Geometry, Geometry, Geometry

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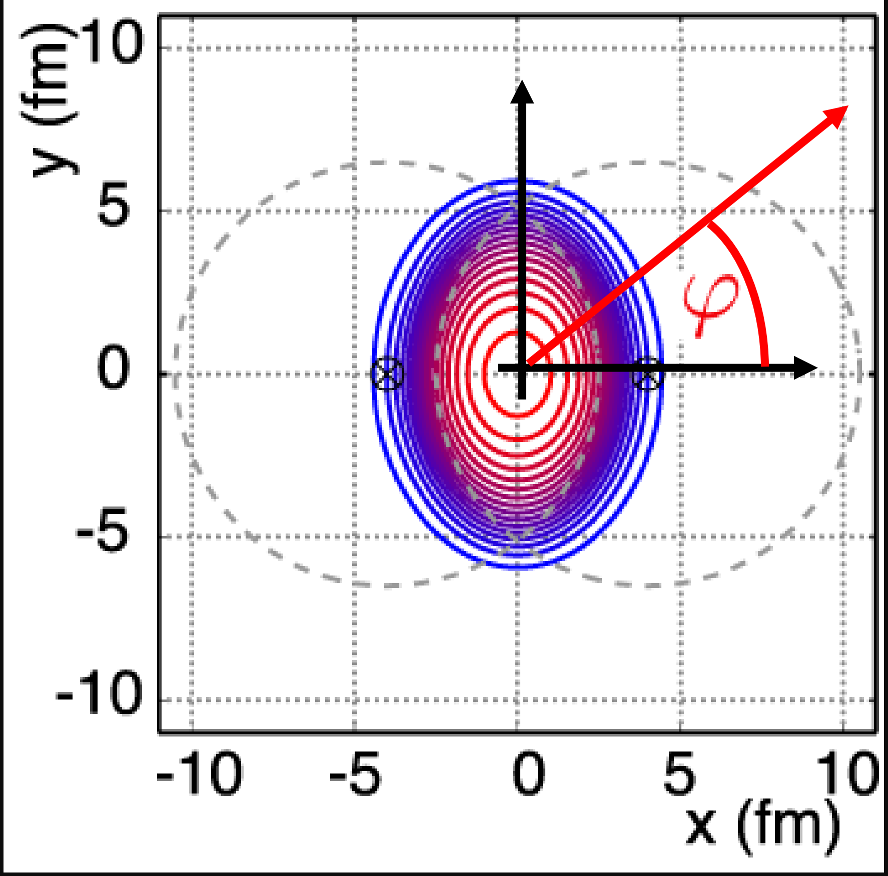
Discovery

Heavy ions: Experiments Confront Theory

7-9 November 2011 *Niels Bohr Institute*

Europe/Copenhagen timezone

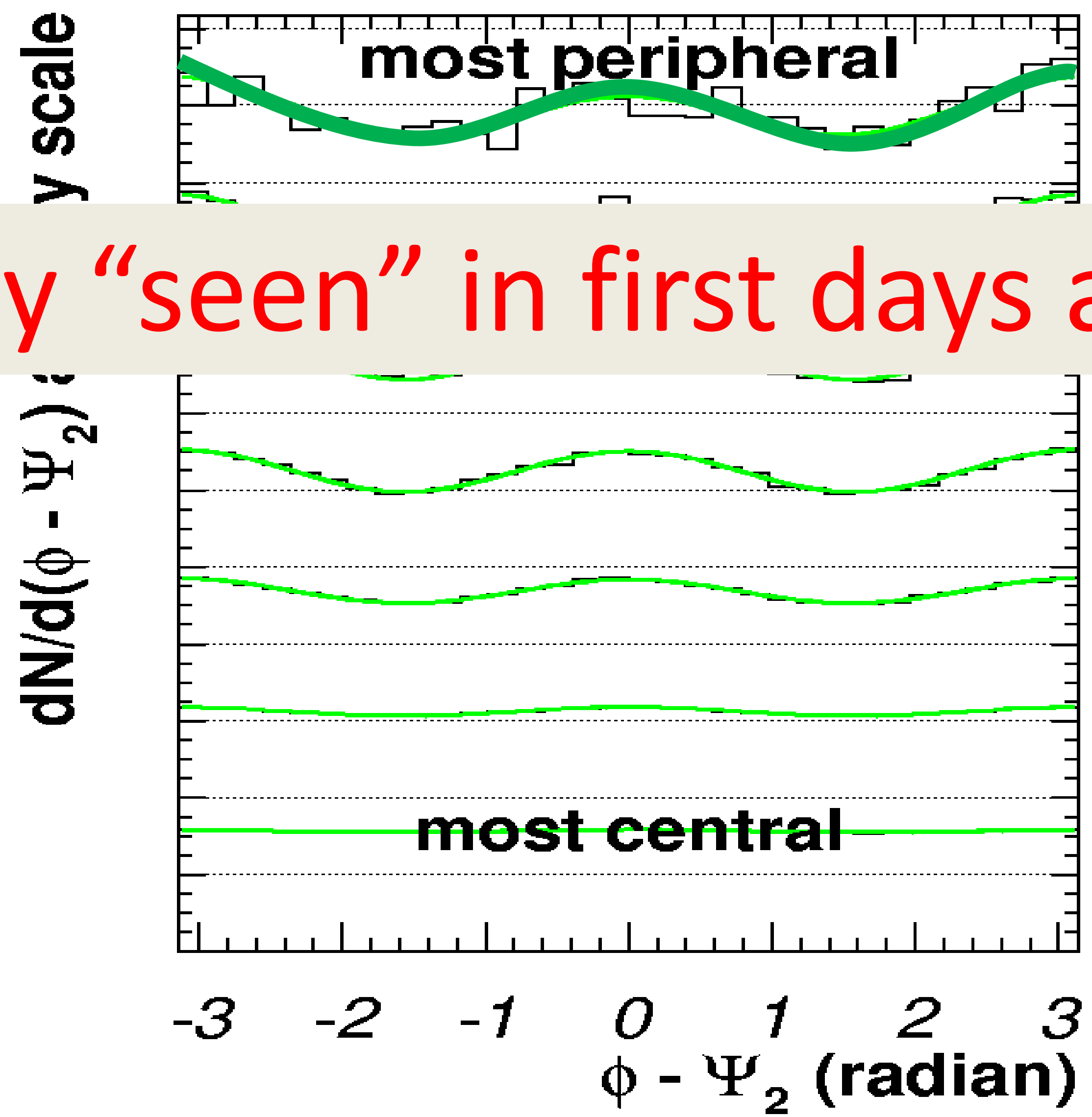
Simple Geometry



$$\frac{dN}{p_T dp_T dy d\varphi}(p_T,\varphi;b) = \frac{dN}{2\pi p_T dp_T dy}\left(1 + 2\underline{v_2}(p_T;b)\cos(2\varphi) + \ldots\right)$$

v_2 = "elliptic flow"

Large Elliptic Flow



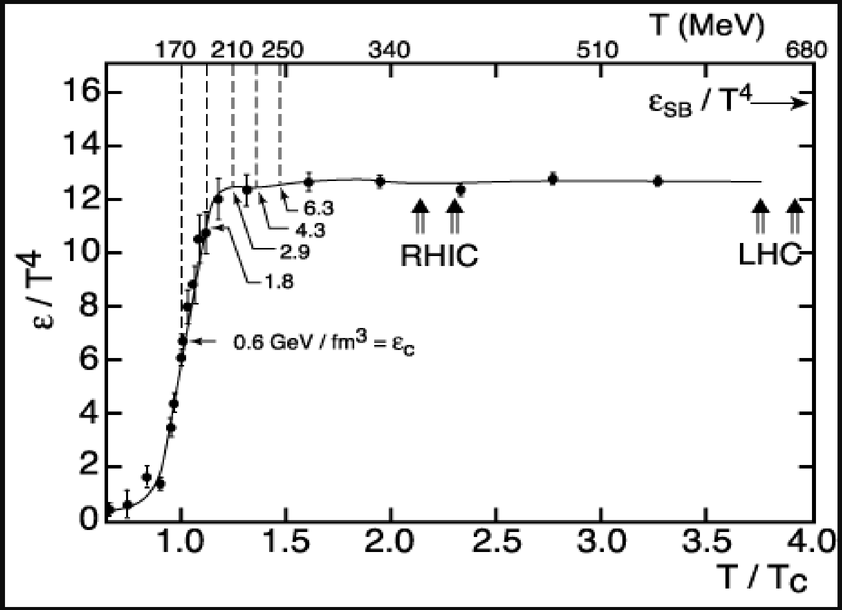
Literally "seen" in first days at RHIC

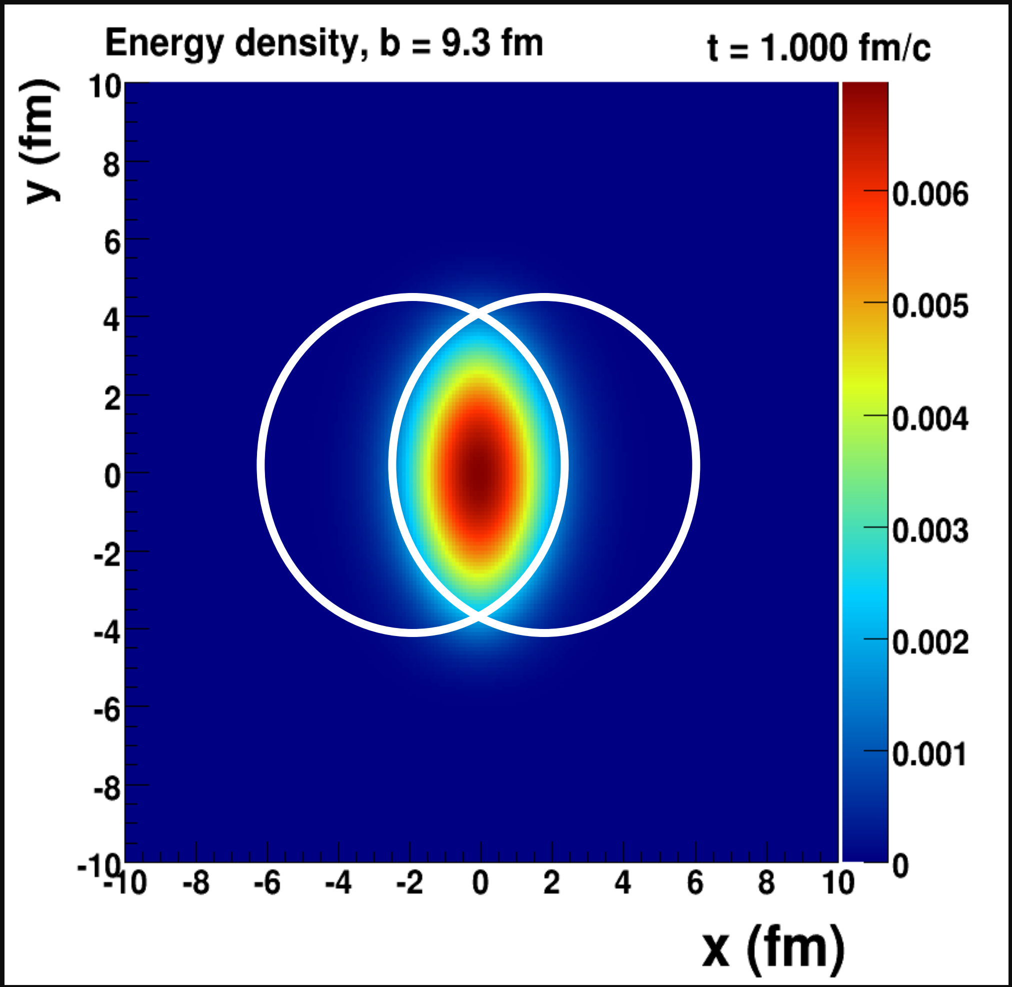
How Large is the Flow Really?

Assume early thermalization and run ideal hydrodynamics
(i.e. no dissipation → zero shear + zero bulk viscosity)

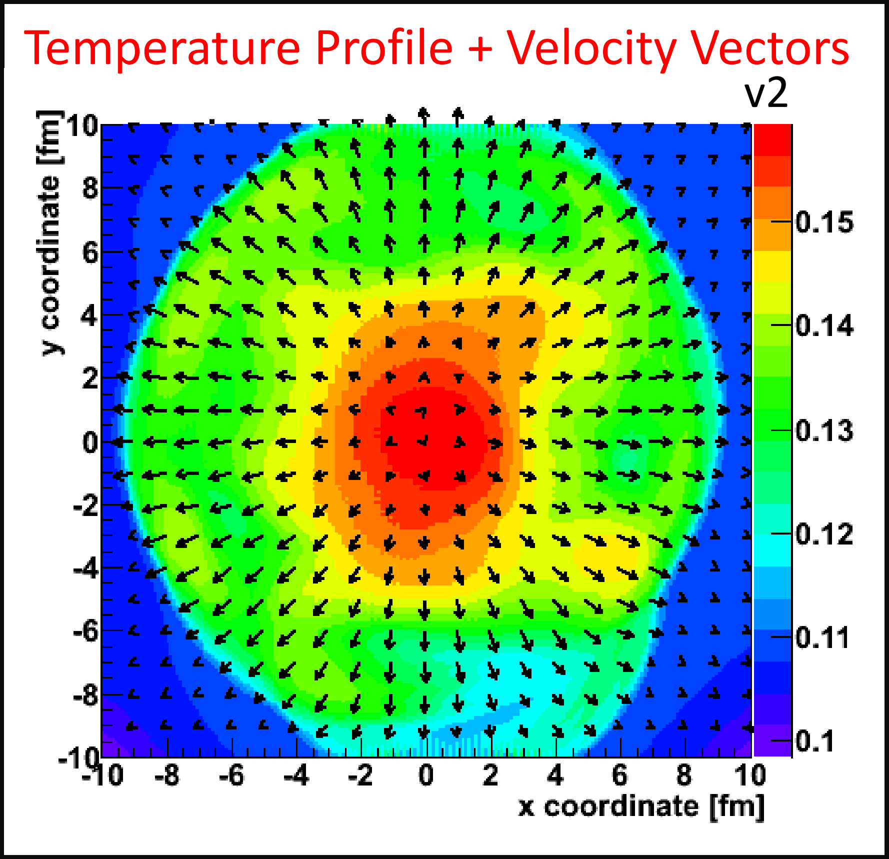
Key Inputs:

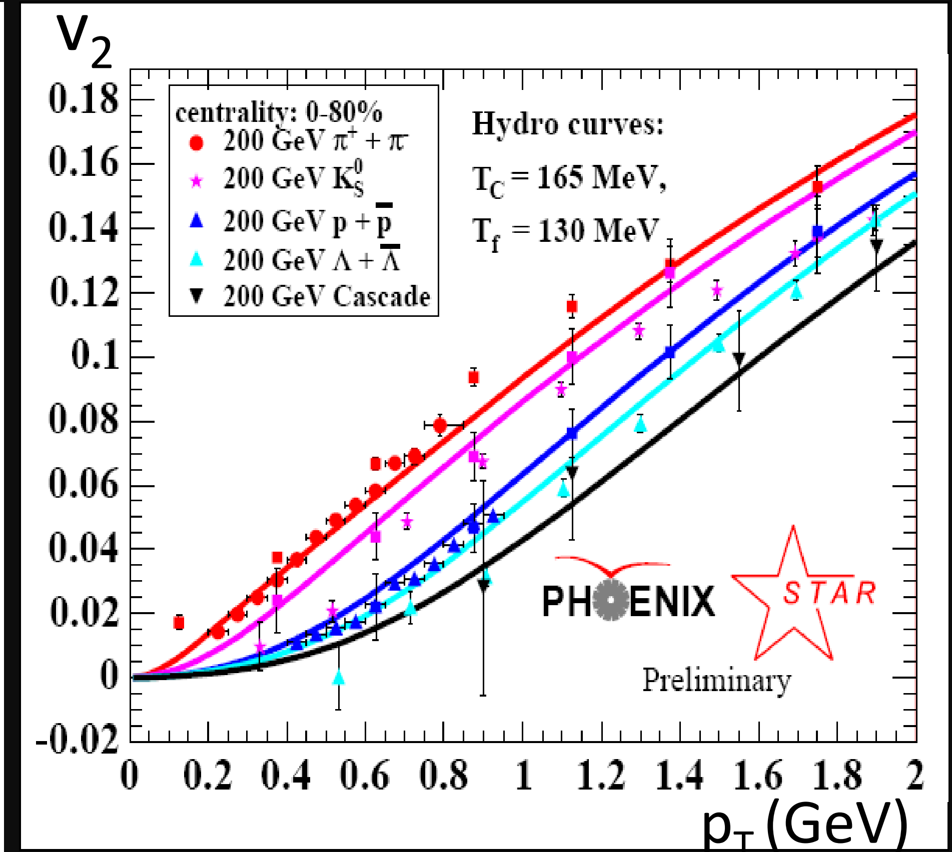
- ***Initial Geometry***
- ℓQCD Equation of State





Fluid cells "freeze-out" below T_f
Isotropic hadrons in cell rest frame, then boosted



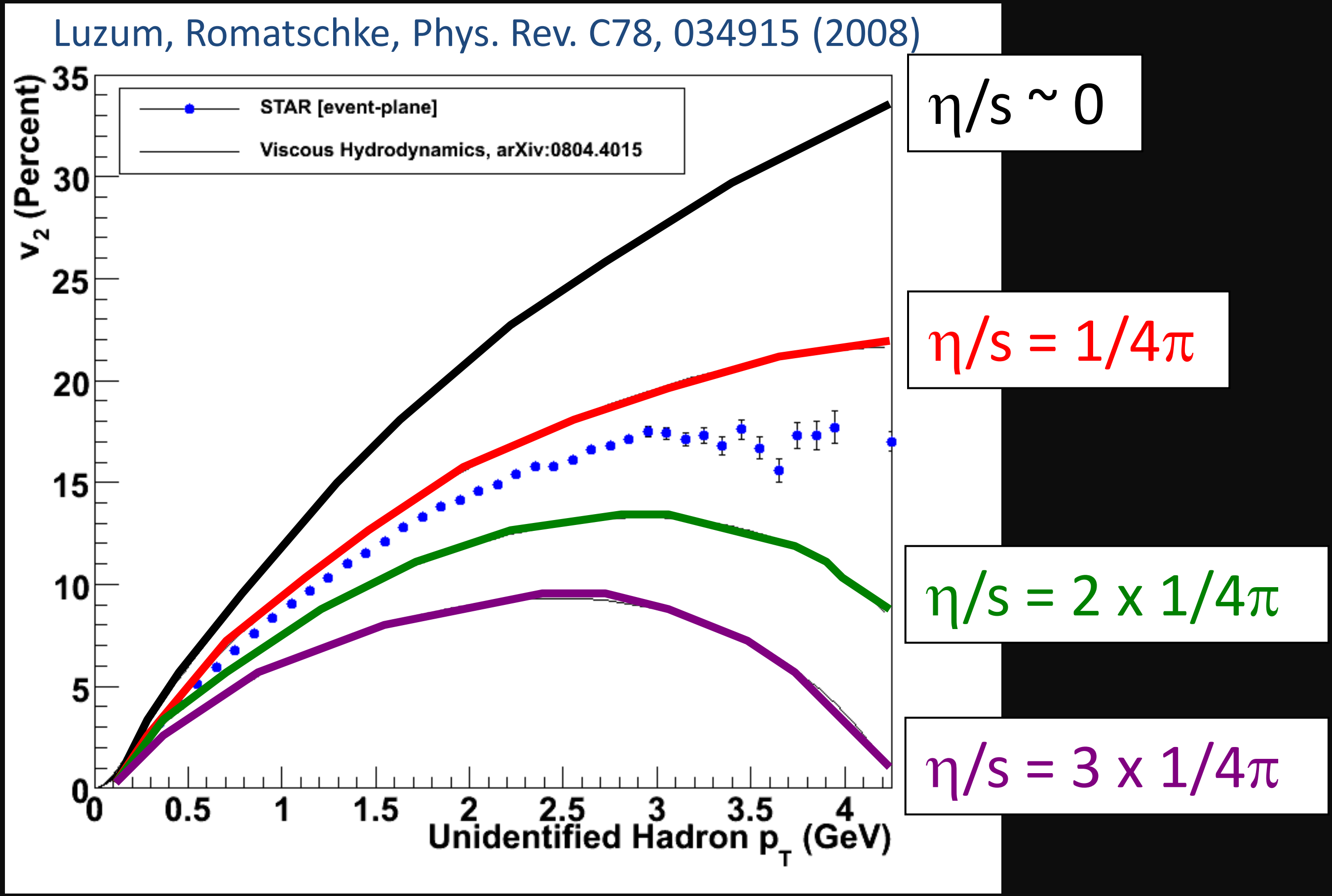


Characteristic flow pattern observed for $p_T < 2$ GeV

Circa 2005: Quark-Gluon Plasma = Perfect Fluid

How to Quantify QGP η/s?

