



Meeting SIM e PRIN2022
Laboratori Nazionali del Sud (LNS) – INFN
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SPIN ALIGNMENT OF VECTOR MESONS IN HEAVY-ION COLLISIONS

Lucia Oliva

Collaborators

Vincenzo Greco, Salvatore Plumari

Xin-Li Sheng, Qun Wang

Zuo-Tang Liang, Xin-Nian Wang



UNIVERSITÀ
degli STUDI
di CATANIA



DIPARTIMENTO DI
FISICA E
ASTRONOMIA
"ETTORE MAJORANA"

INTENSE FIELDS IN HEAVY-ION COLLISIONS

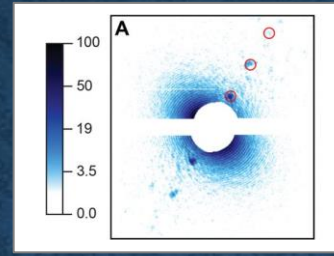
vorticity
 ω



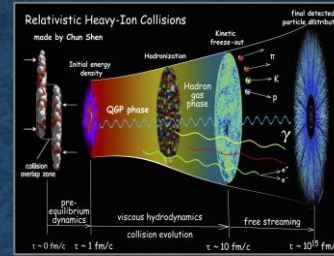
tornado cores
 $\sim 10^{-1} \text{ s}^{-1}$



Jupiter's spot
 $\sim 10^{-4} \text{ s}^{-1}$



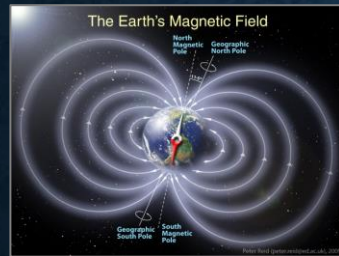
He nanodroplets
 $\sim 10^7 \text{ s}^{-1}$



urHICs
 $\sim 10^{22} - 10^{23} \text{ s}^{-1}$

**HUGE ANGULAR MOMENTUM
GENERATING A STRONG
VORTICITY**

magnetic
field
 B



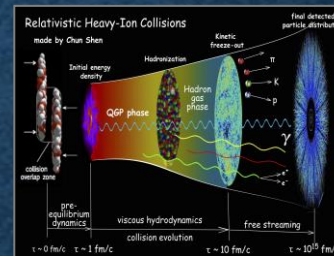
Earth's field
 $\sim 1 \text{ G}$



laboratory
 $\sim 10^6 \text{ G}$



magnetars
 $\sim 10^{14} - 10^{15} \text{ G}$



urHICs
 $\sim 10^{18} - 10^{19} \text{ G}$

**INTENSE ELECTRIC AND
MAGNETIC FIELDS**

How to probe them in
heavy-ion collisions?



INTENSE FIELDS IN HEAVY-ION COLLISIONS

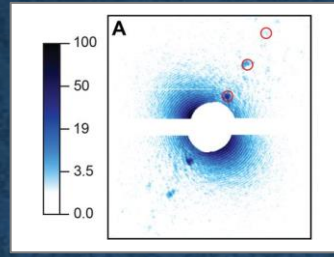
vorticity
 ω



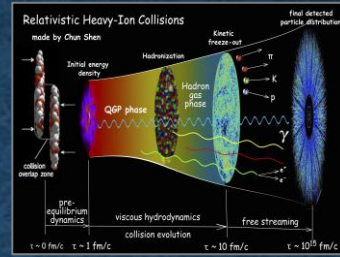
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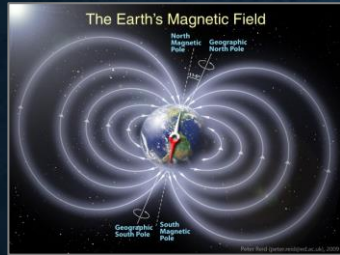
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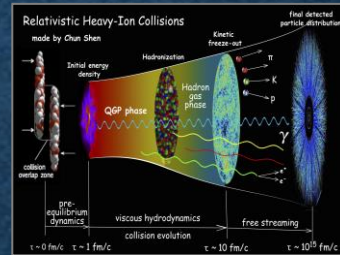
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**INTENSE ELECTRIC AND
MAGNETIC FIELDS**

How to probe them in
heavy-ion collisions?



DIRECTED FLOW

SPIN POLARIZATION



*hitherto unknown influence
of the strong force?*

INTENSE FIELDS IN HEAVY-ION COLLISIONS

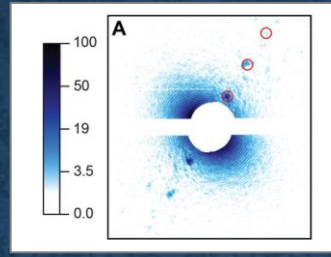
vorticity
 ω



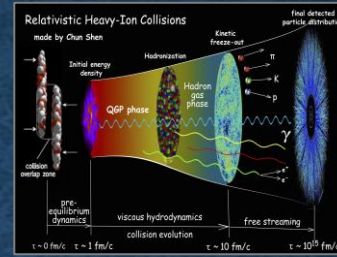
tornado cores
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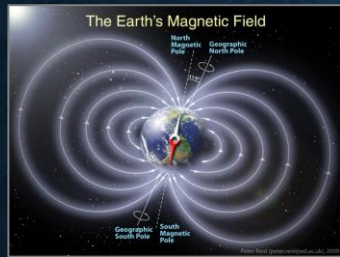
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GENERATING A STRONG
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magnetic
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 B



