QuarkMatter 2023

New Insights into Global Spin Alignment in Heavy-Ion Collisions: Measurements of ϕ, J/Ψ and ρ^0 at STAR

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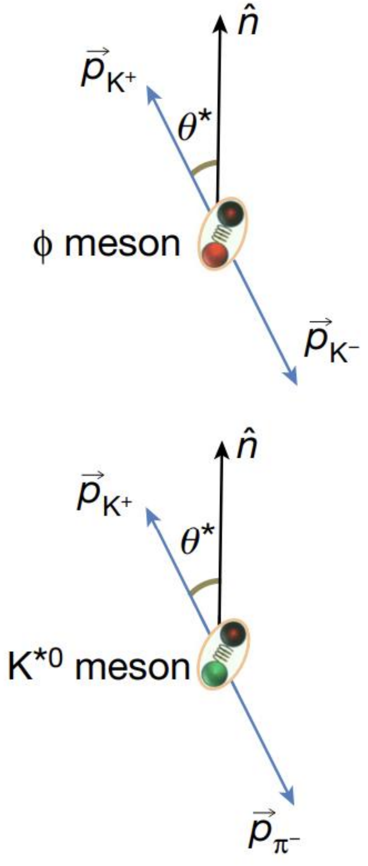
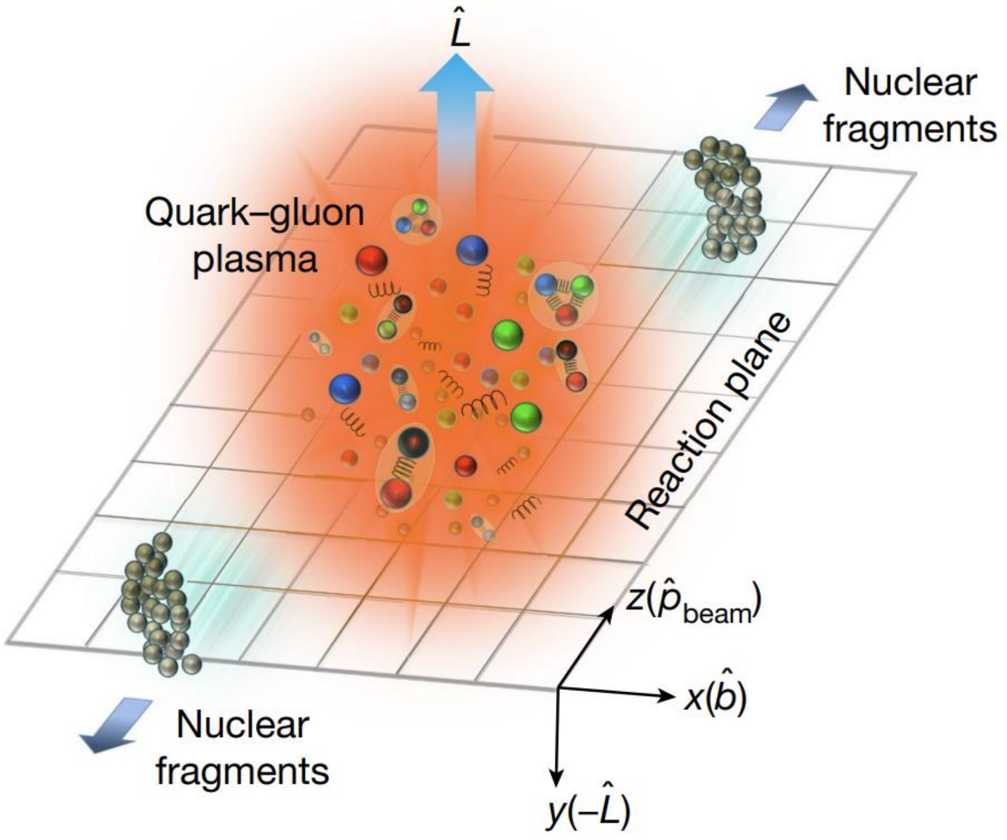
Outline

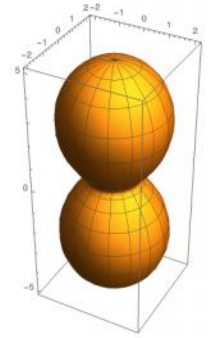
- Introduction & Motivation
- New measurement of ϕ mesons in BES-II
- New measurement of J/Ψ in isobar collisions at 200 GeV
- Summary

QGP matter under rotation

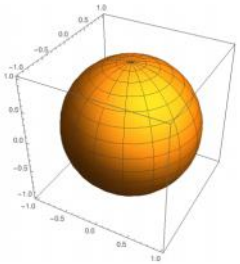




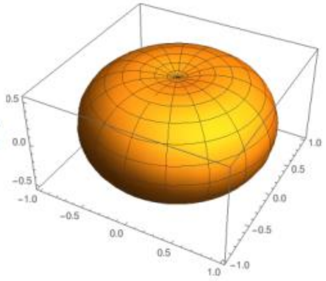
ρ00>1/3:



ρ00=1/3:



ρ00<1/3:

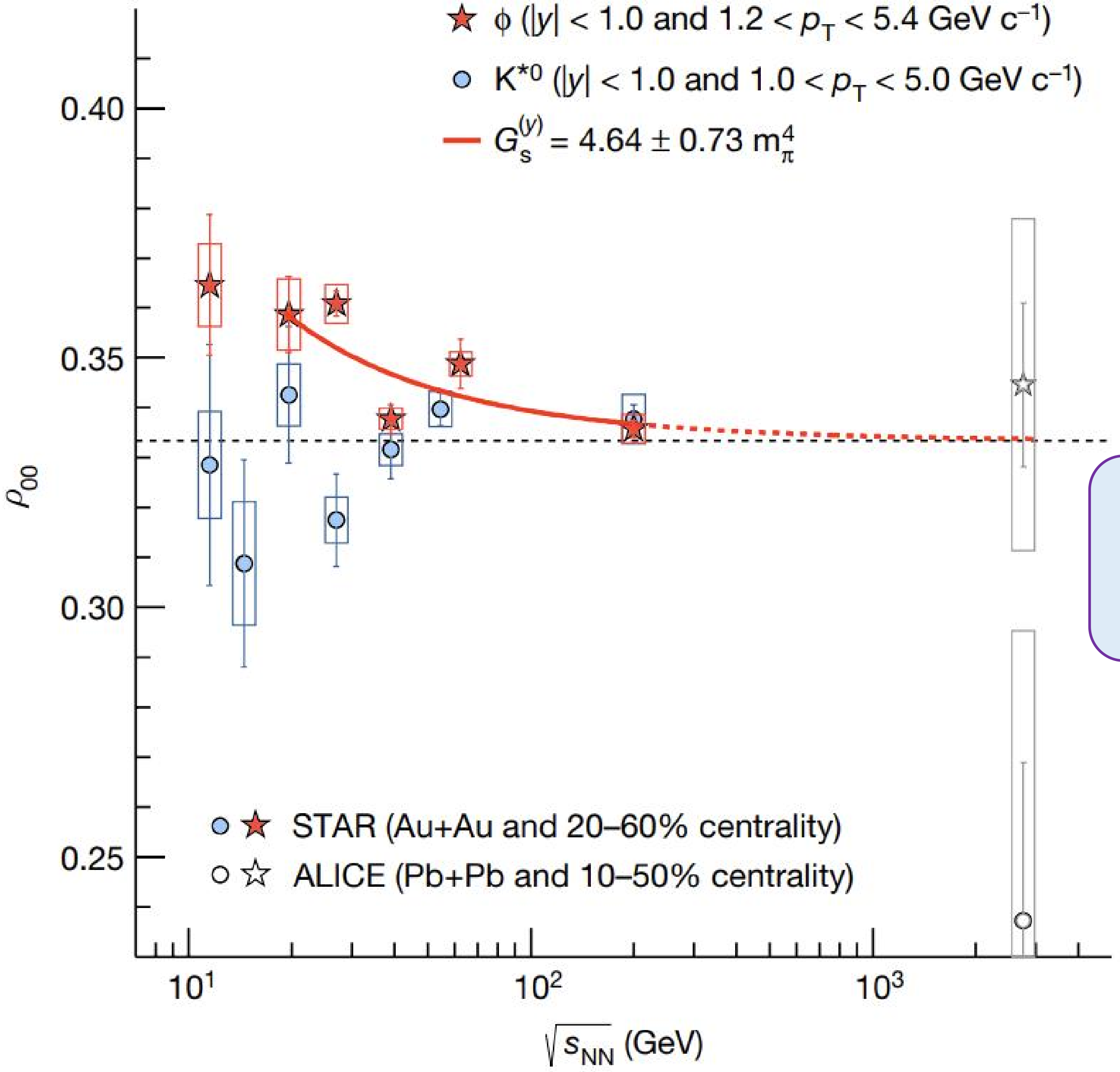


$$\frac{dN}{dcos\theta^*} = N_0 \times \left[\left(1-\rho_{00}^{obs}\right) + \left(\rho_{00}^{obs}-1\right)cos^2\theta^*\right]$$

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

STAR Collaboration, Nature 614 (2023) 7947.
Z. T. Liang and X. N. Wang, Phys. Lett. B 629, (2005) 20

STAR measurement of global spin alignment



STAR Collaboration, Nature 614 (2023) 7947.

ϕ meson ρ_{00} > 1/3.

↓

Global spin alignment.

↓

The large value of ρ_{00} at lower energies can be accommodated by a model which includes ϕ meson vector field coupling to s and $\bar{s}$ quark.

↓

Insights into the strong interaction.

In addition, data suggests nonmonotonic behavior with χ^2/ndf = 11.24/3. The p-value to curve ~ 1%.

