# Collectivity and Fluctuations in Au+Au with PHENIX

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# Collectivity in A+A

Developments in the last 10 years show event-wise $v_n$ fluctuations are an important part of the flow picture

- Different analysis methods are sensitive to fluctuations in different ways
- Phys.Rev. C80 (2009) 014904 (Ollitrault, Poskanzer, Voloshin)

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We present results of $v_2$ and $v_3$ and their fluctuations using two complementary techniques:

- Multiparticle cumulants
- Event-by-event folding procedure

Paper on arxiv: https://arxiv.org/abs/1804.10024

# Analysis Methods

## Multiparticle cumulants

- Insensitive to detector response
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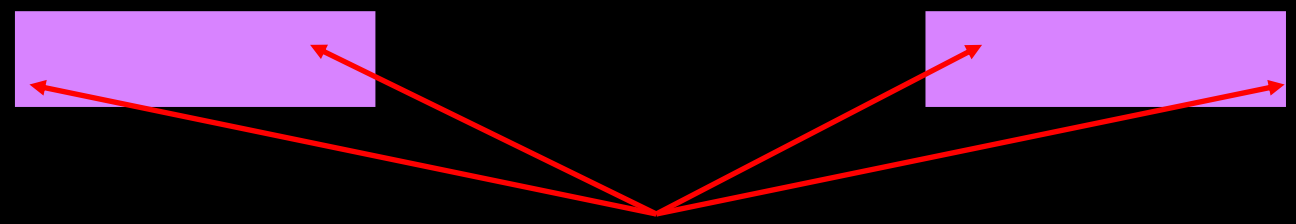
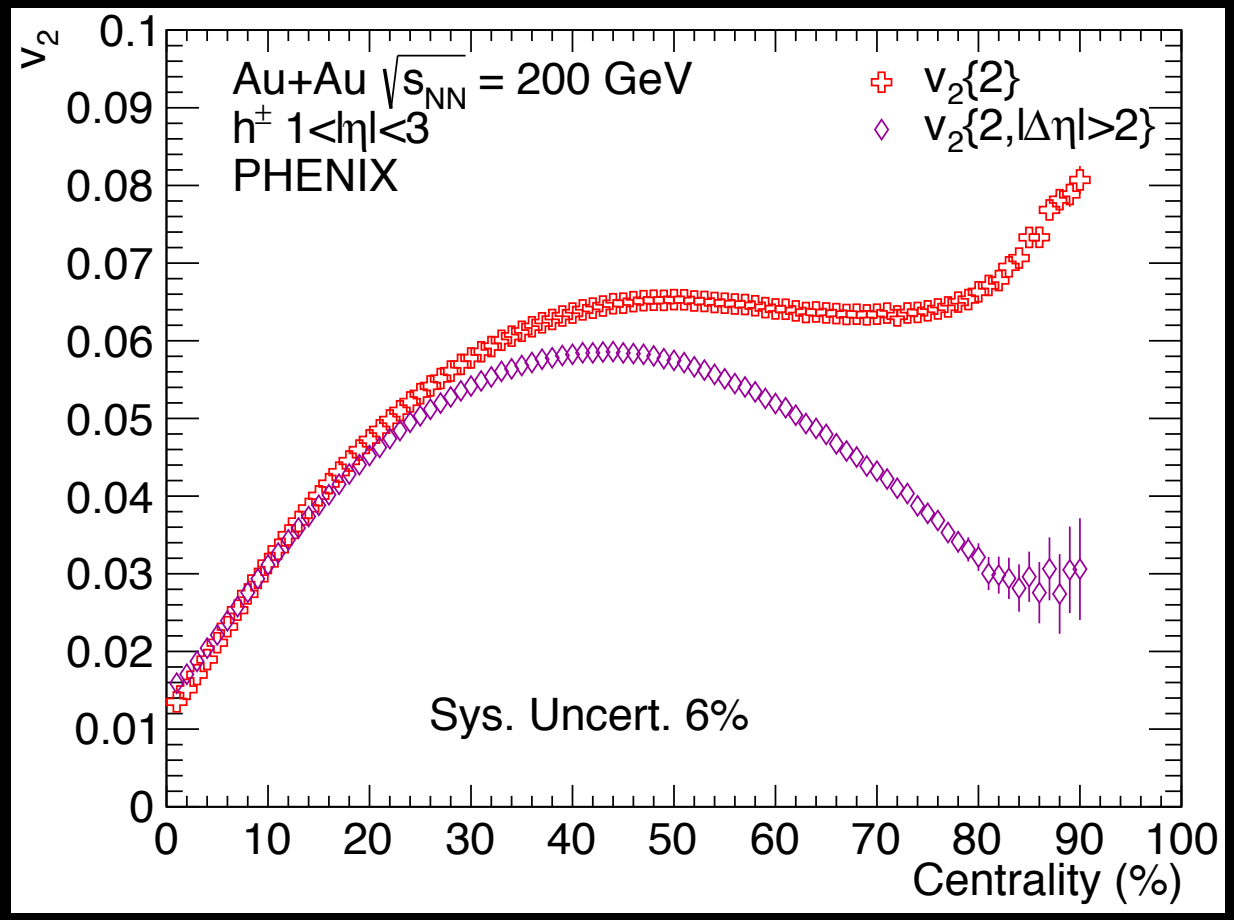
Tracks for this analysis measured in PHENIX FVTX: $1 < |\eta| < 3$



$p_T \gtrsim 0.3$ GeV/c

# $v_2$ via Multiparticle Cumulants

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$v_2\{2\}$ from one sub event agrees with $v_2\{2,|\Delta\eta|>2\}$ in the most central events

More peripheral

- ➡ Lower multiplicity
- ➡ Non-flow relatively more dominant

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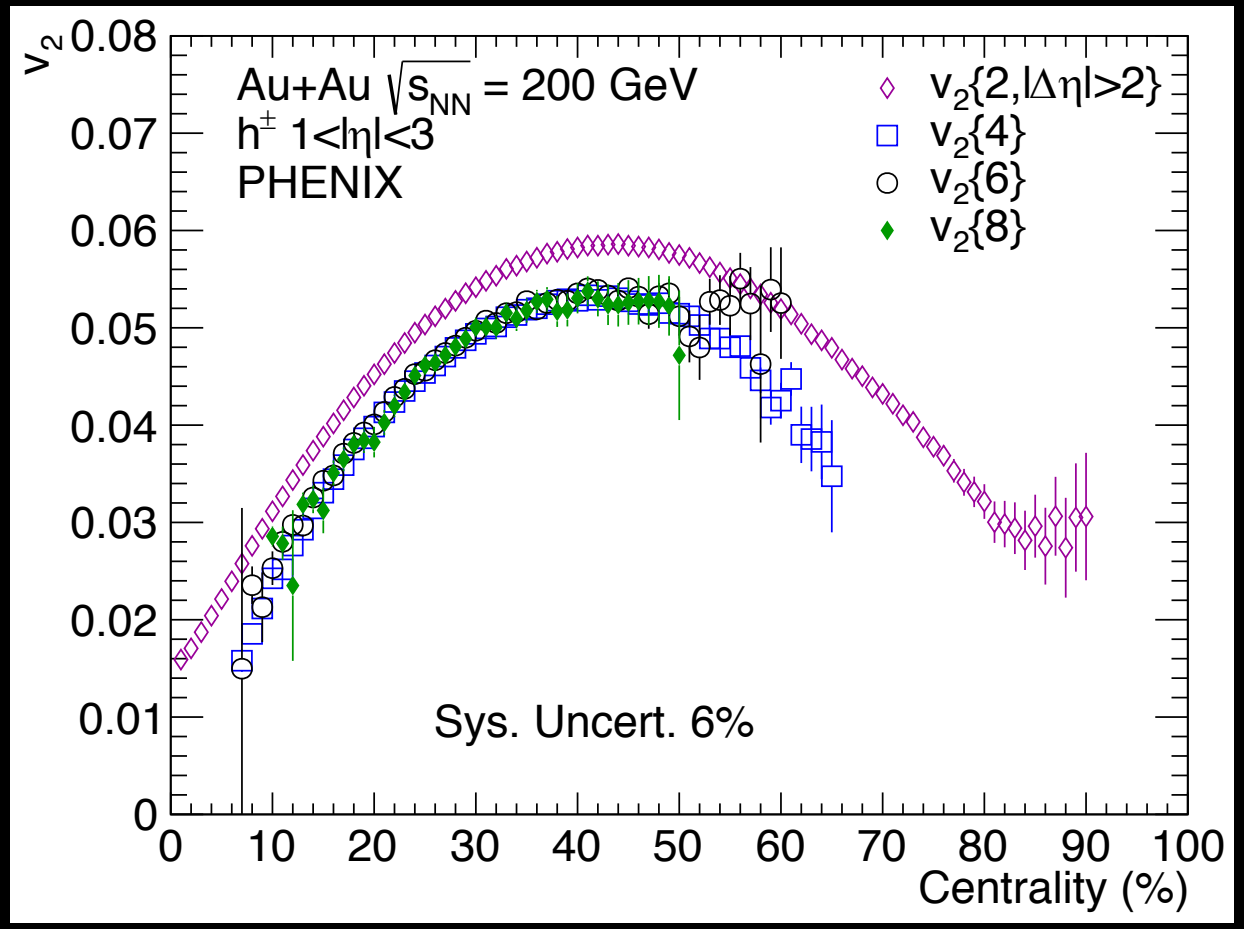


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$$v_2\{2\} > v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$$

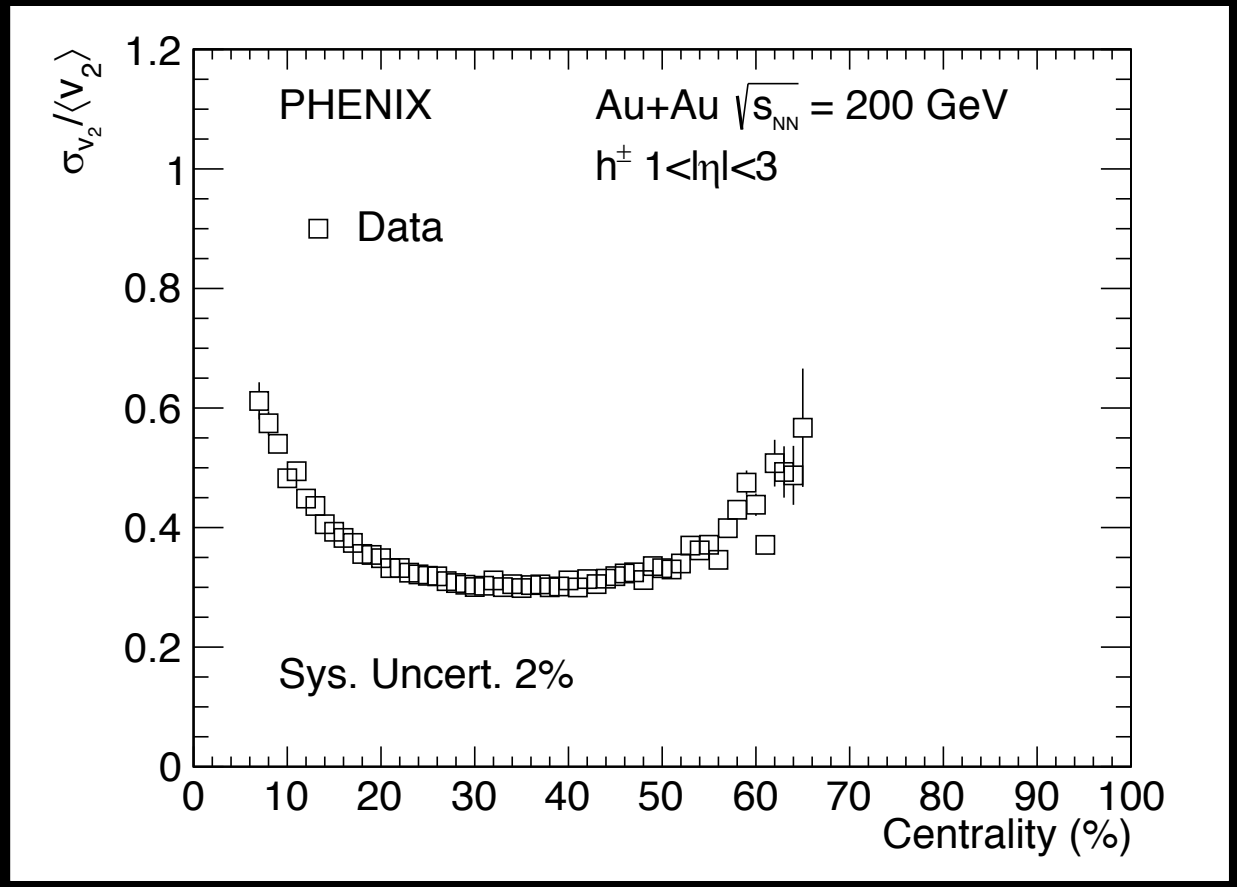
Consistent with expectations given Gaussian fluctuations and small variance

