Measurement of global spin alignment of vector mesons at RHIC

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Outline

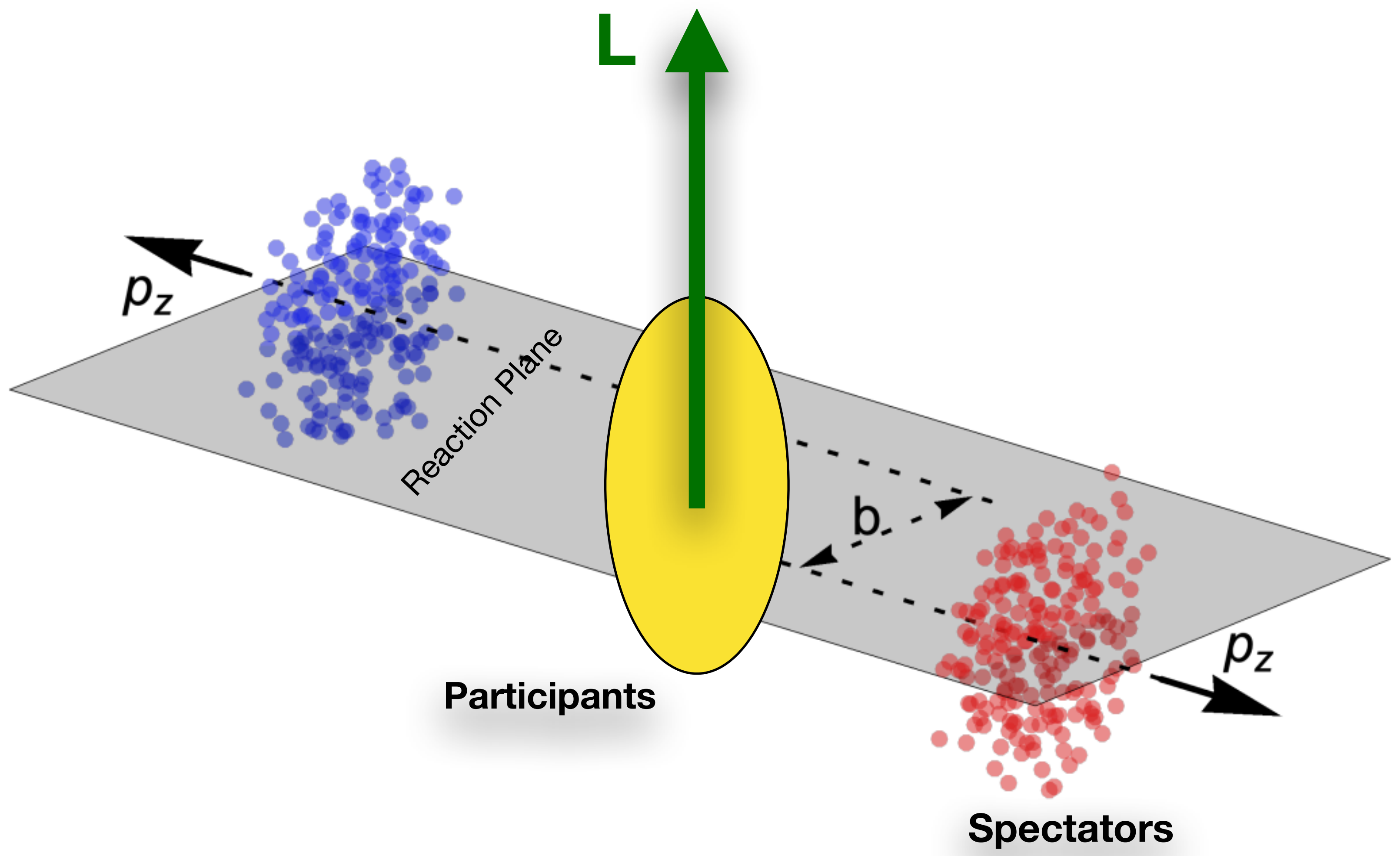
- Motivation
- Global spin alignment (ρ_{00}) analysis method
- Results:

  Au+Au at $\sqrt{s_{NN}}$ = 11.5 - 200 GeV (BES): **ϕ and K*^{0}**

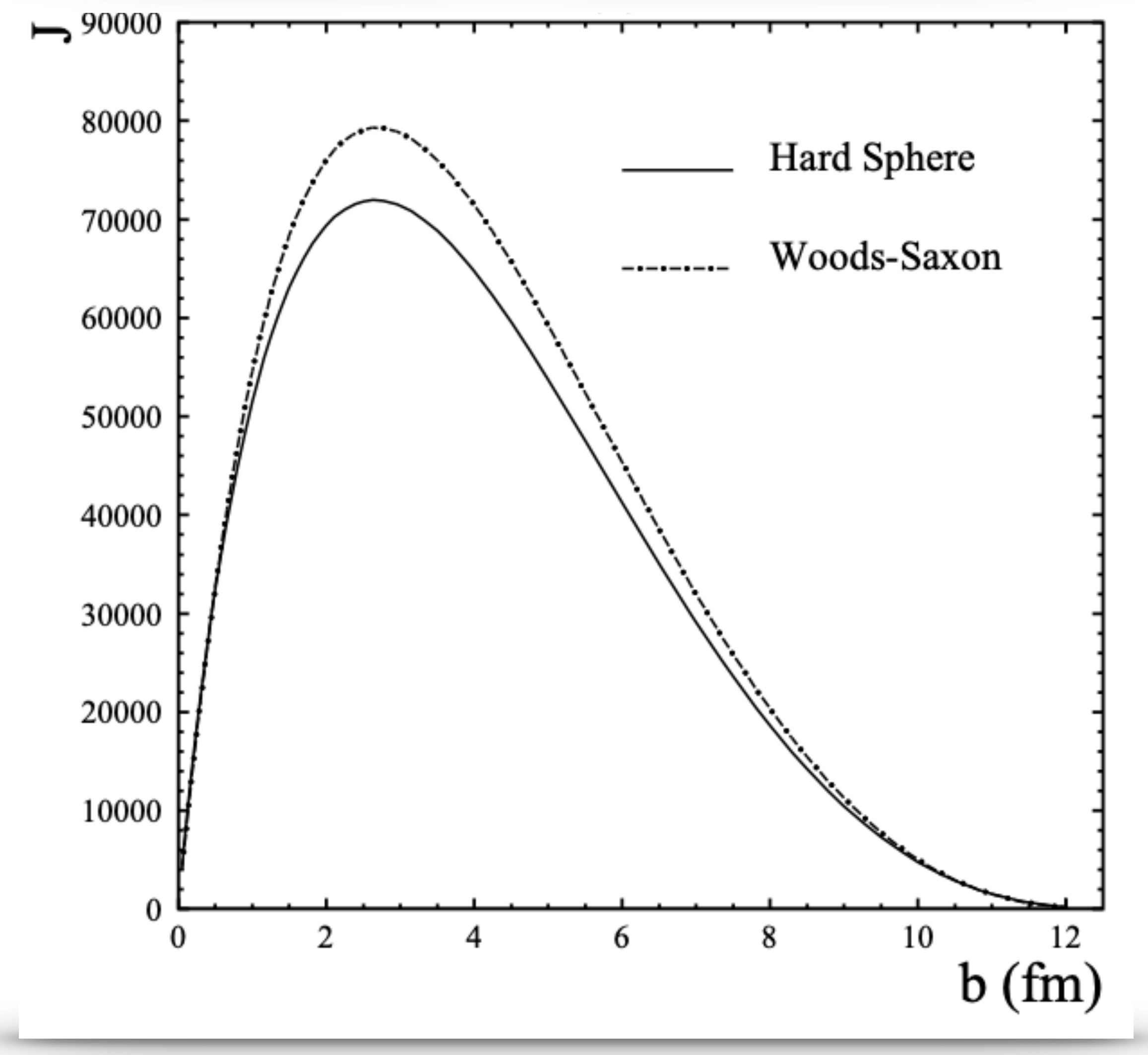
  Ru+Ru & Zr+Zr at $\sqrt{s_{NN}}$ = 200 GeV (Isobar): **K*^{0} and K*$^{+/-}$**

- Summary

Motivation



Angular momentum



Becattini et. al., Phys. Rev. C. 77, 024906 (2008)

In non-central heavy-ion collisions

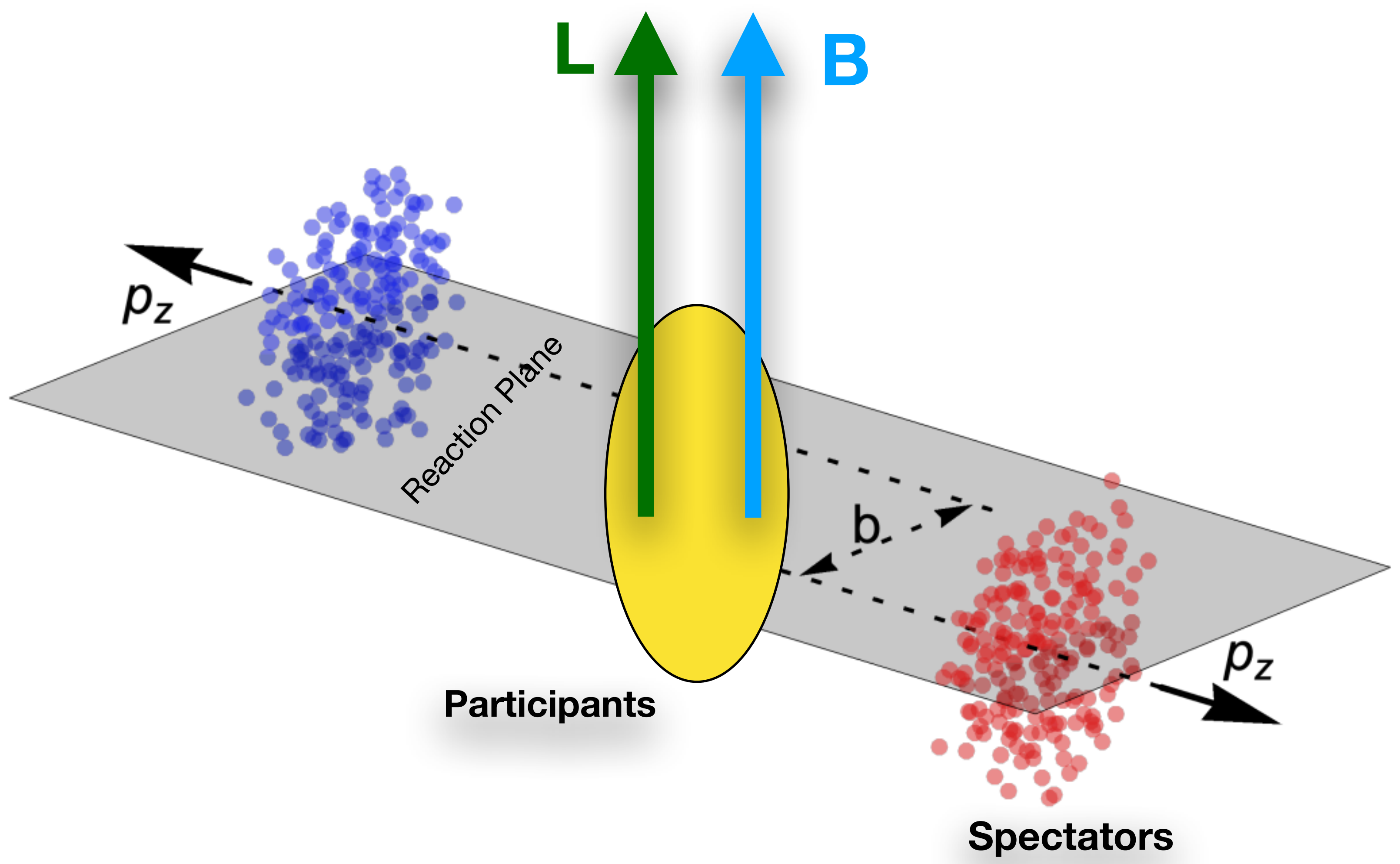
- A **large orbital angular momentum** (OAM) imparted into the system

$$L = r \times p \sim bA\sqrt{s_{NN}} \sim 10^4\ \hbar$$

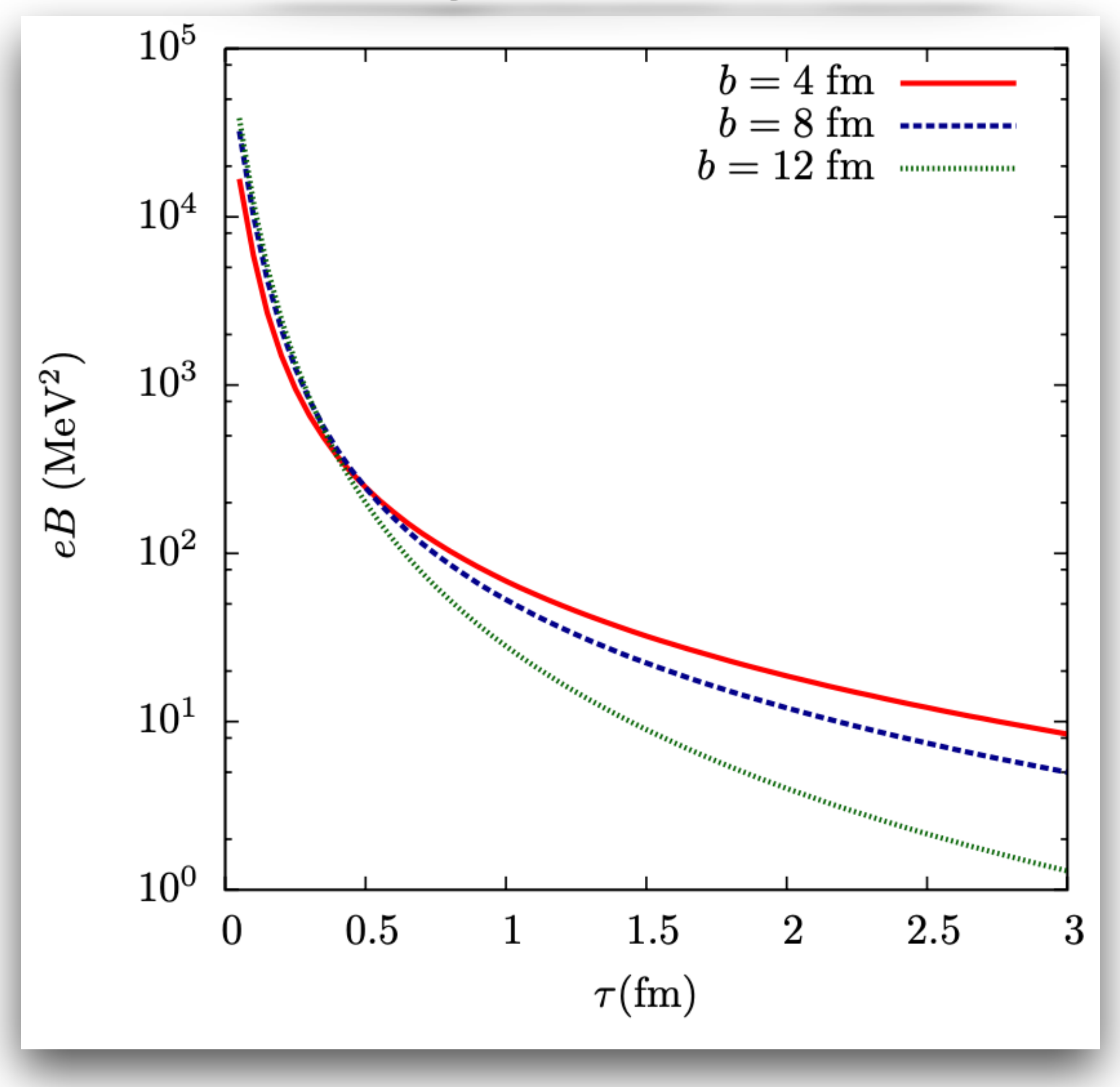
- Such a huge OAM can polarize quarks and anti-quarks due to "spin-orbit" interaction.

