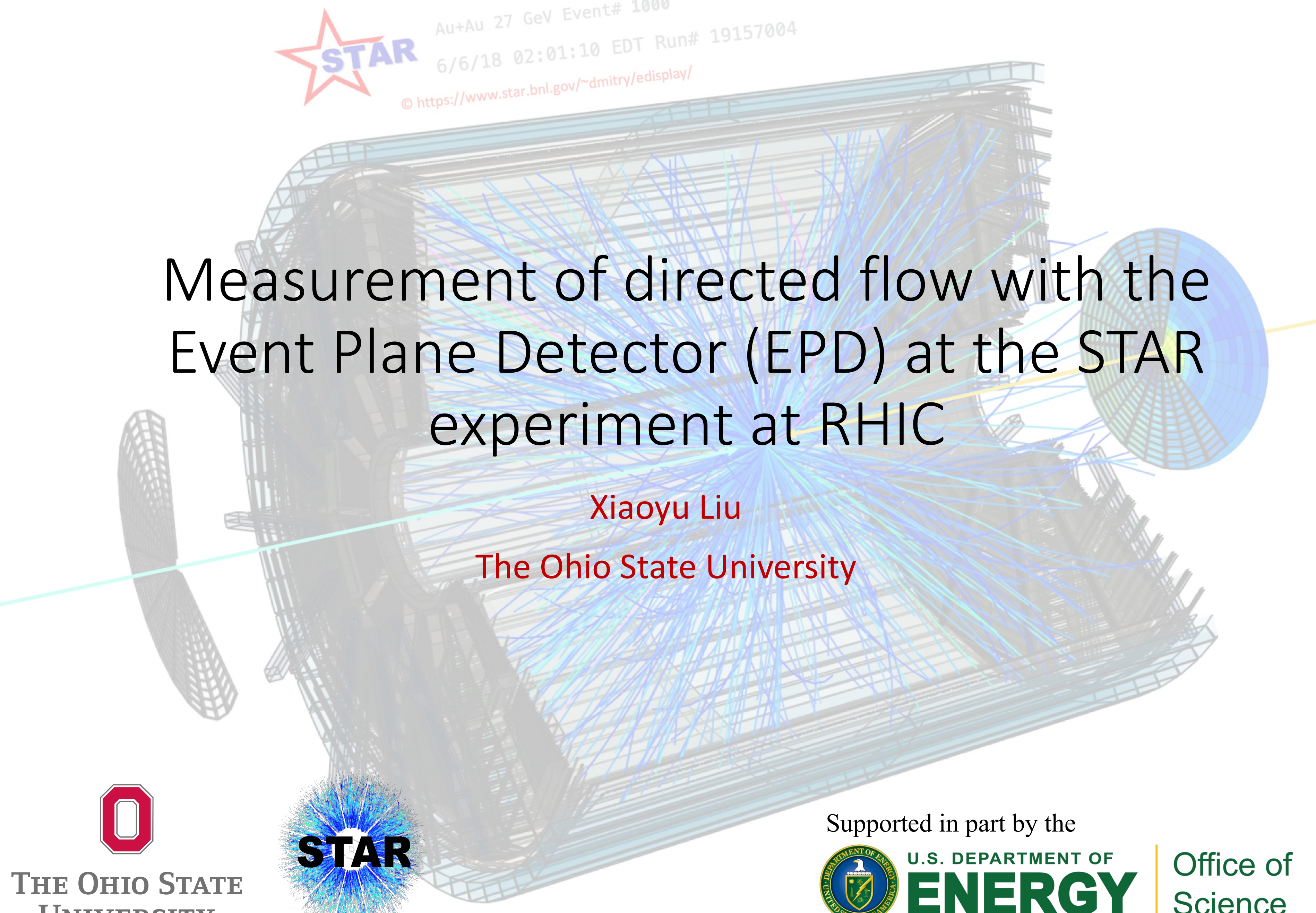

Measurement of directed flow with the Event Plane Detector (EPD) at the STAR experiment at RHIC

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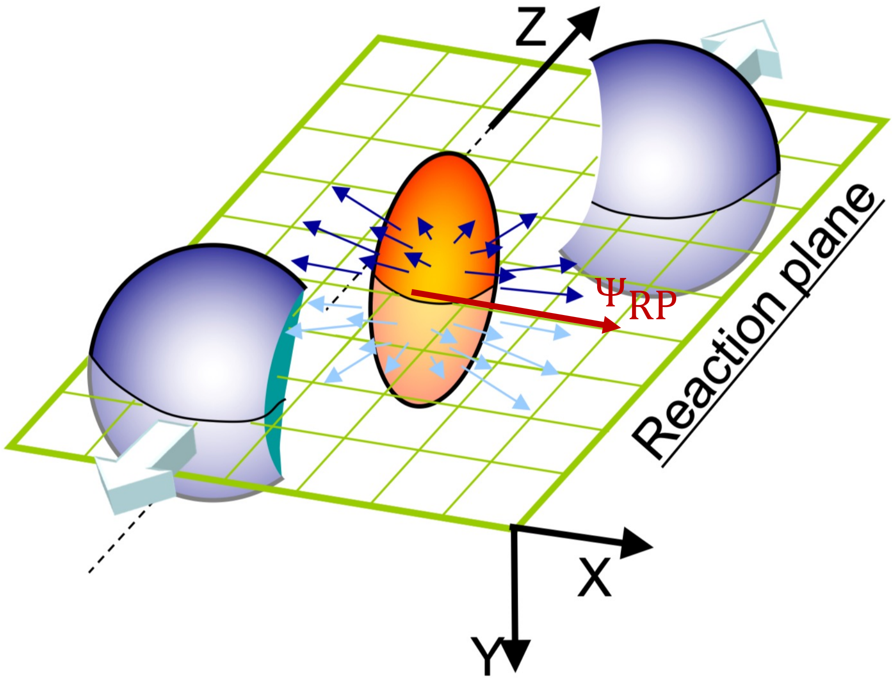
THE OHIO STATE UNIVERSITY

STAR

Supported in part by the U.S. DEPARTMENT OF ENERGY | Office of Science

Anisotropic Flow (v_n)

[1] Poskanzer, Arthur M., and Sergei A. Voloshin. Physical Review C 58.3 (1998): 1671



- Flow measures the space-momentum correlation of final state particles.

- It can be quantified by the harmonic in the Fourier expansion of azimuthal particle distribtuion with respect to the reaction plane (Ψ_{RP}) [1]:

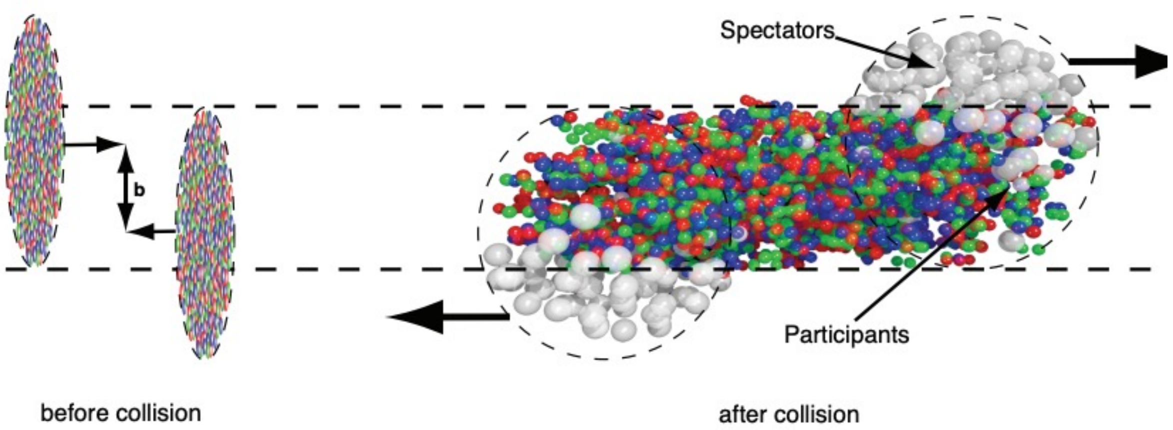
$$\frac{\mathrm{dN}}{\mathrm{d}(\phi - \Psi_{\mathrm{RP}})} = k\{1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\phi - \Psi_{\mathrm{RP}})]\}$$

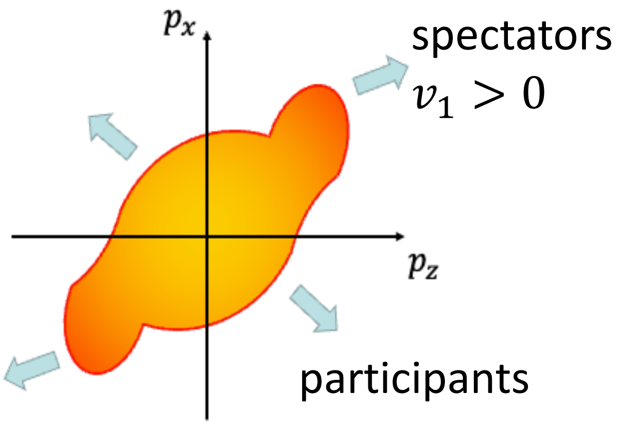
Directed Flow at Forward/Backward η

[2] STAR. Physical Review Letters 101.25 (2008): 252301

- Directed flow (v_1) describes the collective sideward motion of produced particles and nuclear fragments in heavy-ion collisions.

- It probes the system at the early non-equilibrium stage because the deflection takes place during the passing time of the colliding nuclei [2].





