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

Subhash Singha
(subhash@impcas.ac.cn)
Institute of Modern Physics Chinese Academy of Sciences, Lanzhou

The 7th International Conference on Chirality, Vorticity and Magnetic Field in Heavy Ion Collisions

July 15-19, 2023, Beijing

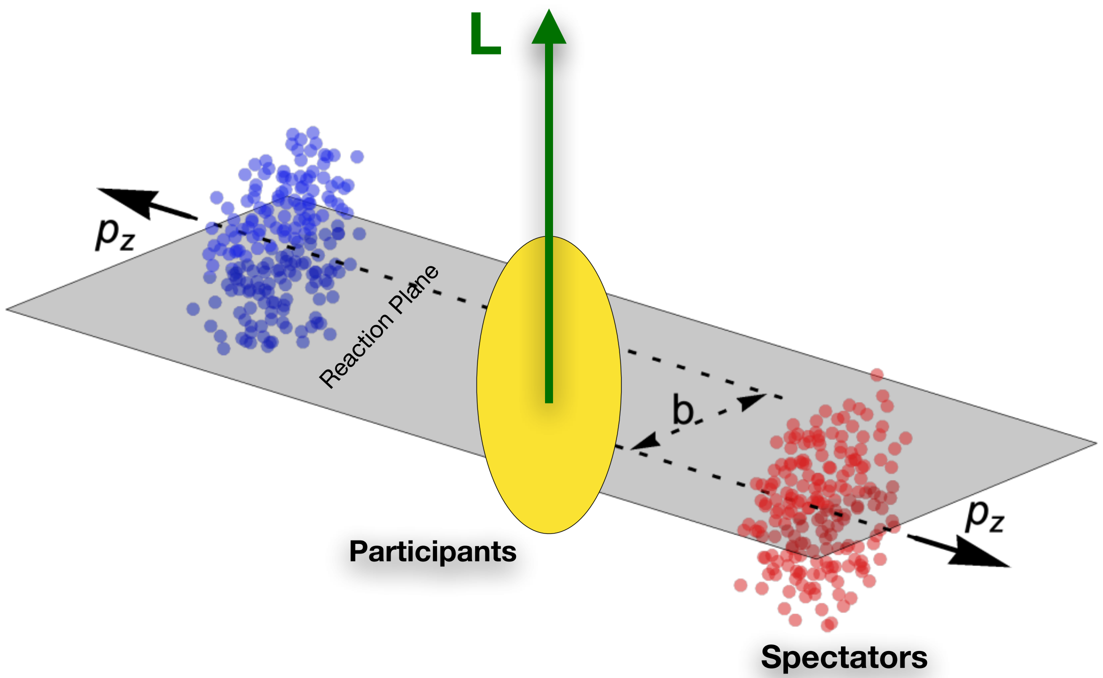
STAR
U.S. DEPARTMENT OF ENERGY | Office of Science
This work is supported by the grant from DOE office of science
IMP

Outline

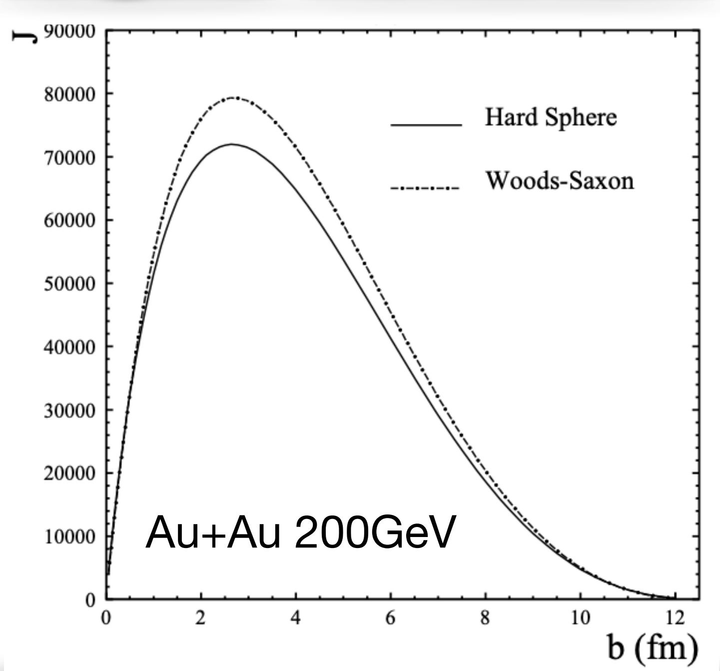
- Introduction
- STAR detector and analysis details
- Results from RHIC Beam Energy Scan
- Summary

Introduction

Initial condition in Heavy ion collision



Angular momentum



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

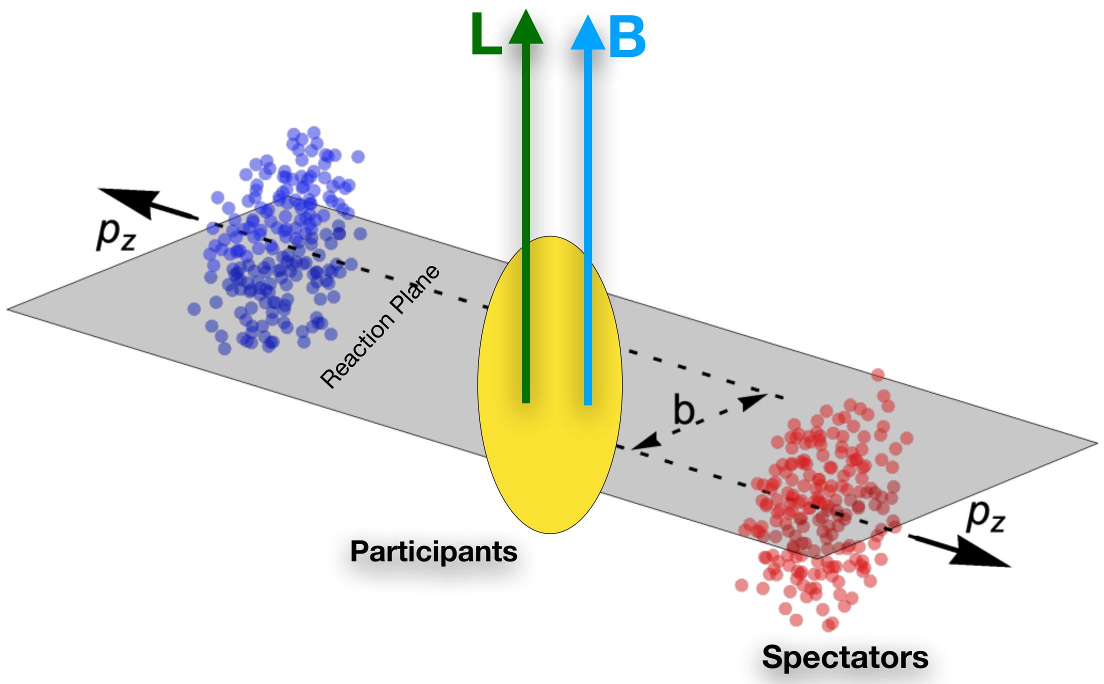
In non-central heavy-ion collisions

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

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

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

Initial condition in Heavy ion collision



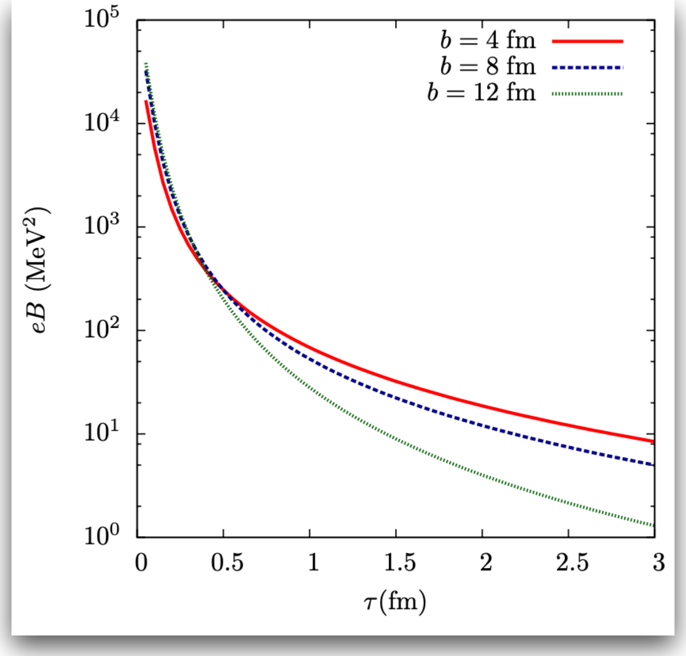
In non-central heavy-ion collisions

- **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



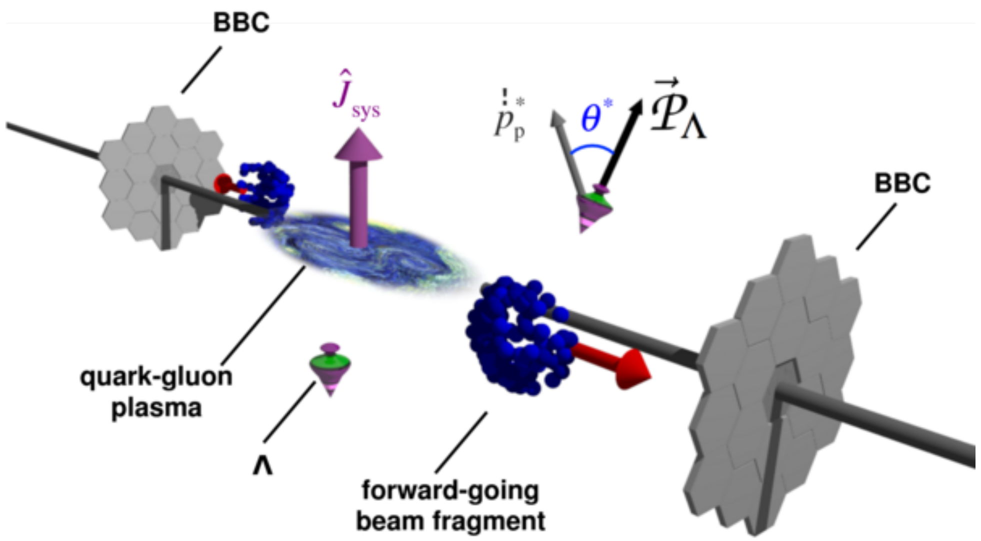
Kharzeev, Nucl Phys A803, 227 (2008)

Through polarization measurements

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

Global spin polarization of Λ

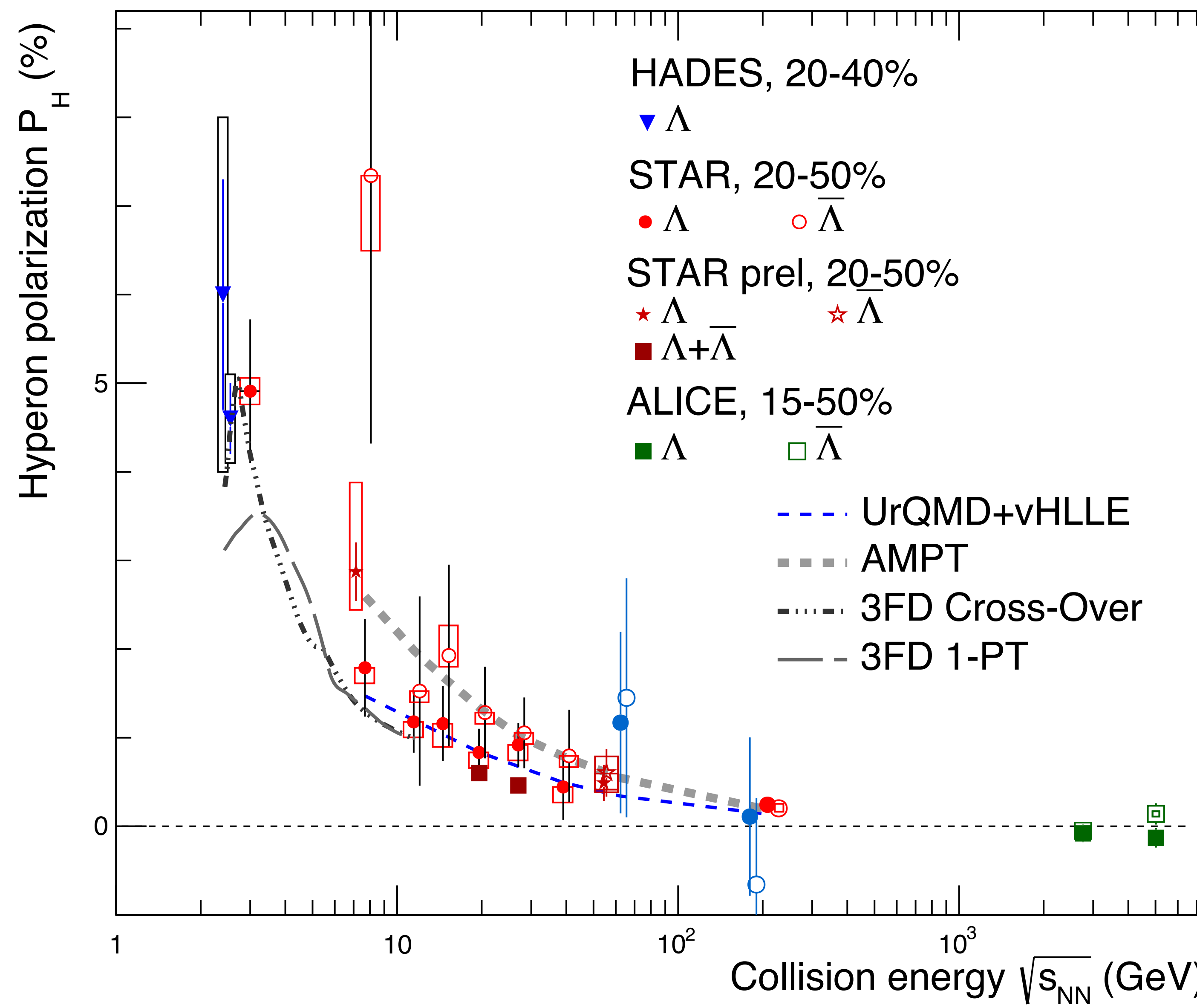
- Λ: parity violating weak decay and hence "self analyzing"



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

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

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

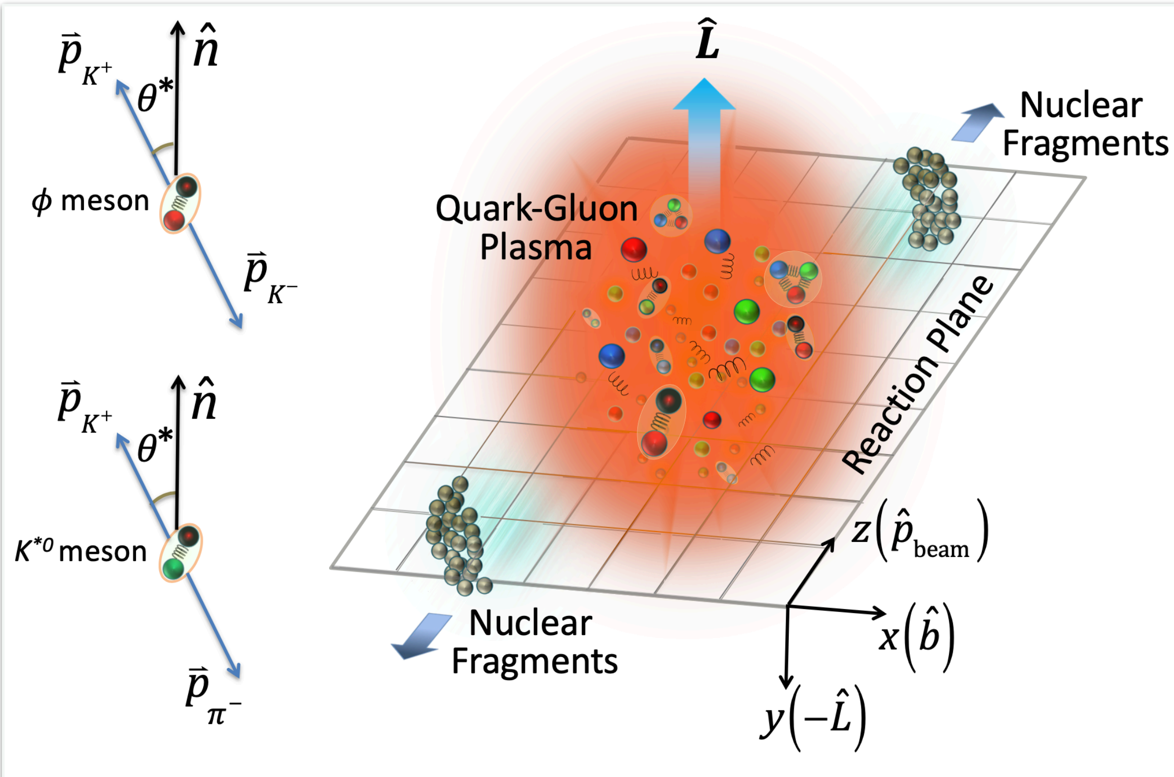


Presence of extreme vorticity induced by angular momentum

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



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

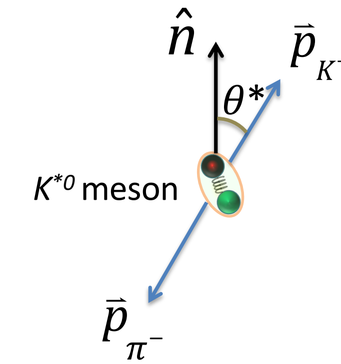
- Vector mesons (K* and ϕ): Spin 1^-, Strong decay
- One can measure 00th component of spin density matrix from angular distribution of daughter