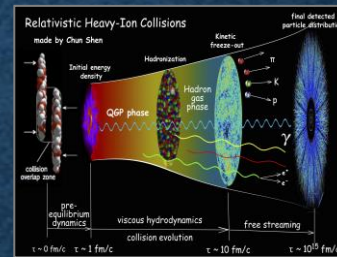
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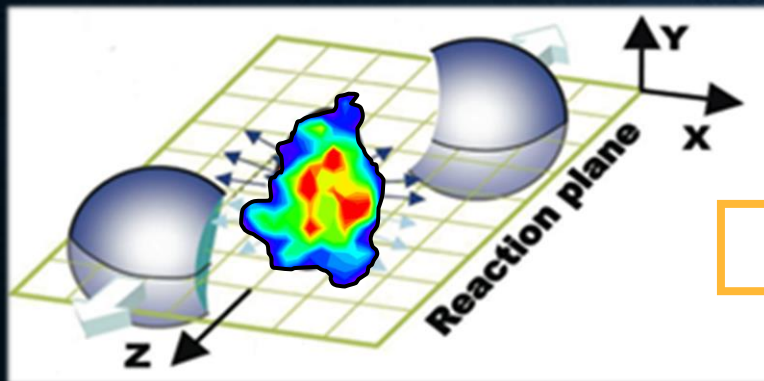
magnetars
 $\sim 10^{14} - 10^{15} \text{ G}$



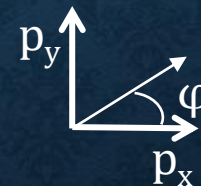
urHICs
 $\sim 10^{18} - 10^{19} \text{ G}$

**INTENSE ELECTRIC AND
MAGNETIC FIELDS**

How to probe them?



anisotropic azimuthal
particle distributions



$$\frac{dN}{d\phi} \propto 1 + \sum_n 2 v_n \cos[n\phi]$$

DIRECTED FLOW v_1

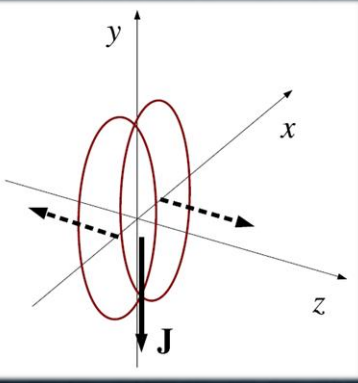
$$v_1(y) = \langle \cos[\phi(y)] \rangle$$

collective sideways
particle deflection

THE VORTICAL QUARK-GLUON PLASMA

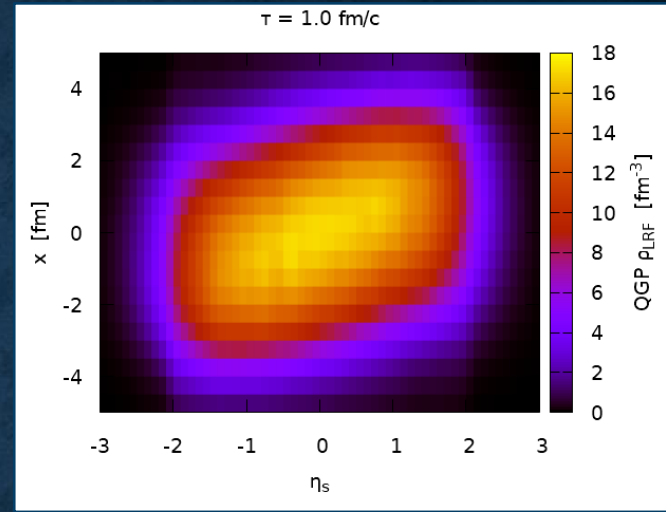
Huge orbital angular momentum of colliding system

- in ultra-relativistic HICs $J \approx 10^5 - 10^6 \hbar$
- partly transferred to the plasma



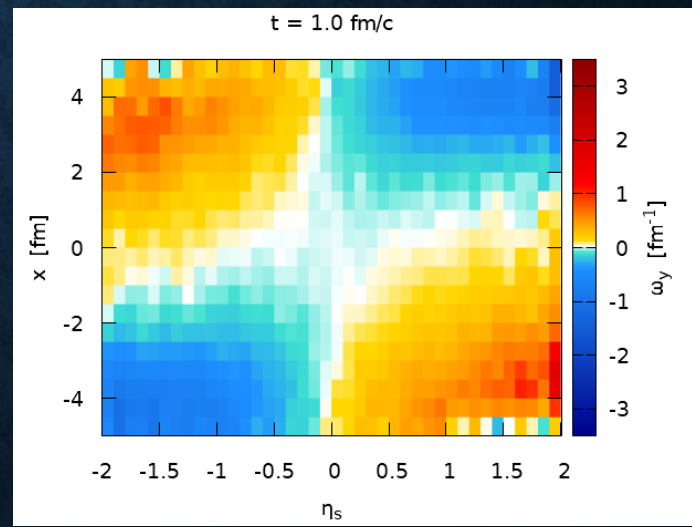
asymmetry in local participant density from forward and backward going nuclei

