ϕ spin alignment in high energy nuclear collisions at RHIC

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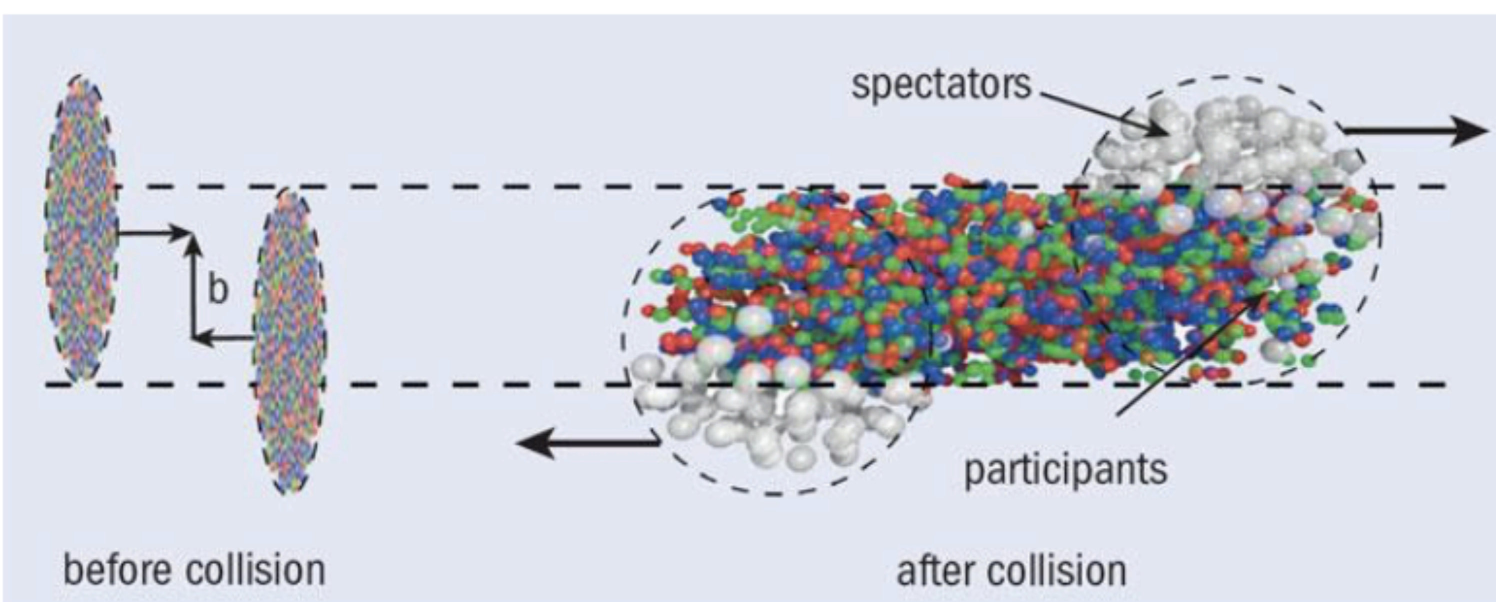
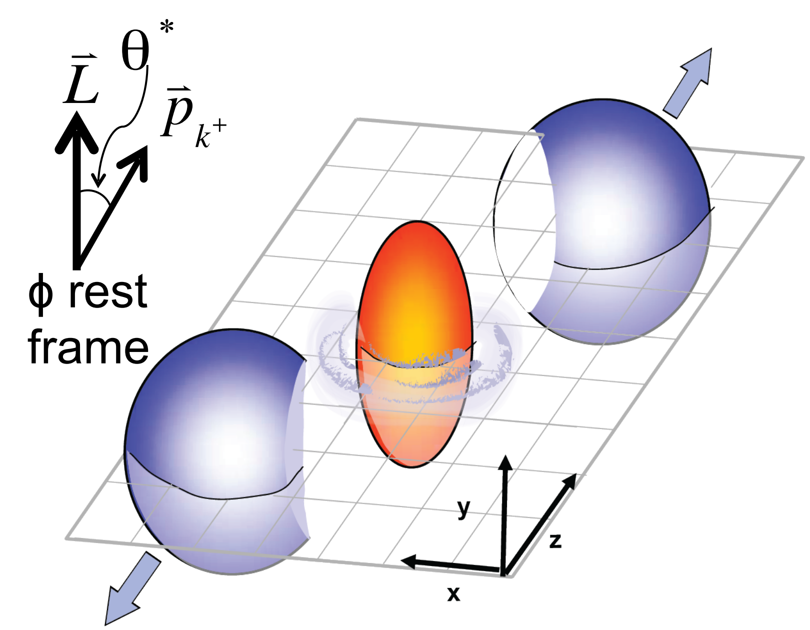
Particles and Nuclei International Conference 2017
Sept-2017, Beijing

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

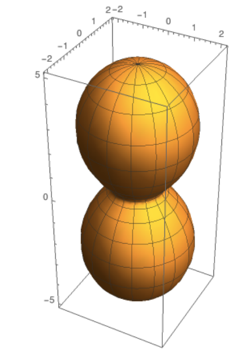
- Spin alignment can be determined from the angular distribution of the decay products*:

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

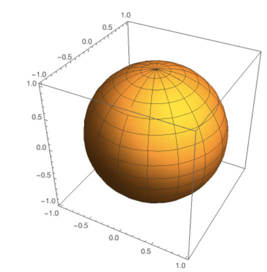
where N_0 is the normalization and θ^* is the angle between the polarization direction ***L*** and the momentum direction of a daughter particle in the rest frame of the parent vector meson.

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

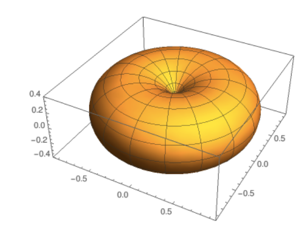
$\rho_{00}>1/3$:

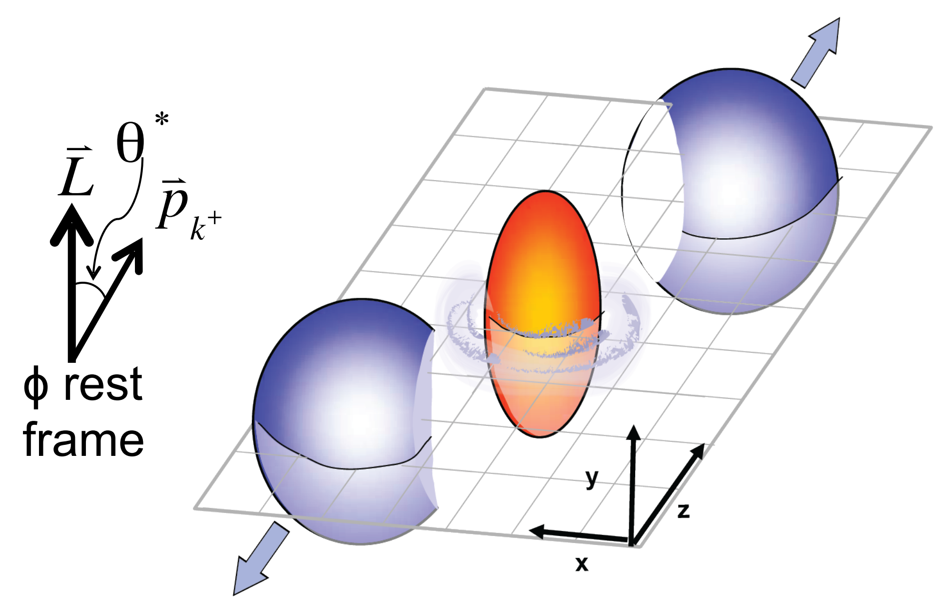


$\rho_{00}=1/3$:



$\rho_{00}<1/3$:





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

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

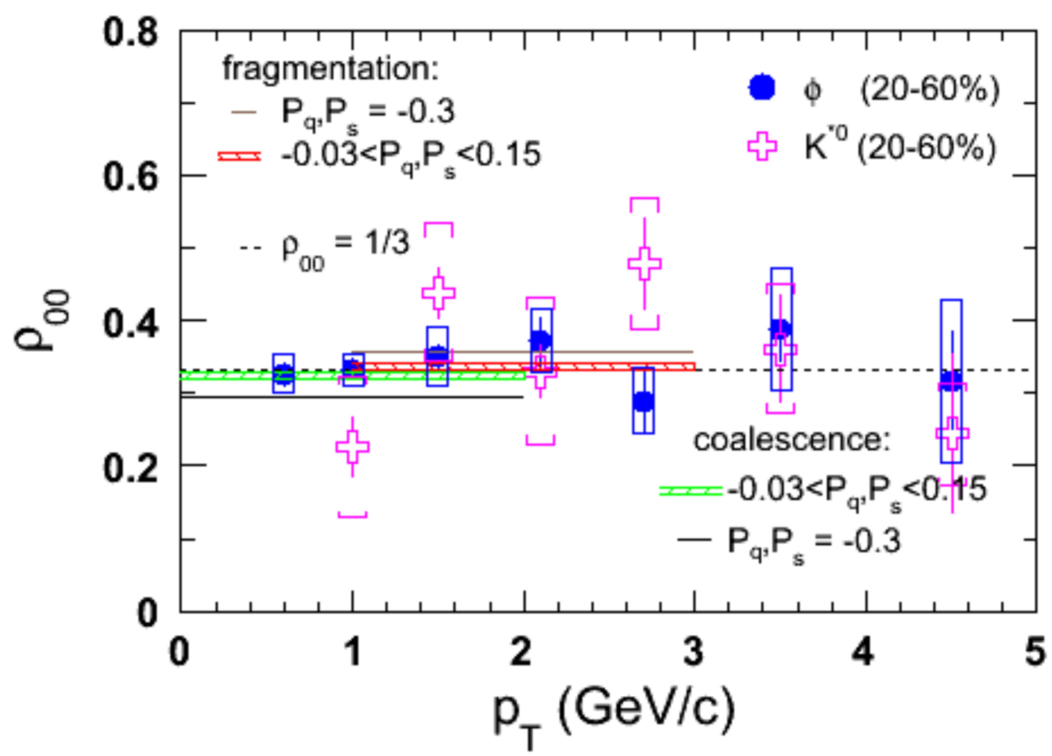
$P_{\bar{s}}^{frag} = -\beta P_s$ is the polarization of the anti-quark created in the fragmentation process