Liang et. al., Phys. Rev. Lett. B. 94, 102301 (2005)

Motivation



Magnetic Field



Kharzeev, Nucl Phys A803, 227 (2008)

In non-central heavy-ion collisions

- **Initial strong magnetic field** (**B**) is expected

$$eB \sim m_\pi^2 \sim 10^{18}\ \text{Gauss}$$

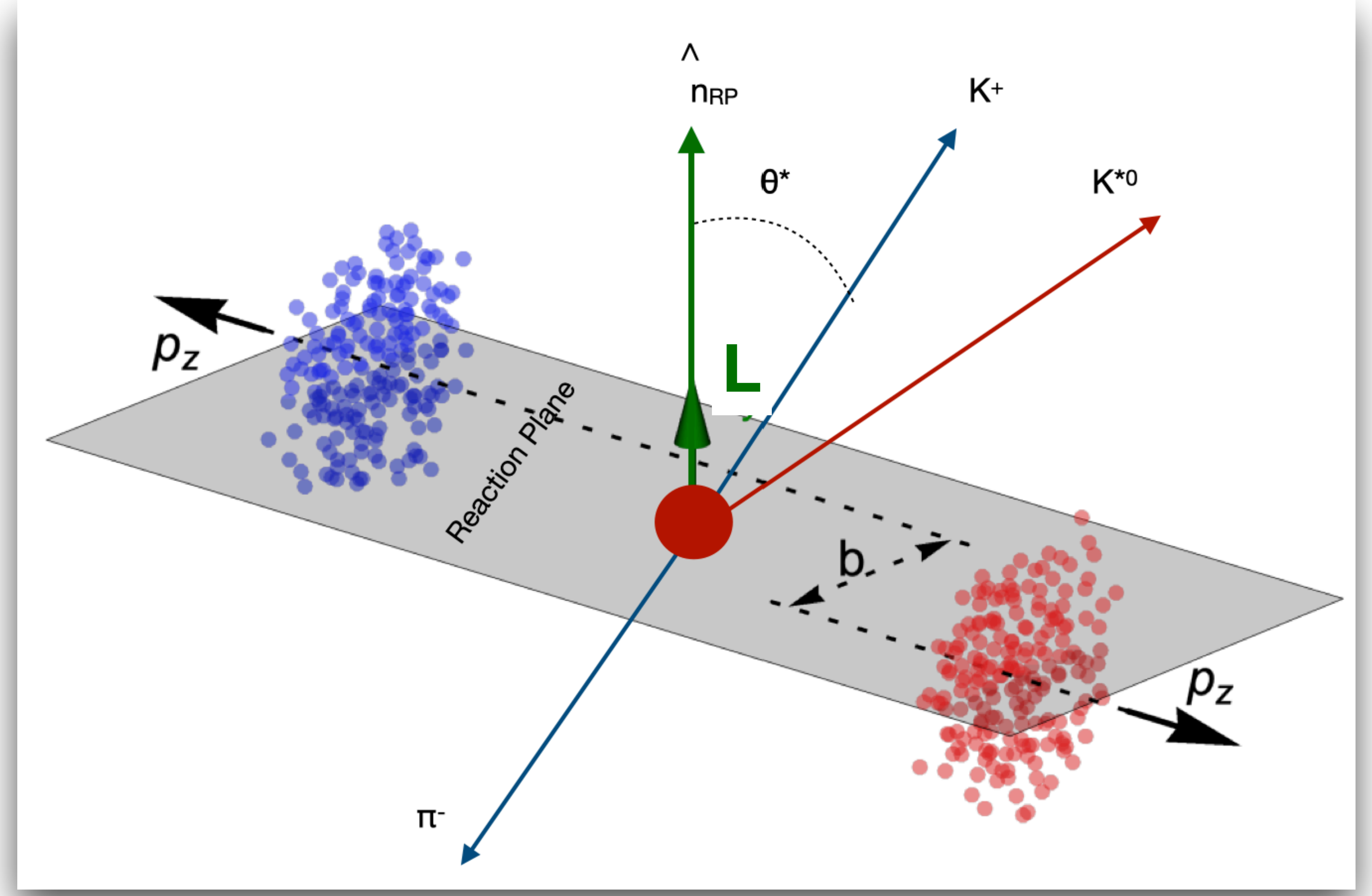
- Such strong **B** field can also polarize quarks. Can induce different spin polarization for quarks and anti-quarks with different magnetic moments

Yang, et. al., Phys Rev C 97, 034917 (2018)

Vector meson spin alignment (ρ_{00})

Spin alignment (ρ_{00}):
Measured from the angular distribution (θ*) of the daughter particle in parent's rest frame

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



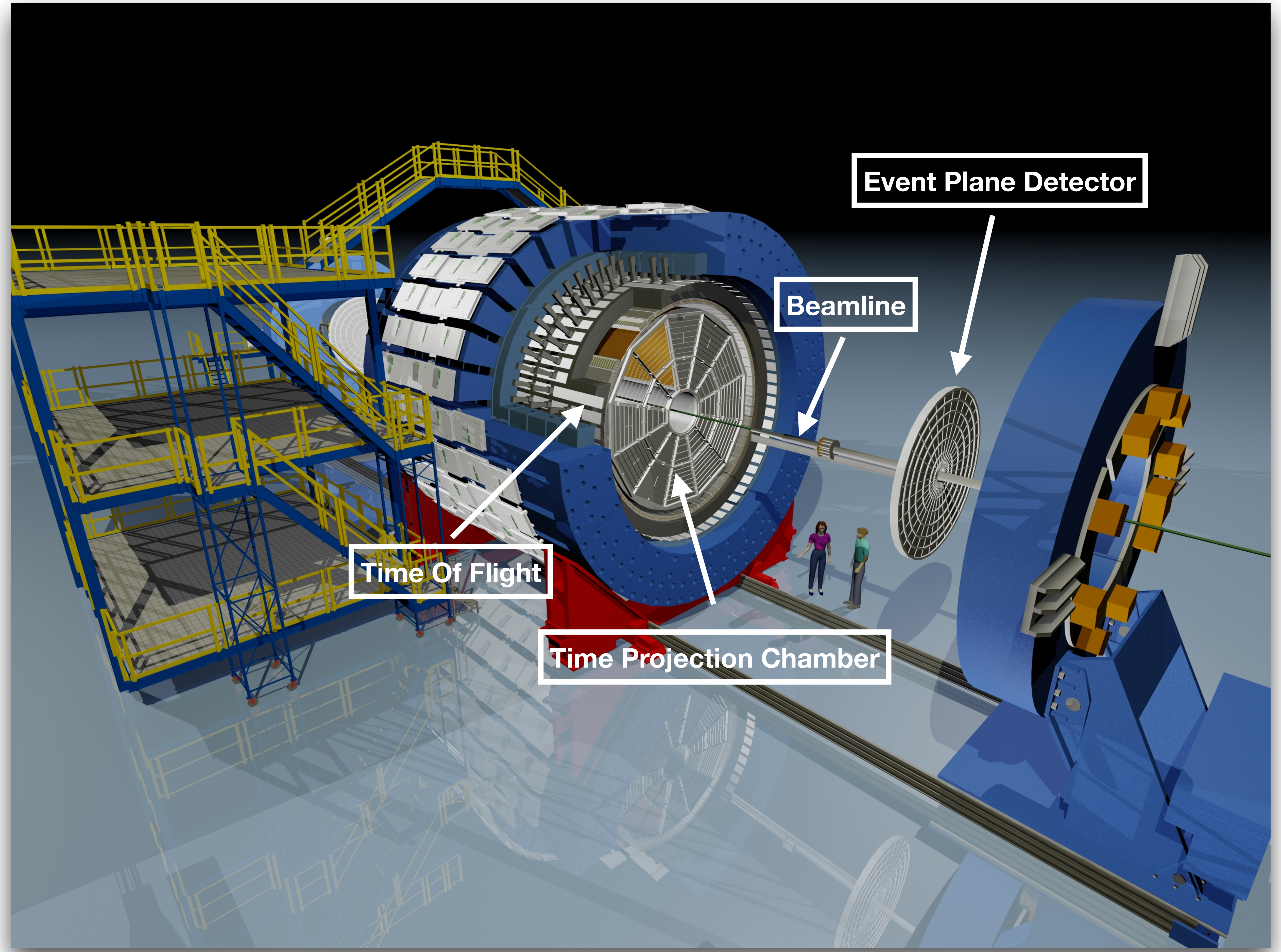
ρ_{00} : 00^{th} component of spin density matrix

θ^* : Angle between momentum of daughter and polarization axis in parent's rest frame

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

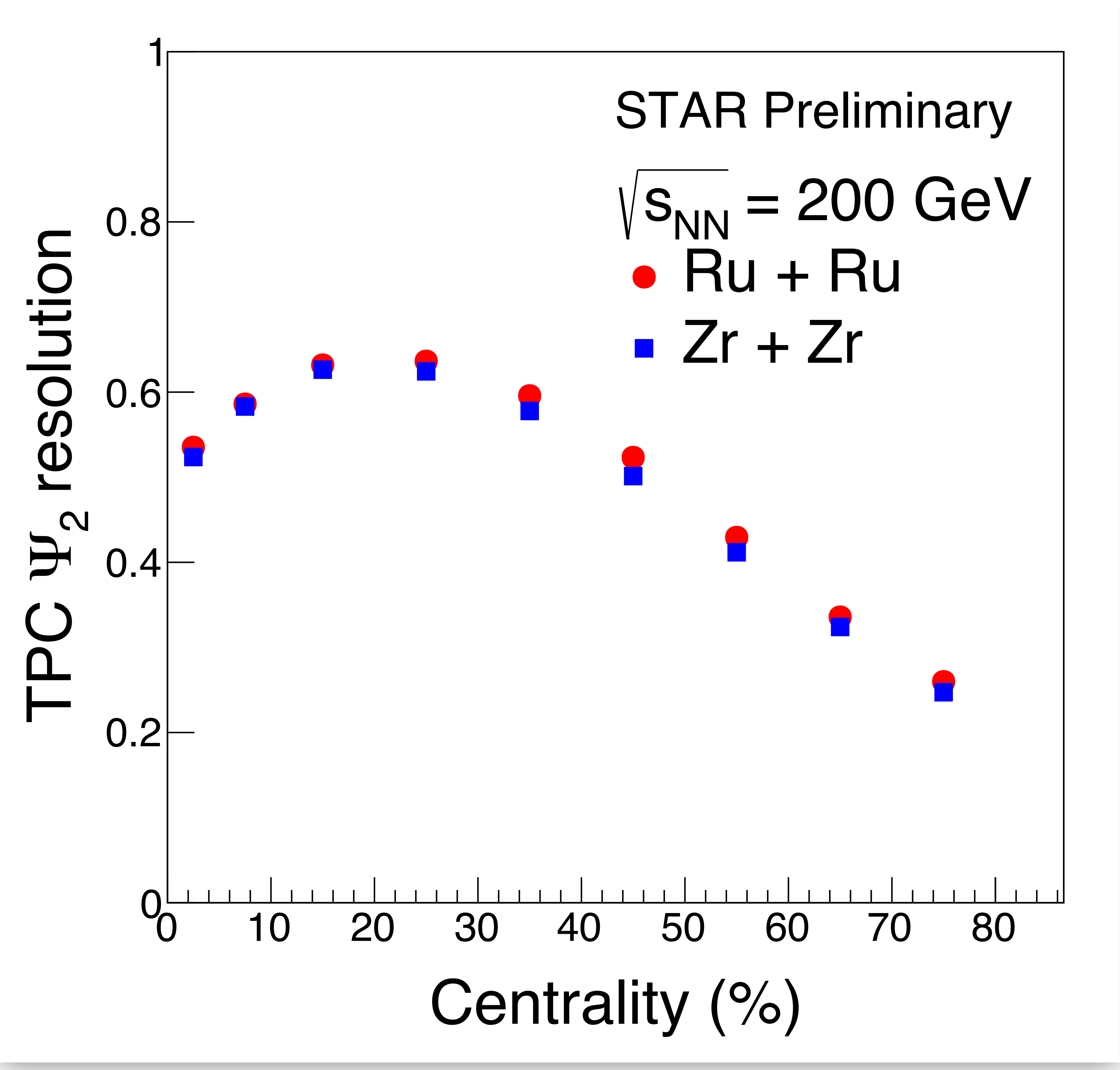
Schiling et. al., Nucl. Phys. B 15, 397 (1970)
(STAR Collaboration) Phys. Rev. C 77, 61902 (2008)

