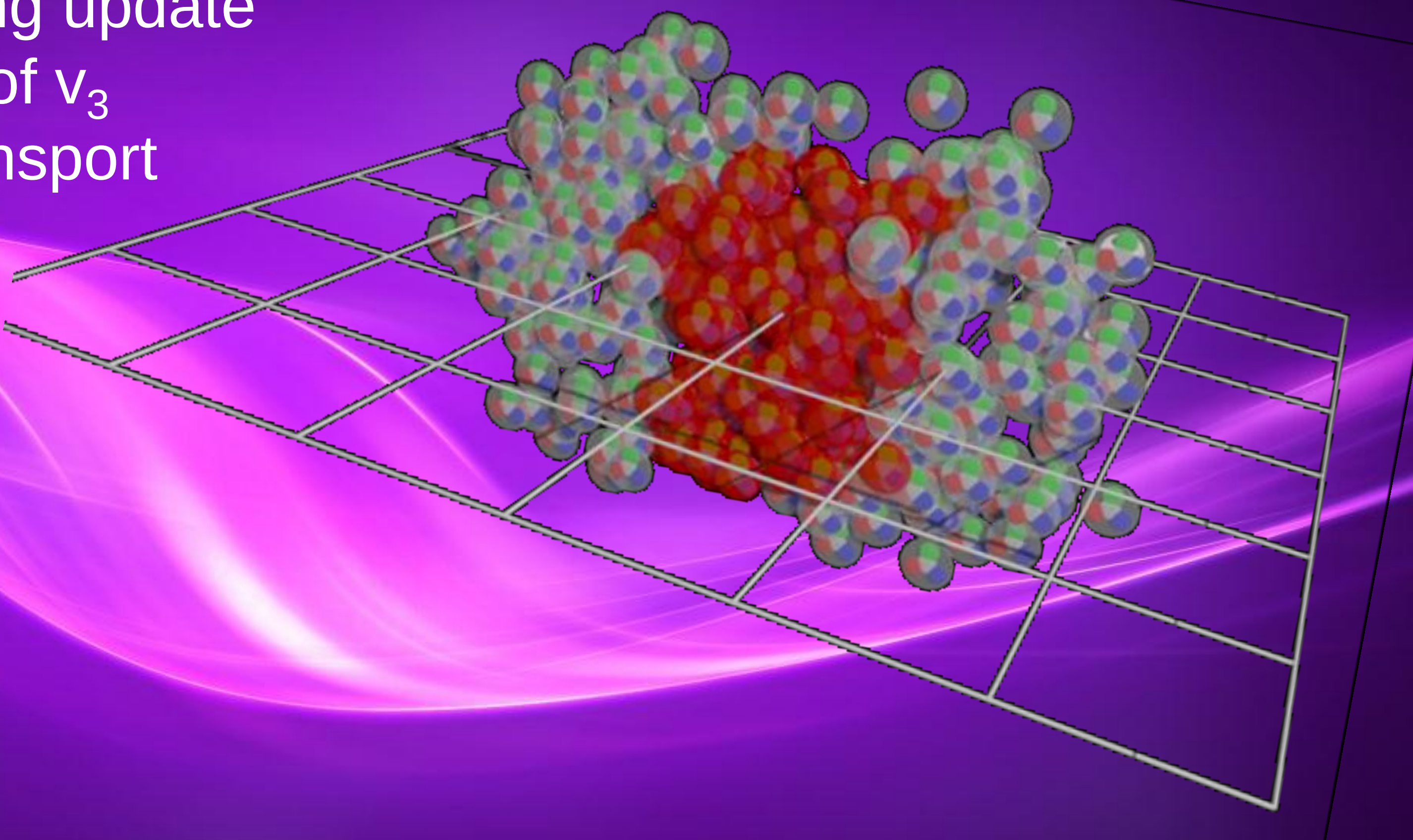
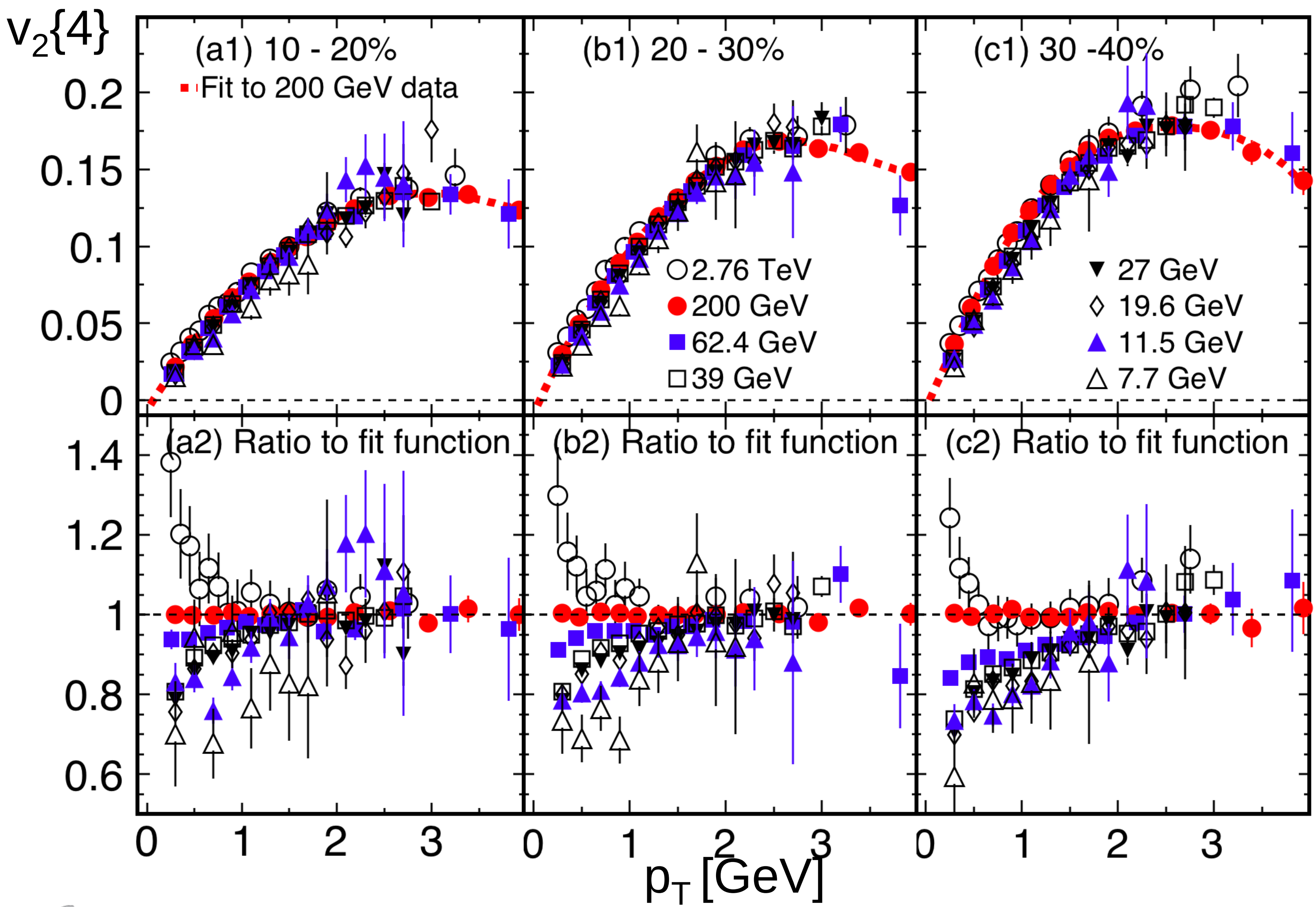
Experimental Flow Overview

s_{NN} independence of $v_2\{4\}$
Imaging the ellipse
NCQ scaling update
Geometry of v_3
Baryon transport
U+U

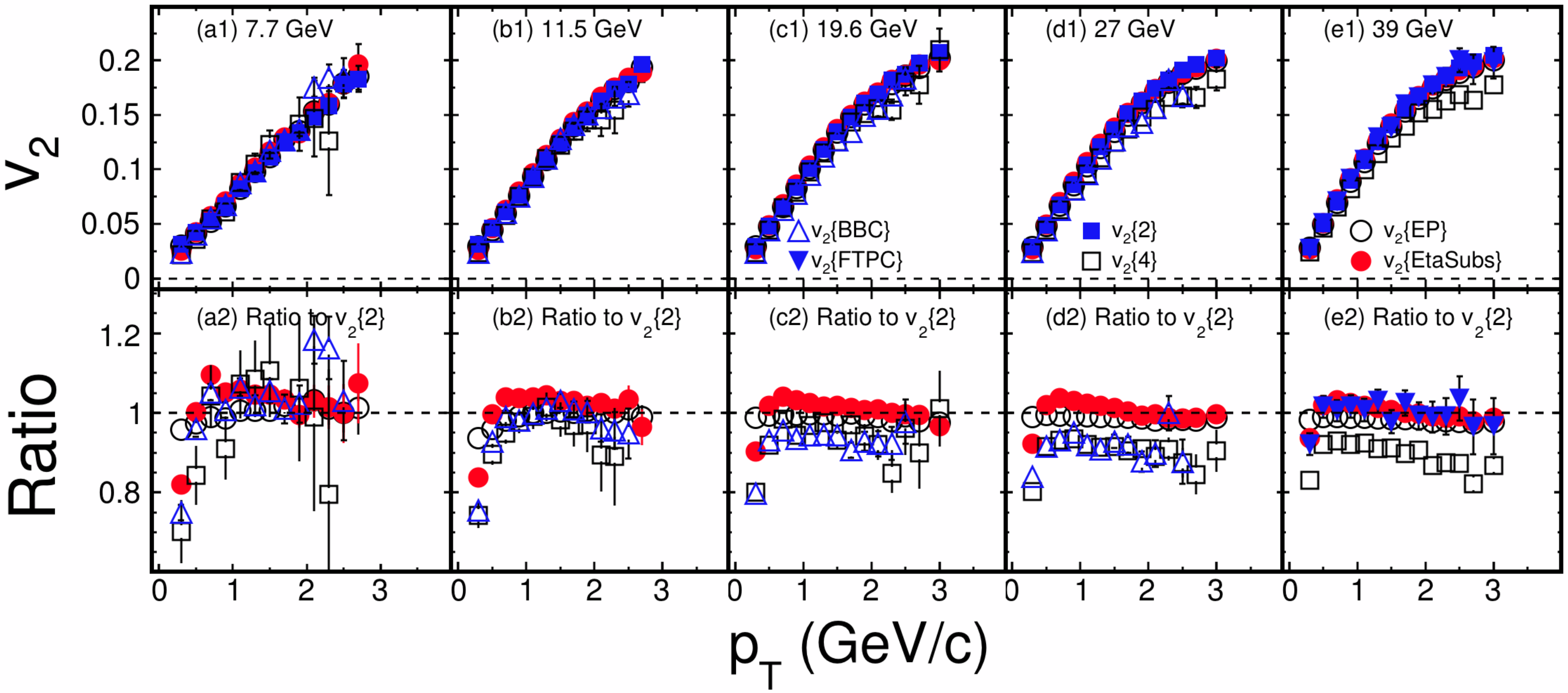


Paul Sorensen
BROOKHAVEN NATIONAL LABORATORY

Invariance of $v_2\{4\}$ with s_{NN} @ p_T=2 GeV



Comparison of Observables



Conclusions about invariance depends on the observable

Discussion: Just Geometry?

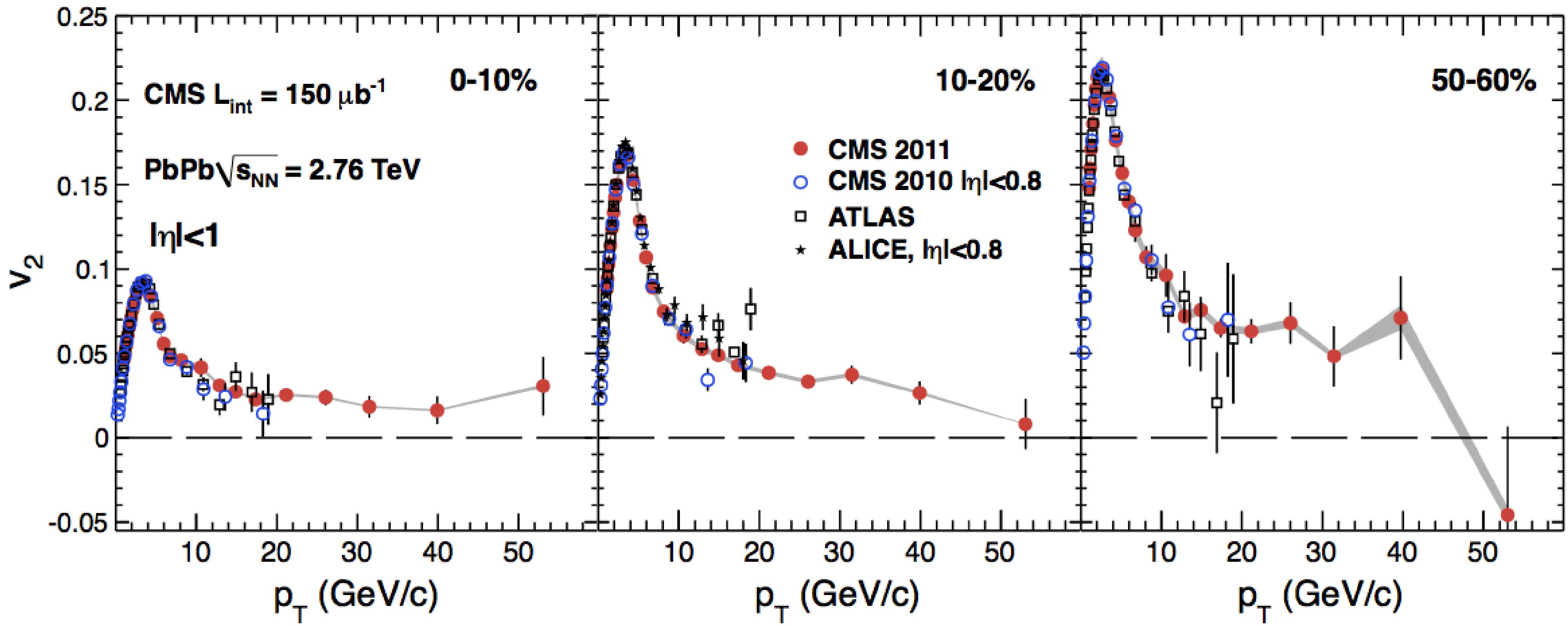
Perhaps relevant facts to consider for $v_2\{4\}$ at $p_T = 2$ GeV

- if ε fluctuations dominate v_2 fluctuations, $v_2\{4\} = \langle\cos2(\varphi-\Psi_{RP})\rangle$
- In hydro, intermediate p_T particles tend to be emitted early and reflect the initial geometry

$v_2\{4\}$ at $p_T = 2$ GeV may be relatively insensitive to the actual expansion; *but this idea needs to be followed up with more detailed theoretical investigation*

Any way you slice it: this is an extremely interesting observation to pursue.

