重离子碰撞中强磁场、自旋极化的实验测量

陈金辉

复旦大学

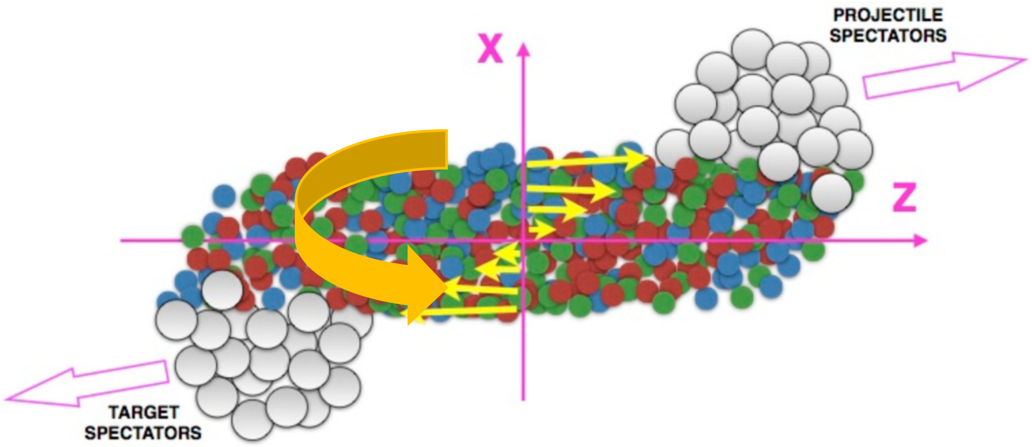
USTC-PNP-Nuclear Physics Mini Workshop Series, 2024/1

Outline

- Introduction
- Measurements in heavy-ion collisions
    - Hyperon polarization
    - Charge-dependence direct flow
    - Vector meson spin alignment
- Summary

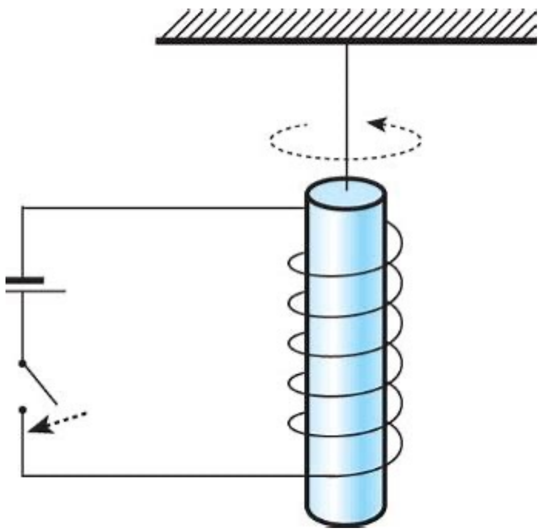
Global polarization in HIC

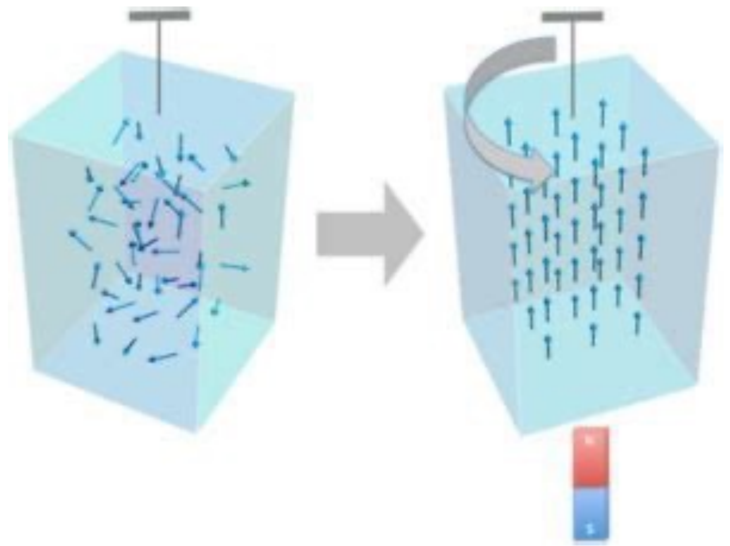
Liang, Wang Phys. Rev. Lett. **94**, 102301(2005); Phys. Lett. B **629**, 20 (2005)



Large OAM L is deposited in the interaction region

Einstein-de-Hass effect, Barnett effect
Einstein, de Haas, Deut. Phys. Gesellsch. Verhandlungen **17**,152 (1915);
Richardson, Phys. Rev. **26**, 248 (1908)
Barnett, Phys. Rev. **6**, 239 (1915); Science **30**, 413 (1909); Rev. Mod. Phys. **7**, 129 (1935)

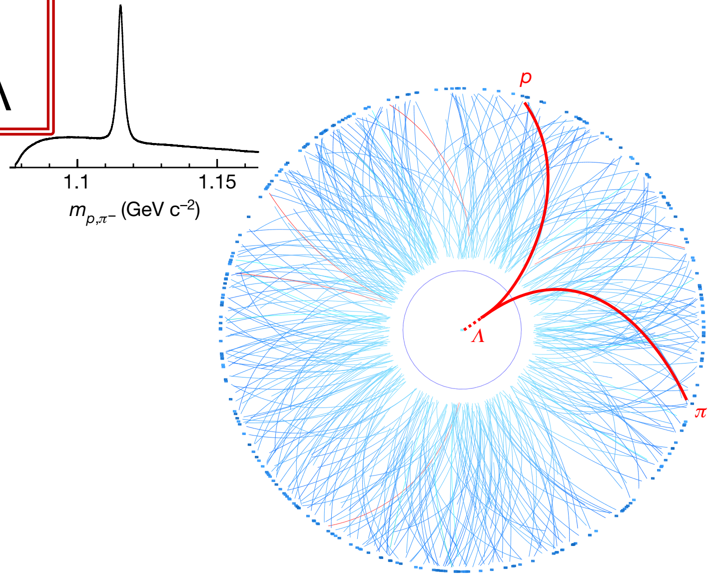


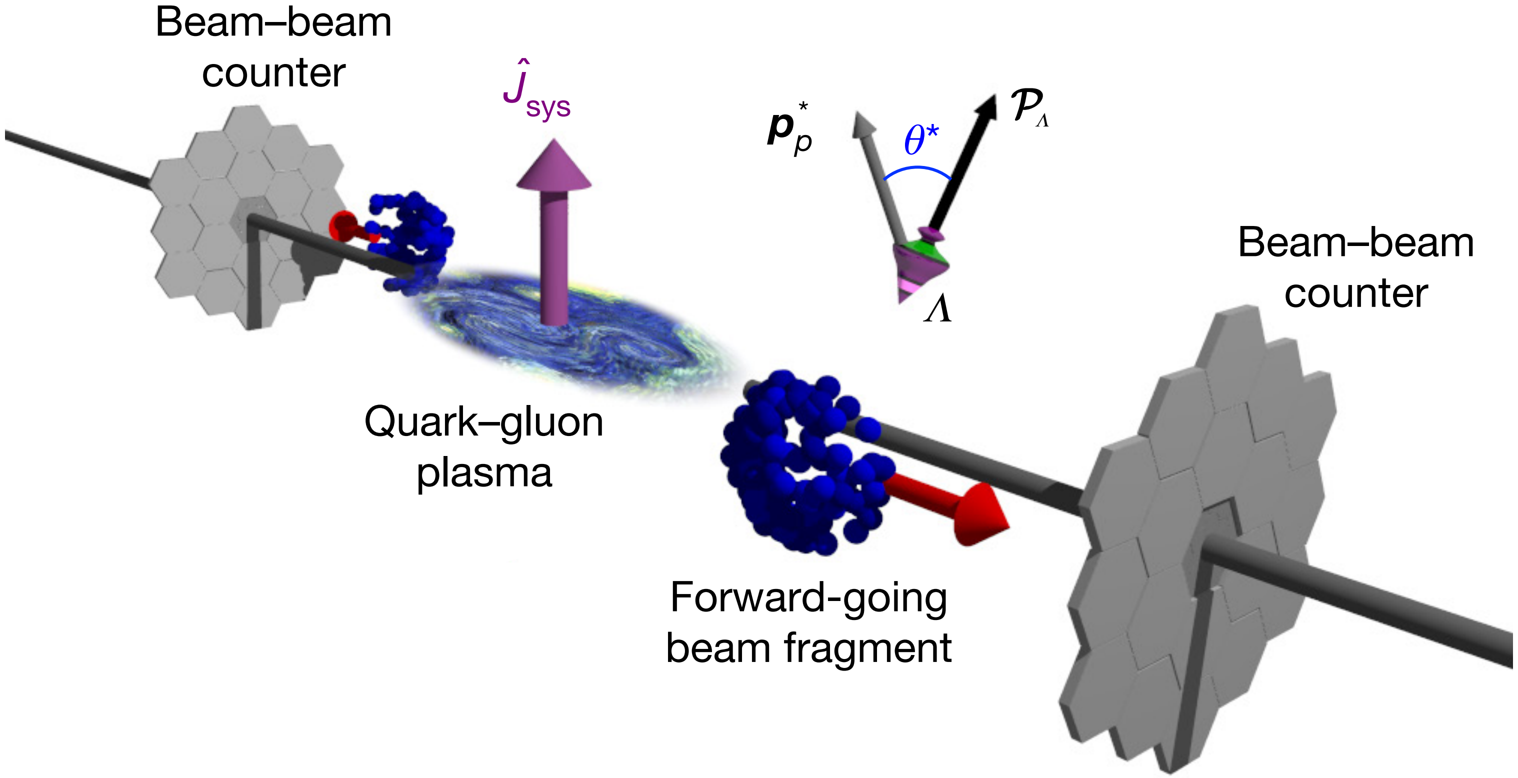


- The initial momentum gradient should result in a net angular momentum (shear) in this direction that will be transferred to quark spin via spin-orbit interaction, this effect may not be washed out during interaction and hadronization
- Spin-vorticity coupling   Betz, Gyulassy, Torrieri Phys. Rev. C **76**, 044901 (2007); Becattini, Piccinini, Rizzo Phys. Rev. C **77**, 024906 (2008)
- Connection to classical world, the Barnett effect, a fraction of the L associated with the body rotation is transformed into the spin L of the electron

