Measurements of Vector Meson Global Spin Alignment in Heavy-Ion Collisions at RHIC

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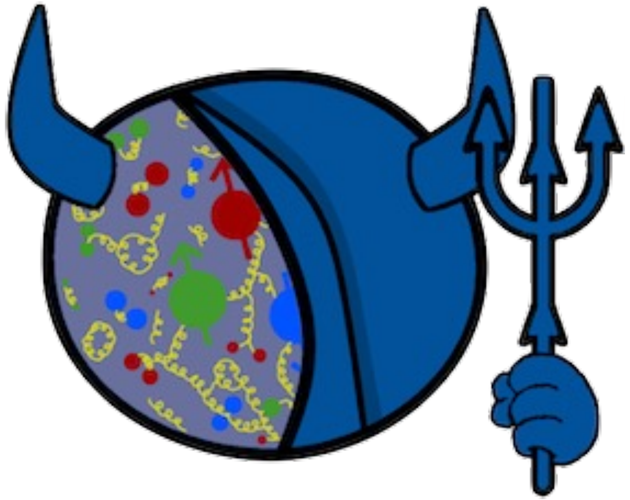


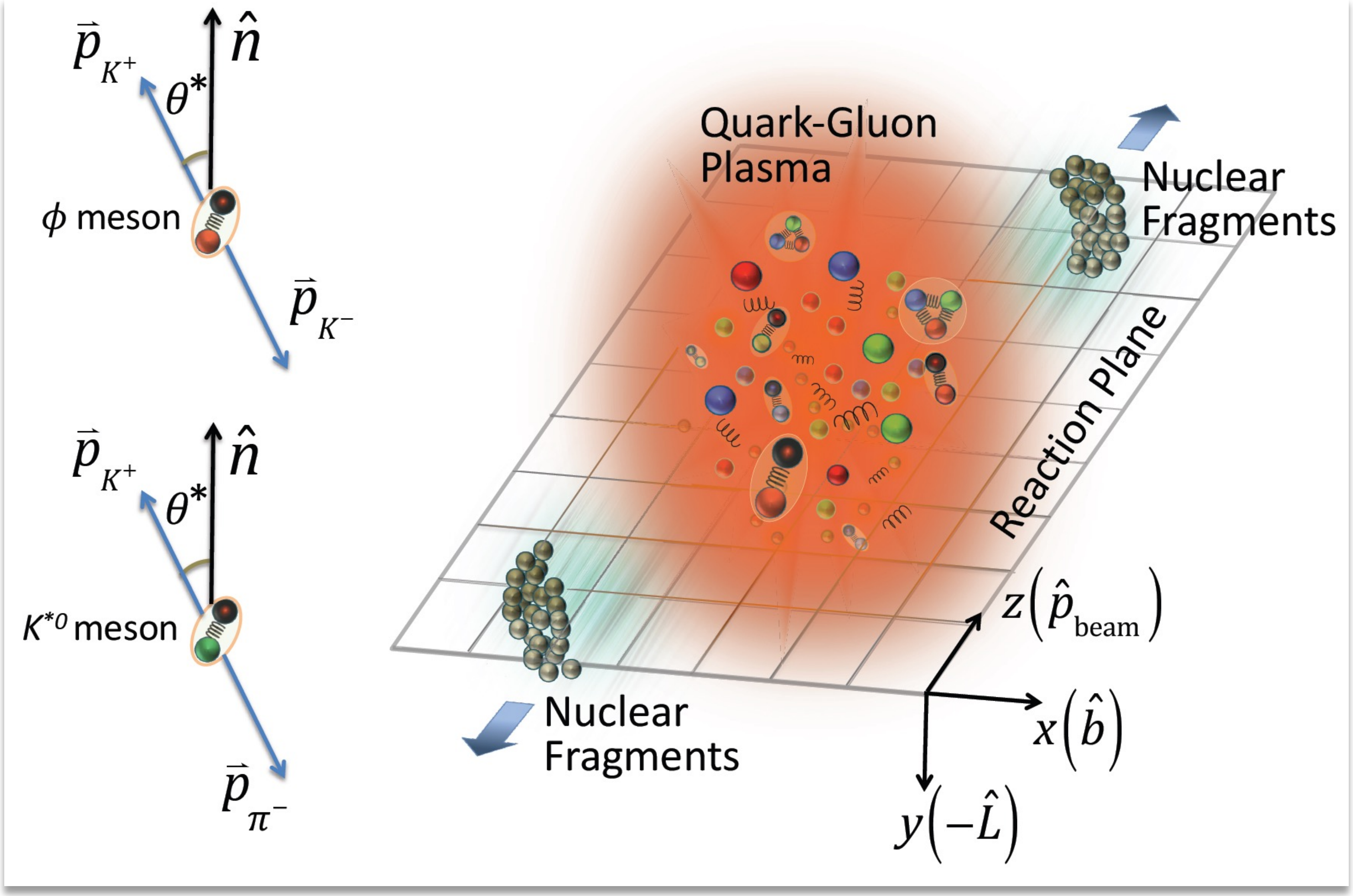
This work is supported in part by the DOE Office of Science

Outline

- Introduction to global spin alignment
- Motivation for this analysis
- Analysis method
- Results for ϕ meson ρ_{00} from Au+Au collisions in the second phase of the Beam Energy Scan at RHIC (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

