Spin Alignment

- Experimental Overview

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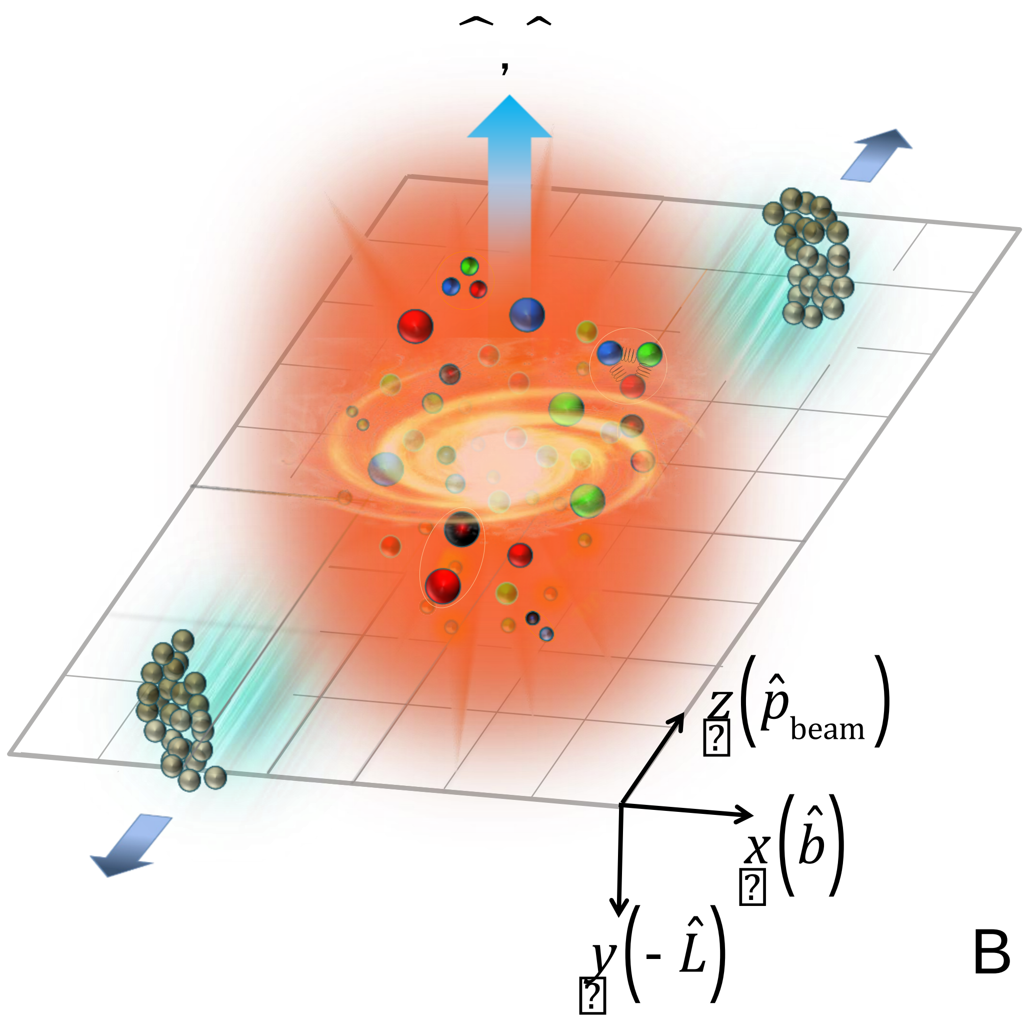
Strongly Interacting Matter under Rotation



$\text{B} \sim 10^{18}$ Gauss

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

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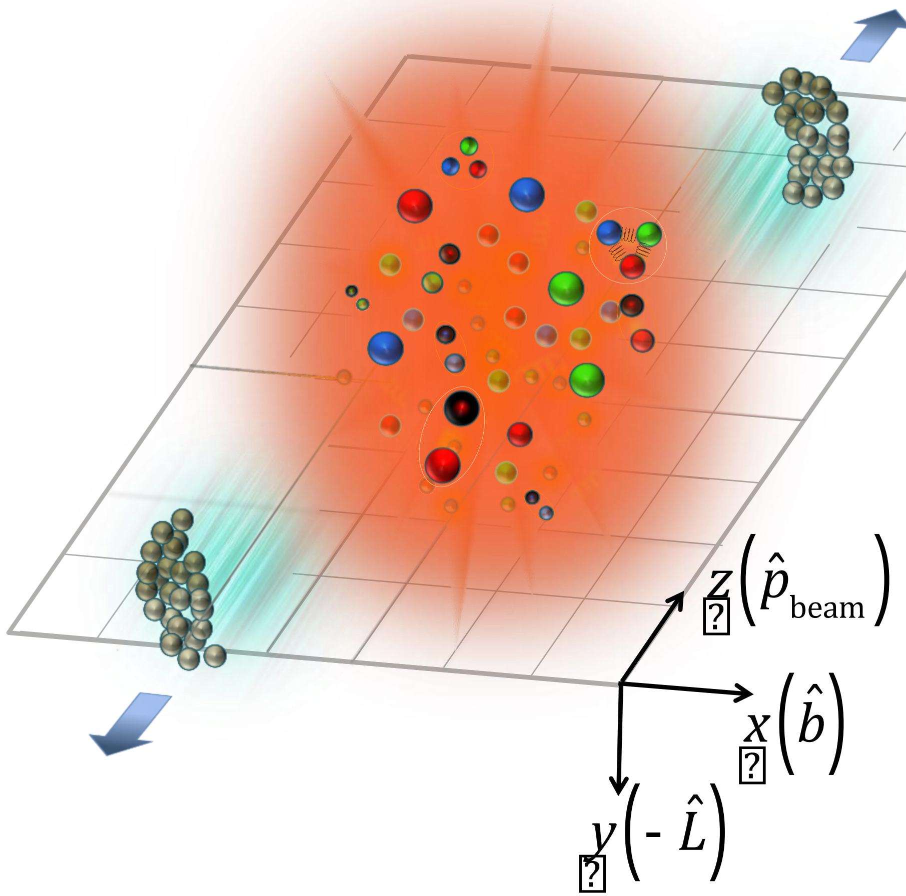
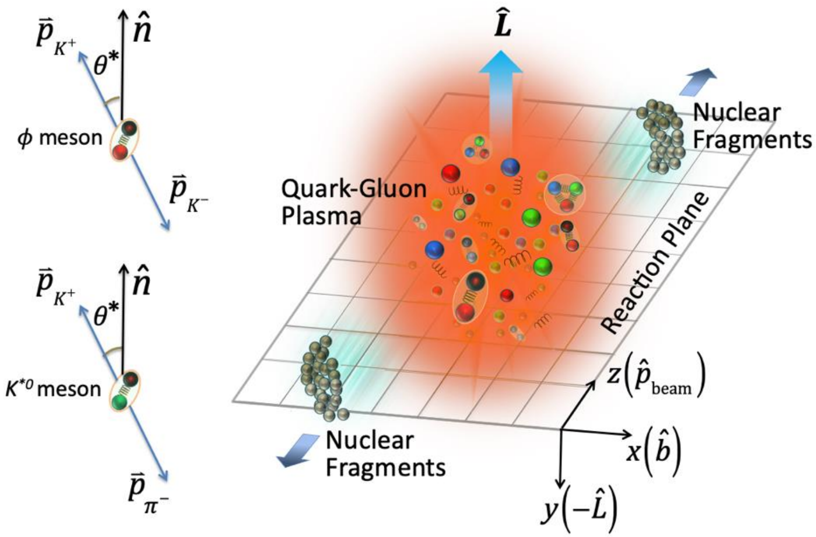


Global Spin Alignment



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.

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

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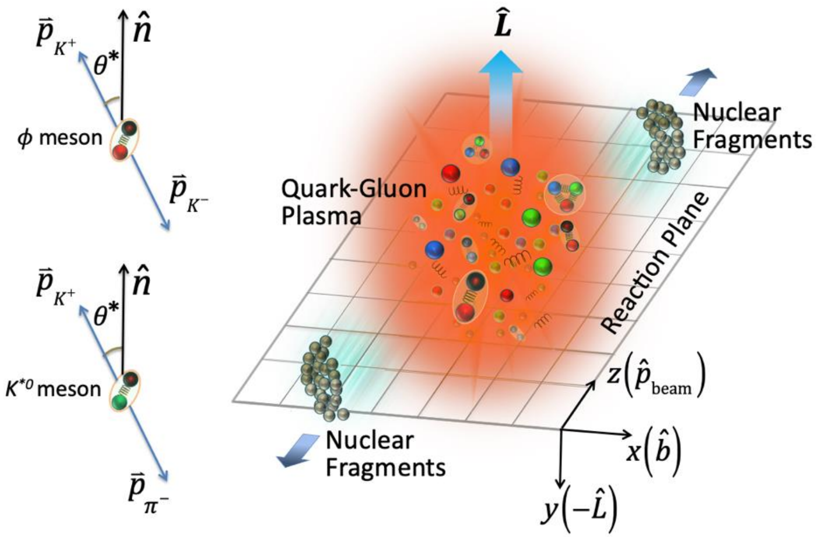

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- No local cancelation when integrating over phase space as opposed to spin-1/2 particles.
- Access to spin-orbital force **S**•(**E**$_\phi$ x **P**), a term which is canceled in Λ polarization.
- Some mesons, like ϕ, are expected to originate predominantly from primordial production
➔ less decay contributions if compared to hyperons, more sensitive to early dynamics.

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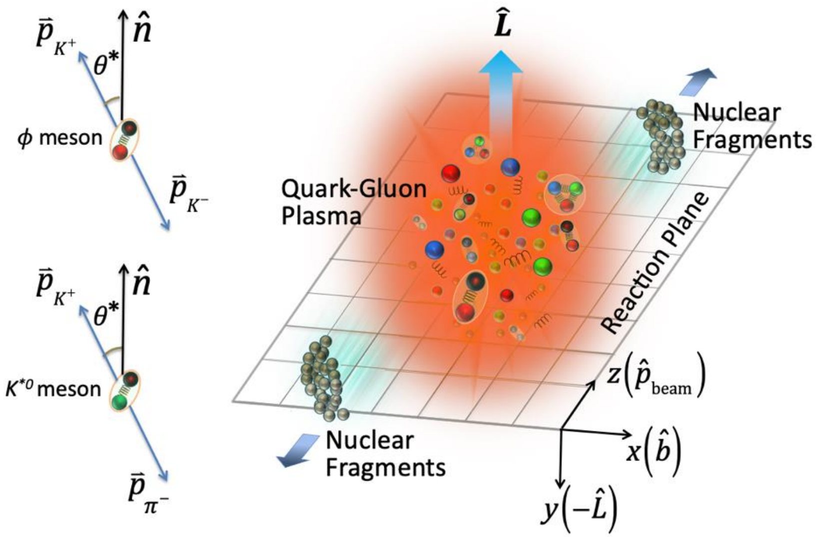

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Strong p-wave decay

$\phi\ (s\bar{s}) \rightarrow k^+ + k^-$

$k^{*0}\ (d\bar{s}) \rightarrow k^+ + \pi^-$

Dilepton decay

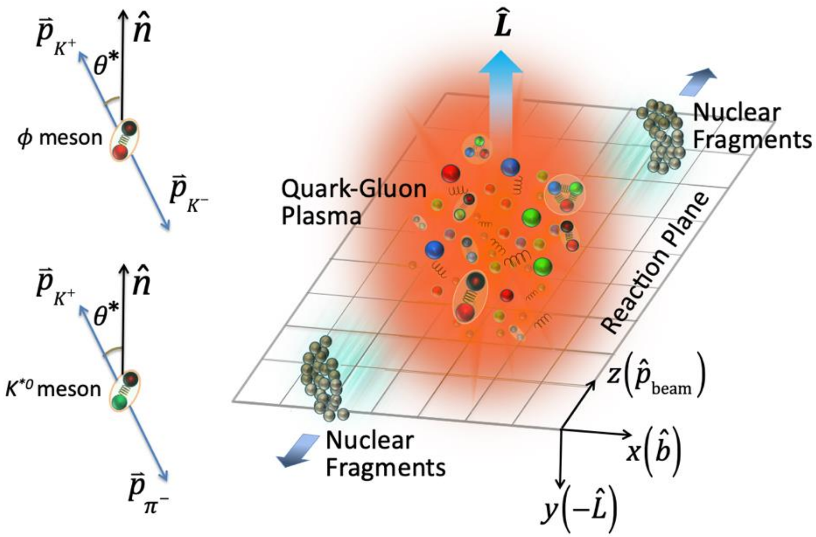
$J/\psi(c\bar{c}) \rightarrow \mu^+ + \mu^-$

$J/\psi(c\bar{c}) \rightarrow e^+ + e^-$

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

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

Global Spin Alignment



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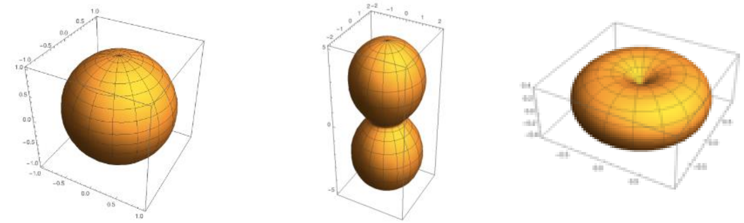

$r_{00} = \frac{1}{3}$ $\quad r_{00} > \frac{1}{3}$ $\quad r_{00} < \frac{1}{3}$

Strong p-wave decay

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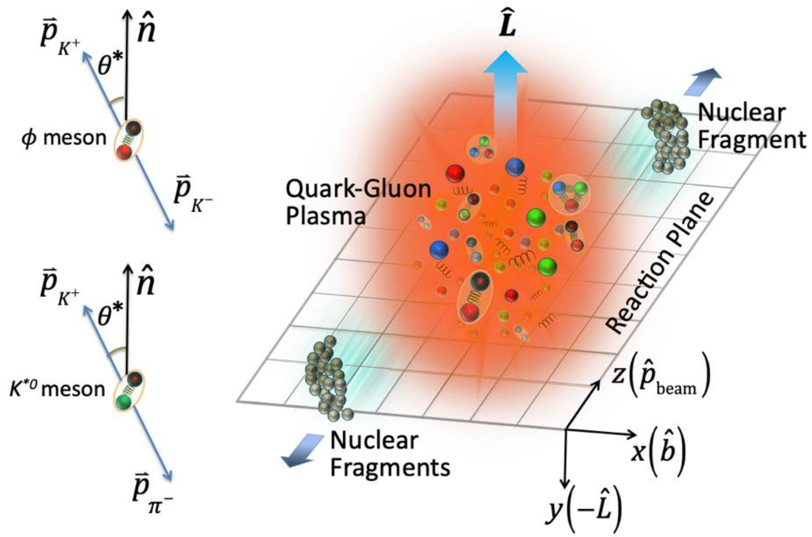
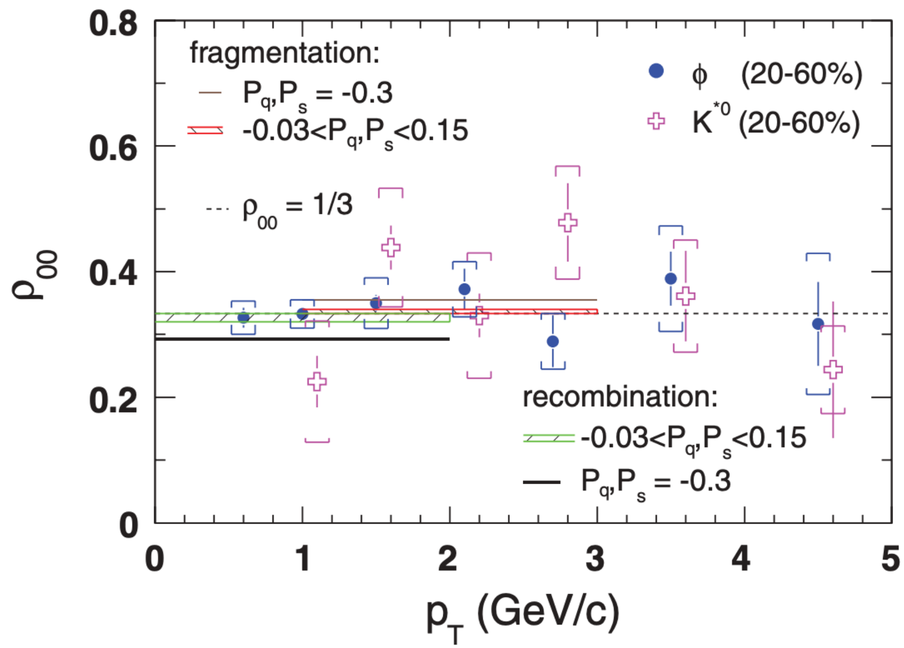
$$\frac{dN}{d(\cos\theta^*)} \sim (1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta^*$$

