

Measurement of Global spin alignment of vector mesons at RHIC

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May 09, 2023

On-line seminar series VI on “RHIC Beam Energy Scan” Spring 2023



Outline

- Introduction
- STAR detector and analysis details
- Results from RHIC Beam Energy Scan
- Summary

Introduction

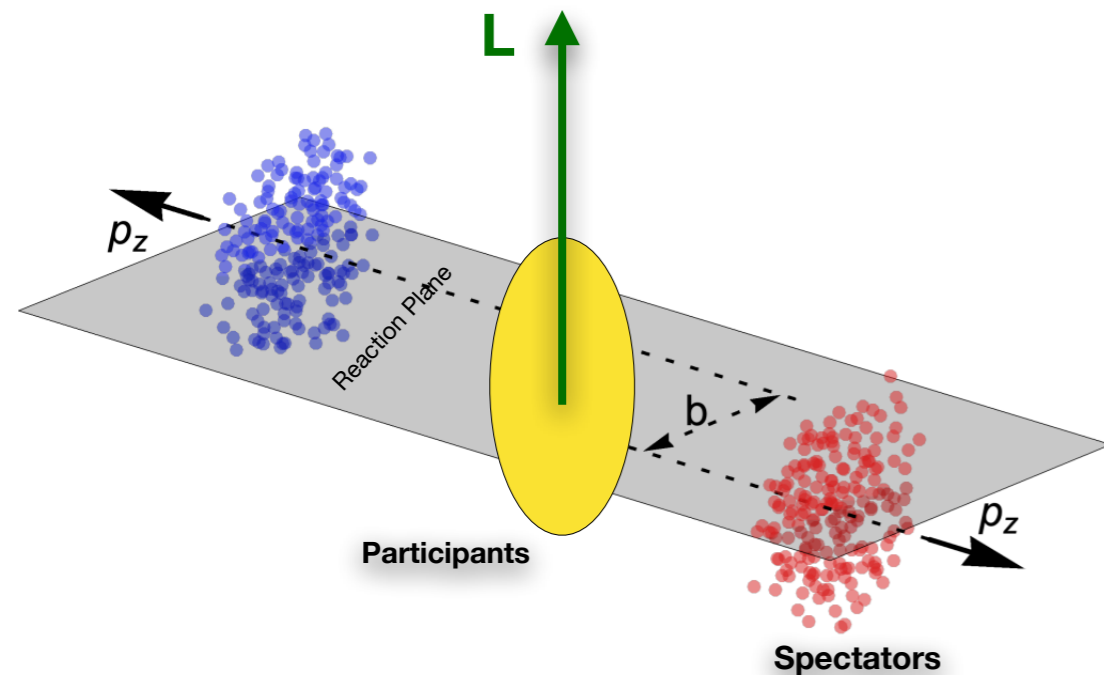
Initial condition in Heavy ion collision

In non-central heavy-ion collisions

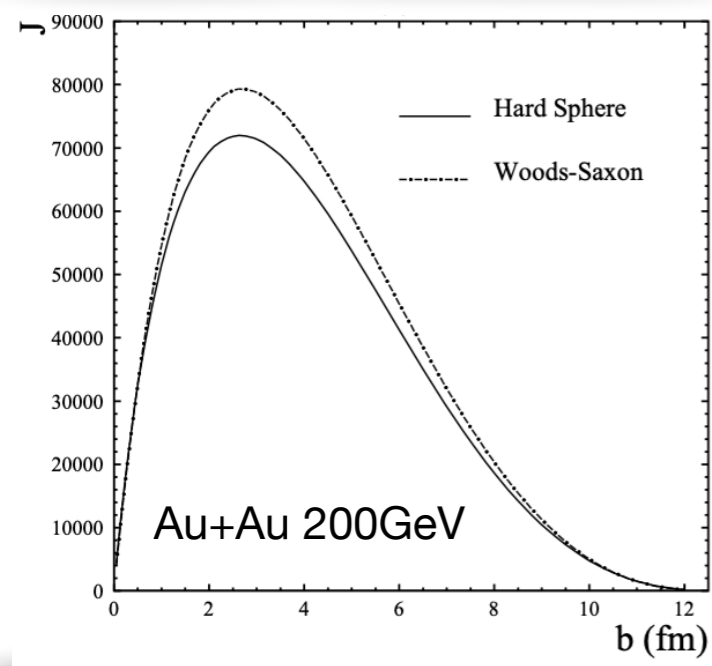
- A **large orbital angular momentum** (OAM) imparted into the system

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

- Part of OAM transferred to QGP can polarize quarks and anti-quarks due to “*spin-orbit*” interaction.



Angular momentum



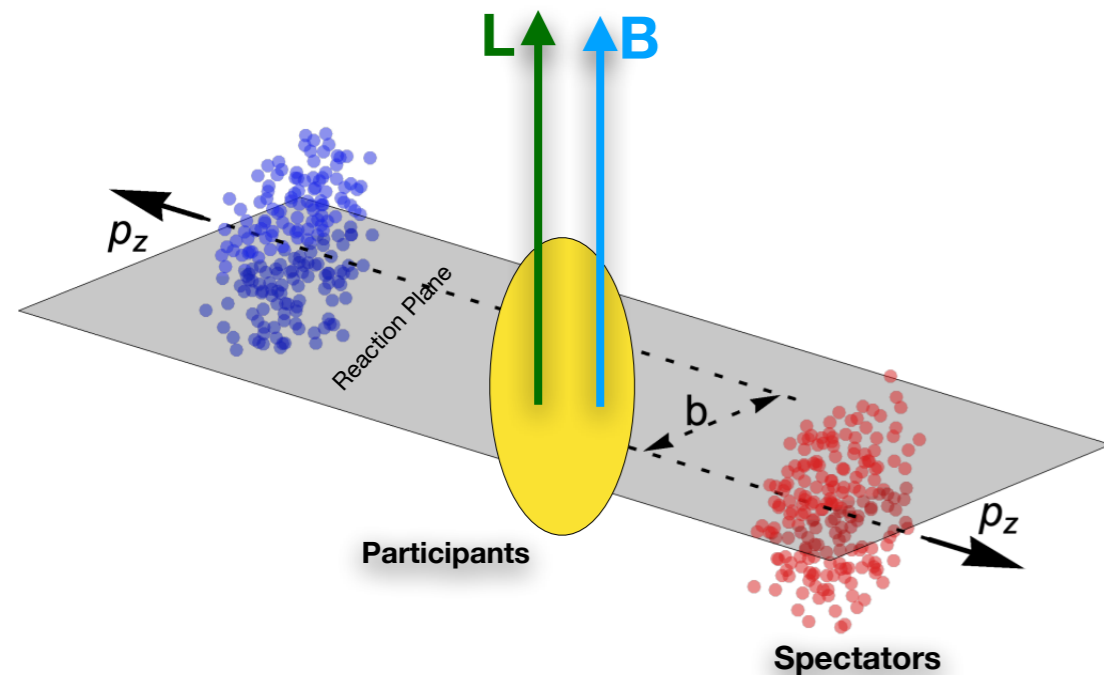
Initial condition in Heavy ion collision

In non-central heavy-ion collisions

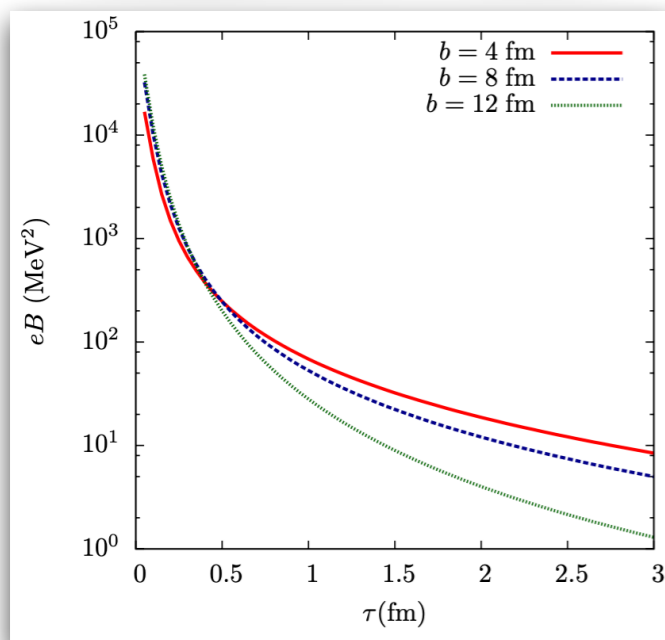
- **Initial strong magnetic field (**B**)** is expected

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

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



Magnetic Field

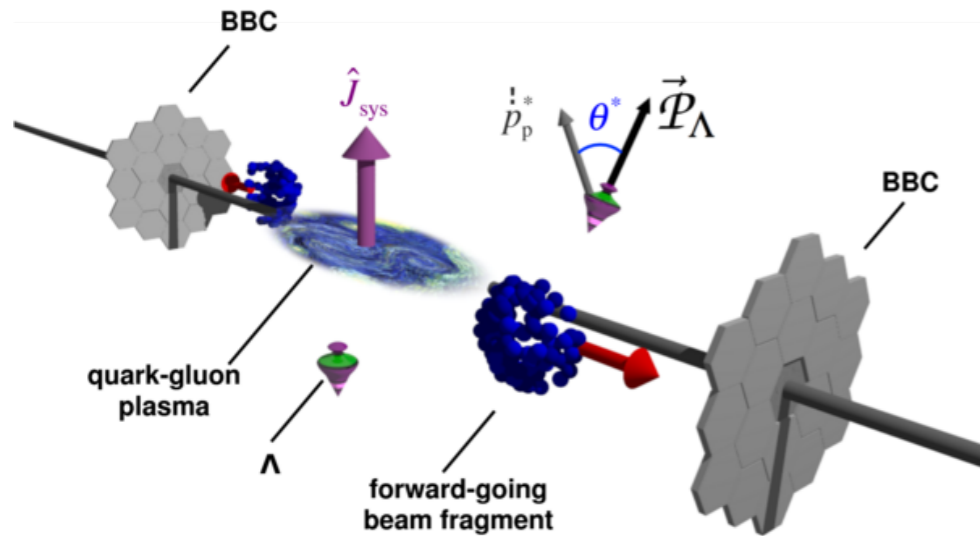


Through polarization measurements

- 1) Study role external rotation and magnetic field
- 2) Response of QCD matter under external strong fields

Global spin polarization of Λ

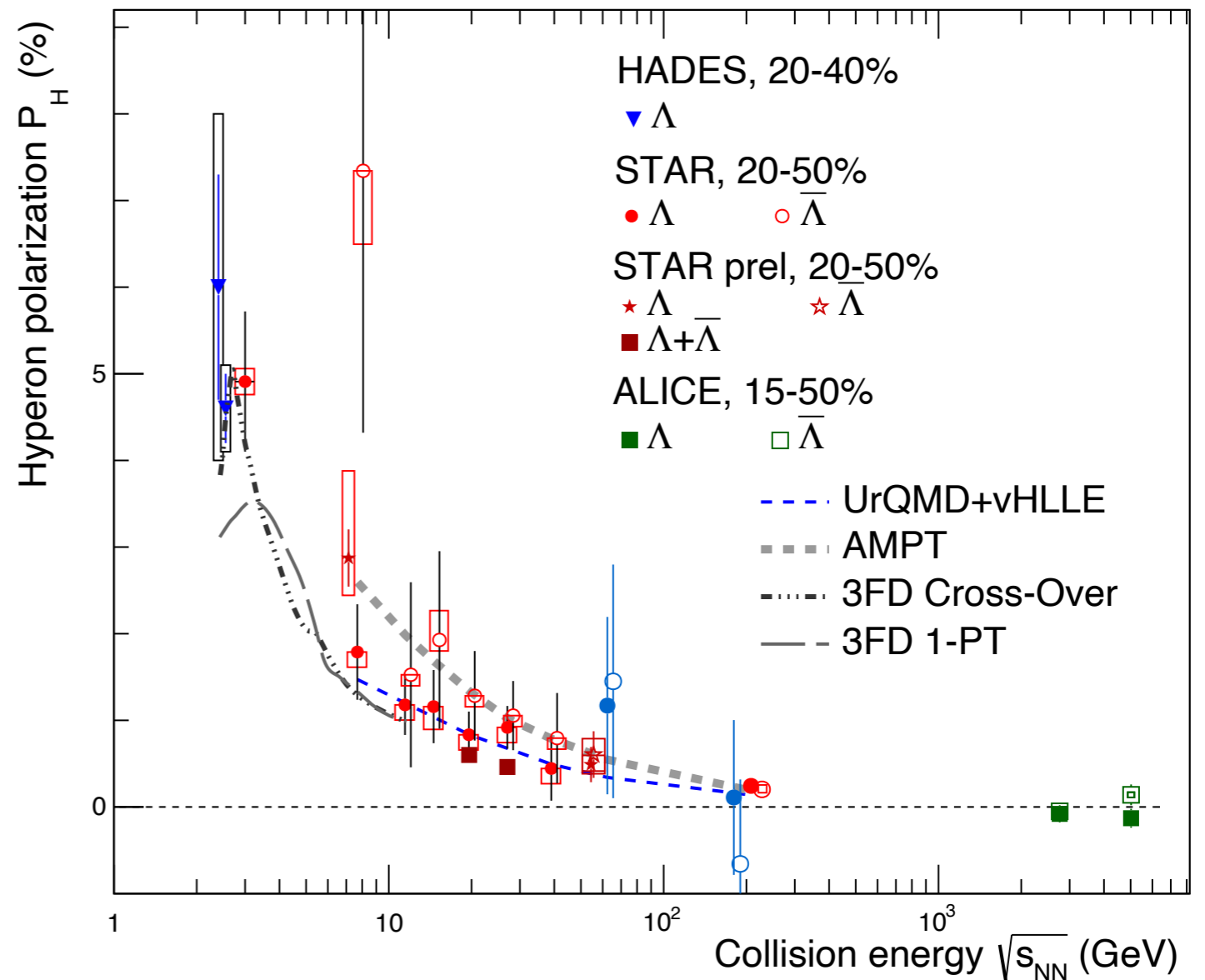
- Λ : parity violating weak decay and hence “self analyzing”



$$P_{\Lambda} = \frac{8}{\pi\alpha_{\Lambda}} \frac{\langle \sin(\Psi_1 - \phi_p^*) \rangle}{\text{Res}(\Psi_1)}$$

Thermal vorticity: $\omega = k_B T (P_{\Lambda} + P_{\bar{\Lambda}}) / \hbar$

$$\omega \sim (9 \pm 1) \times 10^{21} \text{ s}^{-1}$$

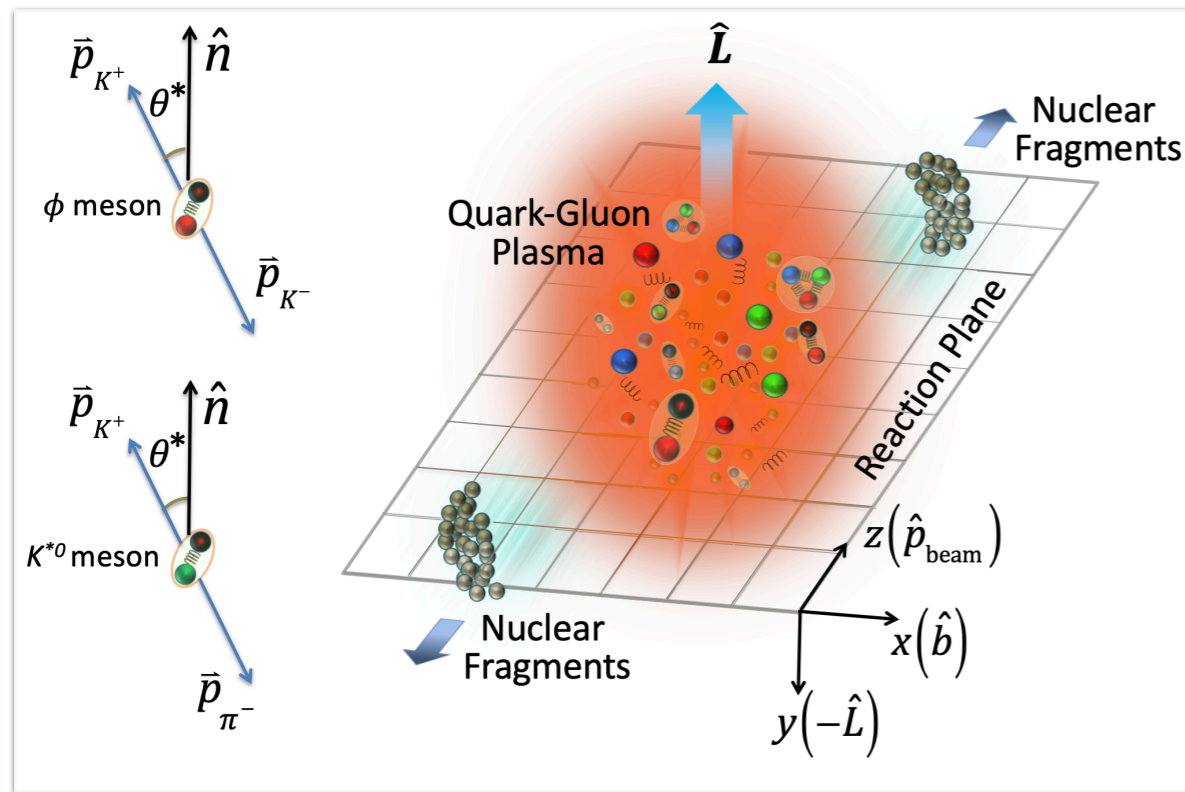


Presence of extreme vorticity induced by angular momentum interactions

STAR: Phys. Rev. C 76, 024915 (2007); Nature 548, 62 (2017); Phys. Rev. C 101, 044611 (2020); Phys. Rev. C 104, 061901 (2021)
 ALICE: Phys. Rev. C 101, 044611 (2020); HADES: Phys. Lett. B 137506 (2022)

Spin alignment of vector mesons

$\hat{n} \rightarrow$ quantization axis



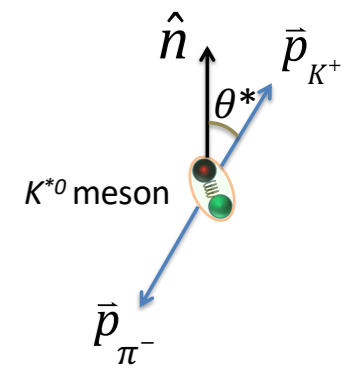
$$\rho^V = \begin{pmatrix} \rho_{11} & \rho_{10} & \rho_{1-1} \\ \rho_{01} & \rho_{00} & \rho_{0-1} \\ \rho_{-11} & \rho_{-10} & \rho_{-1-1} \end{pmatrix}$$

- Vector mesons (K^* and ϕ): Spin 1-, Strong decay
- One can measure 00th component of spin density matrix from angular distribution of daughter

