Measurements of elliptic flow in forward and backward pseudo-rapidity in Au+Au Collisions at $\sqrt{s_{NN}}$ = 19.6 GeV in RHIC-STAR

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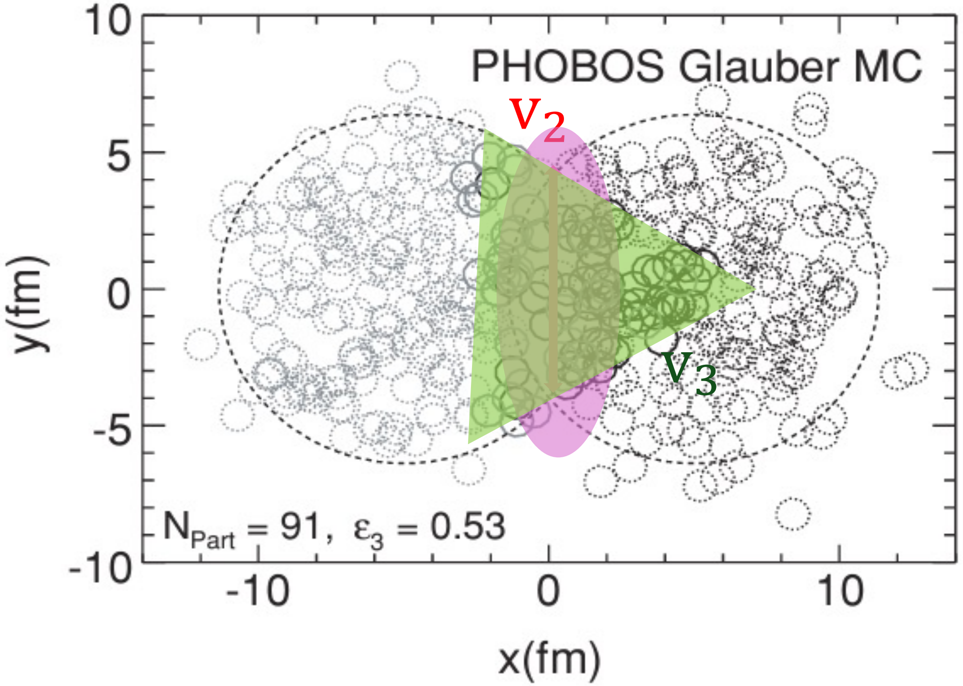
Hot Quarks 2025 @Hefei, China

2025.05.11-17

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

Azimuthal anisotropy

B. Alver and G. Roland, PRC81, 054905 (2010)



Anisotropic flow:

- The initial spatial anisotropy is converted into momentum-space anisotropy through fluid expansion.
- The flow strength can be quantified by Fourier coefficient of azimuthal distribution of produced particles:

$$\boxed{\frac{dN}{d(\phi-\Phi)} = \frac{1}{2\pi}\left\{1 + \sum_{n=1}^{\infty} 2\boldsymbol{v_n}\cos[n(\phi-\Phi)]\right\}}$$

Φ: reaction plane

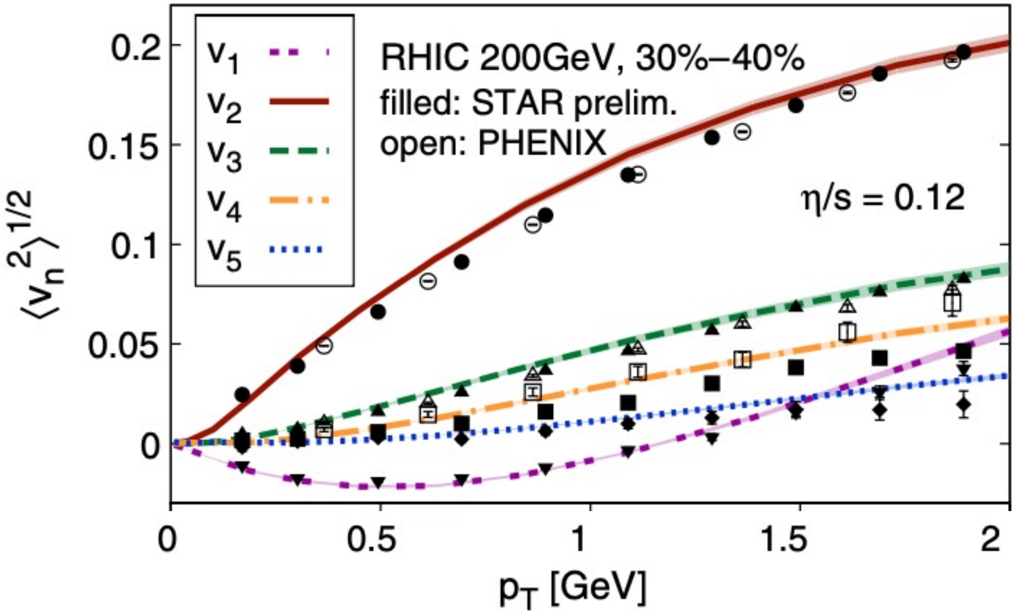
- Elliptic flow (v_2): caused by the pressure gradient coming from the initial almond shape.
- Triangular flow(v_3): originating from the initial triangular shape caused by event-by-event density fluctuation.

Constraining power of flow on shear viscosity

- **IP-Glasma + MUSIC** model shows good agreement with v_n with η/s= 0.12-0.20.
- Recent studies based on Bayesian analysis further constrain η/s(T).

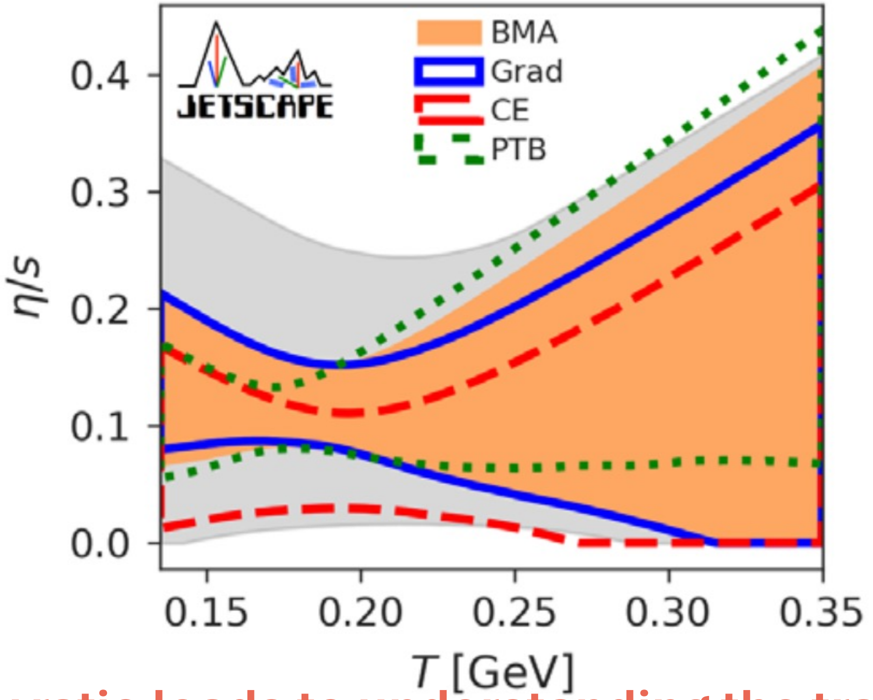
IP-Glasma + MUSIC

Charles et al,PRL 110, 012302 (2013)



