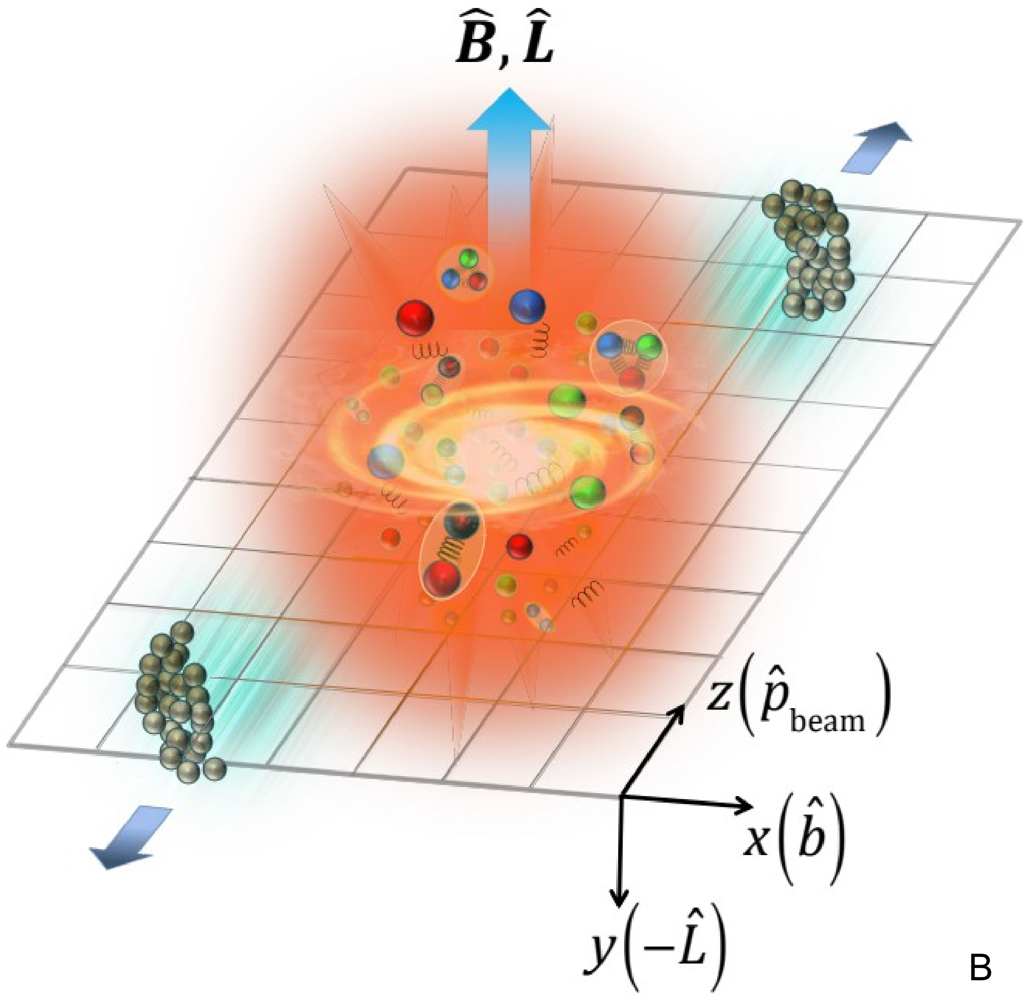
Probing Spin Dynamics and Magnetic Fields in Heavy Ion Collisions

Aihong Tang

9th Conference on Chirality, Vorticity and Magnetic Fields in Quantum Matter, Sao Paulo July 7-11 2025

Strongly Interacting Matter Under Rotation



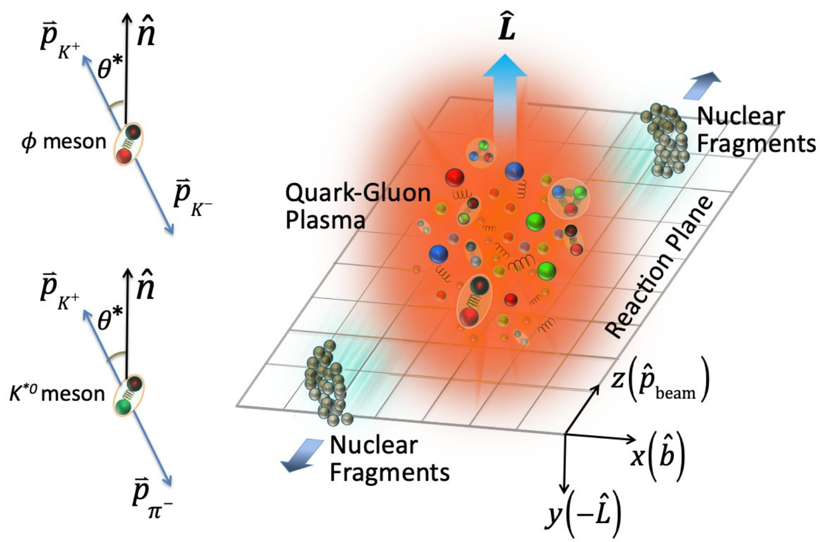
B

$L \quad 10^3 - 10^7 \hbar$

Part I : Spin Dynamics

Mostly on spin alignment, for polarization measurements, see Voloshin and Lisa's talk

Global Spin Alignment



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

The diagonal element ρ00 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 ρ00 from 1/3 would indicate

a non-zero spin alignment.

Strong p-wave decay

$\to k^+ + k^-$

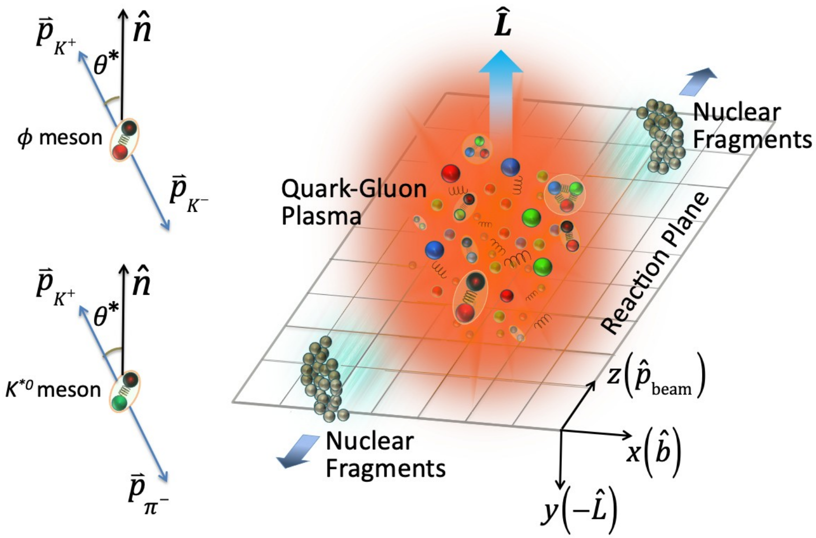
$k^{*0} \to k^+ +$

Dilepton decay

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

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

Global Spin Alignment



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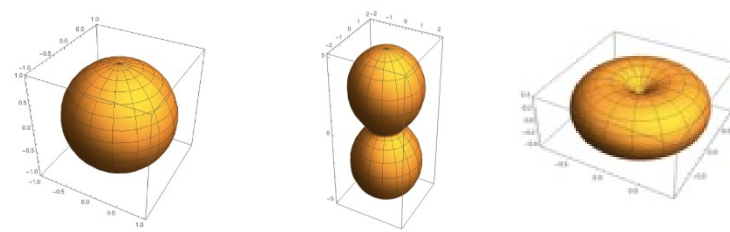


$\rho_{00} = \frac{1}{3}$ $\rho_{00} > \frac{1}{3}$ $\rho_{00} < \frac{1}{3}$

Strong p-wave decay

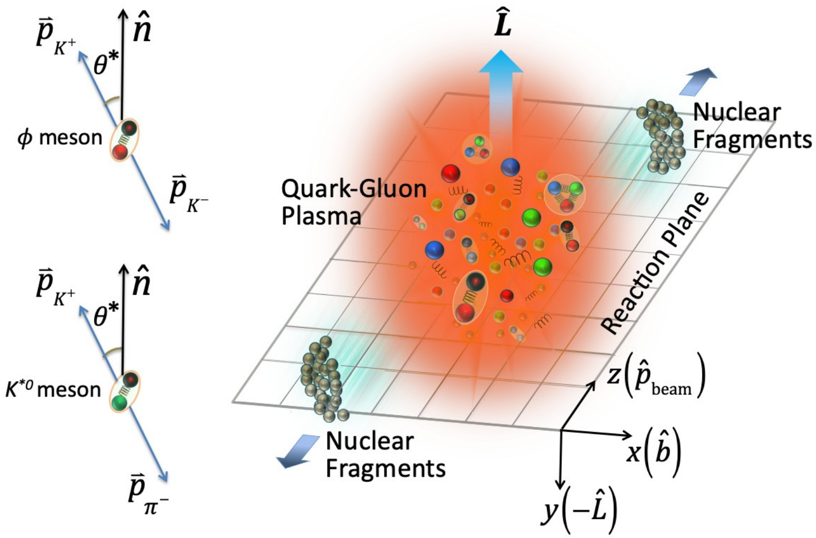
$\to k^{+} + k^{-}$

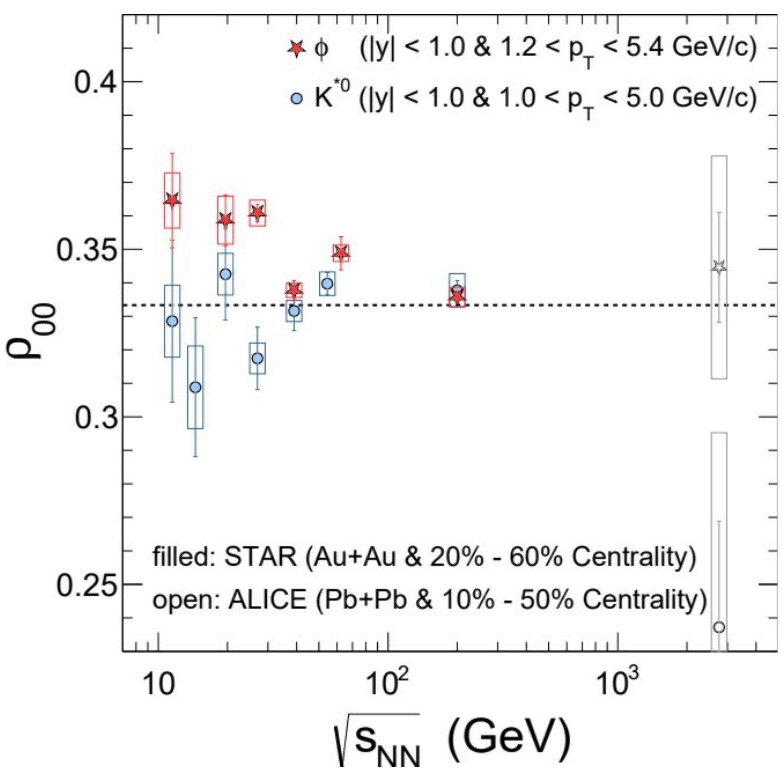
$k^{*0} \to k^{+} +$

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

From quark combination :

