Preliminary figures request: Global spin alignment of ϕ-meson in Au+Au collisions in BES-II

Gavin Wilks

05/30/2022

Contact Information

PA name: Gavin Wilks

PA email address: gwilks3@uic.edu

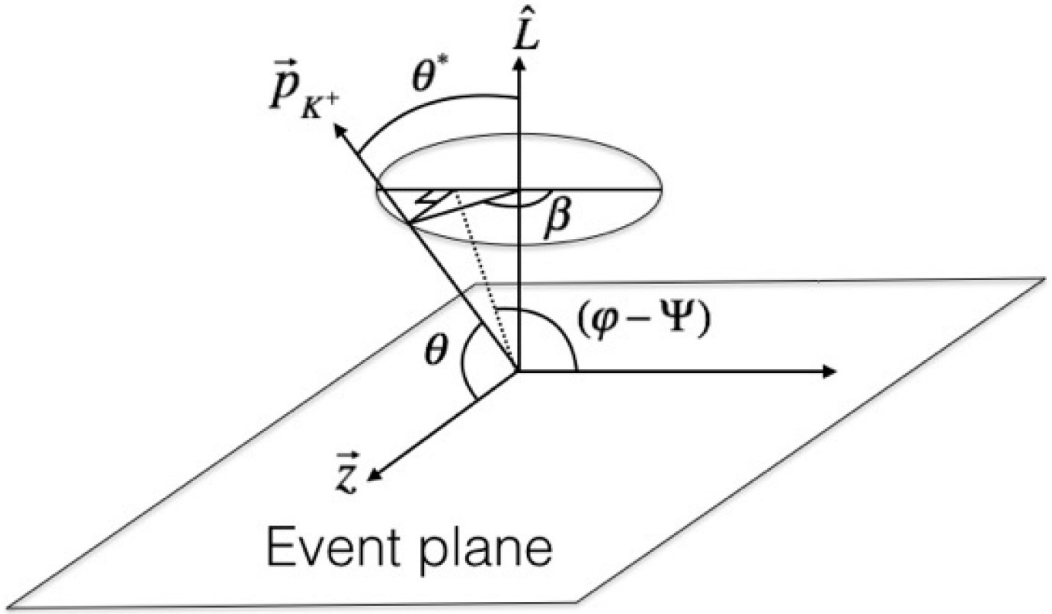
Supervisor email address: yezhenyu@uic.edu

Introduction to Spin Alignment

Preferential alignment of a particle's spin with respect to the orbital angular momentum produced in heavy-ion collisions.

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

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



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

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

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

Nucl. Phys.B18,332(1970)

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

Physics Motivation

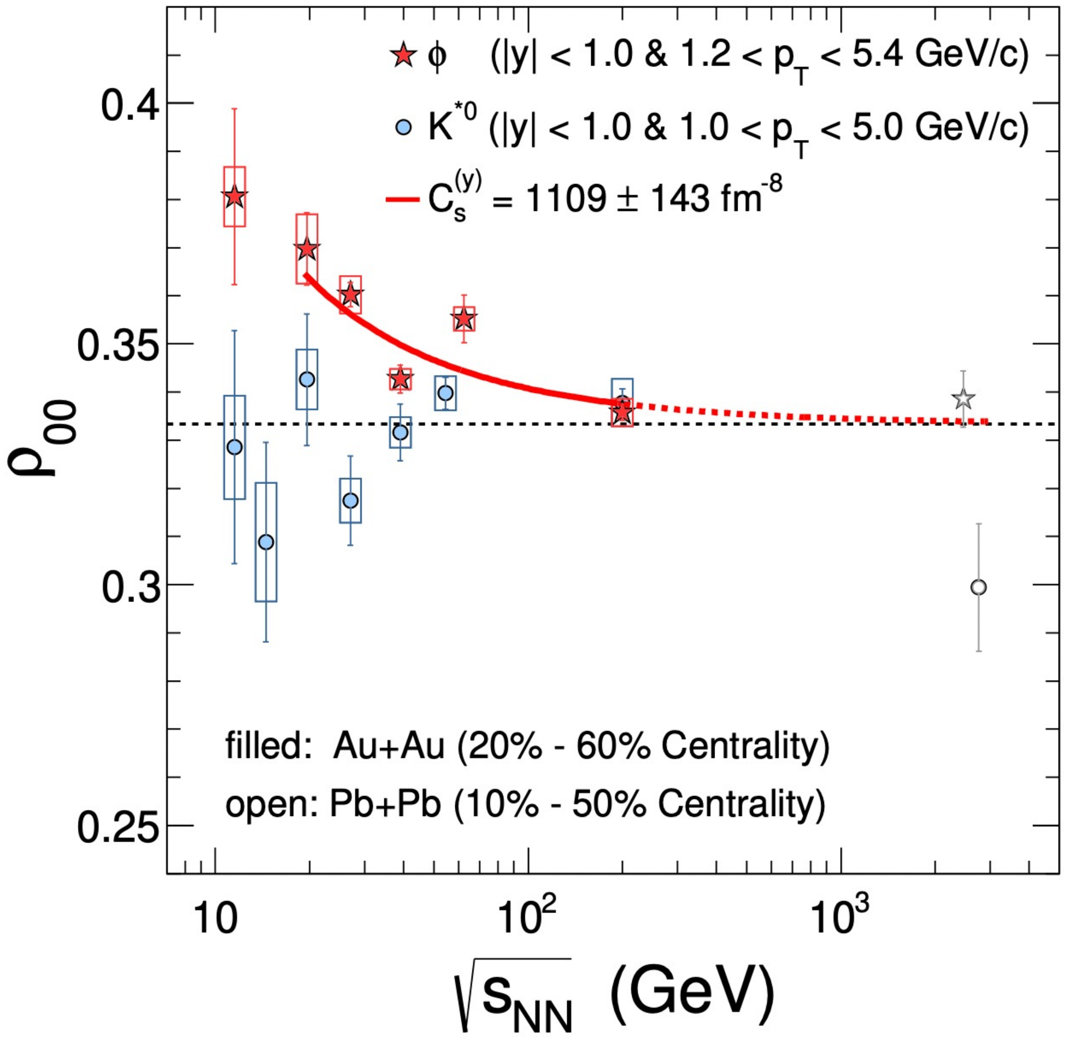
- Preliminary studies from BES-I data found a large positive global spin alignment (ρ_{00}>1/3) for ϕ mesons.
- Conventional methods cannot support this value.
- Supported by a theoretical model considering a ϕ meson vector field coupling to s and $\bar{s}$ quarks.

$$C_s^{(y)} \equiv g_\phi^4 \langle \tilde{E}_{\phi,z}^2 + \tilde{E}_{\phi,x}^2 \rangle$$

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

Phys. Rev. D **101**, 096005 (2020).

STAR Collaboration, arXiv: 2204.02302



Analysis Motivation

- Preliminary results for BES-I energies show increasing global spin alignment for ϕ-meson at lower Au+Au collision energies ($\leq$ 19.6GeV).
  - Clarify ρ_{00} behavior in lower energy regime.

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

Dataset

- 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

Event level cuts

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

- No. of event before event cuts ~ 1.05×10^9
- No. of event after event cuts ~ 4.60×10^8