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, PRC 77 061902 (2008)

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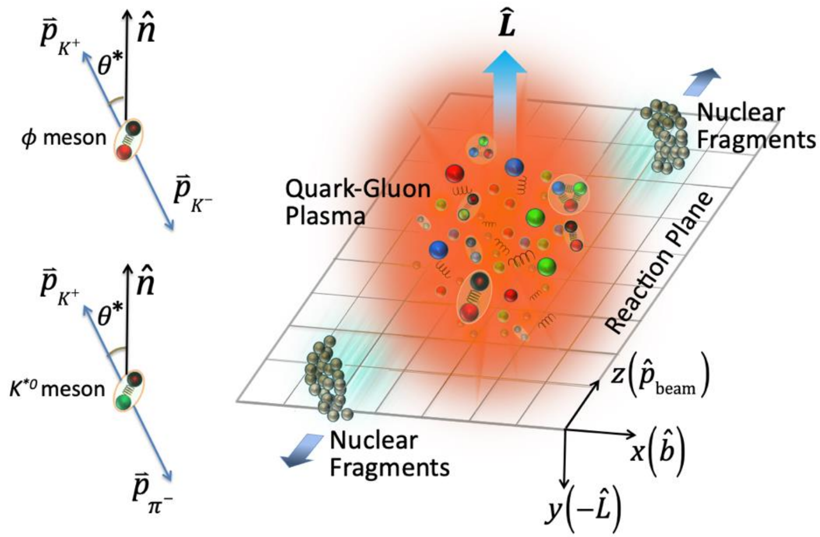

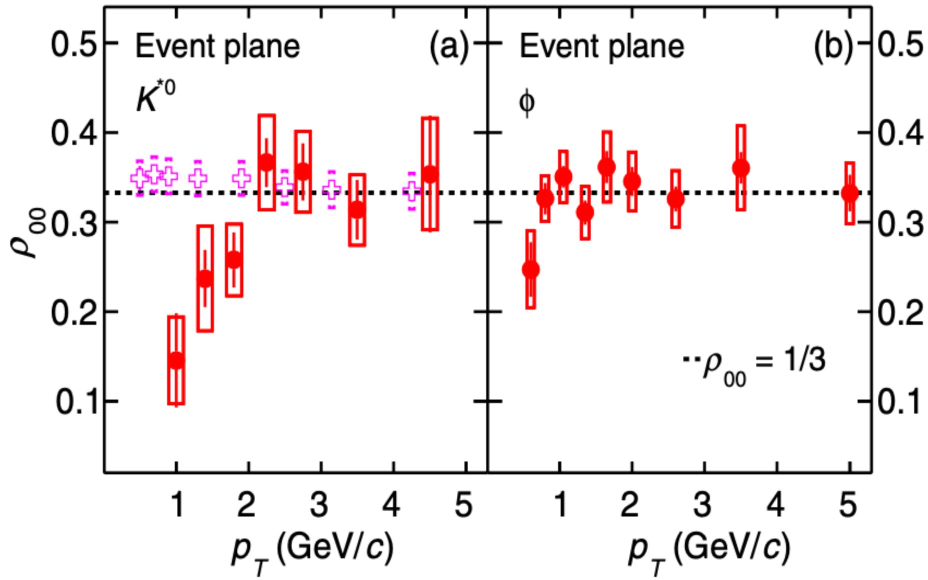

ALICE, PRL 125 012301 (2020)

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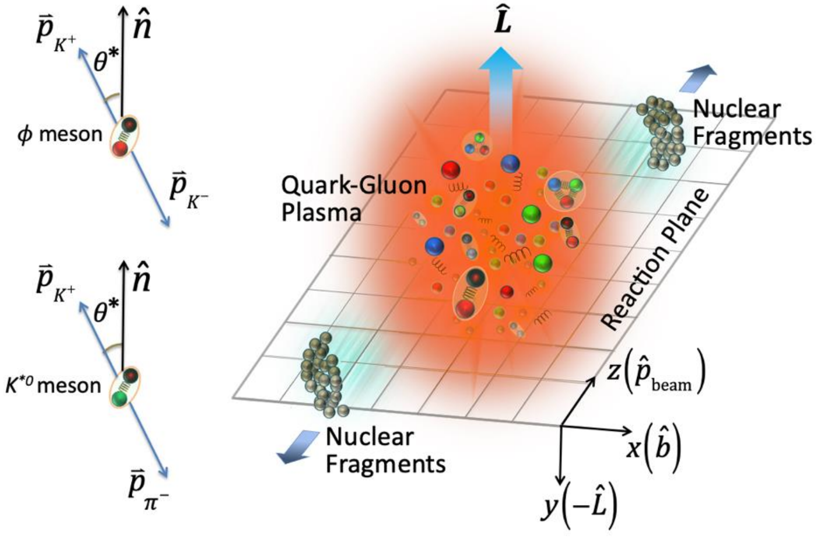

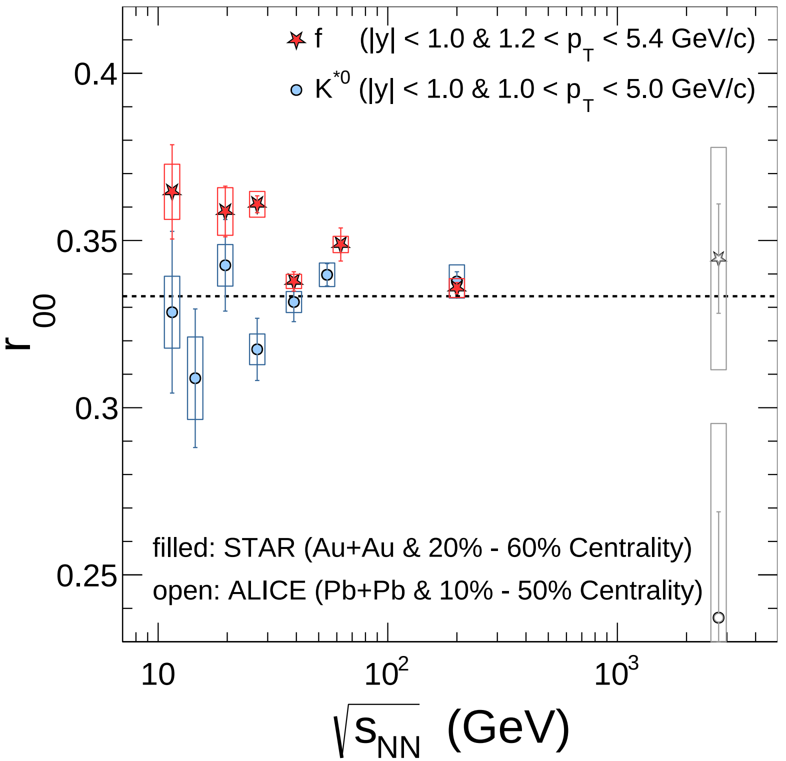

STAR, Nature 614 244 (2023)

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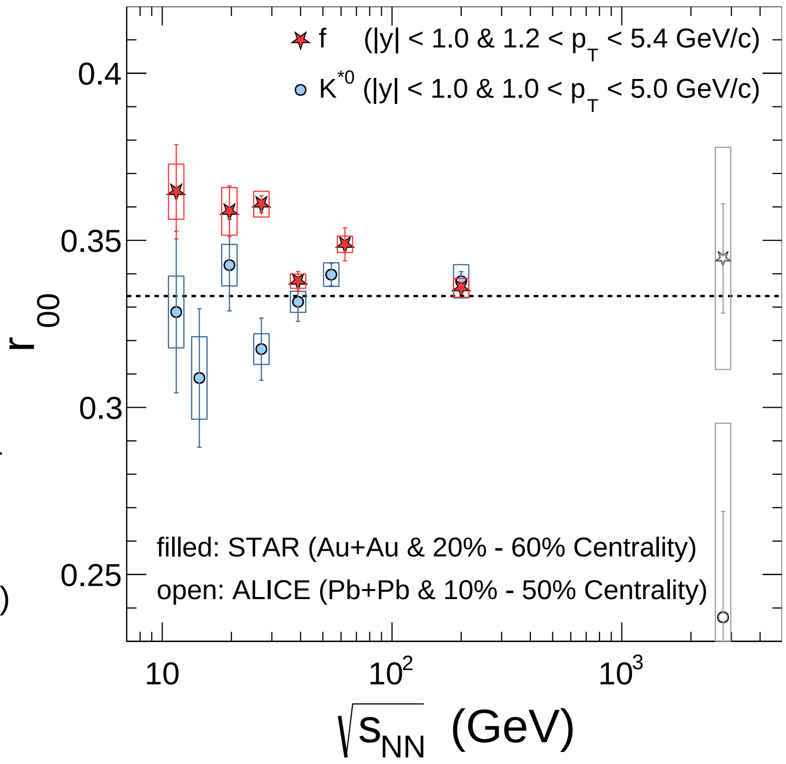
Global Spin Alignment : STAR Results

[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)



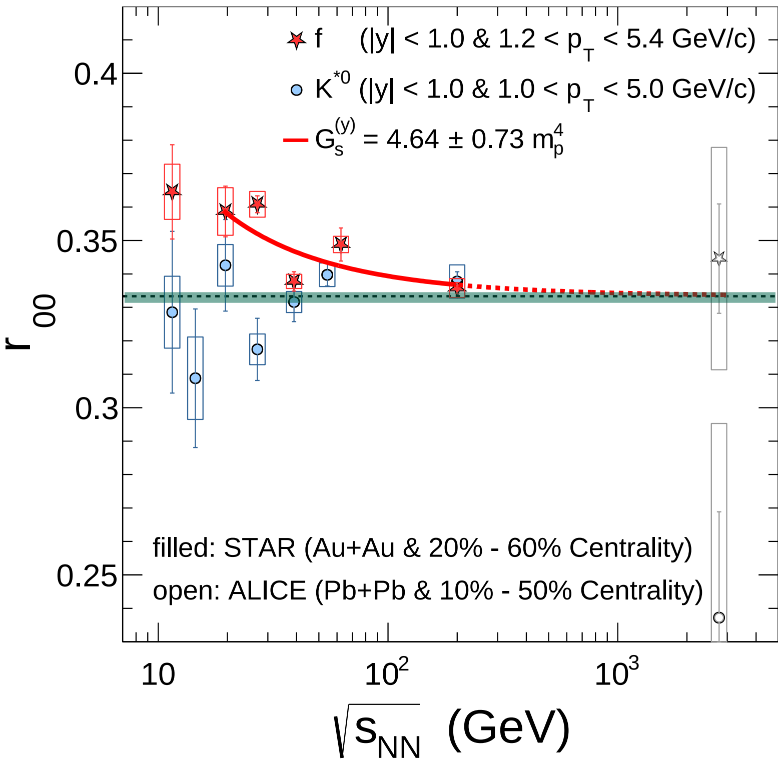
STAR, Nature 614 244 (2023)

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

The Large ρ_{00} Surprise

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

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

$$C_\phi = \frac{G_s^{(y)}}{27 m_s^2 T_{eff}^2}, \qquad G_s^{(y)} = g_\phi^2 \left[3\langle B_{\phi,y}^2 \rangle - \frac{\langle P^2 \rangle_\phi}{m_s^2} \langle E_{\phi,z}^2 + E_{\phi,x}^2 \rangle \right]$$

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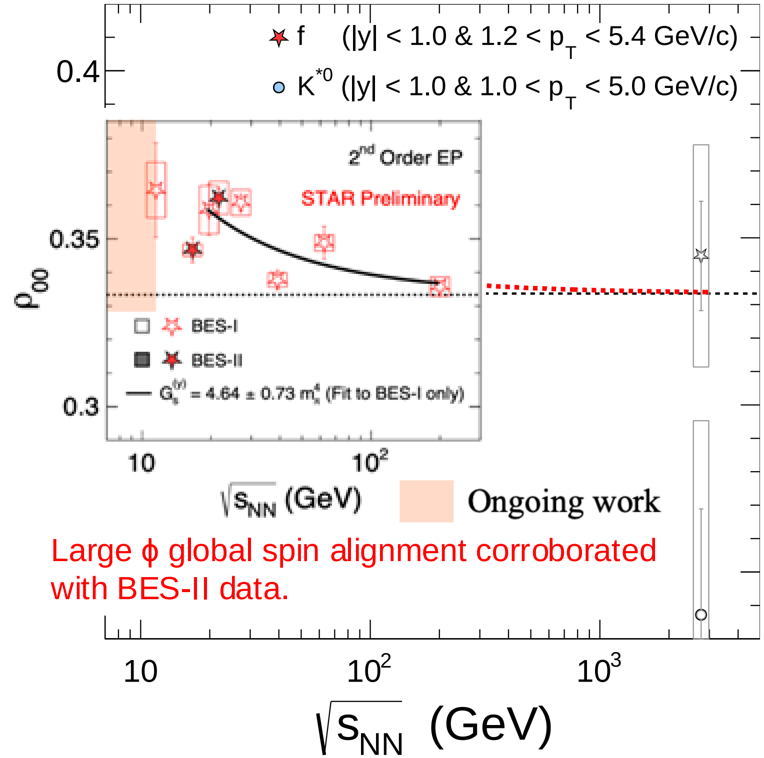

Large ϕ global spin alignment corroborated with BES-II data.

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The Large ρ_{00} Surprise

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

Like electric charges in motion can generate an EM field, s and $\bar{s}$ quarks in motion can generate an effective ϕ-meson field.