P. Bozek and I. Wyskiel,
Phys. Rev. C 81, 054902 (2010) [\[1\]](#)

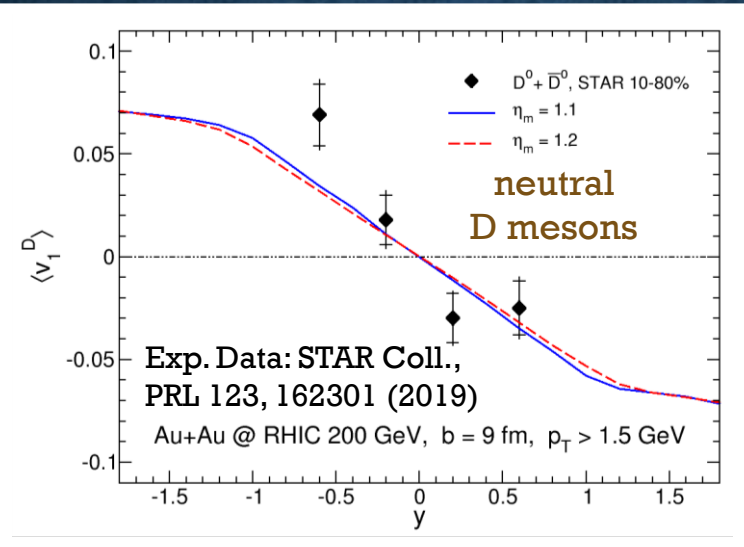
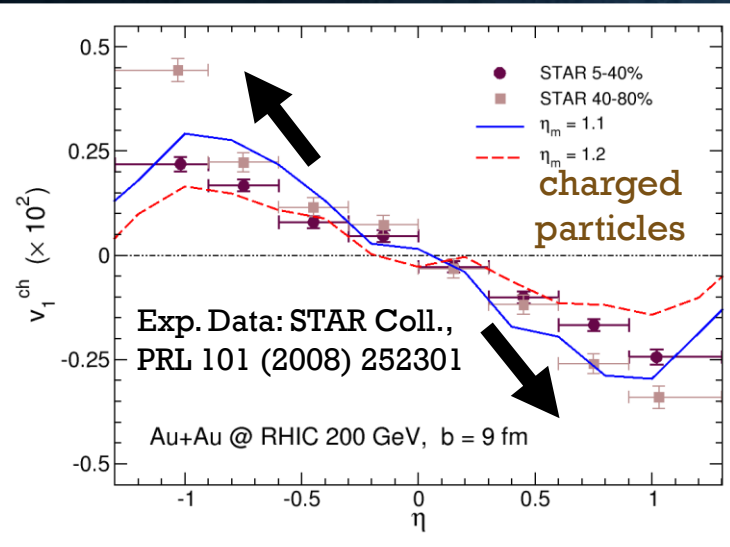


TILTED FIREBALL

huge vorticity ω_y



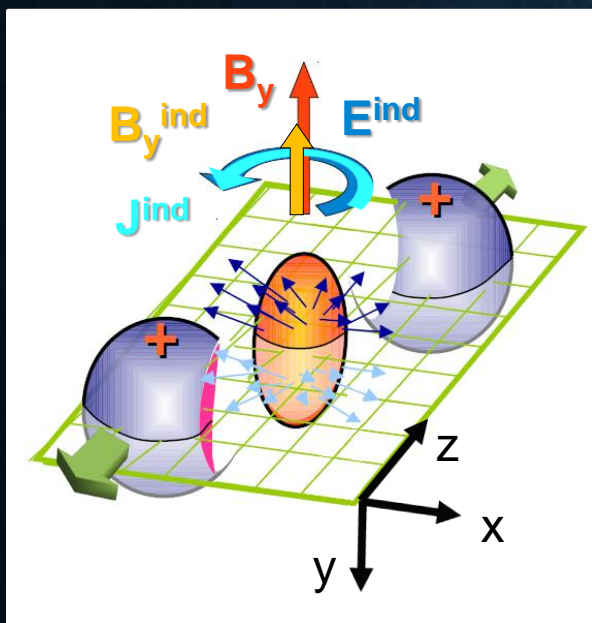
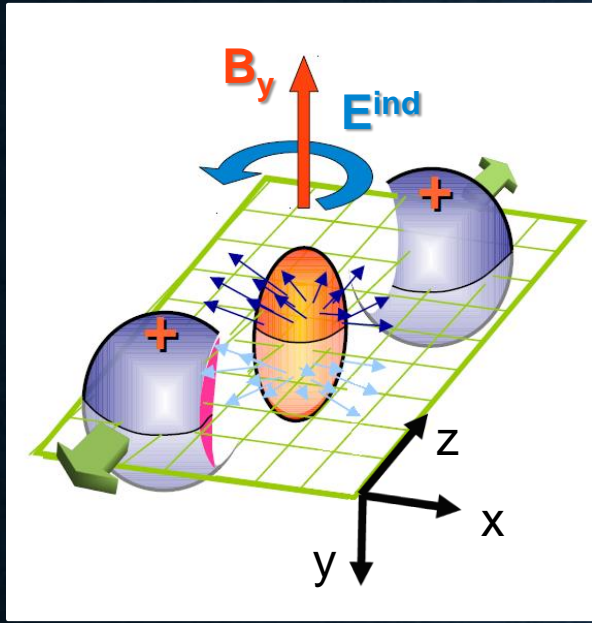
negative slope of $v_1(\eta)$



D-meson v_1 studied also in Turin group
A. Beraudo et al., JHEP 05, 279 (2021) [\[2\]](#)