Track level cuts

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

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: $0.16 < M^2 < 0.36$

TPC Event Plane

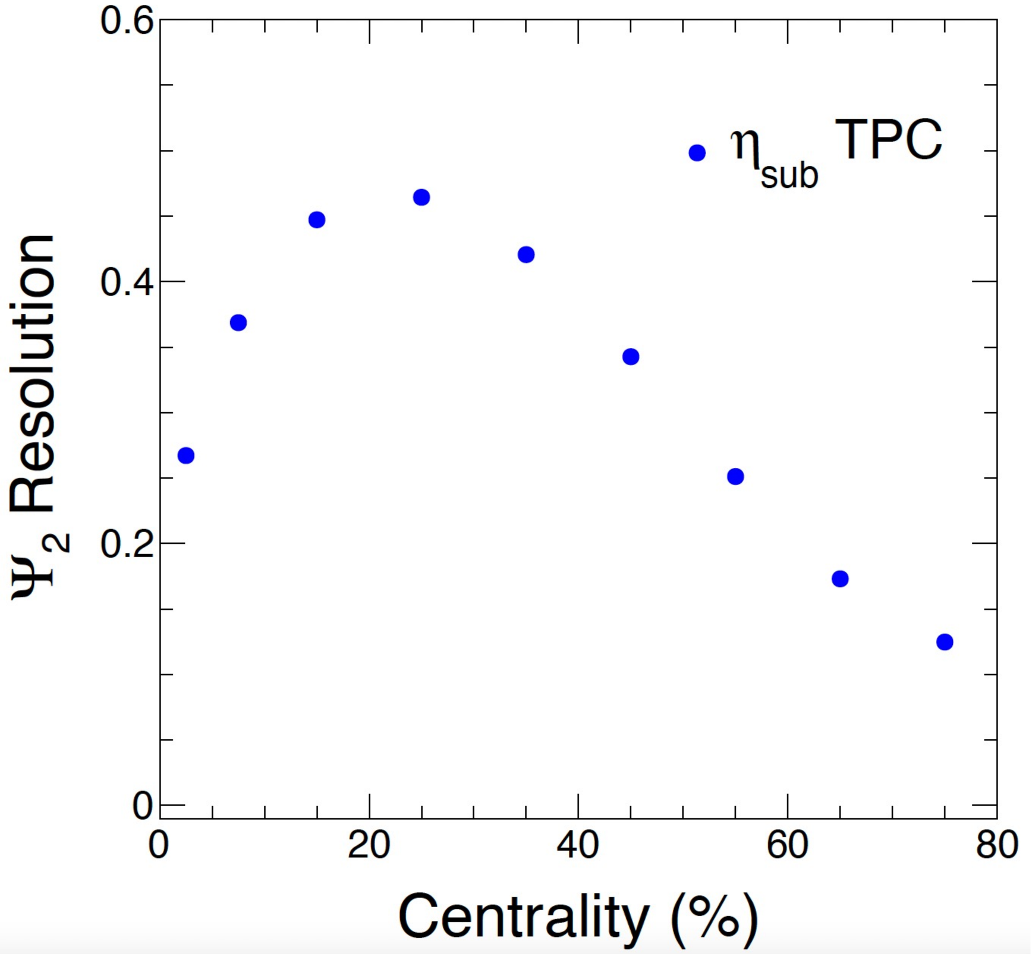
TPC Event Plane Cuts

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

Sub-event plane method

- η gap = 0.1

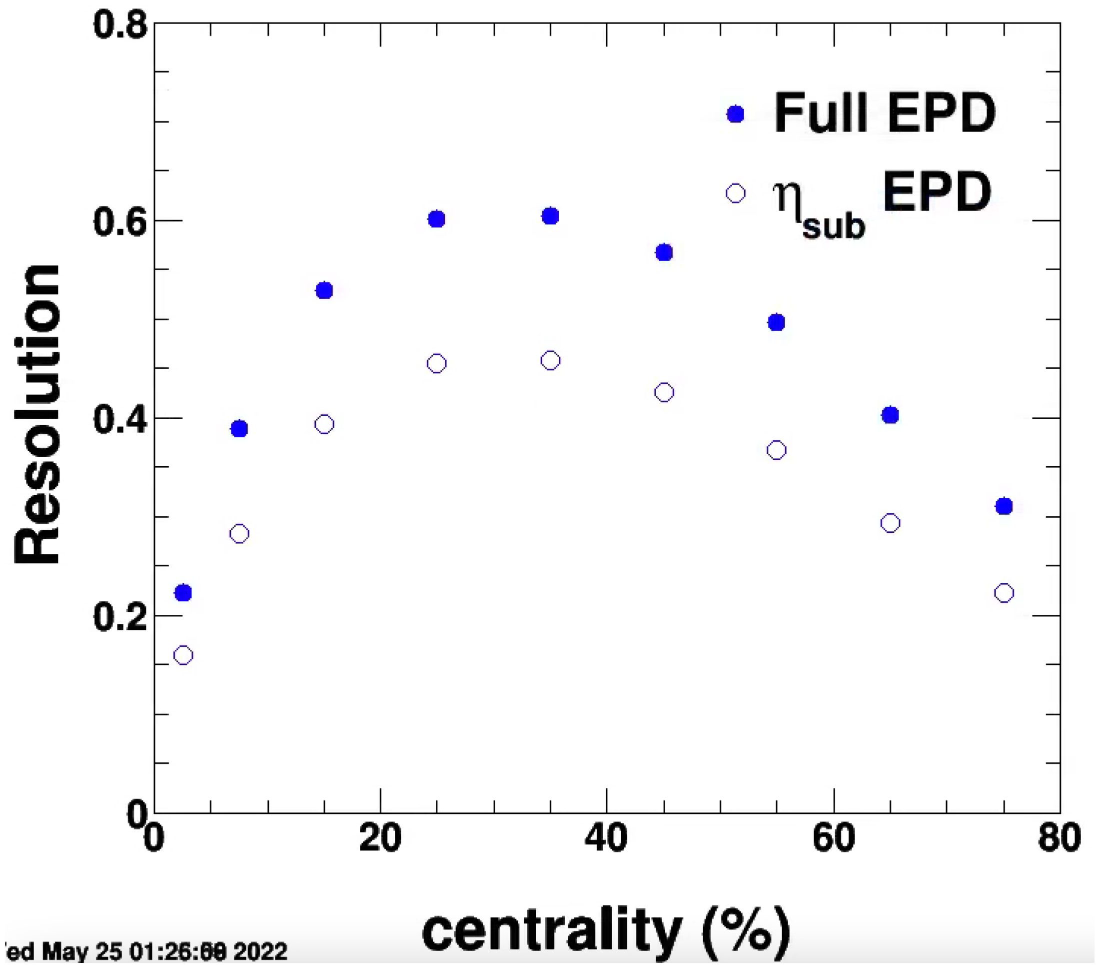
Apply run-by-run, centrality and v_z wise re-centering and shift calibrations

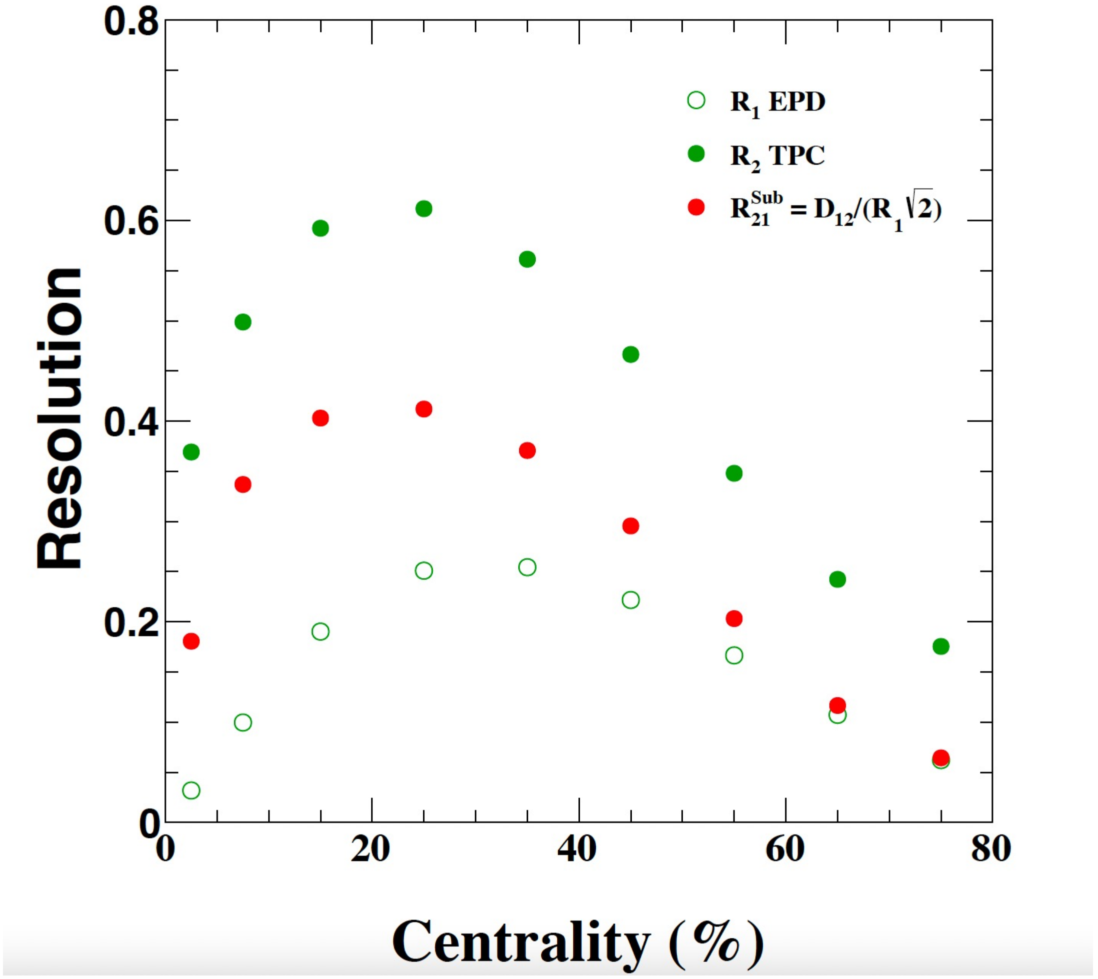


1^{st} Order EPD EP Resolution & R_{21}^{Sub}

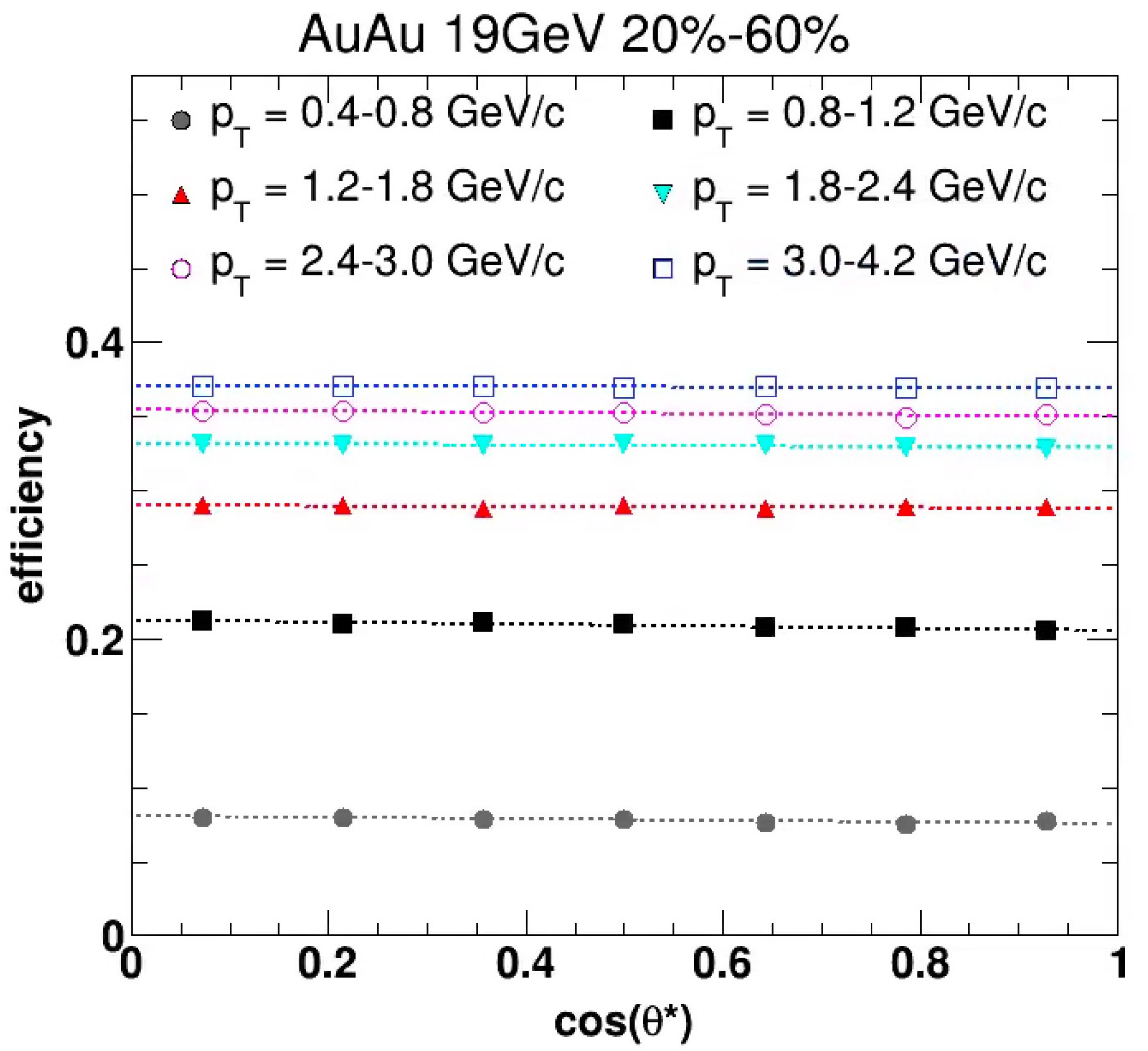
η weights implemented

See slide 24 for R_{21}^{Sub} calculation.



