Measurement of Directed Flow with the Event Plane Detector at the STAR Experiment

Xiaoyu Liu

The Ohio State University

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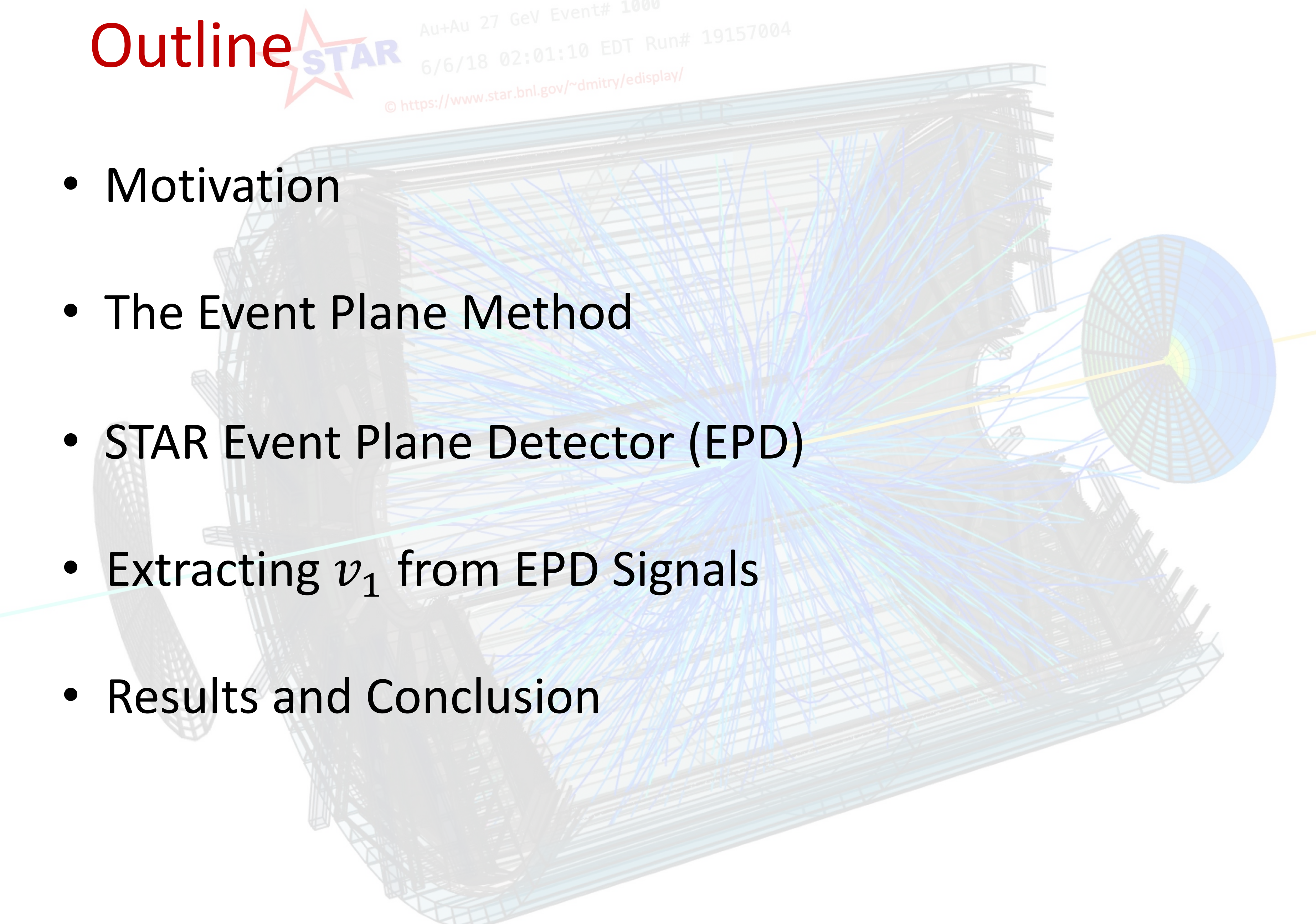
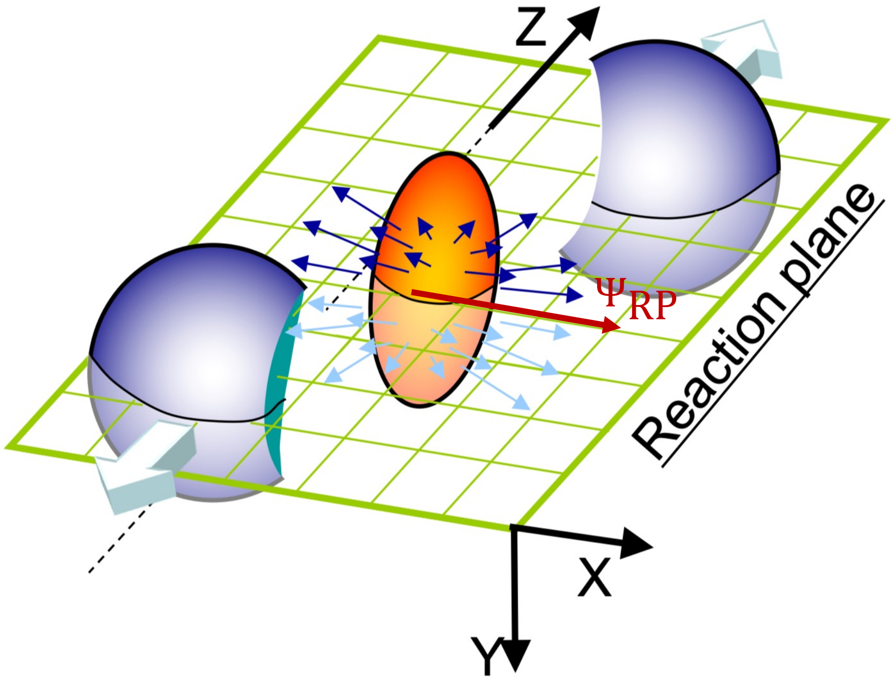
Outline

- Motivation
- The Event Plane Method
- STAR Event Plane Detector (EPD)
- Extracting v_1 from EPD Signals
- Results and Conclusion



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.

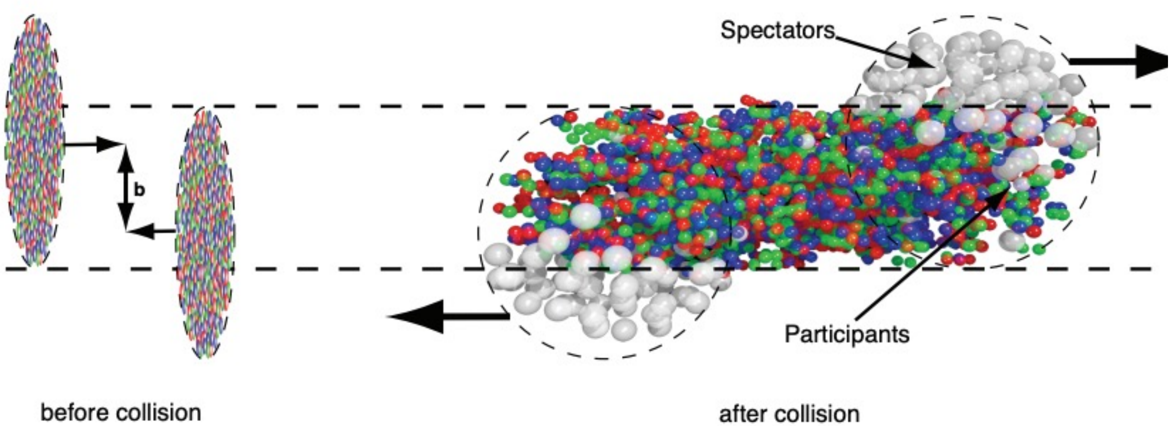
- It can be quantified by the harmonic in the Fourier expansion of azimuthal particle distribtuion with respect to the reaction plane (Ψ_{RP}) [1]:

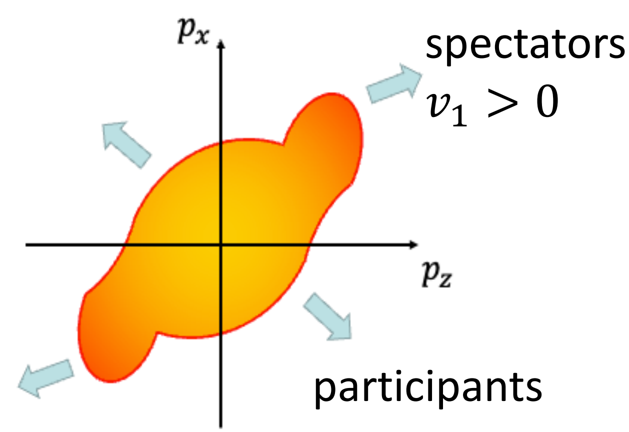
$$\frac{\mathrm{dN}}{\mathrm{d}(\phi - \Psi_{\mathrm{RP}})} = k\{1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\phi - \Psi_{\mathrm{RP}})]\}$$

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].



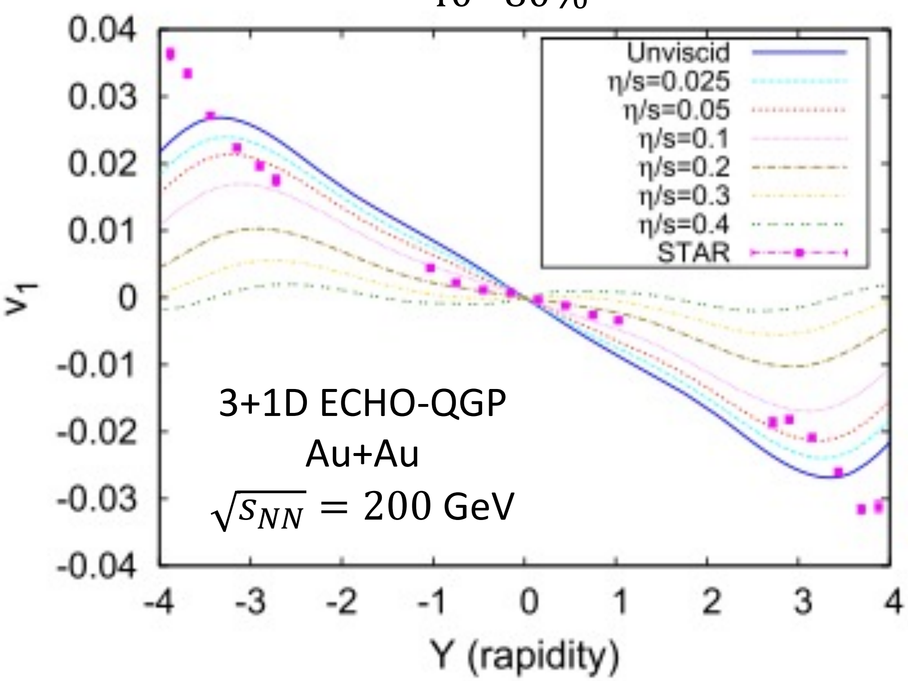


[3] Becattini, F., et al. The European Physical Journal C 75 (2015)
[4] Du, Lipei, et al. arXiv preprint arXiv:2211.16408 (2022)

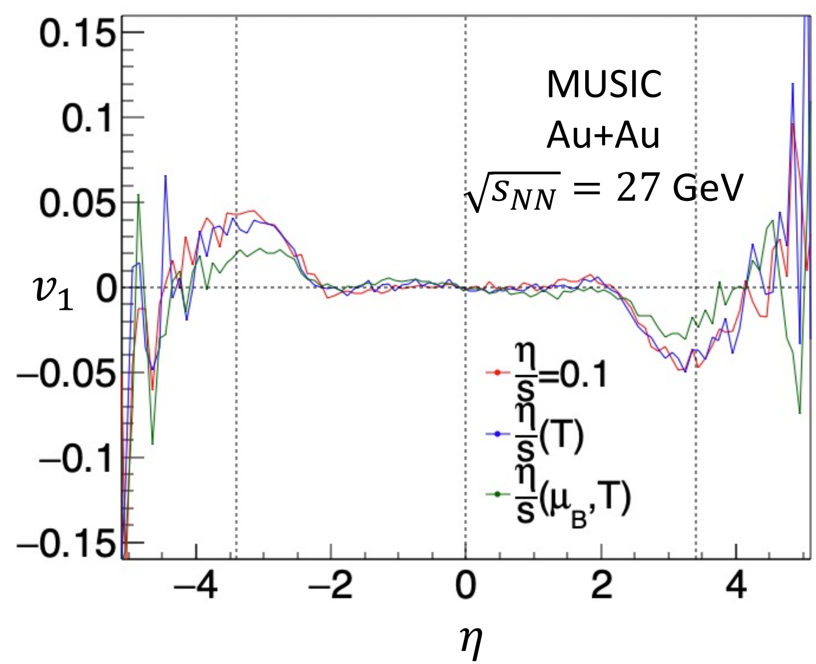
Motivation

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

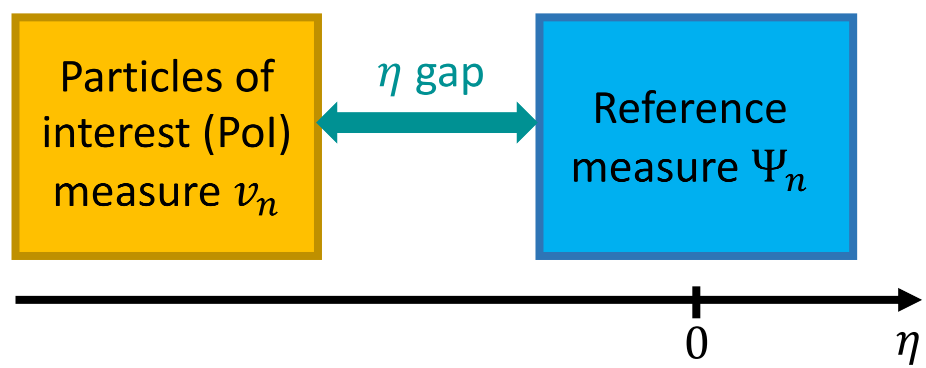
$$v_n\{\mathrm{EP}\} = \frac{\langle \cos[n(\phi_i - \Psi_n)] \rangle}{R_n}$$

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

Reference matters!

