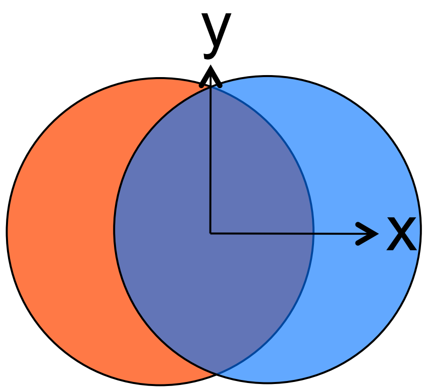
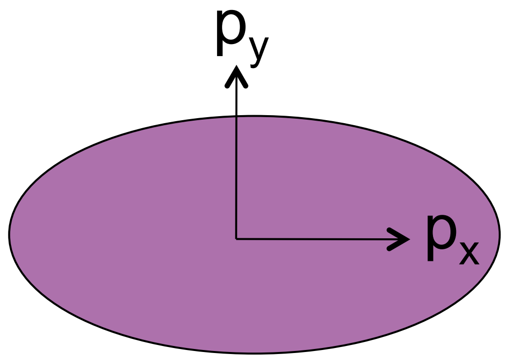
Higher Flow Harmonics from the STAR Collaboration at RHIC

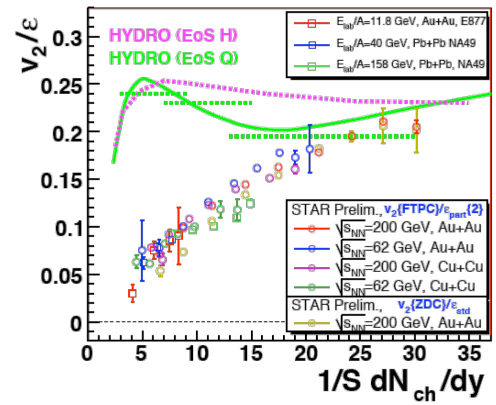
Paul Sorensen (BROOKHAVEN NATIONAL LABORATORY) for the STAR Collaboration

Why v_n Matters & What It Means



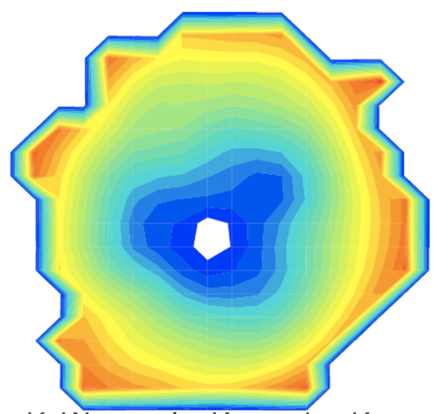


Voloshin, Poskanzer, Snellings, arXiv:0809.2949

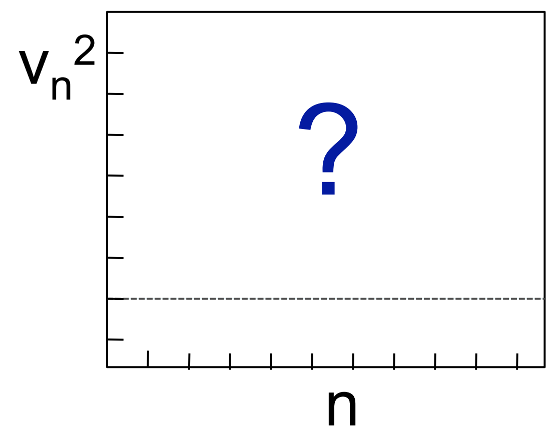


$$N_{pairs} \propto 1 + 2v_1^2 \cos\Delta\varphi + 2v_2^2 \cos 2\Delta\varphi + 2v_3^2 \cos 3\Delta\varphi + 2v_4^2 \cos 4\Delta\varphi + \ldots$$

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



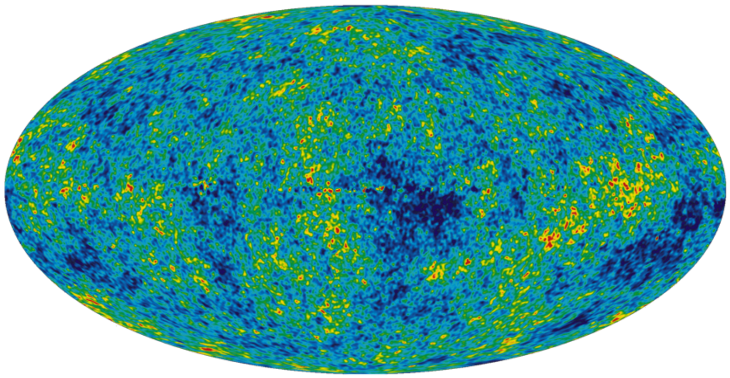
K. Werner, Iu. Karpenko, K. Mikhailov, T. Pierog, arXiv:11043269



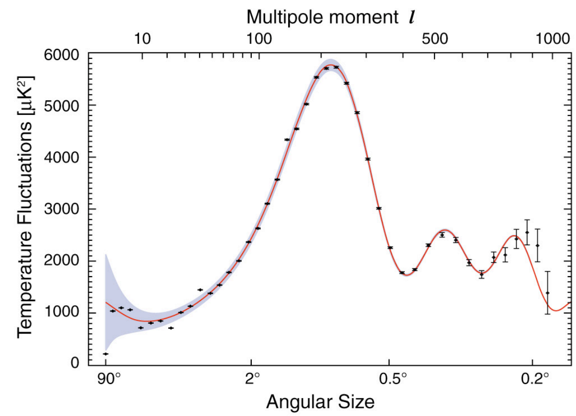
Fluctuations imply odd terms aren't necessarily zero and v_n^2 vs n will provide information about the system like lifetime, viscosity, etc.

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

Why v_n Matters & What It Means



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



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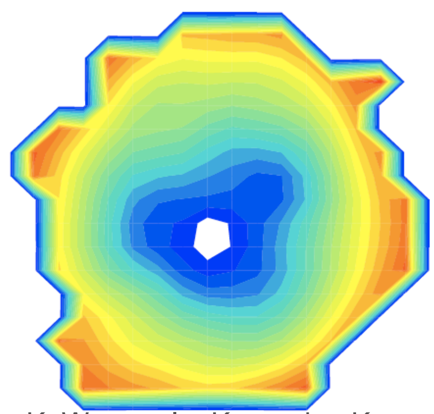

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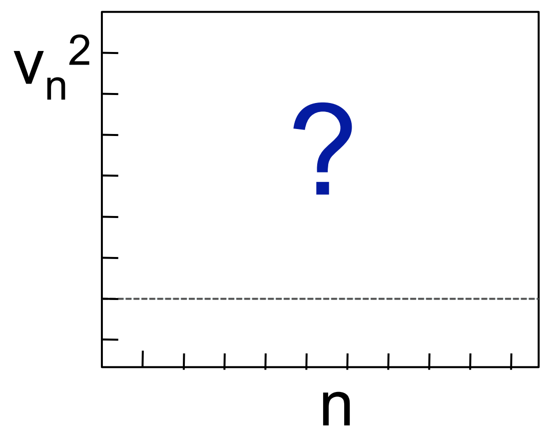