Experimental measurements: Λ

- The global quark polarization along L have many observable consequences in non-central HIC
- Λ are self-analyzing, proton tends to be emitted along the spin direction of the Λ



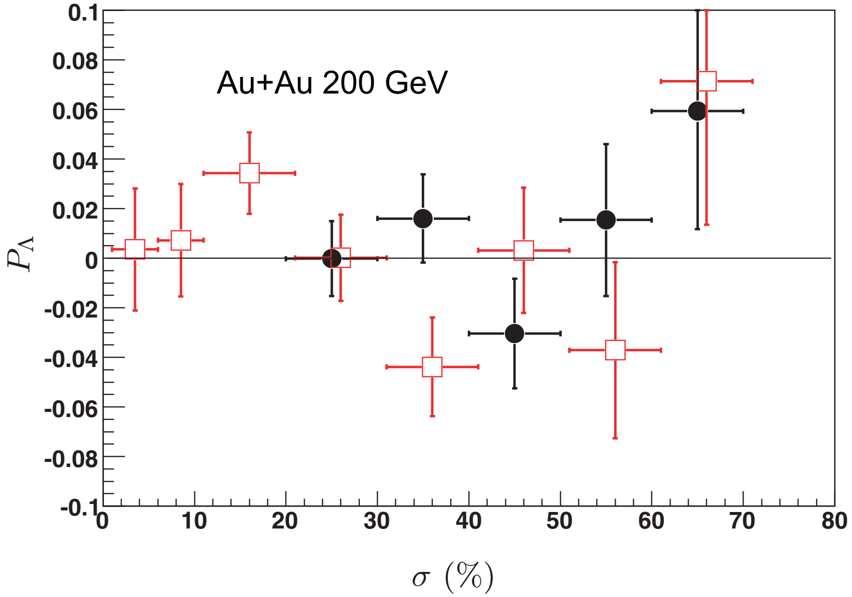


$$\frac{\mathrm{d}N}{\mathrm{d}\cos\theta^*} = \frac{1}{2}(1 + \alpha_{\mathrm{H}}|\mathcal{P}_{\mathrm{H}}|\cos\theta^*)$$

$$P_H = \frac{8}{\pi\alpha_H}\frac{\langle\sin(\Psi_1^{\mathrm{obs}} - \phi_p^*)\rangle}{\mathrm{Res}(\Psi_1)}$$

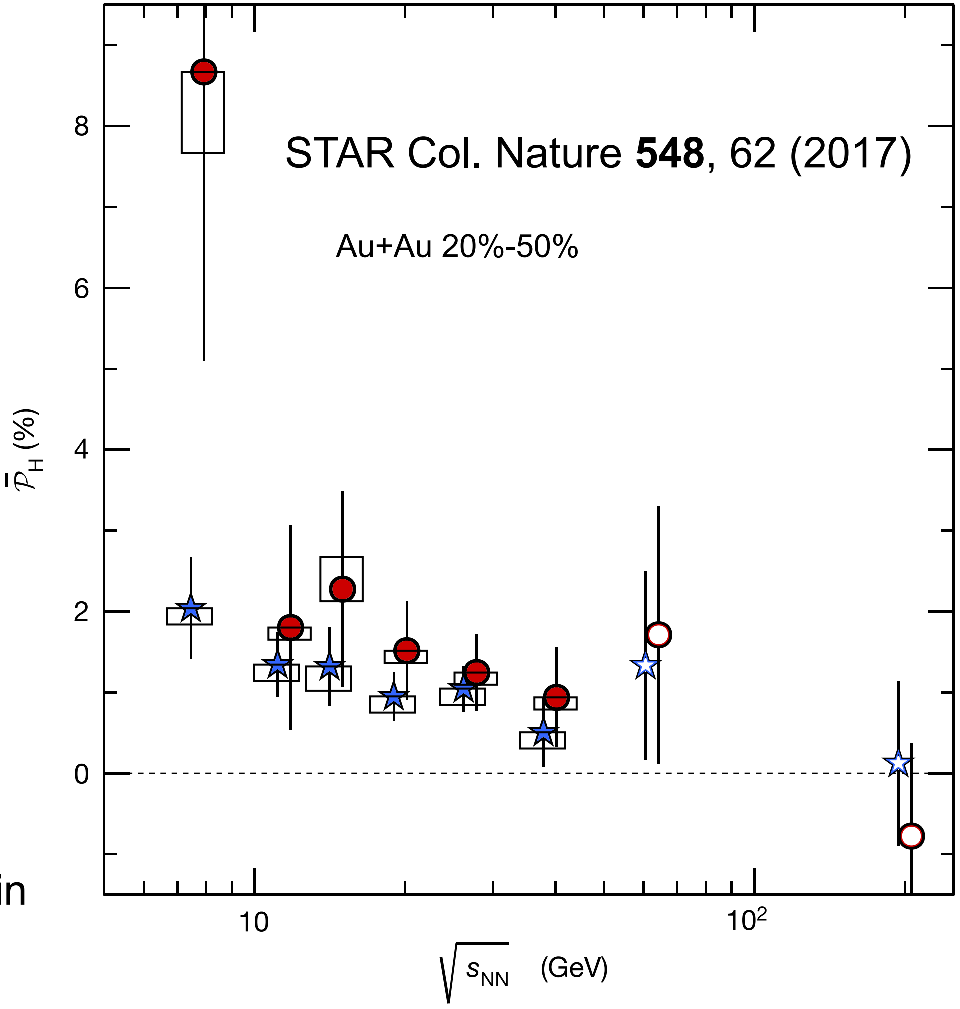
Experimental measurements: Λ (cont.)

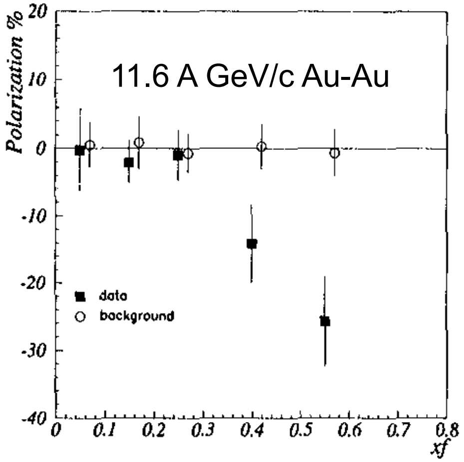
STAR Col. Phys. Rev. C **76**, 024915 (2007)



from 2007 to 2017

Lambda hyperons show a positive polarization of the order of a few percent





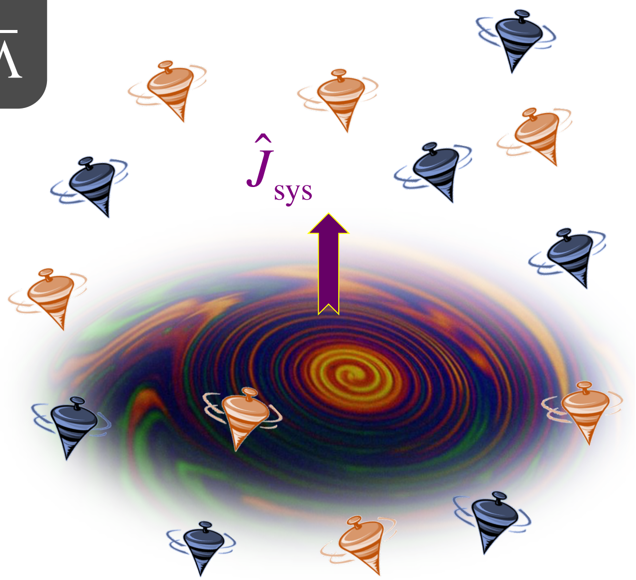
R. Bellwied for E896 Col.
QM2001, Nucl. Phys. A 698, 499 (2002)

“The produced Λ are polarized at freeze-out in the heaviest collision system”

…

“The STAR detector will be capable of repeating these measurements at RHIC energies”

Experimental measurements: Λ (cont.2)



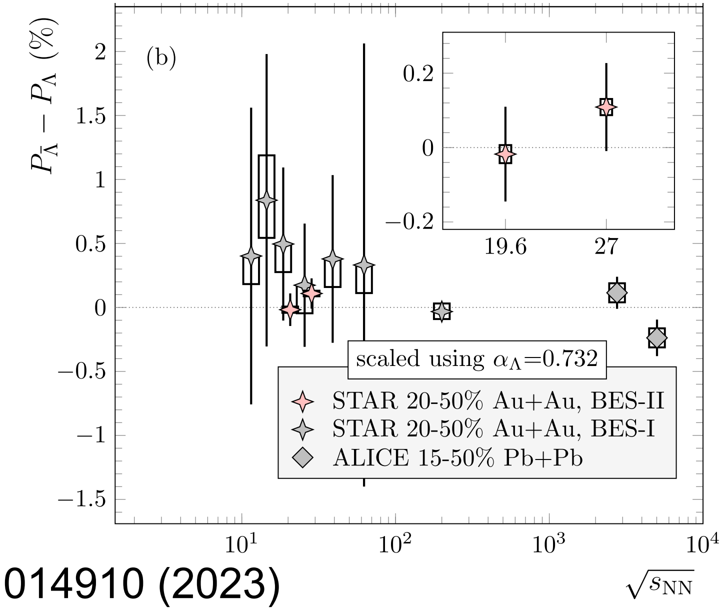
- The fluid vorticity was estimated from the data using hydrodynamics relation

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

- The collision energy-average polarization data from STAR BES-I indicate a vorticity of **(9±1)x10^{21} *s*$^{-1}$**
  →experimental access to the vortical structure of the QGP

