PWGC preview: Differential measurements of ϕ-meson global spin alignment in Au+Au collisions at RHIC

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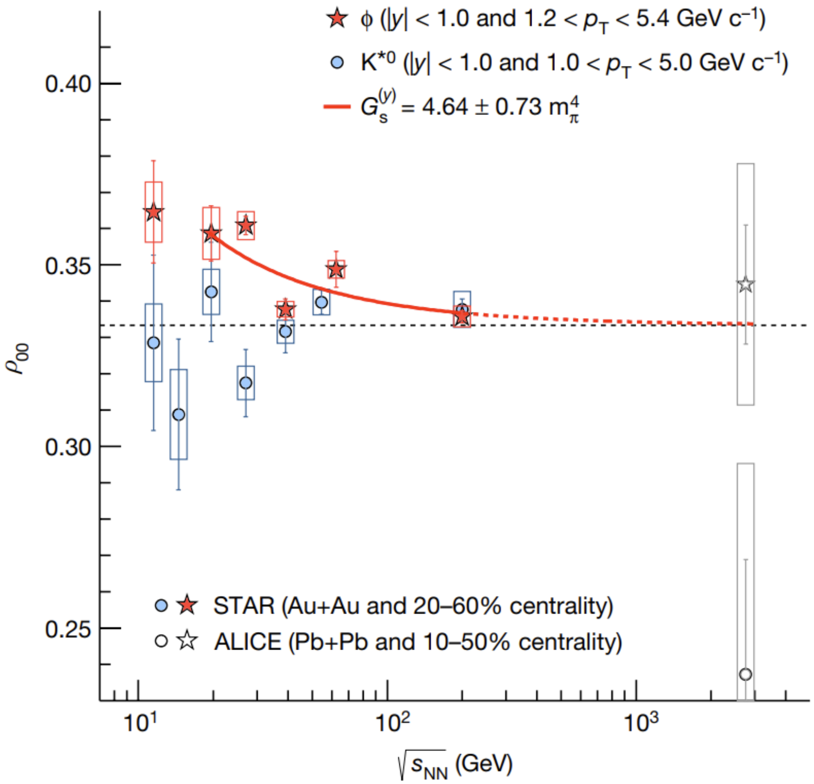
General Information

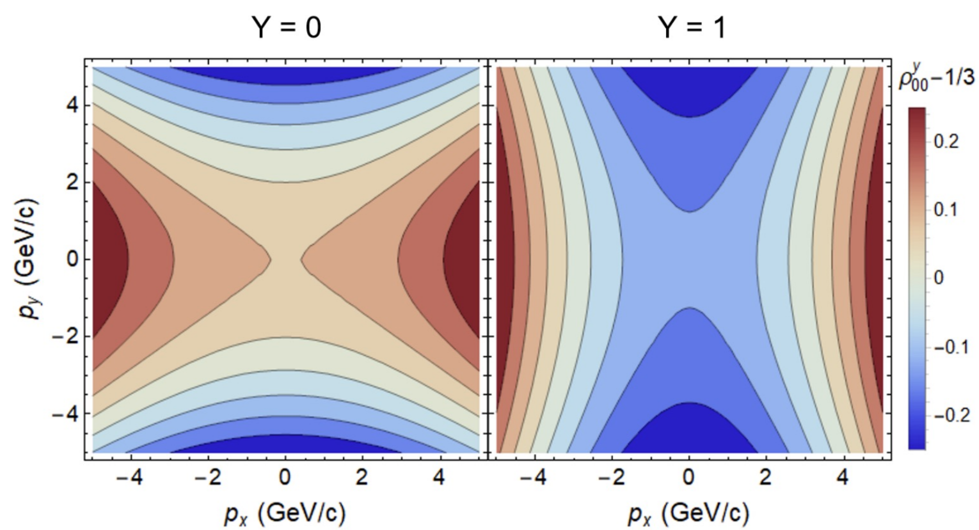
- Paper title: Differential measurements of ϕ-meson global spin alignment in Au+Au collisions at RHIC
- PAs: Diyu Shen (Fudan), Xu Sun (IMP), Aihong Tang (BNL), Gavin Wilks (UIC), Zhenyu Ye (UIC)
- Targeted journal: Physical Review Letters
- Webpage:https://drupal.star.bnl.gov/STAR/blog/gwilks3/Differential-Measurements-phi-meson-Global-Spin-Alignment-Paper-Proposal

Motivation

STAR Collaboration, Nature 614 (2023) 7947.



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



- Large positive global spin alignment (ρ_{00}>1/3) for ϕ-meson was measured for the first time at mid-central collisions.
- Increased statistics for new and identical energies from BES-II.
  - Consistence with higher precision?
- Where does this large signal come from in the ϕ-meson phase space?
- Can the leading theory predict the rapidity dependence?

Analysis Information

- Dataset: Au+Au 19.6 GeV BES-II
- Year: 2019
- Production tag: production_19GeV_2019
- Triggers used: 640001, 640011, 640021, 640031, 640041, 640051
- Embedding request id: 20214203, 20214204
- Bad run list from StRefMultCorr

- Dataset: Au+Au 14.6 GeV BES-II
- Year: 2019
- Production tag: production_14p5GeV_2019
- Triggers used: 650000
- Embedding request id: 20221502, 20221503
- Bad run list from StRefMultCorr

Analysis Information

Event Level Cuts

- $|v_z| < 70$ cm
- $|v_r| < 2$ cm
- nBToFMatch > 2
- Pile-up rejection cuts from StRefMultCorr
- Centrality from StRefMultCorr

TPC Track Cuts for $K^{+/-}$

- $0.1 < p_T < 10$ GeV/c
- $|DCA| < 2$ cm
- No. TPC hits > 15
- TPC hit ratio > 0.52
- $|\eta| < 1$

PID Cuts for $K^{+/-}$

- $|n\sigma_K| < 2.5$
- ToF: $0.16 < M^2 < 0.36$

$$\phi \to K^+K^-$$

EPD Event Plane Cuts (1st Order)

- Use StEpdEpFinder
- v_1 vs. η weighting as described here: https://drupal.star.bnl.gov/STAR/blog/iupsal/determining-eta-weights-epd-event-plane-analysis

TPC Event Plane Cuts (2nd Order)

- $0.15 < p_T < 2$ GeV/c
- $|DCA| < 1$ cm
- No. TPC hits > 15
- TPC hit ratio > 0.52
- $|\eta| < 1$
- Sub-event plane method (η gap = 0.1)
- Apply run-by-run, centrality and v_z wise re-centering and shift calibrations

Analysis Information

$$Q_n \cos(n\Psi_n) = \sum_i w_i \cos(n\varphi_i)\,; \quad Q_n \sin(n\Psi_n) = \sum_i w_i \sin(n\varphi_i)$$

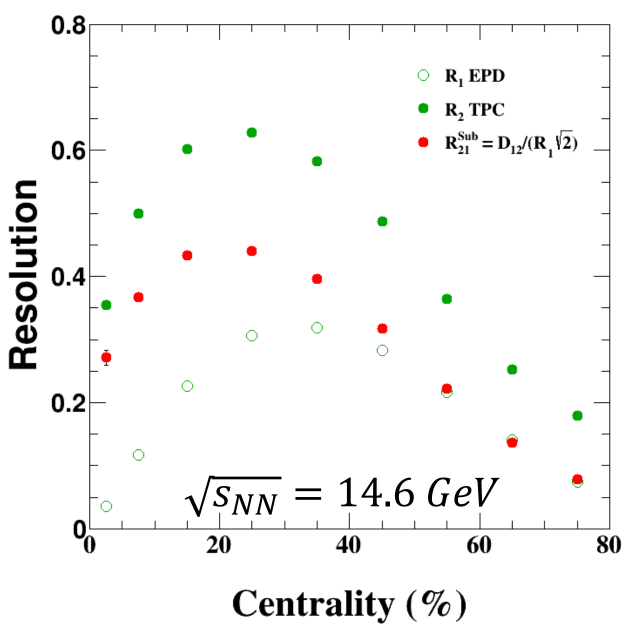
$$\Psi_n = \left(\tan^{-1}\frac{\sum_i w_i \sin(n\varphi_i)}{\sum_i w_i \cos(n\varphi_i)}\right)/n$$

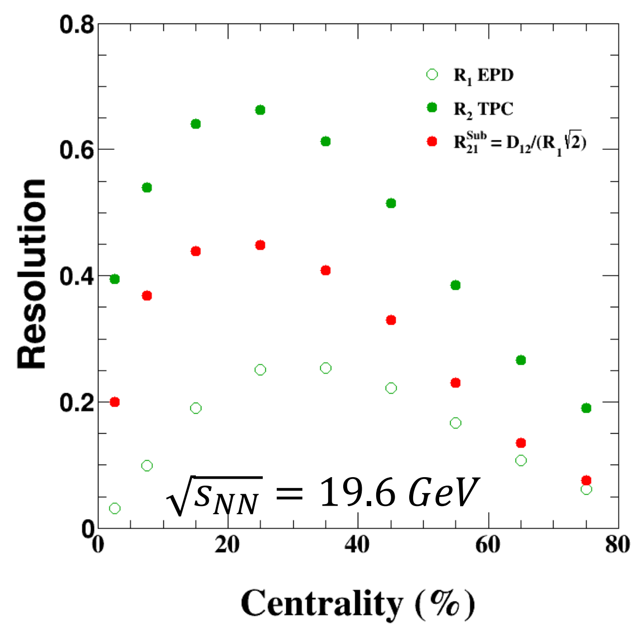
$$R_1 = \sqrt{\langle \cos 2(\Psi_1 - \Psi_{1,r})\rangle}$$

$$R_2 = \sqrt{\langle \cos 2(\Psi_2 - \Psi_{2,r})\rangle}$$

n: harmonic order in anisotropic flow distribution
i: i[th] particle in event
Q_n: flow vector
φ_i: angle of particle trajectory in lab frame
w_i: weight (determined by transverse momentum)
if p_T<2 GeV/c, w_i=p_T; if $p_T \geq 2$ GeV/c, w_i=2

See slide XX for information about deriving R_{21}^{sub}.





