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Recent progress on global spin alignment of $\varphi(1020)$ and $K^*(892)$ in heavy-ion collisions

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Outline

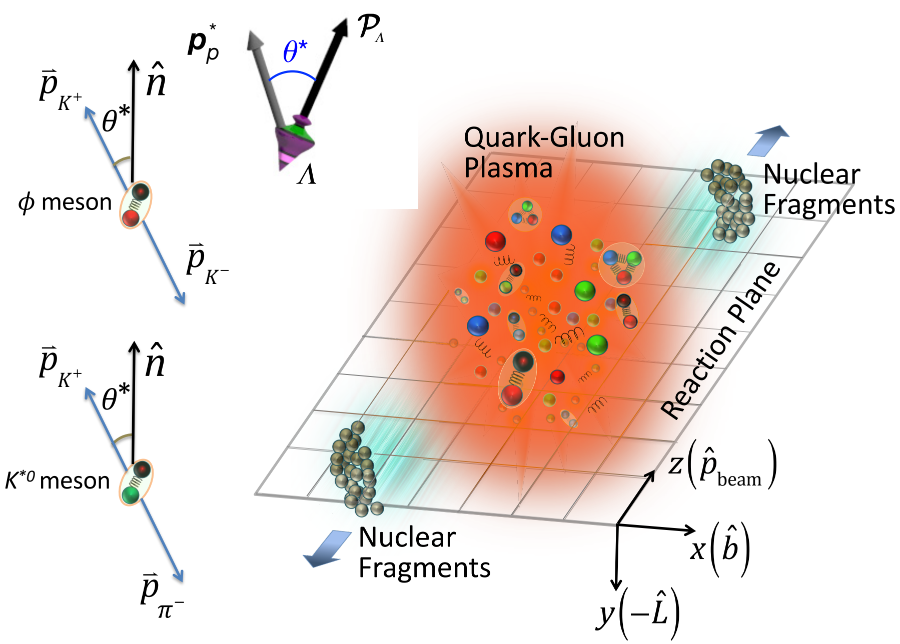
一 Introduction

二 Focus on vector meson measurements

三 Summary and Outlook

Global polarization in HIC

Liang, Wang PRL 94, 102301(2005); PLB 629 (2005) 20

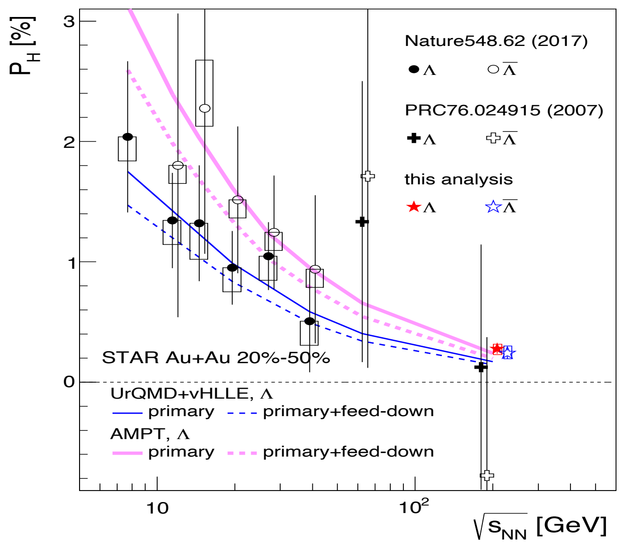


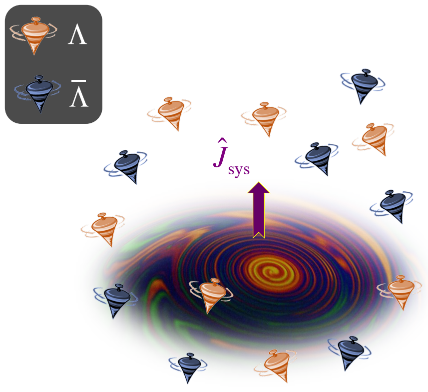
- In non-central HIC, large OAM L ($\sim 10^3\hbar$ at RHIC energies) is deposited in the interaction region
- Hyperon/vector meson global polarization

$$\frac{dN}{dcos\theta^*} \propto \alpha_\Lambda \overrightarrow{P_\Lambda} \cdot \widehat{p_p^*} \quad (1)$$

$$\propto (3\rho_{00}-1)cos^2\theta^* \quad (2)$$

- New feature of QGP, the most vortical fluid $(9\pm1)\times10^{21}\ s^{-1}$

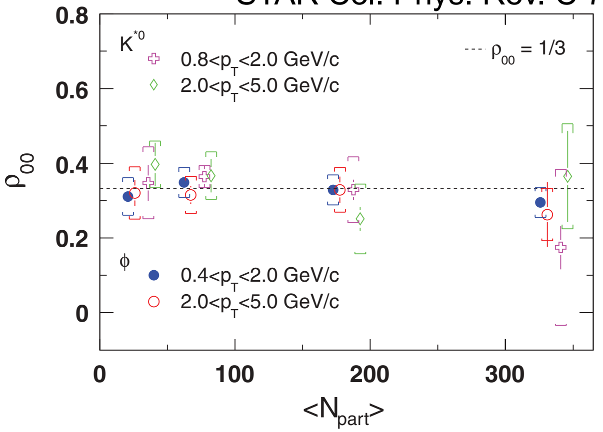


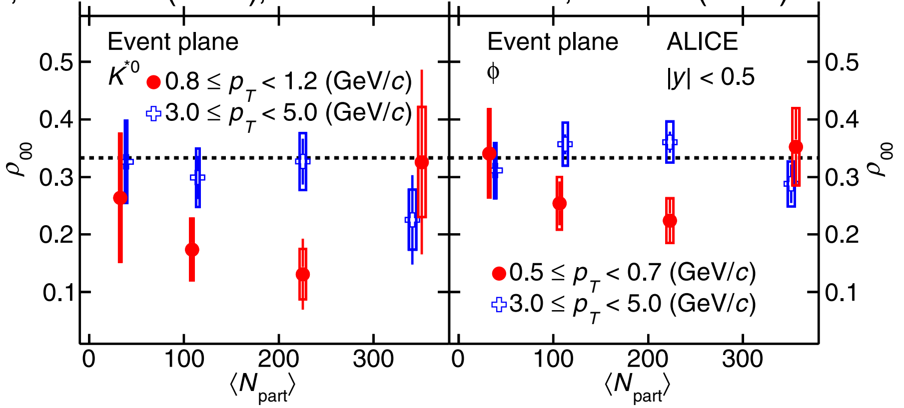


STAR Col. Phys. Rev. C 76, 024915 (2007); 98, 014910 (2018); Nature 548, 62 (2017); PRL 126, 162301 (2021) ; ALICE Col. Phys. Rev. C 101, 044611 (2020)