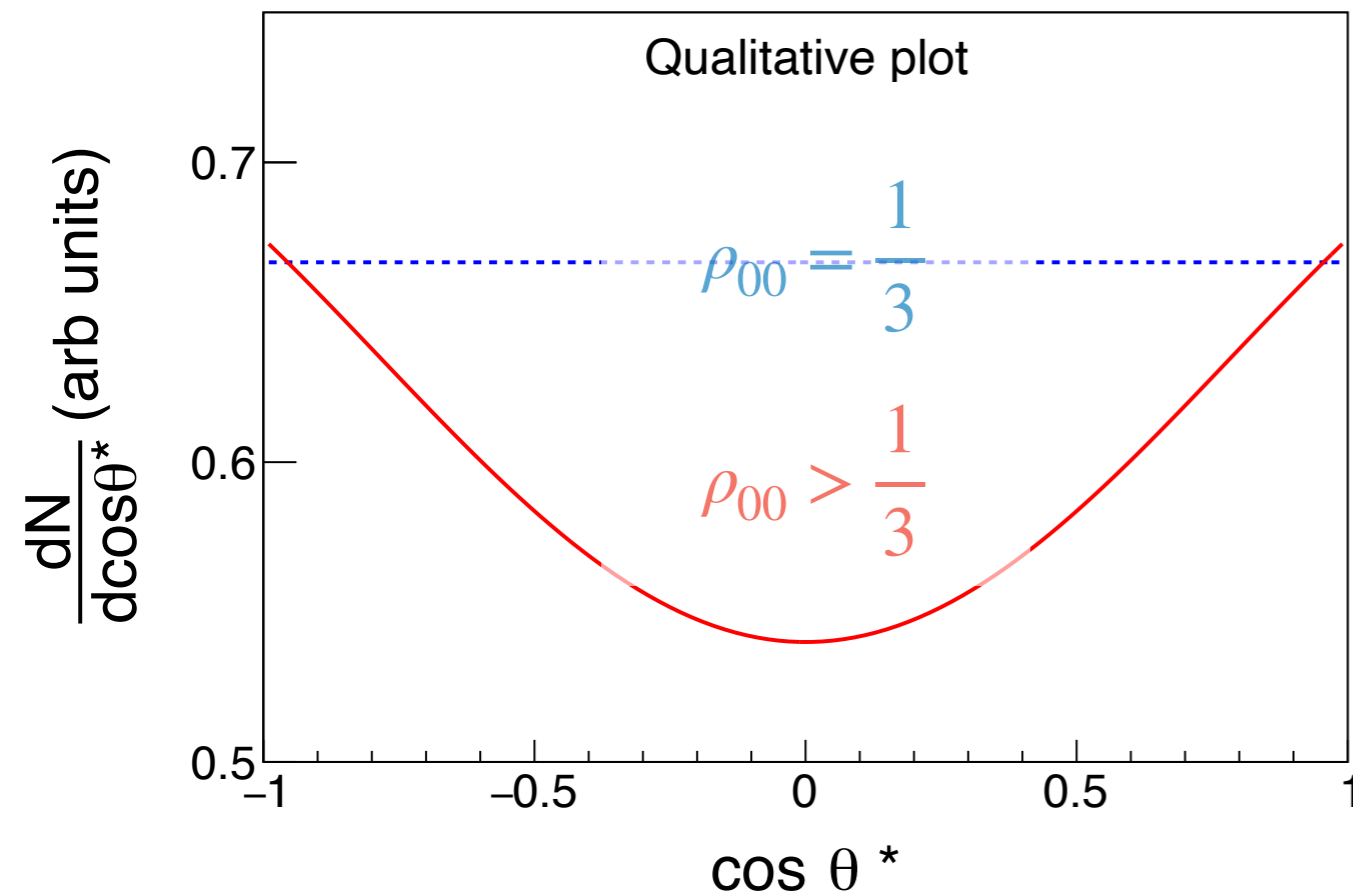
$$\frac{dN}{d\cos\theta^*} = N_0 \times \left((1 - \rho_{00}) + (3\rho_{00} - 1)\cos^2\theta^* \right)$$

$\rho_{00} \rightarrow$ Probability of finding a vector meson in spin state “0” out of (1, 0, -1)

Angular distribution of daughter



- Qualitative expectation of angular distribution

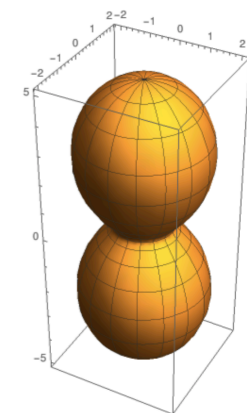
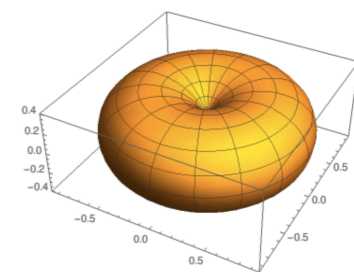
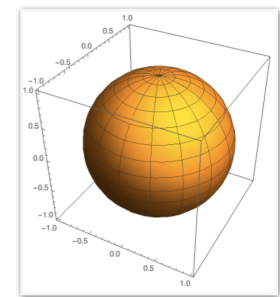


$$\rho_{00} = \frac{1}{3} \rightarrow \text{No spin alignment}$$

$$\rho_{00} < \frac{1}{3}$$

$$\rho_{00} > \frac{1}{3}$$

→ Spin alignment

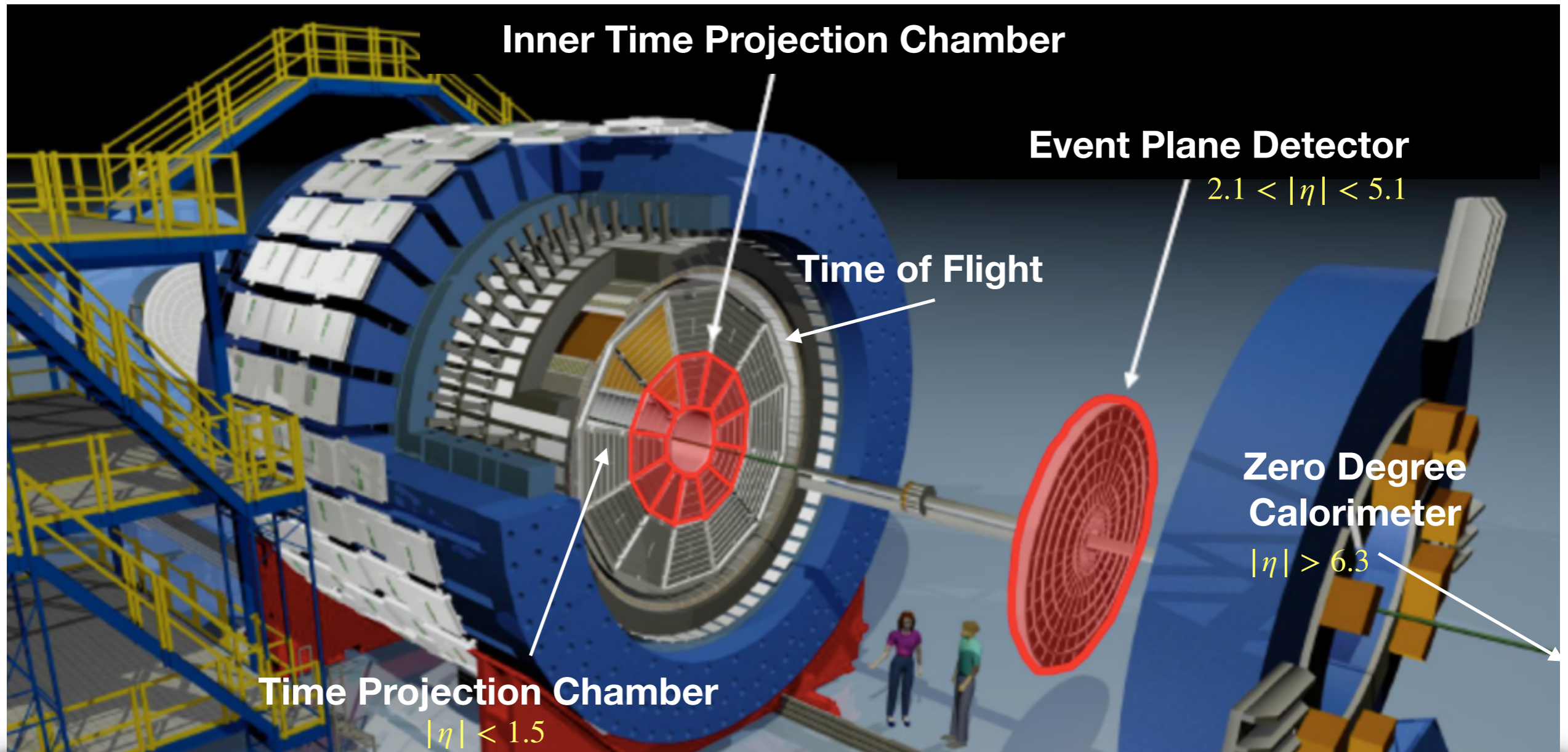


Vector mesons vs hyperons

Species	Quark content	J^P	Decay	Feeddown	Direction of Ang. Mom.
K^{*0}	$d\bar{s}$	1^-	$K\pi$ (strong decay)	negligible (primordial)	not reqd. (Ψ_2, Ψ_1)
ϕ	$s\bar{s}$	1^-	KK (strong decay)	negligible (primordial)	not reqd. (Ψ_2, Ψ_1)
Λ	uds	$1/2^+$	$\rho\pi$ (weak decay)	substantial	required (Ψ_1)

STAR detector and analysis details

STAR detector



- Uniform acceptance, full azimuthal coverage, excellent PID capability
- TPC: tracking, centrality
- TPC, ZDC, EPD: event plane
- TPC+TOF: particle identification

Analysis Procedure

ρ_{00} calculation from angular distribution of decay daughters:

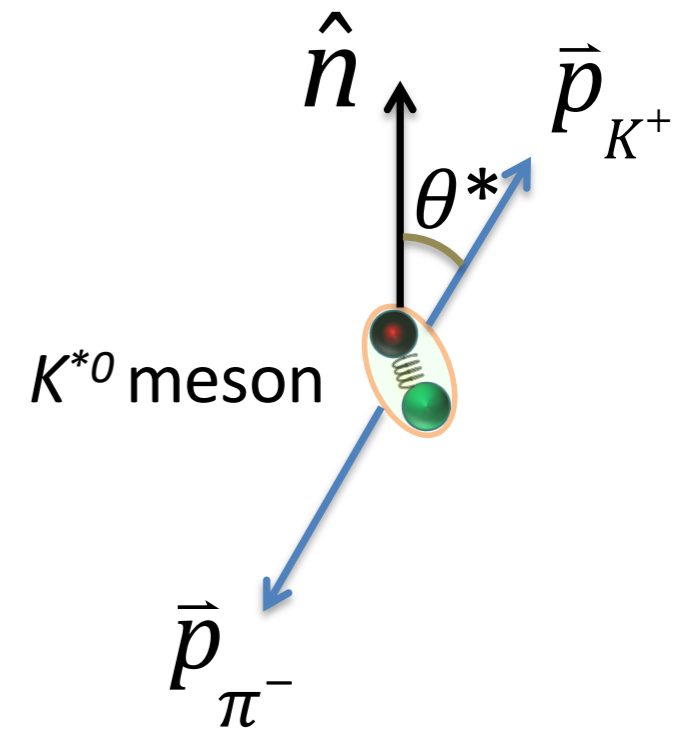
- Yield of vector mesons is extracted in $\cos \theta^*$ bins
- Observed ρ_{00}^{obs} is calculated from fitting the yield with function:

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

- Observed ρ_{00}^{obs} is corrected for detector acceptance and efficiency using detector simulation framework
- Observed ρ_{00}^{obs} is corrected for event plane resolution

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

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



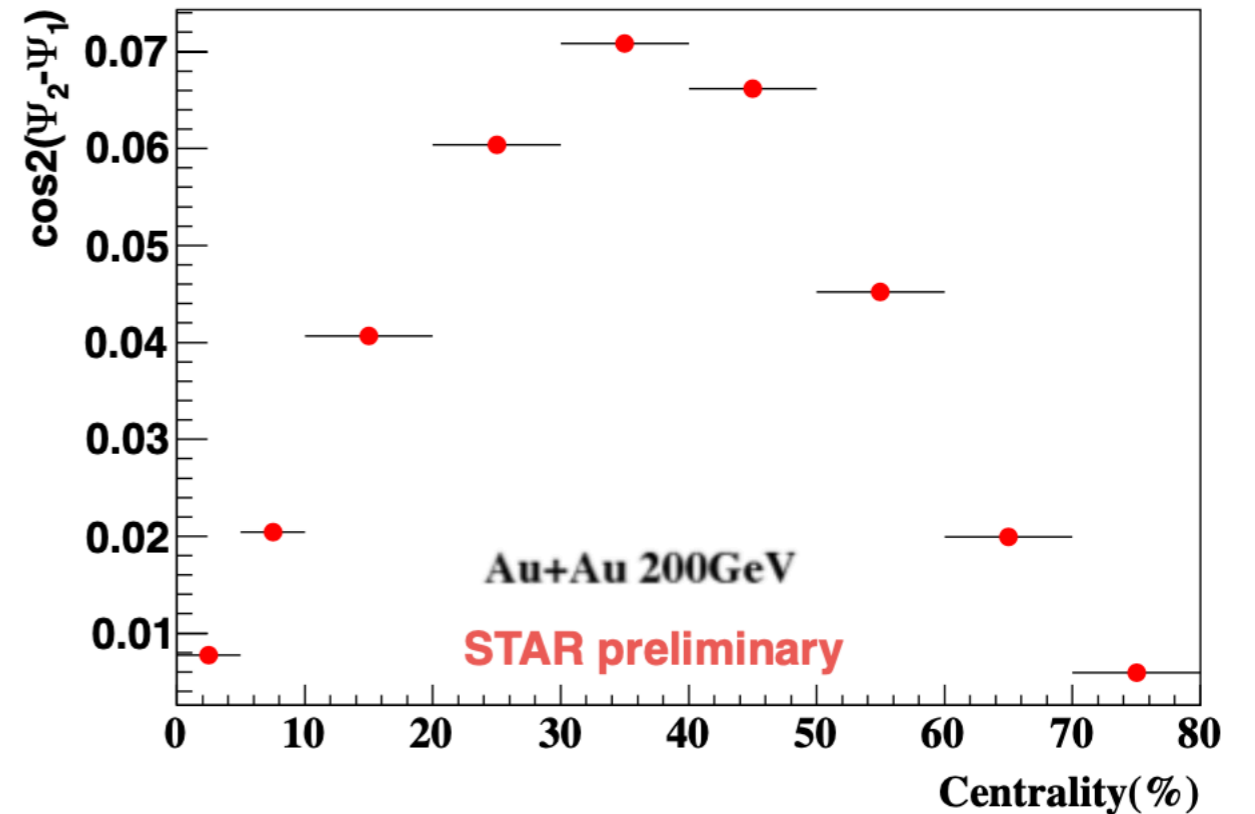
Event plane de-correlation effect

ρ_{00} can be measured using Ψ_2 (2nd order event plane, TPC) and Ψ_1 (1st order event plane, ZDC)

$$\rho_{00,\text{obs}}^{\Psi_2} - \frac{1}{3} = \left(\rho_{00}^{\Psi_2} - \frac{1}{3} \right) \frac{1 + 3R_2}{4}$$

$$\rho_{00,\text{obs}}^{\Psi_2} - \frac{1}{3} = \left(\rho_{00}^{\Psi_1} - \frac{1}{3} \right) \frac{1 + 3D_{12} R_1}{4}$$

$$\rho_{00}^{\Psi_2} - \frac{1}{3} = \left(\rho_{00}^{\Psi_1} - \frac{1}{3} \right) \frac{1 + 3D_{12} R_1}{1 + 3R_2}$$



Event plane de-correlation effect needed to be considered carefully

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

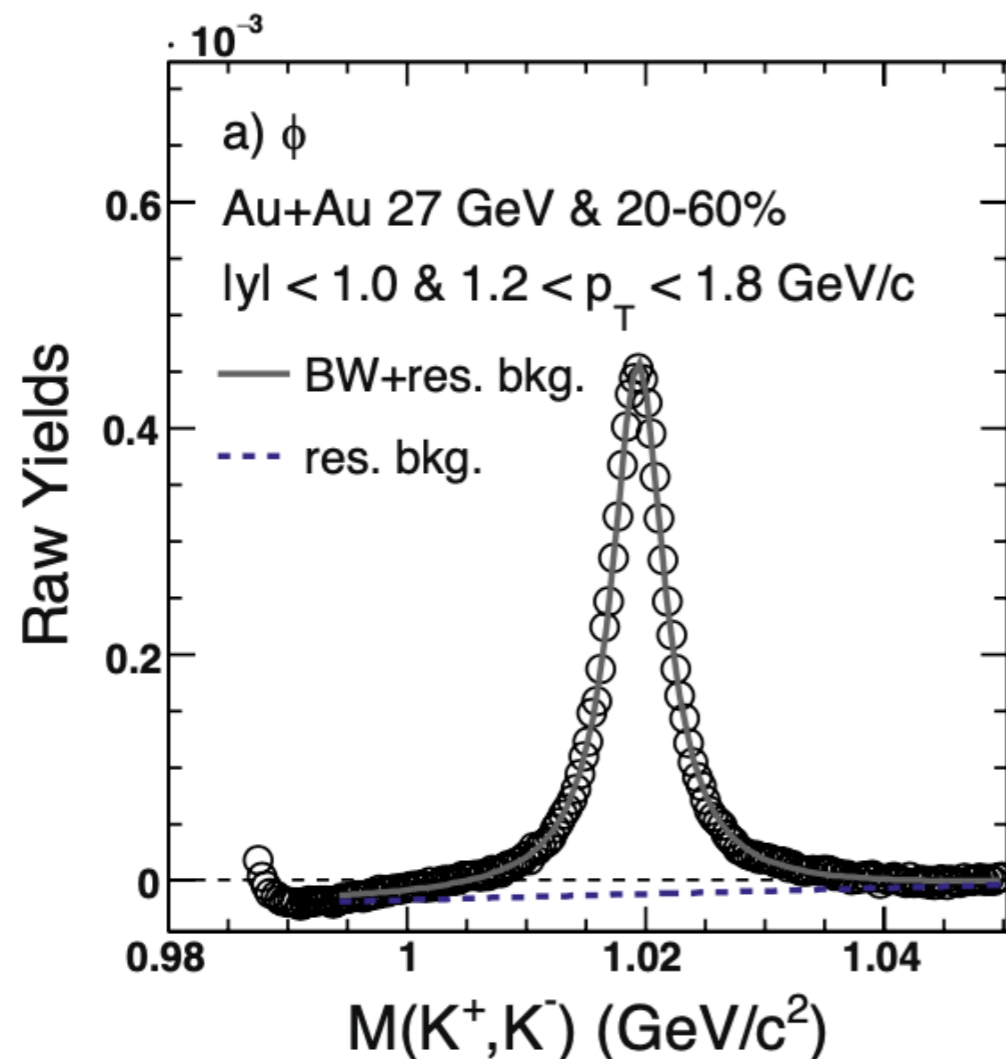
Results and discussions

Dataset and analysis details

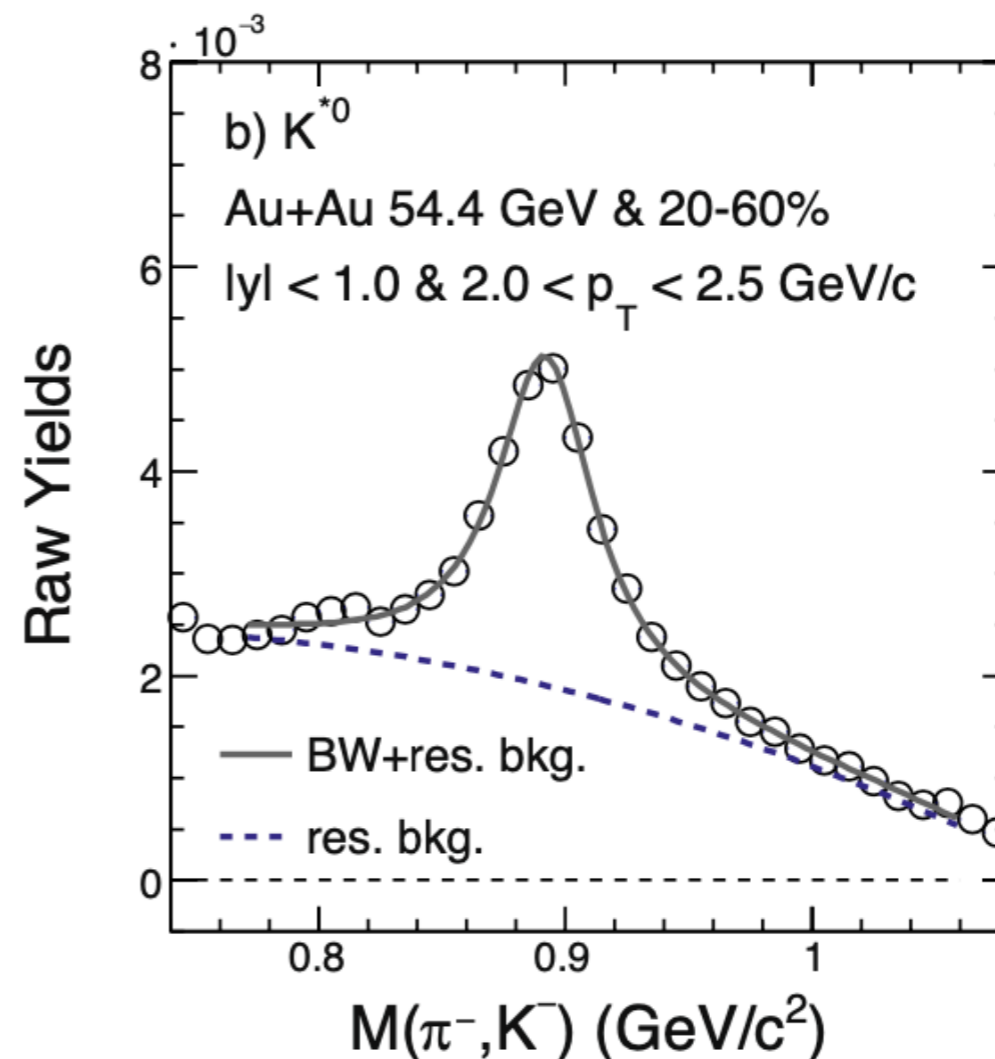
Collision system	Au+Au
Beam energy	11.5, 14.5, 19.6, 27, 39, 54.4, 62.4 and 200 GeV
Trigger	Minimum bias trigger
Pair rapidity	$ y < 1.0$
Background	Mixed event and track rotation method
Polarization axis	Perpendicular to TPC 2 nd order EP and ZDC 1 st order EP
Consistency check	3D-random plane

