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


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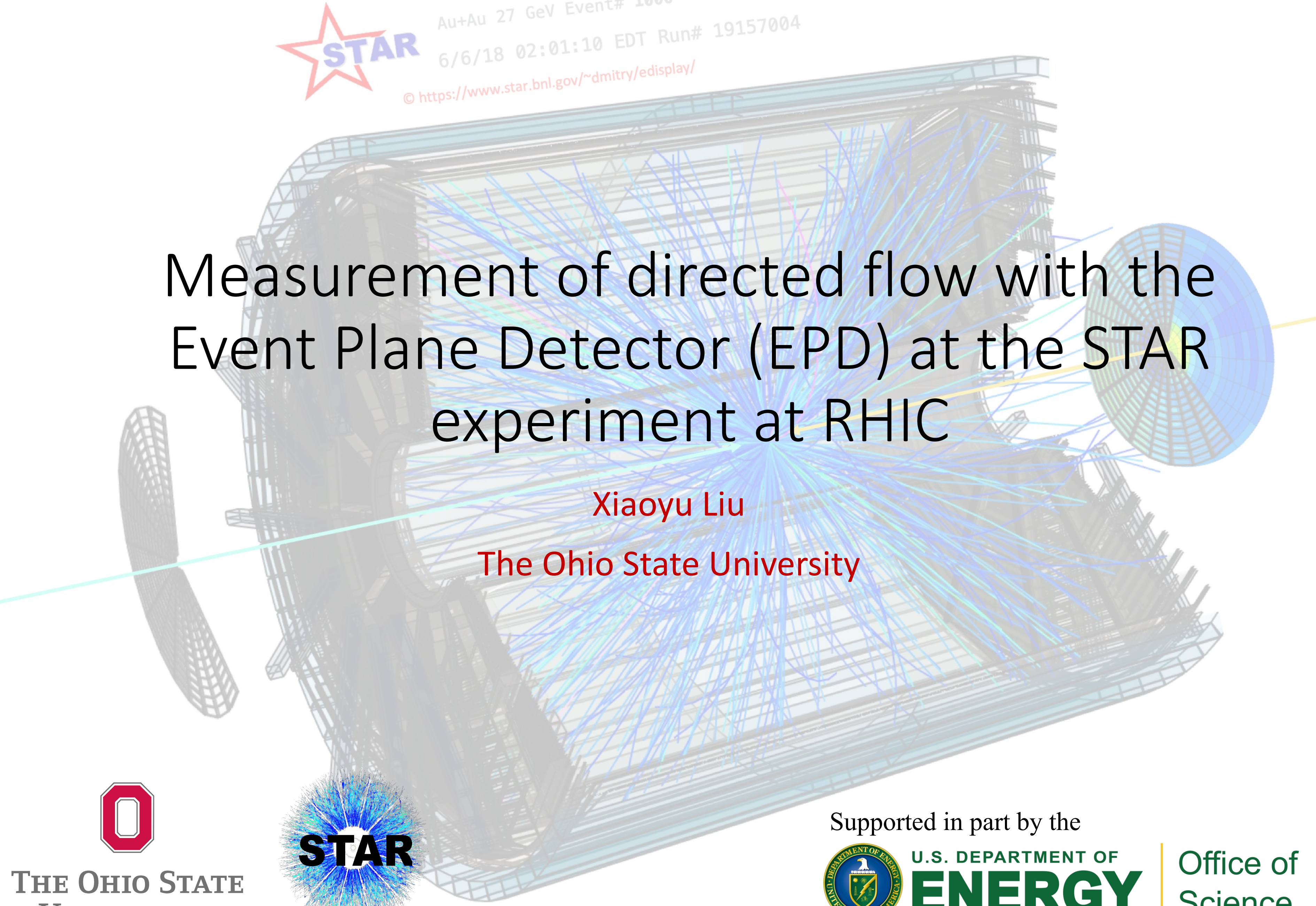


THE OHIO STATE UNIVERSITY

STAR


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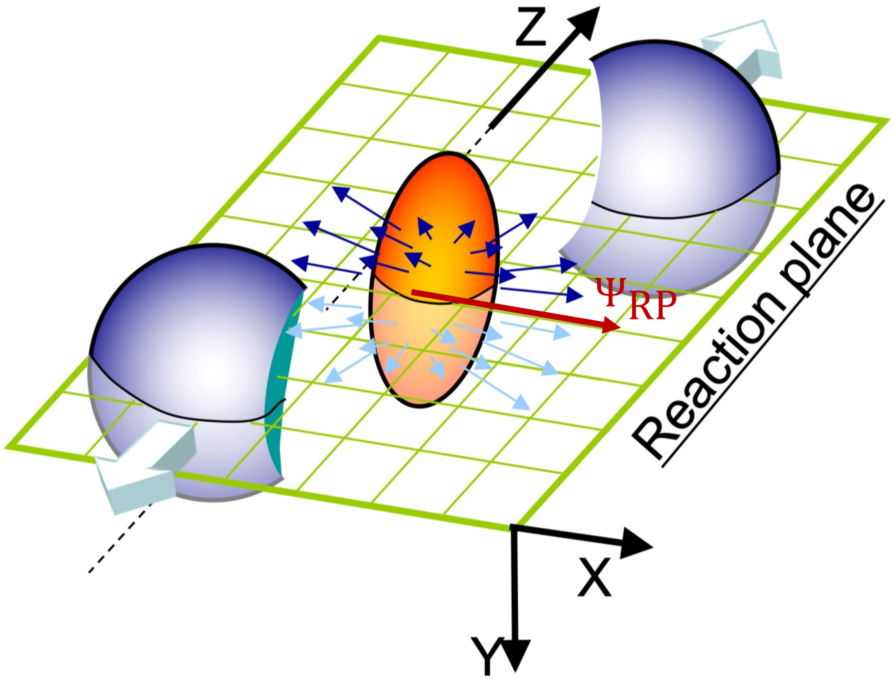
# Anisotropic Flow ($v_n$)

[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.

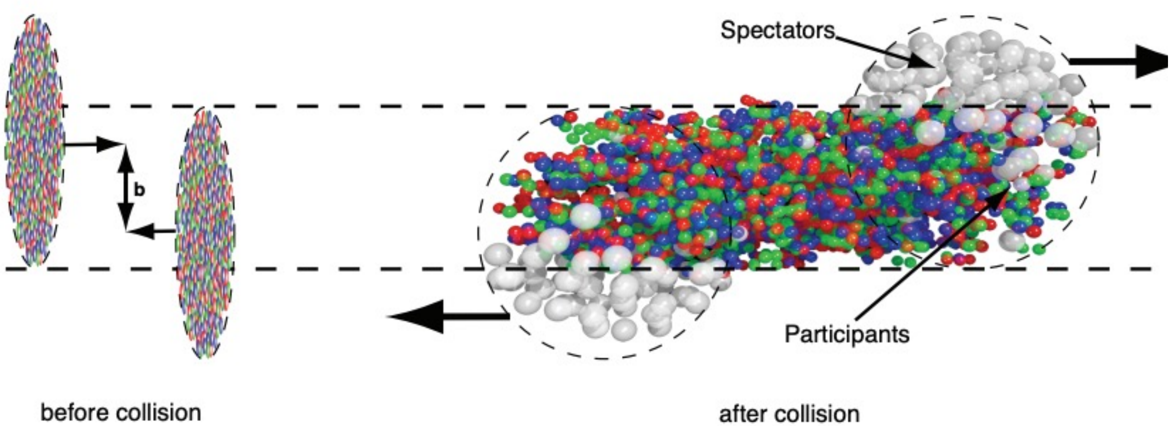
- It can be quantified by the harmonic in the Fourier expansion of azimuthal particle distribtuion with respect to the reaction plane ($\Psi_{RP}$) [1]:

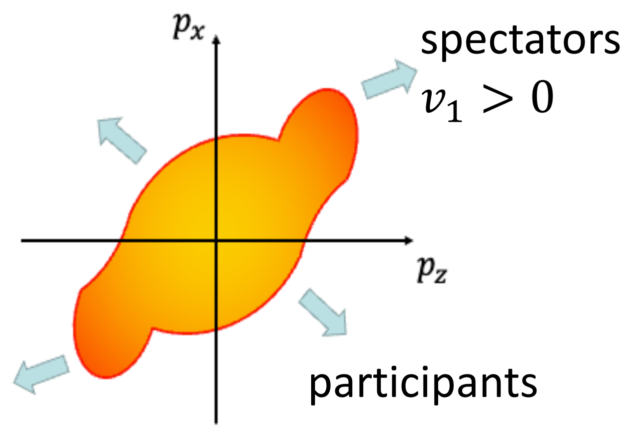
$$\frac{\mathrm{dN}}{\mathrm{d}(\phi - \Psi_{\mathrm{RP}})} = k\{1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\phi - \Psi_{\mathrm{RP}})]\}$$

# Directed Flow at Forward/Backward $\eta$

[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].



