Differential Measurements of ϕ-meson Global Spin Alignment in Au+Au Collisions at STAR

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STAR

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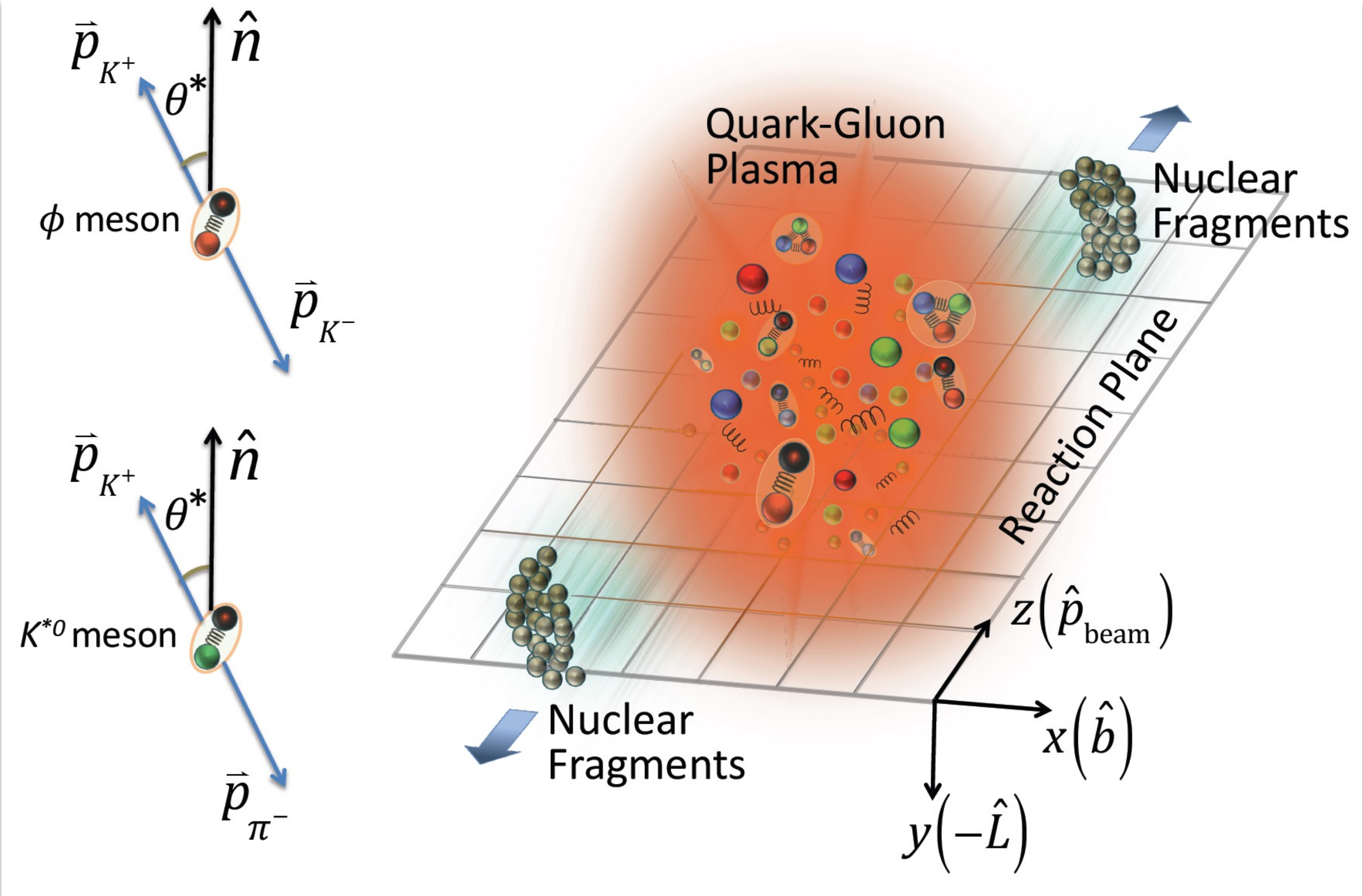
Outline

- Introduction to global spin alignment
- Motivation for this analysis
- Analysis method
- Results for ϕ-meson ρ_{00} from Au+Au collisions in STAR BES-II
- Summary

Introduction to Spin Alignment

- Non-central heavy-ion collisions generate large orbital angular momentum (OAM).
- This OAM can preferentially align a particle's spin projection along the spin quantization axis through spin-orbit coupling(1).



STAR Collaboration, Nature 614 (2023) 7947.

[1] Liang et al., Phys. Lett. B 629, 20–26 (2005).

Introduction to Spin Alignment

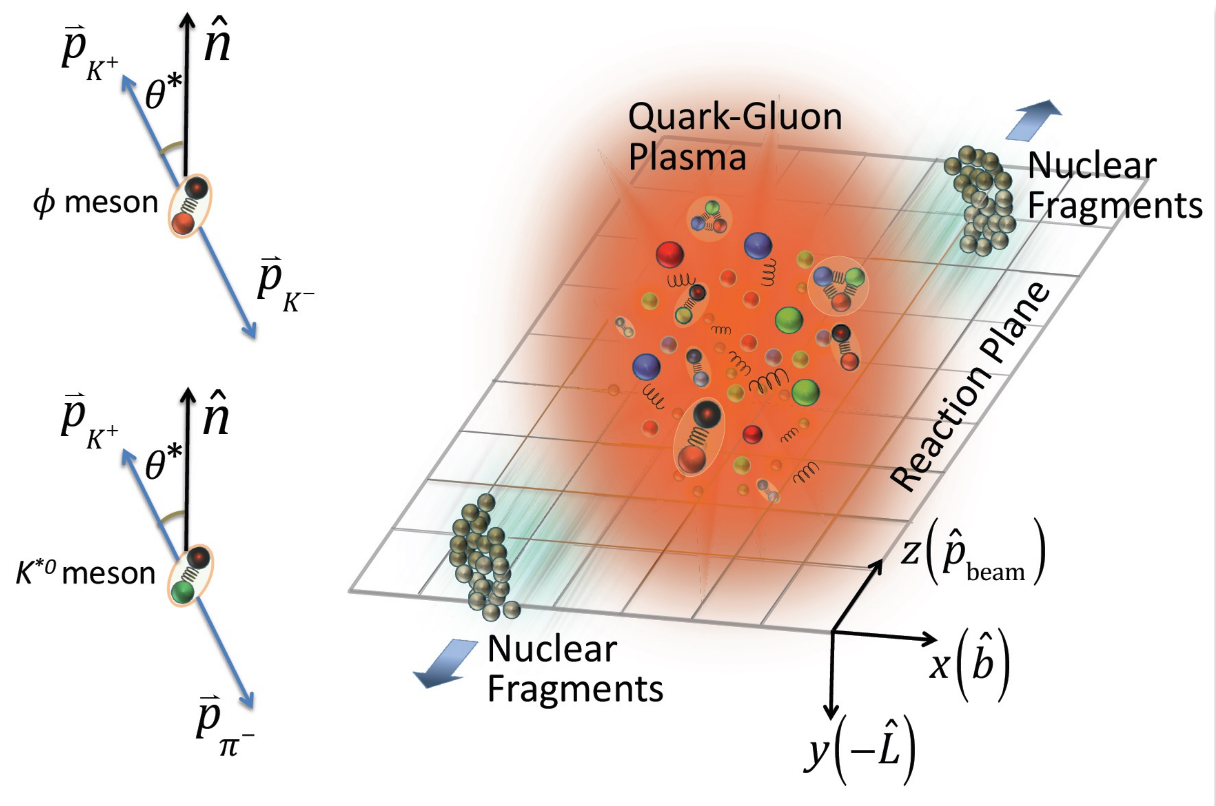
ρ_{00}: 00th element of the spin density matrix.

