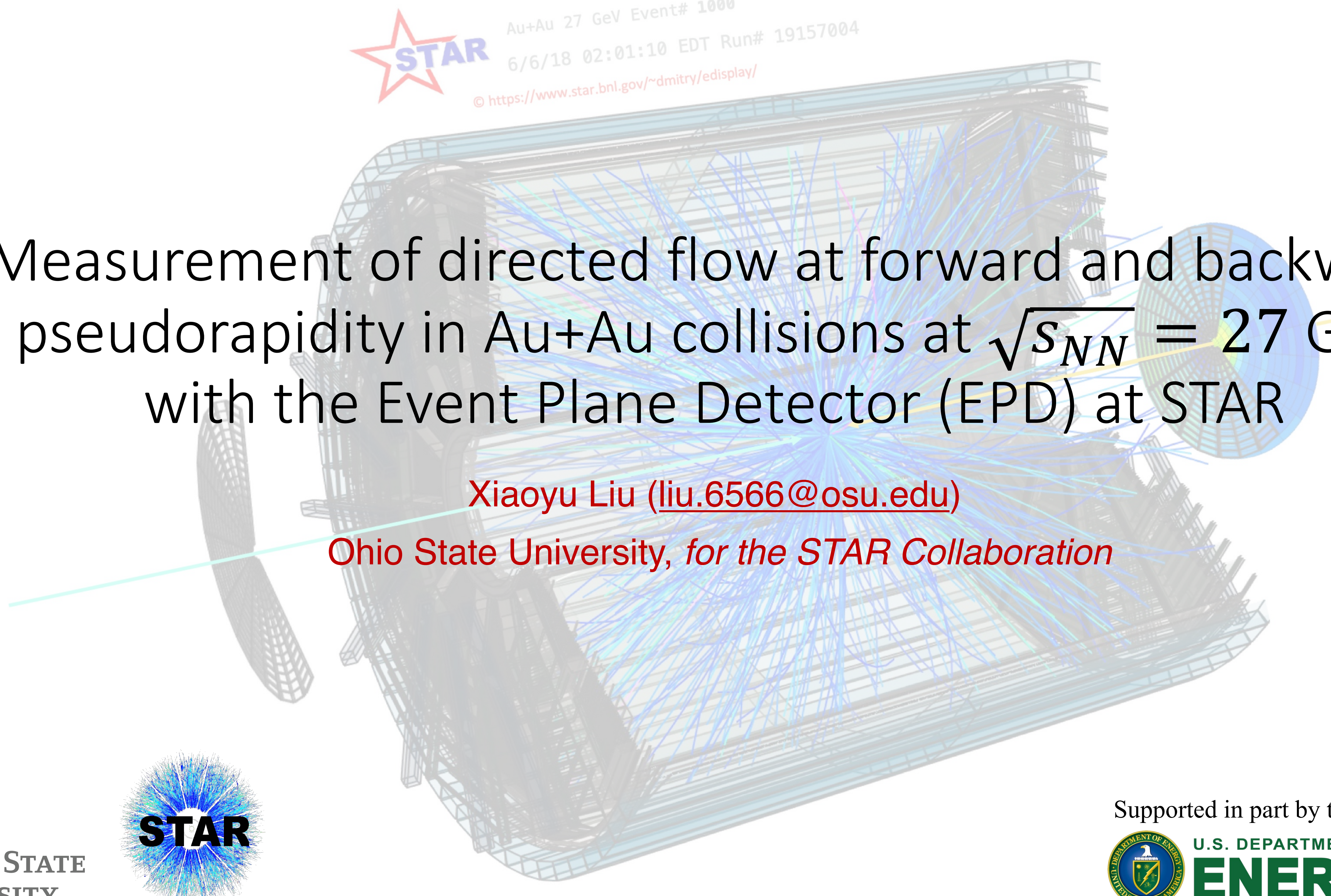


Measurement of directed flow at forward and backward pseudorapidity in Au+Au collisions at $\sqrt{s_{NN}} = 27$ GeV with the Event Plane Detector (EPD) at STAR

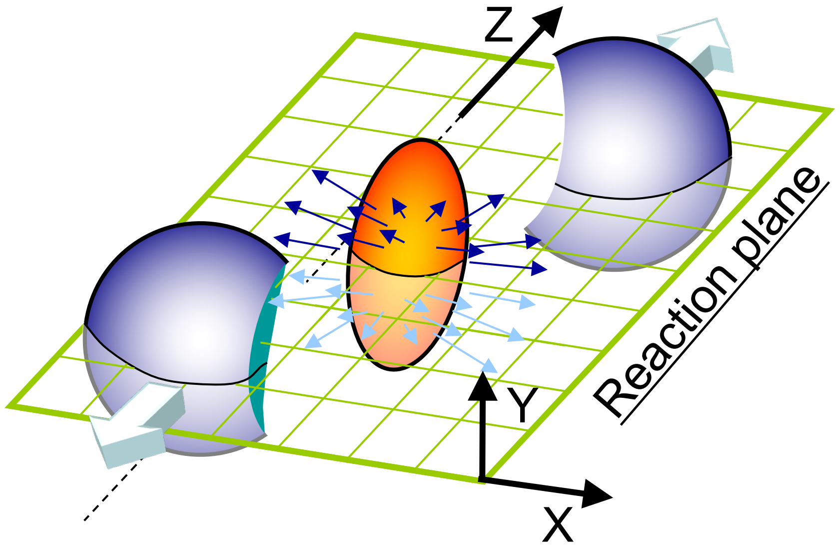
Xiaoyu Liu (liu.6566@osu.edu)
Ohio State University, *for the STAR Collaboration*

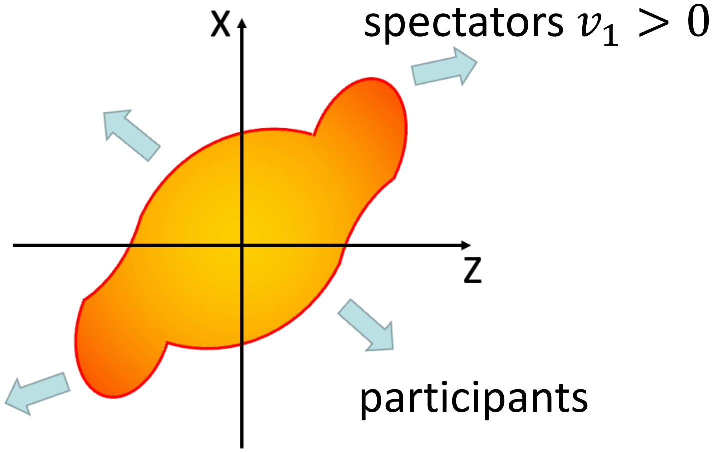
THE OHIO STATE UNIVERSITY

STAR

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

Directed Flow





- In heavy ion collisions, the particle azimuthal distribution measured with respect to the reaction plane (Ψ_{RP}) is anisotropic and can be expanded into a Fourier series [1]:

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

- v_1 describes the collective sideward motion of produced particles and nuclear fragments. It carries information on the very early stages of the collision.

Challenges with forward v_1 measurement

1. Momentum conservation effect
2. EPD is not a tracking detector
3. EPD is far away from the primary vertex, so the measured v_1 is influenced by the STAR material budget.

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

First-order event plane (Ψ_1)

- Reaction planes cannot be measured experimentally. Instead, event planes are used to measure flow.

- In this analysis, v_1 is measured with respect to the first-order event plane (Ψ_1) from the Time Projection Chamber (TPC, $|\eta| < 1$, $0.15 < p_T < 2.0$ GeV/c) to avoid the momentum conservation effect [2].

- Ψ_1^{TPC} is calculated by:

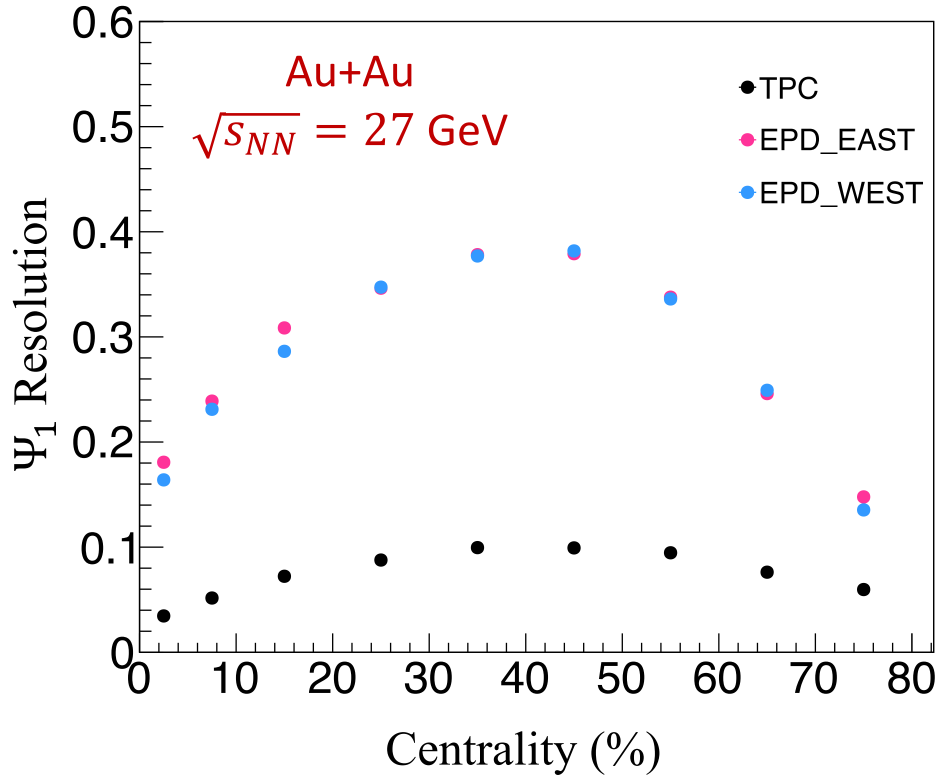
$$\Psi_1^{\mathrm{TPC}} = \arctan 2 \frac{\sum_i w_i \sin\phi_i}{\sum_j w_j \cos\phi_j}$$

where $w_i = -\eta_i$.

