

Chirality, Vorticity and Spin Polarization

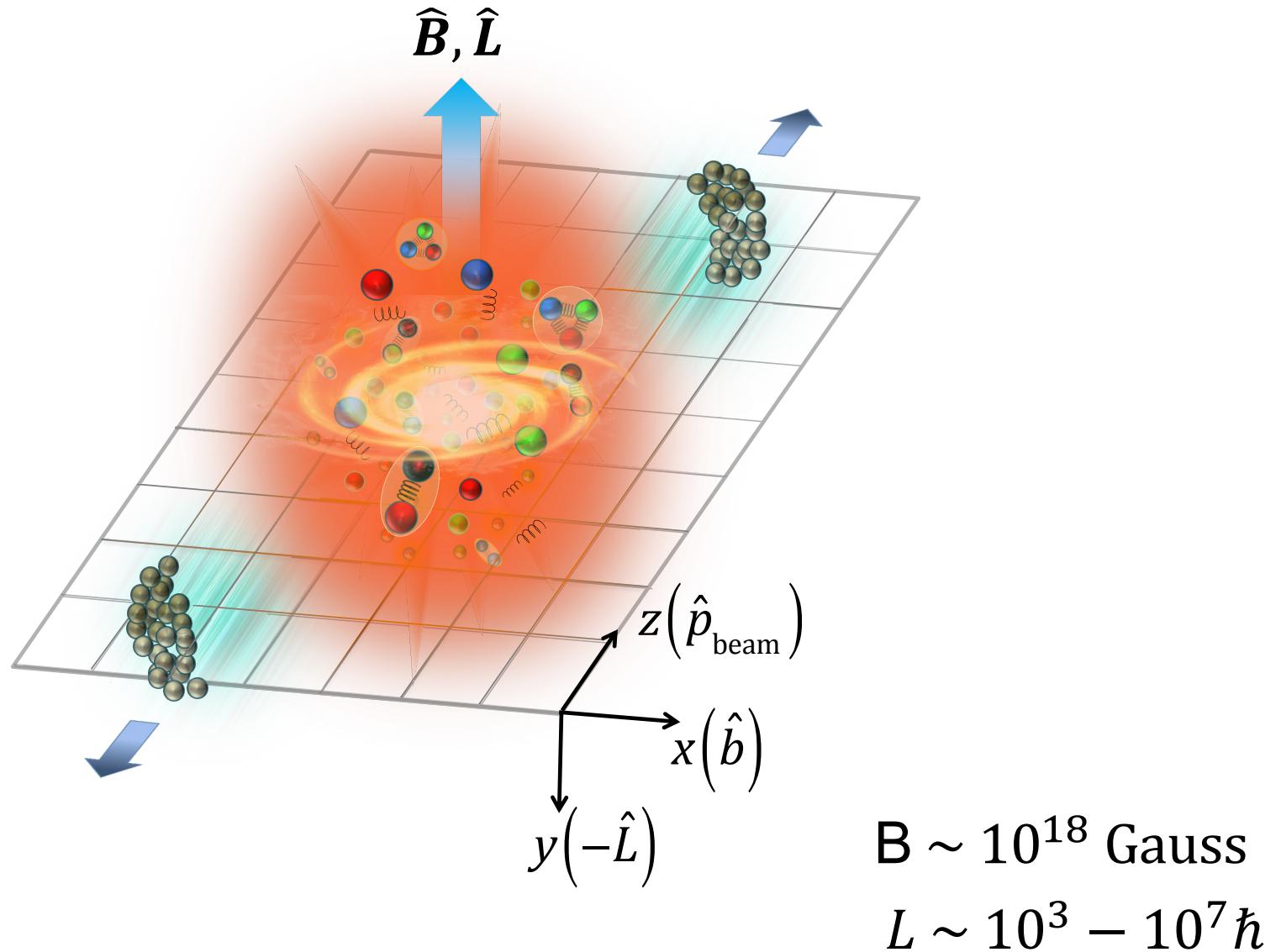


- Experimental Overview

Aihong Tang



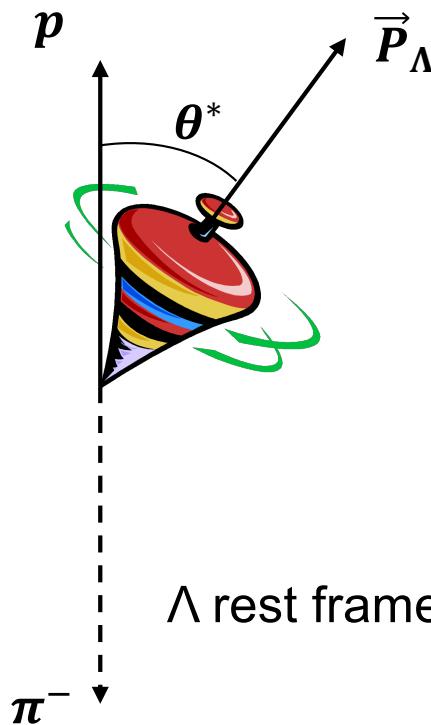
Strongly Interacting Matter under Rotation



Λ Global Polarization

Parity-violating weak decay of hyperons (“self-analyzing”)

Daughter baryon is preferentially emitted in the direction of hyperon’s spin (opposite for anti-particle)



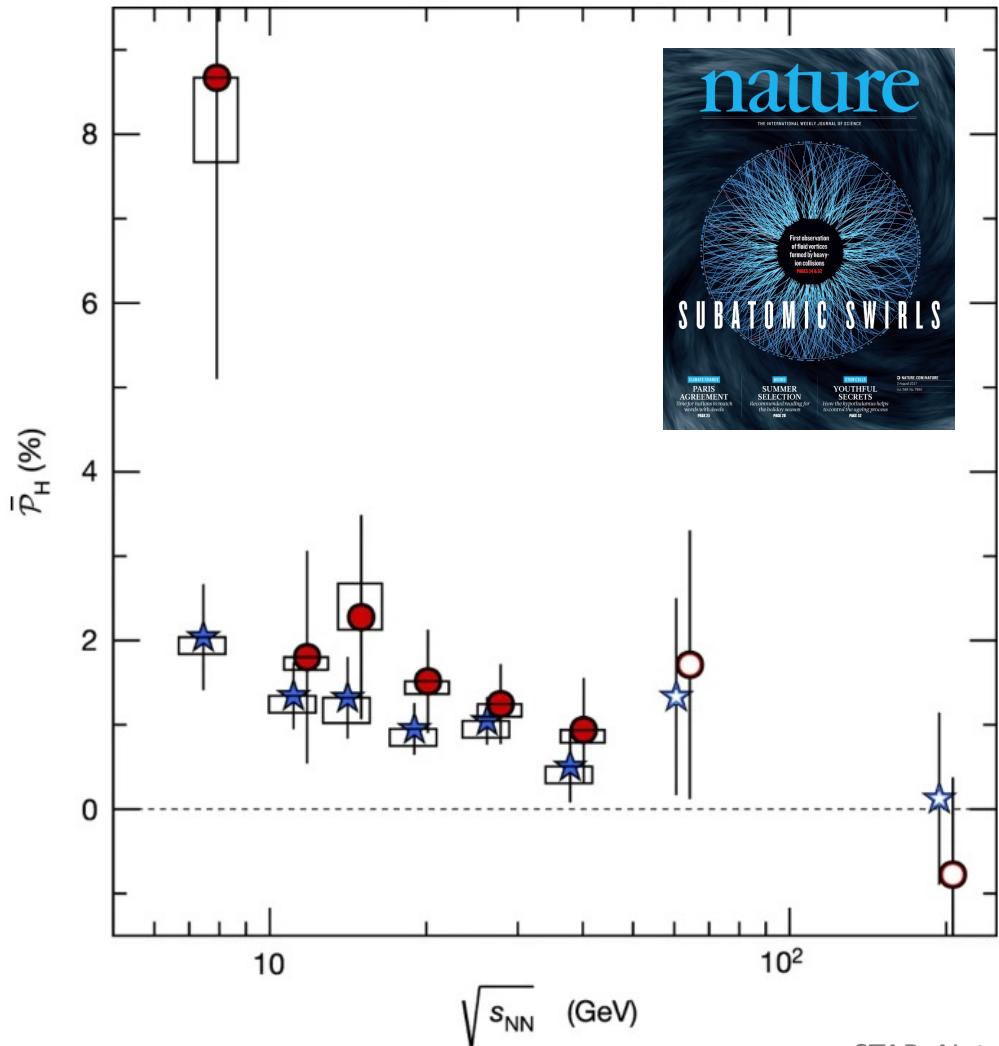
$$\frac{dN}{d\Omega^*} = \frac{1}{4\pi} (1 + \alpha_H P_H \cos \theta^*)$$

P_H : Λ polarization

θ^* : polar angle of daughter w.r.t. polarization direction

α_H : Λ decay parameter (0.732 ± 0.014)

Λ Global Polarization



Most vortical fluid

$$S^\mu_\omega(p) = -\frac{1}{8m} \epsilon^{\mu\rho\sigma\tau} p_\tau \frac{\int_\Sigma d\Sigma \cdot p n_F (1 - n_F) \boxed{\omega_{\rho\sigma}}}{\int_\Sigma d\Sigma \cdot p n_F}$$

$$\boxed{\omega_{\mu\nu}} = -\frac{1}{2} (\partial_\mu \beta_\nu - \partial_\nu \beta_\mu)$$

$$s = \frac{1}{2} P \approx \frac{1}{4} \frac{\omega}{T}$$

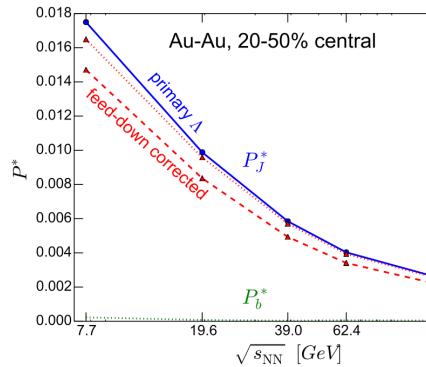
$$P_\Lambda \approx \frac{1}{2} \frac{\omega}{T} + \frac{\mu_\Lambda B}{T} \quad P_{\bar{\Lambda}} \approx \frac{1}{2} \frac{\omega}{T} - \frac{\mu_\Lambda B}{T}$$



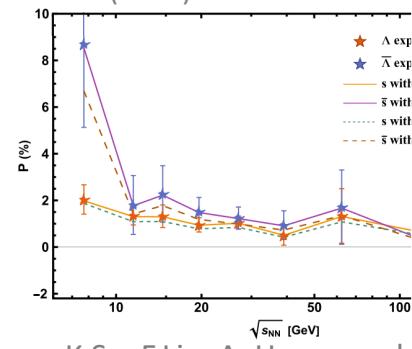
$$\omega = (P_\Lambda + P_{\bar{\Lambda}}) k_B T / \hbar \sim 10^{22} s^{-1}$$

STAR, Nature 548 62 (2017)

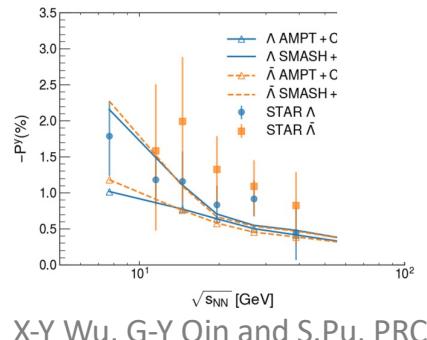
Λ Global Polarization



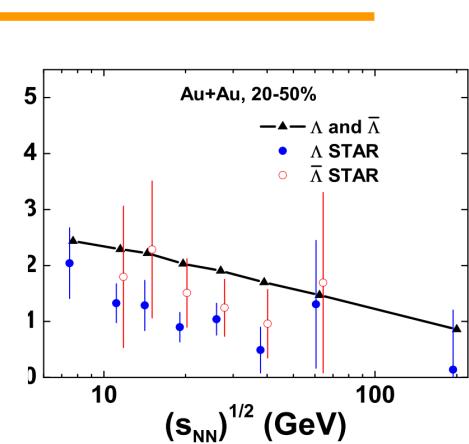
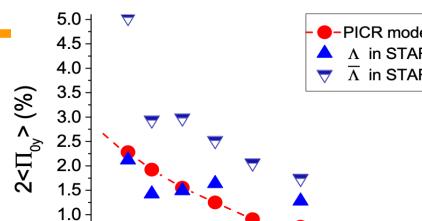
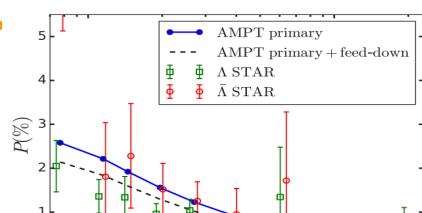
Iu. Karpenko and F. Becattini, EPJ C 77 213 (2017)



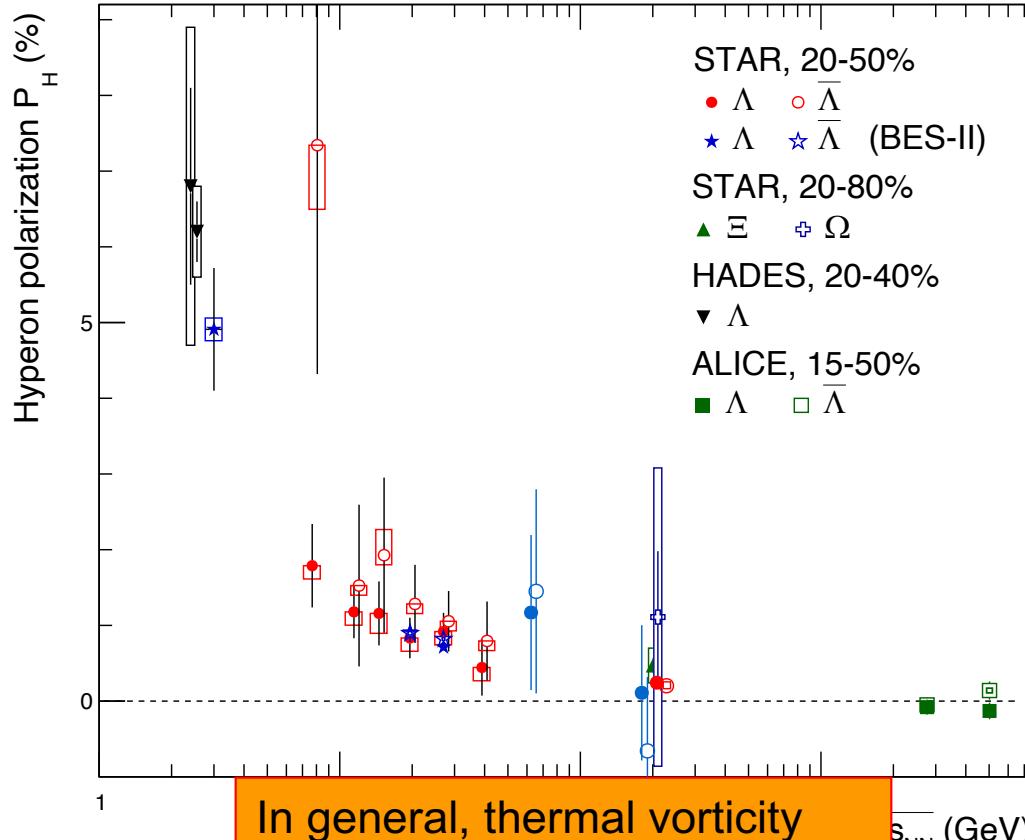
K.Su, F.Lin, A. Huang and Huang PRD 106 L071502



X-Y Wu, G-Y Qin and S.Pu, PRC 105 064909 (2022)

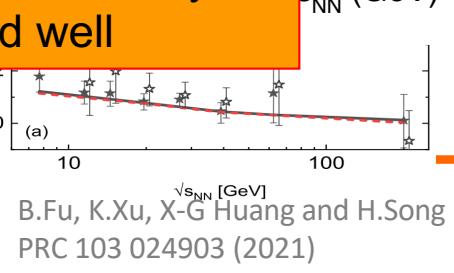


. Sun and C-M Ko, PRC 96 024906 (2017)



