ϕ spin alignment with respect to the global angular momentum reconstructed with the 1st-order event plane

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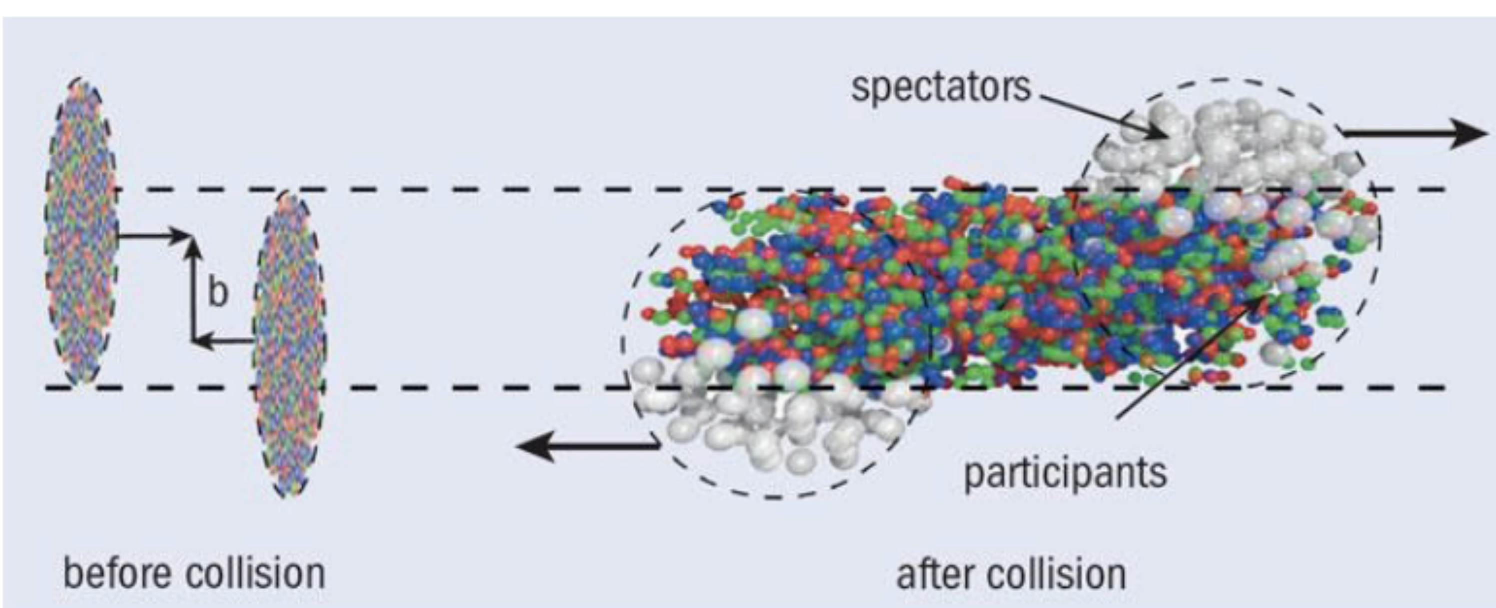
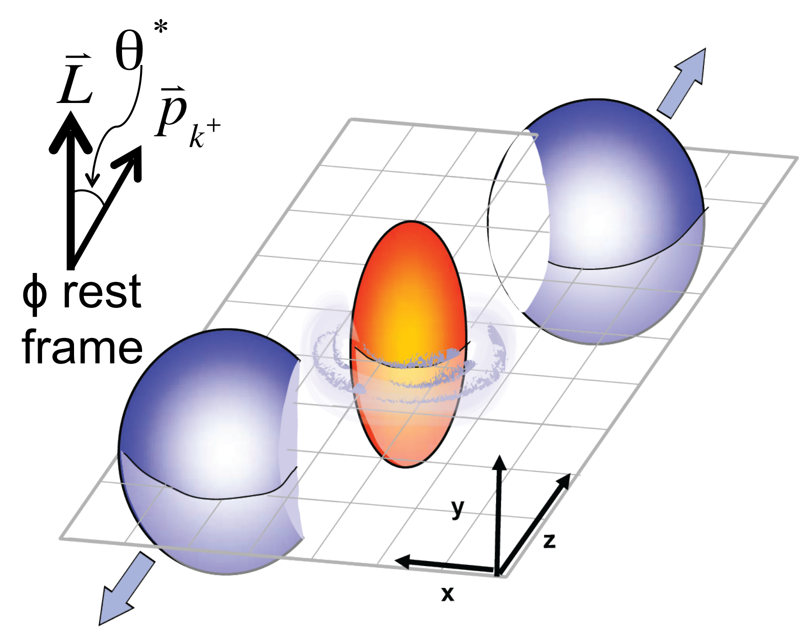
Introduction

- Initial angular momentum $\boldsymbol{L} \sim 10^3\ \hbar$ in non-central heavy-ion collisions.
- Baryon stopping may transfer this angular momentum, in part, to the fireball.
- Due to vorticity and spin-orbit coupling, ϕ-meson spin may align with L.





Spin alignment

- Spin alignment can be determined from the angular distribution of the decay products*:

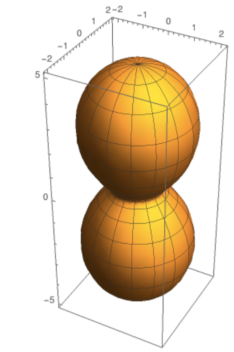
$$\frac{dN}{d(\cos\theta^*)} = N_0 \times \left[(1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta^*\right]$$

where N_0 is the normalization and θ^* is the angle between the polarization direction ***L*** and the momentum direction of a daughter particle in the rest frame of the parent vector meson.

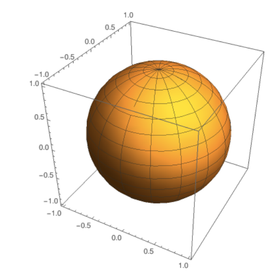
- A deviation of ρ_{00} from 1/3 signals net spin alignment.

*K. Schilling el al., Nucl. Phys. B 15, 397 (1970)

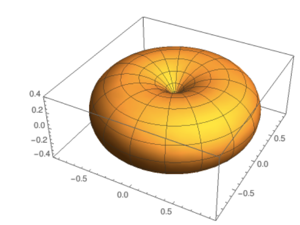
ρ_{00}>1/3:

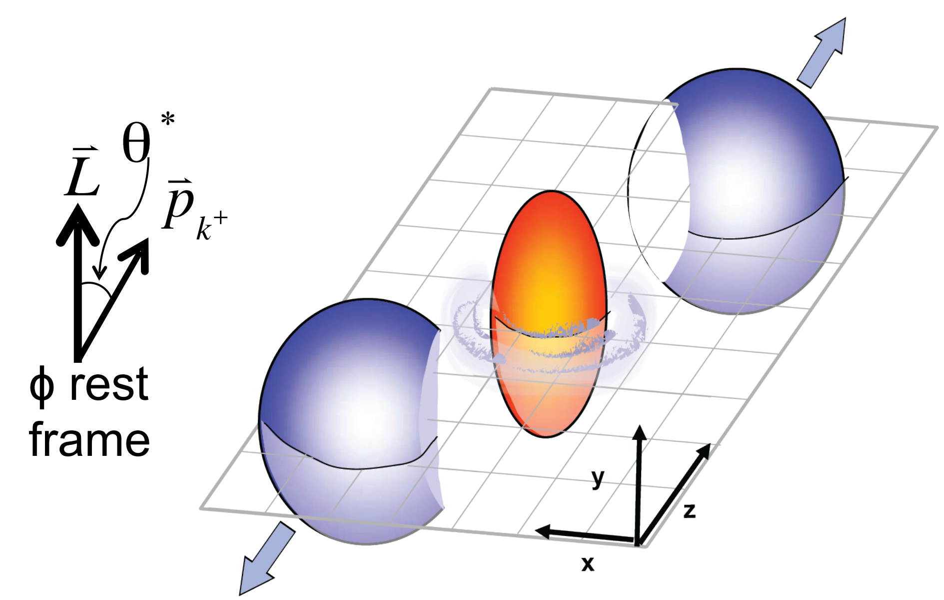


ρ_{00}=1/3:



ρ_{00}<1/3:





Hadronization scenarios

- Recombination of polarized quarks and anti-quarks in QGP likely dominates in the low p_T and central rapidity region.

$$\rho_{00}^{\varphi(rec)} = \frac{1-P_s^2}{3+P_s^2}$$

Always smaller than 1/3

- Fragmentation of polarized quarks q -> V + X, likely happens in the intermediate p_T and forward rapidity region. (V is the vector meson, which is ϕ in our analysis)

$$\rho_{00}^{\varphi(frag)} = \frac{1+\beta P_s^2}{3-\beta P_s^2}$$

Always larger than 1/3

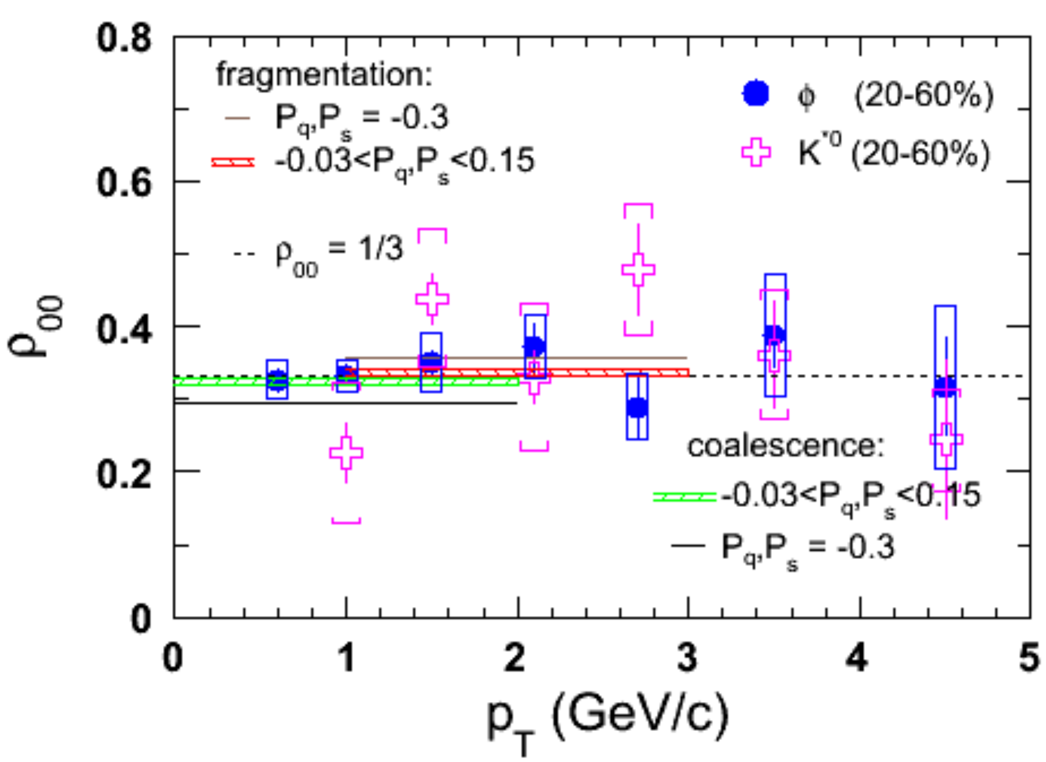
$P_s = -\frac{\pi}{4}\frac{\mu p}{E(E+m_s)}$ is the global quark polarization

