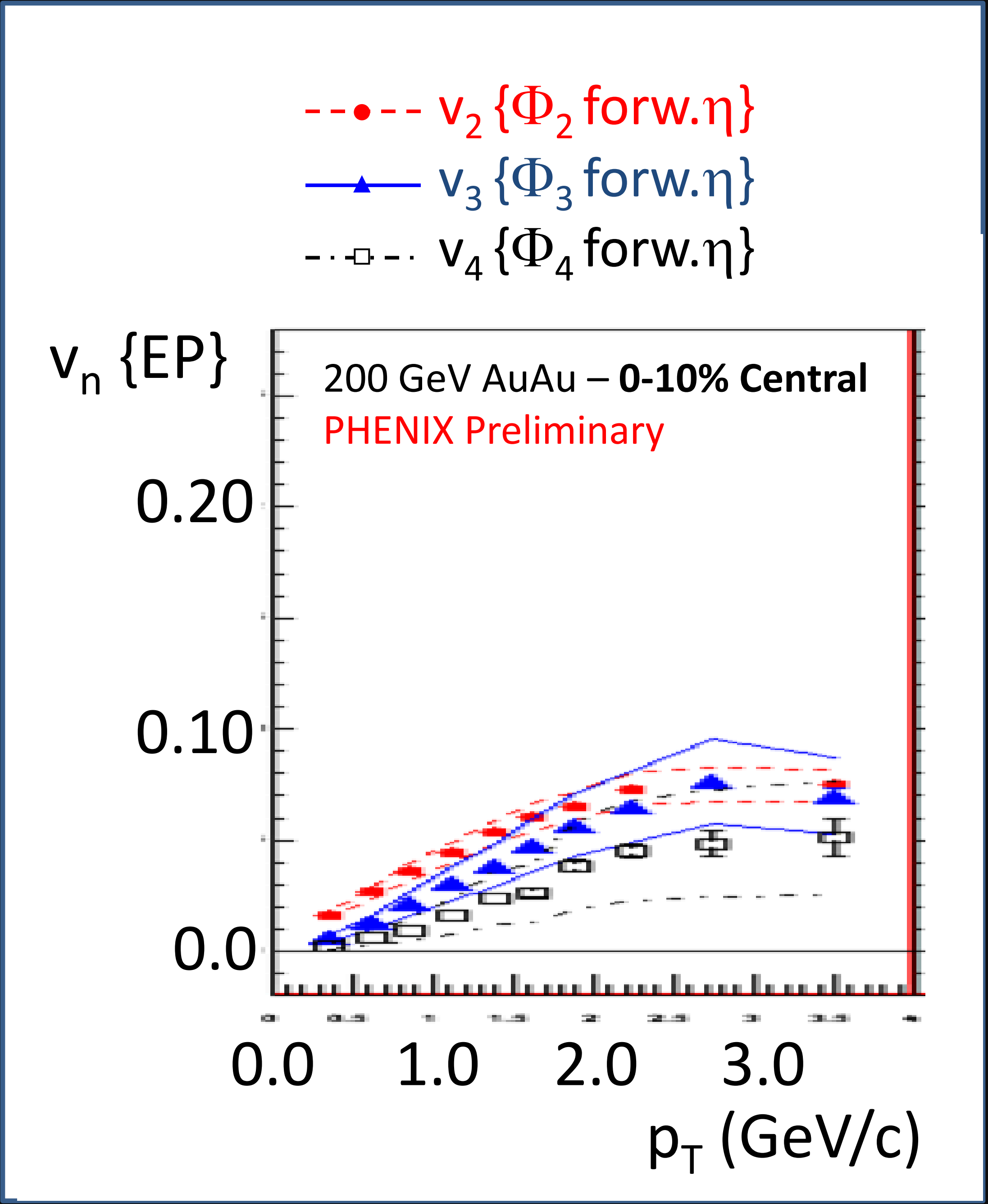


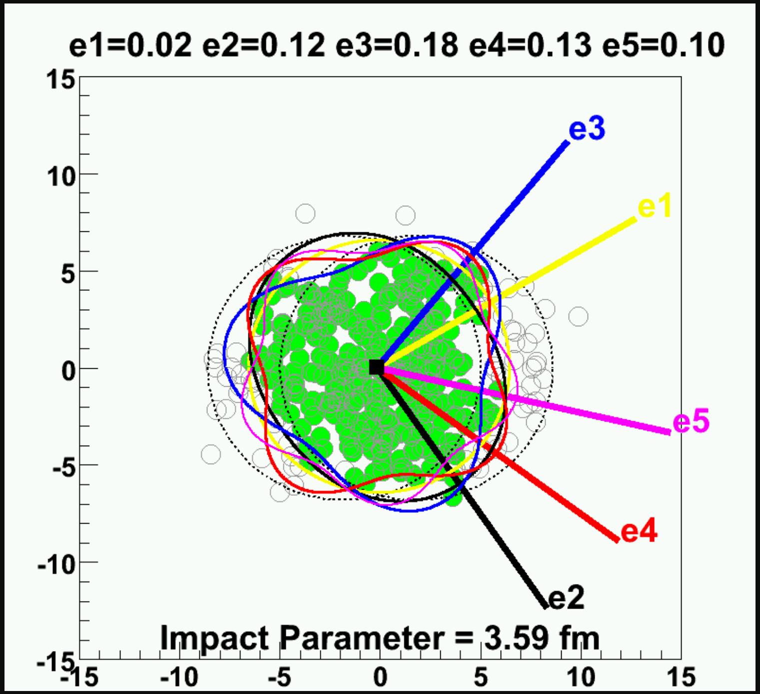


Systematic uncertainties defined by the variations with Φ_n from different $\Delta\eta$ and from different methods.



$$\varepsilon_2 \approx 2 \text{ x } \varepsilon_3 \approx 2 \text{ x } \varepsilon_4$$





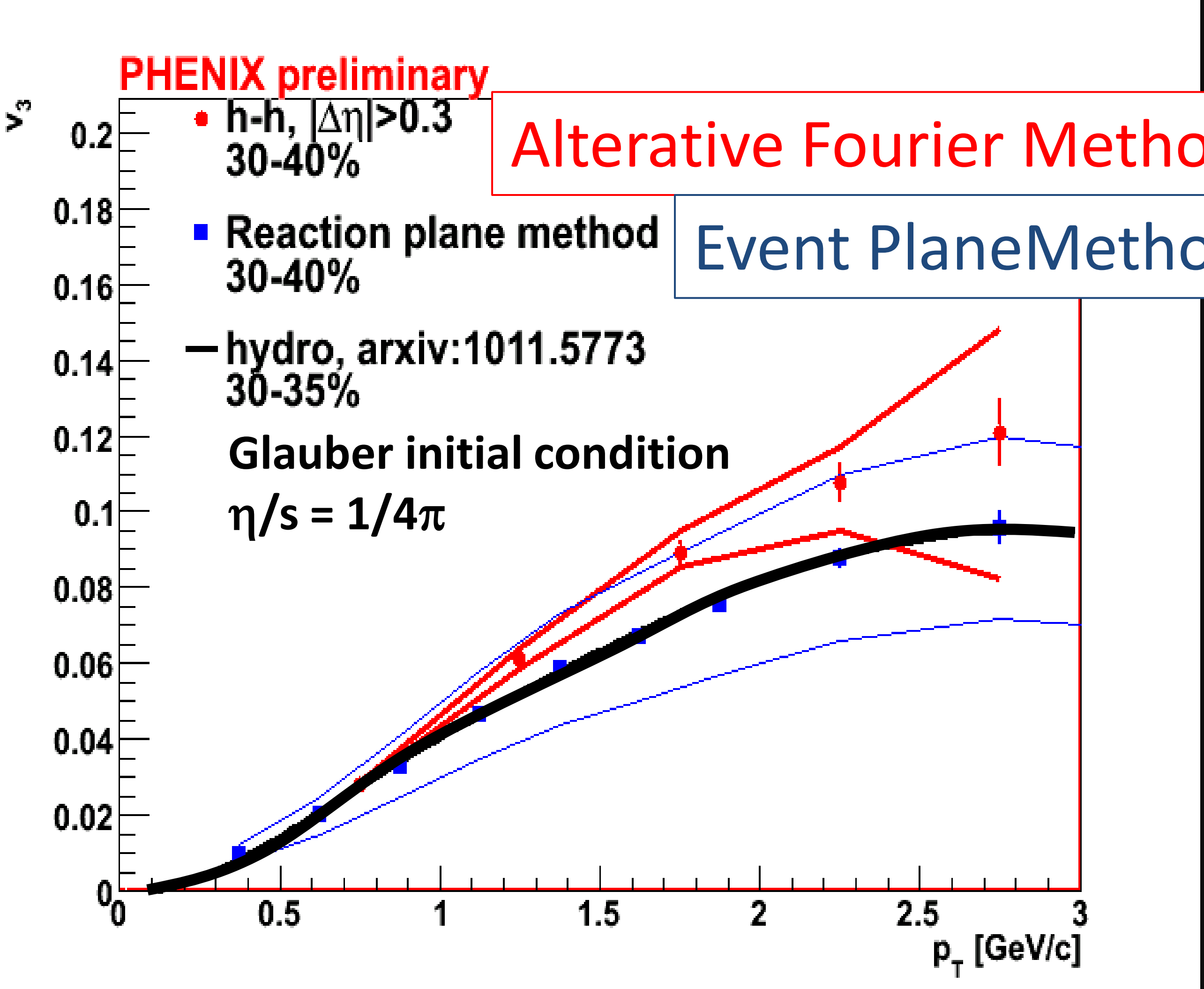
$$\varepsilon_2 \approx \varepsilon_3 \approx \varepsilon_4$$

Forces the question of how many moments are important? 5,6,7th

Like white noise?

