Global Spin Alignment of ϕ-meson in 19.6 GeV Au+Au Collisions from STAR BES-II

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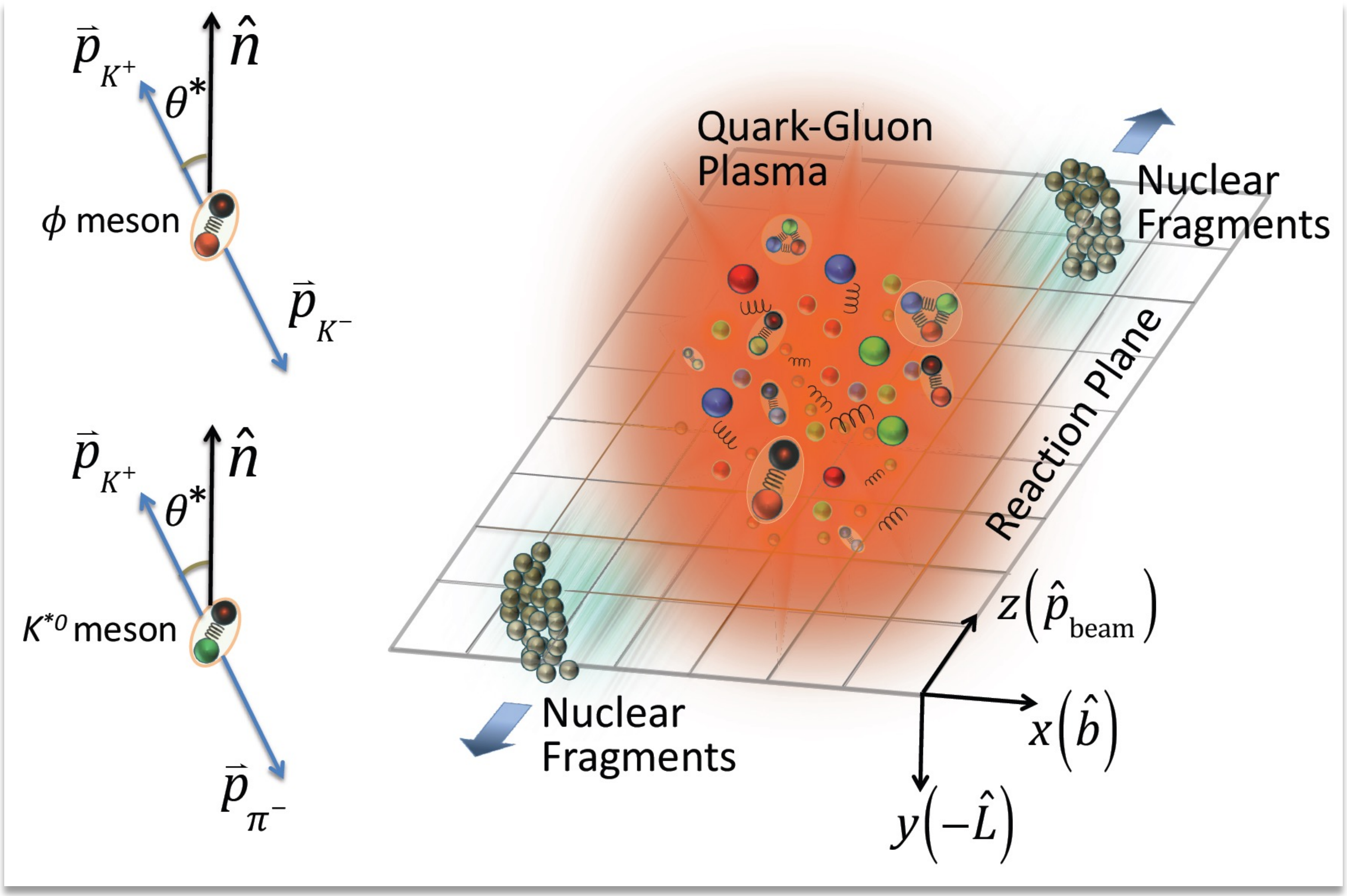
Outline

- Introduction to global spin alignment
- Results for K^{*0} and ϕ-meson ρ_{00} from Au+Au BES-I at 11.5 - 200 GeV[1]
- Motivation for this analysis
- Analysis method for global spin alignment (ρ_{00})
- Results for ϕ meson ρ_{00} (p_T) from 19.6 GeV BES-II Au+Au collisions
- Summary

[1] STAR Collaboration, arXiv: 2204.02302 (2022).

Introduction to Spin Alignment

- In non-central heavy-ion collisions, large orbital angular momentum (OAM) is generated.
- OAM can preferentially align a particle's spin projection on the spin quantization axis.
    - Spin-orbit coupling.[1]



STAR Collaboration, arXiv: 2204.02302 (2022).

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

Introduction to Spin Alignment

Preferential alignment of a particle's spin with respect to the large OAM produced in heavy-ion collisions.

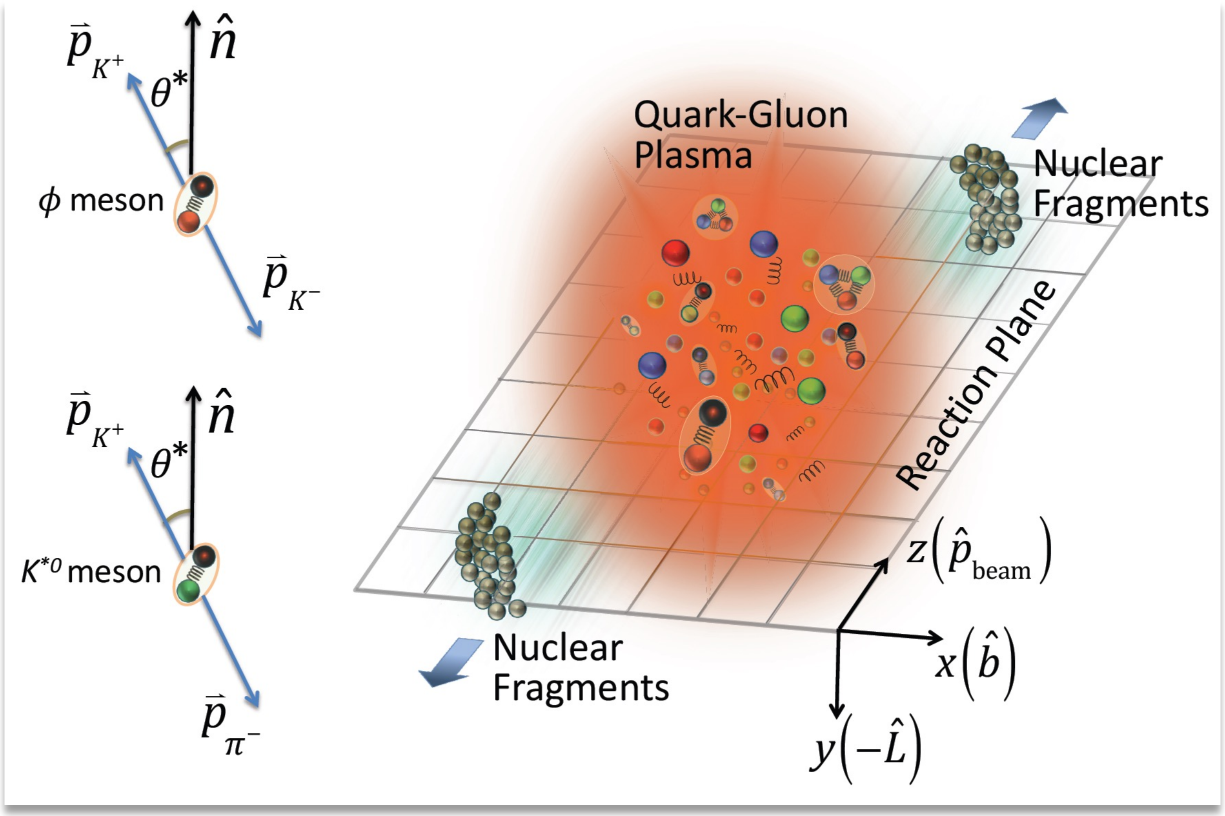
ρ_{00}: 00th element of the spin density matrix.