Relativistic viscous hydrodynamics compared to data



$$\left(\frac{\eta}{s}\right) \Big/ \left(\frac{1}{4\pi}\right) = 1.3 \pm 1.3\,(\text{theory}) \pm 1.0\,(\text{experiment})$$

Very close to the bound!

$$\left(\frac{\eta}{s}\right) \Big/ \left(\frac{1}{4\pi}\right) = 1.3 \pm 1.3\,(\text{theory}) \pm 1.0\,(\text{experiment})$$

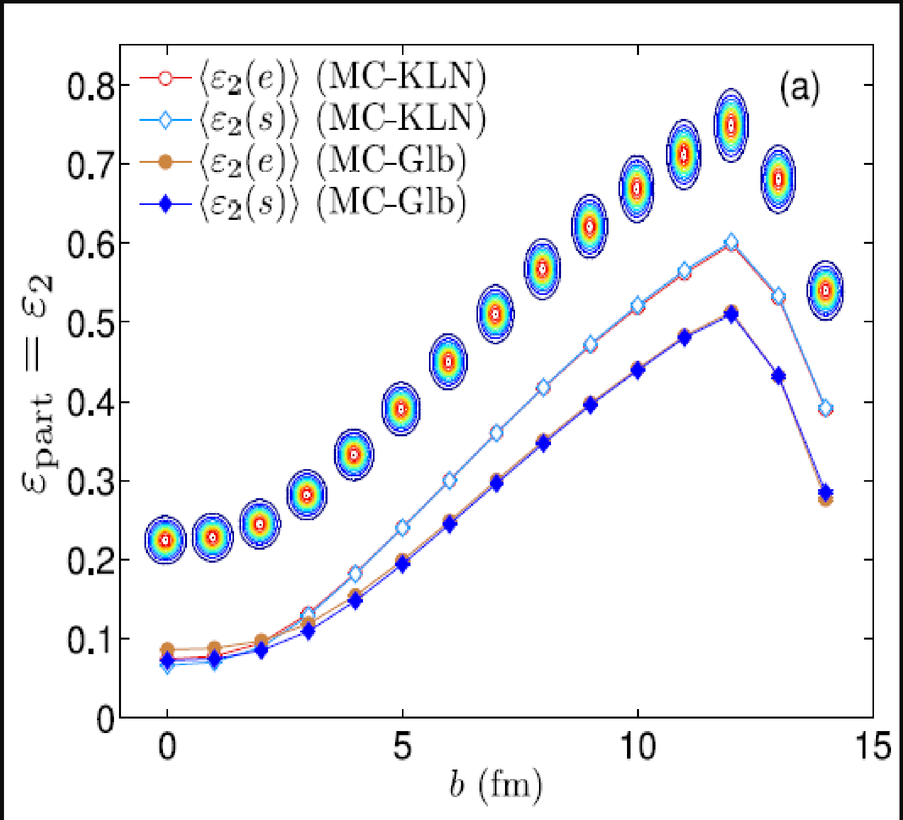
What dominated these uncertainties a few years ago?

Different ways of measuring v_2 gave ±20% variations.
Now resolved that the methods have different sensitivities to "nonflow" and fluctuations.
For example Ollitrault, Poskanzer, Voloshin Phys. Rev. C80, 014904 (2009).

In ideal hydrodynamics $v_2 \propto \varepsilon_2$ (initial eccentricity)
Uncertainty on η/s from initial geometry was ~100%.

Other sources subdominant:
hadronization, EOS, pre-flow, … (worth re-examination)

Initial Condition Uncertainty



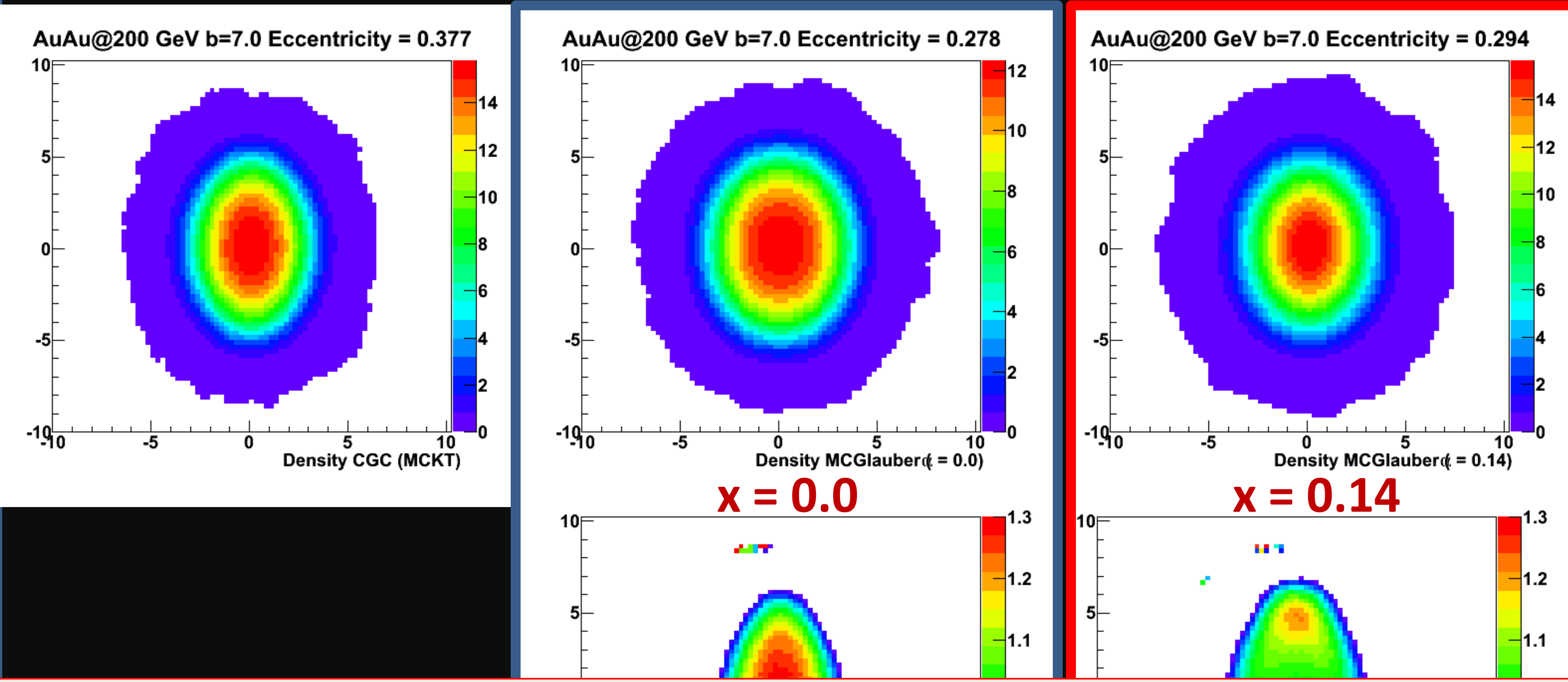
Elliptic Flow reasonably described by either:

A) Smaller eccentricity (Glauber) + Less Dissipation (**$\eta/s \approx 1/4\pi$**)

B) Larger eccentricity (Gluon Saturation) + More Dissipation (**$\eta/s \approx 2/4\pi$**)

Neither **A** nor **B**, and yet these give a range of uncertainty

Examine b = 7 fm case

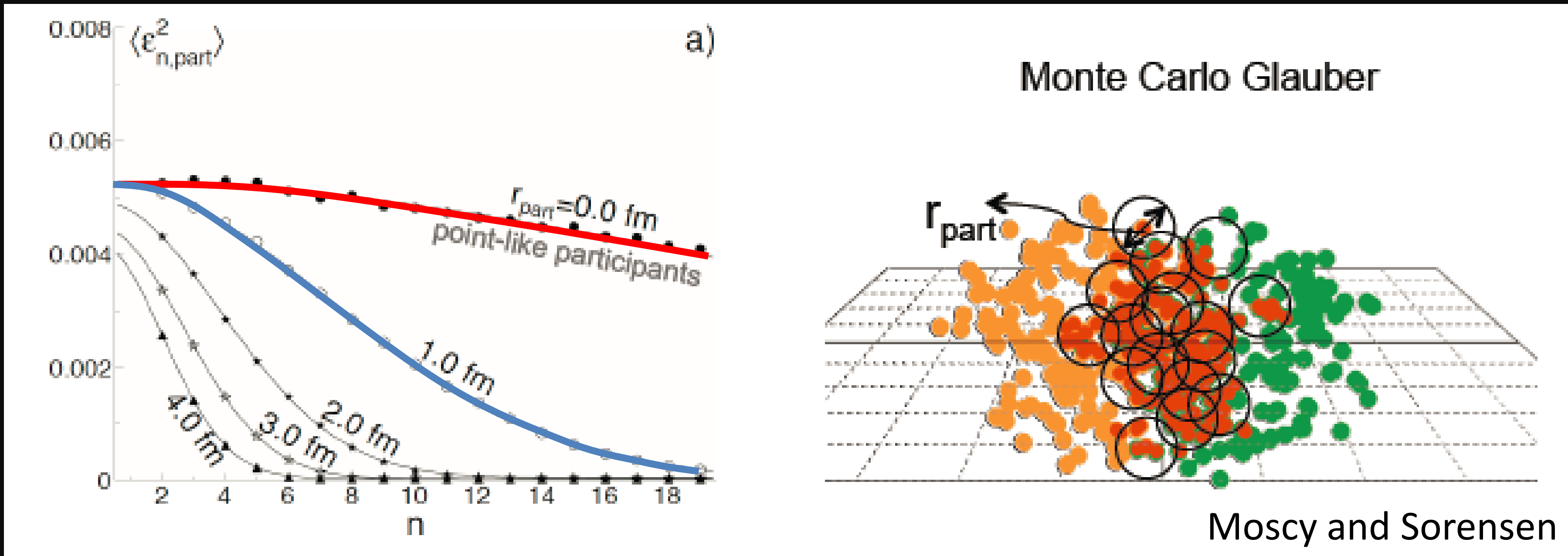


Just saying "Glauber" is not enough (different variants).

$$\frac{dN_{ch}}{d\eta} = n_{pp}\left[(1-x)\frac{N_{part}}{2} + xN_{coll}\right]$$

MC Glauber variations have 26 and 22% lower eccentricities than MCKT (with saturation effects).

Spatial Moments Initial Smearing



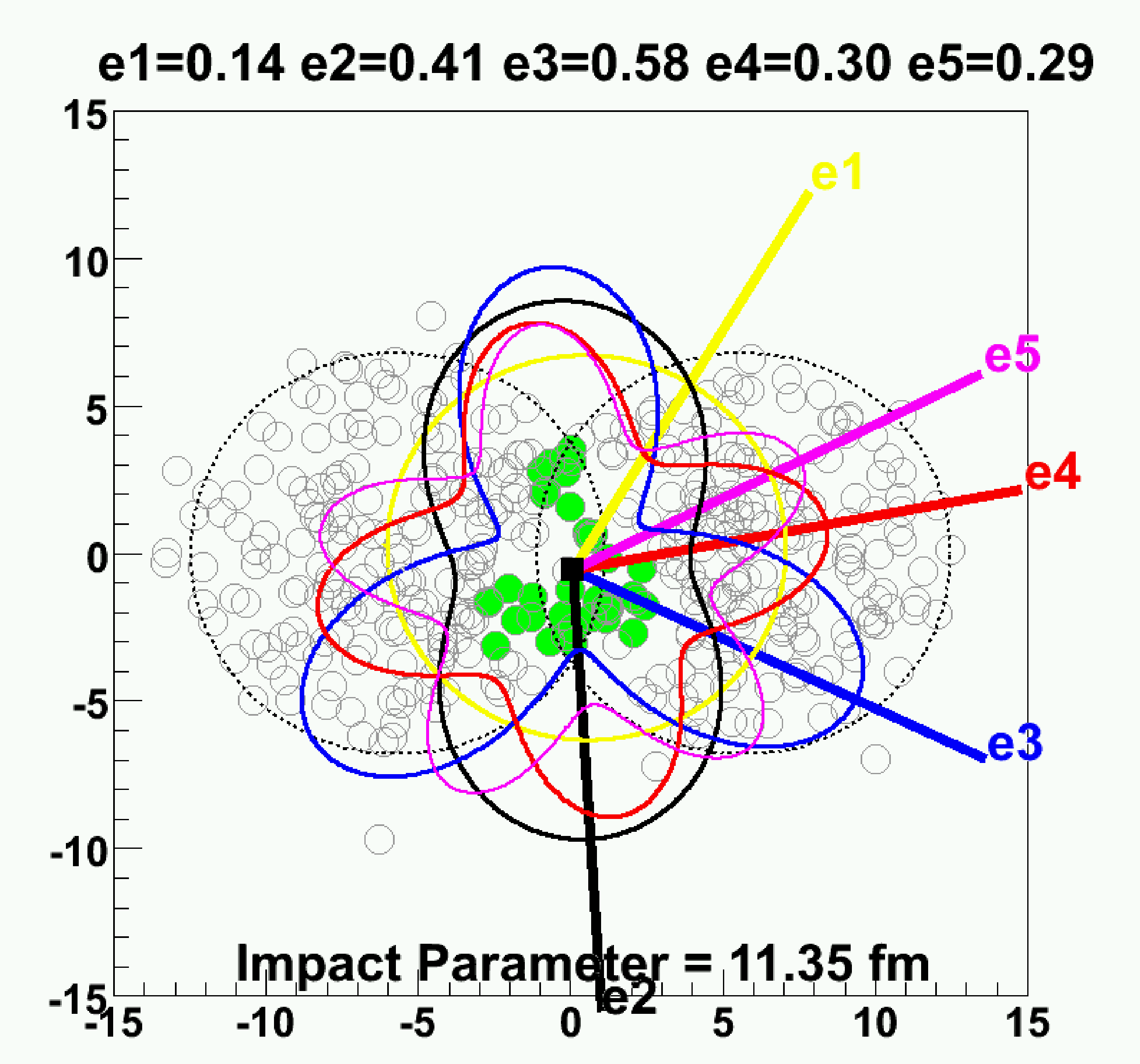
The initial smearing for the starting distribution suppresses the higher moments almost like a Gaussian drop off. Spatial smearing could be in initial state (e.g. size of nucleon) or during evolution.

For a 1 fm smearing this effect is modest for the n=2,3,4 moments.

Au-Au 30-40% Central

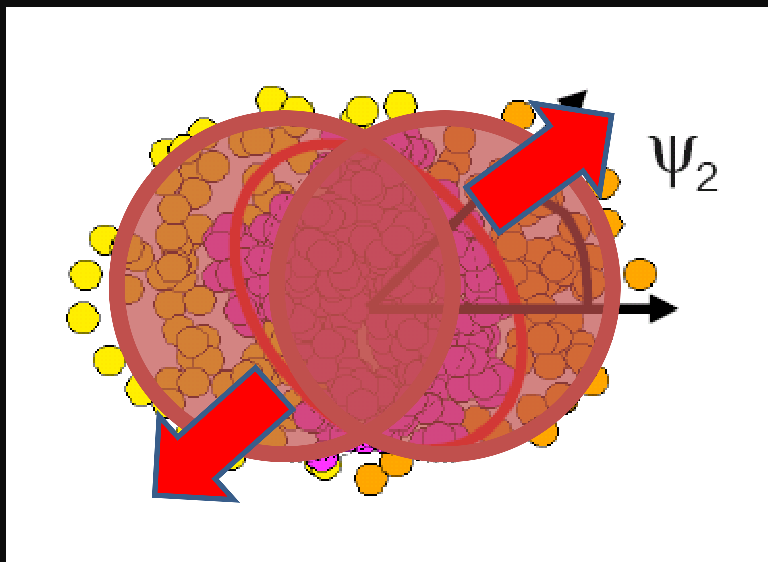
	Point-like	Smear (1 fm radius)	
$\langle\varepsilon_2\rangle$	0.359	0.346	-4%
$\langle\varepsilon_3\rangle$	0.197	0.185	-6%
$\langle\varepsilon_4\rangle$	0.197	0.179	-9%