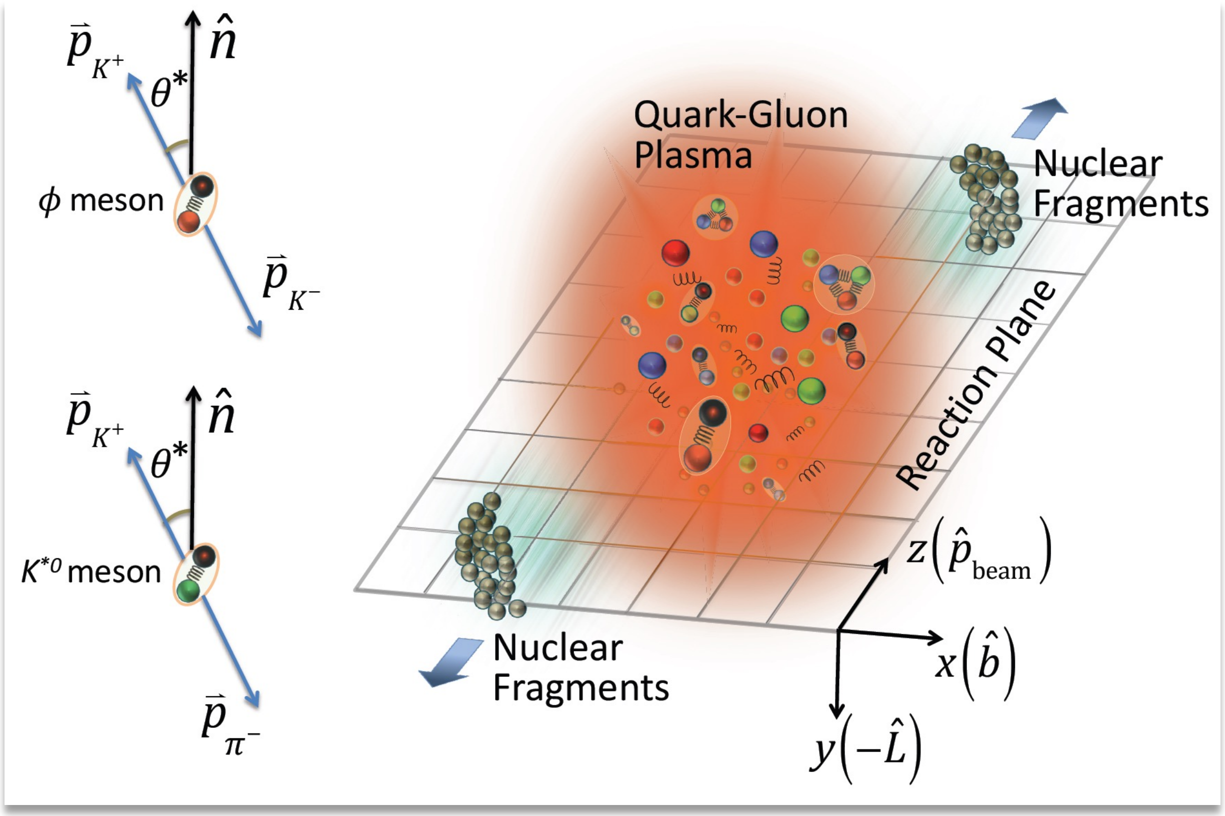
ρ_{00}: 00^{th} element of the spin density matrix.

θ^* : angle between K^+ daughter momentum and polarization axis in parent's rest frame.

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

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

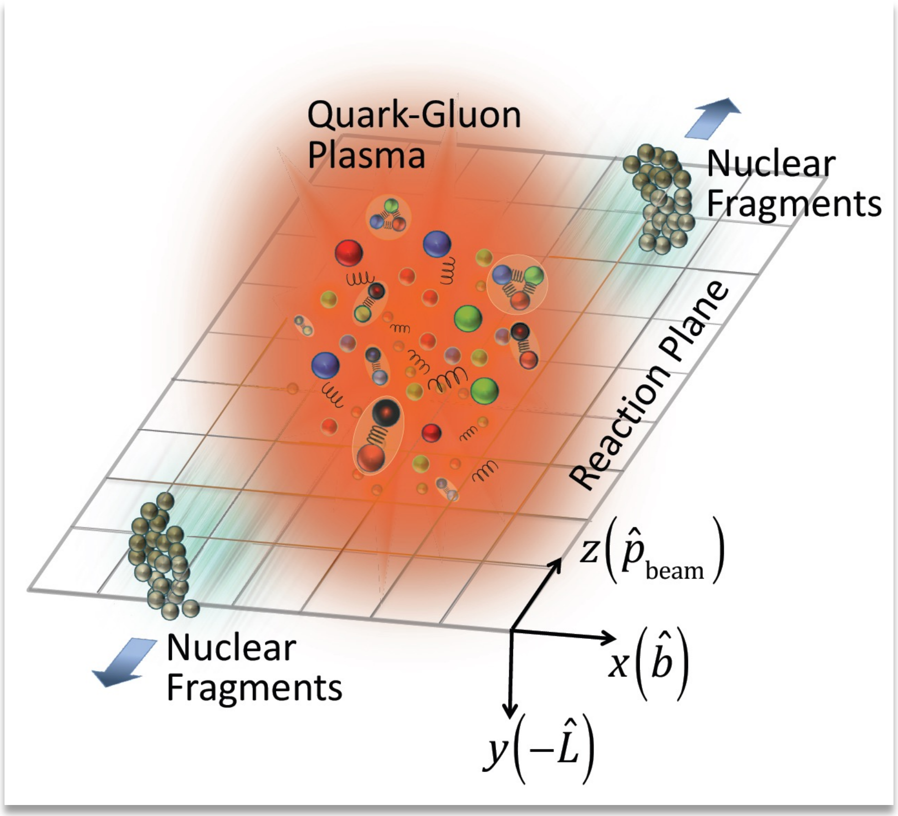
$\rho_{00} \neq 1/3$ indicates spin alignment.



STAR Collaboration, Nature 614 (2023) 7947.

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

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: n$^{\text{th}}$ harmonic of the anisotropic flow distribution.[1]
- ρ_{00} calculated with respect to 1$^{\text{st}}$ and 2$^{\text{nd}}$ order EP should be consistent.

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

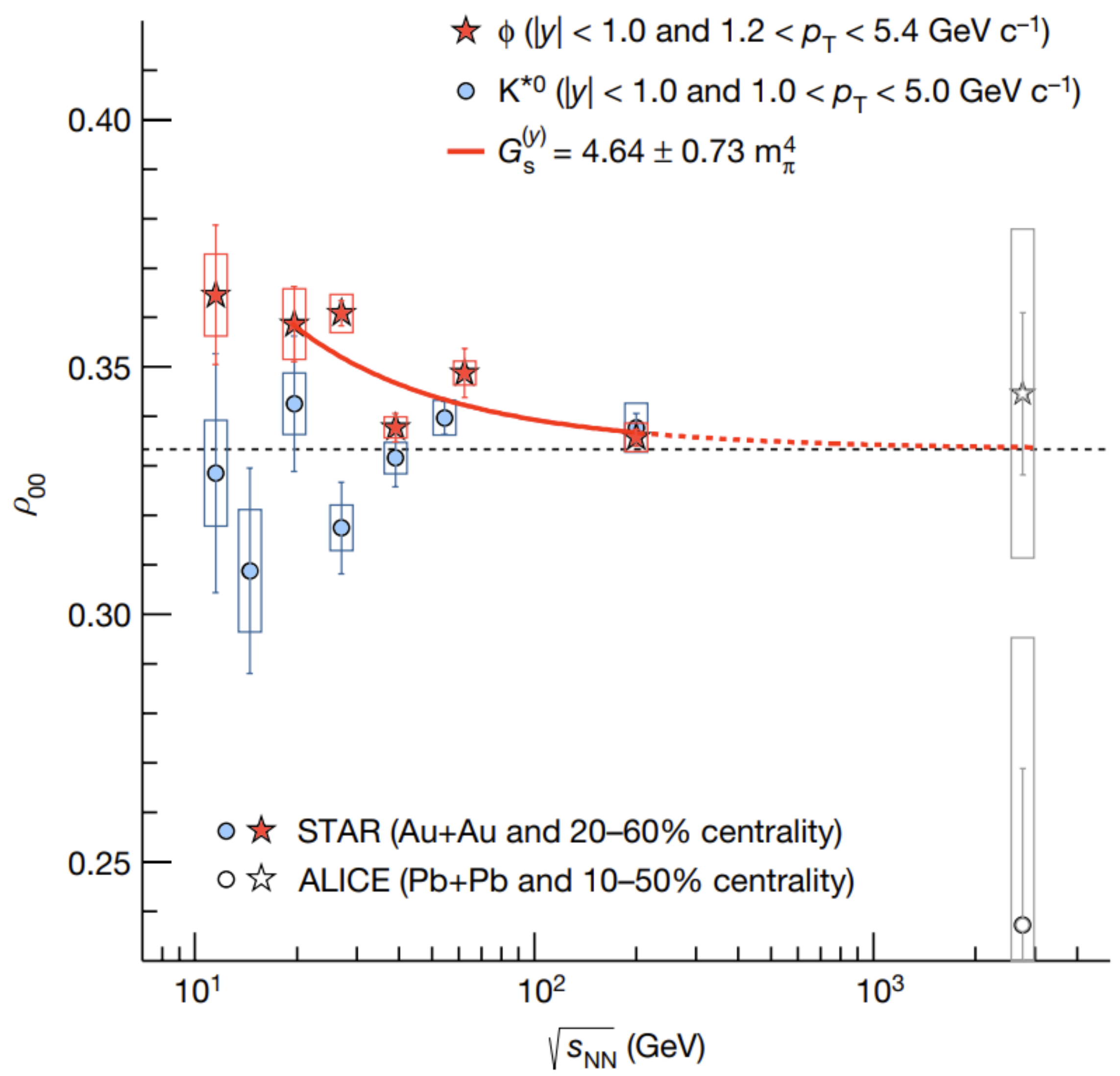
$$\Psi_n = \left(\tan^{-1} \frac{\sum_i w_i \sin(n\varphi_i)}{\sum_i w_i \cos(n\varphi_i)}\right)/n$$