Motivation for studying ϕ spin alignment in BES-II

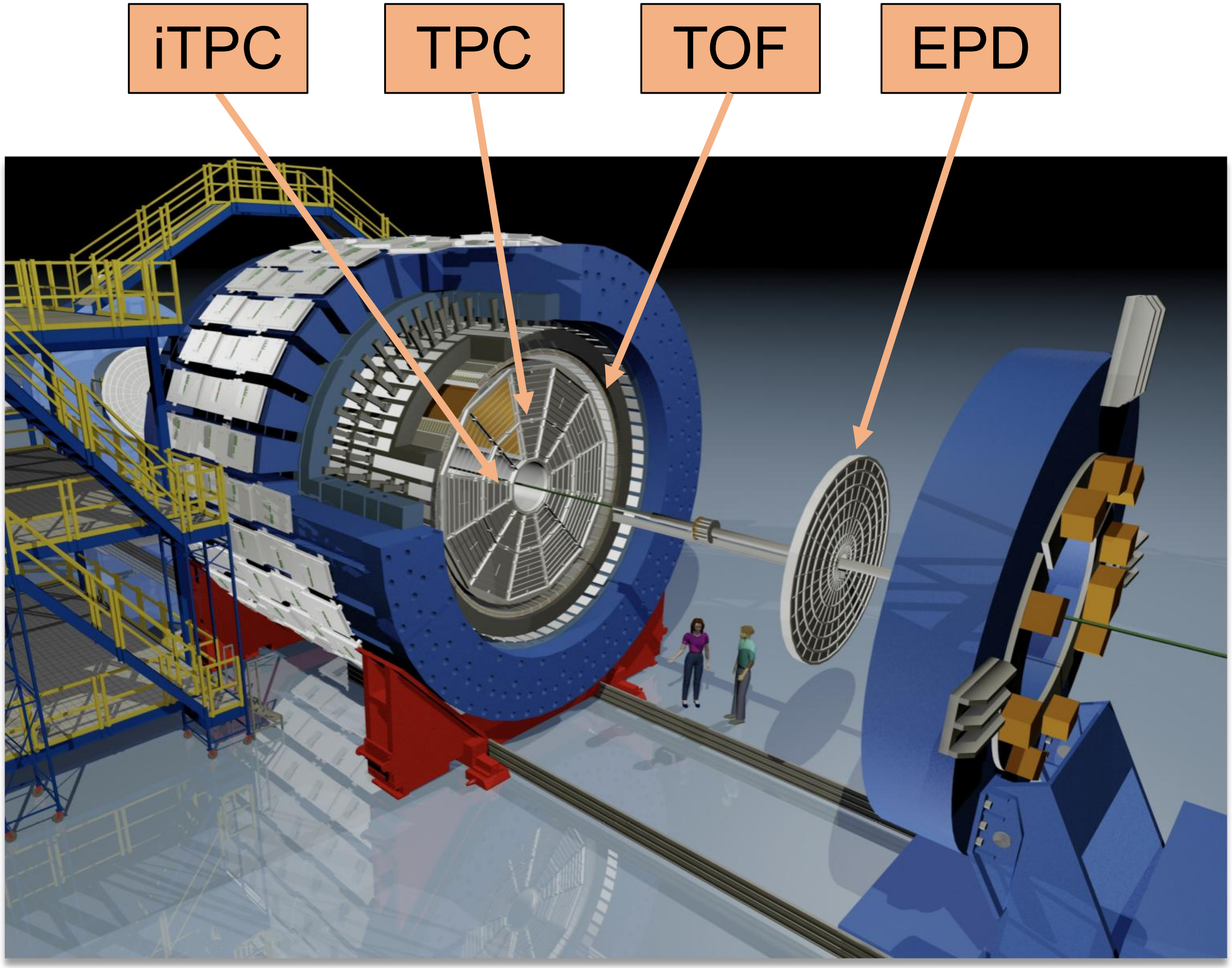
- Large global spin alignment for ϕ-meson observed, so far can be accommodated by local fluctuation of strong force field. Various theory explanations are rapidly developing.

STAR Collaboration, Nature 614 (2023) 7947.
X. L. Sheng, L. Oliva, Q. Wang, Phys. Rev. D 101 (2020) 9.

- Increasing with decreasing energy, will trend remains at lower energies?
  Clarify ρ_{00} behavior in lower energy regime.

- BES-II provides significantly more statistics for lower collision energies.
  BES-I 19.6 GeV: ~ 1.9 x 10^7 events after cuts.
  BES-II 19.6 GeV: ~ 4.6 x 10^8 events after cuts.

The STAR Detector



Full azimuthal coverage

TPC* : $|\eta| < 1$

iTPC*: $|\eta| < 1.5$

tracking, centrality, particle identification, and event plane.

TOF* : $|\eta| < 0.9$

eTOF: $-1.6 < \eta < -1.1$ (not shown)

particle identification

BBC : $3.3 < |\eta| < 5$ (not shown)