$P_{\bar{s}}^{frag} = -\beta P_s$ is the polarization of the anti-quark created in the fragmentation process

Z.T. Liang and X.N. Wang, Phys. Lett. B629, 20 (2005)

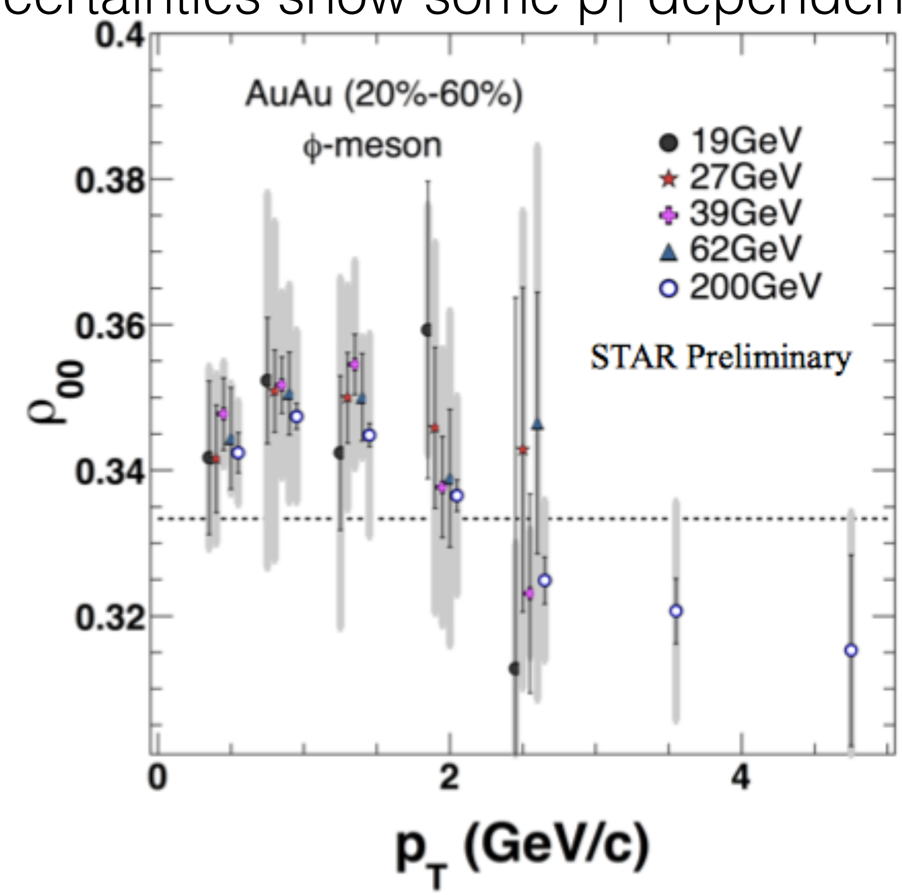
STAR's previous results

- STAR has published results with data taken in year 2004.
- Updated results have been shown at QM2017 (Xu Sun's poster), with data taken in year 2010 & 2011.
- Both of the above use the 2nd-order event plane obtained from TPC. The published result is consistent with 1/3; New results with reduced uncertainties show some p_T dependence.



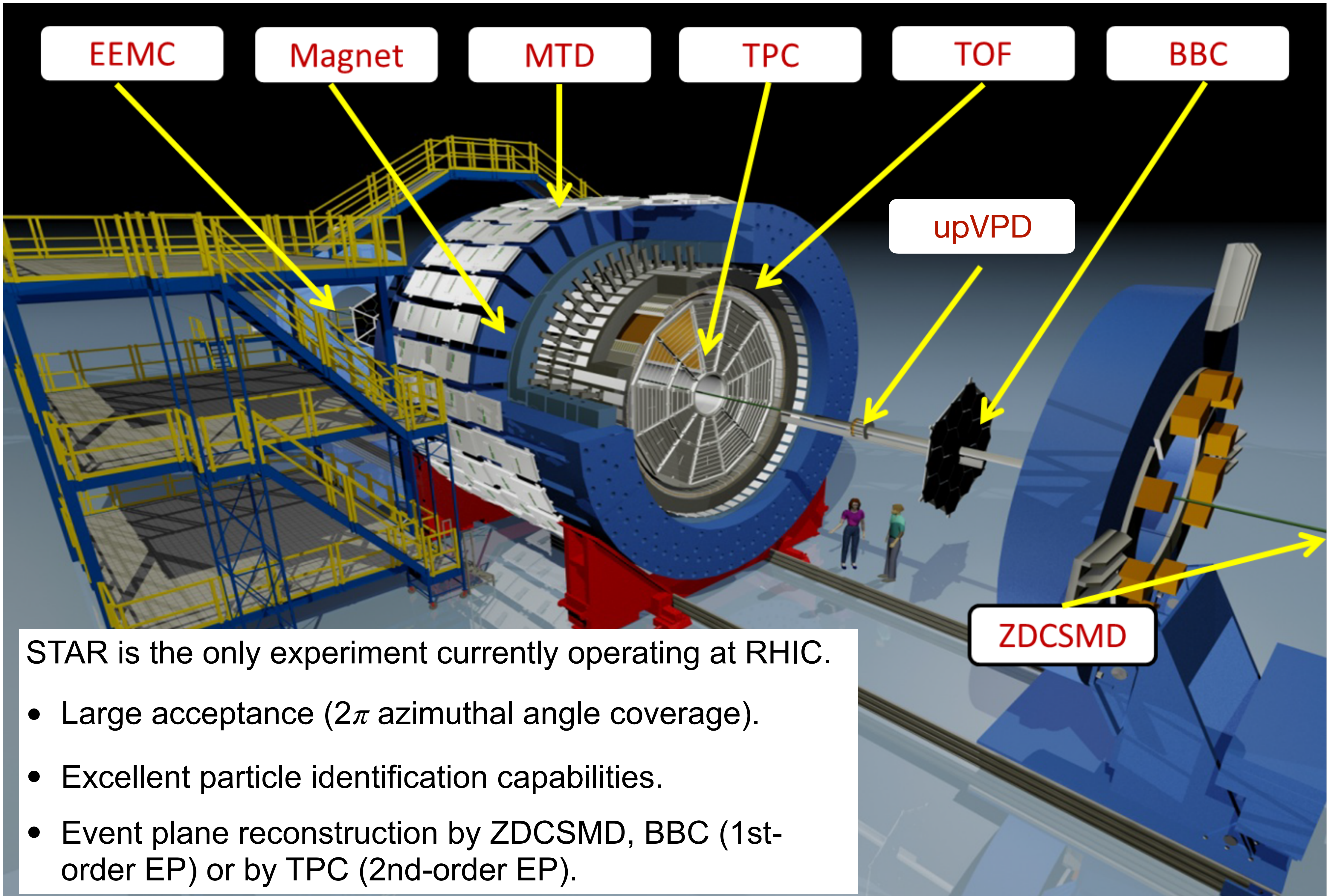
STAR's Published results

B.I.Abelev et al (STAR Collaboration), Phys. Rev. C77, 061902(R) (2008)



Xu Sun's QM2017 poster

STAR detector



STAR is the only experiment currently operating at RHIC.

- Large acceptance (2π azimuthal angle coverage).
- Excellent particle identification capabilities.
- Event plane reconstruction by ZDCSMD, BBC (1st-order EP) or by TPC (2nd-order EP).

Datasets and cuts

- **Number of events:**
  Au+Au 200 GeV ~ 500M
  Au+Au 39 GeV ~ 100M
  Au+Au 27 GeV ~ 30M
  Au+Au 19.6 GeV ~ 10M
  Au+Au 11.5 GeV ~ 3M

- **Event cuts:**
  -30.0 < Vz < 30.0 cm
  Vr < 2.0 cm
  -3.0 < Vz-VzVPD < 3.0 cm
  Number ToF matched point > 3
  Minimum Bias Event
  Bad runs are rejected

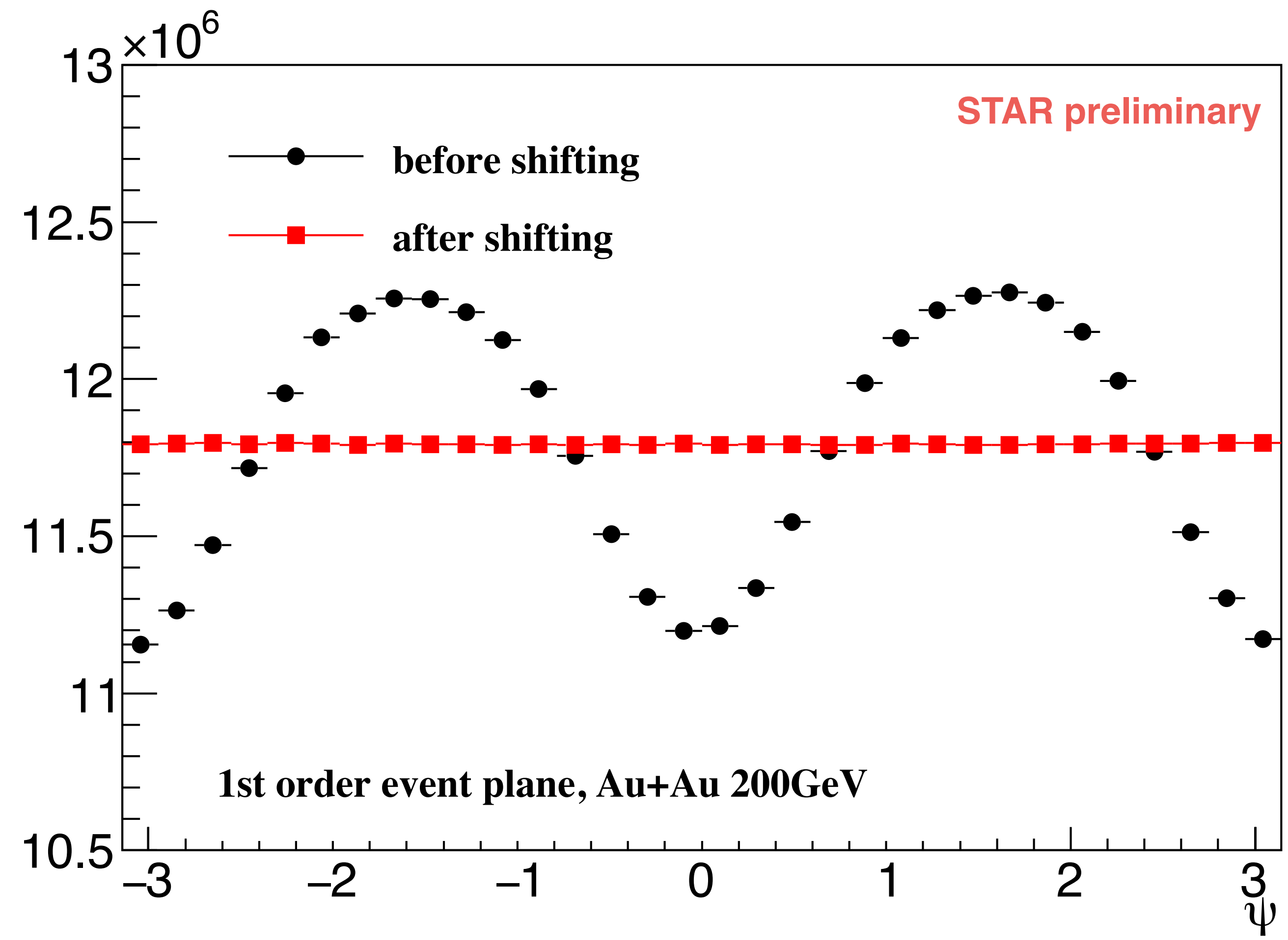
- **Track cuts:**
  nHitsFit > 15
  nHitsFit/nHitsMax > 0.52
  -1.0 < eta < 1.0
  dca < 2.0 cm
  $p_T > 0.1$ GeV/c
  p<10 GeV/c
  invariant mass < 1.1 GeV/c^2