LO, S. Plumari and V. Greco,
JHEP 05, 034 (2021) [\[3\]](#)

ELECTROMAGNETIC (EM) FIELDS



Huge magnetic field in the overlap area

- in uRHICs up to $eB \approx 5-50 m_\pi^2$
- intense Faraday-induced **electric field**
- charged currents induced in the conducting QGP sustain the **magnetic field**

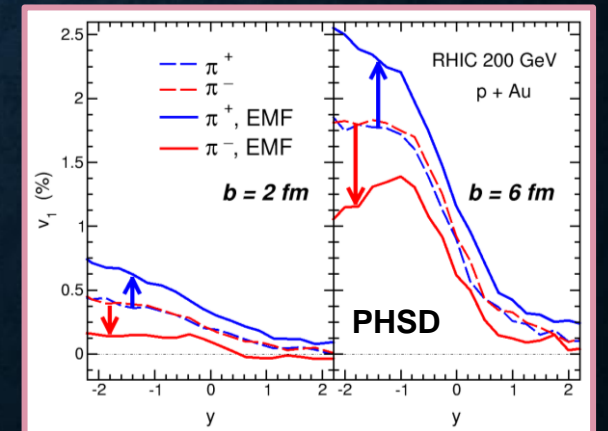
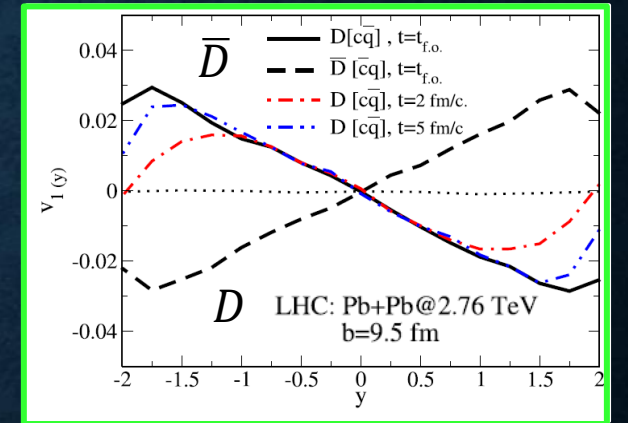
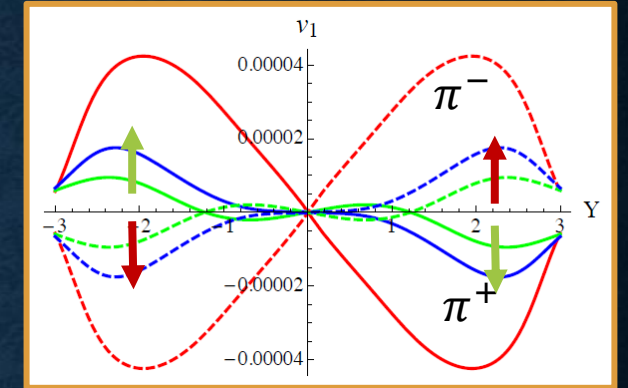


splitting in the v_1 of particles with same mass and opposite charge

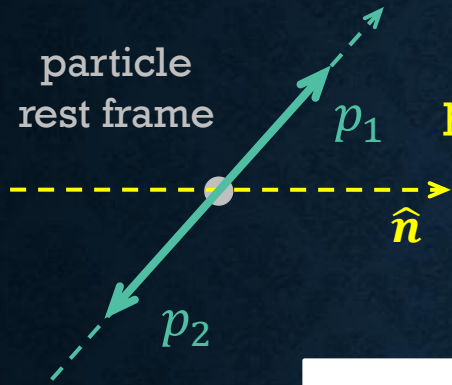
- Δv_1 of light hadrons in AA: $O(10^{-4}-10^{-3})$
U. Gursoy et al., Phys. Rev. C 89, 054905 (2014)
- Δv_1 of heavy mesons in AA: $O(10^{-2})$
S.K. Das et al., Phys. Lett. B 768, 260 (2017)
- Δv_1 of light mesons in pA: $O(10^{-2})$
LO et al., Phys. Rev. C 101, 014917 (2020)
- Δv_1 of heavy mesons in pA: $O(10^{-2})$
Y. Sun et al., Phys. Lett. B 843, 138043 (2023)

LO, Eur. Phys. J. A 56, 255 (2020)
 A. Dubla, U. Gursoy and R. Snellings,
 Mod. Phys. Lett. A 35, 2050324 (2020)

reviews

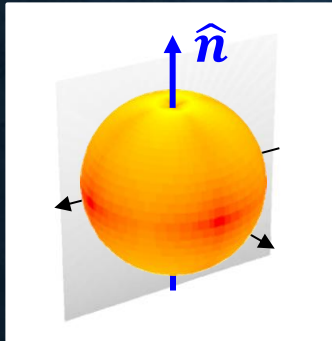


SPIN POLARIZATION

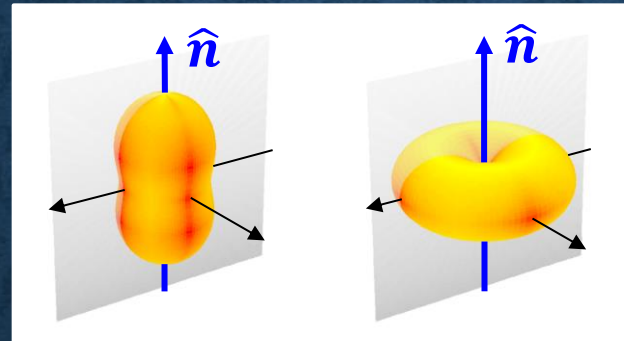


Spin polarization is the degree of alignment of the particle spin with a given direction (quantization axis)