- Evidence of spin-orbital angular momentum interaction

STAR Col. Phys. Rev. C 77, 061902® (2008); ALICE Col. PRL 125, 012301 (2020)





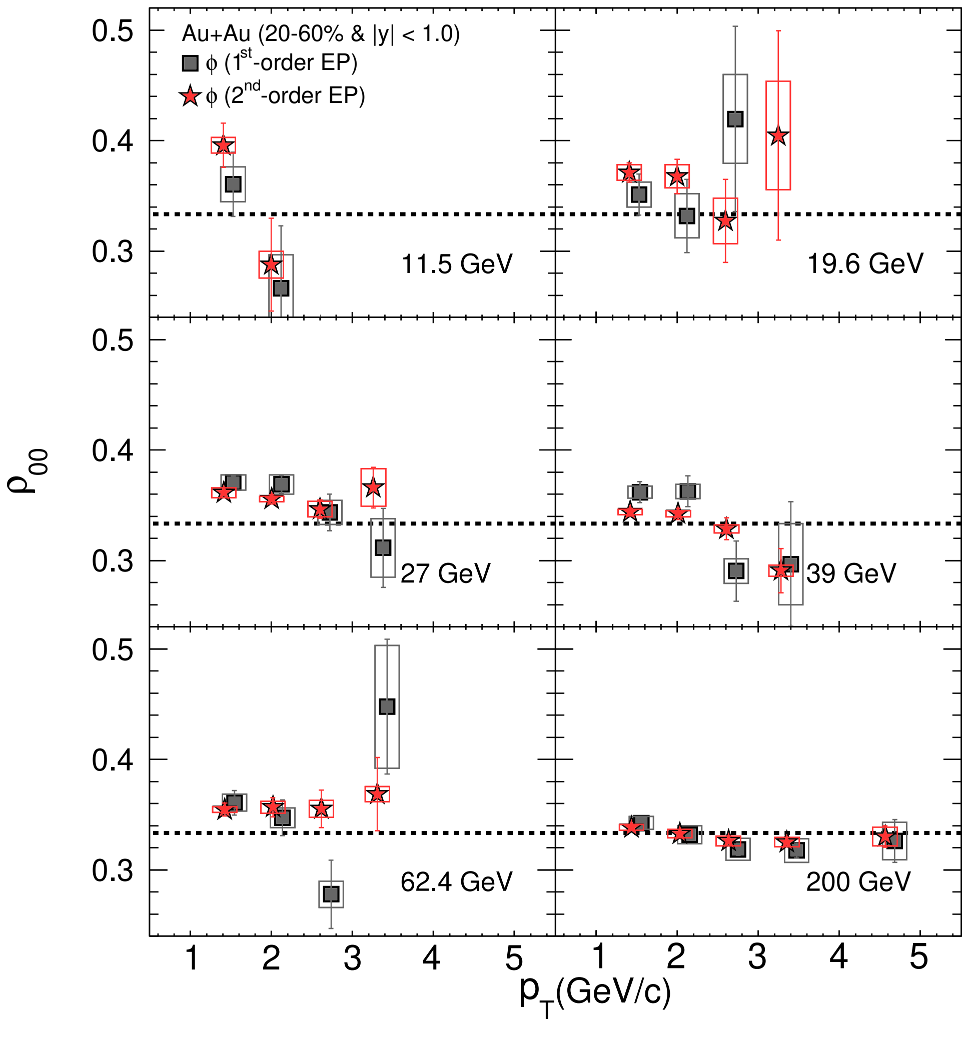
Motivations to do vector meson

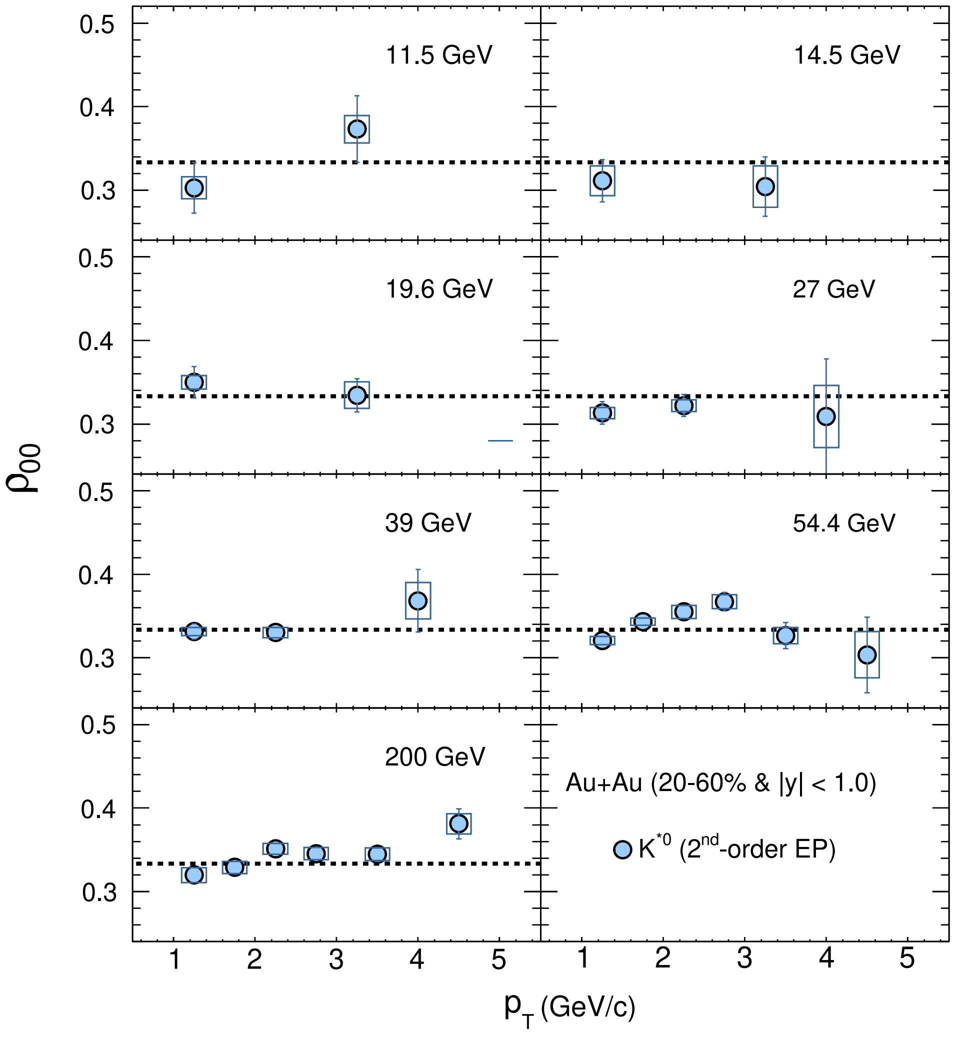
- No local cancelation when integrating over phase space as opposed to spin-1/2 particles
- Access to spin-orbital forces S•(E_{ϕ} × P), a term which is canceled in Λ polarization
