Measurements of vector meson spin alignment in heavy-ion collisions

Diyu Shen

Fudan University

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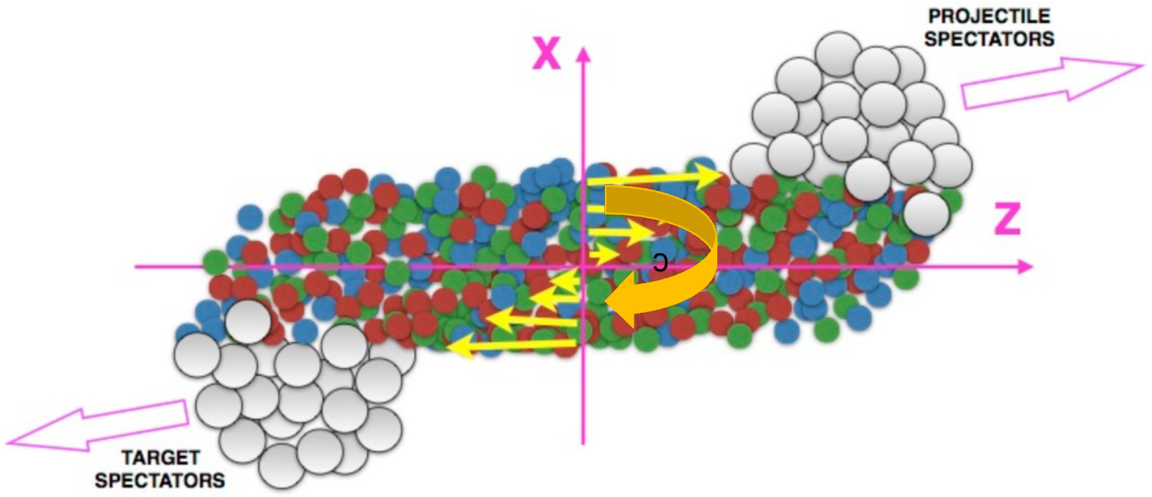
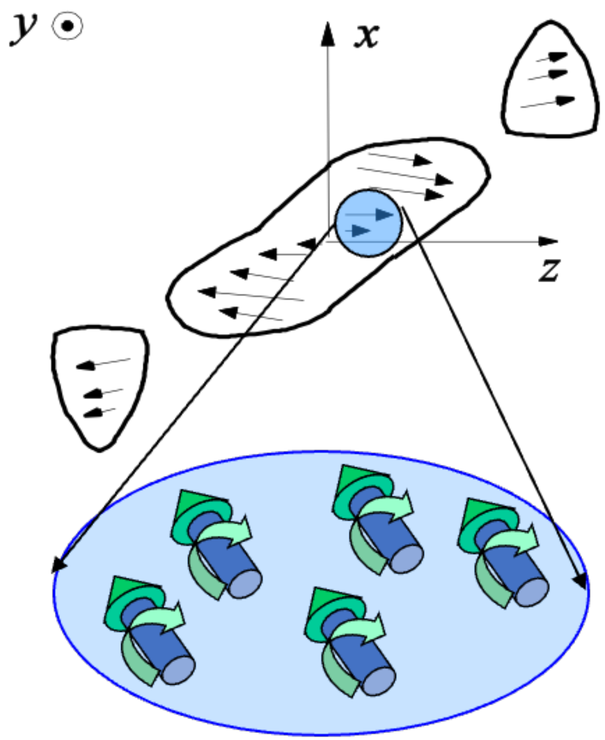
Outline

- Introduction of global polarization in heavy-ion collisions
- Measurements of spin alignment of vector mesons at RHIC and LHC
- Summary and outlook

Global polarization in HIC

Liang, Wang Phys. Rev. Lett. **94**, 102301(2005); Phys. Lett. B **629**, 20 (2005)

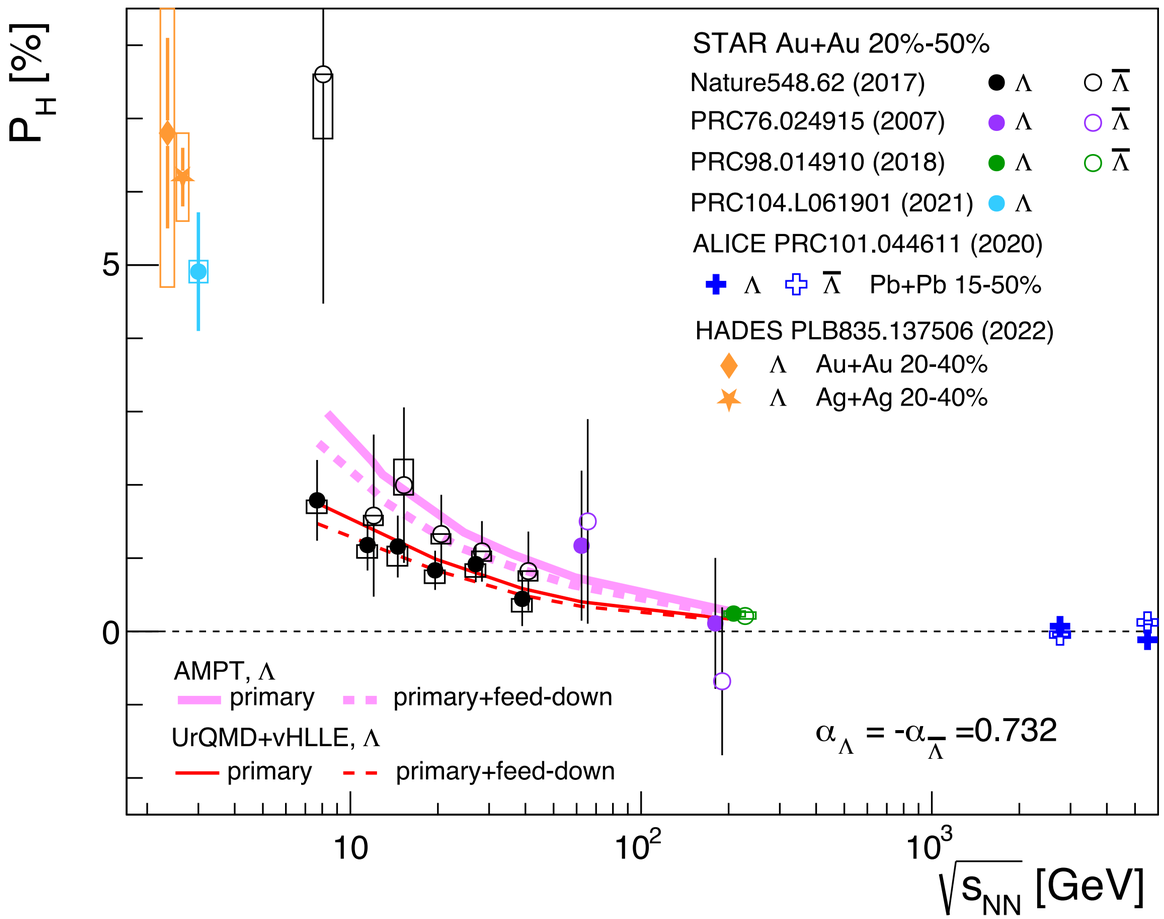


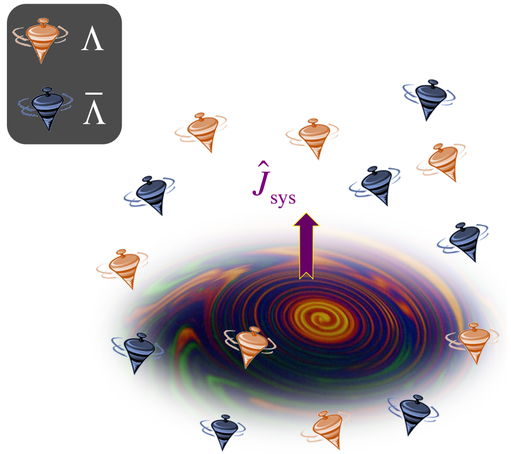


Large OAM is deposited in the interaction region

- The initial momentum gradient will result in a rotating QGP in non-central heavy-ion collisions.
- Quarks with spin 1/2 will be polarized due to spin-orbit coupling.
- This effect may not be washed out during interactions and hadronization.

Global polarization of Λ



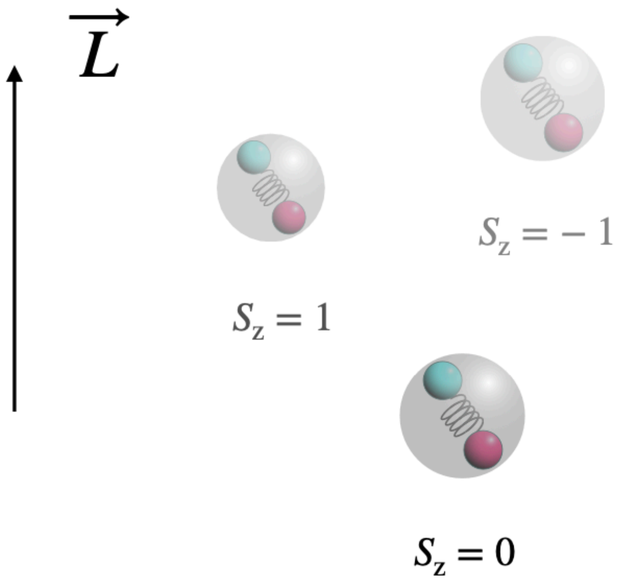


$$\omega \approx k_B T(\overline{\mathcal{P}}_{\Lambda'} + \overline{\mathcal{P}}_{\bar{\Lambda}'})/\hbar$$

- The global polarization of Lambda serves the evidence of the rotating QGP, the most vortical fluid $(9\pm1)\times10^{21}$ s^{-1}

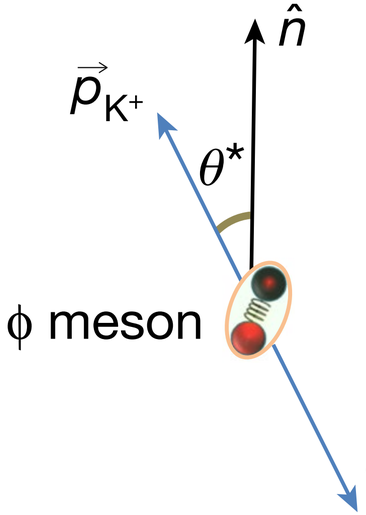
Spin alignment of vector mesons

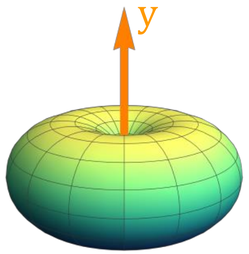
Z.T. Liang et al., Physics Letters B 629 (2005) 20–26



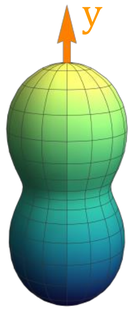
$$\rho^V = \begin{pmatrix} \rho_{11} & \rho_{10} & \rho_{1-1} \\ \rho_{01} & \rho_{00} & \rho_{0-1} \\ \rho_{-11} & \rho_{-10} & \rho_{-1-1} \end{pmatrix}$$

- Spin state of spin 1 particle along OAM.
- ρ_{00} can be determined by the momentum distribution of decay products.
- From the measurements of Lambda polarization, the ρ_{00} was expected to be ρ_{00} - 1/3 ~ -10^{-4} (recombination).