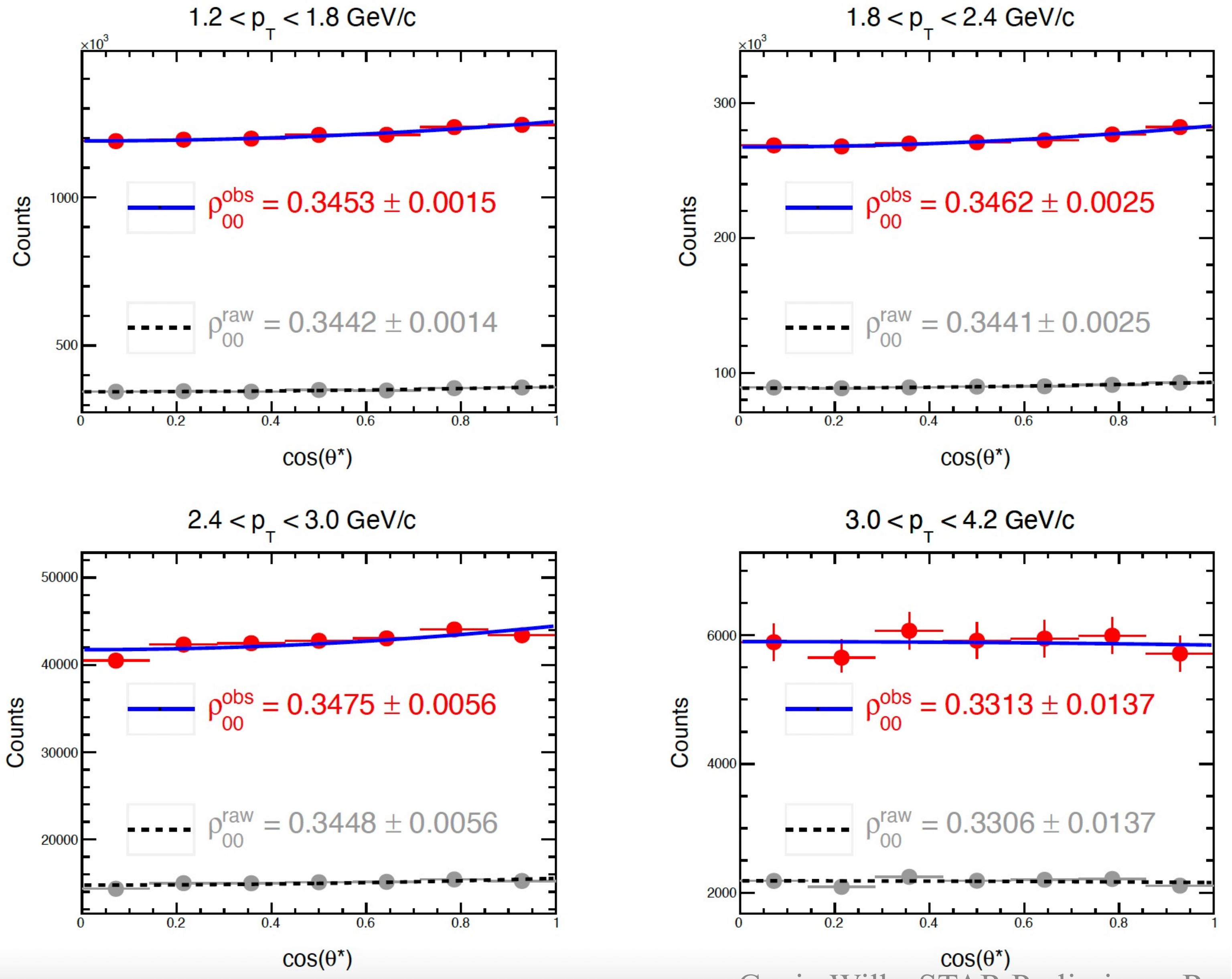


Efficiency vs. cos(θ*)



- Use Pythia6 to decay $\phi \rightarrow K^+K^-$
- MC ϕ input flat in rapidity, p_T and φ.
- Drop tracks using TPC tracking and ToF matching efficiency of K^+ and K^- in each η & φ bin.
- If both kaons pass efficiency cuts, reconstruct ϕ meson.
- Fill histogram for RC and MC counts in each cos(θ*) bin.
- See slides 20-21 for TPC tracking and ToF matching efficiencies.

Signal Reconstruction



Au+Au 19.6GeV
20-60% Centrality
$\phi \to K^+K^-$

ρ_{00}^{obs} is calculated after efficiency corrections.

Both ρ_{00}^{obs} and ρ_{00}^{raw} are found by fitting yields with:

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

Nucl. Phys.B18,332(1970)

Analysis Procedure

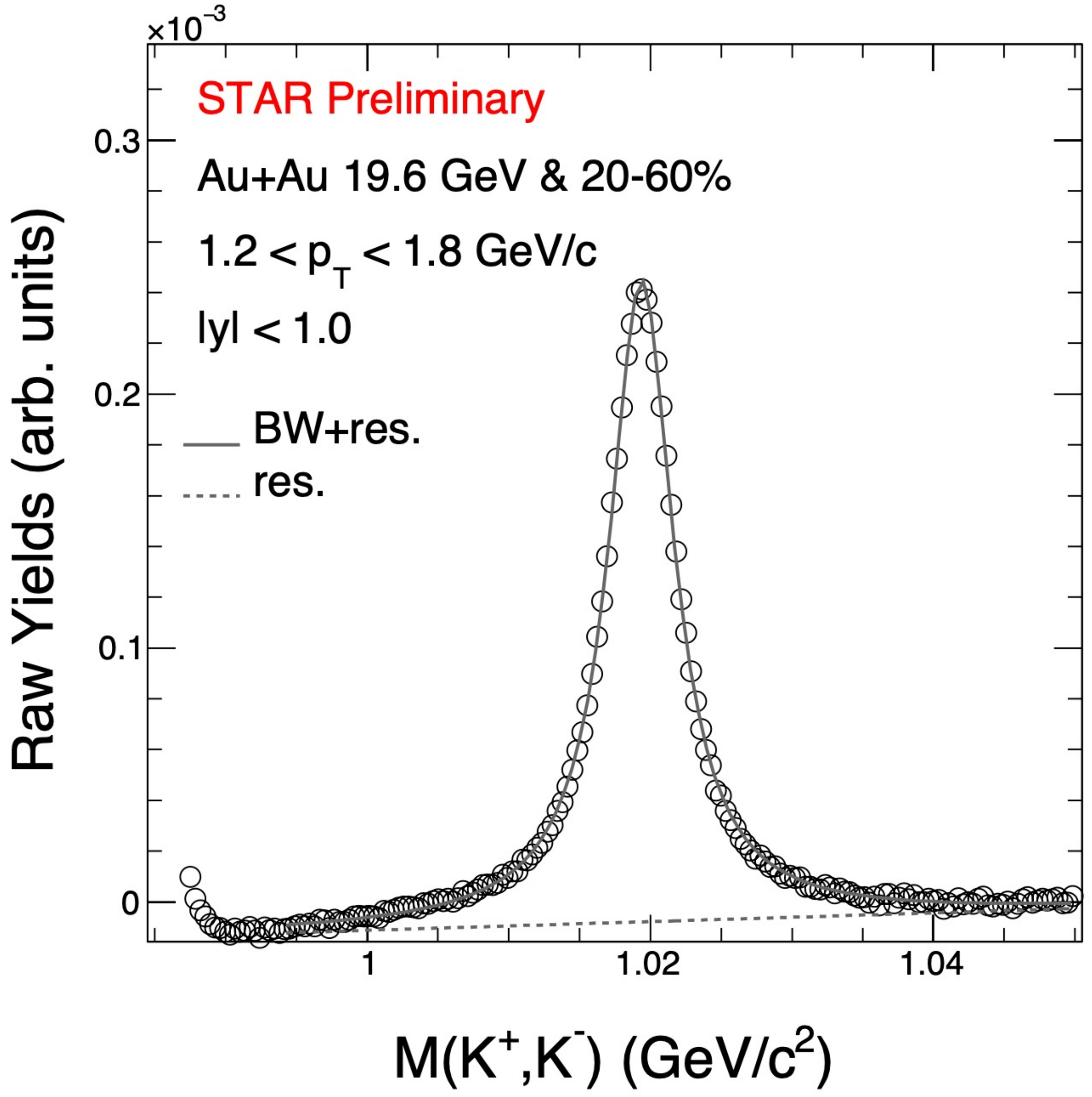
Calculating ρ_{00} from angular distribution of decay daughters:

- Total ϕ meson yield calculated for each cos(θ*) bin.
- Correct yields for TPC tracking x ToF matching efficiency. Simulate ϕ decay in Pythia6 and apply efficiency to decay daughters to find efficiency vs. cos(θ*).
- Finite η acceptance correction calculated through simulated ϕ decay in Pythia6.
- η acceptance correction and event plane resolution (R_{21}^{sub}) correction applied by fitting efficiency corrected ρ_{00}^{obs} using the function:

$$[\frac{dN}{d(cos\theta^*)}]_\eta = N_0 \times [\left(1 + \frac{B'F}{2}\right) + (A' + F)cos^2\theta^* + \left(A'F - \frac{B'F}{2}\right) cos^4\theta^*]$$

- F = acceptance parameter, A' & B' depend on ρ_{00}^{obs} and R_{21}^{sub}. (See slides 22-25 for details)

Analysis Method



Event mixing is used to produce ϕ-meson background.