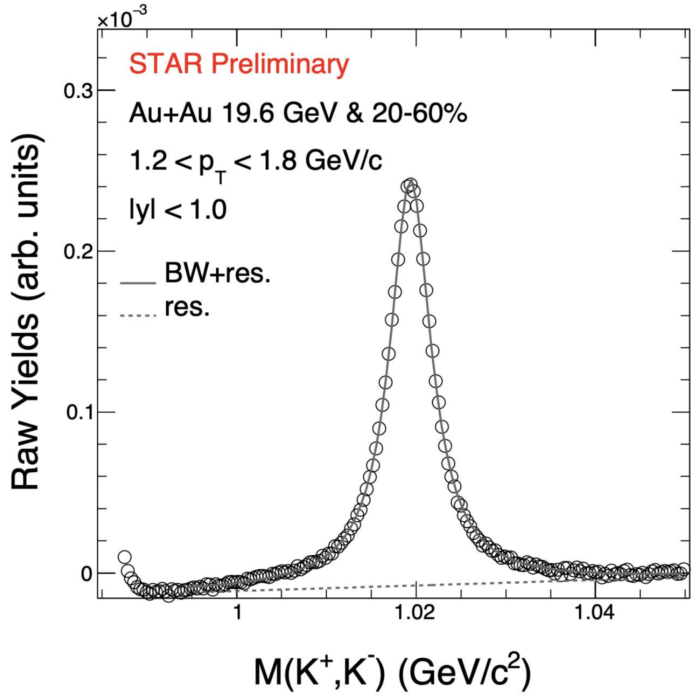
EPD*: $2.1 < |\eta| < 5.1$

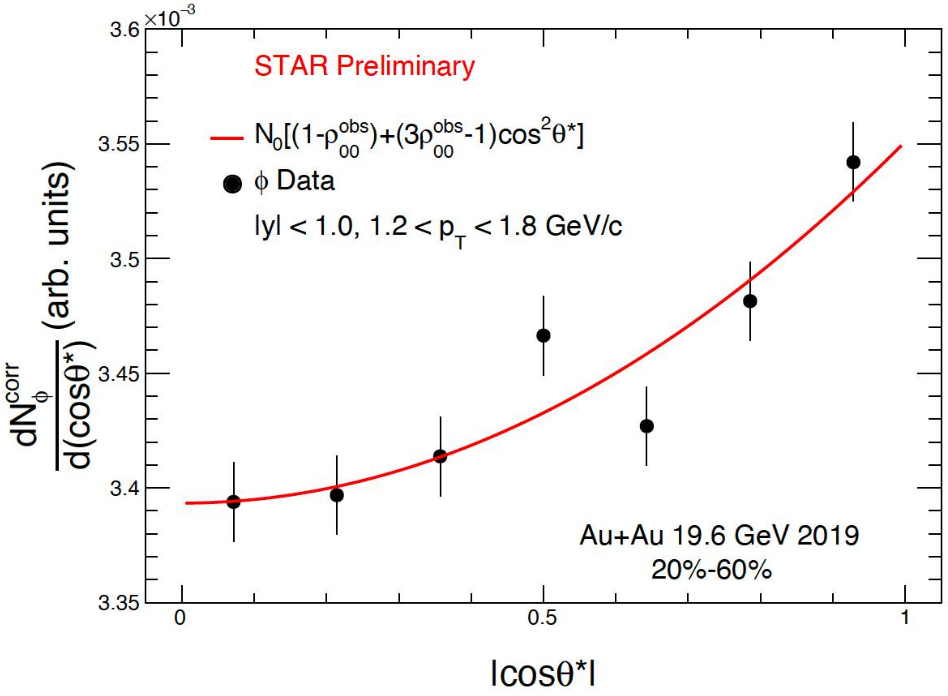
event plane reconstruction

Greater EP resolution with EPD

*Used in ϕ analysis

Signal reconstruction

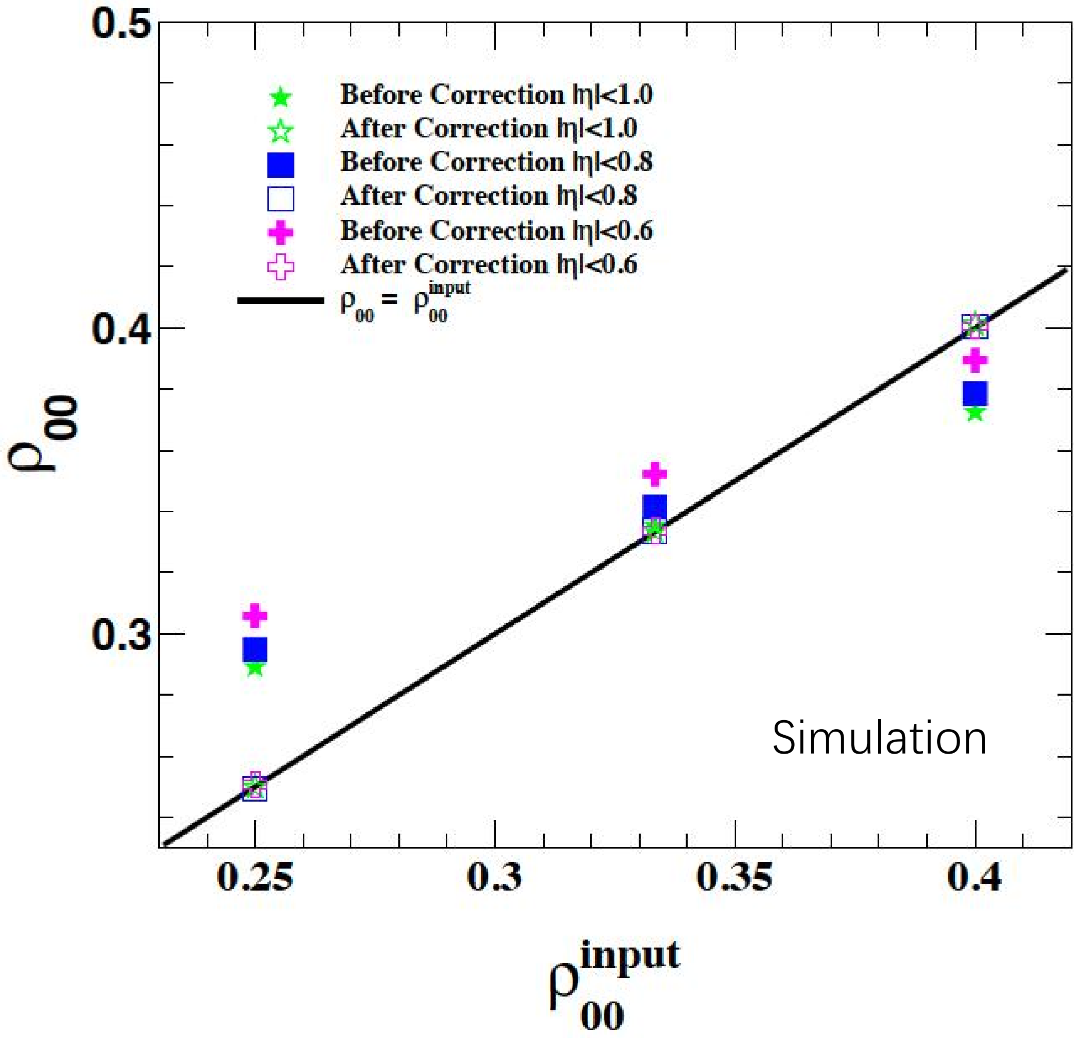




- Use event-mixing to subtract background and extract yields from histogram integration in seven cosθ* bins.
- Yields vs. |cosθ*| are corrected for the acceptance and efficiency.
- ρ_{00}^{obs} is extracted from a fit to the corrected yields vs. |cosθ*|
- Then calculate ρ_{00} from ρ_{00}^{obs} accounting for EP resolution: $\rho_{00} = \frac{1}{3} + \frac{4}{1+3R}\left(\rho_{00}^{obs} - \frac{1}{3}\right)$.

[1] K. Schilling et al., Nucl. Phys. B 15 (1970) 397
[2] Tang et al., Phys. Rev. C 98 (2018) 4, 044907, Phys. Rev. C 107 (2023) 3, 039901 (erratum).

Acceptance and Resolution Correction QA

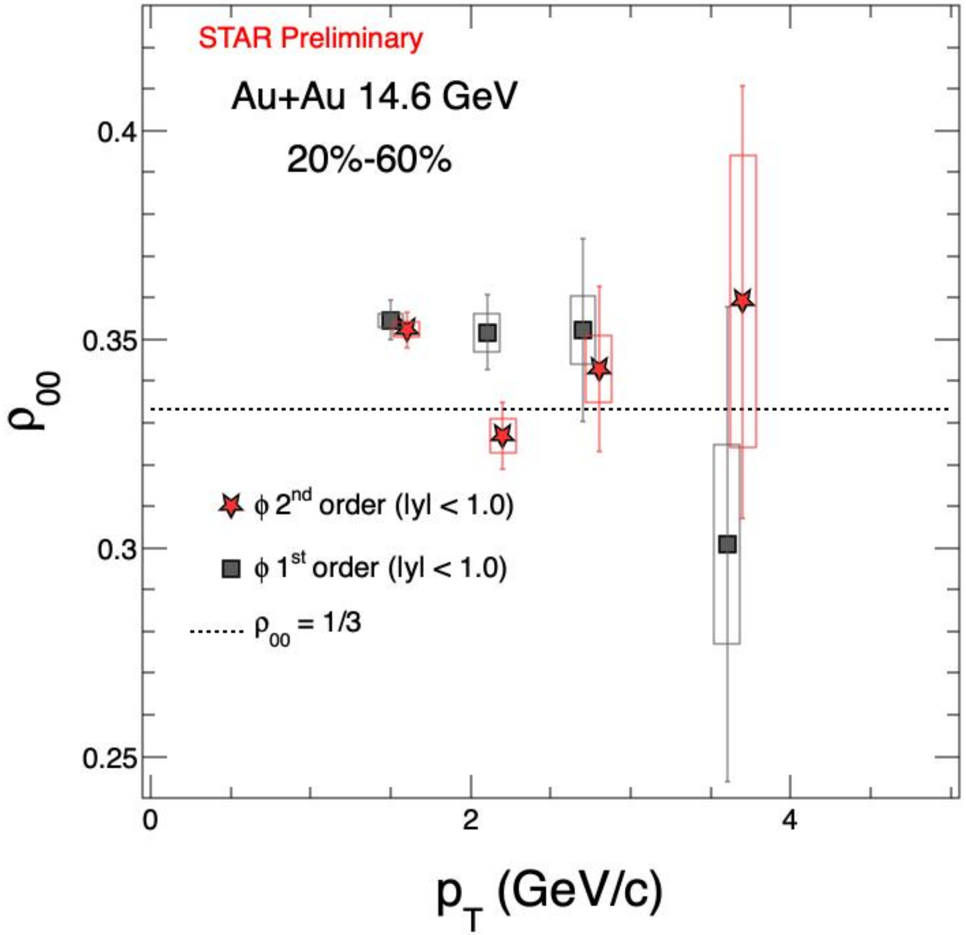


- We simulated ϕ-mesons with the following inputs:
  - 3 input ρ_{00} values: {0.25,0.3333,0.4}
  - p_T = 1.5 GeV/c
  - v_2 = 0.075
  - y = [-1.0,1.0] flat

- We cut on the daughters with three different |η| cuts: |η| < {0.6,0.8,1.0}.

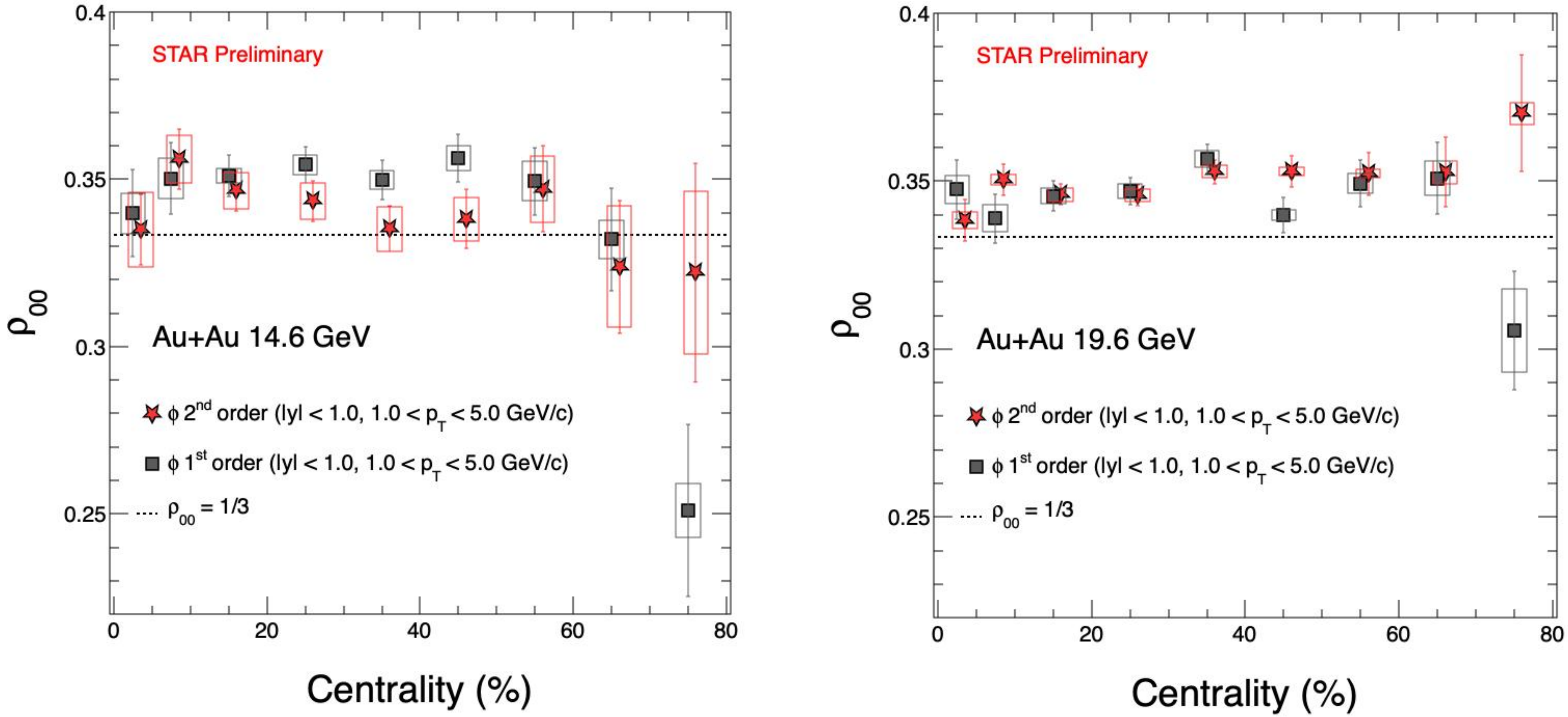
- What we show is that before corrections the ρ_{00} we recover is not the same as the input. After we apply the acceptance and resolution corrections, the reconstructed values are equivalent to the input.