$\rho_{00} < 1/3$

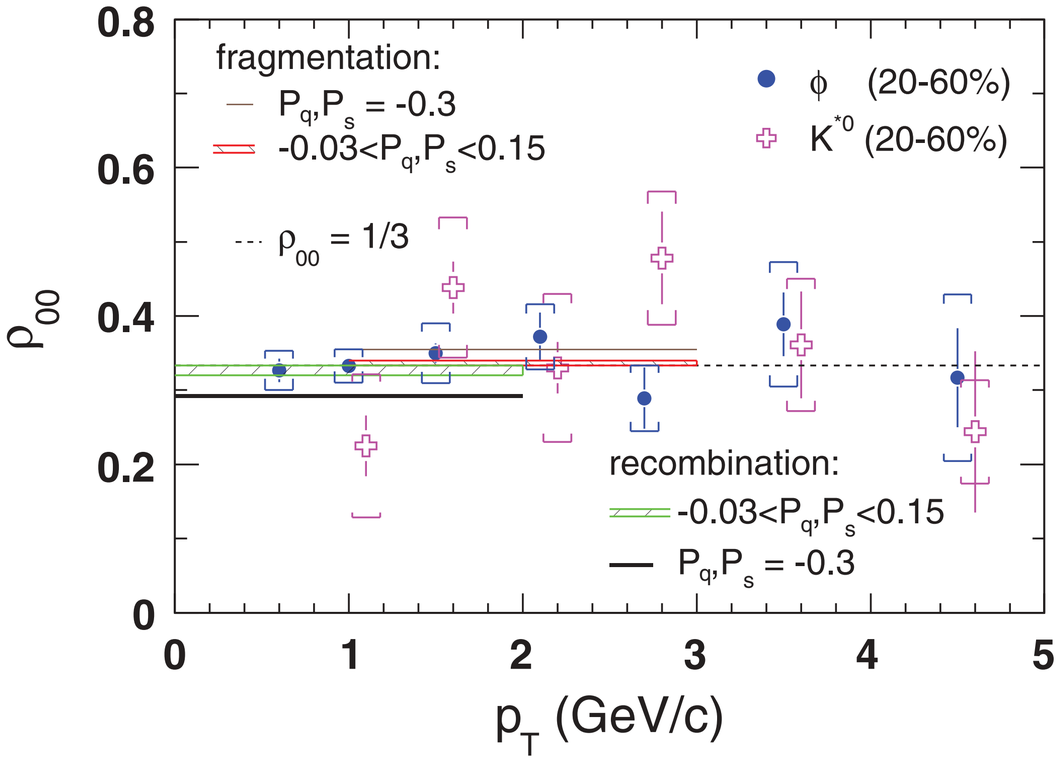


$\rho_{00} > 1/3$

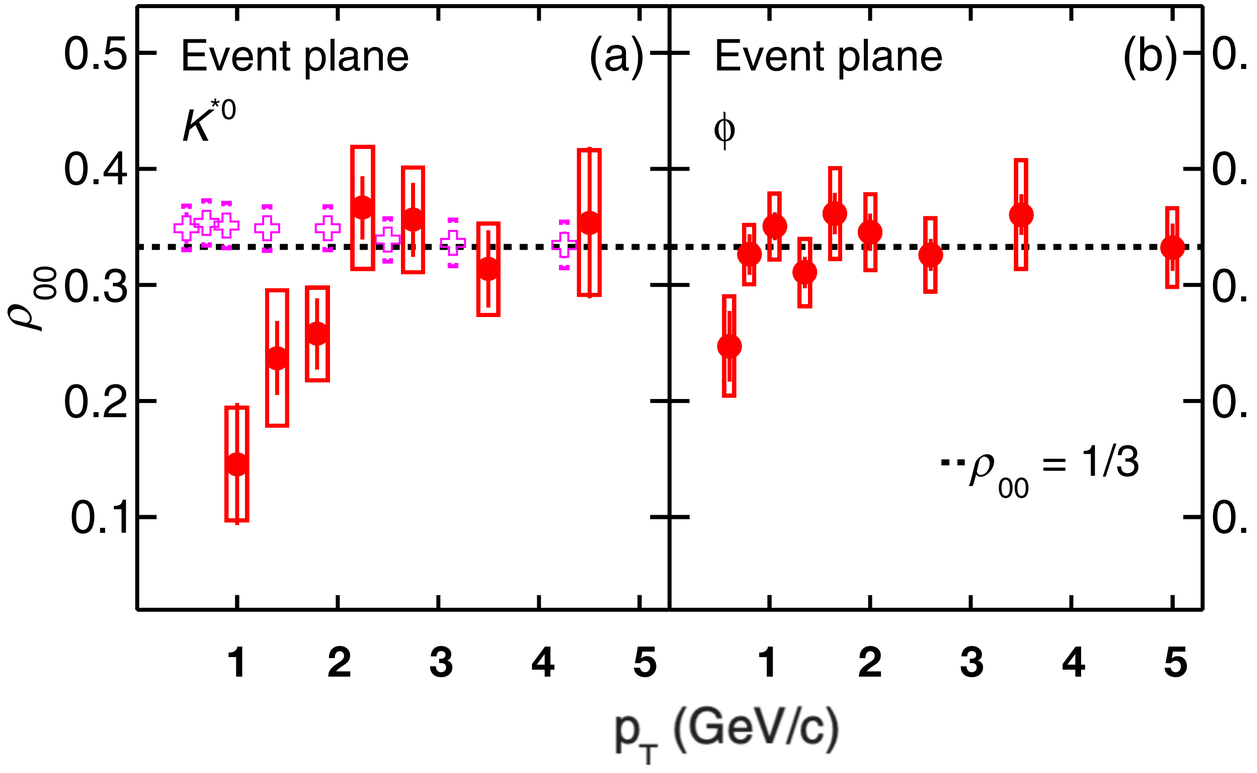
$$\frac{dN}{d(\cos\theta^*)} \propto (1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta^*$$

Experimental measurements of ϕ, K*

STAR Col. Phys. Rev. C **77**, 061902® (2008)

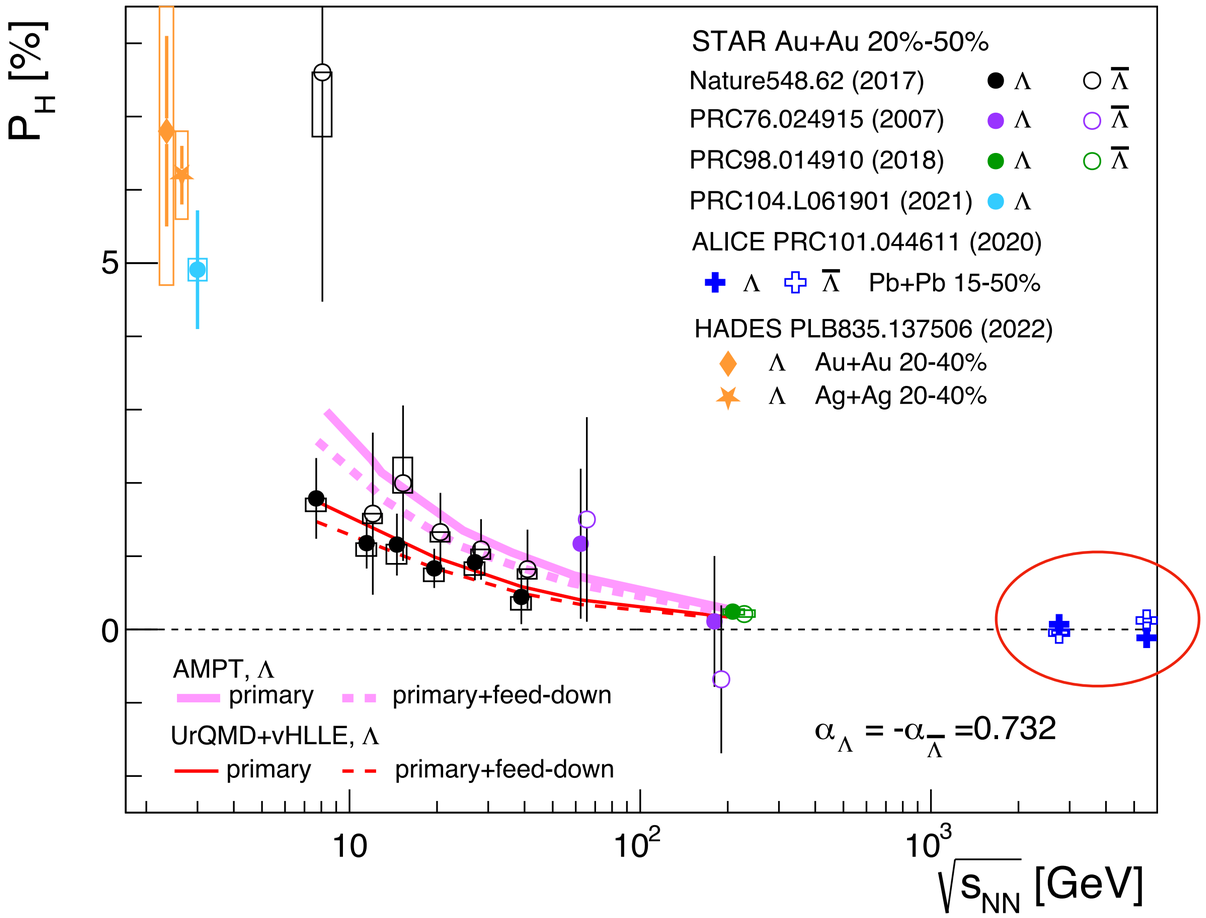


ALICE Col. Phys. Rev. Lett. 125, 012301 (2020)

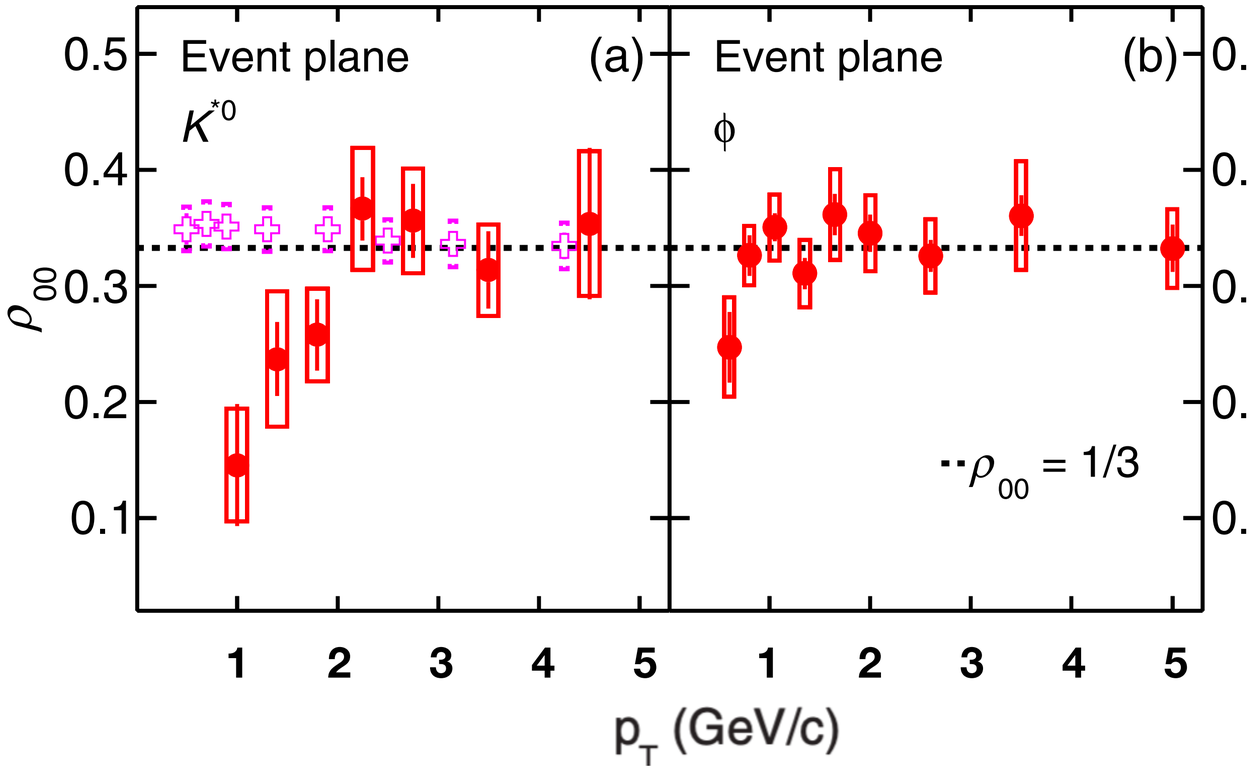


- Early data in Au+Au 200 GeV have large uncertainties.
- ρ_{00} is found to be less than 1/3 (~3σ) at low p_T in Pb-Pb 2.76 TeV, unexpectedly large.