Normalize mixed event background to signal+background and subtract background

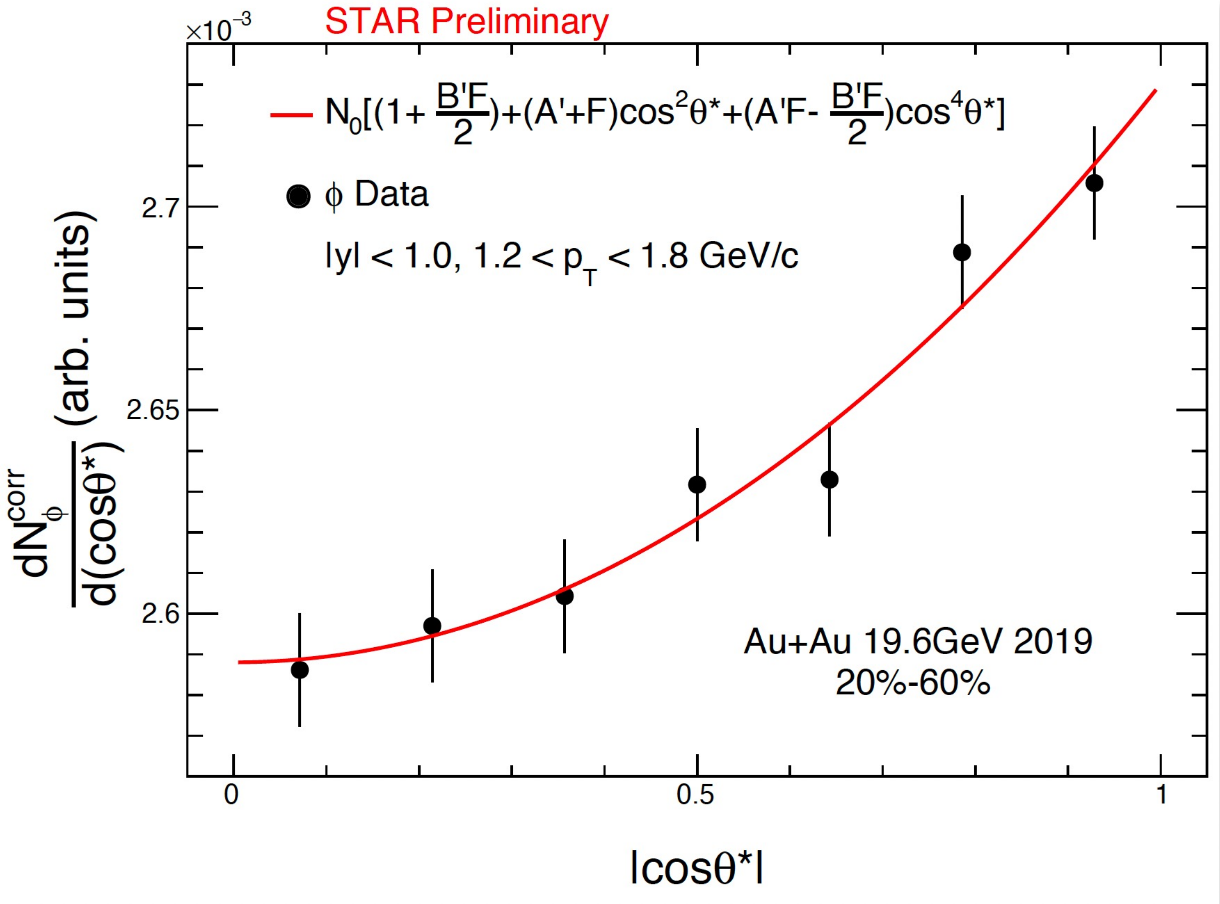
Fit signal histogram with Breit Wigner + 1st order polynomial

$$\frac{1}{2\pi}\frac{AF}{(m-m_{\phi})+(\Gamma/2)^2}+a+bm$$

Yields are extracted by histogram integration.

Final ρ_{00} Extraction

$$[\frac{dN}{d(cos\theta^*)}]_\eta = N_0 \times [\left(1 + \frac{B'F}{2}\right) + (A' + F)cos^2\theta^* + \left(A'F - \frac{B'F}{2}\right) cos^4\theta^*]$$



$$A' = \frac{A(1 + 3R_{21}^{sub})}{4 + A(1 - R_{21}^{sub})}$$

$$B' = \frac{A(1 - R_{21}^{sub})}{4 + A(1 - R_{21}^{sub})}$$

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

Details for finding F on slide 22.

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

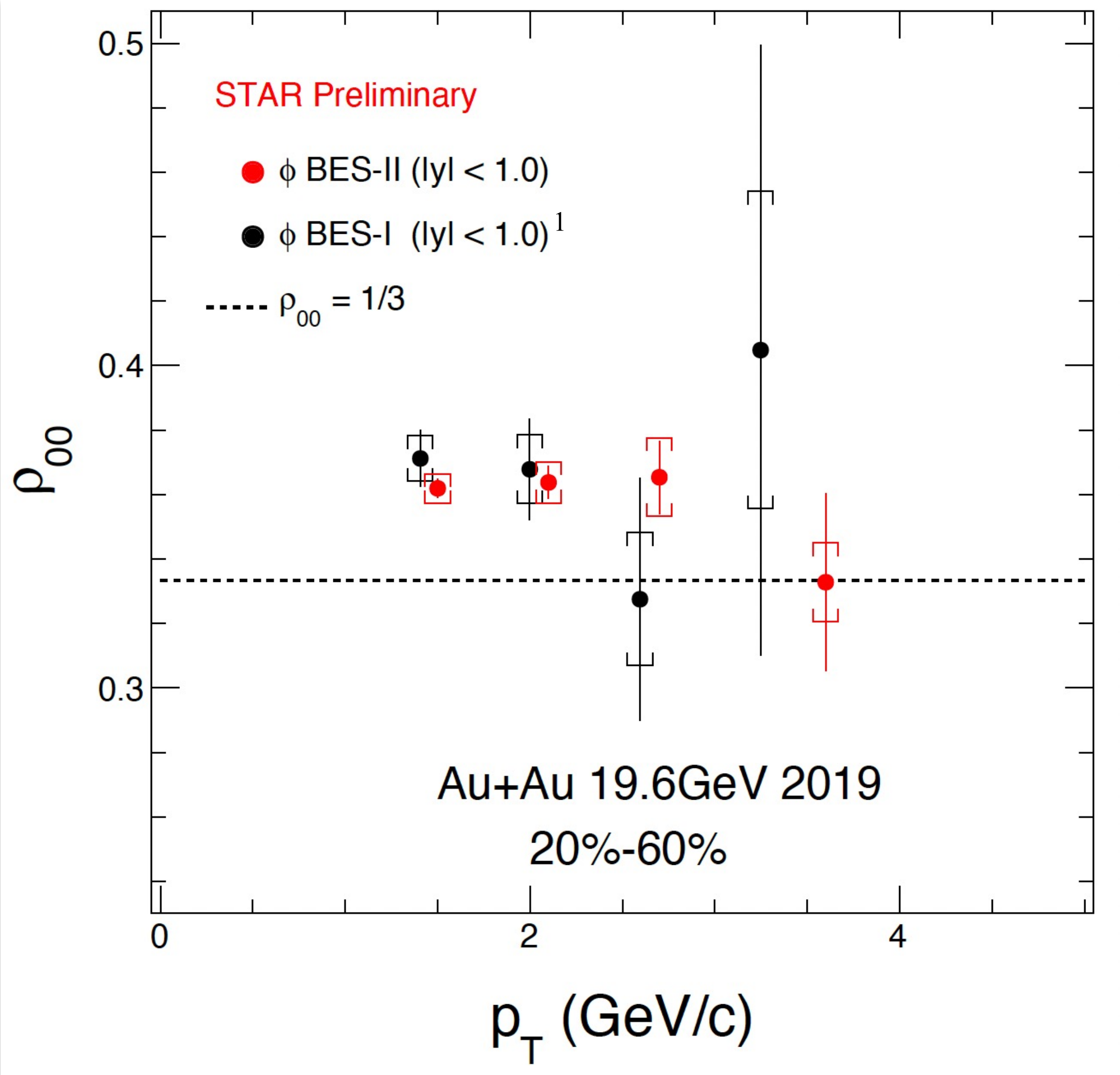
Systematics

Systematic Source	Central Value	Variations
dca	< 2.0 cm	< 2.0 cm, < 2.5 cm, < 3.0 cm
$\lvert n\sigma_K \rvert$	< 2.5	< 2.0, < 2.5, < 3.0
Background normalization range	[1.04,1.05]	[0.99,1.0], [1.04,1.05], average of both
Yield extraction method	Breit-Wigner integration	Bin counting and Breit-Wigner integration
Yield extraction range	< 2.0σ	< 2.0σ, < 2.5σ, < 3.0σ
Acceptance parameter, F	BES-I analysis	BES-I analysis, BES-II analysis

Another source of systematic error to consider is different options for the efficiency inputs to efficiency vs cos(θ*) simulation.

