Measurement of global spin alignment of K^{*0} and ϕ vector mesons using the STAR detector at RHIC

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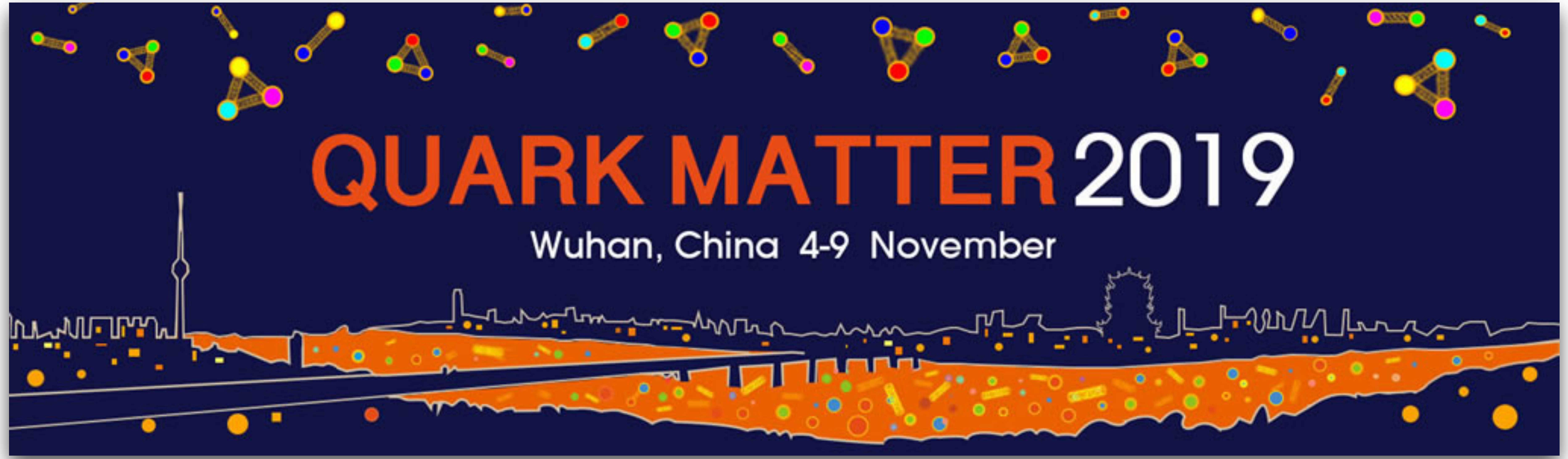

STAR

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This work in part supported by grant from DOE Office of Science

KENT STATE UNIVERSITY

IMP

Outline

- Motivation
- Analysis method
- Results:

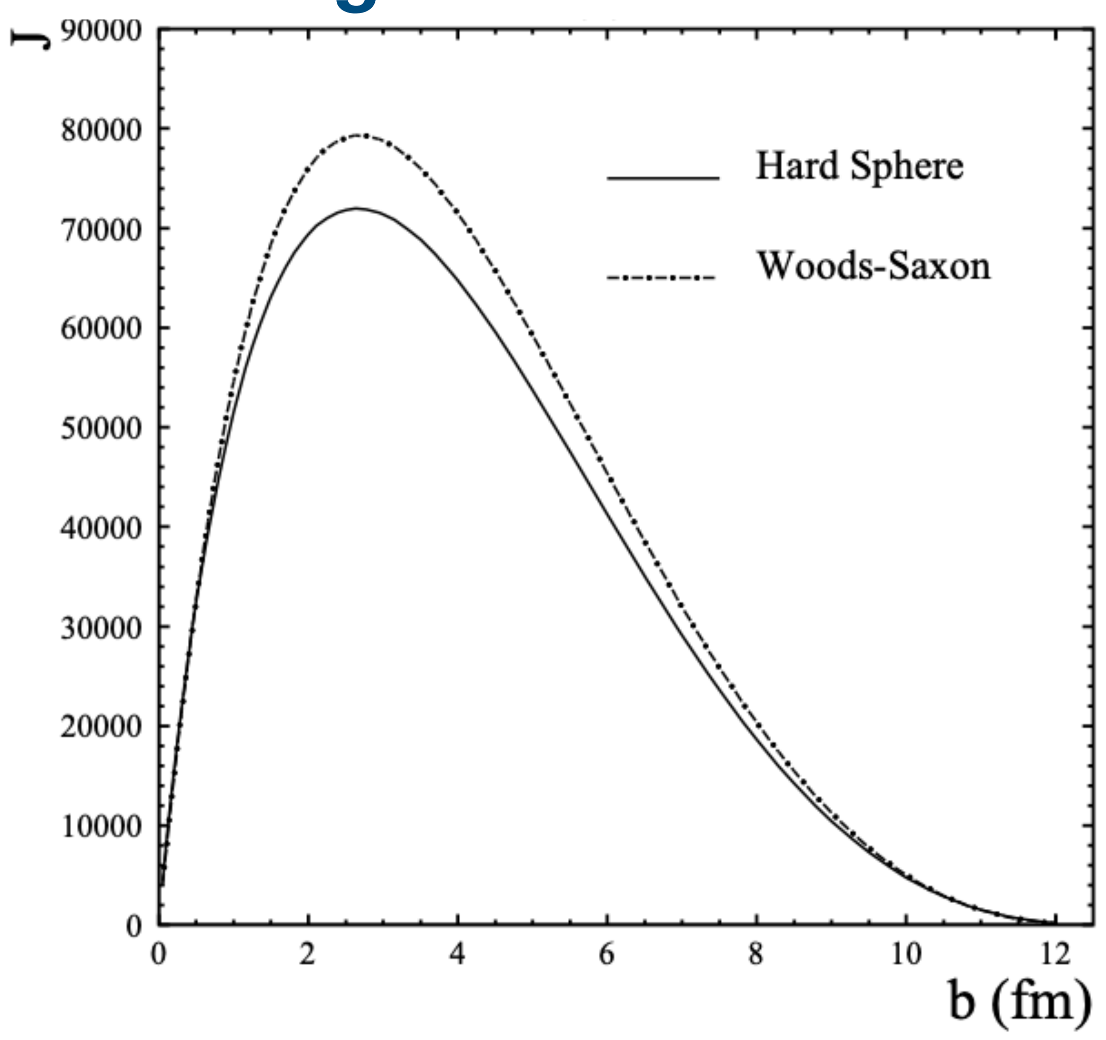
  Spin alignment of K^{*0}
  Comparison with ϕ meson (QM 2018)
  Comparison with ALICE results

- Summary and outlook

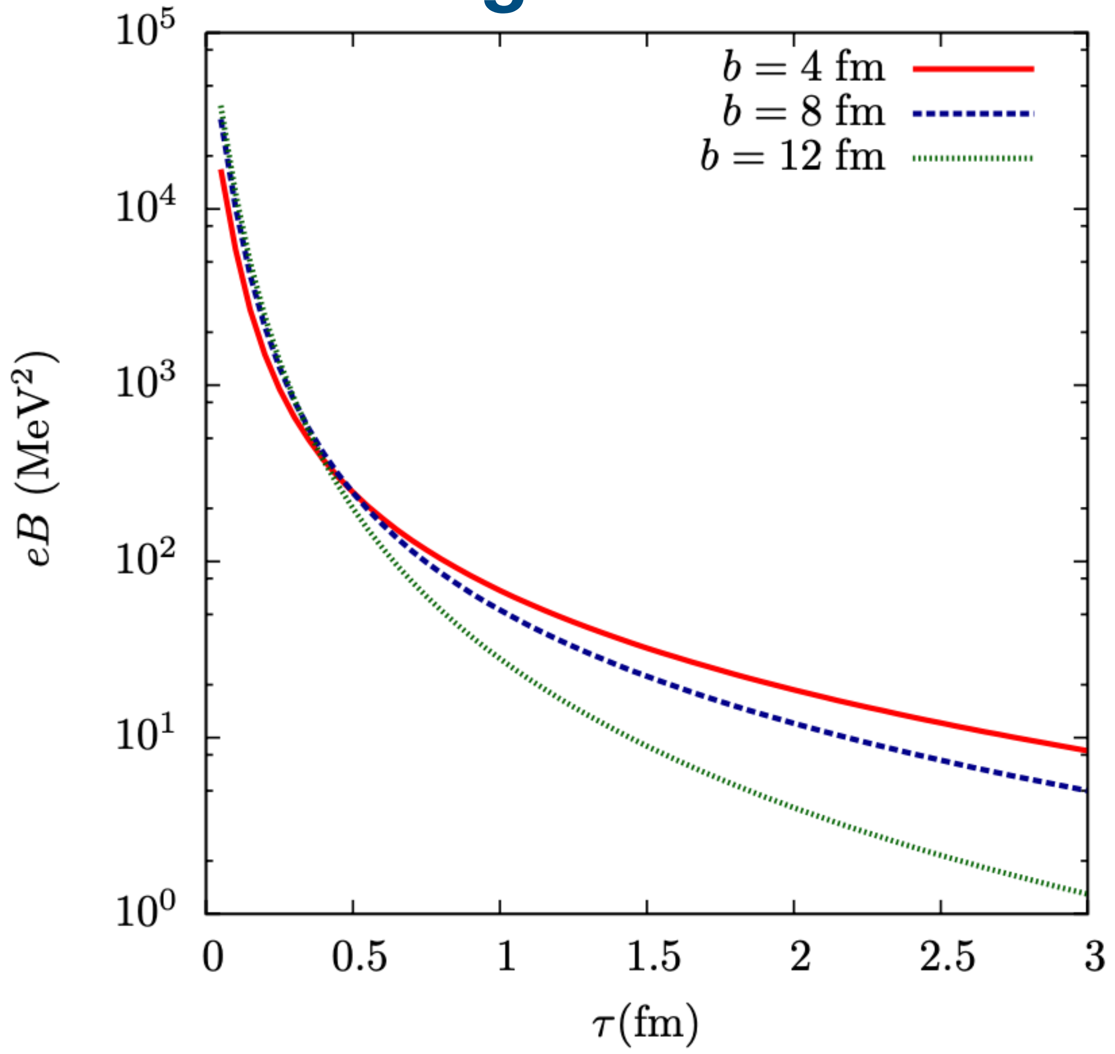
Probe initial stages in HIC

Nature 548, 62 (2017)
(STAR Collaboration)
Phys Rev C 98, 14910 (2018)
(STAR Collaboration)

Angular momentum

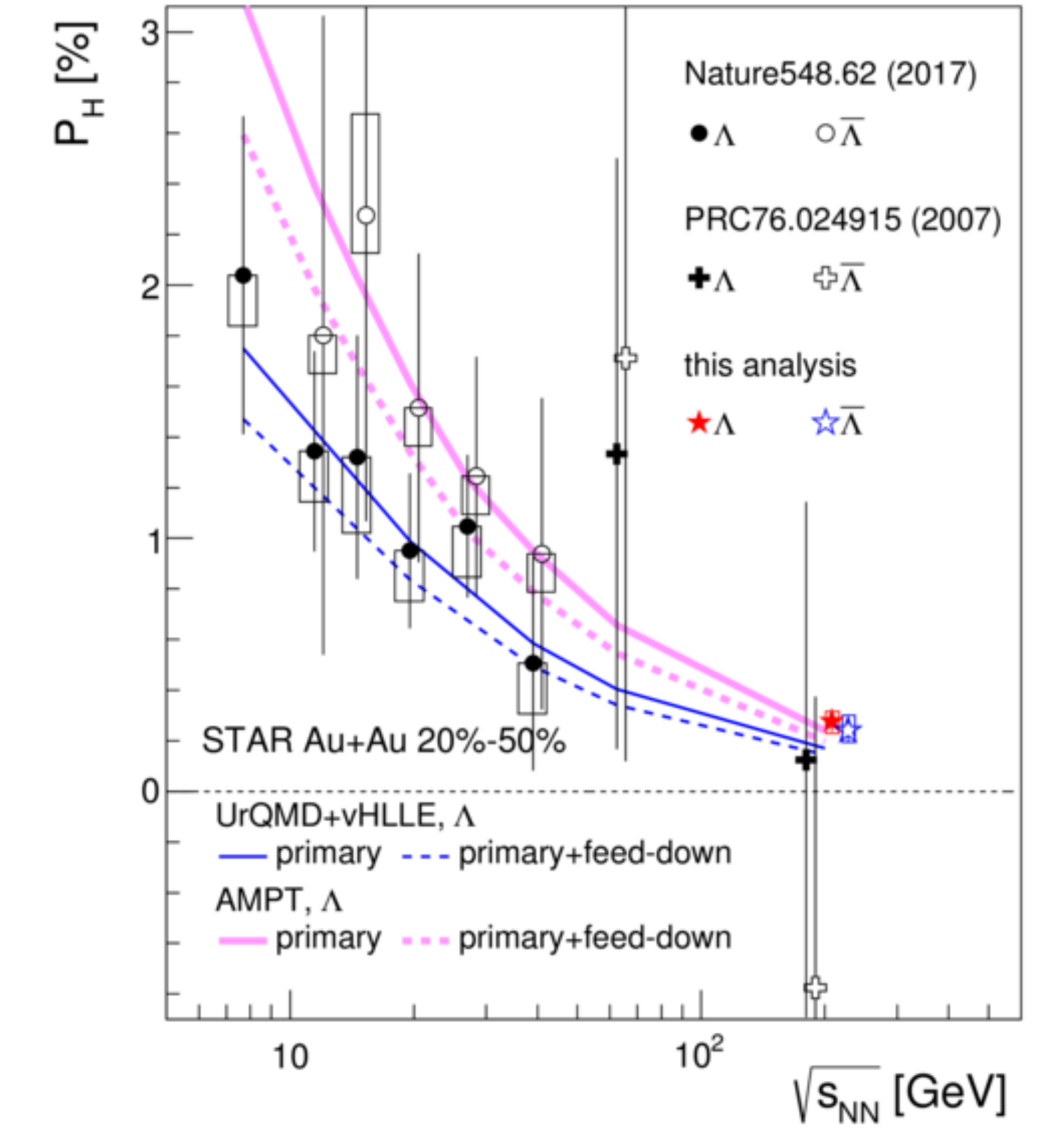


Magnetic field



F. Becattini, et. al., Phys Rev. C. 77, 024906 (2008)
D. Kharzeev, Nucl Phys A803, 227 (2008)

Λ Polarization



See talk by J. Adams 06/11, 2.00 pm

- Initial large angular momentum (**L**) ~ $10^4 \hbar$
- Initial large magnetic field (**B**) ~ 10^{18} Gauss at RHIC
- Can polarize quarks in medium

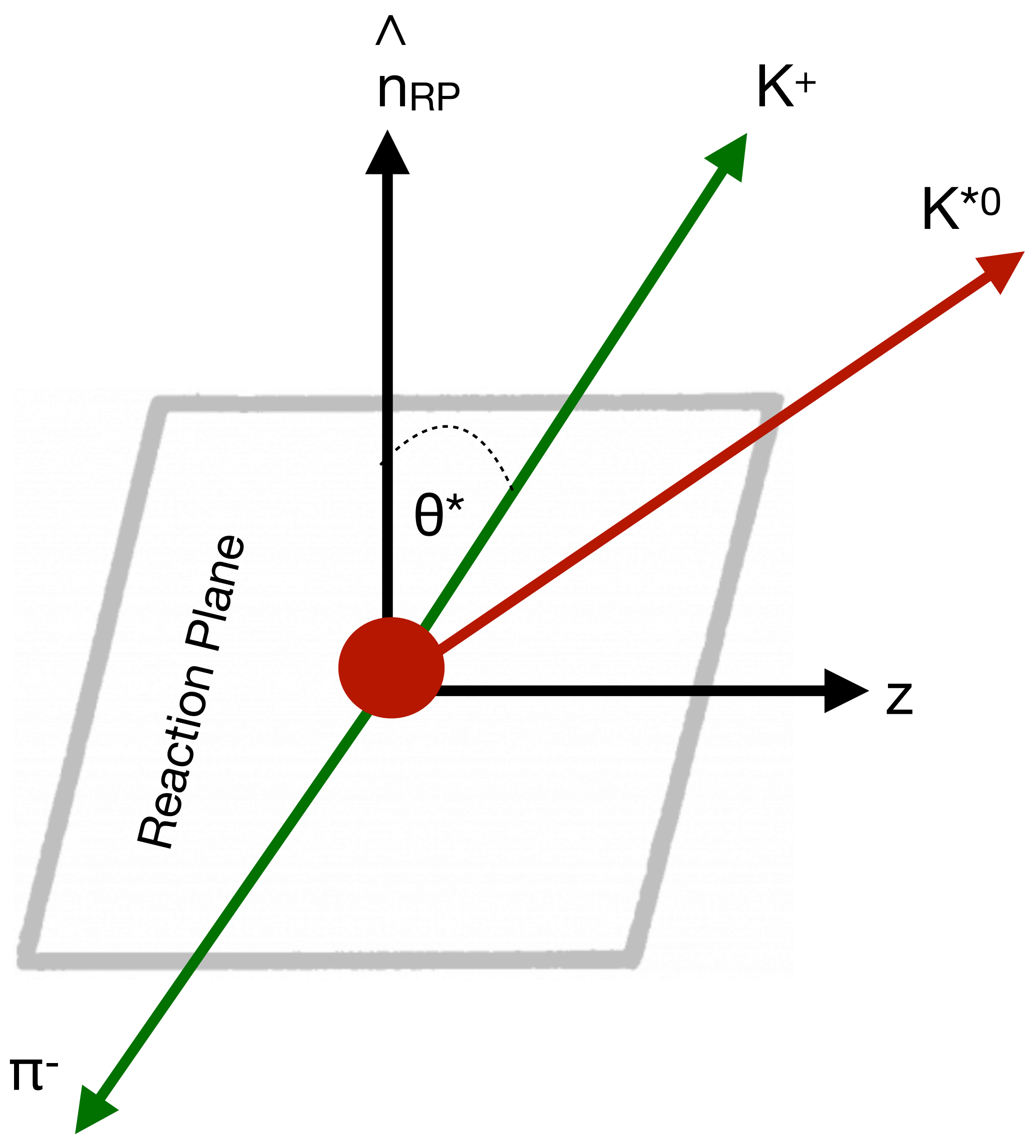
- $P_H(\Lambda)$ & $P_H(\bar{\Lambda}) > 0$ → Positive vorticity
- $P_H(\bar{\Lambda}) > P_H(\Lambda)$ → Hints of magnetic coupling

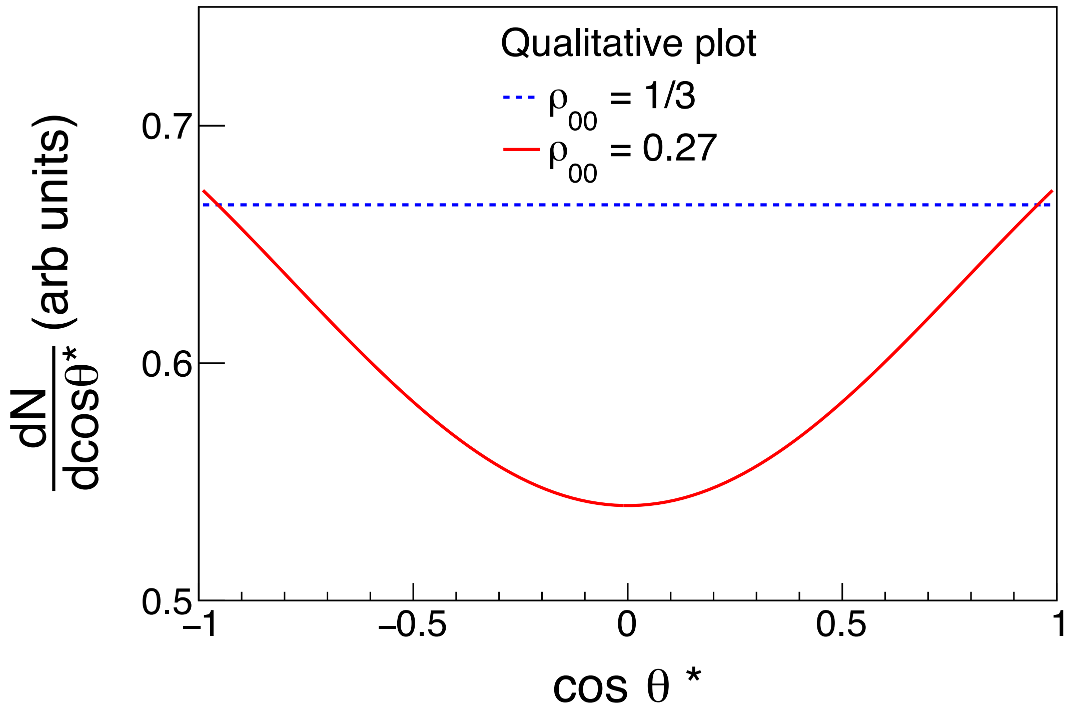
▸ First experimental access to study the vorticity of the medium

