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Pattern of global spin alignment of φ(1020) and K^{*0}(892) in heavy-ion collisions

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2023-2-28

STAR Collaboration, *Nature* **614** (2023) 244

Outline

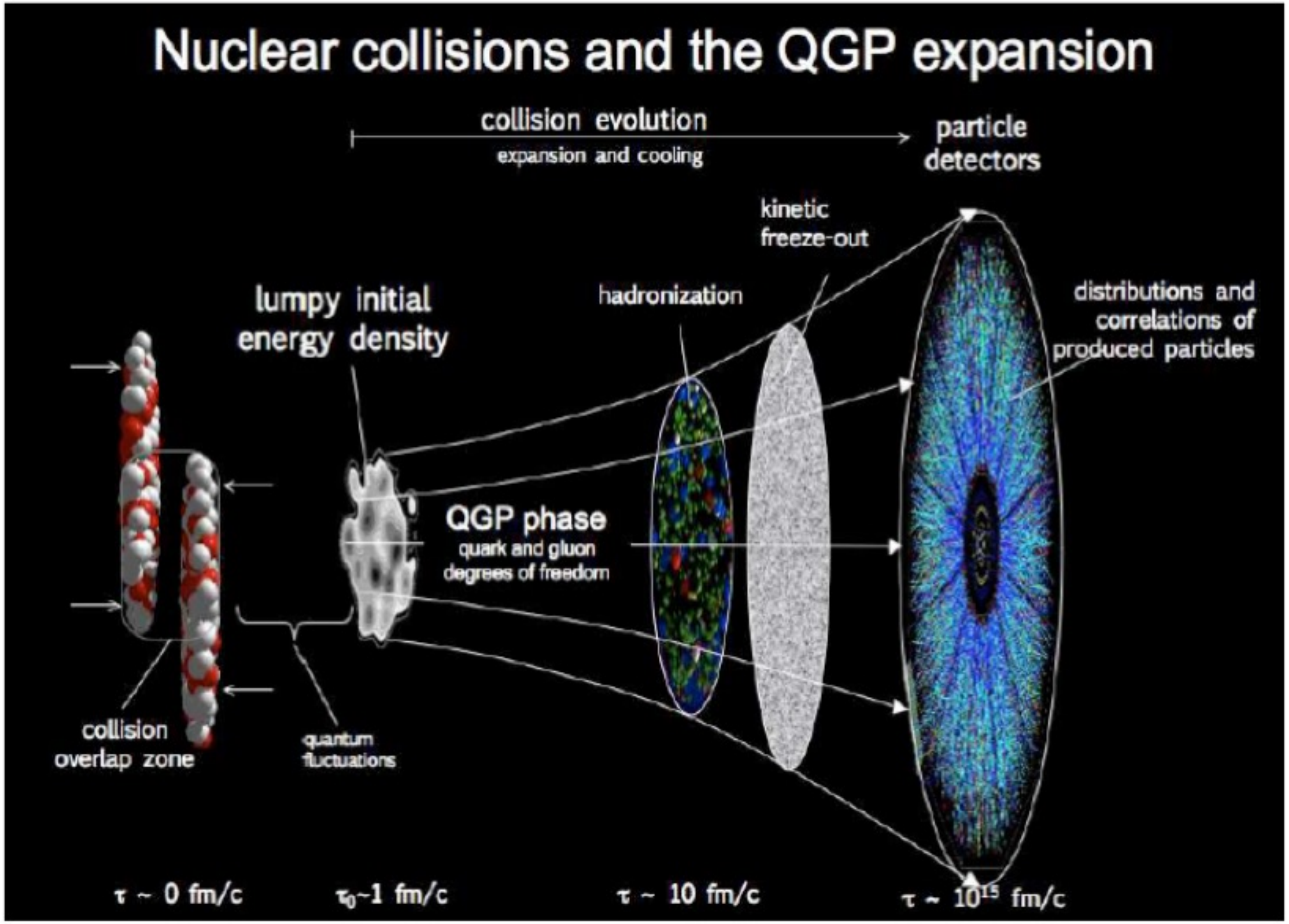
- Introduction
- Focus on vector meson measurements
- Summary and Outlook

Relativistic heavy-ion collisions

- RHIC: a QCD machine, small bang
  - ✓ Two decades of RHIC exp. provide strong evidences pointing to a “dense, opaque, low-viscous, pre-hadronic liquid state of matter not anticipated before RHIC”

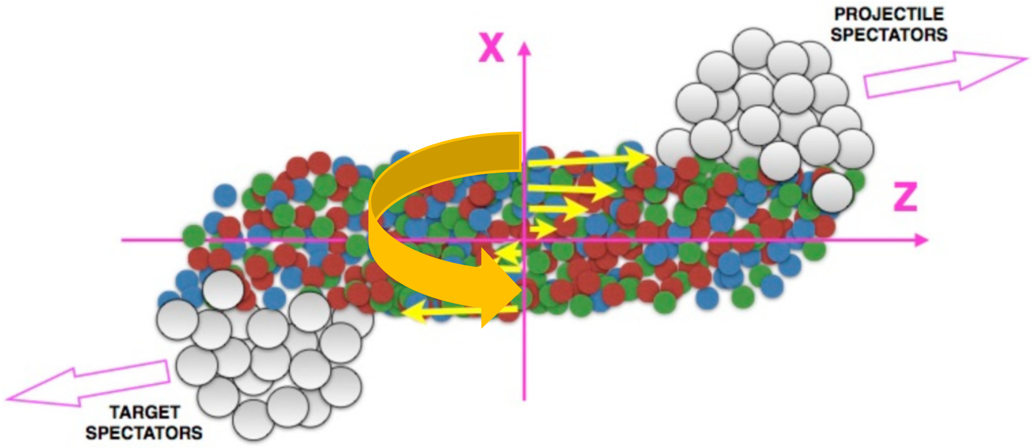
RHIC white paper: Nucl. Phys. A **757** (2005)

- Study the ‘emergent property’ of QCD

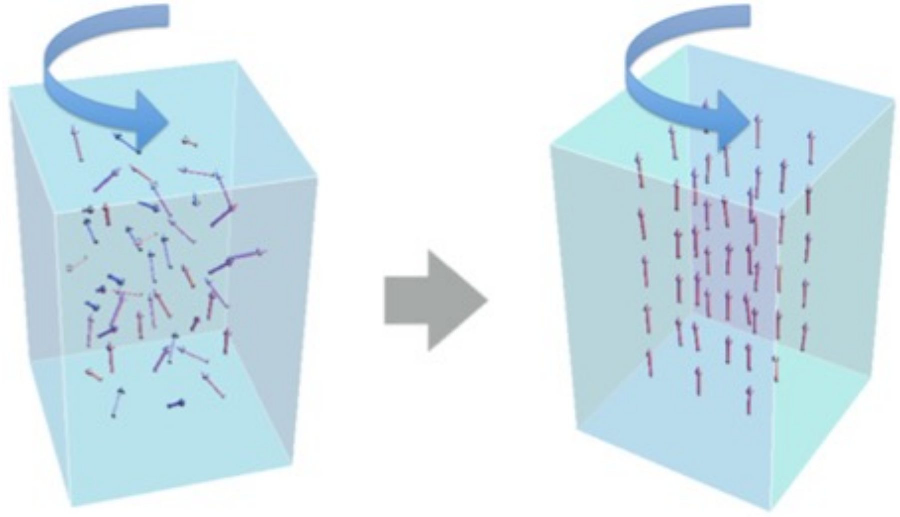


Global polarization in high-energy HIC

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



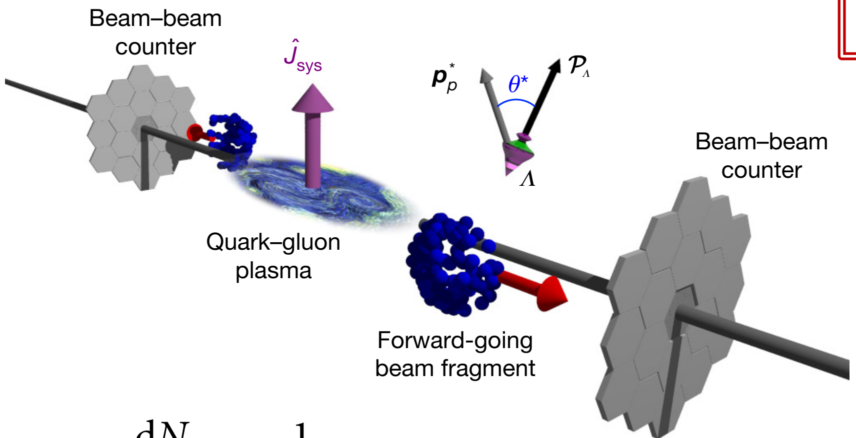
S.J. Barnett, Phys. Rev. **6**, 239 (1915); Science **30**, 413 (1909); Rev. Mod. Phys. **7**, 129 (1935)