The ϕ-meson field can polarize s and $\bar{s}$ quarks with a large magnitude due to strong interaction, in analogy to how EM field polarize (anti)quarks.

$$P^y_{s/\bar{s}}(t, \mathbf{x}, \mathbf{P}_{s/\bar{s}}) = \frac{1}{2}\omega_y + \frac{1}{2m_s}\hat{\mathbf{y}} \cdot (\varepsilon \times \mathbf{P}_{s/\bar{s}}) \quad \Leftarrow \text{vorticity}$$

$$\pm \frac{Q_s}{2m_s T} B_y \pm \frac{Q_s}{2m_s^2 T}\hat{\mathbf{y}} \cdot (\boldsymbol{E} \times \mathbf{P}_{s/\bar{s}}) \quad \Leftarrow \text{EM field}$$

$$\pm \frac{g_\phi}{2m_s T} B_{\phi,y} \pm \frac{g_\phi}{2m_s^2 T}\hat{\mathbf{y}} \cdot (\boldsymbol{E}_\phi \times \mathbf{P}_{s/\bar{s}}) \quad \Leftarrow \text{strong force field}$$

“magnetic” components

“electric” components

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

Sheng et., al., Phys. Rev. D 101, 096005 (2020)

The first time the strong force field is experimentally supported as a key mechanism that leads to global spin alignment.

ϕ-meson Vector Field

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

Rapid Communications

Λ and $\bar{\Lambda}$ spin interaction with meson fields generated by the baryon current in high energy nuclear collisions

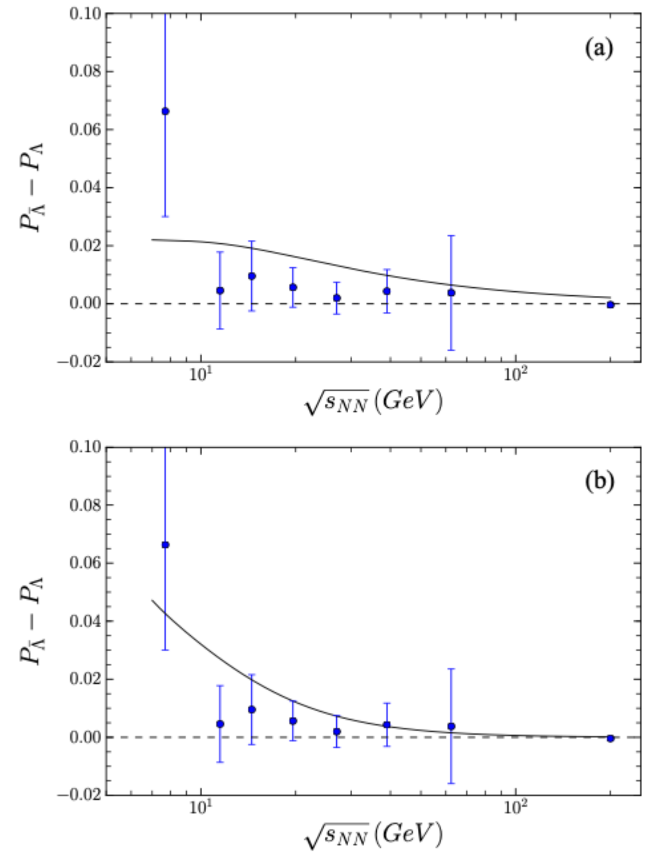
L. P. Csernai,[1] J. I. Kapusta,[2] and T. Welle[2]

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

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

(Received 1 August 2018; revised manuscript received 12 December 2018; published 19 February 2019)

We propose a dynamical mechanism which provides an interaction between the spins of hyperons and antihyperons and the vorticity of the baryon current in noncentral high energy nuclear collisions. The interaction is mediated by massive vector and scalar bosons, which is well known to describe the nuclear spin-orbit force. It follows from the Foldy-Wouthuysen transformation and leads to a strong-interaction Zeeman effect. The interaction may explain the difference in polarizations of Λ and $\bar{\Lambda}$ hyperons as measured by the STAR Collaboration at the BNL Relativistic Heavy Ion Collider. The signs and magnitudes of the meson-baryon couplings are closely connected to the binding energies of hypernuclei and to the abundance of hyperons in neutron stars.

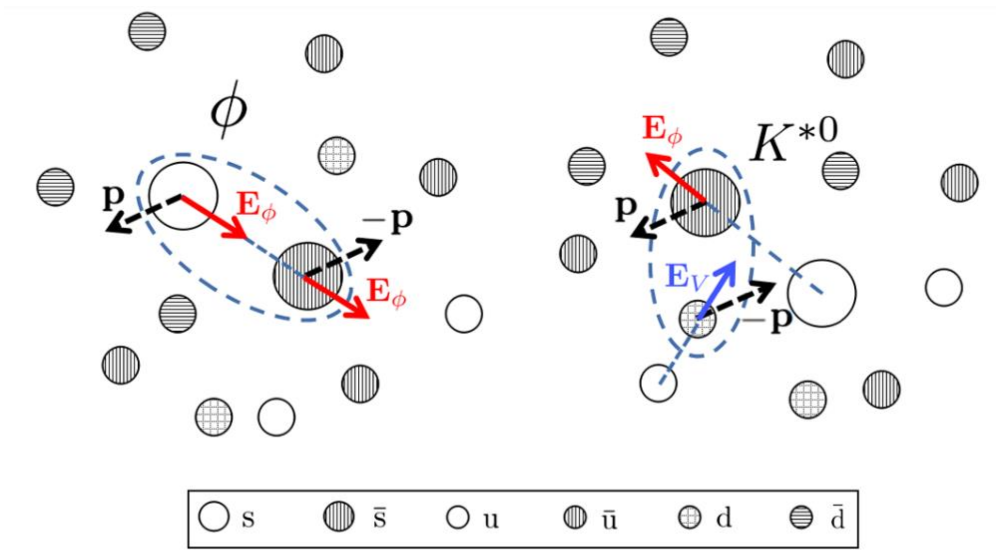


Similar idea to explain $P_{\Lambda} - P_{\overline{\Lambda}}$

What About K^{*0} meson ?

Particle Species	Quark content	Mass (GeV/c²)	Spin	Lifetime (fm/c)
ϕ	$s\bar{s}$	1.092	1	45
K^{*0}	$d\bar{s}$	0.896	1	4

Sheng et., al., Phys. Rev. D 102, 056013 (2020)



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

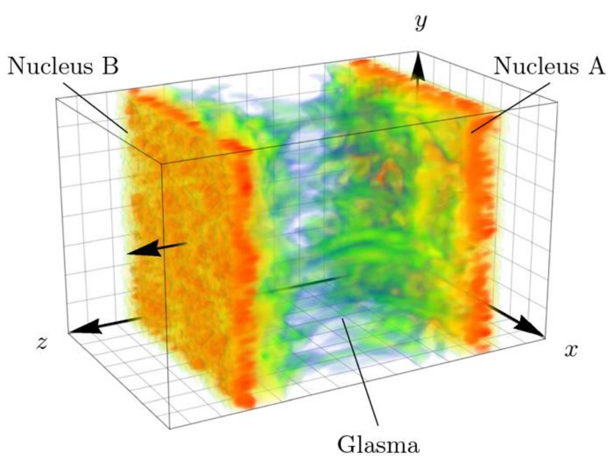
Fluctuation Matters

What do we learn ?

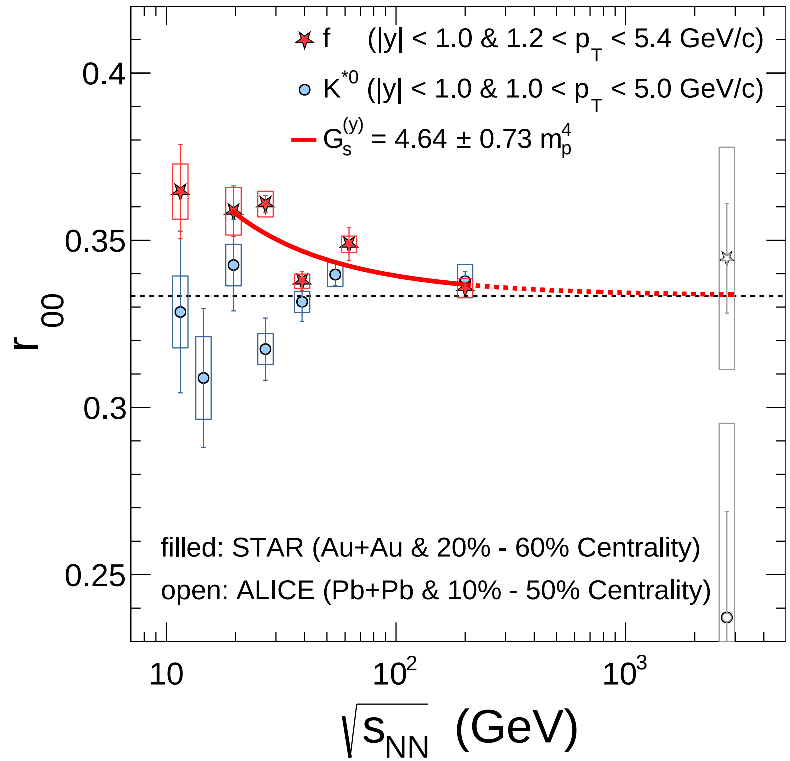
$$\rho_{00}^{V} - \frac{1}{3} \gg P_{\Lambda}^{2} \approx P_{q}^{2}$$

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

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



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

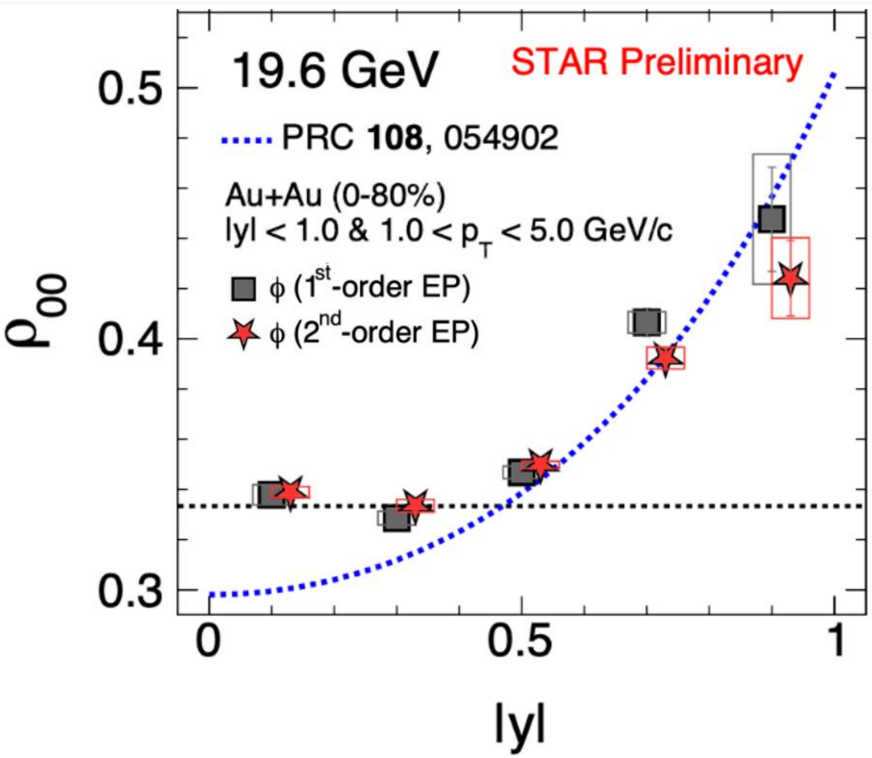


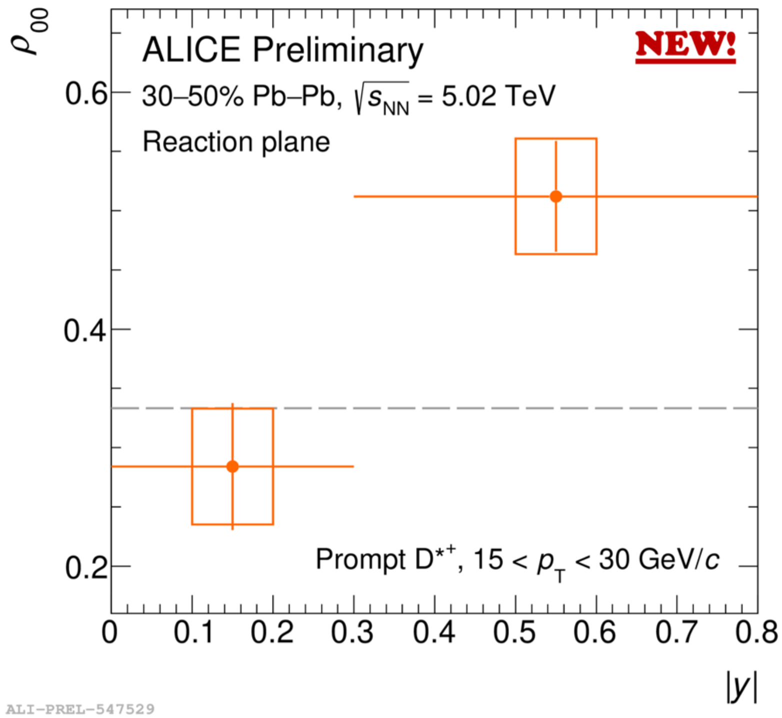
STAR, Nature 614 244 (2023)

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

What does it predict on the rapidity dependence ?