Technical Details

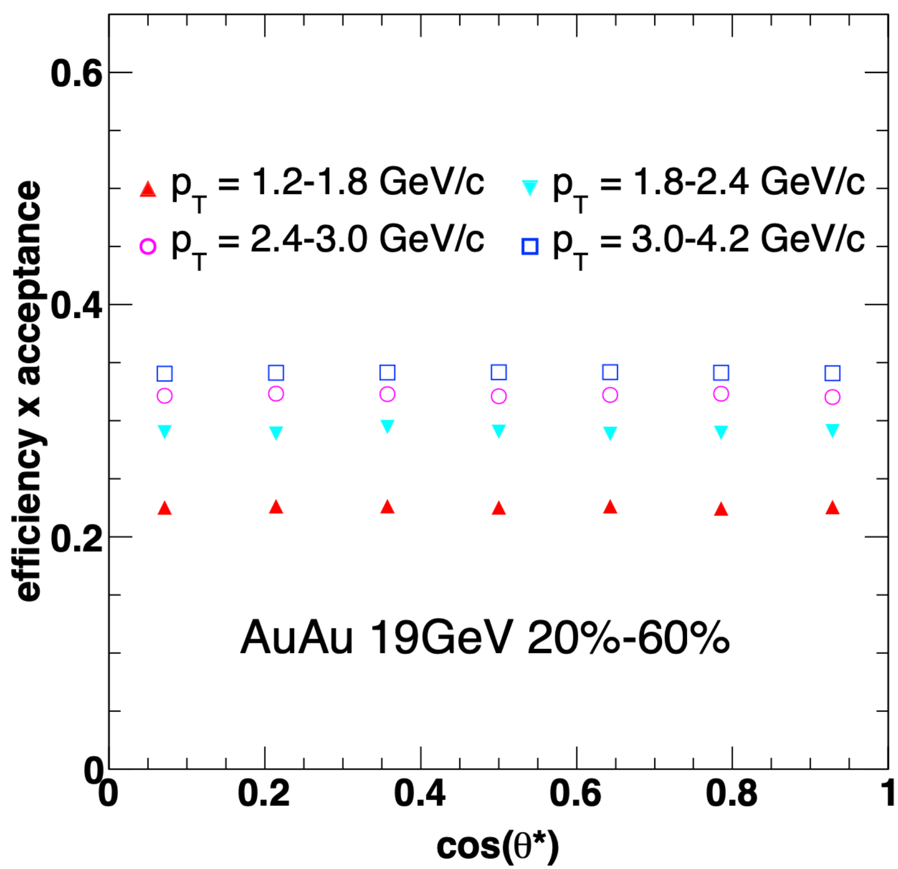
Calculating ρ_{00} from angular distribution of decay daughters:

- Total ϕ meson yield calculated for each cos(θ*) bin.
- Correct yields for TPC tracking x ToF matching efficiency and acceptance.
  - Simulate ϕ decay in Pythia6 and apply efficiency and acceptance cuts to decay daughters to find efficiency vs. cos(θ*).
- Event plane resolution (R_1 or R_{21}^{sub}) correction applied with following formula:

$$\rho_{00} = \frac{1}{3} + \frac{4}{1+3R}\left(\rho_{00}^{obs} - \frac{1}{3}\right)$$

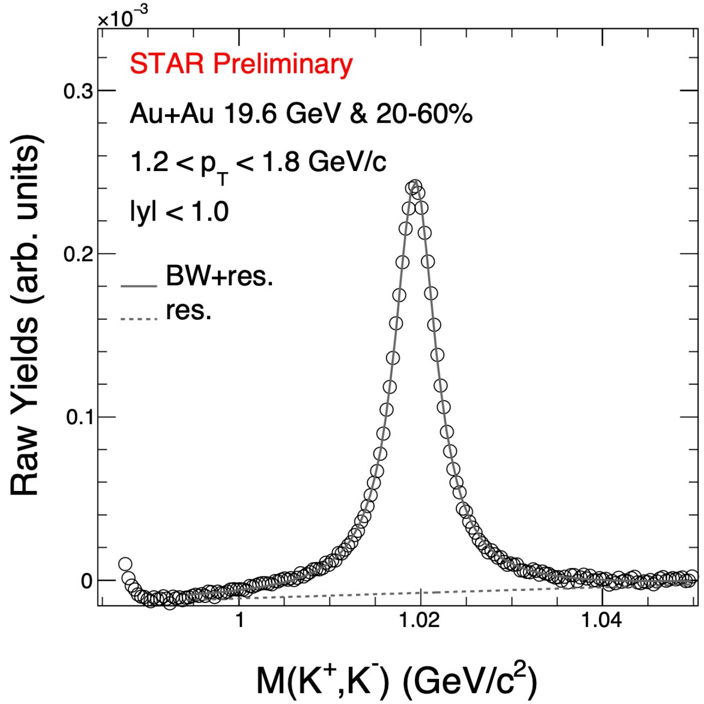
Extra information regarding rapidity dependent ϕ-meson ρ_{00} extraction and efficiency x acceptance corrections: https://drupal.star.bnl.gov/STAR/blog/gwilks3/Preliminary-Request-Details-ϕ-meson-global-spin-alignment

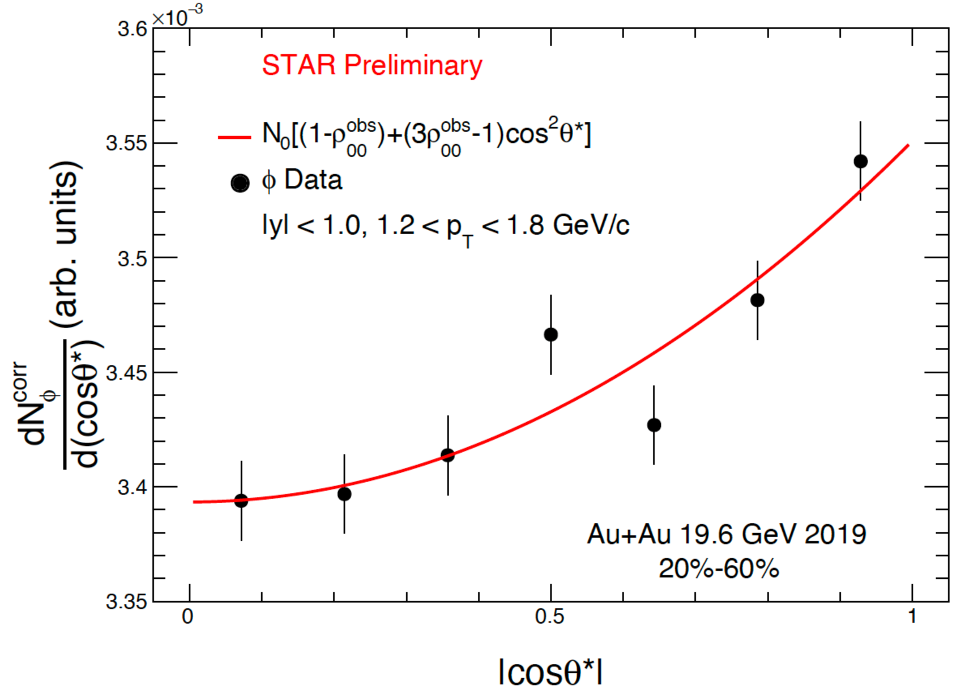
Technical Details



- Use Pythia6 to decay
- MC ϕ input flat in rapidity
  - p_T from spectra or interpolated
  - φ from v_2 distribution.
- Drop tracks using TPC tracking and ToF matching efficiency of K^+ and K^- in each η & φ bin.
- If both kaons pass efficiency cuts and η acceptance cut, reconstruct ϕ meson.
- Smear EP according to known EP resolution in each centrality.
- Fill histogram for RC and MC counts in each cos(θ*) bin.