- Late-stage B field

$$|B| \approx \frac{T_s|P_{\bar{\Lambda}} - P_{\Lambda}|}{2|\mu_{\Lambda}|}$$

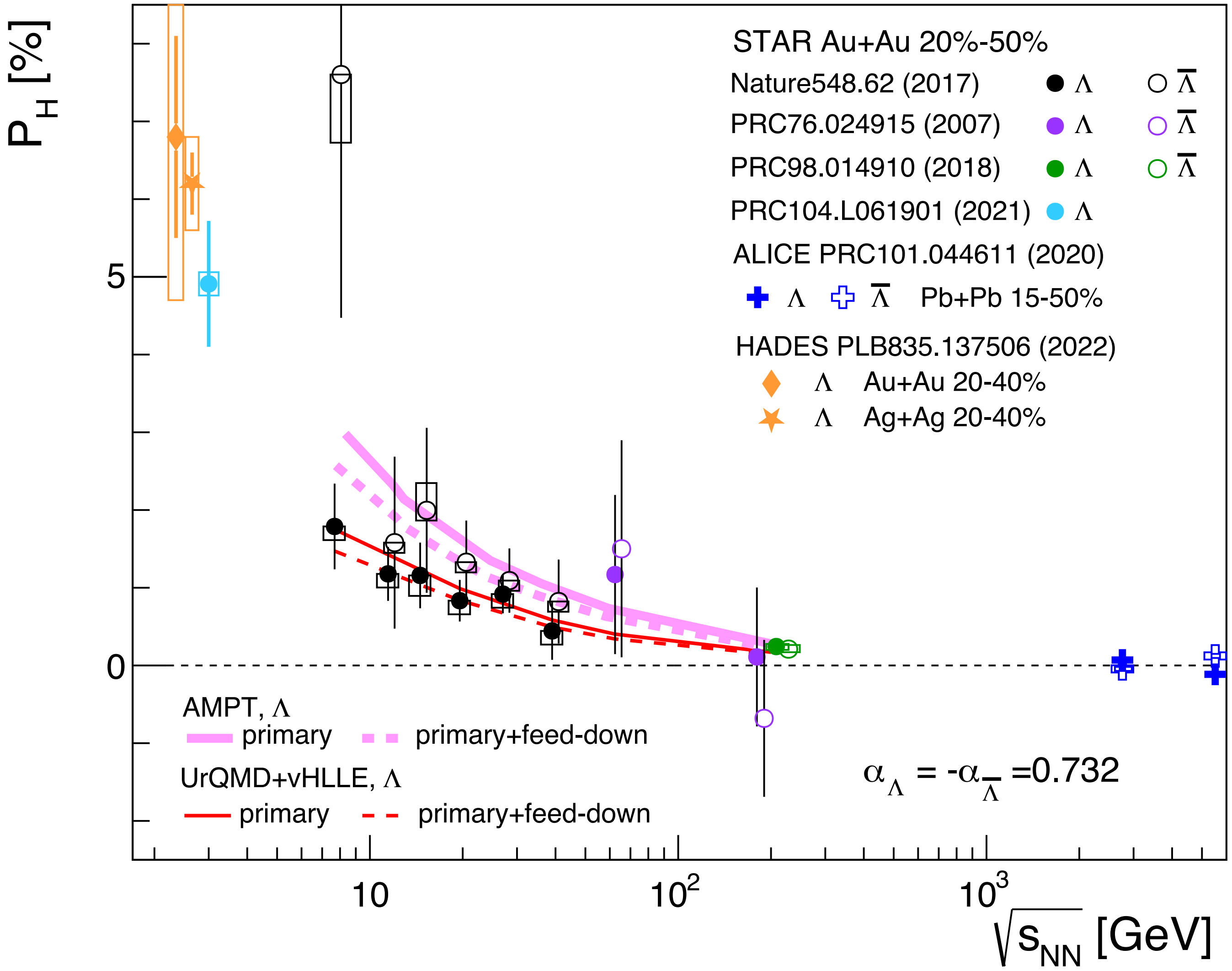


STAR Col. Phys. Rev. C **108**, 014910 (2023)

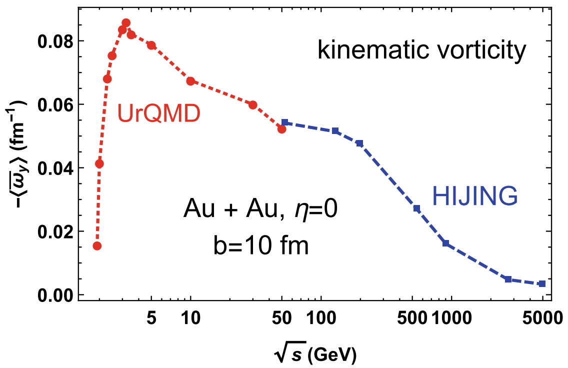
- High precision BES-II data of 19.6 and 27 GeV
  - -0.018 ± 0.127 (stat.) ± 0.024 (syst.)
  - 0.109 ± 0.118 (stat.) ± 0.022 (syst.)

$B < 9.4 \times 10^{12}$ T and $B < 1.4 \times 10^{13}$ T

Measurements of Λ and Ξ,Ω



- Measurements in different Exps.
  -didn't see the "drop" trend?



Deng et al., Phys. Rev. C **101**, 064908 (2020)
Guo et al., Phys. Rev. C **104**, L041902 (2021)…

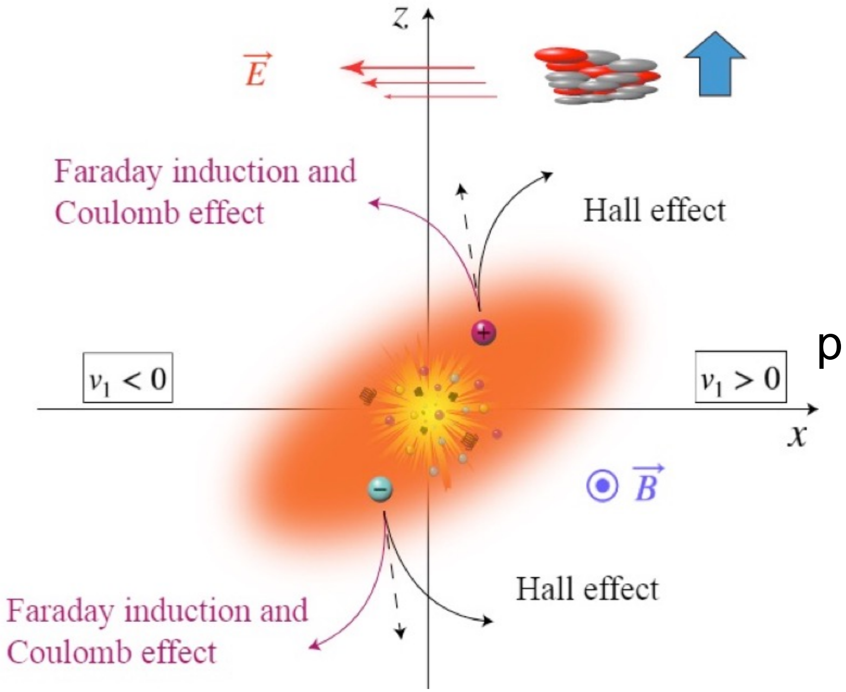
- Measurements extend to multistrange

STAR Col. Phys. Rev. Lett. **126**, 162301 (2021)

$$\langle P_{\Xi}\rangle = 0.47 \pm 0.10(\text{stat}) \pm 0.23(\text{syst})\%$$

$$\langle P_{\Omega}\rangle = 1.11 \pm 0.87(\text{stat}) \pm 1.97(\text{syst})\%$$

Another approach to study B-field



$p : uud$ $\quad v_1^p > v_1^{\bar{p}}$ at $\eta > 0$

$\bar{p} : \bar{u}\bar{u}\bar{d}$

$K^+ : u\bar{s}$ $\quad v_1^{K^+} > v_1^{K^-}$ at $\eta > 0$

$K^- : \bar{u}s$

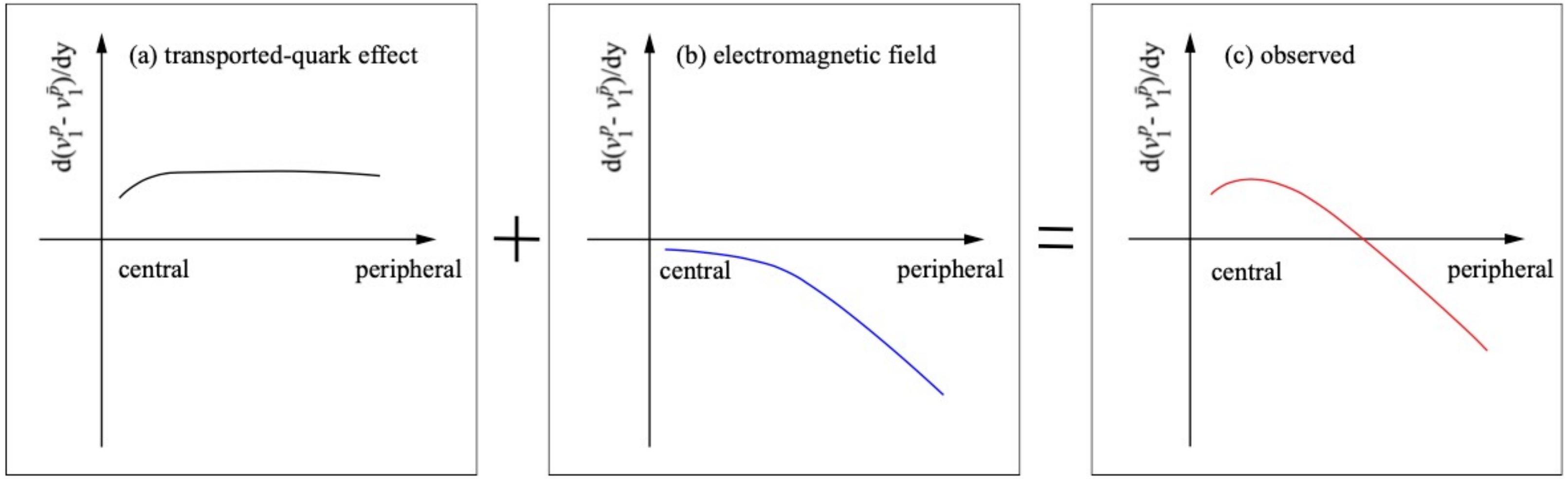
$\pi^+ : u\bar{d}$ $\quad v_1^{\pi^-} > v_1^{\pi^+}$ at $\eta > 0$

$\pi^- : \bar{u}d$ (#d>#u, Au neutron rich)

Quarks experience forces due to

- Hall effect: $\vec{F} = q(\vec{v} \times \vec{B})$
- Coulomb effect: $\vec{E}$ from spectators
- Faraday induction: $\vec{E}$ generated by decreasing *B*-field