Vector meson spin alignment (ρ_{00})

Observable

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





▸ Deviation of ρ_{00} from (1/3) indicates spin alignment

K. Schiling et. al., Nucl. Phys. B 15 (1970) 397
Phys. Rev. C 77 (2008) 61902 (STAR Collaboration)

Angular momentum and magnetic field can induce spin alignment of vector mesons

Theoretical expectation of ρ_{00}

Vorticity	$\rho_{00}(\omega) < 1/3$	
Magnetic field	$\rho_{00}(B) > 1/3$	Electrically neutral vector mesons
	$\rho_{00}(B) < 1/3$	Electrically charged vector mesons
Hadronization	$\rho_{00}(\mathrm{rec}) < 1/3$	Recombination
	$\rho_{00}(\mathrm{frag}) > 1/3$	Fragmentation

Z. Liang et. al., Phys. Lett. B629, 20 (2005)
Y. Yang et. al., Phys. Rev. C 97, 034917 (2018)

K^{*0} and φ

<u>Characteristic of K^{*0} and φ:</u>

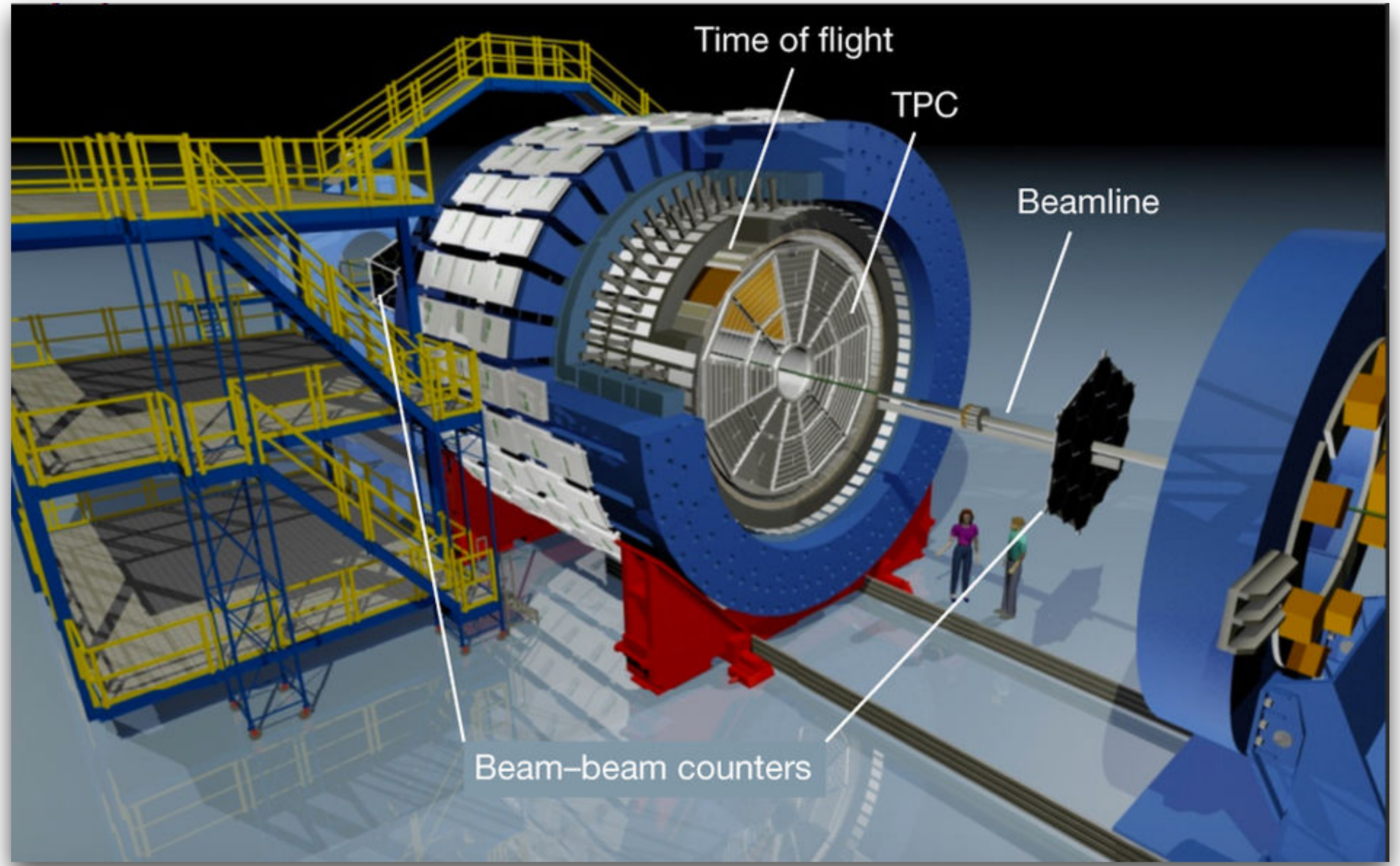
Species	K^{*0}	φ
Quark content	$\bar{d}s$	$s\bar{s}$
Mass (MeV/c^2)	896	1020
Lifetime (fm/c)	4	45
Spin (J^P)	1^-	1^-
Decays	Kπ	KK
Branching ratio	49%	66%

- Predominantly produced in primordial production
- Negligible feed-down compared to Λ and $\bar{\Lambda}$

- Λ spin polarization (P_H):
  Required knowledge of orientation of the angular momentum vector, estimated by deflection of spectators (can use 1st-order event plane)

- Vector meson spin alignment (ρ_{00}):
  Polarization direction not required.
  Not subject to local cancellation.
  (can use both 1st-order and 2nd-order event plane)

The STAR detector and analysis details

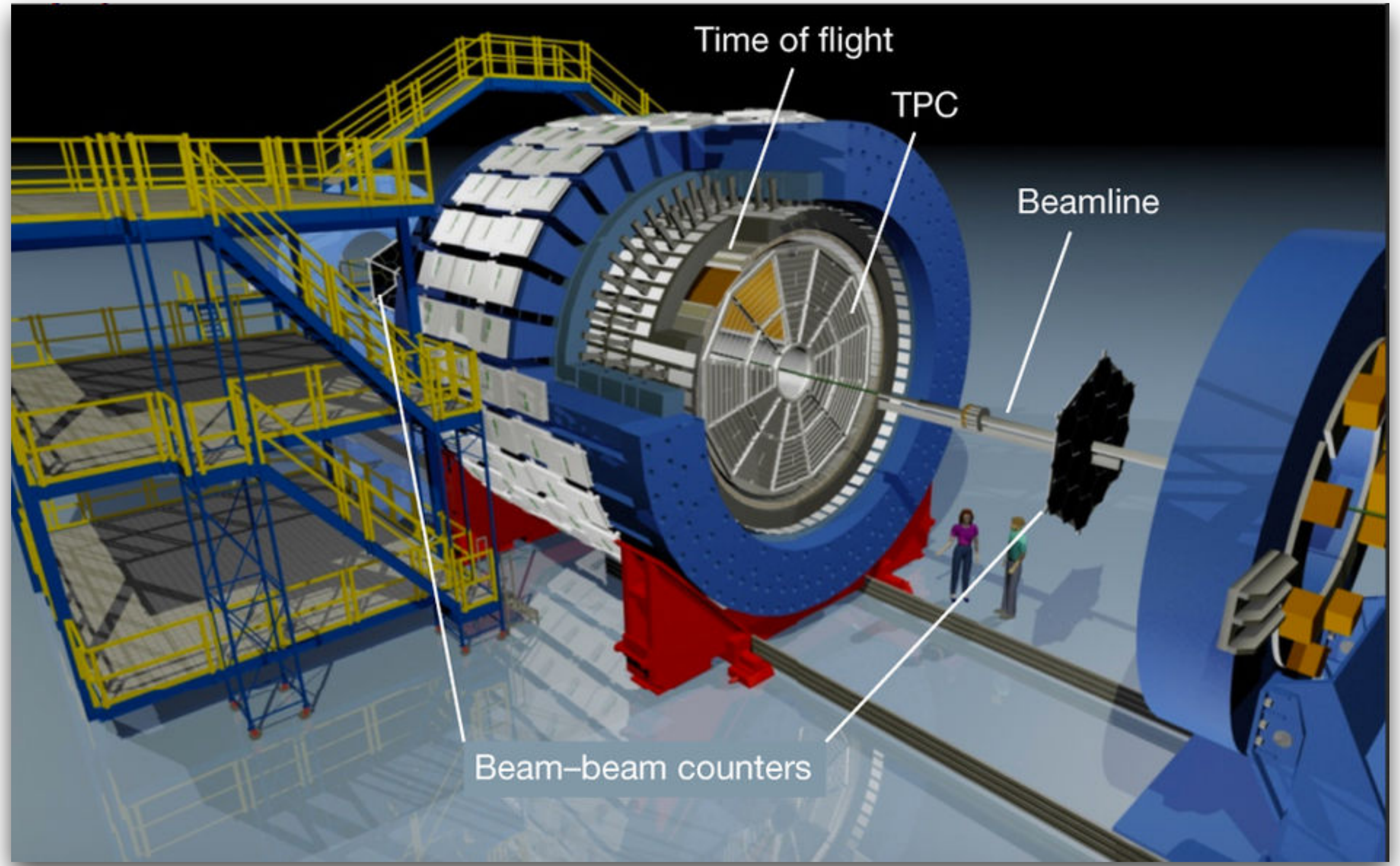


- Uniform acceptance, full azimuthal coverage
- TPC: tracking, centrality and event plane
- TPC+TOF: particle identification

collision system	Au+Au
collision energy	54.4 and 200 GeV
# of good events	520 and 350 M
rapidity	$|y| < 0.5$
background	rotation of daughters
polarization axis	perpendicular to TPC 2nd-order event plane
consistency check	3D-random event plane

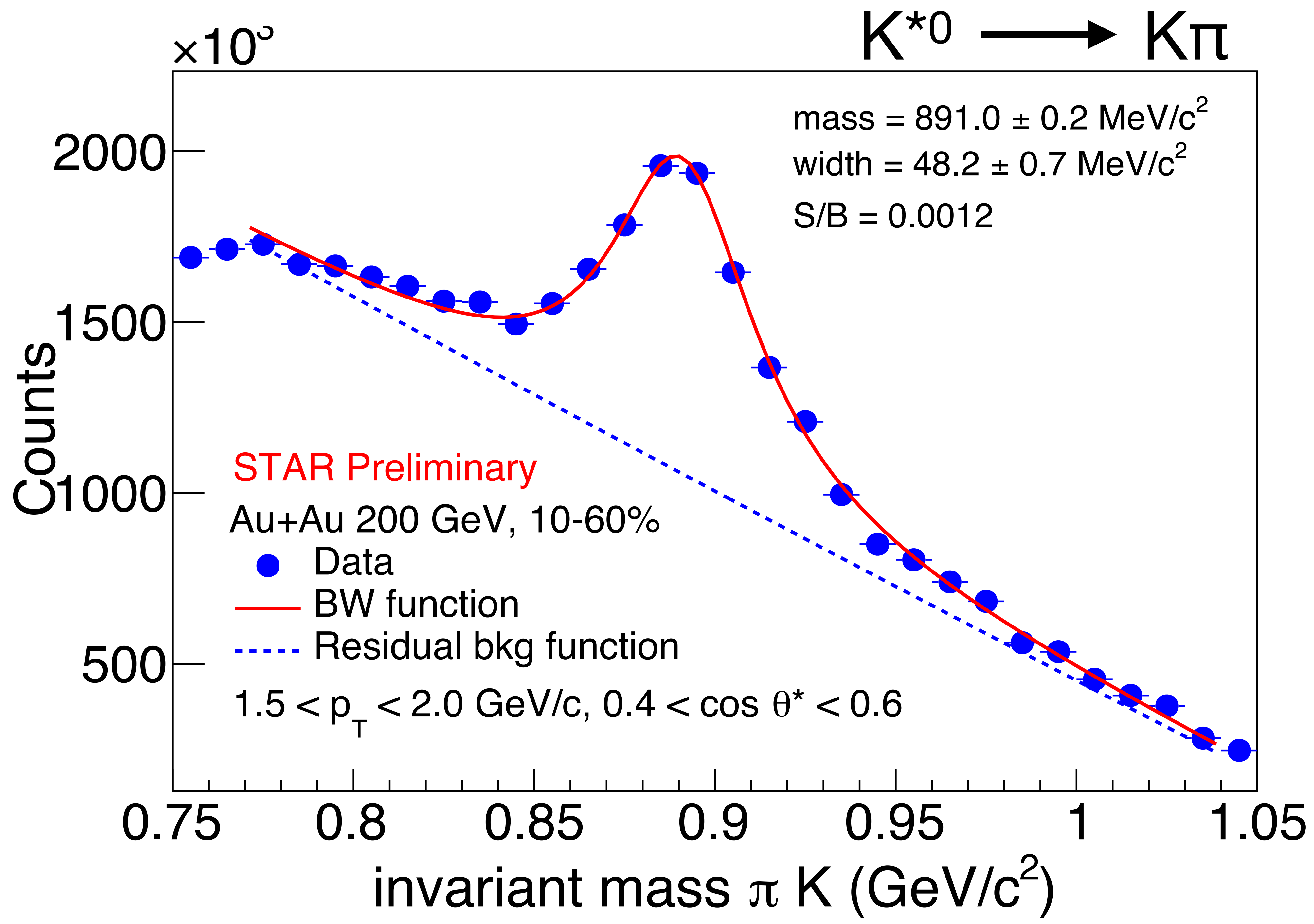
Report K^{*0} ρ_{00} as function of transverse momentum and centrality

The STAR detector and signal reconstruction



- Uniform acceptance, full azimuthal coverage
- TPC: tracking, centrality and event plane
- TPC+TOF: particle identification

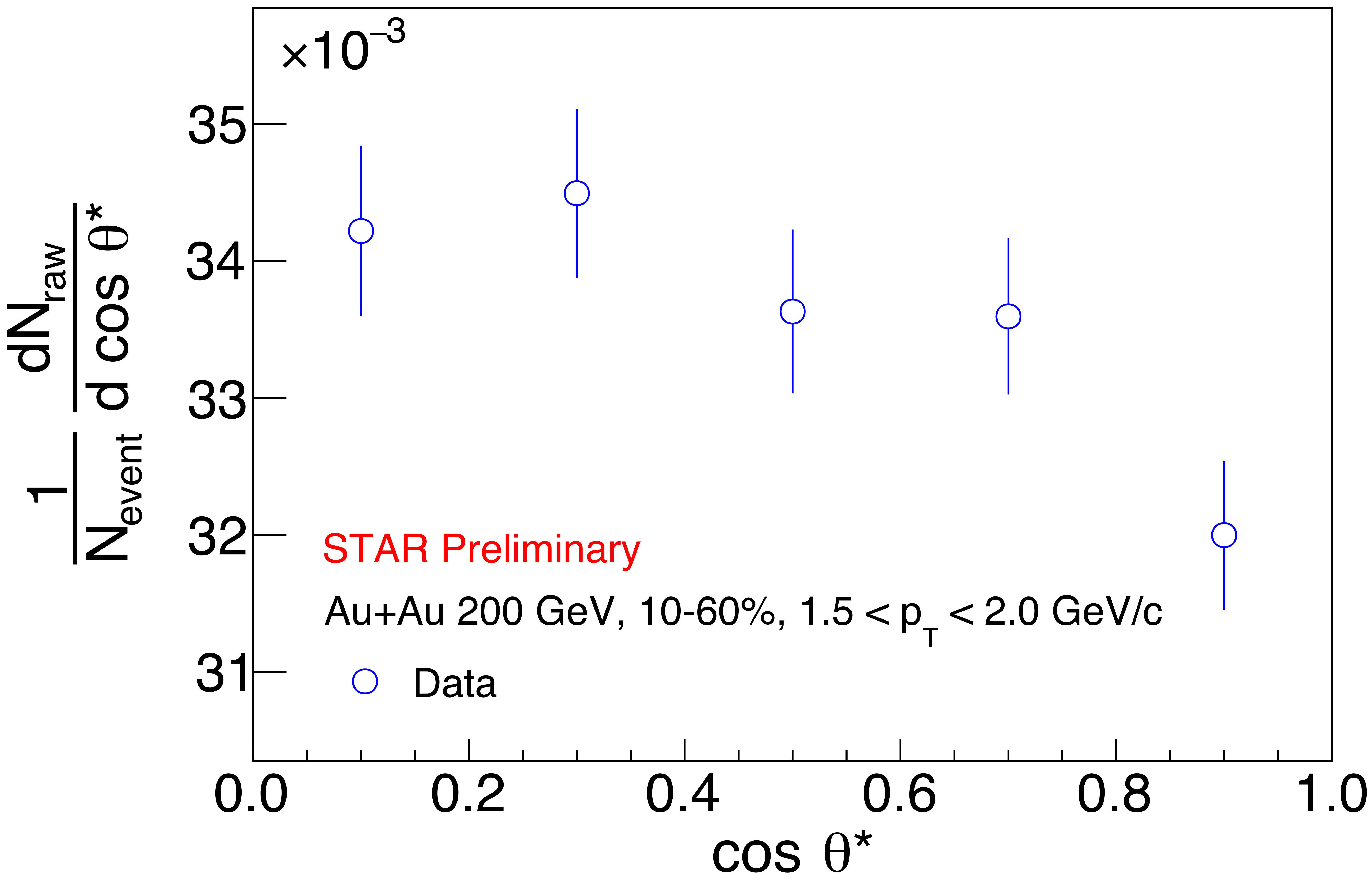
K^{*0} reconstruction:

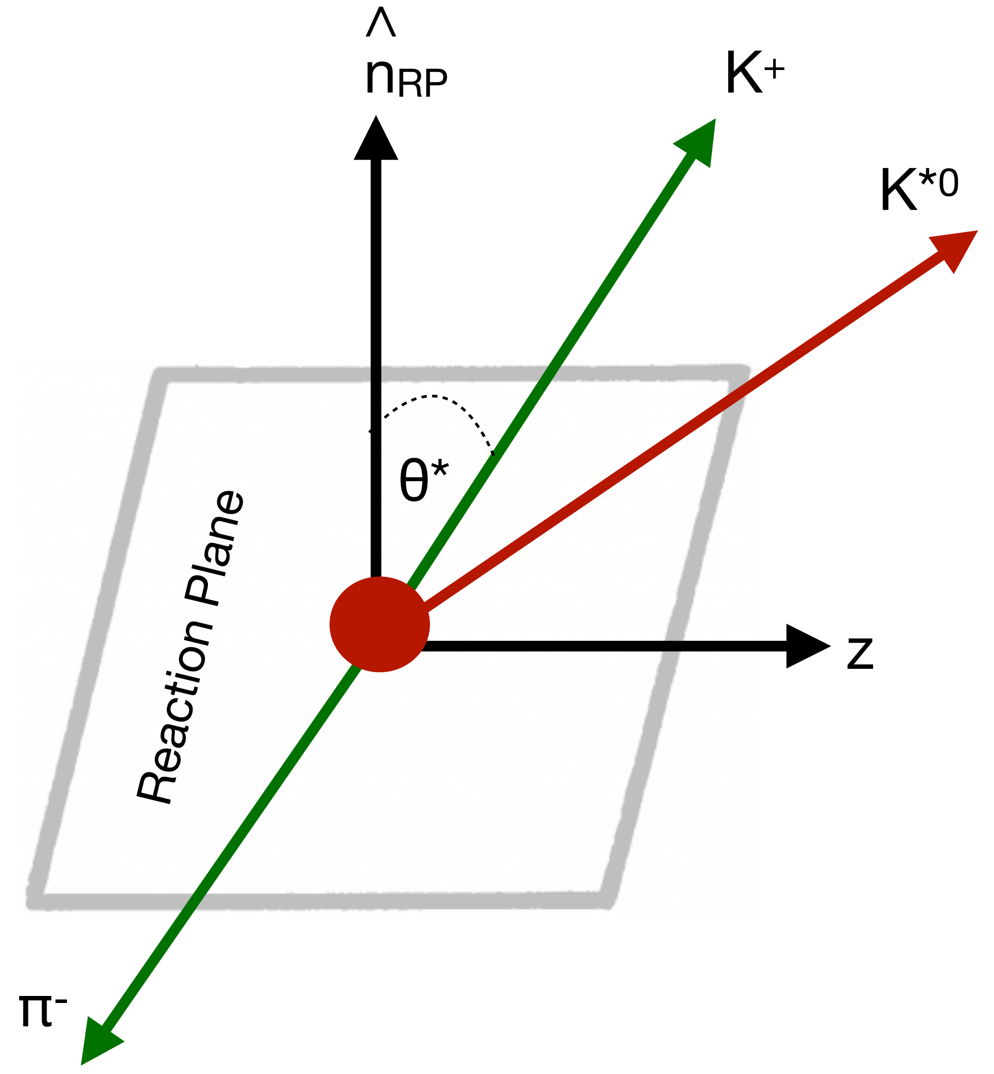


- Rotational background subtraction
- mass/width consistent with published value
- K* yield is the area under the Breit-Wigner function

Analysis method

- Raw yield of K^{*0} is extracted from 5 cos θ* bins

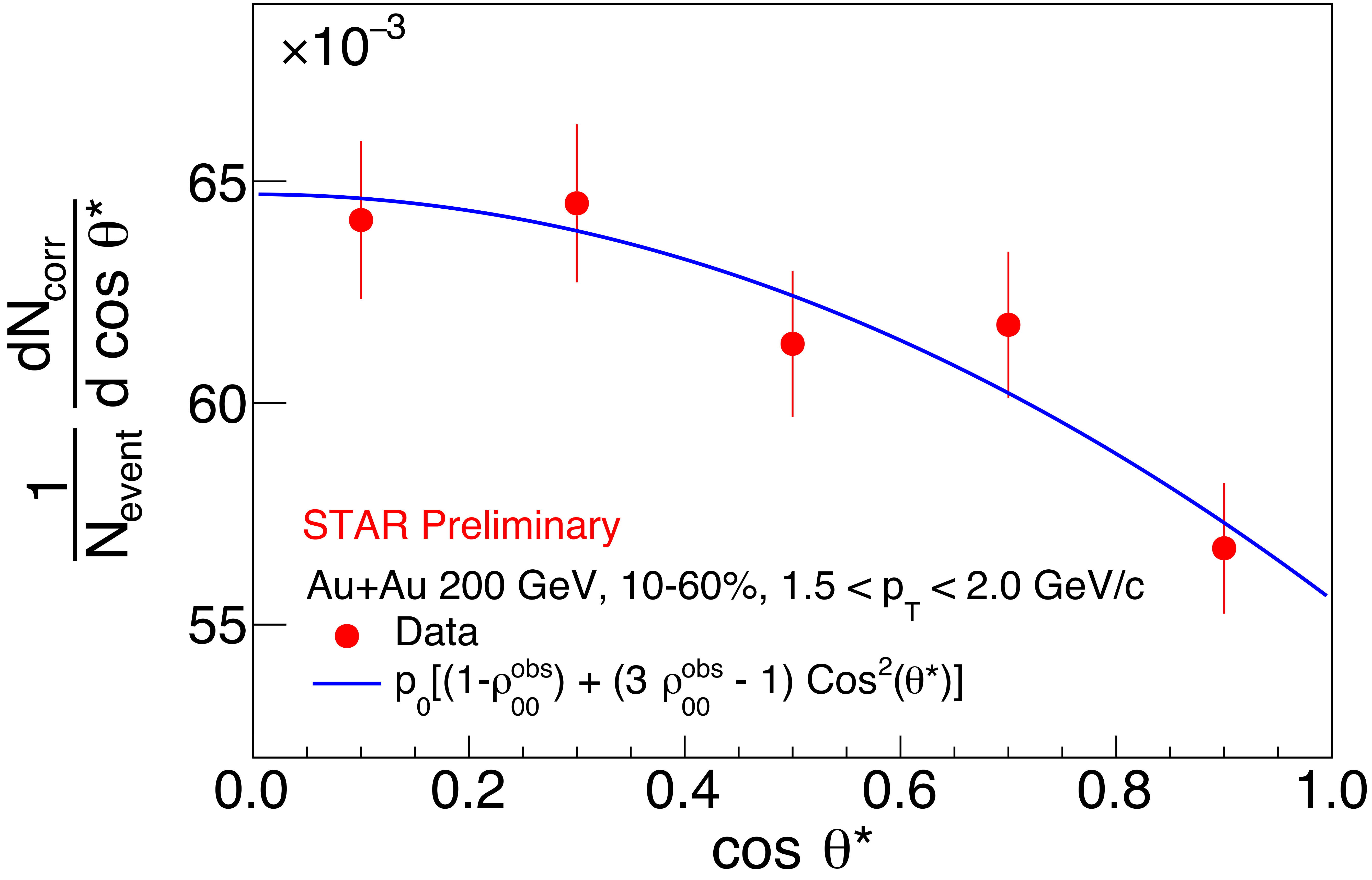




- Here polarization axis ($\hat{n}_{RP}$) is the direction perpendicular to the TPC 2nd-order event plane (Ψ_2)
- θ* is the angle between the daughter (K^+) momentum of K^{*0} in its rest frame and $\hat{n}_{RP}$

Analysis method

- Yield of K^{*0} is corrected for efficiency and acceptance



- Observed ρ_{00}^{obs} is calculated from fitting the yield with function:

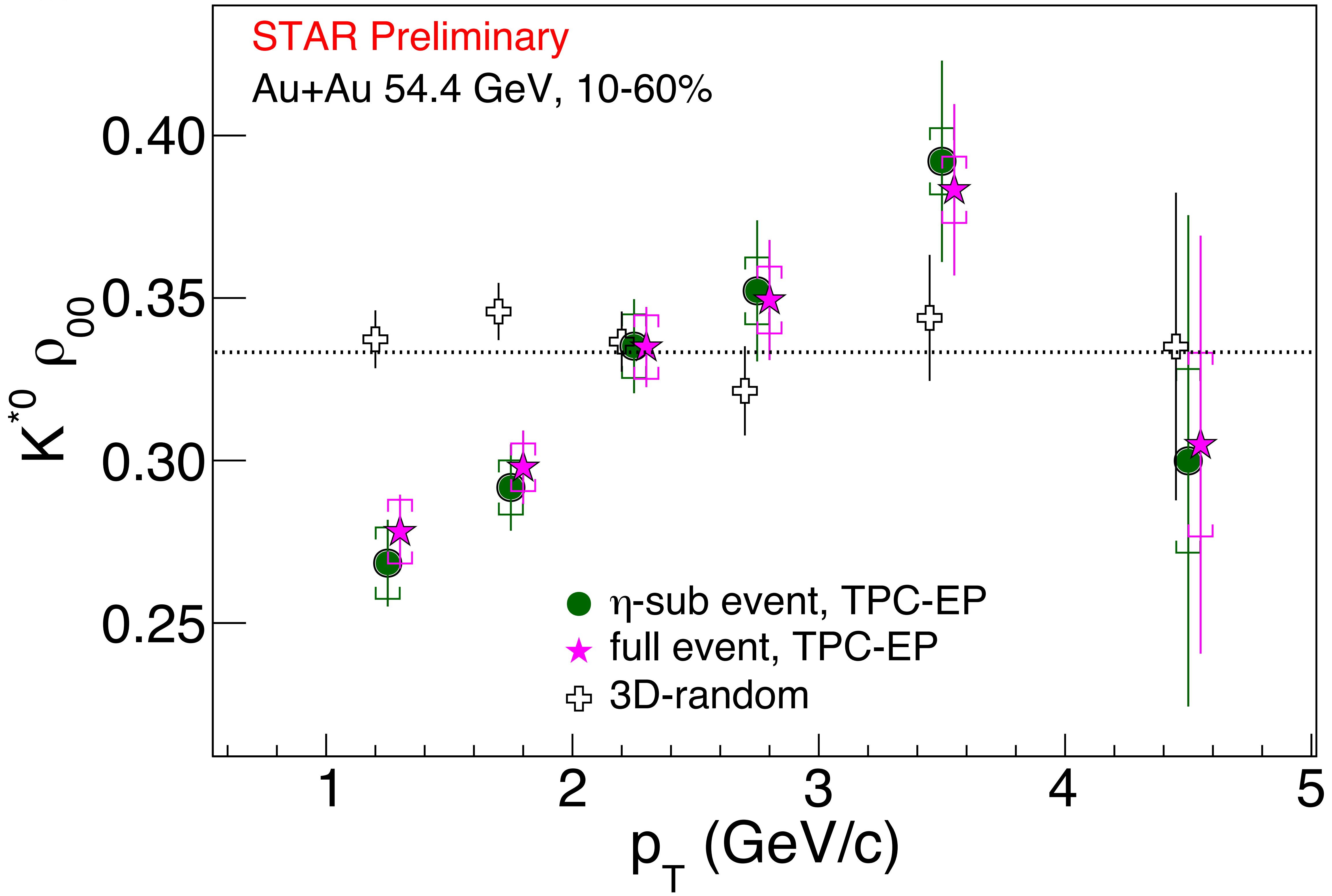
$$\frac{dN}{d(\cos\theta^*)} = N_0 \times [(1-\rho_{00}^{obs}) + (3\rho_{00}^{obs}-1)\cos^2\theta^*)]$$

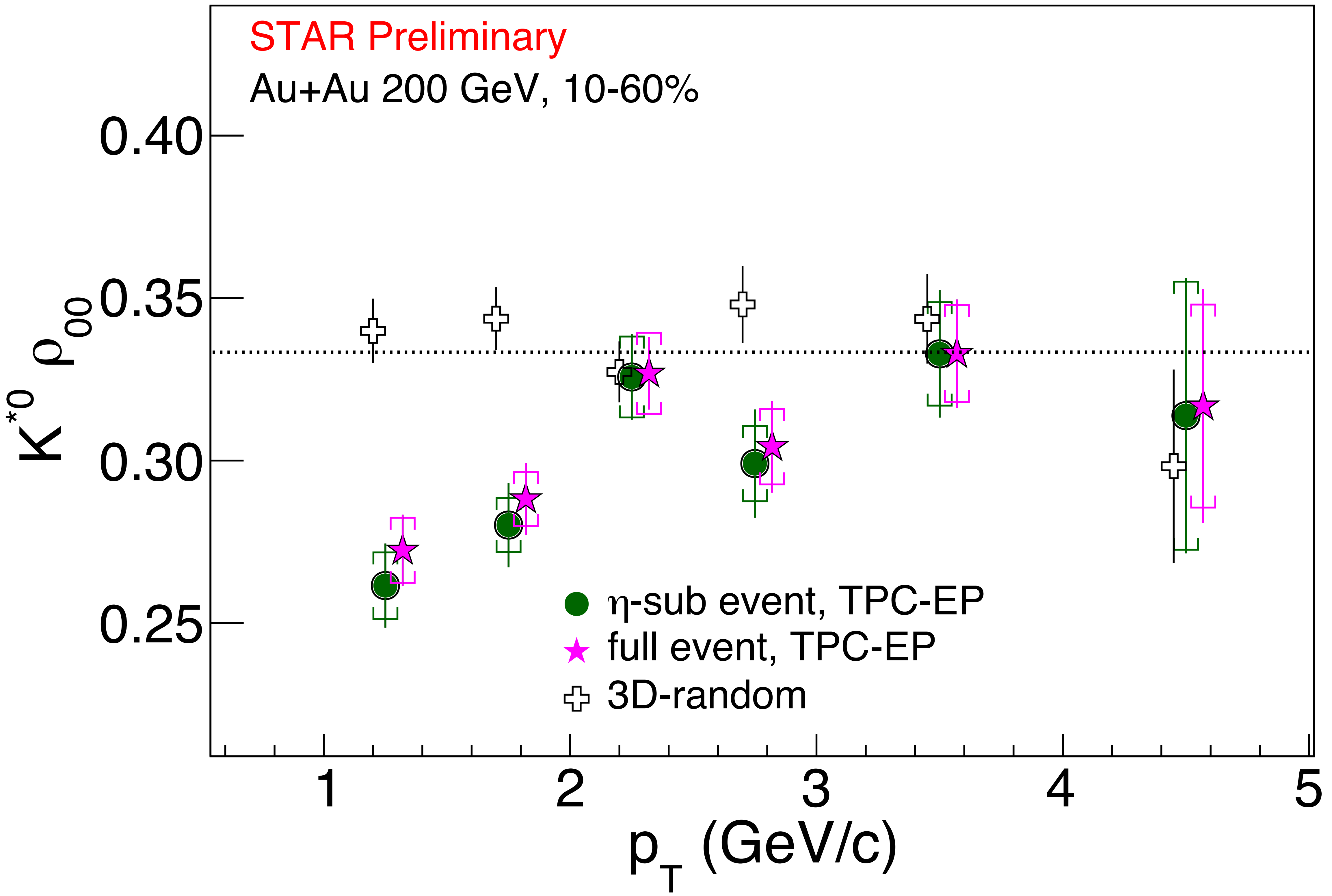
- Observed ρ_{00}^{obs} is corrected for TPC event plane resolution (R)

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

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

K^{*0} ρ_{00} (p_T)





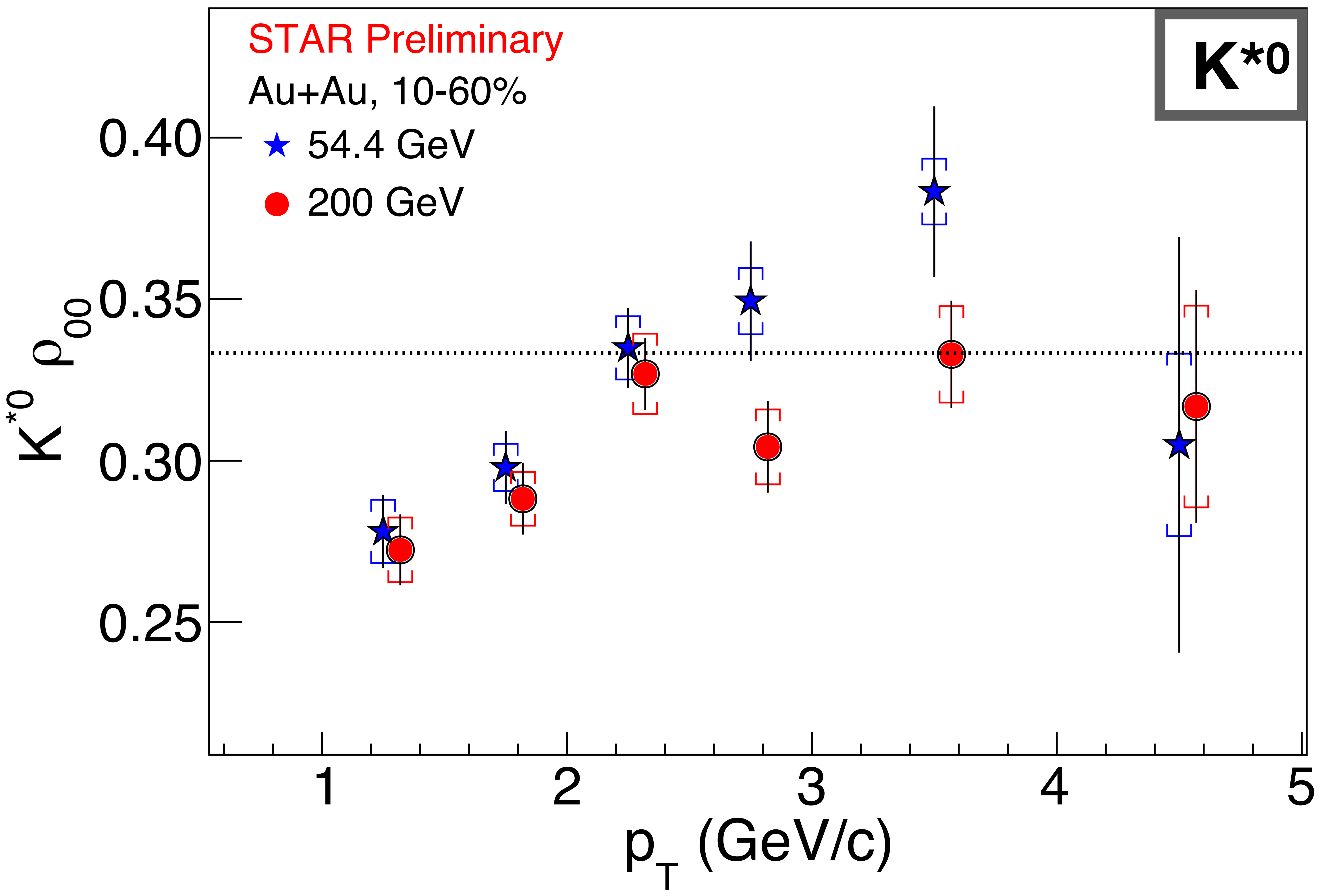
- ρ_{00} results from 3D-random plane consistent with 1/3 as expected

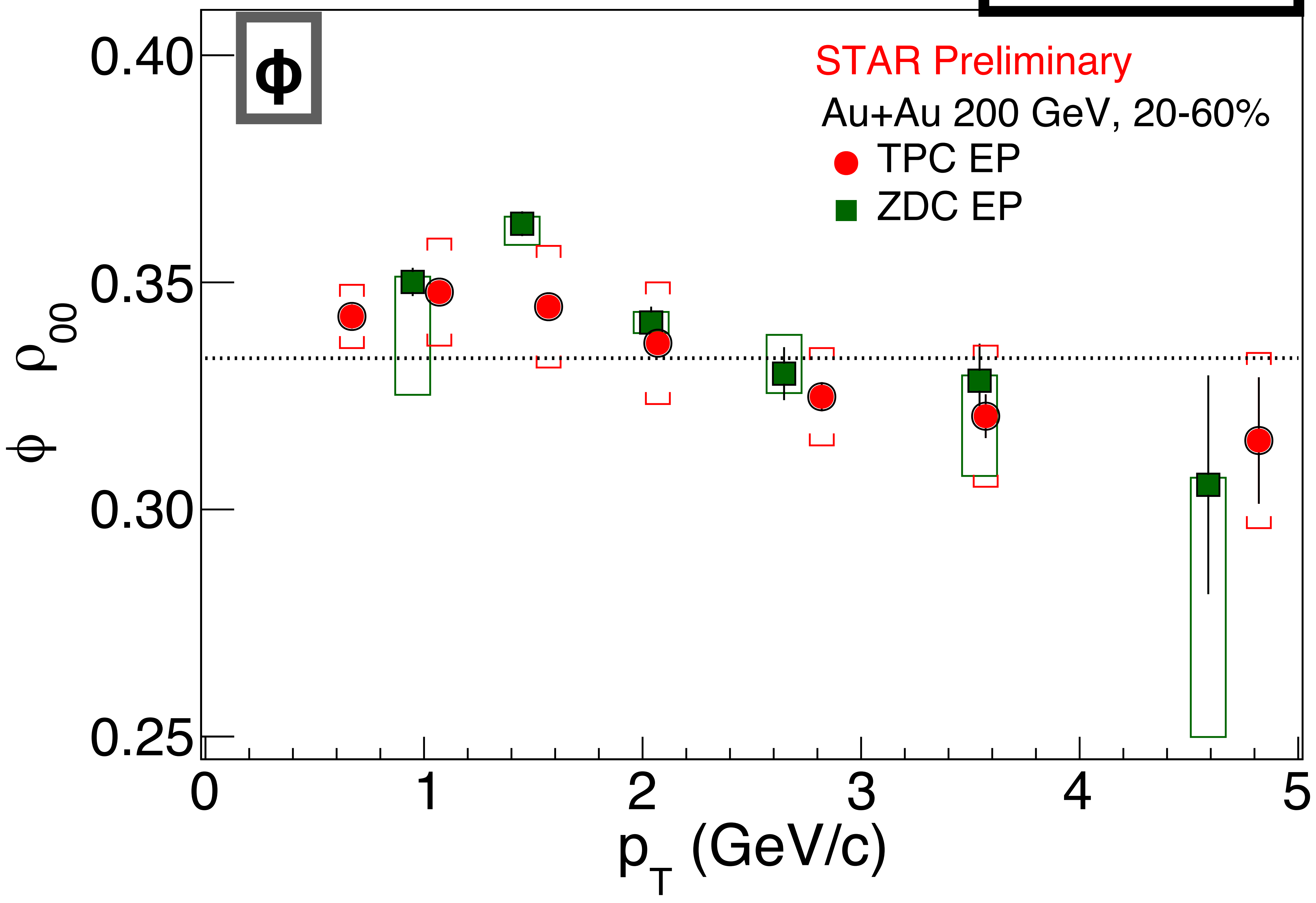
- Significant deviation of ρ_{00} from 1/3 is observed at low p_T for both 54.4 and 200 GeV
- ρ_{00} from TPC η-sub and full event plane are consistent despite of different event plane resolutions