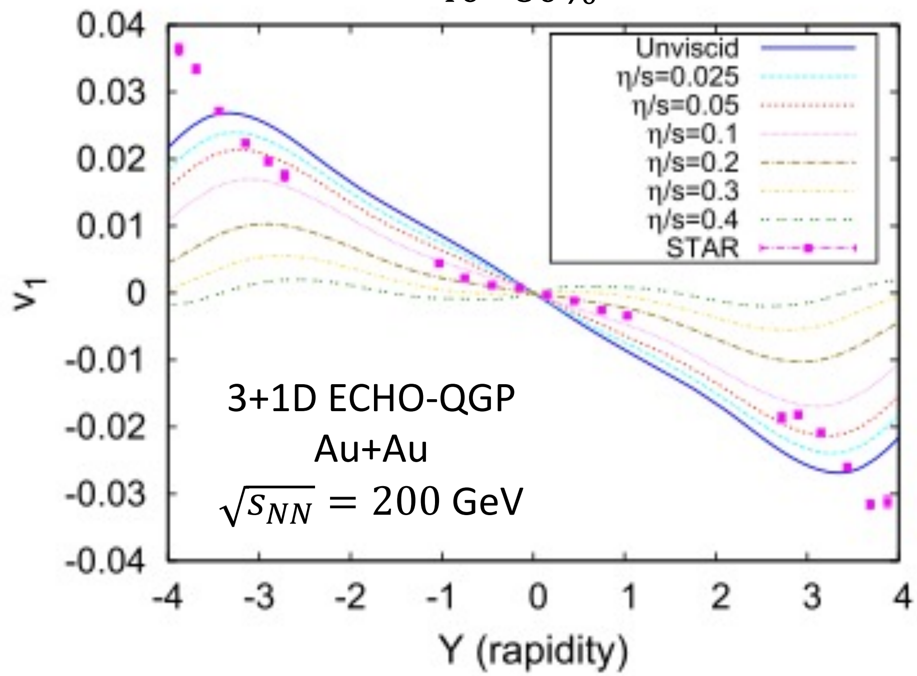



[3] Becattini, F., et al. The European Physical Journal C 75 (2015)
[4] Du, Lipei, et al. arXiv preprint arXiv:2211.16408 (2022)

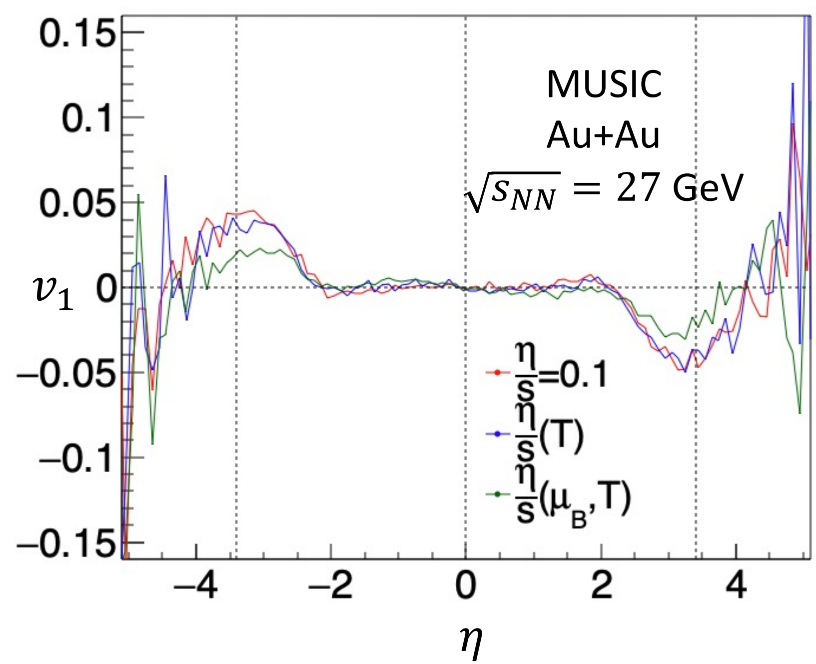
# Motivation

- The pseudorapidity ($\eta$) dependence of $v_1$ can provide unique constraints on the shear viscosity of the QCD matter ( $\frac{\eta}{s}(T, \mu_B)$ ) [3].
- Measuring $v_1(\eta)$ in both spectator and participant regions may provide insights into the baryon stopping mechanism [4].

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:

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

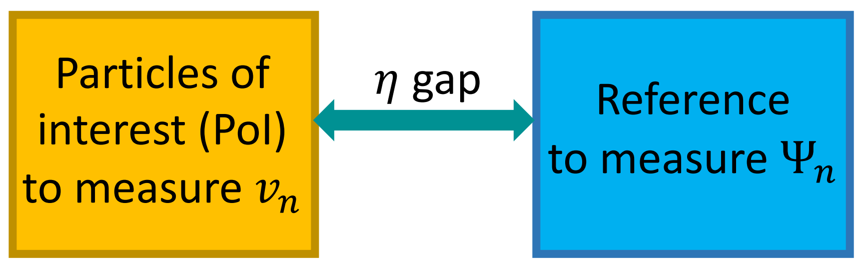
- The anisotropic flows are measured as:

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

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

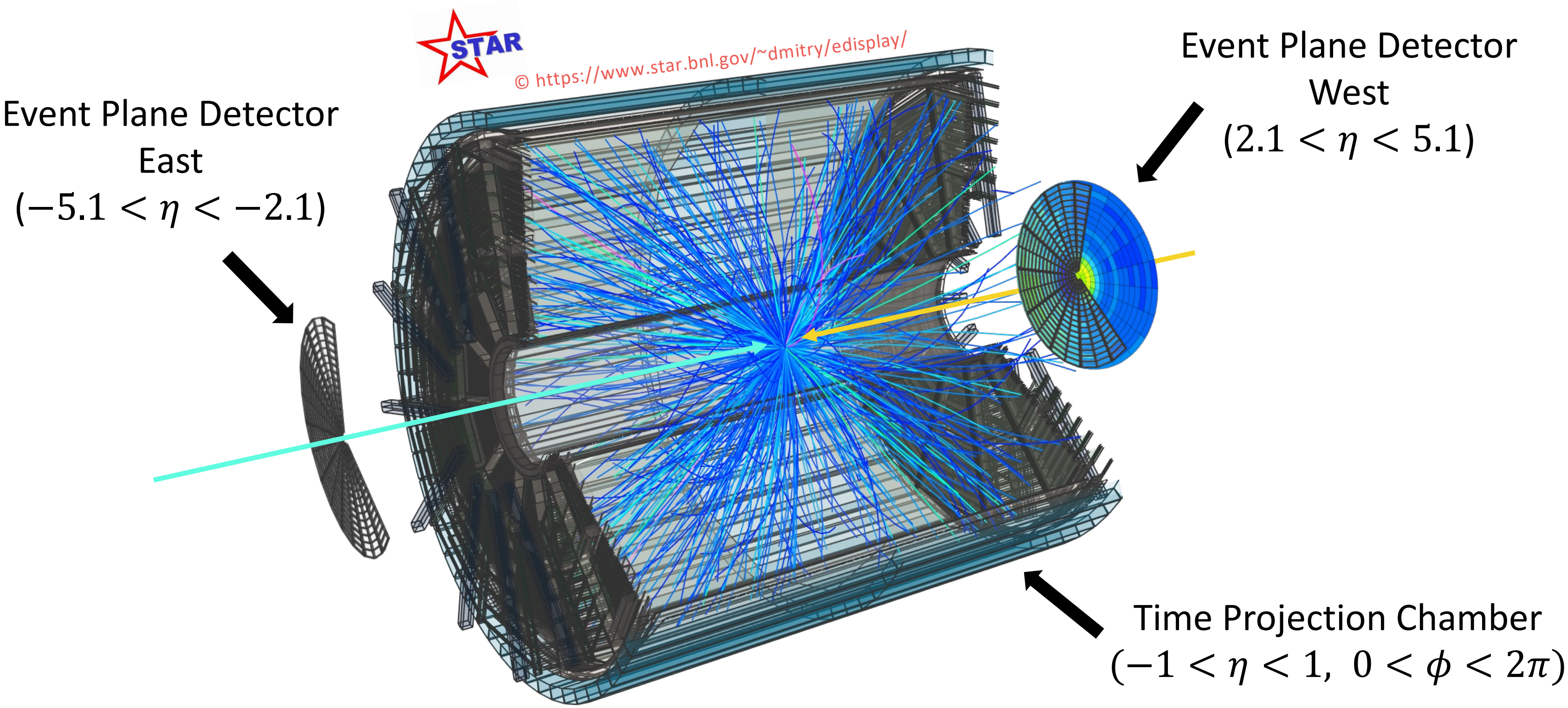
Reference matters!

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



# STAR Detector Subsystems

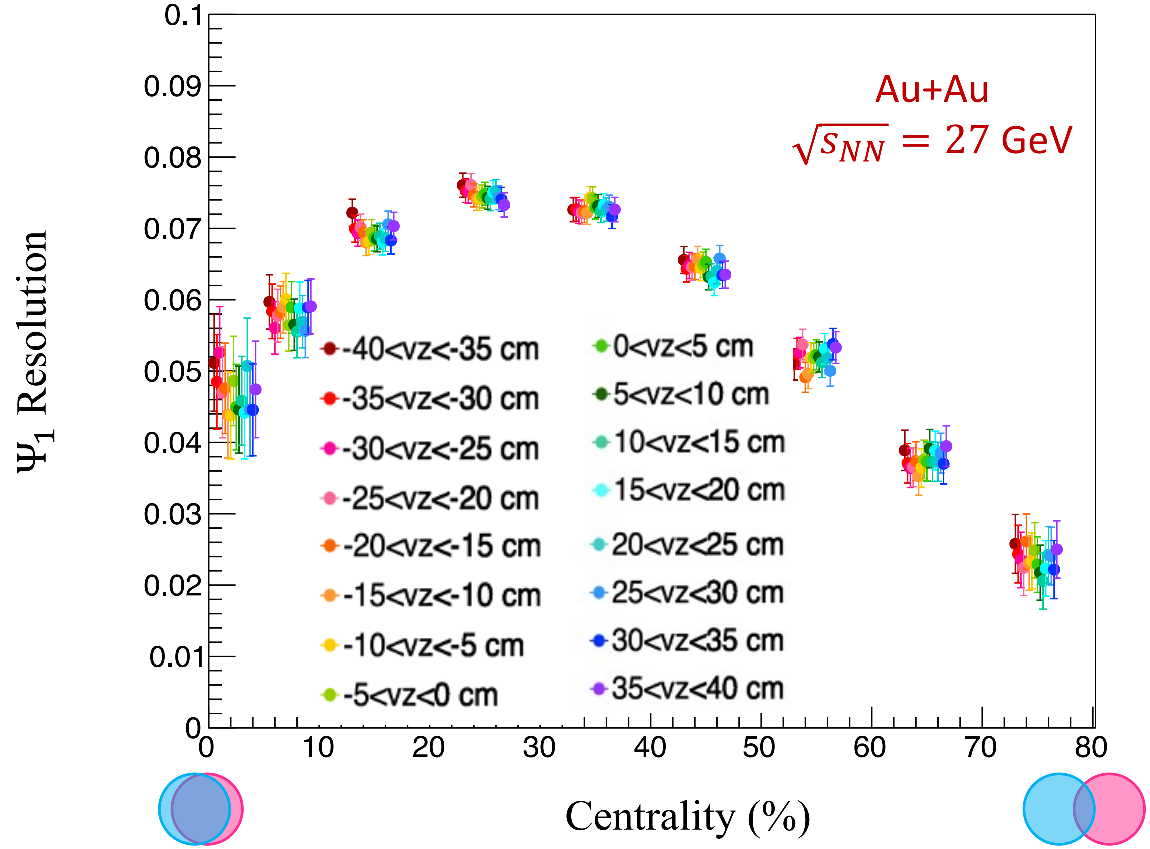
[5] Borghini, Nicolas, et al. Physical Review C 66.1 (2002): 014901.