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

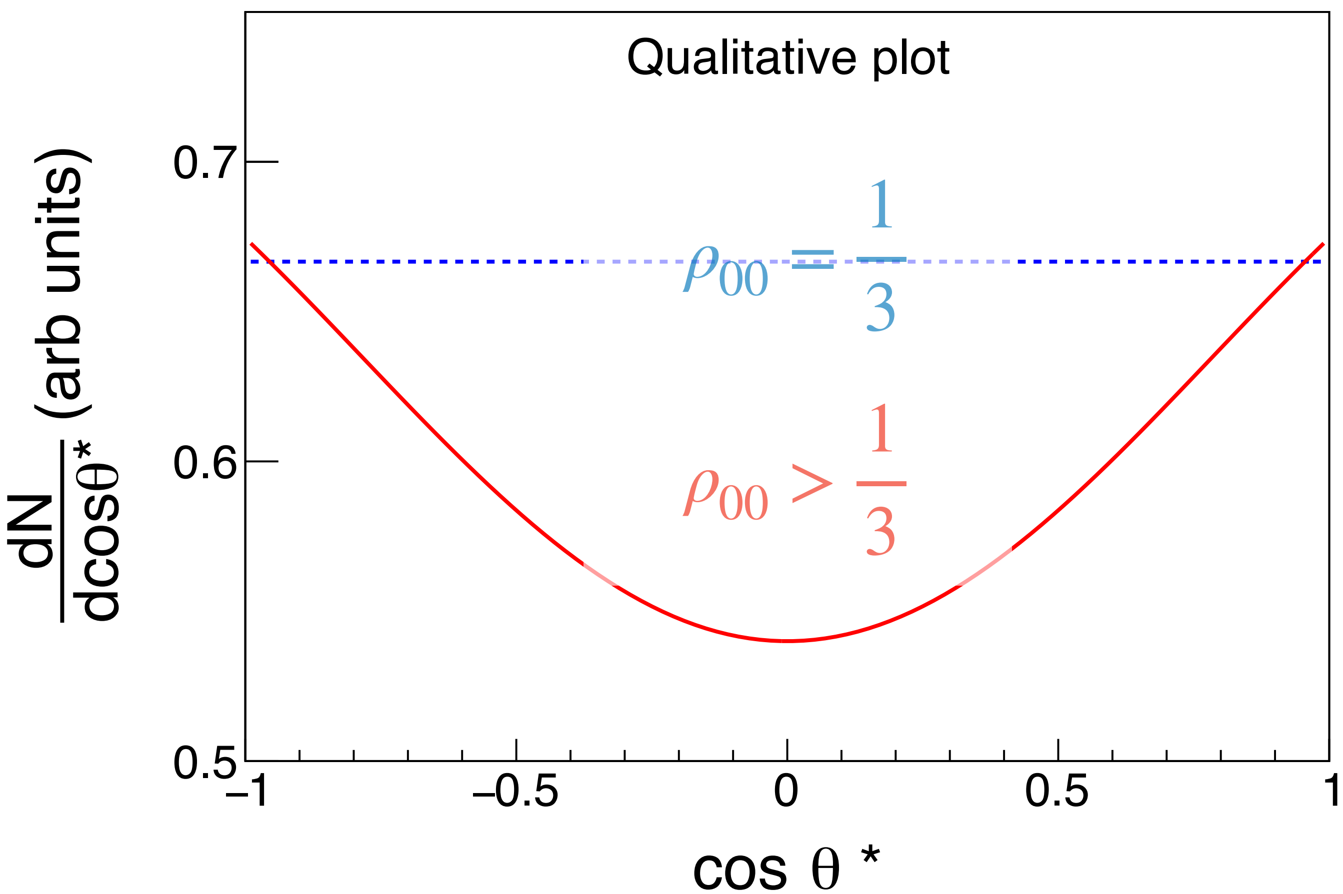
$\rho_{00} \rightarrow$ Probability of finding a vector meson in spin state "0" out of (1, 0, -1)

Schilling et al, Nucl. Phys. B 15, 397 (1970)
STAR: Phys. Rev. C 77, 061902 (2008)

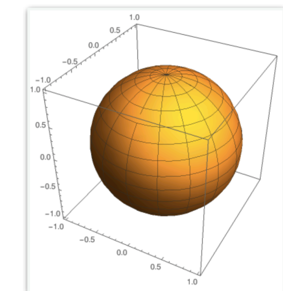
Angular distribution of daughter



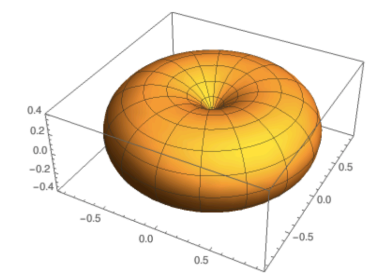
- Qualitative expectation of angular distribution



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

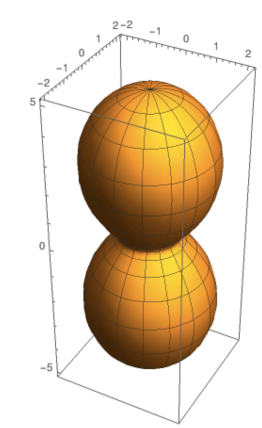


$\rho_{00} < \frac{1}{3}$



→ Spin alignment

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

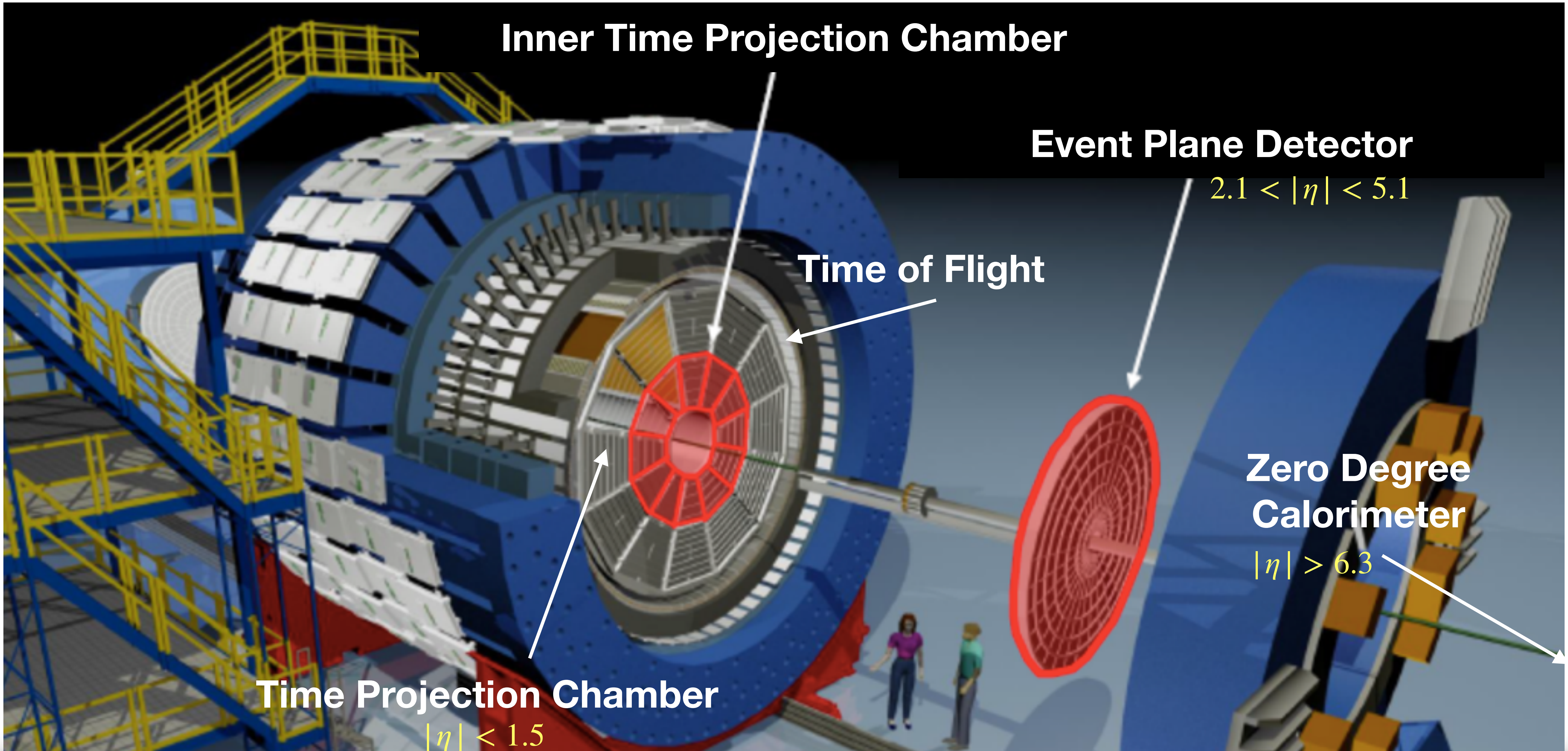


Vector mesons *vs* hyperons

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	$1/2^+$	$p\pi$ (weak decay)	substantial	required (Ψ_1)

STAR detector and analysis details

STAR detector

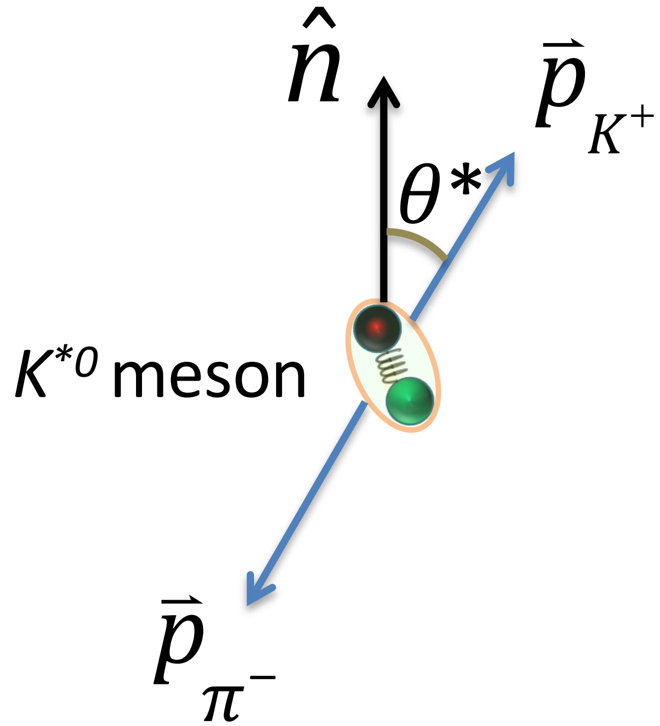


- Uniform acceptance, full azimuthal coverage, excellent PID capability
- TPC: tracking, centrality
- TPC, ZDC, EPD: event plane
- TPC+TOF: particle identification

Analysis Procedure

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

- Yield of vector mesons is extracted in cos θ* 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

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

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

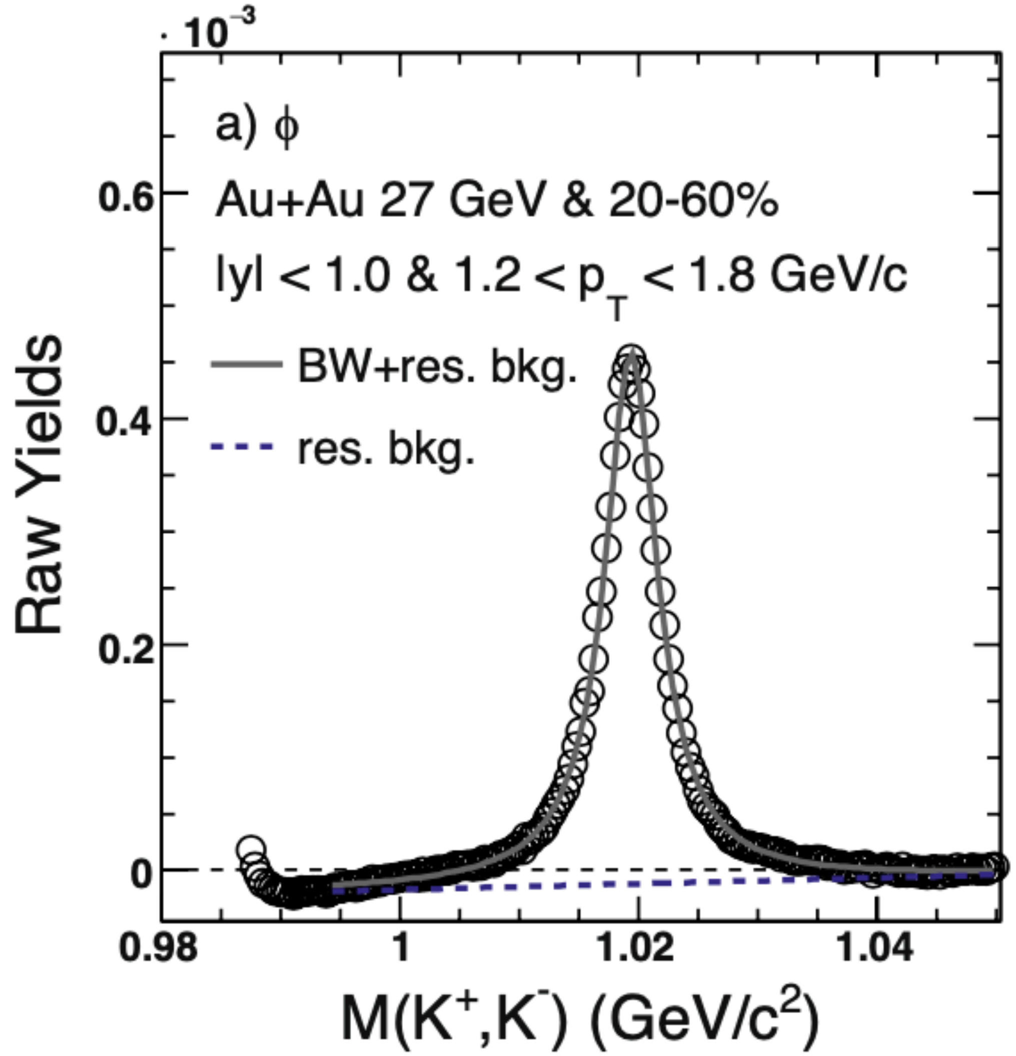
Results and discussions

Dataset and analysis details

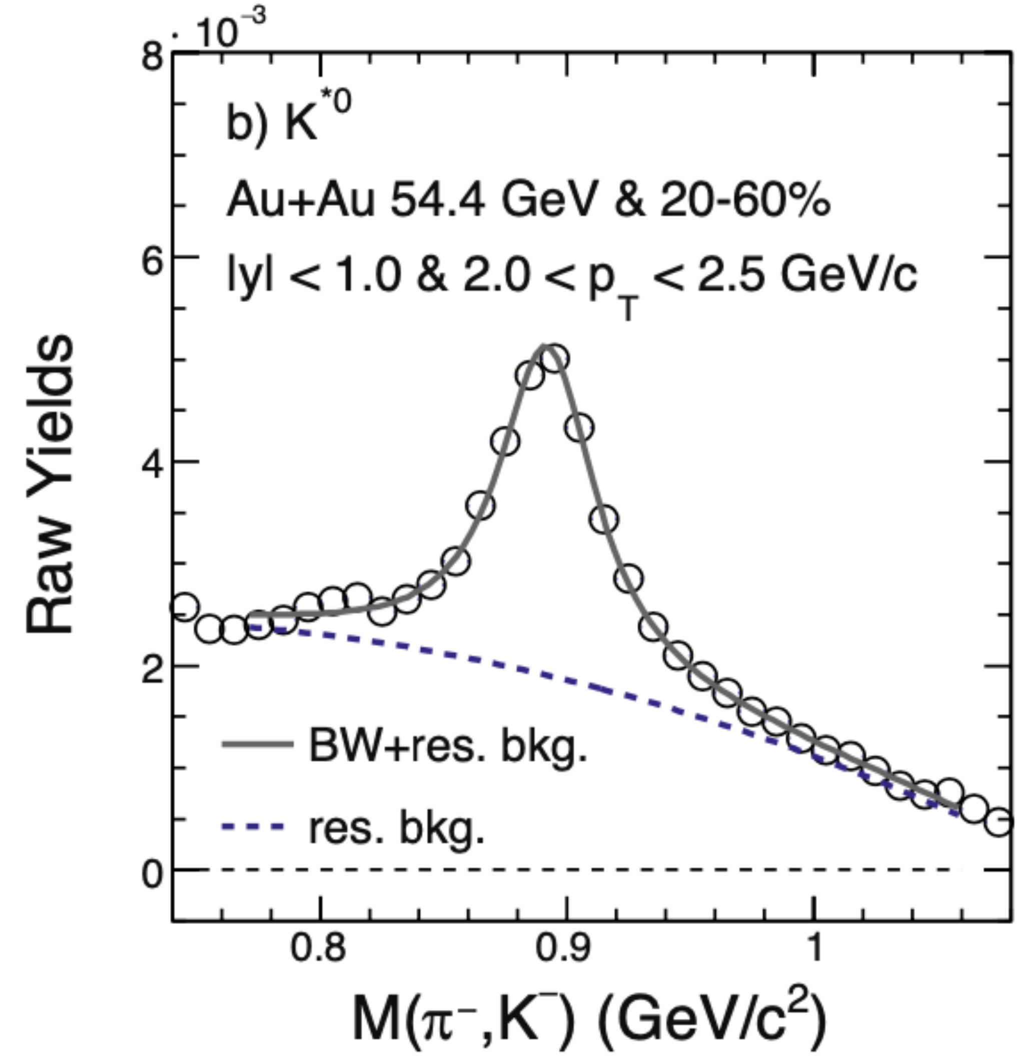
Collision system	Au+Au, Isobar (Ru+Ru and Zr+Zr)
Beam energy	11.5, 14.5, 19.6, 27, 39, 54.4, 62.4 and 200 GeV
Trigger	MInimum bias trigger
Pair rapidity	$\lvert y \rvert < 1.0$
Background	Mixed event and track rotation method
Polarization axis	Perpendicular to TPC 2^{nd} order EP and ZDC 1^{st} order EP
Consistency check	3D-random plane