For Au+Au 200 GeV, 10-60% centrality:
TPC (Ψ_2) resolution ~ 0.55 for η-sub event plane
TPC (Ψ_2) resolution ~ 0.77 for full event plane

ρ_{00} (p_T): K^{*0} vs. ϕ

QM 2018

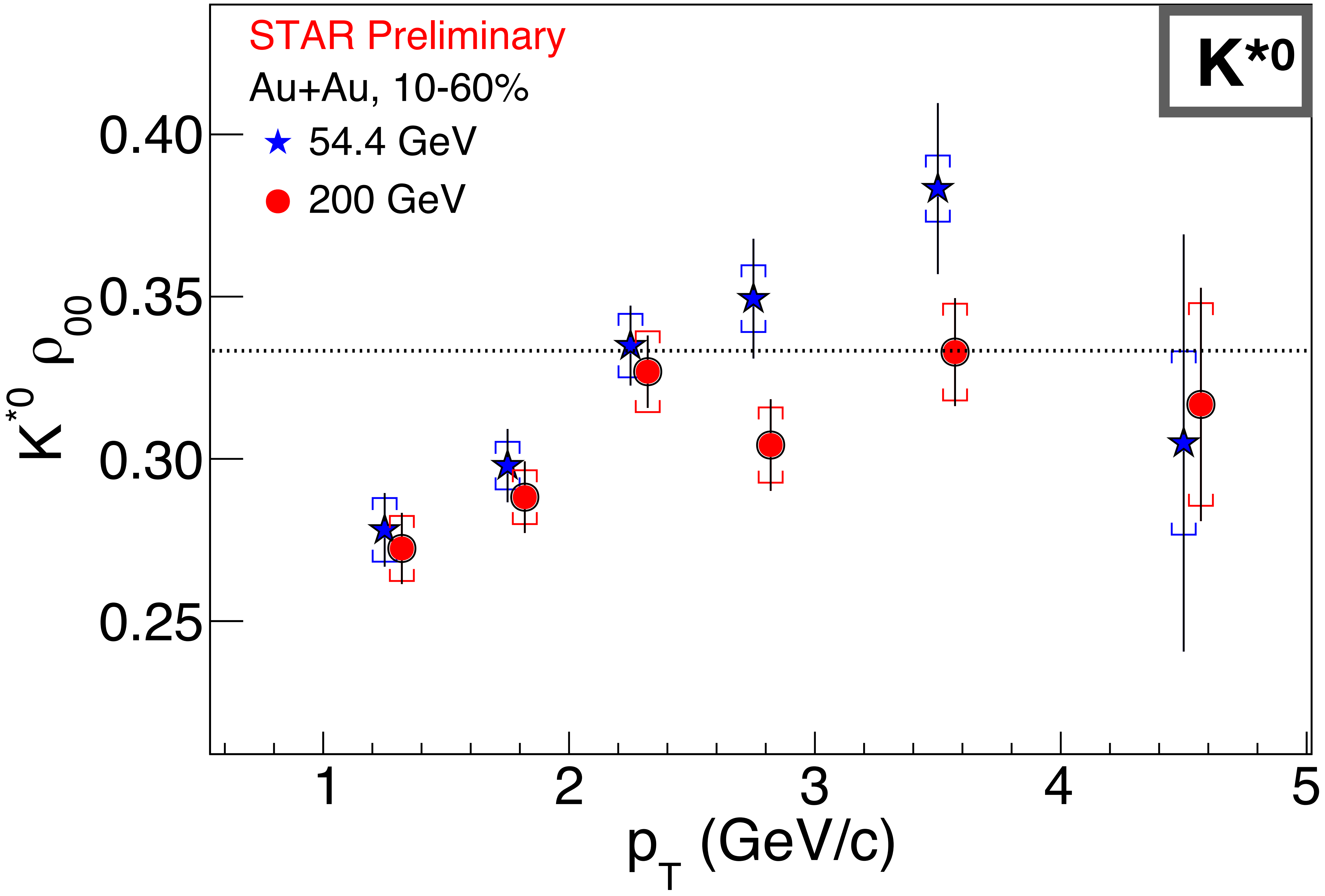


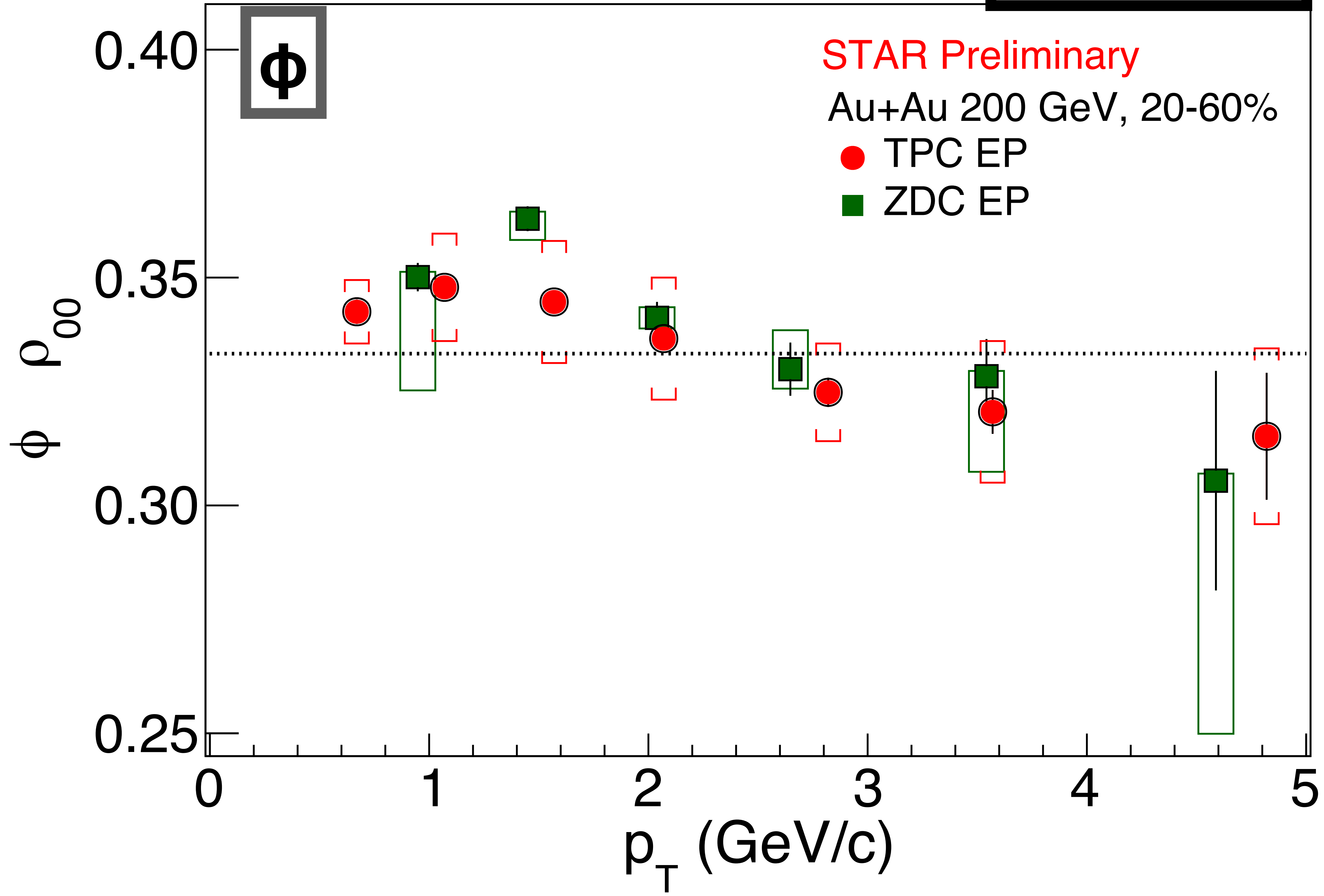


- Non-trivial and opposite p_T dependence observed for K^{*0} and ϕ

ρ_{00} (p_T): K^{*0} vs. ϕ

QM 2018

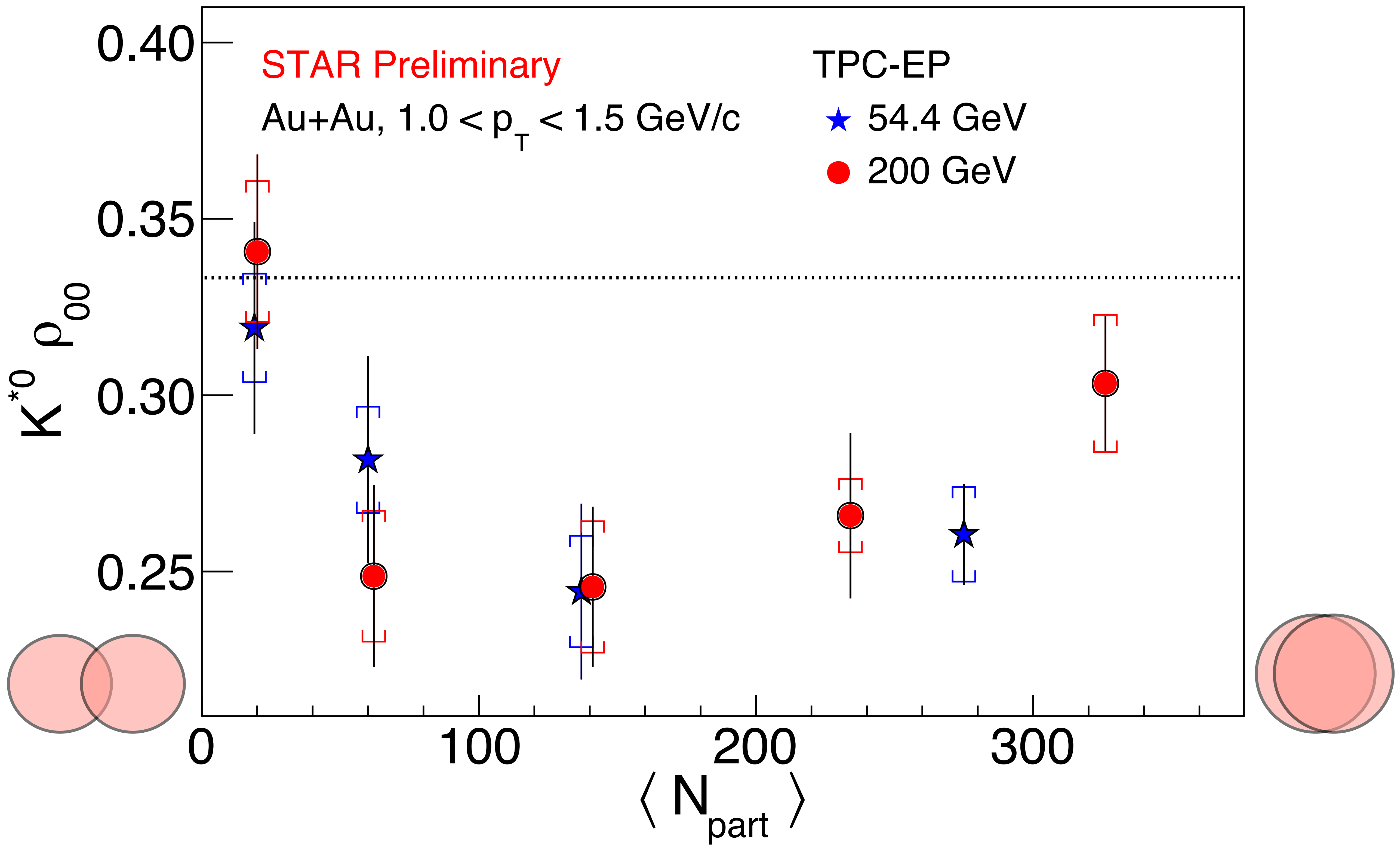




- Trend for K^{*0} ρ_{00} is qualitatively consistent with the naive expectation from recombination/fragmentation of polarized quarks [1] but the magnitude is much larger
- ϕ ρ_{00} does not fit into naive recombination/fragmentation picture [1]
- But it can be explained by the existence of coherent ϕ meson field [2]

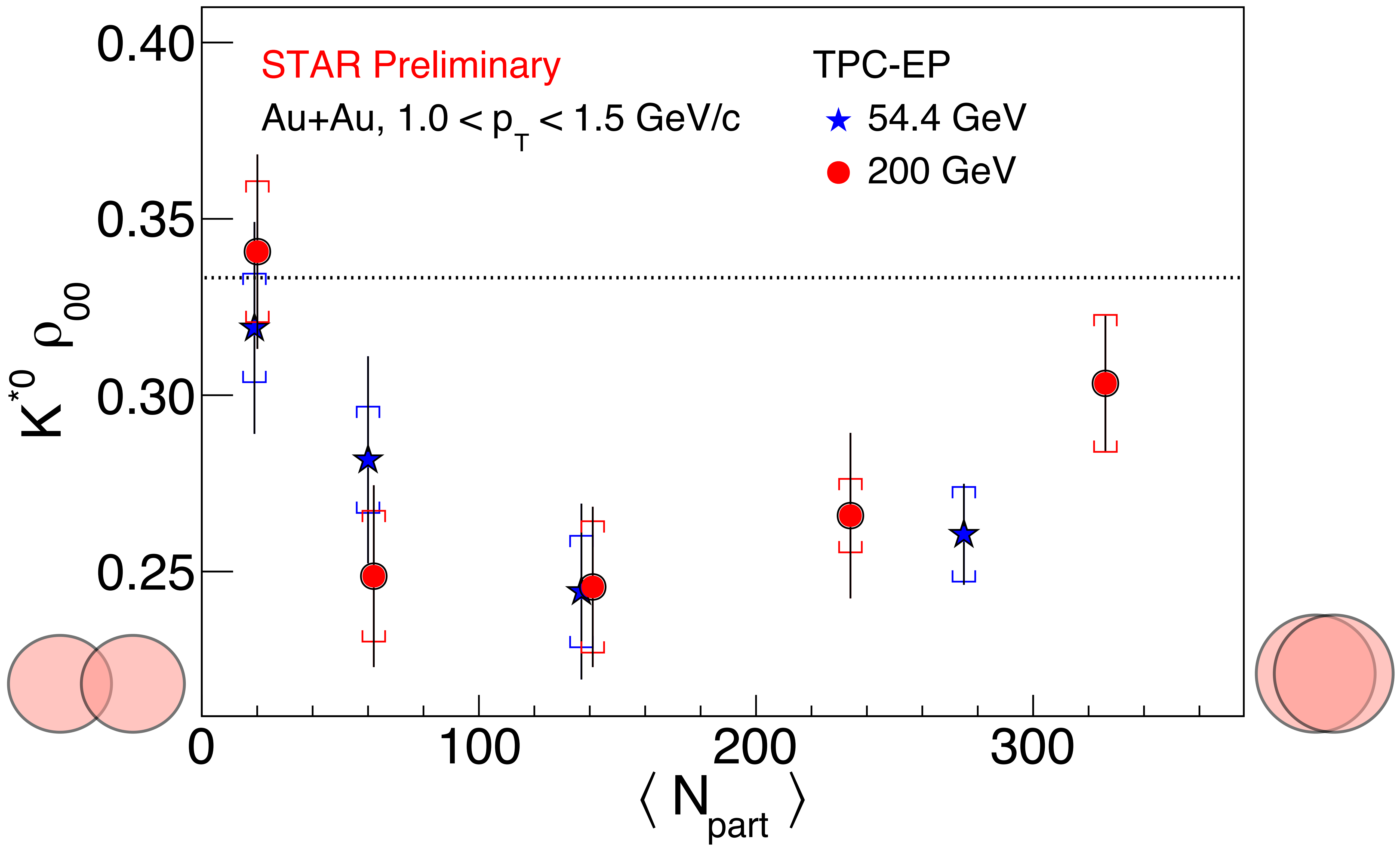
[1] Z. Liang et. al., Phys. Lett. B629, 20 (2005)
[2] X. Sheng et. al., arXiv:1910.13684 (2019)

K^{*0} ρ_{00} (centrality)

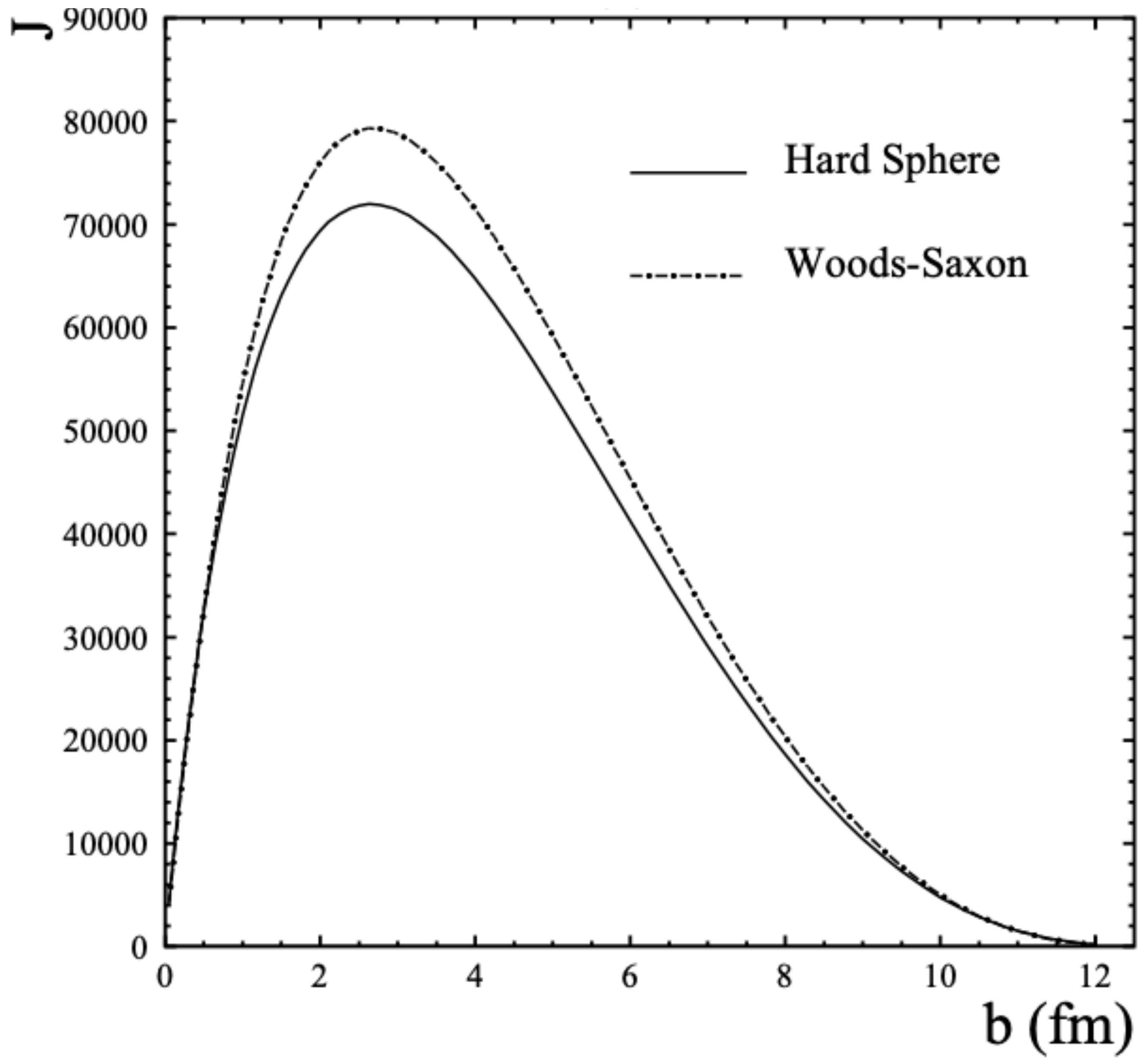


- For peripheral collisions $\rho_{00} \sim 1/3$
- For midcentral collisions $\rho_{00} < 1/3$
- For central collisions ρ_{00} close to 1/3