- TPC was chosen as the reference to suppress the momentum conservation effect [5].
- An $\eta$ gap is imposed between the PoI and reference.

# First-Order Event Plane ($\Psi_1$)

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

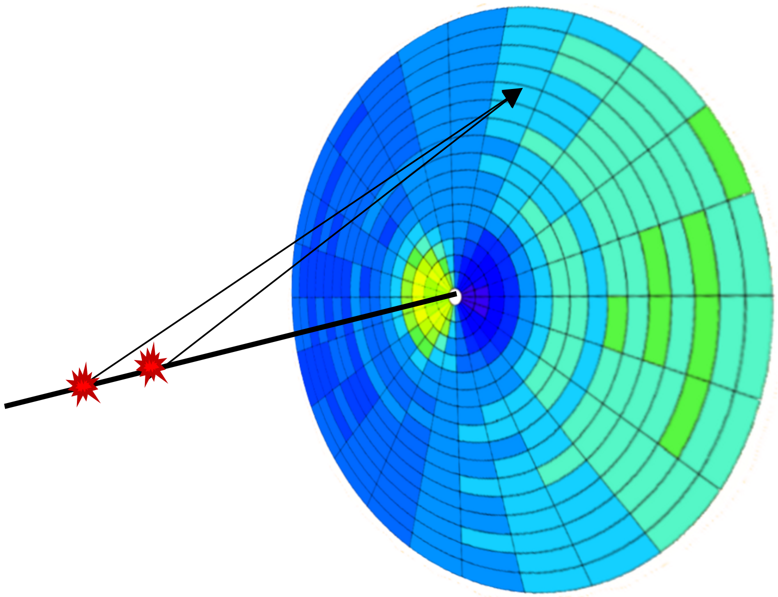


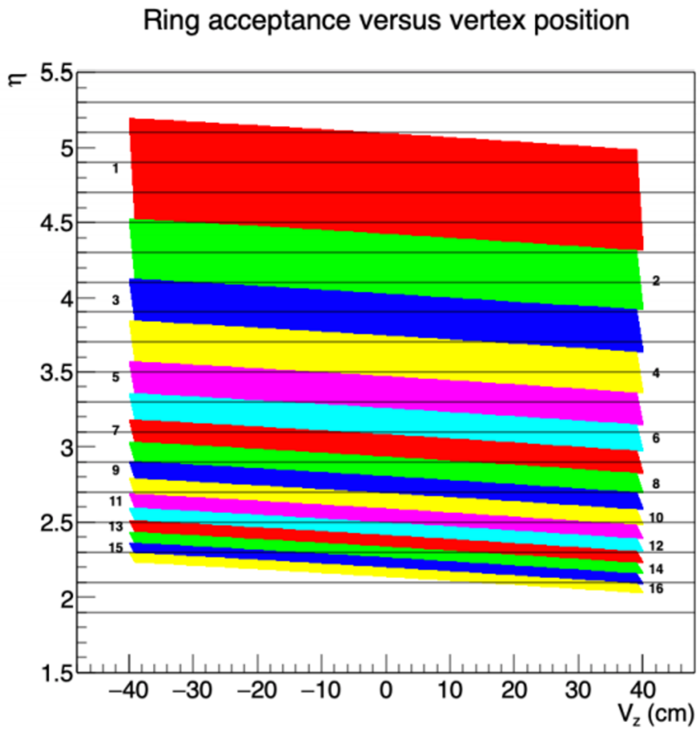

- Data points are offset along the x axis for the demonstration purpose.
- The event plane resolution is calculated by the three sub-event method:

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

# Event Plane Detector (EPD)

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



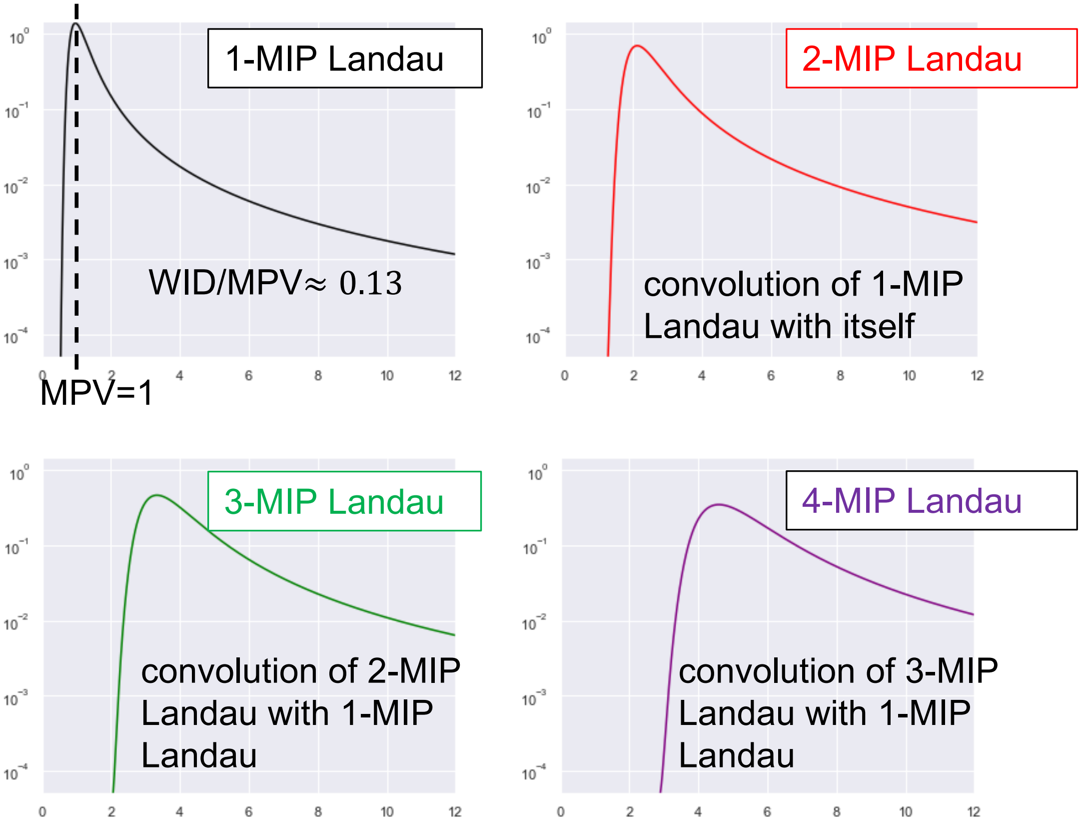


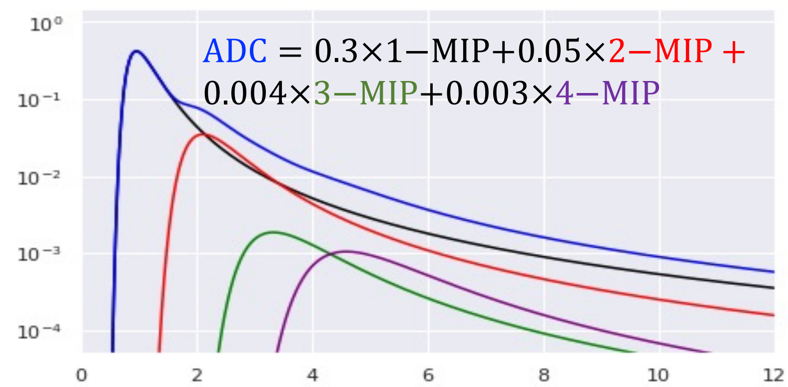

- The pseudorapidity ($\eta$) and $\phi$ of a EPD tile are determined by a straight line between the primary vertex and a random point on the tile.

