Preliminary figures request:
Global spin alignment of ϕ-meson in 14.6 and 19.6 GeV Au+Au collisions in BES-II

Gavin Wilks

University of Illinois at Chicago

08/16/23

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}: 00th element of the spin density matrix.

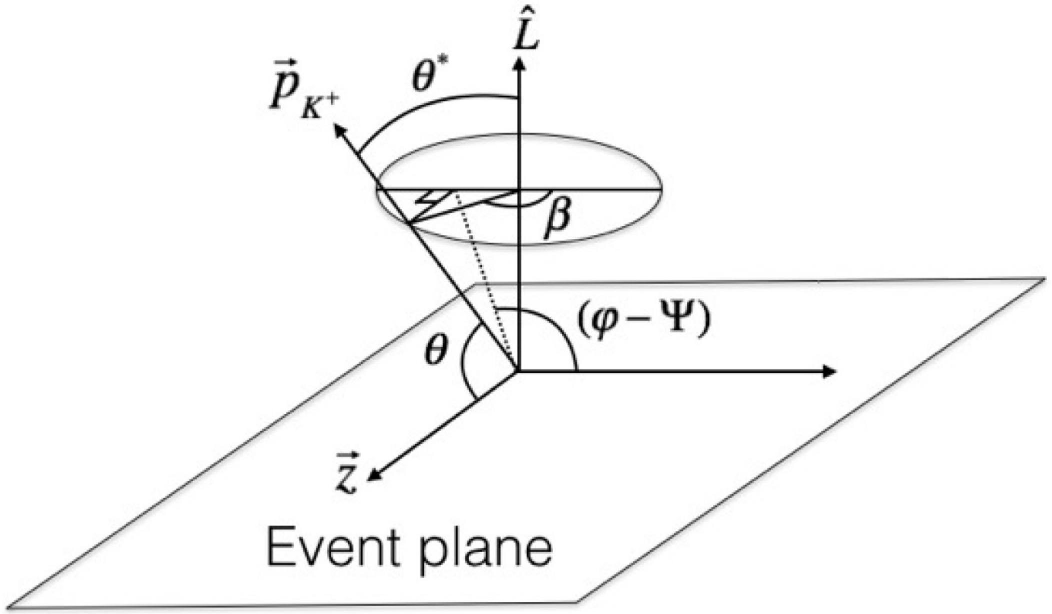
θ^* : angle between K^+ daughter and polarization axis in parent's rest frame.

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

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

Nucl. Phys.B18,332(1970)

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

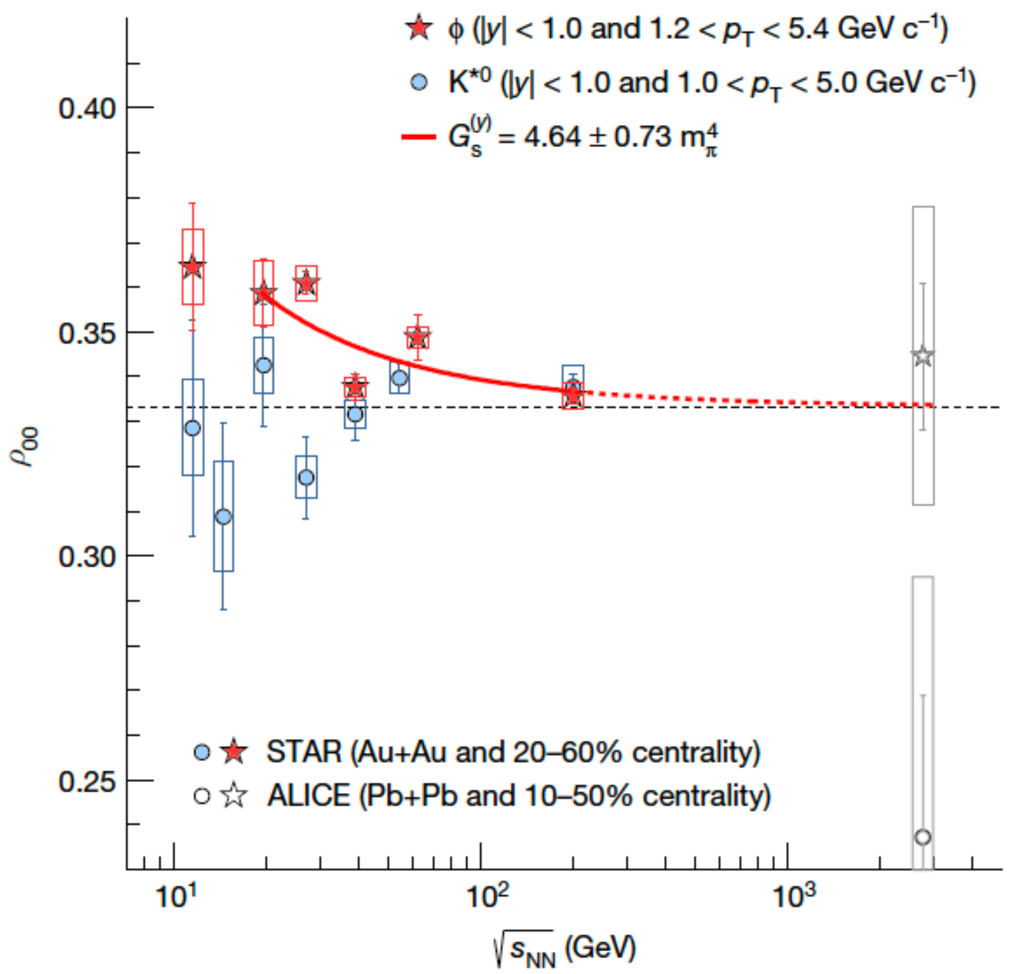


Phys. Rev. C **98**, 044907

Physics Motivation

STAR Collaboration. Nature 614, 244–248 (2023)

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



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

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.
  - BES-I 19.6 GeV: ~ 1.9×10^7 events after cuts
  - BES-II 19.6 GeV: ~ 4.6×10^8 events after cuts

Datasets

- 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

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

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

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 2^{nd} Order Event Plane

TPC Event Plane Cuts

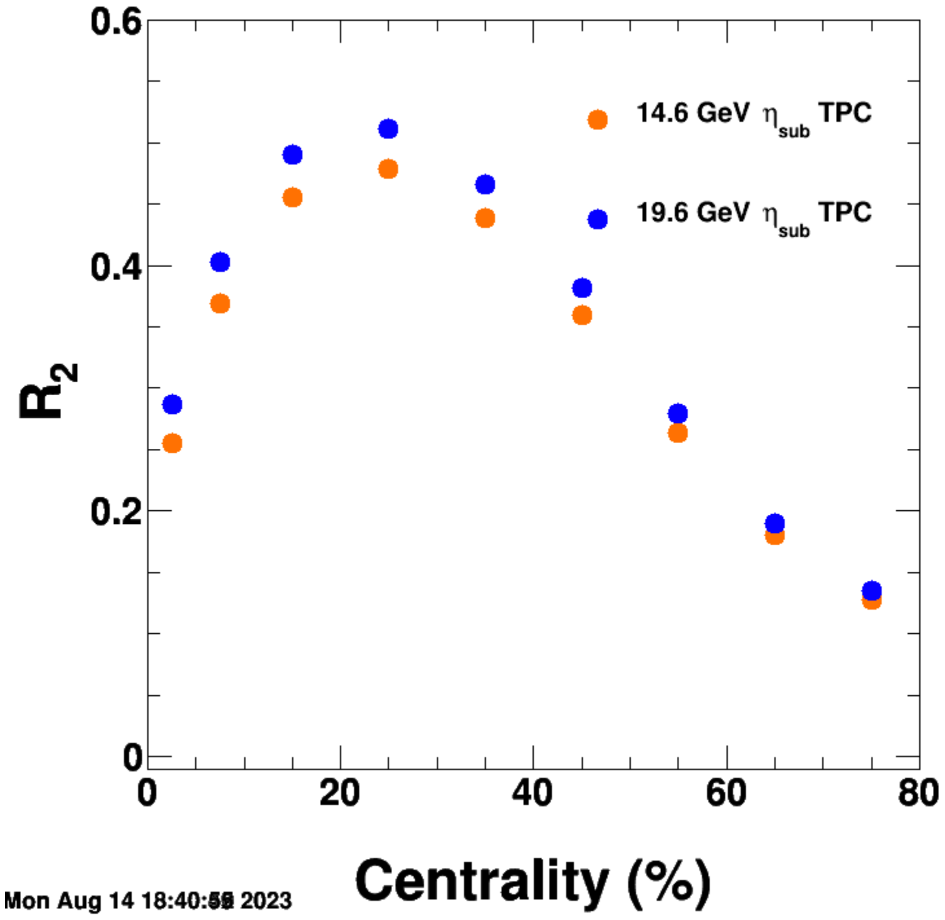
- $0.15 < p_T < 2$ GeV/c
- $|DCA| < 1$ cm
- No. TPC hits > 15
- TPC hit ratio > 0.52
- $|\eta| < 1$

Sub-event plane method

- η gap = 0.1

$$R_2 = \sqrt{\langle \cos 2(\Psi_{2,w} - \Psi_{2,e} \rangle}$$

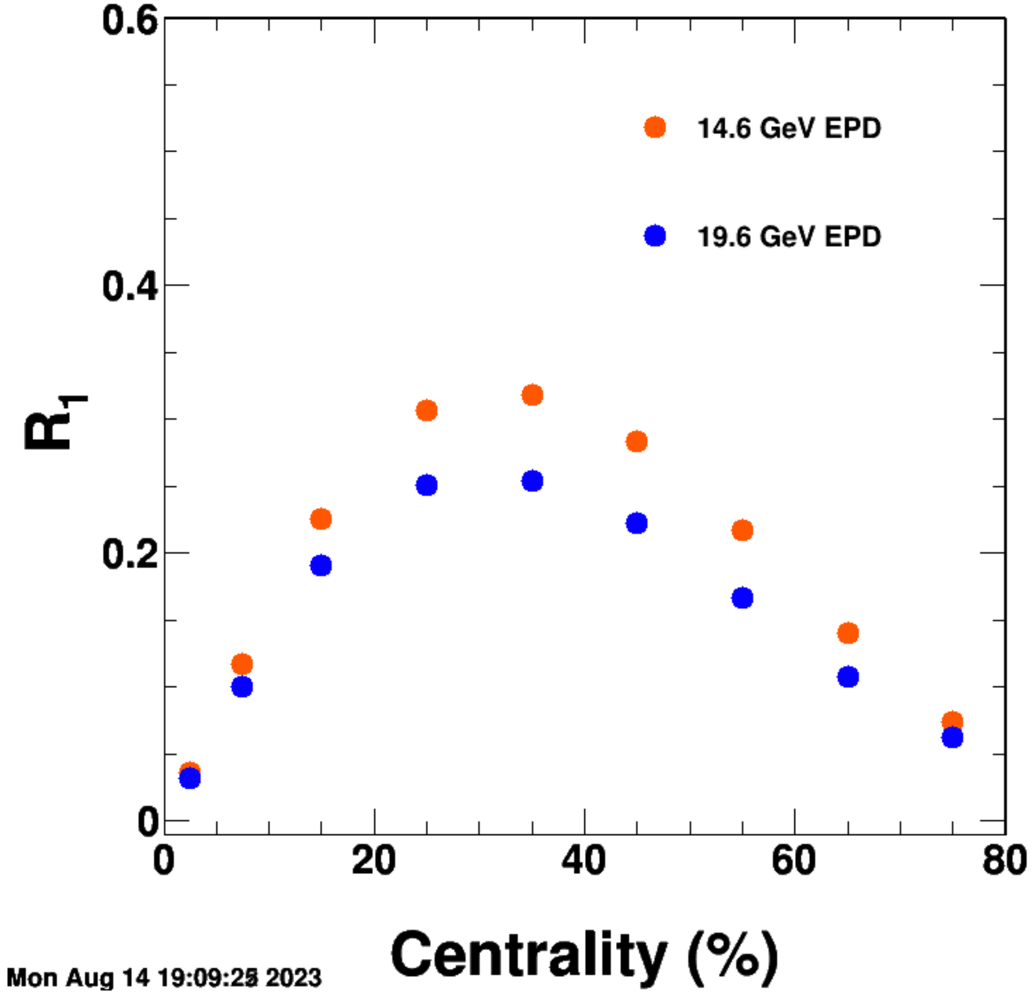
Apply run-by-run, centrality and v_z wise re-centering and shift calibrations