$\theta*$: angle between K^+ daughter momentum and polarization axis (normal of reaction plane) in parent's rest frame.

ρ_{00} is found by fitting the parent particle's yield (N) vs cos($\theta*$).(1)

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

$\rho_{00} \neq 1/3$ indicates spin alignment.

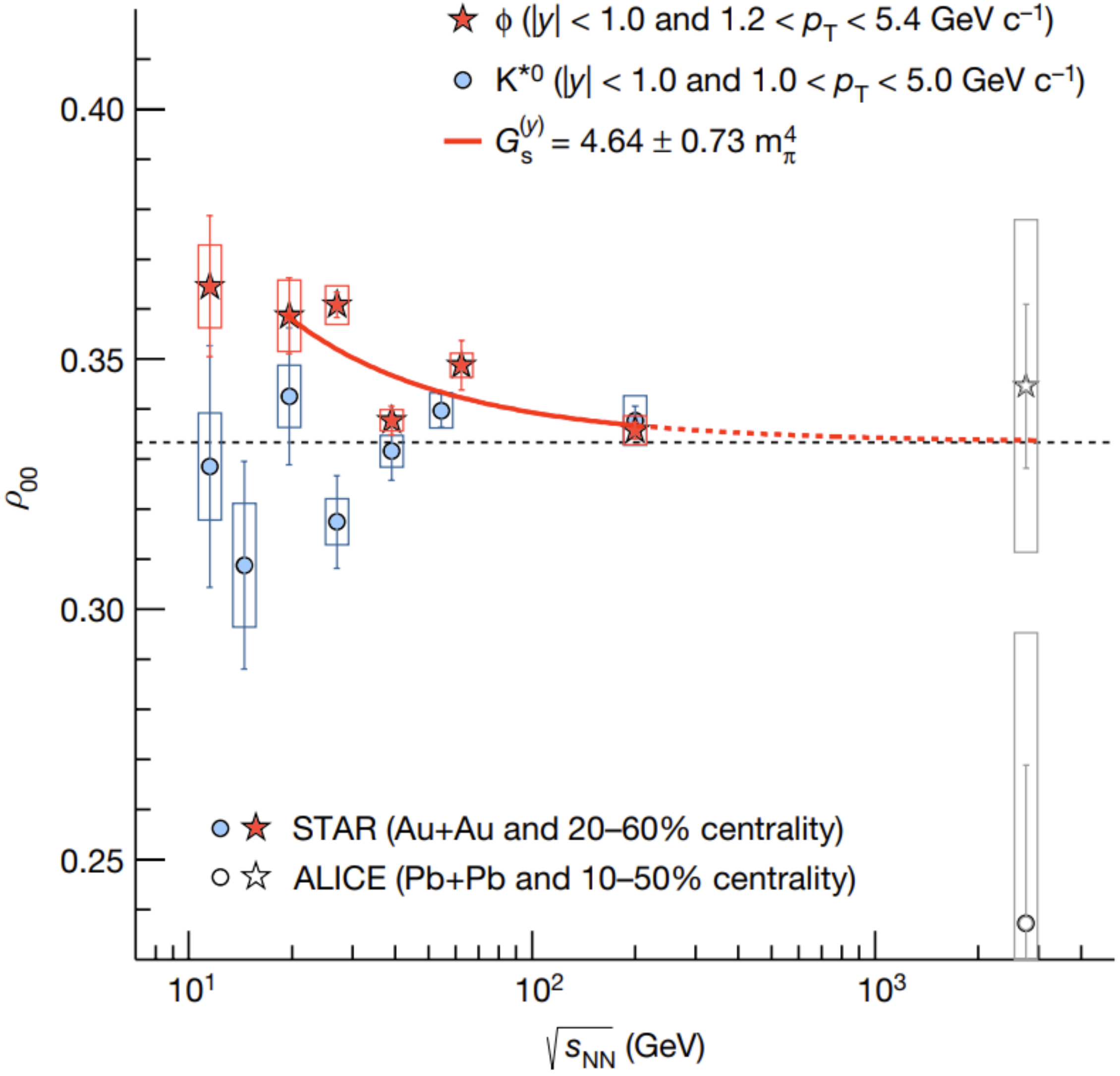


STAR Collaboration, Nature 614 (2023) 7947.

[1] Schilling et al., Nucl. Phys.B18, 332 (1970).

ρ_{00} from BES-I

[1] STAR Collaboration, Nature 614 (2023) 7947.



- Significant positive global spin alignment (ρ_{00}>1/3) for ϕ-meson was measured for the first time in mid-central collisions.$^{(1)}$
- ρ_{00} ~ 1/3 for K^{*0} in mid-central collisions.
  - Mean lifetime of K^{*0} is ~10x smaller than ϕ (different in-medium interactions).
  - If global spin alignment is driven by fluctuations in vector meson fields, fluctuations for *d* and $\bar{s}$ are expected to be weaker than for *s* and $\bar{s}$.

Potential Contributions to ϕ-meson ρ_{00}

Physics Mechanism	**ρ_{00}**	
Fragmentation of polarized quarks(1)	$\lesssim 1/3$	$\sim 10^{-5}$
Quark coalescence Magnetic components of EM and vorticity fields(1,2,3)	$< 1/3$	$\sim 10^{-5}$
Electric part of vorticity tensor(2)	$< 1/3$	$\sim 10^{-4}$
Electric field(2)	$> 1/3$	$\sim 10^{-5}$
Helicity polarization(4)	$< 1/3$	
Locally fluctuating axial charge currents(5)	$< 1/3$	
Local vorticity loop + coalescence(6)	$< 1/3$	
Vector meson strong force field(2,7)	$> 1/3$	

- Significant positive global spin alignment ($\rho_{00}>1/3$) for ϕ-meson was measured at midcentral collisions from BES-I.(8)
- Cannot be explained by conventional polarization mechanisms.
- Supported by a theoretical model considering a ϕ-meson strong force field (2,7).
  - Couples to s and $\bar{s}$ quarks.

[1] Liang et al., PLB 629, 20–26 (2005).
[2] Sheng et al., PRD 101, 096005 (2020).
[3] Yang et al., PRC 97, 034917 (2018).
[4] Gao et al., PRD 104, 076016 (2021).
[5] Müller et al., PRD 105, L011901 (2022).
[6] Xia et al., PLB 817, 136325 (2021).
[7] Sheng et al., PRD 102, 056013 (2020).
[8] STAR, Nature 614 (2023) 7947.