- 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

↓

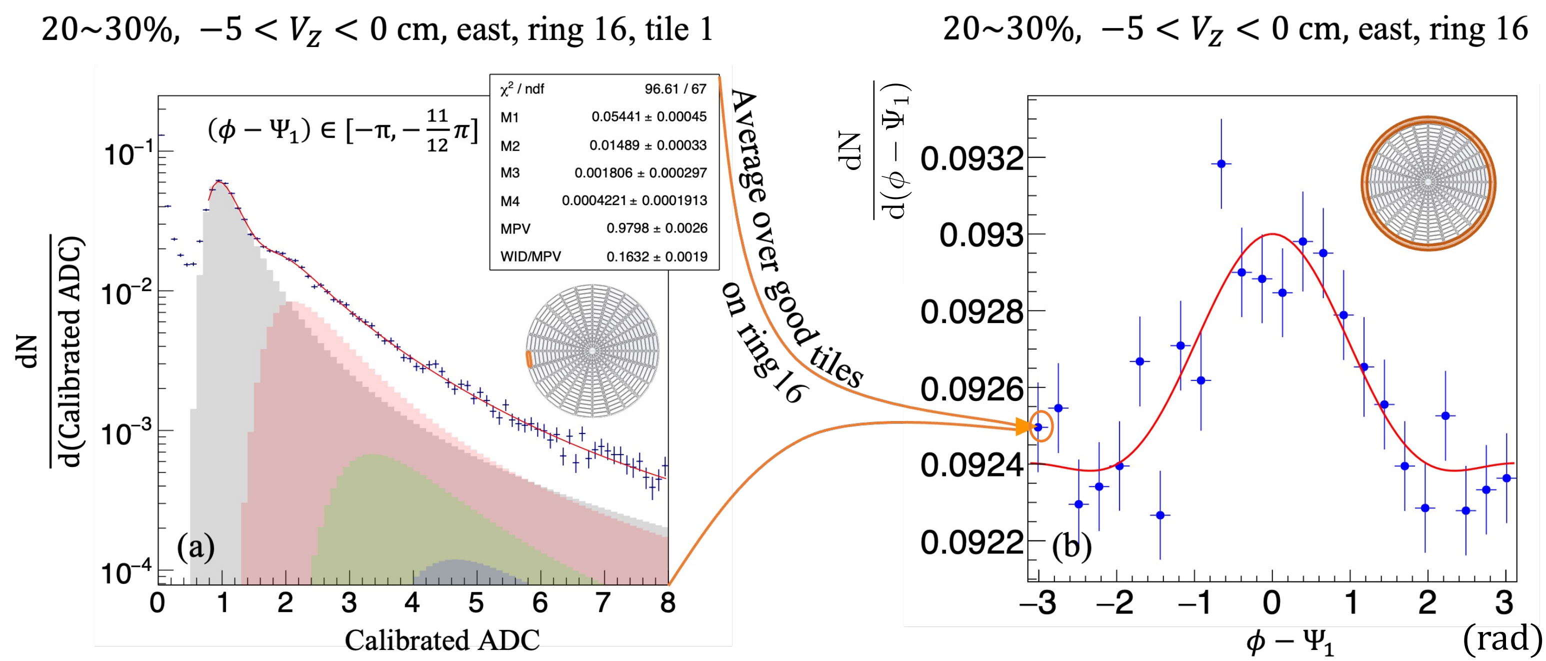
The Law of Large Number doesn't apply

↓

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:

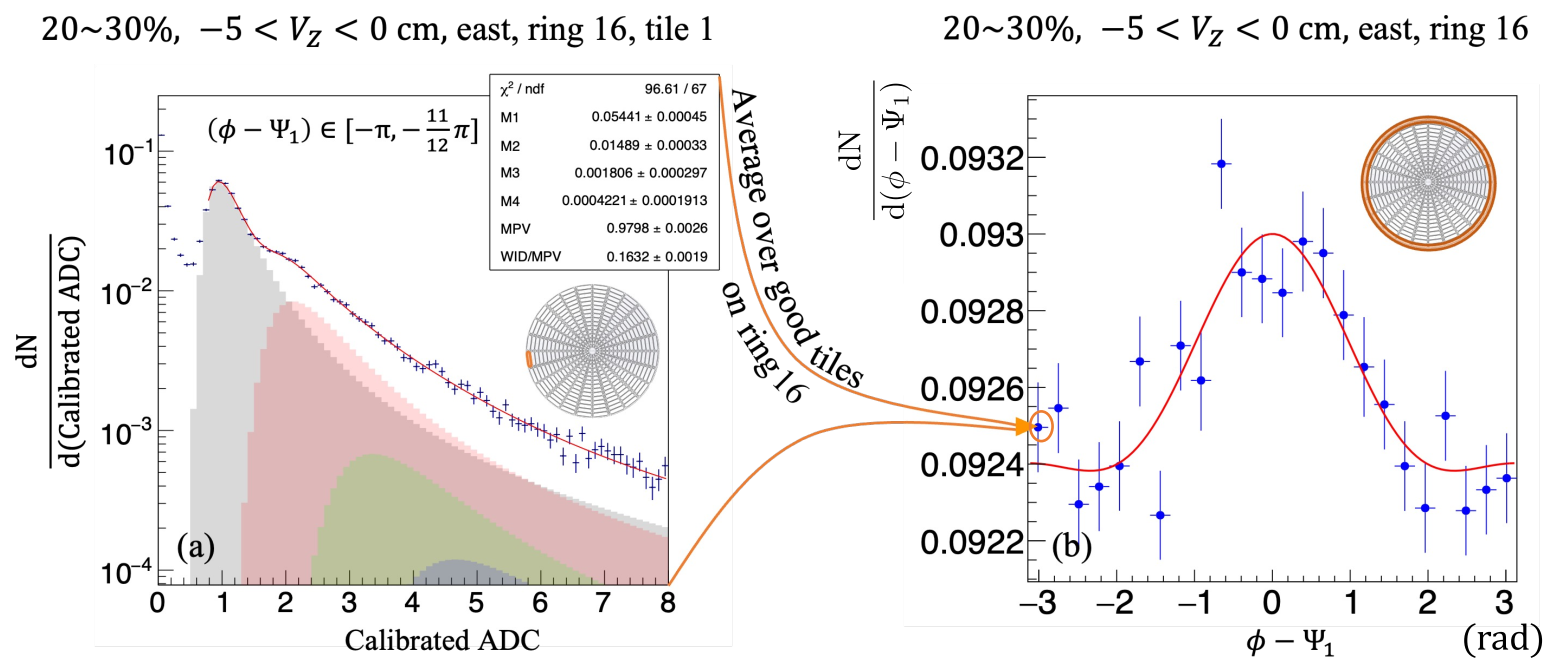
$$N = \sum_{k=1}^{k=4} k \times M_k$$

- The associated error can be calculated by:

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

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

# Extracting $v_1$



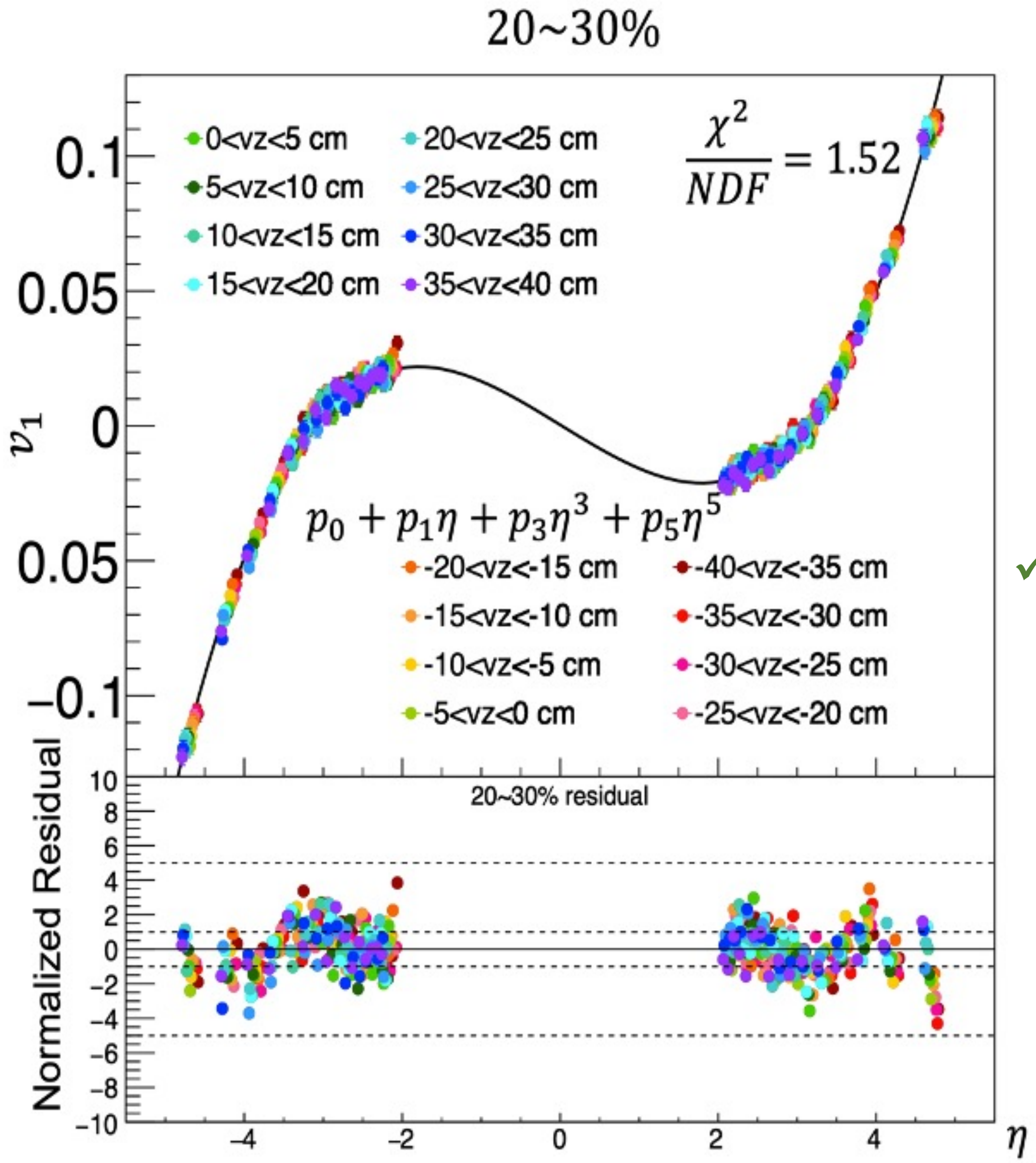

- $v_1$ (before the resolution correction) can be extracted by fitting the Fourier decomposition of the $(\phi - \Psi_1)$ distribution:

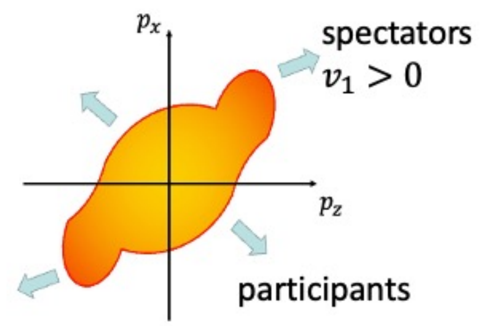
$$\frac{\mathrm{dN}}{\mathrm{d}(\phi - \Psi_1^{\mathrm{TPC}})} = k\{1 + 2v_1 \cos(\phi - \Psi_1^{\mathrm{TPC}}) + 2v_2 \cos[2(\phi - \Psi_1^{\mathrm{TPC}})]\}$$

