Two- and Multi-particle Cumulant Measurements of v_n and Isolation of Flow and Nonflow in $\sqrt{s_{NN}} = 200$ GeV Au+Au Collisions by STAR

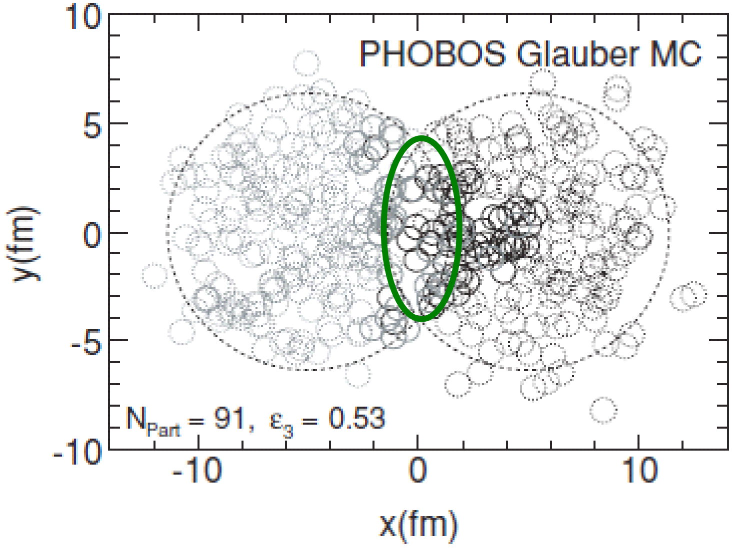
Li Yi (for the STAR collaboration)
Purdue University

Outline

- Physics motivation
- Results
  - 2- and multi-particle anisotropy
  - 2- and 4-particle η-η cumulants
    → Isolation of flow and nonflow
- Summary

Azimuthal Anisotropy
Flow and Nonflow

Alver, Roland, PRC 81, 054905 (2010)



- Hydrodynamic expansion
  → anisotropic flow;
- Flow is sensitive to early stage of heavy ions collisions

$$dN/d\phi \propto 1+\sum_{n=1}^{\infty} 2v_n \cos(n(\phi-\Psi_{nR}))$$

Azimuthal Anisotropy
Flow and Nonflow

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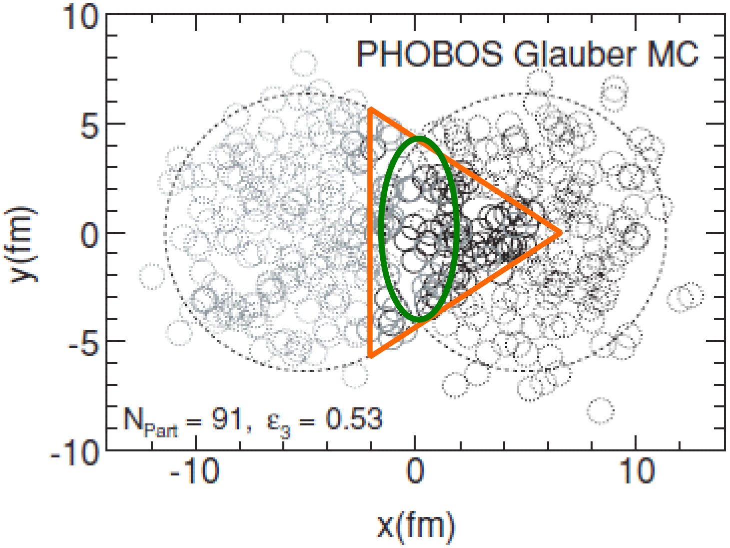

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- Event-by-event initial geometry fluctuation → odd harmonics

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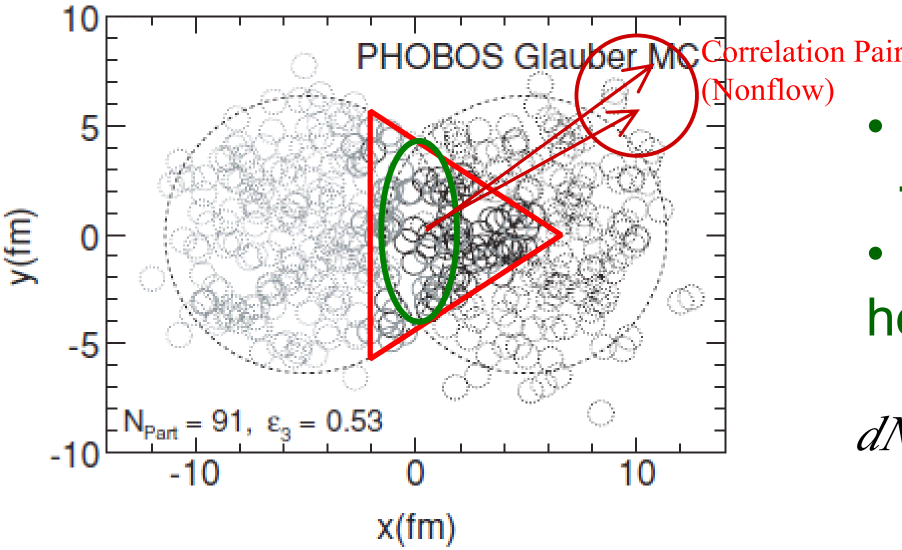

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$$dN/d\varphi \propto 1 + \sum_{n=1}^{\infty} 2v_n \cos(n(\varphi - \Psi_{nR}))$$

- Event-by-event initial geometry fluctuation
  → odd harmonics

- The reaction plane azimuthal angle is unknown
  → the measured anisotropies = flow(v) + flow fluctuation (σ) + nonflow (δ)

particle correlation unrelated to the reaction plane

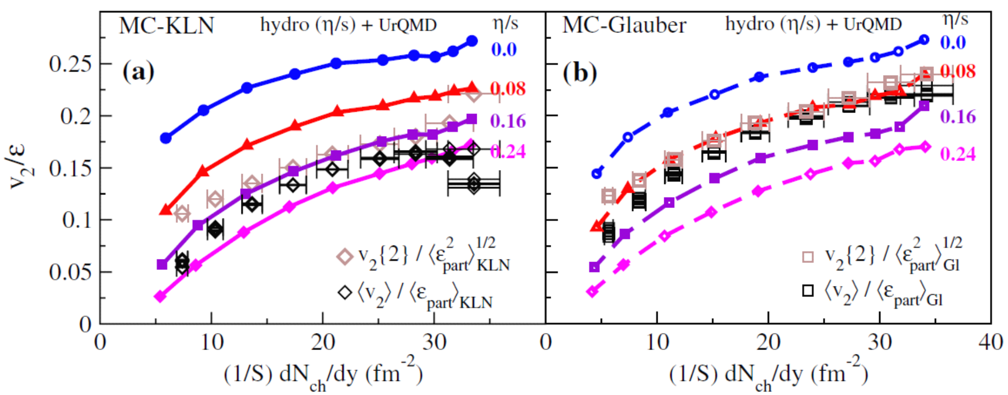
Constraint on η/s

20% uncertainty in v_2/ε → 100% uncertainty in η/s

The question is how to reduce uncertainty in v_2/ε :

1. ε from theoretical part
2. v_2 from experimental part

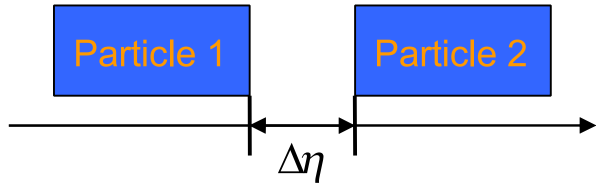
Song, Bass, Heinz, etal. PRL 106, 192301 (2011)



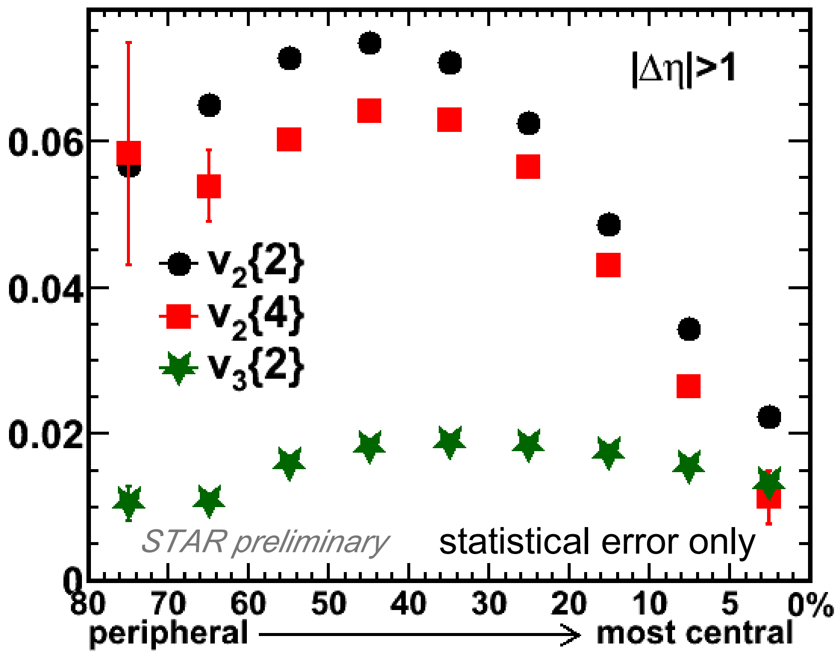
"The extraction of η/s from a comparison with hydrodynamics thus requires careful treatment of both fluctuation and nonflow effects"