Invariant mass reconstruction

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



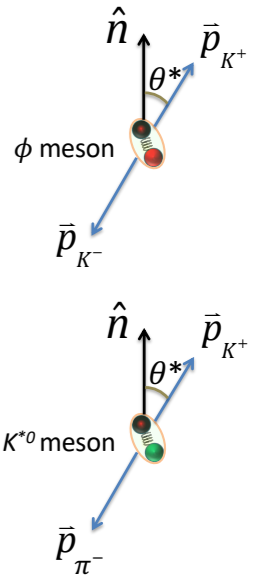
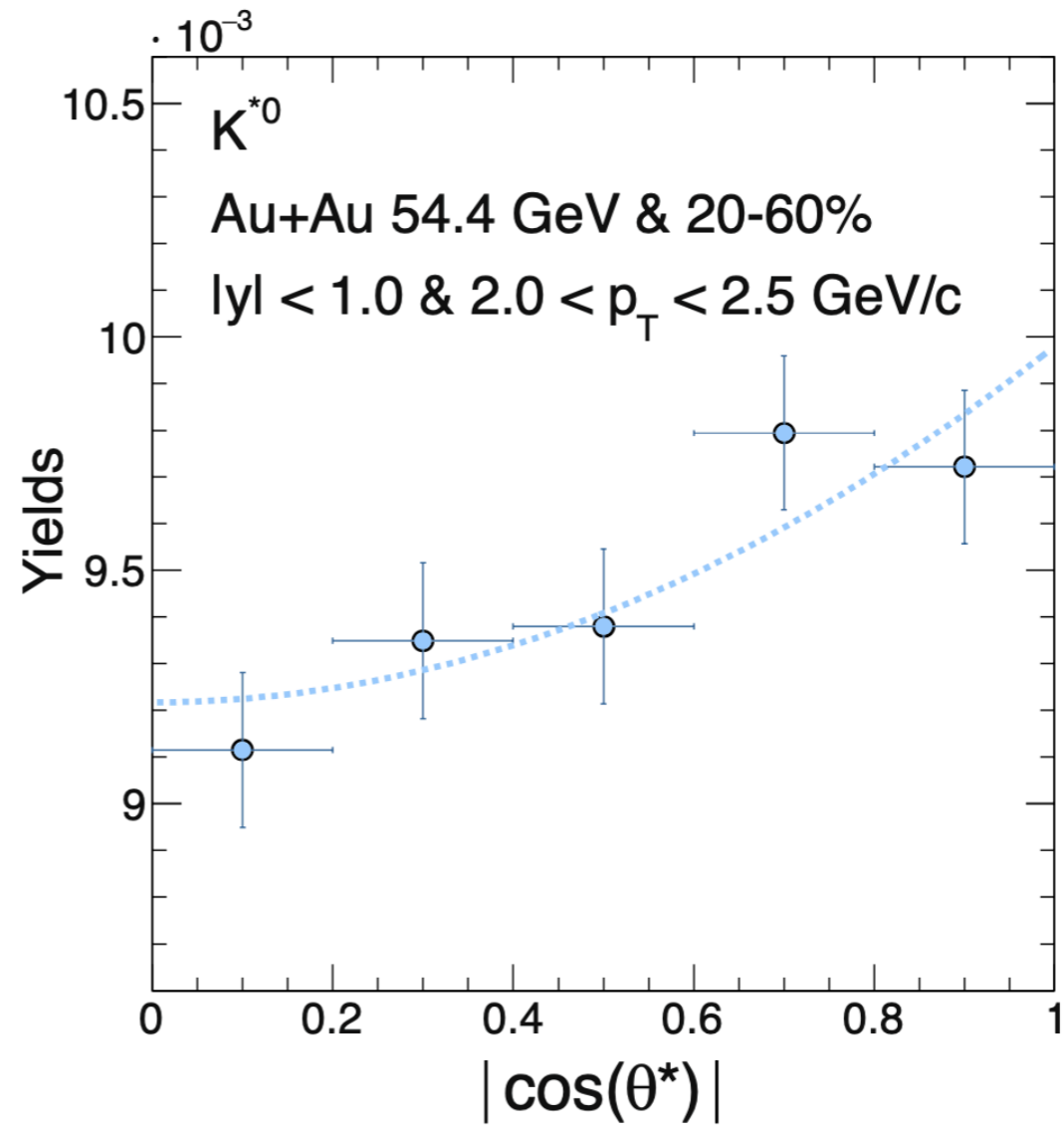
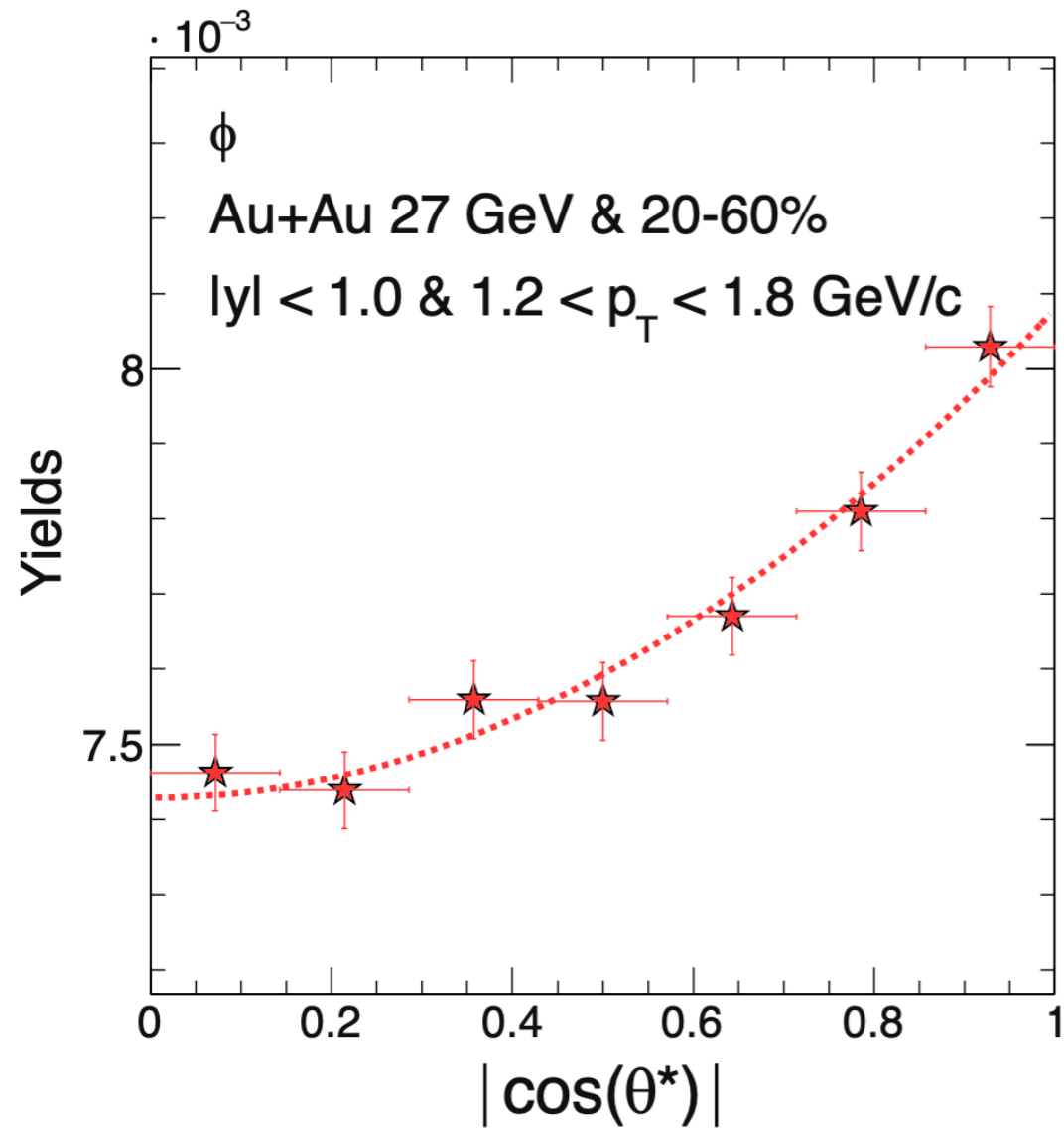
$$K^{*0} \rightarrow K^+ + \pi^-$$



Invariant mass is reconstructed using mixed event and track-rotation methods

Invariant mass signal obtained in $\cos \theta^*$ bins

Corrected yield vs. $\cos \theta^*$



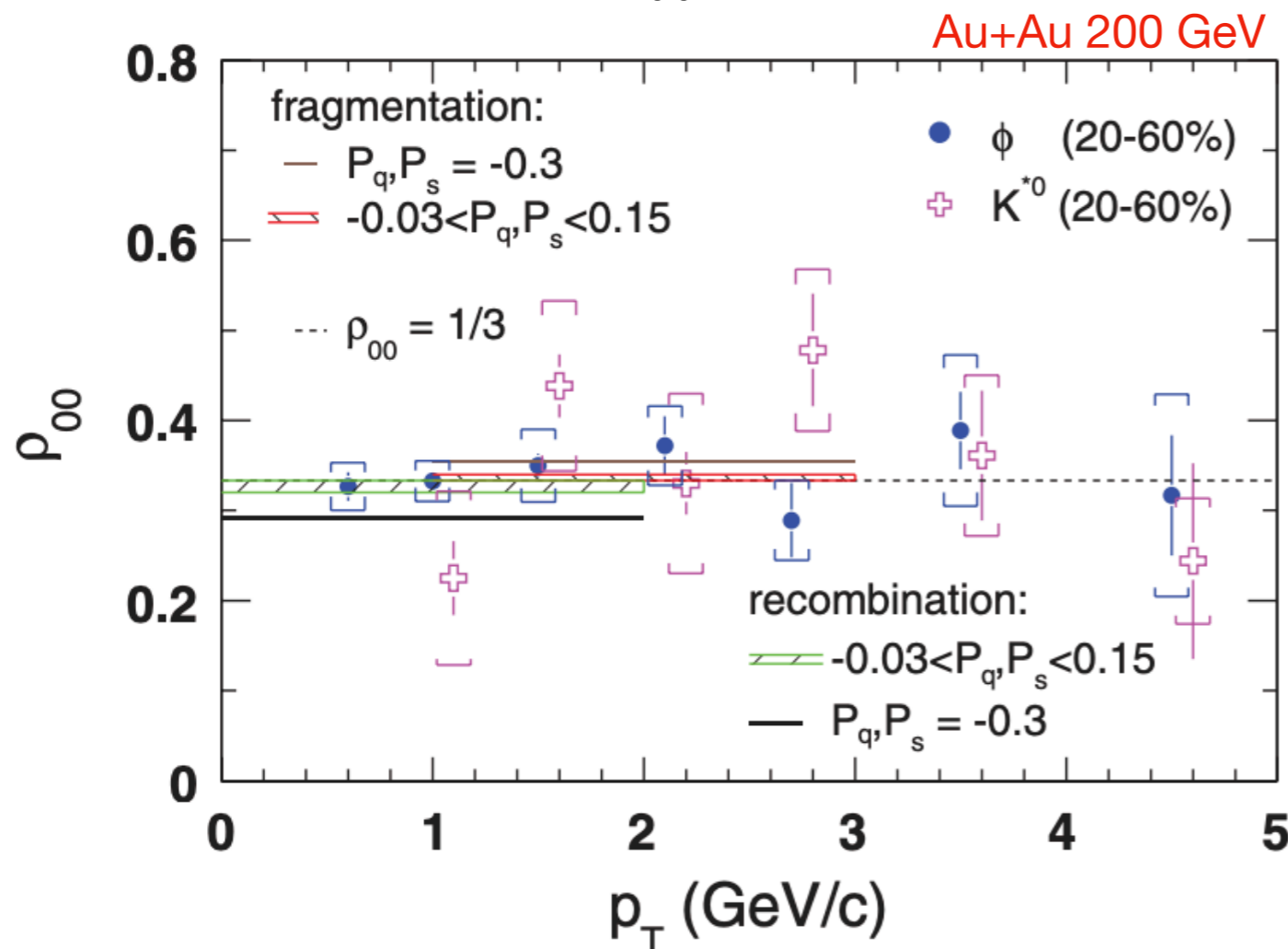
Yields in $\cos \theta^*$ bins are fitted with

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

Apply event plane resolution correction: $\rho_{00} - \frac{1}{3} = \left(\rho_{00,\text{obs}} - \frac{1}{3} \right) \frac{4}{1 + 3R}$

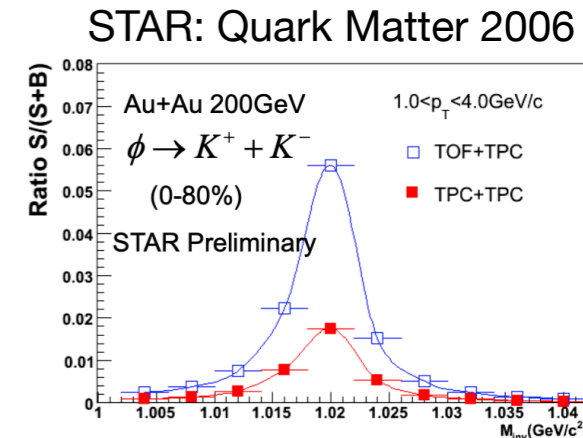
First spin alignment from RHIC

- STAR reported first ρ_{00} of ϕ and K^* wrt reaction plane in 2008 using ~ 23 million events:



- For both ϕ and K^* :
- results were **in-conclusive**, dominated by large uncertainty

STAR: Phys. Rev. C 77, 061902 (2008)



Advantages in measurements from BES

- STAR upgrade: Benefitted from Time of Flight (ToF), better particle identification, improved signal-to-noise ratio
- Analysis method: Improved understanding of detector corrections (efficiency, acceptance and event plane resolutions)

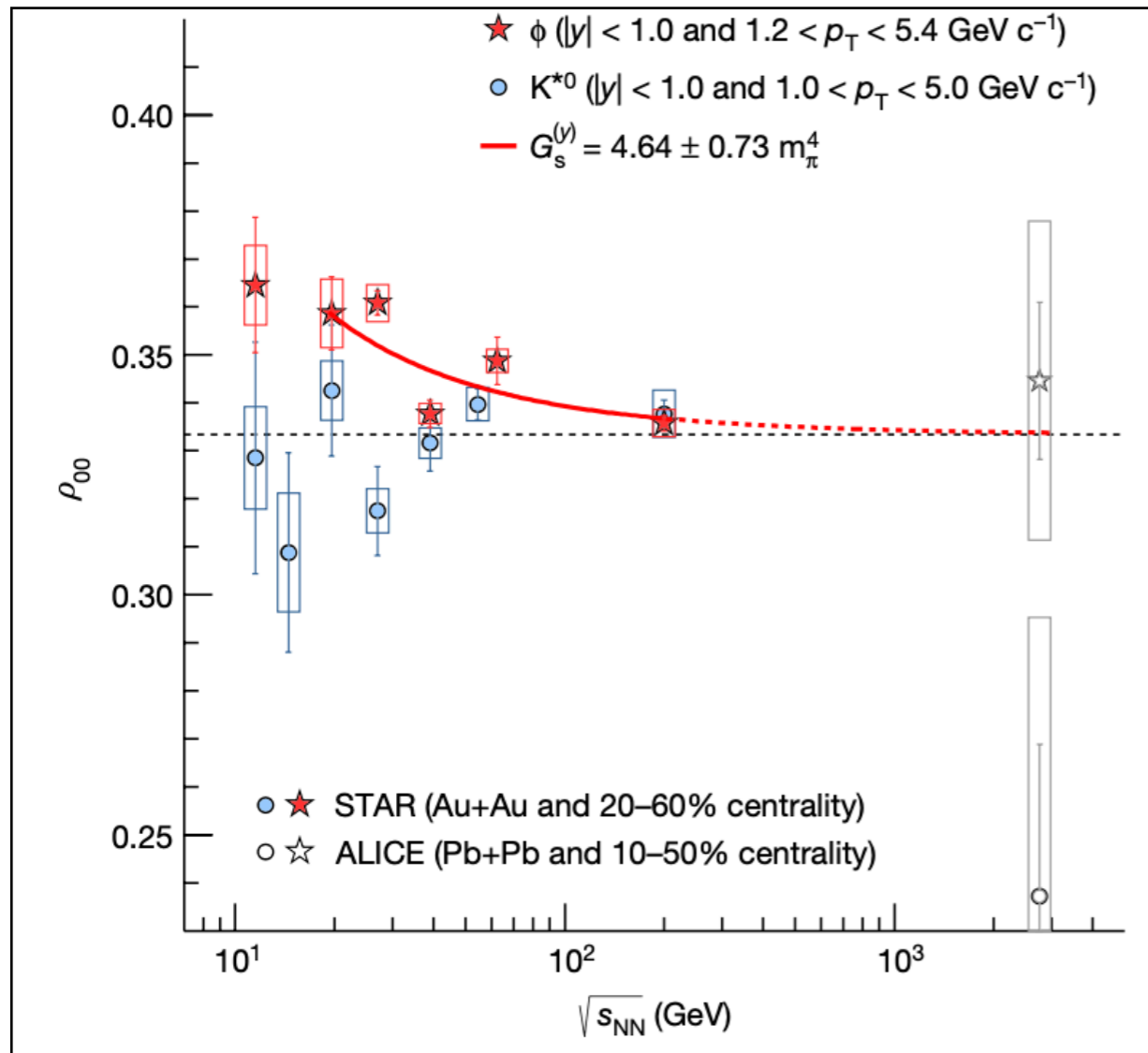
Spin alignment from RHIC BES

Article | Published: 18 January 2023

Pattern of global spin alignment of ϕ and K^{*0} mesons in heavy-ion collisions

STAR Collaboration

Nature 614, 244–248 (2023) | Cite this article



For 20-60%:

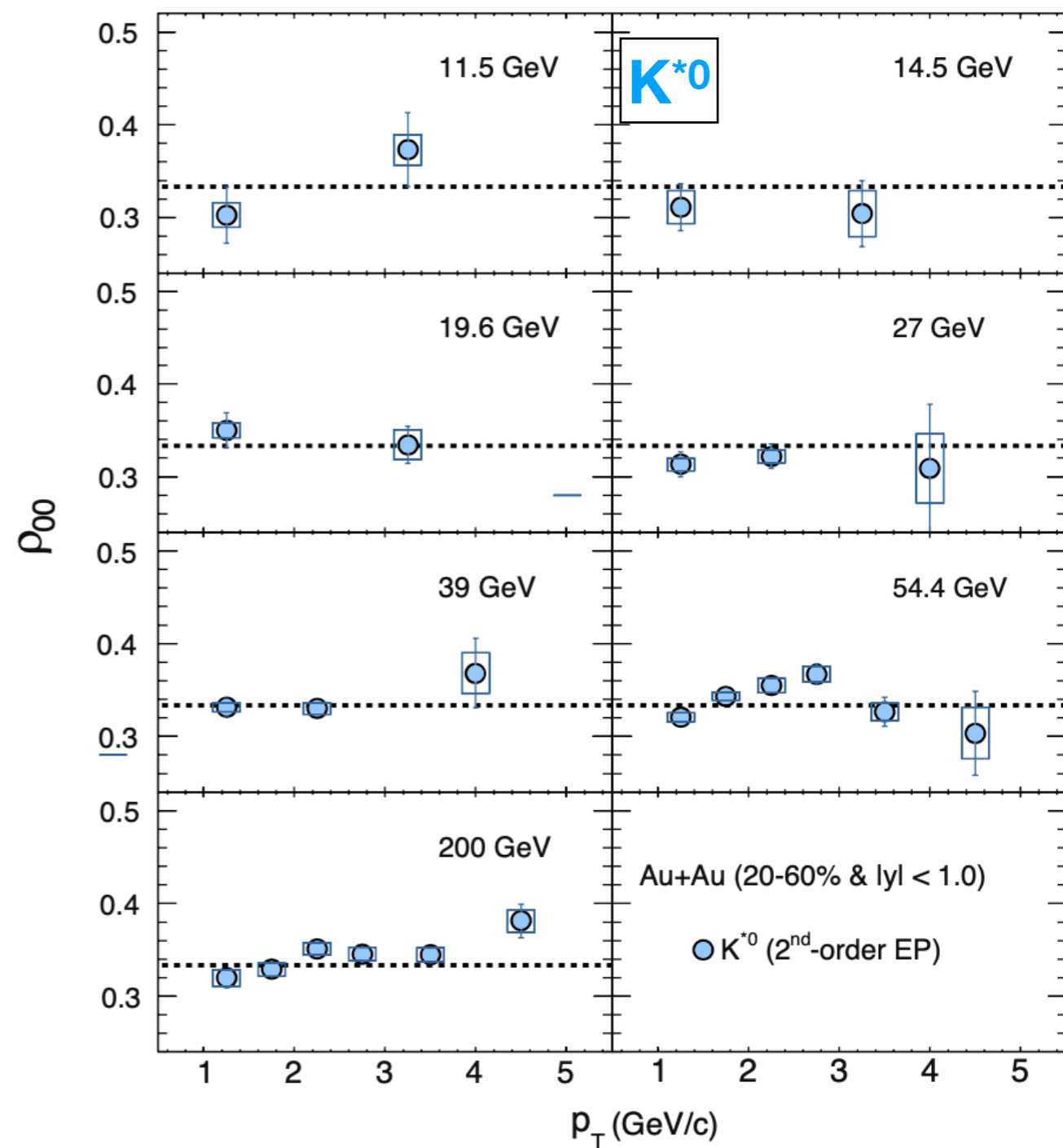
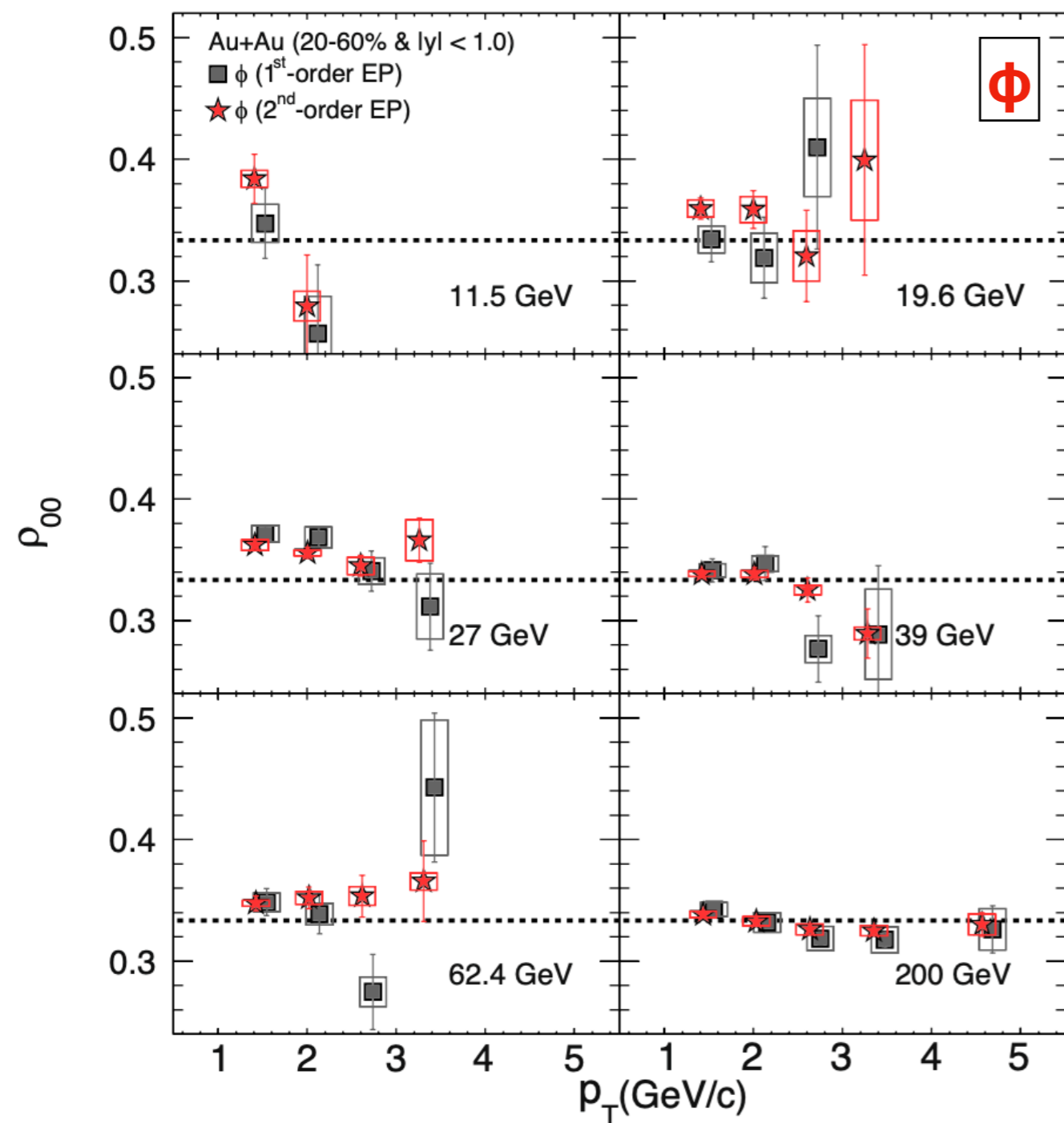
- For $\sqrt{s_{NN}} \leq 62.4$ GeV:

- ϕ $\rho_{00} = 0.3512 \pm 0.0017$ (stat.) ± 0.0017 (sys.)
 $\rho_{00} > 1/3$ with 7.4σ

- For $\sqrt{s_{NN}} \leq 54.4$ GeV:

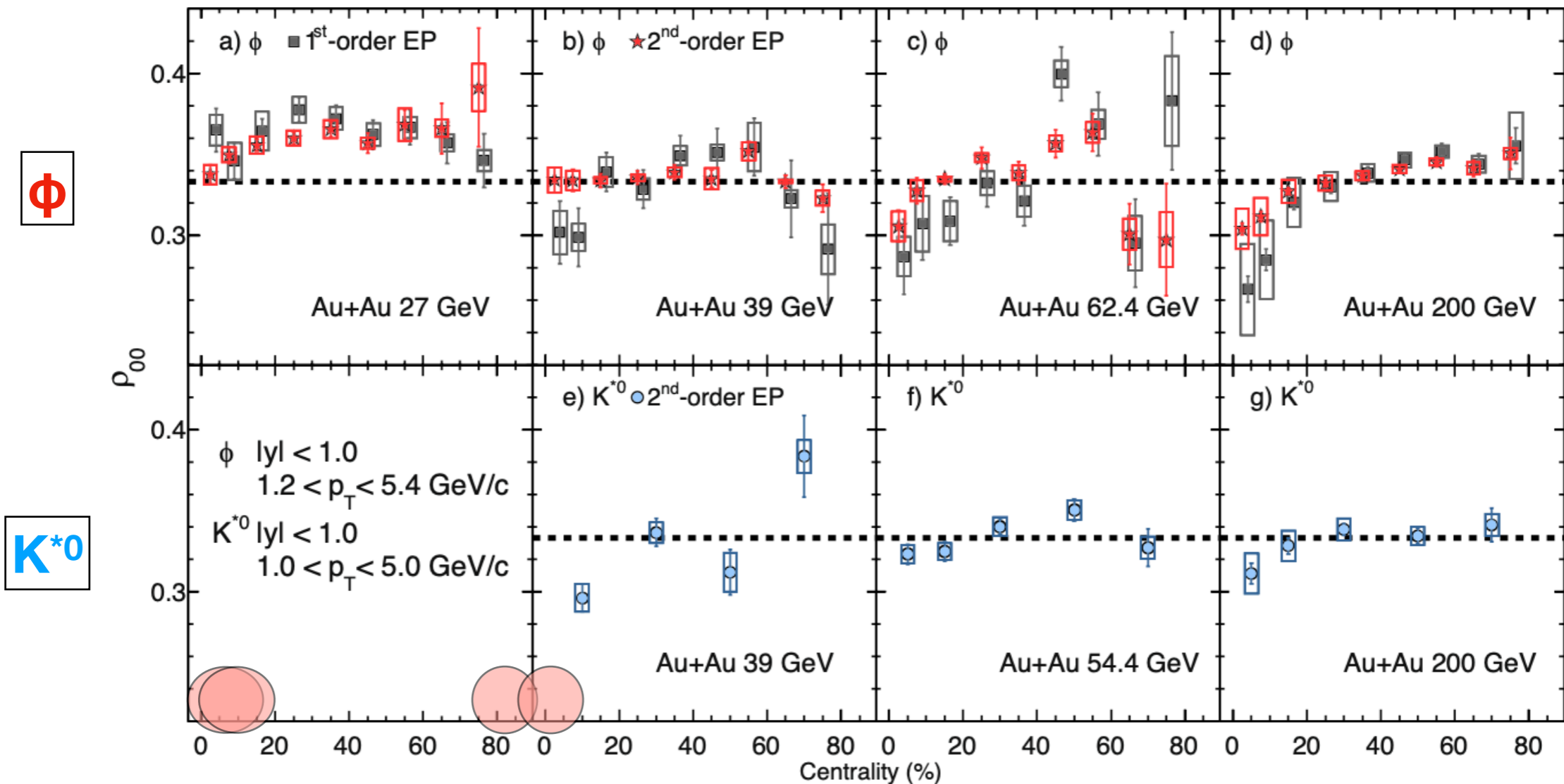
- K^{*0} $\rho_{00} = 0.3356 \pm 0.0034$ (stat.) ± 0.0043 (sys.)
 $\rho_{00} \sim 1/3$

Transverse momentum dependence of ρ_{00}



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

Centrality dependence of ρ_{00}



• For mid-central and peripheral:

● $\phi, K^{*0} \rho_{00} > \sim 1/3$

• For central at 200 GeV:

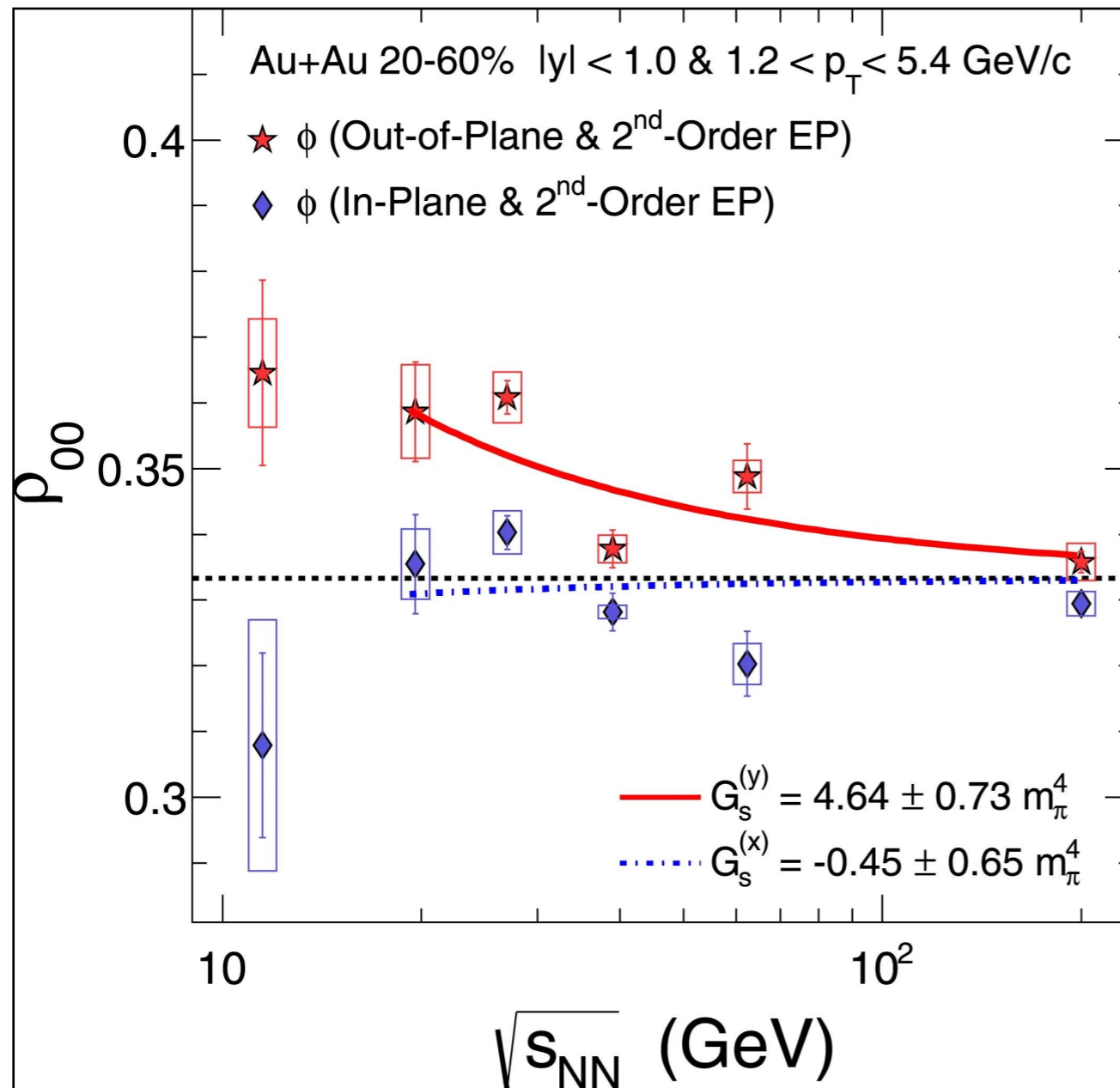
● $\phi, K^{*0} \rho_{00} < 1/3$

Local spin alignment^[1]

or, helicity contribution^[2]

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

ϕ meson ρ_{00} : in-plane vs out-plane



- For mid-central:
- ϕ ρ_{00} : in-plane < out-of-plane
- Effect from elliptic flow

Expectation of spin alignment

Physics Mechanisms	$\langle \rho_{00} \rangle$
c_Λ : Quark coalescence vorticity & magnetic field ^[1]	$< 1/3$ (Negative $\sim 10^{-5}$)
c_ϵ : Vorticity tensor ^[1]	$< 1/3$ (Negative $\sim 10^{-4}$)
c_E : Electric field ^[2]	$> 1/3$ (Positive $\sim 10^{-5}$)
c_F : Fragmentation ^[3]	$> \text{or}, < 1/3$ ($\sim 10^{-5}$)
c_L : Local spin alignment and helicity ^[4]	$< 1/3$
c_T : Turbulent color field ^[5]	$< 1/3$
c_ϕ : Vector meson strong force field ^[6]	$> 1/3$ (Can accommodate large positive signal)

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

- [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 spin alignment

Physics Mechanisms	$\langle \rho_{00} \rangle$
c_Λ : Quark coalescence vorticity & magnetic field ^[1]	$< 1/3$ (Negative $\sim 10^{-5}$)
c_ε : Vorticity tensor ^[1]	$< 1/3$ (Negative $\sim 10^{-4}$)
c_E : Electric field ^[2]	$> 1/3$ (Positive $\sim 10^{-5}$)
c_F : Fragmentation ^[3]	$> \text{or}, < 1/3$ ($\sim 10^{-5}$)
c_L : Local spin alignment and helicity ^[4]	$< 1/3$
c_T : Turbulent color field ^[5]	$< 1/3$
c_ϕ : Vector meson strong force field ^[6]	$> 1/3$ (Can accommodate large positive signal)

Conventional mechanisms that can capture global spin polarization of Λ and its energy dependence can not accommodate large deviations observed in ρ_{00}

$$c_\Lambda = \frac{4}{9} \langle P_\Lambda P_{\bar{\Lambda}} \rangle = -\frac{1}{9} \langle \omega_y^2 \rangle + \frac{Q_s^2}{9m_s^2 T_{\text{eff}}^2} \langle B_y^2 \rangle$$

(Contribution from vorticity and magnetic field are constrained by Λ polarization)

Expectation of spin alignment

Physics Mechanisms	(ρ_{00})
\mathbf{c}_Λ : Quark coalescence vorticity & magnetic field ^[1]	$< 1/3$ (Negative $\sim 10^{-5}$)
\mathbf{c}_ε : Vorticity tensor ^[1]	$< 1/3$ (Negative $\sim 10^{-4}$)
\mathbf{c}_E : Electric field ^[2]	$> 1/3$ (Positive $\sim 10^{-5}$)
\mathbf{c}_F : Fragmentation ^[3]	$> \text{or}, < 1/3$ ($\sim 10^{-5}$)
\mathbf{c}_L : Local spin alignment and helicity ^[4]	$< 1/3$
\mathbf{c}_T : Turbulent color field ^[5]	$< 1/3$
\mathbf{c}_ϕ : Vector meson strong force field ^[6]	$> 1/3$ (Can accommodate large positive signal)

$$\rho_{00}^\phi = \frac{1}{3} - \frac{4}{9} \langle P_\Lambda P_{\bar{\Lambda}} \rangle + \frac{1}{27m_s^2} \langle p^2 \rangle_\phi \langle \epsilon_x^2 + \epsilon_z^2 \rangle$$

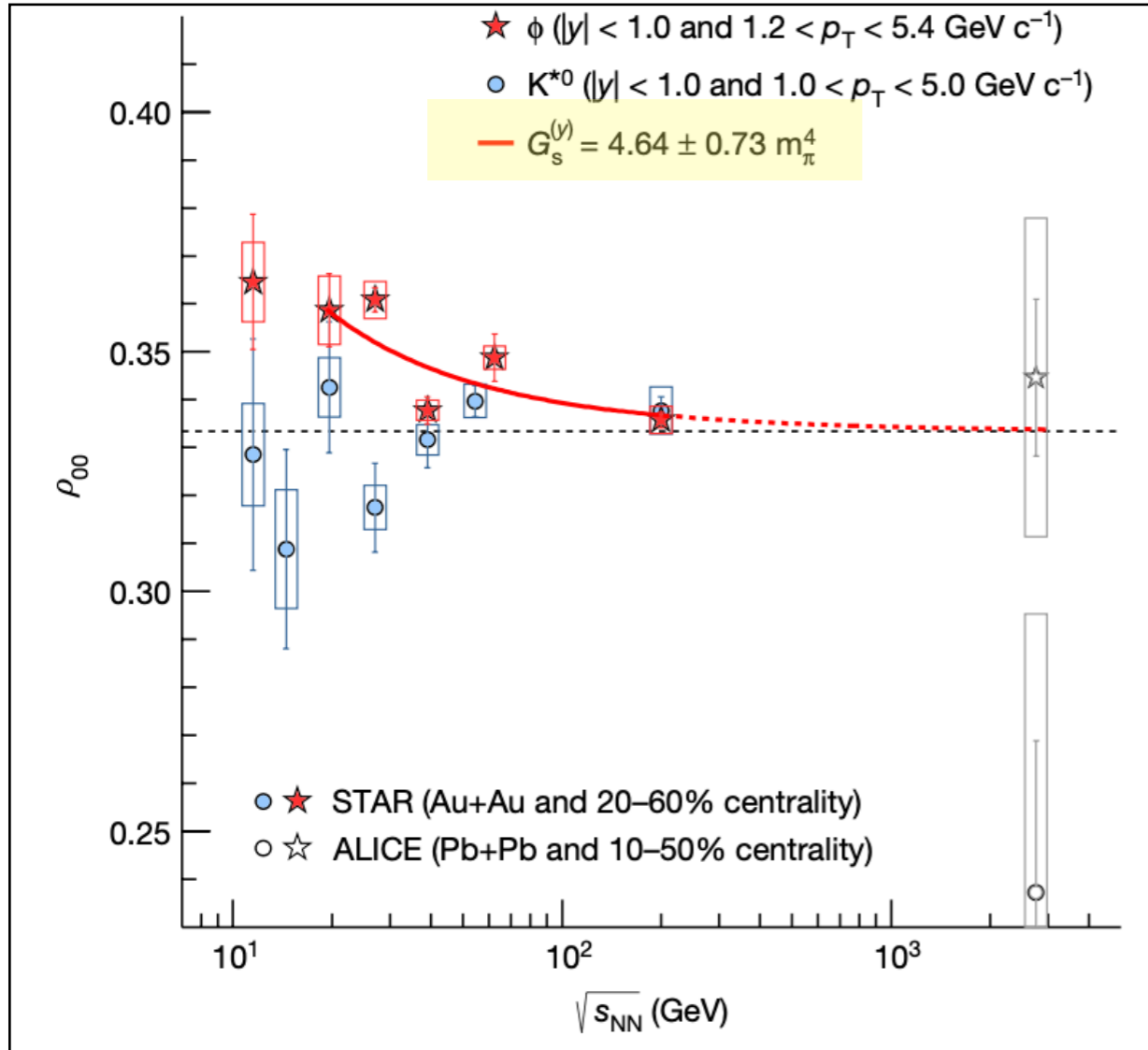
Expectation of spin alignment

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

- 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 ϕ -meson field can polarize s and \bar{s} quarks with a large magnitude due to strong interaction (large coupling constant g_ϕ)

$$\rho_{00}^\phi = \frac{1}{3} - \frac{4}{9} \langle P_\Lambda P_{\bar{\Lambda}} \rangle + \frac{1}{27m_s^2} \langle p^2 \rangle_\phi \langle \epsilon_x^2 + \epsilon_z^2 \rangle - \frac{g_\phi^4}{27m_s^4 m_\phi^4 T_{\text{eff}}} \langle E_{\phi,z}^2 + E_{\phi,x}^2 \rangle$$