The STAR detector and event plane



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

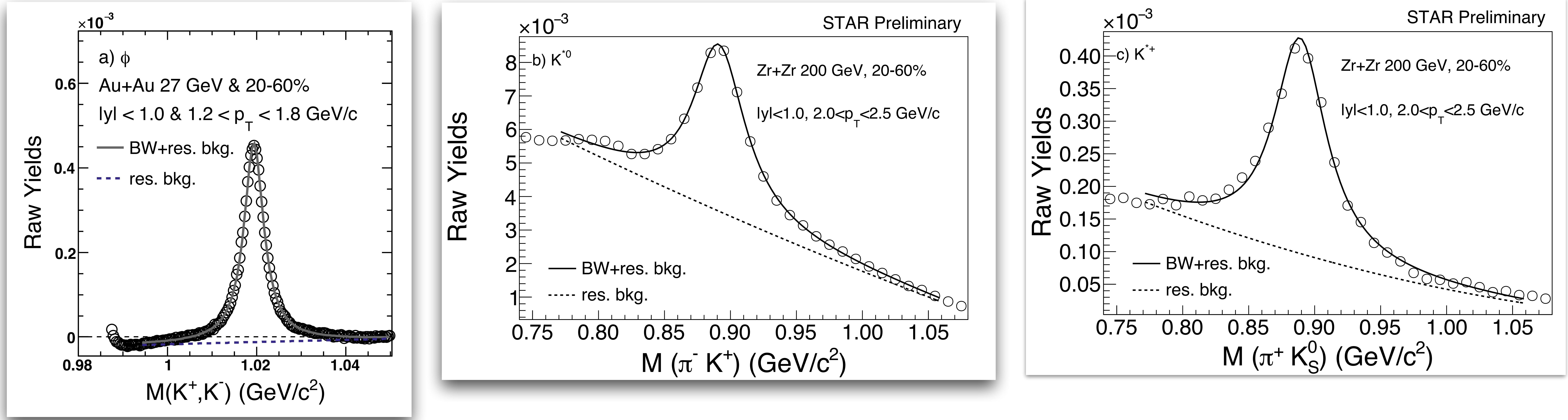
- Second order event plane (Ψ_2) is measured using the TPC with $0.15 < p_T < 2.0$ GeV/c



Polarization axis → Perpendicular to Ψ_2

Signal reconstruction

$\phi \longrightarrow K^+K^-$ $K^{*0} \longrightarrow K^+\pi^-$ $K^{*+} \longrightarrow K_S^0\, \pi^+$

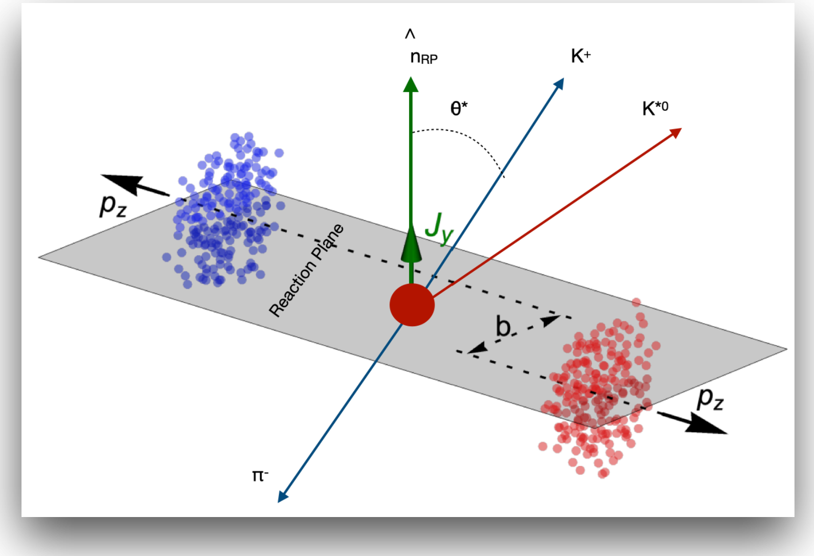


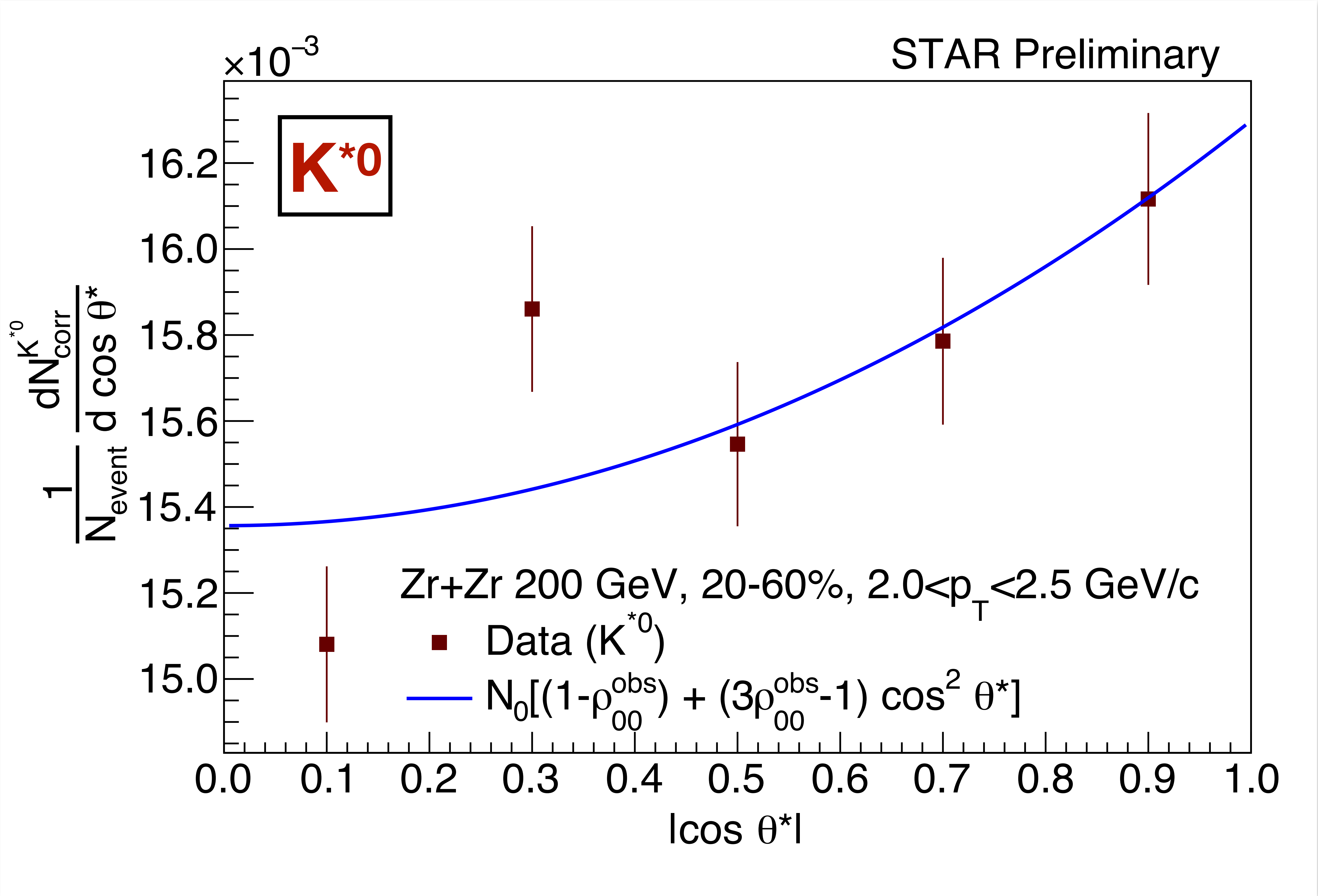
$$\text{Breit Wigner} = \frac{1}{2\pi}\frac{A\Gamma}{(m - m_0)^2 + (\Gamma/2)^2}$$

- Mixed event (ϕ) and rotational background (K^{*0} and $K^{*+/-}$) subtraction
- Yield is calculated from histogram integration

Analysis method

- Raw yield of K^{*0} is extracted from five |cos θ*| bins
- Yield of K^{*0} is corrected for efficiency and acceptance using STAR detector simulations





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

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

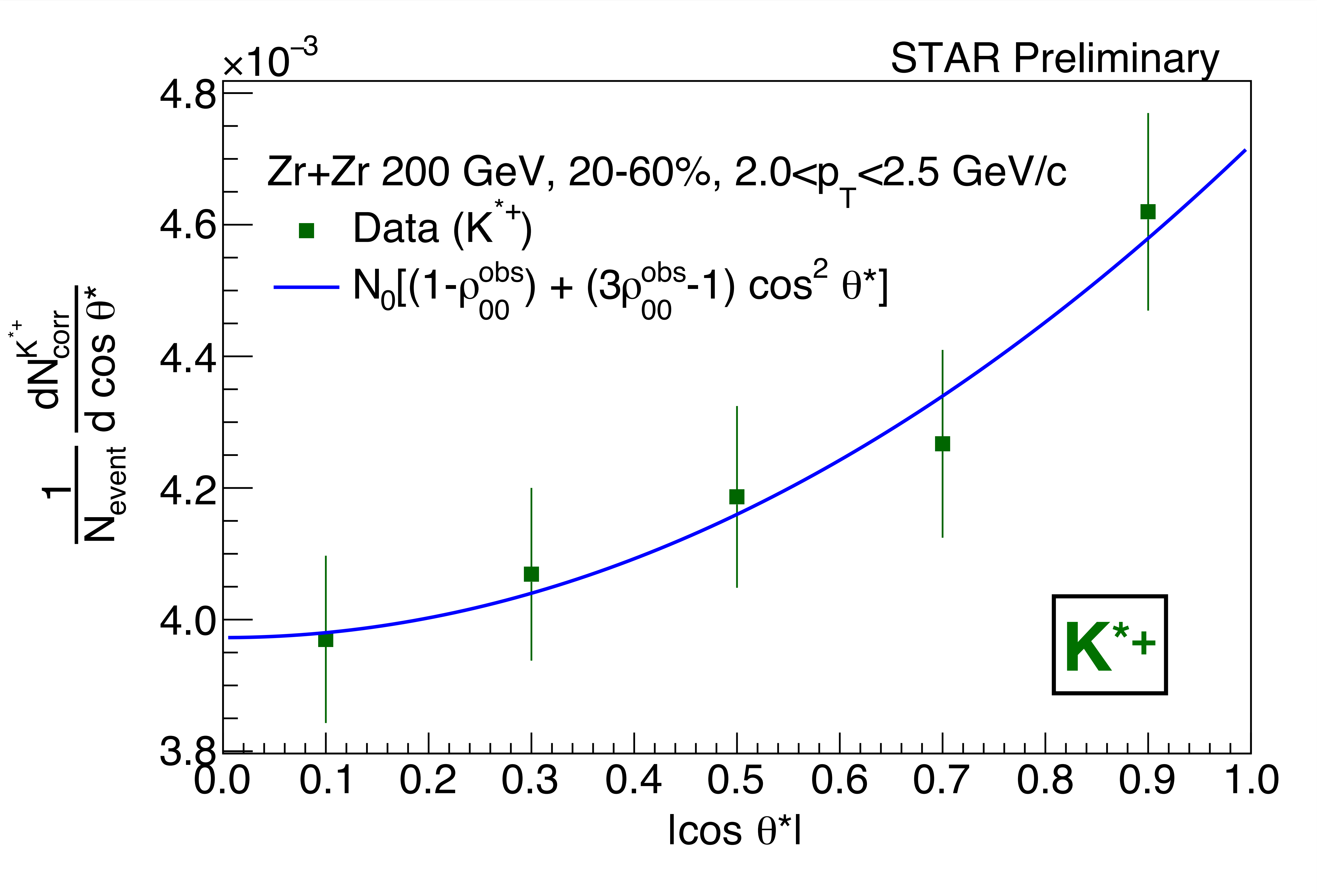
- Observed ρ_{00}^{obs} is corrected for TPC event plane resolution (R)

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

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

Analysis method

- Raw yield of K^{*+} is extracted from five |cos θ*| bins
- Yield of K^{*+} is corrected for efficiency and acceptance using STAR detector simulations



- Observed $\rho_{00}^{\rm obs}$ is calculated from fitting the yield with function:

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

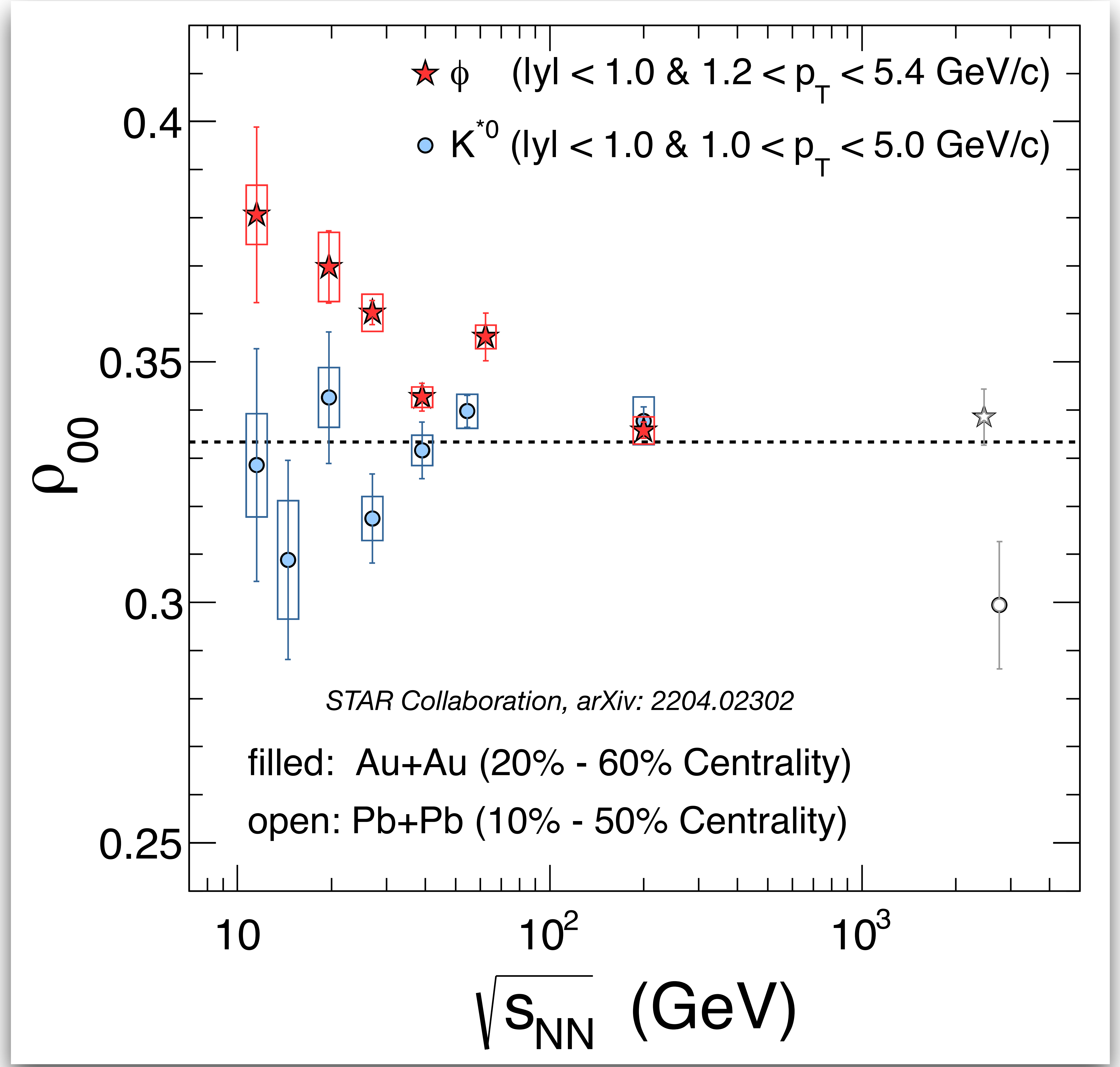
STAR

Results: Au+Au Beam Energy Scan

$\sqrt{s_{NN}}$ = 11.5 - 200 GeV : ϕ and K^{*0}

Particle Species	Quark content	Mass (GeV/c²)	Spin	Lifetime (fm/c)
ϕ	$s\bar{s}$	1.092	1	45
K^{*0}	$d\bar{s}$	0.896	1	4