- Vector mesons, like φ-meson, are expected to originate predominantly from primordial production. It suffers less decay contributions if compared to hyperons, more sensitive to early dynamics.

Results from BES-I data @non-central collisions

STAR Col. arXiv: 2204.02302

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

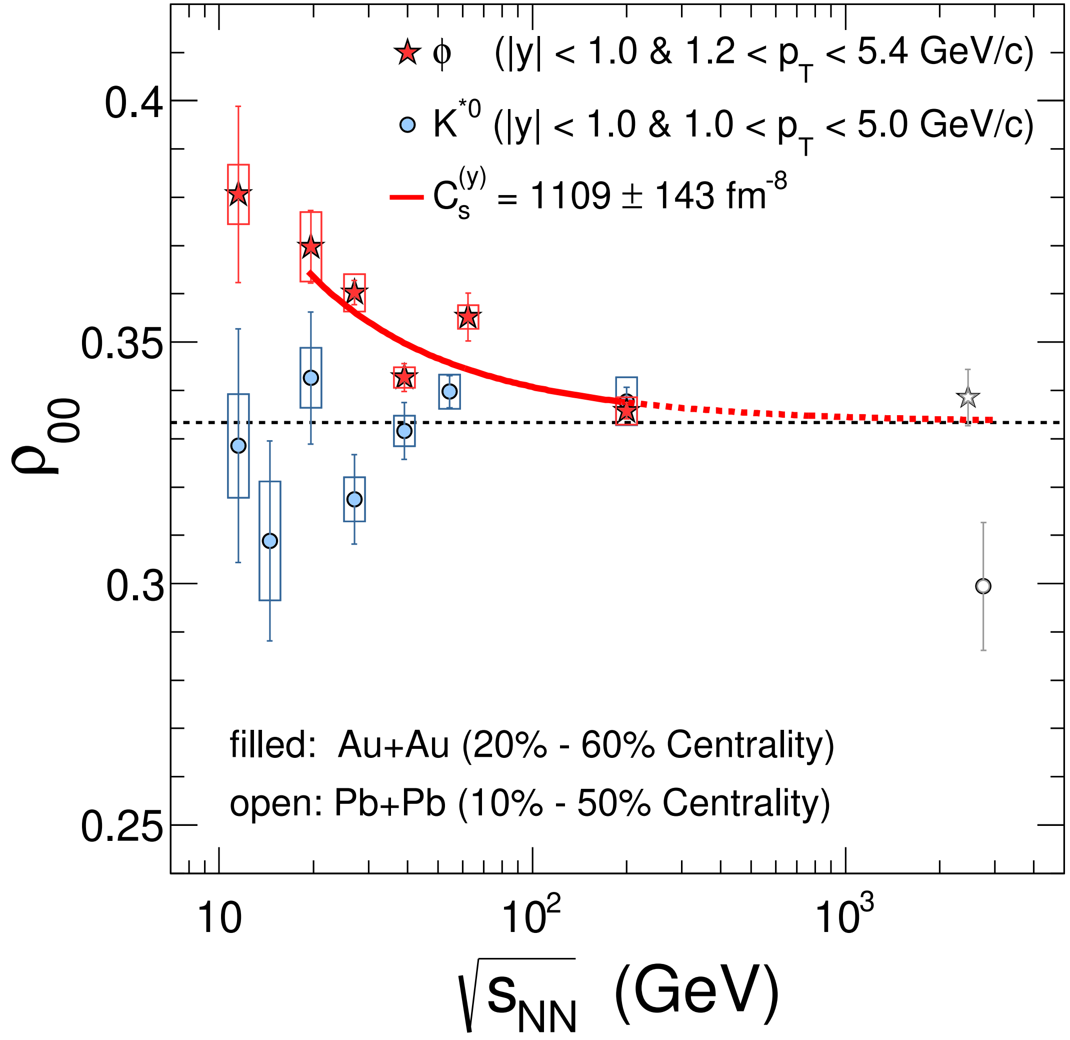




- We see that the signal for the φ meson occurs mainly witihn ~1.0-2.4 GeV/c; at larger p_T the results can be regarded as being consistent with 1/3 within ~2sigma or less.