Technical Details





- Event-mixing is used to subtract background and extract yields from histogram integration in seven |cosθ*| bins using Breit-Wigner + poly3 residual background:
  - $\frac{1}{2\pi}\frac{AF}{(m-m_{\phi})+(^{\Gamma}/_{2})^2} + poly3(m)$
- Yields vs. |cosθ*| are corrected for the geometric acceptance and tracking/PID efficiencies from previous slide.
- ρ_{00}^{obs} is extracted from a fit to the corrected yields vs. |cosθ*| [1]: $\frac{dN}{dcos\theta^*} = N_0 \times [(1-\rho_{00}^{obs}) + (\rho_{00}^{obs}-1)cos^2\theta^*]$

Abstract

In this Letter, we report differential measurements of ϕ-meson global spin alignment (ρ_{00}) in Au+Au collisions at $\sqrt{s_{NN}}$ = 14.6 and 19.6 GeV in the second phase of the Beam Energy Scan at RHIC (BES-II) using the STAR detector. Following the STAR measurement of $\rho_{00} > 1/3$ for the ϕ-meson at $\sqrt{s_{NN}} \leq 62.4$ GeV [1], this study aims to clarify the source of this ρ_{00} signal in the ϕ-meson phase space using increased statistics available from BES-II. The first rapidity (y) dependent ρ_{00} results for ϕ-mesons are shown for $\sqrt{s_{NN}}$ = 14.6 and 19.6 GeV, in addition to new centrality and transverse momentum (p_T) dependent measurements. After developments of a theoretical model with a connection to strong force fields [2-6], predictions of the rapidity dependence at $\sqrt{s_{NN}}$ = 19.6 GeV were calculated in [7] and are consistent with our measurements. Additionally, we extracted a single integrated ρ_{00} for each collision energy, a new measurement at $\sqrt{s_{NN}}$ = 14.6 GeV, and we show consistency with the previous measurement at $\sqrt{s_{NN}}$ = 19.6 GeV. The results reported in this Letter help solidify our understanding of ρ_{00} as a proxy measurement of vector meson fields, crucial components of the nuclear force.

[1] STAR Collaboration. Nature **614**, 244–248 (2023)

[2] X.L. Sheng et al. PRD **101**, 096005 (2020).

[3] X.L. Sheng et al. PRD **105**, 099903 (2022).

[4] X.L. Sheng et al. PRD **102**, 056013 (2020).

[5] X.L. Sheng et al. arXiv:2206.05868 **[hep-ph]** (2023).

[6] X.L. Sheng et al. PRL **131**, 042304 (2023).

[7] X.L. Sheng et al. arXiv:2308.14038 **[nucl-th]** (2023)

Systematic Uncertainties

Red marks the default value

- $n\sigma_\pi$: 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
- Difference between negative and positive rapidity bins for rapidity dependent study. Default is statistical error weighted mean of positive and negative bin.

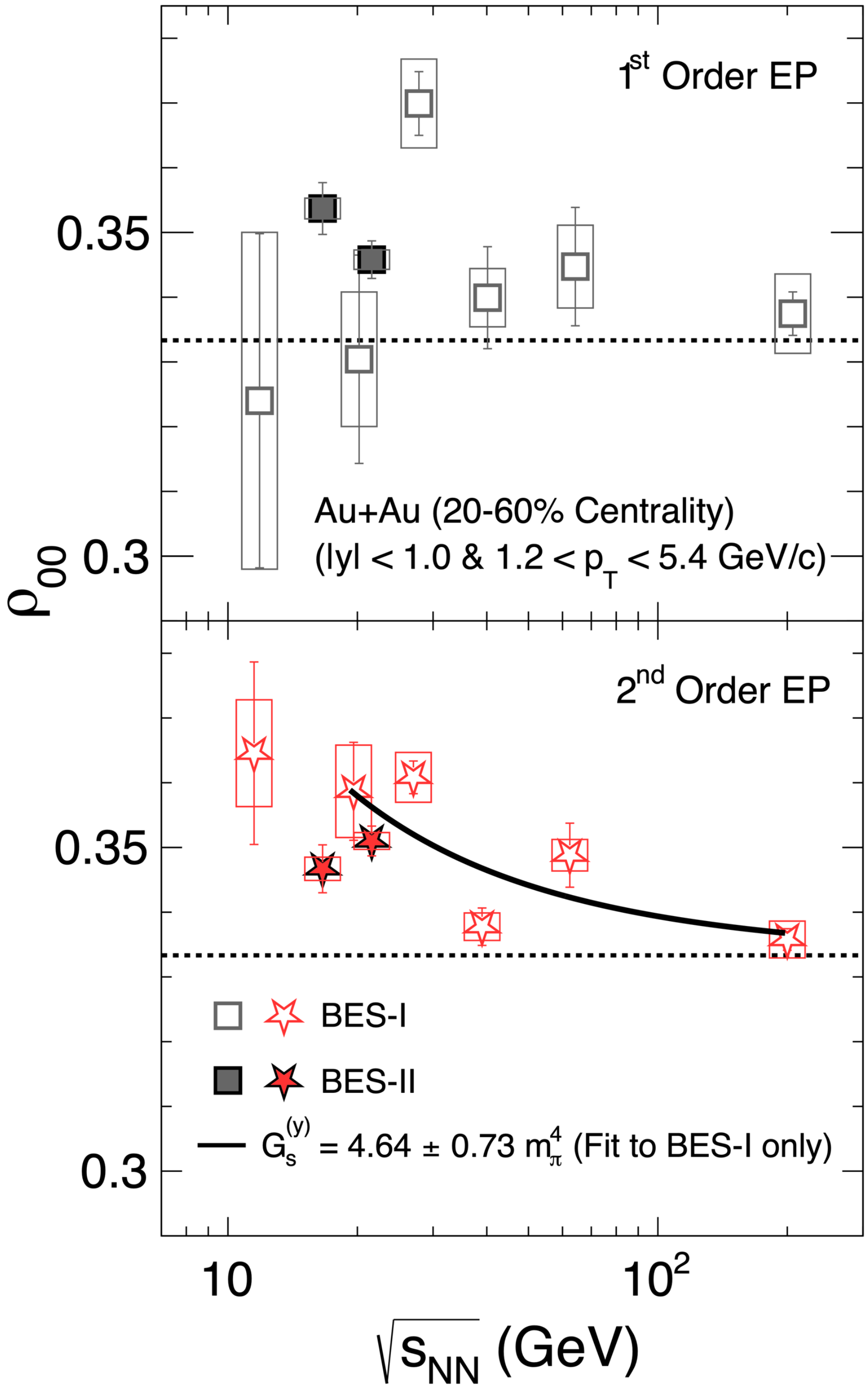


Figure 1.

Collision energy ($\sqrt{s_{NN}}$) dependent ρ_{00} for 20-60% centrality Au+Au collisions using first (top) and second (bottom) order event planes. The BES-II results are slightly shifted horizontally. The vertical lines are statistical uncertainties and boxes represent systematic uncertainties. A fit to BES-I measurements between $\sqrt{s_{NN}} = 19.6$ to 200 GeV is shown as a solid black curve, based on theoretical model in [2-6]. $G^{(y)}_{s}$ is the fitted parameter and is displayed with uncertainty. The black dashed line represents $\rho_{00}=1/3$.

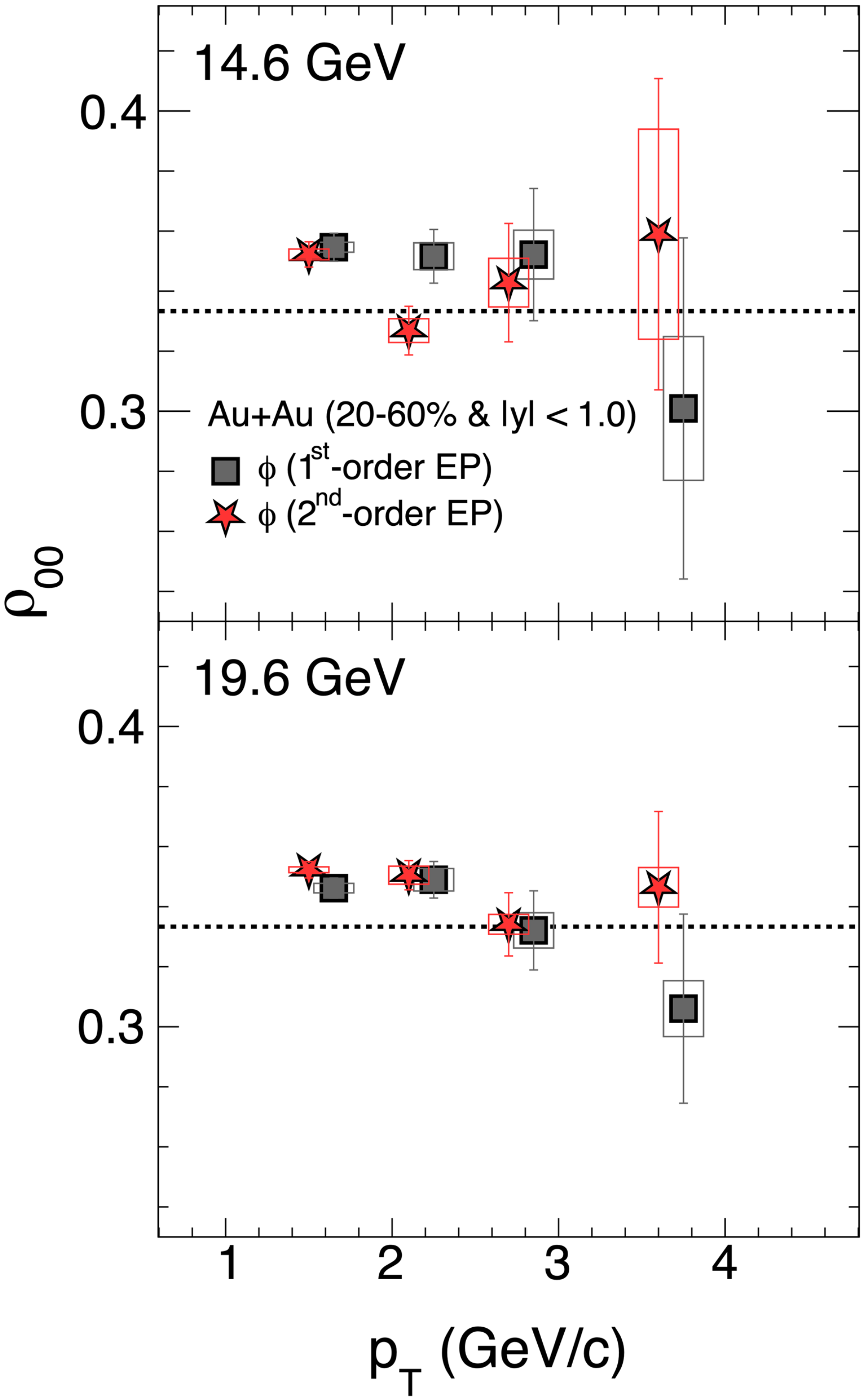


Figure 2.