Also 1st moment!

What do we Learn?

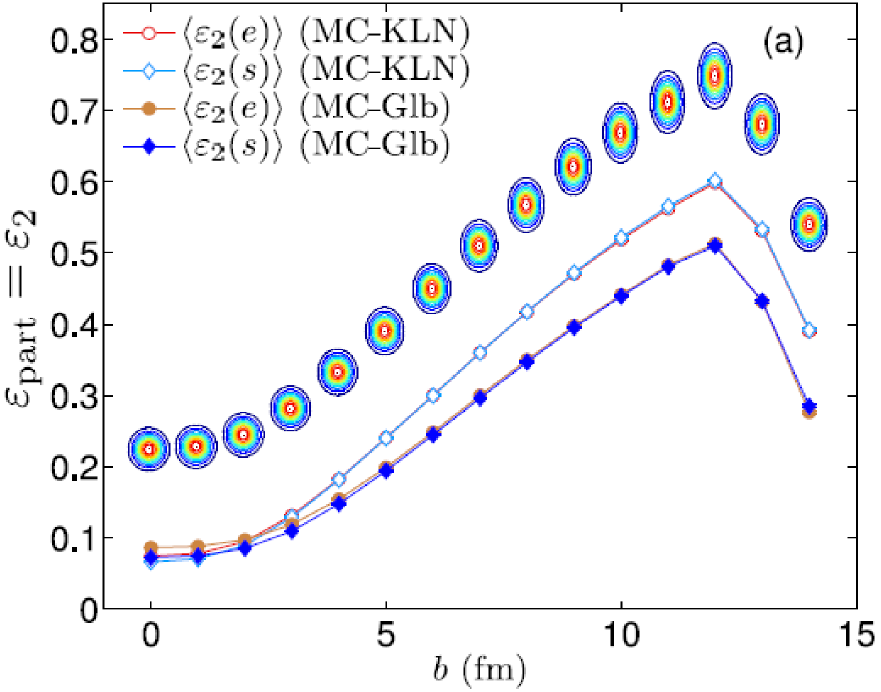


Alterative Fourier Method

Event PlaneMethod

Good agreement with viscous hydrodynamics calculations
(ask Matt Luzum for calculation details)

Key Point



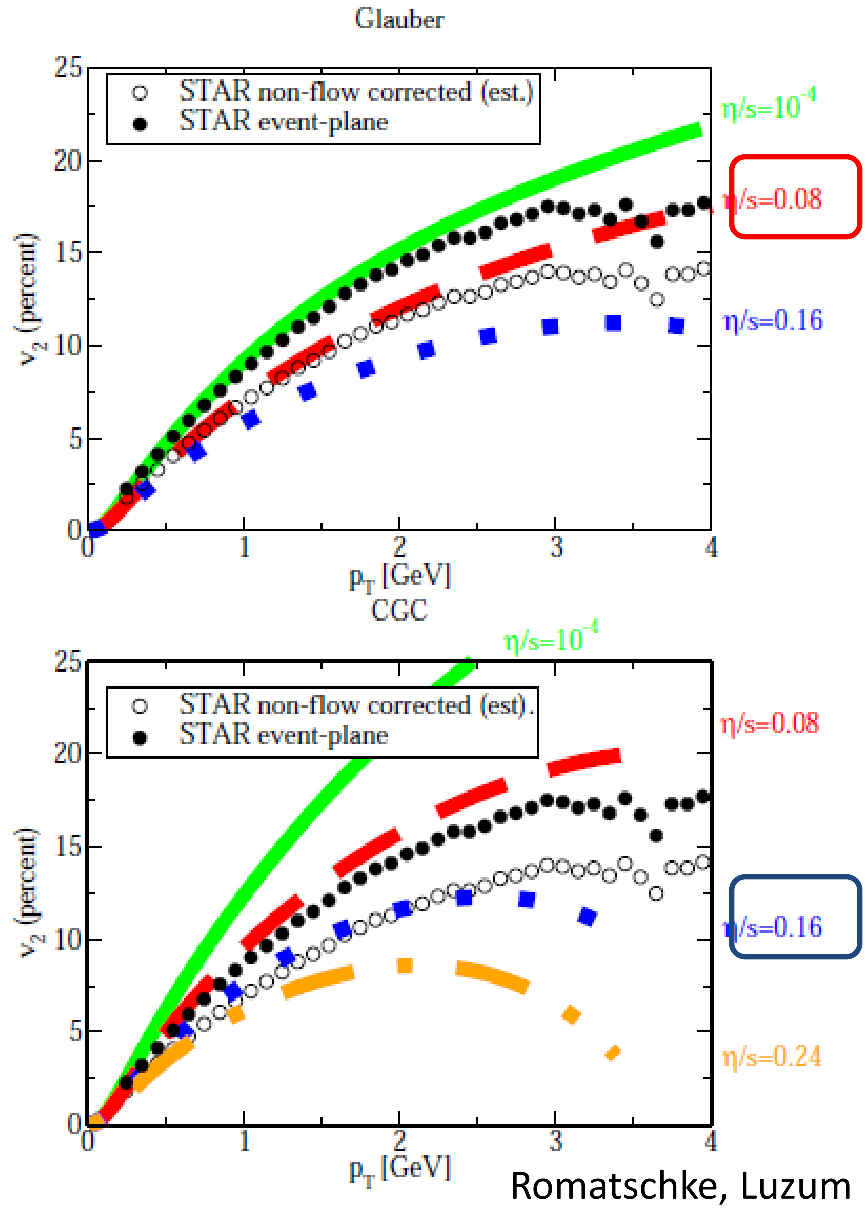
Qiu, Heinz, arXiv:1104.0650v2

Color Glass Condensate versus Glauber results in different ε_2 by ~ 20%. This is because gluon saturation reweights local entropy density – and thus different initial shape.

However, for ε_3, CGC and Glauber are nearly identical!

See also R. Lacey *et al.*, arXiv:1009.5230v2

Why is this so important?



Romatschke, Luzum

Glauber initial ε_2 requires $\eta/s \approx 1/4\pi$ to match v_2 data

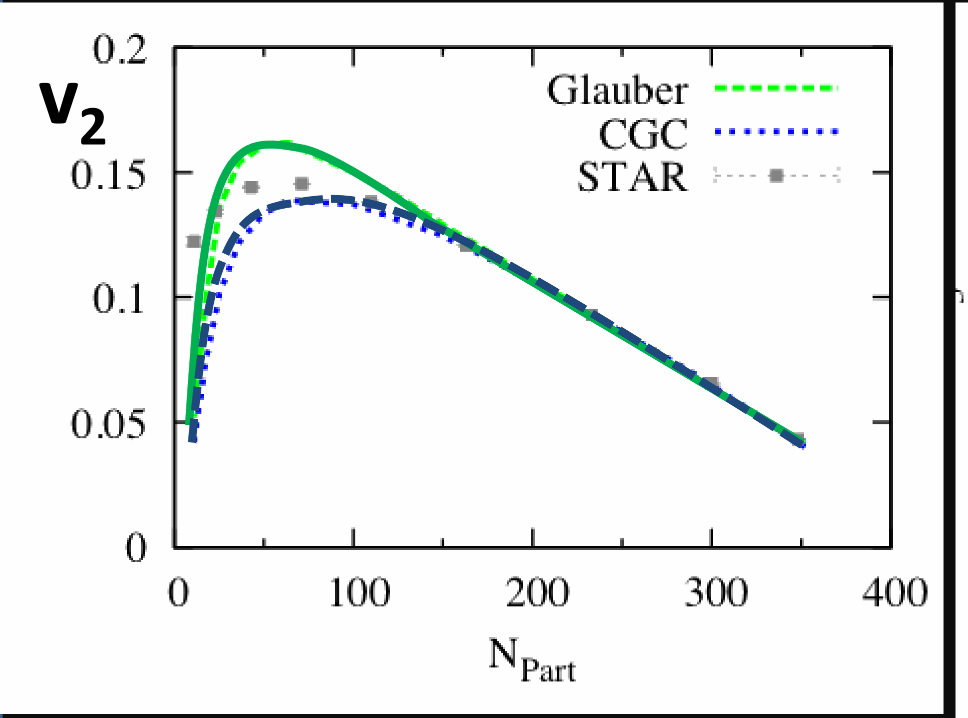
Color Glass Condensate initial ε_2 is larger by 20% and thus requires more dissipation to get the same flow and thus $\eta/s \approx 2/4\pi$