The Rapidity Dependence





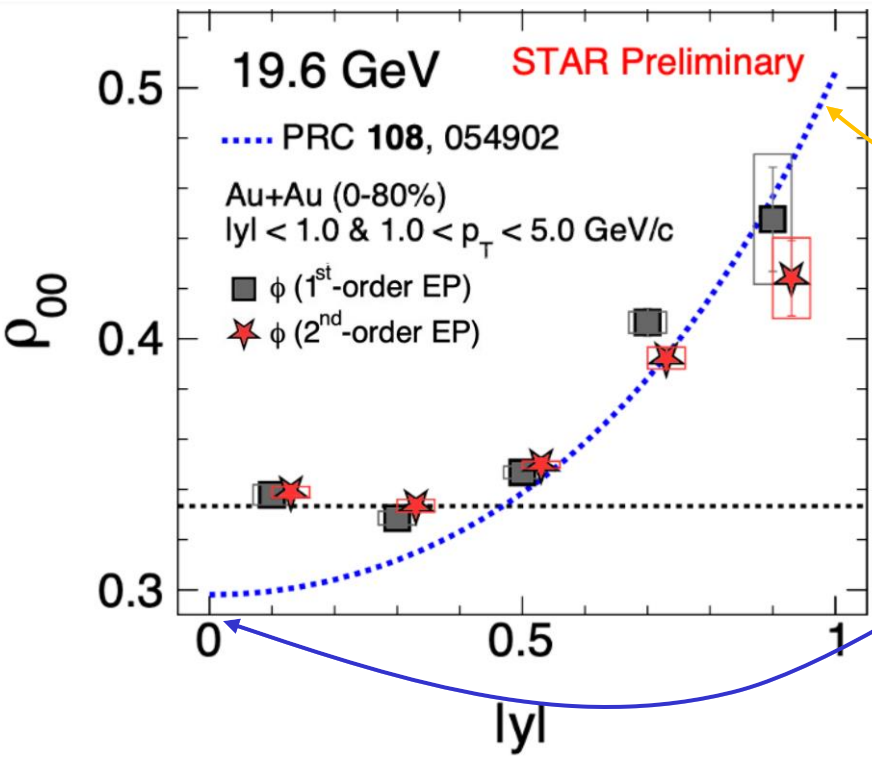
$$D^{*+}\ (c\bar{d}) \rightarrow D^0 + \pi^+$$
$$\quad\hookrightarrow k^- + \pi^+$$

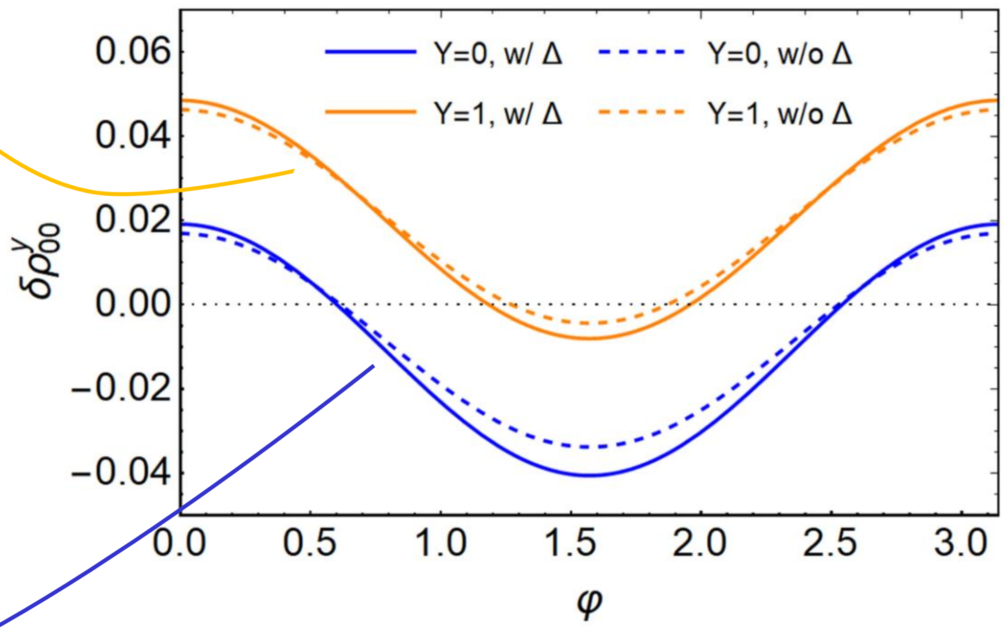
G. Wilks for STAR, SQM 2024
Theory curve : X.L. Sheng, et al., PRC 108 054902 (2023)

L. Micheletti for ALICE, QM2023

Strong rapidity dependence at both RHIC and LHC.
Trend consistent with prediction invoking strong force field.

The Rapidity Dependence





Relative motion to bulk induce asymmetry of fluctuation in rest frame (more severe at forward rapidity), leading to ρ^{z}_{00} < 1/3.

$\rho^{z}_{00} < 1/3 \quad \Rightarrow \quad \rho^{x}_{00} = \rho^{y}_{00} > 1/3$

G. Wilks for STAR, SQM 2024
Theory curve : X.L. Sheng, et al., PRC 108 054902 (2023)

X.L. Sheng, S. Pu and Q. Wang, PRC 108 054902 (2023)

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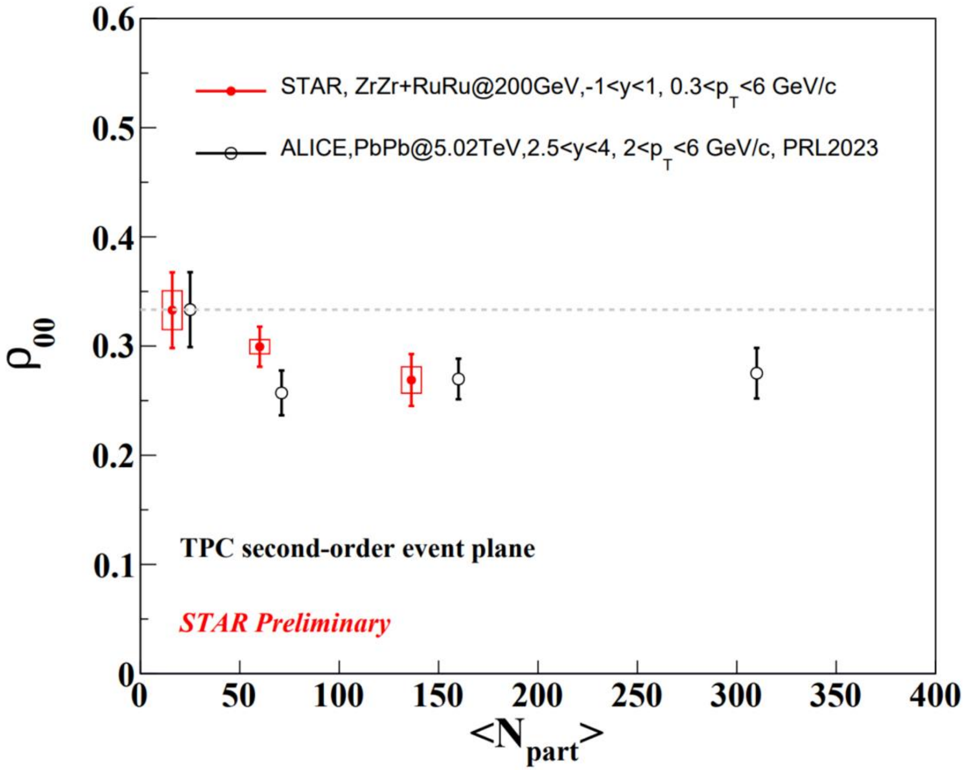
What about J/ψ ?

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

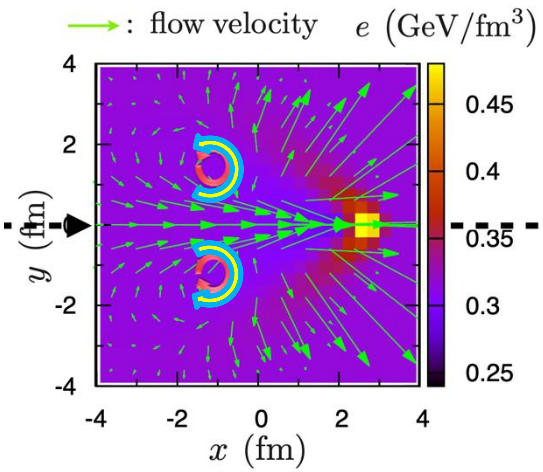


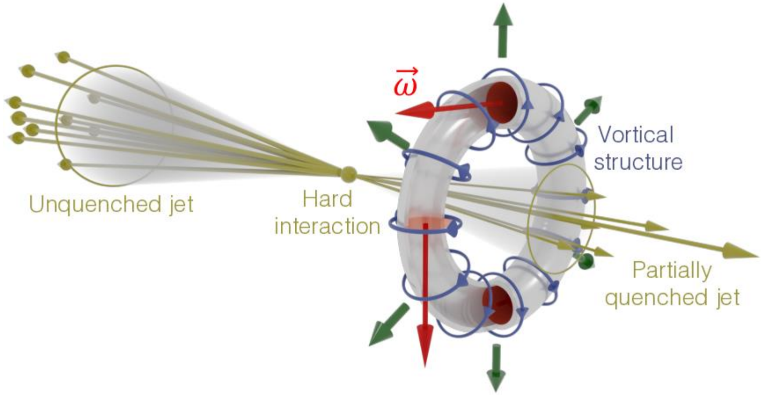
D. Shen for STAR, SPIN 2023
X. Bai for ALICE, SPIN 2023

Forward J/ψ ρ_{00} at LHC and midrapidity J/ψ ρ_{00} < 1/3 at RHIC, both < 1/3.

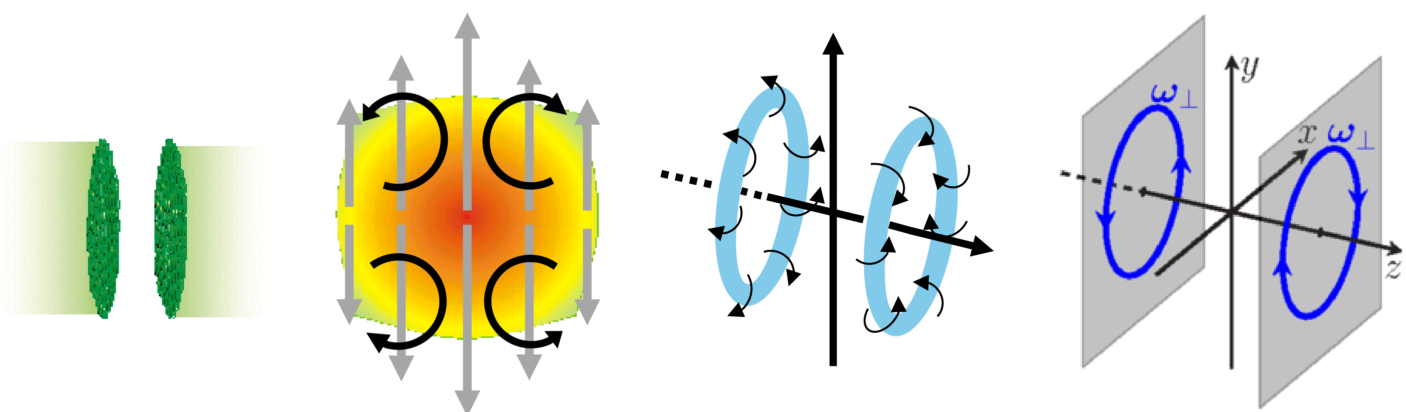
How do we understand J/ψ ρ_{00} ?

Any Hint on Vortical Structure ?





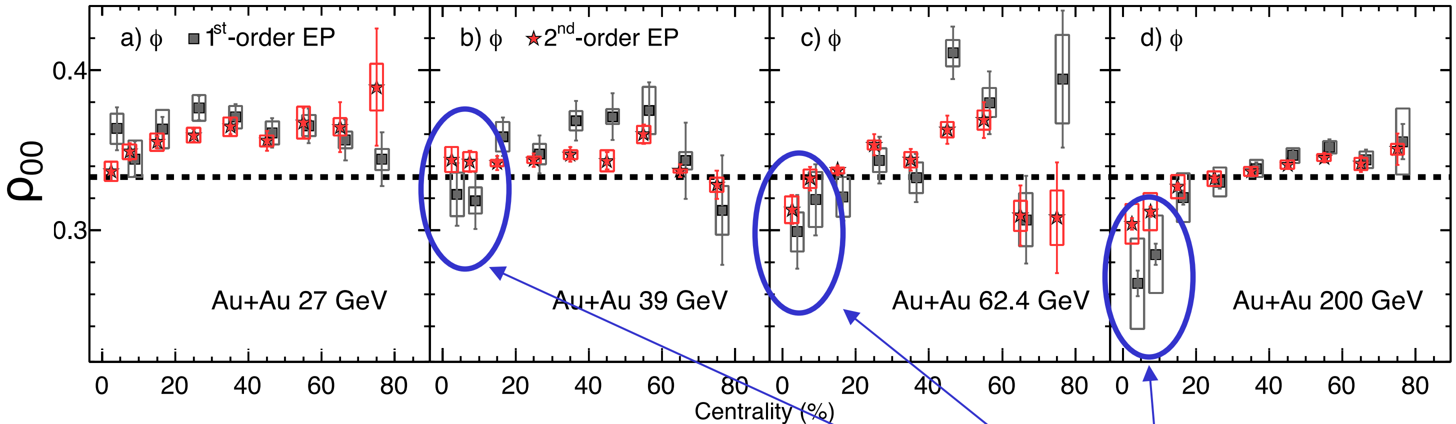
B. Bets, M. Gyulassy and G. Torrieri, PRC 76 044901 (2007)
Y. Tachibana and T. Hirano, NPA 904 1023c (2013)
W.M. Serenone et al, PLB 820 136500 (2021)



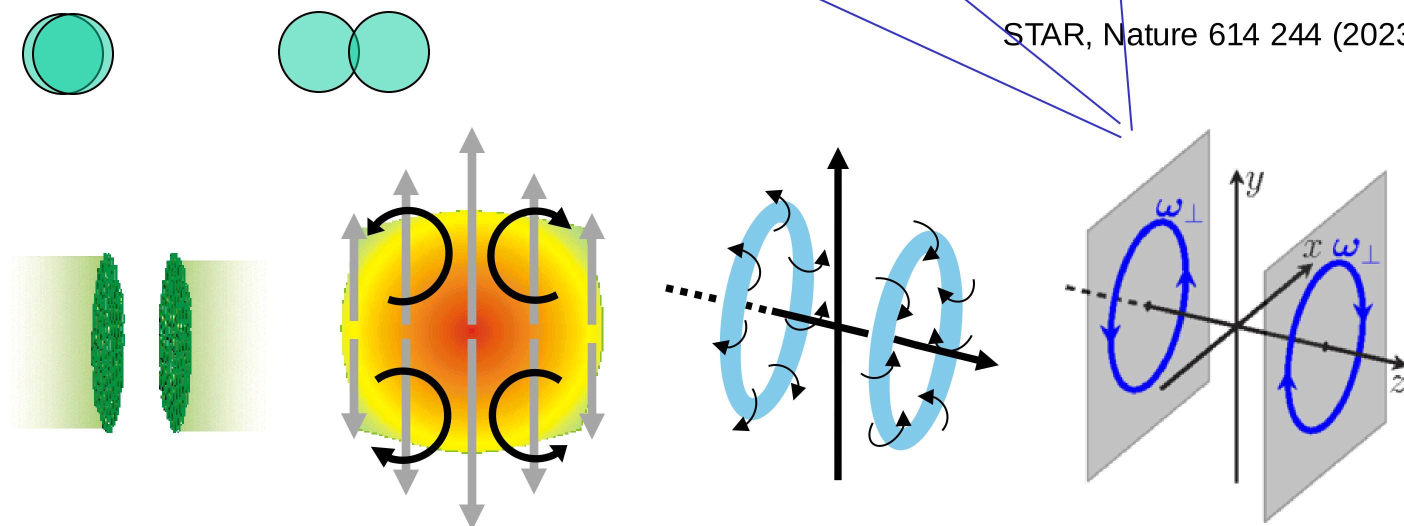
Xia et. al., PRC 98 024905 (2018)
Xia et. al., Phys. Lett. B 817 136325 (2021)

