Measurements of ϕ, ω, ρ^0, and J/ψ spin alignment

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Outline

- Introduction to global spin alignment
- Motivation and Status for ϕ BES-II Analysis
- Motivation and Status for ϕ and ω Leptonic Channel Isobar Analysis
- Motivation and Status for ρ^0 Au+Au and Isobar Analysis
- Motivation and Status for J/ψ Isobar Analysis
- Summary

Introduction to Spin Alignment

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

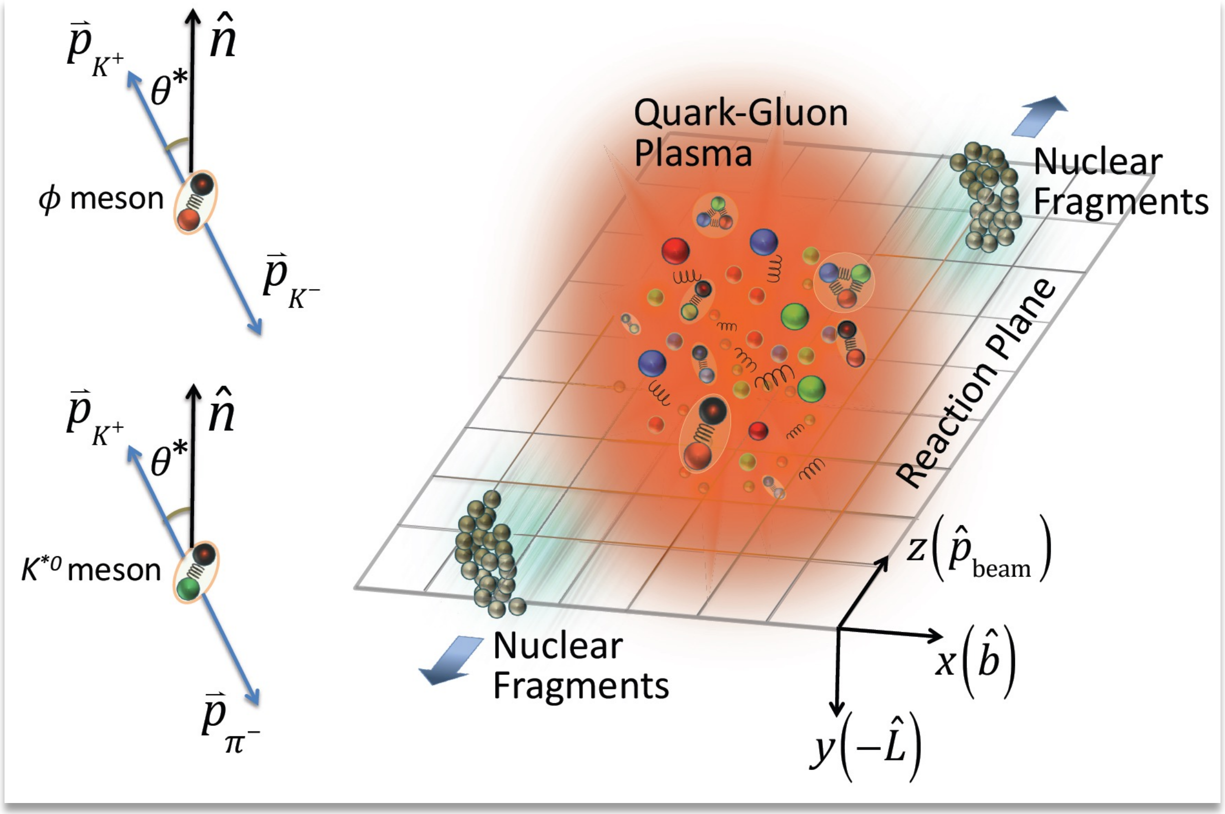
ρ_{00}: 00^{th} element of the spin density matrix.

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

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, 244248 (2023)

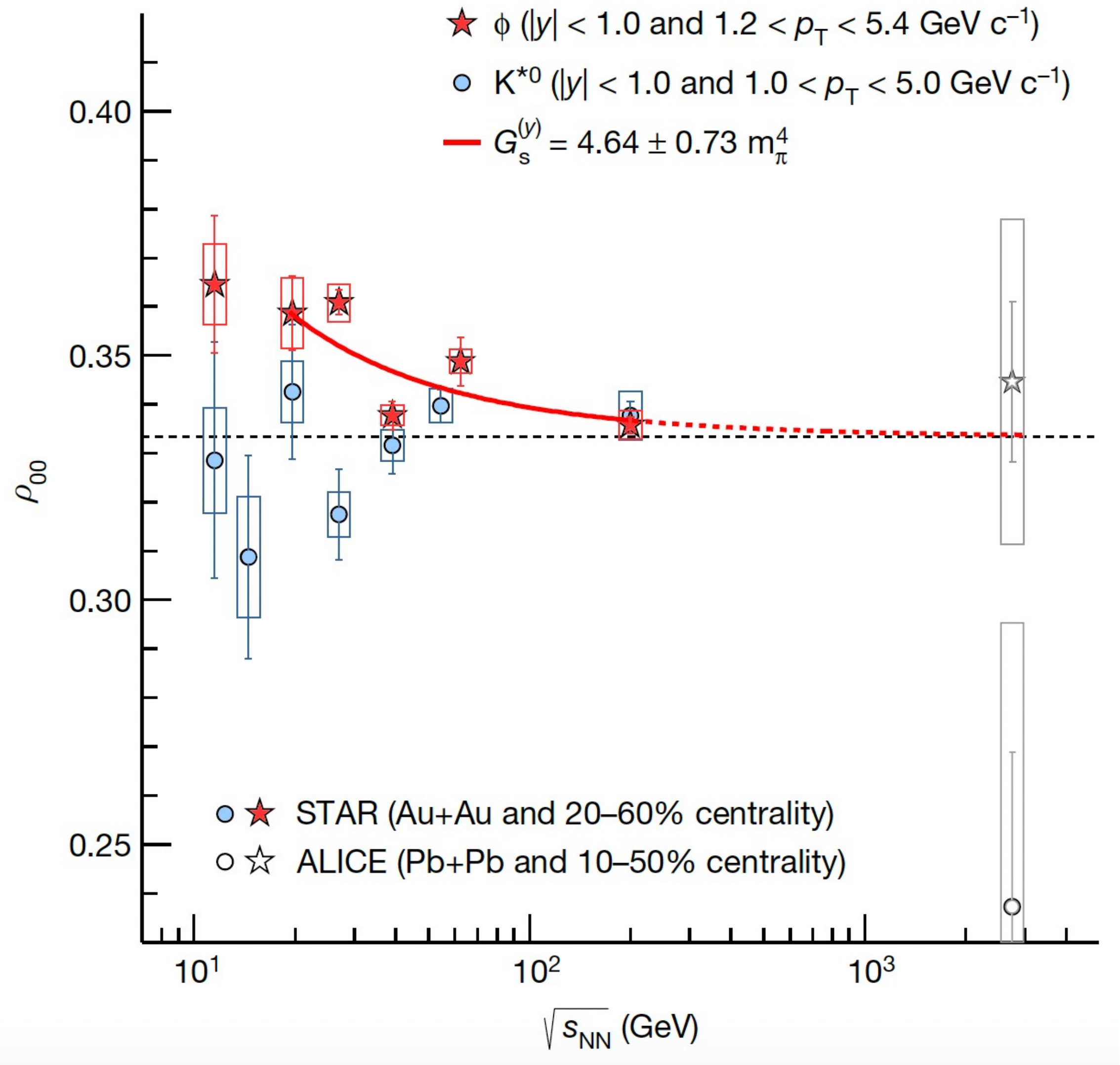
[1] Schilling et al., Nucl. Phys.B18, 332 (1970).

ϕ BES-II Analysis

Gavin Wilks (gwilks3@uic.edu, University of Illinois at Chicago)

For more details see slides 78-83

Motivation



STAR Collaboration. Nature 614, 244248 (2023)

- For the first time, a large positive global spin alignment (ρ_{00}>1/3) for φ-meson was measured at mid-central collisions.
- We have significantly more statistics in BES-II for the lower energies <= 19.6GeV
- Differential studies to help guide theory.

Dataset and Cuts

System	Trigger IDs
Au+Au 14.6 GeV BES-II (2019)	650000 (minbias)
Au+Au 19.6 GeV BES-II (2019)	640001, 640011, 640021, 640031, 640041, 640051 (all minbias)

Event Level Cuts

$|v_z| < 70$ cm

$|v_r| < 2$ cm

nBToFMatch > 2

TPC Track Cuts for $K^{+/-}, \pi^{+/-}$

$p_T > 0.1$ GeV/c

$|p| < 10$ GeV/c

$|DCA| < 2$ cm

No. TPC hits > 15

TPC hit ratio > 0.52

$|\eta| < 1.0$

PID Cuts for φ-meson $K^{+/-}$

TPC: $|n\sigma_K| < 2.5$

&& TOF: $0.16 < M^2 < 0.36$

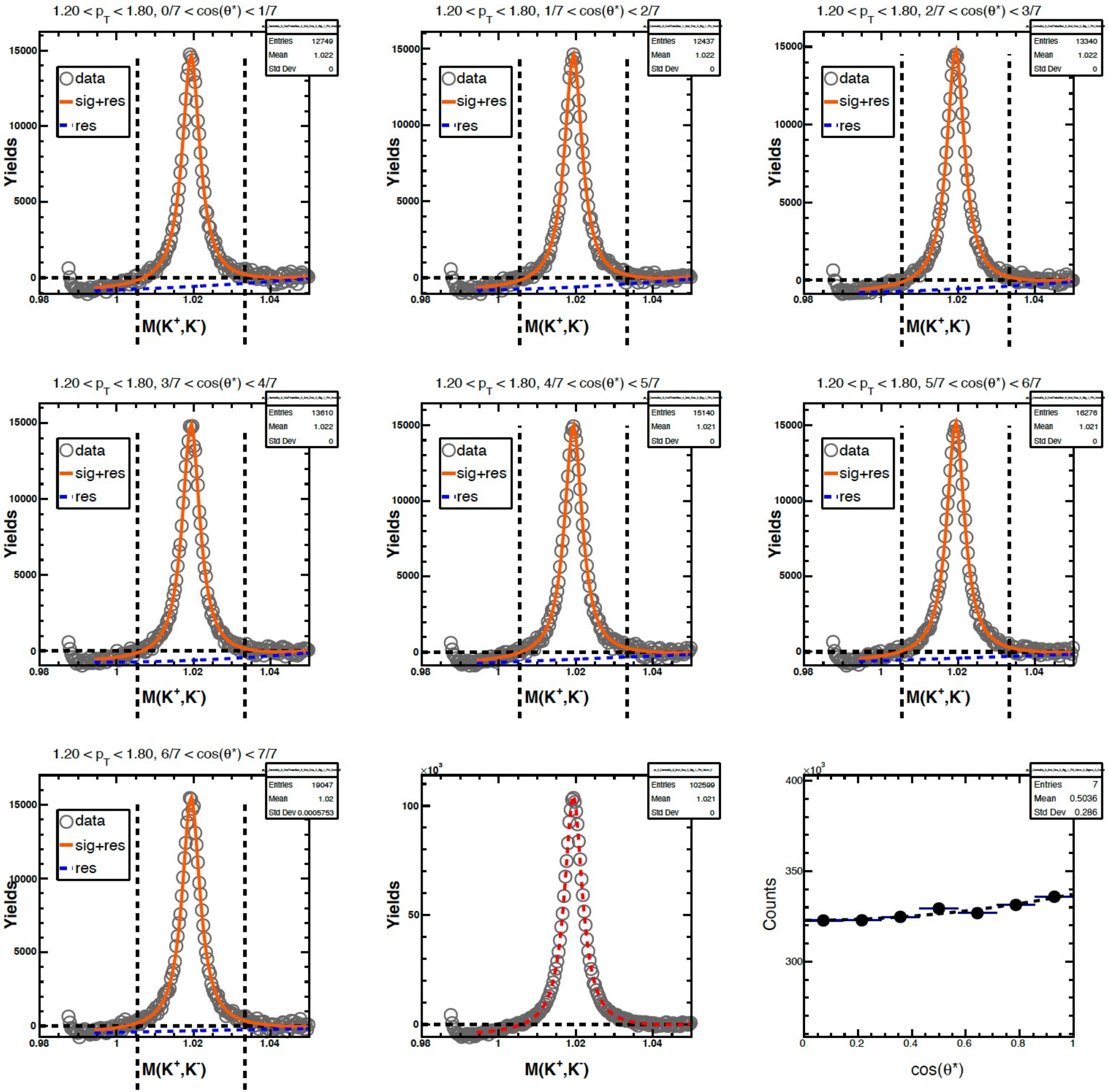
Analysis Procedure

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 correction applied by fitting efficiency corrected ρ_{00}^{obs} using the function:

$$\left[\frac{dN}{d\cos\theta^{*\prime}}\right]_{|\eta|} \propto 2 + F^* - \frac{B'F^*}{2} + \frac{3G^*}{4} - \frac{B'G^*}{2}$$
$$+ \left[2A' - F^*(1 - A' - B') - G^*\left(\frac{3}{2} - \frac{3A'}{4} - \frac{3B'}{2}\right)\right]\cos^2\theta^{*\prime}$$
$$+ \left[-F^*\left(A' + \frac{B'}{2}\right) + G^*\left(\frac{3}{4} - \frac{3A'}{2} - \frac{3B'}{2}\right)\right]\cos^4\theta^{*\prime}$$
$$+ \left[G^*\left(\frac{3A'}{4} + \frac{B'}{2}\right)\right]\cos^6\theta^{*\prime}.$$

$$A' = \frac{A(1+3R)}{4 + A(1-R)}, \quad B' = \frac{A(1-R)}{4 + A(1-R)}, \quad A = \frac{3\rho_{00} - 1}{1 - \rho_{00}}$$



Event mixing is used to produce φ-meson background.

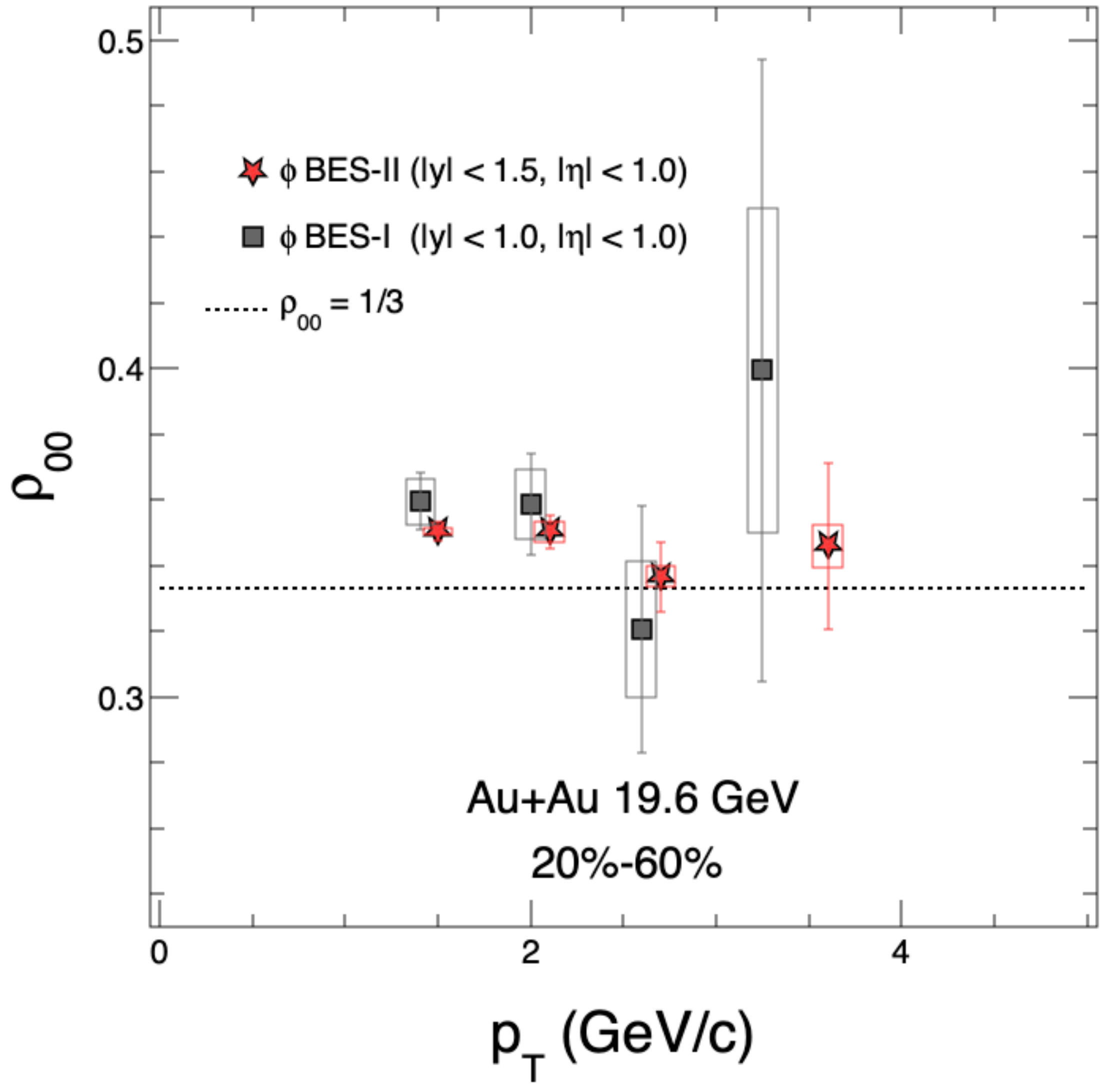
Normalize mixed event background to signal+background and subtract background

Fit signal histogram with Breit Wigner + 3rd order polynomial

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

Yields are extracted by histogram integration.

ϕ meson ρ_{00} (p_T)



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

BES-II Yield weighted average over p_T (1.2-4.2 GeV/c)

ρ_{00}^{II} = 0.3503 ± 0.0025 (stat.) ± 0.0013 (sys.)

ρ_{00}^{II} > 1/3 with 6.12σ

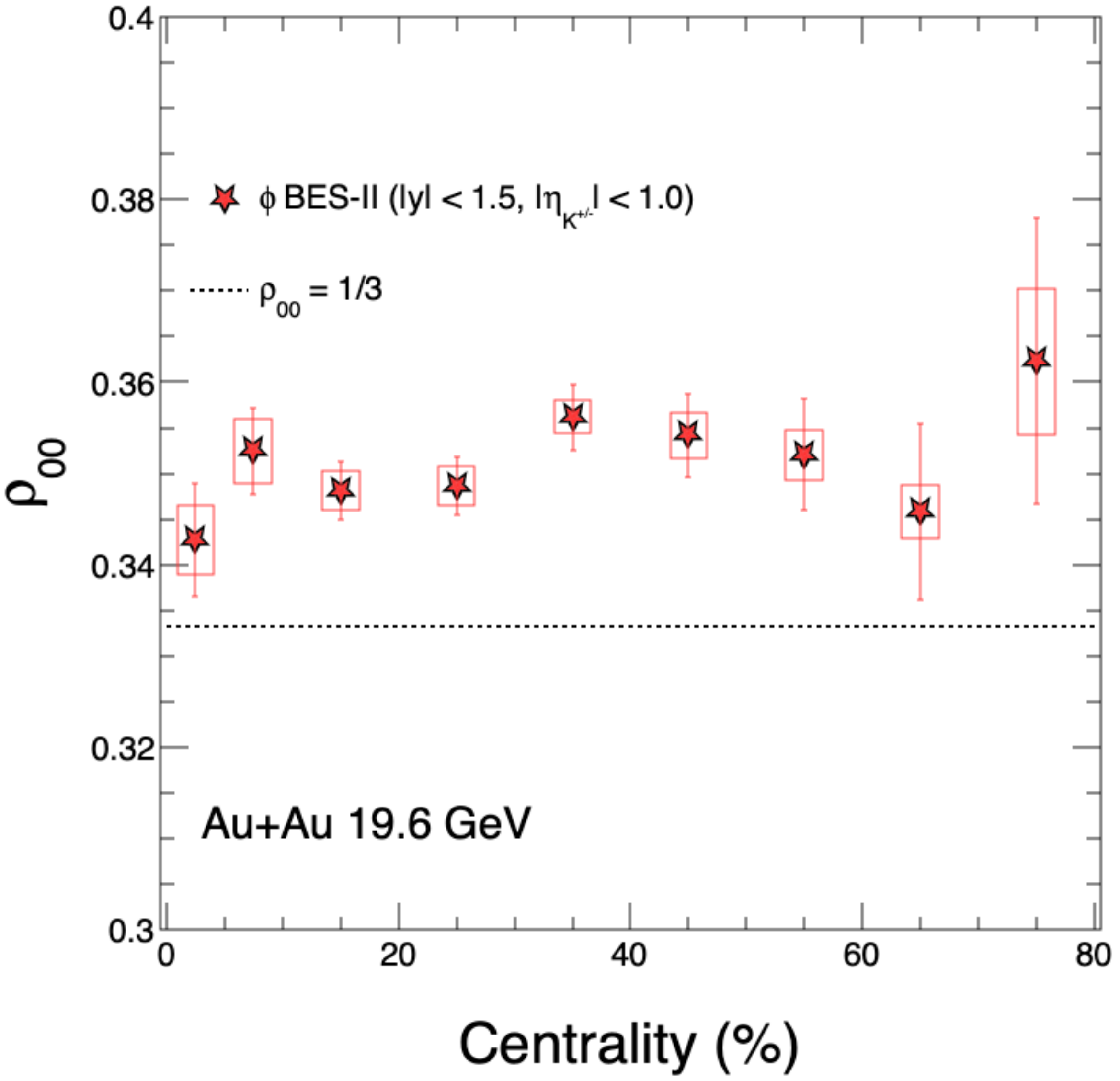
BES-I Yield weighted average over p_T (1.2-4.2 GeV/c)

ρ_{00}^{I} = 0.3587 ± 0.0076 (stat.) ± 0.0071 (sys.)

ρ_{00}^{I} > 1/3 with 2.44σ

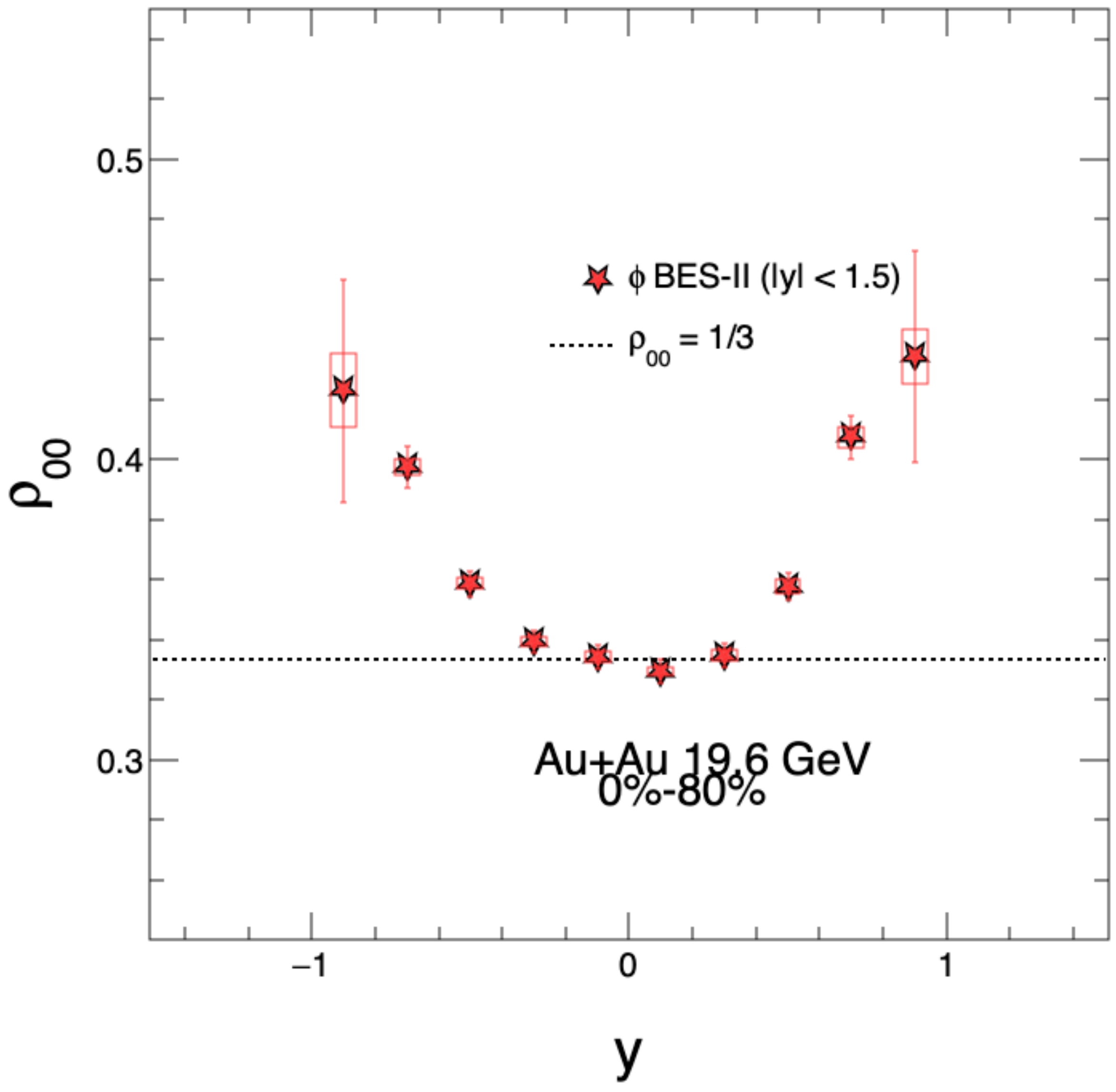
$\rho_{00}^{II} \sim \rho_{00}^{I}$ with 0.8σ

ϕ meson ρ_{00} (Centrality)



- $1.0 < p_T < 5.0$
- Value for each centrality calculated in 3 p_T bins with edges: {1.0,1.6,2.4,5.0}
- Then integrated over these bins.
- 0-80%, $1.0 < |p_T| < 5.0$
  - ρ_{00}^{II} = 0.3491 ± 0.0019 (stat.) ± 0.0012 (sys.)
- 20-60%, $1.0 < |p_T| < 5.0$
  - ρ_{00}^{II} = 0.3519 ± 0.0021 (stat.) ± 0.0012 (sys.)
  - consistent with p_T dependent study, p_T ranges differ slightly.

ϕ meson ρ_{00} (y, rapidity)

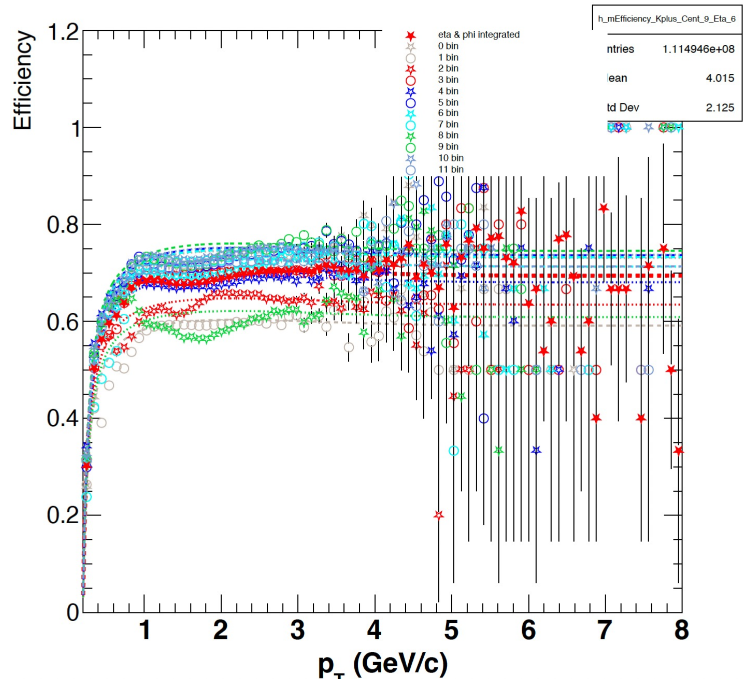


- $1.0 < p_T < 5.0$
- Value for each centrality calculated in 2 p_T bins with edges: {1.0,2.0,5.0}
  - Also binned in centrality: {0-10%,10-40%,40-80%}
- Then integrated over these bins.
- 0-80%, $1.0 < |p_T| < 5.0$
  - ρ_{00}^{II} = 0.3647 ± 0.0038 (stat.) ± 0.0012 (sys.)
  - Not consistent with integrated minbias result from centrality study.
  - We are currently investigated the acceptance correction for the rapidity dependent ρ_{00}.