Invariant mass reconstruction

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



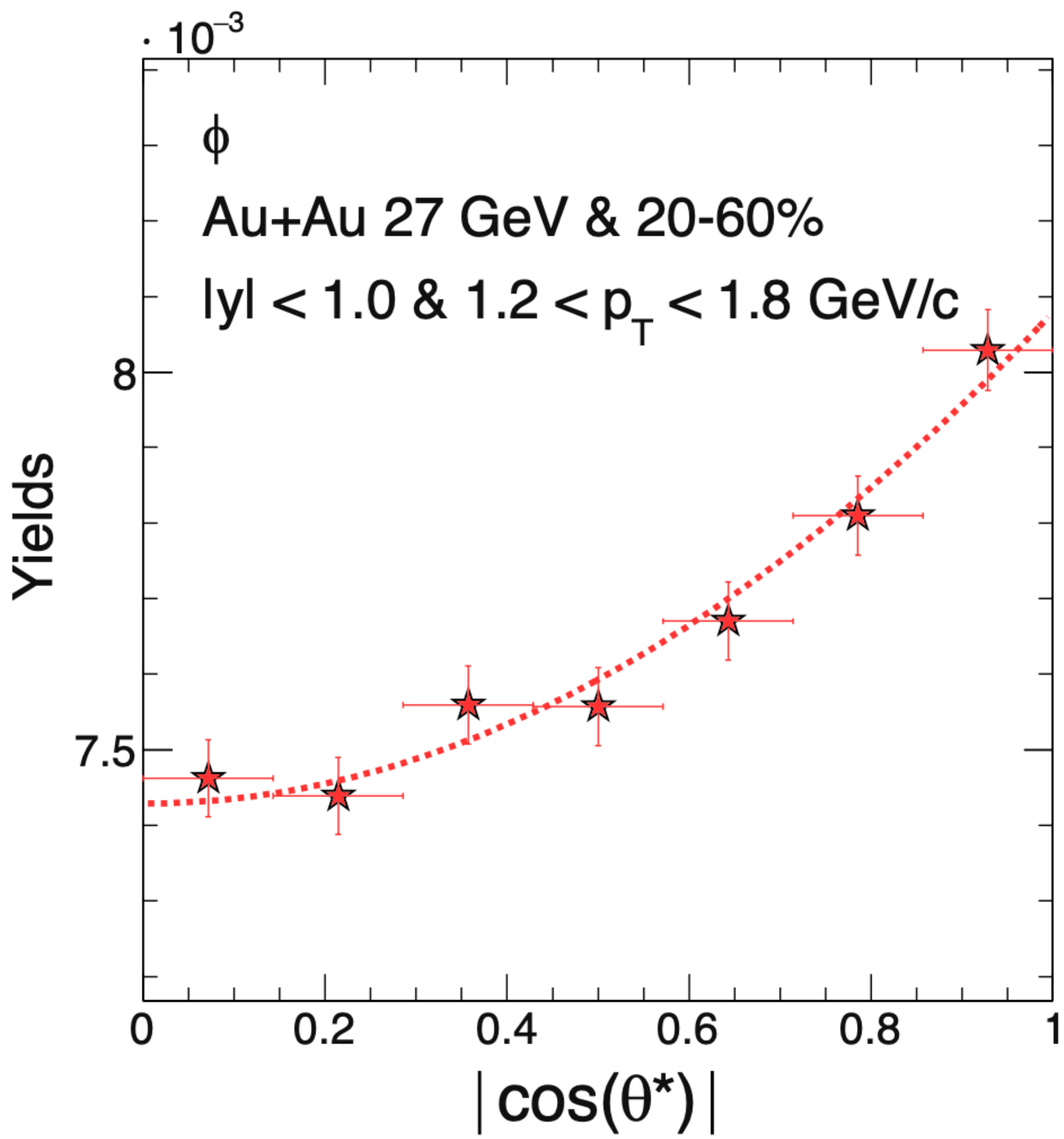
$K^{*0} \rightarrow K^{+} + \pi^{-}$

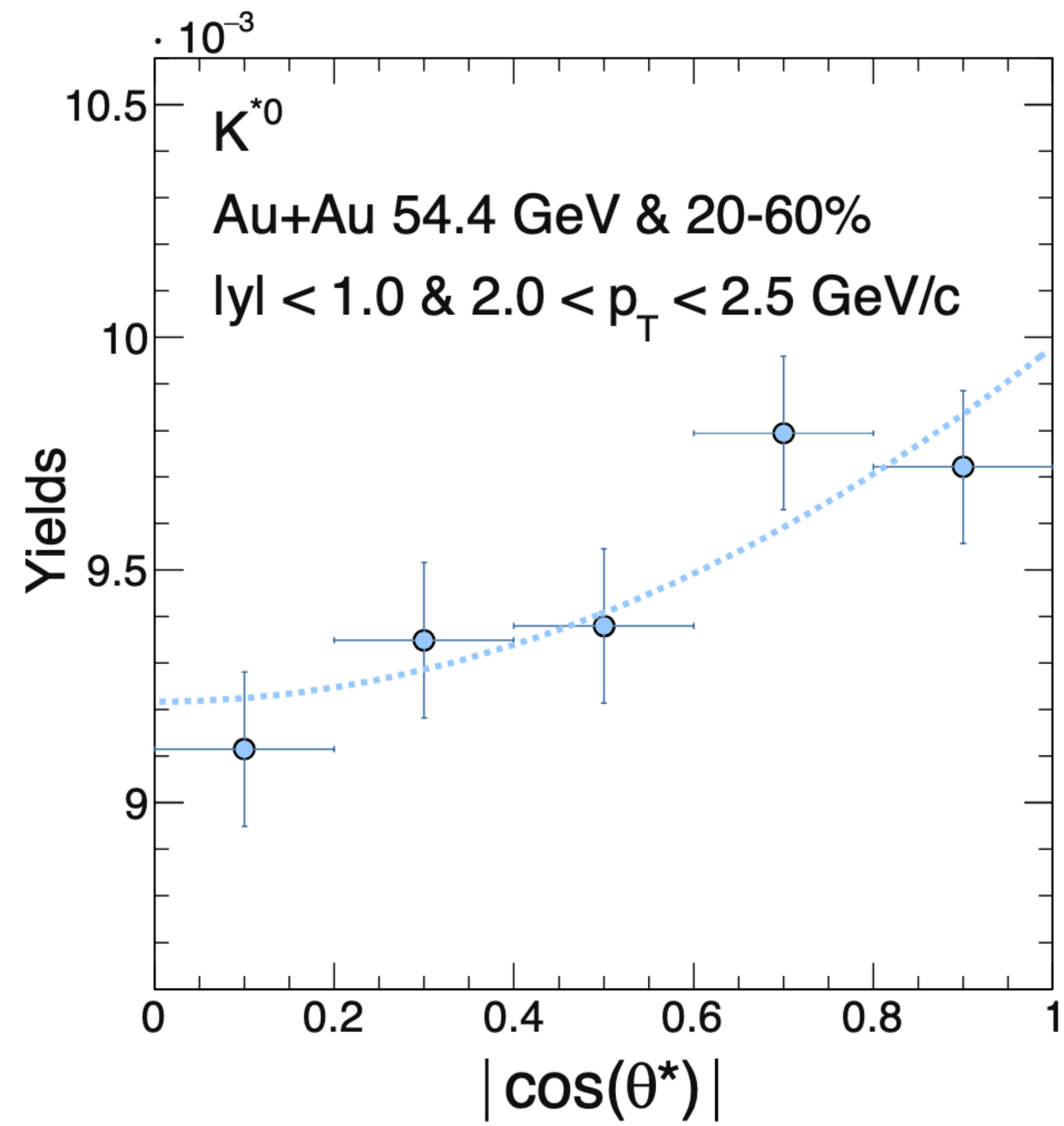


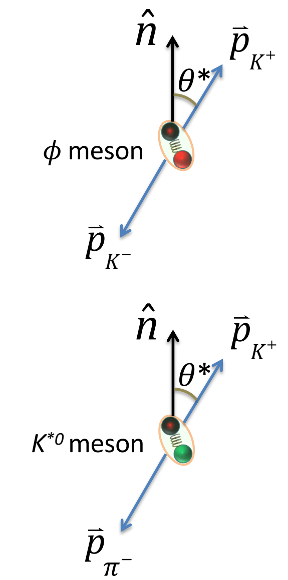
Invariant mass is reconstructed using mixed event and track-rotation methods

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

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







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

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

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

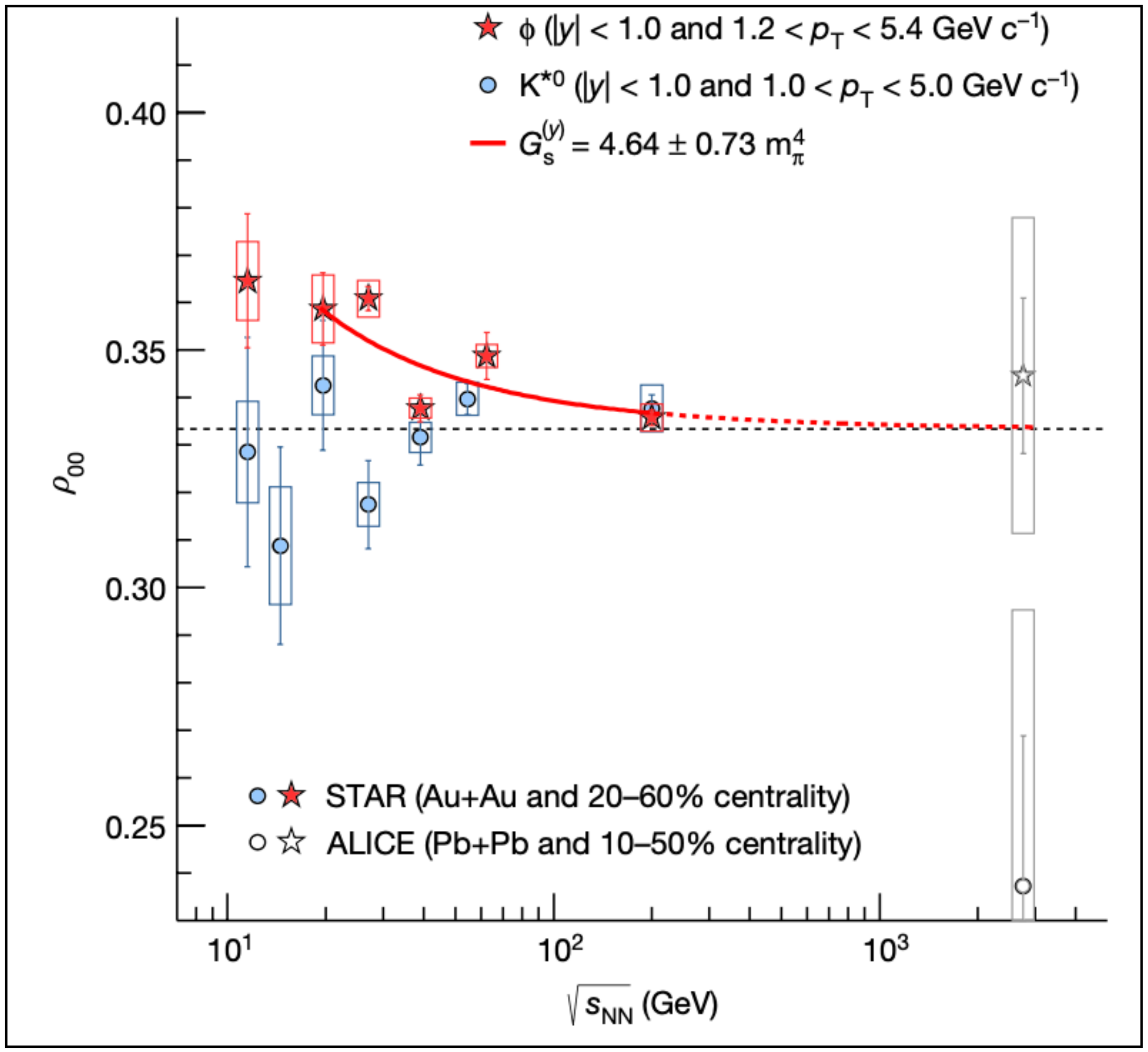
Spin alignment from RHIC BES

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%:

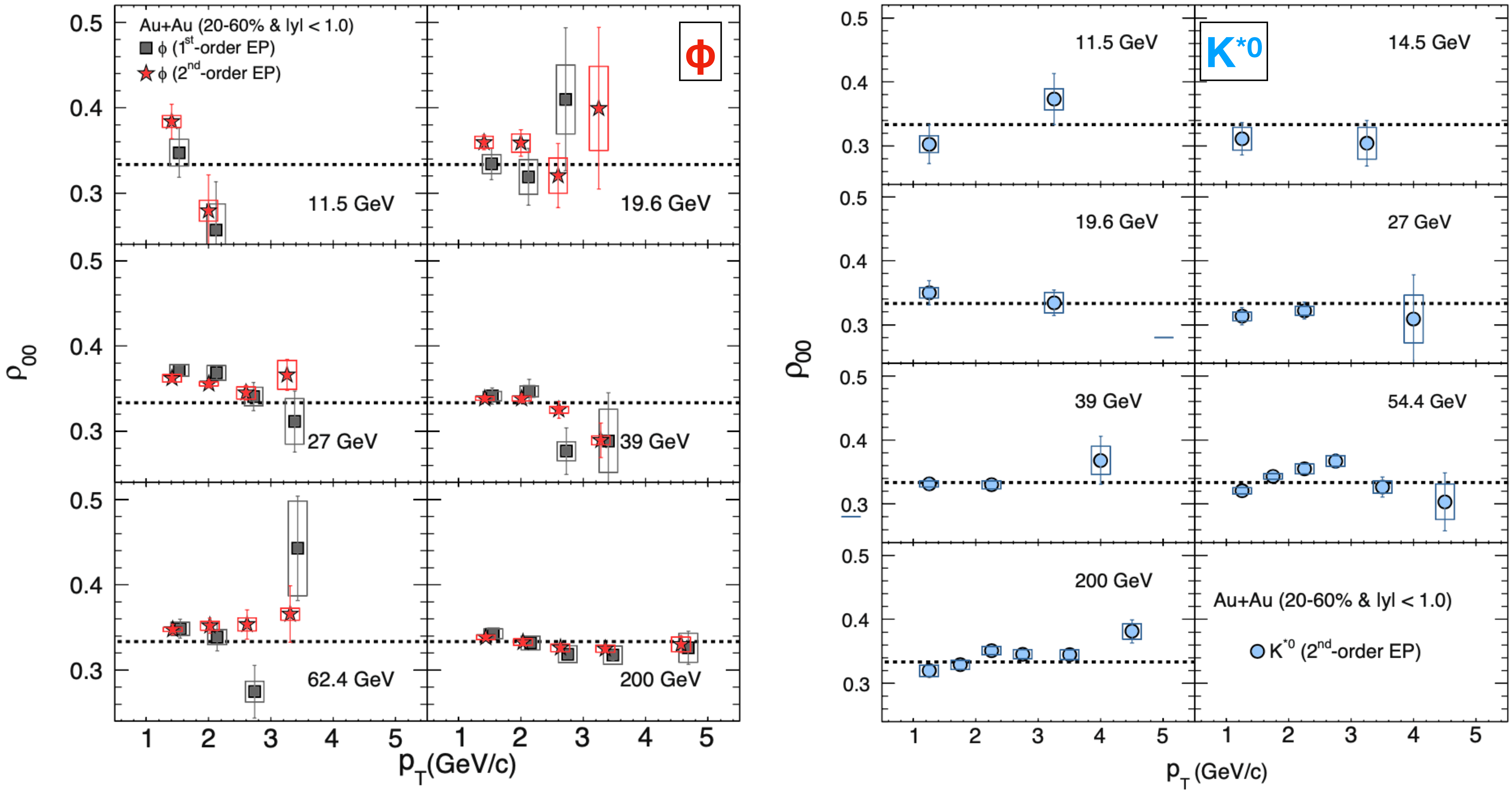
- For $\sqrt{s_{NN}}$ <= 62.4 GeV:
  - φ ρ_{00} = 0.3512 ± 0.0017 (stat.) ± 0.0017 (sys.)