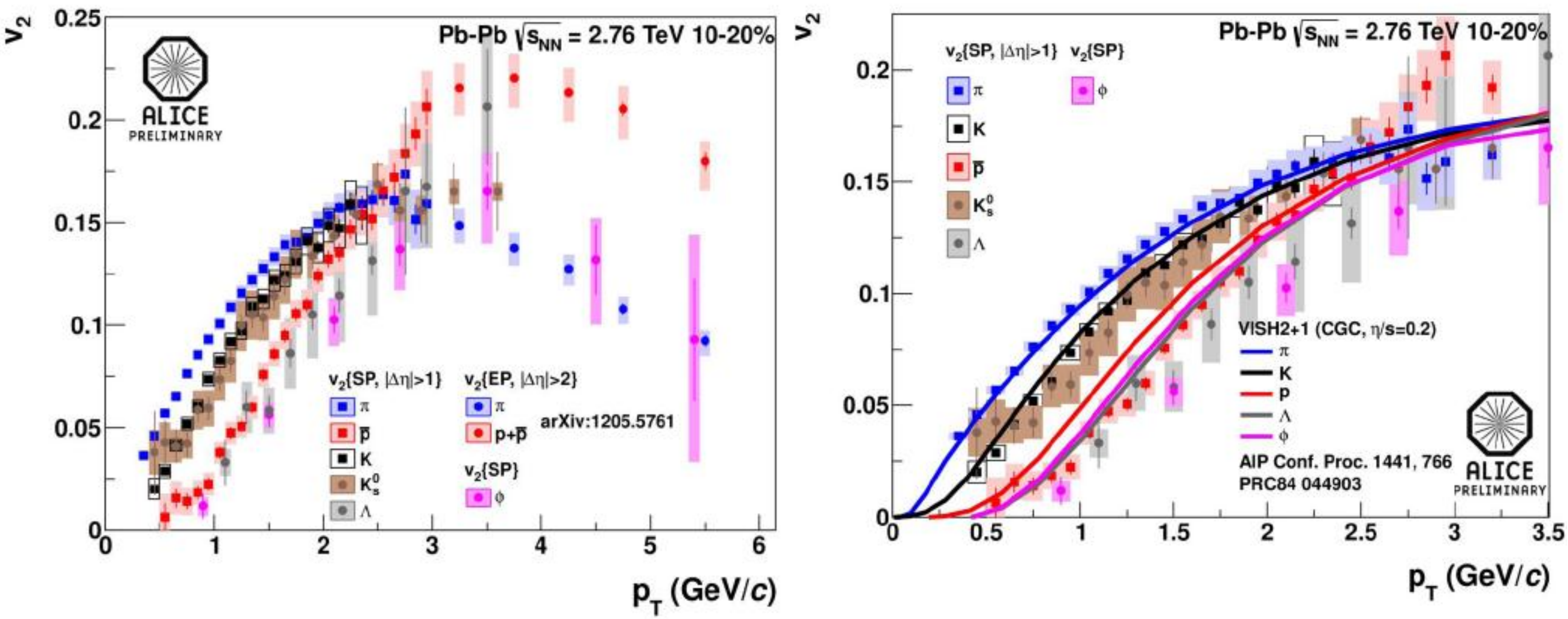
Imaging the Ellipse



We finally see the v_2 expected from quenching in the ellipse

Taken at face value, the tail of the "hydro" distribution persists to ~8 GeV: *the tail of a fluctuating spectrum can extend far beyond the scales associated with the source temperature*

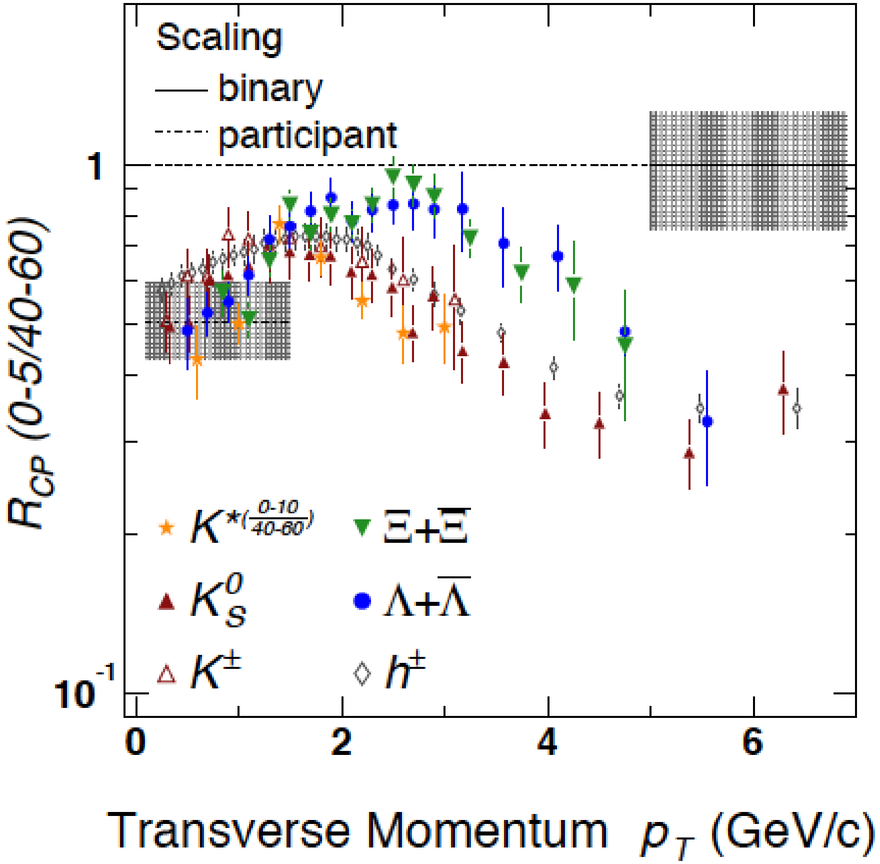
NCQ Scaling at p_T<8 GeV

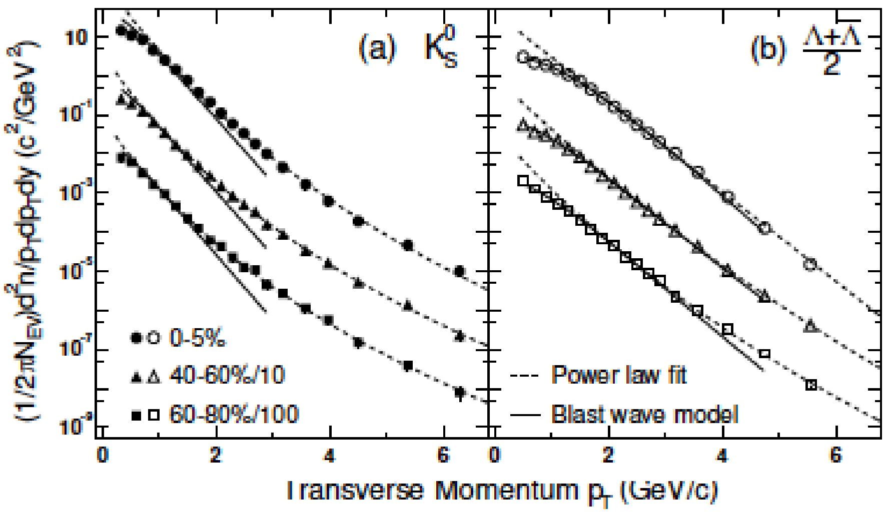


As at RHIC, baryon v_2 continues to rise far past meson v_2

not consistent with hydro unless different relaxation times for baryons and mesons are considered

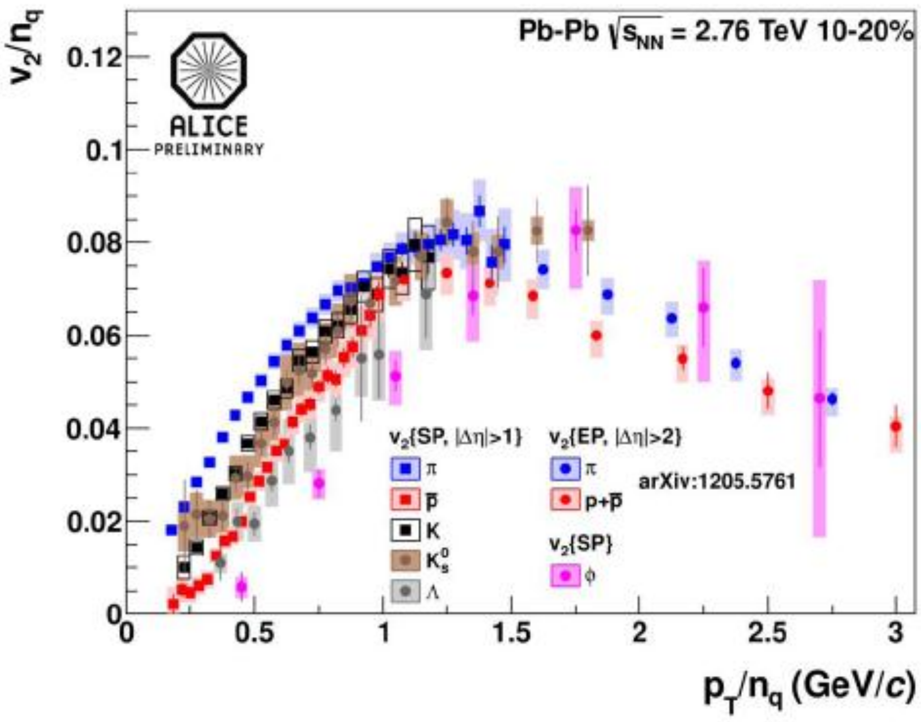
2 vs 3 in the spectrum

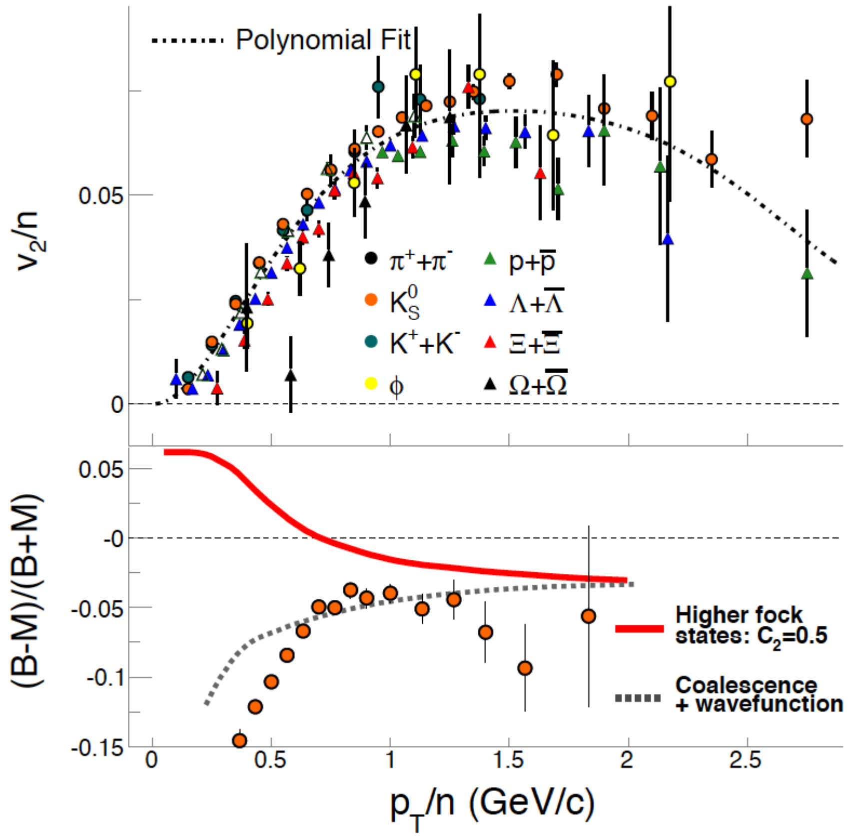




R_{CP} shows that the spectral shape for baryons changes at 3/2 the p_T for mesons