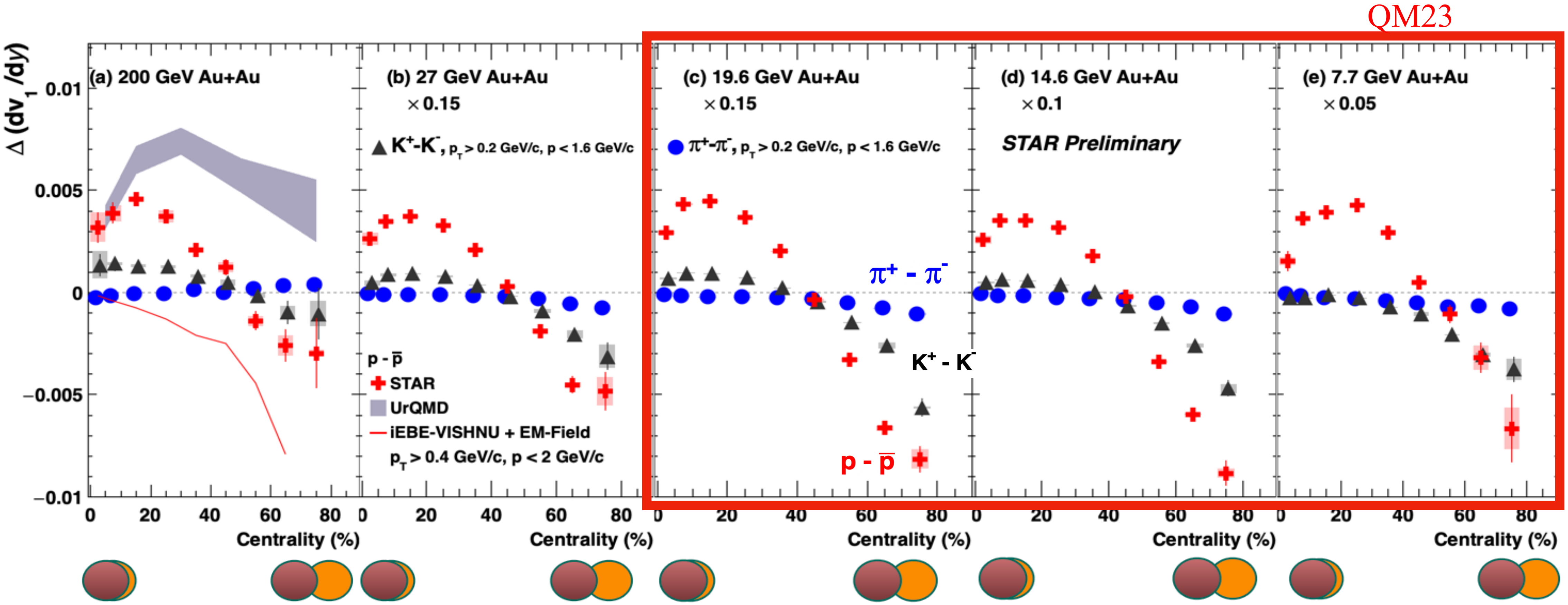
proton $d(v_1^+ - v_1^-)/dy$: transported quark ⇧ Lorentz ⇧ Faraday ⇩ Coulomb ⇩



Look for the charge-dependence direct flow

- Protons may behave differently in different centrality
- Kaons may behave similar as Protonts
- Pions may not feel the effect

EM field of QGP via charge-dep. v_1 measurement

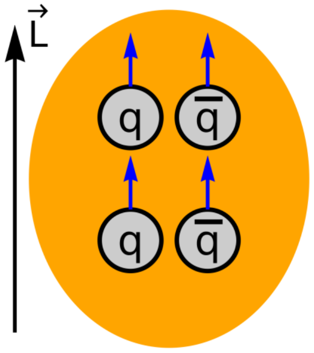


200 GeV and 27 GeV data, STAR Col. arXiv: 2304.03430, PRX (in press)

- **Negative Δ(dv1/dy) in peripheral collisions consistent with expectation from EM effects**
  - Suggests dominance of Faraday+Coulomb effect in **peripheral** collisions
  - Other mechanisms are under investigation (e.g. meanfield)

Experimental measurements: φ,K*

- Vector meson ($J=1^-$) spin alignment

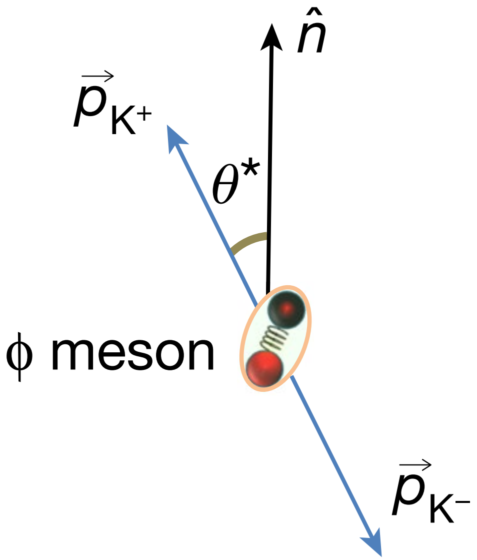


✓ Spin tensor polarization
✓ Different probabilities among three spin states
✓ Only ρ_{00} is measurable

$$|11\rangle = |\uparrow\uparrow\rangle$$

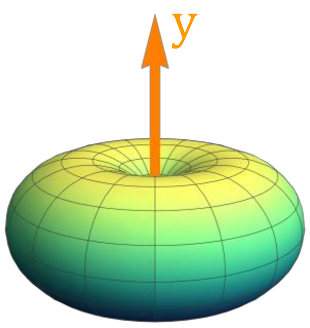
$$|10\rangle = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle)$$