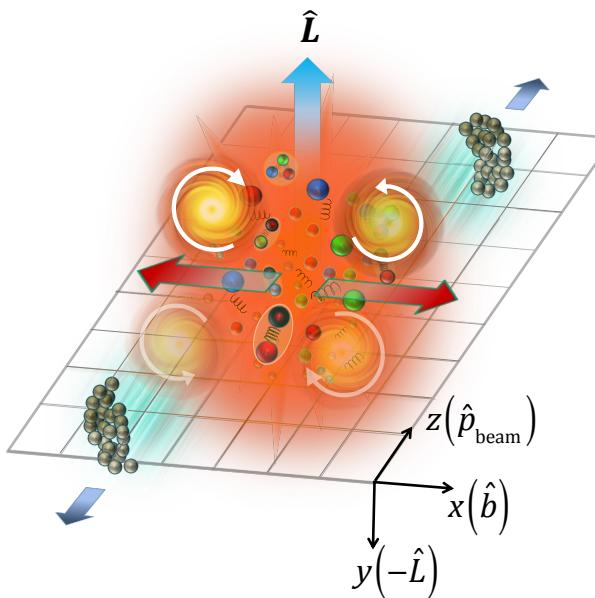
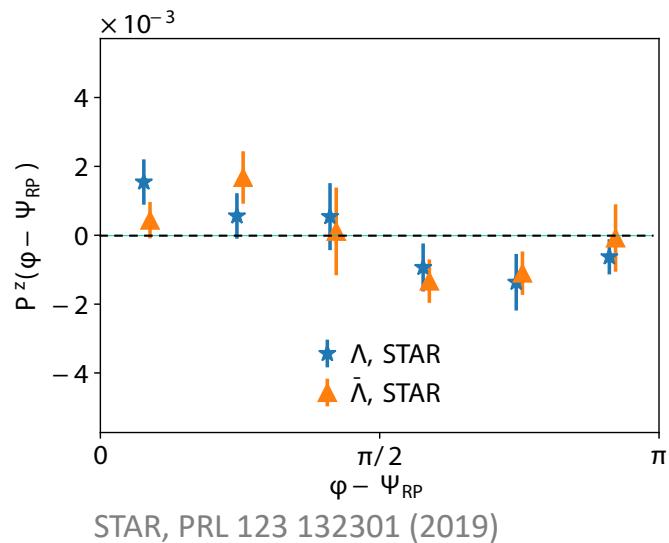
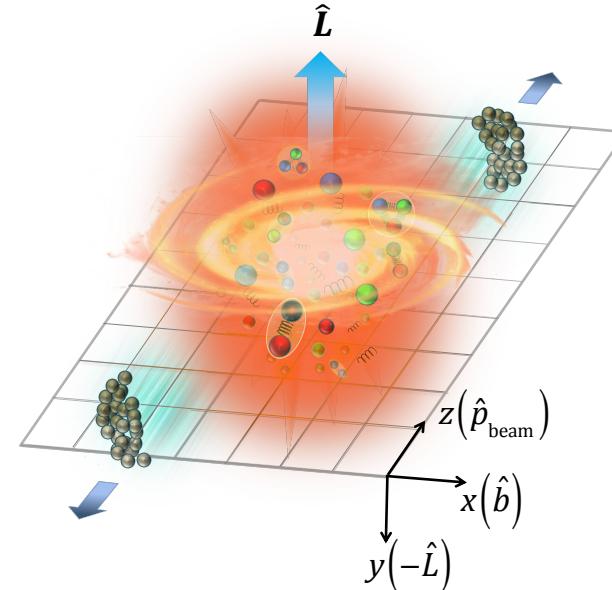
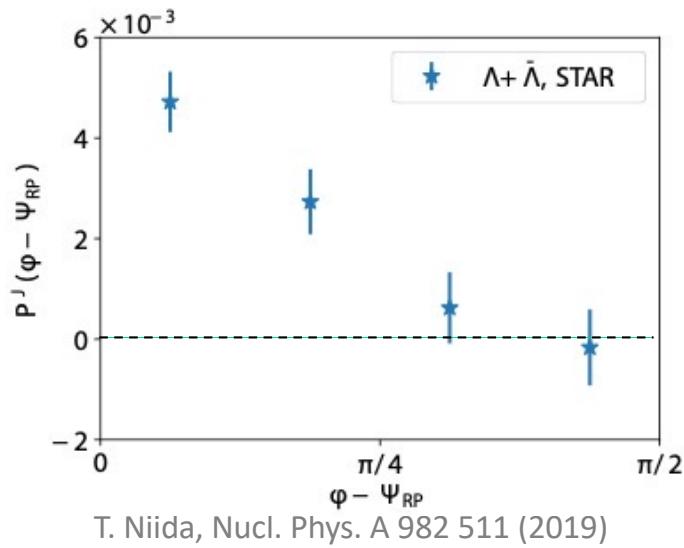
In general, thermal vorticity explains the trend well

S.Ryu, V. Jupic and C. Shen, PRC 104 5, 054908 (2021)

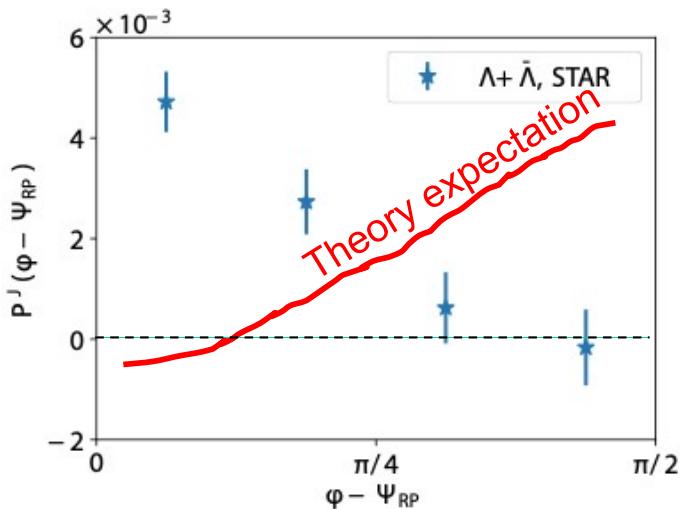


D-X Wei, W-T Deng and X-G Huang PRC 99 014905 (2019)

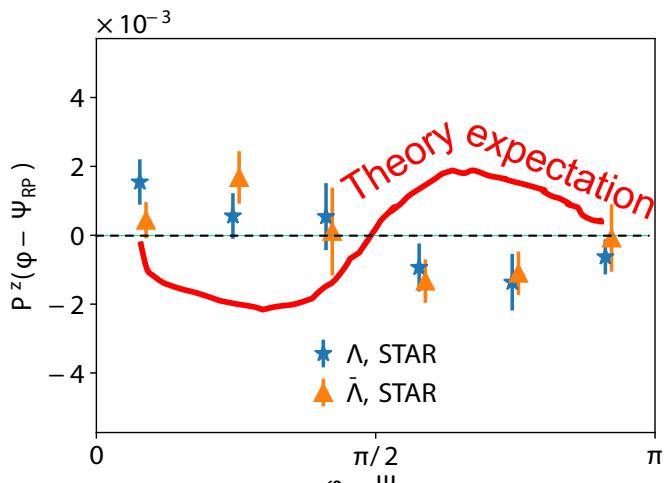
The Sign Puzzle



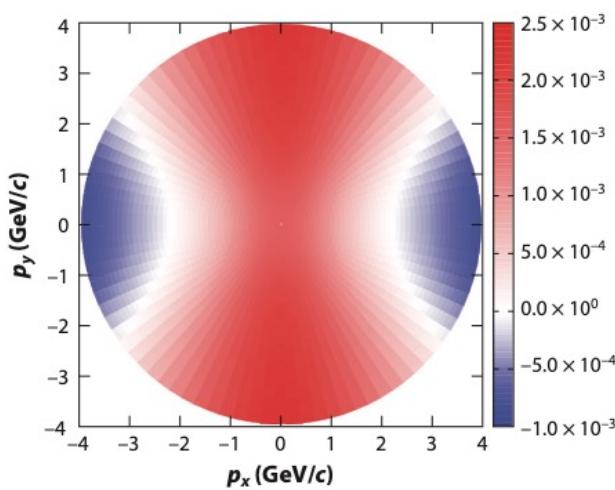
The Sign Puzzle



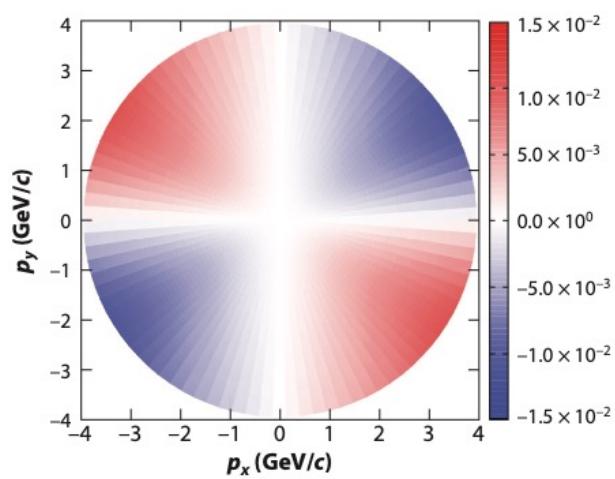
T. Niida, Nucl. Phys. A 982 511 (2019)



STAR, PRL 123 132301 (2019)

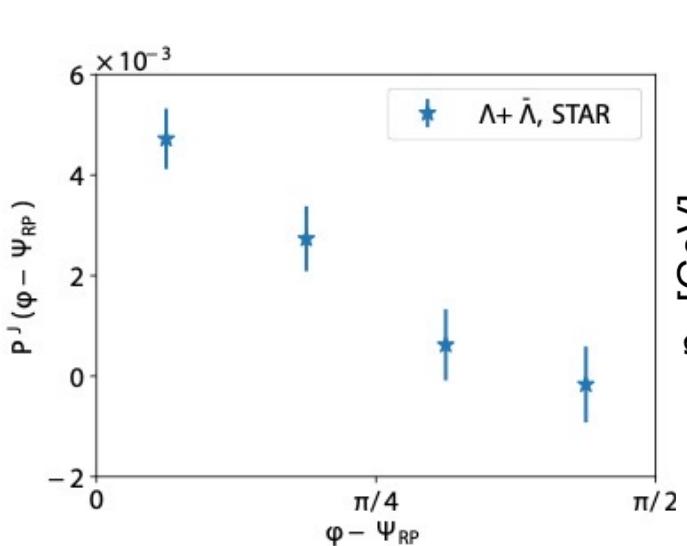


- F. Becattini, L. Csernai and D. J. Wang, PRC 88 034905 (2013)
- F. Becattini, et al. Eur. Phys. J. C 75 406 (2015)
- W.T. Deng and X.G. Huang, PRC 93 064907 (2016)
- Y.L.Xie et al., PRC 94 054907 (2016)
- I.Karpenkon and F. Becattini, Eur.Phys.J. C 77 213 (2017)
- Y.Xie, D.Wang and L.P.Csernai, PRC 95 031901 (2017)
- H.Li et al., NPA 967 772 (2017)
- B.Fu, K.Xu, X.G.Huang and H.Song, PRC 103 024903 (2021)

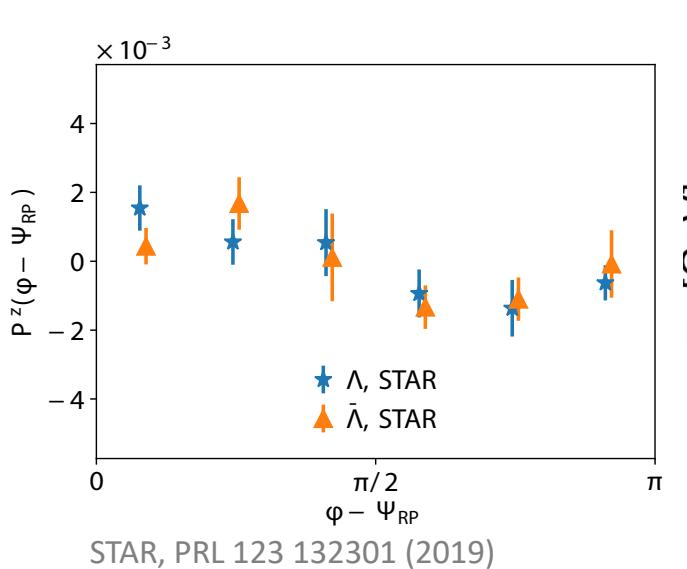


- F. Becattini, et al. Eur. Phys. J. C 75 406 (2015)
- F. Becattini and Iu. Karpenko, PRL 120 012302 (2018)
- X.L. Xia et al. PRC 98 024905 (2018)
- D.X. Wei, W.T. Deng and X.G. Huang, PRC 99 014905 (2019)
- Y. Sun and K.M. Ko, PRC 99 011903 (2019), [Explains the sign but non magnitude.]
- Y.F. Liu, Y.Sun and C.M. Ko PRL 125 062301 (2020). [explains the sign, sort of].
- B.Fu, K.Xu, X.G.Huang and H.Song, PRC 103 024903 (2021)

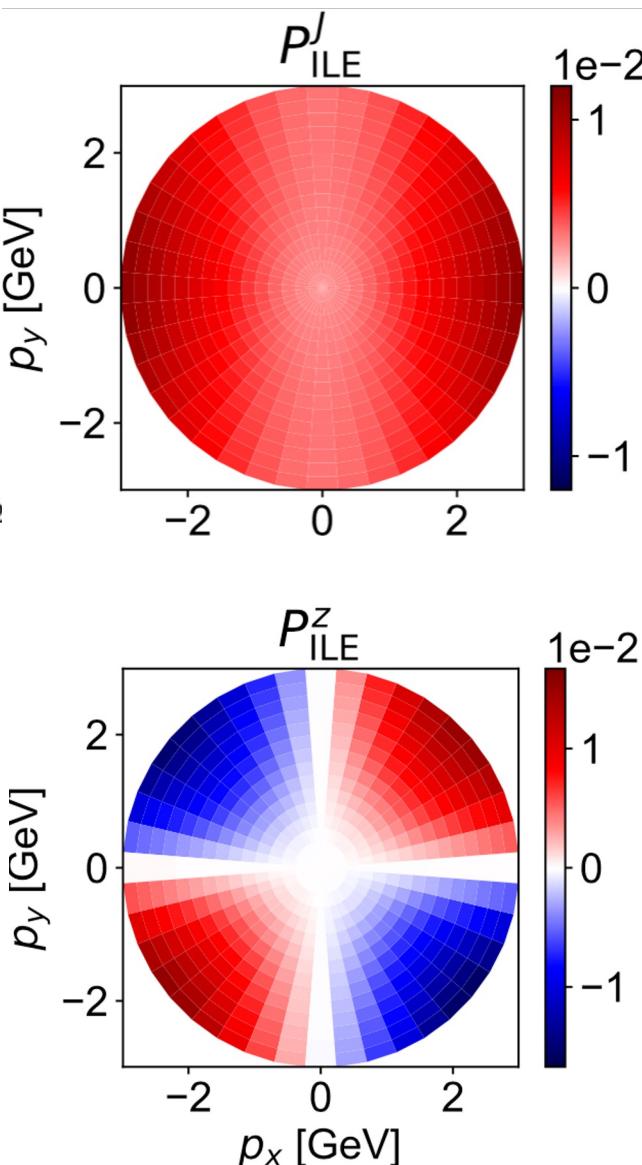
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T. Niida, Nucl. Phys. A 982 511 (2019)



STAR, PRL 123 132301 (2019)



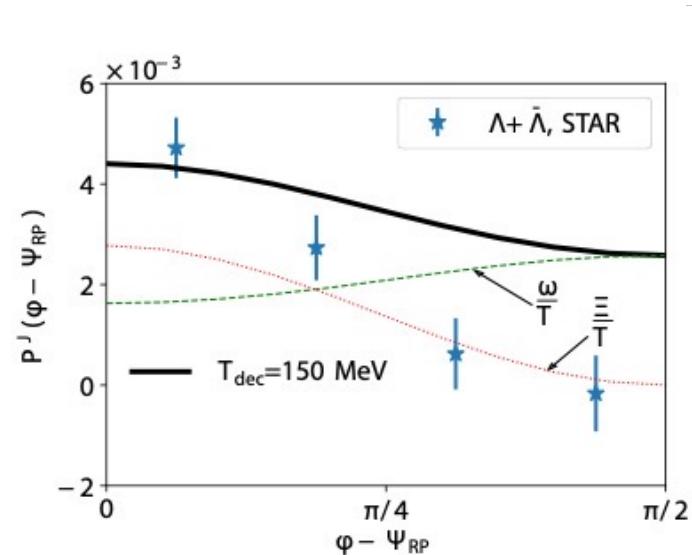
Models with thermal shear :

- F.Becattini, M.Buzzegoli and A. Palermo, PLB 820 136519 (2021)
- S.Liu and Y. Yin, JHEP 07 188 (2021)
- B. Fu et al., PRL 127 142301 (2021)
- F. Becattini et al., PRL 127 272302 (2021)
- C.Yi, S.Pu and D.L. Yang, PRC 104 064901 (2021)
- W. Florkowski et al., PRC 105 064901 (2022)

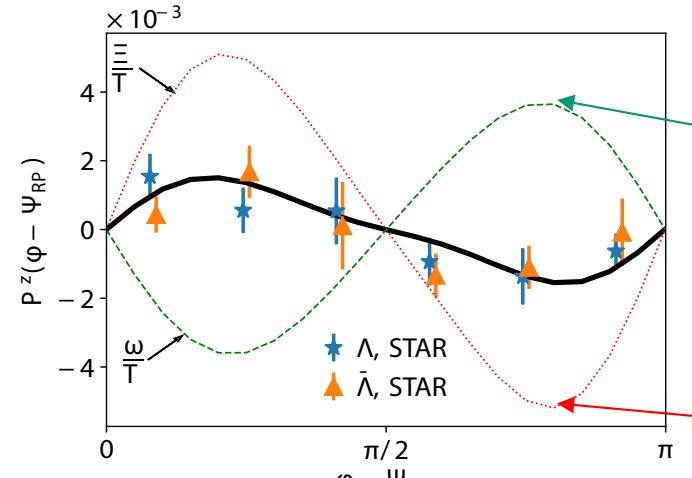
Other phenomenology models :

- H.Z. Wu, L.G. Pang, X.G. Huang and Q. Wang, Phys.Rev.Research 1 033058 (2019)
- Y.Xie, D.Wang and L.P. Csernai, EPJ C 80 39 (2020)
- Y.F. Liu, Y. Sun and C.M. Ko, PRL 125 062301 (2020)
- H.Z. Wu, L.G. Pang, X.G. Huang and Q. Wang, NPA 1005 121831 (2021)

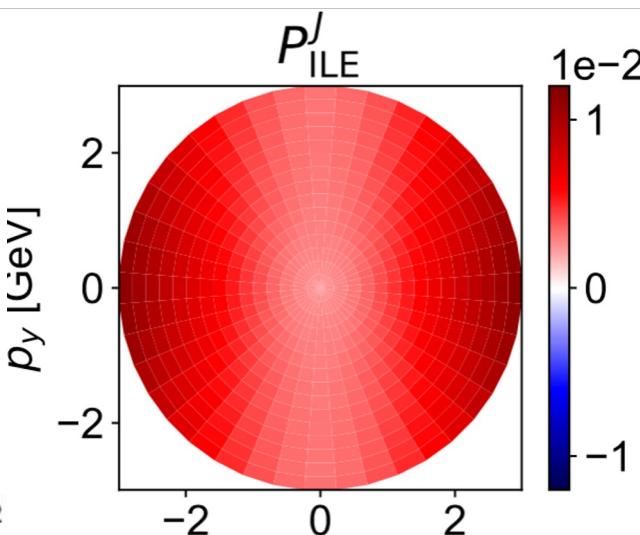
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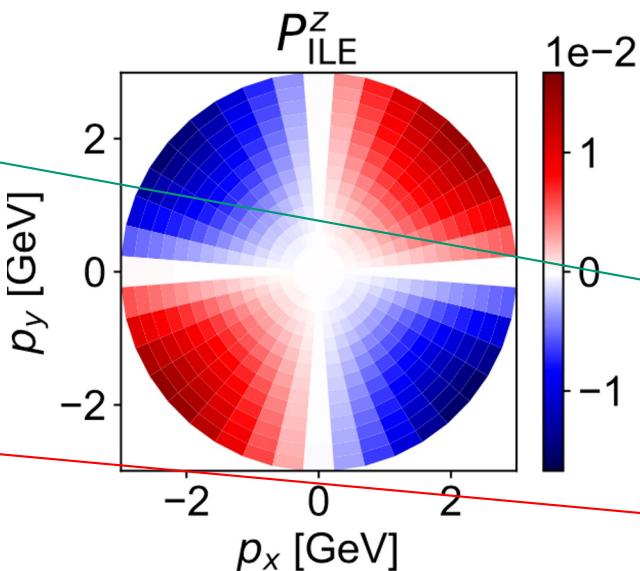
T. Niida, Nucl. Phys. A 982 511 (2019)
 F. Becattini et al., PRL 127 272302 (2021)



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 W. Florkowski et al., PRC 105 064901 (2022)



Thermal shear vorticity can give right signs.