ρ_{00} ($\sqrt{s_{NN}}$): ϕ and K^{*0} from BES-I



<u>For 20-60%:</u>

- For $\sqrt{s_{NN}}$ <= 62.4 GeV:
  - ϕ $\rho_{00} = 0.3451 \pm 0.0017$ (stat.) ± 0.0018 (sys.)
    $\rho_{00} > 1/3$ with 8.4σ
- For $\sqrt{s_{NN}}$ <= 54.4 GeV:
  - K^{*0} $\rho_{00} = 0.3356 \pm 0.0034$ (stat.) ± 0.0043 (sys.)
    $\rho_{00} \sim 1/3$

ALICE Collaboration, Phys. Rev. Lett. 125, 012301 (2020)

Expectation of ρ_{00} from theory

Physics Mechanisms	(ρ_{00})
c_Λ: Quark coalescence vorticity & magnetic field[1]	< 1/3 (Negative ~ 10^{-5})
c_ε: Vorticity tensor[1]	< 1/3 (Negative ~ 10^{-4})
c_E: Electric field[2]	> 1/3 (Positive ~ 10^{-5})
Fragmentation[3]	> or, < 1/3 (~ 10^{-5})
Local spin alignment and helicity[4]	< 1/3
Turbulent color field[5]	< 1/3
c_ϕ: Vector meson strong force field[6]	> 1/3 (Can accomodate large positive signal)

[1]. Liang et., al., Phys. Lett. B 629, (2005);
Yang et., al., Phys. Rev. C 97, 034917 (2018);
Xia et., al., Phys. Lett. B 817, 136325 (2021);
Beccattini et., al., Phys. Rev. C 88, 034905 (2013)
[2]. Sheng et., al., Phys. Rev. D 101, 096005 (2020);
Yang et., al., Phys. Rev. C 97, 034917 (2018)
[3]. Liang et., al., Phys. Lett. B 629, (2005)
[4]. Xia et., al., Phys. Lett. B 817, 136325 (2021);
Guo, Phys. Rev. D 104, 076016 (2021)
[5]. Muller et., al., Phys. Rev. D 105, L011901 (2022)
[6]. Sheng et., al., Phys. Rev. D 101, 096005 (2020);
Sheng et., al., Phys. Rev. D 102, 056013 (2020)

Expectation of ρ_{00} from theory

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c_Λ: Quark coalescence vorticity & magnetic field[1]	< 1/3 (Negative ~ 10^{-5})
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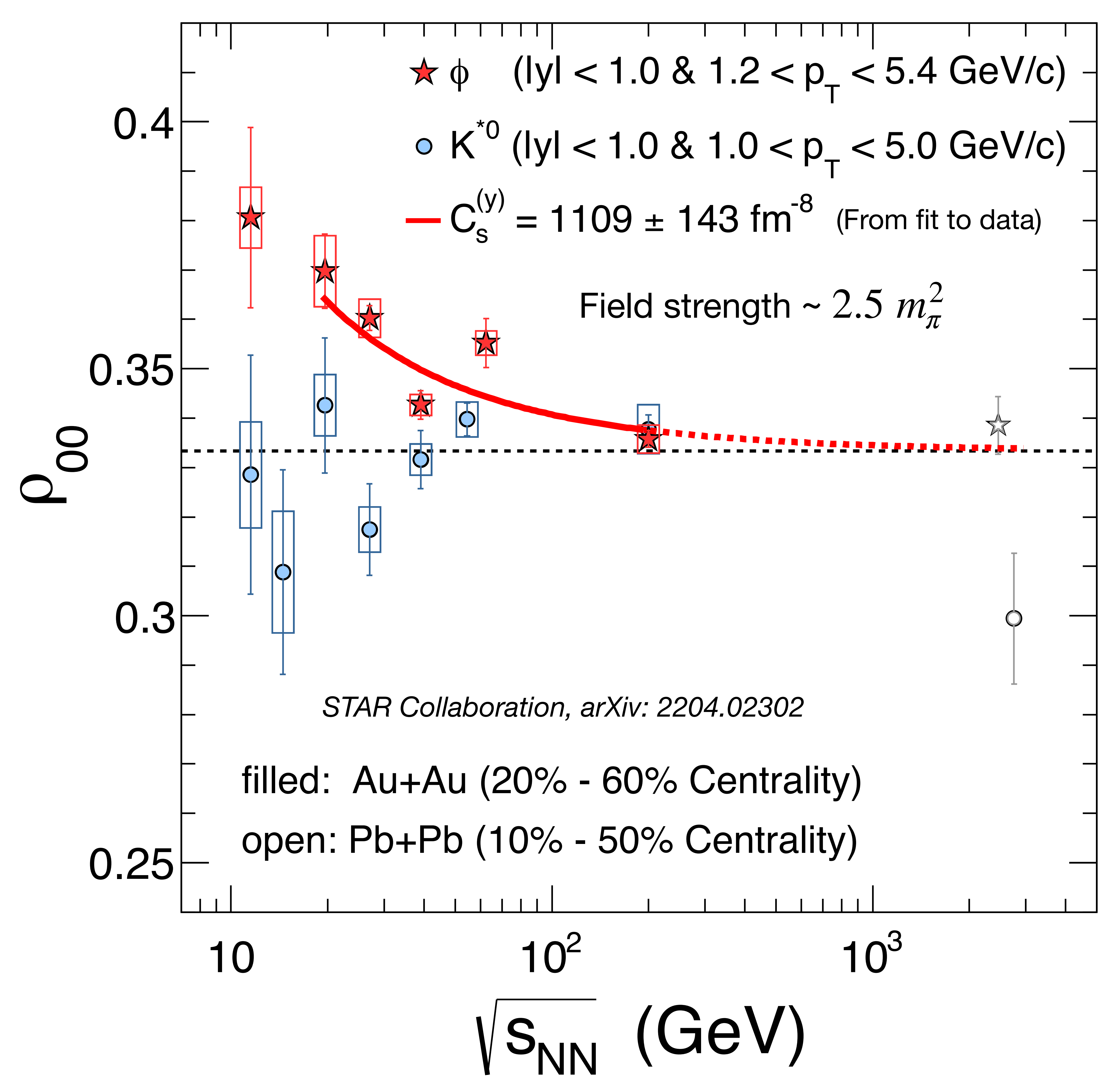
- Like electric charges in motion can generate an EM field, s and $\bar{s}$ quarks in motion can generate an effective ϕ-meson field
- The electric part of the ϕ-meson field can polarize s and $\bar{s}$ quarks with a large magnitude due to strong interaction (large coupling constant g_ϕ)

$$\rho_{00}(\phi) \approx \frac{1}{3} + c_\Lambda + c_\epsilon + c_E + c_\phi;$$

$$c_\phi \equiv \frac{g_\phi^4}{27 m_s^4 m_\phi^4 T_{eff}^2} \langle \boldsymbol{p}^2 \rangle_\phi \langle \tilde{E}_{\phi,z}^2 + \tilde{E}_{\phi,x}^2 \rangle;$$

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

ρ_{00} ($\sqrt{s_{NN}}$): φ and K^{*0} from BES-I



- Surprisingly large φ ρ_{00} can not be accommodated by conventional mechanisms
- Polarization by a strong force field of vector meson → Can accommodate large deviation for φ ρ_{00} at mid-central collisions

$$\rho_{00}(\phi) \approx \frac{1}{3} + c_\Lambda + c_\epsilon + c_E + c_\phi;$$

$$c_\phi \equiv \frac{g_\phi^4}{27 m_s^4 m_\phi^4 T_{eff}^2} \langle \boldsymbol{p}^2 \rangle_\phi \langle \tilde{E}_{\phi,z}^2 + \tilde{E}_{\phi,x}^2 \rangle;$$

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

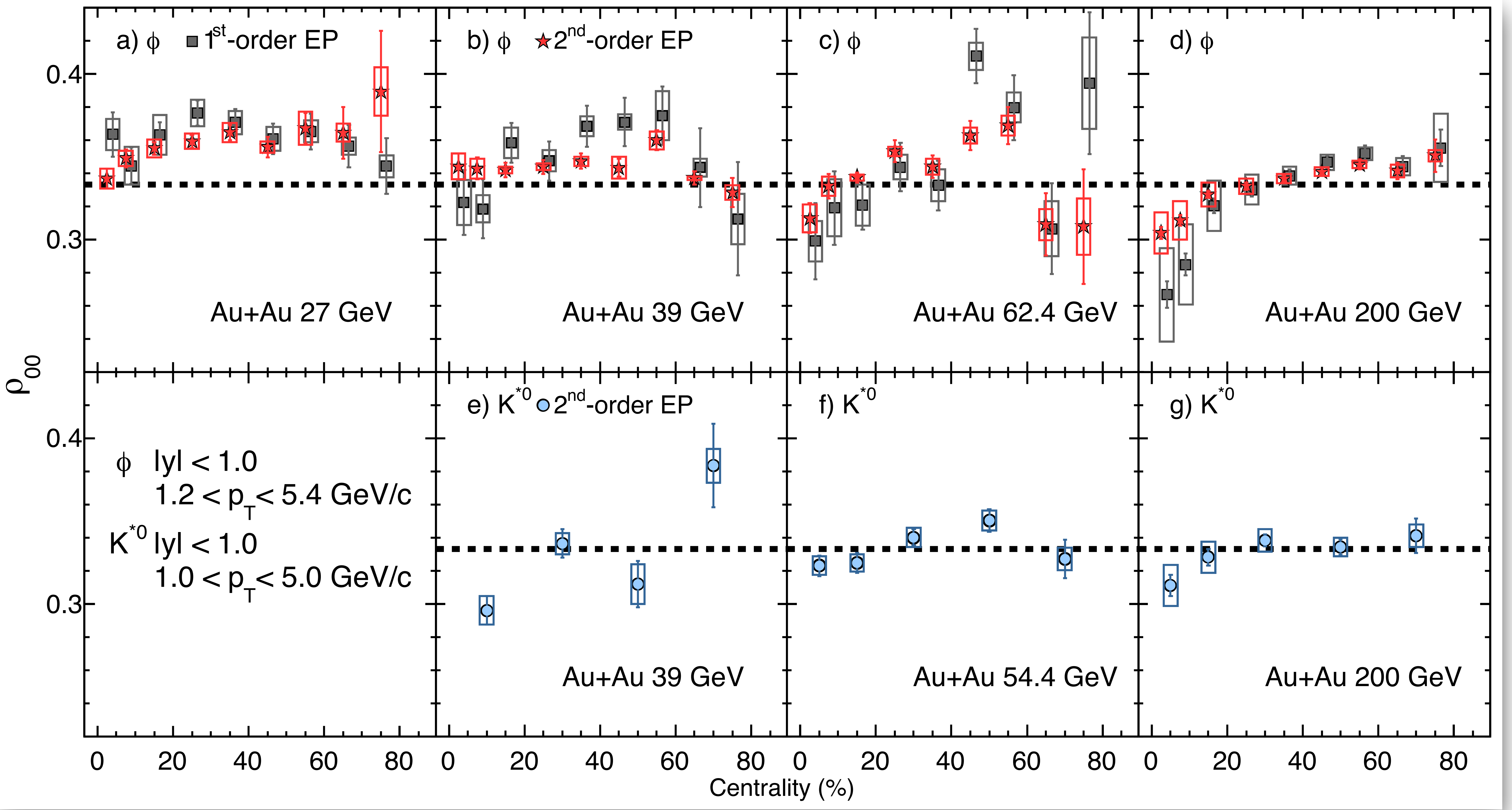
Sheng el. al., Phys. Rev. D 101, 096005 (2020)
Sheng el. al., Phys. Rev. D 102, 056013 (2020)

ρ_{00} (centrality): ϕ and K^{*0} from BES-I

STAR Collaboration, arXiv: 2204.02302

ϕ

K^{*0}



- <u>For central at 200 GeV:</u>
  - ϕ, K^{*0} $\rho_{00} < 1/3$

    Local spin alignment[1]