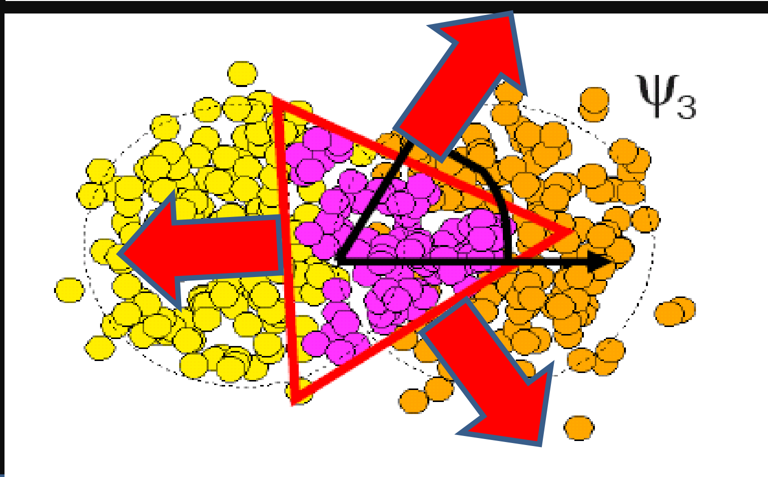
Realization → Lumpy Initial Conditions

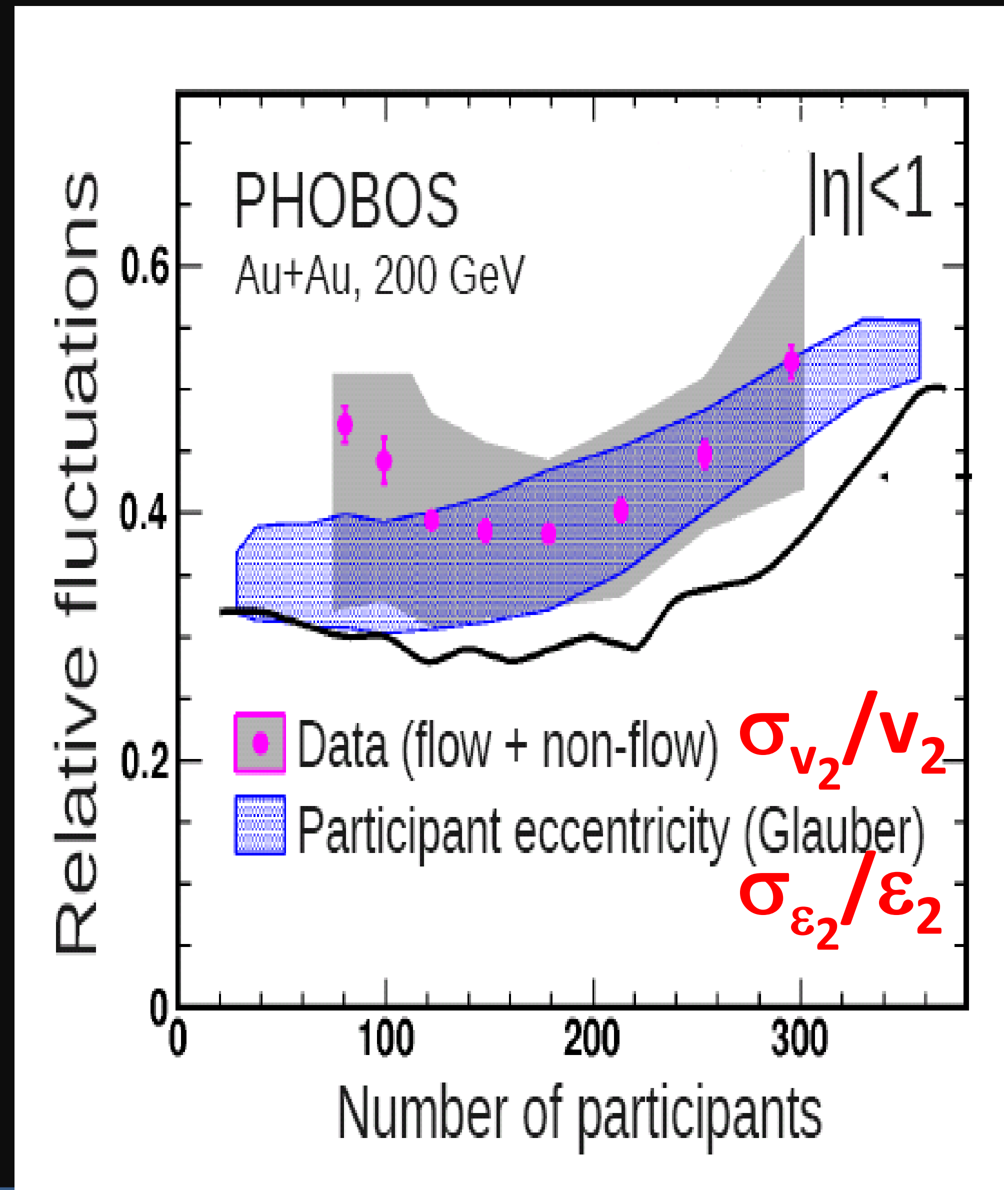


Fluctuations Dominate

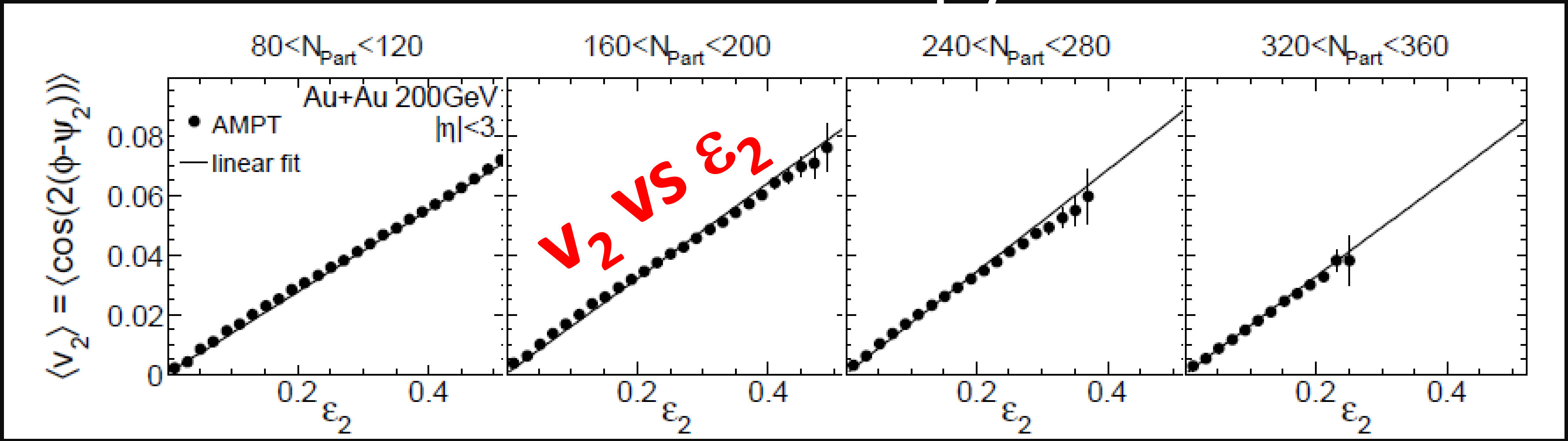
Flow dictated by nucleon geometry







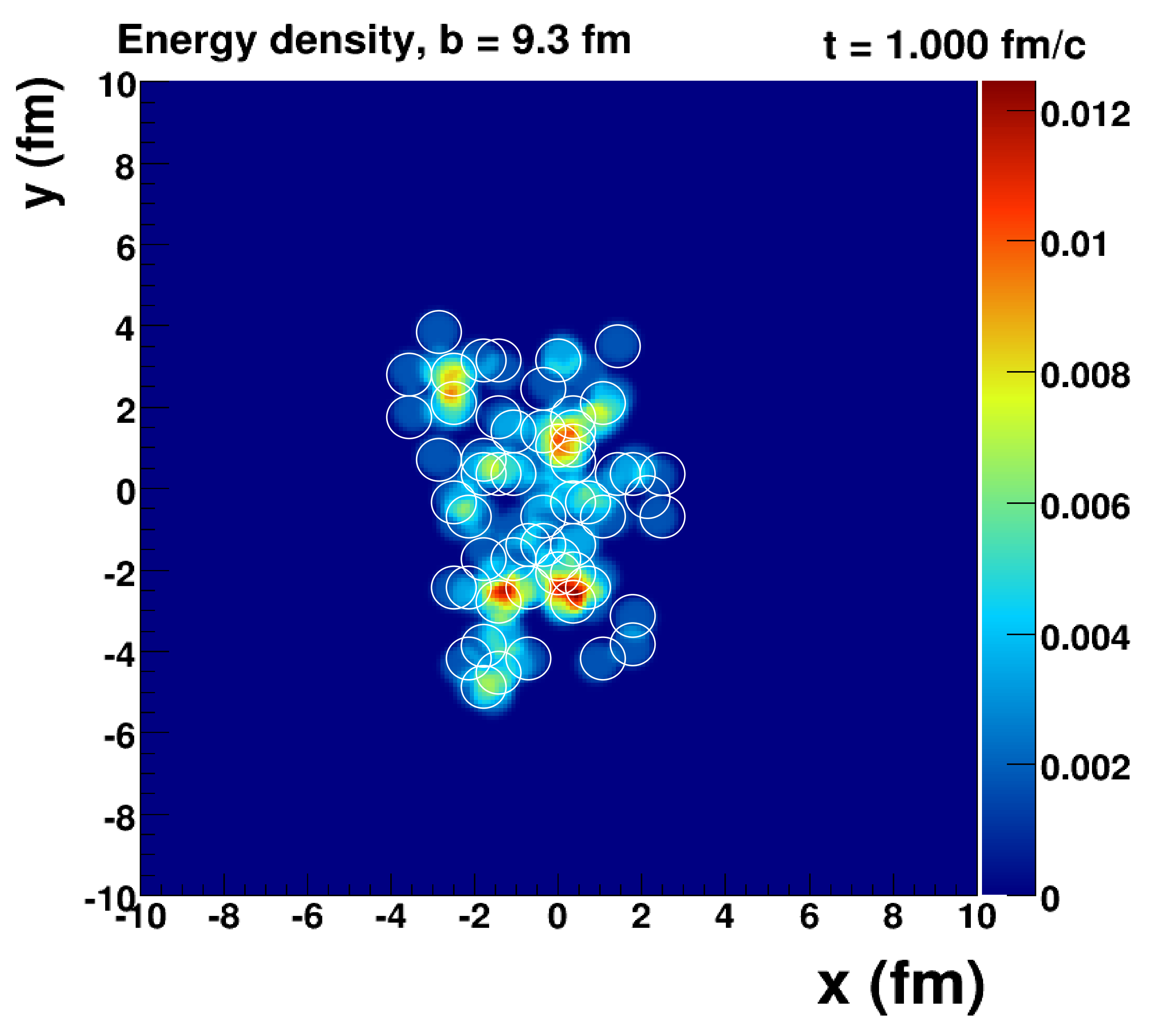
Spatial moments translate into momentum anisotropy moments



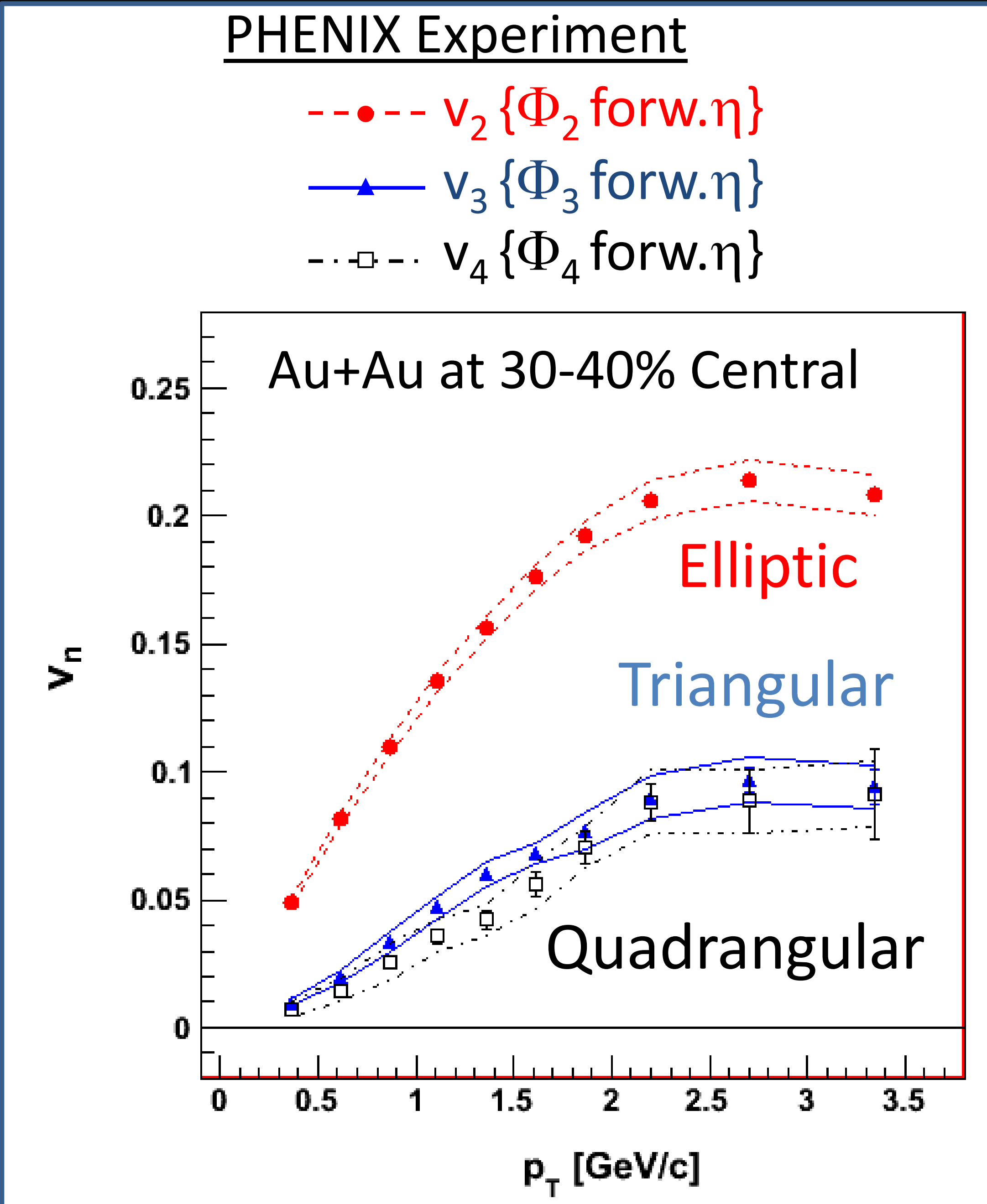
v_3 is as irrefutable as v_2 from ε_2.

Now quantify implications.

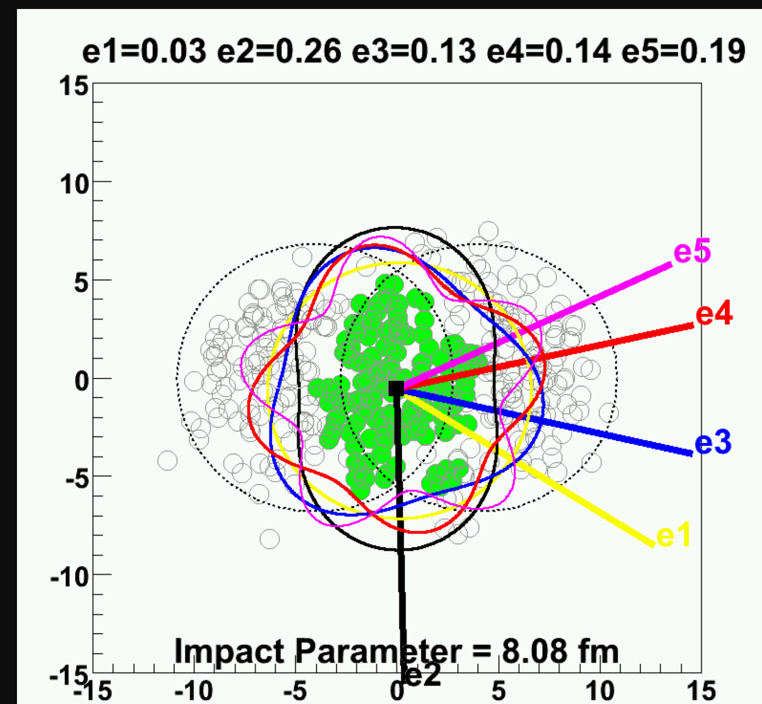
Alver, Roland, arXiv:1003.0194v3



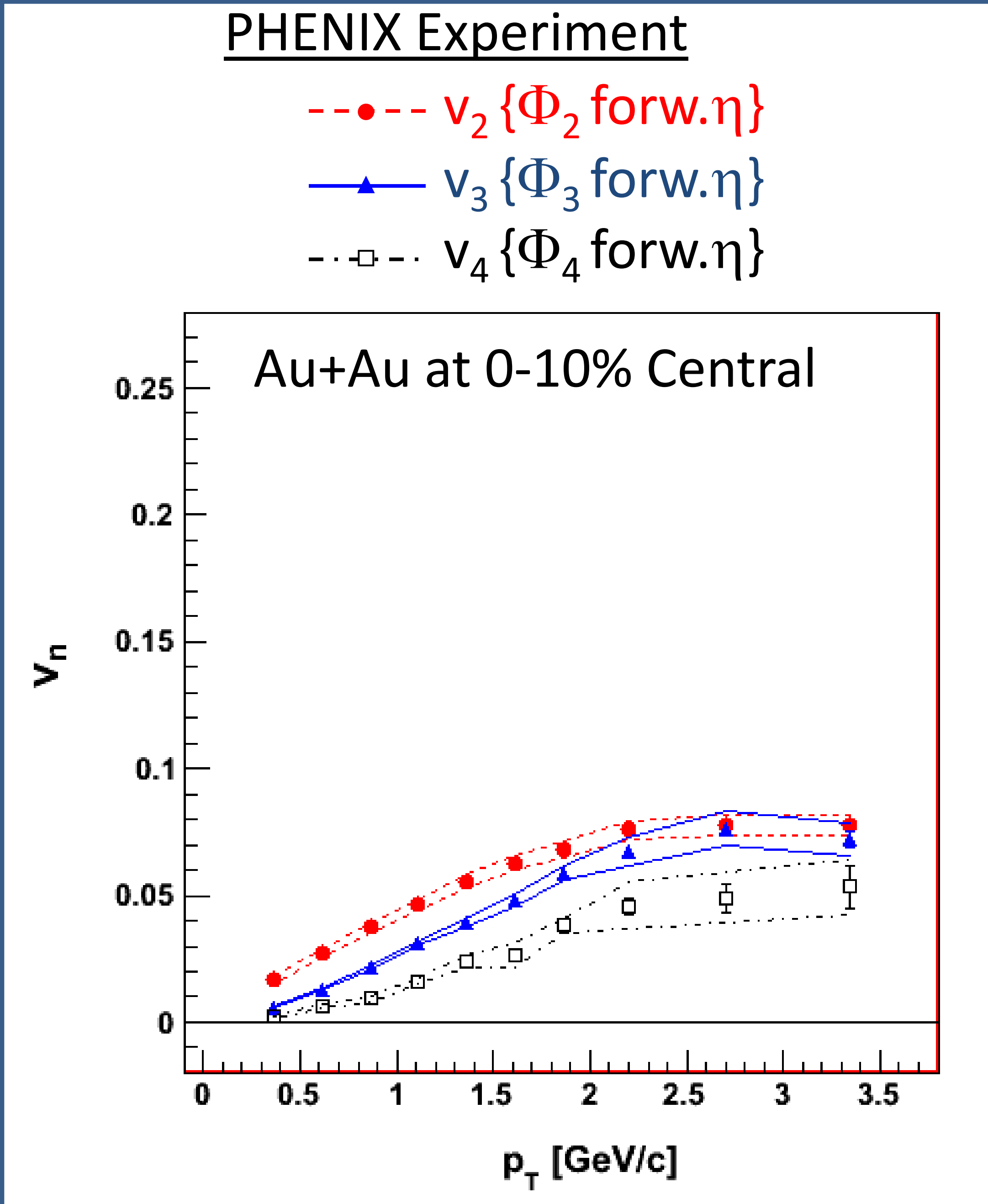
Romatschke=viscous hydrodynamics, McCumber=lumpy conditions + animation

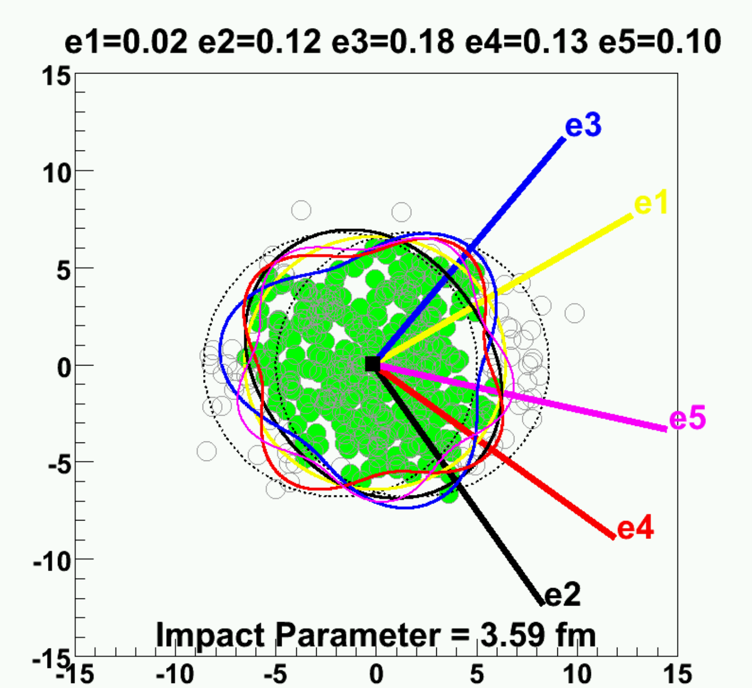


Systematic uncertainties defined by the variations with Φ_n from different $\Delta\eta$ and from different methods.



$$\varepsilon_2 \approx 2 \times \varepsilon_3 \approx 2 \times \varepsilon_4$$





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

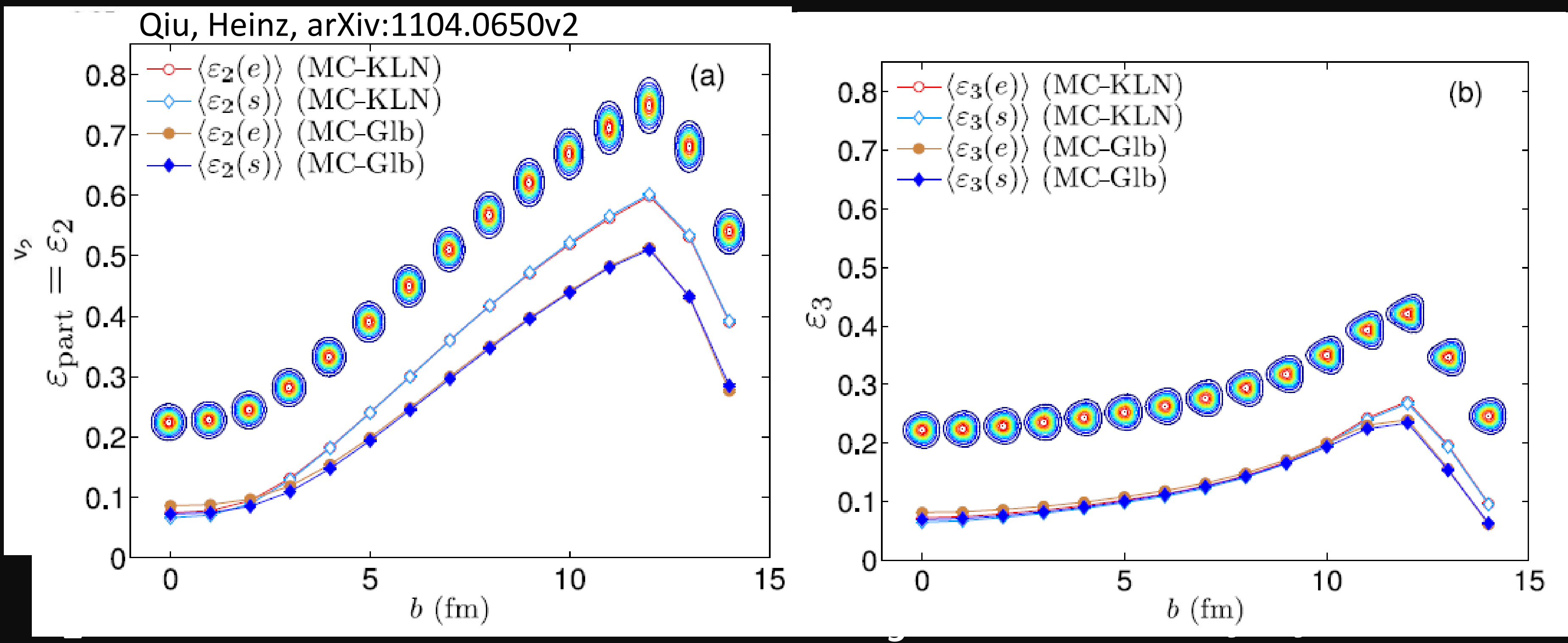
How many moments are important at RHIC? 5,6,7th