- **Track PID:**

Momentum(GeV/c)	With TOF	Without TOF
[0, 0.65]	$0.16<m^2<0.36$, |nSigmaKaon| < 2.5	-1.5<nSigmaKaon<2.5
(0.65, 1.5)	$0.16<m^2<0.36$, |nSigmaKaon| < 2.5	—
[1.5, ∞)	$0.125<m^2<0.36$, |nSigmaKaon| < 2.5	—

1st order event plane

- In our analysis, the event plane is obtained from ZDCSMD (for 200 GeV data) or BBC (for low energy data) and flattened by shifting method*. The flattening is applied for every 10 runs (about 60000 events in Au+Au 200 GeV collisions).



The event plane before/after shifting method

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

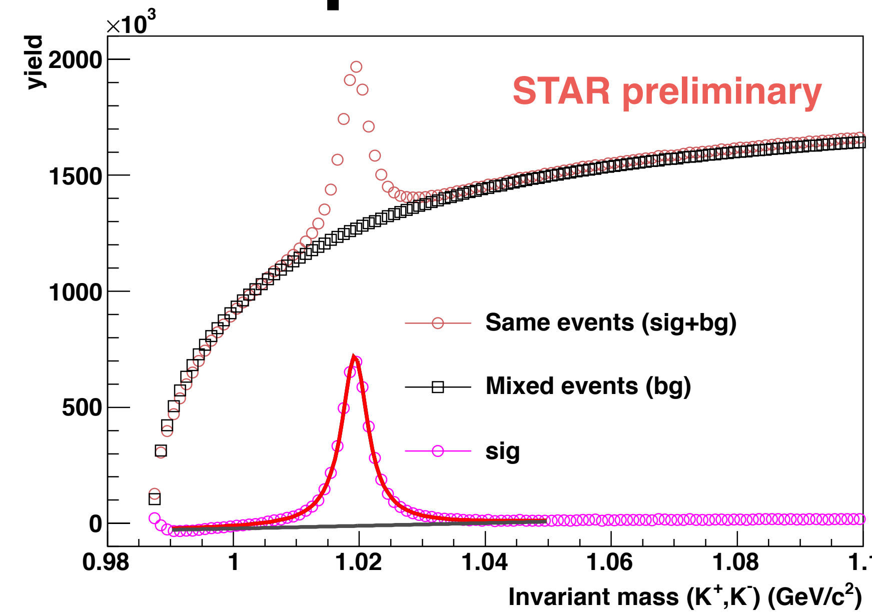
Obtaining yields of ϕ meson

- The background is obtained using event mixing technique.

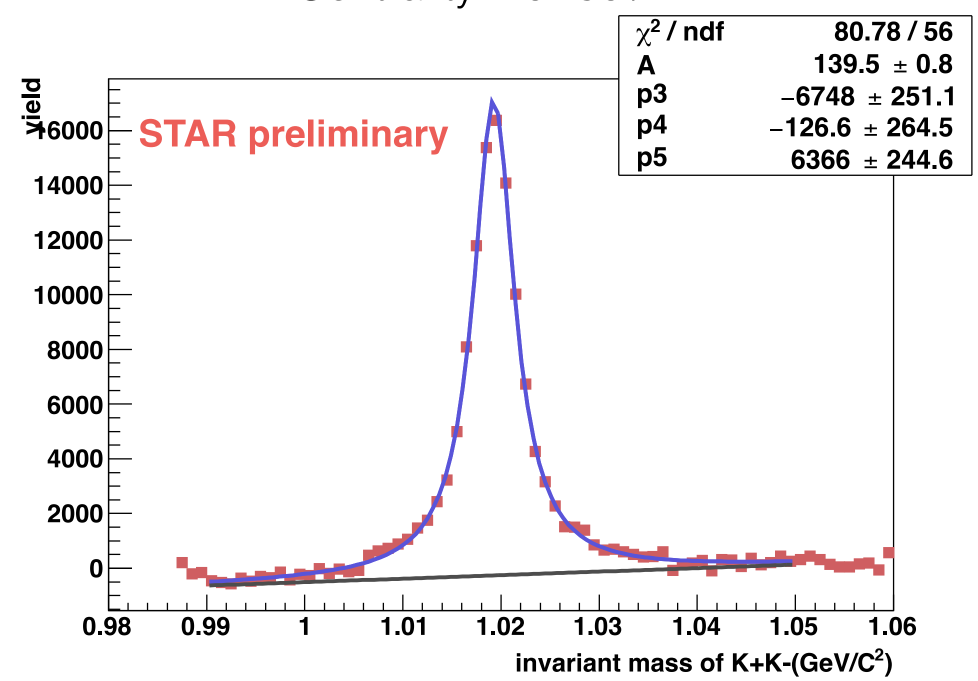
- The ϕ-mesons signal is fitted with Briet-Wigner function and the 2nd order polynomial function for residual background to extract raw ϕ meson yield:

$$BW(\mathrm{m}_{inv}) = \frac{1}{2\pi}\frac{A\Gamma}{(m-m_{\phi})^2+(\Gamma/2)^2}$$

where Γ is the width of the distribution and A is the area of the distribution. A is the raw yield scaled by the bin width (= 0.001 GeV/c^2).



Fitting of all p$_T$ & cosθ* range.
Centrality: 40~50%



Fitting of a single p$_T$ & cosθ* bin.
Centrality: 40%-50% p$_T$: 1.2~1.8 GeV/C cosθ*:-0.6~-0.4

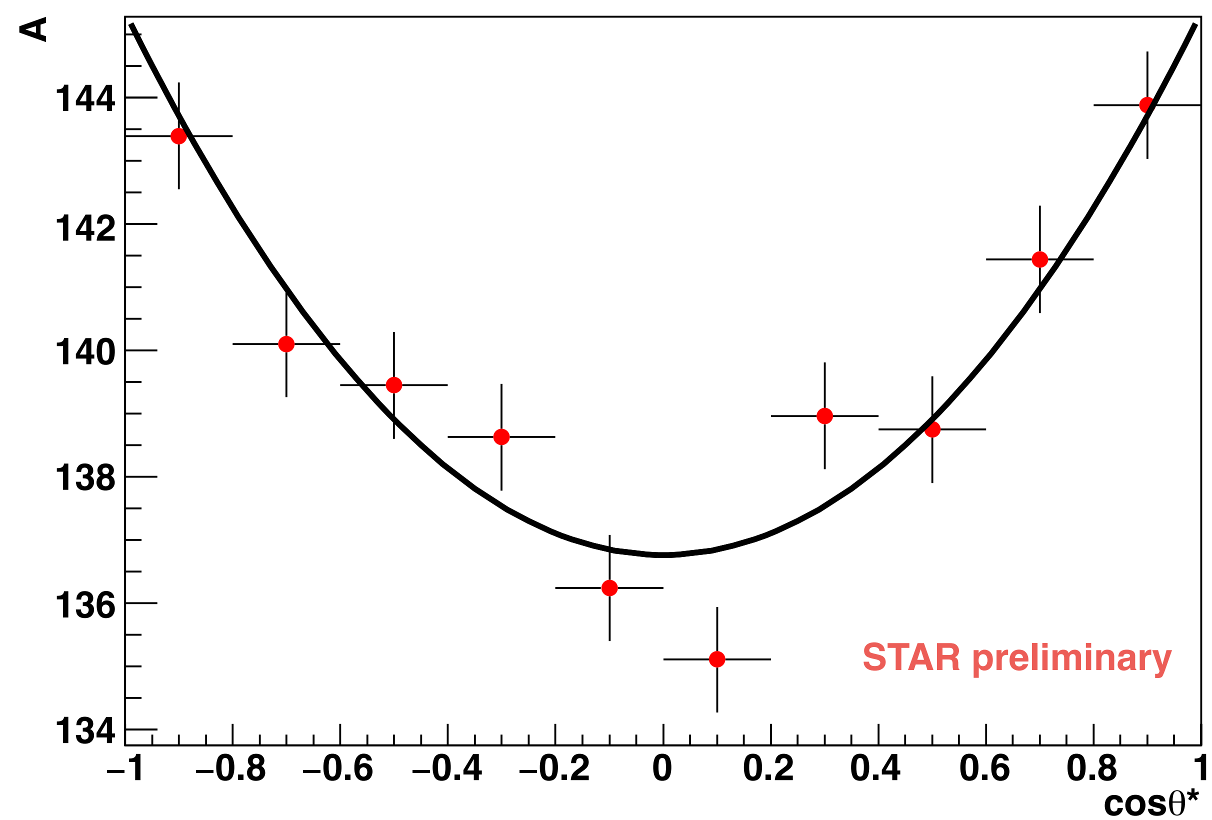
Extracting observed ρ_{00}

- With yield of ϕ for different bins, we can fit the yield distribution and obtain ρ_{00} using

$$\frac{dN}{d(\cos\theta^*)} = N_0 \times \left[\left(1-\rho_{00}\right) + (3\rho_{00}-1)\cos^2\theta^* \right]$$