Experimental measurements of ϕ, K*



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



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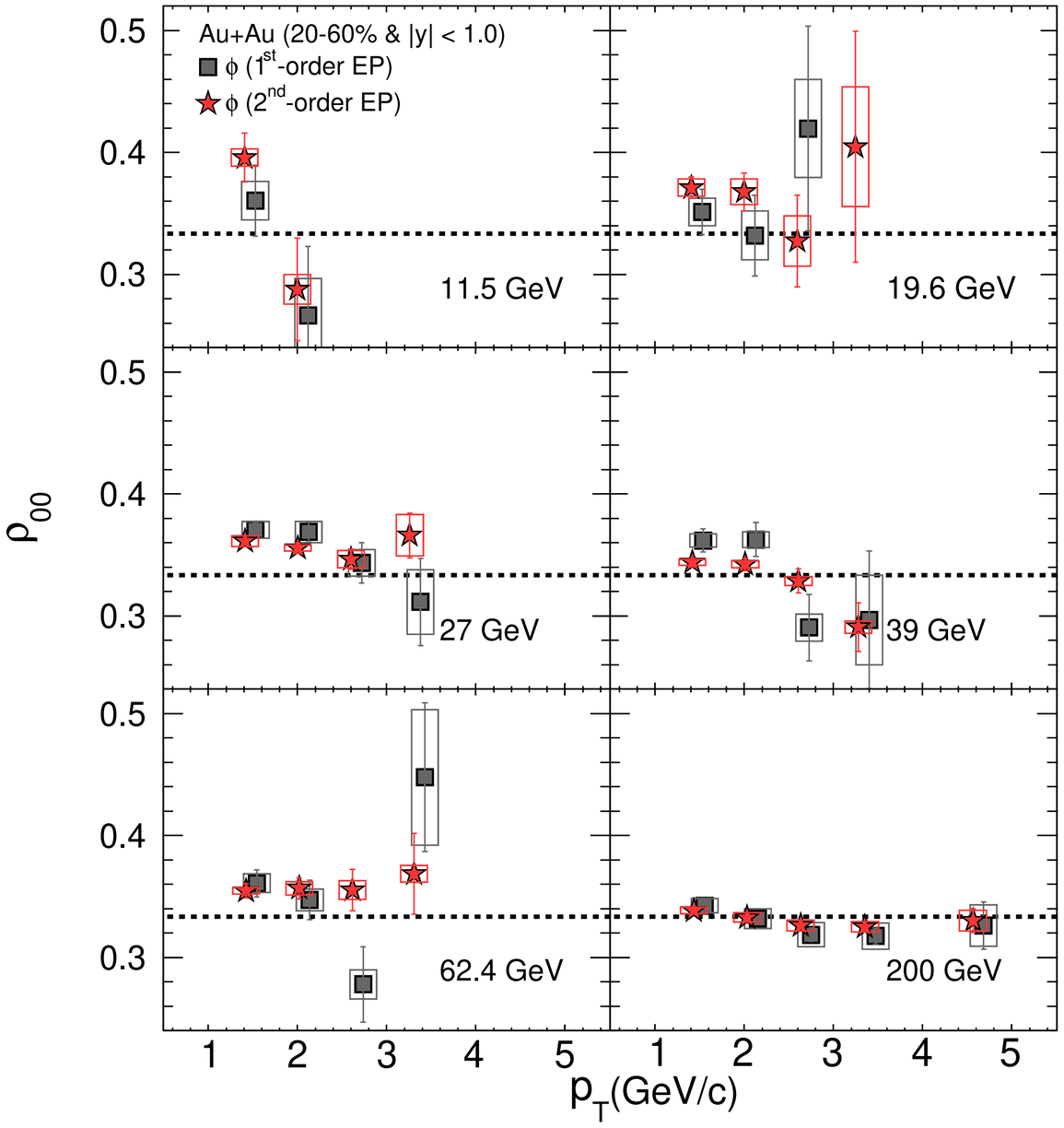
New measurements of ϕ, K* at RHIC



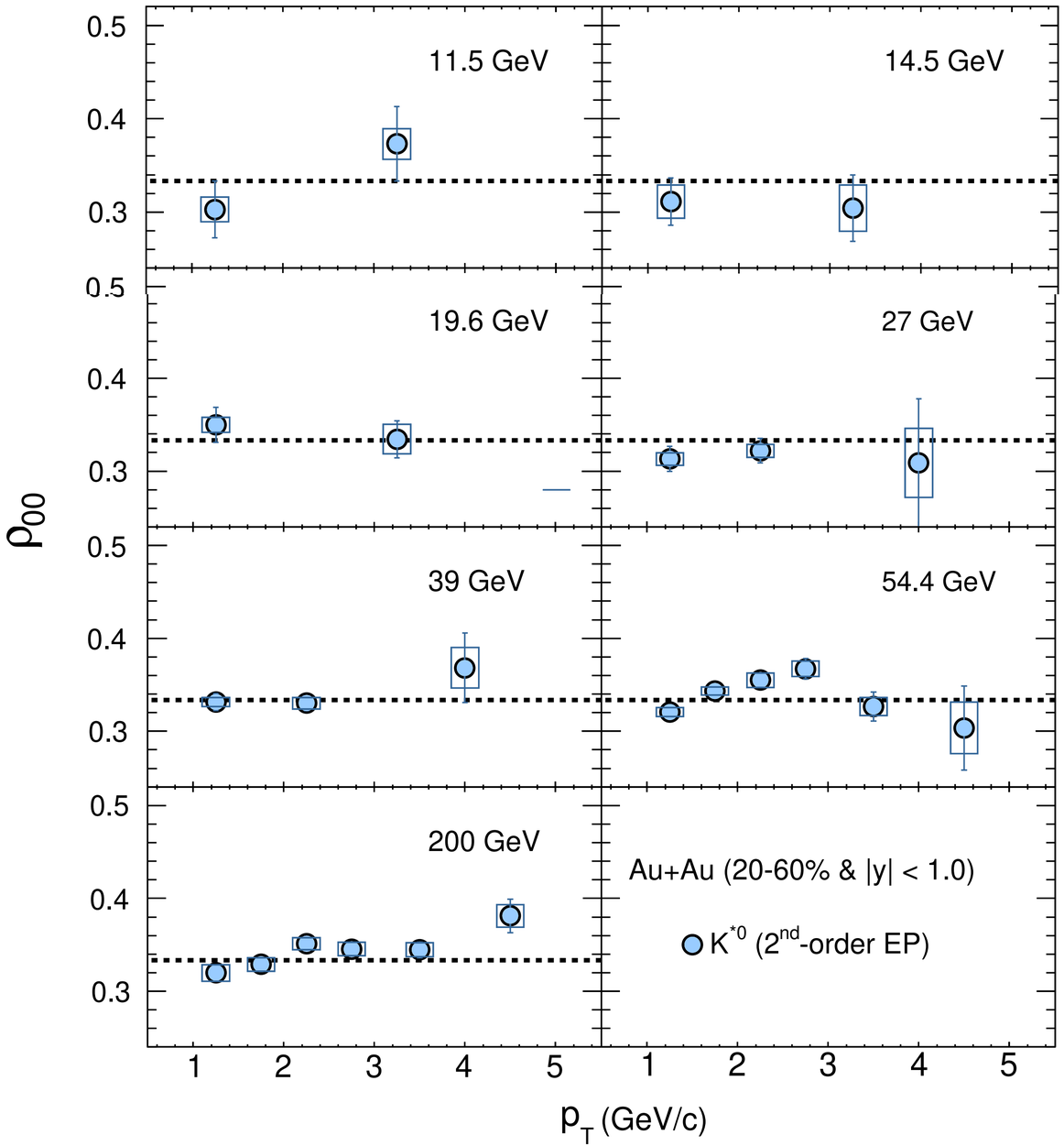
- New measurements extend the study to lower energies with high statistics, @200 GeV, a factor of ~50 more event statistics analyzed.

- We see that the signal for the ϕ meson occurs mainly within ~1.0-2.4 GeV/c; at larger p_T the results can be regarded as being consistent with 1/3 within ~2σ or less.

  * 1st order EP: ZDC or BBC
  * 2nd order EP: TPC

STAR Col. Nature 614, 244 (2023)

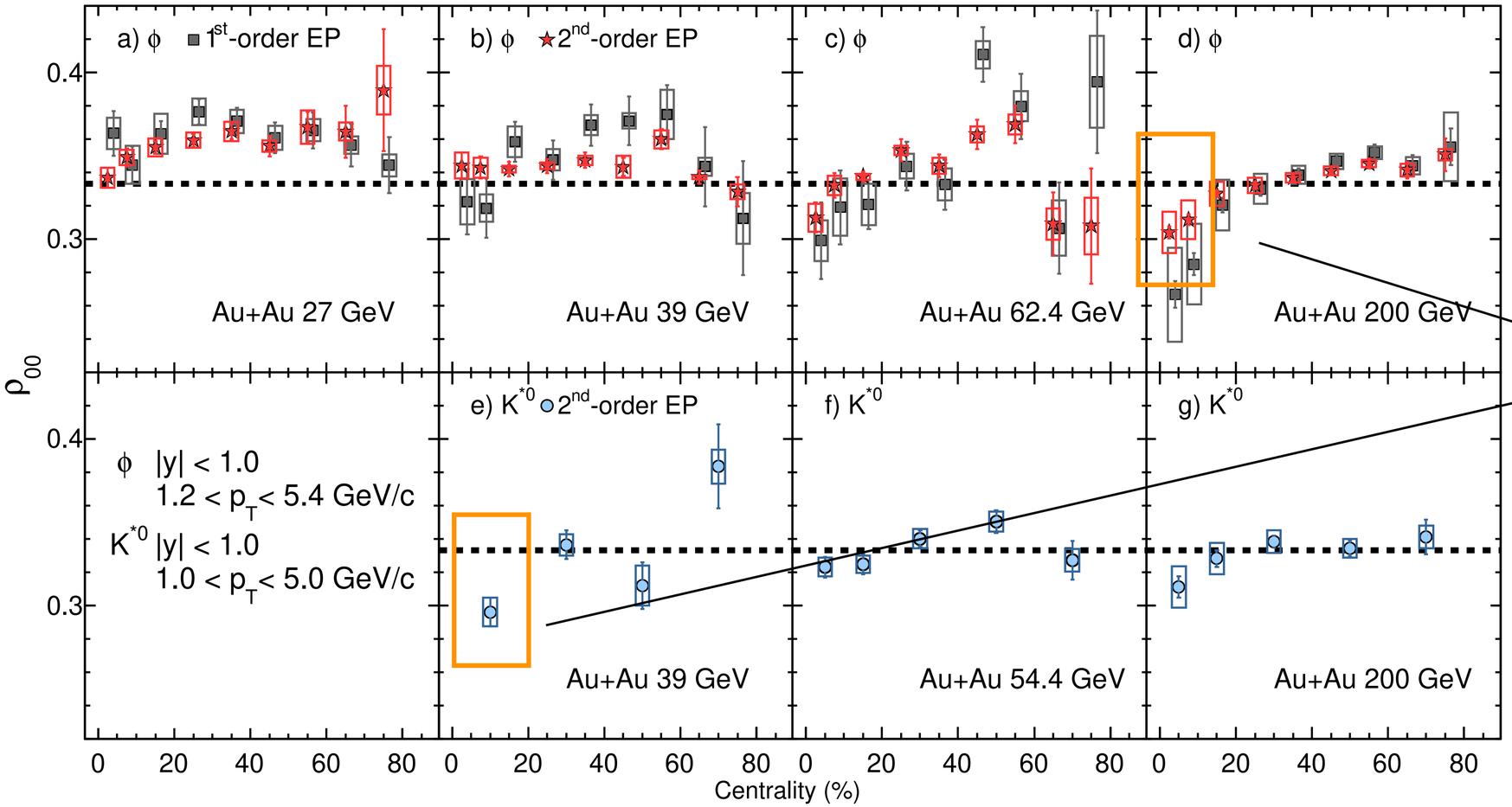
New measurements of ϕ, K* at RHIC



- K^{*0} is a combination of K^{*0} and anti-K^{*0}
- Different from the ϕ meson data, the K^{*0} data is consistent with 1/3, within statistics and systematical uncertainties.