Transverse momentum (p_{T}) dependent ρ_{00} with respect to the first and second order event planes for 20-60% centrality Au+Au collisions at $\sqrt{s_{NN}}$ = 14.6 (top) and 19.6 (bottom) GeV. The first order event plane results are slightly shifted horizontally. The vertical lines are statistical uncertainties and boxes represent systematic uncertainties. The black dashed line represents $\rho_{00}=1/3$.

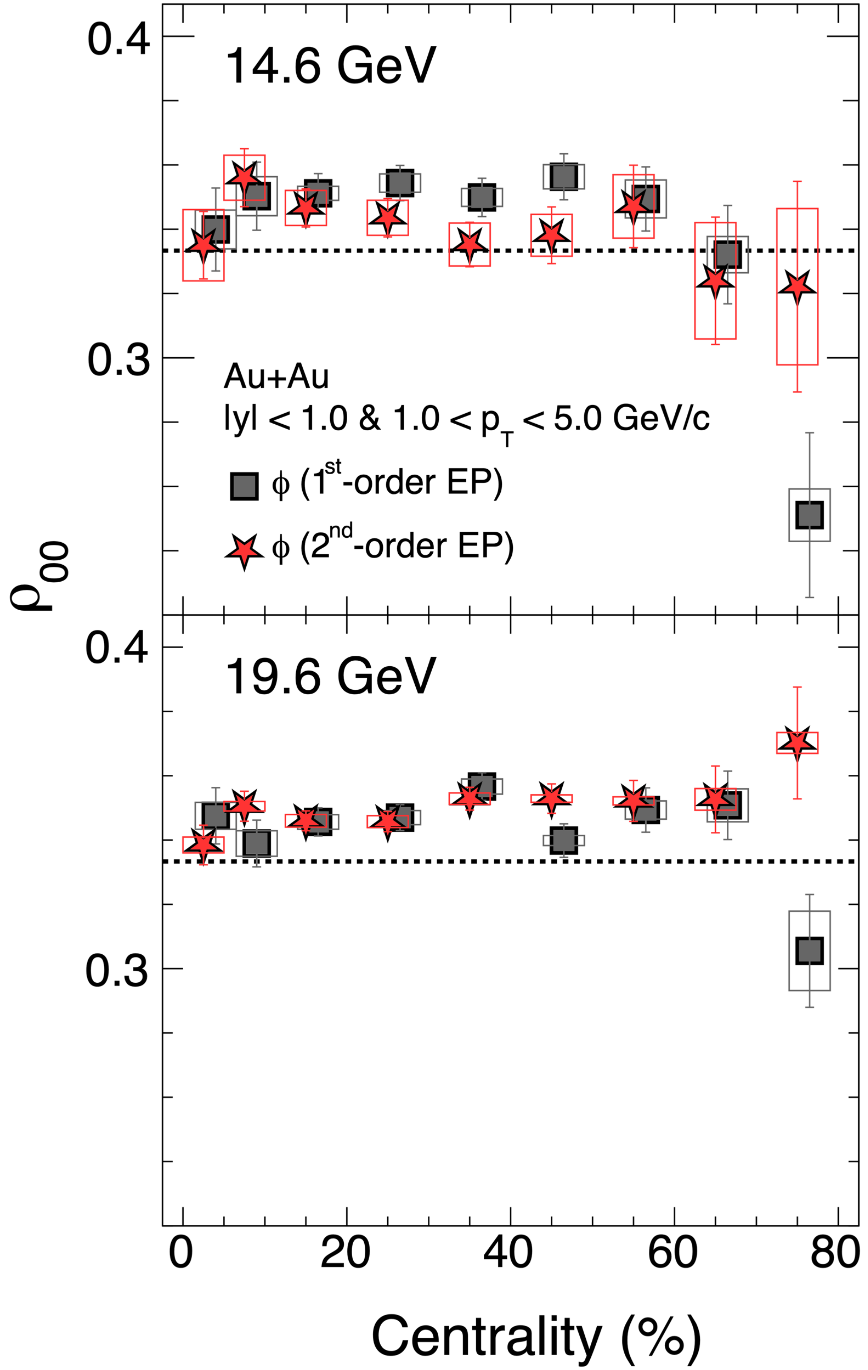


Figure 3.

Centrality dependent ρ_{00} with respect to the first and second order event planes for Au+Au collisions at $\sqrt{s_{NN}}$ = 14.6 (top) and 19.6 (bottom) GeV. The first order event plane results are slightly shifted horizontally. The vertical lines are statistical uncertainties and boxes represent systematic uncertainties. The black dashed line represents $\rho_{00}=1/3$.

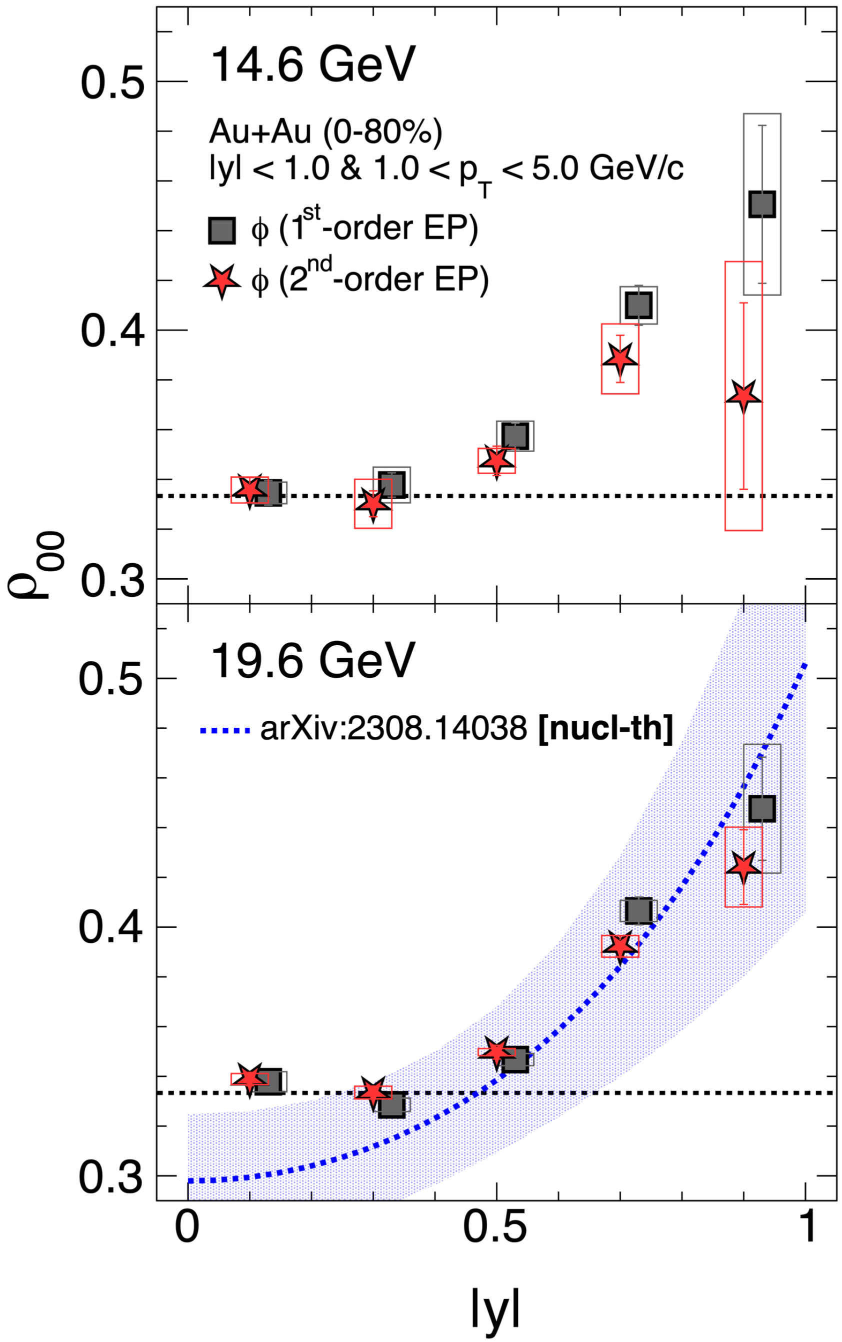


Figure 4.

Rapidity ($\vert y \vert$) dependent ρ_{00} for 0-80% centrality Au+Aucollisions at $\sqrt{s_{NN}}$ = 14.6 (top) and 19.6 (bottom) GeV. Results for ρ_{00} calculated with respect to the first and second order event plane are shown. The first order event plane results are slightly shifted horizontally. The vertical lines are statistical uncertainties and boxes represent systematic uncertainties. The theoretical prediction from [7] for 20-60% centrality and p_{T}=[1.2,5.4] GeV/c is shown as a dashed blue line with a shaded band representing its uncertainty. The black dashed line represents $\rho_{00}=1/3$.