Potential Contributions to ϕ-meson ρ_{00}

Physics Mechanism	ρ_{00}	
Fragmentation of polarized quarks(1)	$\lessgtr 1/3$	$\sim 10^{-5}$
Quark coalescence Magnetic components of EM and vorticity fields(1,2,3)	$< 1/3$	$\sim 10^{-5}$
Electric part of vorticity tensor(2)	$< 1/3$	$\sim 10^{-4}$
Electric field(2)	$> 1/3$	$\sim 10^{-5}$
Helicity polarization(4)	$< 1/3$	
Locally fluctuating axial charge currents(5)	$< 1/3$	
Local vorticity loop + coalescence(6)	$< 1/3$	
Vector meson strong force field(2,7)	$> 1/3$	

- ϕ-meson mean field (if exists), can polarize $s\bar{s}$ → global spin alignment.
- Electric and magnetic components of ϕ field from field potential, ϕ^{μ}.

$$F_{\phi}^{\mu\nu} = \partial^{\mu}\phi^{\nu} - \partial^{\nu}\phi^{\mu}$$

$$\phi^{\mu} \approx -(g_{\phi}/m_{\phi}^{2})J_{s}^{\mu}$$

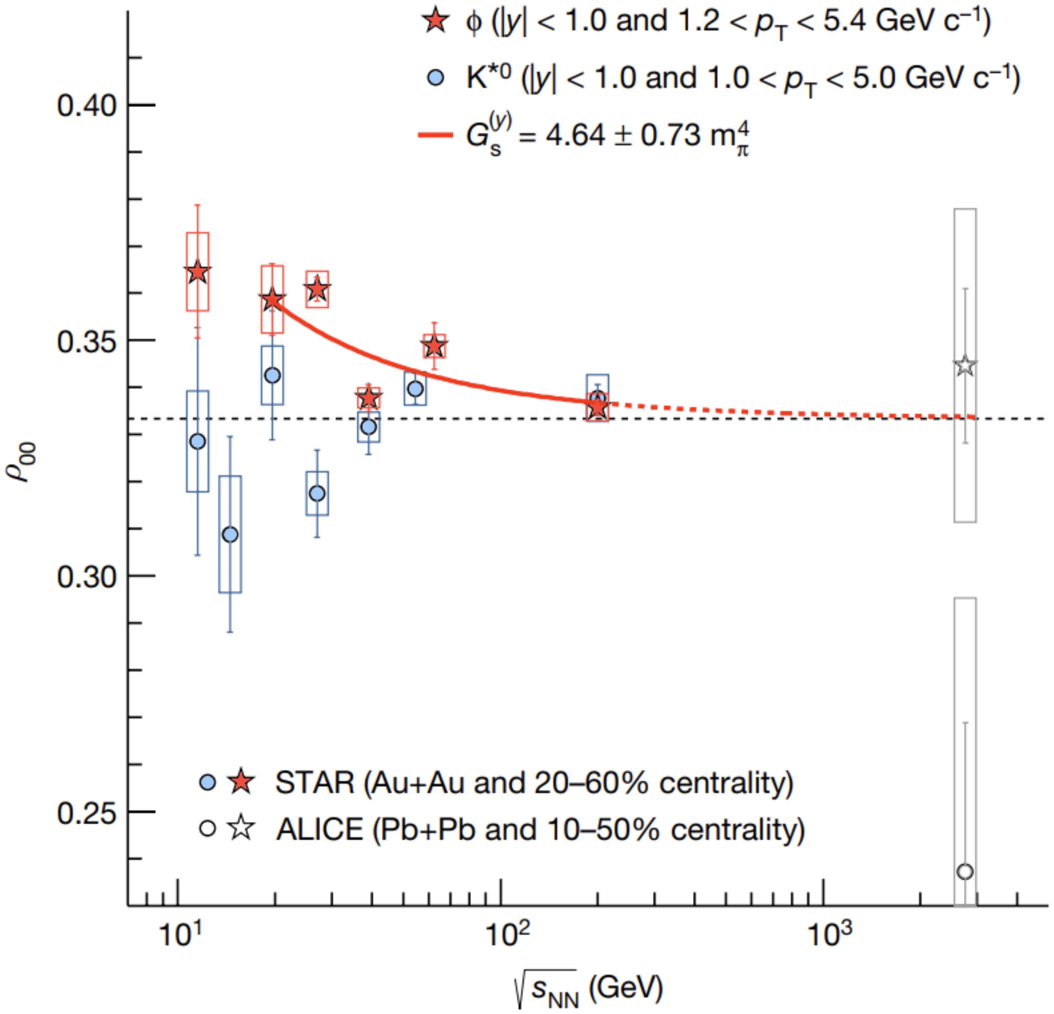
$$J_{s}^{\mu}(t,\mathbf{x}) = (\rho_{s},\mathbf{J}_{s}) = (\rho_{s}, j_{s}^{x}, j_{s}^{y}, j_{s}^{z})$$

Strangeness Conservation	Zero Net Strangeness
$\partial_{\mu}J_{s}^{\mu} = 0$	$\int d^{3}\mathbf{x}\rho_{s}(t,\mathbf{x}) = 0$

- Strangeness current in heavy-ion collisions could occur from nonequivalent PDFs, $s(x_{\mathrm{B}}) \neq \bar{s}(x_{\mathrm{B}})$.

Leading theory prediction for ϕ-meson ρ_{00}

STAR Collaboration, Nature 614 (2023) 7947.



- BES-I results suggest non-monotonic behavior.

Fit to ϕ-meson data is described by:

$$\rho_{00}(\sqrt{s_{NN}}) = \frac{1}{3} + \frac{1}{27 m_s^2 [T_{eff}(\sqrt{s_{NN}})]^2} G_s^{(y)}$$

With free parameter $G_s^{(y)}$:

$$G_s^{(y)} = g_\phi \left[3\langle B_{\phi,y}^2 \rangle + \frac{\langle \boldsymbol{p}^2 \rangle_\phi}{m_s^2} \langle E_{\phi,y}^2 \rangle - \frac{3}{2} \langle B_{\phi,x}^2 + B_{\phi,z}^2 \rangle - \frac{\langle \boldsymbol{p}^2 \rangle_\phi}{2 m_s^2} \langle E_{\phi,x}^2 + E_{\phi,z}^2 \rangle \right]$$