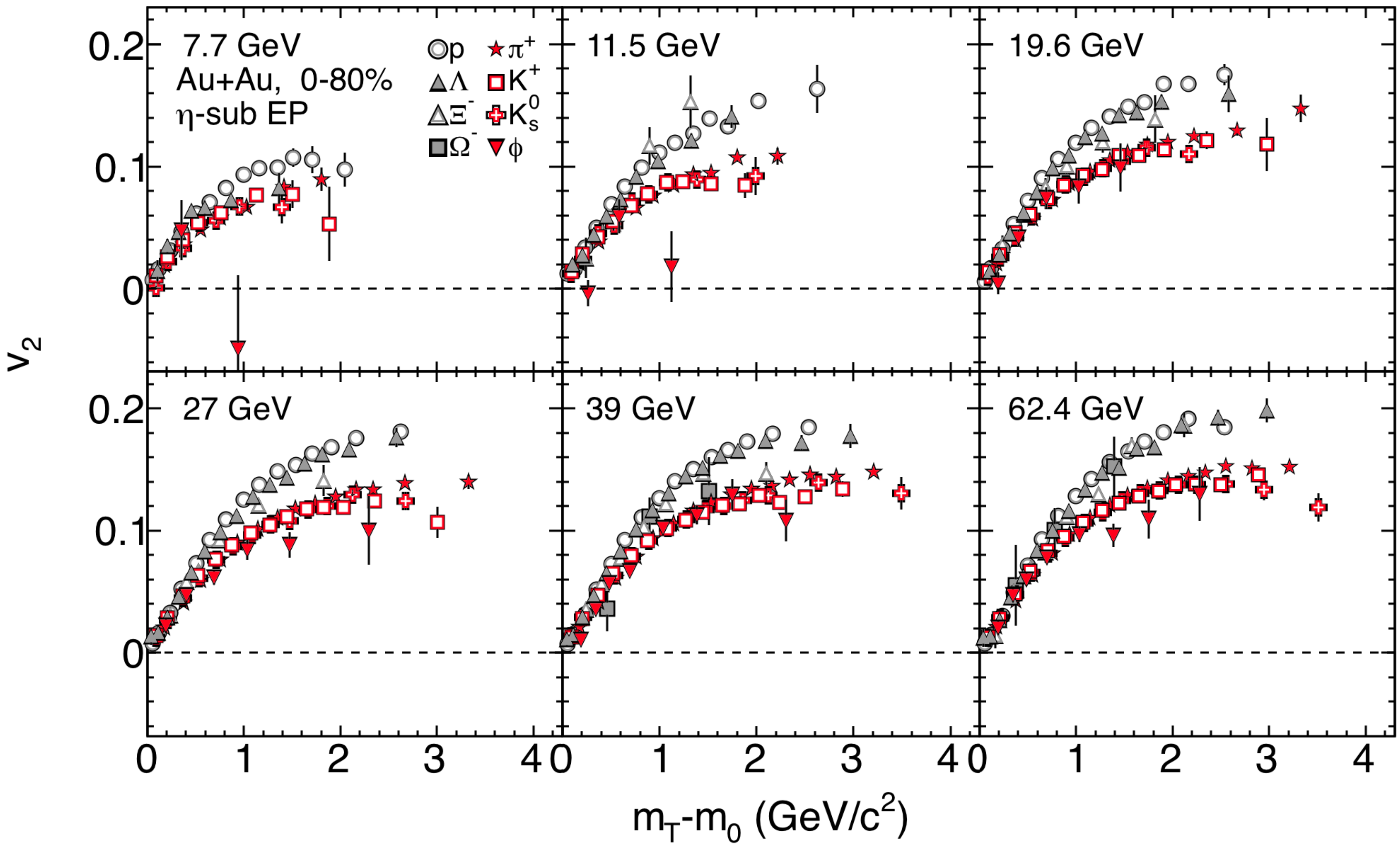
NCQ Scaling





BTW; deviations from the naïve NCQ scaling were studied long ago (QM2005). *Are the deviations at the LHC qualitatively different from those observed at RHIC?*

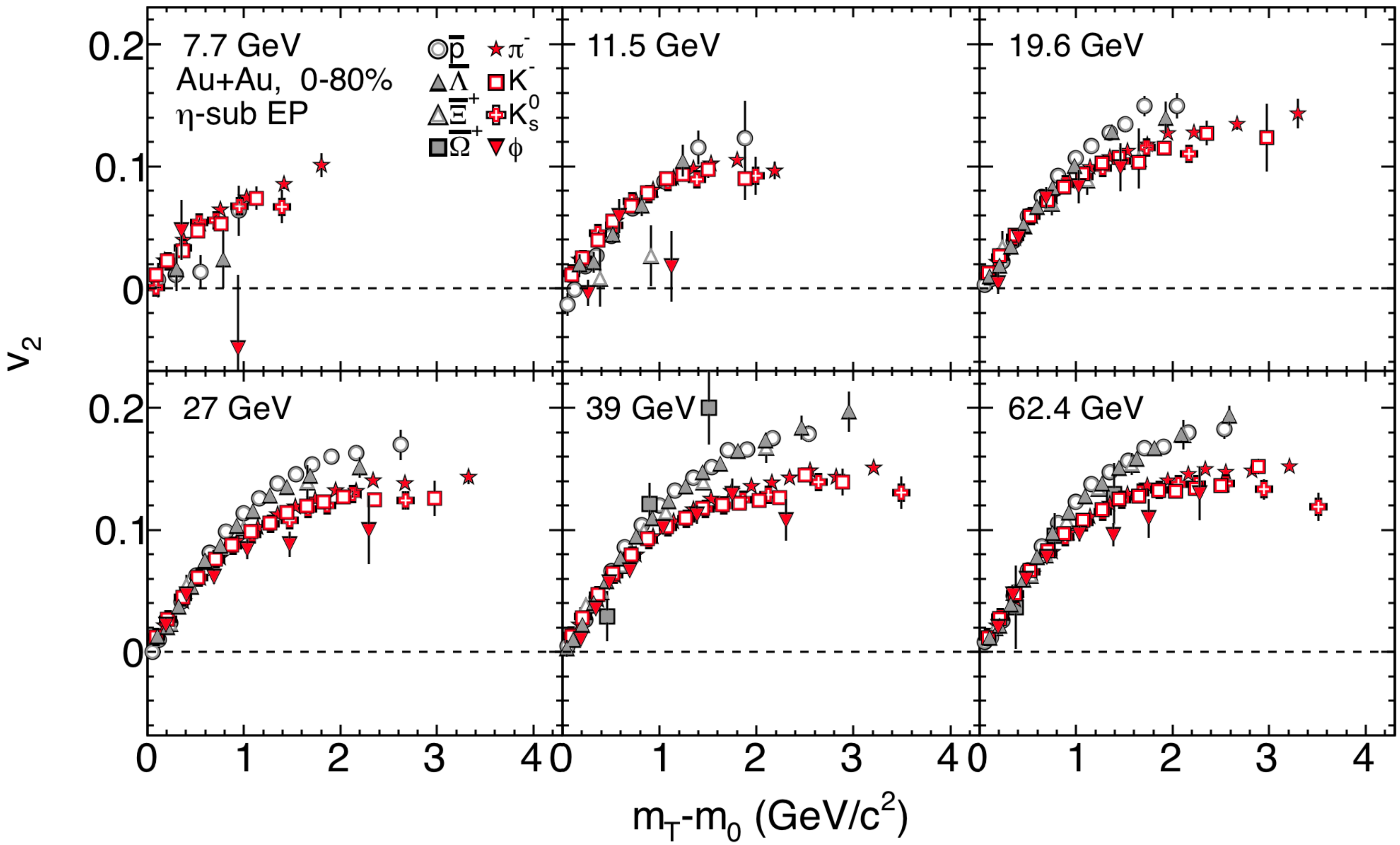
Lower Energy NCQ



Baryon meson splitting persists down to 11.5 GeV

(But not for anti-baryons)

Lower Energy NCQ



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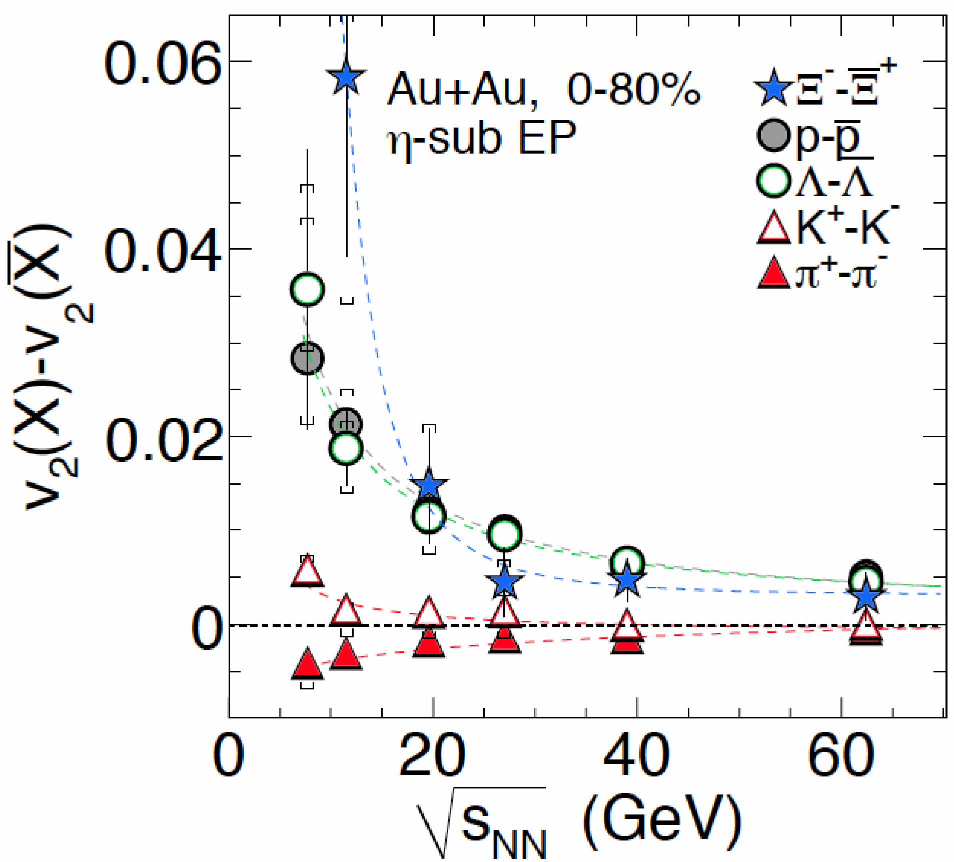
Lower Energy NCQ



Deviation increases continuously with μ_B: no onset

Difference probably there at LHC too

Not an indication of dominance of hadronic phase

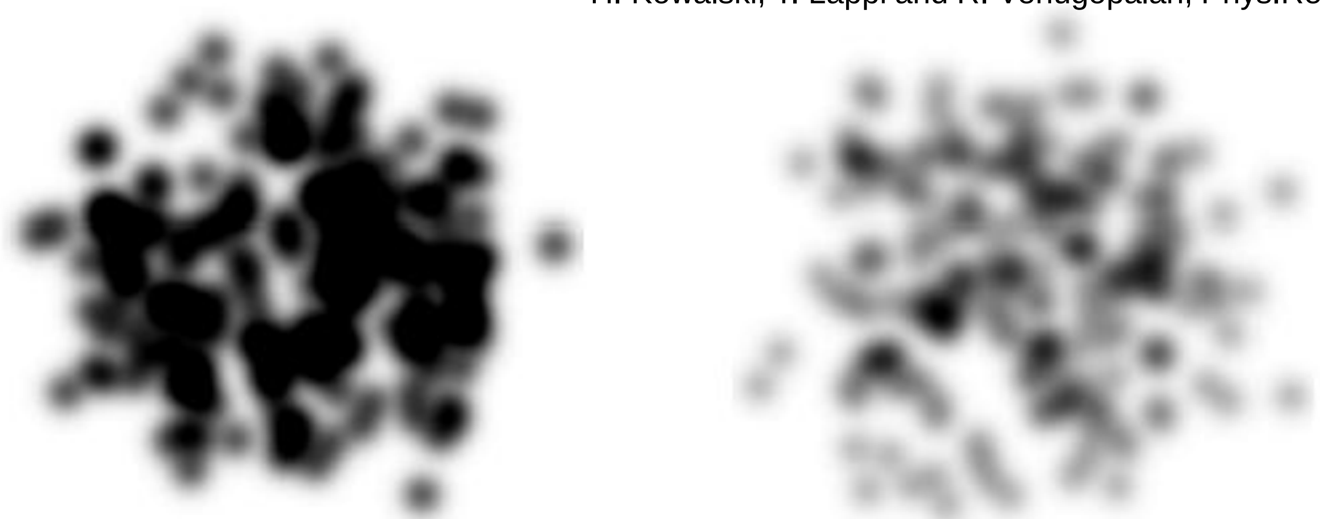
Geometry Really Matters

Strong interactions build space-momentum correlations lead

The system remembers the geometry

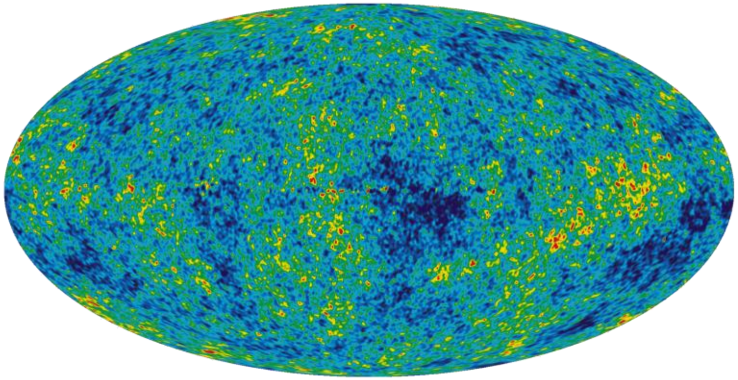
This is a more detailed view of the initial conditions

H. Kowalski, T. Lappi and R. Venugopalan, Phys.Rev.Lett. 100:022303

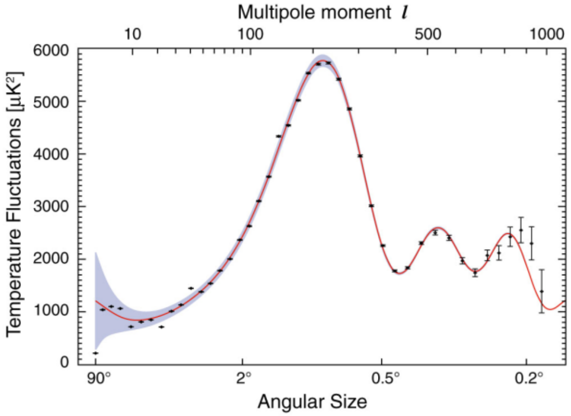


How much of this structure survives to freeze-out tells us about the plasma phase