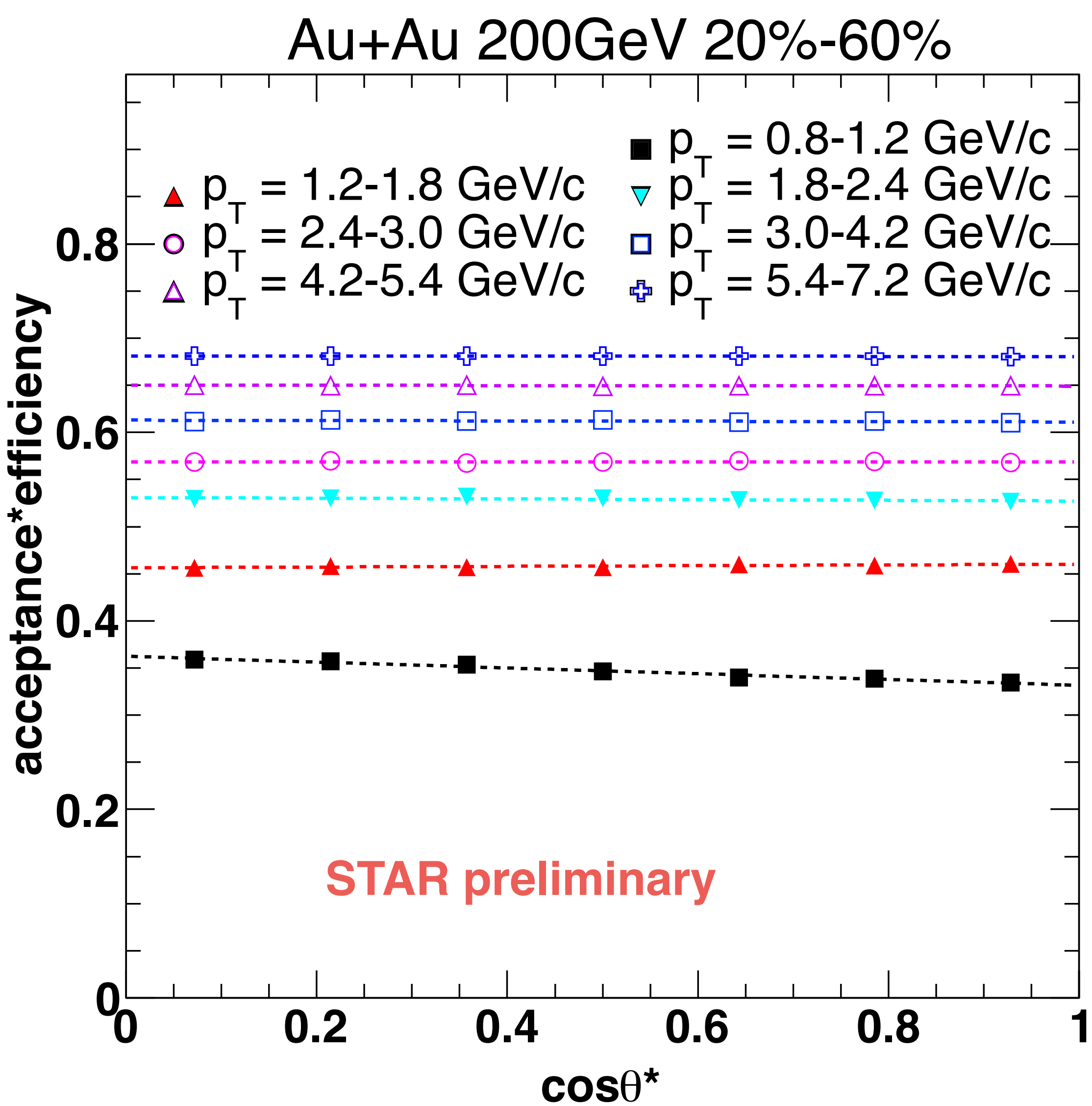
θ^* is the angle between the polarization direction ***L*** and the momentum direction of a daughter particle in the rest frame of the parent vector meson.

- What we extracted here is the ρ_{00} before event plane resolution correction (observed ρ_{00}).



Fitting of yield Vs cosθ*
Au+Au 200 GeV
Centrality: 40-50%
p_T: 0.8~1.2 GeV/c

Efficiency and acceptance



- ϕ-meson efficiency*acceptance is calculated with K^+ and K^- embedding data and shows very weak cosθ* dependence, and the effect on ρ_{00} is negligible.

Derivation of event plane resolution correction

- For spin =1 particles, their daughter's angular distribution can be written in a general form as a function of θ^* and β (the azimuthal angle w.r.t ***L***, see the picture at bottom right):

$$\frac{dN}{d\cos\theta^* d\beta} \propto 1 + A\cos^2\theta^* + B\sin^2\theta^*\cos 2\beta + C\sin 2\theta^*\cos\beta$$

- where

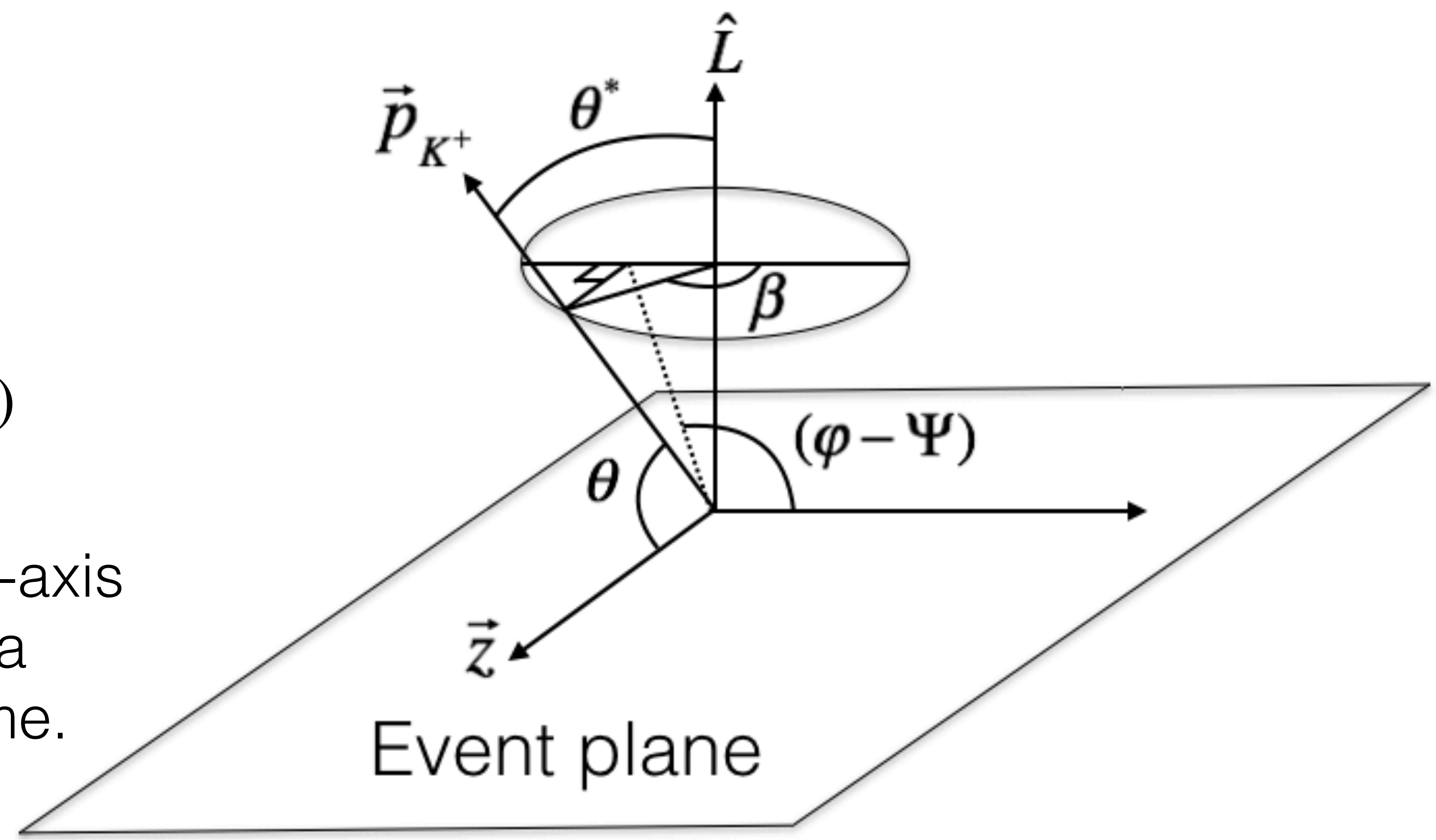
$$A = (3\rho_{00} - 1)/(1 - \rho_{00})$$

- We have

$$\cos\theta^* = \sin\theta\sin(\varphi - \psi)$$

$$\cos\theta = \sin\theta^*\sin\beta$$

where θ is the angle between Z-axis and the momentum direction of a daughter particle in the rest frame.



Derivation of event plane resolution correction

- The observed event plane ψ' may be different from the real event plane:

$$\psi' = \psi + \Delta$$

- The distribution of Δ is supposed to follow an even function, so we can assume

$$\langle \cos 2\Delta \rangle = R, \quad \langle \sin 2\Delta \rangle = 0$$

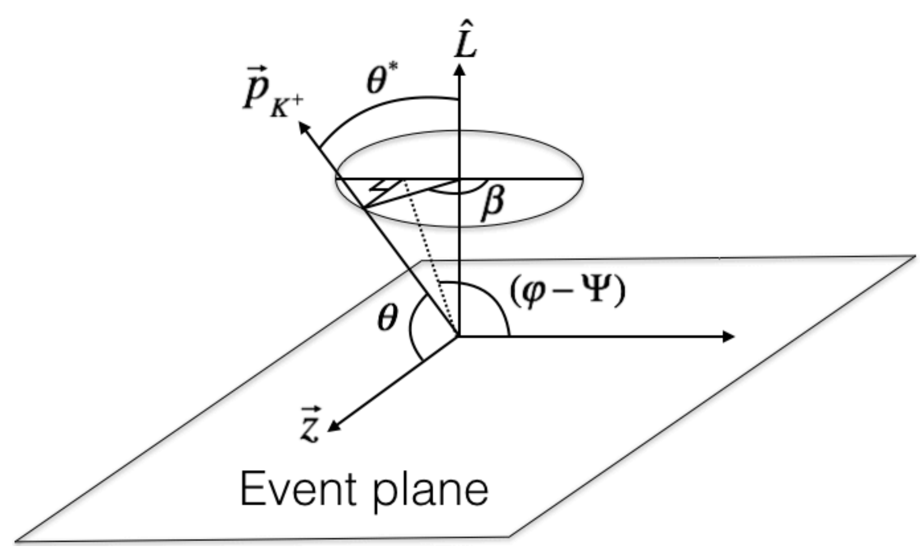
- When $\psi \to \psi'$, $\theta^* \to \theta'^*$, $\beta \to \beta'$, we have

$$\begin{pmatrix} 1 \\ A \\ B \\ C \end{pmatrix} \to \begin{pmatrix} 1 \\ A' \\ B' \\ C' \end{pmatrix} = \begin{pmatrix} 1 \\ \dfrac{A(1+3R)+B(3-3R)}{4+A(1-R)+B(-1+R)} \\ \dfrac{A(1-R)+B(3+R)}{4+A(1-R)+B(-1+R)} \\ \dfrac{4\cdot C\cdot R}{4+A(1-R)+B(-1+R)} \end{pmatrix}$$