EPD 1st Order Event Plane

- 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

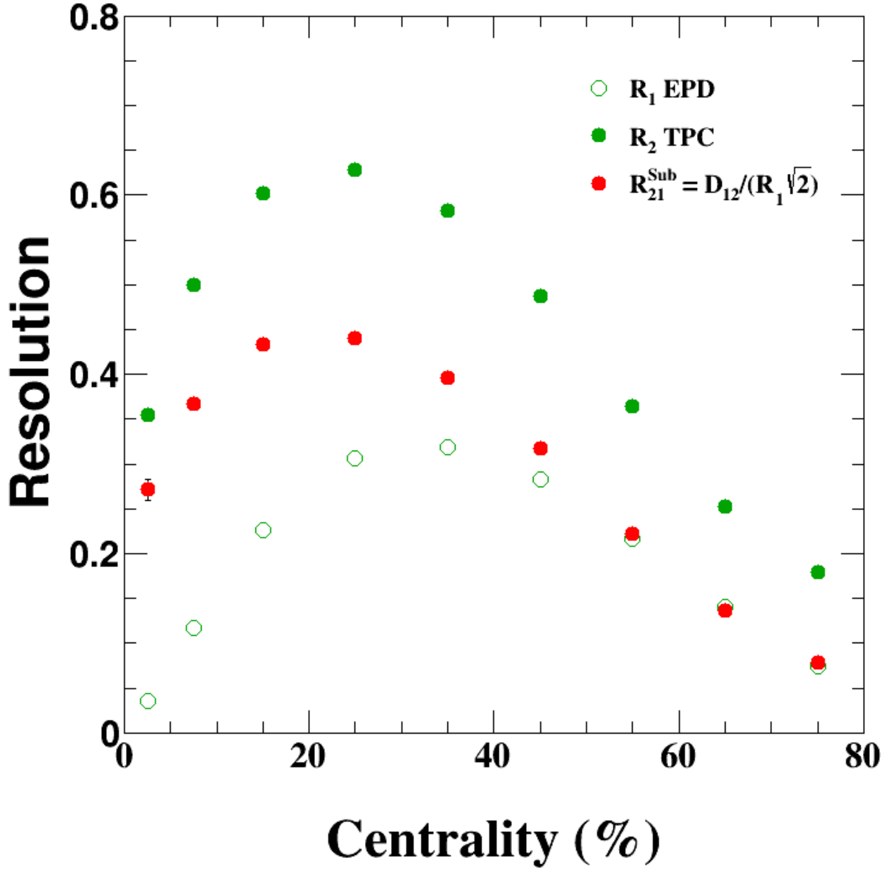
$$R_1 = \sqrt{\langle \cos 2(\Psi_1 - \Psi_{1,r}) \rangle}$$



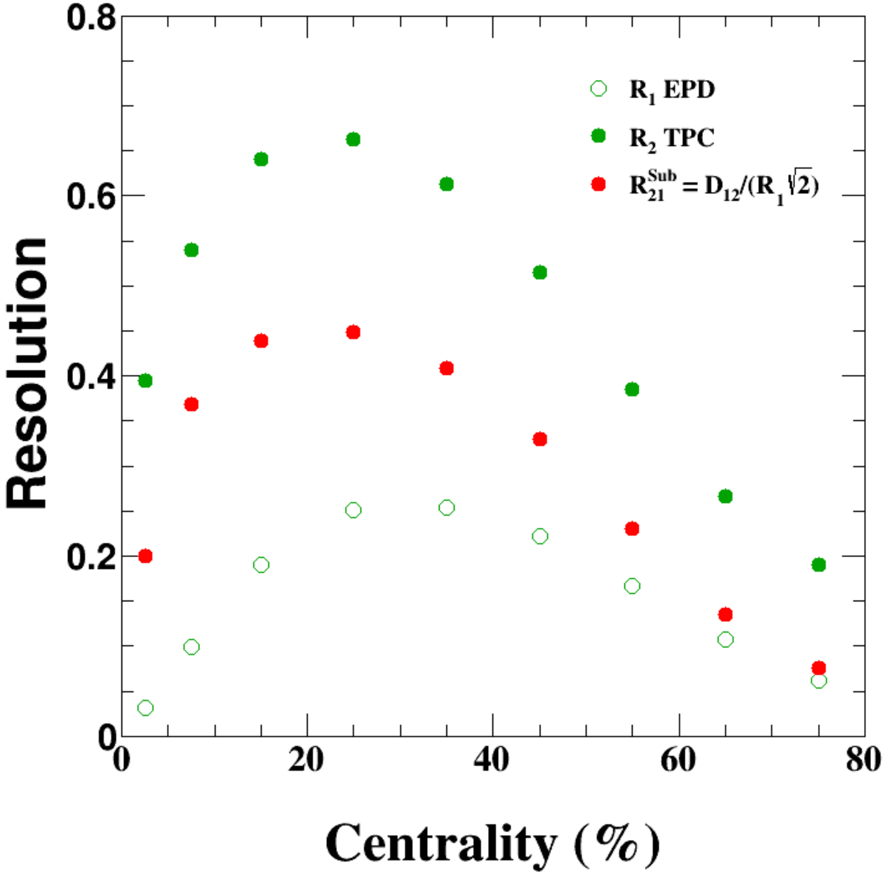
$R_{21}{}^{Sub}$

See slide 39 for $R_{21}{}^{Sub}$ calculation. This resolution is used to correct the second order EP results such that they are compatible with first order EP.

14.6 GeV



19.6 GeV



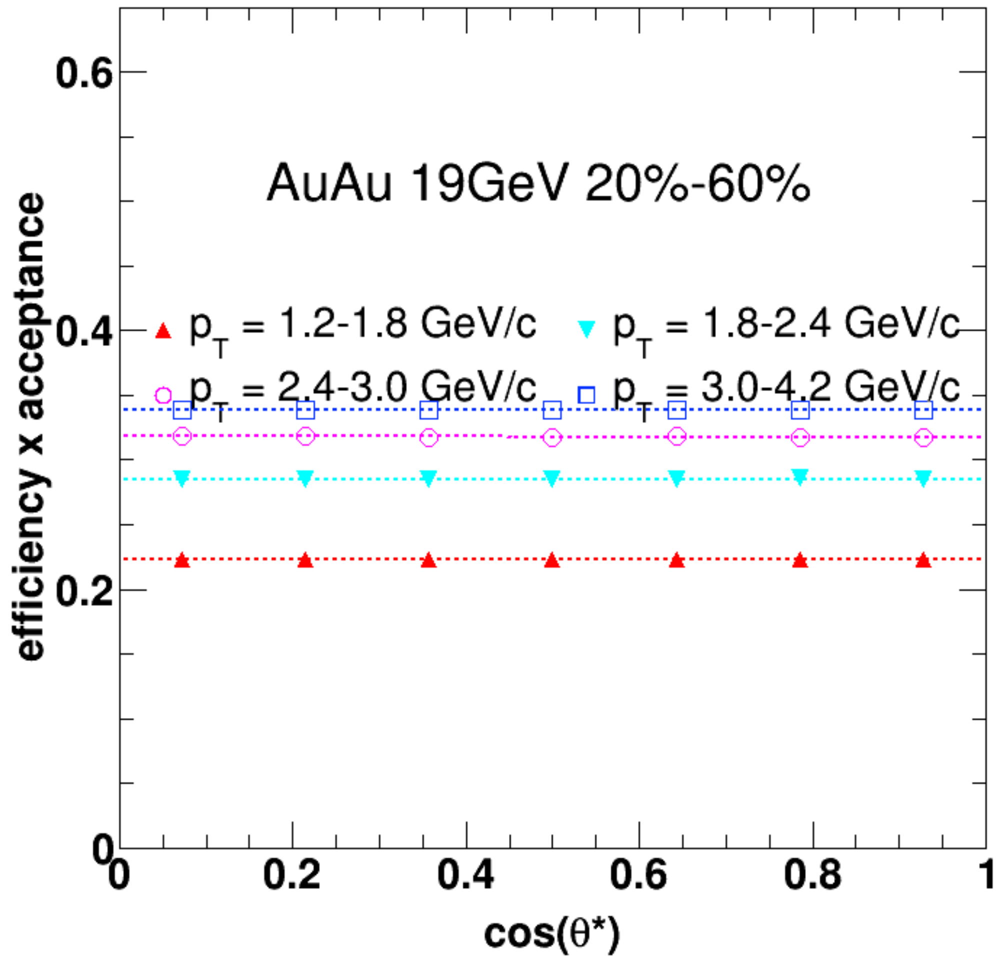
Analysis Procedure

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 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:

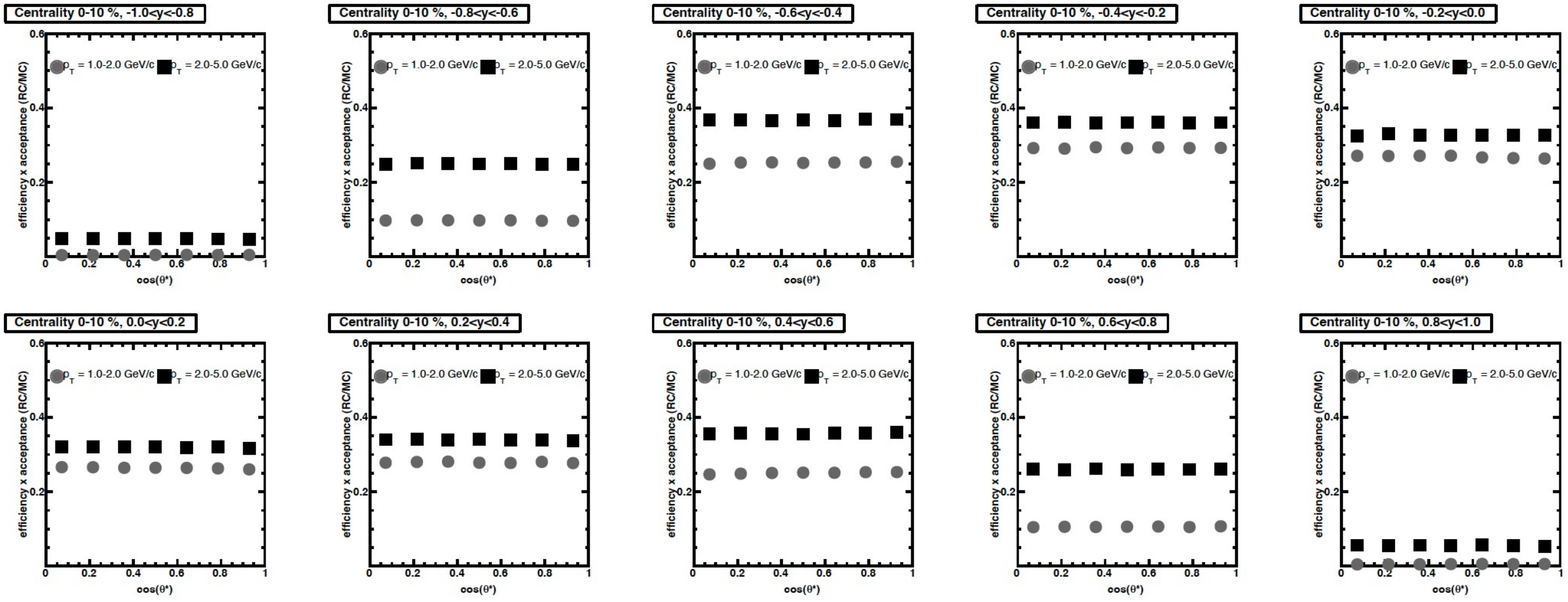
$$\rho_{00} = \frac{1}{3} + \frac{4}{1+3R}\left(\rho_{00}^{obs} - \frac{1}{3}\right)$$

Efficiency × Acceptance vs. cos(θ*)