- $v_1$ needs to be corrected by the $\Psi_1^{\mathrm{TPC}}$ resolution:

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

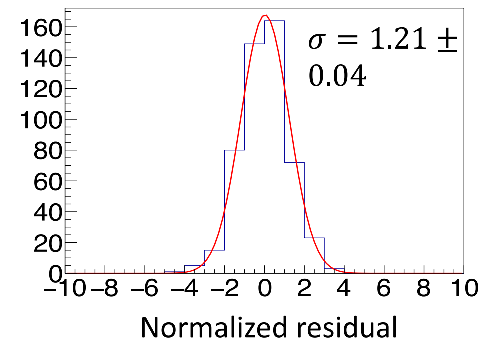
# $v_1$ for 16 $V_z$ Bins



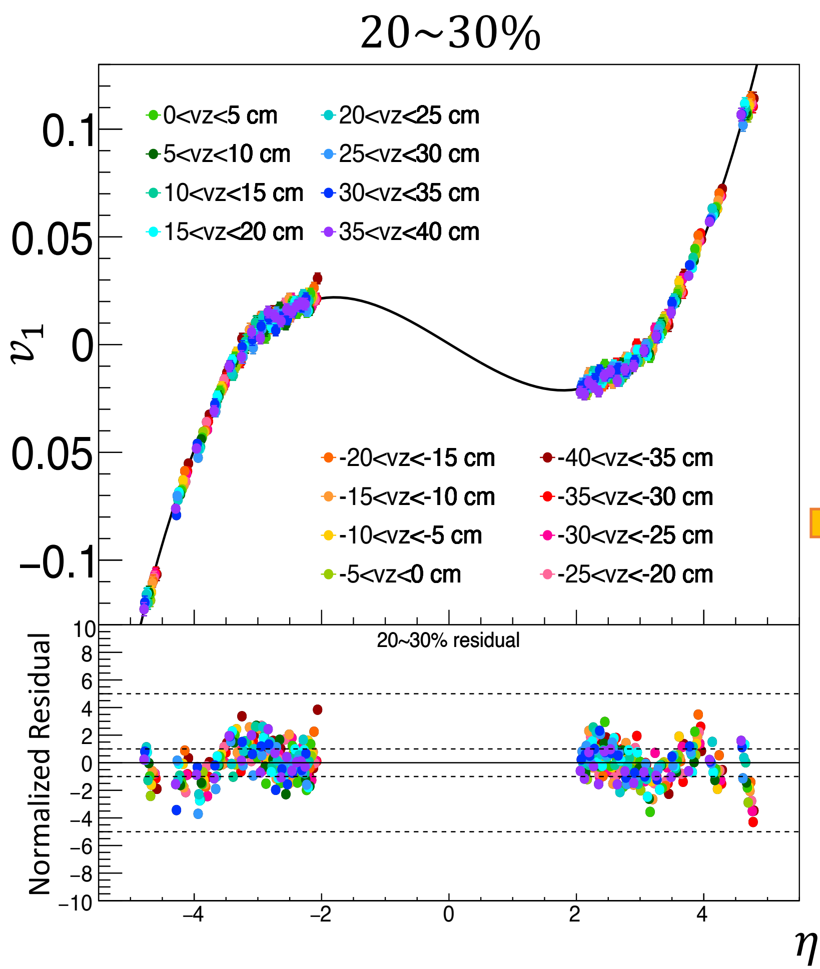




✓ fluctuation and error bars of the data points are reasonable.