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

Results averaged over p_T



STAR Col. arXiv: 2204.02302

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

*2) K** is largely consistent with 1/3

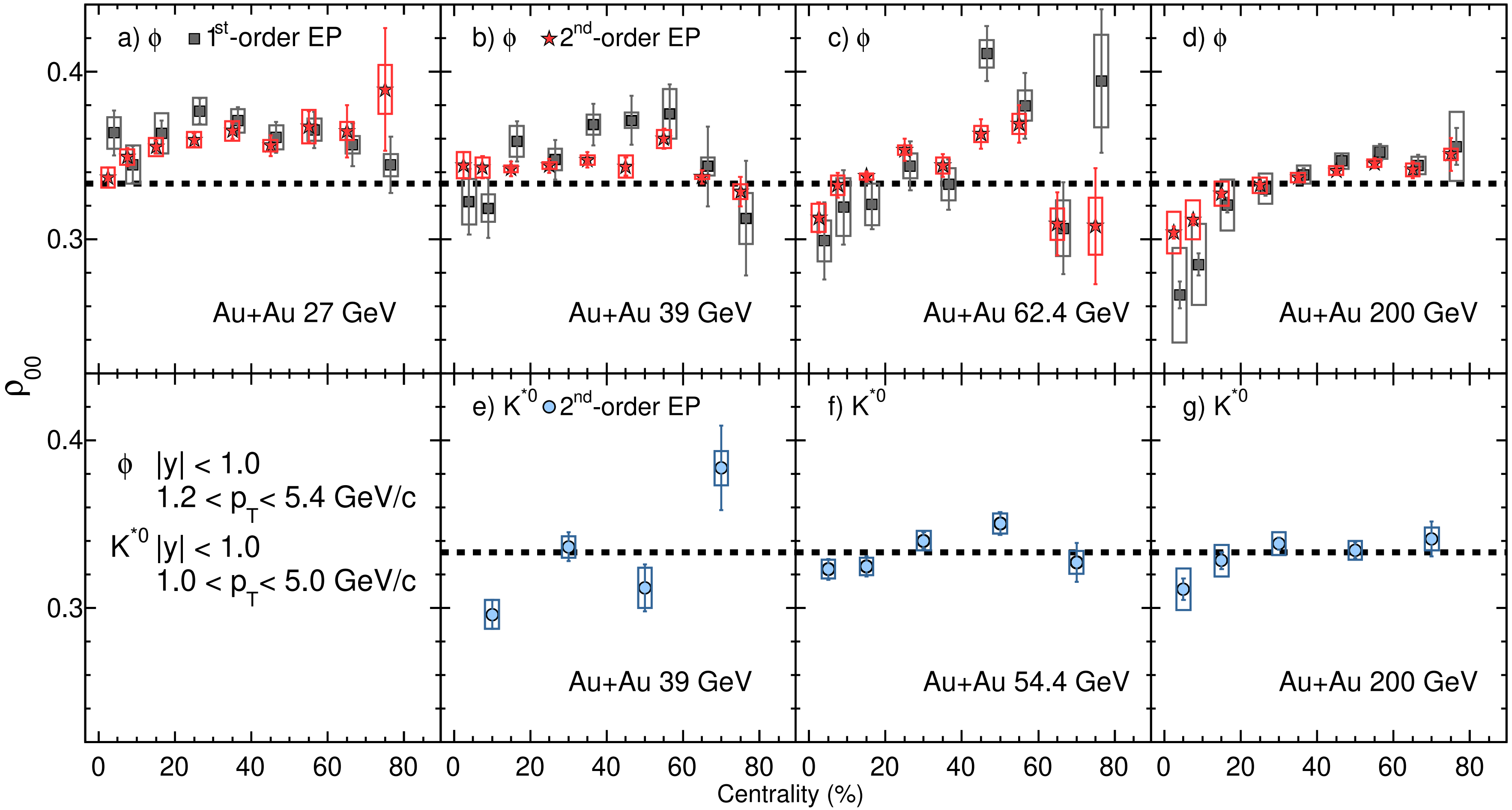
3) Averaged over 62 GeV and below:

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

* Different approaches are used in combinatorial bg. analysis
** Errors displayed for ALICE data are statistical only