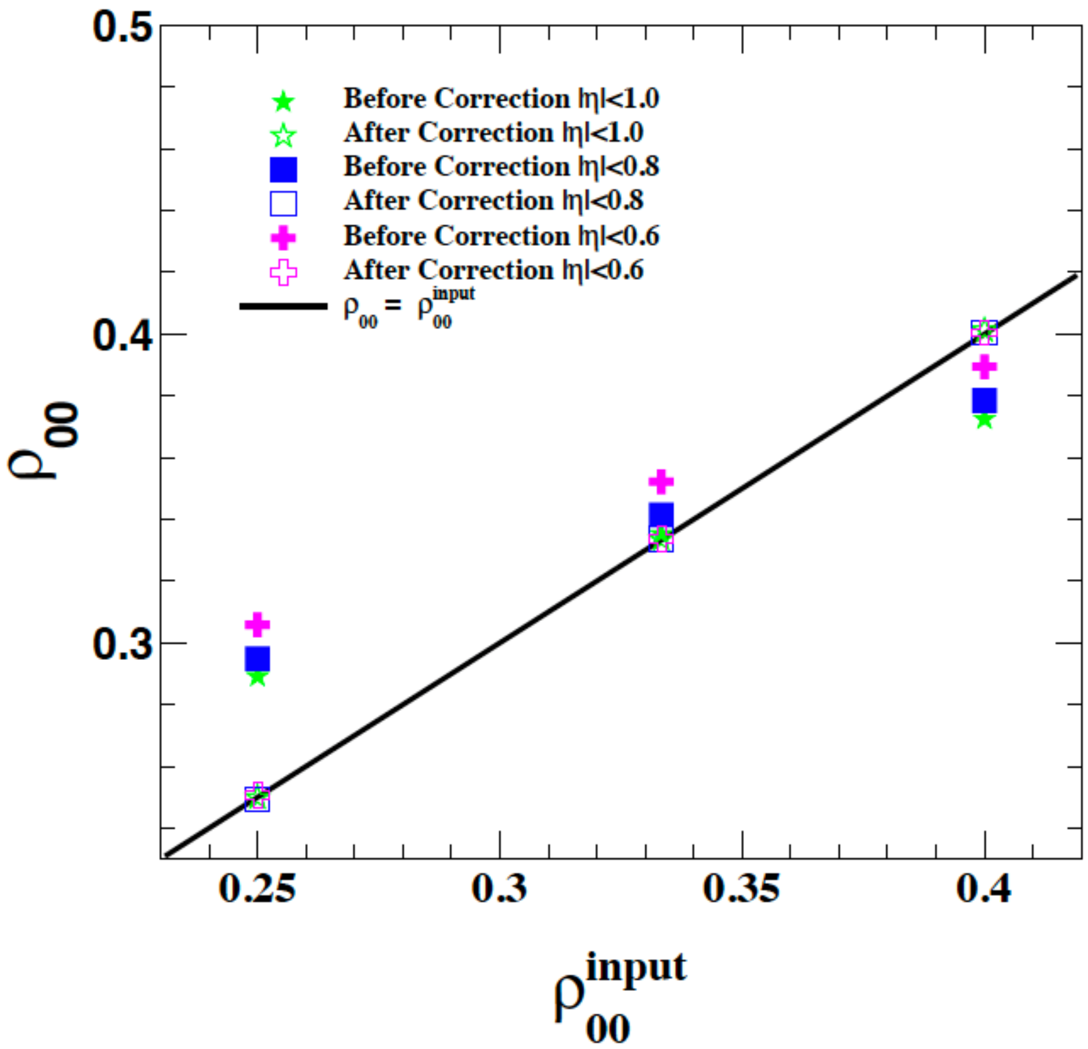
- Use Pythia6 to decay $\phi \rightarrow K^+K^-$
- MC ϕ input flat in rapidity
  - p_T from spectra or interpolated
  - φ from v_2 distribution.
- Drop tracks using TPC tracking and ToF matching efficiency of K^+ and K^- in each η & φ bin.
- If both kaons pass efficiency cuts and η acceptance cut, reconstruct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

Efficiency ╳ Acceptance vs. cos(θ*) y dependence



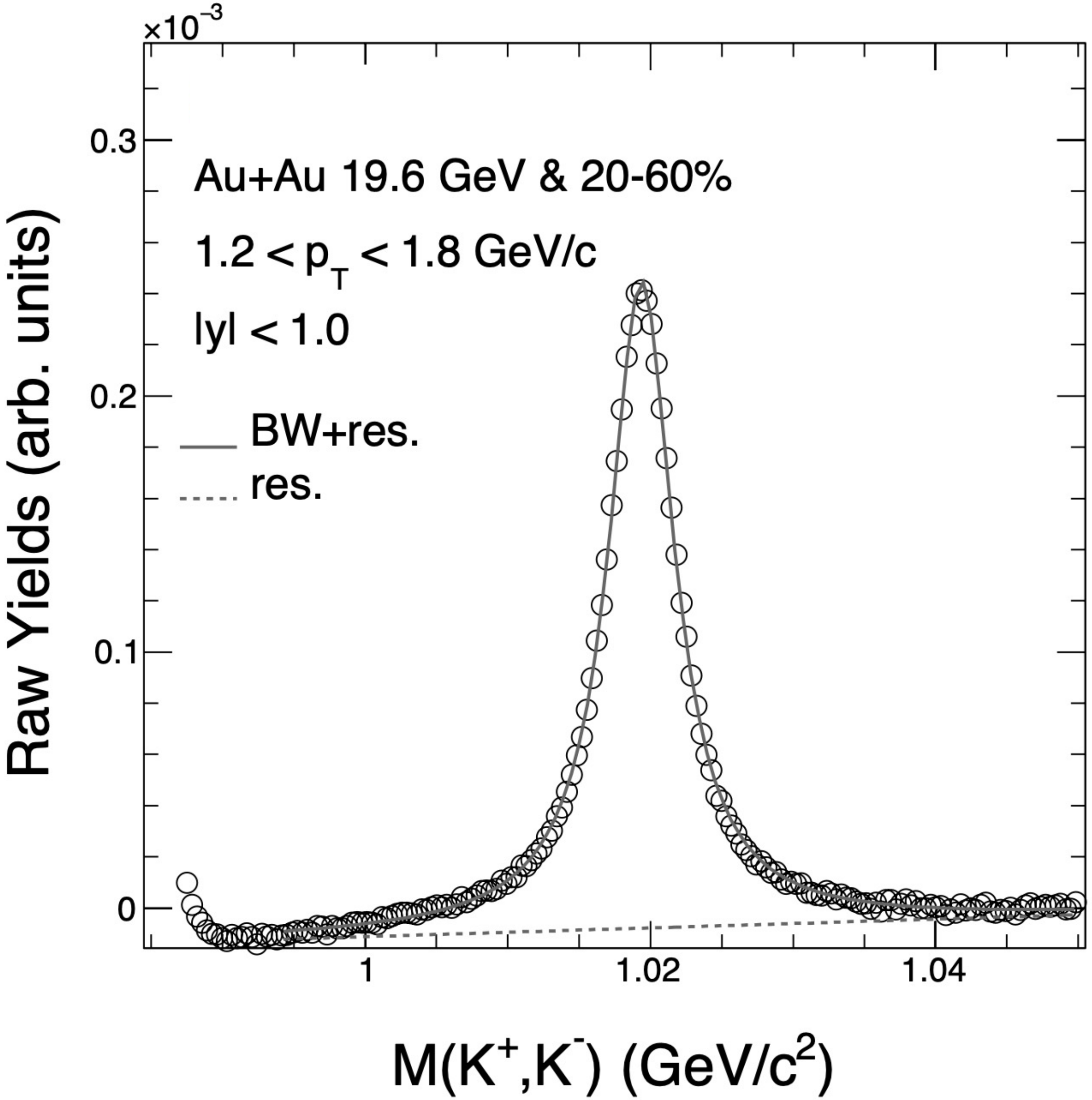
- All cases for our analysis can be found here: https://drupal.star.bnl.gov/STAR/blog/gwilks3/Preliminary-Request-Details-φ-meson-global-spin-alignment
- Note that the values for p_T = [1.0,2.0] at 0.8 < |y| < 1.0 are non-zero and on the order of 10^-2

Acceptance and Resolution Correction QA



- We simulated φ-mesons with the following inputs:
  - 3 input ρ_{00} values: {0.25,0.3333,0.4}
  - p_T = 1.5 GeV/c
  - v_2 = 0.075
  - y = [-1.0,1.0] flat
- We cut on the daughters with 3 different |η| cuts: |η| < {0.6,0.8,1.0}.
- What we show is that before corrections the ρ_{00} we recover is not the same as the input. After we apply the acceptance and resolution corrections, the reconstructed values are equivalent to the input.

Analysis Method



Event mixing is used to produce ϕ-meson background.

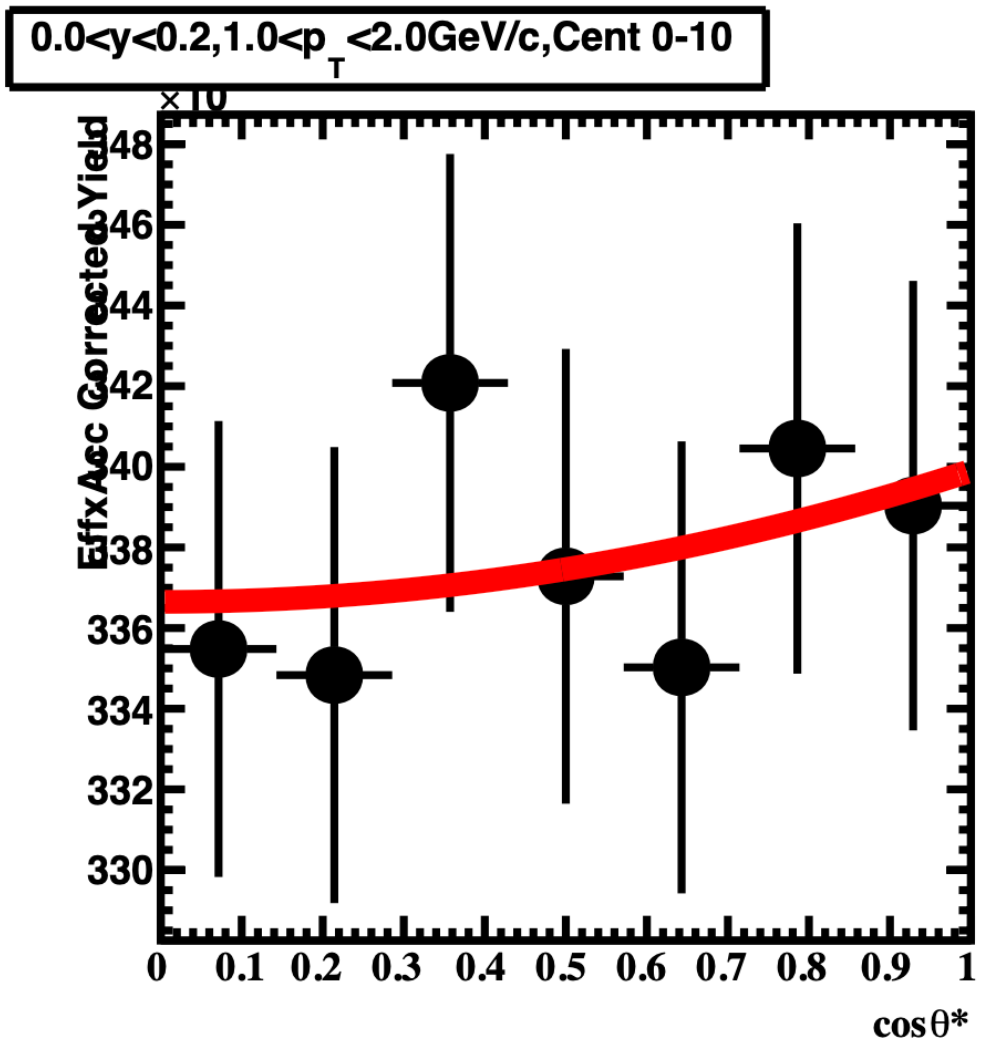
Normalize mixed event background to signal+background and subtract background

Fit signal histogram with Breit Wigner + 3rd order polynomial

$$\frac{1}{2\pi}\frac{AF}{(m-m_{\phi})+(\Gamma/_{2})^{2}}+poly3(m)$$

Yields are extracted by histogram integration.

Signal Reconstruction



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

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

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

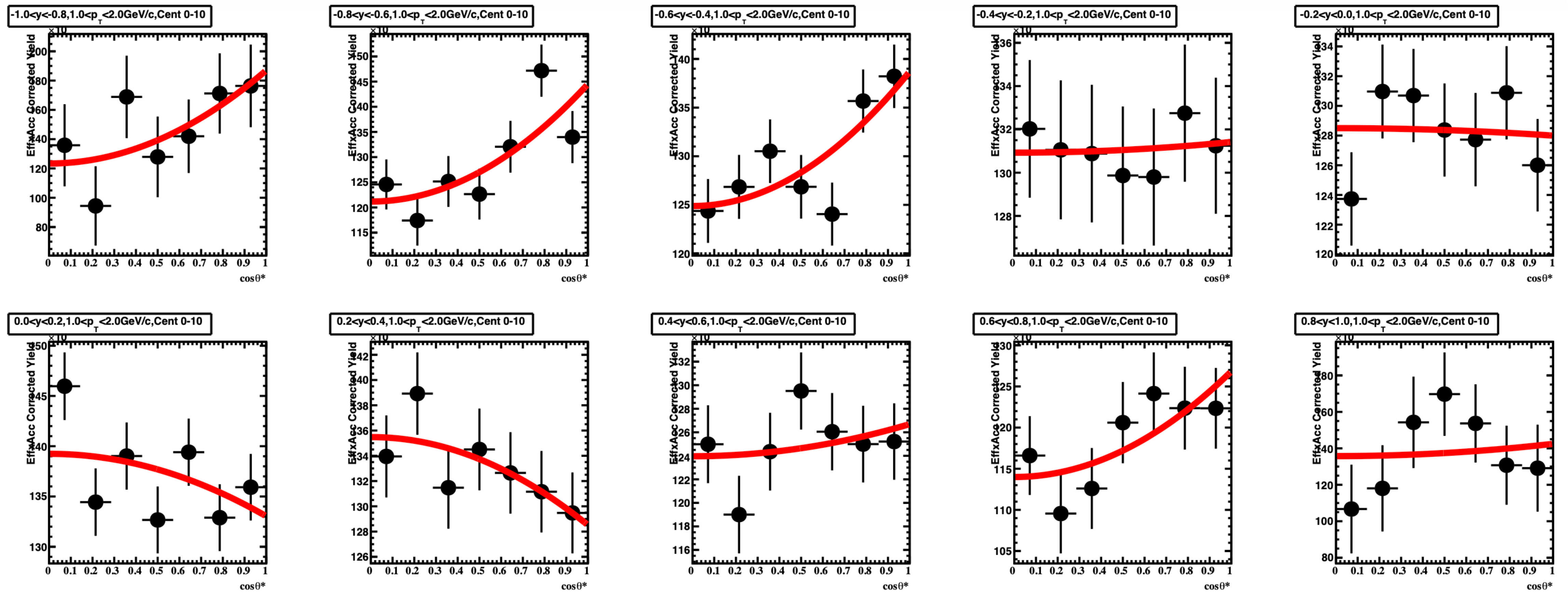
Then calculate ρ_{00} from ρ_{00}^{obs} accounting for EP resolution.