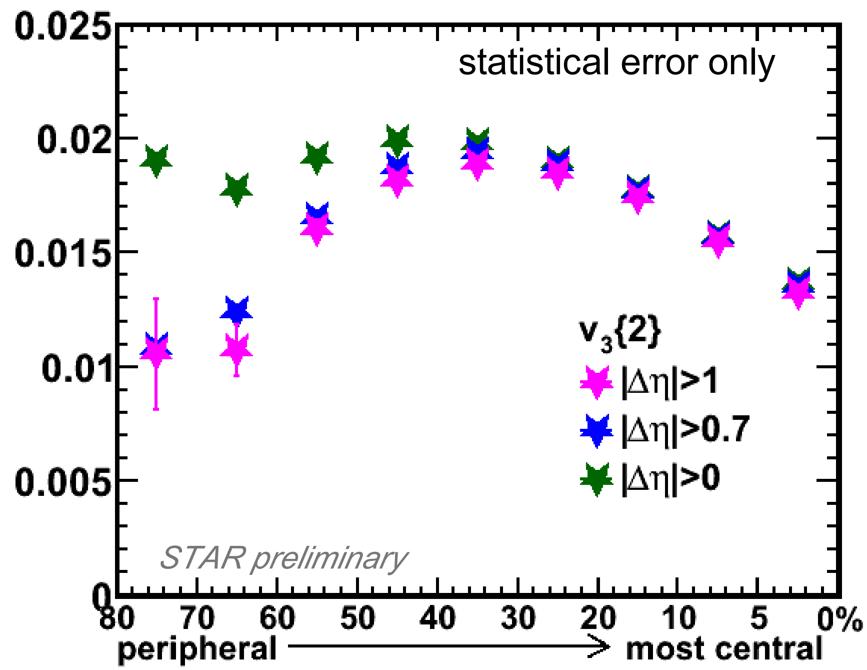
v_3 vs Centrality

AuAu@200GeV
$-1<\eta<1$
$p_T < 2$ GeV/c



Q-Cumulant Method with η-gap

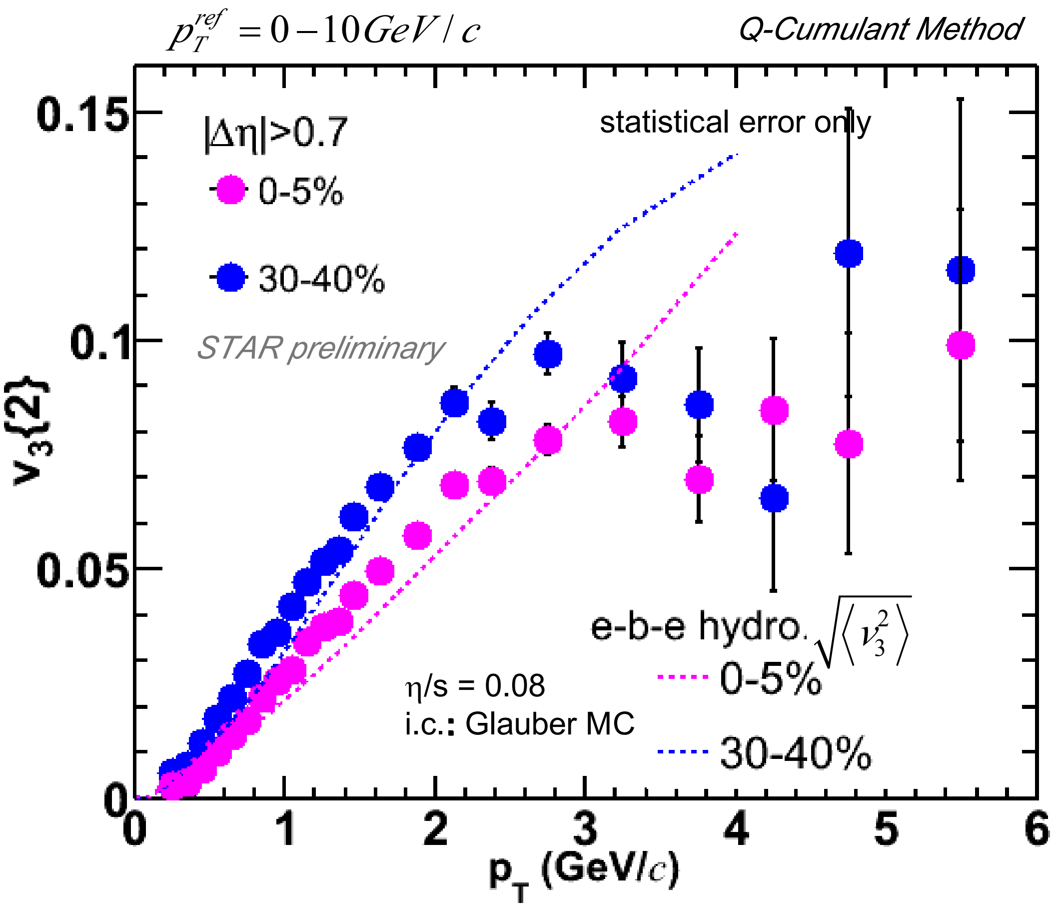




- v_3 shows modest centrality dependence (Also see: Pandit, 1A, Tue.)
- v_3 is 3$\times$ smaller than v_2 in peripheral to mid-central collisions

v_3 vs p_T

- v_3: more sensitive to η/s than v_2



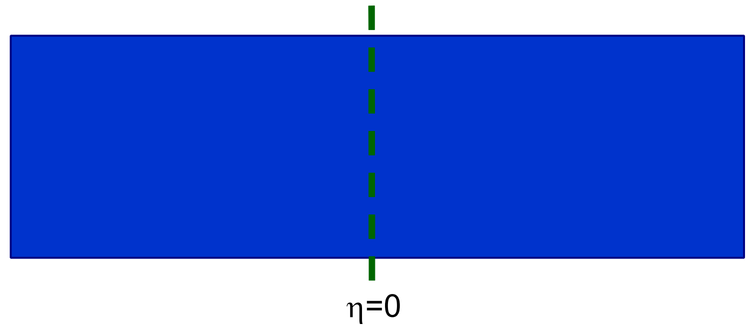
- hydro describes data trend well at p_T<2 GeV/c
- Data may contain nonflow

* Schenke, Jeon, Gale, PRL 106, private commu.

Isolation of Flow and Nonflow

using 2-, and 4-Particle η-η Cumulants

Xu, LY, arXiv:1204.2815



- 2-particle cumulant:

$$\mathcal{V}\{\eta_\alpha,\eta_\beta\} = \nu(\eta_\alpha)\nu(\eta_\beta) + \sigma(\eta_\alpha)\sigma(\eta_\beta) + \sigma'(\Delta\eta) + \delta(\Delta\eta)$$

'flow' — flow fluct. — Δη-dep fluct. — Δη-dep nonflow

$$\Delta\mathcal{V}\{2\} = \mathcal{V}\{-\eta_\alpha,-\eta_\beta\} - \mathcal{V}\{-\eta_\alpha,\eta_\beta\} = \Delta\sigma' + \Delta\delta$$

$$\nu(-\eta_\beta) = \nu(\eta_\beta) \qquad \sigma(-\eta_\beta) = \sigma(\eta_\beta)$$

- 4-particle cumulant:

$$\mathcal{V}^{1/2}\{\eta_\alpha,\eta_\alpha,\eta_\beta,\eta_\beta\} = \nu(\eta_\alpha)\nu(\eta_\beta) - \sigma(\eta_\alpha)\sigma(\eta_\beta) - \underline{\underline{\sigma'(\Delta\eta)}}$$

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$$\Delta\mathcal{V}\{4\}^{1/2} = -\Delta\sigma'$$

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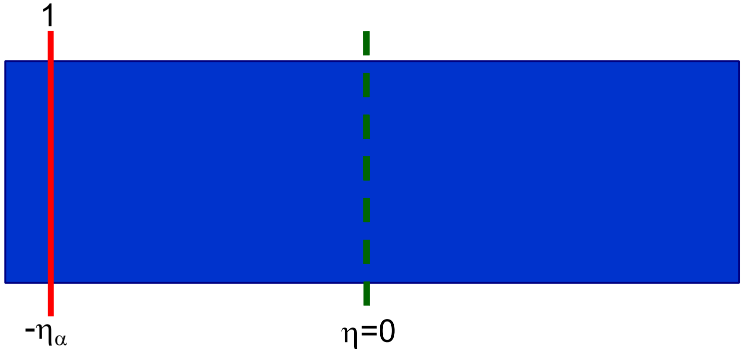

$$\mathcal{V}\{\eta_\alpha,\eta_\beta\} = v(\eta_\alpha)v(\eta_\beta)+\sigma(\eta_\alpha)\sigma(\eta_\beta)+\sigma'(\Delta\eta)+\delta(\Delta\eta)$$

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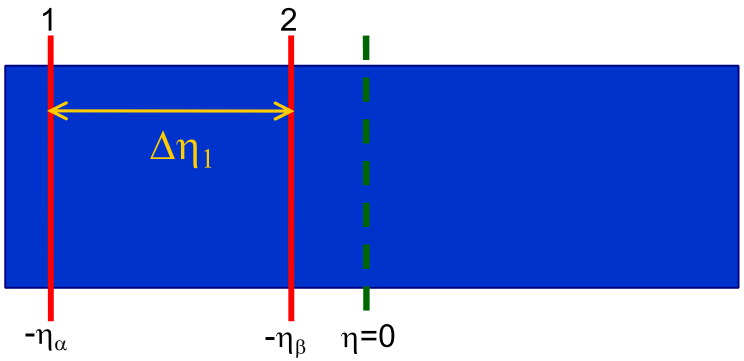

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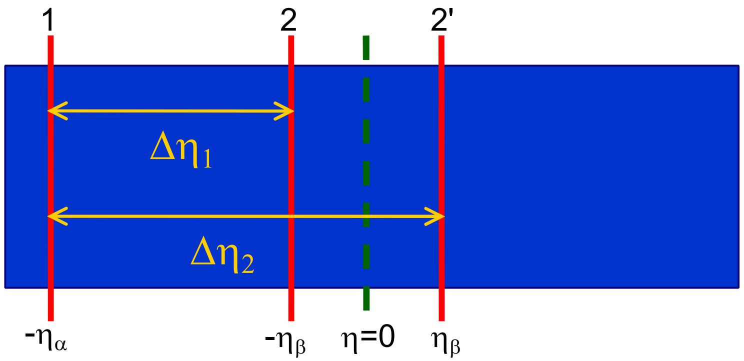

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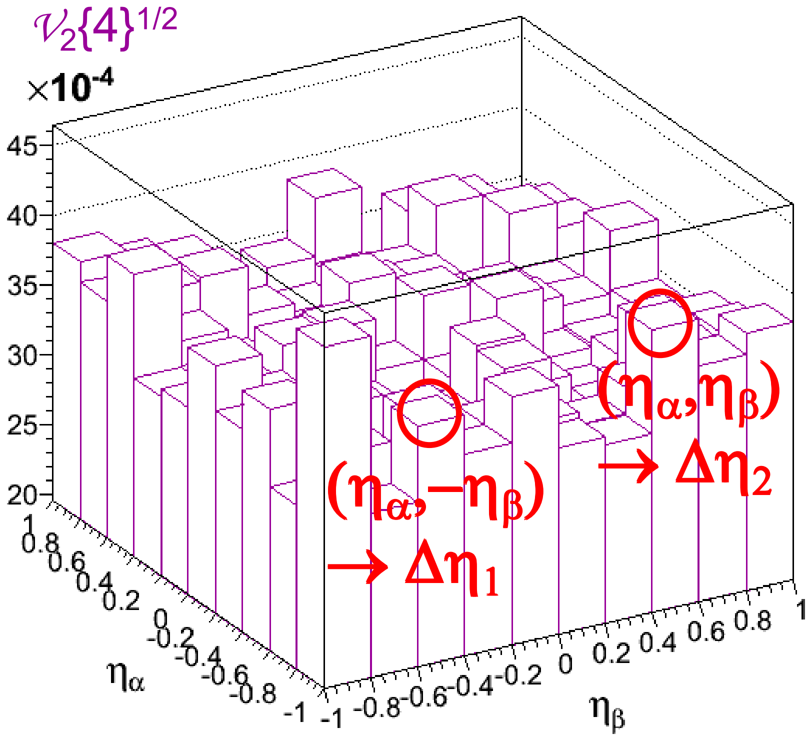
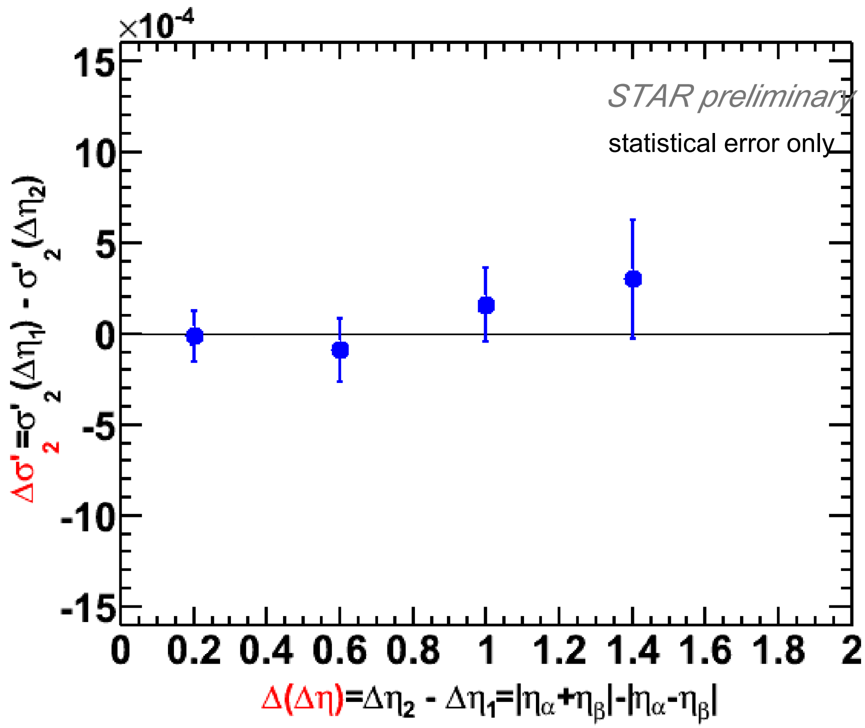
$\Delta\eta$-dependence $\sigma'(\Delta\eta)$

AuAu@200GeV 20-30%

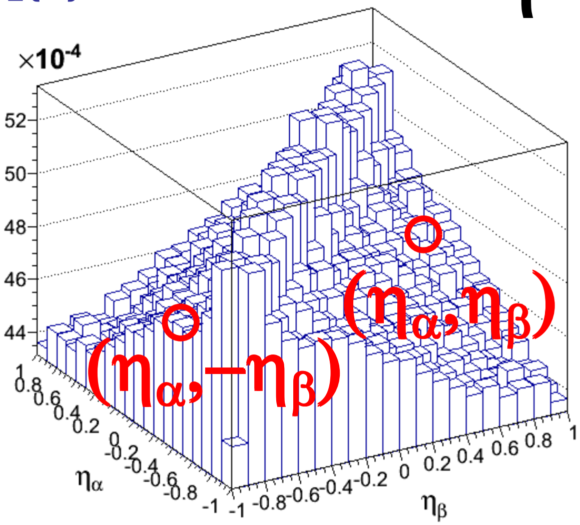




Flow fluctuation appears independent of $\Delta\eta$.