n: harmonic order in anisotropic flow distribution
i: i$^{\text{th}}$ 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).

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 at mid-central collisions.[1]
- $\rho_{00} \sim 1/3$ for K^{*0} at mid-central collisions.
  - Mean lifetime is ~10x smaller than ϕ (different in medium interactions).
  - Fluctuations in vector meson fields for d and $\bar{s}$ expected to be weaker than s and $\bar{s}$.

Potential Contributions to ϕ-meson ρ_{00}

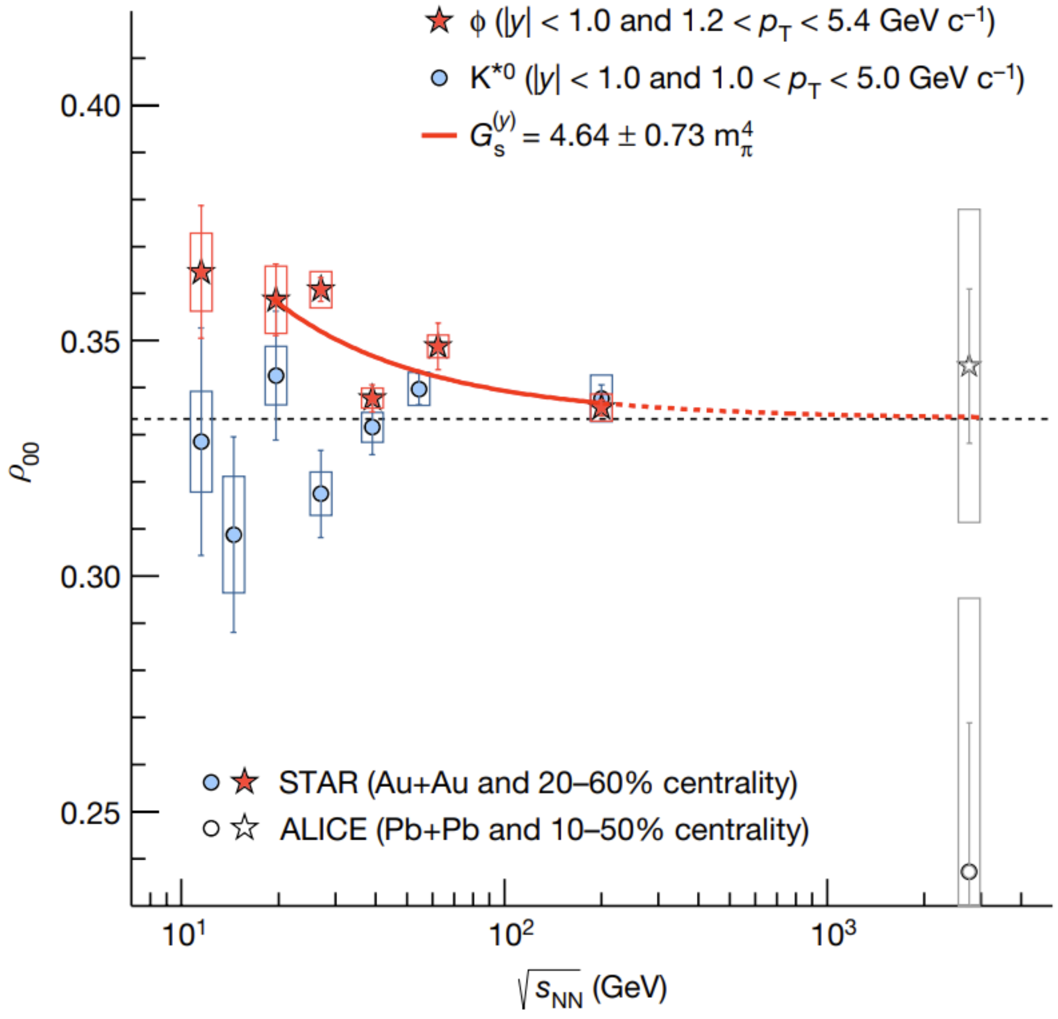
Physics Mechanism	ρ_{00}	
Electric field(1)	< 1/3	~10^{-5}
Electric part of vorticity tensor(1)	< 1/3	~10^{-4}
Magnetic components of EM and vorticity fields(1,2,3)	< 1/3	~10^{-5}
Helicity polarization(4)	< 1/3	
Locally fluctuating axial charge currents(5)	< 1/3	
Local vorticity loop + coalescence(6)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

- Significant positive global spin alignment (ρ_{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.
  - Couples to s and $\bar{s}$ quarks.

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

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 values with χ^2/ndf = 11.24/3. The p-value of curve is ~1%.