Energy dependence of spin alignment



A model with vector meson strong force field can accommodate the large positive signal of ϕ meson ρ_{00}

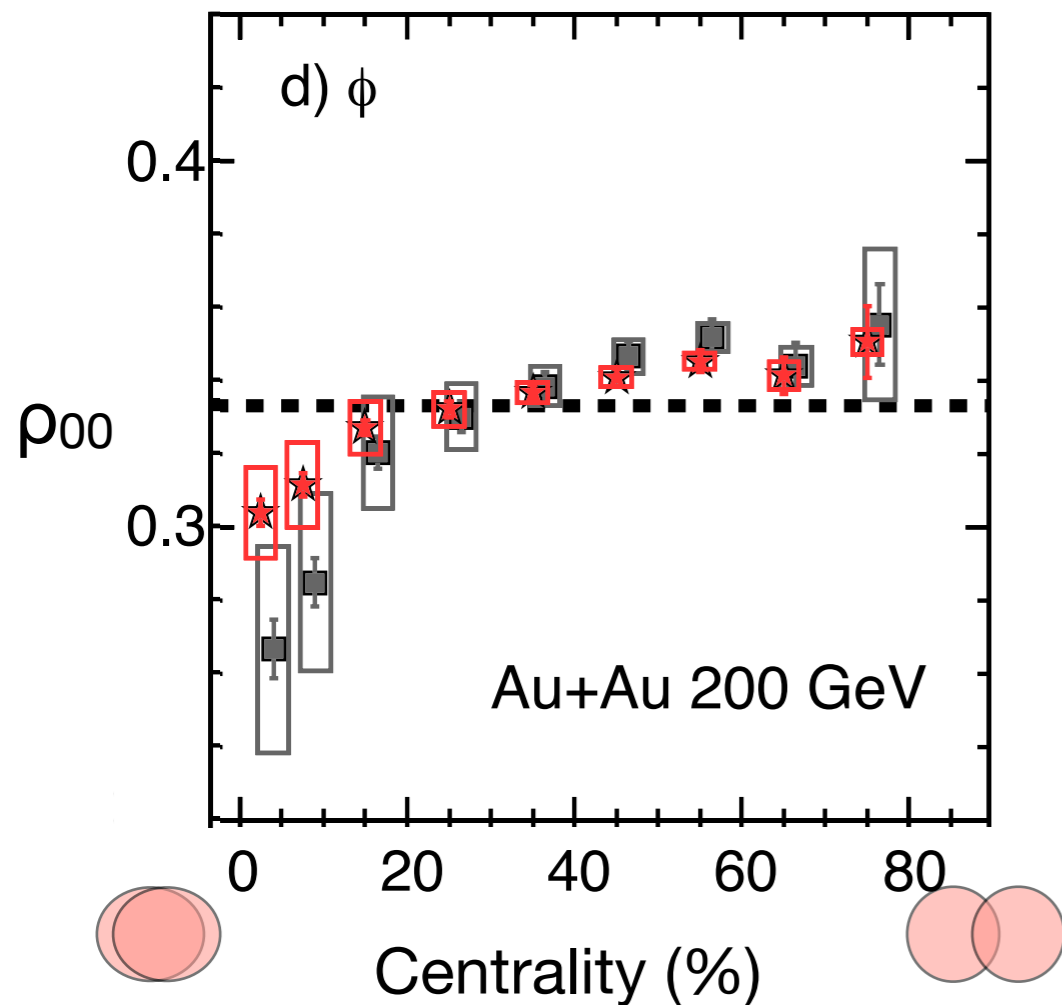
$$\rho_{00}(\phi) \approx \frac{1}{3} + c_\Lambda + c_\epsilon + c_E + c_\phi;$$

$$c_\phi = \frac{G_s^y}{27m_s^2 T_{\text{eff}}^2}$$

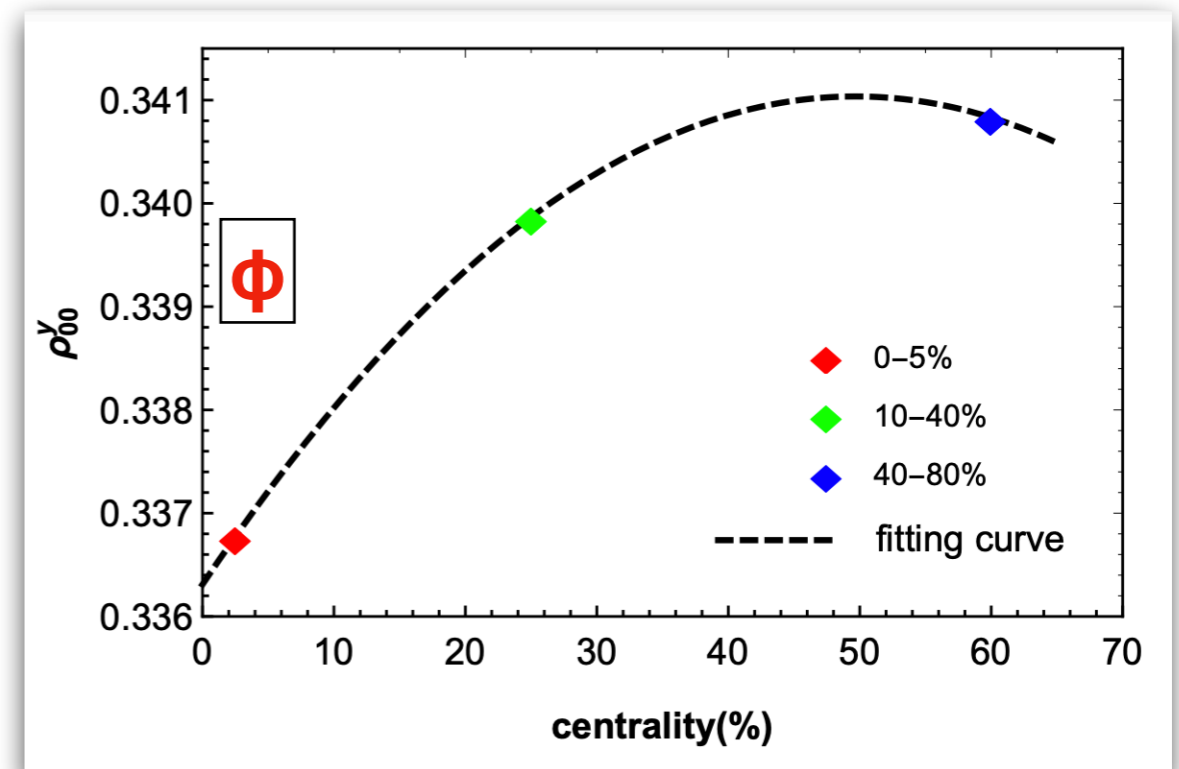
$$G_s^y = g_\phi^2 \left[3 \langle B_{\phi,y}^2 \rangle - \frac{\langle P^2 \rangle_\phi}{m_s^2} \langle E_{\phi,z}^2 + E_{\phi,x}^2 \rangle \right]$$

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

Centrality dependence of ϕ ρ_{00}



Expectation from model with vector meson field



Can accommodate positive deviation in mid-central and peripheral collisions

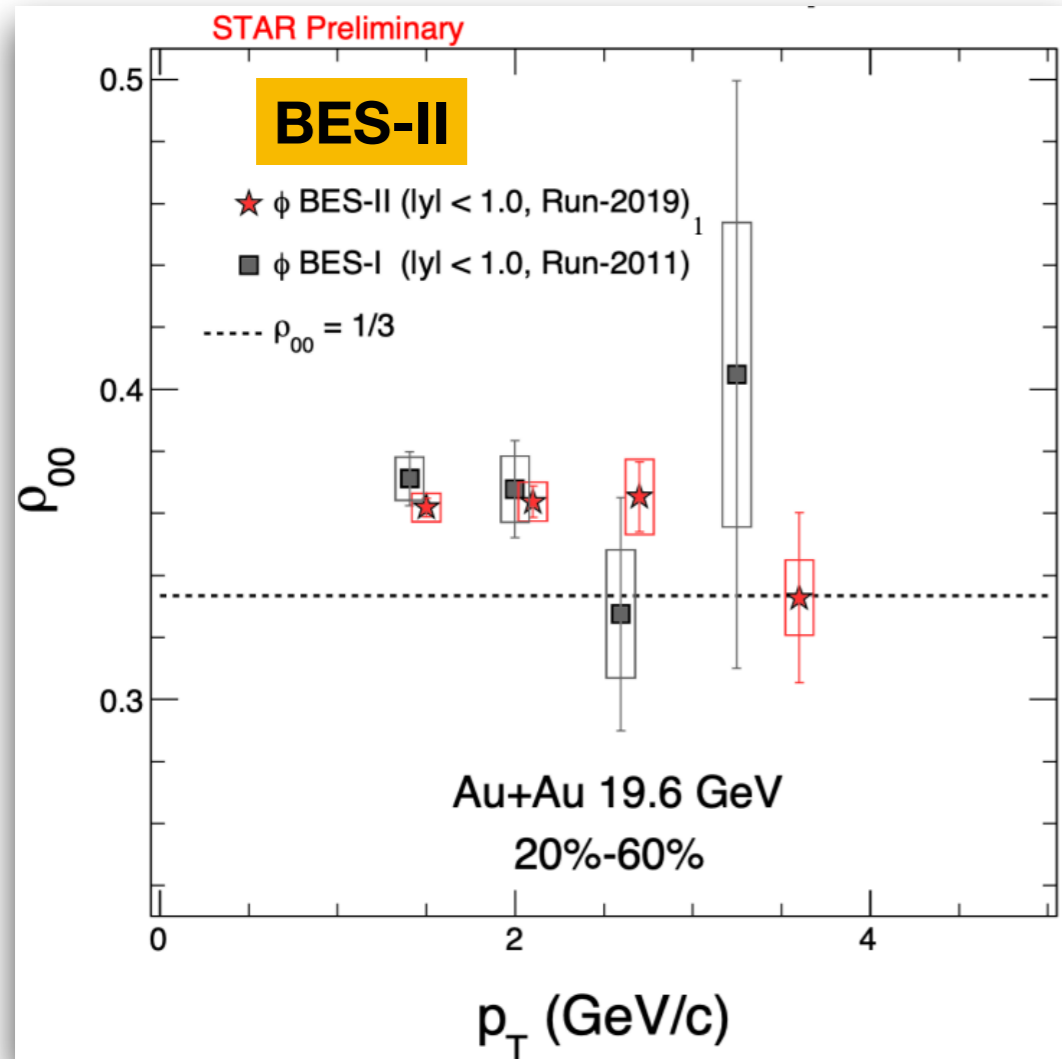
Is the contribution from local spin alignment dominant in central collisions and at higher energies?

Sheng et. al., arXiv: 2205.15689
 Sheng et. al., Phys Rev D 101, 096005 (2020)
 Sheng et. al., Phys Rev D 102, 056013 (2020)

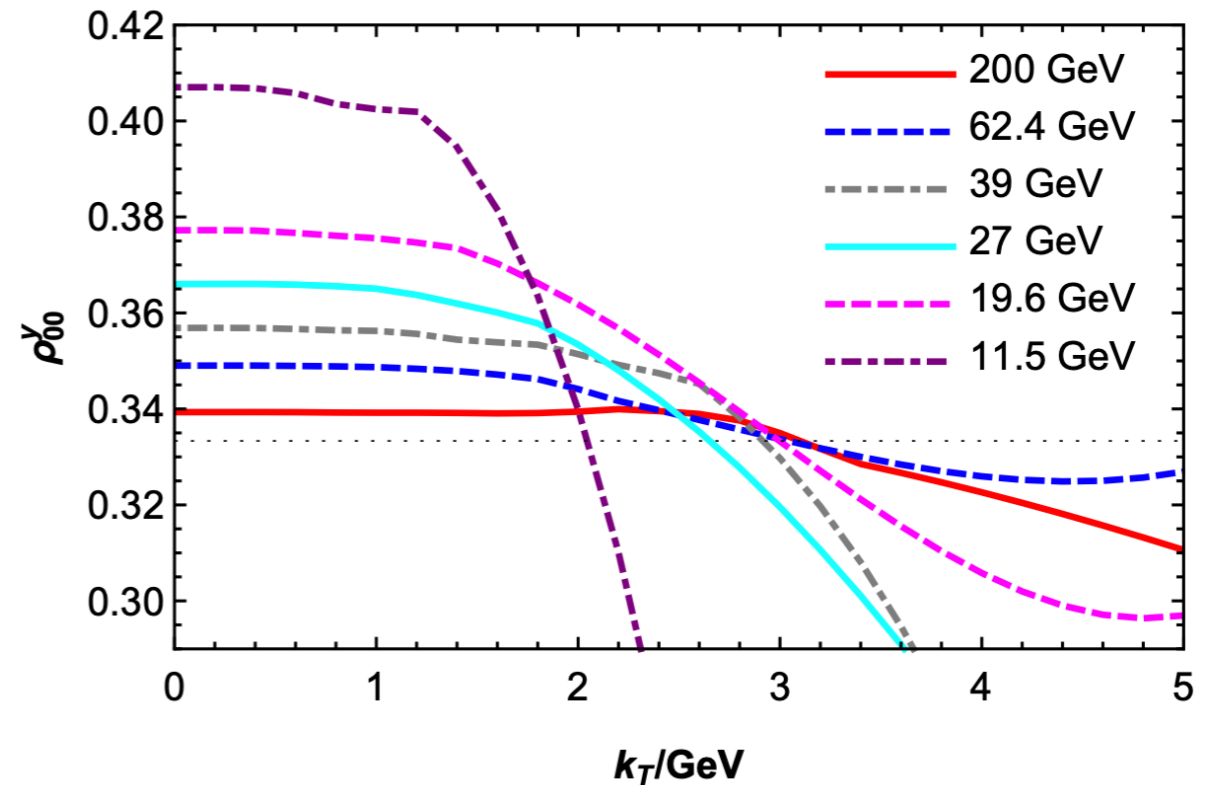
Xia et., al., Phys Lett B 817, 136325 (2021)

Transverse momentum dependence of ϕ ρ_{00}

STAR: Strange Quark Matter 2022



Expectation from model with vector meson field



Sheng et. al., arXiv: 2205.15689

Sheng et. al., Phys Rev D 101, 096005 (2020)

Sheng et. al., Phys Rev D 102, 056013 (2020)

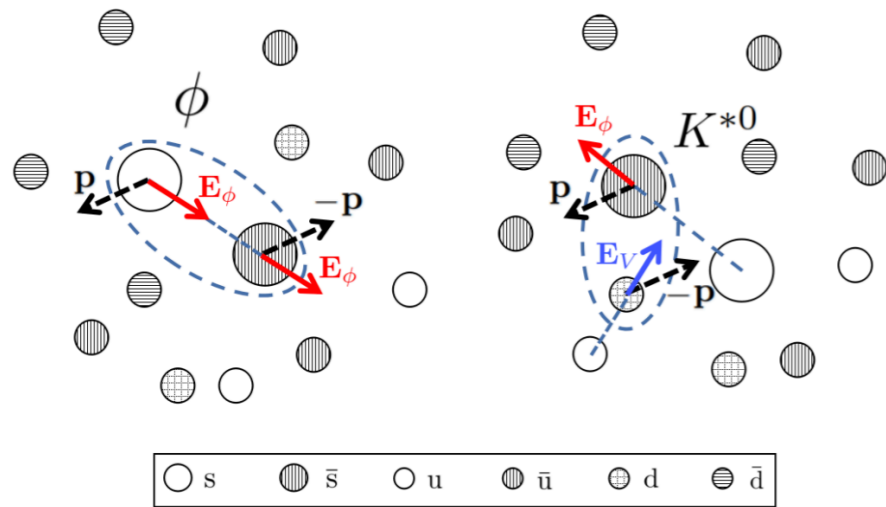
Precision from BES-II:

- $\rho_{00} > \frac{1}{3}$ (about $\sim 5\sigma$ significance)

About $K^* \rho_{00}$

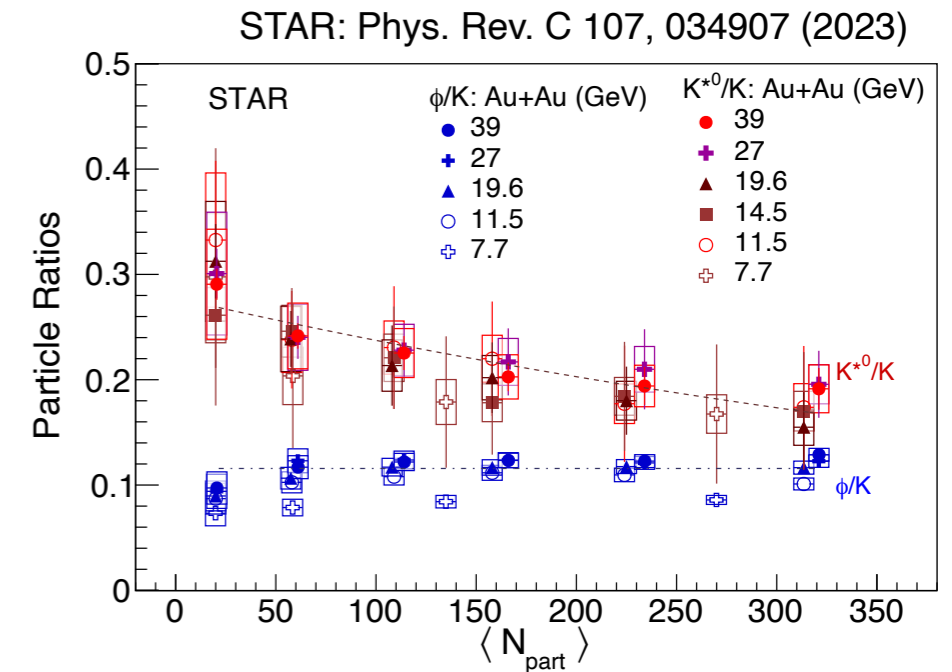
Species	Quarks	J^P	Decay	Lifetime (fm/c)
K^{*0}	ds	1-	$K\pi$	4
ϕ	ss	1-	KK	45

Expectation from model with vector meson field



We note that the above arguments are only valid for primary K^{*0} . The life time of K^{*0} is much shorter and the interaction of K^{*0} with the surrounding matter is much stronger than the ϕ meson. This may bring other contributions to $\rho_{00}^{K^*}$ from the interaction of K^{*0} with medium. A caveat is that the above arguments are based on the approximation that different fields do not have large correlation in space as compared with the correlation between the same fields. This seems to work for ρ_{00}^ϕ since there are squares of the same vector meson field. However it is not the case for $\rho_{00}^{K^*}$ that all terms of vector meson fields are mixture of different fields which are thought to be equally small. In this case, in order to justify the approximation, we may need to evaluate these terms and compare their magnitudes with the negative contribution from vorticity tensor fields. This is beyond the scope of this paper and will be studied in the future.