# $v_2$ Relative fluctuations

$$v_2\{2\}^2 = \langle v \rangle^2 + \sigma_v^2$$

In small variance:

$$v_2\{4\}^2 \approx \langle v \rangle^2 - \sigma_v^2$$

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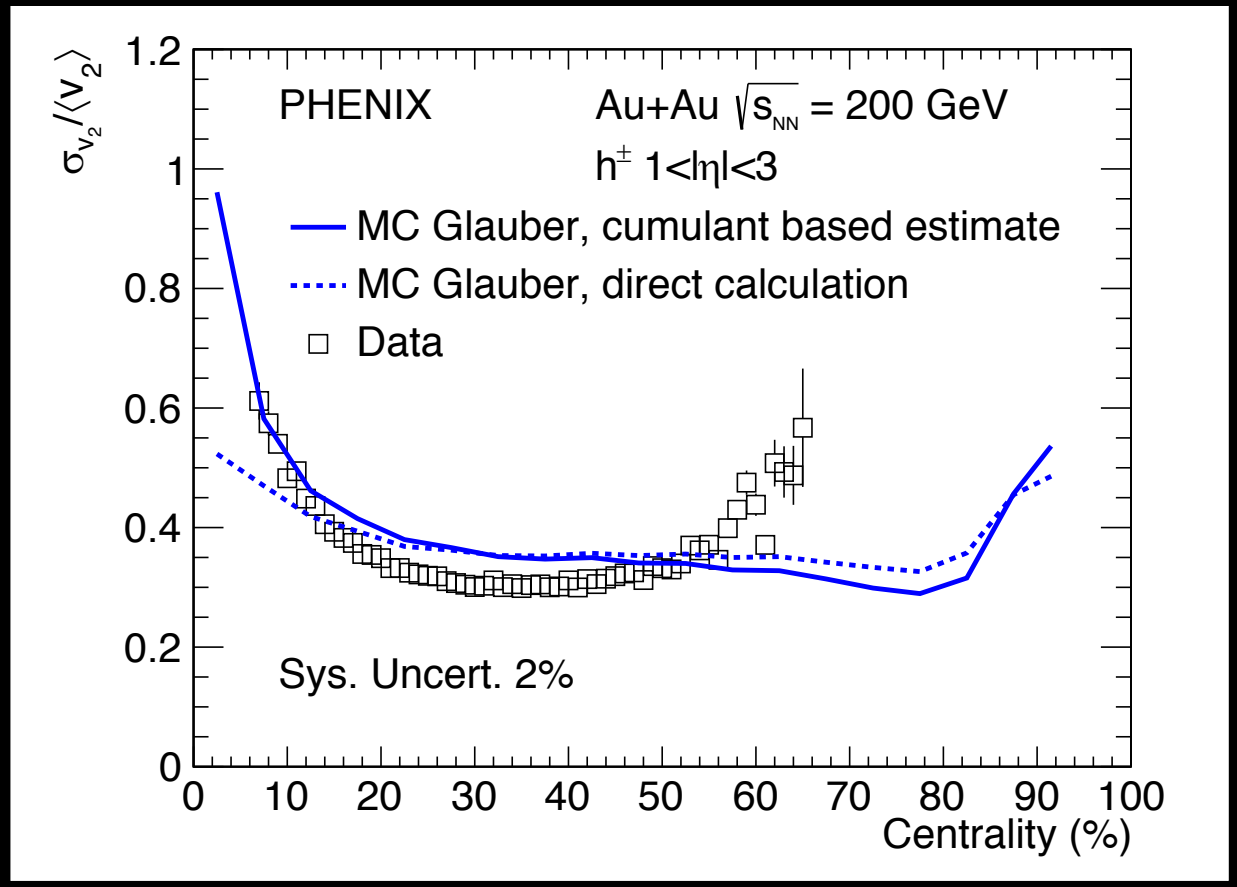


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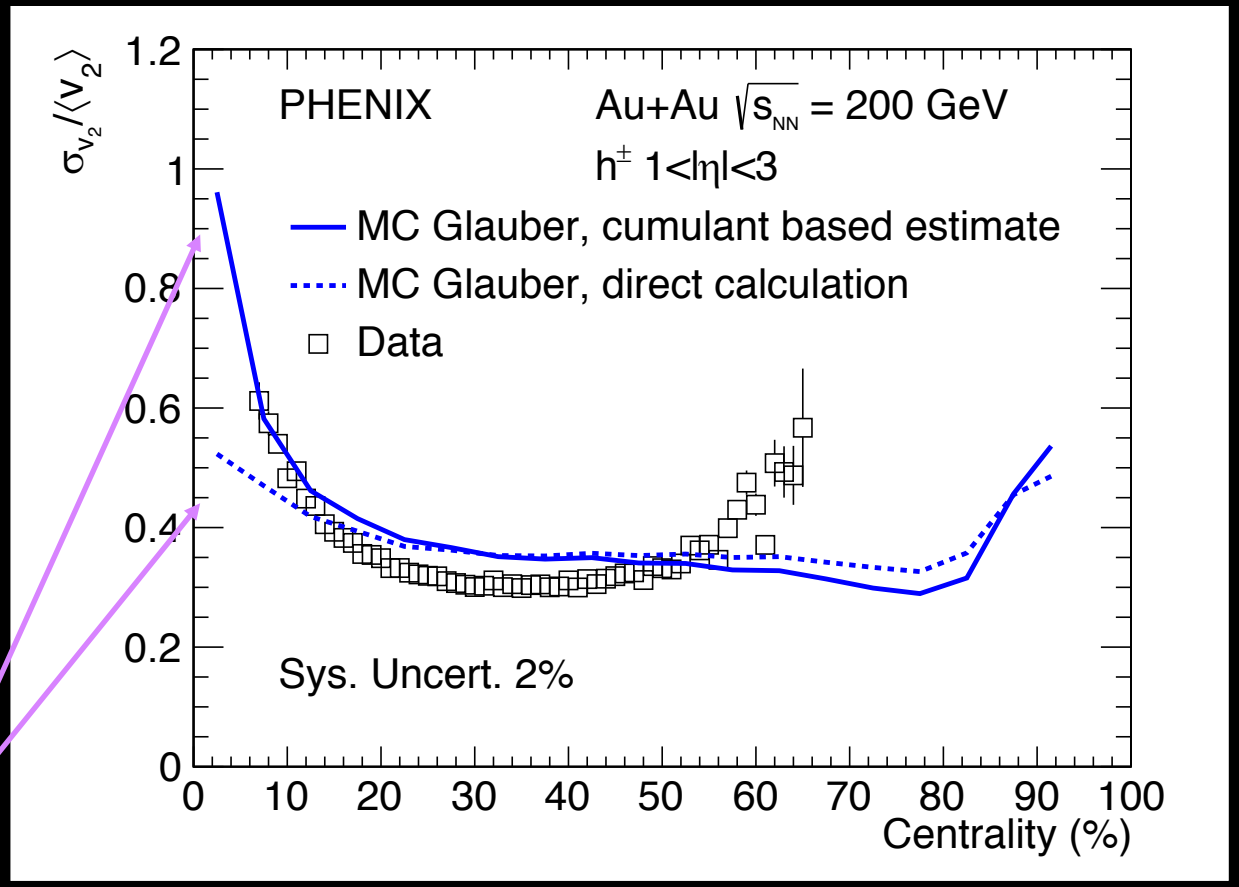
**Small variance not valid in very central**

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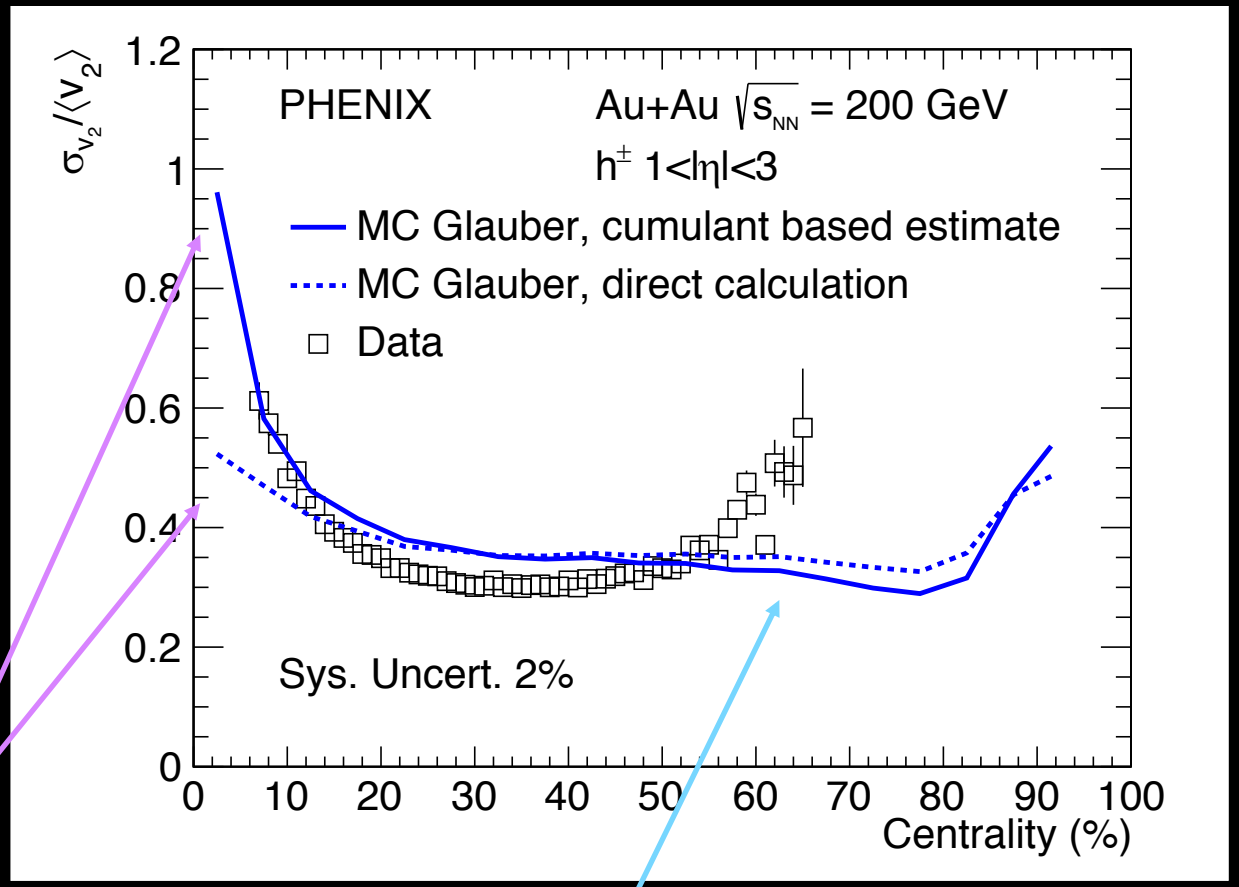


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**Non-linearity in hydro?**
J. Noronha-Hostler et al Phys. Rev. C 93, 014909 (2016)