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

STAR

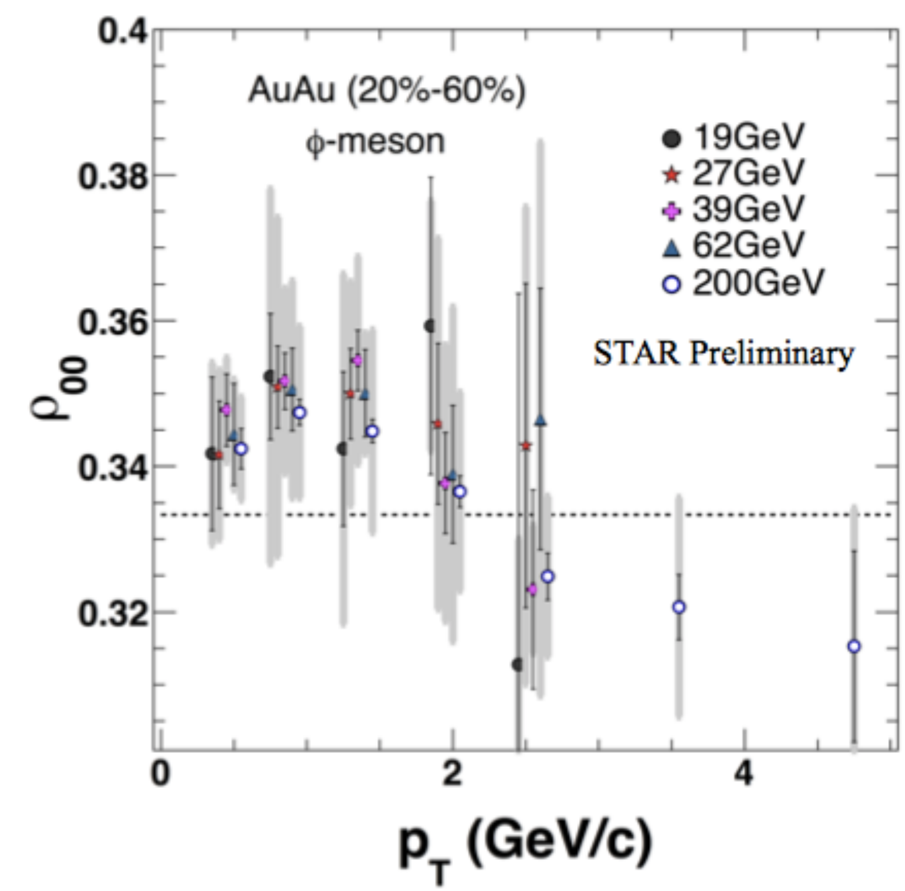
STAR's previous results

- STAR has published results with data taken in year 2004.
- Updated results have been shown at QM2017, 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.



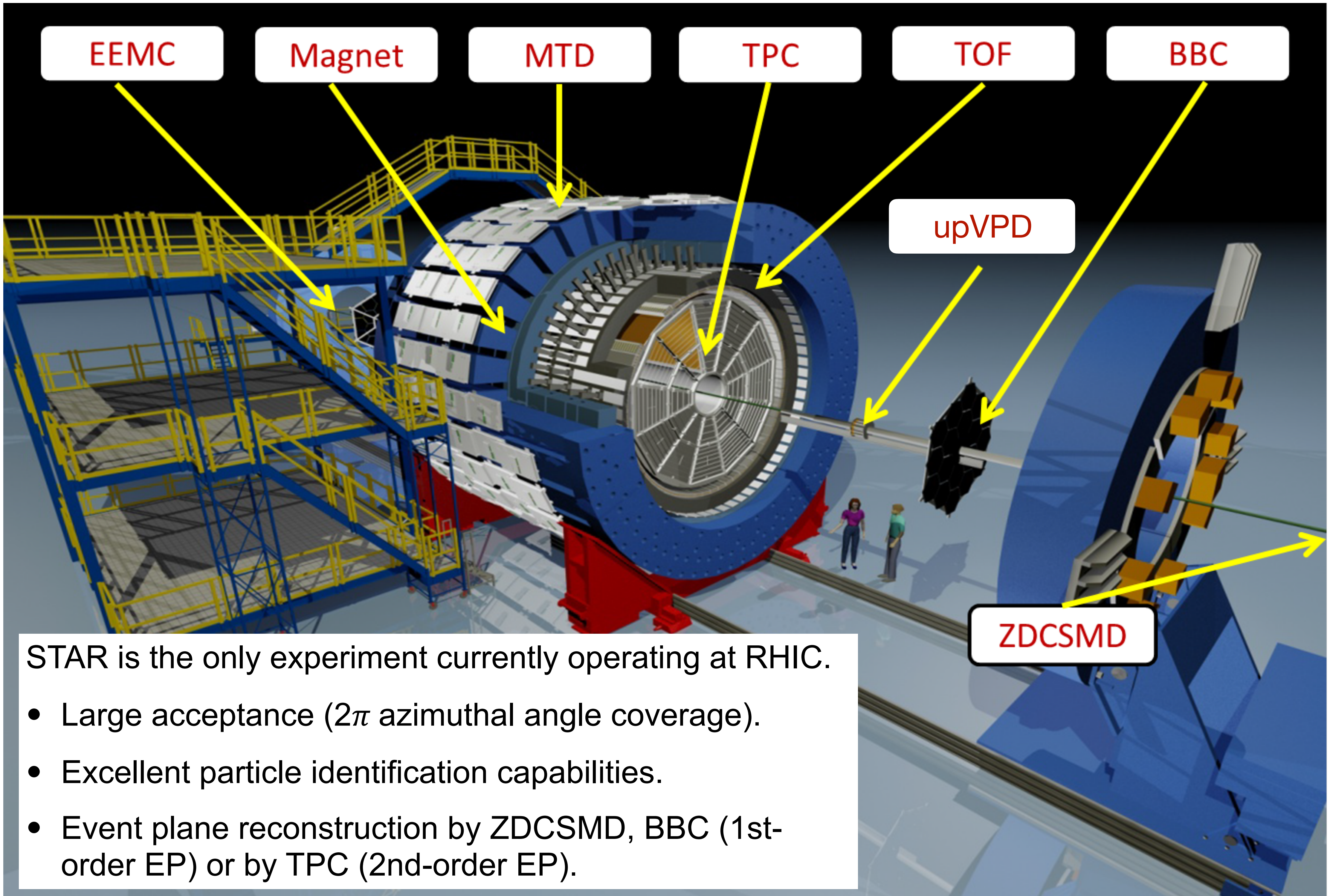
STAR's Published results

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



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).

STAR

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

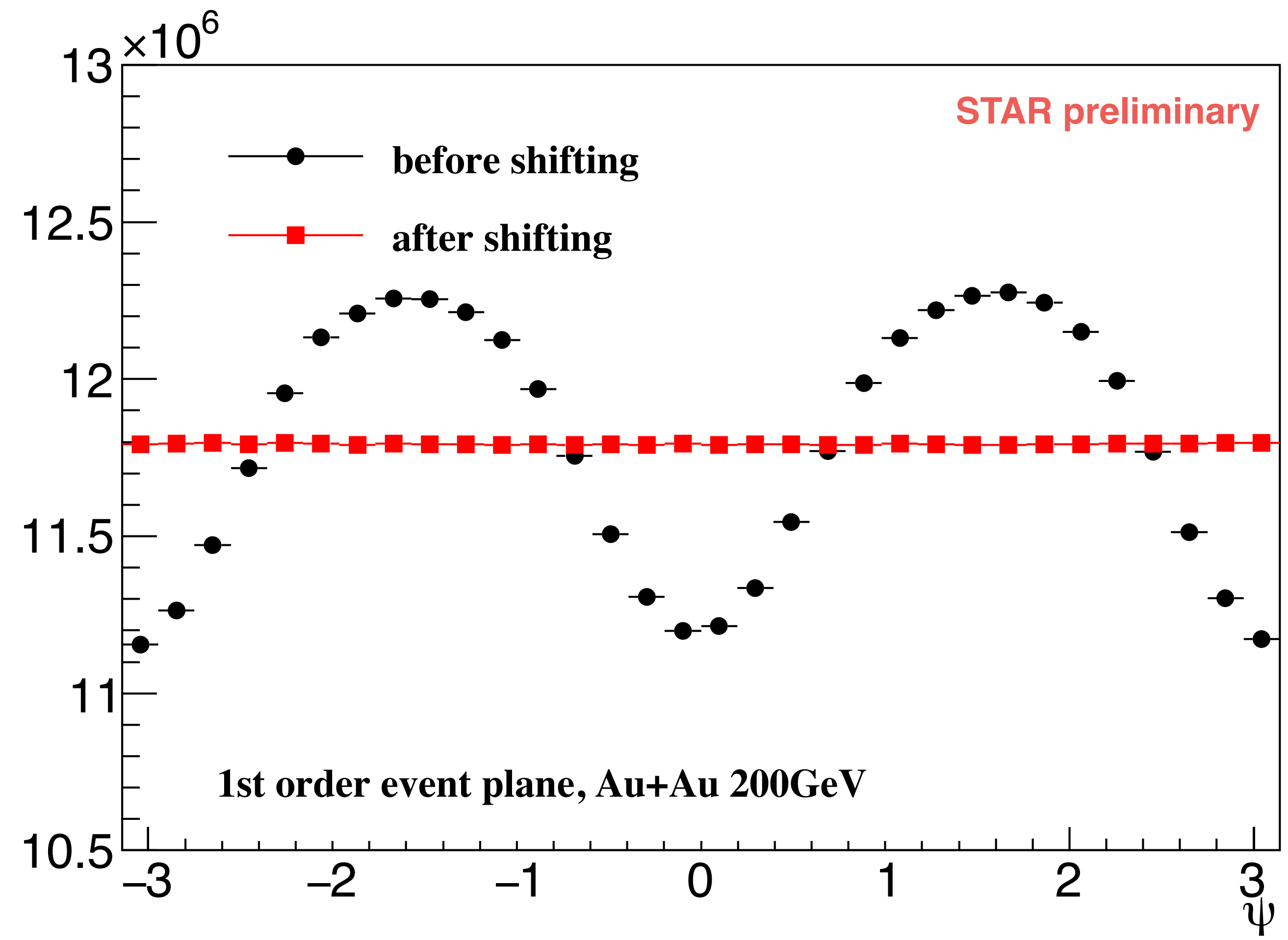
- **Track cuts:**
  nHitsFit > 15
  nHitsFit/nHitsMax > 0.52
  -1.0 < eta < 1.0
  dca < 2.0 cm
  p_T > 0.1 GeV/c
  p<10 GeV/c
  invariant mass < 1.1 GeV/c^2