- Resolutions are calculated by the three sub-events method:

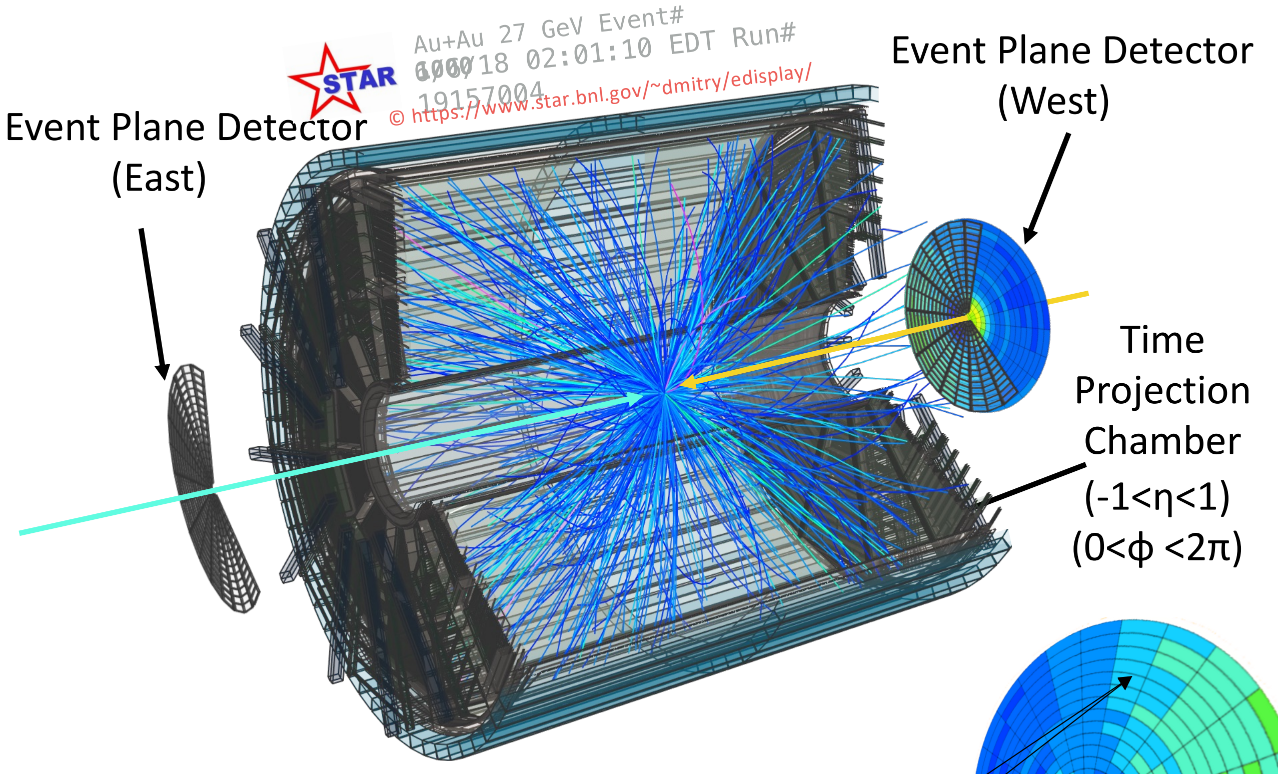
$$R_1^{\mathrm{TPC}} = \sqrt{\frac{\langle\cos(\Psi_1^{\mathrm{TPC}} - \Psi_1^{\mathrm{EAST\_EPD}})\rangle\langle\cos(\Psi_1^{\mathrm{TPC}} - \Psi_1^{\mathrm{WEST\_EPD}})\rangle}{\langle\cos(\Psi_1^{\mathrm{EAST\_EPD}} - \Psi_1^{\mathrm{WEST\_EPD}})\rangle}}$$

$-5 < V_z < 0$ cm

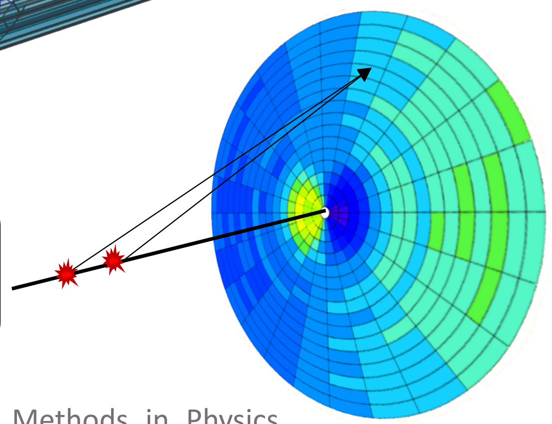


[2] Borghini, Nicolas, et al. Physical Review C 66.1 (2002): 014901.

Event Plane Detector (EPD)



The EPD acceptance is $2.1 < |\eta| < 5.1$ when (V_x, V_y, V_z) = (0,0,0).



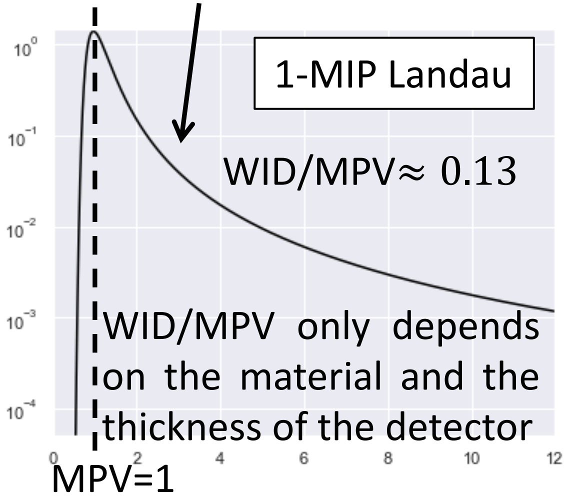
[3] Adams, Joseph, et al. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 968 (2020): 163970.

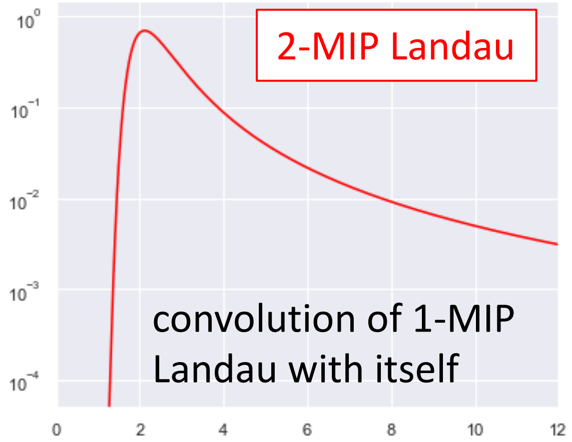
- EPD has two wheels located on the east and west side of the STAR detector. Each wheel consists of 744 tiles [3].
- The pseudorapidity (η) and ϕ of a EPD tile are determined by a straight line between the primary vertex and a random point on the tile.
- Despite the high granularity, as a scintillator detector, EPD cannot count the exact number of particles hitting a tile in each event. Instead, the ADC value of each tile is recorded, and the signal depends on:
  1. the number of particles hitting the tile,
  2. the energy loss of each particle.
- The number of particles passing through a tile, averaged over events, can be probabilistically determined from the ADC distributions.

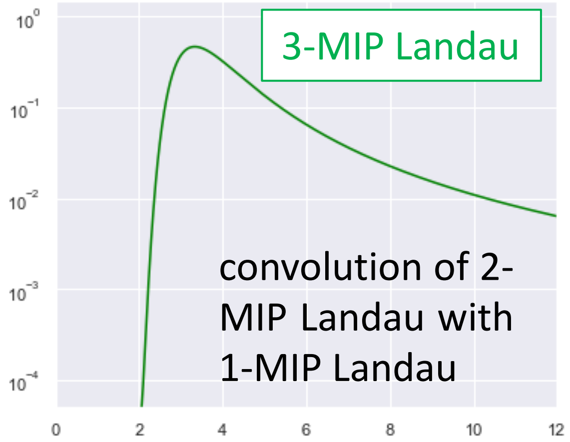
“Count” particles from the ADC spectrum

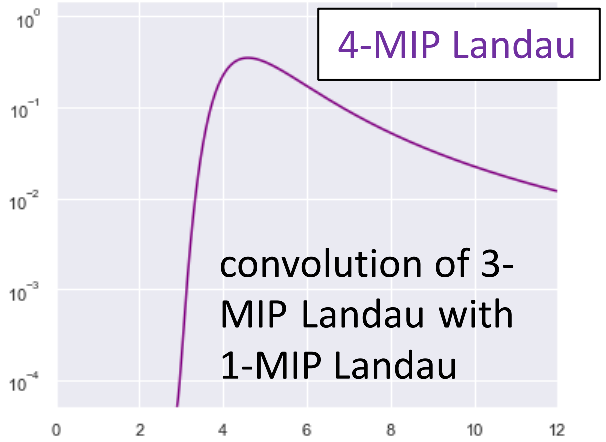
When a Minimum Ionizing Particle (MIP) goes through a scintillator tile, the energy loss (therefore the ADC spectrum) follows a Landau distribution.

The forms of all the Landau distributions are known

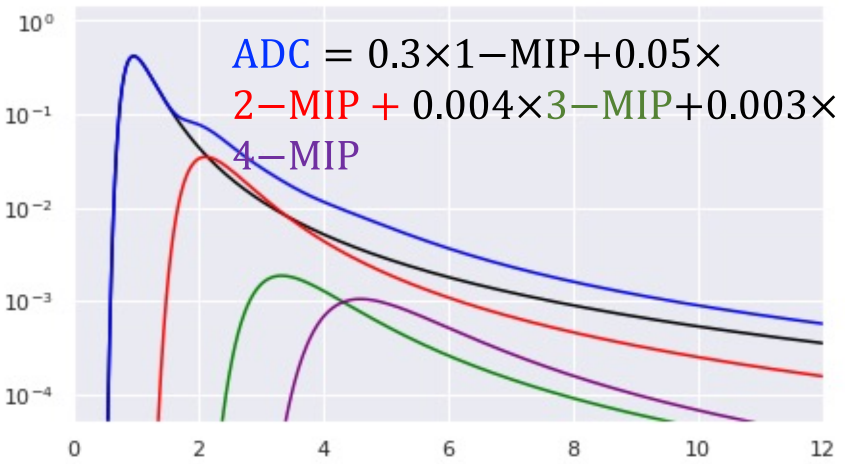








Example: In 30% of the events, 1 MIP hits a EPD tile; in 5% of the events, 2 MIPs hit the tile; in 0.4% of the events, 3 MIPs hit the tile and in 0.3% of the events, 4 MIPs hit the tile. What will the ADC spectrum look like?



Given the ADC spectrum, can we find the fractions of i-MIP events?