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

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

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

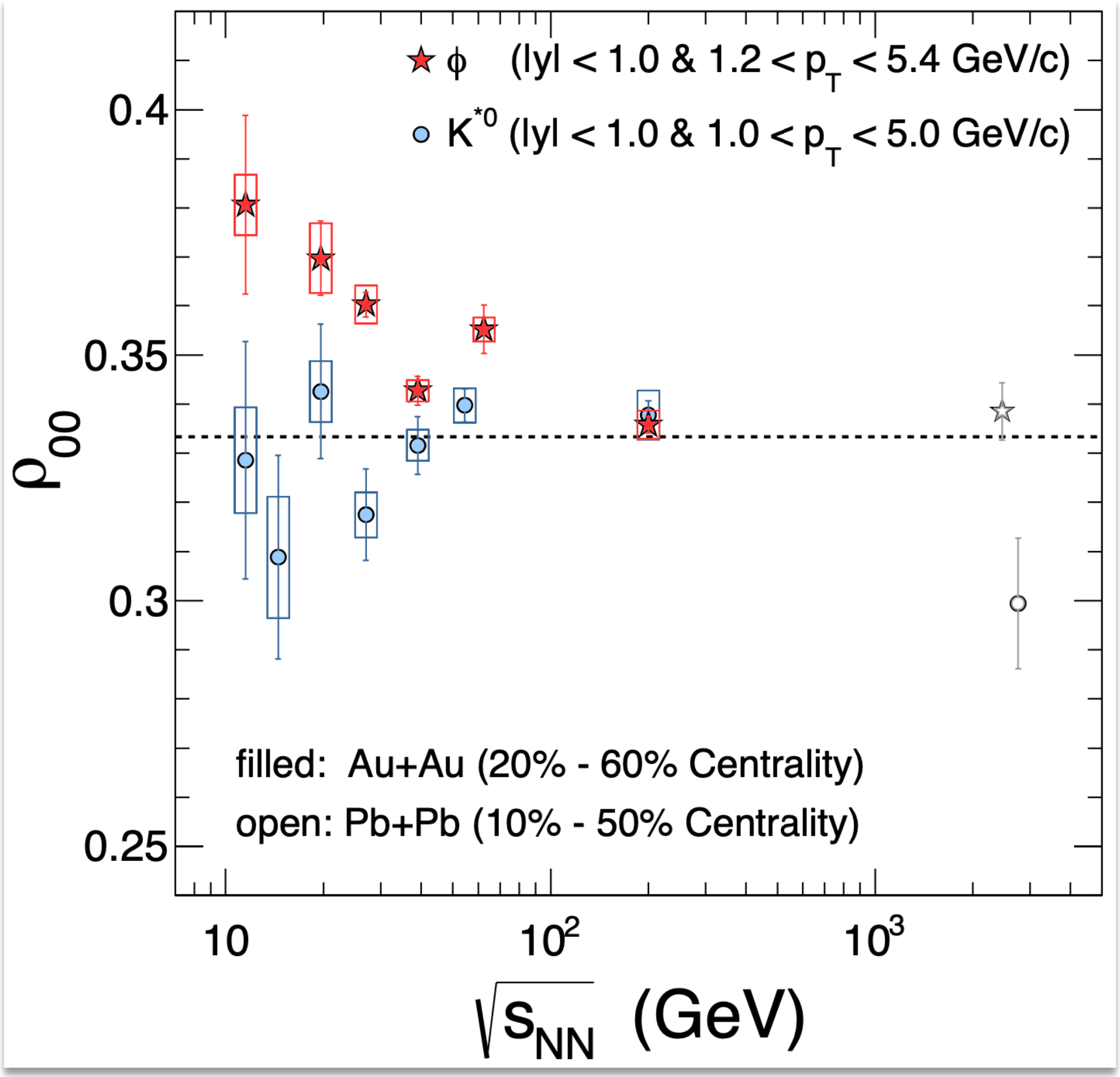
$\rho_{00} \neq 1/3$ indicates spin alignment.



STAR Collaboration, arXiv: 2204.02302 (2022).

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

ρ_{00} from BES-I



STAR Collaboration, arXiv: 2204.02302 (2022).

- For the first time, a large positive global spin alignment (ρ_{00}>1/3) for ϕ-meson was measured at mid-central collisions.
- ρ_{00} ~ 1/3 for K^{*0} at mid-central collisions.

Contributions to ϕ-meson ρ_{00} from Theory

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Physics Mechanism	ρ_{00}	
Electric field[1]	< 1/3	~10^{-5}
Electric part of vorticity tensor[1]	< 1/3	~10^{-4}
Fragmentation of polarized quarks[2]	≷ 1/3	~10^{-5}
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	
Vector meson strong force field[1,7]	> 1/3	

- A large positive global spin alignment (ρ_{00}>1/3) for ϕ-meson was measured at midcentral collisions from BES-I.
- 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).