ρ_{00}: 1st order EP vs. 2nd order EP in BES-II



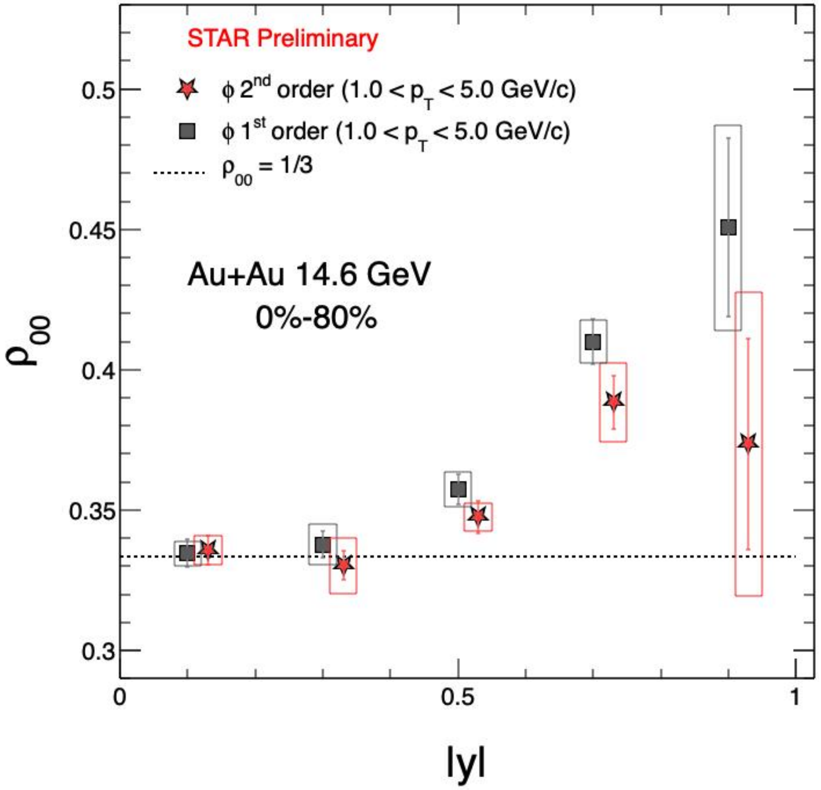
Results obtained with 1st and 2nd order EP are consistent with each other to the first order.
No indication of significant difference in physics contribution w.r.t Participant Plane / Spectator Plane.

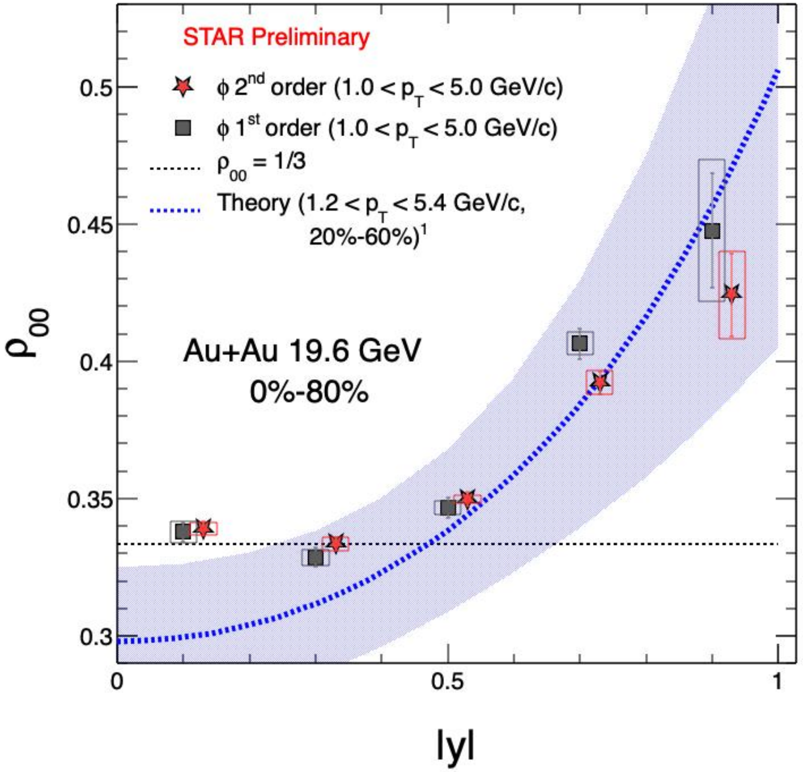
ρ_{00} of ϕ as a function of centrality

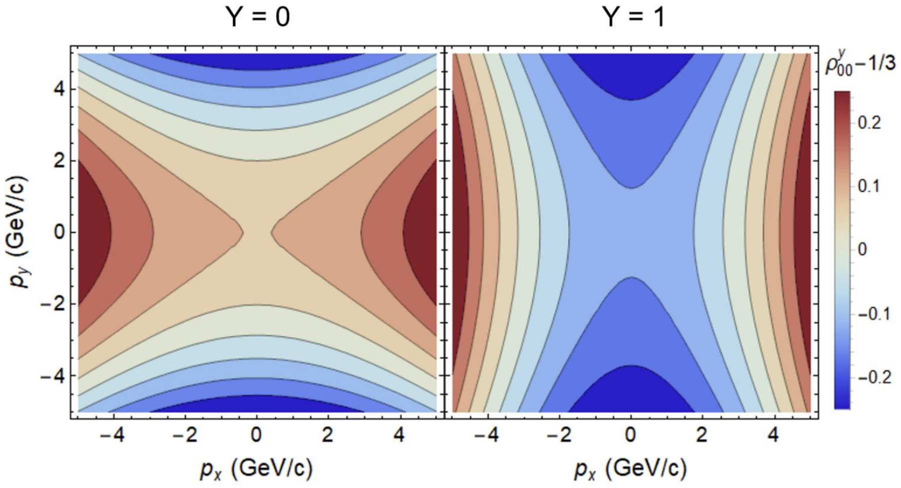


1st and 2nd order EP results have similar centrality dependence.

ρ_{00} of ϕ as a function of rapidity (y)