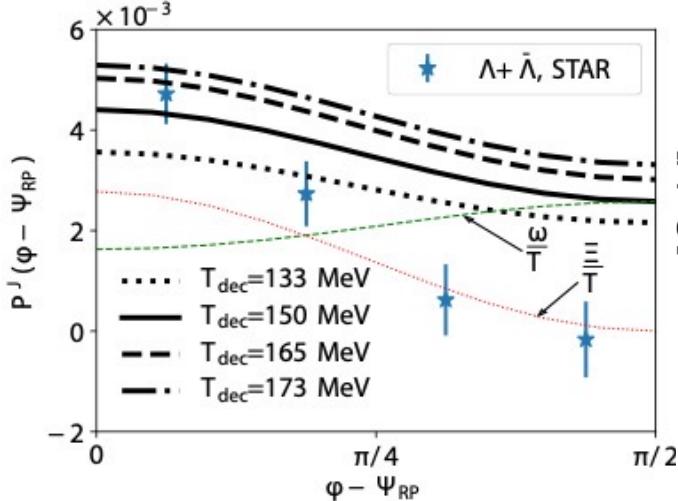
$$S^\mu_{\varpi}(p) = -\frac{1}{8m} \epsilon^{\mu\rho\sigma\tau} p_\tau \frac{\int_\Sigma d\Sigma \cdot p n_F (1 - n_F) \varpi_{\rho\sigma}}{\int_\Sigma d\Sigma \cdot p n_F}$$

$$\varpi_{\mu\nu} = -\frac{1}{2} (\partial_\mu \beta_\nu - \partial_\nu \beta_\mu) \quad \text{Thermal vorticity}$$

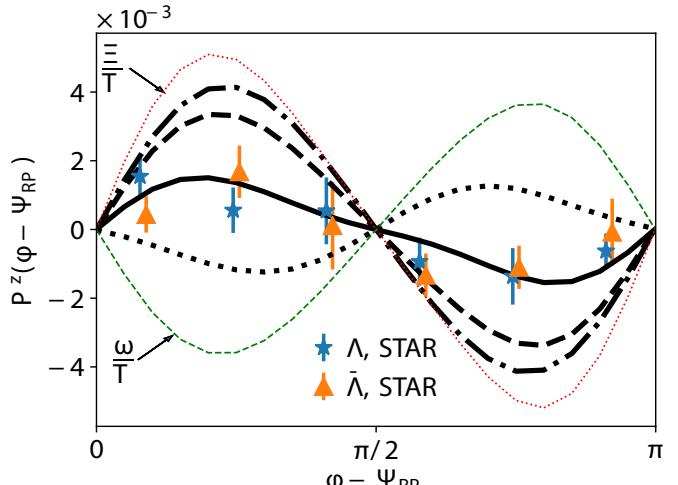
$$S^\mu_{\xi}(p) = -\frac{1}{4m} \epsilon^{\mu\rho\sigma\tau} \frac{p_\tau p^\lambda}{\varepsilon} \frac{\int_\Sigma d\Sigma \cdot p n_F (1 - n_F) \hat{t}_\rho \xi_{\sigma\lambda}}{\int_\Sigma d\Sigma \cdot p n_F}$$

$$\xi_{\mu\nu} = \frac{1}{2} (\partial_\mu \beta_\nu + \partial_\nu \beta_\mu) \quad \text{Thermal shear}$$

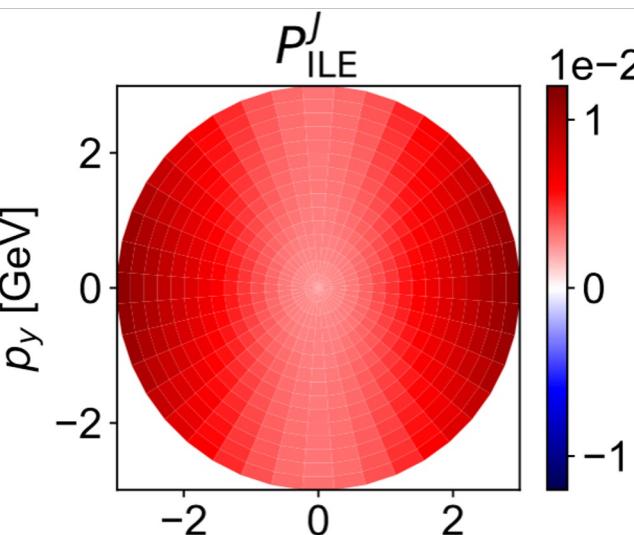
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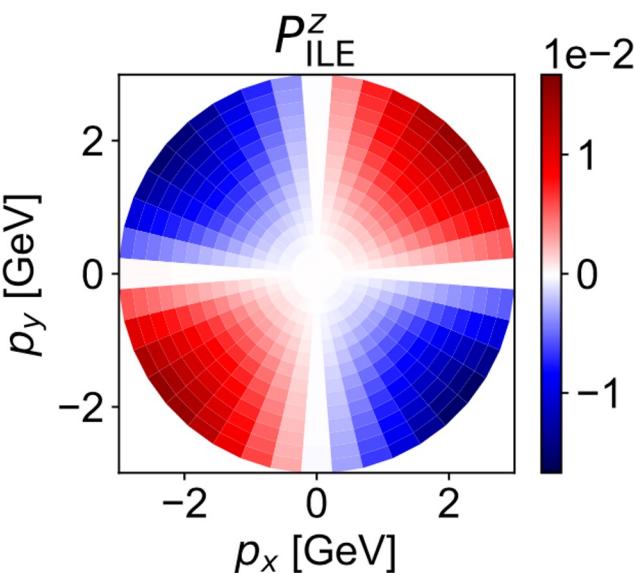
T. Niida, Nucl. Phys. A 982 511 (2019)
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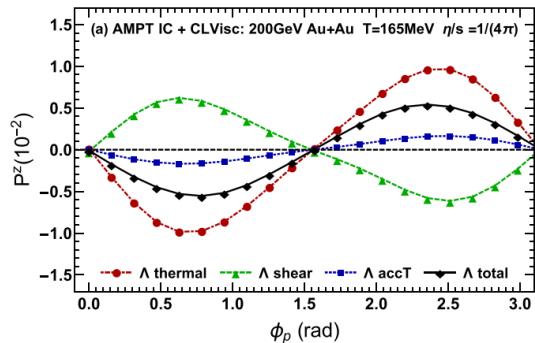
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 C.Yi, S.Pu and D.L. Yang, PRC 104 064901 (2021)
 W. Florkowski et al., PRC 105 064901 (2022)



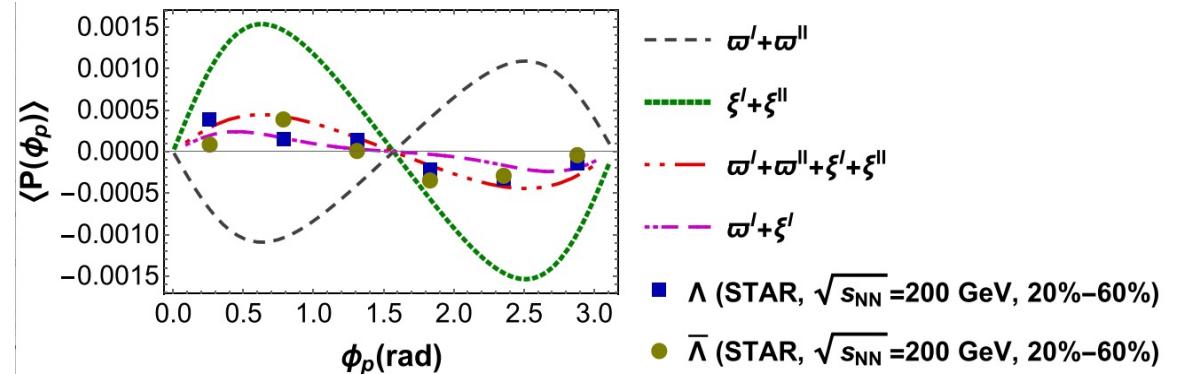
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 Y.F. Liu, Y. Sun and C.M. Ko, PRL 125 062301 (2020)
 H.Z. Wu, L.G. Pang, X.G. Huang and Q. Wang, NPA 1005 121831 (2021)

Thermal shear vorticity can give right signs. **Is that all ?**

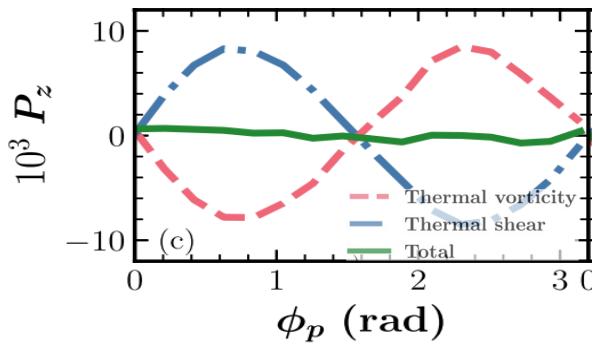
Is the Puzzle Solved ?



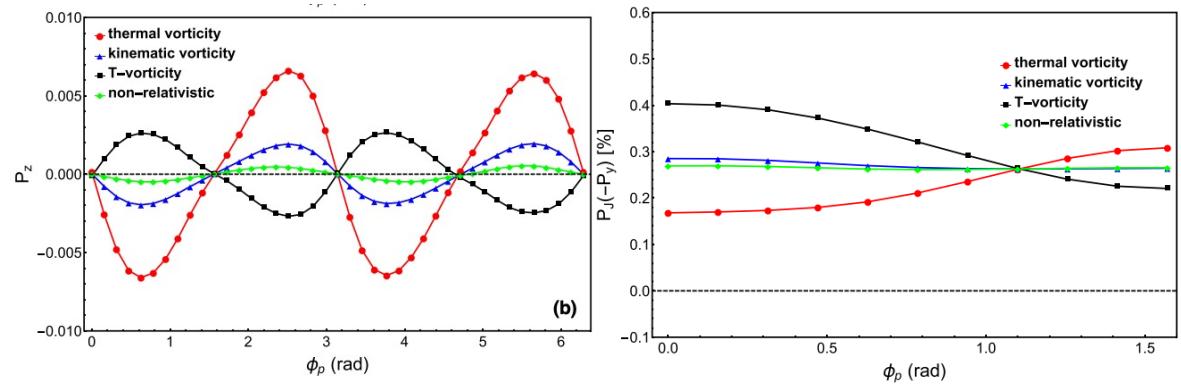
C. Yi, S. Pu and D-L Yang, PRC
104 064901 (2021)



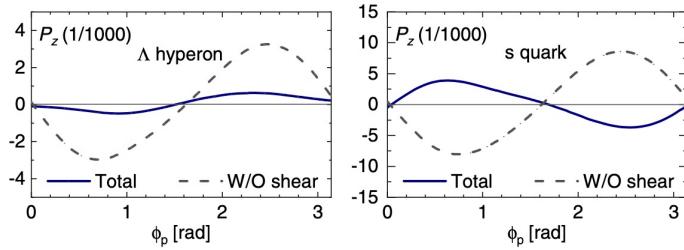
W. Florkowski, A. Kumar,,A.Mazeliauskas and R. Ryblewski PRC 105
064901 (2022)



Y.Sun, Z.Zhang, C-M Ko and W Zhao PRC 105 034911 (2022)



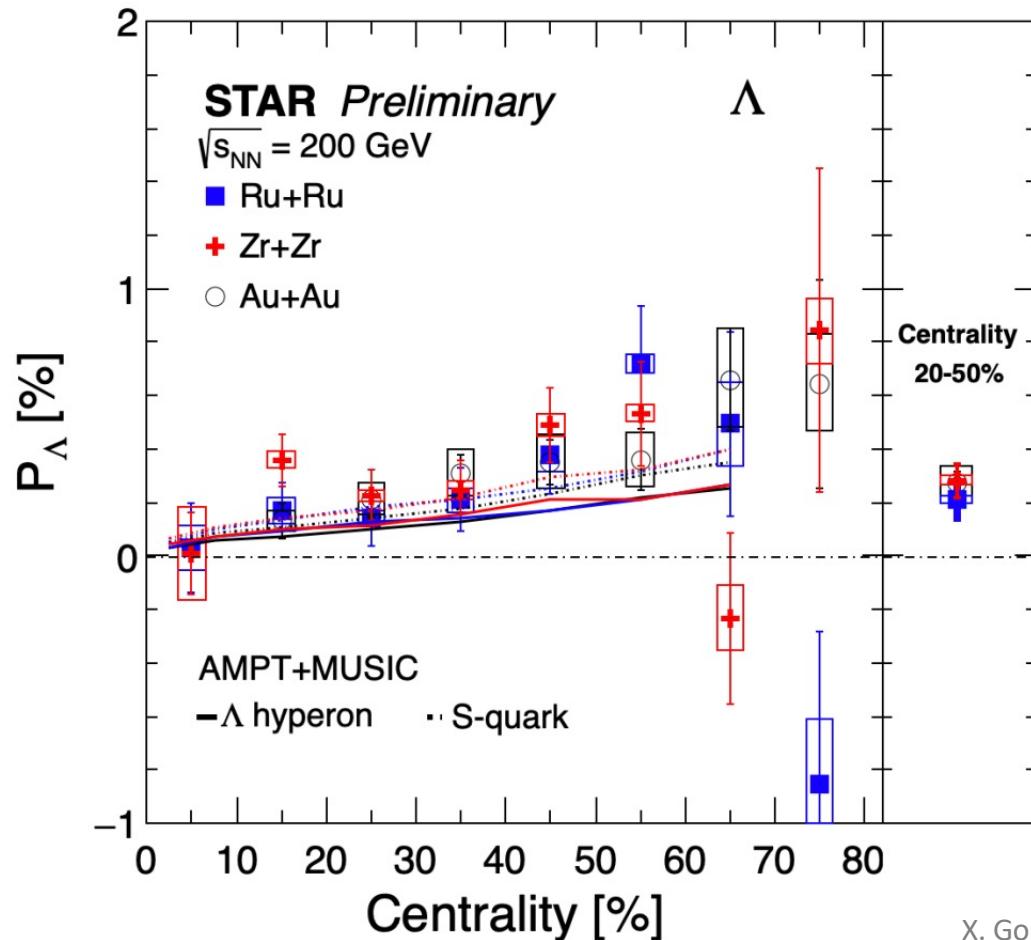
H-Z Wu, L-G Pang, X-G Huang and Q.Wang PRR 033058 (2019)