A. Mocsy, et. al. arXiv:1008.3381 [hep-ph]

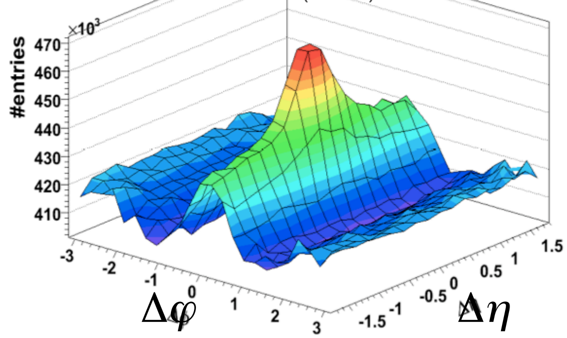
Analagous to the Power Spectrum extracted from the Cosmic Microwave Background Radiation

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

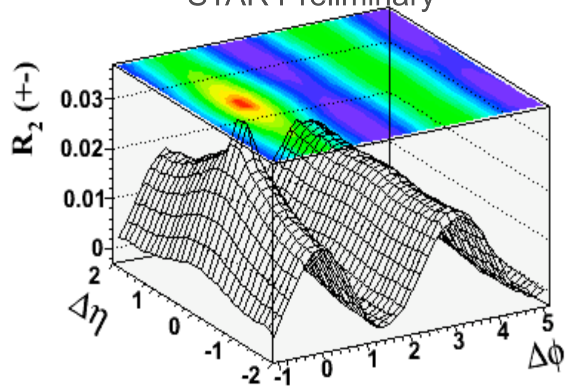
Correlation Landscape at RHIC

The correlation landscape −is rich in information− *on jets, jet modification, transport, early-times, and space-momentum correlations like flow*

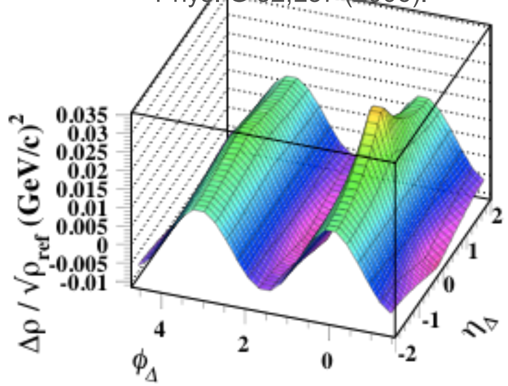
B. I. Abelev et al.[STAR Collaboration], Phys. Rev. C 80 (2009) 6491



STAR Preliminary



J. Adams et al. [STAR Collaboration], J. Phys. G 32 L37 (2006).



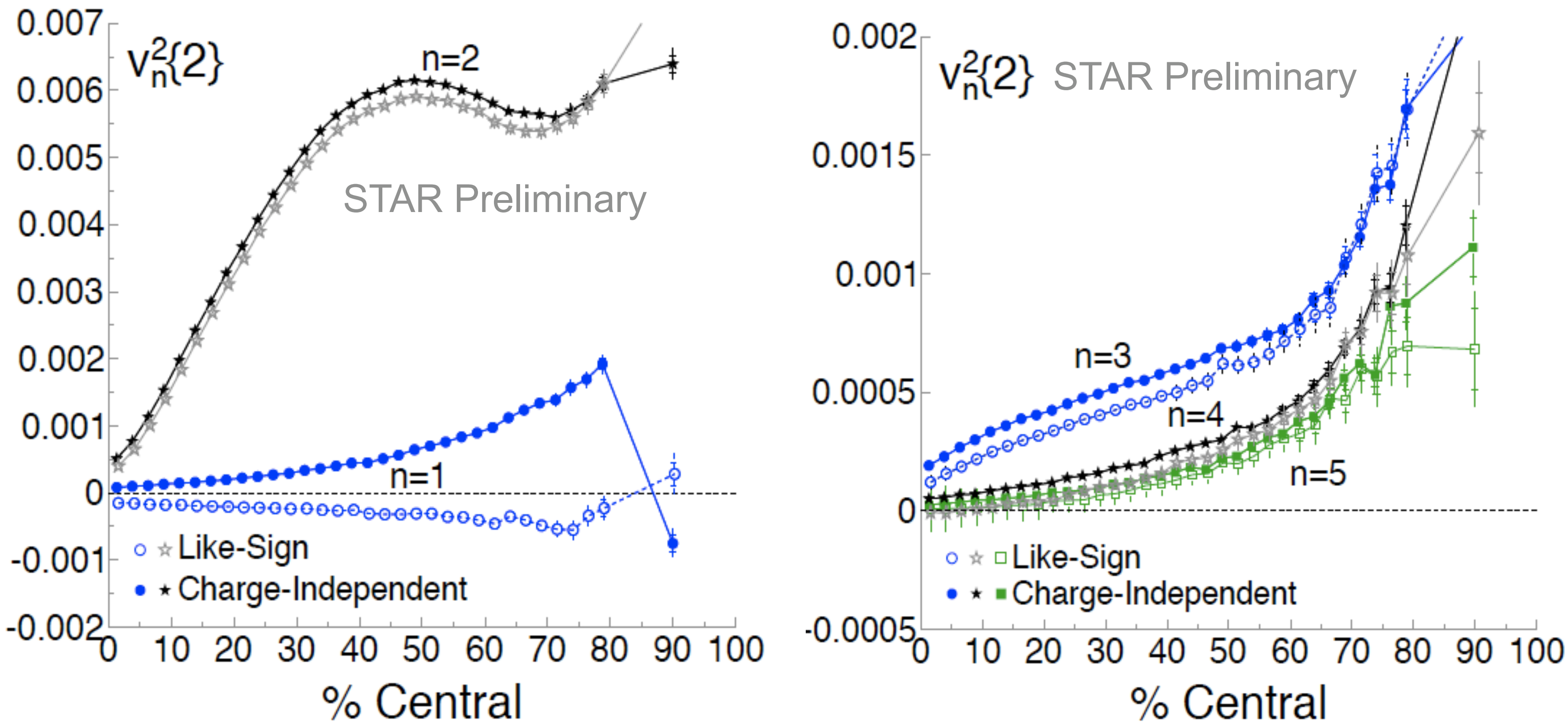
The understanding of higher harmonic v_n^2 is central to understanding the meaning of the correlations landscape in heavy ion collisions

P. Sorensen, arXiv:0808.0503; J. Phys. G37: 094011, 2010;
B. Alver, G. Roland Phys. Rev. C81:054905, 2010;
B. Alver, Gombeaud, Luzum, Ollitrault, Phys.Rev.C82:034913,2010
P. S., A. Mocsy, B. Bolliet, Y. Pandit, arXiv:1102.1403

We'll use correlations to extract the power spectrum from heavy-ions and investigate it's possible relationship to the early times

Higher v_n from 2 Particle Correlations

Q-Cumulants: 200 GeV Au+Au |η|<1.0



n=1 shows large difference between LS and CI: charge and momentum conserv?