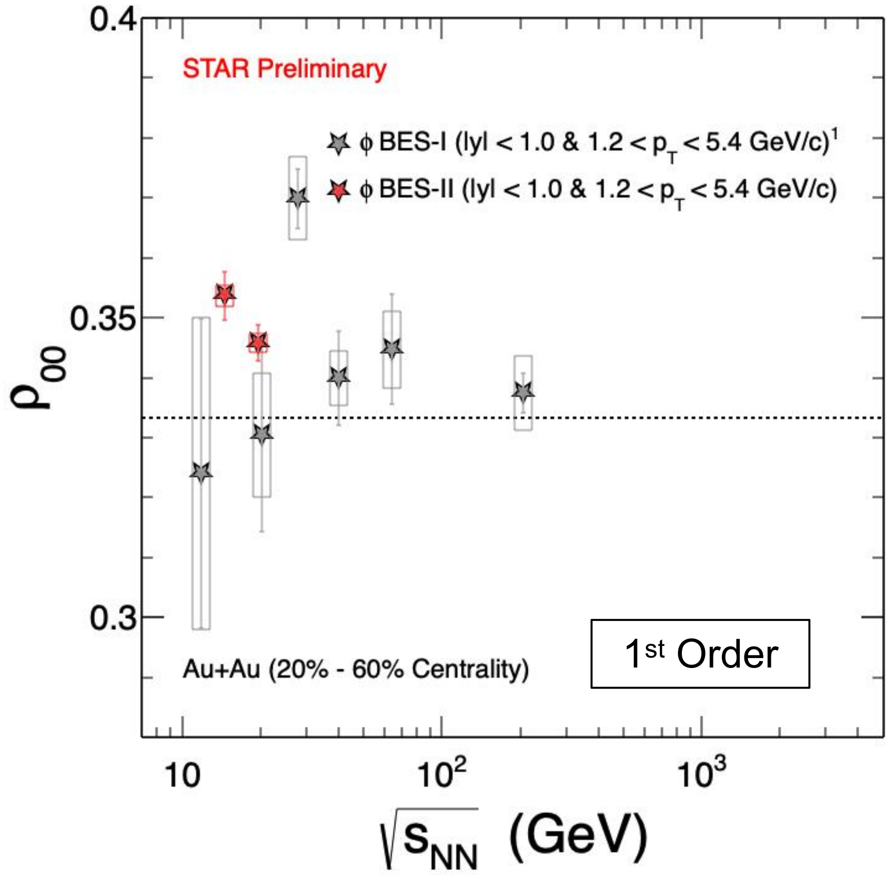


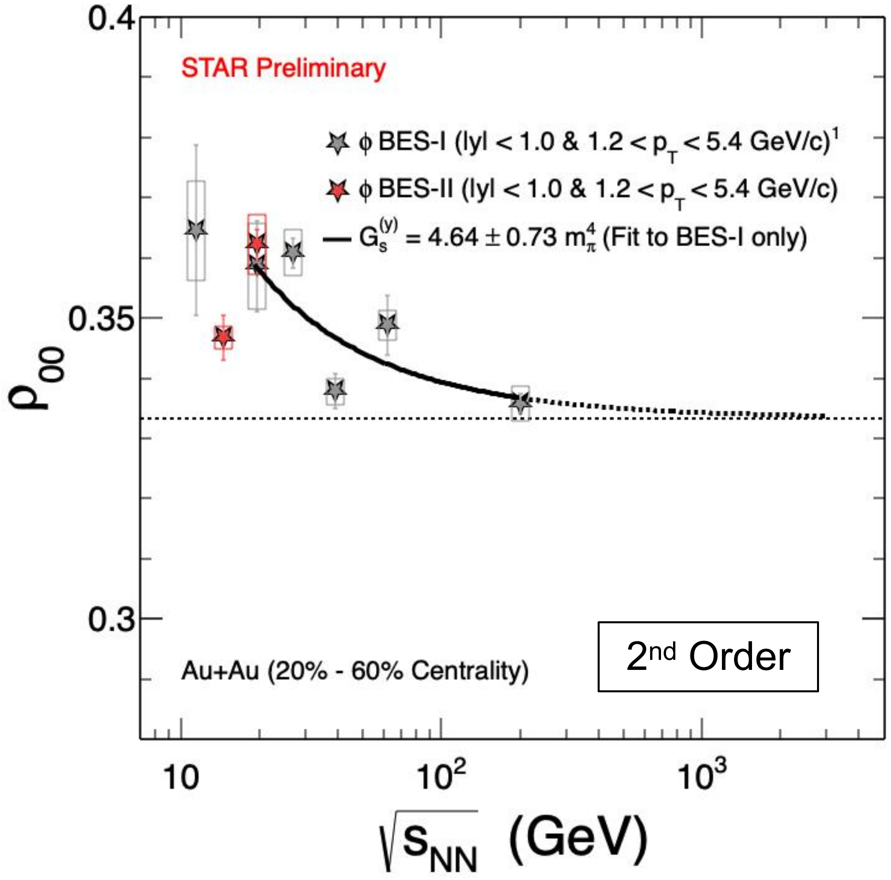


X. L. Sheng, et al., arXiv:2308.14038 [nucl-th].

The trend is consistent with theoretical calculation.
The behavior is due to larger fluctuation in the direction perpendicular to the motion direction.

ρ_{00} of ϕ as a function of collision energy ($\sqrt{s_{NN}}$)

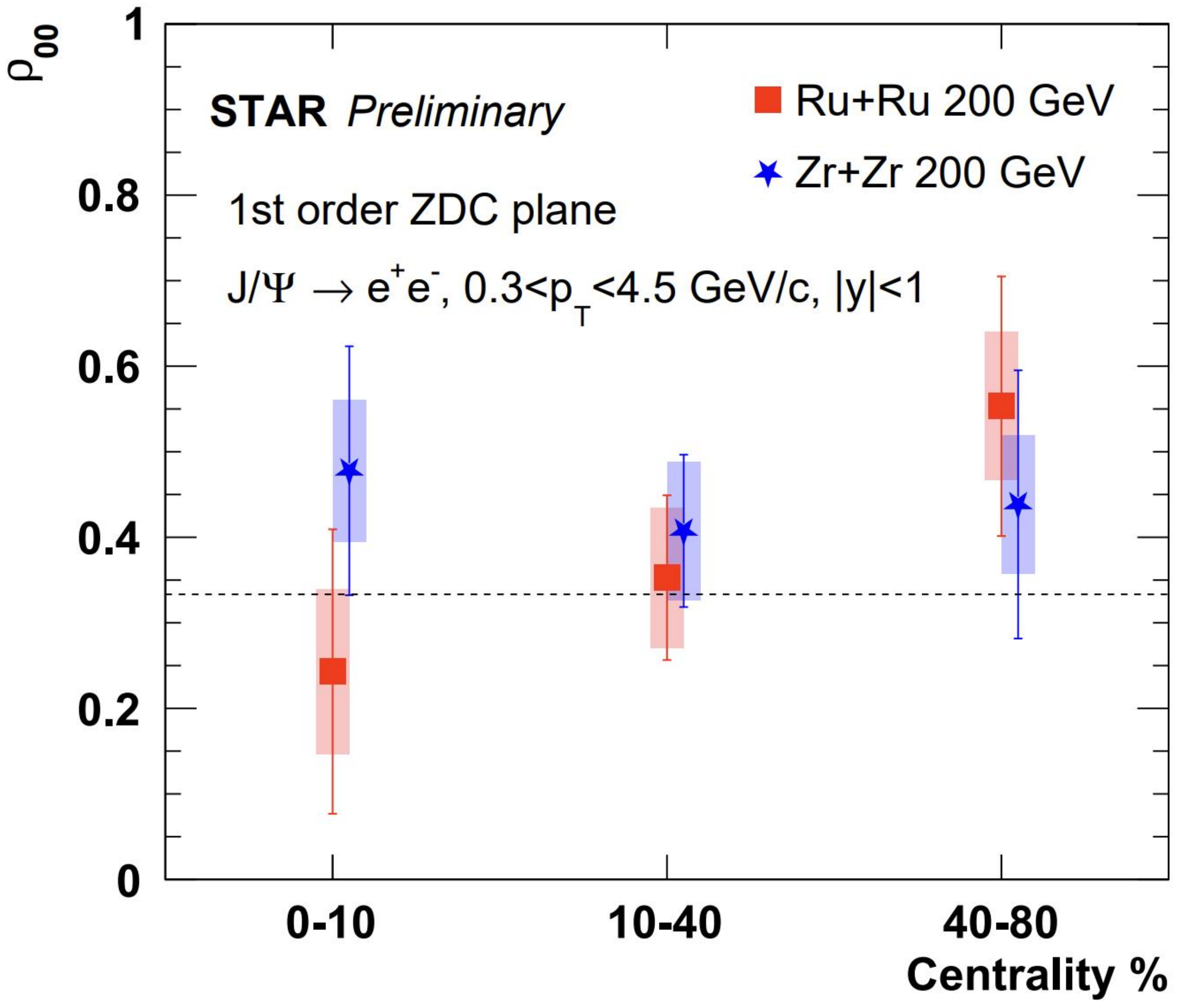




[1] STAR Collaboration, Nature 614 (2023) 7947.
[2] Sheng et al., Phys. Rev. D 101 (2020) 9, 096005.
[3] Sheng et al., Phys. Rev. D 102 (2020) 5, 056013.

Significant global spin alignment confirmed at 14.6 GeV and 19.6 GeV.

ρ_{00} of J/Ψ obtained with first order EP

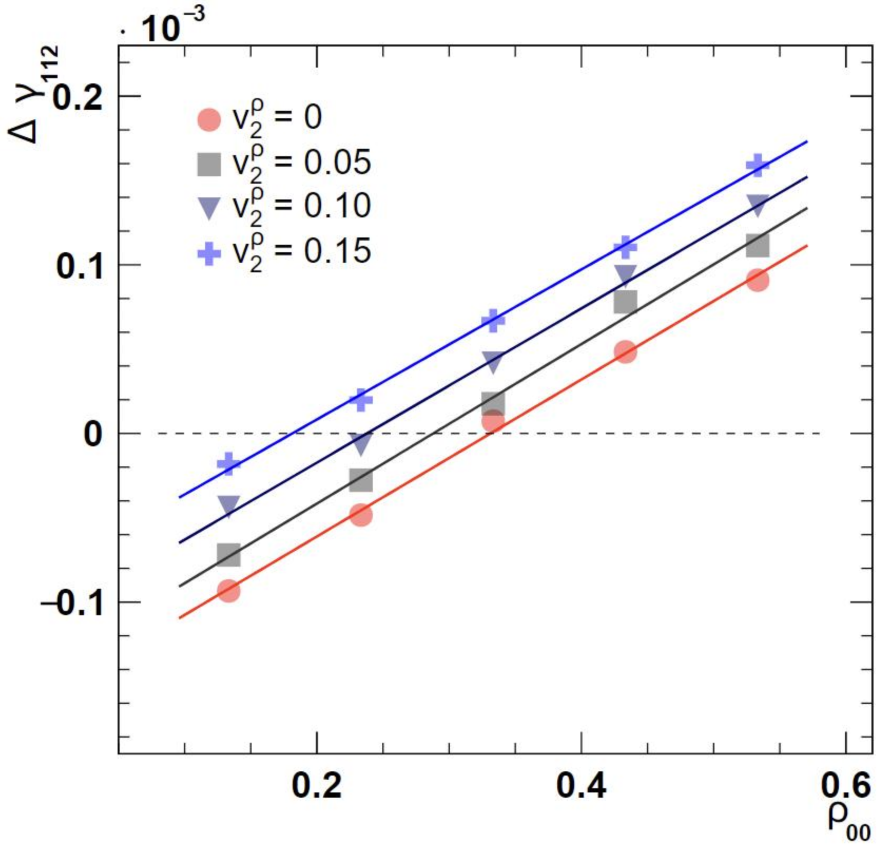


- J/Ψ , like ϕ, has also two quarks from same flavor family, making its ρ_{00} an interesting measurement.
- Within error, ρ_{00} of J/ψ is consistent with 1/3.
- we are working to improve our understanding of the systematic uncertainties that arise from extracting the J/Ψ yield.
- Results obtained from 2nd EP will improve statistical precision.

Motivation for studying ρ^0 spin alignment

- ρ^0-meson consists of a mixture of quark flavor $(u\bar{u} - d\bar{d})/\sqrt{2}$.
- ρ^0-mesons are mostly regenerated, not directly from quark coalescence.
- The two reasons above make it not a good probe to local fluctuation of strong force field like ϕ $(s\bar{s})$ meson.
- However, the global spin alignment of ρ^0-meson has notable implication on CME analyses.

Implications of ρ^0 spin alignment on CME search



Toy model simulations of the $\pi-\pi$ $\Delta\gamma_{112}$ correlation as a function of ρ^0 meson ρ_{00} with various inputs of v_2^ρ.

Global spin alignment of ρ^0 meson can contribute to background in CME observables, similar to resonance v_2 effect.

($\rho_{00} > 1/3$) will enhance apparent values of CME observables.
($\rho_{00} < 1/3$) will decrease apparent values of CME observables.