- Vary input TPC efficiency for each η bin or each η & φ bin.
- Vary fit method for ToF matching efficiency
  - Default "Fit to plateau": shape set by η bin integrated over φ, normalization set by plateau in each η & φ bin.
  - Variation "Fit to η": shape and normalization set by η bin integrated over φ.

ϕ meson ρ_{00} (p_T)



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

BES-II Yield weighted average over p_T:

ρ_{00}^{II} = 0.3622 ± 0.0026 (stat.) ± 0.0049 (sys.)

ρ_{00}^{II} > 1/3 with 5.3σ

BES-I Yield weighted average over p_T:[1]

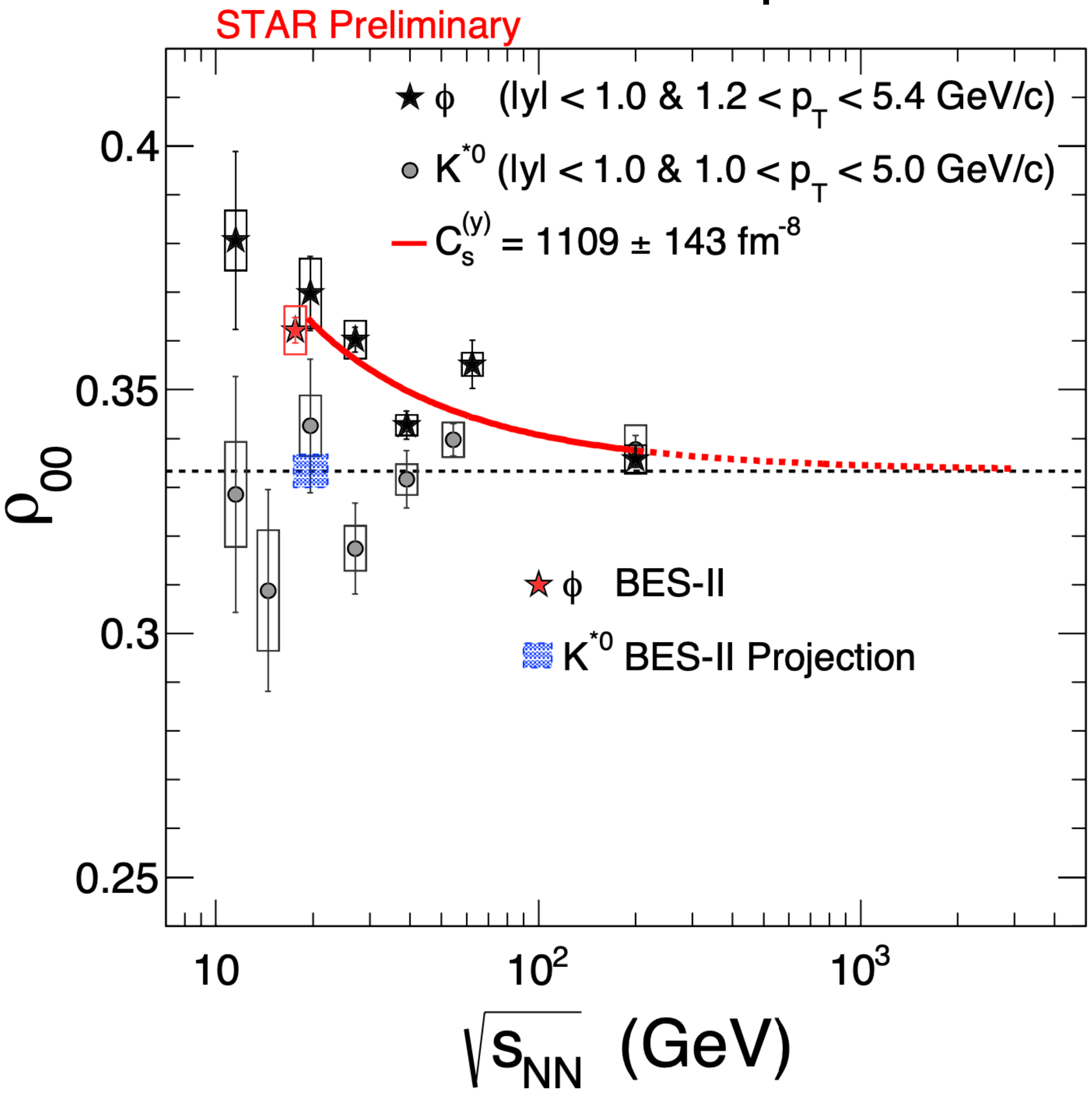
ρ_{00}^{I} = 0.370 ± 0.008 (stat.) ± 0.007 (sys.)

ρ_{00}^{I} > 1/3 with 3.5σ

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

[1] STAR Collaboration, arXiv: 2204.02302

ϕ meson ρ_{00} ($\sqrt{s_{NN}}$)



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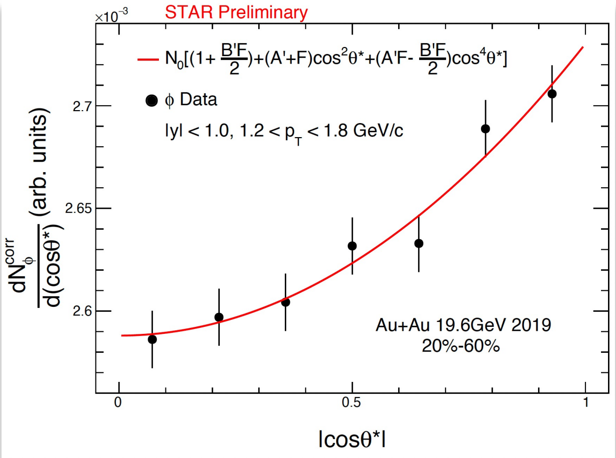
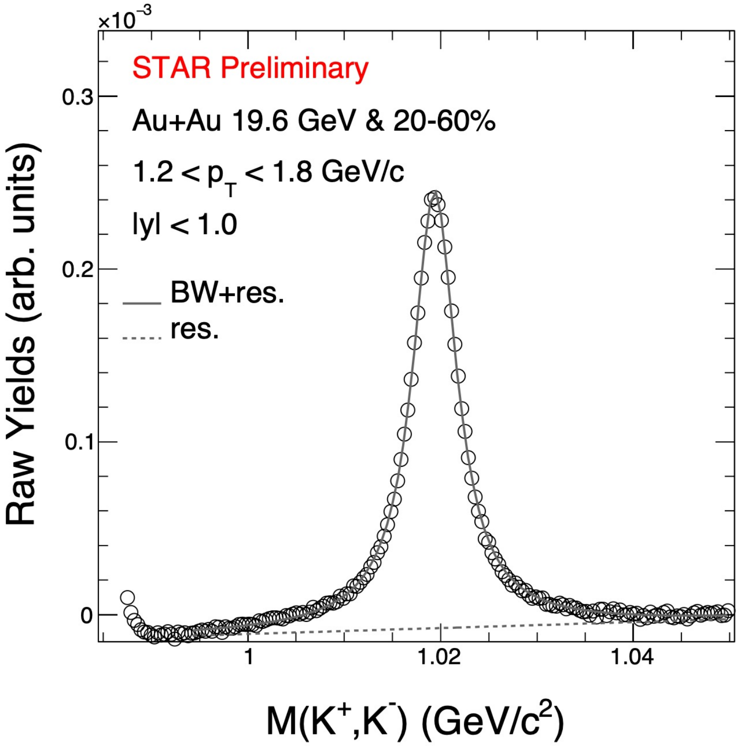
$\rho_{00}^{II} \sim \rho_{00}^{I}$ with 0.65σ