STAR Col. Nature 614, 244 (2023)

Centrality dependence of ϕ, K* at RHIC



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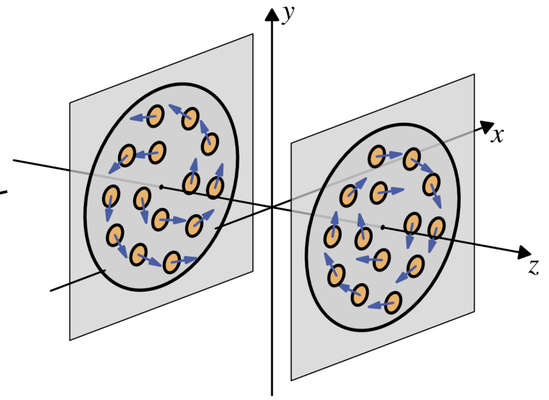
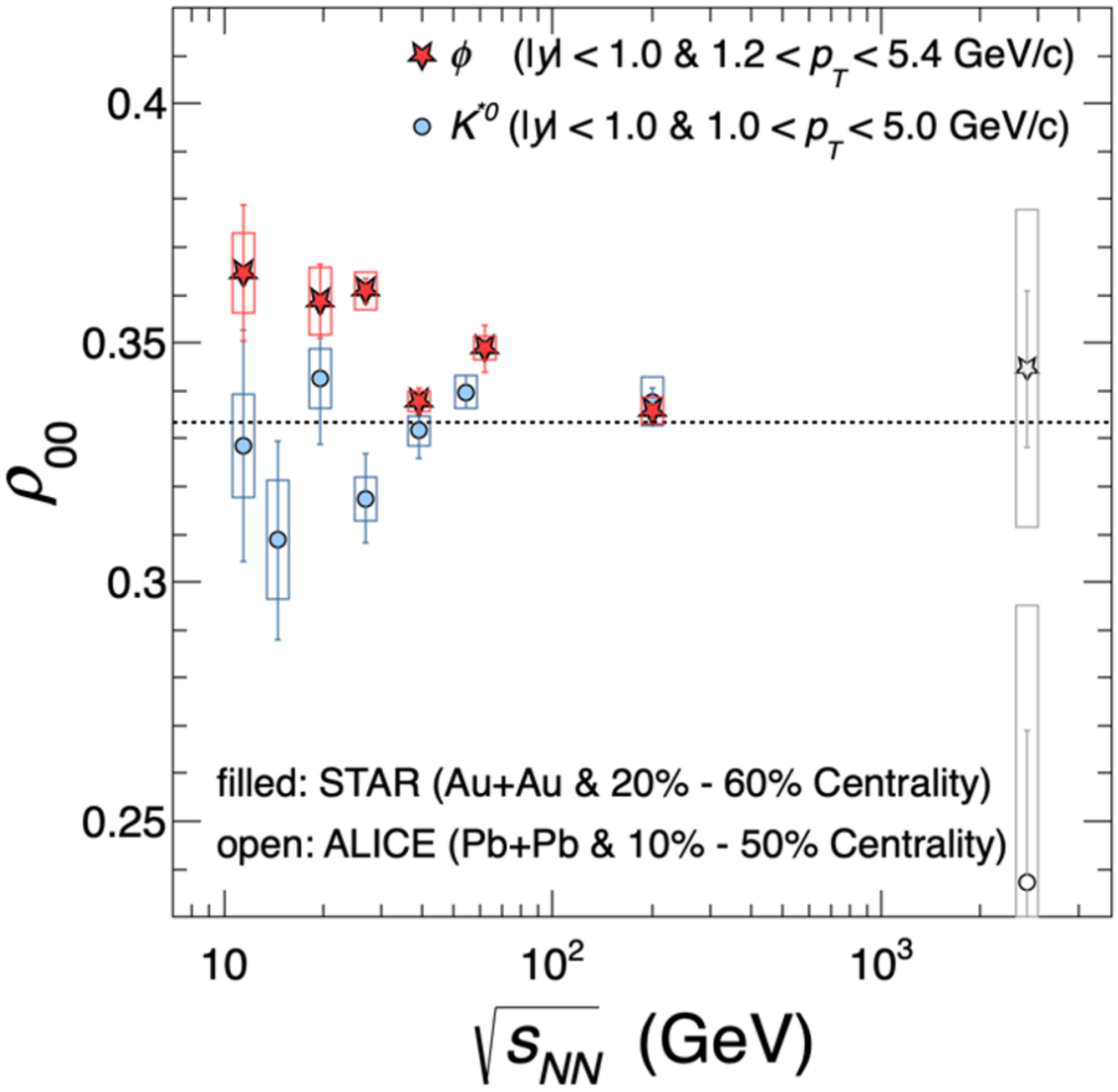


Xia et., al., Phys. Lett. B 817, 136325 (2021);

At high energies (≥62.4 GeV) for ϕ, and (≥39 GeV) for K*0, ρ_{00} in central collisions tends to ≤1/3. This might be caused by transverse local spin alignment and a contribution from the helicity polarization of quarks.

Beam energy dependence of ϕ, K*



STAR Col. Nature 614, 244 (2023)

1)ϕ-meson is significantly above 1/3 for sqrt{s}≤ 62 GeV

2)K* is almost consistent with 1/3

3)Averaged over 62 GeV and below:

- 0.3541 ± 0.0017 (stat.) ± 0.0018 (sys.) for ϕ
- 0.3356 ± 0.0034 (stat.) ± 0.0043 (sys.) for K*

Expectations 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

$$\rho_{00}^{\phi} \approx \frac{1}{3} + c_\omega + c_\varepsilon + c_{\mathrm{EM}} + c_\phi + c_{\mathrm{LV}} + c_h + c_{\mathrm{TC}} + c_{\mathrm{shear}}$$

[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); Gao, 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); Phys. Rev. D 102, 056013 (2020); Phys Rev. Lett. 131 042304 (2023); arXiv:2206.05868 (2022)

[7] A. Kumar, B. Muller and D.-L Yang, PRD 108 016020 (2023)

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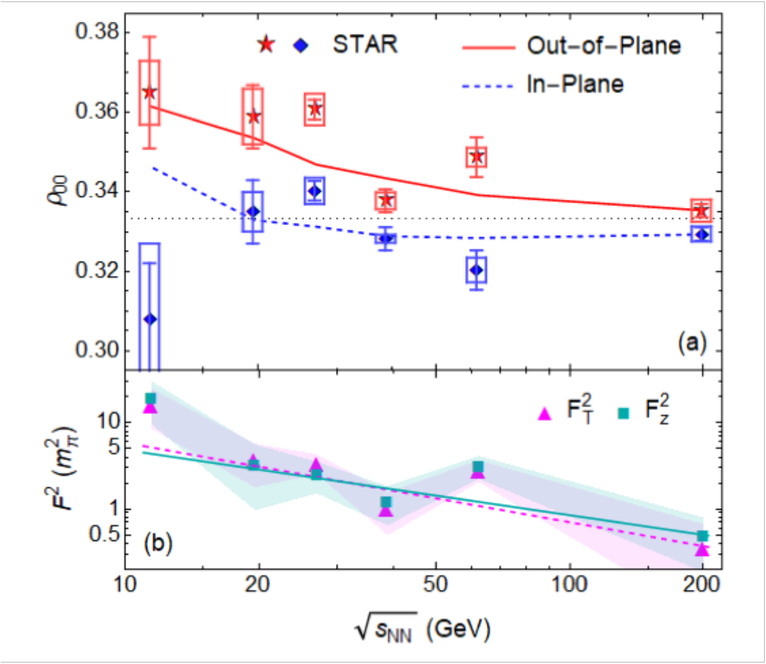
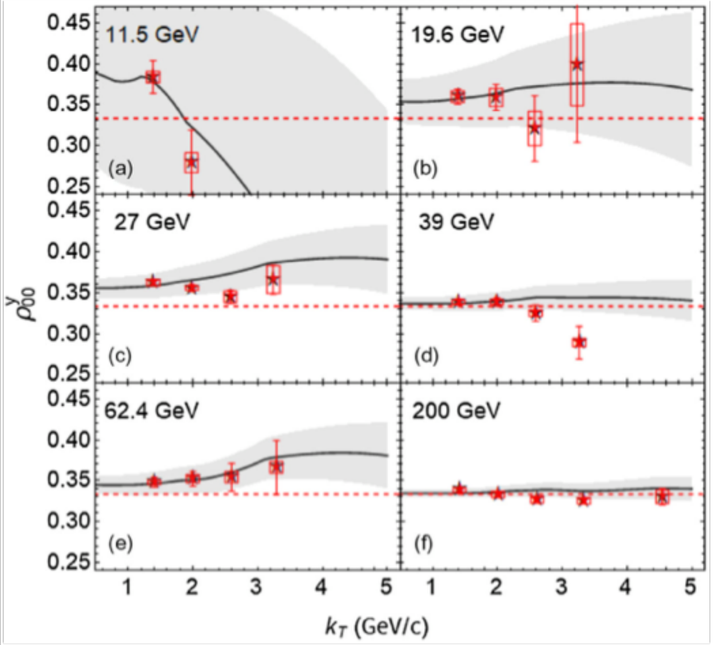
$$\rho_{00}^{\phi} \approx \frac{1}{3} + c_\omega + c_\varepsilon + c_{\mathrm{EM}} + c_\phi + c_{\mathrm{LV}} + c_h + c_{\mathrm{TC}} + c_{\mathrm{shear}}$$

The local correlation or fluctuation of ϕ fields is the dominant mechanism for the observed ϕ-meson ρ_{00}

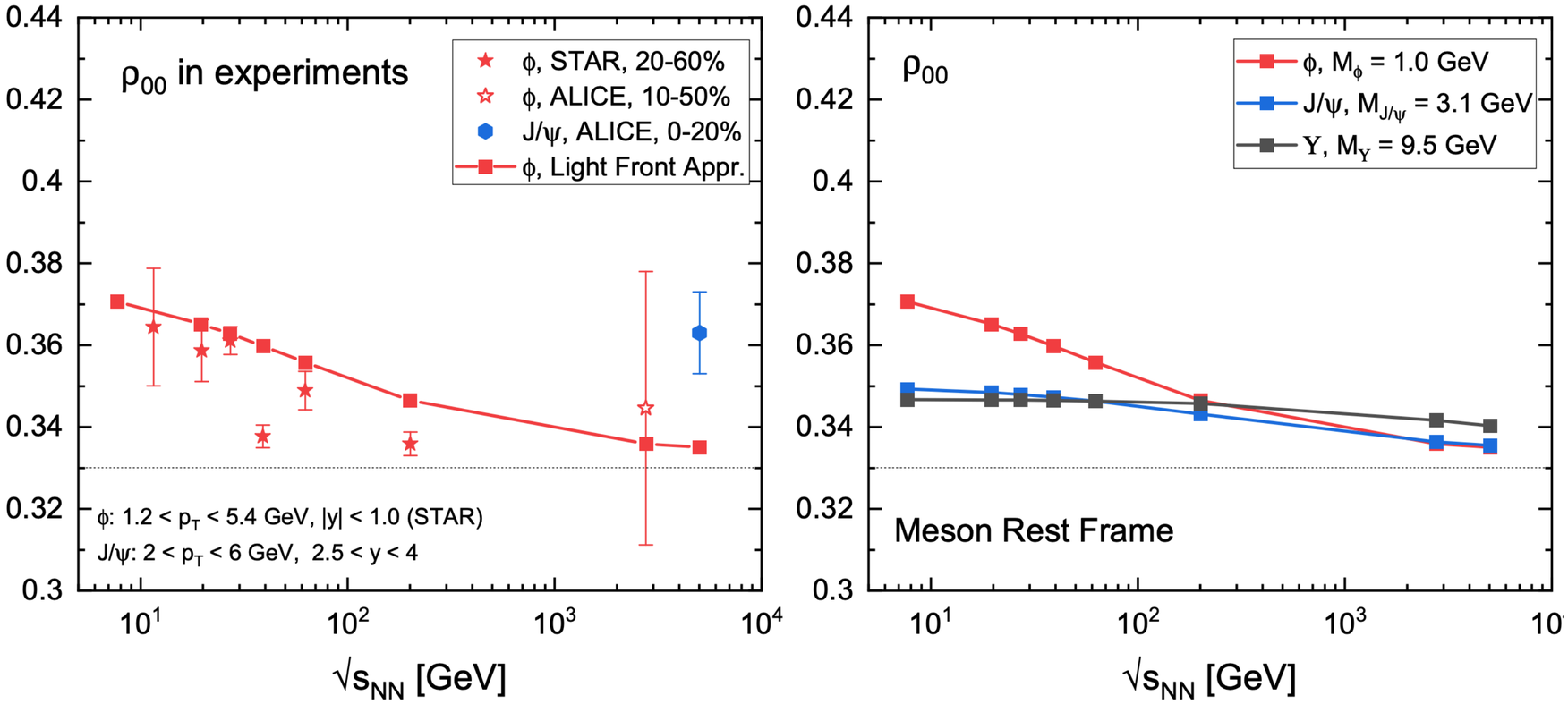
Sheng, et al., Phys. Rev. Lett. **131**, 042304 (2023)





Light front framework

Fu et.al., arXiv: 2308.0793



By introducing light front spinor, the polarization of vector mesons with $\rho_{00} > 1/3$ can be naturally derived.