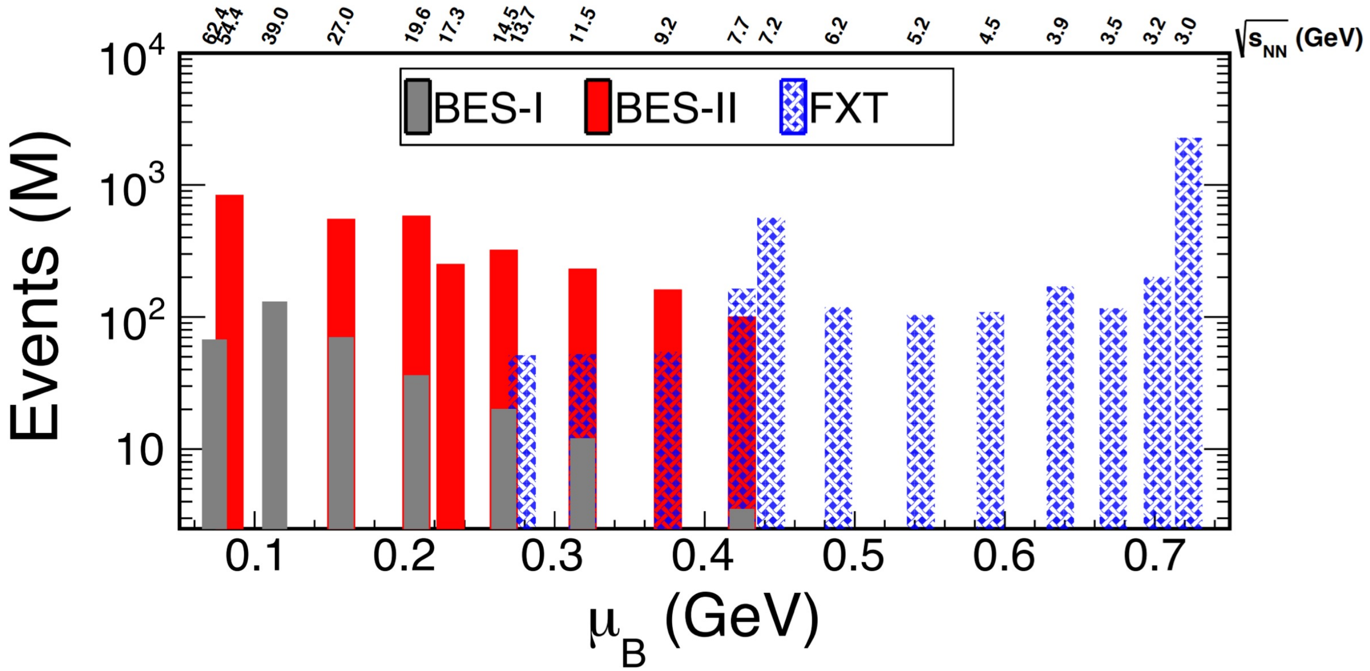
T_{eff}: effective temperature of quark gluon plasma (QGP) fireball
g_ϕ: ϕ-meson field coupling constant
$E_{\phi,i}(B_{\phi,i})$: ith component of electric (magnetic) parts of ϕ-meson field
m_s: strange quark mass
$\boldsymbol{p}$: strange quark momentum in ϕ rest frame
$\langle\ \rangle$: average over the spacetime volume of polarization in QGP fireball

[1] Sheng et al., Phys. Rev. D 101, 096005 (2020).
[2] Sheng et al., Phys. Rev. D 102, 056013 (2020).

STAR BES-II

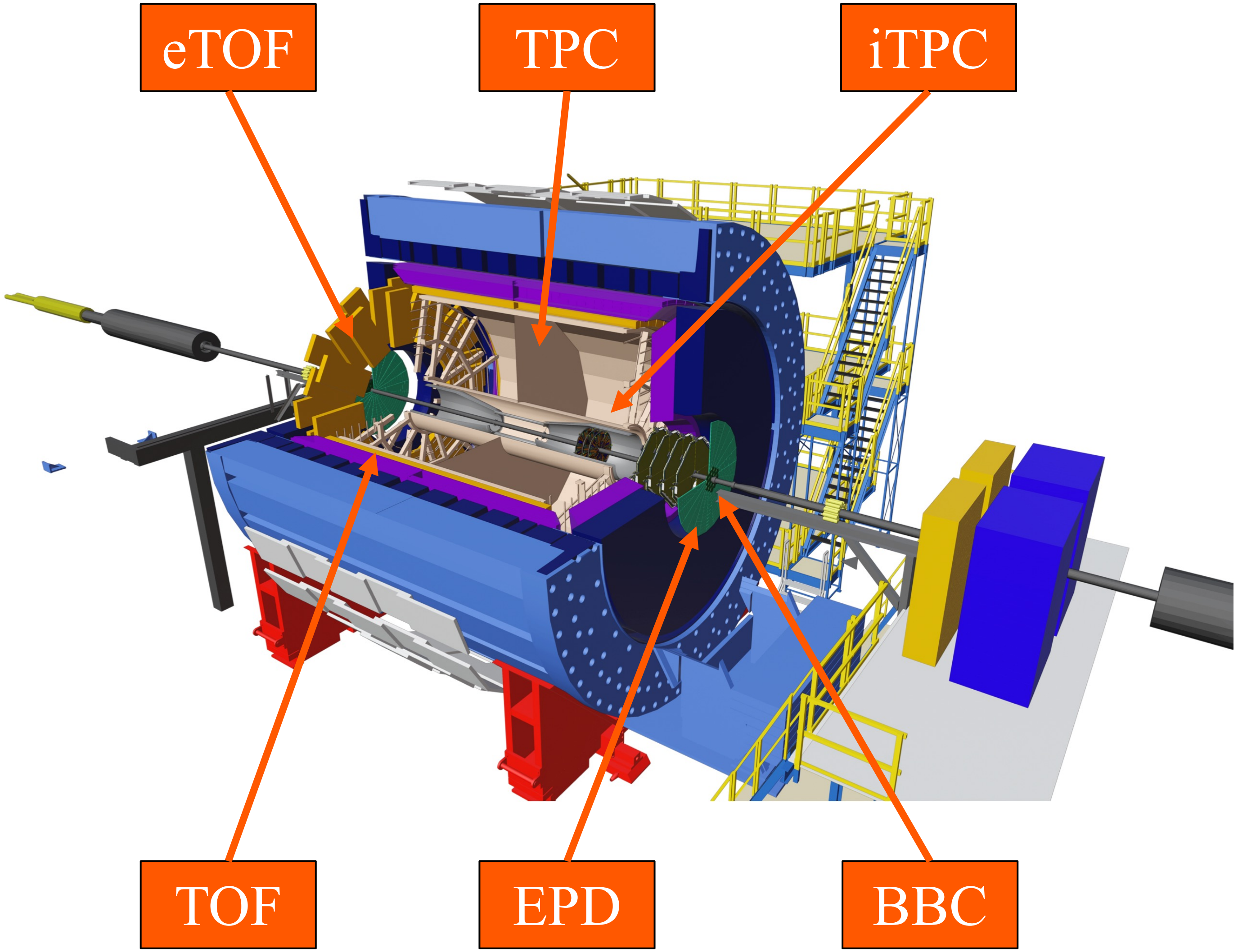
$\sqrt{s_{NN}}$ (GeV)	BES-I ($x10^6$ events)	BES-II ($x10^6$ events)
19.6	36[1]	478
14.6	18	324
11.5	12[1]	235
9.2	---	162
7.7	4	101

[1] STAR Collaboration, Nature 614 (2023) 7947.



- Significantly increased sample sizes available from BES-II for identical energies.
- Improvements to the STAR detector.
  - Increased event plane resolution.
  - Tracking improvements.
- Many new collision energies available.
  - Clarify behavior of ρ_{00} for lower collision energies and higher baryon densities.
- High precision differential measurements of ϕ-meson ρ_{00}.
  - Provide guidance for future theoretical developments.

