Intense field and vorticity (Experiment)

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ATHIC2023

Outline

- Introduction
- Brief review on the global hyperon polarization
- Focus on the vector meson spin alignment and the new measurement from STAR BES data
- Summary and Discussion

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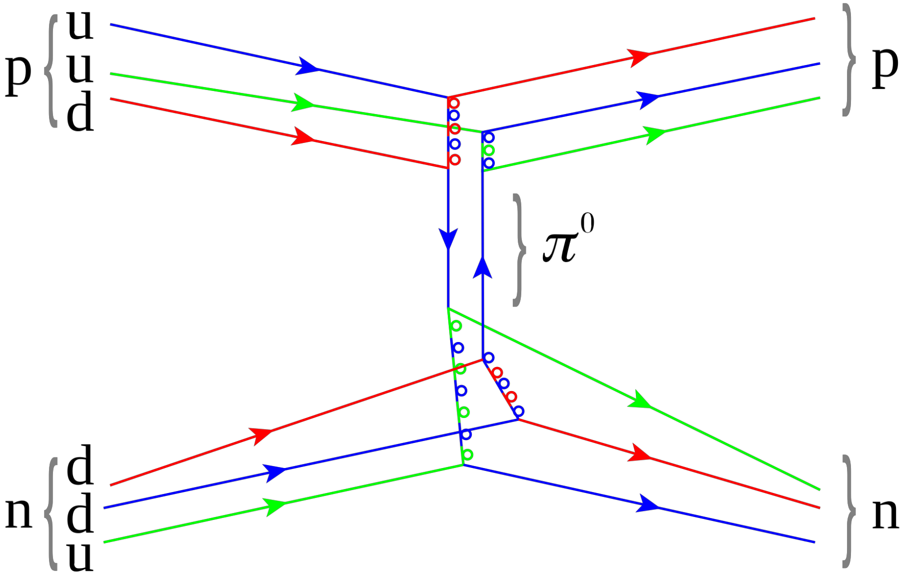
Strong interaction and its mediator

Yukawa, *Proc. Phys. Math. Soc. Jap.* **17** (1935) 48



"The transition of a heavy particle from neutron state to proton state is not always accompanied by the emission of light particles, i. e., a neutrino and an electron, but the energy liberated by the transition is taken up sometimes by another heavy particle…"

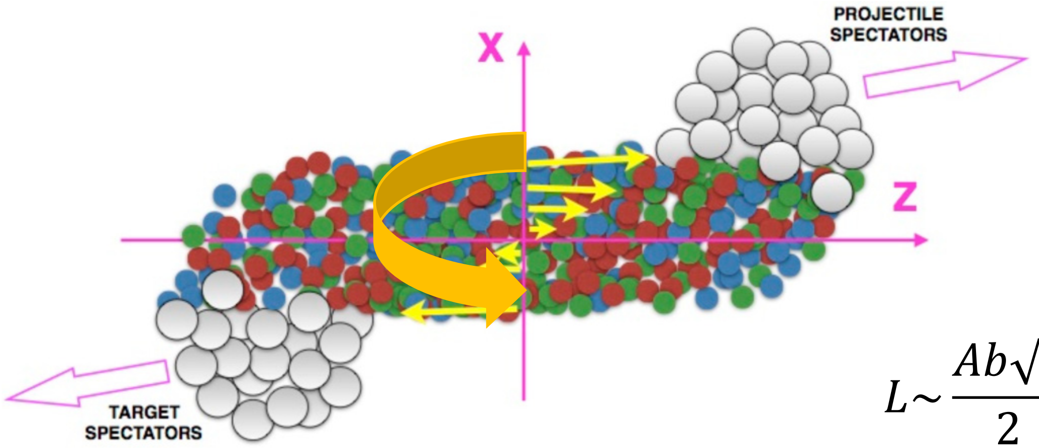
- Particles and fields are two fundamental forms of matter in our natural world
- At low energy scales, strong interactions is often characterized by mesons as effective dof of quarks and gluons, whose existence was proposed by Yukawa

  "Now such interaction between the elementary particles can be described by means of a field of force, just as the interaction between the charged particles is described by the electromagnetic field."
- As the energy scale increases, other meson fields carrying strangeness quantum number may come into play

Strong interaction and Global polarization

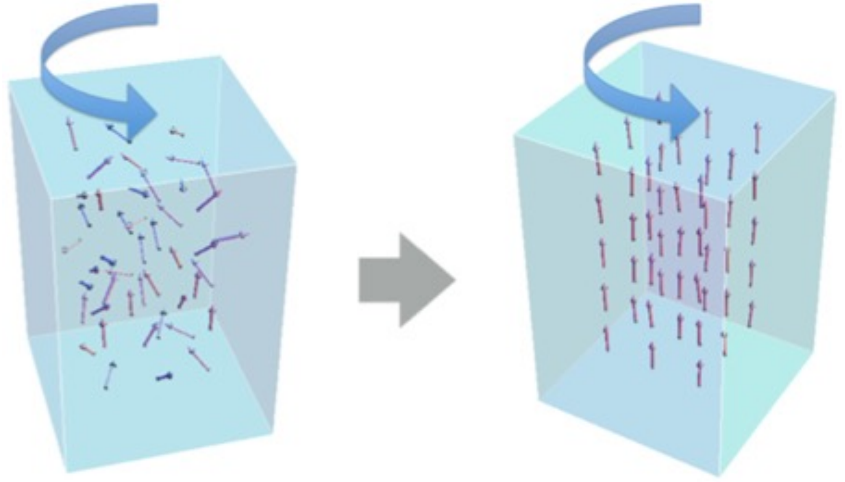
Liang, Wang Phys. Rev. Lett. **94**, 102301(2005); Phys. Lett. B **629**, 20 (2005)

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



$$L \sim \frac{Ab\sqrt{s}}{2}$$

Large OAM *L* is deposited in the interaction region



Rotation → Polarization
Spontaneous magnetization

- Ideas:
  - ✓ 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)

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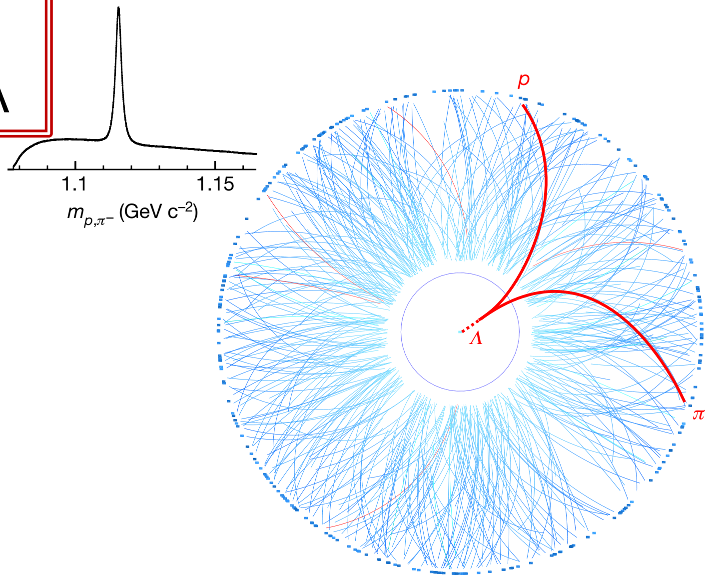
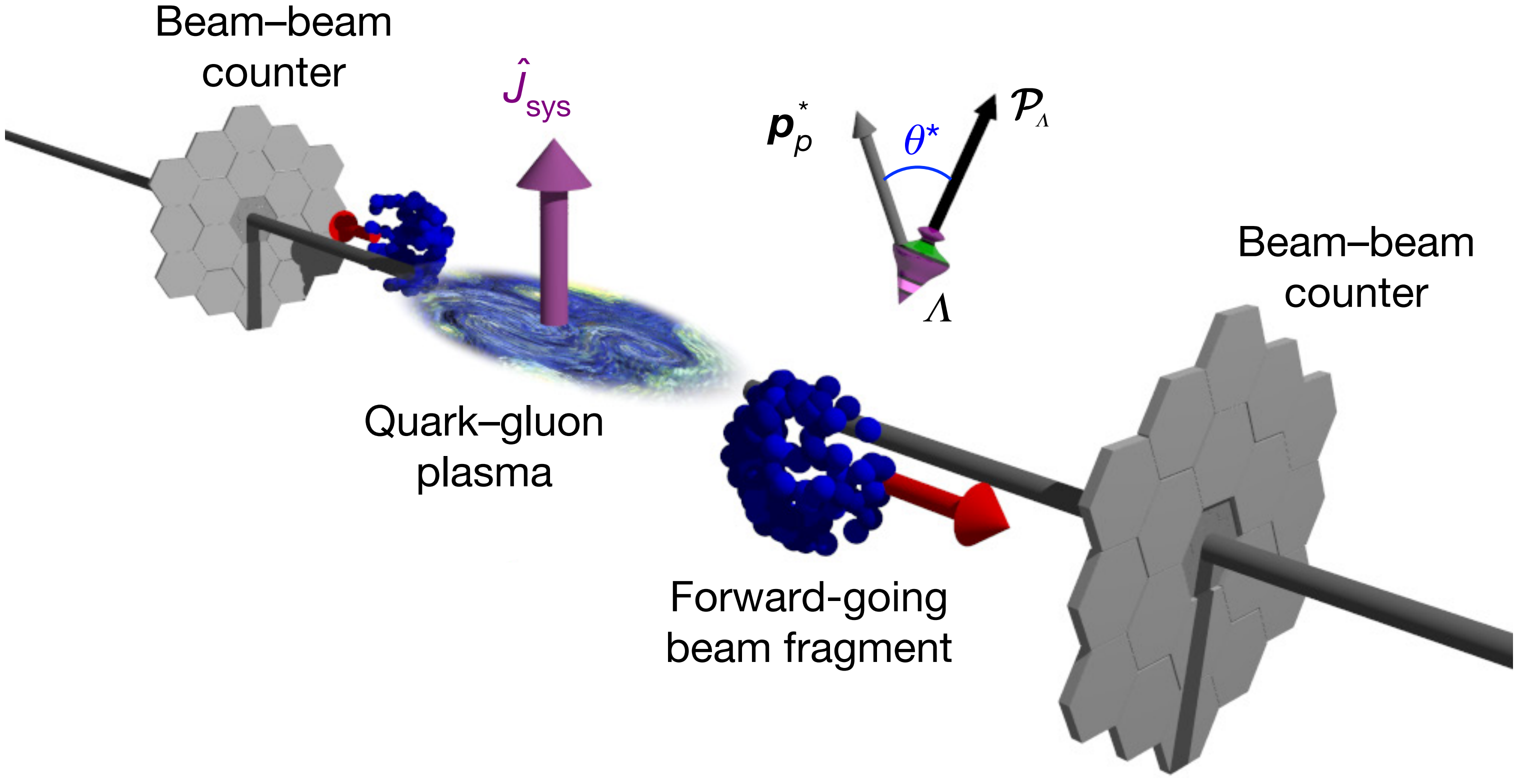
Experimental measurements: Λ

