Global Spin Alignment of ϕ and K^{*0} Mesons in 19.6 GeV Au+Au Collisions from BES-II

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05/25/2022

Motivation for Analysis

- BES-II provides significantly more statistics for lower collision energies.
  - BES-I 19.6 GeV: ~19M events after cuts
  - BES-II 19.6 GeV: ~400M events after cuts

- Preliminary results for BES-I energies show increasing global spin alignment for φ-meson at lower AuAu collision energies ≤ 19.6 GeV.
  - Clarify ρ_{00} behavior in lower energy regime.

- Cross-check ρ_{00} values for K^{*0} from BES-I. No significant deviation from 1/3.

Introduction to Spin Alignment

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

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

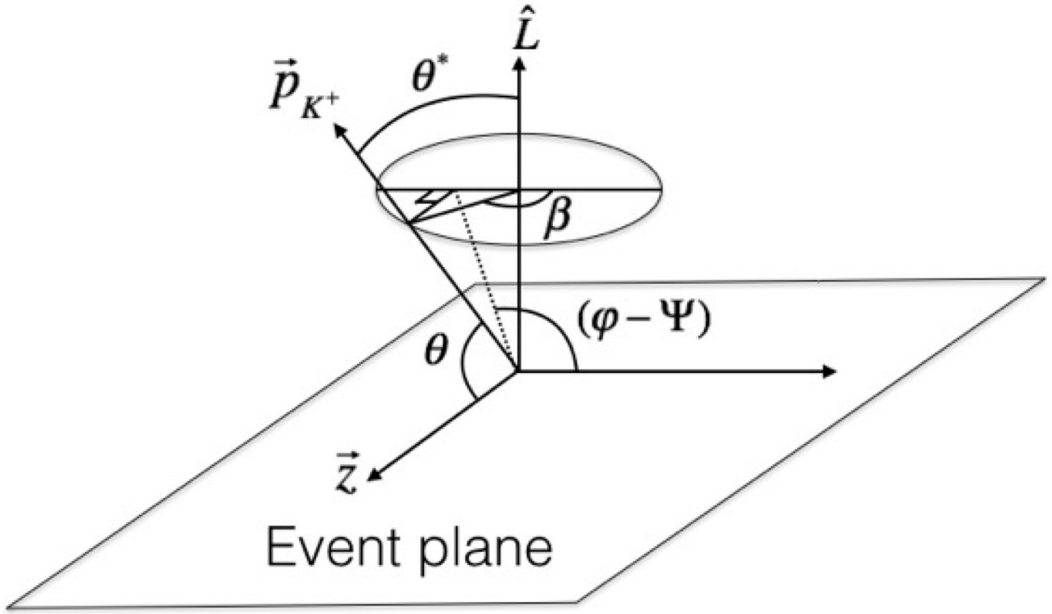
θ^* : angle between K^+ daughter and polarization axis in parent's rest frame.

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

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

Nucl. Phys.B18,332(1970)

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



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

Data and analysis cuts

Au+Au 19.6 GeV, BES-II

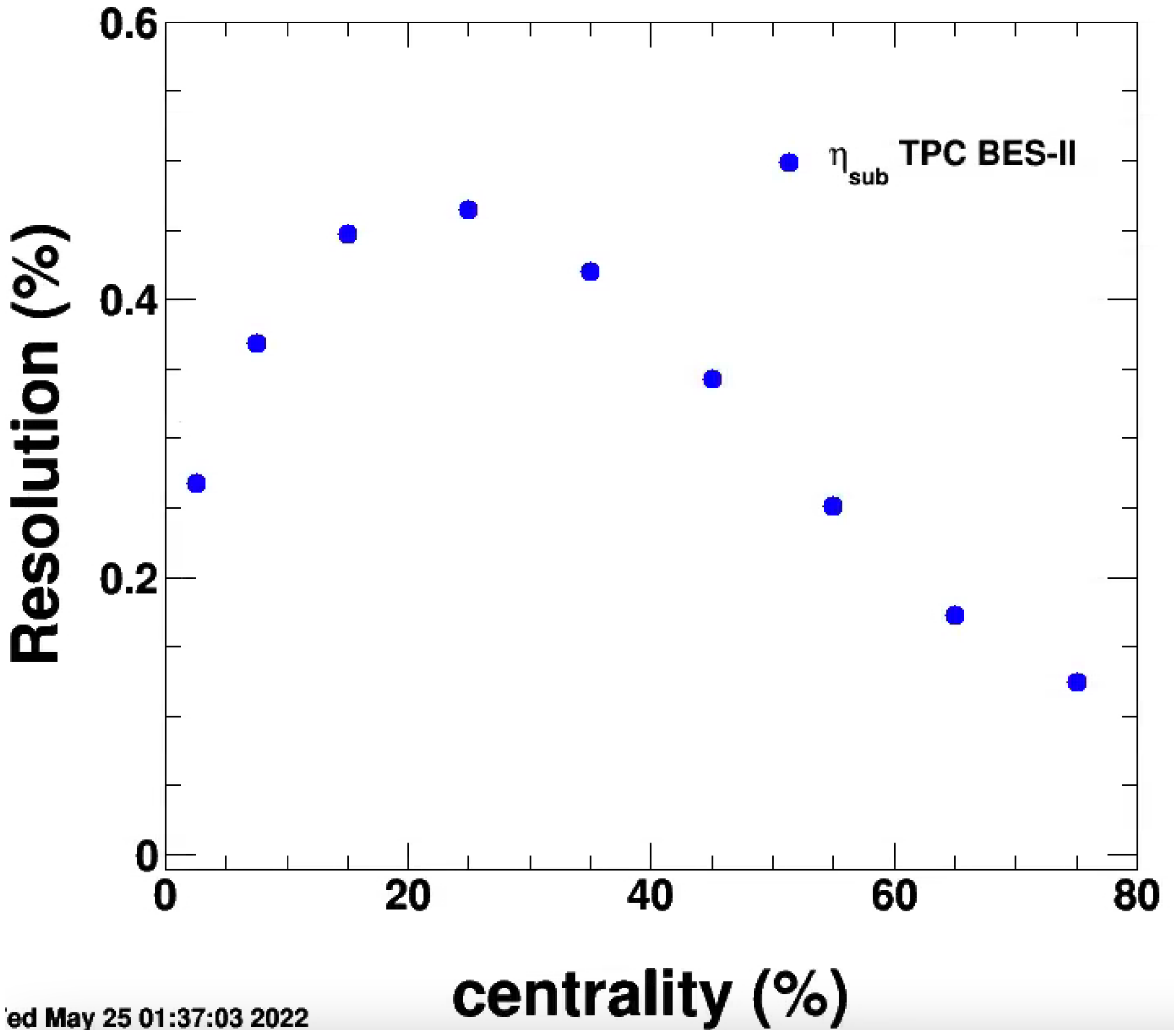
Event Cuts

- Vertex: |Vz| < 70 cm
  |Vr| < 2 cm
- nBTOFMatch > 2
- Trigger IDs (minbias): 640001, 640011, 640021, 640031, 640041, 640051

Track Cuts

- 0.1 < |pT| < 10.0 GeV/c
- |DCA| < 3.0 cm
- TPC hits > 15
- TPC hit ratio > 0.52
- $|\eta| < 1.0$

TPC Event Plane (2^{nd} order)



2^{nd} Order EP Cuts

- 0.15GeV/c < |pT| < 2.0 GeV/c
  |DCA| < 1.0 cm
  $|\eta| < 1.0$
- Total η separation for sub-event planes = 0.10

- Run-by-run, Centrality, and Vz binning for re-centering and shift calibrations.
  -Vz bins = {(-70,-30], (-30,0],(0,30],(30,70)}

Default ϕ PID and Reconstruction settings

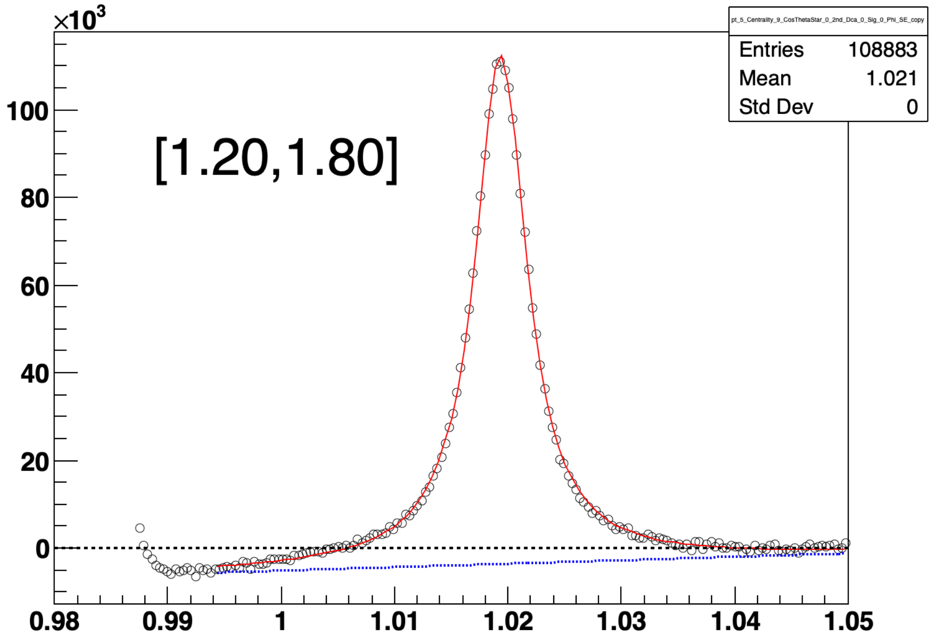
PID

$K^{+/-}$

|DCA| < 2.0

TPC: $|n\sigma_K| < 2.0$

TOF: 0.16 < m2 < 0.36



Fitting+BG subtraction

Mixed event background

Background normalized to tail of signal+background, m=[1.04,1.05] GeV

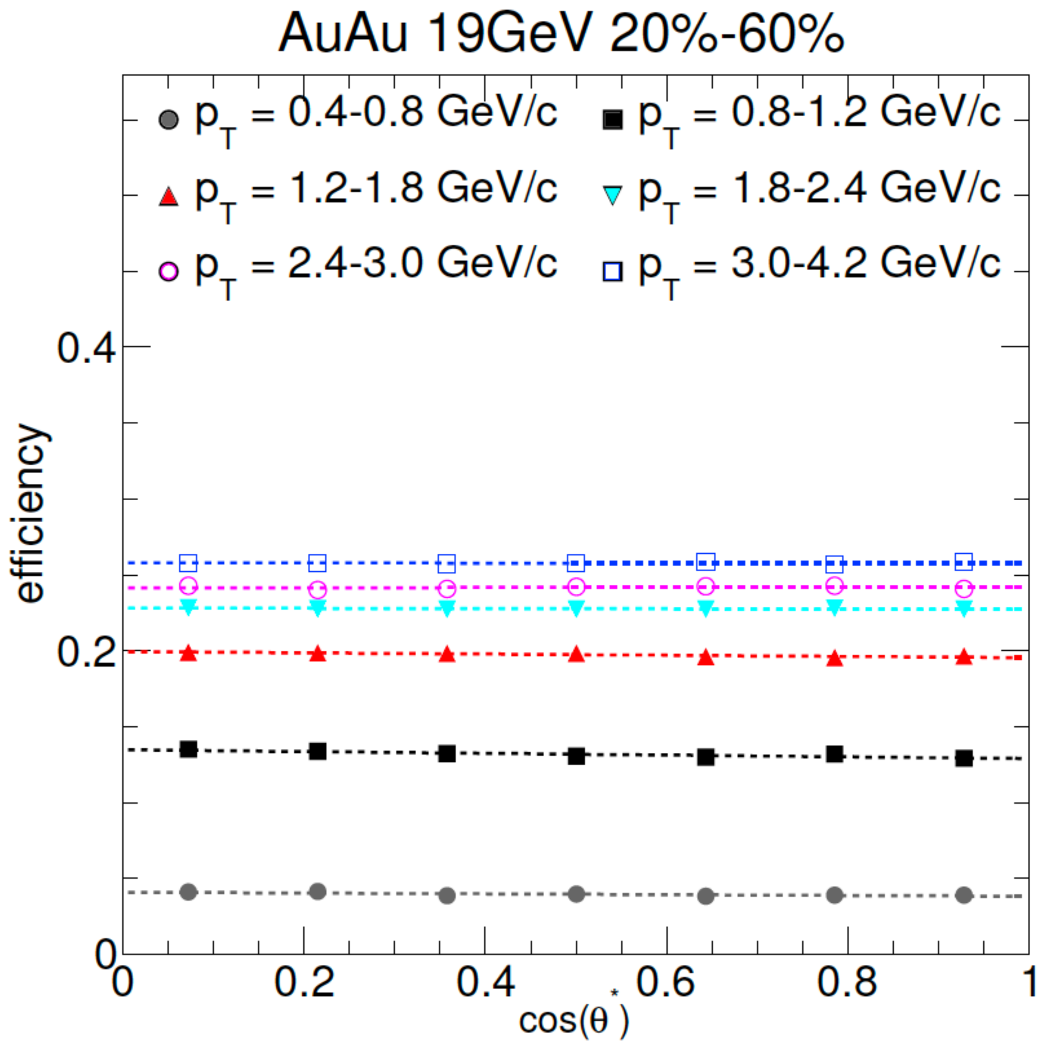
Breit-wigner + residual poly1 for fit

Fit region m = [0.994,1.05] GeV

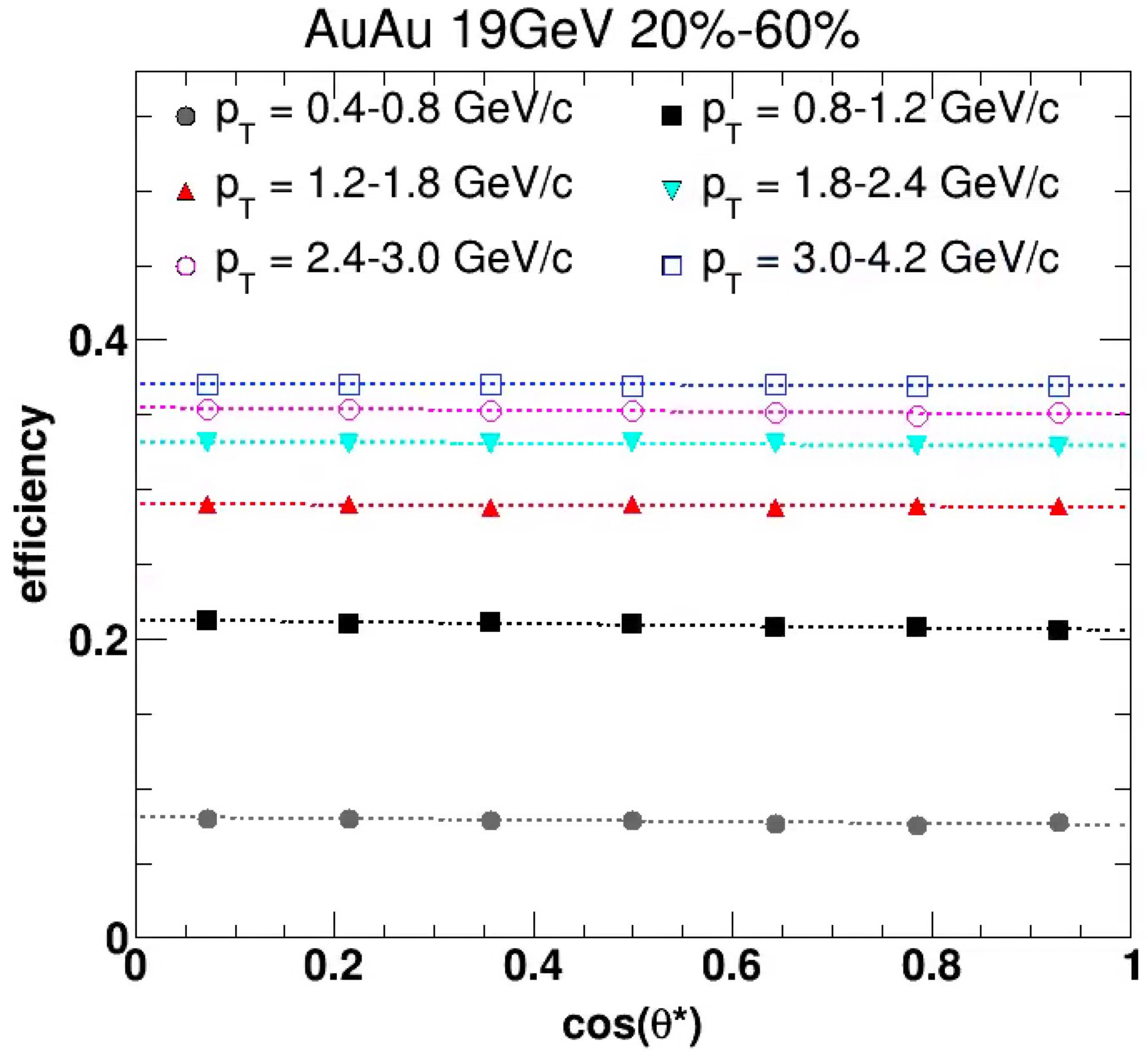
Integration signal extraction in region [m-2**Γ**,m-2**Γ**]

ϕ meson Efficiency vs cos(θ*)

BES-I



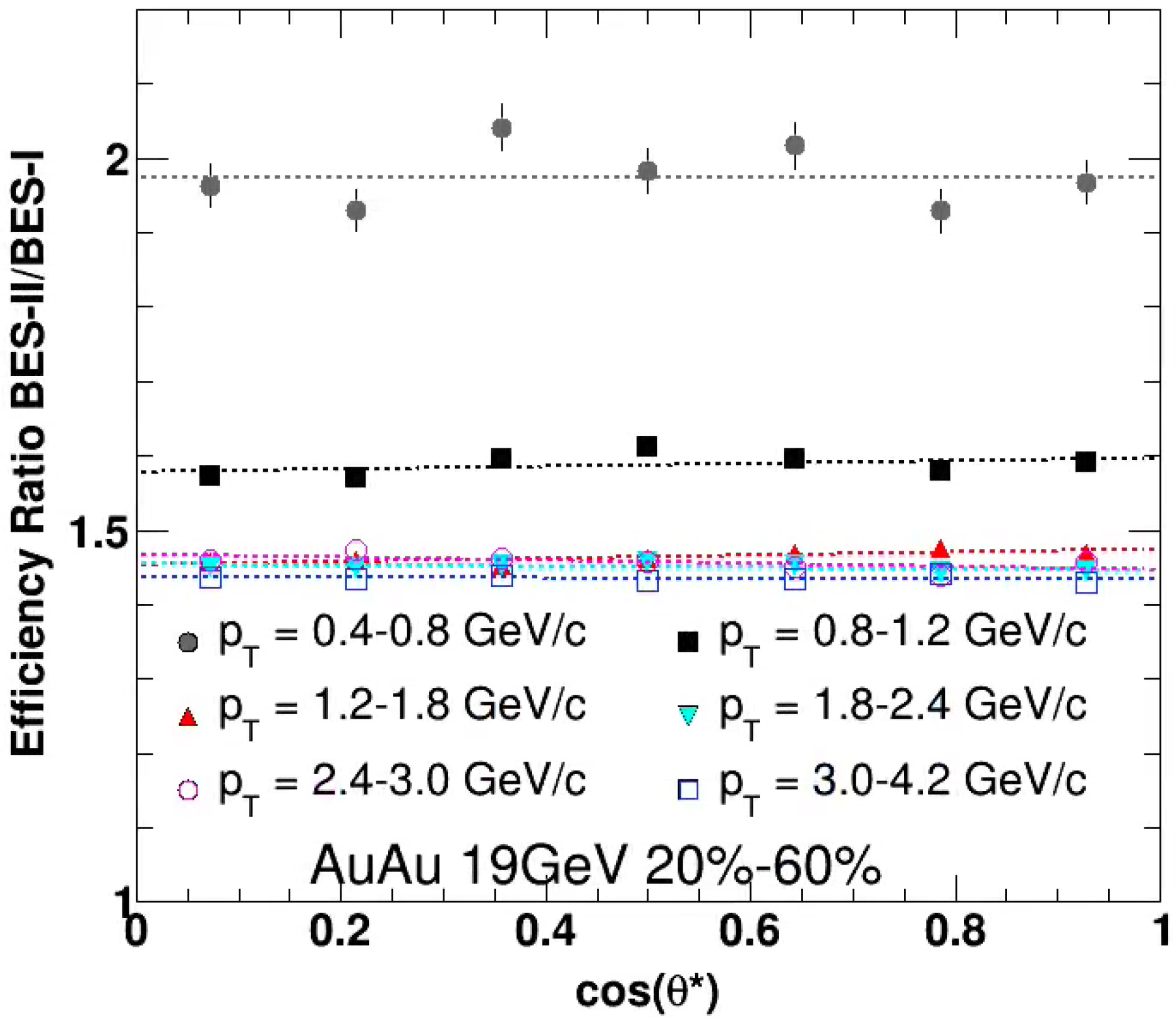
BES-II



Efficiency vs cos(θ*)

No direct answer to why we see a slight negative linear slope with respect to cos(θ*).