K^{*0} ρ_{00} (centrality)



Angular momentum vs. impact parameter

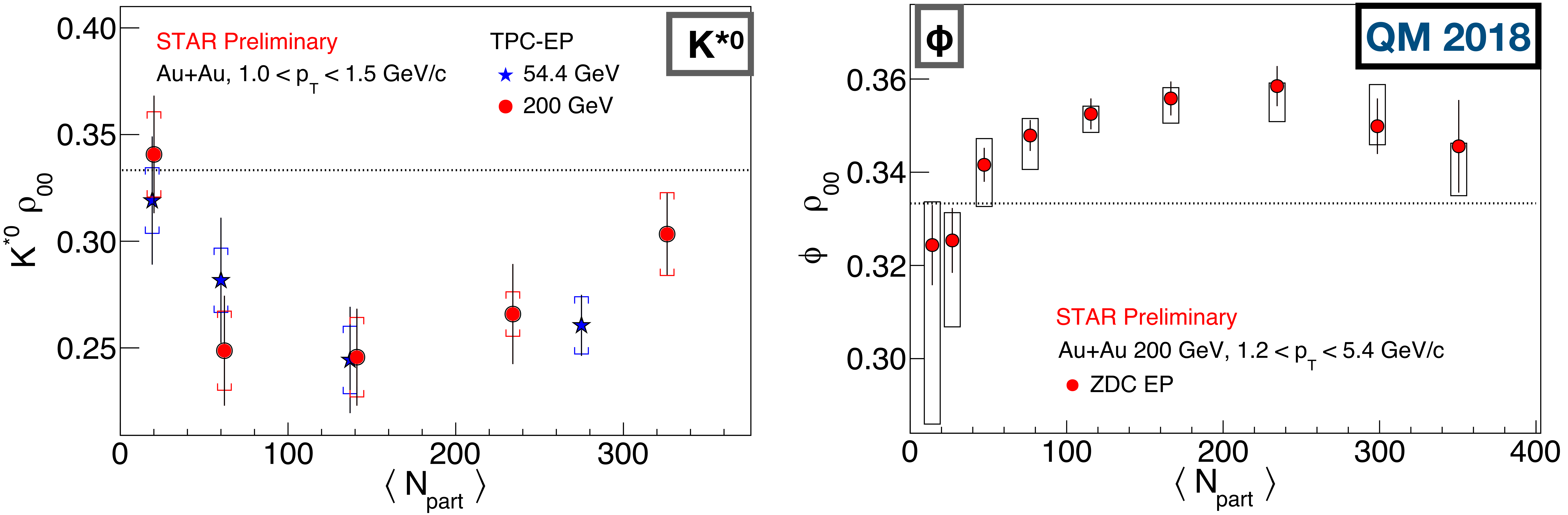


- For peripheral collisions $\rho_{00} \sim 1/3$
- For midcentral collisions $\rho_{00} < 1/3$
- For central collisions ρ_{00} close to 1/3
- Trend similar to angular momentum vs. centrality

Subhash Singha, QM 2019

ρ_{00} (centrality): K^{*0} vs. ϕ

Meson	τ(fm/c)
Φ	45
K^{*0}	4

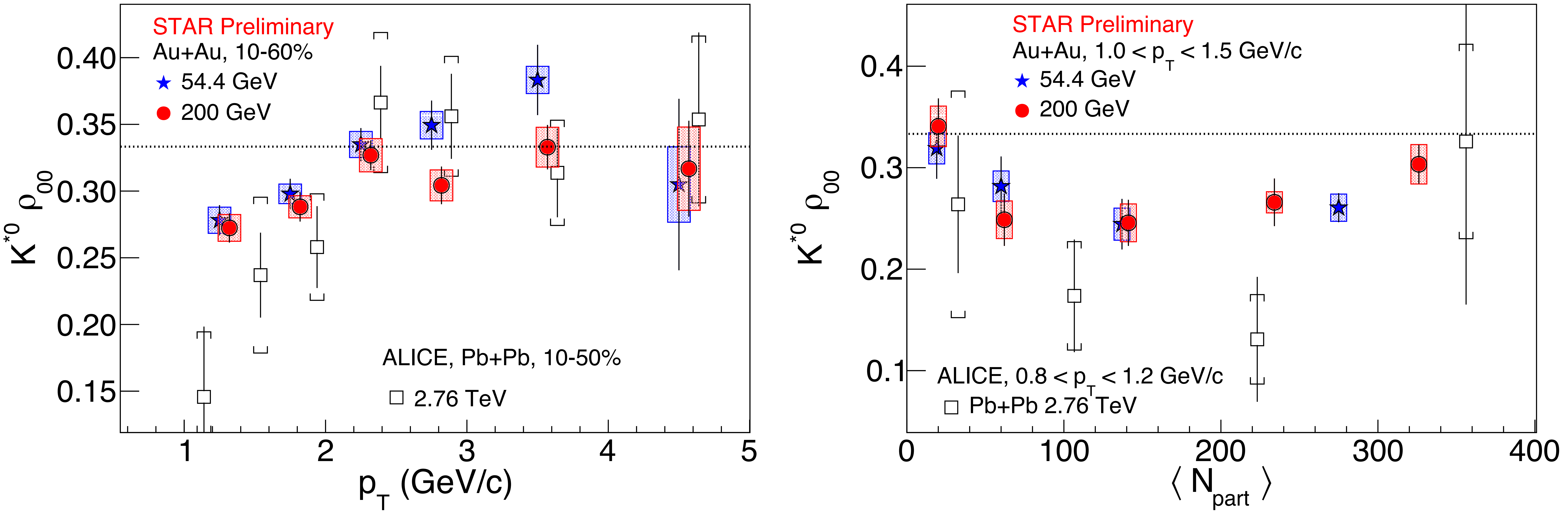


- For midcentral collisions

- K^{*0} $\rho_{00} < 1/3$

- ϕ $\rho_{00} > 1/3$

K^{*0} ρ_{00} : RHIC vs. LHC



- p_T and centrality dependence of ρ_{00} at RHIC is similar to LHC energies but with much better precision
- At low p_T and midcentral collisions hint that LHC measurements are lower than RHIC by 1-1.5σ

Summary of ρ_{00}/P_H measurements from RHIC and LHC

For midcentral collisions

Species	Quark content	J^P	ρ_{00}/P_H at top-RHIC	ρ_{00}/P_H at LHC
K^{*0}	$d\bar{s}$	1^-	$\rho_{00} < 1/3$ (~4σ)	$\rho_{00} < 1/3$ (~3σ)
φ	$s\bar{s}$	1^-	$\rho_{00} > 1/3$ (~3σ)	$\rho_{00} < 1/3$ (~2σ)
Λ	uds	$1/2^+$	$P_H > 0$ (~4σ)	$P_H \sim 0$ (~1σ)

- From current theoretical understanding $P_H \propto P_q$, while $\rho_{00} \propto P_q^2$ P_q: quark polarization
- Given the small P_H values observed at top RHIC and LHC energies, ρ_{00} expected to be close to 1/3
- Hence, the current ρ_{00} measurements are surprising!

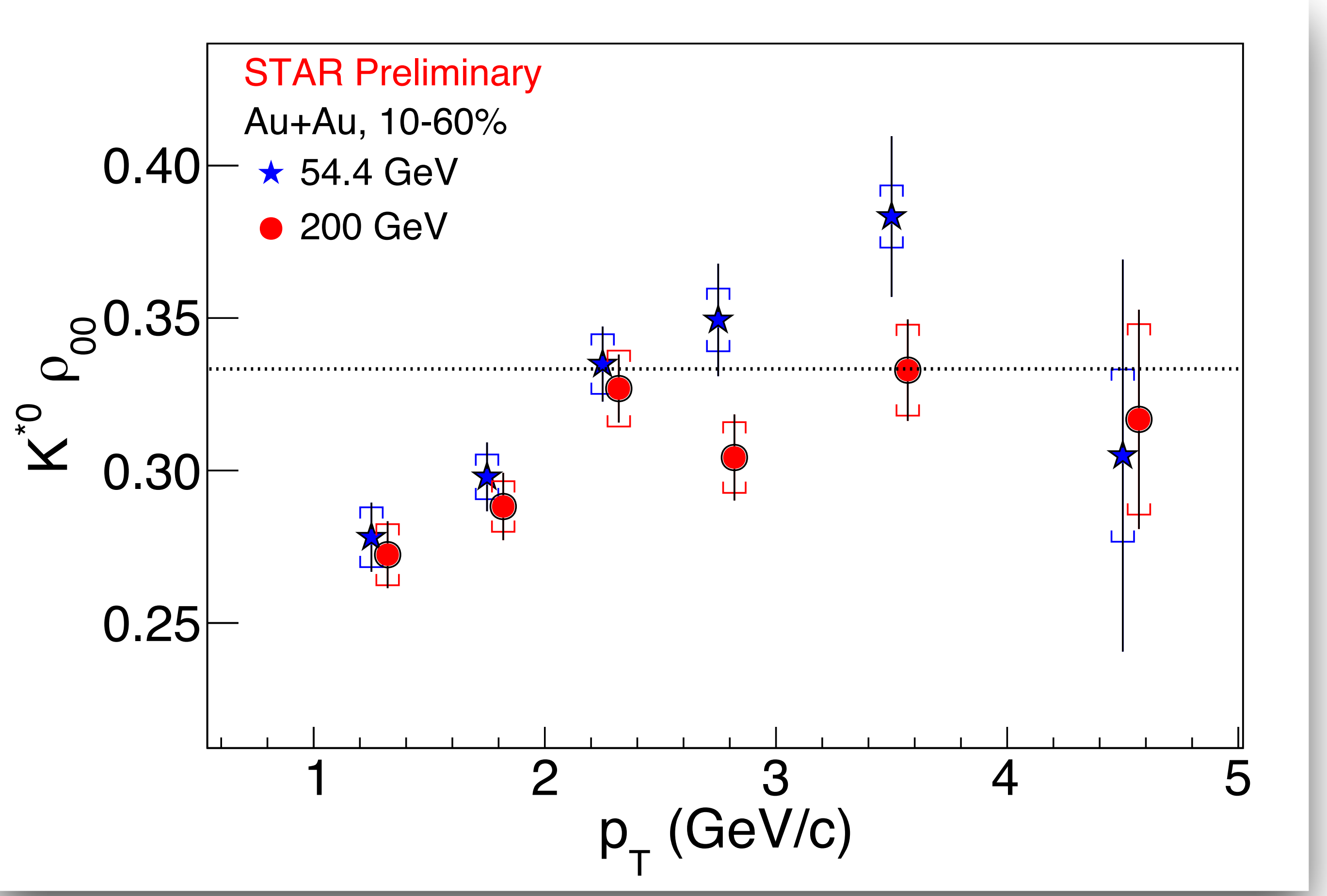
Nature 548, 62 (2017) (STAR Collaboration)
Phys Rev C 98, 14910 (2018) (STAR Collaboration)
arXiv: 1909.01281 (2019) (ALICE Collaboration)
arXiv: 1910.14408 (2019) (ALICE Collaboration)

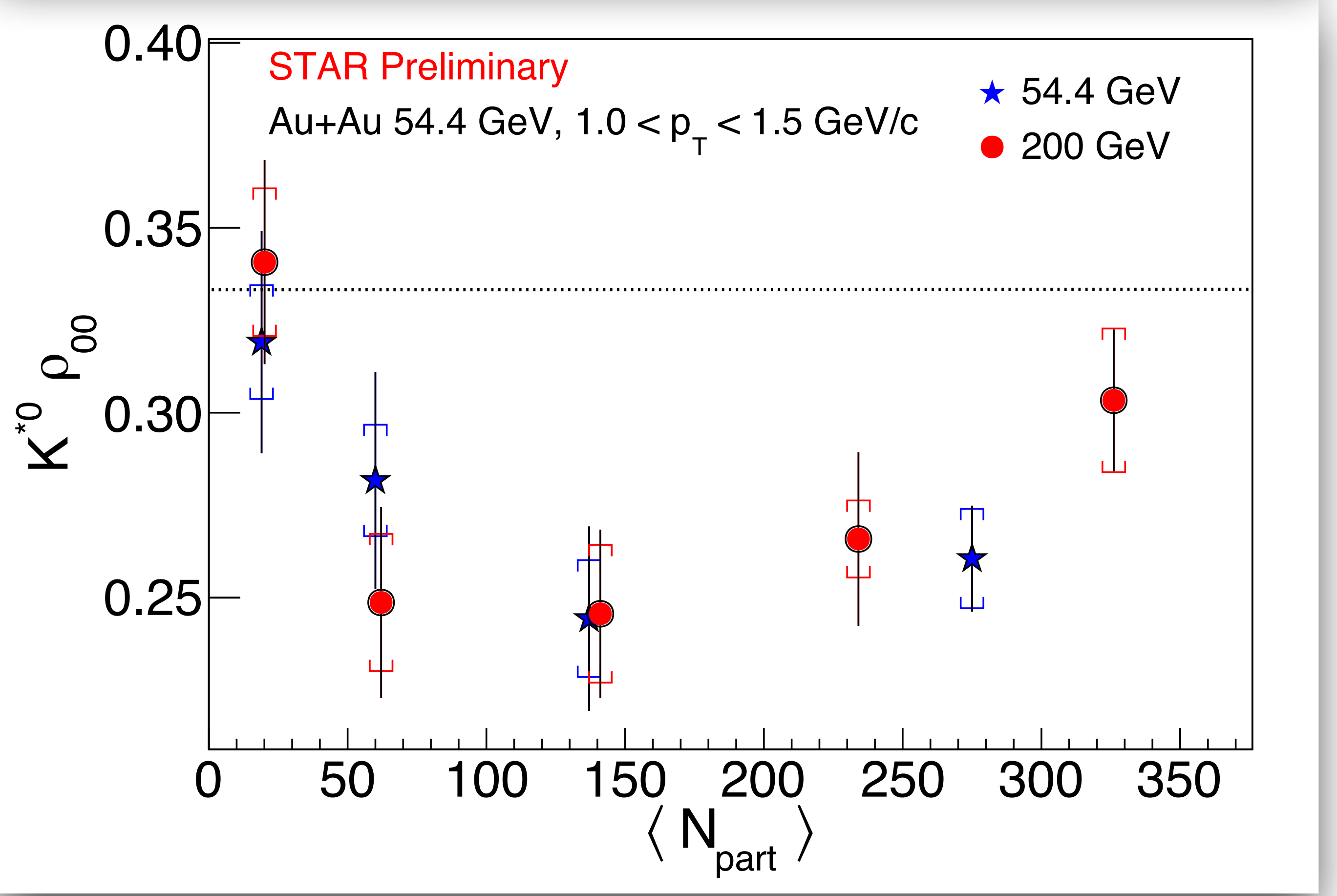
- ρ_{00} can depend on hadronization, vorticity, electromagnetic and mesonic field
- More theoretical input is needed to understand the data

Z. Liang et. al., Phys. Lett. B629, 20 (2005)
Y. Yang et. al., Phys. Rev. C 97, 034917 (2018)
X. Sheng et. al., arXiv:1910.13684 (2019)

Summary

- We presented p_T and centrality dependence of ρ_{00} of neutral K* from 54.4 GeV and 200 GeV.
- K^{*0} $\rho_{00} < 1/3$ is observed for both 54.4 and 200 GeV
- Observation of K^{*0} spin alignment at RHIC energies
- p_T and centrality dependence of ρ_{00} similar between RHIC and LHC





- For midcentral collisions, ρ_{00} (K^{*0}) < 1/3, while ρ_{00} (ϕ) > 1/3
- Need quantitative estimation from models to better understand the data

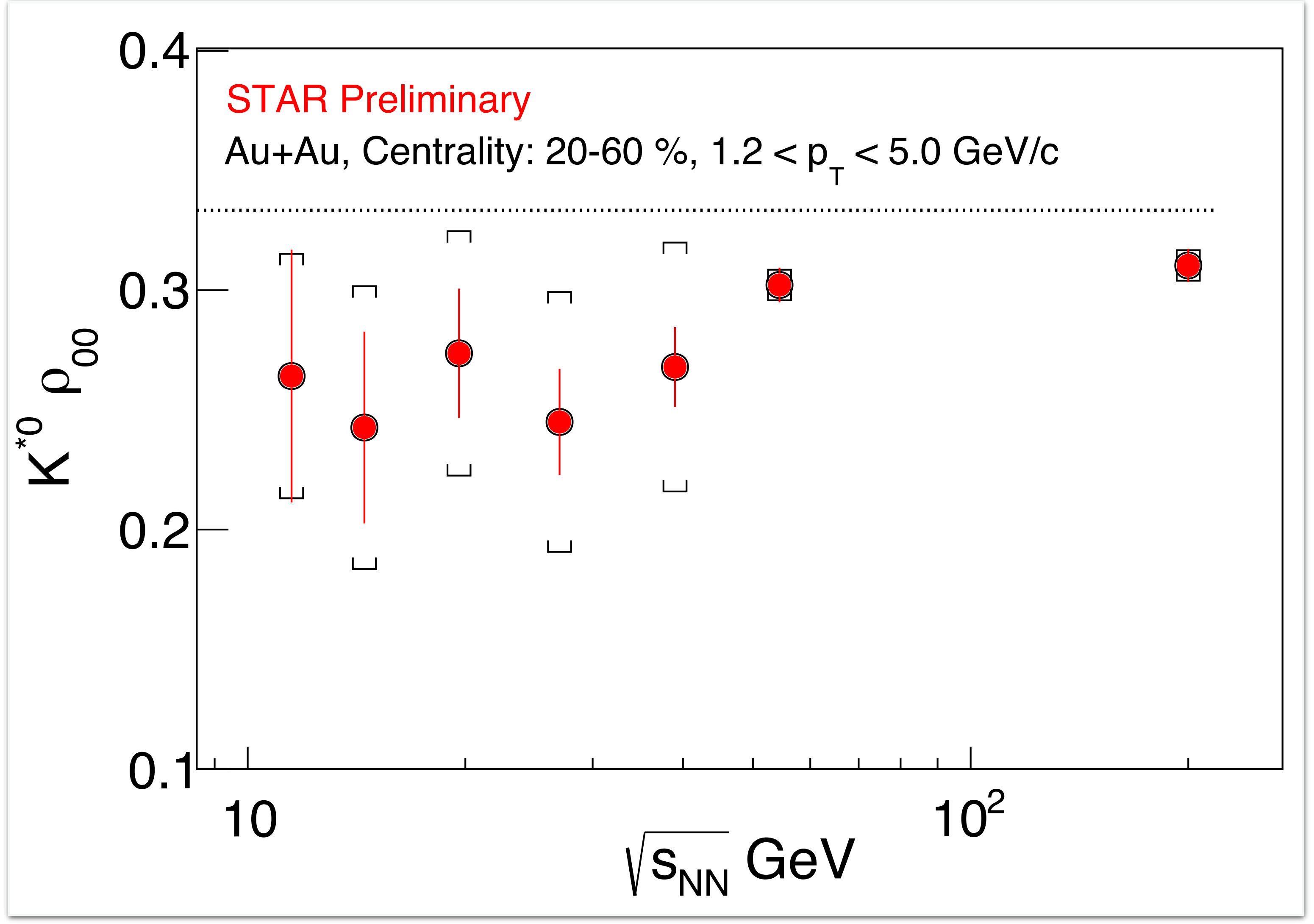
Theoretical expectation of ρ_{00}

Vorticity	$\rho_{00}(\omega) < 1/3$	
Magnetic field	$\rho_{00}(B) > 1/3$	Electrically neutral vector mesons
	$\rho_{00}(B) < 1/3$	Electrically charged vector mesons
Hadronization	$\rho_{00}(\mathrm{rec}) < 1/3$	Recombination
	$\rho_{00}(\mathrm{frag}) > 1/3$	Fragmentation
Mesonic field	$\rho_{00}(\phi) > 1/3$	For ϕ meson