ϕ and K^{*0} (ρ_{00})

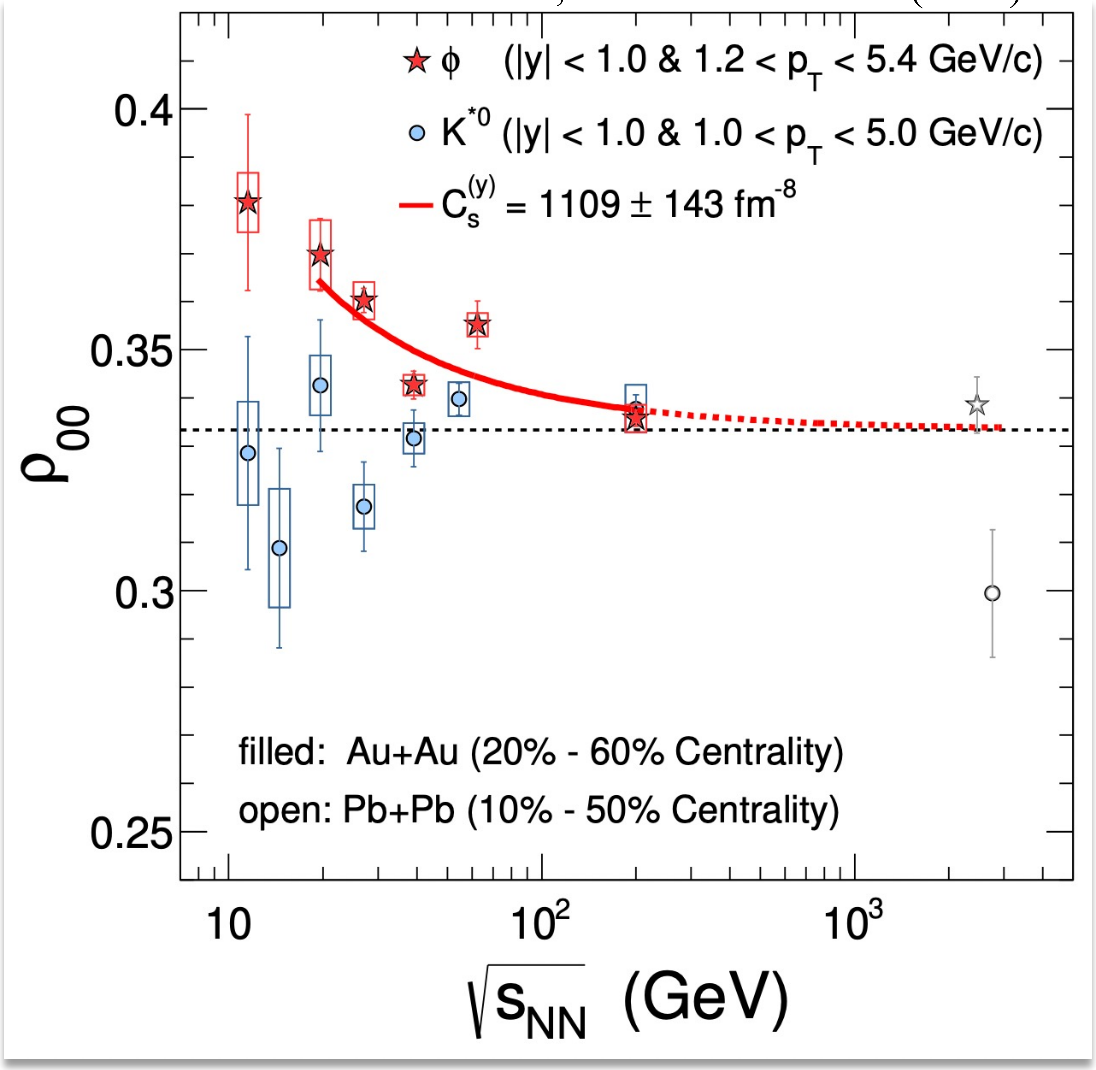
Meson Species	ρ_{00}	Constituent quarks	Mean Lifetime (fm/c)	Spin
ϕ	> 1/3	$s\bar{s}$	45	1
K^{*0}	~ 1/3	$d\bar{s}$	4.1	1

- Mean lifetime of K^{*0} is ~10 times smaller than that of ϕ.
  - Different in medium interactions.
  - Different late stage of hadronic interactions.[1]
- Fluctuating vector meson fields for d and $\bar{s}$ are expected to be weaker than s and $\bar{s}$.
  - Leads to negligible contribution to ρ_{00} of K^{*0}.
- Electric component of vorticity tensor is larger for K^{*0}.
  - Negative contribution to ρ_{00}.[2]

[1] Karpenko et al., Eur. Phys. J. C 77, 213 (2017).
[2] Sheng et al., Phys. Rev. D 102, 056013 (2020).

Contributions to ϕ-meson ρ_{00} from Theory

STAR Collaboration, arXiv: 2204.02302 (2022).



- A large positive global spin alignment (ρ_{00}>1/3) for ϕ-meson was measured in mid-central collisions from BES-I.
- Supported by a theoretical model considering a ϕ-meson strong force field.[1,2]
  - Couples to s and $\bar{s}$ quarks.

$$C_s^{(y)} \equiv g_\phi^4 \langle \tilde{E}_{\phi,z}^2 + \tilde{E}_{\phi,x}^2 \rangle = 1109 \pm 143\,\mathrm{fm}^{-8}$$

Corresponds to field strength: $g_\phi \sqrt{\langle E_{\phi,z}^2 + E_{\phi,x}^2 \rangle} \sim 2.5 m_\pi^2$

$$\widetilde{E}_{\phi,z} = (m_\phi^2/g_\phi)E_{\phi,z} \quad \widetilde{E}_{\phi,x} = (m_\phi^2/g_\phi)E_{\phi,x}$$