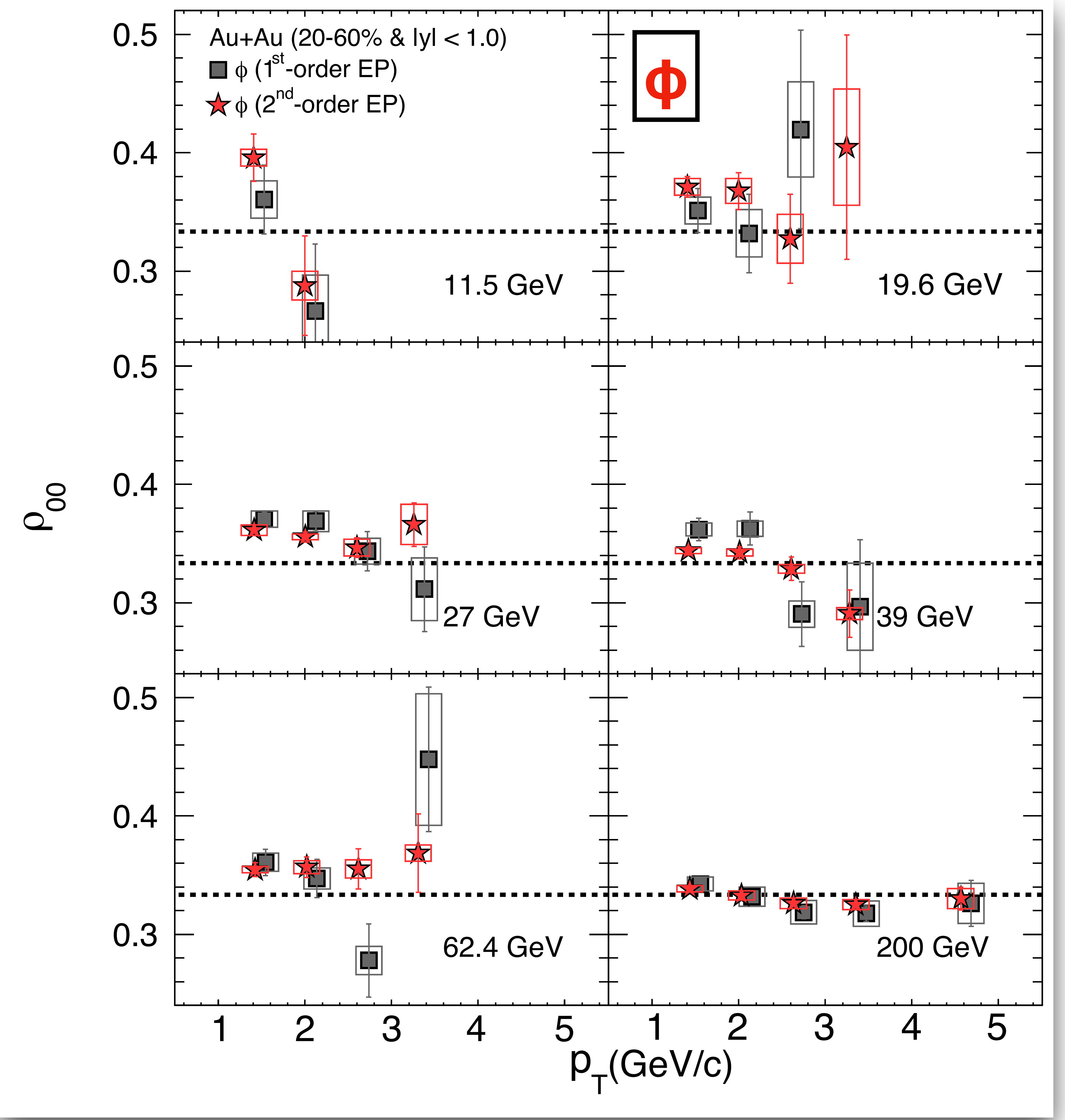
    or, helicity contribution[2]
- <u>For mid-central and peripheral:</u>
  - ϕ, K^{*0} ρ_{00} >~ 1/3

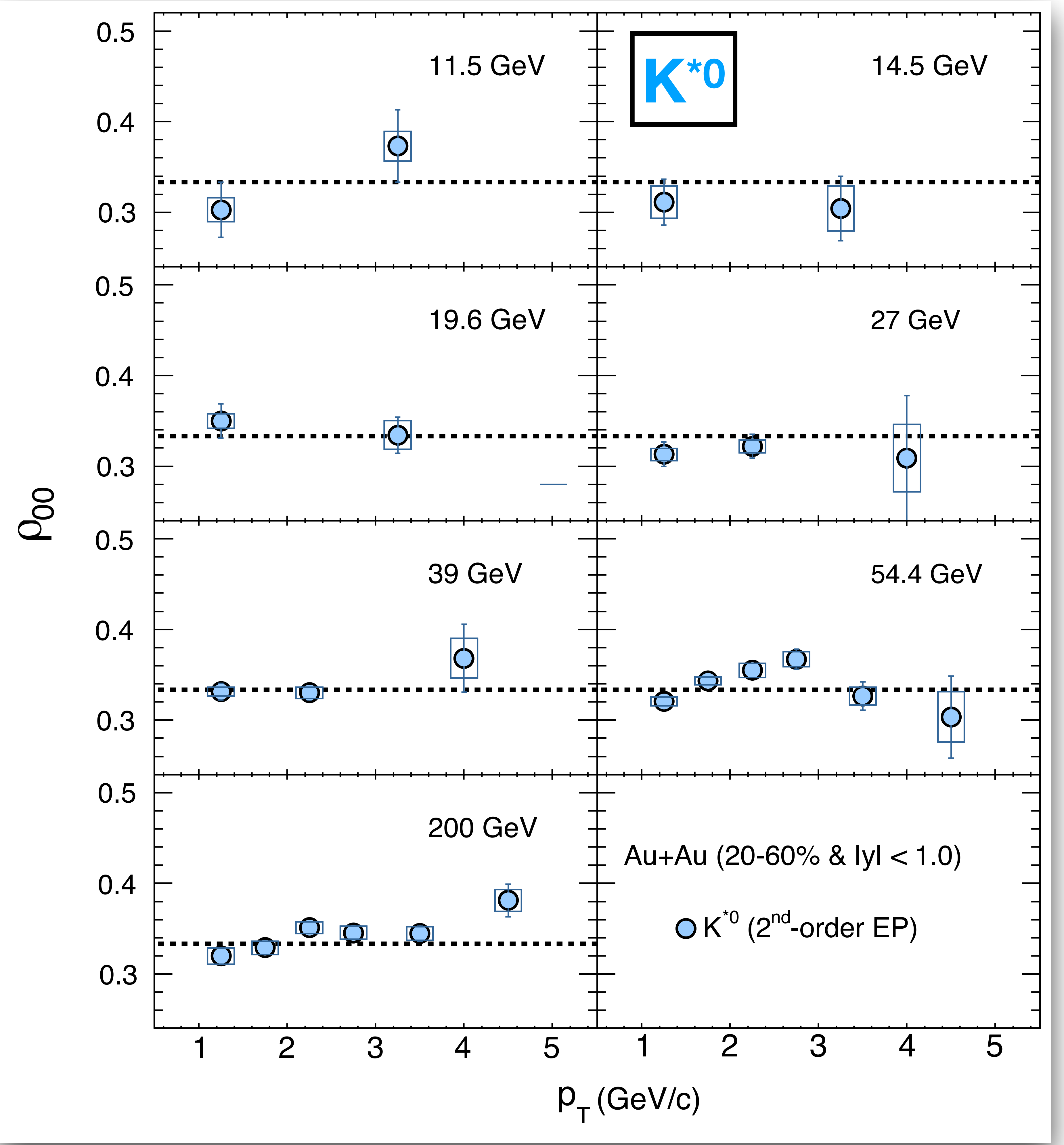
- Need inputs from theory to understand centrality differential ρ_{00}

[1]. Xia et al, Phys. Lett. B 817, 136325 (2021)
[2]. Gao, Phys. Rev. D 104, 076016 (2021)

ρ_{00} (p_T): ϕ and K^{*0} from BES-I

STAR Collaboration, arXiv: 2204.02302





- For 20-60%: non-trivial p_T dependence

- Need inputs from theory to understand p_T differential ρ_{00}

Results: Zr+Zr and Ru+Ru (Isobar collisions)

$\sqrt{s_{\mathrm{NN}}}$ = 200 GeV: K^{*0} and $K^{*+/-}$

Particle Species	Quark content	Mass (GeV/c²)	Spin	Lifetime (fm/c)	Magnetic moment
K^{*0} (anti-K^{*0})	$d\bar{s}$ ($\bar{d}s$)	0.896	1	4	$\mu_d \approx -0.97\mu_N$
$K^{*+/-}$	$u\bar{s}$ ($\bar{u}s$)	0.892	1	4	$\mu_u \approx 1.85\mu_N$

$\mu_{\bar{s}} \approx 0.61\mu_N$

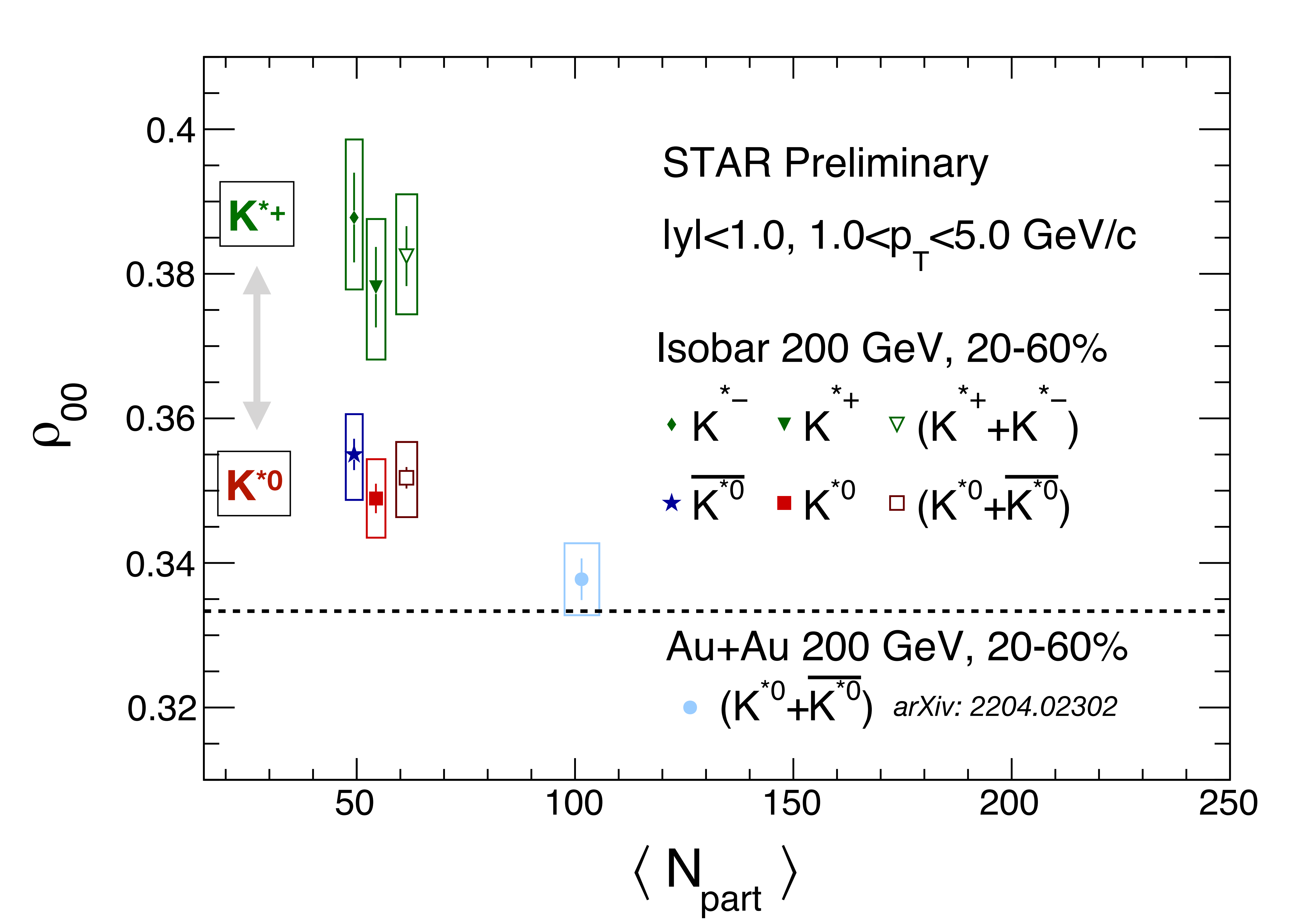
$$\rho_{00}(B) \approx \frac{1}{3} - \frac{4}{9}\beta^2 \mu_{q_1}\mu_{q_2} B^2$$

(Expect negligible contribution)

ρ_{00} (B) > 1/3 for K^{*0}
ρ_{00} (B) < 1/3 for $K^{*+/-}$

Yang, et. al., Phys Rev C 97, 034917 (2018)

K^* ρ_{00} from Isobar collisions



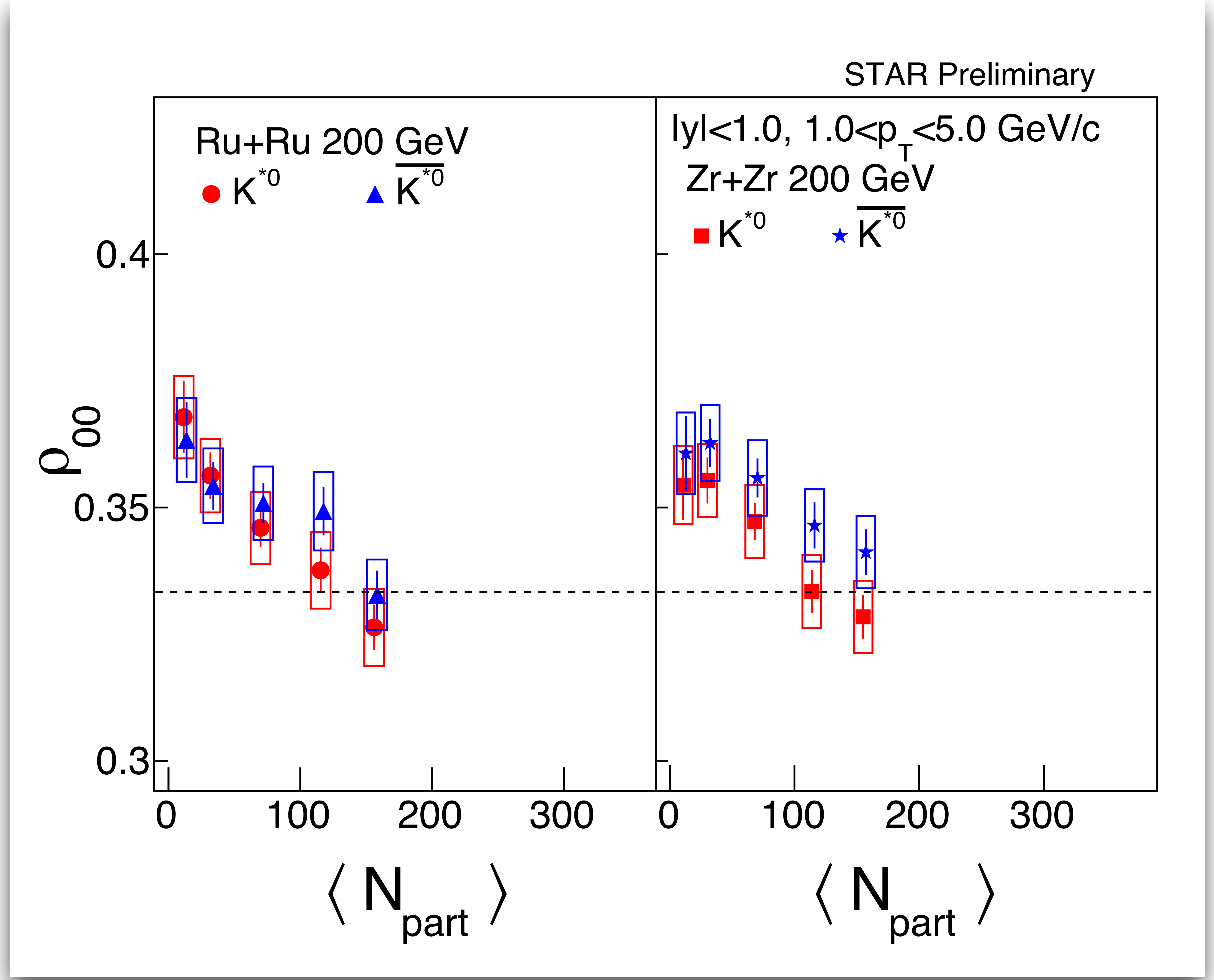
X-axis for isobar data are shifted for clarity

- $K^{*+/-}$: First measurement of global ρ_{00}
- K^{*0} vs. $K^{*+/-}$: ~ 3.9σ difference
  - Ordering opposite to the expectation from **B** field
  - Contribution from vector meson strong force field?