Of course!

v_1 extraction

- The iMIPweight (M_i) in the fitting parameters represents the fraction of the i-MIP events. Therefore, the $(\phi - \Psi_1)$ distribution can be obtained by:

$$\mathrm{N} = \mathbf{k}\mathbf{M}^{\top},$$

where $\mathbf{k} = (1, 2, 3, 4)$ and $\mathbf{M} = (M_1, M_2, M_3, M_4)$.

- The associated error bar can be calculated by:

$$\sigma^2 = \mathbf{k}\boldsymbol{\Sigma}\mathbf{k}^{\top}$$

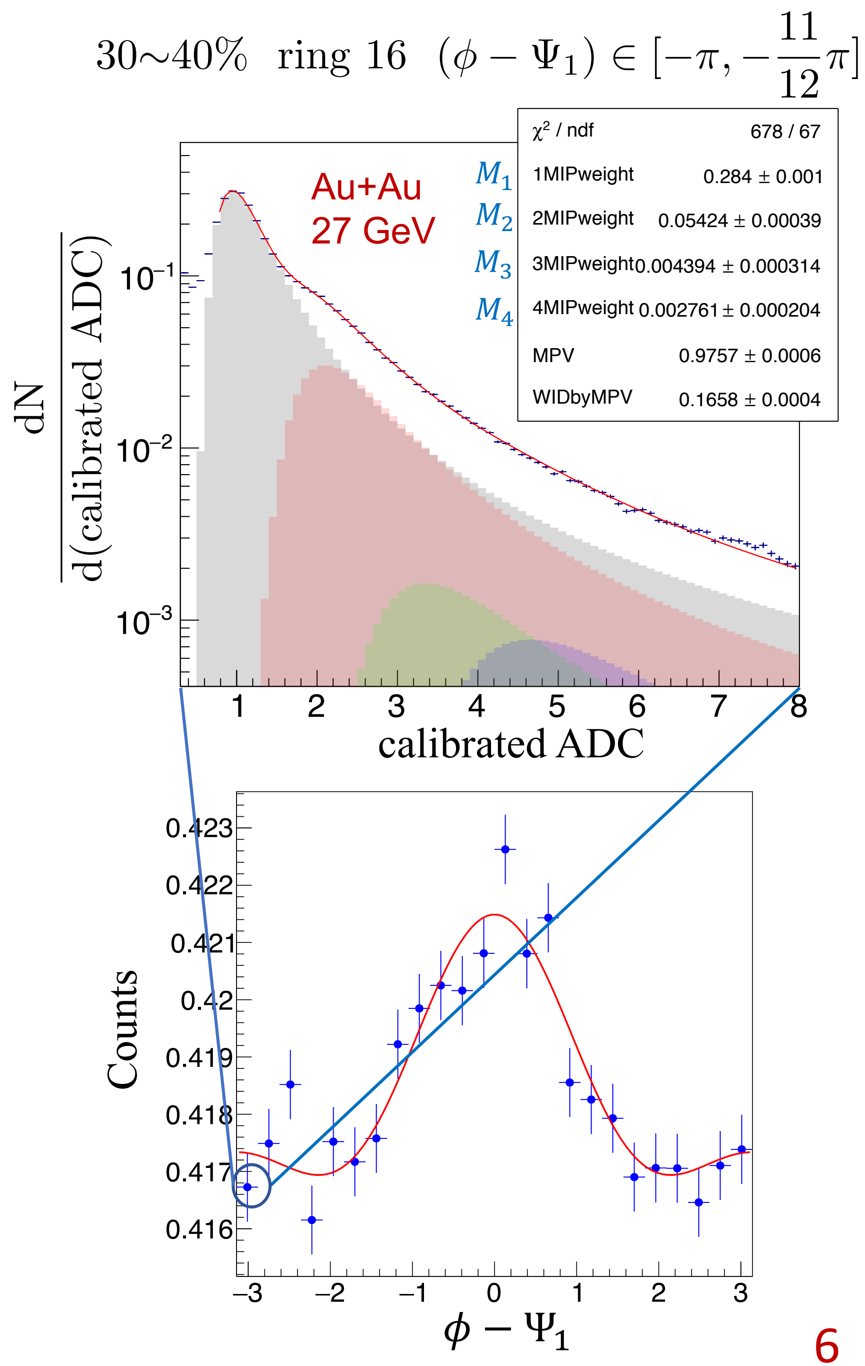
where $\boldsymbol{\Sigma}$ is the covariance matrix of the iMIPweights.

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

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

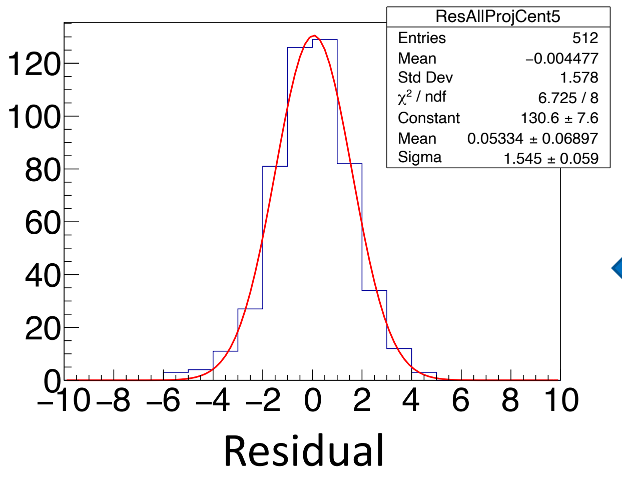
- v_1 needs to be corrected by the Ψ_1^{TPC} resolution:

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

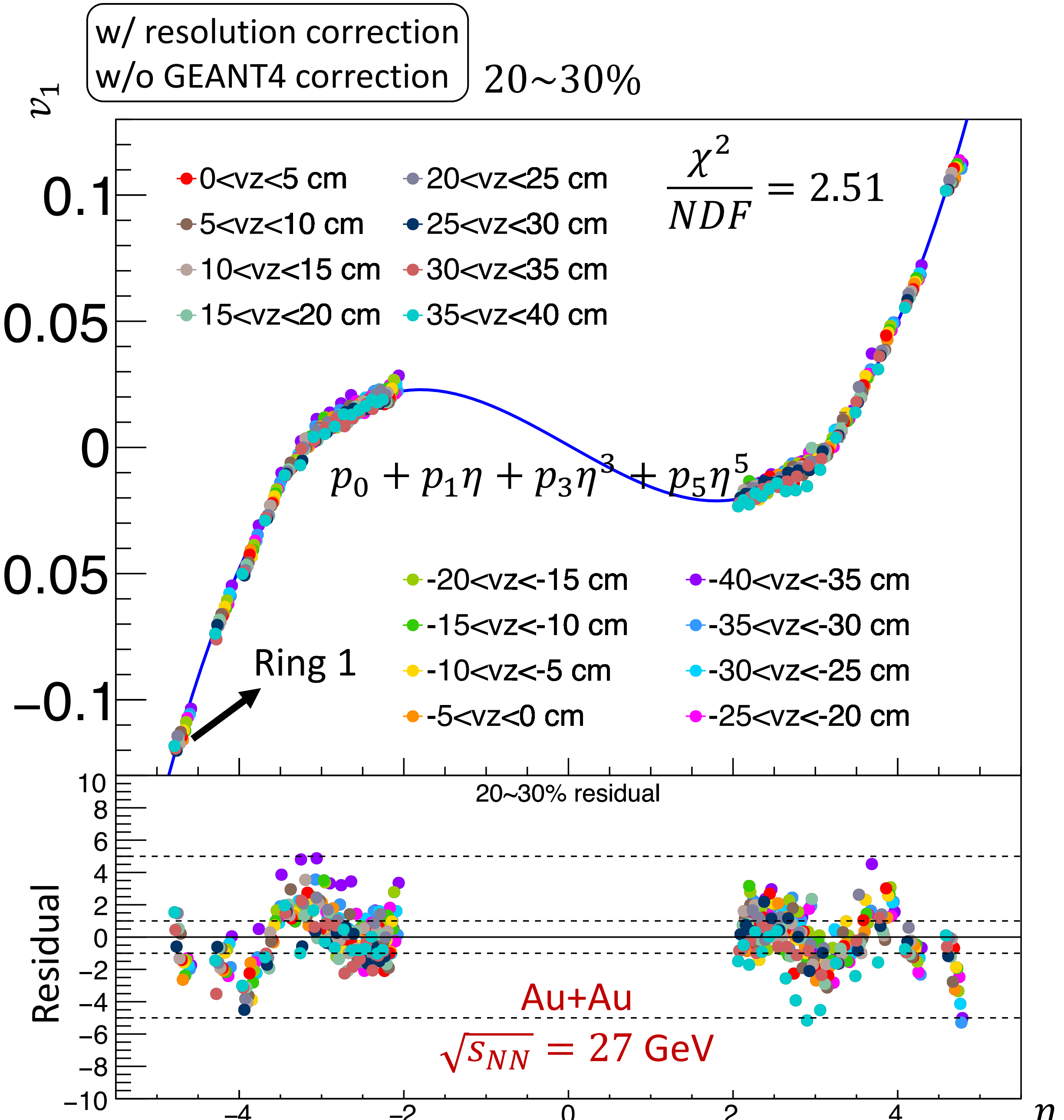


v_1 for 16 V_z bins

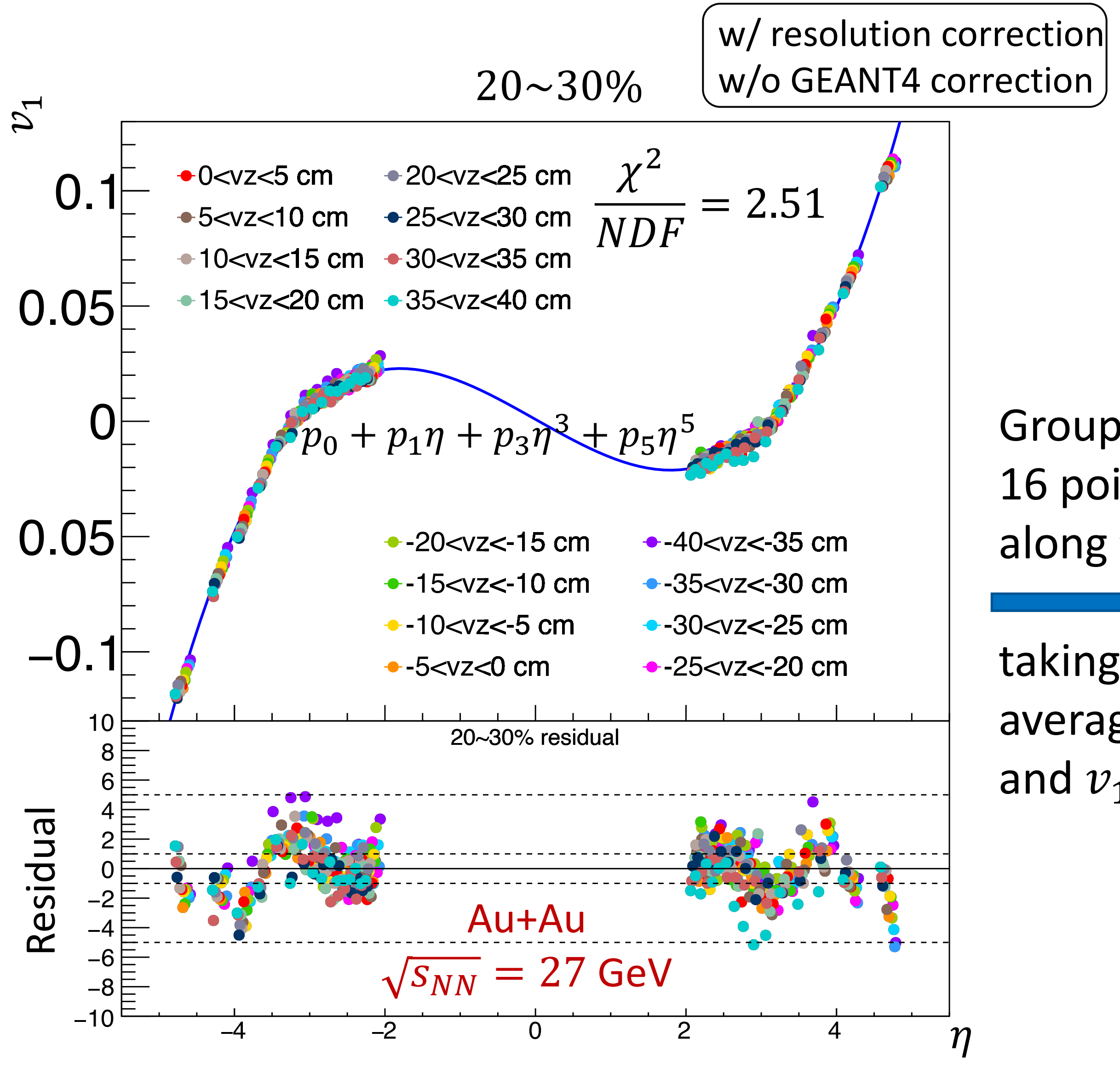
- v_1 was measured at 16 different V_z bins. The η of a EPD ring is different for different V_z.
- Results from 16 V_z bins are consistent: all the data points can be fitted by the same smooth curve.
- Residual is the difference between the data value and the fitting value divided by the error bar of the data. The residual distribution follows a Gaussian distribution of $\sigma = 1.5$, which indicates the error bars are reasonable.



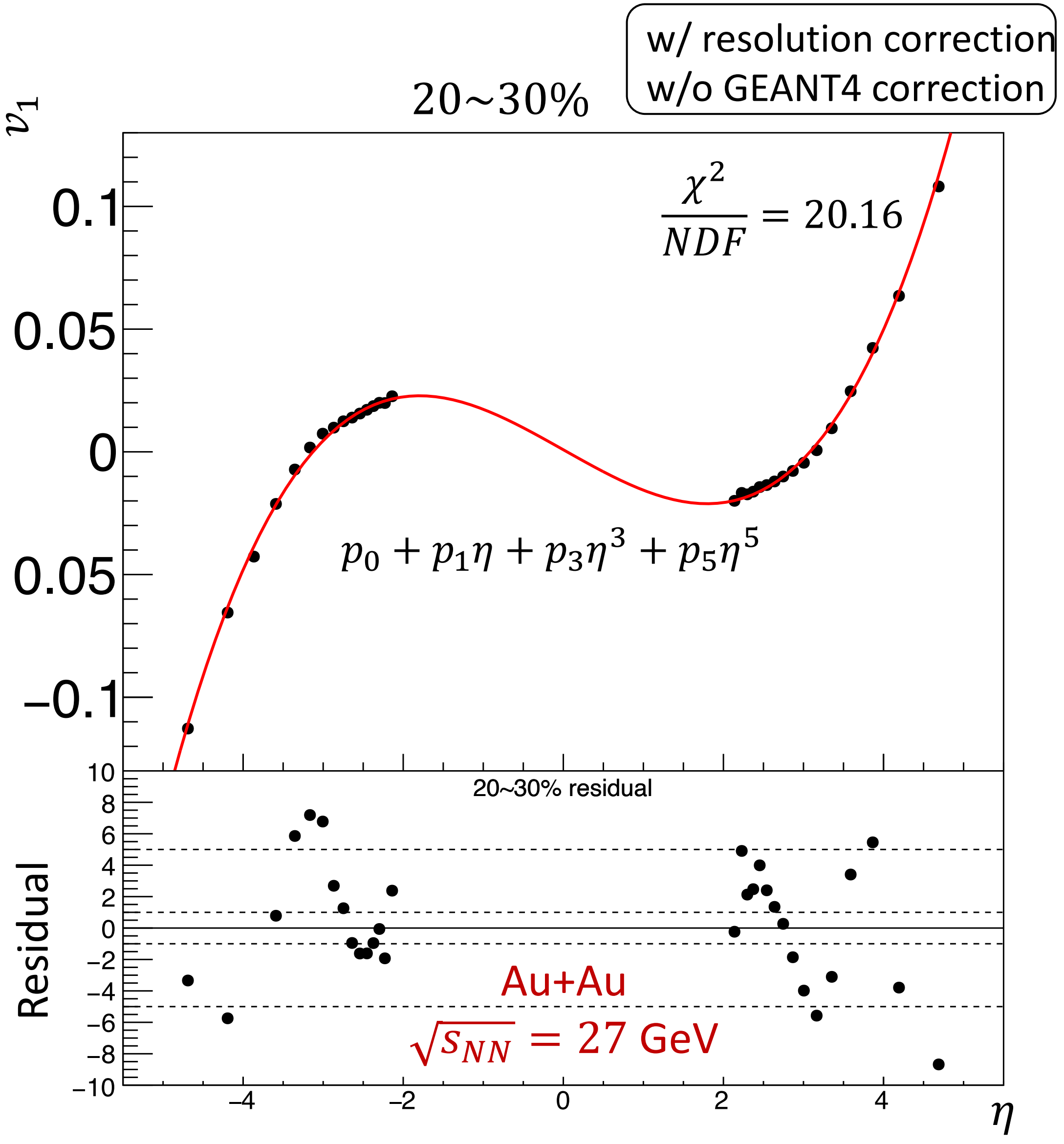
Project on the Y axis



Combine 16 V_z bins

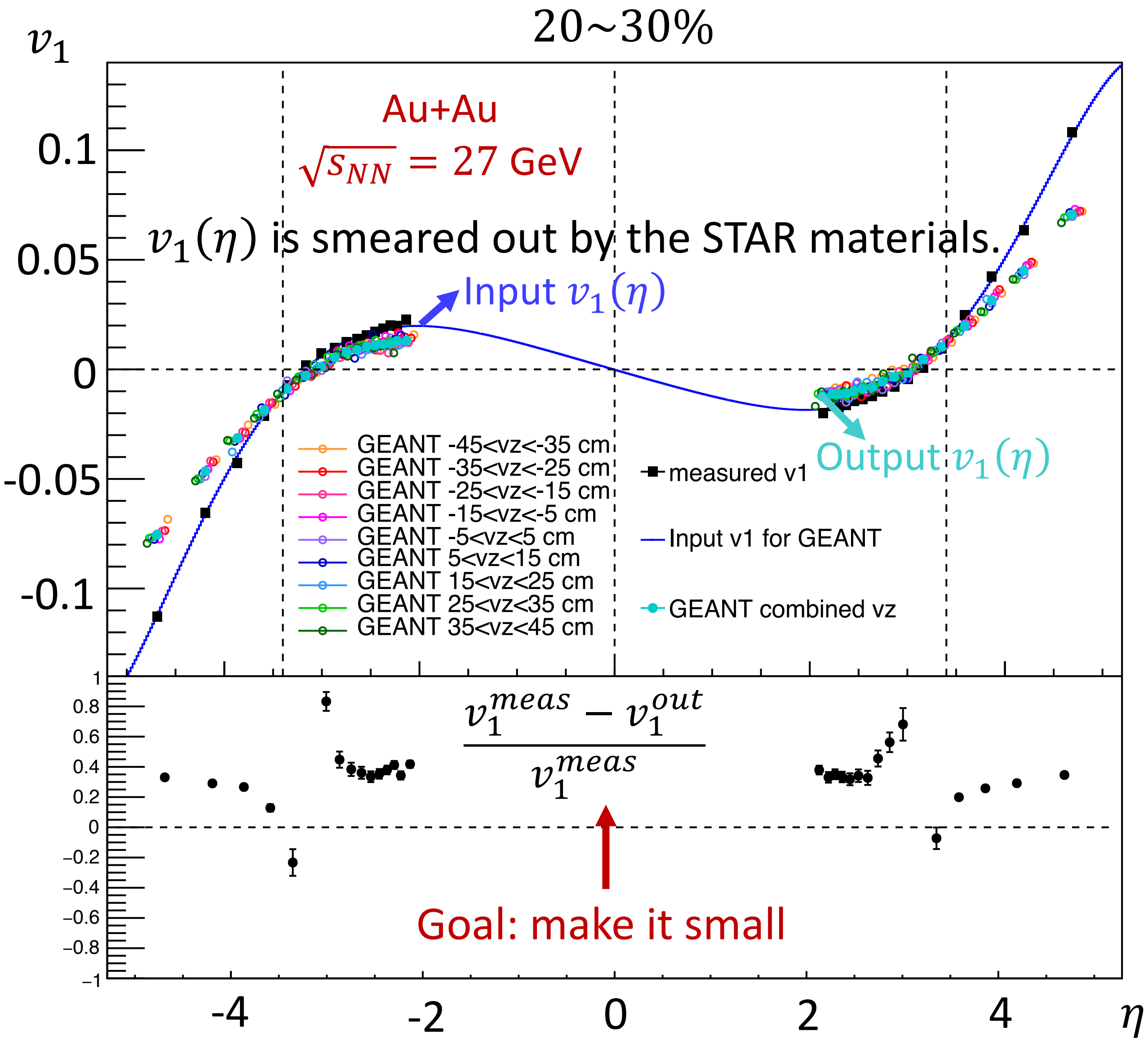


Group every 16 points along η by taking the average of η and v_1.