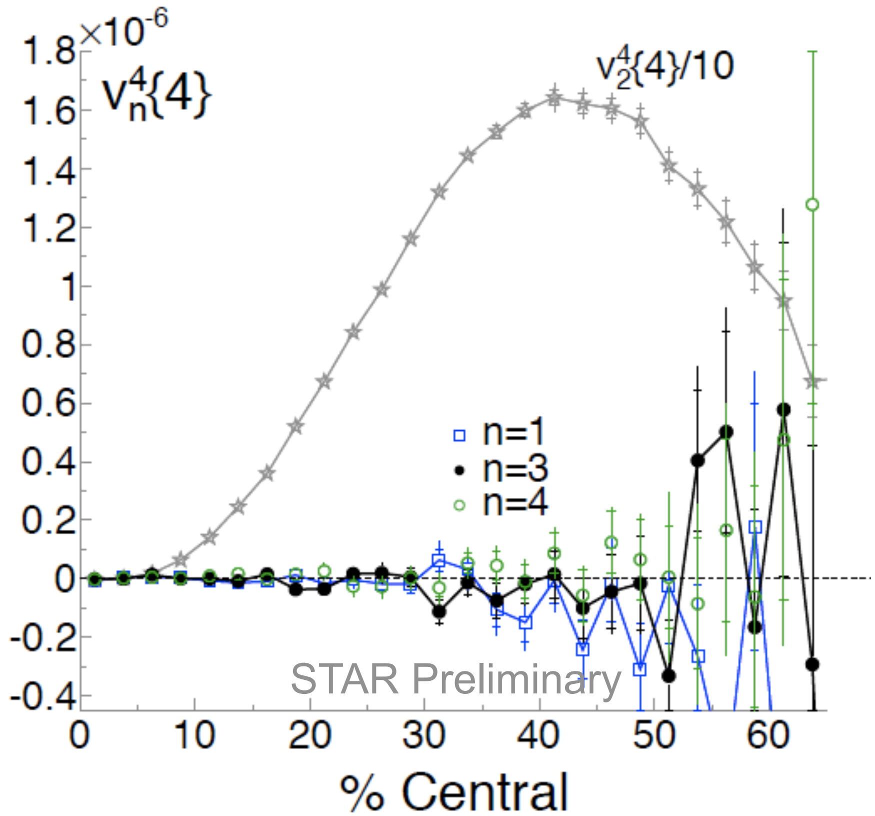
n=3 exhibits effects of elliptic overlap geometry

n=4 and larger show 1/N dependence typical of non-flow correlations

Q-Cumulants: A. Bilandzic, R. Snellings, S. Voloshin, Phys. Rev. C 83, 044913 (2011)

Higher v_n from 4 Particle Correlations

Q-Cumulants: 200 GeV Au+Au |η|<1.0



v_4 from mixed harmonics is within errors of $v_4^4\{4\}$:
$v_4 \sim v_2^2 \sim 0.1^2$
$v_4^4 \sim 10^{-8}$

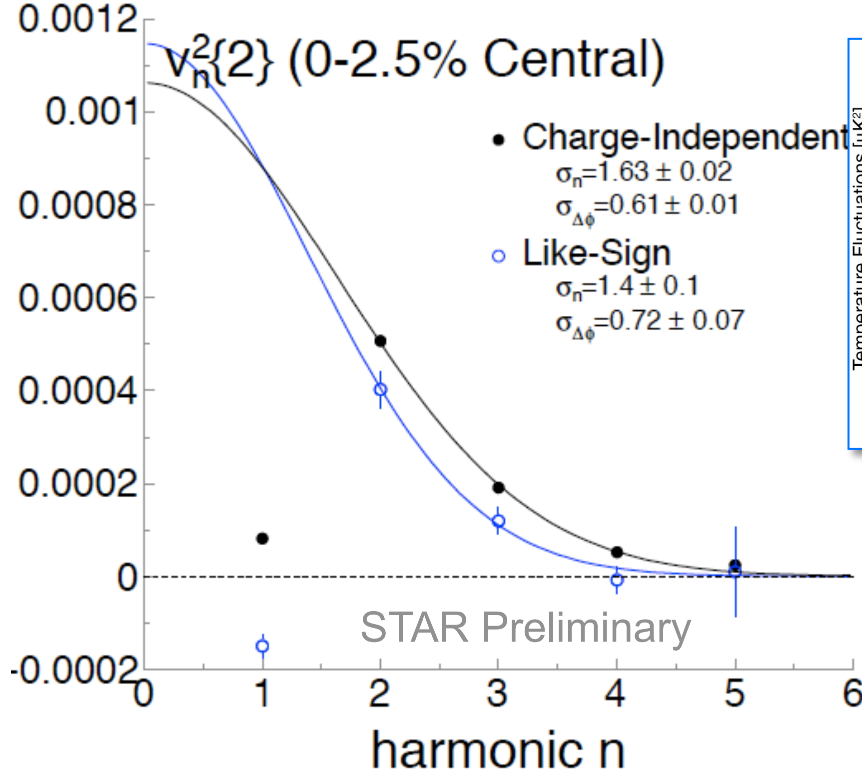
$v_n\{4\}$ consistent with zero for odd terms. Consistent with $v_3^2\{2\}$ being due to non-flow **and/or** with $v_n \propto \varepsilon_{n,part}$: for $v_n \propto \varepsilon_{n,part}$, $v_n\{4\} \propto \varepsilon_{n,std}$

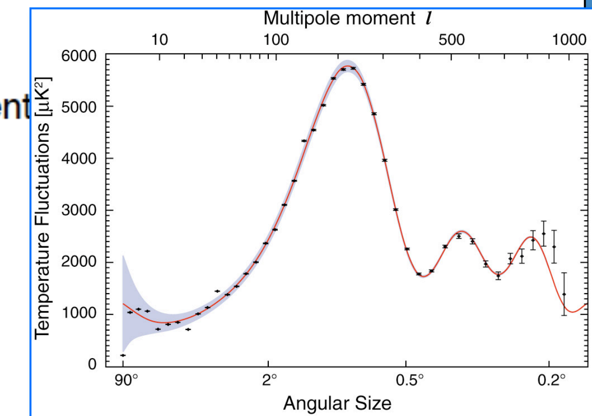
R.S. Bhalerao and J-Y.Ollitrault, Phys.Lett.B641:260-264 (2006)
S. Voloshin, A. Poskanzer, A. Tang, G. Wang, Phys.Lett.B659:537-541 (2008)

For 0-2.5% central $v_2\{4\} \approx 0$ indicates elliptic shape is nearly gone. We'll look at the shape of $v_n^2\{2\}$ vs n for nearly symmetric collisions

$v_n^2\{2\}$ vs n for 0-2.5% Central

This is the Power Spectrum of Heavy-Ion Collisions





|η|<1

$v_n\{4\}$ is zero for 0-2.5% central: look at $v_2^2\{2\}$ vs n to extract power spectrum in nearly symmetric collisions

Fit by a Gaussian except for n=1 (momentum conservation): width can be related to lenth scales: viscous, acoustic horizon, 1/2πT…

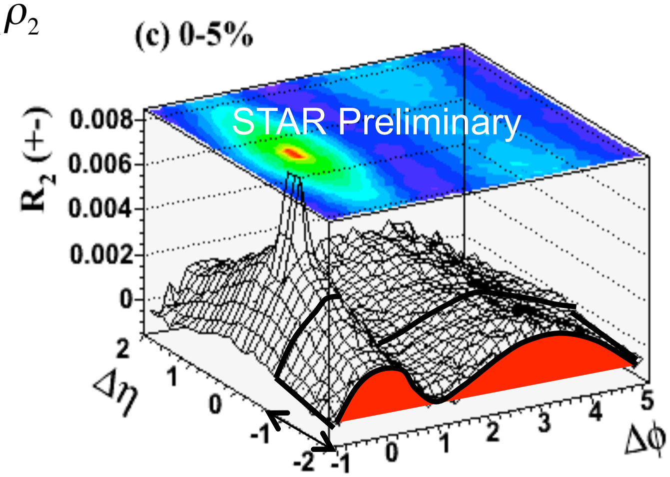
P. Staig and E. Shuryak, arXiv:1008.3139 [nucl-th]
A. Mocsy, P. S., arXiv:1008.3381 [hep-ph]
A. Adare [PHENIX], arXiv:1105:3928