Rotation → Polarization

- Ideas:
  - ✓ In non-central HIC, large OAM L is deposited in the interaction region $L \sim \frac{Ab\sqrt{s}}{2}$
  - ✓ Quarks may be polarized along L due to spin-orbit interaction, this polarization may not be washed out during interaction and hadronization
  - ✓ spin-vorticity coupling Betz, Gyulassy, Torrieri Phys. Rev. C **76**, 044901 (2007); Becattini, Piccinini, Rizzo Phys. Rev. C **77**, 024906 (2008)

Experimental measurements: Λ

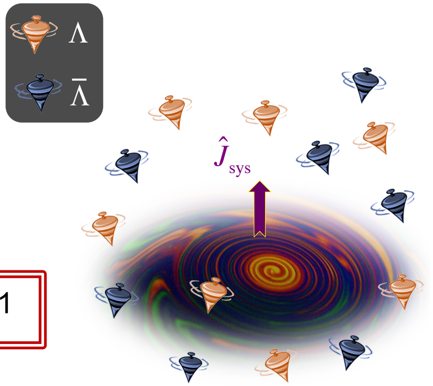


$$\frac{\mathrm{d}N}{\mathrm{d}\cos\theta^*} = \frac{1}{2}(1+\alpha_\mathrm{H}|\mathcal{P}_\mathrm{H}|\cos\theta^*)$$

- Λ are self-analyzing, proton tends to be emitted along the spin direction of the Λ

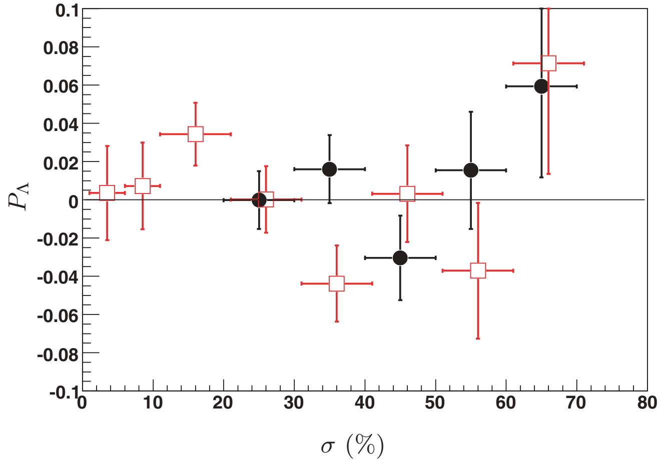
$$\overline{\mathcal{P}}_\mathrm{H} \equiv \langle \mathcal{P}_\mathrm{H}\cdot\hat{J}_\mathrm{sys}\rangle = \frac{8}{\pi\alpha_\mathrm{H}}\frac{\left\langle \cos\left(\phi_\mathrm{p}^* - \phi_{\hat{J}_\mathrm{sys}}\right)\right\rangle}{R_\mathrm{EP}^{(1)}}$$

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

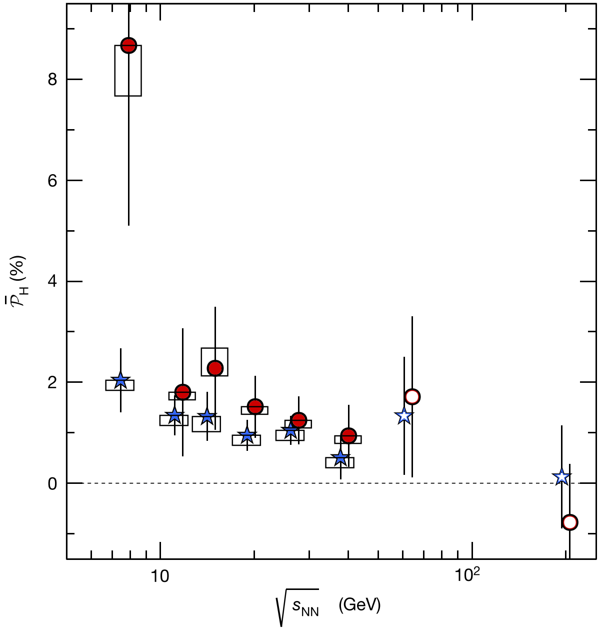


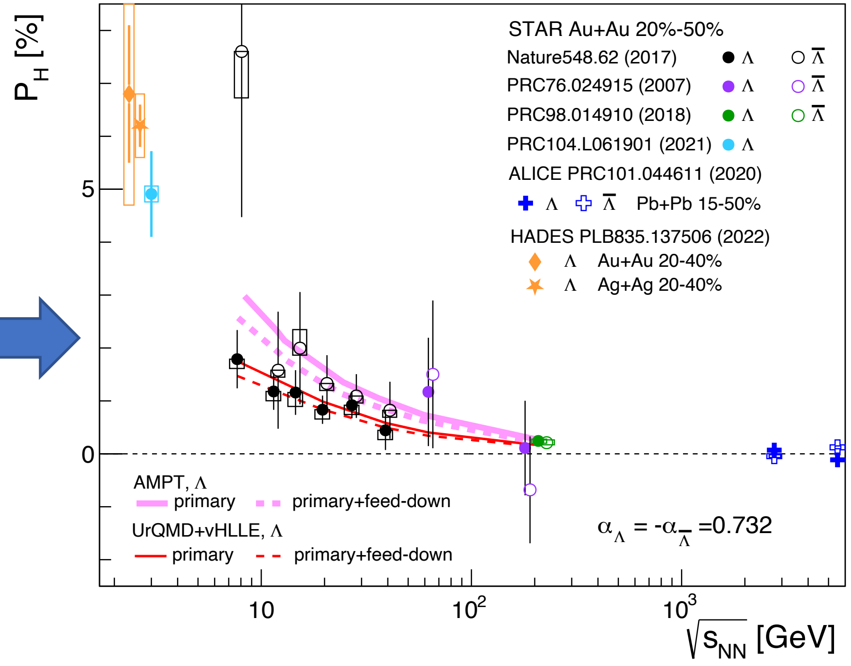
- New feature of QGP, the most vortical fluid (9±1)x10^{21} s^{-1}

STAR Col. Phys. Rev. C **76**, 024915 (2007)



STAR Col. Nature **548**, 62 (2017)

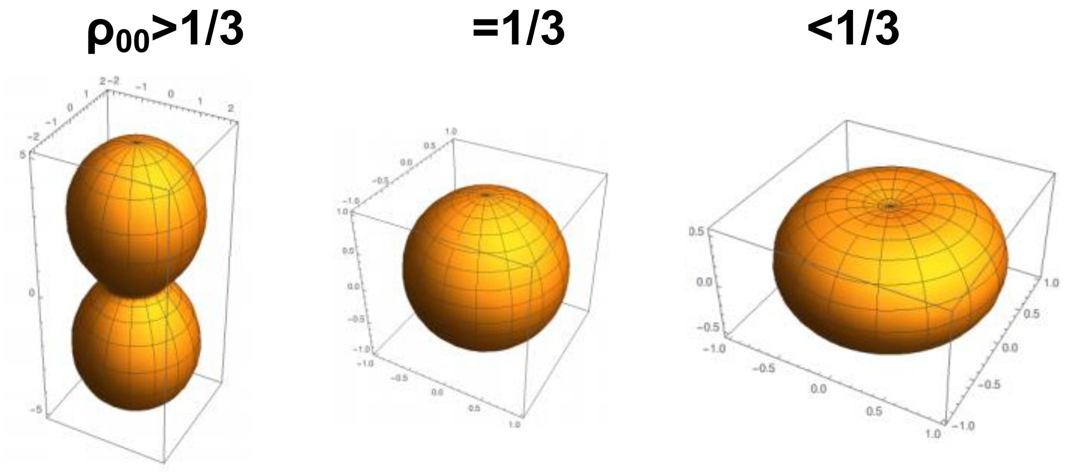




Experimental measurements: φ,K*

- Vector meson ($J=1^-$) spin alignment
  - ✓ Spin tensor polarization
  - ✓ Cannot measure the polarization sign
  - ✓ Do not need the reaction plane direction