$$|1\text{-}1\rangle = |\downarrow\downarrow\rangle$$



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

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

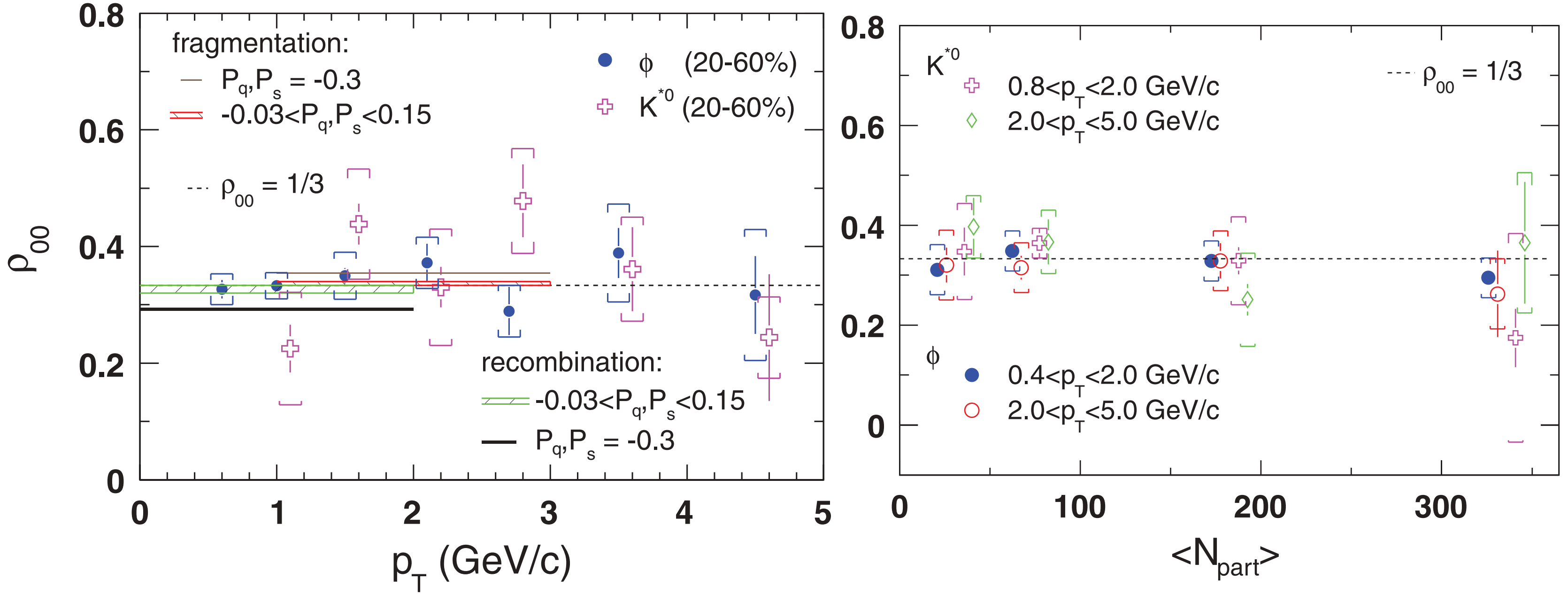


$\rho_{00} < 1/3$

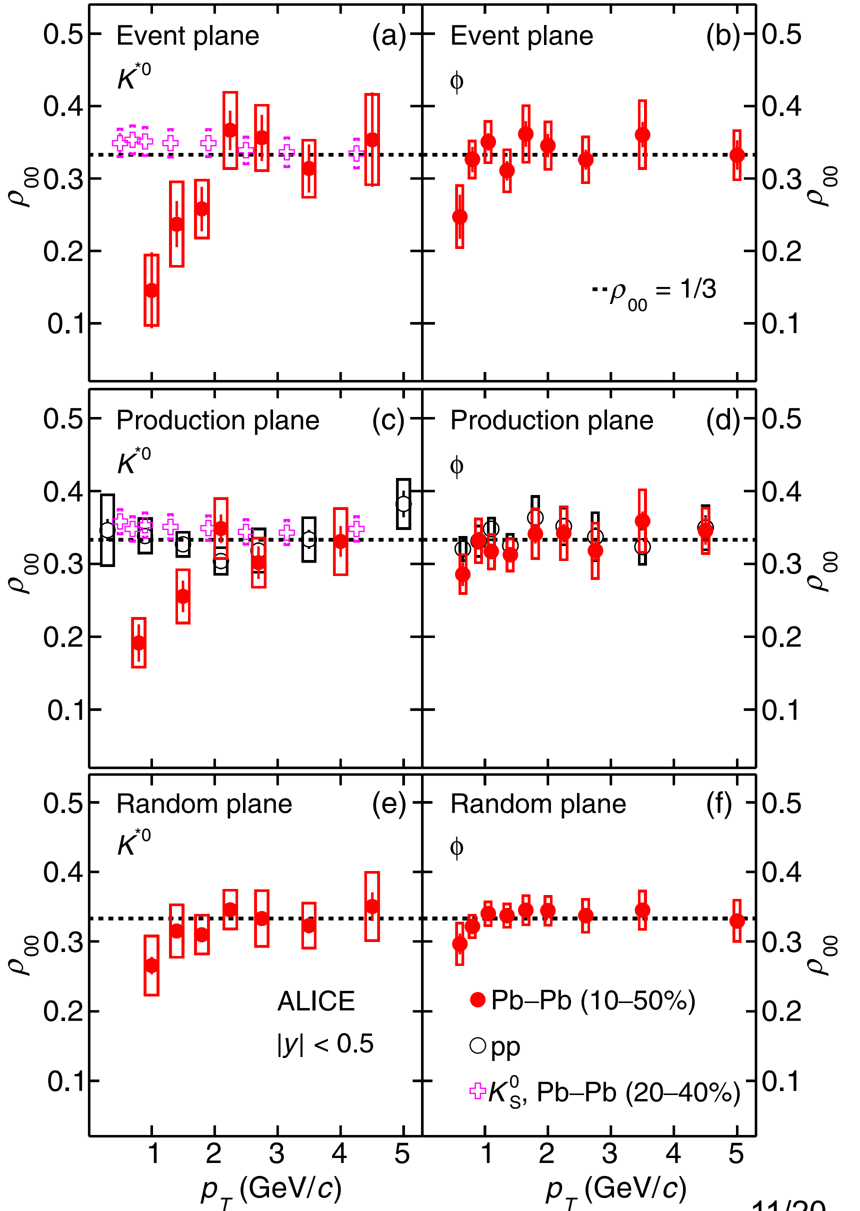
$\rho_{00} > 1/3$

Experimental measurements: φ,K*(cont.)

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

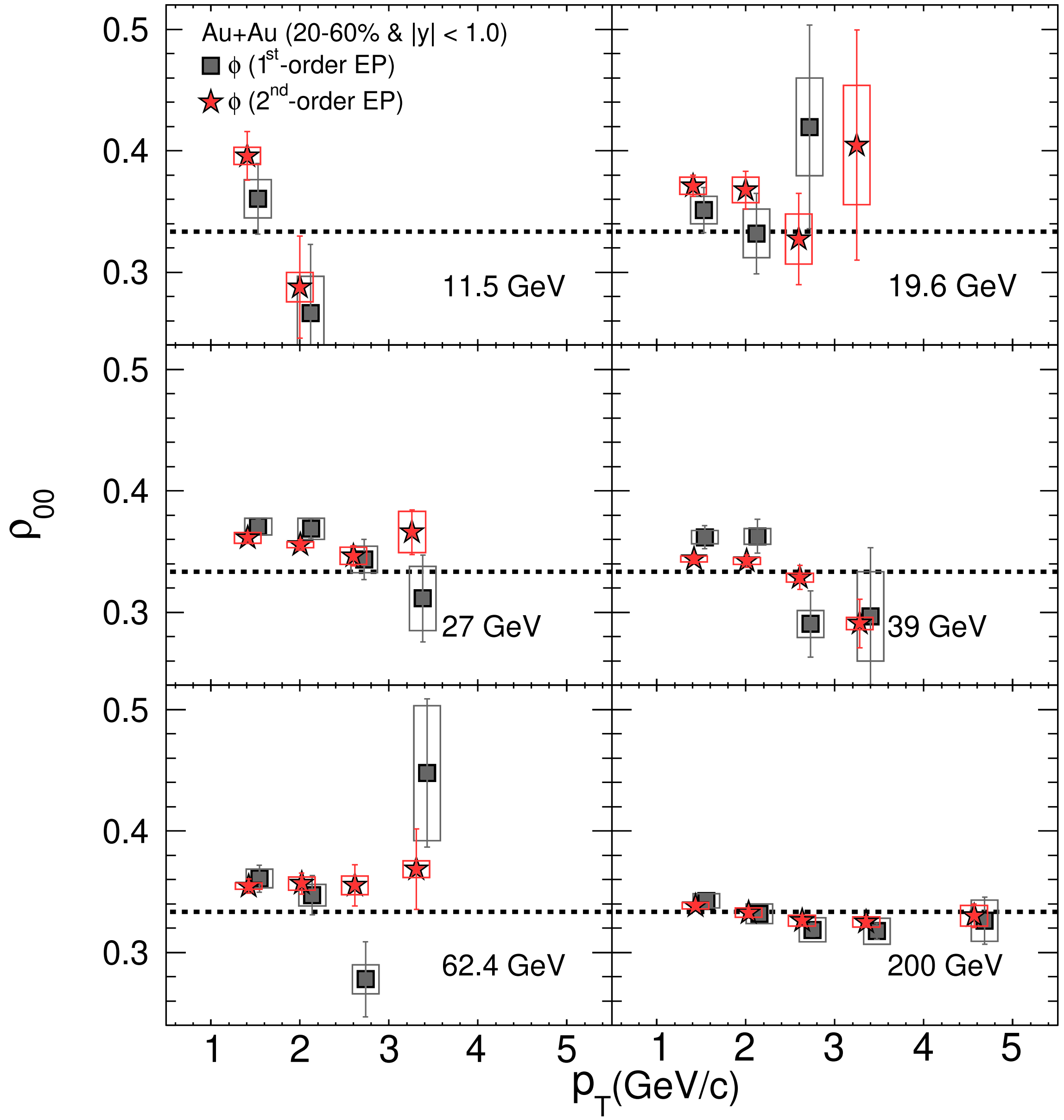


ALICE Col. Phys. Rev. Lett. **125**, 012301 (2020)



- Early data of Au+Au 200 GeV suffer from large uncertainties
- Updated measurements seem to provide evidence of spin-orbital angular momentum interactions, but production plane and random plane also show deviation at small p_T

New Measurements φ,K*0@non-central collisions

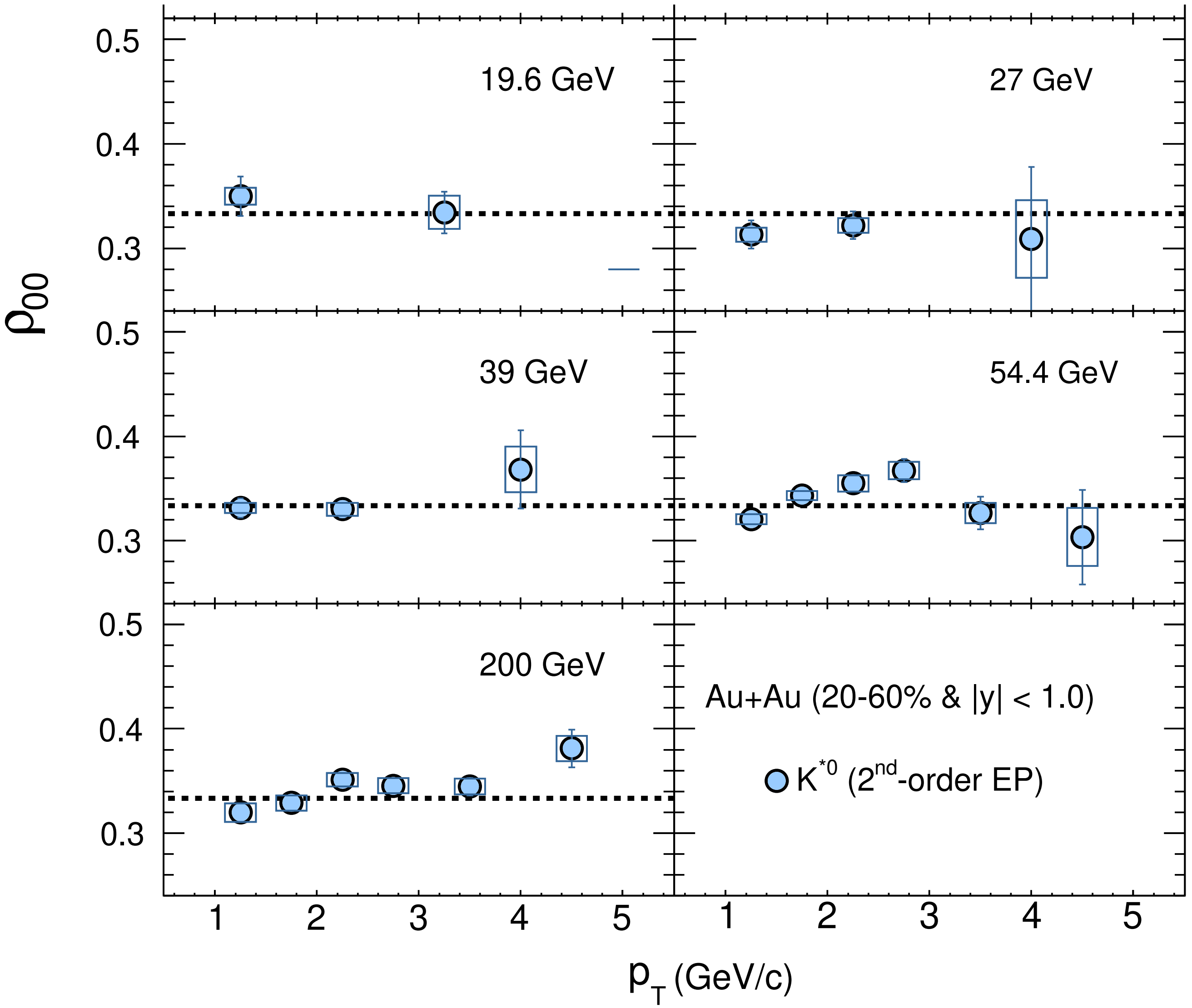


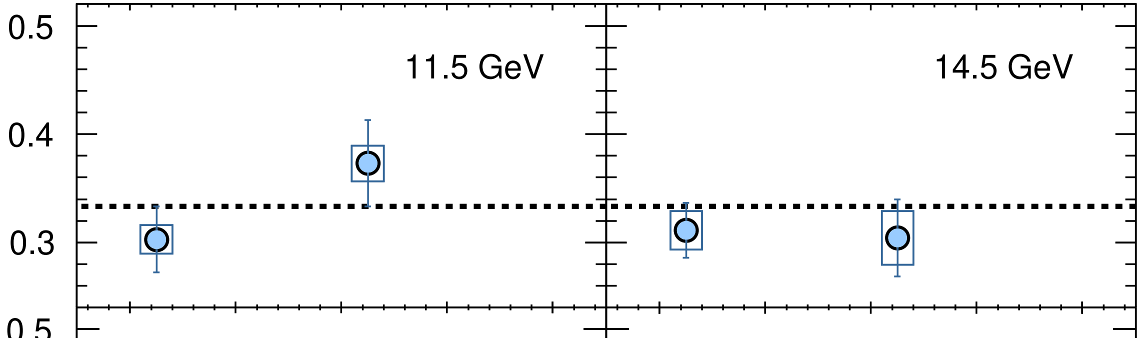
- New measurements extend the study to lower energies with high statistics, @200 GeV, a factor of ~50 more event statistics analyzed.
- We see that the signal for the φ meson occurs mainly within ~1.0-2.4 GeV/c; at larger p_T the results can be regarded as being consistent with 1/3 within ~2σ or less.