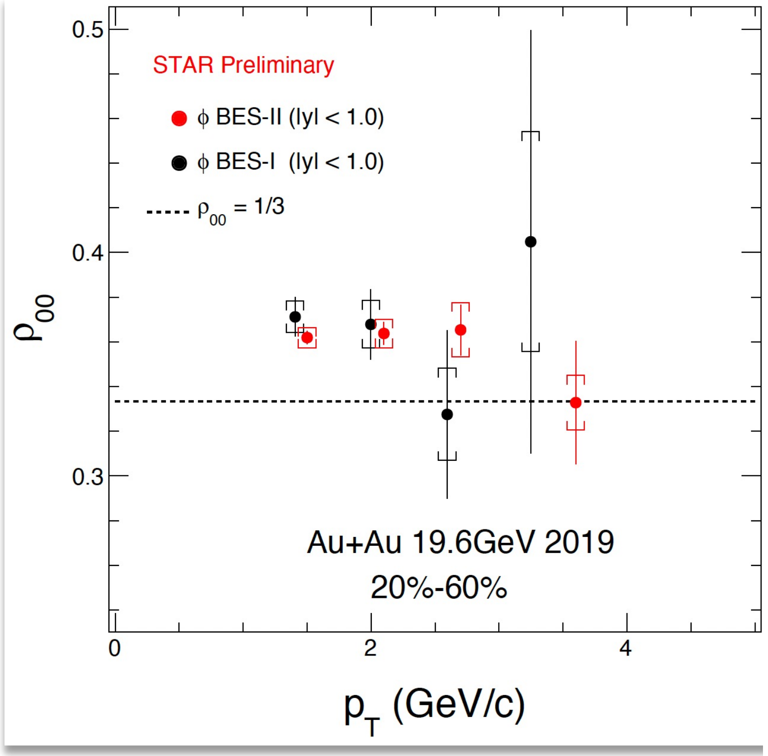
K^{*0} is projected using K

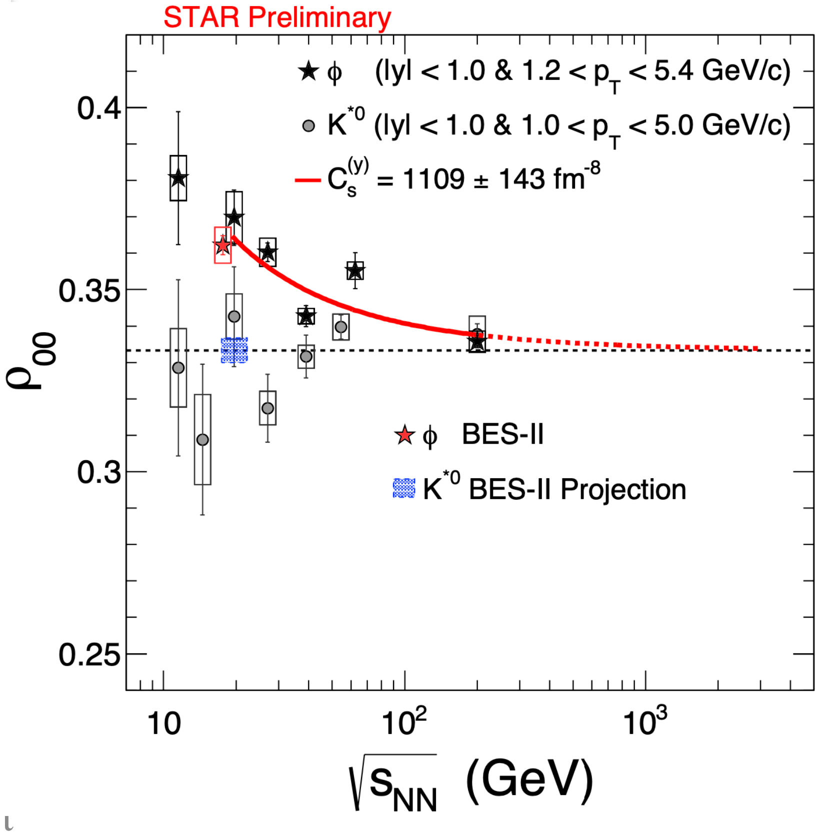
[1] STAR Collaboration, arXiv: 2204.02302

Figures to show at sQM









Summary

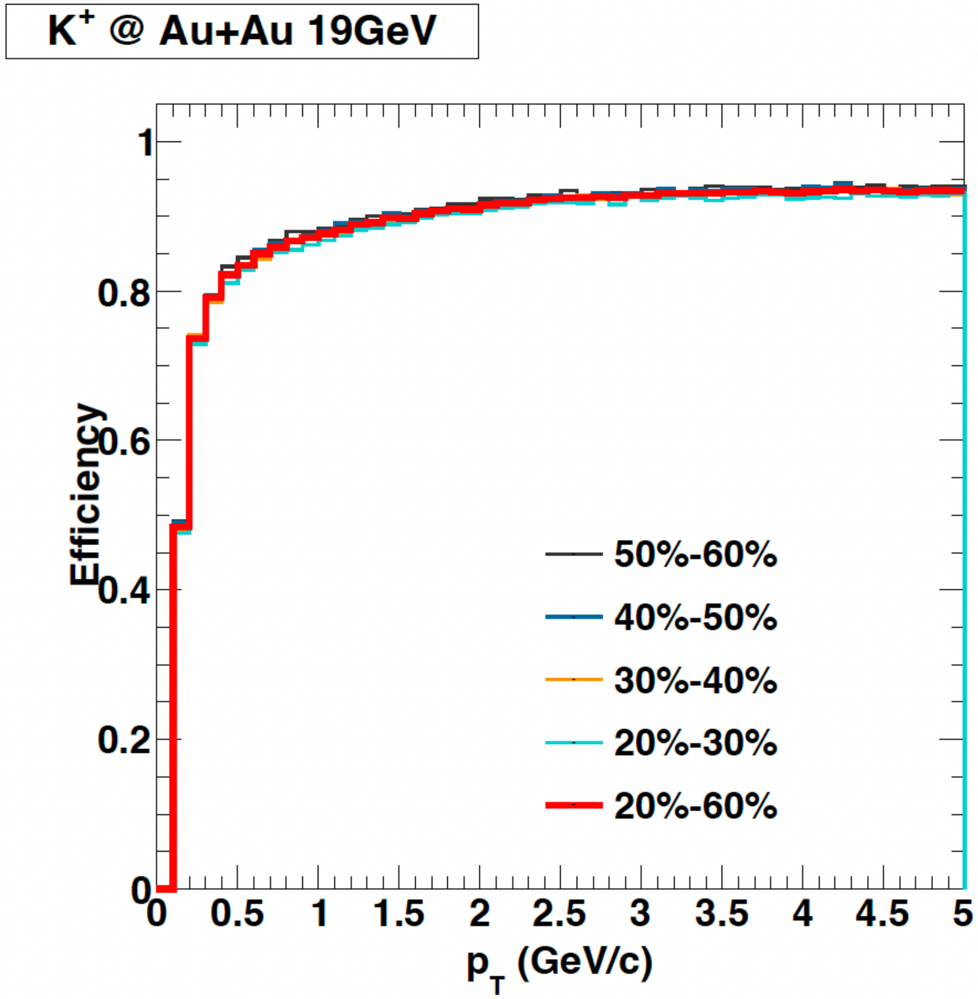
- We presented measurements of ϕ meson ρ_{00} (p_T) for BES-II 19.6 GeV Au+Au collisions.
- $\rho_{00}^{II} > 1/3$ with 5.3σ
- $\rho_{00}^{II} \sim \rho_{00}^{I}$ with 0.65σ

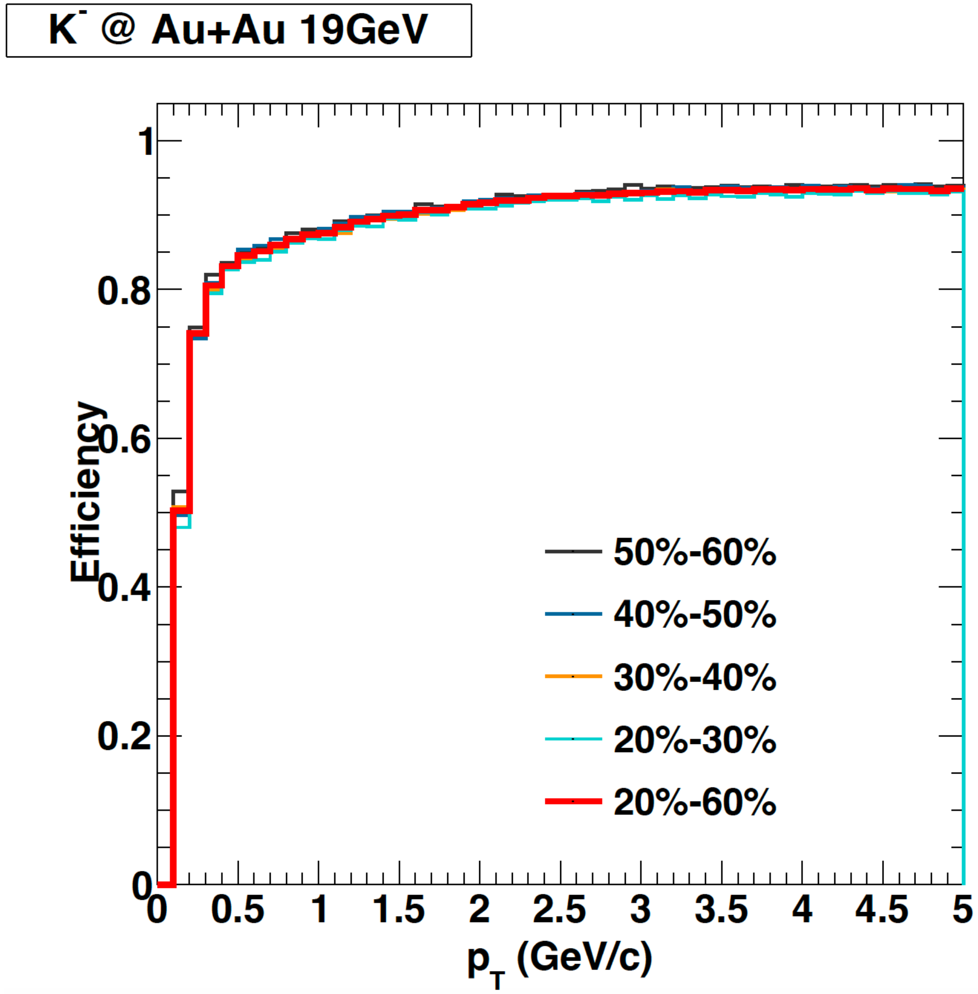
- 3D random EP sanity check for ϕ meson ρ_{00} (p_T) found on slide 26.

BACKUP

TPC Tracking Efficiency

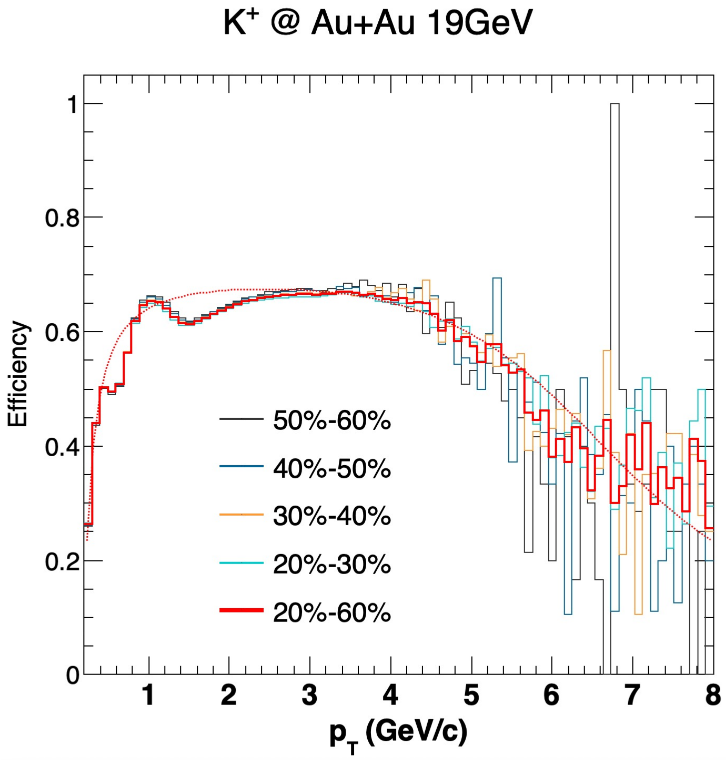
Calculated from STAR standard embedding.