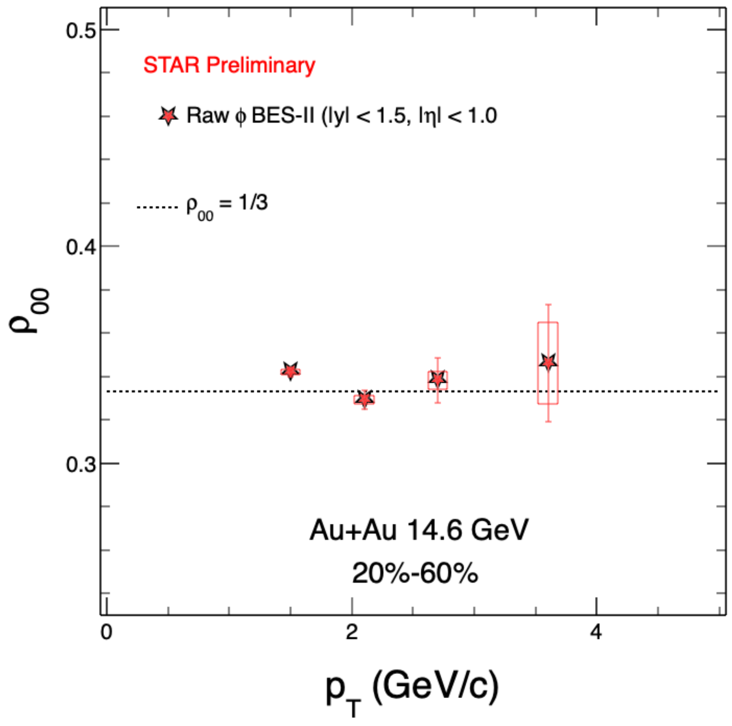
Systematics

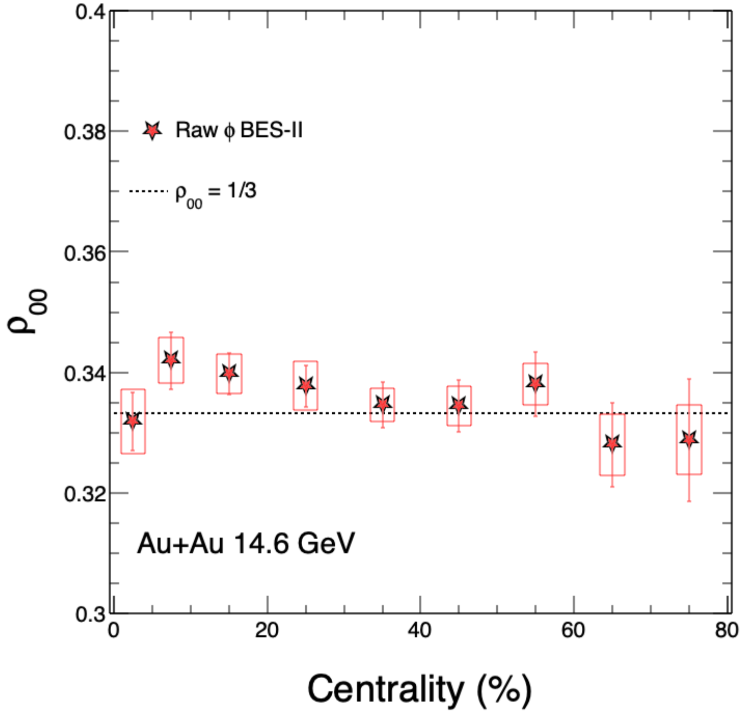
Systematic Source	Central Value	Variations
dca	< 2.0 cm	< 2.0 cm, < 2.5 cm, < 3.0 cm
$\lvert n\sigma_K \rvert$	< 2.5	< 2.0, < 2.5, < 3.0
Background normalization range	[1.04,1.05]	[0.99,1.0], [1.04,1.05], average of both
Yield extraction method	Breit-Wigner integration	Bin counting and Breit-Wigner integration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

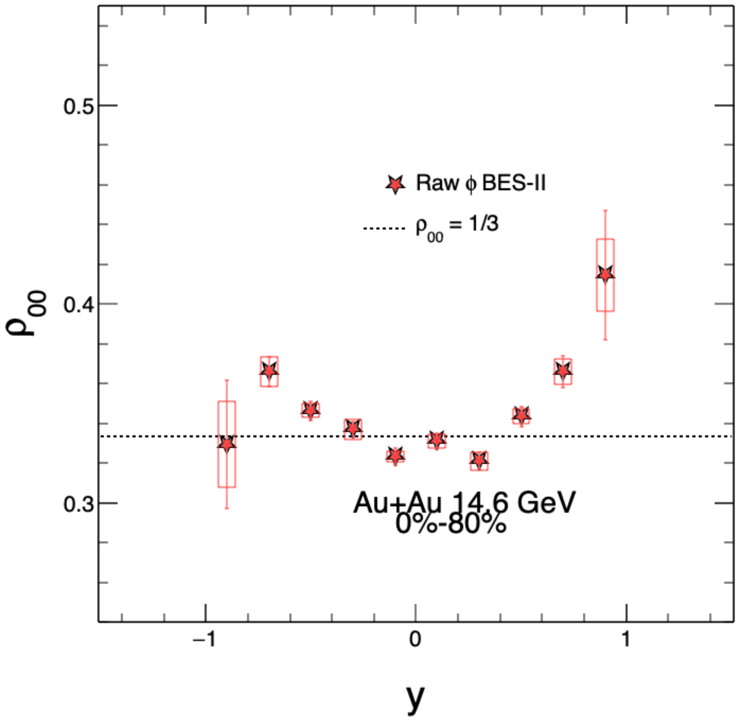
- We want to add varying input for TPC efficiency for each η bin or each η & φ bin later.
- Vary fit method for ToF matching efficiency
  - Default "Fit to plateau": shape set by η bin integrated over φ, normalization set by plateau in each η & φ bin.
  - Variation "Fit to η": shape and normalization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



Uncorrected 14.6 GeV Results







Roadmap to QM2023

- Need official centrality, bad runs, embedding, etc for 7.7 GeV BES-II.
- Need to produce ϕ meson spectra for 14.6 and 7.7 GeV (used in efficiency and acceptance correction simulations).
  - v_2 is also needed and is near completion.
- 19.6 GeV will be finished once we address issues with rapidity dependence (seems to be an acceptance correction issue).

- ρ_{00} with respect to first order event plane will also be studied.
  - All inputs to simulation should be identical, so this analysis will not require much more work.

ϕ and ω Leptonic Channel Isobar Analysis

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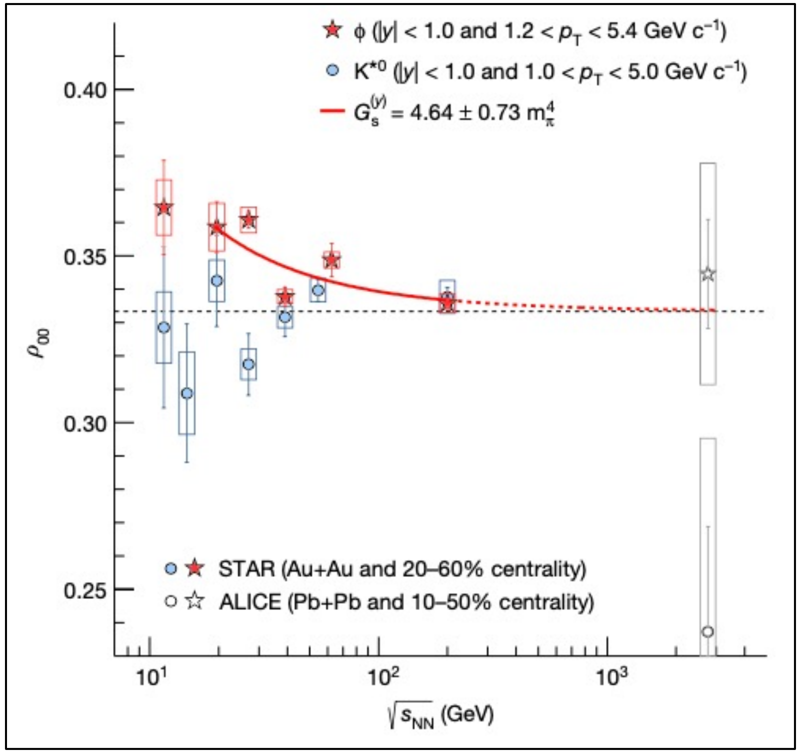
For more detail see slides 64-77

Motivation

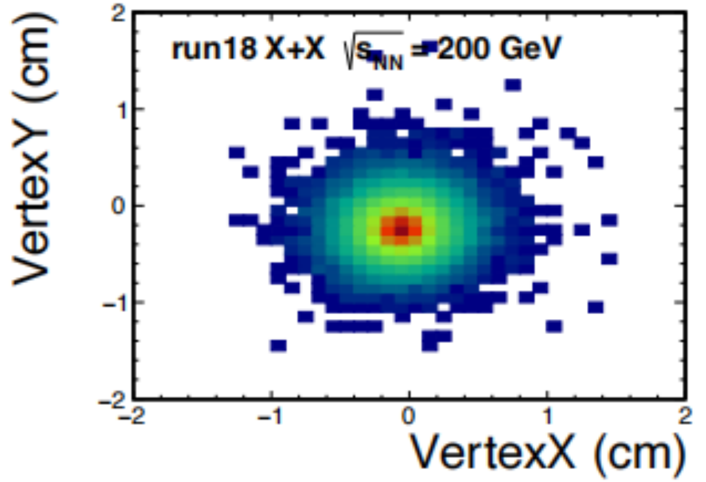


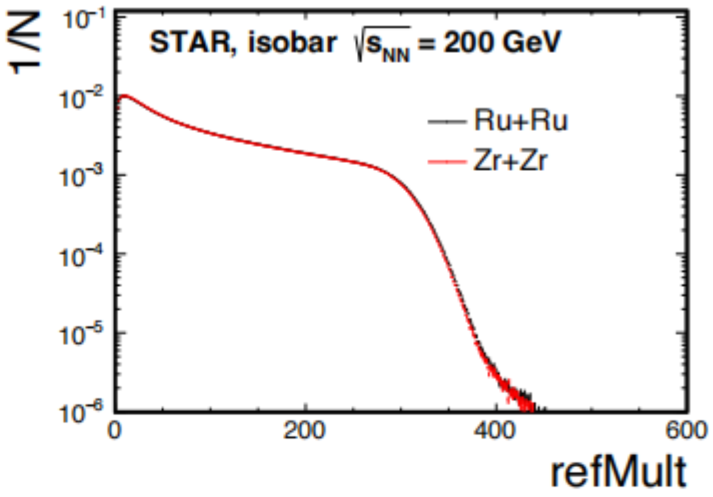
STAR, Nature, 614, 244 (2023)

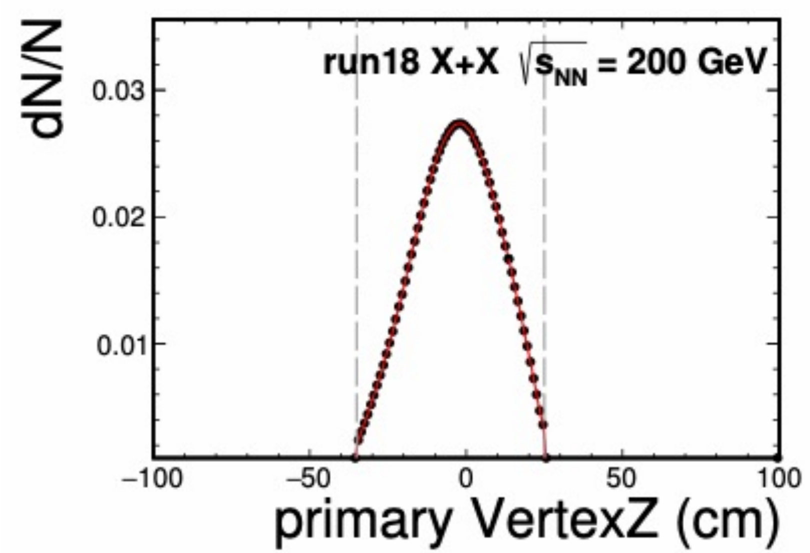
- strong force field s-sbar? depends on flavor? how about the light quarks, such as ω
- ϕ meson, kaon spin 0, electron spin ½, depends on daughter spin?
- ω comprises light quarks similar to π, k, but larger mass (782 MeV), hadronization

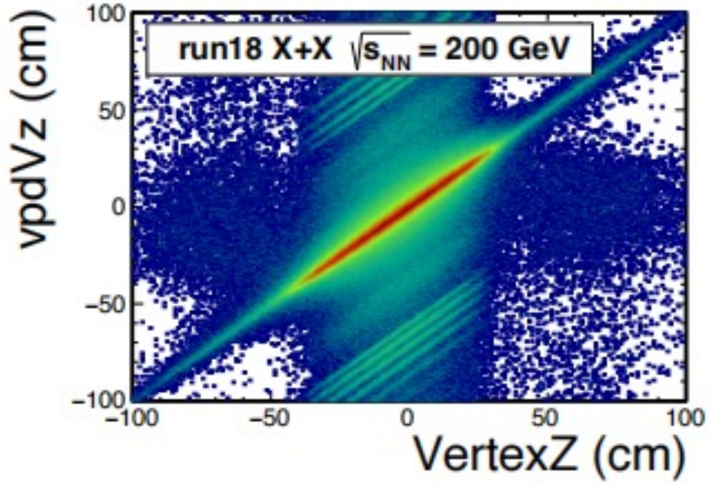
Event selection

Collisions	Trigger	V_z	V_r	$\lvert vpdV_z - V_z \rvert$
Run18 Zr+Zr	MinBias	$-35, 25cm$	$< 2cm$	$< 3cm$
Run18 Ru+Ru	MinBias	$-35, 25cm$	$< 2cm$	$< 3cm$





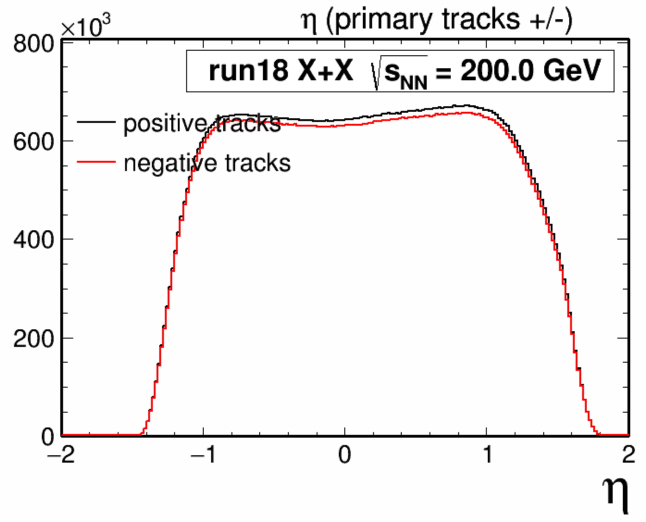


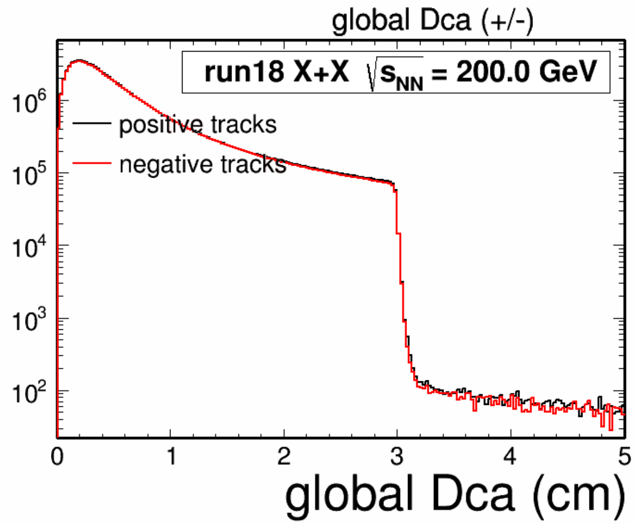


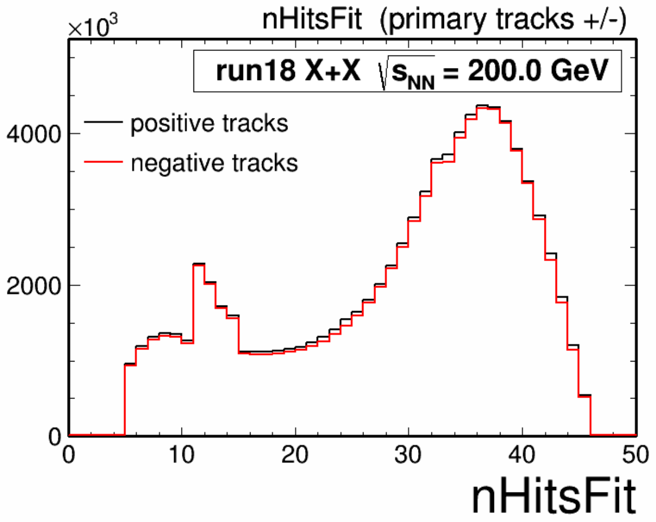
➢Bad run and centrality from the official isobar blinded analysis

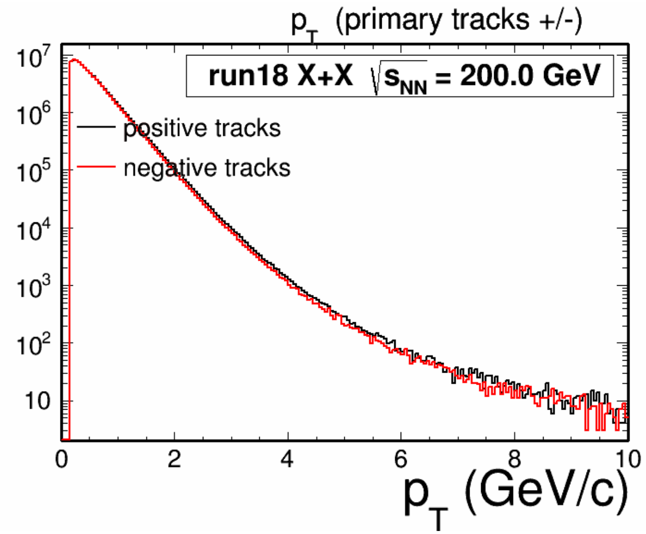
Track selection

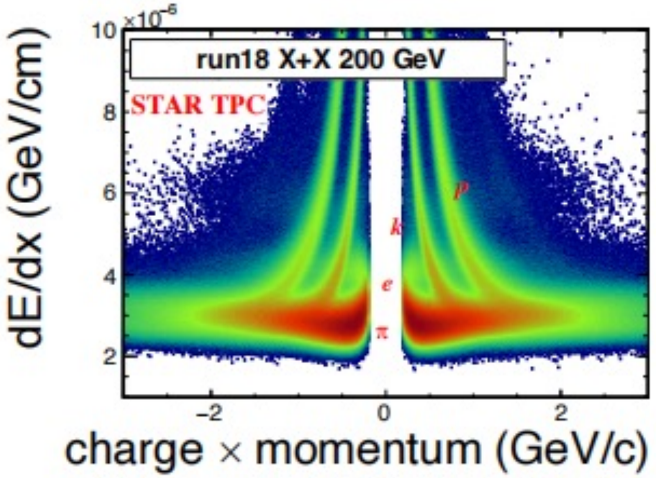
p_T	0.2-2.0 GeV/c
dca	< 3cm
nHitsFit	>15
η	within ±1



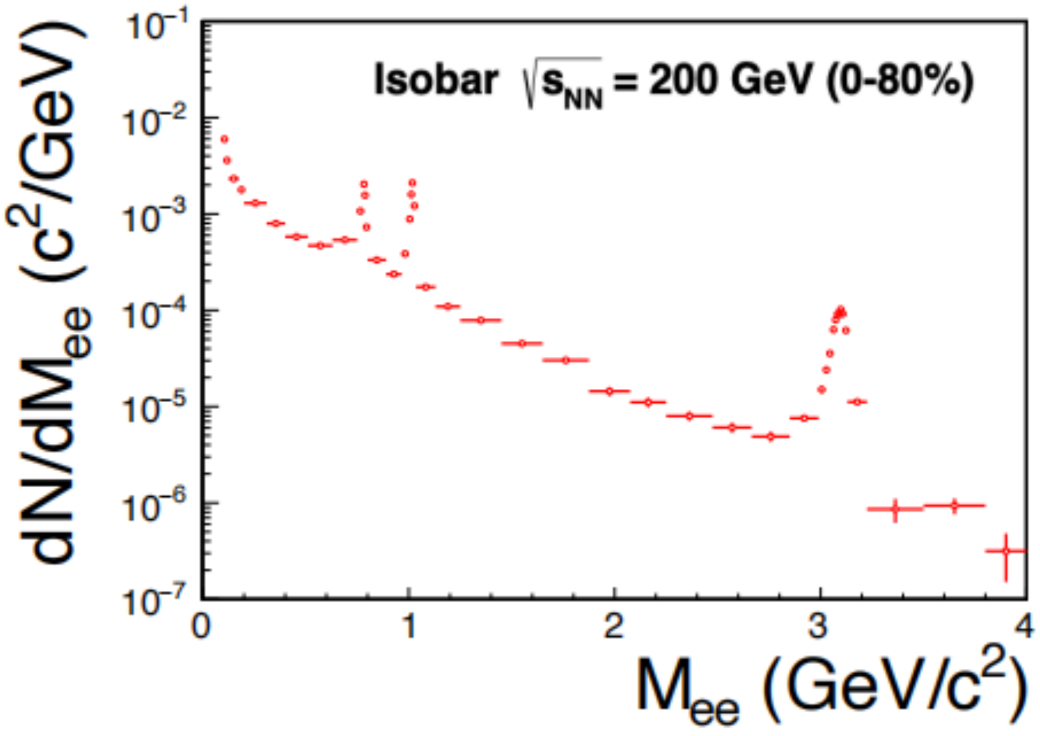


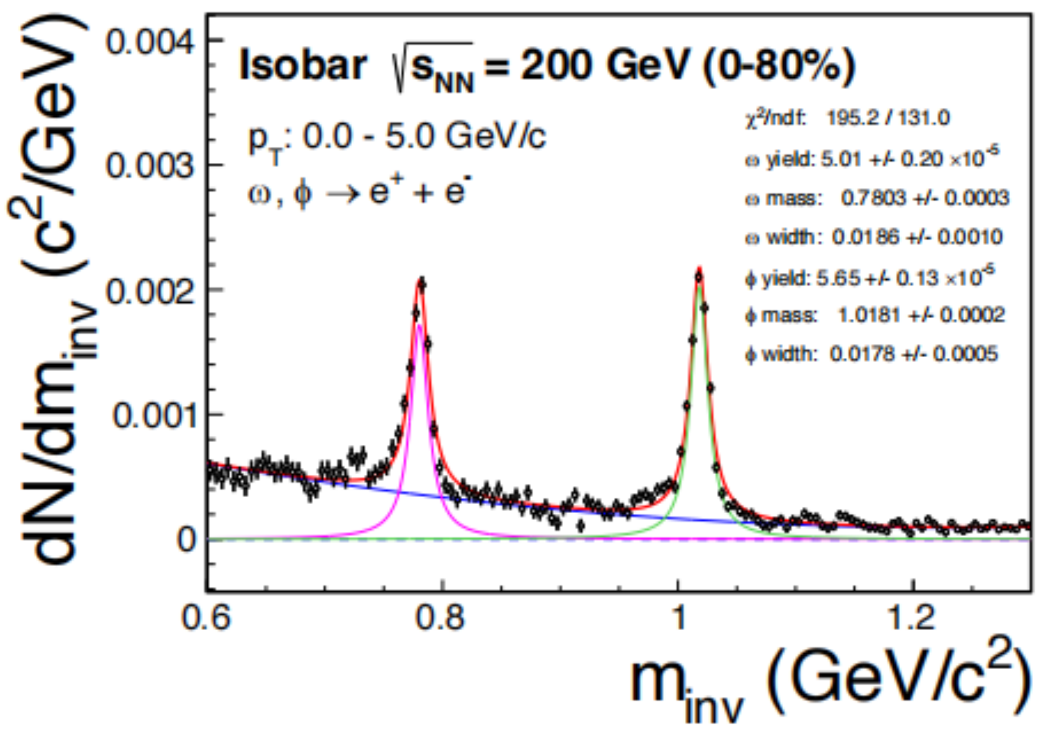






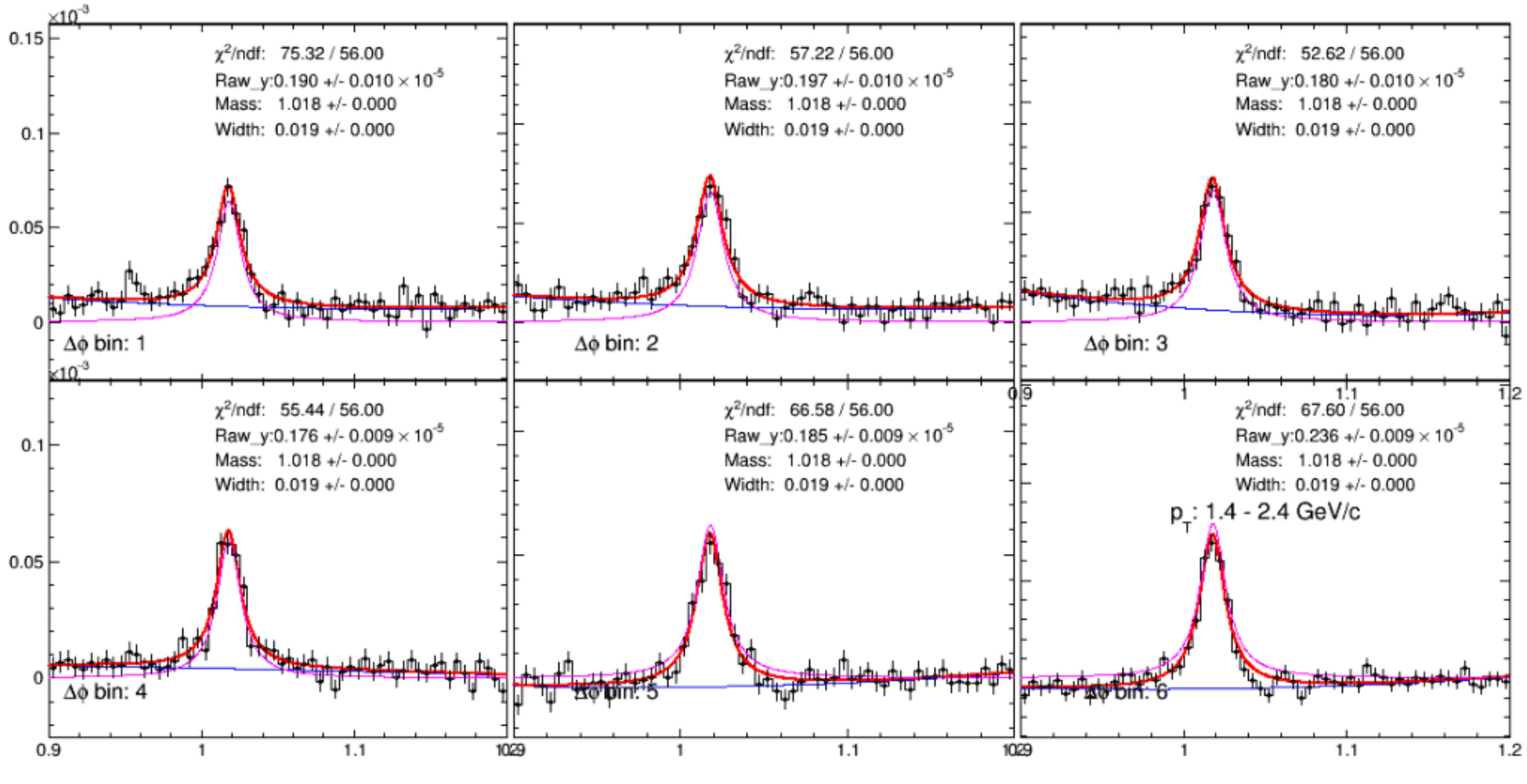
Di-electron signal





- clear ω and ϕ meson signal

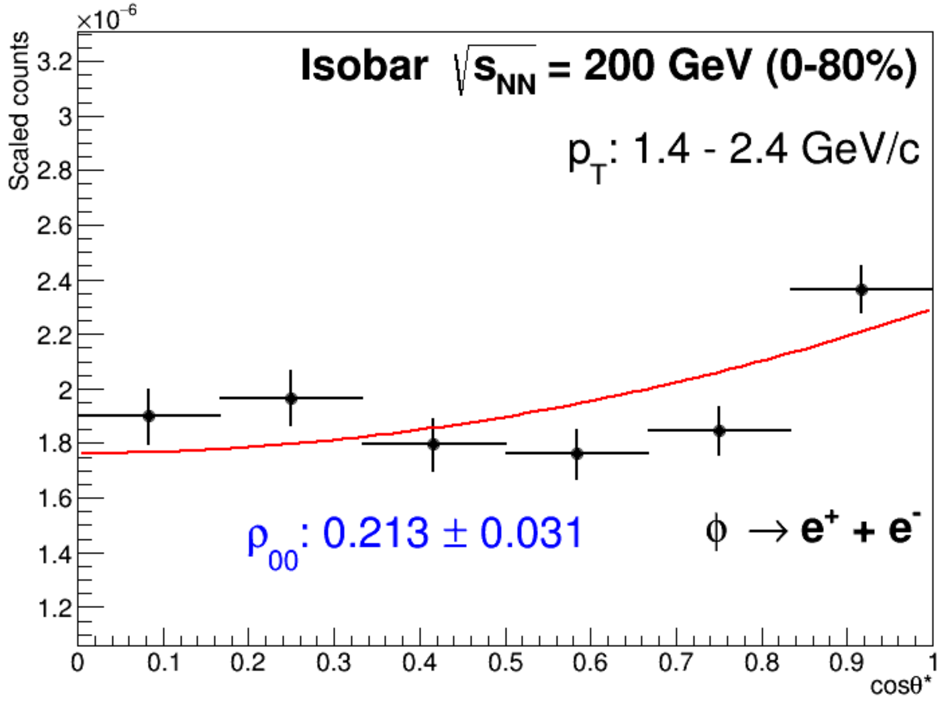
$\cos\theta^*$ (φ → e^+e^-) in Isobar

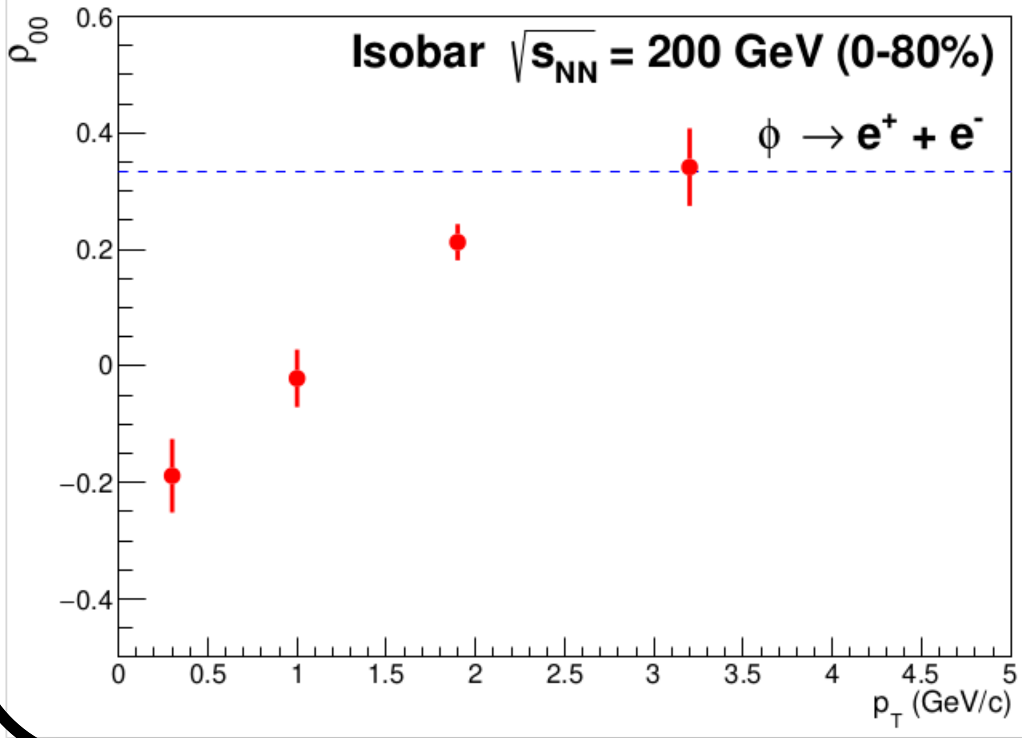


ρ_{00} ($\phi \rightarrow e^+e^-$) in Isobar

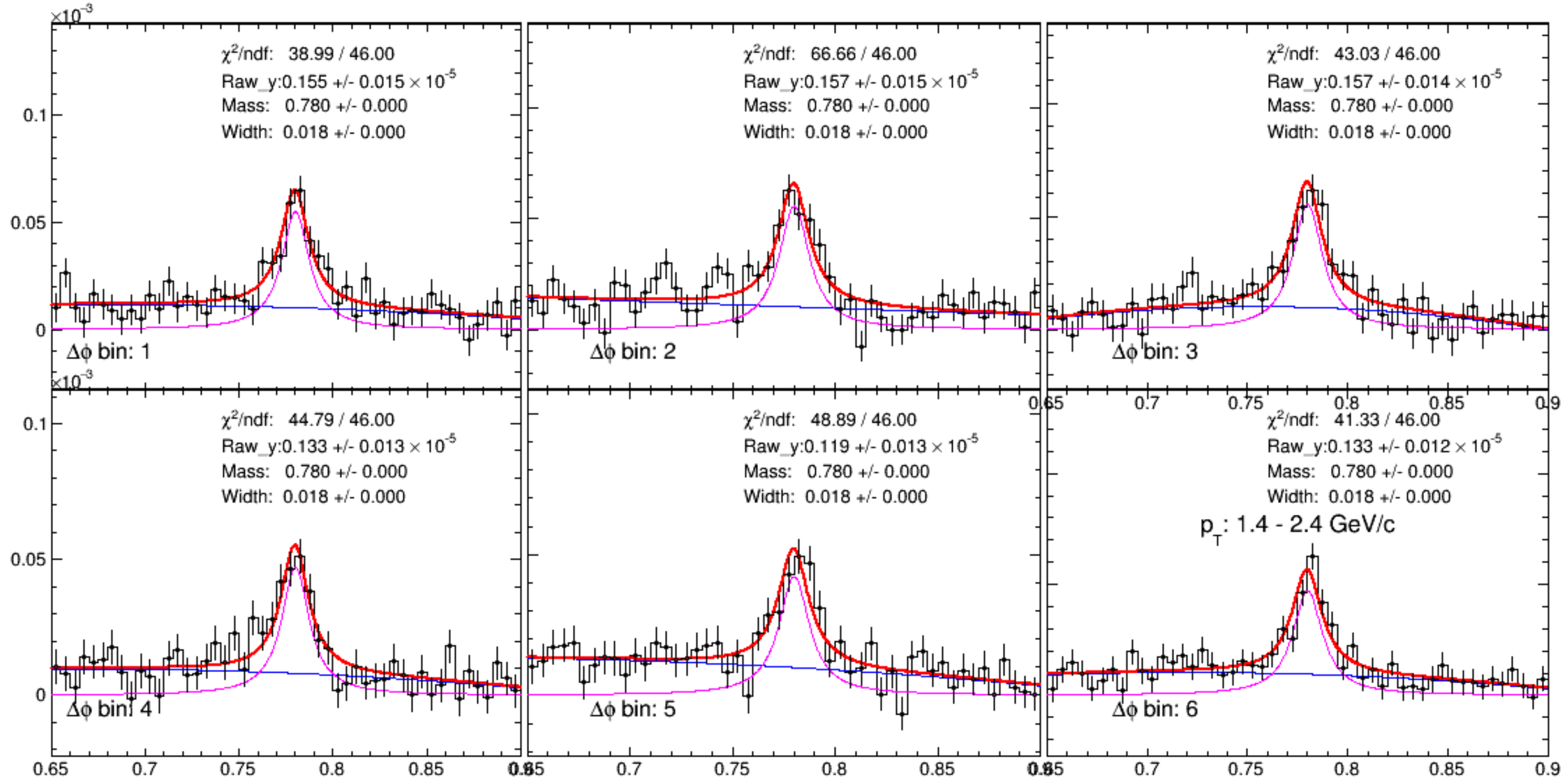
$$\frac{dN}{d\cos\theta^*} \propto (1+\rho_{00})+(1-3\rho_{00})\cos^2\theta^*$$