Yang, et. al., Phys Rev C 97, 034917 (2018)

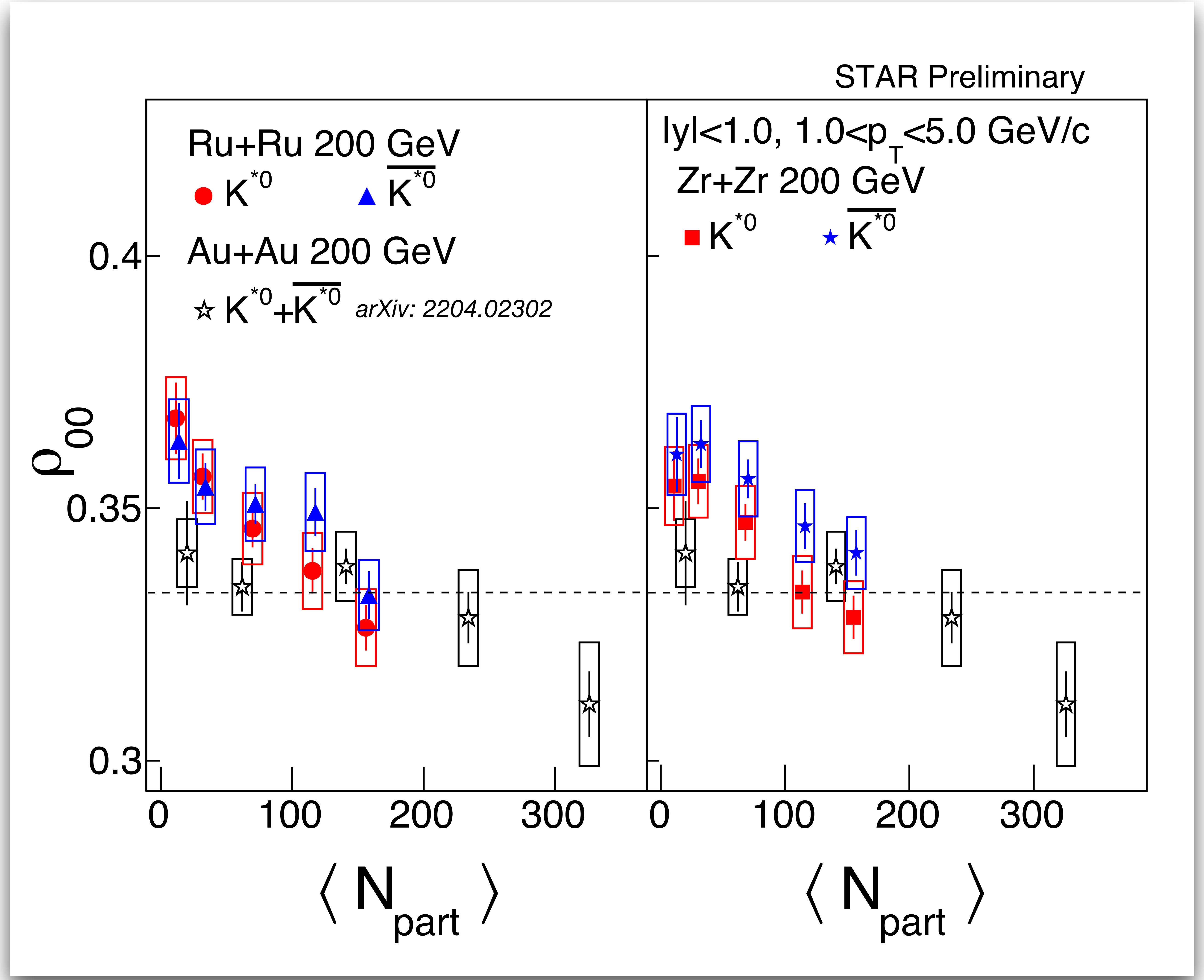
- Need inputs from theory to understand this behavior

ρ_{00} (Centrality): K^{*0} and anti-K^{*0}



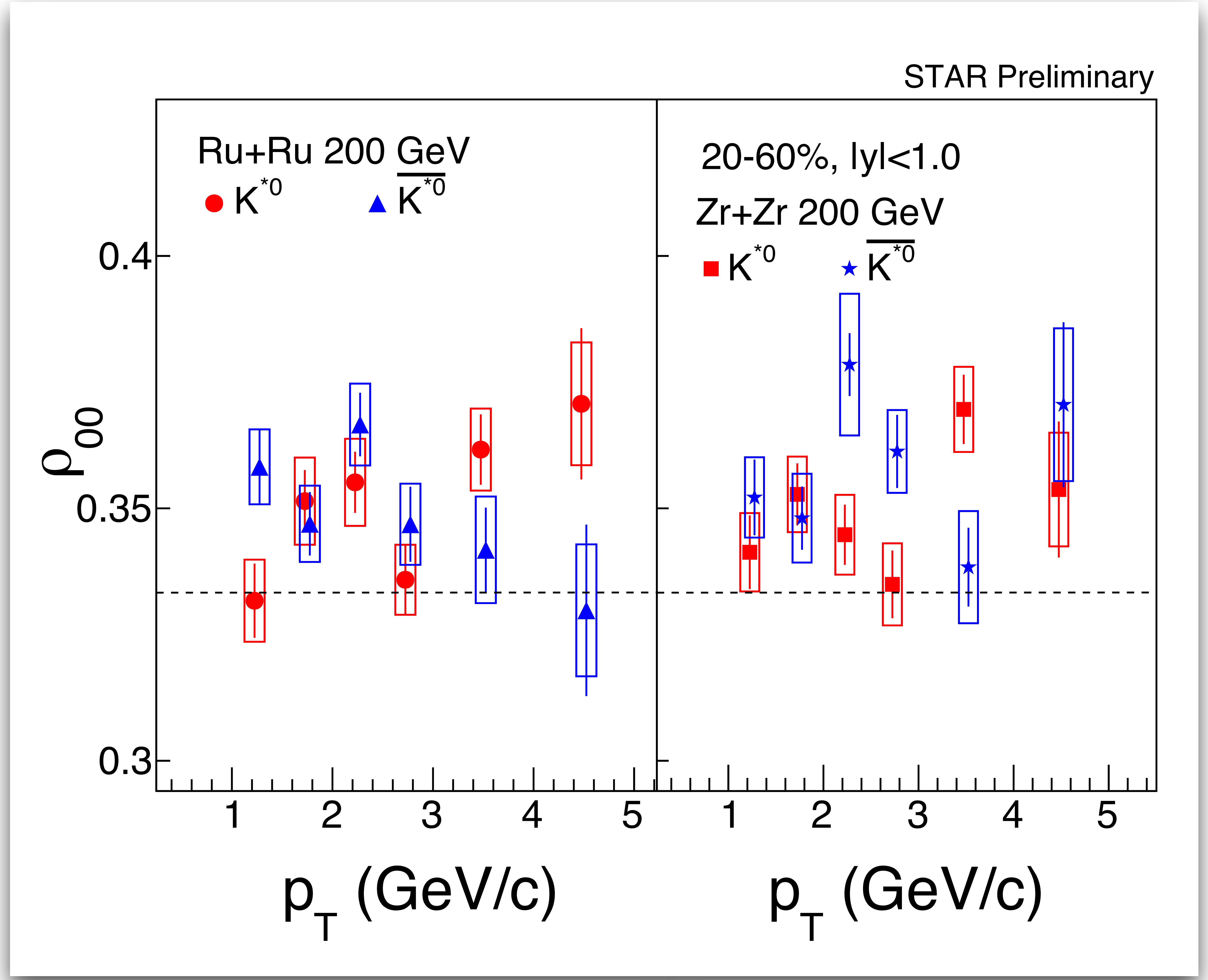
- <u>Species dependence:</u>
  - K^{*0} ρ_{00} ~ anti-K^{*0} ρ_{00}

ρ_{00} (Centrality): K^{*0} and anti-K^{*0}



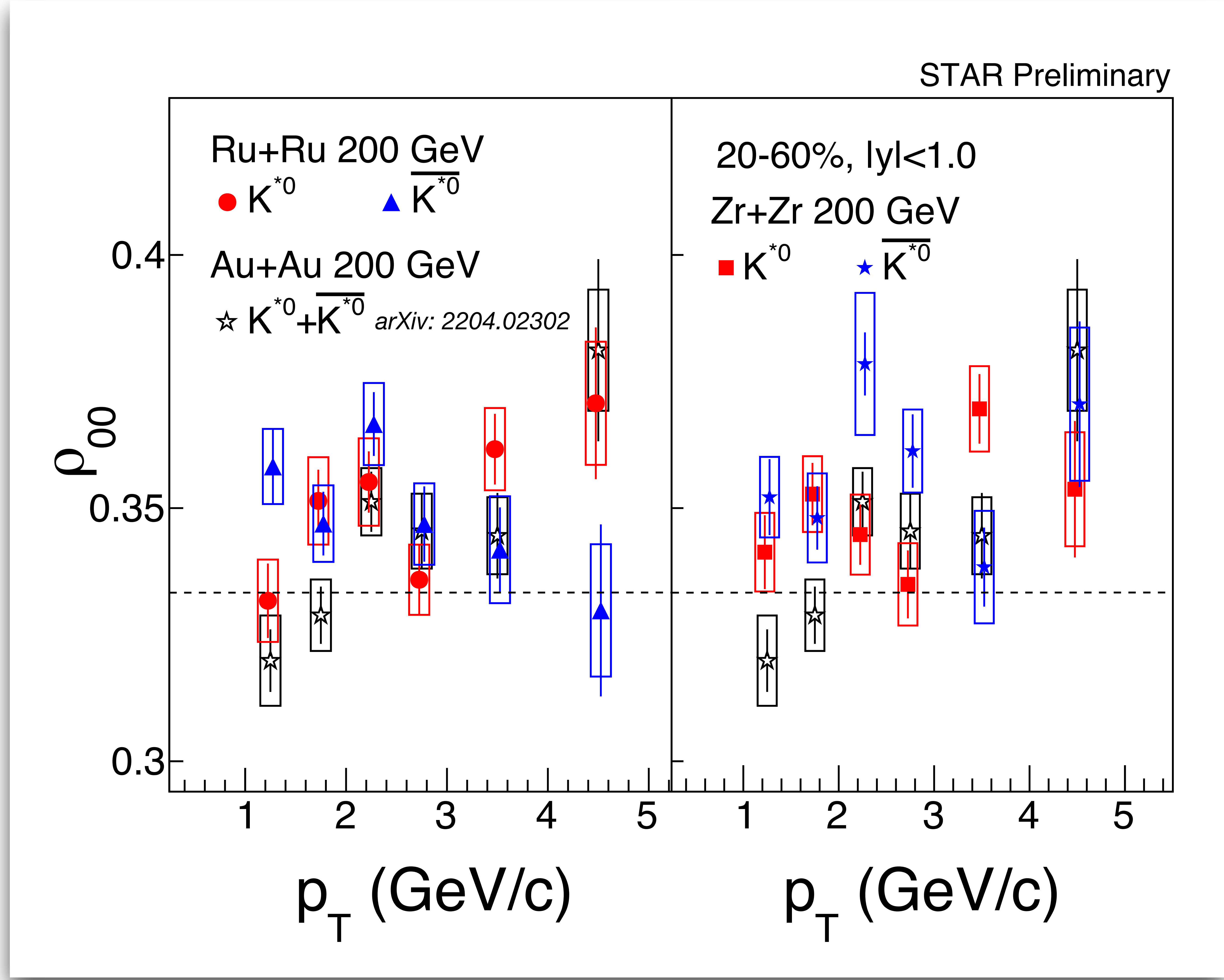
- <u>Species dependence:</u>
  - K^{*0} ρ_{00} ~ anti-K^{*0} ρ_{00}
- <u>System size dependence:</u>
  - ρ_{00} Au+Au ~ Zr+Zr ~ Ru+Ru