- 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



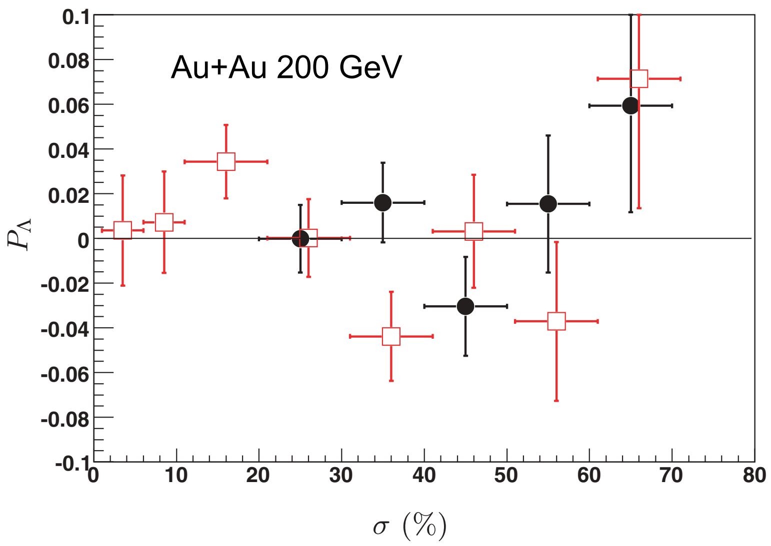


$$\frac{\mathrm{d}N}{\mathrm{d}\cos\theta^*} = \frac{1}{2}(1 + \alpha_{\mathrm{H}}|\mathcal{P}_{\mathrm{H}}|\cos\theta^*)$$

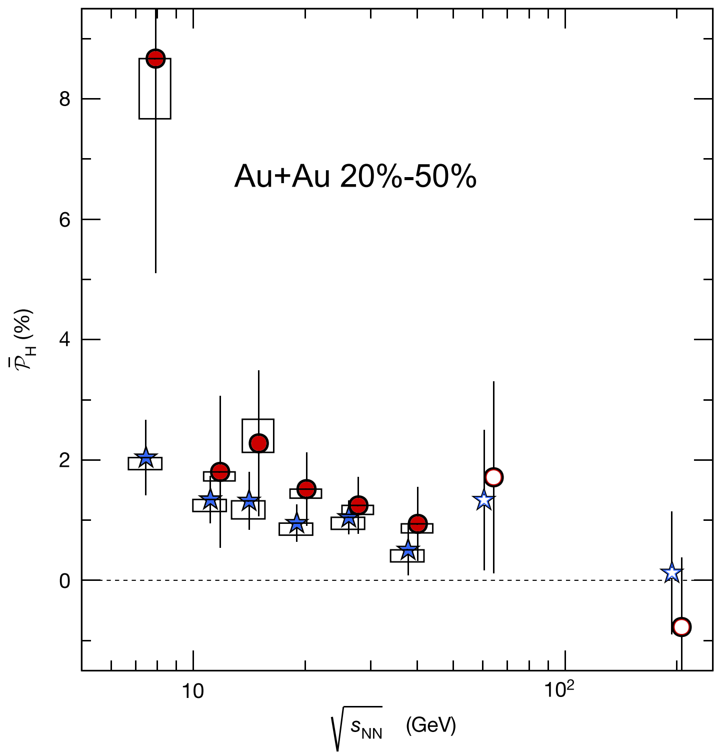
$$P_H = \frac{8}{\pi\alpha_H}\frac{\langle\sin(\Psi_1^{\mathrm{obs}} - \phi_p^*)\rangle}{\mathrm{Res}(\Psi_1)}$$

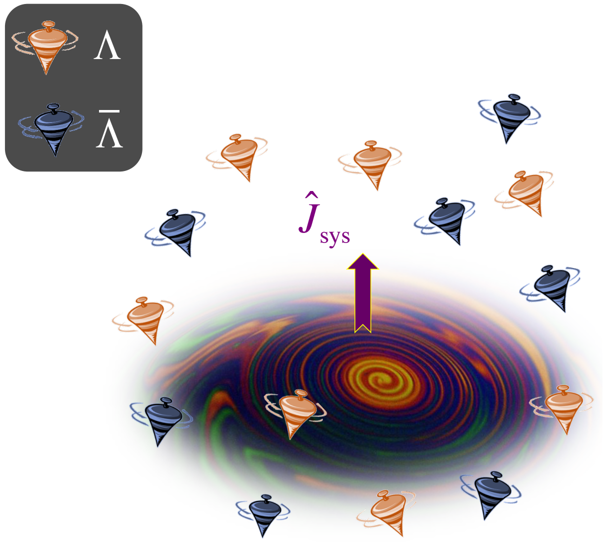
Experimental measurements: Λ (cont.)

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



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

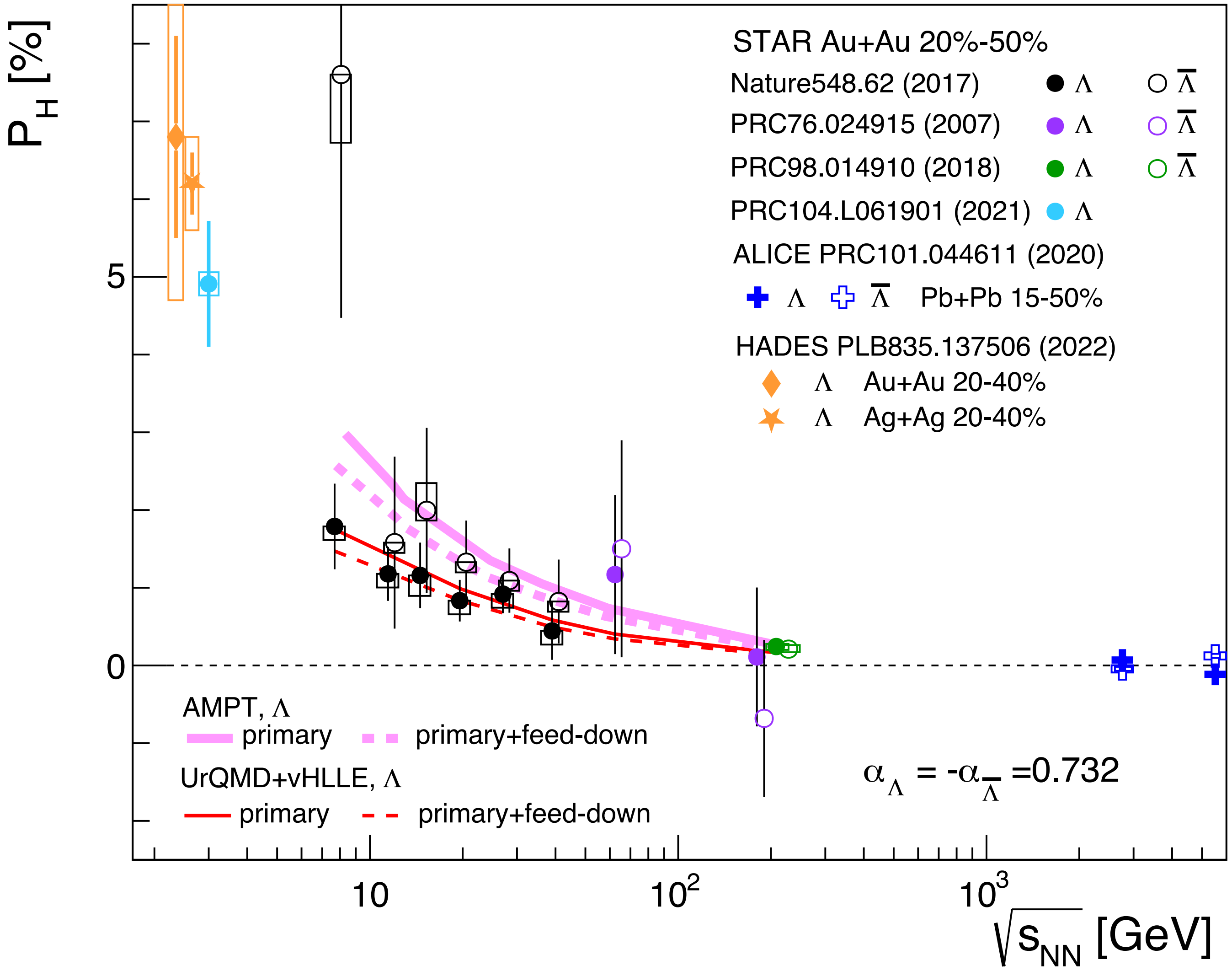




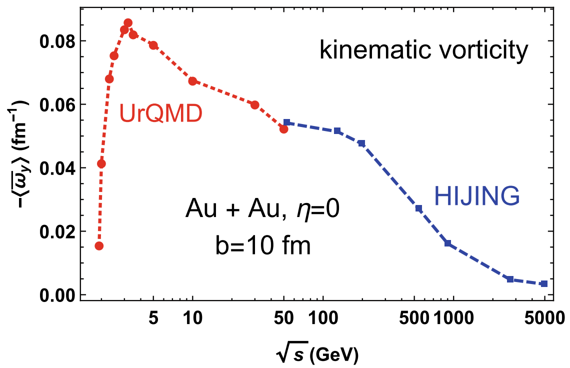
- Lambda hyperons show a positive polarization of the order of a few percent
- Experimental access to the vortical structure of the QGP, the most vortical fluid (9±1)x10^{21} s^{-1}