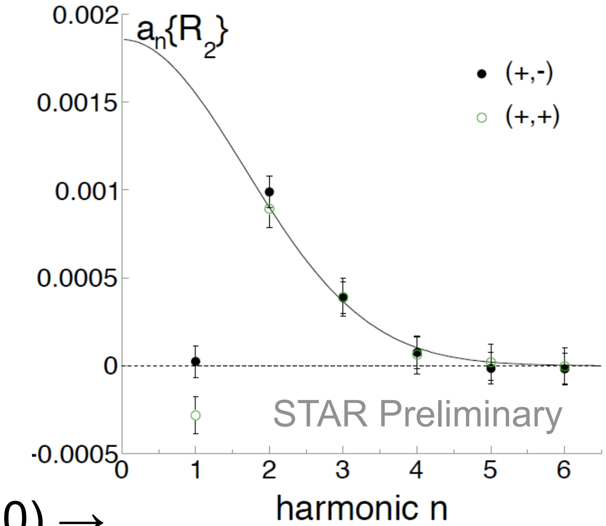
Integrates all Δη within acceptance: we can look more differentially to assess non-flow

Large Δη Power Spectrum $a_n$necy

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

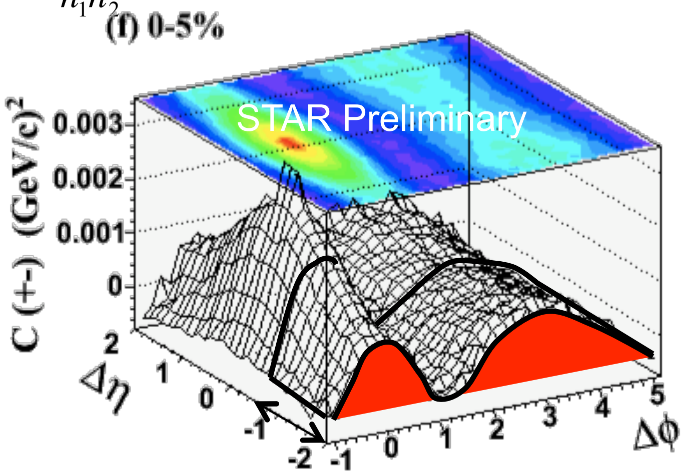
$$R_2 = \frac{\rho_{12}}{\rho_1 \rho_2} - 1$$

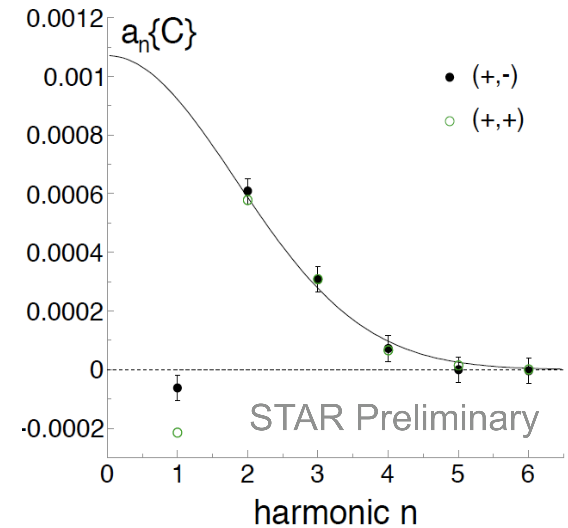




→ Fourier Tr. (0.7<Δη<2.0) →

$$C = \frac{\left\langle \sum_{i=1}^{n_1} \sum_{j=1 \neq i}^{n_2} p_{T,i} p_{T,j} \right\rangle}{\bar{n}_1 \bar{n}_2} - \bar{p}_{T,1} \bar{p}_{T,2}$$

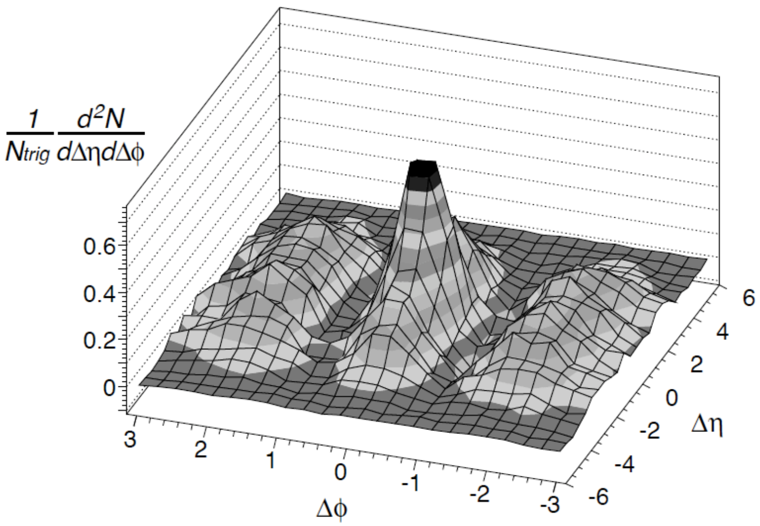




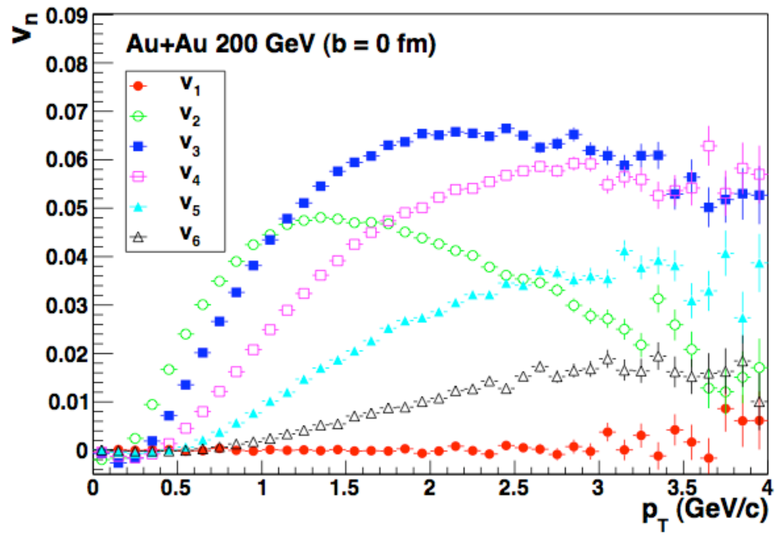
See also: A. Mocsy, P. S., arXiv:1008.3381 [hep-ph]

Recent Theoretical Developments

In a system where space-momentum correlations develop, the initial density fluctuations can manifest in momentum space



J.Takahashi, B.Tavares, W.Qian, F.Grassi, Y.Hama, T.Kodama & N.Xu and many others