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

Motivation

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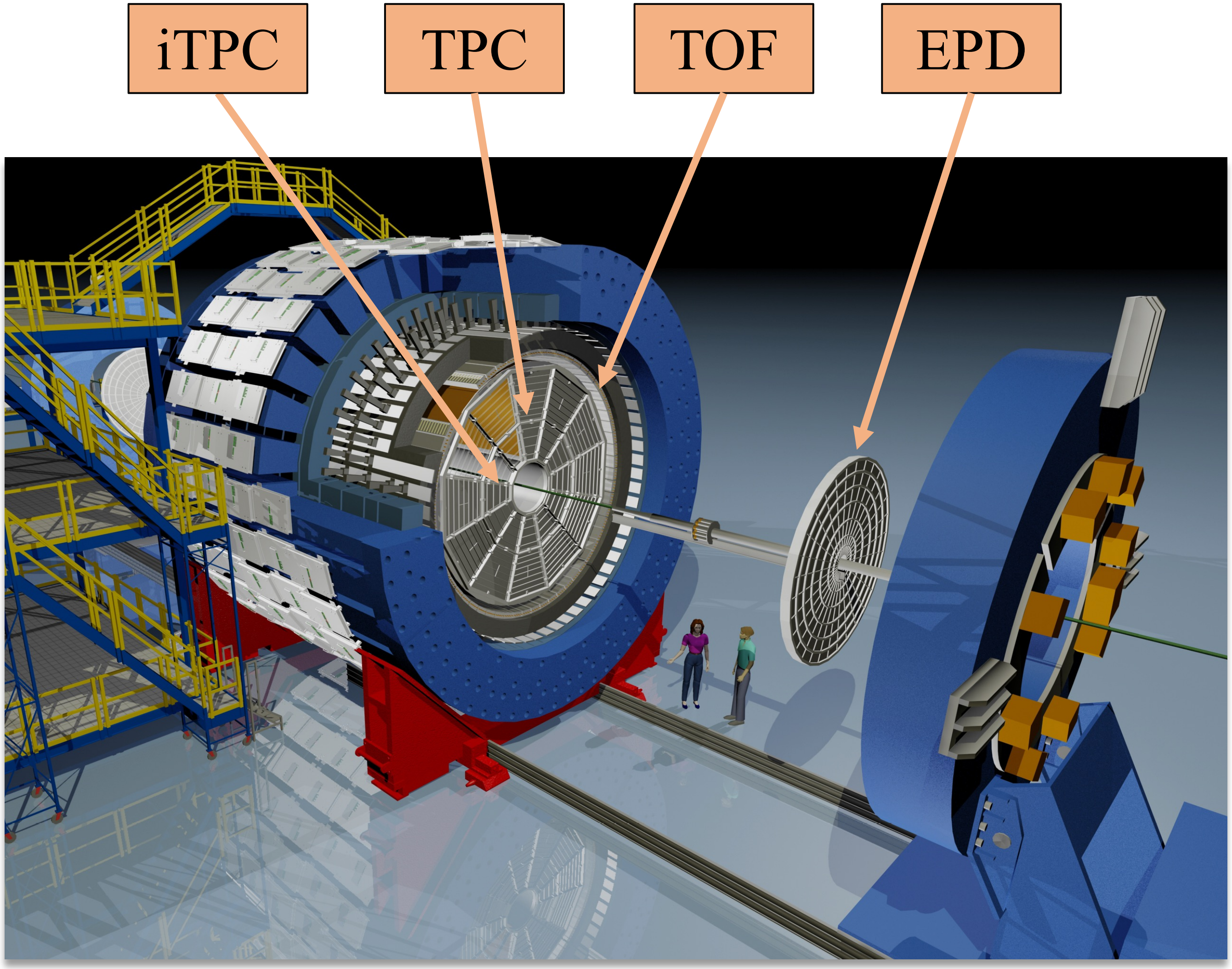
$\sqrt{s_{NN}}$ (GeV)	BES-I (x10[6] events)	BES-II (x10[6] events)
19.6	36	478
14.6	18	324
11.5	12	235
9.2	---	162
7.7	4	101
7.7 (FXT)	---	163
7.2 (FXT)	---	561
6.2 (FXT)	---	118
5.2 (FXT)	---	103
4.5 (FXT)	---	108
3.9 (FXT)	---	170
3.5 (FXT)	---	116
3.2 (FXT)	---	201
3.0 (FXT)	---	2361

- 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.
- Improvements to the STAR detector.
  - Increased acceptance in $|\eta|$.
  - Increased event plane resolution.
  - Tracking improvements.
- High precision differential measurements of K^{*0} and ϕ-meson ρ_{00}.
  - Could 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 event plane

TOF* : $|\eta| < 0.9$

eTOF^II: $1.1 < \eta < 1.5$ (not shown)

particle identification

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

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

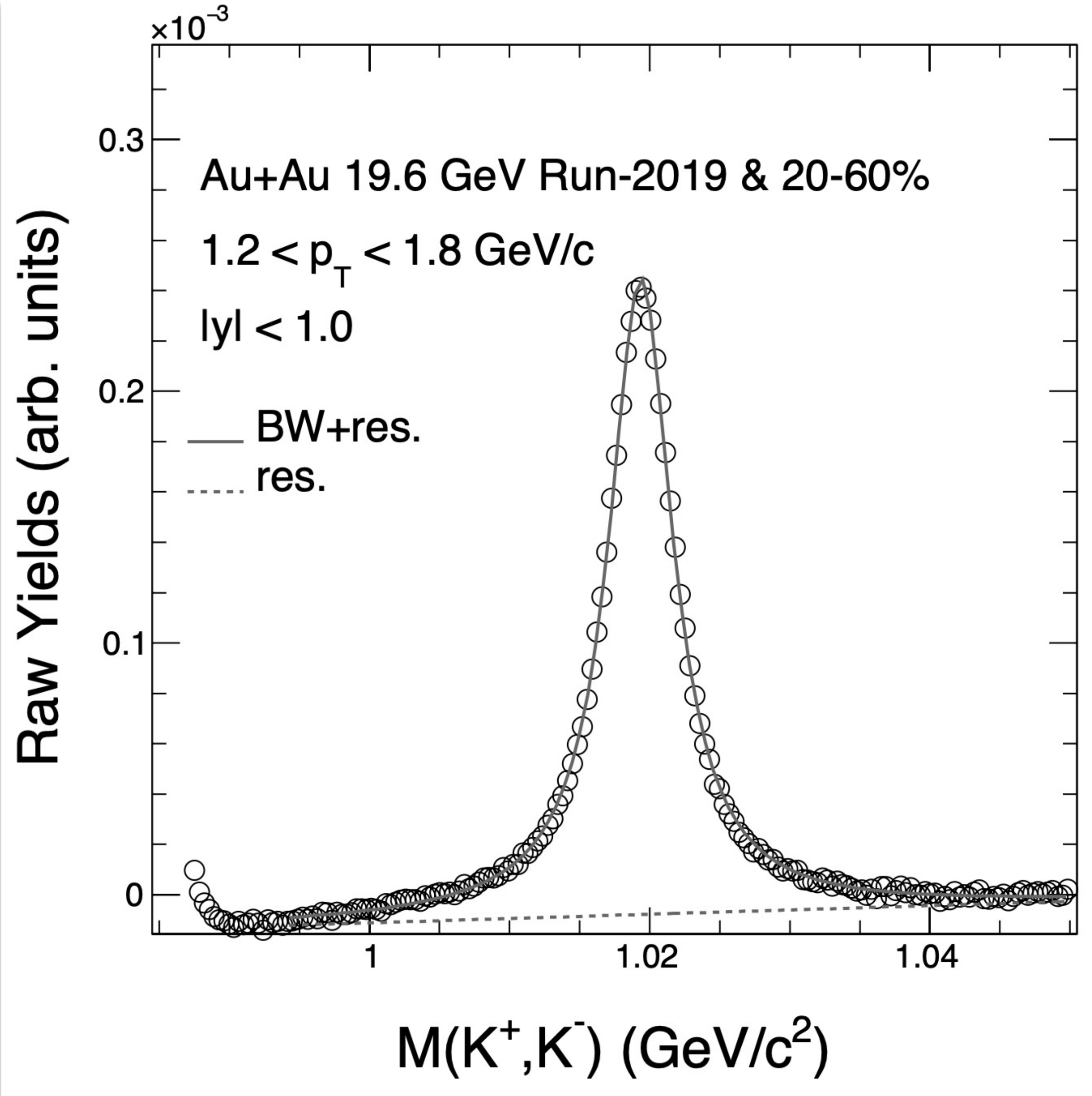
event plane reconstruction

~2x greater EP resolution with EPD

*Used in this analysis

II: Upgrades to STAR since BES-I

Analysis Method



Event mixing is used to produce ϕ-meson background.