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

Measurements on Λ and multistrange



- 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)…

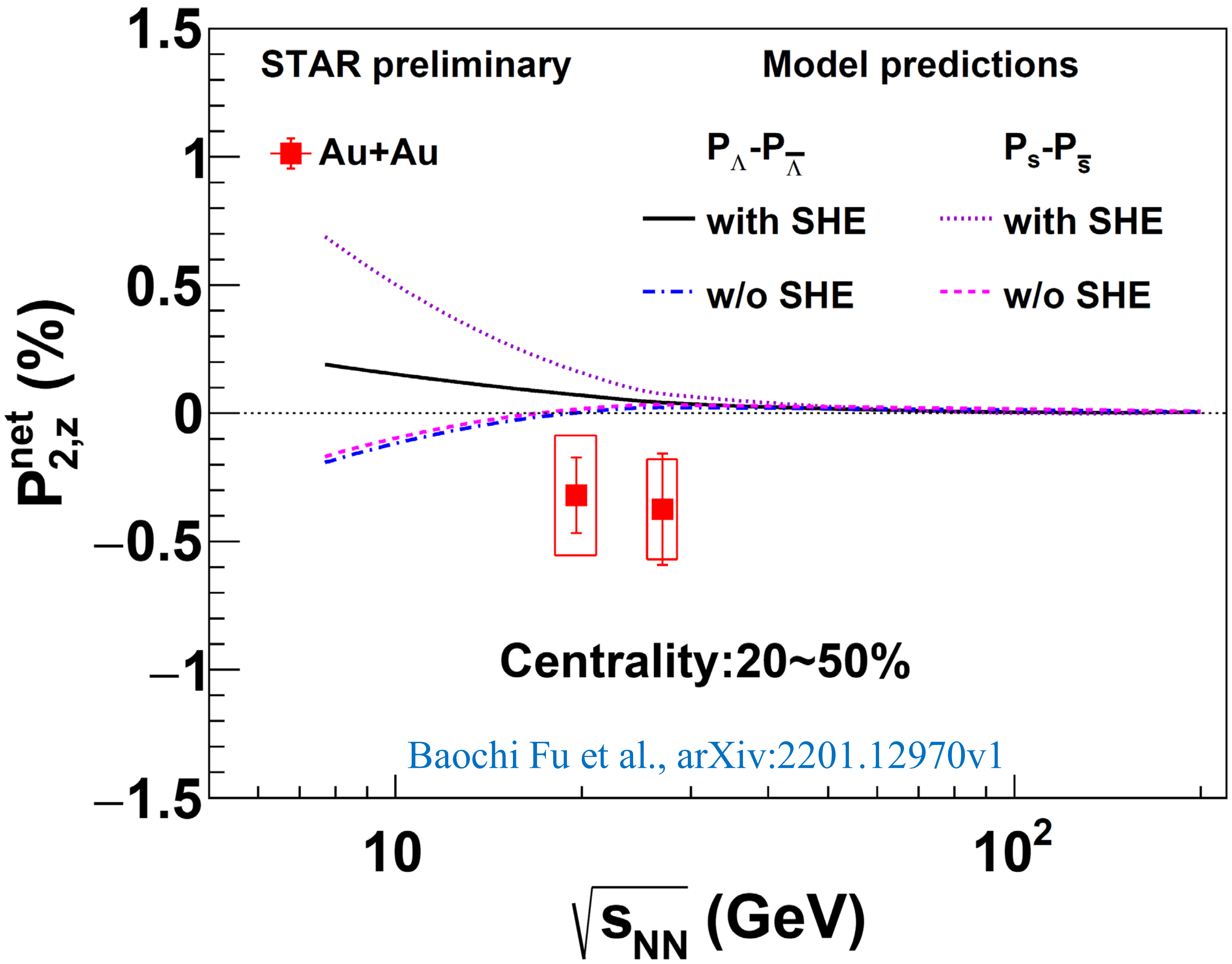
- Measurements extend to multistrange

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

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

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

New ideas to see the Λ polarization diff.



Talk by Hu (Monday)

- Λs Spin polarization along p_Z, and the diff. to probe the spin hall effect. (maximum at ~11.5 GeV?)

"Spin-orbit" interaction

$$\boldsymbol{P} \propto \pm \boldsymbol{p} \times \boldsymbol{E}$$

$$P_z^{net} = P_z - \overline{P}_z$$

- Preliminary study on 19.6 and 27 GeV data show negative p_Z diff., no significant energy dependence

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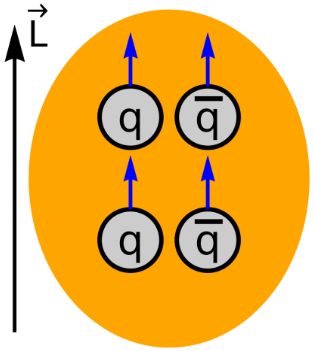
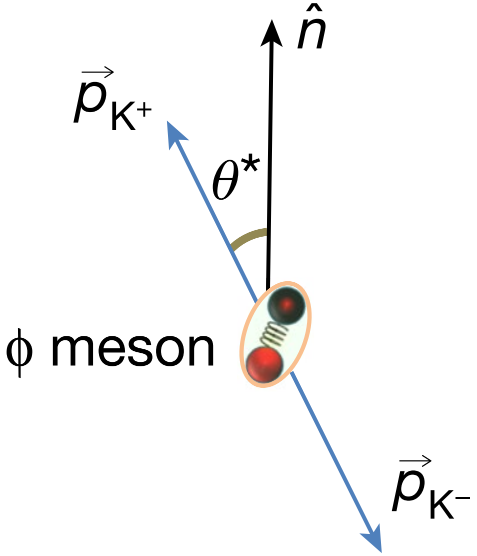
Experimental measurements: φ,K*

- Vector meson (J=1⁻) spin alignment



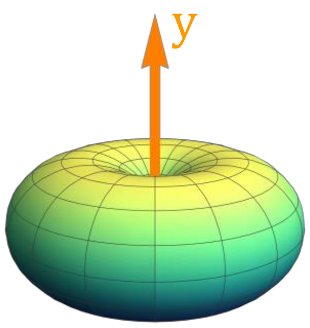
✓ Spin tensor polarization
✓ Different probabilities among three spin states
✓ Only ρ_{00} is measurable

$$|11\rangle = |\uparrow\uparrow\rangle$$
$$|10\rangle = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle)$$
$$|1\text{-}1\rangle = |\downarrow\downarrow\rangle$$

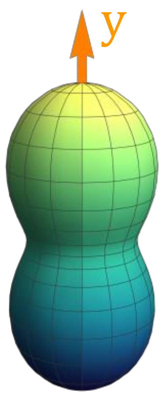


$$\rho^V = \begin{pmatrix} \rho_{11} & \rho_{10} & \rho_{1-1} \\ \rho_{01} & \rho_{00} & \rho_{0-1} \\ \rho_{-11} & \rho_{-10} & \rho_{-1-1} \end{pmatrix}$$

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



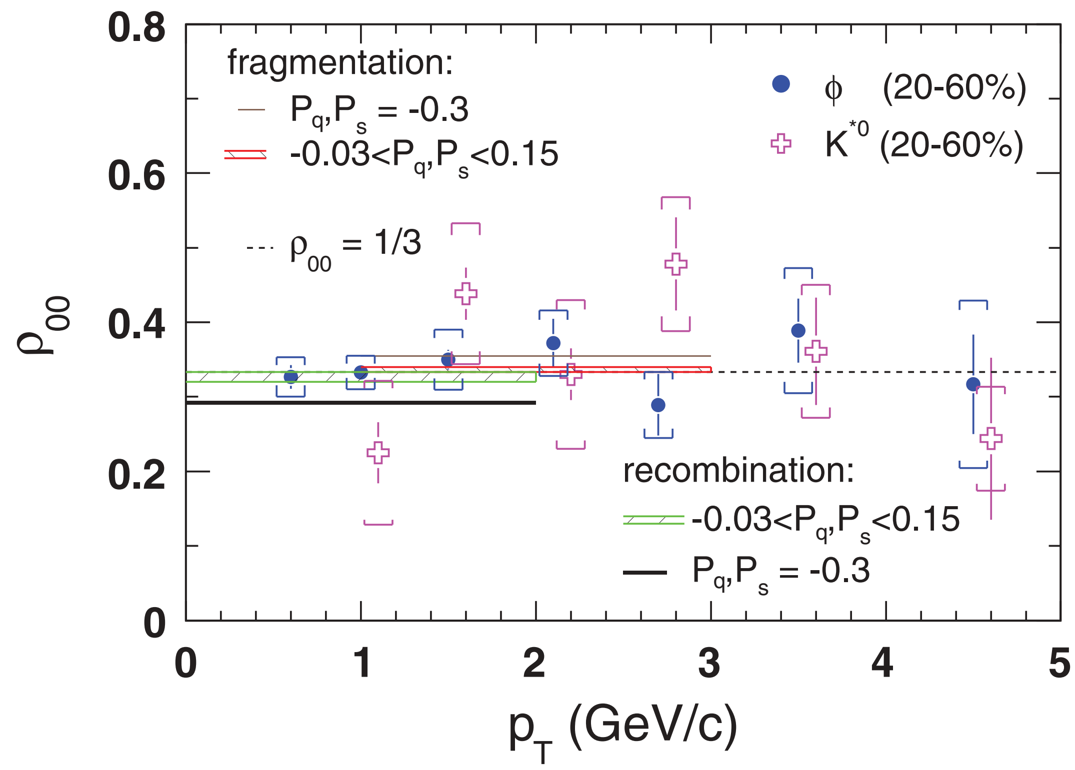
$\rho_{00} < 1/3$



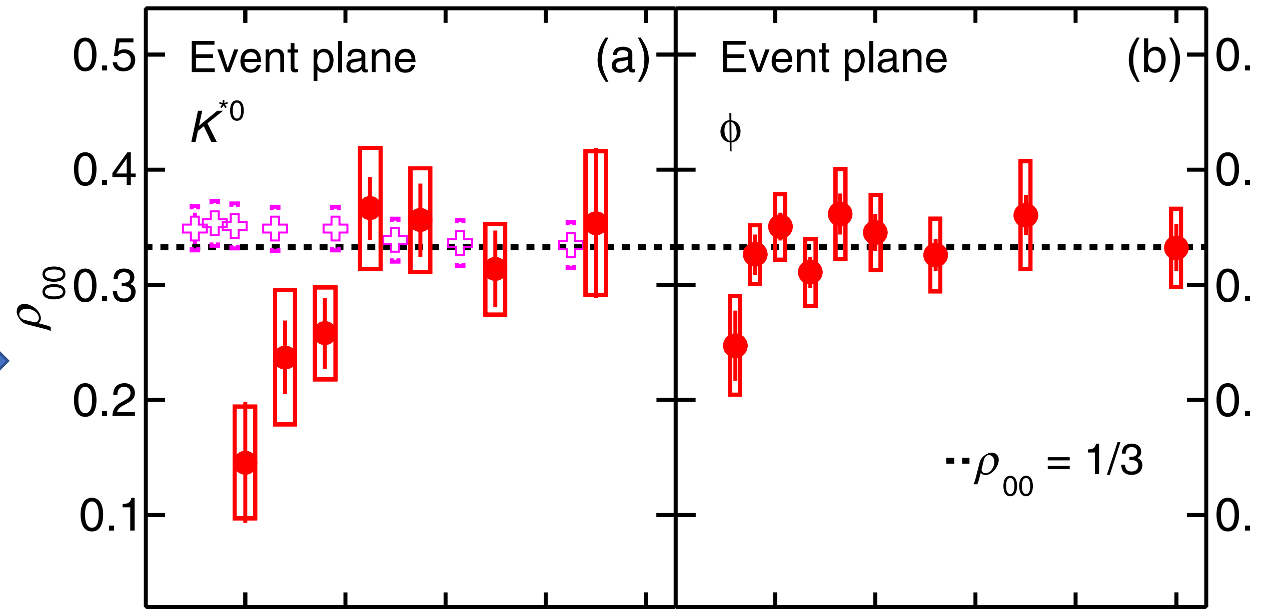
$\rho_{00} > 1/3$

Experimental measurements: φ,K*(cont.)