Global Spin Alignment





Strong p-wave decay

$\rightarrow k^+ + k^-$

$k^{*0} \rightarrow k^+ + ^-$

STAR, Nature 614 244 (2023)

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

From quark combination :

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); Phys. Rev. D 109, 036004 (2024)

[7] A. Kumar, B. Muller and D.-L Yang, PRD 108 016020 (2023)

[8] Sheng, Pu and Wang, Phys. Rev. C 108 054902 (2023)

[9] Sheng et., al., arXiv:2403.07522

[10] Lv et. al., Phys. Rev. D 109, 114003 (2024)

[11] D.-L. Yang, PRD 111 056005 (2025)

[12] H. Ahmed, Y. Chen and M. Huang, arXiv:2501.13401 (2025)

[13] Andrea Palermo , Chirality workshop 2025

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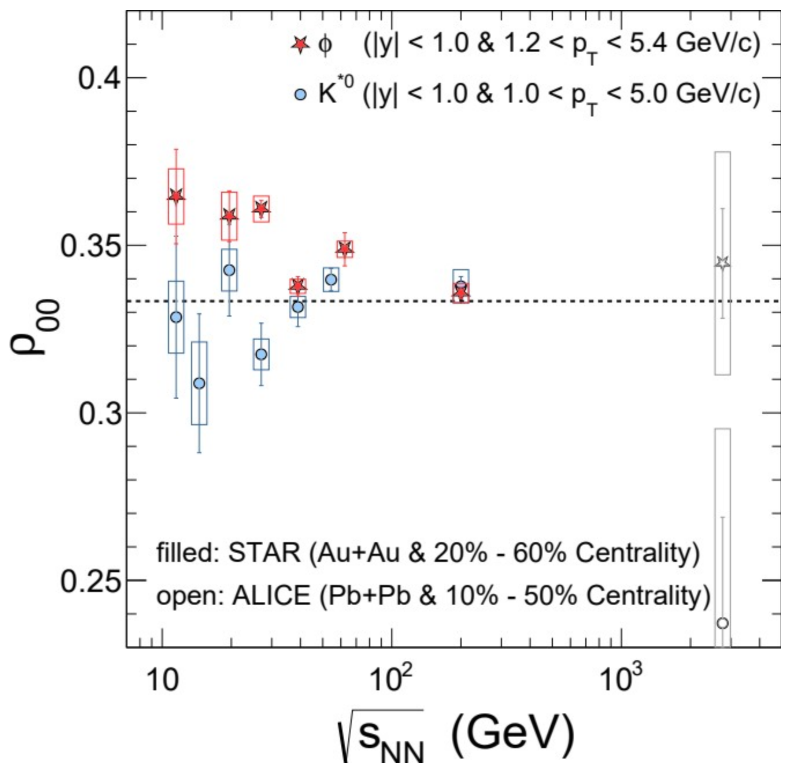
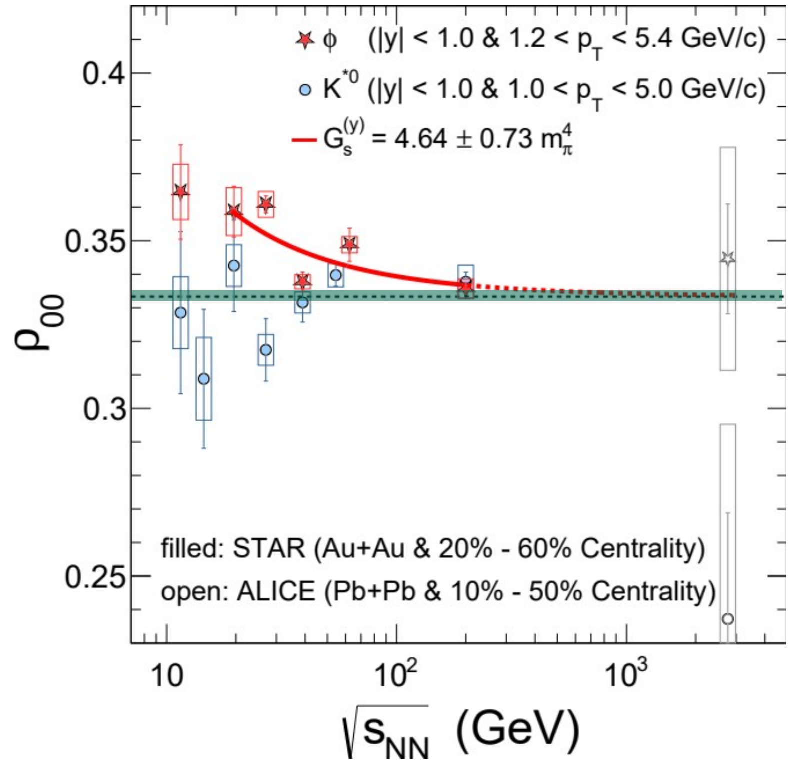


STAR, Nature 614 244 (2023)

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

The Large ρ00 Surprise

Physics Mechanisms	(ρ_{00})
c_Λ: Quark coalescence vorticity & magnetic field[1]	< 1/3 (Negative ~ 10^{-5})
c_ε: E-comp. of Vorticity tensor[1]	< 1/3 (Negative ~ 10^{-4})
c_E: Electric field[2]	> 1/3 (Positive ~ 10^{-5})
c_F: Fragmentation[3]	> or, < 1/3 (~ 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[7]	could be significant



STAR, Nature 614 244 (2023)

strong force

$$G_s^{(y)} = g_{\phi}^2 \left[3\langle B_{\phi,y}^2 \rangle - \frac{\langle P^2 \rangle_{\phi}}{m_s^2} \langle E_{\phi,z}^2 + E \right.$$

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

ρ00 from BES-II

Physics Mechanisms	(ρ_{00})
c_Λ: Quark coalescence vorticity & magnetic field[1]	< 1/3 (Negative ~ 10^{-5})
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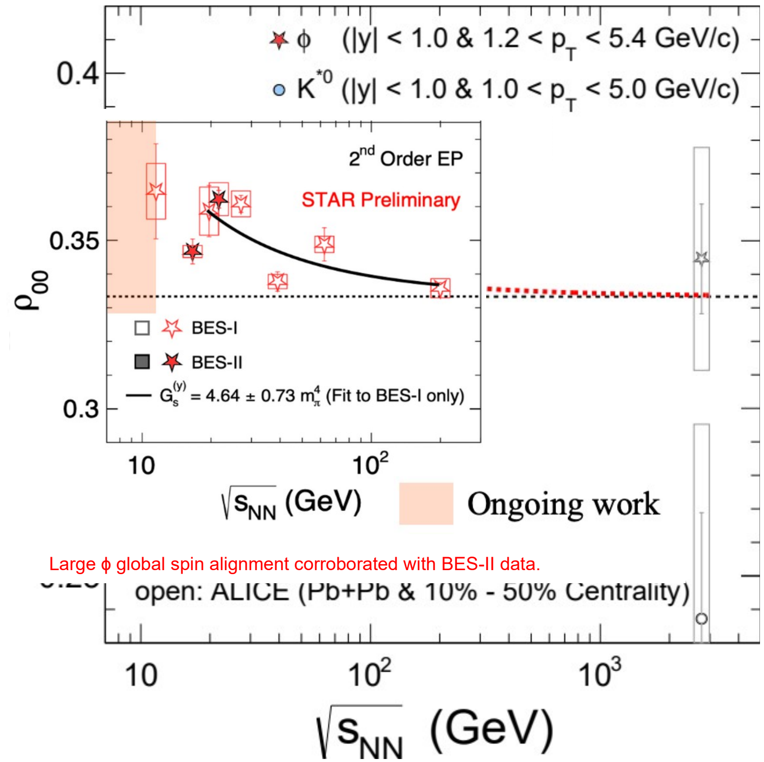

strong force

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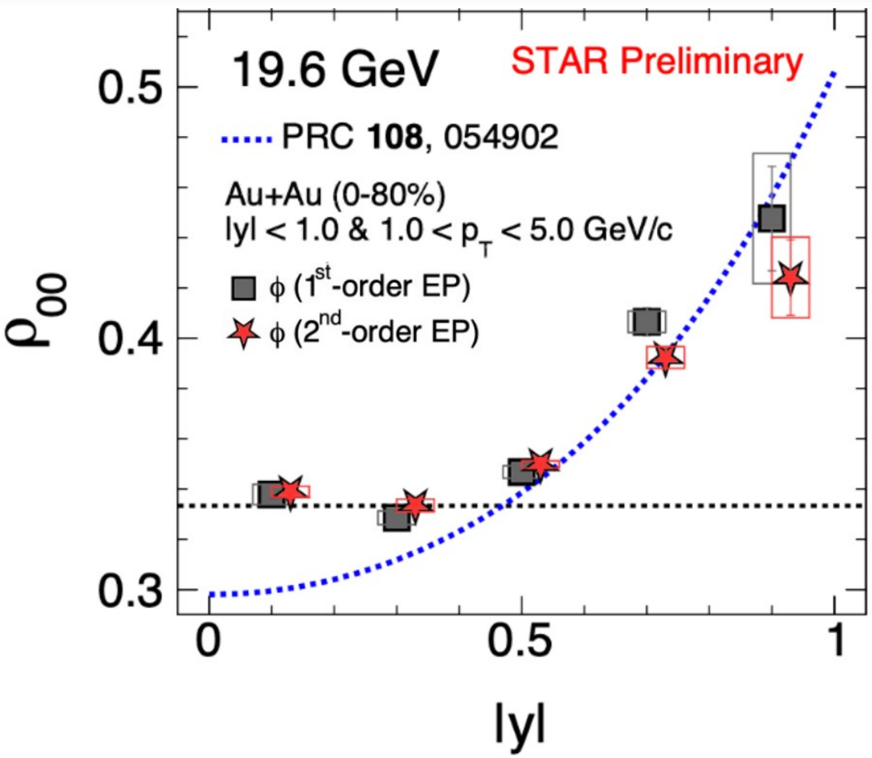
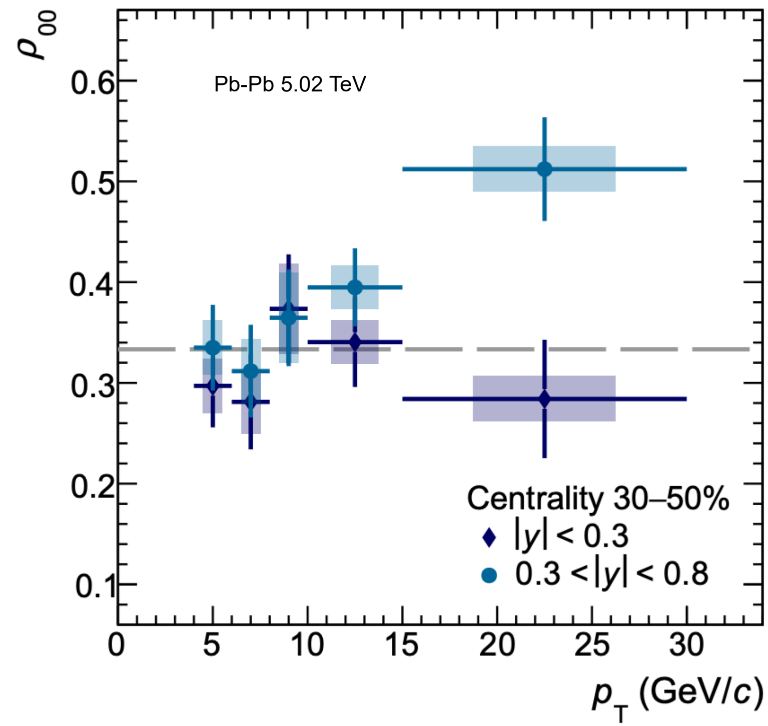
The Rapidity Dependence