Without efficiency and acceptance corrections





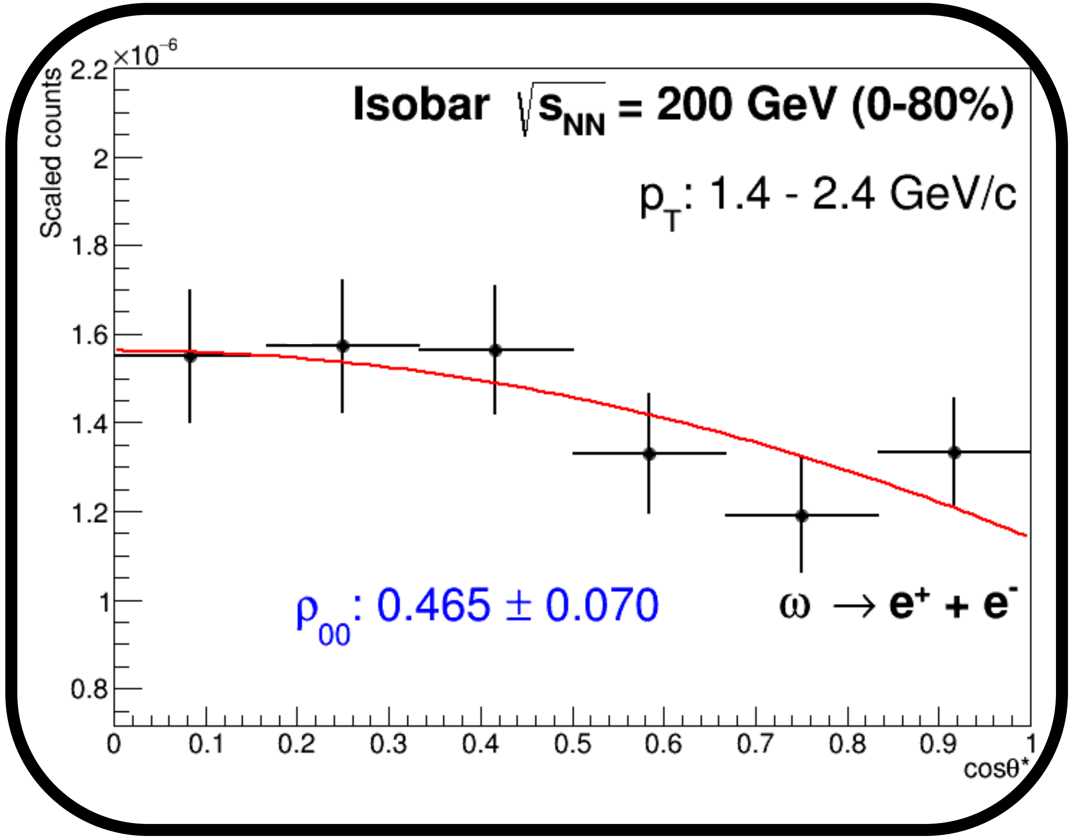
$\cos\theta^*(\omega \to e^+e^-)$in Isobar

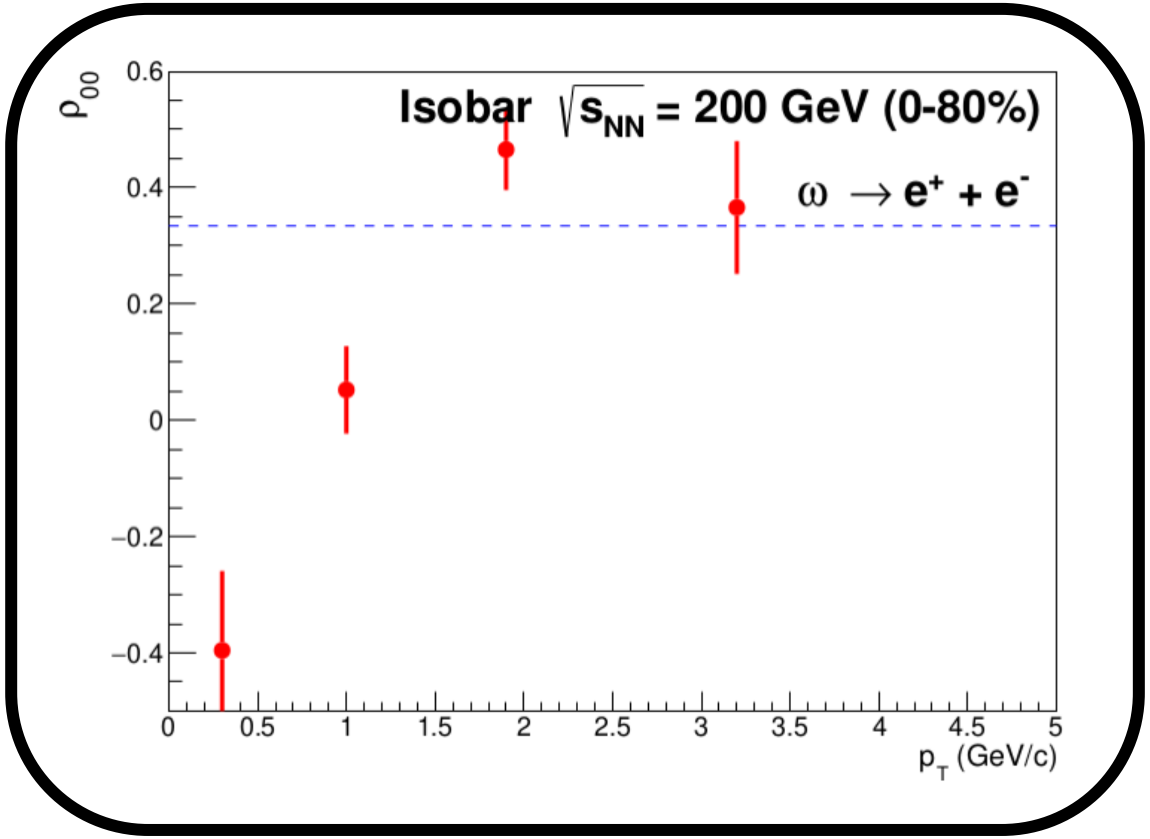


ρ_{00} ($\omega \to e^+e^-$)in Isobar(Zr+Zr&Ru+Ru)

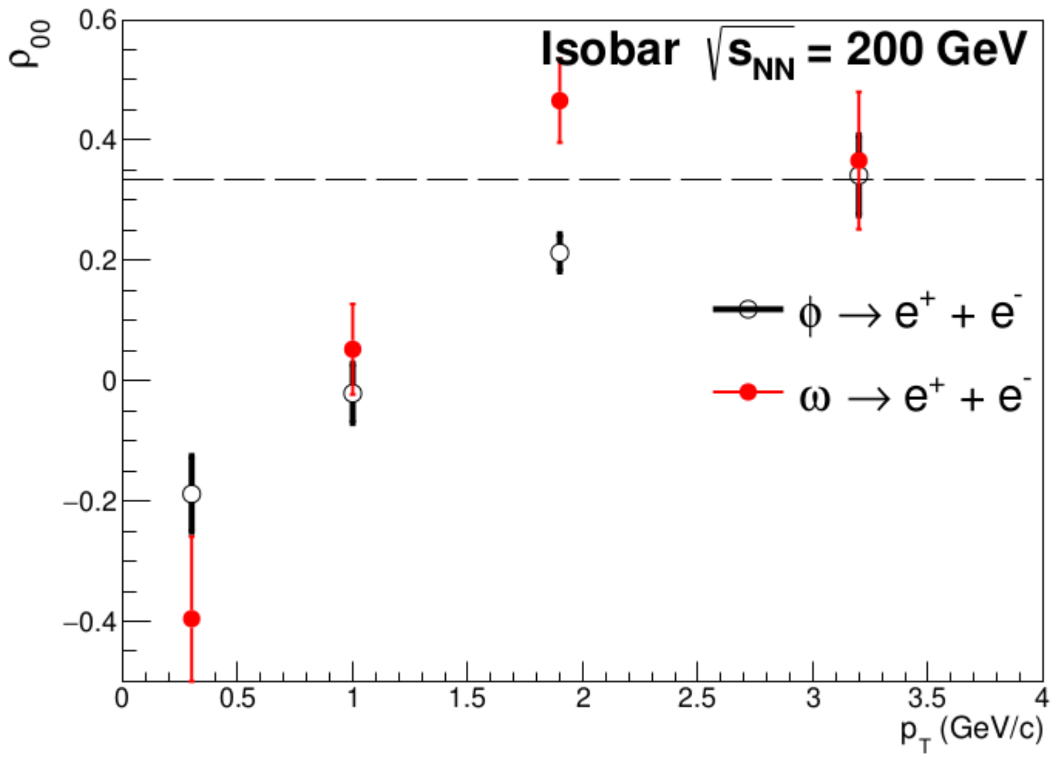
$$\frac{dN}{d\cos\theta^*} \propto (1+\rho_{00})+(1-3\rho_{00})\cos^2\theta^*$$

Without efficiency and acceptance corrections





Summary of ρ_{00} of ϕ,ω without the correction of detector effects and event plane resolution



- ➢Results of ρ_{00} of ϕ,ω need futher work of corrections

Summary and outlook

- Preliminary study ρ_{00}(obs) of phi omega(e+e- channel) in isobar are shown.
- Efficiency and acceptance correction for ρ_{00} will be studied.
- 10 times statistics from 2023 and 2025 will improve the precision.

ρ^0 Analysis

Baoshan Xi (xibaoshan@sinap.ac.cn, Shanghai Institute of Applied Physics)

For more detail see slides 53-63

Research motivation

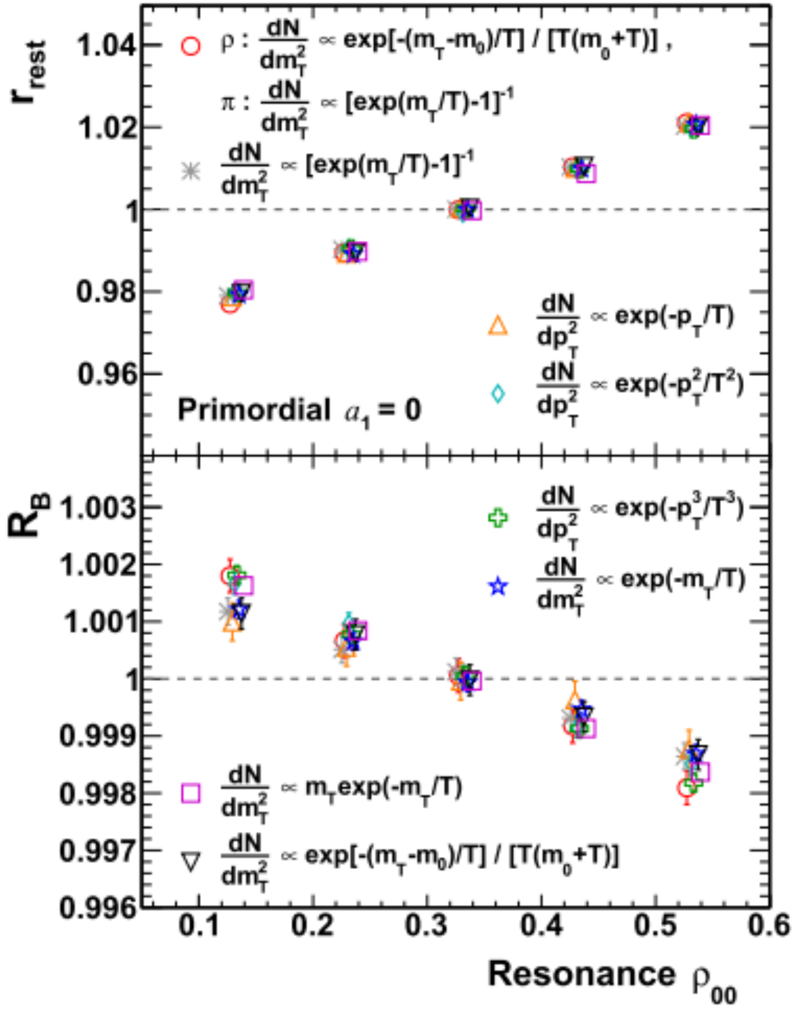


Fig. 9. (color online) r_{rest} and R_B as a function of resonance ρ_{00} for various transverse spectra. Choices of spectra are the same as in Fig. 7.

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Global spin alignment of ρ^0 meson can contribute to background in CME observables, similar to resonance v_2 effect.

($\rho_{00} > 1/3$) will enhance apparent values of CME observables.
($\rho_{00} < 1/3$) will decrease apparent values of CME observables.

To assess its effect in CME observables, it would be desirable to study ρ^0 meson ρ_{00}.

Research motivation

Global spin alignment of ρ mesons is a crucial component in the background estimation for the CME measurements involving pions.

$$\Delta\gamma^{*}_{112} = \frac{N_\rho}{N_+N_-}\frac{3\rho_{00}-1}{4}$$

$$\mathrm{Sign}(S_{\mathrm{concavity}}) = \mathrm{Sign}\left[-\frac{N_\rho}{2N_+N_-}(3\rho_{00}-1)\right]$$

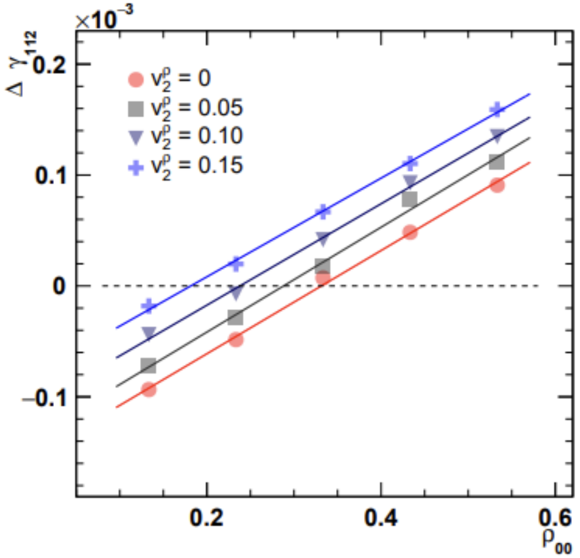


Figure 2: Toy model simulations of the π-π $\Delta\gamma_{112}$ correlation as a function of ρ-meson ρ_{00} with various inputs of v_2^ρ. Linear fits are applied to guide eyes.

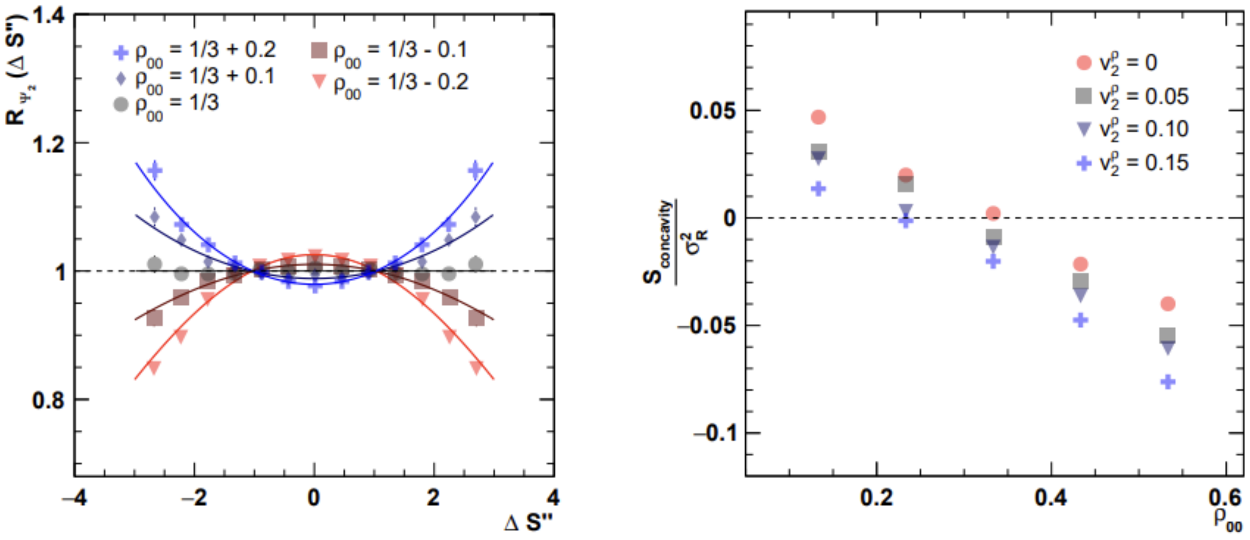


Figure 4: (Left) toy model simulations of the $R_{\Psi_2}(\Delta S'')$ distribution for events with zero v_2^ρ and different ρ_{00} inputs. The distributions are symmetrized around $\Delta S''$ =0. (Right) $S_{\mathrm{concavity}}/\sigma_R^2$ extracted using Gaussian fits to $R_{\Psi_2}(\Delta S'')$ for different v_2^ρ and ρ_{00} inputs. A positive value indicates the convex shape, and a negative one represents the concave shape.

arXiv:2212.03056

Datasets and cuts of Run 11

Minimum Bias Event of AuAu 200GeV from 2011 (~500 M before event cuts. ~300M after event cuts)

Event cuts:

-30.0 cm < Vz < 30.0 cm

Vr < 2.0 cm

-3.0 cm < Vz-VzVPD < 3.0 cm

Number ToF matched point > 3

Bad runs are rejected by StRefMultCorr and abnormal data

Track cuts:

nHitsFit > 15

nHitsFit/nHitsMax > 0.55

|nSigmaPion| < 1.5

-0.8 < eta < 0.8

dca < 2.0 cm

p_T >0.2 GeV/c && p< 10 GeV/c

-0.1 < mass2 < 0.2

Datasets and cuts of isobar (Referring to those used in UCLA CME blind analysis)

Minimum Bias Event of isobar (For RuRu: ~2000 M before event cuts. ~1600M after event cuts.
For ZrZr: ~2200 M before event cuts. ~1800M after event cuts.)

Event cuts:

-35 cm < Vz < 25 cm
Vr < 2.0 cm
-3.0 cm < Vz-VzVPD < 3.0 cm
Number ToF matched point > 3
Bad runs are rejected by StRefMultCorr

Track cuts:

nHitsFit > 15
nHitsFit/nHitsMax > 0.55
|nSigmaPion| < 1.5
-0.8 < eta < 0.8
dca < 2.0 cm
p_T >0.2 GeV/c && p< 10 GeV/c
-0.1 < mass2 < 0.2

Invariant mass and residual background

- We first subtract the rotated background.
- The normalization is taken at the place where the invariant mass has its lowest value after the first step.
- After that we use a second order polynomial to take care of residual background.

Obtaining yields of ρ^0 meson

We fit with contributions from 7 particles (hadronic cocktail) :

ω, ρ^0, f_0, f_2, σ^0, k_S^0 , η.

The fitting range is 0.4-1.6 GeV.

The general principle is to stick to pdg values in peripheral collisions, where the environment is not dense (less multiple scattering) and mass and width can be regarded as close-to-vacuum value. At each $\mathrm{p_T}$ interval, we fit the mass and width of the particles from peripheral collisions, then apply these parameters to the central collision case.

F(ρ^0, or $\mathrm{f_0}$, $\mathrm{f_2}$, σ^0) = PS(M) × BW(M)

$$PS\,(M_{\pi\pi}) = \frac{M_{\pi\pi}}{\sqrt{M_{\pi\pi}^2 + p_T^2}} \times exp(-\sqrt{M_{\pi\pi}^2 + p_T^2}/T)$$

$$BW\,(M_{\pi\pi}) = \frac{AM_{\pi\pi}M_0\Gamma\,(M_{\pi\pi})}{[(M_0{}^2 - M_{\pi\pi}{}^2)^2 + M_0{}^2\Gamma^2\,(M_{\pi\pi})]}$$

$$\Gamma\,(M_{\pi\pi}) = \left[\frac{(M_{\pi\pi}^2 - 4m_\pi^2)}{(M_0^2 - 4m_\pi^2)}\right]^{(2J+1)/2} \times \Gamma_0 \times (M_0/M_{\pi\pi})$$

J. Adams, et al. (STAR Collaboration), Phys. Rev. Lett. 92, 092301 (2004).

Prabhat R. Pujahari (for the STAR collaboration), Nucl. Phys. A 862, 297 (2011).

We do an overall fitting in each p_T and centrality bin with the constrain of parameters is:

ρ^0 : mass: 0.7-0.8 width: free parameter

f_0 : mass: 0.98 (fixed) width: free parameter

σ^0: mass: 0.4 - 0.8 width: 0.1 - 0.8(PDG)

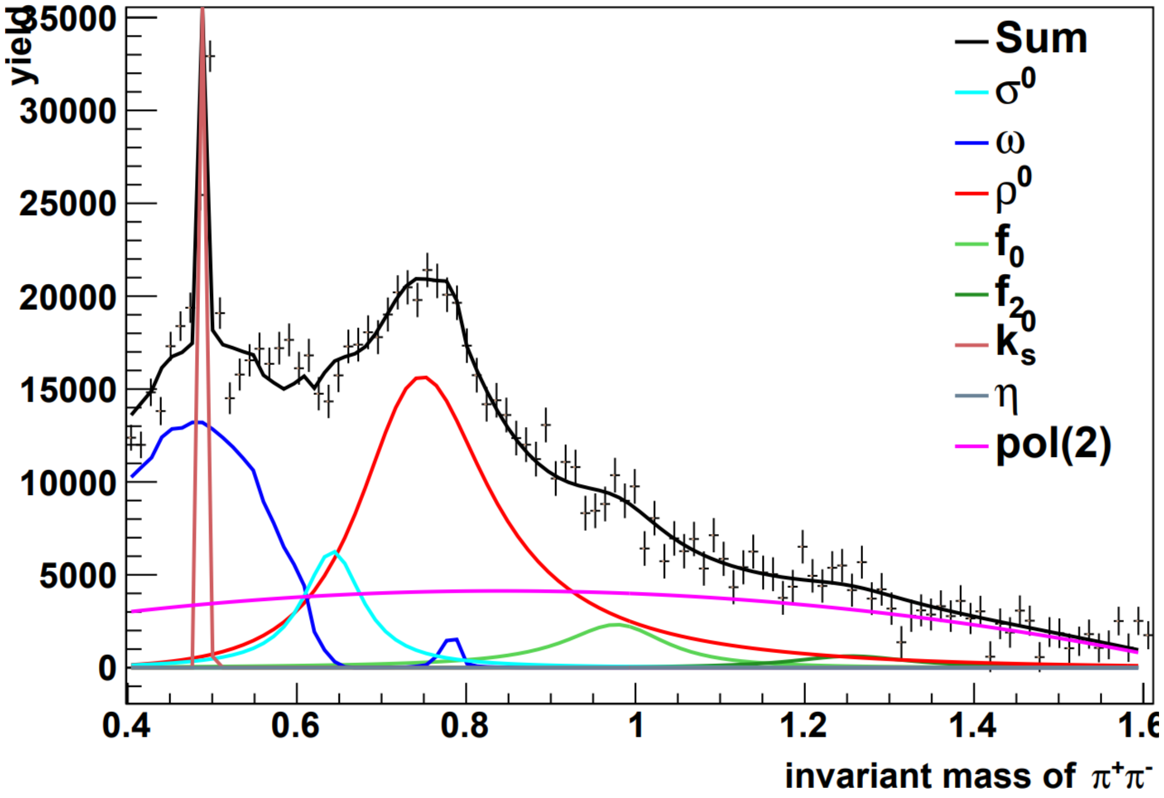
k_s^0: Gaussian function with mass and width as free parameters.

ω, η: with function shapes obtained from hijing simulation.

f_2 : mass 1.275 width 0.185

Then for each $\cos\theta^*$ bin:

On the basis of the overall fitting, we fix the mass and width of σ^0 and k_s^0, and fix the width of ρ^0 and f_0.

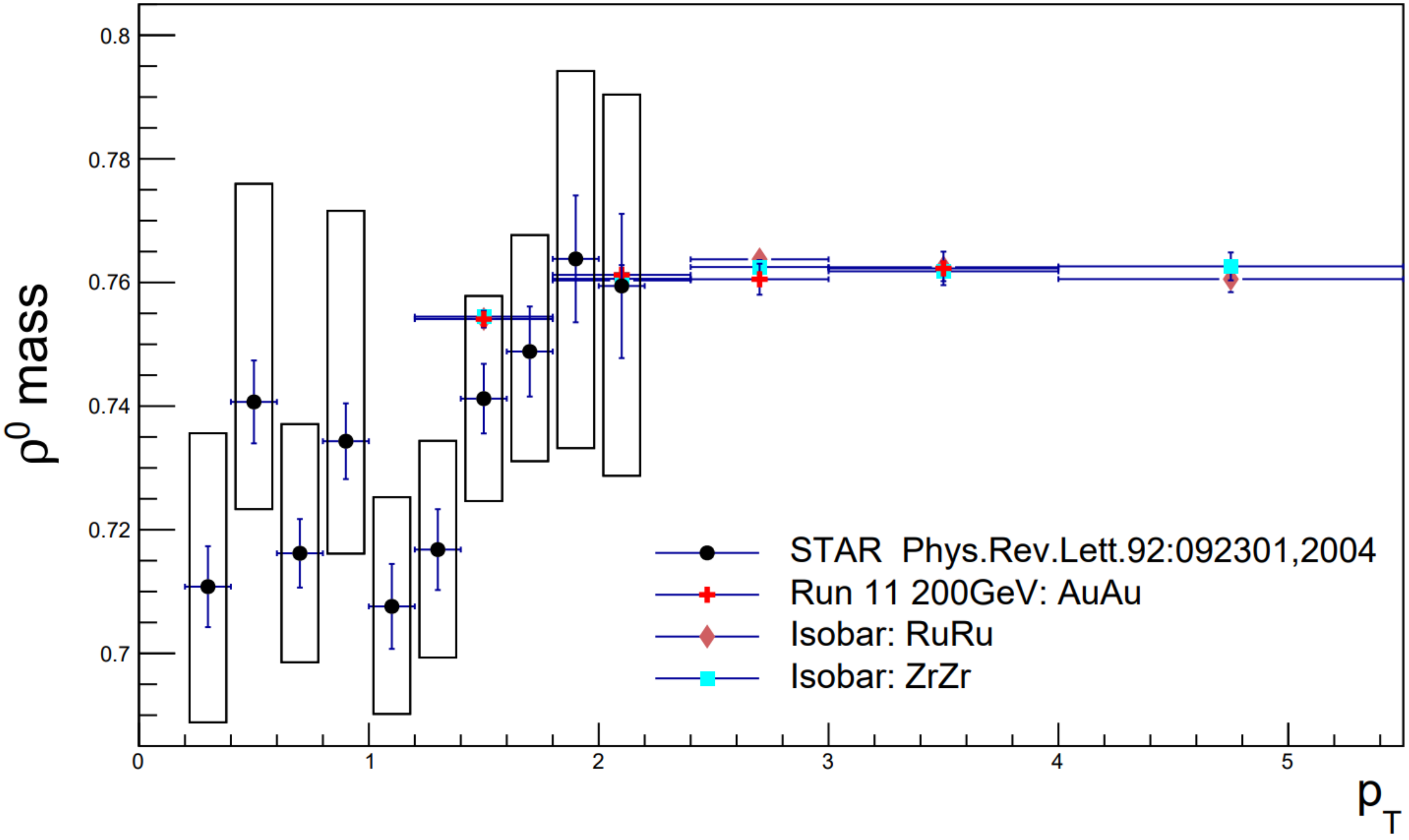


Through cocktail fitting, the yield of ρ^0 can be obtained.