Sheng et al., arXiv: 2205.15689
 Sheng et al., Phys Rev D 101, 096005 (2020)
 Sheng et al., Phys Rev D 102, 056013 (2020)



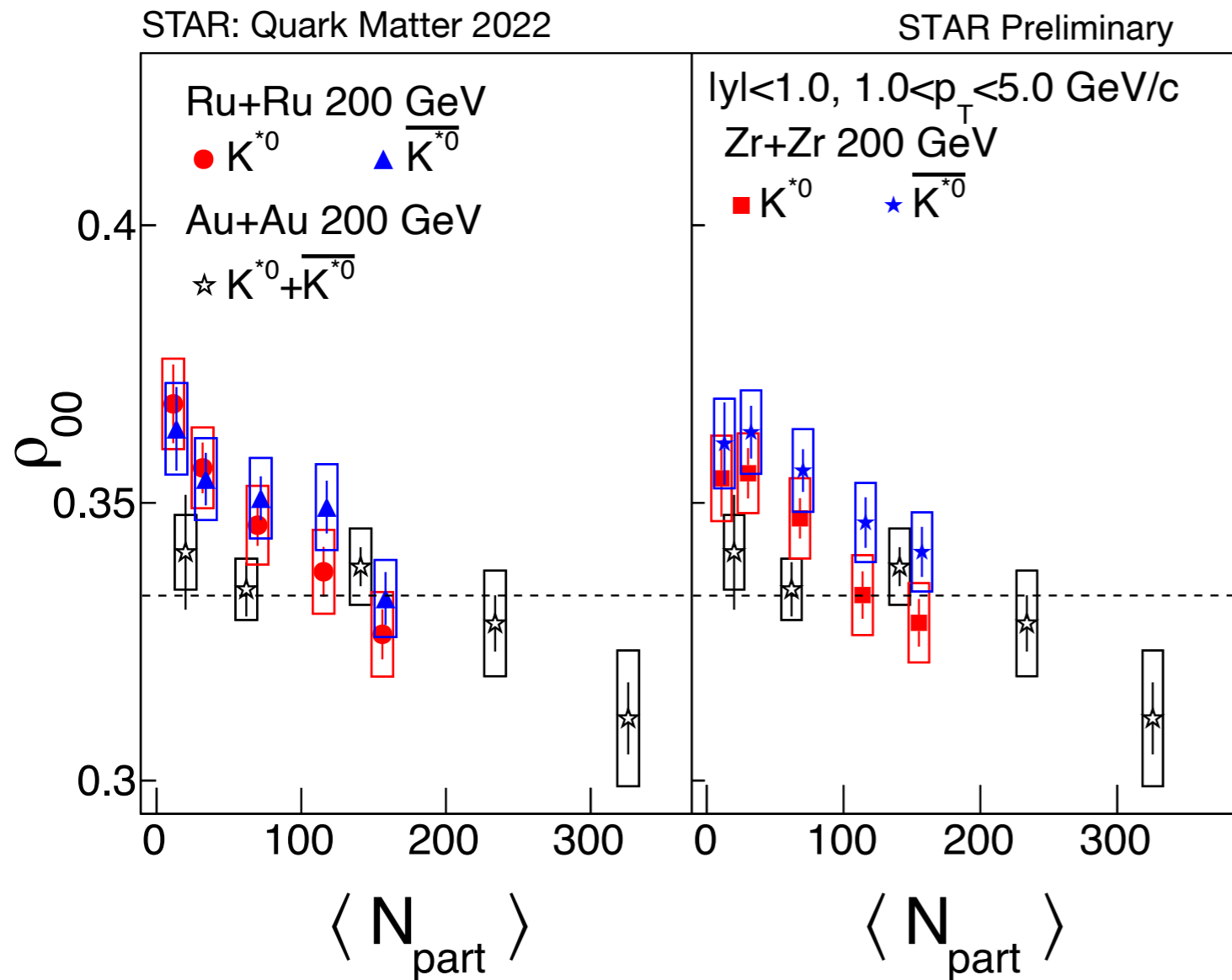
- $(K^*/K)_{\text{central}} < (K^*/K)_{\text{peripheral}}$
- $(\phi/K) \sim$ centrality independent

Compared to ϕ :

- K^* have un-equal constituent quarks, have different response to vector meson field
- K^* shorter lifetime, more susceptible to in-medium interactions

Need more input for K^* from theory

$K^* \rho_{00}$ from isobar collisions



- Species dependence:
 - $K^{*0} \rho_{00} \sim \text{anti-}K^{*0} \rho_{00}$
- System size dependence:
 - $\rho_{00} : \text{Au+Au} \sim \text{Zr+Zr} \sim \text{Ru+Ru}$
 - $\rho_{00} \sim \text{scales with } \langle N_{\text{part}} \rangle$

Summary

- At RHIC BES:
- For the first time significantly **large ϕ meson $\rho_{00} > 1/3$** ($\sim 7.4\sigma$)
- **K^* meson $\rho_{00} \sim 1/3$**
- Surprising magnitude of ϕ ρ_{00} : defeated conventional mechanisms of polarization (e.g. driven by vorticity, EM fields ...)
- Many players:
 - Influence of vector meson strong force field (*Sheng et. al.*)
 - Effects from gluon and glasma field (*Muller et. al.*)
 - Contribution from local spin alignment, helicity (*Xia et. al., Gao*)
 - Shear induced tensor polarization (*Liu et. al.*)
 - ...

Outlook

Experiment side: High precision measurements from RHIC BES-II and other datasets; ρ_{00} of different vector meson species ($\rho, \omega, J/\Psi$) at RHIC are ongoing
Stay tuned

Article | Published: 18 January 2023

Pattern of global spin alignment of ϕ and K^{*0} mesons in heavy-ion collisions

[STAR Collaboration](#)

[Nature](#) 614, 244–248 (2023) | [Cite this article](#)

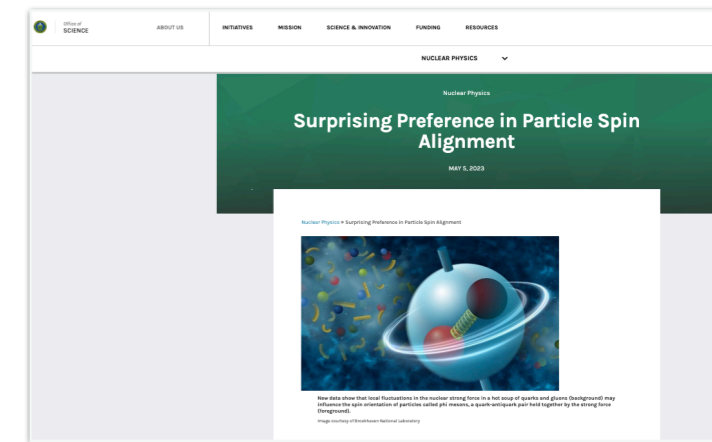
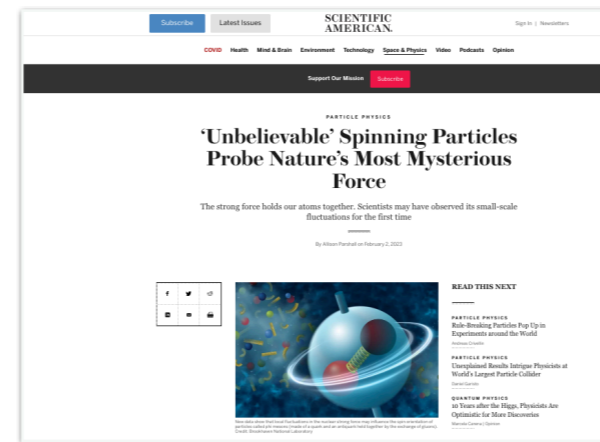
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Pattern of global spin alignment of ϕ and K^{*0} mesons in heavy-ion collisions #1

STAR Collaboration · M.S. Abdallah (American U., Cairo) et al. (Apr 5, 2022)

Published in: *Nature* 614 (2023) 7947, 244–248, *Nature* (2023) · e-Print: [2204.02302](#) [hep-ph]

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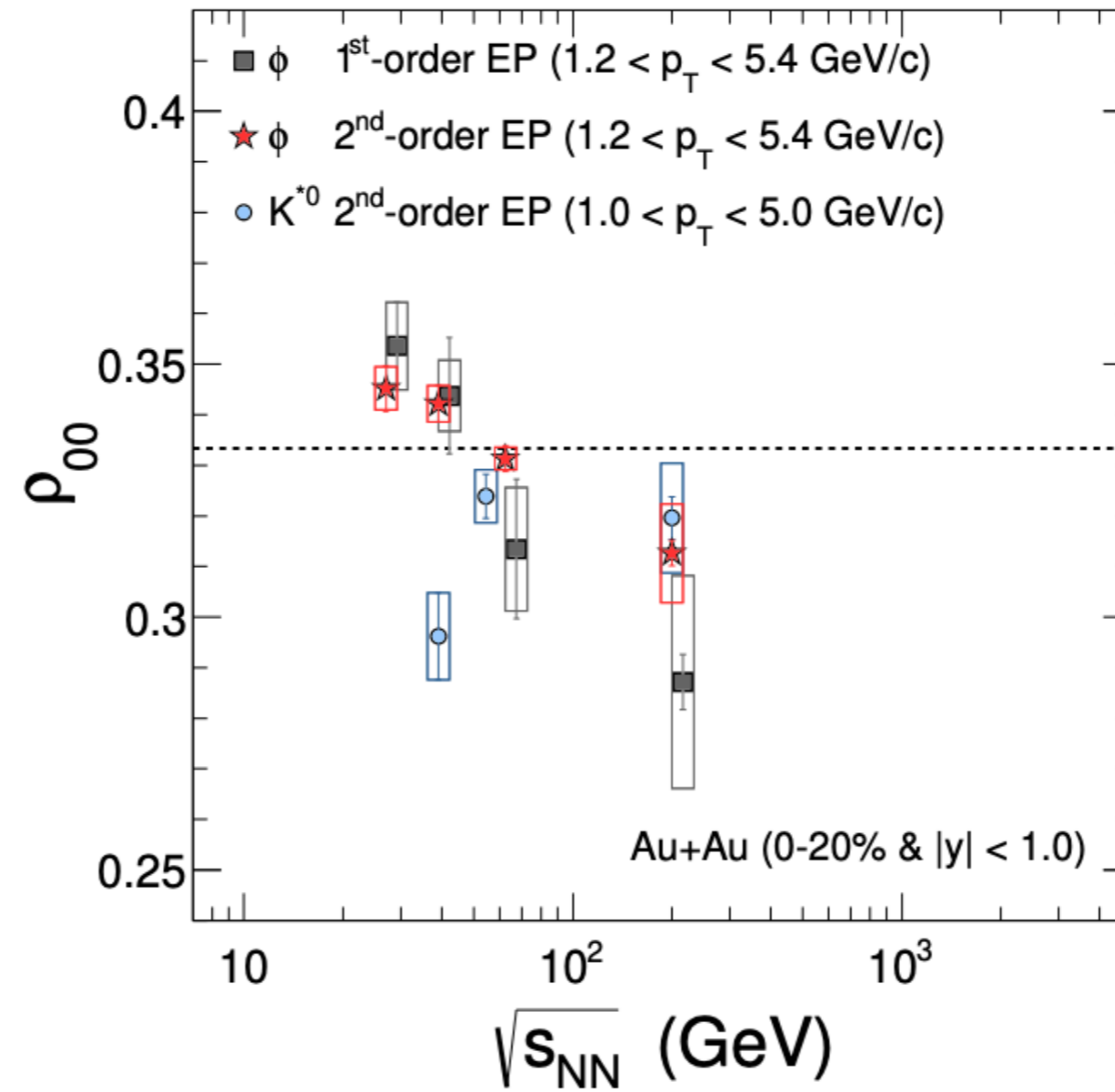
Thanks to: all the *STAR Collaboration* members

especially, Jin-Hui Chen (Fudan Univ.), Declan Keane (Kent State Univ.), Yu-Gang Ma (Fudan Univ.), **Xu Sun (IMPCAS, UIC)**, Aihong Tang (BNL) and **Chensheng Zhou (Fudan Univ.)**

Thank you for your attention

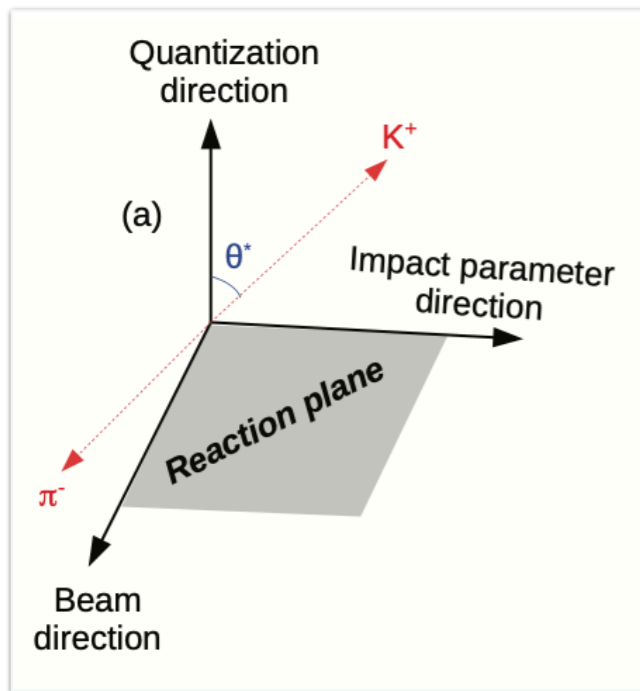
Back up slides

Energy dependence of ϕ and $K^* \rho_{00}$ in central collisions

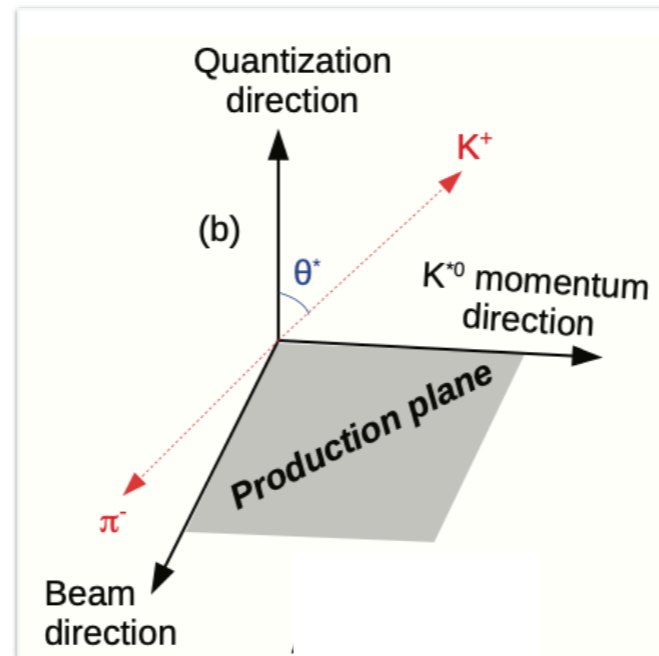


Quantization axis

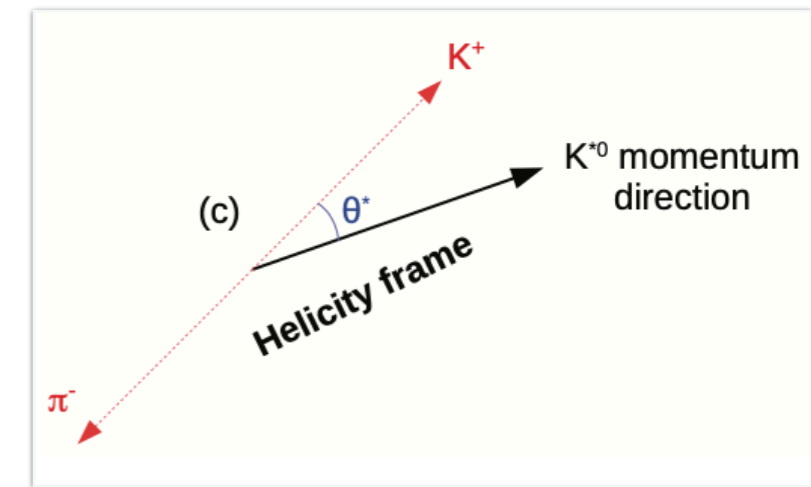
Choice of Quantization direction (or Polarization axis)



Reaction Plane



Production Plane



Helicity

Experimentally, we can't measure impact parameter direction. We use "**event plane**" as a proxy for reaction plane

Angular distribution of daughter

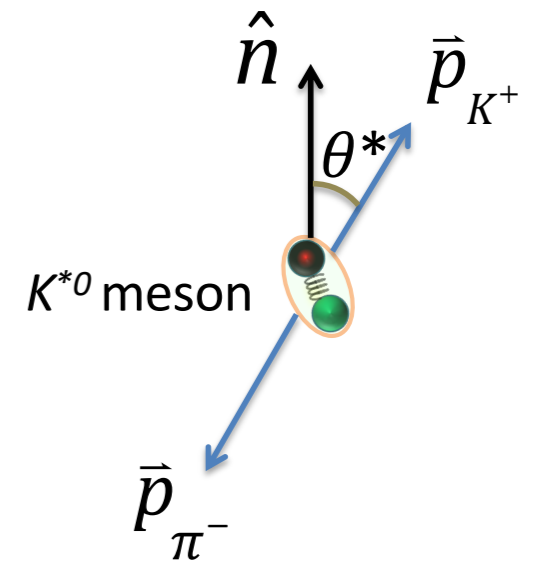
One can express, the angular distribution of vector meson's daughter:

$$\frac{dN}{d\cos\theta d\phi} = \langle \theta, \phi, \lambda_1, \lambda_2 | T\rho T^\dagger | \theta, \phi, \lambda_1, \lambda_2 \rangle$$

λ = Helicity

T = Transition Matrix

ρ = Spin density matrix



$$\frac{dN}{d\cos\theta d\phi} = |C|^2 \times \sum_{m_1, m_2} Y_{1, m_1}^*(\theta, \phi) Y_{1, m_2}(\theta, \phi) \rho_{m_1, m_2}$$

Expressed in terms of spherical harmonics

By integrating over ϕ ,

$$\frac{dN}{d\cos\theta} = |C|^2 \times \frac{3}{8\pi} (\sin^2\theta \rho_{-1-1} + 2\cos^2\theta \rho_{00} + \sin^2\theta \rho_{11}) \times 2\pi$$

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

Polarization wrt event plane

Reconstruct event plane (Ψ_n):

$$Q_{n,y} = \sum_i w_i \sin(n\phi_i); \quad Q_{n,x} = \sum_i w_i \cos(n\phi_i)$$

$$\Psi_n = \arctan2(Q_{n,y}, Q_{n,x})/n$$

Unit vectors in reaction plane and event plane are related by:

$$\hat{x} = \cos(\Psi) \hat{x}' - \sin(\Psi) \hat{y}'; \quad \hat{y} = \sin(\Psi) \hat{x}' + \cos(\Psi) \hat{y}'; \quad \hat{z} = \hat{z}'$$

.....

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

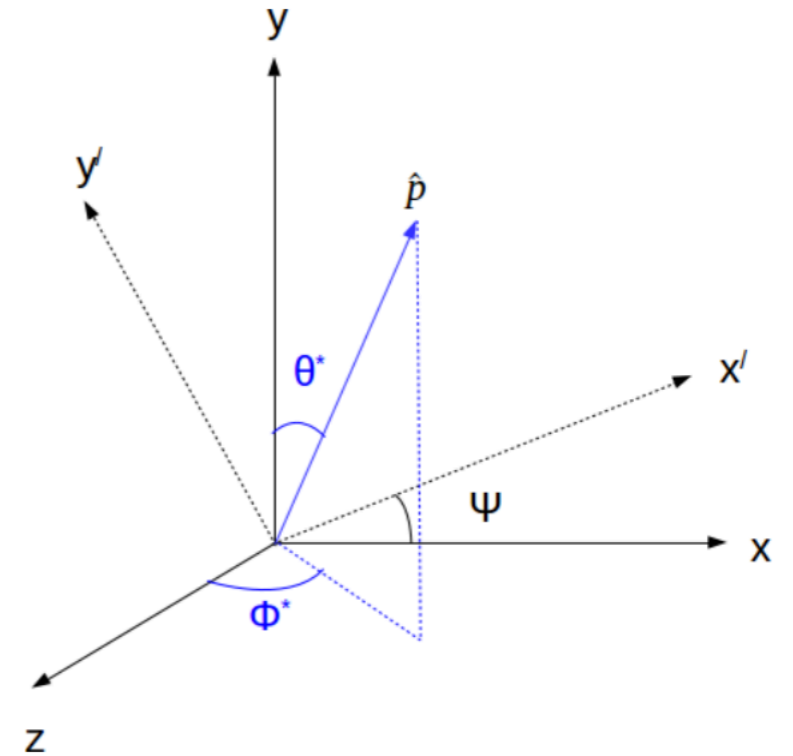
.....

$$\rho_{00}^{EP} = \rho_{00}^{RP} - \frac{1}{2}(3 \rho_{00}^{RP} - 1) \sin^2(\Psi)$$

Averaging over all events:

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

$R \rightarrow$ Event plane resolution

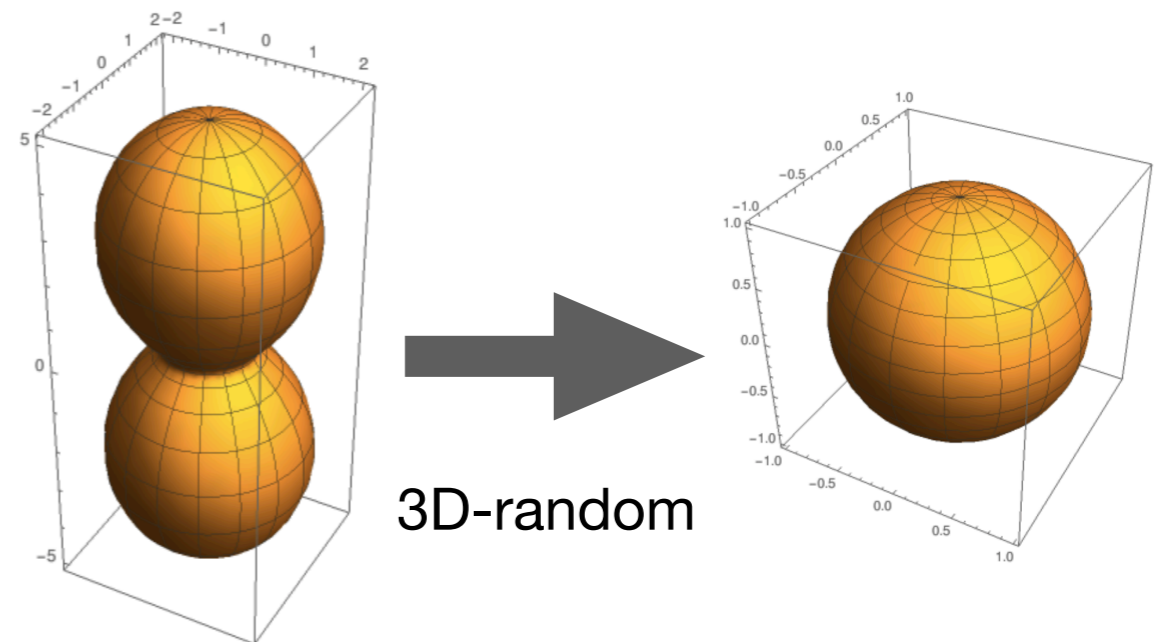
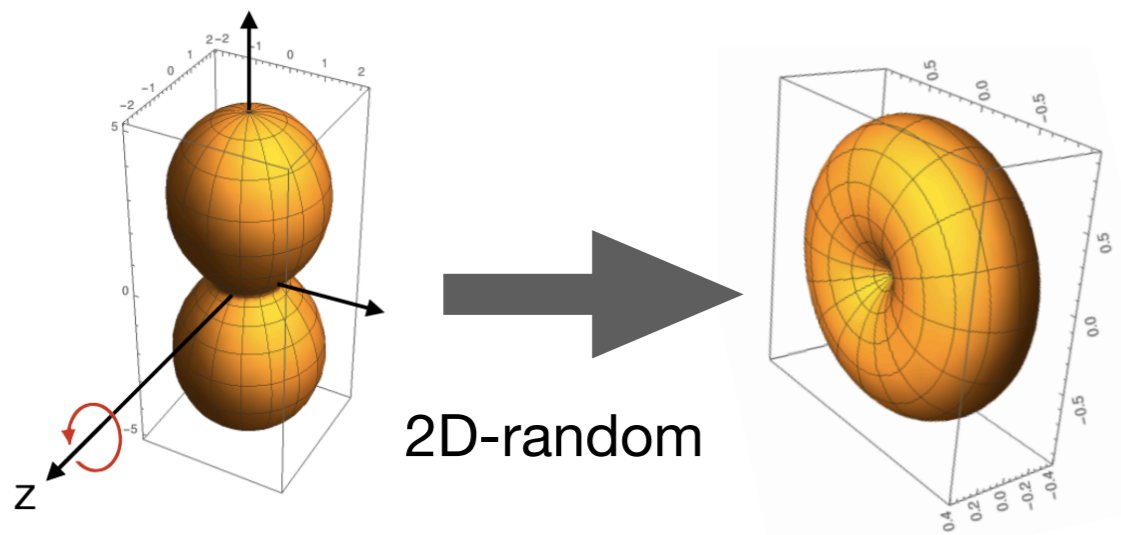


Tang et.al. Phys. Rev. C 98, 044907 (2018)
Mohanty et., al, Mod. Phys. Lett. A, 36, 2130026 (2021)

Polarization wrt random plane

ρ_{00} can be measured using a random plane; Naive expectation $\rho_{00}^{\text{random}} \sim \frac{1}{3}$
(e.g. using random number but depends on how it is randomized)

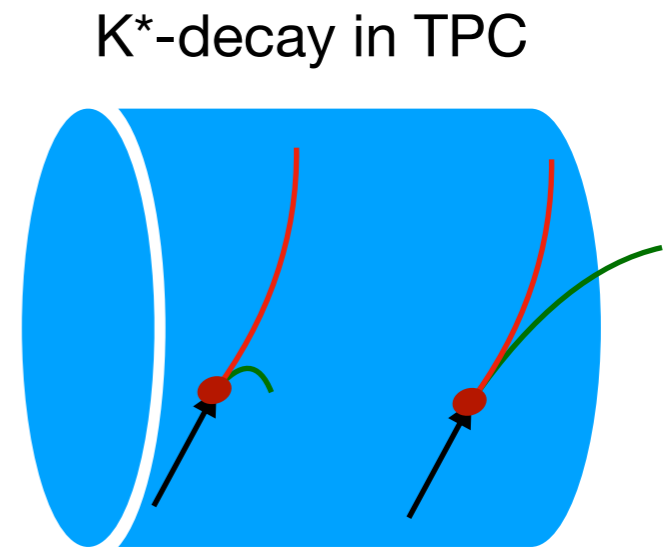
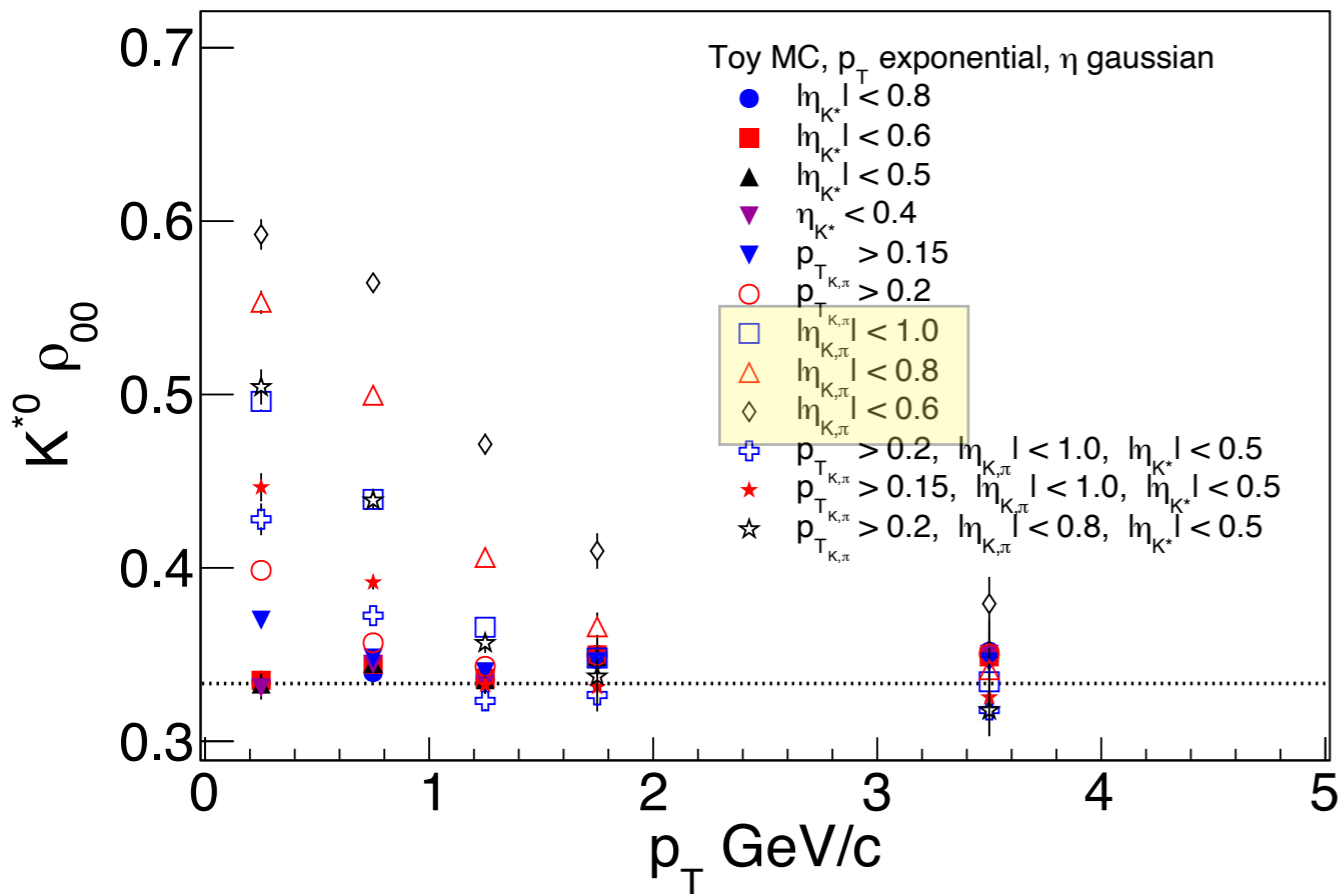
If the quantization axis is randomized in 2D-plane (x, y), it does not guarantee the ρ_{00} to be 1/3



So the quantization axis has to be randomized in 3D-plane (x, y, z), to get the ρ_{00} to be $\sim 1/3$

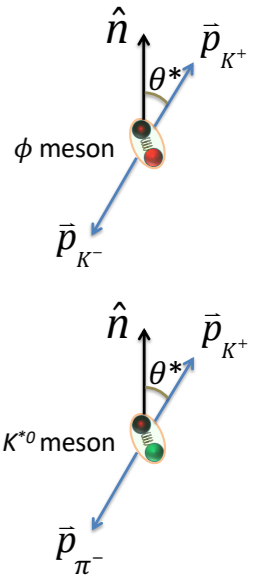
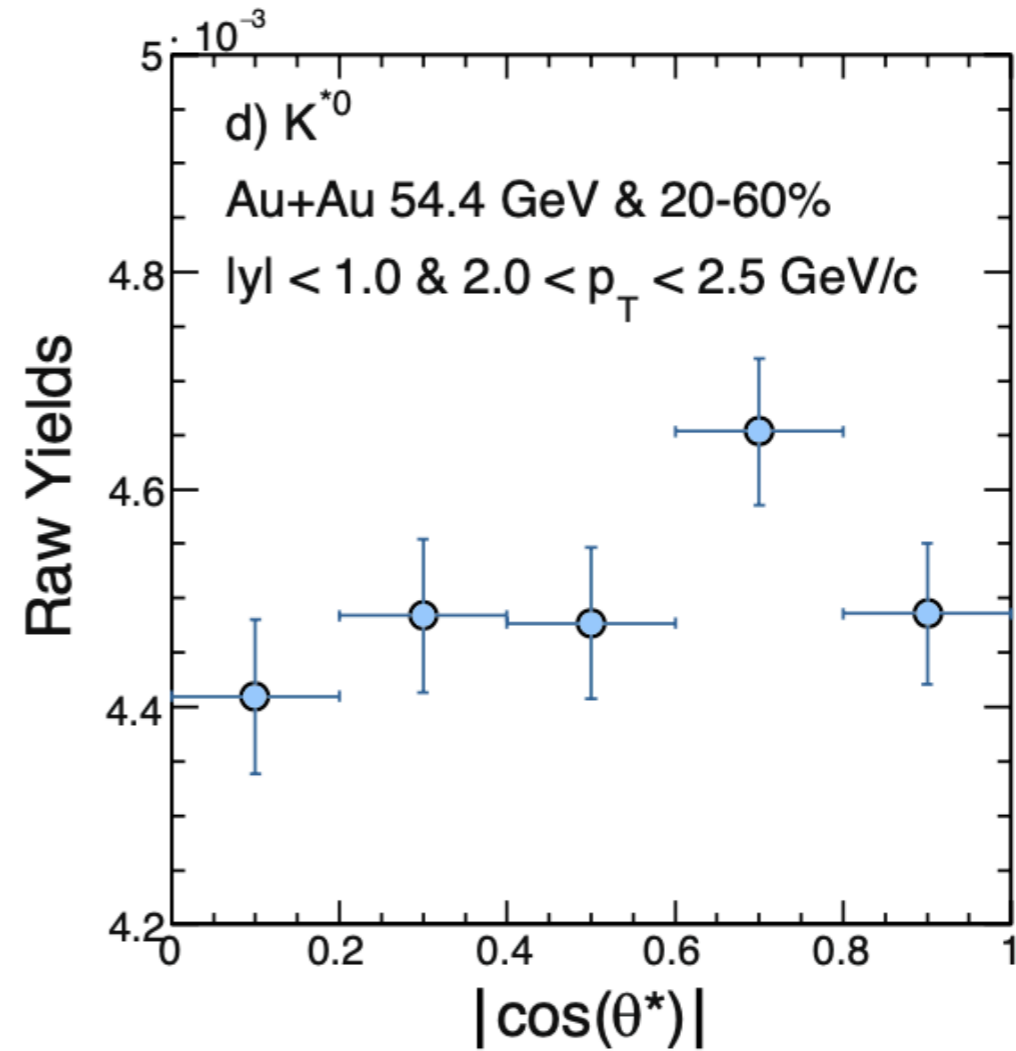
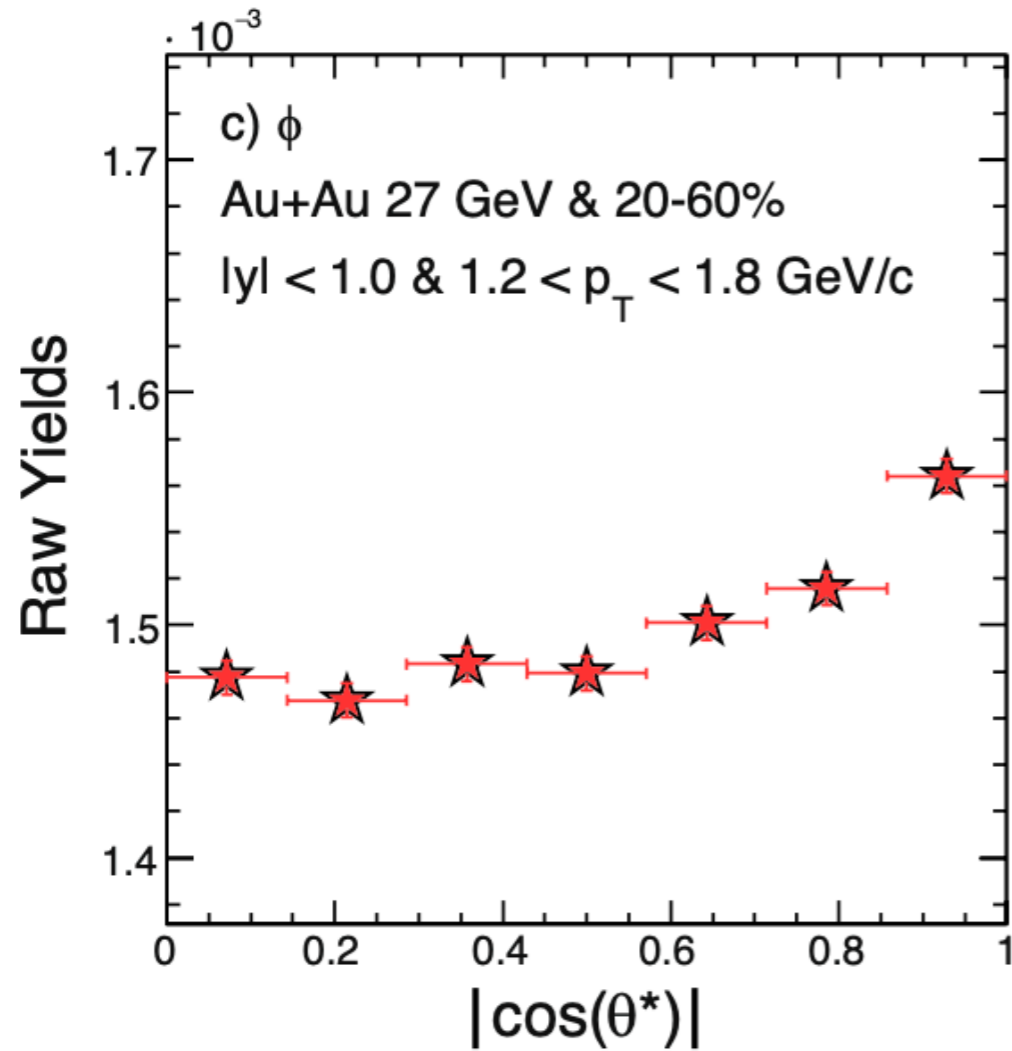
Acceptance effect in spin alignment