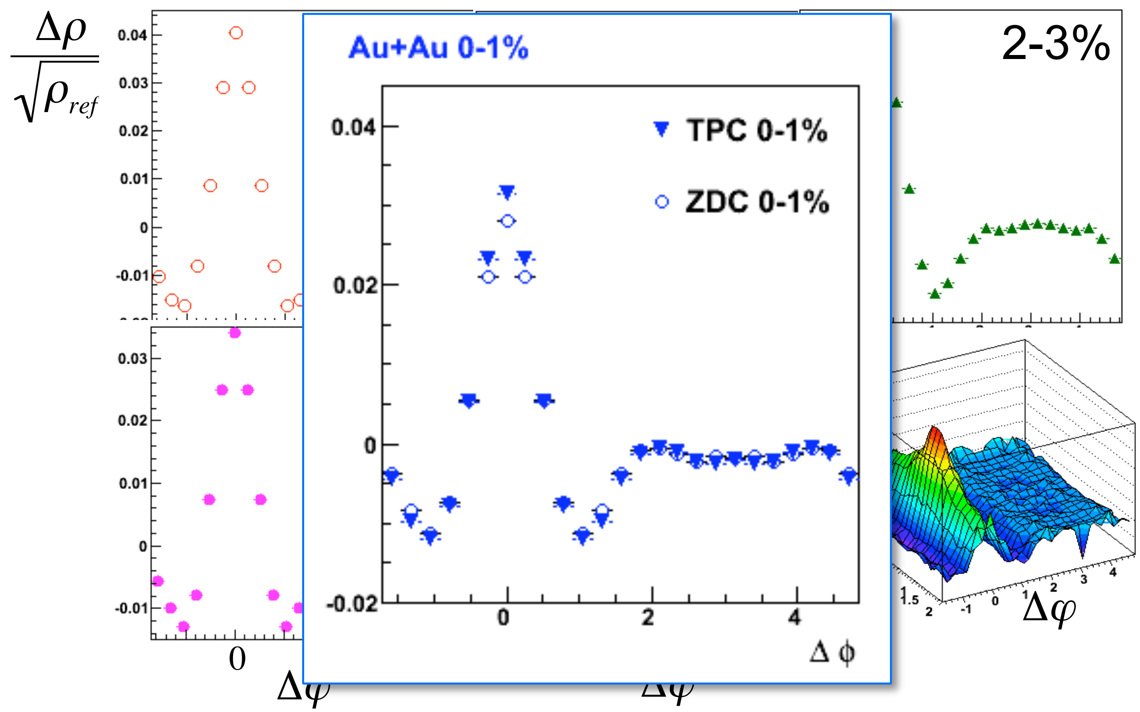
G. L. Ma and X. N. Wang, PRL106, 162301 (2011)

Ridge appears in hydro calculations with fluctuating initial conditions: doesn’t require a jet explanation

For b=0 fm, at low p_T, v_n drops with n, but at intermediate p_T, $v_3 > v_2$

Correlations at Intermediate p_T

v_3 should be most evident at intermediate p_T and for central collisions where the overlap geometry is most symmetric



See Poster: C. de Silva (255, Board 15)

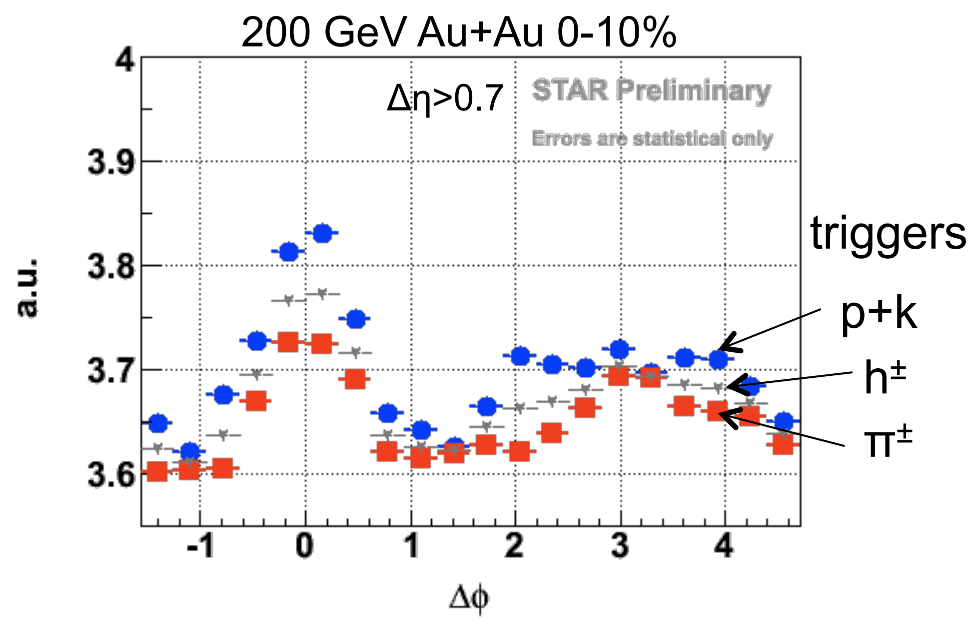
For 0-1% central, n=3 double hump is present on the away-side without v_2 subtraction

We see effects consistent with expectations, we'll investigate further by looking at various measurements related to v_n

Correlations at Intermediate p_T

v_3 should be most evident at intermediate p_T and for central collisions where the overlap geometry is most symmetric

See Talk: K. Kauder



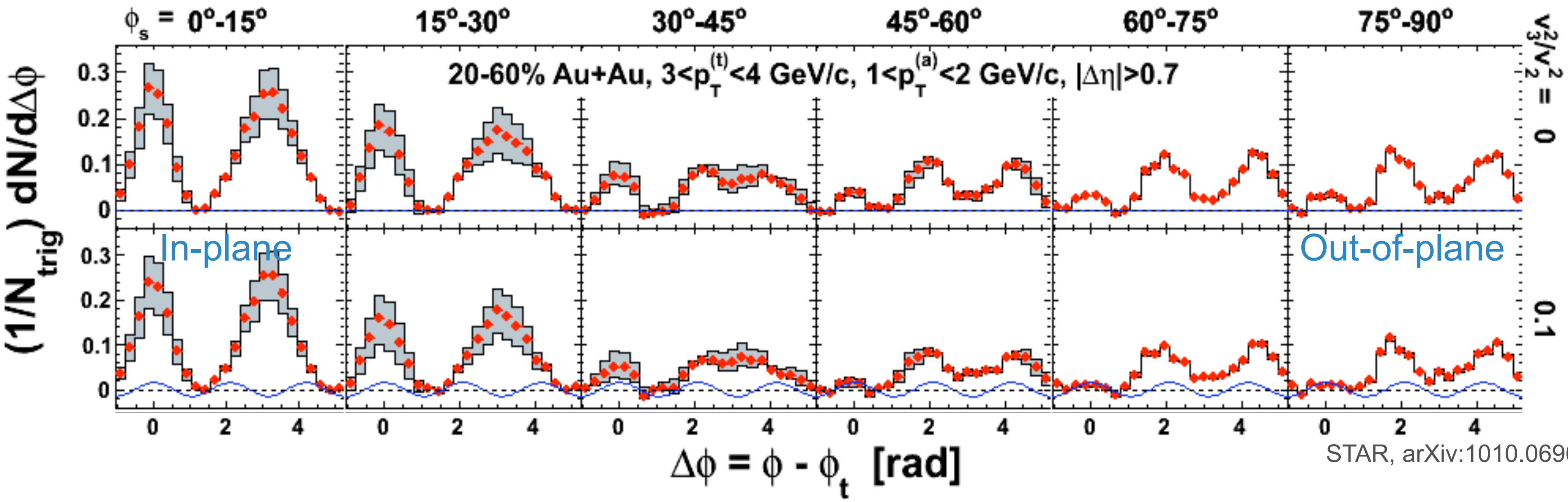
Trigger p_T>4-6 GeV and associate hadron p_T>1.5 GeV (Trigger is highest p_T particle in the event)

Interesting structure is also seen in **raw** correlations for non-pion triggers (mostly protons) at $\Delta\eta$>0.7

We see effects consistent with expectations, we'll investigate further by looking at various measurements related to v_n

Non-flow or Flow

v_2 subtracted di-hadron correlations: v_2 estimated using $\Psi_{EP}(2.8<|\eta|<3.8)$



STAR, arXiv:1010.0690

Subtracting v_2 measured relative to the event-plane at large η leads to residual structure: adding v_3 doesn't account for residual

Unless there's a Δη-dependence to $\langle \Psi_{EP,1} \bullet \Psi_{EP,2} \rangle$, these structures are non-flow