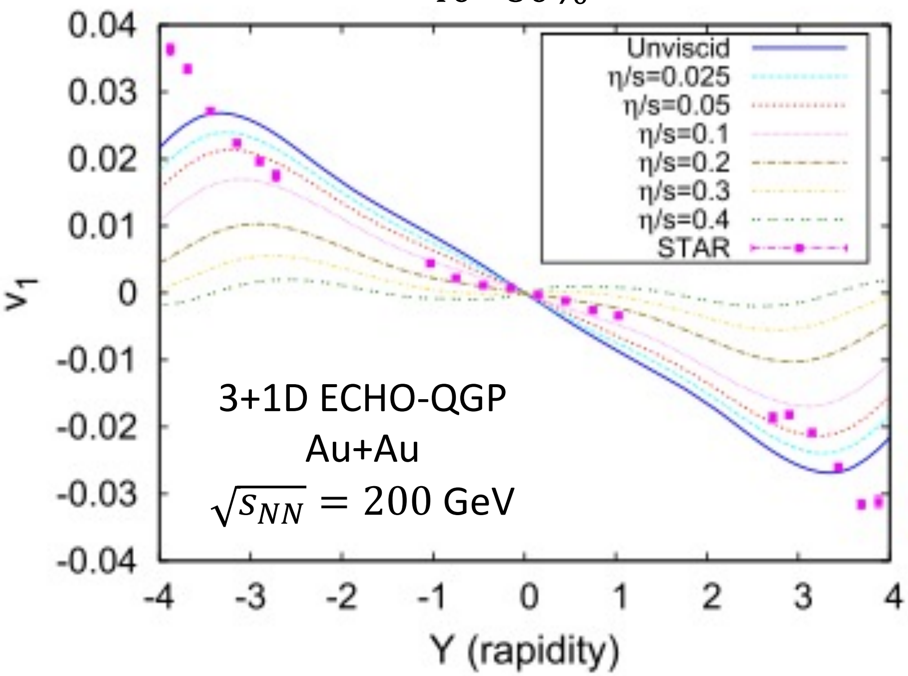
[2] Becattini, F., et al. The European Physical Journal C 75 (2015)
[3] Du, Lipei, et al. arXiv preprint arXiv:2211.16408 (2022)

Motivation

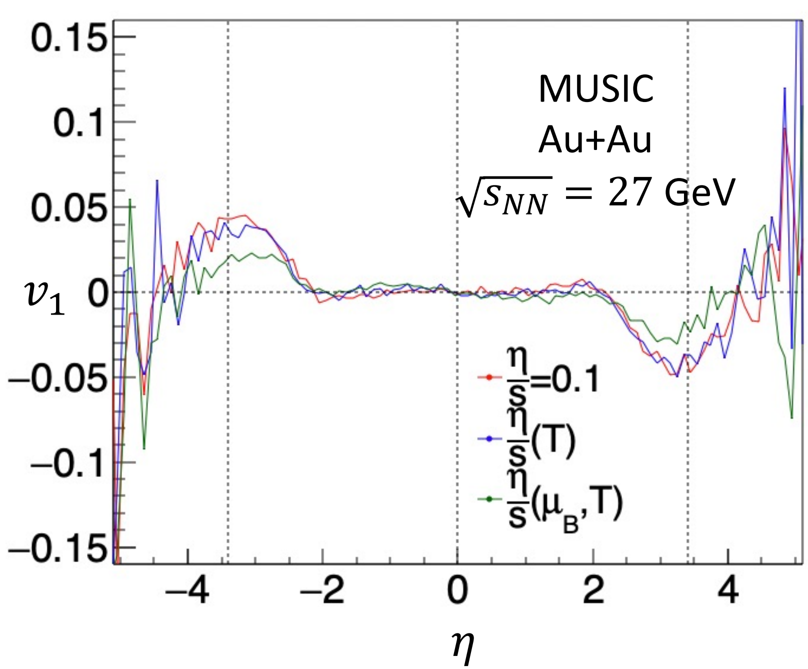
- The pseudorapidity (η) dependence of v_1 can provide unique constraints on the shear viscosity of the QCD matter ($\frac{\eta}{s}(T, \mu_B)$) [2].

- Measuring $v_1(\eta)$ in both spectator and participant regions may provide insights into the baryon stopping mechanism [3].

40~80%



20~30%



Event Plane Method

- Experimentally, the reaction plane angle cannot be measured. So, the event plane angle is used as an approximation:

$$\Psi_n = \frac{1}{n} \arctan \frac{\sum_i w_i \sin(n\phi_i)}{\sum_j w_i \cos(n\phi_j)}$$

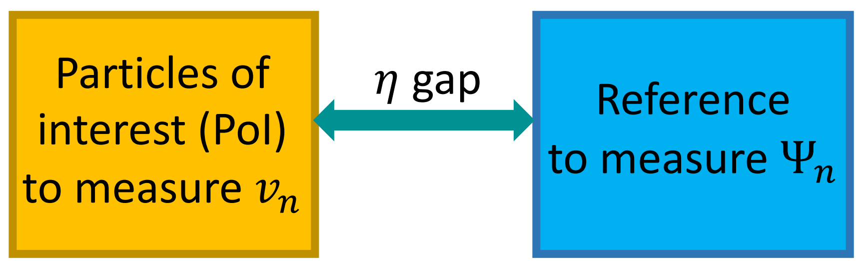
- The anisotropic flows are measured as:

$$v_n\{\mathrm{EP}\} = \frac{\langle \cos[n(\phi_i - \Psi_n)] \rangle}{R_n}$$

where R_n is the event plane resolution: $R_n = \langle \cos[n(\Psi_n - \Psi_{\mathrm{RP}}] \rangle$

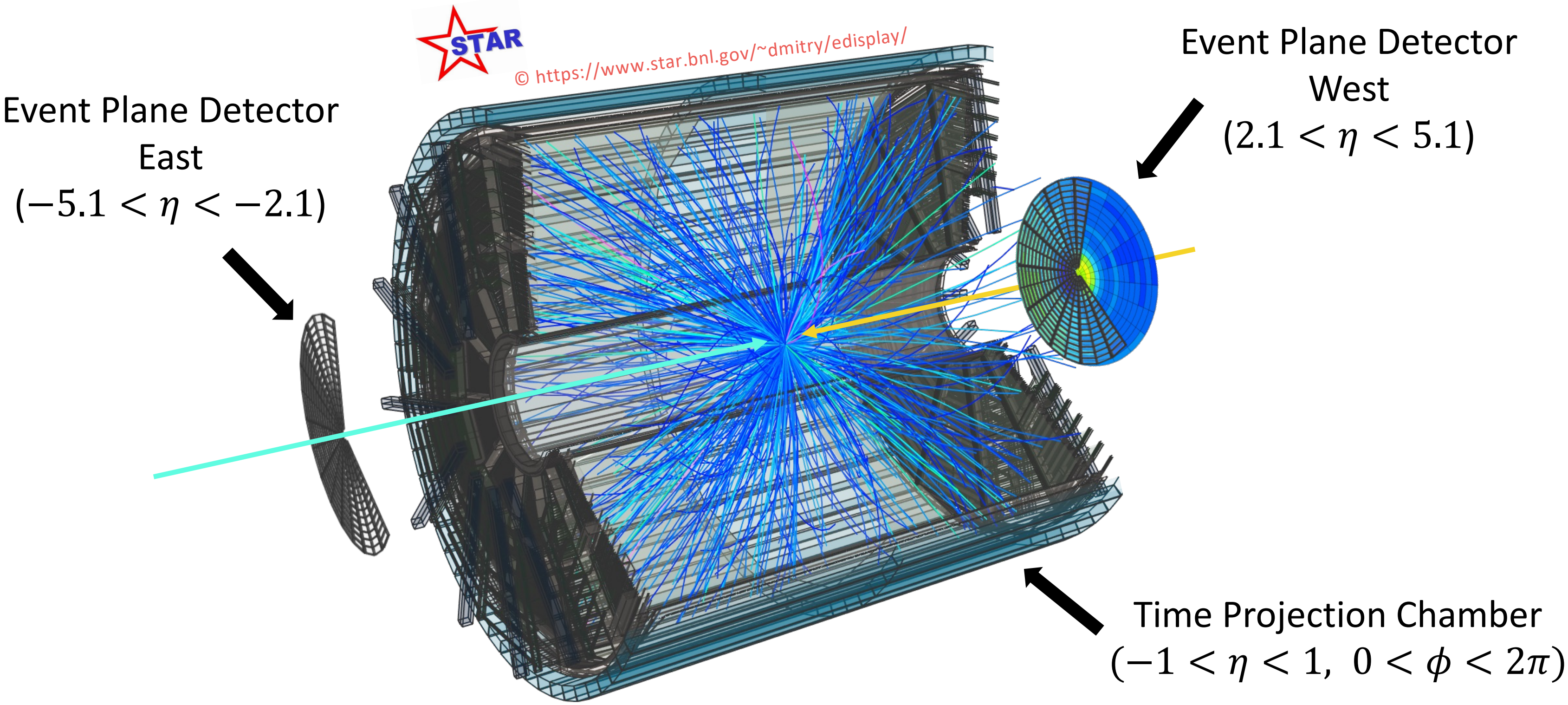
Reference matters!

Non-flow effects
resonances decay, self correlations, di-jets, momentum conservation effect…



[4] Borghini, Nicolas, et al. Physical Review C 66.1 (2002): 014901.

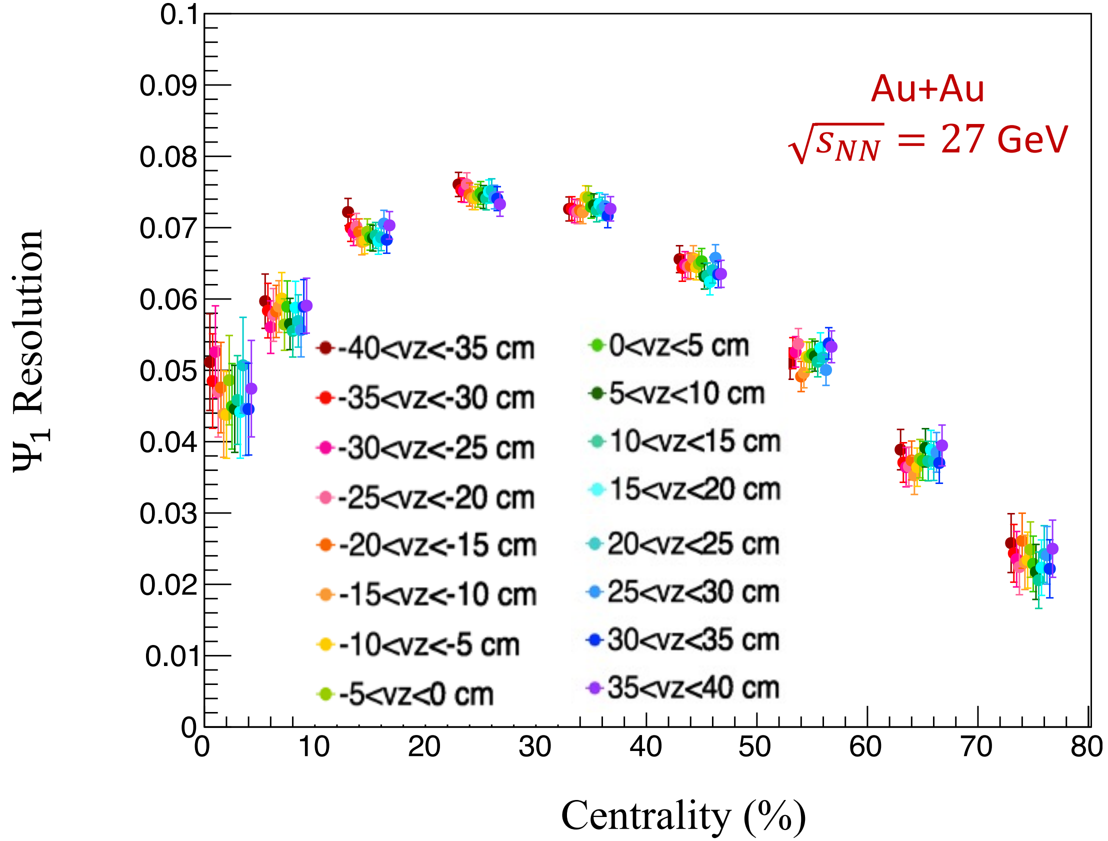
STAR Detector Subsystems



- TPC was chosen as the reference to suppress the momentum conservation effect [4].
- An η gap is imposed between the PoI and reference.