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

Nucl. Phys.B18,332(1970)

Efficiency and Acceptance Corrected Signal Distributions

1st Order 14.6 GeV



- Other distributions can be found here: https://drupal.star.bnl.gov/STAR/blog/gwilks3/Preliminary-Request-Details-φ-meson-global-spin-alignment

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

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:

$$\Delta\rho_{00,sys} = \sqrt{\sum_i (\Delta\rho^i_{00,sys})^2} \tag{40}$$

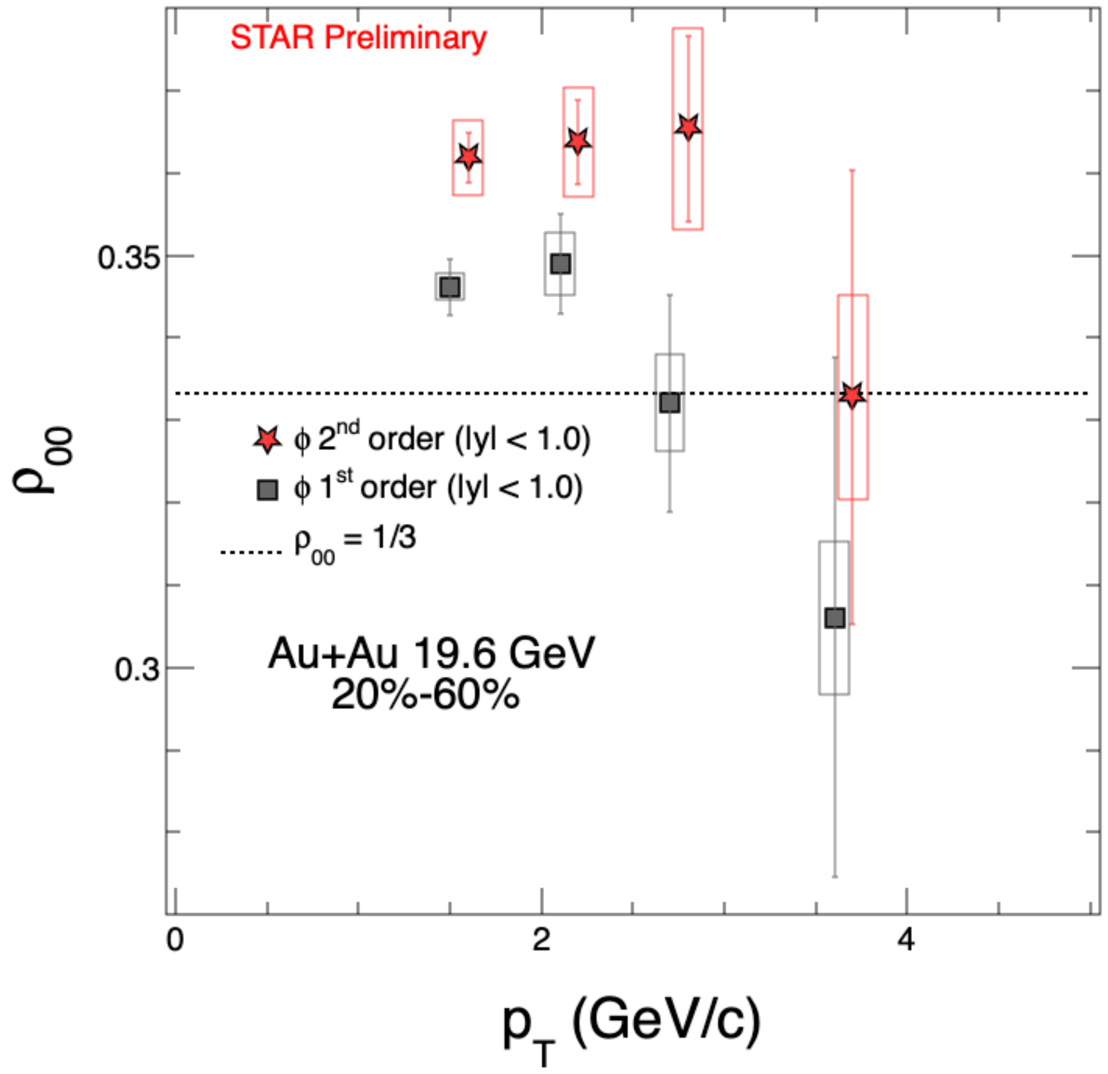
https://drupal.star.bnl.gov/STAR/system/files/AnalysisNote_phiSpinAlignment_v08_01.pdf

The following slides contain new preliminary requests for data already in preliminary state for STAR

At the SQM 2022 conference, I showed the second order EP results for φ-meson ρ_{00} in Au+Au 19.6 GeV (BES-II). After this point we found that there was an issue with the correction values for acceptance. Namely, they did not include the p_T spectra or v_2 in the simulation from which they are derived, and this significantly impacts the acceptance parameter values. This was an issue in my analysis and the BES-I analysis and was quickly fixed after the conference. I understand there is a STAR policy that we are not able to override preliminary results, but I thought I would include the new results and the old results just in case.

SQM2022 RESULTS FOR 19.6 GEV

ϕ meson ρ_{00} (p_T) 19.6 GeV



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

BES-II 1st Order Stat weighted average over p_T:

$\rho_{00}^{1} = 0.3458 \pm 0.0029$ (stat.) ± 0.0015 (sys.)

$\rho_{00}^{1} > 1/3$ with 3.8σ

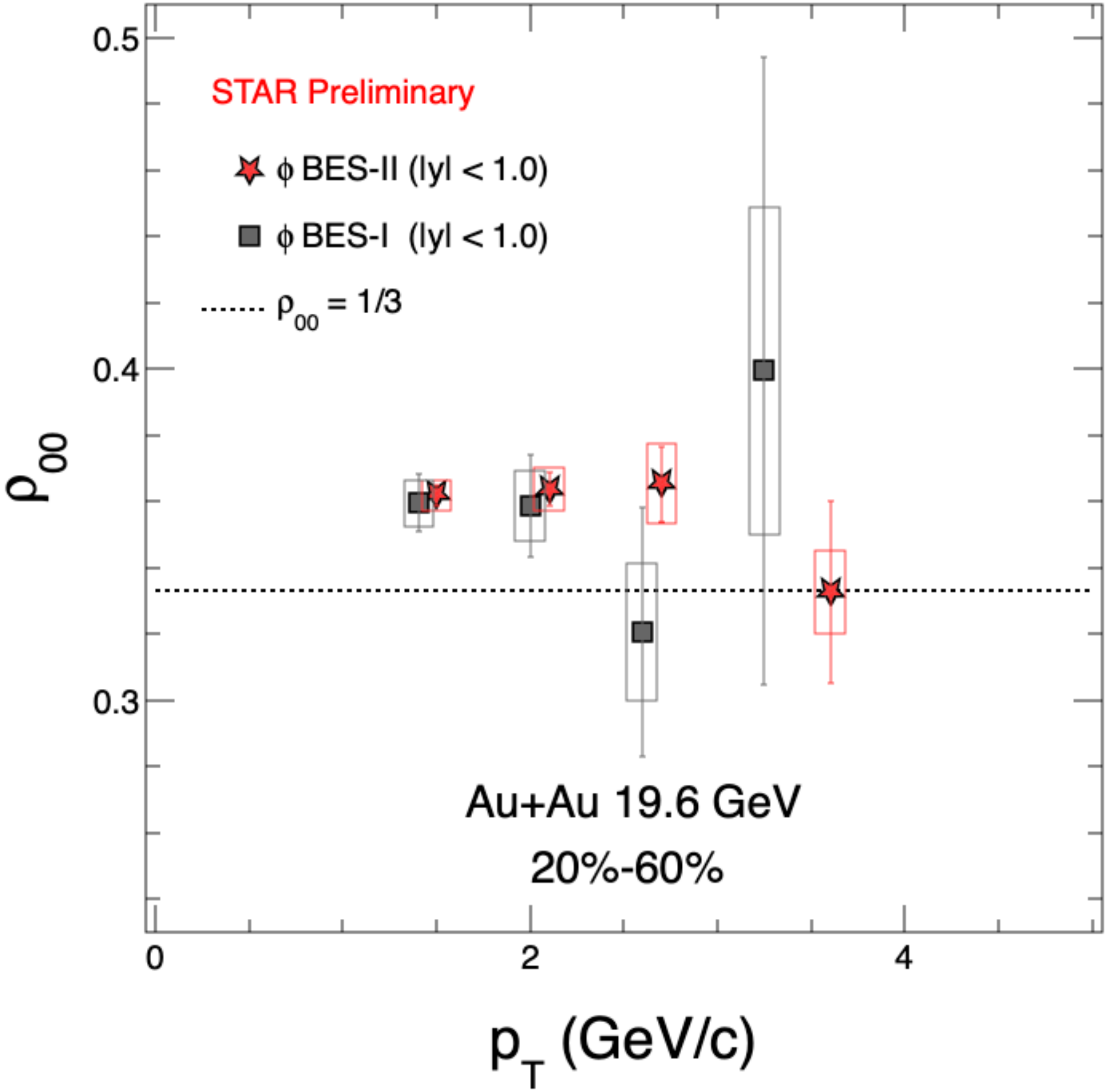
BES-II 2nd Order Stat weighted average over p_T:

$\rho_{00}^{2} = 0.3622 \pm 0.0026$ (stat.) ± 0.0049 (sys.)

$\rho_{00}^{2} > 1/3$ with 5.2σ

$\rho_{00}^{1} < \rho_{00}^{2}$ with 2.5σ

ϕ meson ρ_{00} (p_T) Second Order EP 19.6 GeV



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

BES-II Yield weighted average over p_{T}:

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

$\rho_{00}^{II} > 1/3$ with 5.2σ

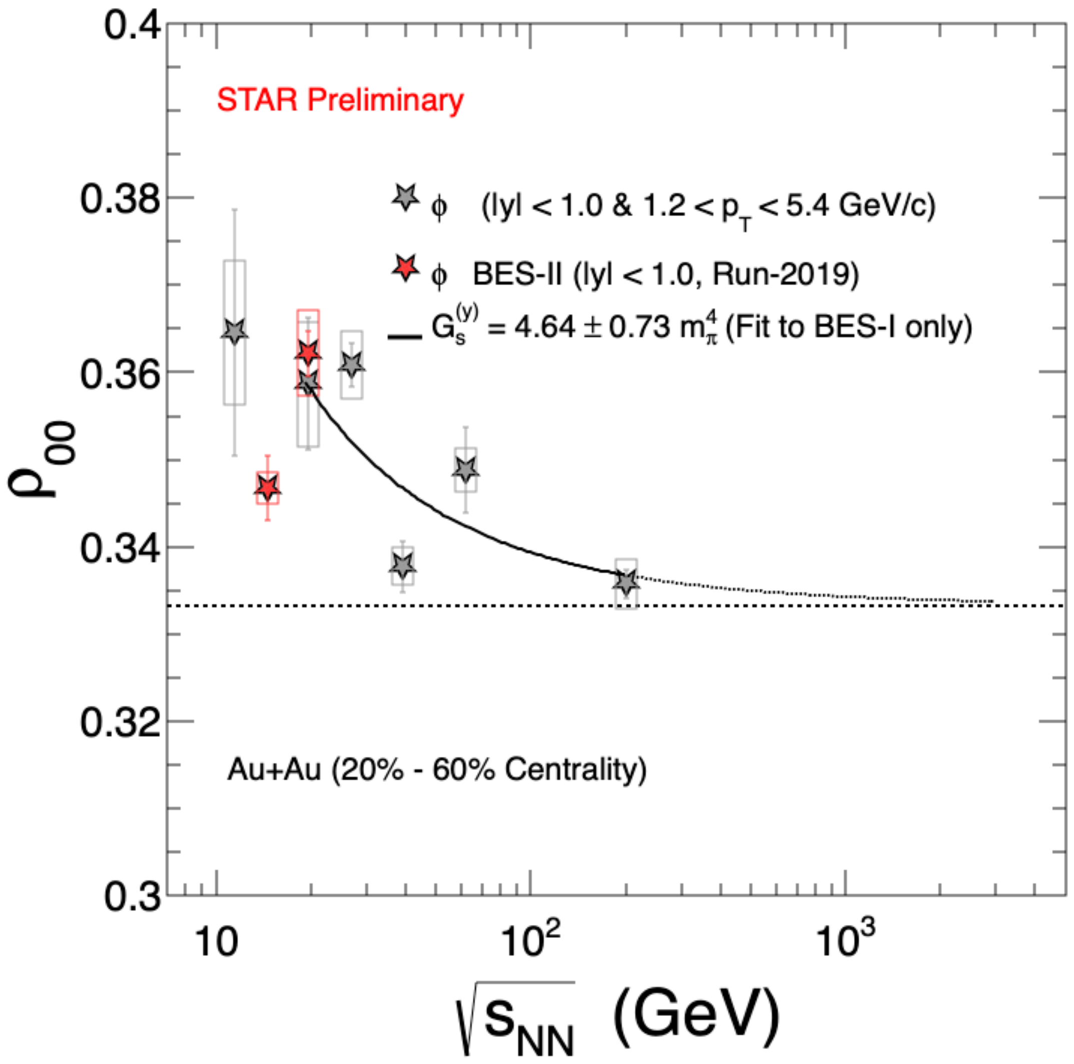
BES-I Yield weighted average over p_{T}:[1]

$\rho_{00}^{I} = 0.3587 \pm 0.0076$ (stat.) ± 0.0071 (sys.)