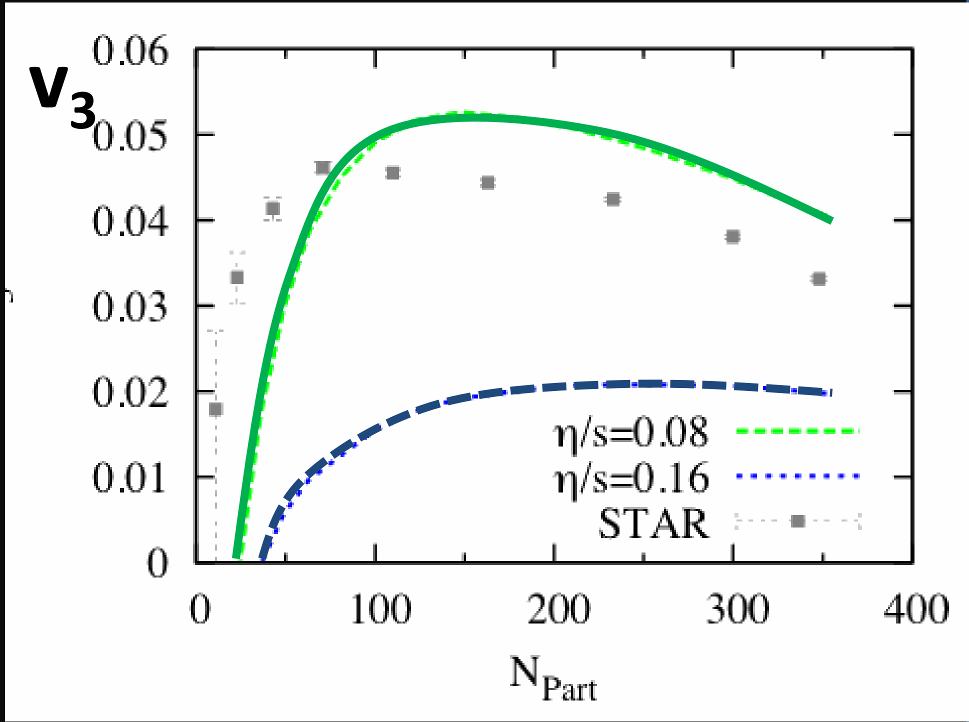
This ambiguity has troubled the field for 3 years.

If both have the same ε_3 then CGC with $\eta/s = 2/4\pi$ should give much lower v_3

Further Proof

Luzum, arXiv: 1007.5469

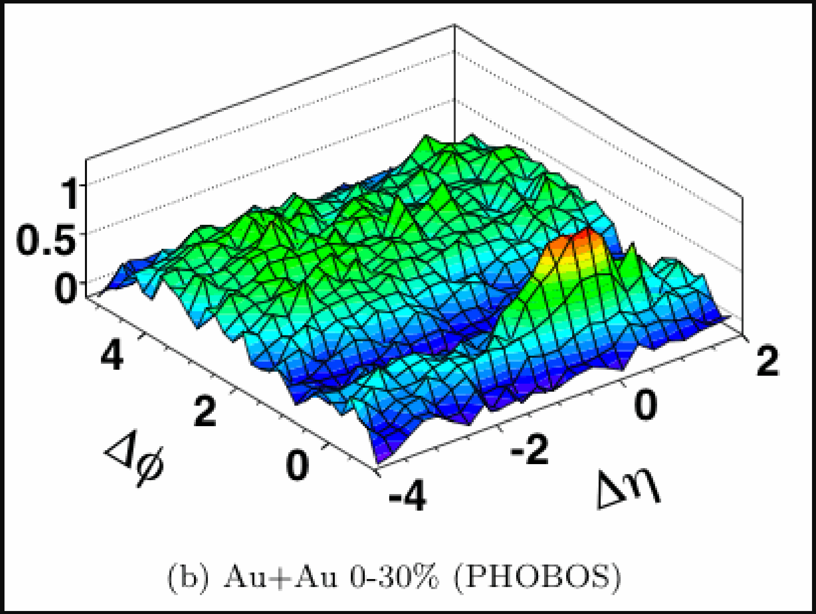




STAR states in their paper that v_3 flow is not the explanation.

"Thus, we conclude that the away-side double-peak structure is not an artifact of the ZYAM flow subtraction procedure used in this analysis."
STAR: arXiv:1010.0690v1

"Ridge" and "Shoulders"

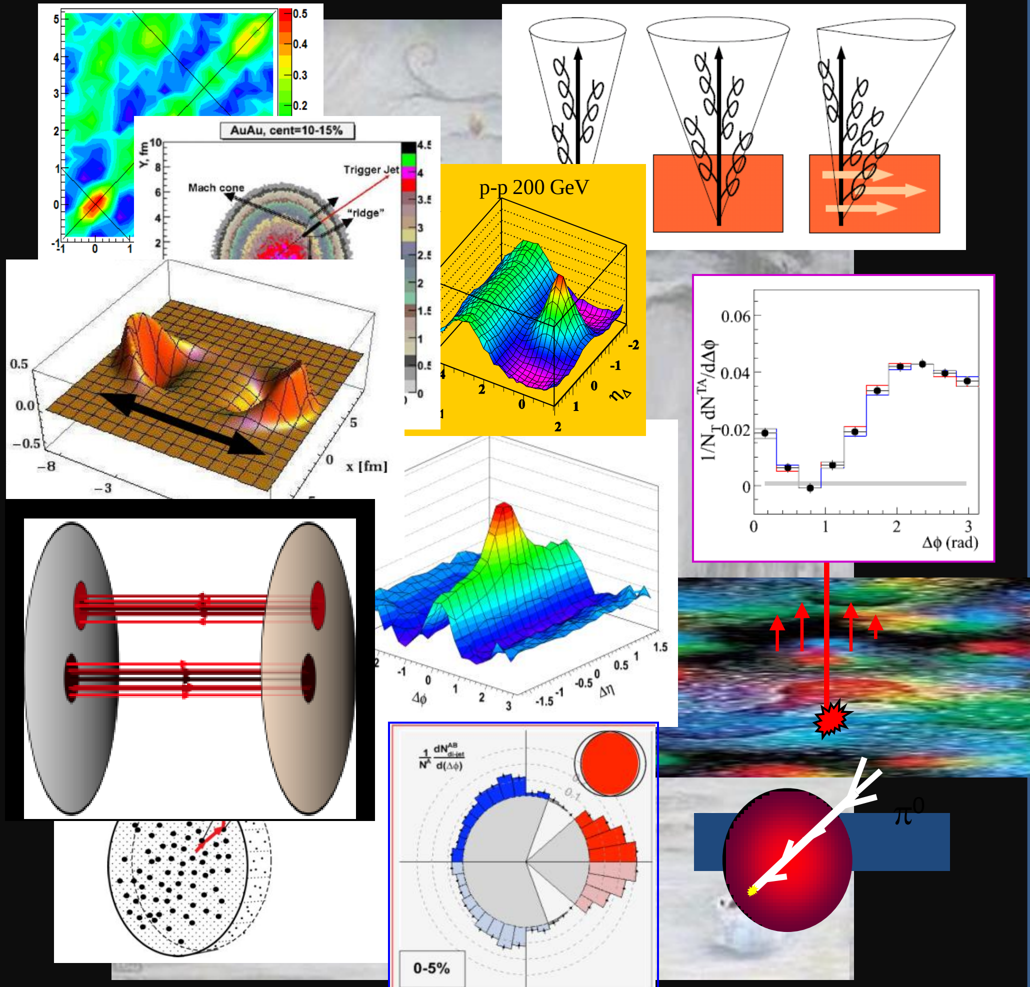


(b) Au+Au 0-30% (PHOBOS)

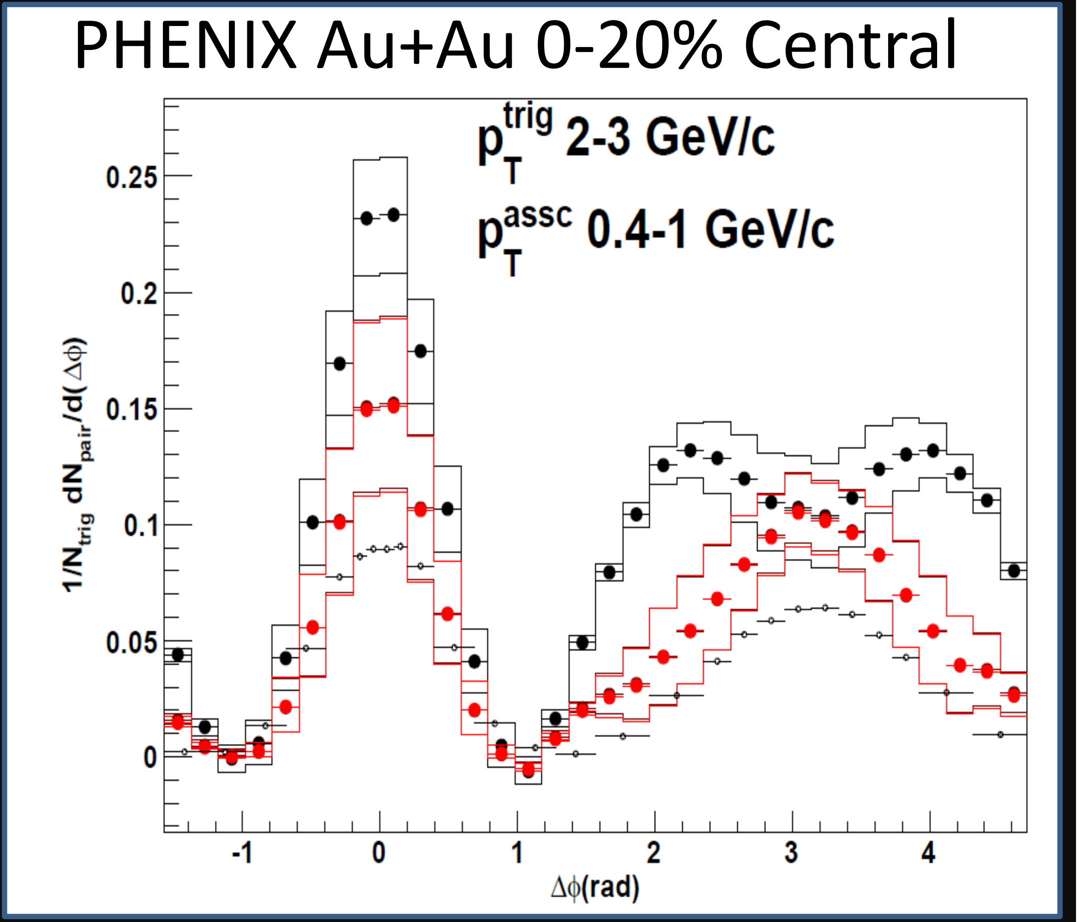
Features in two-particle correlations that have generated a lot of excitement.