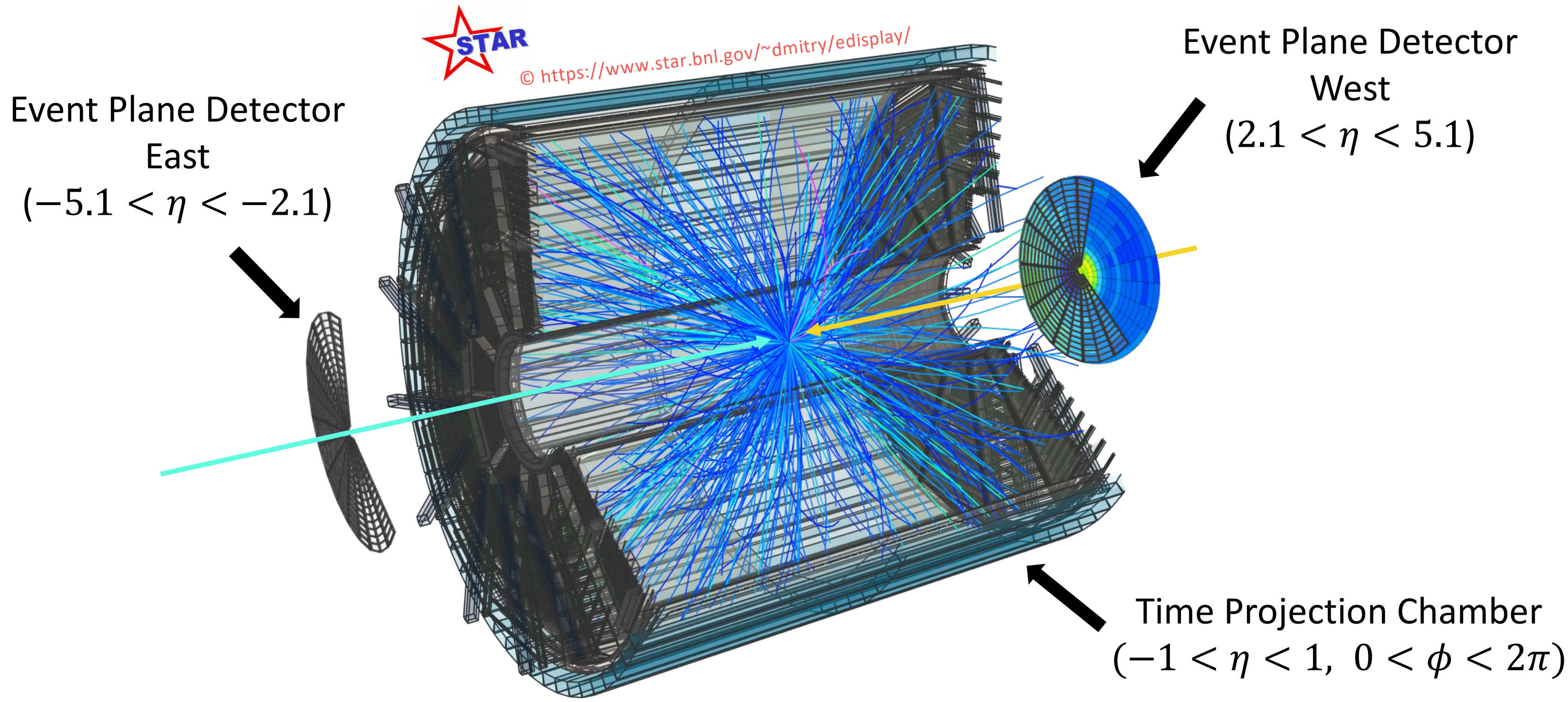
Non-flow effects
resonances decay,
self correlations, di-jets,
momentum conservation
effect…

symmetric reference



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 η gap is imposed between the PoI and reference.

First-Order Event Plane (Ψ_1)

[6] Borghini, Nicolas, et al. Physical Review C 66.1 (2002): 014901.
[7] A. M. Poskanzer and S. A. Voloshin Phys. Rev. C 58, 1671

- Chose the Time Projection Chamber (TPC, $|\eta| < 0.8$) as the reference to suppress the momentum conservation effect [6] .

- The first-order event plane is calculated as:

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

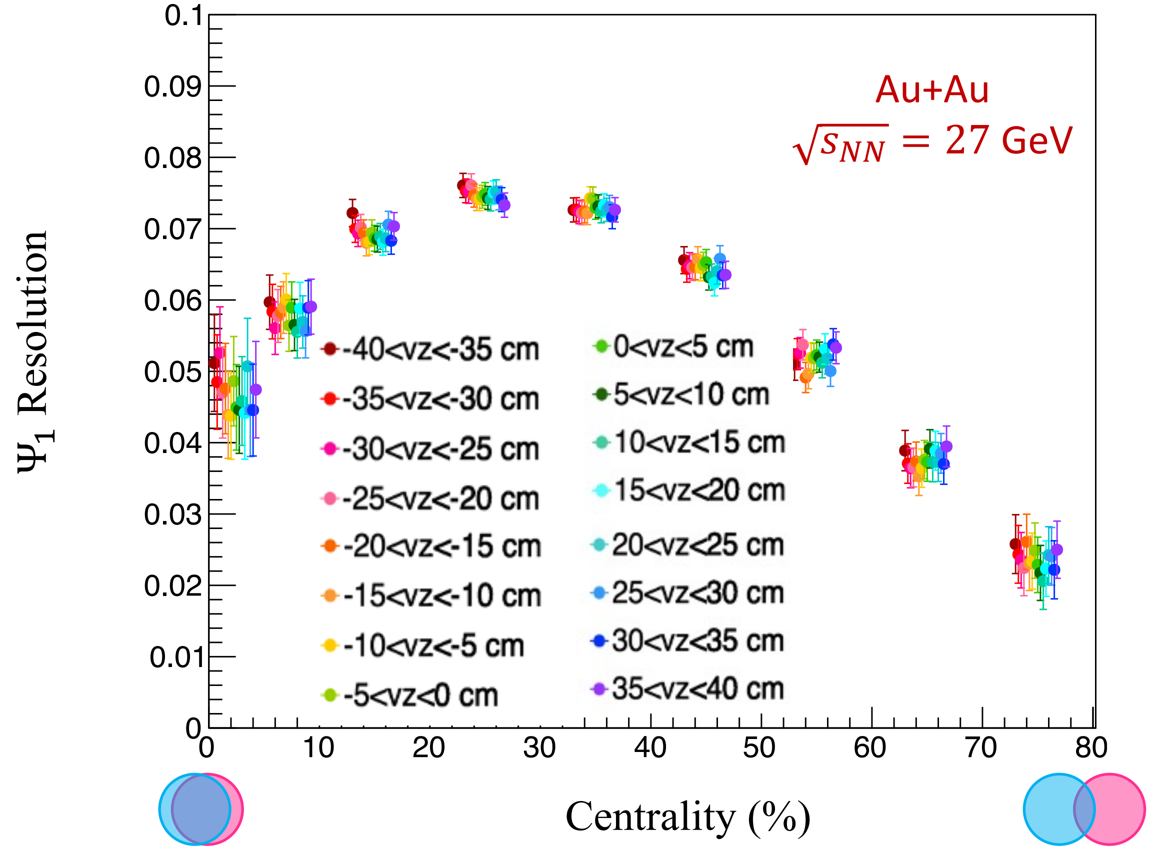
- Three weightings are assigned to TPC tracks:
  - w_ϕ to make the $\frac{dN}{d\phi}$ distribution uniform;
  - w_{sym} to make the $\frac{dN}{d\eta}$ distribution symmetric;
  - $w_\eta = -\eta$ to maximize the TPC event plane resolution.

$$w_i = w_\phi \times w_{\mathrm{sym}} \times w_\eta$$

- All the event planes are shifted to further correct for the detector effects [7].

First-Order Event Plane (Ψ_1)

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

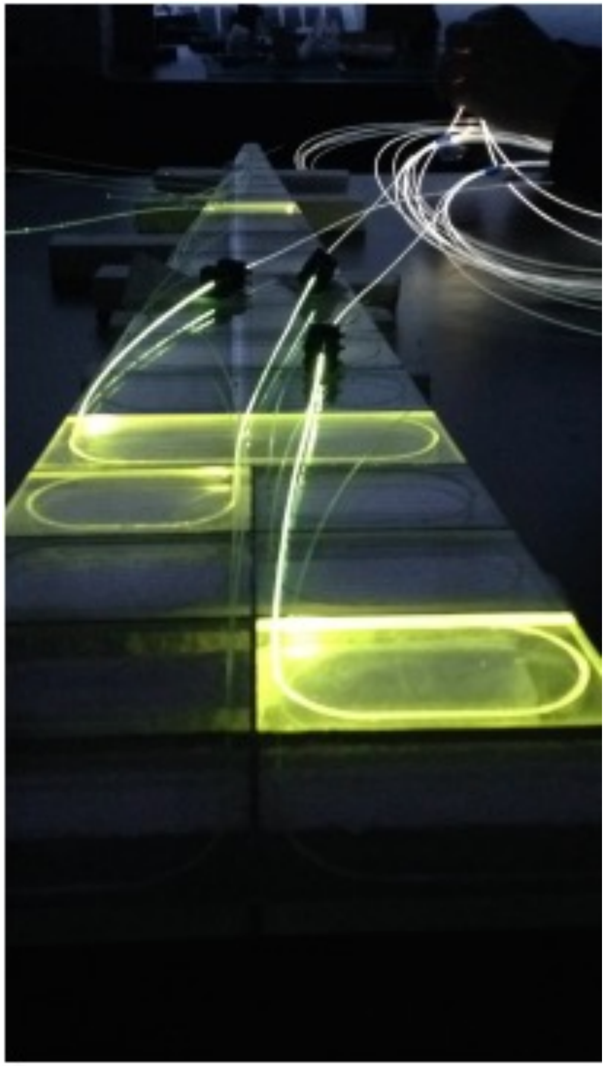


- Data points are offset along the x axis for the demonstration purpose.
- The event plane resolution is calculated by the three sub-event method:

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

Event Plane Detector (EPD) [8]

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



Particles (MIPs) transverse an EPD tile

↓

Scintillator absorbs energy and emits photons

↓

Optical fibers transport light to a silicon photomultiplier (SiPM)

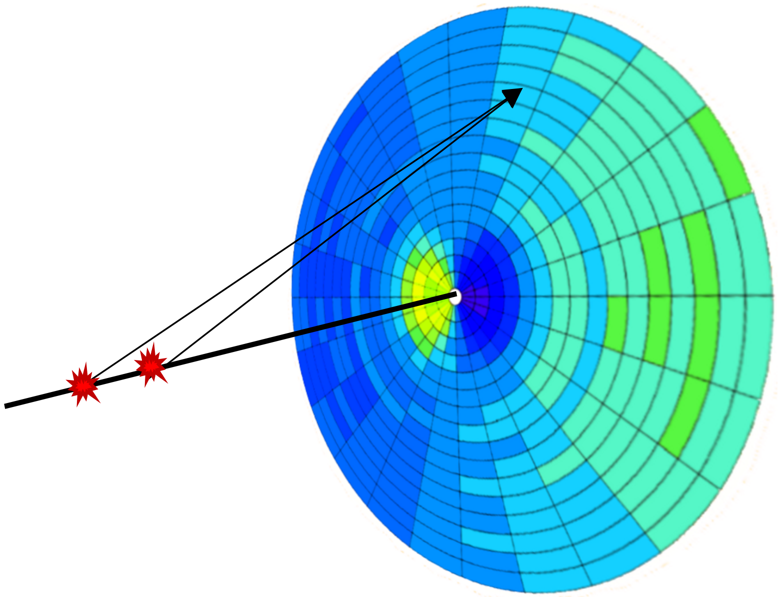
↓

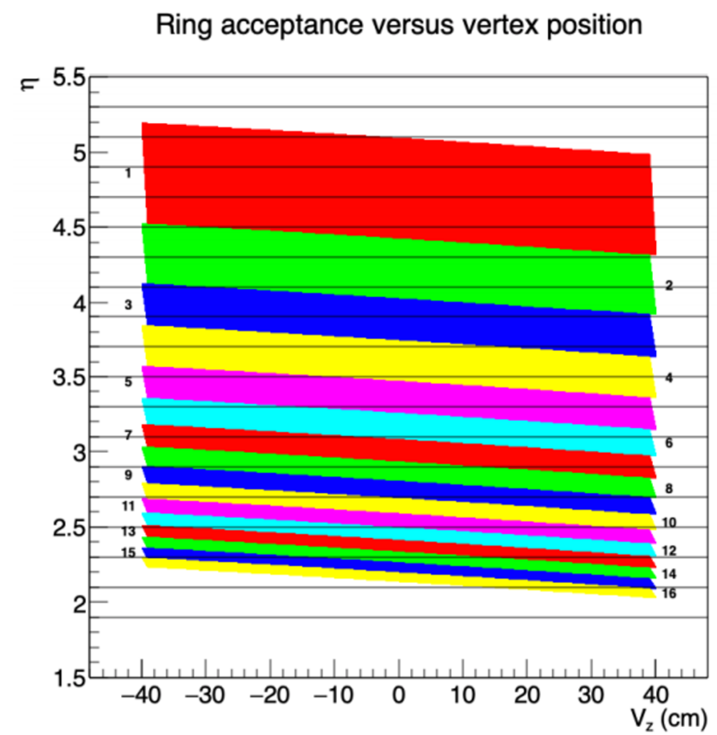
Signals from SiPM are amplified and sent to the digitizing and acquisition system