Study acceptance effect in a toy MC simulation



- Most dominant effect effect comes from η (and p_T) selection cuts on daughters

Raw yield vs. $\cos \theta^*$

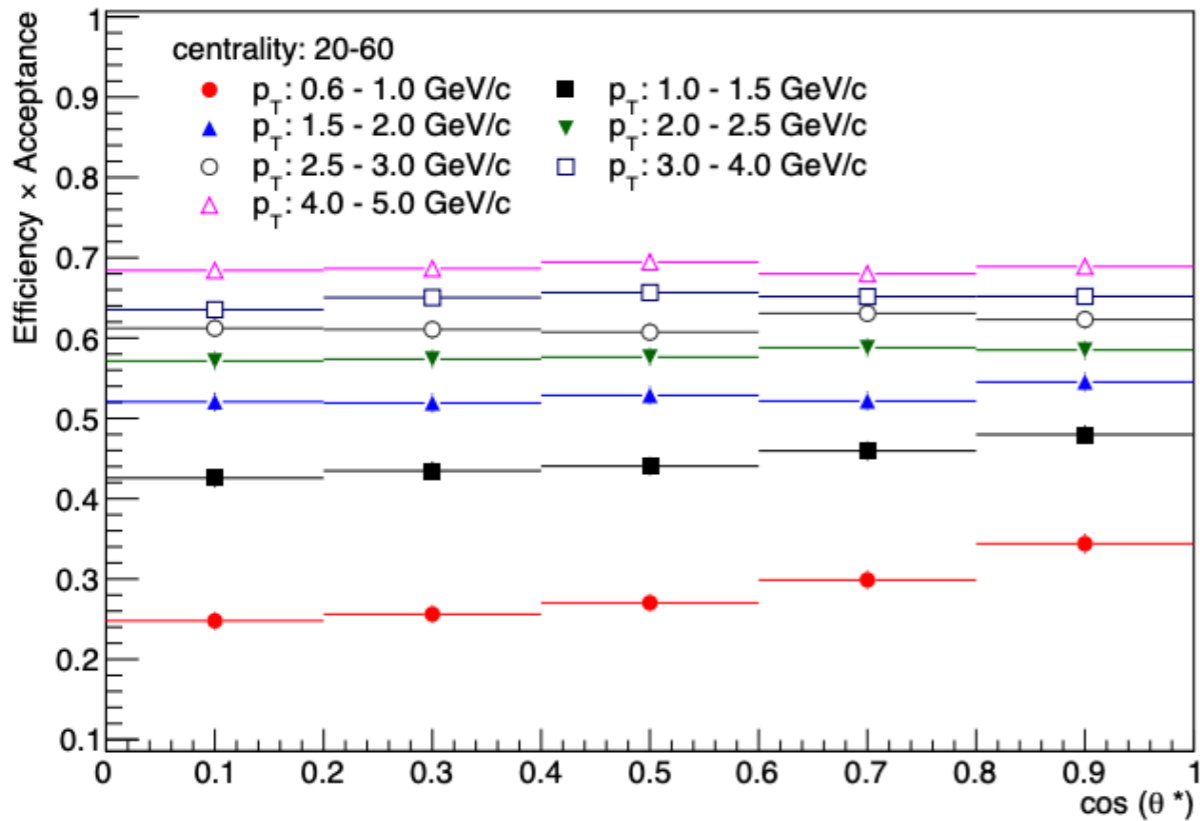


Raw yield is calculated in $\cos \theta^*$ bins

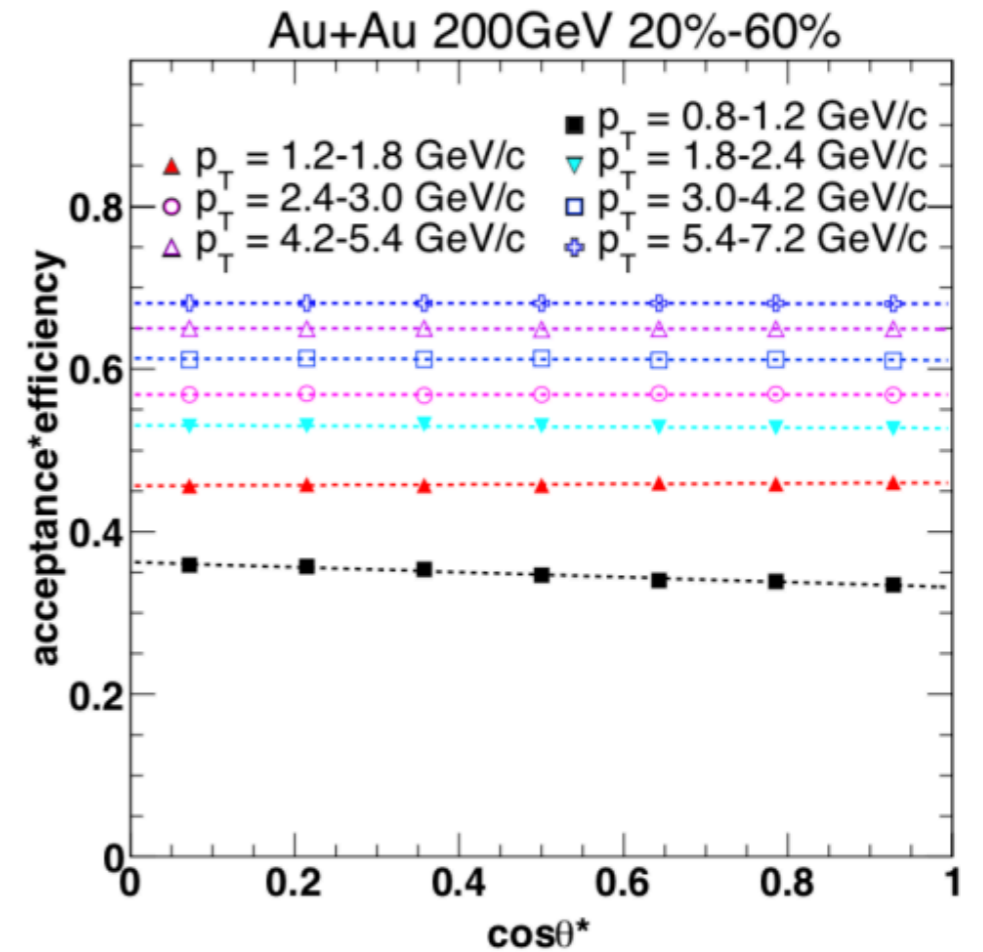
Acceptance x efficiency

Acceptance x efficiency as function of $\cos \theta^*$

K^*0



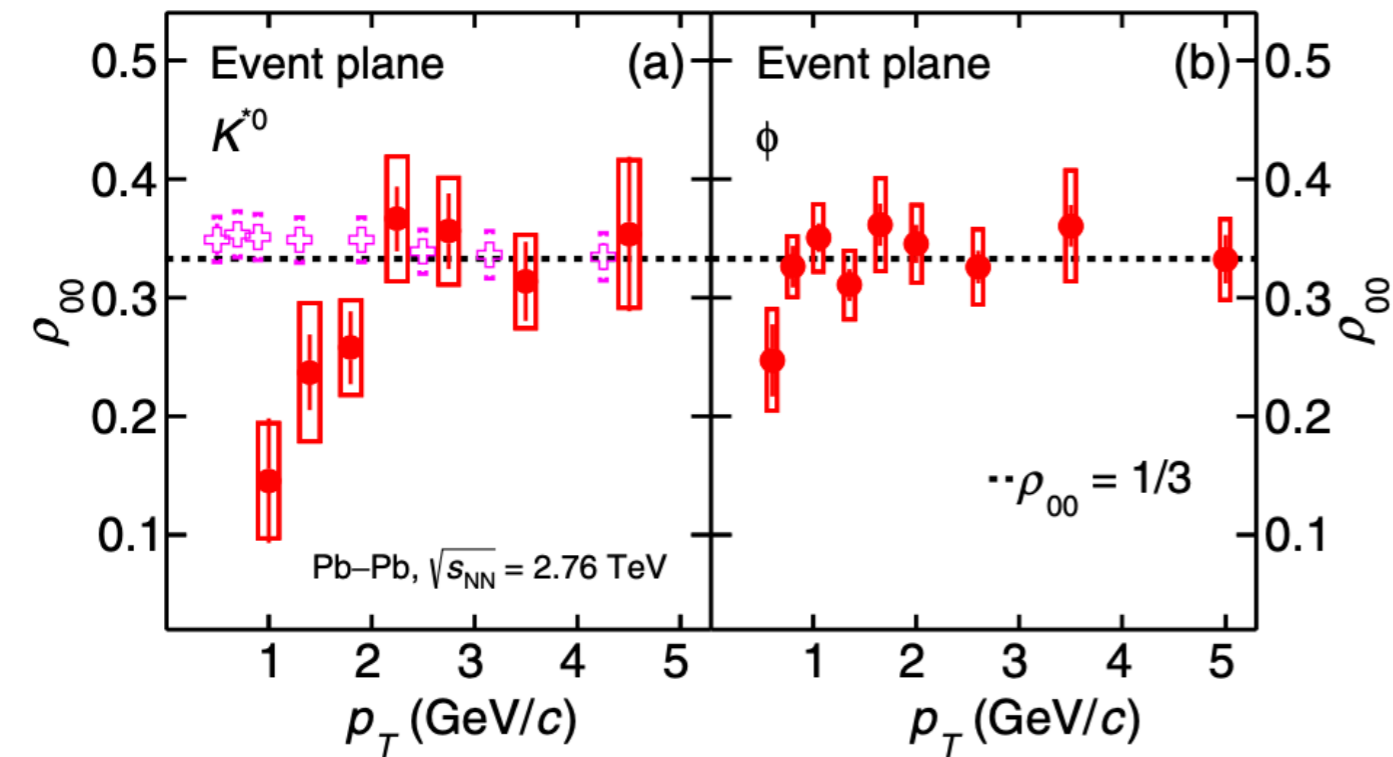
Φ



Acceptance effect dominant at low p_T region

Spin alignment from Pb+Pb collisions at LHC

In Pb+Pb collisions, we measured ρ_{00} wrt event plane



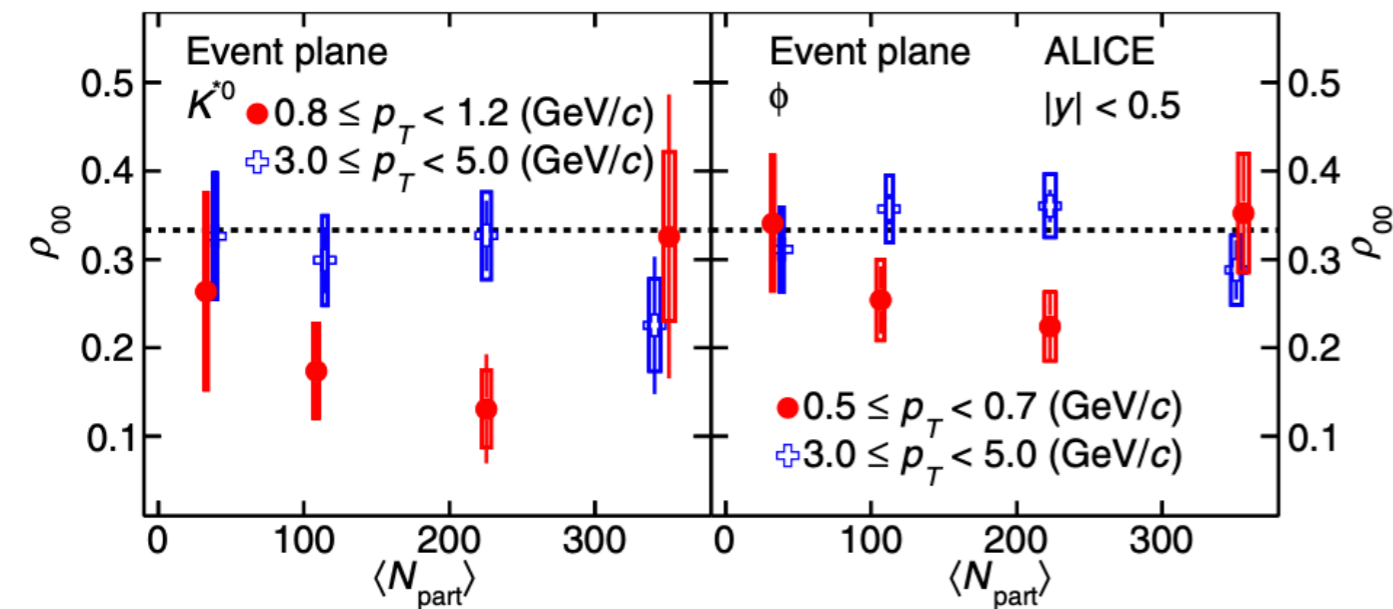
- For both K^* and ϕ :

- $\rho_{00}^{EP} \leq \frac{1}{3}$

Significance of deviation

for $K^* \leq 2.6\sigma$

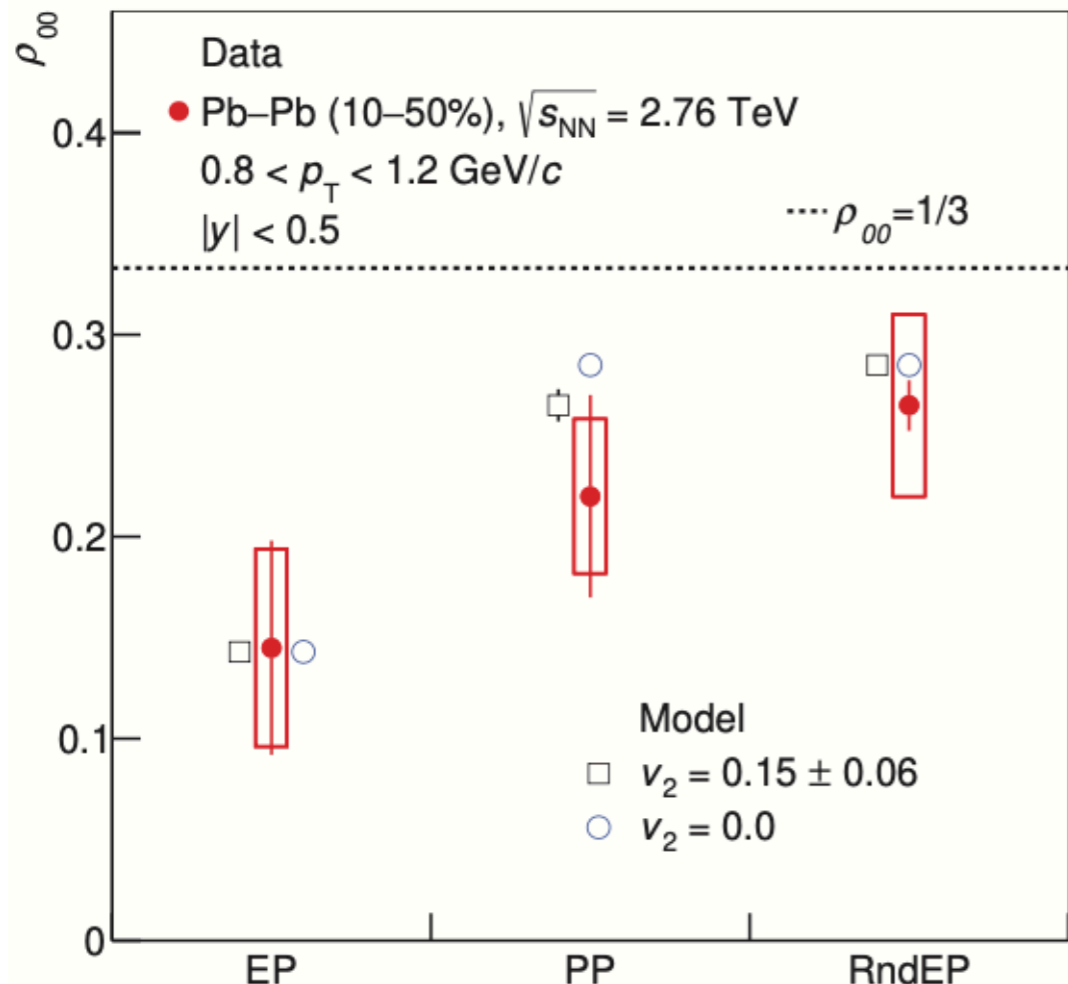
for $\phi \leq 1.9\sigma$



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

Spin alignment between PP and EP

ρ_{00} wrt production (PP) and event plane (EP)



Event plane **Production plane** **2D-random plane**

- ρ_{00}^{EP} and ρ_{00}^{PP} are related by:

- $$\left(\rho_{00}^{PP} - \frac{1}{3} \right) = \left(\rho_{00}^{EP} - \frac{1}{3} \right) \frac{1 + 3v_2}{4}$$

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

First measurement of charged $K^* \rho_{00}$

Naive expectation

Particle Species	Magnetic moment (μ_N)
$K^{*0}(d\bar{s})$	$\mu_d \approx -0.97, \mu_{\bar{s}} \approx 0.61\mu_N$
$K^{*+}(u\bar{s})$	$\mu_u \approx 1.85, \mu_{\bar{s}} \approx 0.61\mu_N$

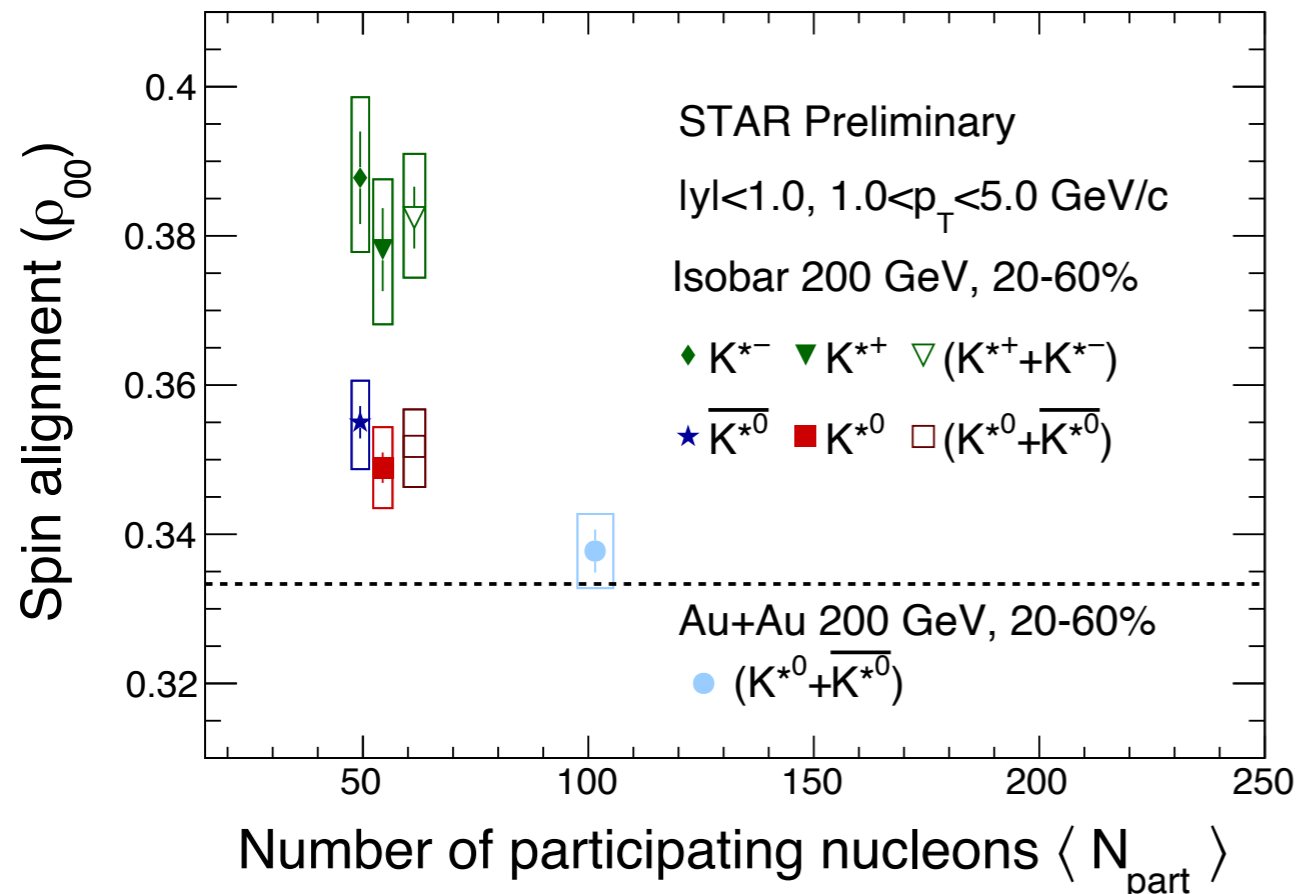
Yang, et. al.,

Phys. Rev. C 97, 034917 (2018)

$$\rho_{00}(K^{*0}) > \rho_{00}(K^{*\pm})$$

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

Observation from STAR



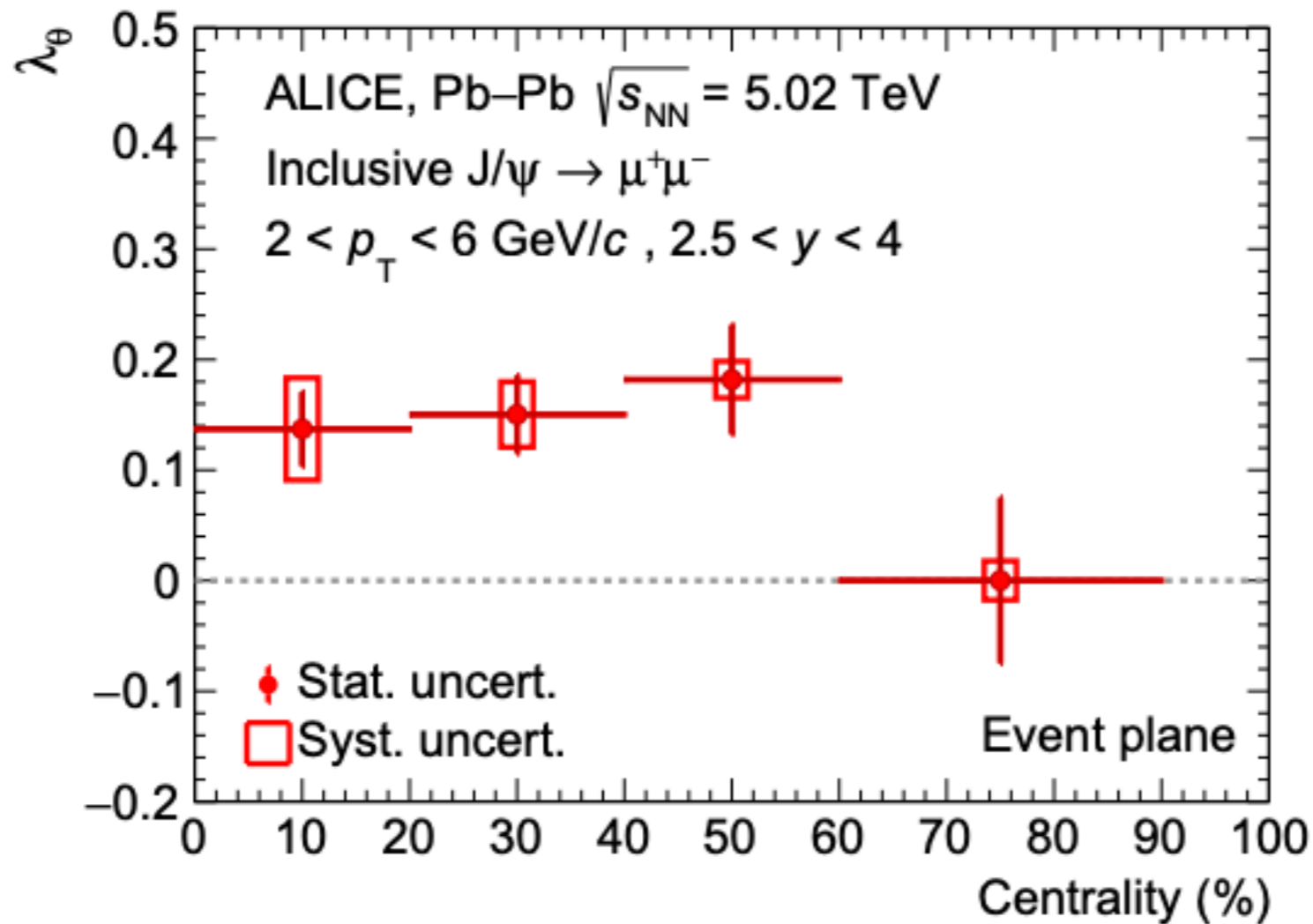
- First observation of $K^{*\pm} \rho_{00}$ in HIC

- Surprising ordering in ρ_{00}

$$K^{*+} + K^{*-} \gg K^{*0} + \bar{K}^{*0}$$

(Opposite to naive expectation from B-field)

J/Ψ spin alignment in Pb+Pb collisions at LHC



First observation of global spin alignment of J/Ψ at LHC

- J/ψ : $\lambda_\theta \sim 0.2$, $\rho_{00} \sim 0.37$ ($> \frac{1}{3}$)
- K^{*0} $\rho_{00} \sim -0.2$, ϕ $\rho_{00} \sim -0.1$

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