B. Fu et al, PRL 127 142301 (2021)

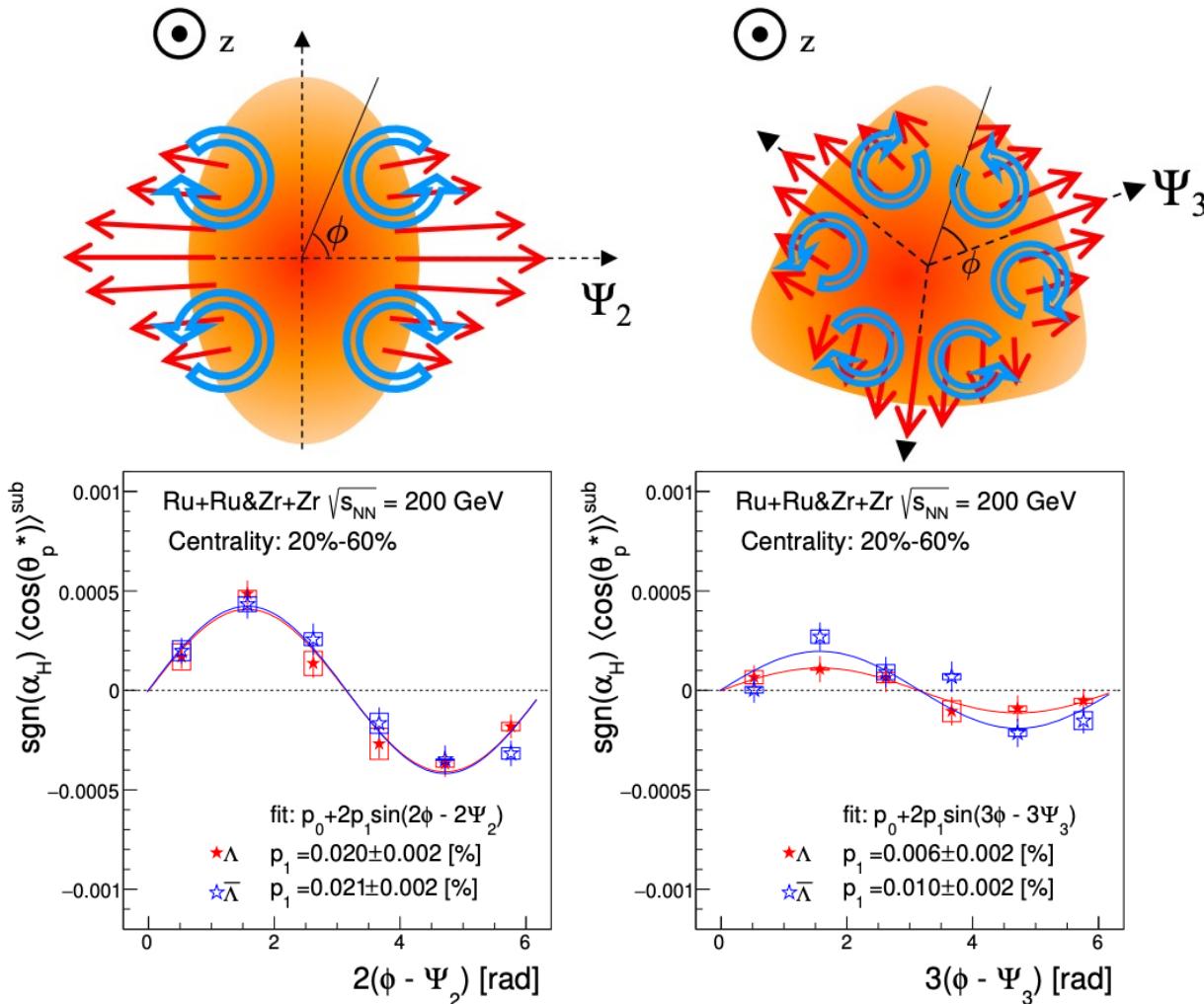
How to control large cancellations ?
How to control sensitive components ?
Why T-vorticity gives right sign ?
S-quark memory ?
....

Is the Puzzle Solved ?



System size does not matter much ?
More and refined measurements are needed.

Probing the QGP by Spin Polarization



STAR, arXiv:2303.09074 (2023)

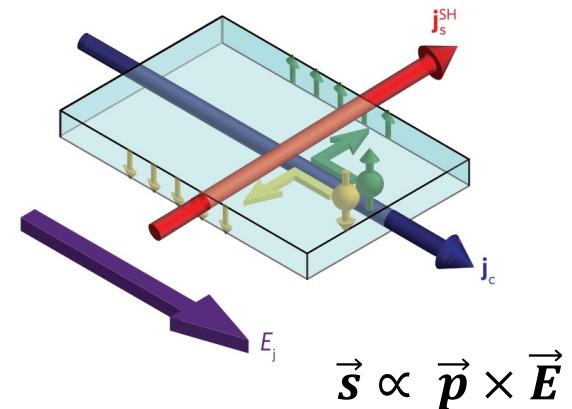
X. Gou for STAR, QM 2023 #864, Tues 8:30

Complex vortical structure → Initial density fluctuations.

Probing the QGP by Spin Polarization

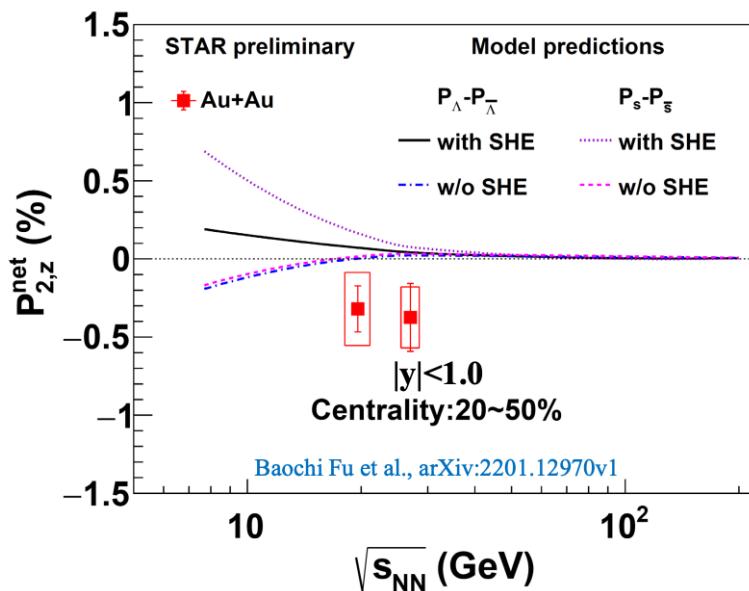
Spin Hall Effect (in condensed-matter)

Transverse spin-current induced by spin-orbital coupling under external electric field.



Baryonic Spin Hall Effect (in hot QCD matter)

Replacing the electric field \vec{E} with the gradient of baryon chemical potential $\vec{\nabla}\mu_B$ → Polarization separation between Λ and $\bar{\Lambda}$

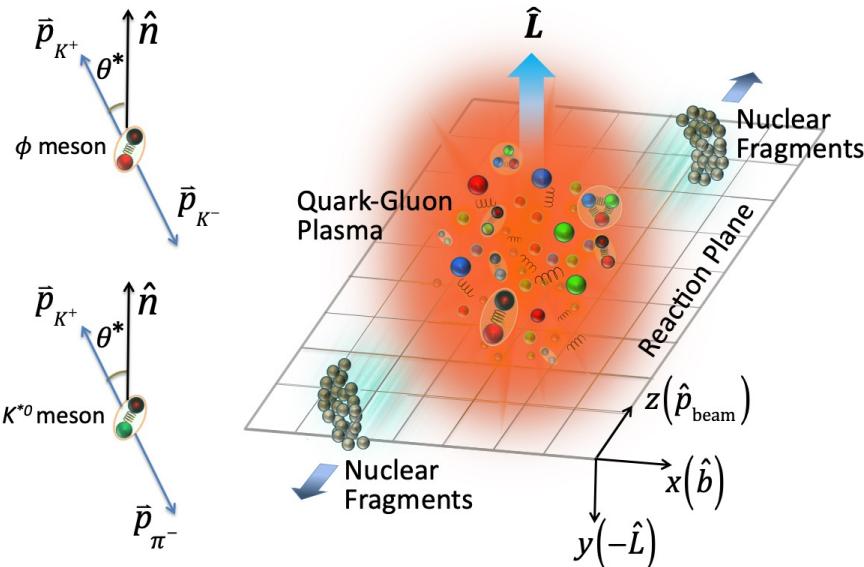


$$\vec{P}_{\pm} \propto \pm \vec{p} \times \vec{\nabla}\mu_B$$

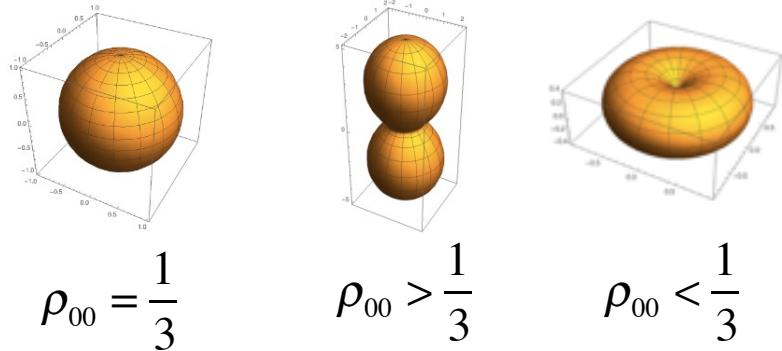
S. Y.F. Liu and Y. Yin PRD 104 054043 (2021)
S. Ryu, V. Jupic and C.Shen PRC 104 054908 (2021)
X-Y Wu, C. Yi, G-Y Qin and S. Pu PRC 105 064909 (2022)
B.Fu, L-G Pang, H. Song and Y. Yin arXiv 2201.12970 (2022)
Q. Hu for STAR, Chirality 2023, Beijing.

Possible detection at BES energies

Global Spin Alignment



$$\frac{dN}{d(\cos \theta^*)} = N_0 \times [(1 - \rho_{00}) + (3\rho_{00} - 1)\cos^2 \theta^*]$$



The spin state of a vector meson can be described by a 3x3 spin density matrix.

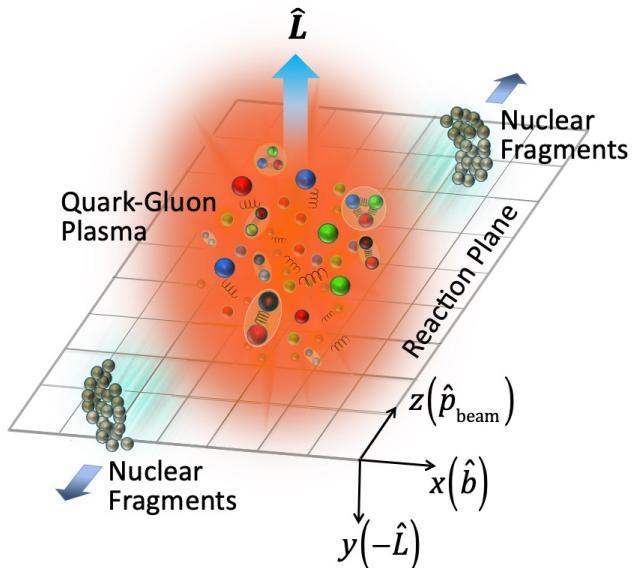
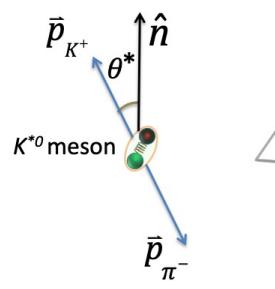
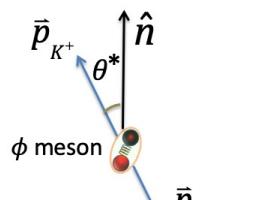
The diagonal element ρ_{00} corresponds to the probability of finding a vector meson in spin state 0 out of 3 possible spin states of -1, 0 and 1.

A deviation of ρ_{00} from 1/3 would indicate a non-zero spin alignment.

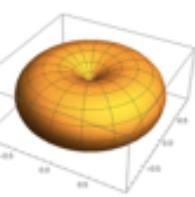
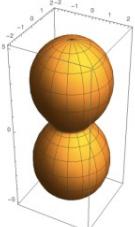
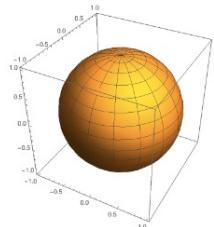
From quark combination :

$$\rho_{00}^V = \frac{1 - \langle P_q P_{\bar{q}} \rangle}{3 + \langle P_q P_{\bar{q}} \rangle} \approx \frac{1}{3} - \frac{4}{9} \langle P_q P_{\bar{q}} \rangle$$

Global Spin Alignment : STAR Results



$$\frac{dN}{d(\cos \theta^*)} = N_0 \times [(1 - \rho_{00}) + (3\rho_{00} - 1)\cos^2 \theta^*]$$

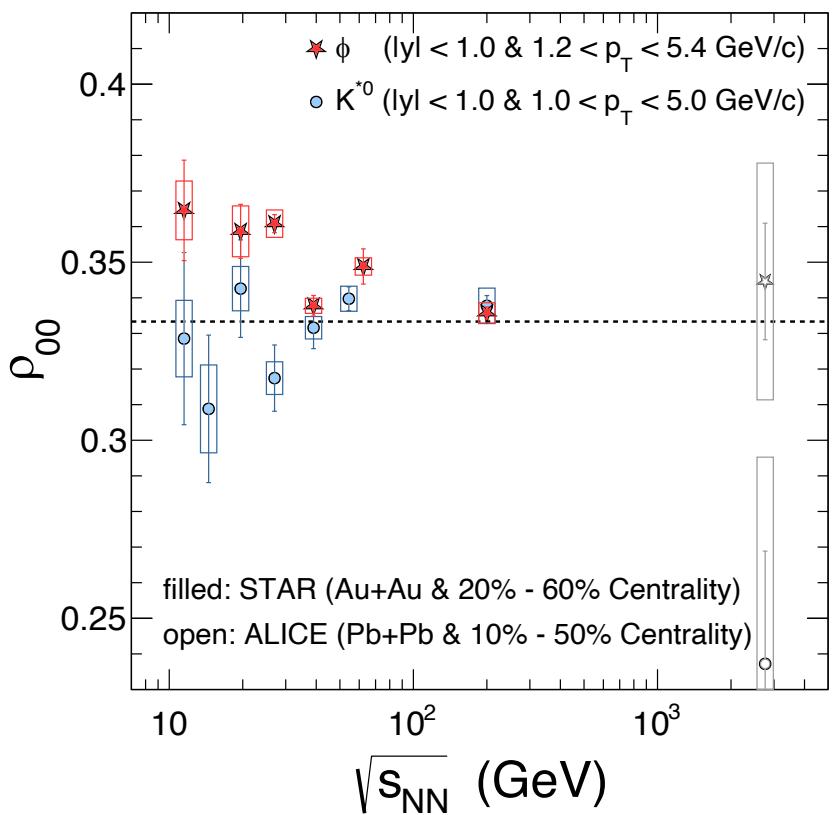


$$\rho_{00} = \frac{1}{3}$$

$$\rho_{00} > \frac{1}{3}$$

$$\rho_{00} < \frac{1}{3}$$

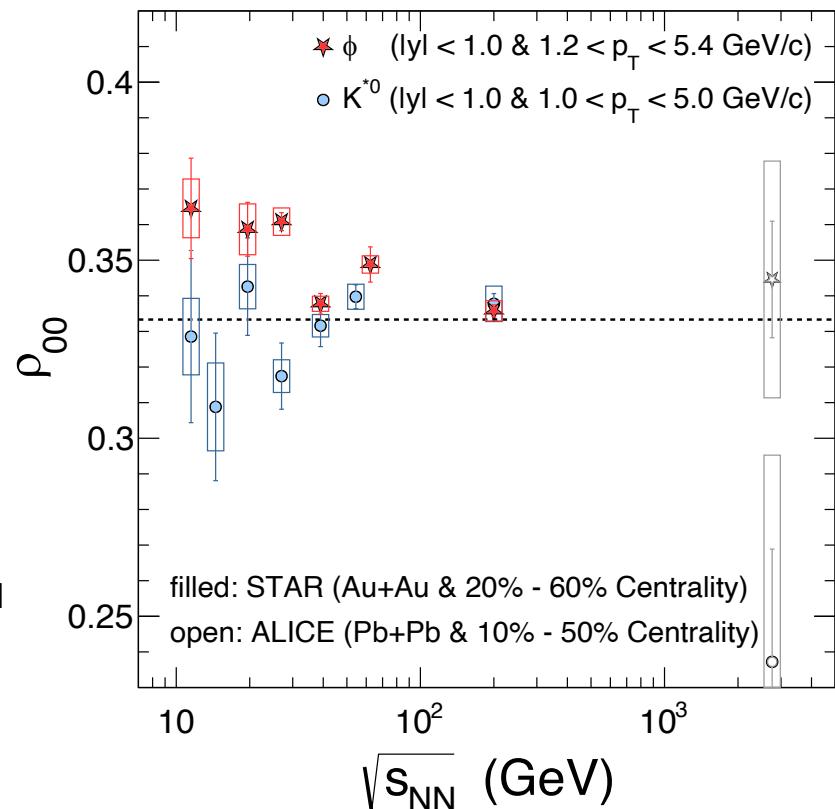
ϕ exhibits surprisingly large global spin alignment while K^* displays little.