Two years ago (QM09) I gave a talk with my prediction.

The "death" of the ridge and shoulders.



So what about the "Ridge" and "Shoulders"?


PHENIX Au+Au 0-20% Central

Black points

PHENIX published with v_2 background modulation and ZYAM.

Red points

(NOT PHENIX OFFICIAL)

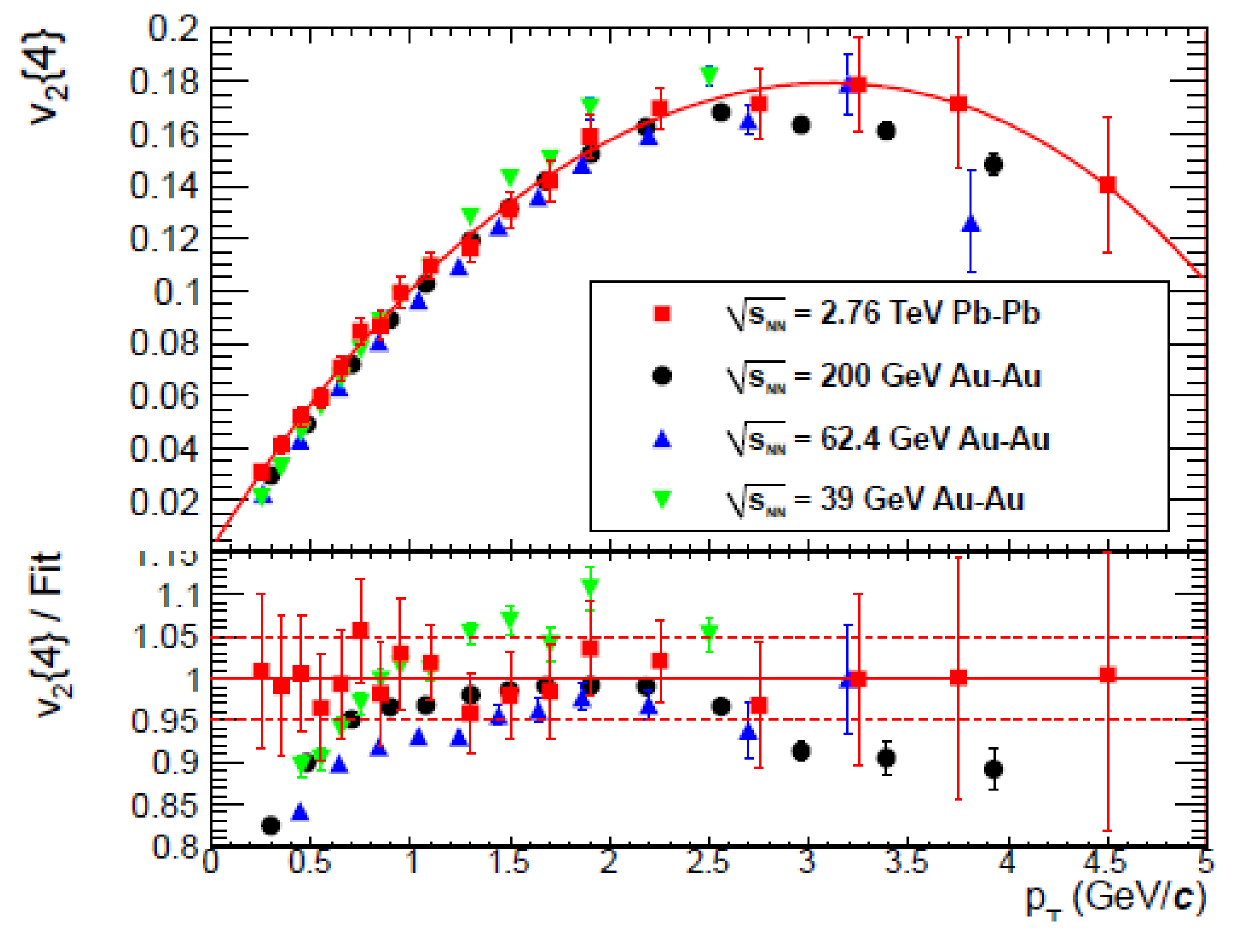
Use AMPT v_3/v_2 ratio and include v_2 and v_3 background modulation.

Calculation by A. Adare

Dominant ridge and shoulders will be gone.

Detailed careful analysis needs v_1 … v_5 and method checks.

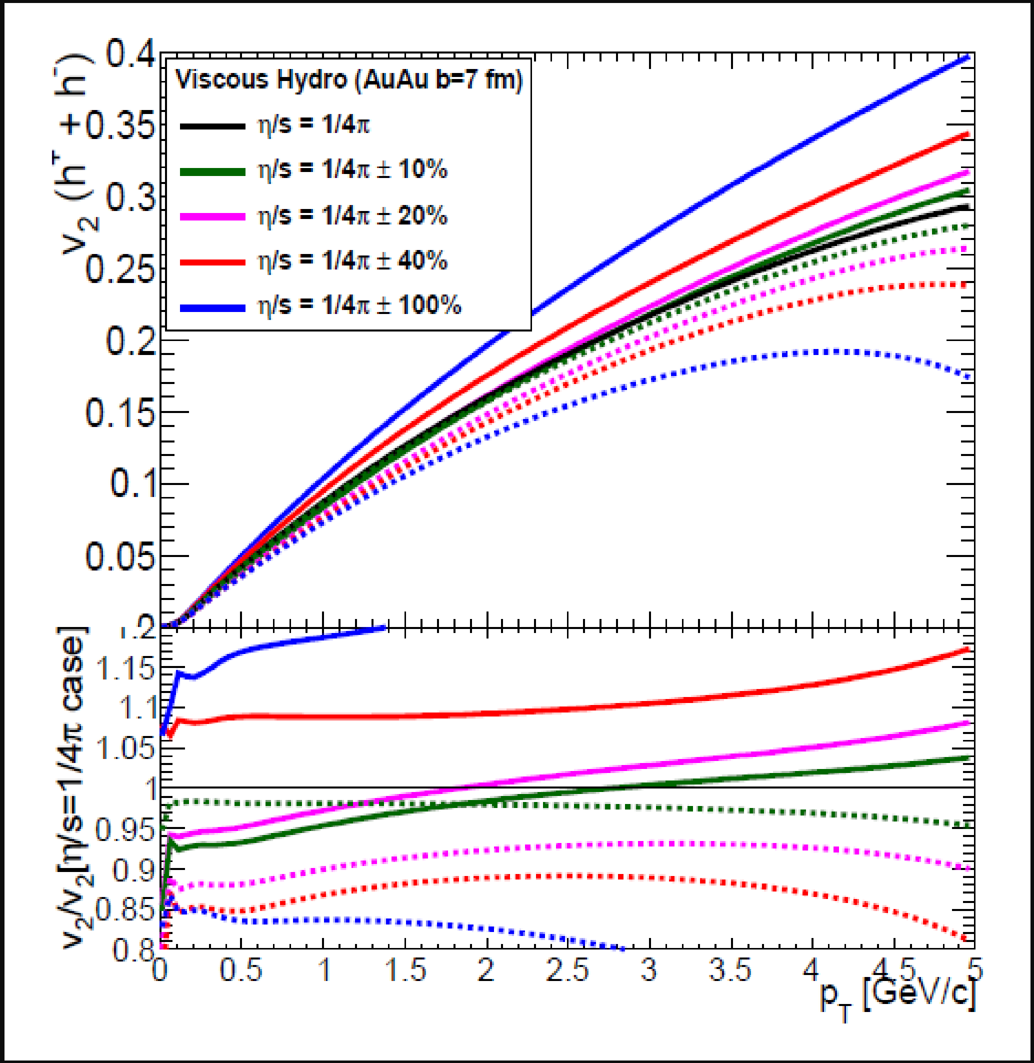
What if we crank up the energy?



Bill Zajc, Ian Bearden and I wondered what is required to get this remarkable agreement (arXiv:1102.0680).

Use Romatschke's <u>publicly</u> available viscous hydro code…

Q1: How much does a constant η/s need to change to get a 5% change in v_2?