Local ring and toroidal vorticity : unique fluid structures

Centrality Dependence



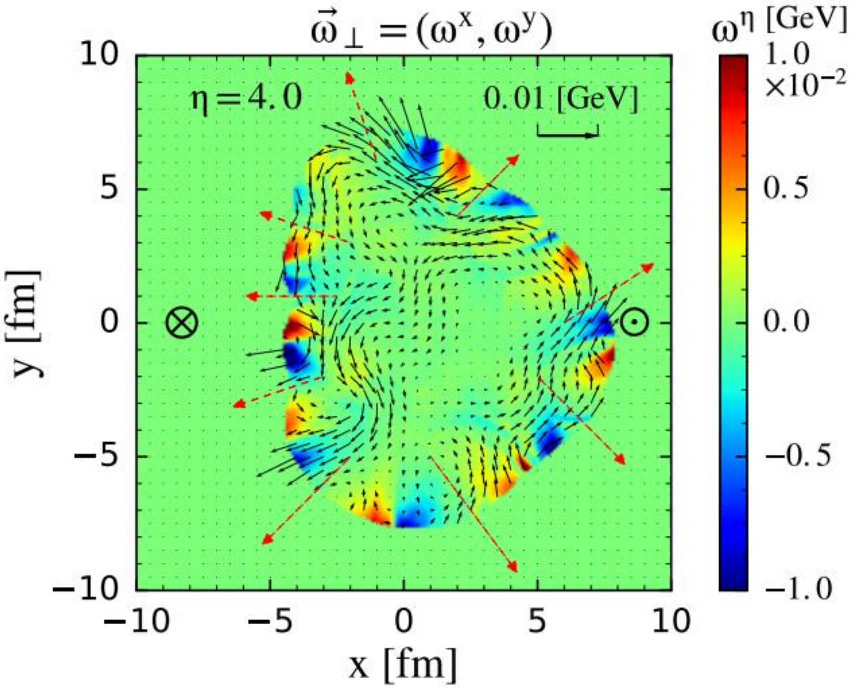
STAR, Nature 614 244 (2023)

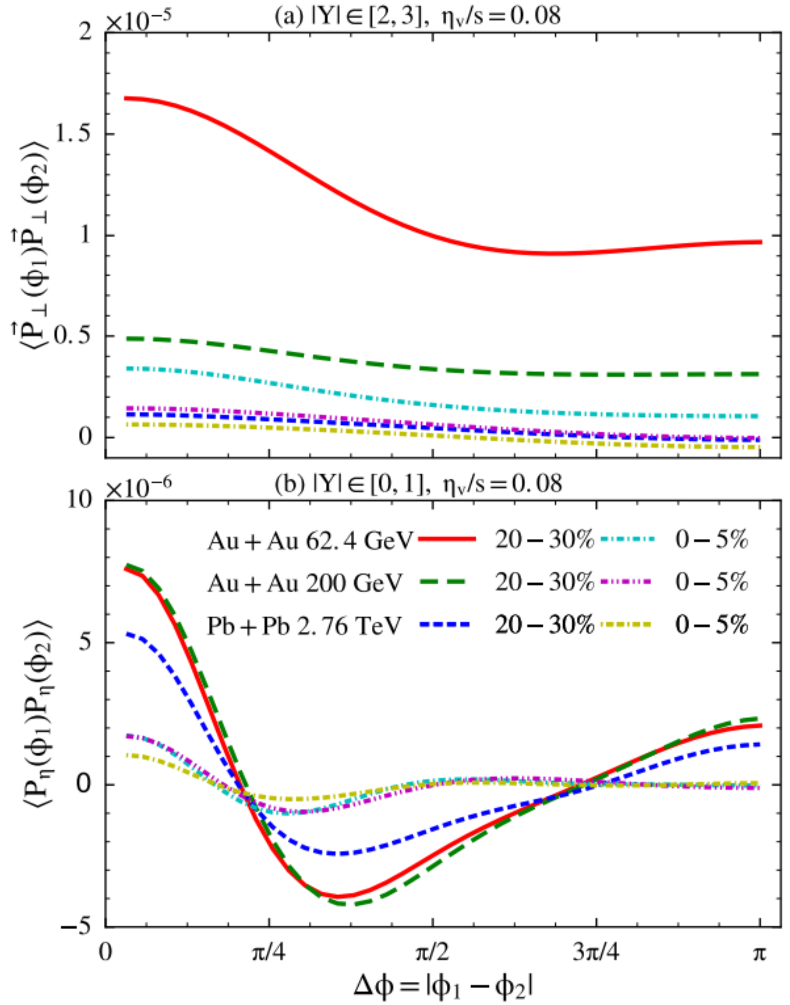


Xia et. al., PRC 98 024905 (2018)
Xia et. al., Phys. Lett. B 817 136325 (2021)

Local ring vorticity from fluid nature in the system ?

Spin-Spin Correlation : Vortical Structure

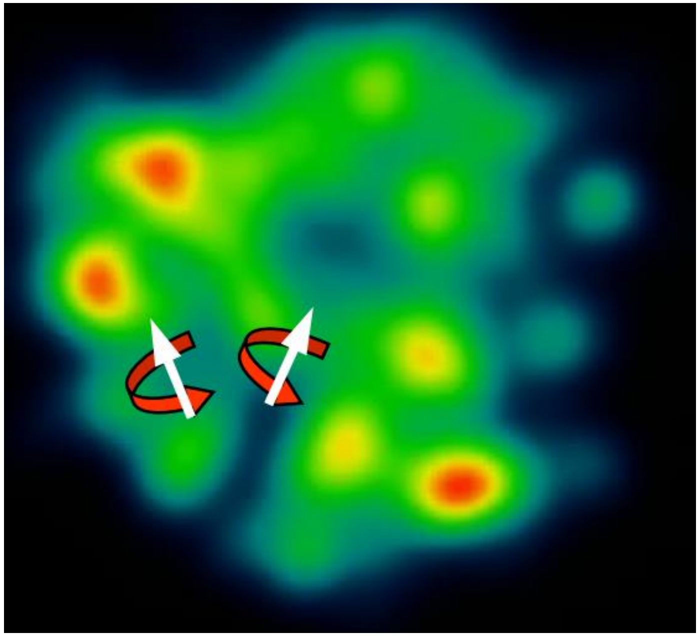




Vortical structure induced spin-spin correlation

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 | $m_1 m_2$ ⟩

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

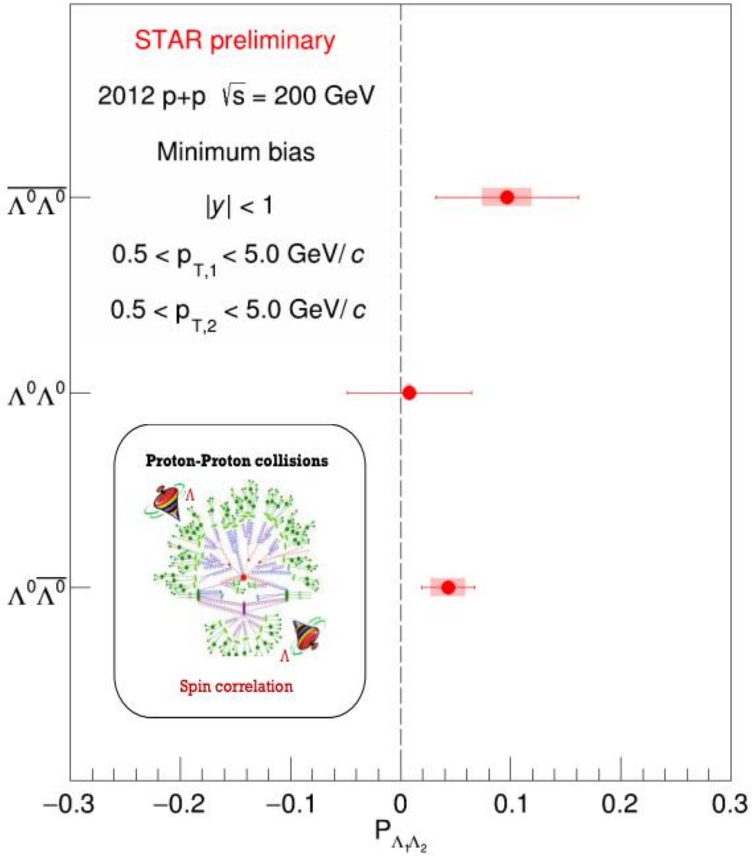
$$c'_{\Lambda\Lambda} = \frac{64}{\pi^2 \alpha_\Lambda^2} \frac{\langle \sin(\phi_i^* - \Psi_{\mathrm{EP}}) \sin(\phi_j^* - \Psi_{\mathrm{EP}}) \rangle}{\langle \cos^2(\Psi_{\mathrm{EP}} - \Psi_{\mathrm{RP}}) \rangle} - P_\Lambda^2$$

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 in pp



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

Jan Vanek for STAR, DIS 2024

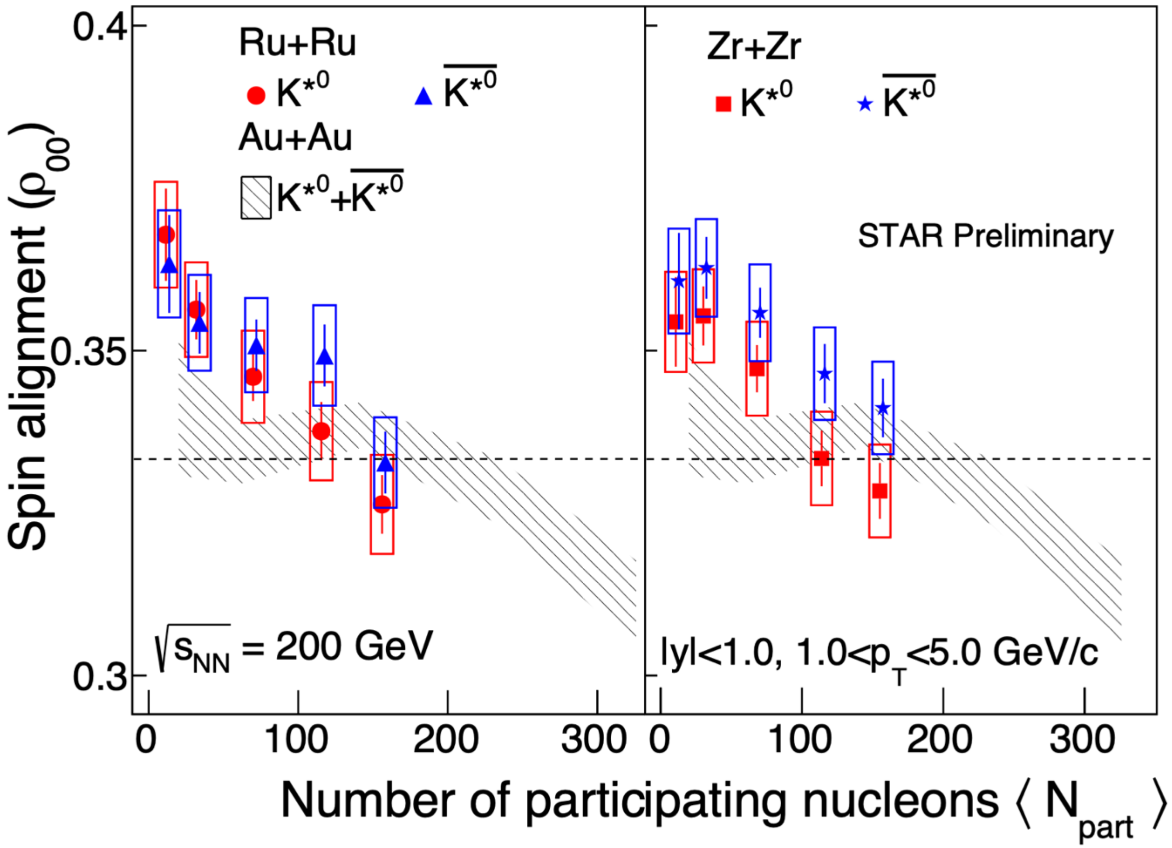
Correlation induced by
parton spin correlation and/or entanglement ?
fragmentation and hadronization ?

Within uncertainty no signal is seen when integrated over phase space.

Desirable to study it differentially.

K^{*0} in Isobar

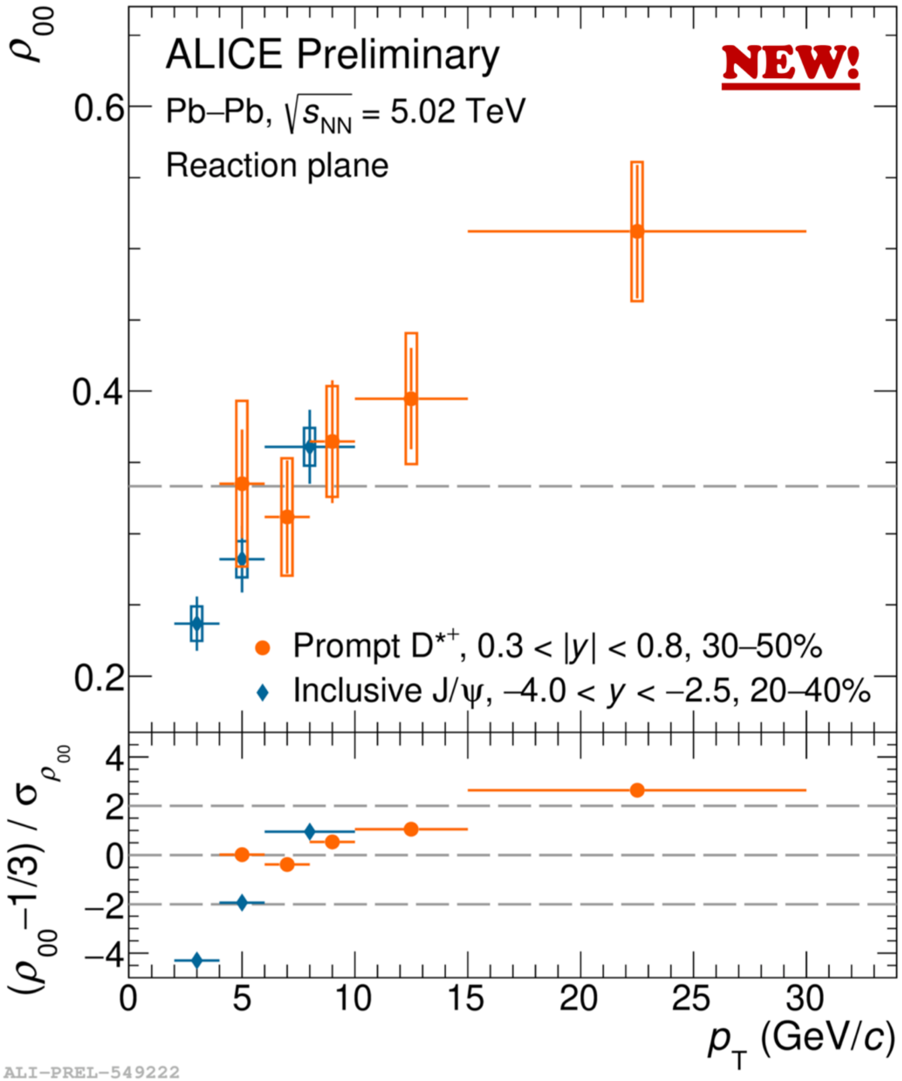
$k^{*0}\ (d\bar{s}) \rightarrow k^{+} + \pi^{-}$



STAR, QM 2022

K^{*0} ρ_{00} > 1/3 at small Npart in isobar.
comparable to AuAu at similar Npart

D^{*+} ρ_{00}



X. Bai for ALICE, SPIN2023

D^{*+} $(c\bar{d}) \rightarrow D^0 + \pi^+$
$\hookrightarrow k^- + \pi^+$

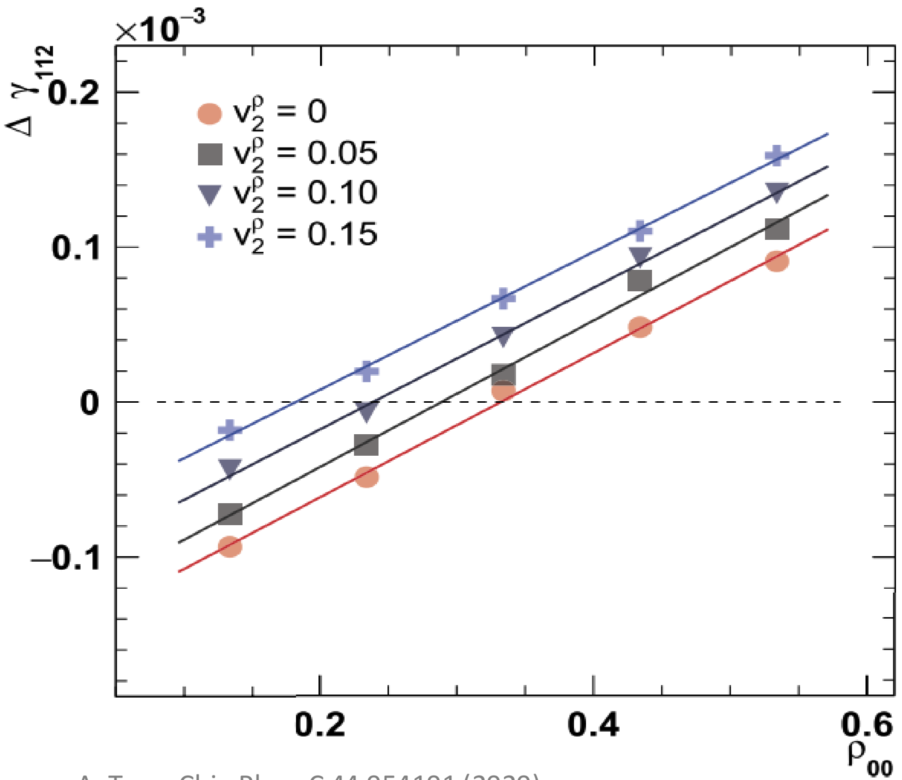
Expectation :
from Recombination : < 1/3
from Fragmentation : > 1/3

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 pt.