Linear trends of the two data sets appear consistent overall.



pT = 0.4-0.8 GeV/c	y-int = 1.9745 +/- 0.0225	slope = -0.0010 +/- 0.0391
pT = 0.8-1.2 GeV/c	y-int = 1.5781 +/- 0.0080	slope = 0.0185 +/- 0.0139
pT = 1.2-1.8 GeV/c	y-int = 1.4535 +/- 0.0044	slope = 0.0209 +/- 0.0077
pT = 1.8-2.4 GeV/c	y-int = 1.4545 +/- 0.0038	slope = -0.0081 +/- 0.0066
pT = 2.4-3.0 GeV/c	y-int = 1.4675 +/- 0.0036	slope = -0.0206 +/- 0.0063
pT = 3.0-4.2 GeV/c	y-int = 1.4370 +/- 0.0024	slope = -0.0037 +/- 0.0041

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)

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

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

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

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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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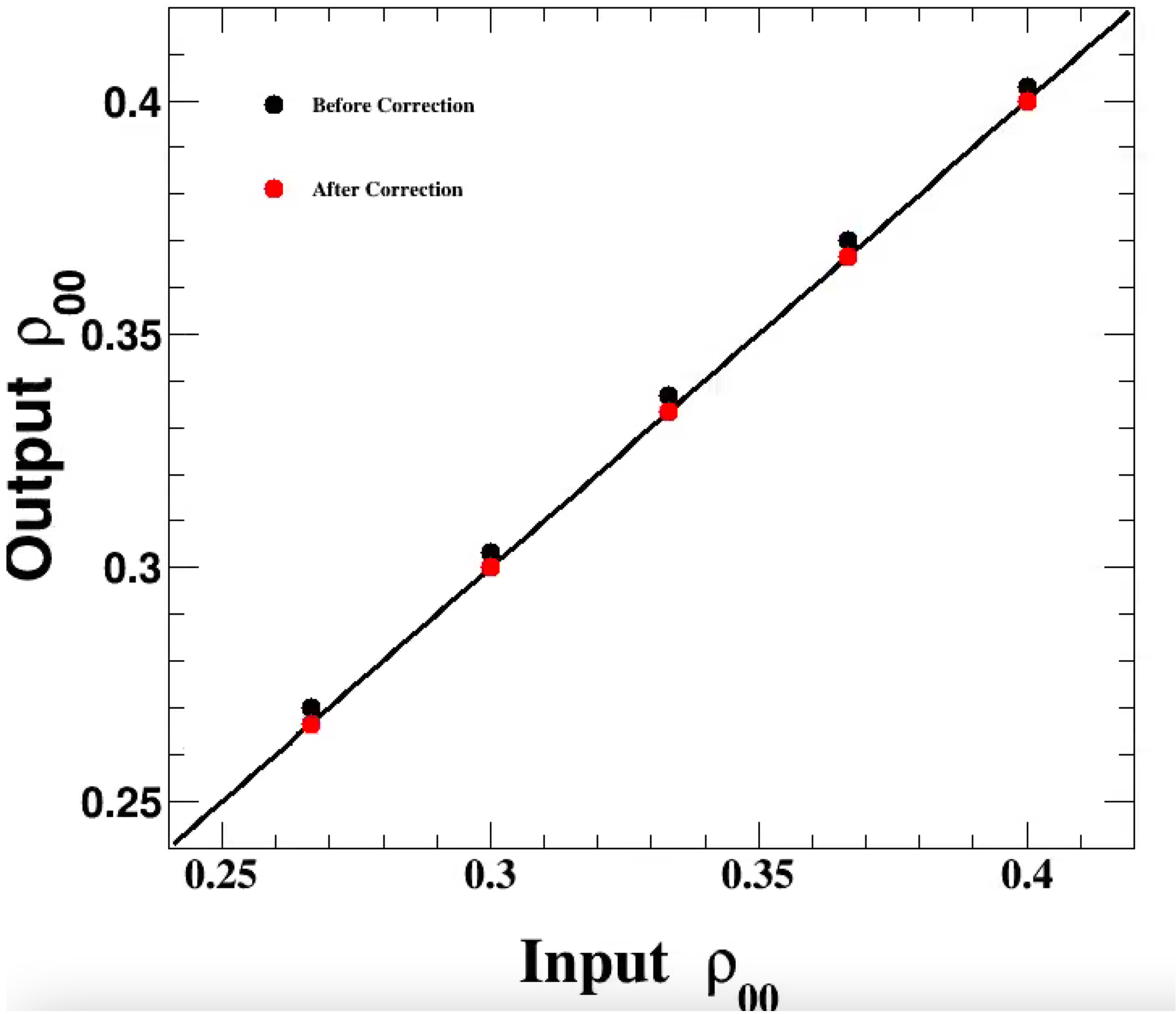
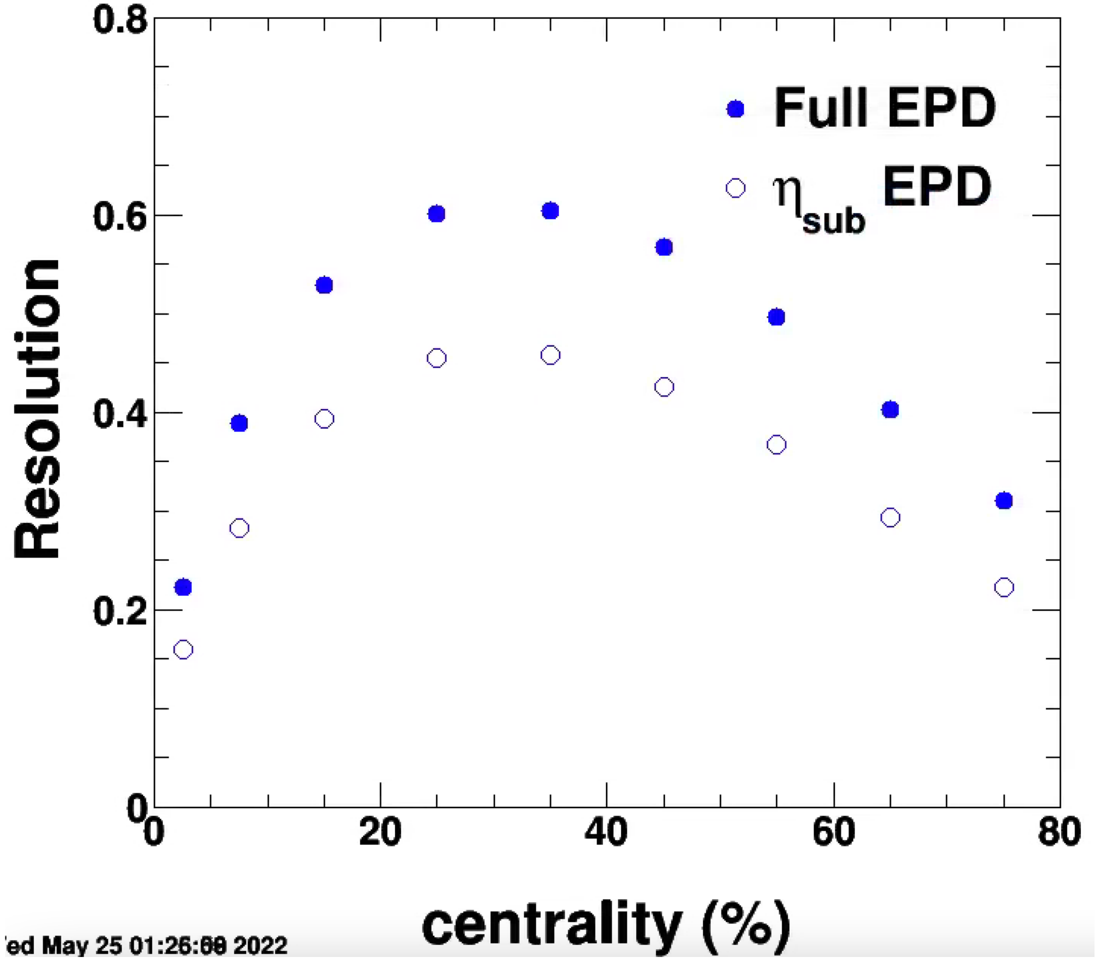
Acceptance Correction QA

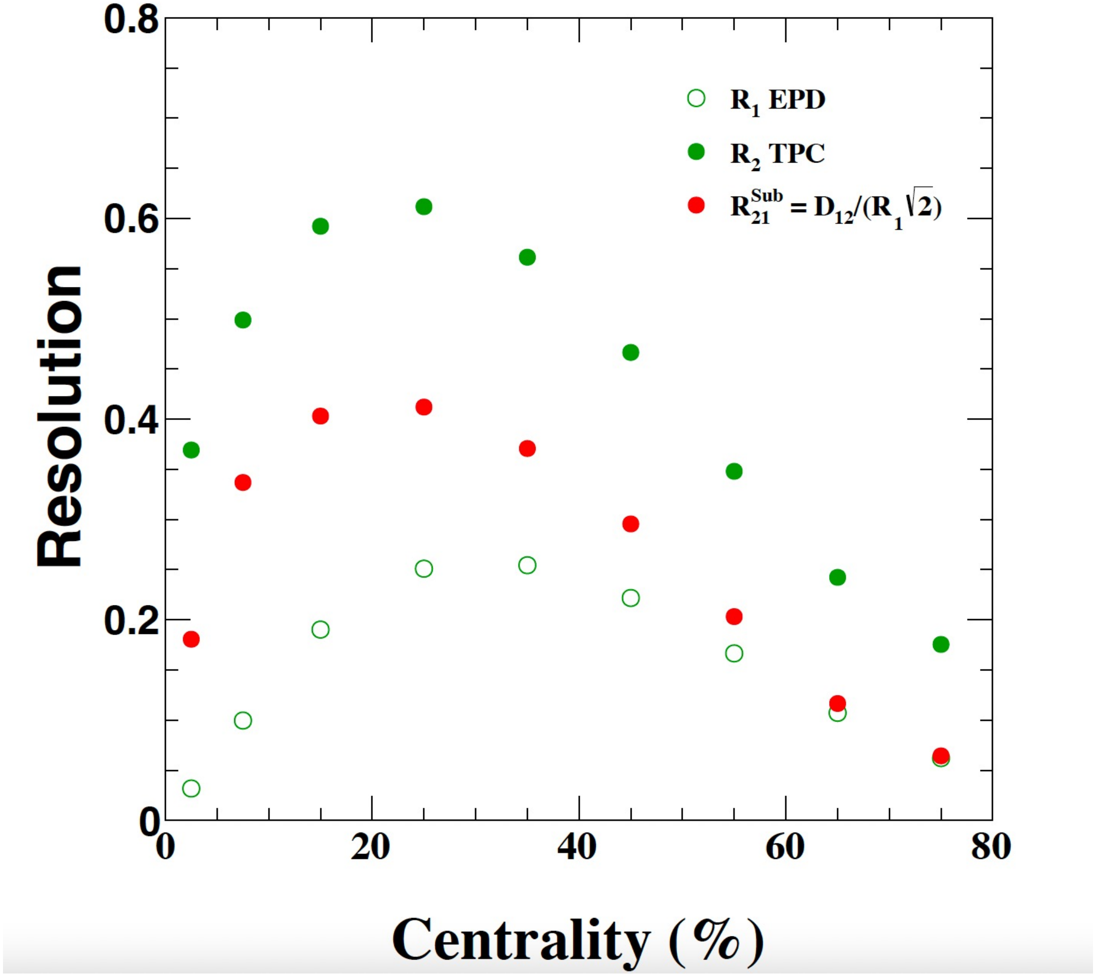


- Input a ρ_{00} value to acceptance simulation.
- Grab output ρ_{00} and apply acceptance correction.
- Input and acceptance corrected output match!

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

η weights implemented





ϕ-meson ρ_{00} vs p_T

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

BES-II Weighted average over p_T:

$\rho_{00}^{II} = 0.3512 \pm 0.0026$ (stat) ± 0.0013 (sys)

$\rho_{00}^{II} > 1/3$ with 6.15σ

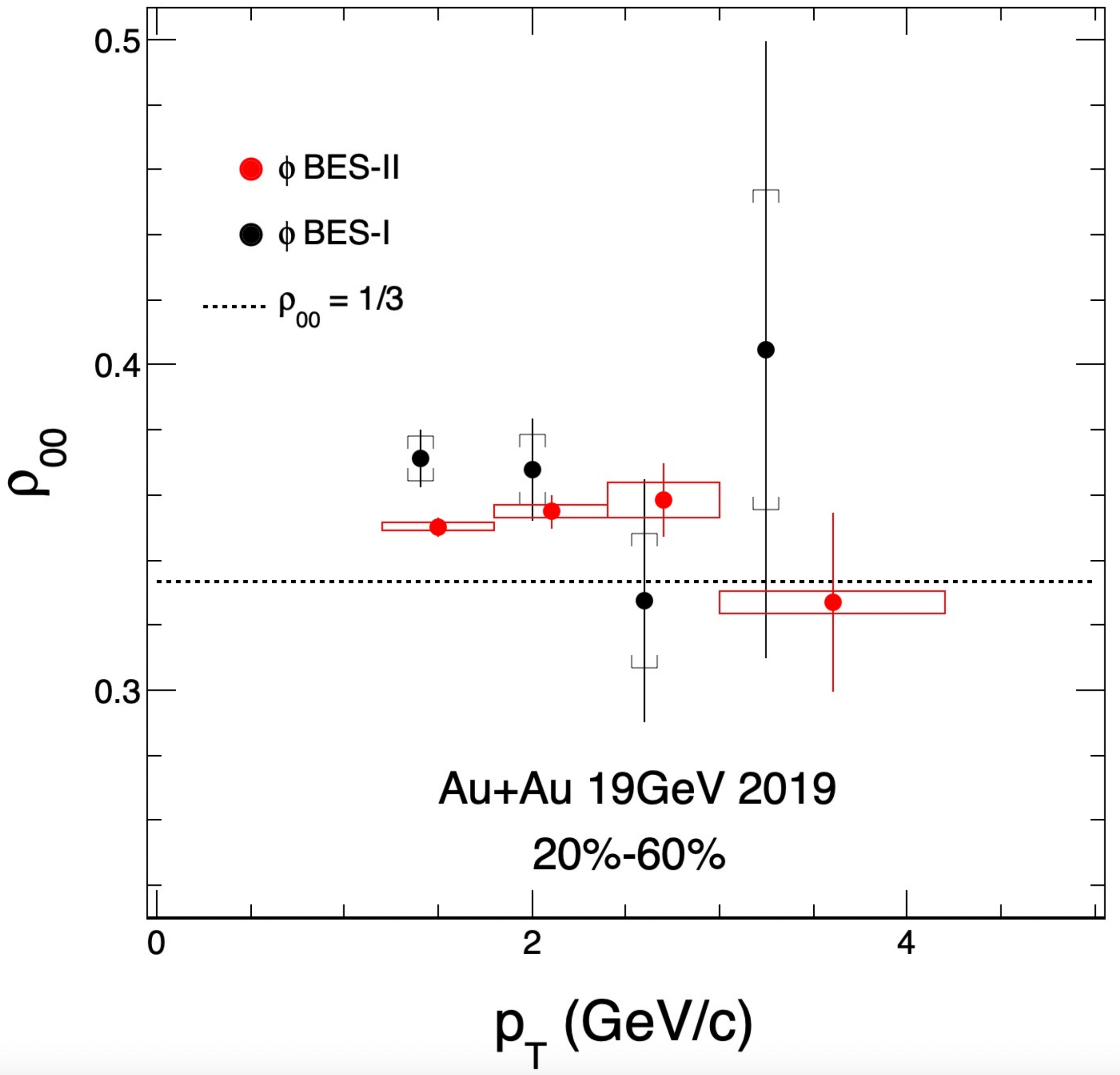
BES-I Weighted average over p_T:

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

$\rho_{00}^{I} > 1/3$ with 3.5σ

$\rho_{00}^{II} < \rho_{00}^{I}$ with 1.7σ

Non-trivial p_T dependence.



Default K^{*0} PID and Reconstruction settings

PID

$K^{+/-}$

$|DCA| < 2.0$

If TPC: $|n\sigma_K| < 2.0$

Else, use TOF: $0.16 < m2 < 0.36$

$\pi^{+/-}$

$|DCA| < 2.0$

If TPC: $|n\sigma_\pi| < 2.0$

Else, use TOF: $-0.2 < m2 < 0.15$

Fitting+BG subtraction

Rotated pairs background

Background normalized to tail of signal+background, m=[1.15,1.2] GeV

Breit-wigner + residual poly2 for fit

Fit region m = [0.77,1.06] GeV

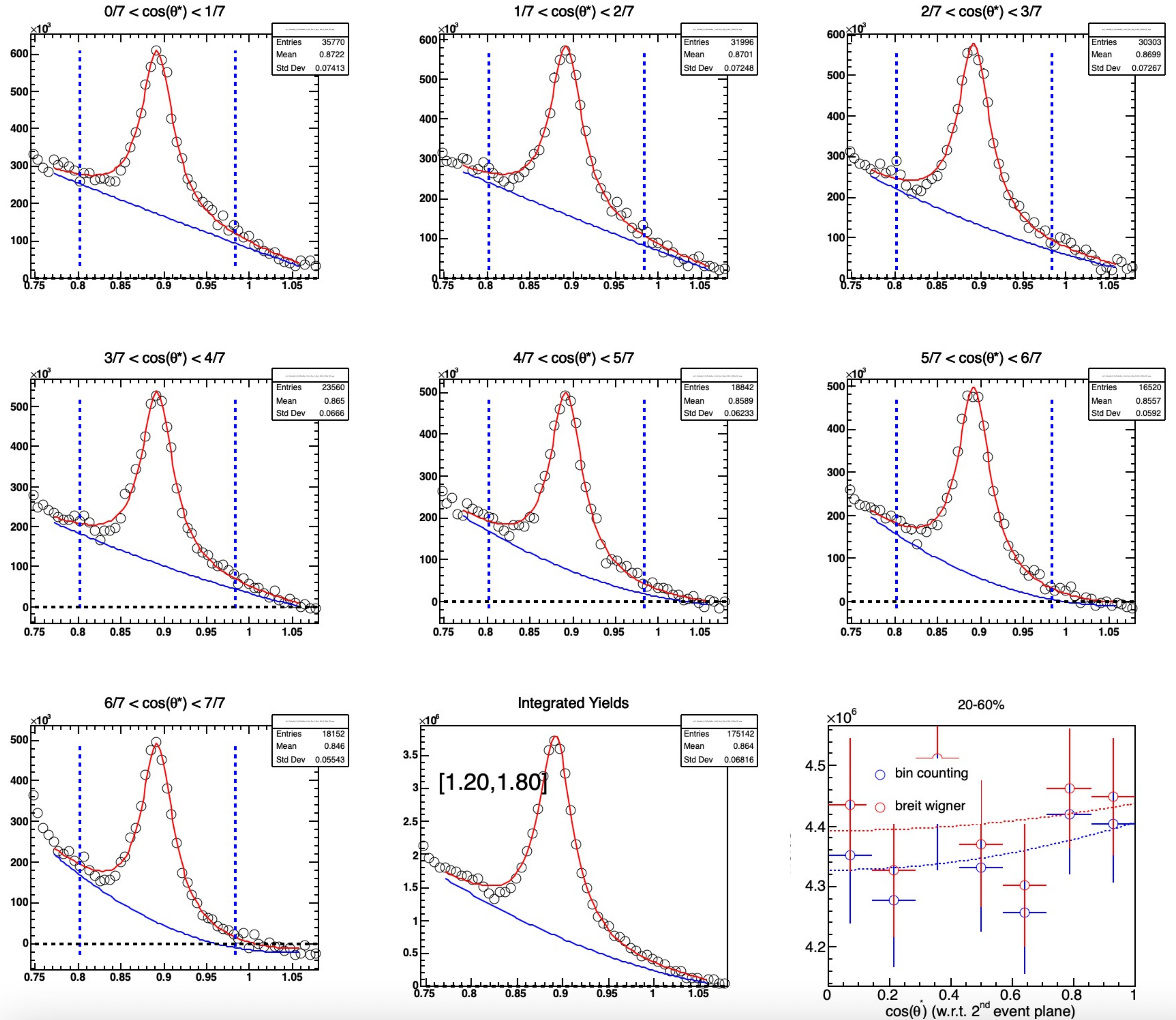
Integration signal extraction in region [m-2**Γ**,m-2**Γ**]

Raw K^{*0} Yields vs $\cos(\theta^{*})$

20-60% Centrality

$p_T = [1.2, 1.8]$ GeV/c

Poly2 residual backgrounds have similar shapes in each $\cos(\theta^{*})$ bin.