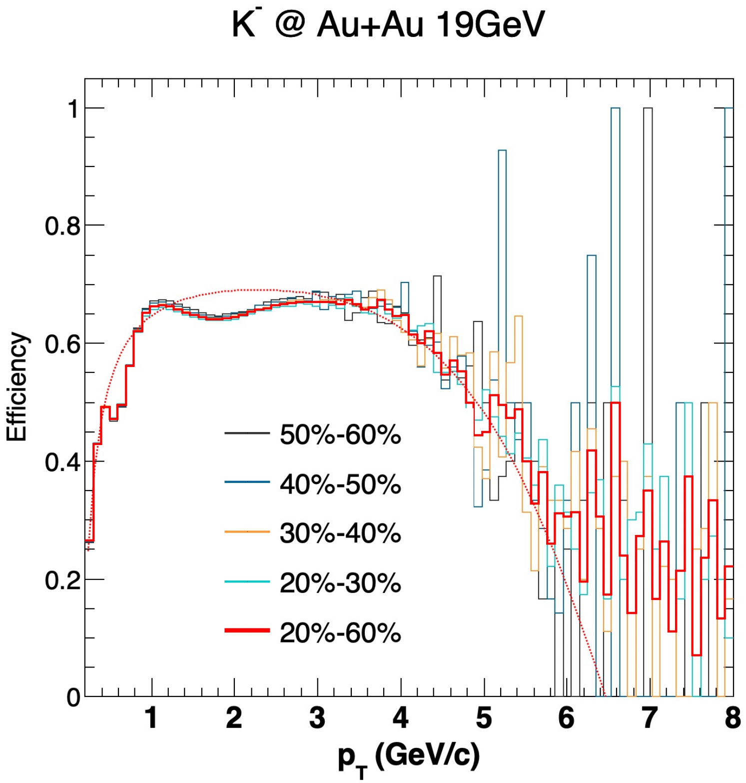




ToF Matching Efficiency

- Evaluated using real data.
- N_{TPC} = tracks passing strict $|n\sigma_K| < 0.6$ cut in addition to TPC performance cuts in attempts to accurately identify desired daughter particle, $K^{+/-}$.
- N_{ToF} = tracks with $\beta > 0$ and pass the above cuts.
- Matching Efficiency = N_{ToF}/ N_{TPC}.





- Fitting is performed in each η and φ bin.
- Red dashed line = fit for η & φ integrated efficiency.
- This fit sets the initial parameters for bin-by-bin fitting.

EP Resolution and Acceptance Correction

- Decay ϕ-meson in Pythia6 with the following kinematics.
  - Random p_T from measured spectra in specific p_T bin.
  - Random rapidity from uniform distribution over [-1,1]
  - Random φ using measured elliptic flow as input.
- Calculate $\cos(\theta^*)$ for K^+ daughter.
- Use ϕ-meson yield vs $\cos(\theta^*)$ from simulation to calculate F (acceptance coefficient)

$$\left[\frac{dN}{d\cos\theta^* d\beta}\right]_{|\eta|} = \frac{dN}{d\cos\theta^* d\beta} \times g(\theta^*, \beta).$$

$$g(\theta^*, \beta) \propto 1 + F\cos^2\theta^* + F\sin^2\theta^*\cos 2\beta$$

$$g(\theta^*) \propto 1 + F\cos^2\theta^*$$

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EP Resolution and Acceptance Correction

- Since we do not know the reaction plane and can only calculate the event plane with a finite resolution, we must change coordinates to a primed frame for our calculation in which,

$$\Psi' = \Psi + \Delta.$$

- We can extract ρ_{00} from the the updated function where F is set by simulation.

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

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

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

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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.

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

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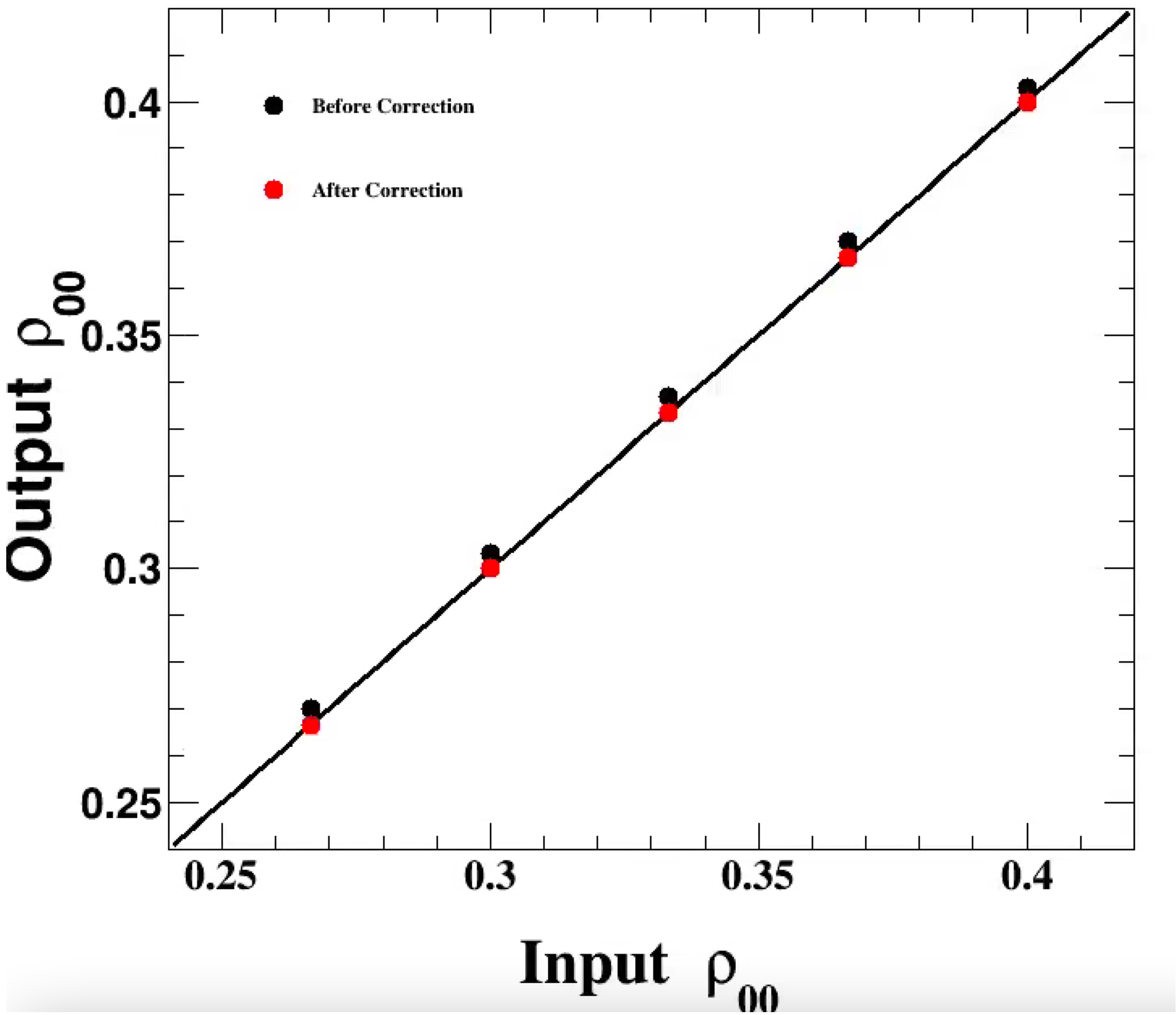
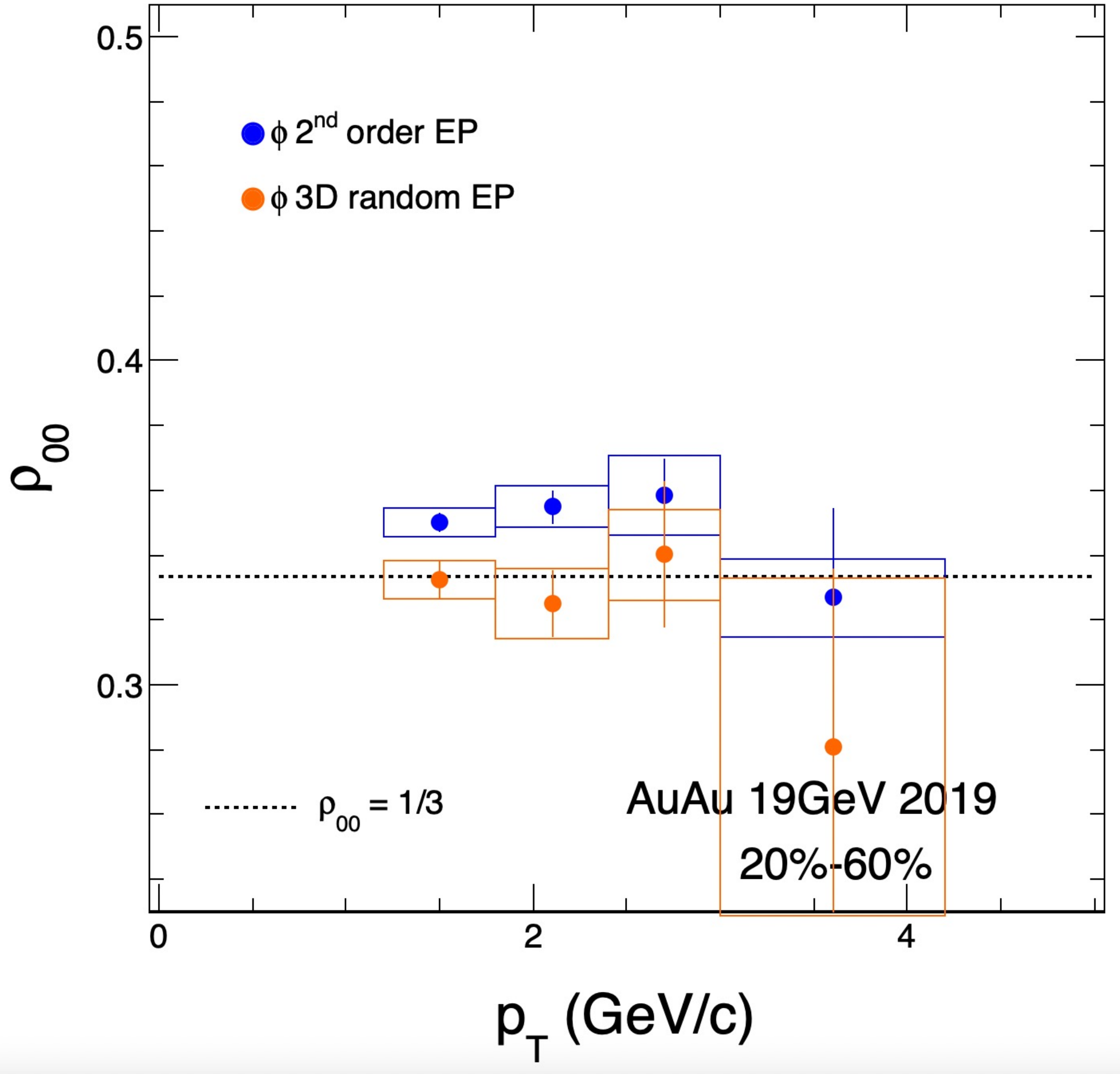
Acceptance Correction QA