A. H. Tang, Chin. Phys. C 44 (2020) 054101.
D. Shen, J. Chen, A. Tang and G. Wang, Phys. Lett. B 839 (2023) 137777.

To assess its effect in CME observables, it would be desirable to study ρ^0 meson ρ_{00}.

Yield extraction for ρ^0 meson

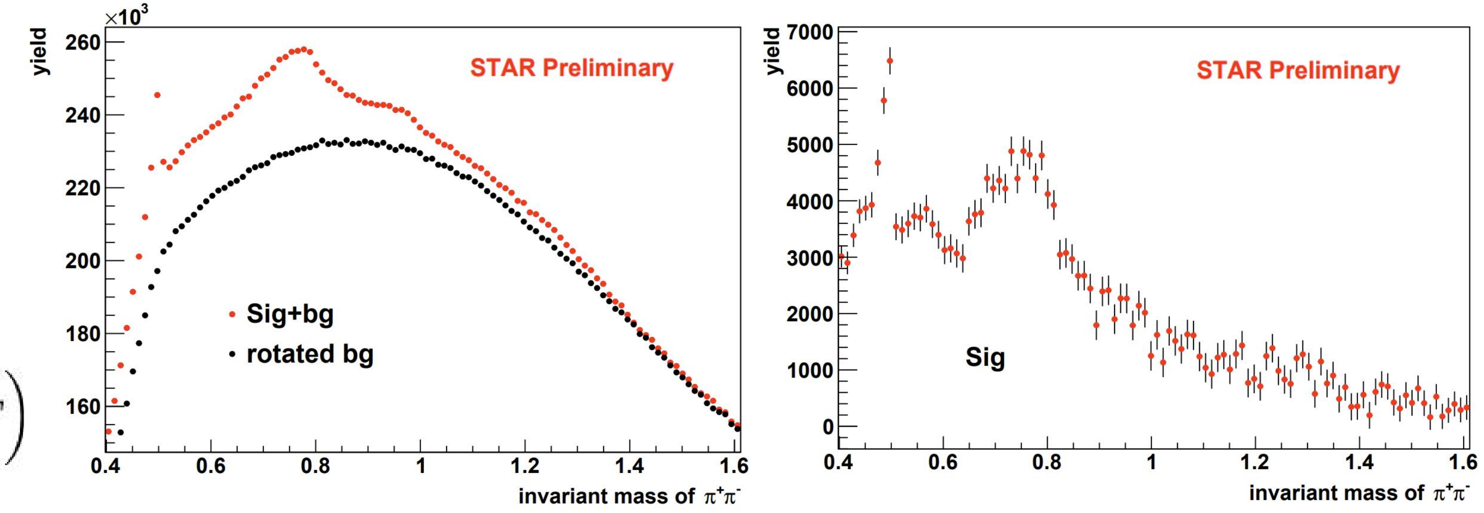
- We first subtract the rotated background. Then do normalization and use a second order polynomial to take care of residual background.
- We fit with contributions from 7 particles (hadronic cocktail fitting) : $\omega, \rho^0, f_0, f_2, \sigma^0, k_s^0, \eta$.
- At each p_T interval, we fit the mass and width of the particles.

$$F(\rho^0, \text{ or } f_0, f_2, \sigma^0) = PS(M_{\pi\pi}) \times BW(M_{\pi\pi})$$

$$BW(M_{\pi\pi}) = \frac{AM_{\pi\pi}M_0\Gamma(M_{\pi\pi})}{\left[(M_0^2 - M_{\pi\pi}^2)^2 + M_0^2\Gamma^2(M_{\pi\pi})\right]}$$

$$PS(M_{\pi\pi}) = \frac{M_{\pi\pi}}{\sqrt{M_{\pi\pi} + p_T^2}} \times \exp\left(-\sqrt{M_{\pi\pi} + p_T^2}/T\right)$$

$$\Gamma(M_{\pi\pi}) = \left[\frac{(M_{\pi\pi}^2 - 4m_\pi^2)}{(M_0^2 - 4m_\pi^2)}\right]^{(2J+1)/2} \times \Gamma_0 \times (M_0/M_{\pi\pi})$$



J. Adams, et al. (STAR Collaboration), Phys. Rev. Lett. 92, (2004) 092301.
Prabhat R. Pujahari (for the STAR collaboration), Nucl. Phys. A 862, (2011) 297.

Overall fitting (Integrating 7 $\cos\theta^*$ bins together)

We do an overall fitting for each p_T bin at 60-80% with the following constraints of parameters:

ρ^0 : mass: 0.7-0.8 width: free parameter

f_0 : mass: 0.98 (fixed) width: free parameter

σ^0: mass: 0.4 - 0.8 width: 0.1 - 0.8(PDG)

k_s^0: Gaussian function with mass and width as free parameters.

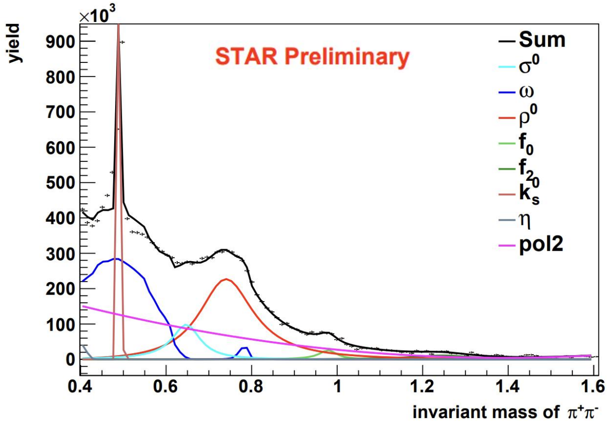
ω, η: with function shapes obtained from hijing simulation.

f_2 : mass 1.275 width 0.185

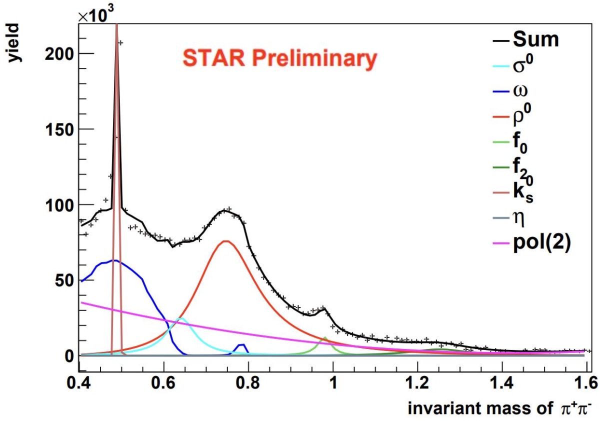
Through cocktail fitting, we get the mass and width of particles.

As an example, we show the overall fitting results of AuAu collision in different p_T at 60-80% centrality.