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 $G_s^{(y)}$:

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

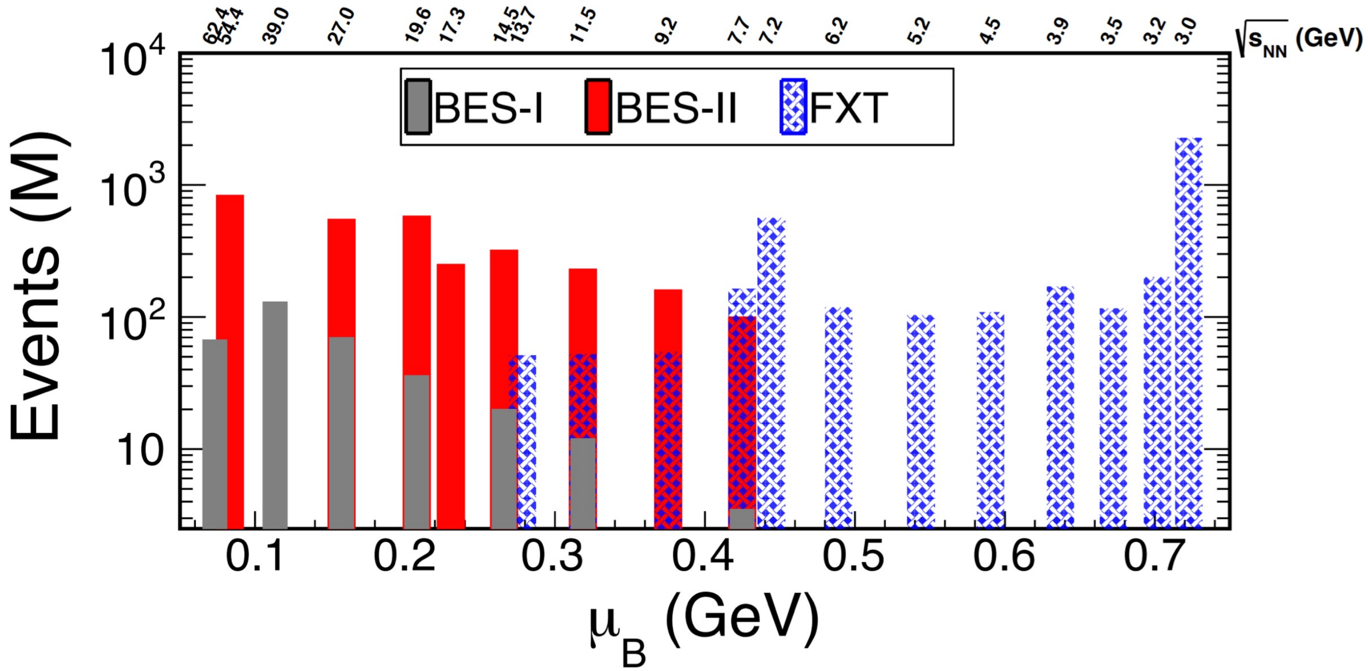
T_{eff}: effective temperature of quark gluon plasma (QGP) fireball
g_ϕ: ϕ-meson field coupling constant
$E_{\phi,i}(B_{\phi,i})$: i^{th} component of electric (magnetic) parts of ϕ-meson field
m_s: strange quark mass
$\boldsymbol{p}$: strange quark momentum in ϕ rest frame
⟨ ⟩: average over the spacetime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

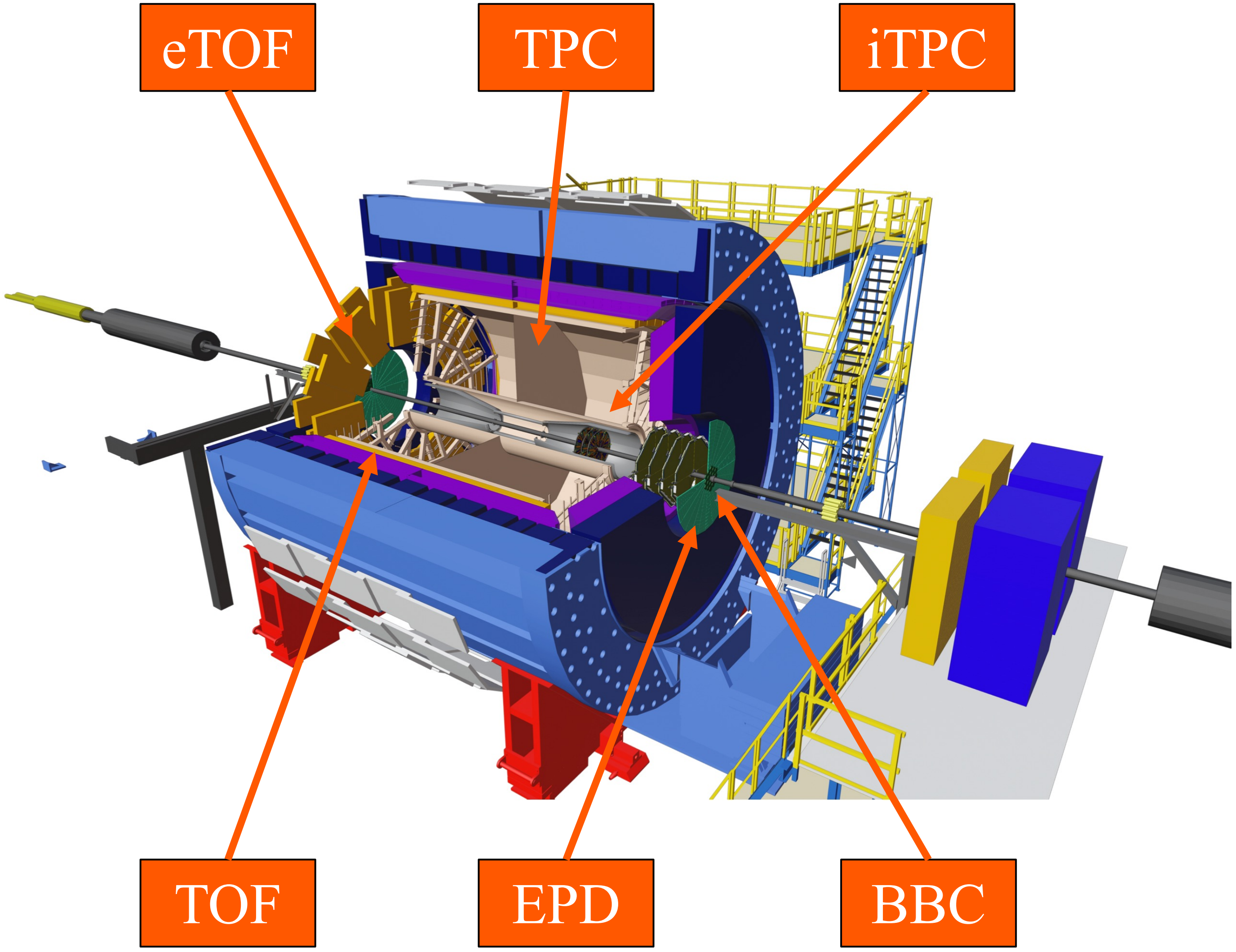
$\sqrt{s_{NN}}$ (GeV)	BES-I (x10^6 events)	BES-II (x10^6 events)
19.6	36[1]	478
14.6	18	324
11.5	12[1]	235
9.2	---	162
7.7	4	101