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



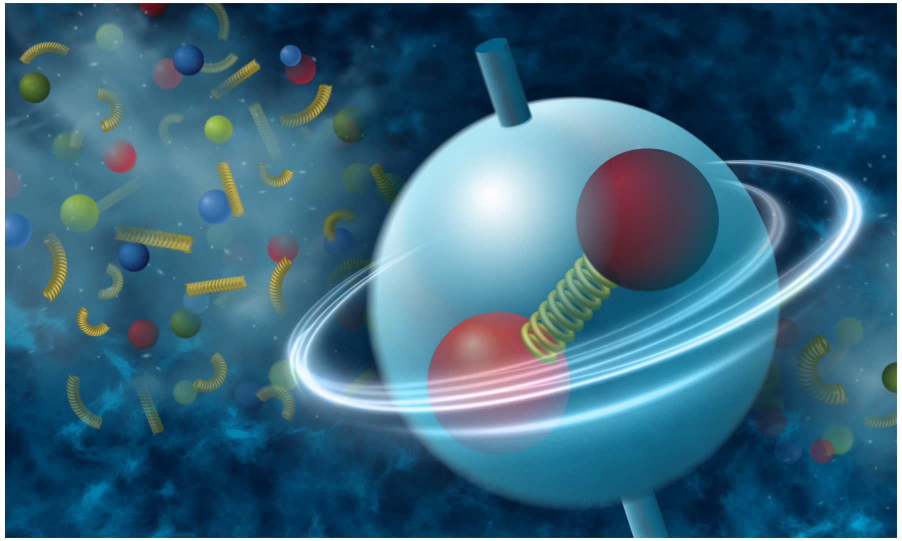
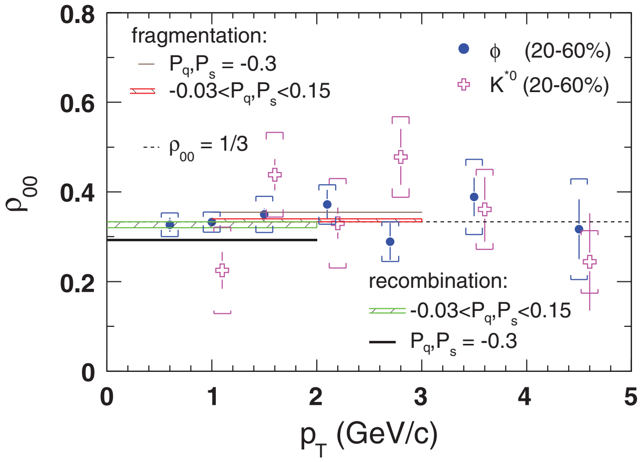
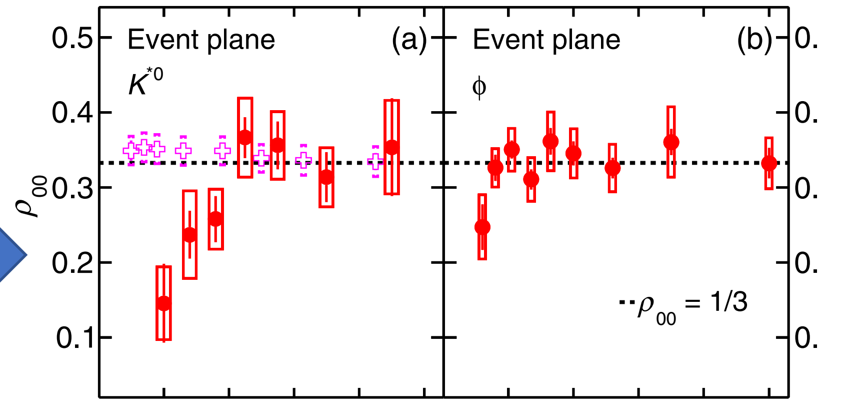


Image credit : Brookhaven National Laboratory

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

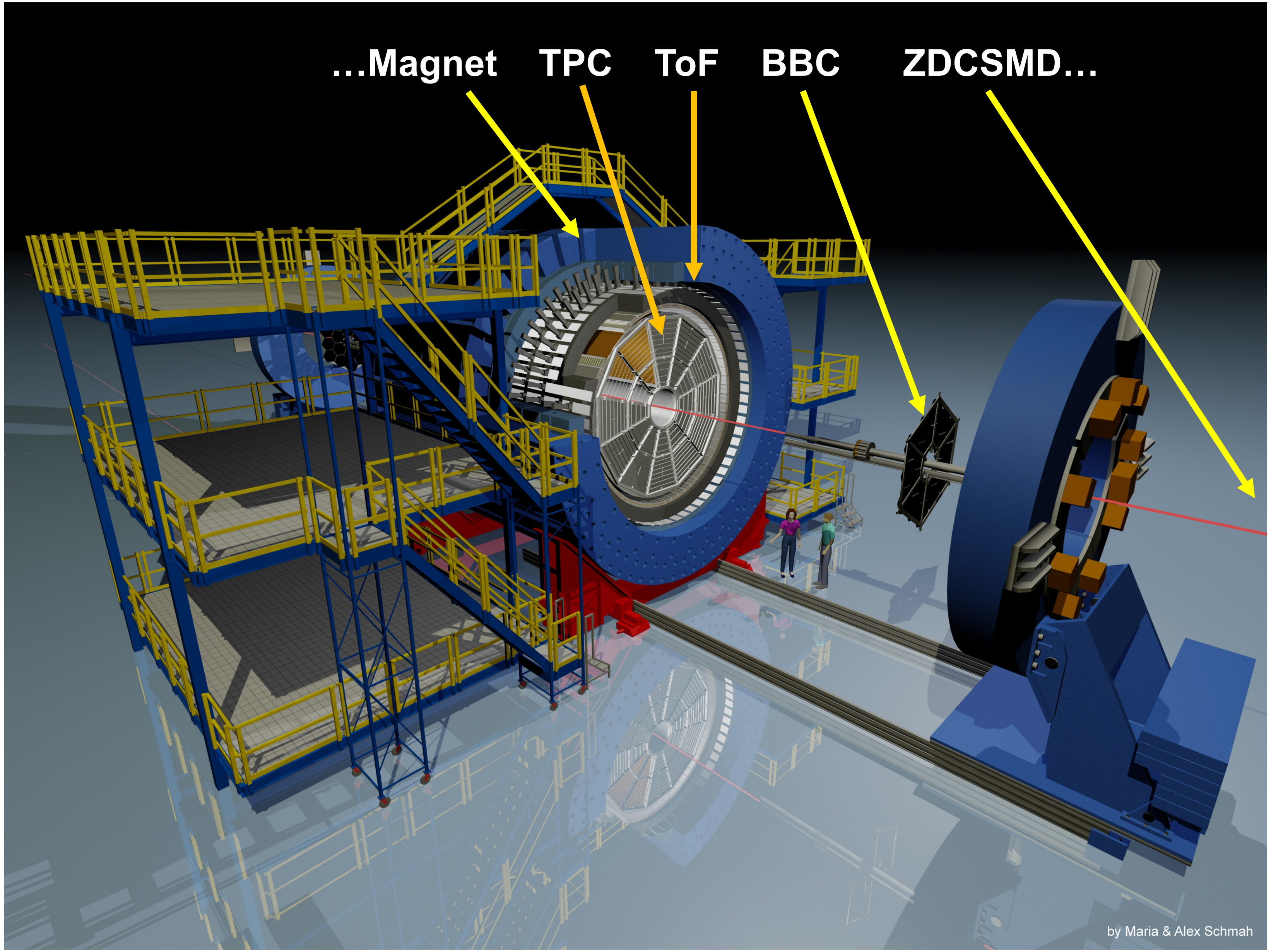


ALICE Col. Phys. Rev. Lett. **125**, 012301 (2020)