$$D^{*+} \rightarrow D^{0} + \pi^{+}$$
$$\hookrightarrow k^{-} + \pi^{+}$$

G. Wilks for STAR, SQM 2024

Theory curve : X.L. Sheng, et al., PRC 108 054902 (2023)

ALICE arXiv:2504.00714 (2025)

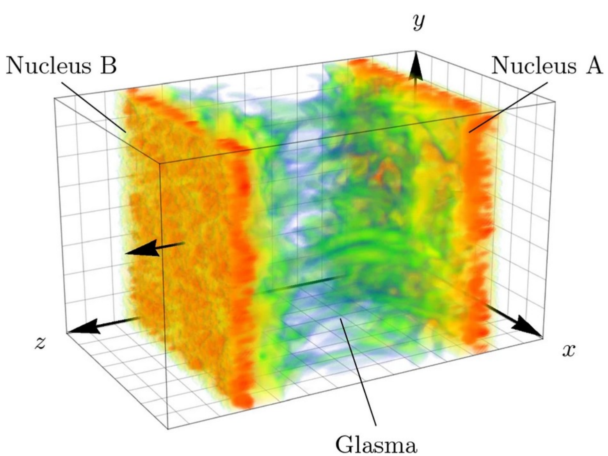
Strong rapidity dependence at both RHIC and LHC.

STAR’s data consistent with prediction invoking strong force field.

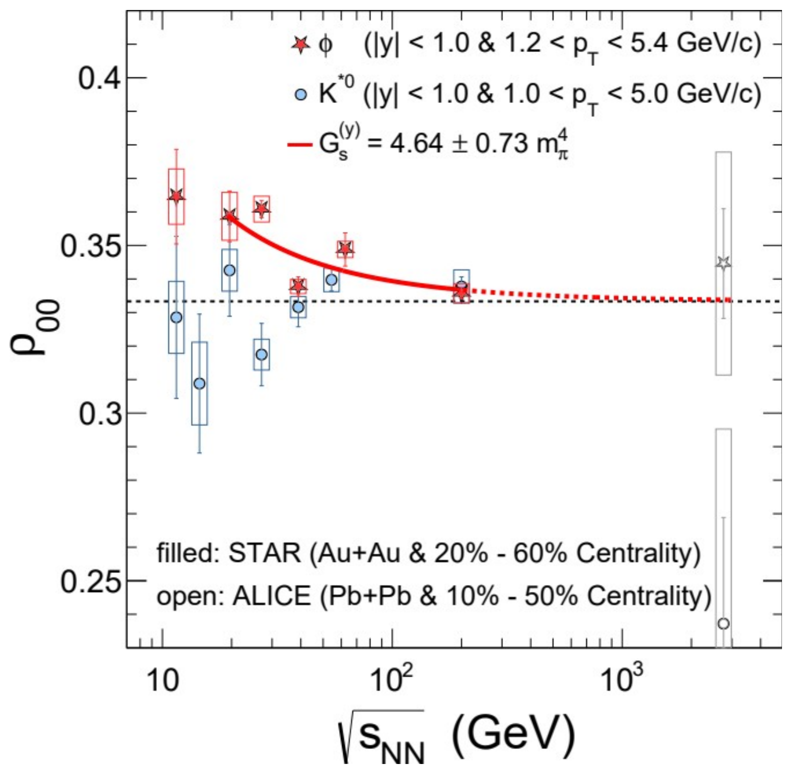
Fluctuation Matters

What do we learn ?

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



A. Ipp and D. Muller. EPA 56 243 (2020)

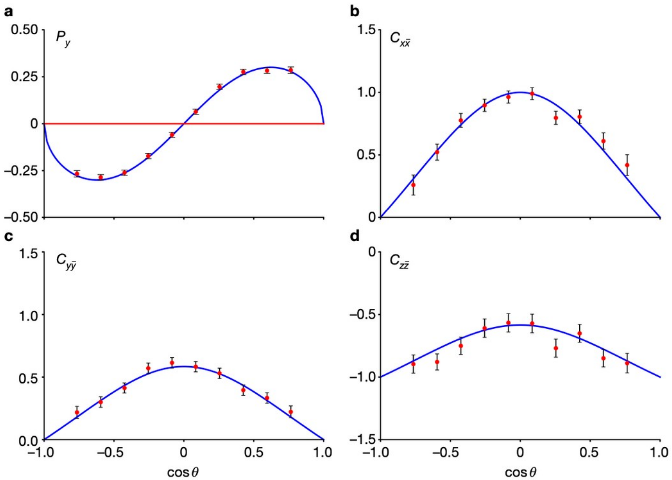


STAR, Nature 614 244 (2023)

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

Spin-Spin interaction at work !

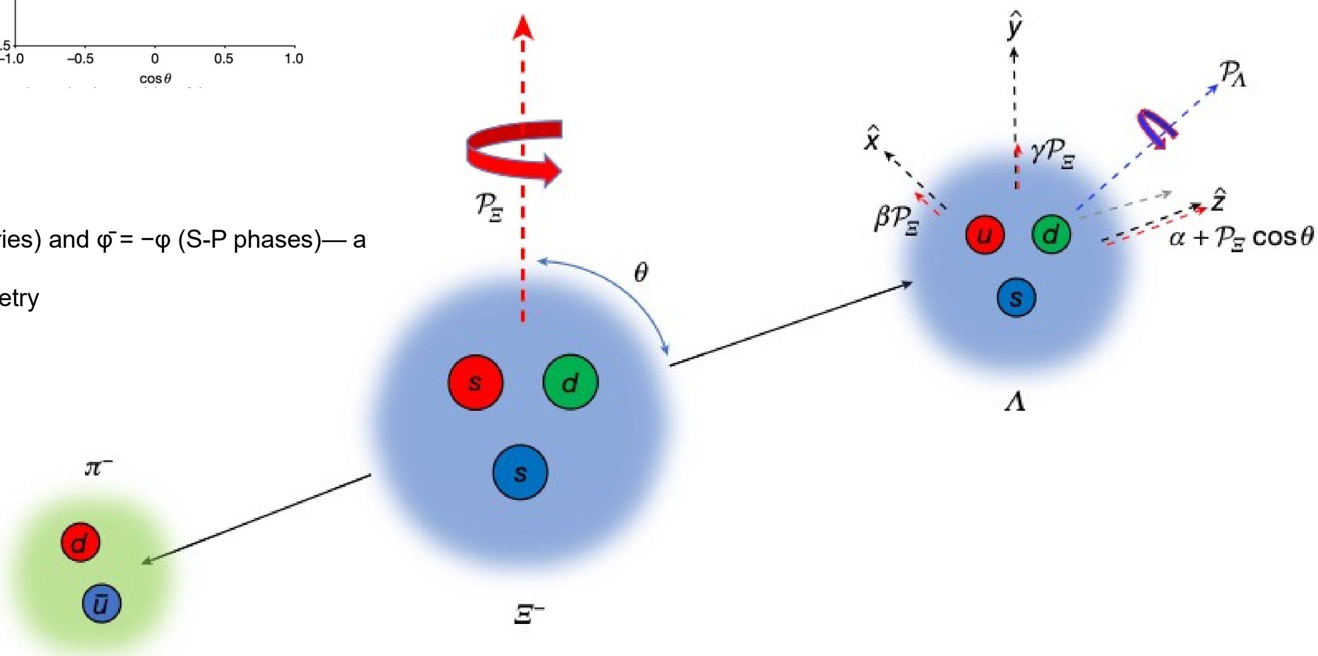
Spin Entanglement for CP Tests



e+e- collisions at BESIII

The sharpest hyperon CP-symmetry check via entangled $\Xi^+ \Xi^-$ pairs.

For Ξ and Ξ̄, $\bar{\alpha} = -\alpha$ (decay asymmetries) and $\bar{\varphi} = -\varphi$ (S-P phases)— a direct, high-precision test of CP symmetry



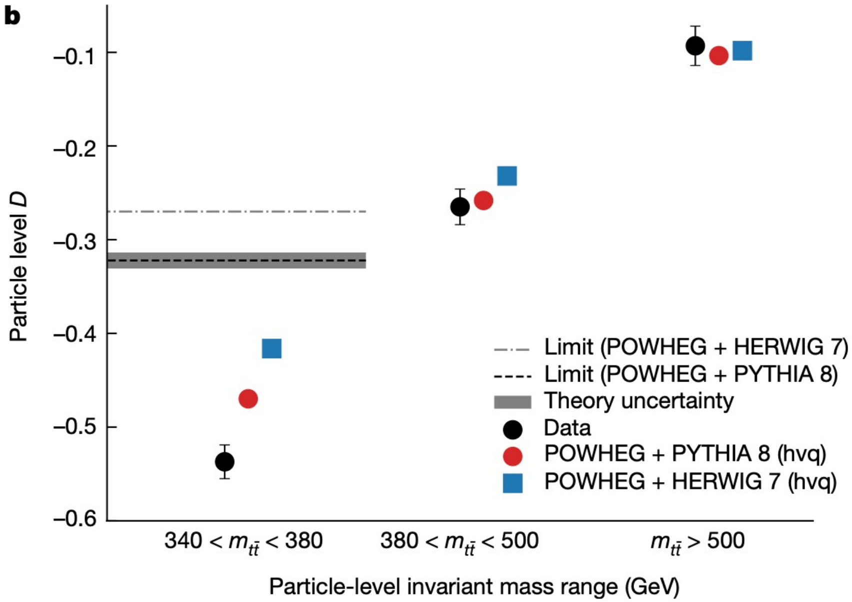
BESIII Nature 64 606 (2022)