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



- Significantly increased statistics available from BES-II for identical energies.
  - Increased statistical precision.
- 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: $2.1 < |\eta| < 5.1$

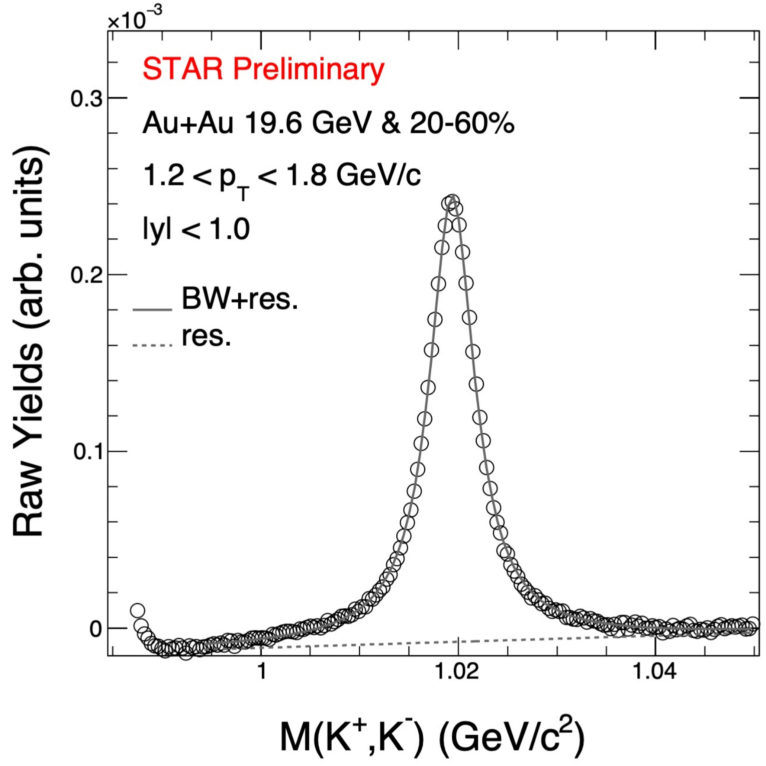
1st order event plane reconstruction

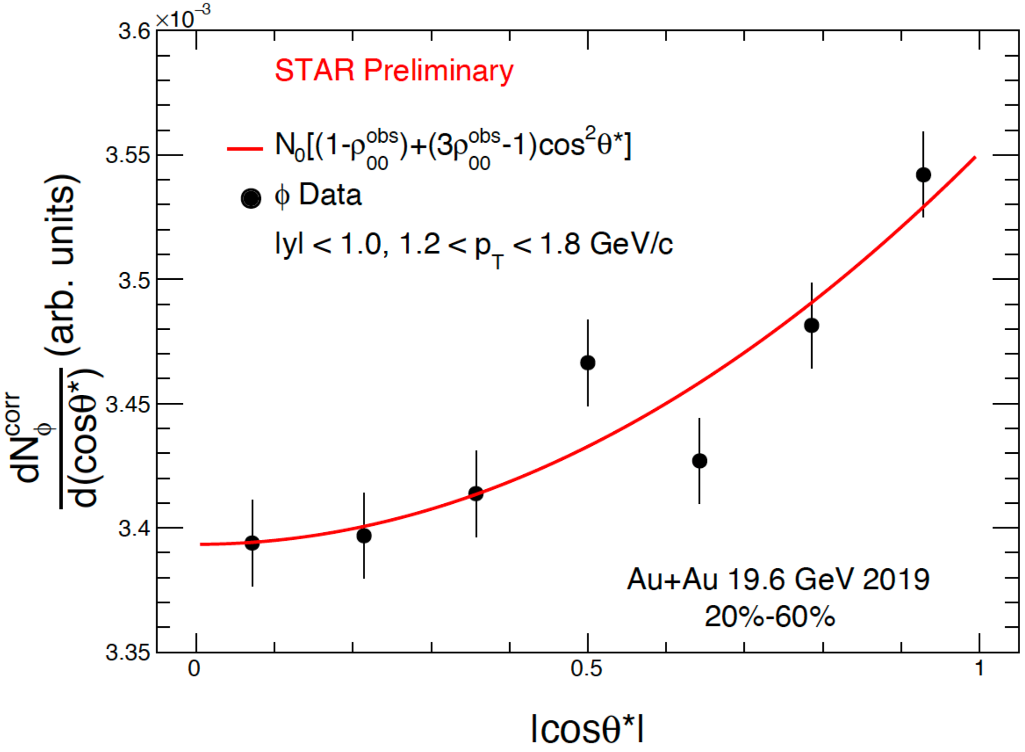
~2x greater EP resolution with EPD

Used in this analysis

^II Upgrades to STAR since BES-I

ρ_{00} Extraction

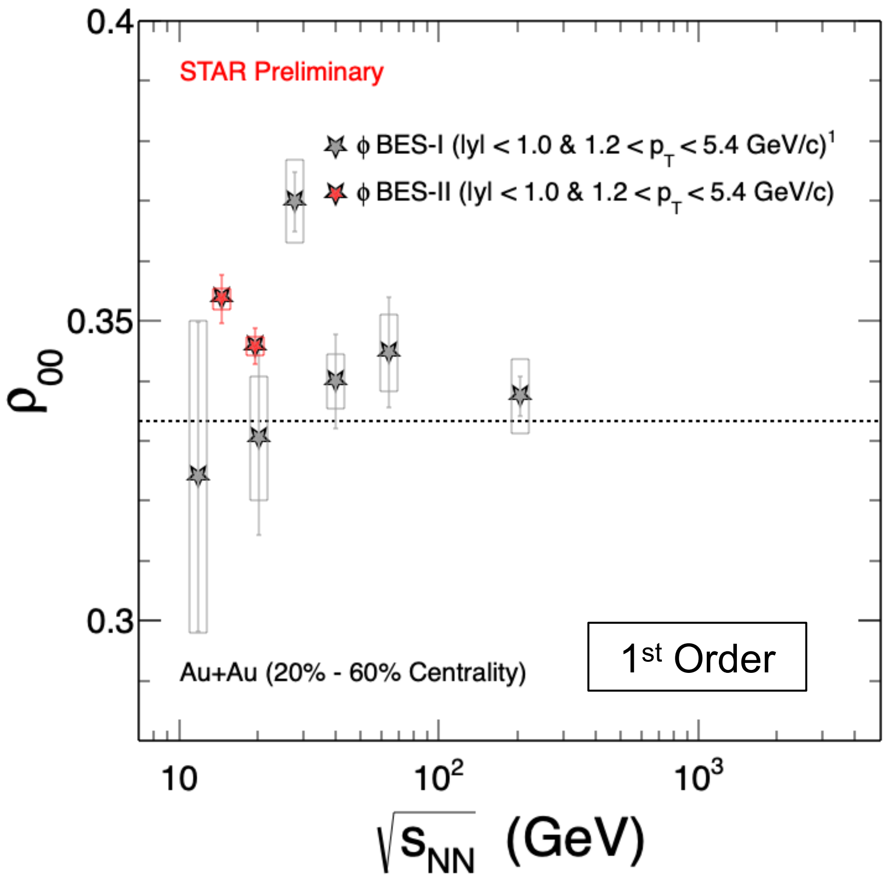