The STAR Detector



Full azimuthal coverage

TPC : $|\eta| < 1$

iTPC^{II}: $|\eta| < 1.5$

tracking, centrality, particle identification, and 2nd order event plane reconstruction

TOF : $|\eta| < 0.9$

eTOF^{II}: $-1.1 < \eta < -1.6$

particle identification

BBC : $3.9 < |\eta| < 5$

EPD^{II}: $2.1 < |\eta| < 5.1$

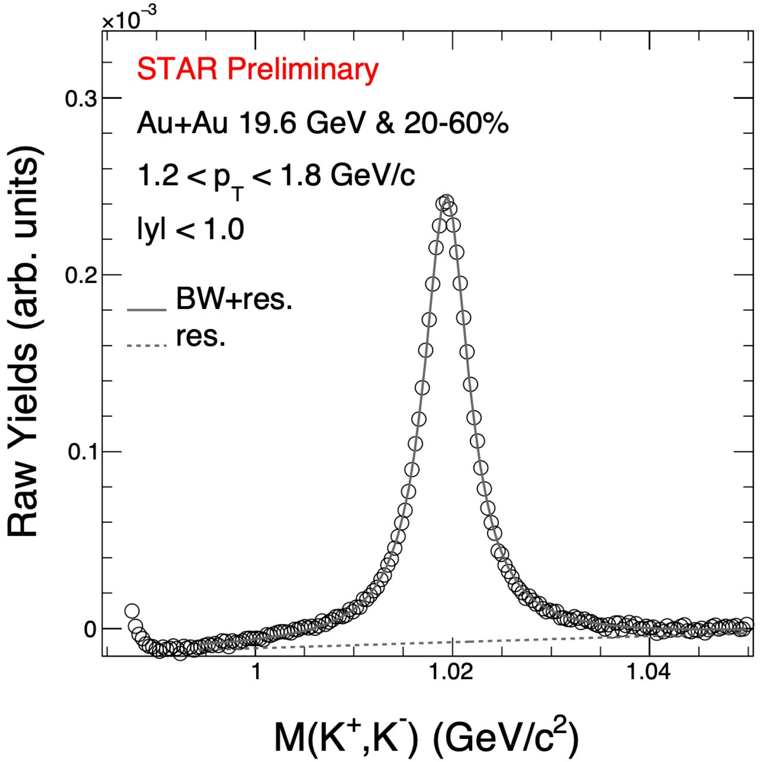
1st order event plane reconstruction

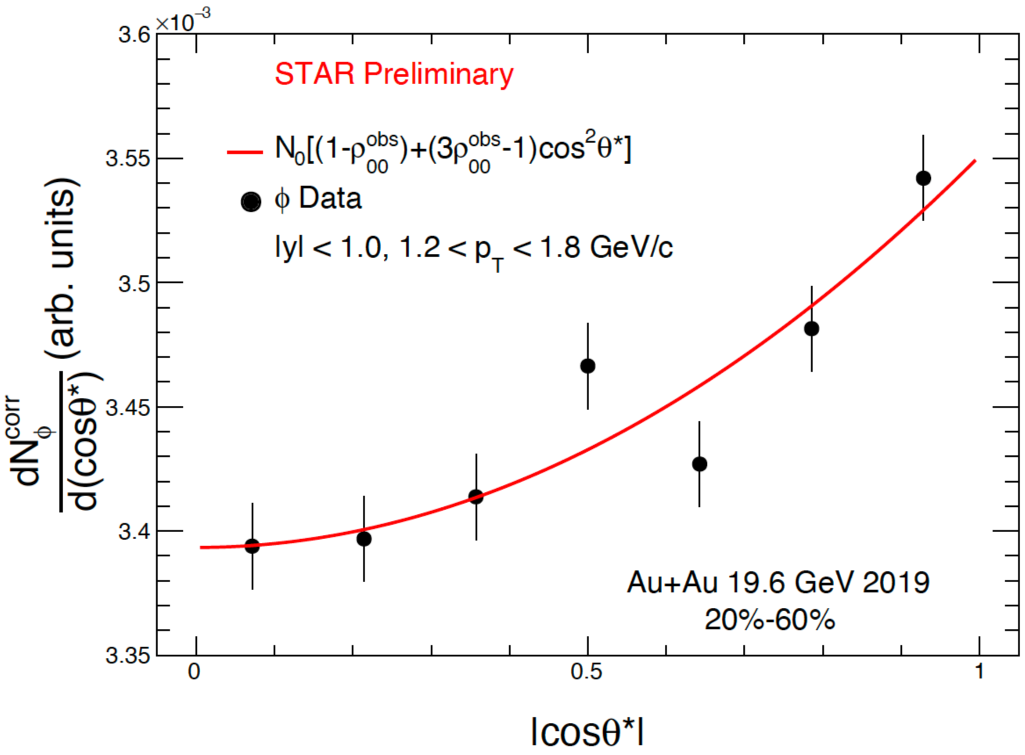
~2x greater EP resolution with EPD

Used in this analysis

[II] Upgrades to STAR since BES-I

ρ_{00} Extraction

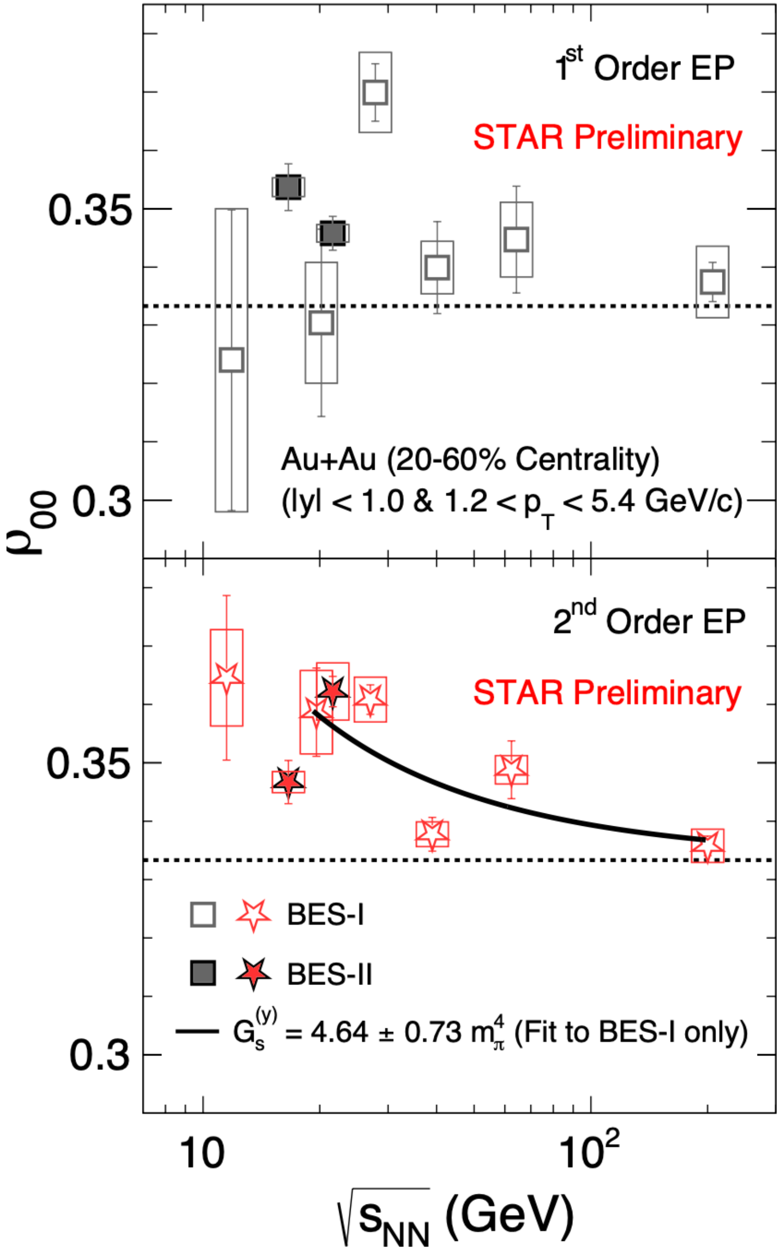




- Event-mixing is used to subtract background and extract yields from histogram integration in seven |cosθ*| bins.
- Yields vs. |cosθ*| are corrected for the geometric acceptance, tracking, and PID related efficiencies.