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

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

New Measurements φ,K*0@non-central collisions



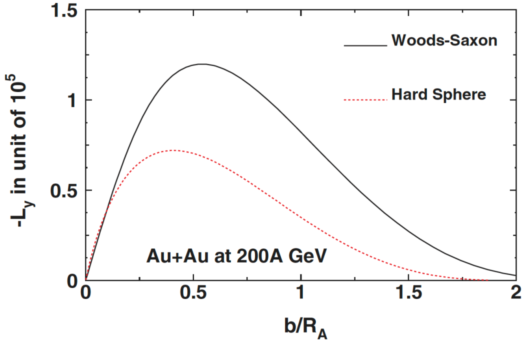


- K^{*0} is a combination of K^{*0} and anti-K^{*0}
- Independent analysis
- Different from the φ meson data, the K^{*0} data is largely consistent with 1/3, within statistics and systematical uncertainties

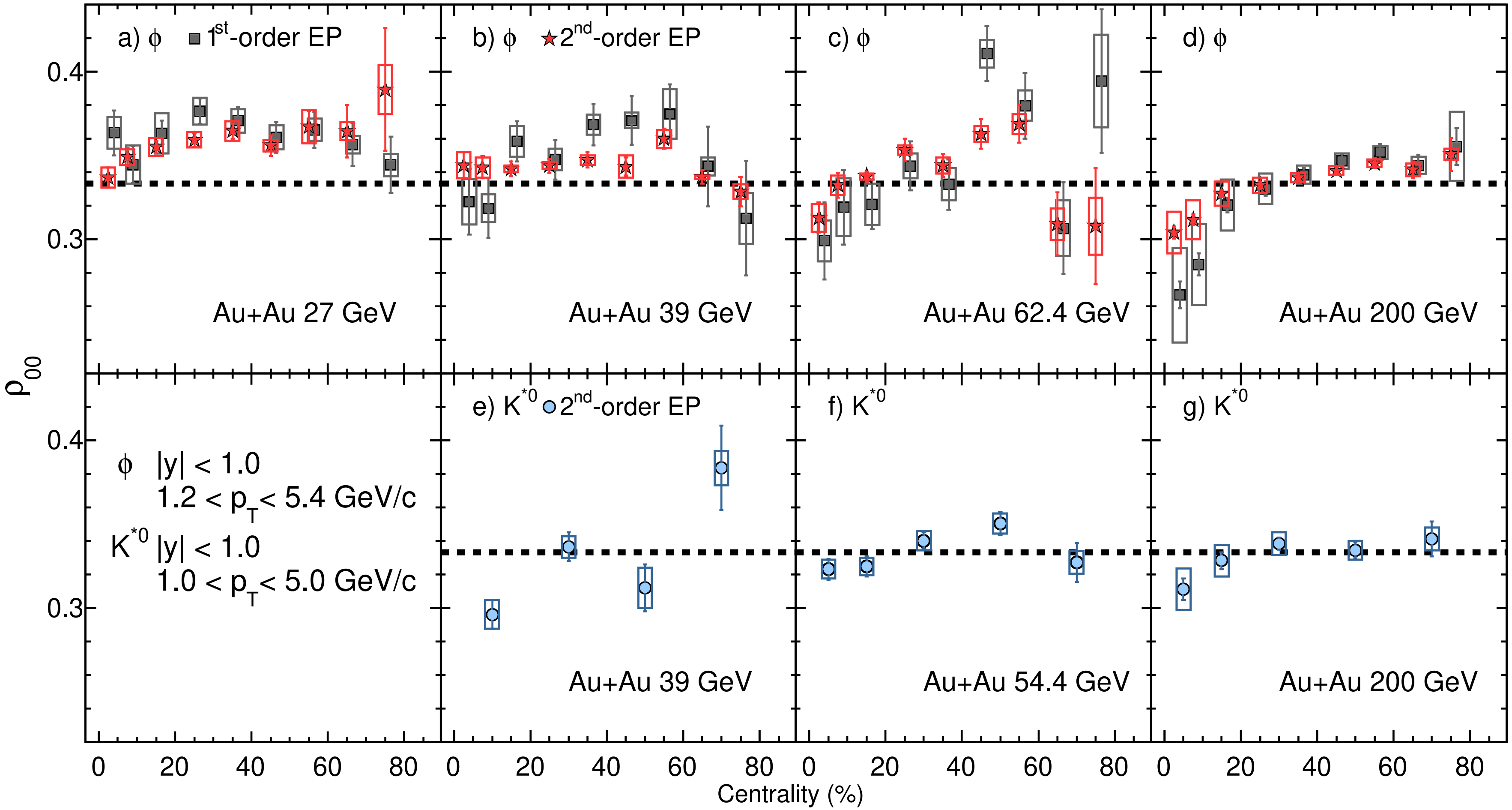
STAR Col. Nature **614**, 244 (2023)

Study the fine structure vs. centrality

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

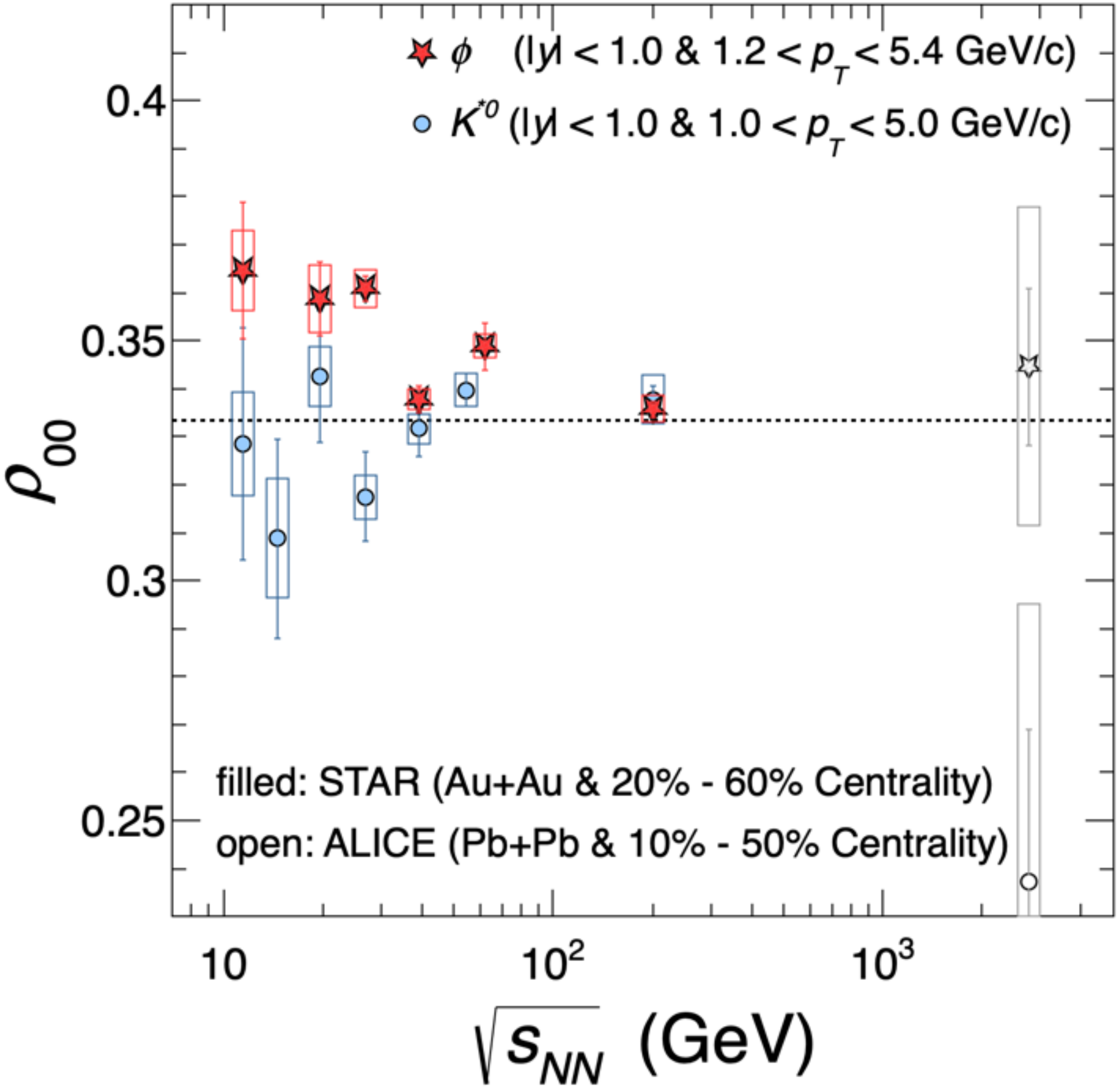


Gao, Chen, Deng, Liang, Wang, Wang
Phys. Rev. C **76**, 044901 (2007)



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 transerve local spin alignment and a contribution from the helicity polarization of quarks.