  ρ_{00} > 1/3 with 7.4σ

- For $\sqrt{s_{NN}}$ <= 54.4 GeV:
  - K*0 ρ_{00} = 0.3356 ± 0.0034 (stat.) ± 0.0043 (sys.)

  ρ_{00} ~ 1/3

Transverse momentum dependence of ρ_{00}

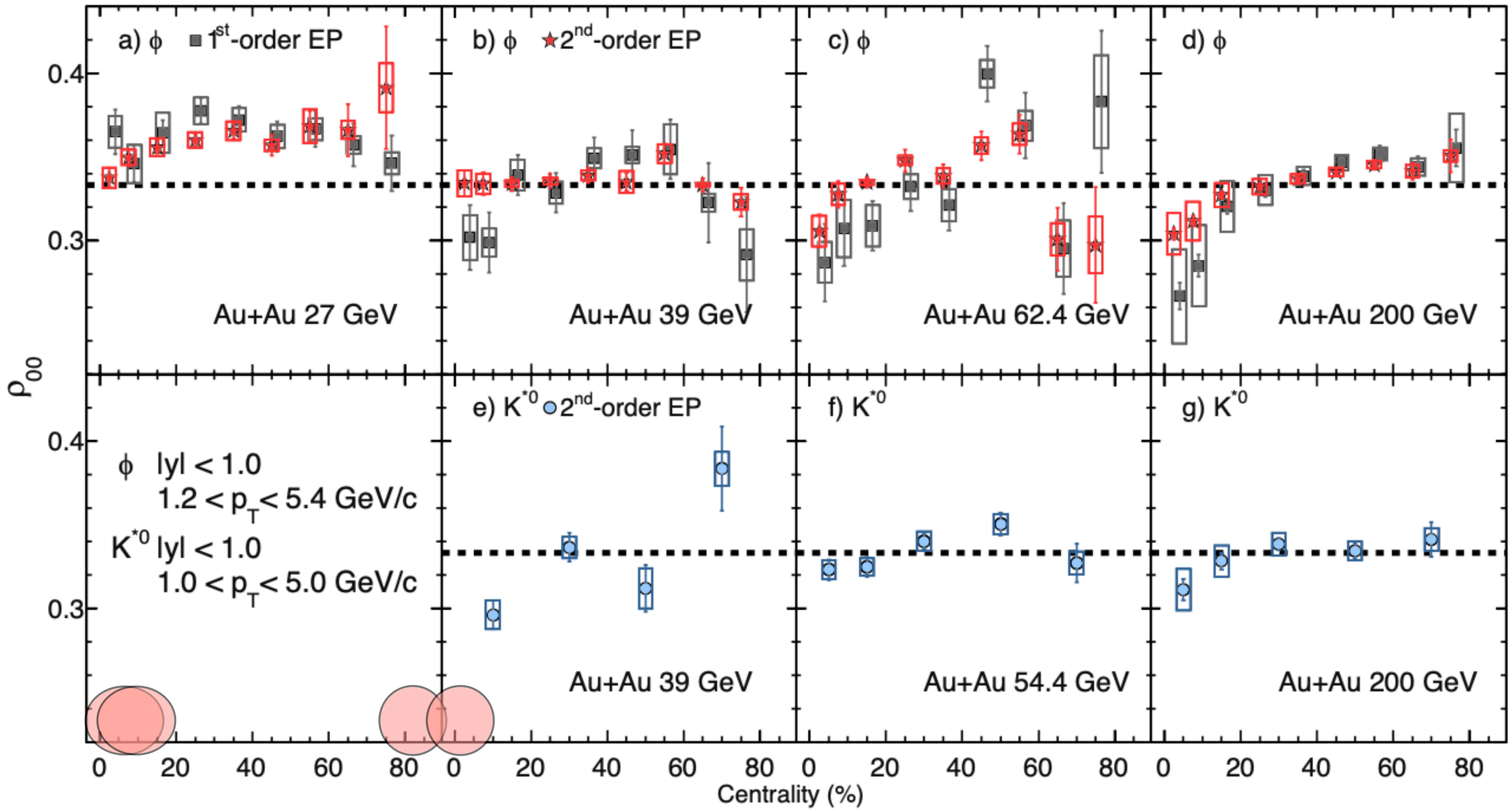


- For 20-60%: non-trivial p_T dependence

Centrality dependence of ρ_{00}

φ

K*0



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

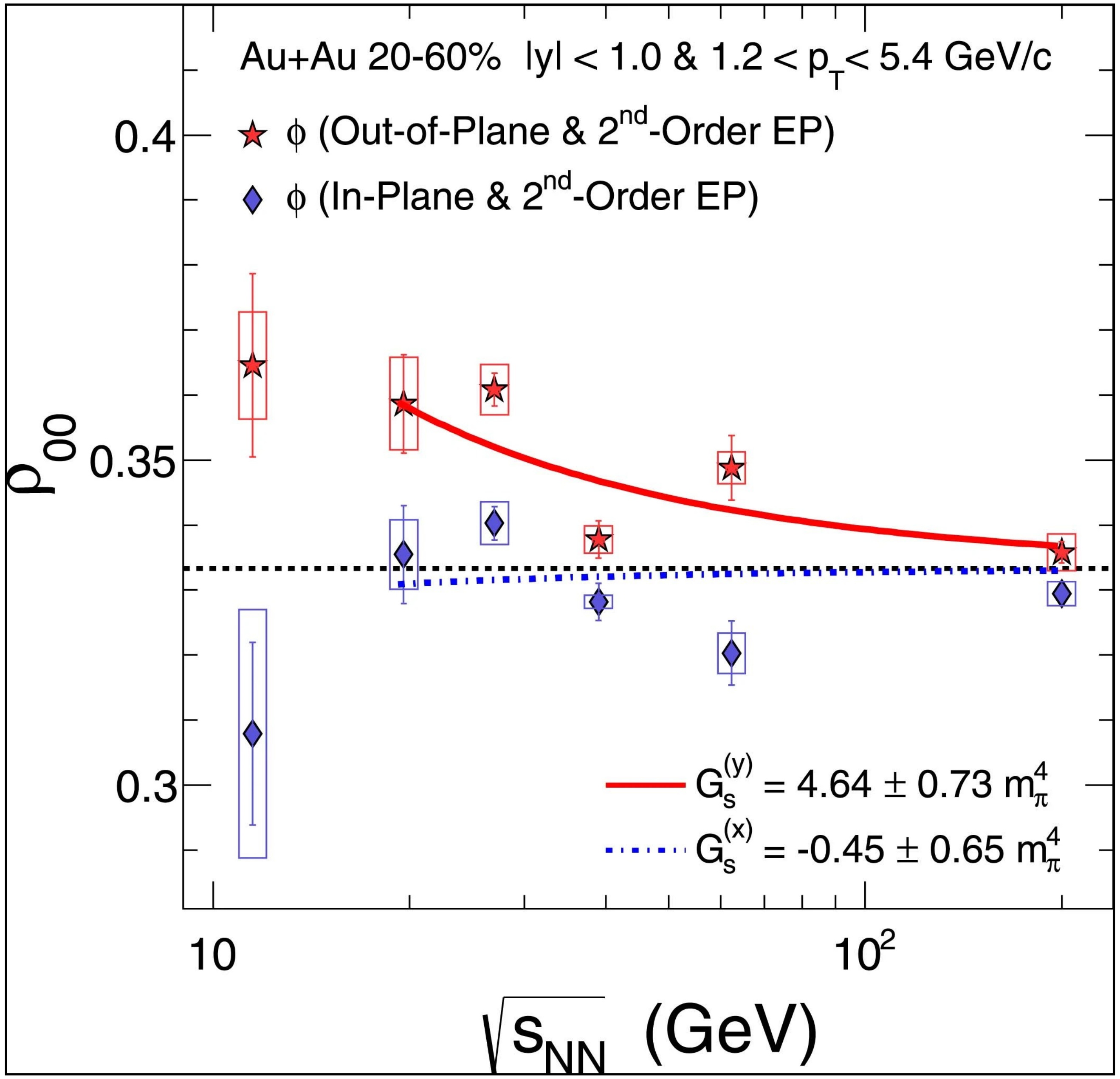
- <u>For central at 200 GeV:</u>
  - φ, K^{*0} $\rho_{00} < 1/3$

  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



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

Expectation of spin alignment

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})
c_F:Fragmentation[3]	> or, < 1/3 (~ 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 accomodate 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	(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})
c_F:Fragmentation[3]	> or, < 1/3 (~ 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 accomodate large positive signal)

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

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

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

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

Expectation of spin alignment

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})
c_F:Fragmentation[3]	> or, < 1/3 (~ 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 accomodate large positive signal)

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

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

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

Expectation of spin alignment

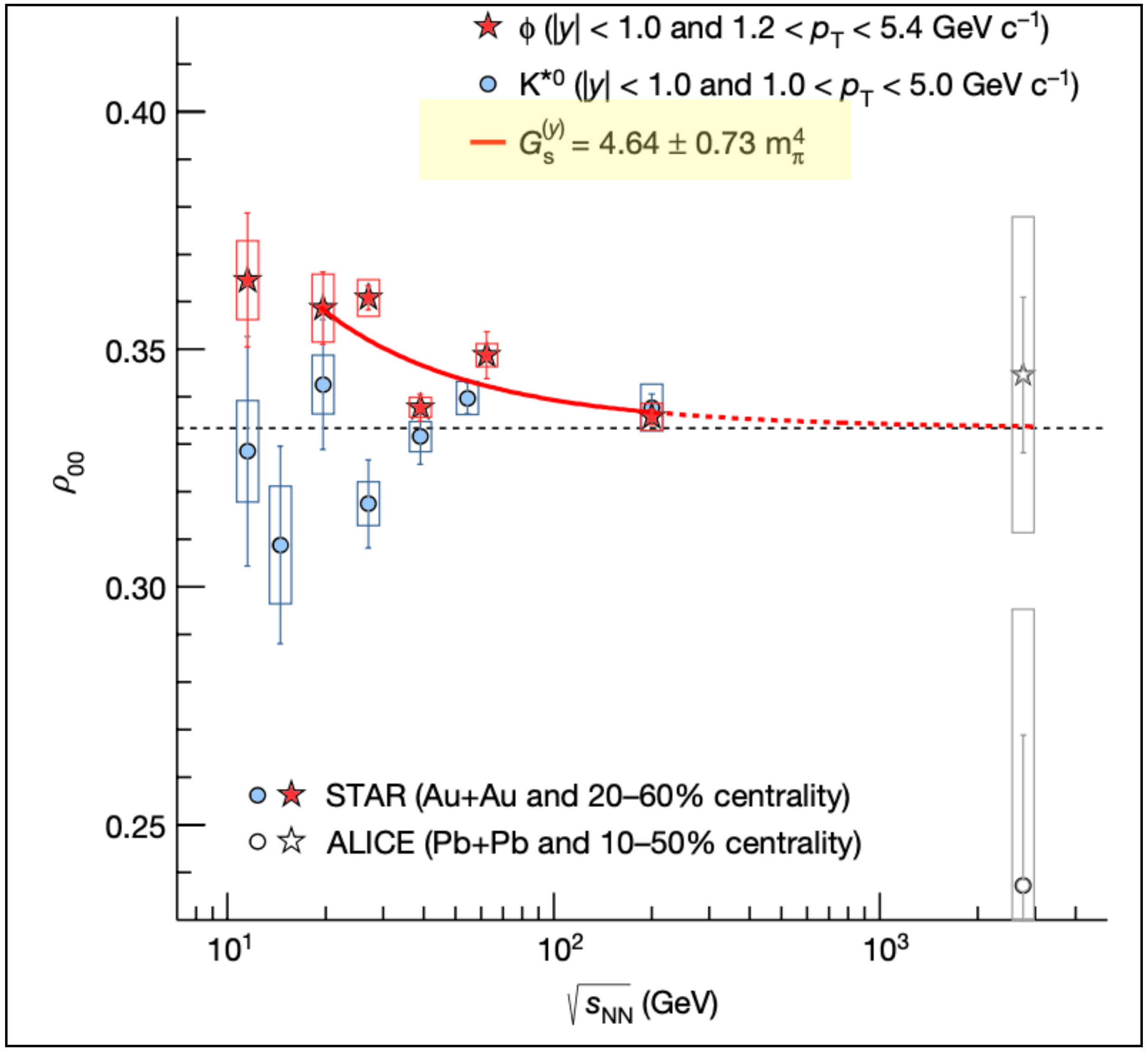
Physics Mechanisms	(ρ_{00})
c_Λ: Quark coalescence vorticity & magnetic field[1]	< 1/3 (Negative ~ 10^{-5})
c_ϵ: Vorticity tensor[1]	< 1/3 (Negative ~ 10^{-4})
c_E: Electric field[2]	> 1/3 (Positive ~ 10^{-5})
c_F:Fragmentation[3]	> or, < 1/3 (~ 10^{-5})
c_L:Local spin alignment and helicity[4]	< 1/3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

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

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

- 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)

Energy dependence of spin alignment



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

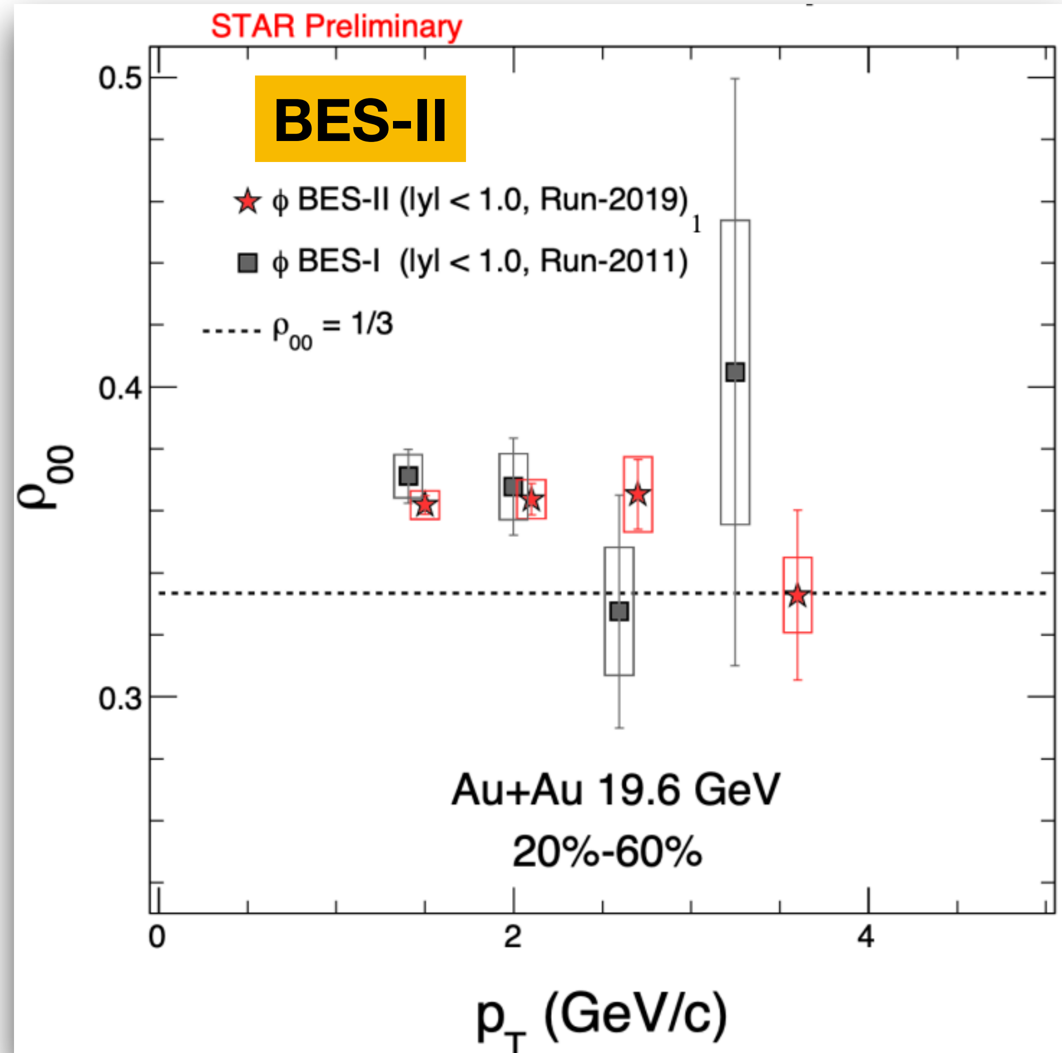
$$\rho_{00}(\phi) \approx \frac{1}{3} + c_\Lambda + c_\epsilon + c_E + c_\phi;$$