$\rho_{00}^{I} > 1/3$ with 2.4σ

$\rho_{00}^{II} \sim \rho_{00}^{I}$ with 0.3σ

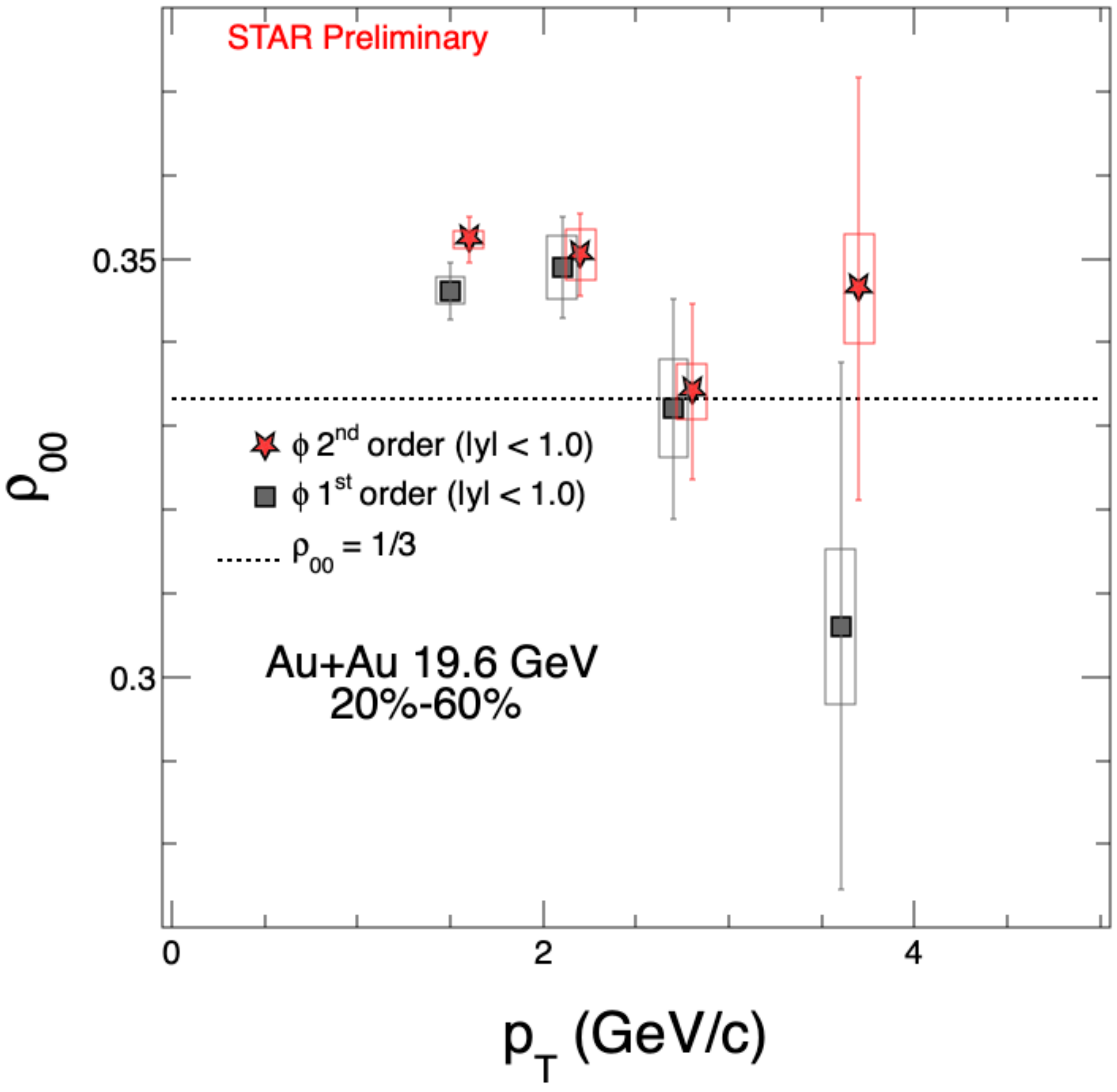
ϕ meson $\rho_{00}(\sqrt{s_{NN}})$ Second Order EP



- Second order EP ρ_{00} collision energy dependence for mid-centrality.
- Solid black line is a fit to the BES-I data.
- Dashed black line is an extrapolation of the fit.

NEW RESULTS FOR 19.6 GEV

ϕ meson ρ_{00} (p_T) 19.6 GeV



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

BES-II 1st Order Stat weighted average over p_T:

$\rho_{00}^1 = 0.3458 \pm 0.0029$ (stat.) ± 0.0015 (sys.)

$\rho_{00}^1 > 1/3$ with 3.8σ

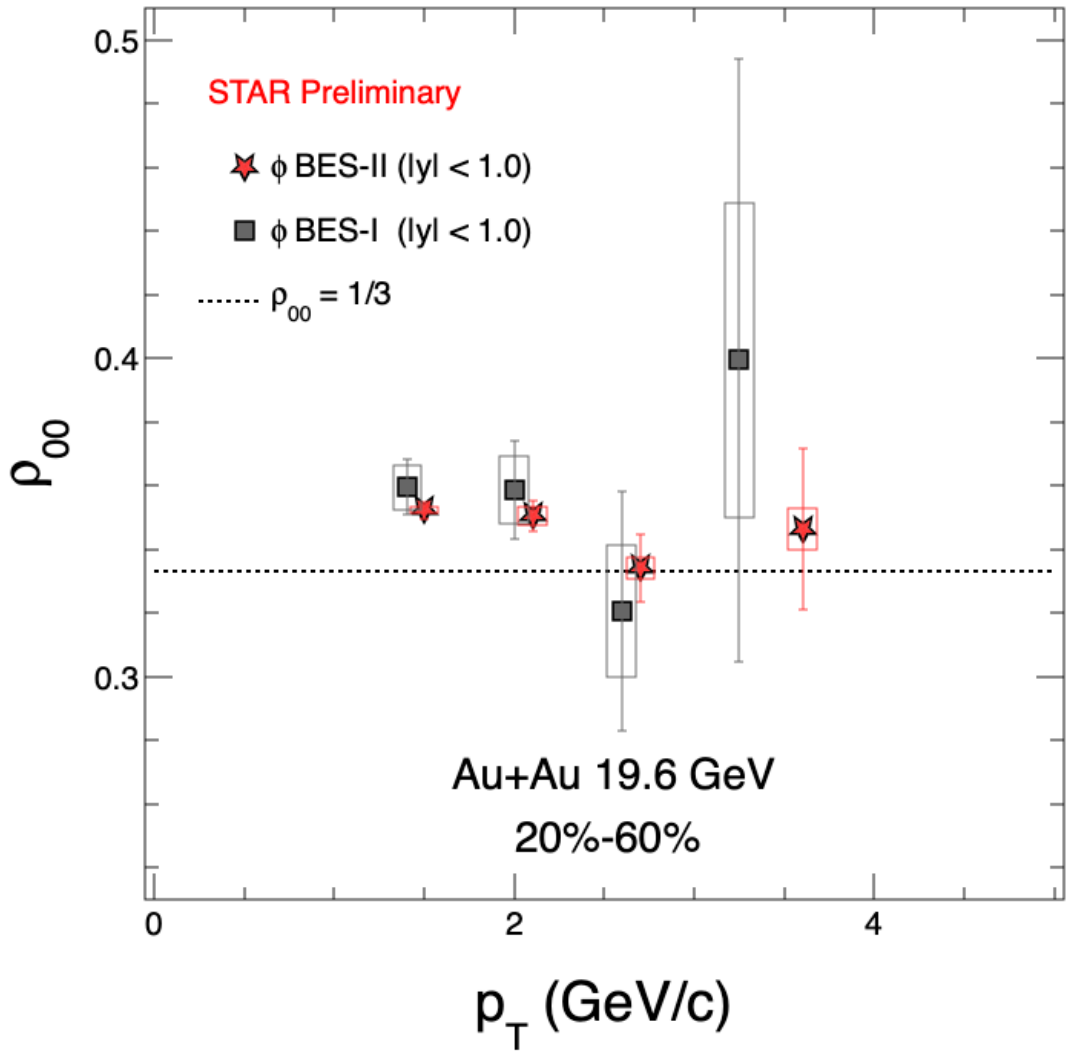
BES-II 2nd Order Stat weighted average over p_T:

$\rho_{00}^2 = 0.3510 \pm 0.0023$ (stat.) ± 0.0013 (sys.)

$\rho_{00}^2 > 1/3$ with 6.7σ

$\rho_{00}^1 \sim \rho_{00}^2$ with 1.2σ

ϕ meson ρ_{00} (p_T) Second Order EP 19.6 GeV



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

BES-II Yield weighted average over $p_{T:}$

$\rho_{00}^{II} = 0.3510 \pm 0.0023$ (stat.) ± 0.0013 (sys.)

$\rho_{00}^{II} > 1/3$ with 6.7σ

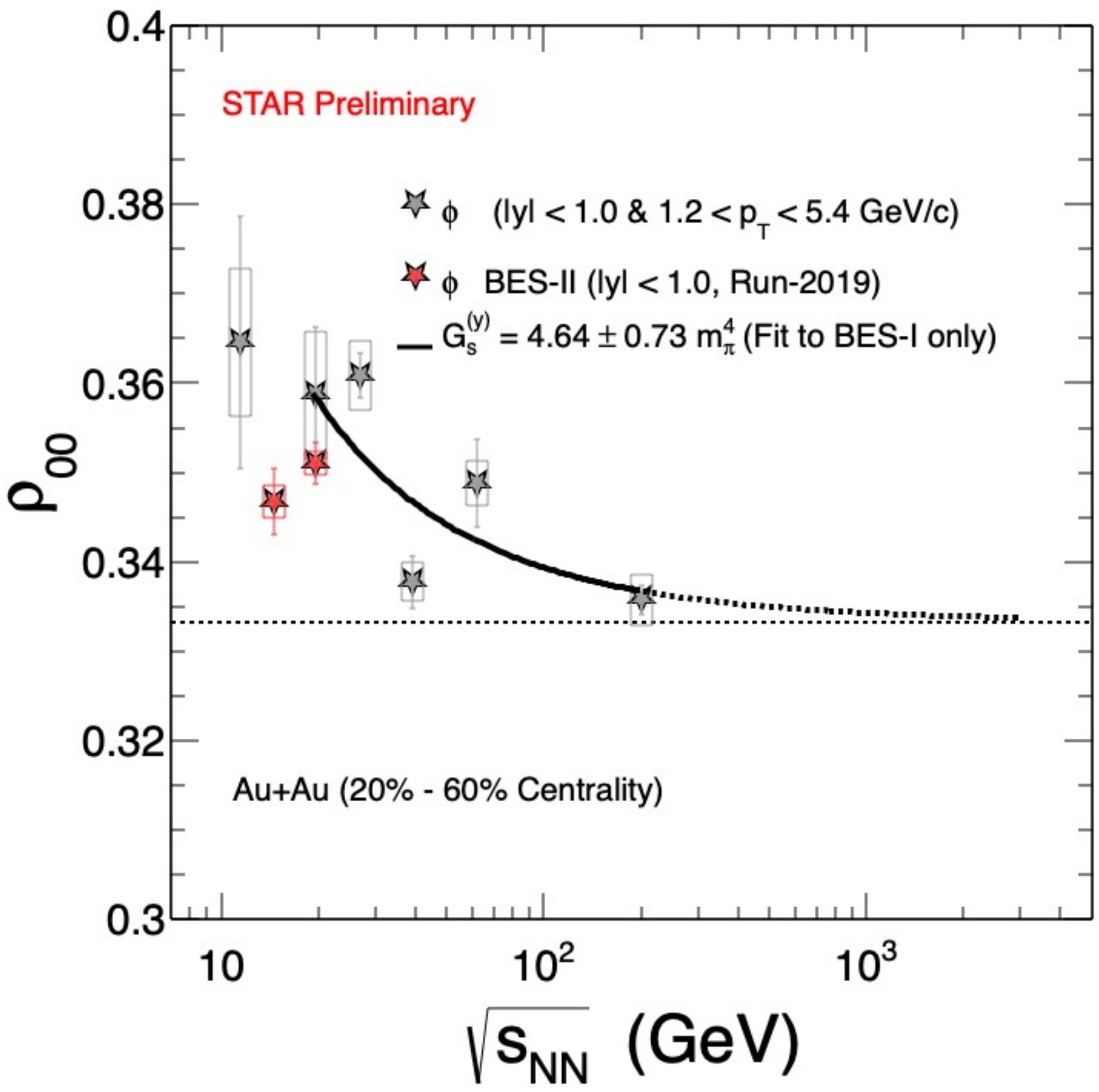
BES-I Yield weighted average over $p_{T:}$[1]

$\rho_{00}^{I} = 0.3587 \pm 0.0076$ (stat.) ± 0.0071 (sys.)