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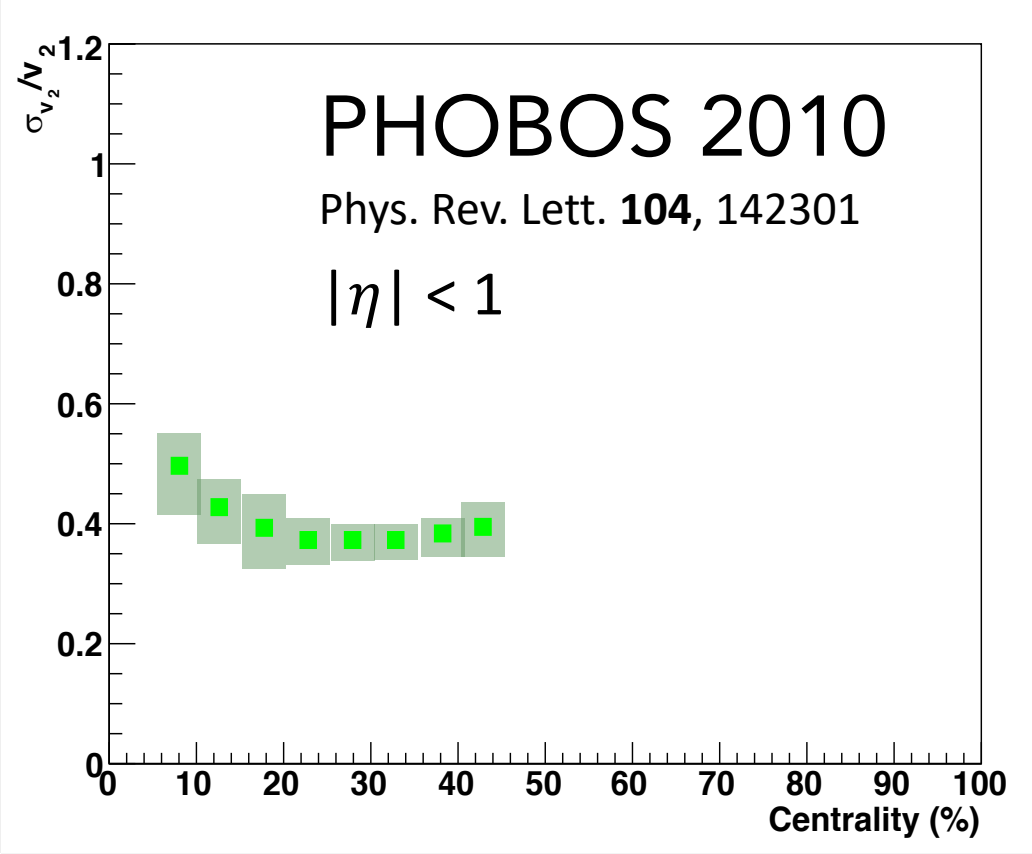


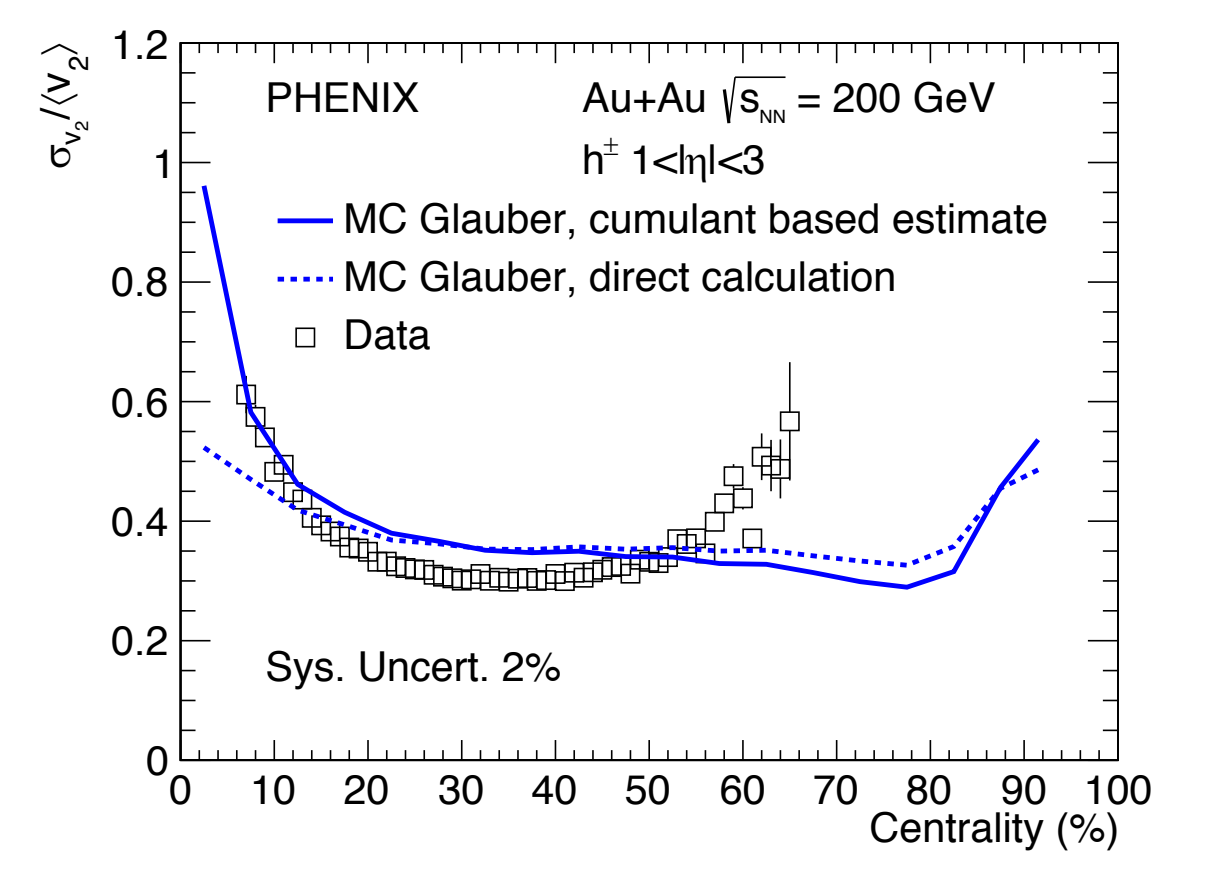


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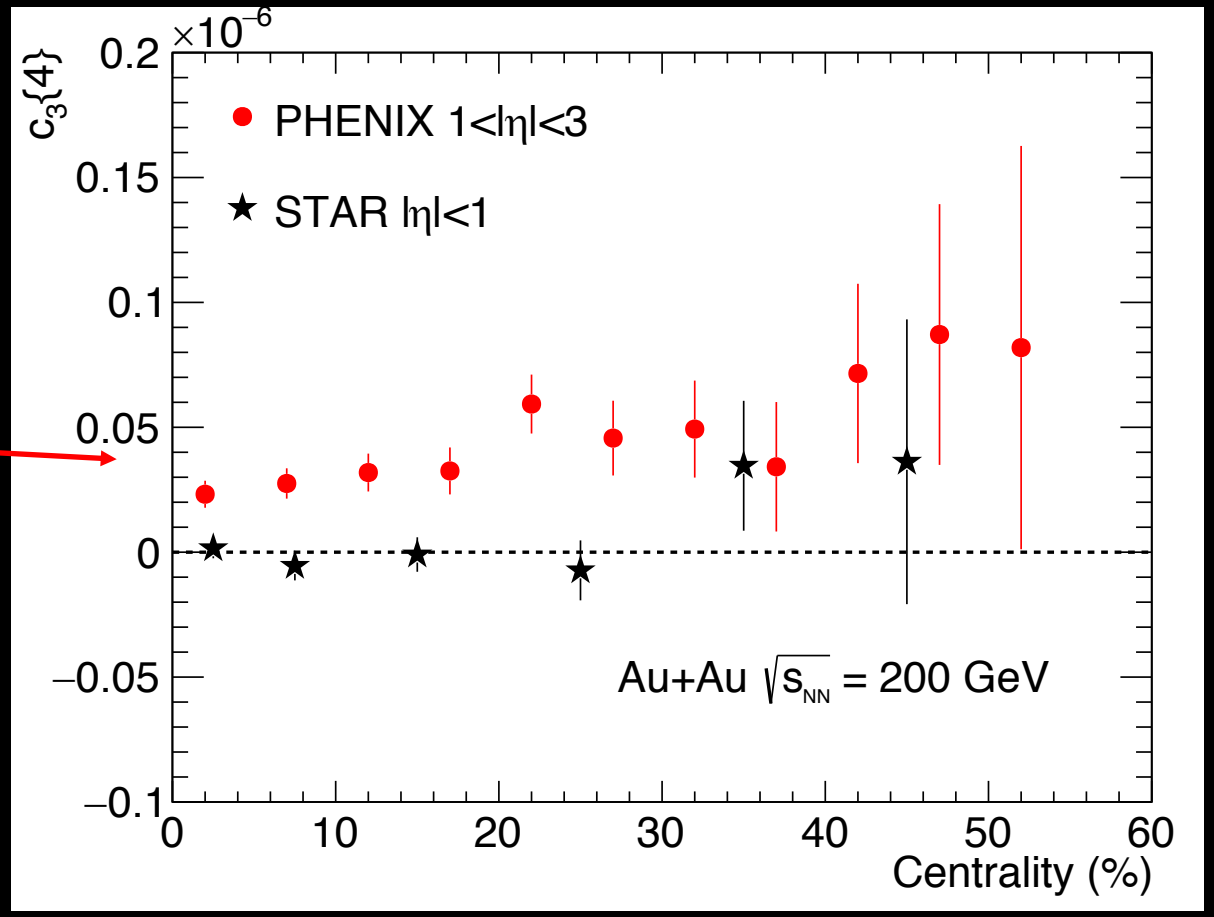
# $v_3$ Cumulants

$$v_3\{4\} = (-c_3\{4\})^{1/4}$$

Complex valued $v_3\{4\}$

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(STAR) Phys. Rev. C 88, 014904 (2013)

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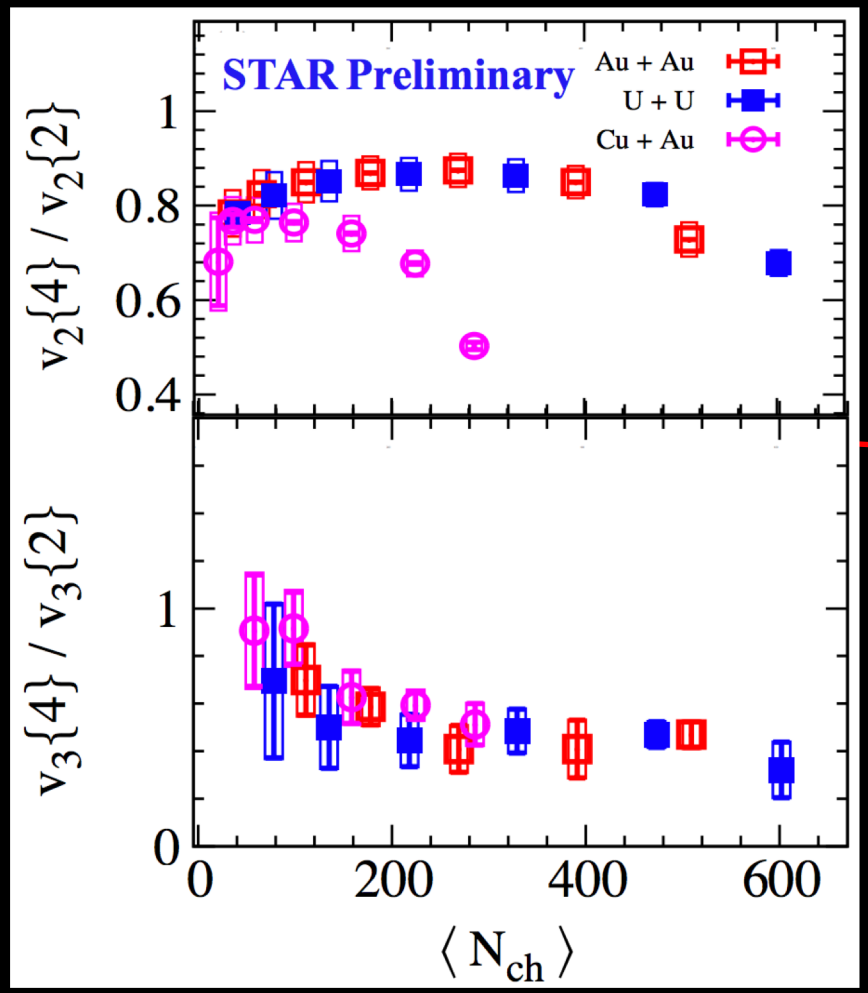