- **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)

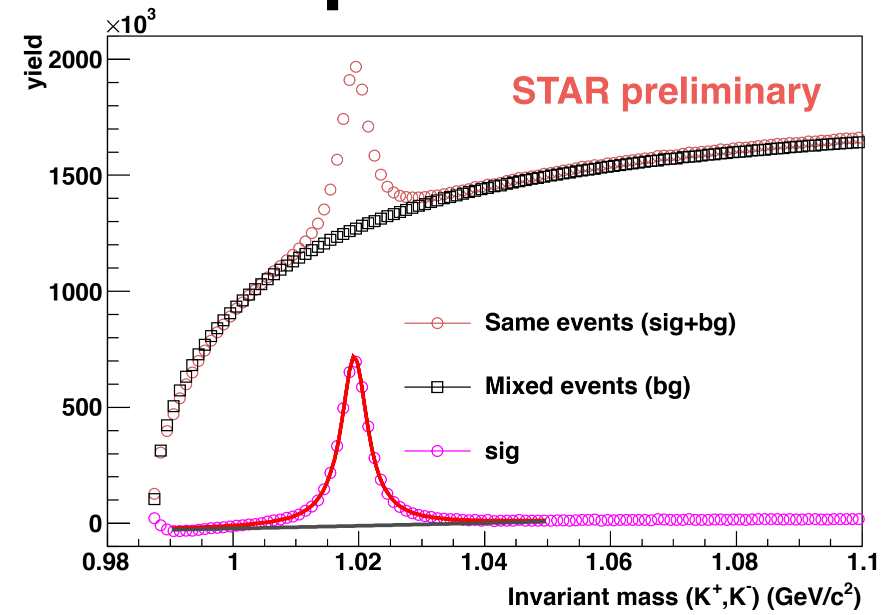
Obtaining yields of ϕ meson

- The background is obtained using event mixing technique.

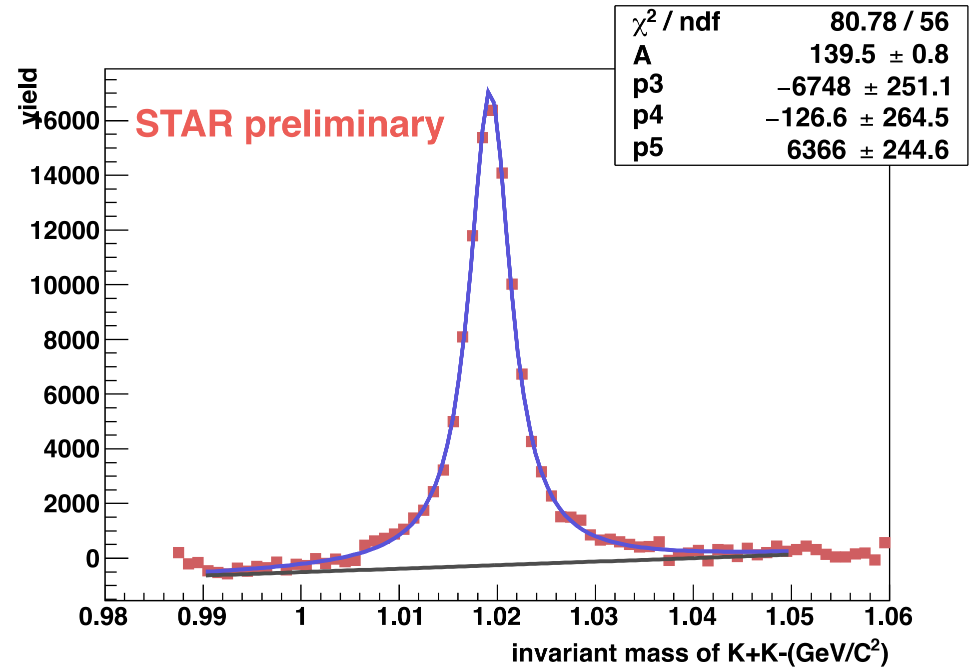
- The ϕ-mesons signal is fitted with Briet-Wigner function and the 2nd order polynomial function for residual background to extract raw ϕ meson yield:

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

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

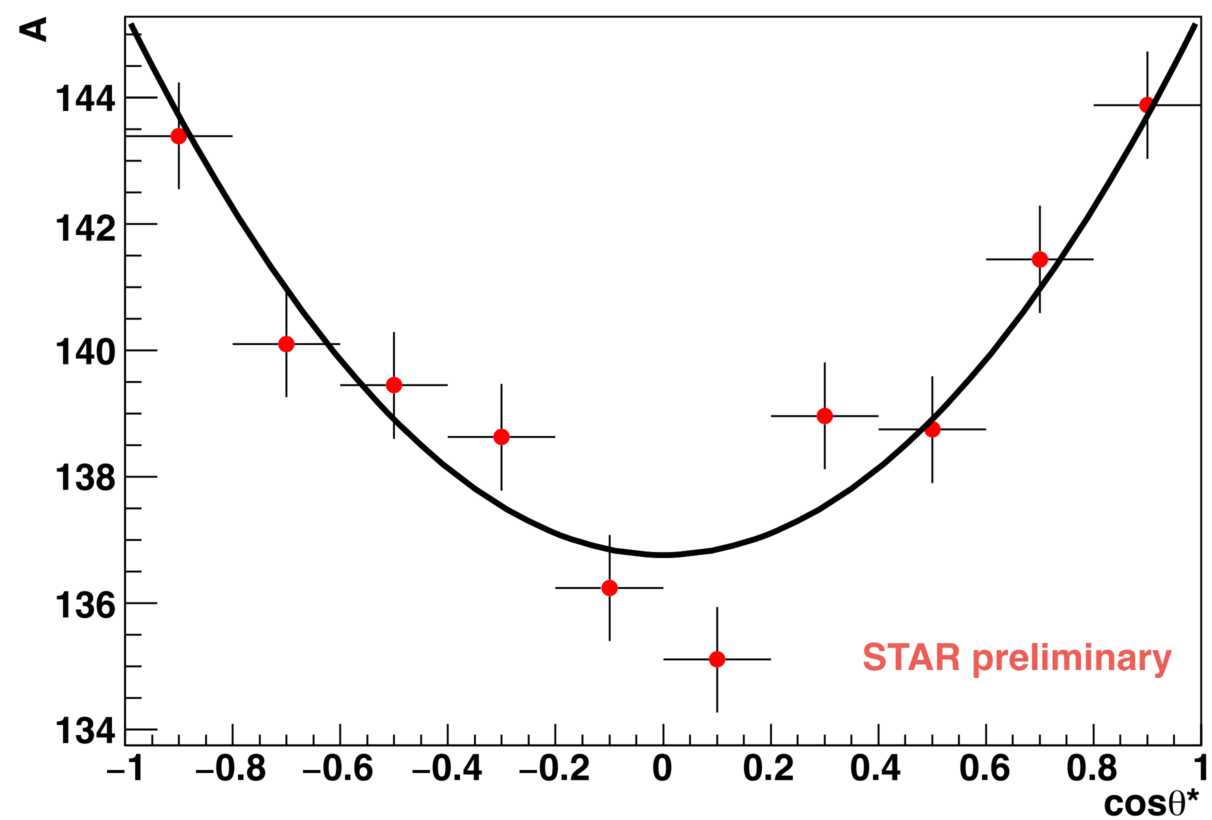
Extracting observed ρ_{00}

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

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

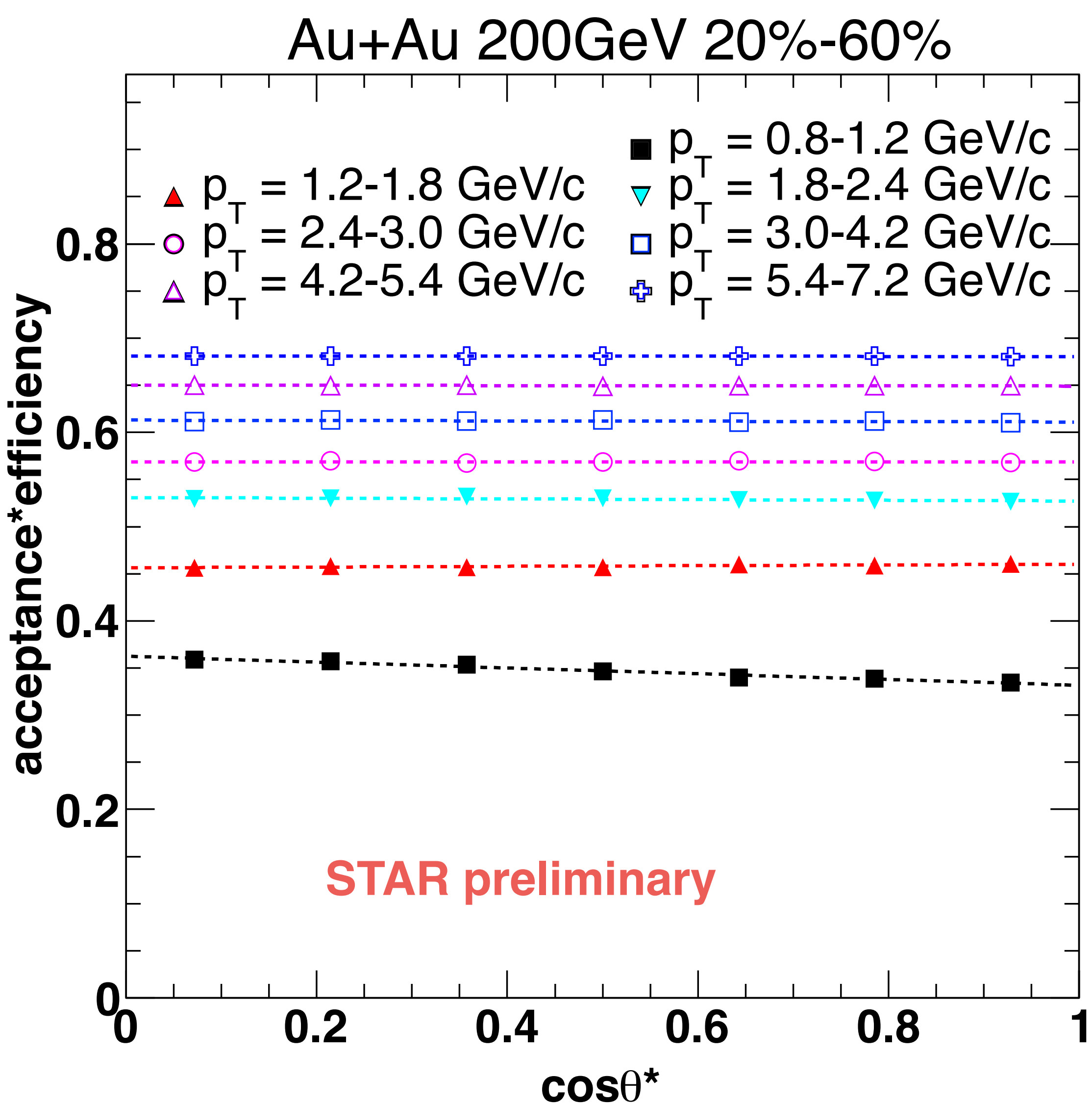
θ^* is the angle between the polarization direction ***L*** and the momentum direction of a daughter particle in the rest frame of the parent vector meson.

- 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.

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

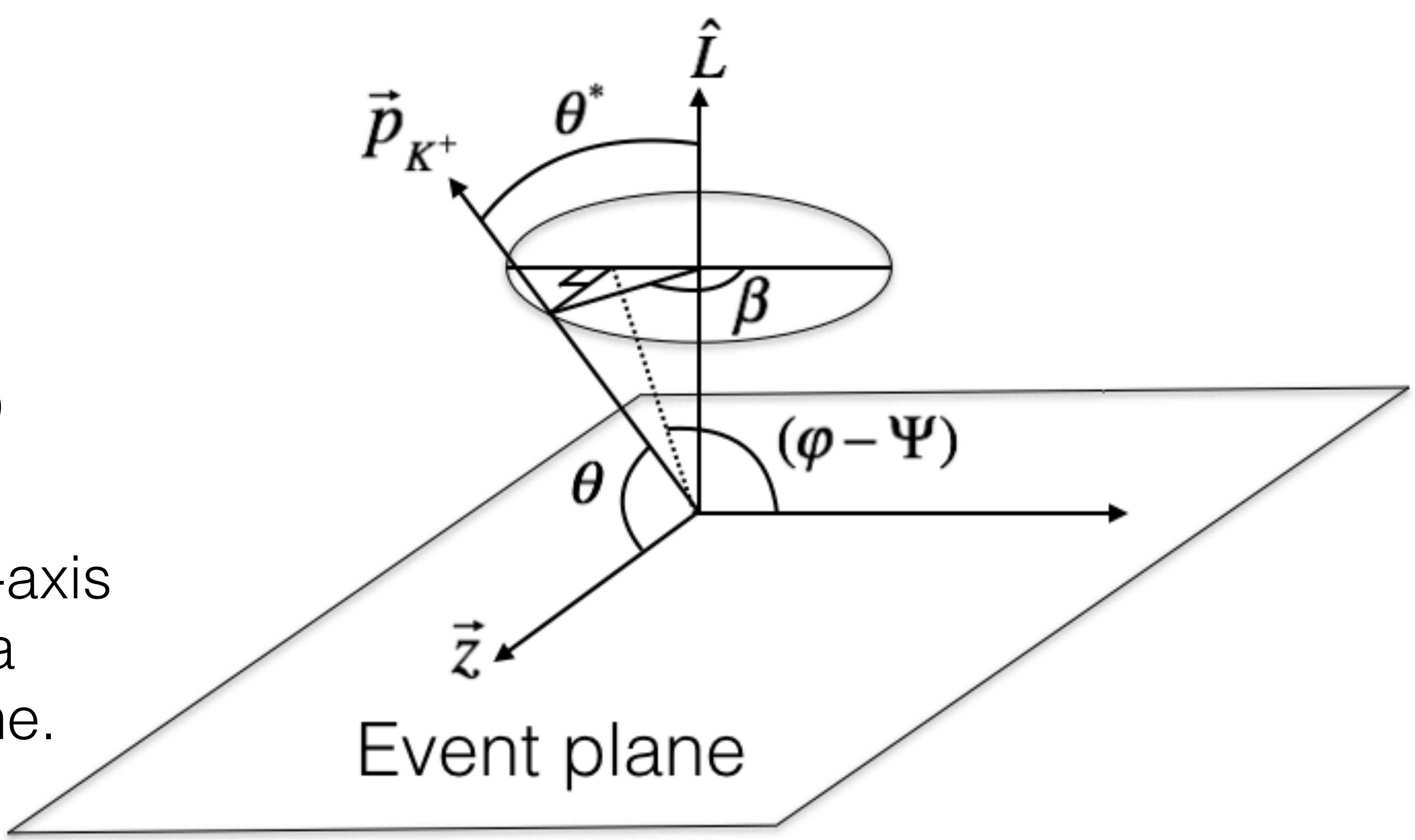
$$A = (3\rho_{00} - 1)/(1 - \rho_{00})$$

- 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.



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

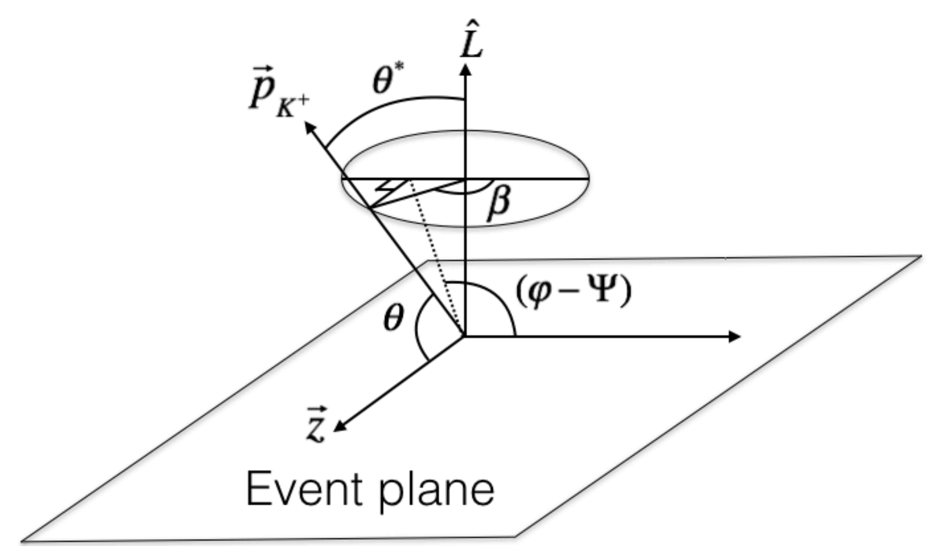
$$\begin{pmatrix} 1 \\ A \\ B \\ C \end{pmatrix} \to \begin{pmatrix} 1 \\ A' \\ B' \\ C' \end{pmatrix} = \begin{pmatrix} 1 \\ \dfrac{A(1+3R)+B(3-3R)}{4+A(1-R)+B(-1+R)} \\ \dfrac{A(1-R)+B(3+R)}{4+A(1-R)+B(-1+R)} \\ \dfrac{4 \cdot C \cdot R}{4+A(1-R)+B(-1+R)} \end{pmatrix}$$