- ρ_{00}^{obs} is extracted from a fit to the corrected yields vs. |cosθ*|$^{(1)}$: $\frac{dN}{dcos\theta^*} = N_0 \times \left[\left(1-\rho_{00}^{obs}\right)+\left(3\rho_{00}^{obs}-1\right)cos^2\theta^*\right]$
- Calculate ρ_{00} from ρ_{00}^{obs} accounting for EP resolution$^{(2)}$: $\rho_{00} = \frac{1}{3}+\frac{4}{1+3R}\left(\rho_{00}^{obs}-\frac{1}{3}\right)$; R = Event plane resolution.

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

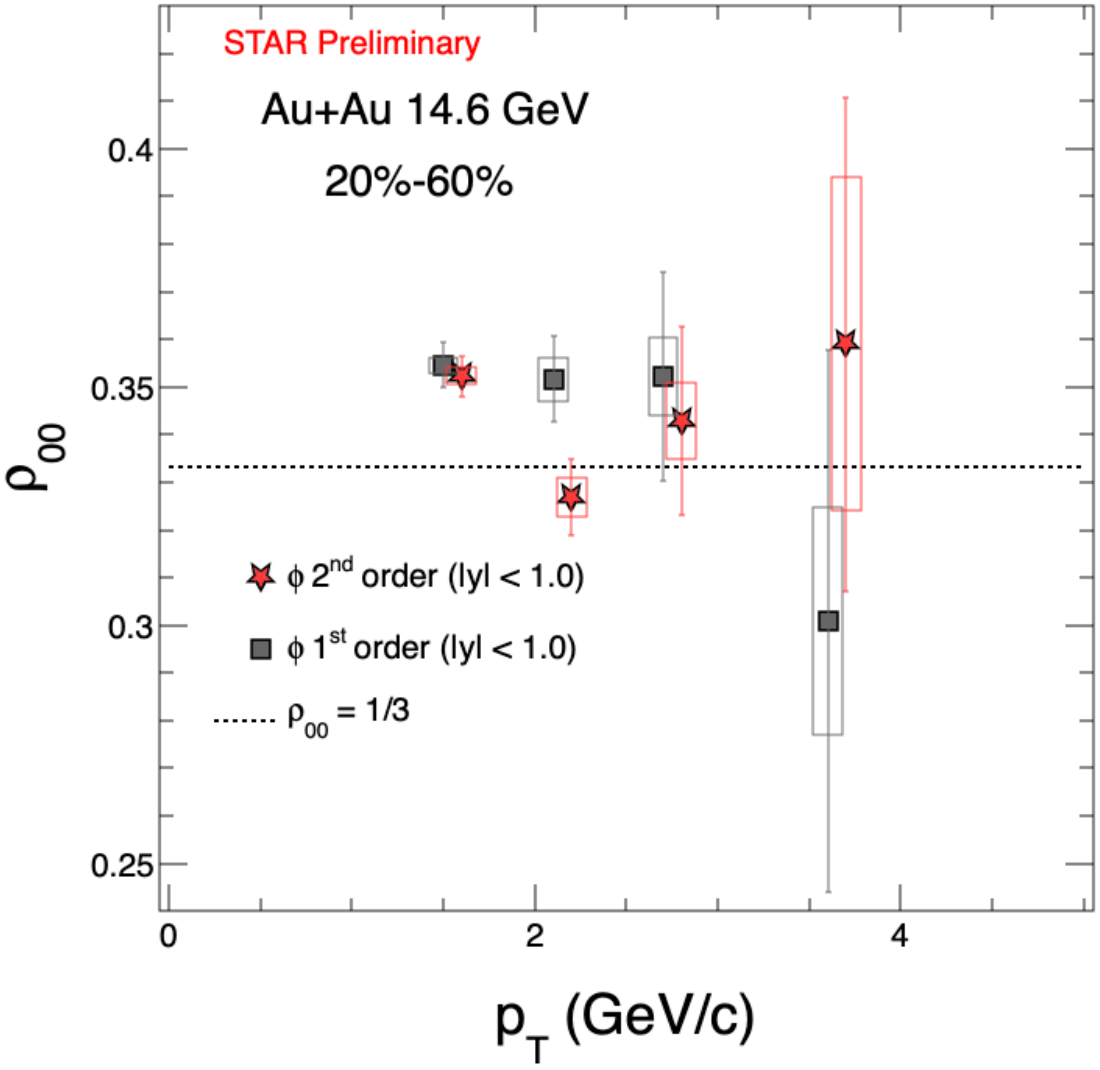
ϕ-meson $\sqrt{s_{NN}}$-dependent ρ_{00}



- Significant ϕ-meson global spin alignment confirmed in 14.6 and 19.6 GeV mid-central Au+Au collisions from BES-II.
- Significant for both orders of EP.
- Consistent with BES-I at 19.6 GeV, but with higher precision.

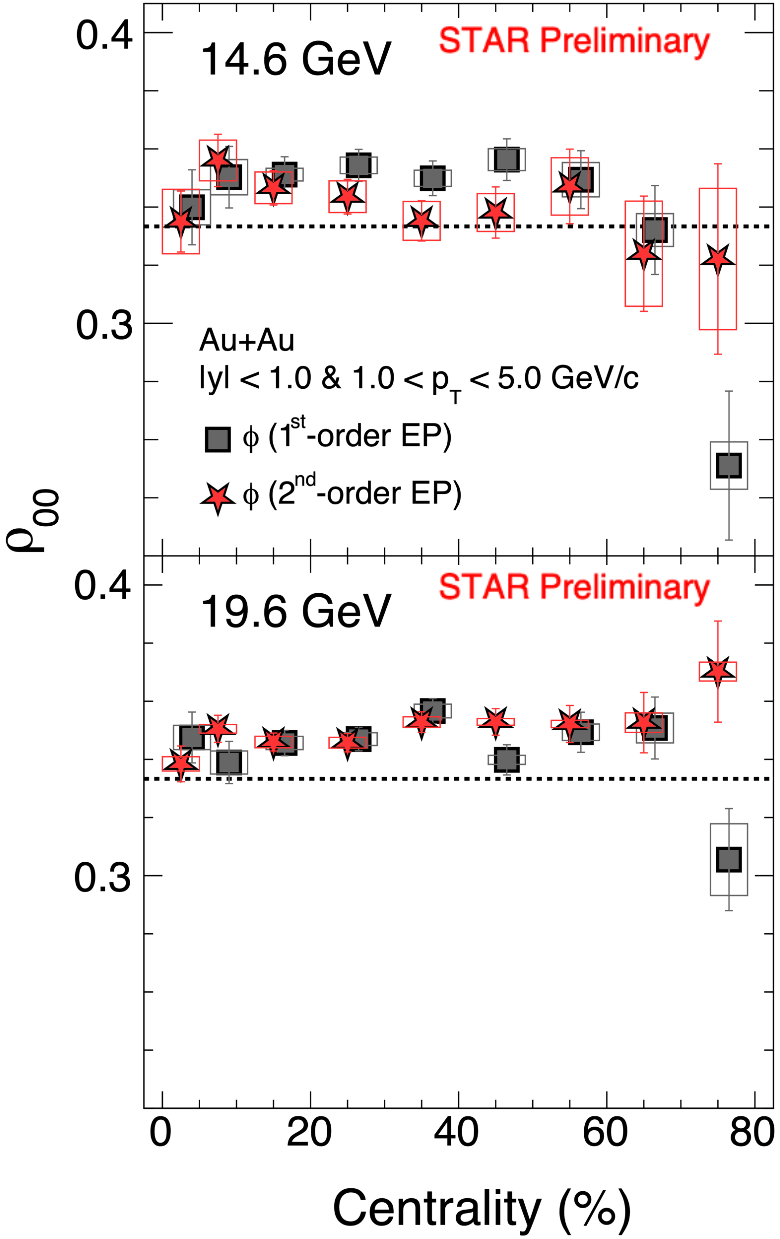
STAR, Nature 614 (2023) 7947.
Sheng et al., PRD 101 (2020) 9, 096005.
Sheng et al., PRD 102 (2020) 5, 056013.