First-Order Event Plane (Ψ_1)

$$\Psi_1^{\mathrm{TPC}} = \arctan \frac{\sum_i w_i \sin \phi_i}{\sum_j w_i \cos \phi_j}$$

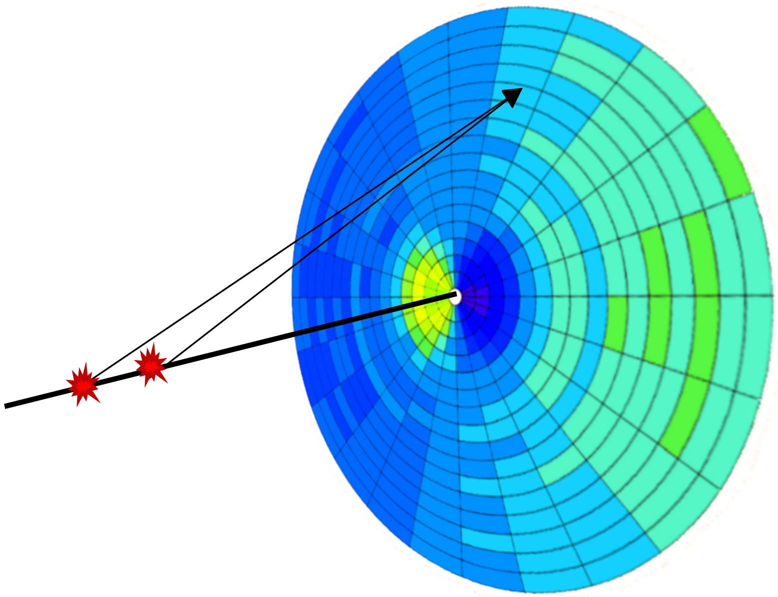


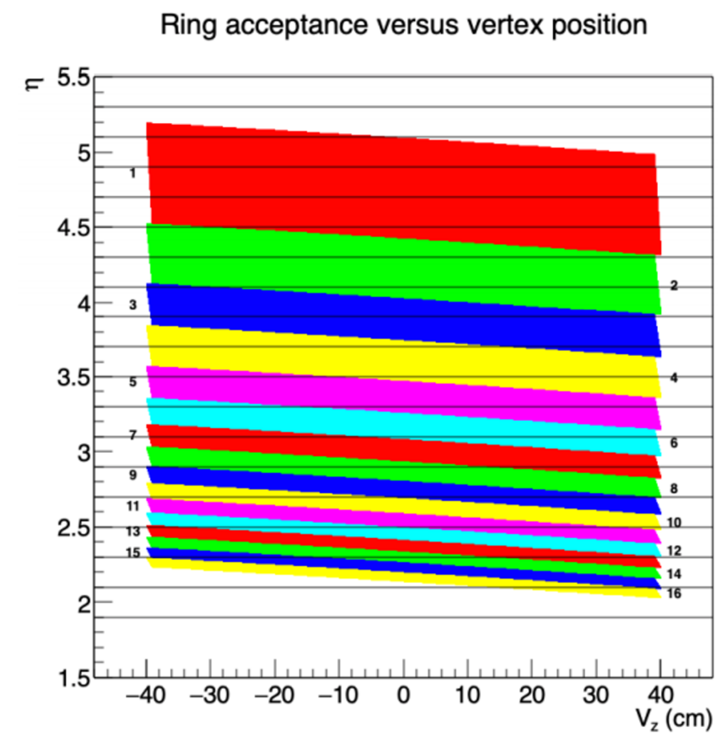
- Data points are offset along the x axis for the demonstration purpose.
- The event plane resolution is calculated by the three sub-event method:

$$R_1^{\mathrm{TPC}} = \sqrt{\frac{\langle \cos(\Psi_1^{\mathrm{TPC}} - \Psi_1^{\mathrm{EPDW}}) \rangle \langle \cos(\Psi_1^{\mathrm{TPC}} - \Psi_1^{\mathrm{EPDW}}) \rangle}{\langle \cos(\Psi_1^{\mathrm{EPDE}} - \Psi_1^{\mathrm{EPDW}}) \rangle}}$$

Event Plane Detector (EPD)

[5] Adams, Joseph, et al. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 968 (2020): 163970.



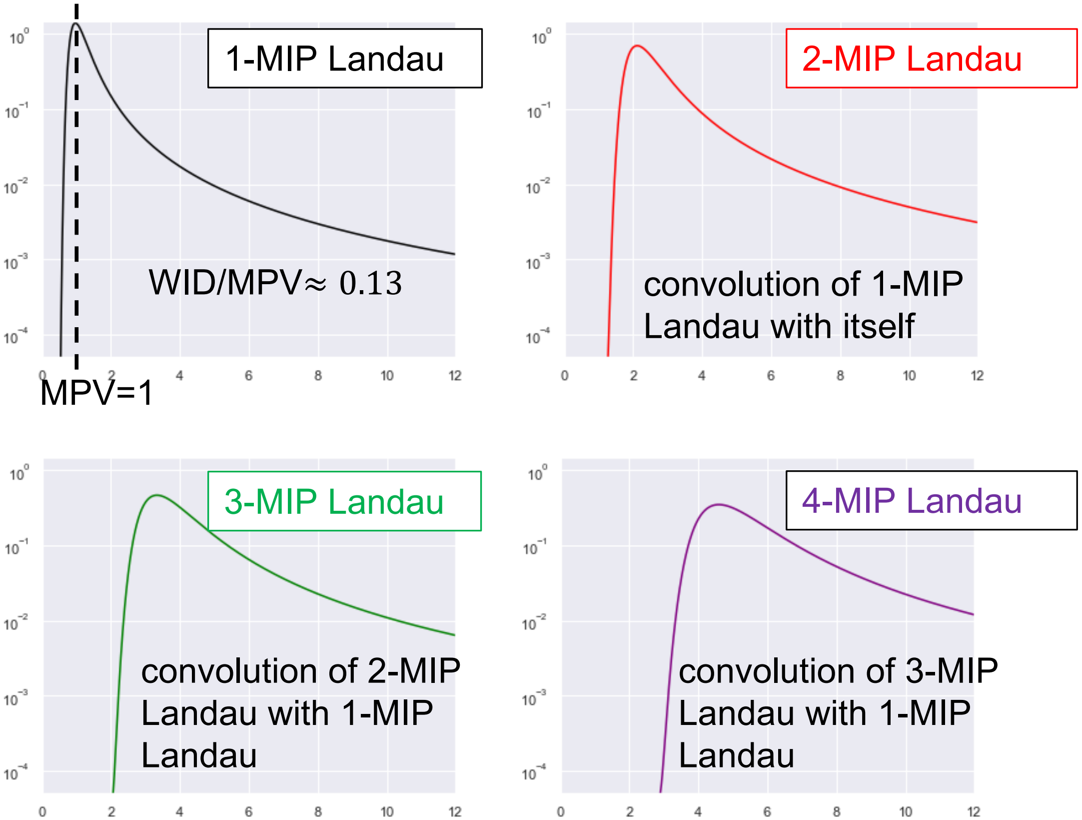


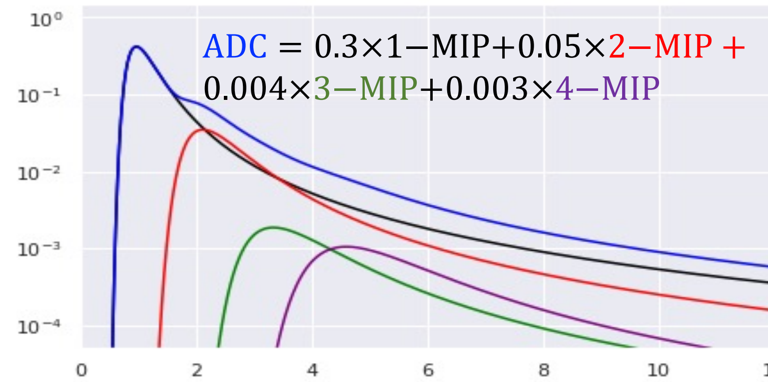
- The pseudorapidity (η) and ϕ of a EPD tile are determined by a straight line between the primary vertex and a random point on the tile.

- The number of particles traversing a tile, averaged over events, can be probabilistically determined from the ADC distributions.