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

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

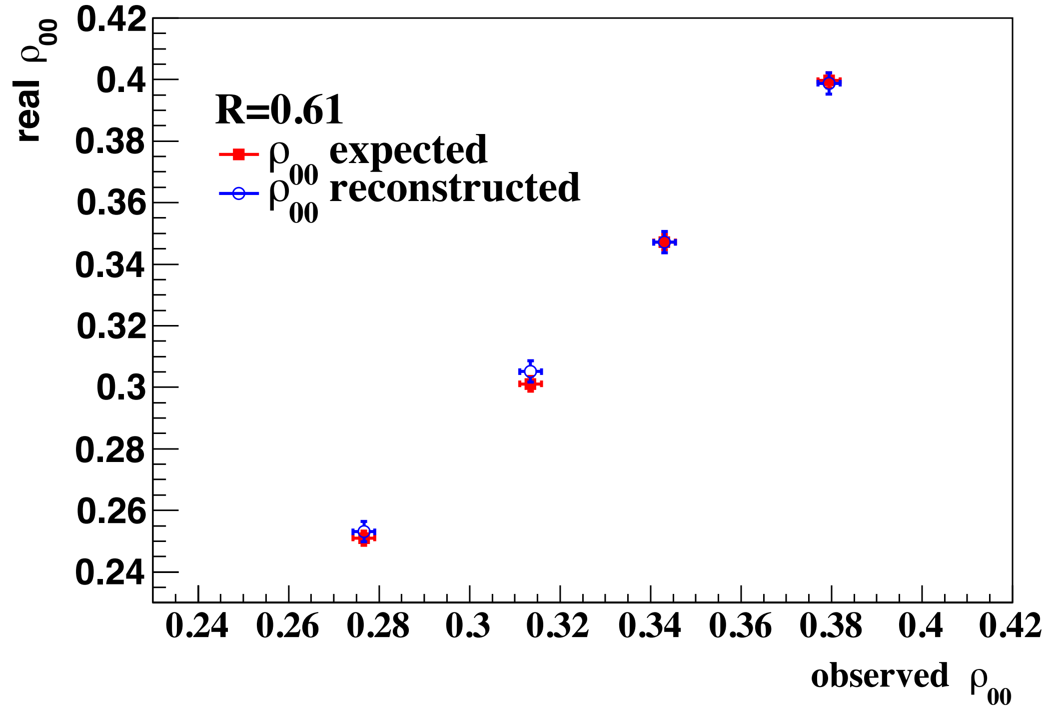


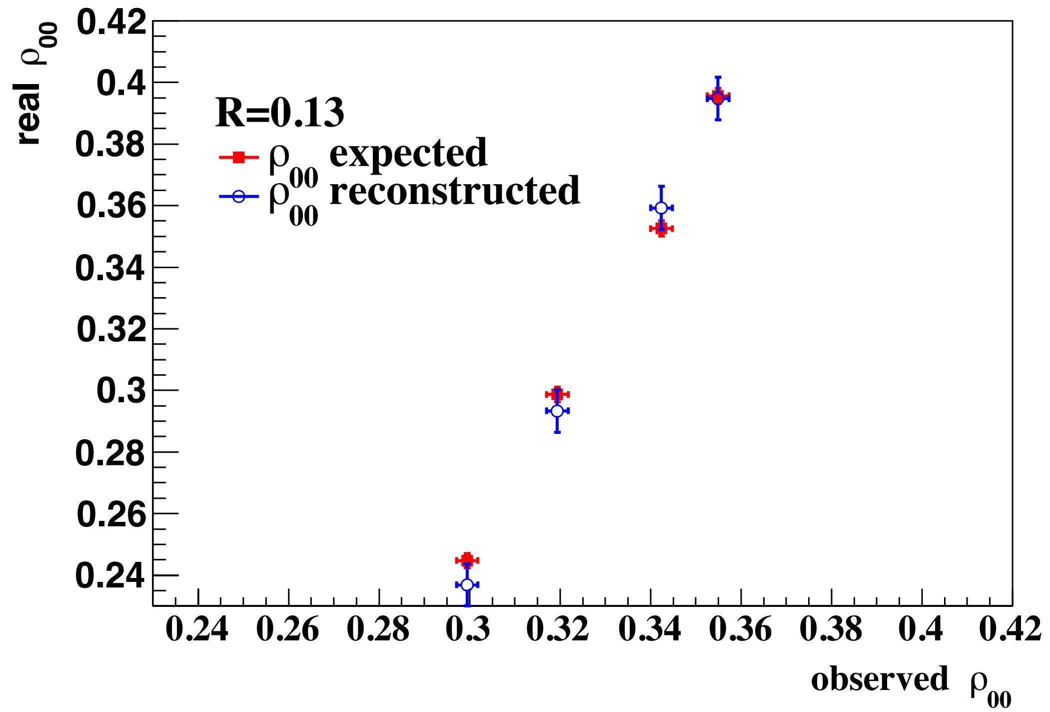
Verify the resolution correction formula with simulations

- To test the formula of resolution correction, we generate Monte Carlo events by Pythia with Δ following gaussian distributions.

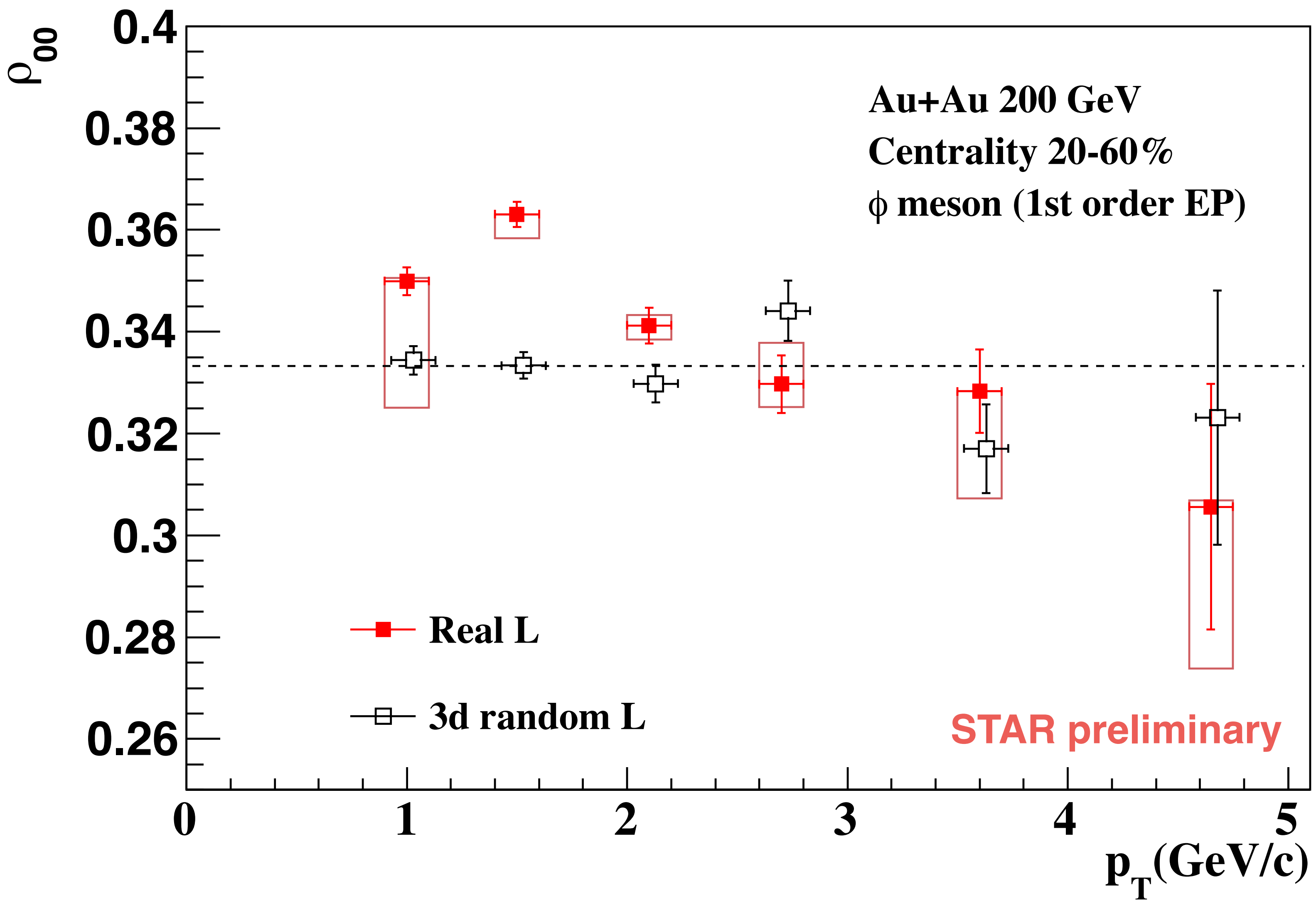
- ρ_{00}^{real} can be either obtained by fitting the yield with real event plane (without Δ), or by calculation with the correction formula we derived.

- The plots show the comparison of results between two methods. The correction works well even when the resolution is low.