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

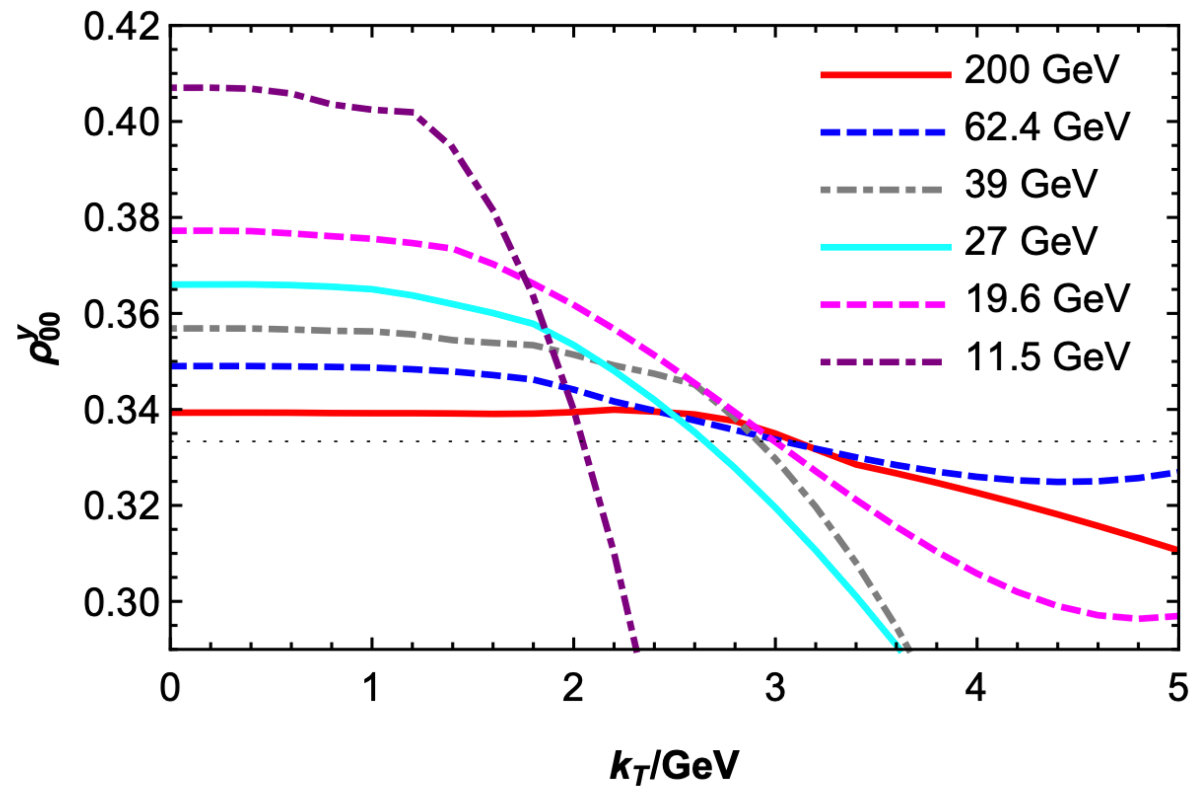
$$G_s^y = g_\phi^2 \left[3\langle B_{\phi,y}^2 \rangle - \frac{\langle P^2 \rangle_\phi}{m_s^2} \langle E_{\phi,z}^2 + E_{\phi,x}^2 \rangle \right]$$

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

Transverse momentum dependence of $\phi\ \rho_{00}$



Expectation from model with vector meson field



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

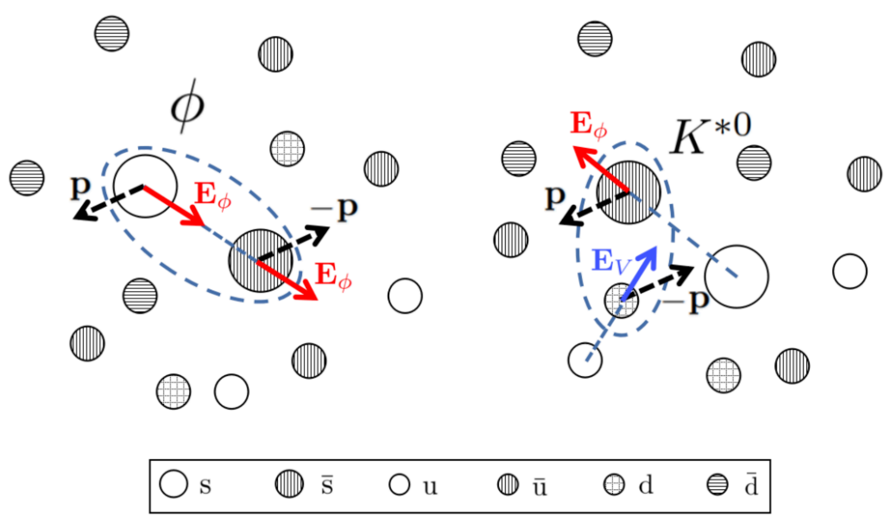
Precision from BES-II:

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

About K* ρ_{00}

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

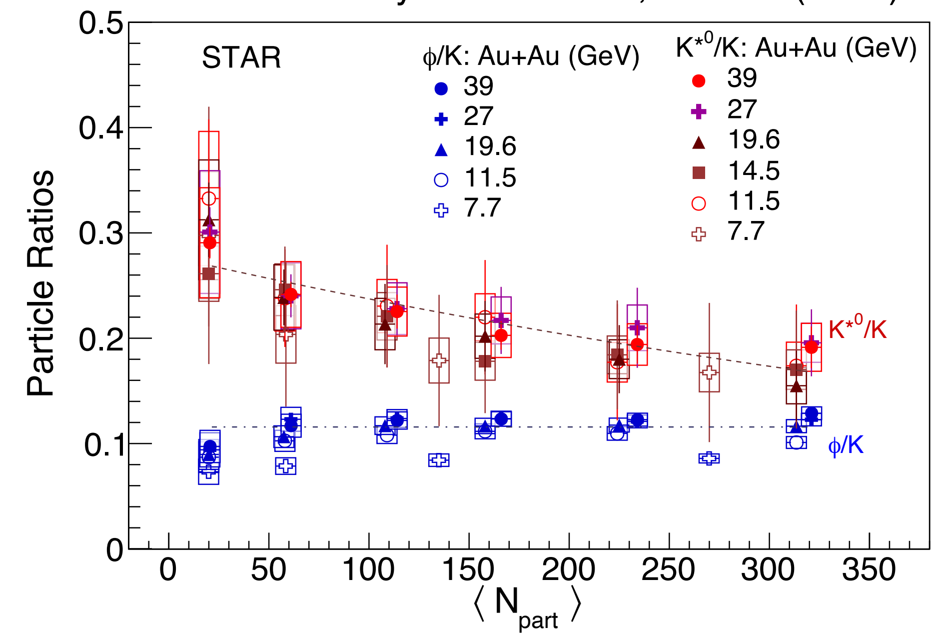
Expectation from model with vector meson field



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 differenct 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 comtribution from vorticity tensor fields. This is beyond the scope of this paper and will be studied in the future.

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

STAR: Phys. Rev. C 107, 034907 (2023)

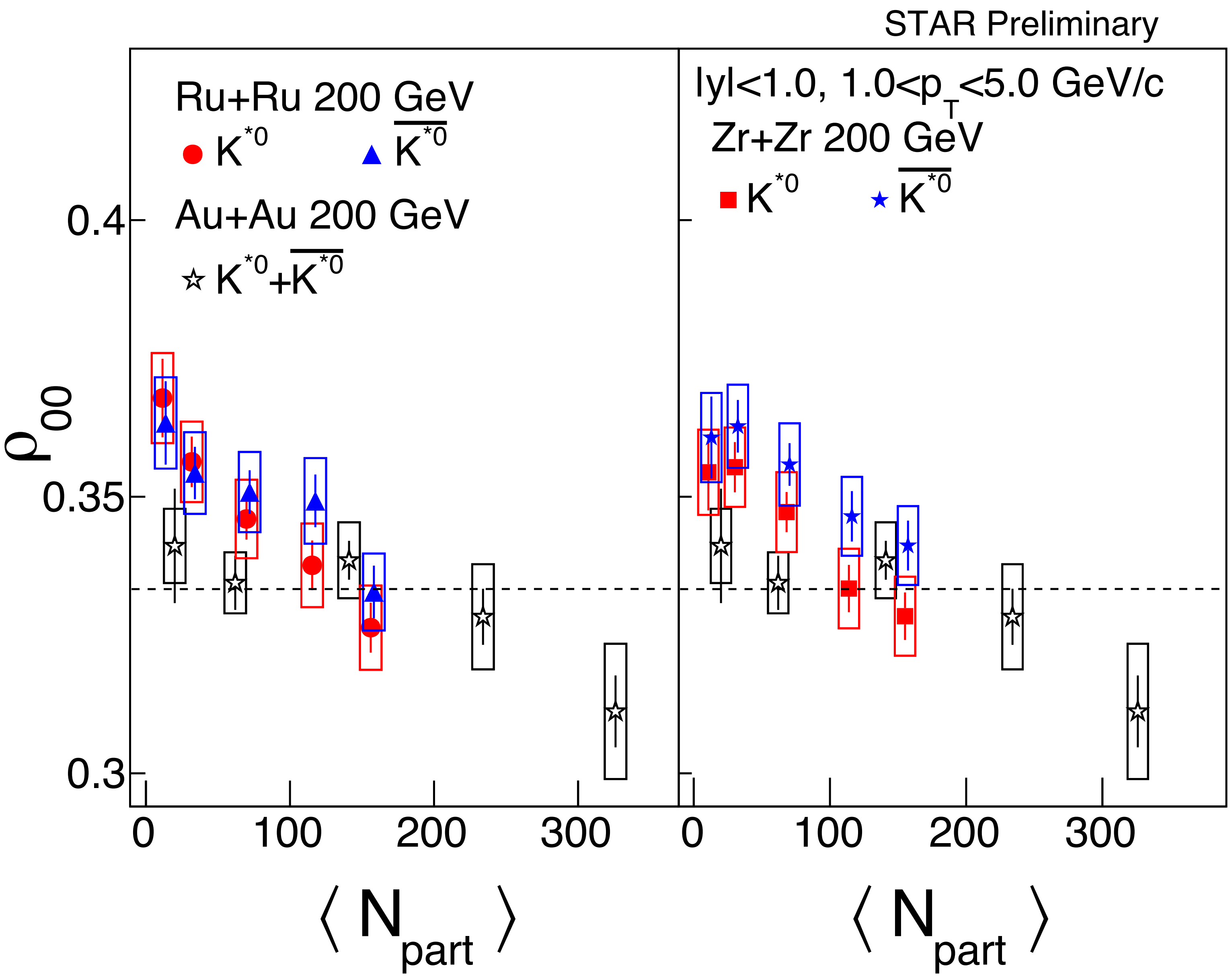


- $(K^*/K)_{central} < (K^*/K)_{peripheral}$
- (ϕ/K) ~ centrality independent

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* ρ_{00} from isobar collisions



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

Summary

- <u>At *RHIC BES*</u>:
- For the first time significantly large ϕ meson ρ_{00} > 1/3 ($\sim 7.4\sigma$)
- K* meson ρ_{00} ~ 1/3

- Surprising magnitude of ϕ ρ_{00}: can not be explained by conventional mechanisms of polarization (e.g. driven by vorticity, EM fields …)

- Many players and new developments:

— 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

<u>Experiment side:</u> 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

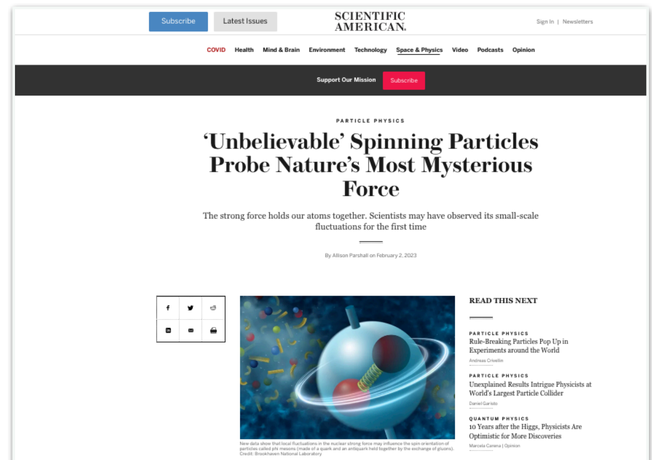
2988 Accesses | **8** Citations | **165** Altmetric | Metrics

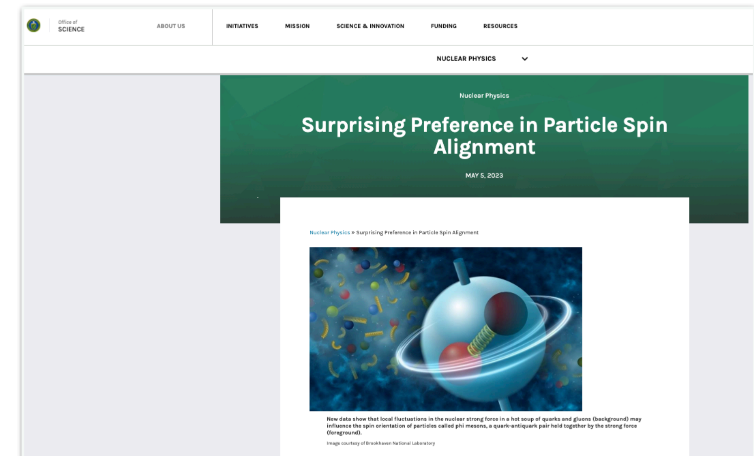
Pattern of global spin alignment of ϕ and K^{*0} mesons in heavy-ion collisions #1

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]

pdf links DOI cite datasets claim reference search 27 citations



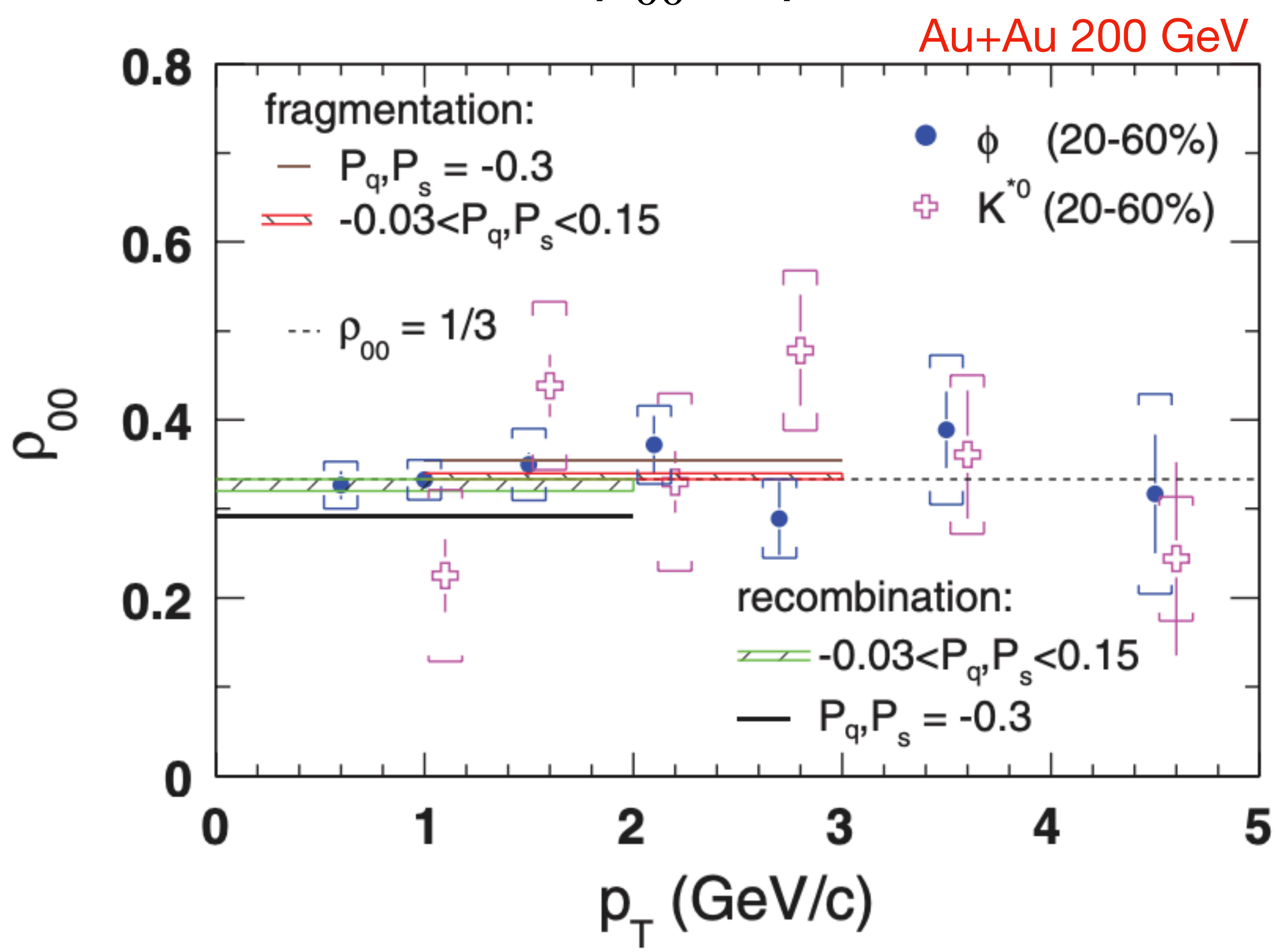


Thank you for your attention

Back up slides

First spin alignment from RHIC

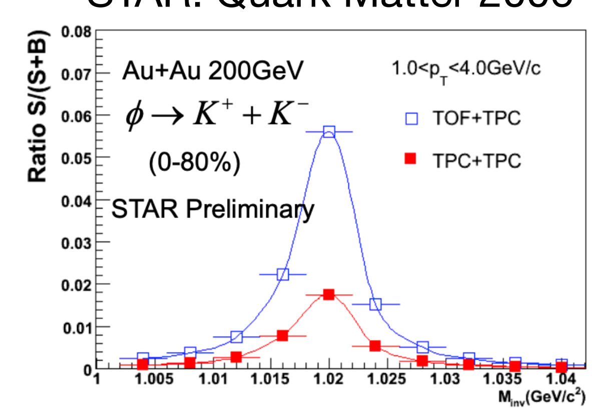
- STAR reported first ρ_{00} of ϕ and K* wrt reaction plane in 2008 using ~ 23 million events:



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

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

STAR: Quark Matter 2006

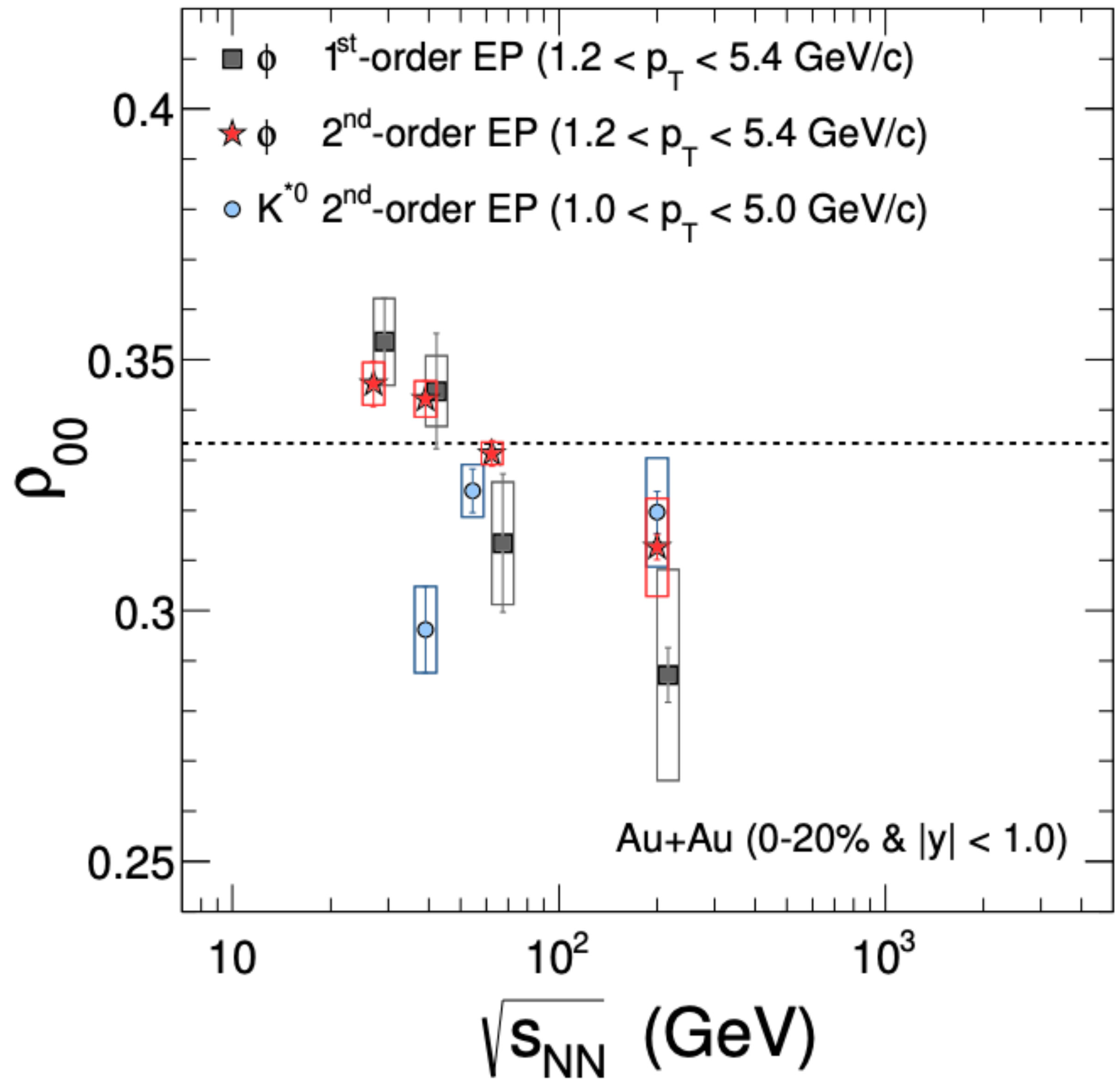


Advantages in measurements from BES

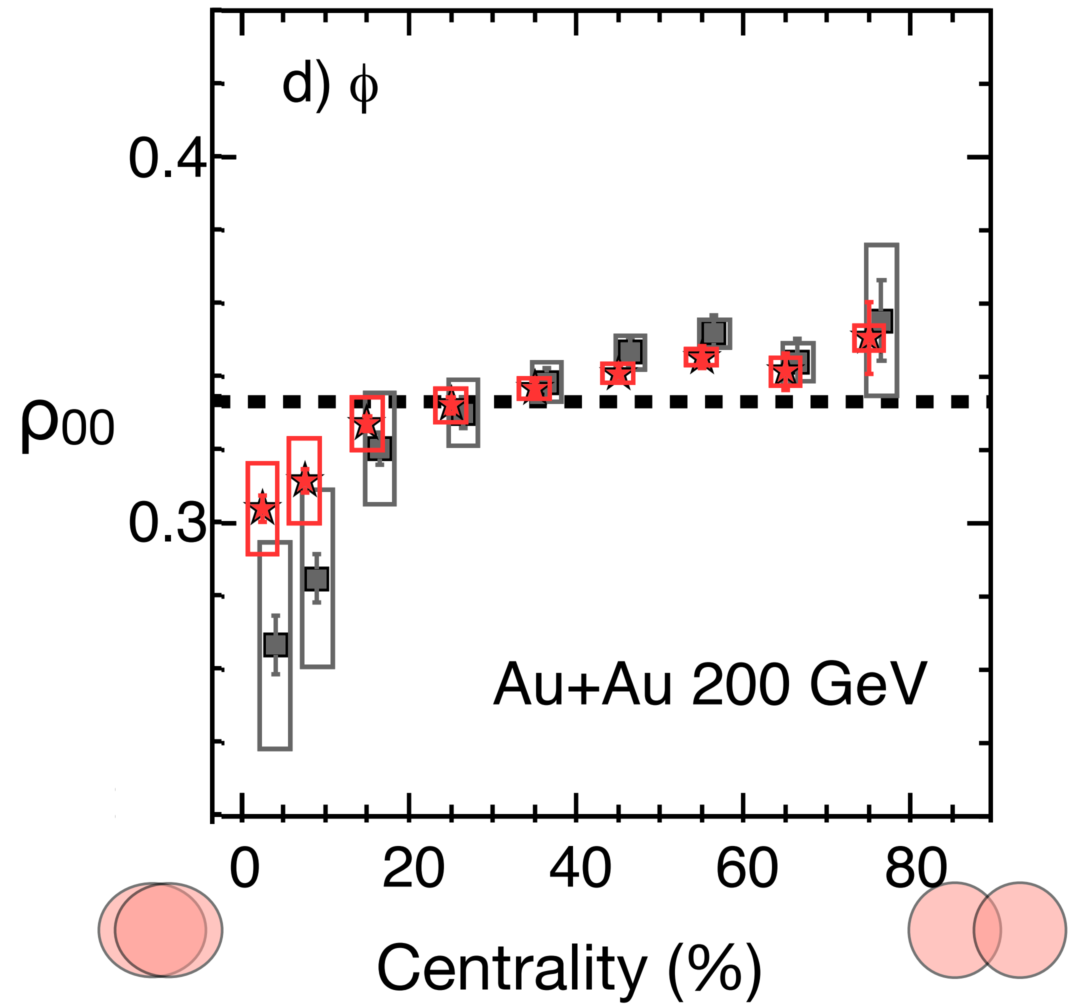
- STAR upgrade: Benefitted from Time of Flight (ToF), better particle identification, improved signal-to-noise ratio
- Analysis method: Improved understanding of detector corrections (efficiency, acceptance and event plane resolutions)

Tang et.al. Phys. Rev. C 98, 044907 (2018)
Lan et. al. Phys. Lett. B 780, 319, (2018)

Energy dependence of ϕ and K* ρ_{00} in central collisions



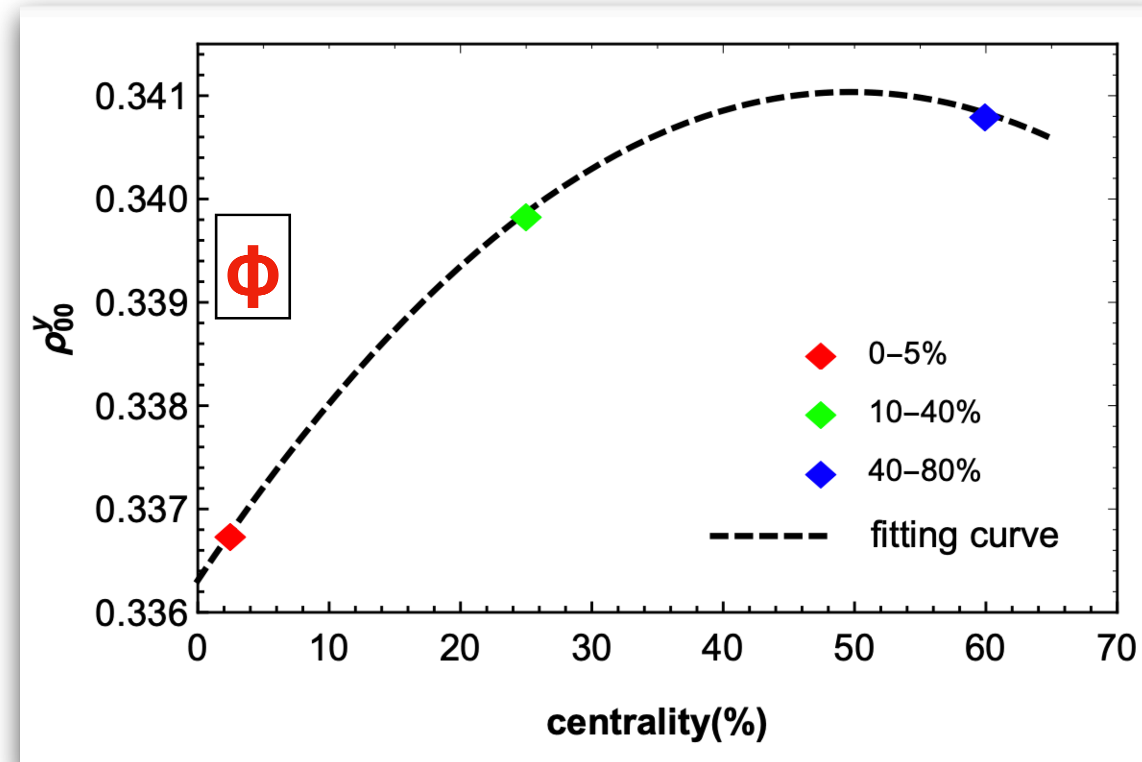
Centrality dependence of ϕ ρ_{00}



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

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

Expectation from model with vector meson field

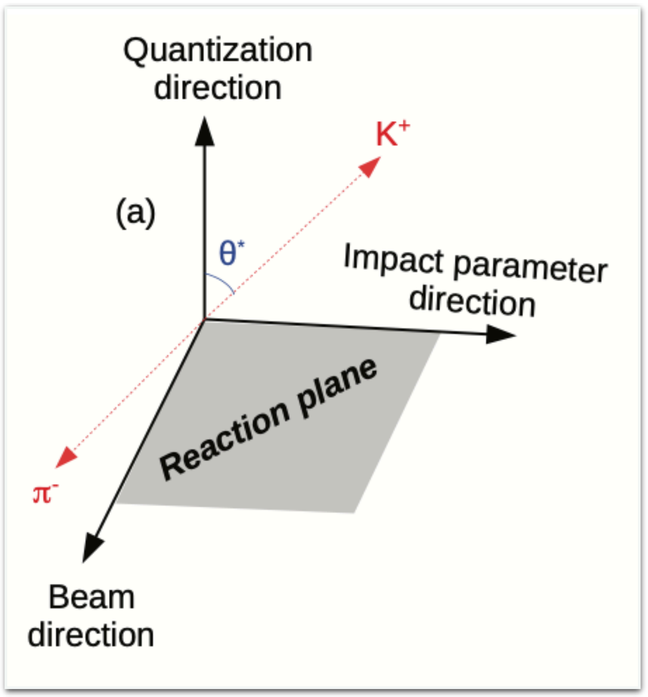


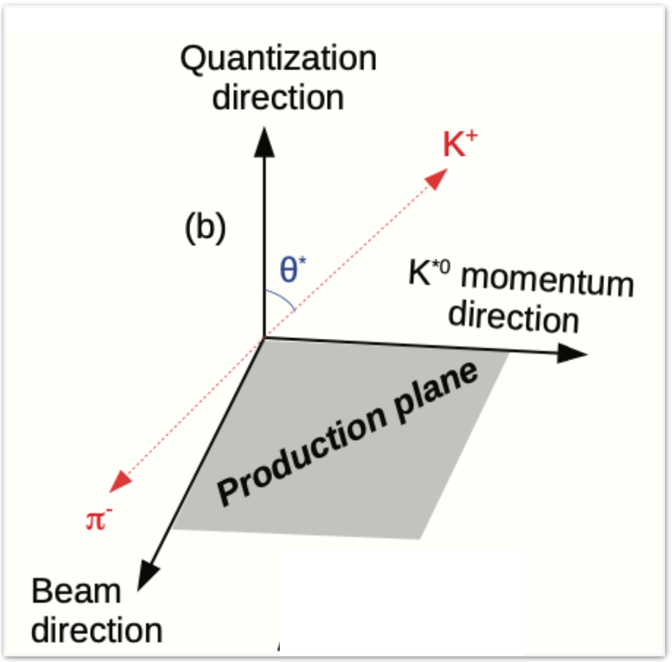
Can accommodate positive deviation in mid-central and peripheral collisions

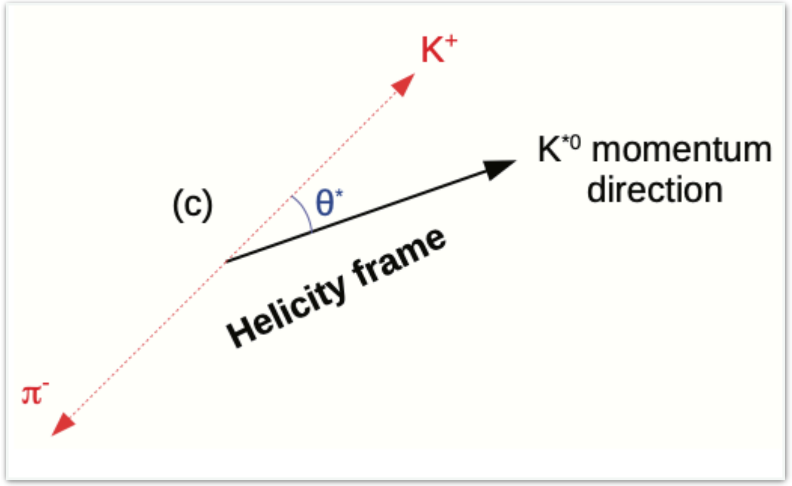
Sheng el. al., arXiv: 2205.15689
Sheng el. al., Phys Rev D 101, 096005 (2020)
Sheng el. al., Phys Rev D 102, 056013 (2020)