Results mid-central & averaged over p_T



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 the combinatorial bg. analysis

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

Expectations of ρ_{00} from theory

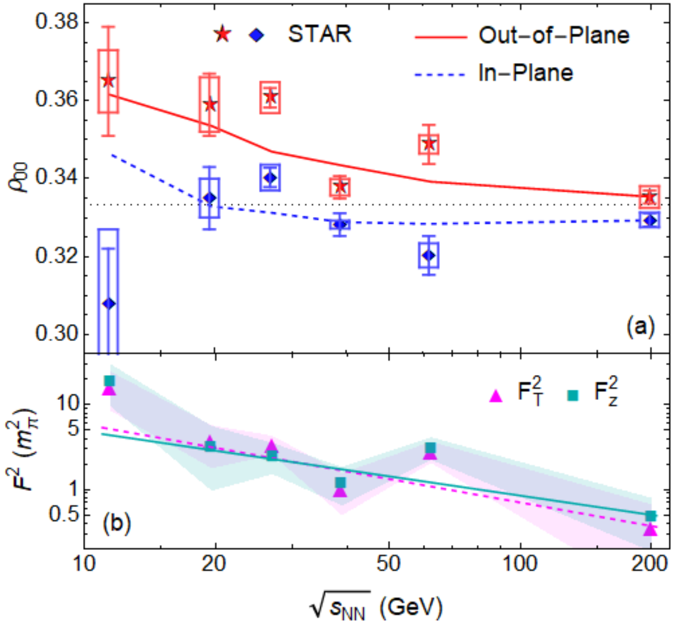
Physics Mechanisms	(ρ_{00})
c_Λ: Quark coalescence vorticity & magnetic field[1]	< 1/3 (Negative ~ 10^{-5})
c_ε: Vorticity tensor[1]	< 1/3 (Negative ~ 10^{-4})
c_E: Electric field[2]	> 1/3 (Positive ~ 10^{-5})
Fragmentation[3]	> or, < 1/3 (~ 10^{-5})
Local spin alignment and helicity[4]	< 1/3
Turbulent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

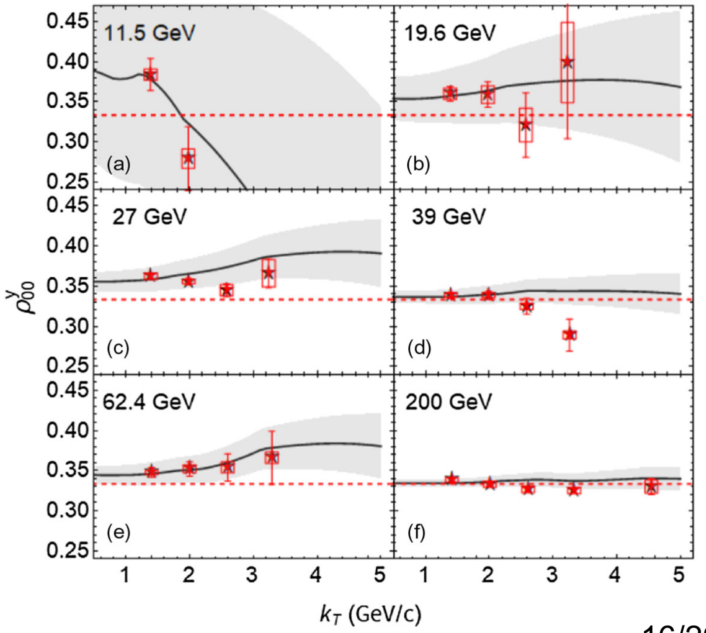
$$\rho_{00}^{\phi} \approx \frac{1}{3} + c_\omega + c_\varepsilon + c_{\mathrm{EM}} + c_\phi + c_{\mathrm{LV}} + c_h + c_{\mathrm{TC}} + c_{\mathrm{shear}}$$

[1]. Yang et al., Phys. Rev. C **97**, 034917 (2018) [2]. Sheng et al., Phys. Rev. D **101**, 096005 (2020)
[3]. Xia et al., Phys. Lett. B **817**, 136325 (2021) [4]. Gao, Phys. Rev. D **104**, 076016 (2021)
[5]. Muller, Yang, Phys. Rev. D **105**, L011901 (2022) [6]. Li, Liu, arXiv:2206.11890,
Wagner, Weickgenannt, Speranza, arXiv:2207.01111

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)





The small Λ vs. large φ-meson signal

Z. T. Liang, Chirality 2023

$$\left|\rho_{00}^{V}-\frac{1}{3}\right| \gg P_{\Lambda}^{2} \sim P_{q}^{2}$$

$$\rho_{00}^{V}-\frac{1}{3} \sim \langle P_q P_{\bar{q}} \rangle$$

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

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 $P_{\bar{q}}$.

How to separate long range or local correlations

$$C_{NN}^{H_i\bar{H}_j} \equiv \frac{N_{H_i\bar{H}_j}^{\uparrow\uparrow} + N_{H_i\bar{H}_j}^{\downarrow\downarrow} - N_{H_i\bar{H}_j}^{\uparrow\downarrow} - N_{H_i\bar{H}_j}^{\downarrow\uparrow}}{N_{H_i\bar{H}_j}^{\uparrow\uparrow} + N_{H_i\bar{H}_j}^{\downarrow\downarrow} + N_{H_i\bar{H}_j}^{\uparrow\downarrow} + N_{H_i\bar{H}_j}^{\downarrow\uparrow}}$$

sensitive to the long range correlation

$$\rho_{10}^{V} = \frac{P_{qz}(1+P_{\bar{q}y}) + (1+P_{qy})P_{\bar{q}z} - iP_{qx}(1+P_{\bar{q}y}) - i(1+P_{qy})P_{\bar{q}x}}{\sqrt{2}(3+\vec{P}_q \cdot \vec{P}_{\bar{q}})}$$

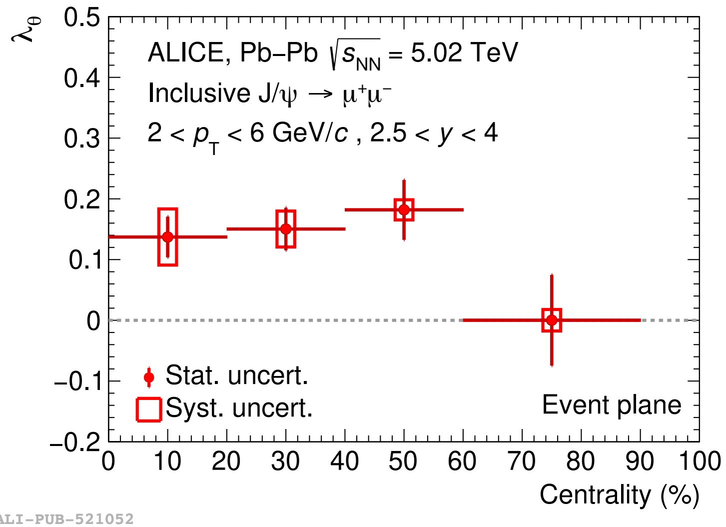
$$\rho_{0-1}^{V} = \frac{P_{qz}(1-P_{\bar{q}y}) + (1-P_{qy})P_{\bar{q}z} - iP_{qx}(1-P_{\bar{q}y}) - i(1-P_{qy})P_{\bar{q}x}}{\sqrt{2}(3+\vec{P}_q \cdot \vec{P}_{\bar{q}})}$$

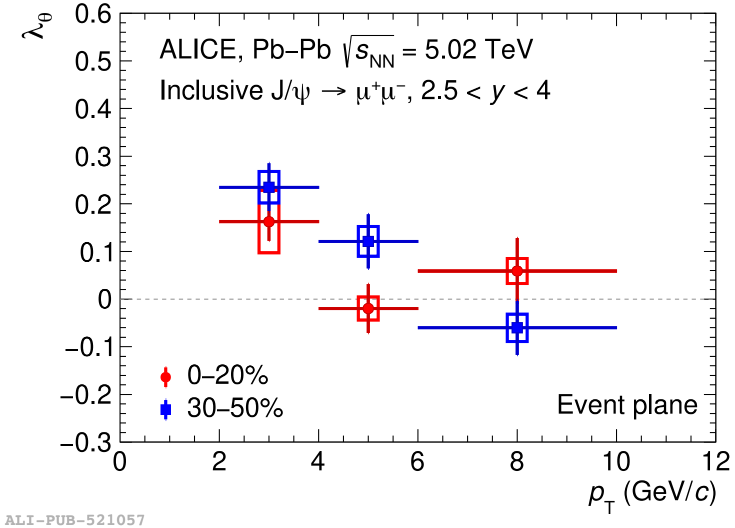
$$\rho_{1-1}^{V} = \frac{P_{qz}P_{\bar{q}z} - P_{qx}P_{\bar{q}x} + i(P_{qx}P_{\bar{q}y} + P_{qy}P_{\bar{q}x})}{3+\vec{P}_q \cdot \vec{P}_{\bar{q}}}$$

They should be sensitive to the local correlations.