Bayesian analysis

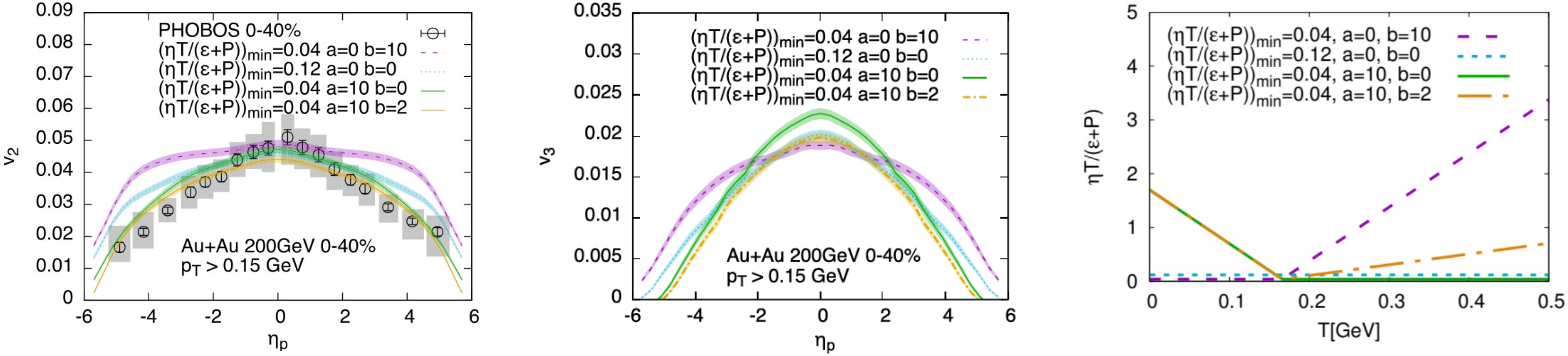
JE Bernhard, et al., Nat. Phys.15,1113(2019)
D. Everett et al.,PRL.126,242301(2021)(JETSCAPE)



- **Constraining the shear viscosity to entropy density ratio leads to understanding the transport properties of QGP.**
- η/s still has a large uncertainty.

Constraining power of flow on shear viscosity

Denicol et.al, PRL 116, 212301 (2016)

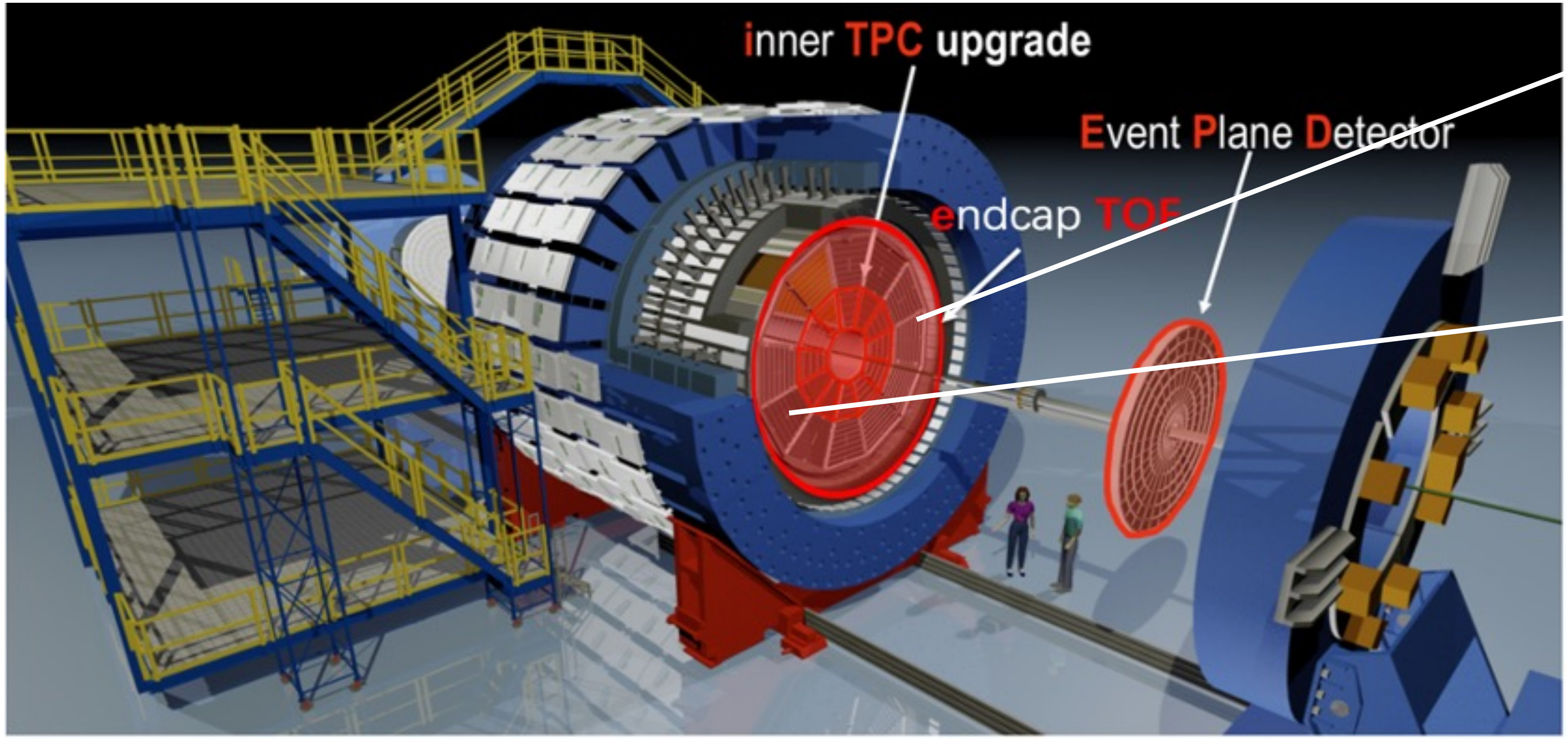


- According to the theoretical study, the η dependence of v_2 and v_3 is sensitive to T-dependence of η/s. PHOBOS v_2 exhibits a downward trend with considerable uncertainties, posing challenges for accurate determination.
- Acceptance in our forward detectors allows to capture spectators at lower energies, which remains under-explored.

Final Goal

- Precise measurements of η dependence of v_n to constrain the temperature-dependent shear viscosity η/s(T).