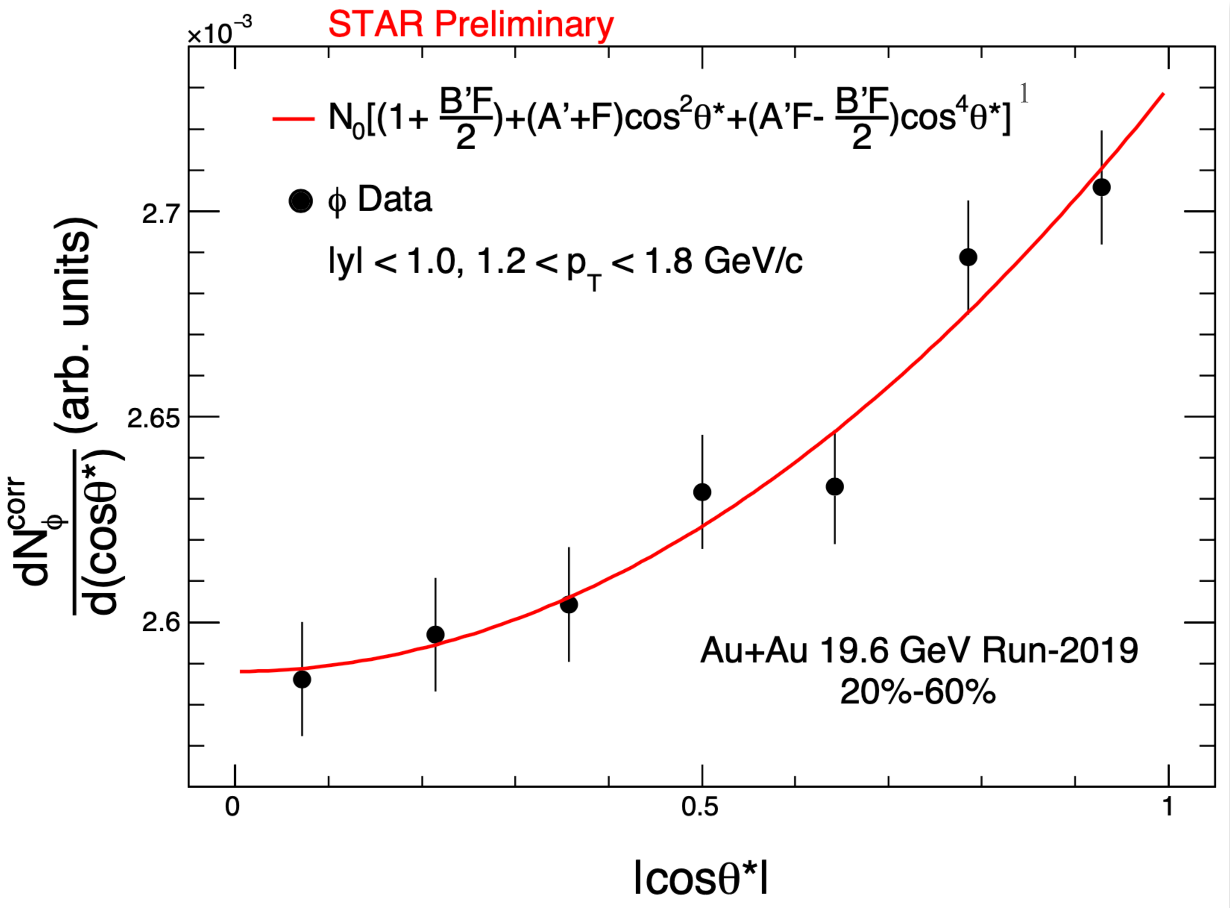
Fit histogram with Breit Wigner + 1st order polynomial,

$$\frac{1}{2\pi}\frac{A\Gamma}{(m - m_\phi) + (\Gamma/2)^2} + B + Cm$$

Yields are extracted by histogram integration.

Analysis Method

For a given p_T bin, raw yields are extracted for seven $|\cos\theta^*|$ bins.
Correct yields using efficiency calculated from STAR detector simulations.



ρ_{00} is extracted from fit of efficiency corrected yields where A' and B' are functions of ρ_{00} and event plane resolution.[1]

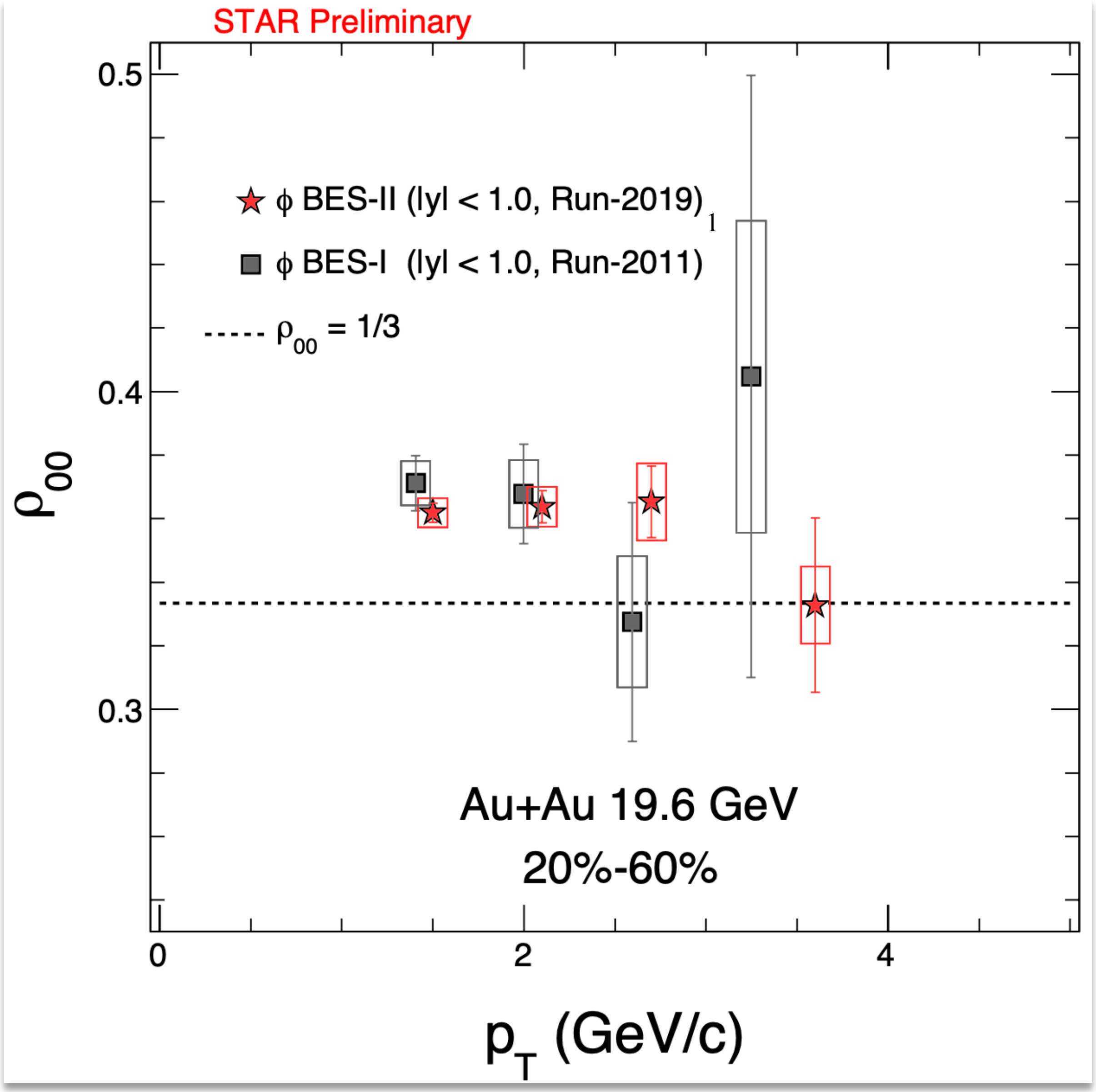
$$A' = \frac{A(1+3R)}{4+A(1-R)} \qquad B' = \frac{A(1-R)}{4+A(1-R)}$$