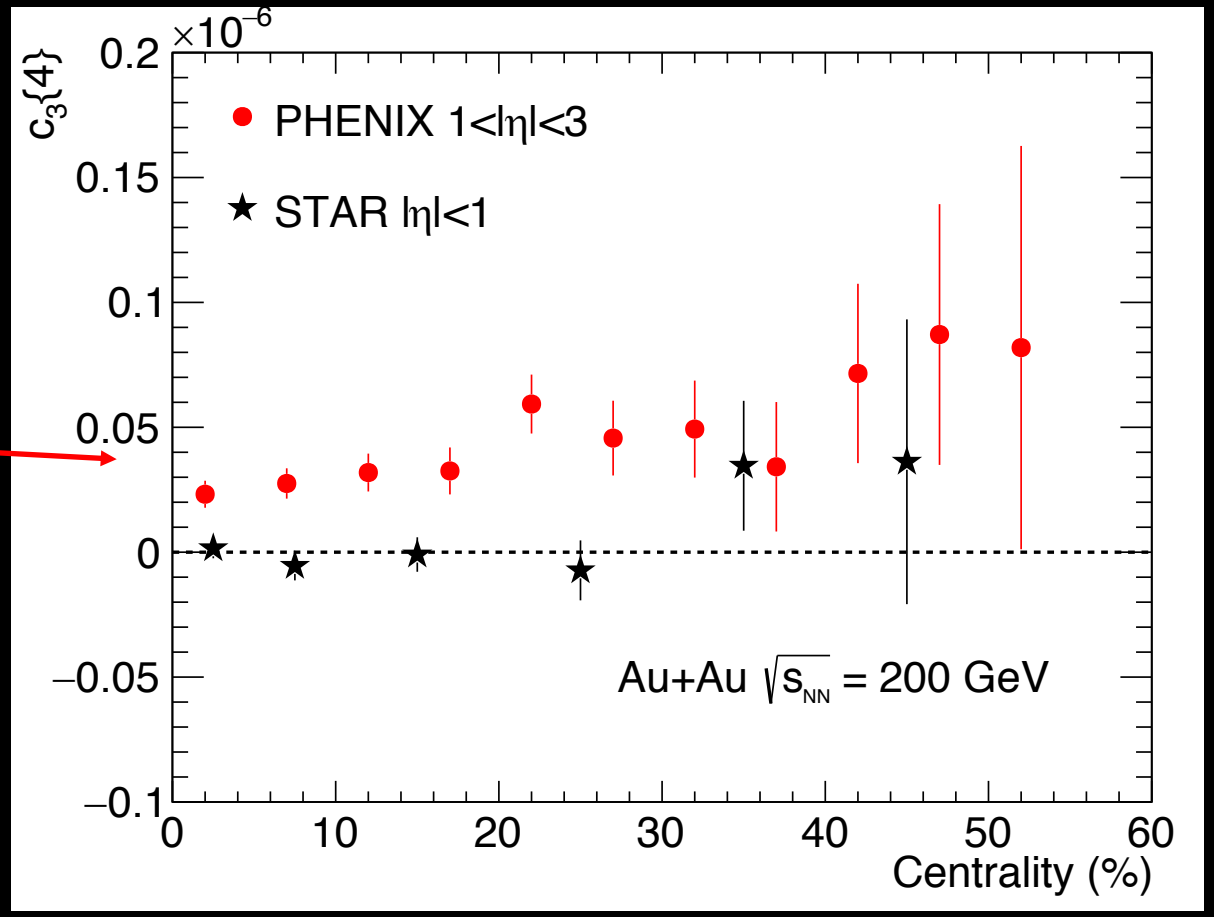


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Niseem Magdy QM2018 #588, May 15, 11:30

# Event-by-Event Flow

Flow vector measured event-by-event will have multiple sources of fluctuations

## Intrinsic

- Impact parameter
- Nucleon positions

## Measurement/response

- Detector resolution
- Acceptance
- ❖ Finite particle sampling

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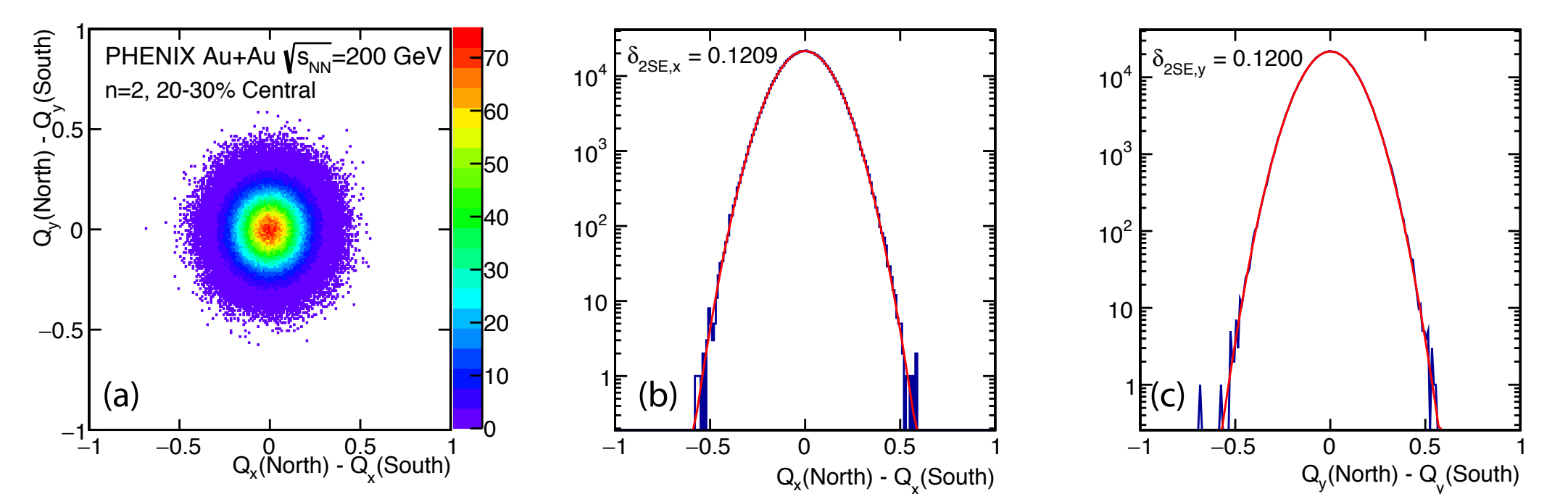
ATLAS: J. HEP(2013) 2013: 183 CMS: https://arxiv.org/abs/1711.05594

# Flow Vector Response

Observed to be Gaussian over 4 orders of magnitude

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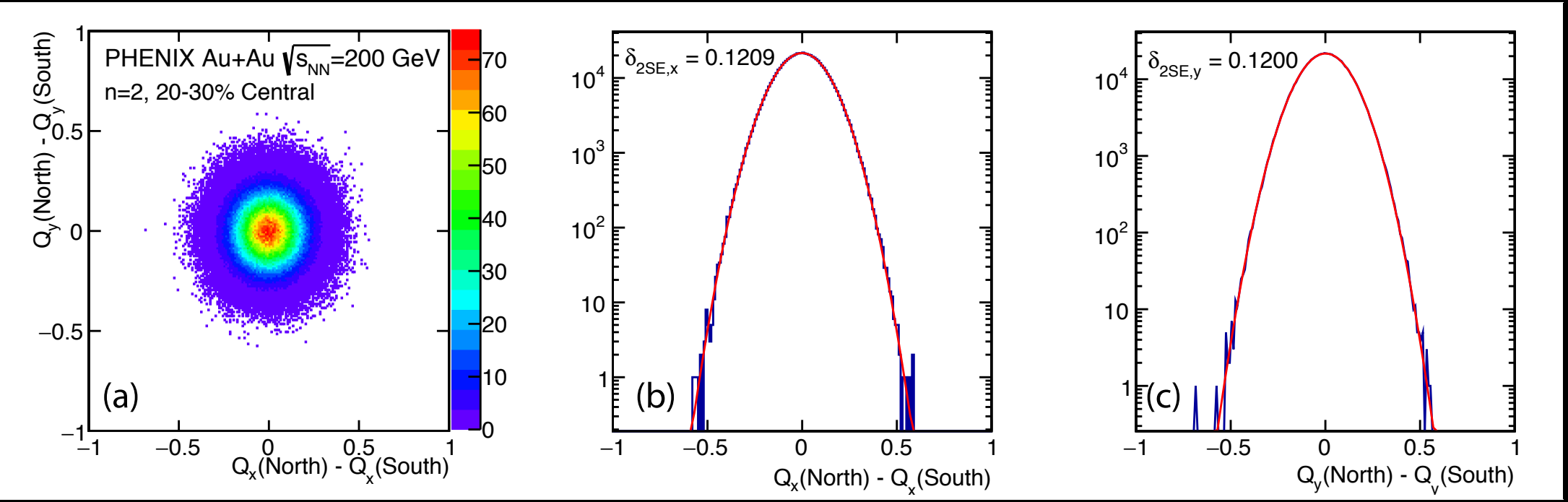



https://arxiv.org/abs/1804.10024

If observed flow vector is Gaussian about truth, PDF of observed $|\vec{v_n}|$ is *Bessel-Gaussian*:

$$p(v_n^{\mathrm{obs}}|v_n) \propto v_n^{\mathrm{obs}} e^{-\frac{(v_n^{\mathrm{obs}})^2+v_n^2}{2\delta^2}} I_0\left(\frac{v_n^{\mathrm{obs}} v_n}{\delta^2}\right)$$

1 parameter

# Unfolding

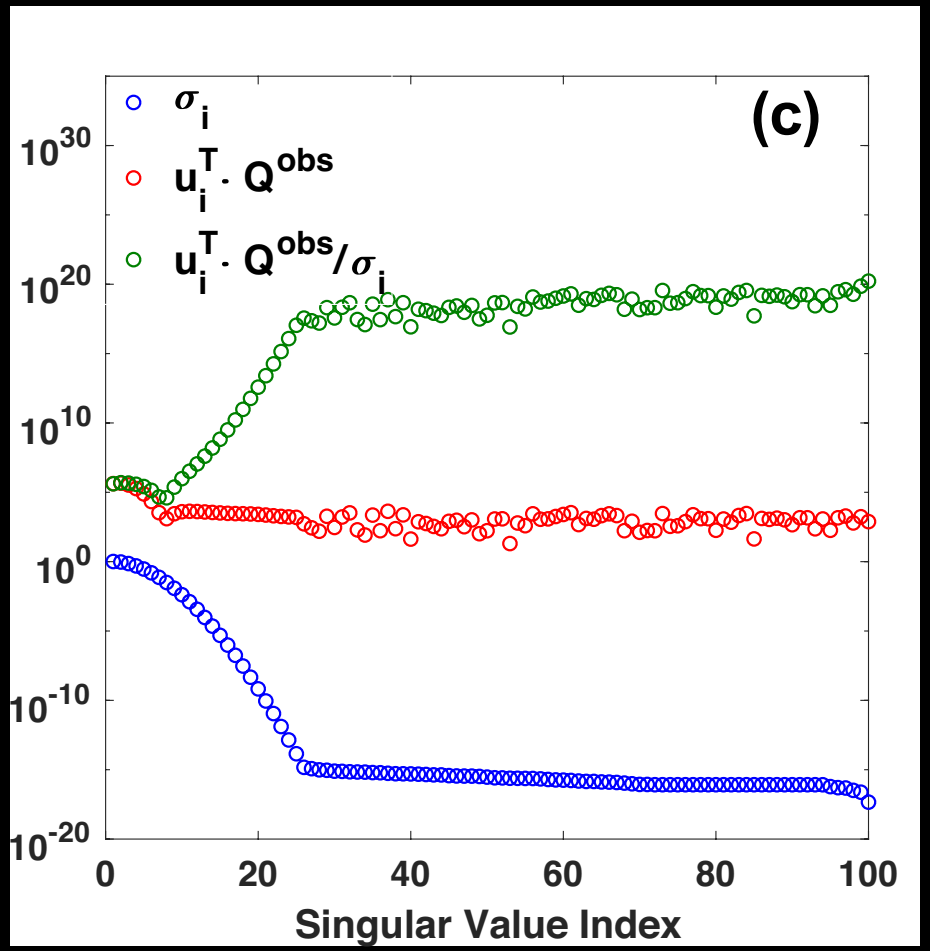
Given the Bessel-Gaussian response, we can try to unfold the observed distribution to the truth