STAR experiment (BES-II 2019~)



TOF
Time of flight measurement of charged particles, $|\eta| < 0.9$

TPC+iTPC(inner readout upgrade)
Measure dE/dx, reconstruct the tracks
$|\eta| < 1.5, 0 < \phi < 2\pi$

EPD
Provided the event planes covering 2.1< $|\eta|$ < 5.1
Scintillation detector

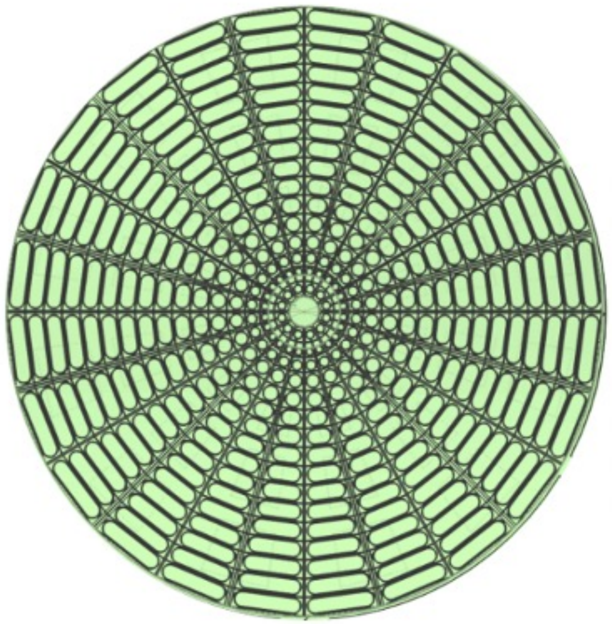
Beam Energy Scan II Program (BES-II)

- For the search of the QCD critical point.
- Upgraded EPD (Event Plane Detector), iTPC (inner TPC), and forward detectors.
- Wider rapidity coverage and higher statistics than BES-I.
- BES-II energy: $\sqrt{s_{NN}}$ = 3 GeV to 27 GeV (including FXT mode).

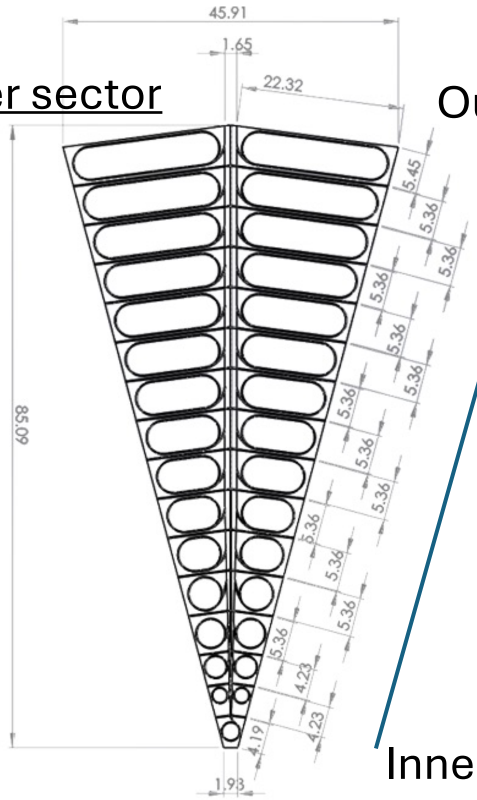
Event Plane detector

- scintillation detector, so **TRACKING is not possible.**
- Particles lose energy in the EPD tile (ADC)

ϕ direction has 12 super sectors



Super sector



Outer(For mid-rapidity)

16 rows(rings)

Inner(forward/backward)

Covered forward and backward region 2.1<|η|<5.1!!!

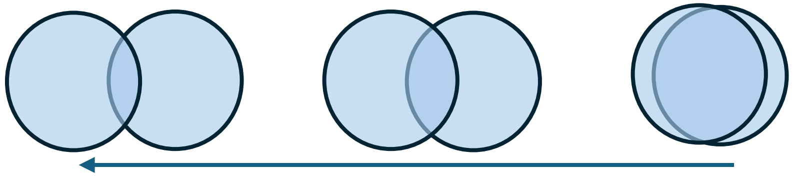
Covered η acceptance

Row	r_i (cm)	r_f (cm)	η_i	η_f
1	4.6	9.0	5.09	4.42
2	9.0	13.4	4.42	4.03
3	13.4	17.8	4.03	3.74
4	17.8	23.33	3.74	3.47
5	23.33	28.86	3.47	3.26
6	28.86	34.39	3.26	3.08
7	34.39	39.92	3.08	2.94
8	39.92	45.45	2.94	2.81
9	45.45	50.98	2.81	2.69
10	50.98	56.51	2.69	2.59
11	56.51	62.05	2.59	2.50
12	62.05	67.58	2.50	2.41
13	67.58	73.11	2.41	2.34
14	73.11	78.64	2.34	2.27
15	78.64	84.17	2.27	2.20
16	84.17	89.70	2.20	2.14

Data set

- STAR Bes-II Au+Au 19.6 GeV (2019)
- 260 billion events (after event cut)
- Trigger: minimum bias
- Pileup events: rejected based on the matched timing information of TOF and TPC
- Centrality: determined by multiplicity

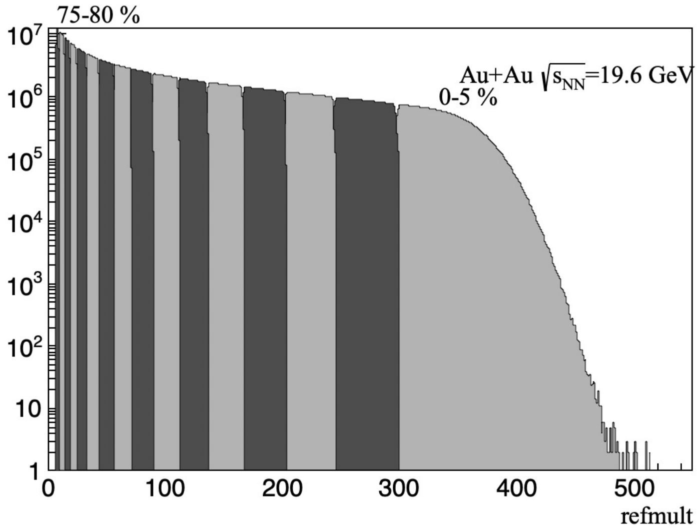
Cut	**parameters**
Event cut	$\lvert V_r \rvert$ <= 2.0 cm, $\lvert V_z \rvert$ <= 40 cm, centrality 0-80%
Trackcut	p_T >= 0.1 (GeV/c) ,$\lvert\eta\rvert$ <= 1.5
EPD cut	0.3 <= nMip



peripheral. 80%

Central. 0%

centrality



Event plane determination

Event plane definition

A. M. Poskanzer and S. A. Voloshin. PRC.58,1671(1998)

This study used the event plane method to measure v_n,

$$Q_x = \int_0^{2\pi} d\phi \frac{dN}{d\phi}\cos(n\phi) = \sum_i^M w_i cos(n_i) \quad .$$

$$Q_y = \int_0^{2\pi} d\phi \frac{dN}{d\phi}\sin(n\phi) = \sum_i^M w_i sin(n_i)$$

$$\Psi_n = \frac{1}{n}\, tan^{-1}\left(\frac{Q_y}{Q_x}\right)$$

n:order of harmonics

$$v_n = \frac{\langle \cos n(\varphi - \Psi_n)\rangle}{Res\{\Psi_n\}}$$

EPD event plane for $v_n(|\eta| < 1.5)$: outer 8 rings (participant region)