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



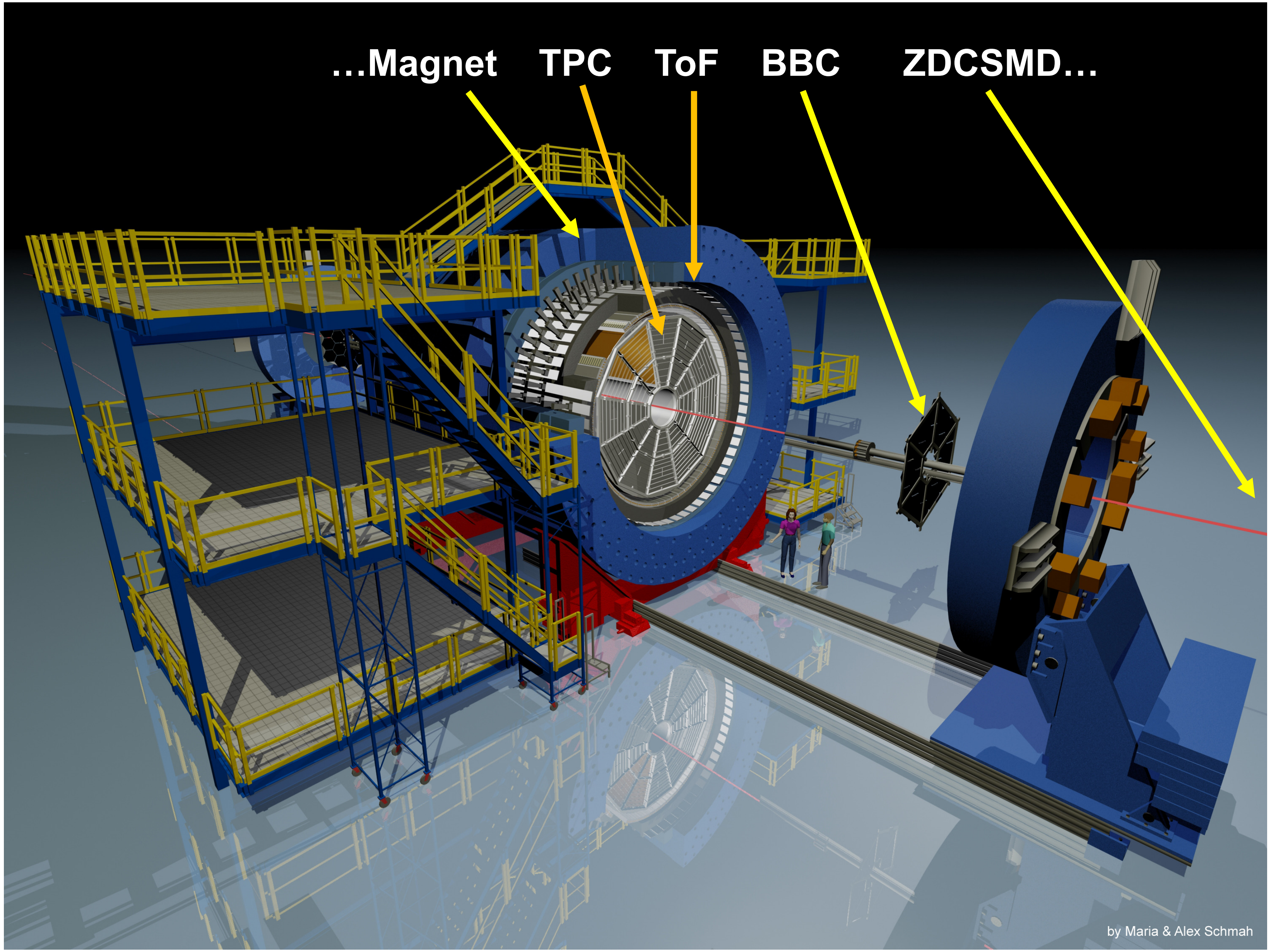
ALICE Col. Phys. Rev. Lett. **125**, 012301 (2020)



($|y| < 0.5$) in Pb-Pb collisions at a center-of-mass energy ($\sqrt{s_{NN}}$) of 2.76 TeV with the ALICE detector. ρ_{00} values are found to be less than 1/3 (1/3 implies no spin alignment) at low transverse momentum ($p_T < 2$ GeV/c) for K^{*0} and ϕ at a level of 3σ and 2σ, respectively. No significant spin alignment is

- Early data suffer from large uncertainties
- Updated measurements seem to provide evidence of spin-orbital angular momentum interactions

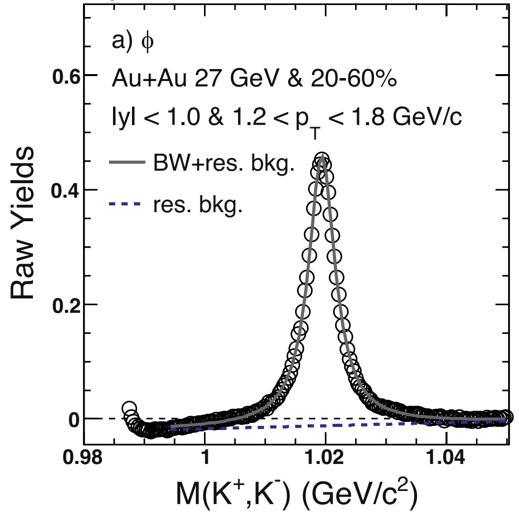
The STAR Detector at BES-I



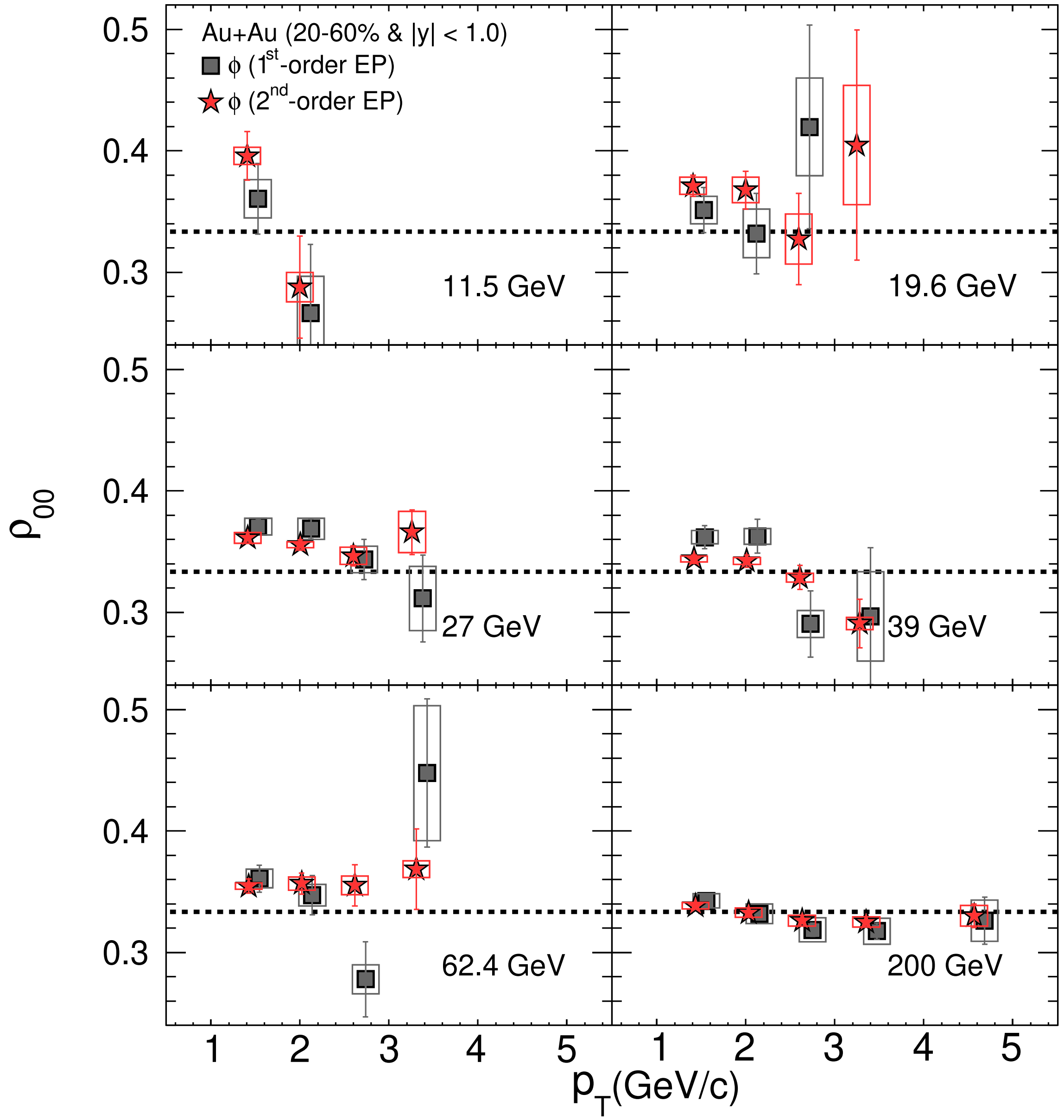
- TPC: effectively 3-D ionization camera with over 50 million pixels