↓

Recorded as ADC values

Event Plane Detector (EPD)



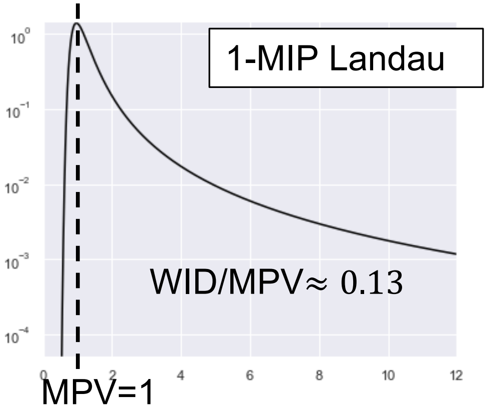


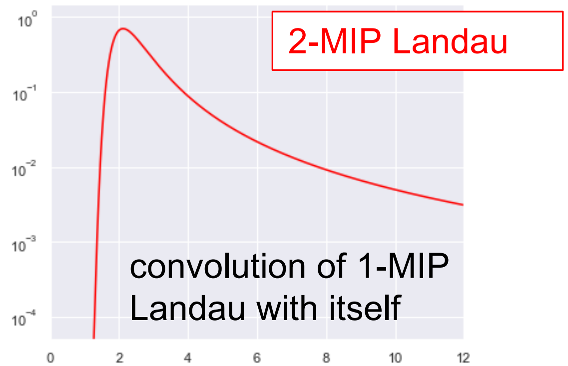
- The pseudorapidity (η) and ϕ of a EPD tile are determined by a straight line between the primary vertex and a random point on the tile.

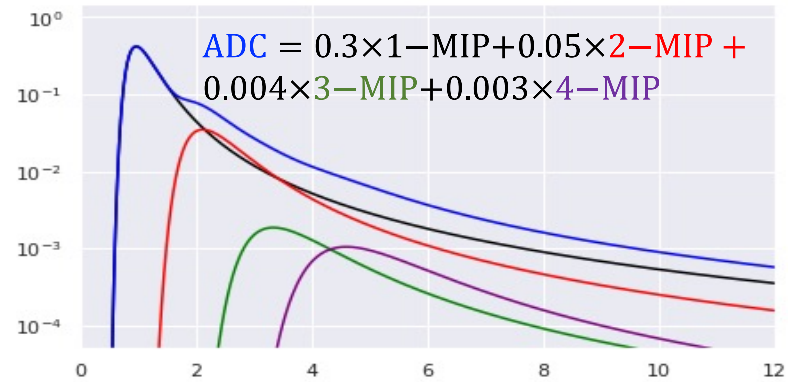
- The number of particles traversing a tile, averaged over events, can be probabilistically determined from the ADC distributions.

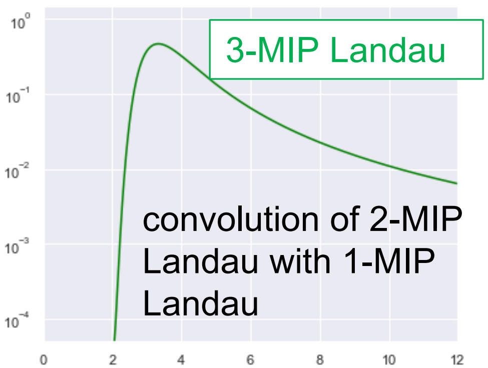
ADC Spectra of EPD

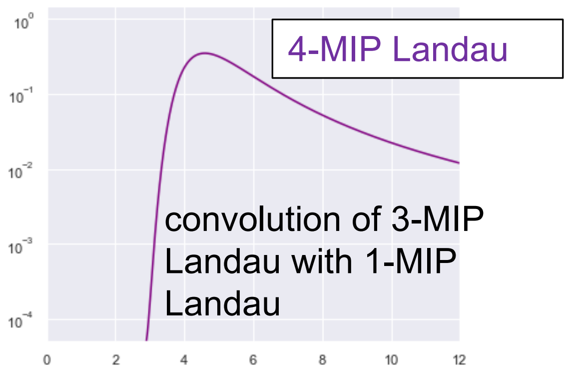
MIP (Minimum Ionizing Particle)











Mean of Landau distribution is undefined

↓

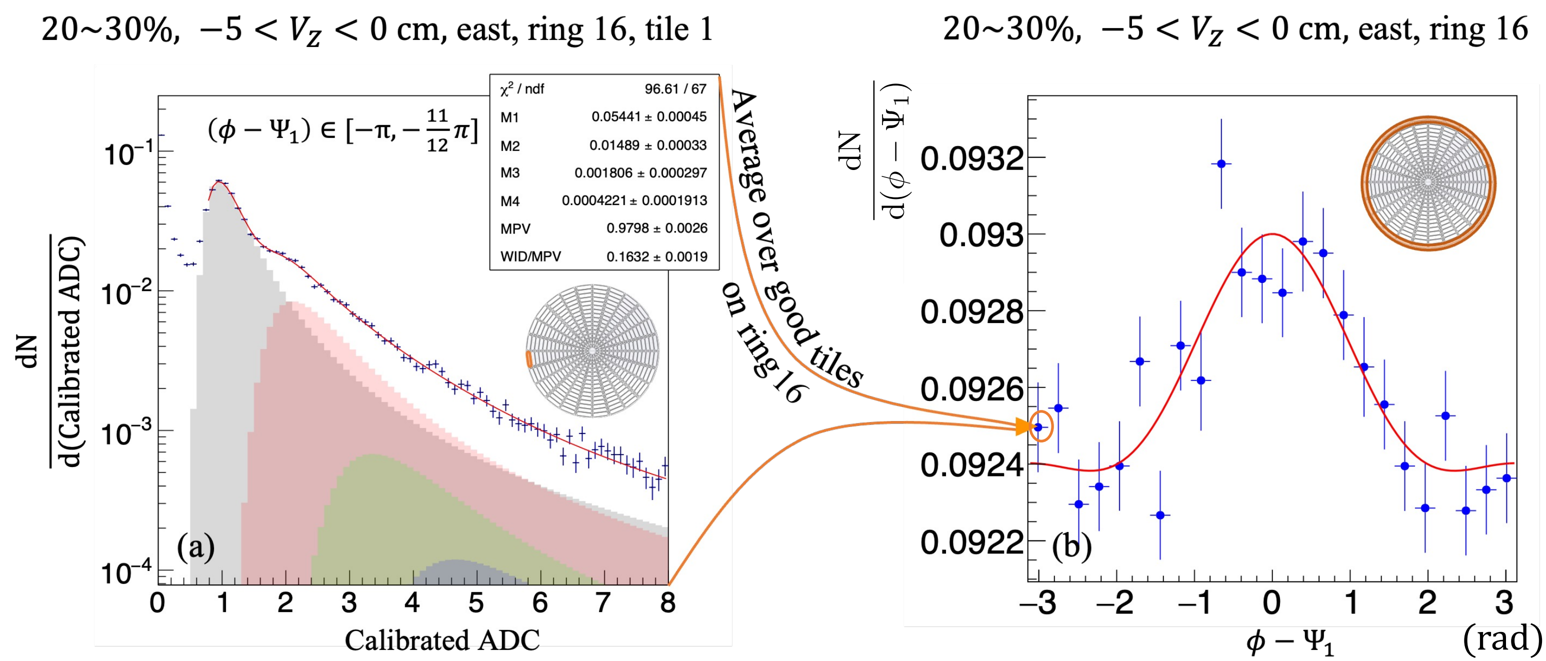
The Law of Large Number doesn't apply

↓

Averaged ADC ≠ Averaged number of particles.

- WID/MPV only depends on the material and thickness of the detector
- The function form 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:

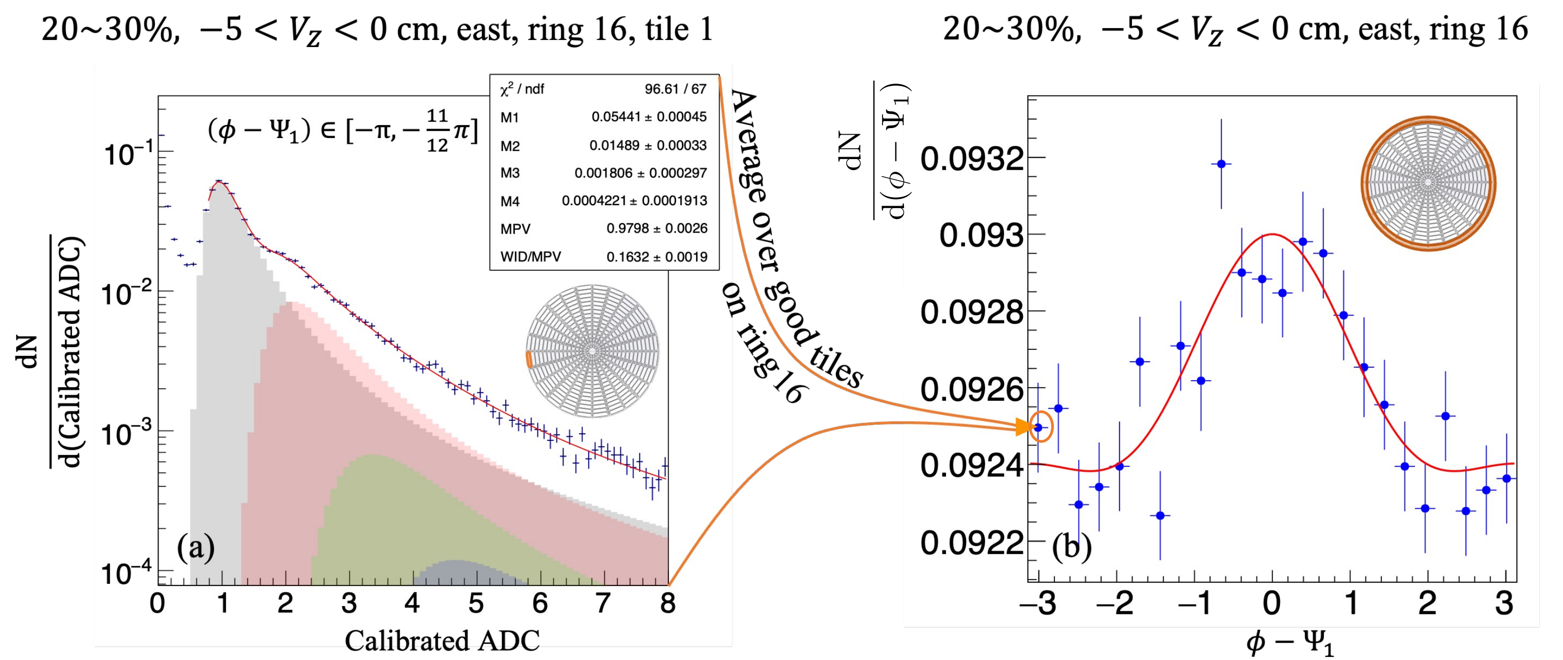
$$N = \sum_{k=1}^{k=6} k \times M_k$$

- The associated error can be calculated by:

$$\sigma^2 = \mathbf{k}\boldsymbol{\Sigma}\mathbf{k}^\top, \mathbf{k} = (1,2,3,4,0,0)$$