measured through the angular distribution of the decay products of the particle in its rest frame



spherically symmetric
 \Rightarrow unpolarized production



anisotropic distribution
 \Rightarrow polarized production

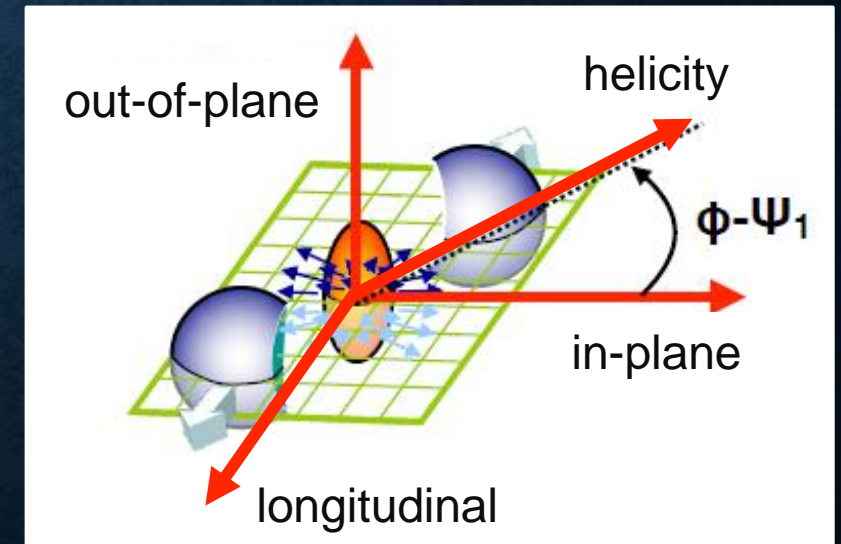
Picture credit: P. Faccioli

different possible choices for \hat{n}

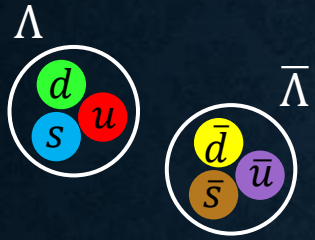
- in-plane (x direction)
- **out-of-plane (y direction) \simeq event plane**
- longitudinal (z direction)
- helicity (momentum direction of decaying particle)
- ...



"Spin Family (Bosons and Fermions)"
 sculptures by Julian Voss-Andreae (2009)



HYPERON POLARIZATION



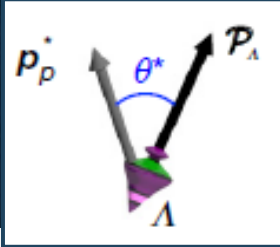
Λ hyperon is a spin-1/2 particle decaying through weak interaction

$$\Lambda \rightarrow p + \pi^- \quad (\text{BR} \sim 64\%)$$

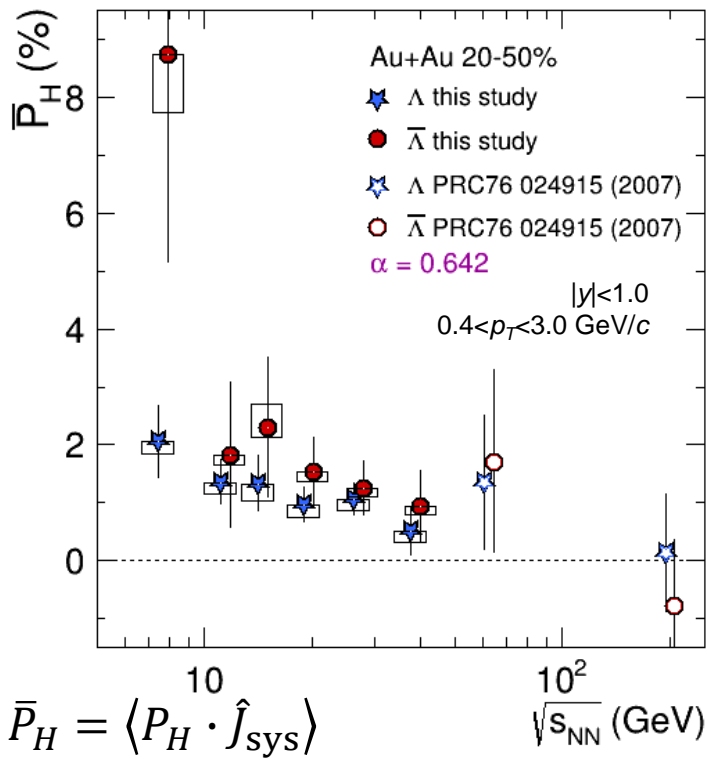
\Rightarrow measure **POLARIZATION**

$$\frac{dN}{d \cos \theta^*} = \frac{1}{2} (1 + \alpha_H |P_H| \cos \theta^*)$$

parity-violating weak decays:
daughter proton preferentially
emitted in the direction of Λ spin