X.L. Sheng et al. PRL **131**, 042304 (2023).

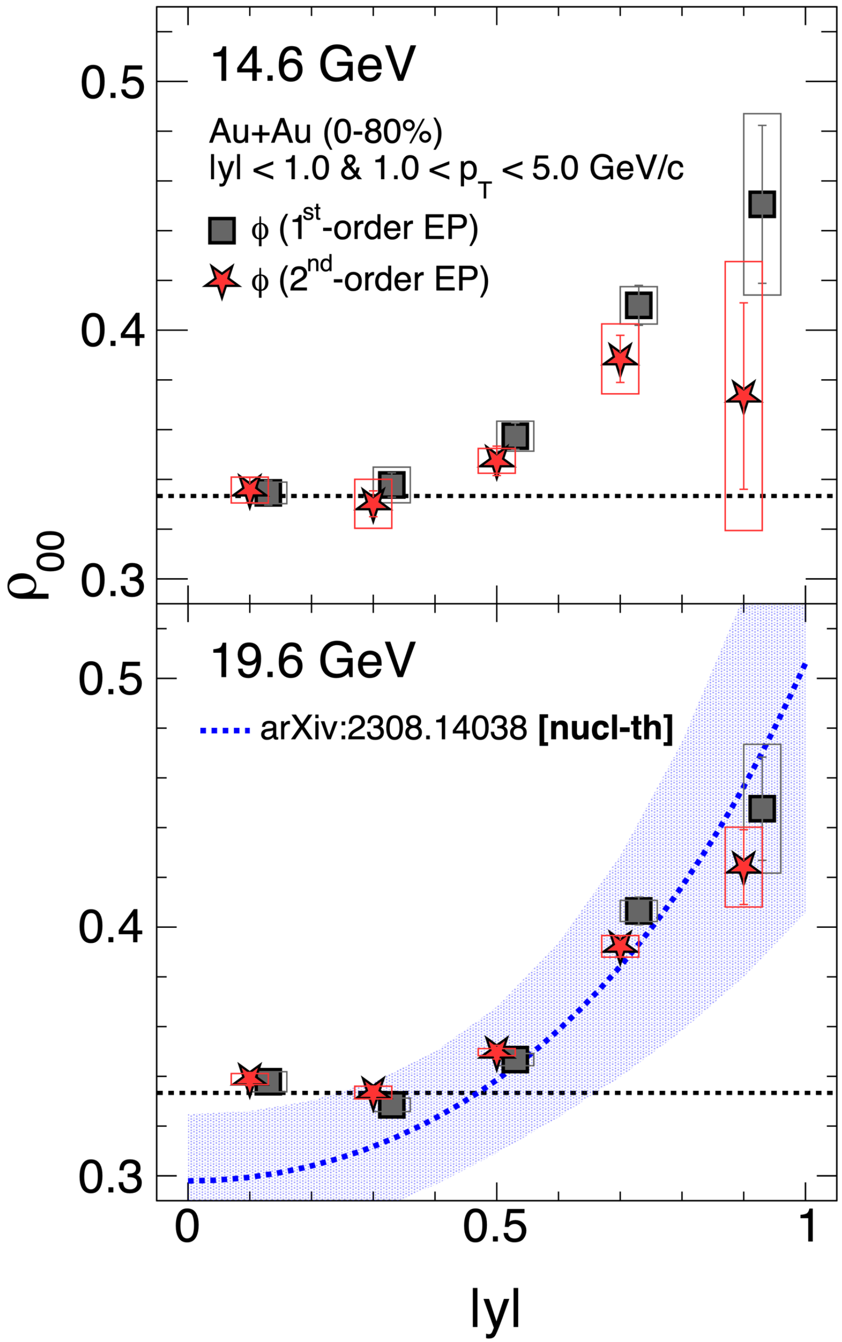


Figure 4.

Rapidity ($\vert y \vert$) dependent ρ_{00} for 0-80% centrality Au+Aucollisions at $\sqrt{s_{NN}}$ = 14.6 (top) and 19.6 (bottom) GeV. Results for ρ_{00} calculated with respect to the first and second order event plane are shown. The first order event plane results are slightly shifted horizontally. The vertical lines are statistical uncertainties and boxes represent systematic uncertainties. The theoretical prediction from [3] for 20-60% centrality and p_{T}=[1.2,5.4] GeV/c is shown as a dashed blue line with a shaded band representing its uncertainty. The black dashed line represents $\rho_{00}=1/3$.

X.L. Sheng et al. PRL **131**, 042304 (2023).

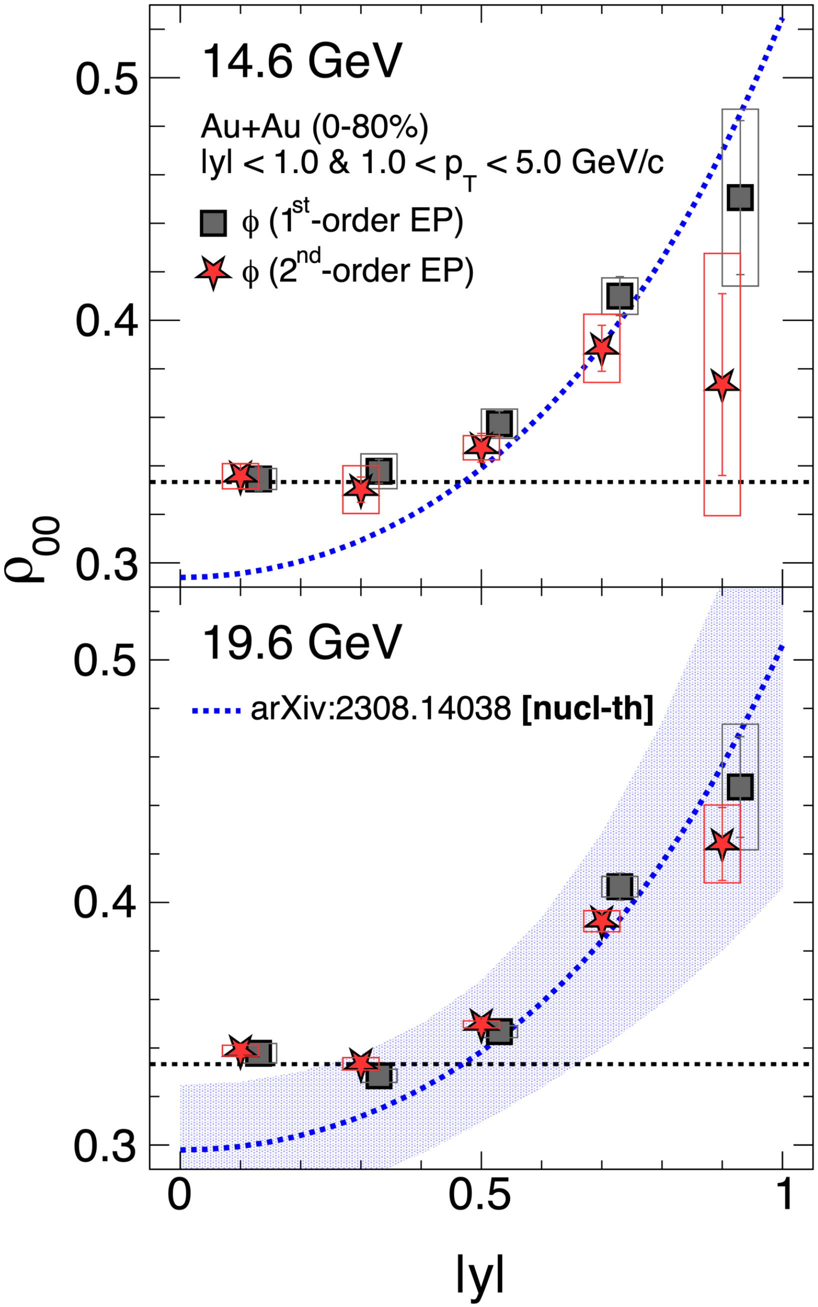
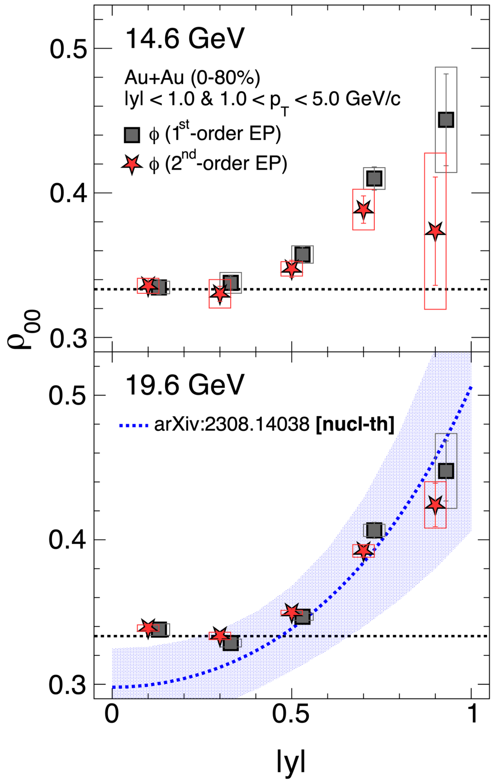


Figure 4.