$$\frac{dN}{d\cos\theta^* d\beta} \propto 1 + A\cos^2\theta^* + B\sin^2\theta^*\cos 2\beta + C\sin 2\theta^*\cos\beta$$

rotate w.r.t z-axis by Δ

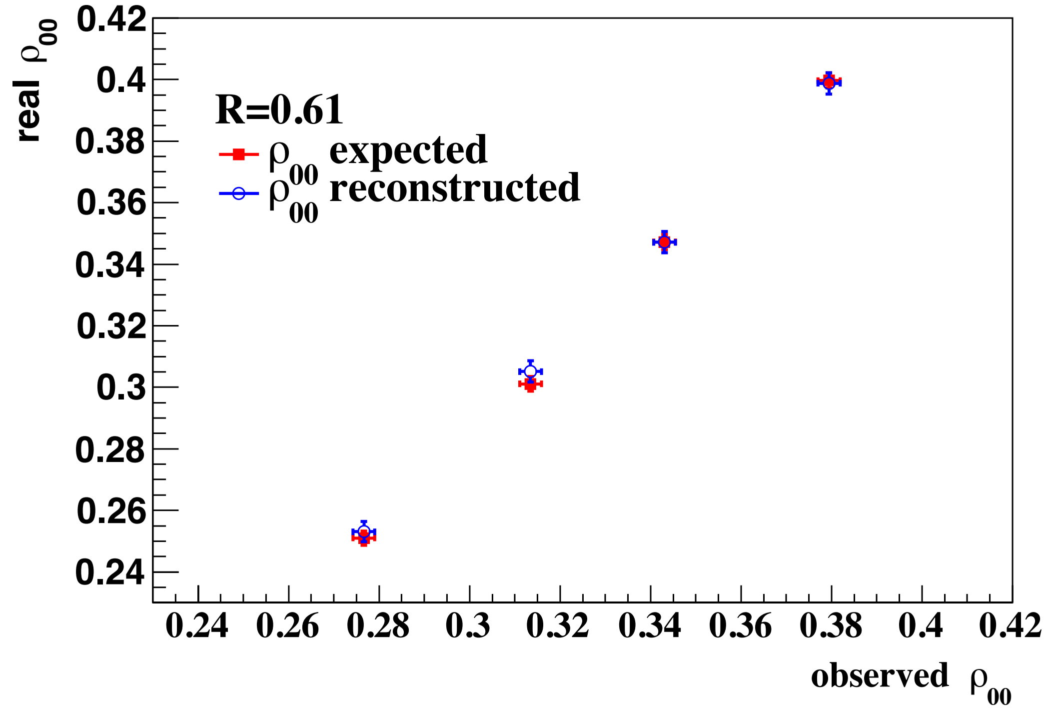
$$\frac{dN}{d\cos\theta'^* d\beta'} \propto 1 + A'\cos^2\theta'^* + B'\sin^2\theta'^*\cos 2\beta + C'\sin 2\theta'^*\cos\beta'$$

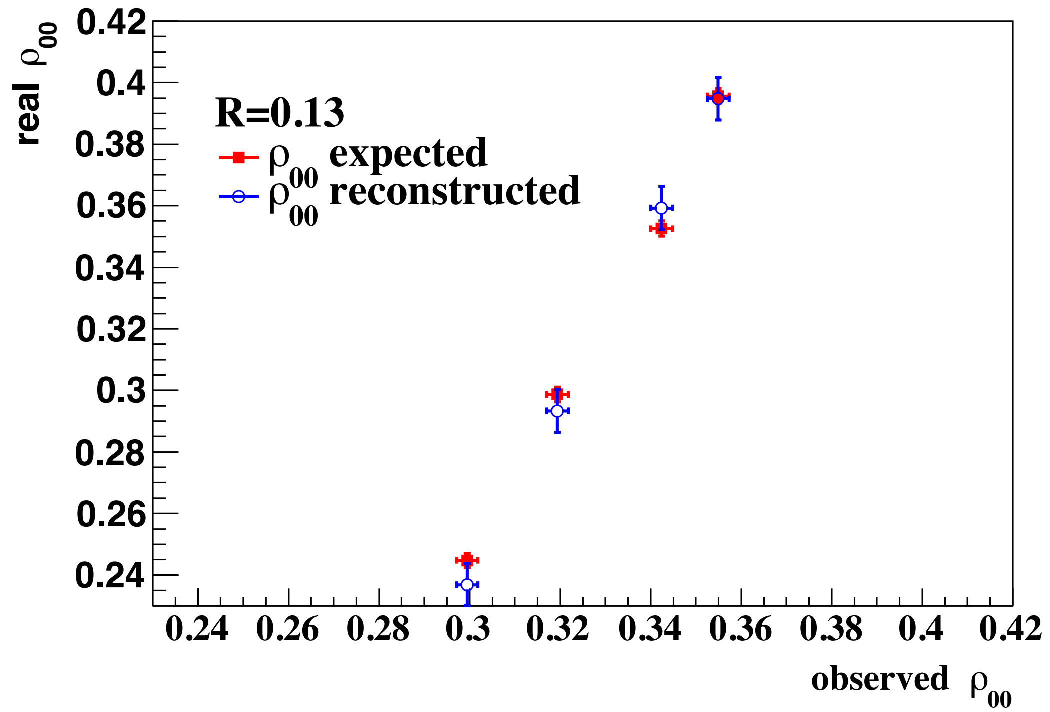


- When $B = 0$, $A' = \dfrac{A(1+3R)}{4+A(1-R)}$, $\boxed{\rho_{00}^{real} - \dfrac{1}{3} = \dfrac{4}{1+3R}(\rho_{00}^{obv} - \dfrac{1}{3})}$

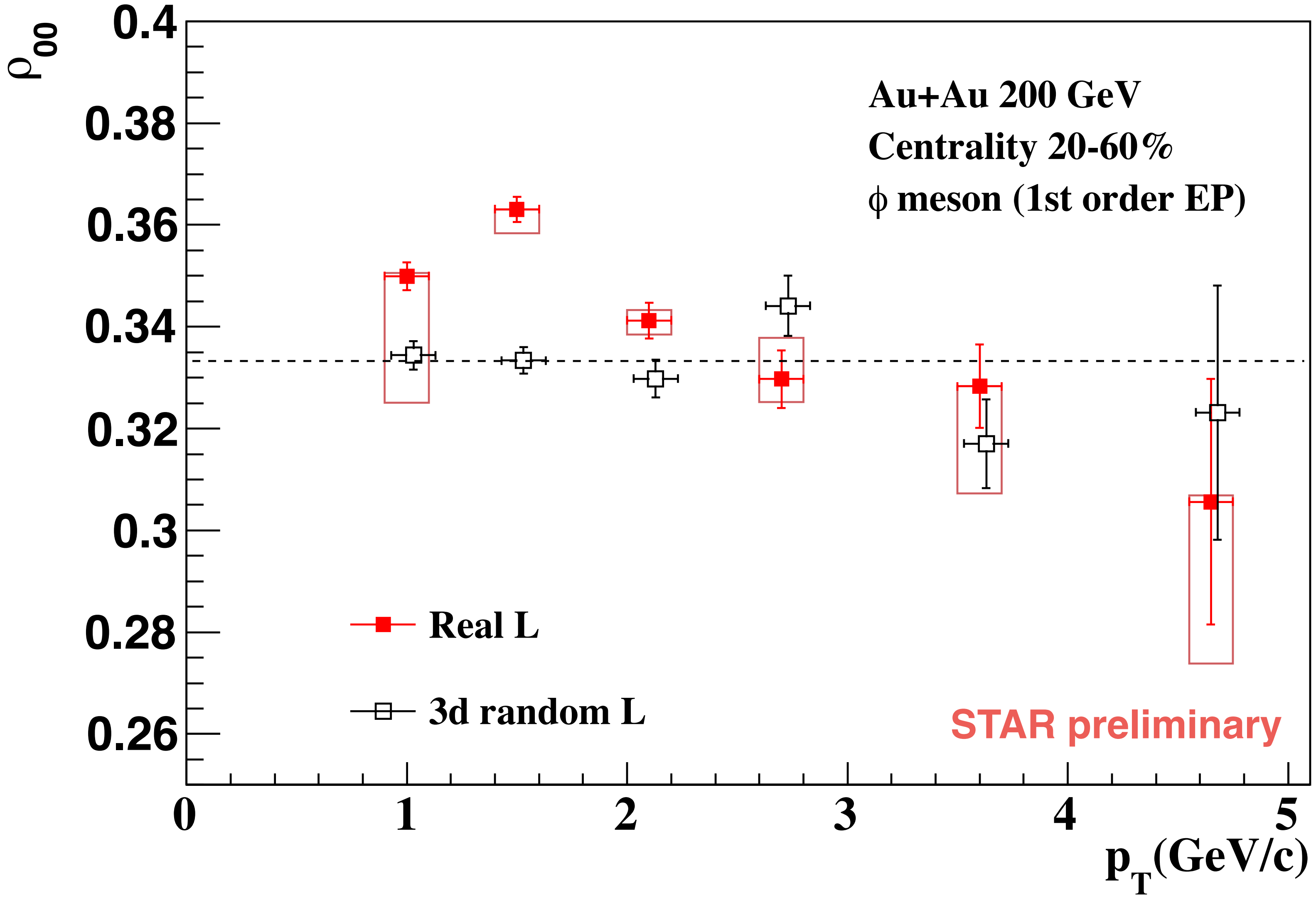
Verify the resolution correction formula with simulations

- To test the formula of resolution correction, we generate Monte Carlo events by Pythia with Δ following gaussian distributions.
- ρ_{00}^{real} can be either obtained by fitting the yield with real event plane (without Δ), or by calculation with the correction formula we derived.
- The plots show the comparison of results between two methods. The correction works well even when the resolution is low.