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

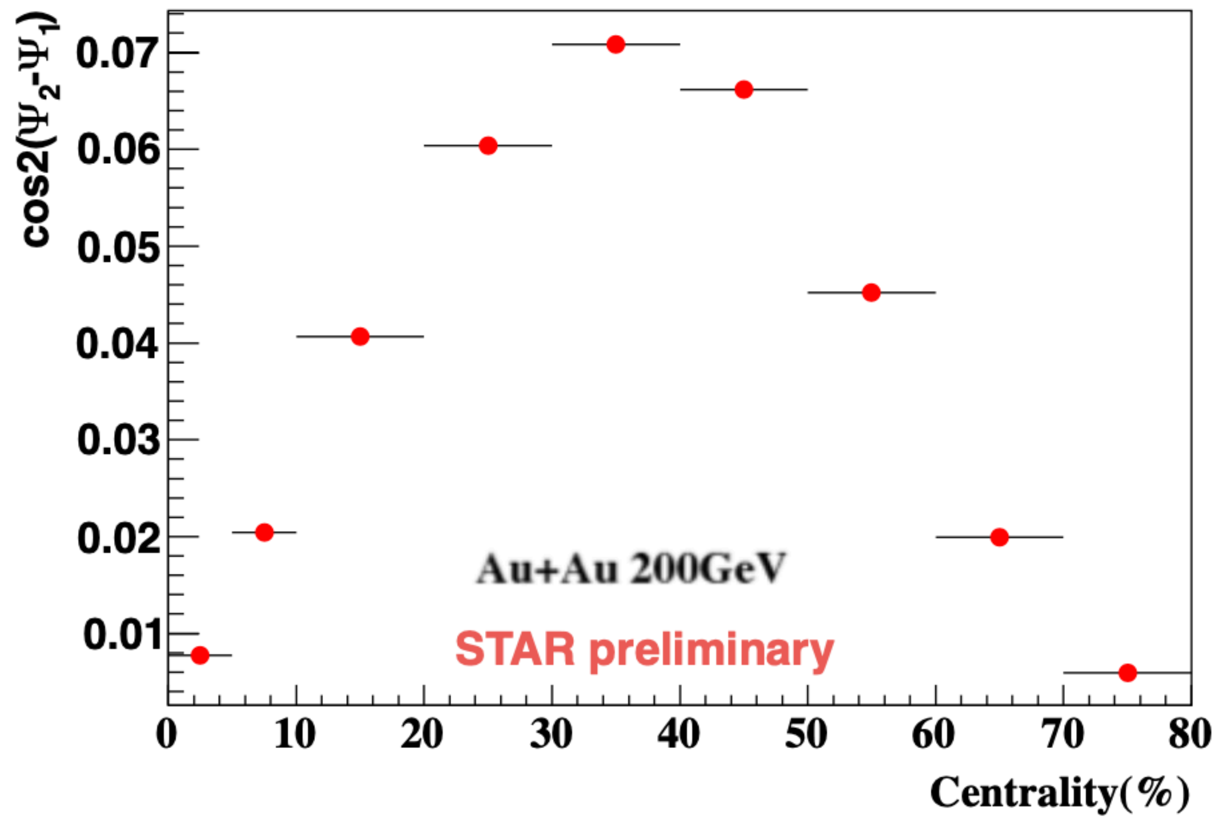
Event plane de-correlation effect

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

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

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

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



Event plane de-correlation effect needed to be considered carefully

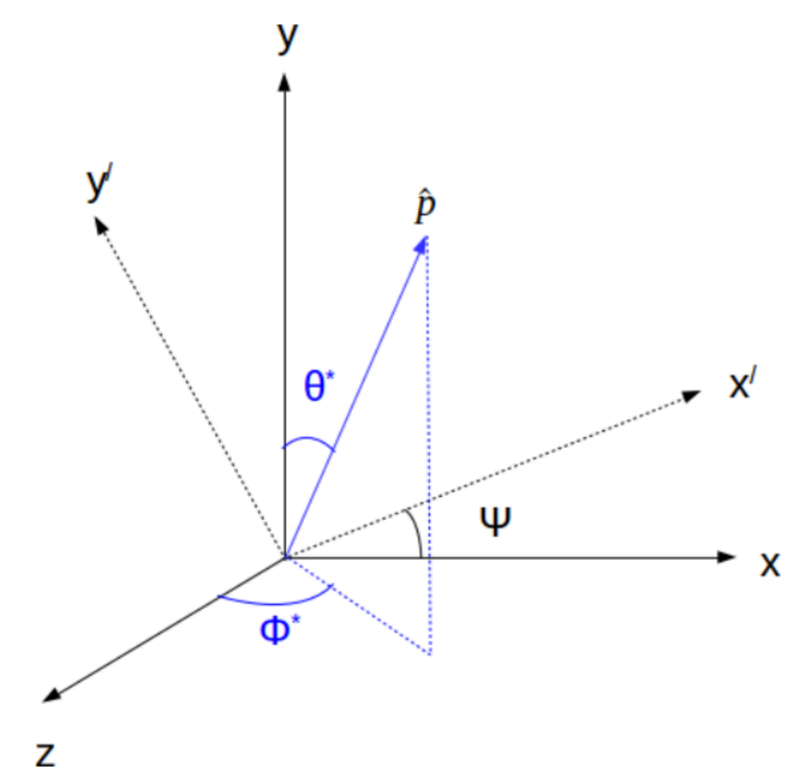
Tang et.al. Phys. Rev. C 98, 044907 (2018)

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:

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

....

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

....

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

Averaging over all events:

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

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

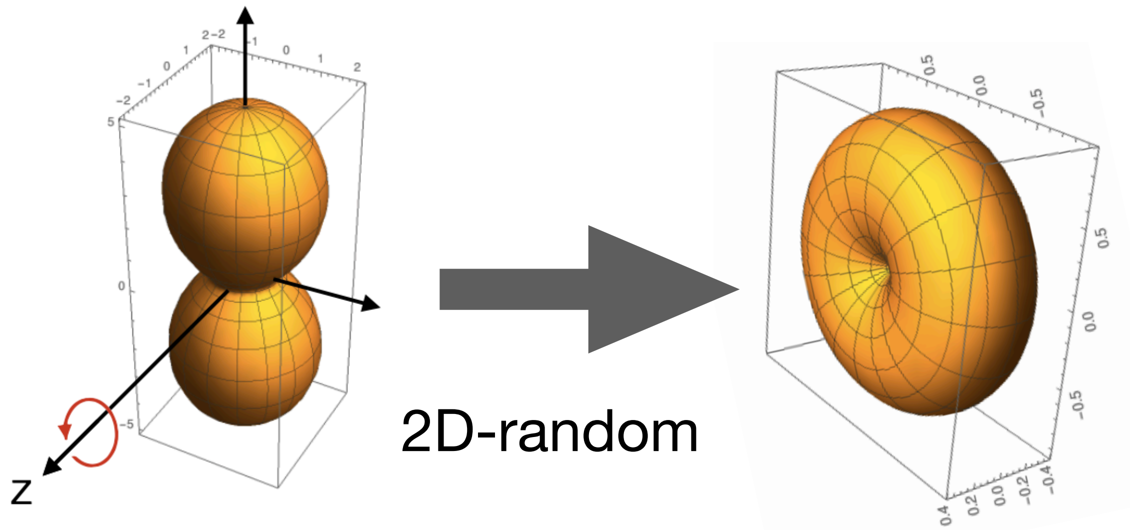
$R \rightarrow$ Event plane resolution

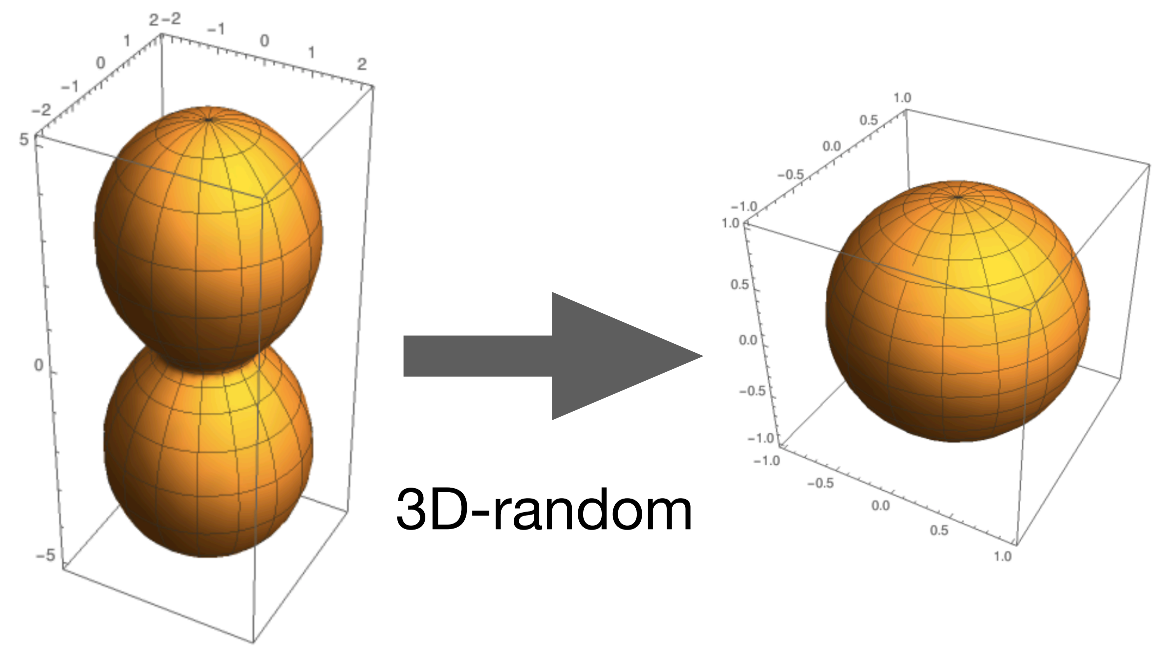
Polarization wrt random plane

ρ_{00} can be measured using a random plane; Naive expectation $\rho_{00}^{\text{random}} \sim \dfrac{1}{3}$

(e.g. using random number but depends on how it is randomized)

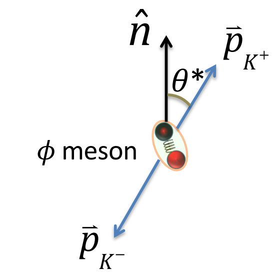
If the quantization axis is randomized in 2D-plane (x, y), it does not guarantee the ρ_{00} to be 1/3

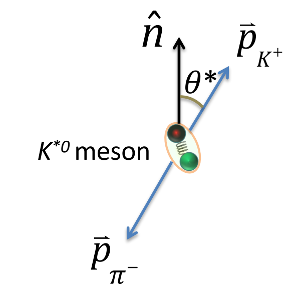


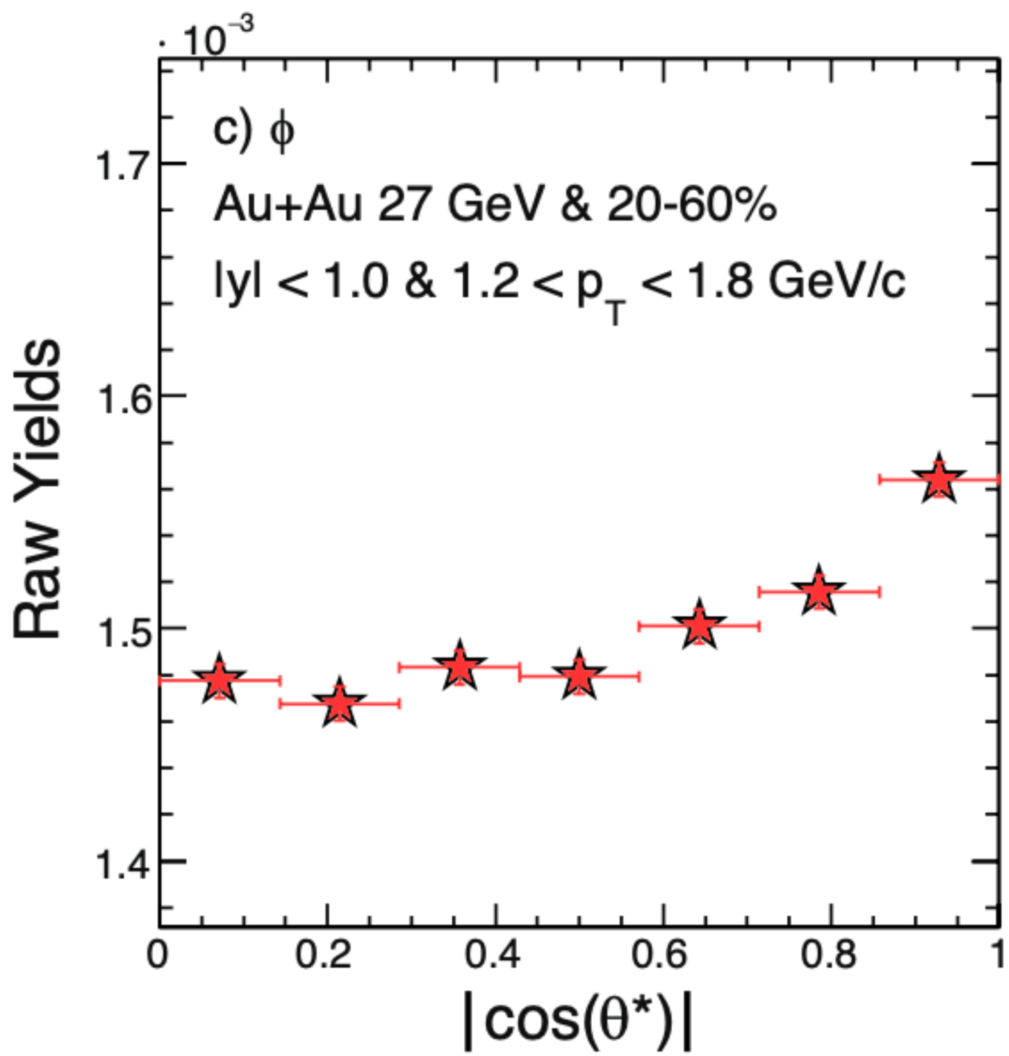


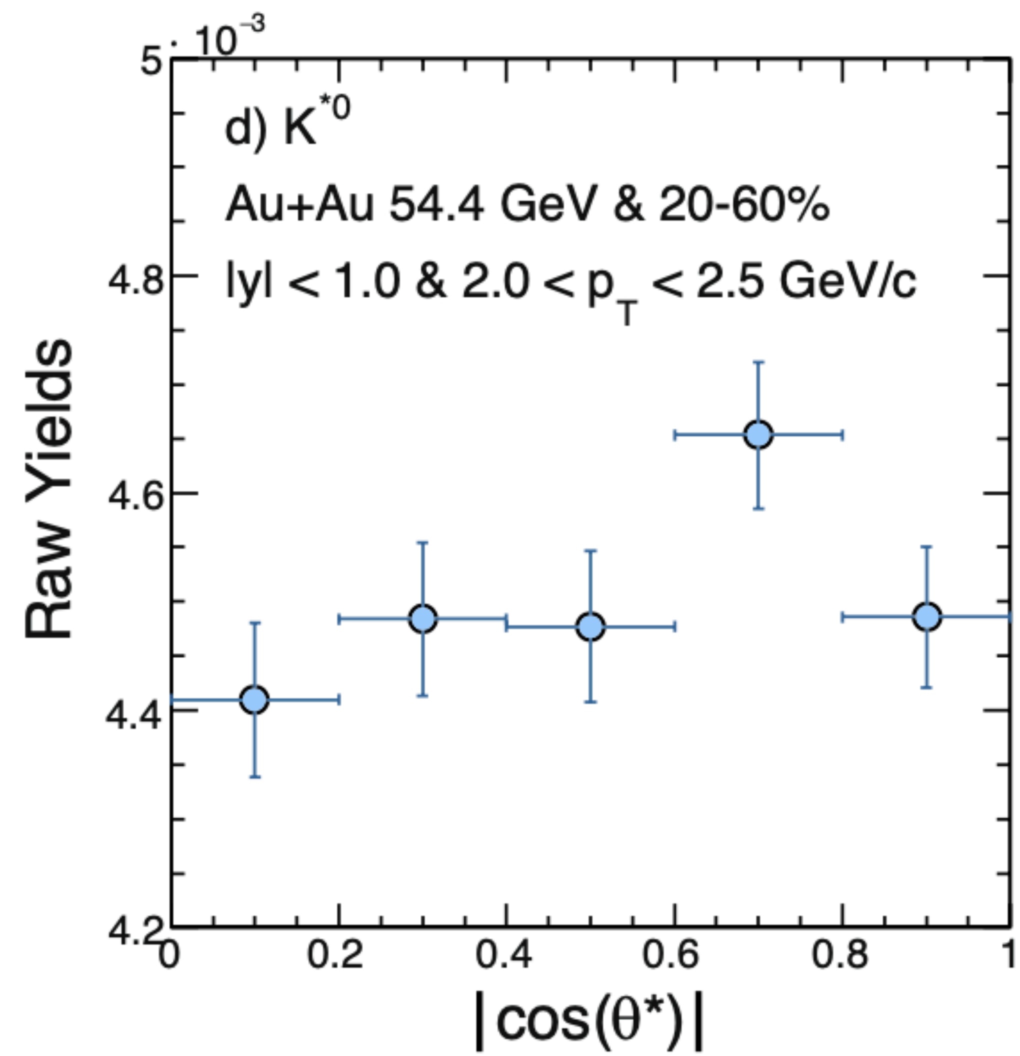
So the quantization axis has to be randomized in 3D-plane (x, y, z), to get the ρ_{00} to be ~ 1/3