ADC Spectra of EPD

MIP (Minimum Ionizing Particle)
MPV (Most Probable Value)
WID (Width)





Mean of Landau distribution is undefined

↓

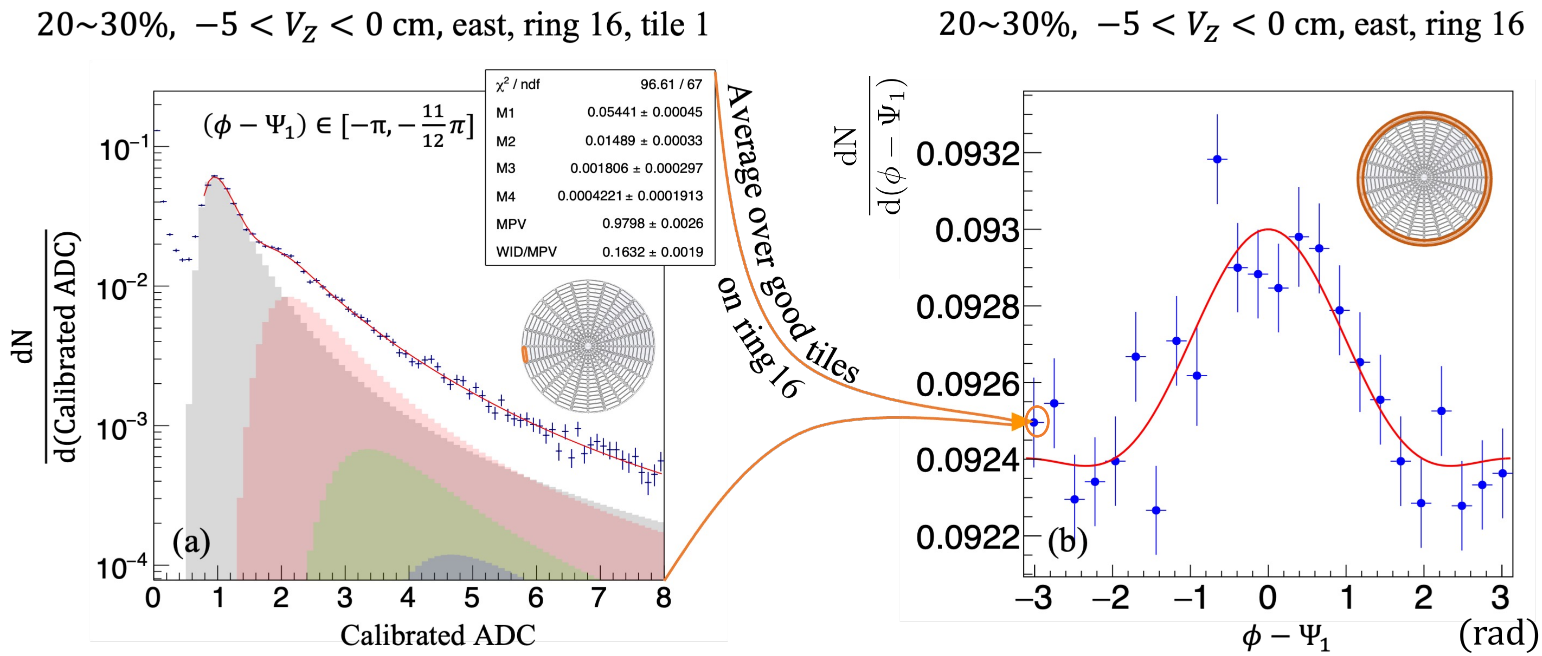
The Law of Big Number doesn't apply

↓

Averaged ADC ≠ Averaged number of particles.

- WID/MPV only depends on the material and thickness of the detector
- The function forms of all the Landau distributions are known

Extracting v_1



- The M_k in the fitting parameters represents the fraction of the k-MIP events. Therefore, the averaged number of MIPs can be calaculated by:

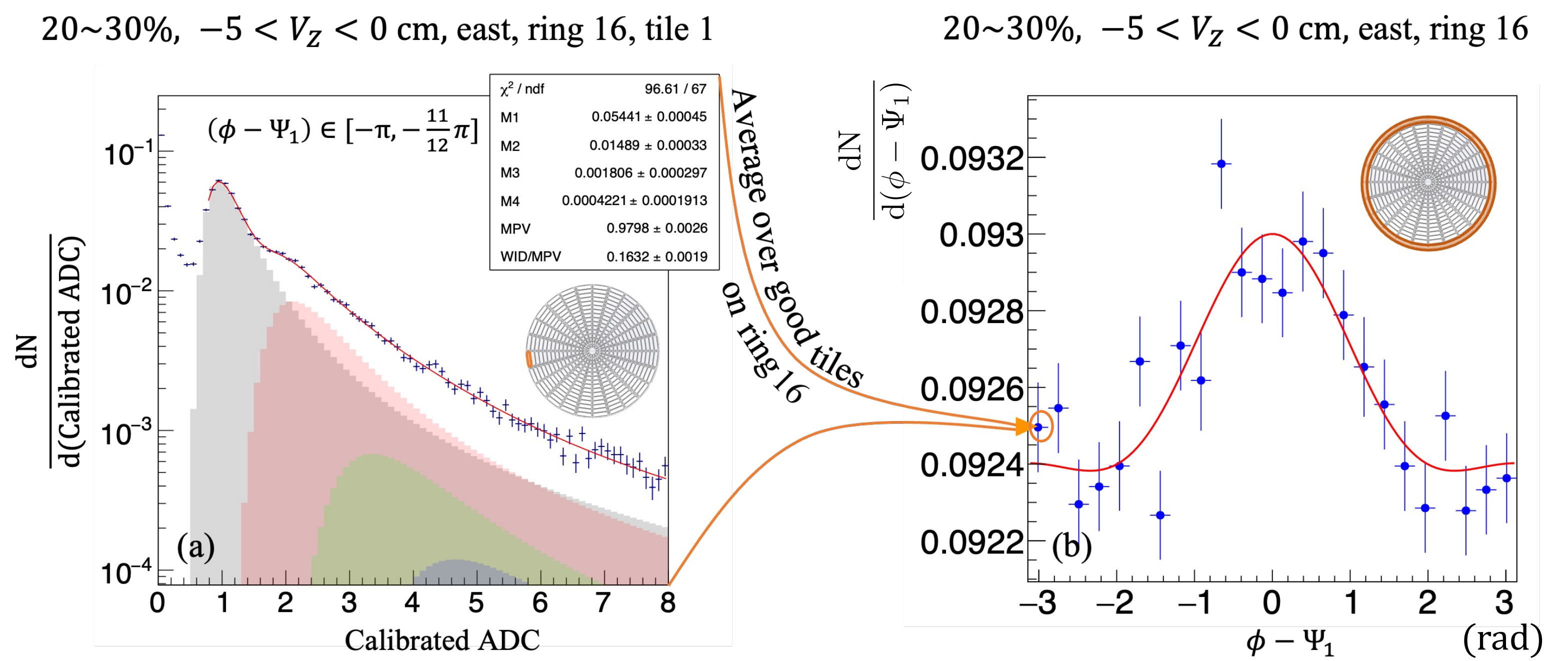
$$N = \sum_{k=1}^{k=4} k \times M_k$$

- The associated error can be calculated by:

$$\sigma^2 = \mathbf{k\Sigma k}^\top, \mathbf{k} = (1, 2, 3, 4)$$

where $\boldsymbol{\Sigma}$ is the covariance matrix of M_k.

Extracting v_1



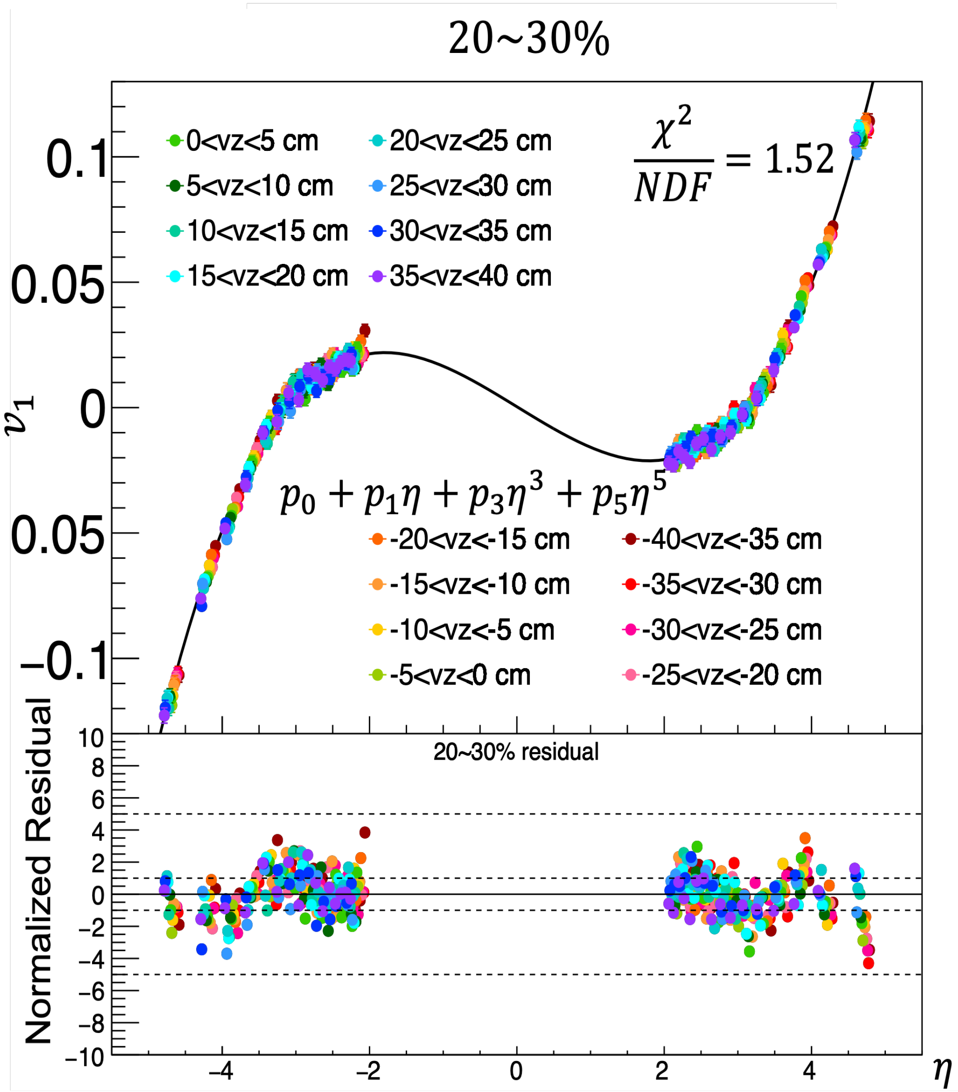
- v_1 (before the resolution correction) can be extracted by fitting the Fourier decomposition of the $(\phi - \Psi_1)$ distribution:

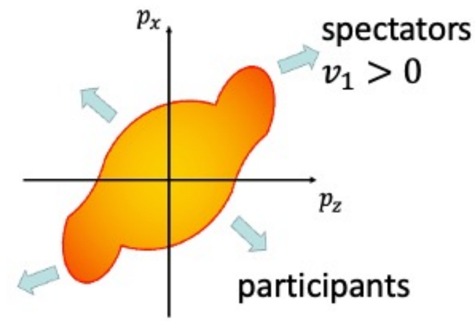
$$\frac{\mathrm{dN}}{\mathrm{d}(\phi - \Psi_1^{\mathrm{TPC}})} = k\{1 + 2v_1 \cos(\phi - \Psi_1^{\mathrm{TPC}}) + 2v_2 \cos[2(\phi - \Psi_1^{\mathrm{TPC}})]\}$$

- v_1 needs to be corrected by the Ψ_1^{TPC} resolution:

$$v_1 = \frac{v_1^{\mathrm{uncorrected}}}{R_1^{\mathrm{TPC}}}$$

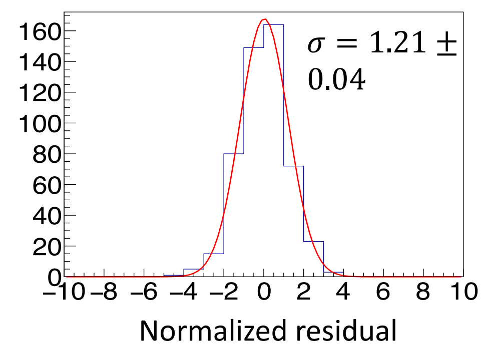
v_1 for 16 V_z Bins



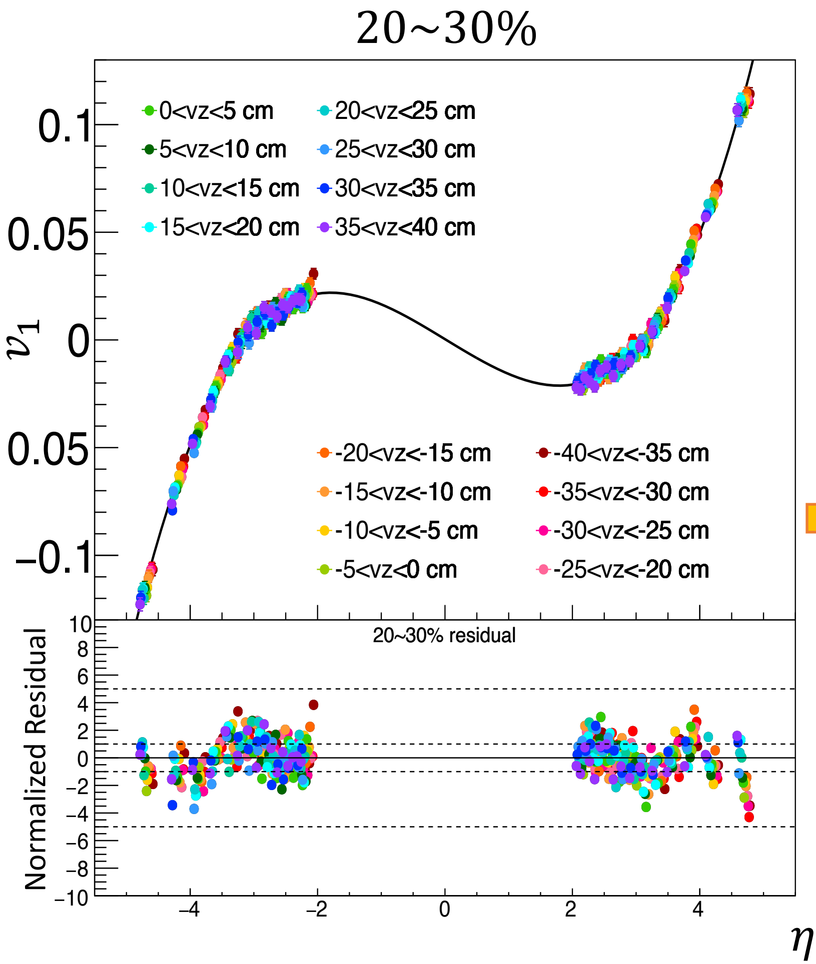


✓ fluctuation and error bars of the data points are reasonable.