STAR, Nature 614 244 (2023)

Global Spin Alignment : STAR Results

- [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)



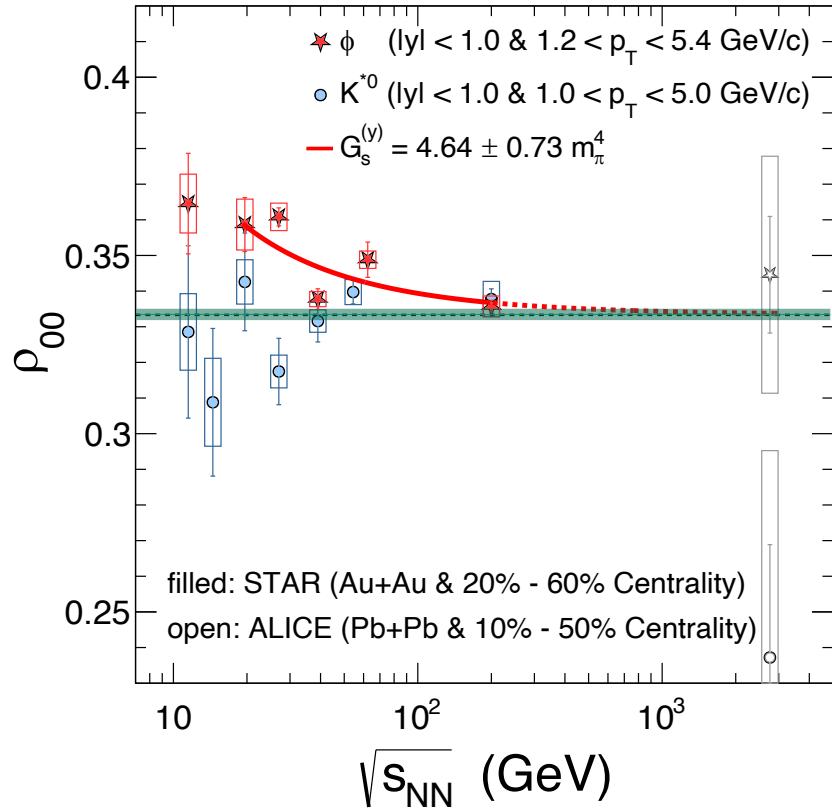
STAR, Nature 614 244 (2023)

ϕ exhibits surprisingly large global spin alignment while K* displays little.

The large ρ_{00} puzzle

$$\rho_{00} \approx \frac{1}{3} + C_\Lambda + C_\varepsilon + C_E + C_F + C_L + C_A + C_\varphi + C_g$$

Physics Mechanisms	(ρ_{00})
c_Λ : Quark coalescence vorticity & magnetic field ^[1]	< 1/3 (Negative $\sim 10^{-5}$)
c_ε : E-comp. of Vorticity tensor ^[1]	< 1/3 (Negative $\sim 10^{-4}$)
c_E : Electric field ^[2]	> 1/3 (Positive $\sim 10^{-5}$)
c_F : Fragmentation ^[3]	> or, < 1/3 ($\sim 10^{-5}$)
c_L : Local spin alignments ^[4]	< 1/3
c_A : Turbulent color field ^[5]	< 1/3
c_φ : Vector meson strong force field ^[6]	> 1/3 (Can accommodate large positive signal)
c_g : Glasma fields + effective potential	could be significant



STAR, Nature 614 244 (2023)

strong force

ϕ exhibits surprisingly large global spin alignment while K^* displays little.

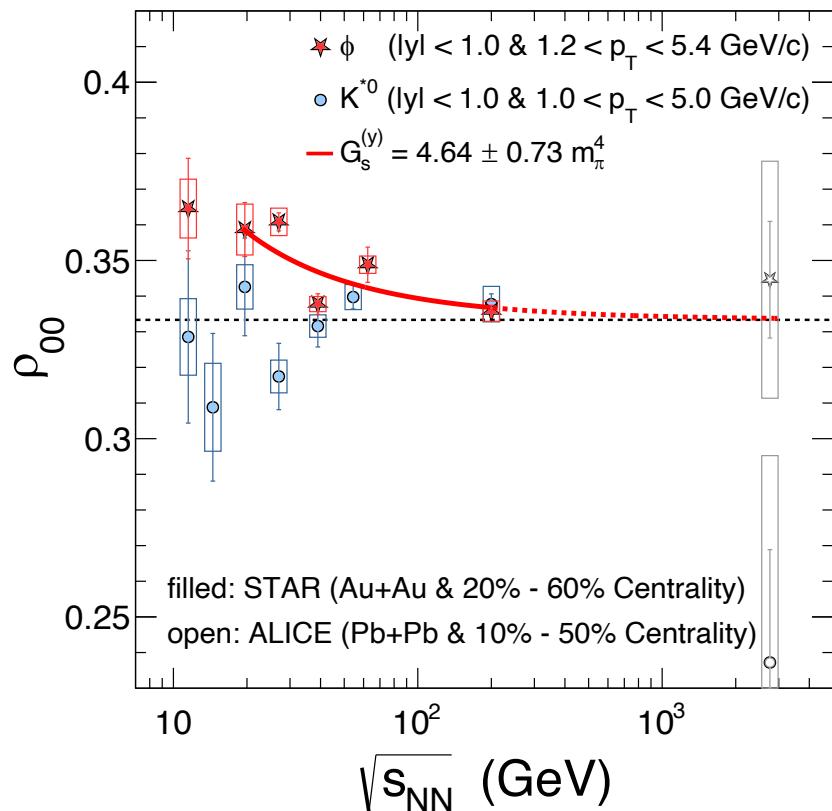
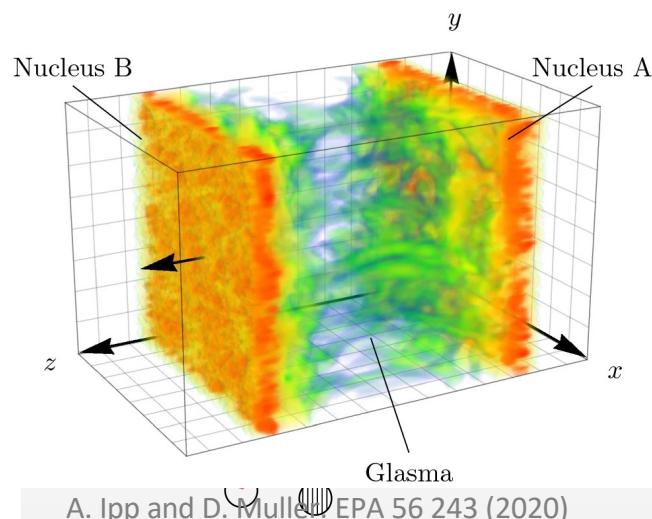
The large ρ_{00} puzzle

What do we learn ?

$$\rho_{00}^V - \frac{1}{3} \gg P_\Lambda^2 \approx P_q^2$$

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

$$\langle P_q P_{\bar{q}} \rangle \neq \langle P_q \rangle \langle P_{\bar{q}} \rangle$$



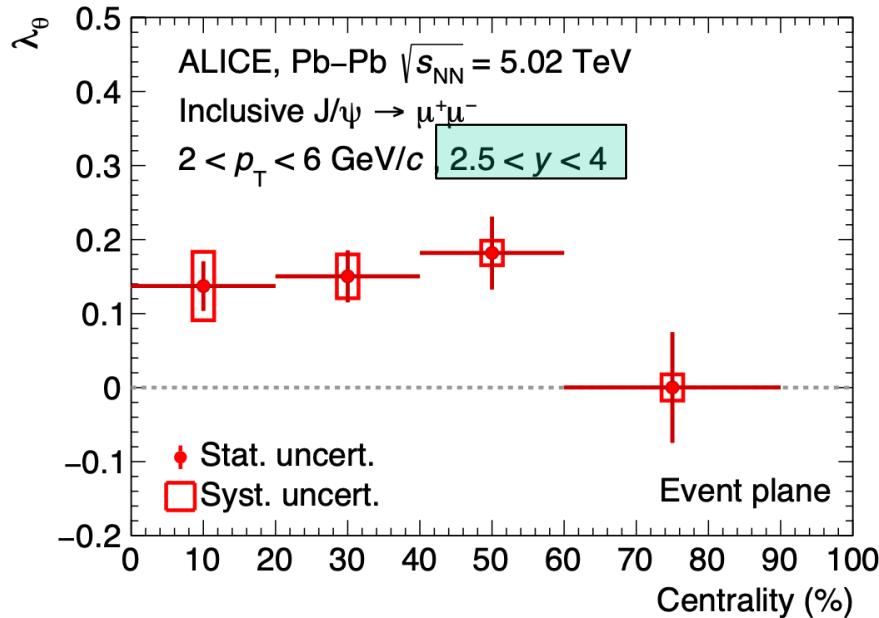
STAR, Nature 614 244 (2023)

Global spin alignment measures local field fluctuations, while hyperon polarization measures the mean.

What about J/ ψ ?

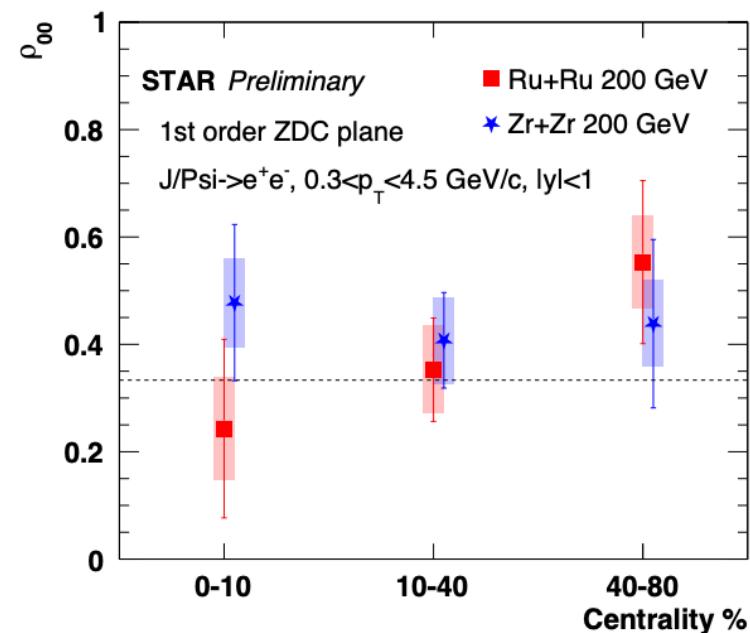
Naïve expectation from fluctuating strong force field : $\rho_{00} > 1/3$ at midrapidity

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



ALICE, PRL 131 042303 (2023)

Forward J/ψ $\rho_{00} < 1/3$ at LHC

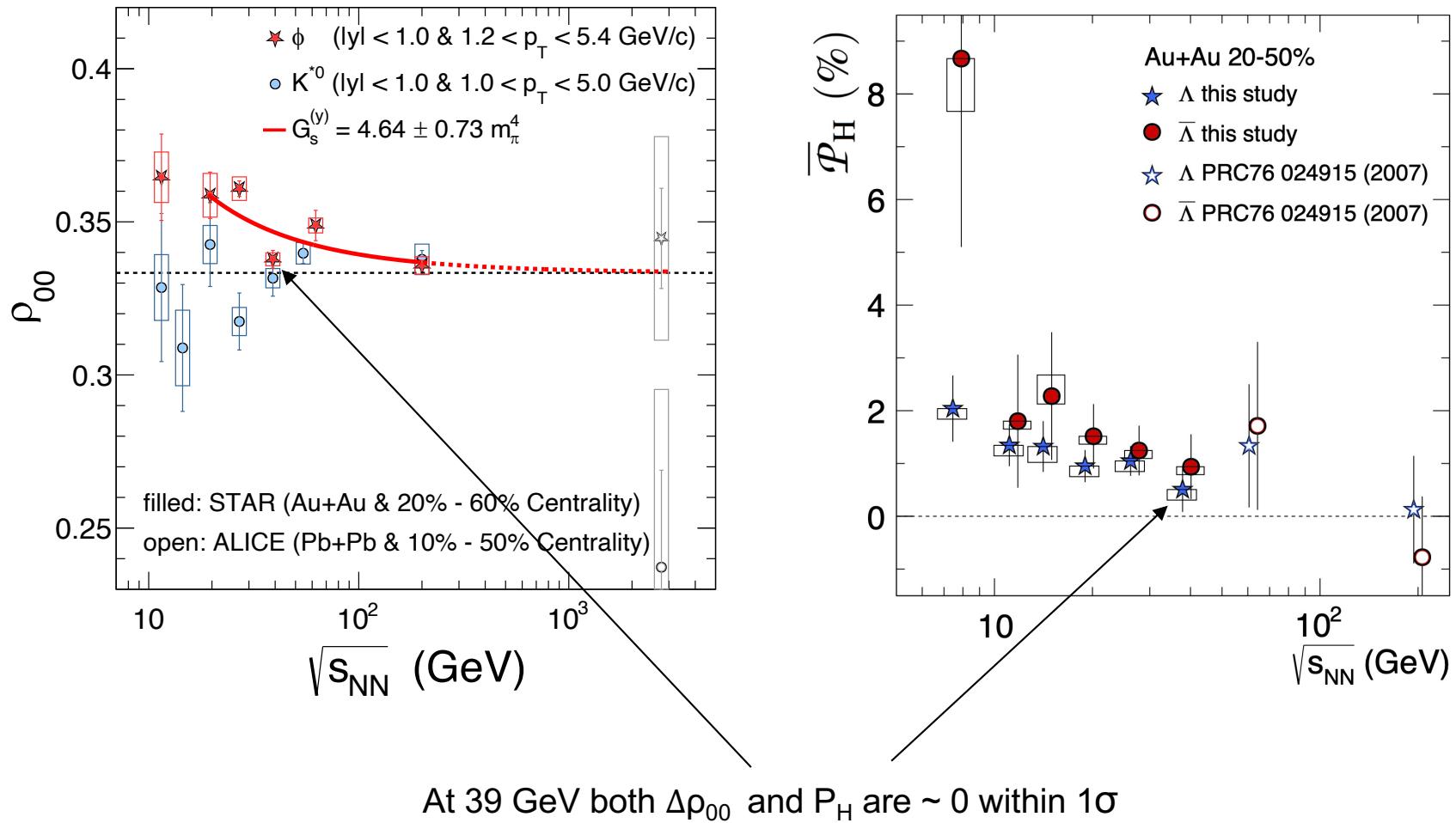


B. Xi for STAR, QM 2023
#353 TUES 9:30

Midrapidity J/ψ $\rho_{00} \sim 1/3$ at RHIC

How do we understand $J/\psi \rho_{00}$?

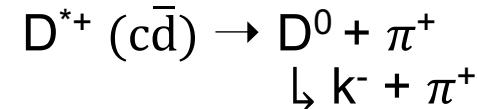
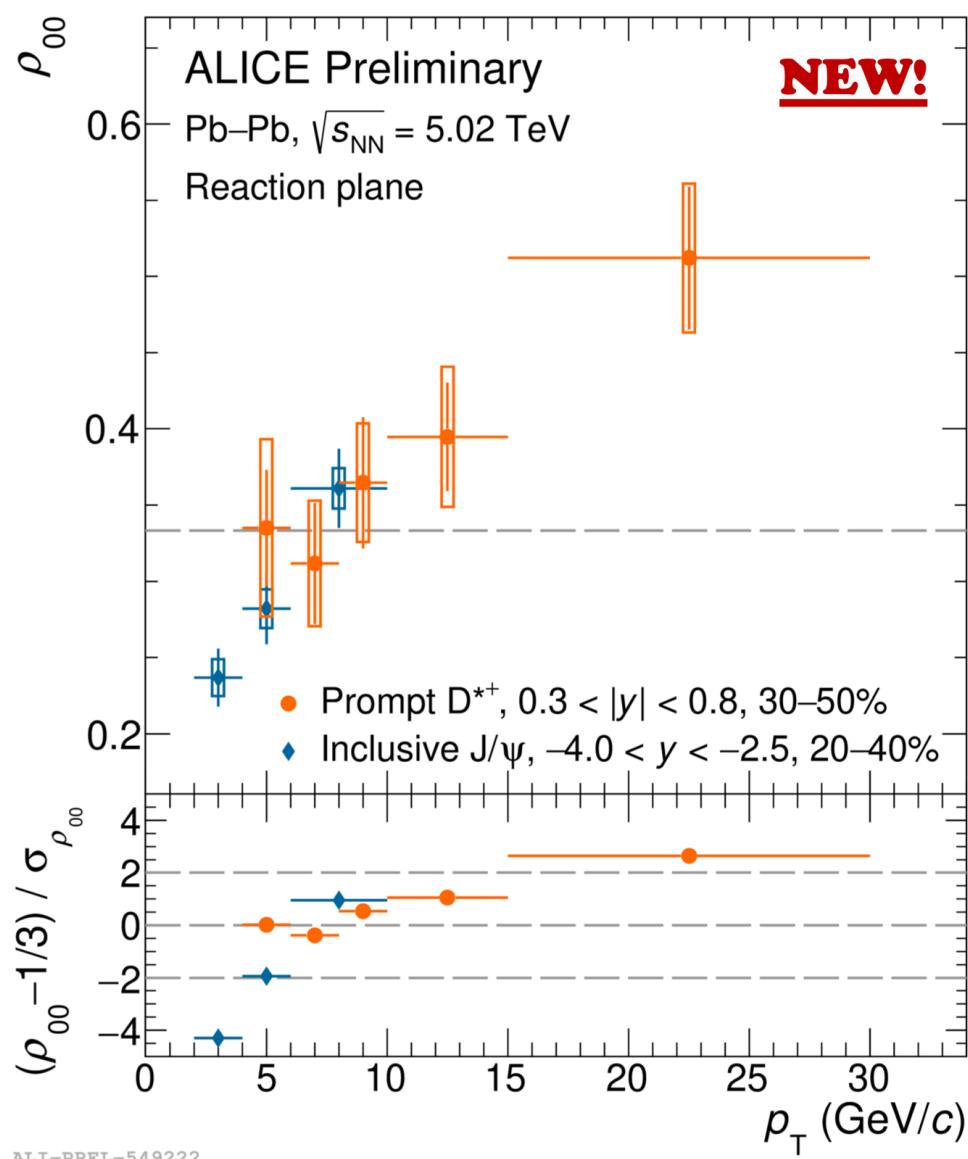
Is the Puzzle Solved ?