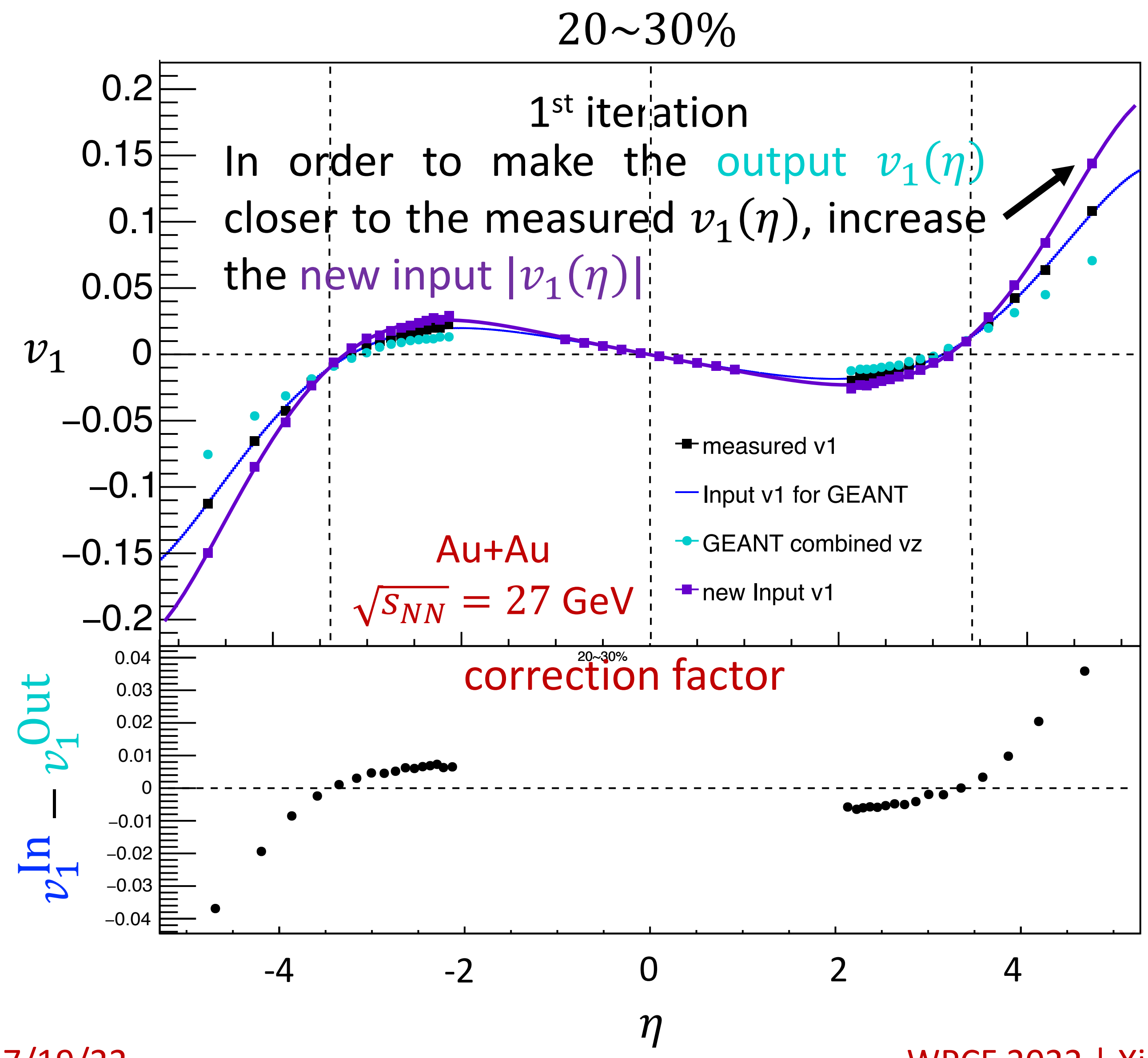


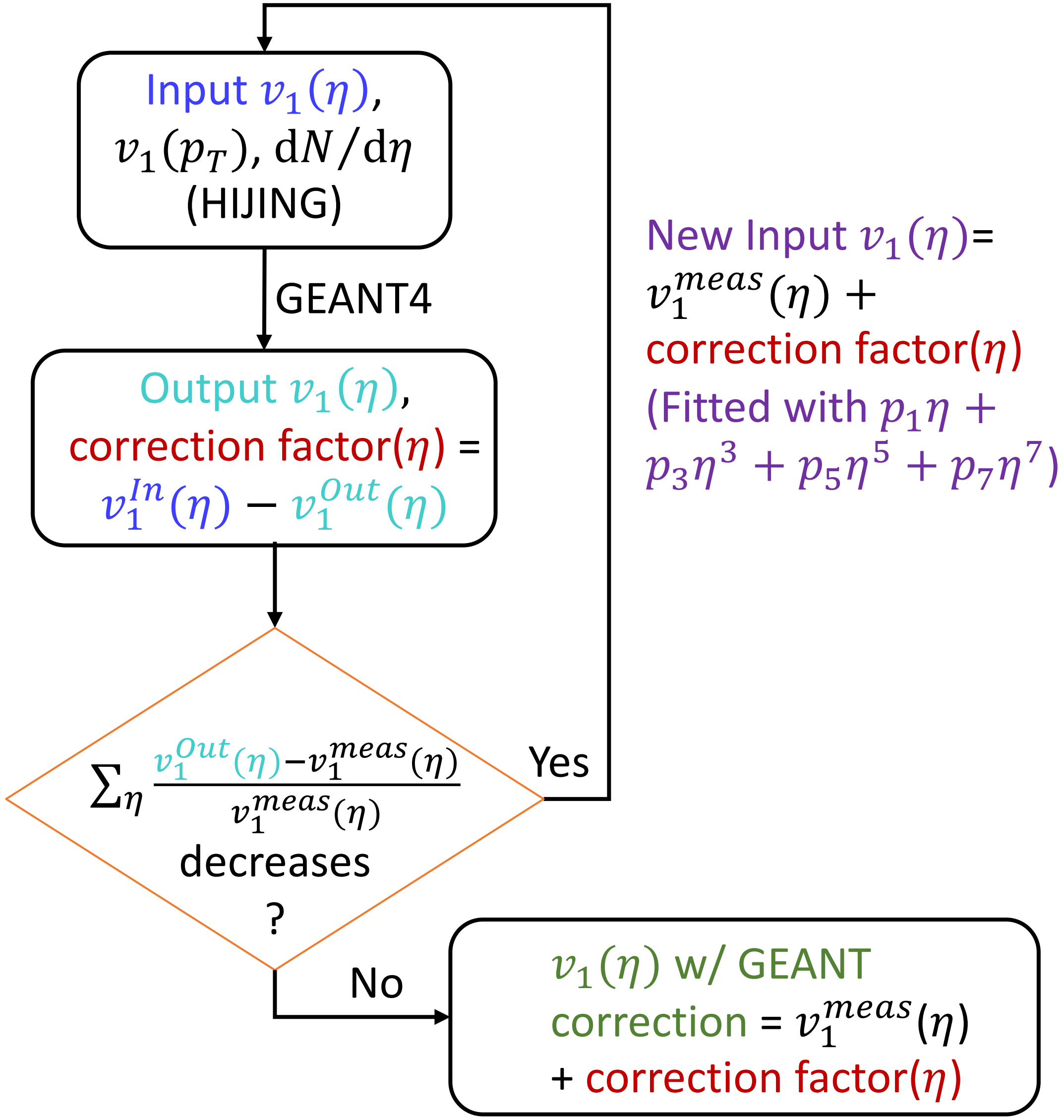
GEANT4 simulation

- In the HIJING + GEANT4 simulation, we have access to the primary tracks of the HIJING events (including neutral particles) and their corresponding EPD hits.
- How exactly the materials influence the output $v_1(\eta)$ depends on the input $v_1(\eta)$, $v_1(p_T)$ and $\mathrm{d}N/\mathrm{d}\eta$.
- The input particle distributions can be set by weighting the HIJING tracks. The same weights must be applied to the corresponding EPD hits, too.
- Adjust the input v_1 (HIJING) until the output v_1 (GEANT4) is consistent with the measured v_1. Then the input v_1 is the flow without the influence from the material budget.