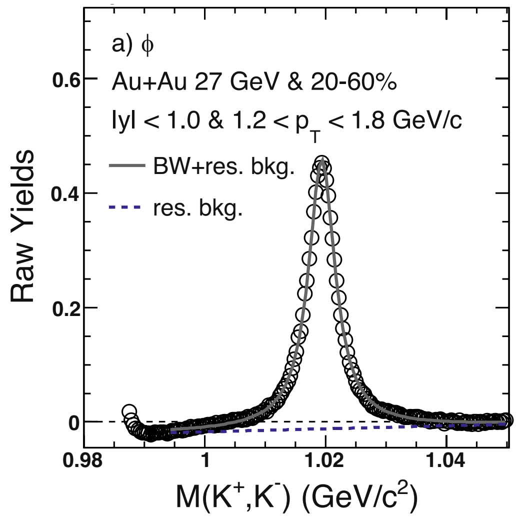


- Evidence of spin-orbital angular momentum interactions

The STAR Detector at BES-I



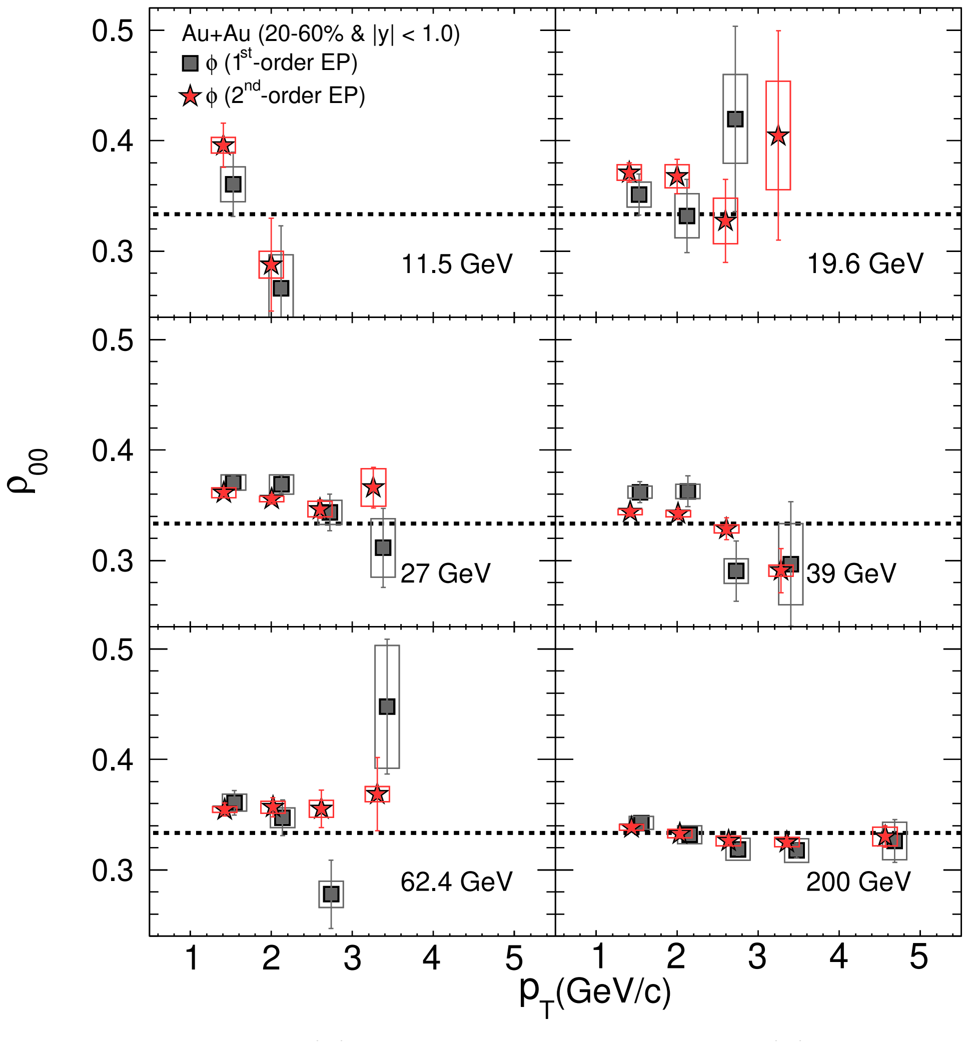
- TPC: effectively 3-D ionization camera with over 50 million pixels
- STAR: a complex set of various detectors, a wide range of measurements and a broad coverage of different physics topics
- Zoom in this analysis:
  - ✓ Excellent PID & EP
  - ✓ Uniform acceptance for all beam energies

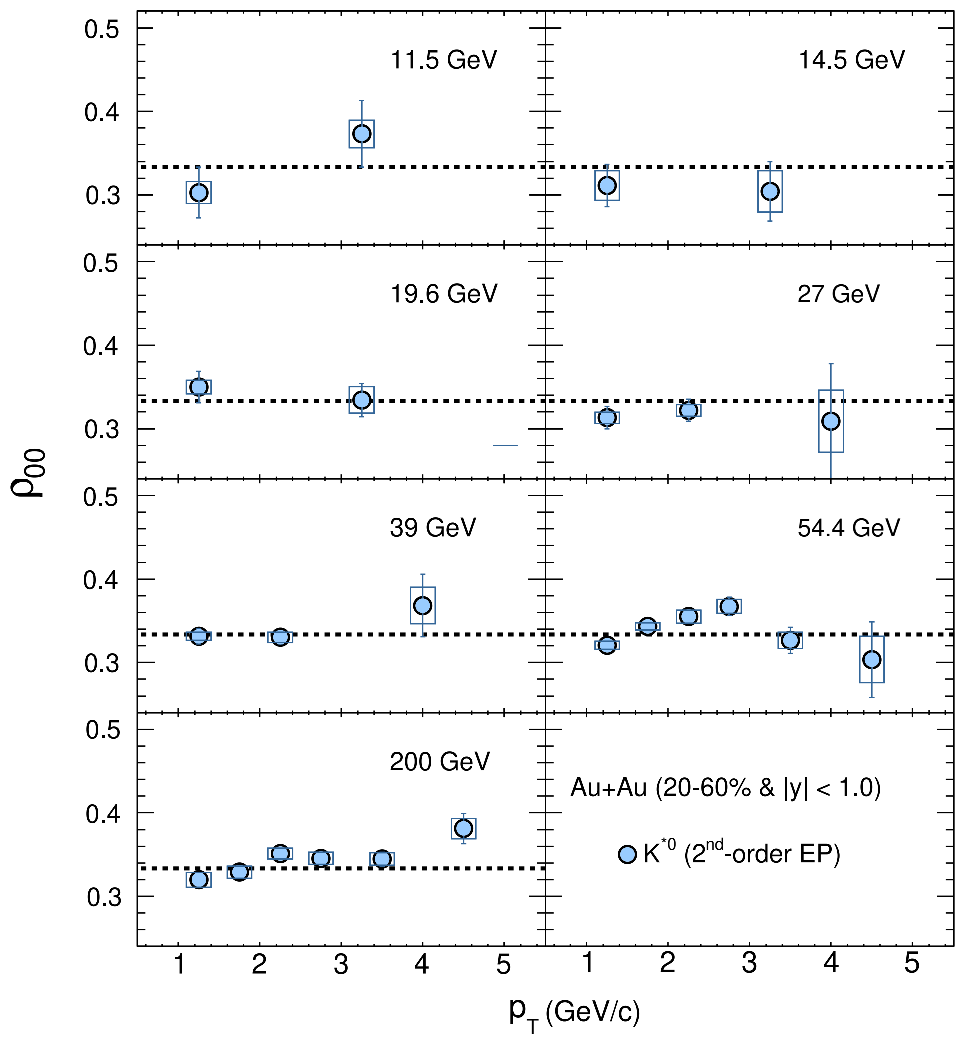


New Measurements φ,K*@non-central collisions

STAR Col. Nature **614**, 244 (2023)