Study the fine structure of centrality

STAR Col. arXiv: 2204.02302



- 1^{st} order EP: ZDC or BBC
- 2^{nd} order EP: TPC

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

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

$$\rho_{00}(\omega) \sim \frac{1}{3} - \frac{1}{9}(\beta\omega)^2$$

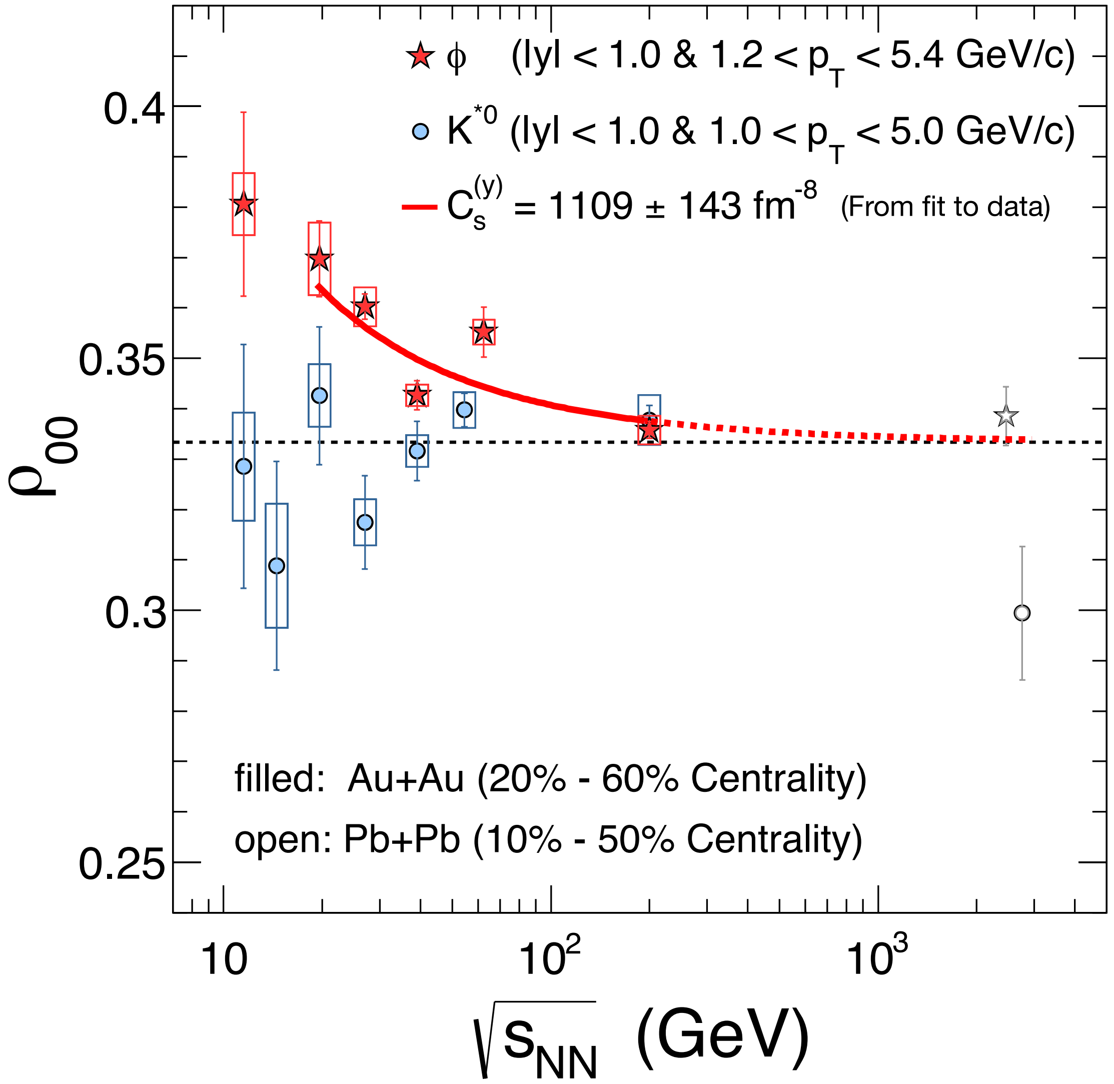
$$\rho_{00}(\mathrm{coal}) \sim \frac{1 - \mathrm{P_q P_q}}{3 + \mathrm{P_q P_q}}$$

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

$$\rho_{00}(\mathrm{frag}) \sim \frac{1 + \beta \mathrm{P_q P_q}}{3 - \beta \mathrm{P_q P_q}}$$

[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)

Can we explain the large ρ_{00} of φ-meson?



- Polarization by a strong force field of vector meson → Can accommodate large deviation for φ meson ρ00 at midcentral collisions

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

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

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

Vector meson field strength ~ $2.5\ m_\pi^2$

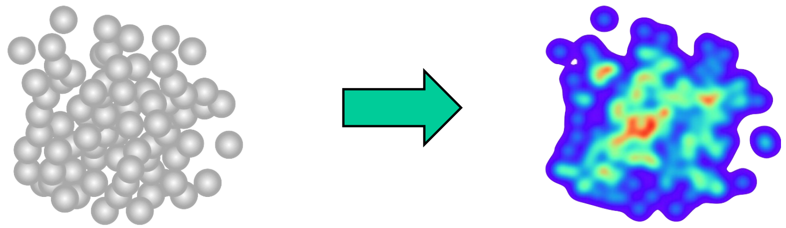
Sheng el. al., Phys Rev D 101, 096005 (2020)
Sheng el. al., Phys Rev D 102, 056013 (2020)

HIC : a highly volatile environment

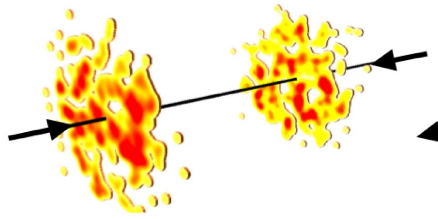
Gribov, Levin, Ryskin, 1981
McLerran, Venugopalan
hep-ph/9309289

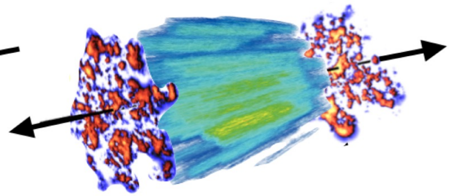
Strongest color field

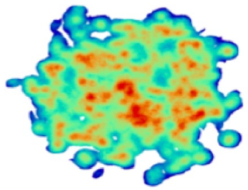
Nucleus at rest



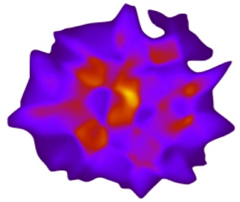
Nucleus at relativistic energies

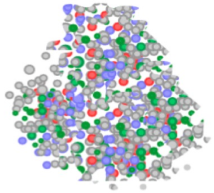


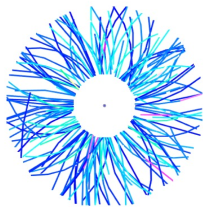




Hadronization







Color Glass Condensate (CGC)

Gluon Condensate Plasma (Glasma)

Quark Gluon Plasma (QGP)

Detection

- Fluctuation of quark and gluon fields → local net-quark current

Φ-meson vector field

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, in analogy to how EM field polarize (anti)quarks.

$$P^{y}_{s/\bar{s}}\left(\mathrm{t},\mathbf{x},\mathbf{P}_{s/\bar{s}}\right) = \frac{1}{2}\omega_y + \frac{1}{2m_s}\hat{\mathbf{y}}\cdot\left(\varepsilon\times\mathbf{P}_{s/\bar{s}}\right) \quad \Leftarrow \text{vorticity}$$

$$\pm\frac{Q_s}{2m_sT}B_y \pm \frac{Q_s}{2m_s^2T}\hat{\mathbf{y}}\cdot\left(\boldsymbol{E}\times\mathbf{P}_{s/\bar{s}}\right) \quad \Leftarrow \text{EM field}$$

$$\pm\frac{g_\phi}{2m_sT}B_{\phi,y} \pm \frac{g_\phi}{2m_s^2T}\hat{\mathbf{y}}\cdot\left(\boldsymbol{E}_\phi\times\mathbf{P}_{s/\bar{s}}\right) \quad \Leftarrow \text{strong force field}$$

Quark version of the spin-orbit force. Not accessible via P_Λ.