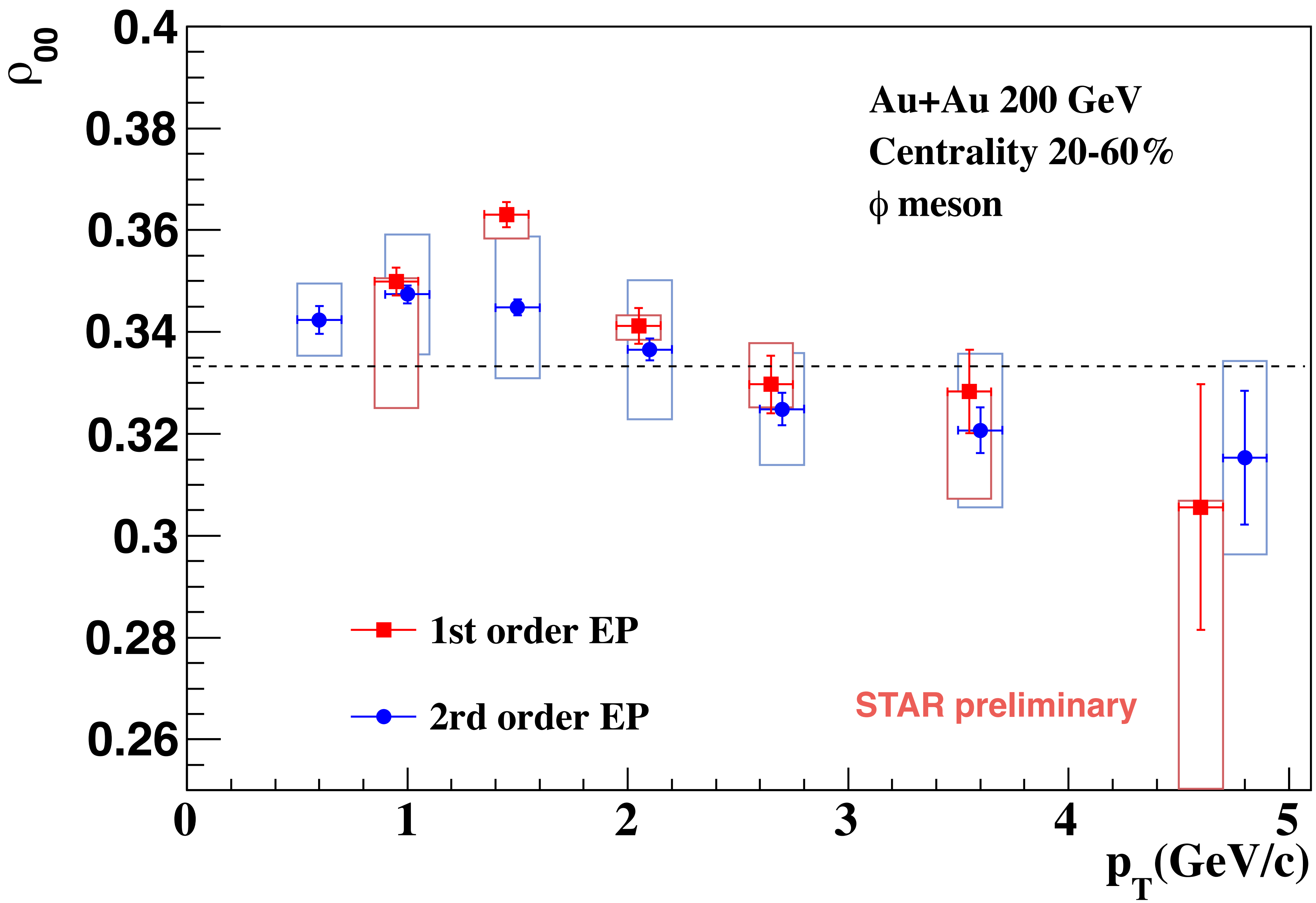
ρ_{00} vs. p_T



- Non-trivial p_T dependence is seen. 6σ away from 1/3 at p_T =1.5 GeV/c.

- As a consistency check, the ρ_{00} is also studied with an ***L*** direction randomized in 3d-space, which is at the expected value of 1/3.

1st EP vs. 2nd EP



- To explain the difference at p_T ~ 1.5 GeV/c, we need to consider the de-correlation between the two EPs.

De-correlation between 1st and 2nd order event planes

- In the derivation of resolution, we have correction term R as:

$$R = \langle \cos 2\Delta \rangle$$

for 1st(2nd) order EP, the corresponding correction term becomes $R_{1,2} = \langle \cos 2(\Psi_{1,2} - \Psi) \rangle$,

and for 2nd order EP with the consideration of de-correlation, the correction term can be written down as:

$R_{12} = \langle \cos 2(\Psi_2 - \Psi_1 + \Psi_1 - \Psi) \rangle = D_{12} \bullet R_1$,

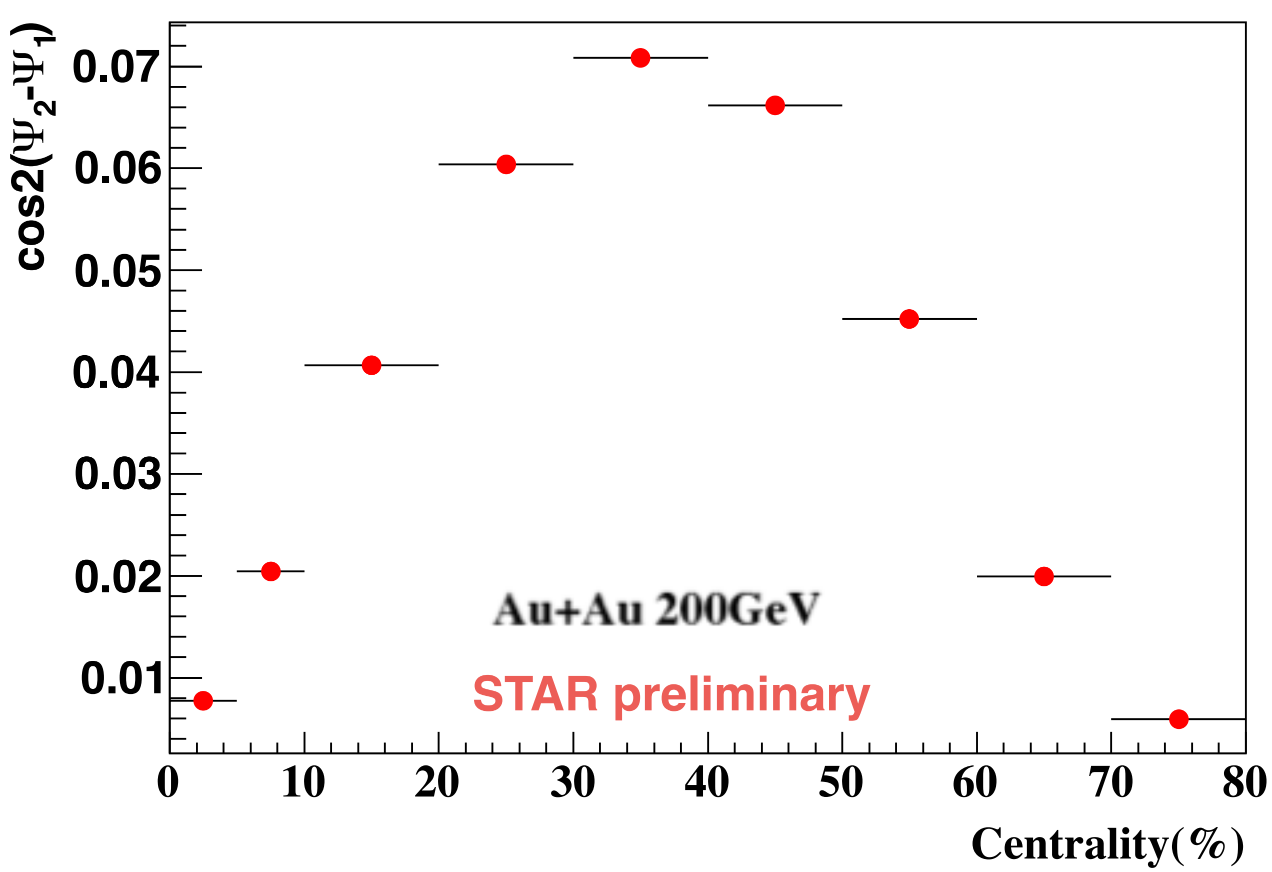
where $\mathrm{D}_{12} = \langle \cos 2(\Psi_2 - \Psi_1) \rangle$

- Then we can take the corrected ρ_{00} from 1st order EP as real ρ_{00}, and use the resolution correction formula to recover 2nd order EP result:

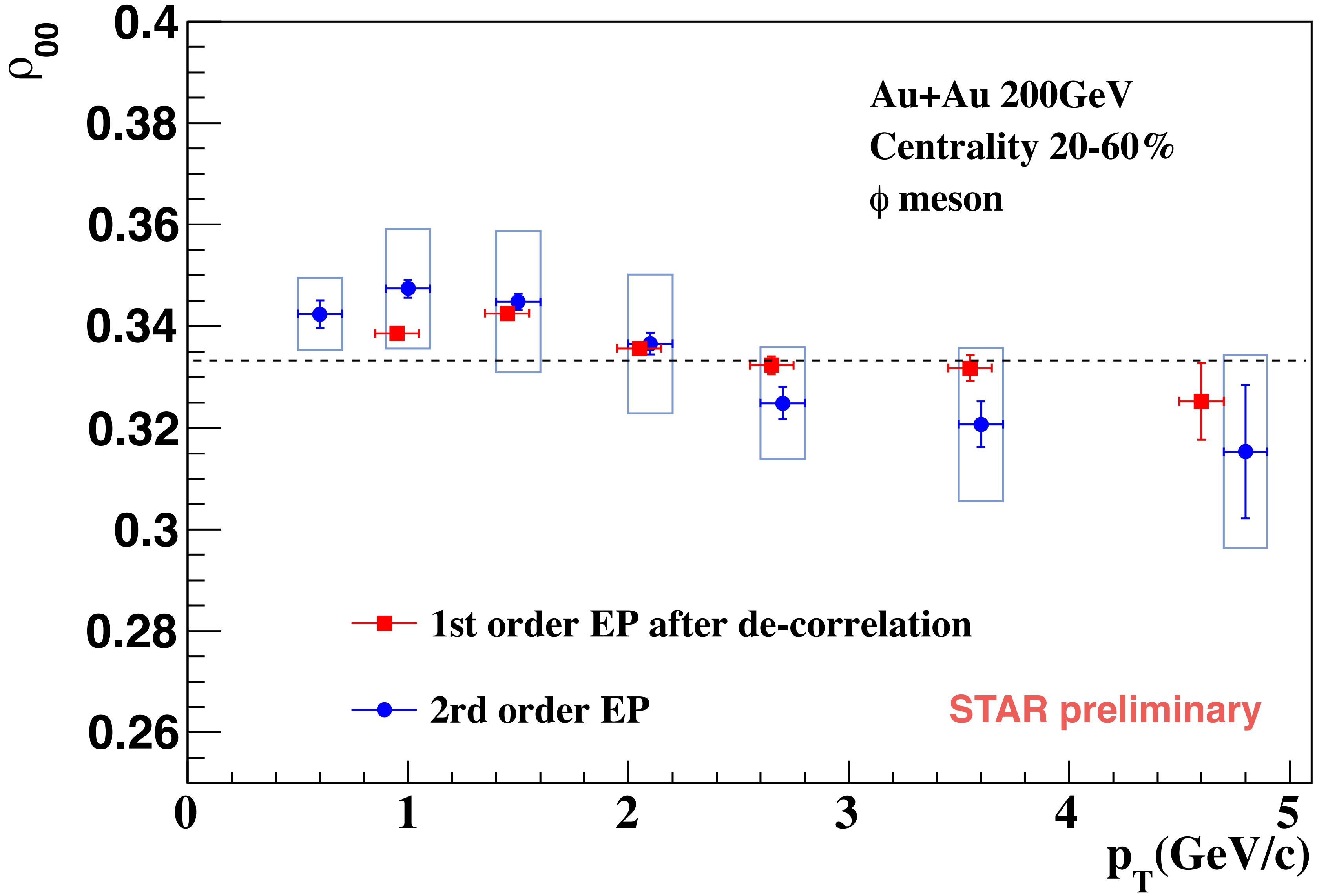
$$\rho_{\mathrm{obv}}^{\mathrm{2nd}} - \frac{1}{3} = \frac{1+3R_2}{4}(\rho_{00}^{\mathrm{2nd}} - \frac{1}{3})$$

$$\rho_{\mathrm{obv}}^{\mathrm{2nd}} - \frac{1}{3} = \frac{1+3D_{12} \cdot R_1}{4}(\rho_{00}^{\mathrm{1st}} - \frac{1}{3})$$

$$\Rightarrow \rho_{00}^{\mathrm{2nd}} - \frac{1}{3} = \frac{1+3D_{12} \cdot R_1}{1+3R_2}(\rho_{00}^{\mathrm{1st}} - \frac{1}{3})$$