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

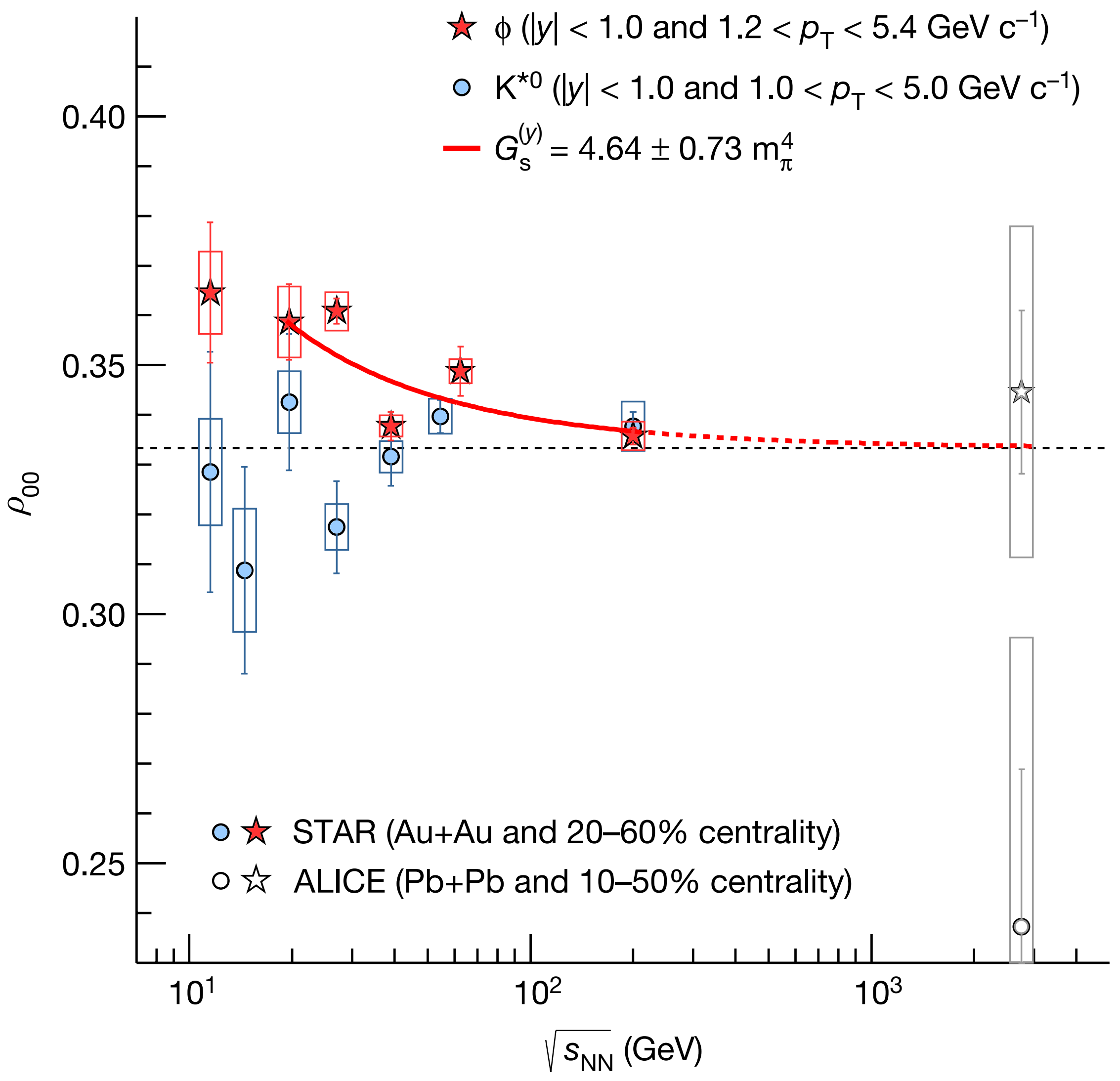




- We see that the signal for the φ meson occurs mainly withn ~1.0-2.4 GeV/c; at larger p_T the results can be regarded as being consistent with 1/3 within ~2sigma or less.

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

Results averaged over p_T



STAR Col. Nature **614**, 244 (2023)

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

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

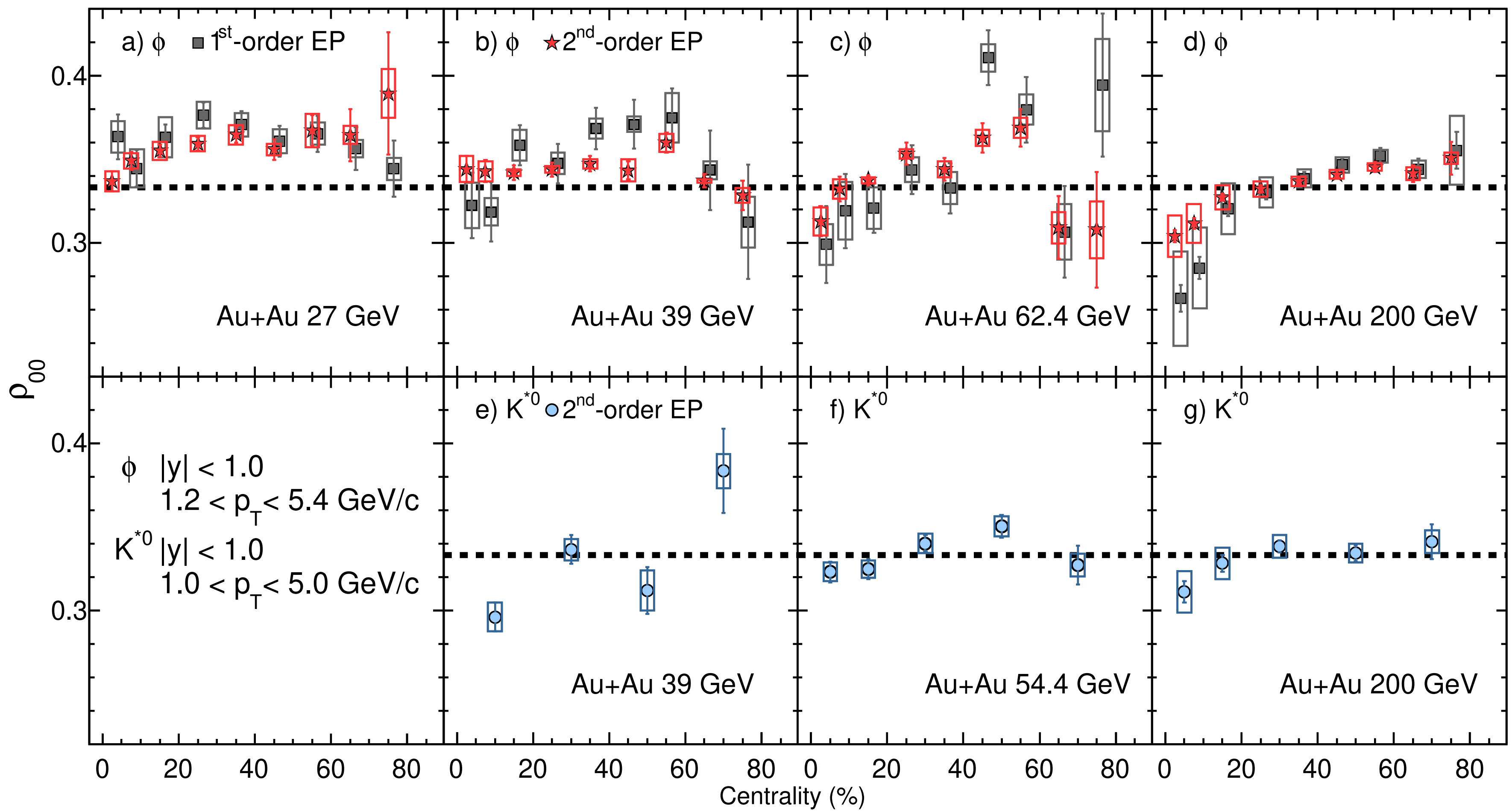
3) Averaged over 62 GeV and below:

- 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. Nature 614, 244 (2023)