- 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*0@non-central collisions

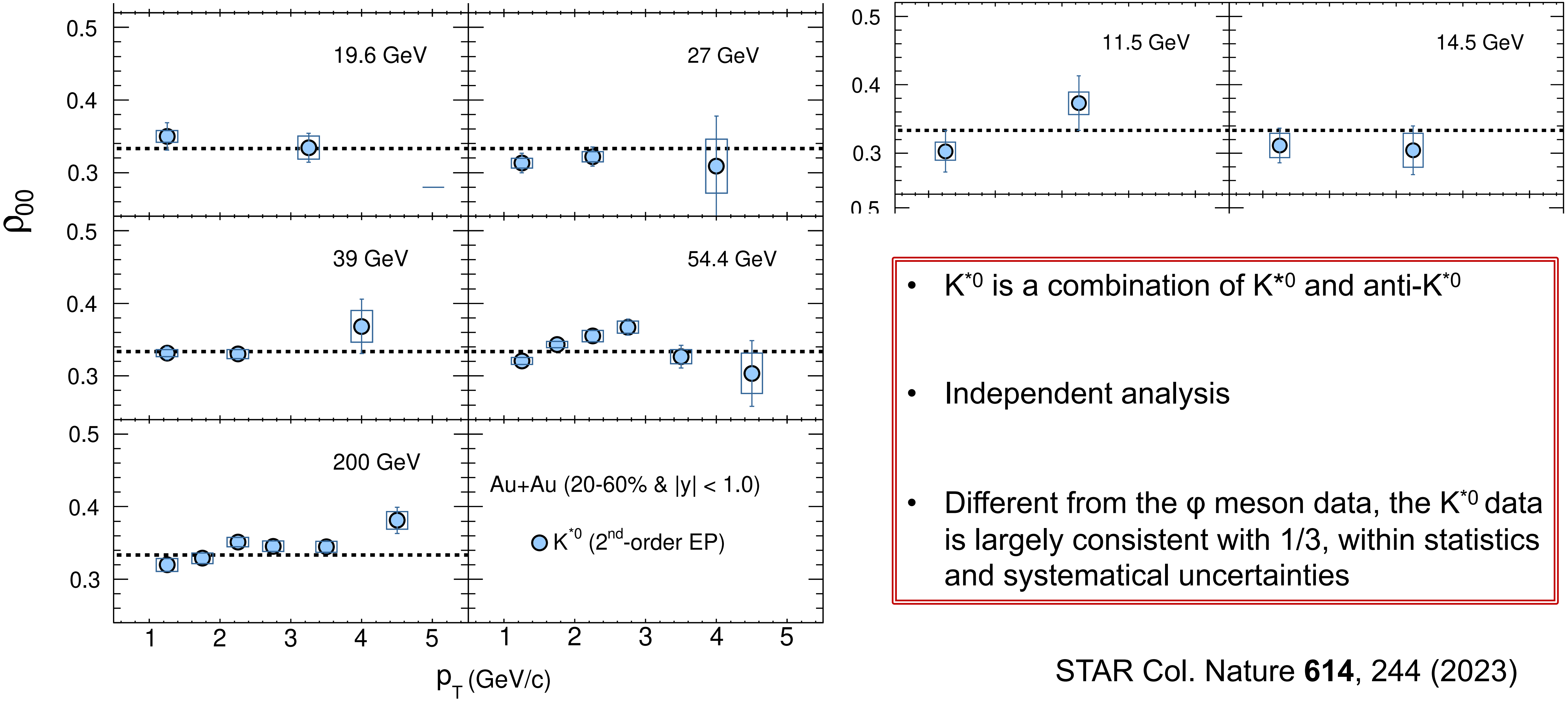


- New measurements extend the study to lower energies with high statistics, @200 GeV, a factor of ~50 more event statistics analyzed.
- We see that the signal for the φ meson occurs mainly within ~1.0-2.4 GeV/c; at larger p_T the results can be regarded as being consistent with 1/3 within ~2σ or less.

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

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

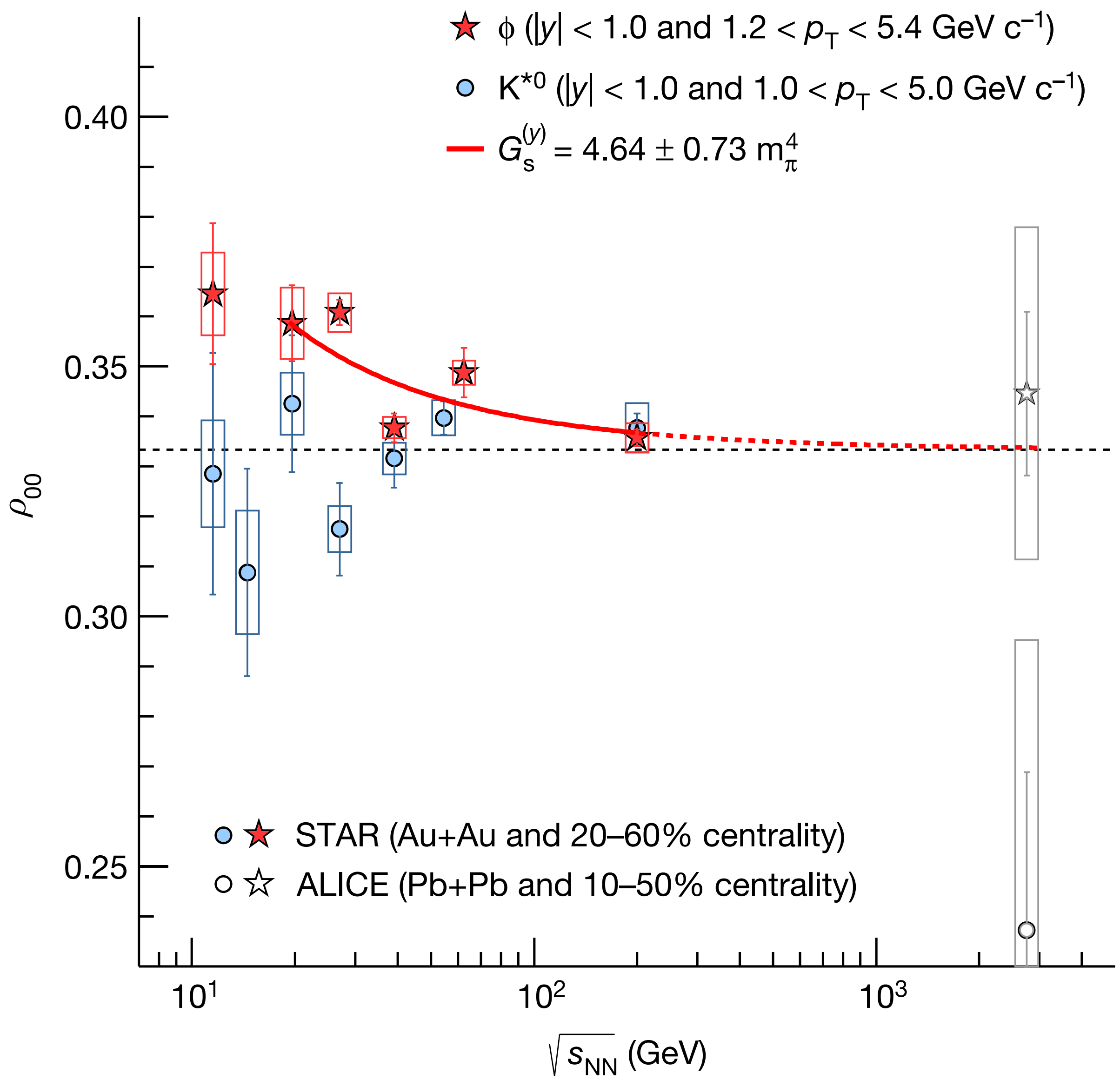
New Measurements φ,K*0@non-central collisions



- 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)

Results 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:

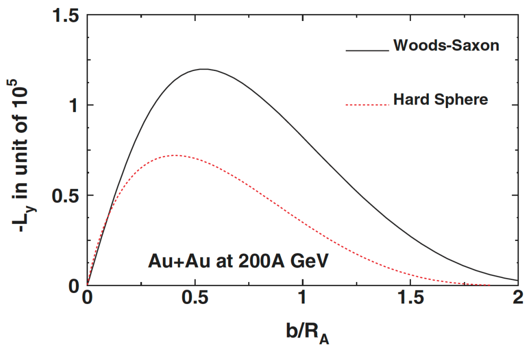
- 0.3541 ± 0.0017 (stat.) ± 0.0018 (sys.) for φ
- 0.3356 ± 0.0034 (stat.) ± 0.0043 (sys.) for K*

* Different approaches are used in the combinatorial bg. analysis

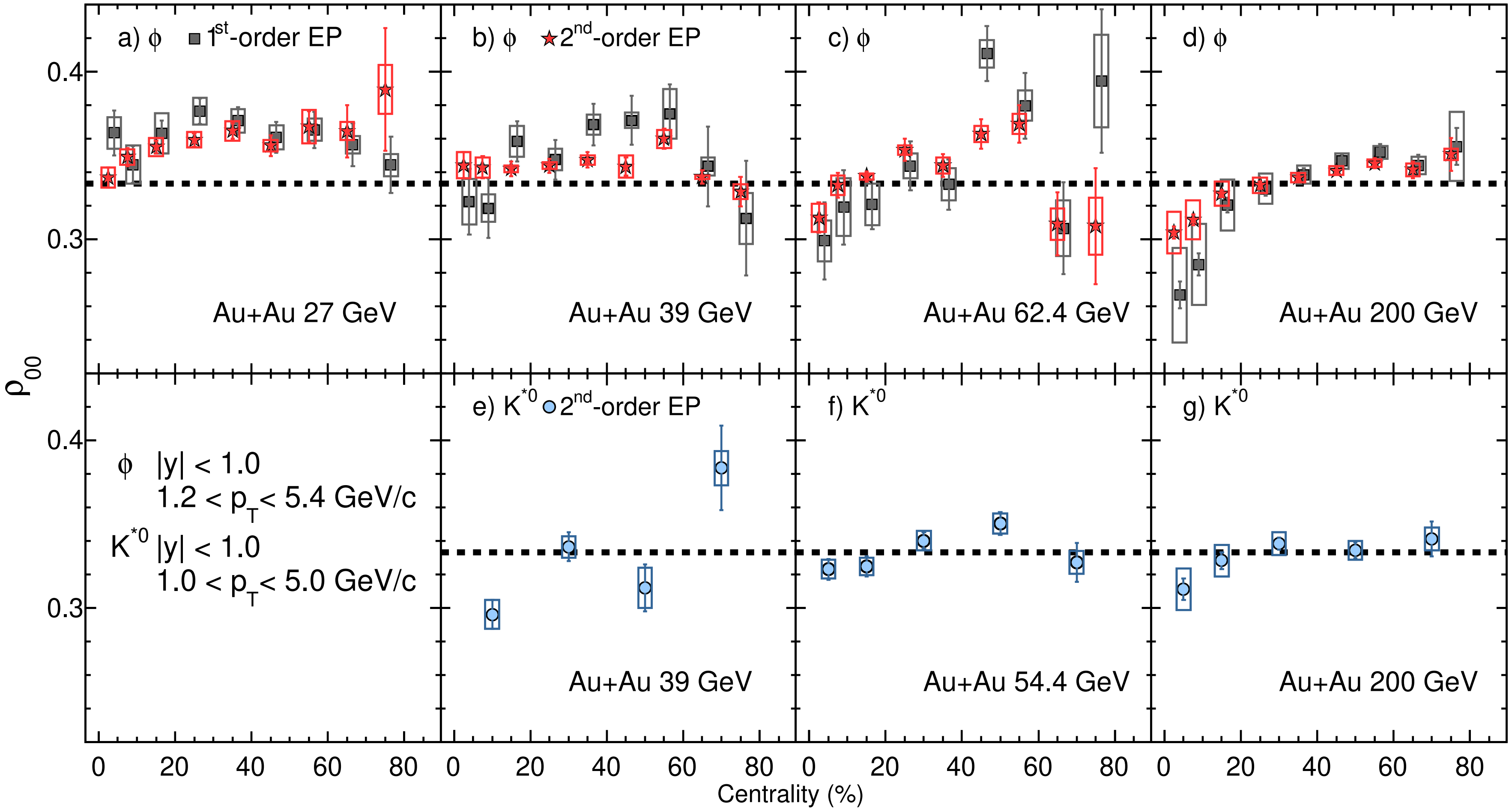
STAR Col. Nature **614**, 244 (2023)

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.

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

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

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

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

Fluctuating axial charge current

$\boldsymbol{\rho}_{00}(K^{*0}) < \boldsymbol{\rho}_{00}(\boldsymbol{\phi}) < 1/3$

[1]. Liang, Wang, Phys. Lett. B **629**, 20 (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, Wang, Phys. Lett. B **629**, 20 (2005)

[4]. Xia et al., Phys. Lett. B **817**, 136325 (2021);
Gao, Phys. Rev. D **104**, 076016 (2021)

[5]. Muller, Yang, 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?