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

Extracting v_1



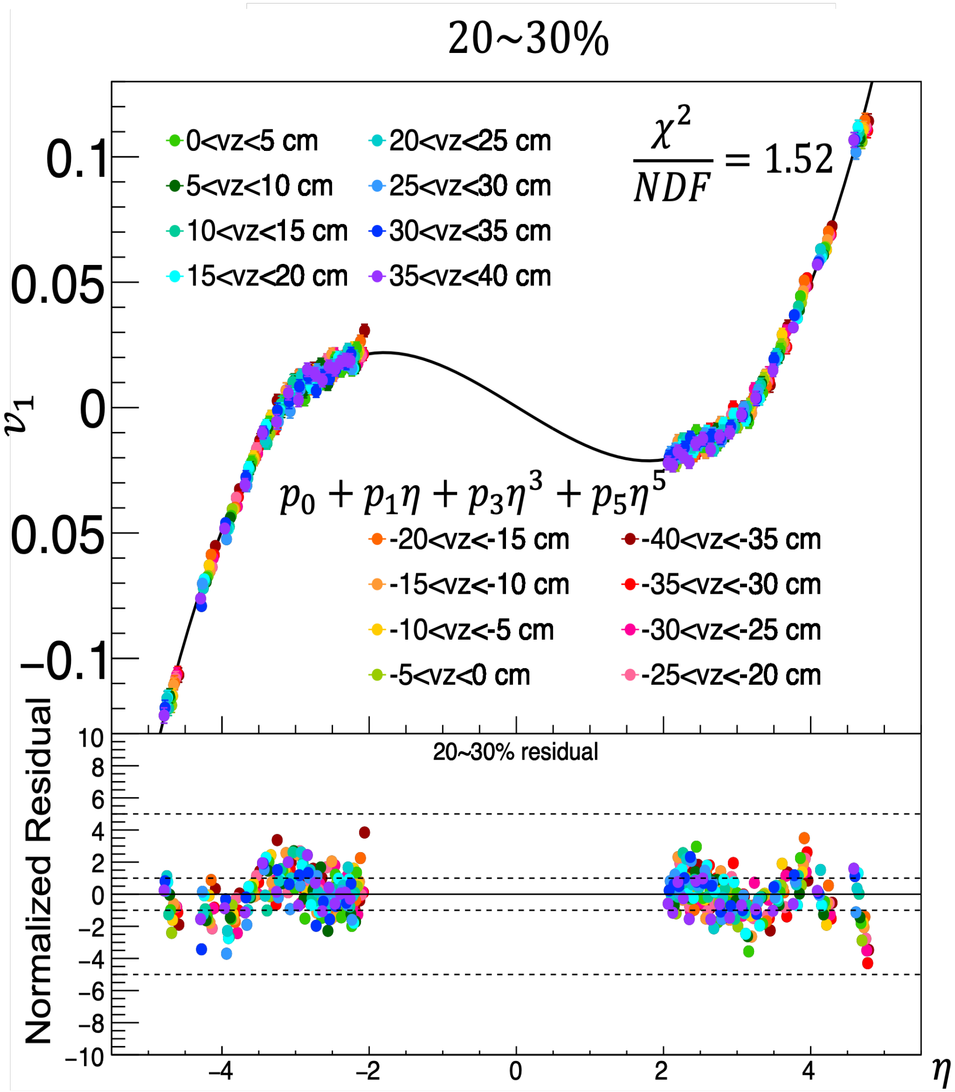
- v_1 (before the resolution correction) can be extracted by fitting the Fourier decomposition of the $(\phi - \Psi_1)$ distribution:

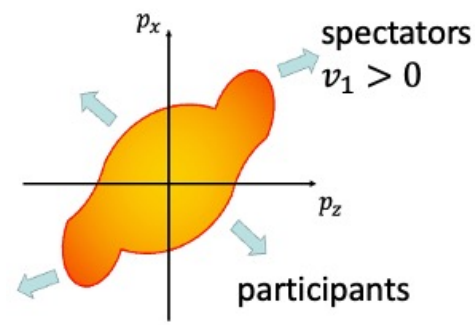
$$\frac{\mathrm{dN}}{\mathrm{d}(\phi - \Psi_1^{\mathrm{TPC}})} = k\{1 + 2v_1 \cos(\phi - \Psi_1^{\mathrm{TPC}}) + 2v_2 \cos[2(\phi - \Psi_1^{\mathrm{TPC}})]\}$$

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

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

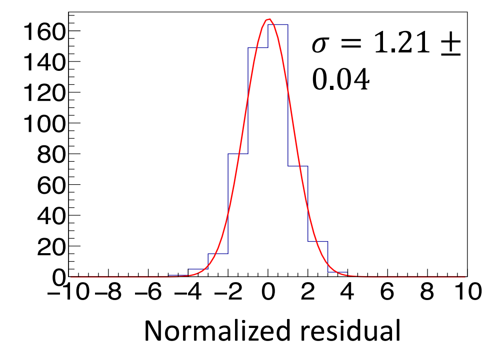
v_1 for 16 V_z Bins



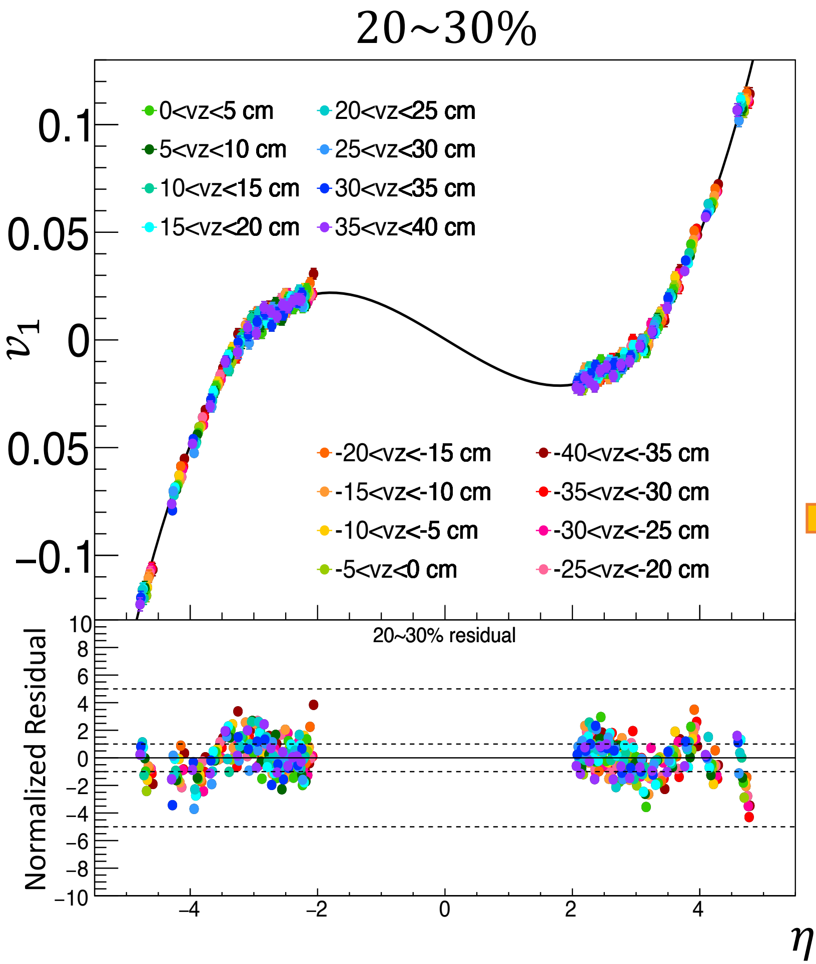


✓ fluctuation and error bars of the data points are reasonable.