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

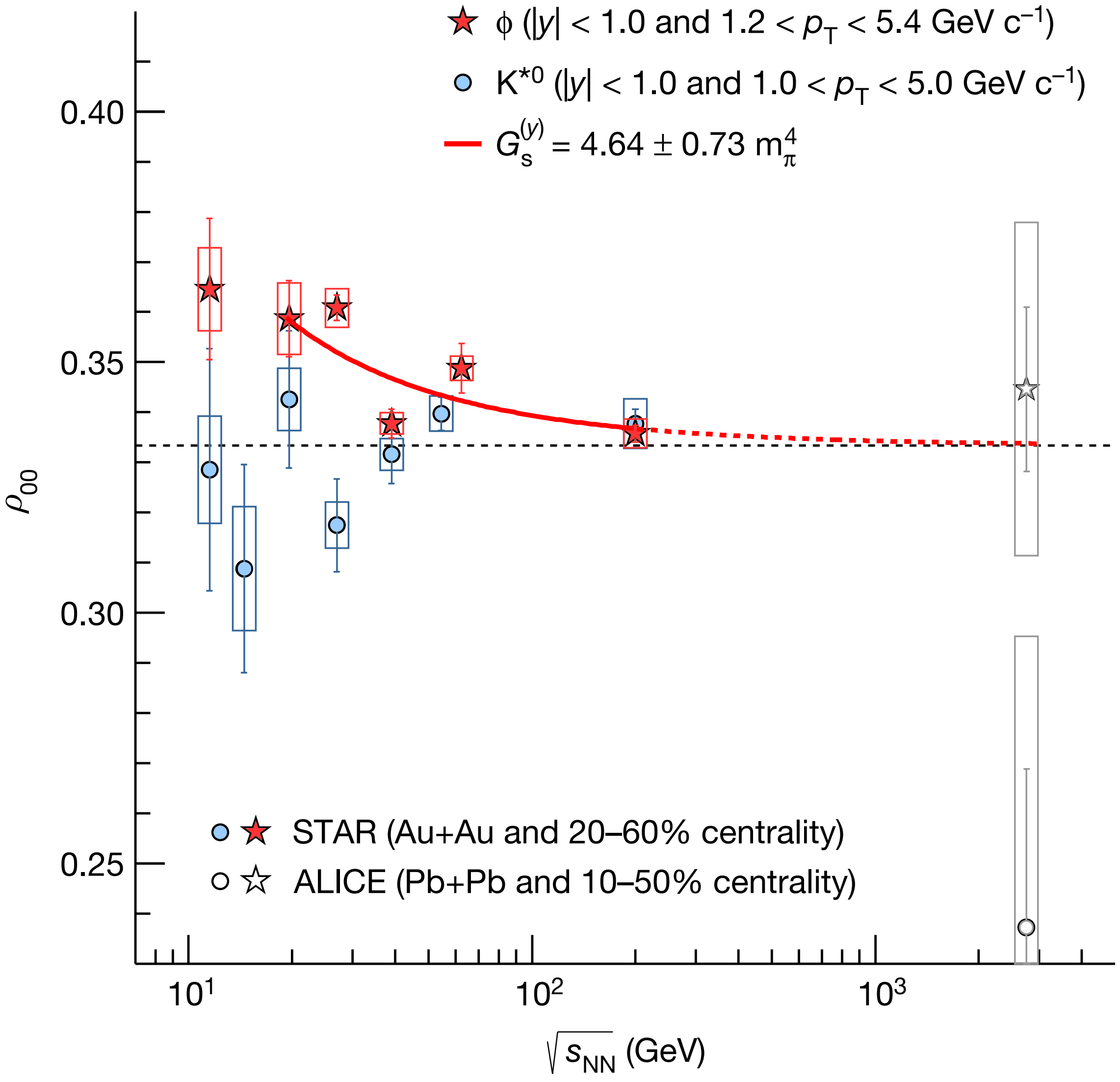
$$\rho_{00}(\omega) \sim \frac{1}{3} - \frac{1}{9}(\beta\omega)^2$$

$$\rho_{00}(\text{coal}) \sim \frac{1 - \mathrm{P_q P_q}}{3 + \mathrm{P_q P_q}} \qquad \rho_{00}(B) \approx \frac{1}{3} - \frac{4}{9}\beta^2 \mu_{q_1}\mu_{q_2} B^2$$

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

[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 ρ_{00} at midcentral collisions

$$\rho_{00}^{\phi} \approx \frac{1}{3} + c_\Lambda + c_\varepsilon + c_E + c_\phi$$

$$c_\phi \equiv \frac{g_\phi^2}{27 m_s^2 T_{\text{eff}}^2}\left[3\langle B_{\phi,y}^2\rangle - \frac{\langle \mathbf{p}^2\rangle_\phi}{m_s^2}\langle E_{\phi,z}^2 + E_{\phi,x}^2\rangle\right]$$

$$G_s^{(y)} \equiv g_\phi^2\left[3\langle B_{\phi,y}^2\rangle - \frac{\langle \mathbf{p}^2\rangle_\phi}{m_s^2}\langle E_{\phi,z}^2 + E_{\phi,x}^2\rangle\right]$$

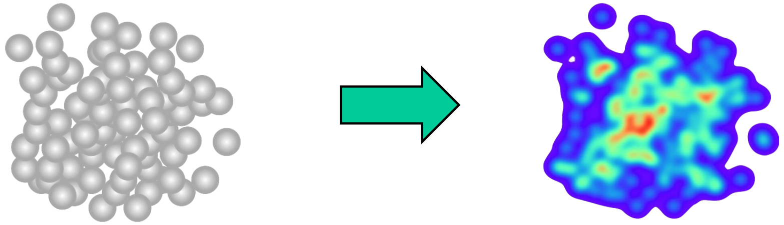
Sheng, Oliva, Wang Phys. Rev. D 101 (2020) 096005
Sheng, Wang, Wang Phys. Rev. D 102 (2020) 056013

HIC : a highly volatile environment

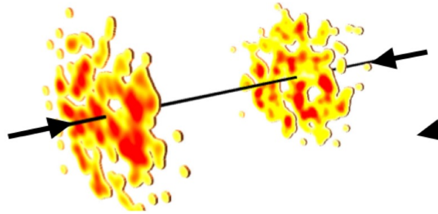
Gribov, Levin, Ryskin, 1981
McLerran, Venugopalan
hep-ph/9309289

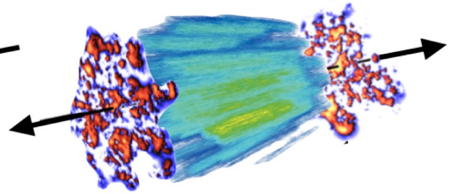
Strongest color field

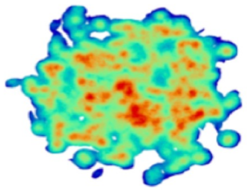
Nucleus at rest

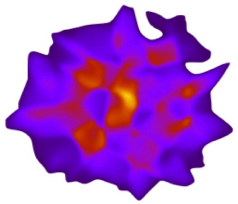


Nucleus at relativistic energies

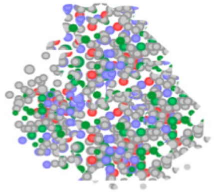


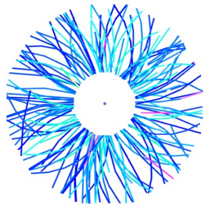






Hadronization





Color Glass Condensate (CGC)

Gluon Condensate Plasma (Glasma)

Quark Gluon Plasma (QGP)

Detection

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

The φ-meson 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.

$$
\begin{aligned}
P^{y}_{s/\bar{s}}\left(\mathrm{t}, \mathbf{x}, \mathbf{P}_{s/\bar{s}}\right) = {} & \frac{1}{2}\omega_y + \frac{1}{2m_s}\hat{\mathbf{y}} \cdot \left(\varepsilon \times \mathbf{P}_{s/\bar{s}}\right) && \Leftarrow \text{vorticity} \\
& \pm \frac{Q_s}{2m_s T} B_y \pm \frac{Q_s}{2m_s^2 T}\hat{\mathbf{y}} \cdot \left(\boldsymbol{E} \times \mathbf{P}_{s/\bar{s}}\right) && \Leftarrow \text{EM field} \\
& \pm \frac{g_\phi}{2m_s T} B_{\phi,y} \pm \frac{g_\phi}{2m_s^2 T}\hat{\mathbf{y}} \cdot \left(\boldsymbol{E}_\phi \times \mathbf{P}_{s/\bar{s}}\right) && \Leftarrow \text{strong force field}
\end{aligned}
$$

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

"magnetic" components

"electric" components

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

Meson fields and Λ polarization

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

L. P. Csernai,[1] J. I. Kapusta,[2] and T. Welle[2]

[1] *Institute of Physics and Technology, University of Bergen, Allegaten 55, 5007 Bergen, Norway*