K^{*0} raw ρ_{00} vs p_T

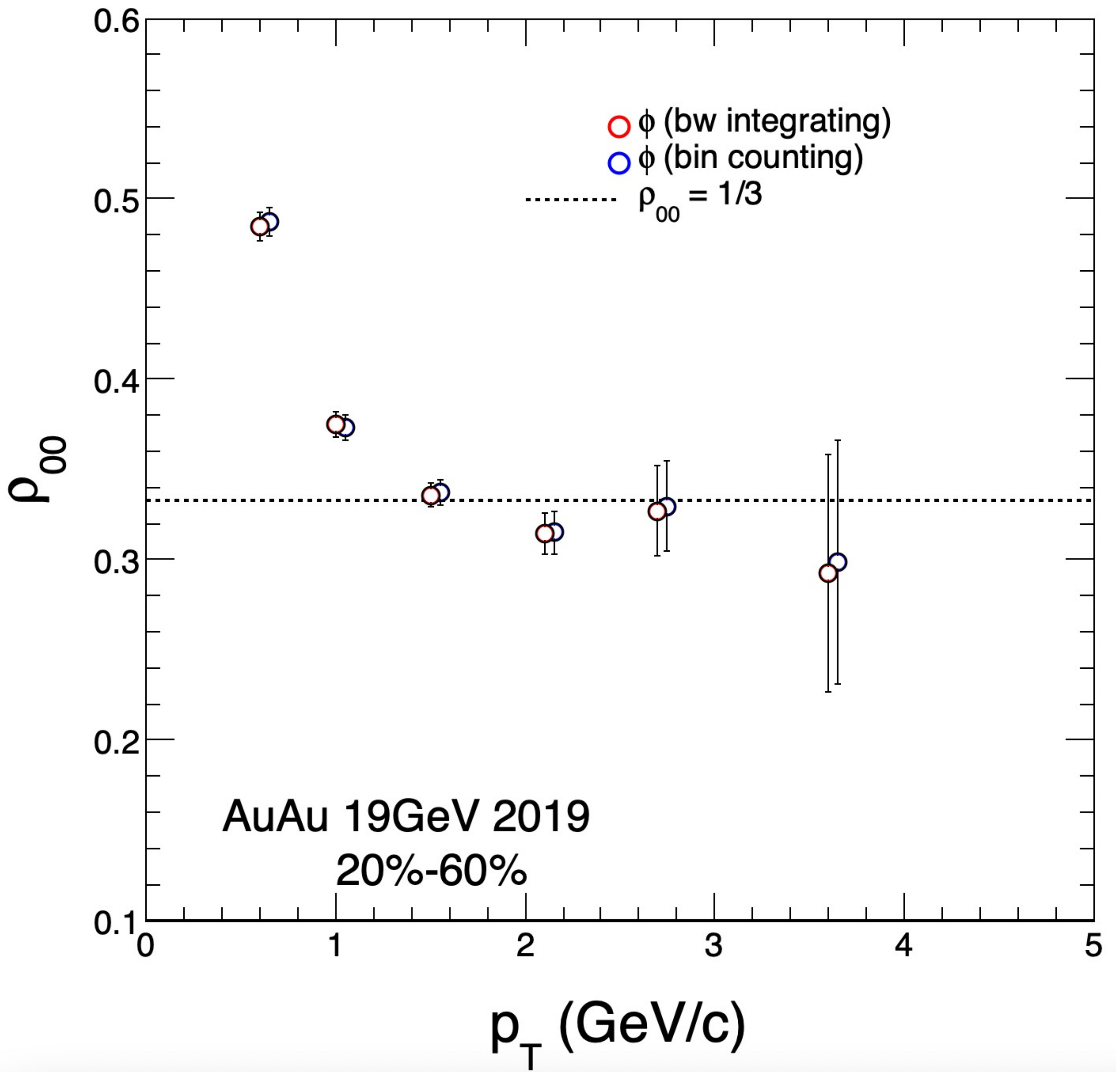
20-60% Centrality

Efficiency vs cos(θ*) will be performed with the same simulation procedure as ϕ.

No ToF Matching Efficiency.

Acceptance + Resolution correction.

We have everything for the resolution correction already.



Summary and Outlook

Efficiency vs. cos(θ*) linear trends are consistent between BES-I and BES-II.

First look at fully corrected ϕ-meson ρ_{00} for 19.6 GeV BES-II data set.

We want to do some more QA for the acceptance + resolution correction step.

First look at raw ρ_{00} for K^{*0} for 19.6 GeV BES-II data set.

We will perform efficiency, acceptance and resolution corrections very similarly to ϕ.

THANK YOU FOR YOUR ATTENTION!

BACKUP SLIDES

φ Meson Efficiency vs cos(θ*)

Using method laid out by Xu Sun in his analysis note from BES-I:

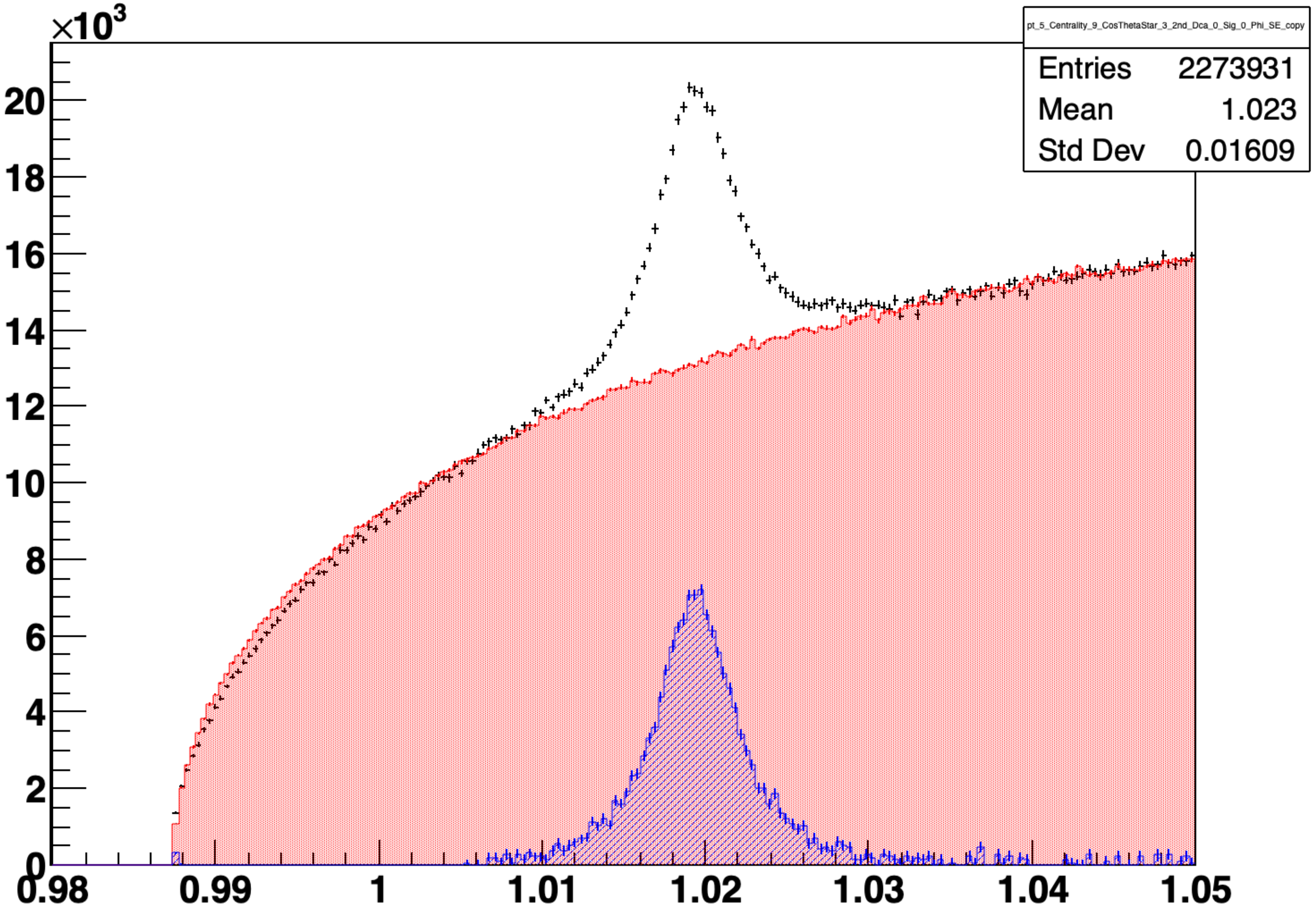
- Use Pythia6 for sim.

- Decayed K^+ and K^- will go through a MC process to simulate TPC and ToF effect.
- Two independent random numbers will be generated for each decay daughter and compared with TPC Kaon tracking efficiency and ToF matching efficiency (with different fitting procedure described in 3.1.3) in a specific binning as shown in Sec. 3.1.1 and 3.1.3.
- If both random numbers are smaller than the corresponding Kaon efficiency, this track will be kept, otherwise, this track will be killed ($\epsilon_{p_T,|\eta|<1} = \epsilon_{TPC} * \epsilon_{ToF}$).
- If both K^+ and K^- survived from above MC process, reconstructed ϕ-meson will be filled into a $\cos(\theta^*)$ histogram and compared with MC distribution to extract ϕ-meson efficiency.

ToF Matching Efficiency

- Evaluated using real data.
- N_{TPC} = tracks passing strict $|n\sigma|<0.6$ 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}
- There is some hadron contamination addressed by applying fit excluding specific regions of matching efficiency.

φ Meson Signal Extraction



Kaon cuts
$0.16 < M^2 < 0.36$ GeV/c²
$|n\sigma| < 2.5$

Full 19.6 GeV data set.

Mixed event background normalized to the same event signal between [1.04,1.05].

Subtract normalized mixed event background from same event signal.

φ Meson Invariant Mass

20-60% Centrality
$1.2 < p_T < 1.8$ GeV/c

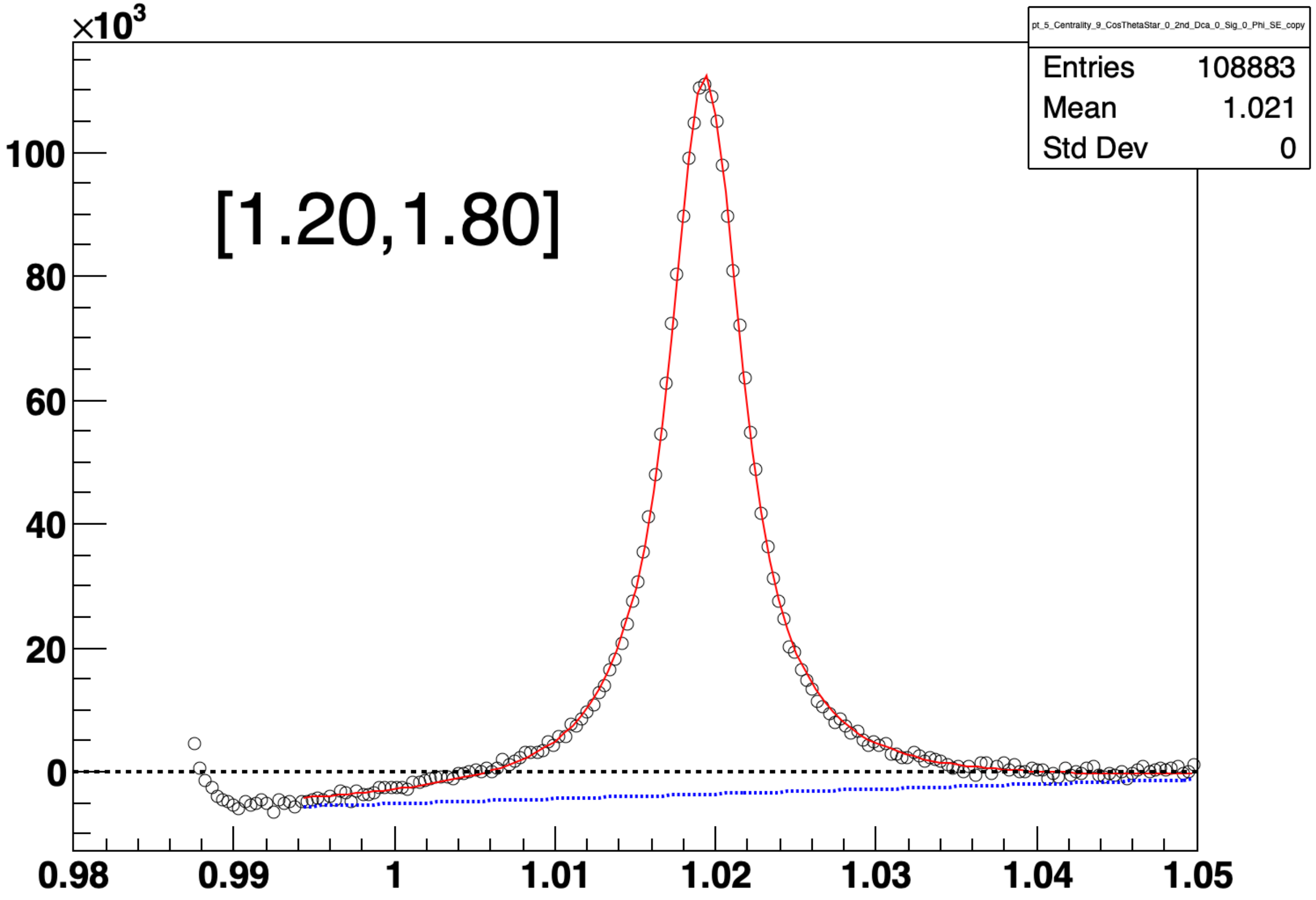
Mass yields fit with Breit-Wigner + poly1:

$$BW(m_{inv}) = \frac{1}{2\pi}\frac{A\Gamma}{(m-m_{\phi})^2+(\Gamma/2)^2}$$

φ-meson yields are found by bin counting and integrating between $[m_{\phi}-2\Gamma, m_{\phi}+2\Gamma]$ in each $\cos(\theta^*)$ bin

Γ and m_{φ} are fixed from $\cos(\theta^*)$ integrated yields.

Fit each $\cos(\theta^*)$ with BW+poly1 with fixed values from above .



Invariant Mass Yields

Bin counting

- Simply count the individual bins between $[m_\phi - 2\Gamma, m_\phi + 2\Gamma]$ and subtract integrated linear background in same range.

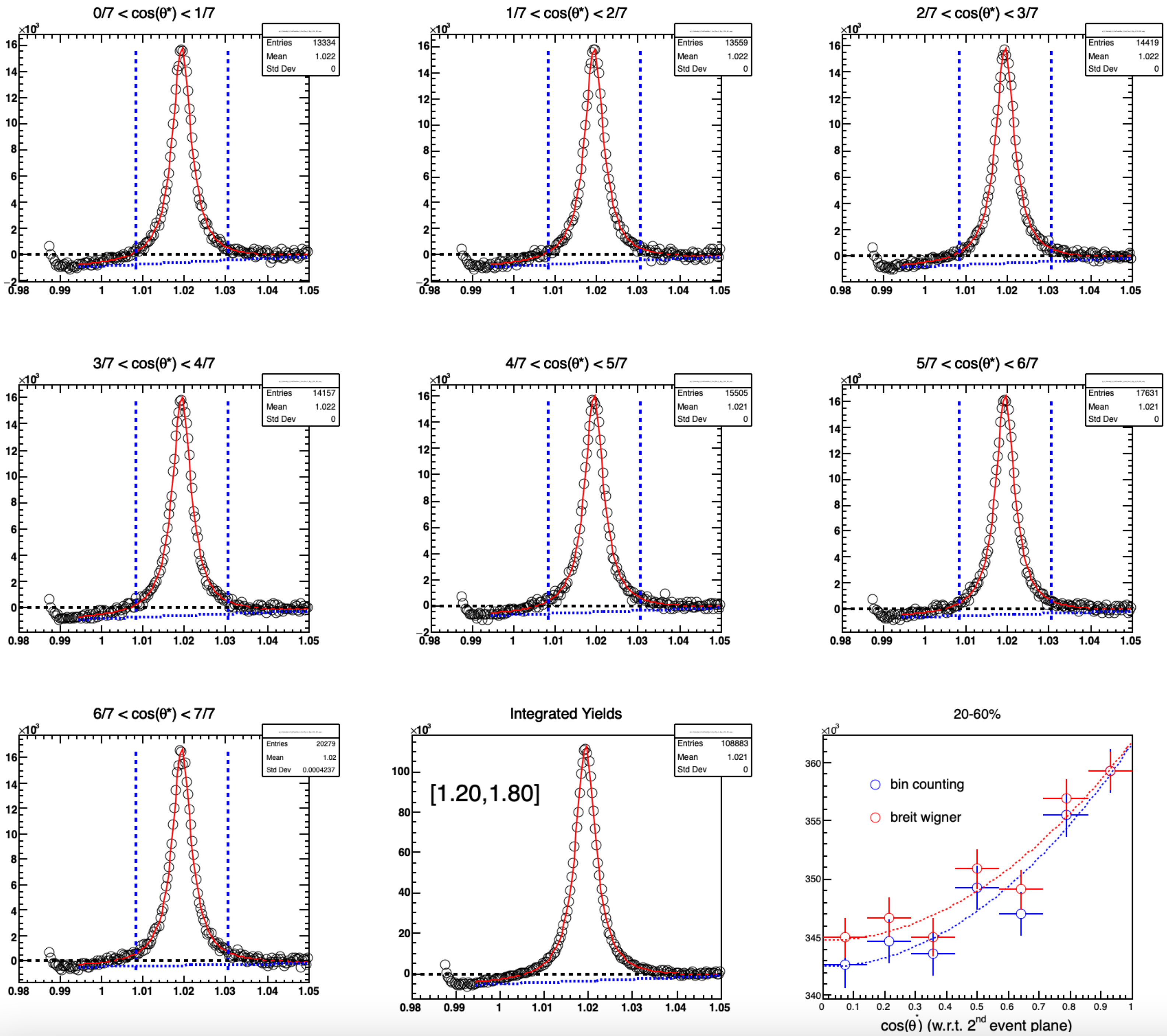
Integrated

- Use BW+poly1 fit in individual $\cos(\theta^*)$ bins and subtract integrated linear background in same range.

Fit yields vs $\cos(\theta^*)$ with following function to extract ρ_{00}.

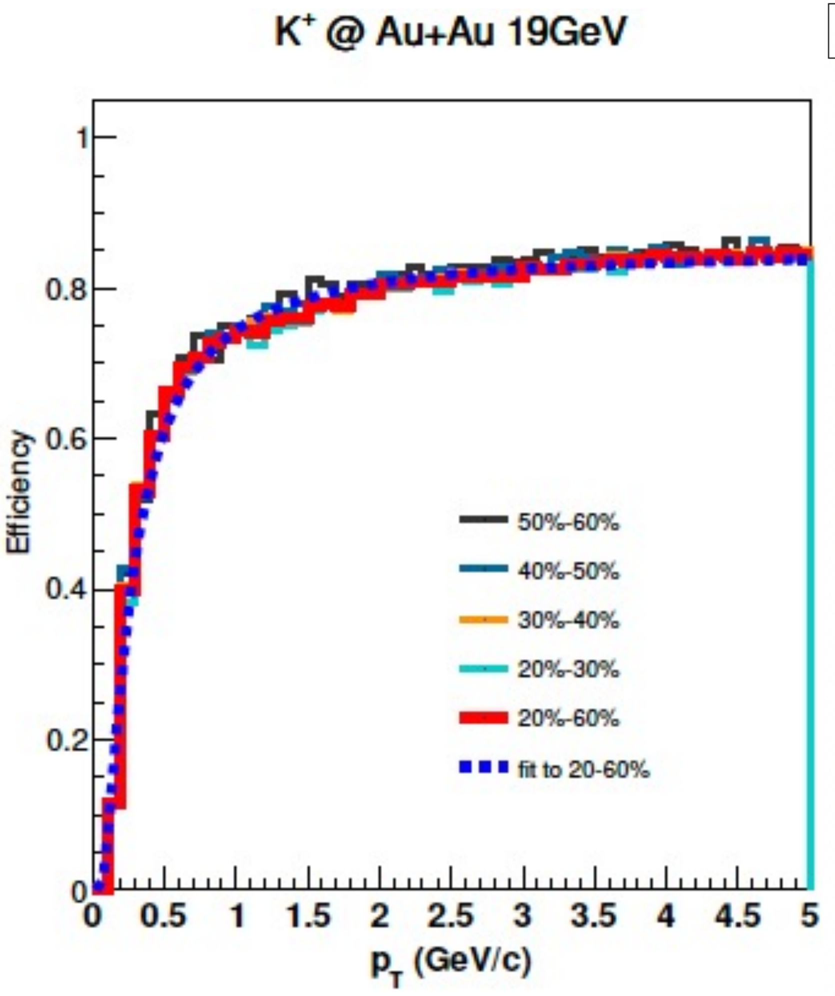
$$\frac{dN}{d\cos\theta^*} = N_0 \times [(1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta$$

Nucl. Phys.B18,332(1970)