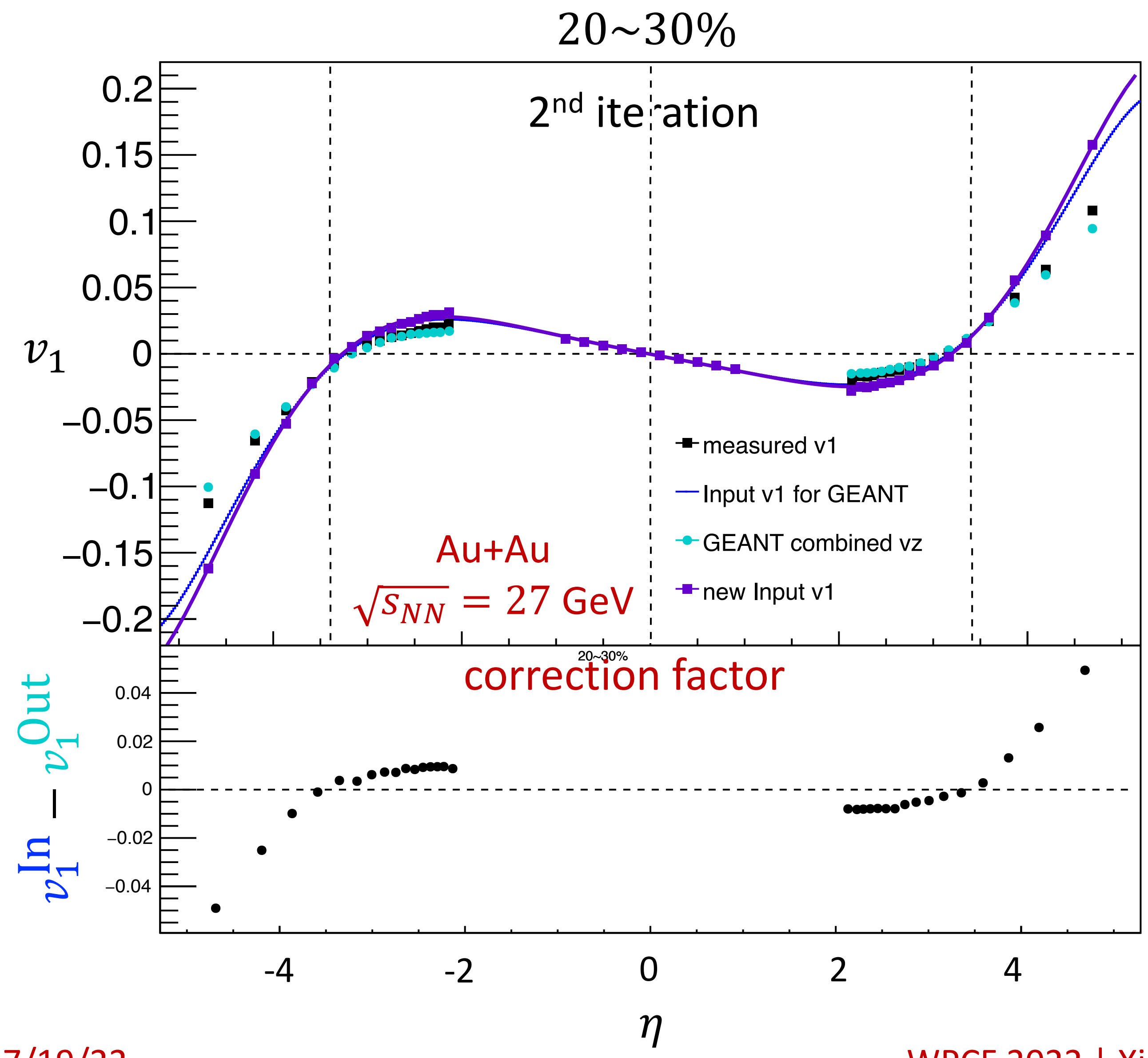


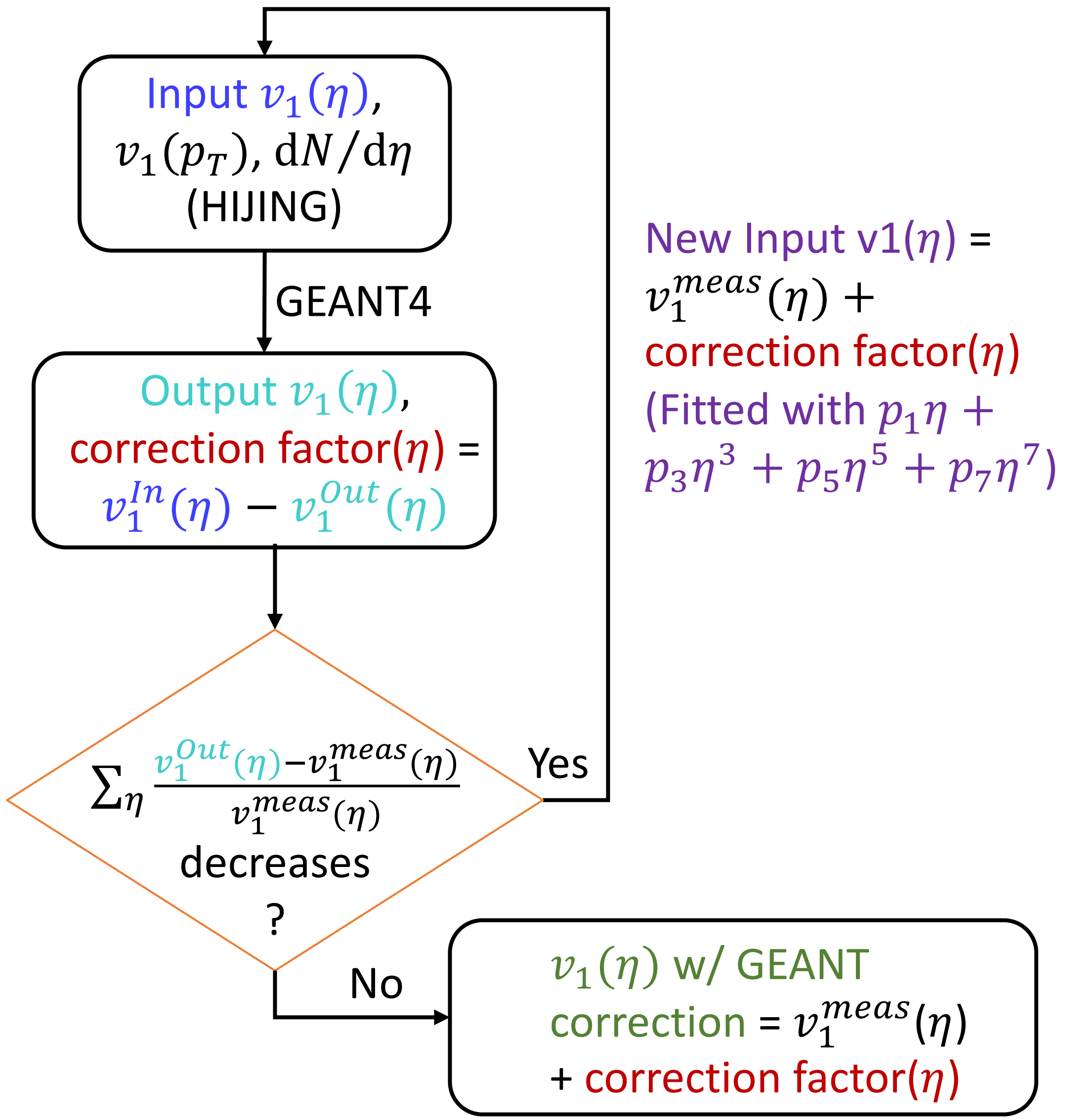
Correct for the STAR material budget



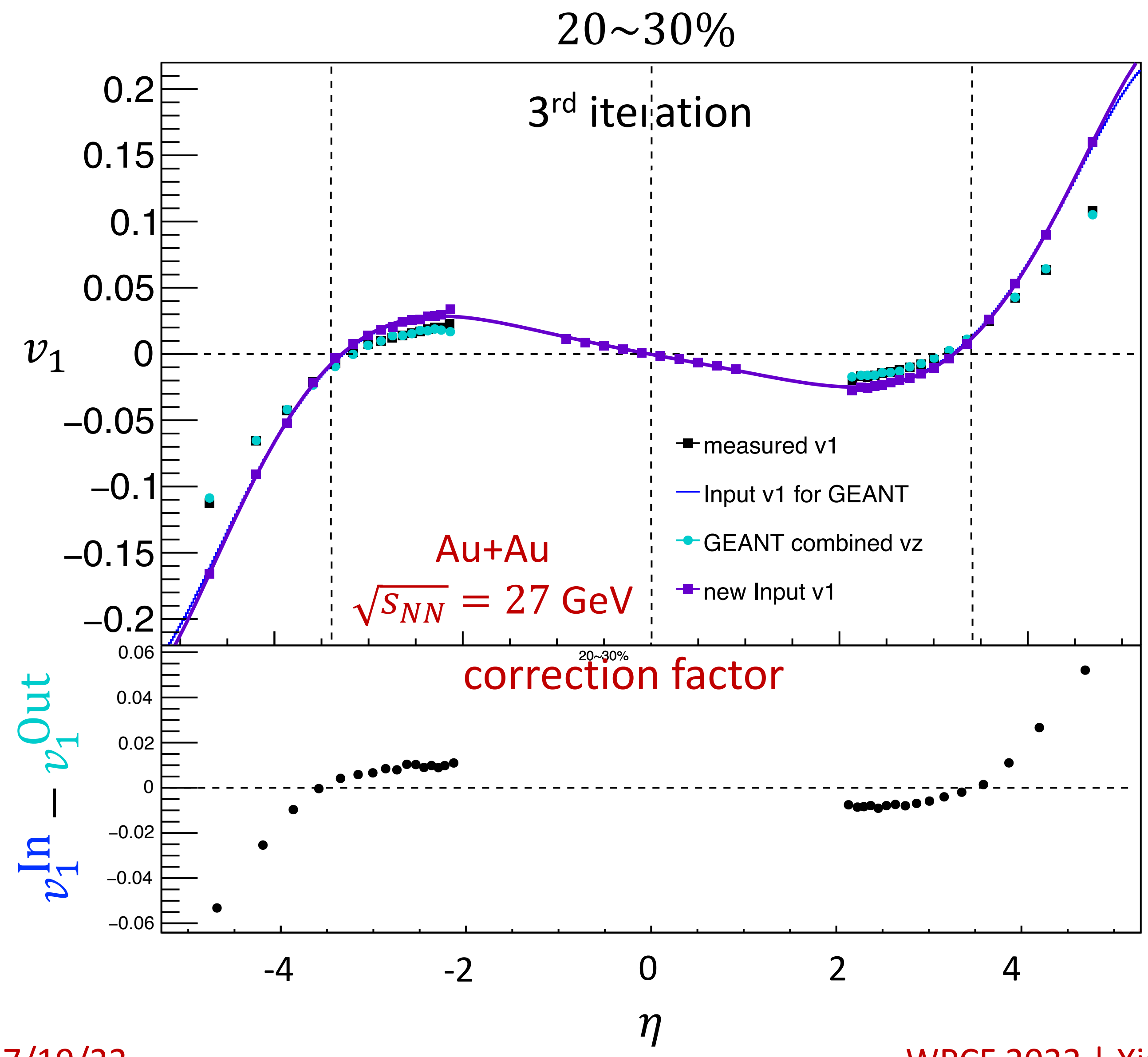


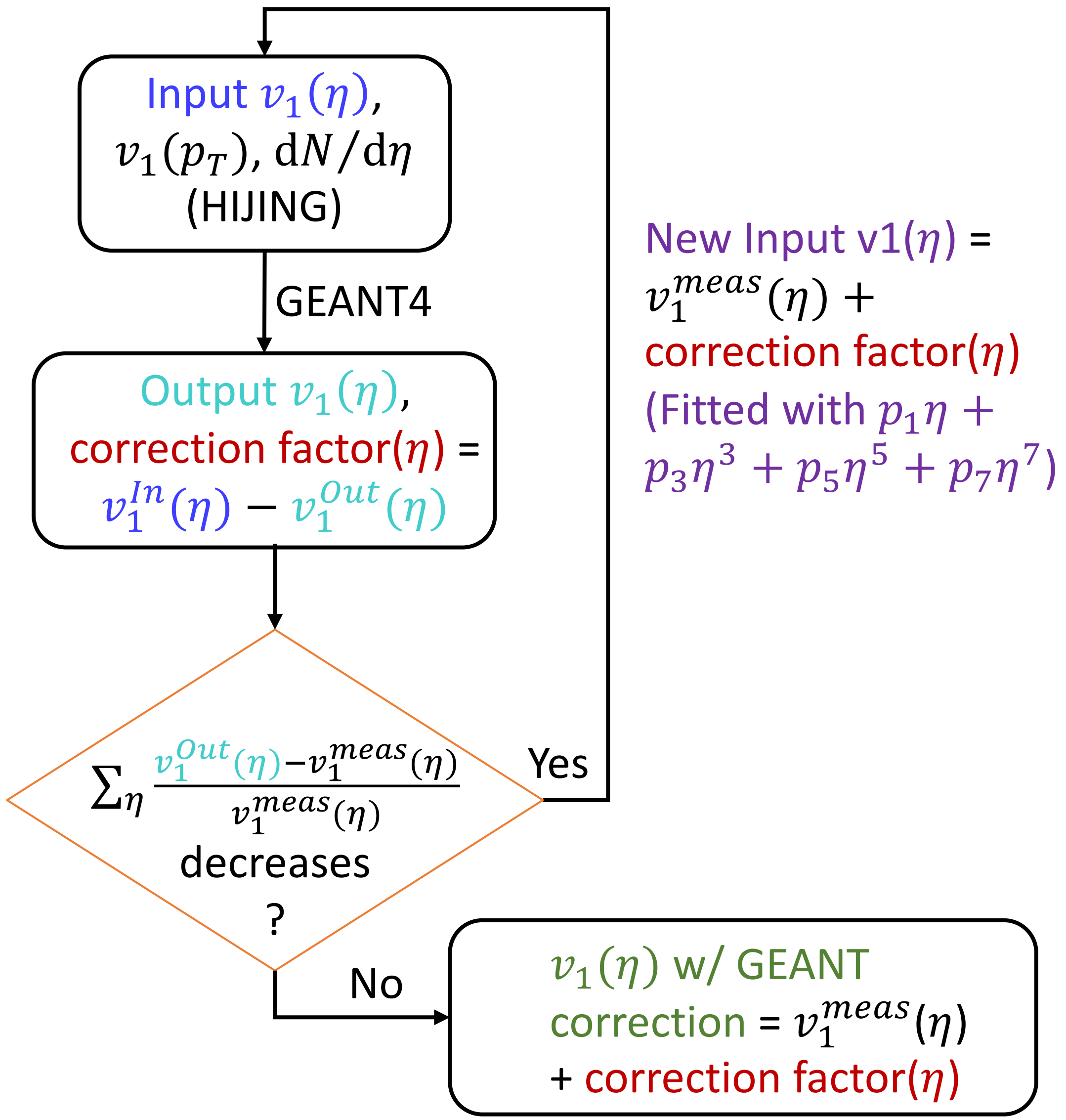
Correct for the STAR material budget



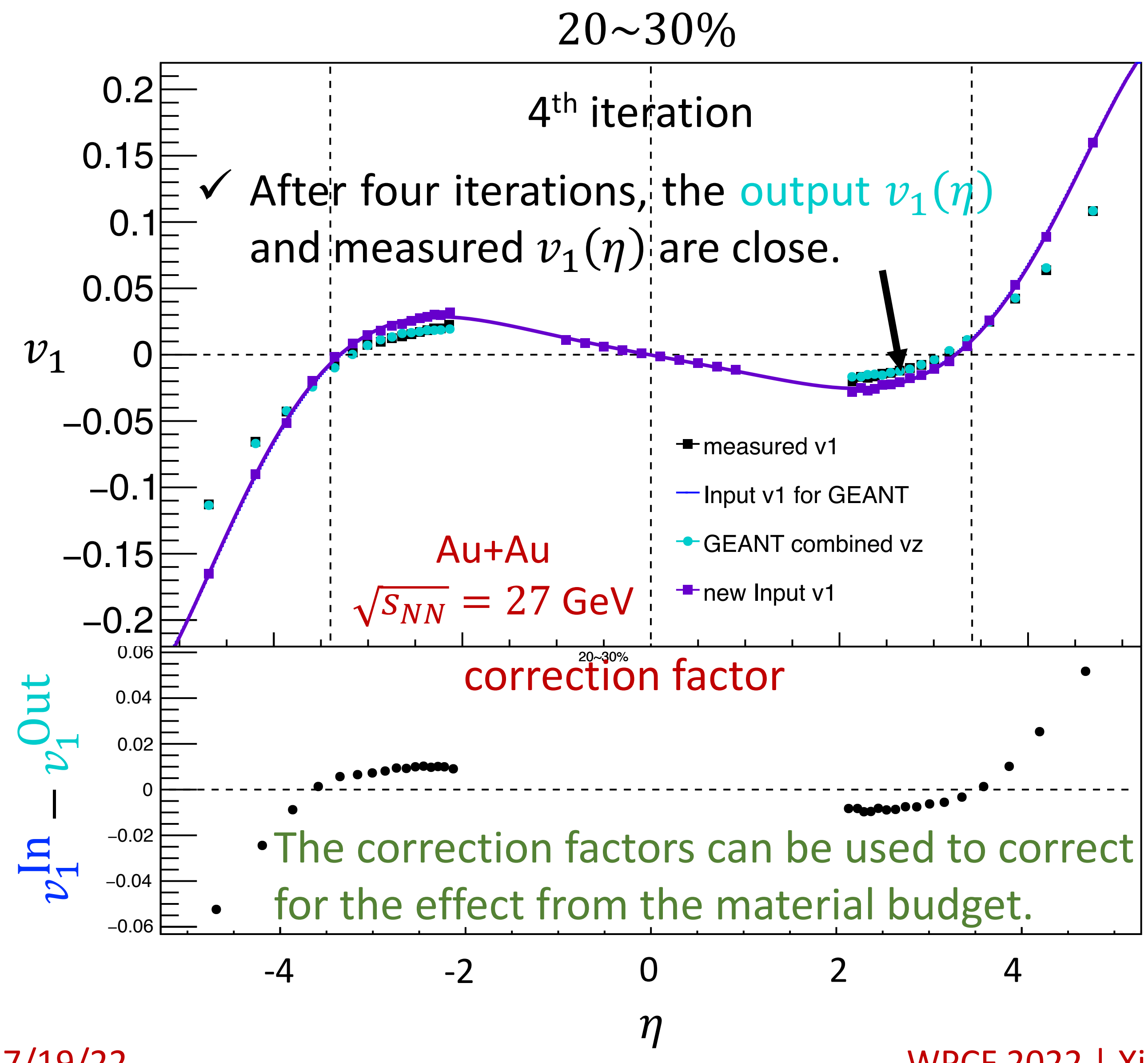


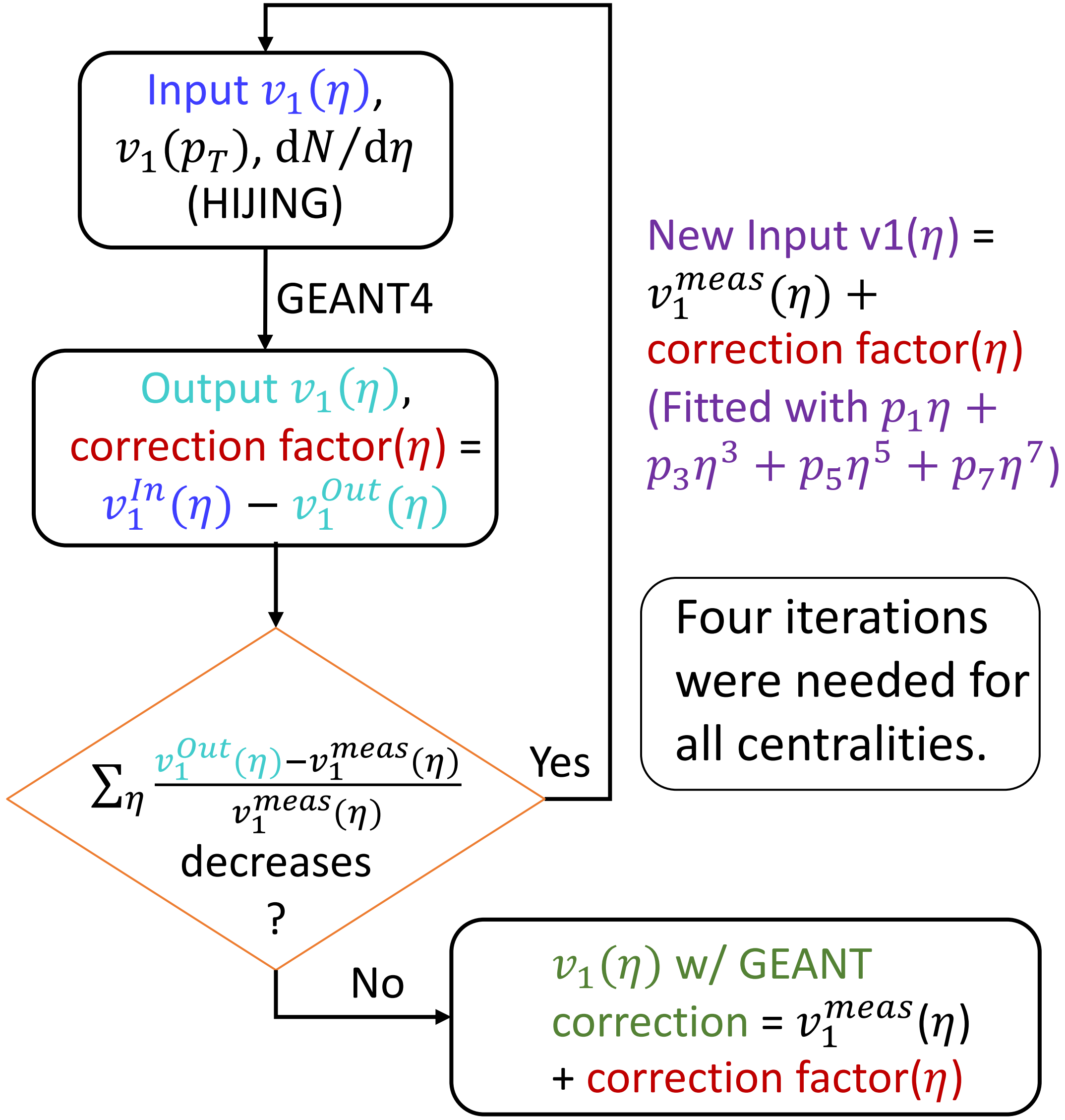
Correct for the STAR material budget



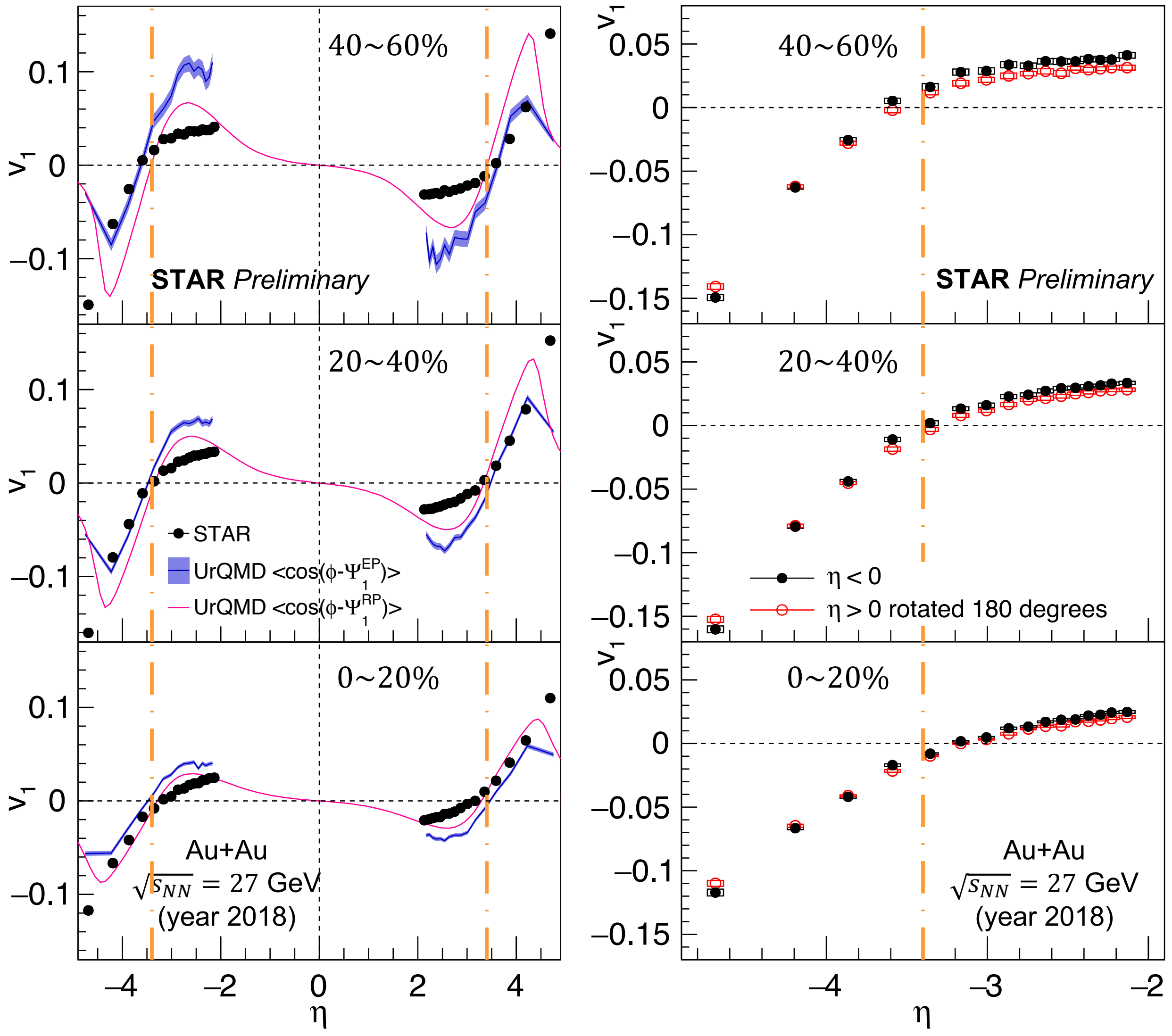


Correct for the STAR material budget





Results



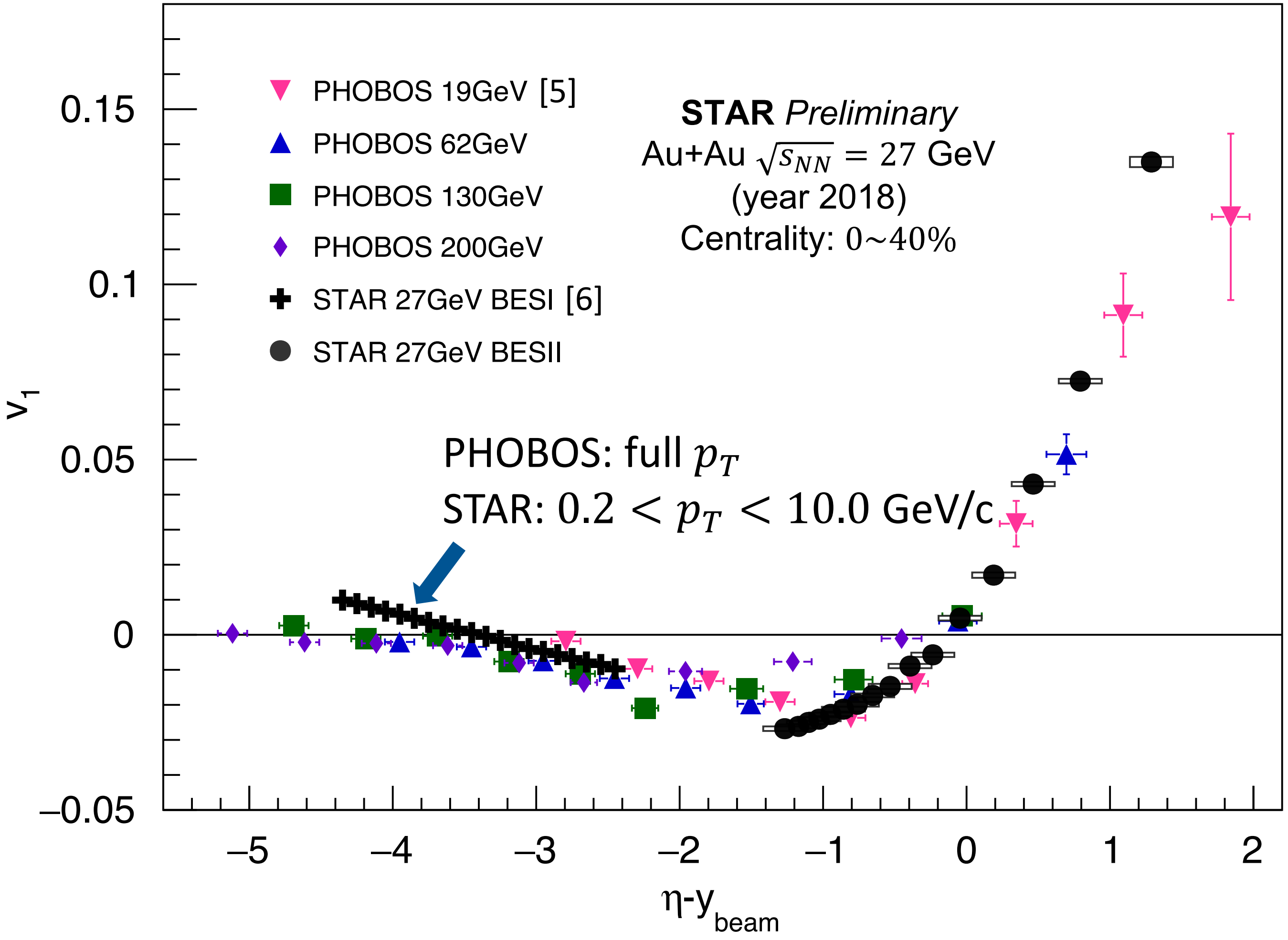
- $v_1(\eta)$ has all corrections applied. Both statistical errors (smaller than markers) and systematic errors (boxes) are plotted. The dashed orange line corresponds to where the incident ions would lie on a rapidity scale.

- $v_1(\eta)$ changes sign around the beam rapidity.