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





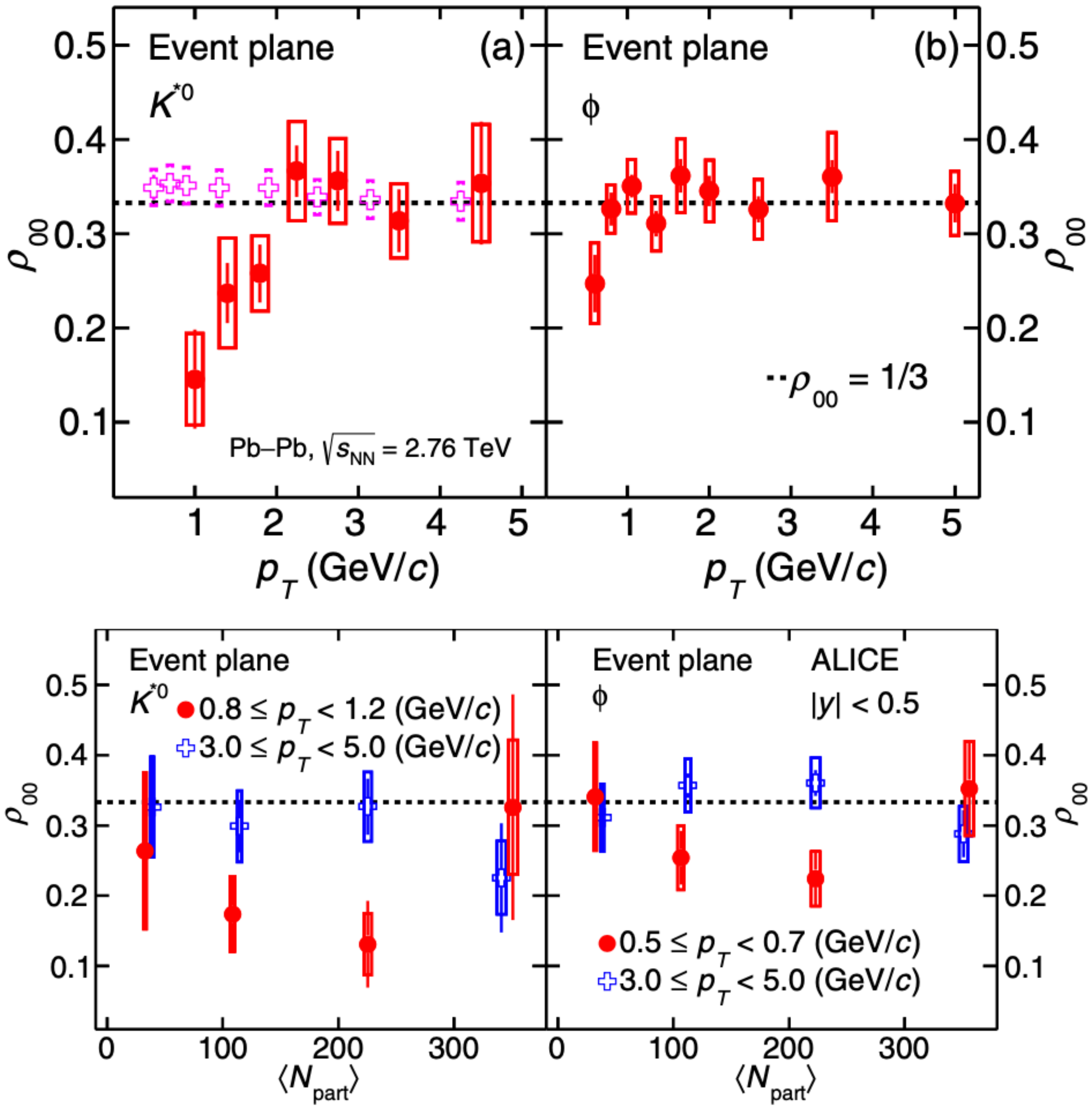




Raw yield is calculated in $\cos\theta^*$ bins

Spin alignment from Pb+Pb collisions at LHC

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



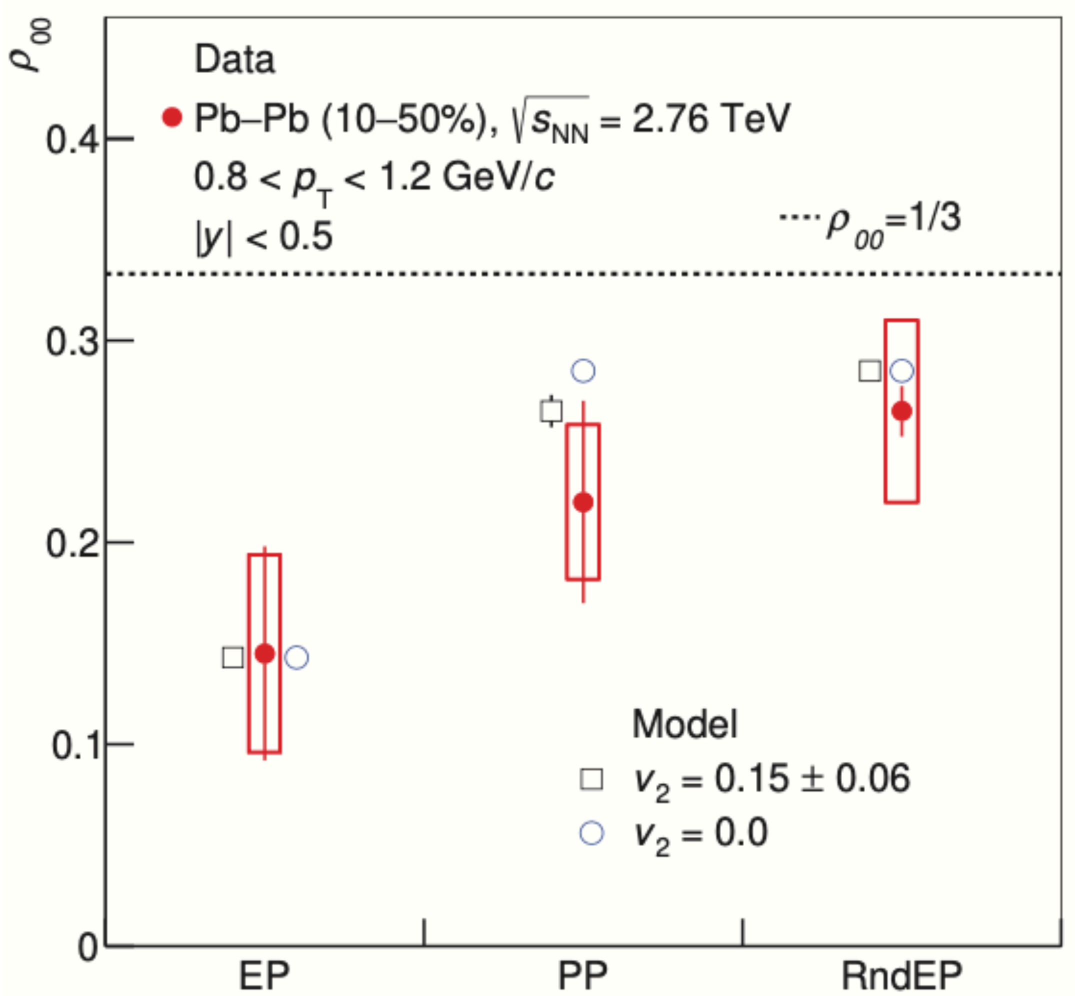
ALICE: Phys. Rev Lett 125, 012301 (2020)

- For both K* and ϕ:
- $\rho_{00}^{EP} \leq \frac{1}{3}$

Significance of deviation
for K* $\leq 2.6\sigma$
for $\phi \leq$ 1.9σ

Spin alignment between PP and EP

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



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

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

- ρ_{00}^{EP} and ρ_{00}^{PP} are related by:
- $\left(\rho_{00}^{PP} - \frac{1}{3}\right) = \left(\rho_{00}^{EP} - \frac{1}{3}\right)\frac{1+3v_2}{4}$

First measurement of charged K* ρ_{00}

Naive expectation

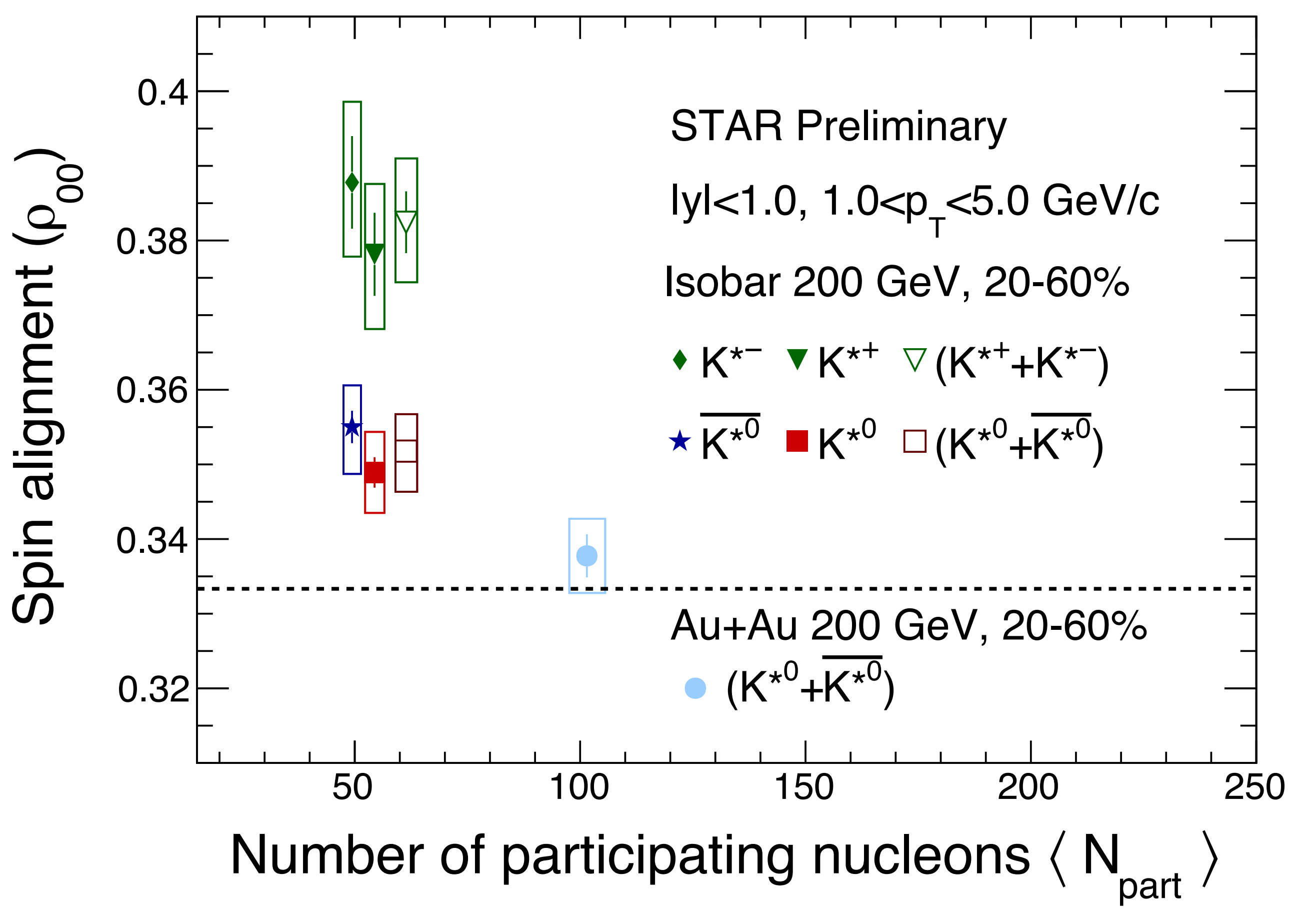
Particle Species	Magnetic moment (μ_N)
$K^{*0}(d\bar{s})$	$\mu_d \approx -0.97,\ \mu_{\bar{s}} \approx 0.61\mu_N$
$K^{*+}(u\bar{s})$	$\mu_d \approx 1.85,\ \mu_{\bar{s}} \approx 0.61\mu_N$

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

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

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

Observation from STAR



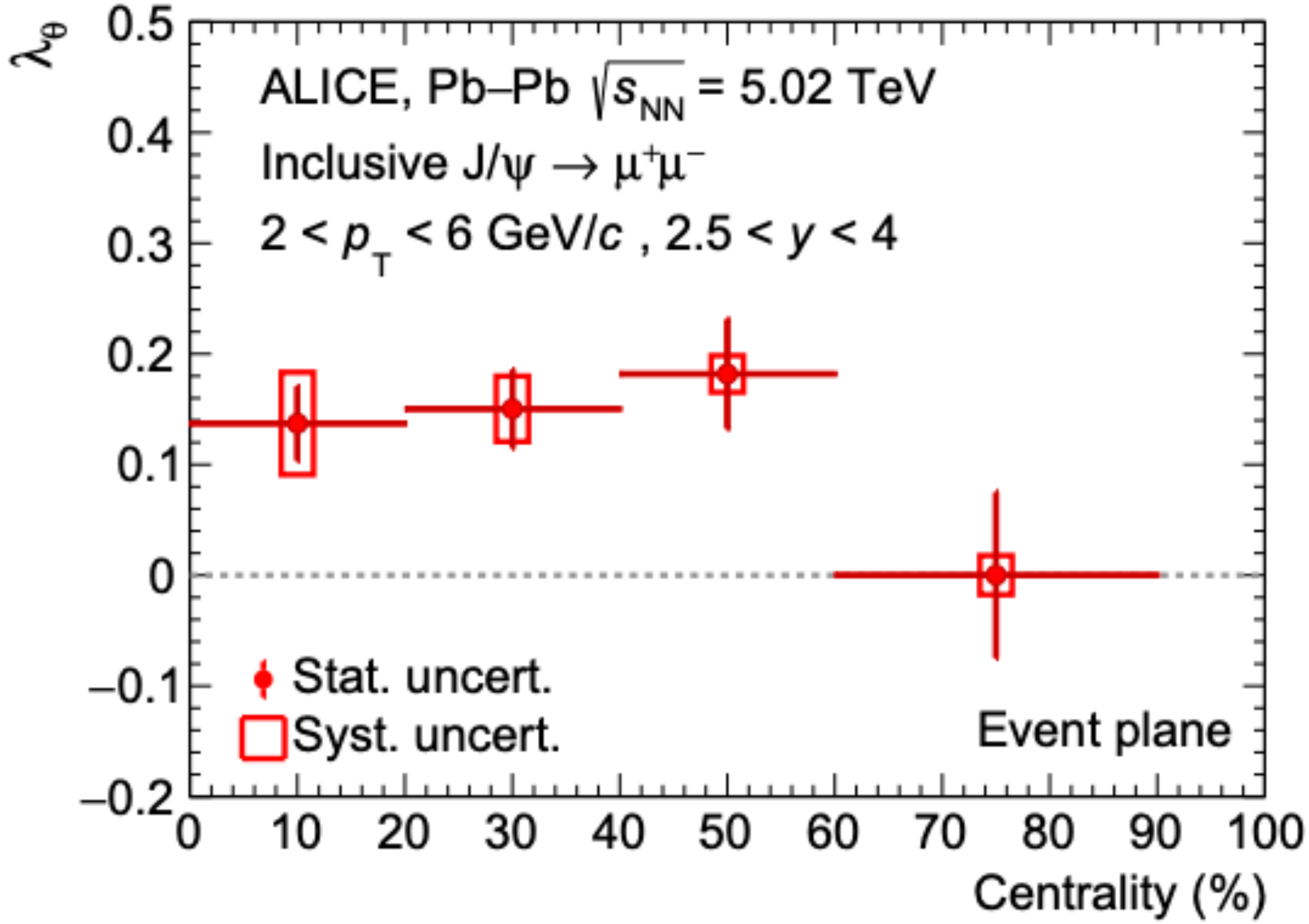
STAR: Quark Matter 2022

- First observation of $K^{*\pm}$ ρ_{00} in HIC
- Surprising ordering in ρ_{00}

$$K^{*+} + K^{*-} \ >> \ K^{*0} + \overline{K}^{*0}$$

(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

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

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

ALICE: 2204.10171