Outlook

<u>For Au+Au 200 GeV data:</u>

- STAR has collected more than 2 B events during 2014, 2016 and 2018. We expect to reach better statistical precision
- Analysis of charged K* ρ_{00} with high statistics 200 GeV data is underway



<u>(BES-II)</u>

Energy (GeV)	# events (M)
7.7	100
9.1	160
11.5	200
14.5	320
19.6	580
27	500

<u>For lower energy Au+Au data (< 39 GeV):</u>

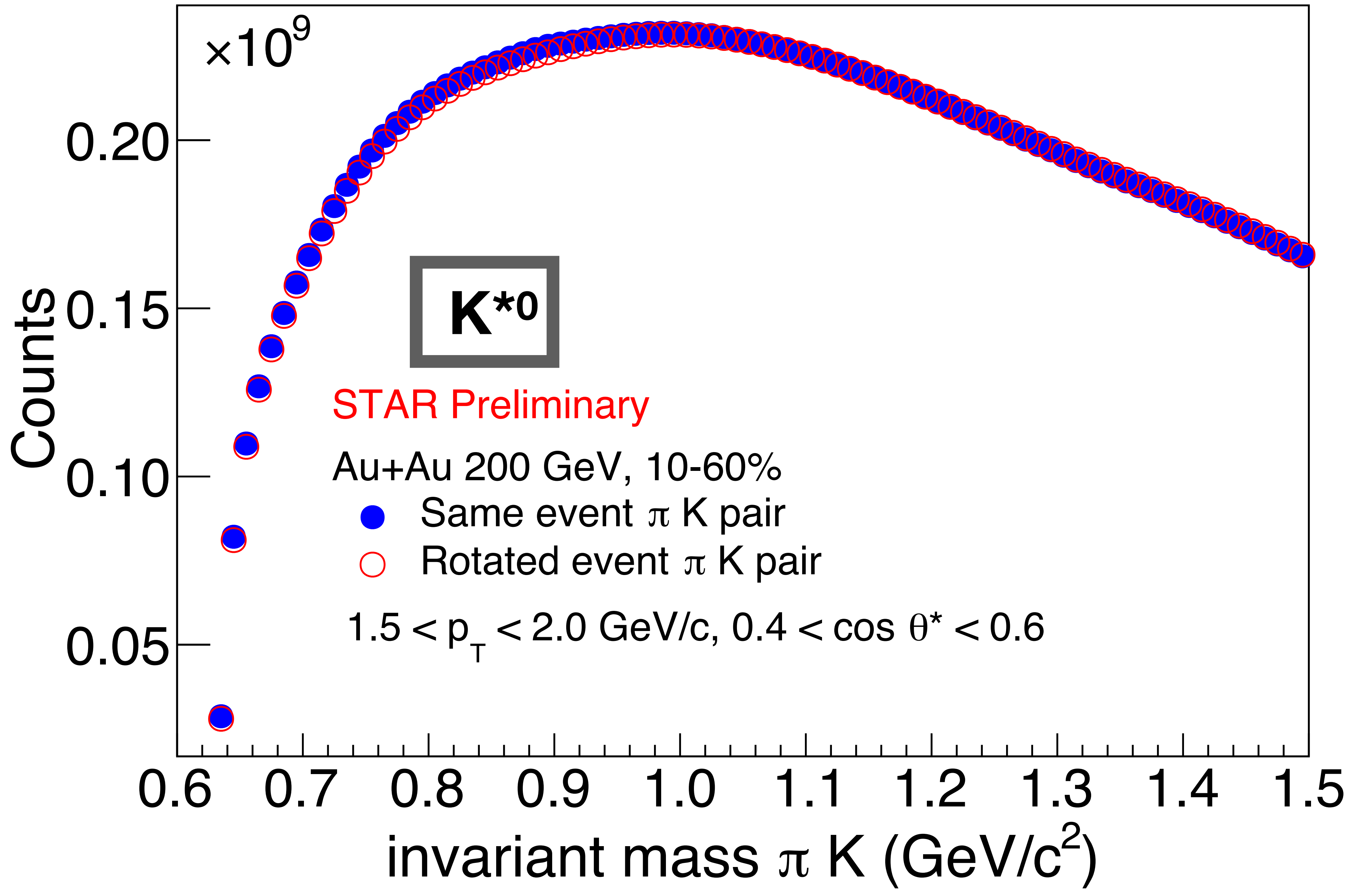
- High statistics and detector upgrades in 2nd phase of BES will improve precision of vector meson ρ_{00} measurements

Thank you

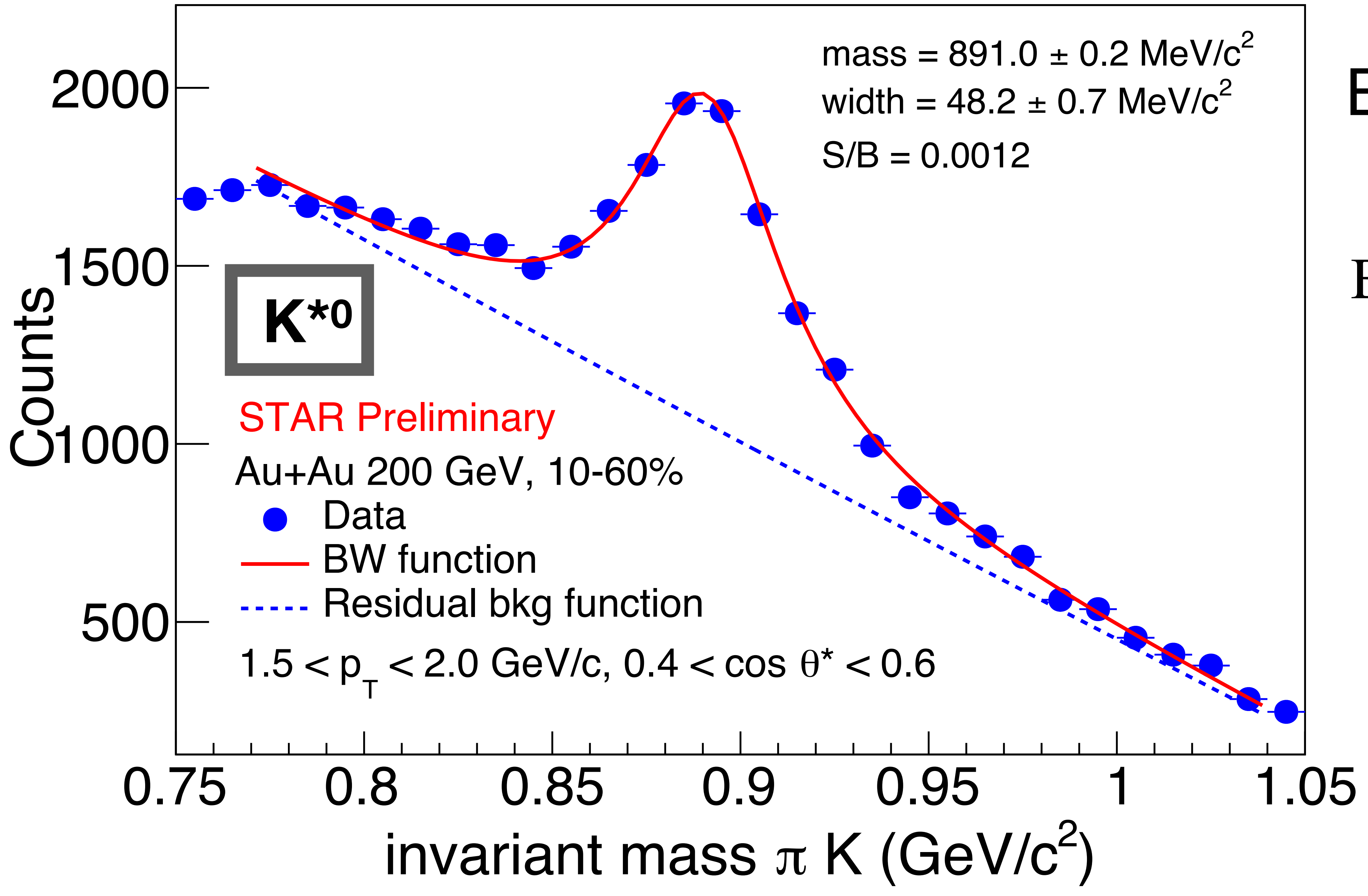
Backup slides

Invariant mass signal reconstruction

Before background subtraction



After background subtraction



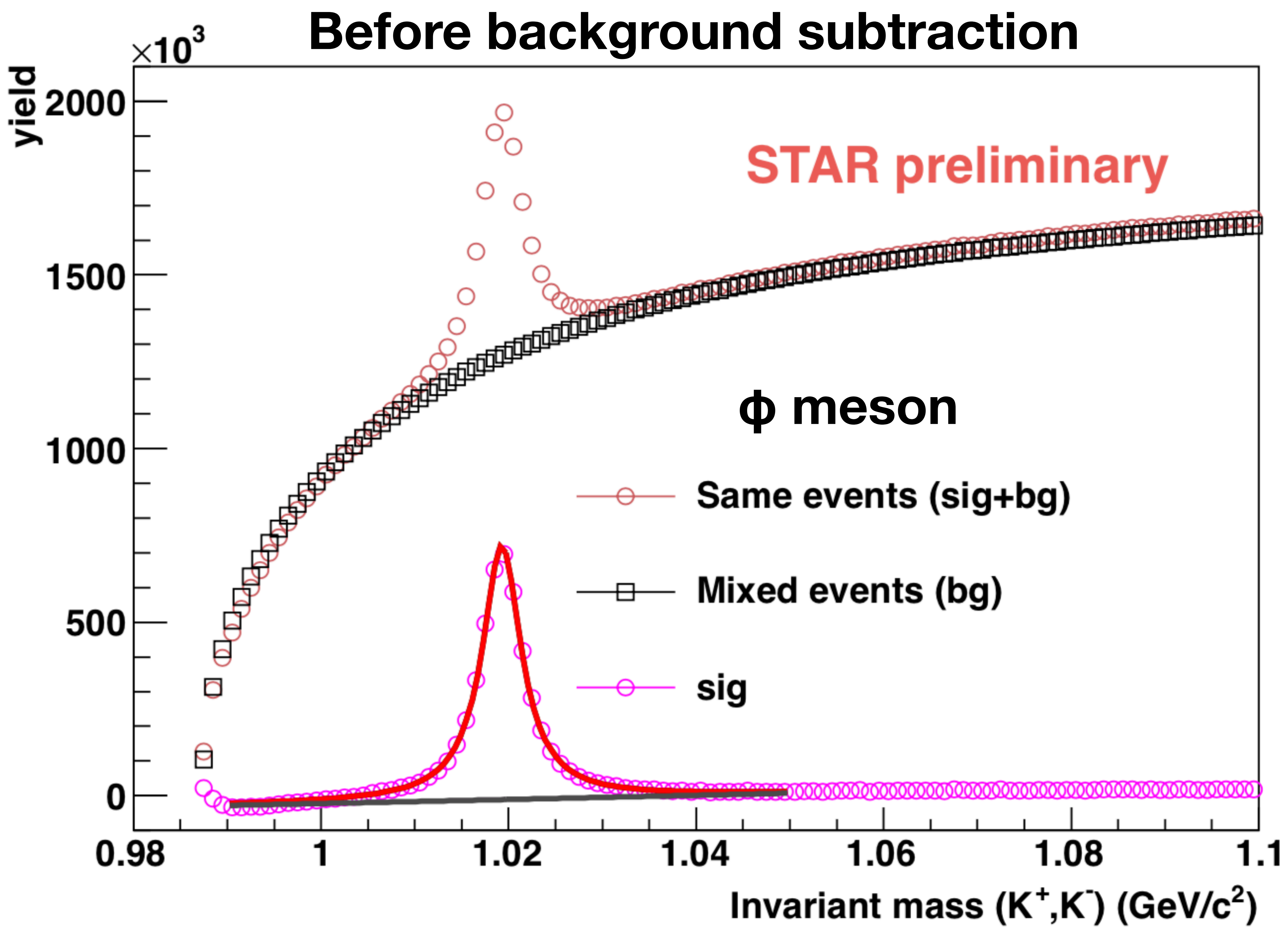
Breit Wigner function

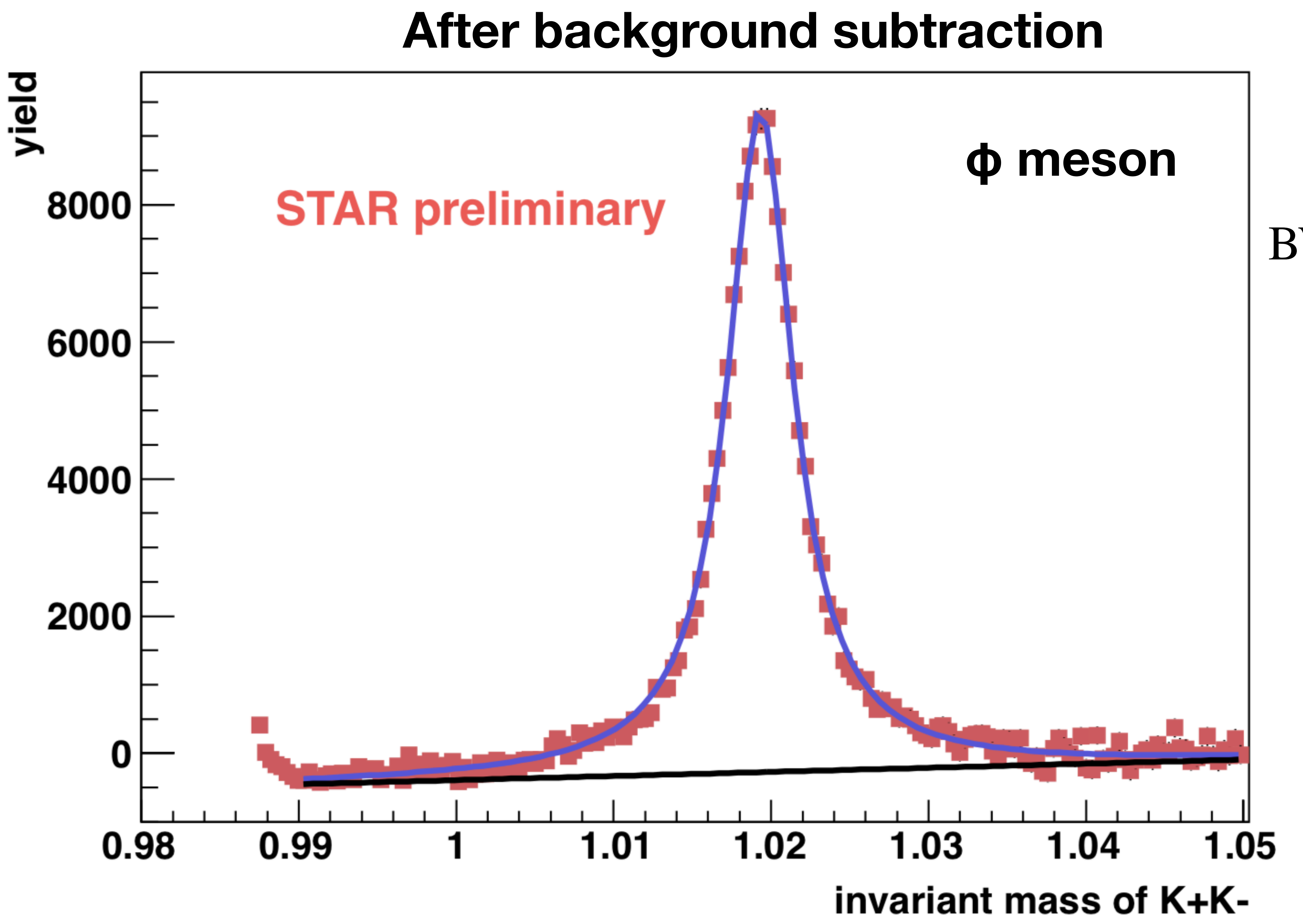
$$BW = \frac{1}{2\pi}\frac{A\Gamma}{(m - m_0)^2 + (\Gamma/2)^2}$$

- K^{*0} signal is extracted by using rotational background subtraction method
- Signal fitted with Breit Wigner function plus second order polynomial as residual background
- K^{*0} mass and width consistent with published values
- K^{*0} yield is the area under the Breit Wigner function

Invariant mass signal reconstruction

Au+Au 200 GeV, centrality: 40-50%, p_T: 1.2-1.8 GeV/c, cos θ*: 1/7- 2/7





$$\mathrm{BW} = \frac{1}{2\pi}\frac{A\Gamma}{(\mathrm{m}-\mathrm{m}_0)^2 + (\Gamma/2)^2}$$

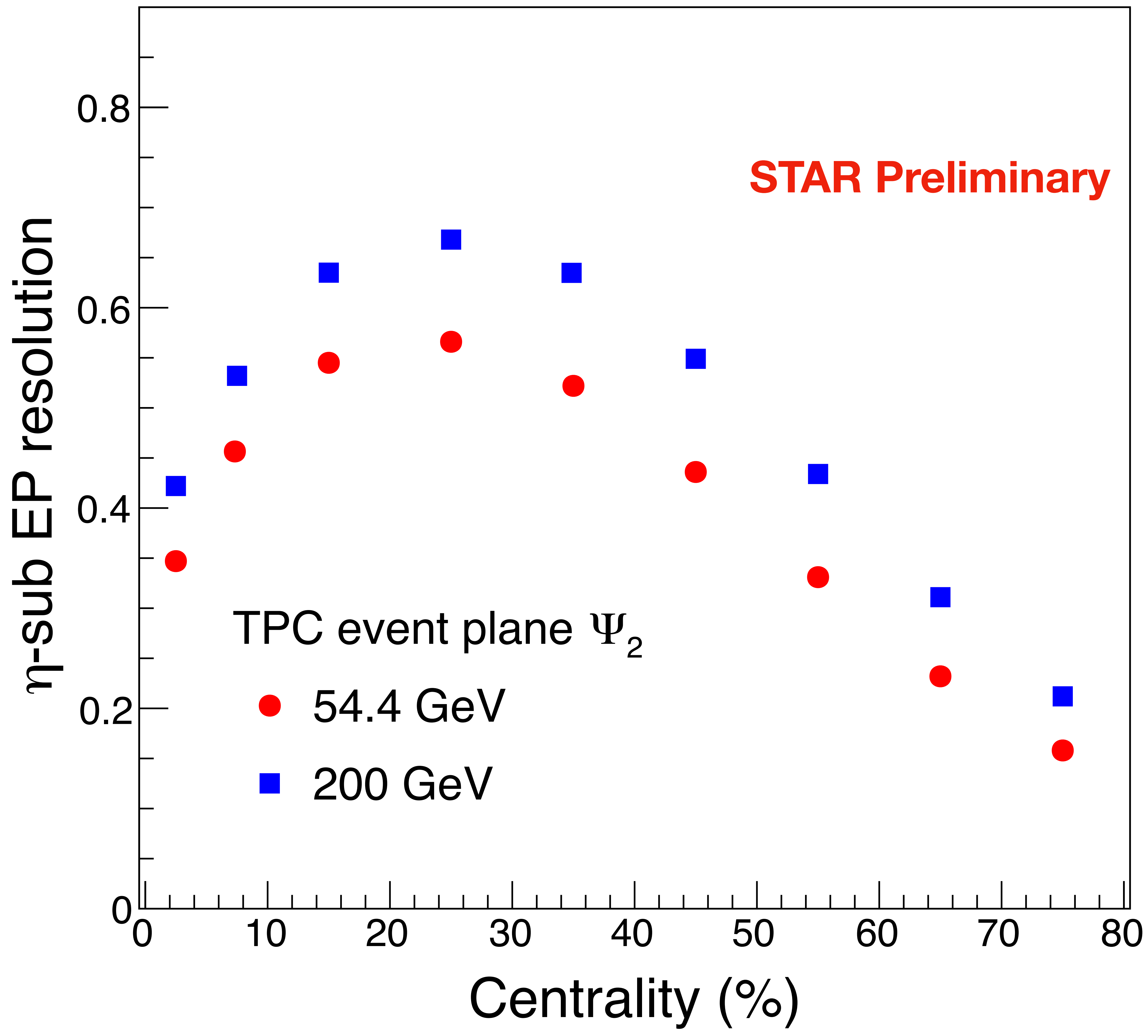
- ϕ signal is extracted by using mixed event background subtraction method
- Signal fitted with Breit Wigner function plus first order polynomial as residual background
- ϕ yield is the area under Breit Wigner function