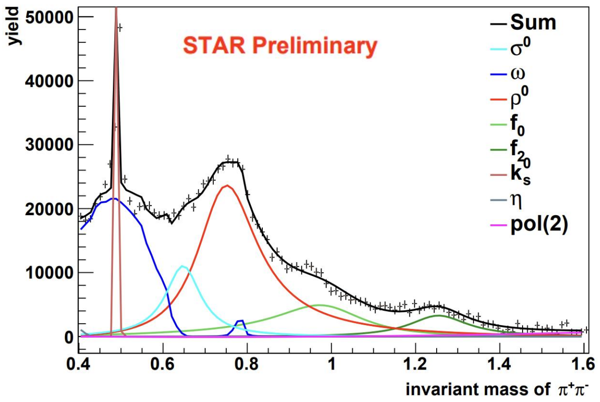
p_T 1.2-1.8GeV/c



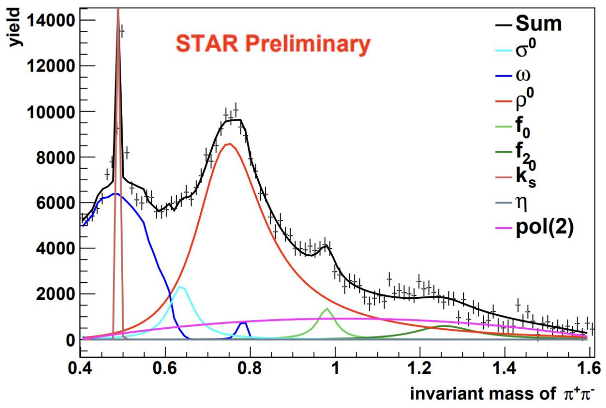
p_T 1.8-2.4GeV/c



p_T 2.4-3.0GeV/c

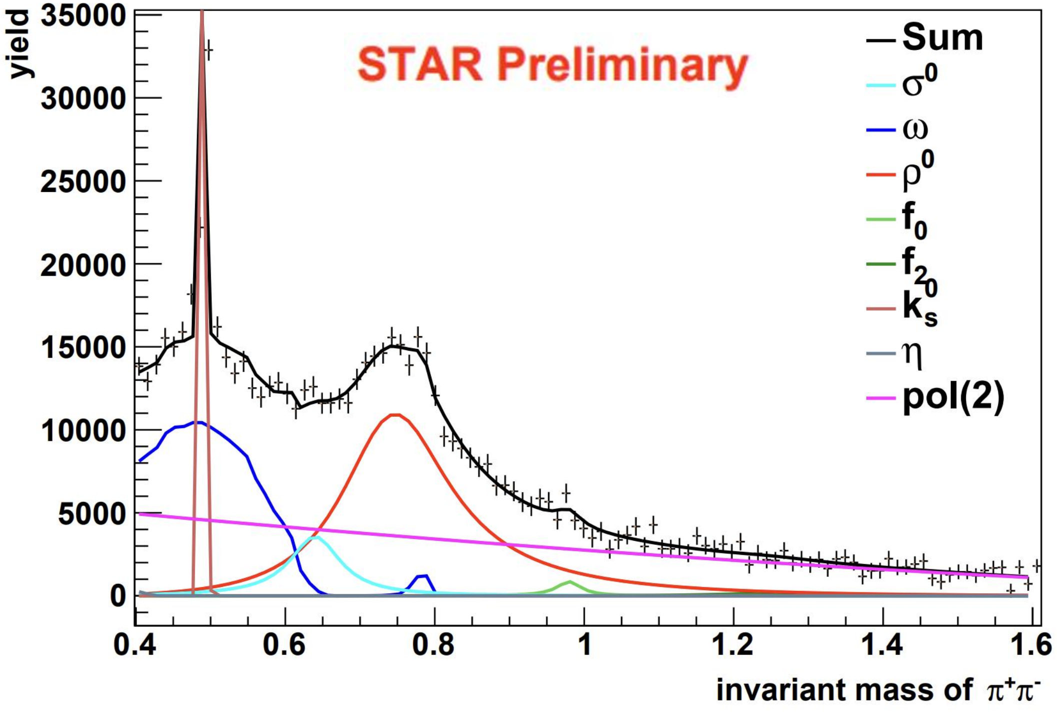


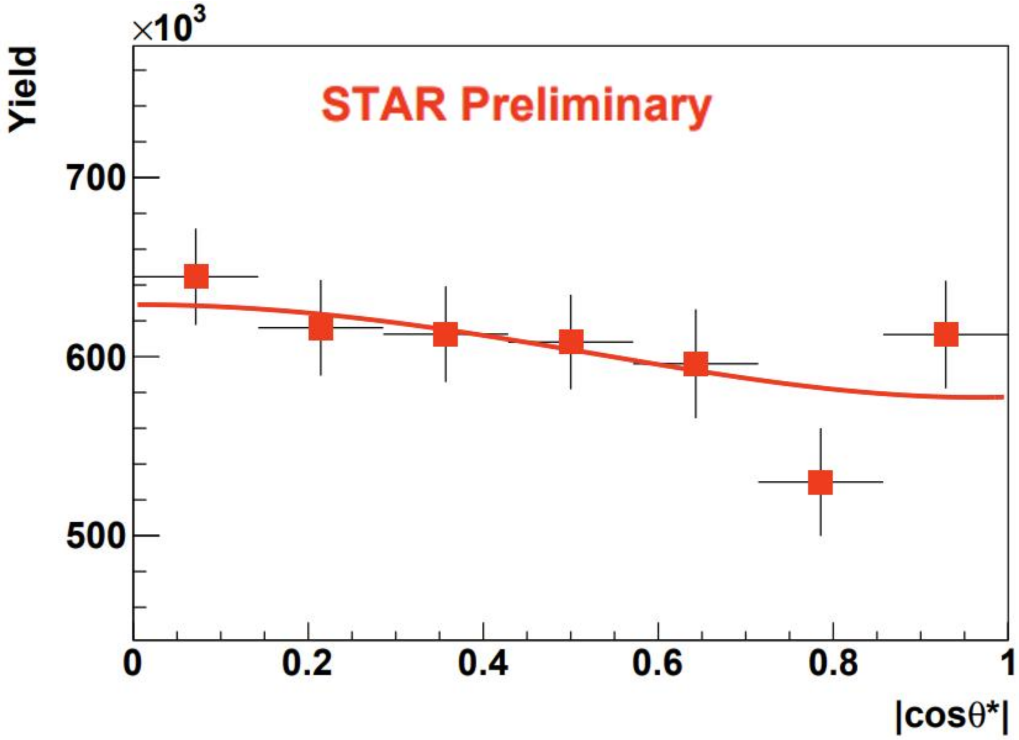
p_T 3.0-4.0GeV/c



For each cosθ^* bin

Based on the information obtained from the overall fitting, we fix the mass and width of σ^0 and k_s^0, and fix the width of ρ^0 and f_0.
Through cocktail fitting, the yields of ρ^0 can be obtained.
Then corrected for efficiency.

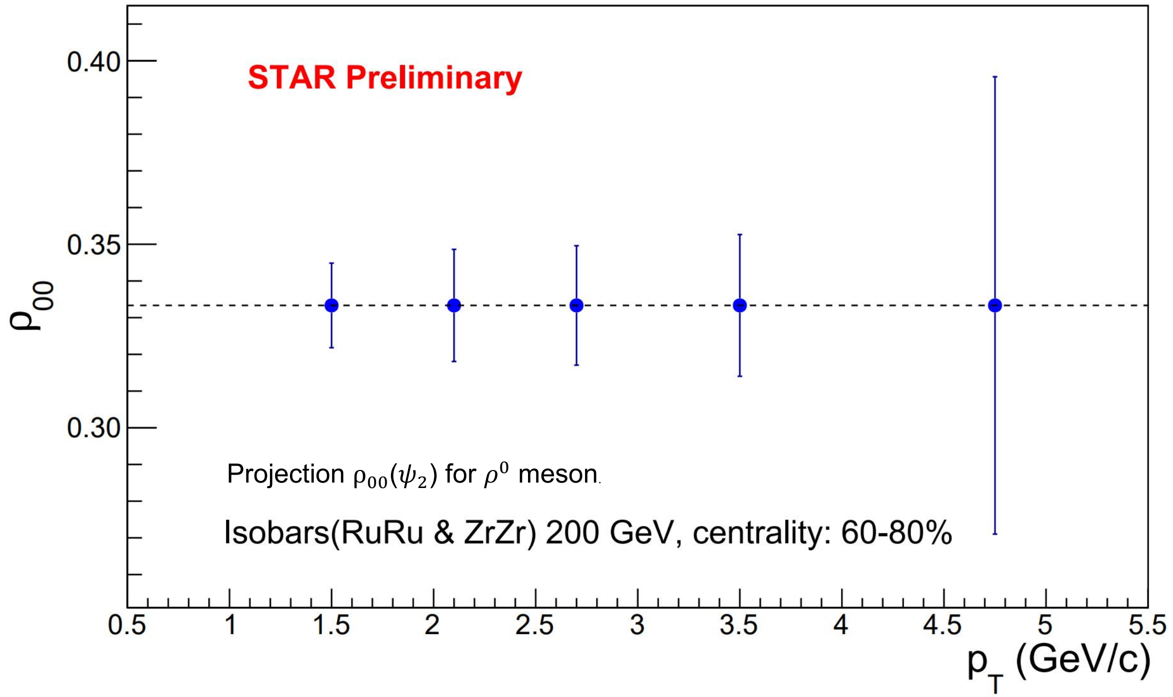




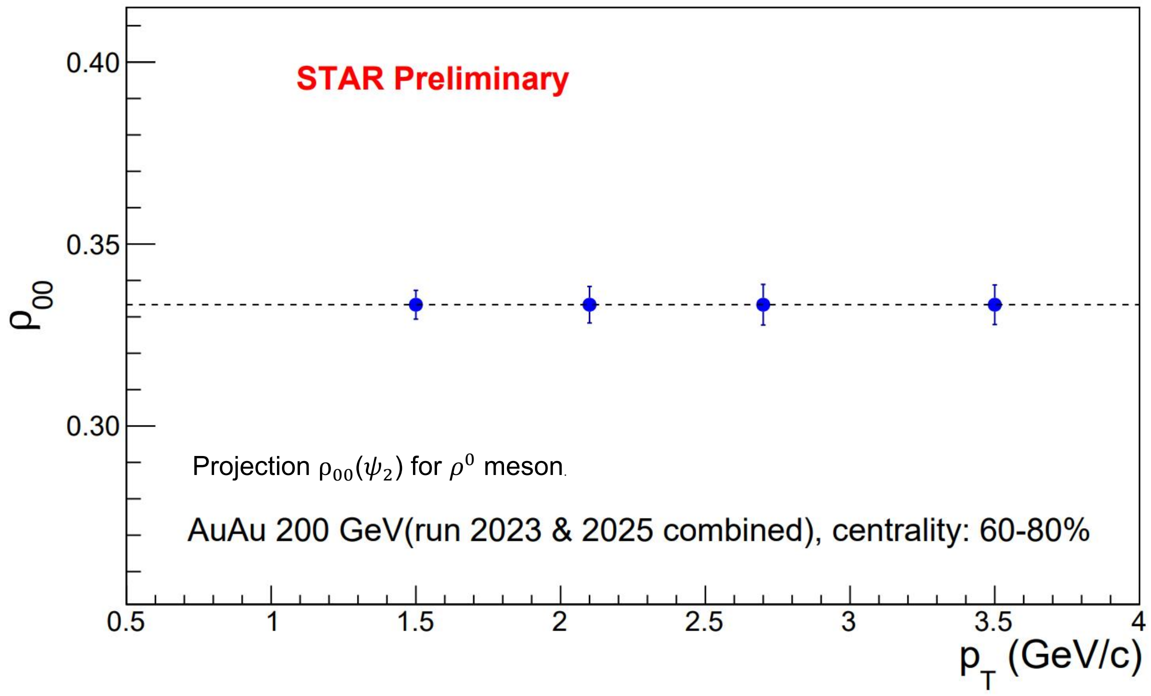
AuAu for run 2011 at 200 GeV, Centrality: 60-80%, p_T: 1.8-2.4 GeV/c

Error projection for ρ^0 meson ρ_{00} for isobar and AuAu 200 GeV

Statistical error projection for isobar at 200 GeV.



Statistical error projection for AuAu 200 GeV, run 2023 & 2025 combined.



The analysis is ongoing, here we show the error projection.

Summary

- ϕ-meson ρ_{00} from BES-II is consistent with BES-I. Significant global spin alignment at 14.6 and 19.6 GeV.
- ϕ-meson ρ_{00} is found to increase with rapidity at 19.6 GeV, the trend is roughly consistent with theoretical prediction invoking local fluctuations of strong force field. Looking forward to more theoretical developments.
- Within error, ρ_{00} of J/ψ obtained with 1^{st} order EP is consistent with 1/3.
- Stay tuned for updates on ρ^0-meson ρ_{00}.