Hint of spin related phase transition ?

Xin-Li Sheng, Qingdao QCD meeting 2023.

D^{*+} ρ₀₀



Expectation :

from Recombination : $< 1/3$
from Fragmentation : $> 1/3$

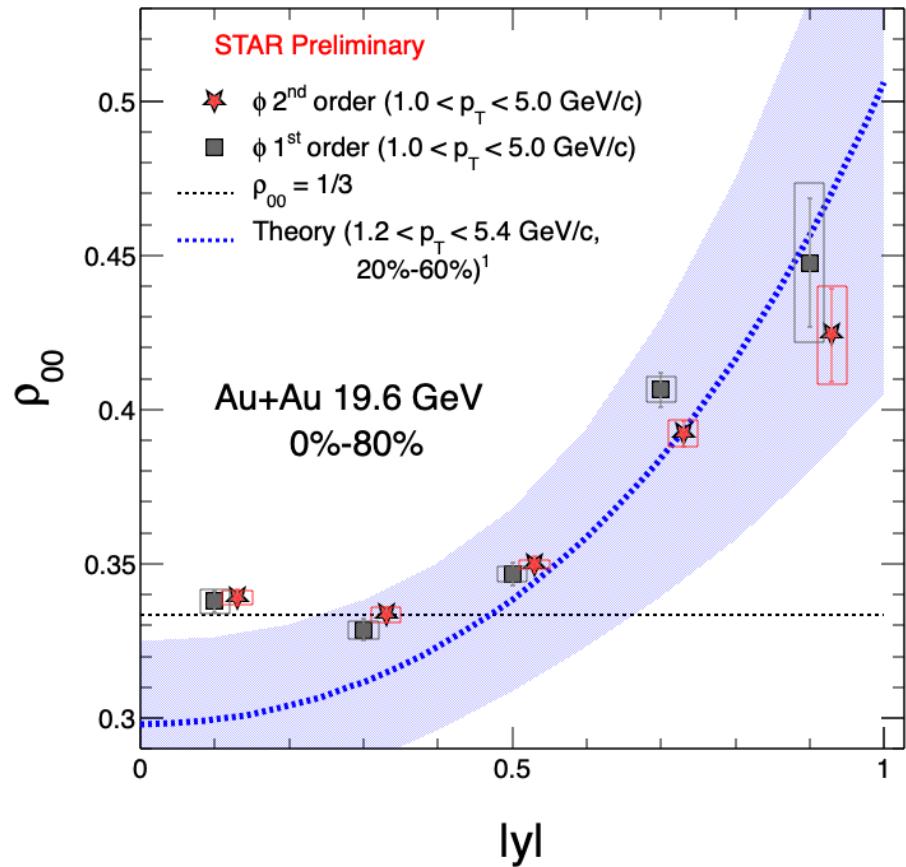
Observation :

Low $p_t < 1/3$
High $p_t > 1/3$

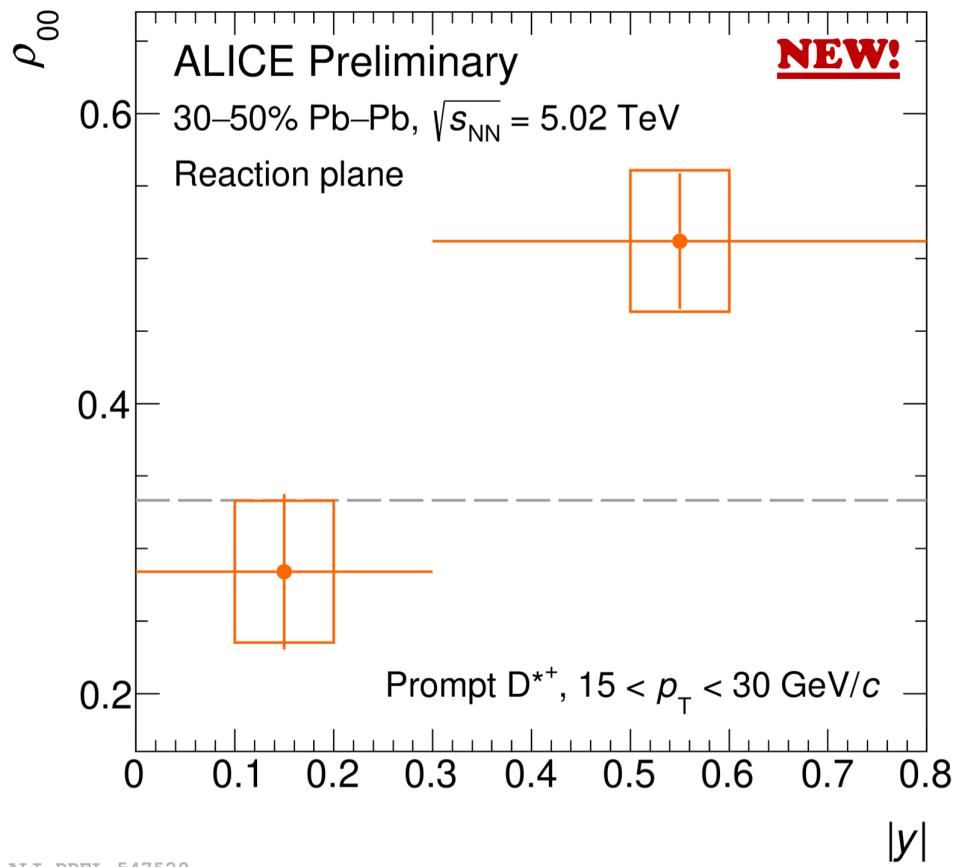
--- Qualitatively agree with expectation that recombination is relevant at low while fragmentation is relevant at high p_t .

However, quantitative agreement could be very challenging.

Is the Puzzle Solved ?



B. Xi for STAR, QM 2023 #353 Tues 9:30
Theory curve : X.L. Sheng, et al., arXiv:2308.14038



L. Micheletti for ALICE, QM2023
#479 TUES 14:50

Strong rapidity dependence at both RHIC and LHC.

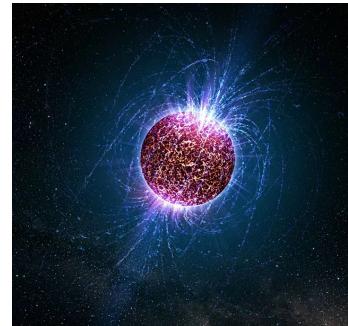
The Strongest EM Field, But Do We “See” It ?



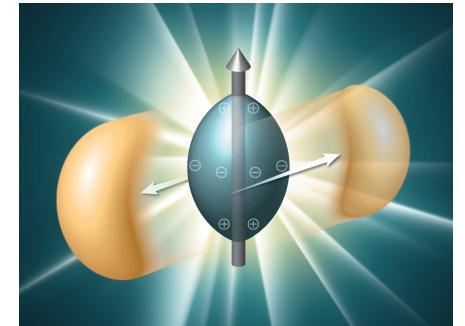
Earth
~ 0.5 Gauss



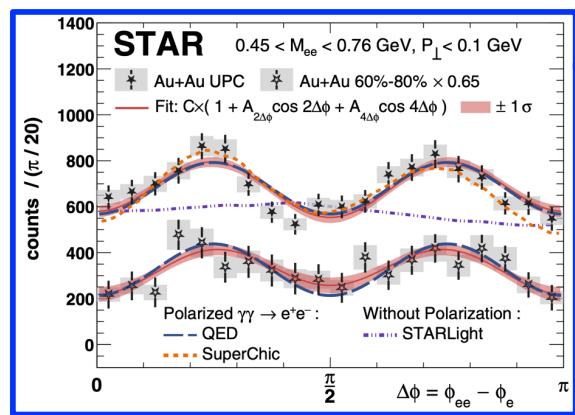
Lightning
~ 10^3 - 10^4 Gauss



Neutron Star (Magnetar)
~ 10^{14} Gauss

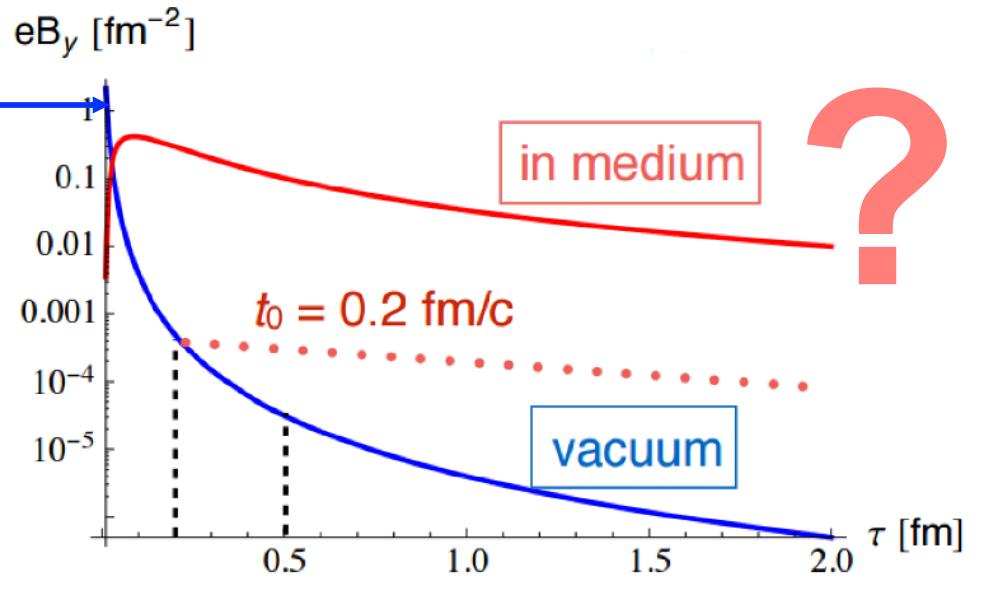


Heavy ion collisions
~ 10^{18} Gauss



STAR, PRL 127, 052302 (2021)

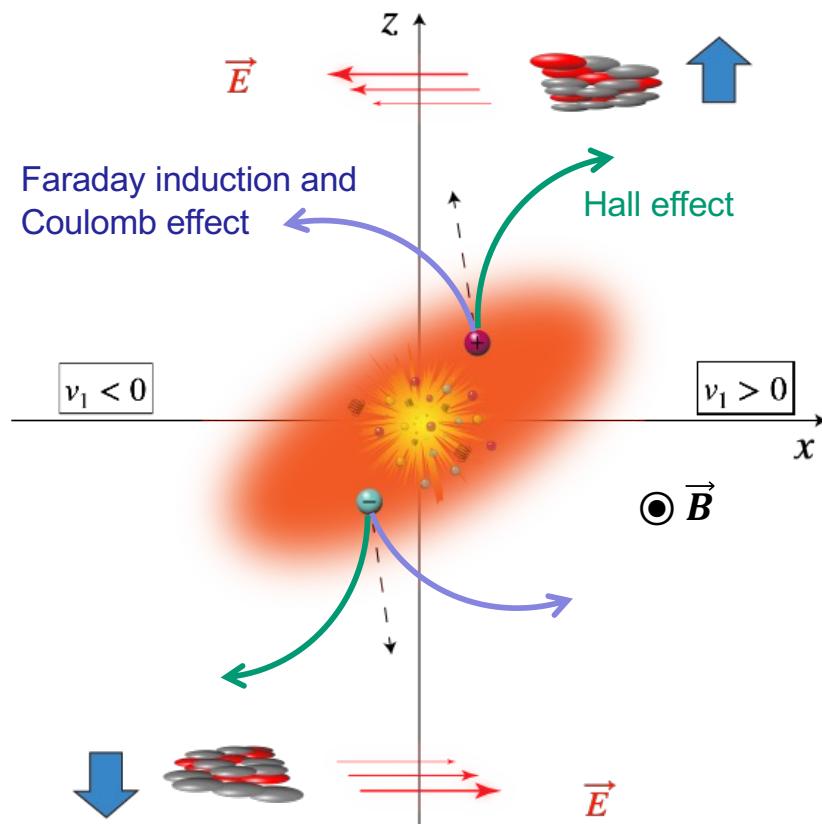
Vacuum birefringence
vacuum + strong B



Gürsoy, Kharzeev & Rajagopal, Phys. Rev. C 89, 054905 (2014) ...

Despite wide expectation of its existence, its imprint in QGP has been elusive.

EM field : Hall, Faraday and Coulomb Effect



Hall effect (Lorentz force) and Faraday + Coulomb effect compete each other.

Hall effect is more relevant for heavy quarks at early stage.

Calculations indicate Faraday + Coulomb effect dominate over Hall effect for light hadrons.

Gursoy, Kharzeev and Rajagopal, PRC 89 054905 (2014)
S.K. Das et al., PLB 768 260 (2017)

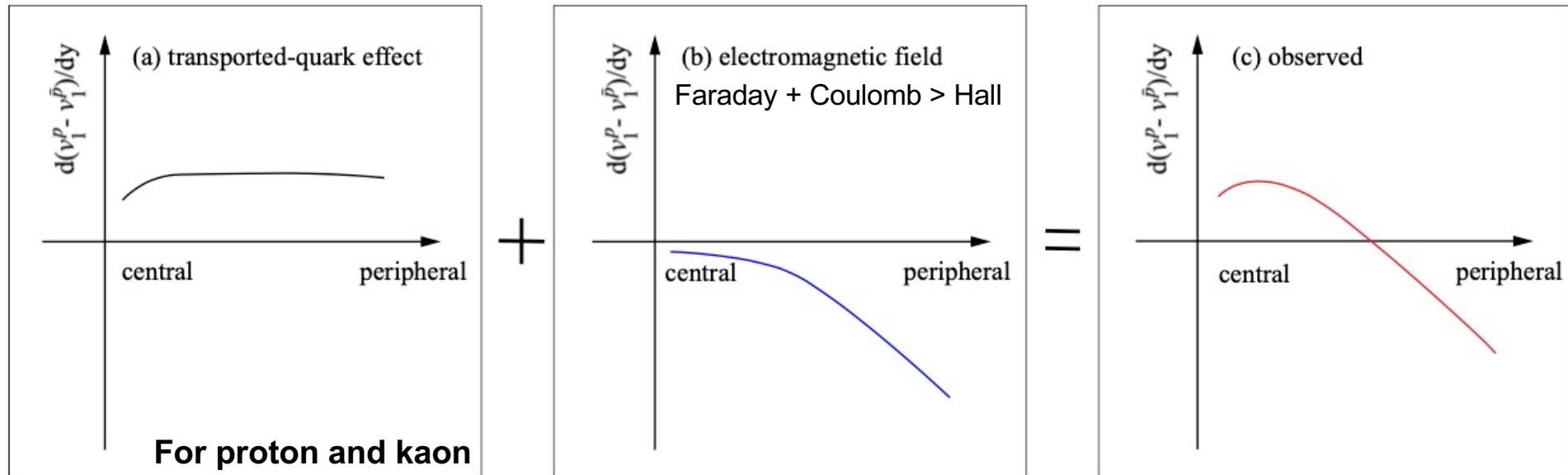
Umut Gursoy, et al., PRC 98 055201 (2018)
K. Nakamura et. al., PRC 107 034912 (2023)

K. Nakamura et. Al., PRC 107 014901 (2023)

Interplay between Effects

$d(v_1^+ - v_1^-)/dy$: Hall \uparrow transported quark \uparrow Faraday \downarrow Coulomb \downarrow

(Heavy quarks) (Light quarks)



Transported quark effect :

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

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

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

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

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

$$\pi^- : \bar{u}d$$

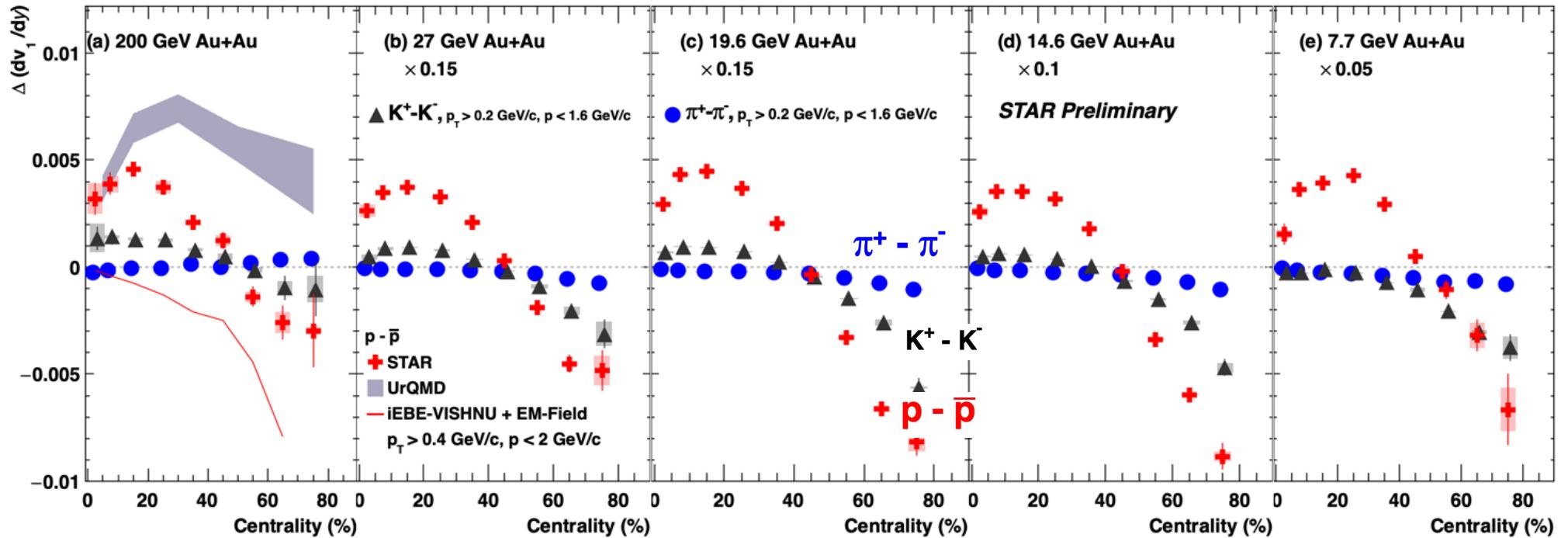
(#d > #u, Au neutron rich)

v_1 slope difference between protons and antiprotons:
sign change as a function of centrality.