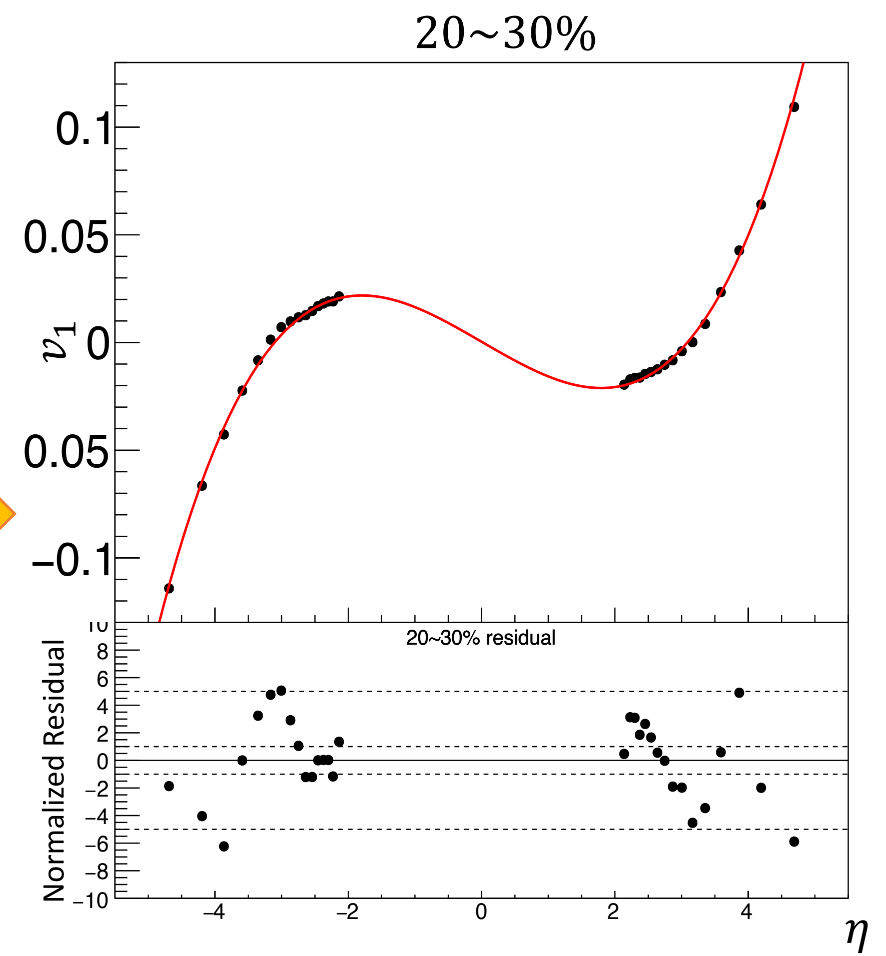
Project on the Y axis



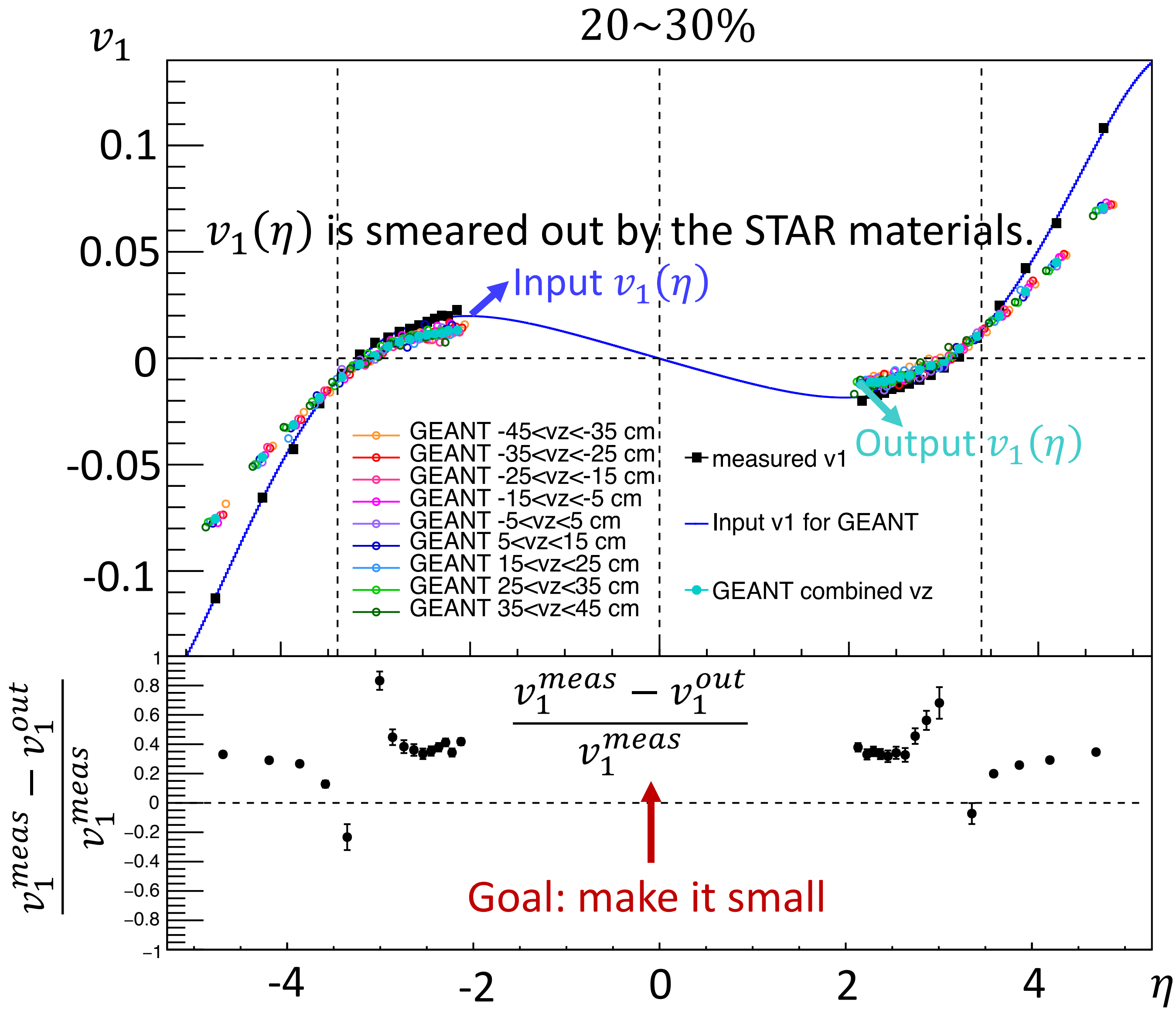
# Combine 16 $V_z$ Bins



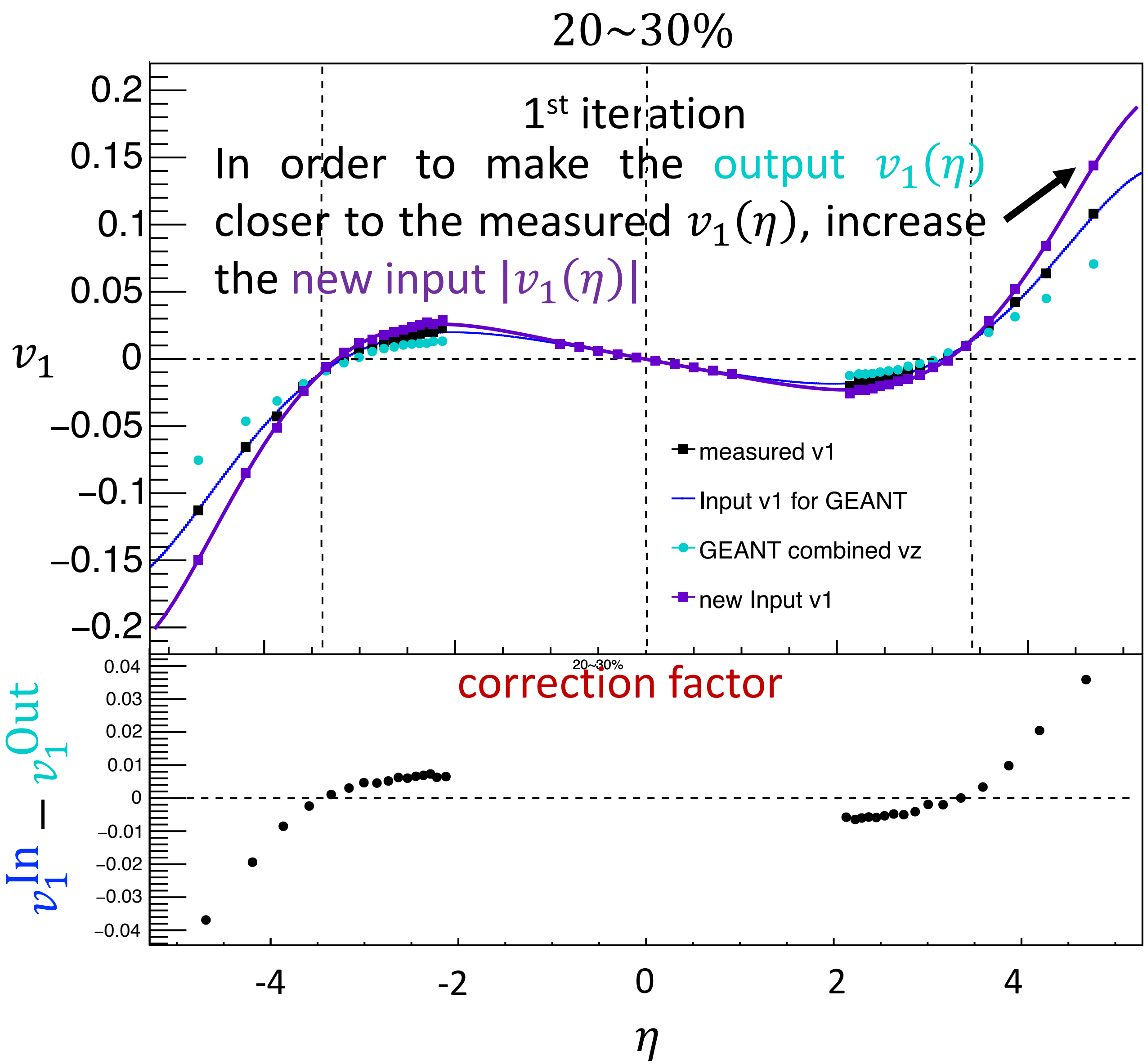

Group every 16 points along $\eta$ by taking the average of $\eta$ and $v_1$



# STAR Materials Smear Out $v_1$



# Iteration Process



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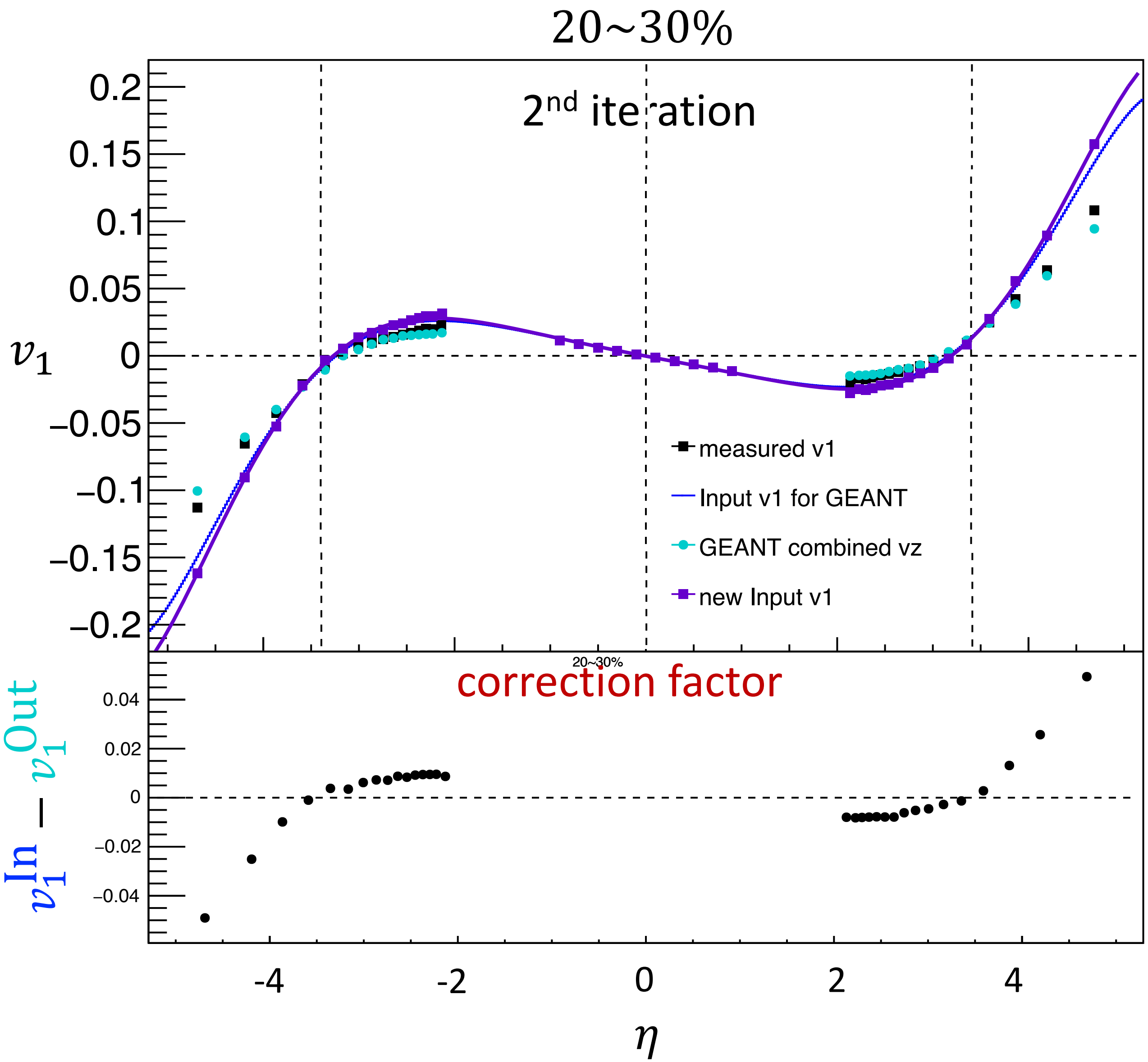