We employed SVD to decompose the response matrix

$$\hat{A} = \hat{U}\hat{\Sigma}\hat{W}^T$$

In which case, the truth distribution is expressed as

$$\vec{Q}_2 = \sum_{i=1}^{\mathrm{Dim}(A)} \varphi_i \left( \frac{\vec{u}_i^T \cdot \vec{Q}_2^{\mathrm{obs}}}{\sigma_i} \right) \vec{w}_i$$

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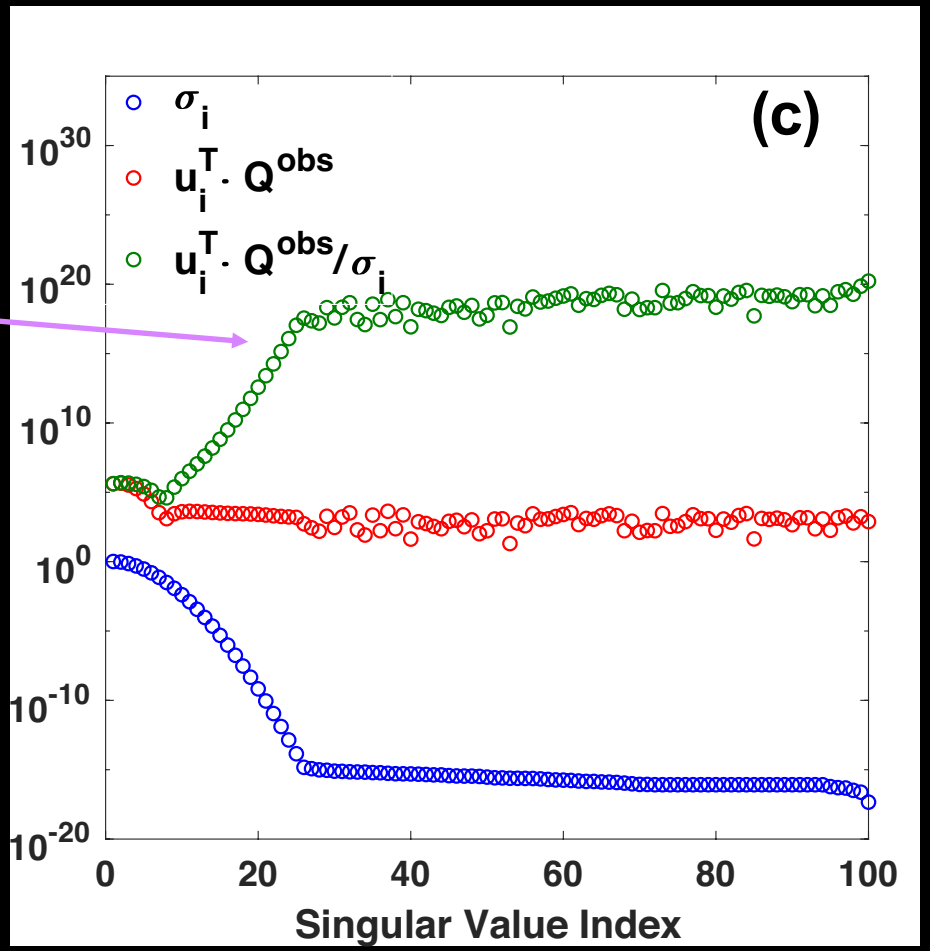
**Fails the "Picard condition"**

$$A = U \Sigma W$$

In w … is exp…

**Procedure highly sensitive to statistical fluctuations in observed distribution**

$$\vec{Q}_2 = \sum_{i=1} \varphi_i \left( \frac{\ldots}{\sigma_i} \right) \vec{w}_i$$

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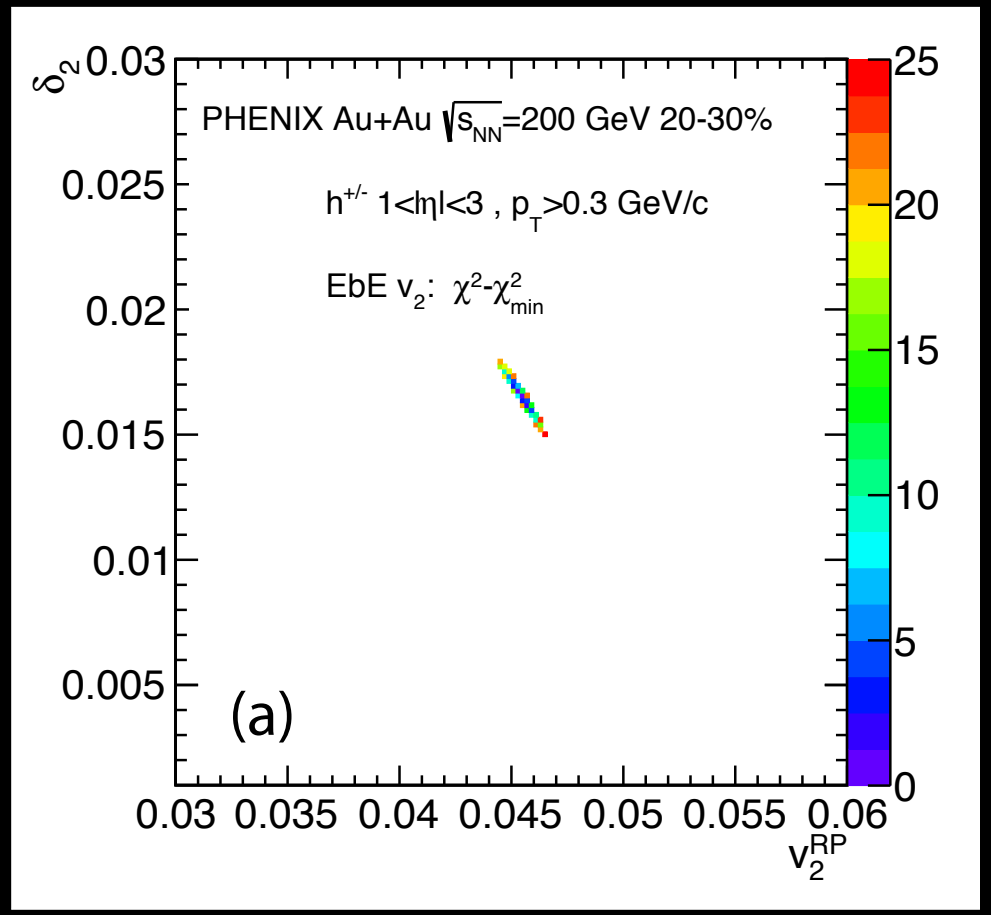
# Fit to Observed $v_2$

If we make the ***ansatz*** that the intrinsic fluctuations are Gaussian, the truth $v_n$ distribution is also Bessel-Gaussian

$$p(v_n) = \frac{v_n}{\delta_{v_n}^2} e^{-\frac{(v_n^2+(v_n^{\mathrm{RP}})^2)}{2\delta_{v_n}^2}} I_0\left(\frac{v_n v_n^{\mathrm{RP}}}{\delta_{v_n}^2}\right)$$

*Forward-fold* truth distributions through the response matrix

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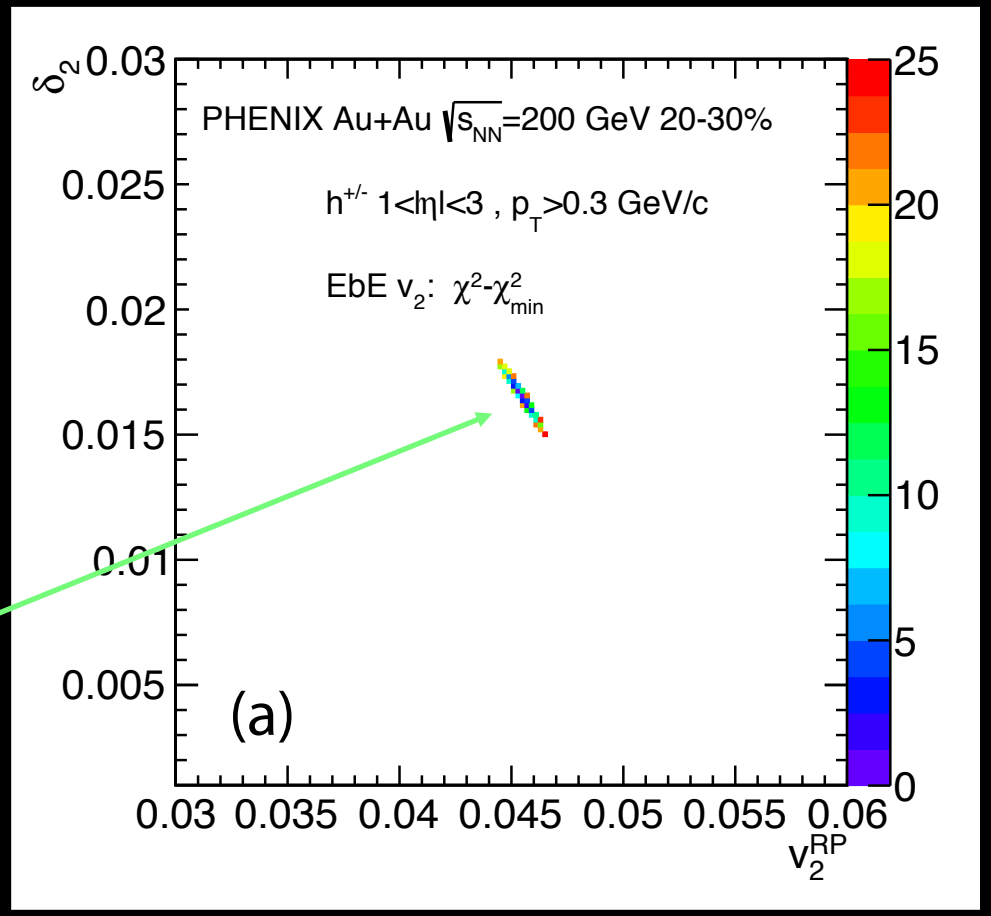
$v_2$ parameters tightly constrained

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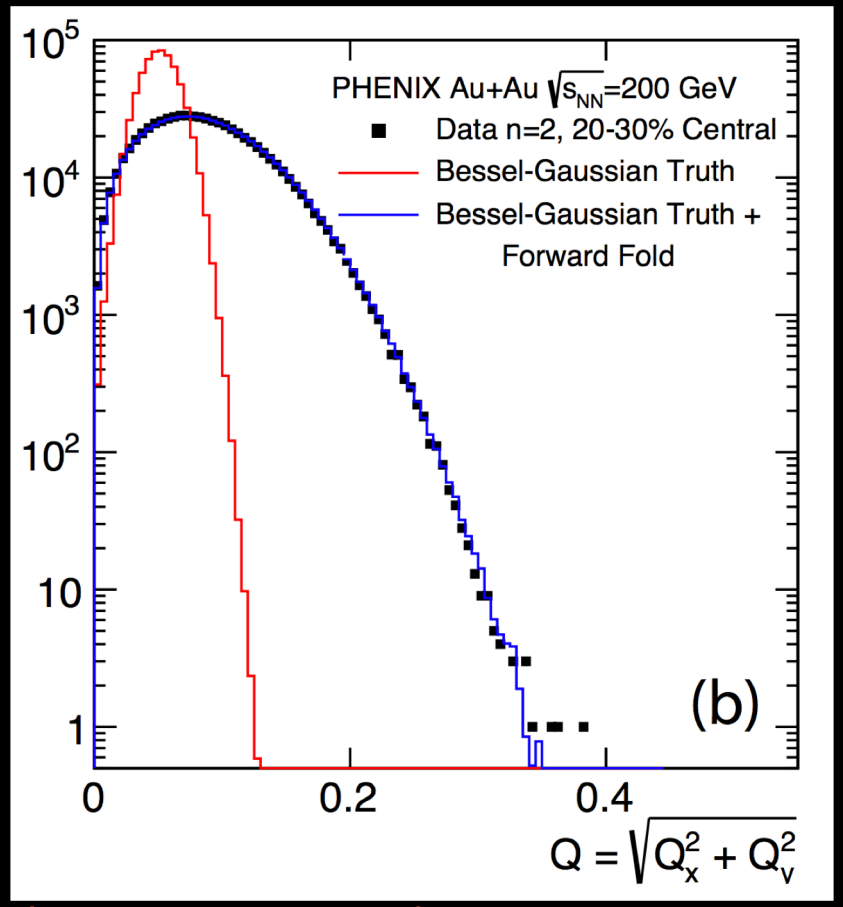