TPC event plane for $v_n(|\eta| > 2.1)$: $0.5 < |\eta| < 1.5$

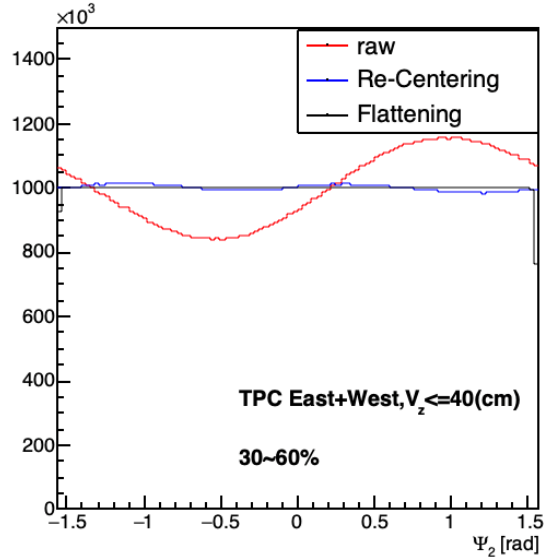
Event plane resolution

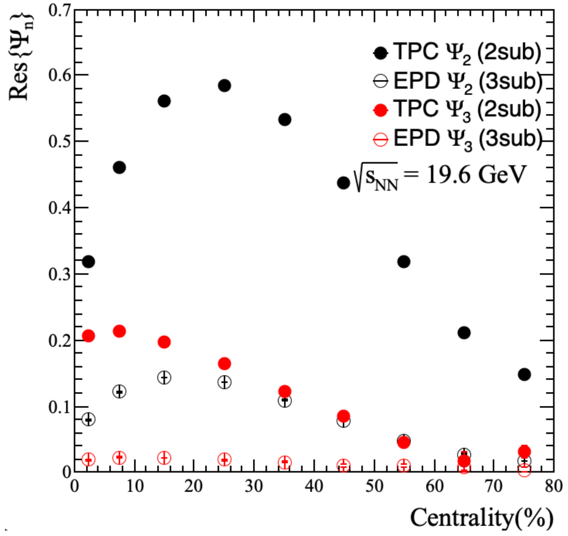
3sub-event method: effective when the resolutions differ between 2 detectors.

$$\mathrm{Res}\{\Psi_{nTPC(E+W)}\} = \sqrt{\frac{\langle\cos(n[\Psi_n{}^{EPDE} - \Psi_n{}^{TPC(E+W)}])\rangle\langle\cos(n[\Psi_n{}^{EPDW} - \Psi_n{}^{TPC(E+W)}])\rangle}{\langle\cos(n[\Psi_n{}^{EPDE} - \Psi_n{}^{EPDW}])\rangle}}$$

$$\mathrm{Res}\{\Psi_{nEPD(E+W)}\} = \sqrt{\frac{\langle\cos(n[\Psi_n{}^{TPCE} - \Psi_n{}^{EPD(E+W)}])\rangle\langle\cos(n[\Psi_n{}^{TPCW} - \Psi_n{}^{EPD(E+W)}])\rangle}{\langle\cos(n[\Psi_n{}^{TPCE} - \Psi_n{}^{TPCW}])\rangle}}$$

Event plane distribution





Determination of average multiplicity in EPD tile

- EPD: TRACKING is not possible.
- Estimate the average number of incident particles based on the energy loss value.

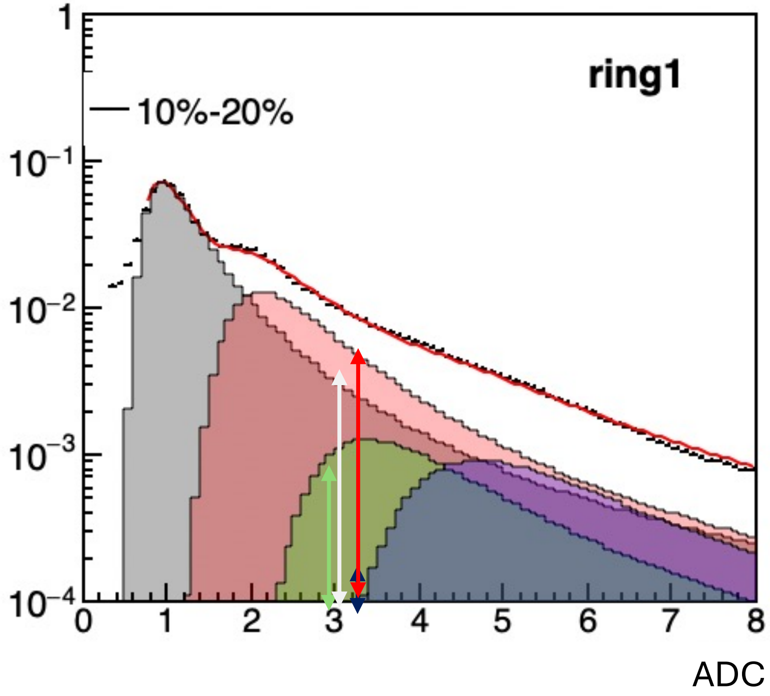
-Integral of ADC in the same ring and normalized to 1

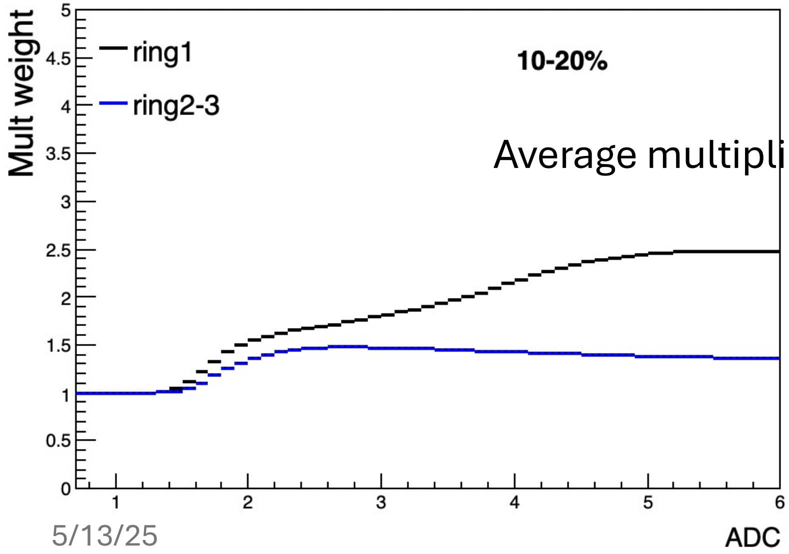
-Fit with 3 or 4 Landau convolution functions

- Average multiplicity M_{EPD}=1* $M_1{}'$ +2* $M_2{}'$ + $3 * M_3{}'$+4* $M_4{}'$

$$M_i{}' = \frac{M_i}{\sum_{j=1}^{4} M_j}$$

$M_i(i = 1\sim4)$:Contribution of each n-mip dist. for a given ADC.





Average multiplicity vs ADC

For example,in the case of ADC=3

$$M_{EPD}(\text{ADC=3}) = 1* \frac{0.003}{0.01191} + 2* \frac{0.008}{0.01191} + 3* \frac{0.0009}{0.01191} + 4* \frac{0.00001}{0.01191}$$

=1.825..

Correction: Detector material effect

What's the detector material effect?

Particles generated by collisions may interact with other materials and cause secondary particles.

→Need to estimate the effect caused by interactions with detector materials **for EPD**.