$\Delta\eta$-dependent $\delta(\Delta\eta)$

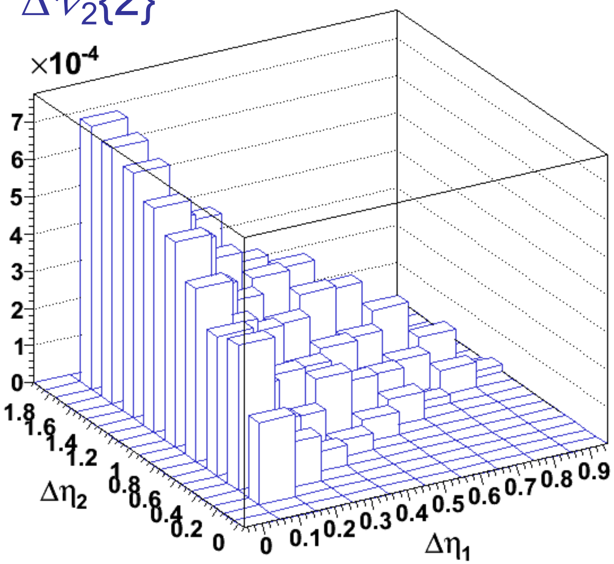
$\mathcal{V}_2\{2\}$

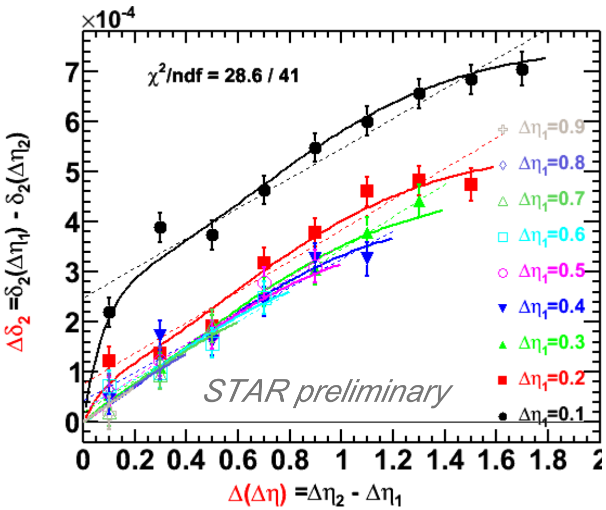


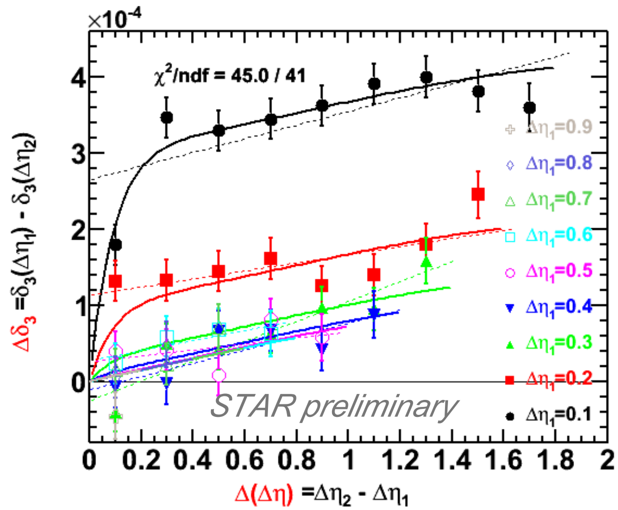
AuAu@200GeV 20-30%

- $\delta(\Delta\eta_2)$-$\delta(\Delta\eta_1)$ linear in $\Delta\eta_2$-$\Delta\eta_1$ at a given $\Delta\eta_1$ with similar slopes
- Intercept changes with $\Delta\eta_1$ exponentially

$\Delta\mathcal{V}_2\{2\}$







statistics error only

$$\Delta\delta(\Delta\eta_1,\Delta\eta_2) = a(e^{-\Delta\eta_1/b} - e^{-\Delta\eta_2/b}) + A(e^{-\Delta\eta_1^2/2\sigma^2} - e^{-\Delta\eta_2^2/2\sigma^2})$$

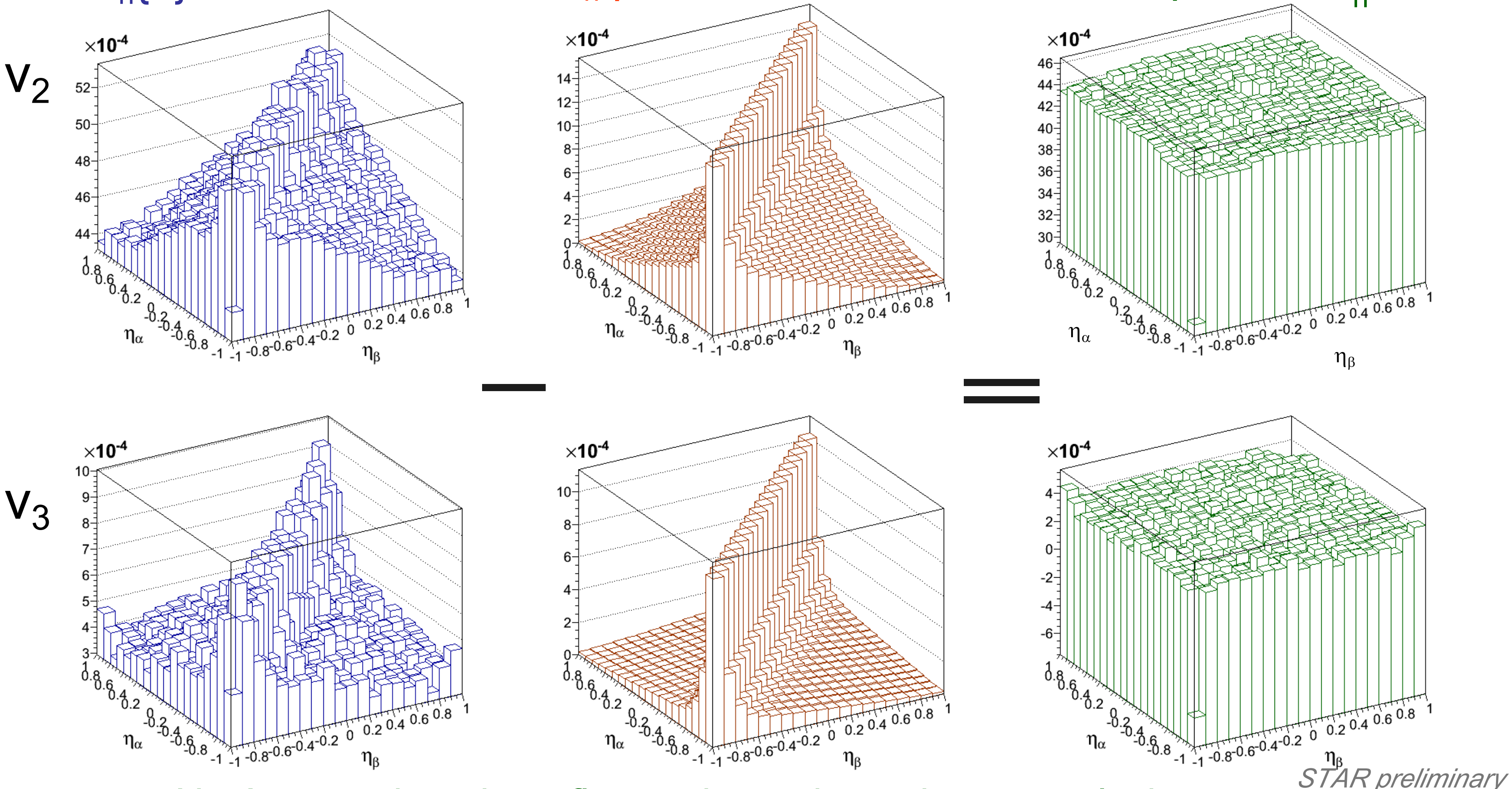
$$\delta(\Delta\eta) = ae^{-\Delta\eta/b} + Ae^{-\Delta\eta^2/2\sigma^2}$$

STAR preliminary

Cumulant $\mathcal{V}\{2\}$, Nonflow δ, 'Flow' v_n^2

AuAu@200GeV 20-30%

$\mathcal{V}_n\{2\}$ — δ_n parameterized = decomposed $\langle v_n^2 \rangle$



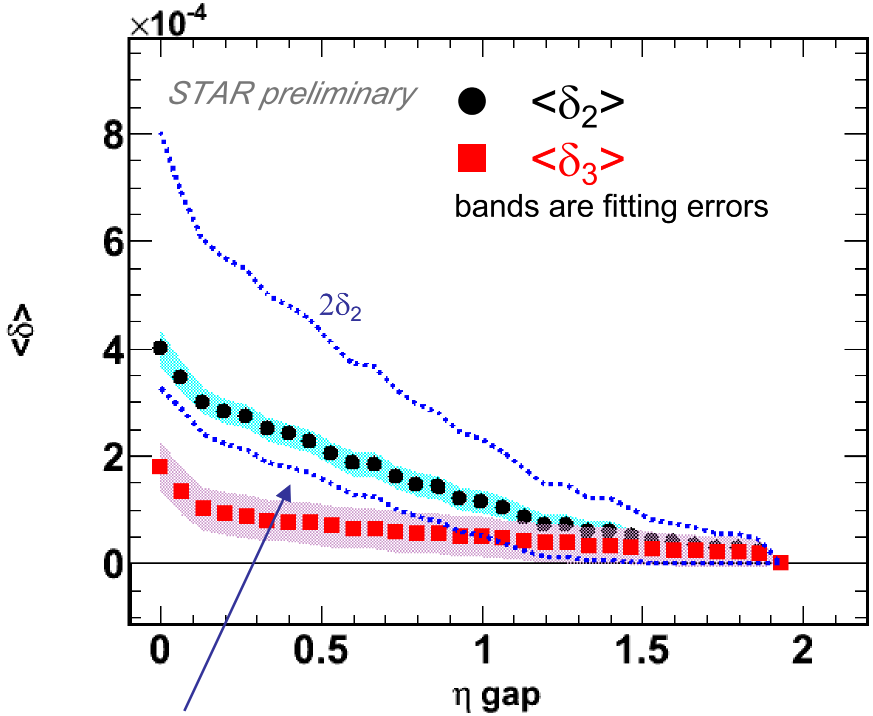
No Assumption about flow η dependence in our analysis

The decomposed 'flow' appears to be independent of η .