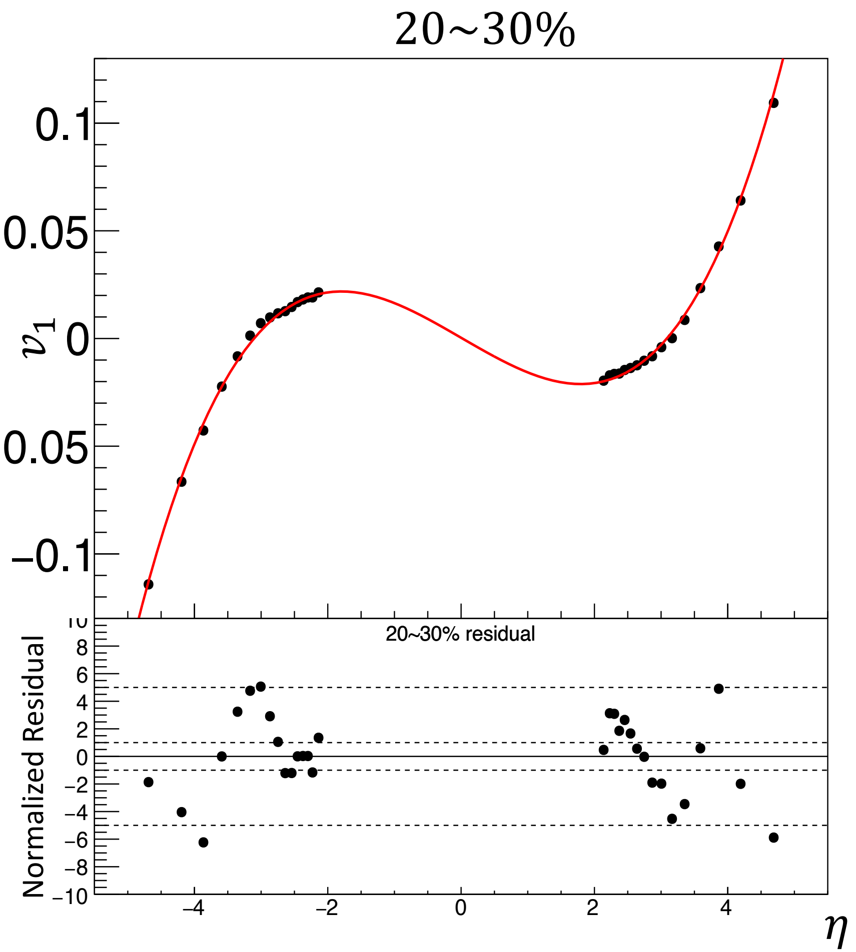
Project on the Y axis



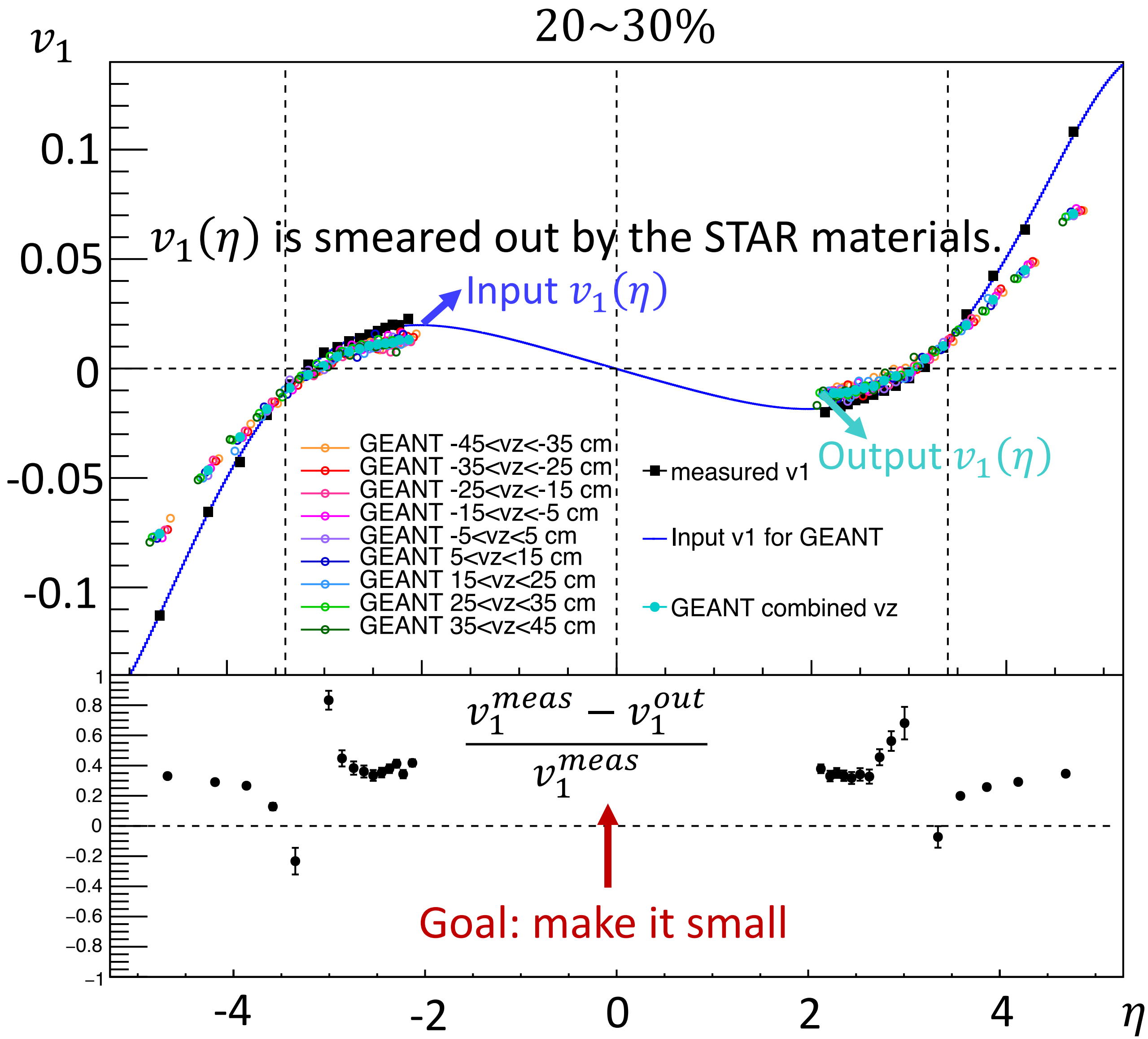
Combine 16 V_z Bins



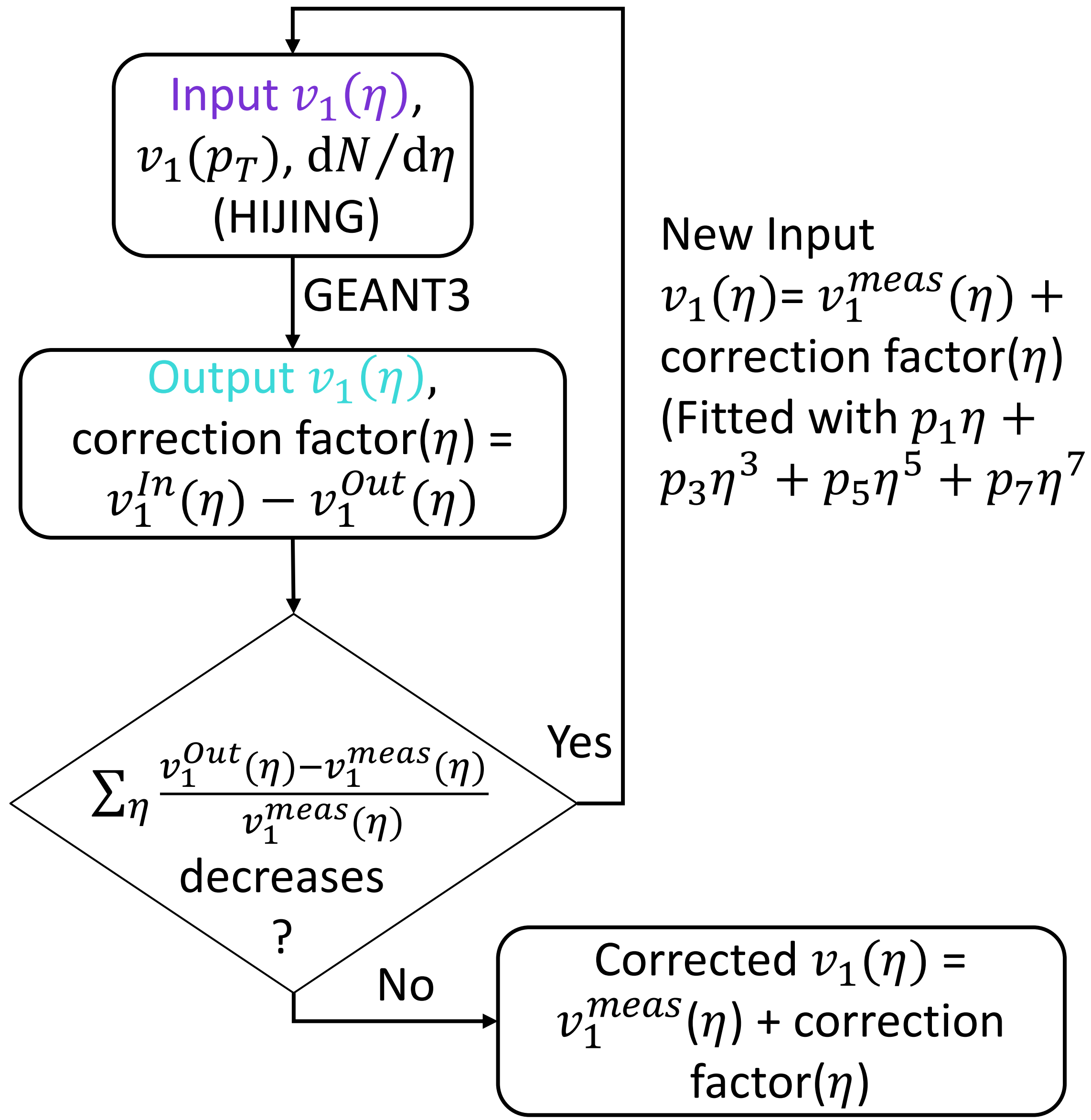
Group every 16 points along η by taking the average of η and v_1