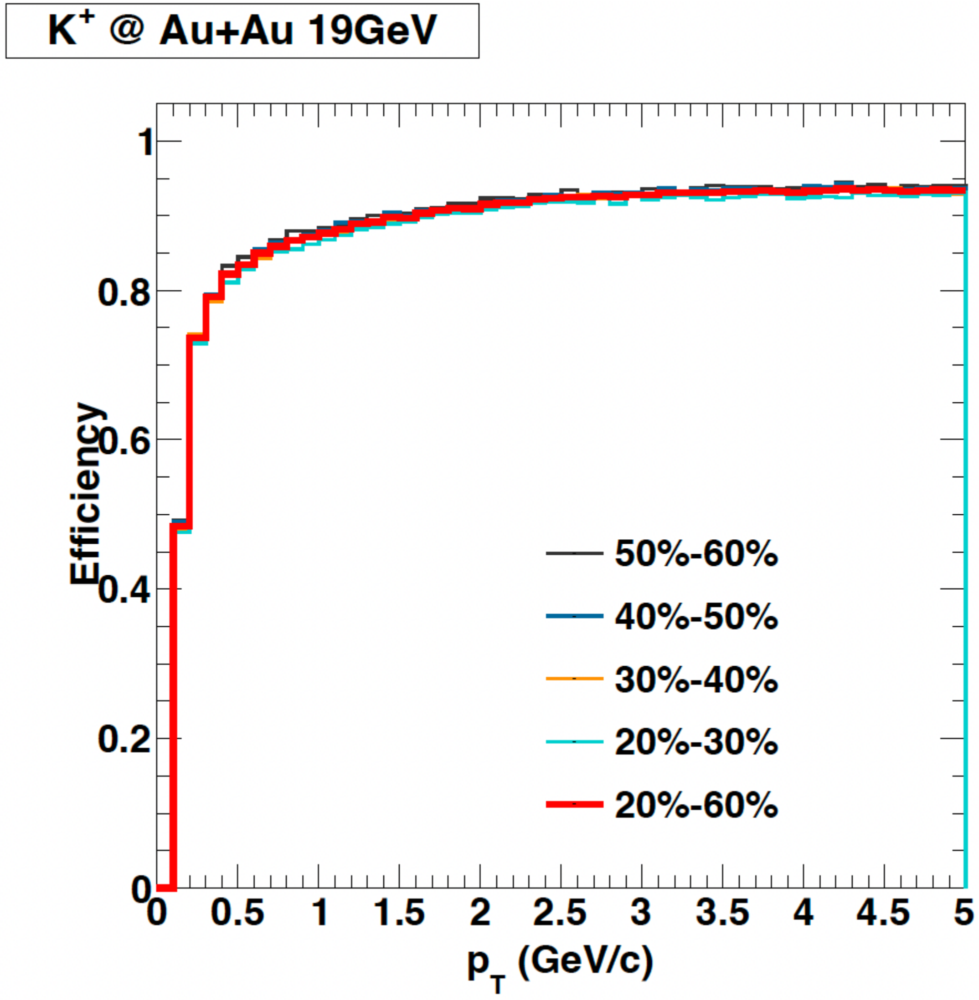


BES-I/II TPC Efficiency Comparison

BES-I



BES-II

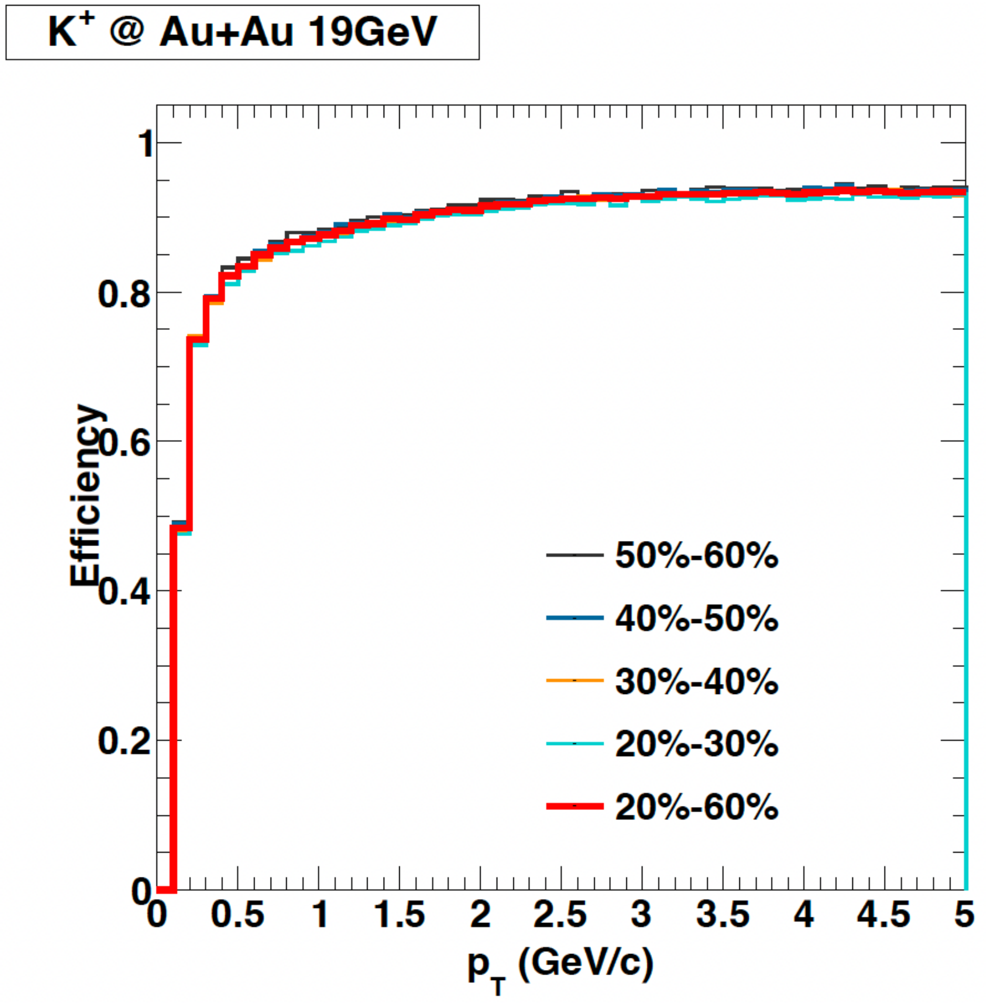


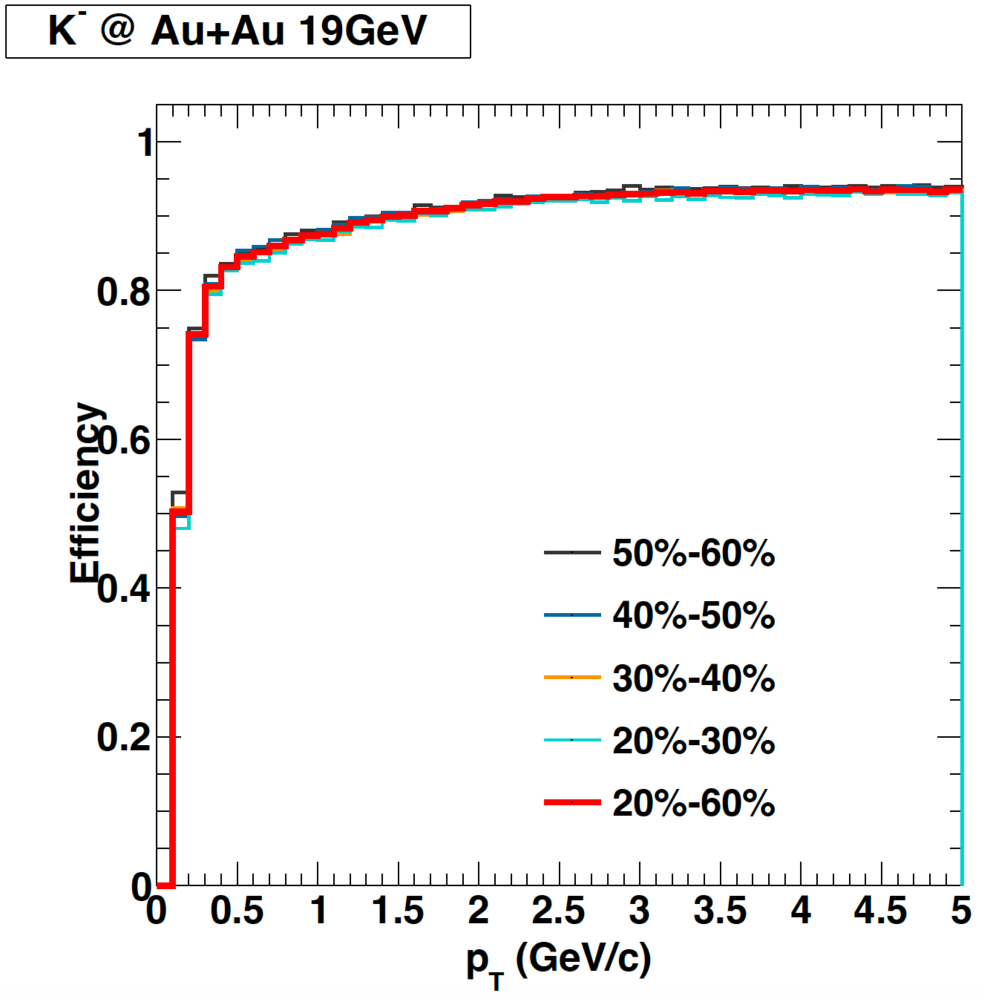
Standard STAR embedding procedure.

We embed individual daughter particles $K^{+/-}$

BES-II has ~10% higher TPC Tracking efficiency than BES-I.

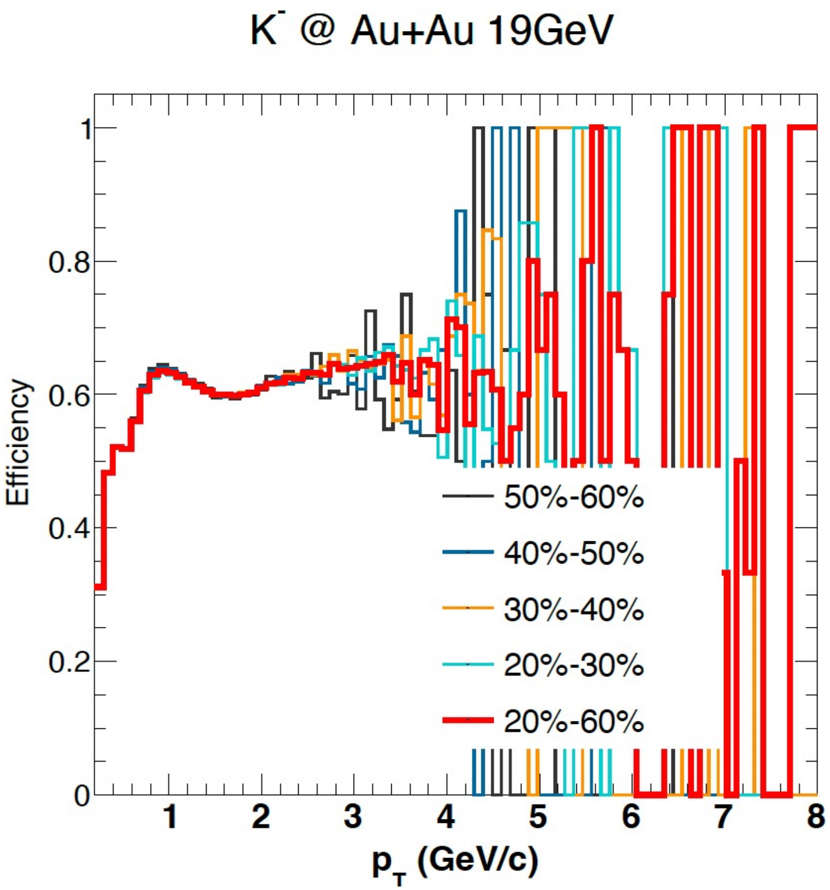
- TPC upgrades


K+ @ Au+Au 19GeV
Efficiency
1
0.8
0.6
0.4
0.2
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
pT (GeV/c)
50%-60%
40%-50%
30%-40%
20%-30%
20%-60%

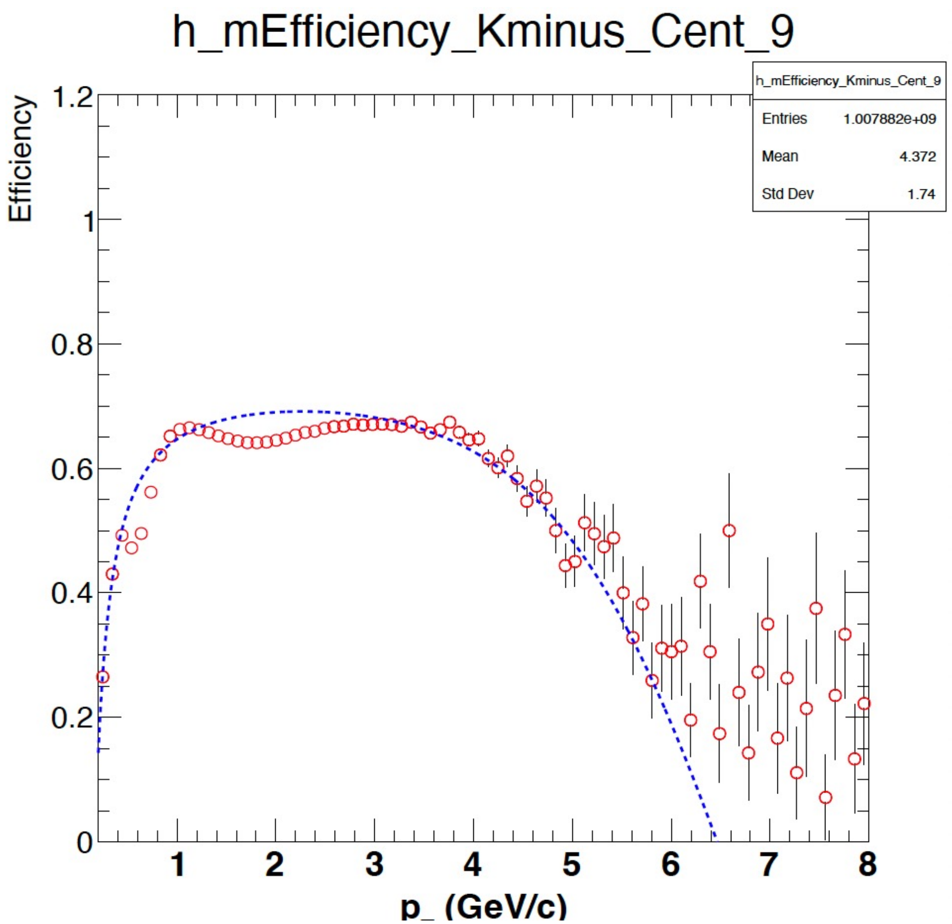

K- @ Au+Au 19GeV
Efficiency
1
0.8
0.6
0.4
0.2
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
pT (GeV/c)
50%-60%
40%-50%
30%-40%
20%-30%
20%-60%