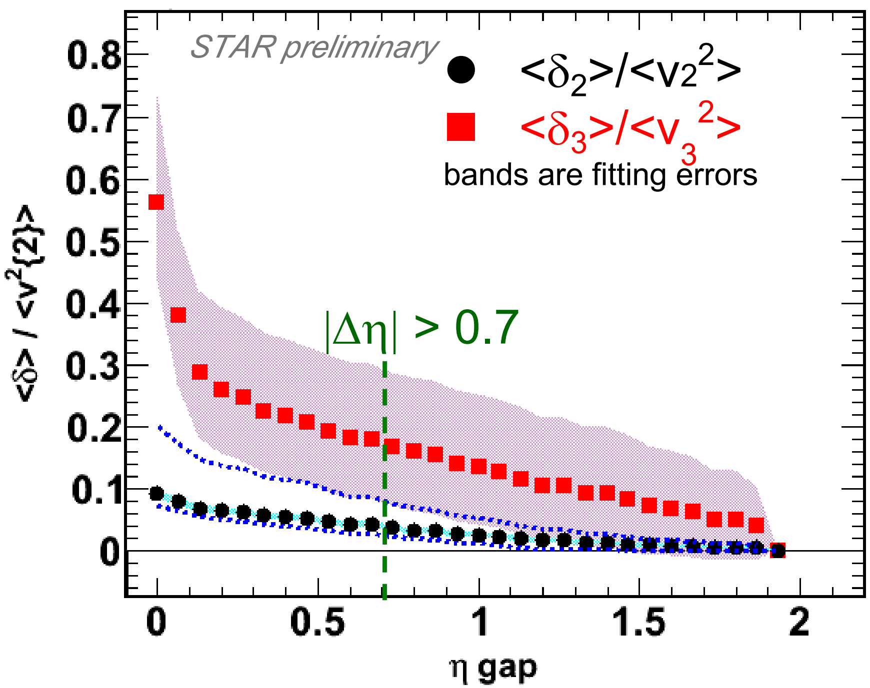
$\Delta\eta$-dep Near-side Nonflow

AuAu@200GeV 20-30%

- Calculate <nonflow> of all $(\eta_\alpha, \eta_\beta)$ bins with x < η-gap < 2. (x = horizontal axis).



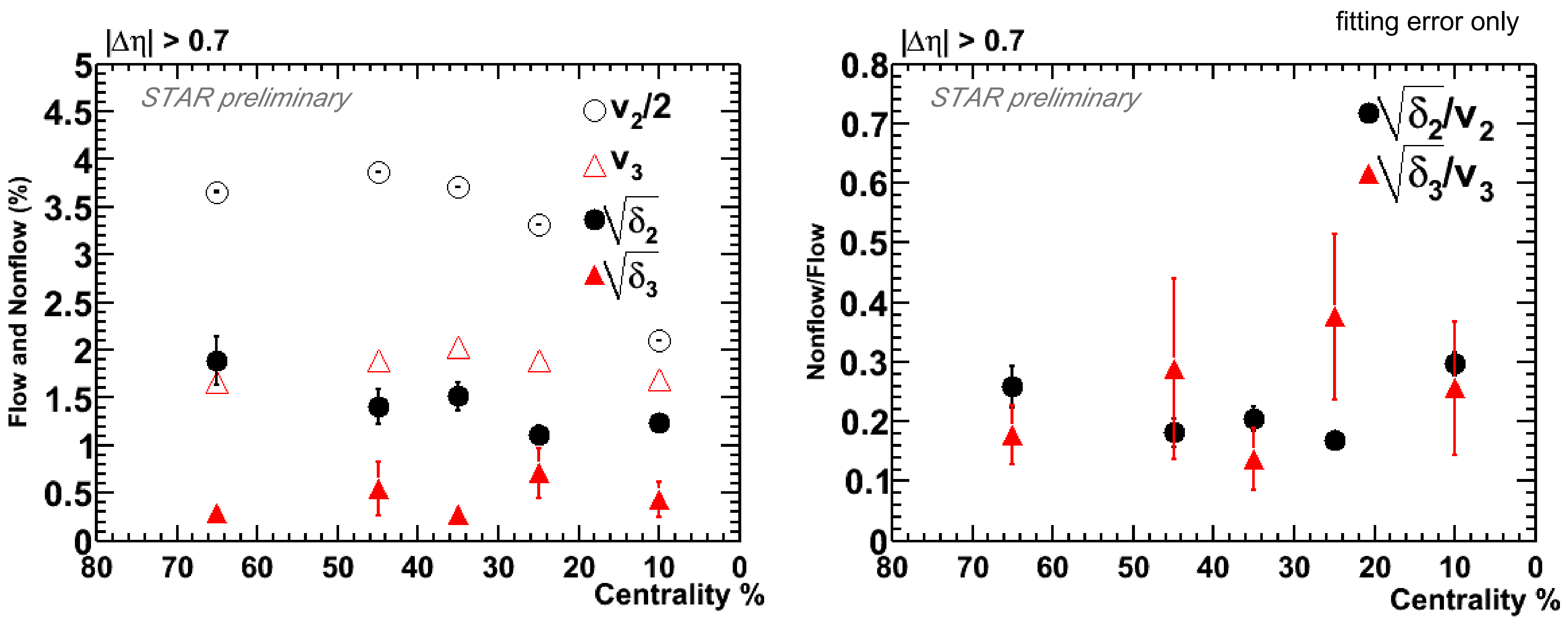
δ_2: replace Gaus by $e^{(-(x/\sigma)4)}$



- With $|\Delta\eta| > 0.7$, significant nonflow still exits.

'Flow' and Nonflow vs Centrality

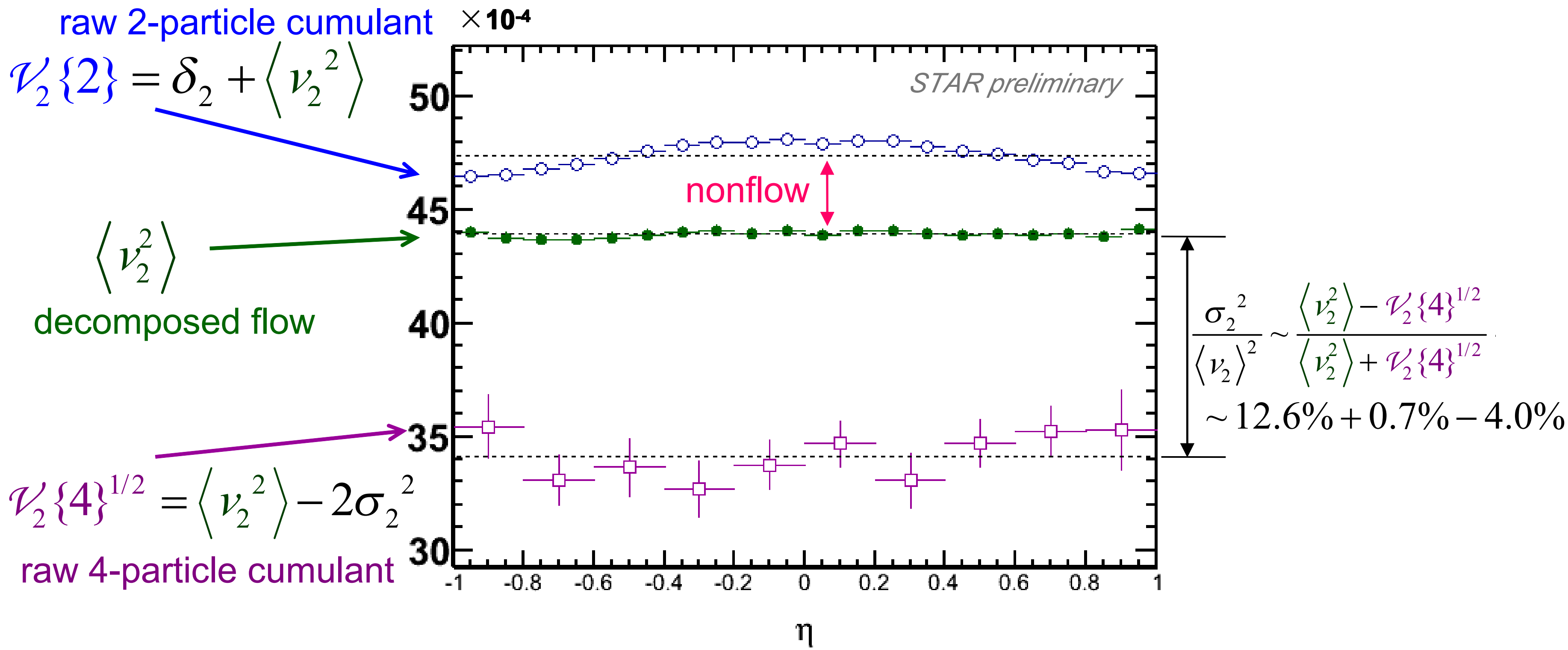
Au+Au@200GeV



- $\sqrt{\delta_2} / v_2$ ~ 20% for |Δη|>0.7
  δ_2 / v_2^2~ 4%

'Flow' vs η

AuAu@200GeV 20-30%



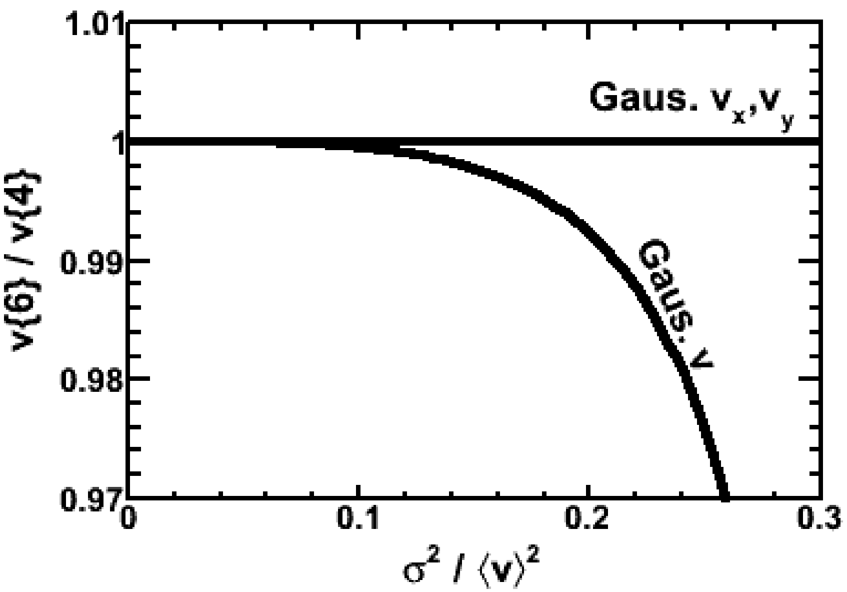
- Flow seems independent of η. Note no assumption of η dependence in our approach.
- (Fluctuation / flow)^2 ~ 13%

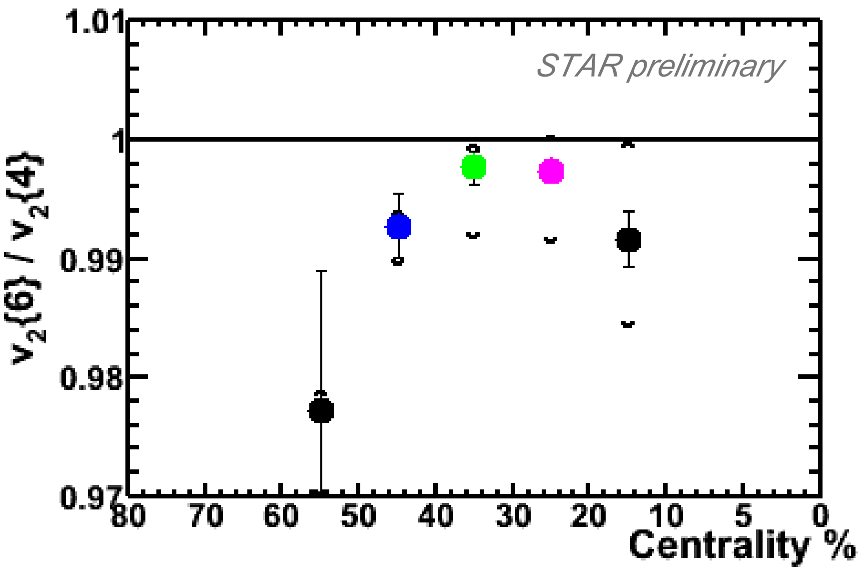
4- and 6-Particle Cumulant

Assuming the flow fluctuations are Gaussian, we have two options:

1. v_x, v_y are Gaussian: v{6} = v{4}   Voloshin, Poskanzer, Tang, Wang, PLB
2. v is Gaussian: LY, Wang, Tang, arXiv: 1101.4646

$$v_n\{6\}/v_n\{4\} \approx 1 - \sigma^6 / 3\langle v_n \rangle^6 \;,\; \text{if } \sigma^2/\langle v_n \rangle^2 << 1$$





* No-weight applied, non-uniform acceptance corrected. Systematic errors estimated by applying weight and no acceptance correction

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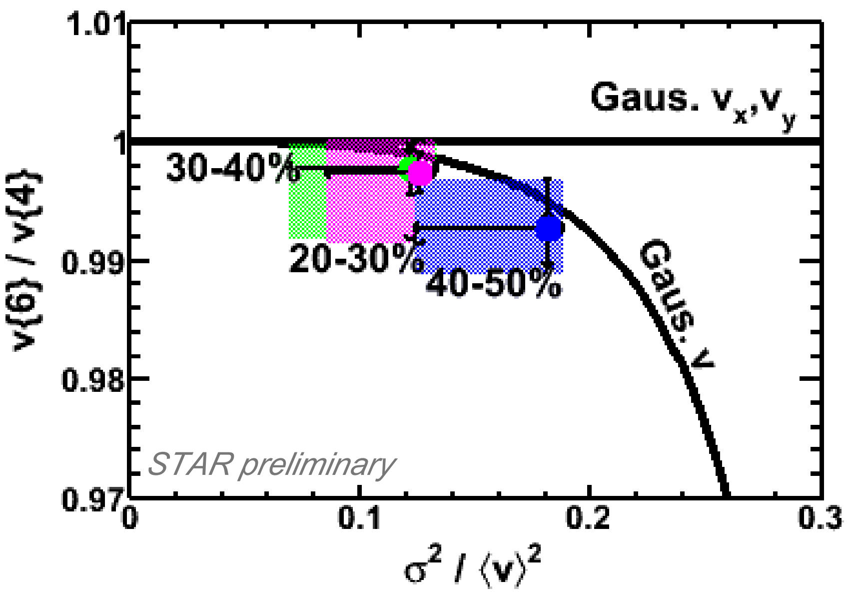

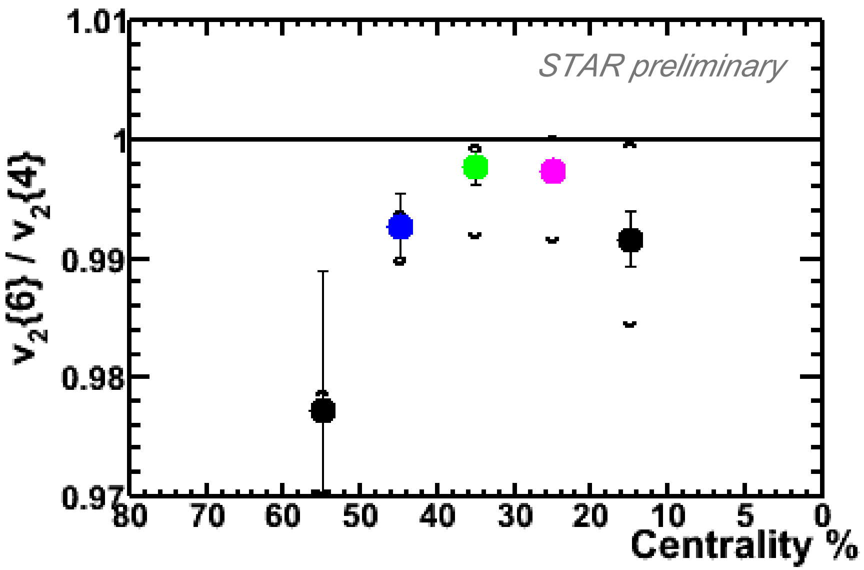

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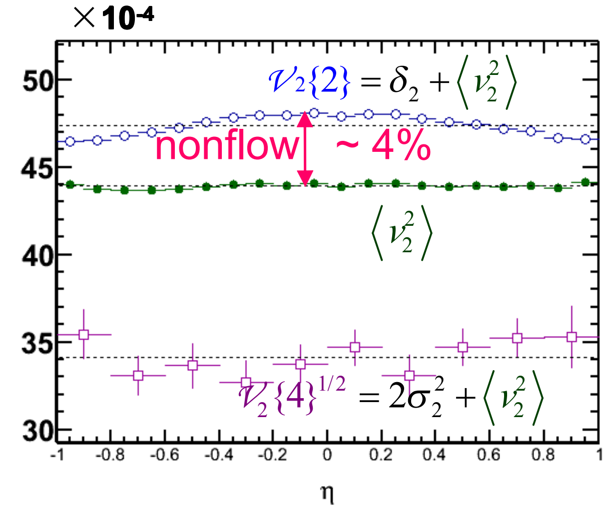
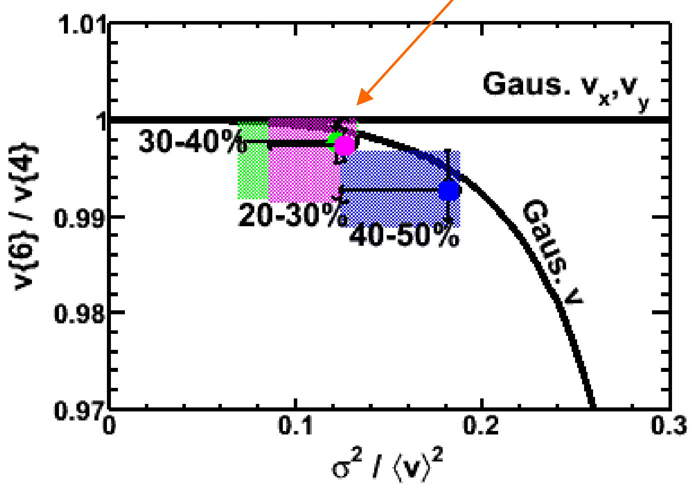
Summary

- 2-, 4- and 6-particle cumulants vs p_T, centrality are presented.
- Isolation of $\Delta\eta$-dependent (near-side nonflow) and $\Delta\eta$-independent (flow-dominant + small away-side nonflow) correlations, using 2- and 4-particle cumulants between η bins
  - the decomposed 'flow' appears to be independent of η within ±1 unit
  - nonflow estimation ~ 4% in v_2^2
  - flow fluctuation estimation ~13% in $v_2^{\,2}$

AuAu@200GeV 20-30%
$-1<\eta<1$ $p_T<2$GeV/c



$$\frac{\sigma_2{}^2}{\langle v_2 \rangle^2} \sim \frac{\langle v_2^2 \rangle - \mathcal{V}_2\{4\}^{1/2}}{\langle v_2^2 \rangle + \mathcal{V}_2\{4\}^{1/2}} \sim 12.6\% + 0.7\% - 4.0\%$$



Abstract

Azimuthal anisotropic flows vn, arising from the anisotropic collision geometry, reflect the hydrodynamic properties of the quark gluon plasma created in relativistic heavy-ion collisions. A long standing issue in vn measurements is the contamination of nonflow, caused by intrinsic particle correlations unrelated to the collision geometry. Nonflow limits, in part, the precise extraction of the viscosity to entropy density ratio eta/s from data-model comparisons. Isolation of flow and nonflow is critical to the interpretation of the Fourier decomposition of dihadron correlations.

In this talk we report measurements of vn azimuthal anisotropies using the two- and mult-particle Q-cumulants method from STAR in Au+Au collisions at 200 GeV. The centrality and pT dependence of vn will be presented. We compare the four- and six-particle cumulant measurements to gain insights on the nature of flow fluctuations [1,2]. We further analyze two- and four-particle cumulants between pseudo-rapidity (eta) bins. Exploiting the collision symmetry about mid-rapidity, we isolate the \Delta\eta-dependent and \Delta\eta-independent correlations in the data with a data-driven method [3]. The \Delta\eta-dependent part arises from near-side nonflow correlations, such as HBT interferometry, resonance decays, and jet-correlations. The \Delta\eta-independent part is dominated by flow and flow fluctuations with relatively small contribution from away-side jet-correlations. The method does not make assumptions about the eta dependence of flow. Our isolated \Delta\eta-independent part from data, dominated by flow, however, is found to be also eta-independent within the STAR TPC of +-1 unit of pseudo-rapidity. The \Delta\eta drop in the measured two-particle cumulant appears to entirely come from nonflow. We assess the effect of the nonflow on eta/s extraction. We reexamine the high-pT triggered dihadron correlations with background subtraction of our decomposed flows.

[1] S.A. Voloshin, A.M. Poskanzer, A. Tang, and G. Wang, Phys. Lett. B659, 537 (2008).
[2] L. Yi, F. Wang, and A. Tang, arXiv:1101.4646 [nucl-ex].
[3] L. Xu, L. Yi, D. Kikola, J. Konzer, F. Wang, and W. Xie, arXiv:1204.2815 [nucl-ex].

Analysis Cuts

AuAu@200GeV

Year2004 data

19 million min-bias events

|Vertex z| < 30 cm

$|\eta| < 1$

Dca < 2 cm

nfit >= 20

nhits / nfit-pos > 0.51

Year2010 data

80 million min-bias events

|Vertex z| < 30 cm

|vpdvz-Vz|<3

|Vr|<2

TiggerId: 260001, 260011, 260021, 260031

$|\eta| < 1$

Dca < 2 cm

nfit >= 15

1.02 > nhits / nfit-pos > 0.52

flag()<1000

2-, 4-, 6-Particle Q-Cumulant Method

- Particle azimuthal moments:

In a single event δ is nonflow

$$\langle 2\rangle_n = \left\langle e^{in(\phi_i-\phi_j)}\right\rangle = v_n^{\ 2} + \delta_n$$

$$\langle 2\rangle_n = \frac{|Q_n|^2 - M}{M(M-1)} \qquad Q_n \equiv \sum_{i=1}^{M} e^{in\phi_i}$$

$$\langle 4\rangle_n = \left\langle e^{in(\phi_i+\phi_j-\phi_k-\phi_l)}\right\rangle \approx v_n^{\ 4} + 4v_n^{\ 2}\delta_n + 2\delta_n^{\ 2}$$

$$\langle 6\rangle_n = \left\langle e^{in(\phi_i+\phi_j+\phi_k-\phi_l-\phi_m-\phi_n)}\right\rangle \approx v_n^{\ 6} + 9v_n^{\ 4}\delta_n + 18v_n^{\ 2}\delta_n^{\ 2} + 6\delta_n^{\ 3}$$

- 2-, 4-, 6-particle azimuthal anisotropy

Average over all events

$$v_n\{2\}^2 \equiv \langle\langle 2\rangle\rangle_n$$

$$v_n\{4\}^4 \equiv 2\langle\langle 2\rangle\rangle_n^{\ 2} - \langle\langle 4\rangle\rangle_n$$

$$v_n\{6\}^6 \equiv (\langle\langle 6\rangle\rangle_n - 9\langle\langle 2\rangle\rangle_n\langle\langle 4\rangle\rangle_n + 12\langle\langle 2\rangle\rangle_n^{\ 3})/4$$

For exclusive region :

$$\langle 2'\rangle_n = \left\langle e^{in(\phi'_i-\phi_j)}\right\rangle = v'_n v_n + \delta'_n$$