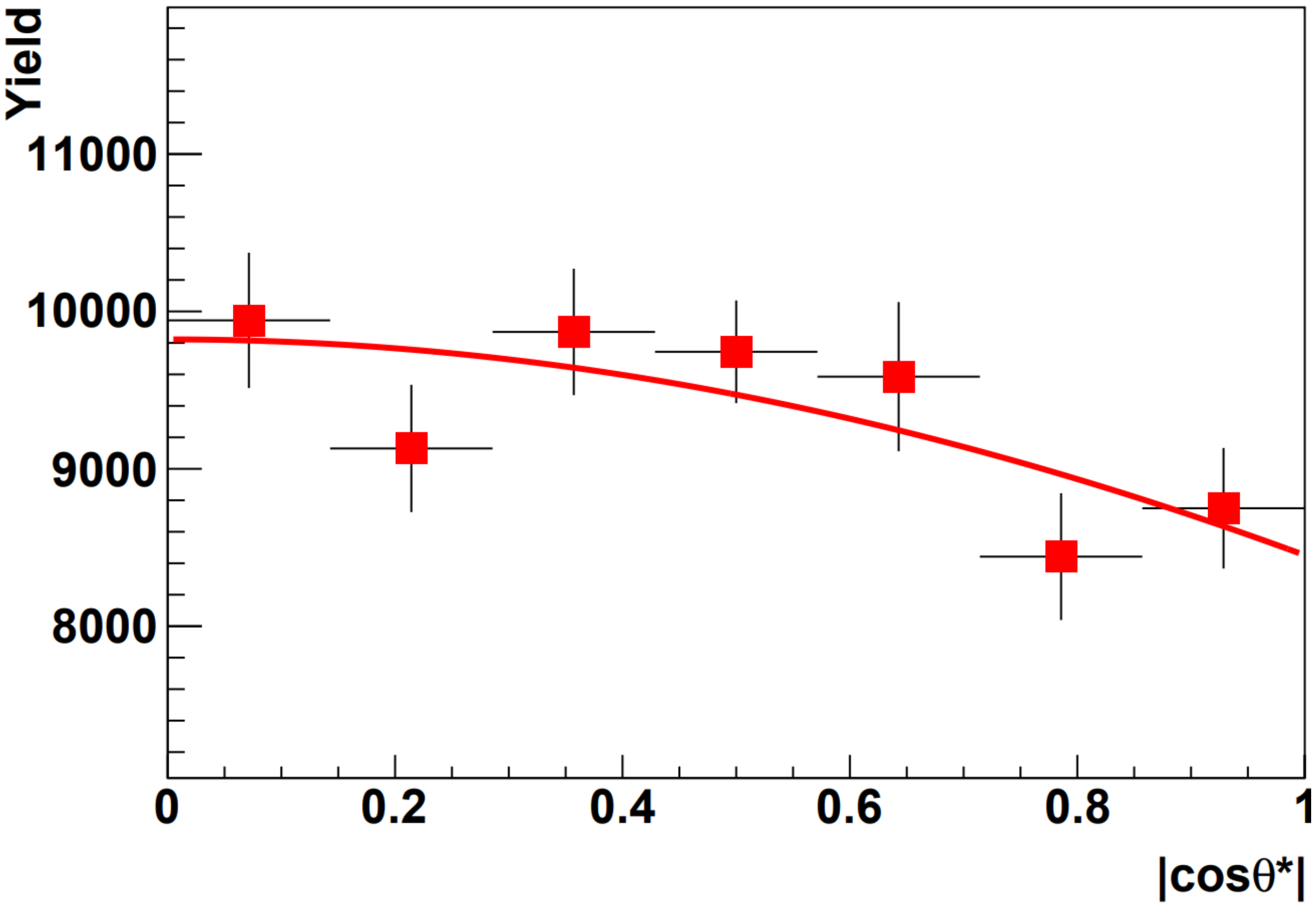
J. Adams, et al. (STAR Collaboration), Phys. Rev. Lett. 92, 092301 (2004).

Justifications for the choice of such setting are given in backup slides.

Here we compare the mass of the ρ^0 meson obtained by fitting with the previous results of STAR and find that they are consistent.



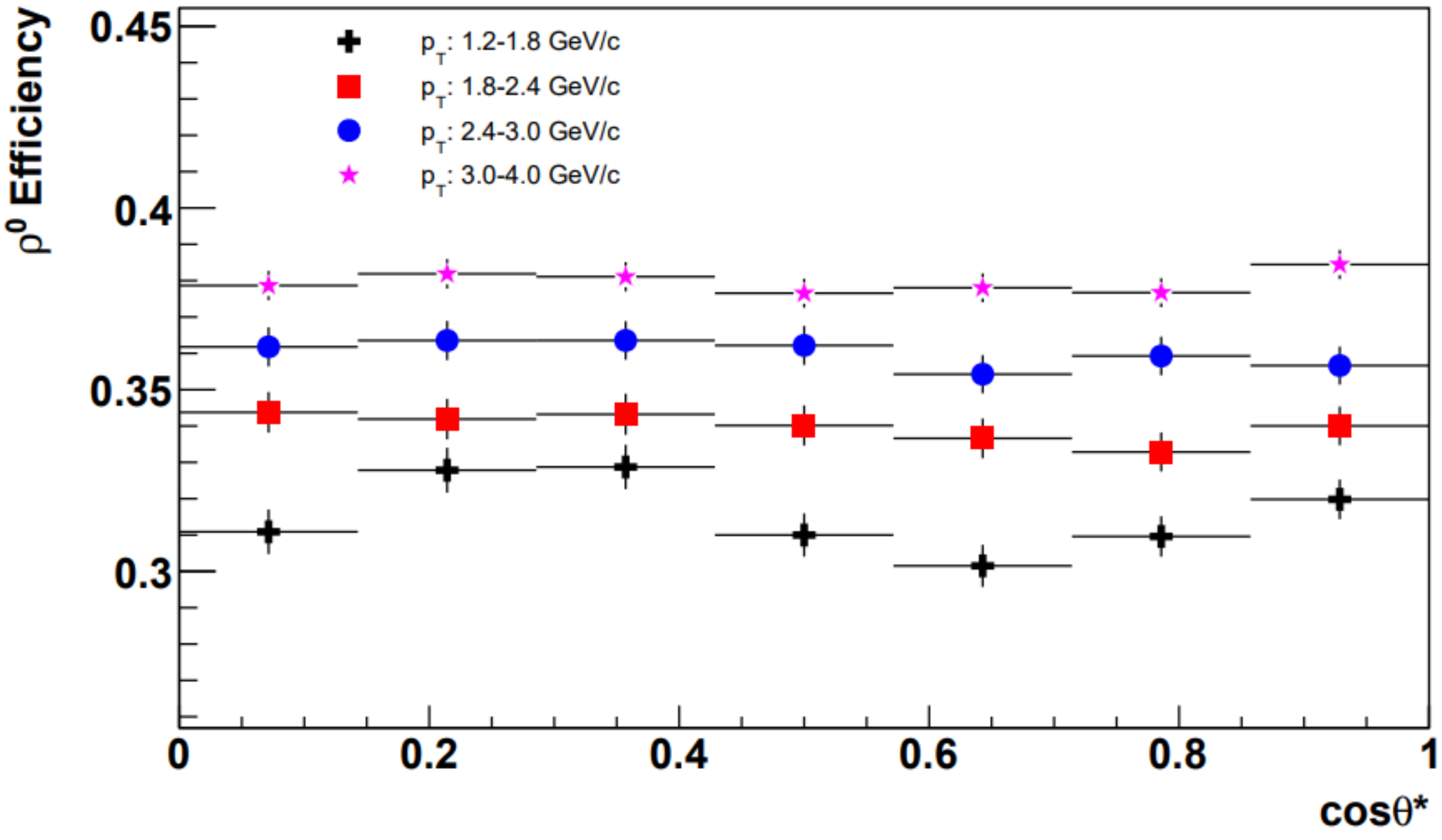
The yield of ρ^0 meson is obtained by cocktail fitting and the distribution has been corrected for efficiency.



Run 11
p_T : 2.4-3.0 GeV/c
centrality : 40-60%

ρ^0 efficiency of Run 11

Then according to the TPC and TOF efficiency of pion's, the distribution of ρ^0 efficiency with respect to $\cos\theta^*$ in each p_T bin is obtained.



Acceptance and EP resolution

Corrections for finite EP resolution, efficiency, and acceptance

i) **ϕ-meson ρ_{00} analysis** Detector efficiency within the acceptance is corrected using the STAR Monte Carlo embedding method [8–10]. To account for finite EP resolution and finite acceptance in pseudo-rapidity (η) [11], the observed $\cos\theta^*$ distribution is not fitted using Eq. 1 in the main text, but is instead described by the correction procedure derived in Ref. [7] wherein the data are fitted using

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

where

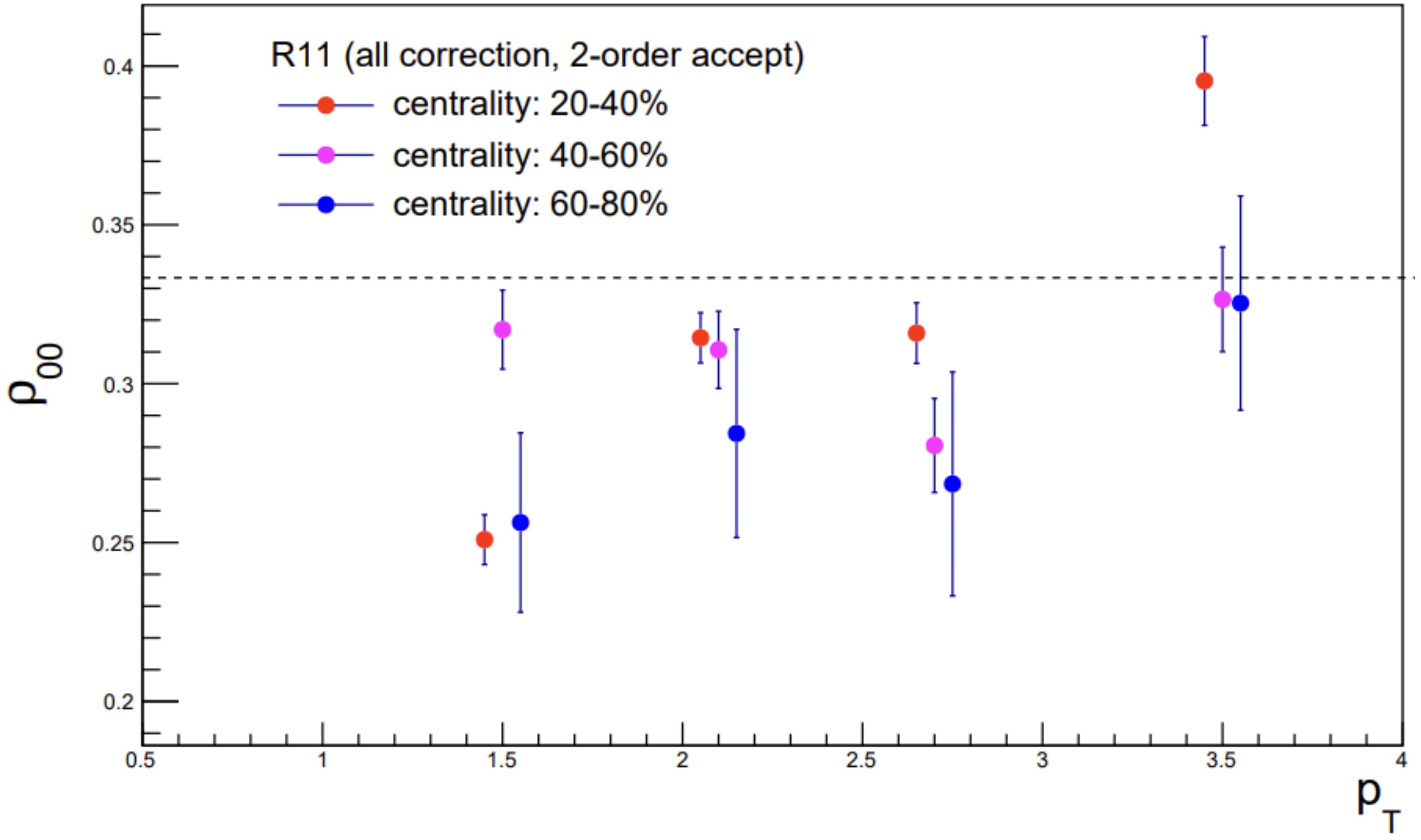
$$A' = \frac{A(1+3R)}{4+A(1-R)}, \quad B' = \frac{A(1-R)}{4+A(1-R)}, \tag{2}$$

and

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

- We follow the same procedure used in φ global spin alignment.

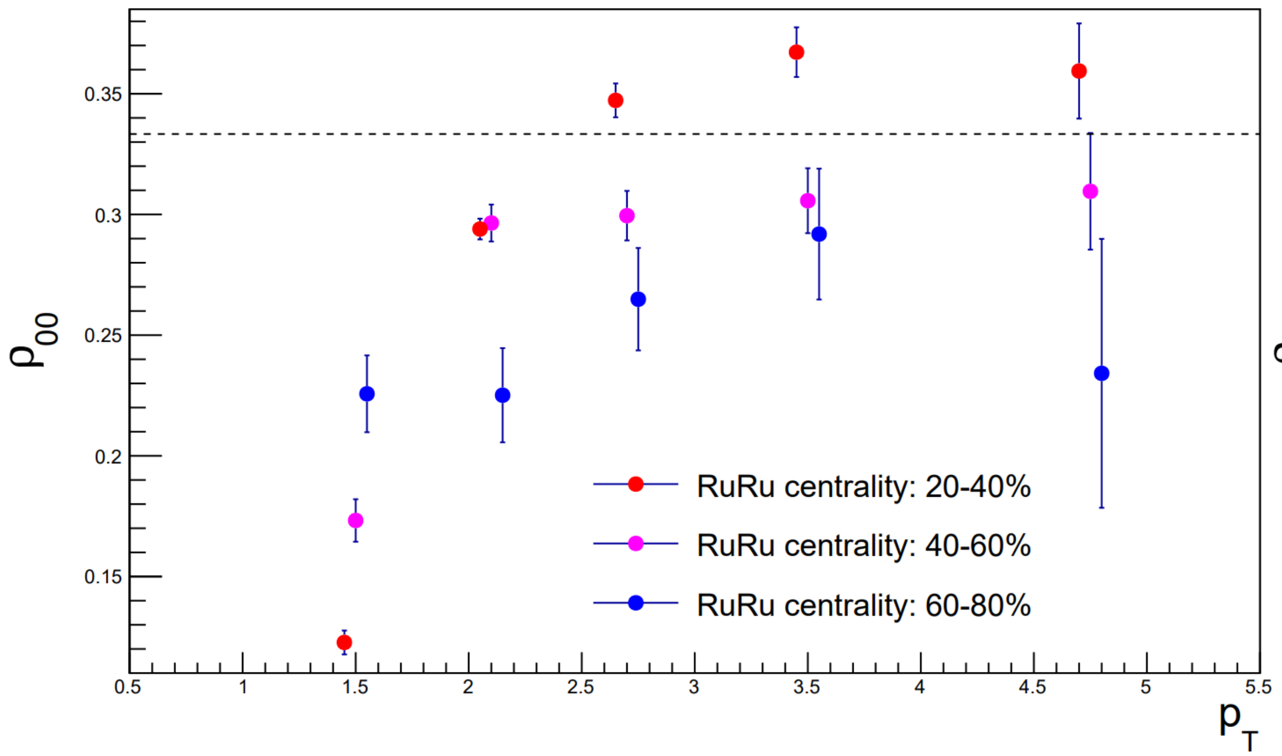
ρ_{00} as a function of p_T of Run 11 AuAu



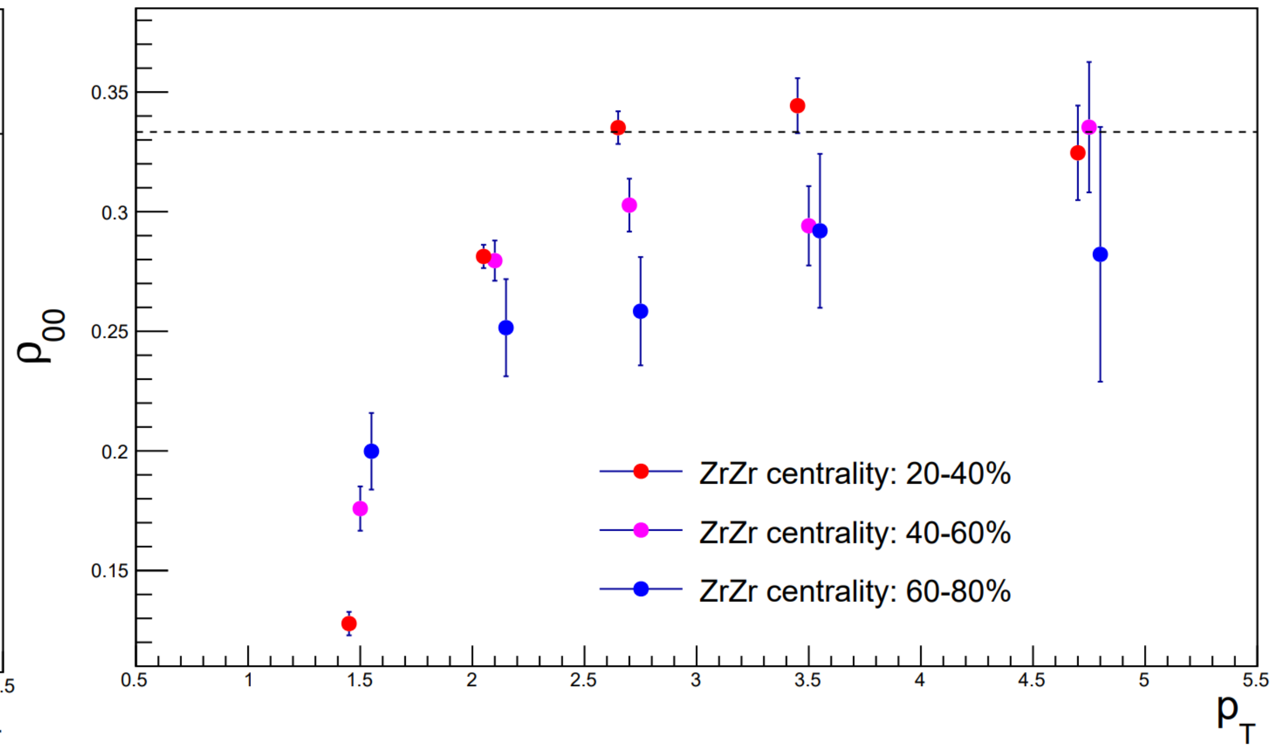
ρ_{00} as a function of p_T of isobar

Since there is no embedding data of isobar at present, there is no efficiency correction here, and we will do the efficiency correction when the embedding data is available.

RuRu



ZrZr



Systematic to be studied

- $n\sigma_{\pi}$: 1.0, 1.5, 2.0
- dca : 1.5, 2.0, 2.5
- Normalization factor (small medium large)
- Residual background subtraction
- Fitting procedure (The fixed value of the width of ρ^0 and f_0 is obtained by overall fitting, ρ^0 width fixed in 0.16 or PDG value , f_0 width fixed in 0.75 or 0.1, ρ^0 mass fixed from overall fitting)
- Count and integration range: 1.5*Γ, 1.0*Γ, 0.5*Γ
- Yield extraction (bin counting, integration)

Bin counting are used in all parts(as in the analysis of ϕ).

Summary and to-do-list

- We have studied ρ^0 meson global spin alignment with data of 2011 and isobar. Our preliminary study indicates that ρ_{00} is smaller than 1/3.
- A smaller than 1/3 ρ_{00} means negative contribution to most CME observables, that is, in opposite direction to most flow contributions. This means that our current CME fraction at 200 GeV is under stated.
- Good news for plain CME analyses, but complicates CME analyses that rely on ratios (Ru/Zr, PP/SP).

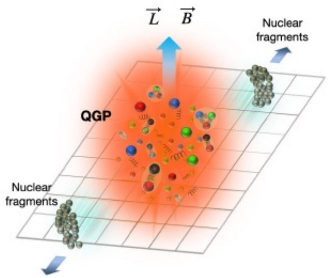
- We will work on systematic uncertainty.

J/ψ Isobar Analysis

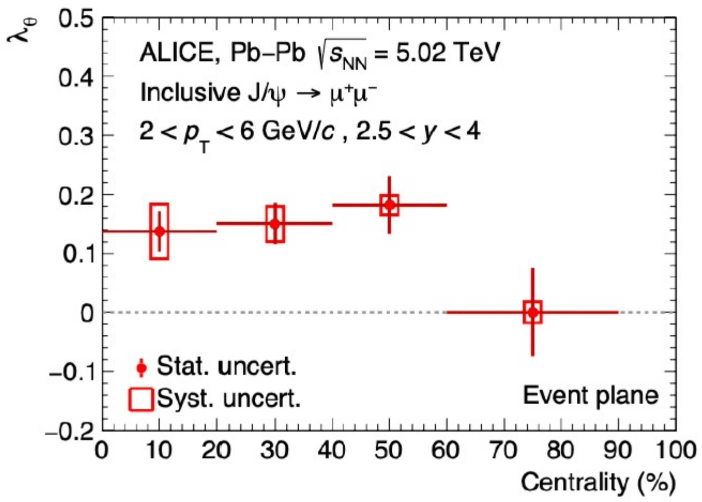
Dandan Shen (shendandan@mail.sdu.edu.cn, Shandong University),

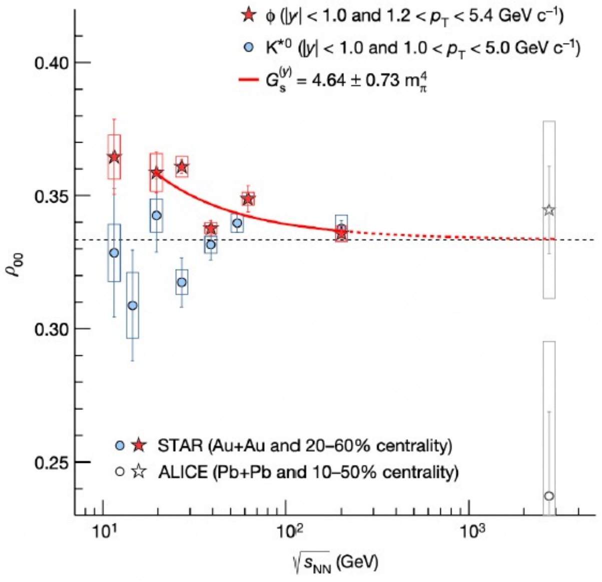
For more detail see slides 84-92

Motivation



- Large orbital angular momentum
- Strong magnetic field





φ meson spin alignment signals
Clear energy dependence
Mainly from coalescence of two s quarks

J/ψ at LHC energy:

- Significant coalescence contribution at low-pT range
- Spin alignment signal up to 60% Centrality
  (Spin-orbital coupling or strong magnetic field? Or et. Al)

What is the case at RHIC energy?

- Strong coupling between J/ψ and QGP
- Limited v_2

Data Set and cuts

- **Data:** Isobar ($^{96}_{40}Zr + ^{96}_{40}Zr$, $^{96}_{44}Ru + ^{96}_{44}Ru$) ≈ 3.5Billions
- **Trigger:**

  VPDMB-30 (600001, 600011, 600021 and 600031)

- **Vertex selection**:

  $|V_x| \geq 10^{-5} cm$, $|V_y| \geq 10^{-5} cm$, $|V_z| \geq 10^{-5} cm$

  $|V_r| < 2\ cm, -35 < V_z < 25\ cm, |V_{TPCz} - V_{VPDz}| < 3\ cm$

- **Track quality cuts**

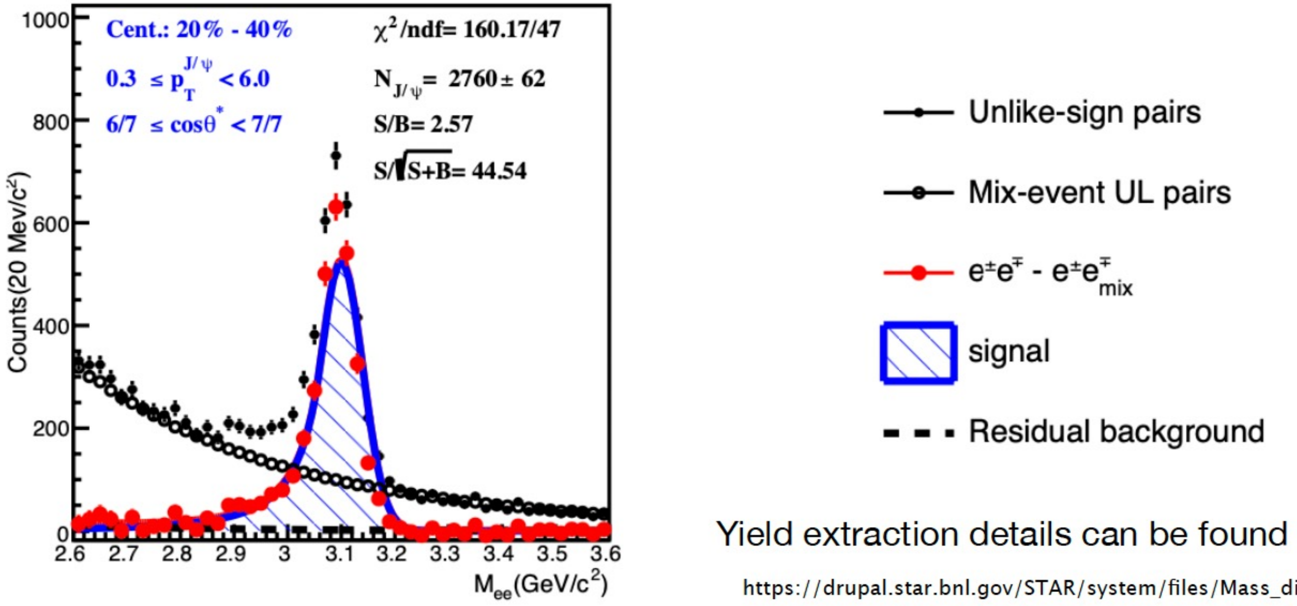
TPC: $0.2 < p_T < 30\ GeV/c$ $|\eta| < 1.0$

$nHitsFit \geq 20$ $\frac{nHitsFit}{nHitsPoss} \geq 0.52$

$nHitsDedx \geq 15$ $dca < 1.0\ cm$

- **Electron identification:**
  - $p_T \leq 1$
    - p<=0.8: 3×p-3.15< nσ_E <2. |1-1/β| < 0.025
    - P>0.8: -0.75 < nσ_E < 2. |1-1/β| < 0.025
  - $p_T > 1$
    - Only TOF: -0.75 < nσ_E < 2. |1-1/β| < 0.025
    - Only BEMC: -1.< nσ_E <2. .5< E0/p <1.5
    - TOF & BEMC: -1.5 < nσ_E < 2 . |1-1/β| < 0.025 0.5< E_0/p <1.5

Yield extraction



Yield extraction details can be found in:

https://drupal.star.bnl.gov/STAR/system/files/Mass_dist_PT_Buff2.pdf

https://drupal.star.bnl.gov/STAR/system/files/Mass_dist_Cent_Buff2.pdf

Background estimation:

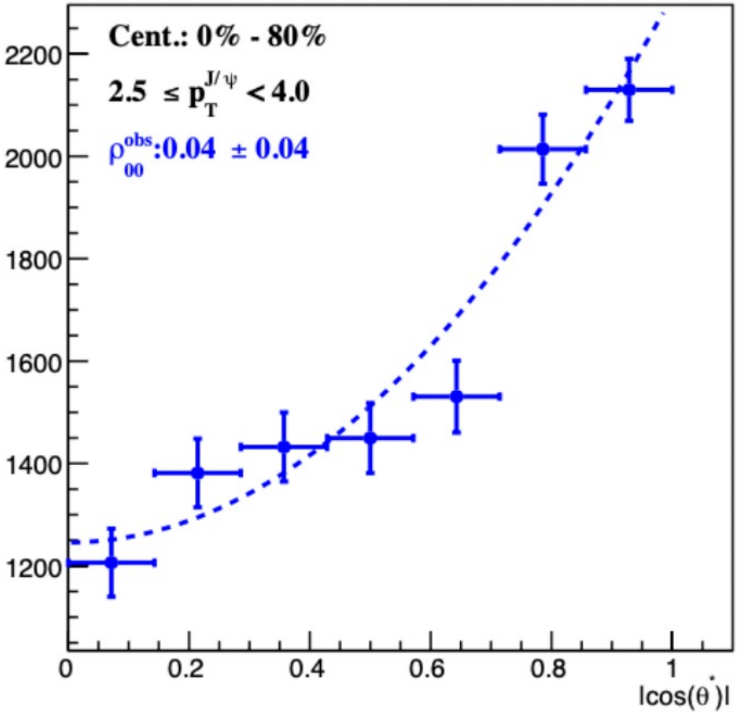
Combinational: Mix-event UL, normalization range (3.3 - 3.6 GeV/c2)

Residual : Exp. function, fitting range [2.6, 2.7] && [3.3, 3.6]

J/ψ raw yield :

Bin counting method: [3.0, 3.2] GeV/c2

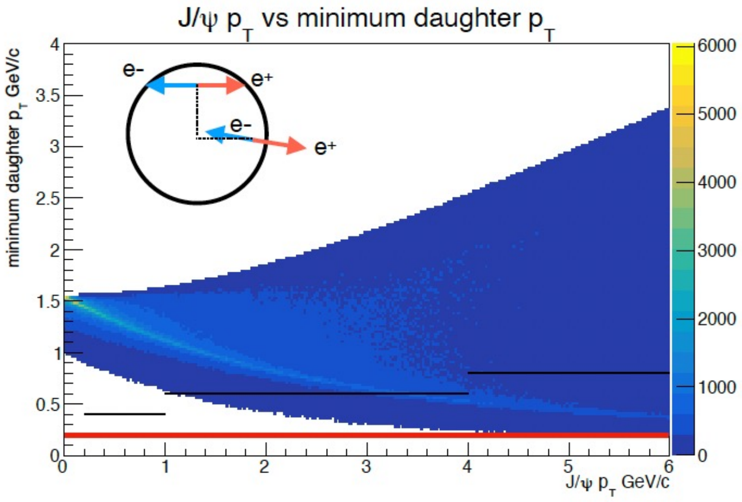
Yield vs. cos(θ*)



Fitting function:

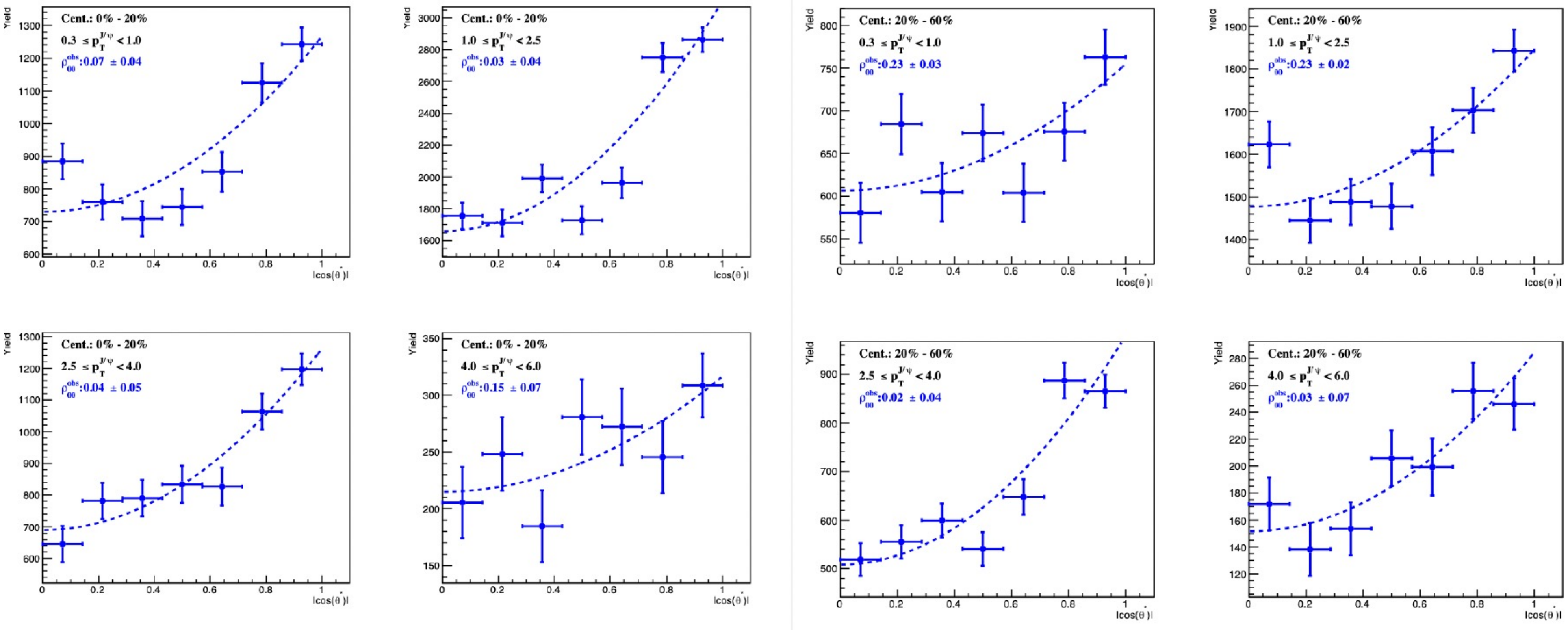
$$\frac{dN}{dcos\theta^*} = C \times [(1+\rho_{00}^{obs}) + (1-3\rho_{00}^{obs})cos^2\theta^*]$$

Without efficiency and acceptance correction



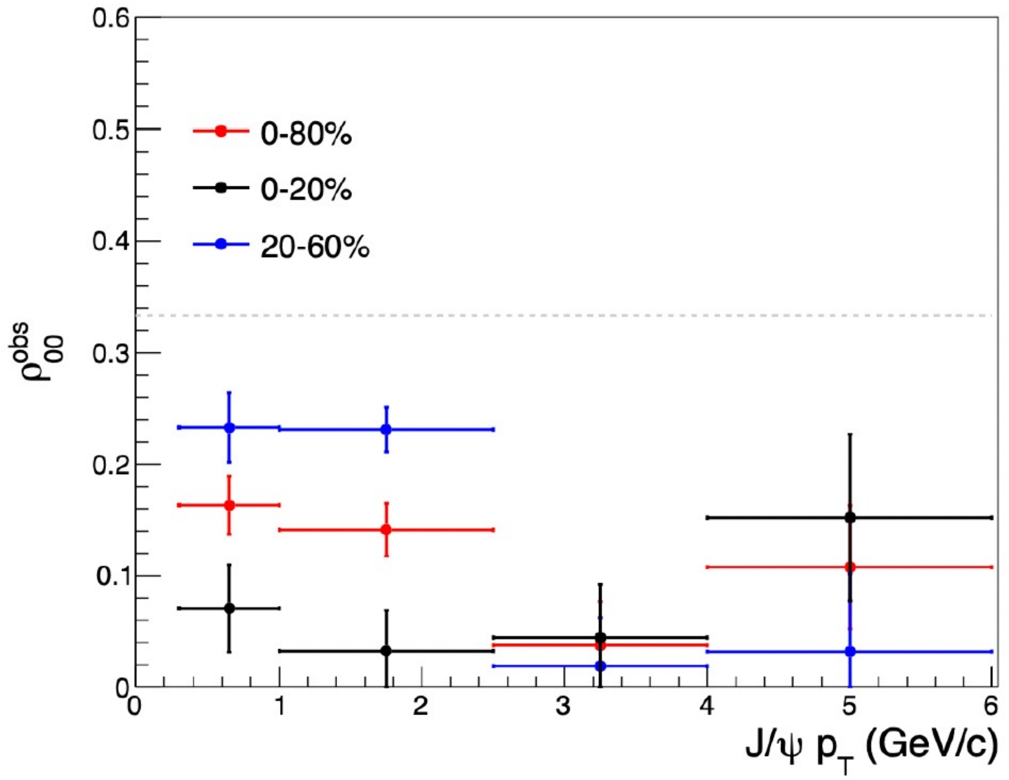
Very limited daughter p_T unbalance effect due to large mass of J/ψ up to 6 GeV/c

Yield in different pT range



Significant spin alignment signal in both 0-20% and 20-60% centrality .

ρ_{00}^{obs} vs pT

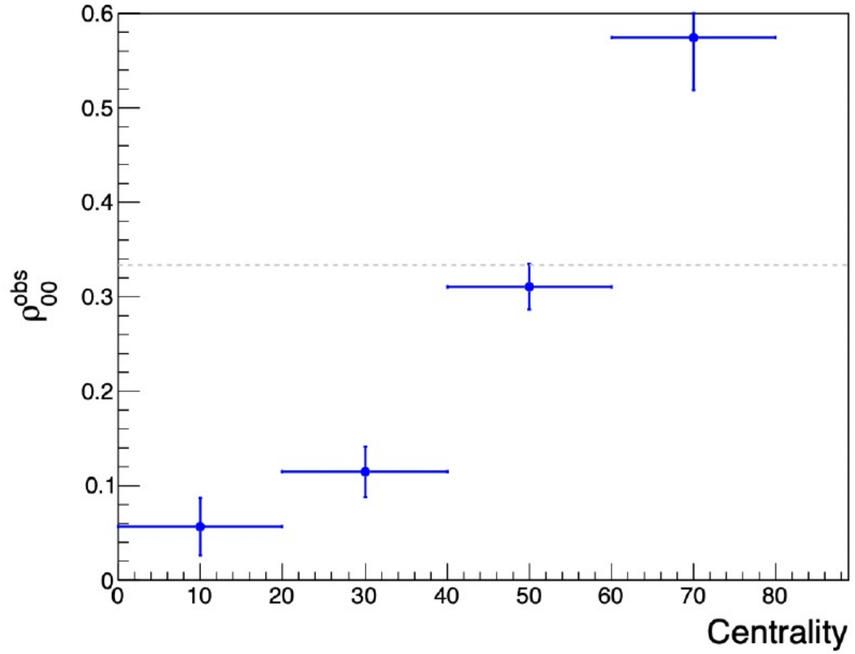


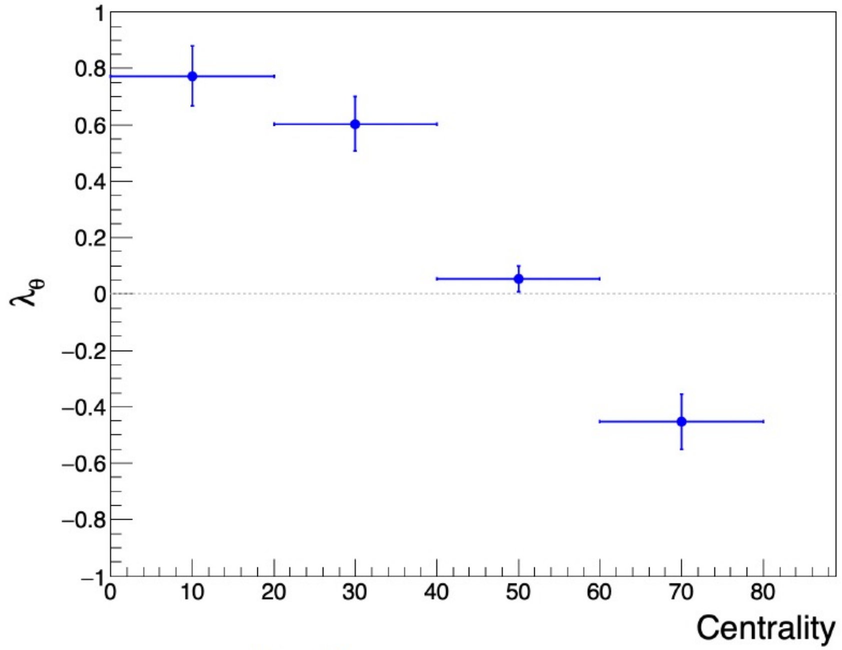
$$\rho_{00} - \frac{1}{3} = \frac{4}{1+3R}(\rho_{00}^{obs} - \frac{1}{3})$$

PRC **98**, 044907 (2018)

Significant spin alignment signal with no pT dependence?

ρ_{00}^{obs} vs Centrality

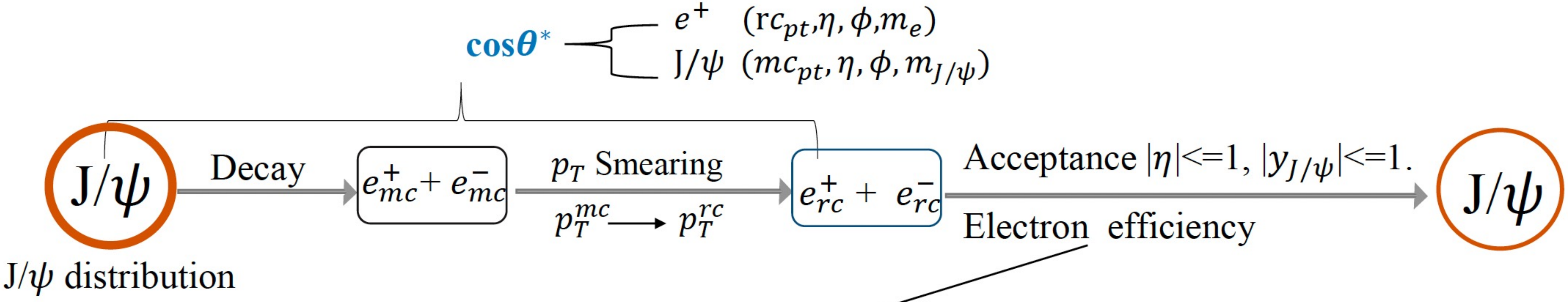




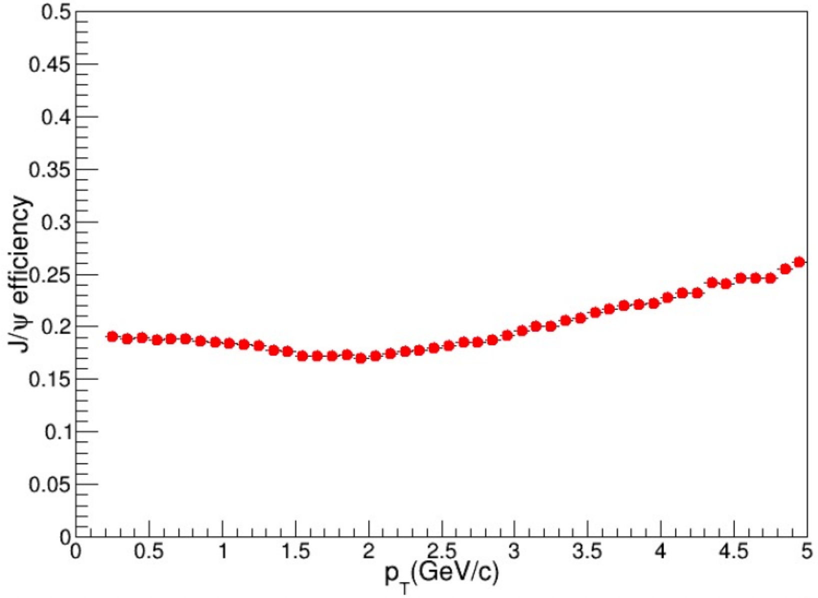
$$\lambda_\theta = \frac{1 - 3\rho_{00}}{1 + \rho_{00}}$$

Signal flip over centrality?
The mean pT is different in different centrality

J/ψ Efficiency



J/ψ efficiency: $\epsilon_{J/\psi} = \epsilon_{e^+} \times \epsilon_{e^-}$



Summary and next to do

- **Summary**

- Very clear spin alignment signals but more check is needed

- Use the EPD event plane and ZDC event plane for non-flow correlations check

- We obtain single electron efficiency.

- **Next to do**

  We will do systematic uncertainties estimation.

Roadmap to QM2023 for all analyses

- ϕ BES-II:
  - 19.6 GeV centrality and p_T analyses are near completion, working on rapidity dependence.
  - Raw results for 14.6 GeV presented.
  - Working on corrections for 14.6 GeV and 19.6 GeV.
  - Need official centrality definitions for 7.7 GeV, also embedding.
- ϕ and ω (Isobar):
  - Raw ρ_{00} for ϕ and ω were presented.
  - Studying efficiency and acceptance effects.
- ρ^0 (Au+Au Run 11 + Isobar)
  - Run 11 p_T dependent analysis is in final stages.
  - Waiting for isobar embedding data for efficiency corrections.
  - Systematic uncertainty calculations.
- J/ψ (Isobar)
  - Efficiency and acceptance corrections are determined.
  - Use the EPD and ZDC event planes for non-flow correlations check.
  - Systematic uncertainty calculations.

Backup Slides ρ^0

Global spin alignment of ρ^0 meson

Baoshan Xi

06-26-2023

In collaboration with: Chengsheng Zhou, Yugang Ma, Jinhui Chen, Xu Sun, Aihong Tang

Analysis goals

- System

Run11: AuAu, Isobar: RuRu & ZrZr

- Analysis

Dependence of ρ_{00} on pt and centrality

- Status:

Default value of R11 AuAu data with all correction

Default value of Isobar data with no efficiency correction

- Requirements:

Efficiency of ρ^0 of isobar data

System err of Run11 AuAu and Isobar

- Previous reports on collaboration meeting and fcv meeting

https://drupal.star.bnl.gov/STAR/system/files/2021_03_revisedV01.pdf

https://drupal.star.bnl.gov/STAR/system/files/2022_04_25_0.pdf

https://drupal.star.bnl.gov/STAR/system/files/2022_09_14.pdf

https://drupal.star.bnl.gov/STAR/system/files/fcv_2023_02_08.pdf

https://drupal.star.bnl.gov/STAR/system/files/collaboration_2023_03_02.pdf

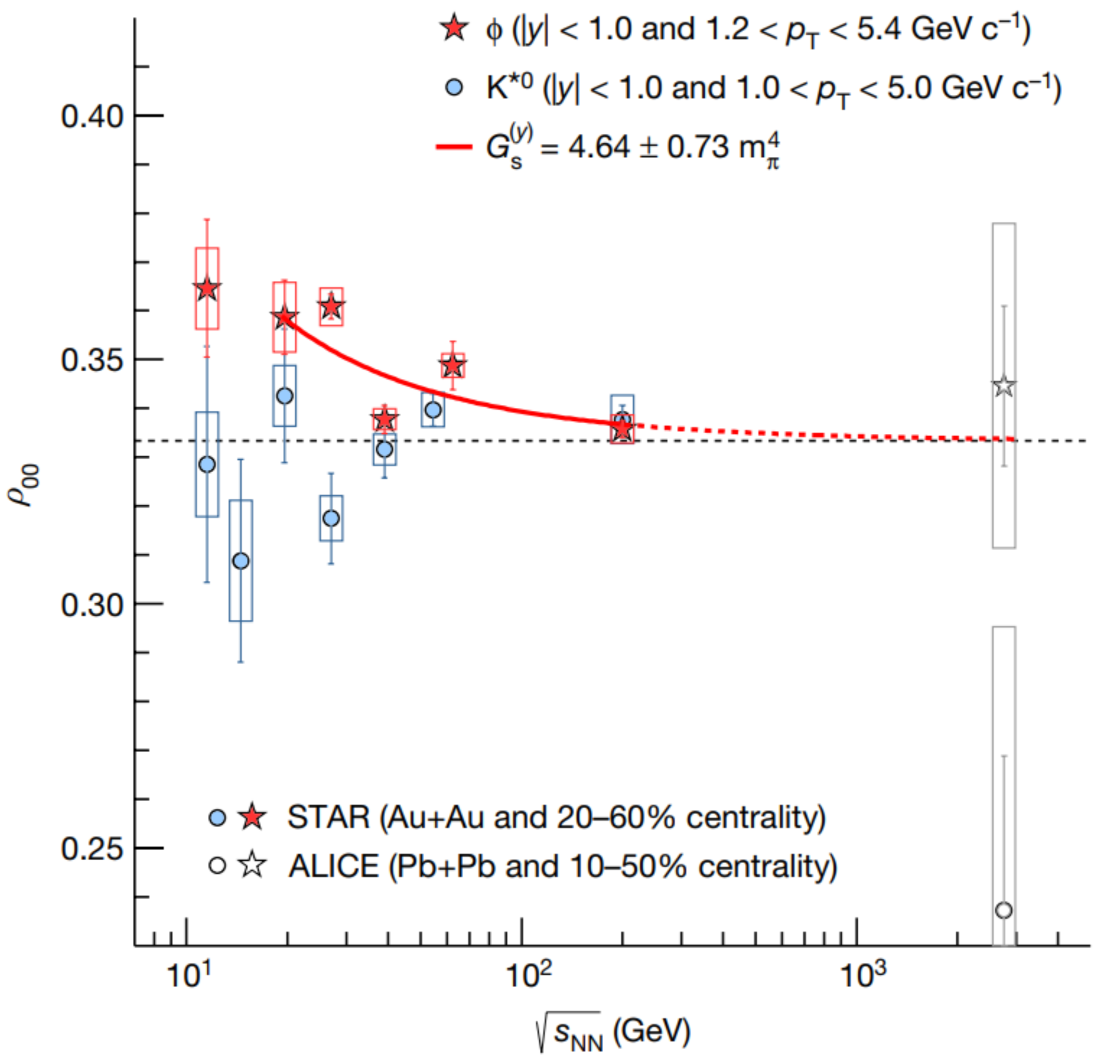
- Roadmap to QM:

We don't have data production, centrality, and special embedding requests.

After all corrections, ρ_{00} and its system error will be expected to be finished before QM2023.

We reported preliminary results for 2011 data and isobar. Since then, we have improved our cocktail fitting procedure to better constrain the fitting in (mid)central collisions. Here we report the final ρ_{00} value after all corrections of 2011 data, and results with no efficiency correction of isobar data.

Motivation



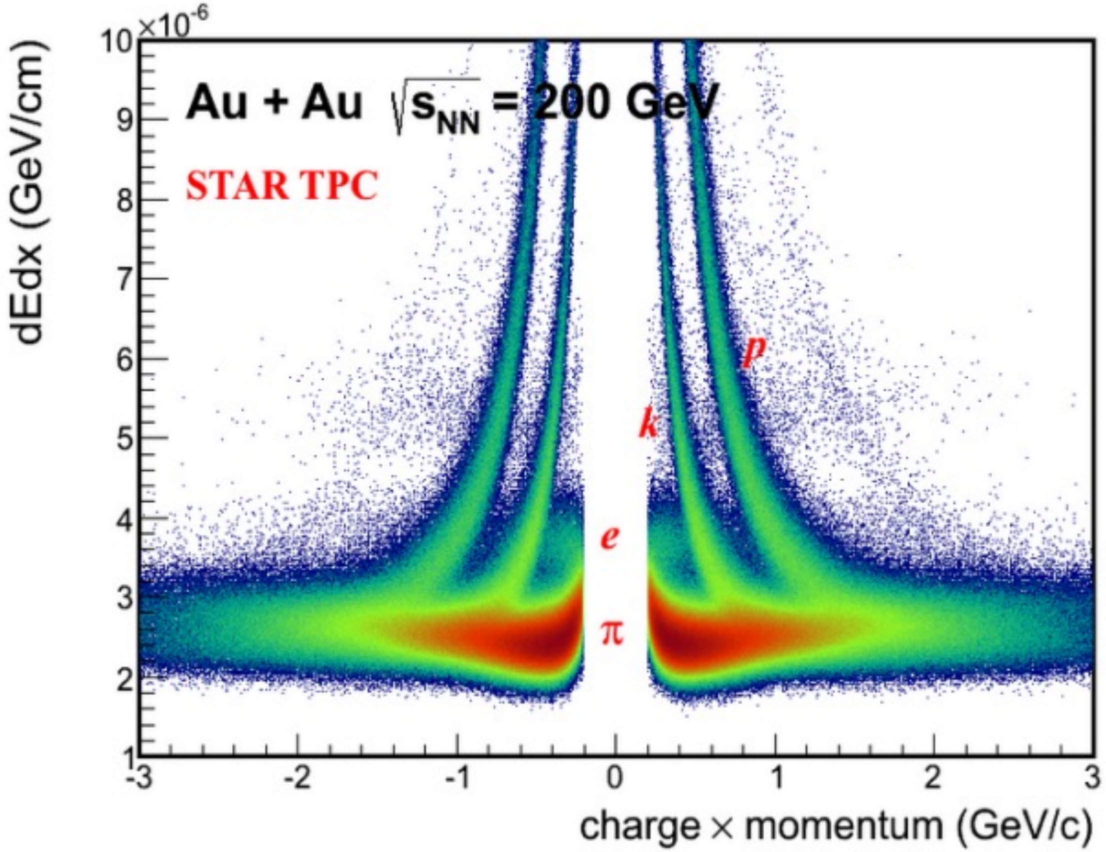
Vector mesons may possess global spin alignment, which can be probed by the study of daughter's angle distribution w.r.t. to the quantization axis in parent's rest frames.

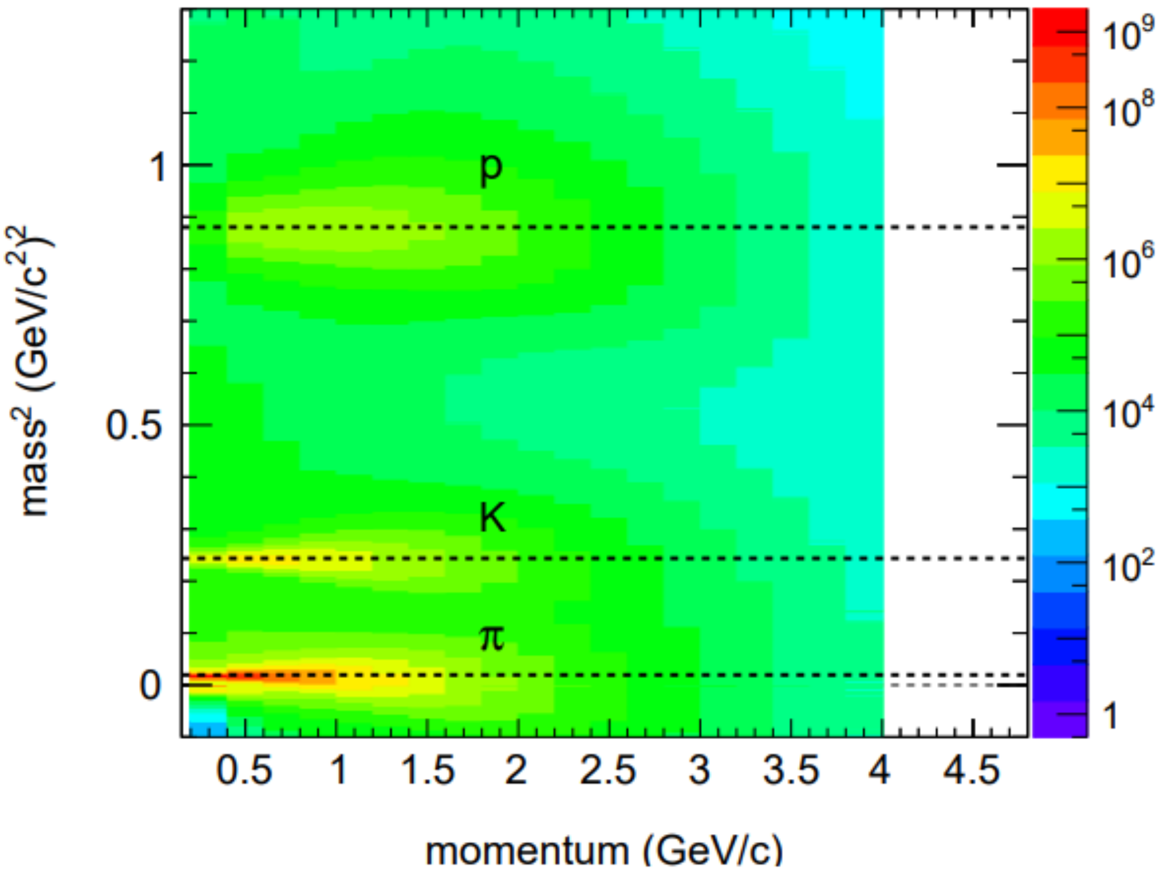
Z. T. Liang and X. N. Wang, Phys. Rev. Lett., 94: 102301(2005).
Erratum: [Phys. Rev. Lett., 96: 039901(E) (2006)] 37 38
Z. T. Liang and X. N. Wang, Phys. Lett. B, 629: 20 (2005) 39
Z. T. Liang, J. Phys. G, 34: S323 (2007)
B. Betz, M. Gyulassy, and G. Torrieri, Phys. Rev. C, 76: 044901 (2007) 40
J. H. Gao, S. W. Chen, W. T. Deng et al., Phys. Rev. C, 77: 044902 (2008) 41
F. Becattini, L. P. Csernai, and D. J. Wang, Phys. Rev. C, 88: no. 3, 034905(2013).
Erratum: [Phys. Rev. C, 93: no. 6, 069901(E) (2016)]

Global spin alignment has been measured by STAR, they show supporting evidence of the influence of strong force field, the paper has been published in Nature.

Nature **614**, 244 (2023)

Particle identification





Second order event plane

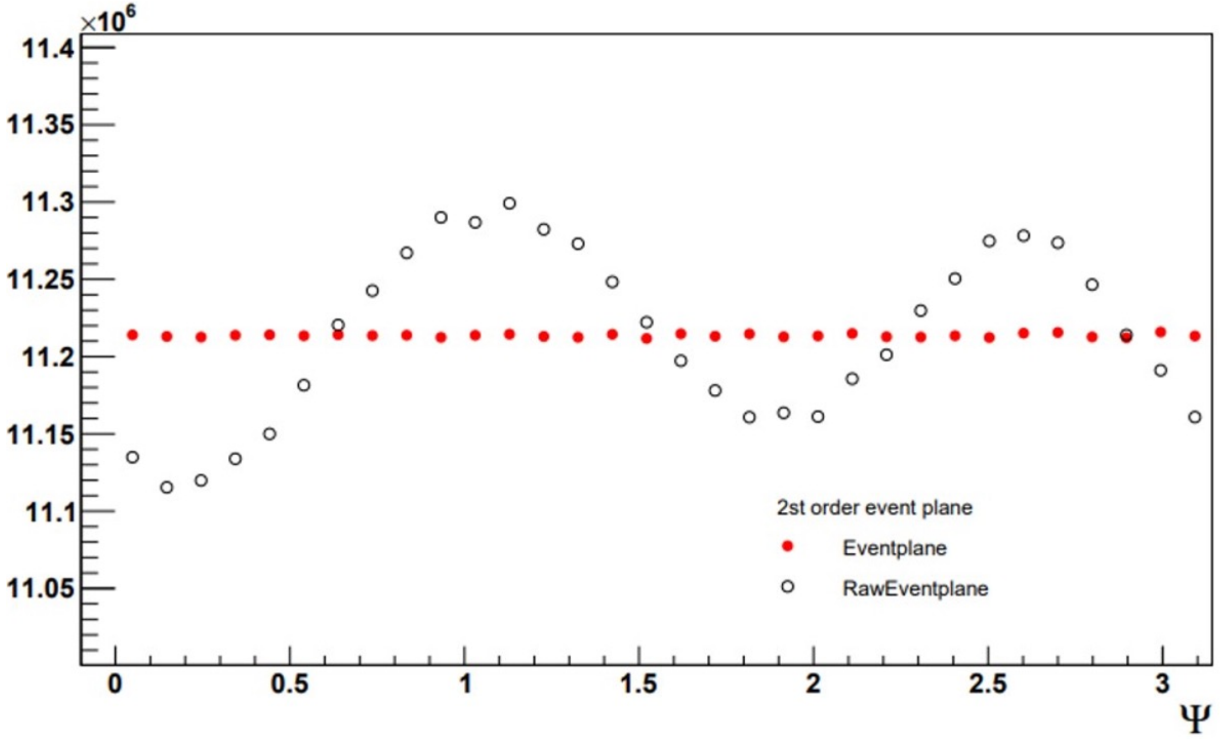
The second event plane is obtained from TPC (for 200GeV data) and flattened by recentering and shifting (performed every 10 runs).

After the recenter corrected, we get the recenter factors:

$$Q_x = \sum W \cdot p_T \cdot \cos 2\phi \qquad Q_y = \sum W \cdot p_T \cdot \sin 2\phi$$

Then we do the shift

$$2\Psi_2 = 2\Psi_2' + \sum_{i=1}^{n} \frac{2}{i} \left[-\left\langle \sin(i2\Psi_2') \right\rangle \cos(i2\Psi_2') + \left\langle \cos(i2\Psi_2') \right\rangle \sin(i2\Psi_2') \right]$$



Spin alignment

Spin alignment can be determined from the angular distribution of the decay products:

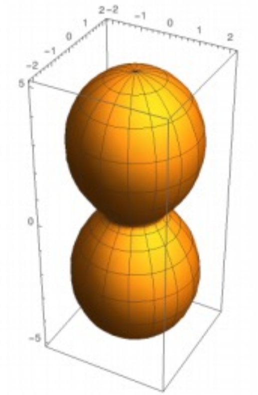
$$\frac{dN}{d(\cos\theta^*)} = N_0 \times \left[(1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta^*\right]$$

where N_0 is the normalization and θ^* is the angle between the polarization direction L and the momentum direction of a daughter particle in the rest frame of the parent vector meson.

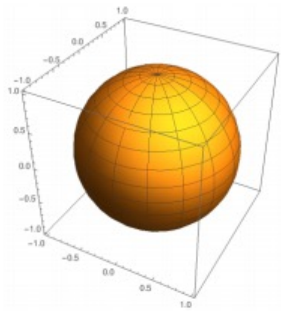
A deviation of ρ_{00} from 1/3 signals net spin alignment.