BES-I/II ToF Matching Efficiency Comparison

BES-I



BES-II

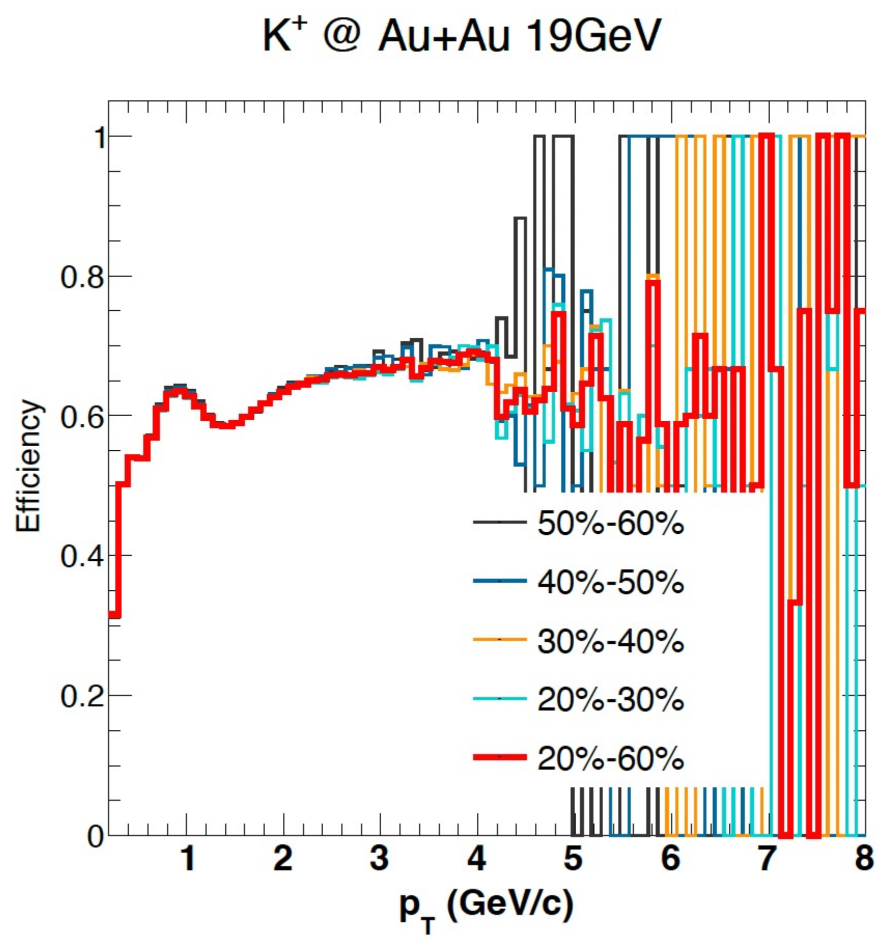


Comparing K- 20-60% for BES-I to BES-II

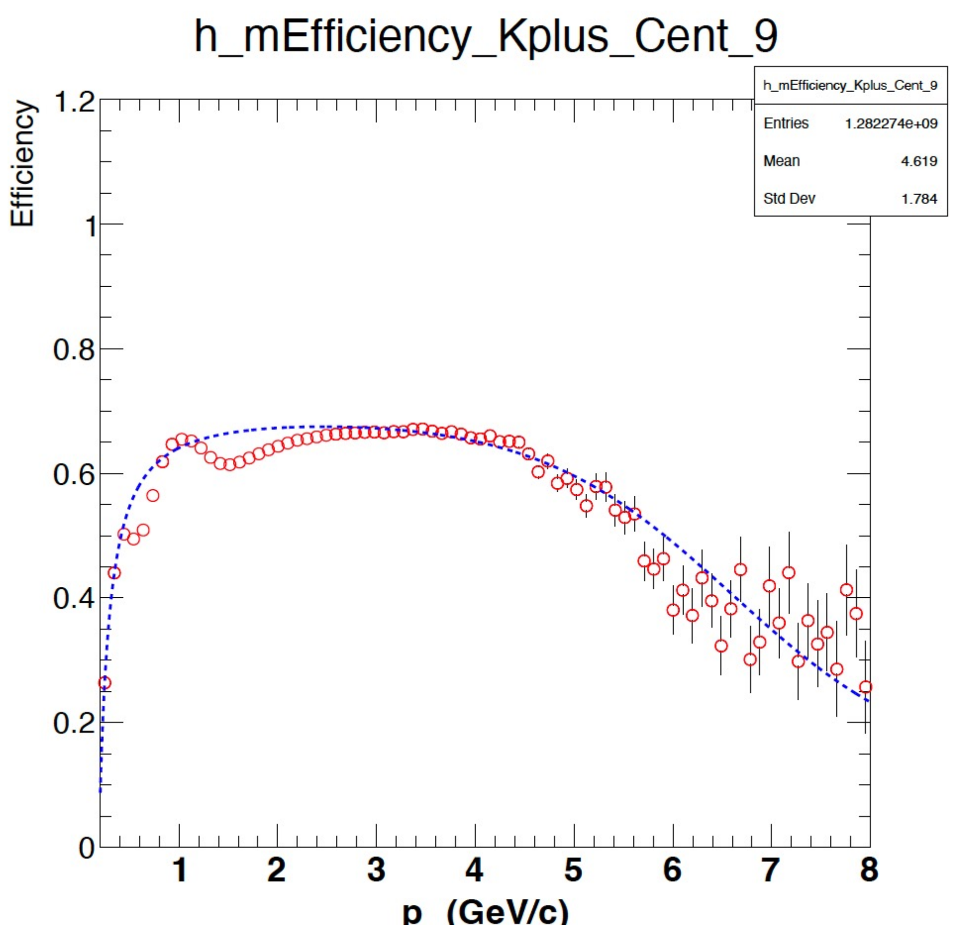
Note: Scales are slightly different

BES-I/II ToF Matching Efficiency Comparison

BES-I



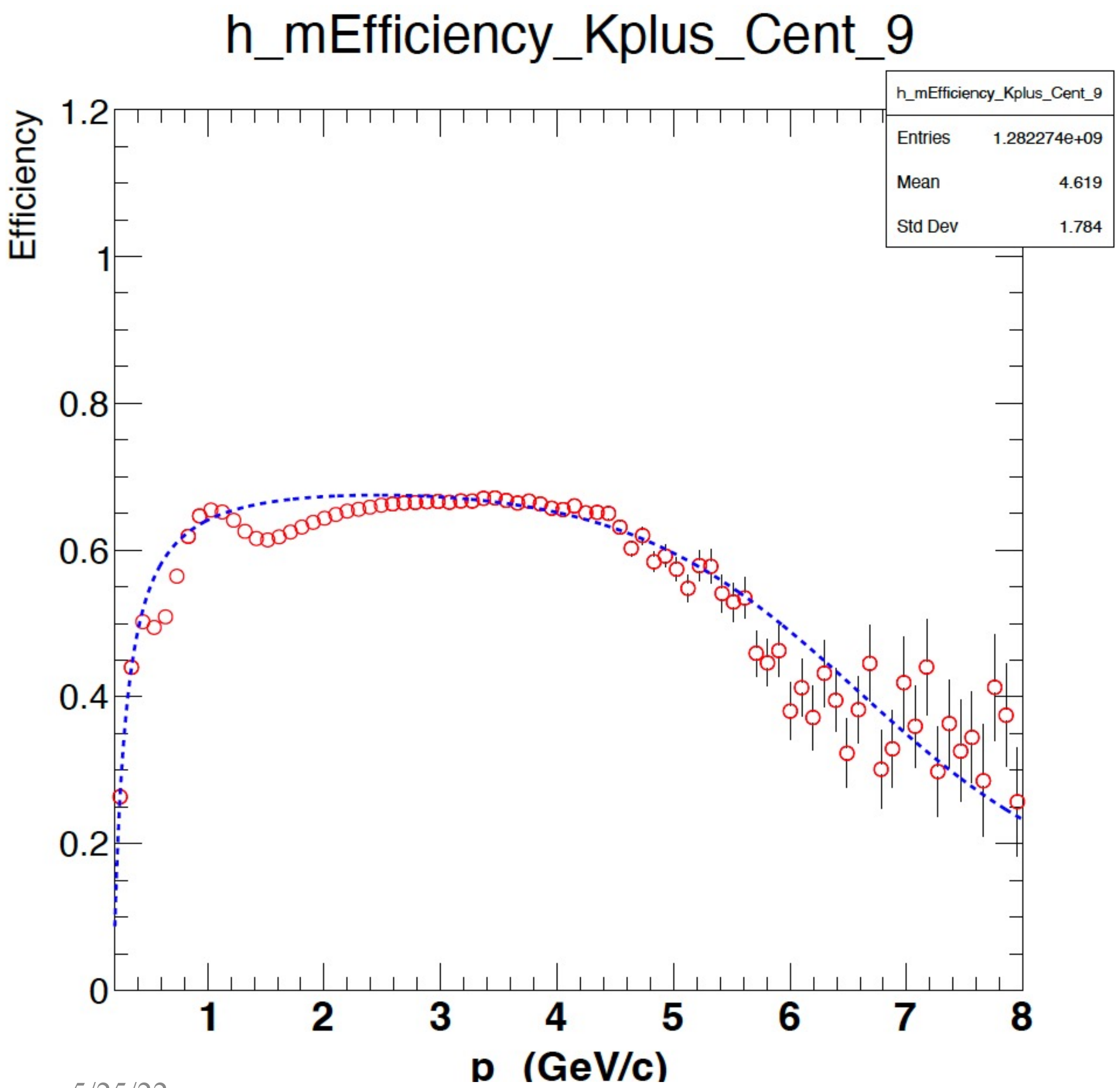
BES-II

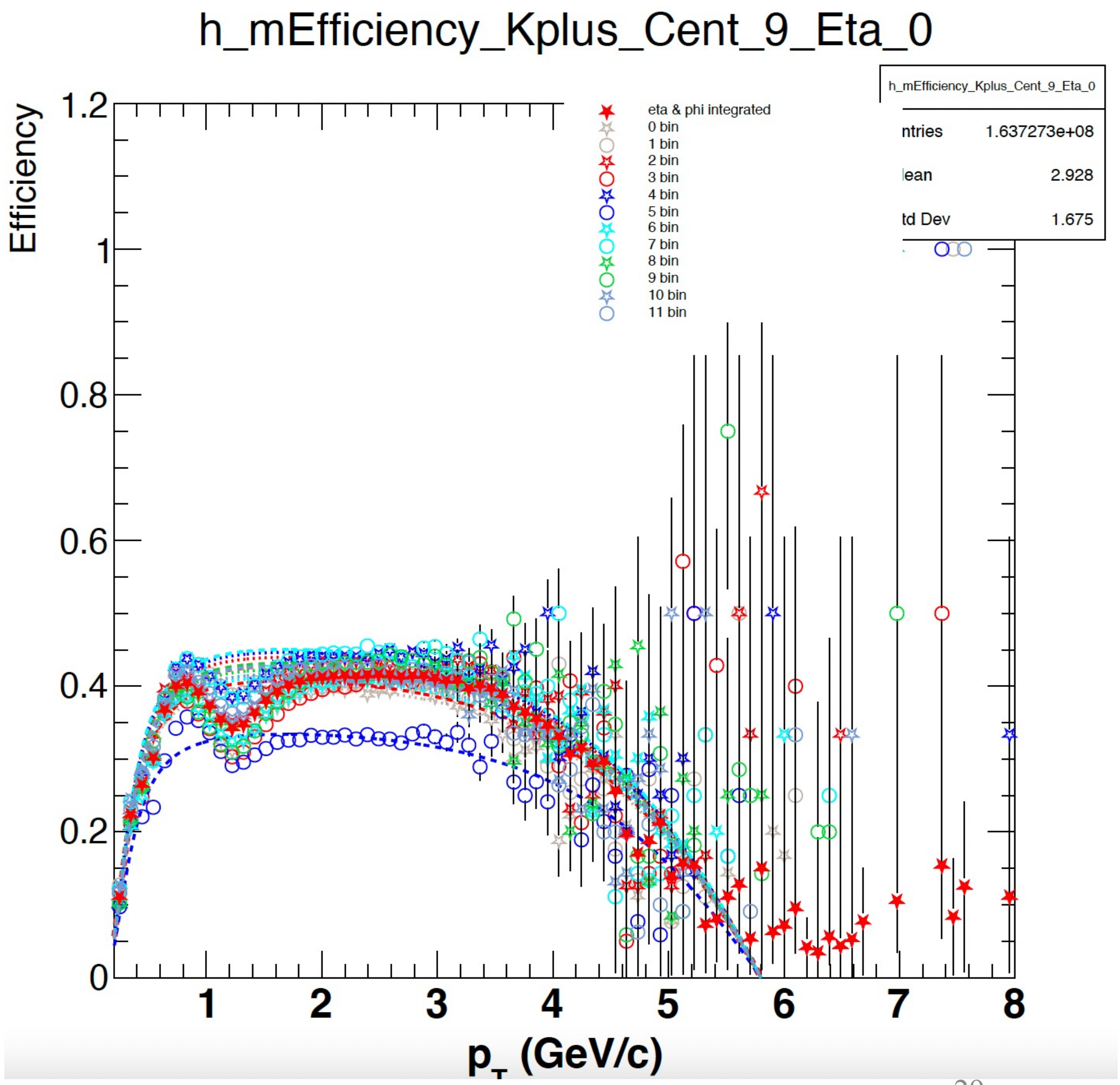


Comparing K+

20-60% for BES-I to BES-II

Note: scales are slightly different


h_mEfficiency_Kplus_Cent_9
h_mEfficiency_Kplus_Cent_9
Entries 1.282274e+09
Mean 4.619
Std Dev 1.784
Efficiency
p (GeV/c)


h_mEfficiency_Kplus_Cent_9_Eta_0
h_mEfficiency_Kplus_Cent_9_Eta_0
ntries 1.637273e+08
lean 2.928
td Dev 1.675
eta & phi integrated
0 bin
1 bin
2 bin
3 bin
4 bin
5 bin
6 bin
7 bin
8 bin
9 bin
10 bin
11 bin
Efficiency
p_T (GeV/c)

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. Calculate ρ_{00} for each variation and calculate the sources error with:

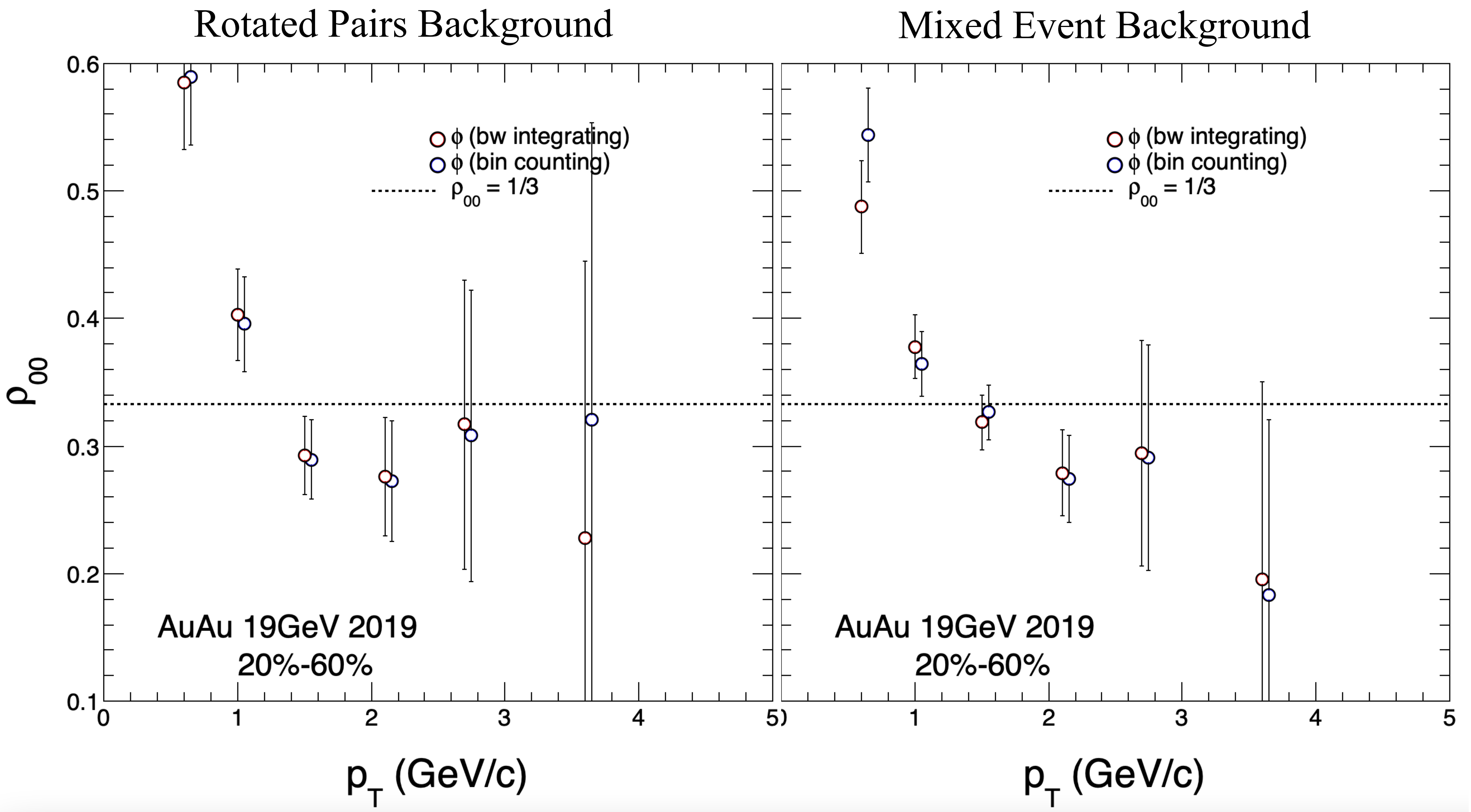
$$\Delta\rho^i_{00,sys} = \frac{\rho^i_{00,max} - \rho^i_{00,min}}{\sqrt{12}}$$

3. Combine all sources of systematics:

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

	Central	Variations
dca	< 2.0	< 2.0, < 2.5, < 3.0
$\lvert n\sigma_K \rvert$	< 2.5	< 2.0, < 2.5, < 3.0
Normalization range for mixed-events background	[1.04, 1.05]	[1.04, 1.05], [0.99,1.00] and both
Yield extraction	breit-wigner integration	bin counting and breit-wigner integration
Counting and integration range	$< 2.0\sigma$	$< 2.0\sigma$, $< 2.5\sigma$, $< 3.0\sigma$

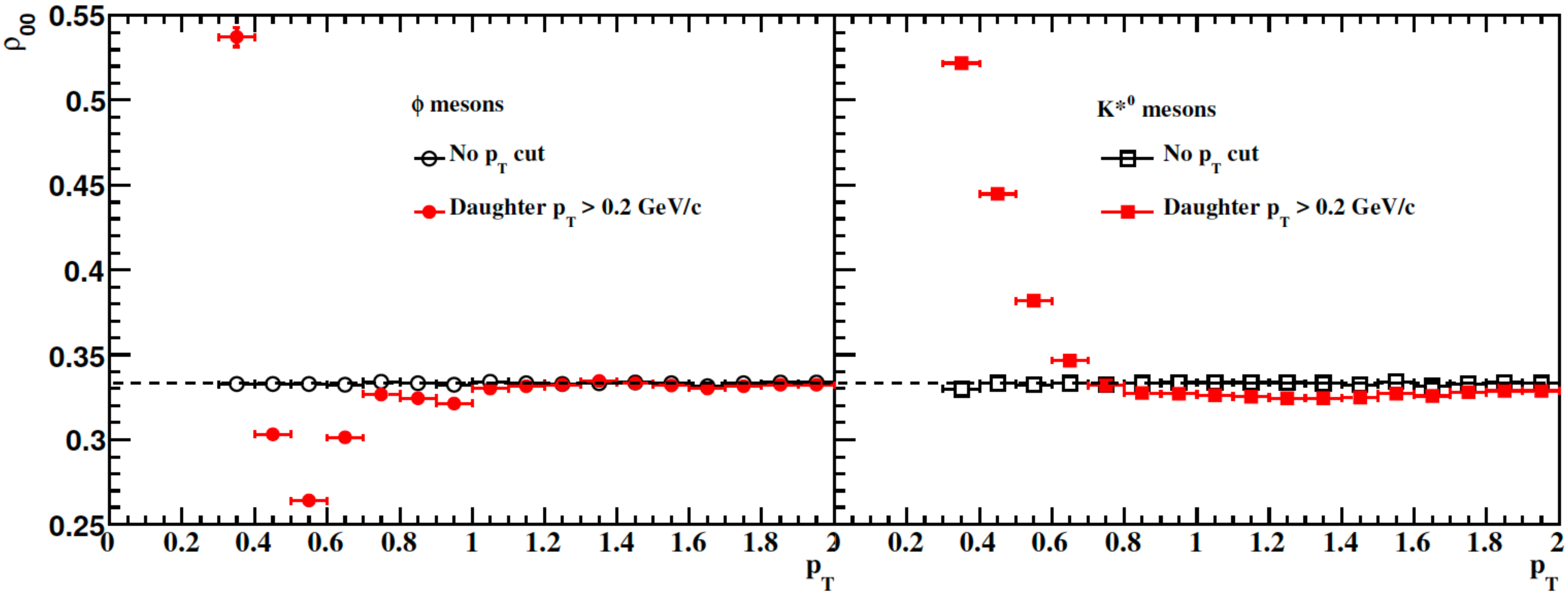
K^{*0} ρ_{00} vs p_T



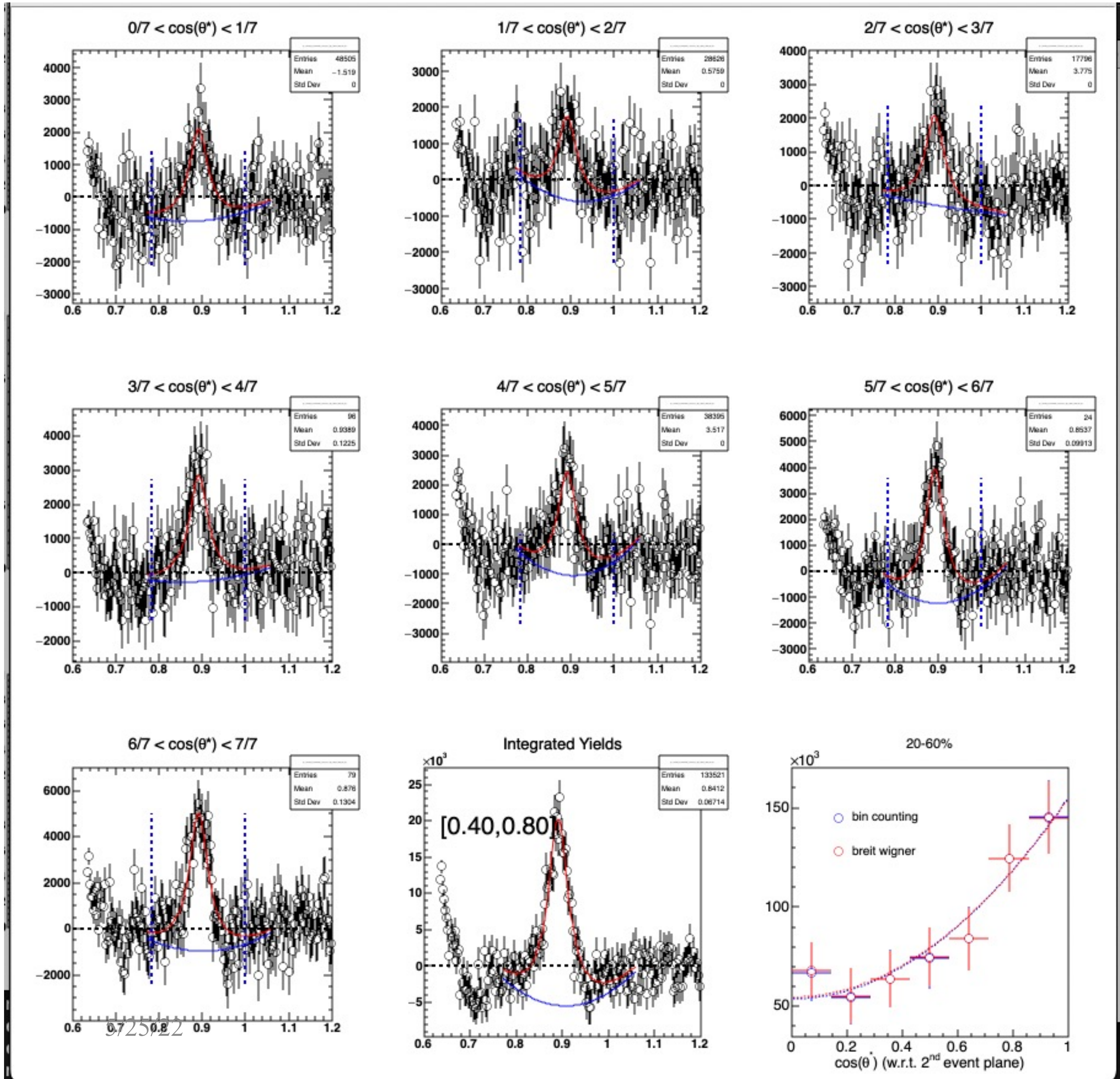
Methods consistent within uncertainties for $p_T > 0.8$ GeV/c.

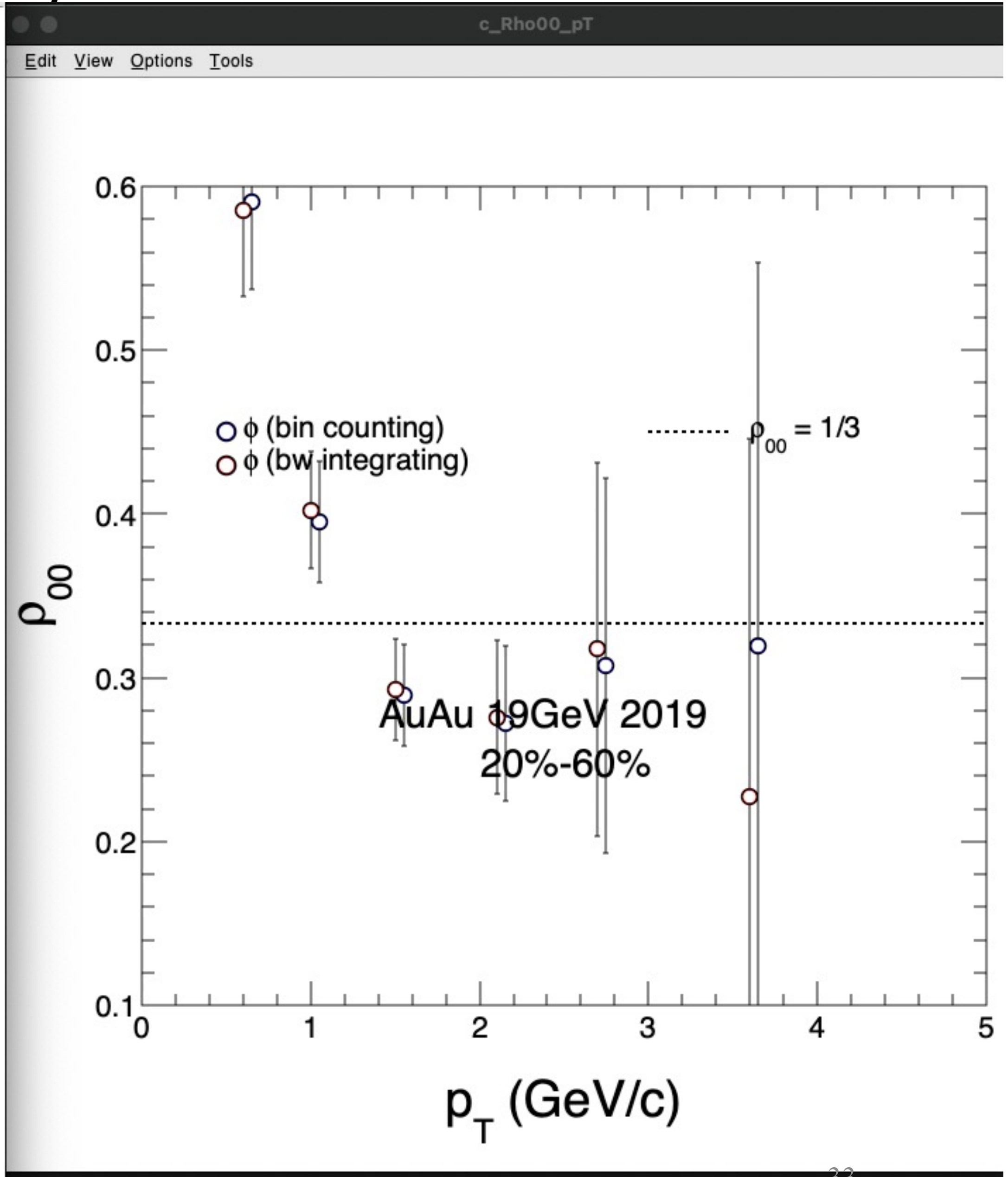
Increase in K^{*0} ρ_{00} in low p_T region

- Loss of information due to minimum p_T cut.
- Below results are from simulation.