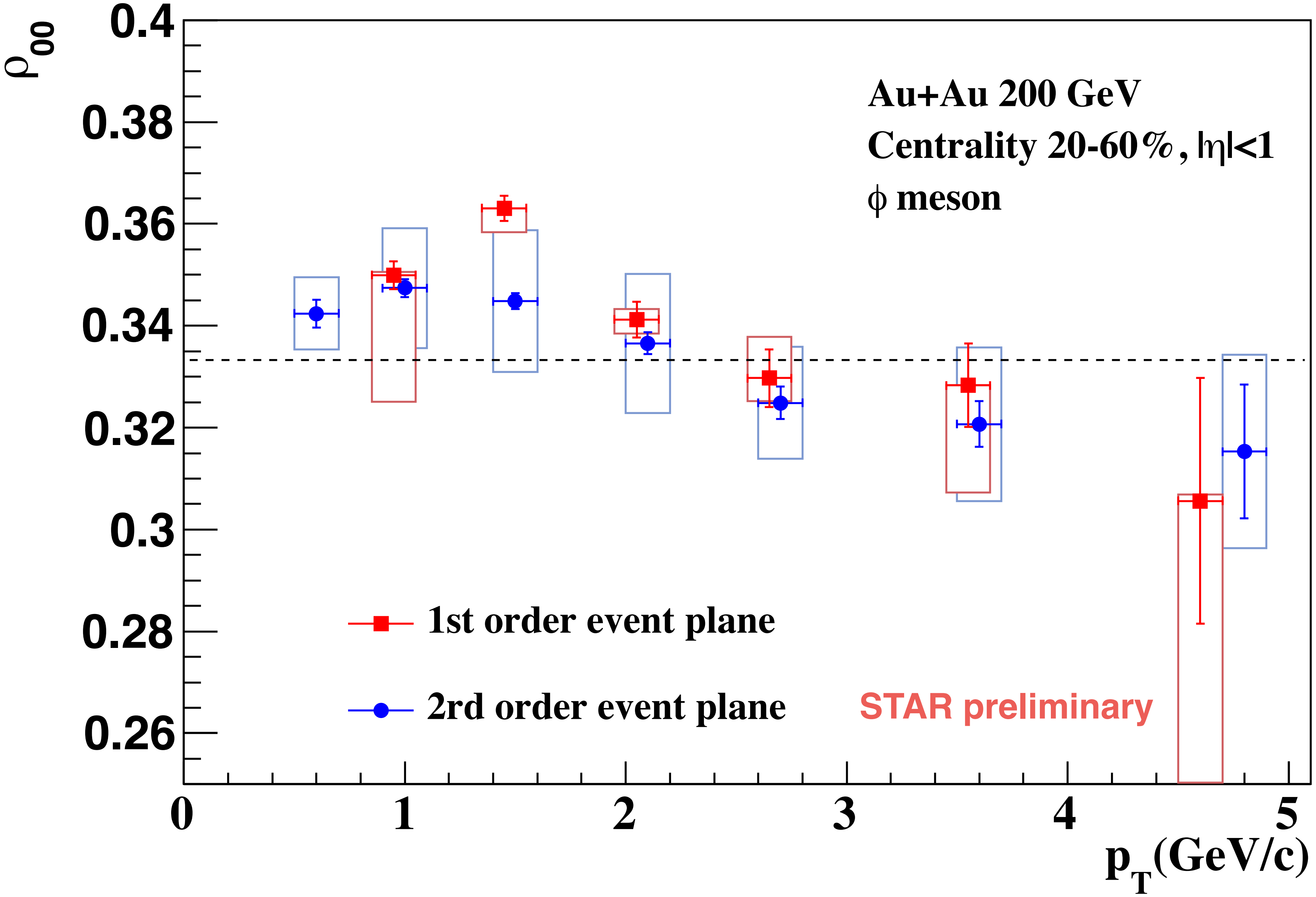


ρ_{00} vs. p_T



- 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:

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

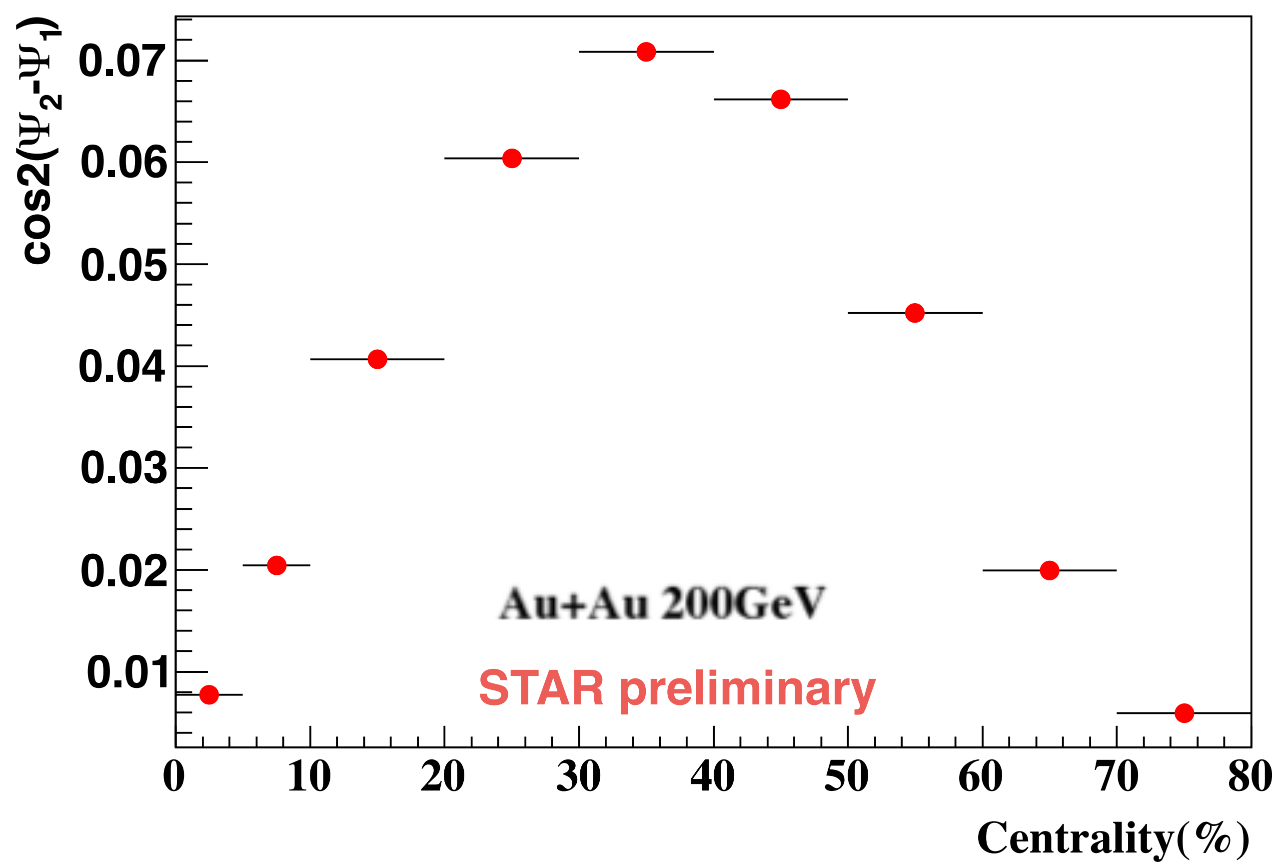
where $\mathrm{D}_{12} = \langle \cos 2(\Psi_2 - \Psi_1) \rangle$

- 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:

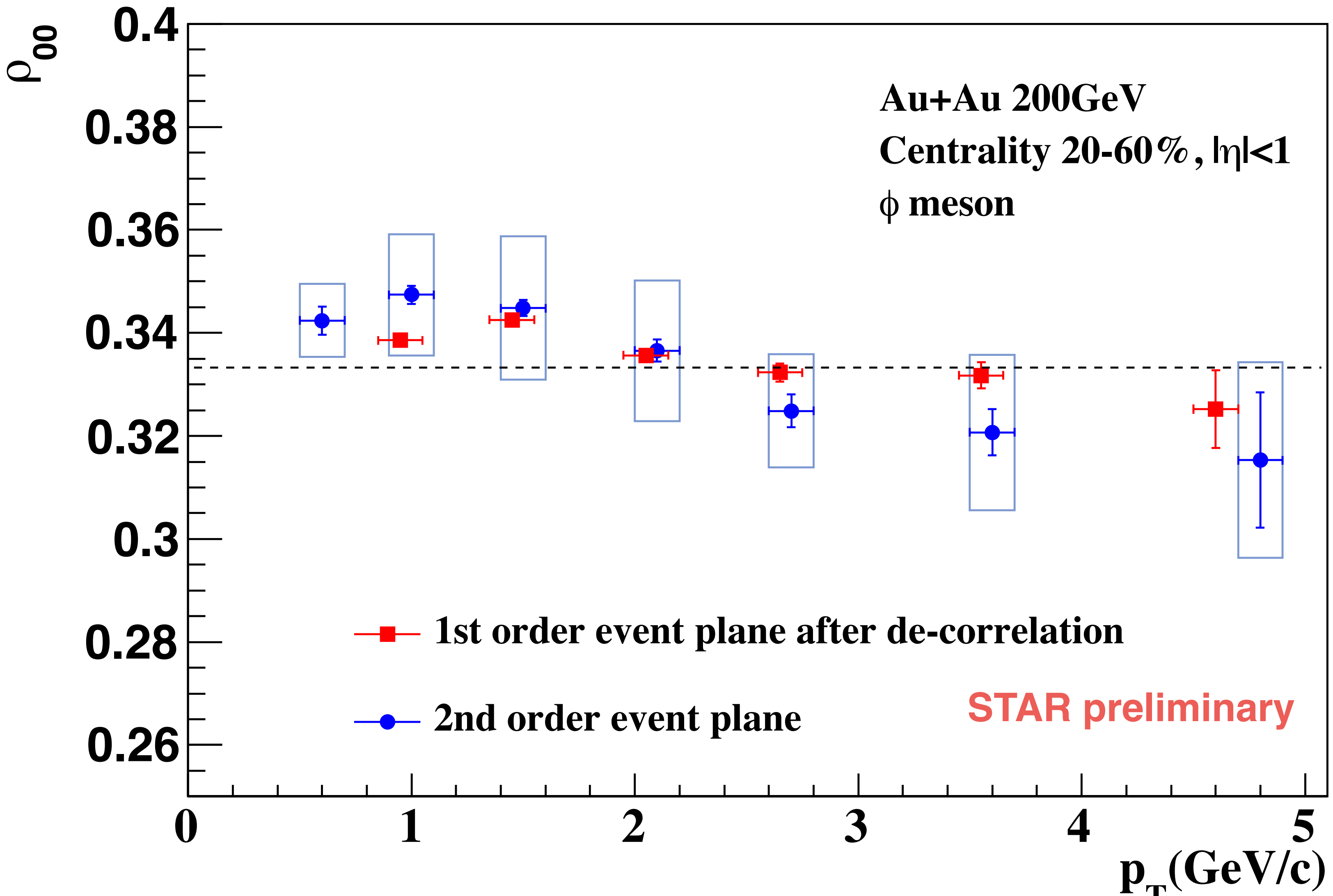
$$\rho_{\mathrm{obv}}^{\mathrm{2nd}} - \frac{1}{3} = \frac{1+3R_2}{4}(\rho_{00}^{\mathrm{2nd}} - \frac{1}{3})$$