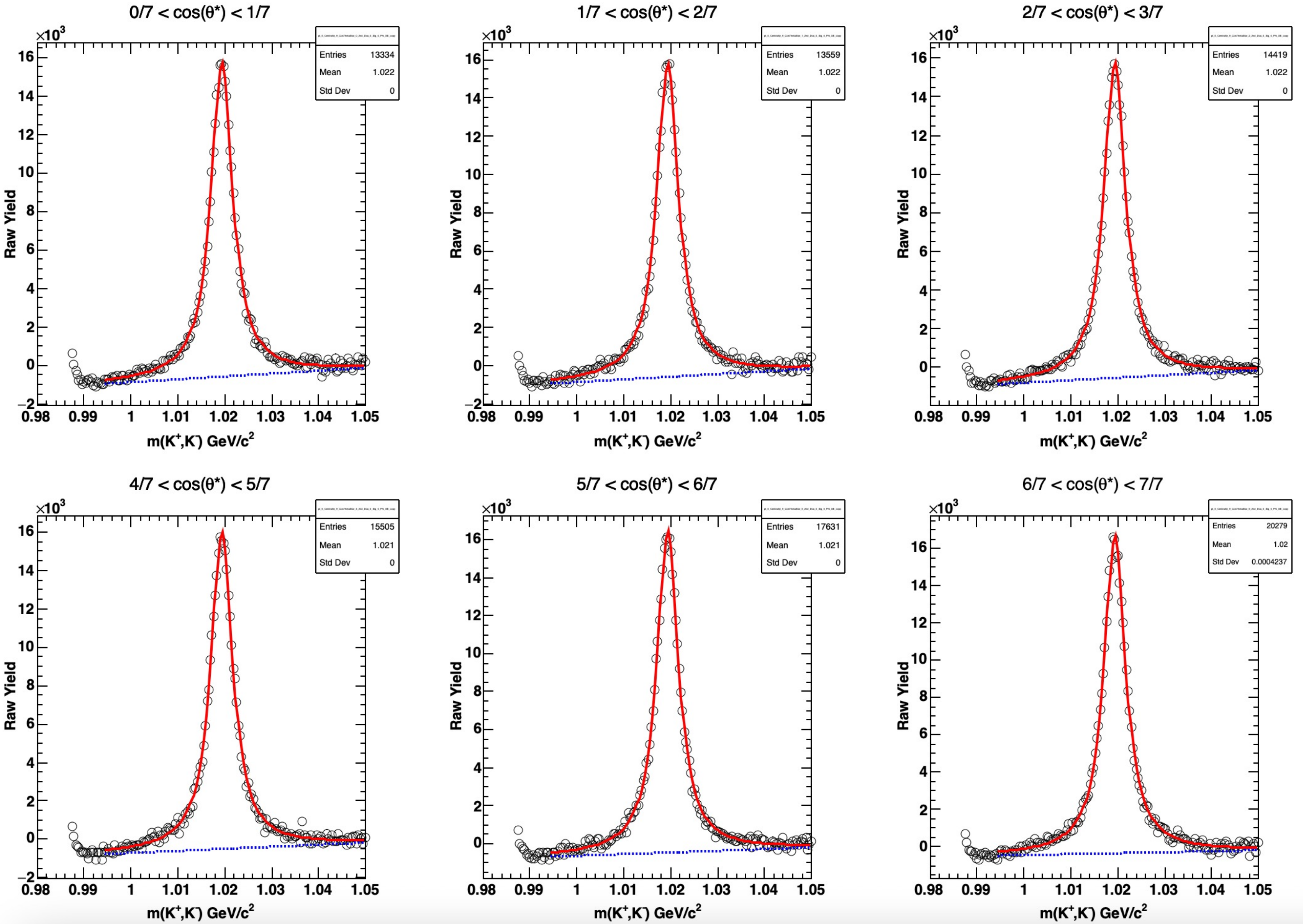
- Input a ρ_{00} value to acceptance simulation.
- Calculate output ρ_{00} from yield vs $\cos(\theta^*)$ distribution.
- Calculate acceptance parameter, F, from yield ratio (after η cuts / before η cuts) vs $\cos(\theta^*)$
- Apply F in acceptance fit function and extract ρ_{00}.
- Input ρ_{00} and acceptance corrected ρ_{00} match!

ϕ meson ρ_{00} (p_T) 3D random EP



- Randomize EP in 3D and calculate cos(θ*).
- Results in random uniform distribution for yield vs cos(θ*).
- Results are consistent with ρ_{00}=1/3 as expected.

Signal Reconstruction

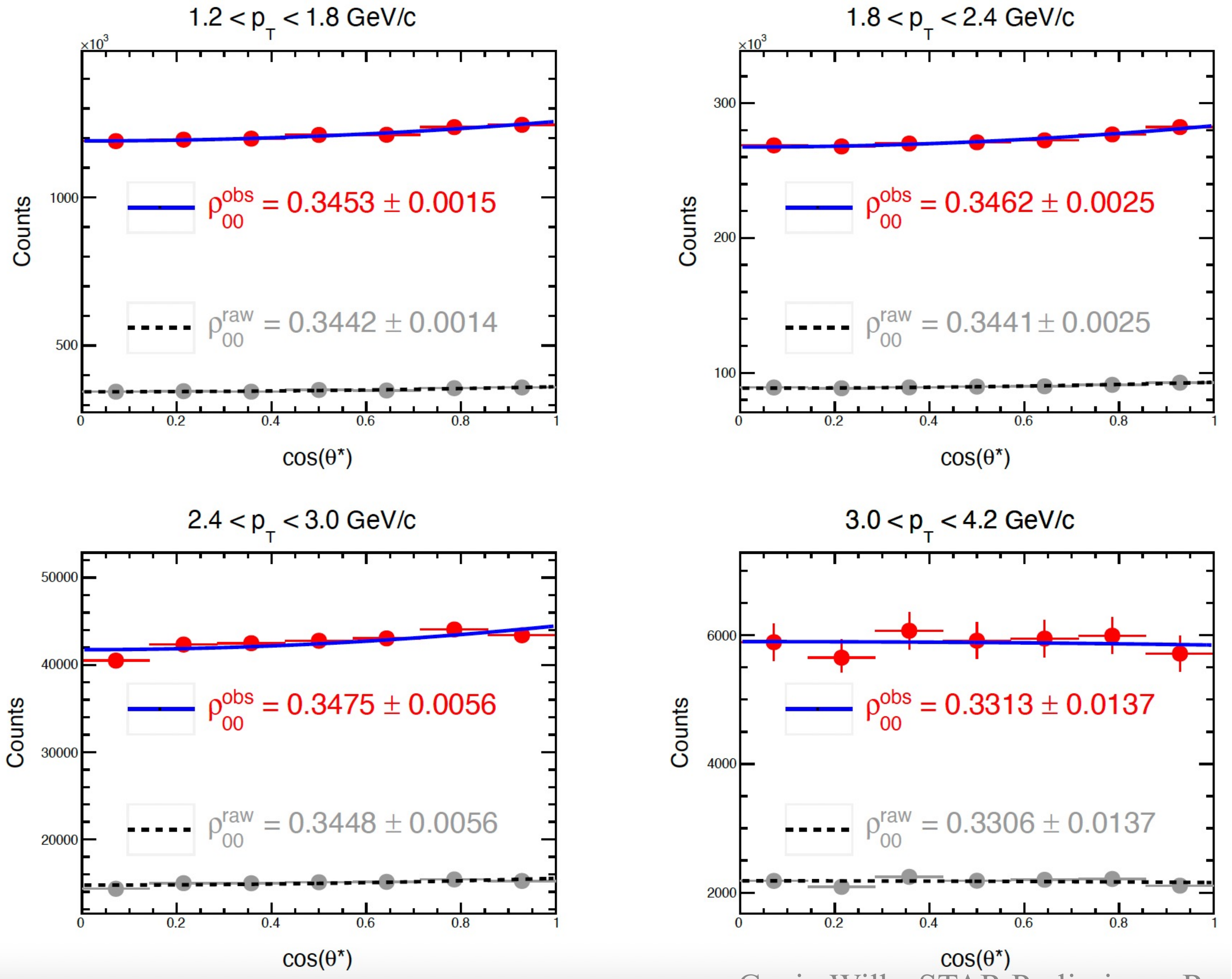


Au+Au 19.6GeV
20-60% Centrality
1.2 < p_T < 1.8 GeV/c

$$\phi \rightarrow K^+K^-$$

Mixed Event Background with binning in centrality, v_z and Ψ_2.

Signal Reconstruction



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