Phys.Lett.B629,20-26(2005)

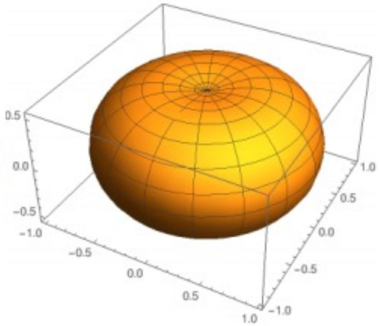
$\rho_{00}>1/3$:



$\rho_{00}=1/3$:



$\rho_{00}<1/3$:



The constrain of parameters:

ρ^0 : mass: 0.7-0.8 [1] width: free parameter

f_0 : mass: 0.98[2] width: free parameter

σ^0: mass: 0.4 - 0.8[2] width: 0.1 - 0.8[2]

k_s^0: Gaussian function with mass and width as free parameters [4].

f_2 : mass 1.275 width 0.185 [3]

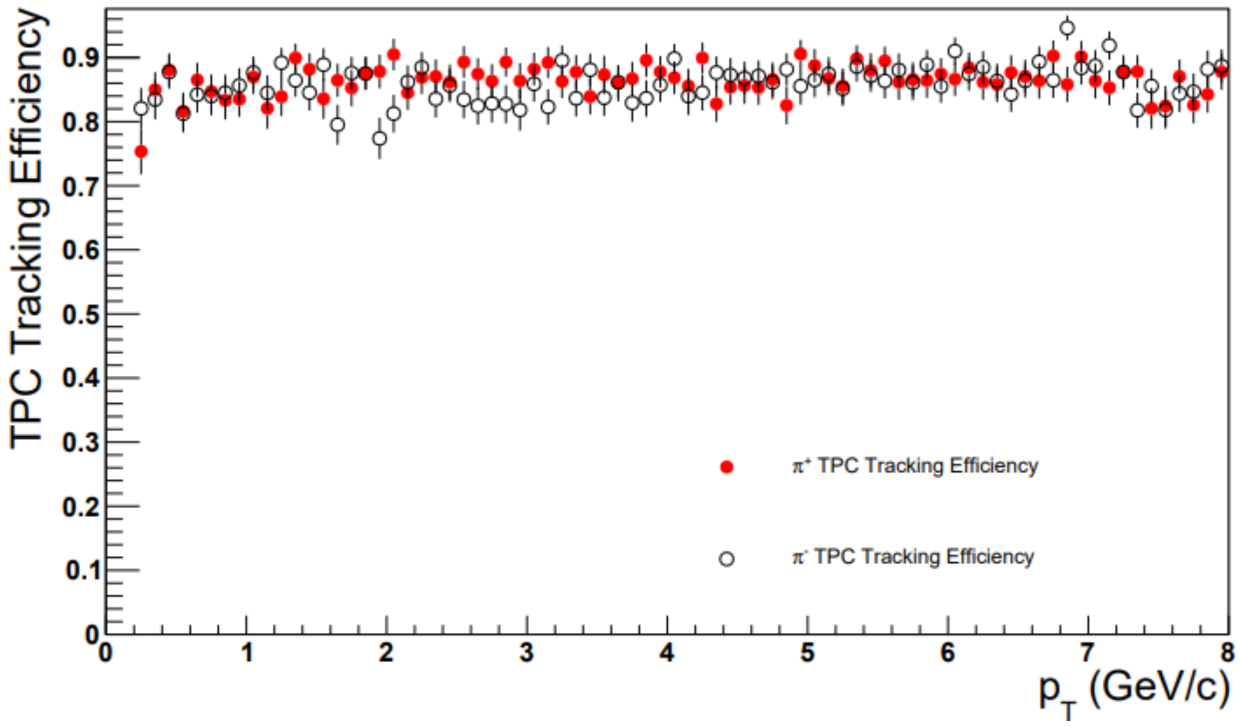
ω and η : Its function shape comes from Hijing event generator [3].

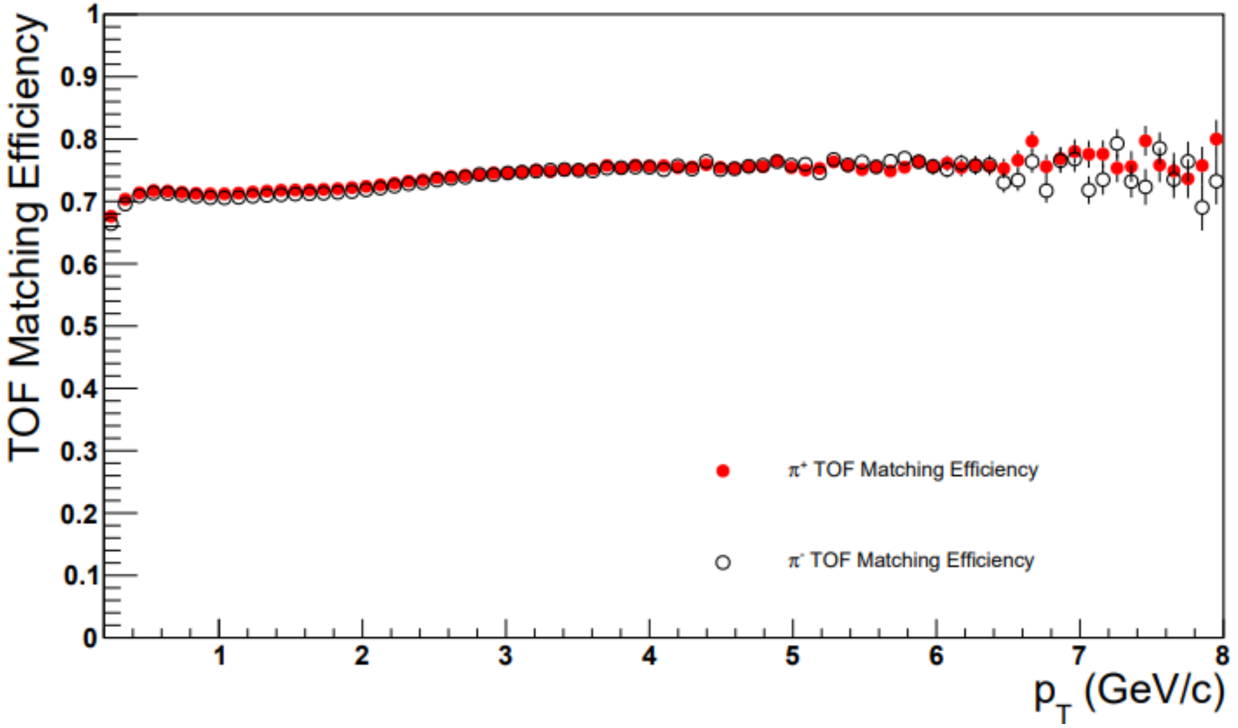
The results of all cacktail fitting of ρ^0 are located at:
https://drupal.star.bnl.gov/STAR/system/files/cacktail_fitting_rho_20230207.pdf

[1] J. Adams, et al. (STAR Collaboration), Phys. Rev. Lett. 92, 092301 (2004).
[2] https://pdg.lbl.gov/2020/listings/rpp2020-list-rho-770.pdf
[3] Xiangli Cui, Thesis proceedings.
[4] B. I. Abelev, et al. (STAR Collaboration), Phys. Rev. C 78, 044906 (2008).

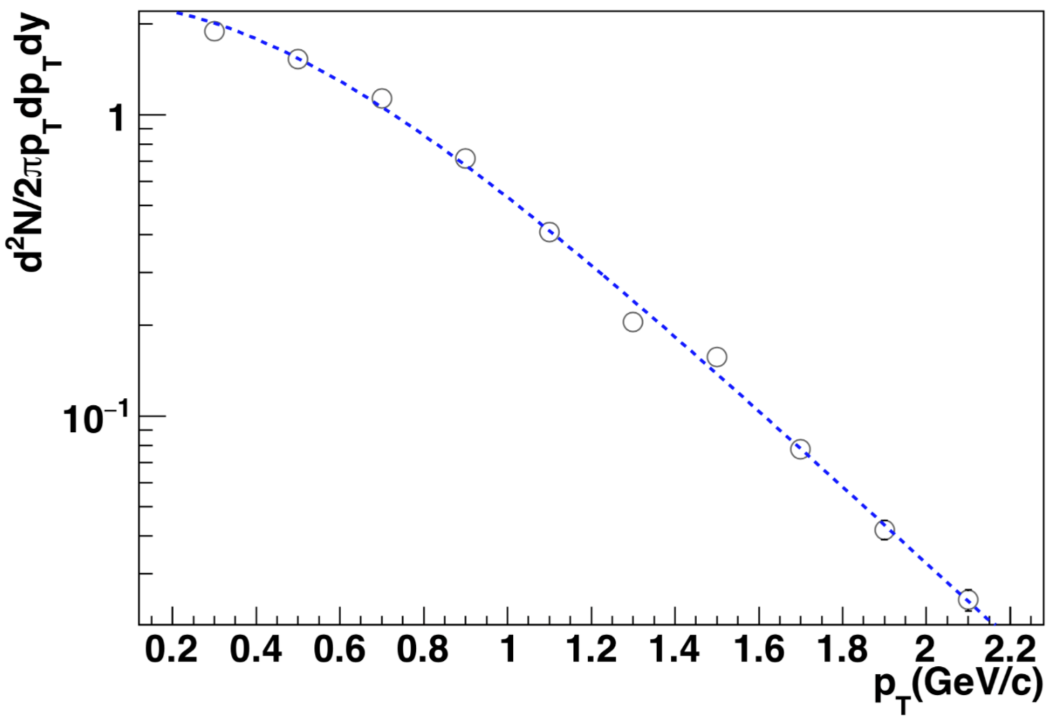
Pion TPC and TOF efficiency of Run 11 (p_T > 0.2 GeV/c)

We obtain the TPC tracking efficiency of pion from embedding data, and TOF efficiency is obtained from TPC track to TOF hit matching based on real data.

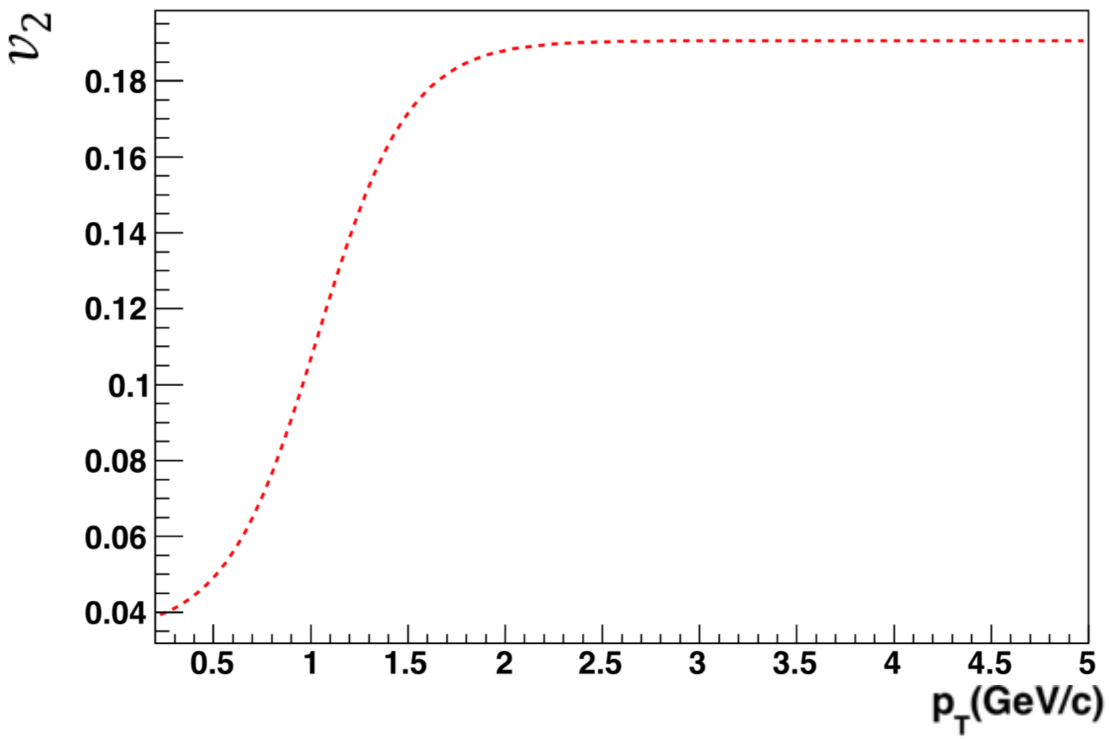




The spectrum and v_2 of ρ^0 used as a input in the Pythia6.



J. Adams, et al. (STAR Collaboration), Phys. Rev. Lett. 92, 092301 (2004).



Prabhat R. Pujahari (for the STAR collaboration), Nucl. Phys. A 862, 297 (2011).

Backup Slides
leptonic ω and φ

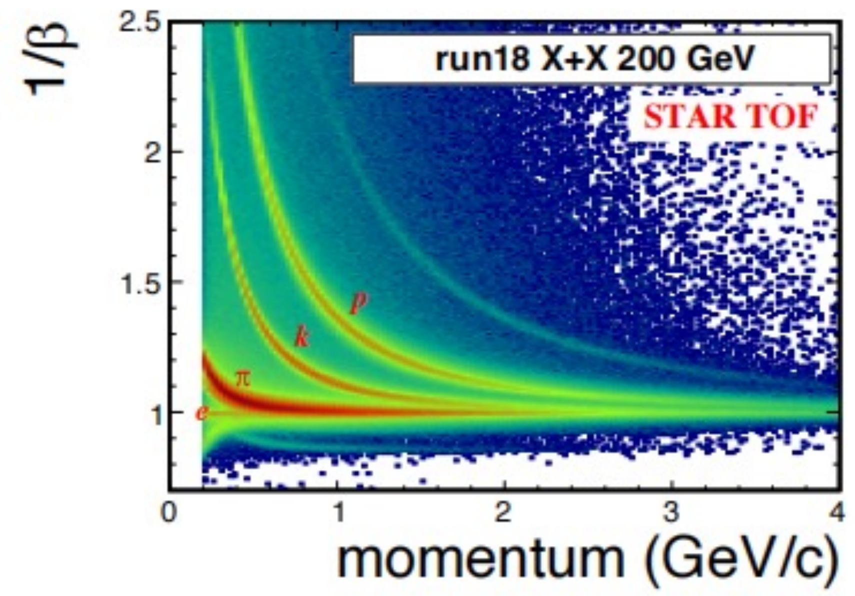
Analysis methods

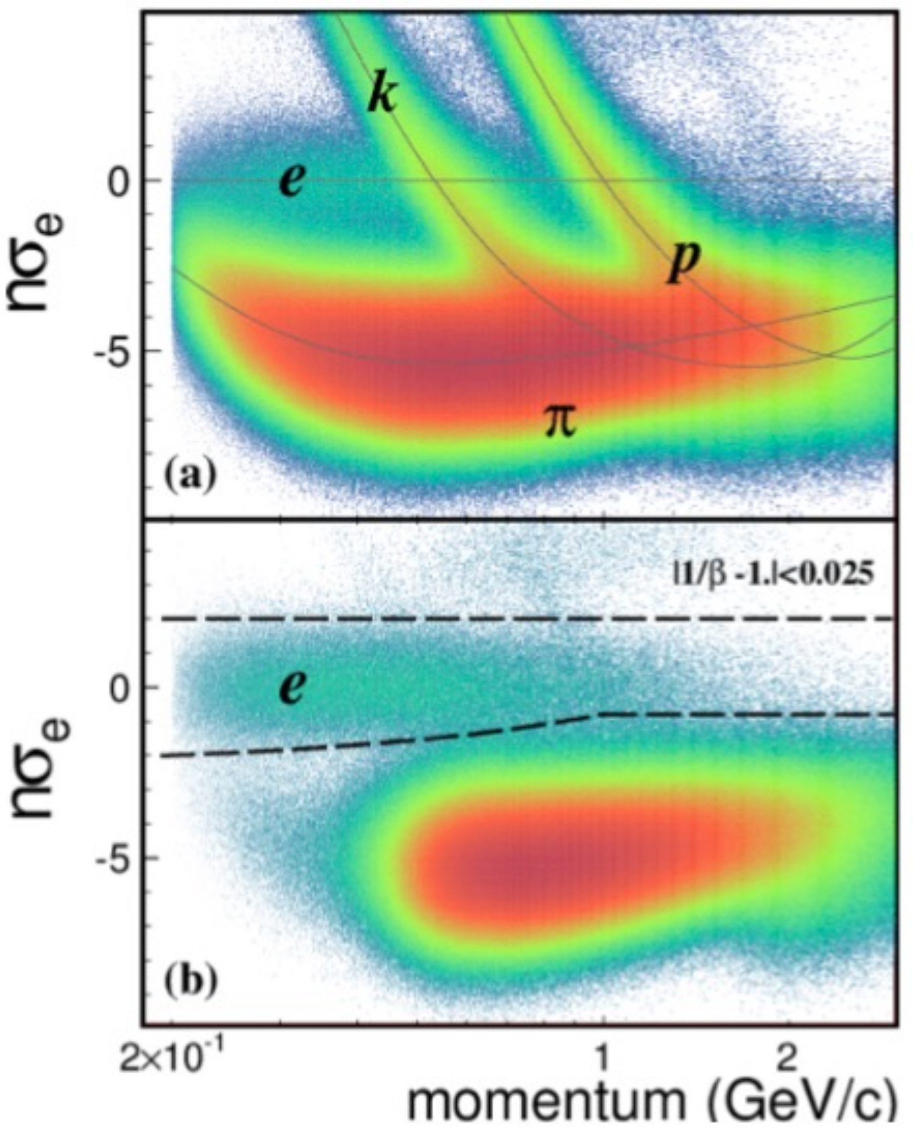
- Particle production in heavy ion collisions with respect to the reaction plane

$$W(\theta) \propto \frac{3}{8}[(1+\rho_{00}) + (1-3\rho_{00})\cos^2\theta^*]$$

STAR Collaboration, Phys. Rev. C 92, 024912

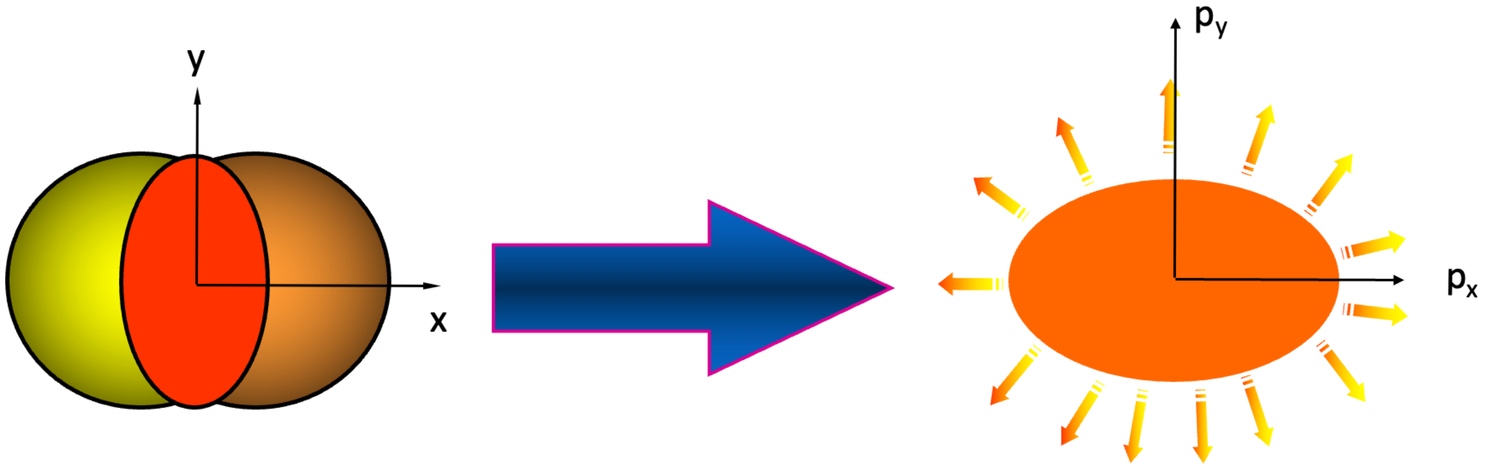
Electron Identification





- First, TOF velocity cut to remove slow hadrons
  applying the TOF velocity cut $|1/\beta - 1| < 0.025$
- Second, select high purity electron:
  based on the TPC dE/dx ($n\sigma_e$) cuts

Event plane reconstruction



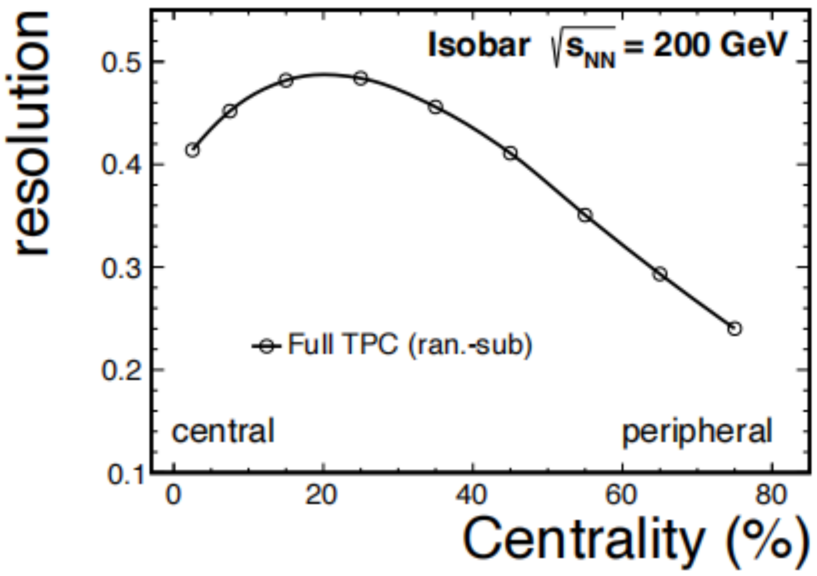
$$Q_n cos(n\Psi_n) = Q_{nx} = \sum w_i cos(n\phi_i),$$
$$Q_n sin(n\Psi_n) = Q_{ny} = \sum w_i sin(n\phi_i),$$
$$\Psi_n = \left(\arctan \frac{Q_{ny}}{Q_{nx}}\right)/n,$$

A. M. Poskanzer and S. A. Voloshin, PRC.58.3(1998)

- The 2nd-order event plane was reconstructed with a conventional method using charged tracks in the TPC with 0.2 < pT < 5 GeV/c and |η| < 1

Resolution

A. M. Poskanzer and S. A. Voloshin, PRC.58.3(1998)

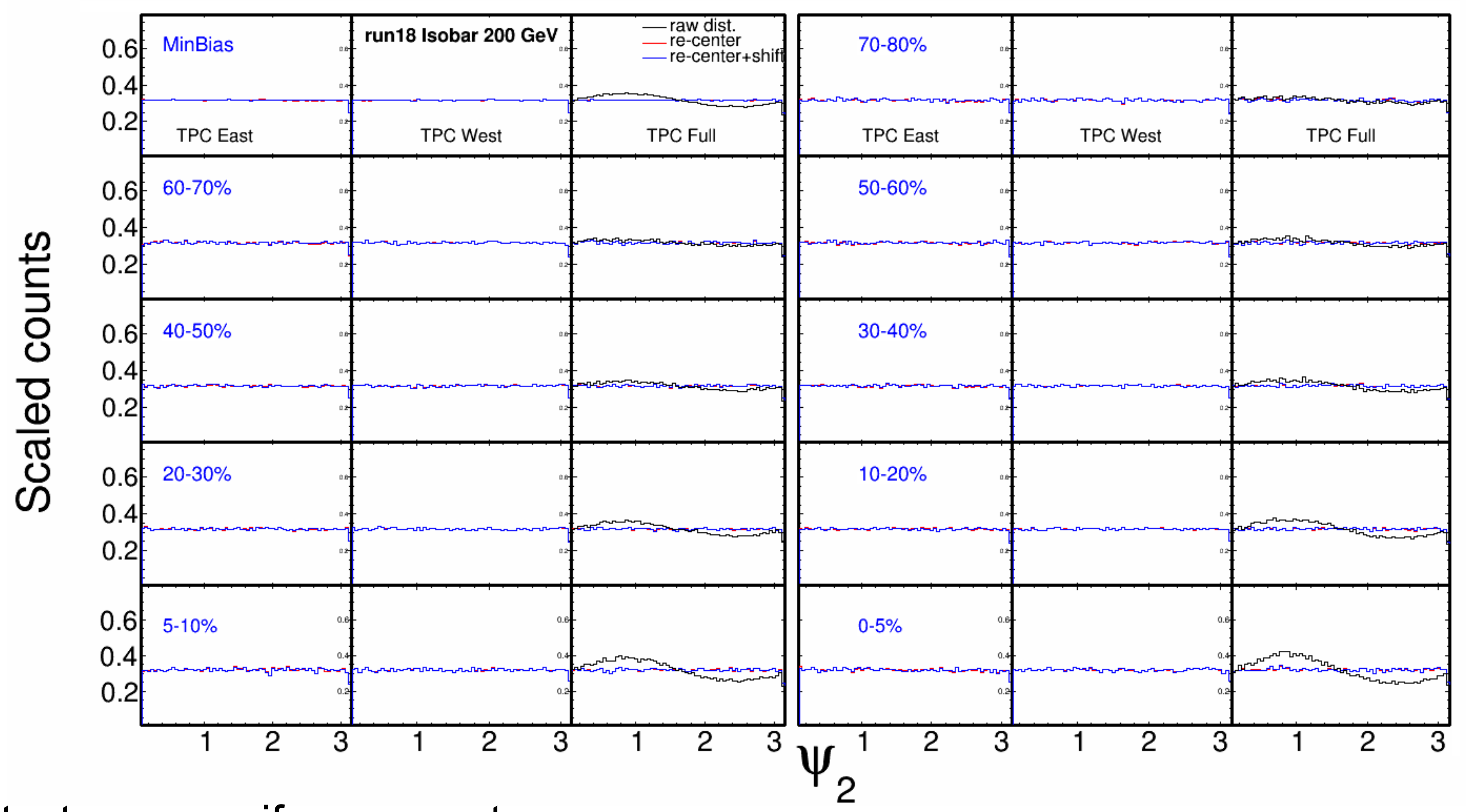


$$\langle coskm(\Psi_m - \Psi_r)\rangle = \frac{\sqrt{\pi}}{2\sqrt{2}}\chi_m exp(-\chi_m^2/4)[I_{(k-1)/2}(\chi_m^2/4) + I_{(k+1)/2}(\chi_m^2/4)]$$

- modified Bessel function used to calculate the resolution
- random-sub event are used to calculate the resolution for full TPC event-plane

Event plane reconstruction

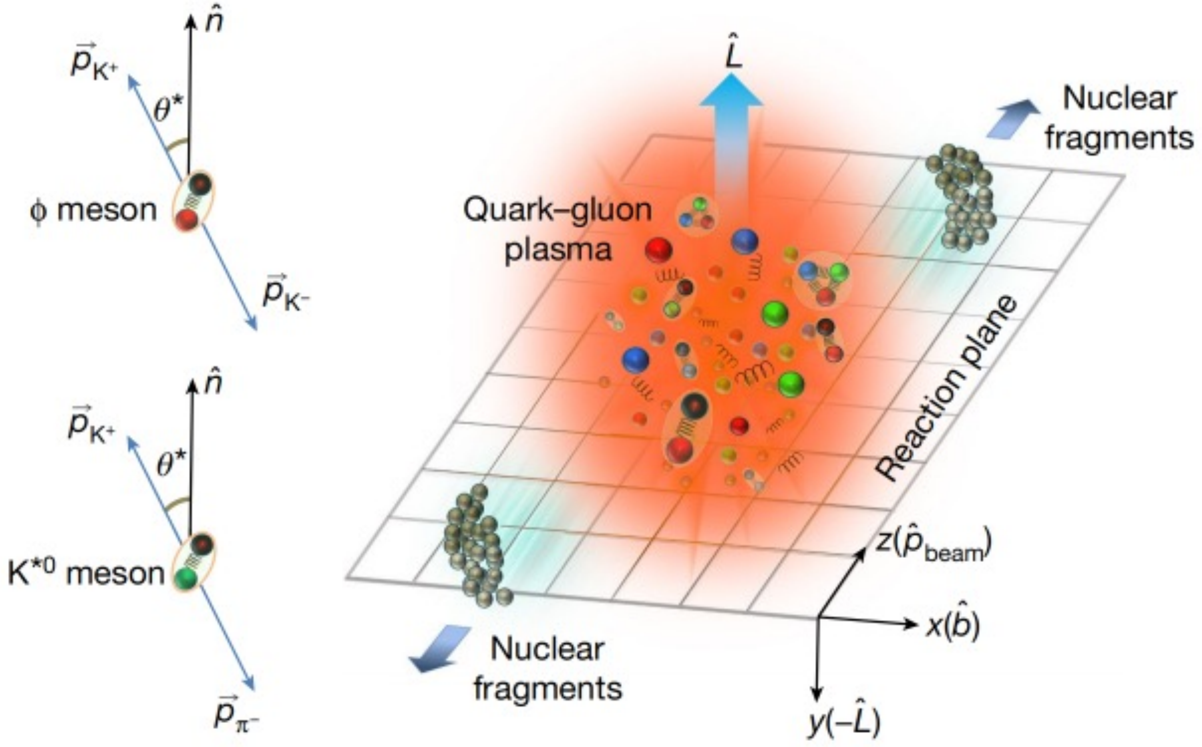
A. M. Poskanzer and S. A. Voloshin, PRC.58.3(1998)



Detector non-uniform acceptance

Re-center + shift method are used to flatten the event-plane

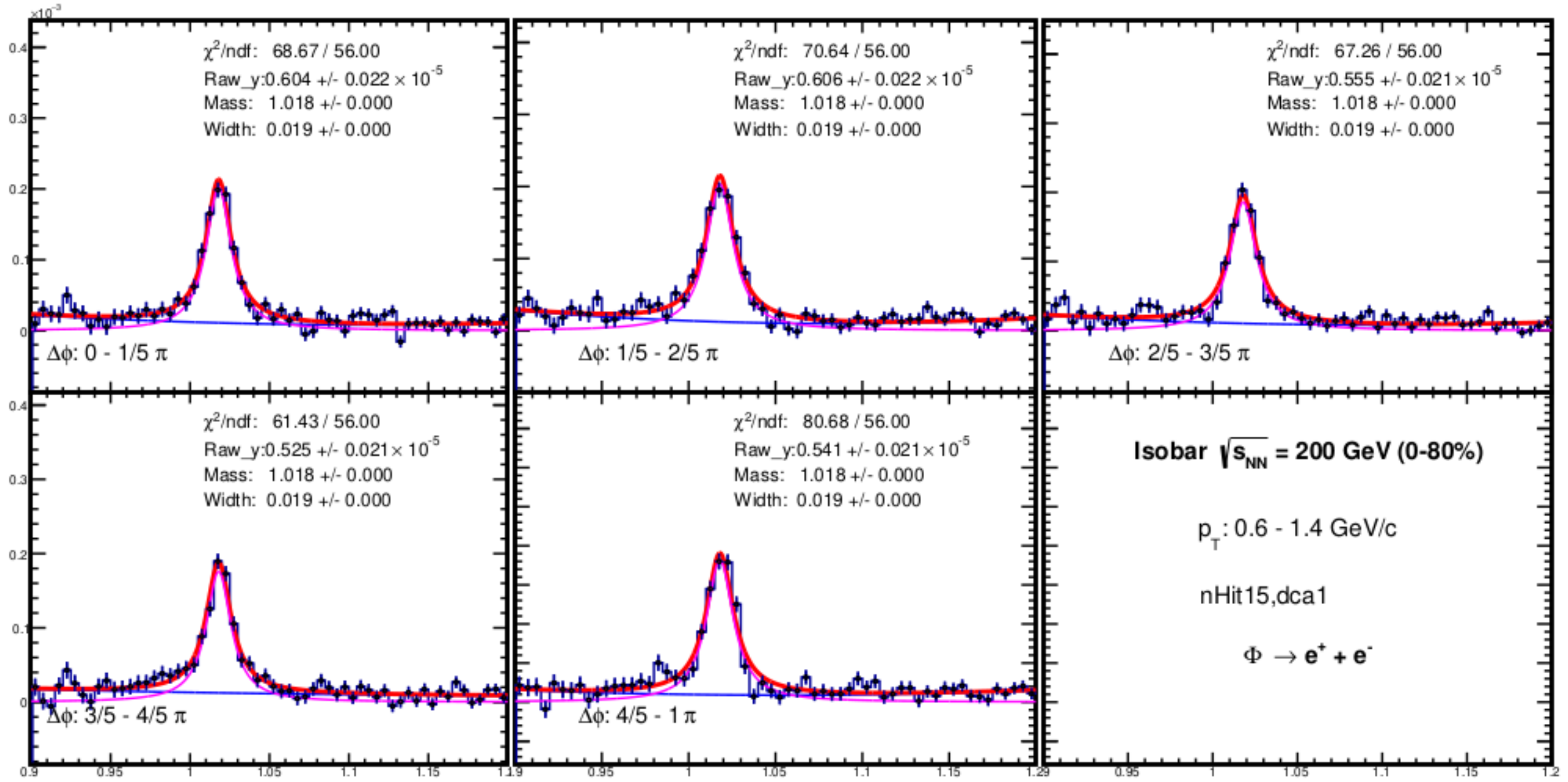
ρ_{00} analysis



$$\frac{dN}{d(\phi - \Psi_2)} \propto 1 + 2v_2\cos[2(\phi - \Psi_2)]$$

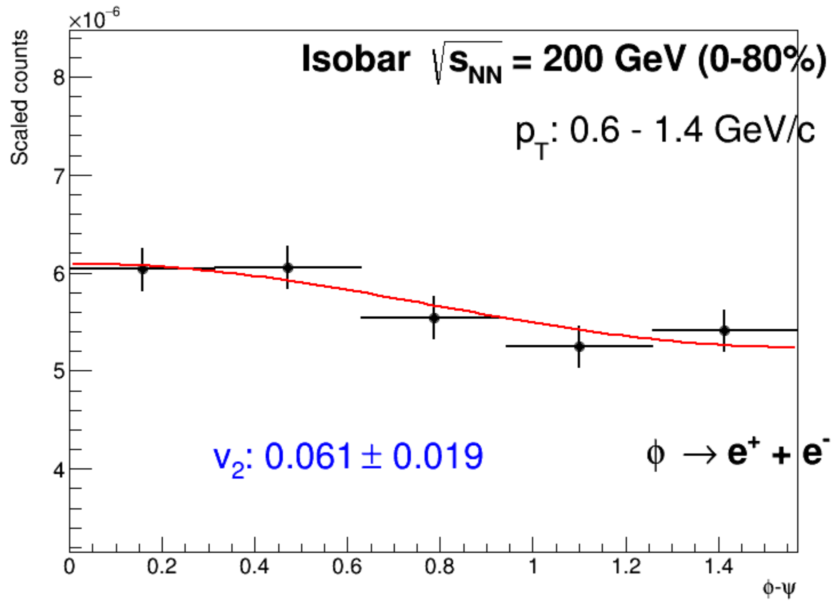
- The daughter angular distribution in the parent’s rest frame with respect to reaction plane.