STAR Materials Smear Out v_1

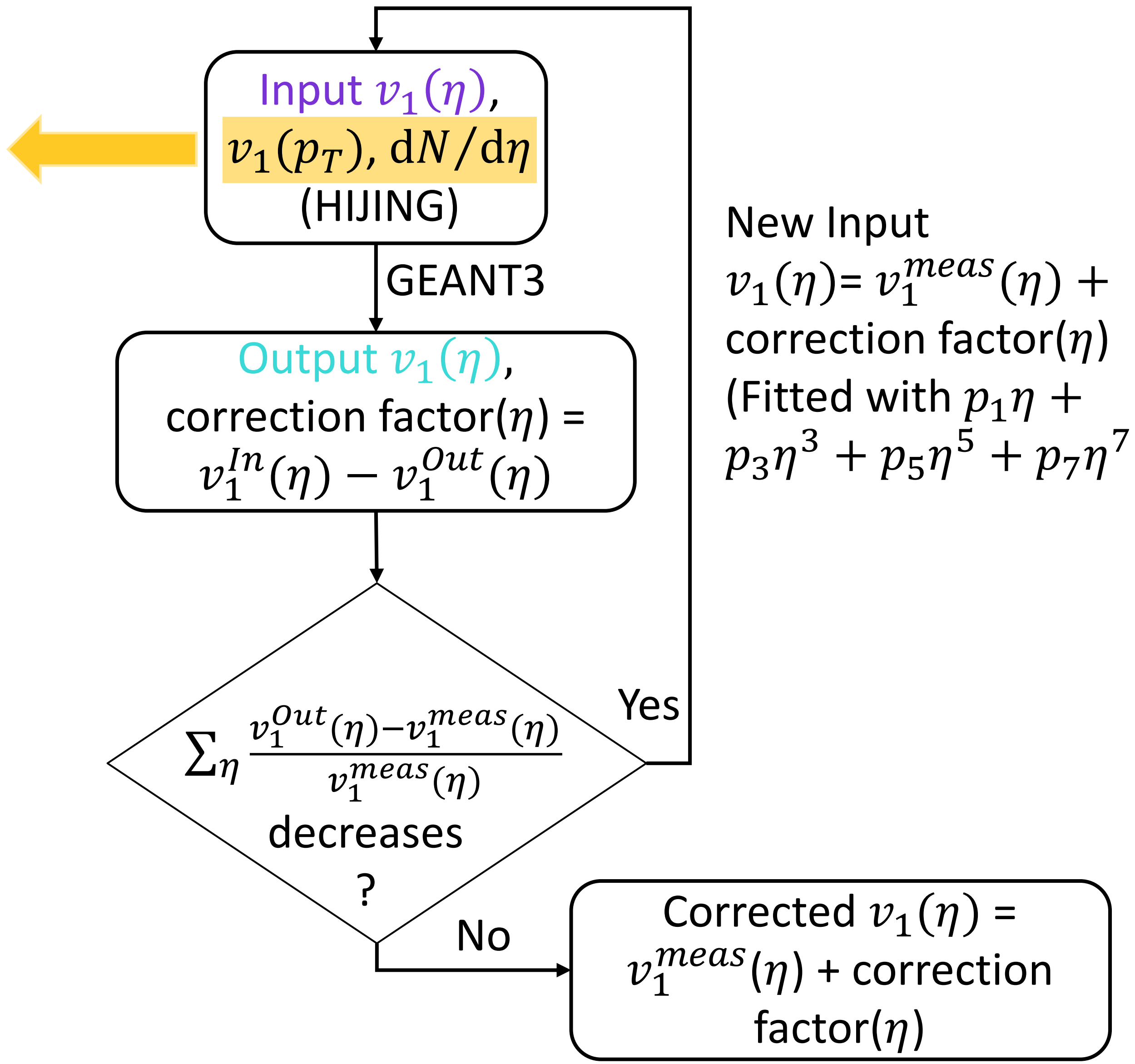


Flowchart for Correcting the Material Budget

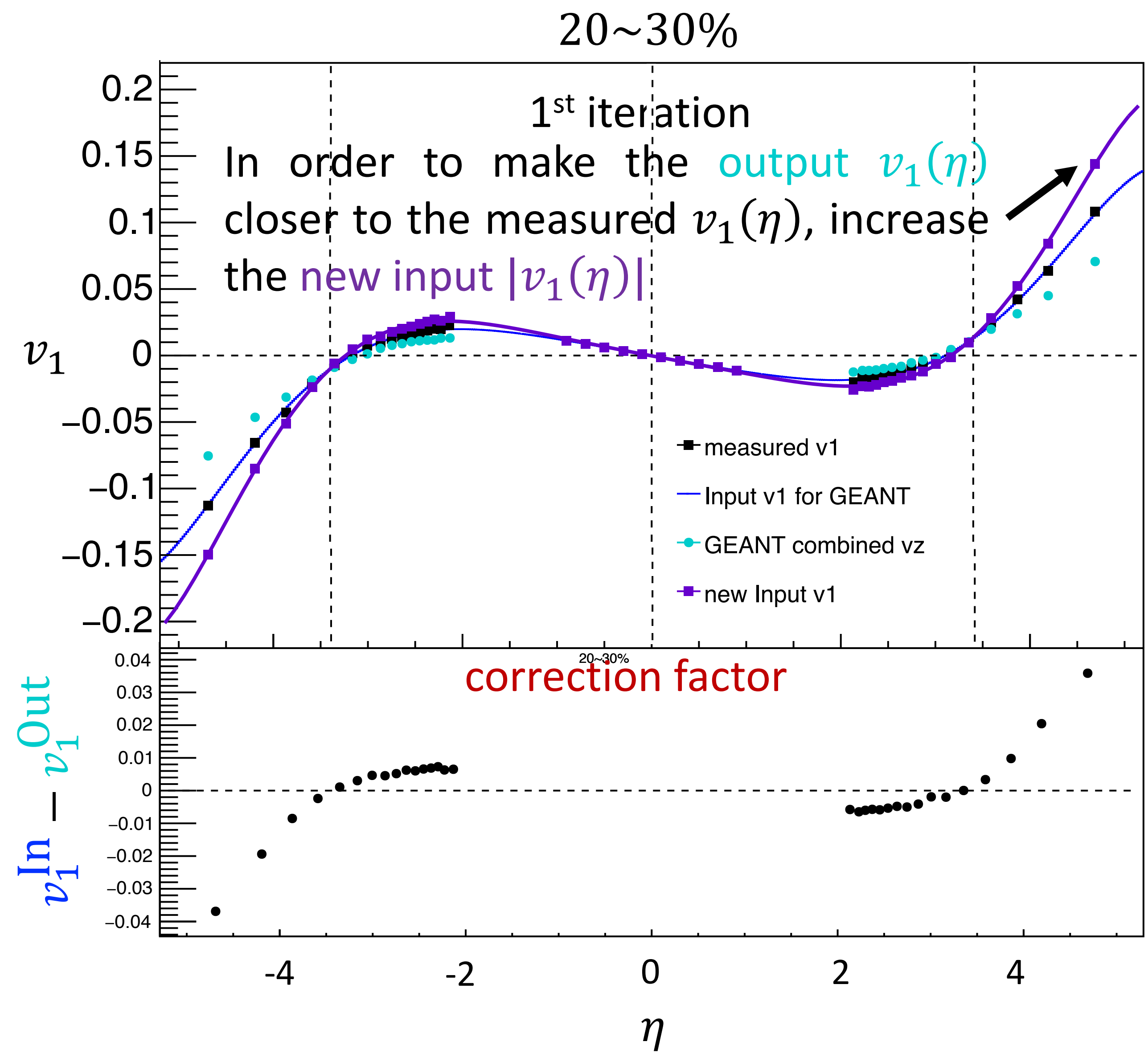


Flowchart for Correcting the Material Budget

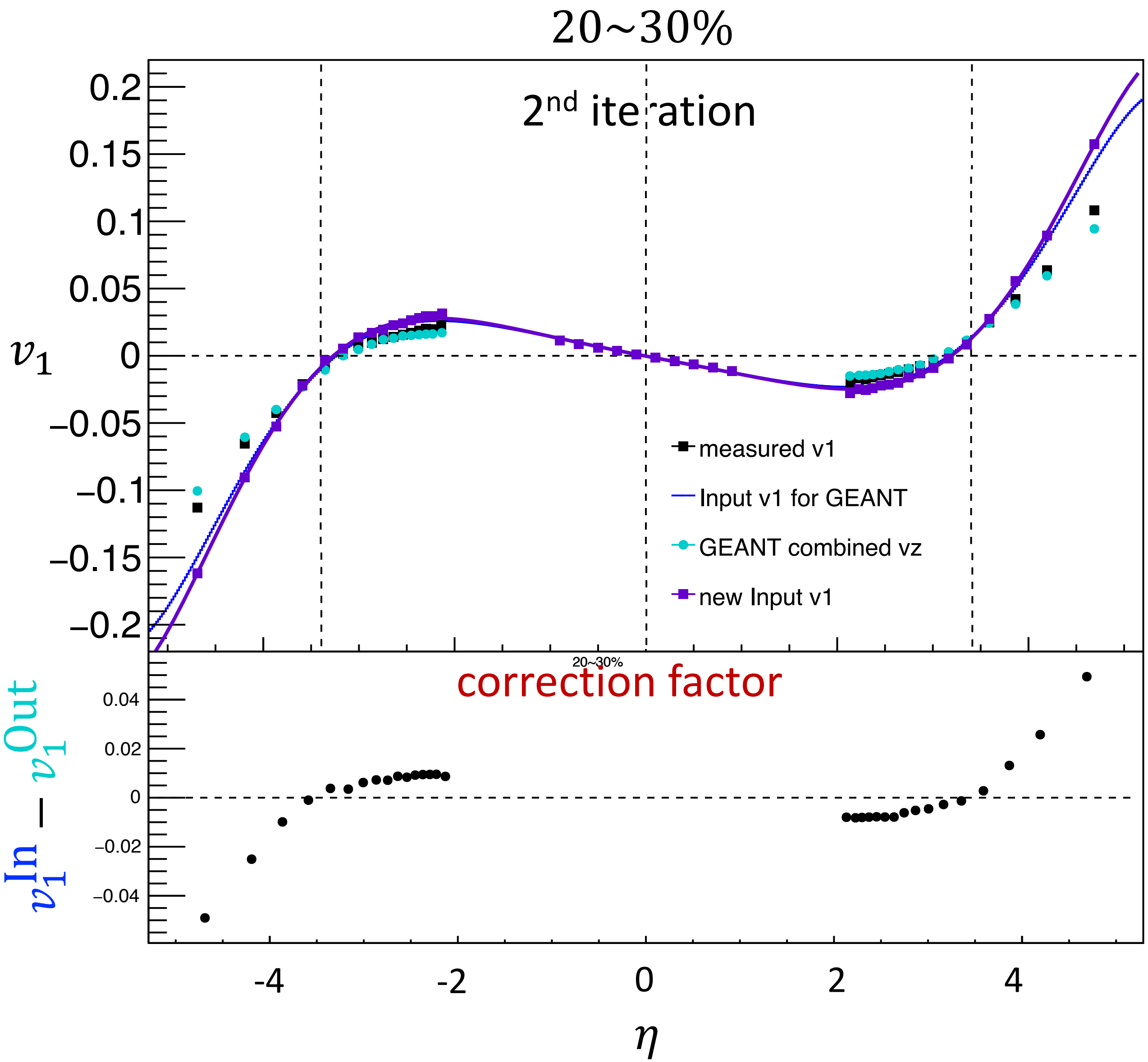
$v_1(p_T)$ and $dN/d\eta$ are unknown. Guess to the best of our knowledge. $v_1(p_T)$ and $dN/d\eta$ are varied as systematic checks.