ρ_{00} (p_T): K^{*0} and anti-K^{*0}



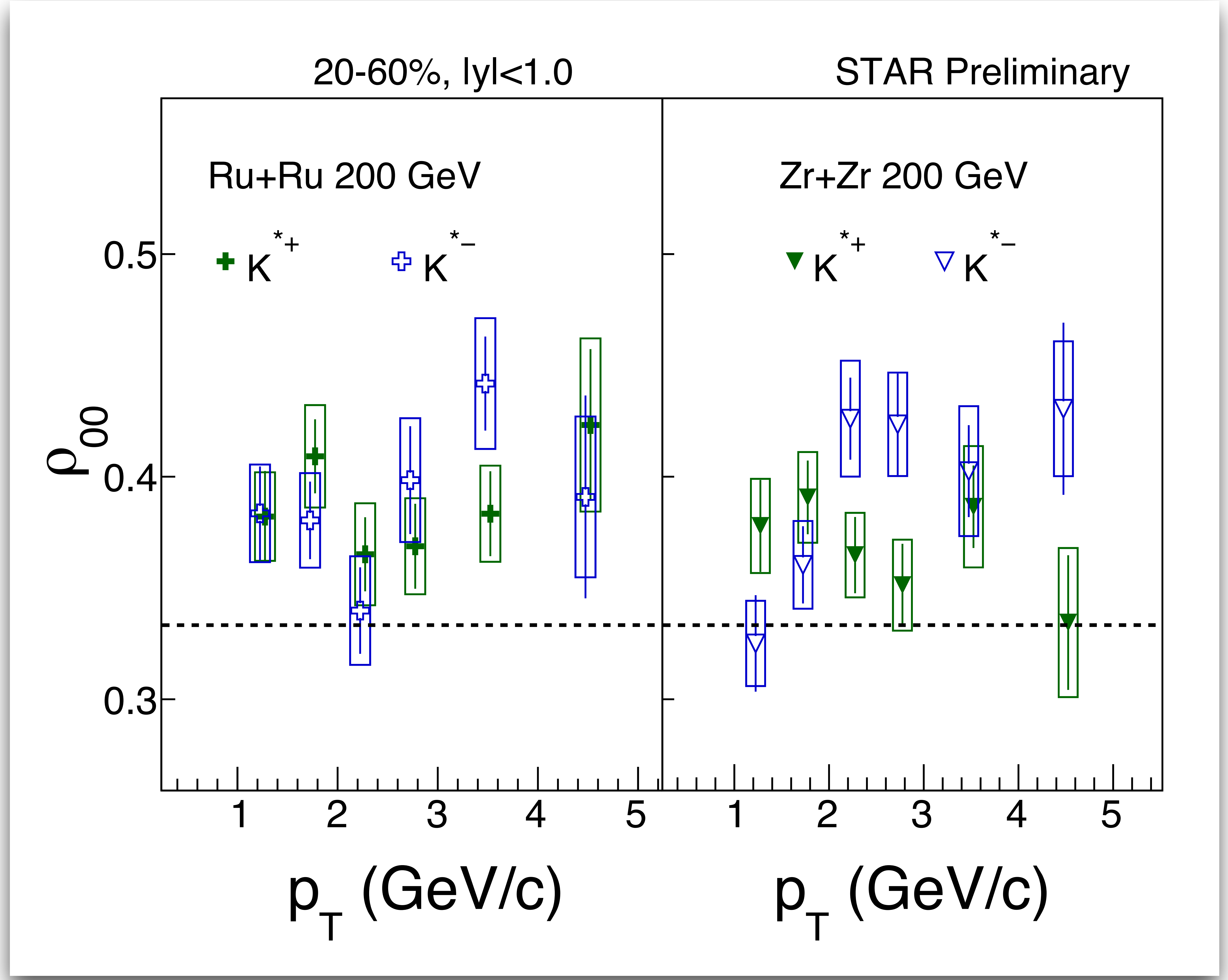
- **Species dependence:**
  - K^{*0} ρ_{00} ~ anti-K^{*0} ρ_{00} ~ 1/3

ρ_{00} (p_T): K^{*0} and anti-K^{*0}



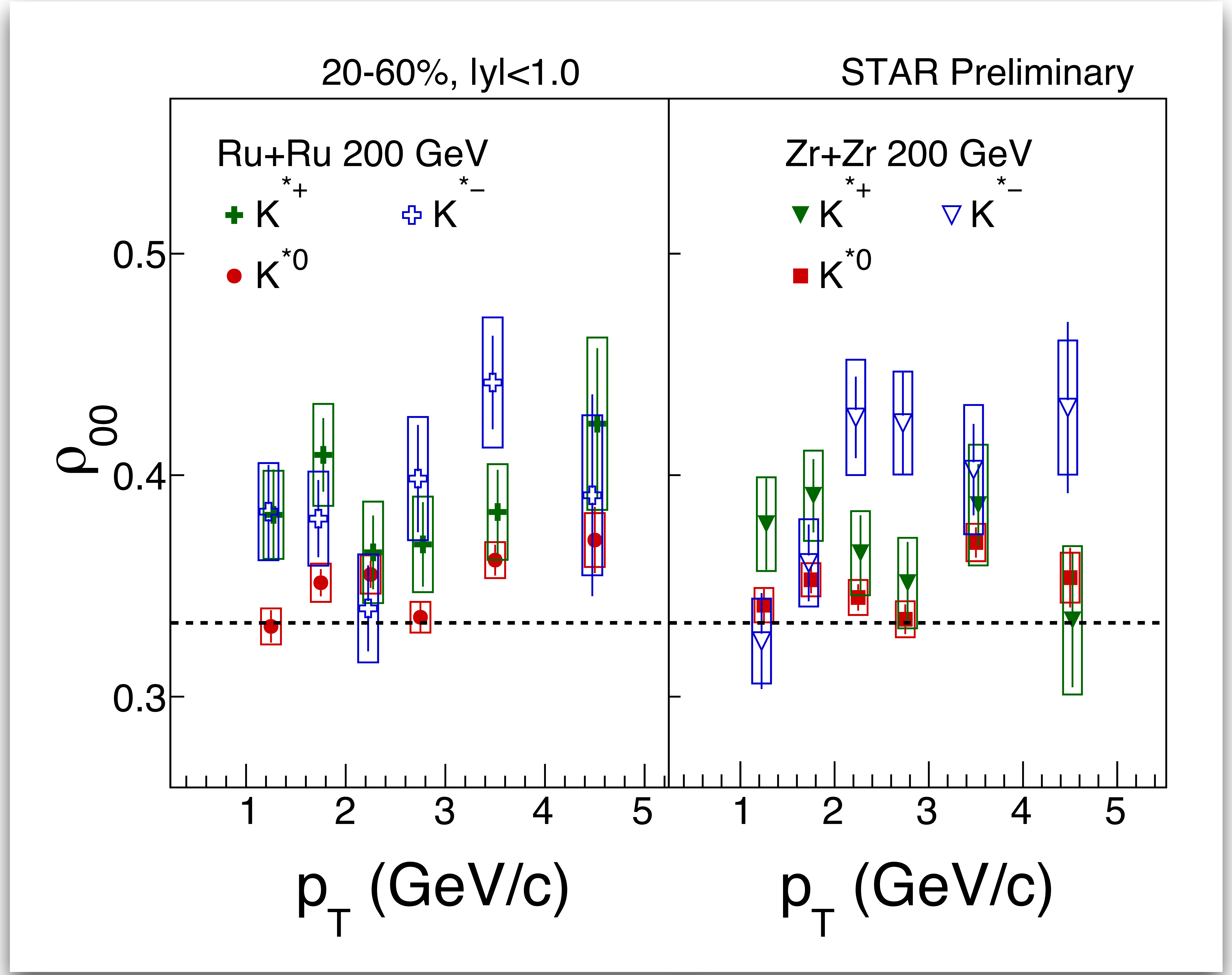
- Species dependence:
  - K^{*0} ρ_{00} ~ anti-K^{*0} ρ_{00} ~ 1/3
- System size dependence:
  - ρ_{00} Au+Au ~ Zr+Zr ~ Ru+Ru

$\rho_{00}(p_T)$: $K^{*+/-}$



- System size dependence:
  - ρ_{00} Zr+Zr ~ Ru+Ru

$\rho_{00}(p_T)$: $K^{*+/-}$ and K^{*0}



- System size dependence:
  - ρ_{00} Zr+Zr ~ Ru+Ru
- Particle species dependence:
  - $K^{*+/-}$ ρ_{00} > K^{*0} ρ_{00}

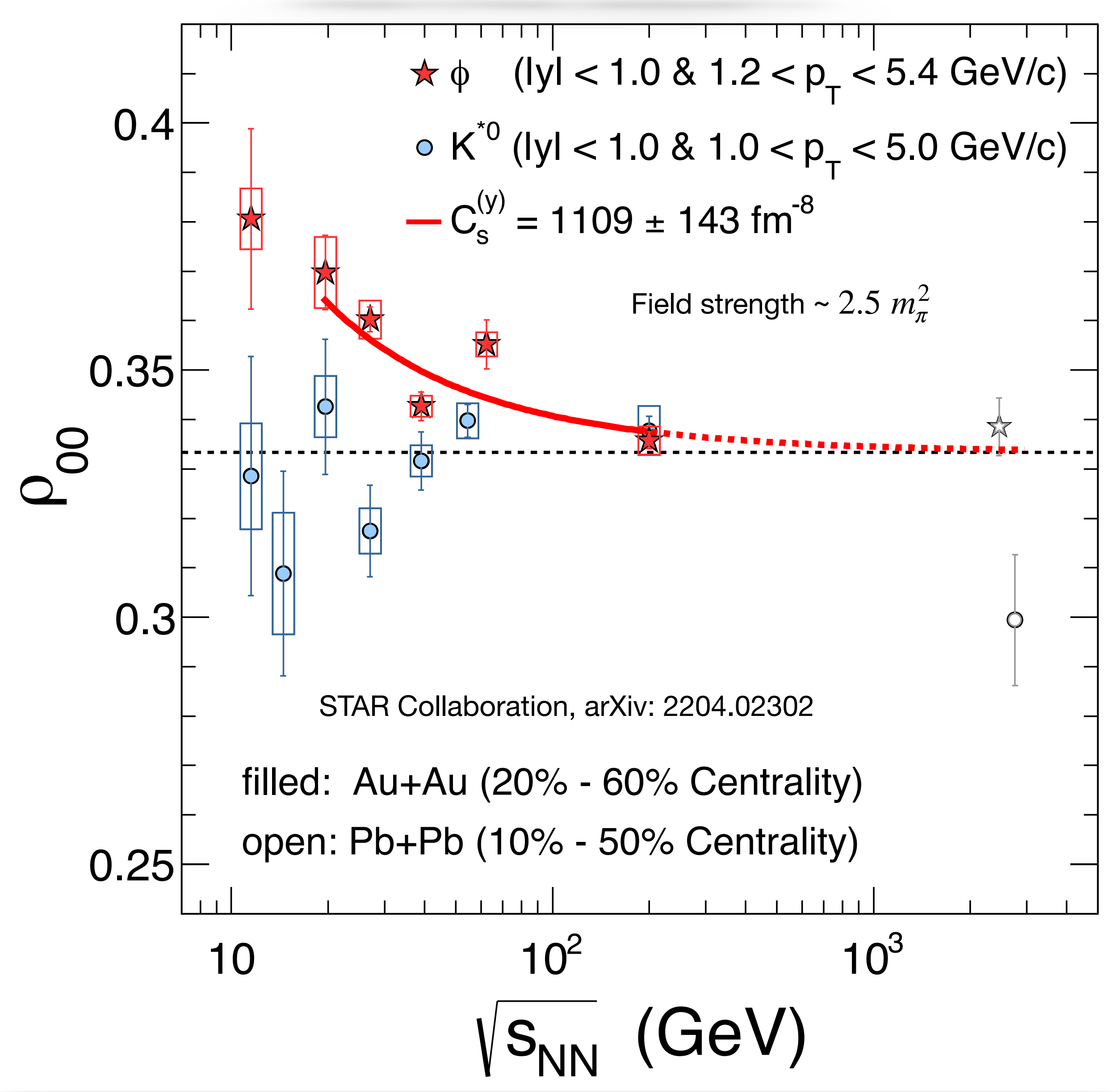
Summary

- We presented ρ_{00} of ϕ and K^{*0} from Au+Au BES-I at 11.5- 200 GeV
- For 20-60%: $\rho_{00}(\phi) > 1/3$, $\rho_{00}(K^{*0}) \sim 1/3$
- Beam energy dependence of ϕ ρ_{00} at mid-central collisions is consistent with a model fitting with *vector meson force fields*

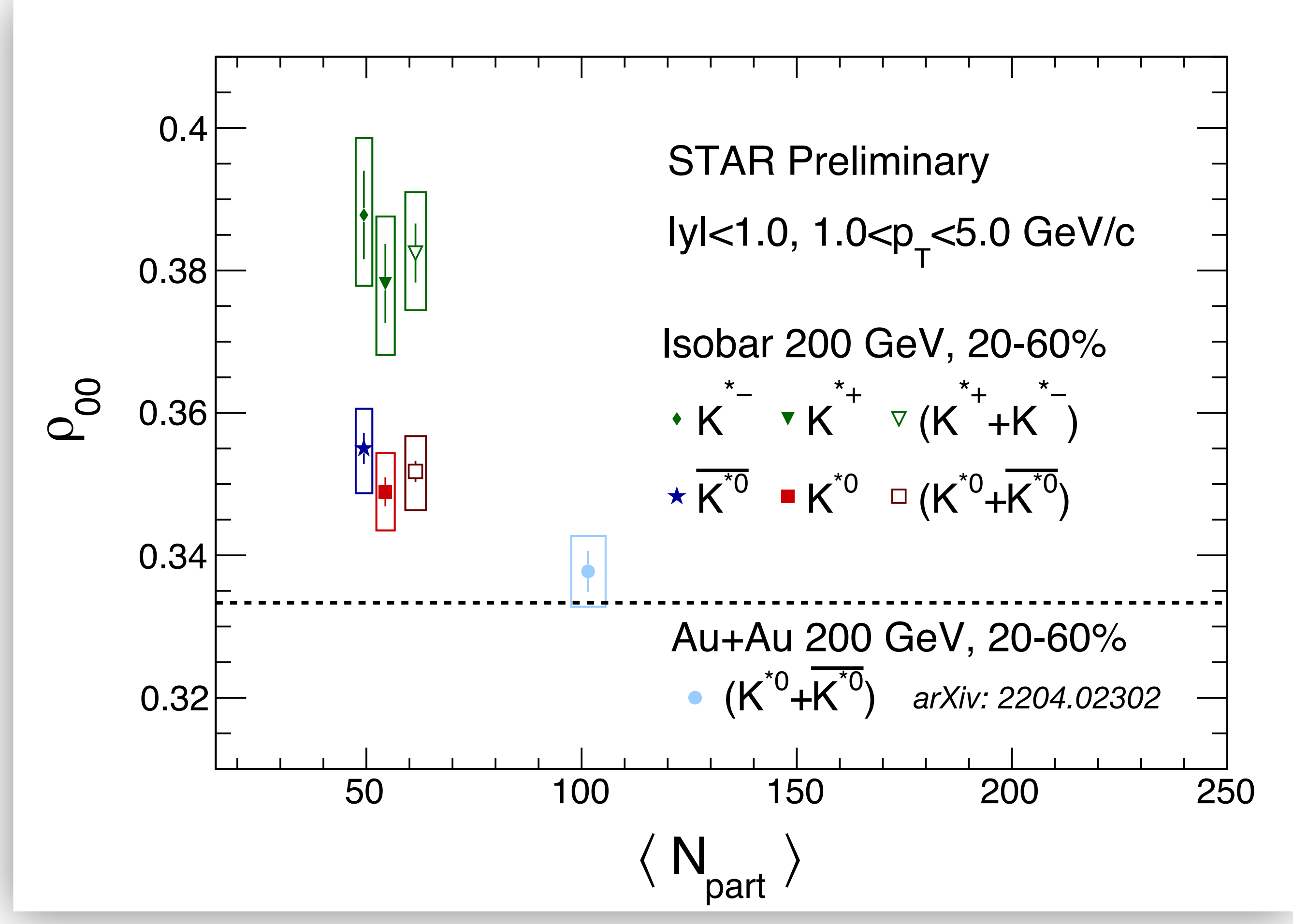
- We presented ρ_{00} of K^{*0} and $K^{*+/-}$ from RHIC Isobar (Ru+Ru & Zr+Zr) at 200 GeV
- For 20-60%: $\rho_{00}(K^{*+/-}) > \rho_{00}(K^{*0})$
- $\rho_{00}(K^{*0})$: Zr+Zr ~ Ru+Ru ~ Au+Au