Initial Condition Constraints

Glauber and CGC similar spatial triangularity ε_3

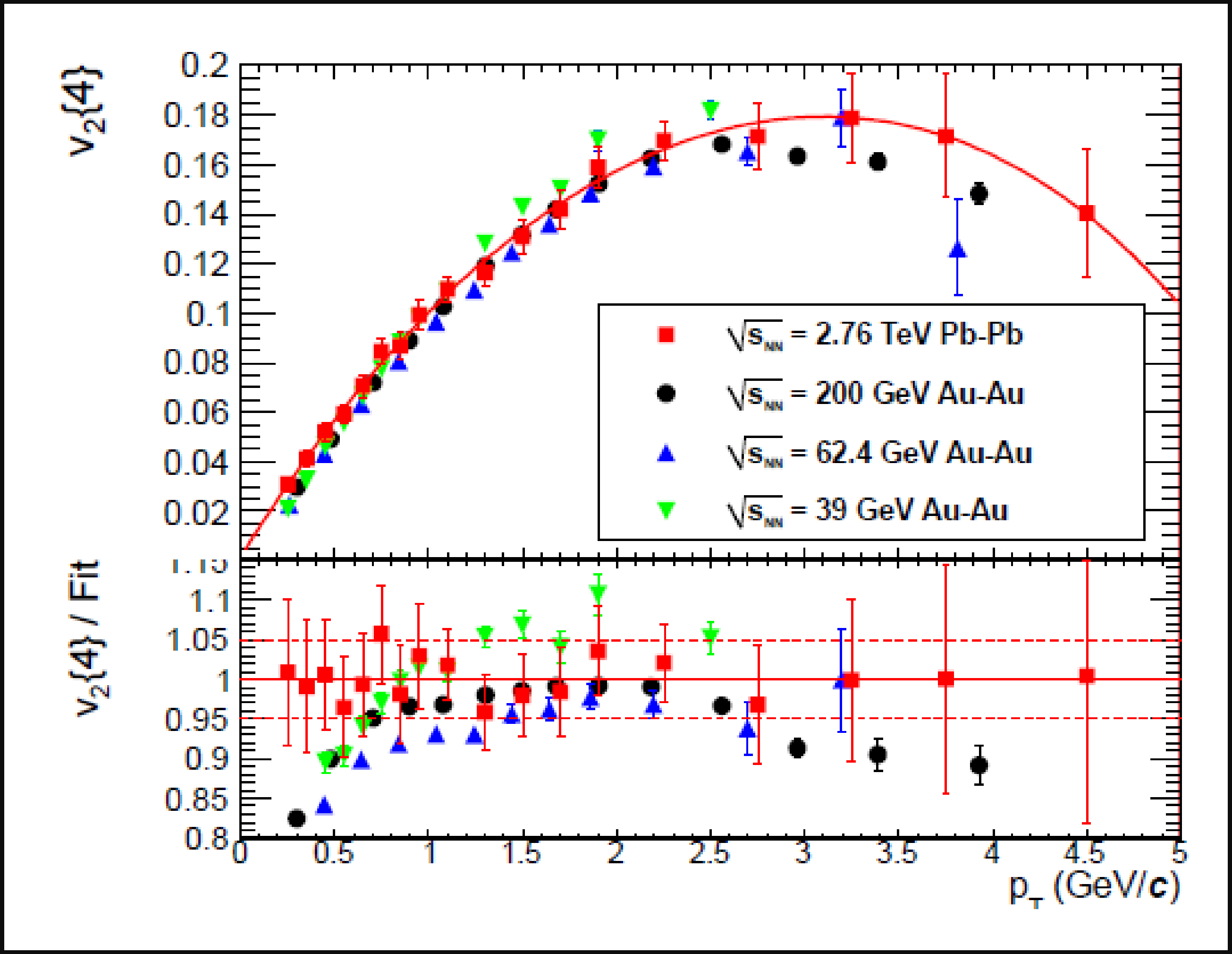
Thus CGC with larger η/s gives smaller v_3

Real Prediction!



Needs theory calculation with full event-by-event fluctuations and confirmation at LHC energies.

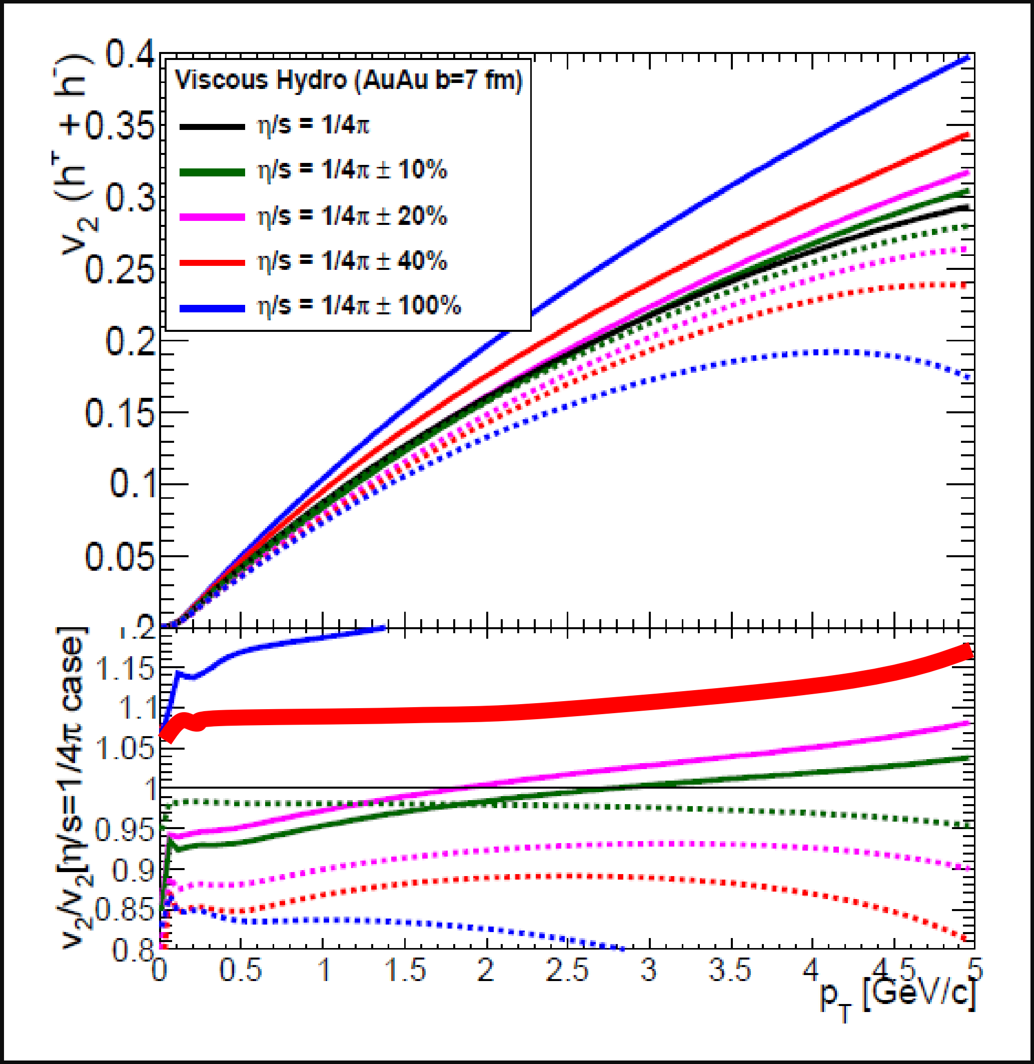
How does flow change with 14 x energy?



What is required to get this remarkable agreement?

JN, Bearden, Zajc, arXiv:1102.0680

Change in η/s to change v_2 by 5%?



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

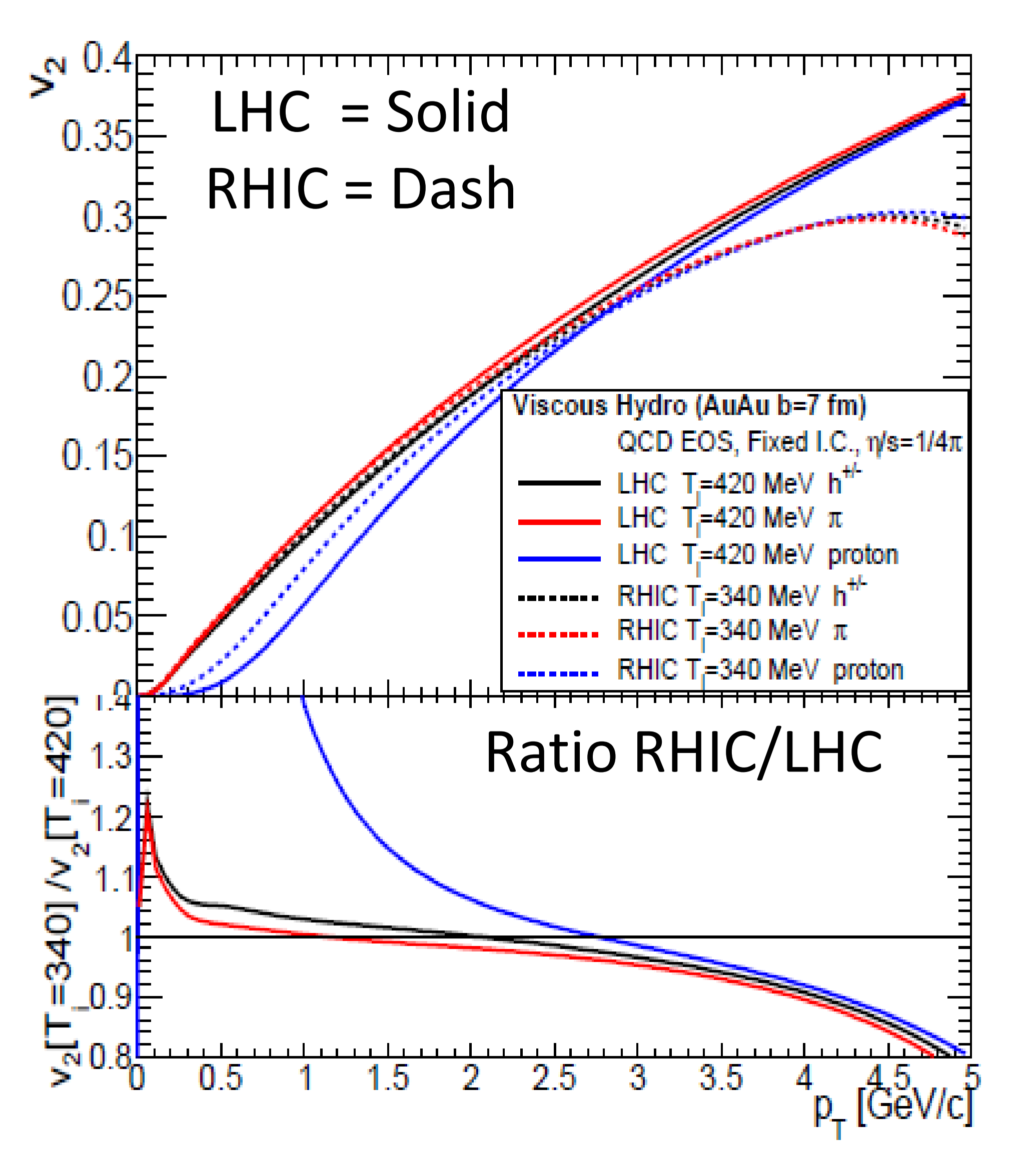
$\Delta(\eta/s) \sim 40\% \rightarrow \Delta v_2 \sim 10\%$

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

Always take ratios.

Low p_T turn out to be very sensitive and where experiments have smallest uncertainties

T_i = 420 MeV (LHC) versus T_i = 340 MeV (RHIC)?



Black = all hadrons

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

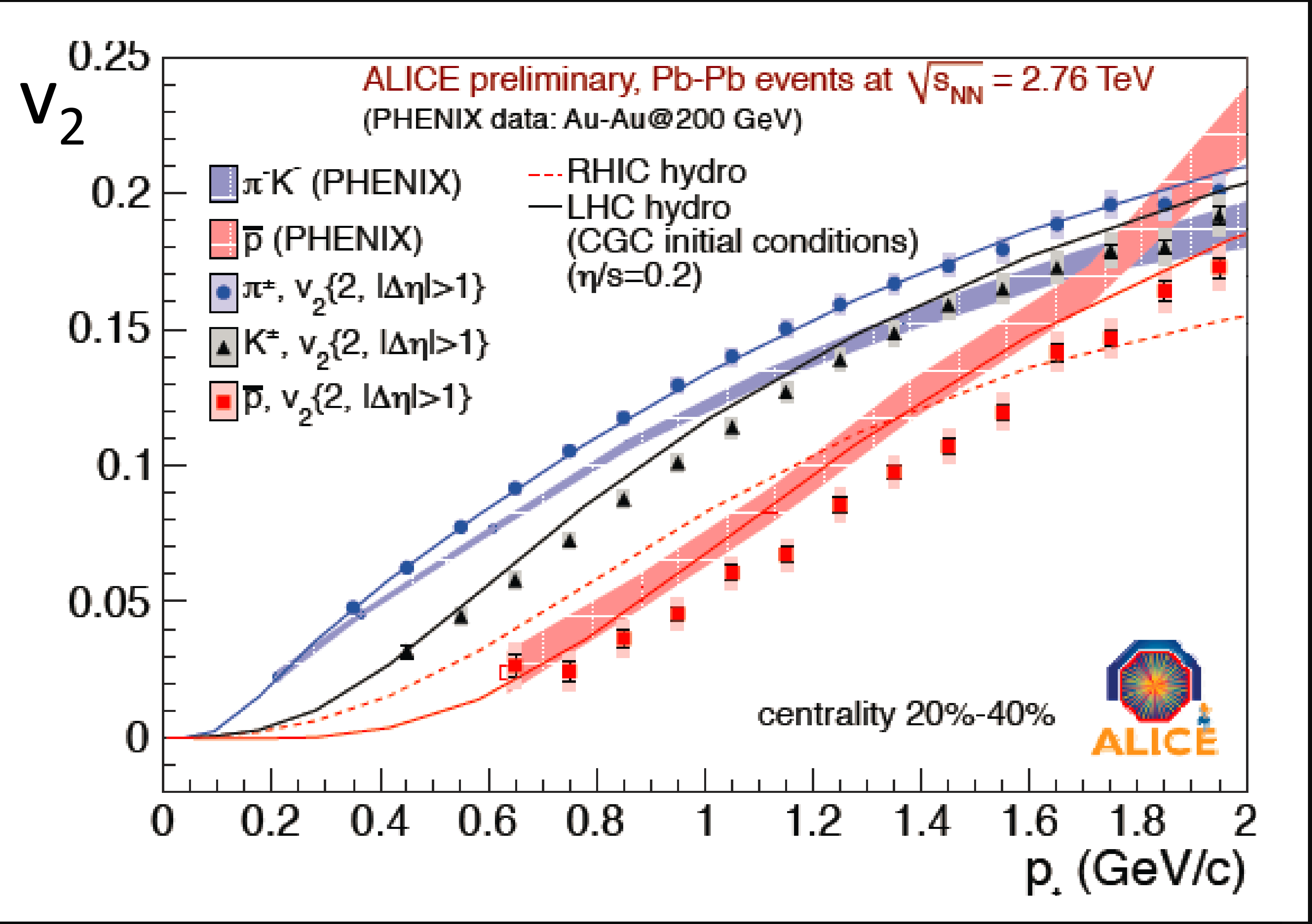
Blue = protons

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

General Feature Confirmed in ALICE Data

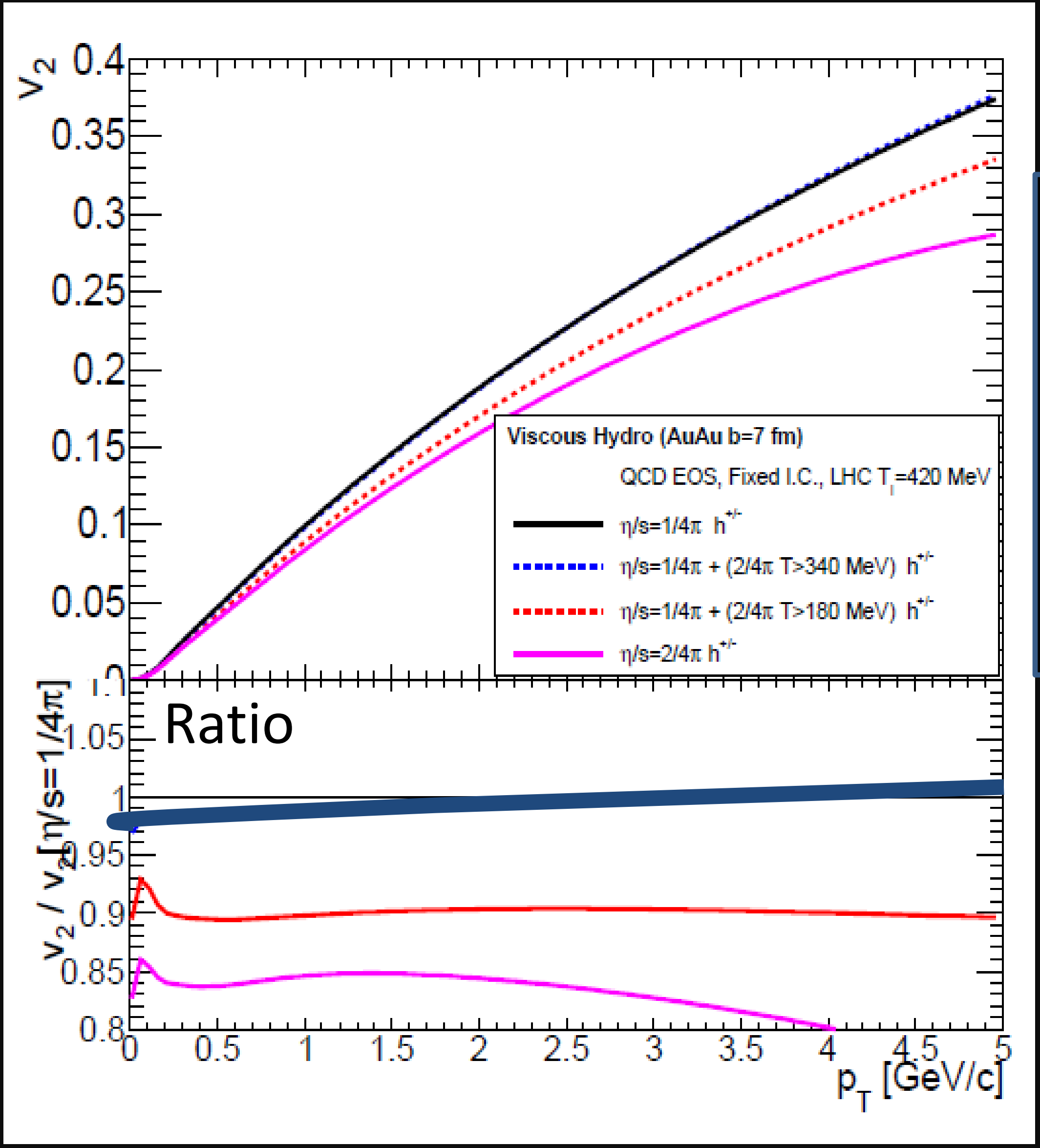


Exact radial boost still not matching in detail

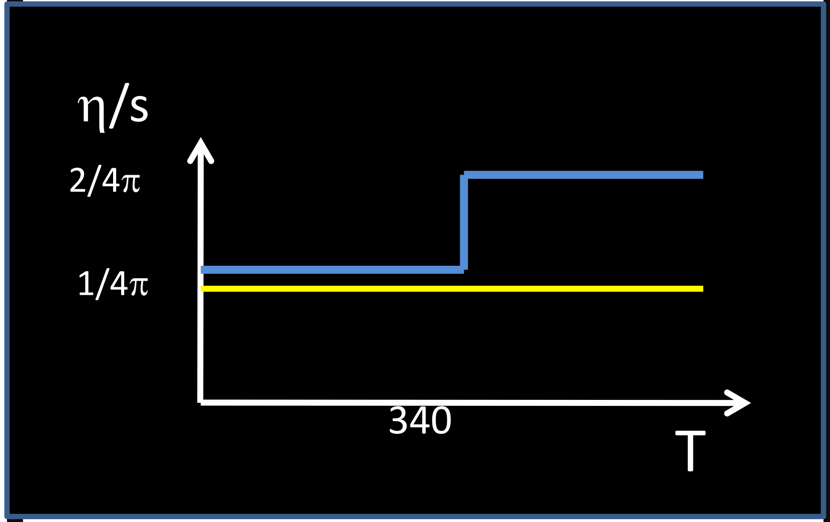
Try Hydro + Cascade afterburner

What if η/s is larger for T > 340 MeV?

(just the range sampled at the LHC in early times)?