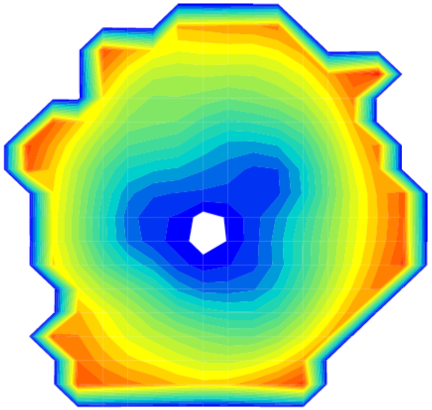
From v_2 to v_n: and what we learn



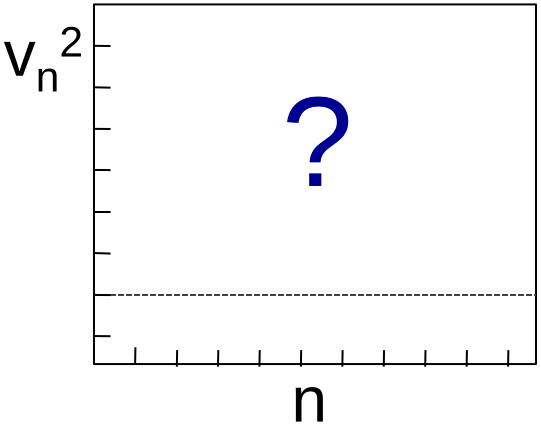
WMAP, Astrophys.J.Suppl.170:288,2007



Kowalski, Lappi and Venugopalan, Phys.Rev.Lett. 100:022303



K. Werner, Iu. Karpenko, K. Mikhailov, T. Pierog, arXiv:11043269

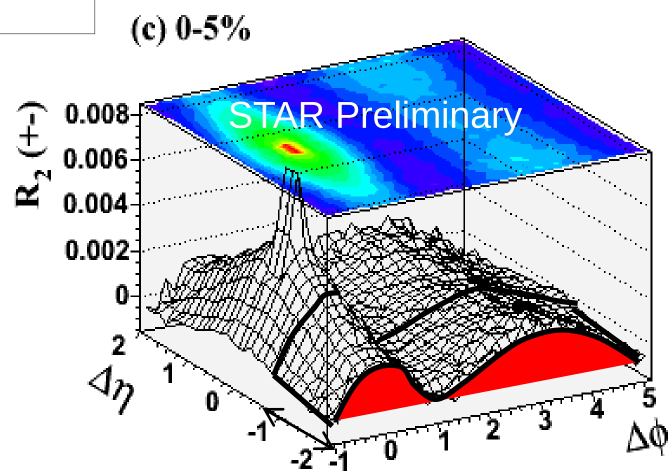


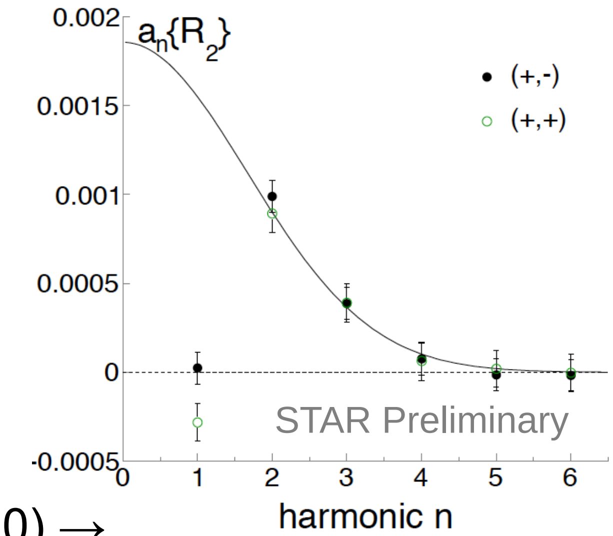
Analogous to the Power Spectrum extracted from the Cosmic Microwave Background Radiation

A.P. Mishra, R. K. Mohapatra, P. S. Saumia, A. M. Srivastava, Phys. Rev. C77: 064902, 2008
P. Sorensen, WWND, arXiv:0808.0503 (2008); J. Phys. G37: 094011, 2010

Spectrum From 2-particle Correlations

if flow dominates the correlations $a_n \approx 2v_n^2$

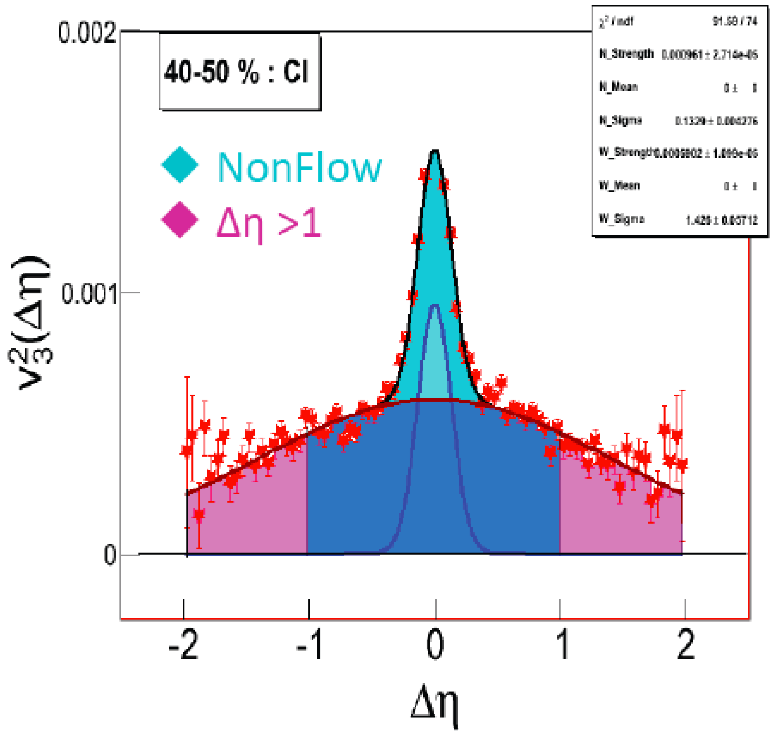


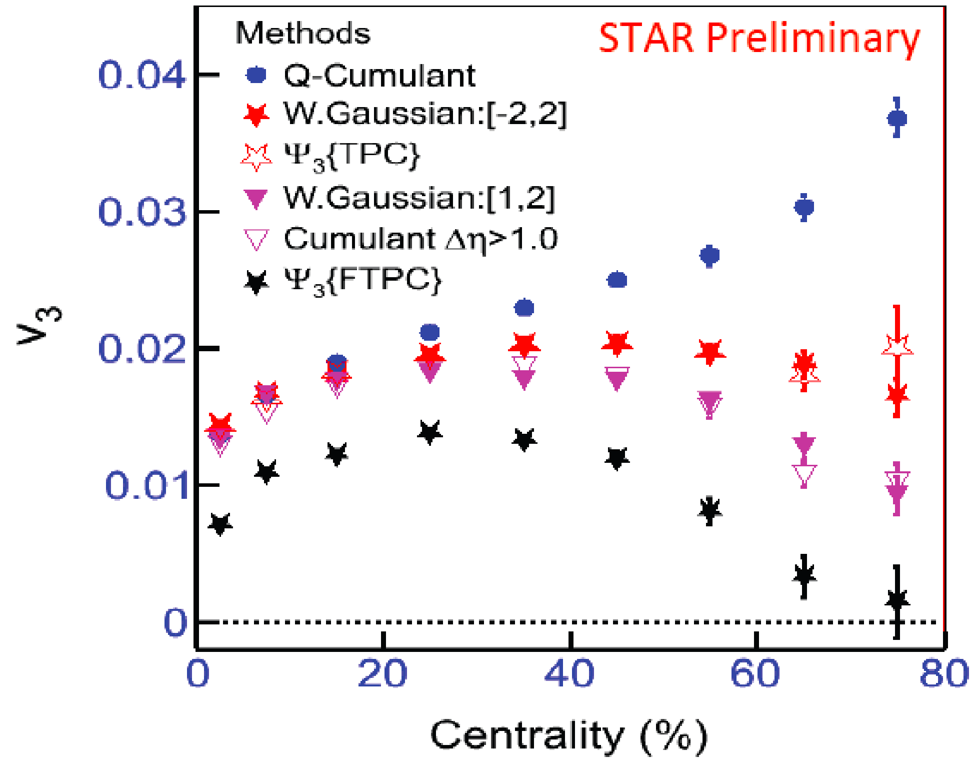


→ Fourier Tr. (0.7<Δη<2.0) →

but clear structure in the longitudinal direction (Δη dependence):
IMO it's shape is NOT fully explained yet

Low momentum v_3

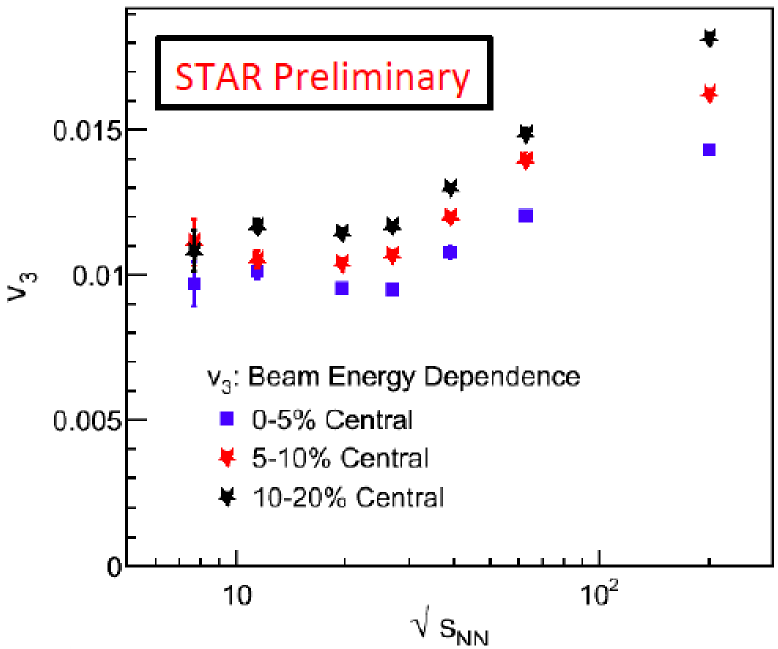


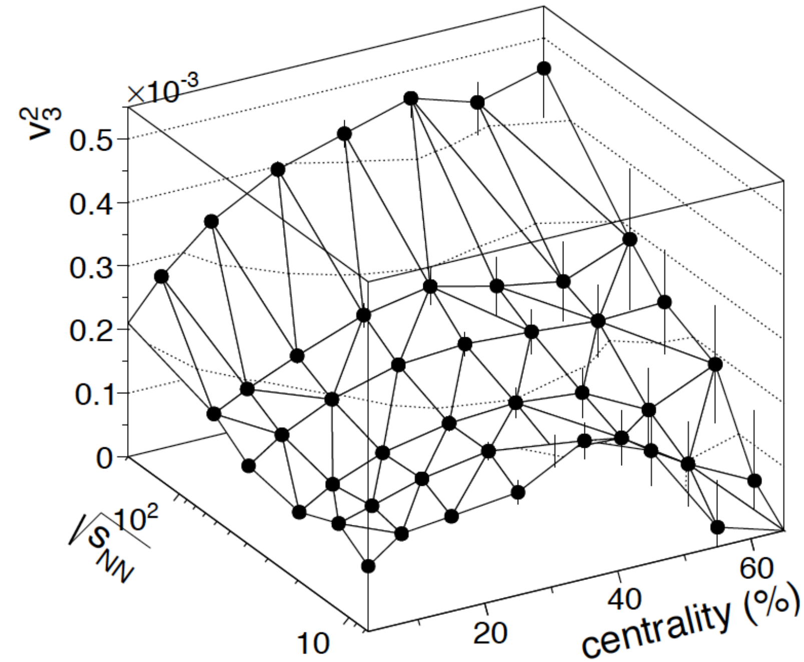


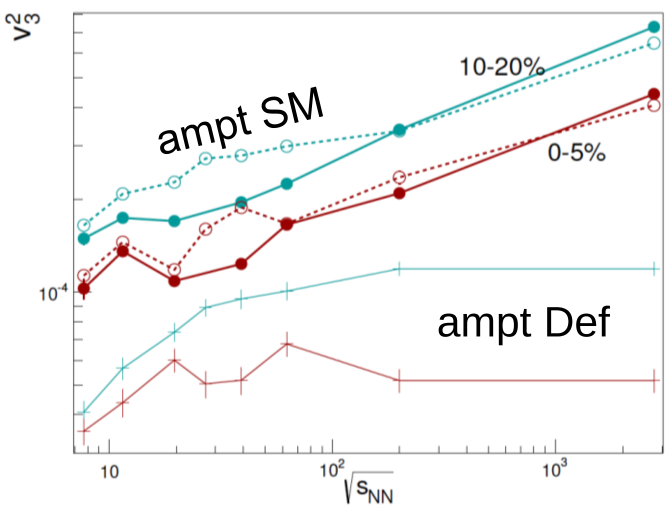
for low p_T, $\langle \cos 3(\varphi_1 - \varphi_2) \rangle$ vs $\eta_1 - \eta_2$ drops off as a gaussian

Different from intermediate p_T where the ridge is flat

Energy Dependence







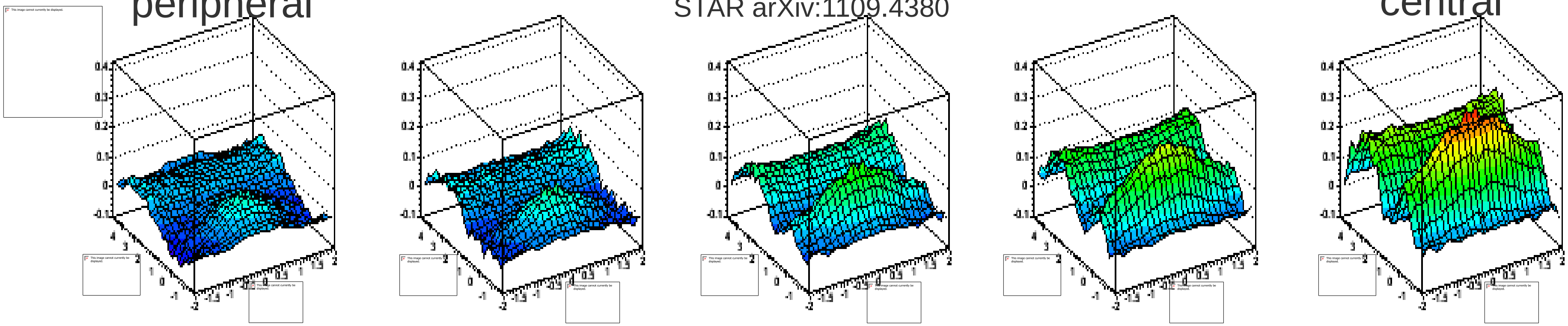
v_3 persists to 7.7 GeV with a similar centrality dependence