$$P_H(\sqrt{s_{NN}})$$



P_H : hyperon polarization

F. Becattini, Iu. Karpenko, M.A. Lisa, I. Upszal, S. Voloshin,
Phys. Rev. C 95, 054902 (2017) [\[1\]](#)

$$P_{\Lambda(\bar{\Lambda})} = \frac{N_{\uparrow} - N_{\downarrow}}{N_{\uparrow} + N_{\downarrow}} \simeq \frac{1}{2} \frac{\omega}{T} \pm \frac{\mu_{\Lambda} B}{T}$$

thermal approach

thermal vorticity

magnetic field

CONVENTIONAL SOURCES OF SPIN POLARIZATION

Huge developments on Λ polarization by Florence group

F. Becattini, Rep. Prog. Phys. 85 122301 (2022) [\[2\]](#)

F. Becattini et al., Int. J. Mod. Phys. E 33, 2430006 (2024) [\[3\]](#)

reviews



VORTICITY AND MAGNETIC FIELD

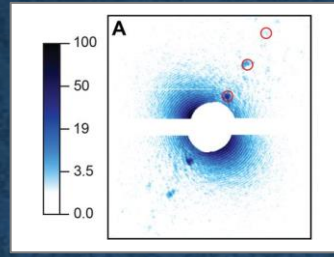
vorticity
 ω



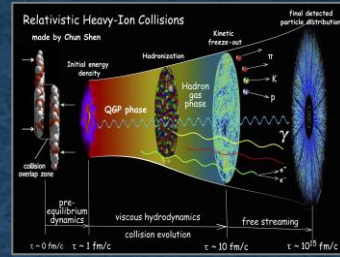
tornado cores
 $\sim 10^{-1} \text{ s}^{-1}$



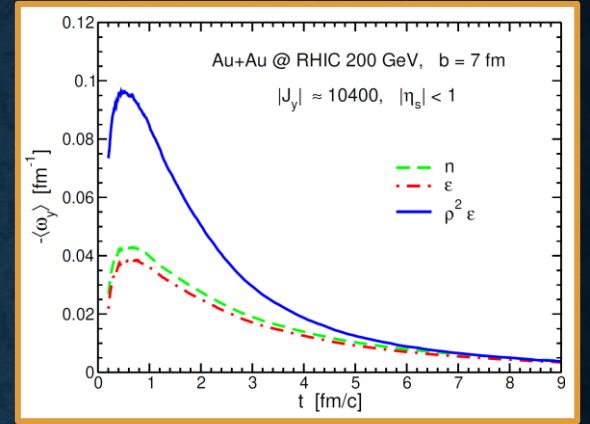
Jupiter's spot
 $\sim 10^{-4} \text{ s}^{-1}$



He nanodroplets
 $\sim 10^7 \text{ s}^{-1}$

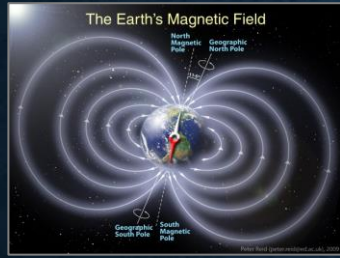


urHICs
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LO, S. Plumari and V. Greco,
JHEP 05, 034 (2021)

magnetic field
 B



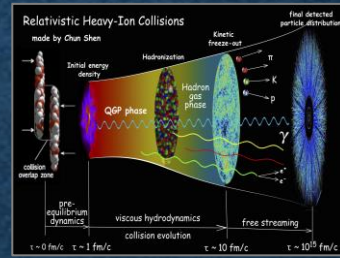
Earth's field
 $\sim 1 \text{ G}$



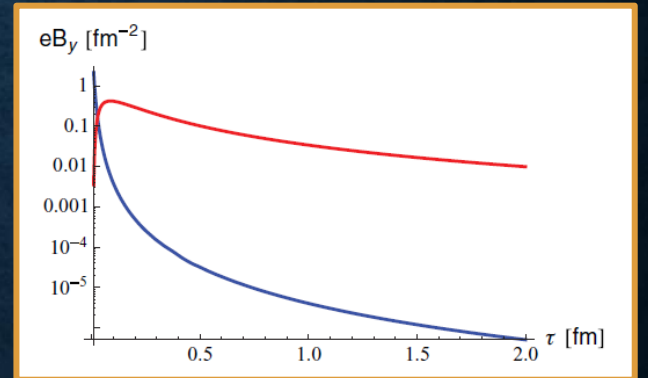
laboratory
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U. Gürsoy, D. Kharzeev, K. Rajagopal,
Phys. Rev. C 89, 054905 (2014)

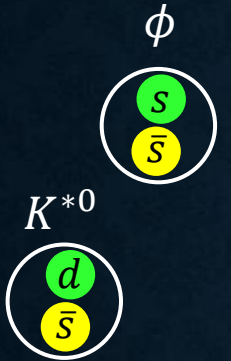
Estimates at freeze-out from $\Lambda - \bar{\Lambda}$ polarization based on thermal approach

$$\omega \approx (P_\Lambda + P_{\bar{\Lambda}})k_B T / \hbar \sim 0.02 - 0.09 \text{ fm}^{-1} \sim 0.6 - 2.7 \times 10^{22} \text{ s}^{-1}$$