HIJING (Heavy Ion Jet INteration Generator) + **GEANT (STAR detector simulation)**

- Collision Energy: $\sqrt{s_{NN}}$ = 19.6 GeV
- All Particles (including the neutral particles)

Procedure of analysis

generate the HIJING events

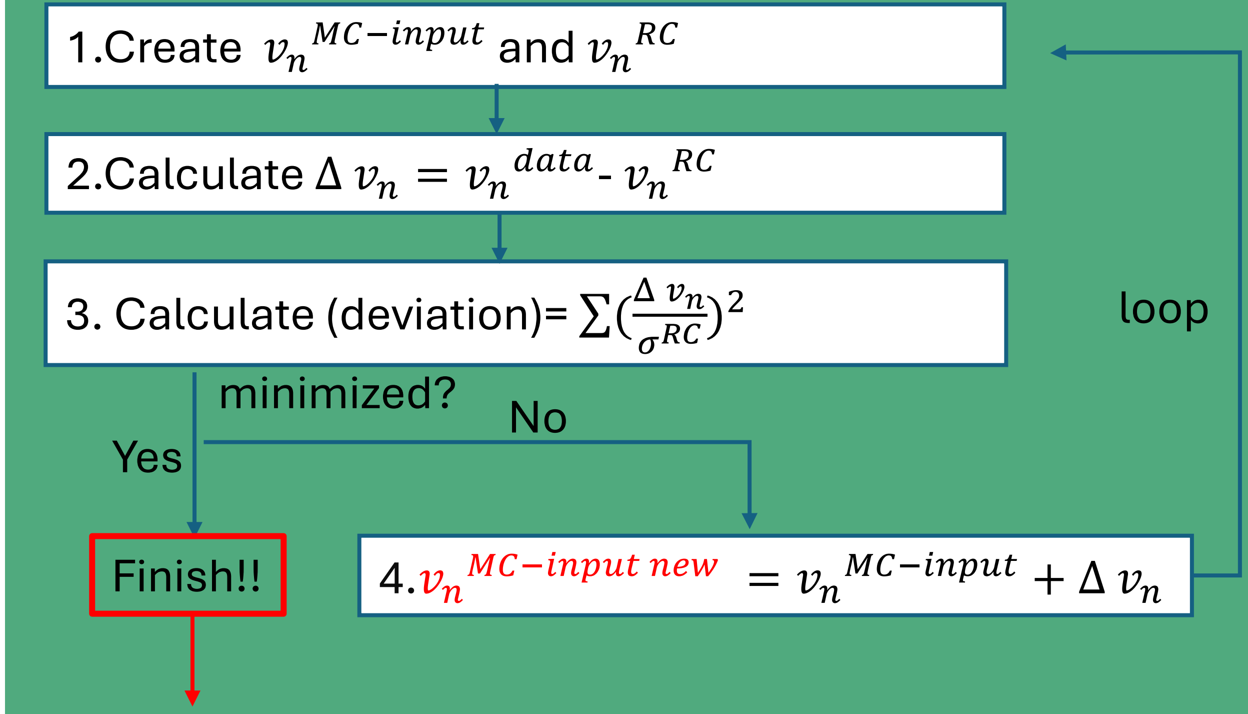
GEANT simulation(MC) + Reconstruction(RC)

Flow simulation analysis

MC and RC v_n

Procedure of Simulation

Iteration process



1.Create ${v_n}^{MC-input}$ and ${v_n}^{RC}$

2.Calculate $\Delta\, v_n = {v_n}^{data}$- ${v_n}^{RC}$

3. Calculate (deviation)= $\sum(\frac{\Delta\, v_n}{\sigma^{RC}})^2$

minimized?

No

Yes

Finish!!

4.${v_n}^{MC-input\ new} = {v_n}^{MC-input} + \Delta\, v_n$

loop

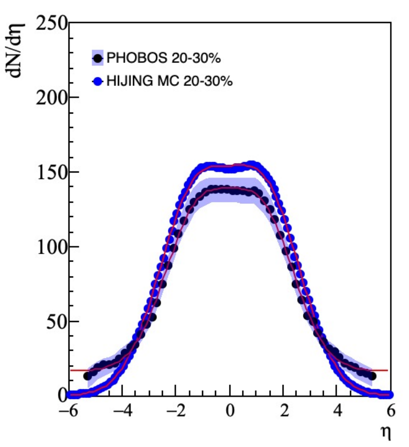
v_n(corrected)=(${v_n}^{MC-input}$- ${v_n}^{RC}$)+ v_n(data)

Calculate $\mathrm{d}N_{ch}/\mathrm{d}\eta$ weight

The difference between $\mathrm{d}N_{ch}/\mathrm{d}\eta$ of PHOBOS and HIJING is included. (HIJING scaled to PHOBOS's data)

$$w_{\mathrm{dN/d}\eta} = \frac{\mathrm{d}N_{ch}/\mathrm{d}\eta_{PHOBOS}}{\mathrm{d}N_{ch}/\mathrm{d}\eta_{HIJING}}$$

for each centrality



Calculate the flow weight

w_{v_n}=1.0+2$\sum_{n=1}^{3} v_n(\eta_{MC})$cos(n($\varphi_{MC}$−RP))

Iteration process

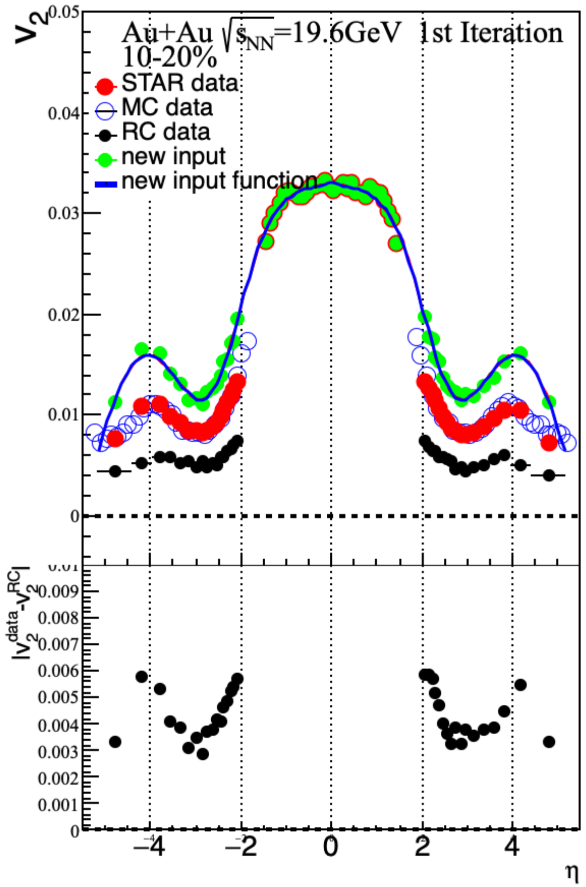
Convergence factor: $\sum\left(\frac{v_n{}^{data}(\eta_i) - v_n{}^{RC}(\eta_i)}{\sigma^{RC}(\eta_i)}\right)^2$ is minimized ?