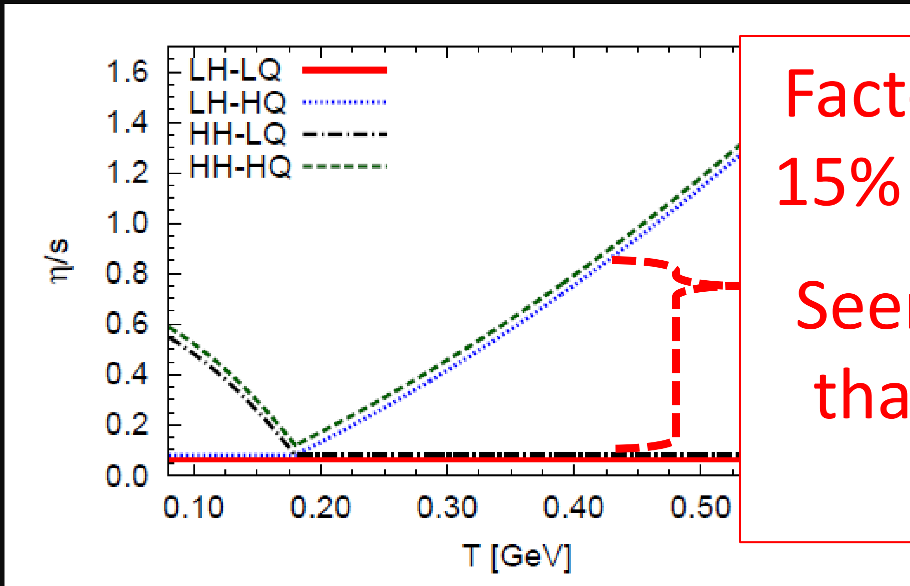
Consider case I:

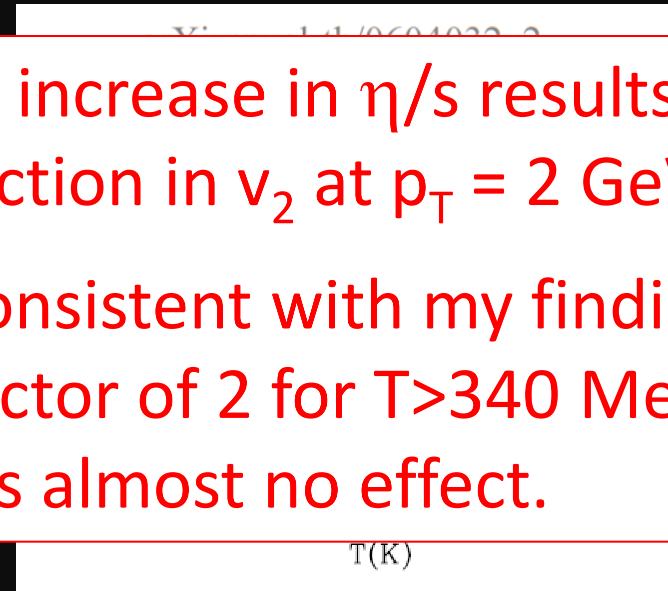


No change in $v_2(p_T)$!

Earliest LHC time has no big impact on η/s.

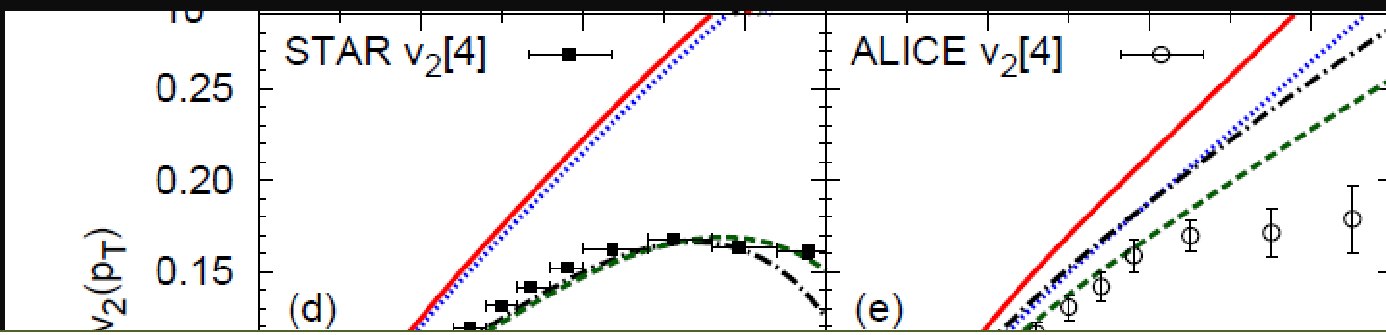
Recent study of η/s (T) – arXiv:1101.2442





Factor 10 increase in η/s results in 15% reduction in v_2 at p_T = 2 GeV/c

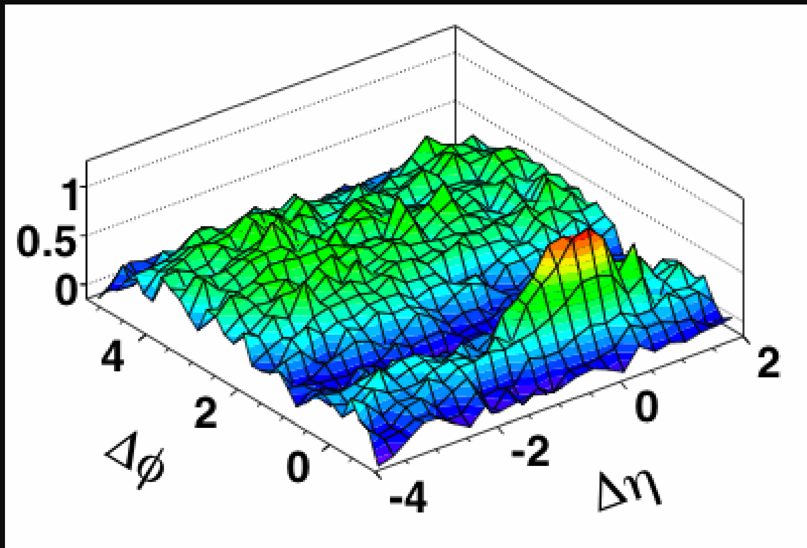
Seems consistent with my finding that a factor of 2 for T>340 MeV has almost no effect.



‘RHIC v_2 is dominated by η/s below T_c and LHC v_2 by η/s above T_c‘

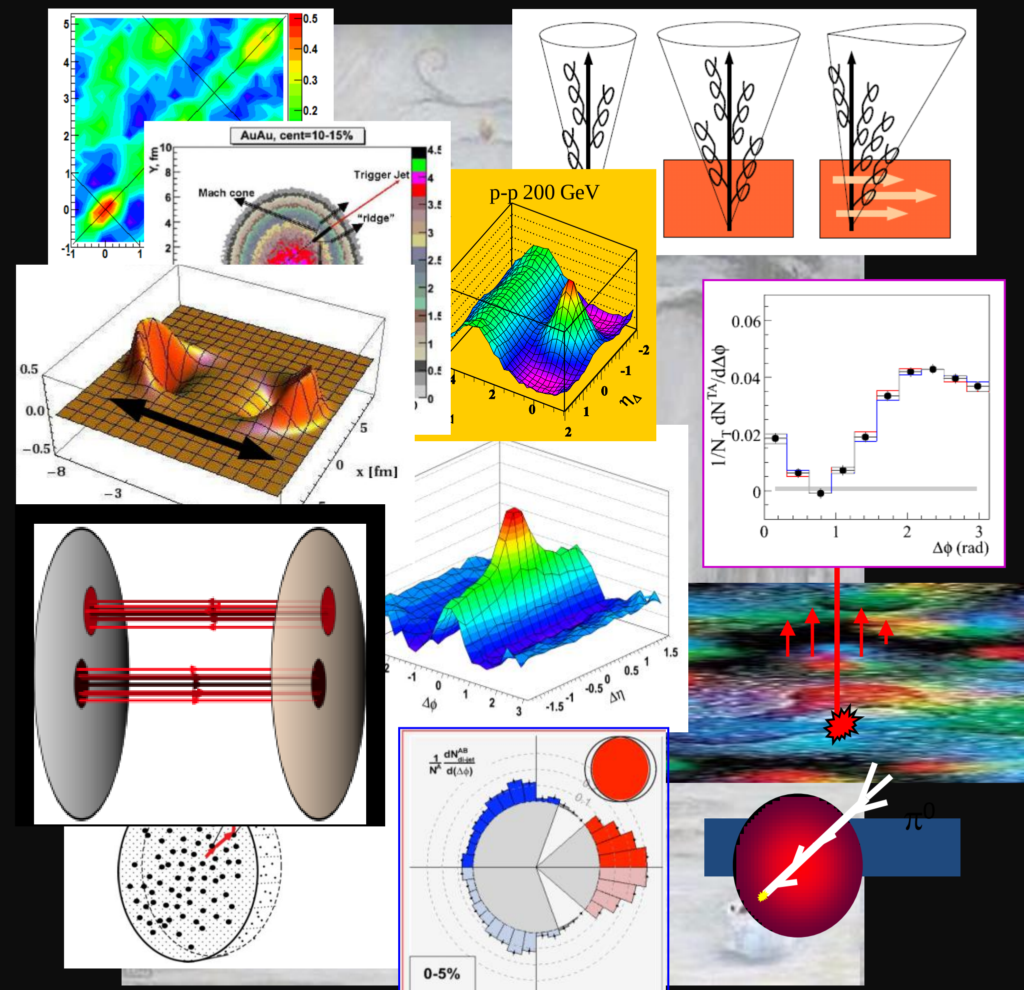
seems an unlikely fine tuning problem

“Ridge” and “Shoulders”



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

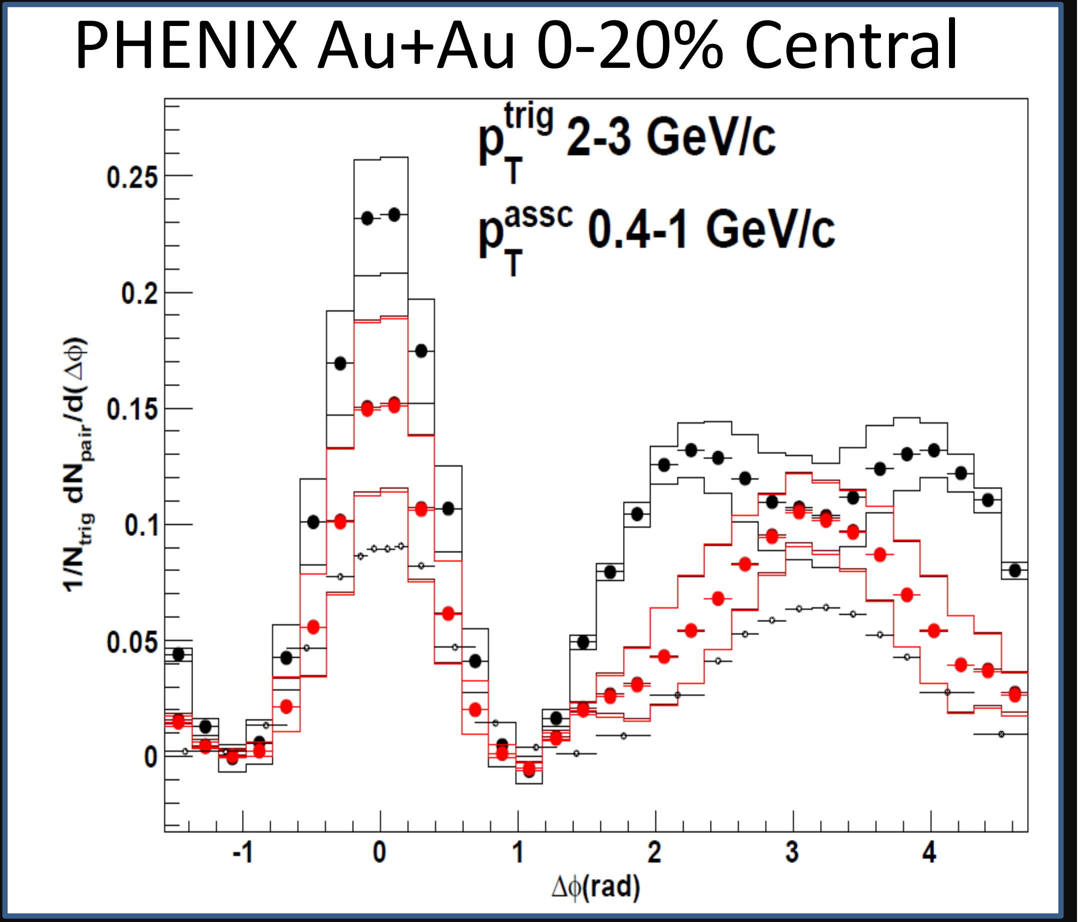
Features in two-particle correlations that have generated a lot of excitement.



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

The “death” of the ridge and shoulders (*aka* shock response)

Re-Evaluation of Shock Response



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.

LHC Results

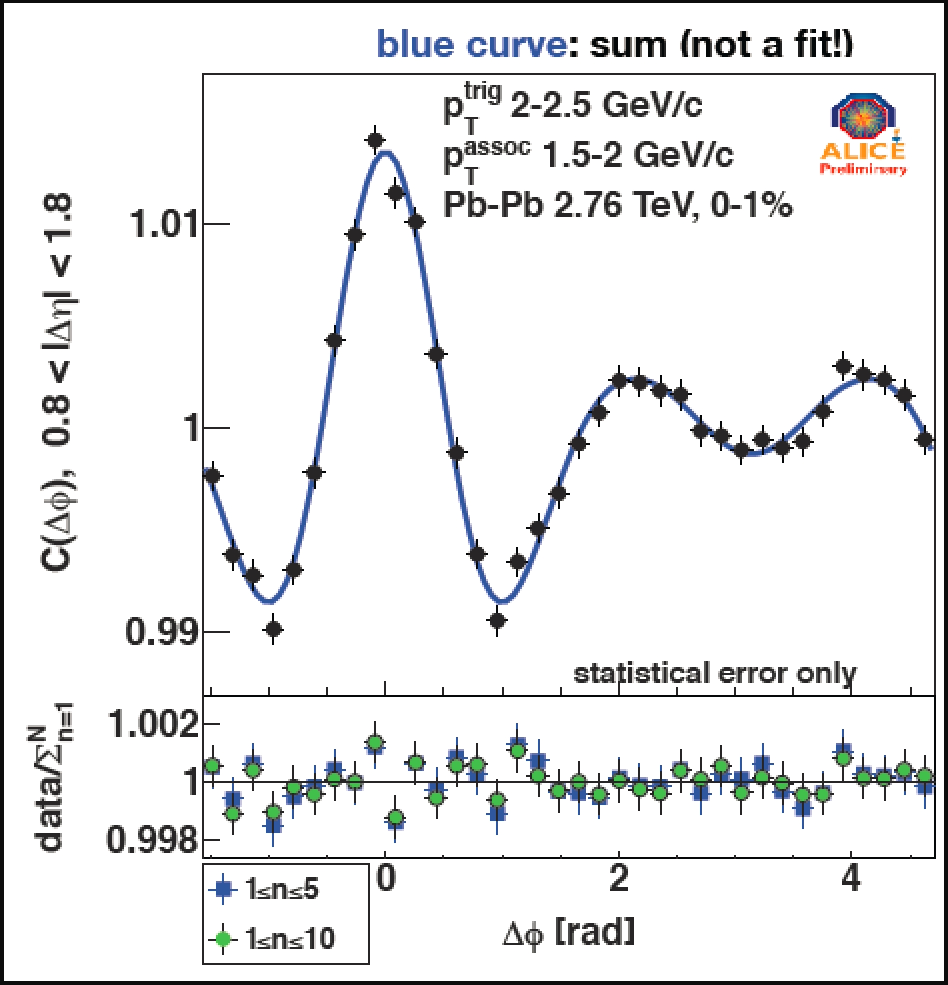
"Ridge" and "Shoulders" seen at LHC as well…

ALICE: arXiv:1105.3865

Fourier Decomposition characterizes the distribution

Are the Fourier Coefficient just the higher order flow moments?

Key Tests



Sound Mode Commentary

Viscous Horizon: "Its verbal definition is that it separates the wavelengths of sound which *are* and *are not* dissipated by viscosity effects." i.e. damped to "un-observably small magnitude" [Shuryak].

Smooth medium and fluctuations $$T_{\mu\nu} = \tilde{T}_{\mu\nu} + \delta T_{\mu\nu}$$

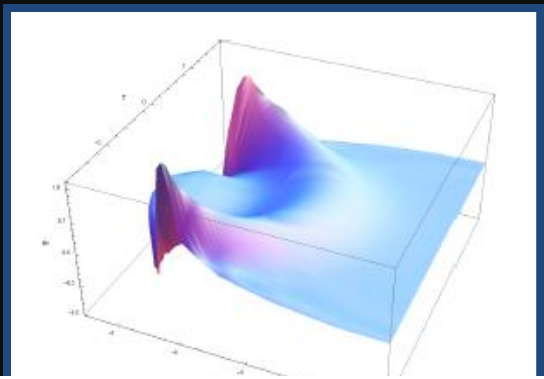
Dispersion relation from shear viscosity $$\omega = c_s k - \frac{i}{2}\frac{4\eta}{3s}\frac{k^2}{T}$$

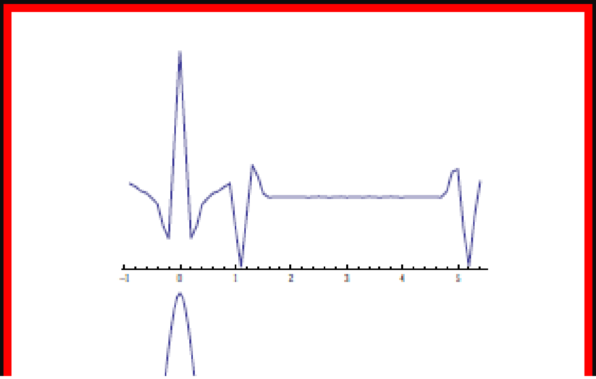
Damping of fluctuations depends on wavenumber (k), time (t), η/s and Temperature.

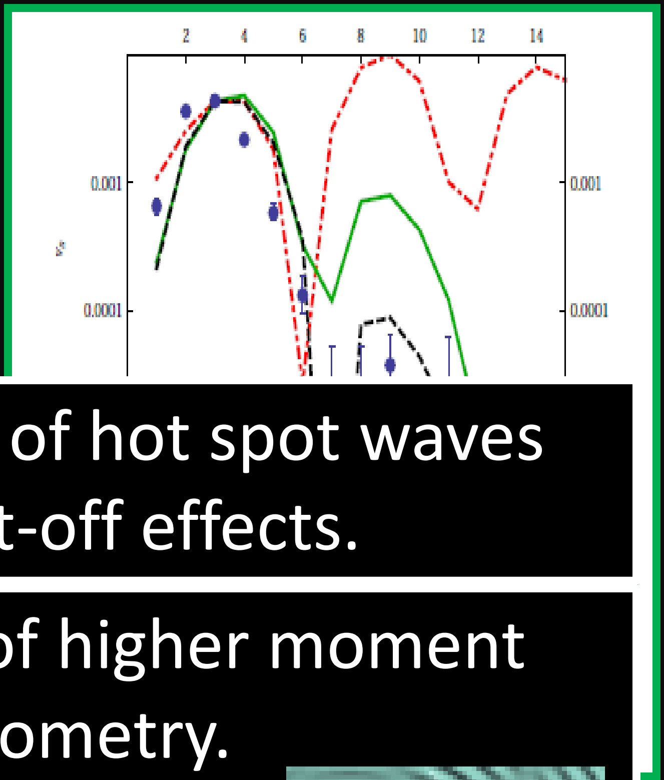
$$\delta T_{\mu\nu}(t) = exp\left(-\frac{2}{3}\frac{\eta}{s}\frac{k^2 t}{T}\right)\delta T_{\mu\nu}(0)$$

Need more formal definition of viscous horizon, e.g. when wavelength mode damped by 1/e. "Un-observably small" depends on experimental sensitivity.

One then evolves with hydrodynamic equations this “hot spot”.
At the freeze-out surface, apply Cooper-Frye hadronization and calculate angular distribution of particles.
Finally, one decomposes the angular distribution into harmonics (n).



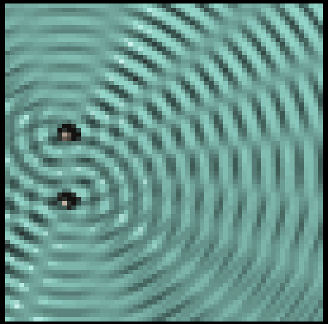




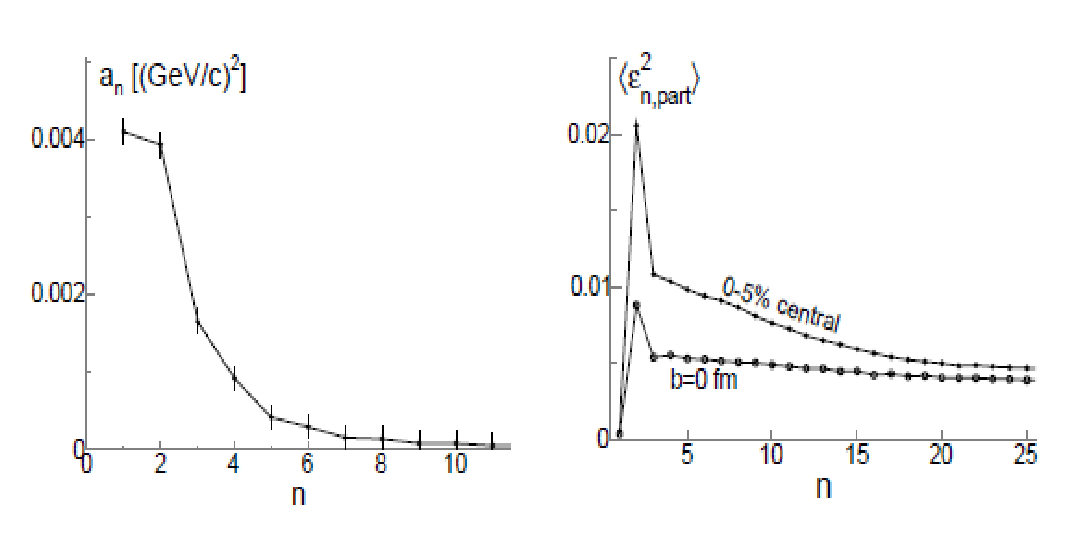
Structure due to detailed interaction of hot spot waves with freeze-out surface and cut-off effects.