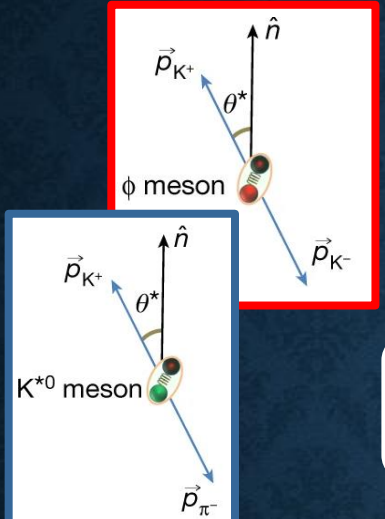
$$B \approx (P_\Lambda - P_{\bar{\Lambda}})T / 2\mu_\Lambda \sim 5 - 100 \times 10^{16} \text{ G} \rightarrow eB \sim 0.02 - 0.4 m_\pi^2$$

- But...
- the initial values of vortical and EM fields are higher
 - the splitting could be also due to other effects

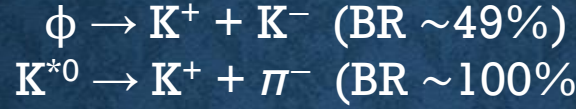
VECTOR MESON SPIN ALIGNMENT



$$\rho_{00}^y(\sqrt{s_{NN}})$$



ϕ and K^{*0} mesons are spin-1 particles decaying through strong interaction



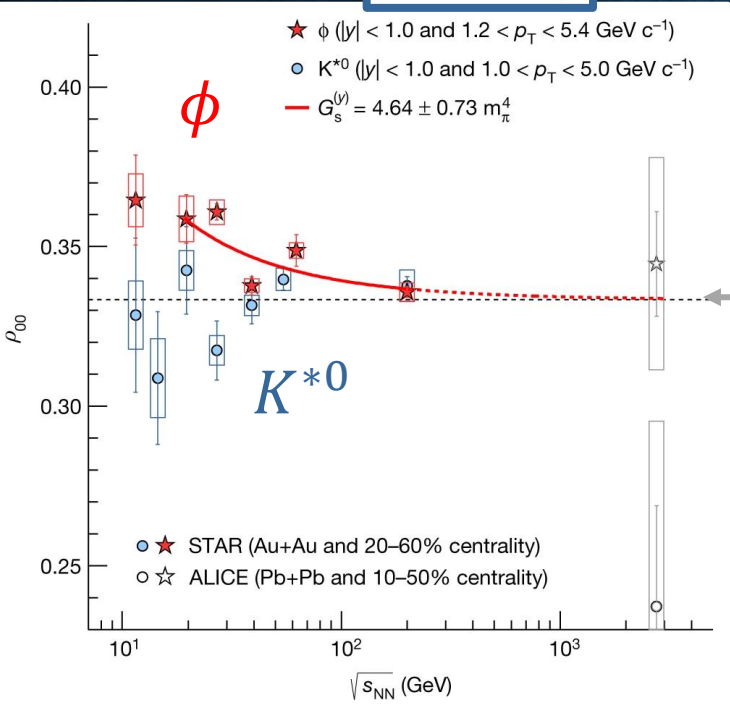
\Rightarrow measure **SPIN ALIGNMENT**

parity-conserving strong decays:
 direction of the polarization
 cannot be determined

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

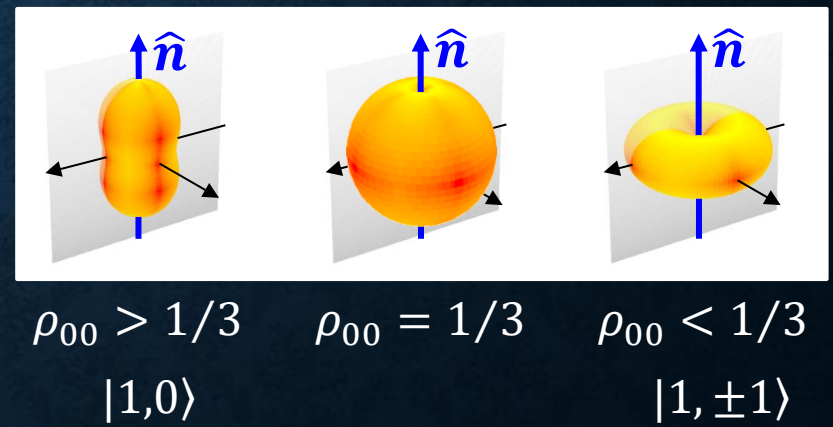
ρ_{00} : 00 element of spin density matrix ρ_{mn}

describes the spin state of a particle ensemble
 $m, n \rightarrow$ spin components along the quantization axis
 for a spin-1 particle: -1, 0, +1



$1/3$
 unpolarized case

- ϕ meson: ρ_{00} significantly larger than $1/3$ for collision energies of 62 GeV and below (7.4σ)
- K^{*0} meson: ρ_{00} consistent with $1/3$ within exp. uncertainties