“magnetic” components

“electric” components

- The 1st time the strong force field is experimentally supported as a key machenism that leads to global alignment

Φ-meson vector field

PHYSICAL REVIEW C **99**, 021901(R) (2019)

Rapid Communications

Λ and $\bar{\Lambda}$ spin interaction with meson fields generated by the baryon current in high energy nuclear collisions

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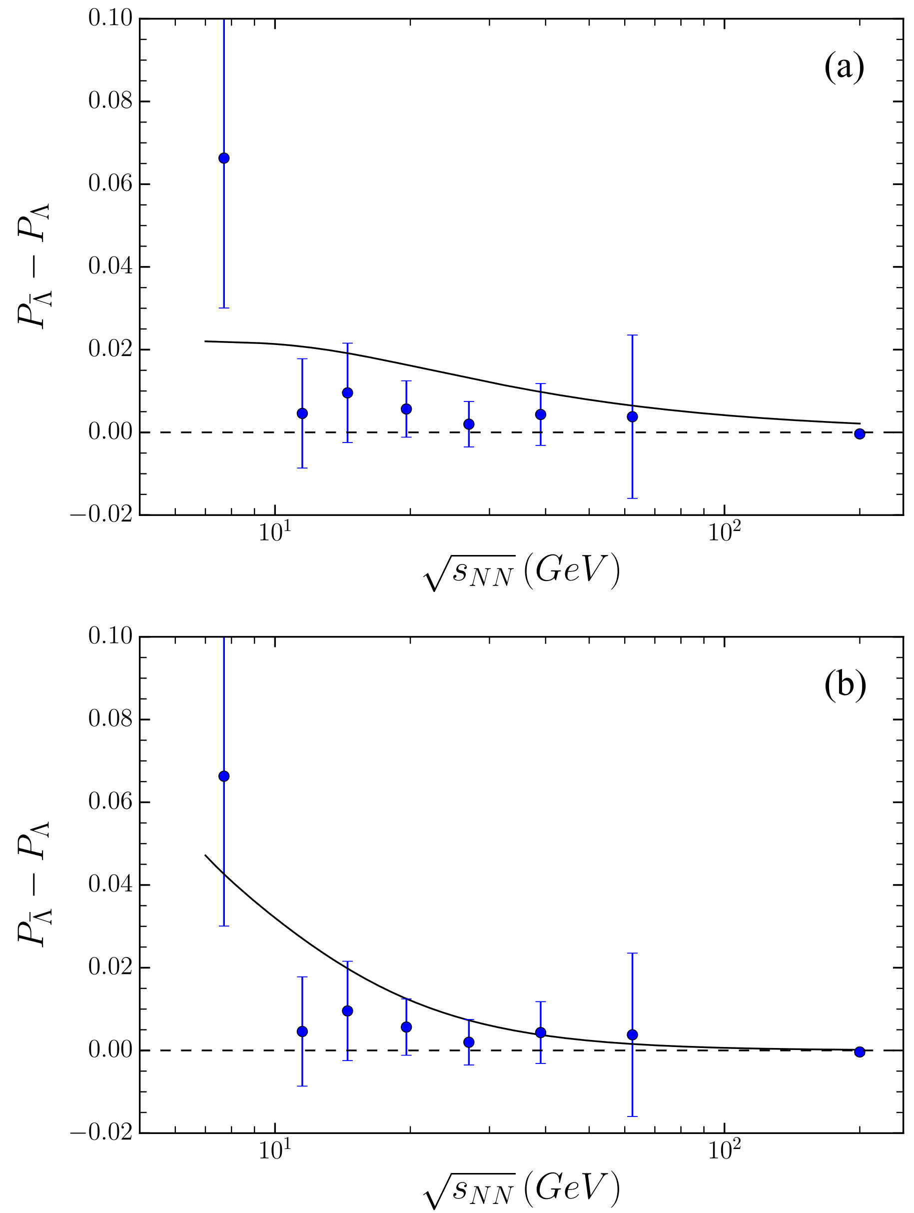
[2] *School of Physics and Astronomy, University of Minnesota, Minneapolis, Minnesota 55455, USA*