$e^+ e^- \to \gamma^* \to J/\psi \to \Xi^- \Xi^+$

Quark-Level Spin Entanglement

pp collisions (13 TeV) at LHC

t → bW → bℓν



Catch the quark pair before QCD binds it

– genuine quark-level entanglement.

$$D = -3\langle \cos\varphi \rangle = \frac{\alpha_1 \alpha_2}{3}\langle P \cdot P \rangle$$

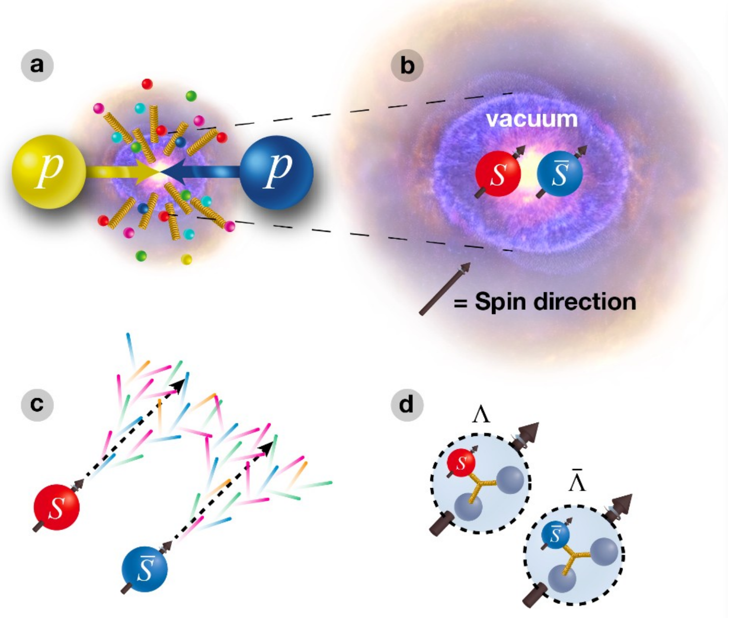
Entangled if D < - 1/3

ATLAS Nature 542 633 (2024)

Significant spin-entanglement between top-antitop observed

Quark Spin Entanglement Survives Confinement

pp collisions (200 GeV) at RHIC



$$\frac{dN}{d\cos(\theta^*)} \sim 1 + \alpha_1\alpha_2 P_{\Lambda_1\Lambda_2}\cos(\theta^*)$$

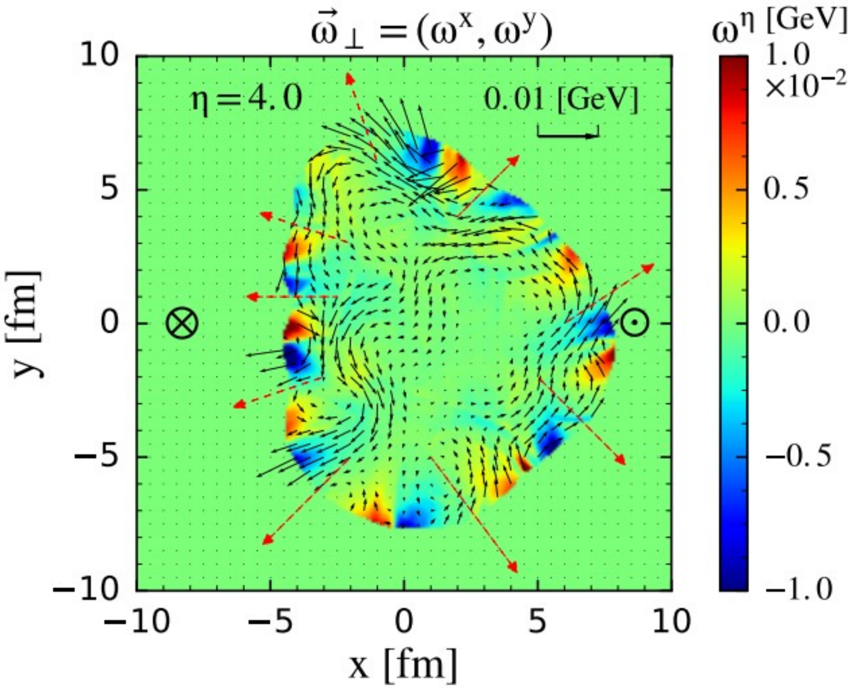
STAR arXiv: 2506.05499

Finite and intriguing results from pp collisions !

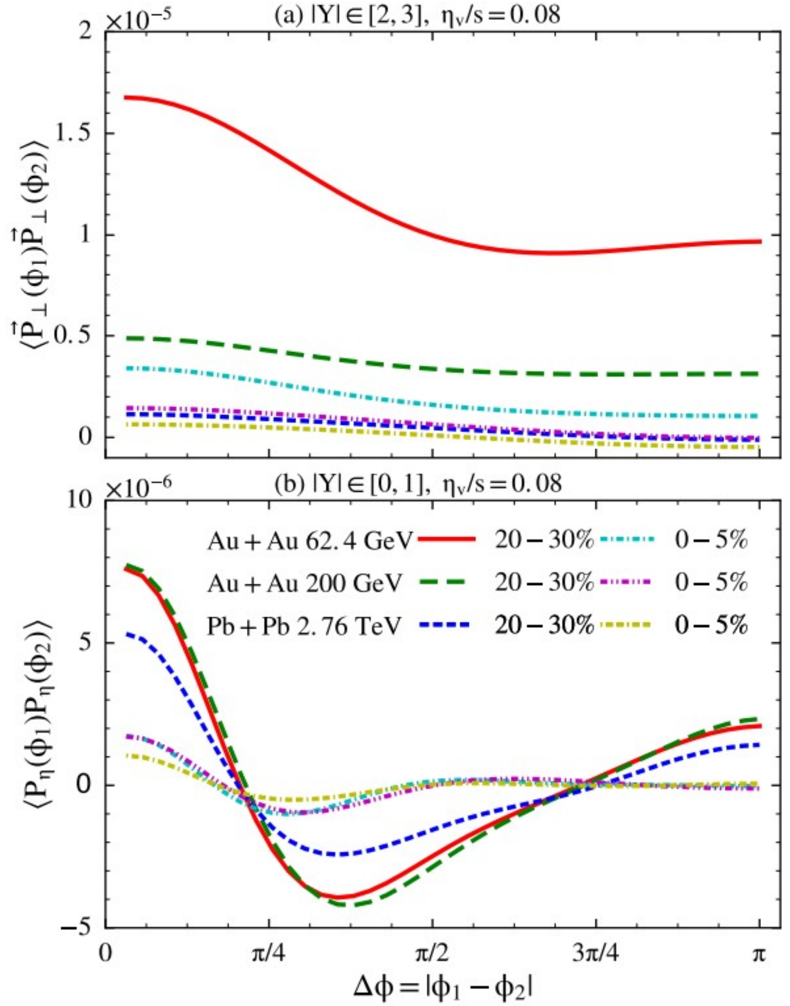
Desirable to study it in AuAu collisions as well.

Quark-antiquark pair stays entangled all the way through QCD confinement and hadronization.

Spin-Spin Correlation : Vortical Structure

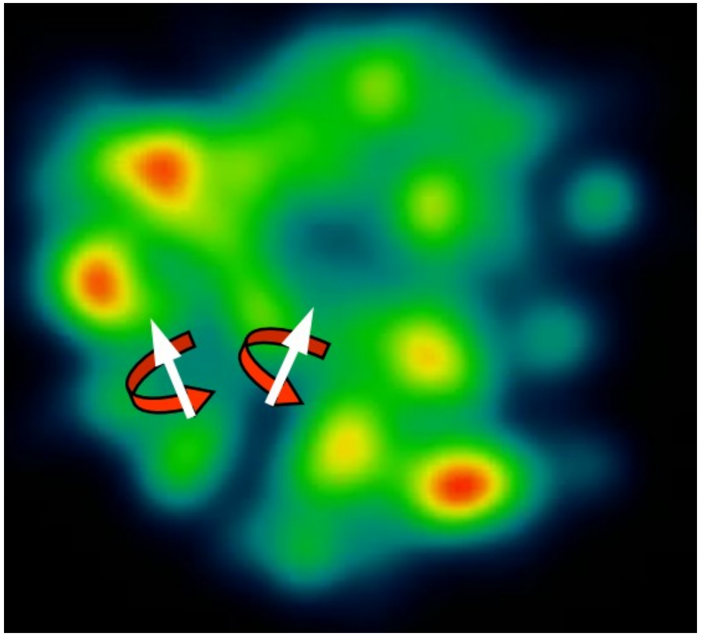


Vortical structure induced spin-spin correlation



Pang et.al., PRL 117 192301 (2016)

Spin-Spin Correlation : Strong Force



Strong force induced hyperon spin correlation

Lv et. al., Phys. Rev. D 109, 114003 (2024)

Spin correlation function :

$$c_{ij} = \frac{f_{\uparrow\uparrow} + f_{\downarrow\downarrow} - f_{\downarrow\uparrow} - f_{\uparrow\downarrow}}{f_{\uparrow\uparrow} + f_{\downarrow\downarrow} + f_{\downarrow\uparrow} + f_{\uparrow\downarrow}}$$

$f_{m_i m_j} = \langle m_i m_j | \hat{\rho} | m_i m_j \rangle$: fraction of particle pair in the spin state | m1m2 ⟩

In heavy ion collisions with finite global polarization,

$$c'_{ij} = c_{ij} - P_i P_j$$

It can be shown that

$$c'_{\Lambda\Lambda} = \frac{9}{\alpha_\Lambda^2} \langle \cos\theta_i^* \cos\theta_j^* \rangle - P_\Lambda^2.$$

In practice with the consideration of EP resolution

$$c'_{\Lambda\Lambda} = \frac{64}{\pi^2 \alpha_\Lambda^2} \frac{\langle \sin(\phi_i^* - \Psi_{\mathrm{EP}}) \sin(\phi_j^* - \Psi_{\mathrm{EP}}) \rangle}{\langle \cos^2(\Psi_{\mathrm{EP}} - \Psi_{\mathrm{RP}}) \rangle} - P_\Lambda^2$$

Lyuboshitz and Lyuboshitz, Phys. Of Atomic Nuclei, 273 805 (2010)

Chen et. al., Phys.Rev. D 95, 034009 (2016)

Lv et. al., Phys. Rev. D 109, 114003 (2024)

Chen, Goldstein, Jaffe and JI, NPB 445 380 (1995)

Zhang and Wei, arXiv:2301.04096

Shen, Chen and Tang, arXiv:2407.21291

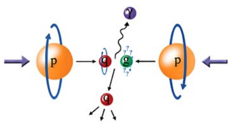
New clue to strong interaction.