$\Delta(\eta/s) \sim 20\% \rightarrow \Delta v_2 \sim 5\%$

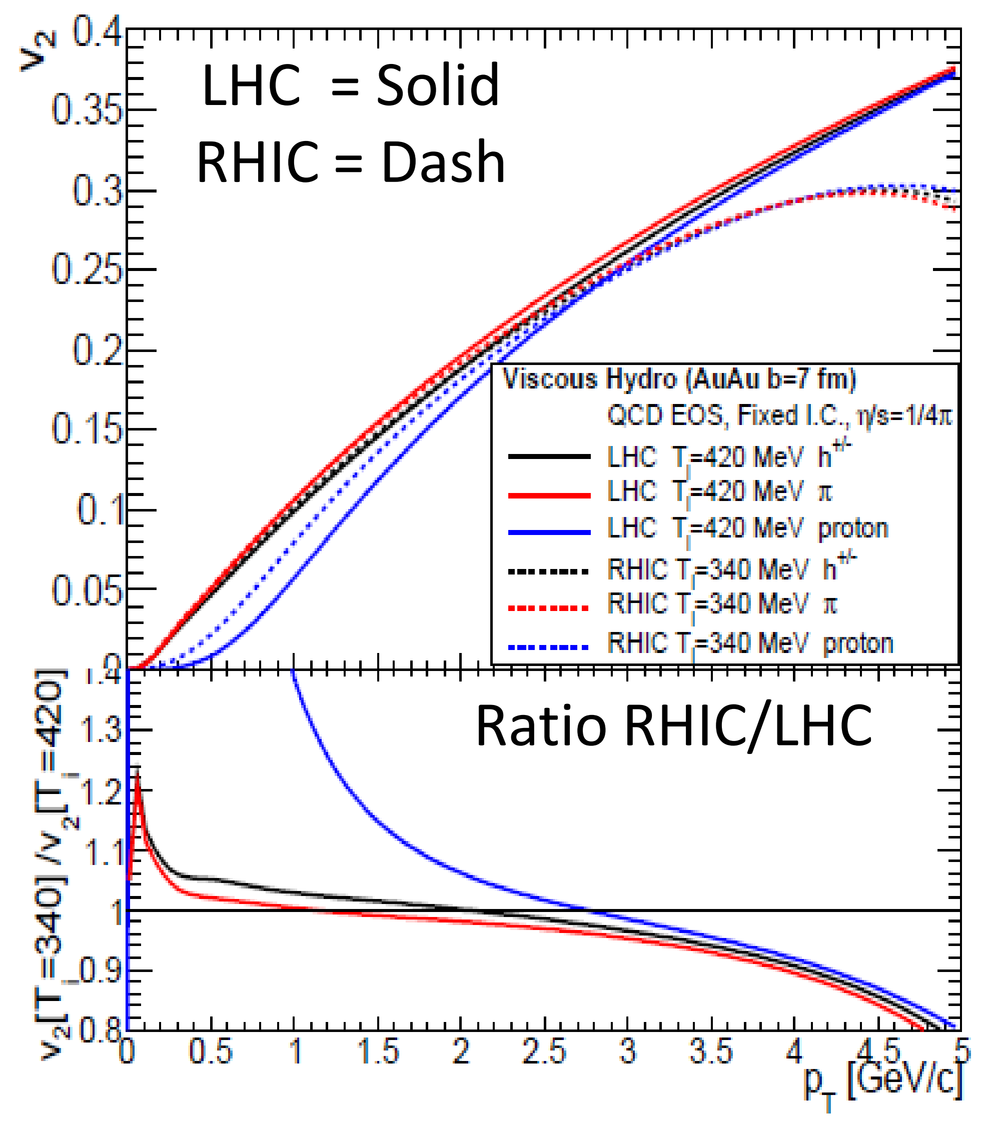
$\Delta(\eta/s) \sim 40\% \rightarrow \Delta v_2 \sim 10\%$

$\Delta(\eta/s) \sim 100\% \rightarrow \Delta v_2 \sim 25\%$

Always take ratios.

What looks like little difference at low p_T, turns out to be very sensitive (and where experiments have the smallest uncertainties).

Q2: How does v_2 change for initial T = 420 MeV (LHC) and T = 340 MeV (RHIC)?



Black = all hadrons

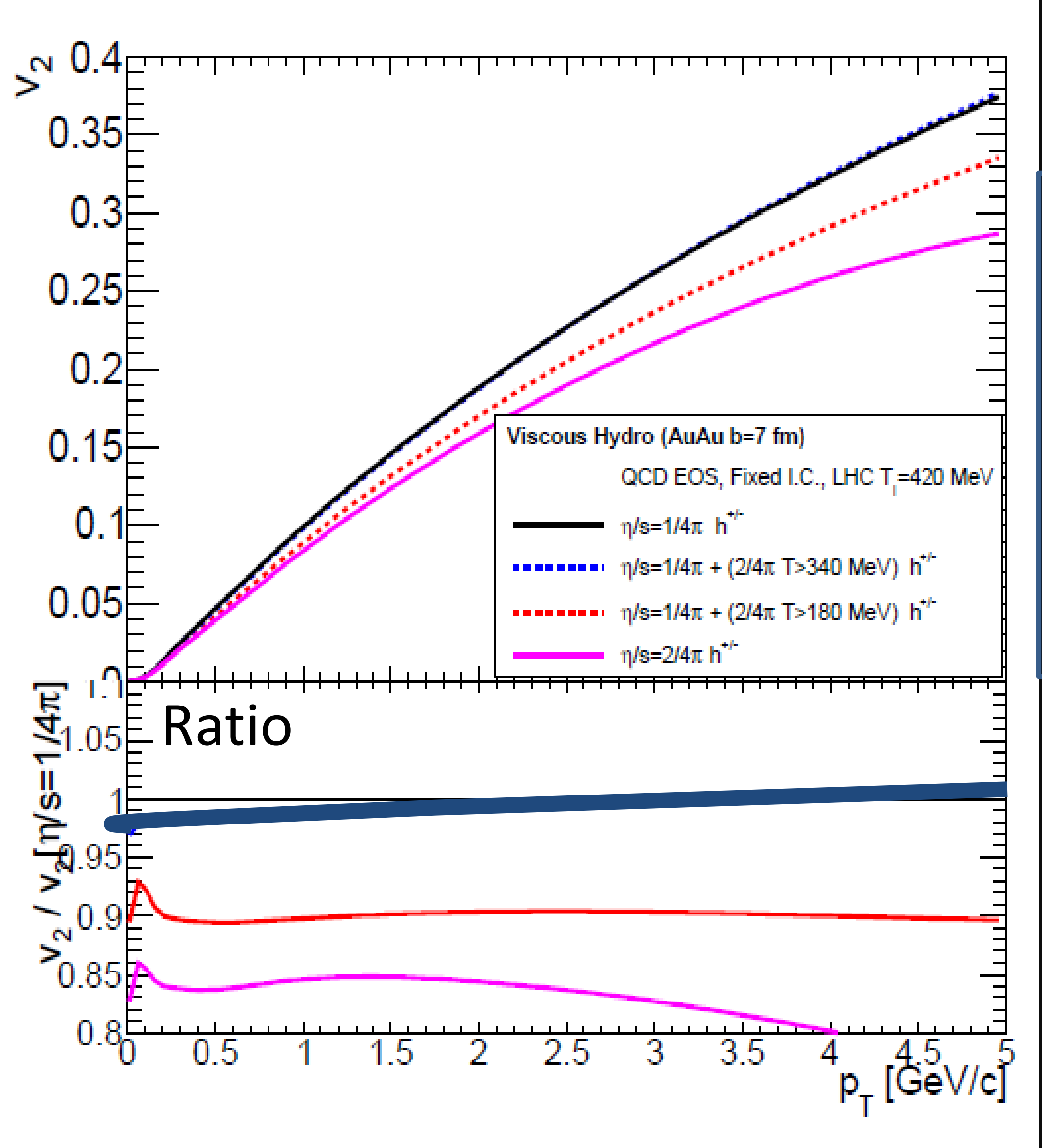
Very similar $v_2(p_T)$ except larger viscous effects for $p_T > 3$ GeV/c

Blue = protons

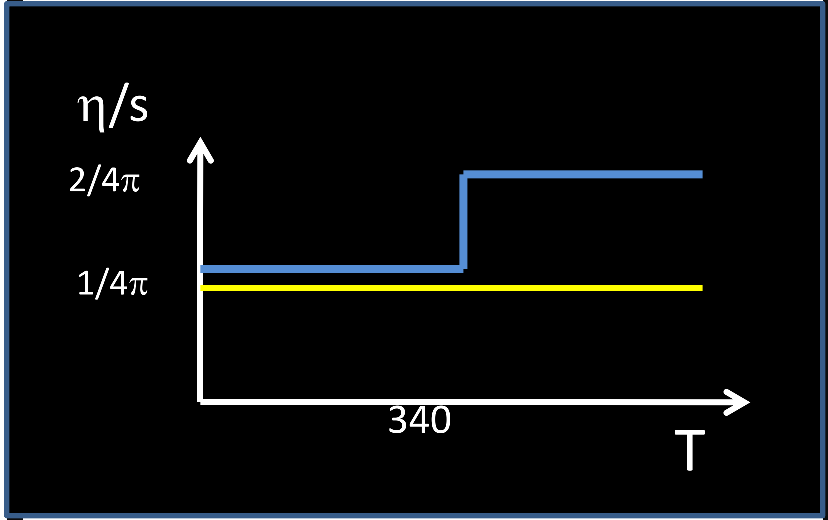
Large difference for $v_2(p_T)$ due to larger radial boost at LHC temperatures. *Solid prediction.*

Previously noted with ideal hydrodynamics by Kestin, Heinz

Q3: What if η/s is larger for $T > 340$ MeV (just the range sampled at the LHC in early times)?