However, quantitative agreement could be very challenging.

ρ_{00} and CME

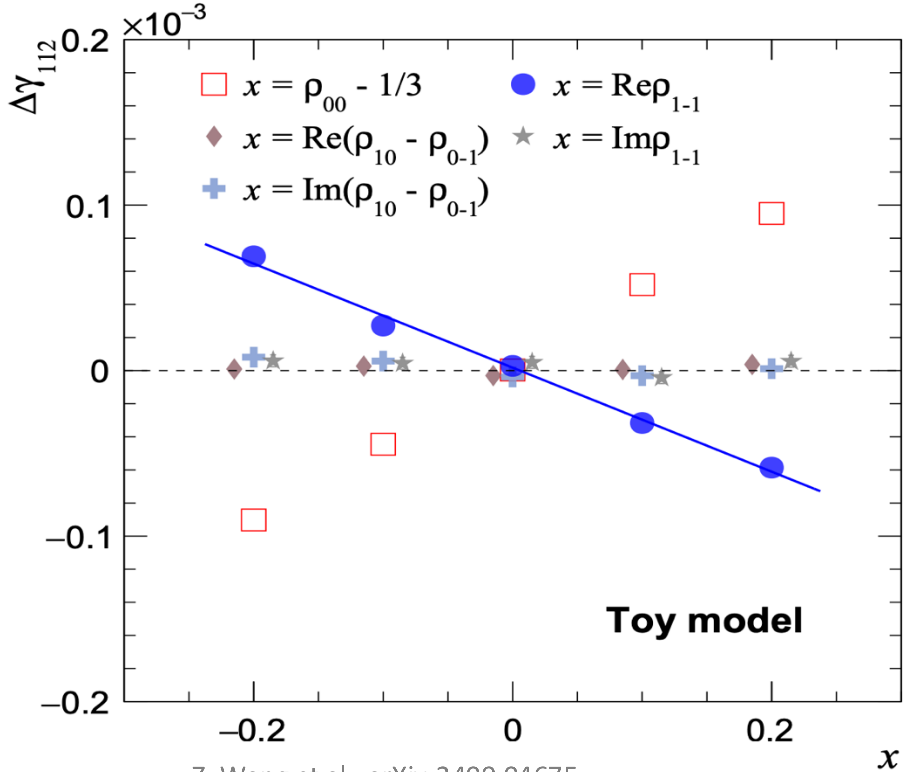


A. Tang, Chin Phys. C 44 054101 (2020)
D. Shen et al., PLB 839 137777 (2023)

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

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

ρ_{1-1} and CME



Z. Wang et al., arXiv:2409.04675

ρ_{1-1} affects $\Delta\gamma$ in opposite way to ρ_{00}

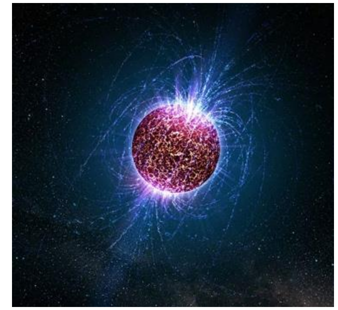
How to properly account for ρ-meson ρ_{00} in CME analyses ?

Spin is aligned, let's add some magnetism to the mix …

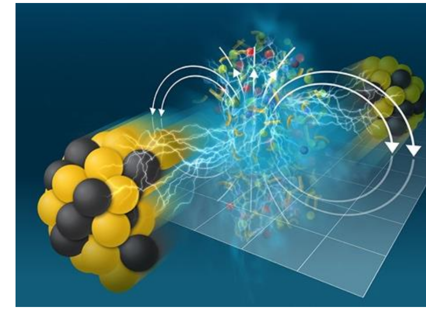
The Strongest EM Field, But Do We "See" It ?

Earth
~ 0.5 Gauss

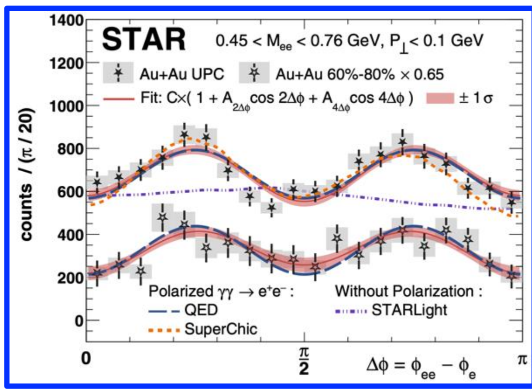
Lightning
~ 10^3 - 10^4 Gauss



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

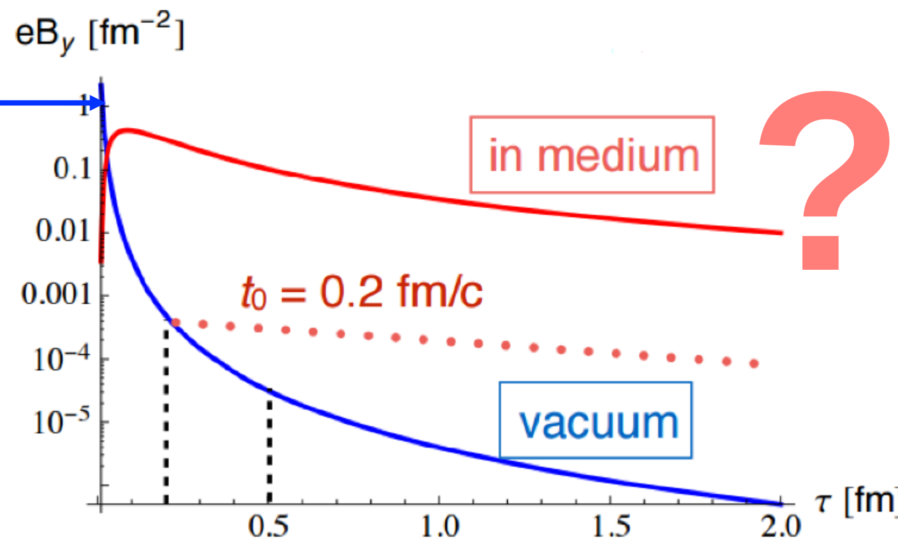


Heavy ion collisions
~ 10^{18} Gauss



STAR, PRL 127, 052302 (2021)

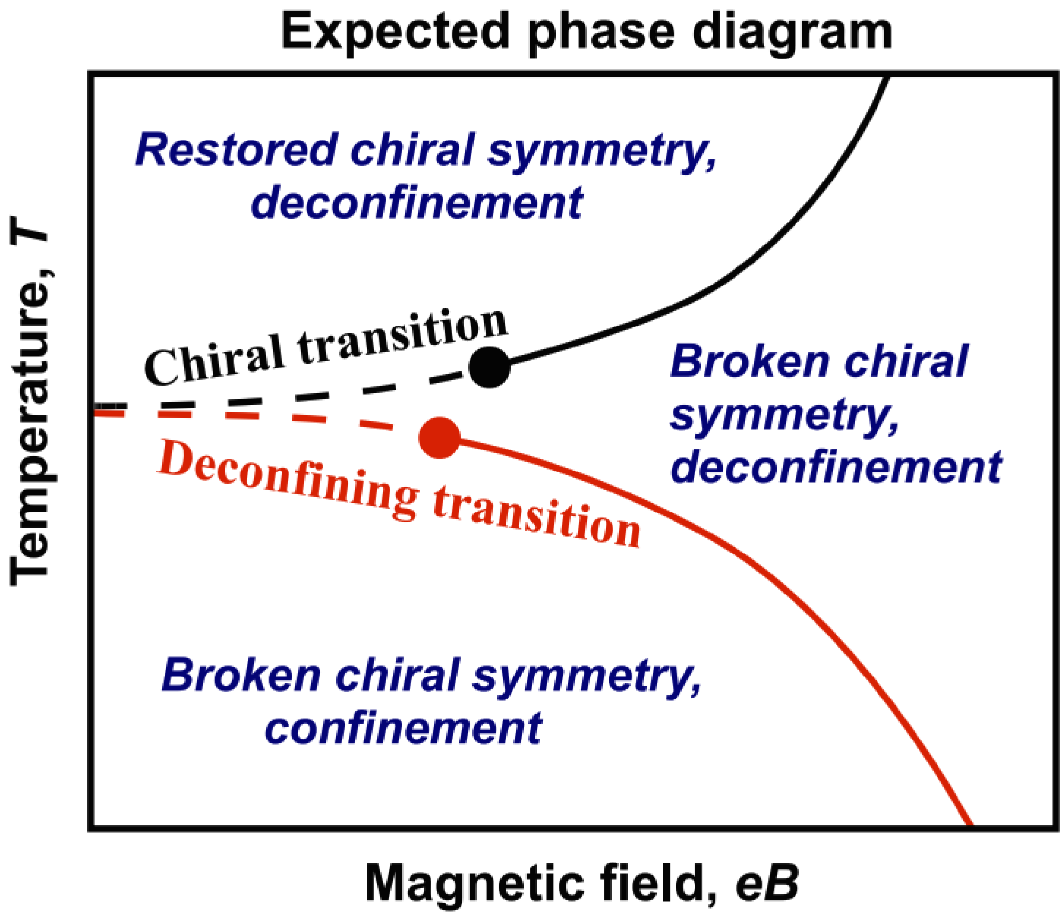
Vacuum birefringence
vacuum + strong B



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

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

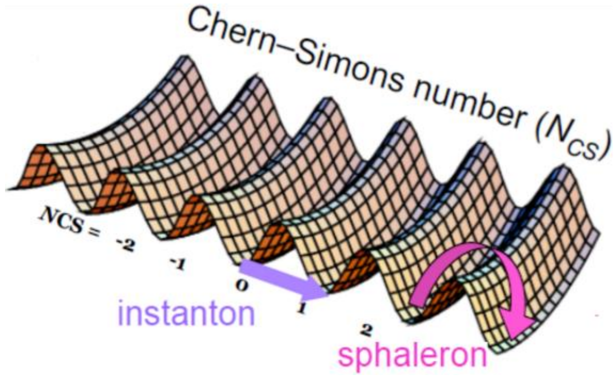
EM Field and Phase Diagram



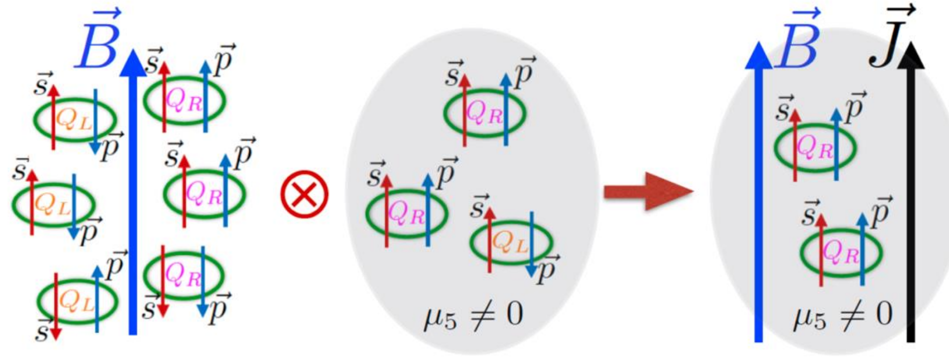
Mizher, Chernodub and Fraga, PRD 82 105016 (2010)
E. Fraga and A. Mizher, PRD 78 025016 (2008)

Rich structure of QCD phase diagram under strong EM field.

EM Field and CME



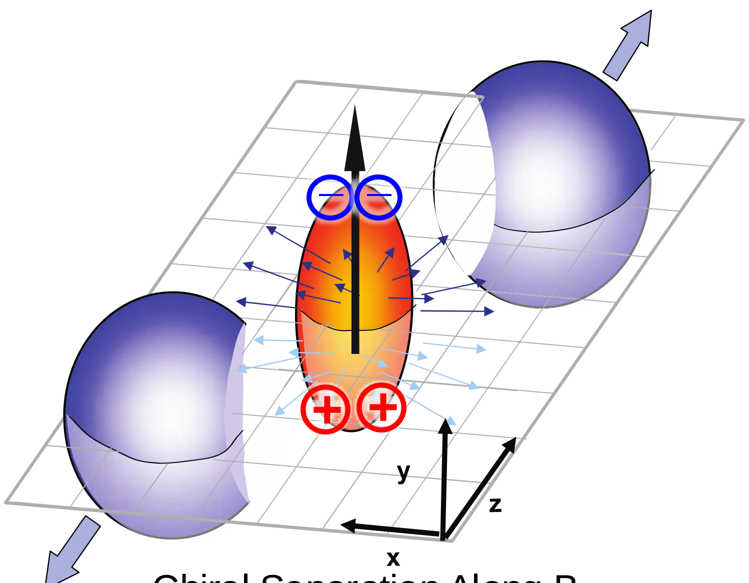
QCD vacuum topology (finite μ_5)



Chiral Magnetic Effect

Charge current

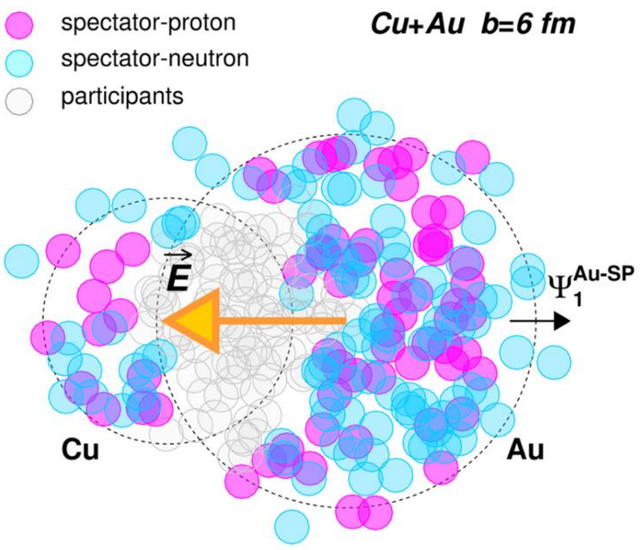
$$j_V = \frac{N_c e}{2\pi^2}\mu_A B$$



Chiral Separation Along B

Chiral Magnetic Effect with strong magnetic field.