Similar pattern expected for kaons.

No sign change expected for pions.

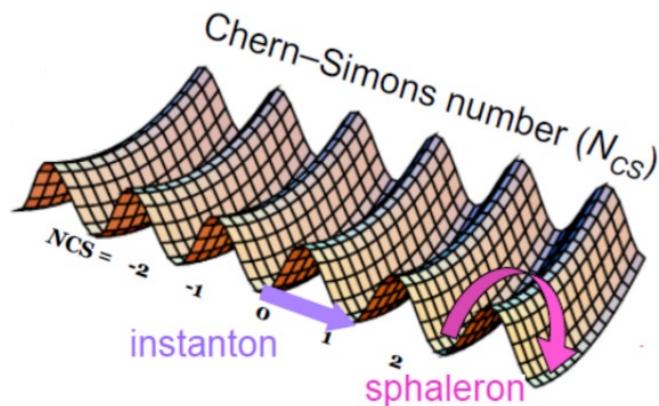
Sign Change in $\Delta(dv_1/dy)$



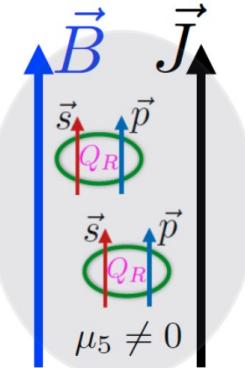
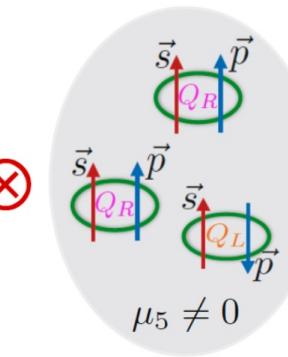
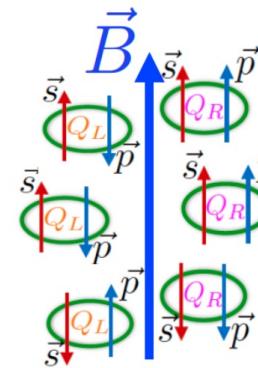
STAR, arXiv:2304.03430 (2023)
 Aditya P. Dash for STAR, QM 2023
 #347 WED 17:10

Feature consistent with EM field effects.
 Can we utilize the information to quantify EM field ?

Chiral Magnetic Effect



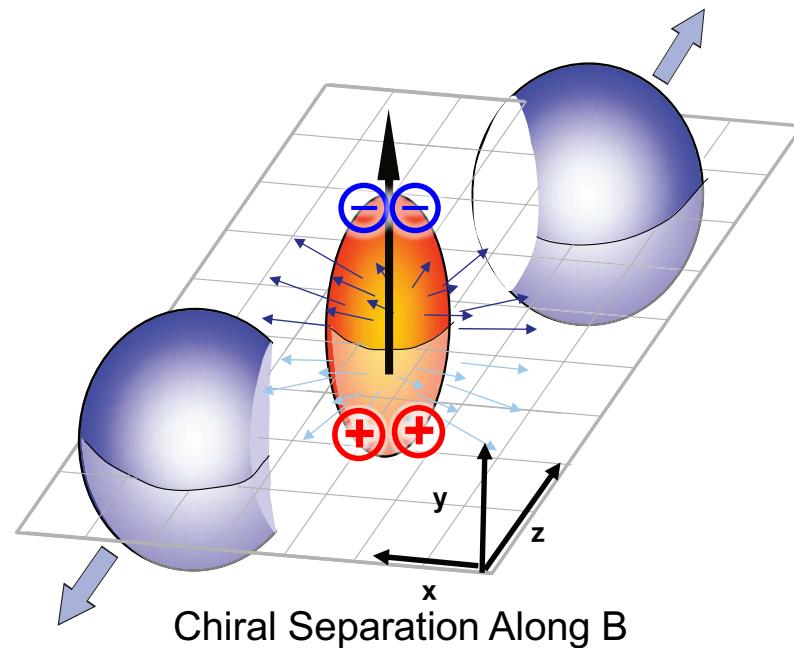
QCD vacuum topology (finite μ_5)



Chiral Magnetic Effect

Charge current

$$j_V = \frac{N_c e}{2\pi^2} \mu_A B$$



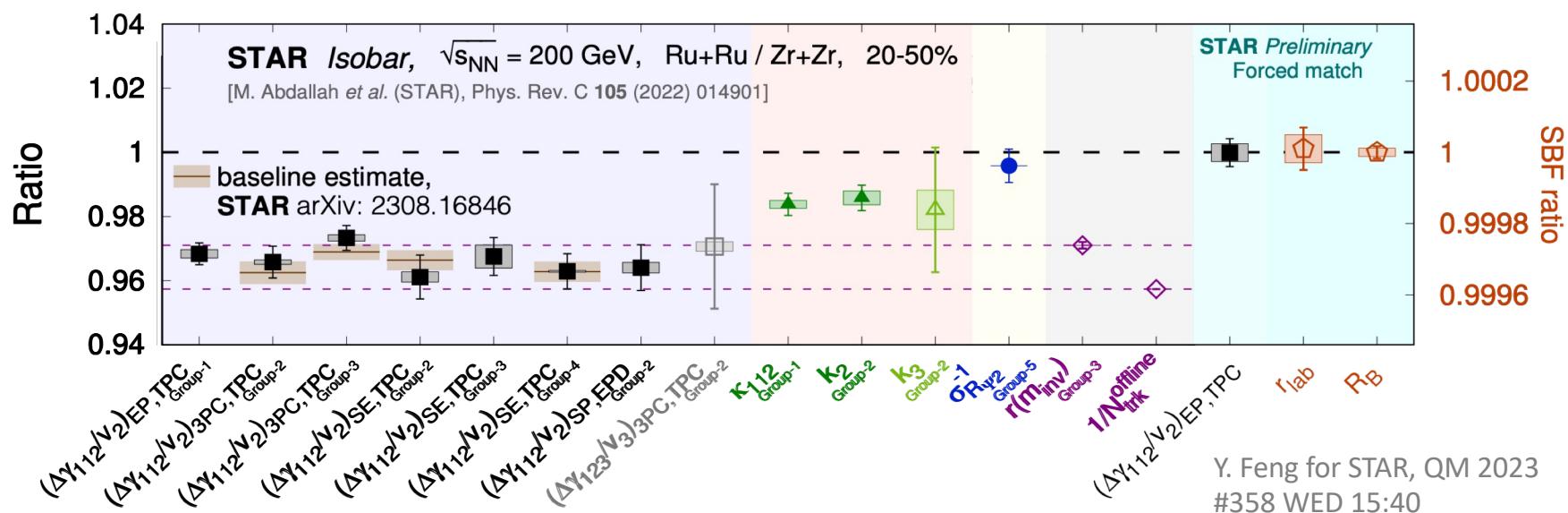
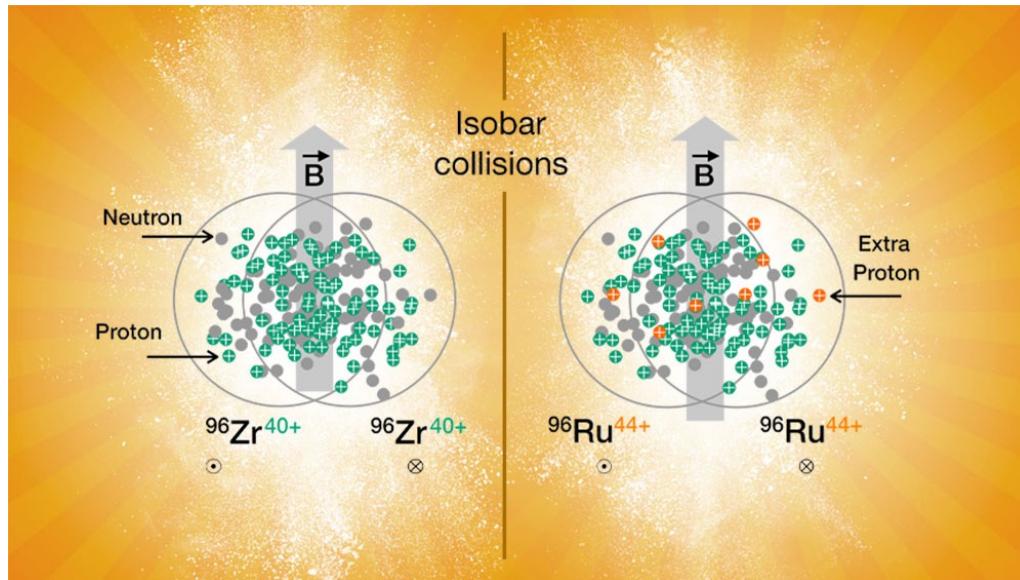
$$\gamma \equiv \langle \cos \phi_\alpha + \phi_\beta - 2\psi_{RP} \rangle$$

$$\gamma_{ss} < \gamma_{os}$$

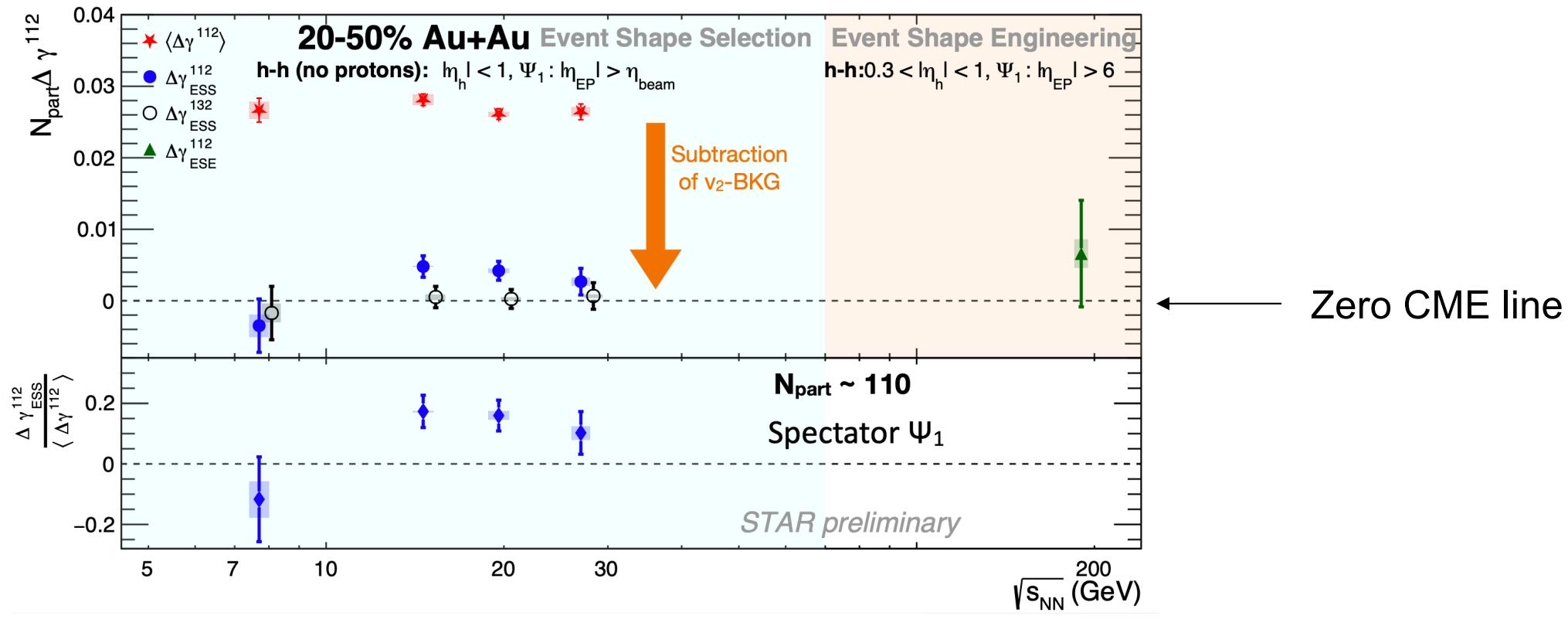
$$\Delta\gamma = \gamma_{os} - \gamma_{ss}$$

ss : α and β have same sign
os : α and β have opposite signs

Chiral Magnetic Effect : Where Are We ?



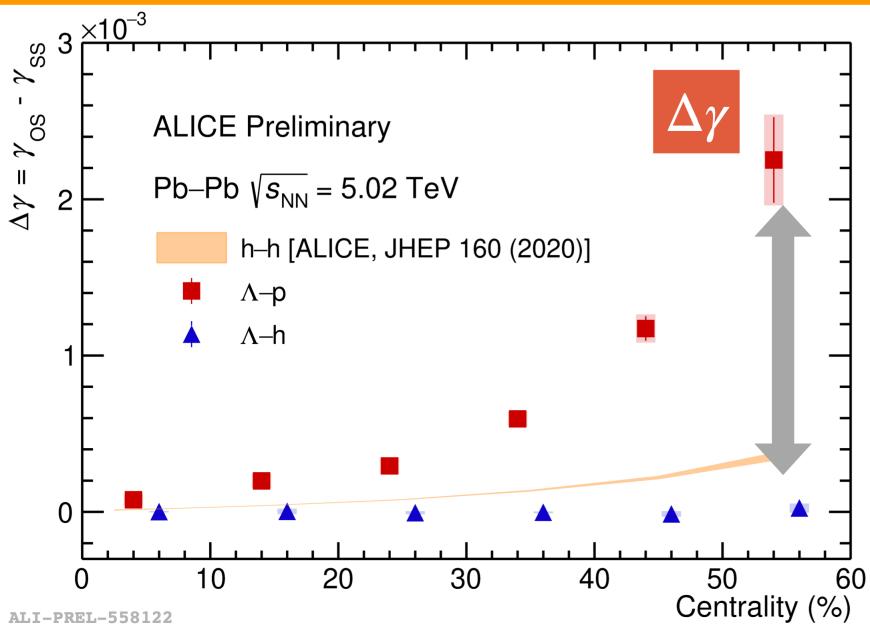
Chiral Magnetic Effect : Where Are We ?



Z. Xu for STAR, QM 2023
#868 TUES 10:10

Hint of excess beyond background.

Chiral Vortical Effect



C. Wang for ALICE, QM 2023
#456 TUES 8:50

B

Chiral Magnetic Effect

Chirality Imbalance (μ_A)

Magnetic Field ($\omega \mu_e$)

Electric Charge (j_e)

Electric Charge Separation

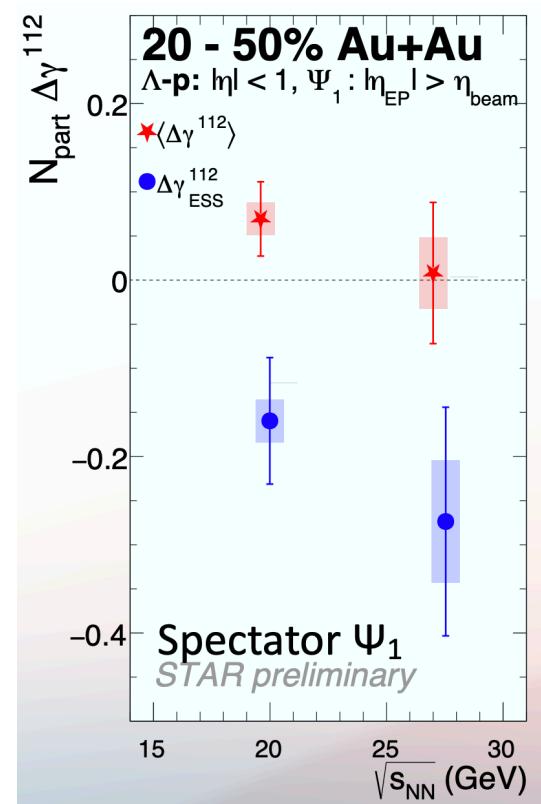
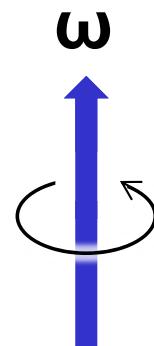
Chiral Vortical Effect

Chirality Imbalance (μ_A)

Fluid Vorticity ($\omega \mu_B$)

Baryon Number (j_B)

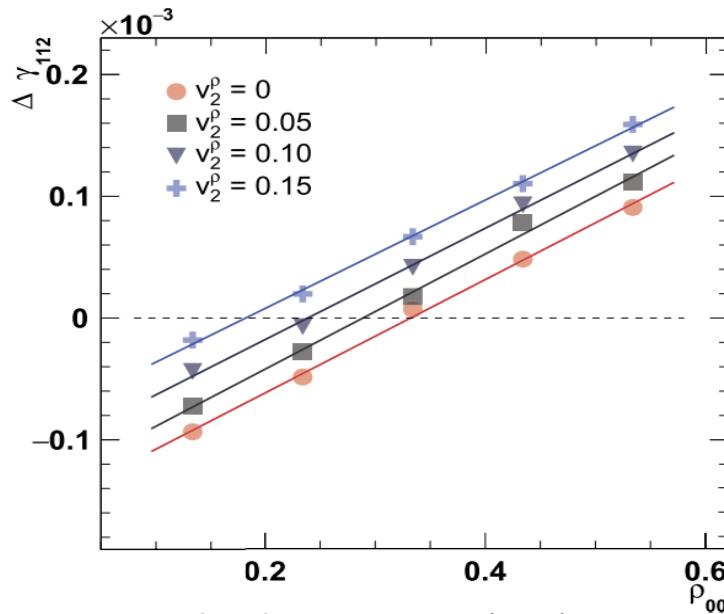
Baryonic Charge Separation



Expectation :
CVE@LHC < CVE@RHIC

Measurement before
background subtraction are
comparable.