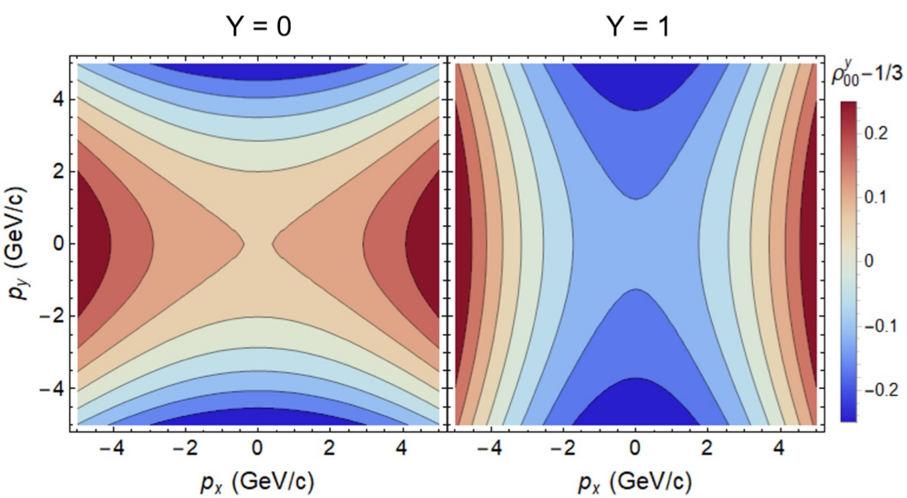
With new 14.6 GeV from Xin-Li Sheng.

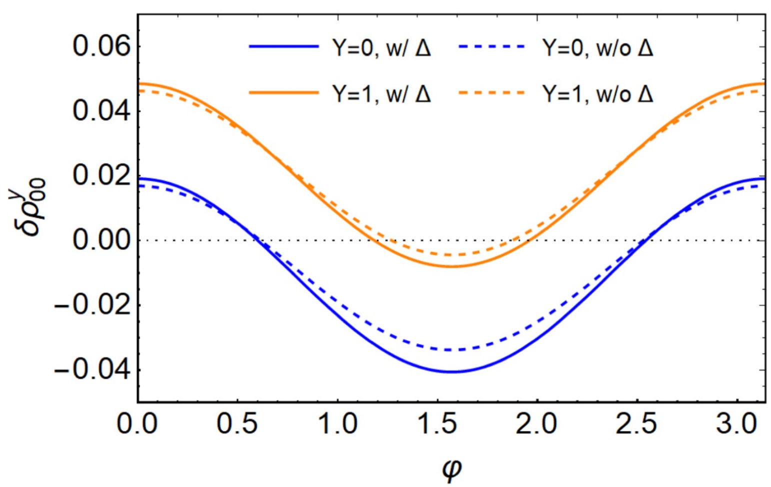


Theory Predictions

- Motion of the ϕ-meson in the lab frame induces anisotropy of field fluctuations in ϕ-meson rest frame perpendicular to the motion.

$$\langle \delta\rho_{00}^{y} \rangle (\mathbf{p}) \propto \frac{1}{2} p_T^2 \left[3\cos(2\varphi) - 1\right] + \sqrt{m_\phi^2 + p_T^2}\, \sinh^2 Y \,.$$





arXiv:2308.14038 [nucl-th]

Conclusions

- All results are consistent for 1st and 2nd order event planes.
- BES-I and BES-II integrated ρ_{00} for mid-central collisions is consistent for 19.6 GeV and we report higher precision.
- We show the p_T and centrality dependent ρ_{00}.
- Rapidity dependent results show an increasing trend with $\rho_{00} \sim 1/3$ at $|y| = 0$ and $\rho_{00} > 1/3$ signal at $|y| = 1$.
  - Consistent with theory predictions in [1].
  - Motion of ϕ-meson induces anisotropy of field fluctuations perpendicular to motion, resulting in larger ρ_{00} in this perpendicular plane [2].

[1] X.L. Sheng et al. PRL **131**, 042304 (2023).
[2] X.L. Sheng et al. arXiv:2308.14038 **[nucl-th]** (2023).

BACKUP

All the plots for each step of this analysis have been posted to the following blog page: https://drupal.star.bnl.gov/STAR/blog/gwilks3/φ-meson-Global-Spin-Alignment-Step-Step-Analysis-Details

EP Resolution and Acceptance Correction

- To ensure ρ_{00} with respect to the 2^{nd} order EP is consistent with ρ_{00} with respect to the 1^{st} order EP one must use the 2^{nd} order EP "resolution" with respect to the reaction plane that the 1^{st} order EP is perturbing around.

$$R_{21} = \langle \cos 2(\Psi_2 - \Psi_{r,1}) \rangle$$

- R_{21} can be found by using the following relation.

$$\begin{aligned} D_{12} &\equiv \langle \cos 2(\Psi_1 - \Psi_2) \rangle \\ &= \langle \cos 2(\Psi_1 - \Psi_{r,1} + \Psi_{r,1} - \Psi_2) \rangle \\ &\approx \langle \cos 2(\Psi_1 - \Psi_{r,1}) \rangle \langle \cos 2(\Psi_{r,1} - \Psi_2) \rangle \\ &= R_1 \cdot R_{21}. \end{aligned}$$

- Since we are using the 2^{nd} order **sub-event** plane for our ρ_{00} calculations, we must use R_{21}^{Sub} instead.

$$R_{21}^{Sub} = R_{21}/\sqrt{2}$$

Phys. Rev. C **98**, 044907

ϕ-meson ρ_{00} vs p_T : Systematics

1. Choose central values for each source of systematic error.
2. Vary one cut at a time while keeping the others at the default value. Vary yield extraction method for non-default cuts. Calculate ρ_{00} for each variation and calculate the sources error with:

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

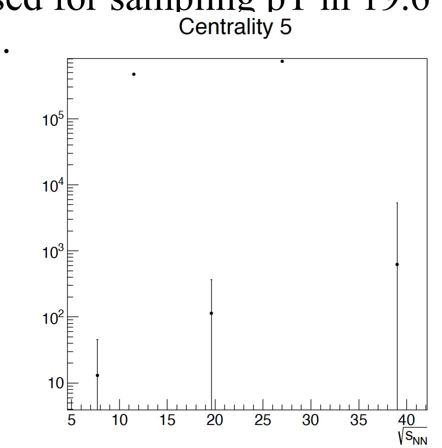
3. Combine all sources of systematics:

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

Au+Au 14.6 GeV p_T spectra interpolation

$$\frac{1}{2\pi m_T}\frac{d^2N}{dm_T dy} = \frac{dN/dy(n-1)(n-2)}{2\pi n T_{\text{Levy}}(nT_{\text{Levy}} + m_0(n-2))} \times \left(1 + \frac{m_T - m_0}{nT_{\text{Levy}}}\right)^{-n},$$

- Using Lévy function for interpolation is difficult due to parameter n varying too much energy to energy.
- Function used for sampling pT in 19.6 GeV simulations.



$$\frac{1}{2\pi m_T}\frac{d^2N}{dm_T\,dy} = \frac{dN/dy}{2\pi T_{\text{exp}}(m_0 + T_{\text{exp}})} e^{-(m_T - m_0)/T_{\text{exp}}},$$

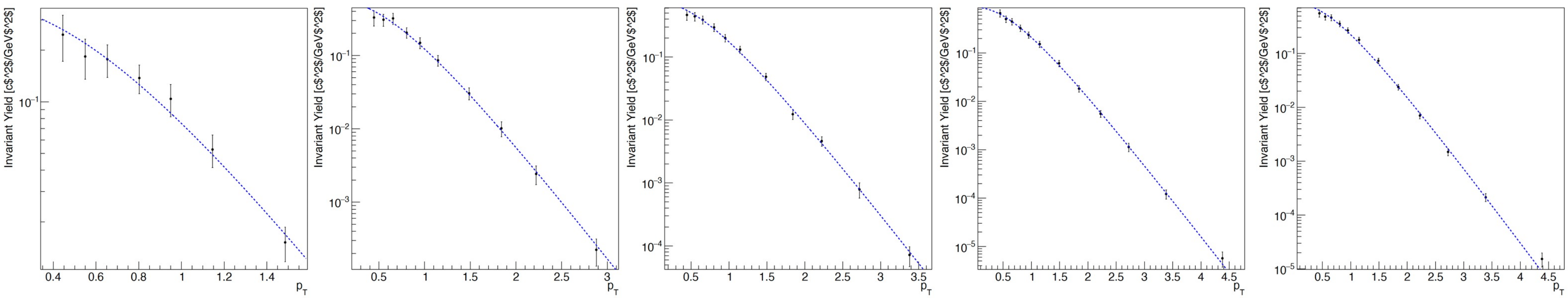
- In exponential function we have two well behaved parameters (dN/dy) and T_{exp}
- This will be used for extrapolation.
- Fit the distributions of the two parameters as a function of collision energy.
  - We really only need T_{exp} since dN/dy is just a normalization and we just want the shape.
- Then we can just grab the interpolated parameters for 14.6 GeV and generate the spectra for simulation.