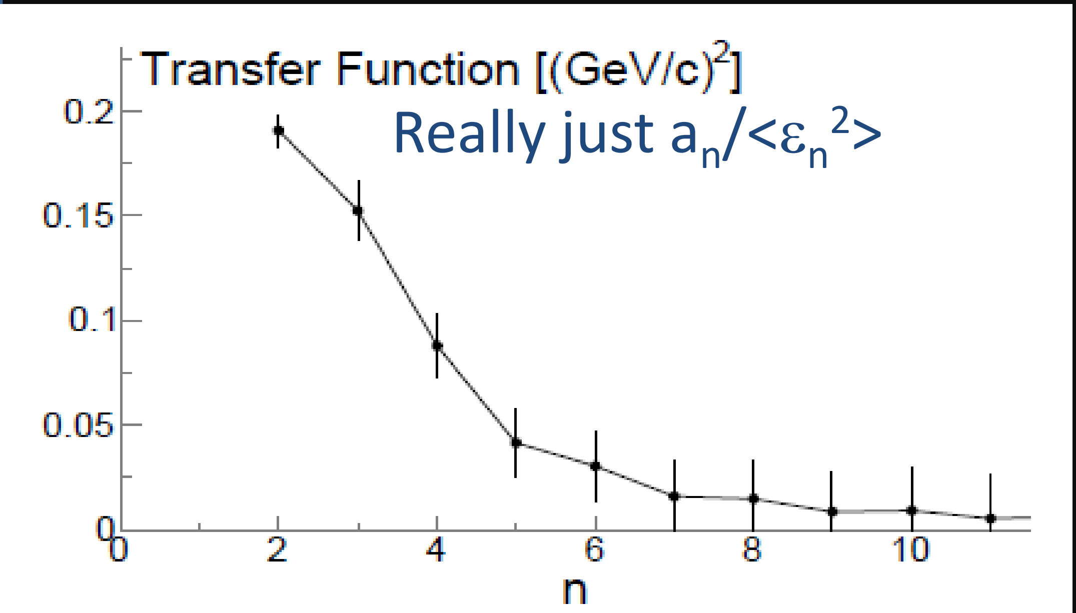
Needs double check on robustness of higher moment structures with realistic geometry.

Also, check of how lumpy medium impacts propagation of state (not small perturbations).



Mocsy, Sorensen use STAR published p_T-p_T and $\Delta\phi$ correlator (a_n) which in the limit of just number correlations ≈ v_n^2.





http://arxiv.org/abs/arXiv:1008.3381 (Mocsy, Sorensen)

They argue that the transfer function goes to zero when ℓ(mean free path) ≈ λ (wavelength of the mode) = $2\pi R/n$

They choose n=5 as the cut-off (viscous horizon) and <R> = 3 fm (average radial position of participants) and get ℓ=3.5 fm.

They state plugging into kinetic formula gives η/s ~ 5 x $1/4\pi$.

Lots of factors of 2 floating around

http://arxiv.org/abs/arXiv:1105.3782 (Lacey, Tananenko, Ajitanand, Alexander)

Shuryak's damping equation by wavenumber (k)

$$\delta T_{\mu\nu}(t) = exp\left(-\frac{2}{3}\frac{\eta}{s}\frac{k^2 t}{T}\right)\delta T_{\mu\nu}(0)$$

They attempt to relate k to angular harmonic moment n
However, k is mode in radial direction and n is angular correlation for momentum vectors.

$$n\lambda = 2\pi R$$

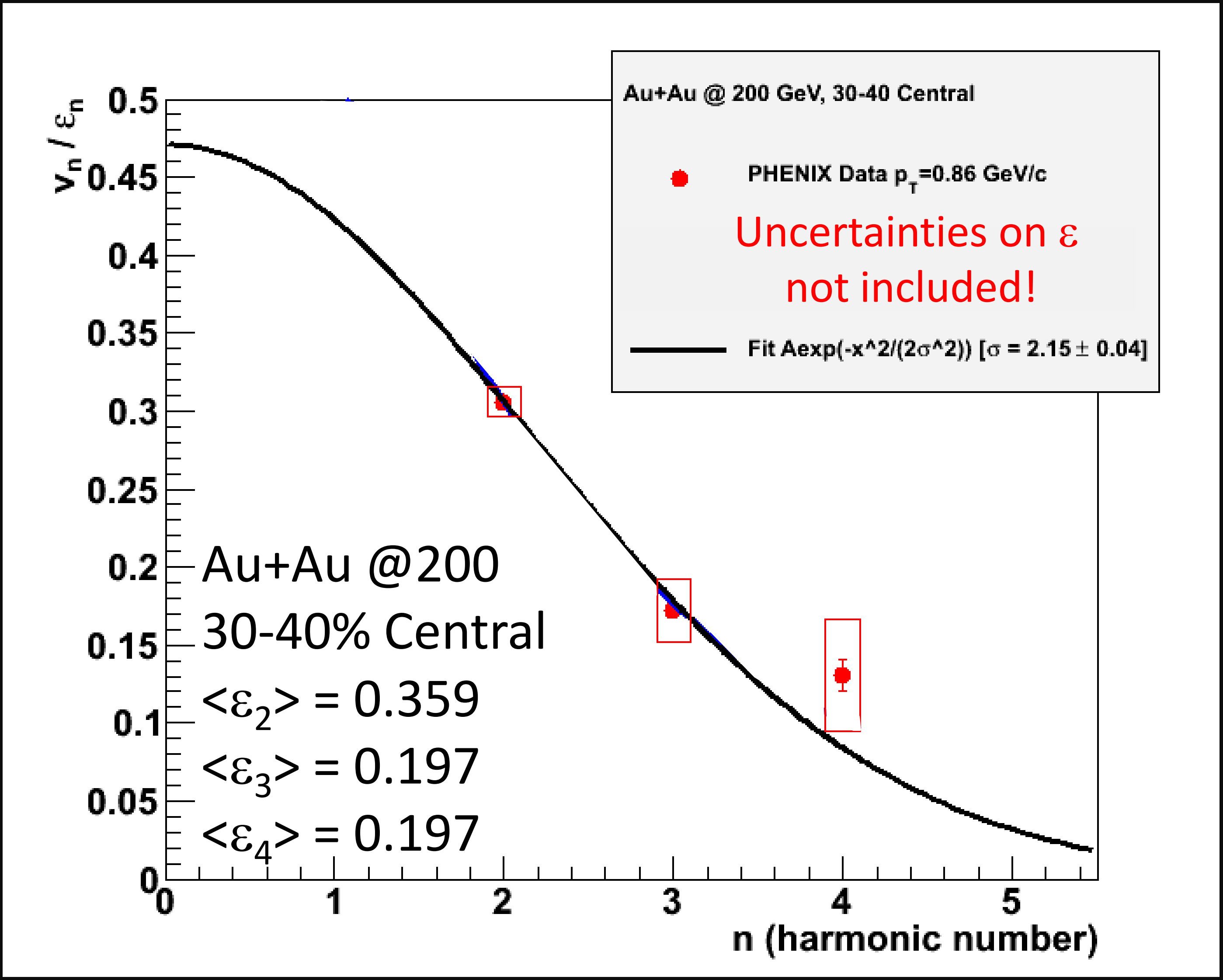
I believe this is simply incorrect.

$$k = \frac{2\pi}{\lambda} = \frac{n}{R}$$

$$\frac{\delta T_{\mu\upsilon}(t)}{\delta T_{\mu\upsilon}(0)} = \exp\left(-\frac{2}{3}\frac{\eta}{s}\frac{n^2}{R^2}\frac{t}{3T}\right)$$

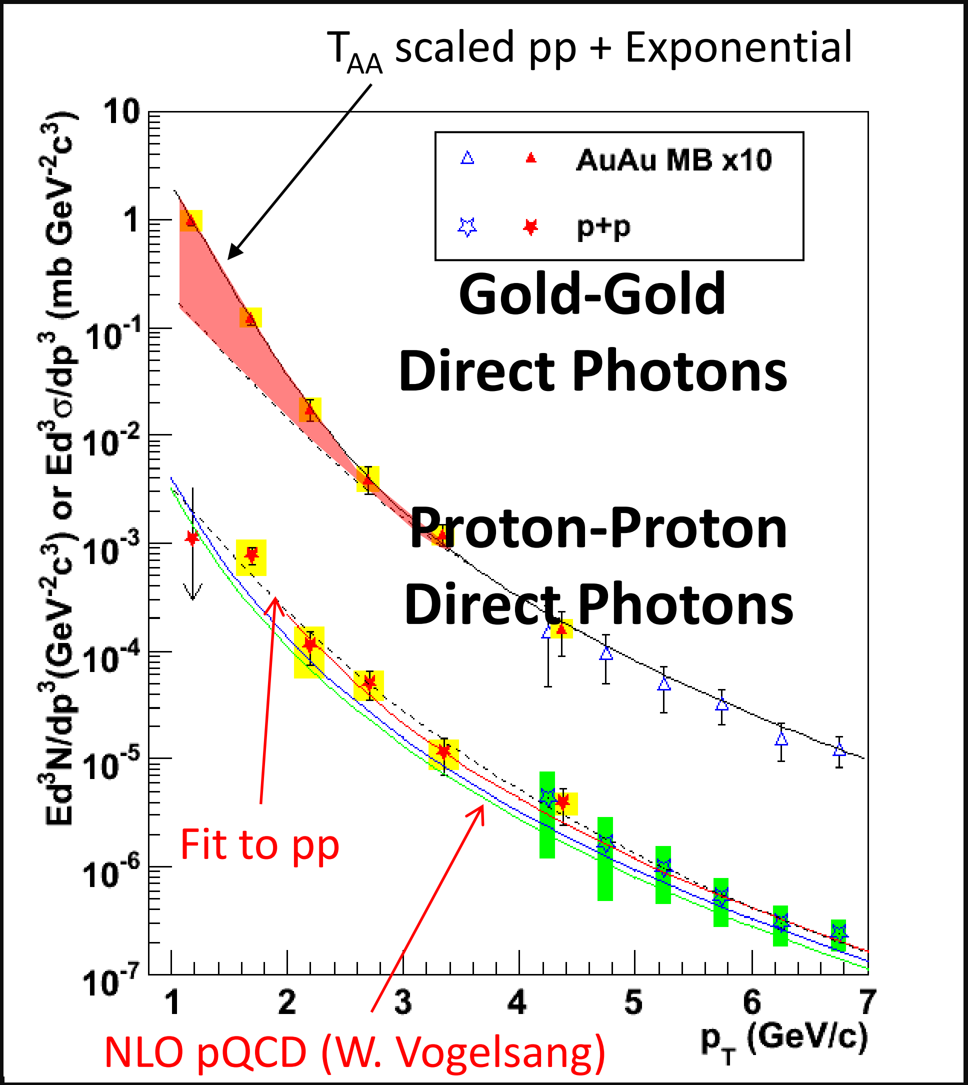
$$\frac{\delta T_{\mu\upsilon}(t)}{\delta T_{\mu\upsilon}(0)} \propto \frac{v_n}{\varepsilon_n} \propto \exp\left(-\frac{2}{3}\frac{\eta}{s}\frac{n^2}{R^2}\frac{t}{3T}\right)$$

Interesting feature of larger damping for higher moments.

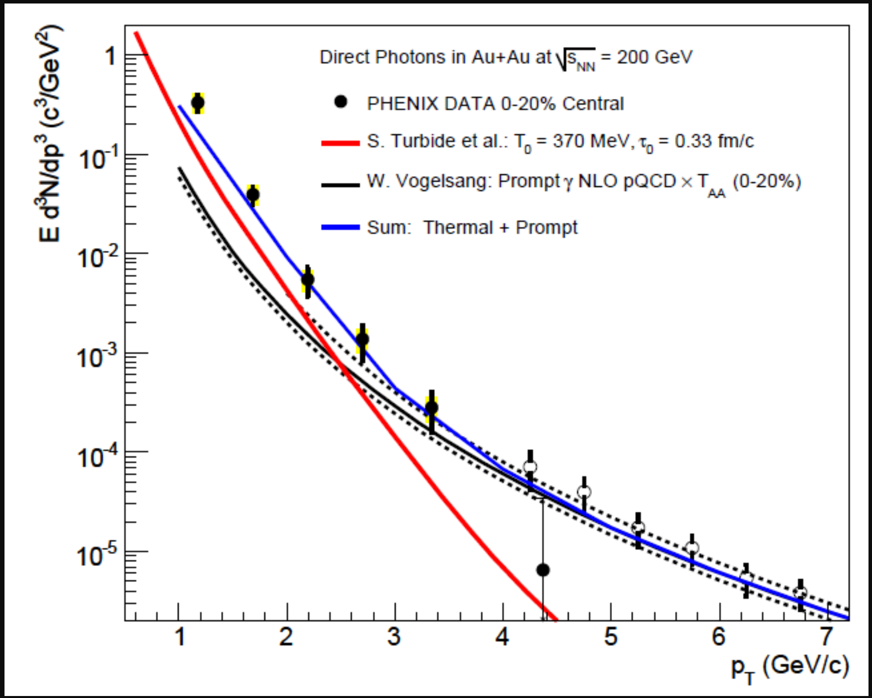


However, I believe full viscous hydrodynamics needed to relate to η/s (***no skipping steps***).