AMPT SM describes values to lowest energy

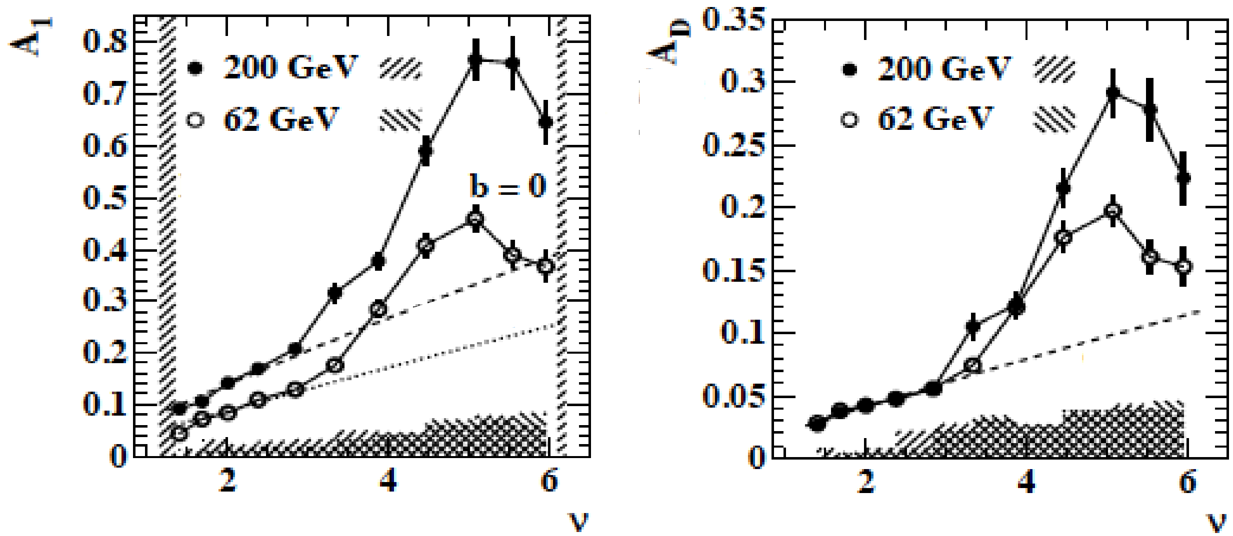
Trends in Low p_T Correlations

200 GeV Au+Au Collisions
STAR arXiv:1109.4380

peripheral | central

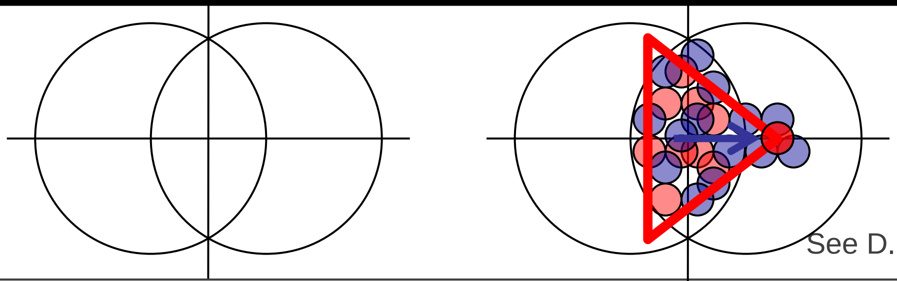


non-trivial evolution from p+p to central Au+Au: centrality dependence points to dominance of geometry



Data summarized in terms of a fit function: Amplitudes show abrupt rise then fall

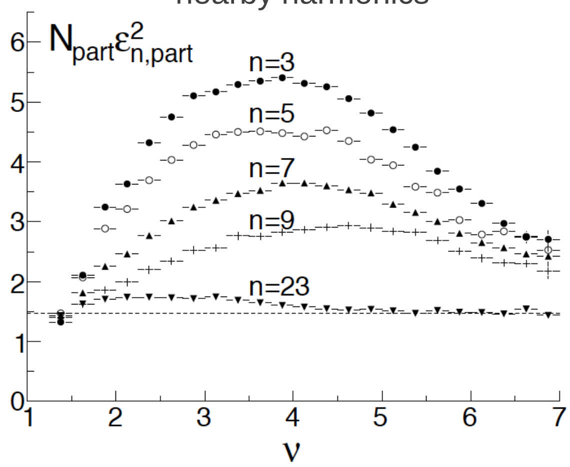
Rise and Fall and the *Almond Shape*

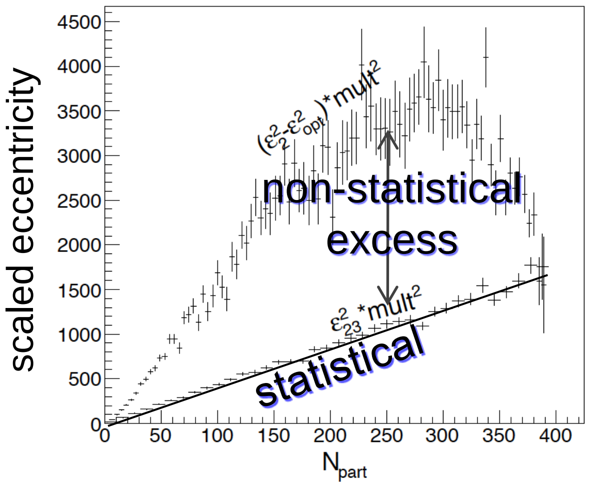


See D. Teaney, L. Yan, arXiv:1010.1876v1

Almond shape enhances fluctuations: In this sketch a rightward shift couples with the ellipse to produce a triangular fluctuation

ellipse couples most strongly to nearby harmonics

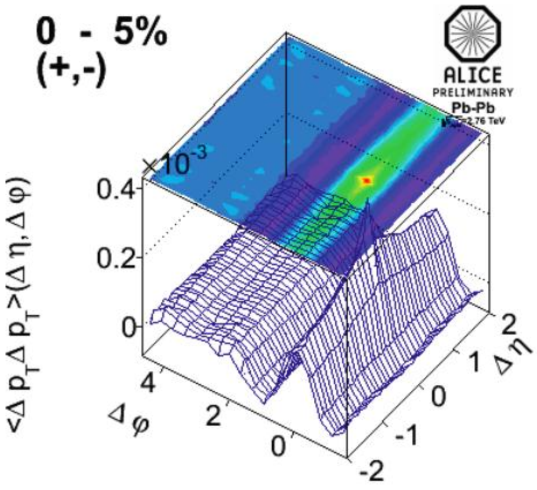




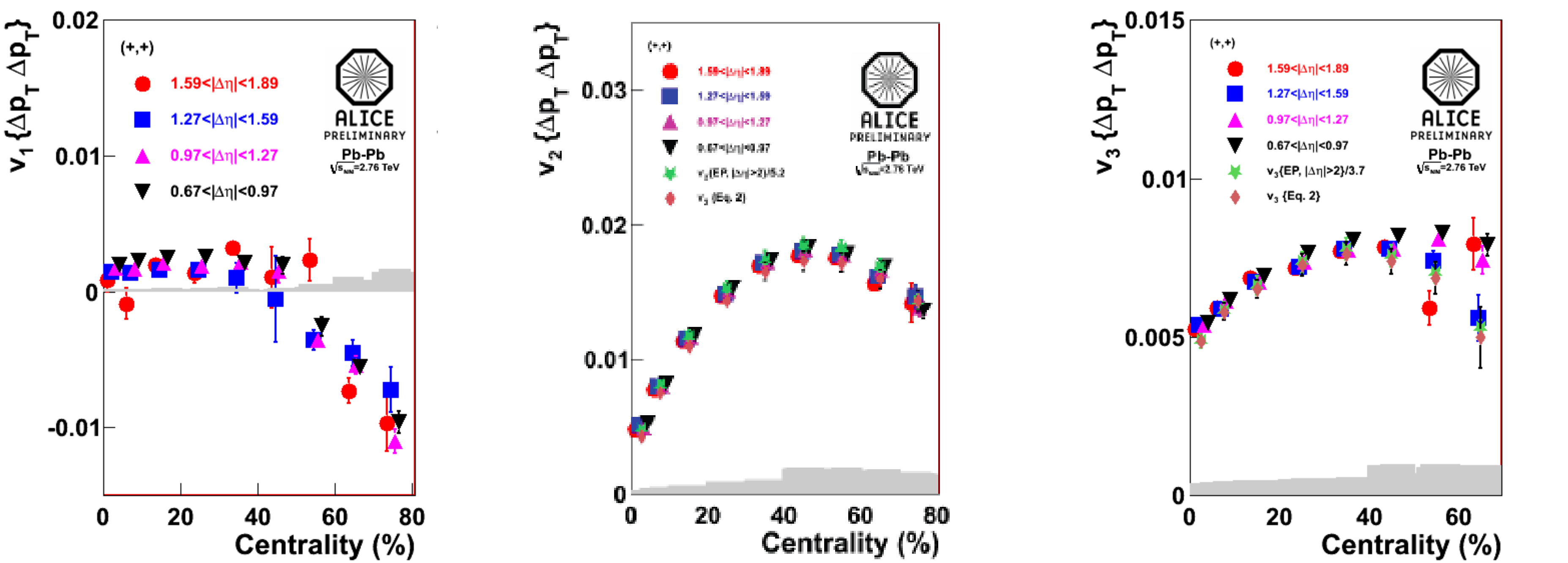
Linking the final-state correlations to initial density fluctuations

- When the collision becomes spherical, the enhancement subsides
- This leads to the **rise and fall**: a feature unique to this explanation

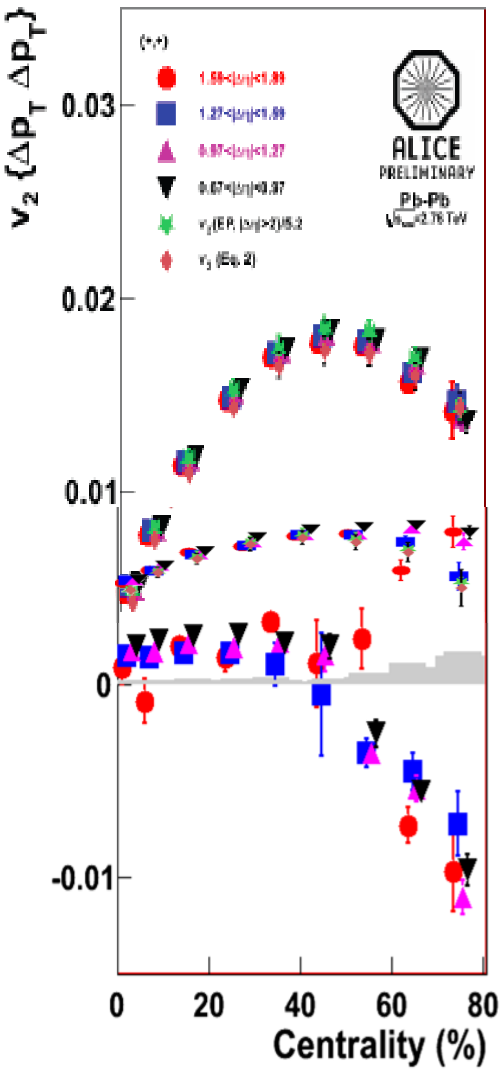
p_T-p_T correlations from ALICE

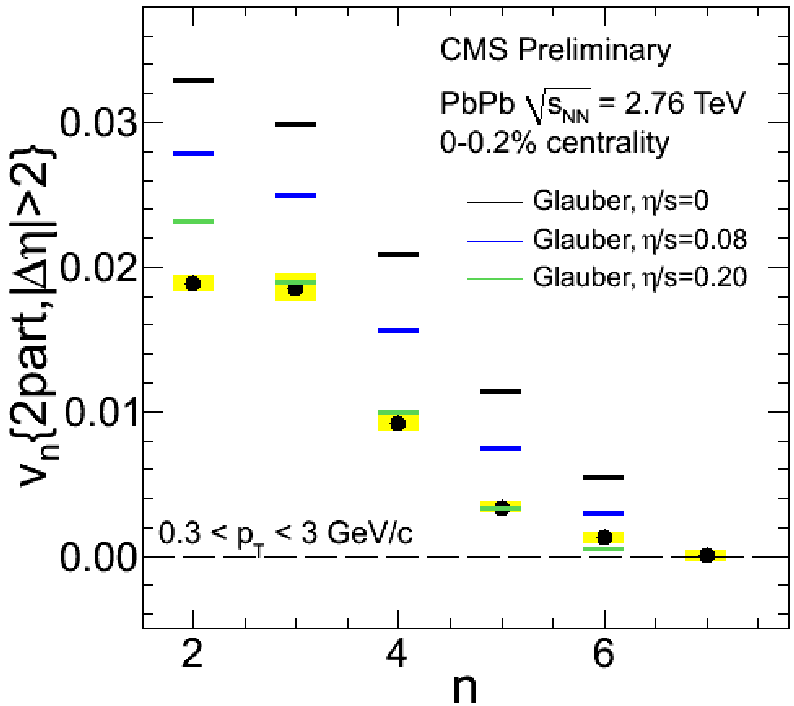


n=1: transition in mom. cons. mechanism (b2b jets → flow)
n=2: found to factorize
n=3: as large as v_2 in central



Suppression of n=2?