$$A = \frac{3\rho_{00}-1}{1-\rho_{00}}$$

F describes the finite acceptance in η for the STAR detector and is determined by simulation.[1]

[1] Tang et al., Phys. Rev. C 98, 044907 (2018).

ϕ-meson ρ_{00} (p_T)



Mid-central Au+Au collisions (20-60%)

BES-II Yield weighted average over $1.2 < p_T < 4.2$ GeV/c:

$\rho_{00}^{II} = 0.3622 \pm 0.0026$ (stat.) ± 0.0049 (sys.)

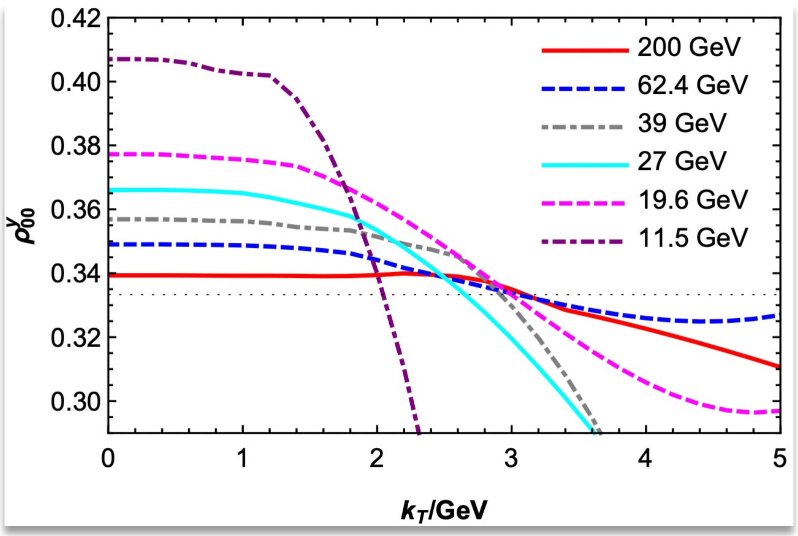
$\rho_{00}^{II} > 1/3$ with 5.3σ

BES-I[1] Yield weighted average over $1.2 < p_T < 4.2$ GeV/c:

$\rho_{00}^{I} = 0.370 \pm 0.008$ (stat.) ± 0.007 (sys.)

$\rho_{00}^{I} > 1/3$ with 3.5σ

$\rho_{00}^{II} \sim \rho_{00}^{I}$ with 0.65σ

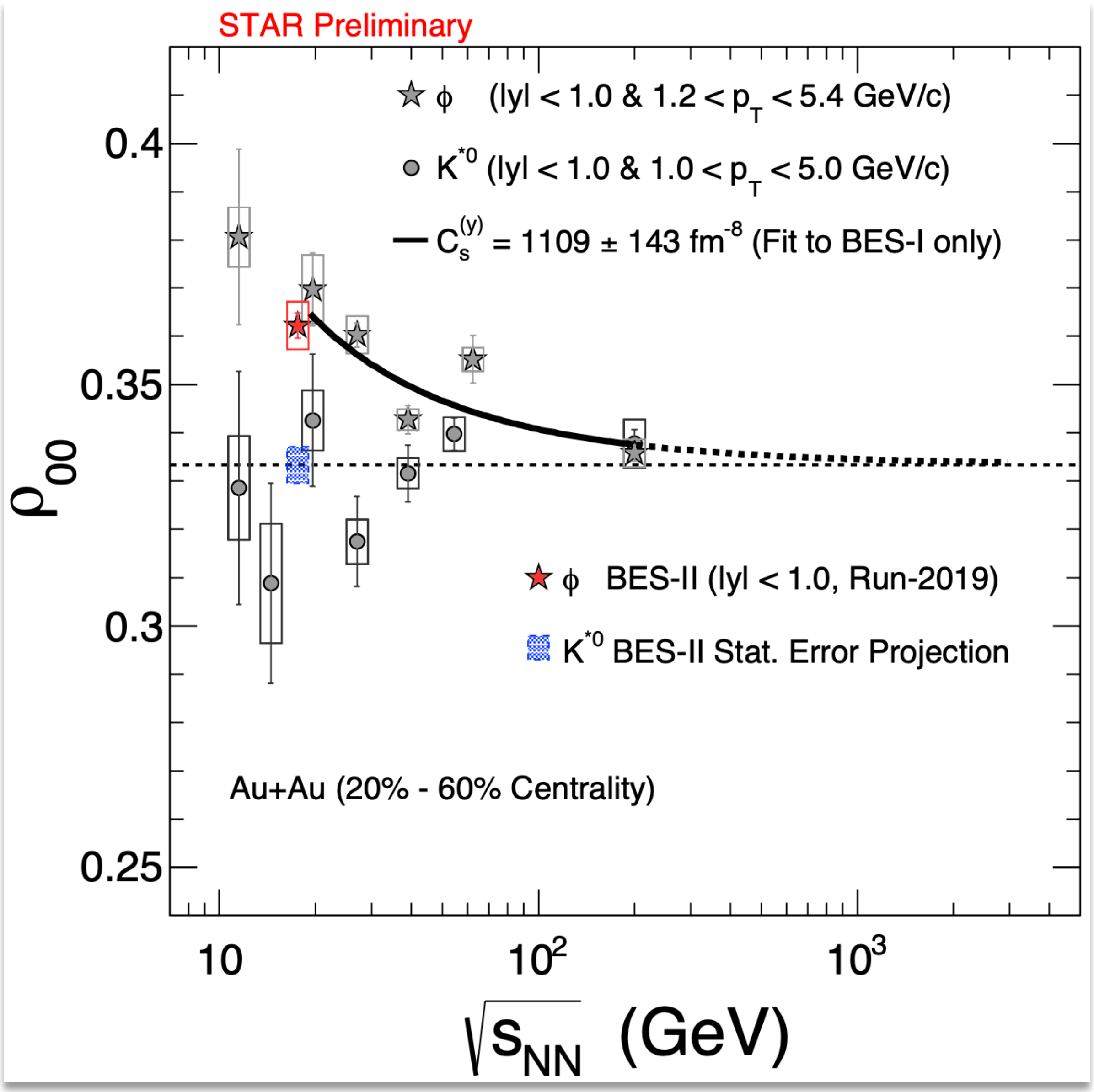


ϕ-meson field model predicts p_T dependence of ρ_{00} at various collision energies.[2]