Consider case I:



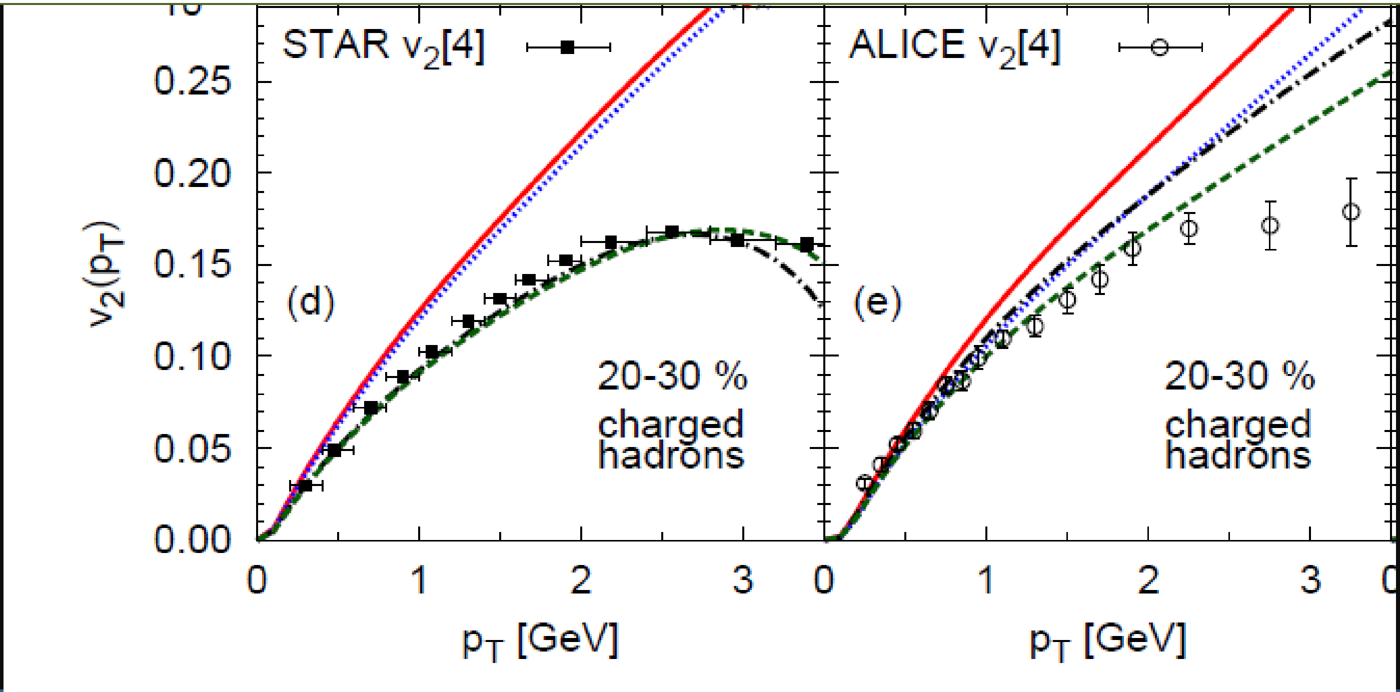
No change in $v_2(p_T)$!

Earliest LHC time not effected by factor 2 change in η/s.

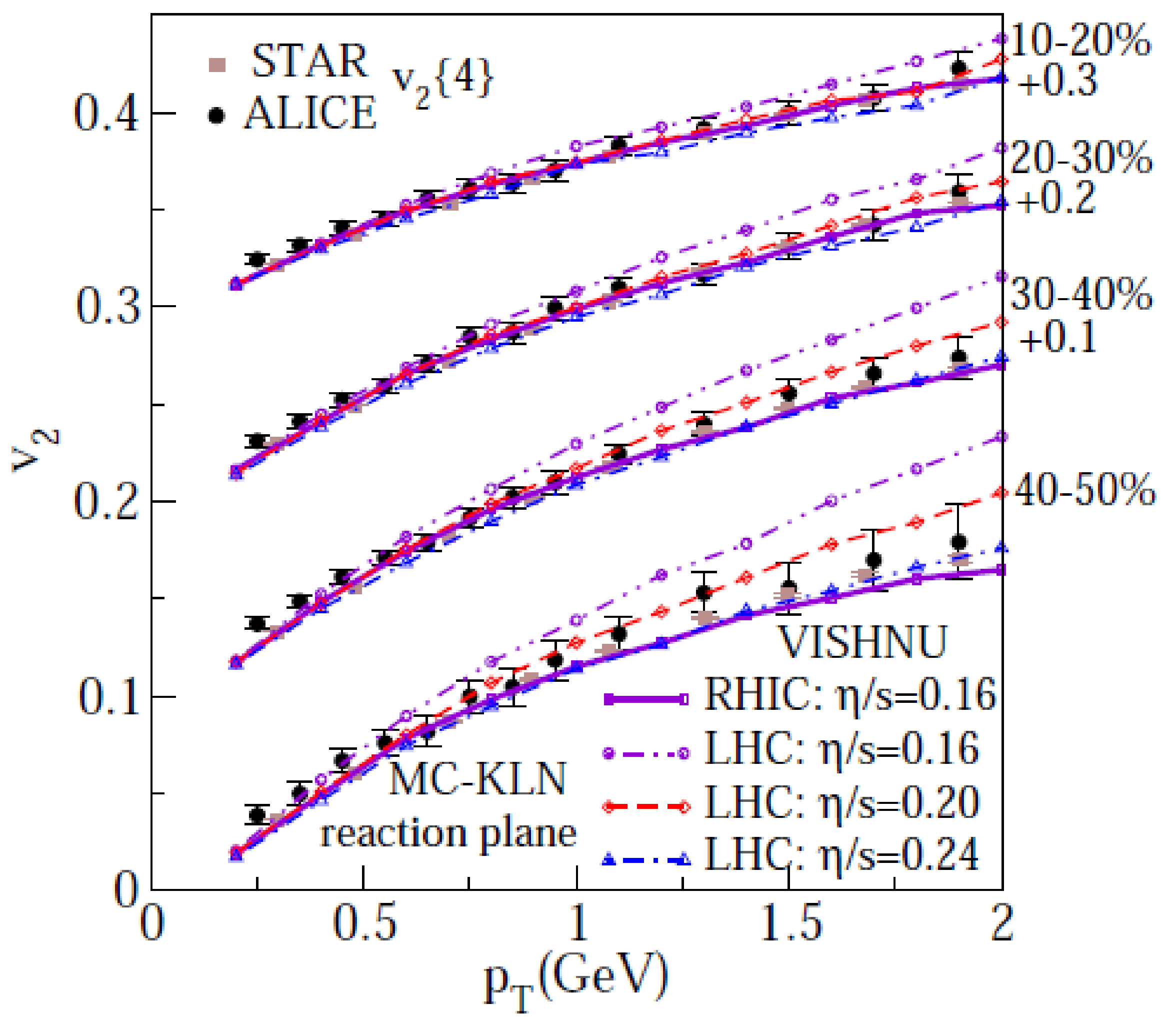
Recent study of η/s (T) – arXiv:1101.2442

Conclusion that RHIC v_2 is dominated by η/s below T_c and LHC v_2 by η/s above T_c seems an unlikely fine tuning problem.

In fact, if one takes the ratios, the green-dash curve fails to describe the differences.



Viscous Hydrodynamics + Hadron Cascade
Fixed η/s case for QGP



LHC needs larger QGP η/s to get the same $v_2(p_T)$.

However, the η/s in the same T range at RHIC cannot be different.

Fine tuning problem again.