Spin-Spin Correlation

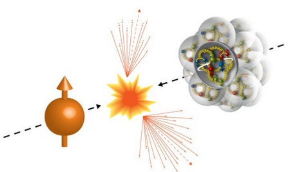
Time

~ 5-10 fm/*c*

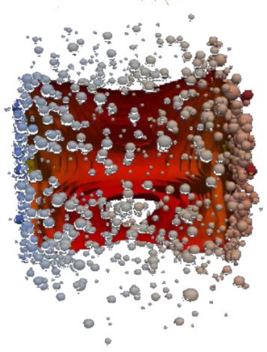
$e^+ e^-$ — Clean CP test



pp — Quark spin entanglement and its survival



pA — “Somewhat” medium effects ?



AA — Strong force ?

Vorticity ?

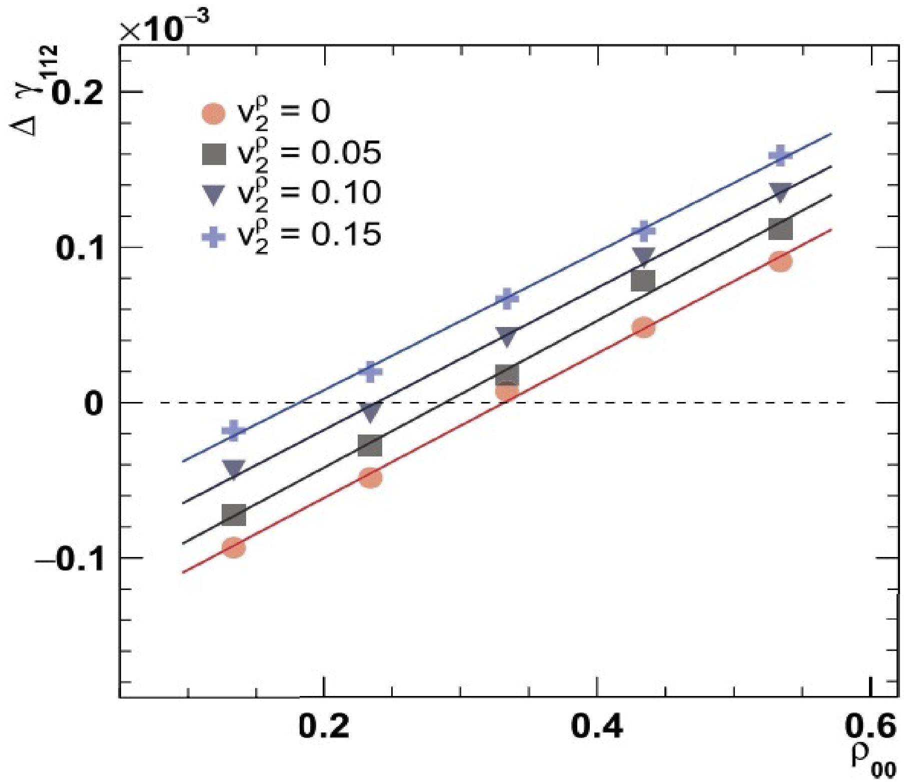
Hard scattering

Pre-eq.

Collective motion

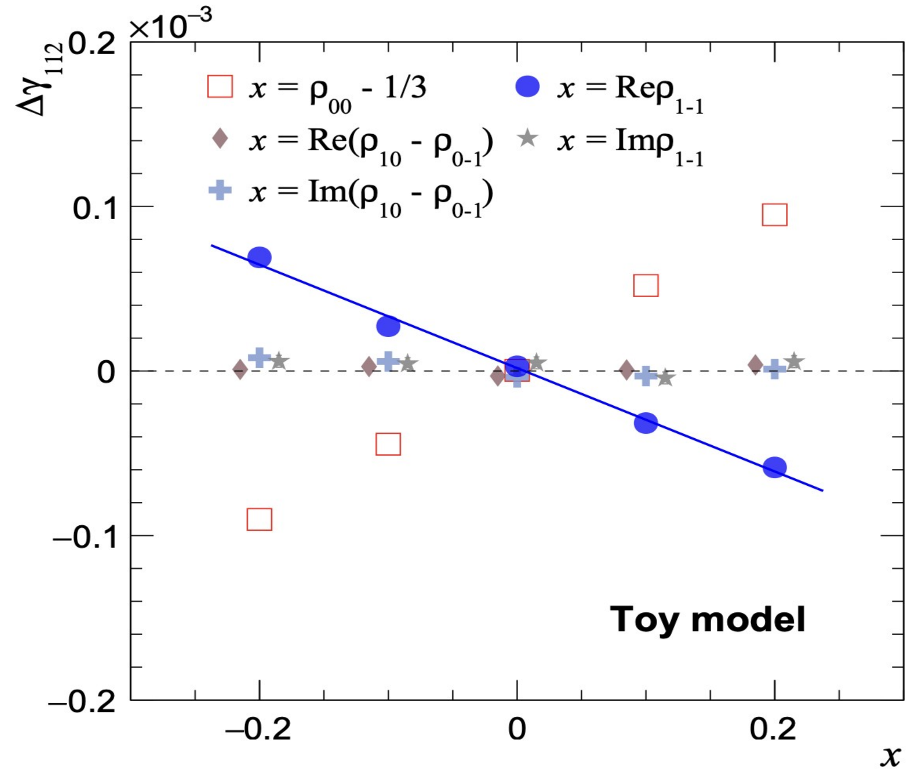
Hydro evolution

Hadronization



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

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



Z. Wang et al., Phys. Rev. C 111 014910 (2025)

$$\Delta\gamma_{112}^{\rho} = f_0 \frac{N_\rho}{N_+ N_-}\left[\frac{3}{4}(\rho_{00} - \frac{1}{3}) - \frac{1}{2}\mathrm{Re}\,\rho_{1-1}\right]$$

Both ρ00 and ρ1-1 affect Δγ, in opposite way

ρ00 and ρ1-1 may cause apparent Δγ

Part II : EM Field

EM Field in Heavy-ion Collisions

Ultra strong

EM field

CME

Kharzeev, McLerran and Warringa, Nucl. Phys. A 803 227 (2008)

Fukushima, Kharzeev and Warringa, PRD 78 074033 (2008)

Jet energy loss

Tuchin, PRC 82 034904 (2010)

Photon and dilepton production

Tuchin PRC 87 (2) 024912 (2013)

Basar, Kharzeev and Shurayak, PRC 90 014905 (2014)

Elliptic and directed flow

Mohapatra, Saumia and Srivastava, PLA 26 2477 (2011)

Tuchin, JPG Nucl.Part.Phys. 39 025010 (2012)

Guo et al., PLB 751 215 (2015)

Fukushima et al., PRD 93 (7) 074028 (2016)

Fiazzo et al., PRD 94 054020 (2016)

Gursoy, Kharzeev and Rajagopal, PRC 89 054905 (2014)

Das etal, PLB 768 260 (2017)

Gursoy et al., PRC 98 055201 (2018)

Breit-Wheeler process

STAR, PRL 127, 052302 (2021)

Fine structure on the phase diagram

Mizher, Chernodub and Fraga, PRD 82 105016 (2010)

Catalyst for chiral symmetry breaking

Gusynin, Miransky and Shovkovy, PRL 73 3499 (1994)

Multiple connections to rich physics !

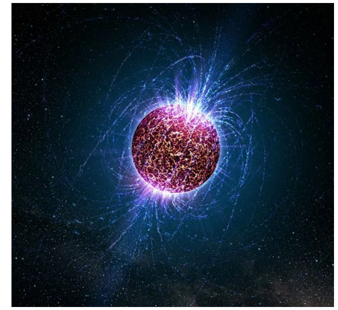
The Strongest EM Field, But Do We "See" It ?

Earth

~ 0.5 Gauss

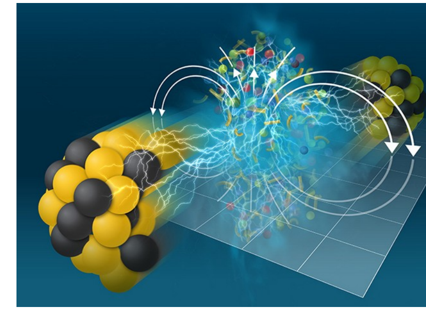
Lightning

$\sim 10^{3} - 10^{4}$ Gauss



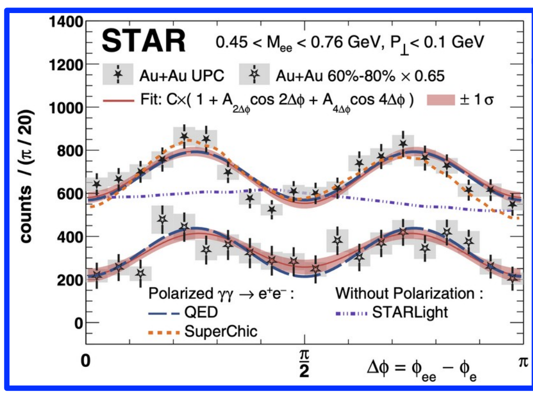
Neutron Star (Magnetar)

$\sim 10^{14}$ Gauss



Heavy ion collisions

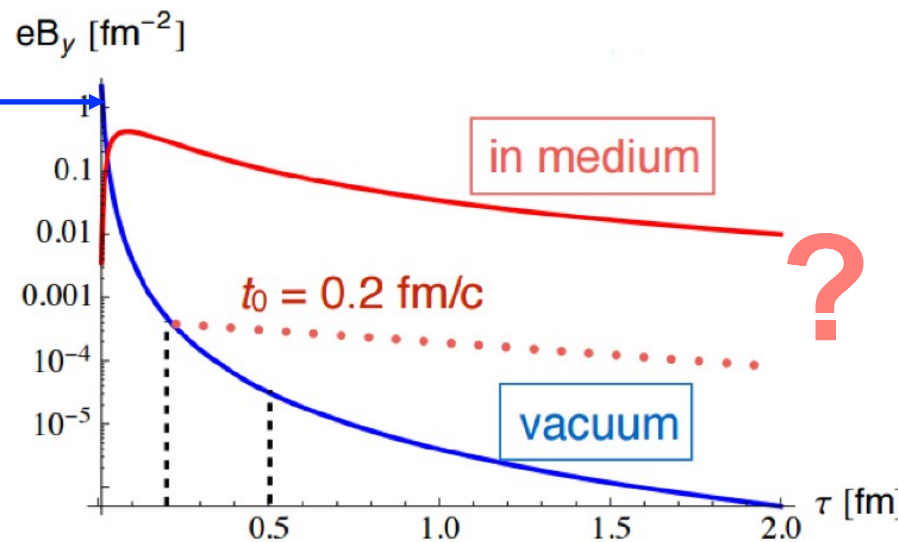
$\sim 10^{18}$ Gauss



STAR, PRL 127, 052302 (2021)