ϕ-meson p_T-dependent ρ_{00}



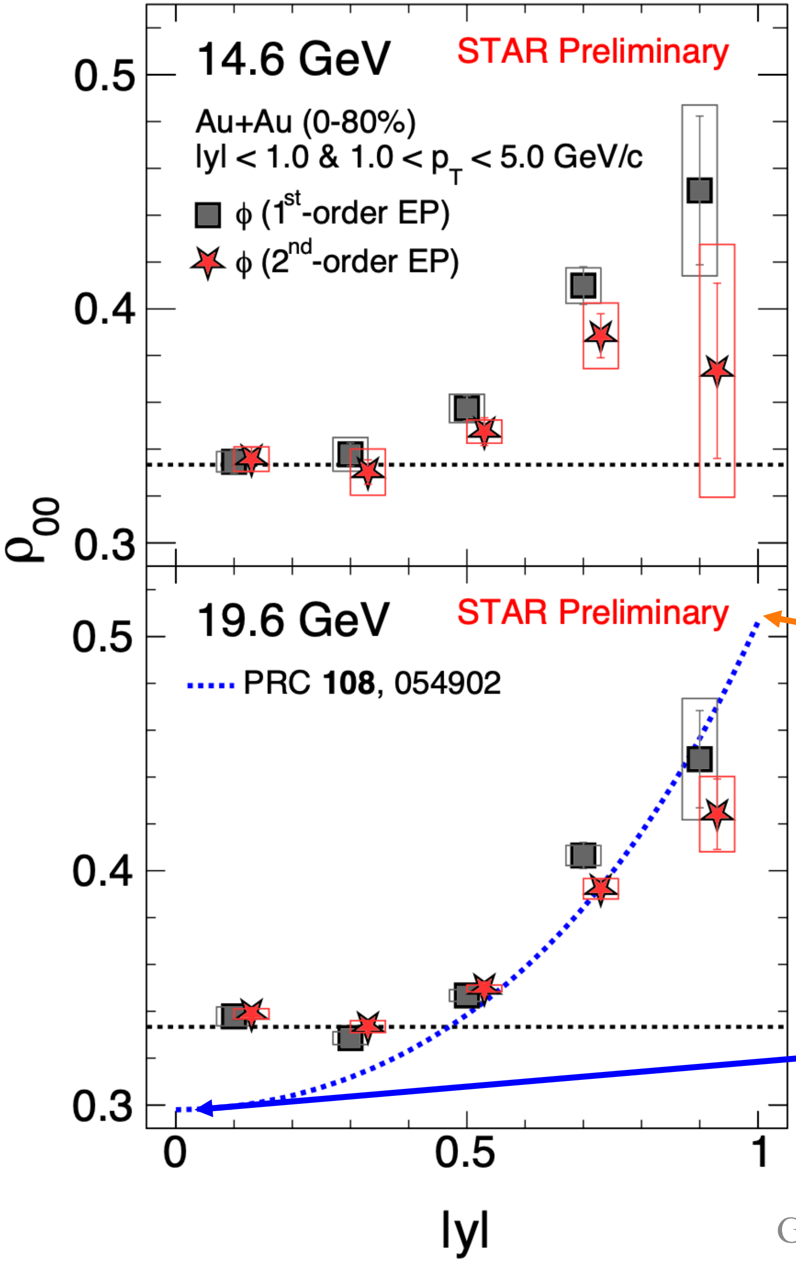
- ρ_{00} obtained with 1st and 2nd order event planes are consistent.

ϕ-meson centrality-dependent ρ_{00}



- Similar centrality dependence for ρ_{00} with respect to 1st and 2nd order EP.
- Theory predictions → ongoing work.

ϕ-meson rapidity-dependent ρ_{00}

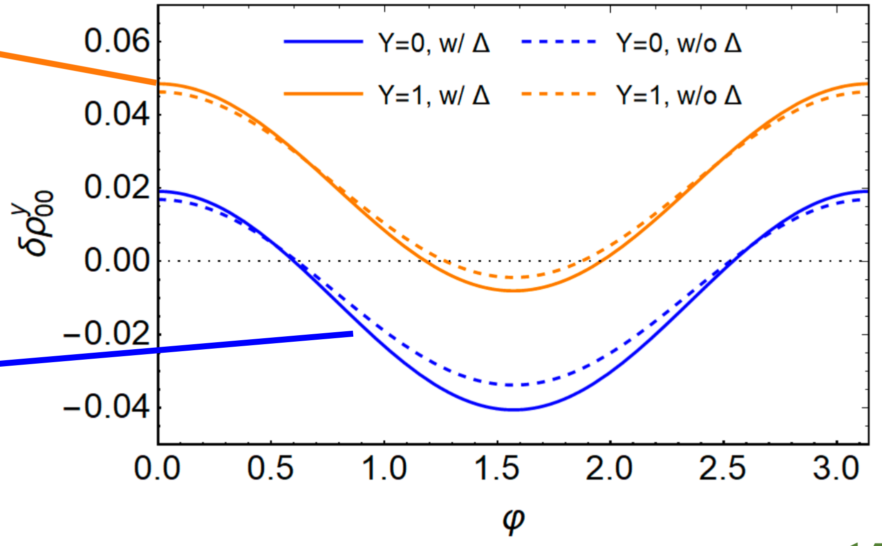


- Anisotropy of field fluctuations leads to $\rho_{00} \neq 1/3$.
- If ϕ-meson field fluctuations are stronger along quantization axis, then $\rho_{00} > 1/3$.
- Motion of ϕ-meson in lab frame leads to increases in field fluctuations perpendicular to the motion after boosting into the ϕ-meson rest frame.
- If |y| = 1, a significant component of the motion is along the z-axis, increasing field fluctuations along the y-direction, leading to $\rho_{00} > 1/3$.

Integrated over φ

Integrated over φ

Sheng et al., PRC 108, 054902 (2023).