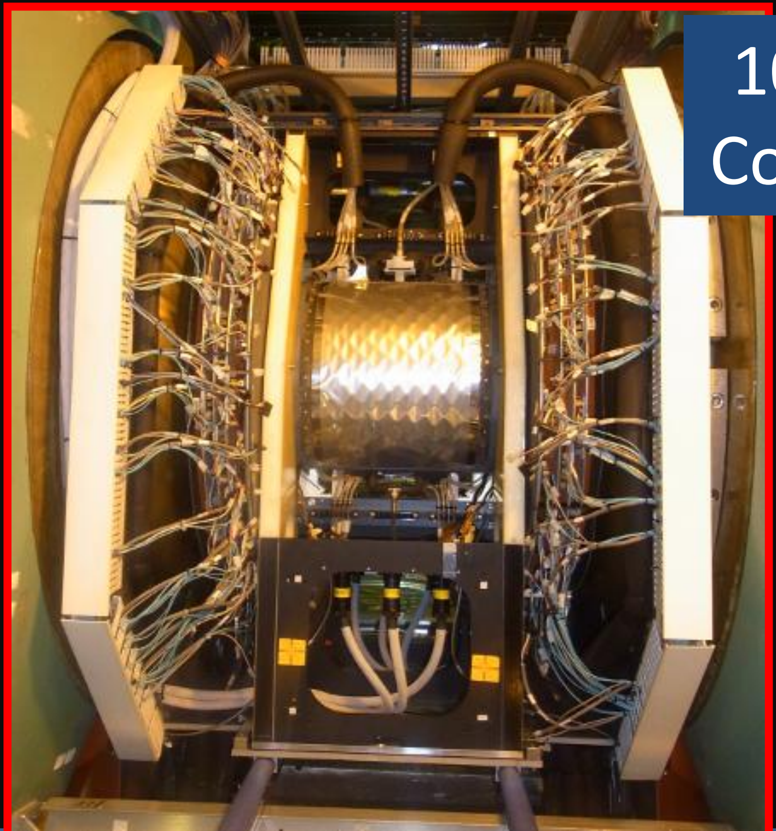
Song *et al.*,arXiv:1103.2380v2

Another Class of η/s Constraints

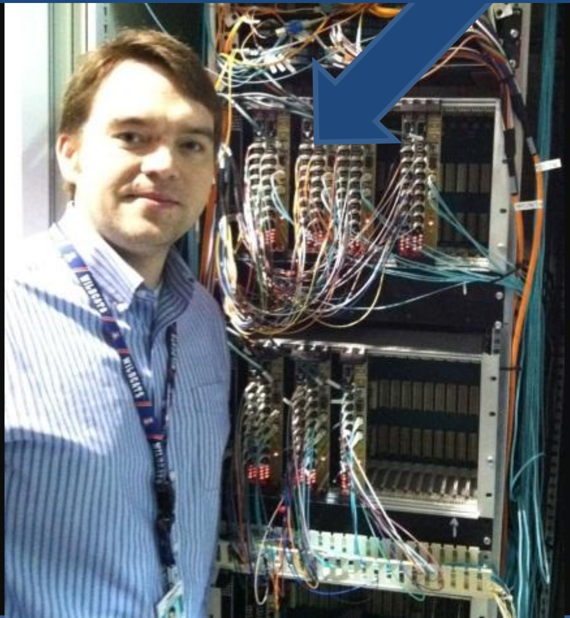
"Does the Charm Flow at RHIC?"

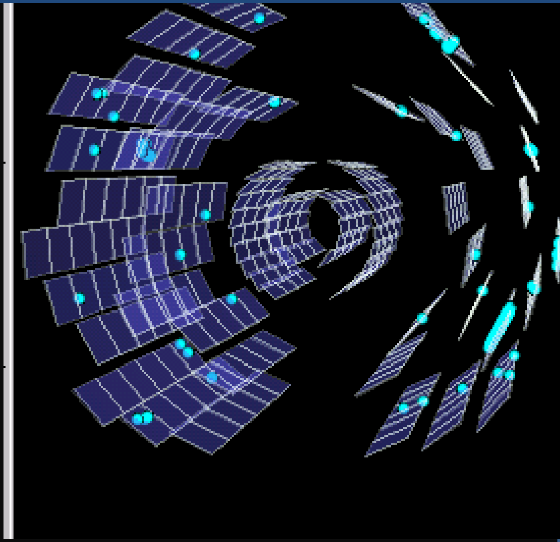
S. Batsouli, S. Kelly, M. Gyulassy (Columbia U.) , J.L. Nagle (Colorado U.) . Dec 2002. 11pp.
Published in **Phys.Lett.B557:26-32,2003**.

Flow of charm and beauty quarks may yet provide the best constraints. PHENIX Silicon Detector now operational.



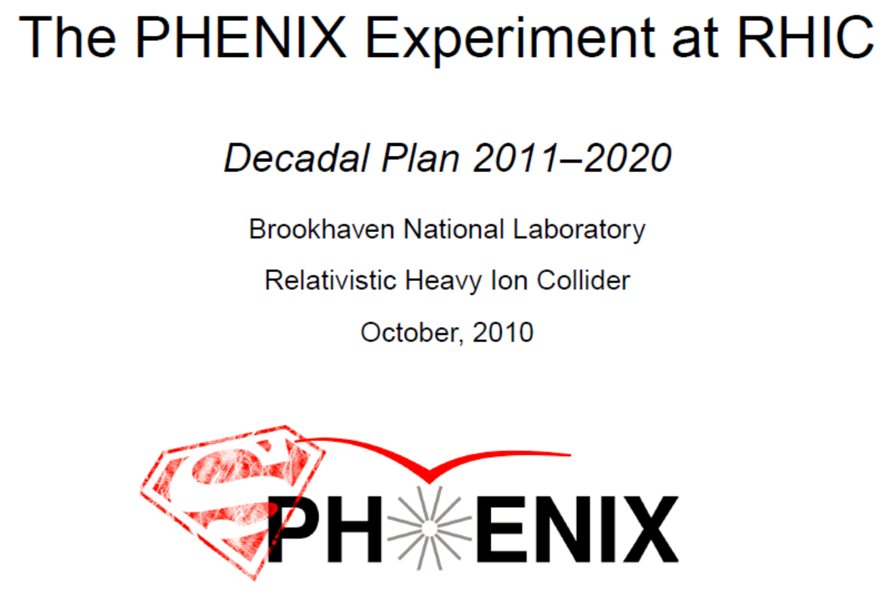
10 Gigabit link Data Collection system
Colorado effort led by Mike McCumber