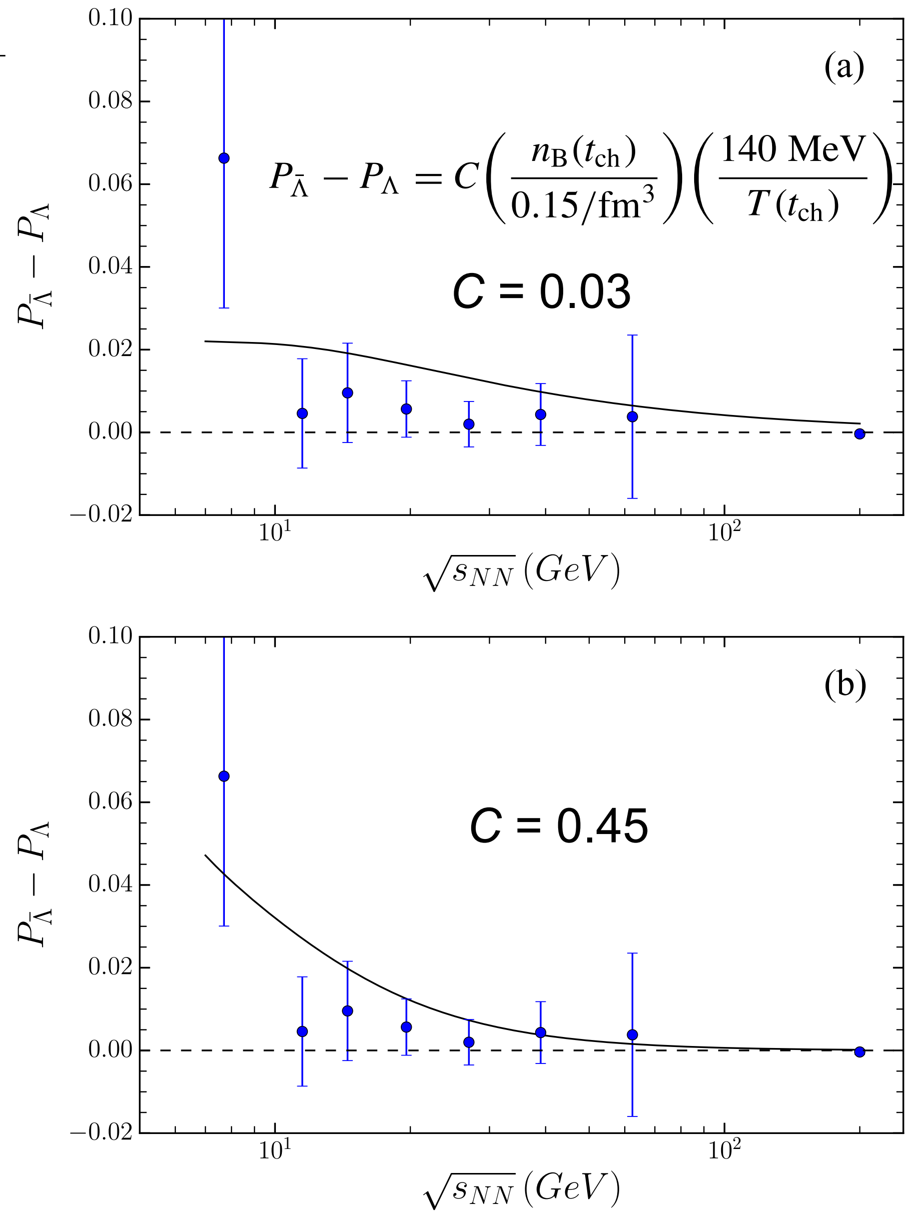
[2] *School of Physics and Astronomy, University of Minnesota, Minneapolis, Minnesota 55455, USA*

(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.

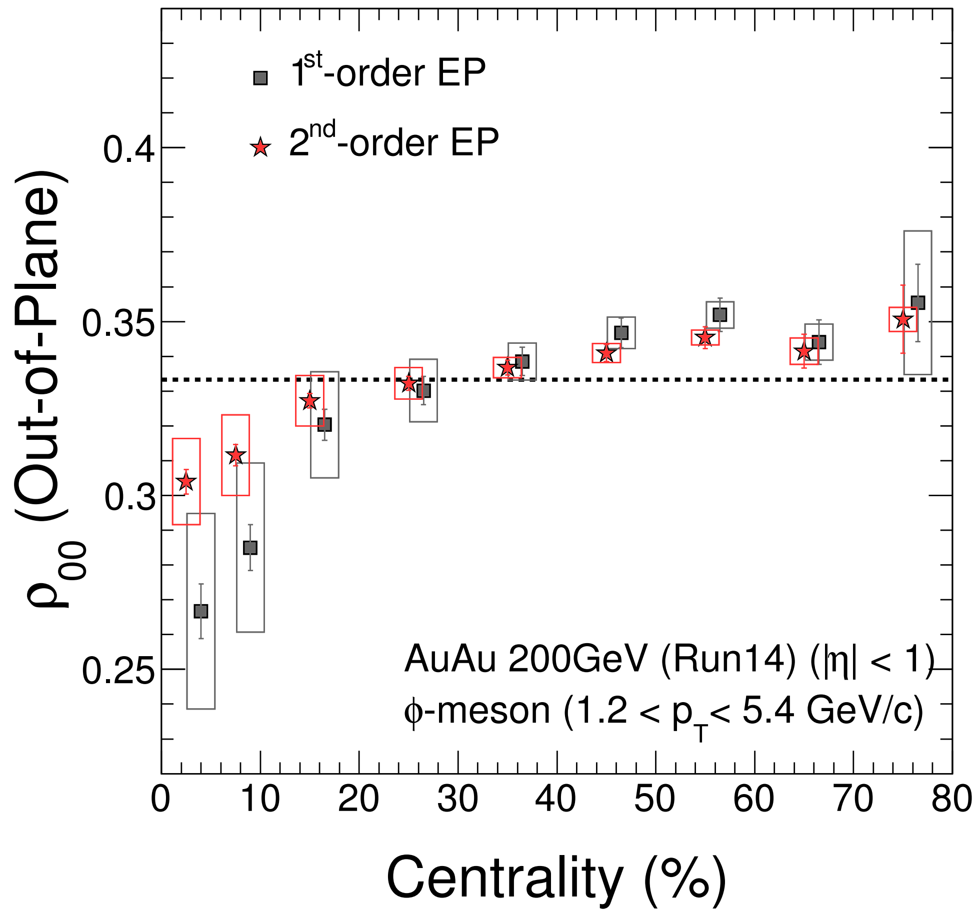
$$H^V_{\text{spin-orbit}} = \frac{g_{V\Lambda}}{2m_\Lambda^2}\frac{1}{r}\frac{\partial V_0}{\partial r}\boldsymbol{S}\cdot\boldsymbol{L}, \qquad H^\sigma_{\text{spin-orbit}} = \frac{g_{\sigma\Lambda}}{2m_\Lambda^2}\boldsymbol{S}\cdot\nabla\sigma\times\boldsymbol{p},$$

- Similar idea to explain the polarization difference between Λs
- The effect is orders of magnitude larger than the one arising from electromagnetic fields

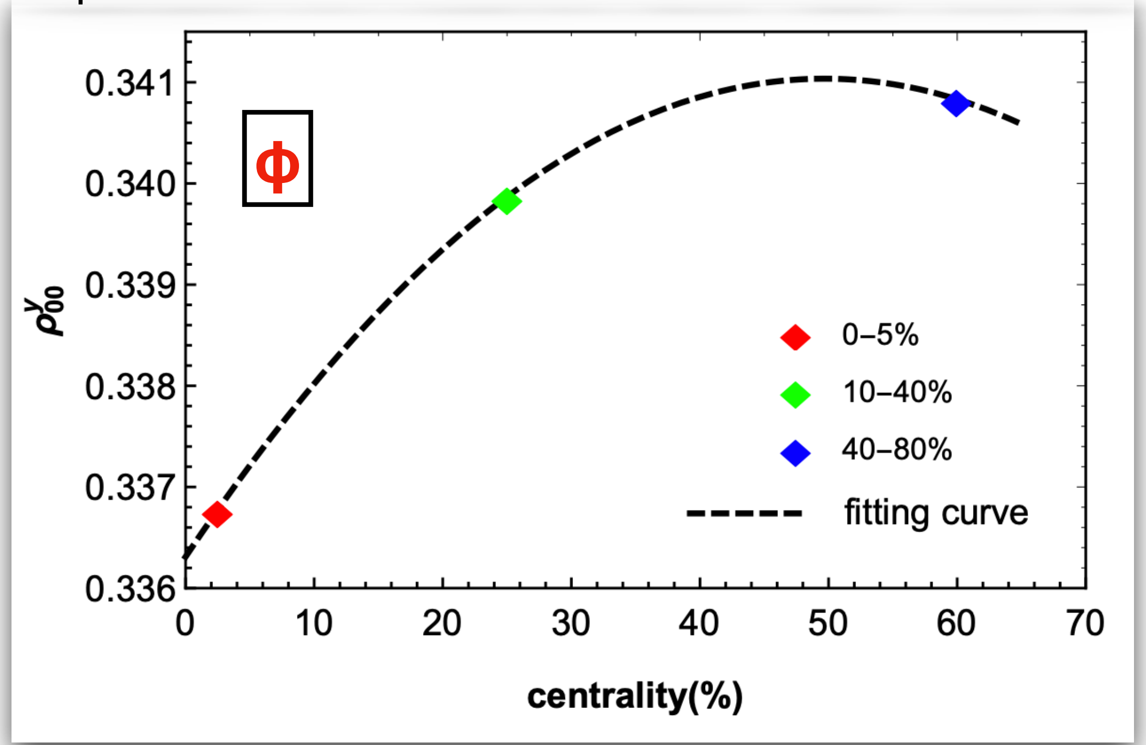


Zoom in the 200 GeV data

STAR Col. Nature 614, 244 (2023)