High precision differential measurements from BES-II can provide theoretical guidance.

[1] STAR Collaboration, arXiv: 2204.02302 (2022).
[2] Sheng et al., arXiv:2205.15689 (2022).

ϕ-meson ρ_{00} ($\sqrt{s_{NN}}$)



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Summary

- ϕ: $\rho_{00} > 1/3$ for mid-central collisions at energies $\leq$ 62 GeV BES-I.
  - Currently supported by vector meson strong force field.[1]
  - More inputs needed from theory.

- Presented results for ρ_{00} from BES-II 19.6 GeV Au+Au.
  - $\rho_{00}^{II} > 1/3$ with 5.3σ compared to $\rho_{00}^{I} > 1/3$ with 3.5σ.[2]
  - Significant improvement in measurement precision.
  - Consistent with BES-I results.

Further work:

- Increase $|\eta|$ coverage available from STAR detector upgrades.
- More precise centrality dependent measurements of ρ_{00}.
- ρ_{00} of K^{*0} for 19.6 GeV.
- ρ_{00} for ϕ and K^{*0} from Au+Au BES-II at 7.7-14.6 GeV and FXT at 3.0-7.7 GeV.
- Additional precise differential studies of ρ_{00} (e.g., η dependence).

[1] Sheng et al., Phys. Rev. D 102, 056013 (2020).
[2] STAR Collaboration, arXiv: 2204.02302 (2022).

THANK YOU FOR YOUR ATTENTION

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BACKUP

TPC 2nd Order Event Plane

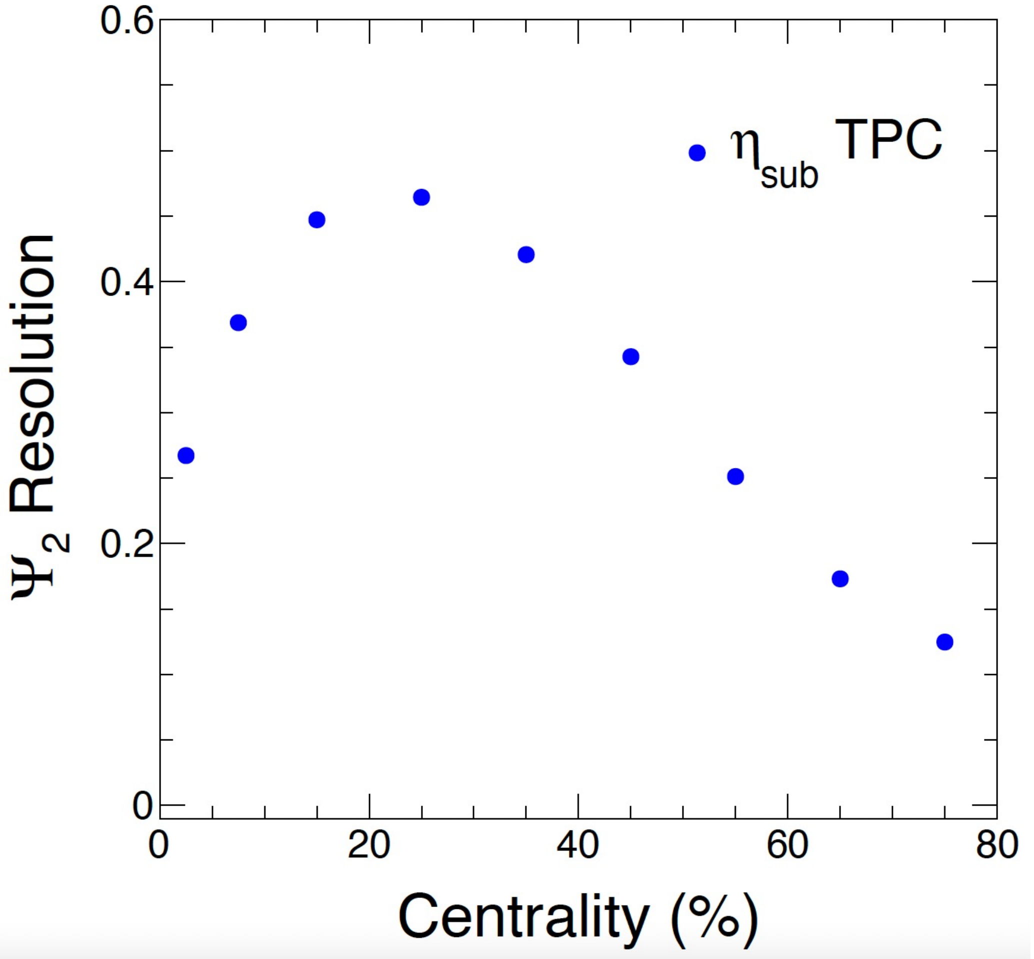
TPC Event Plane Cuts

- $0.15 < p_T < 2$ GeV/c
- $|DCA| < 1$ cm
- No. TPC hits > 15
- TPC hit ratio > 0.52
- $|\eta| < 1$