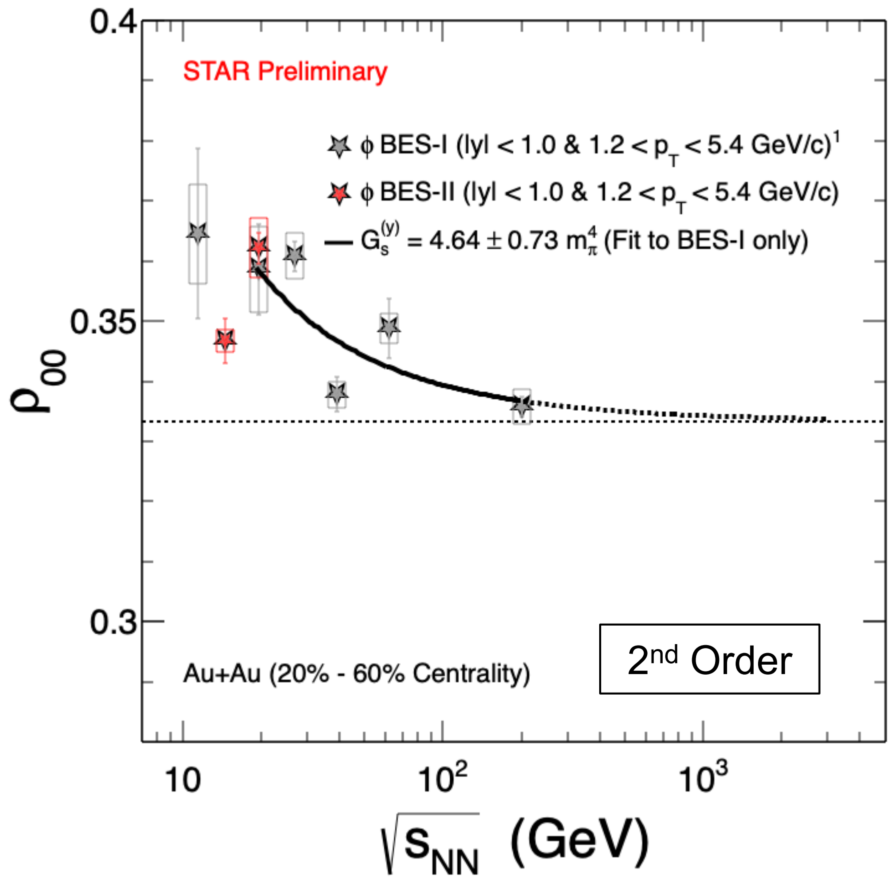


- Event-mixing is used to subtract background and extract yields from histogram integration in seven |cosθ*| bins.
- Yields vs. |cosθ*| are corrected for the geometric acceptance and tracking/PID efficiencies.
- ρ_{00}^{obs} is extracted from a fit to the corrected yields vs. |cosθ*|[1]: $\frac{dN}{dcos\theta^*}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



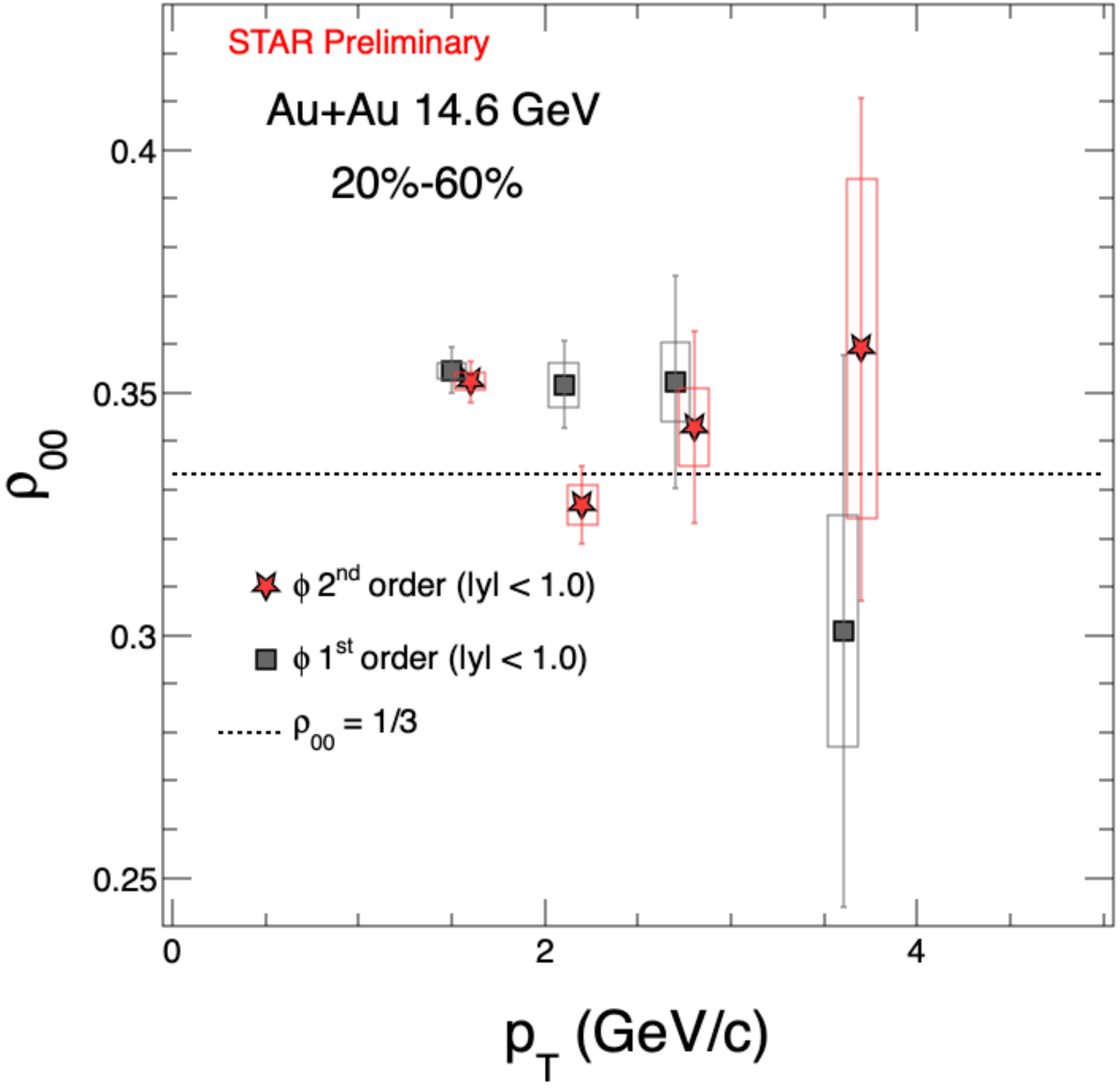


Significant ϕ-meson global spin alignment confirmed in 14.6 and 19.6 GeV mid-central Au+Au collisions.