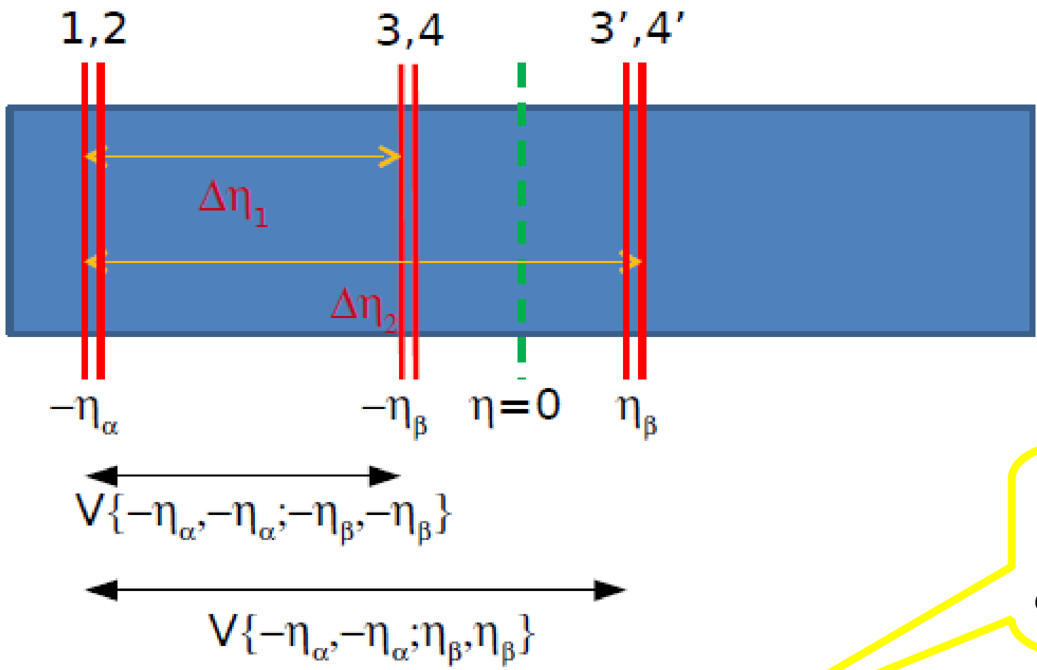
$$v_n\{2'\} \equiv \langle\langle 2'\rangle\rangle_n \Big/ \sqrt{\langle\langle 2\rangle\rangle_n}$$

*Flow analysis with cumulants: direct calculations, Ante Bilandzic, Raimond Snellings and Sergei Voloshin, arXiv:1010.0233 [nucl-ex].
*Li Yi, Fuqiang Wang, and Aihong Tang, arXiv: 1101.4646.

4-Particle Cumulant between η Bins

$$V^{1/2}(\eta_\alpha,\eta_\alpha;\eta_\beta,\eta_\beta) = v(\eta_\alpha)v(\eta_\beta) - \sigma(\eta_\alpha)\sigma(\eta_\beta) - \sigma'(\Delta\eta)$$

fluctuations



$$\nu(-\eta_\beta) = \nu(\eta_\beta)$$
$$\sigma(-\eta_\beta) = \sigma(\eta_\beta)$$

$$V^{1/2}\{-\eta_\alpha,-\eta_\alpha;-\eta_\beta,-\eta_\beta\} - V^{1/2}\{-\eta_\alpha,-\eta_\alpha;\eta_\beta,\eta_\beta\} = -\sigma'(\Delta\eta_1) + \sigma'(\Delta\eta_2)$$

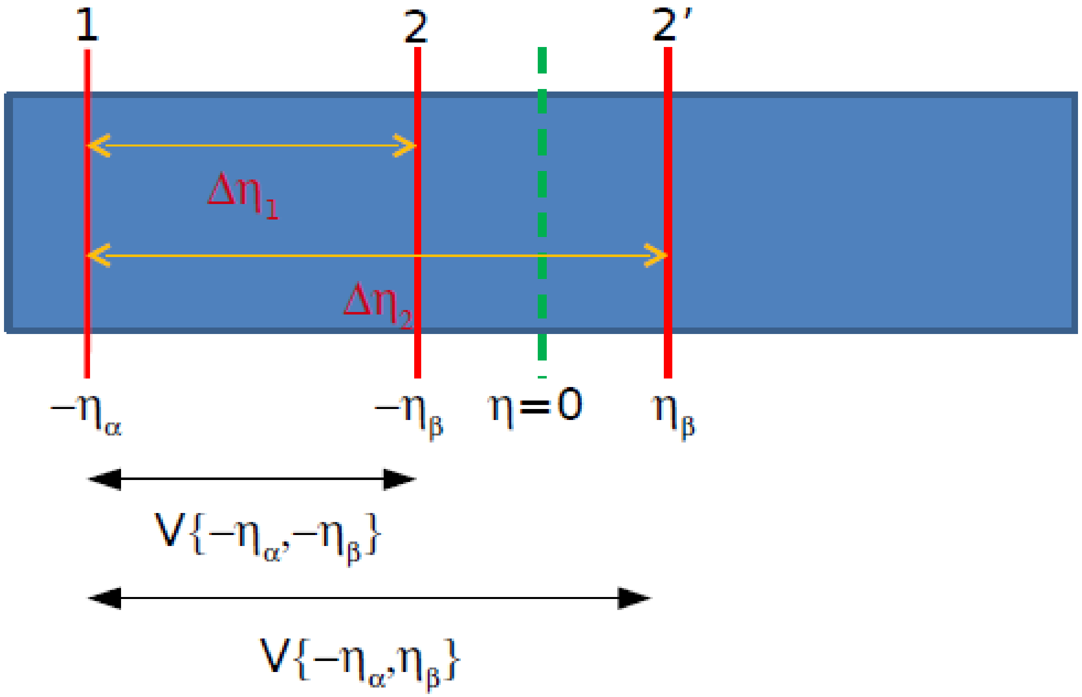
Aug. 15th, 2012

2-Particle Cumulant between η Bins

$$V\{\eta_\alpha,\eta_\beta\} = v(\eta_\alpha)v(\eta_\beta) + \sigma(\eta_\alpha)\sigma(\eta_\beta) + \sigma'(\Delta\eta) + \delta(\Delta\eta)$$

fluctuations

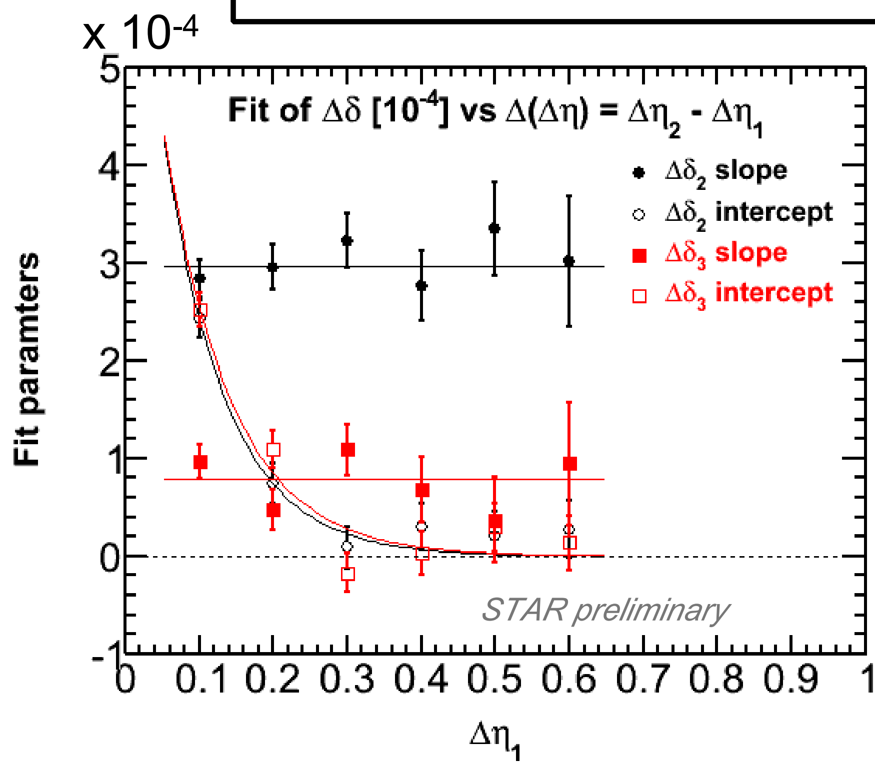
nonflow



$$V(-\eta_\alpha,-\eta_\beta) - V(-\eta_\alpha,\eta_\beta) = \delta(\Delta\eta_1) - \delta(\Delta\eta_2) + \sigma'(\Delta\eta_1) - \sigma'(\Delta\eta_2)$$

Nonflow Parameterization

Run-4 Au+Au 20-30% data



- Intercepts drops quickly at large $\Delta\eta_1$ and then saturates

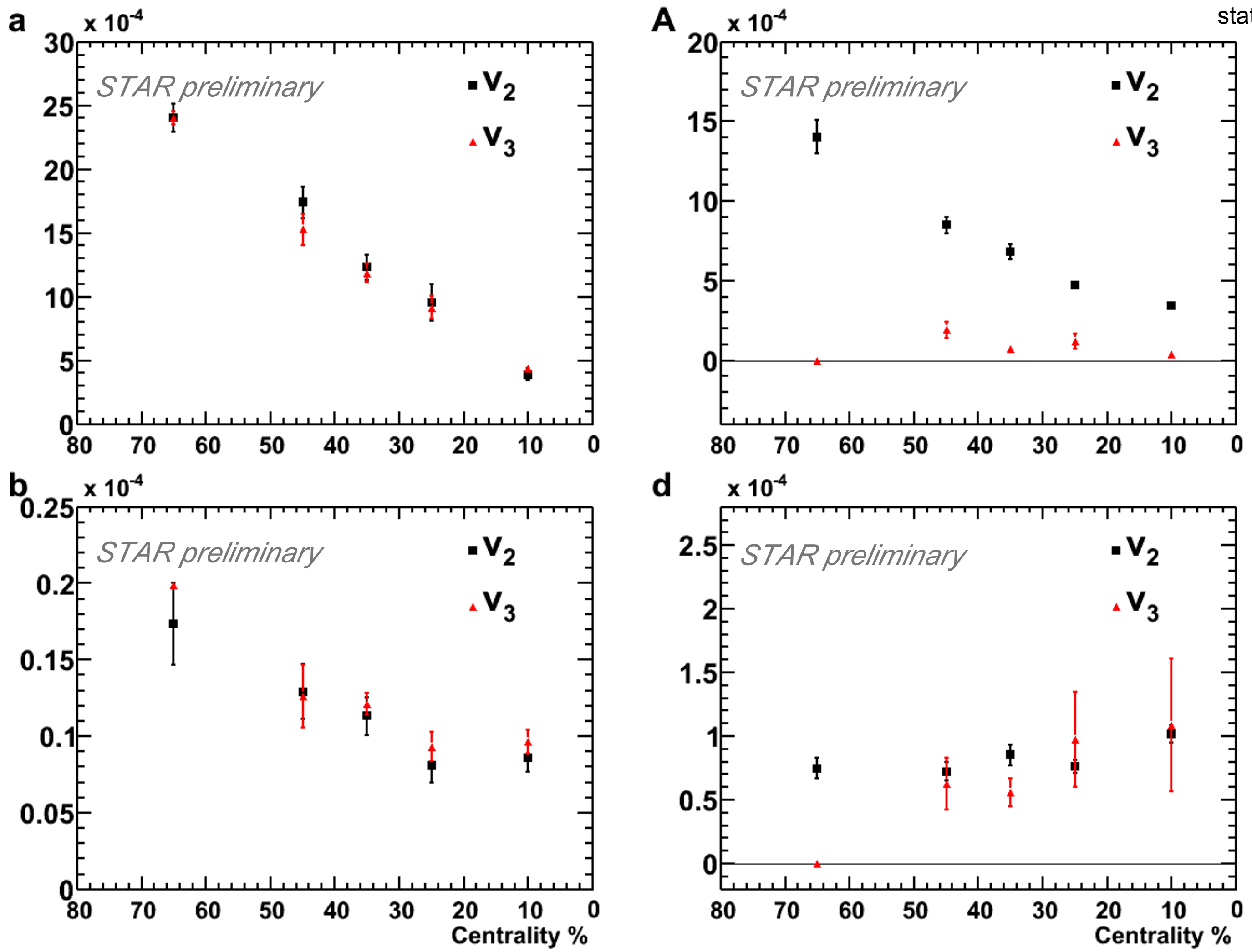
$$\delta(\Delta\eta) = a*\exp(-\Delta\eta/b) - k(\Delta\eta - \Delta\eta_{max}) + c$$

c set to 0 (arbitrary)