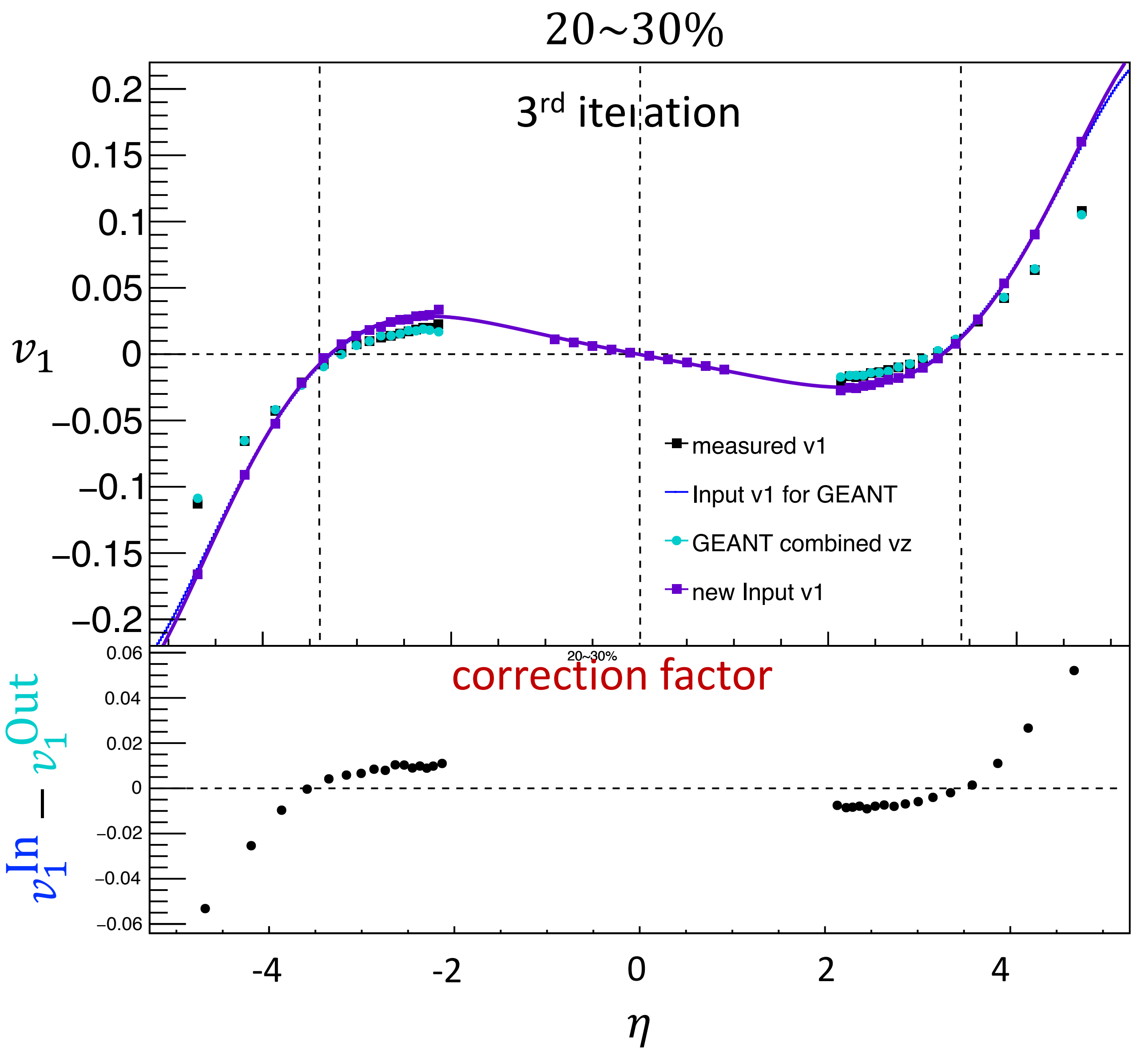
Iteration Process



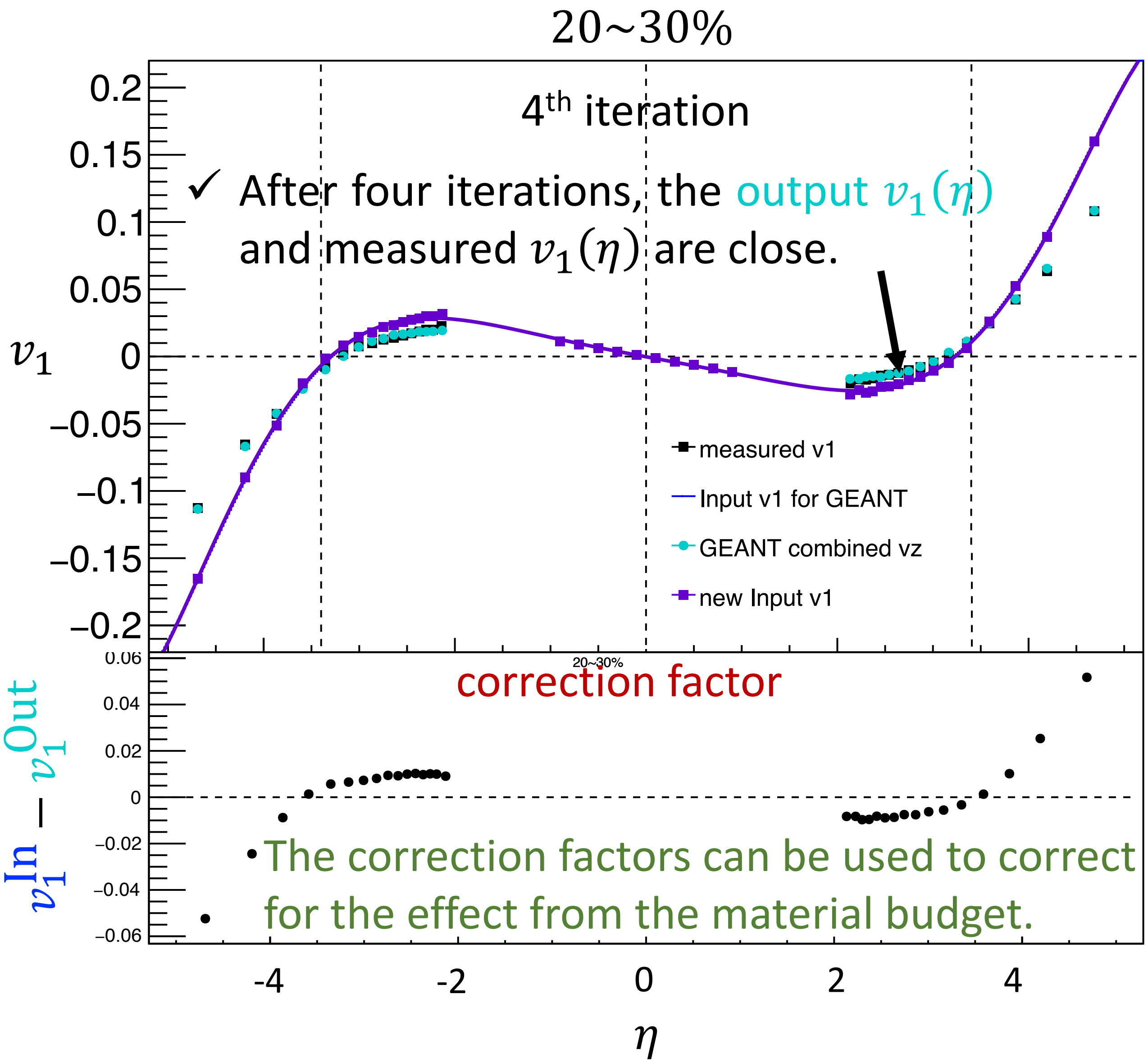
Iteration Process



Iteration Process



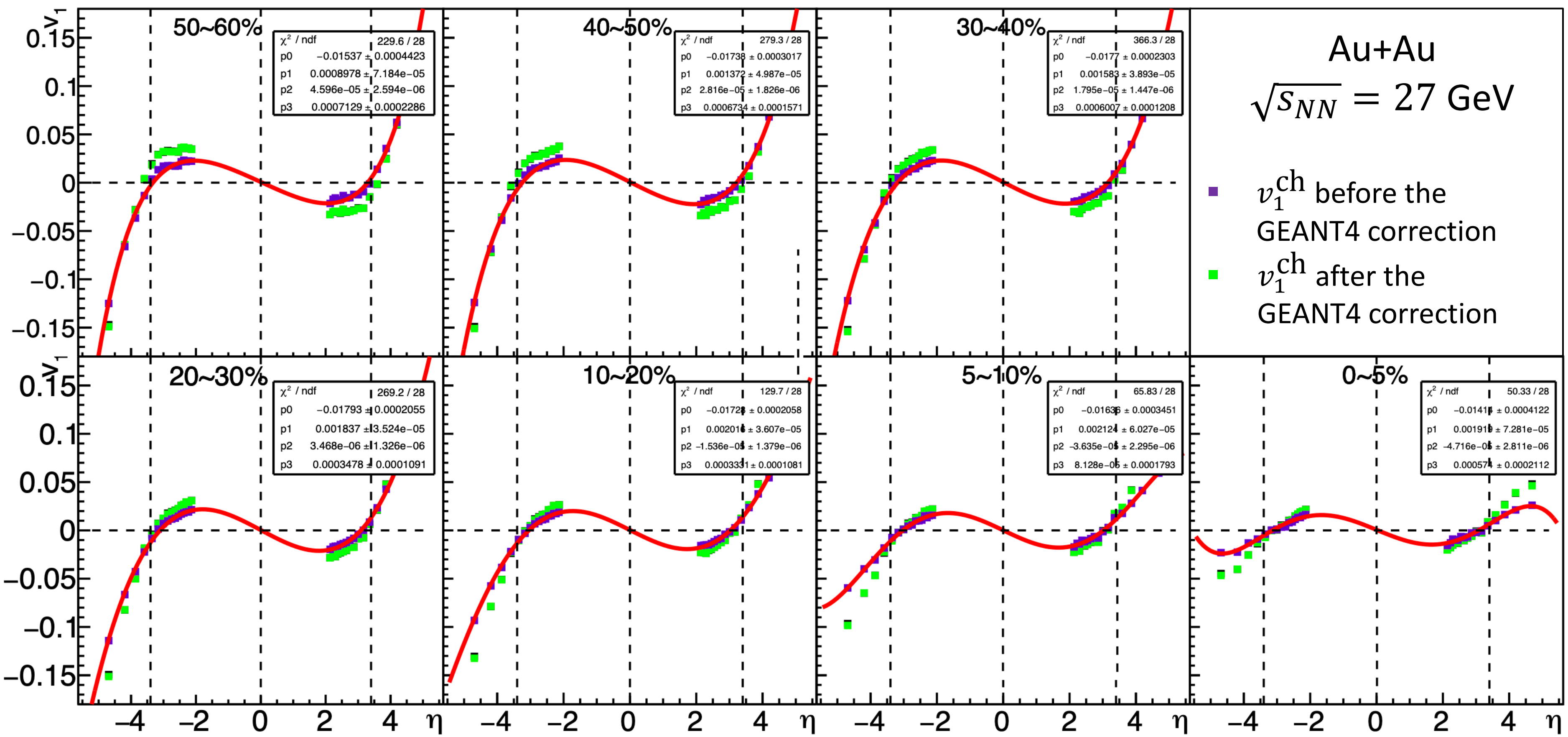
Iteration Process



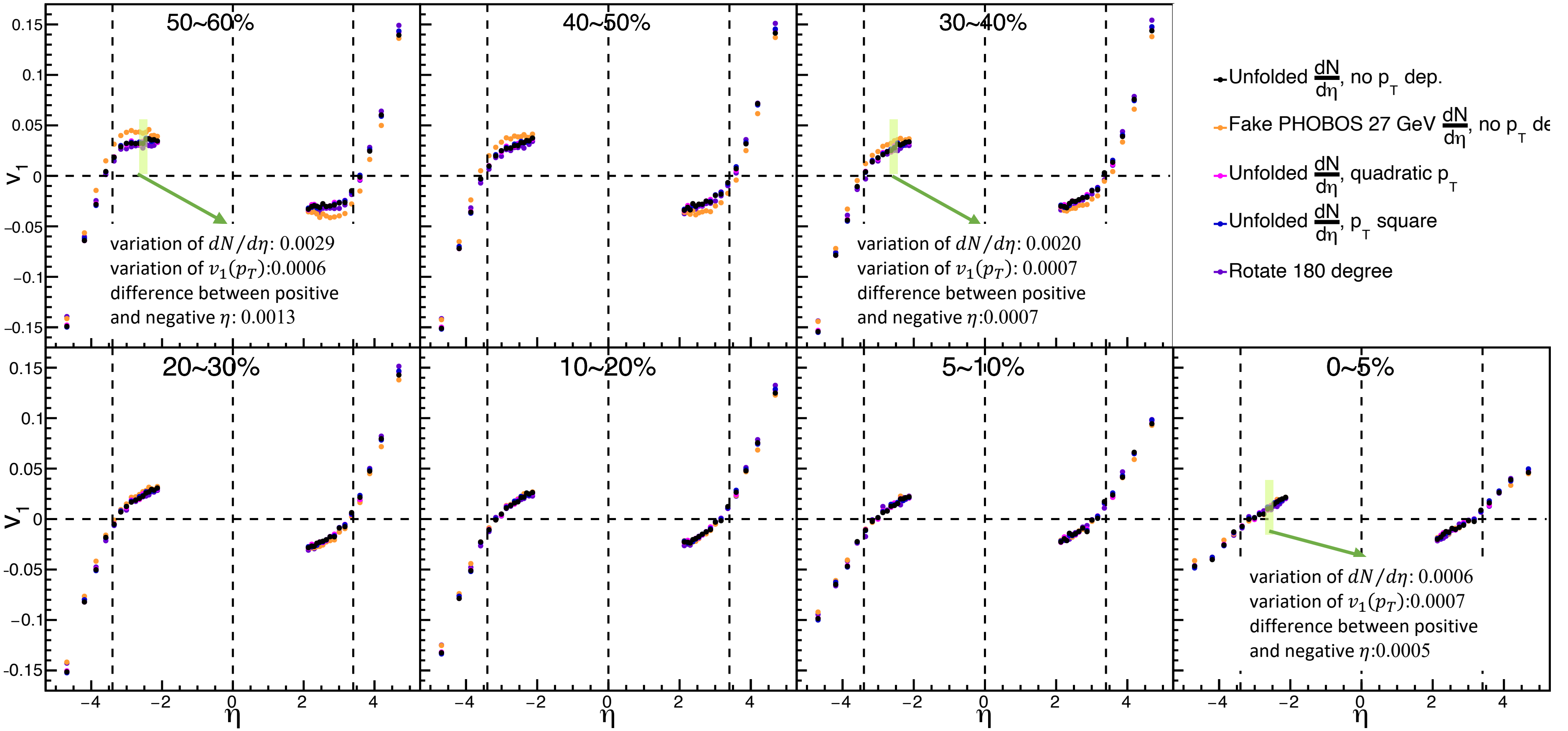
✓ After four iterations, the output $v_1(\eta)$ and measured $v_1(\eta)$ are close.

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

v_1 before and after the GEANT3 Correction

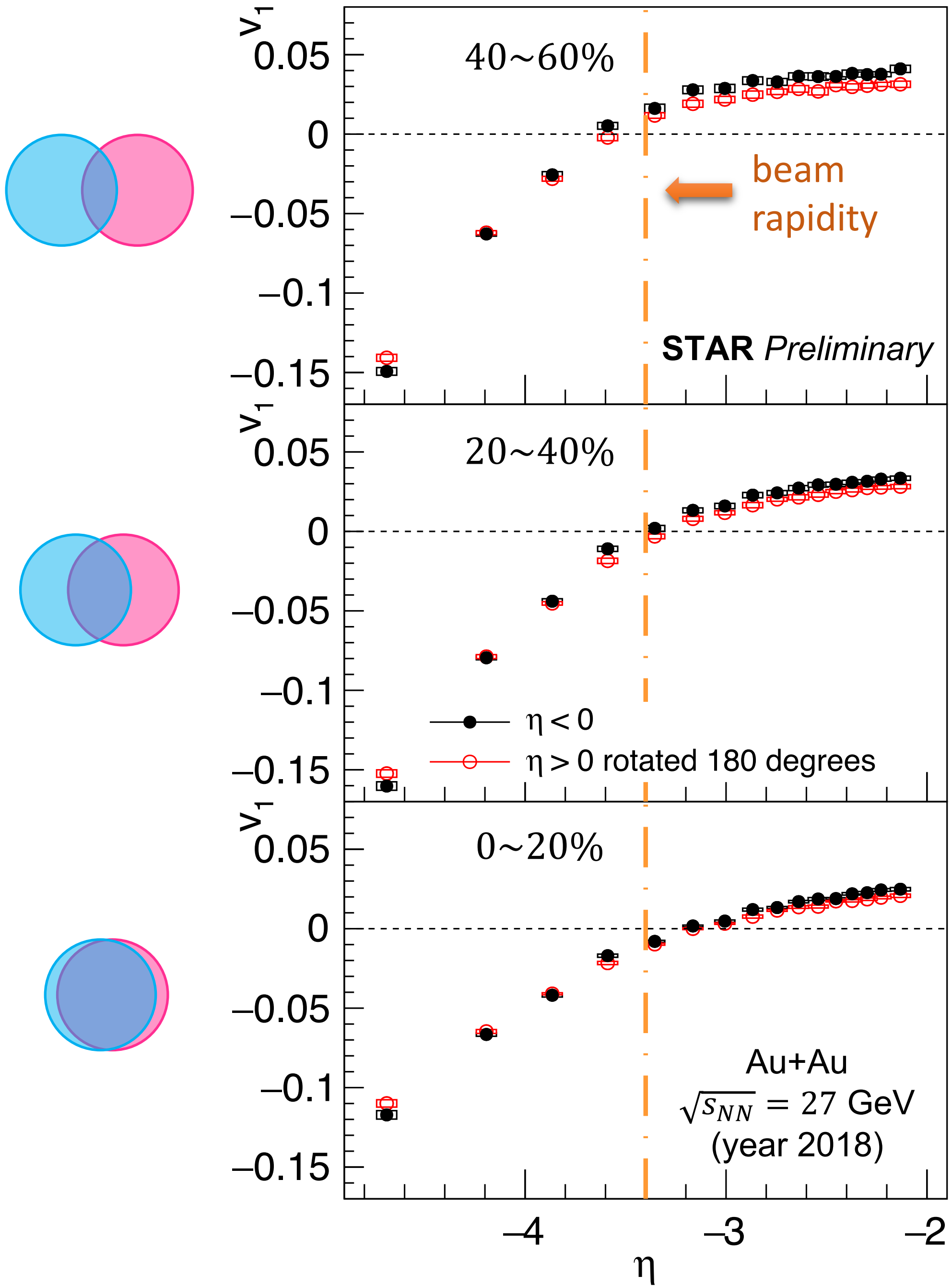


Systematic Checks



- Systematic errors mainly come from the variation of input $\frac{dN}{d\eta}$ in the HIJING + GEANT3 simulation.

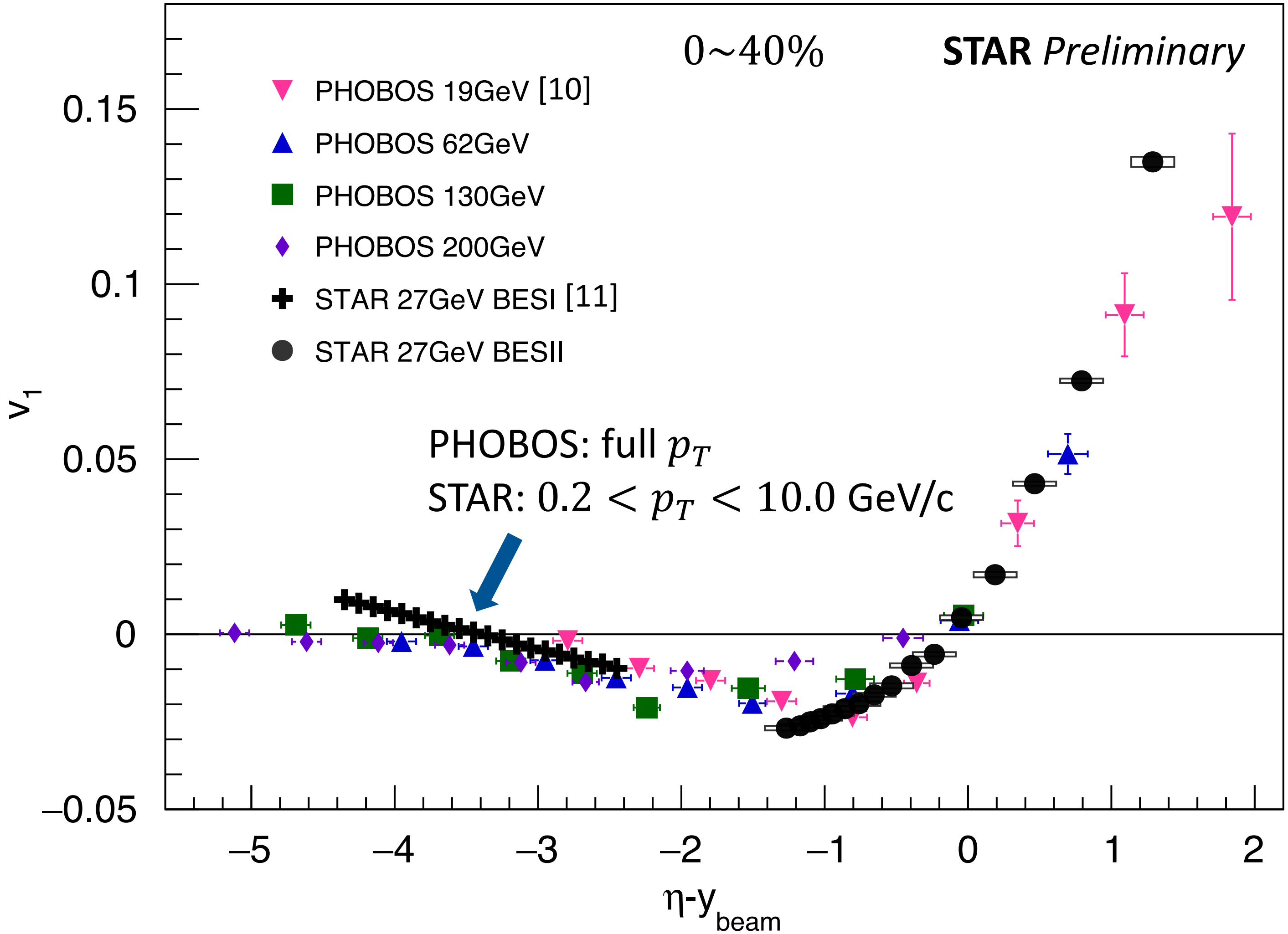
Results



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

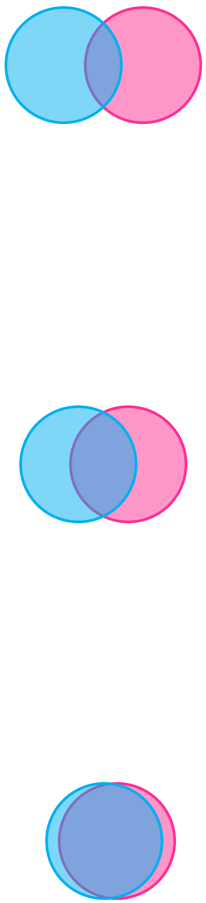
[10] PHOBOS. Phys. Rev. Lett. 97.1 (2006): 012301.
[11] STAR. Phys. Rev. C 101.2 (2020): 024905.