Summary

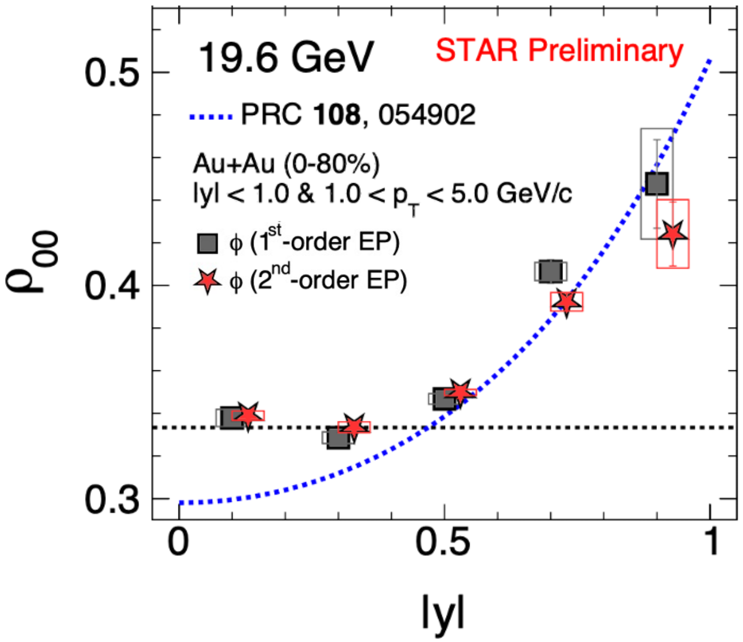
- ϕ: $\rho_{00} > 1/3$ for mid-central Au+Au collisions at energies ≤ 62 GeV BES-I.
  - Currently explained by vector meson strong force field.(1)

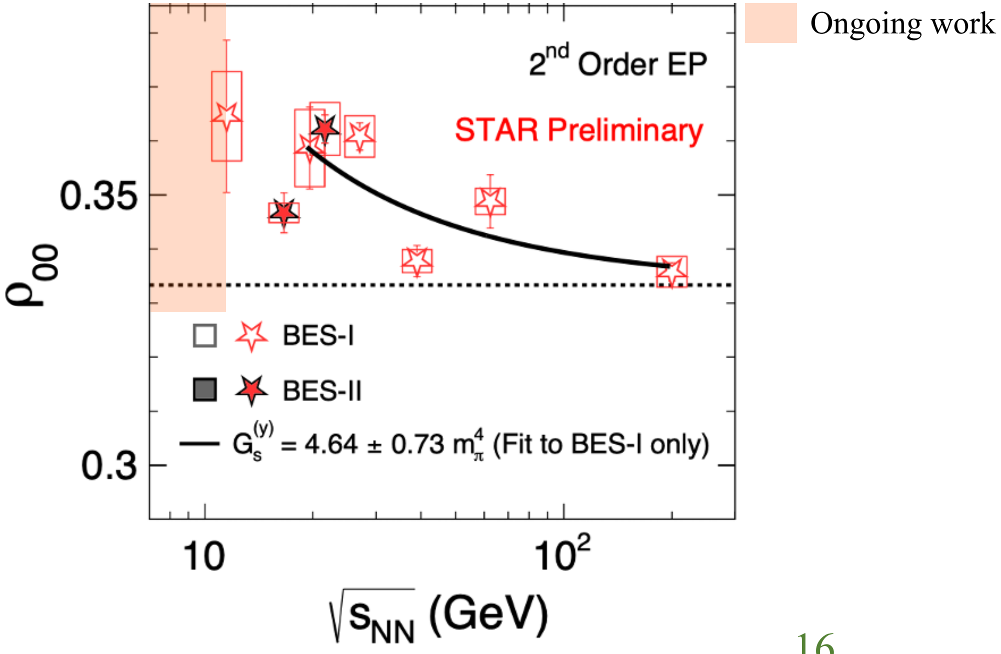
- New differential results for ϕ-meson ρ_{00} from BES-II 14.6 and 19.6 GeV Au+Au.
  - First measurement of the rapidity dependence shows a strong increasing trend towards larger rapidity that is consistent with theory prediction.

Further work:

- Increase |η| coverage available from STAR detector upgrades.
- Lower energy data sets available.

[1] Sheng et al., Phys. Rev. D 102, 056013 (2020).





THANK YOU FOR YOUR ATTENTION

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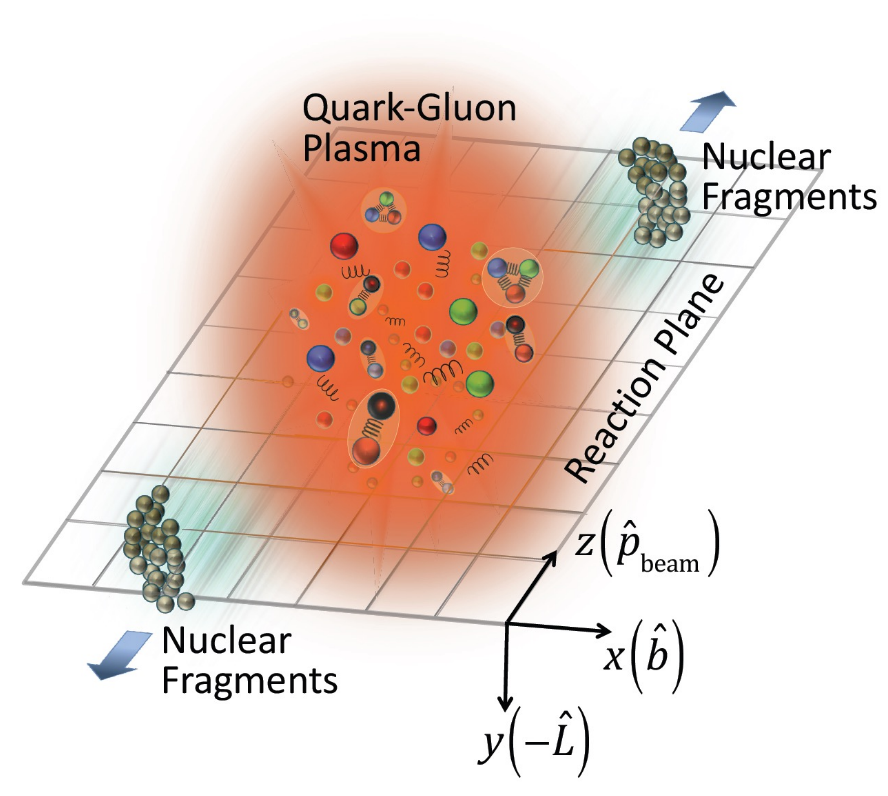
BACKUP

Event Planes



STAR Collaboration, Nature 614 (2023) 7947.

- Reaction plane (RP), Ψ_r: the azimuthal angle of the impact parameter, b, in the lab frame estimated using spectators at far forward rapidity.
- Event plane (EP), Ψ_n: nth harmonic of the anisotropic flow distribution.(1)
- ρ_{00} calculated with respect to 1st and 2nd order EP should be consistent.

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

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

n: harmonic order in anisotropic flow distribution
i: ith particle in event
Q_n: flow vector
φ_i: angle of particle trajectory in lab frame
w_i: weight (determined by transverse momentum, p_T)

[1] Poskanzer et al., Phys. Rev. C 58, 1671–1678 (1998).