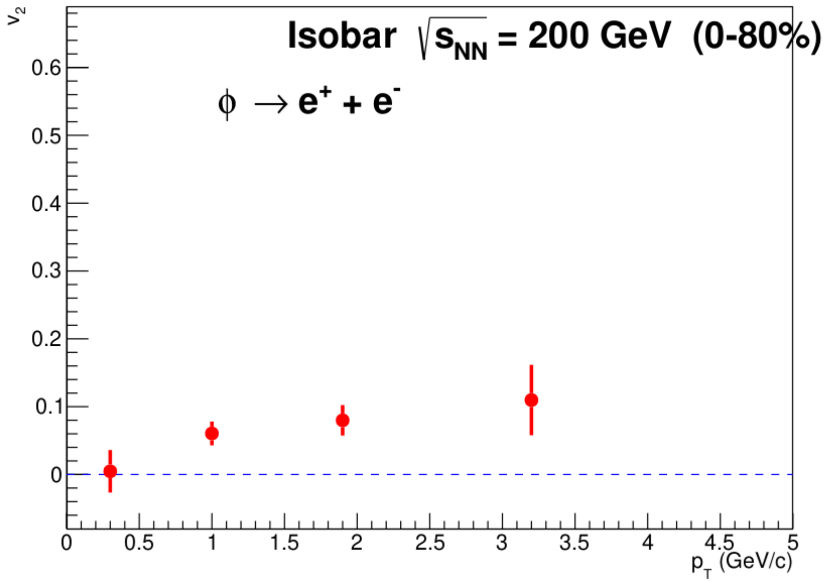
v_2 of φ (φ → e^+e^- channel)



- Event-plane method, signal in different **Δϕ**=ϕ-ψ_2 bins.

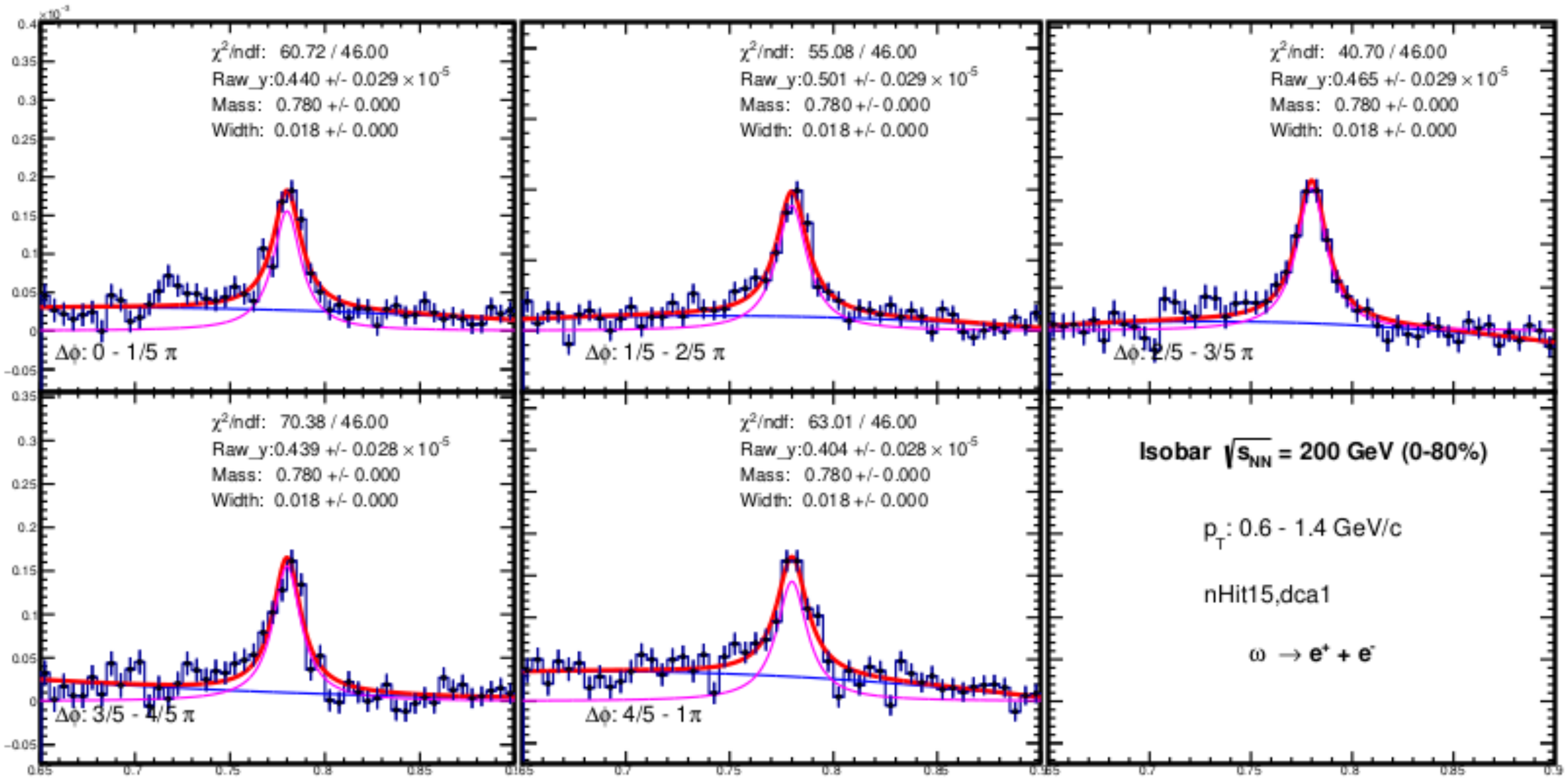
v_2 of φ (φ → e^+e^- channel)





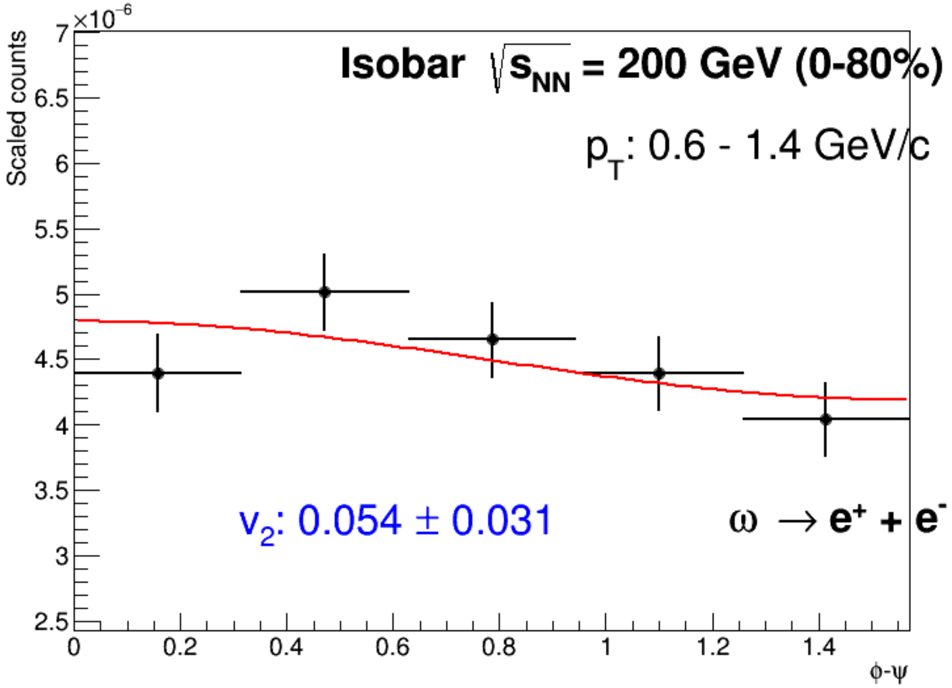
Fitting of $(\phi - \Psi)$ with $\frac{dN}{d(\phi-\Psi)} \propto 1 + 2v_2\cos(\phi - \Psi)$ and correct for event plane resolution

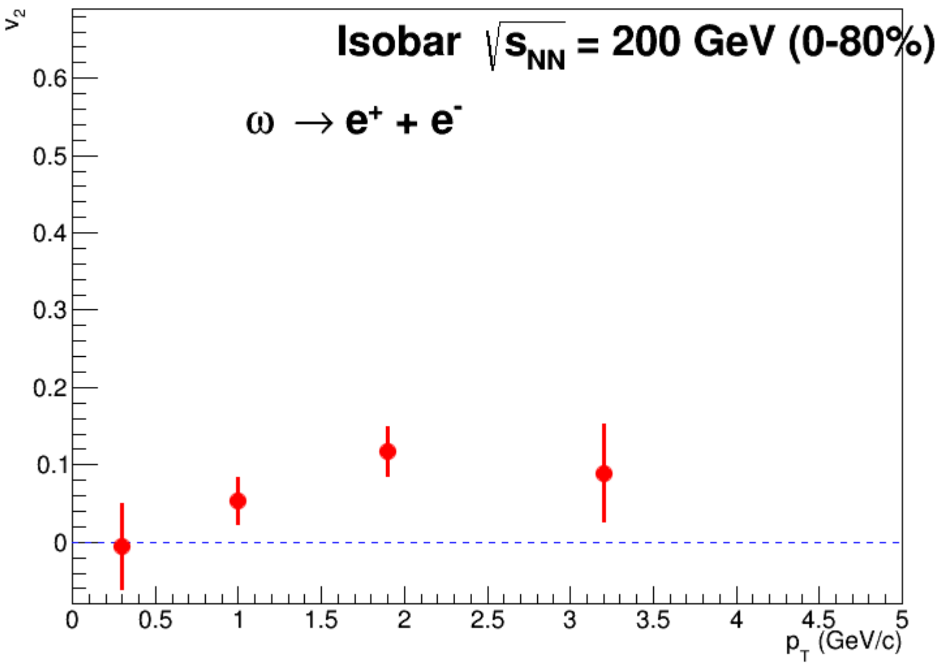
v_2 of ω ($\omega \to e^+e^-$ channel)



- Mass fit of the products in different p_T and different azimuth angles compared to reaction plane ($\omega \to e^+e^-$)

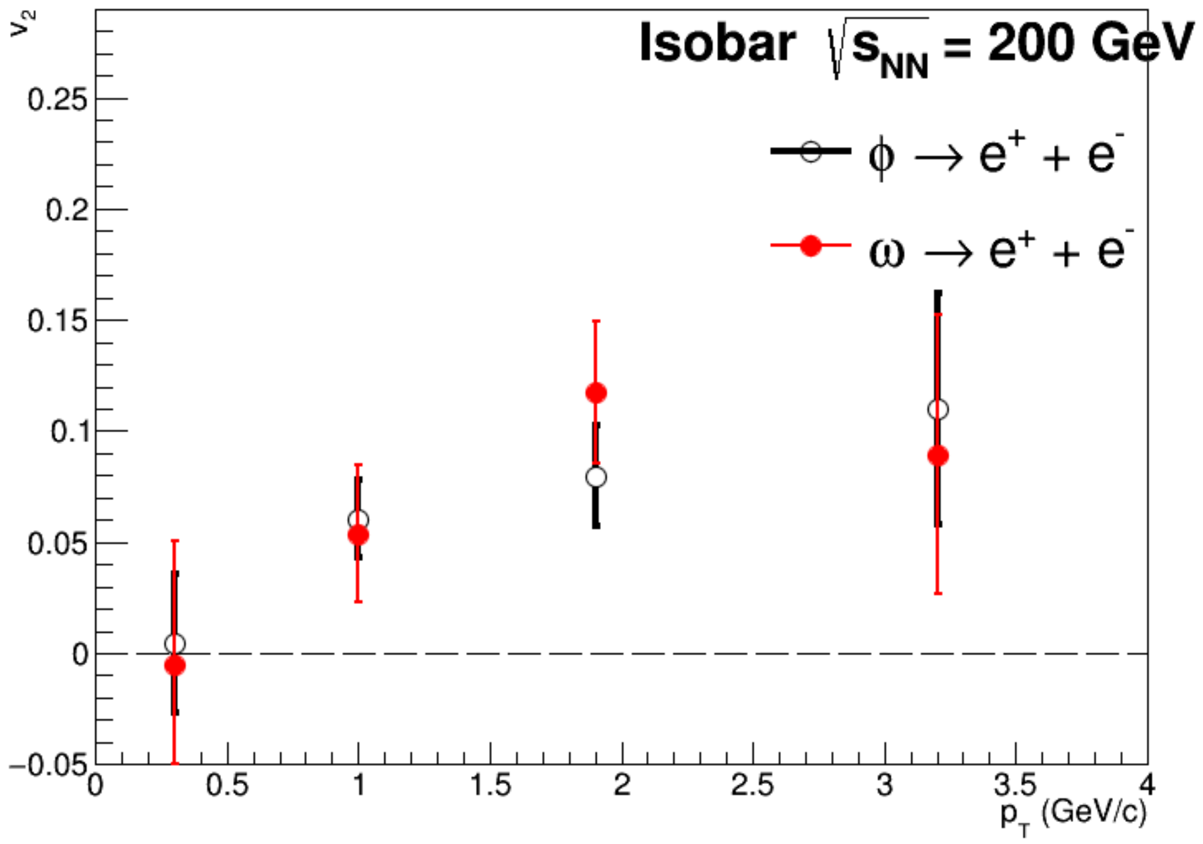
v_2 of ω ($\omega \to e^+e^-$ channel)



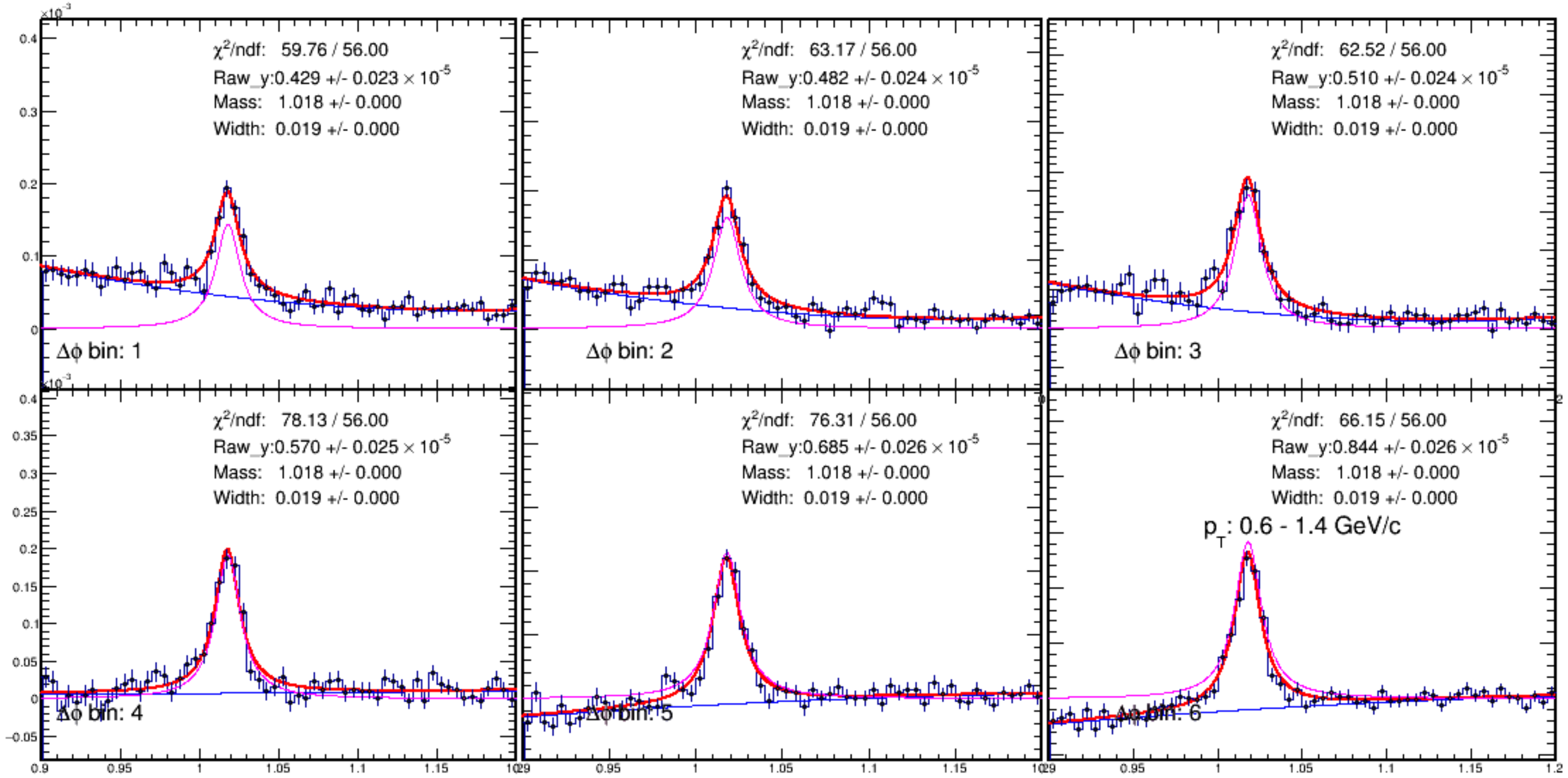


Fitting of $(\phi - \Psi)$ with $\frac{dN}{d(\phi-\Psi)} \propto 1 + 2v_2\cos(\phi - \Psi)$ and correct for event plane resolution

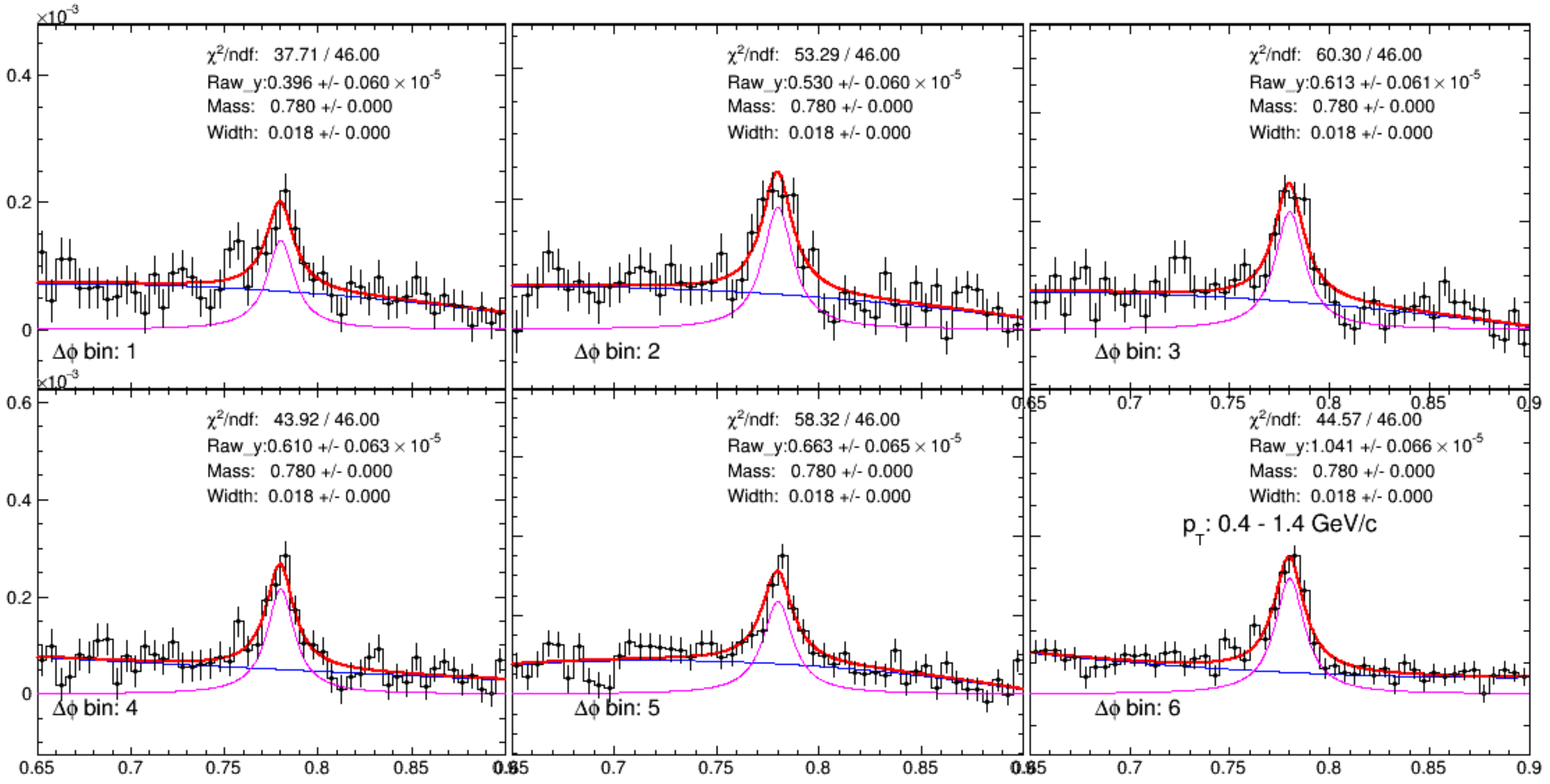
v_2 of φ, ω in collision Isobar(Zr+Zr&Ru+Ru)



$\cos\theta^*$ ($\varphi \rightarrow e^+e^-$) in Isobar

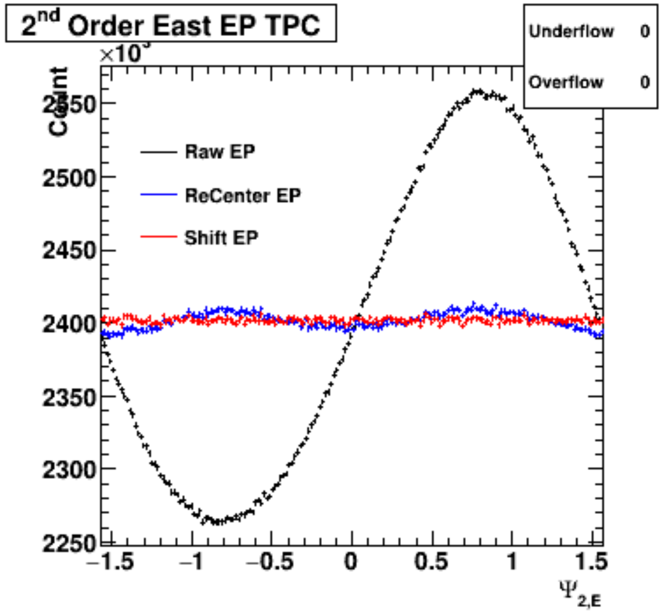


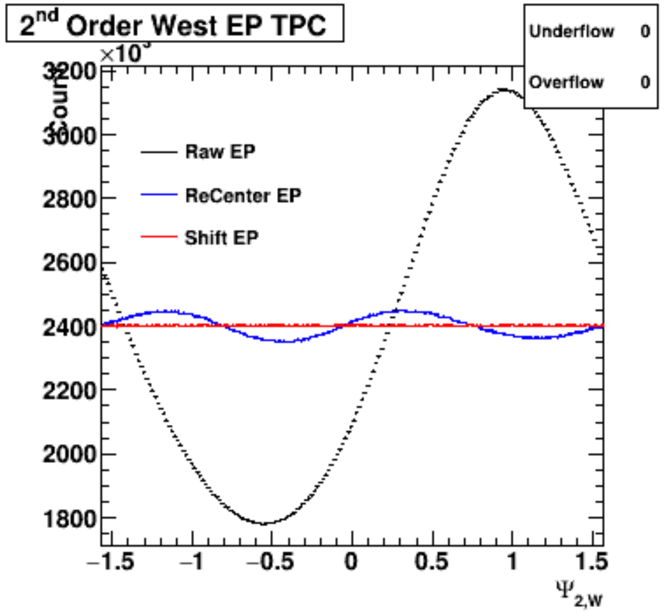
$\cos\theta^*(\omega \rightarrow e^+e^-)$in Isobar



Backup Slides
hadronic decay φ

2^{nd} order TPC EP





TPC Event Plane Cuts (2nd order)

Sub-event plane method with η-gap = 0.1.