- More inputs from theory are needed to interpret the ρ_{00} measurements

Au+Au BES-I



Isobar (Ru+Ru and Zr+Zr)



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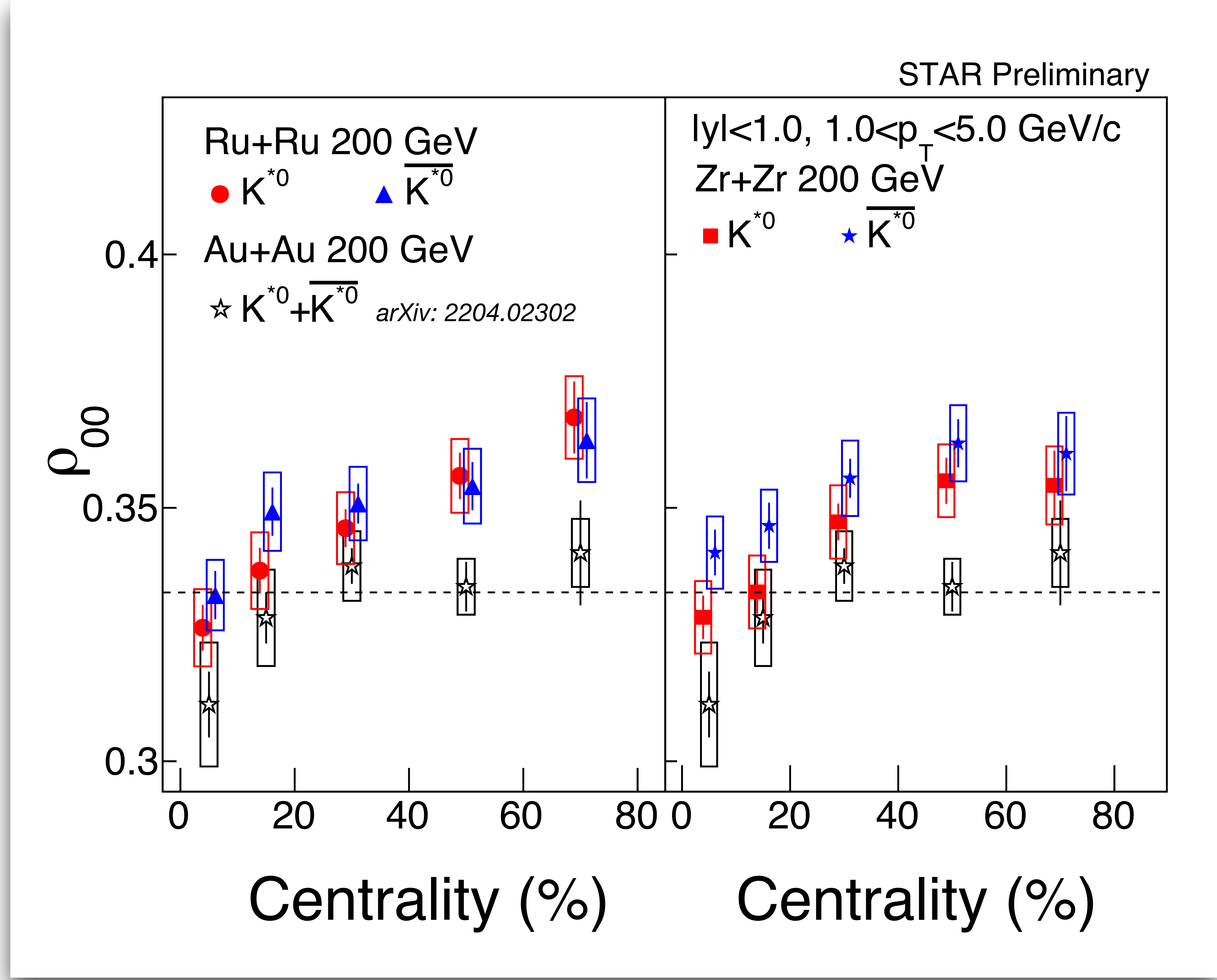
Thank you for your attention

Backup slides

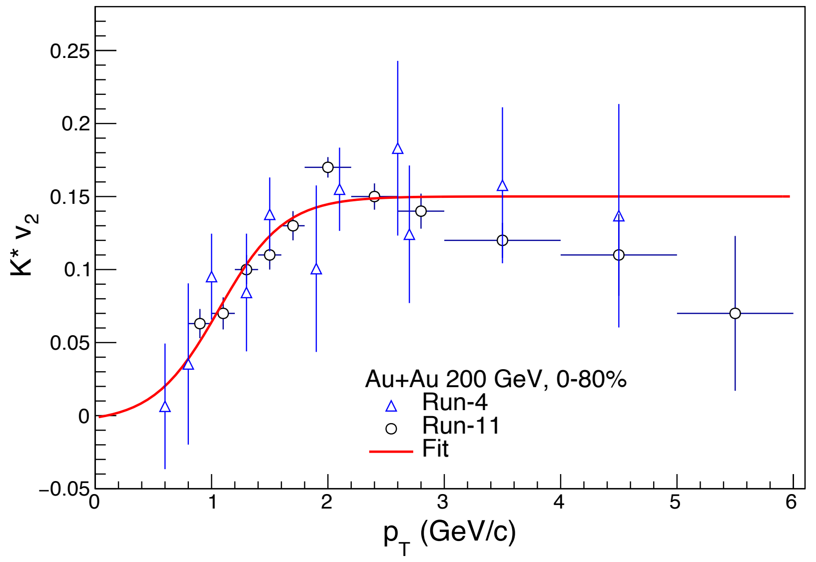
ρ_{00} (Centrality): K^{*0} and anti-K^{*0} from isobar



- Species dependence:
  - K^{*0} ρ_{00} ~ anti-K^{*0} ρ_{00}
- System size dependence:
  - ρ_{00} Au+Au ~ Zr+Zr ~ Ru+Ru

Simulation framework for efficiency and acceptance

Results corrected for K* v_2 bias



Input: embedded MC K* + real data tracks

↓

Calculate Ψ from real data tracks

↓

Reject MC K* in φ-Ψ to mimic measured K* $v_2(p_T)$

↓

Calculate cos θ* wrt Ψ for MC K* tracks

Reconstructed (RC) K*

RC K* and it's daughters
Apply experimental acceptance and track cuts on daughters
&
Consider K* $v_2(p_T)$ effects accordingly

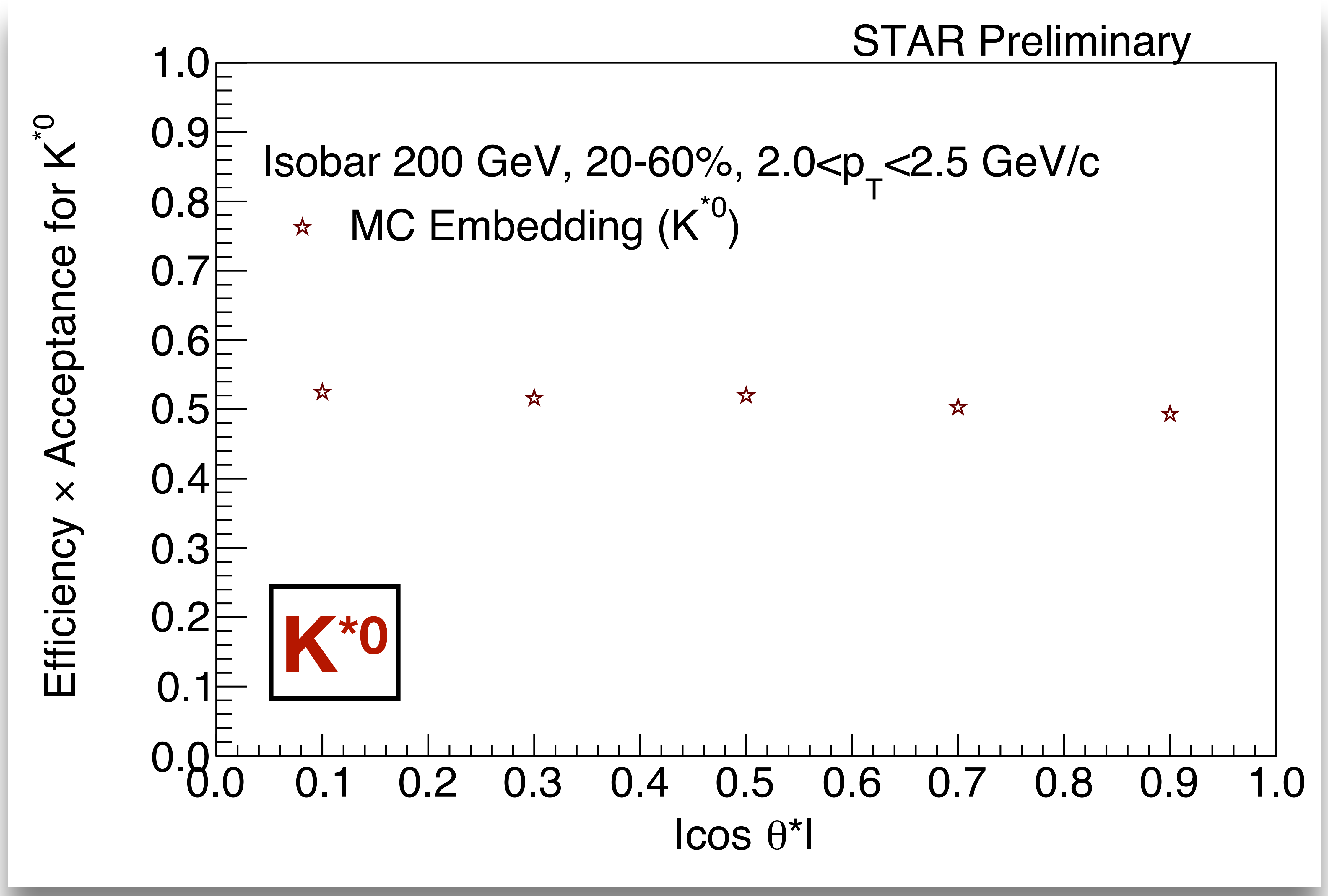
↓

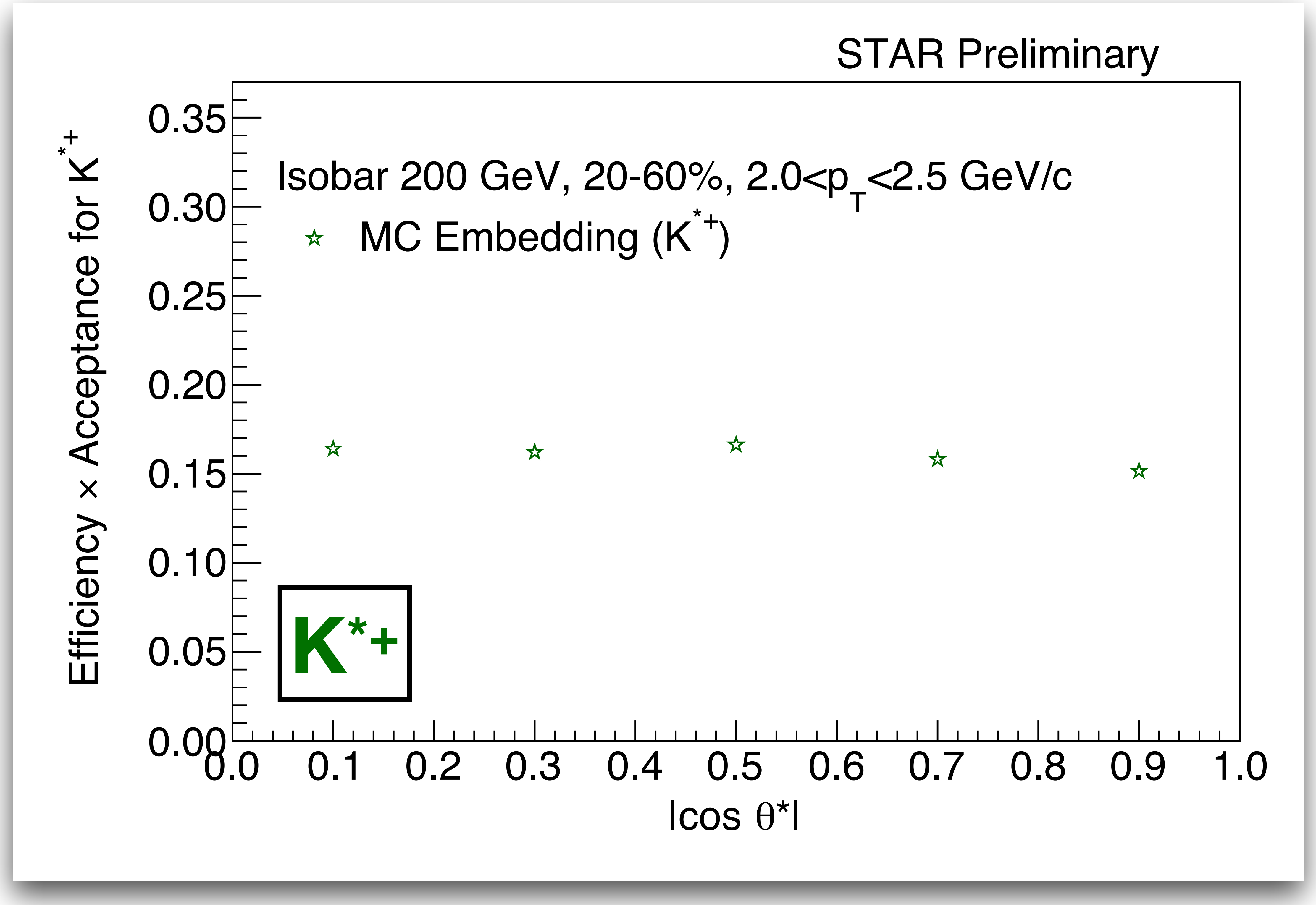
Calculate cos θ* wrt Ψ for RC tracks

Efficiency x Acceptance = RC/MC

Correction factor includes acceptance and efficiency (p_T, φ-Ψ, cos θ*) with v_2 effect included

Efficiency and acceptance for K*





ρ_{00} ($\sqrt{s_{NN}}$): ϕ and K^{*0} for central collisions from BES-I

STAR Collaboration, arXiv: 2204.02302