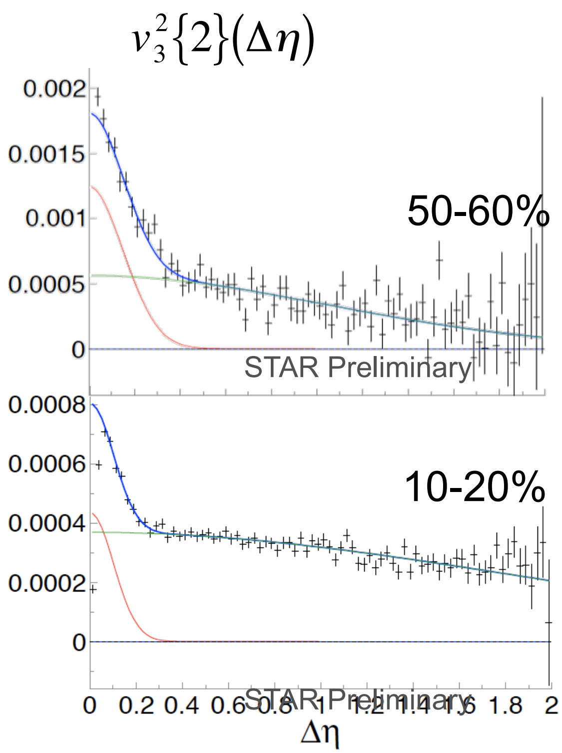
Dusling, Gelis, Lappi & Venugopalan, Nucl. Phys. A 836, 159 (2010); Petersen, Greiner, Bhattacharya & Bass, arXiv:1105.0340
M. Luzum, Phys.Rev.C83:044911,2011

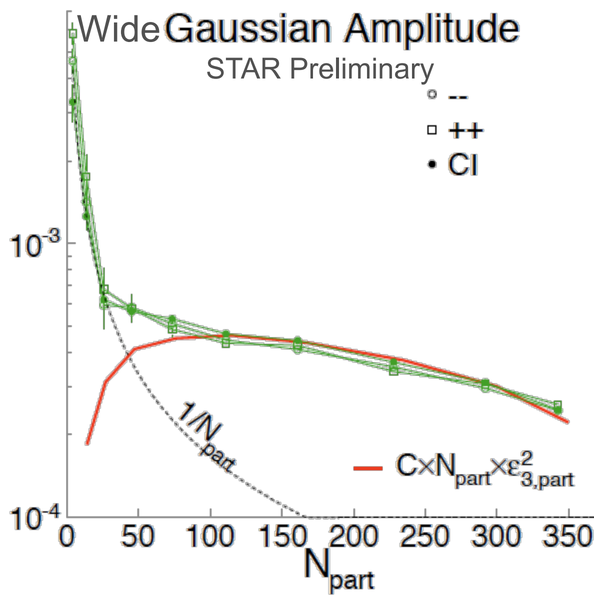
If $\langle \Psi_{EP}(\eta_1) \bullet \Psi_{EP}(\eta_1+\Delta\eta) \rangle$ depends on Δη then v_2 measured with a forward reaction plane underestimates the v_2 for dihadrons at smaller Δη.

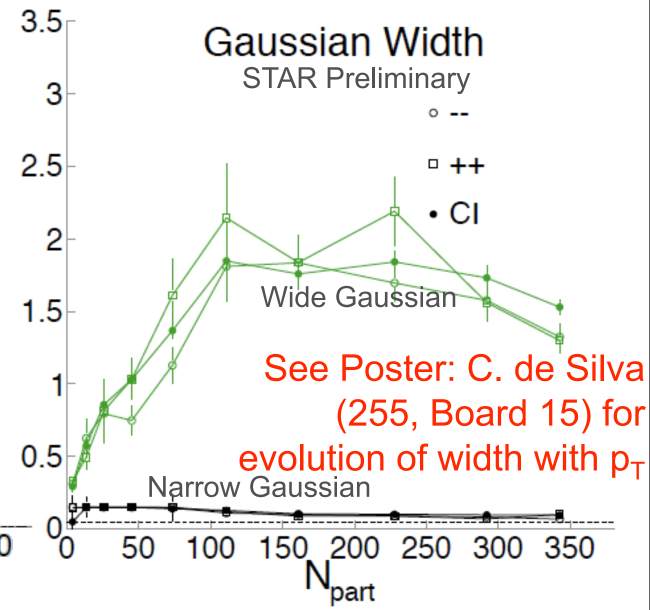
Let's look at the Δη dependence of v_3 from a Fourier Trans. of 2 particle correlations

$v_3^2\{2\}$ vs Δη and Non-flow

$$v_3^2\{2\}(\Delta\eta) = v_3^2\{\text{fit}\}\exp\left(-\frac{\Delta\eta^2}{2\sigma^2_{\Delta\eta,wide}}\right) + A\exp\left(-\frac{\Delta\eta^2}{2\sigma^2_{\Delta\eta,narrow}}\right)$$







σ≈2 is indistinguishable from linear within acceptance

Initial state density correlations may drop with Δy: interesting physics $\sigma_{\Delta y}$~1/α_s?

Dusling, Gelis, Lappi & Venugopalan, Nucl. Phys. A 836, 159 (2010)

Petersen, Greiner, Bhattacharya & Bass, arXiv:1105.0340

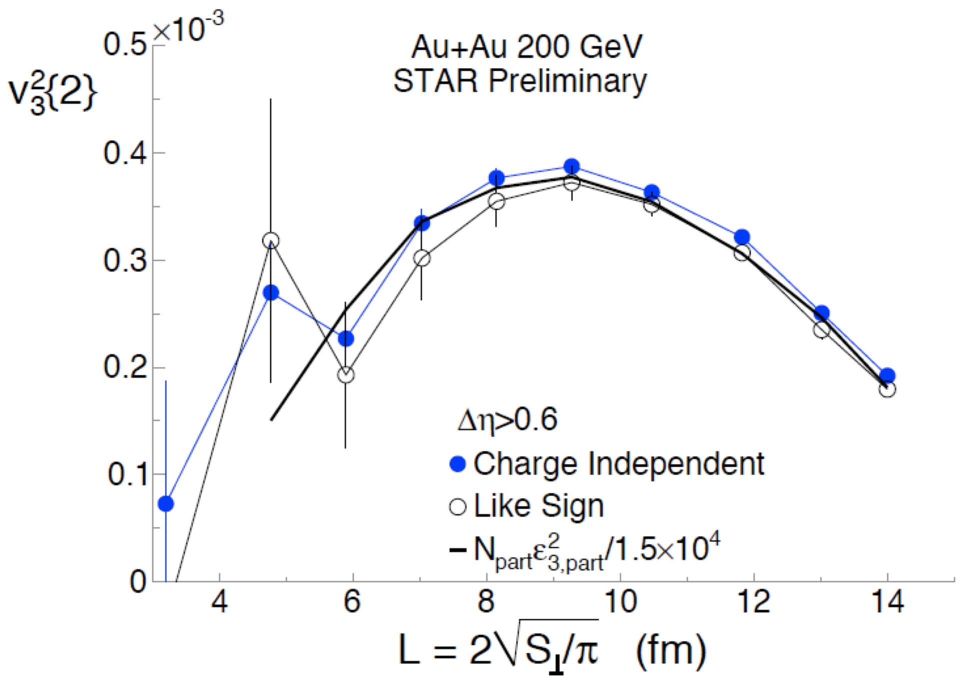
Fit with a wide and a narrow peak. Wide peak amplitude first drops with 1/N but then deviates from trend near N_{part}=50. Above that it follows an $N_{part}\varepsilon^2_{3,part}$ trend

Is the wide Gaussian non-flow as in previous interpretations* and/or Δη dependence of initial density fluctuations?