Probe E Field in Cu + Au Collisions



Asymmetric collisions (Cu+Au) create in-plane E fields.

Charge-dependence of v_1

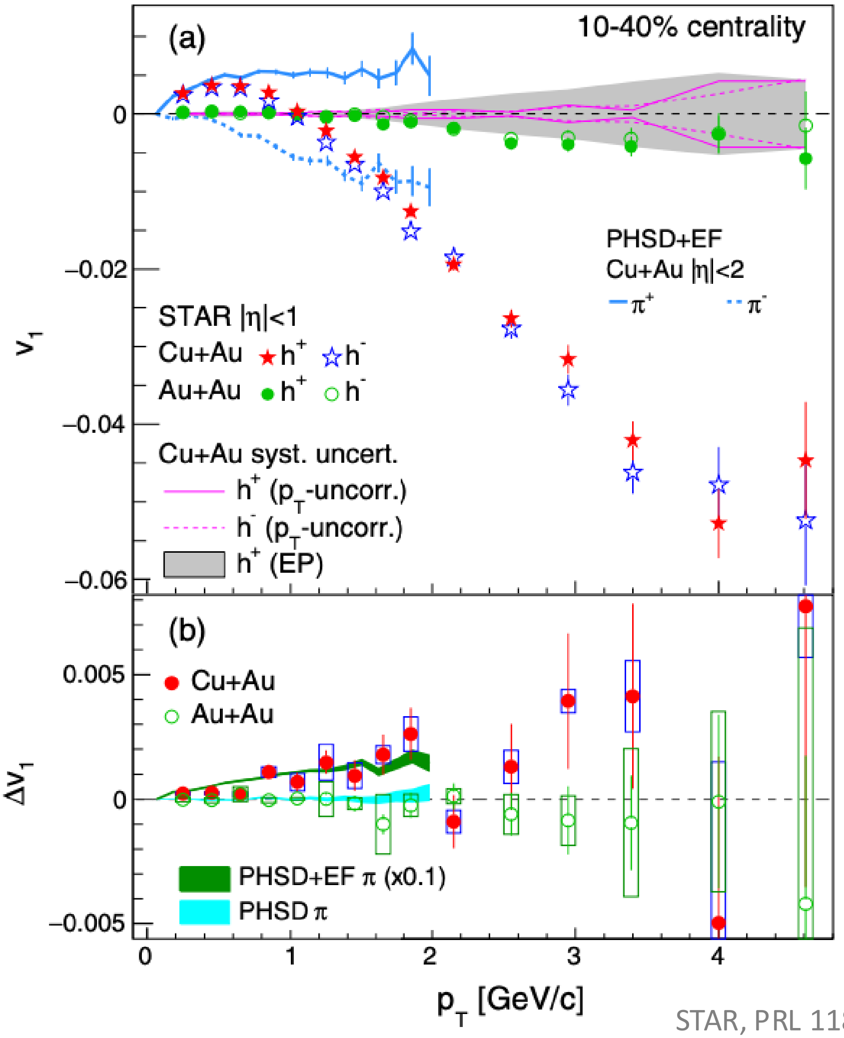
$$v_1^{\pm} = v_1 \pm A d'_e$$

$$A d'_e \sim -\frac{\pi \sigma \tau}{N_{\rm tot}|e|} \int_S \vec{E} \cdot d\vec{S}$$

Hirono, Hongo and Hirano, Phys. Rev. C 90, 021903 (2014)
...

Study electric conductivity of medium via Cu+Au collisions

Evidence of the Coulomb Field



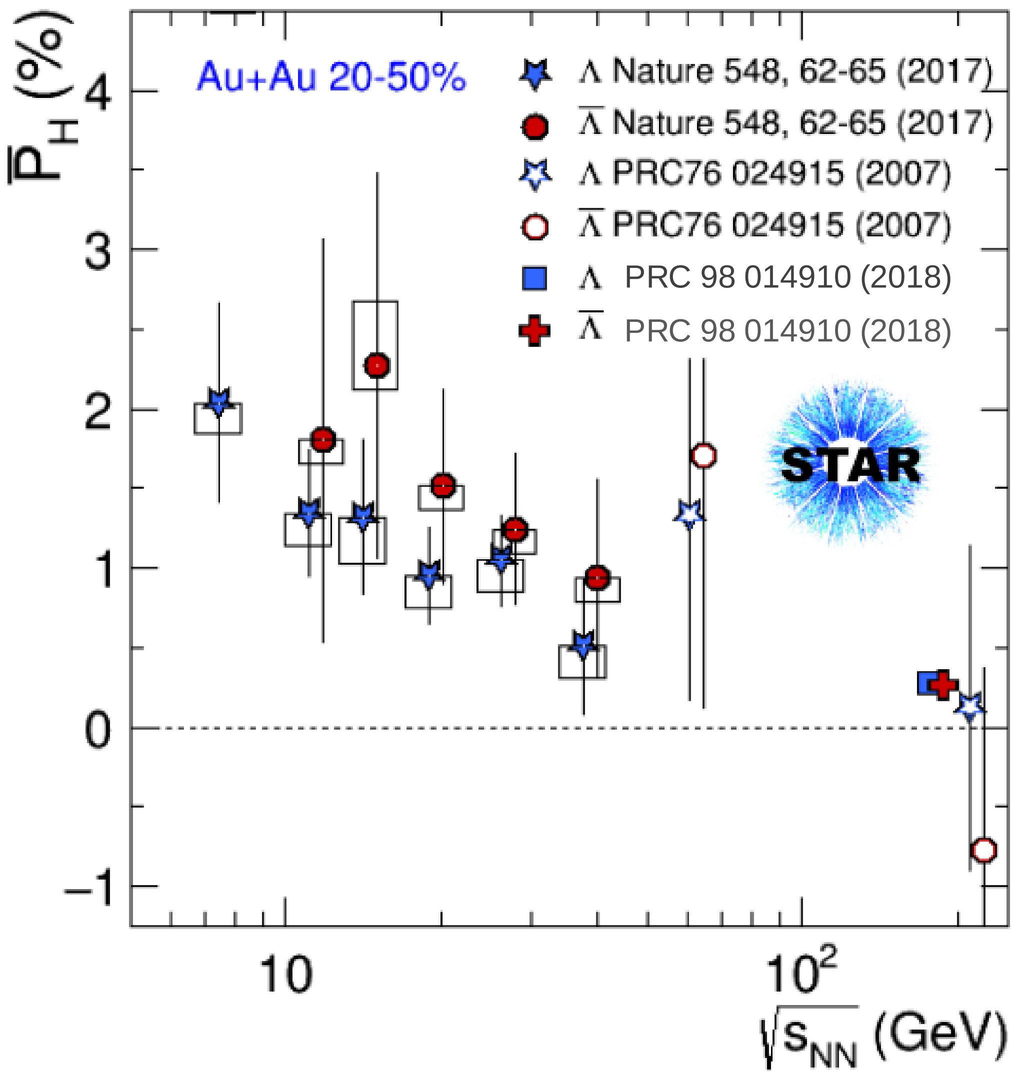
STAR, PRL 118 012301 (2017)

Qualitatively agrees with expectation from strong E field

10 times smaller than PHSD which uses a lower value of σ. Probably due to that (anti)quarks not all created when EF is strong (< 1 fm).

Study electric conductivity of medium via Cu+Au collisions

Λ and anti-Λ Polarization

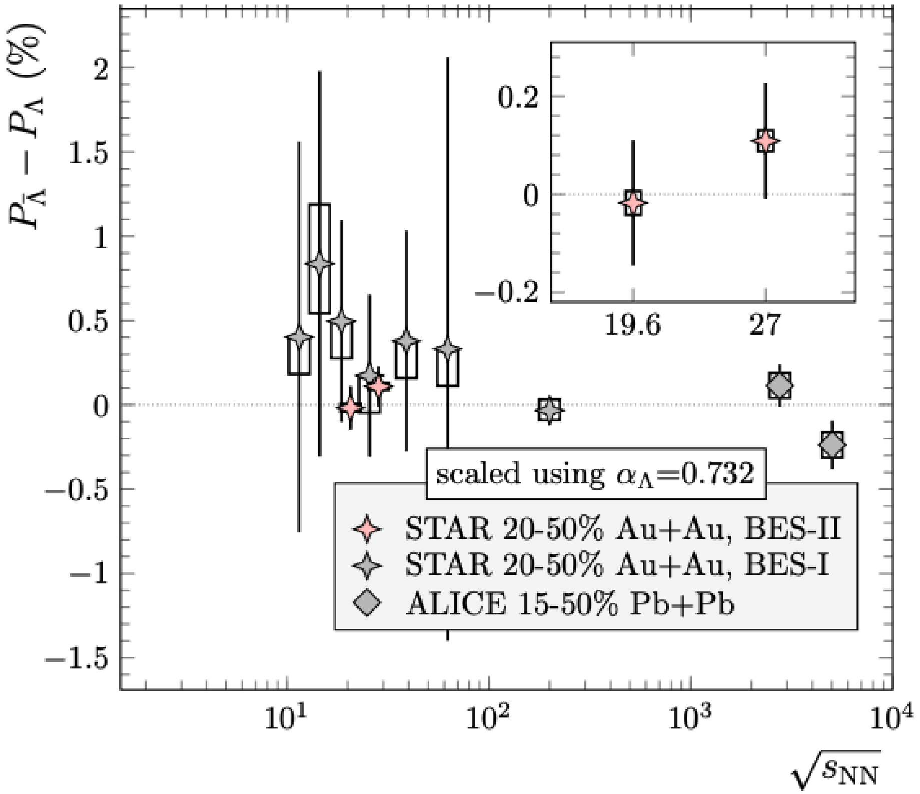


$$P_\Lambda \approx \frac{1}{2}\frac{\omega}{T} + \frac{\mu_\Lambda B}{T}$$

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

Challenging to see the B effect at later stage

Λ and anti-Λ Polarization

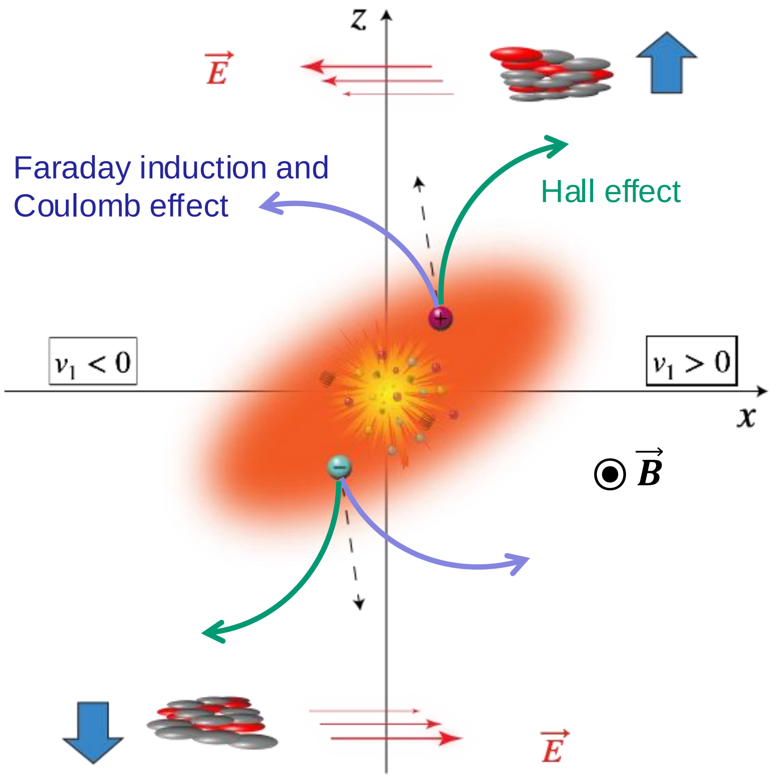


STAR, PRC 108 014910 (2023)

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

Challenging to see the B effect at later stage

EM field : Hall, Faraday and Coulomb Effect



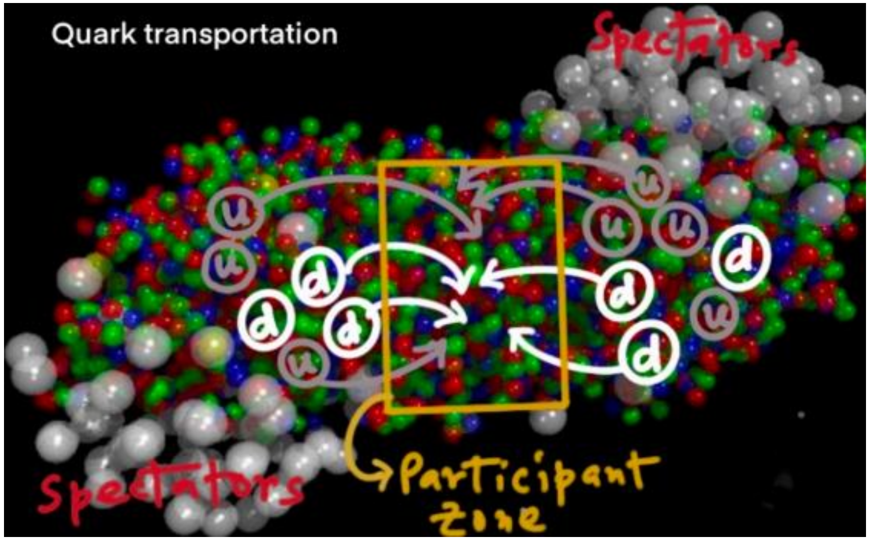
Hall effect (Lorentz force) and Faraday + Coulomb effect compete each other.