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

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



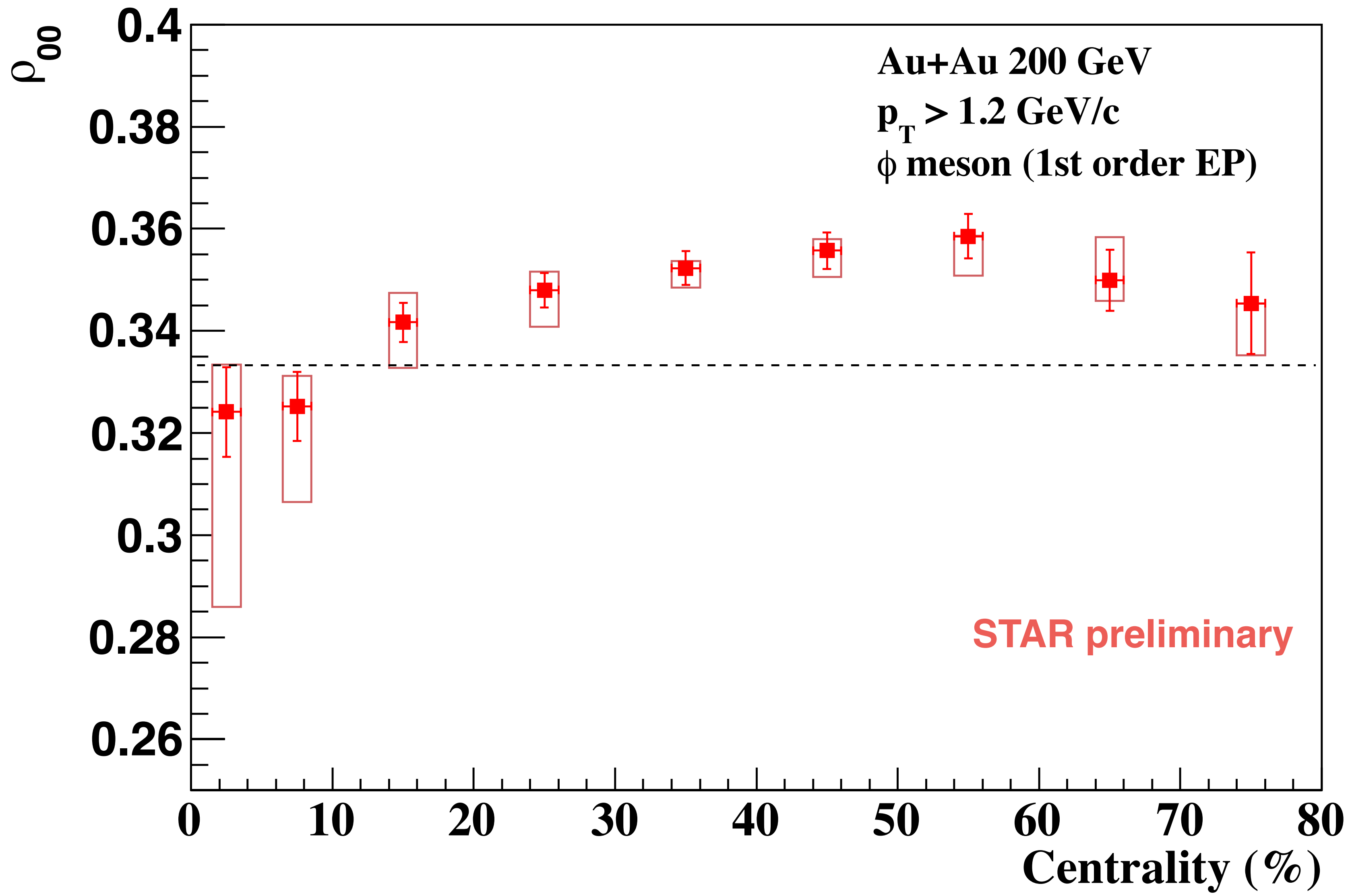
De-correlation results



- 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?):

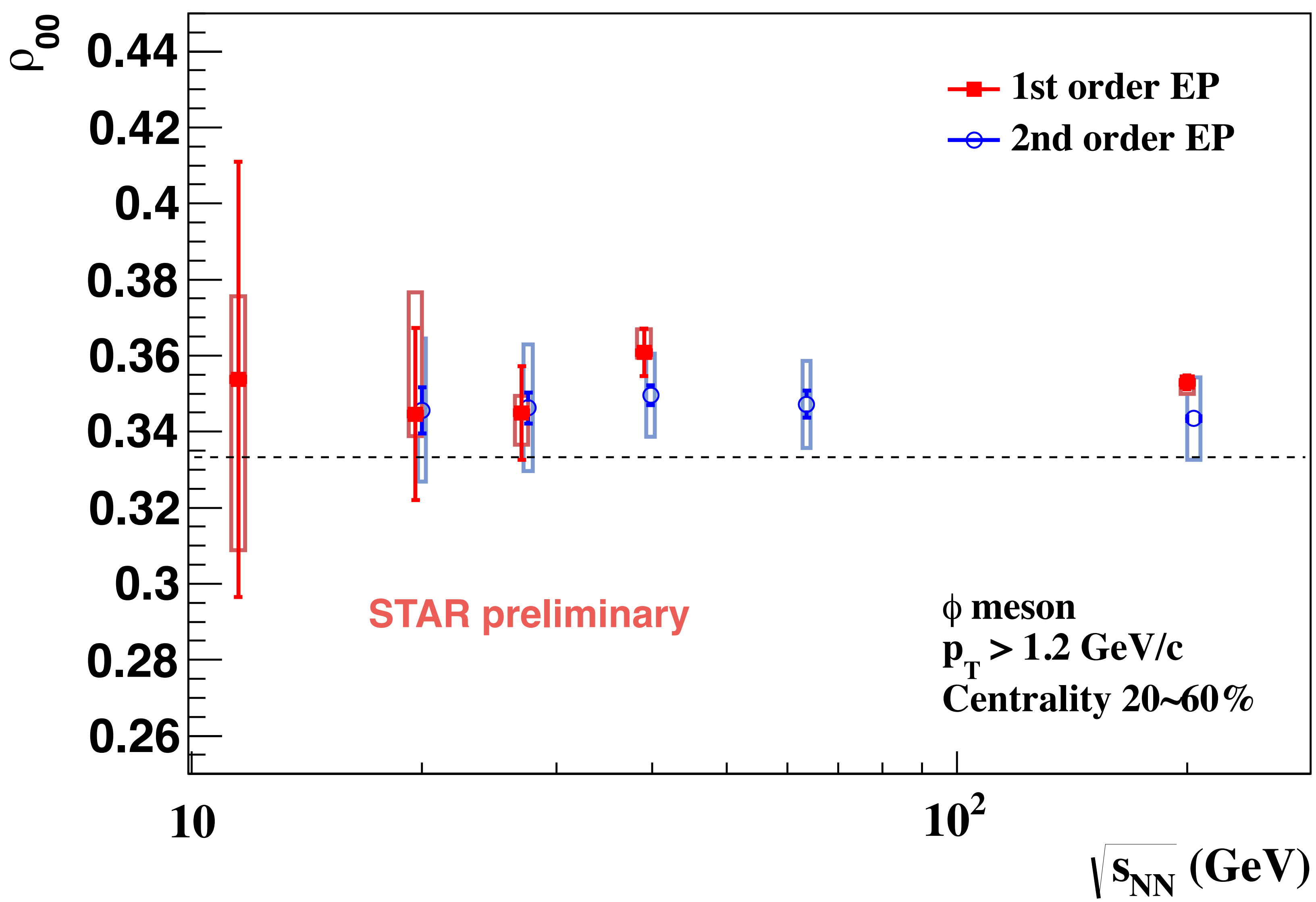
$$\frac{dN}{d\cos\theta^* d\beta} \propto 1 + A\cos^2\theta^* + B\sin^2\theta^* \cos 2\beta + C\sin 2\theta^* \cos\beta$$

ρ_{00} vs. centrality



- ρ_{00} are around 1/3 for both central and peripheral collisions.
- For non-central collisions, ρ_{00} are significantly higher than 1/3. (Fragmentation scenario?)