Thermal Photon Emission

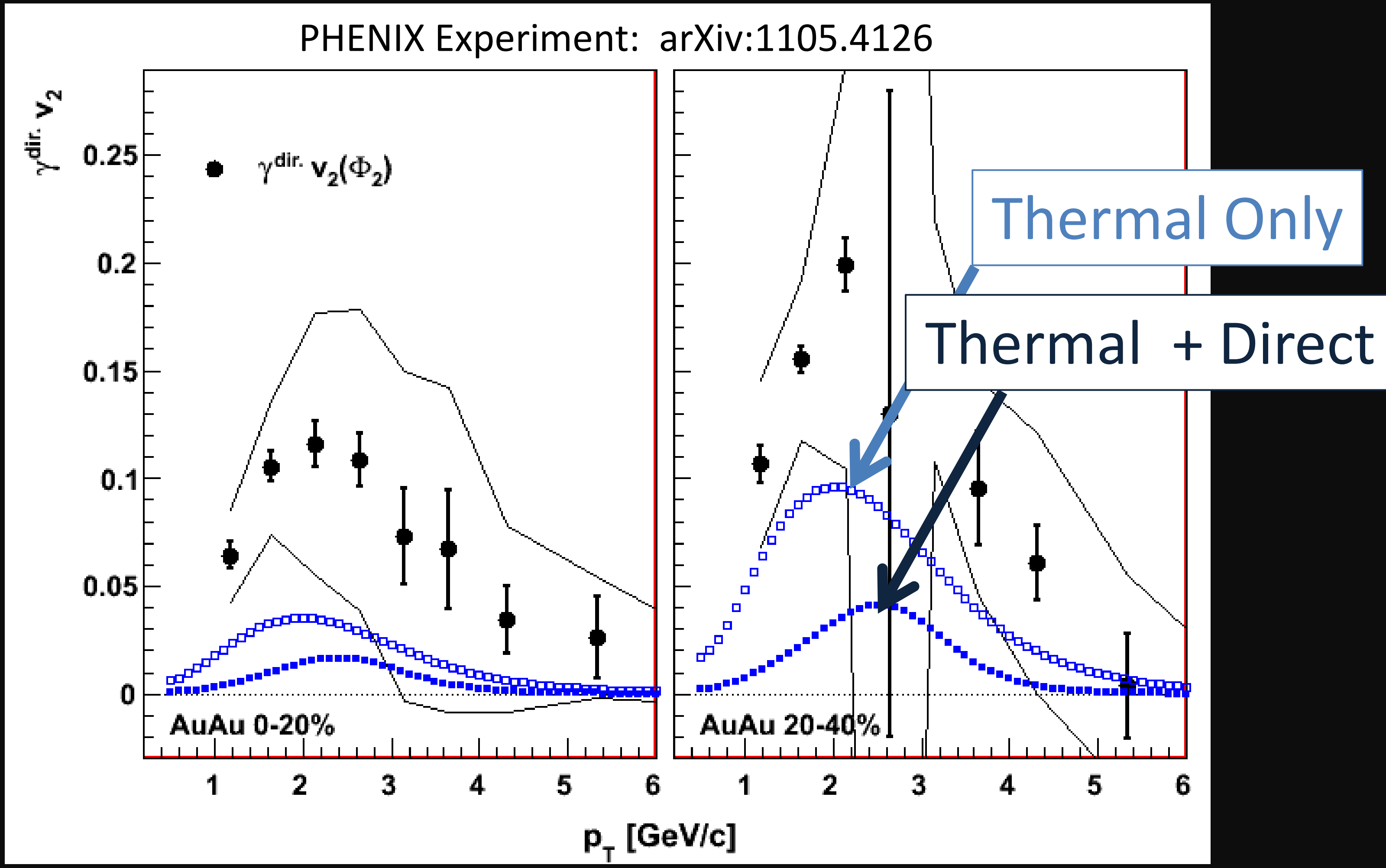


PHENIX: Phys.Rev.Lett. 104 (2010) 132301



Specific prediction for flow (v_2) of thermal photons

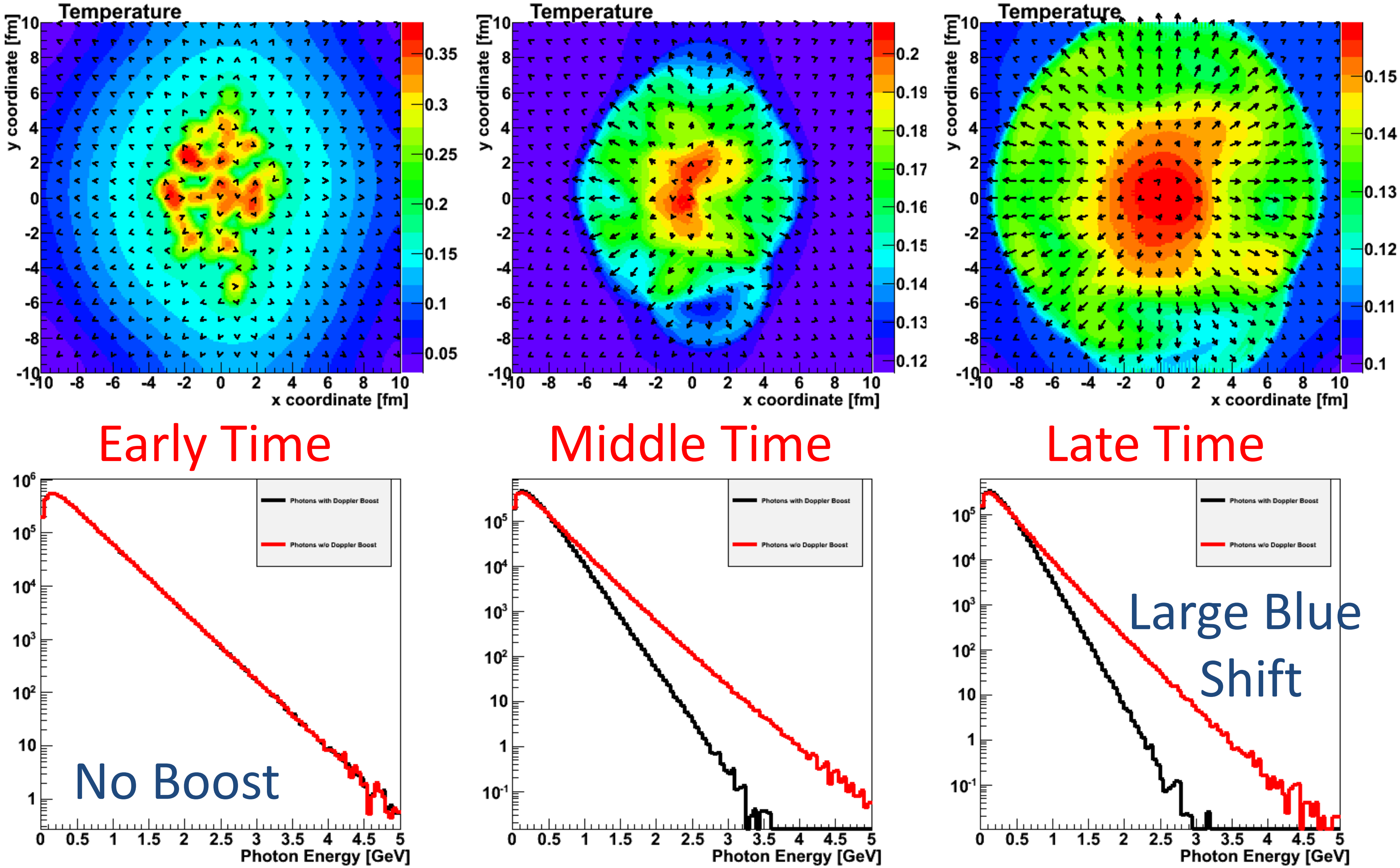
Challenge of Direct Photon Flow



Holopainen, Räsänen, Eskola , arXiv:1104.5371v1

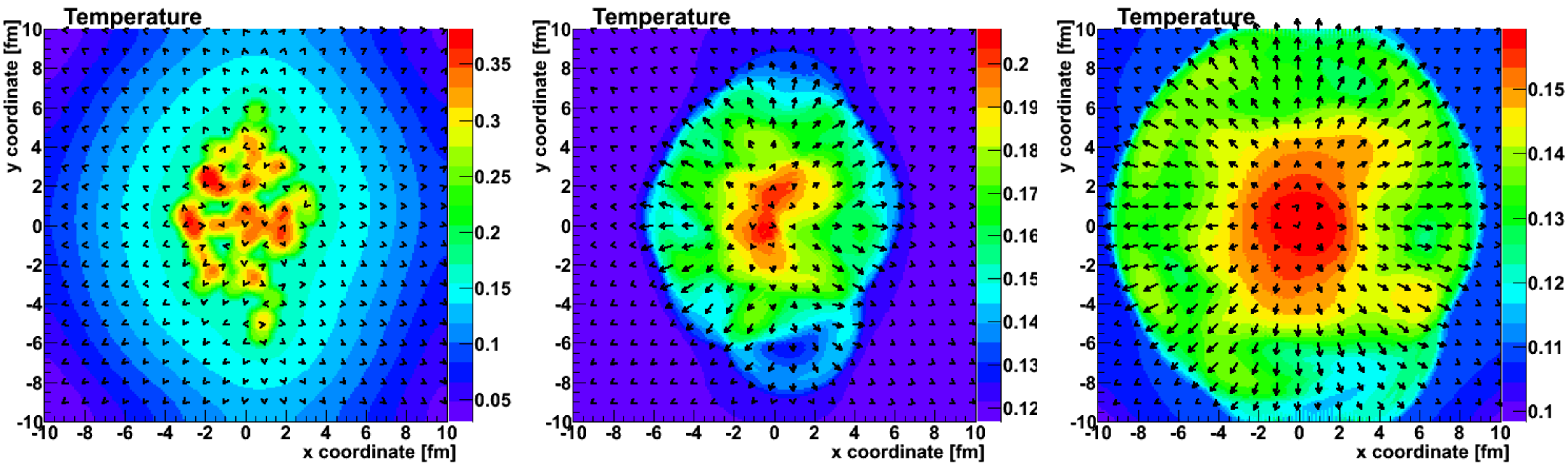
Hydrodynamic Calculation

KZ Mendoza, M. McCumber, JN, P. Romatschke

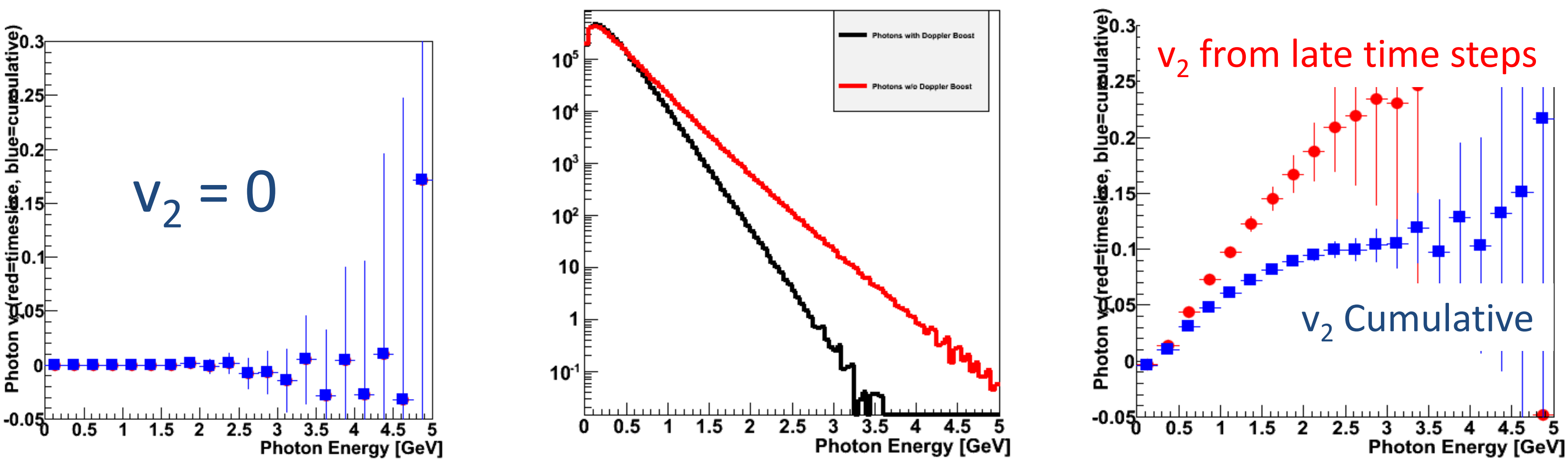


Hydrodynamic Calculation

KZ Mendoza, M. McCumber, JN, P. Romatschke



Early Time | Middle Time | Late Time



Summary

• Enormous progress in this area in the last one year

• Dramatic reduction in η/s uncertainties around the corner

• Exotic shock response and ridge features gone

• Key is now to understand how localized energy is so quickly transformed into effective heating
(nicely related to jet quenching puzzle)

• Major upgrades at RHIC planned.
Critical for complementing the studies at LHC and really measuring the full excitation function

PHENIX Decadal Plan

Major Upgrade Proposed Extending into EIC Era

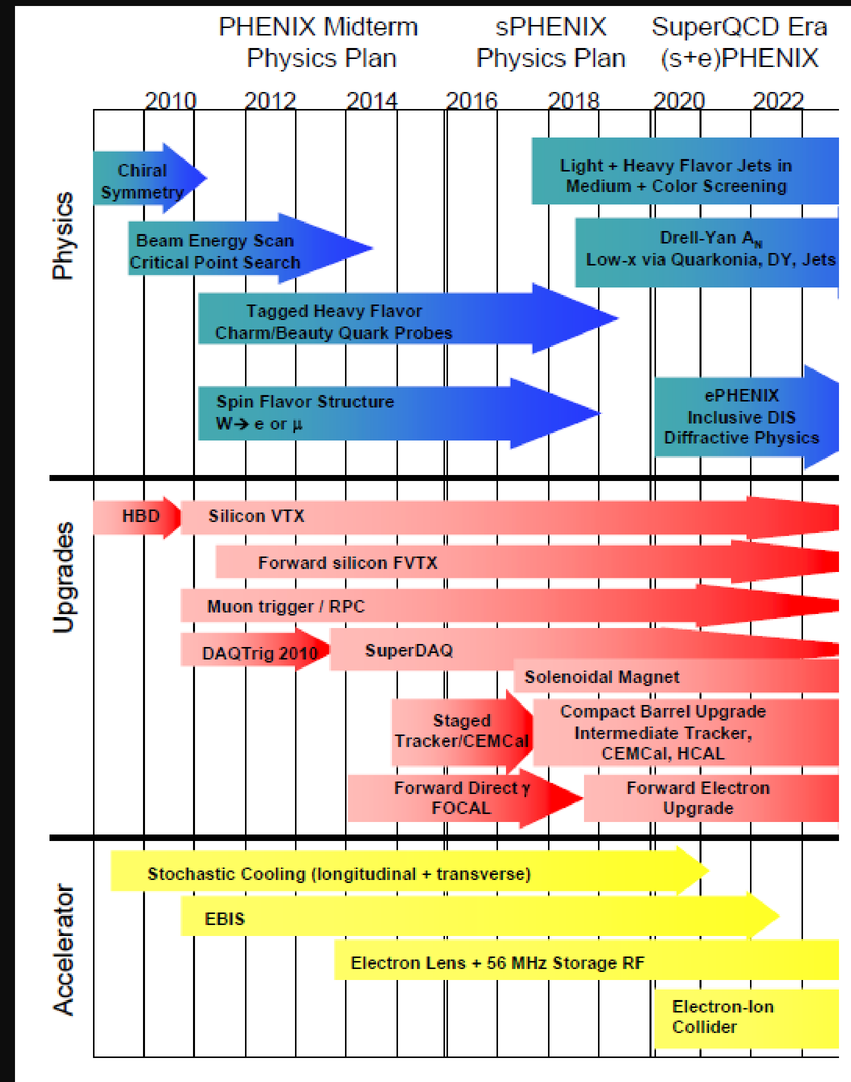

The PHENIX Experiment at RHIC

Decadal Plan 2011–2020

Brookhaven National Laboratory

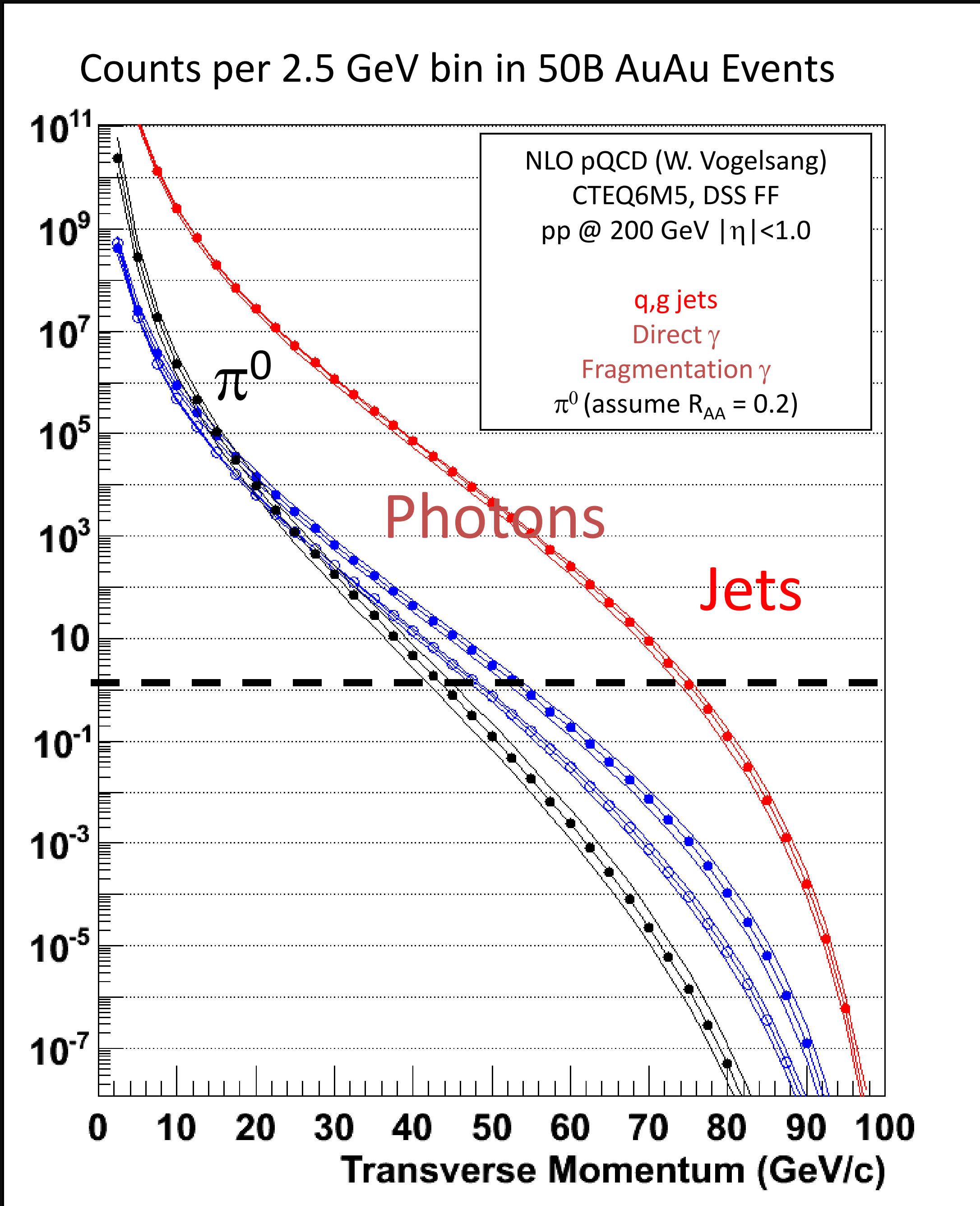
Relativistic Heavy Ion Collider

October, 2010

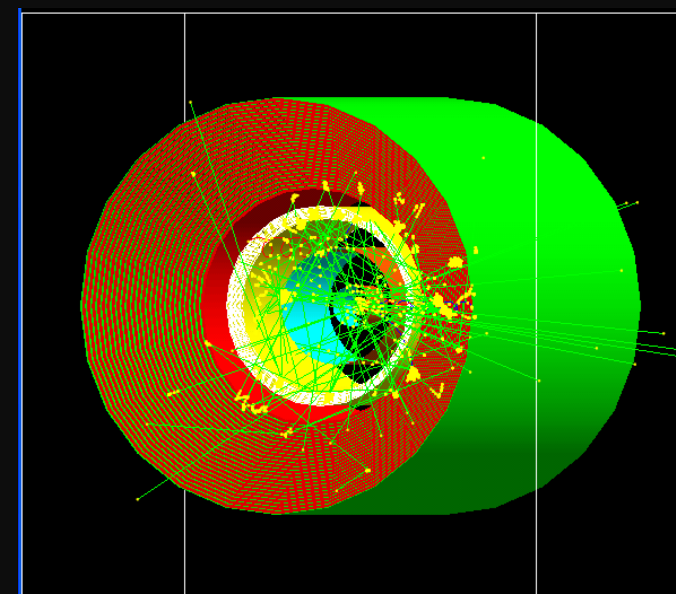


We are interested in feedback, suggestions, involvement.

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



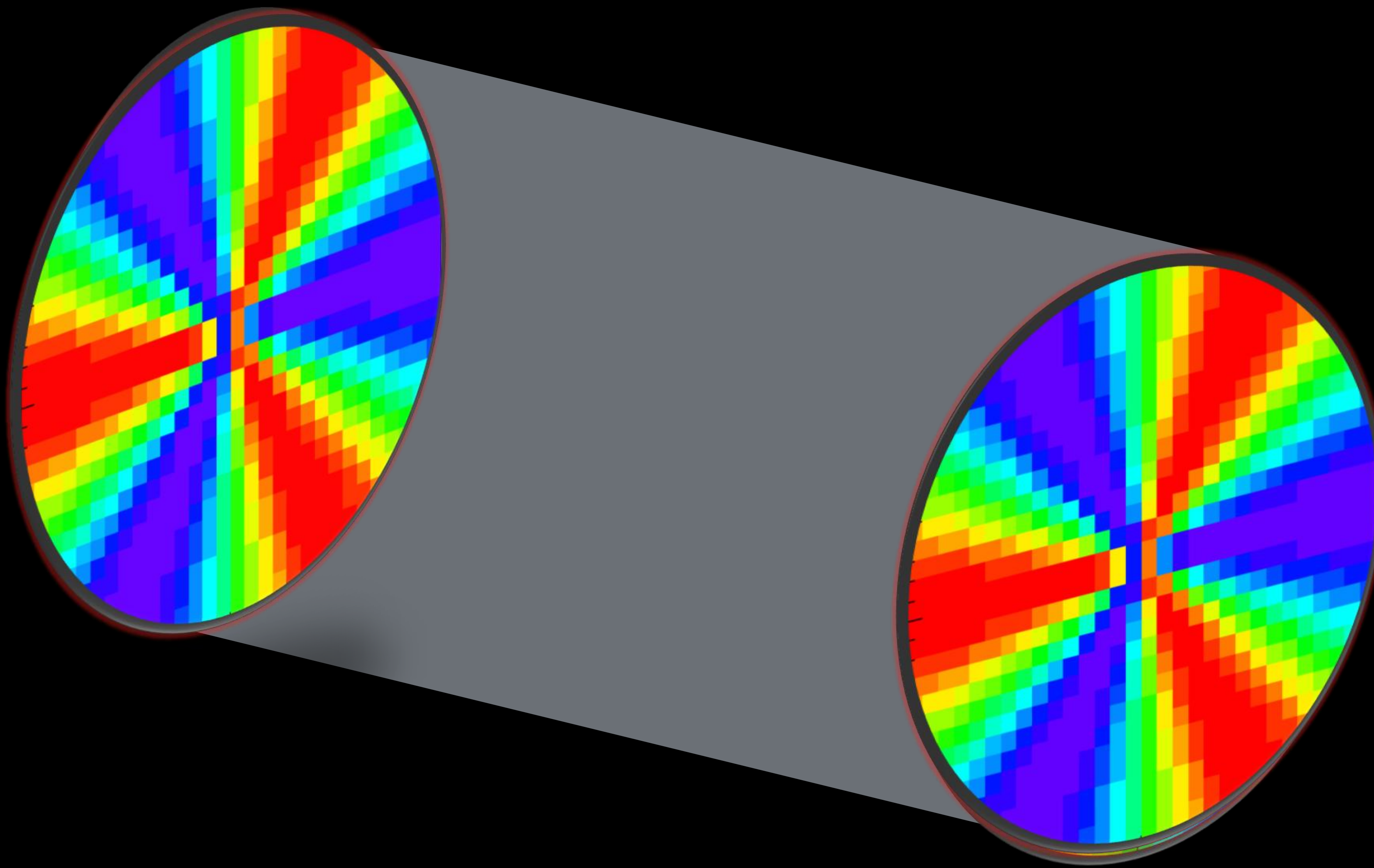
sPHENIX proposal for a hermetic EMCal/HCAL jet detector at RHIC



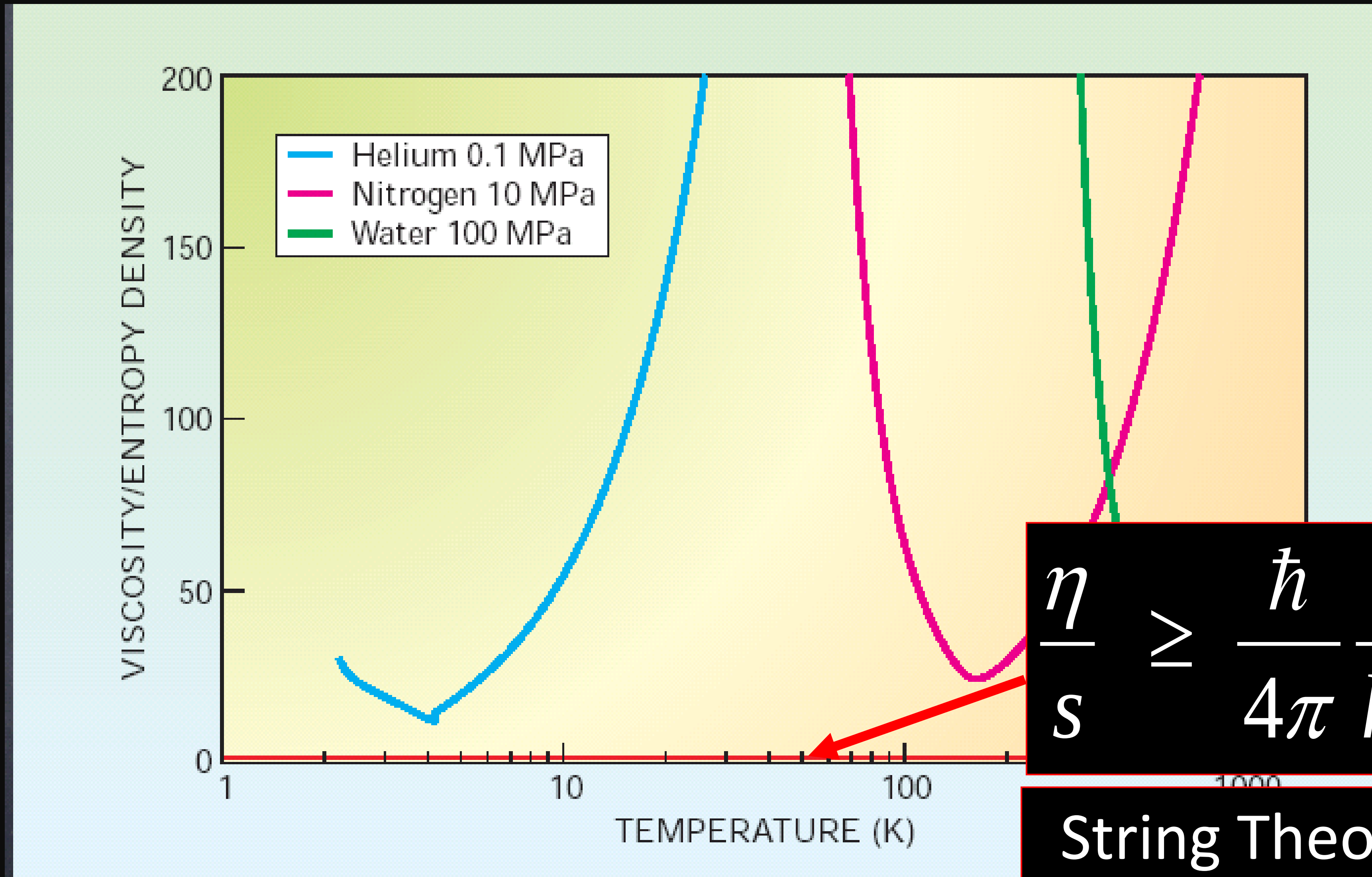
Extras

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?