Nonflow Fit Parameters

$$\delta(\Delta\eta) = \mathbf{a}*\exp(-\Delta\eta/\mathbf{b}) + \mathbf{A}*\exp(-\Delta\eta^2/2\mathbf{d}^2) + c$$

statistics error only



Au+Au@200GeV data

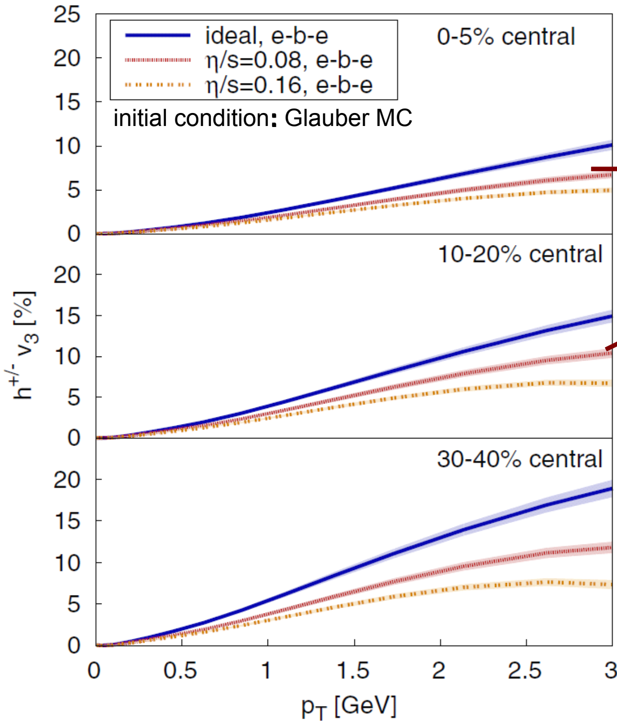
Aug. 15th, 2012

v_3 vs p_T and Model Comparison

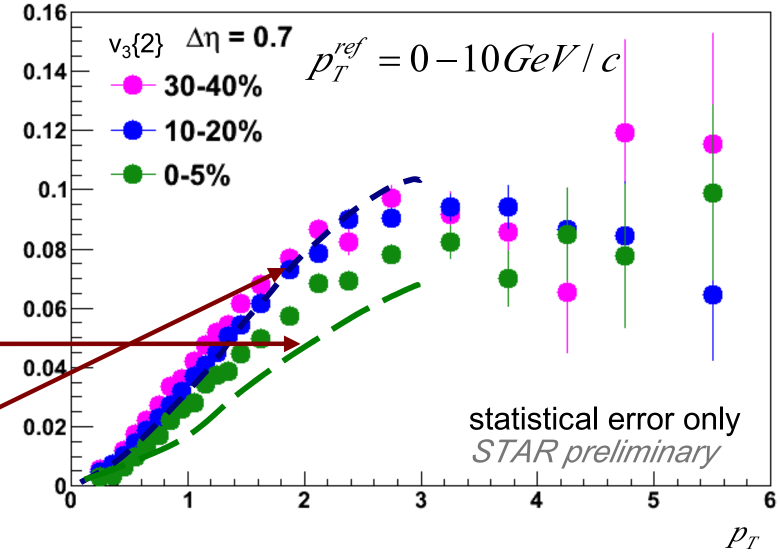
- v_3 more sensitive to η/s than v_2

Q-Cumulant Method with η-gap

B. Schenke, S. Jeon, and C. Gale
PRL 106, 042301 (2011)



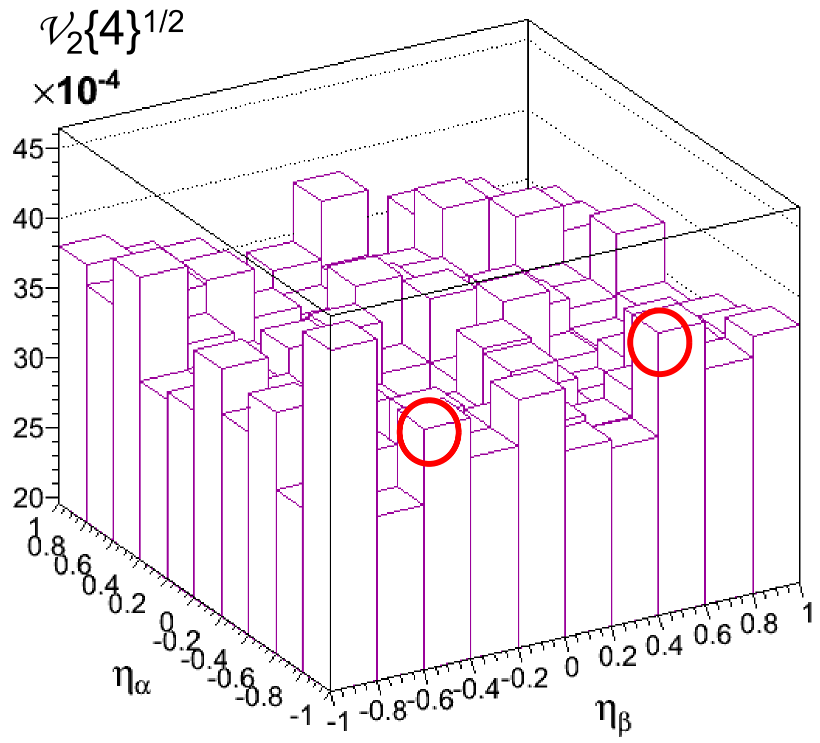
η/s = 0.08

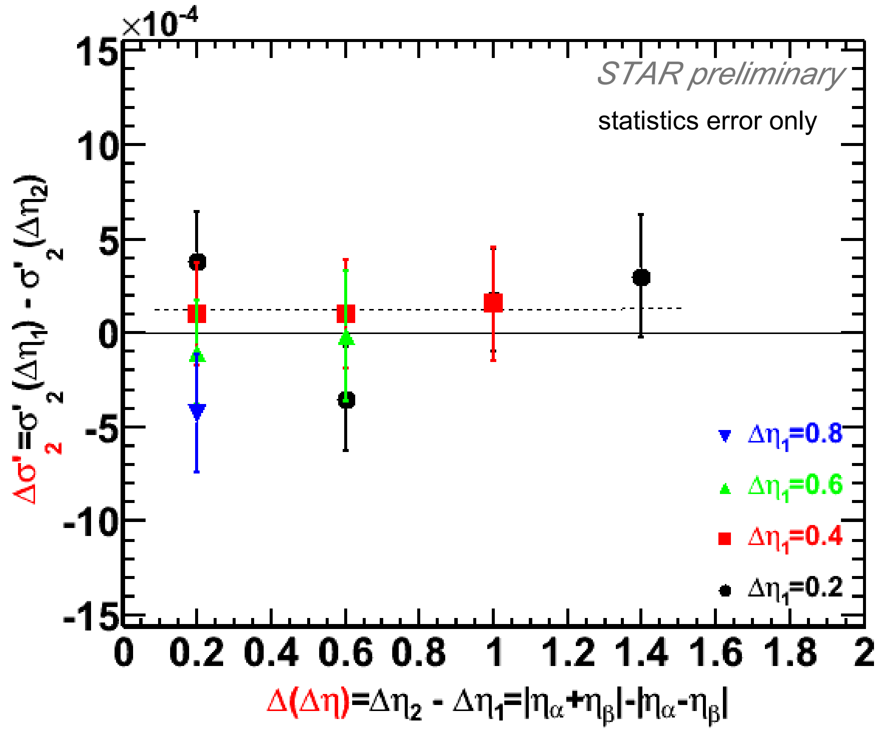


- Top 5%, hydro under-predicts data
- Non-central
  hydro describes data well at p_T<2 GeV
  hydro deviates from data at p_T>2 GeV
- Data may contain nonflow

$\Delta\eta$-dependence $\sigma'(\Delta\eta)$

Au+Au@200 GeV 20-30% data

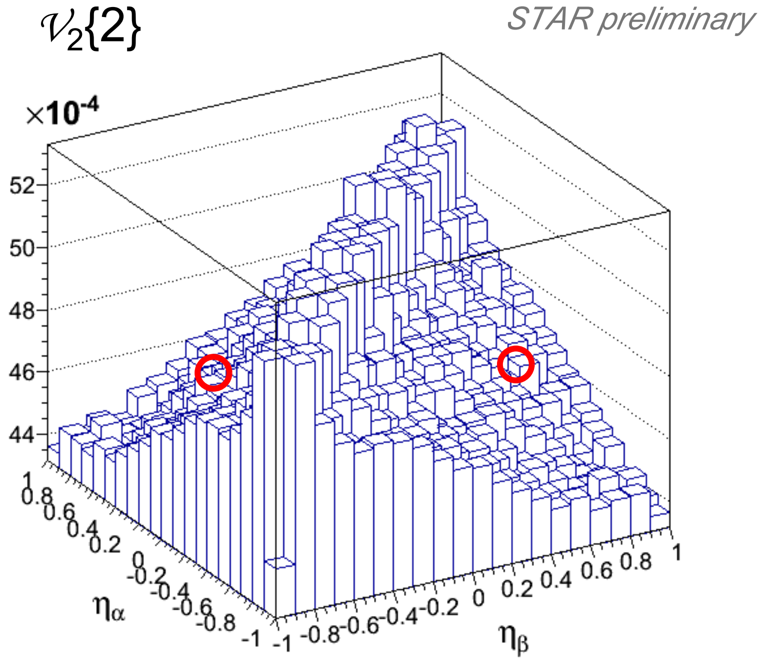


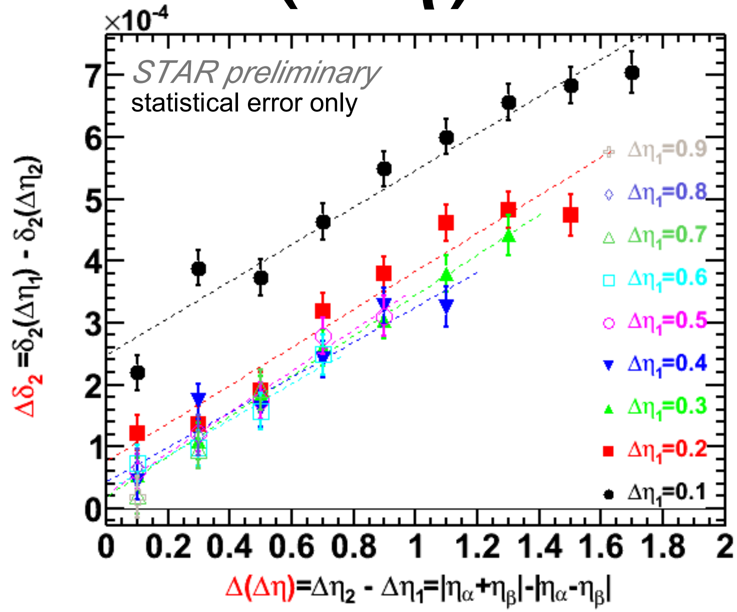


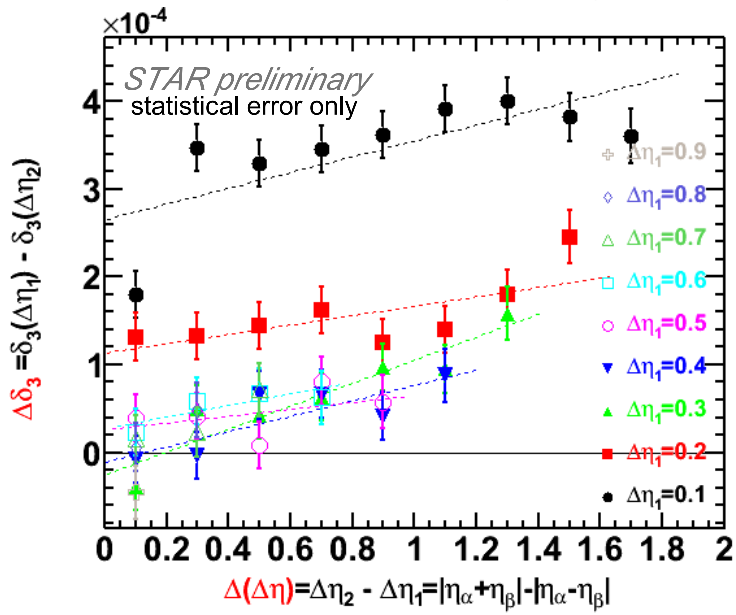
Flow fluctuation appears independent of $\Delta\eta$.