Significant for both orders of EP.

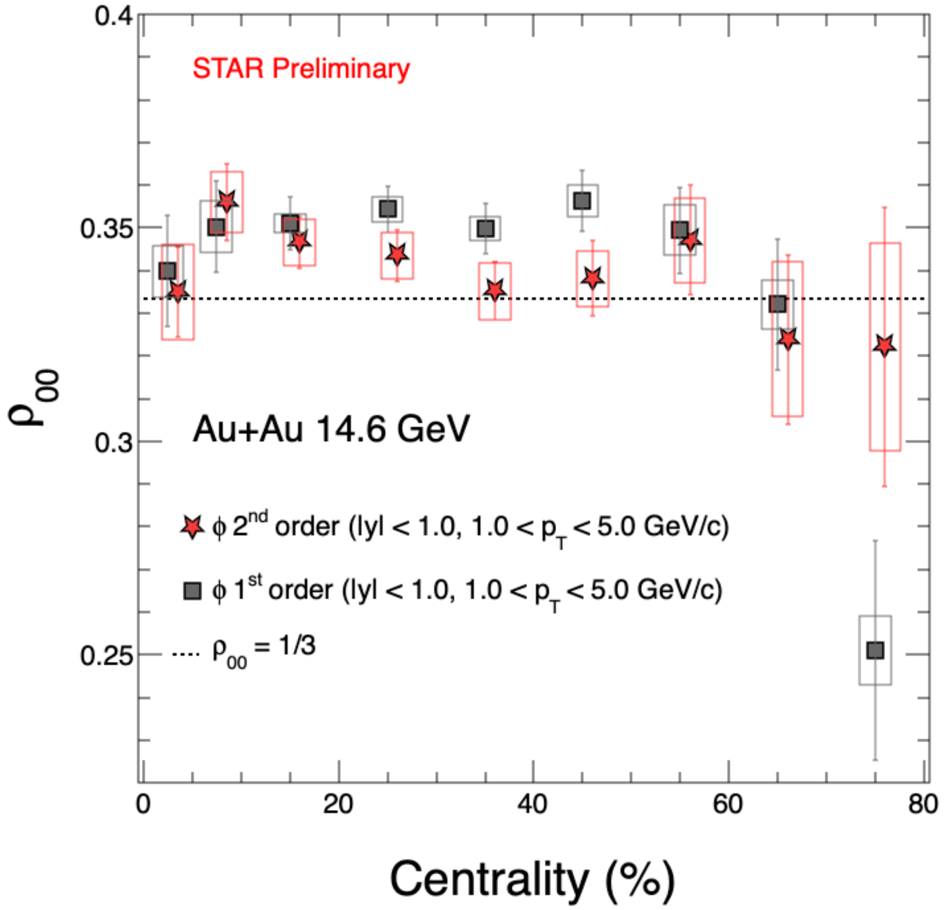
[1] STAR Collaboration, Nature 614 (2023) 7947.
[2] Sheng et al., Phys. Rev. D 101 (2020) 9, 096005.
[3] Sheng et al., Phys. Rev. D 102 (2020) 5, 056013.