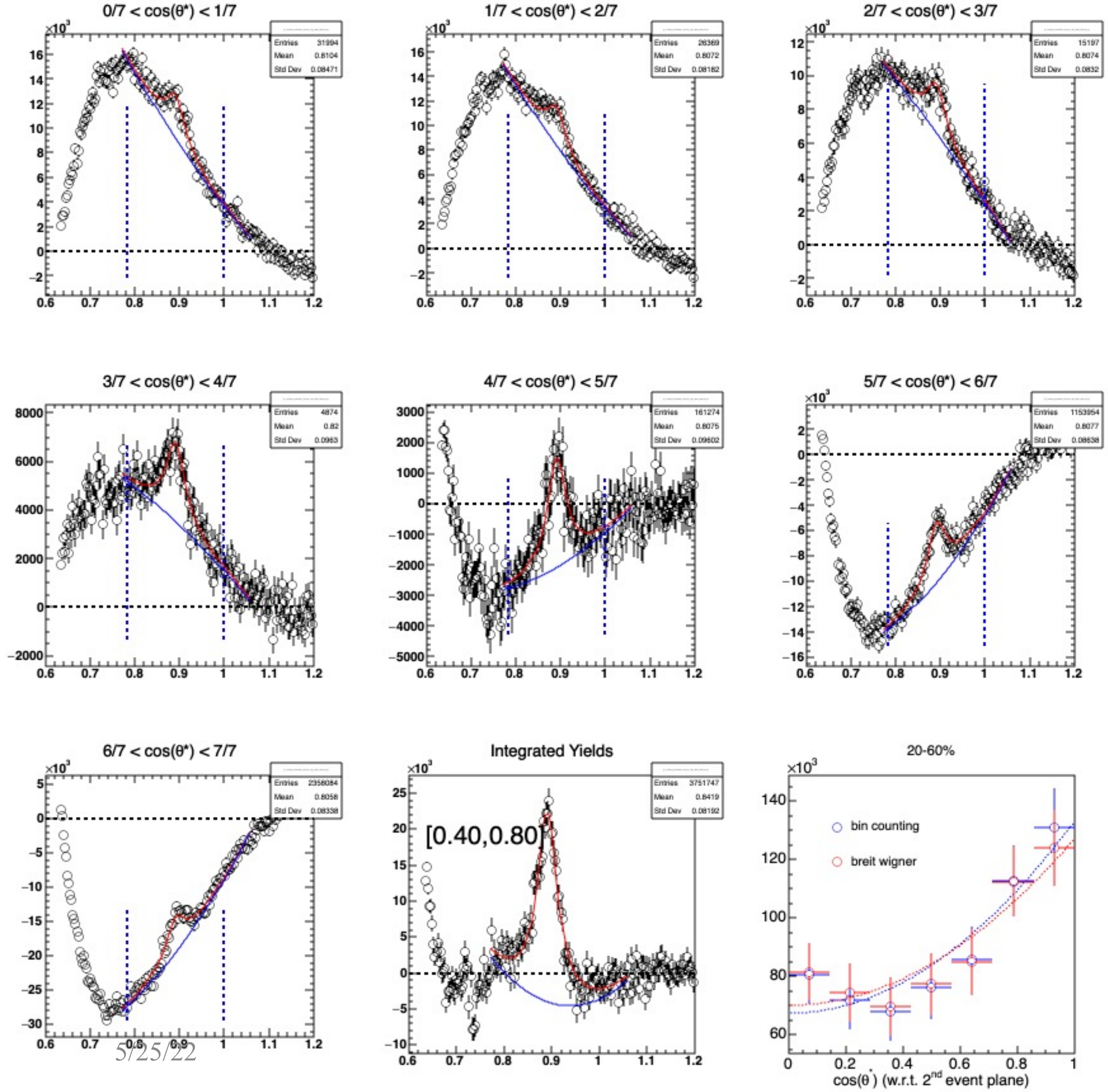


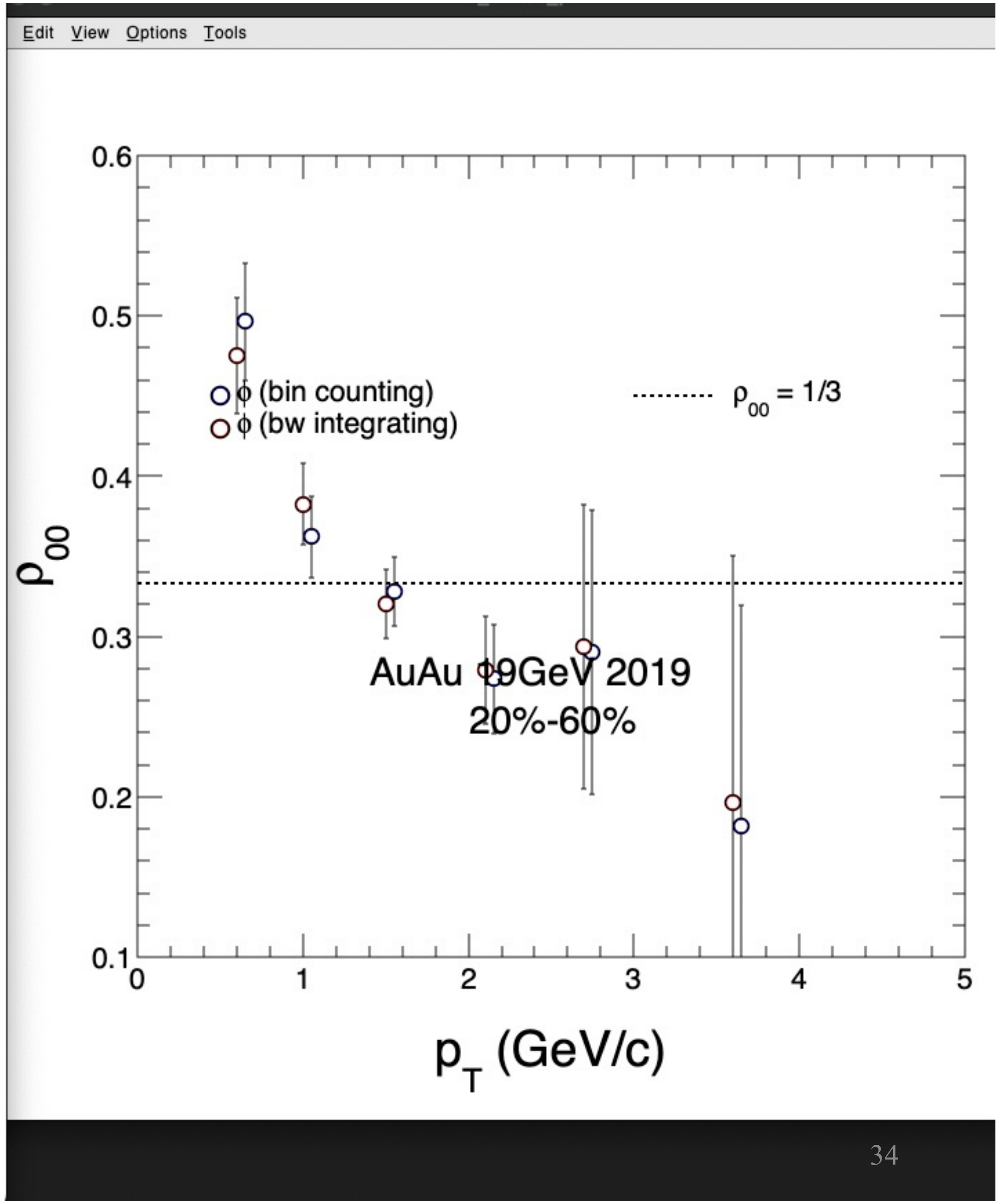
Rotated Same Event BG, ToF && TPC



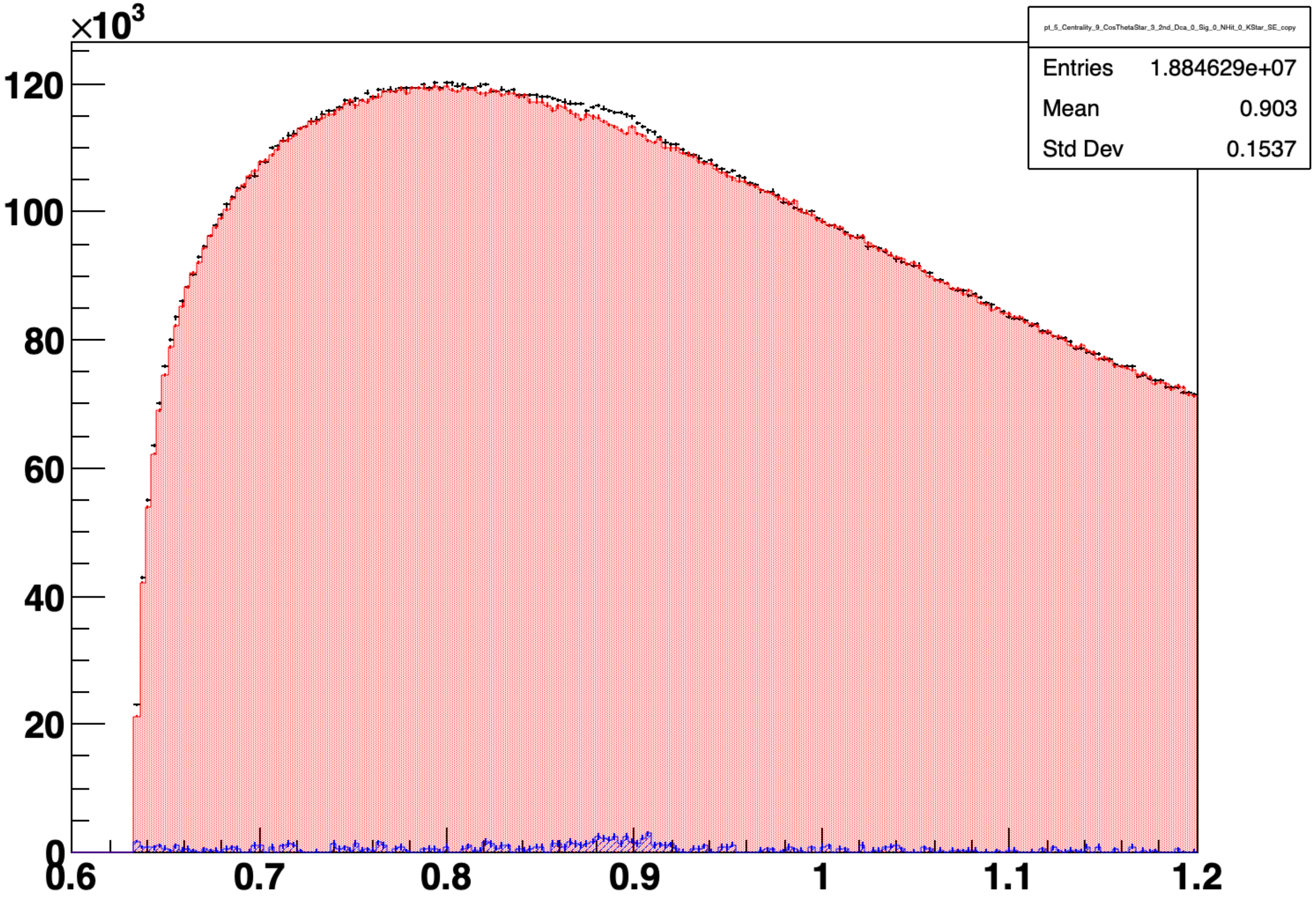


Mixed Event BG – 5 Psi2 bins, 10 v2 bins, ToF && TPC





K^{*0} Meson Signal Extraction



Kaon cuts

$0.16 < M^2 < 0.36$ GeV/c^2

$|n\sigma| < 2.0$

Pion cuts

$-0.2 < M^2 < 0.15$ GeV/c^2

$|n\sigma| < 2.0$

~10% of 19.6 GeV data set.

Rotated pairs background normalized to the same event signal between [1.15,1.20].

Subtract normalized rotated event background from same event signal.

Performed same analysis with mixed event background.

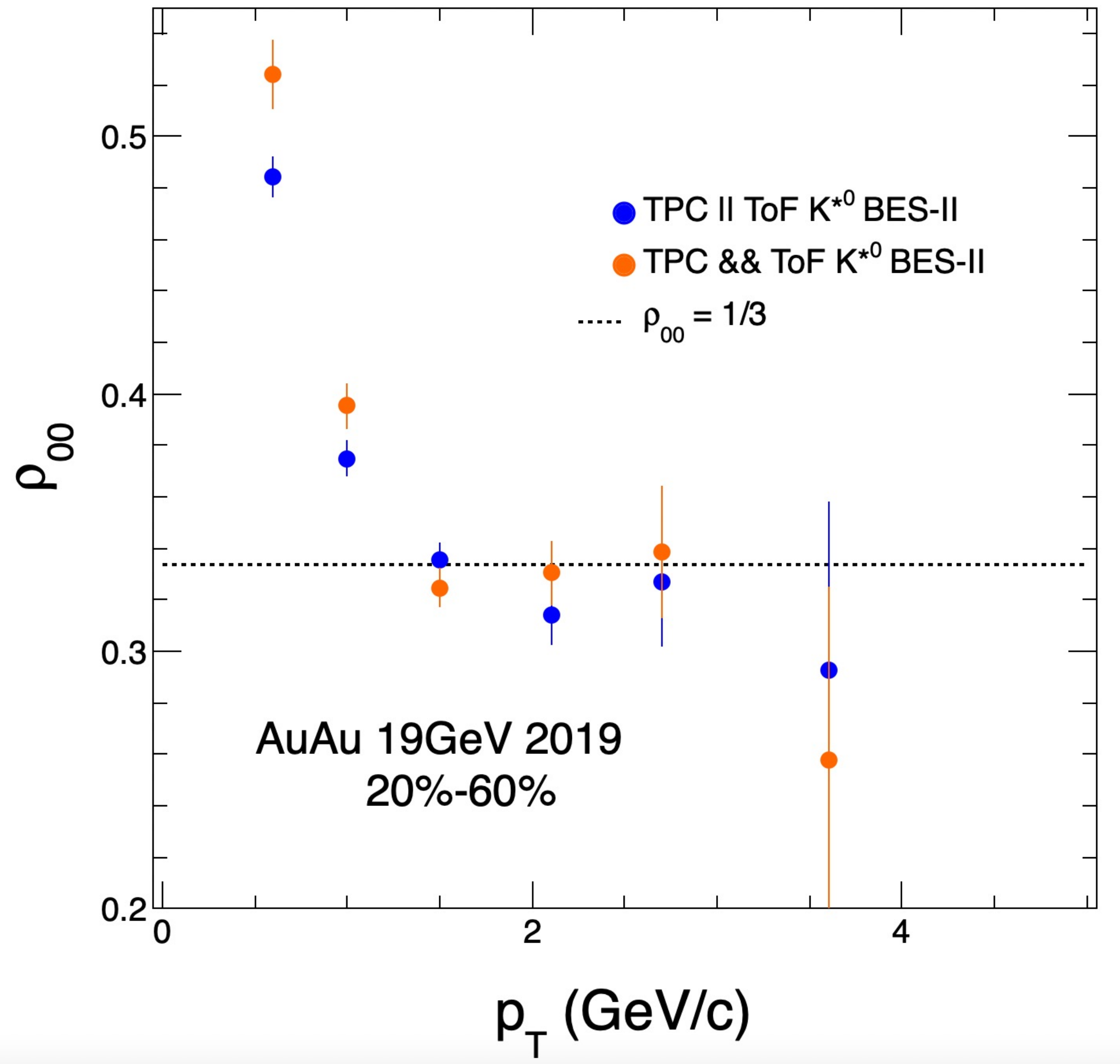
PID Selection Differenc

Raw ρ_{00} using BW integration for yields is shown.

Points are consistent in pT bins >= 1.2 GeV/c.

pT < 1.0 GeV/c was not presented for BES-I. Low pT cut effects.

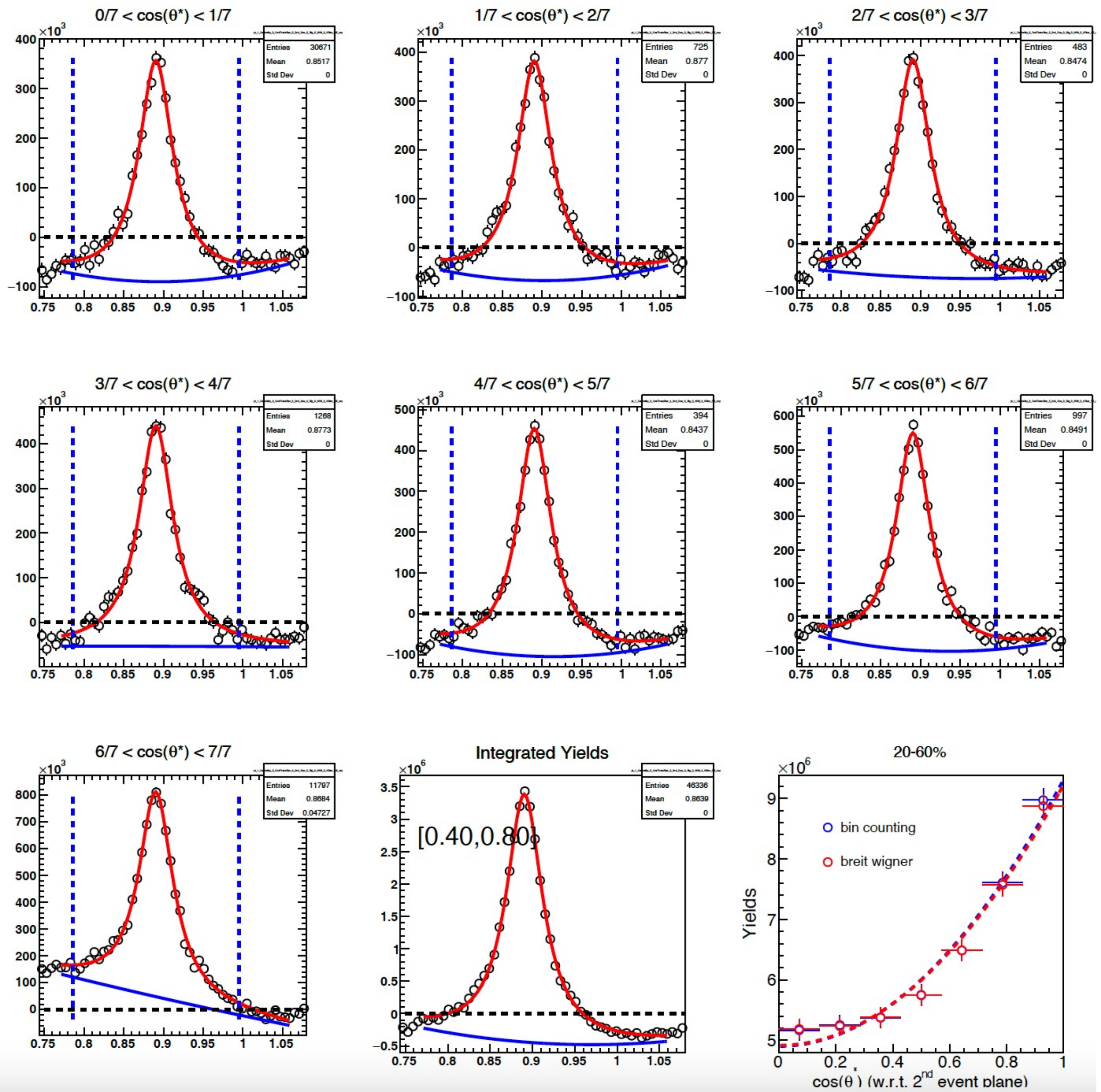
Statistical uncertainty is slightly lower for ToF || TPC (BES-I method).



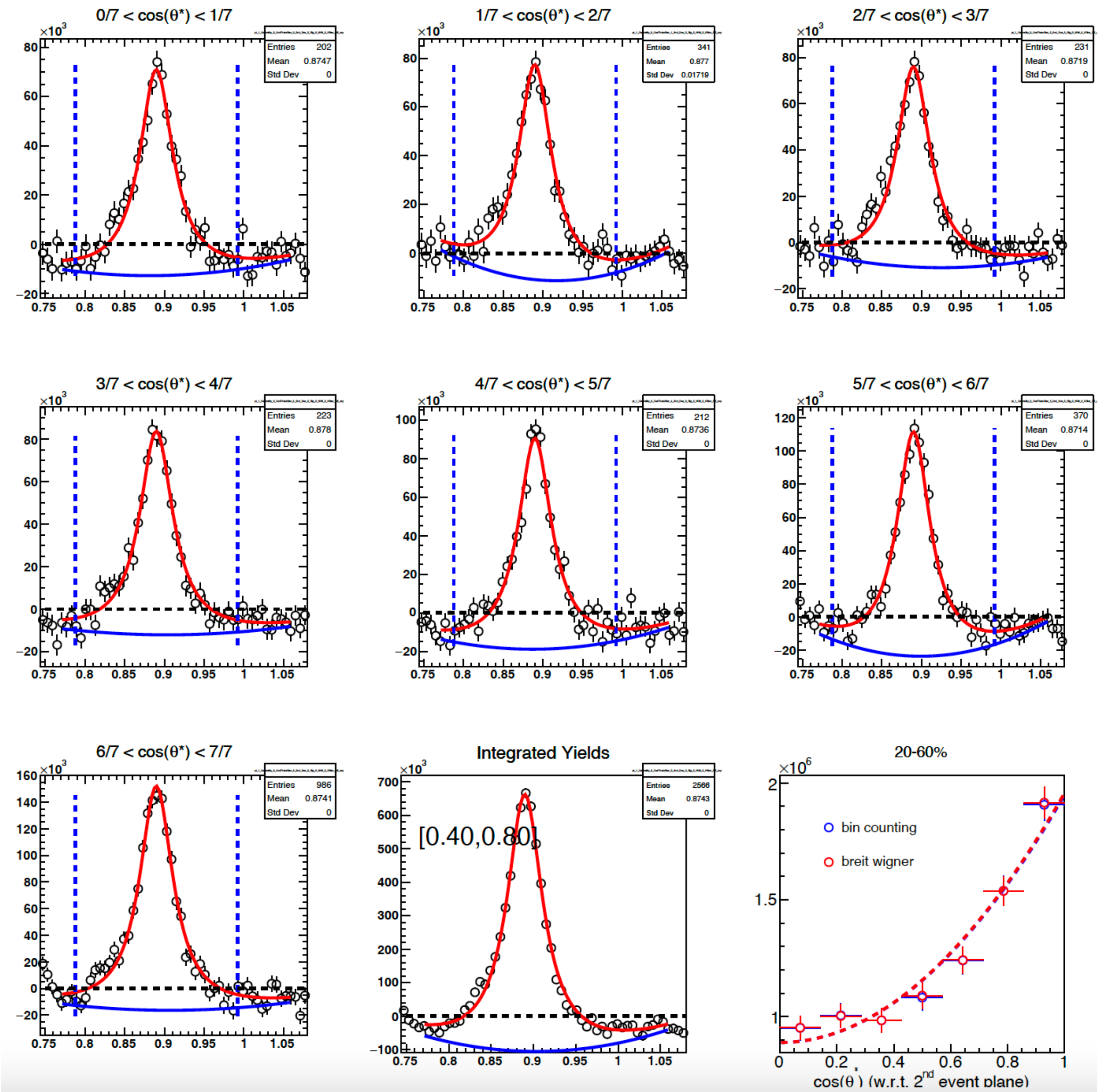

```
pt = 0.6000:    ToF || TPC = 0.4842 +/- 0.0079 (stat)    ToF && TPC = 0.5241 +/- 0.0137 (stat)    sigma = 2.52
pt = 1.0000:    ToF || TPC = 0.3749 +/- 0.0069 (stat)    ToF && TPC = 0.3953 +/- 0.0090 (stat)    sigma = 1.81
pt = 1.5000:    ToF || TPC = 0.3356 +/- 0.0066 (stat)    ToF && TPC = 0.3247 +/- 0.0078 (stat)    sigma = 1.07
pt = 2.1000:    ToF || TPC = 0.3141 +/- 0.0114 (stat)    ToF && TPC = 0.3303 +/- 0.0123 (stat)    sigma = 0.97
pt = 2.7000:    ToF || TPC = 0.3271 +/- 0.0251 (stat)    ToF && TPC = 0.3386 +/- 0.0255 (stat)    sigma = 0.32
pt = 3.6000:    ToF || TPC = 0.2926 +/- 0.0657 (stat)    ToF && TPC = 0.2579 +/- 0.0670 (stat)    sigma = 0.37
```

pT = [0.4,0.8] GeV/c (20-60%)