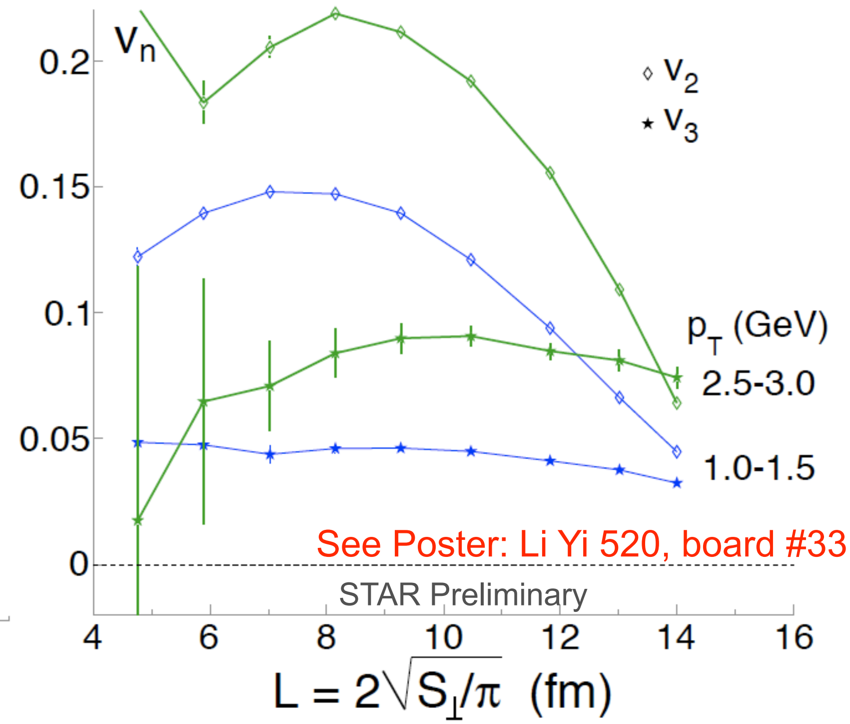
* Trainor, Kettler RefInt.J.Mod.Phys.E17:1219,2008

v_3^2 at Large Δη

⟨cos3(φ₁-φ₂)⟩ for |η₁-η₂|>0.6



η_1>0.5 & η_2<-0.5



Centrality variable L estimates the transverse size of the system

v_3^2 for Δη>0.6 rises then falls with centrality as the overlap shape becomes symmetric. Similar to v_2

Almond shape of the overlap area appears to couple to n=3

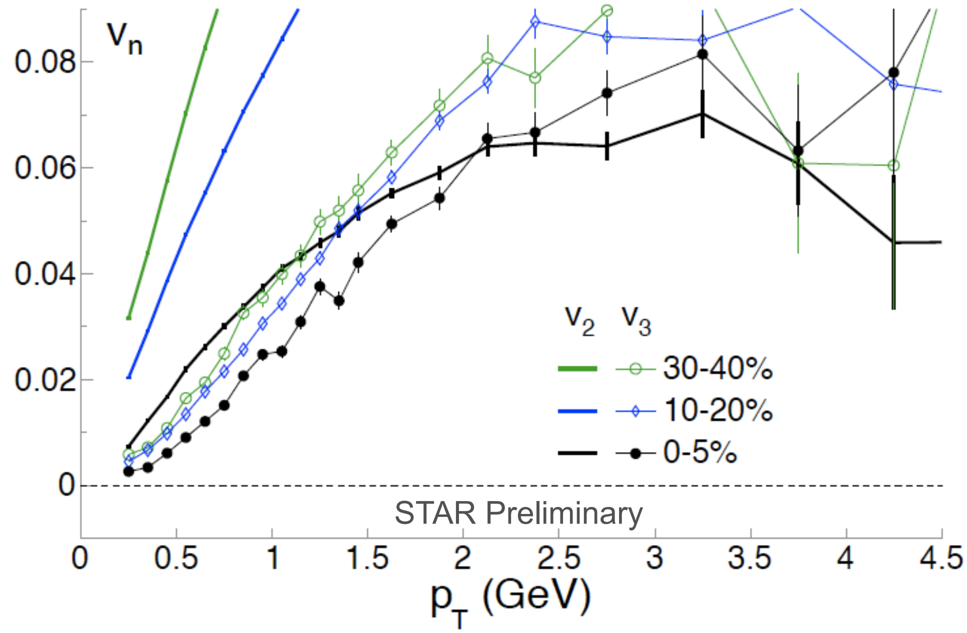
See Poster: J. Thomas (576, Board #43)