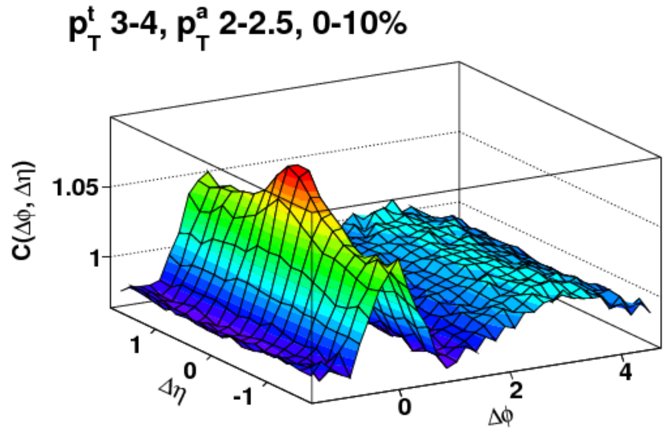


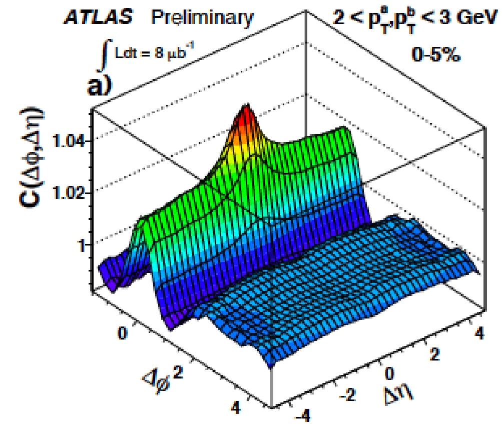


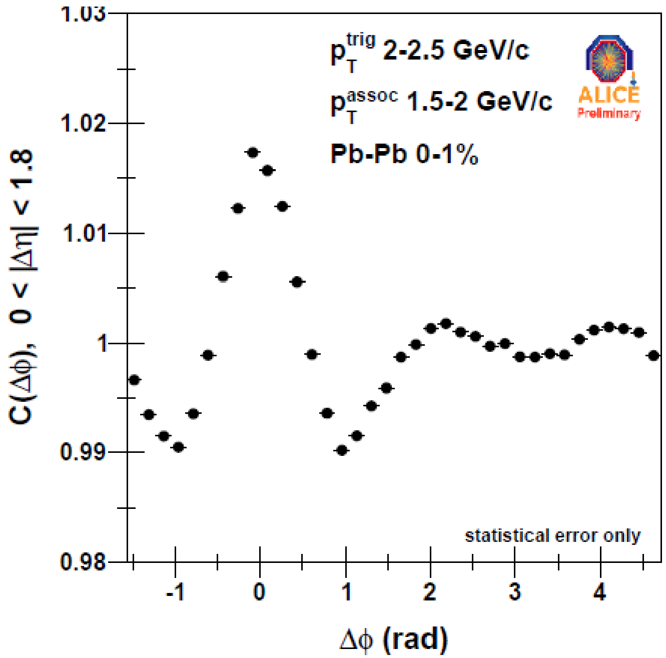
n=3 harmonic larger or equal to n=2

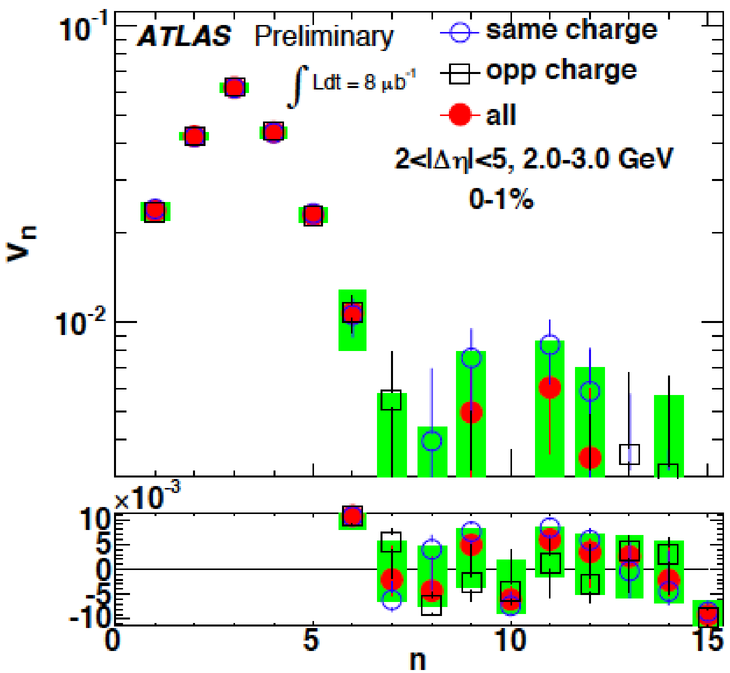
An observation in search of an explanation

Power Spectra: Intermediate p_T

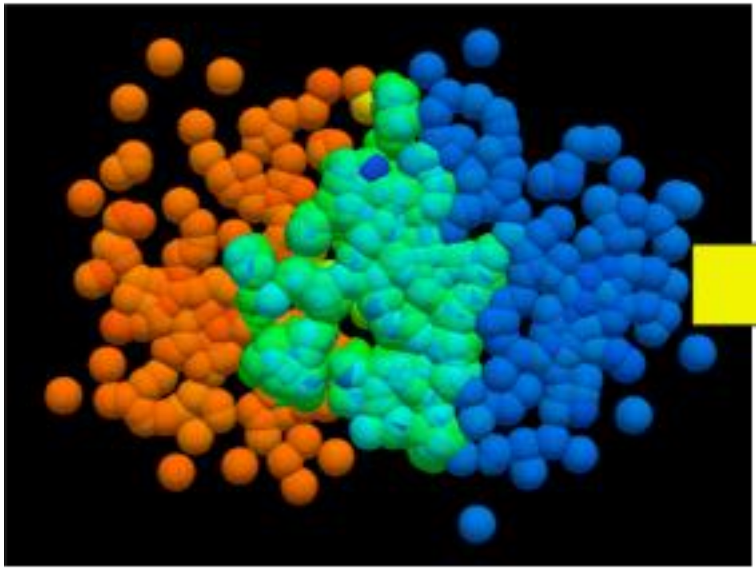




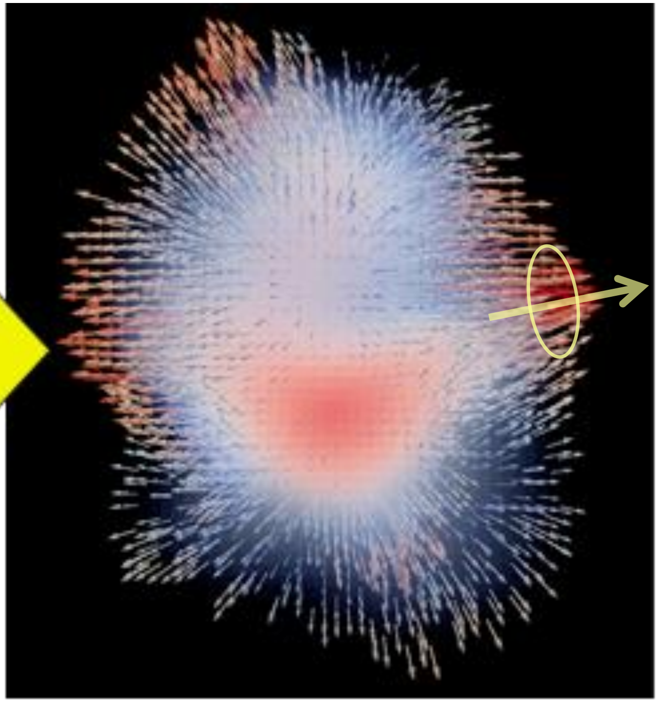




Hot Spots on Freeze-out Surface



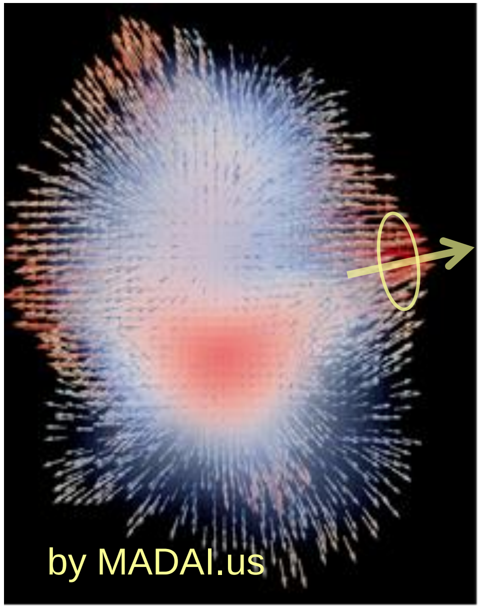
by MADAI.us

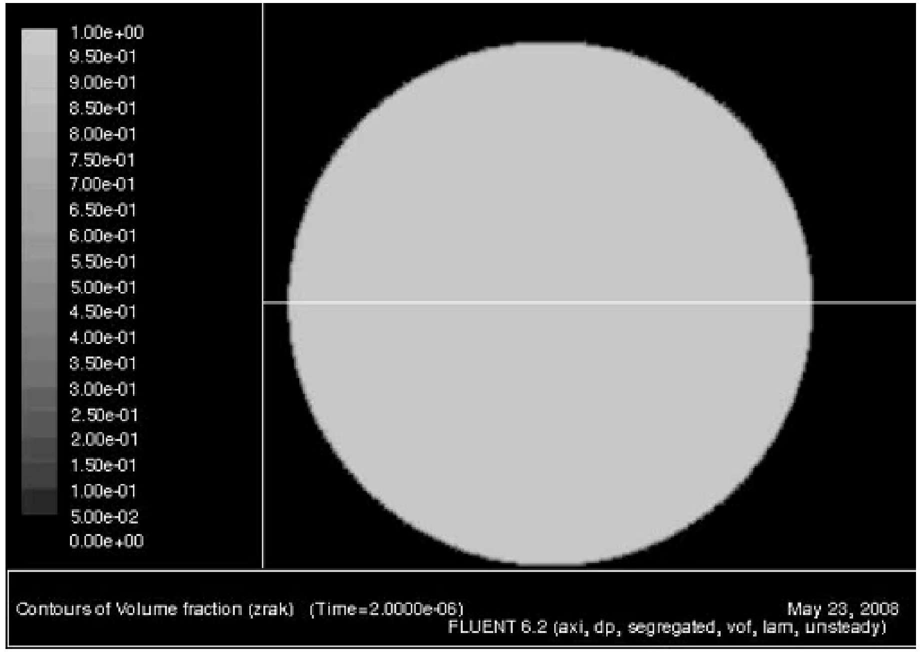


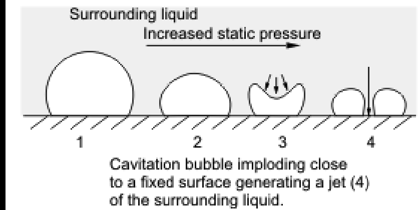
The expansion leads to large, many-body, local fluctuations

Are jet background estimates really accounting for these?
They won't go as √N

Hot Spots on Freeze-out Surface







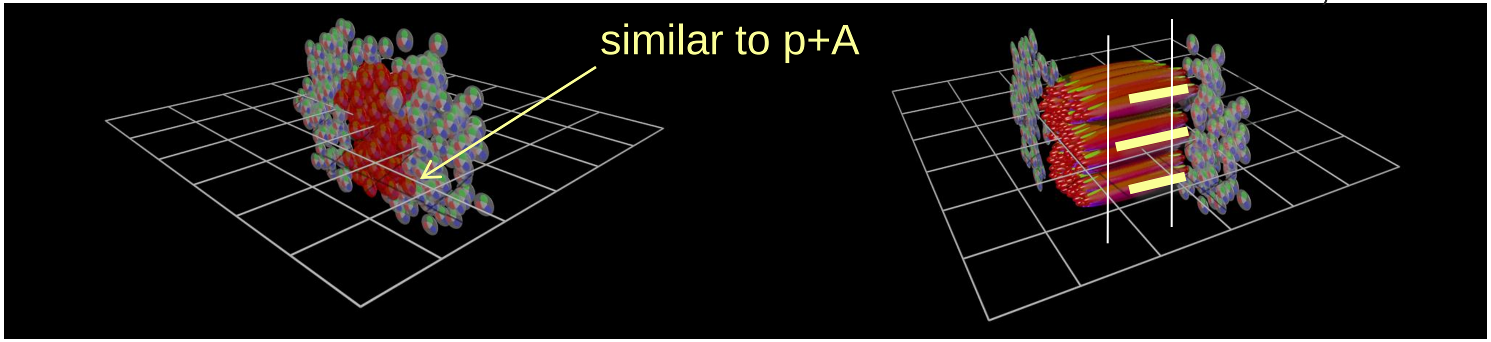
Jets are created by bubble cavitation and collapse

QGP expanding into the vacuum is the same thing but inside out

Geometry Matters

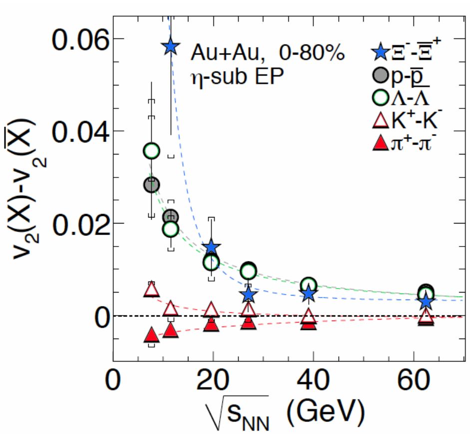
Geometry driving v_3 is not longitudinally symmetric. What affect does this have on correlations for η_1 vs η_2

Bozek, Broniowski, Moreira

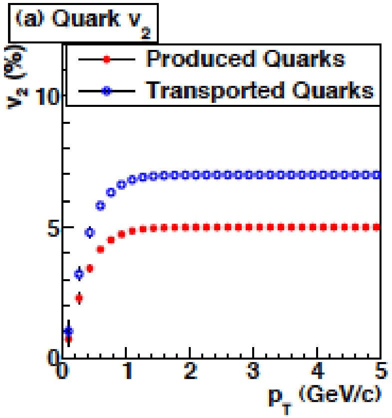


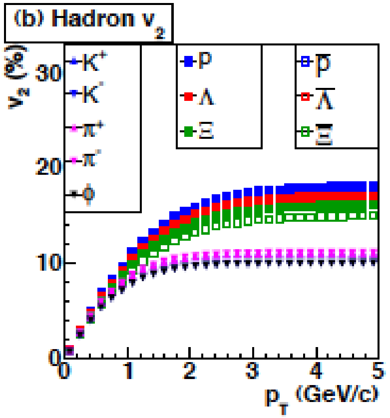
The entropy/baryon and net baryon distribution can vary in the transverse plane difference in v_2 for p and p-bar