$\rho_{00}^{I} > 1/3$ with 2.4σ

$\rho_{00}^{II} \sim \rho_{00}^{I}$ with 0.7σ

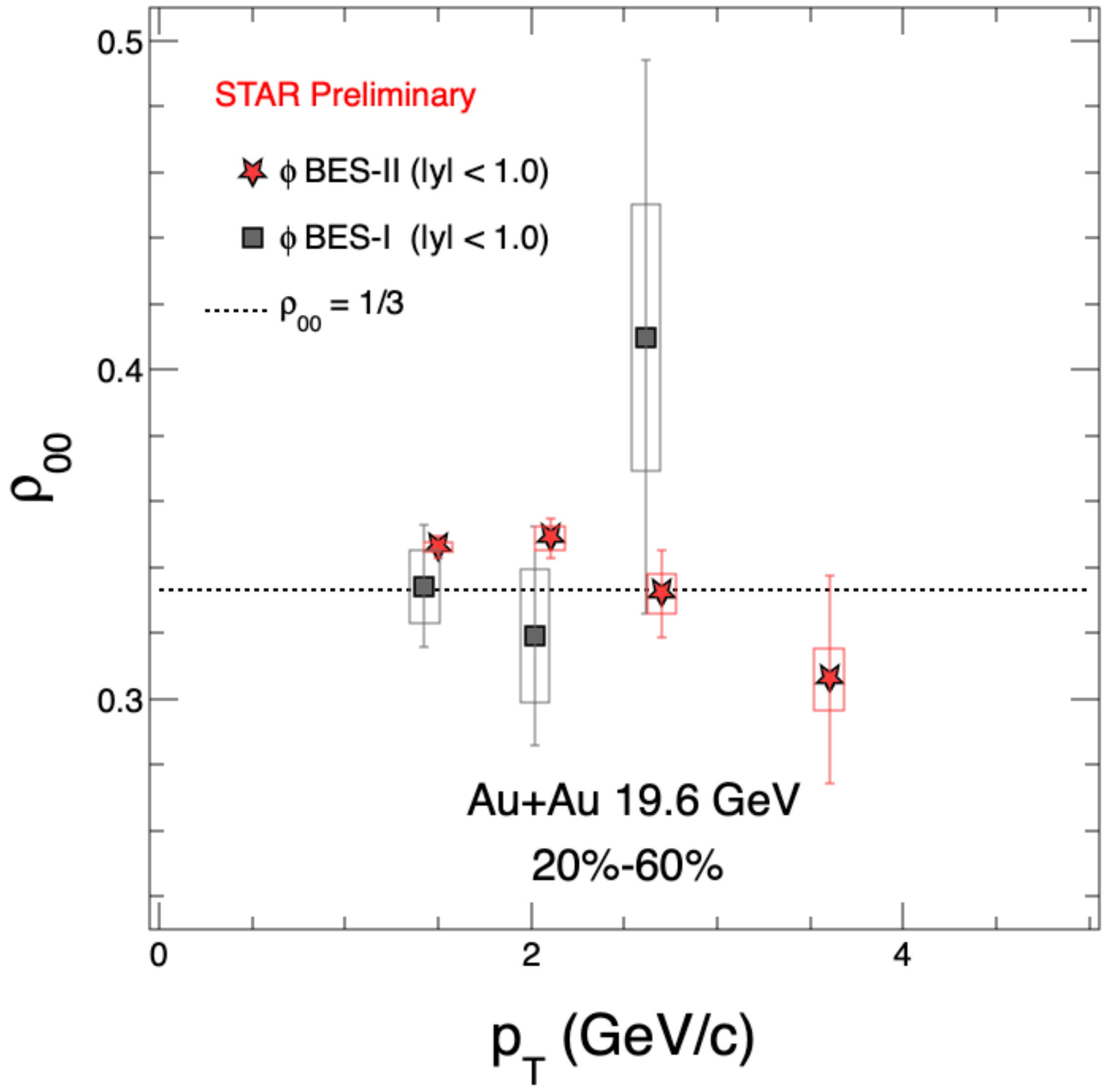
ϕ meson ρ_{00} ($\sqrt{s_{NN}}$) Second Order EP



- Second order EP ρ_{00} collision energy dependence for mid-centrality.
- Solid black line is a fit to the BES-I data.
- Dashed black line is an extrapolation of the fit.

THE FOLLOWING RESULTS ARE ALL NEW PRELIMINARY REQUESTS

ϕ meson ρ_{00} (p_T) First Order EP 19.6 GeV



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

BES-II Stat weighted average over p_T:

$\rho_{00}^{II} = 0.3458 \pm 0.0029$ (stat.) ± 0.0015 (sys.)

$\rho_{00}^{II} > 1/3$ with 3.8σ

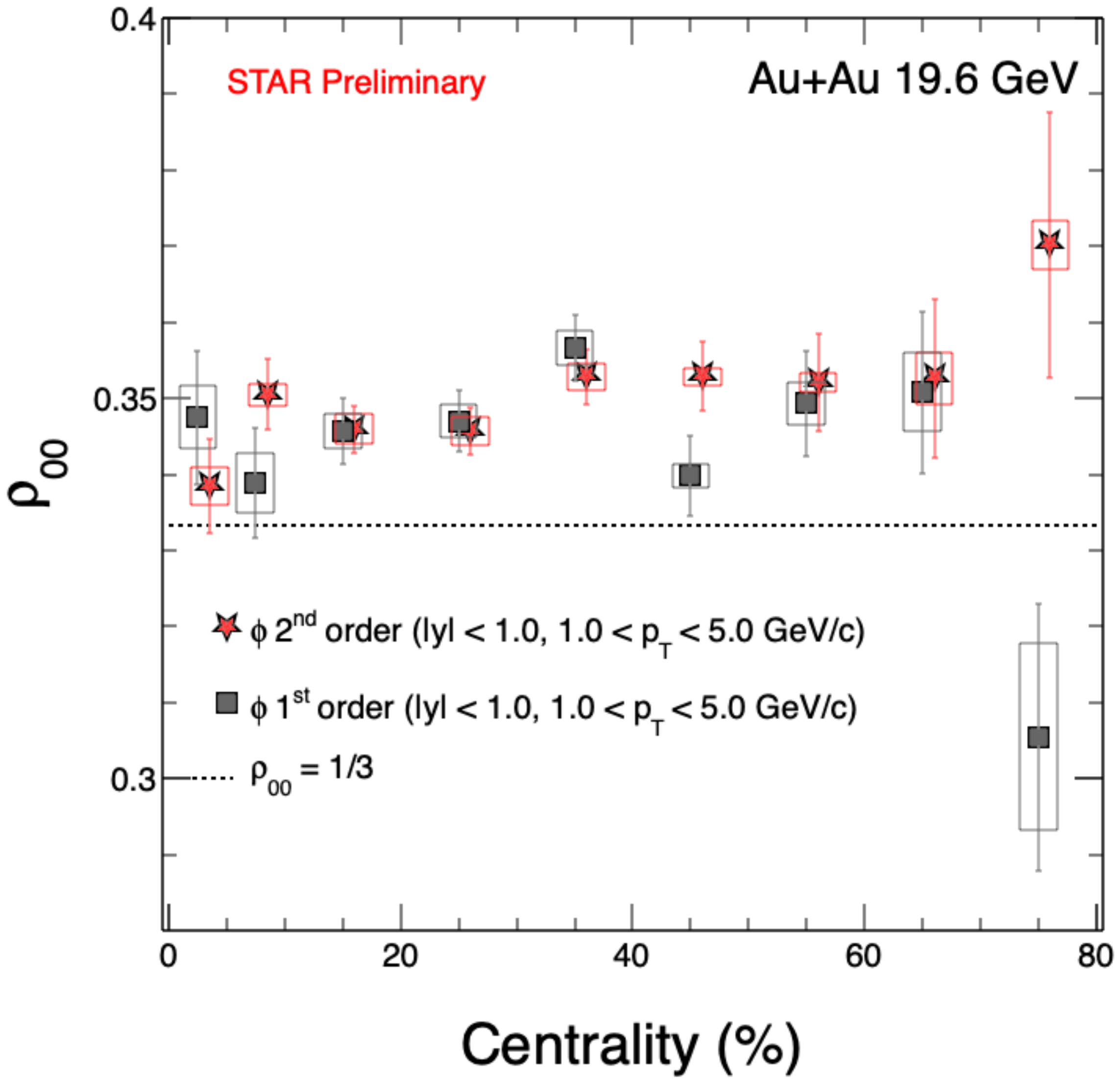
BES-I Stat weighted average over p_T:

$\rho_{00}^{I} = 0.3304 \pm 0.0161$ (stat.) ± 0.0104 (sys.)

$\rho_{00}^{I} \sim 1/3$ with 0.2σ

$\rho_{00}^{II} \sim \rho_{00}^{I}$ with 0.8σ

ϕ meson ρ_{00} (Centrality) 19.6 GeV



Au+Au collisions (0-80%)

BES-II 1st Order Stat weighted average over Centrality:

$\rho_{00}^{1} = 0.3470 \pm 0.0019$ (stat.) ± 0.0016 (sys.)

$\rho_{00}^{1} > 1/3$ with 5.5σ

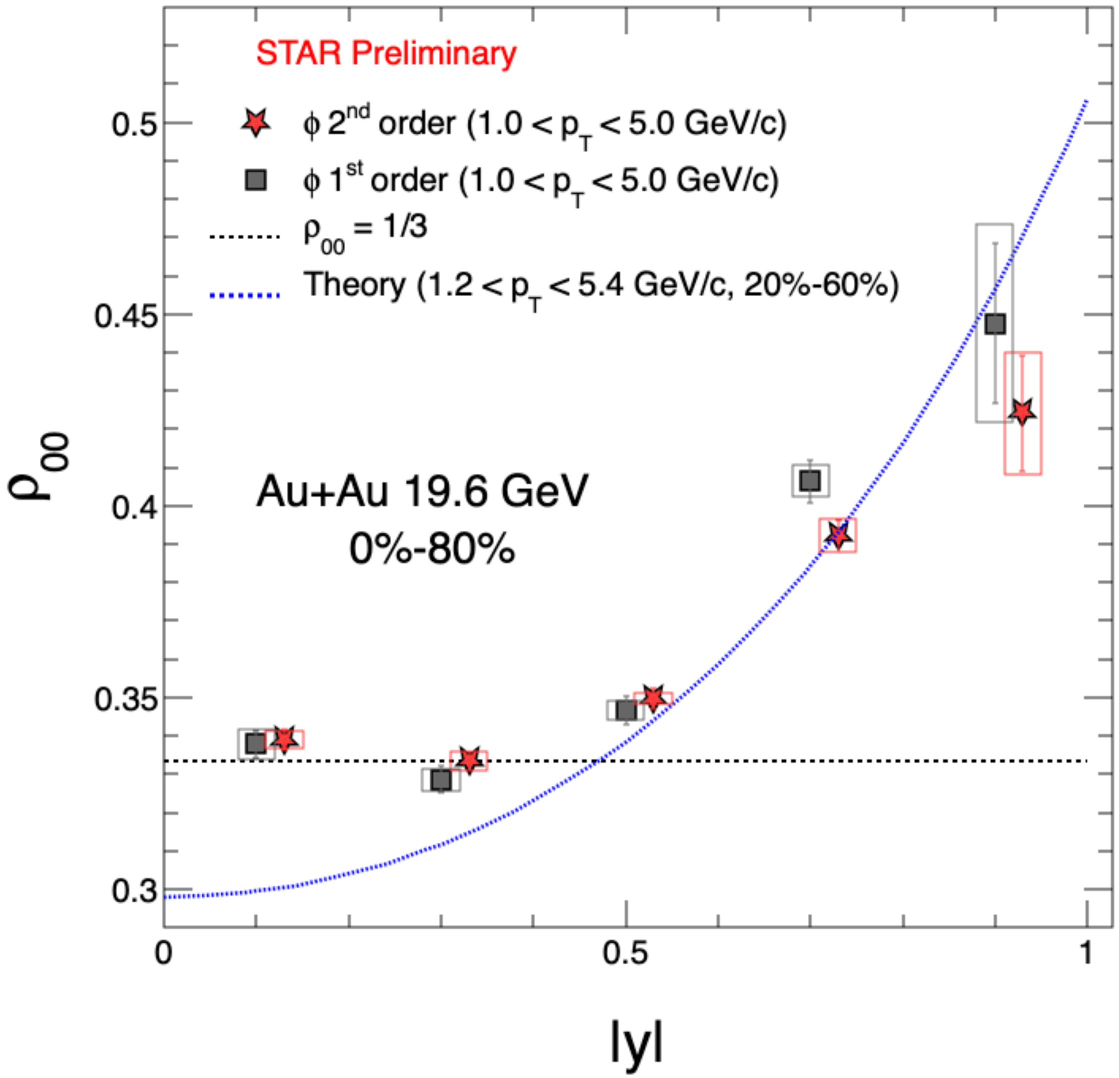
BES-II 2nd Order Stat weighted average over Centrality:

$\rho_{00}^{2} = 0.3486 \pm 0.0015$ (stat.) ± 0.0013 (sys.)