The small Λ P_H vs. large ϕ ρ_{00}

Z. T. Liang, Chirality 2023

For $q_1^{\uparrow} + \bar{q}_2^{\uparrow} \to V$

$$\rho_{00}^{V} = \frac{1 - \langle P_{q_1} P_{\bar{q}_2} \rangle}{3 + \langle P_{q_1} P_{\bar{q}_2} \rangle} \stackrel{?}{=} \frac{1 - P_q^2}{3 + P_q^2}$$

For $q_1^{\uparrow} + q_2^{\uparrow} + q_3^{\uparrow} \to H$

$$P_H = \left\langle \left\langle c_1 P_{q_1} + c_2 P_{q_2} + c_3 P_{q_3} \right\rangle_H \right\rangle_S = \left\langle c_1 \langle P_{q_1} \rangle_H + c_2 \langle P_{q_2} \rangle_H + c_3 \langle P_{q_3} \rangle_H \right\rangle_S$$

$$= c_1 \left\langle \langle P_{q_1} \rangle_H \right\rangle_S + c_2 \left\langle \langle P_{q_2} \rangle_H \right\rangle_S + c_3 \left\langle \langle P_{q_3} \rangle_H \right\rangle_S = c_1 \langle P_{q_1} \rangle + c_2 \langle P_{q_1} \rangle + c_3 \langle P_{q_1} \rangle$$

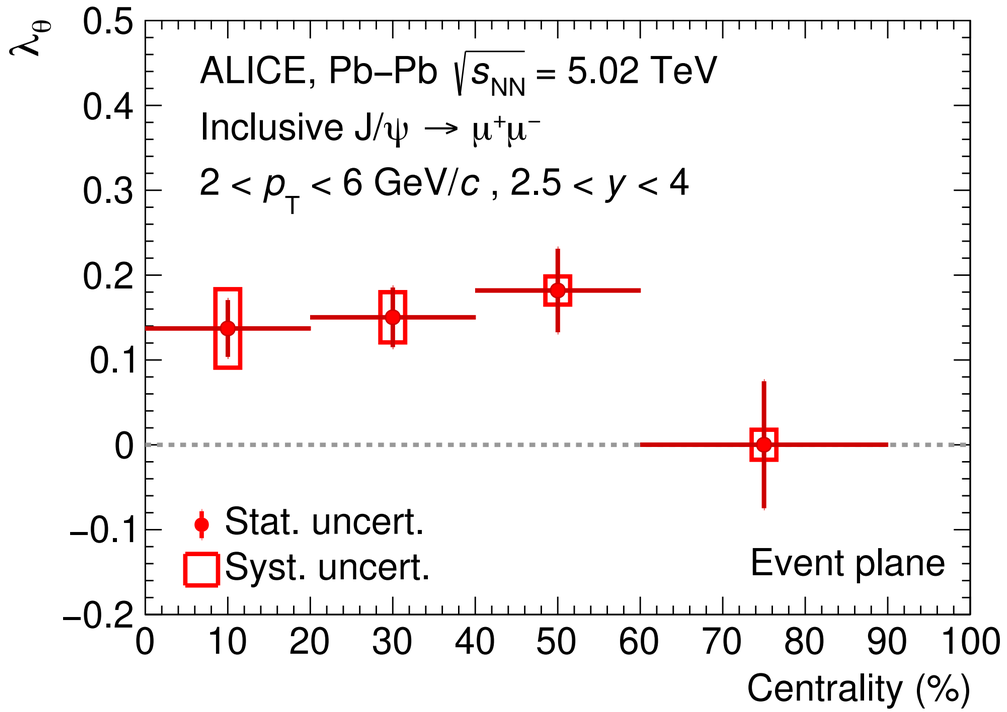
The STAR data show that: $\langle P_q P_{\bar{q}} \rangle \neq \langle P_q \rangle \langle P_{\bar{q}} \rangle$

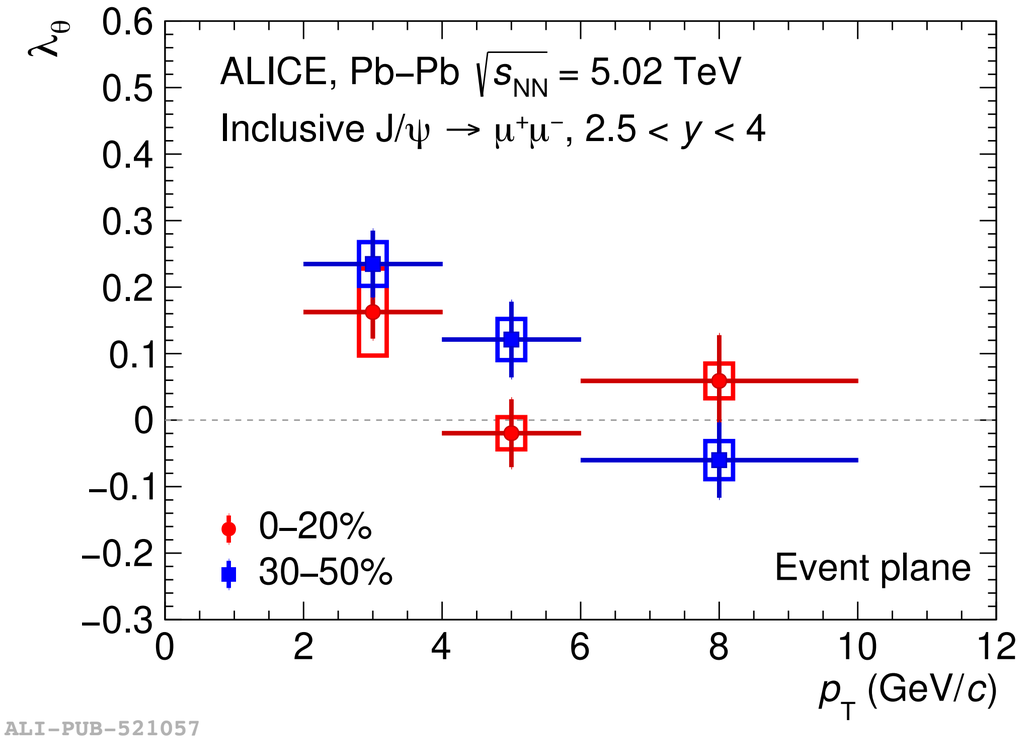
One has to take fluctuations into account, so that: $\langle P_q P_{\bar{q}} \rangle \neq \langle P_q \rangle \langle P_{\bar{q}} \rangle$

By studying P_H, we study the average of quark polarization P_q;
by studying ρ_{00}^{V}, we study the correlation between P_q and $P_{\bar{q}}$.

Measurements of J/ψ spin alignment

ALICE, Phys. Rev. Lett. 131, 042303 (2023)



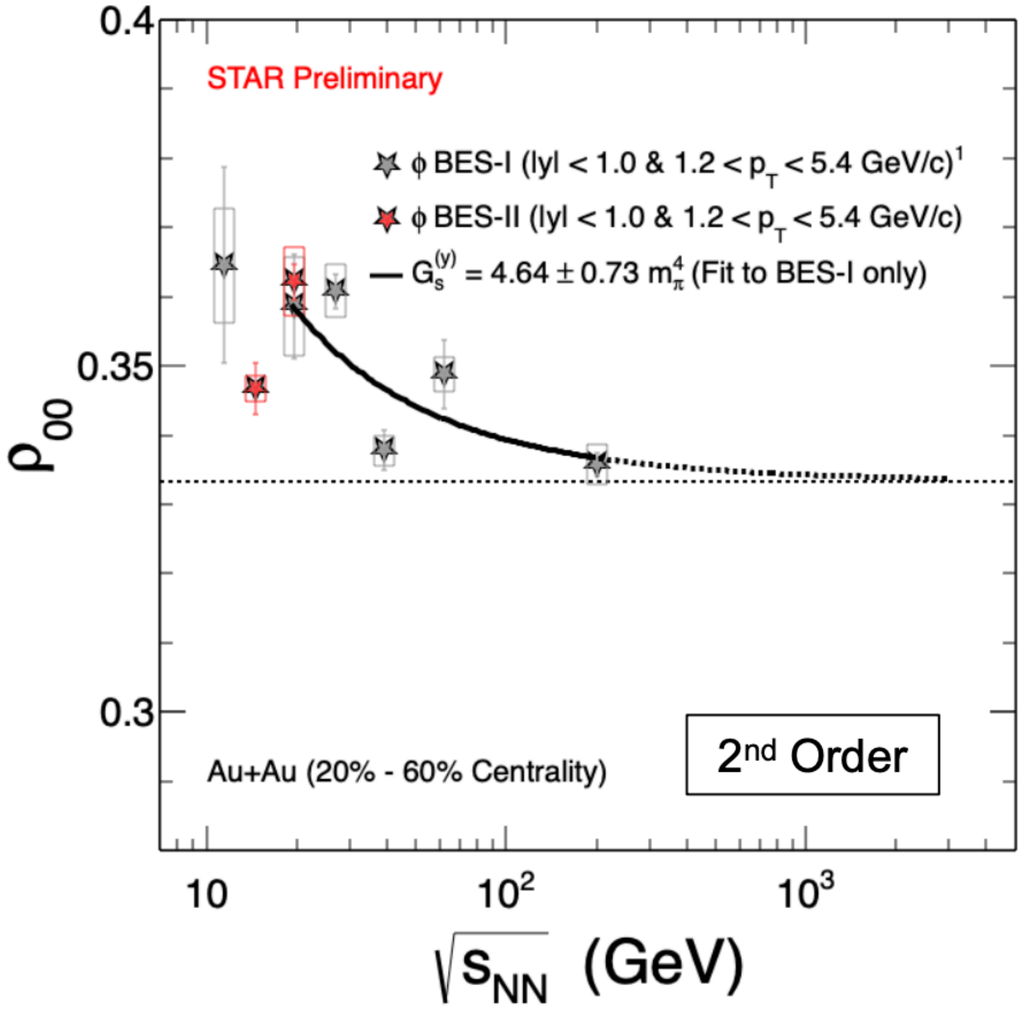


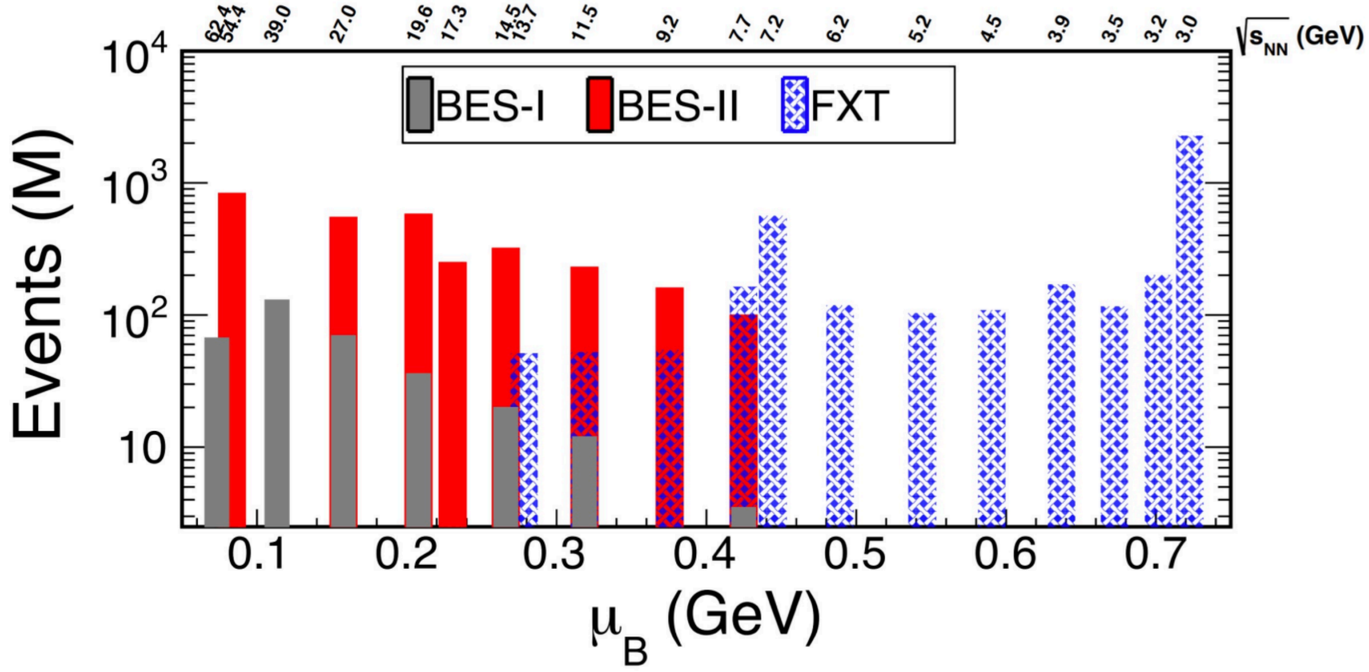
Can we see strong force filed fluctuation in $c\bar{c}$?