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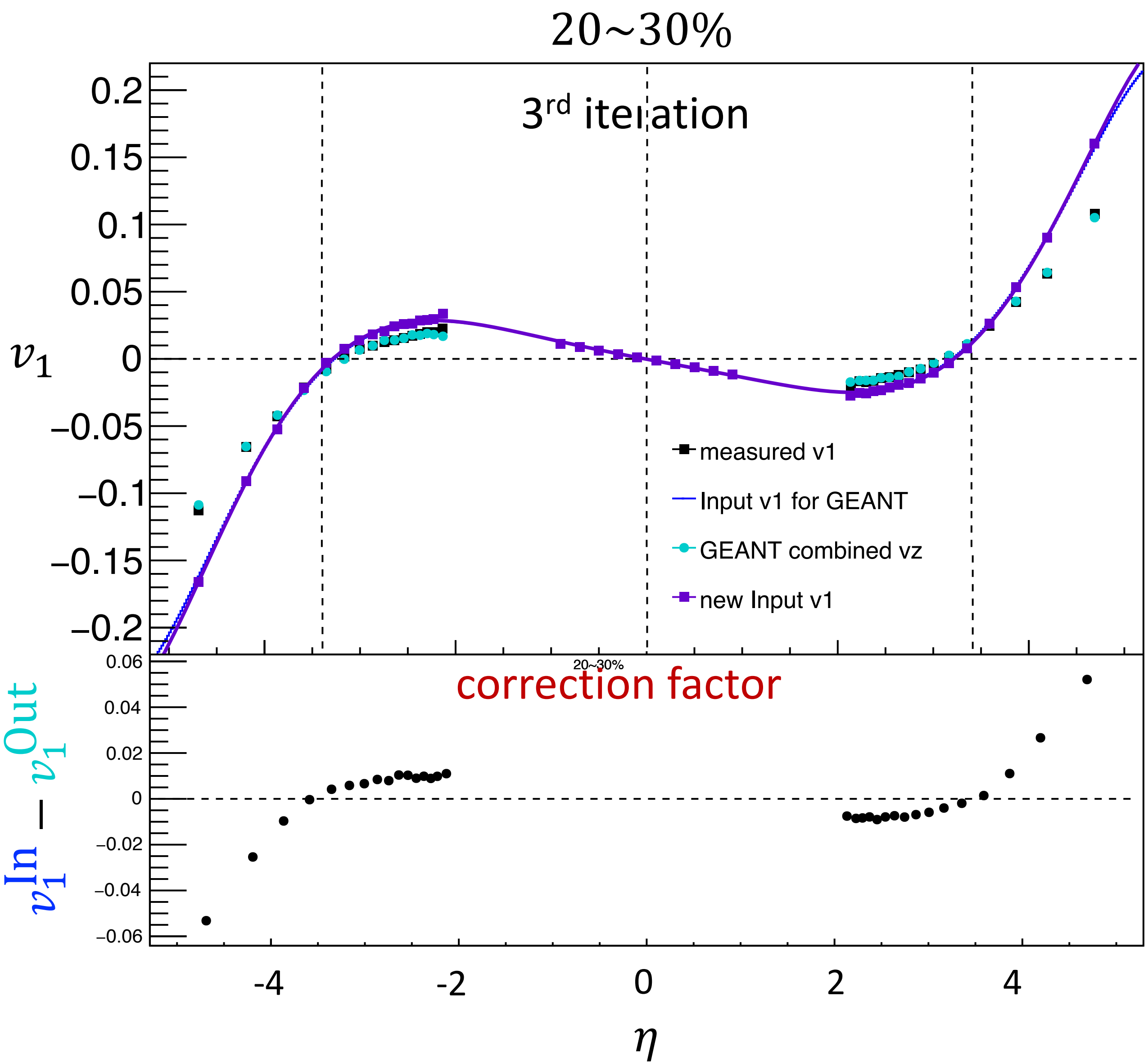

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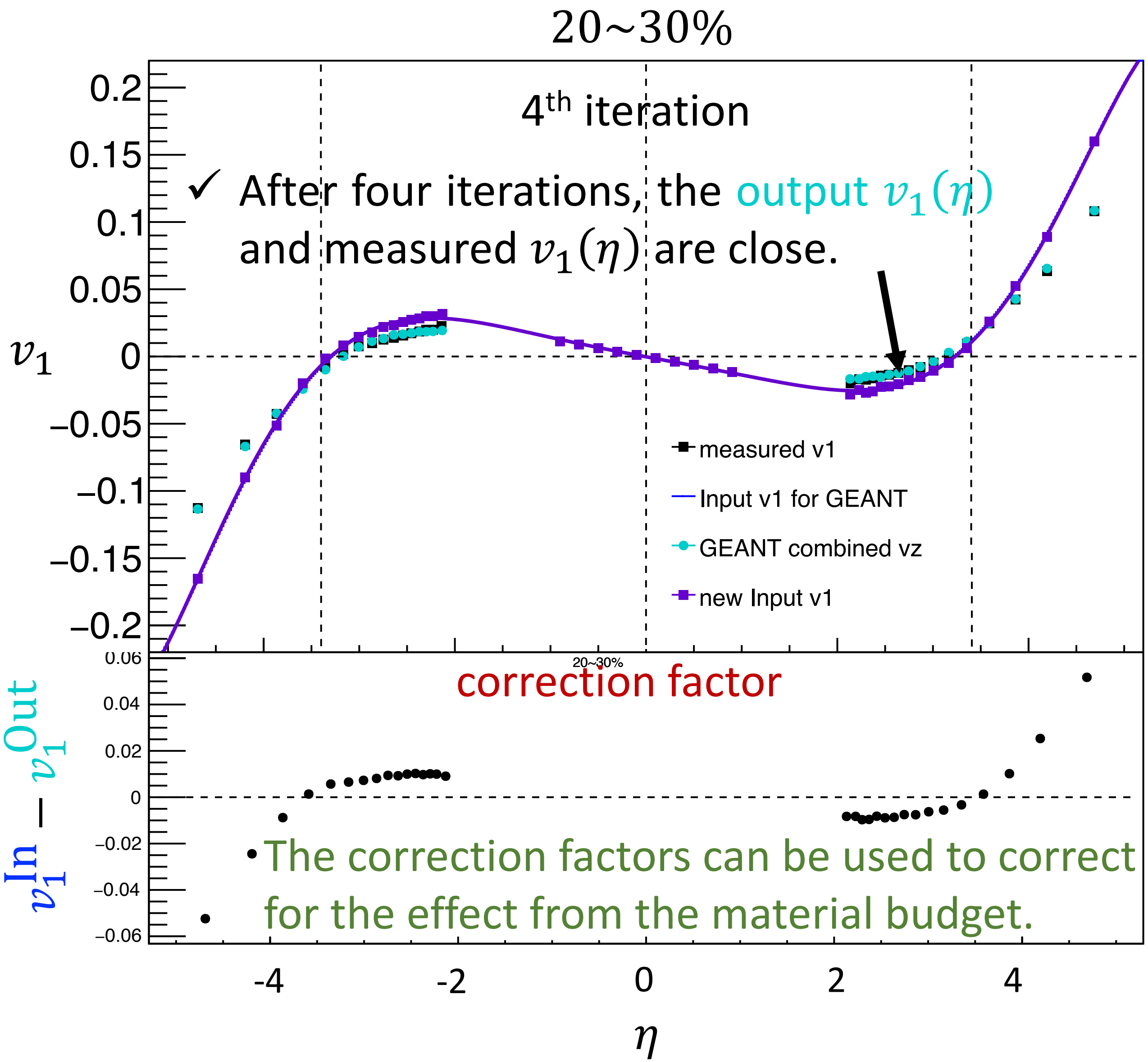
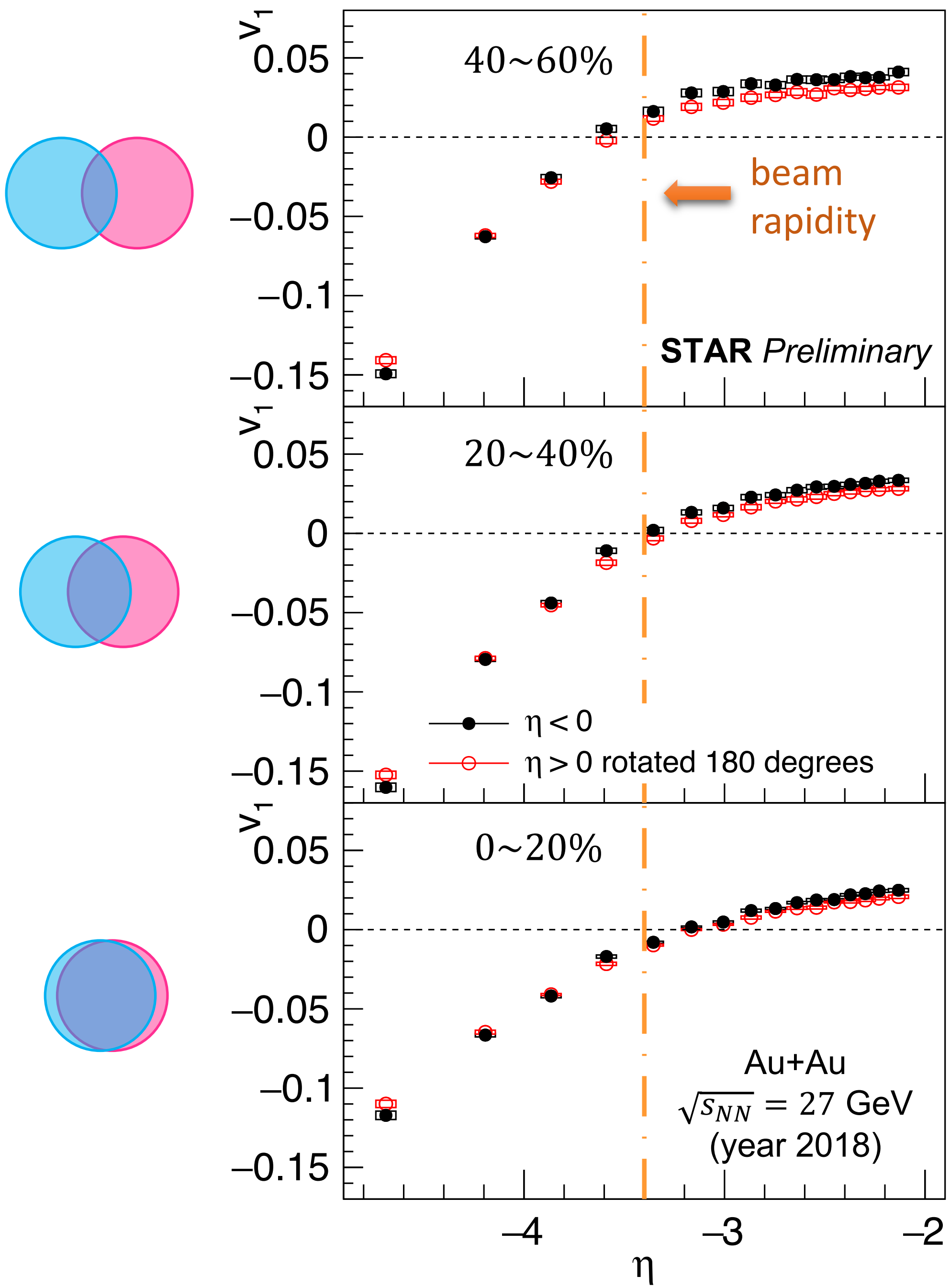



✓ After four iterations, the output $v_1(\eta)$ and measured $v_1(\eta)$ are close.

- The correction factors can be used to correct for the effect from the material budget.