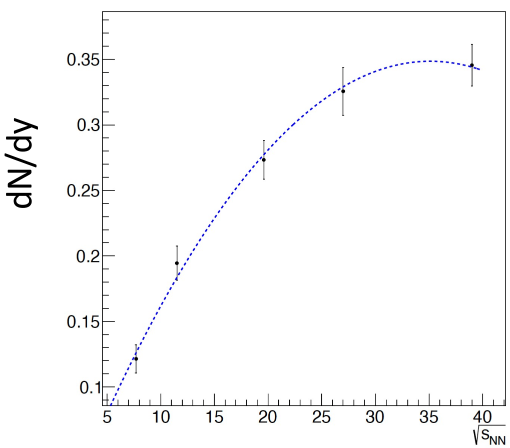
PHYSICAL REVIEW C **79**, 064903 (2009)

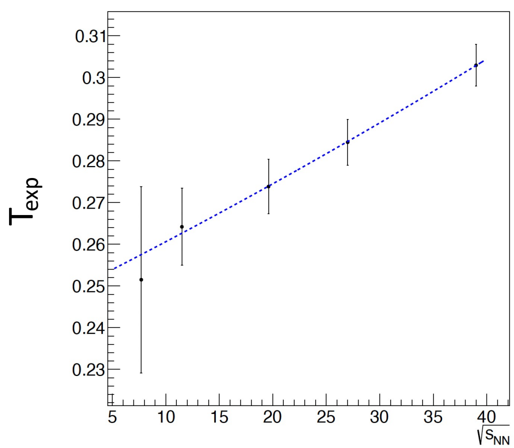
Au+Au 14.6 GeV p_T spectra interpolation

10-20% centrality

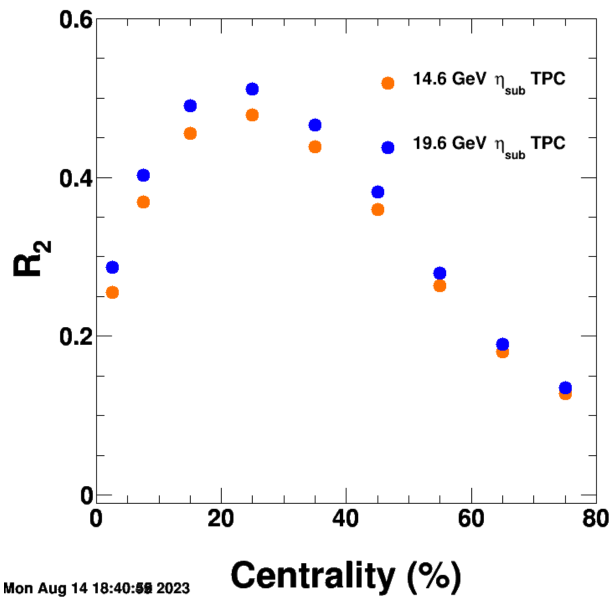
7.7 GeV | 11.5 GeV | 19.6 GeV | 27 GeV | 39 GeV

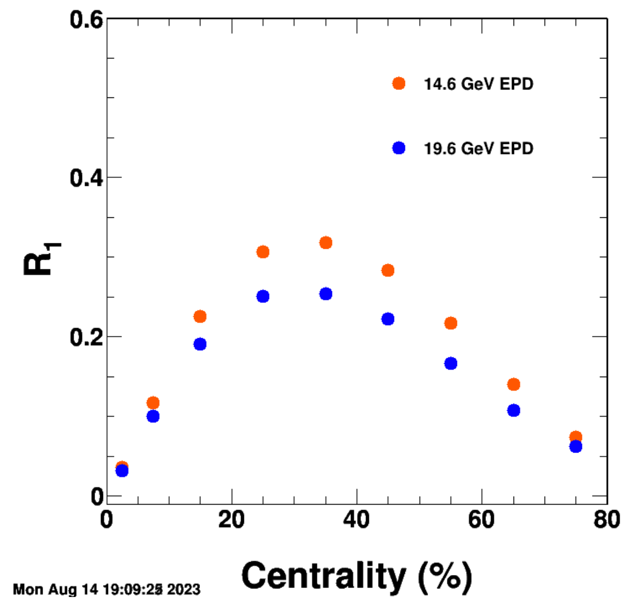




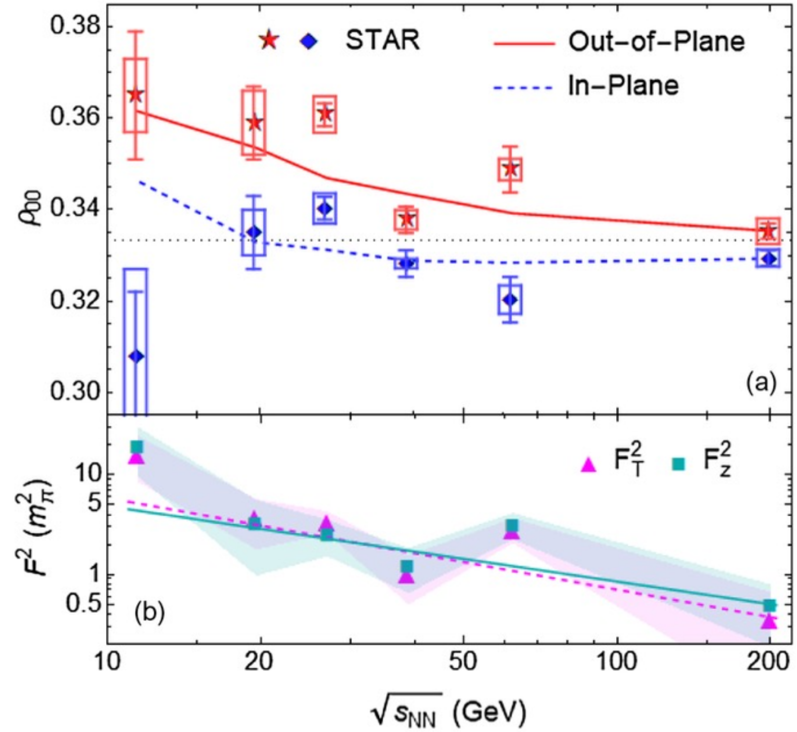


- Use second order polynomial to fit both parameters.
- Fits to parameters are well behaved.
- Performed for each centrality.


0.6
0.4
0.2
0
R_2
14.6 GeV η_{sub} TPC
19.6 GeV η_{sub} TPC
0
20
40
60
80
Centrality (%)


0.6
0.4
0.2
0
R_1
14.6 GeV EPD
19.6 GeV EPD
0
20
40
60
80
Centrality (%)

Theory Uncertainty



From Xin-Li Sheng on uncertainty calculations:

"1. By fitting center values for rho_00^y and rho_00^x, we obtain the center values for parameters F_T^2 and F_z^2. Since we have two parameters and two results, there is no calculation uncertainty in this process.
2. In a similar way, we calculate F_T^2 and F_z^2 using (rho_00^y +- sigma_y) and (rho_00^x +- sigma_x), where sigma denotes the total uncertainty, given by the STAR's paper. So we obtain four sets of parameters. For each parameter, we take the maximum value among these sets as the upper limit for the uncertainty band, and take the minimum value as the lower limit.
3. Using the above four sets of parameters, we calculate rho_00 as a function of rapidity and obtain four results. Again, we take the maximum (minimum) value as the upper (lower) limit for the uncertainty band."

$$\rho_{00}(x,\mathbf{k}) \approx \frac{1}{3} + \boxed{C_1\left[\frac{1}{3}\boldsymbol{\omega}'\cdot\boldsymbol{\omega}' - (\boldsymbol{\epsilon}_0\cdot\boldsymbol{\omega}')^2\right]}$$

vorticity contributions are negligible

$$+\boxed{C_2\left[\frac{1}{3}\boldsymbol{\varepsilon}'\cdot\boldsymbol{\varepsilon}' - (\boldsymbol{\epsilon}_0\cdot\boldsymbol{\varepsilon}')^2\right]}$$

$$-\frac{4g_\phi^2}{m_\phi^2 T_{\mathrm{h}}^2}C_1\left[\frac{1}{3}\mathbf{B}'_\phi\cdot\mathbf{B}'_\phi - (\boldsymbol{\epsilon}_0\cdot\mathbf{B}'_\phi)^2\right]$$

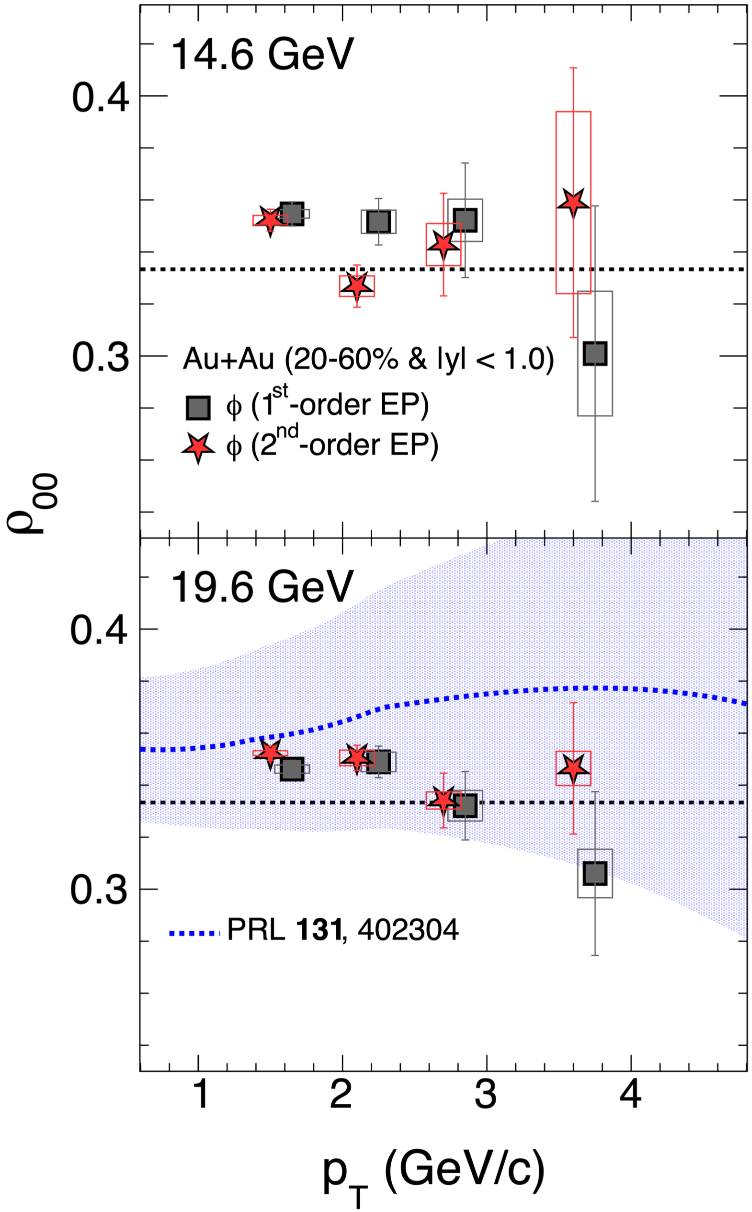
$$-\frac{4g_\phi^2}{m_\phi^2 T_{\mathrm{h}}^2}C_2\left[\frac{1}{3}\mathbf{E}'_\phi\cdot\mathbf{E}'_\phi - (\boldsymbol{\epsilon}_0\cdot\mathbf{E}'_\phi)^2\right],$$