λ_θ = 0.2 corresponding to ρ_{00} = 0.25, how do we understand J/psi?

On going analysis: BESII ϕ mesons

STAR, QM 2023

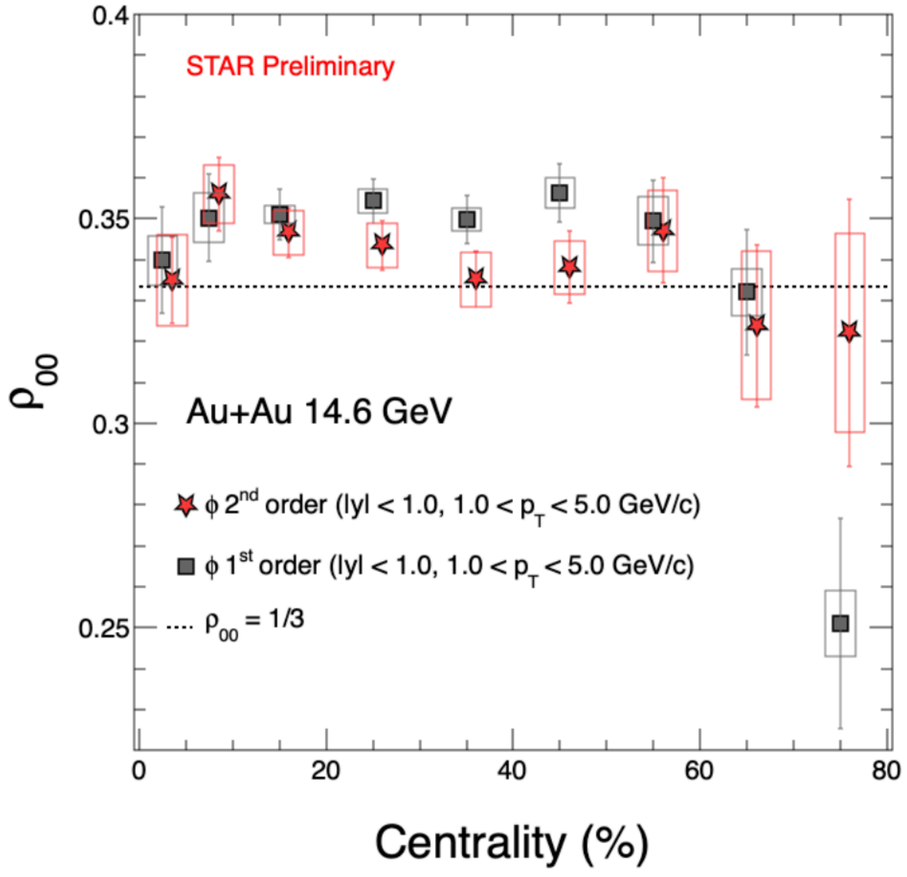


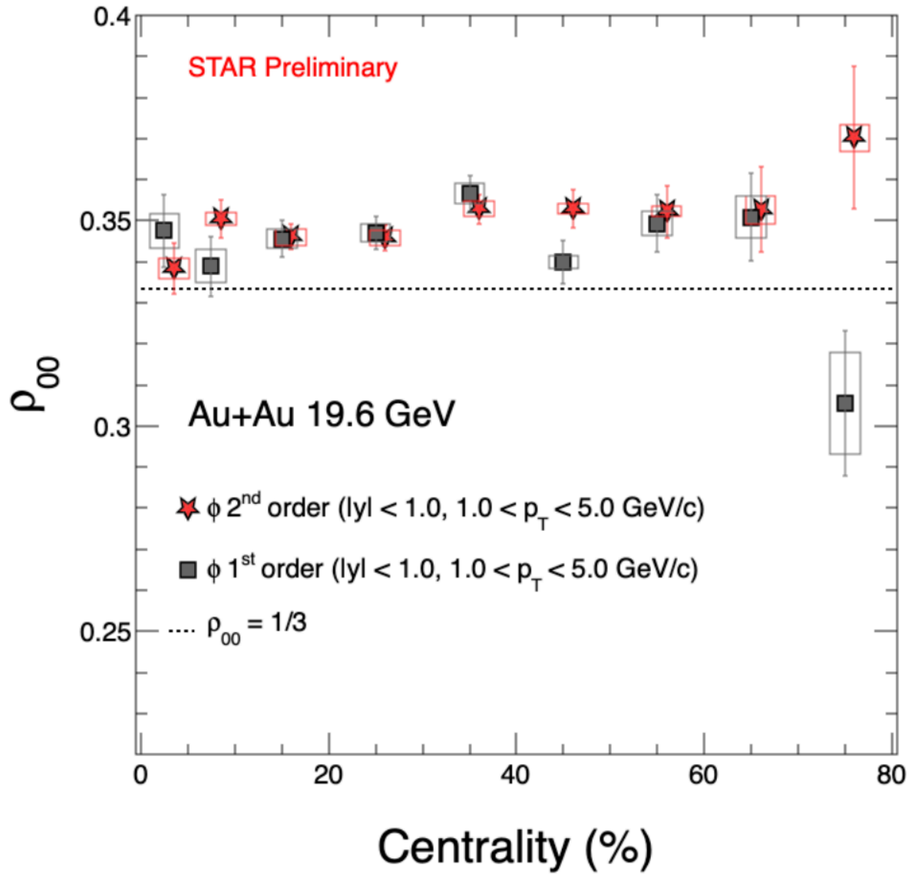


- Significantly increased statistics.
- Differential measurements of ρ_{00}.

On going analysis: BESII ϕ mesons

STAR, QM 2023



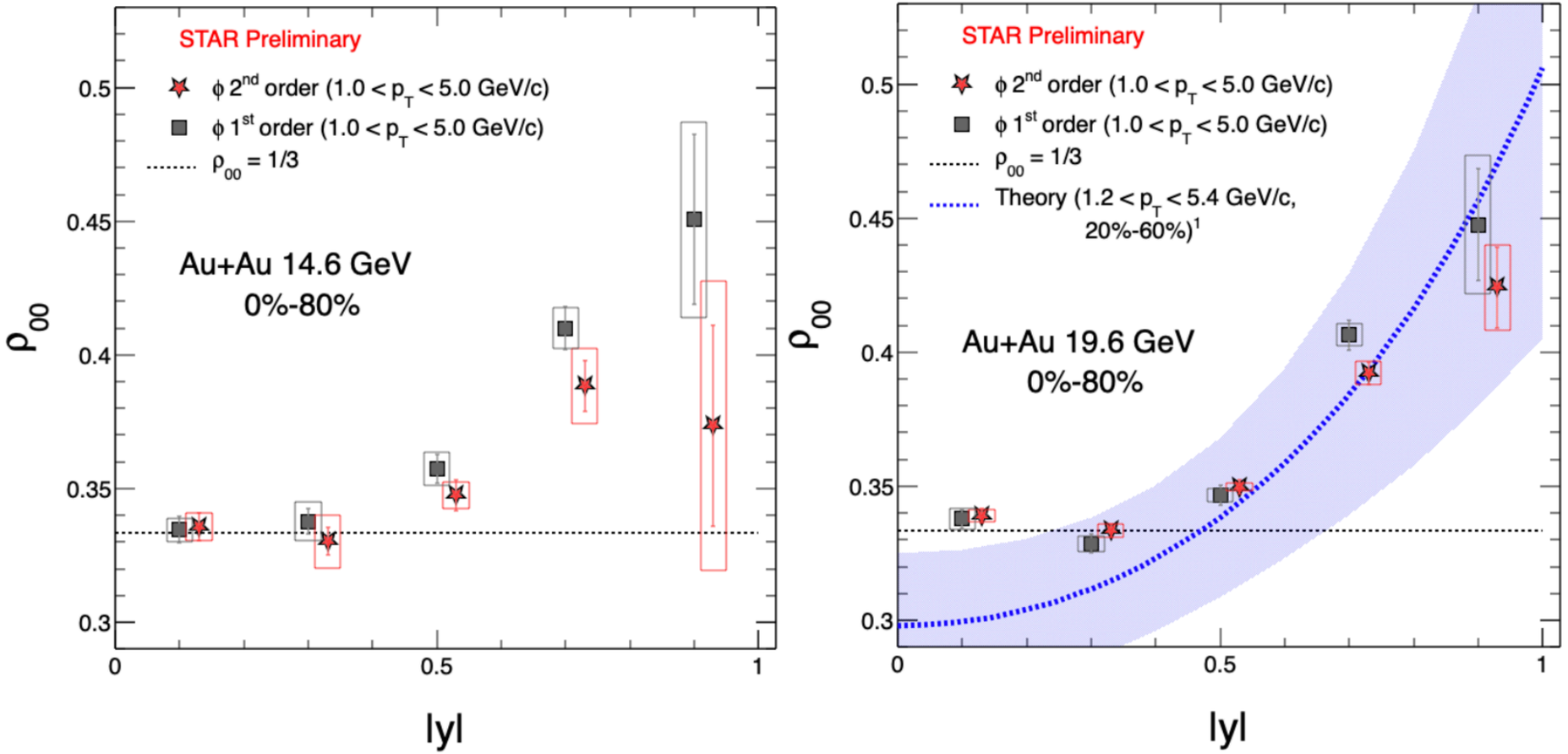


Similar centrality dependence for ρ_{00} with respect to 1st and 2nd order EP.

On going analysis: BESII ϕ mesons

STAR, QM 2023

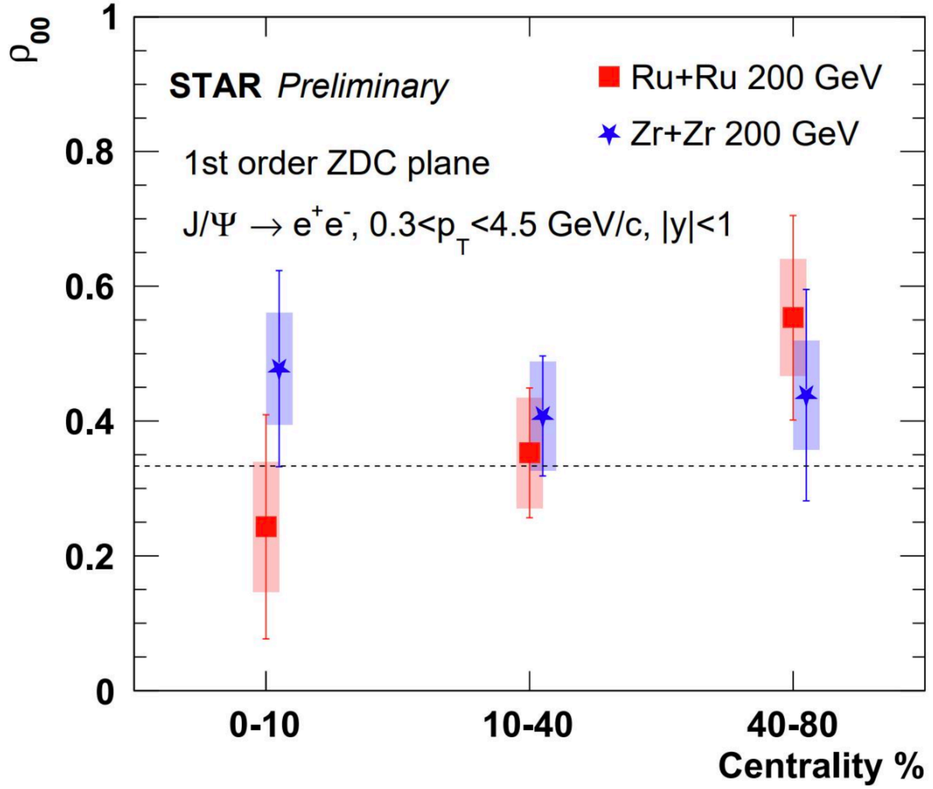
Theory curve: Sheng et al., arXiv:2308.14038 [nucl-th]