- UrQMD particles are sampled 100 fm/c after the beginning of the collision. UrQMD $v_1(\eta)$ shows the same shape as the measured $v_1(\eta)$, although the values are different.

- The difference between the east and west $|v_1|$ comes from the unsymmetric $\mathrm{d}N_{ch}/\mathrm{d}\eta$ in TPC (reference). Correction is underway.

Comparison with PHOBOS



Except for STAR BESII, all other data sets only have statistical errors plotted.

✓ $v_1(\eta - y_{\text{beam}})$ follows the pattern of limiting fragmentation [4].

[4] STAR, Phys. Rev. C 73.3 (2006): 034903.
[5] PHOBOS, Phys. Rev. Lett. 97.1 (2006): 012301.
[6] STAR, Phys. Rev. C 101.2 (2020): 024905.

Summary

- $v_1(\eta)$ was measured within 10 units of pseudorapidity $(\sim +/-5)$ using the Event Plane Detector (EPD) with STAR BES II Au+Au @27 GeV data.
- $v_1(\eta)$ changes sign around the beam rapidity.
- This measurement was compared with the PHOBOS results. $v_1(\eta - y_{\text{beam}})$ follows the pattern of limiting fragmentation.
- The measured $v_1(\eta)$ was compared with the UrQMD results. They follow the same trend, but the values are different.

Challenges & our approaches

1. Momentum conservation effect

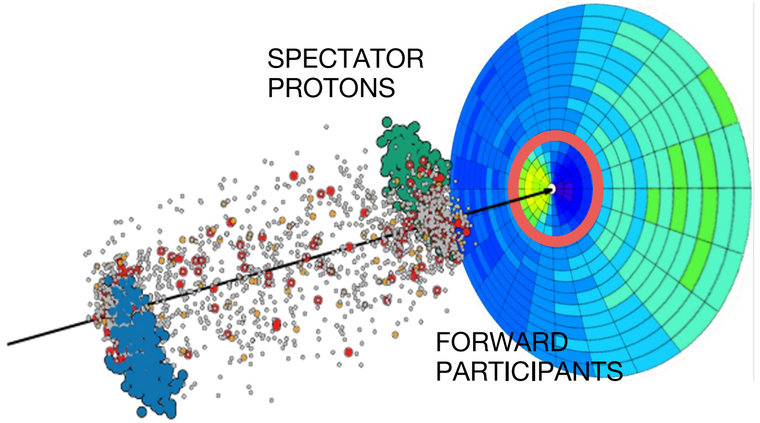
✓ Use a symmetric reference

2. EPD is not a tracking detector

✓ Fit the ADC spectrum

3. EPD is far away from the primary vertex

✓ Use the GEANT4 simulation to correct for the effect from the material budget.



Outlook

- Measure $v_1(\eta)$ at other BES-II energies.

Thank you !