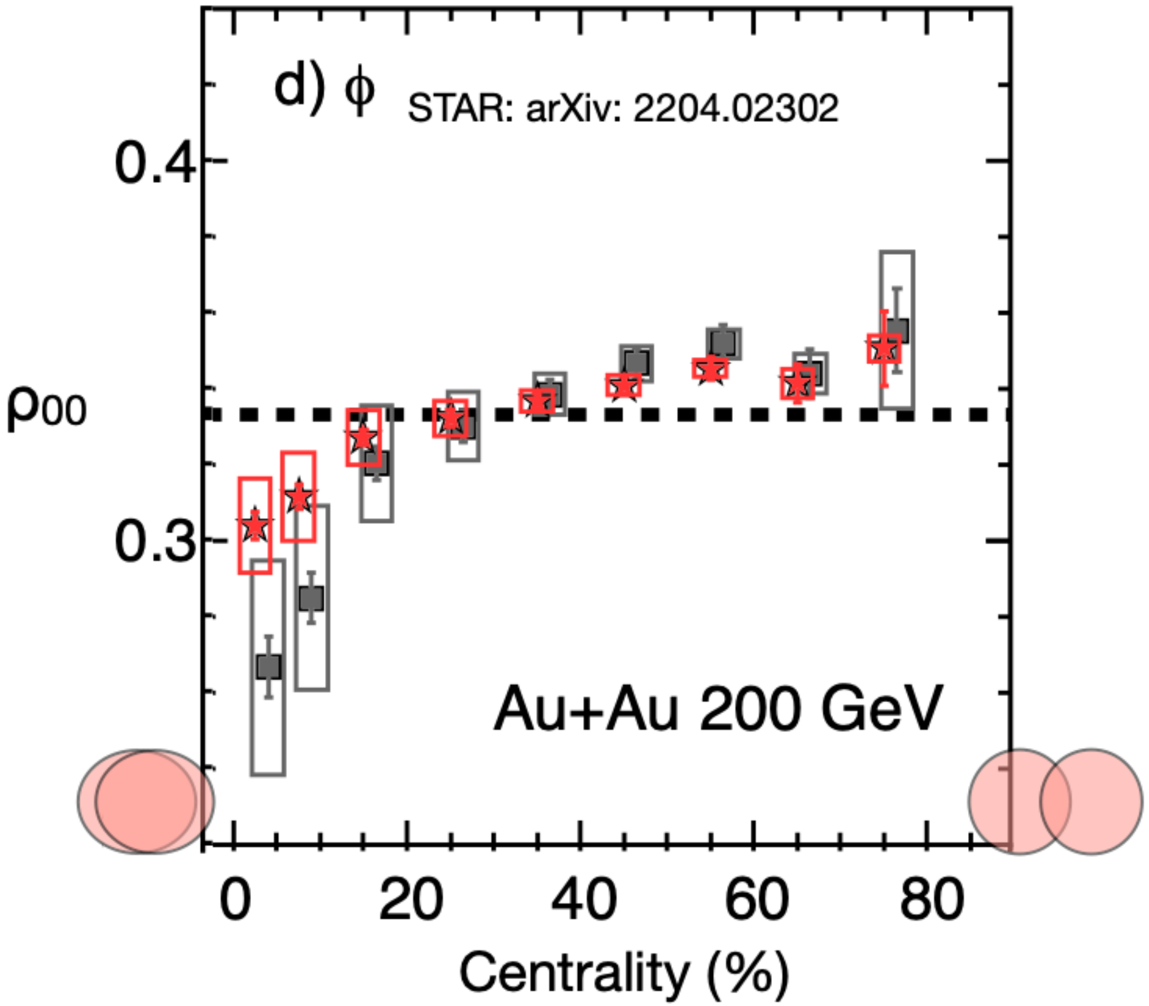
(Received 1 August 2018; revised manuscript received 12 December 2018; published 19 February 2019)

We propose a dynamical mechanism which provides an interaction between the spins of hyperons and antihyperons and the vorticity of the baryon current in noncentral high energy nuclear collisions. The interaction is mediated by massive vector and scalar bosons, which is well known to describe the nuclear spin-orbit force. It follows from the Foldy-Wouthuysen transformation and leads to a strong-interaction Zeeman effect. The interaction may explain the difference in polarizations of Λ and $\bar{\Lambda}$ hyperons as measured by the STAR Collaboration at the BNL Relativistic Heavy Ion Collider. The signs and magnitudes of the meson-baryon couplings are closely connected to the binding energies of hypernuclei and to the abundance of hyperons in neutron stars.

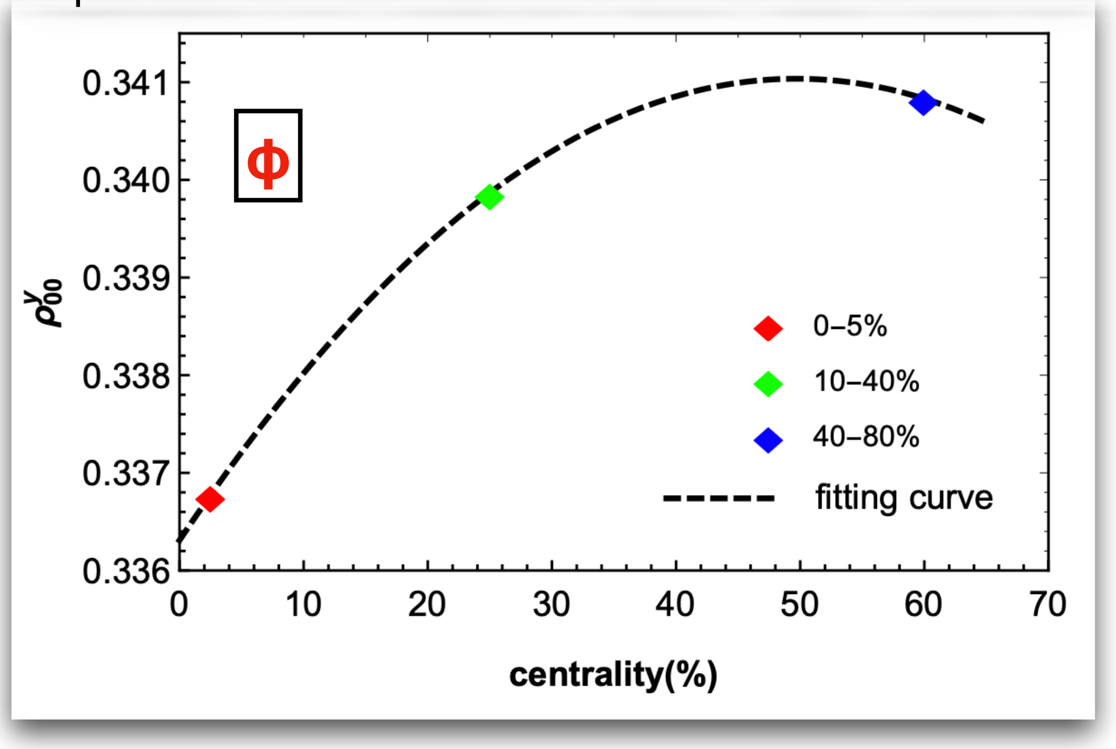
- Similar idea to explain the $P_{\bar{\Lambda}} - P_{\Lambda}$



Zoom in the 200 GeV data



Expectation from model with vector meson force field



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

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

- Can accommodate positive deviation in mid-central and peripheral collisions
- Sheng et al., arXiv:2205.15689

- Measurements of local spin alignment?