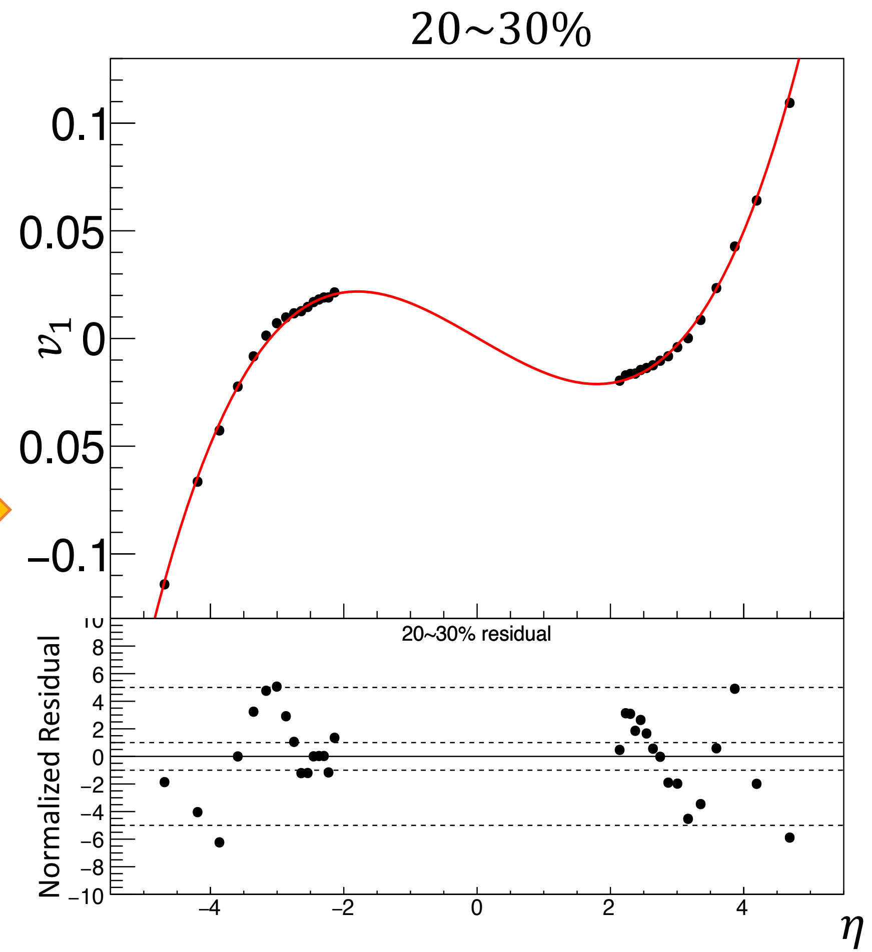
Project on the Y axis



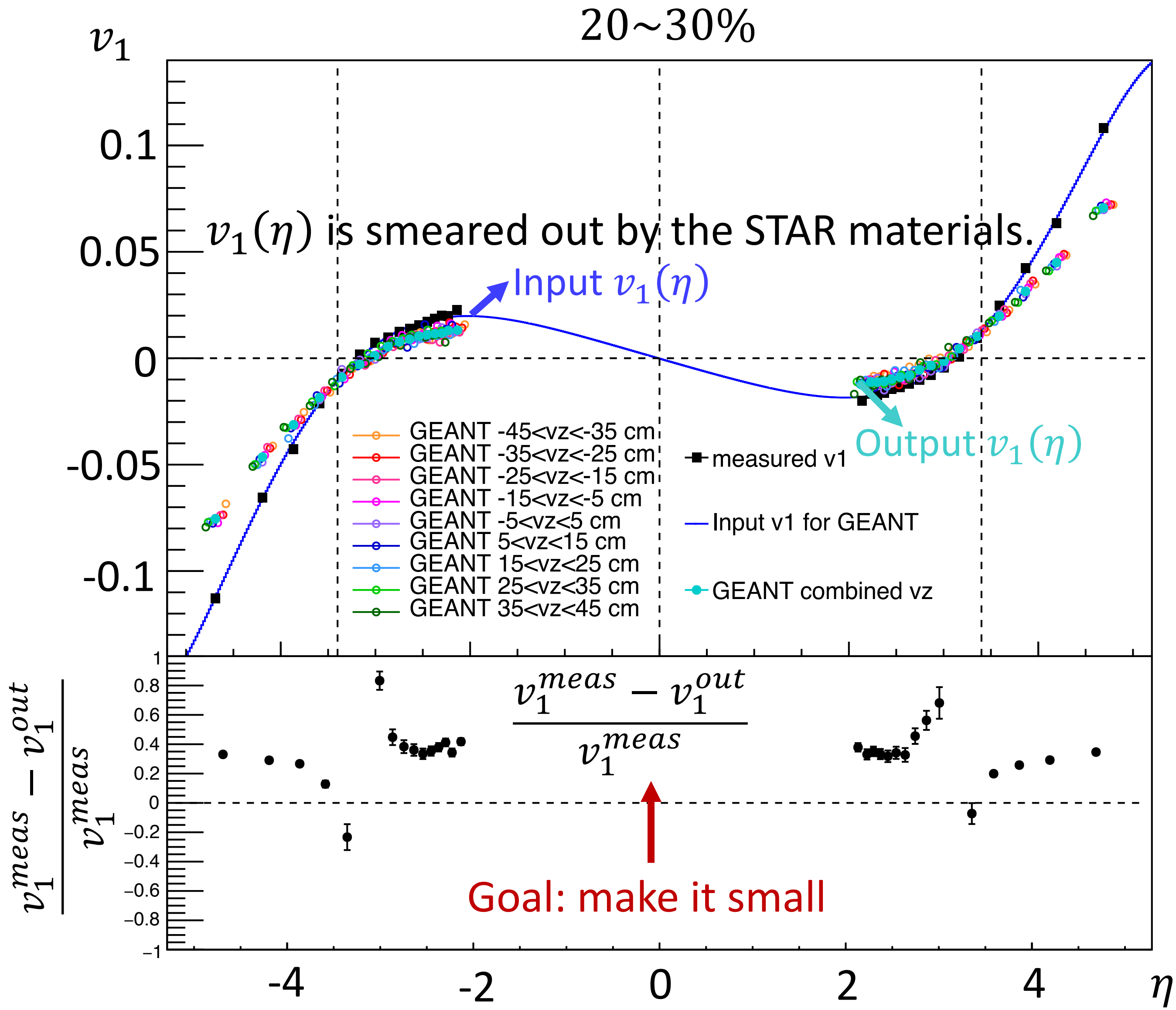
Combine 16 V_z Bins



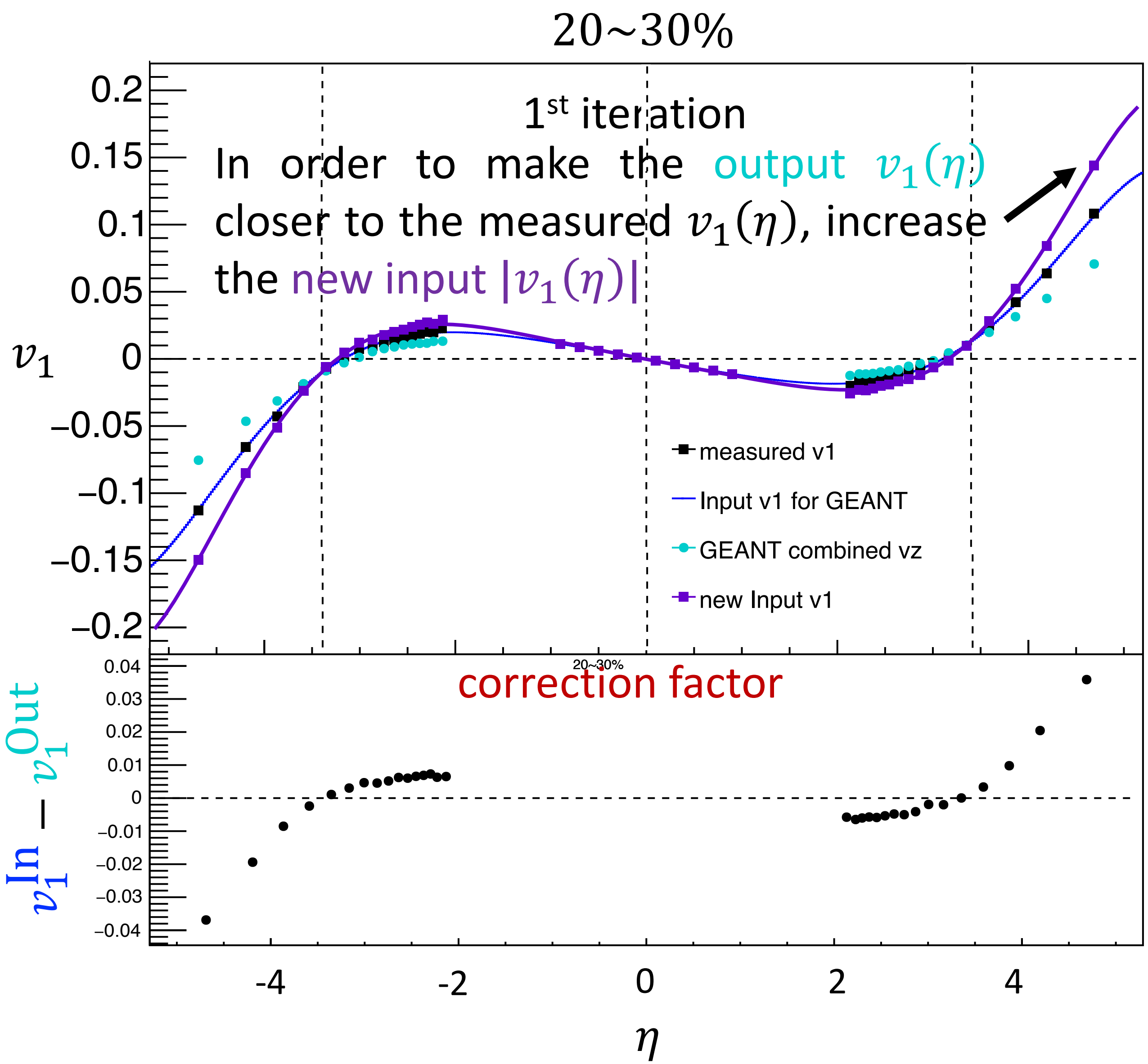
Group every 16 points along η by taking the average of η and v_1