PHENIX Decadal Plan

Major Upgrade Proposed Extending into EIC Era



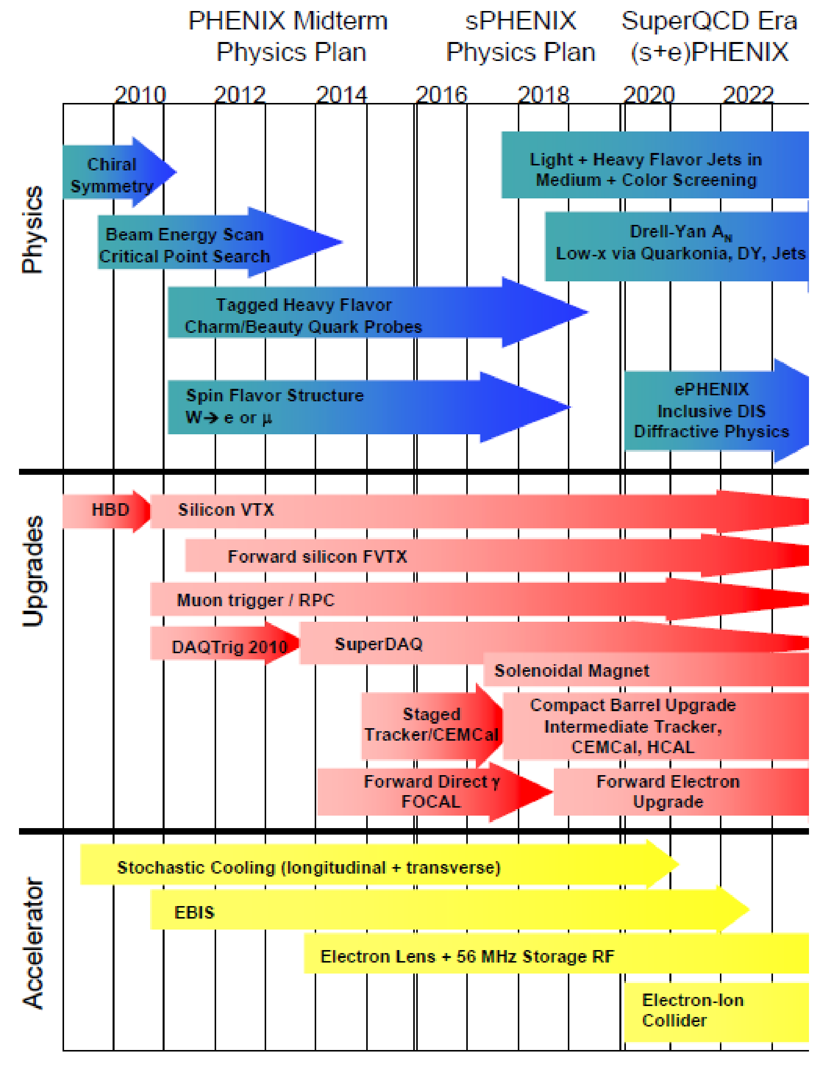
The PHENIX Experiment at RHIC

Decadal Plan 2011–2020

Brookhaven National Laboratory

Relativistic Heavy Ion Collider

October, 2010

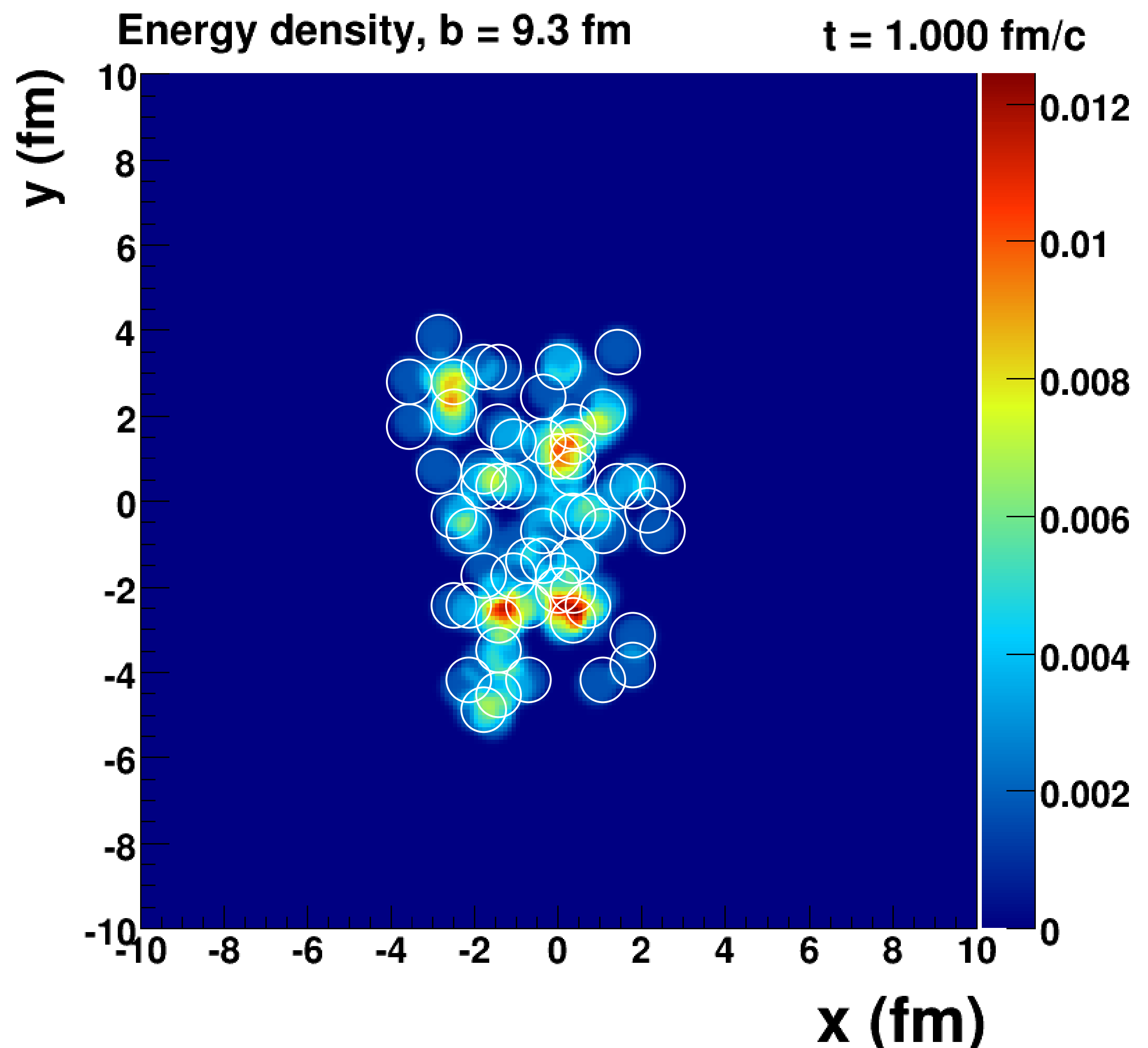


We are interested in feedback, suggestions, involvement.

http://www.phenix.bnl.gov/phenix/WWW/docs/decadal/2010/phenix_decadal10_full_refs.pdf

Summary:

Deviations from smooth geometry have major impact in all areas of heavy ion physics



EXTRAS

Heavy quarks and charmonium at RHIC and LHC within a partonic transport model

J. Uphoff, K. Zhou, O. Fochler, Z. Xu, C. Greiner

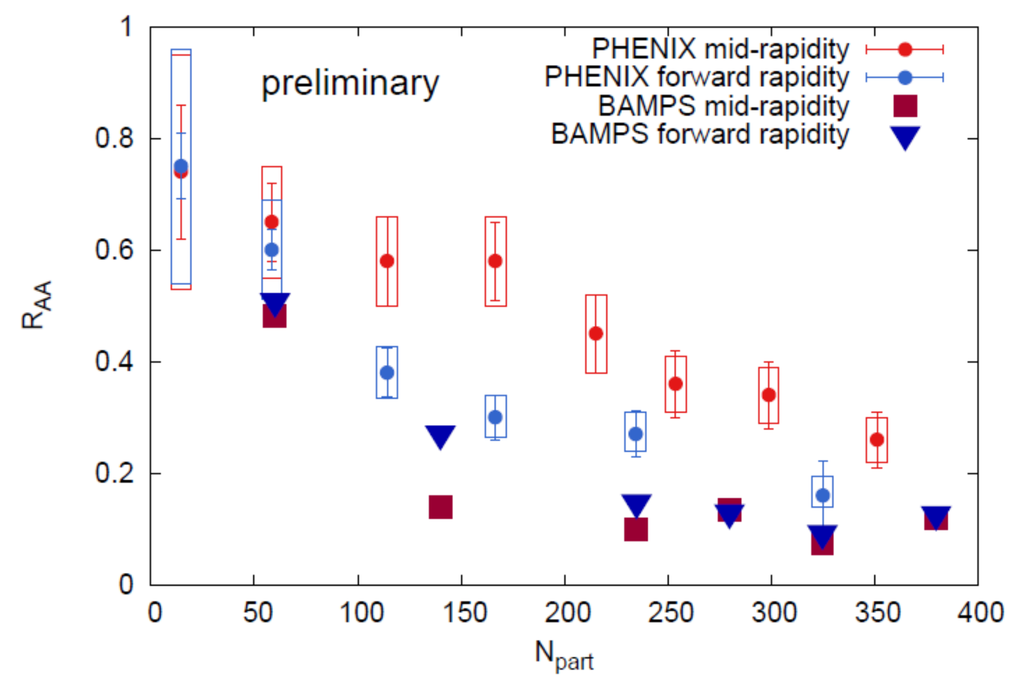
Cold nuclear matter effects linear in thickness....

Should confront dAu data...

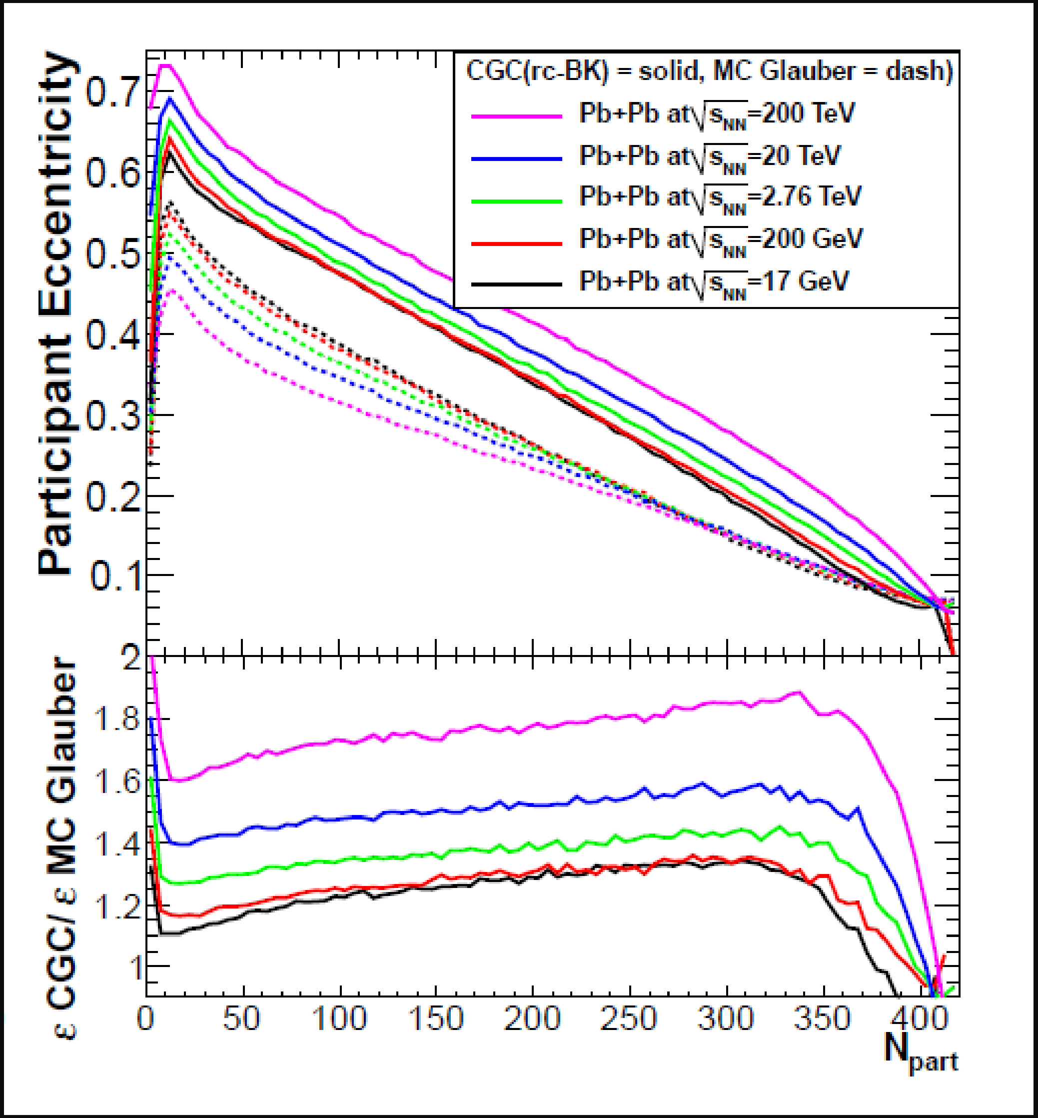
$$\mathscr{R}_i^A(\mathbf{x}_T, x, \mu_F) = 1 + N_{A,\rho}\,\left[R_i^A(x,\mu_F) - 1\right]\,\frac{T_A(\mathbf{x}_T)}{T_A(0)}\,.$$

Far too much J/ψ suppression.

Less suppression at forward rapidity.



Q4: If the initial ε_2 is Glauber, does that predict a change in $v_2(p_T)$ as a function of colliding energy?



Glauber predicts a 5% change from RHIC (200 GeV) to LHC and a 10% change for RHIC (39 GeV).

Color Glass Condensate has an even smaller energy dependence.

That was puzzling to me since saturation effects should be larger for the lower-x partons at LHC.