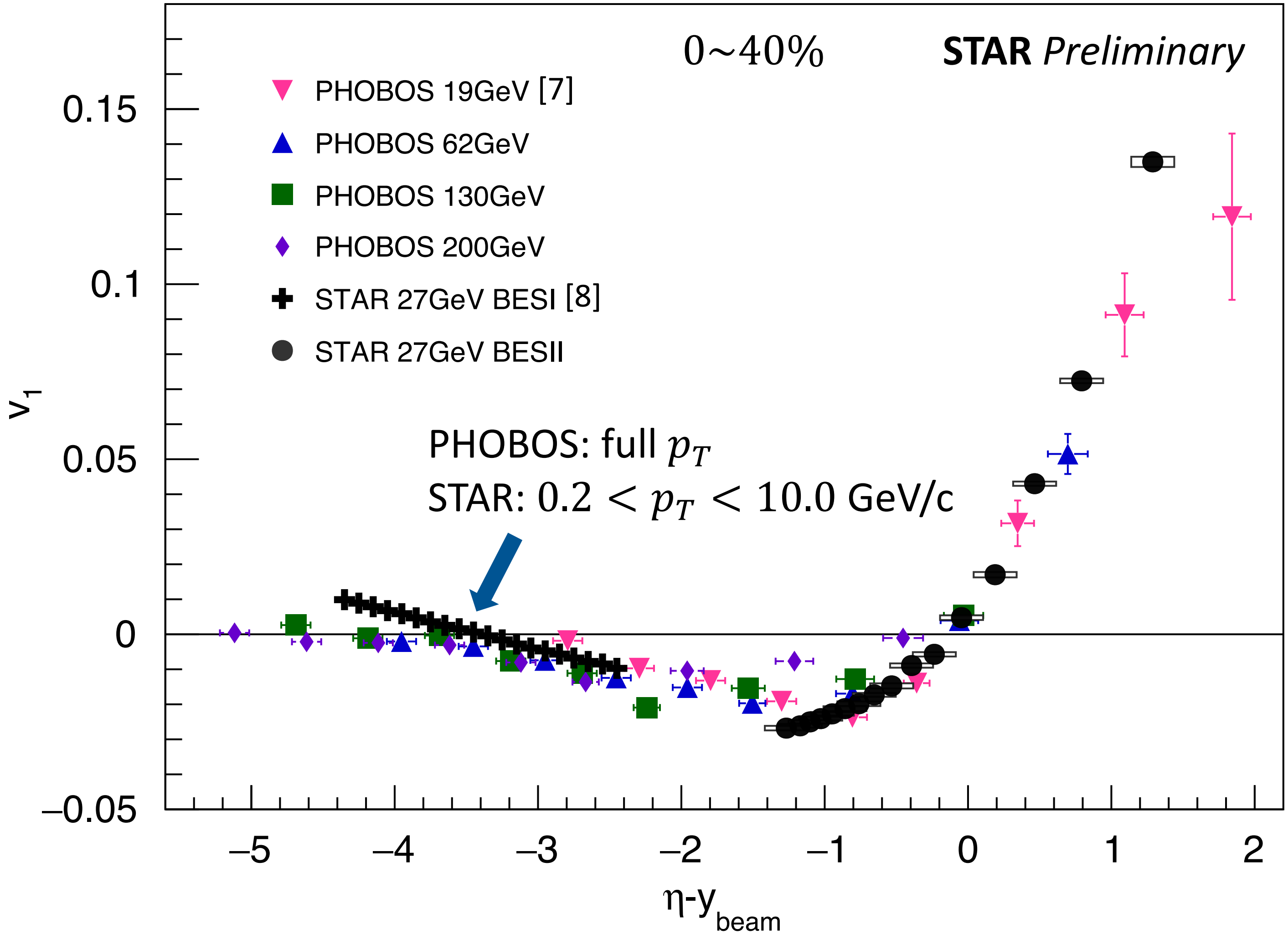
# Results




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

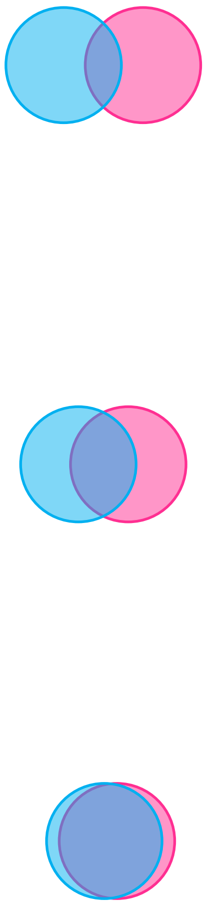
# Comparison with PHOBOS

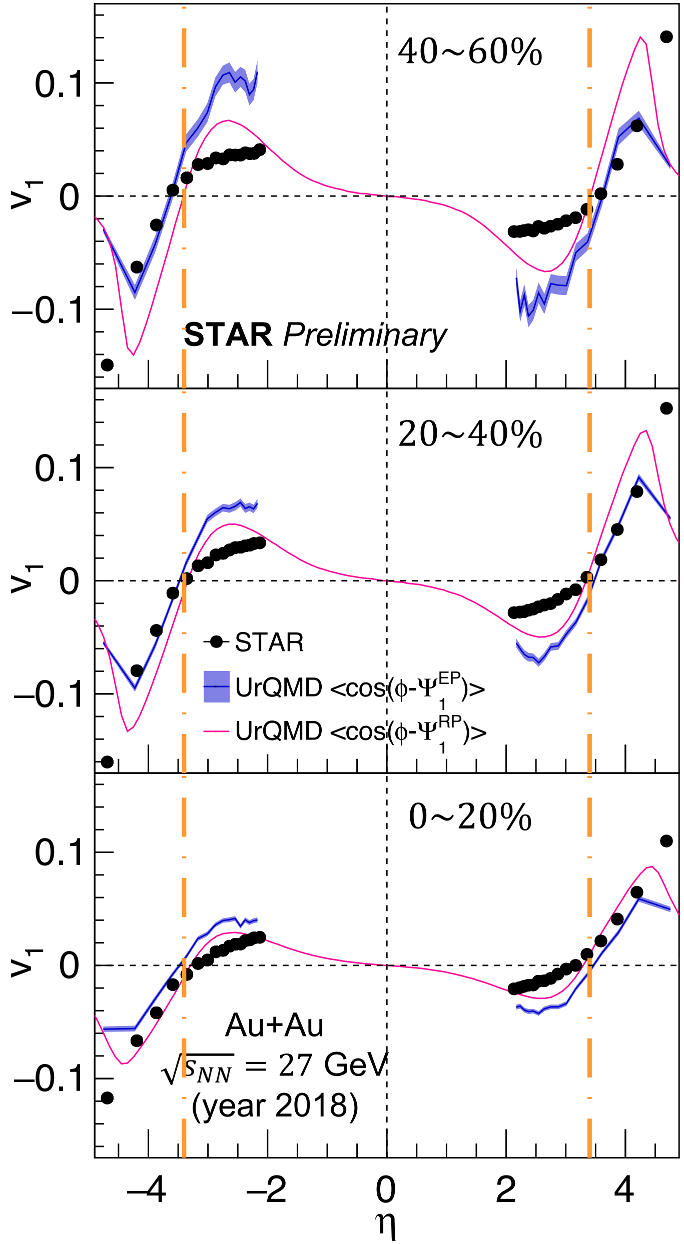
[7] PHOBOS. Phys. Rev. Lett. 97.1 (2006): 012301.
[8] STAR. Phys. Rev. C 101.2 (2020): 024905.




- 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 $\eta$ range at all the BES-II energies.

- First $v_1(\eta)$ measurement at far forward and backward $\eta$ ($|\eta| > 1.0$) using BES-II data, the statistical errors decrease significantly compared to the previous PHOBOS and STAR measurements.

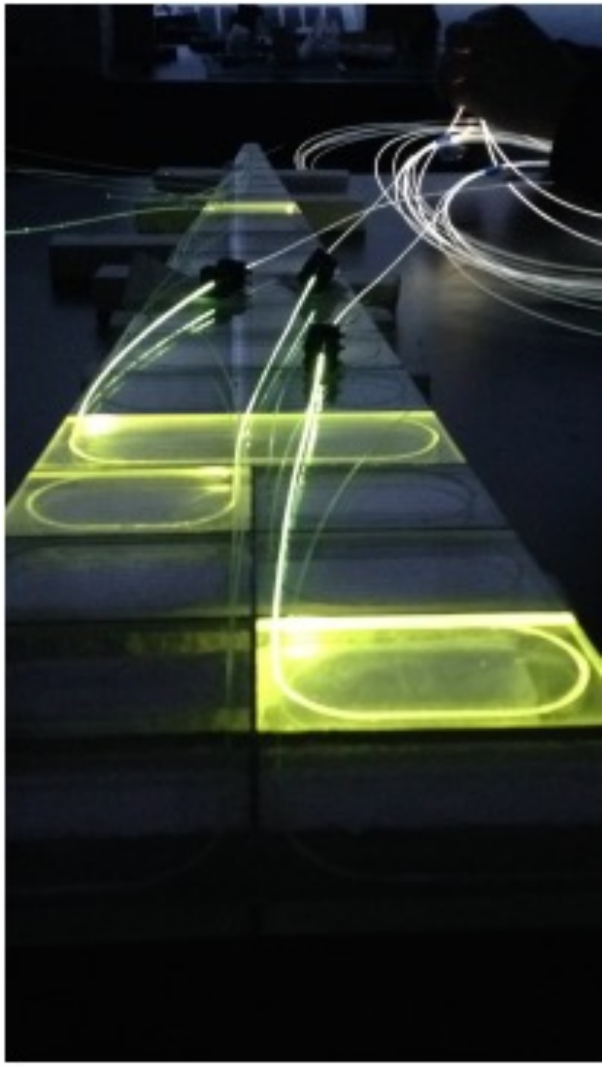
- Future high-precision $v_1(\eta)$ measurement at different BES-II energies and with different collision systems will help us validate several scaling effects more accurately including the limiting fragmentation.

- 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