Summary and Outlook

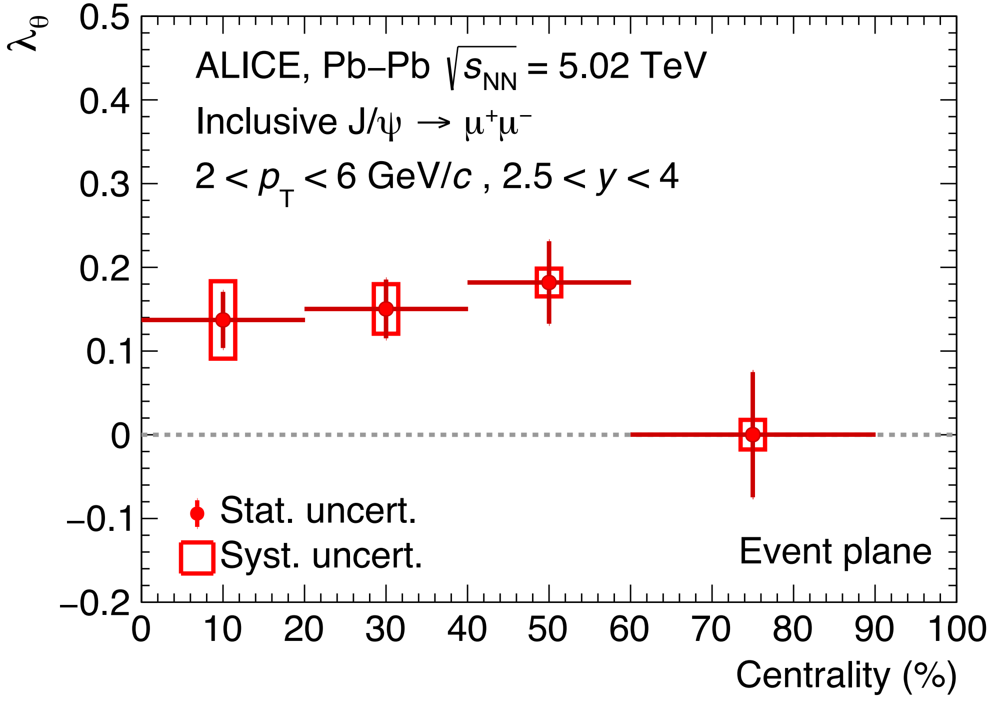
- STAR observes a surprisingly large global spin algiment for φ-meson. It cannot be explained by conventional mechanisms. However, it can be accommodated by a model with strong force field.

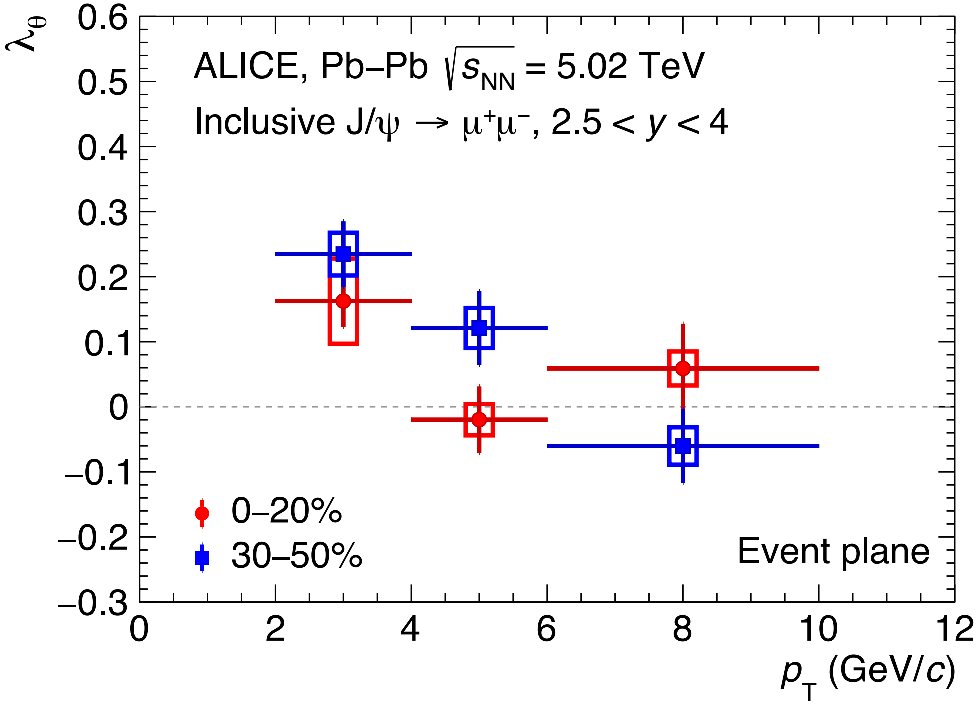
- The measurement provides evidence for quark version of spin-orbital force at work.

- Potential new avenue for understanding the strong interaction.

Summary and Outlook

ALICE Col. 2204.10171





- Observation of global spin alignment of J/ψ at LHC at large rapidity

$$J/\psi : \lambda_\theta \sim 0.2,\ \rho_{00} \sim 0.37\ (> \frac{1}{3}) \qquad \lambda_\theta \propto \frac{3\rho_{00} - 1}{1 - \rho_{00}}$$

- How will be the results at midrapidity?

Thanks to the STAR Col.

Thanks to:

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- Xu Sun (UIC)
- Aihong Tang (BNL)
- Chensheng Zhou (FDU)

Subhash Singha

Xu Sun

Chensheng Zhou

Thank you for your attention!