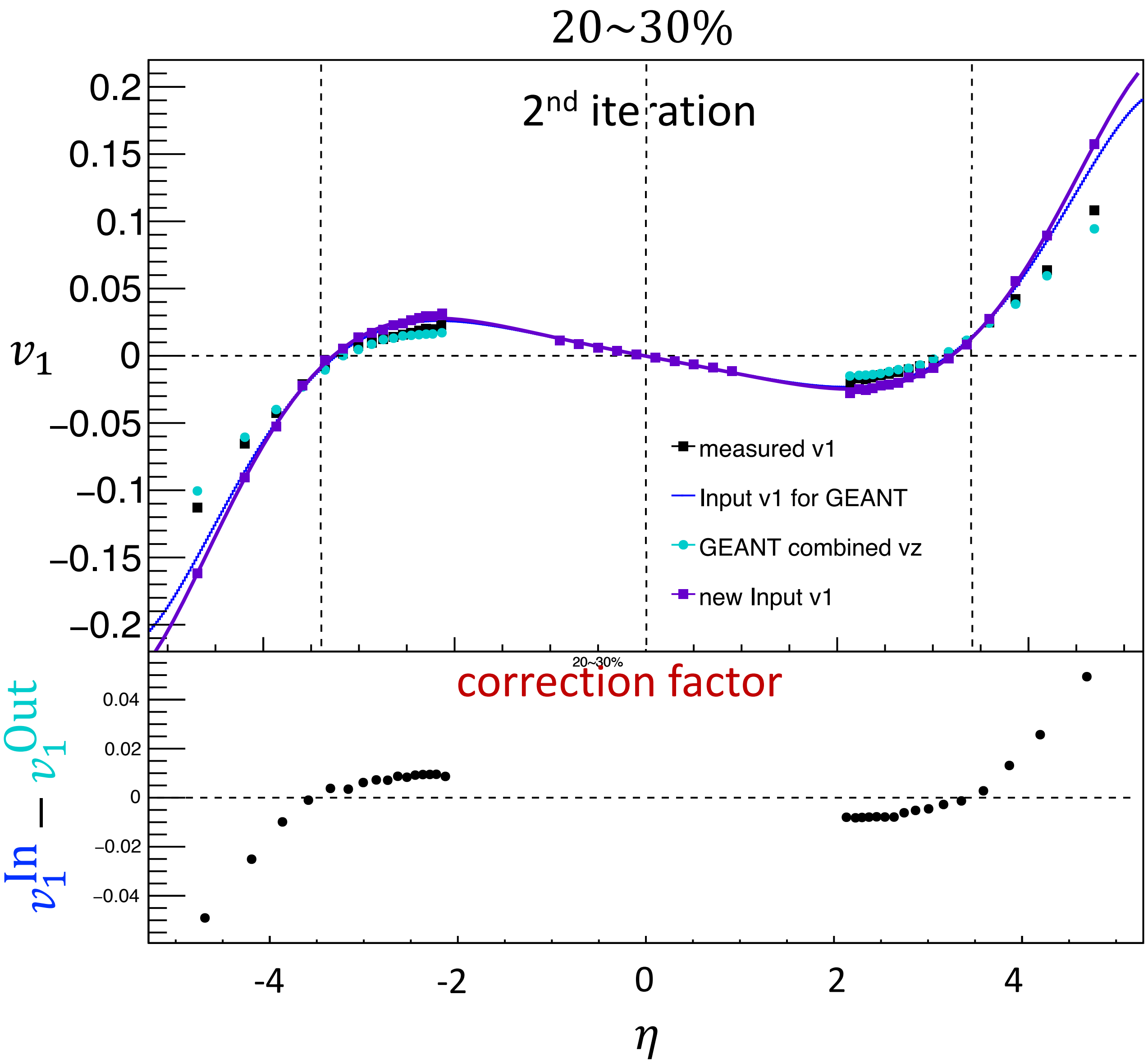
STAR Materials Smear Out v_1



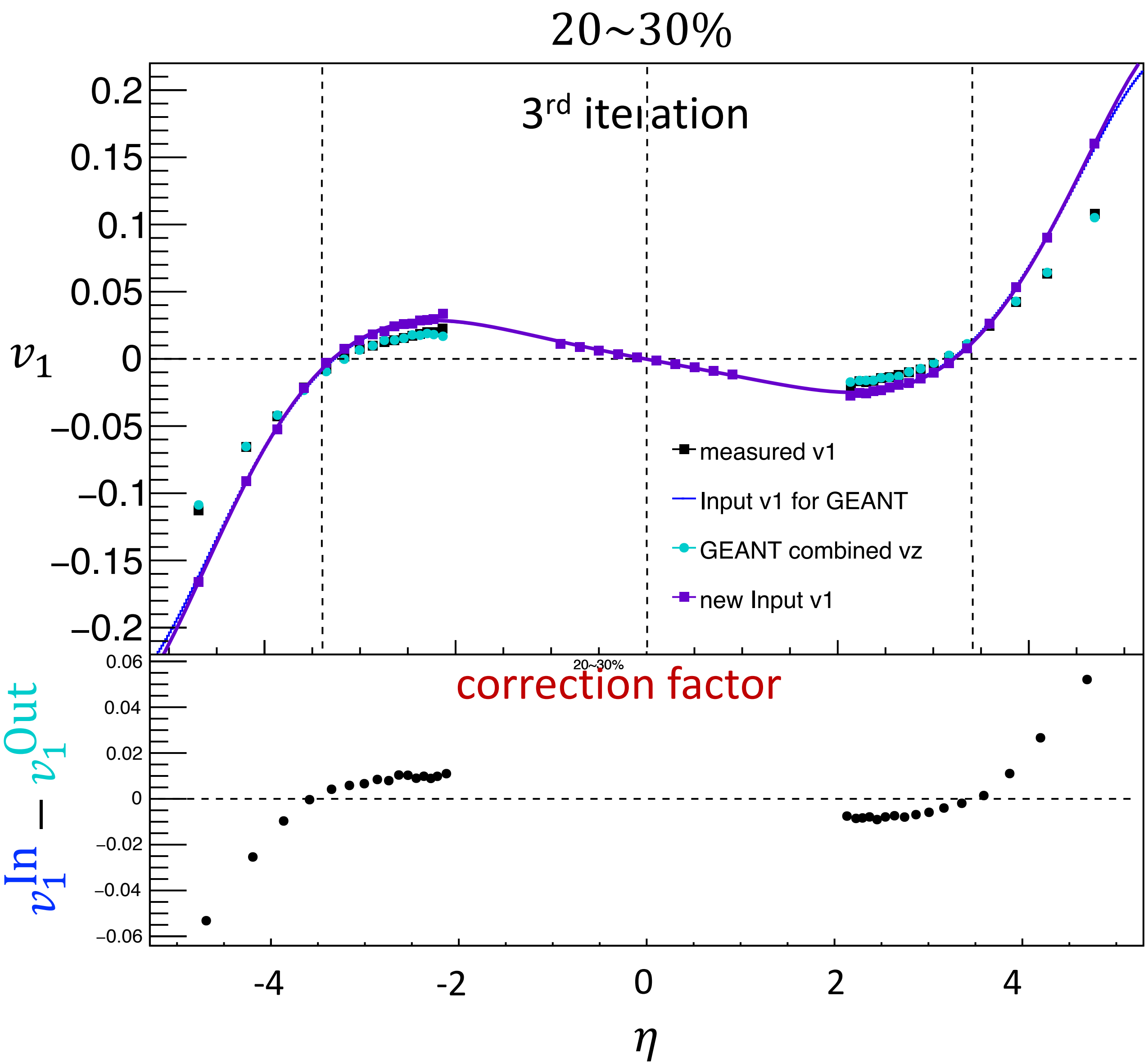
Iteration Process



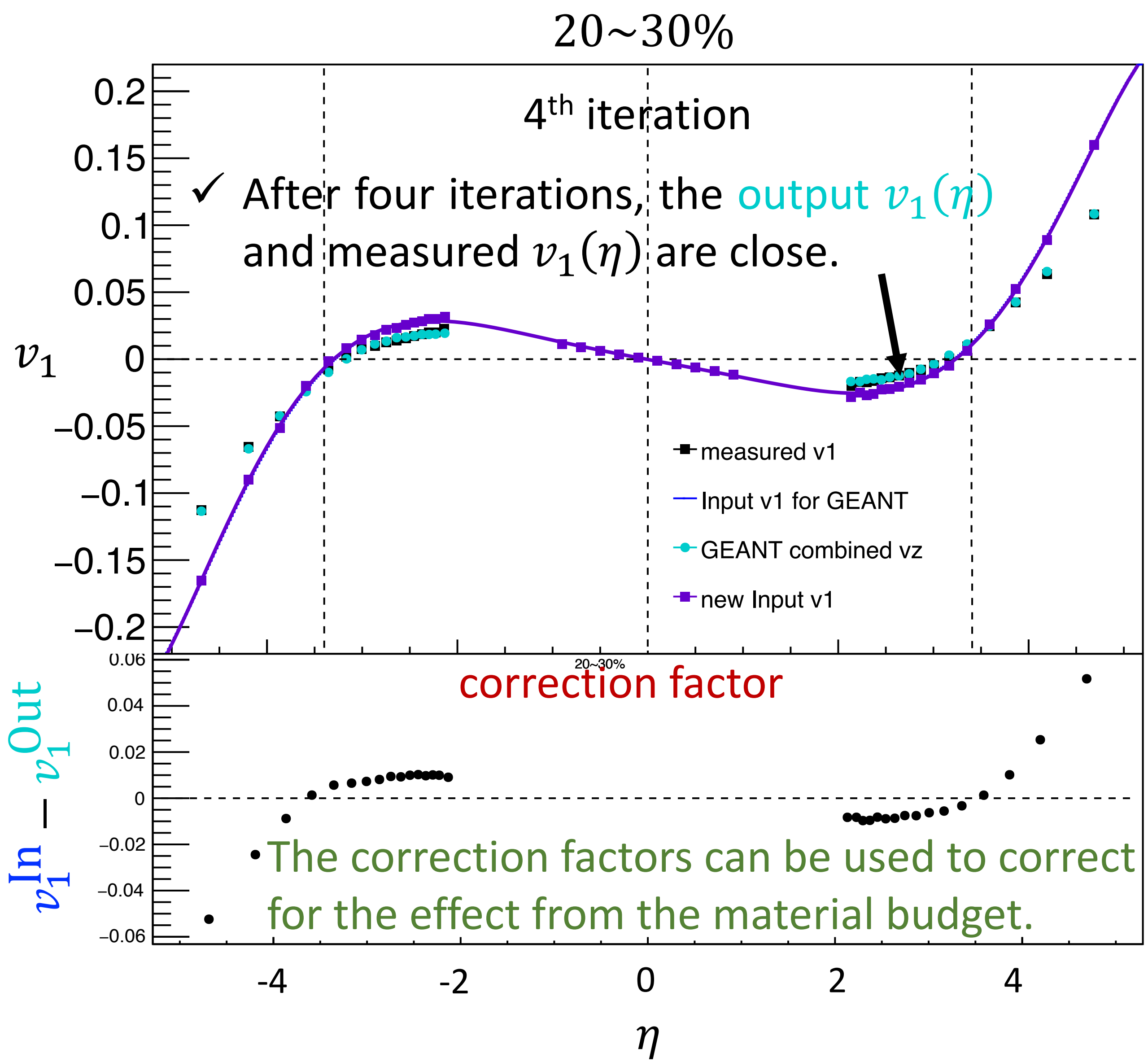
Iteration Process



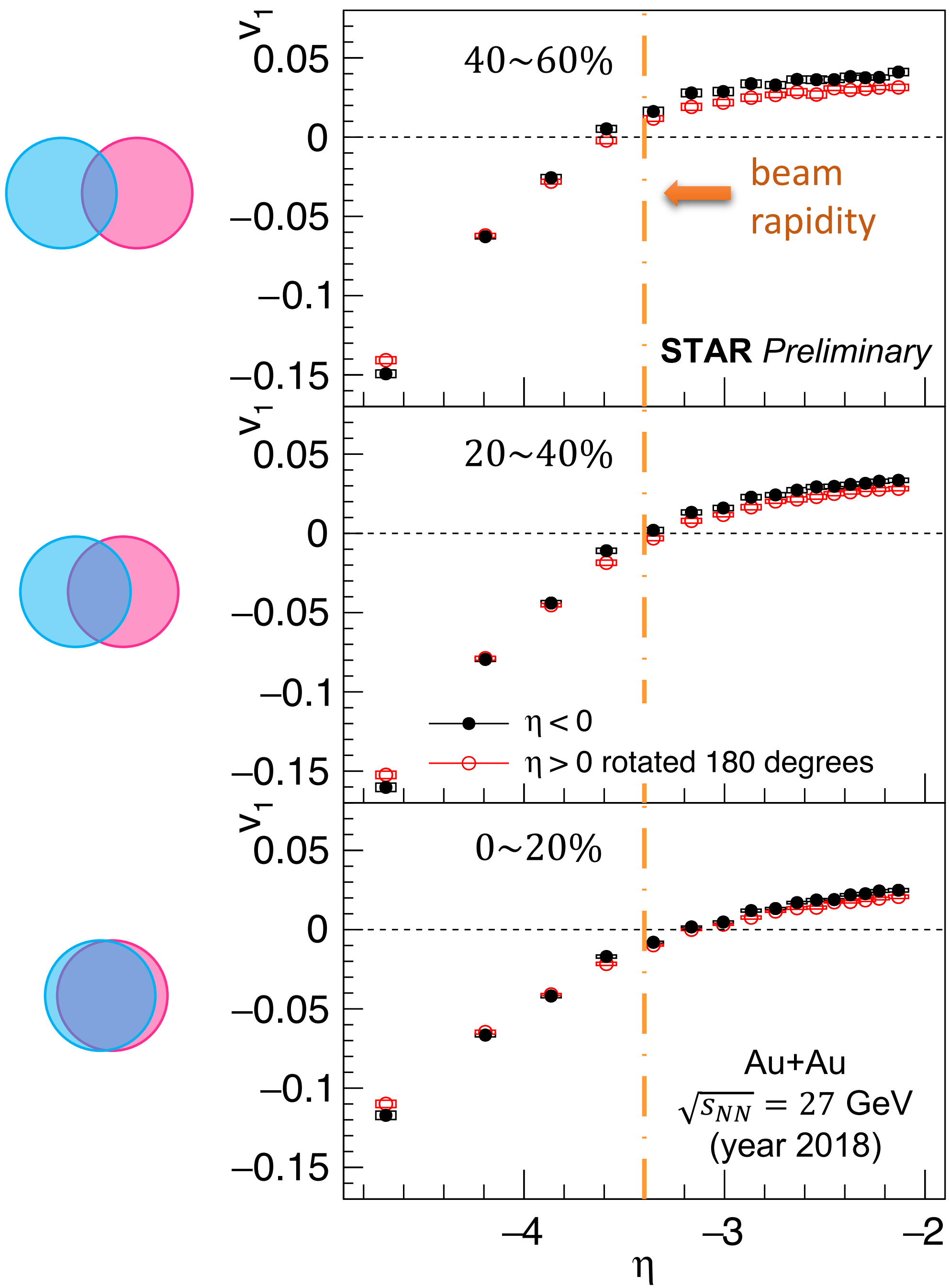
Iteration Process



Iteration Process



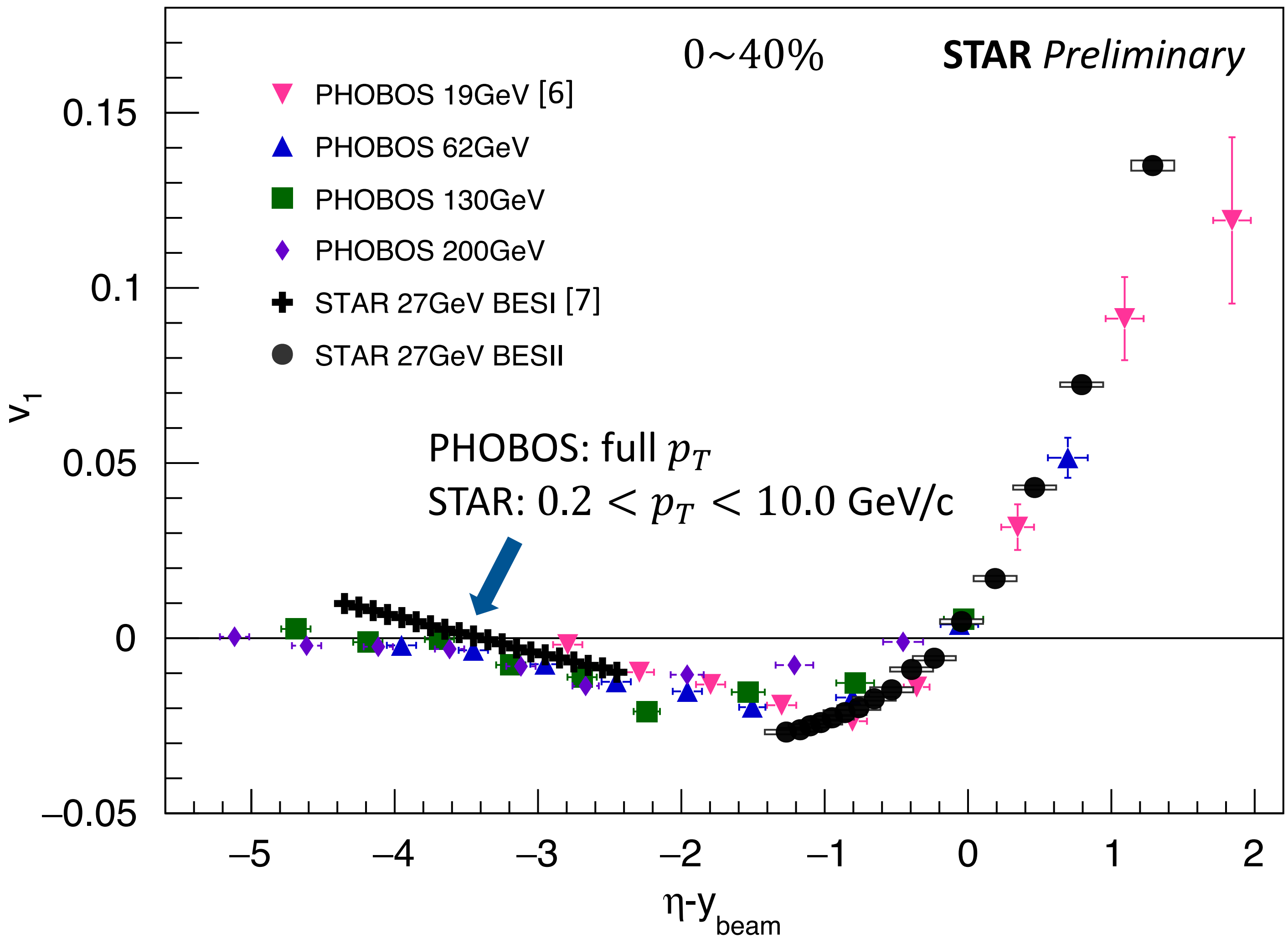
Results



$v_1(\eta)$ changes sign near the beam rapidity for all the centralities.

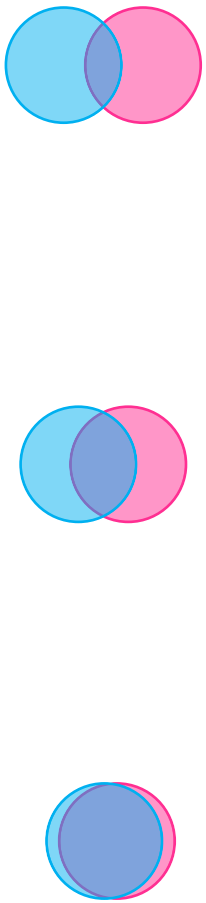
Comparison with PHOBOS

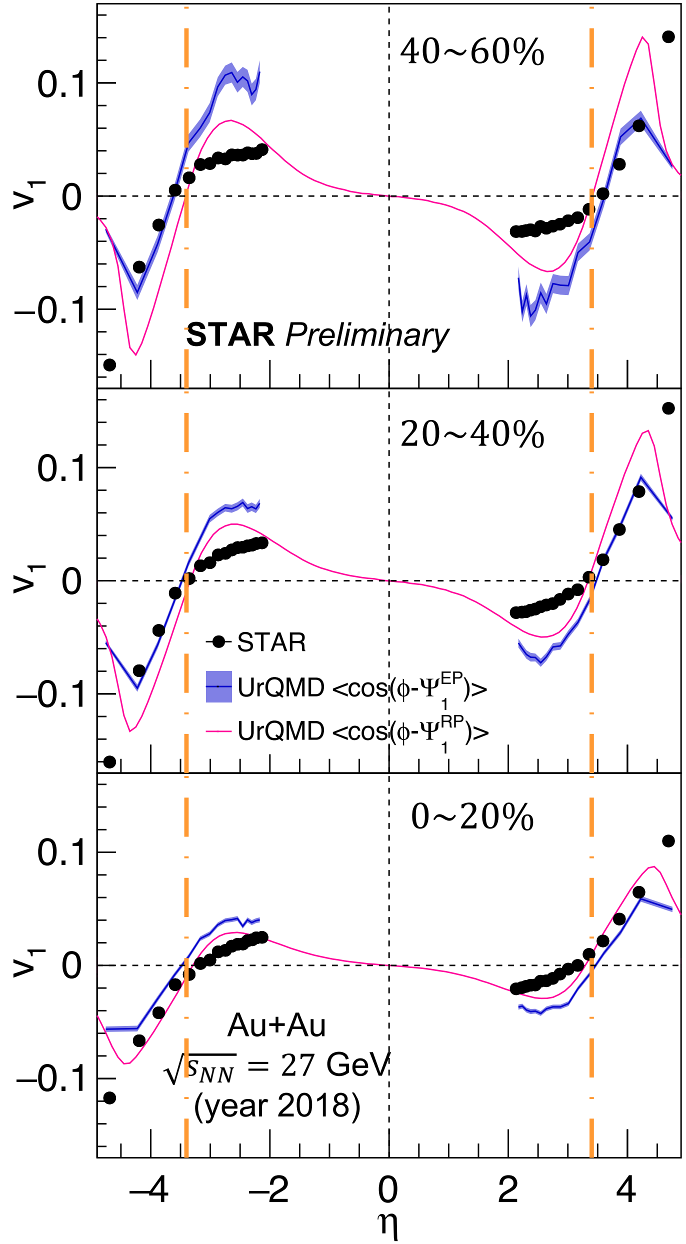
[6] PHOBOS. Phys. Rev. Lett. 97.1 (2006): 012301.
[7] STAR. Phys. Rev. C 101.2 (2020): 024905.



Test the phenomenon of limiting fragmentation

Comparison with UrQMD





Large discrepancy between UrQMD $v_1\{EP\}$ and $v_1\{RP\}$ due to the lumpiness of the colliding nuclei.

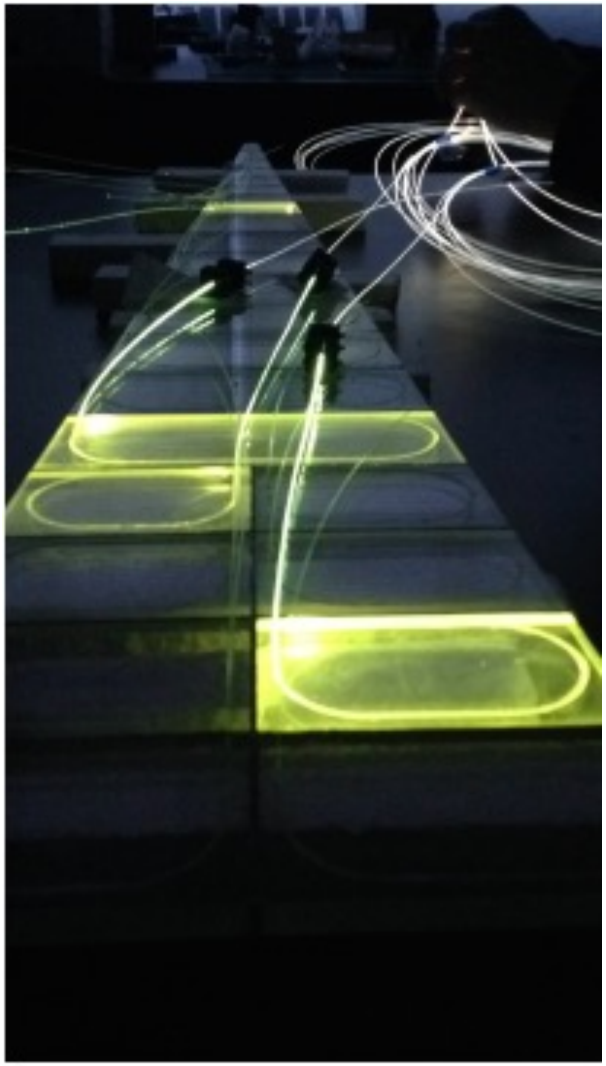
It is important to use the same reference when comparing the experimental results with physics models!

Summary and Conclusion

- First dedicated EPD analysis from STAR, the method will help STAR to extend the flow measurements to a wide η range at all the BES-II energies.
- First $v_1(\eta)$ measurement at far forward and backward η ($|\eta| > 1.0$) using BES-II data, the statistical errors decrease significantly compared to the previous PHOBOS and STAR measurements.
- Future high-precision $v_1(\eta)$ measurement at different BES-II energies and with different collision systems will help us validate several scaling effects more accurately including the limiting fragmentation.
- UrQMD fails to describe the measured $v_1(\eta)$ quantitatively.
- Future comparison with hydro models will help us to constrain $\frac{\eta}{s}(T, \mu_B)$ of the medium.

Back up

Event Plane Detector (EPD)



Particles (MIPs) transverse an EPD tile

↓

Scintillator absorbs energy and emits photons

↓

Optical fibers transport light to a silicon photomultiplier (SiPM)

↓

Signals from SiPM are amplified and sent to the digitizing and acquisition system

↓

Recorded as ADC values

Flowchart for Correcting the Material Budget