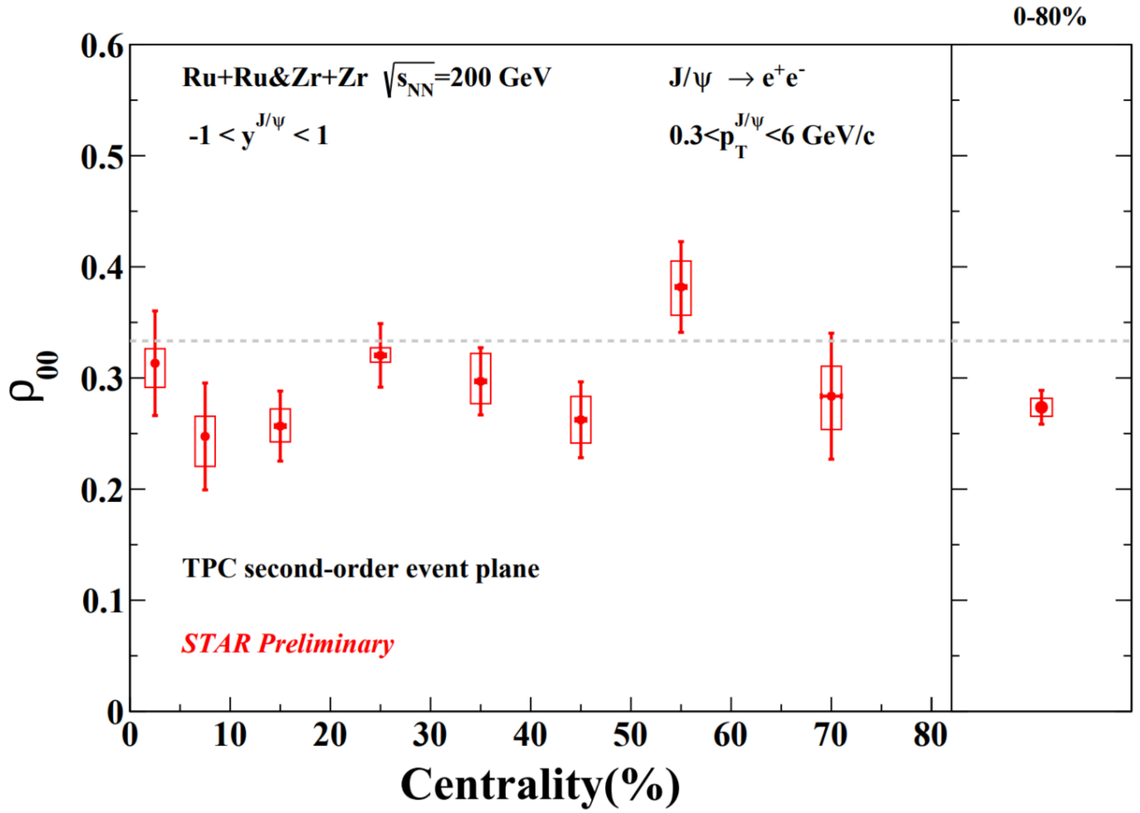
- Rapidity dependence is qualitatively consistent with theoretical calculations from ϕ field.
- Larger field fluctuations in the direction perpendicular to ϕ motion.

On going analysis: J/ψ mesons

STAR, QM 2023



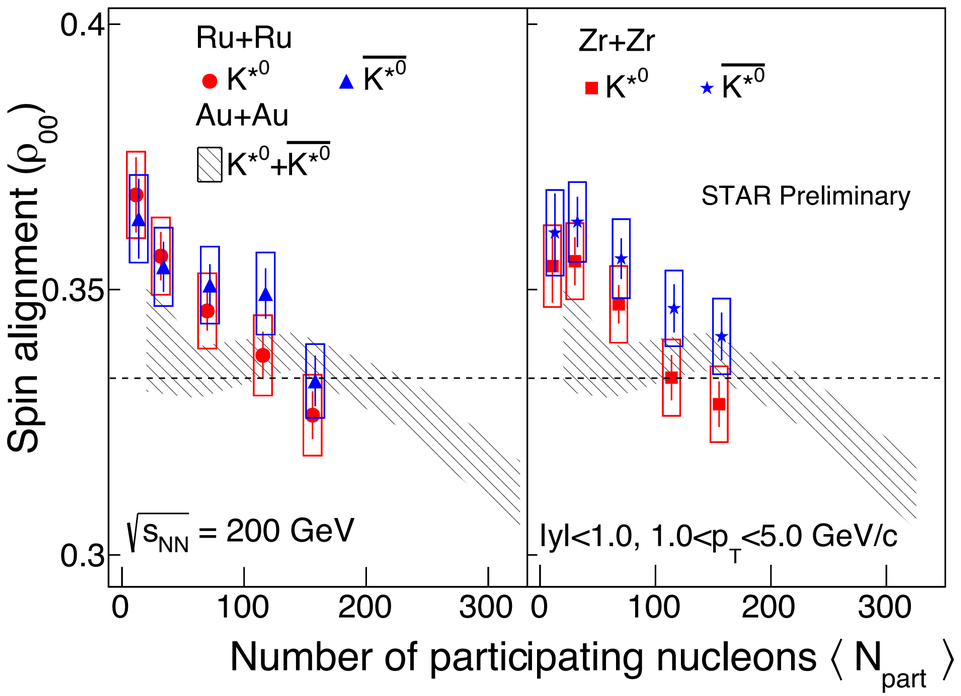
STAR, Spin 2023

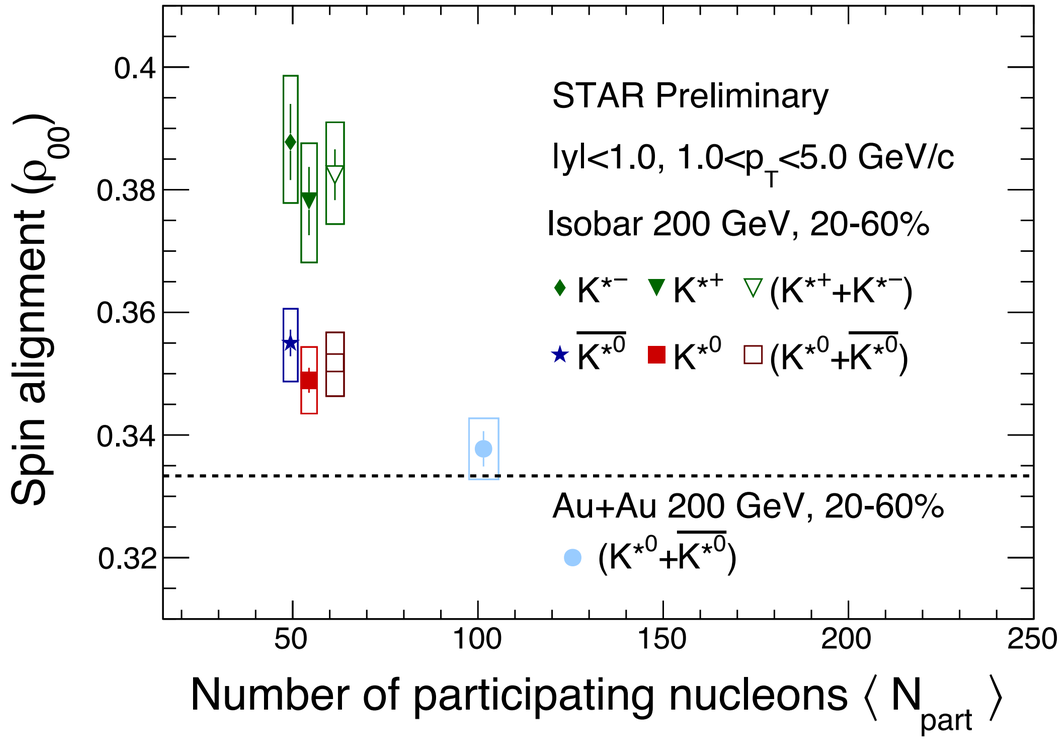


J/psi ρ_{00} w.t. 2nd event plane seems smaller than 1/3 at mid-rapidity in isobaric collisions.

On going analysis: K^{*0}, $K^{*\pm}$ mesons

STAR, QM 2022



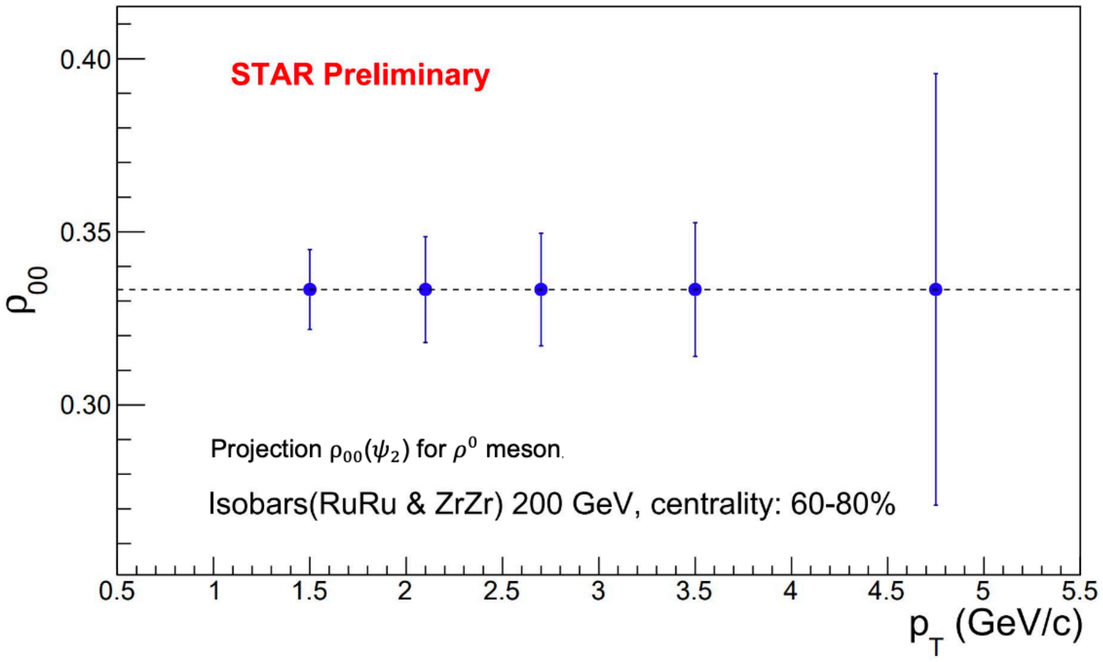


- K^{*0} is larger than 1/3 at smaller N_{part}, it is comparable to Au+Au at a similar N_{part}
- Charged K^{*} is larger than 1/3, it is larger than neutral K^{*} with 3.9σ

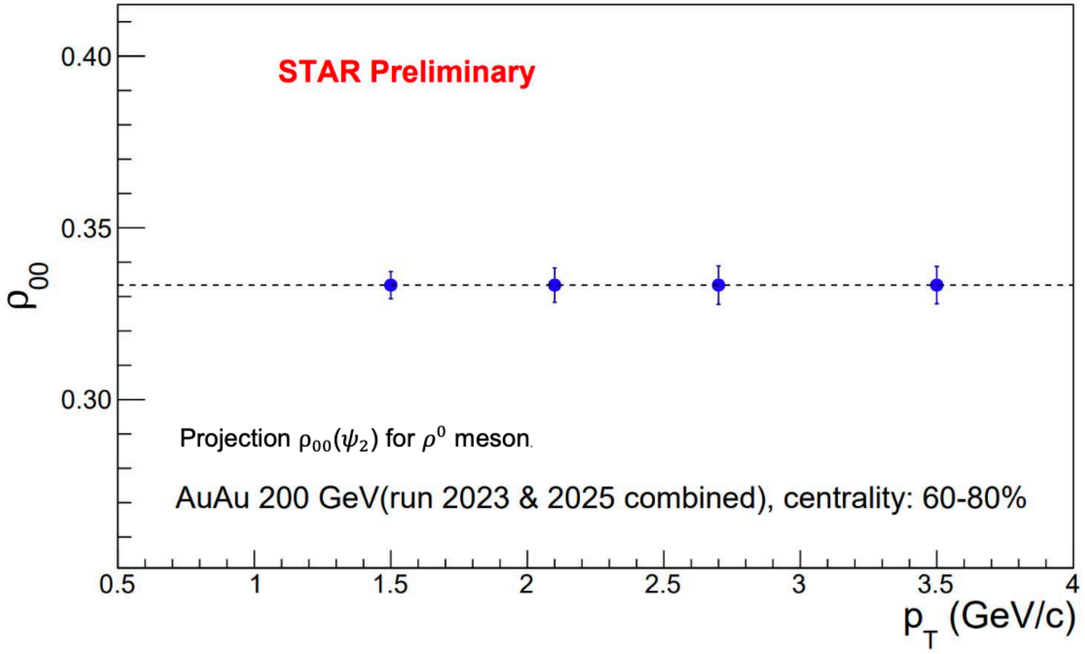
On going analysis: ρ^0 mesons

STAR, QM 2023

Statistical error projection for isobar at 200 GeV.