Energy dependence of the phi meson alignment



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

Summary

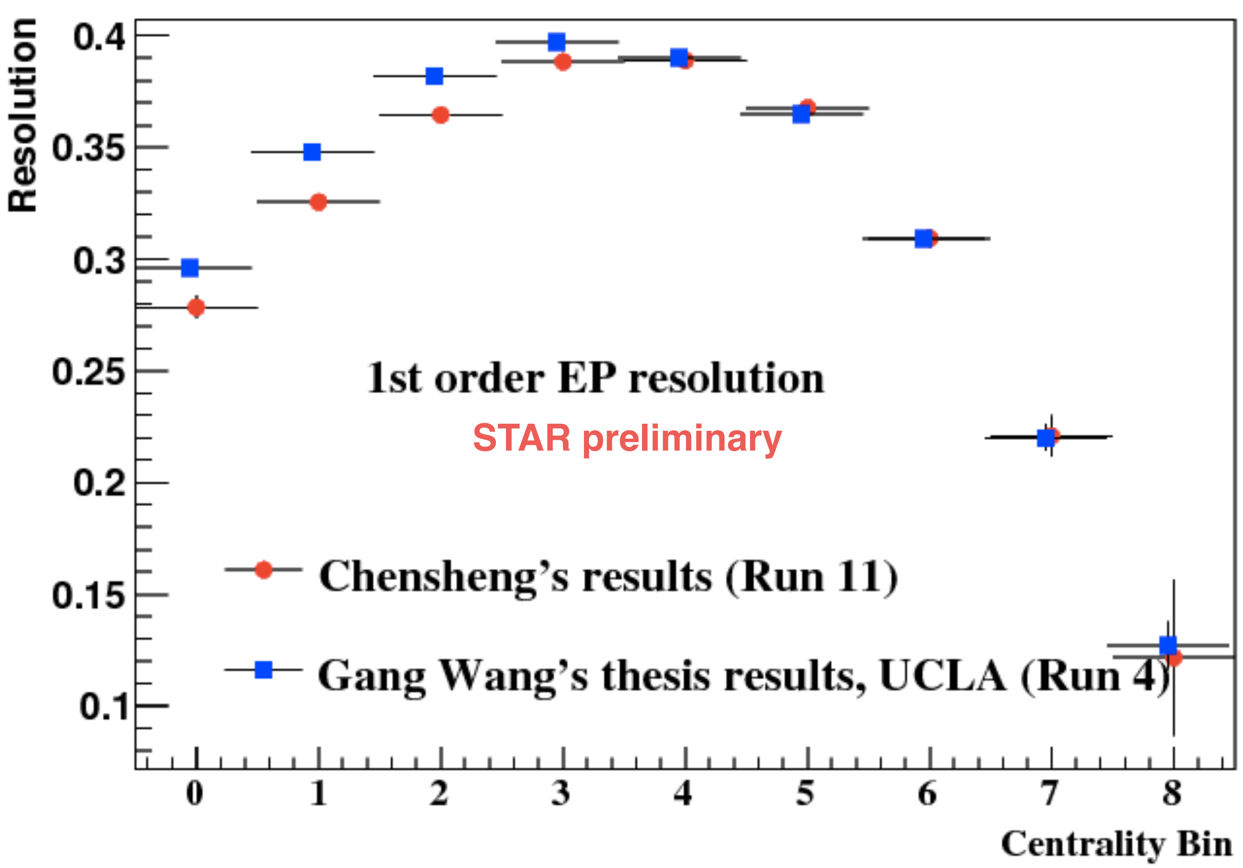
- Non-trivial dependence of ρ_{00} as a function of p_T and centrality has been observed with 1st-order event plane. At 200 GeV Au+Au collisions, the measured ρ_{00} is > 1/3 at p_T ~ 1.5 GeV/c in non-central collisions.

- 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.

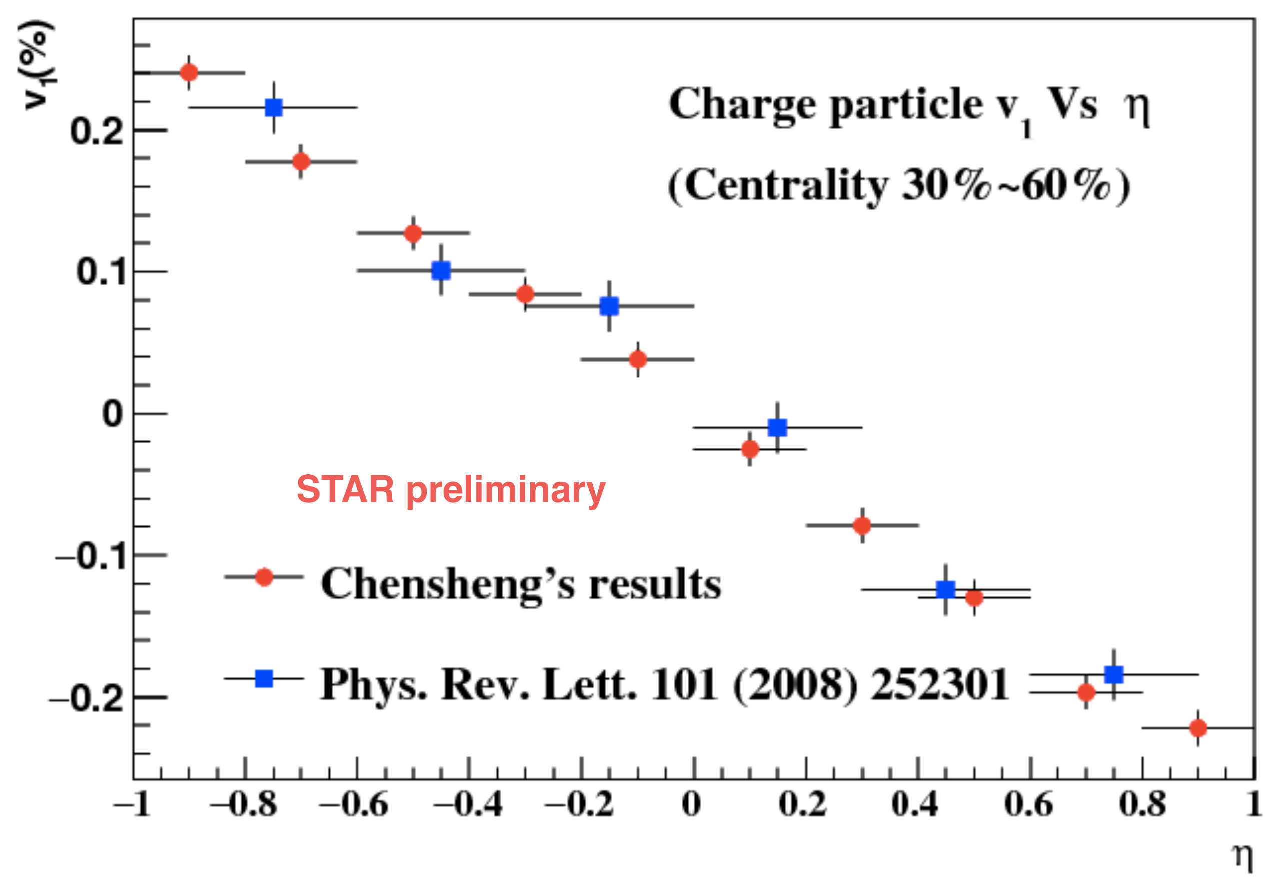
- This is the first time ρ_{00} > 1/3 being observed in heavy ion collisions. Vorticity induced by initial global angular moments, together with particle production from polarized quark fragmentation is a possible source that might contribute to the new observation.

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

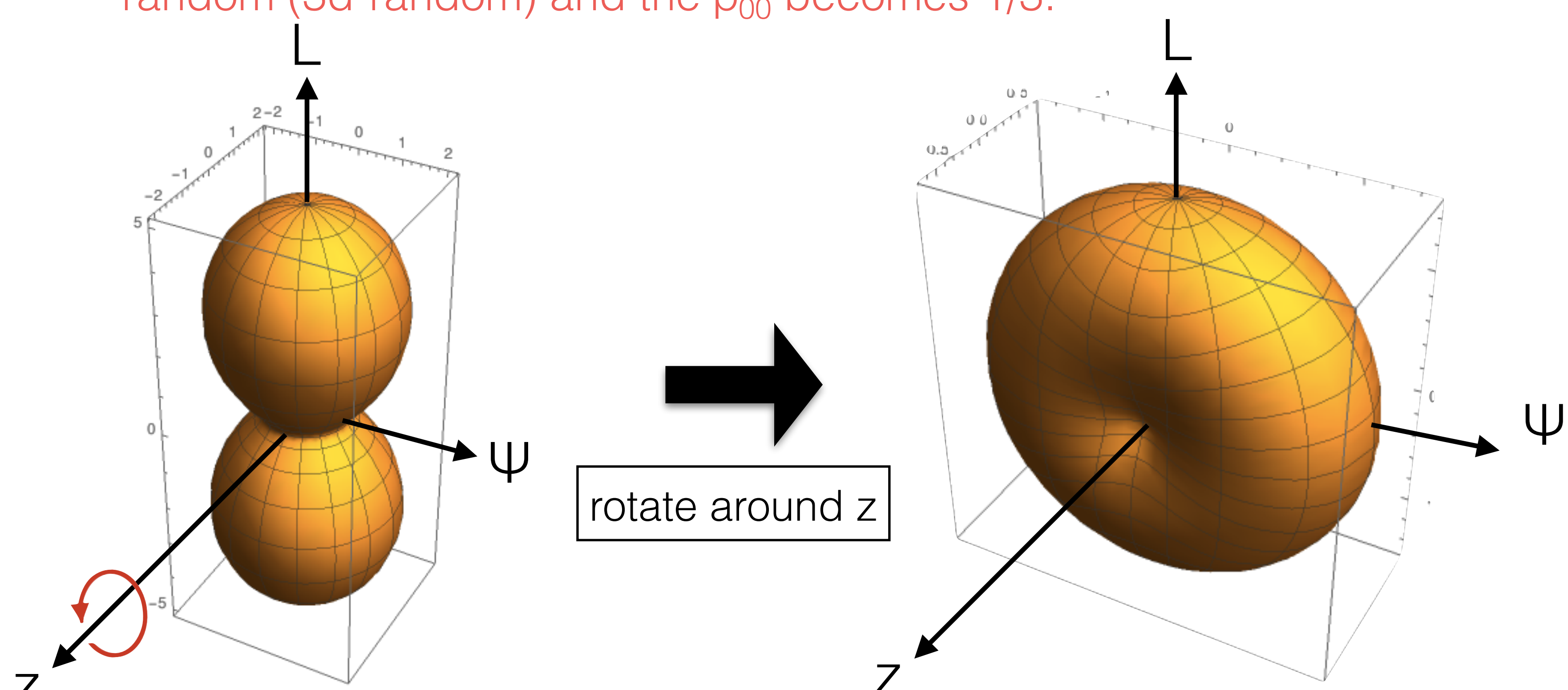
What to expect when using random event plane

- 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)