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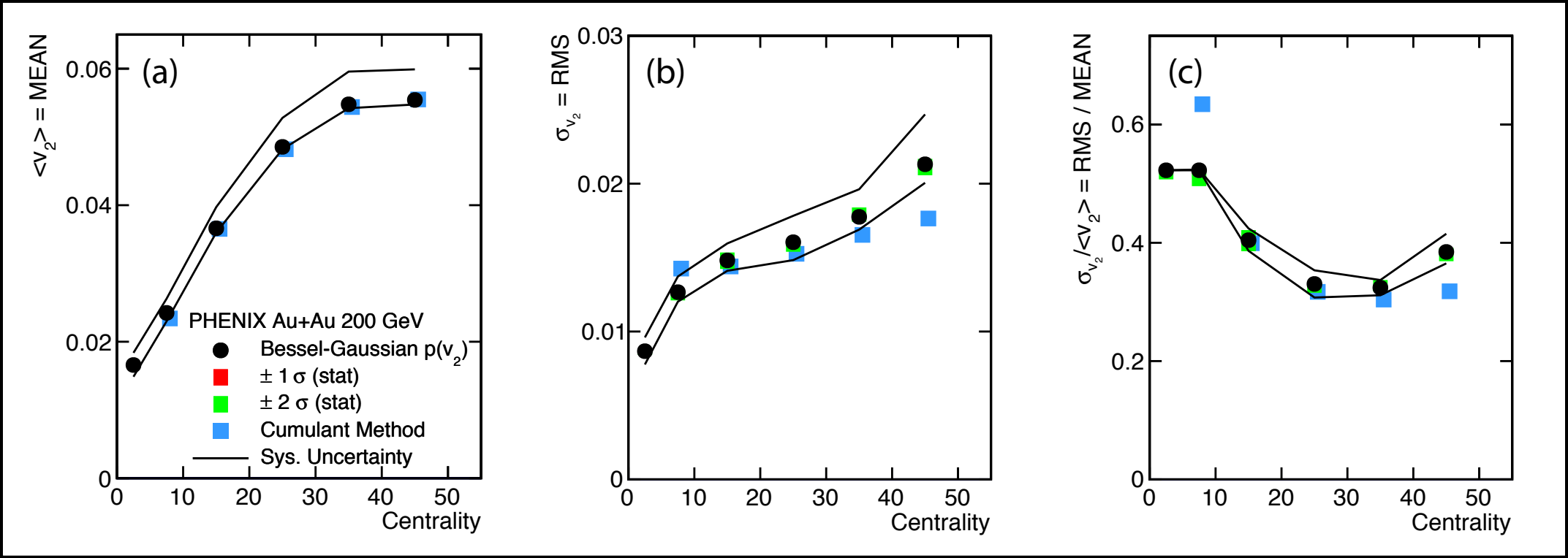
# $v_2$ Results

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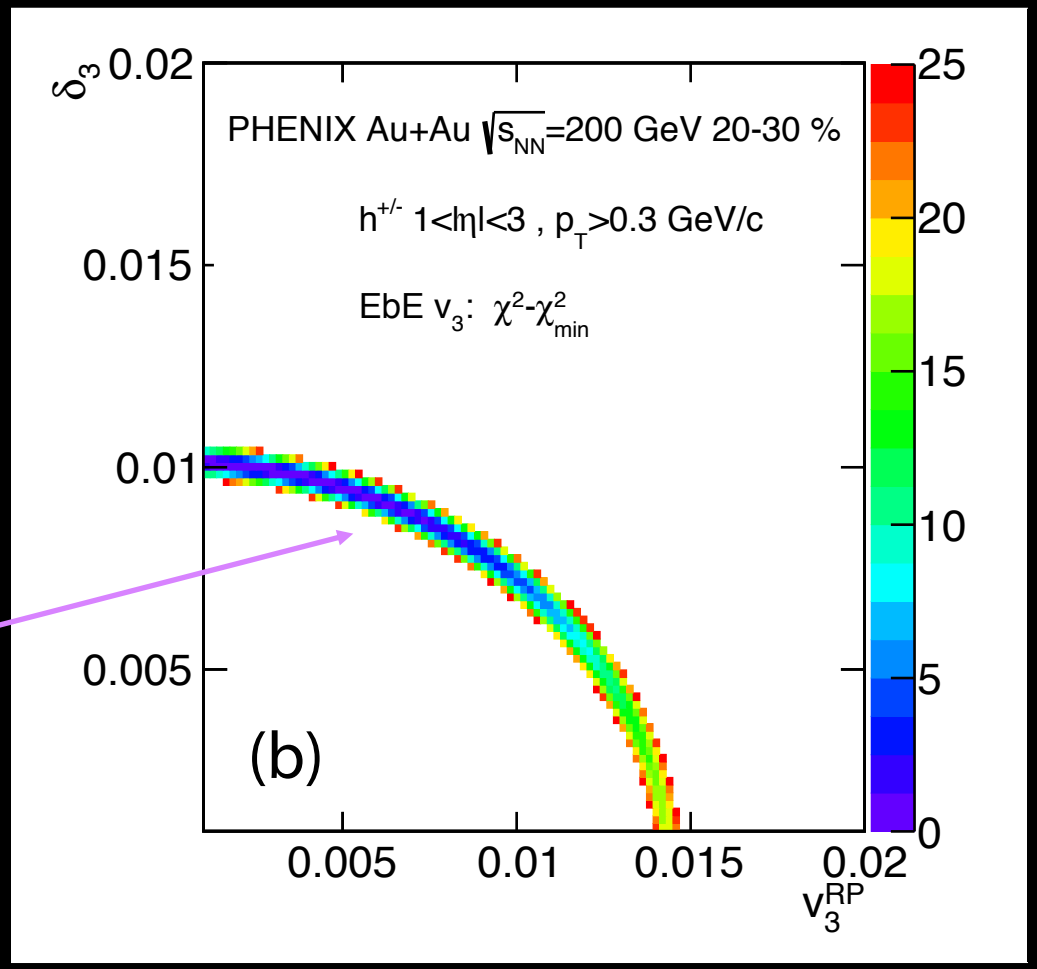
- Extracted $v_2$ in very good agreement
- Fluctuations agree in centrality where small variance expected to hold (>10%)

# Fit to Observed $v_3$

Applying the same logic to $v_3$

$v_3$ has family of parameters

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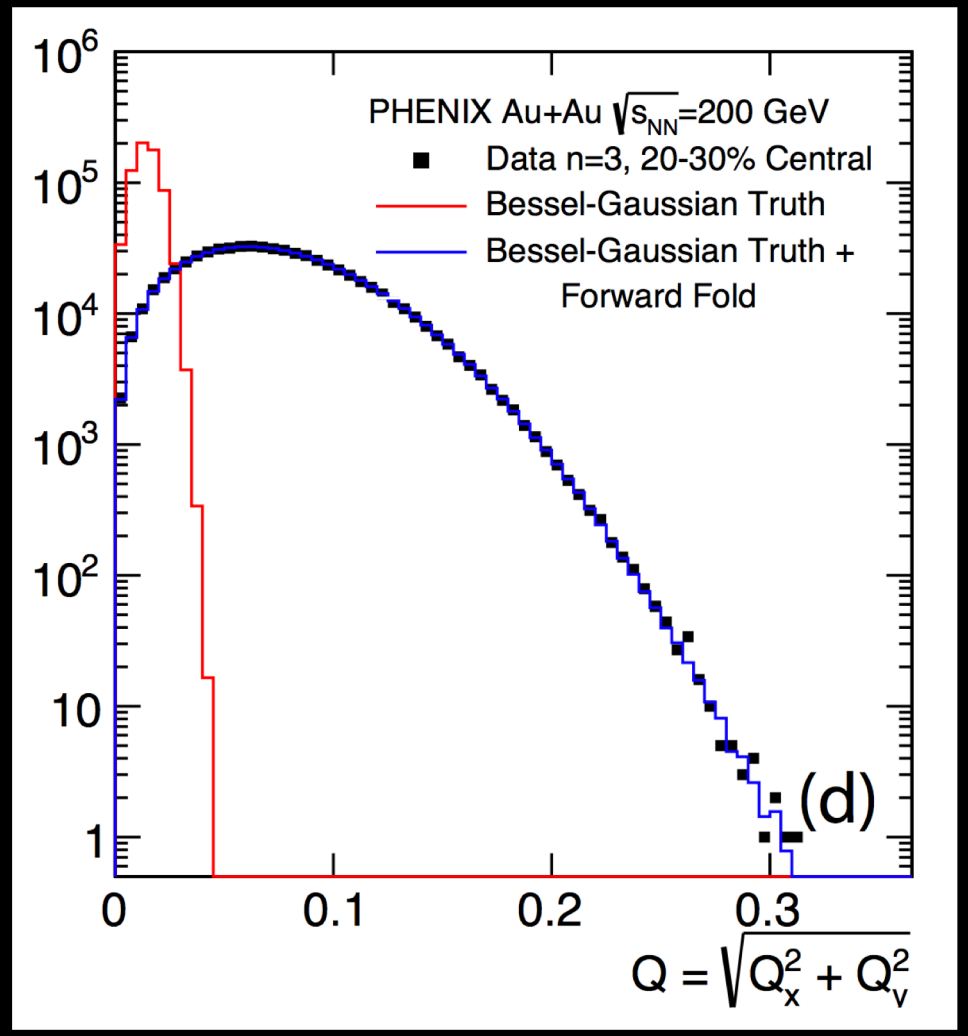


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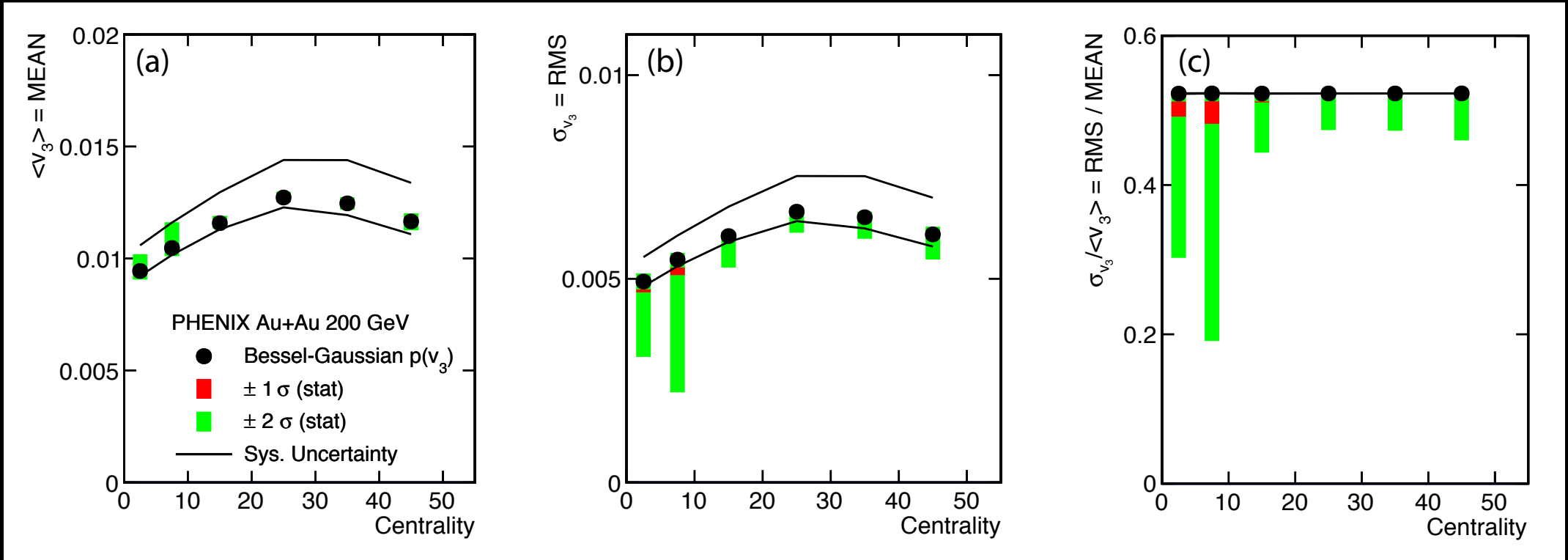