STAR Preliminary QM2011

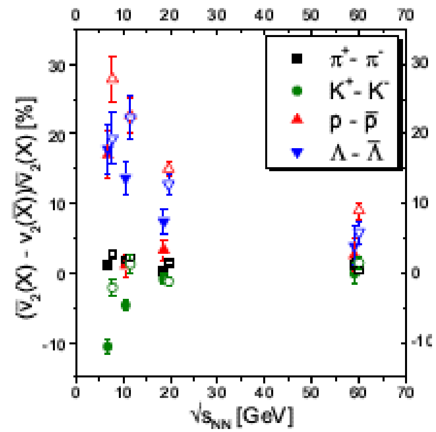


Dunlop, Lisa, Sorensen

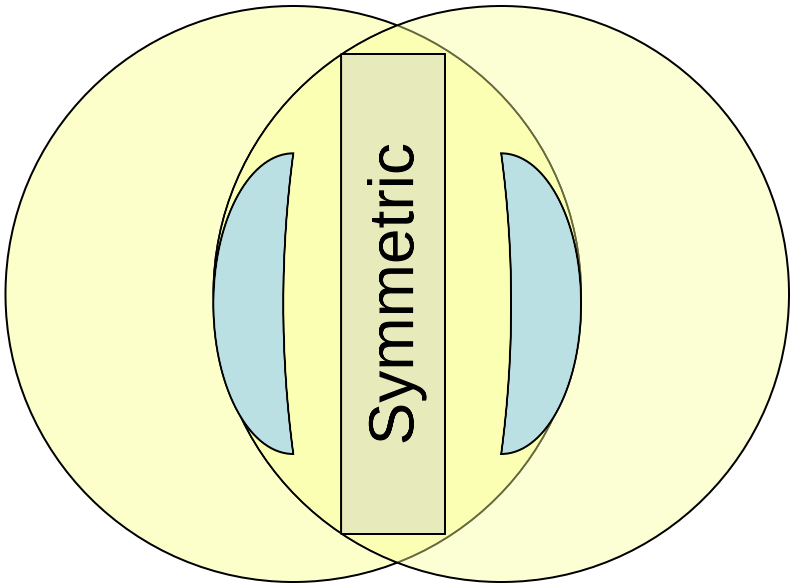


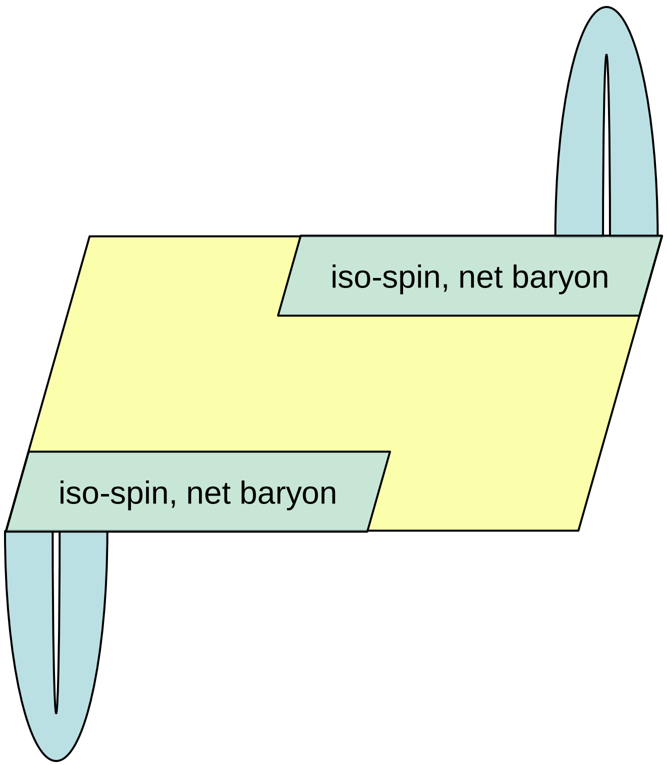


Steinheimer, Koch, Bleicher

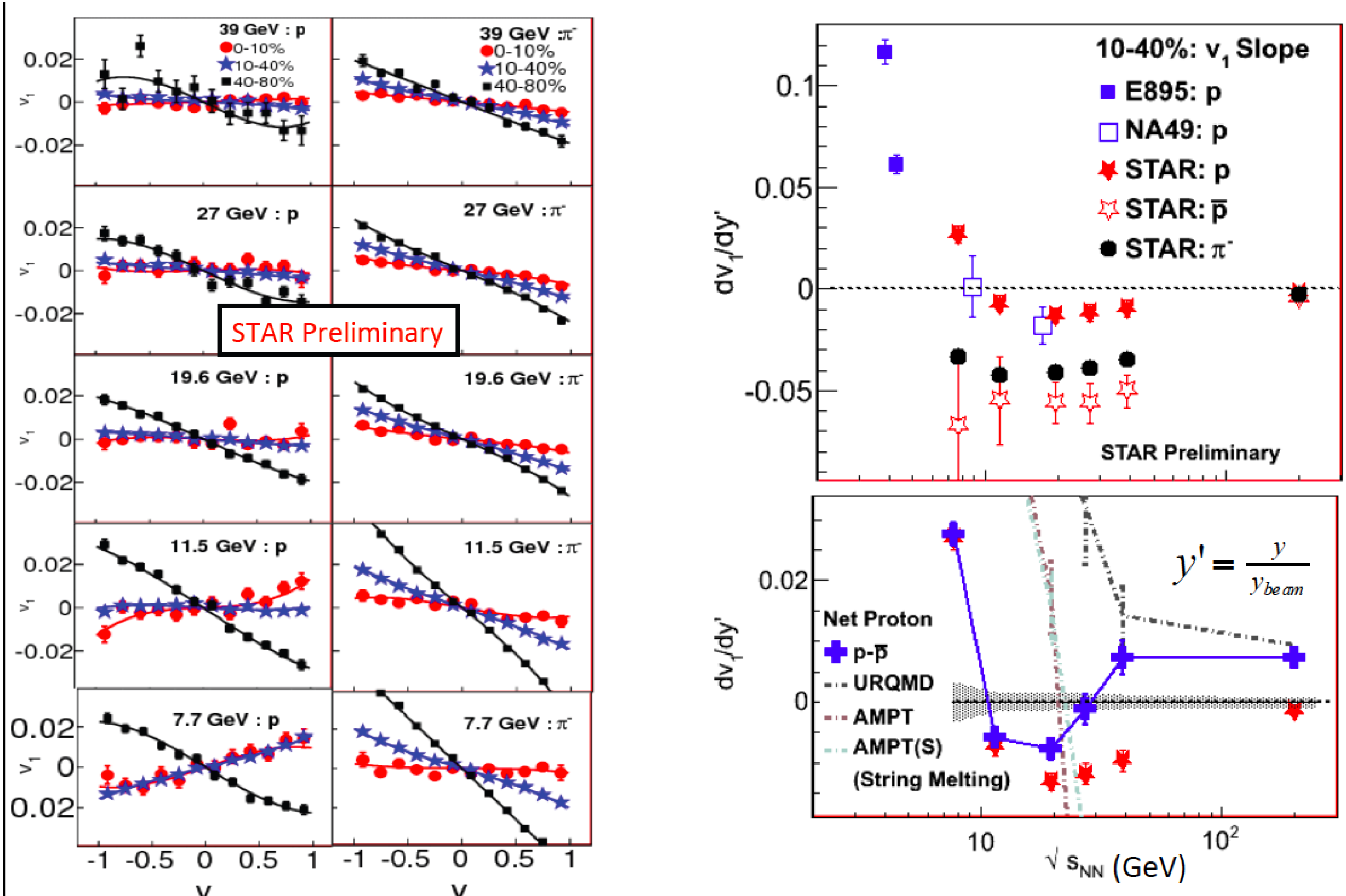


Geometry

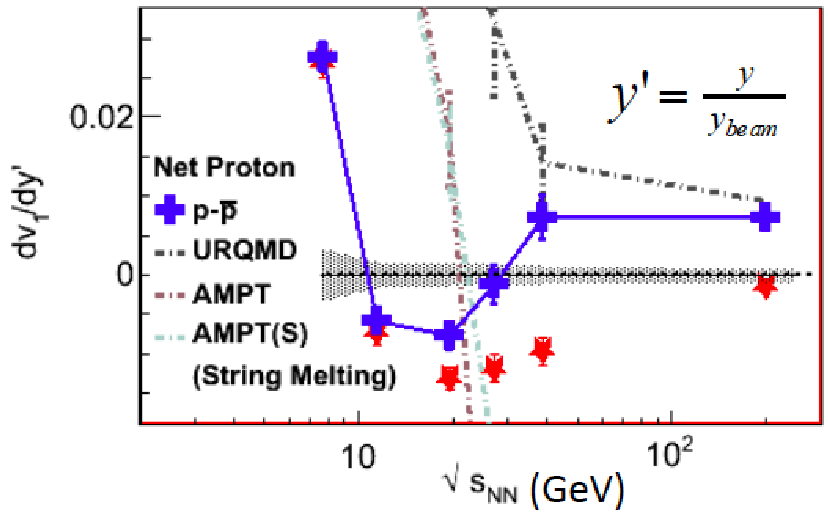


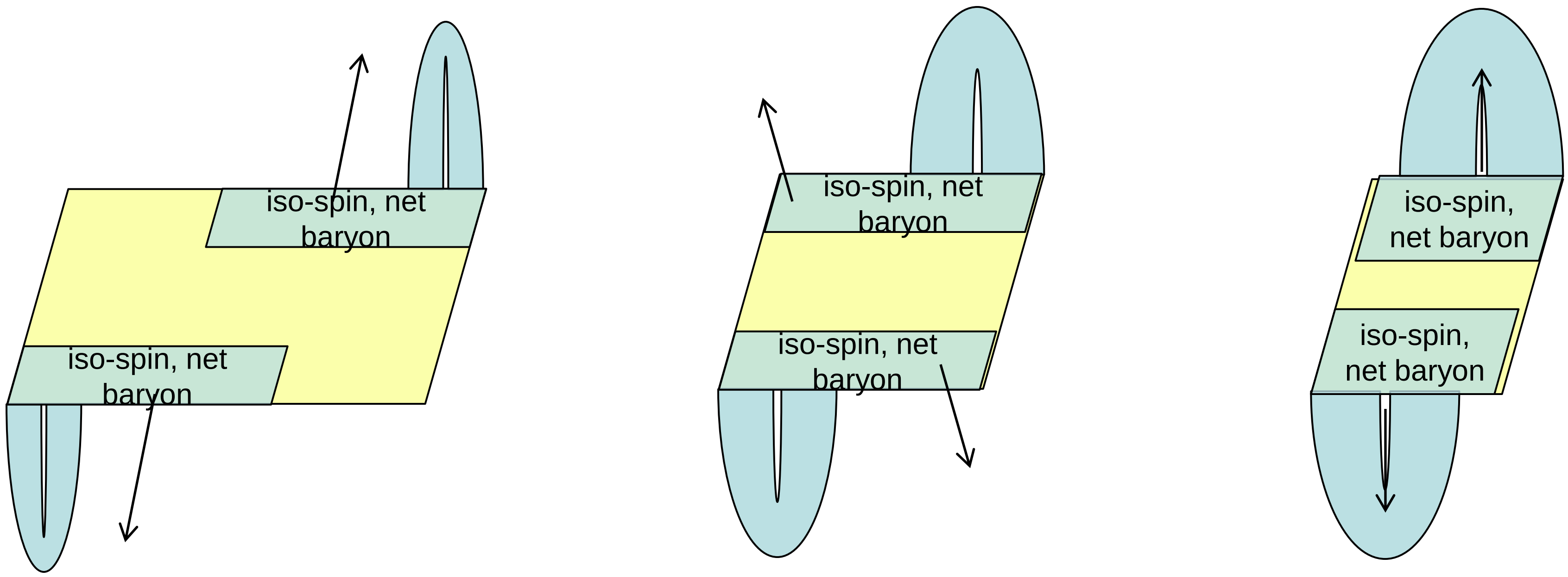


Net Baryon v_1



Tracing the Geometry with Energy





Conclusions

Geometry REALLY matters!

- Where are the baryons distributed?
- What is the longitudinal and transverse shape of the fireball?
- How lumpy are the initial conditions?

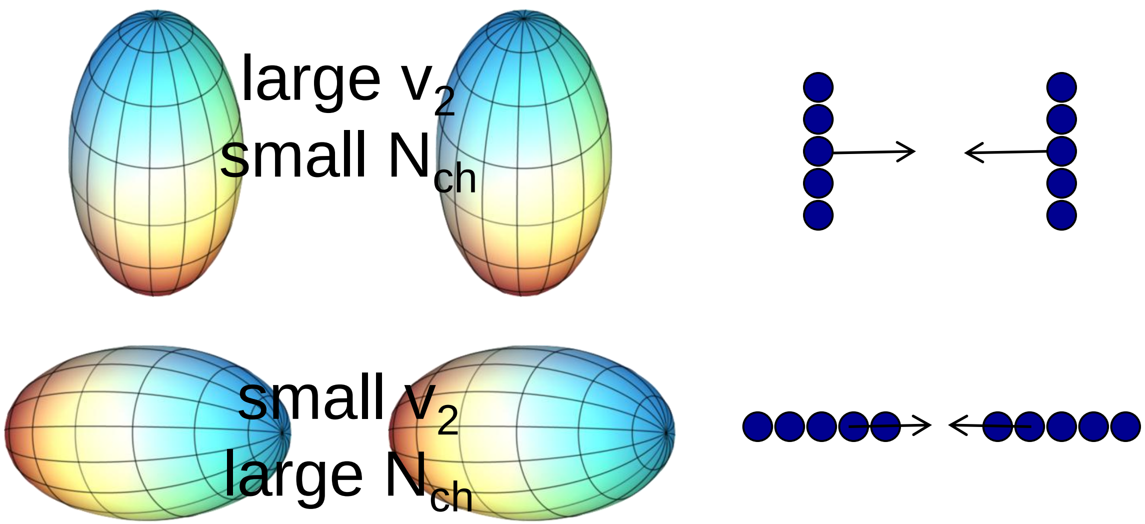
All this structures seems to show up in data

Should be a major background for jets

We can vary the initial geometry using U+U collisions

U+U: Testing Particle Production

We often assume multiplicity depends partially on the number of participants and partially on the number of collisions