Δη-dependent δ(Δη)

Au+Au@200GeV 20-30% data



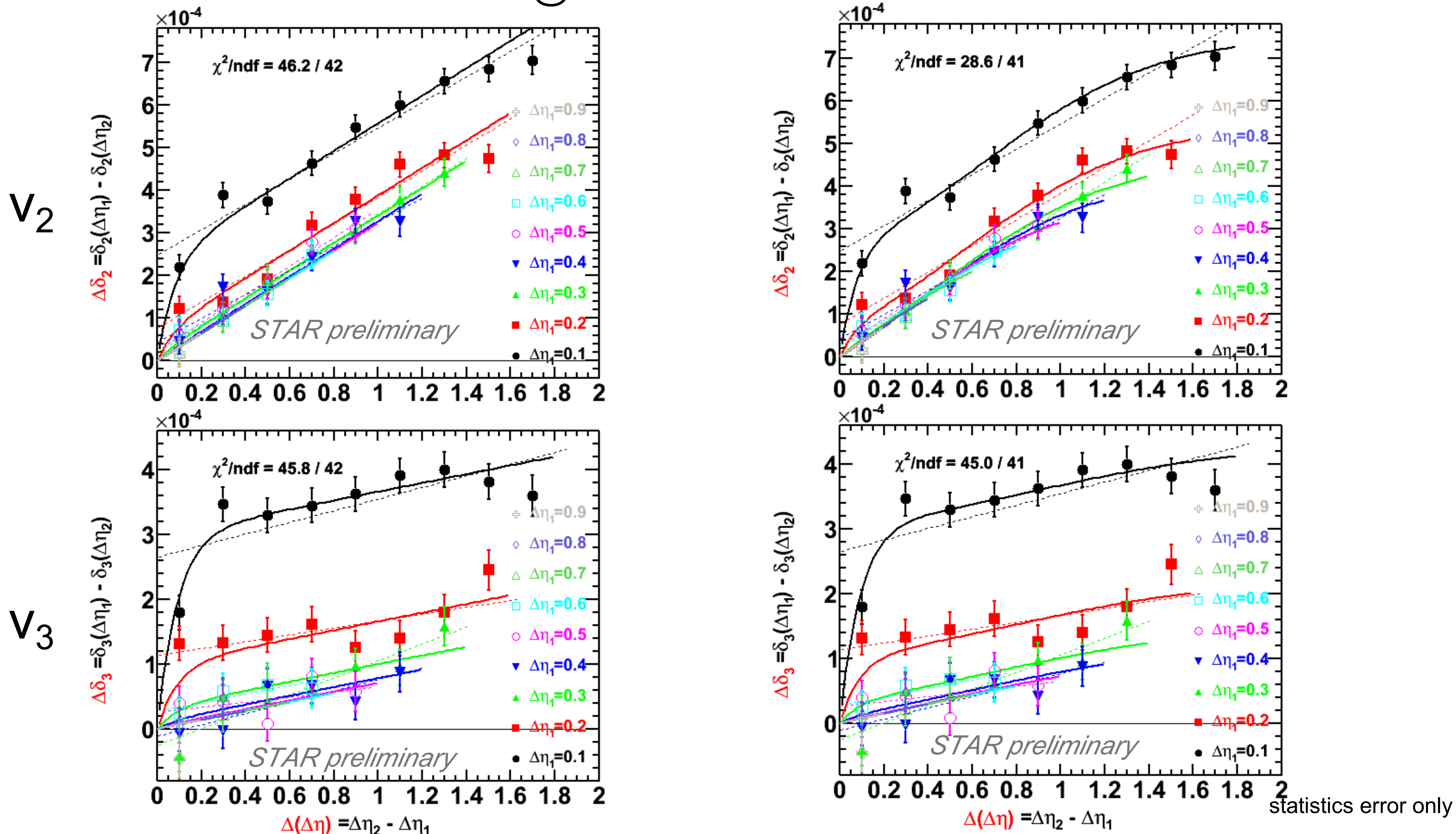




- $\delta(\Delta\eta_2)-\delta(\Delta\eta_1)$ linear in $\Delta\eta_2-\Delta\eta_1$ at a given $\Delta\eta_1$ with similar slopes
- Intercept changes with $\Delta\eta_1$ exponentially

Improved Nonflow Fit

Au+Au@200GeV 20-30% data



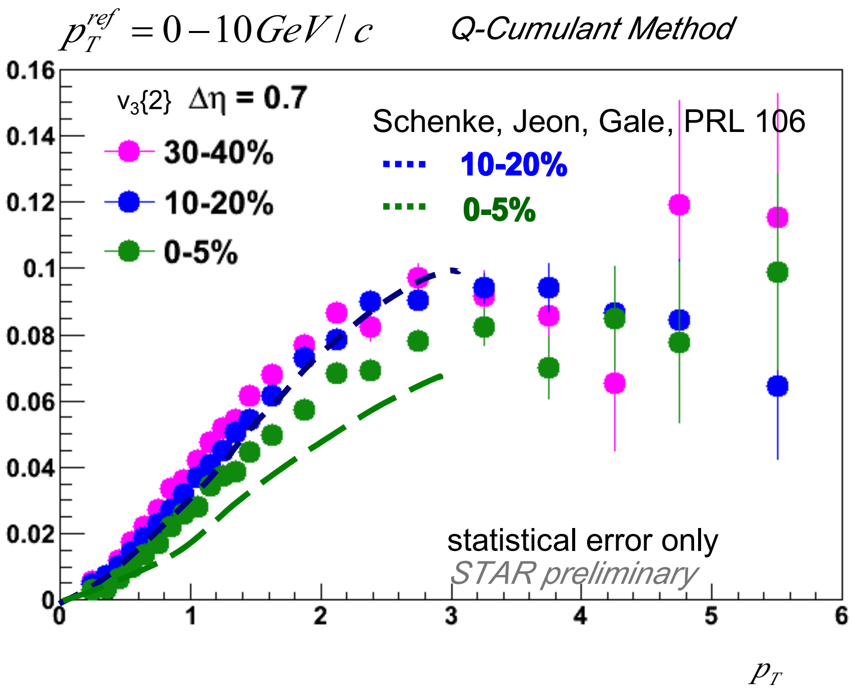
$\Delta\delta(\Delta\eta_1,\Delta\eta_2) = a*[\exp(-\Delta\eta_1/b) - \exp(-\Delta\eta_2/b)]$
$- k(\Delta\eta_1 - \Delta\eta_2)$
$\delta(\Delta\eta) = a*\exp(-\Delta\eta/b) - k\Delta\eta + c$

$\Delta\delta(\Delta\eta_1,\Delta\eta_2) = a*[\exp(-\Delta\eta_1/b) - \exp(-\Delta\eta_2/b)] +$
$A*[\exp(-\Delta\eta_1^2/2d^2) - \exp(-\Delta\eta_2^2/2d^2)]$
$\delta(\Delta\eta) = a*\exp(-\Delta\eta/b) + A*\exp(-\Delta\eta^2/2d^2)$

Aug. 15th, 2012

v_3 vs p_T and Model Comparison

- v_3 more sensitive to η/s than v_2



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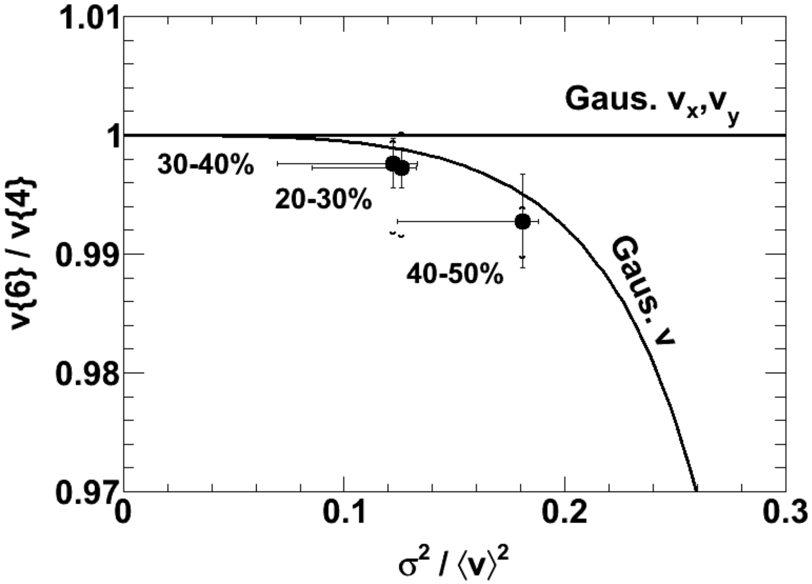
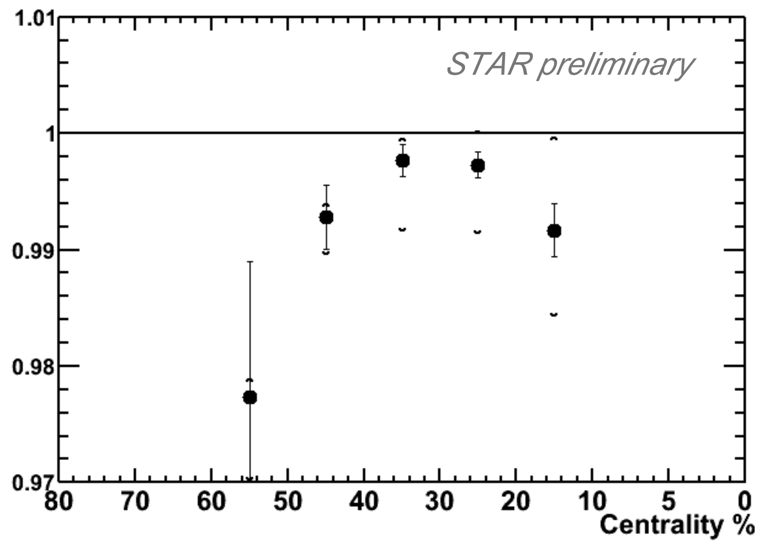
4- and 6-Particle Cumulant

Assuming the flow fluctuations are Gaussian, we have two options:

1. v_x, v_y are Gaussian: v{6} = v{4}   Voloshin, Poskanzer, Tang, Wang, PLB
2. v is Gaussian: LY, Wang, Tang, arXiv: 1101.4646

$$v_n\{6\}/v_n\{4\} \approx 1-\sigma^6/3\langle v_n\rangle^6 \;,\; \text{if } \sigma^2/\langle v_n\rangle^2 << 1$$





* No-weight applied, non-uniform acceptance corrected. Systematic errors estimated by applying weight and no acceptance correction

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