D. Teaney, L. Yan, arXiv:1010.1876 [nucl-th]
P. S., A. Mocsy, B. Bolliet, Y. Pandit, arXiv:1102.1403

v_3 and $(v_3/v_2)^2$ vs centrality and p_T

$v_3\{2\}$ using seperate η ranges: $\eta_1<-0.5$ and $\eta_2>0.5$

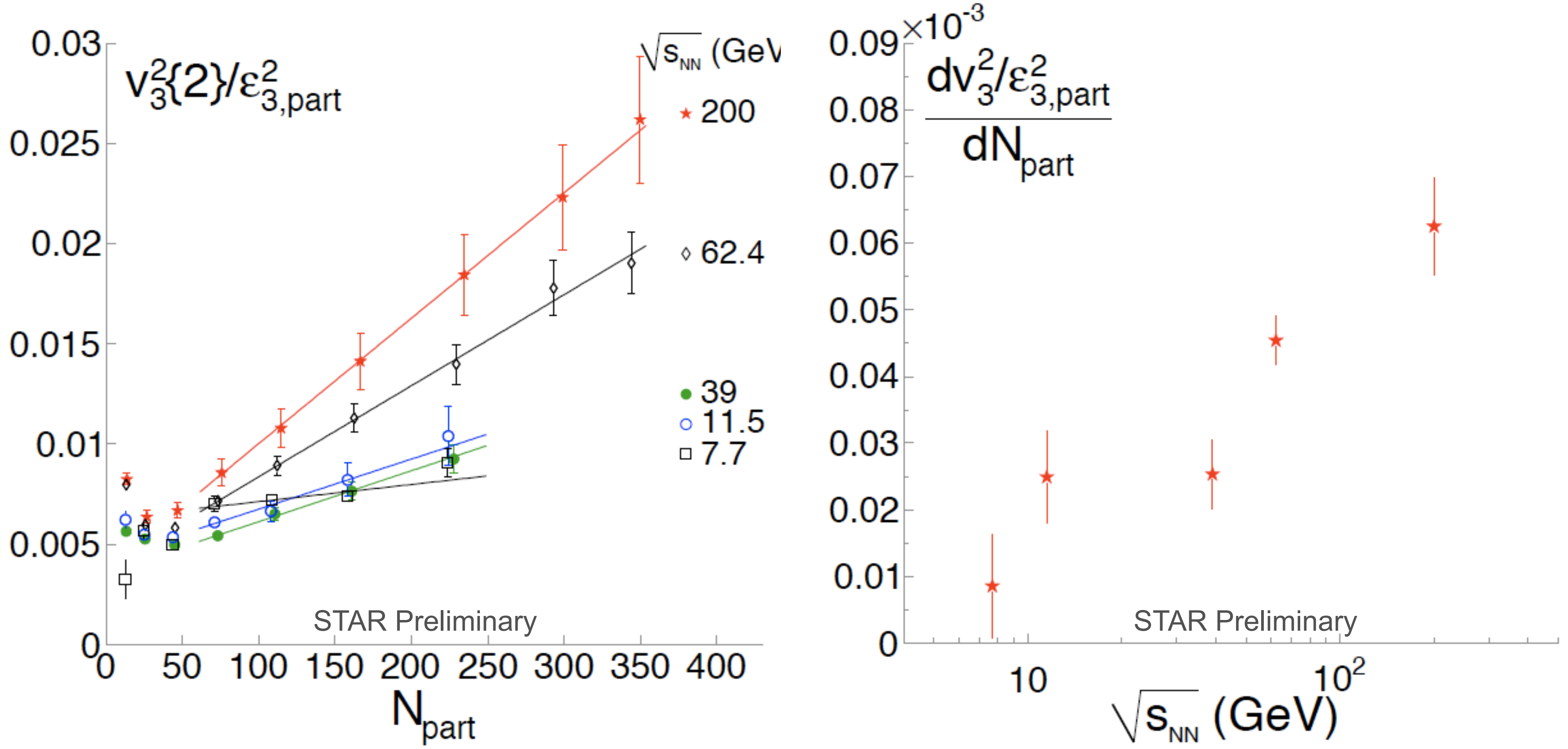
See Poster: Li Yi 520, board #33



For central collisions at intermediate p_T, $v_3\{2\} \geq v_2\{2\}$: what non-flow source would give such a behavior?

Weak $v_3\{2\}$ centrality dependence & $v_3 \geq v_2$ in central were predicted by models based on initial state density inhomogeneity ➪ leading explanation

$v_3^2/\varepsilon^2_{3,part}$ vs Beam Energy



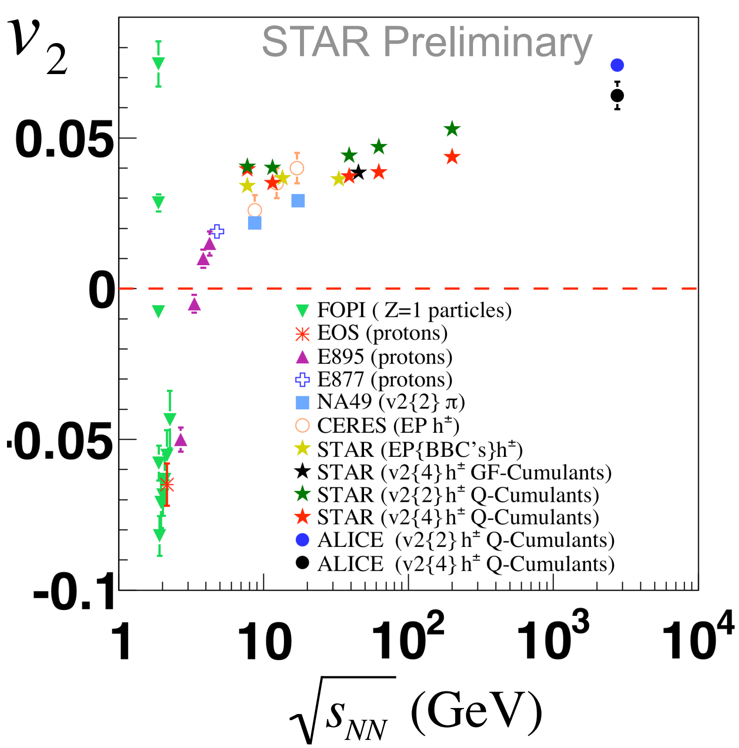
Analysis based on Q-Cumulants for all charges and $-1<\eta<1$

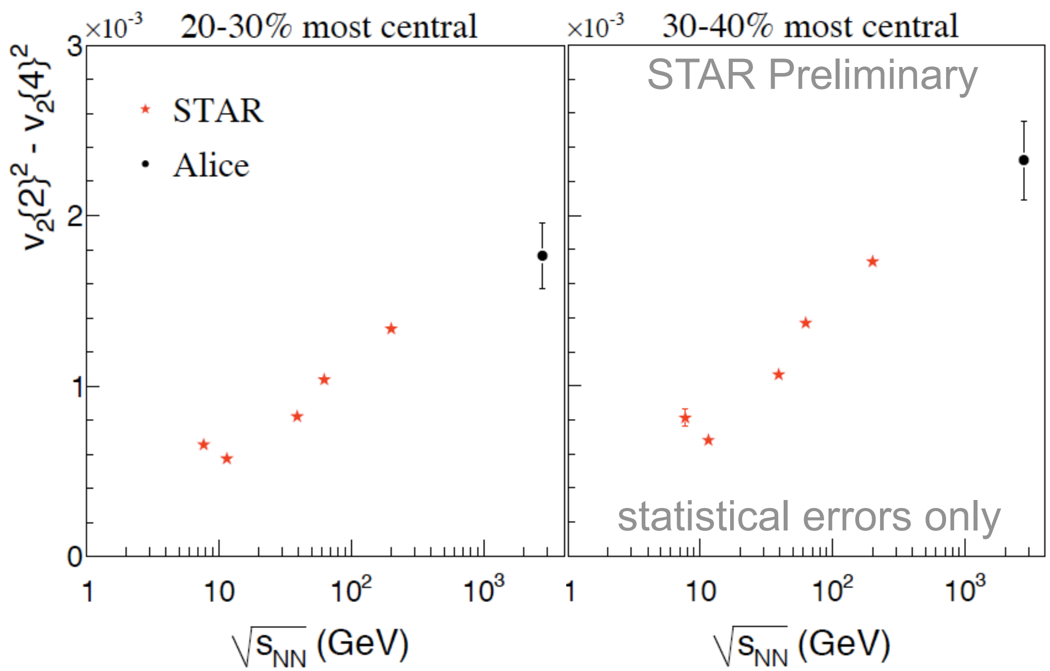
$v_3^2/\varepsilon^2_{3,part}$ follows a simple trend with N_{part}: consistent with fits to $v_3^2\{2\}$ vs $\Delta\eta$

Slope of $v_3^2/\varepsilon^2_{3,part}$ is increasing with beam energy: what about the difference between $v_2^2\{2\}-v_2^2\{4\}$

$v_2\{2\}^2$, $v_2\{4\}^2$ and $v_2\{2\}^2$-$v_2\{4\}^2$ vs Energy

See Posters: Michael Mitrovski (291, Board #19) and Shusu Shi (281, Board #16)





$v_2^2\{2\}$-$v_2^2\{4\} \approx \delta + 2\sigma_v^2$ also shows an intriguing energy dependence: rise of jets or increase in conversion of initial anisotropy into momentum space?

Possible sensitivity to EOS needs to be further investigated

Data at 5, 19.6 (taken) and 27 GeV are needed

Conclusions

We presented the 2 & 4 particle cumulants for v_n up to n=6: results are consistent with $v_n \propto \varepsilon_{part,n}$ and/or non-flow

- Indications of higher harmonic flow seen in RAW dihadron correlations (consistent with initial density fluctuation models)
- We examined the Δη dependence of $v_3^2\{2\}$ and decomposed it into a narrow and wide Gaussian: the centrality evolution of the amplitude of the wide Gaussian follows $N_{part}\varepsilon^2_{part,n}$
- In central collisions, $v_3\{2\}$ at intermediate p_T becomes larger than $v_2\{2\}$ also constistent with models of fluctuating initial conditions

Data appear to favor $v^2_n \propto \varepsilon^2_{part,n}$ and non-neglible higher harmonics; where v^2_n drops with n as a Gaussian. Other non-flow interpretations are also being pursued