Expectation from model with vector meson force field



- Can accommodate positive deviation in mid-central and peripheral collisions

Sheng et al., arXiv:2205.15689

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

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

- 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 (1)

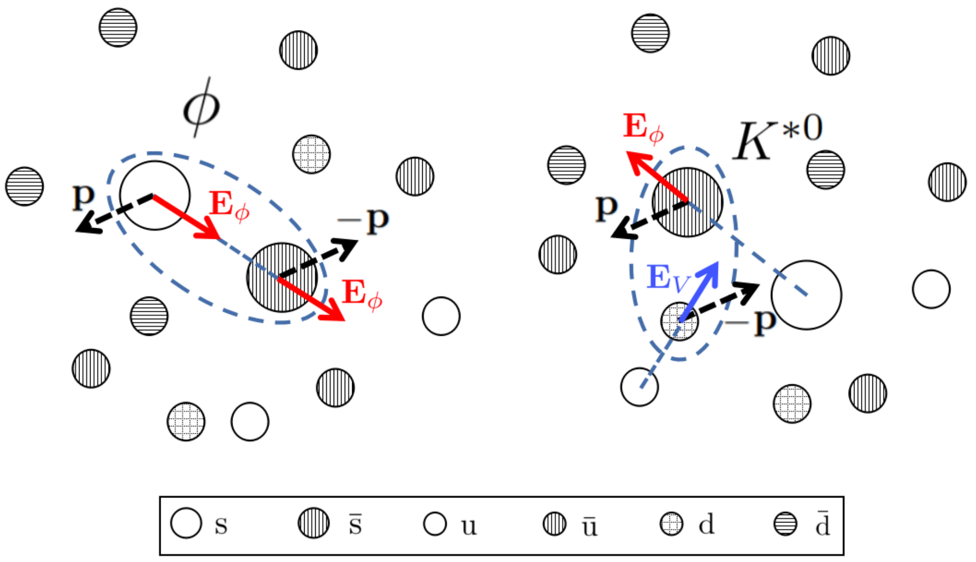
- The strong fields explanation is subject to debate and further verification

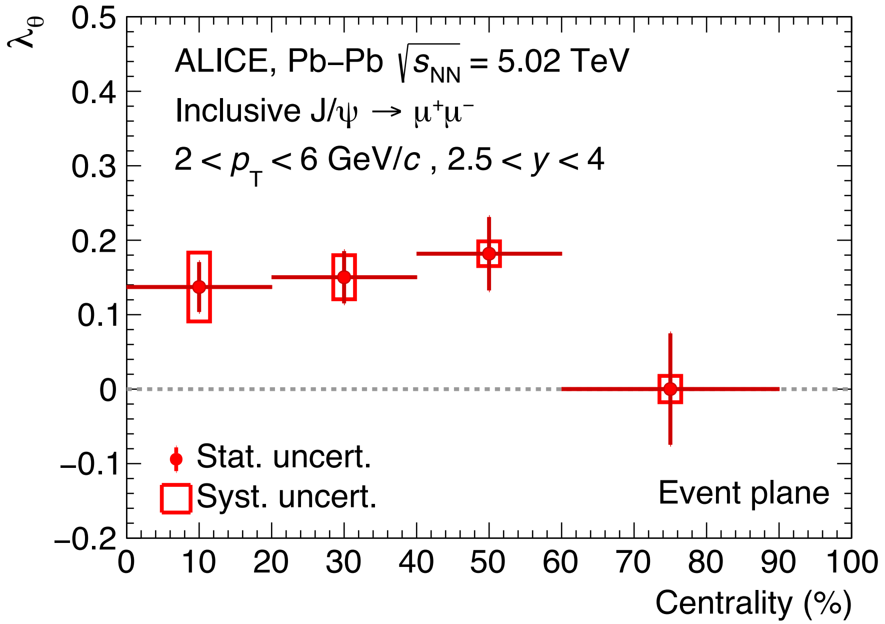
  - ✓ Mixed flavor: ρ-meson
  - ✓ Same flavor: J/ψ-meson
  - ✓ At large rapidity, LHC observed a signal

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

ALICE Col. 2204.10171

- It would be very interesting to carry out the study at midrapidity

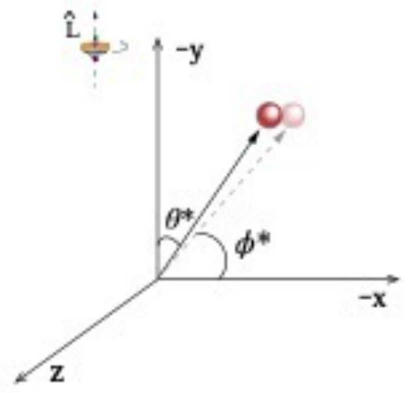




Summary and Outlook (2)

- ρ-meson global spin alignment measurement: another good probe to understand the difference between φ,K*
  - ✓ Due to their short life time, ρ-mesons are constantly being destroyed and regenerated. Most of ρ-mesons reconstructed in HIC experiment are the ones that got regenerated right before freeze out. This, together with that ρ-meson consists of a mixture of quark flavor, makes it not a good probe to local fluctuation of strong force field like φ-meson.
  - ✓ The global spin alignment of ρ-meson has notable implication on CME analyses

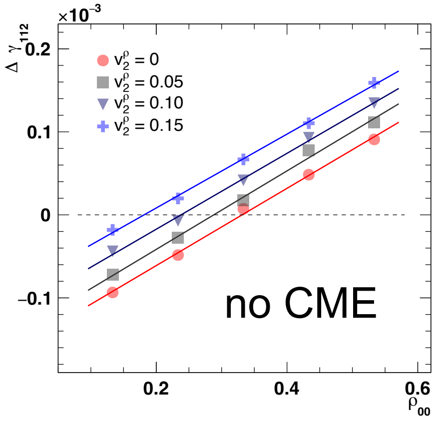
[*CME: interplay between chirality imbalance of quarks and intense magnetic field]



$$
\begin{aligned}
\Delta\gamma_{112} &= \frac{N_\rho}{N_+N_-}\left[\frac{1}{8}(f_c+f_s)(3\rho_{00}-1)-\frac{1}{2}(f_c-f_s)\right] \\
&= \frac{N_\rho}{8N_+N_-}\left[2f_0+\sum_{n=1}^{\infty}(c_n+s_n)(v_2^\rho)^n\right](3\rho_{00}-1) \\
&\quad -\frac{N_\rho}{2N_+N_-}\sum_{n=1}^{\infty}(c_n-s_n)(v_2^\rho)^n. \qquad (12)
\end{aligned}
$$

Shen, Chen, Tang, Wang, arXiv 2212.03056 Phys. Lett. B in press

Shen, Chen, Lin, arXiv 2102.05266 Chin. Phys. C **45** (2021) 054002



- ρ-mesons spin alignment is a crucial component in the background estimation for the CME measurements involving πs

Acknowledgement

Thanks to the STAR Col.

Thanks to:

- Declan Keane (Kent Univeristy)
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- Xu Sun (UIC)
- Aihong Tang (BNL)
- Chensheng Zhou (FDU)

Subhash Singha

Xu Sun

Chensheng Zhou

Thank you for your attention!