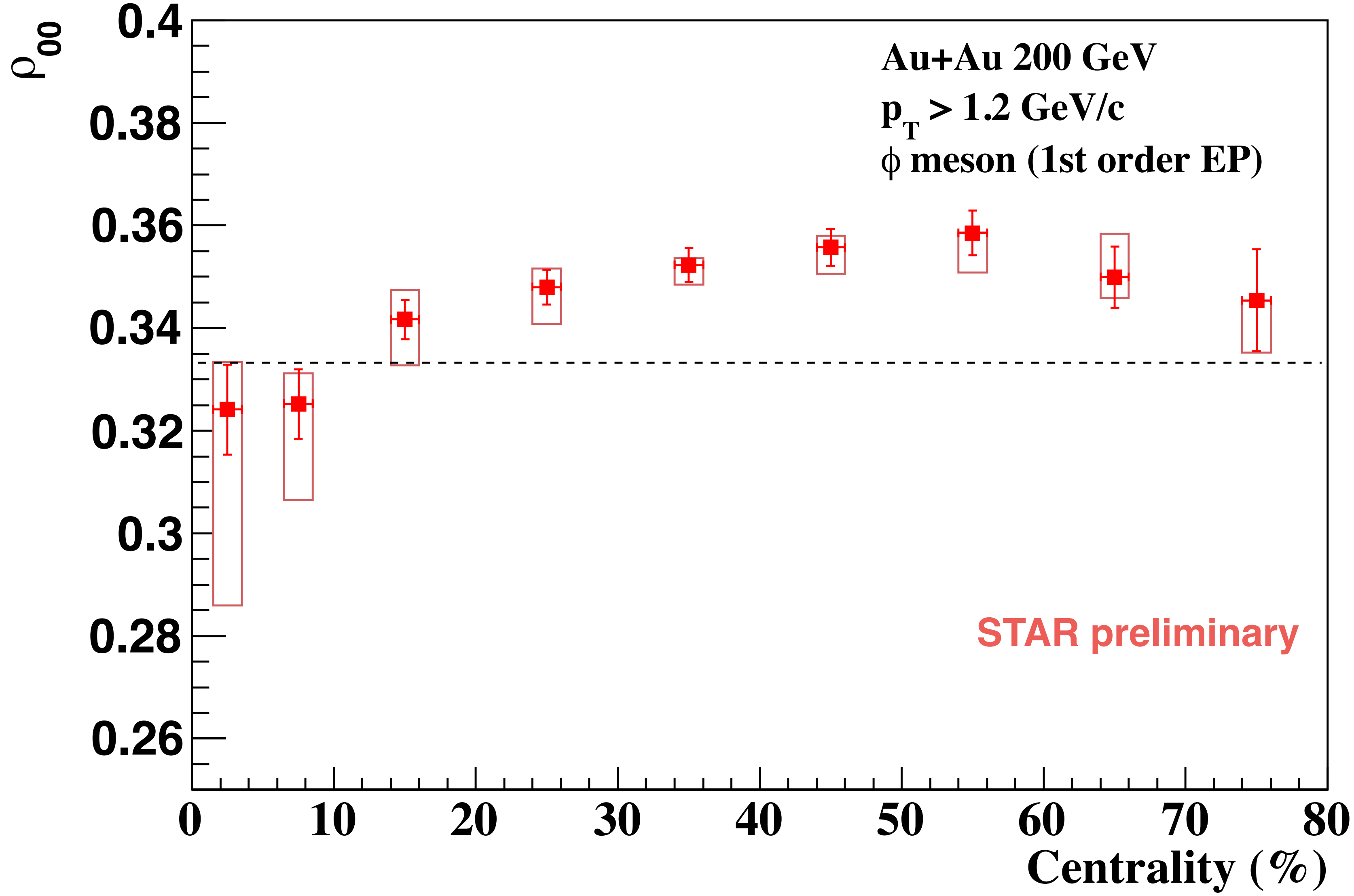
De-correlation results



- The de-correlation between 1st and 2nd-order events plane explains part of the difference.
- The remaining difference may be due to B≠0 in the angular distribution (or other physics origin?):

$$\frac{dN}{d\cos\theta^* d\beta} \propto 1 + A\cos^2\theta^* + B\sin^2\theta^*\cos 2\beta + C\sin 2\theta^*\cos\beta$$

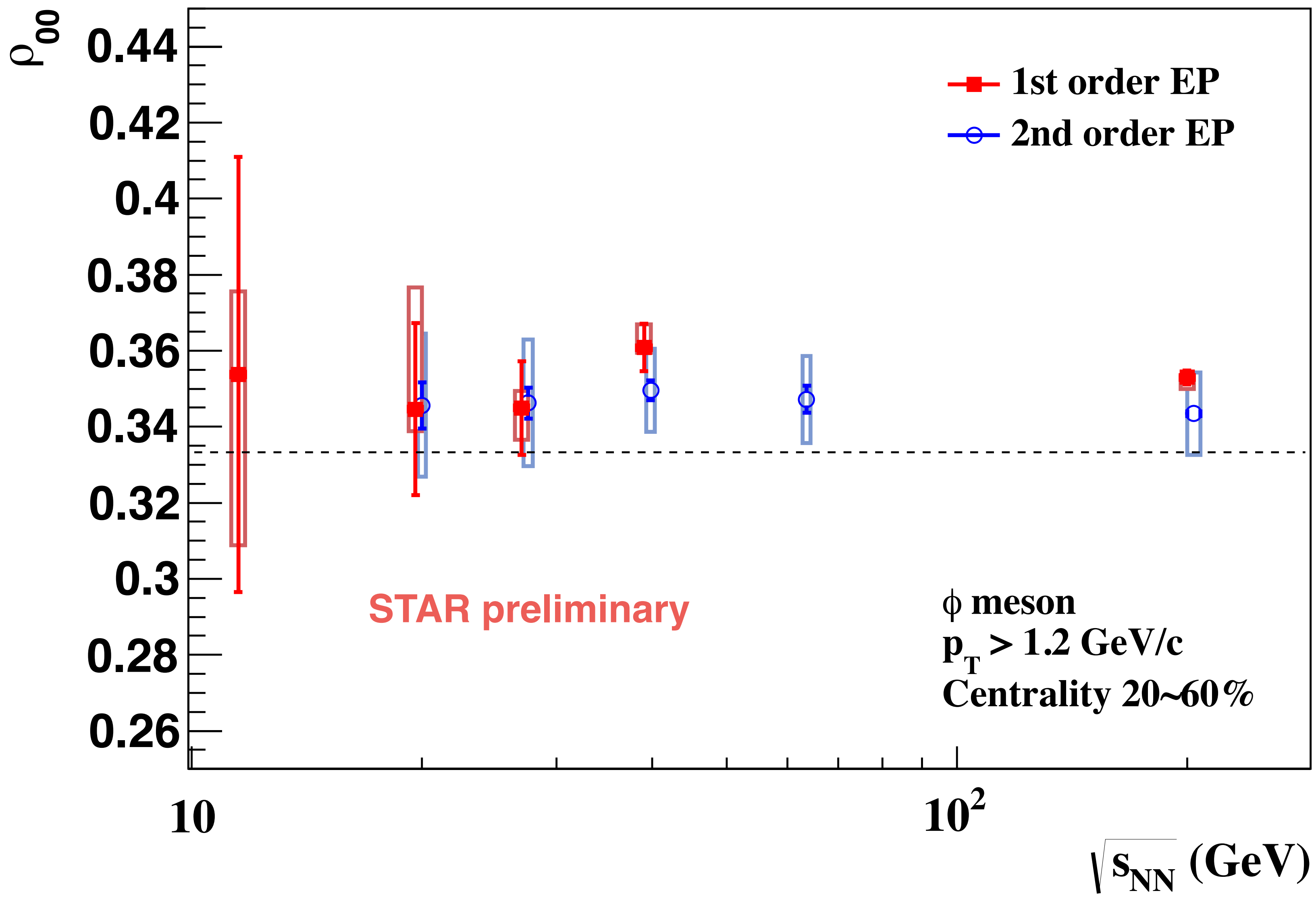
ρ_{00} vs. centrality



- ρ_{00} are around 1/3 at most central collisions.

- For non-central collisions, ρ_{00} are significantly higher than 1/3, supporting the fragmentation scenario?

ρ_{00} vs. energy



- ρ_{00} are significantly higher than 1/3 at 39 and 200 GeV.