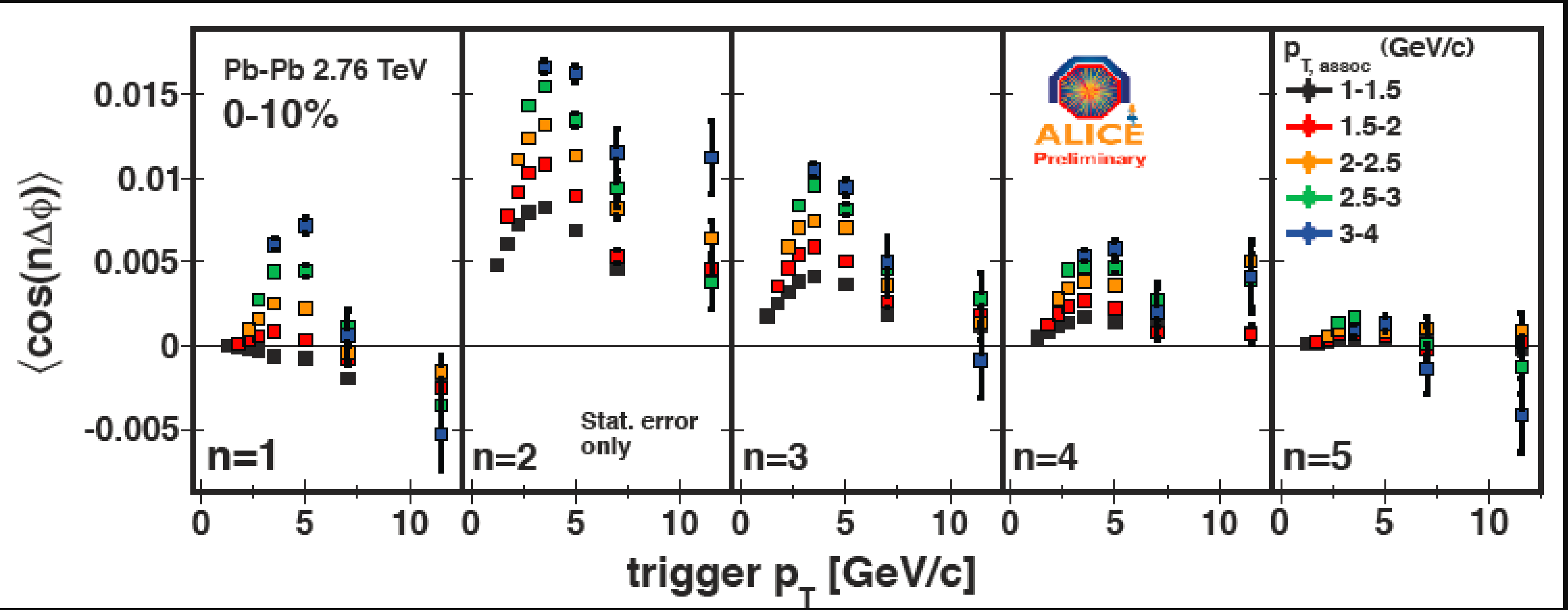
Viscosity Roadmap



$$\frac{\eta}{s} \geq \frac{\hbar}{4\pi}\frac{1}{k_B}$$

String Theory
Lowest Bound!

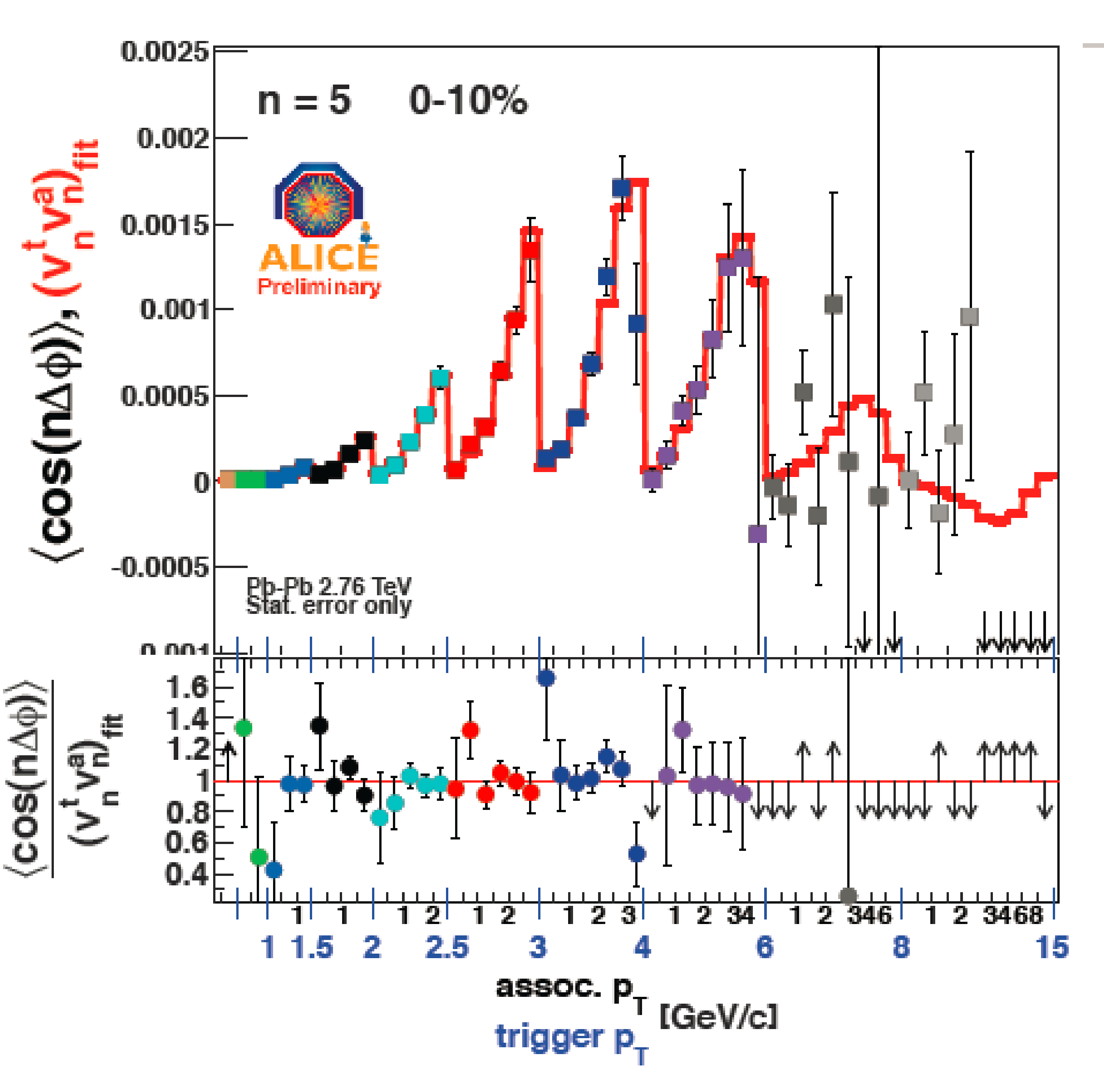
Tests and model comparisons can be done on Coefficients



If entire 2-particle correlation from bulk flow then:

$$\text{Fourier Coefficient } v_{n\Delta}(p_{T1},p_{T2}) = v_n(p_{T1}) \times v_n(p_{T2})$$

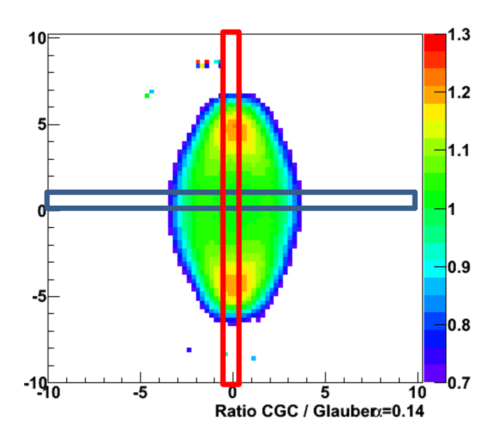
Deviations indicate important non-flow effects (jets and medium response for example)

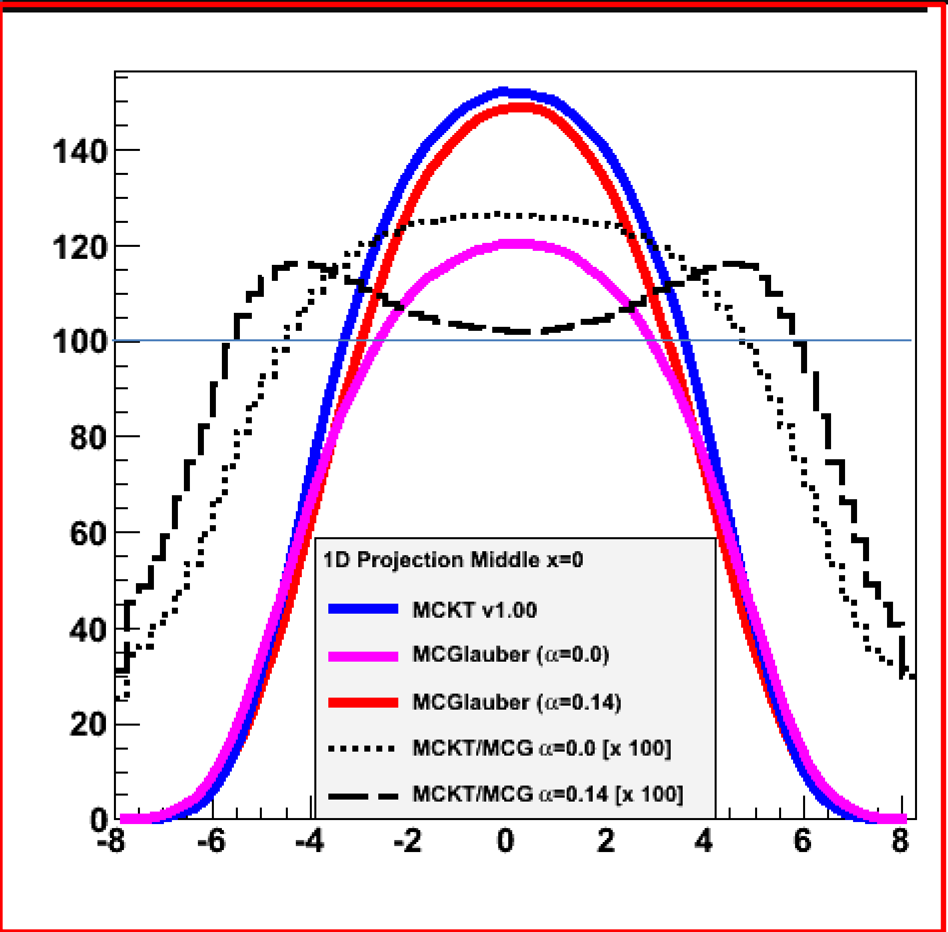


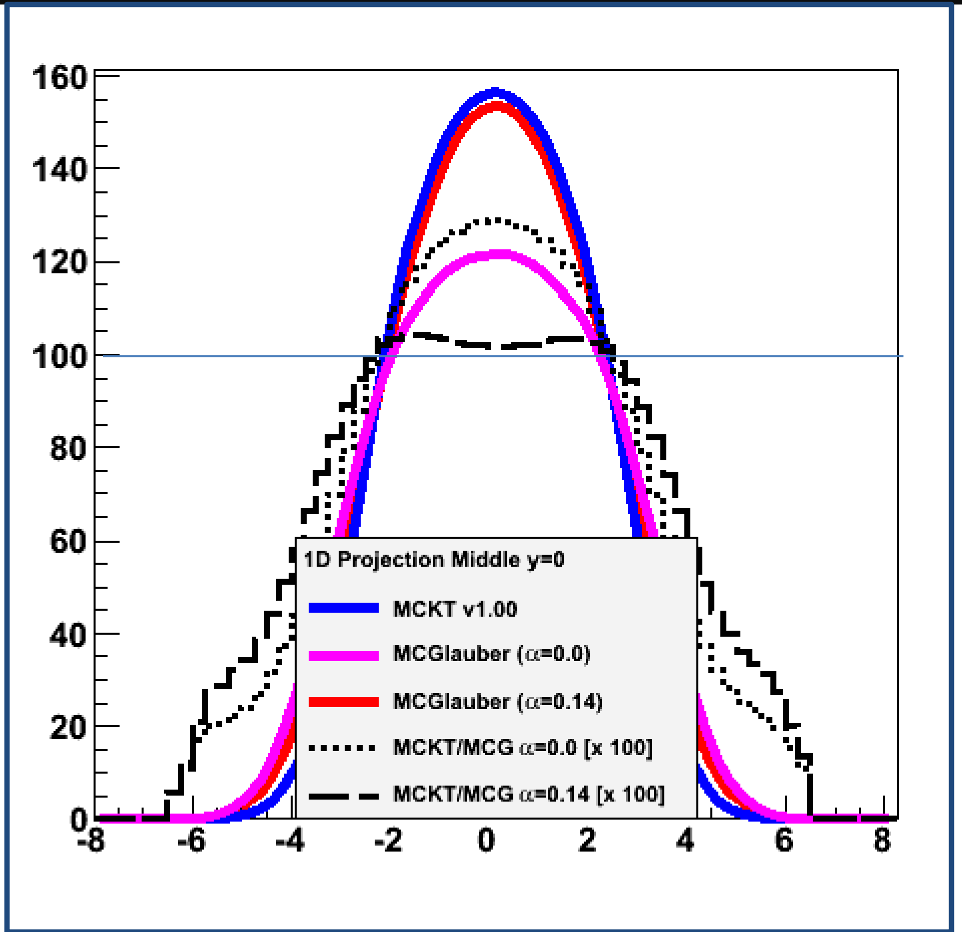
n = 5 0-10%
ALICE
Preliminary
Pb-Pb 2.76 TeV
Stat. error only
⟨cos(nΔφ)⟩, $(v_n^t v_n^a)_{fit}$
$\frac{\langle \cos(n\Delta\phi)\rangle}{(v_n^t v_n^a)_{fit}}$
assoc. p_T [GeV/c]
trigger p_T

Ratio Density MCKT (Saturation) / Glauber

With the normalization, MCKT has a larger entropy density in the middle of the almond than both Glauber cases.

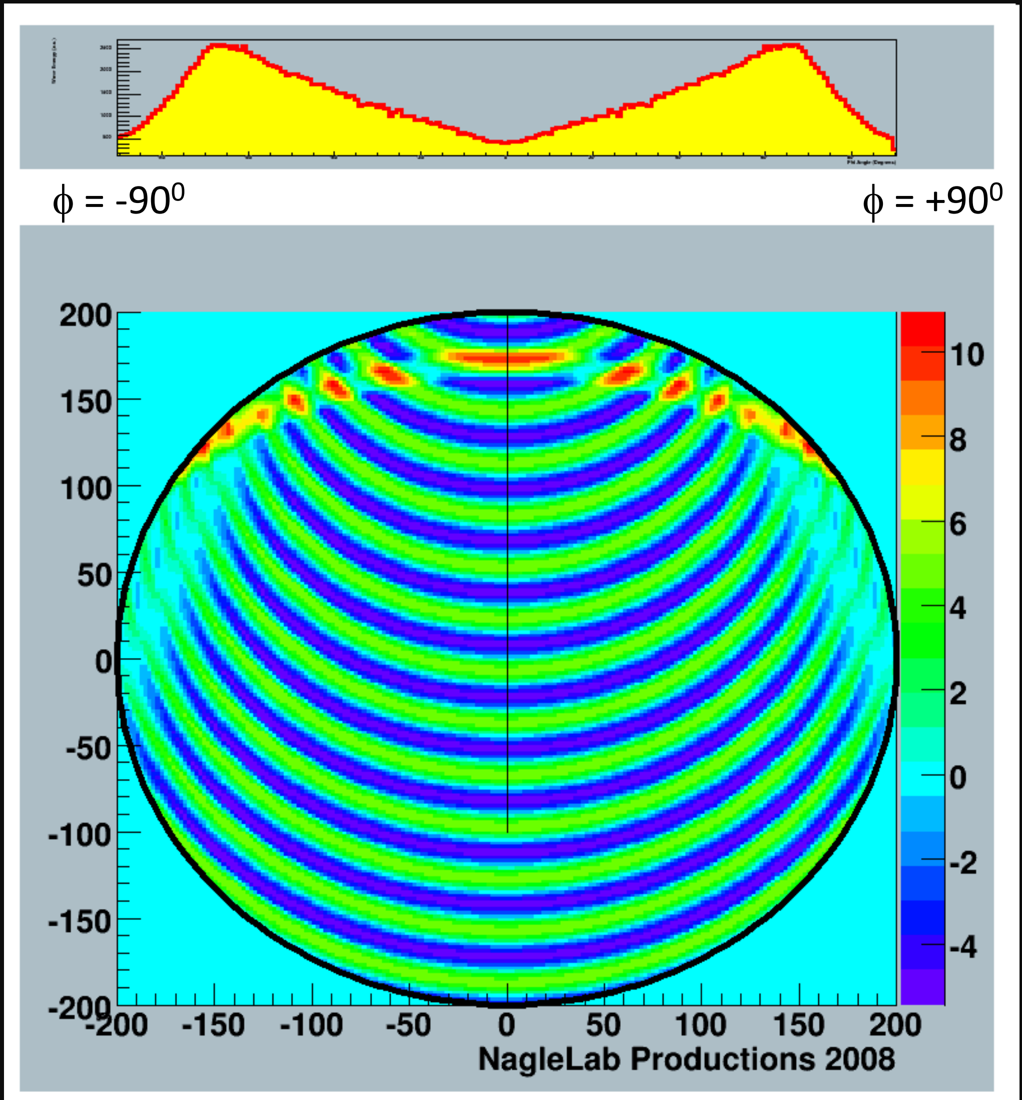




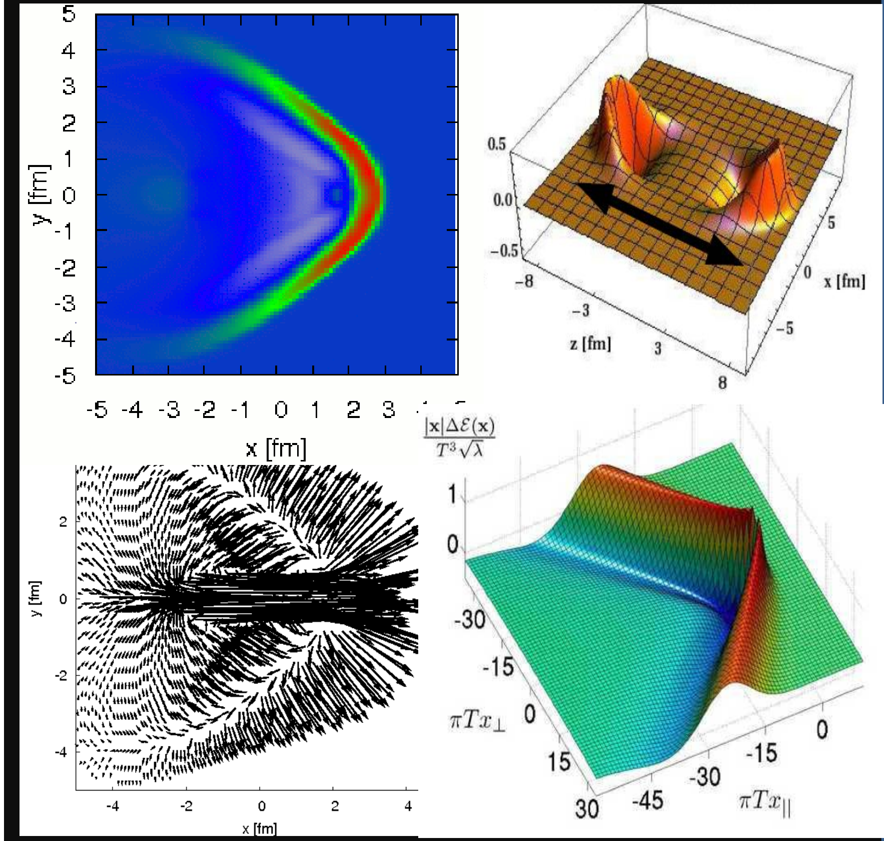


Perfect Fluid Response

Super-sonic quark traversing medium results in shock wave response



Observed in the data?



Lots of theory papers!