Yes

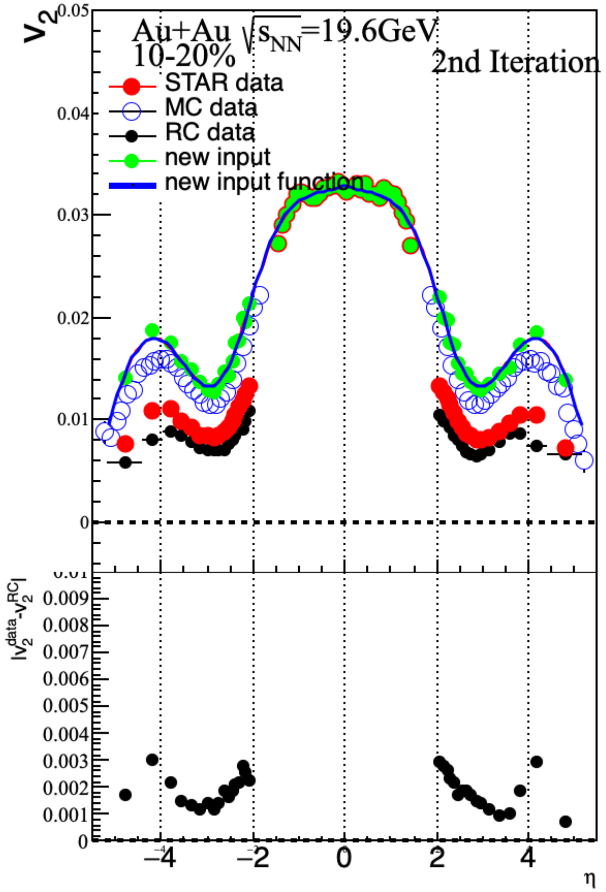
finish

e.g.10-20%

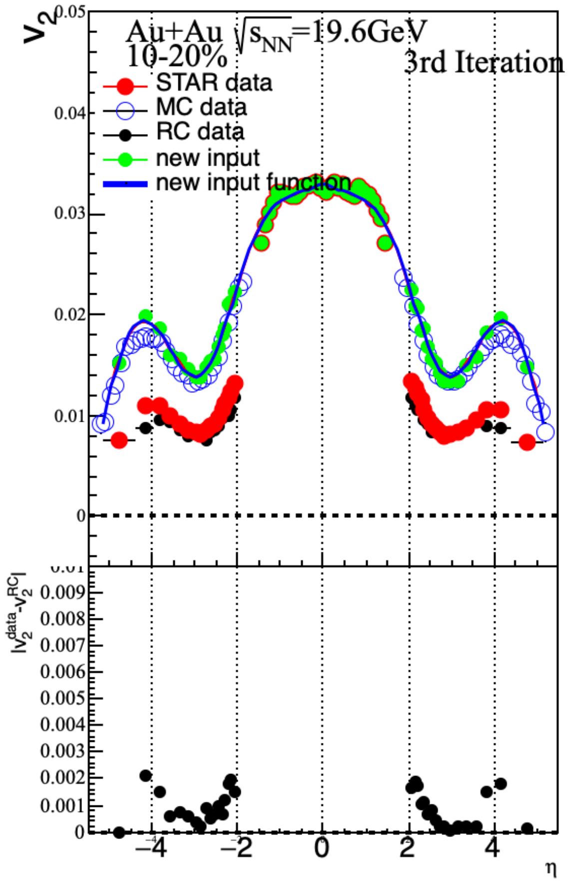
1st iteration



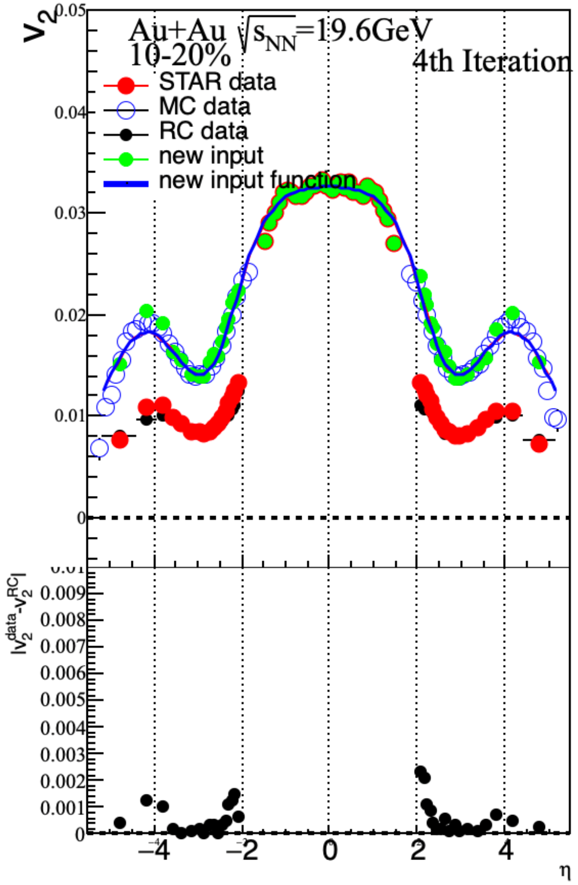
2nd iteration



3rd iteration

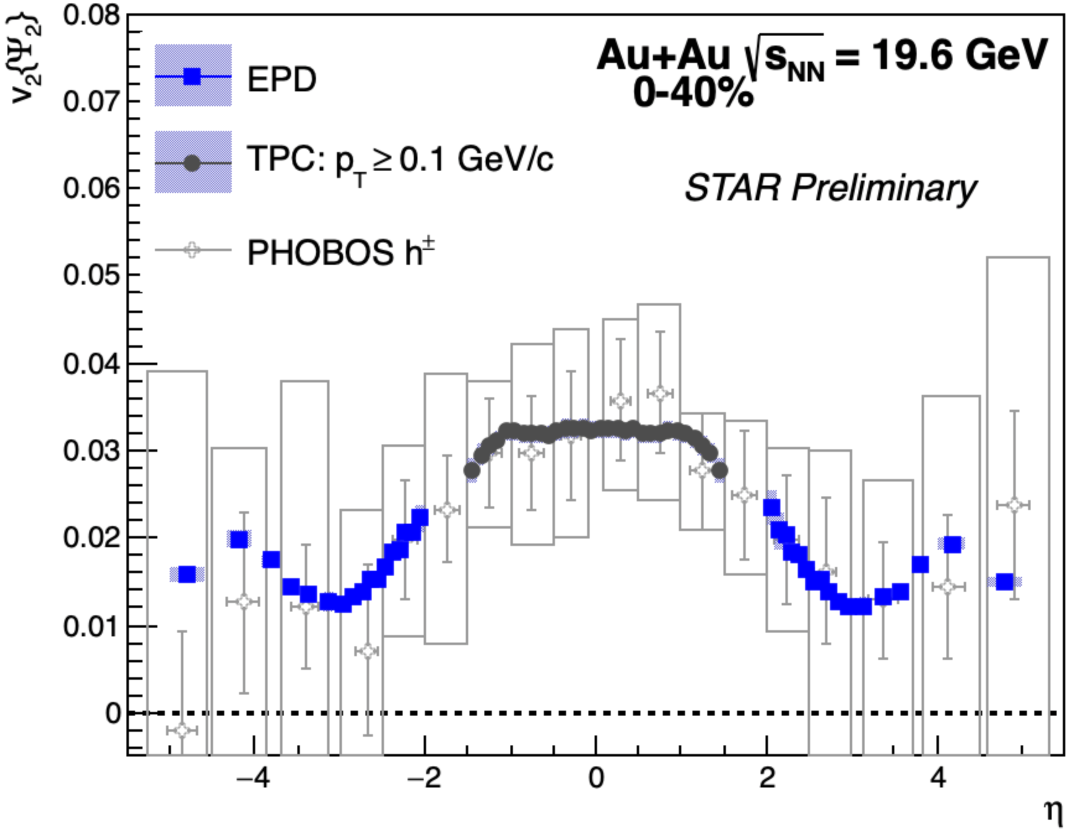


4th iteration



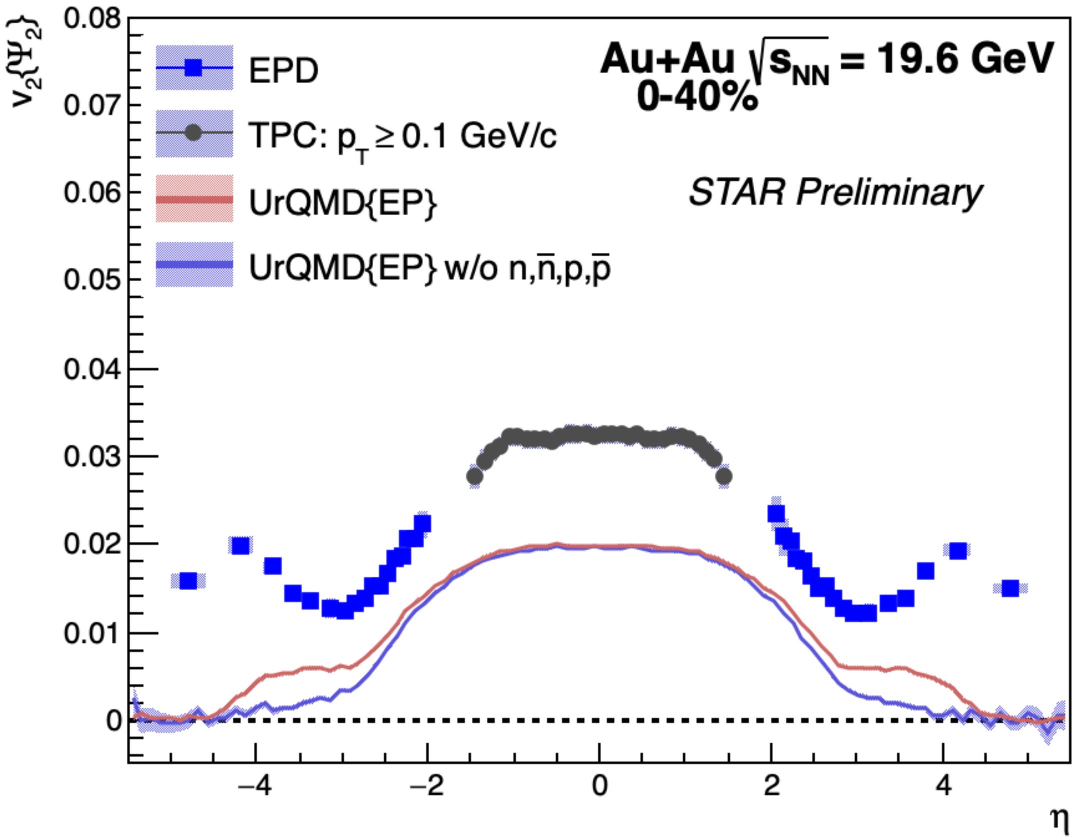
As the iterations progress, the RC data (black data points) become closer to the real data (red data points).

v_2 comparison with PHOBOS's result



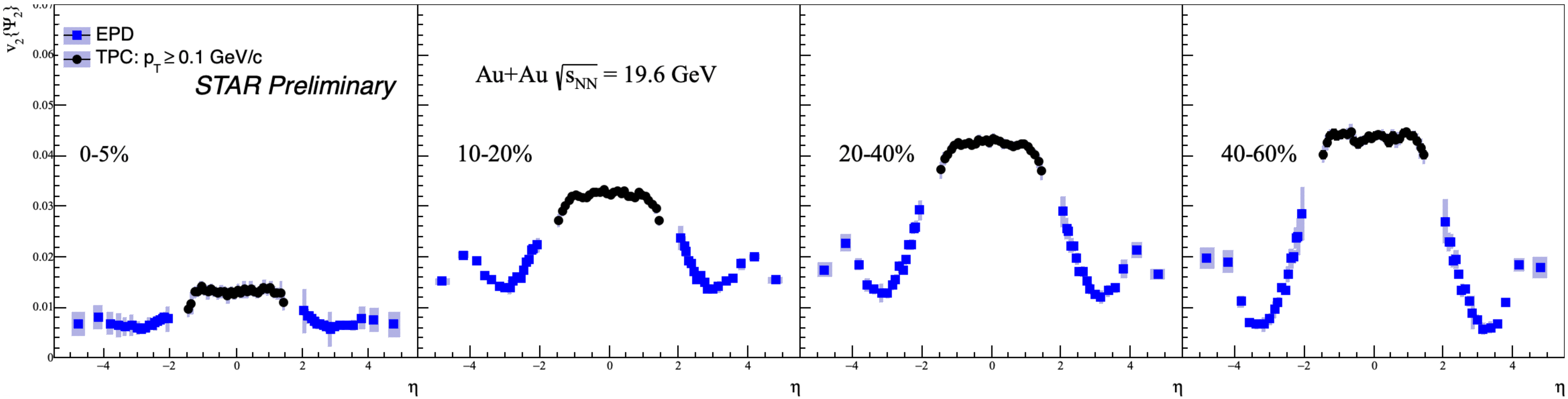
- High-precision measurements performed in the wide η region (2.1< |η |< 5.1).
- This result is consistent with PHOBOS's result, which has large uncertainty.
- Interestingly, there are bump structures at $|\eta|$ ~ 4.
- The bump starts to appear at |η|~3, which matches with the beam rapidity at 19.6 GeV (y_{beam}= 3) where spectator contribution starts to come in.

v_2 comparison with UrQMD model



- Although the absolute value differs, similar bump structures are seen in UrQMD, where spectators propagate throughout the simulation.
- UrQMD v_2 without protons and neutrons (the main components of spectators) doesn't show the bump structure.

Centrality dependence



- A clear trend of increasing v_2 magnitude with centrality is observed.
- The bump increases in more peripheral collisions, likely due to spectators.

Summary

Summary

- Elliptic flow v_2 has been measured in the forward and backward regions using the EPD detector in BES-II Au+Au collisions at 19.6 GeV.
- v_2 is consistent with the PHOBOS result; however, our result shows significantly improved precision.
- The bump structure appears around the beam rapidity (**spectator contribution**).
- The trend of bump structure in UrQMD model is qualitatively consistent with our data, even though the absolute value differs.

Outlook

- Comparison with other theoretical models (e.g., hydrodynamic model) to constrain the temperature dependence of the shear viscosity.
- v_3 measurement is ongoing now.
- Study other collision energies to understand the energy dependence and effects from spectators ($\sqrt{s_{NN}}$ = 7.7 GeV to 200 GeV).

Thank you!!