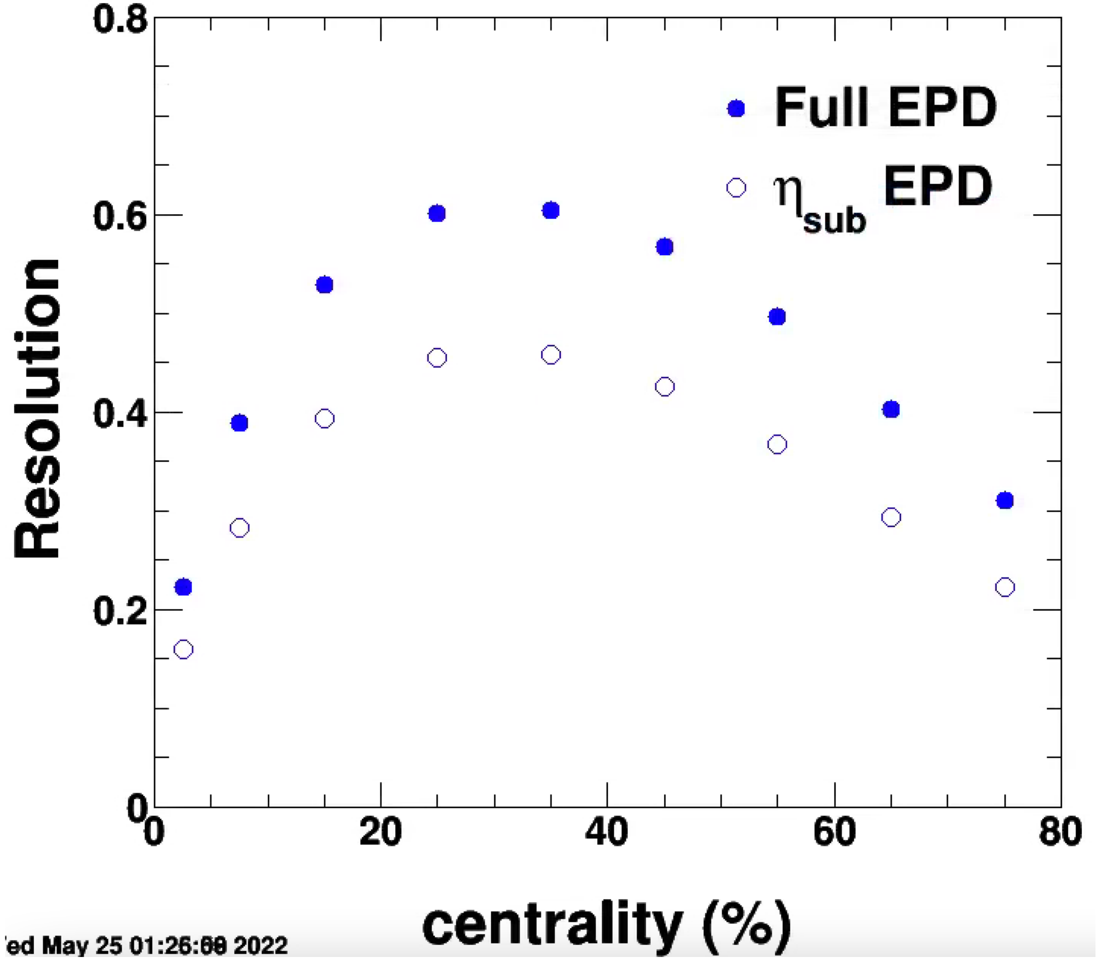
Sub-event plane method

- η gap = 0.1

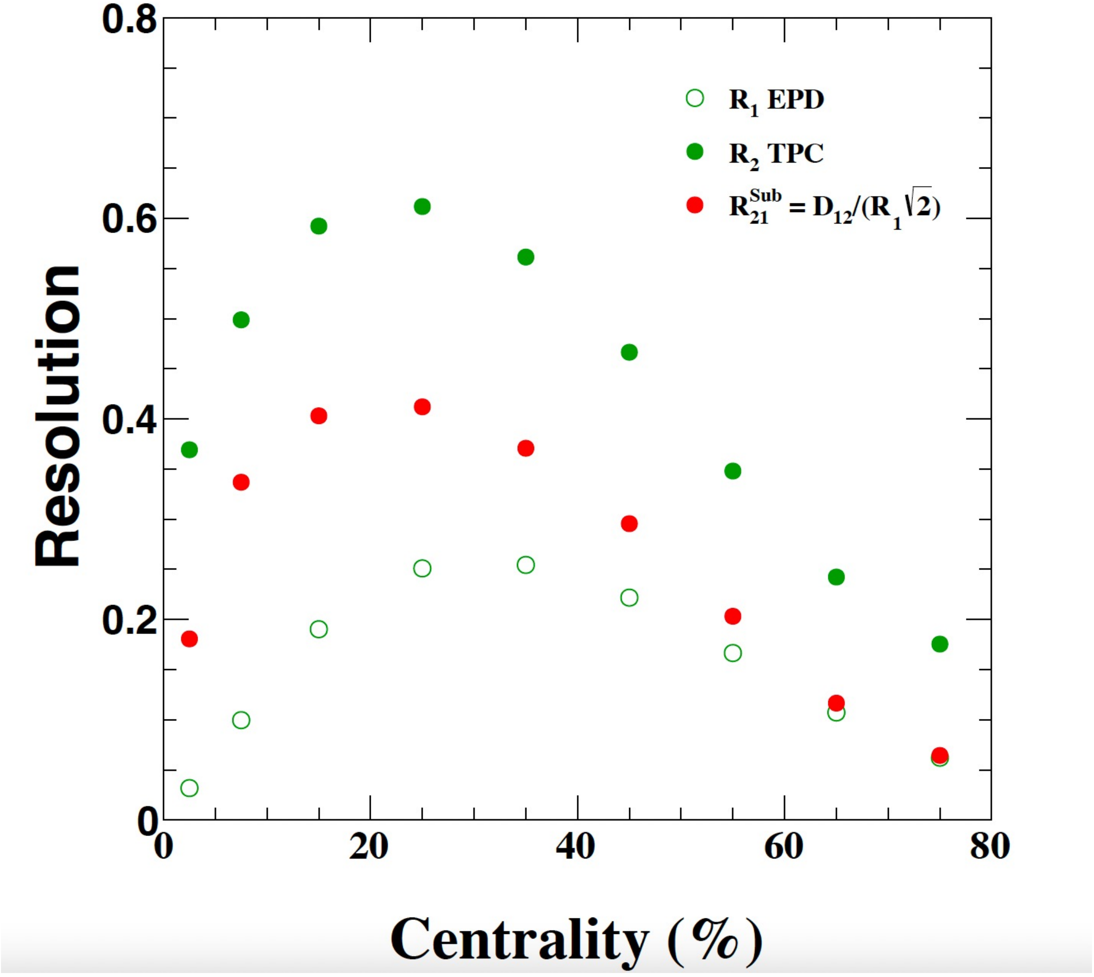
Apply run-by-run, centrality and v_z wise re-centering and shift calibrations



1^{st} Order EPD EP Resolution & R_{21}^{Sub}



1^{st} order EP resolution with EPD.



R_1 : EP resolution with 1^{st} harmonic of EP and 2^{nd} harmonic of flow.

R_2 : EP resolution with 2^{nd} harmonic of EP and 2^{nd} harmonic of flow.

EP Resolution

- To ensure ρ_{00} with respect to the 2nd order EP is consistent with ρ_{00} with respect to the 1st order EP one must use the 2nd order EP "resolution" with respect to the reaction plane that the 1st 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 2nd order **sub-event** plane for our ρ_{00} calculations, we must use R_{21}^{Sub} instead.

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

Tang et al., Phys. Rev. C 98, 044907 (2018).