ToF || TPC

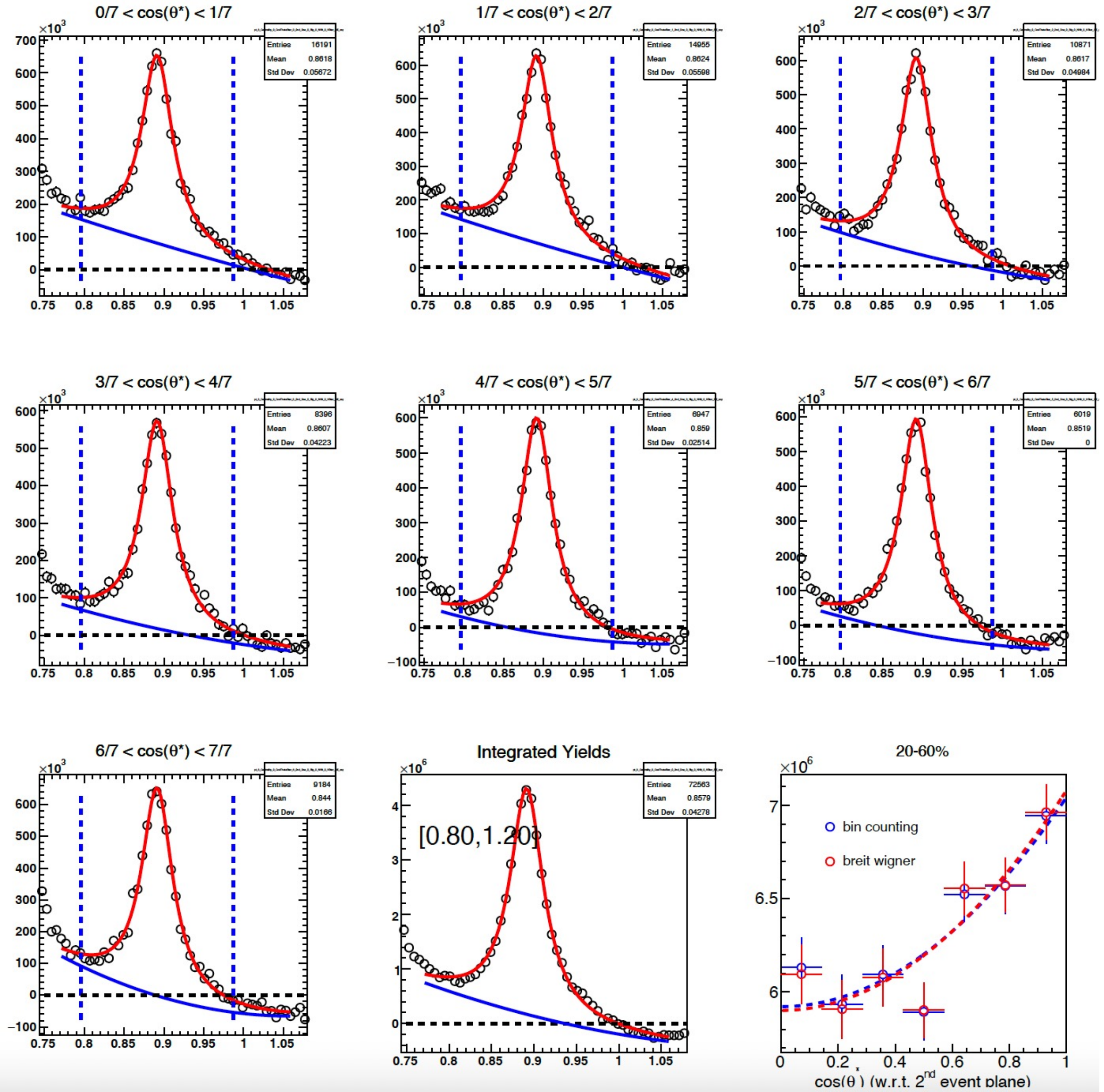


ToF && TPC

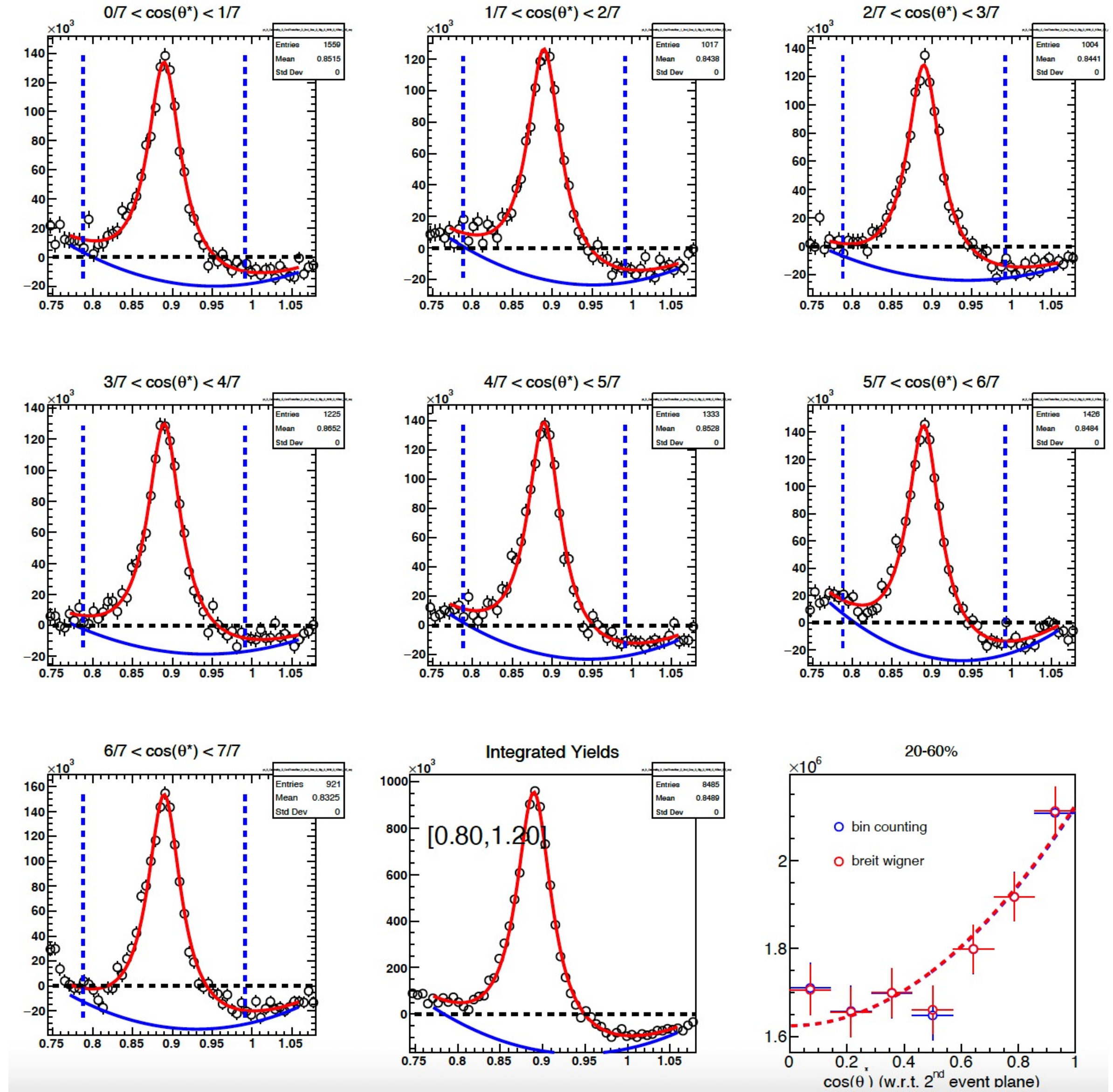


pT = [0.8,1.2] GeV/c (20-60%)

ToF || TPC

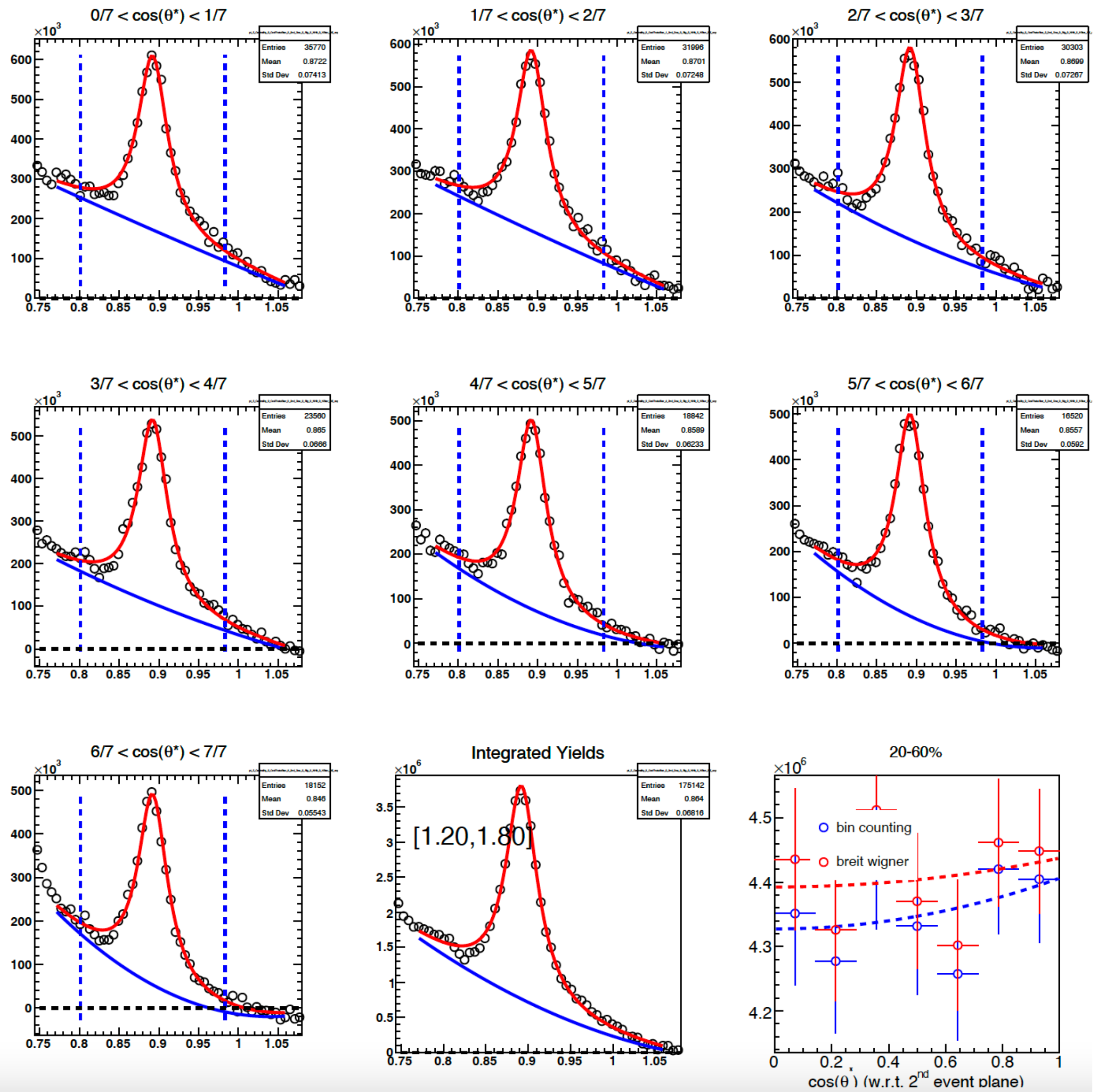


ToF && TPC

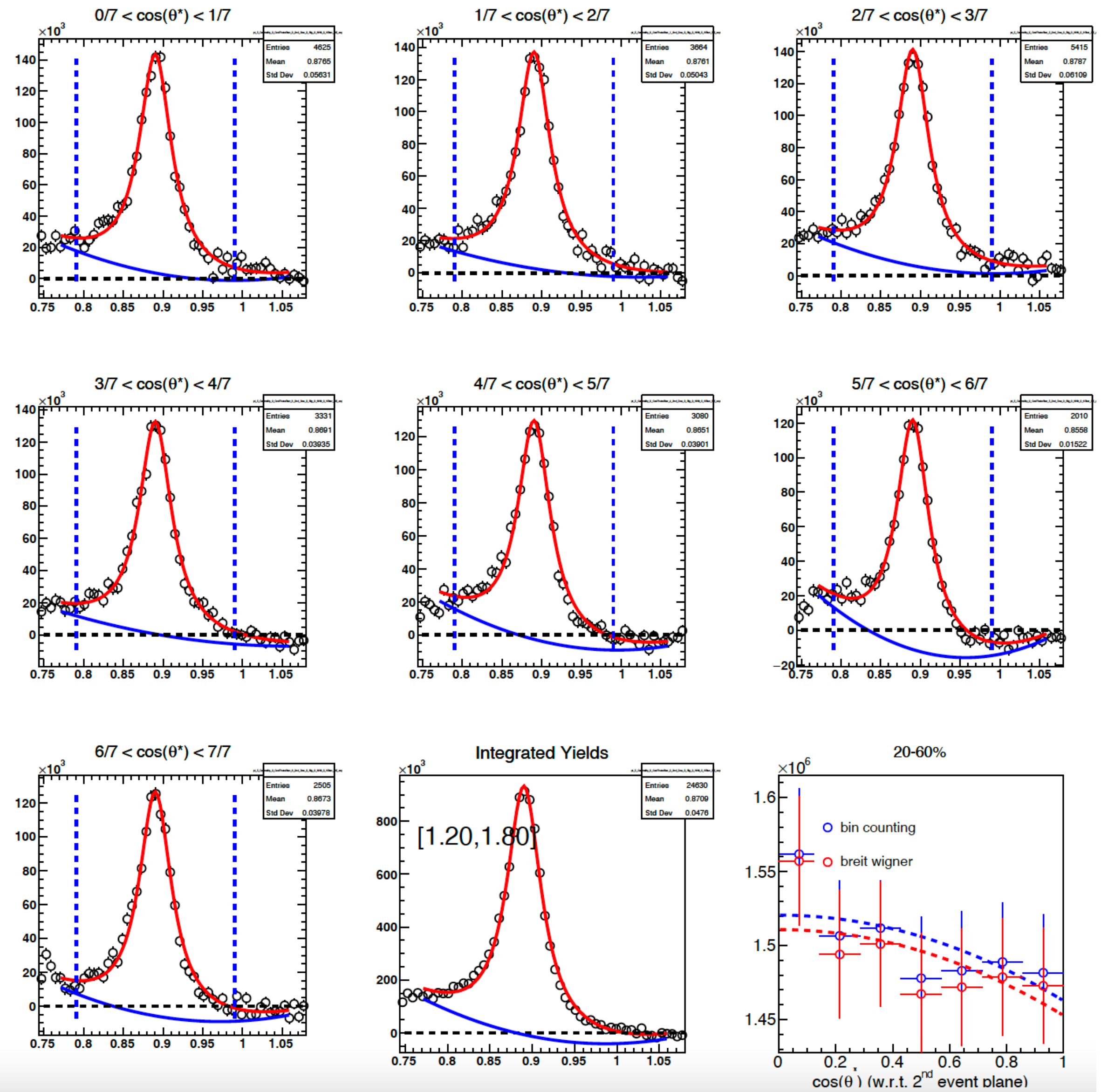


pT = [1.2,1.8] GeV/c (20-60%)

ToF || TPC

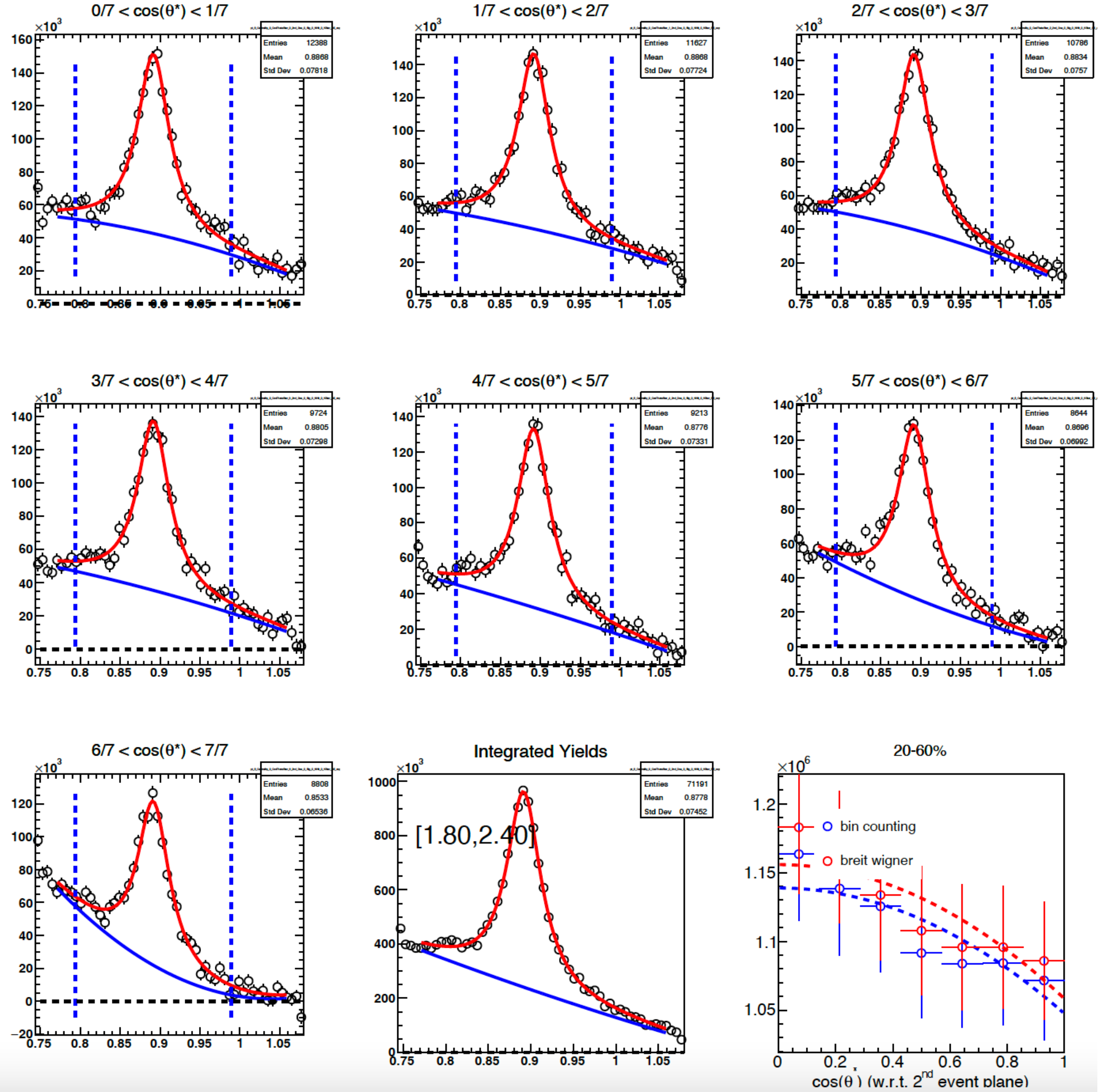


ToF && TPC

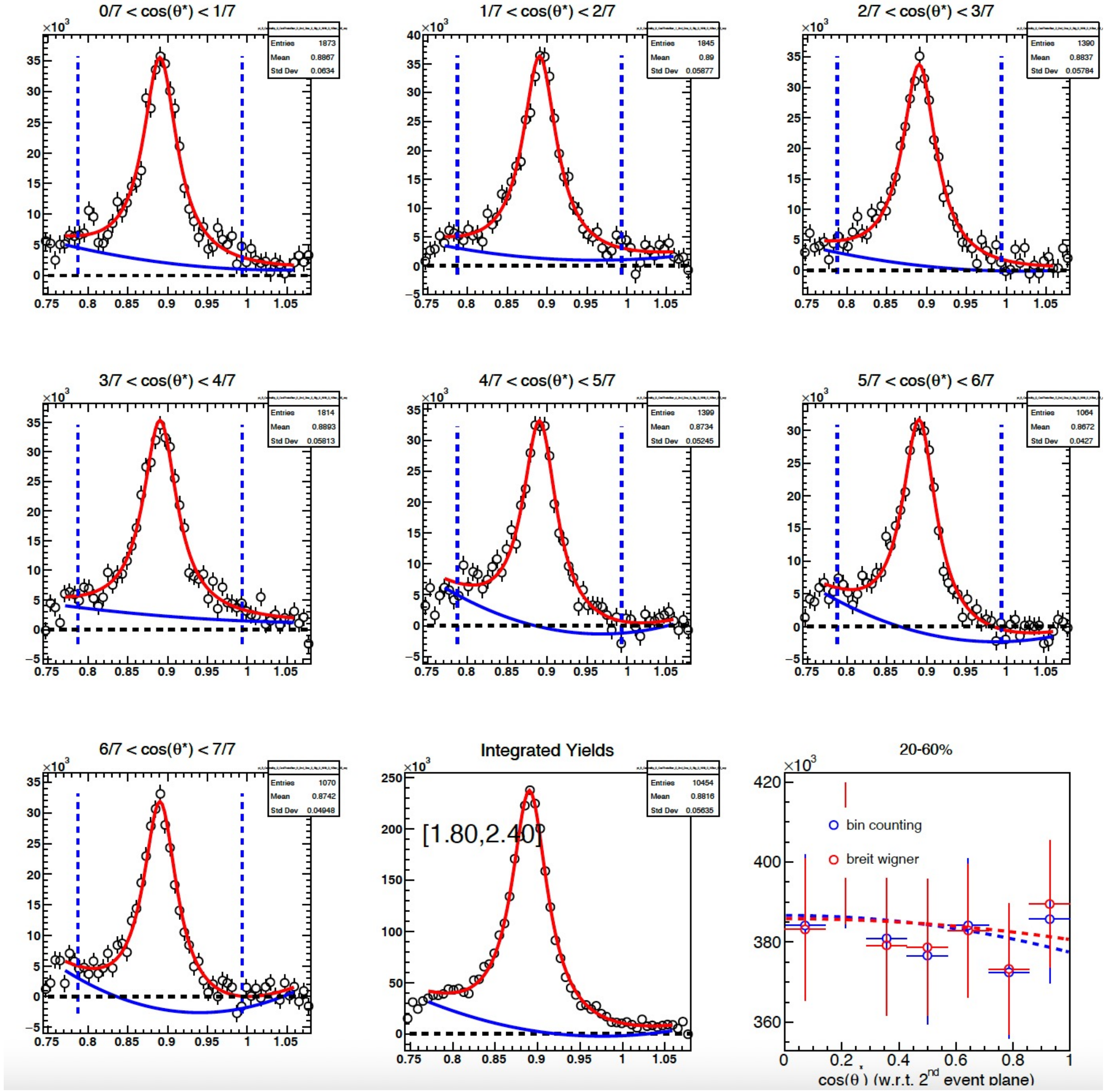


pT = [1.8,2.4] GeV/c (20-60%)