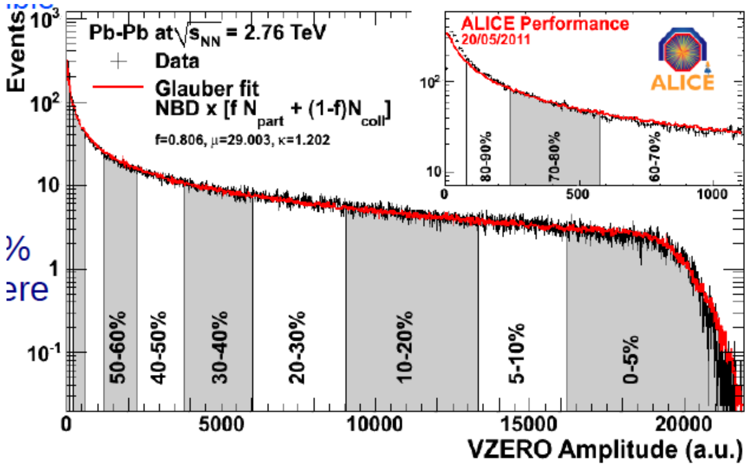


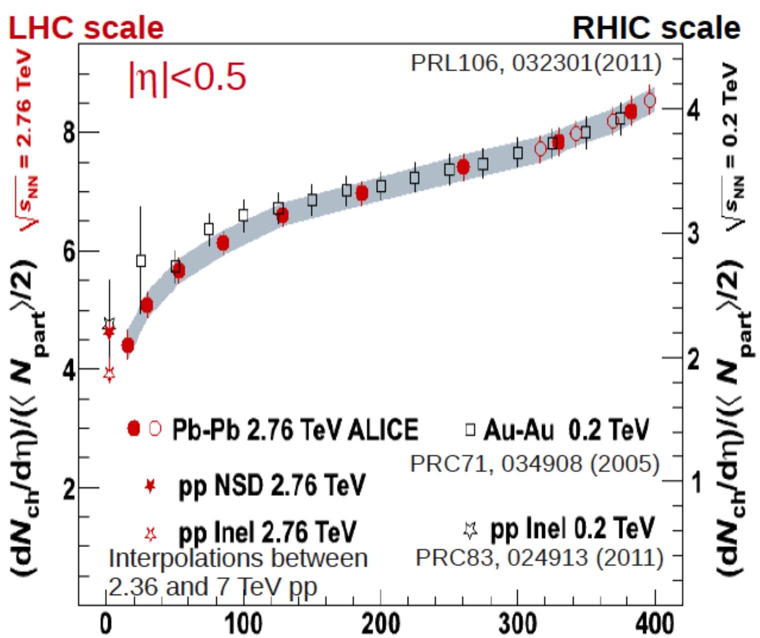
N_{part}	N_{coll}
10	5
10	25

Central U+U collisions are an ideal testing ground for particle production: Is large v_2 associated with lower N_{ch}?

Will the 2-component model bite the dust?

Centrality Dependence of N_{ch}





A. Toia (QM2011)

Multiplicity grows 2.1x larger at 2.76 TeV than 200 GeV

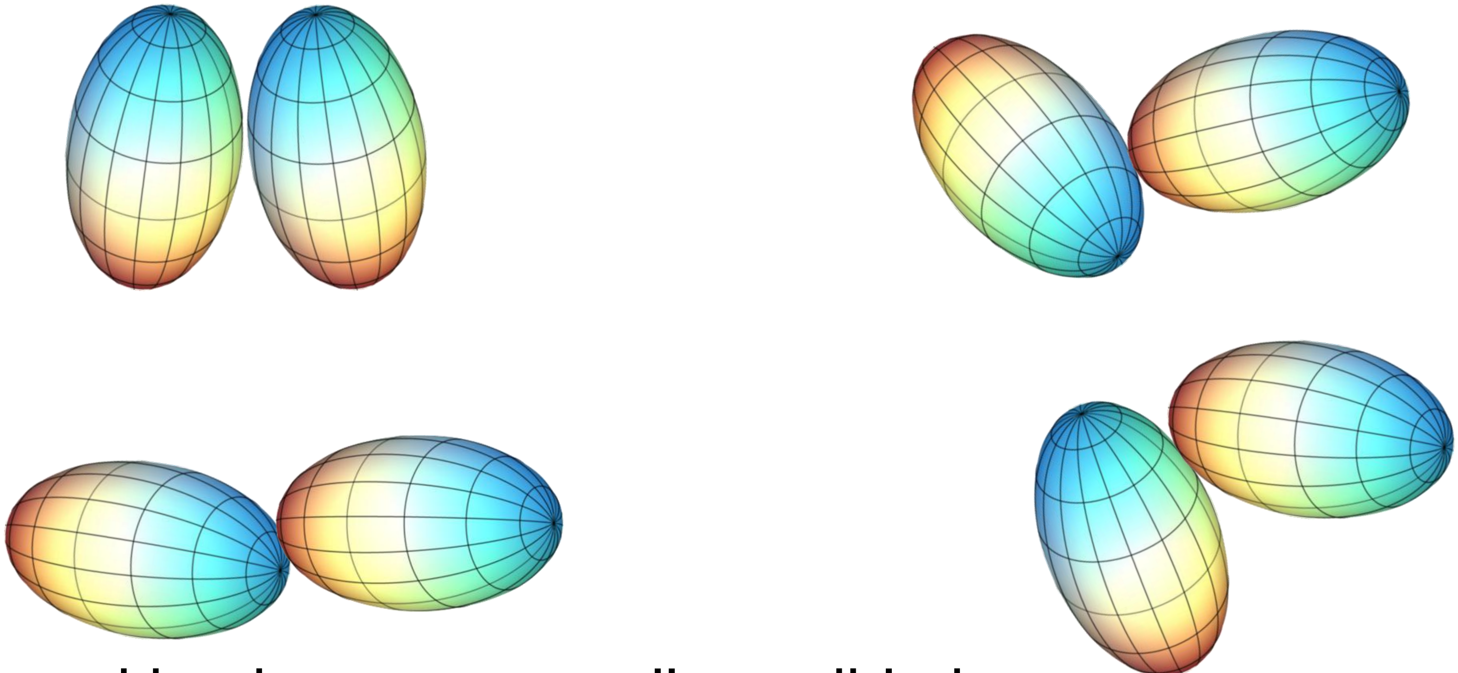
Centrality dependence usually thought to reflect an increase in the number of binary collisions

But why is the shape the same from 20 GeV to 2.76 TeV

Does the two-component model make sense?

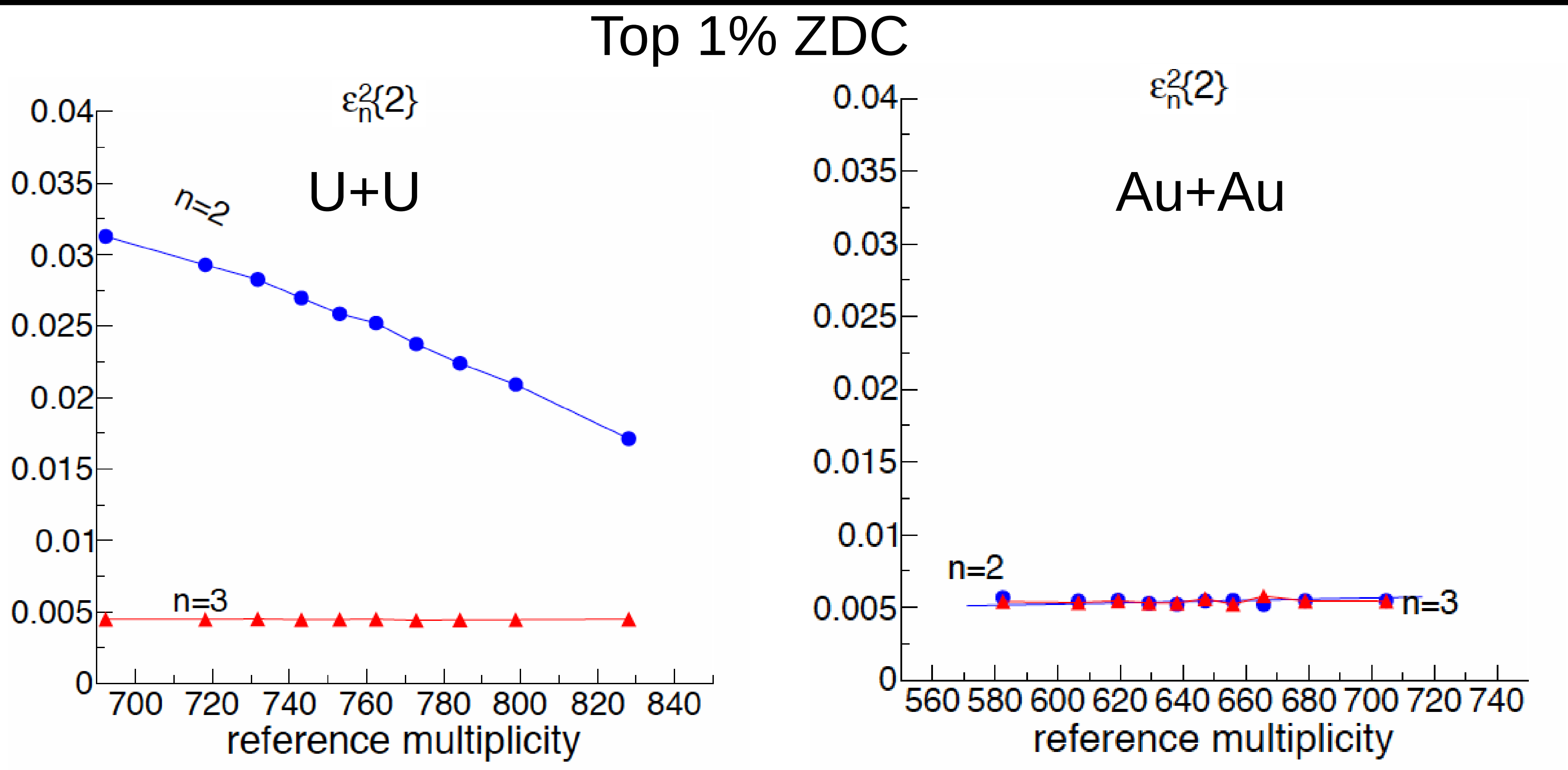
More complications

In addition to multiplicity fluctuations, we need to integrate over all possible geometry fluctuations including positions of nucleons

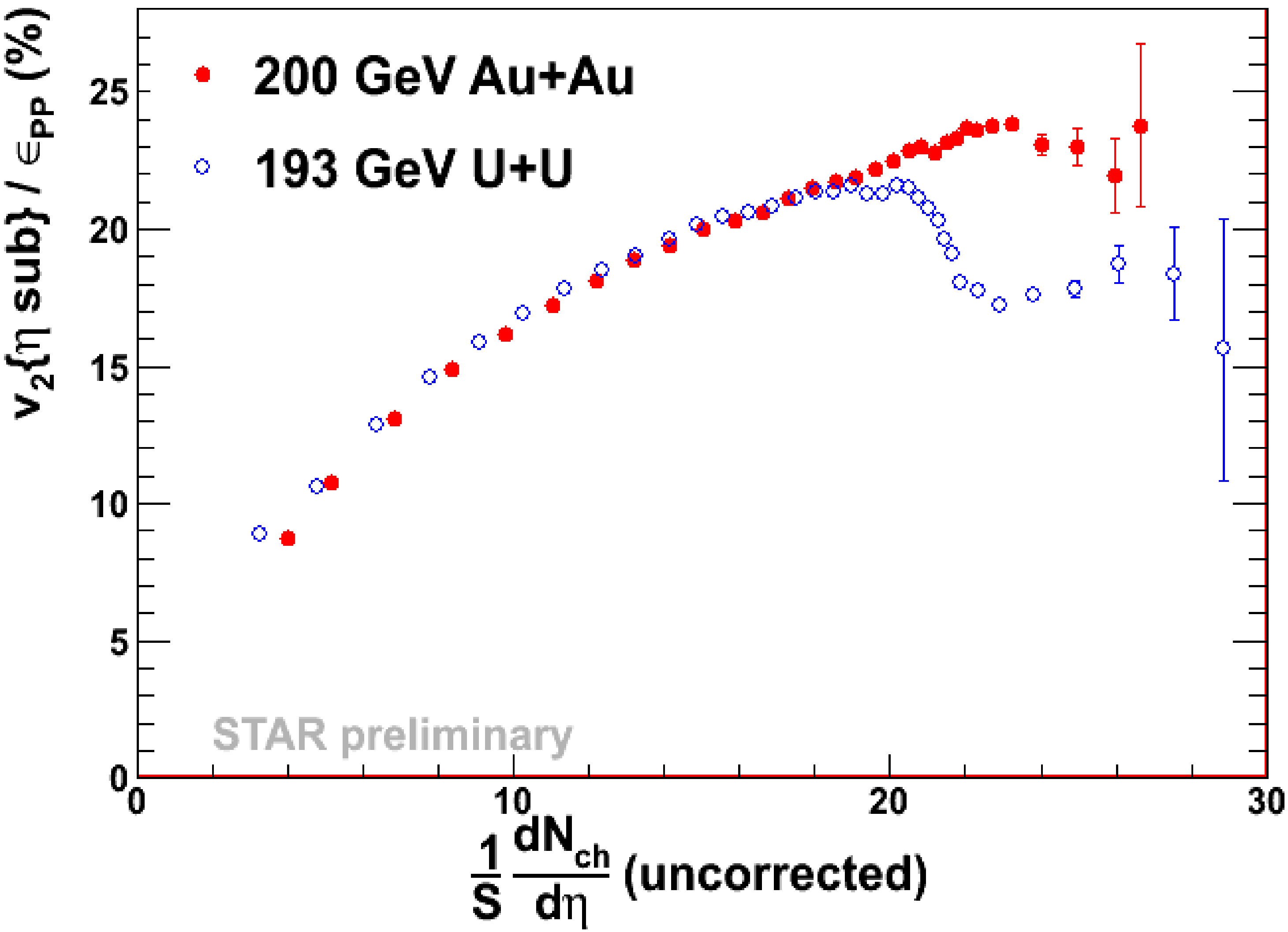


After taking into account all possible impact parameters, angles, multiplicity fluctuations, random variation of participants inside the nucleus, can we still select a sample of collisions that are more tip-on-tip or more side-on-side?

Full Simulation



The simulation indicates v_2 should depend strongly on multiplicity in central U+U but not in central Au+Au: implies high multiplicity U+U is more tip-on-tip than low multiplicity


200 GeV Au+Au
193 GeV U+U
STAR preliminary
$v_2\{\eta\ \mathrm{sub}\} / \epsilon_{PP}$ (%)
$\frac{1}{S}\frac{dN_{ch}}{d\eta}$ (uncorrected)
0
5
10
15
20
25
30

Conclusions

The freeze-out hypersurface is structured and interesting

Hydrodynamic jets are likely created in heavy-ion collisions

Geometry really matters