Event plane reconstruction

Event plane from TPC:

Phys. Rev. C 58 (1998) 1671

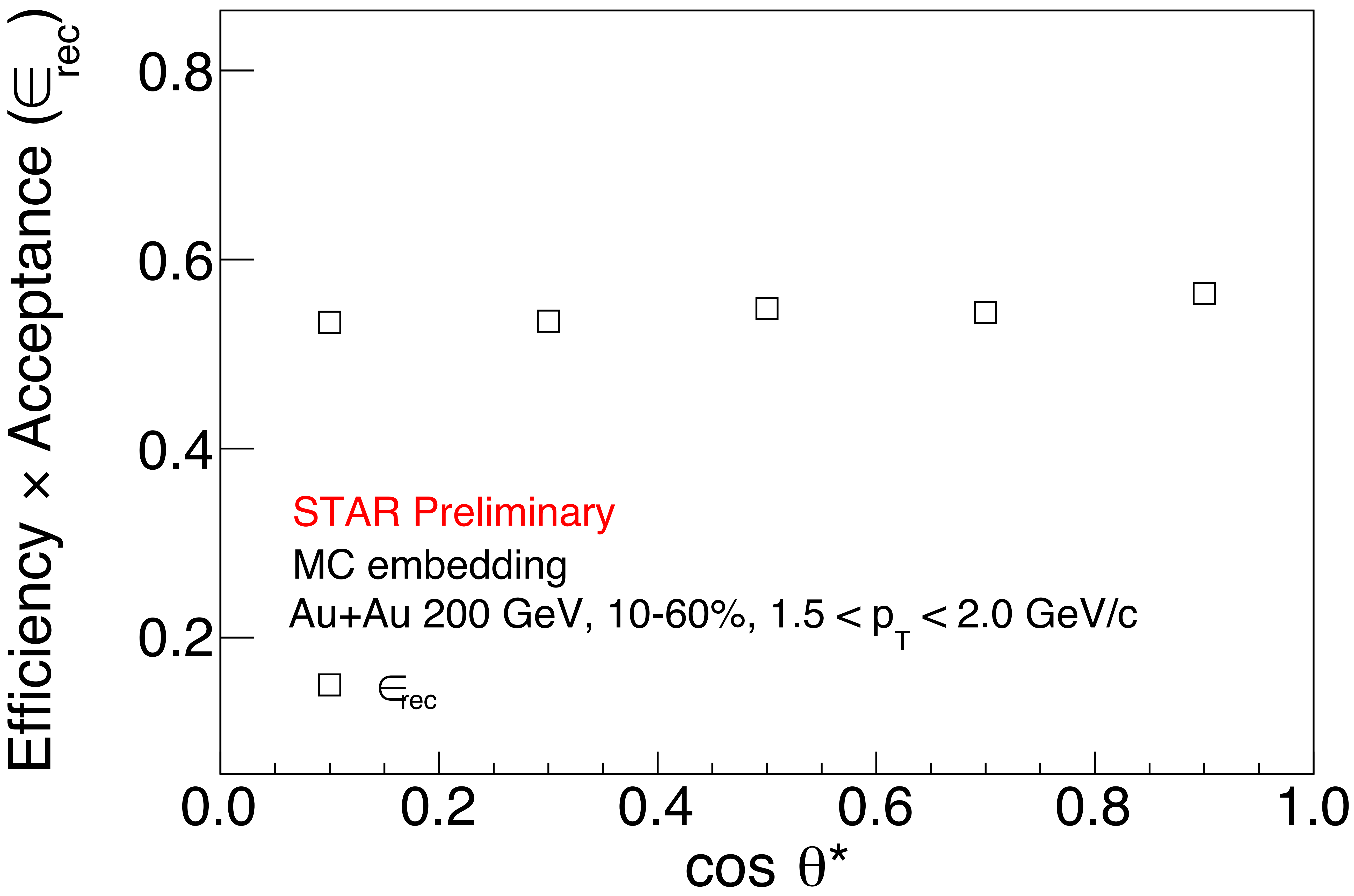
$$\Psi_2 = \frac{1}{2}\frac{\sum w_i \sin(n\phi_i)}{\sum w_i \cos(n\phi_i)}$$

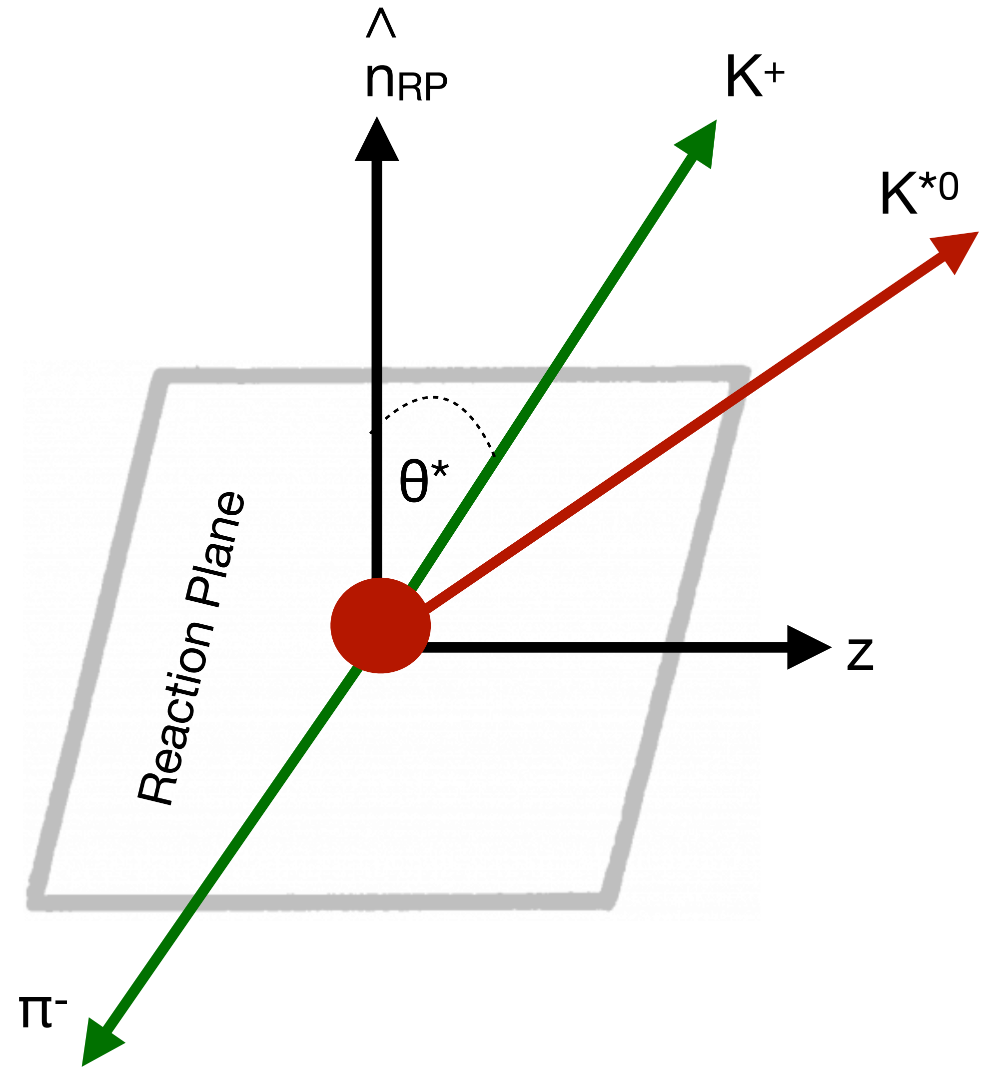


- Second order event plane (ψ_2) is measured using TPC

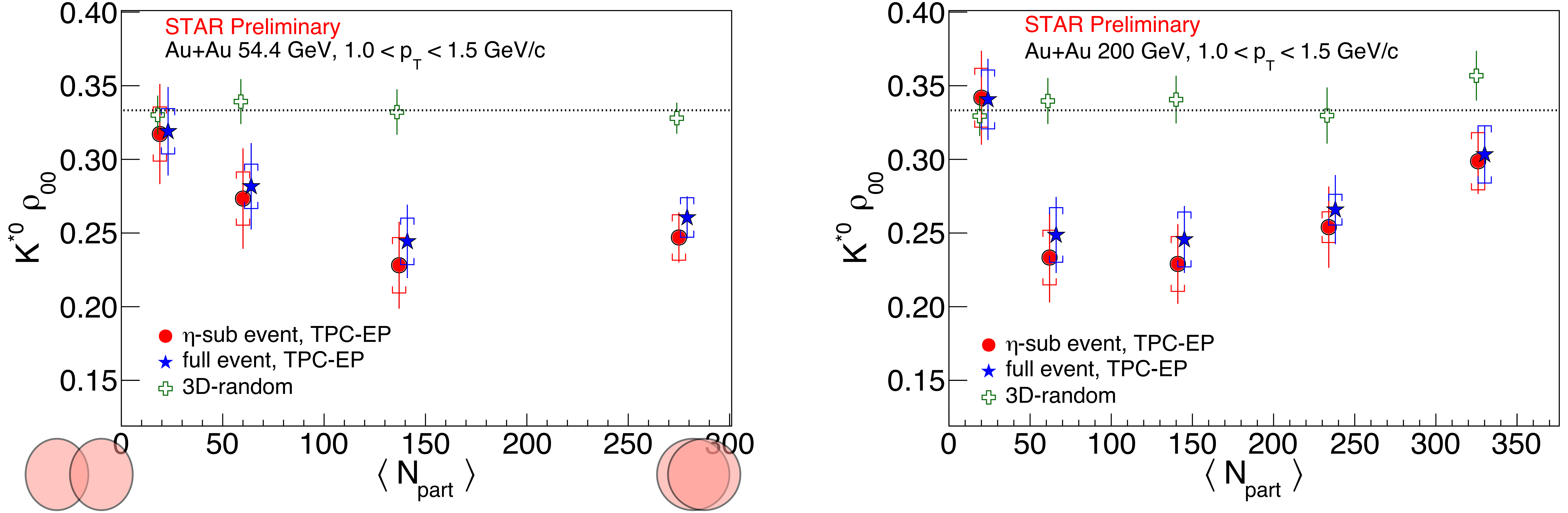
Analysis method

- K^{*0} efficiency x acceptance (ε_{rec}) from embedding data



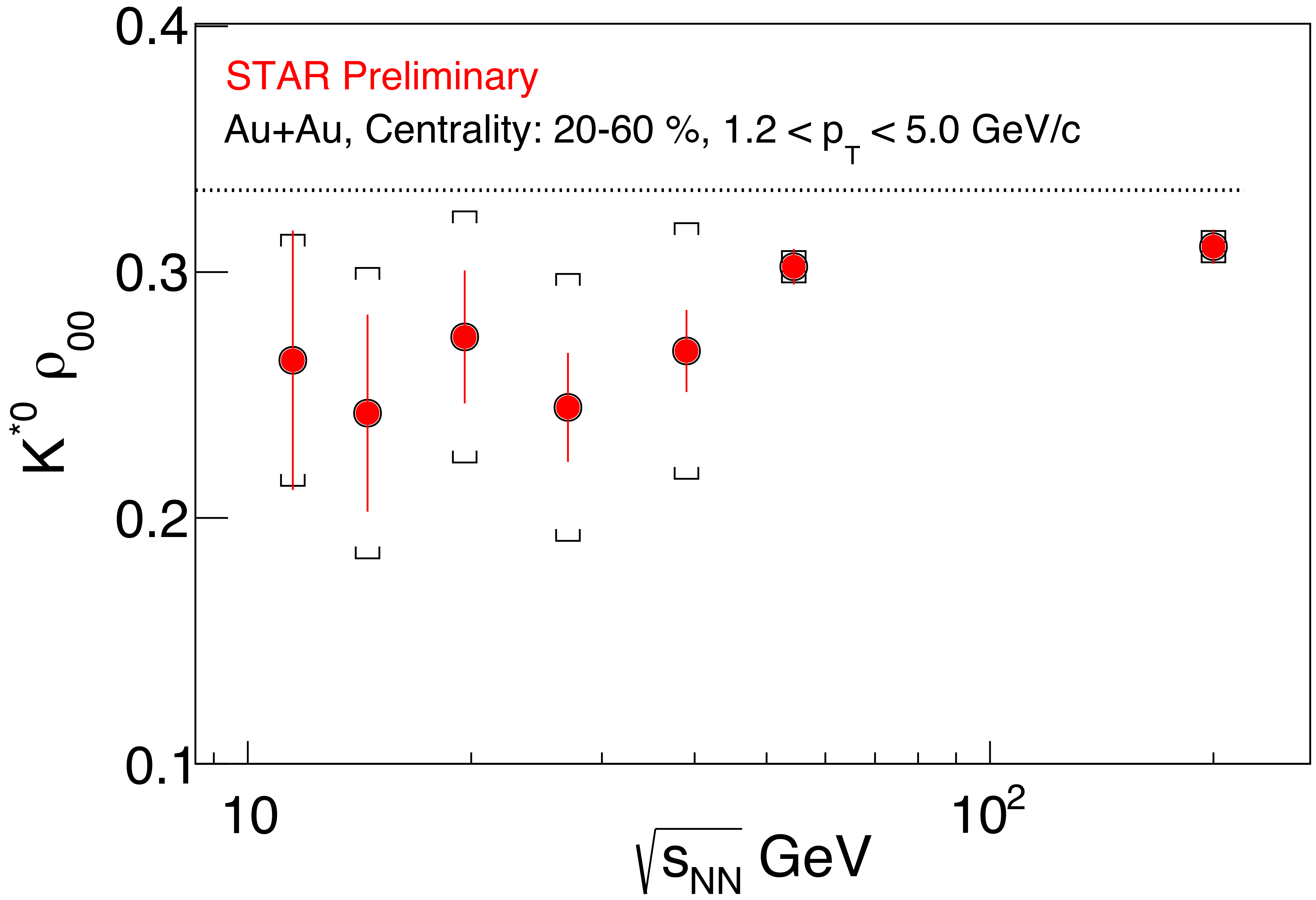


K^{*0} ρ_{00} (centrality)



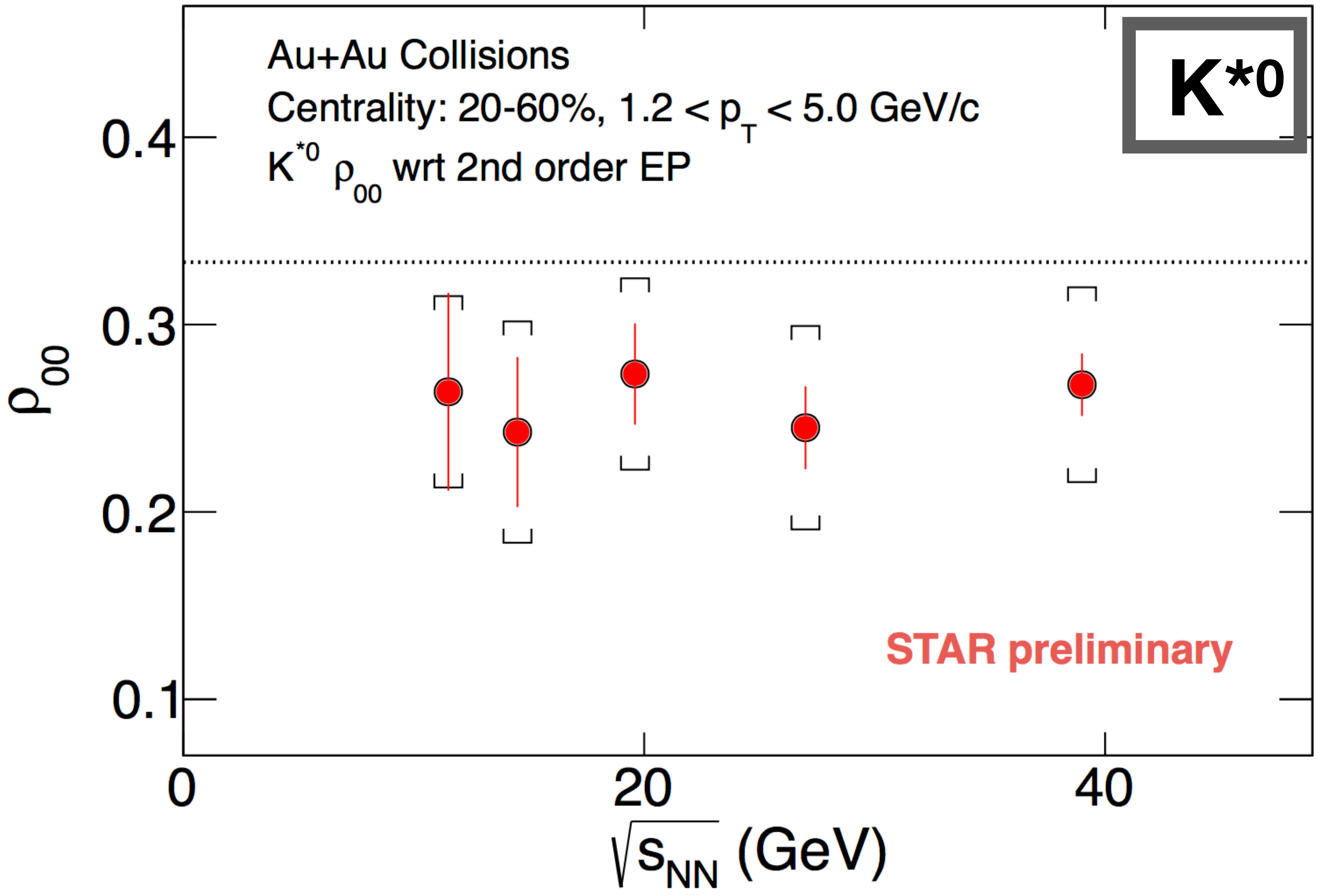
- Deviation of ρ_{00} from 1/3 is observed for mid-central collisions for both 54.4 and 200 GeV
- ρ_{00} results in peripheral collisions consistent with 1/3
- ρ_{00} results from 3D random plane consistent with 1/3