Vacuum birefringence

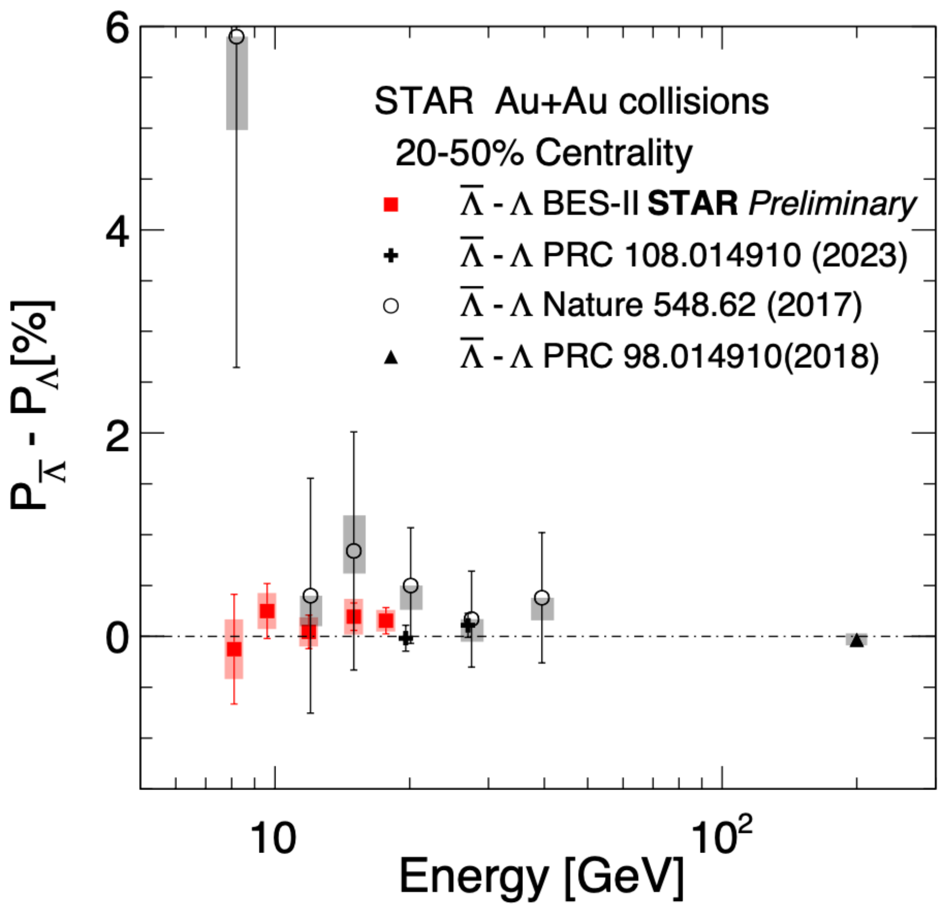
vacuum + strong B



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

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

Λ and Polarization

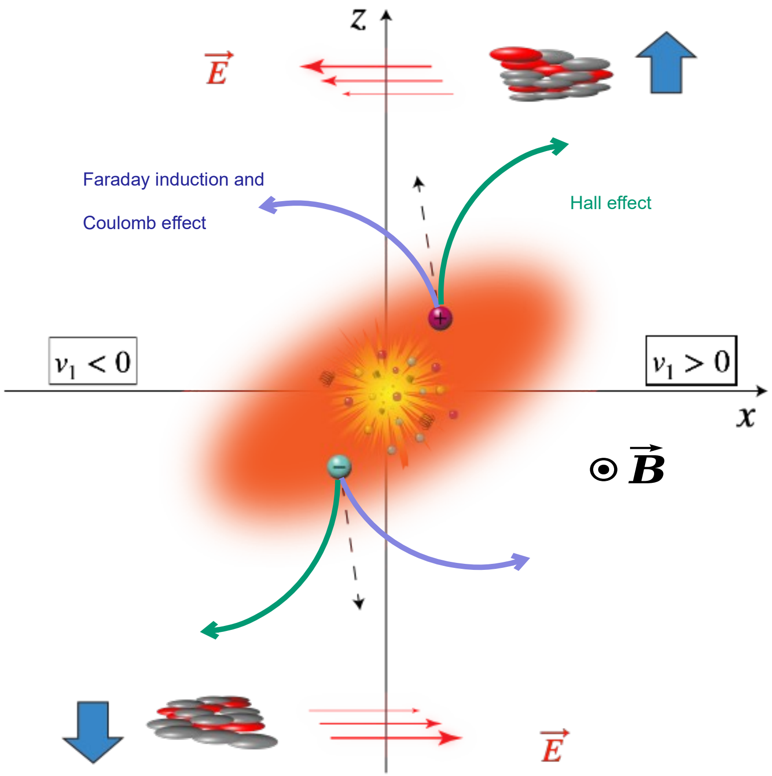


Tan Lu for STAR, QM 2025

$$P_{\bar{\Lambda}} - P_{\Lambda} = -2\frac{\mu_{\Lambda} B}{T}$$

Challenging to see the B effect at later stage

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)

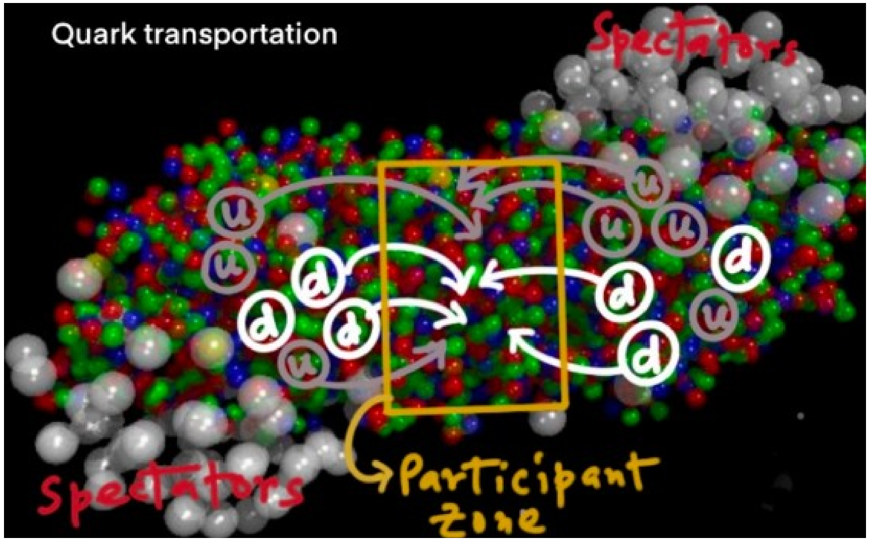
S.K. Das et al., PLB 768 260 (2017)

Umut Gursoy, et al., PRC 98 055201 (2018)

K. Nakamura et. al., PRC 107 034912 (2023)

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

Transported Quarks



$p : uud$

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

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

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

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

$v_1^{K^+} > v_1^{K^-}$ at $\eta > 0$

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

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

$v_1^{\pi^-} > v_1^{\pi^+}$ at $\eta > 0$

(#d>#u, Au neutron rich)

Dunlop, Lisa and Sorensen, PRC 84 044914 (2011)

Guo, Liu and Tang, PRC 86 044901 (2012)

Nayak, Shi, Xu and Lin, PRC 100 054903 (2019)

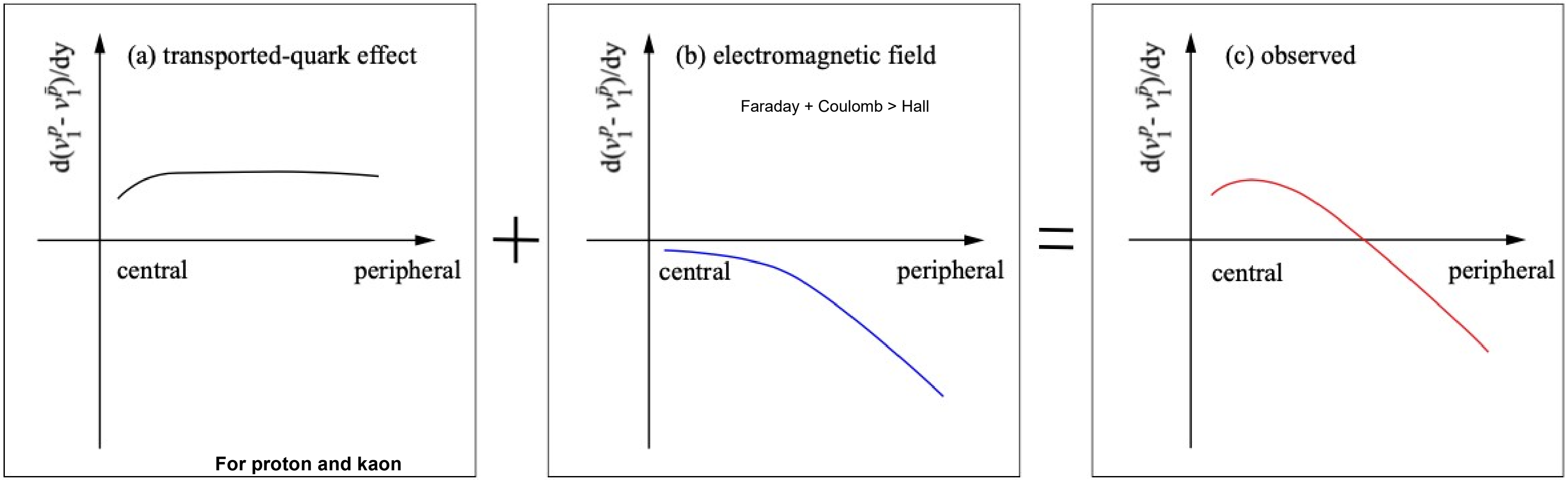
P. Bozek, PRC 106 L061901 (2022)

Transported quarks carry informat on from incident nucleons, causing v1 splitting.