- New idea: local correlation of φ-meson fields, like electric charges in motion can generate an EM fields, strange quarks in motion can generate an effective φ-meson field

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

- Quarks polarized by spin-orbital interaction

Talk by Wang (Monday)

$$\rho_q = \sum_{rs} \int d^3\mathbf{x} \int [d^3\mathbf{p}][d^3\mathbf{q}] e^{-i\mathbf{q}\cdot\mathbf{x}} \times f^q_{rs}(\mathbf{x},\mathbf{p}) \left| r, \mathbf{p} + \frac{\mathbf{q}}{2} \right\rangle \left\langle s, \mathbf{p} - \frac{\mathbf{q}}{2} \right| ,$$

Quark Recombination →

$$\rho^{\phi}_{00}(\mathbf{x},\mathbf{p}) \approx \frac{1}{3} - \frac{2}{3} \left\langle P^y_q(\mathbf{x}_1,\mathbf{p}_1) P^y_{\bar{q}}(\mathbf{x}_2,\mathbf{p}_2) \right\rangle + \frac{2}{9} \left\langle \mathbf{P}_q(\mathbf{x}_1,\mathbf{p}_1) \cdot \mathbf{P}_{\bar{q}}(\mathbf{x}_2,\mathbf{p}_2) \right\rangle ,$$

Greco, Ko, Levai, Phys. Rev. Lett. **90**, 202302 (2003)
Fries, Muller, Nonaka, Bass, Phys. Rev. Lett. **90**, 202303 (2003)
Hua, Yang Phys. Rev. Lett. **90**, 212301 (2003) …

Can we explain the large ρ_{00} of φ-meson?(cont.)

- Polarization by a meson field can accommodate large deviation for φ-meson ρ_{00} at midcentral collisions

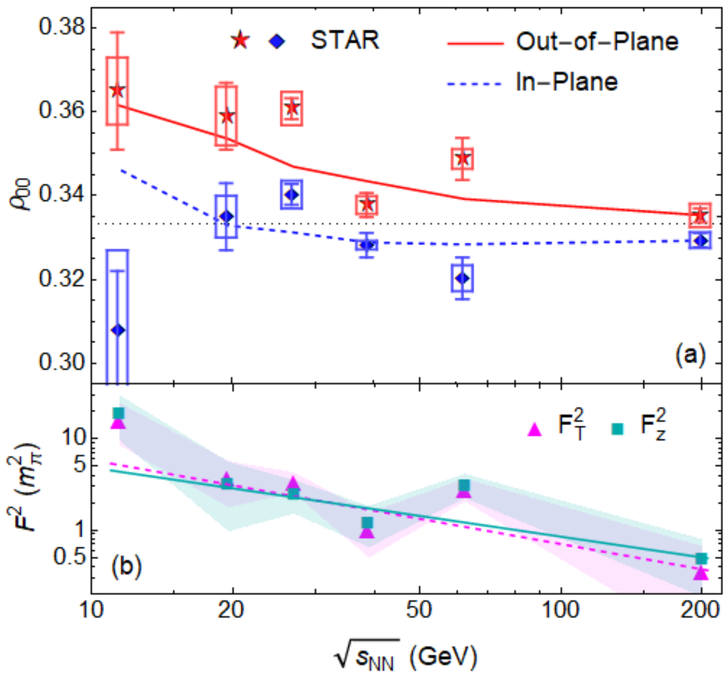
$$\mathbf{P}_{q/\bar{q}} = \frac{1}{2}\boldsymbol{\omega} + \frac{1}{2m_s}\boldsymbol{\varepsilon}\times\mathbf{p}$$
$$\pm\frac{g_\phi}{2m_sT}\mathbf{B}_\phi \pm \frac{g_\phi}{2m_qE_pT}\mathbf{E}_\phi\times\mathbf{p},$$

Sheng, et al., arXiv:2205.15689; 2206.05868

$$\left\langle(g_\phi \mathbf{B}^\phi_{x,y}/T_\mathrm{h})^2\right\rangle = \left\langle(g_\phi \mathbf{E}^\phi_{x,y}/T_\mathrm{h})^2\right\rangle \equiv F_T^2$$
$$\left\langle(g_\phi \mathbf{B}^\phi_{z}/T_\mathrm{h})^2\right\rangle = \left\langle(g_\phi \mathbf{E}^\phi_{z}/T_\mathrm{h})^2\right\rangle \equiv F_z^2$$

represented the fluctuations of transerve and longitudinal fields

$$\rho^\phi_{00}(t,\mathbf{x},\mathbf{p}) \approx \frac{1}{3} + C_1\left[\frac{1}{3}\boldsymbol{\omega}'\cdot\boldsymbol{\omega}' - (\boldsymbol{\epsilon}_0\cdot\boldsymbol{\omega}')^2\right]$$
$$+C_2\left[\frac{1}{3}\boldsymbol{\varepsilon}'\cdot\boldsymbol{\varepsilon}' - (\boldsymbol{\epsilon}_0\cdot\boldsymbol{\varepsilon}')^2\right]$$
$$-\frac{4g_\phi^2}{m_\phi^2T^2}\left\{C_1\left[\frac{1}{3}\mathbf{B}'_\phi\cdot\mathbf{B}'_\phi - (\boldsymbol{\epsilon}_0\cdot\mathbf{B}'_\phi)^2\right]\right.$$
$$\left.+C_2\left[\frac{1}{3}\mathbf{E}'_\phi\cdot\mathbf{E}'_\phi - (\boldsymbol{\epsilon}_0\cdot\mathbf{E}'_\phi)^2\right]\right\}, \qquad ($$

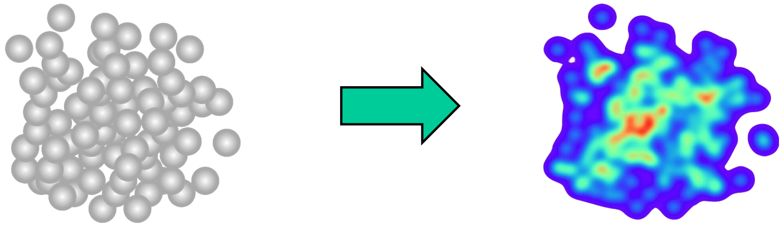


HIC : a highly volatile environment

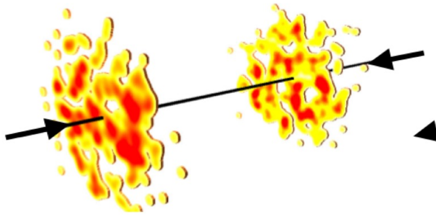
Gribov, Levin, Ryskin, 1981
McLerran, Venugopalan
hep-ph/9309289

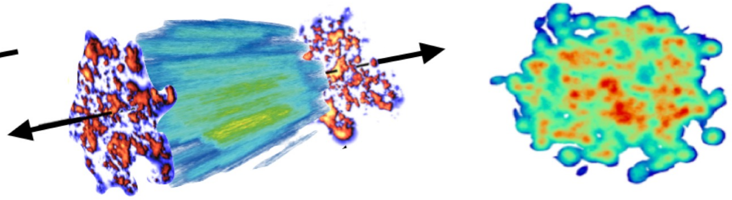
Strongest color field

Nucleus at rest



Nucleus at relativistic energies

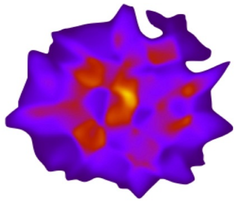


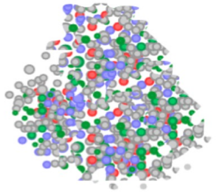


Color Glass Condensate (CGC)

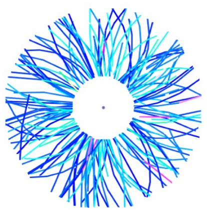
Gluon Condensate Plasma (Glasma)

Hadronization





Quark Gluon Plasma (QGP)



Detection

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

Meson fields and Λ polarization

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

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

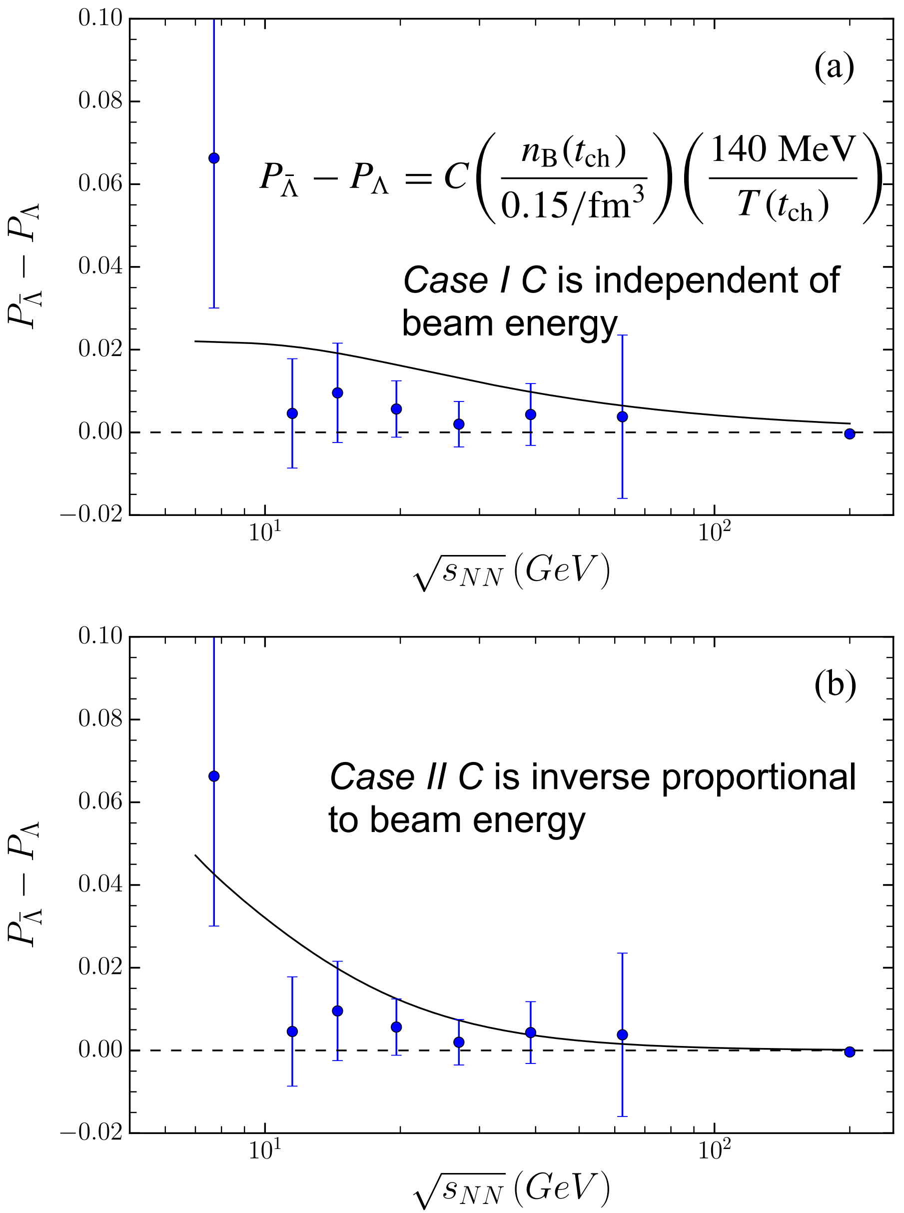
Rapid Communications

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*

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

- The value of the polarization is very sensitive to interplay of thermal vorticity and meson-field term Ivanov, Soldatov Phys. Rev. C 105 (2022), 034915
- New paper by Di-Lun, arXiv:2304.04181, "spin alignment of vector mesons by glasma fields", a local spin correlation could be greatly enhanced