$\rho_{00}^{2} > 1/3$ with 7.7σ

$\rho_{00}^{1} \sim \rho_{00}^{2}$ with 0.5σ

ϕ meson ρ_{00} (rapidity [y]) 19.6 GeV



The blue dashed line is from the φ-meson mean field model prediction with BES-I data as input. This prediction is for $1.2 < p_T < 5.4$ GeV/c and 20-60% Centrality. We include this prediction as it provides some basis for the increase of ρ_{00} with rapidity.

Au+Au collisions (0-80%)

BES-II 1st Order Stat weighted average over y:

$\rho_{00}^{1} = 0.3467 \pm 0.0019$ (stat.) ± 0.0023 (sys.)

$\rho_{00}^{1} > 1/3$ with 4.5σ

BES-II 2nd Order Stat weighted average over y:

$\rho_{00}^{2} = 0.3474 \pm 0.0014$ (stat.) ± 0.0014 (sys.)

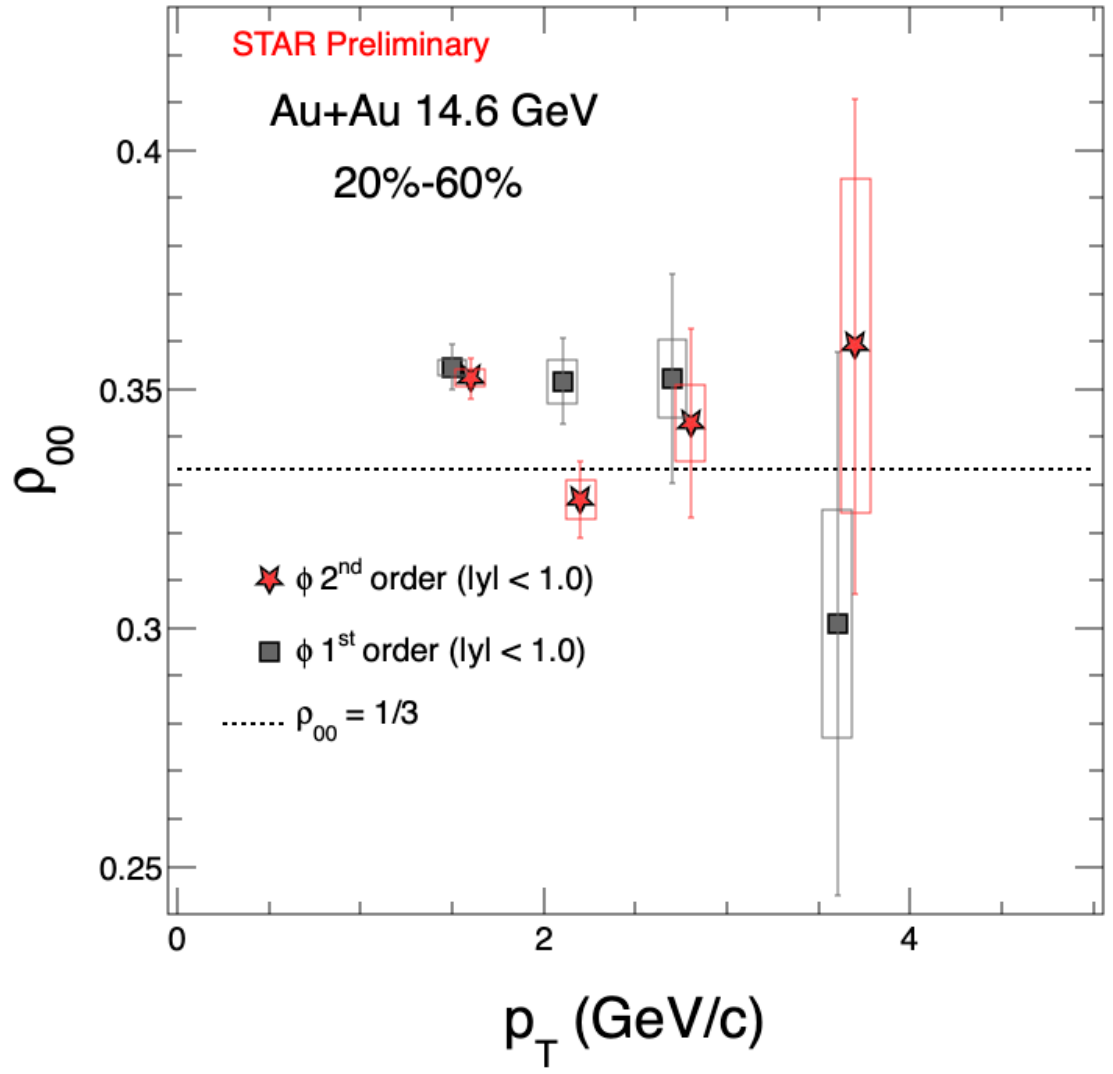
$\rho_{00}^{2} > 1/3$ with 7.1σ

$\rho_{00}^{1} \sim \rho_{00}^{2}$ with 0.2σ

Current Physical Understanding of Rapidity Dependence in Theory

In the theory of the φ-meson strong force field, it is proposed that the spin alignment depends on the anisotropy of field fluctuations in the φ-mesons rest frame. Using the input from BES-I data, it was found that there is a break of symmetry from the motion of the φ-meson, which causes a small anisotropy. In the observation of the φ-meson in the rest frame, the fluctuations in the direction of motion will be smaller than fluctuations in directions perpendicular to the motion. If a meson has $p_x=p_z=0$ and non-zero p_y, the fluctuation along the y-direction will be smaller than that of the x and z directions, which would lead to a $\rho_{00}<1/3$. On the other hand, φ-mesons moving along the x and z directions will have $\rho_{00}>1/3$.

ϕ meson ρ_{00} (p_T) 14.6 GeV



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

BES-II 1st Order Stat weighted average over p_T:

$\rho_{00}^{1} = 0.3537 \pm 0.0040$ (stat.) $\pm\ 0.0017$ (sys.)

$\rho_{00}^{1} > 1/3$ with 4.7σ

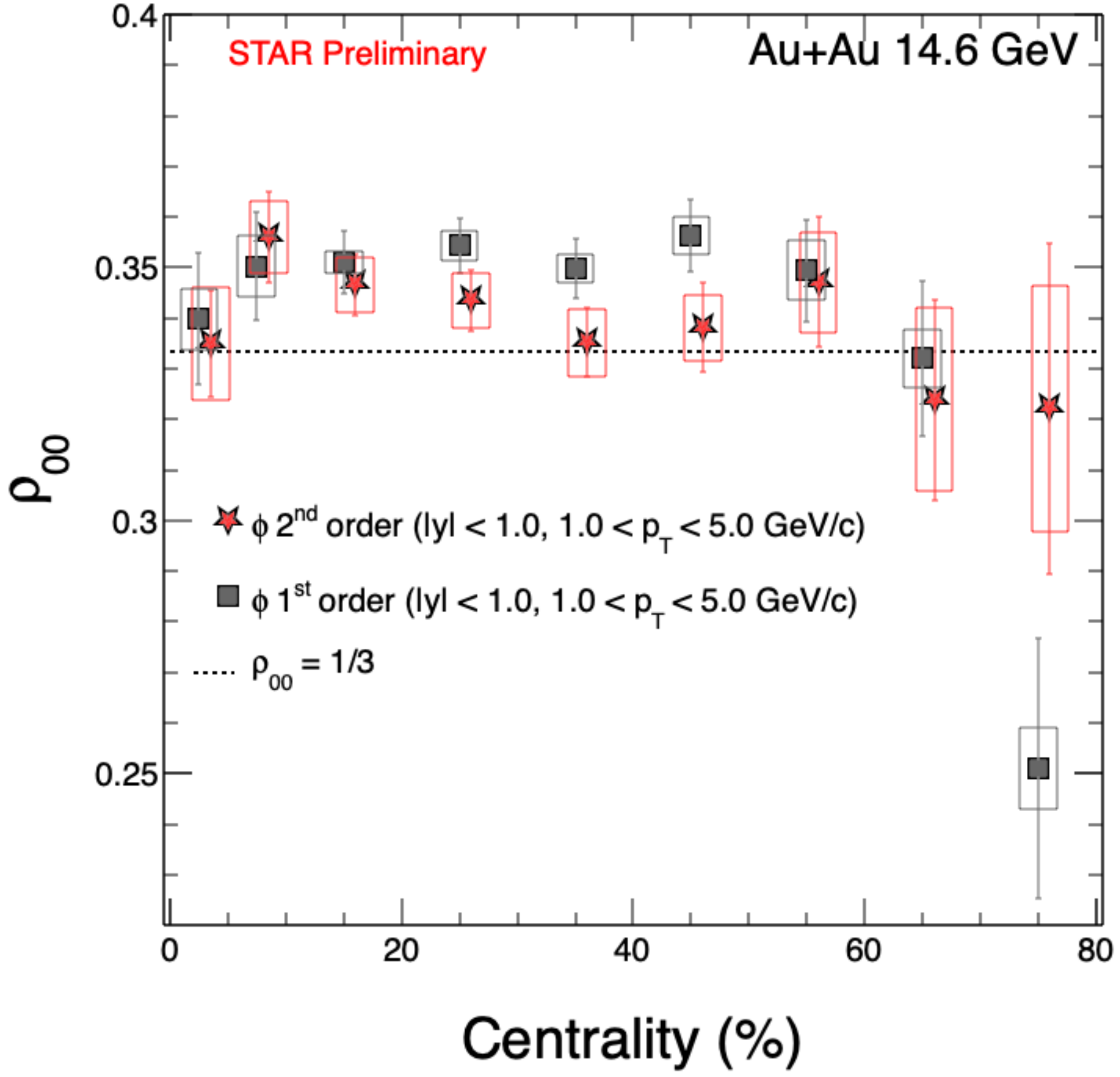
BES-II 2nd Order Stat weighted average over p_T:

$\rho_{00}^{2} = 0.3467 \pm 0.0037$ (stat.) $\pm\ 0.0018$ (sys.)

$\rho_{00}^{2} > 1/3$ with 3.2σ

$\rho_{00}^{1} \sim \rho_{00}^{2}$ with 1.2σ

ϕ meson ρ_{00} (Centrality) 14.6 GeV



Au+Au collisions (0-80%)

BES-II 1st Order Stat weighted average over Centrality:

$\rho_{00}^{1} = 0.3500 \pm 0.0027$ (stat.) ± 0.0013 (sys.)