Statistical error projection for AuAu 200 GeV, run 2023 & 2025 combined.



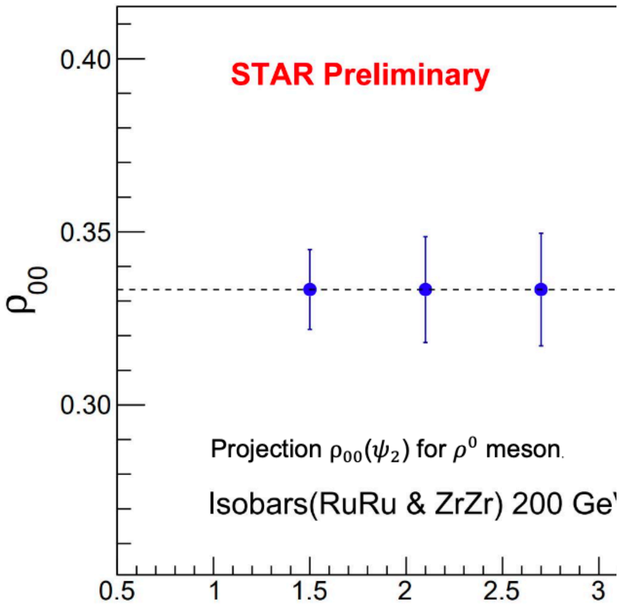
- Reconstruction of ρ^0 is difficult, but we have been putting our efforts on it.

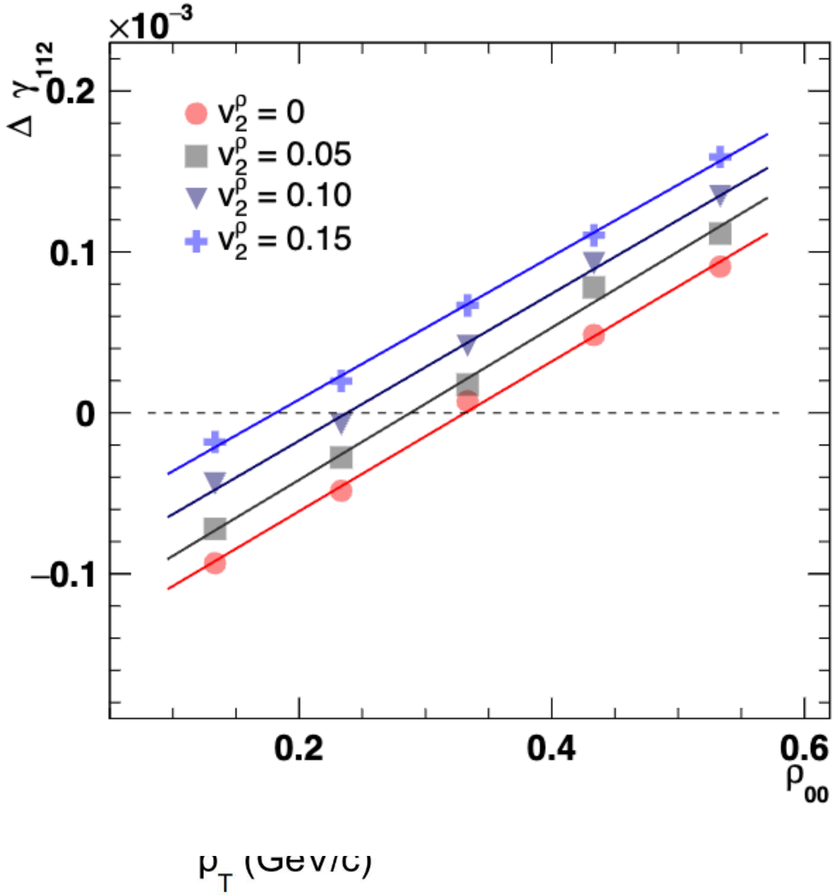
On going analysis: ρ^0 mesons

STAR, QM 2023

Shen et al., PLB 839 137777 (2023)

Statistical error prc
for isobar at 200 (





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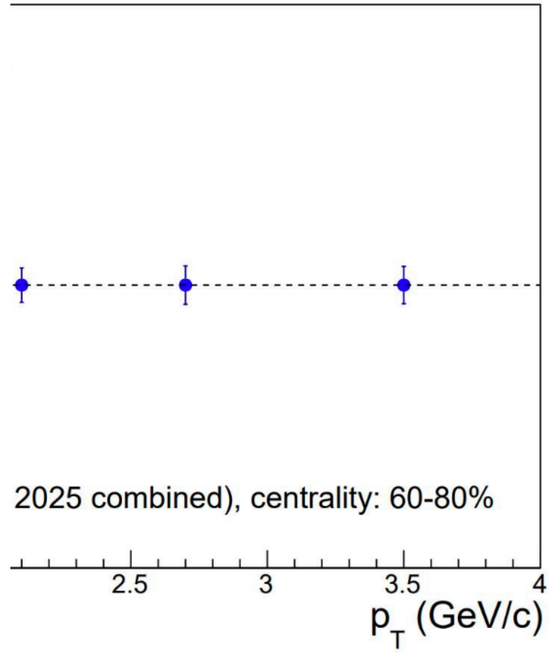
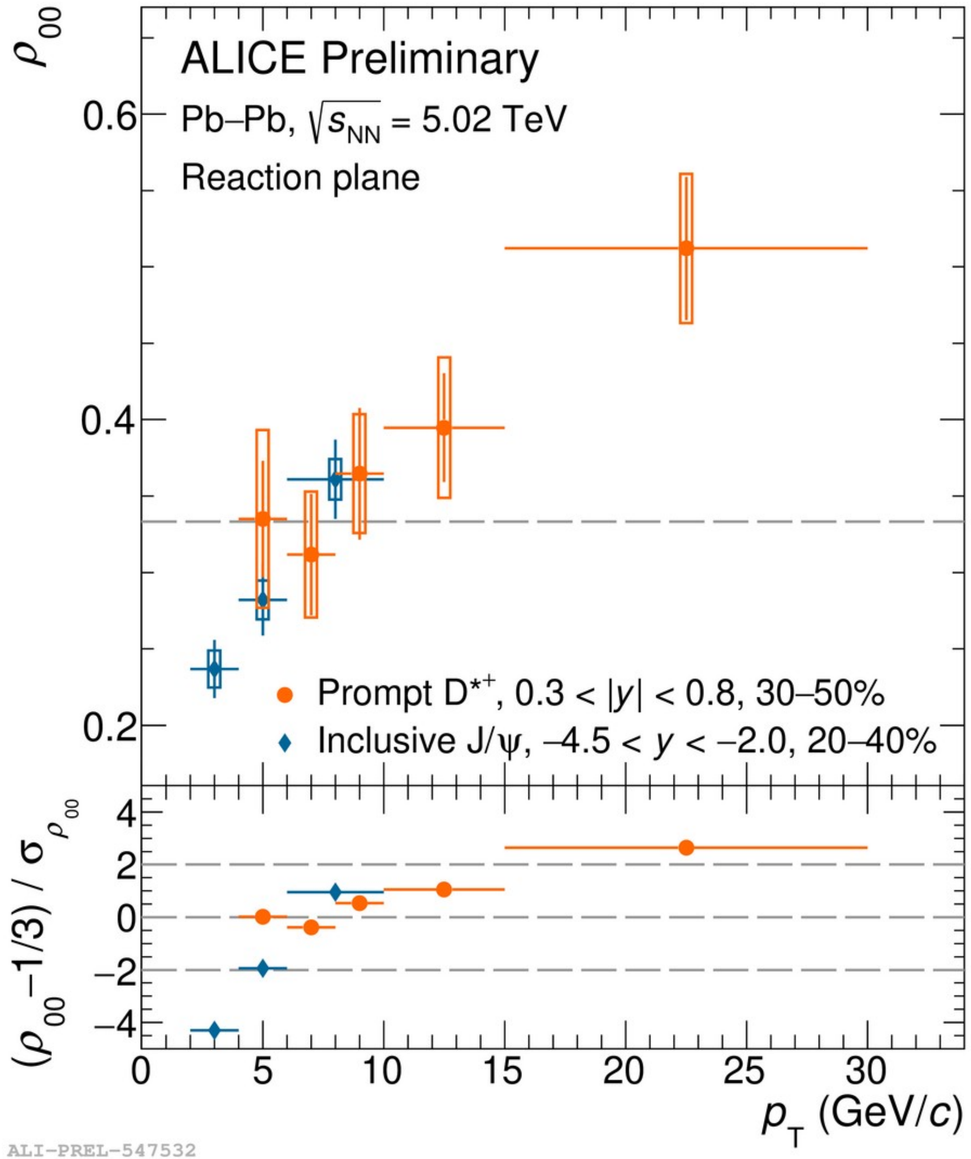
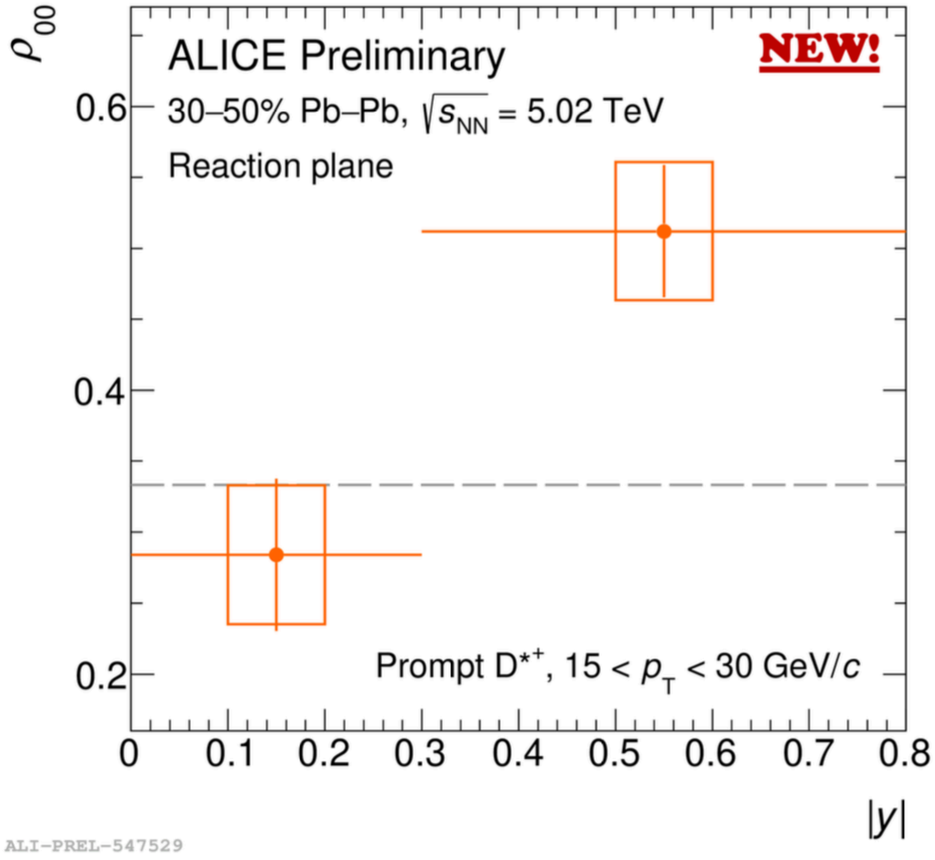


- Reconstruction of ρ^0 is more difficult, but we have been putting our efforts on it.
- It is critical to the search of the CME.

On going analysis: D^{*+} mesons





ALICE, QM 2023

D^{*+} ($c\bar{d}$) → $D^0 + \pi^+$
↳ $k^- + \pi^+$

Similar to ϕ

Low p_T : $\rho_{00} < \frac{1}{3}$ => recombination?

High p_T : $\rho_{00} > \frac{1}{3}$ => fragmentation?

Summary

•Spin polarization opens a new avenue to investigate heavy-ion collisions

•Global hyperon polarization is observed with the order of a few percent. It represents a measure of the average value of the global quark polarization in the system

•Global vector meson spin alignment is observed with a surprisingly large parttern for ϕ-meson. It represents a local fluctuation/correlation between quark and anti-quark polarization

•Measurements as a function of collision energies, different hadron species are on-going, rich physics to be explored


Thank you !