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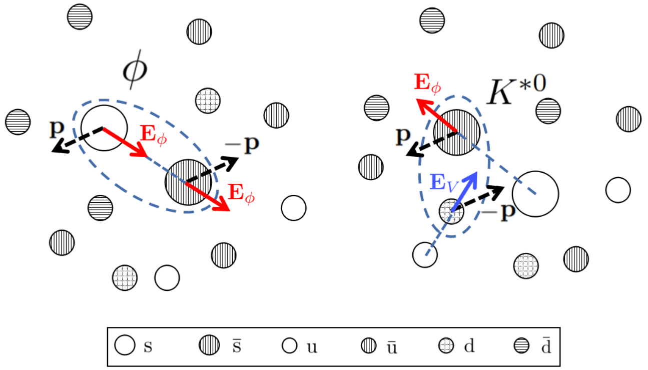
Summary

- Rich data on the physics of intense field and vorticity, many are not covered in this talk…

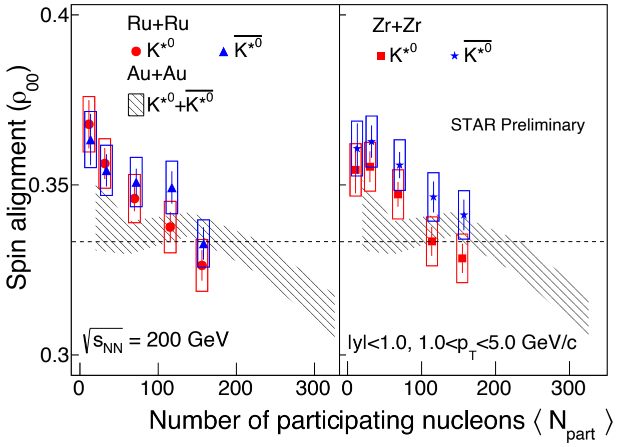
- I hope to convince you that STAR has observed a surprisingly large global spin algiment for φ-meson. It cannot be explained by conventional mechanisms. However, it can be accommodated by a model with strong force field.

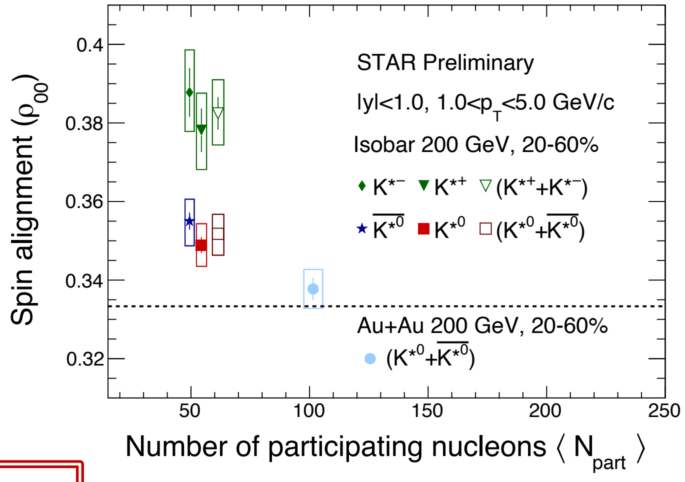
Discussion

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

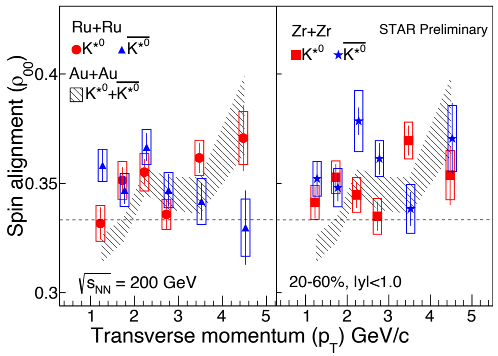


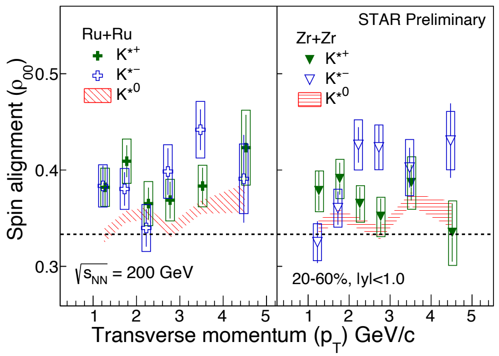
Little field correlation for K^{*0}, causing $\langle P_{\bar{q}} P_q \rangle$ to diminish.





Singha for STAR, QM22





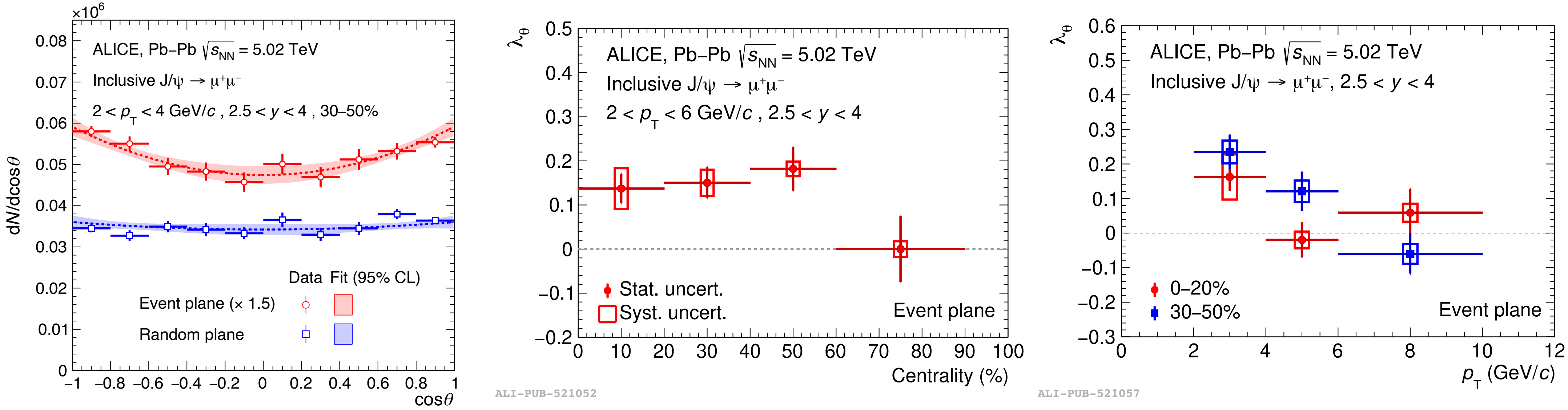
- K^{*0} is larger than 1/3 at smaller N_{part}, it is comparable to Au+Au at a similar N_{part}

- Charged K^* is larger than 1/3, it is larger than neutral K^* with 3.9σ

Due to the interaction between the B-field and the magnetic moment of constituent quarks, one naively expects the neutral K* to be larger than that of charge K*

Discussion (cont.)

- Same flavor: J/ψ-meson, at large rapidity, LHC observed a signal with 3.9σ (arXiv: 2204.10171).



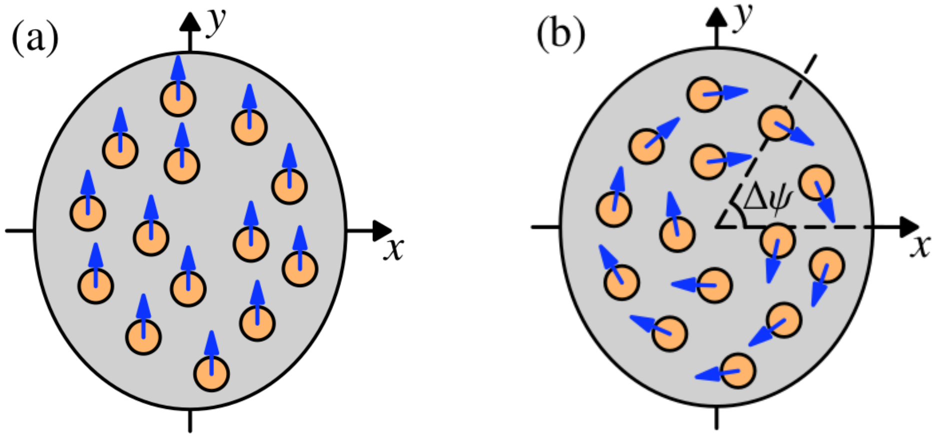
- ρ-meson (rescattering vs. regeneration may dilute the effect)

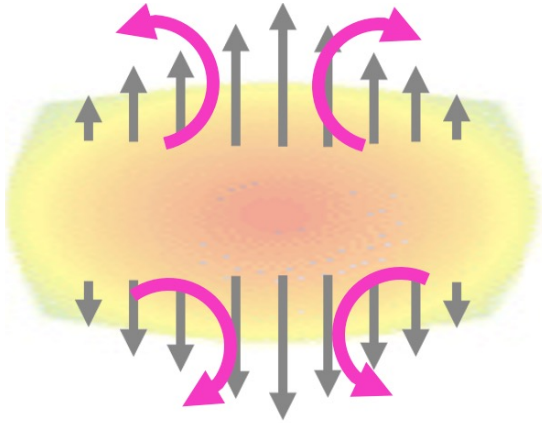
Shen, Chen, Lin, Chin. Phys. C **45**, 054002 (2021)