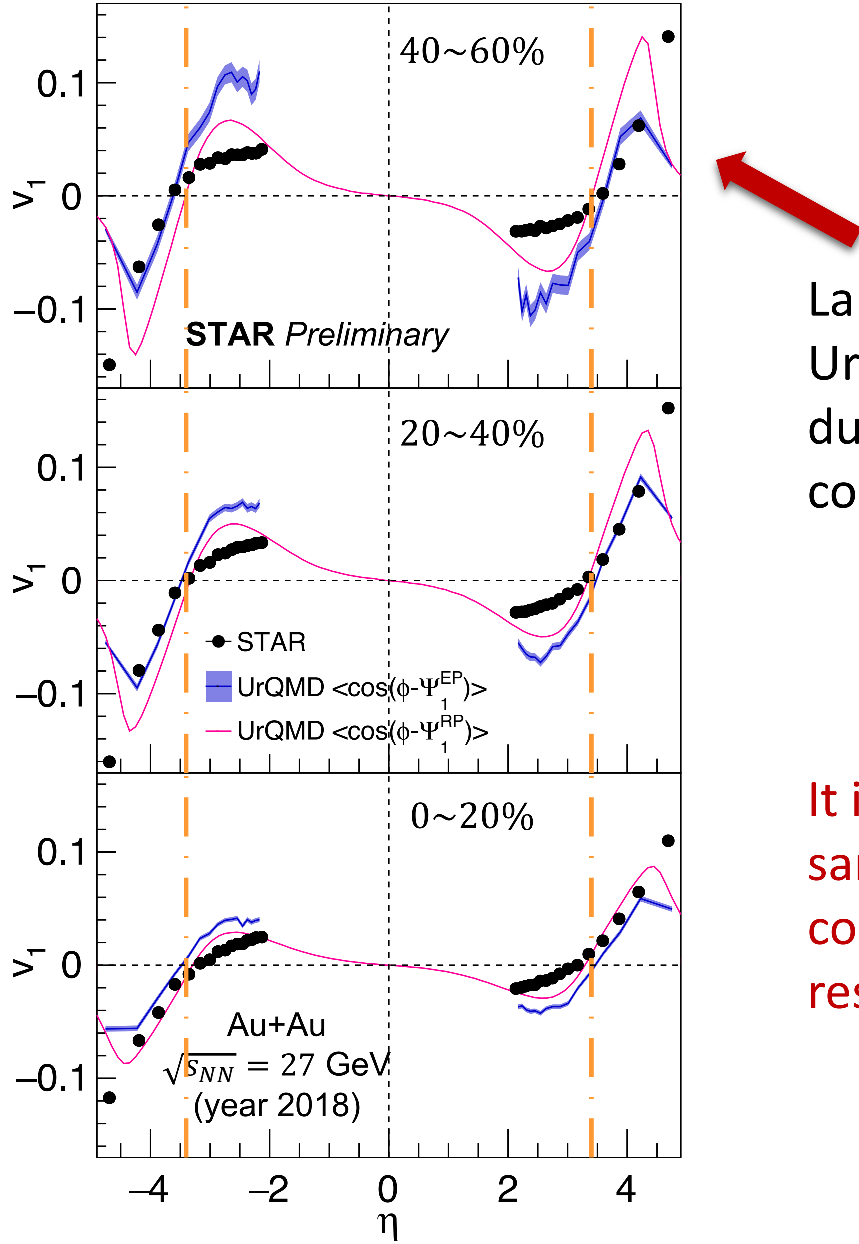
Comparison with PHOBOS



- 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!

More model studies are welcome!

We are preparing a paper for this analysis. Please let us know if you are interested in comparing your model with our measurement!

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 forward and backward η using BES-II data, the statistical errors decrease significantly compared to the previous PHOBOS and STAR measurements.

- UrQMD fails to quantitatively describe the measured $v_1(\eta)$.

- 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.

- Future comparison with hydro models will help us to constrain $\frac{\eta}{s}(T, \mu_B)$ for the hydrodynamic evolution.

Back up

Momentum Conservation Effect

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

$$\langle \cos(\phi - \Psi) \rangle = v_1 R' + \langle \cos(\phi - \Psi) \rangle_{\text{mom.cons.}}$$

particle of interest

$$\langle \cos(\phi - \Psi) \rangle_{\text{mom.cons.}} \sim -\frac{\langle p_T \rangle_{\text{POI}}}{\sqrt{N \langle p_T^2 \rangle}} f$$

reference

All the produced particles

$$f \equiv \frac{\langle w p_T \rangle}{\sqrt{\langle w^2 \rangle \langle p_T^2 \rangle}} = \langle w p_T \rangle_Q \sqrt{\frac{M}{\langle w^2 \rangle_Q N \langle p_T^2 \rangle}},$$

f only depends on the reference, subscript Q refer to the M particles used to calculate the Q vector

System-Size Scaling of $v_1(\eta)$

STAR. Physical Review Letters 101.25 (2008): 252301

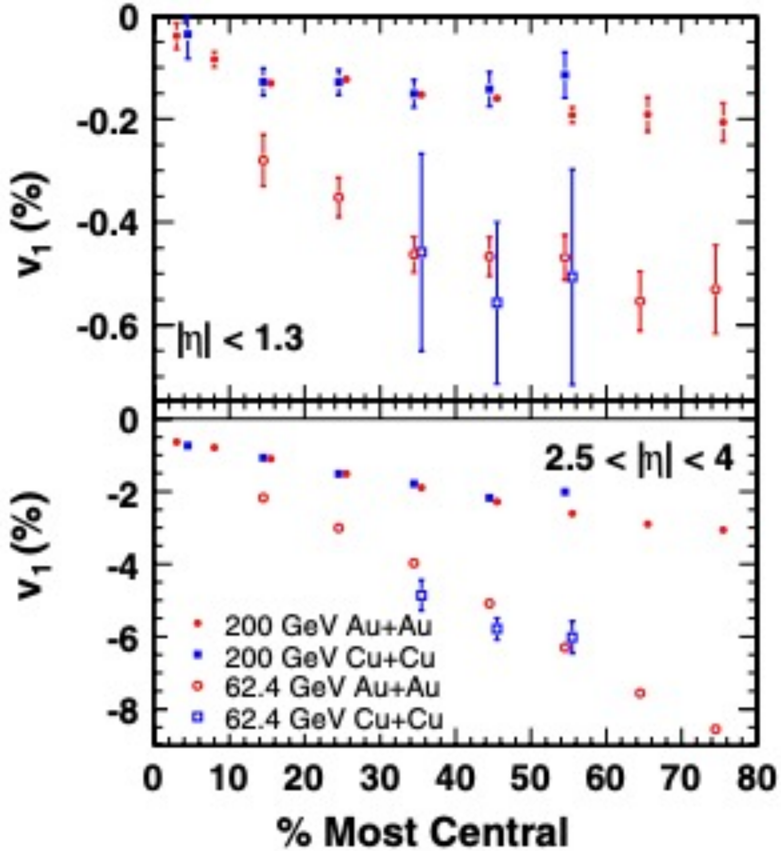


FIG. 4 (color online). Charged particle v_1 versus centrality, for Au + Au and Cu + Cu at 200 and 62.4 GeV. The upper (lower) panels show results from the main TPC (FTPC). The plotted error bars are statistical, and systematic errors (see Figs. 1 and 5) are within 10%.

Incident-Energy Scaling of v_1 (Limiting Fragmentaion)

STAR. Physical Review Letters 101.25 (2008): 252301

PHOBOS. Phys. Rev. Lett. 97.1 (2006): 012301.

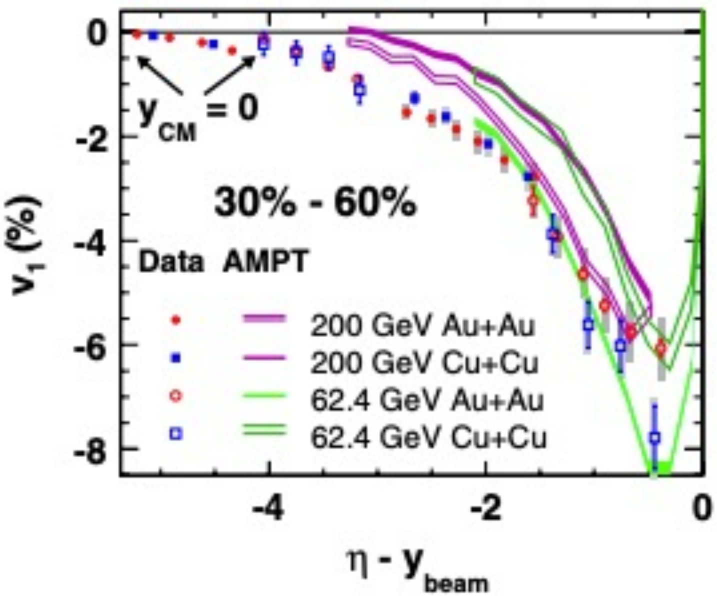


FIG. 5 (color online). Charged particle v_1 versus $\eta - y_{\mathrm{beam}}$, for 30%–60% Au + Au and Cu + Cu at 200 and 62.4 GeV. The plotted error bars are statistical, and the shaded bars show systematic errors.

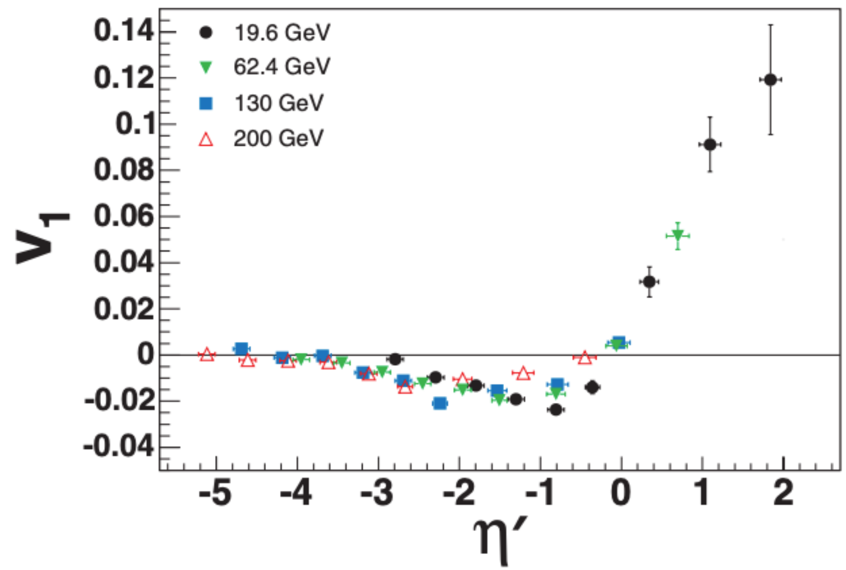


FIG. 3 (color). Directed flow, averaged over centrality (0–40%), as a function of $\eta' = |\eta| - y_{\mathrm{beam}}$ for four beam energies. The error bars represent the 1σ statistical errors only.

η/y_{beam} Scaling of v_1

STAR. Physical Review Letters 101.25 (2008): 252301

Also reported by NA49 and SPS

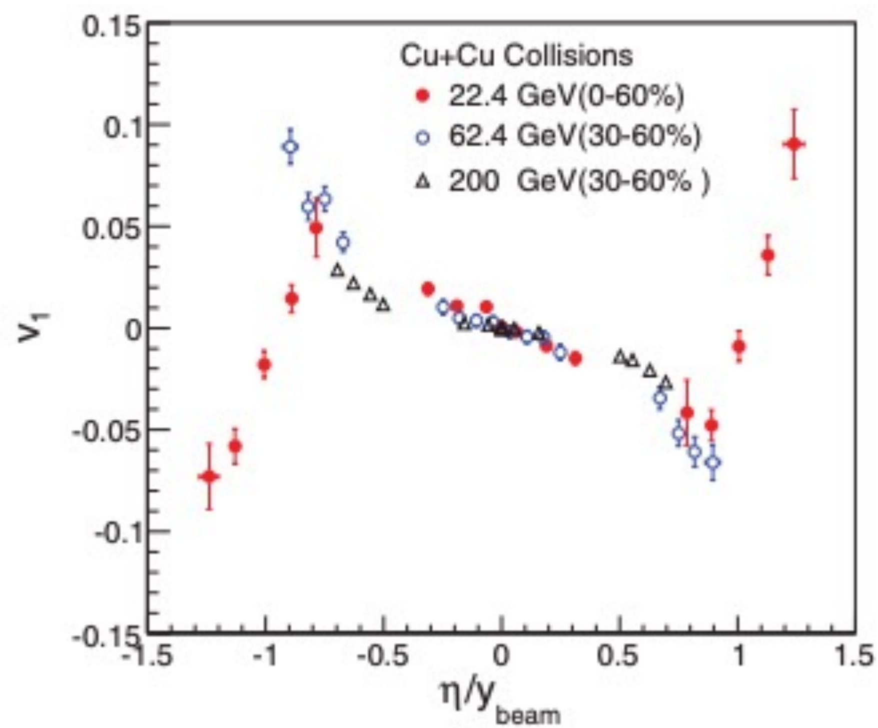


FIG. 5. (Color online) Charged hadron v_1 as a function of η, scaled by the respective y_{beam} for the three beam energies 22.4, 62.4, and 200 GeV. The results for 62.4 and 200 GeV are for 30–60% centrality Cu + Cu collisions previously reported by STAR [11]. For 22.4 GeV, the plotted results are for 0–60% centrality.