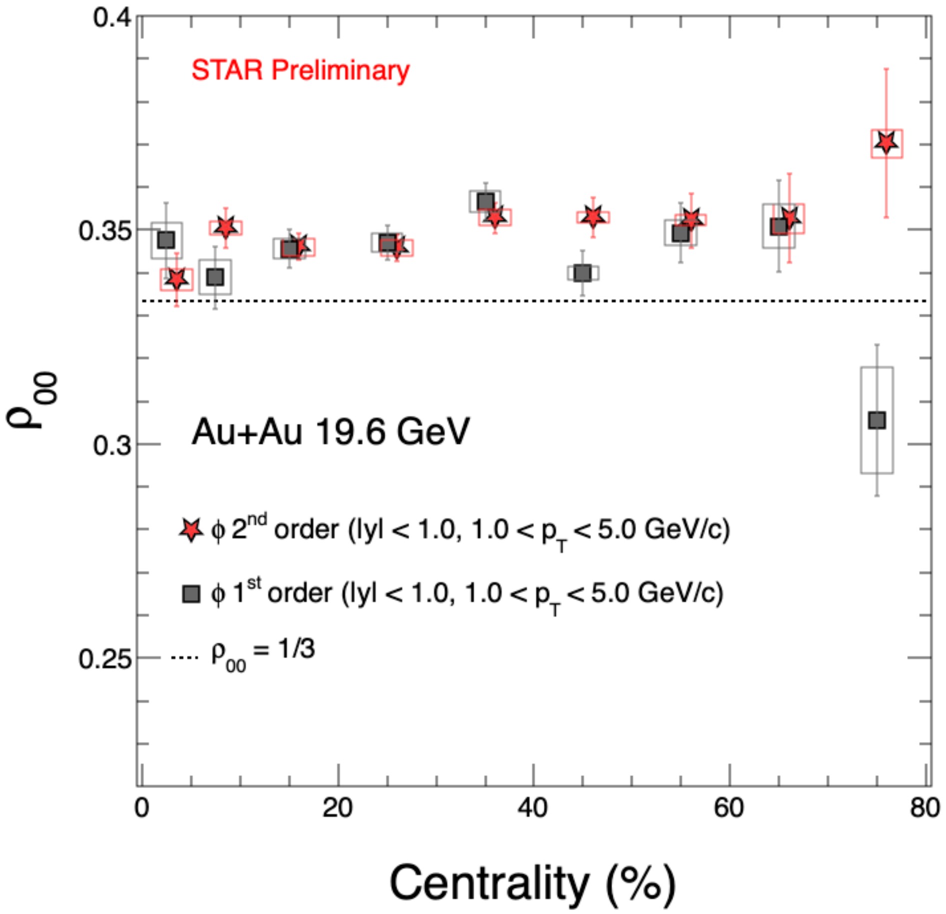
ϕ-meson p_T-dependent ρ_{00}



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

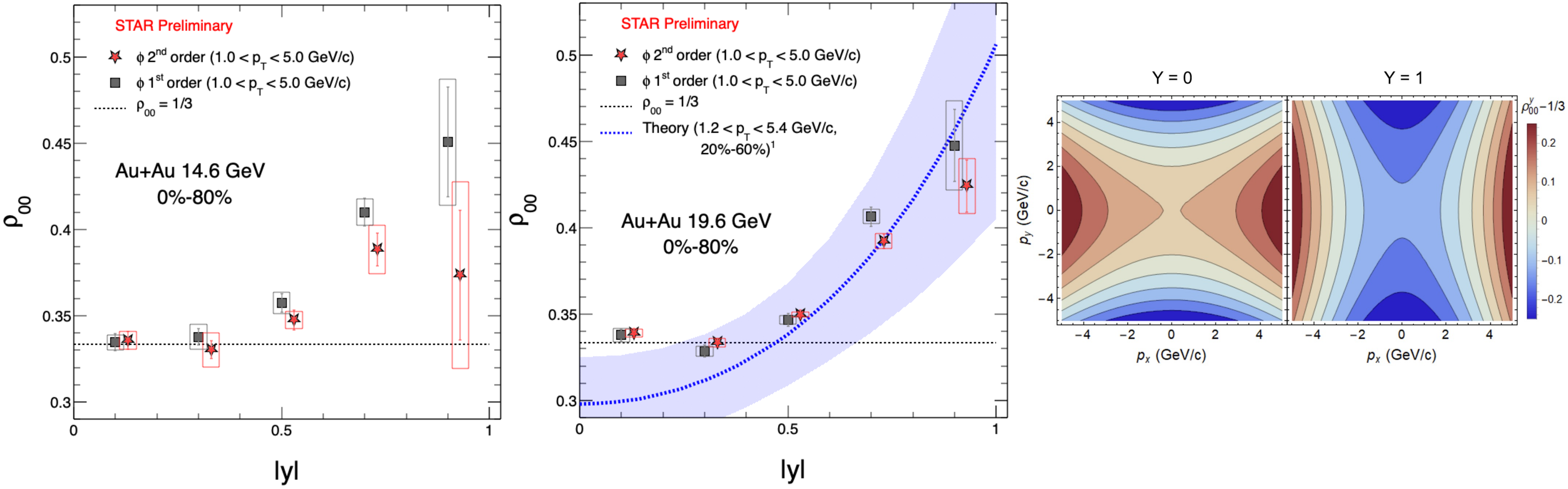
ϕ-meson centrality-dependent ρ_{00}





Similar centrality dependence for ρ_{00} with respect to 1st and 2nd order EP.

ϕ-meson rapidity-dependent ρ_{00}



Trend in 19.6 GeV result is consistent with theoretical calculation in [1].
Explained by larger field fluctuations in direction perpendicular to ϕ-meson motion.

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

Summary

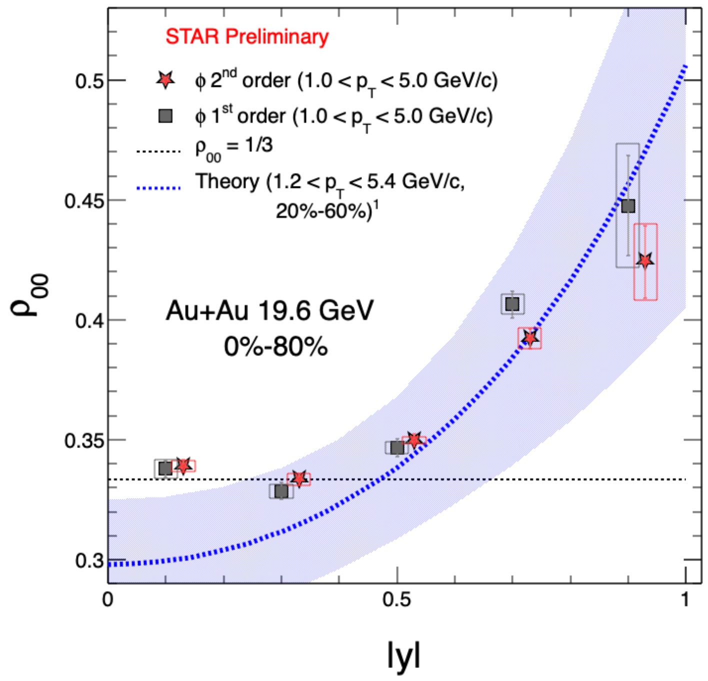
- φ: $\rho_{00} > 1/3$ for mid-central Au+Au collisions at energies ≤ 62 GeV BES-I.
  - Currently explained by vector meson strong force field.[1]

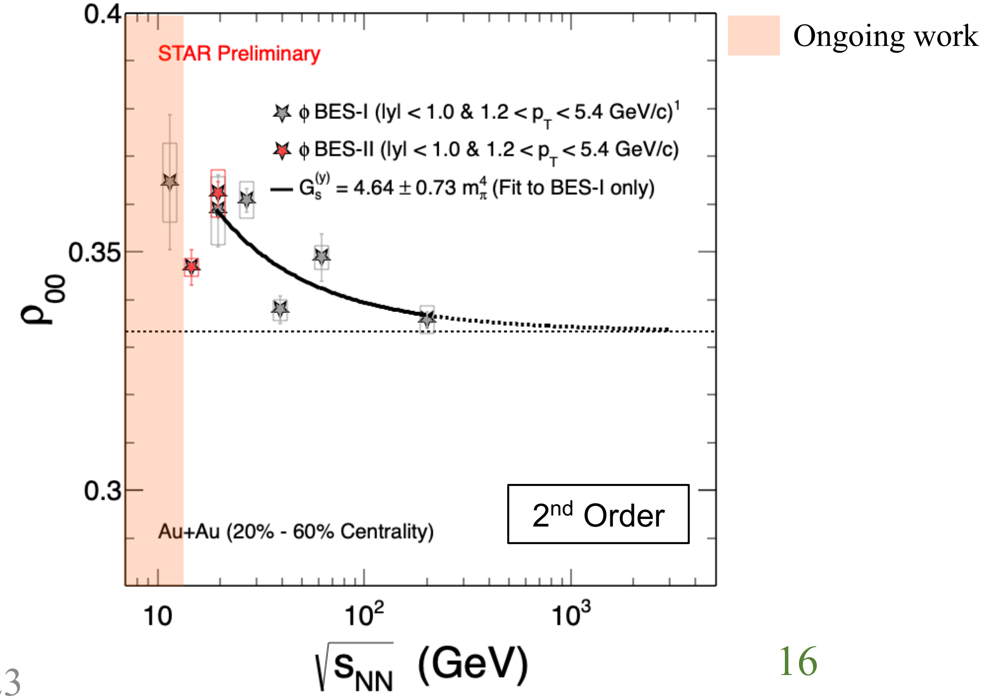
- New differential results for φ-meson ρ_{00} from BES-II 14.6 and 19.6 GeV Au+Au.
  - First look at the rapidity dependence shows a strong increasing trend towards larger rapidity that is consistent with theory prediction.

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

This work is supported in part by the DOE Office of Science

BACKUP

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 ,

| η | < 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:

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

and then combine different sources of uncertainties:

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

* 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.