CME : We Must Consider Global Spin Alignment



A. Tang, Chin Phys. C 44 054101 (2020)

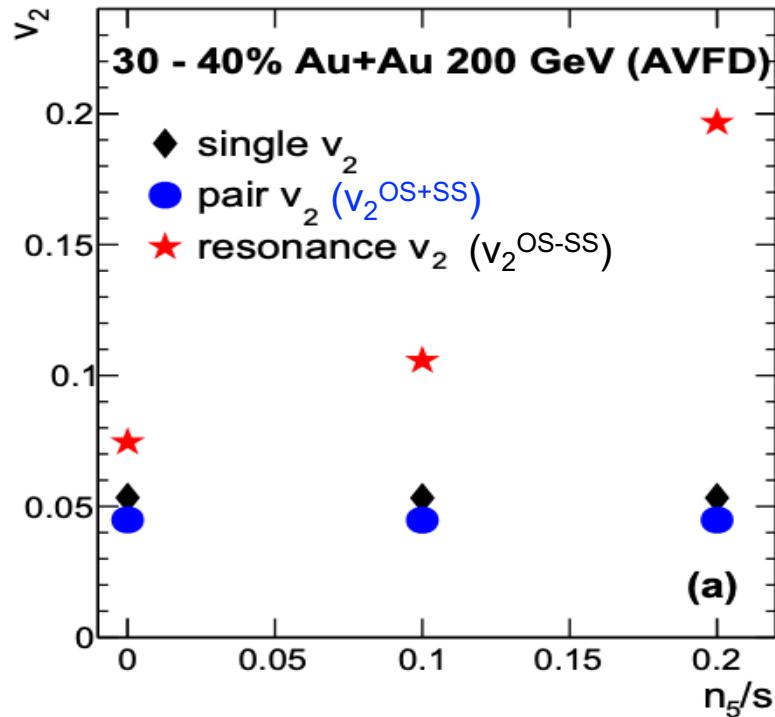
D. Shen et al., PLB 839 137777 (2023)

D. Shen QM2023, #292 WED 15:20

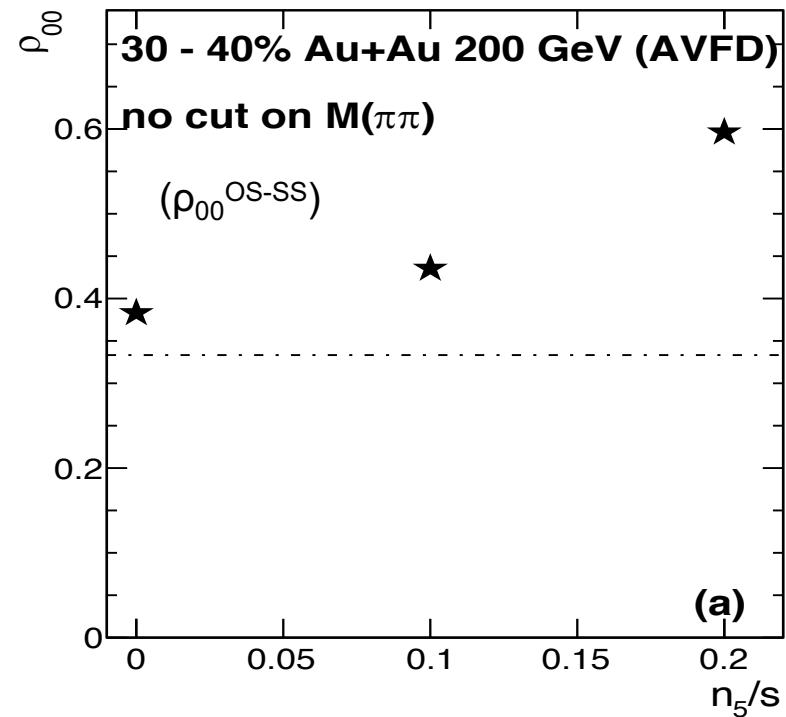
ρ_{00} being larger(smaller) than 1/3 means positive(negative) contribution to CME observables

How to properly account for p-meson ρ_{00} in CME analyses ?

CME backgrounds : Are We Over Subtracting It ?



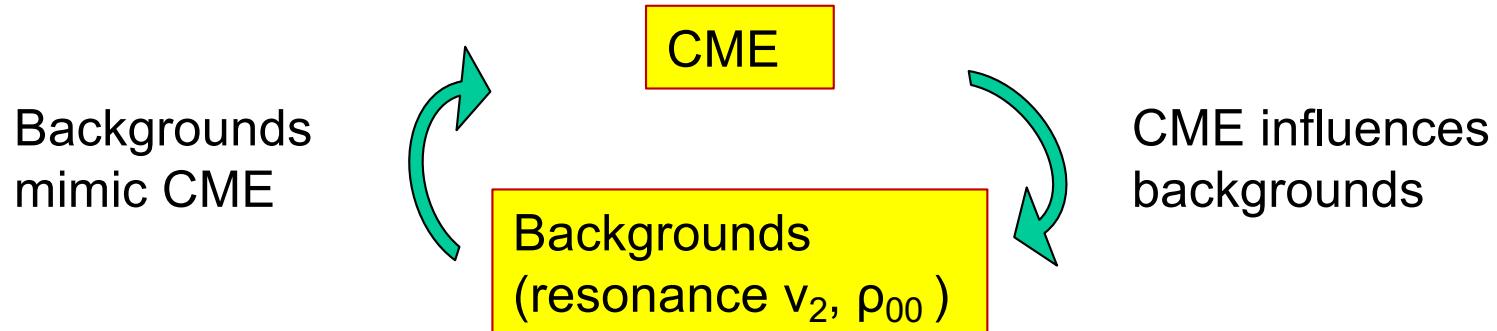
Z.Xu et al., arXiv:2307.14997



D. Shen, talk at this QM
D. Shen QM2023, #292 WED 15:20

Backgrounds are influenced by real CME signal

CME : Taking a Step Back



Signal and noise, which one is cause and which one is consequence ?

So far we regard resonance v_2 and p_{00} as “noise”, but they could be influenced by signal.

Summary



Rotation is a fundamental element of heavy-ion collisions, yet it is still a somewhat elusive phenomenon.

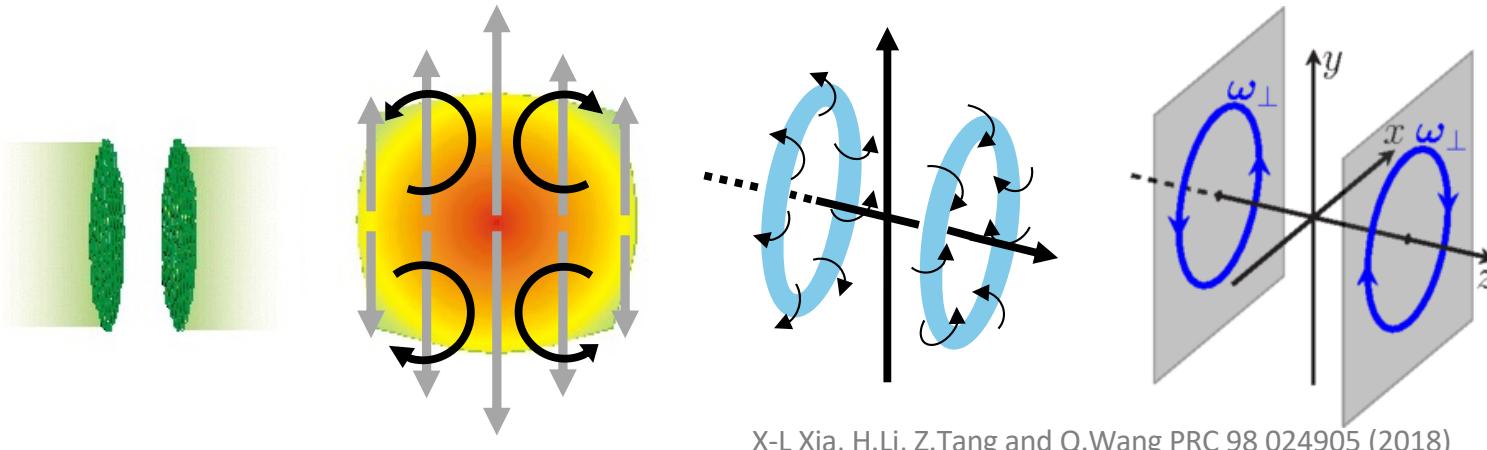
Despite its elegance, our comprehension of rotational dynamics remains limited.

Nevertheless, our exploration of the strongly interacting QGP under rotation and in the presence of a strong magnetic field has unveiled a new and promising realm for research. Its potential is still waiting to be fully explored.

Back Up Slides

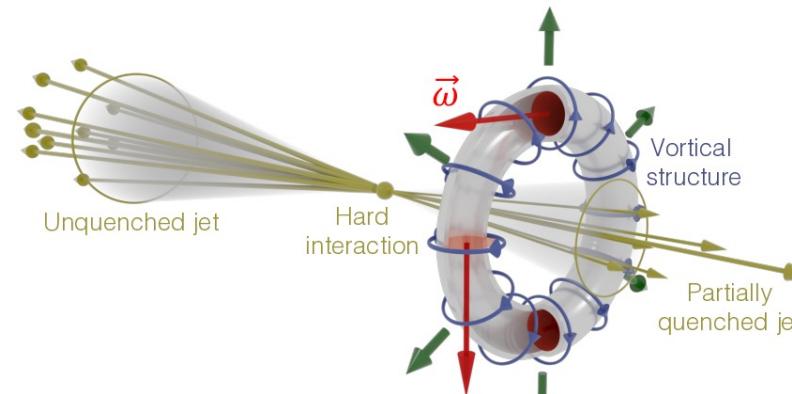
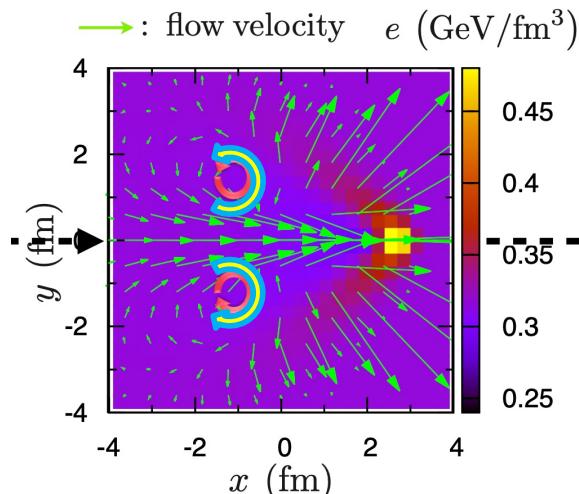
Probing the QGP by Spin Polarization

Ring and Toroidal vorticity : Unique fluid structures



X-L Xia, H.Li, Z.Tang and Q.Wang PRC 98 024905 (2018)

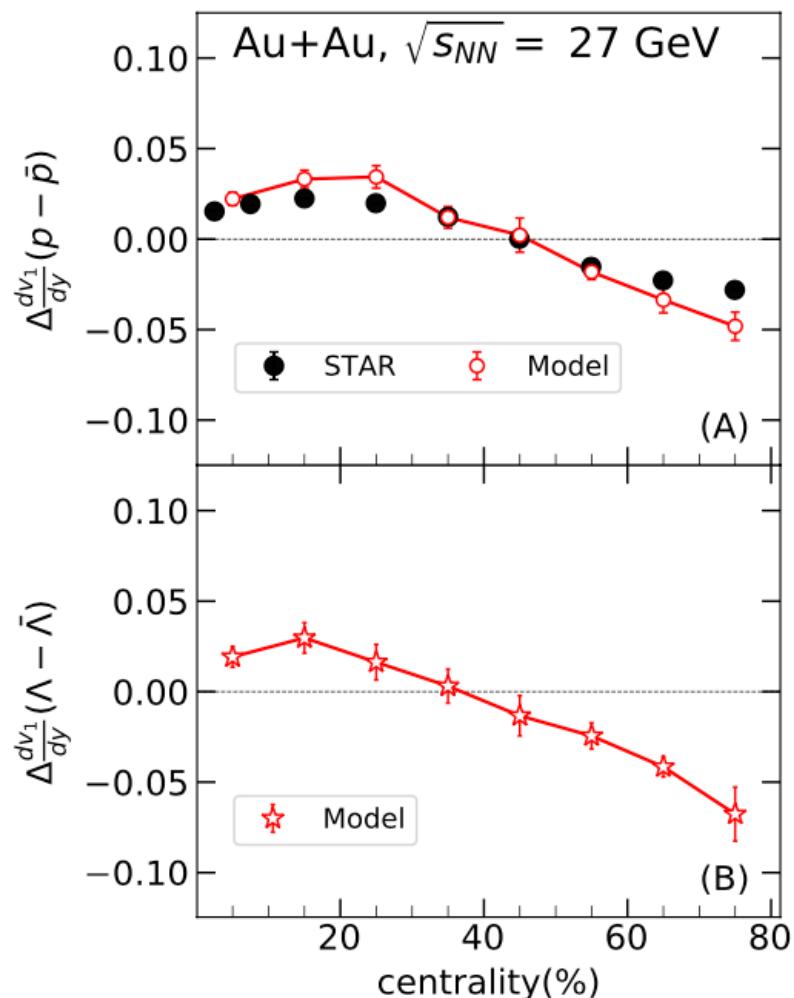
Ring structure → Natural expectation from fluid dynamics



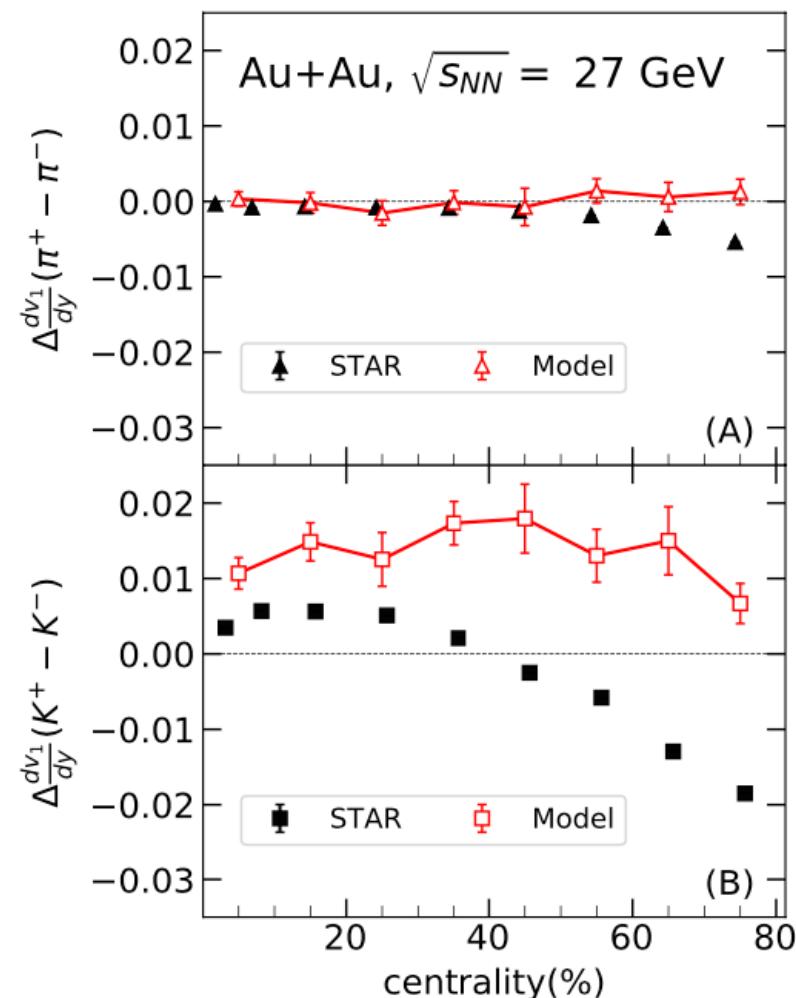
B. Bets, M. Gyulassy and G. Torrieri, PRC 76 044901 (2007)
Y. Tachibana and T. Hirano, NPA 904 1023c (2013)
W.M. Serenone et al, PLB 820 136500 (2021)

Jet-medium interaction → fluid nature in small systems

Sign Change in $\Delta(dv_1/dy)$: Any Alternative Explanation ?



Splitting driven by Baryon inhomogeneities



T. Parida and S. Chatterjee,
arXiv:2305.08806 (2023)

Challenging job to describe all three particle types simultaneously.