Thank You

Backup Slides

Datasets and cuts of ϕ spin alignment in BES-II

Au+Au 14.6 GeV BES-II (2019) (minbias)

Au+Au 19.6 GeV BES-II (2019) (minbias)

Event cuts:

| Vz | < 70 cm , Vr < 2.0 cm , nBToFMatch > 2

Pile-up rejection cuts

Track cuts:

nHitsFit > 15 , nHitsFit/nHitsMax > 0.52 ,

$|\eta| < 1$, dca < 2.0 cm ,

p_T >0.1 GeV/c && p< 10 GeV/c

0.16 < mass2 < 0.36 , |nSigmaKion| < 2.5

Systematic of ϕ-analysis in BES-II

- $n\sigma_{\pi}$: 2.0, 2.5, 3.0
- dca : 2.0, 2.5, 3.0
- Background normalization range: [1.04, 1.05] , [0.99, 1.0] , average of both
- Yield extraction method: bin counting, integration
- Yield extraction range: 2.0σ, 2.5σ, 3.0σ

For a given source of systematic uncertainties, we obtained ρ_{00} with the cut for this sources changed, and other cuts are at the central value. Assuming uniform probability distributions between the maximum and minimum values, the value of the systematic uncertainty for a source is:

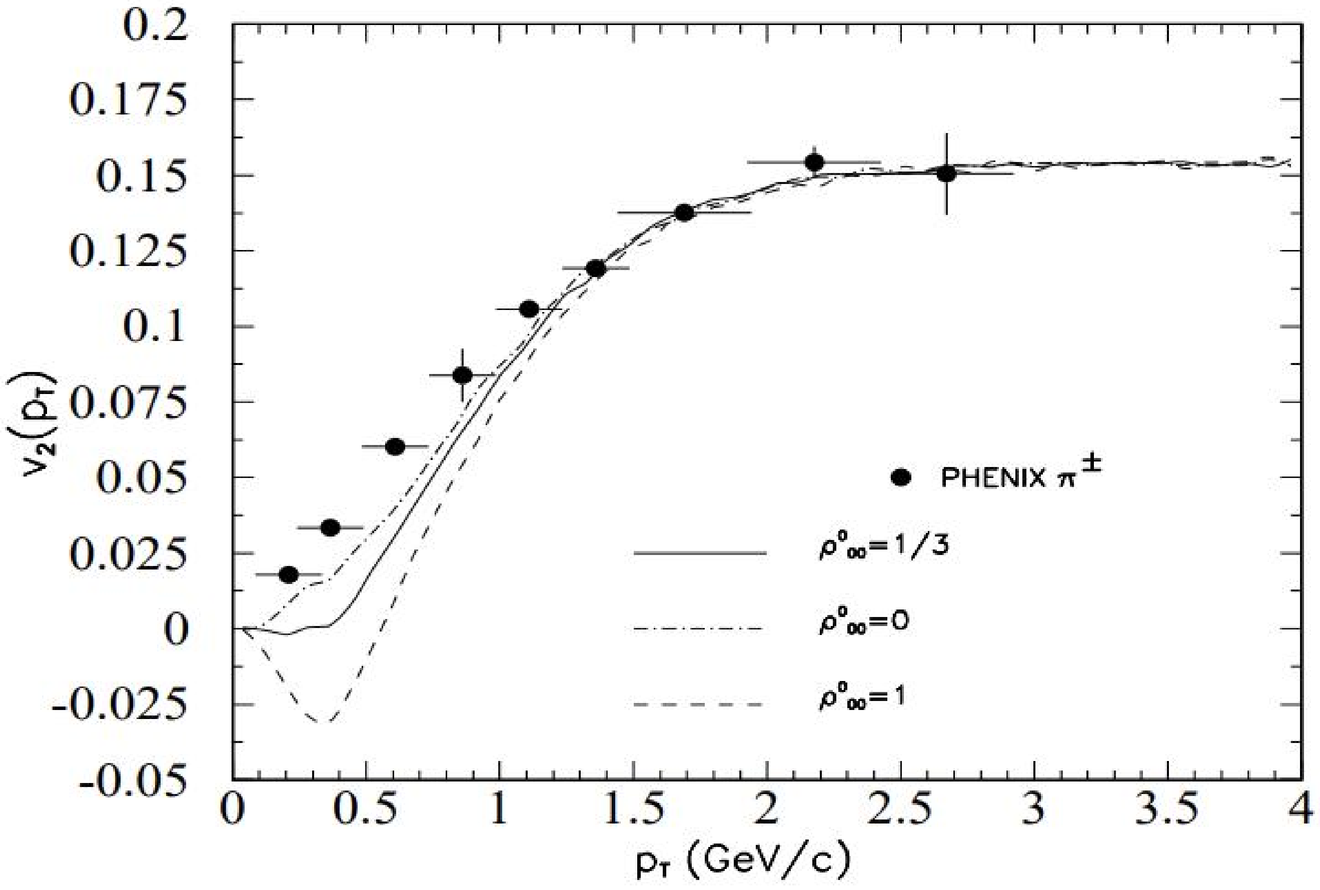
$$\Delta\rho^{i}_{00,sys} = \frac{\rho^{i}_{00,max} - \rho^{i}_{00,min}}{\sqrt{12}} \quad (39)$$

and then combine different sources of uncertainties:

$$\Delta\rho_{00,sys} = \sqrt{\sum_{i}(\Delta\rho^{i}_{00,sys})^{2}} \quad (40)$$

* For rapidity dependence, we took the statistical weighted average of the symmetric negative and positive bins as the central value. The difference between points was added as a source of systematic error.

The v_2 of π considering the decay of ρ^0 mesons with spin arrangement effect



Z. T. Liang and X. N. Wang, Spin alignment of vector mesons in non-central A+A collisions, Phys. Lett. B 629, (2005) 20.

For ρ^0: datasets and cuts of Run 2011 and isobar

Minimum Bias Event of AuAu 200GeV from 2011

(~500 M before event cuts. ~300M after event cuts)

Event cuts:

| Vz | < 30.0 cm, Vr < 2.0 cm, | Vz-VzVPD | < 3.0 cm

Number ToF matched point > 3

Minimum Bias Event of isobar

(For RuRu: ~2000 M before event cuts. ~1600M after event cuts.

For ZrZr: ~2200 M before event cuts. ~1800M after event cuts.)

Event cuts:

-35 cm < Vz < 25 cm, Vr < 2.0 cm, | Vz-VzVPD | < 3.0 cm

Number ToF matched point > 3

Track cuts: (Same for different datasets)

nHitsFit > 15,   nHitsFit/nHitsMax > 0.55

| η | < 0.8,   dca < 2.0 cm, p_T >0.2 GeV/c && p< 10 GeV/c

|nSigmaPion| < 1.5,   -0.1 < mass2 < 0.2

Acceptance and EP resolution

Corrections for finite EP resolution, efficiency, and acceptance

i) ϕ**-meson** ρ_{00} **analysis** Detector efficiency within the acceptance is corrected using the STAR Monte Carlo embedding method [8–10]. To account for finite EP resolution and finite acceptance in pseudo-rapidity (η) [11], the observed $\cos\theta^*$ distribution is not fitted using Eq. 1 in the main text, but is instead described by the correction procedure derived in Ref. [7] wherein the data are fitted using

$$\left[\frac{dN}{d\cos\theta^*}\right]_{|\eta|} \propto (1+\frac{B'F}{2}) + (A'+F)\cos^2\theta^* + (A'F - \frac{B'F}{2})\cos^4\theta^*, \quad (1)$$

where

$$A' = \frac{A(1+3R)}{4+A(1-R)}, \quad B' = \frac{A(1-R)}{4+A(1-R)}, \quad (2)$$

and

$$A = \frac{3\rho_{00}-1}{1-\rho_{00}}, \quad (3)$$

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

$$\left[\frac{dN}{d\cos\theta^* d\beta}\right]_{|\eta|} \propto 2 + F - \frac{BF}{2} + \frac{3G}{4} - \frac{BG}{2} + \left[2A - F(1-A-B) - G\left(\frac{3}{2} - \frac{3A}{4} - \frac{3B}{2}\right)\right]\cos^2\theta^* + \left[-F\left(A+\frac{B}{2}\right) + G\left(\frac{3}{4} - \frac{3A}{2} - \frac{3B}{2}\right)\right]\cos^4\theta^* + \left[G\left(\frac{3A}{4}+\frac{B}{2}\right)\right]\cos^6\theta^*\,.$$

$$A = \frac{A'(1+3R)}{4+A'(1-R)}\,, \qquad B = \frac{A'(1-R)}{4+A'(1-R)}\,, \qquad A' = \frac{3\rho_{00}-1}{1-\rho_{00}}$$

We followed the same correction procedure as used in Nature paper. Instead of expanding the cosθ distribution to the 2nd order, we expanded it to the fourth order. In practice this makes the fitting better but has little effect on the extracted ρ_{00}.

Systematics of ρ^0-analysis

- $n\sigma_{\pi}$: 1.0, 1.5, 2.0
- dca : 1.5, 2.0, 2.5
- Normalization factor (small medium large)
- Residual background subtraction
- Fitting procedure (The fixed value of the width of ρ^0 and f_0 is obtained by overall fitting, ρ^0 width fixed in 0.16 or 0.1491(PDG) and width of f_0 is obtained by overall fitting , f_0 width fixed in 0.075 or 0.1 and width of ρ^0 is obtained by overall fitting)
- Count and integration range: 0.5*Γ, 1.0*Γ, 1.5*Γ
- Yield extraction method: bin counting, integration

Bin counting are used in all parts(as in the analysis of ϕ Nature).

Acceptance and Resolution Correction QA