Interplay Between Effects

$d(v1^{+} - v1^{-})/dy$: Hall ⇧ transported quark ⇧ Faraday ⇩ Coulomb ⇩

(Heavy quarks) (Light quarks)



Transported quark effect :

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

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

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

$v_1^{K^+} > v_1^{K^-}$ at $\eta > 0$

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

$v_1^{\pi^+} < v_1^{\pi^-}$ at $\eta > 0$

(#d > #u, Au neutron rich)

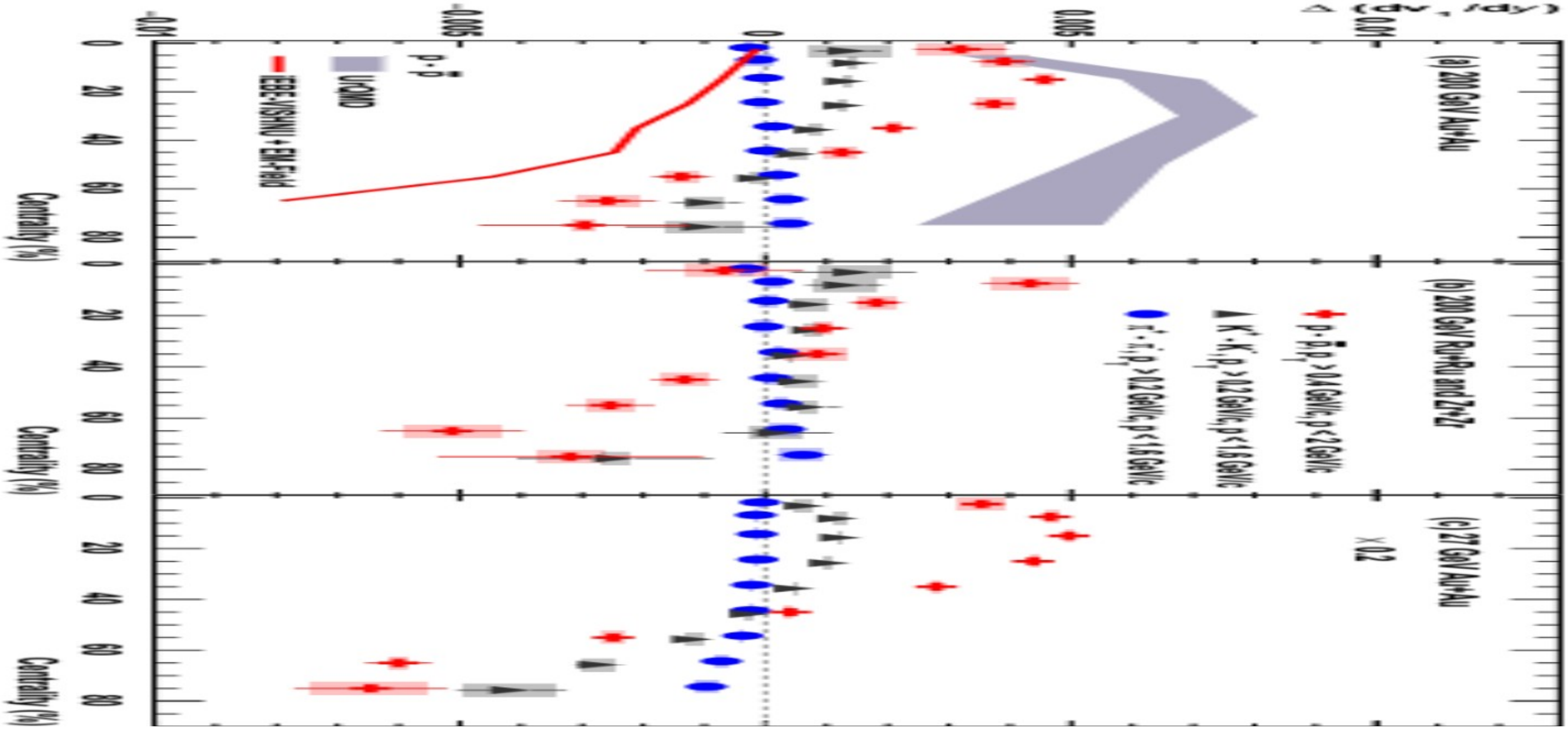
v1 slope difference between protons and antiprotons:

sign change as a function of centrality.

Similar pattern expected for kaons.

No sign change expected for pions.

Sign Change in Δ(dv1/dy)



STAR, PRX 14 011028 (2024)

Sign change in Δ(dv1/dy) occurs for both protons and kaons.

The magnitudes follow the expected ordering between protons and kaons.

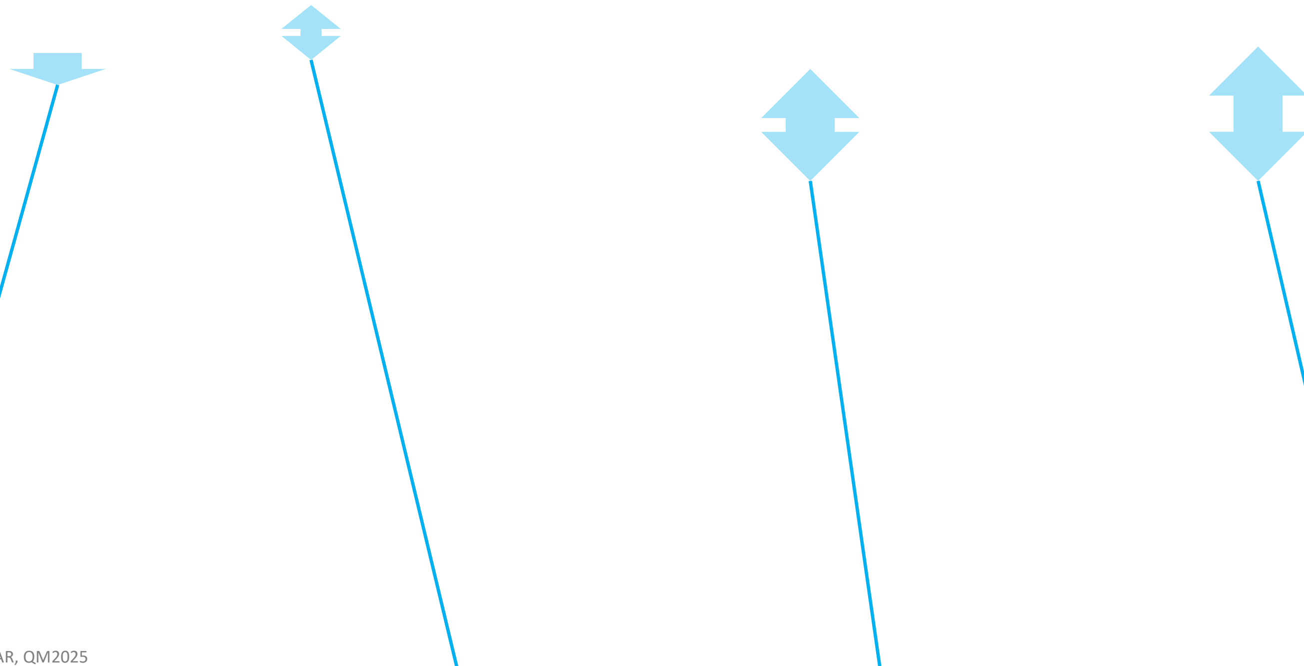
Pion results are either consistent with zero or negative, as expected.

The electric conductivity of QGP used in iEBY-VISHNU+EM model lies within a plausible interval.

(σ=(

Strong evidence in favor of EM field at work in QGP

Δ(dv1/dy) at BES Energies



Aditya Prasad Dash for STAR, QM2025

$\pi^{+}: u\bar{d}$ $K^{+}: u\bar{s}$ $p: uud$

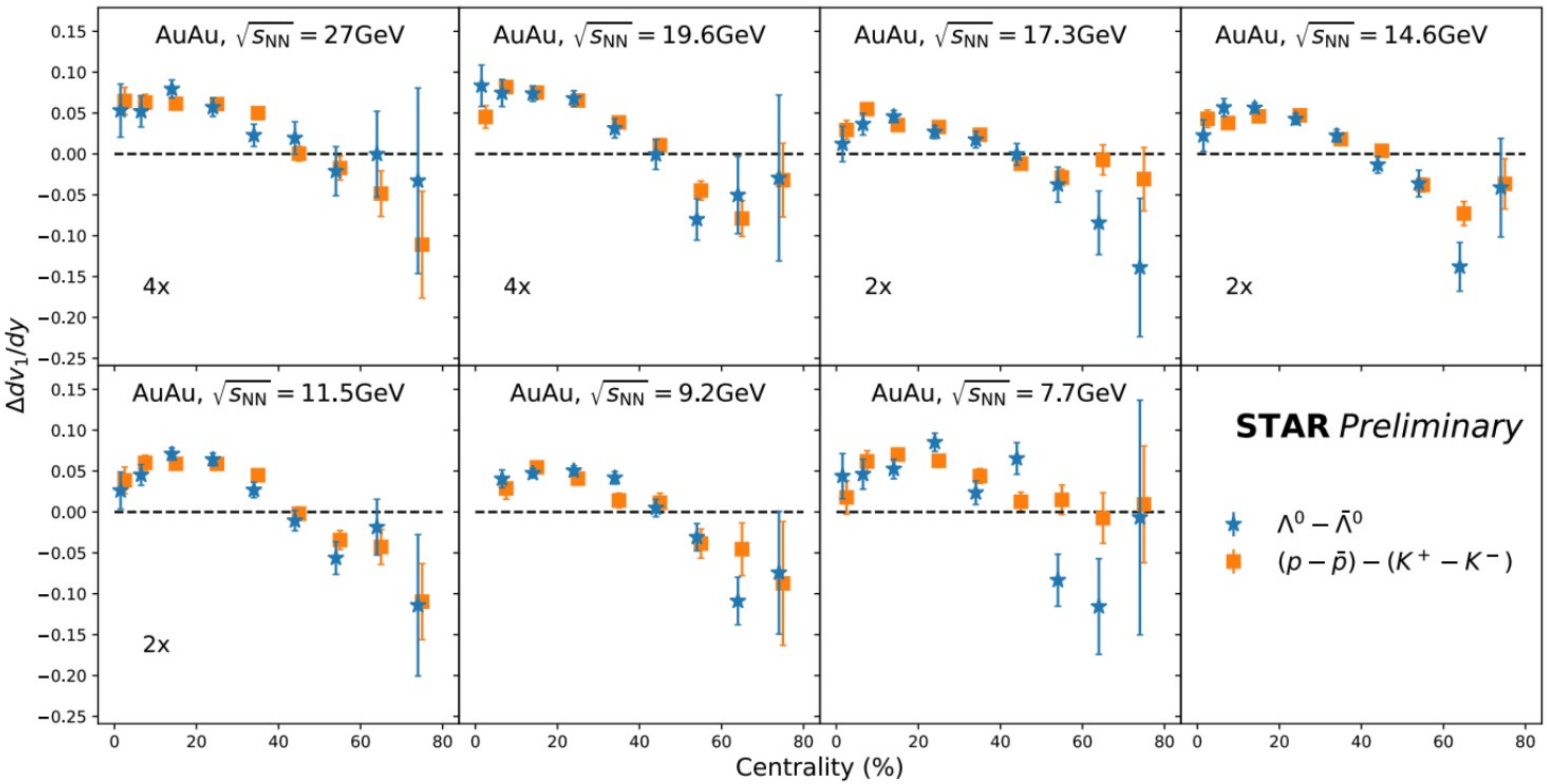
$\pi^{-}: \bar{u}d$ (#d > #u, Au neutron rich) $K^{-}: \bar{u}s$ $\bar{\Lambda}: \bar{u}\bar{d}\bar{s}$ $\bar{p}: \bar{u}\bar{u}\bar{d}$