Summary

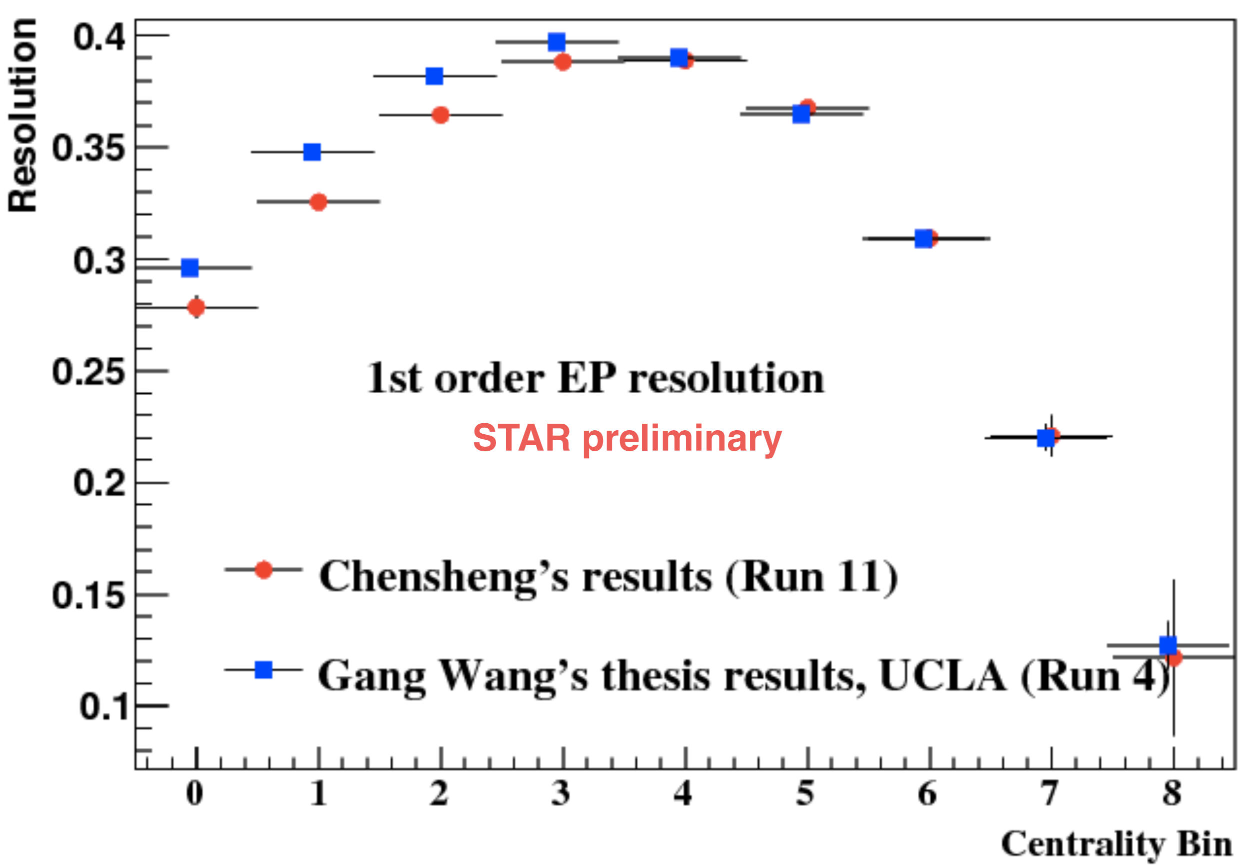
- Non-trivial dependence of ρ_{00} as a function of p_T and centrality has been observed with 1st-order event plane. At 200 GeV the measured ρ_{00} is > 1/3 at p_T ~ 1.5 GeV/c in non-central collisions.

- For ρ_{00} integrated from p_T > 1.2 GeV/c, the deviation from 1/3 is found to be significant at 39 and 200 GeV.

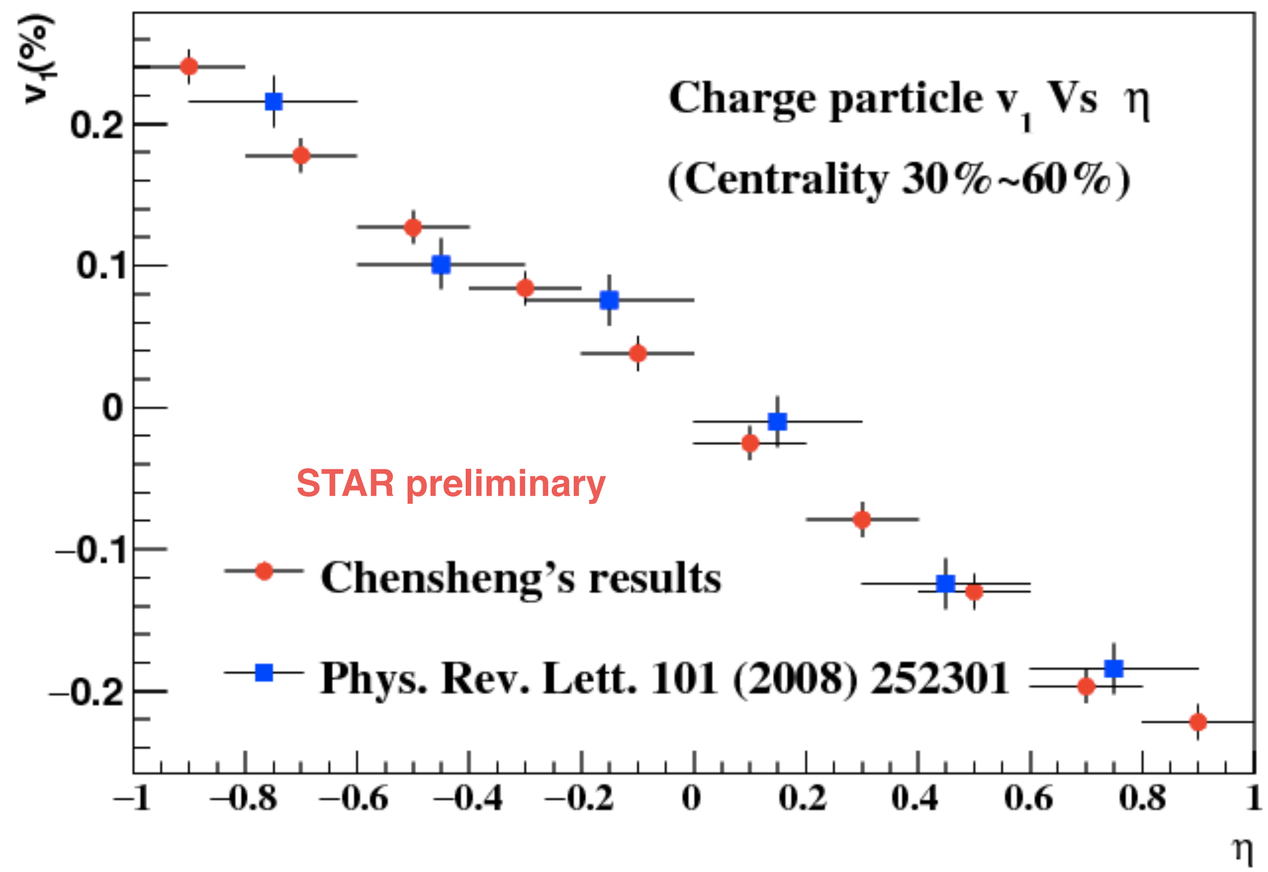
- This is the first time ρ_{00} > 1/3 being observed in heavy ion collisions. Vorticity induced by initial global angular moments and particle production from quark fragmentation are possible sources that might contribute to the new observation.

Backups

Comparing charged particle v1



1st order event plane resolution
Gang's thesis results : Run 4, Au-Au 200GeV
Our analysis: Run 11, Au-Au 200GeV



Charged particle v1 vs Eta

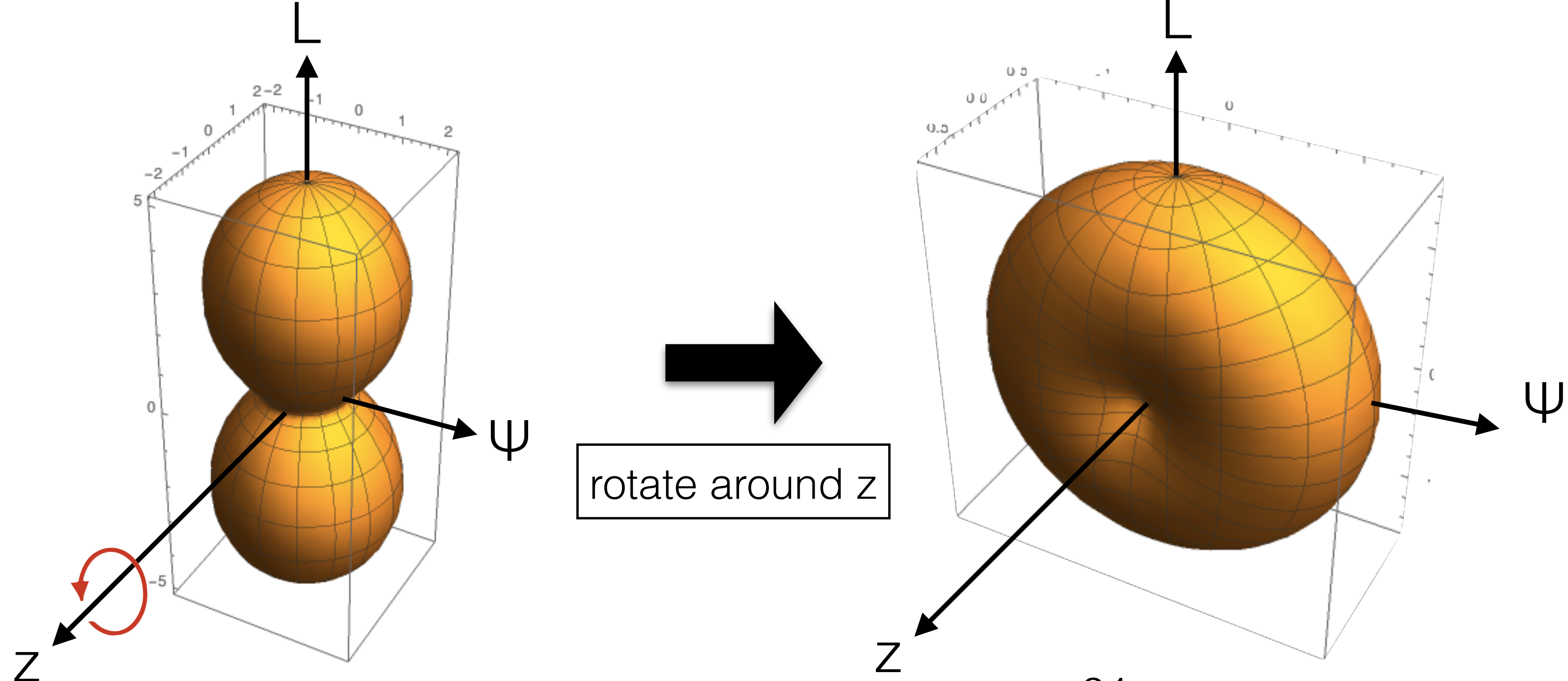
What to expect when using random event plane

- Recall the formula for resolution correction:

$$\rho_{00}^{real} - \frac{1}{3} = \frac{4}{1+3R}(\rho_{00}^{obv} - \frac{1}{3})$$

- For random event plane, ***L*** is random in the transverse plane, and R=0. Only when the real ρ_{00} is 1/3, the observed ρ_{00} from random event plane will become 1/3. Putting it in simple words, an irregular shape won't become a ball when rotated around a fixed axis (z in this case). So the observed random plane result will be closer to ρ_{00} =1/3, but hardly to be right at 1/3. With the resolution correction formula (R=0), we can still obtain the real ρ_{00}.

- Only when ***L*** can take any direction in space (not confined to the transverse plane), it becomes truly random (3d-random) and the ρ_{00} becomes 1/3.



Rotation around z axis will not necessarily make a round shape (strictly speaking, not make a flat distribution in cosθ*)

ρ_{00} vs. p_T (Au+Au 39GeV)