ToF || TPC

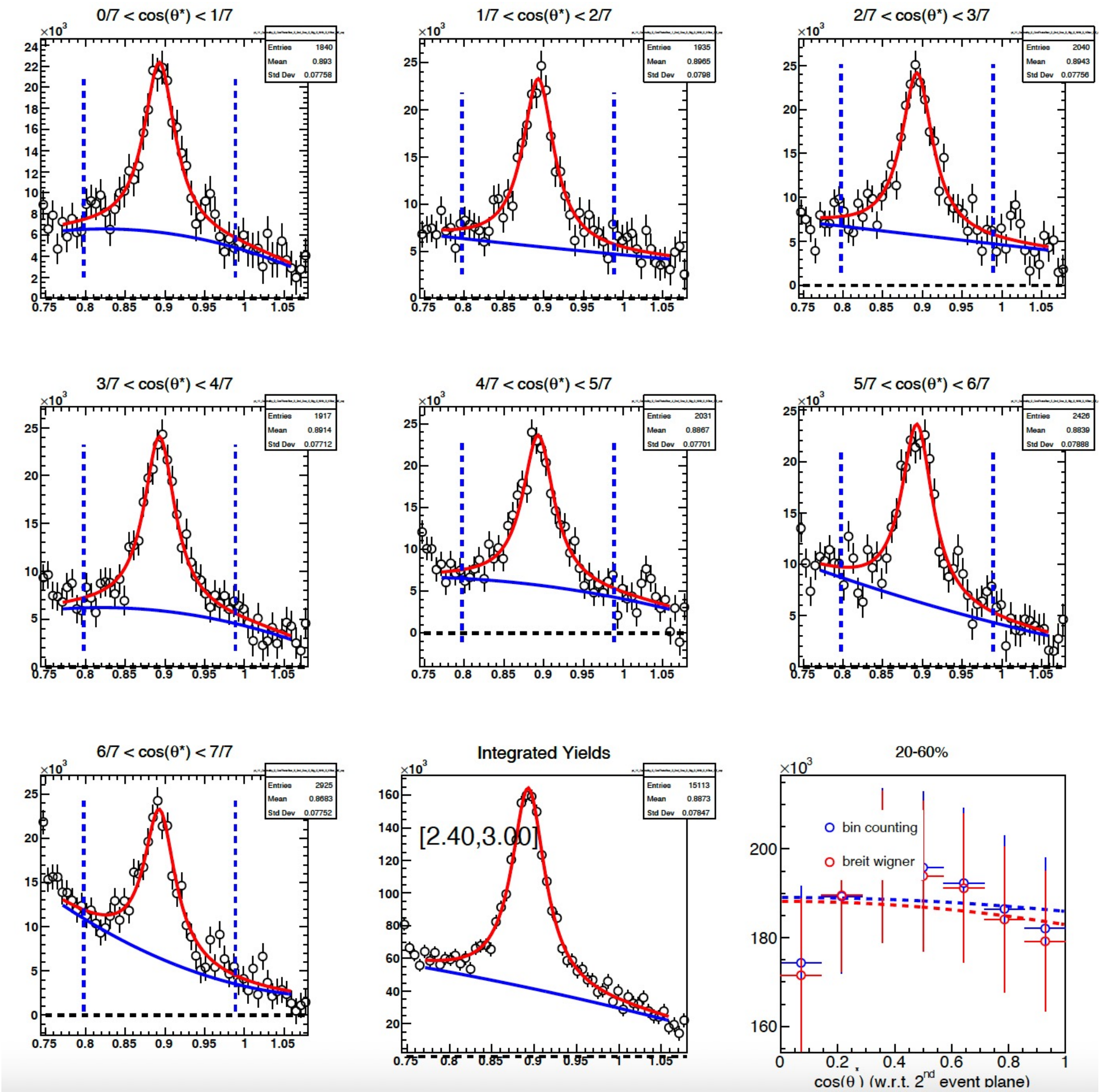


ToF && TPC

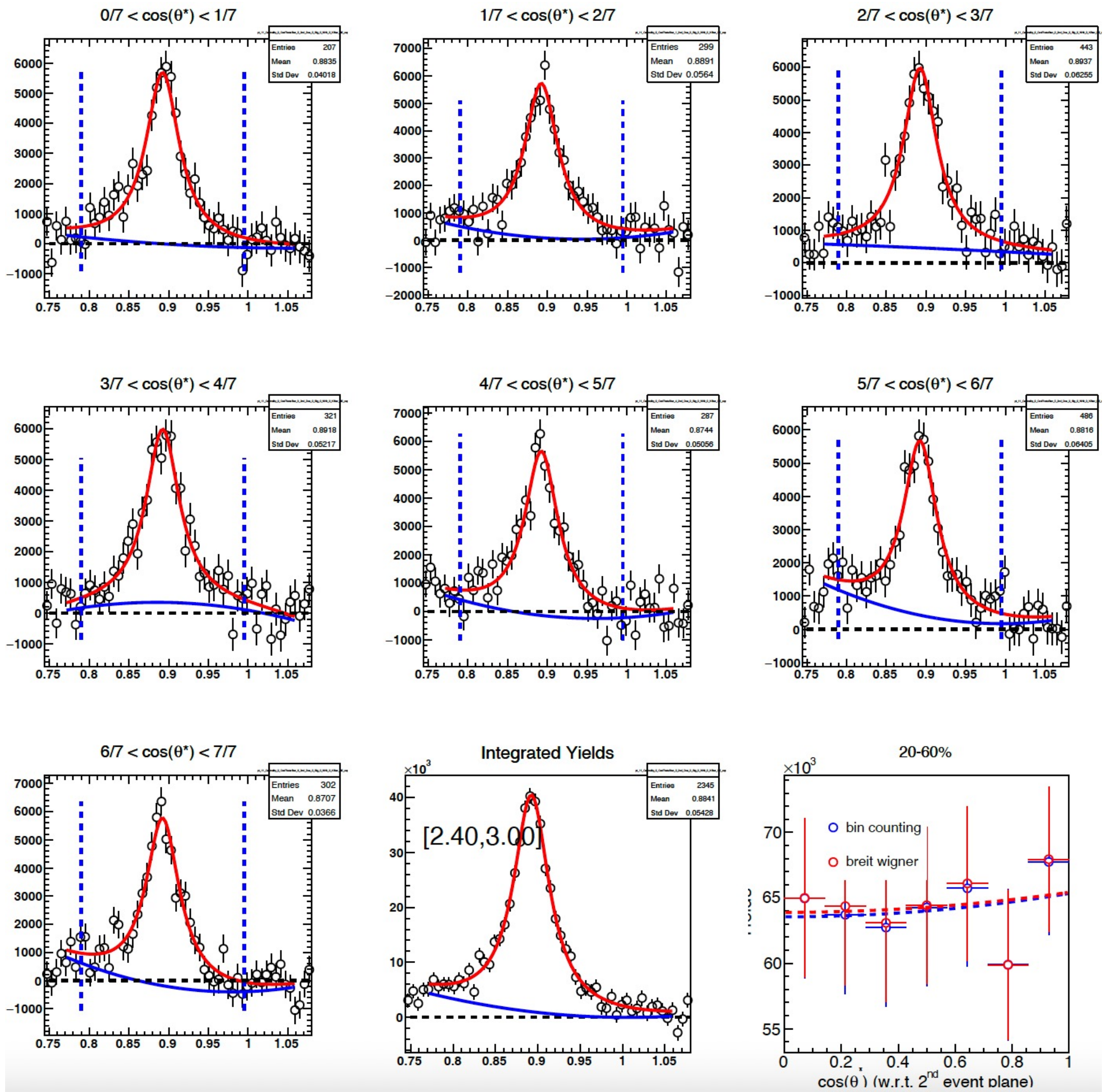


pT = [2.4,3.0] GeV/c (20-60%)

ToF || TPC

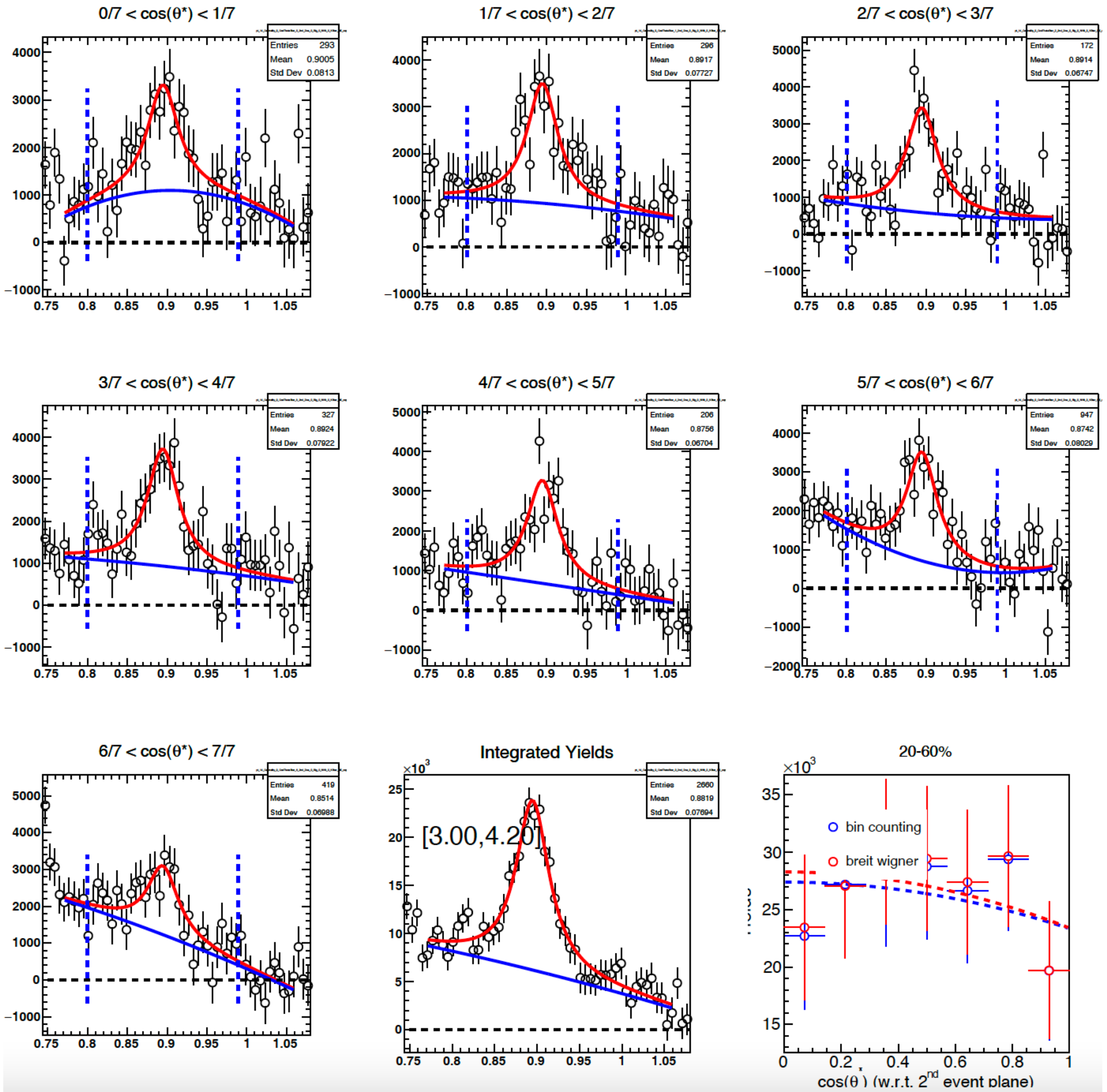


ToF && TPC

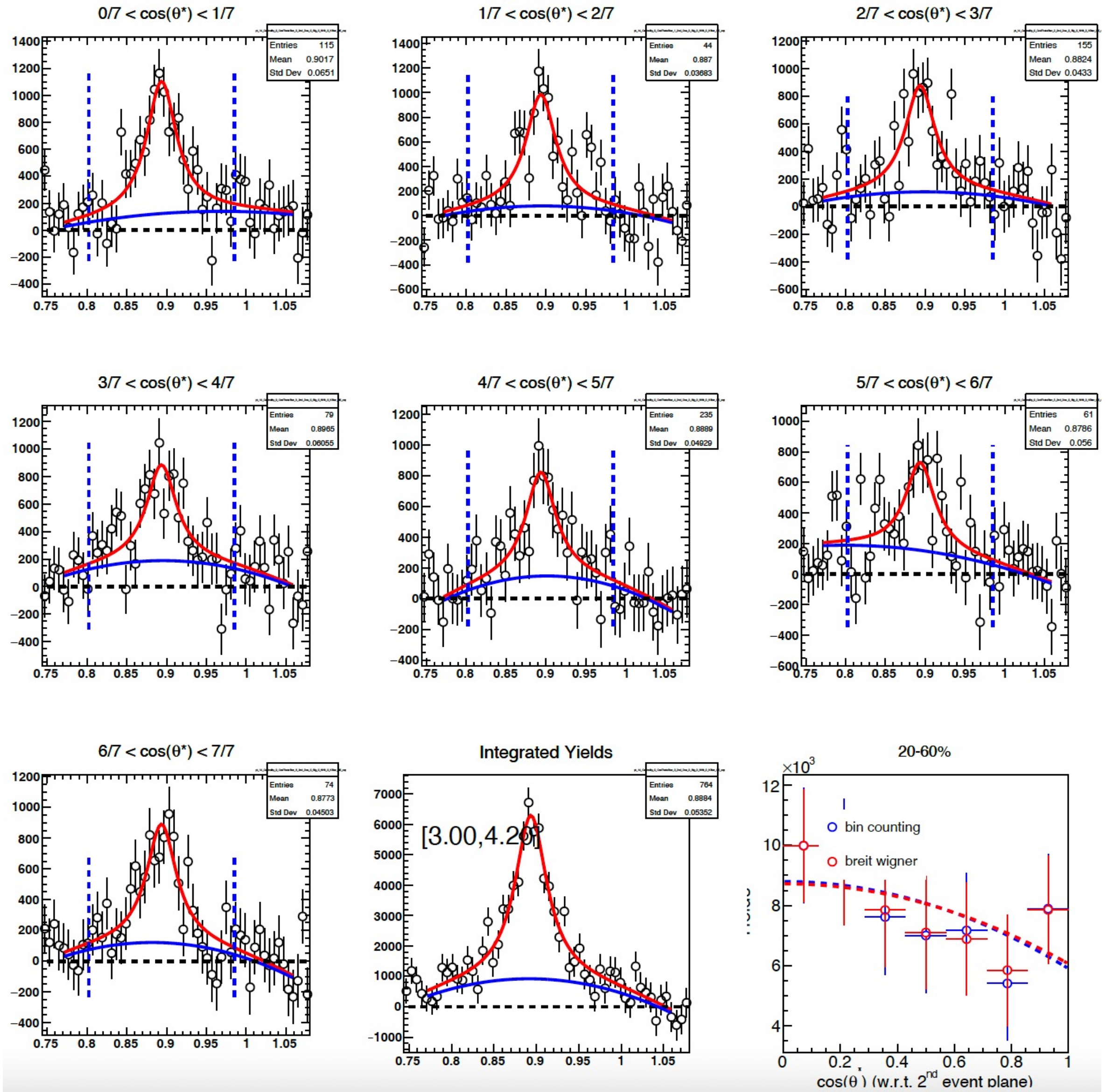


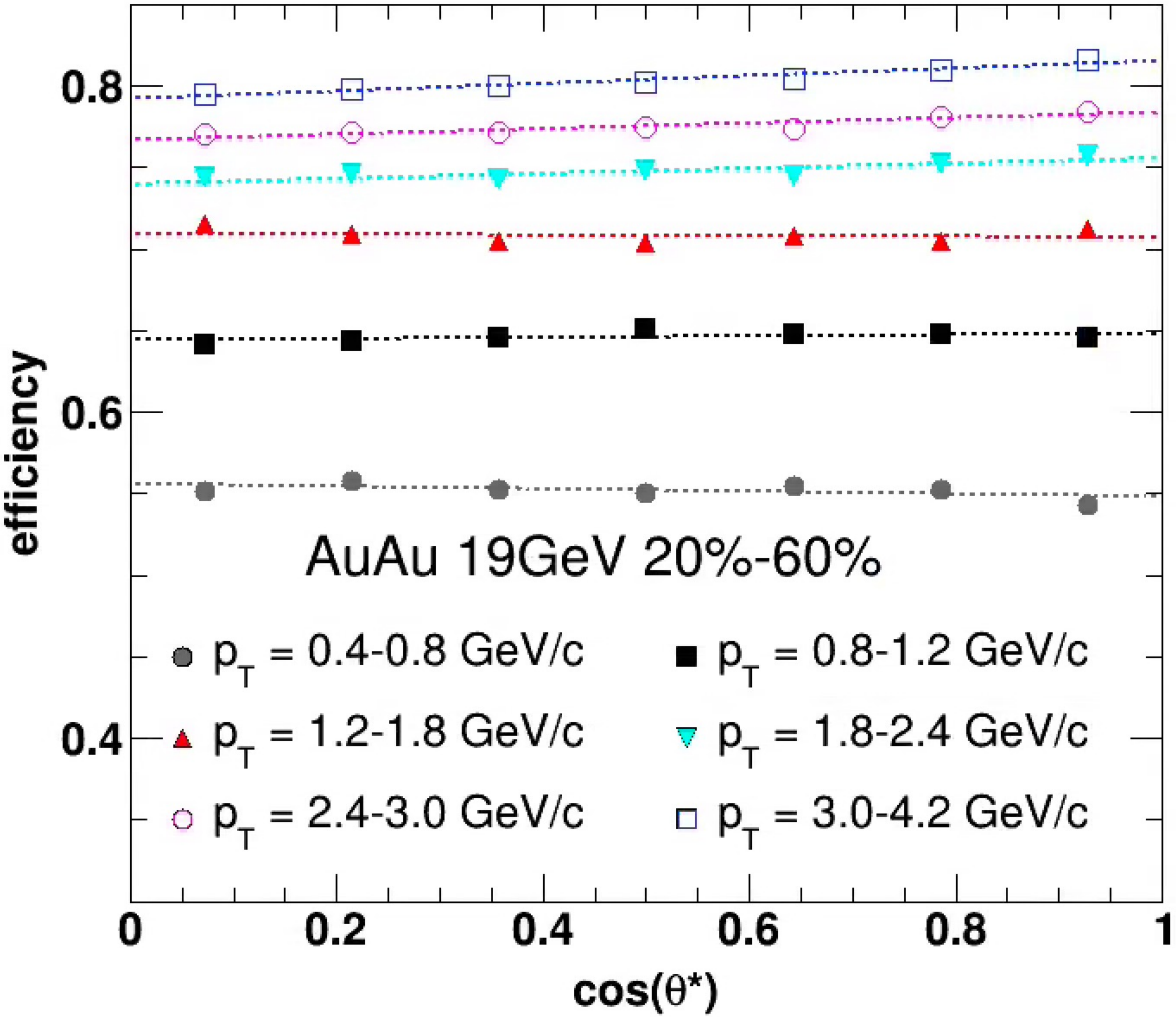
pT = [3.0,4.2] GeV/c (20-60%)

ToF || TPC



ToF && TPC





efficiency
0.8
0.6
0.4
AuAu 19GeV 20%-60%
p_T = 0.4-0.8 GeV/c
p_T = 0.8-1.2 GeV/c
p_T = 1.2-1.8 GeV/c
p_T = 1.8-2.4 GeV/c
p_T = 2.4-3.0 GeV/c
p_T = 3.0-4.2 GeV/c
0
0.2
0.4
0.6
0.8
1
cos(θ*)