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

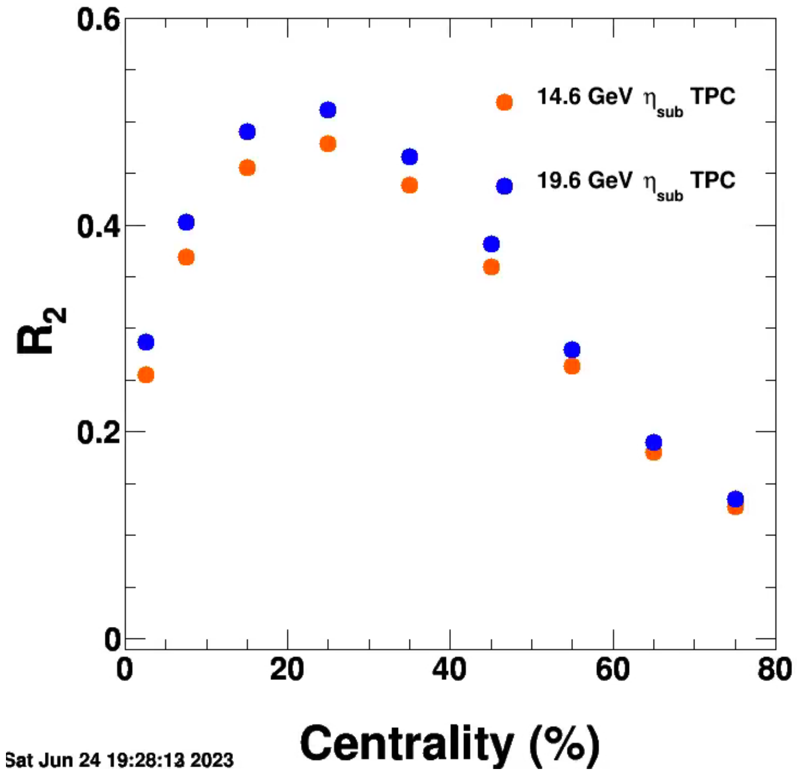
0.15 < pT < 2 GeV/c

|DCA| < 1 cm

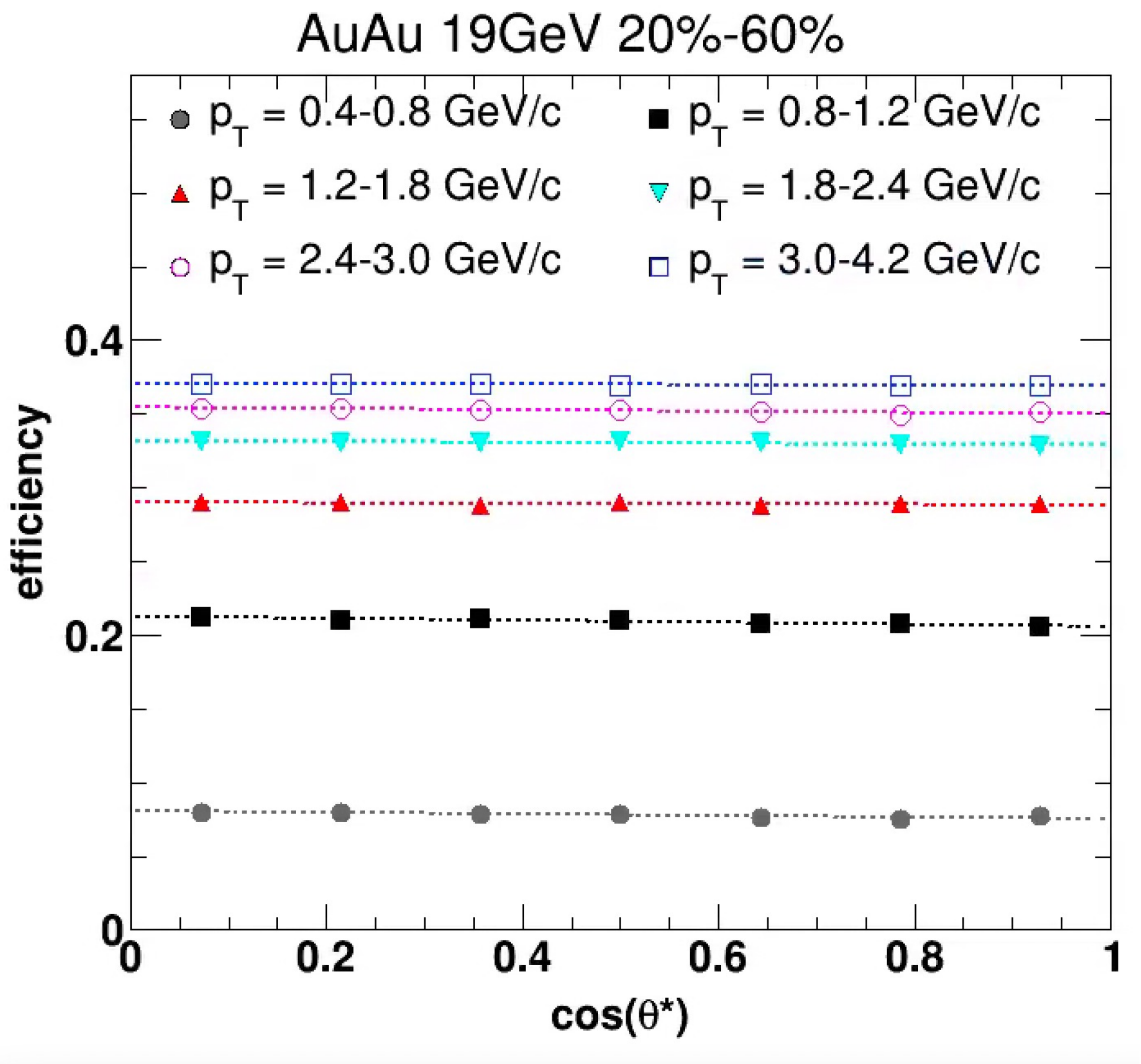
No. TPC hits > 15

TPC hit ratio > 0.52

|η| < 1.5



Efficiency vs. cos(θ*)



- Use Pythia6 to decay $\phi \to K^+K^-$
- 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.

Deriving 4th Order Acceptance Correction

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

$$g(\theta^*,\beta) = 1 + F^*\cos^2\theta + G^*\cos^4\theta$$

$$= 1 + \left(\frac{4F^* + 3G^*}{8}\right) - \left(\frac{2F^* + 3G^*}{4}\right)\cos^2\theta^* + \frac{3G^*}{8}\cos^4\theta^*$$

$$- \frac{\cos 2\beta}{2}\left[F^*(1-\cos^2\theta^*) + G^*(1-\cos^2\theta^* + \cos^4\theta^*)\right]$$

$$+ \frac{G^*\cos 4\beta}{8}\left[1-\cos^2\theta^* + \cos^4\theta^*\right],$$

$$\int_0^{2\pi} d\beta\ g(\theta^*,\beta) = g(\theta^*) \propto 1 + \left(\frac{4F^*+3G^*}{8}\right) - \left(\frac{2F^*+3G^*}{4}\right)\cos^2\theta^* + \frac{3G^*}{8}\cos^4\theta^*.$$

Deriving 4th Order Acceptance Correction

$$\frac{dN}{d\cos\theta^{*\prime}d\beta'} \propto 1 + A'\cos^2\theta^{*\prime} + B'\sin^2\theta^{*\prime}\cos 2\beta' + C'\sin 2\theta^{*\prime}\cos\beta'\,.$$

$$\left[\frac{dN}{d\cos\theta^{*\prime}}\right]_{|\eta|} \propto 2 + F^* - \frac{B'F^*}{2} + \frac{3G^*}{4} - \frac{B'G^*}{2}$$
$$+\left[2A' - F^*(1 - A' - B') - G^*\left(\frac{3}{2} - \frac{3A'}{4} - \frac{3B'}{2}\right)\right]\cos^2\theta^{*\prime}$$
$$+\left[-F^*\left(A' + \frac{B'}{2}\right) + G^*\left(\frac{3}{4} - \frac{3A'}{2} - \frac{3B'}{2}\right)\right]\cos^4\theta^{*\prime}$$
$$+\left[G^*\left(\frac{3A'}{4} + \frac{B'}{2}\right)\right]\cos^6\theta^{*\prime}\,.$$

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

Deriving 4th Order Acceptance Correction

Now let's set $G = 0$ and $F^* = \frac{-2F}{1+F}$ to recover form of equation from PHYSICAL REVIEW C 98, 044907 (2018)

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

Pull out constant factor 2/(1+F).

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

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

THIS MATCHES THE SECOND ORDER ACCEPTANCE CORRECTION FORMULA

J/ψ Backup slides

Analysis strategy

Event level:

Vpdmb-30 (600001, 600011, 600021 and 600031)

|Vr| <2 cm, -35<Vz< 25 cm, and $|V_z^{TPC} - V_z^{VPD}| < 3\ cm$

Bad run rejected, bad run index in backup slides

Track quality cuts

$nHitsFit \geq 20$ $\quad nHitsFit/nHitsPoss \geq 0.52$ $\quad |\eta| < 1.0$

$nHitsDedx \geq 15$ $\quad dca < 1.0\ cm$

Electron identification:

$p_T \leq 1$

- $p \leq 0.8$: $3 \times p - 3/15 < n\sigma_e \leq 2.0$, $|1 - 1/\beta| \leq 0.025$
- $p > 0.8$: $-0.75 \leq n\sigma_e \leq 2.0$, $|1 - 1/\beta| \leq 0.025$

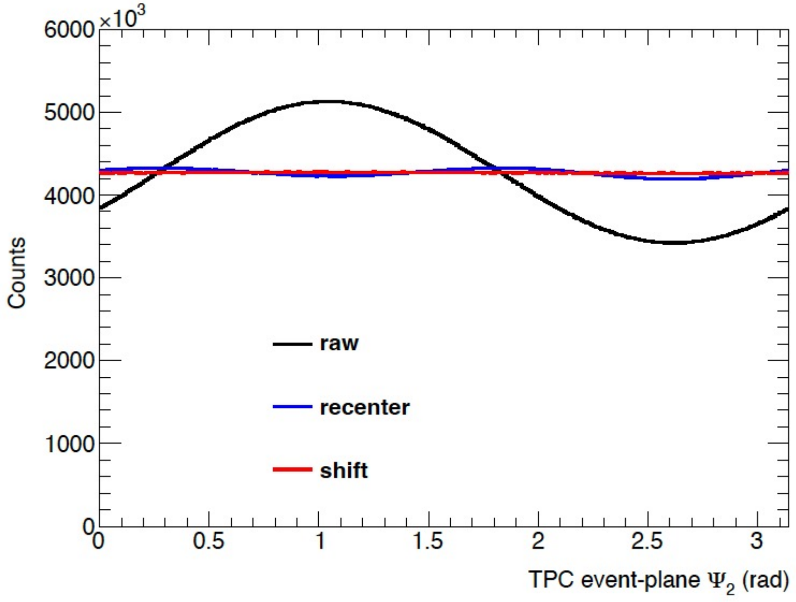
$p_T > 1$

- **Only TOF**: $-0.75 \leq n\sigma_e \leq 2.0$, $|1 - 1/\beta| \leq 0.025$
- **Only BEMC**: $-1. \leq n\sigma_e \leq 2.0$, $0.5 \leq E_0/p \leq 1.5$
- **TOF &BEMC**: $0.5 \leq E_0/p \leq 1.5$, $|1 - 1/\beta| \leq 0.025$, $-1.5 \leq n\sigma_e \leq 2.0$

TPC event-plane reconstruction

2nd order event plane reconstruction:

$0.4 < p_T < 3GeV/c$
$nHitsFit > 15$
$nHitsFit/nHitsPoss > 0.52$
$dca < 1$
$-0.5 < \eta < 0.5$



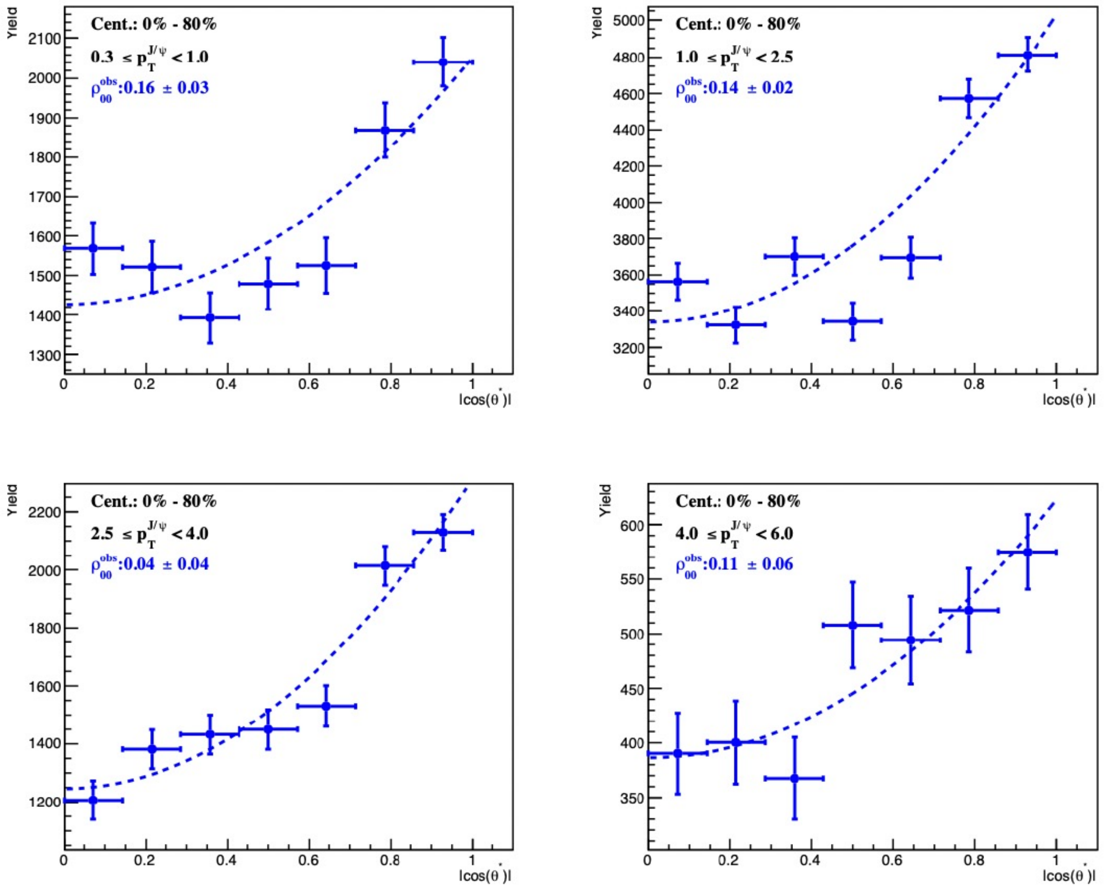
Electron/positron that can be paired within the mass region of (2.8 - 3.25) has been excluded from event-plane reconstruction

Recentering:

- Correct azimuthally TPC non-uniform
- Corrected in each run, and centrality with vz > 0 and vz <0 case respectively

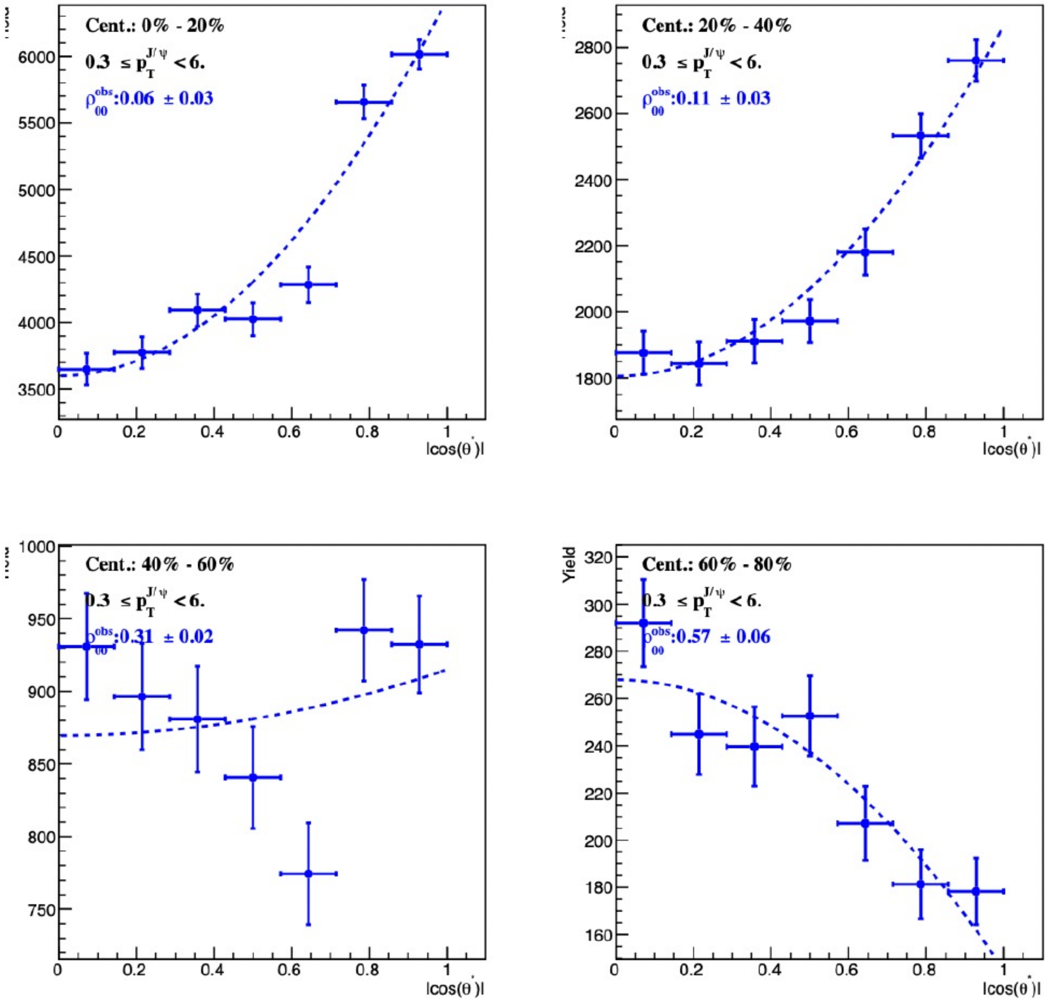
Shift:
To remove higher order harmonics contribution. Up to 10th oder in the analysis

Yield in different pT range



Significant spin alignment signal up to 6 GeV/c in 0-80% centrality range.

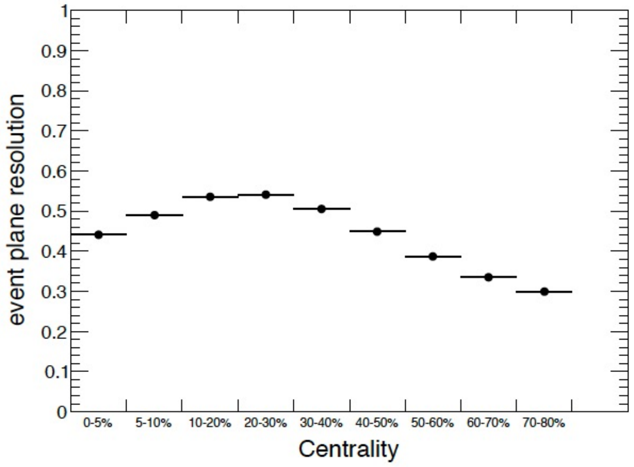
pT integral yield at different centrality



Significant spin alignment signals.
Very different trend over centrality

Summary

- Very clear spin alignment signals but more check is needed
  - Use EPD event plane and ZDC event plane for non-flow correlations check
  - Does BEMC affect the signal? minimum energy deposition
- Corrections
  - Efficiency and Acceptance correction
  - Kinematics correction: positron at J/ψ rest frame for and EP at Lab frame
- Event plane resolution (1st order and 2nd order) correction is need to get final ρ_{00}



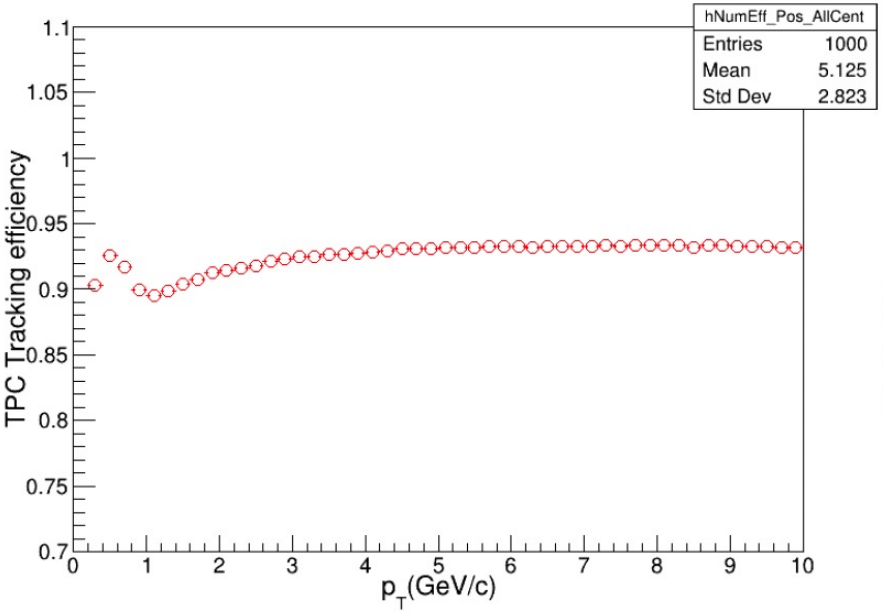
$$\rho_{00} - \frac{1}{3} = \frac{4}{1 + 3R_{21}}(\rho_{00}^{obs-2nd} - \frac{1}{3})$$

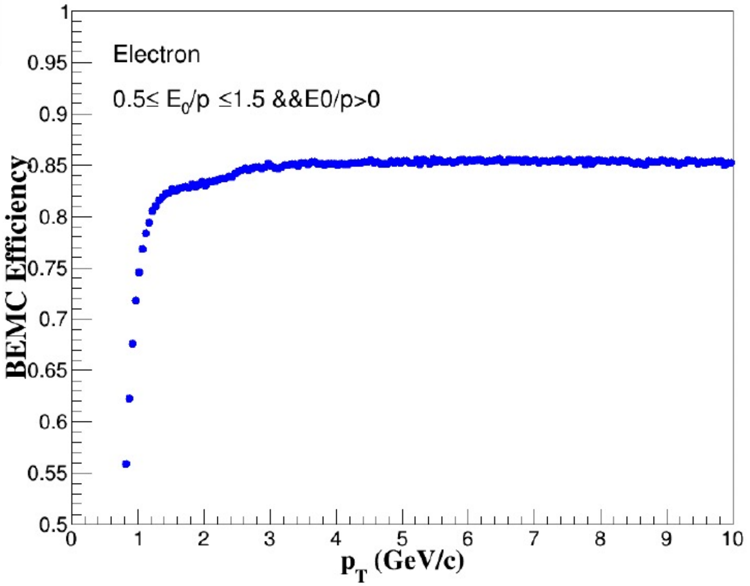
PRC **98**, 044907 (2018)

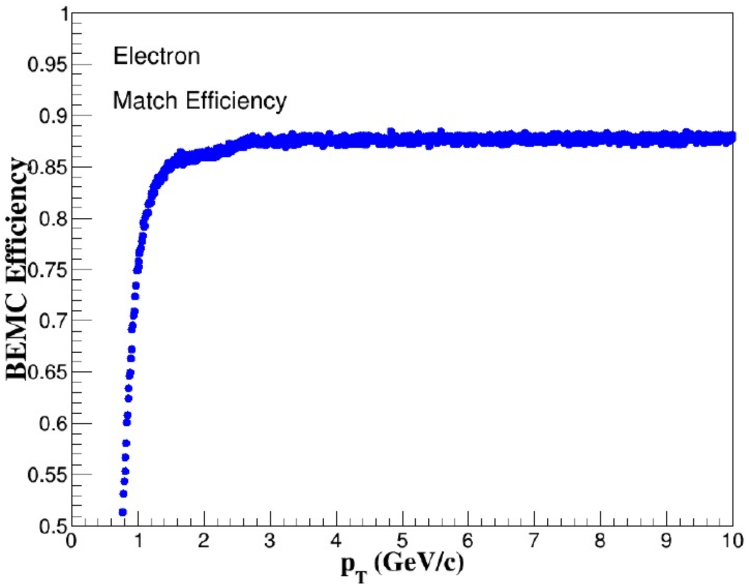
Single electron efficiency

Embedding data

$$\epsilon_e^{TPC} = \frac{N_{rc}\left(nHitsFit \geq 20\ \& \frac{nHitsFit}{nHitsPoss} \geq 0.52\ \& nHitsDedx \geq 15\ \& dca \leq 1\ \&\ |\eta| \leq 1\ \&\ 0.2 < p_T^{rc} < 30 \frac{GeV}{c}\right)}{N_{mc}\ (|\eta \leq 1|)}$$

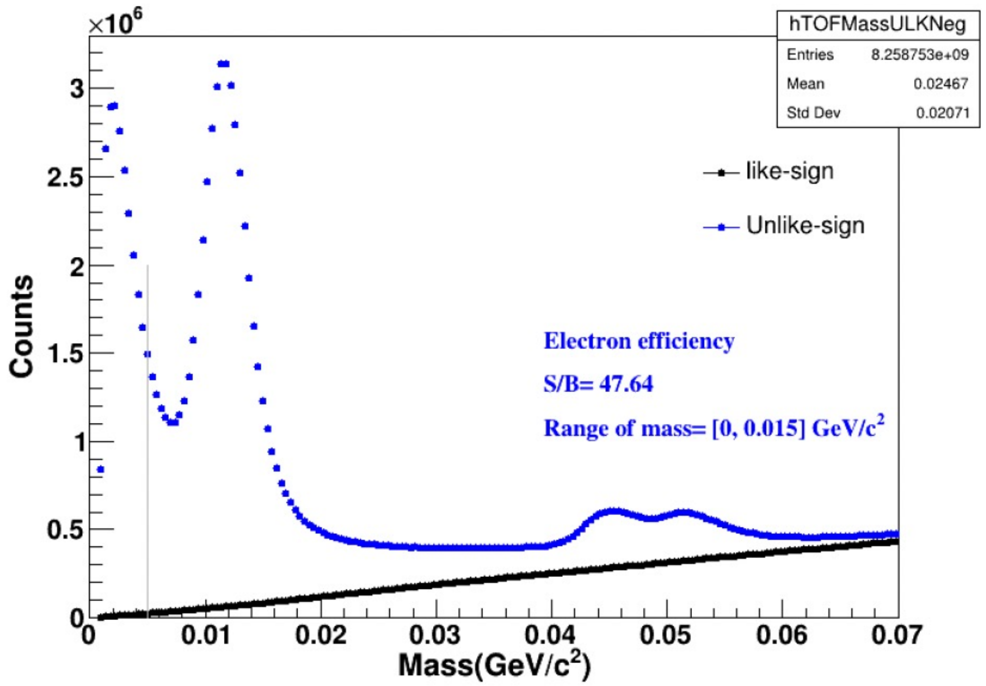


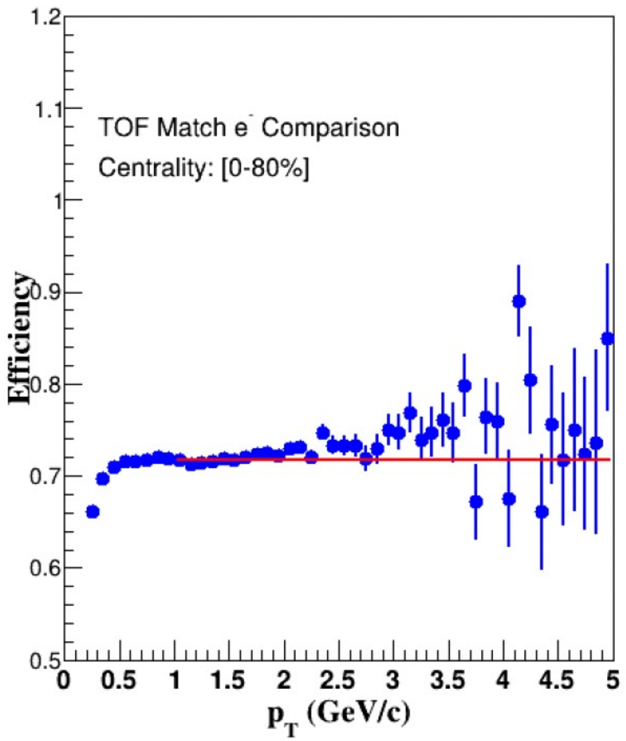


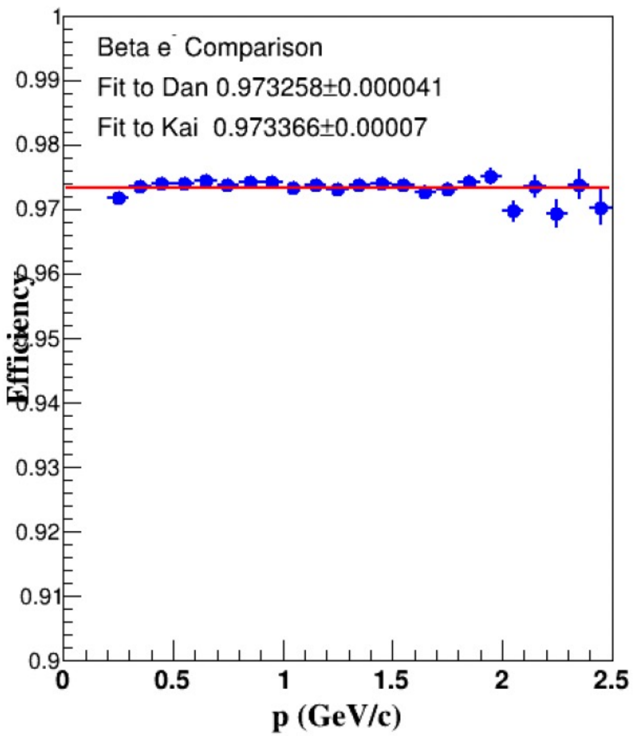


We obtain the TPC tracking and BEMC efficiency of electrons from embedding data.

TOF efficiency

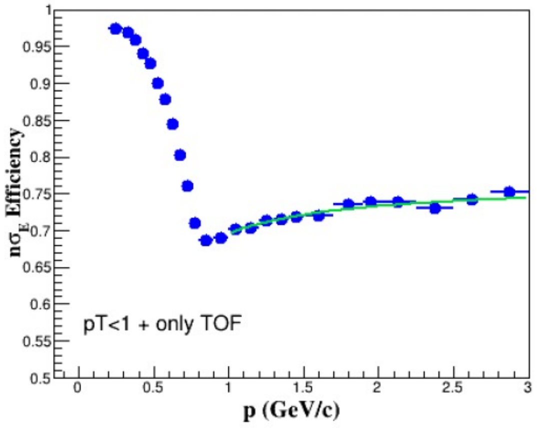


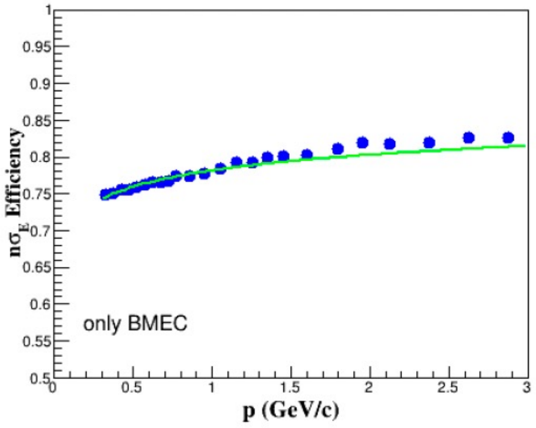


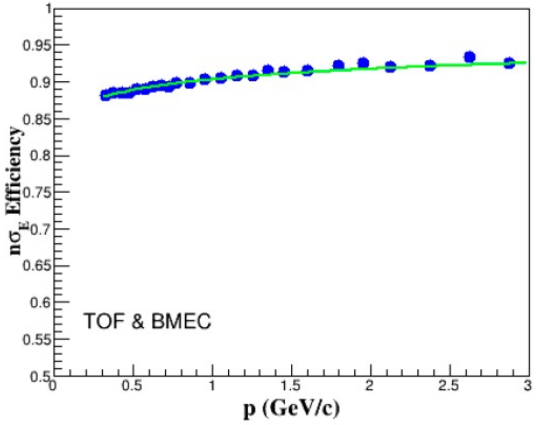


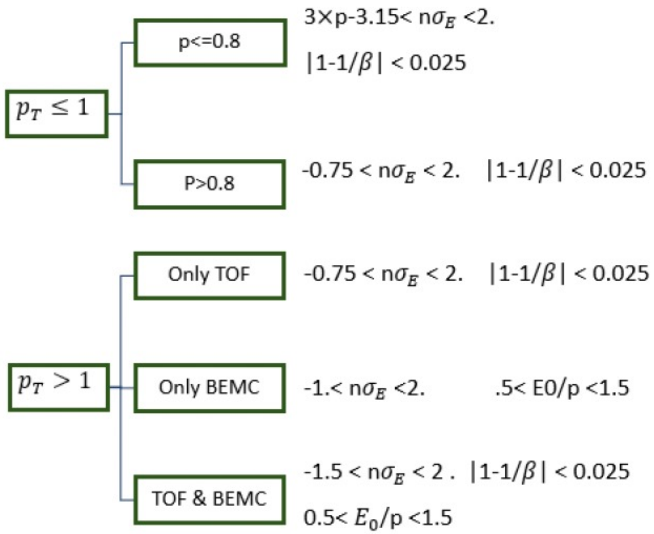
- The pure electron sample is from photon Conversion (Mass≤0.005 GeV/c^2).
- We obtain the TOF efficiency of electrons from real data.

$n\sigma_E$ efficiency









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