# of trans. quarks that may increase Δv1 :	< 0	1	2	3

EM effect increases with decreasing energy

Positive term scales with transported-quark count quark-level origin

Δ(dv1/dy) for Λ()



Xiatong Wu for STAR, QM 2025

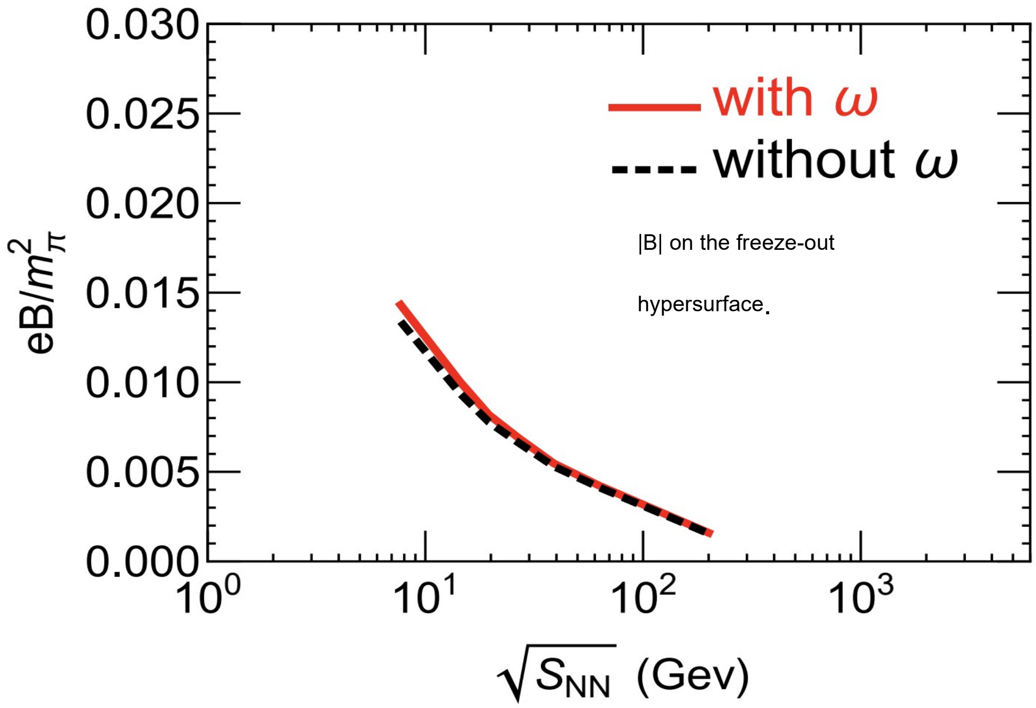
$\Lambda^0 - \bar{\Lambda}^0$: $uds - \bar{u}\bar{d}\bar{s}$

$(p - \bar{p}) - (K^+ - K^-)$: $(uud - \bar{u}\bar{u}\bar{d}) - (u\bar{s} - \bar{u}s)$

Λ(), although being neutral, is not special

What matters is v1 at quark level, not hadron level

B Field on the Freeze-out Hypersurface



v1 splitting for light hadrons is

sensitive to the B at freezeout

A. Huang, X-Y Wu and M. Huang, PRD 110 094032 (2024)

K. Tuchin, arXiv:1301.0099

X-G Huang, Rep. Prog. Phys. 79, 076302 (2016)

Seyed Farid Taghavi and U. Wiedemann, PRC 91 024902 (2015)

W.-T. Deng and X-G Huang, PRC 85 044907 (2012)

V. Voronyuk et. al, PRC 83 054911 (2011)

V. Skokov, A. Illarionov, V.Toneev Int. J. Mod. Phys.A24:5925-5932 (2009)

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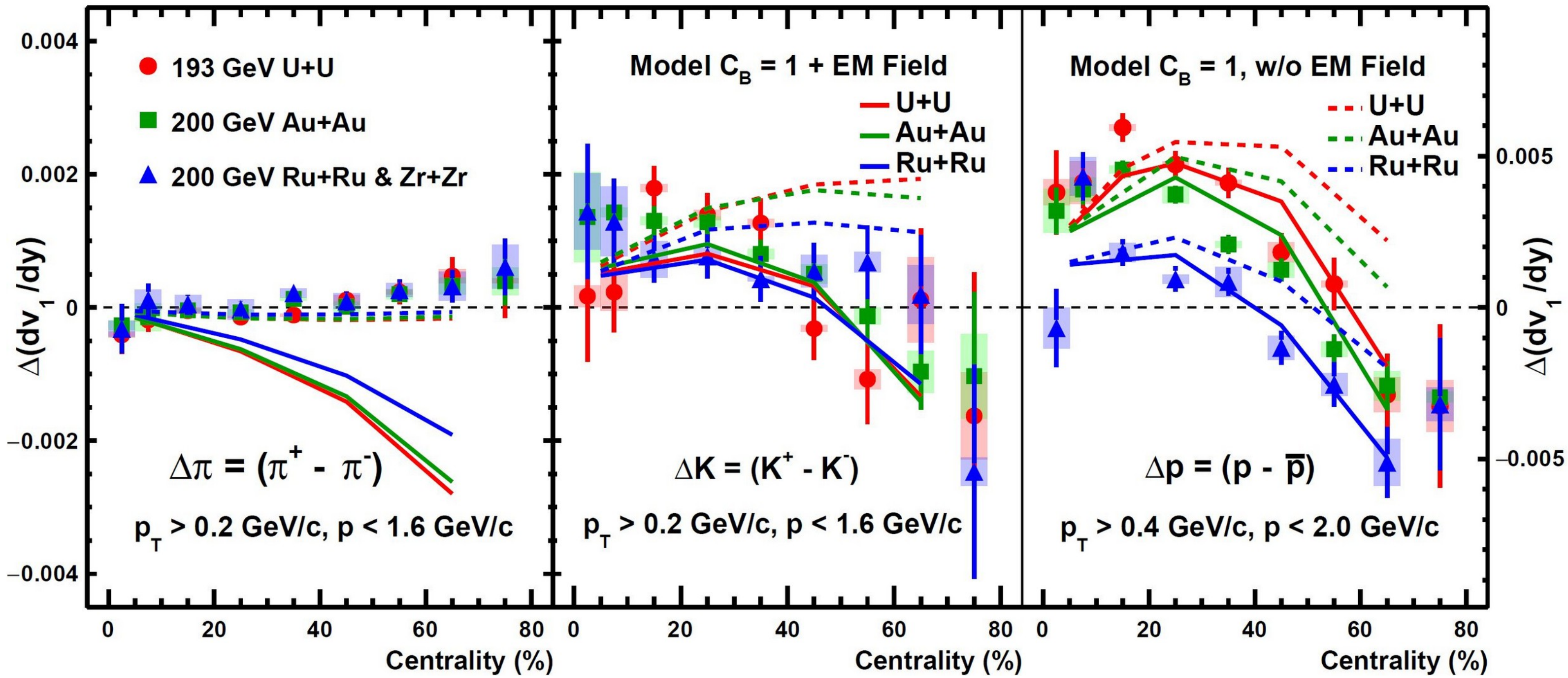
EM effect increases with decreasing energy

Δ(dv1/dy) : System Size Dependence



Muhammad Farhan Taser for STAR, QM2025

Hydro model : T. Parida et al. arXiv: 2305.08806, 2503.04660

Hydro evolution with EM and baryon transport qualitatively explains the general feature

Hydro model : Baryon Transport + EM

Hydro model at finite baryon density with initial tilt

$$T^{\mu\nu} = eu^{\mu}u^{\nu} - (P + \Pi)\Delta^{\mu\nu} + \pi^{\mu\nu},$$

$$J^{\mu}_{B} = n_B u^{\mu} + q^{\mu}.$$

energy-momentum ($T^{\mu\nu}$) and baryon (JB^{μ}) conservation

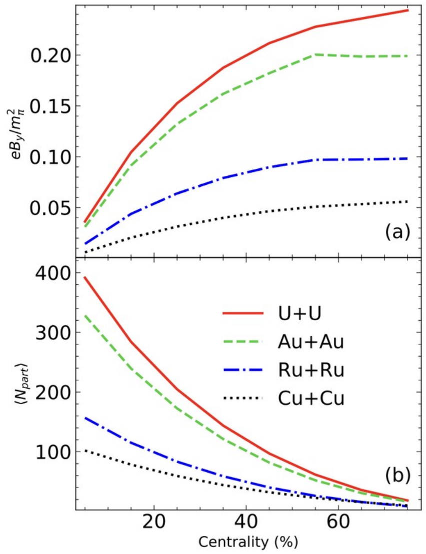
$$\kappa_B = \frac{C_B}{T} n_B \left(\frac{1}{3} \coth\left(\frac{\mu_B}{T} \right) - \frac{n_B T}{e + \mathcal{P}} \right).$$

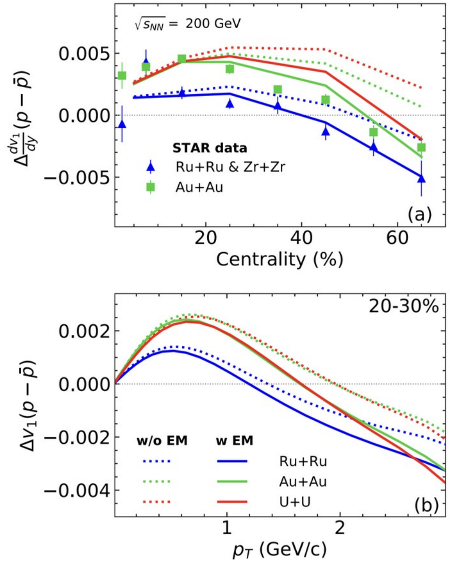
with kB as baryon diffusion coeff., tuned by CB

Denicol et al., PRC 98 034916 (2018)

$$q\vec{v}_{\textbf{drift}} \times \vec{B}' + q\vec{E}' - \mu m \vec{v}_{\textbf{drift}} = 0$$

Gursoy et al., PRC 98 055201 (2018)





and the introduction of EM field

Hydro evolution with EM and baryon transport qualitatively explains the general feature

Hydro model : T. Parida et al. arXiv: 2305.08806, 2503.04660

Take-aways

Global spin alignment reveals strong-force field fluctuations

Quark spin entanglement is now established

ATLAS : first observation at the free-quark level

STAR : entanglement survives confinement

BESIII : the entanglement study delivers the sharpest hyperon CP test

EM fields leave measurable footprints in v1 splitting

Next steps :

Λ and spin correlation in heavy ion collisions to map medium effects

Differential v1 splitting study for electric conductivity

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