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)

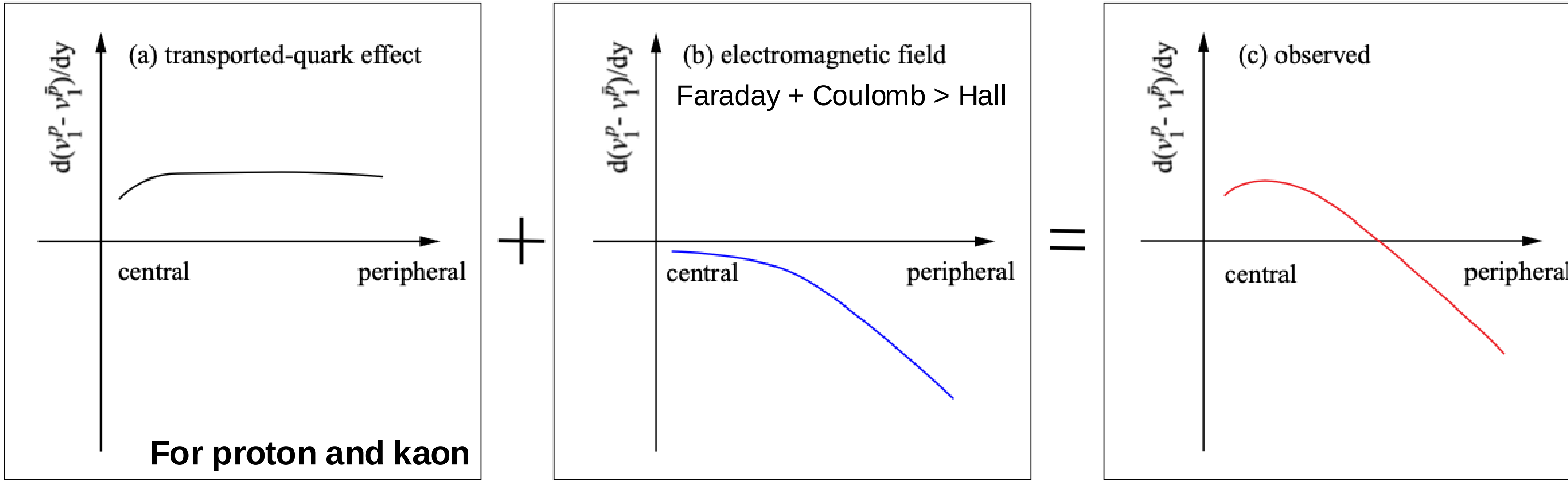
Dunlop, Lisa and Sorensen, PRC 84 044914 (2011)
Guo, Liu and Tang, PRC 86 044901 (2012)
Nayak, Shi, Xu and Lin, PRC 100 054903 (2019)
P. Bozek, PRC 106 L061901 (2022)

Transported quarks carry information from incident nucleons, causing v_1 splitting.

Interplay between Effects

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

(Heavy quarks) (Light quarks)



Transported quark effect :

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

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

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

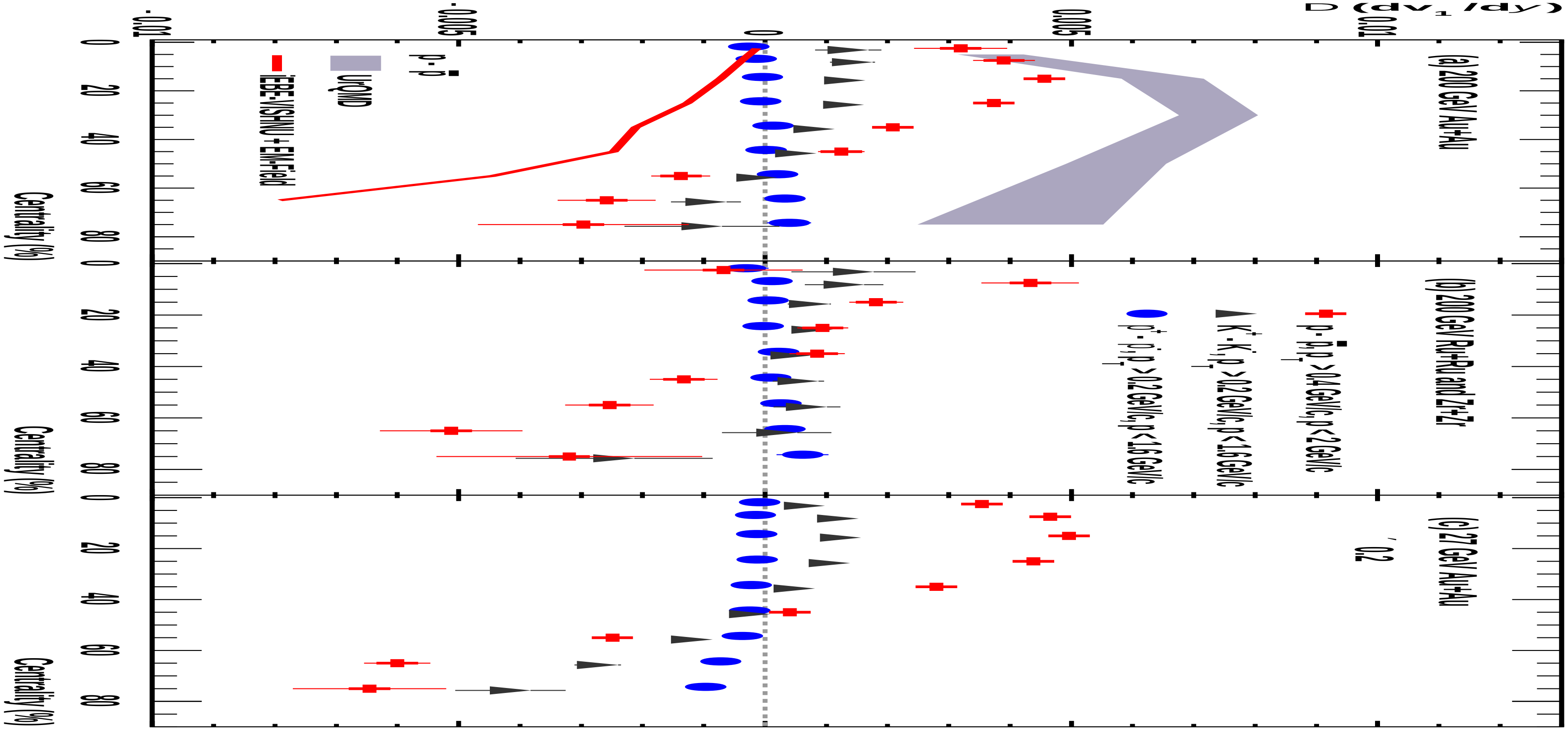
Similar pattern expected for kaons.

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

(#d > #u, Au neutron rich)

No sign change expected for pions.

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



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=0.023 fm^{-1})

Strong evidence in favor of EM field at work in QGP

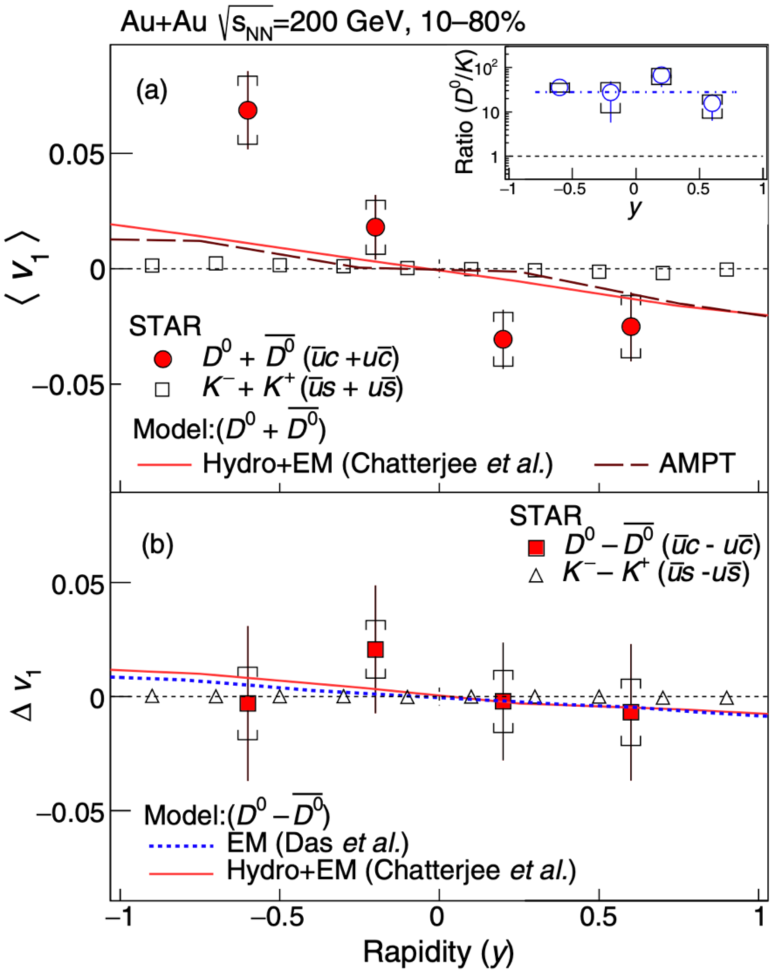
Summary

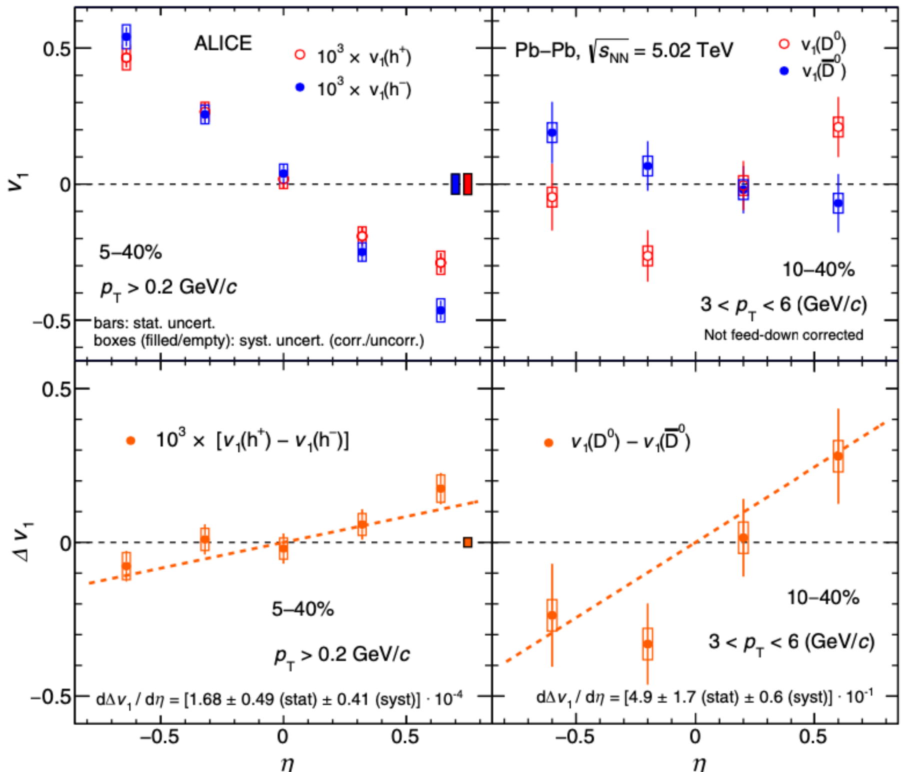
The study of global spin properties in extreme conditions has opened new promising research directions. Recent findings also highlight the significant role of magnetic fields at RHIC, deepening our understanding of spin dynamics.

As is typical in emerging fields, numerous unanswered questions beckon, offering fertile ground for future investigation and inquiry.

Backup Slides

v_1 Splitting of D Mesons





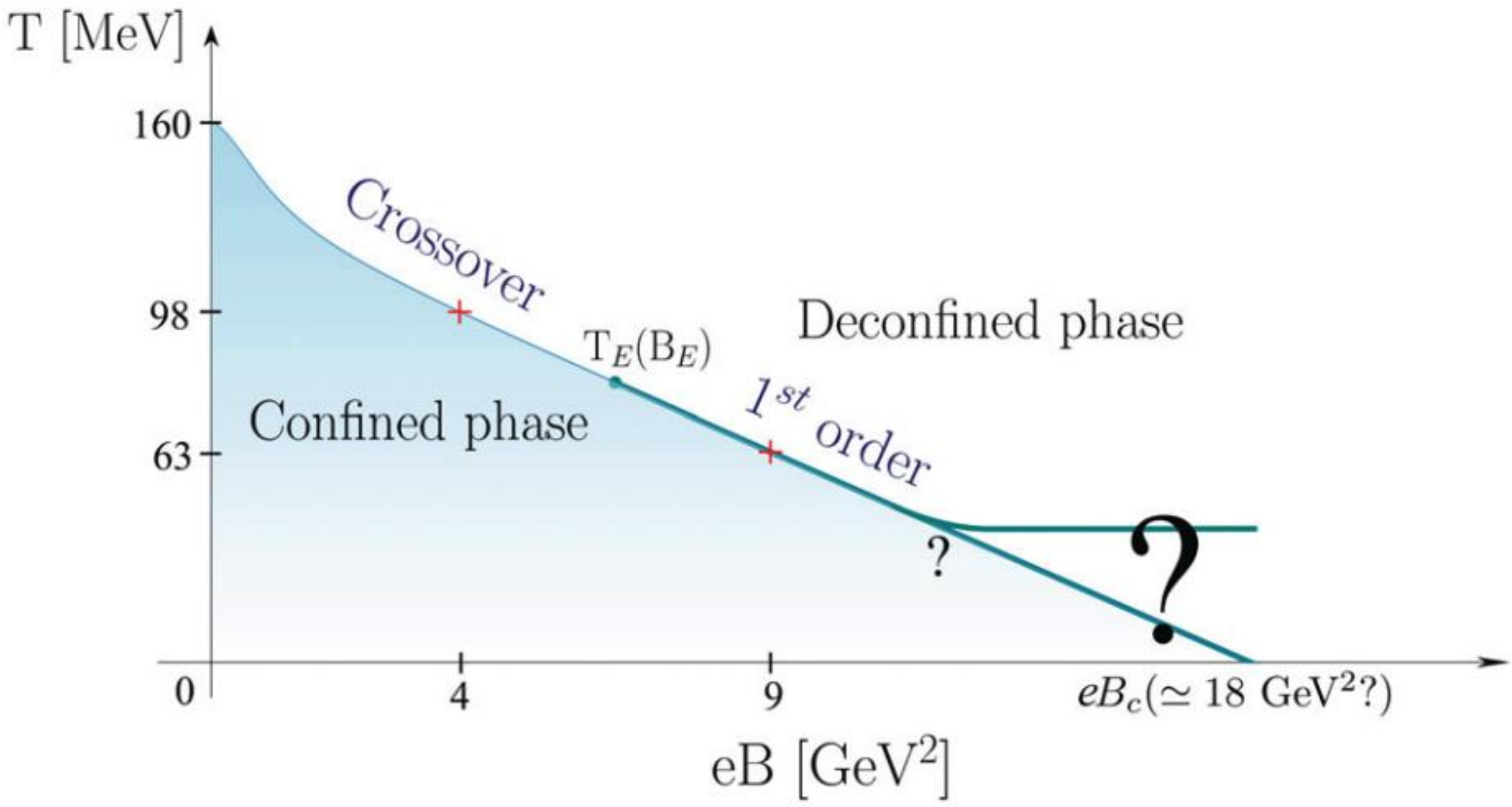
ALICE, PRL 125 022301 (2020)

Large v_1 and large v_1 splitting

STAR, PRL 123 162301 (2019)

Consistent with Hall effect dominating for heavy quarks.

EM Field and Phase Diagram



M Elia, L. Maio, F. Sanfilippo and A. Stanzione, PRD 105 034511 (2022)

QCD phase diagram under strong EM field.