$$\langle(g_\phi\mathbf{B}^\phi_{x,y}/T_{\mathrm{h}})^2\rangle = \langle(g_\phi\mathbf{E}^\phi_{x,y}/T_{\mathrm{h}})^2\rangle \equiv F_T^2$$

$$\langle(g_\phi\mathbf{B}^\phi_{z}/T_{\mathrm{h}})^2\rangle = \langle(g_\phi\mathbf{E}^\phi_{z}/T_{\mathrm{h}})^2\rangle \equiv F_z^2$$

X.L. Sheng et al. PRL **131**, 042304 (2023).

Figure 1.



Transverse momentum (p_{T}) dependent ρ_{00} with respect to the first and second order event planes for 20-60% centrality Au+Au collisions at $\sqrt{s_{NN}}$ = 14.6 (top) and 19.6 (bottom) GeV. The first order event plane results are slightly shifted horizontally. The vertical lines are statistical uncertainties and boxes represent systematic uncertainties. The theoretical prediction from [2] is shown as a dashed blue line with a shaded band representing its uncertainty.

X.L. Sheng et al. PRL **131**, 042304 (2023).

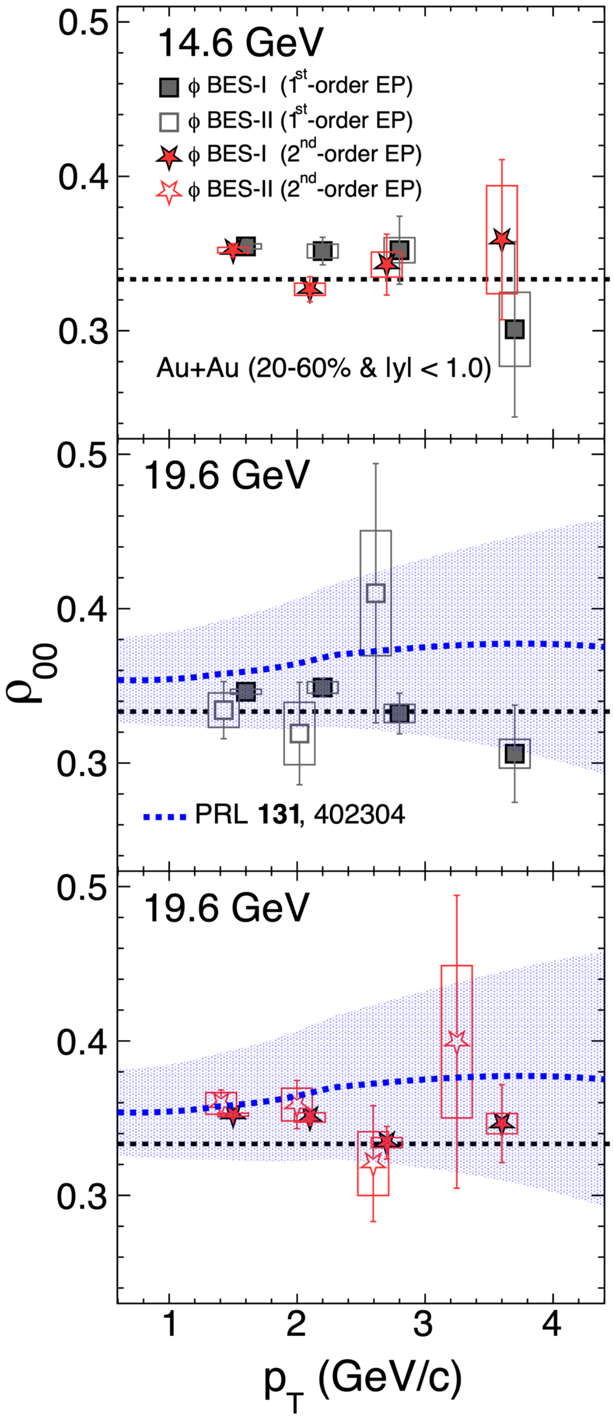
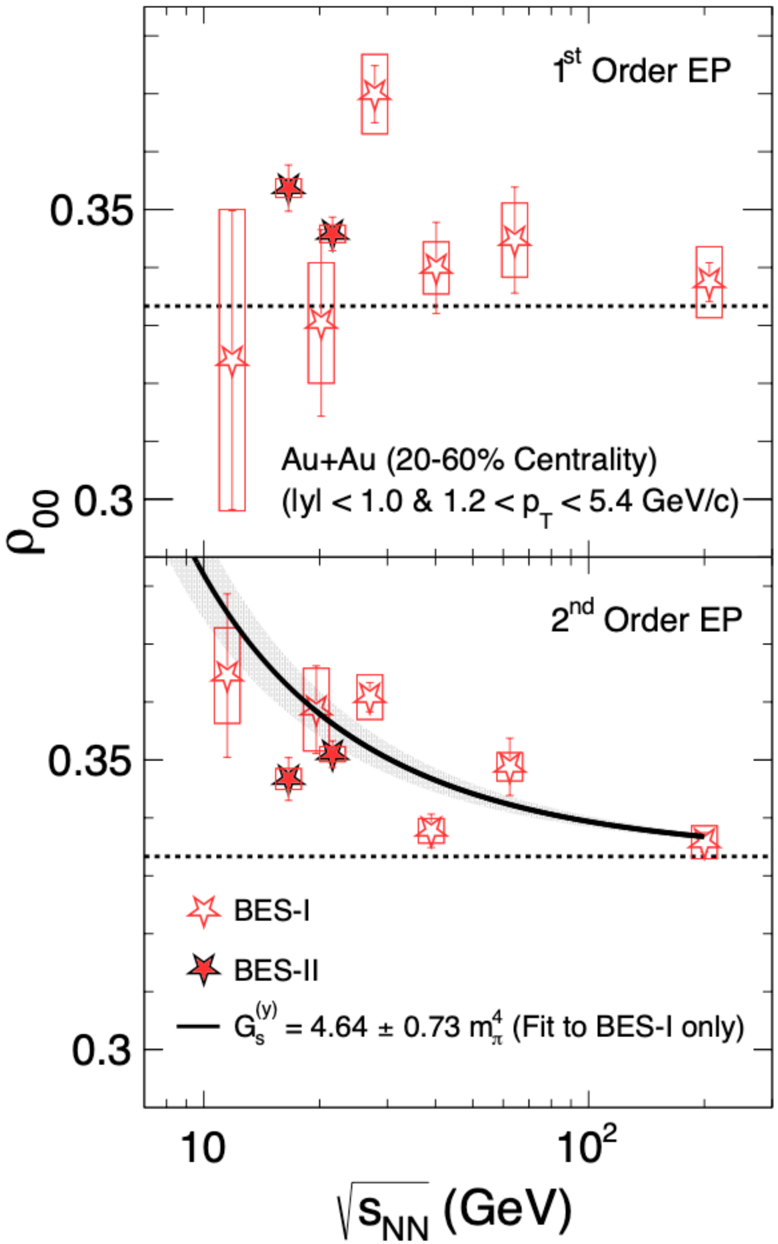


Figure 1. (new)

Transverse momentum (p_{T}) dependent ρ_{00} with respect to the first and second order event planes for 20-60% centrality Au+Au collisions at $\sqrt{s_{NN}}$ = 14.6 (top) and 19.6 (bottom) GeV. BES-I (BES-II) results are shown as unfilled (filled) symbols [1]. All first order event plane results are slightly shifted horizontally. The vertical lines are statistical uncertainties and boxes represent systematic uncertainties. The theoretical prediction from [2] is shown as a dashed blue line with a shaded band representing its uncertainty.

X.L. Sheng et al. PRL **131**, 042304 (2023).


1st Order EP
Au+Au (20-60% Centrality)
(|y| < 1.0 & 1.2 < p_T < 5.4 GeV/c)
2nd Order EP
BES-I
BES-II
$G_s^{(y)}$ = 4.64 ± 0.73 m_π^4 (Fit to BES-I only)
ρ_{00}
0.35
0.3
10
10^2
$\sqrt{s_{NN}}$ (GeV)