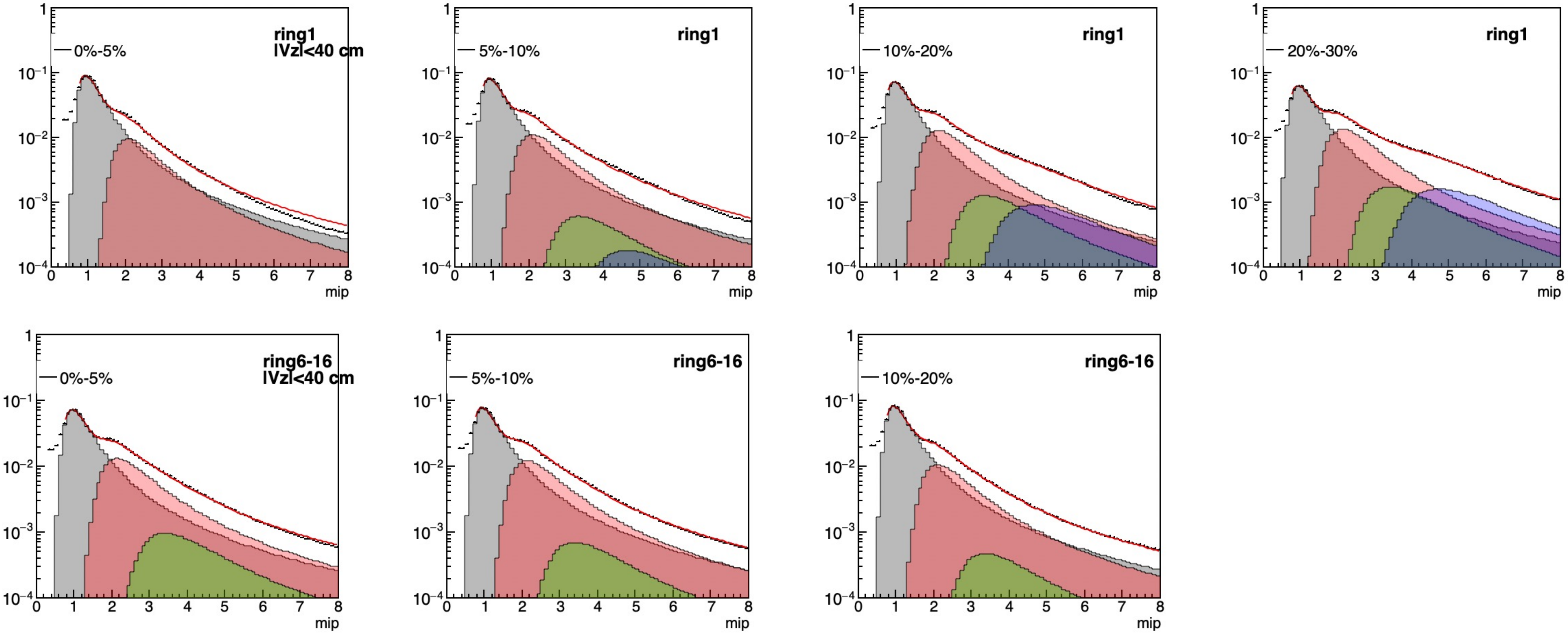
Back up

ADC distribution

-Multi landau fit was performed to calculate average multiplicity.

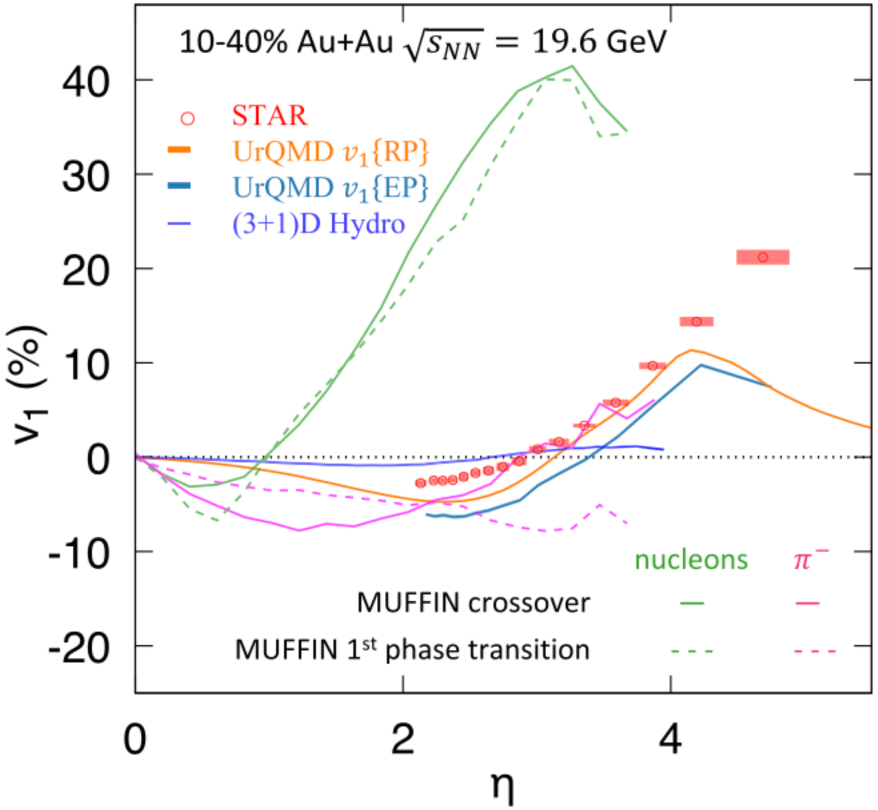
4 landau dist. convolution for ring1

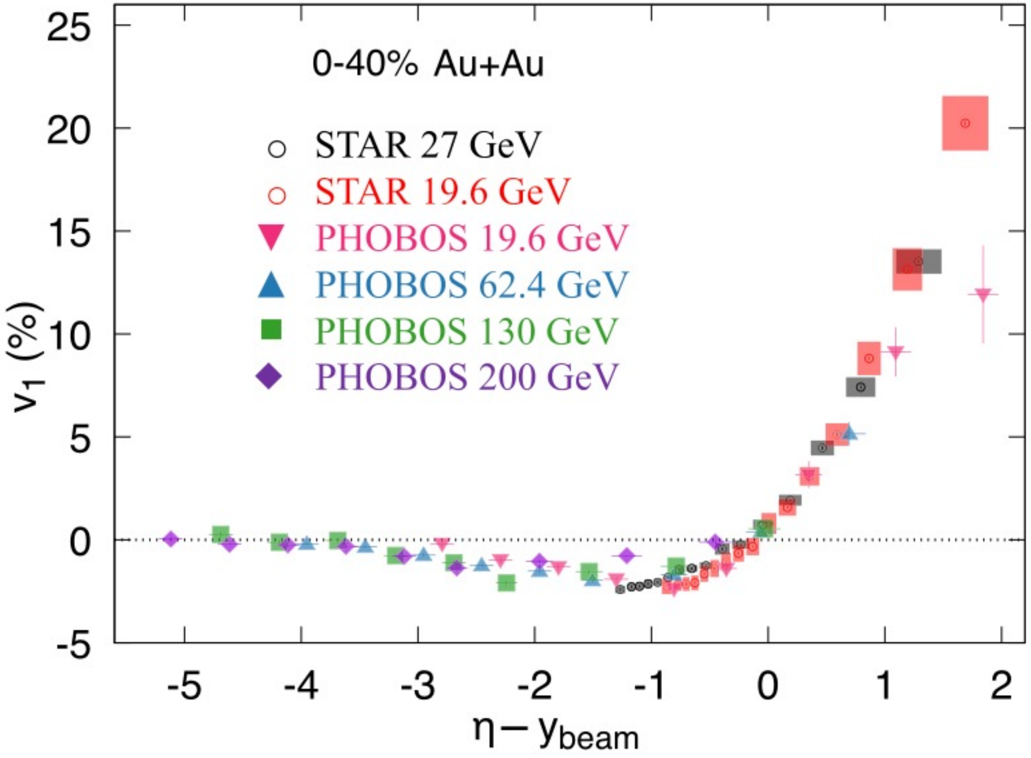
3 landau dist. convolution for ring 2-16



v_1 result from STAR

STAR reported the v_1 result in 2025.





M. I. Abdulhamid *et.al,* Phys. Rev. C **111**, 014906(STAR)