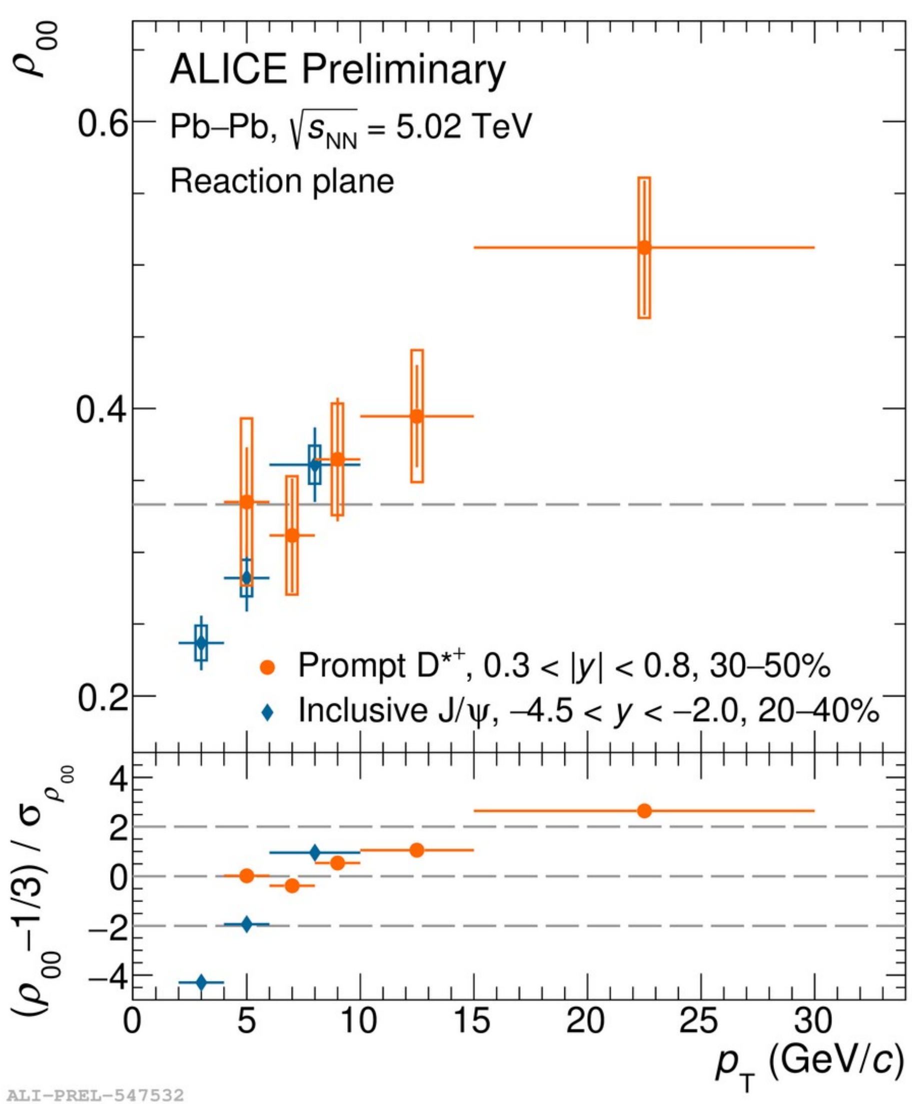
From φ to other mesons

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

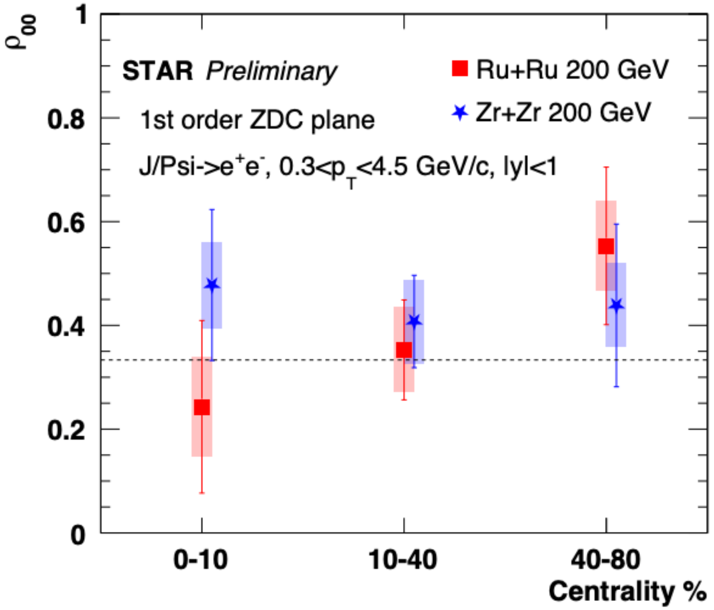




ALICE Col. QM2023



STAR Col. QM2023



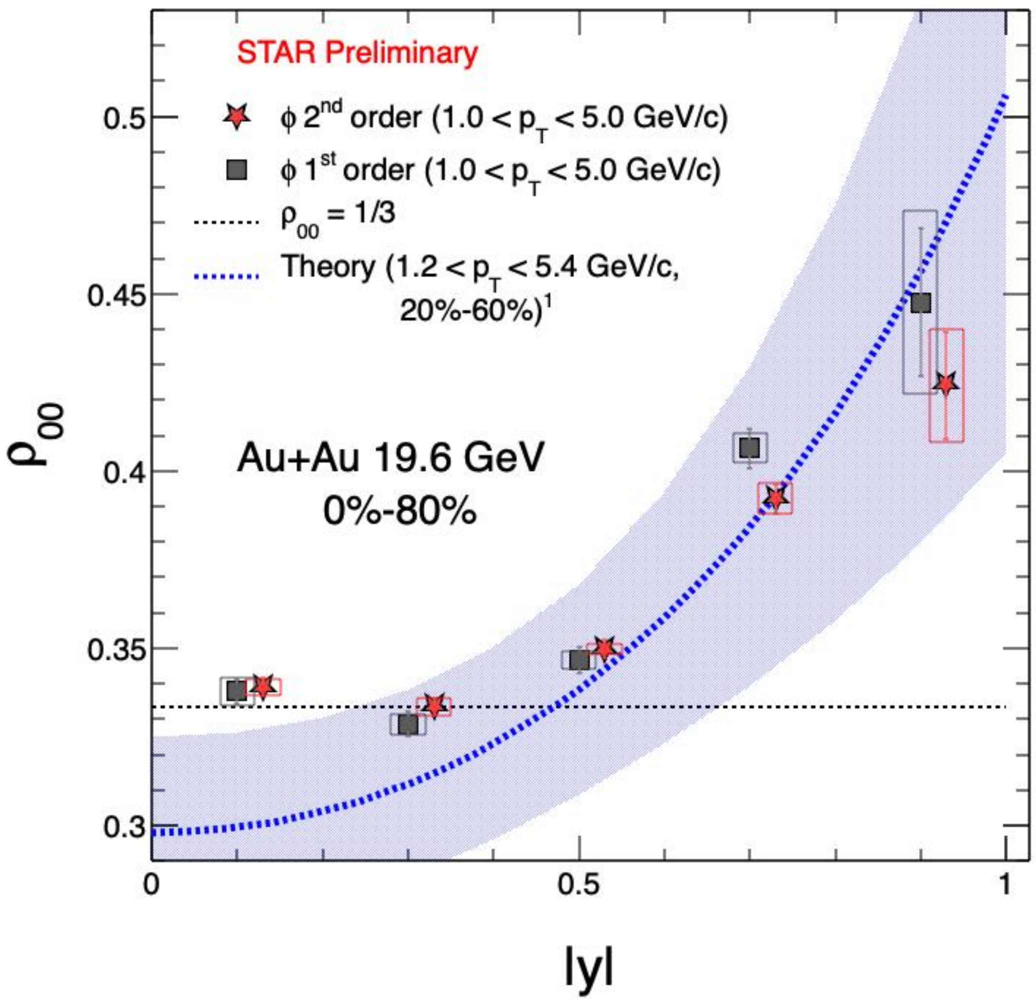
$$\lambda_\theta = \frac{1-3\rho_{00}}{1+\rho_{00}} \qquad \lambda_\theta > 0 \Leftrightarrow \rho_{00} < 1/3$$

- Forward rapidity J/ψ ρ_{00}<1/3 at LHC
- Midrapidity J/ψ ρ_{00} ~ 1/3 at RHIC
- D^{*+} shows a clear p_T dependence

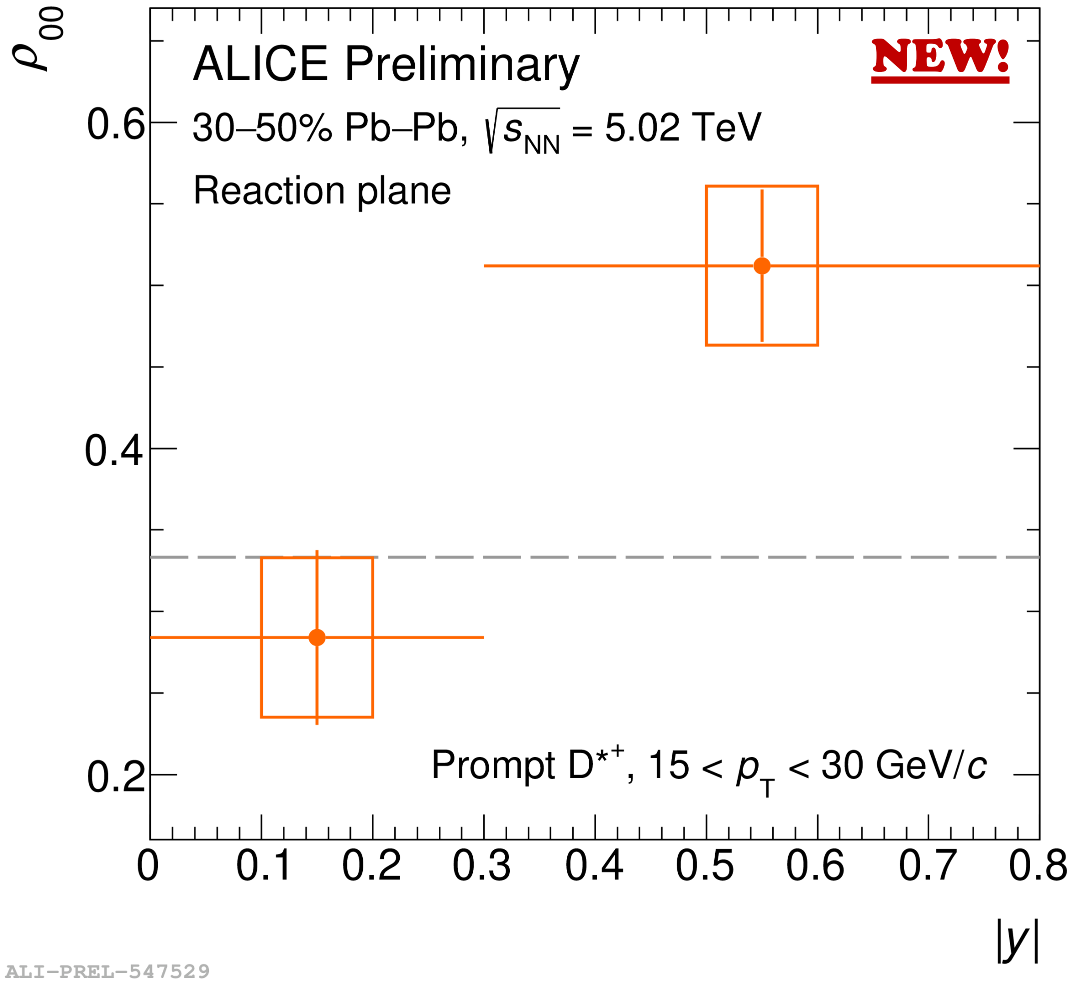
→ The underlying physics seems not converged?

Study the rapidity dependence

STAR Col. QM2023



ALICE Col. QM2023



RHIC & LHC data : strong rapidity dependence

Summary

- Heavy-ion collision is a ideal lab to study QCD dynamics, not only the spin polarization, external field, and many other physics
- 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
- Charged dependent direct flow splitting is observed in peripheral collisions, the imprint of the evolution of strong B-field on the final state particles.