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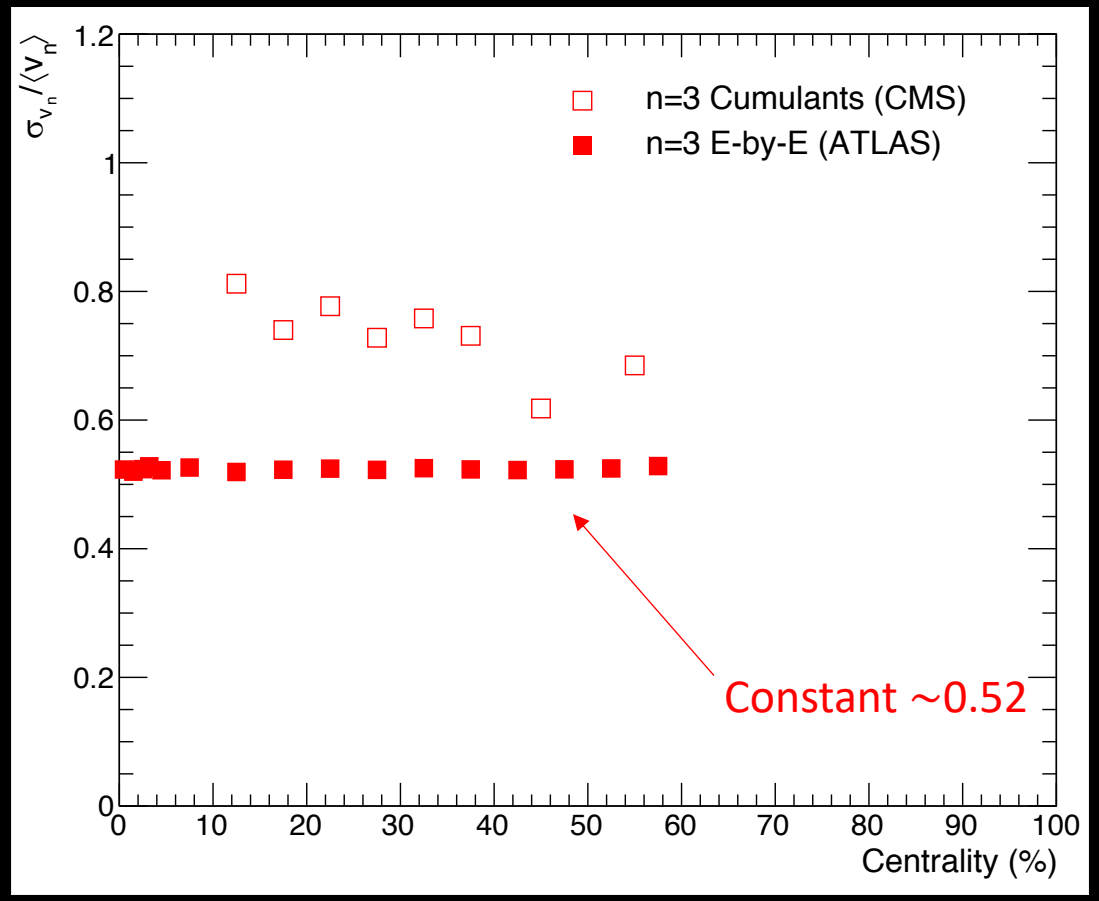
- Family of parameters give good constraints on $\langle v_3 \rangle$ and $\sigma_3$
- Relative fluctuation at constant value of 0.52 – a feature of the Bessel-Gaussian in the large fluctuation limit

# $v_3$ Fluctuations

**n = 3:** Cumulants disagree with E-by-E

➡ Driven by geometry fluctuations




ATLAS: J. High Energy Phys. 11 (2013)
CMS: Phys. Rev. C 89, 044906 (2014)

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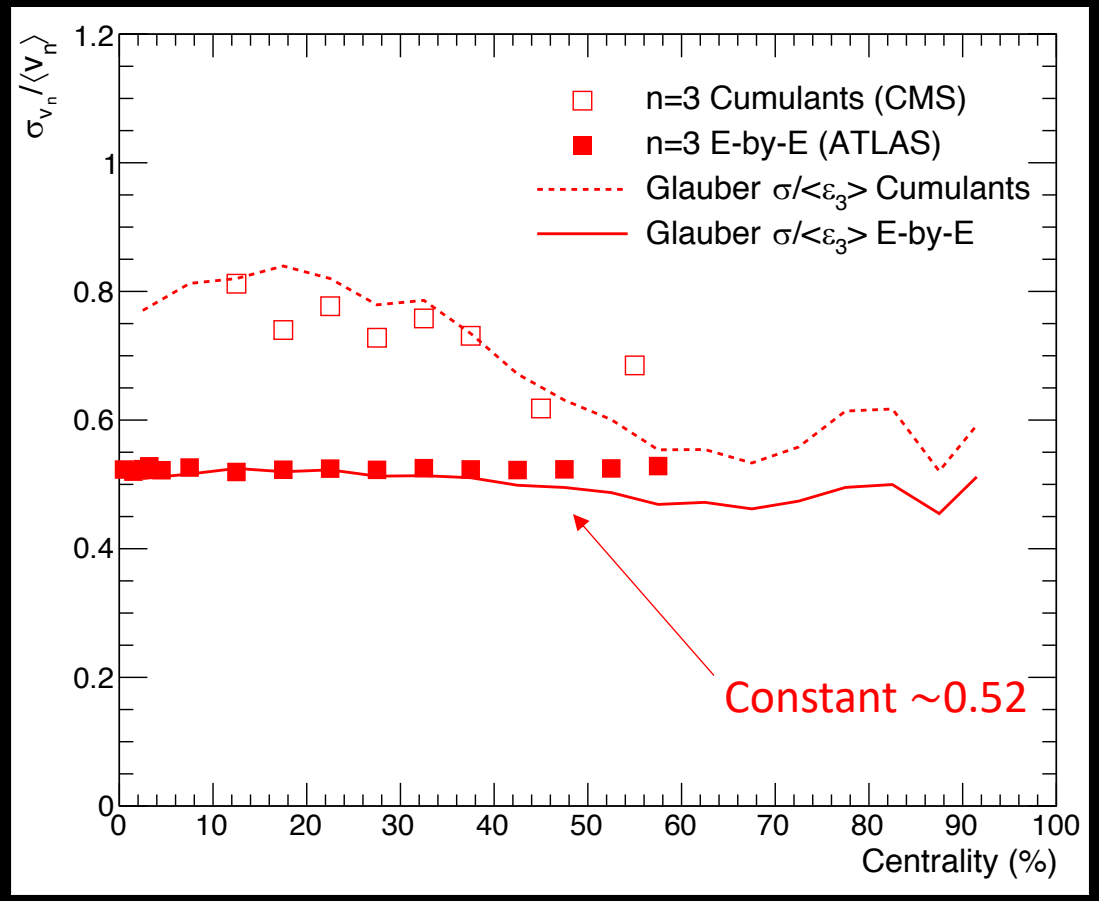
Glauber reproduces same behavior

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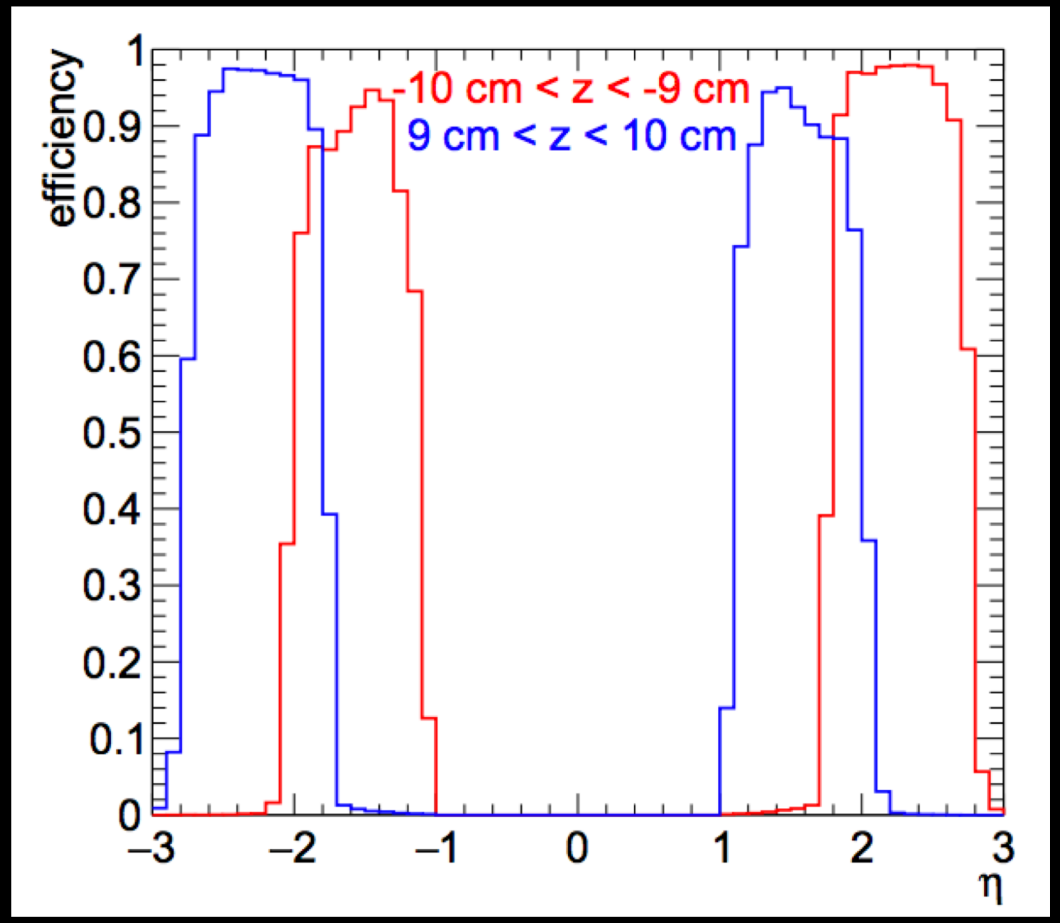
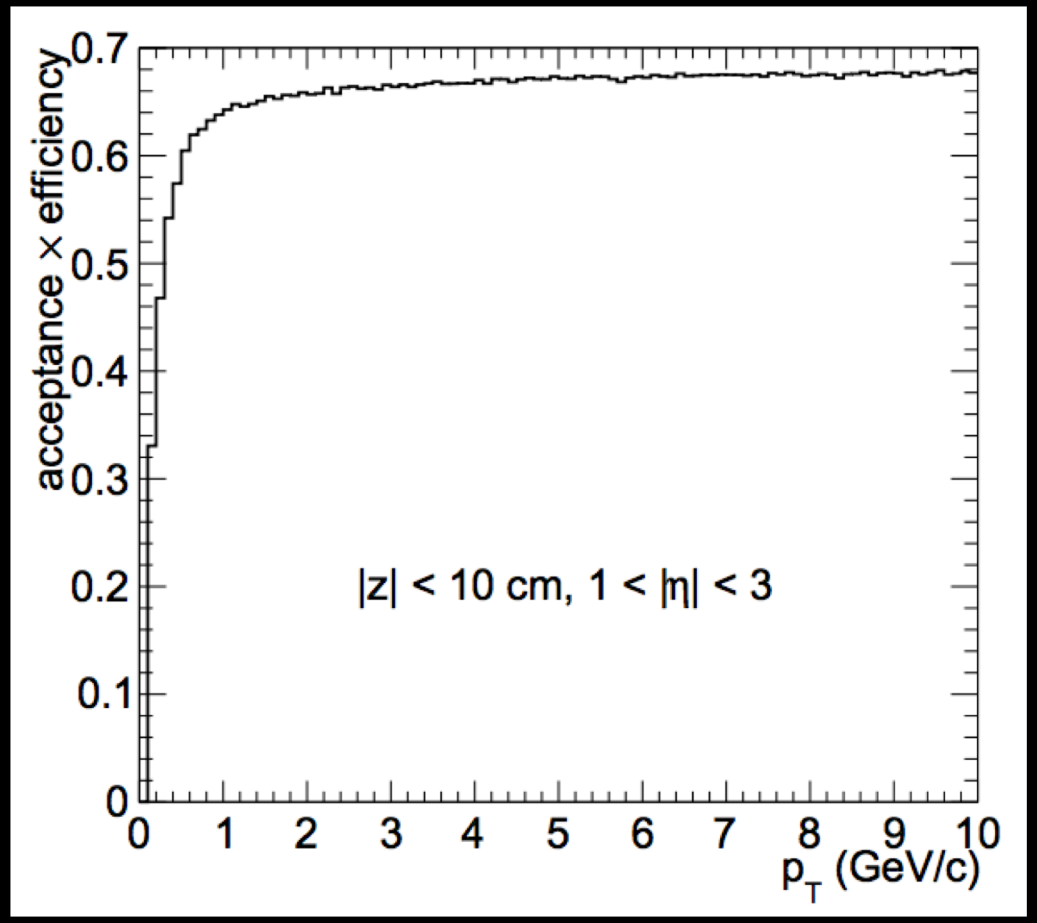
# Summary