$\rho_{00}^{1} > 1/3$ with 5.6σ

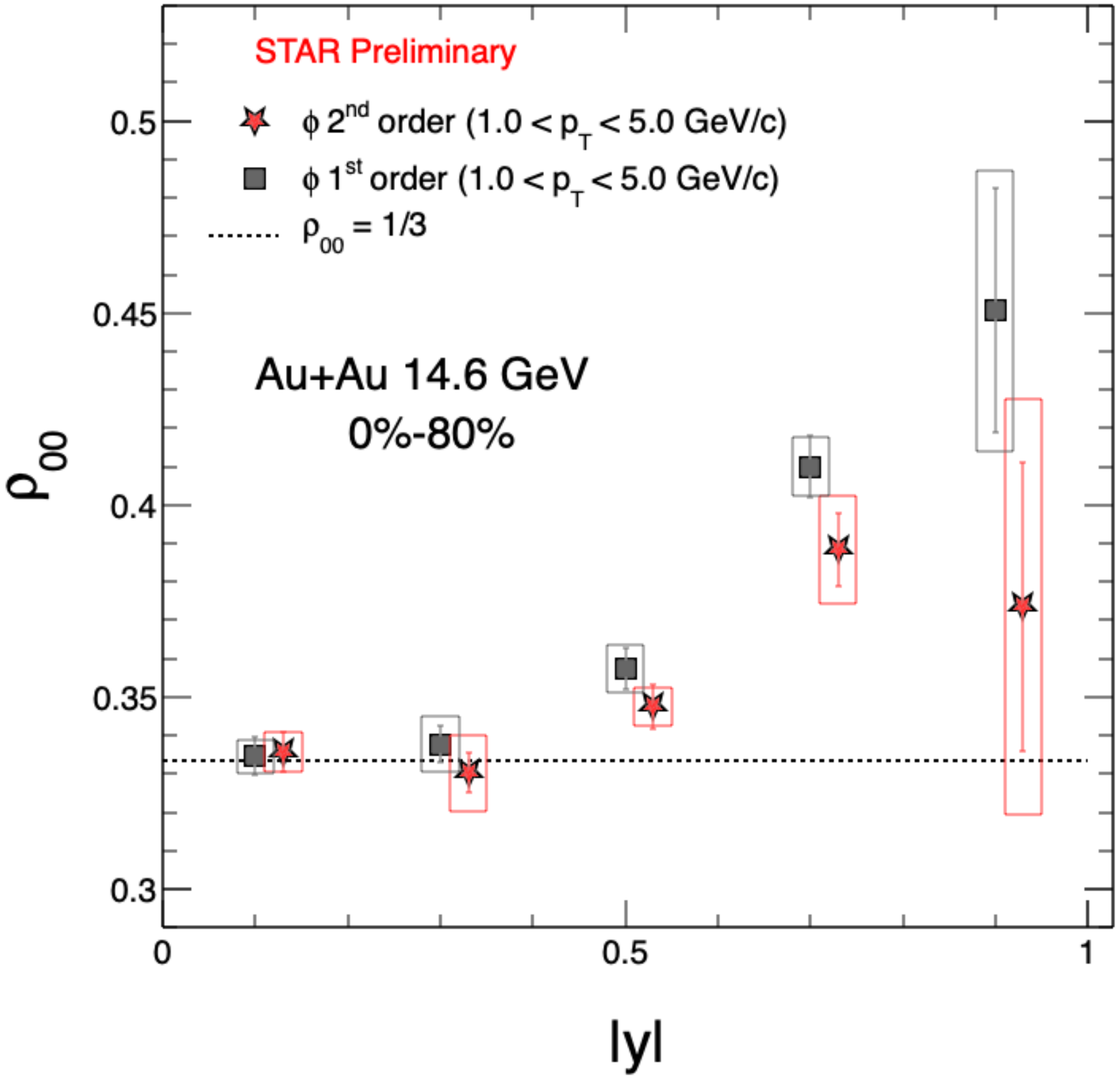
BES-II 2nd Order Stat weighted average over Centrality:

$\rho_{00}^{2} = 0.3425 \pm 0.0029$ (stat.) ± 0.0036 (sys.)

$\rho_{00}^{2} > 1/3$ with 2.0σ

$\rho_{00}^{1} \sim \rho_{00}^{2}$ with 1.4σ

ϕ meson ρ_{00} (rapidity [y]) 14.6 GeV



Au+Au collisions (0-80%)

BES-II 1st Order Stat weighted average over y:

$\rho_{00}^{1} = 0.3512 \pm 0.0027$ (stat.) ± 0.0048 (sys.):

$\rho_{00}^{1} > 1/3$ with 3.2σ

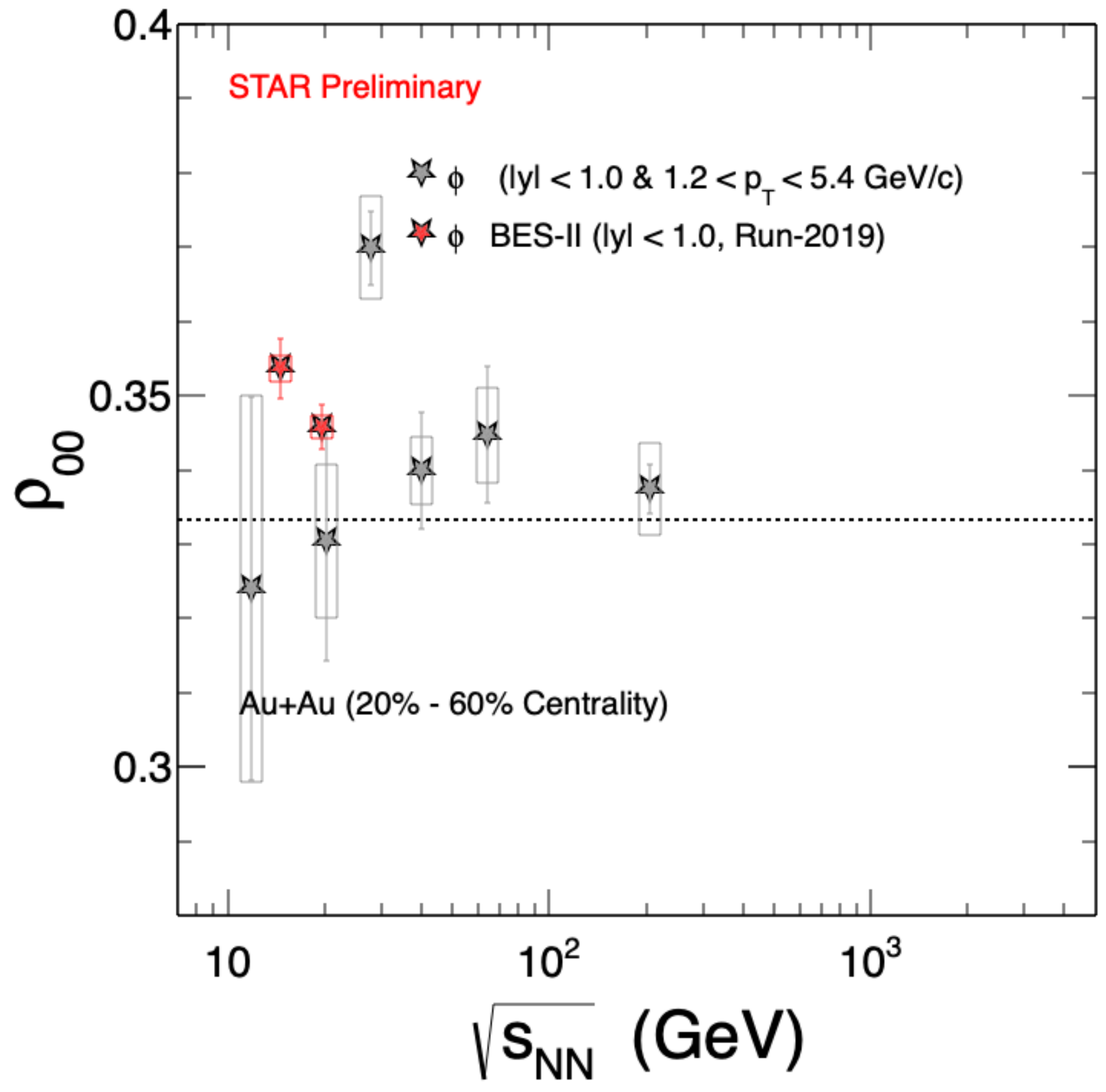
BES-II 2nd Order Stat weighted average over y:

$\rho_{00}^{2} = 0.3421 \pm 0.0029$ (stat.) ± 0.037 (sys.):

$\rho_{00}^{2} > 1/3$ with 1.9σ

$\rho_{00}^{1} \sim \rho_{00}^{2}$ with 1.3σ

ϕ meson ρ_{00} ($\sqrt{s_{NN}}$) First Order EP



- First order EP ρ_{00} collision energy dependence for mid-centrality.

BACKUP

EP Resolution and Acceptance Correction

- 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.

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

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:

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

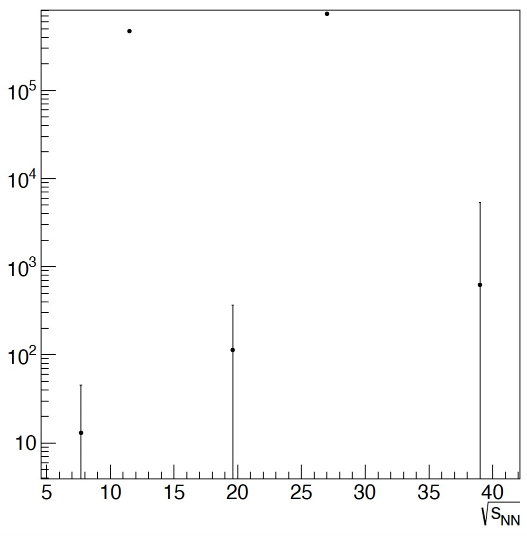
3. Combine all sources of systematics:

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

Au+Au 14.6 GeV p_T spectra interpolation

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

- 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.



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

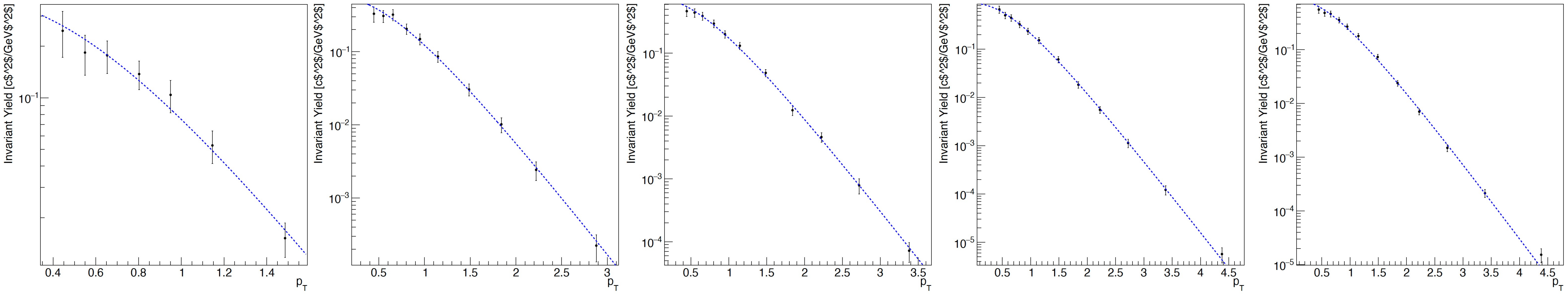
- In exponential function we have two well behaved parameters (dN/dy) and T_{exp}
- This will be used for extrapolation.
- Fit the distributions of the two parameters as a function of collision energy.
  - We really only need T_{exp} since dN/dy is just a normalization and we just want the shape.
- Then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

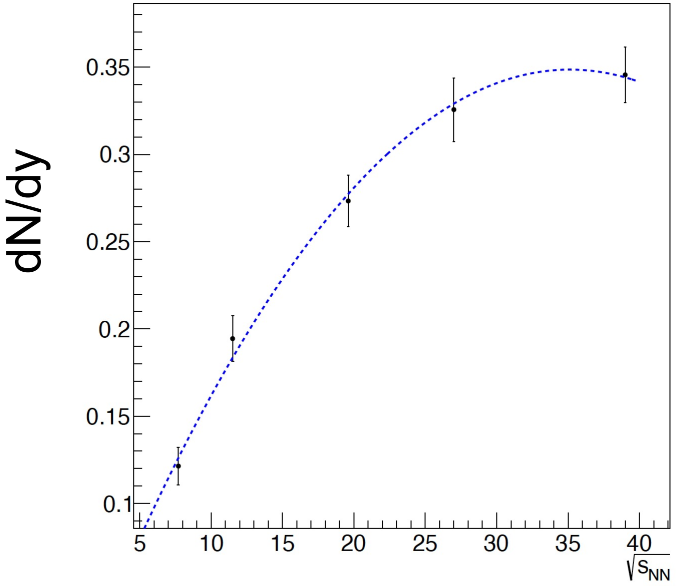
PHYSICAL REVIEW C **79**, 064903 (2009)

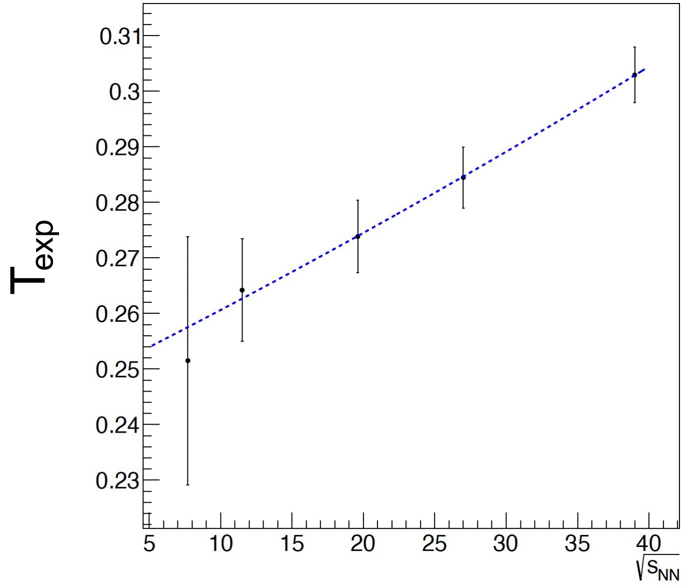
Au+Au 14.6 GeV p_T spectra interpolation

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.