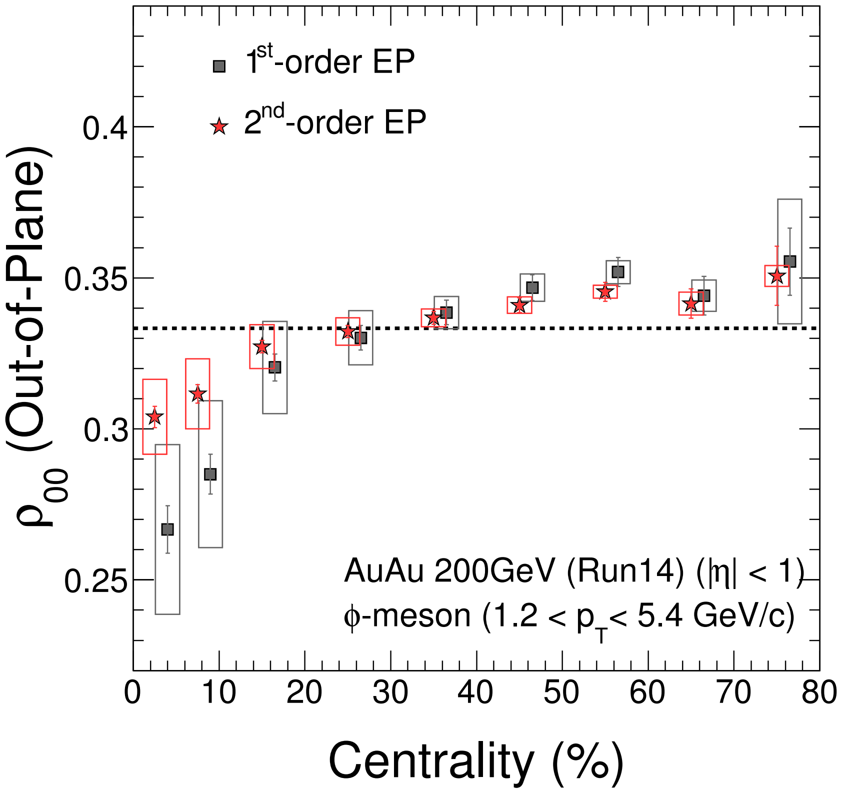
Discussion (cont.2)

Global vs. Local polarization

Xia et al., Phys. Rev. C **98**, 024905 (2018)
Phys. Lett. B **817**, 136325 (2021)







Global polarization

$$\rho_{00} = \frac{1 - P_y^2}{3 + P_y^2}$$

Local polarization

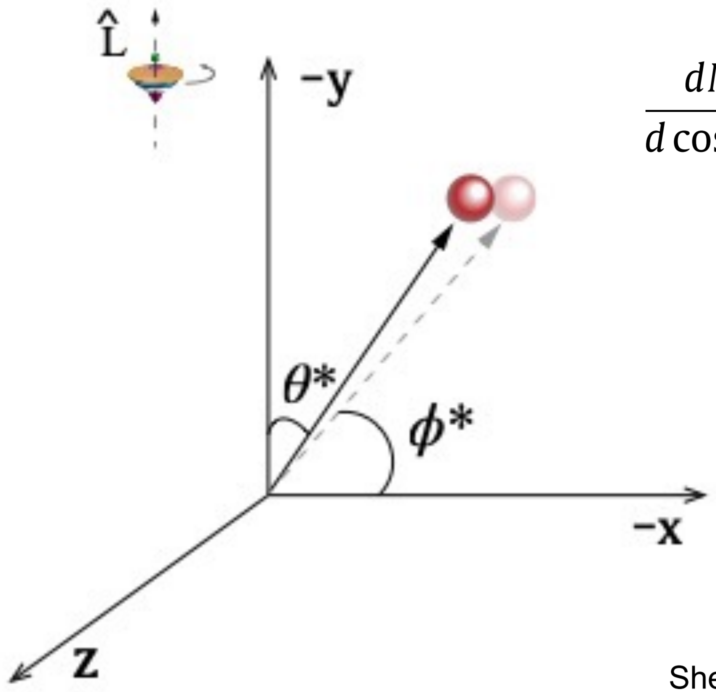
$$\rho_{00} = \frac{1 - P_y^2 + P_x^2 + P_z^2}{3 + P_y^2 + P_x^2 + P_z^2}$$

- Local vorticity structure generates a local polarization?
- Is the contribution from local spin alignment dominant in central collisions and at higher energies?

Discussion (cont. 3)

- In HIC collisions, the direction of magnetic field and OAM are correlated, which may have an effect on CME and global spin alignment

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

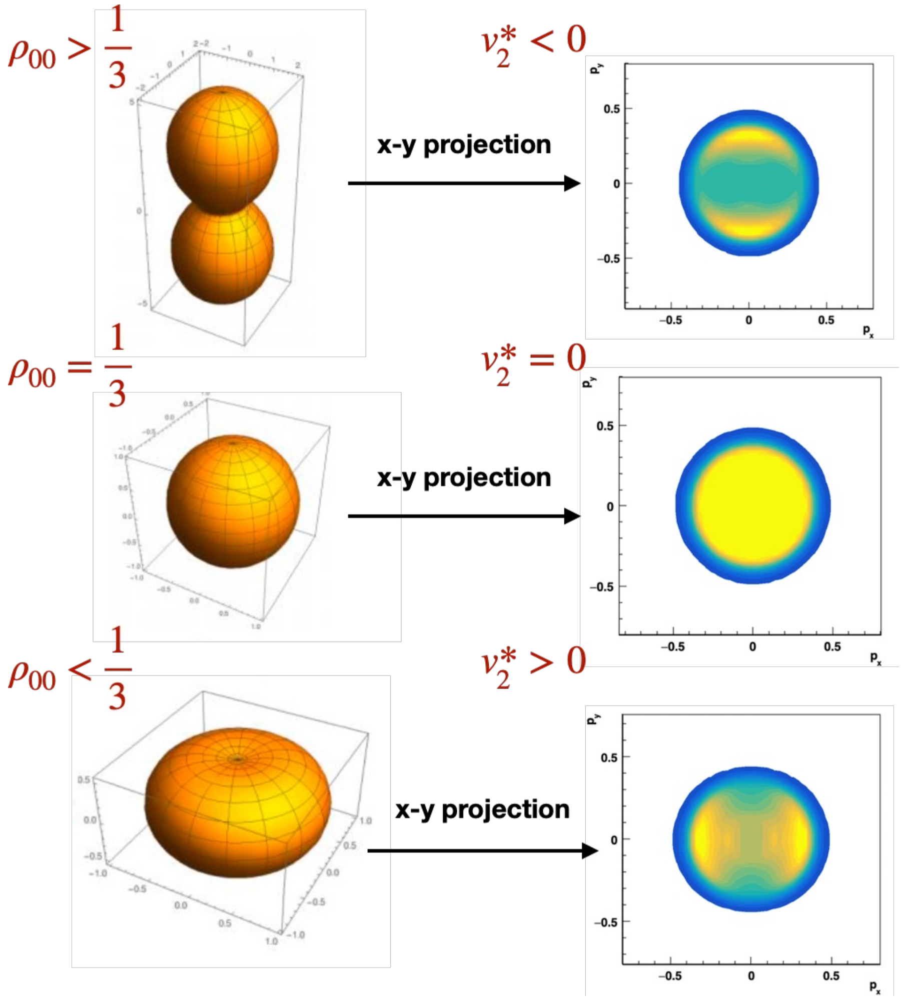


$$\frac{dN}{d\cos\theta^*} = \frac{3}{4}\left[(1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta^*\right],$$

$$\frac{dN}{d\phi^*} = \frac{1}{2\pi}\left[1 - \frac{1}{2}(3\rho_{00}-1)\cos 2\phi^*\right],$$

$$\therefore v_2^* = -\frac{3\rho_{00}-1}{4}$$

Shen, Chen, Tang, Wang, Phys. Lett. B **839**, 137777 (2023)



*Assumed the direction of OAM and the magnetic field are both perpendicular to the reaction plane

Discussion (cont. 4)

- Take the CME-sensitive observable γ_{112} as an example,

$$\gamma_{112} \equiv \left\langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{\rm RP}) \right\rangle$$

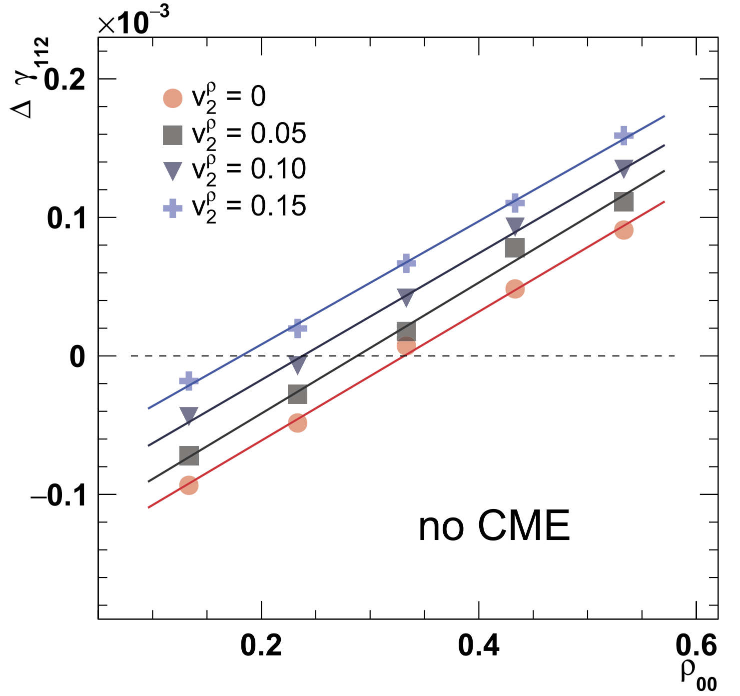
$$\gamma_{112}^{\rm OS} = \langle \cos(\phi_+ + \phi_- - 2\Psi_{\rm RP}) \rangle$$
$$= \langle \cos\Delta\phi_+ \rangle \langle \cos\Delta\phi_- \rangle + \frac{N_\rho}{N_+N_-}{\rm Cov}(\cos\Delta\phi_+, \cos\Delta\phi_-)$$
$$- \langle \sin\Delta\phi_+ \rangle \langle \sin\Delta\phi_- \rangle - \frac{N_\rho}{N_+N_-}{\rm Cov}(\sin\Delta\phi_+, \sin\Delta\phi_-),$$

- In the rest frame of ρ-meson, we calculate the covariance terms

$${\rm Cov}(\cos\phi_+^*, \cos\phi_-^*) = -\left\langle \cos^2\phi_+^* \right\rangle + \left\langle \cos\phi_+^* \right\rangle^2$$
$$= -\frac{1}{2} + \frac{1}{8}(3\rho_{00} - 1),$$
$${\rm Cov}(\sin\phi_+^*, \sin\phi_-^*) = -\left\langle \sin^2\phi_+^* \right\rangle + \left\langle \sin\phi_+^* \right\rangle^2$$
$$= -\frac{1}{2} - \frac{1}{8}(3\rho_{00} - 1).$$

$$\Delta\gamma_{112}^* = \frac{N_\rho}{N_+N_-}\frac{3\rho_{00} - 1}{4},$$

Shen, Chen, Tang, Wang, Phys. Lett. B **839**, 137777 (2023)



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

- Global spin alignment of ρ-meson is a crucial component in the background estimation for the CME measurements involving pions

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Subhash Singha

Xu Sun

Chensheng Zhou