- PHENIX has measured cumulants and Bessel-Gaussian parameters for $v_2$ and $v_3$ at forward rapidity
- $v_2$ results consistent with small variance *except* in most central and most peripheral
- $v_3$ results consistent with large variance limit
- $v_3\{4\}$ complex suggesting larger fluctuations at RHIC than LHC

# Thank You!

# FVTX efficiency

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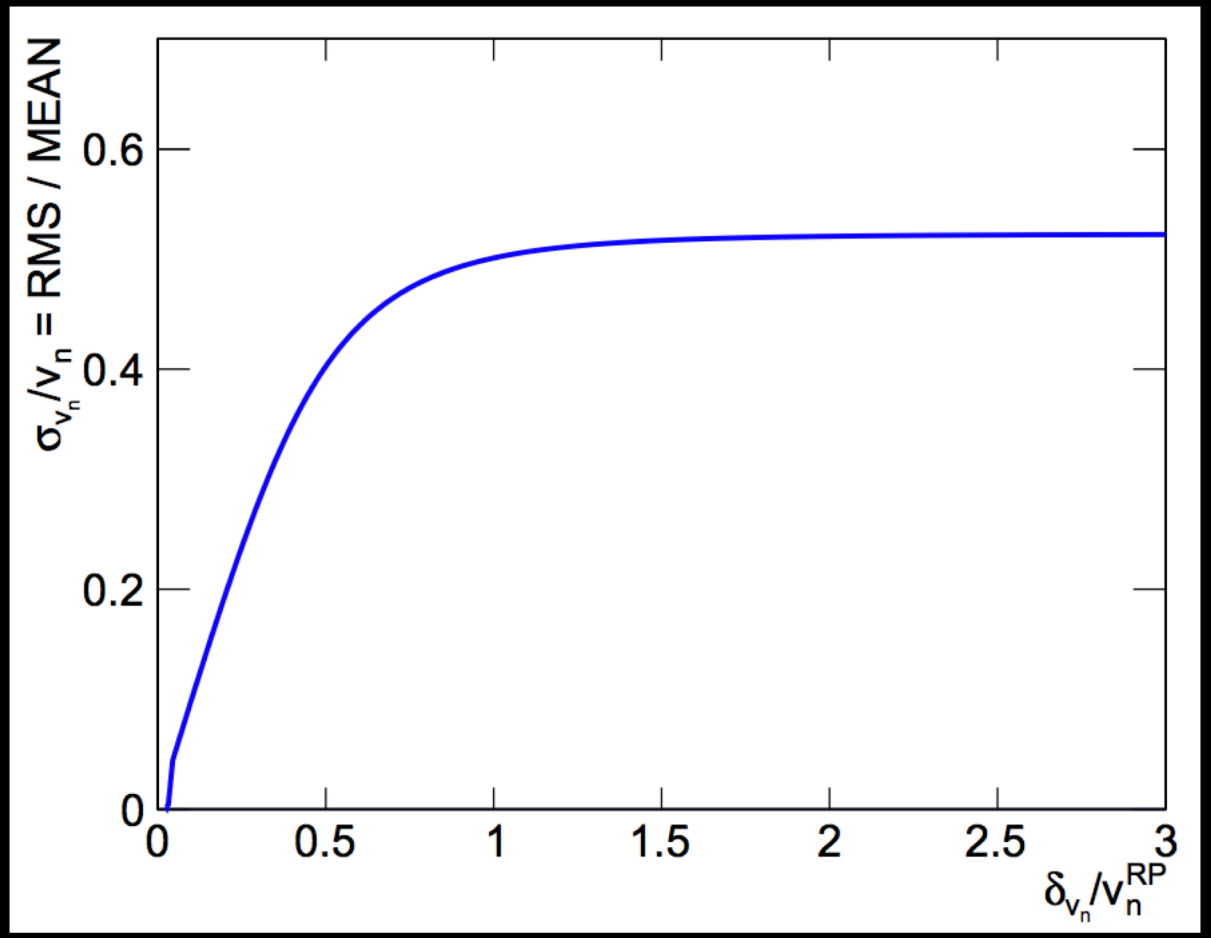
# Bessel-Gaussian fluctuations

Observed relative fluctuation saturates in the large intrinsic fluctuation limit

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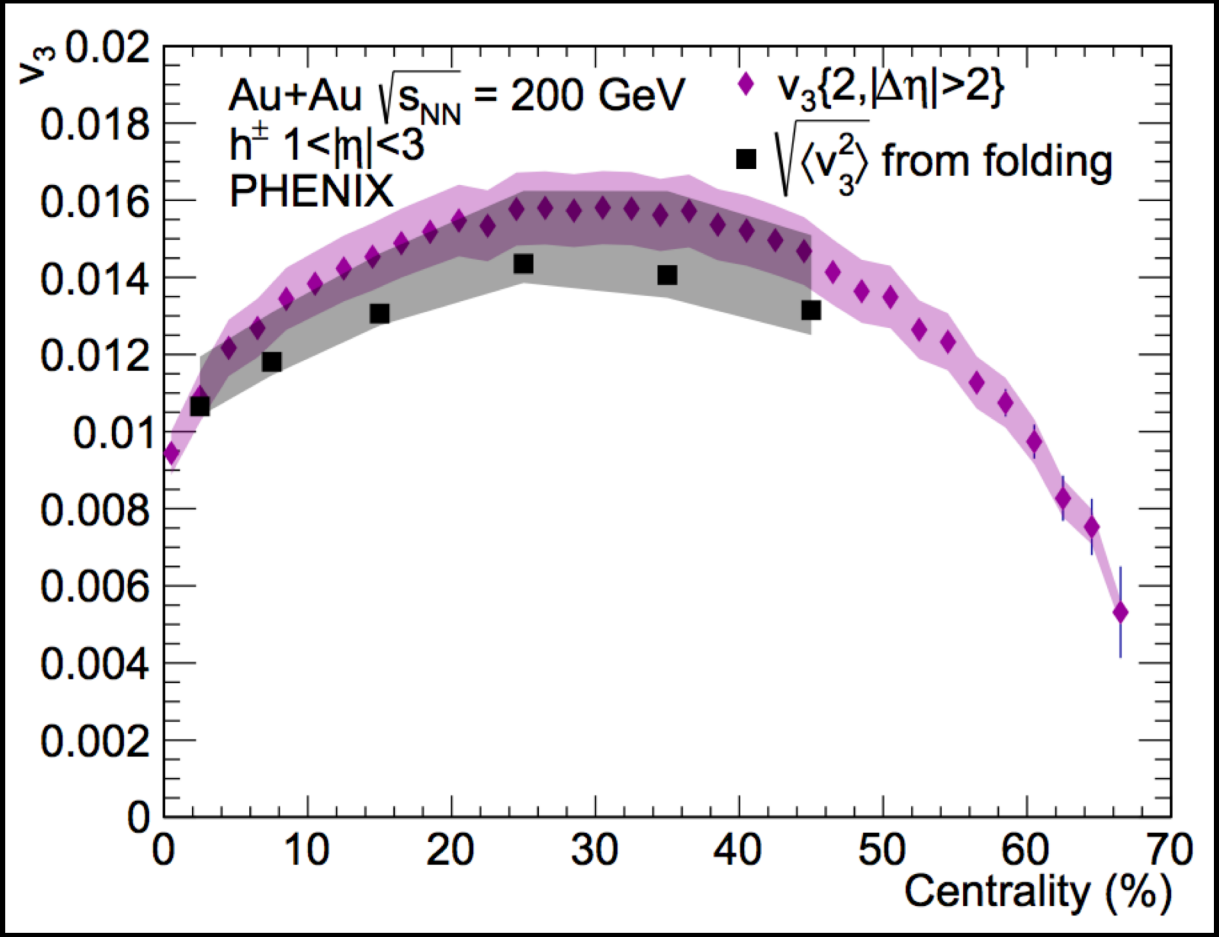
# $v_3$ method comparison

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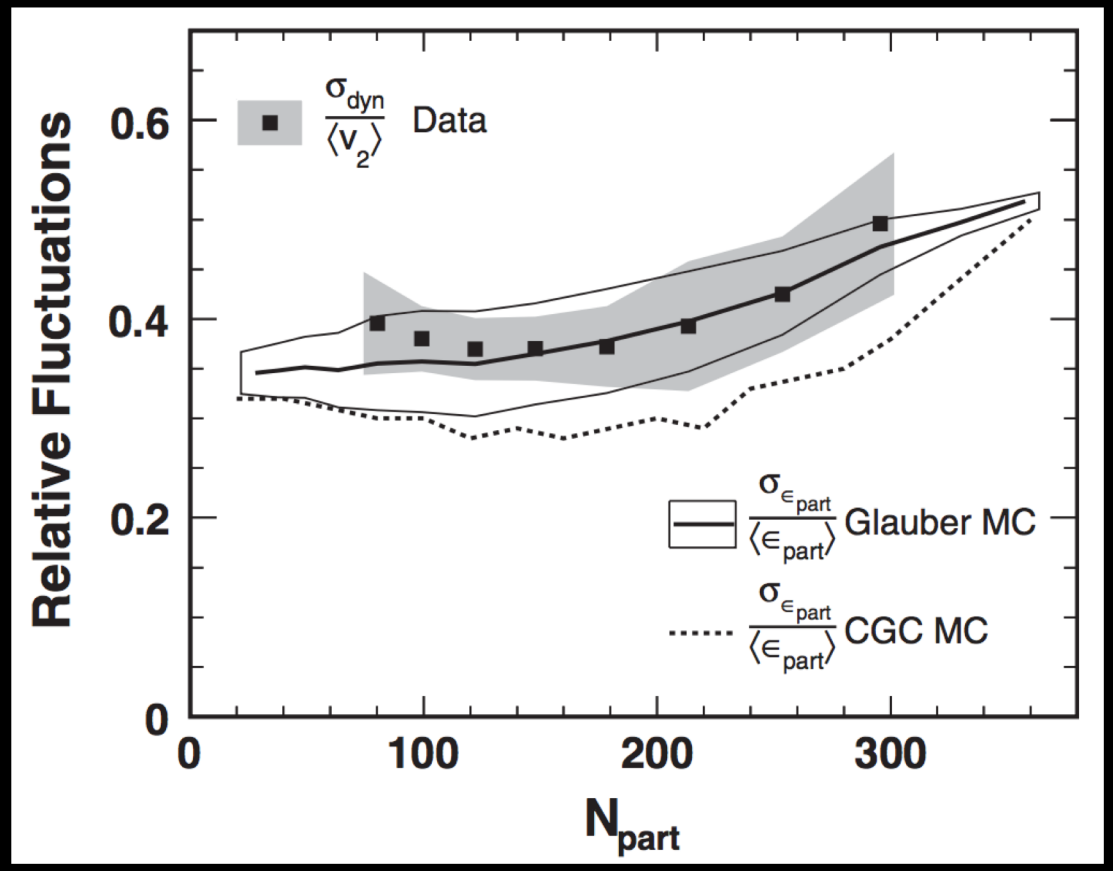
# PHOBOS fluctuations




Phys. Rev. Lett. **104**, 142301