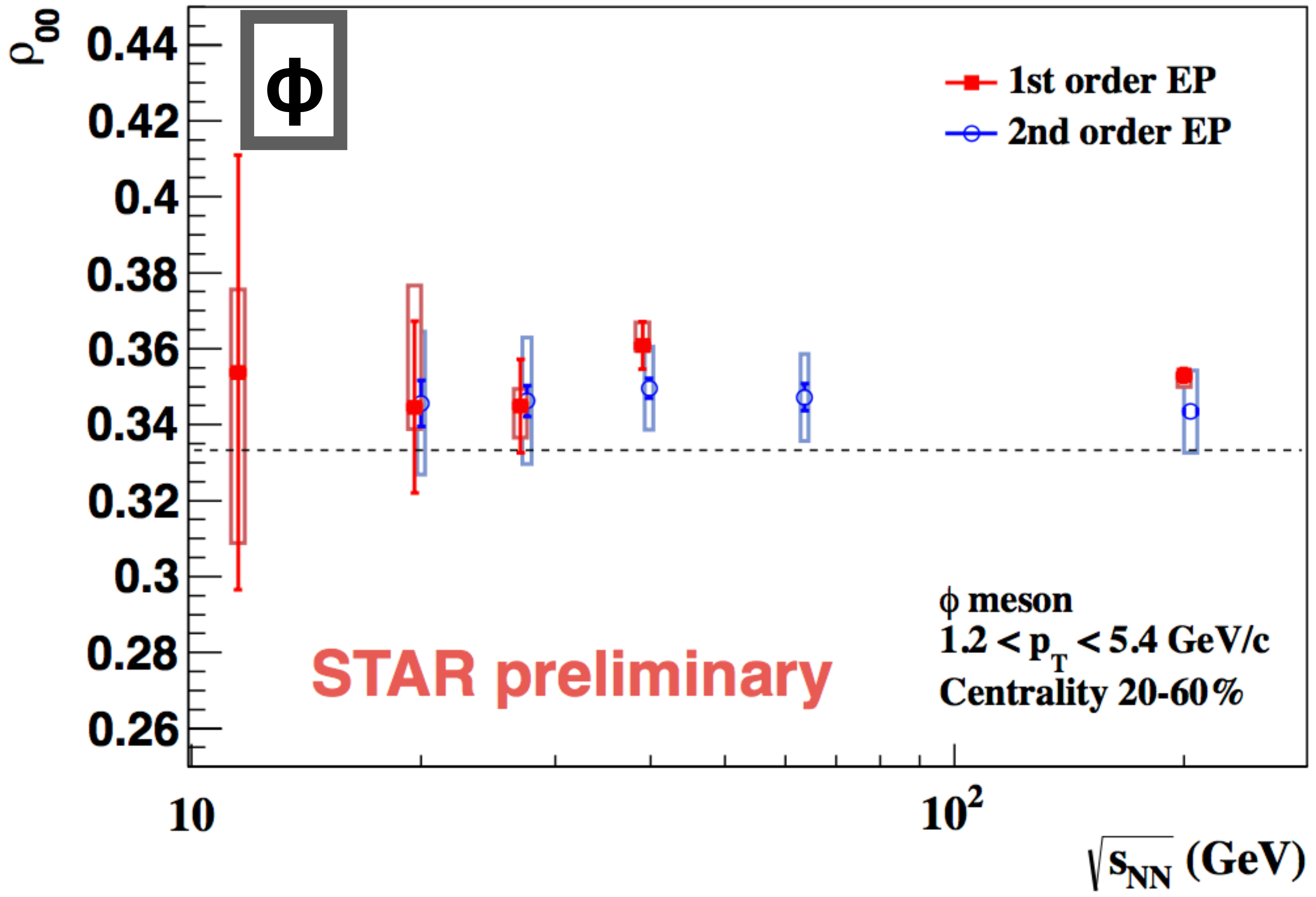
Energy dependence of K*0 ρ_{00}



- No beam energy dependence observed in ρ_{00} with current precision
- High statistics data from STAR BES-II can improve precision in ρ_{00} measurements in lower beam energies

Results shown at QM 2018

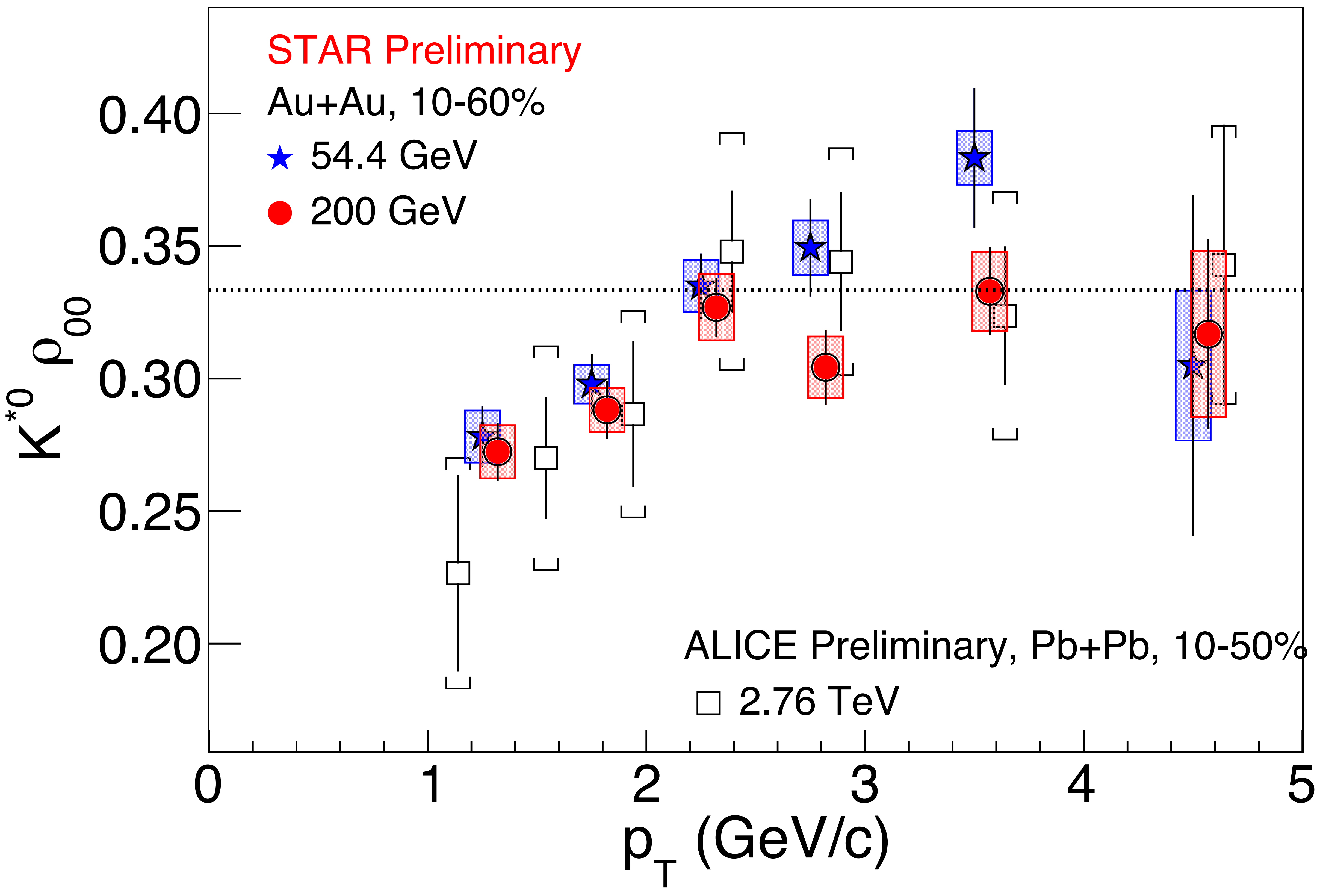


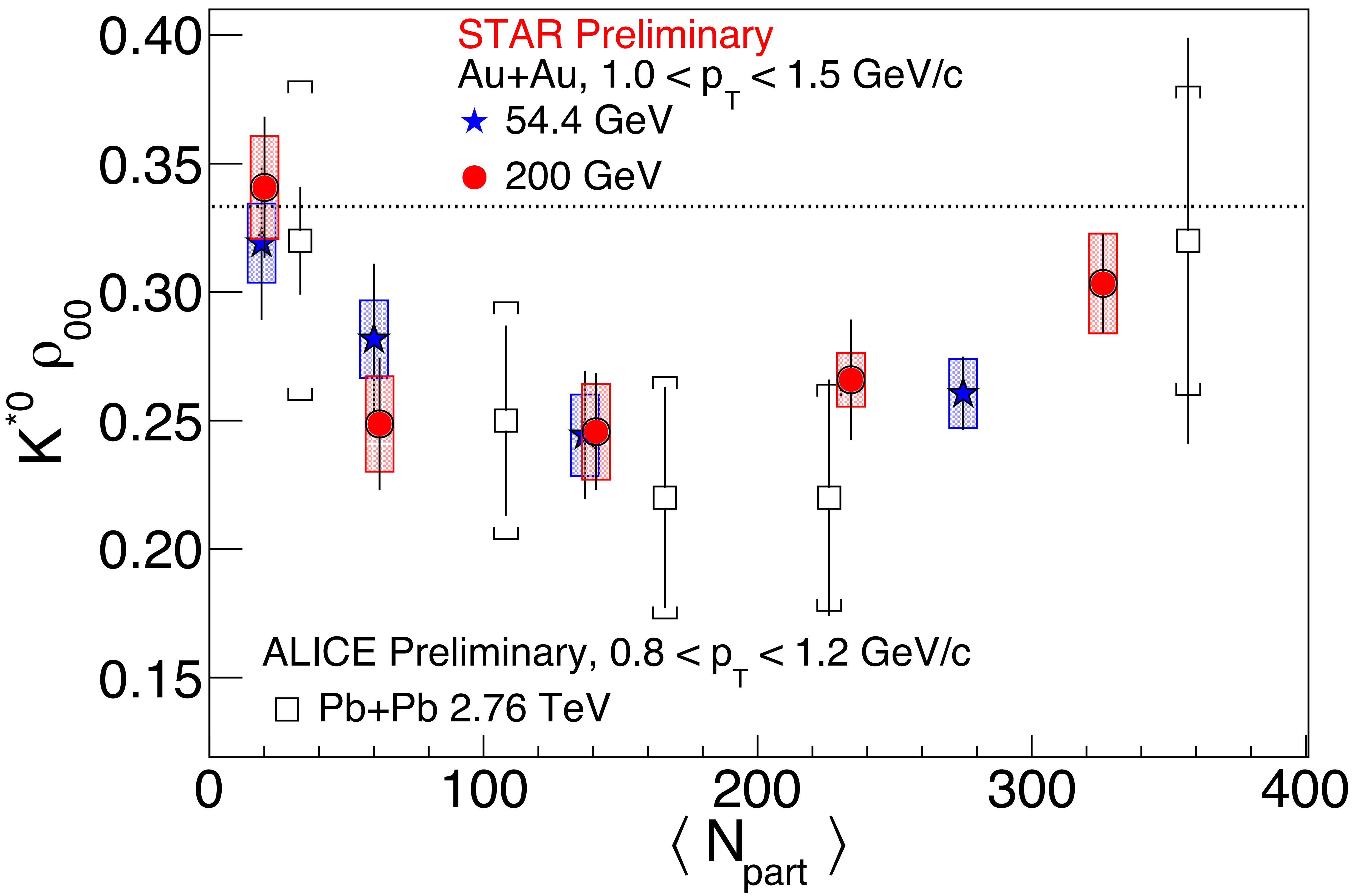


- ρ_{00} (ϕ) > 1/3 for $\sqrt{s_{NN}}$ =39 and 200 GeV with >~ 3σ significance
- ρ_{00} (K^{*0}) < 1/3 for $\sqrt{s_{NN}}$ = 11.5 - 39 GeV within ~ 1-2σ significance

High statistics data in 54.4 and 200 GeV allow precision measurement for centrality and transverse momentum dependence of ρ_{00} for K^{*0} and ϕ

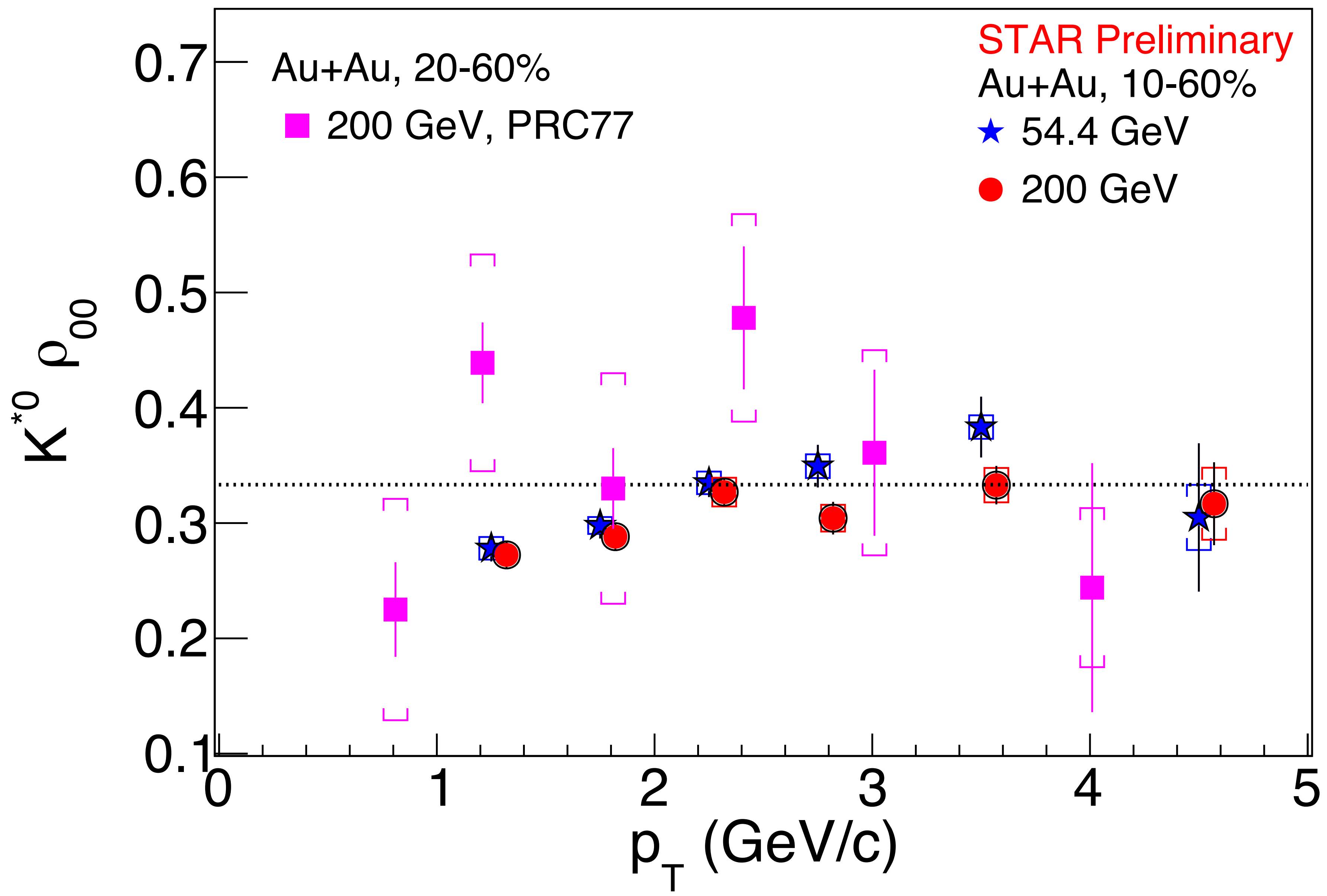
K^{*0} ρ_{00} (centrality): RHIC vs. LHC

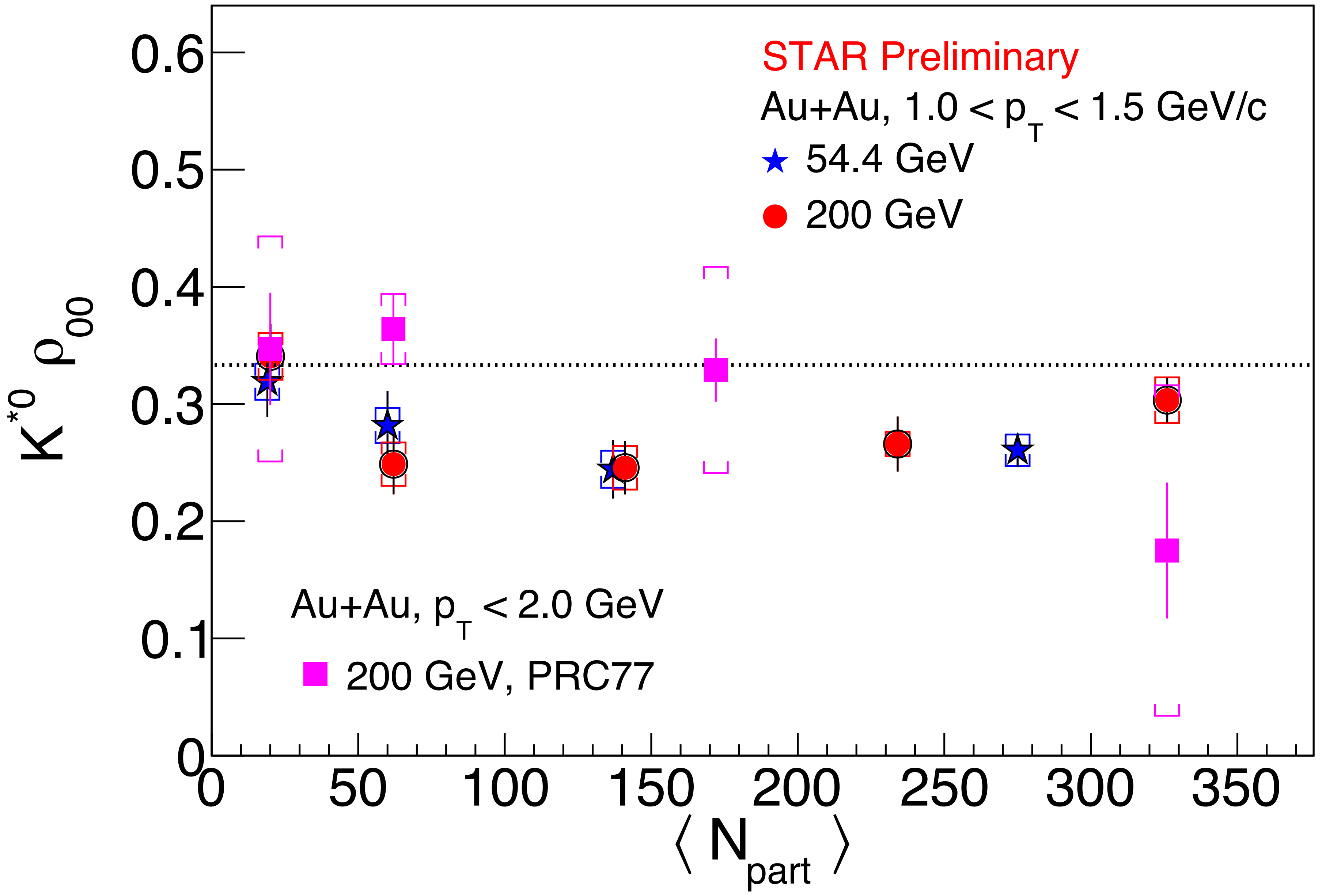




In ALICE Preliminary results, EP resolution correction with "1/*R*" term as a correction

K*0 : comparison with published results





STAR(200 GeV)	Published(Run-04)	Preliminary(Run-11)
Event statistics	20 M	370 M
PID	TPC only (poor S/B ratio)	TPC+TOF
EP resolution correction	$\frac{1}{R}$	$\rho_{00} - \frac{1}{3} = \frac{4}{1+3R}(\rho_{00}^{obs} - \frac{1}{3})$

Phys. Rev. C 77 (2008) 61902 (STAR Collaboration)

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

- K*0 results are consistent with published results within 1-1.5σ considering systematic uncertainties