SPIN POLARIZATION MECHANISMS

the vorticity contribution dominates. STAR measurements of the polarization of Λ and $\bar{\Lambda}$ (refs. ^{18,19}) indicate that the magnetic components of the vorticity and the electromagnetic field tensor in total give^{2,12,25} a negative contribution to ρ_{00} at the level of 10^{-5} . Furthermore, the local vorticity loop in the transverse plane²⁶, when acting together with coalescence, gives a negative contribution to global ρ_{00} . From a hydrodynamic simulation of the vorticity field in heavy-ion collisions, it is known² that the electric component of the vorticity tensor gives a contribution on the order of 10^{-4} . Simulation of the electromagnetic field in heavy-ion collisions indicates² that the electric field gives a contribution on the order of 10^{-5} . Fragmentation of polarized quarks contributes on the order of 10^{-5} and the effect is mainly present in transverse momenta much larger than a few $\text{GeV } c^{-1}$ (ref. ¹²). Helicity polarization gives a negative contribution at all centralities²⁷. Locally fluctuating axial charge currents induced by possible local charge violation gives rise to the expectation²⁹ of $\rho_{00}(K^*) < \rho_{00}(\Phi) < 1/3$. The aforementioned mostly conventional mechanisms make either positive or negative contributions to ϕ -meson ρ_{00} , but none of them can produce a ρ_{00} that is larger than $1/3$ by more than a few times 10^{-4} . Recently, a theoretical model was proposed on the basis of the ϕ -meson vector field coupling to s and \bar{s} quarks²⁻⁶, analogous to the photon vector field coupled to electrically charged particles. In this mechanism, the observed global spin alignment is caused by the local fluctuation of the strong force field and can cause deviations of ρ_{00} from $1/3$ larger than 10^{-4} .

In 2008, the STAR Collaboration reported on a search for global spin

2. X.-L. Sheng, L.O. & Q. Wang, *Phys. Rev. D* 101, 096005 (2020)
3. X.-L. Sheng, L.O. & Q. Wang, *Phys. Rev. D* 105, 099903 (2022)
4. X.-L. Sheng, Q. Wang & X.-N. Wang, *Phys. Rev. D* 102, 056013 (2020)
5. X.-L. Sheng, L.O., Z.-T. Liang, Q. Wang & X.-N. Wang, 2205.15689
6. X.-L. Sheng, L.O., Z.-T. Liang, Q. Wang & X.-N. Wang, 2206.05868
12. Z.-T. Liang & X.-N. Wang, *Phys. Lett. B* 629, 20 (2005)
25. Yang et al., *Phys. Rev. C* 97, 034917 (2018)
26. X.-L. Xia et al., *Phys. Lett. B* 817, 136325 (2021)
27. J.-H. Gao, *Phys. Rev. D* 104, 076016 (2021)
29. B. Müller & D.-L. Yang, *Phys. Rev. D* 105, L011901 (2022)


conventional sources of spin polarization cannot explain the large positive deviation of ρ_{00} from $1/3$

UNCONVENTIONAL SOURCES?



The local correlations of strong force fields may be the key to solve the puzzle

Refs. 2-6

STAR Collaboration, *Nature* 614, 244 (2023) 

SPIN POLARIZATION OF QUARKS

spin polarization vector for massive fermion/antifermion

$$P_{\pm}^{\mu}(x, p) = \frac{1}{4m} \epsilon^{\mu\nu\rho\sigma} \left(\omega_{\rho\sigma}^{\text{th}} \pm \frac{Q}{(u \cdot p)T} F_{\rho\sigma}^{\text{em}} \pm \frac{g_V}{(u \cdot p)T} F_{\rho\sigma}^V \right) p_{\nu} [1 - f_{\text{FD}}(E_p \mp \mu)]$$

thermal vorticity tensor

electromagnetic field strength tensor

vector meson field strength tensor

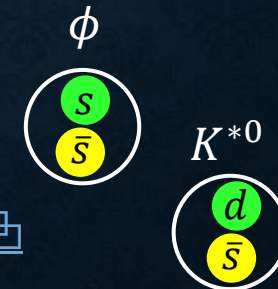
$$\begin{aligned} \text{"electric"} \quad \omega_{\rho\sigma}^{\text{th}} &= \frac{1}{2} (\partial_{\rho}(\beta u_{\sigma}) - \partial_{\sigma}(\beta u_{\rho})) & \text{"magnetic"} \\ \boldsymbol{\varepsilon} &= -\frac{1}{2} (\partial_t(\beta \mathbf{u}) + \nabla(\beta u^0)) & \boldsymbol{\omega} = \frac{1}{2} \nabla \times (\beta \mathbf{u}) \end{aligned}$$

$$\begin{aligned} F_{\rho\sigma}^{\text{em},V} &= \partial_{\rho} A_{\sigma}^{\text{em},V} - \partial_{\sigma} A_{\rho}^{\text{em},V} \\ \text{"electric"} \quad \mathbf{E}_i^{\text{em},V} &= \mathbf{E}_{\text{em},V}^i = F_{\text{em},V}^{i0} & \text{"magnetic"} \\ \mathbf{B}_i^{\text{em},V} &= \mathbf{B}_{\text{em},V}^i = -\frac{1}{2} \epsilon_{ijk} F_{\text{em},V}^{jk} \end{aligned}$$

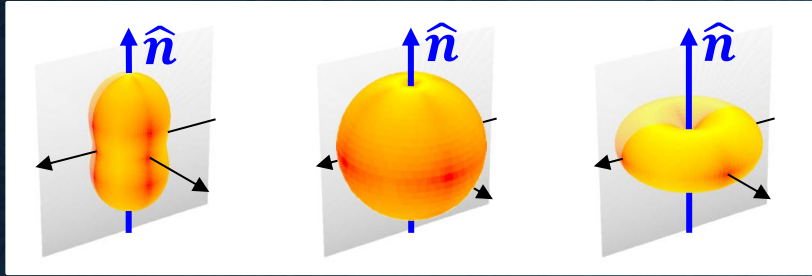
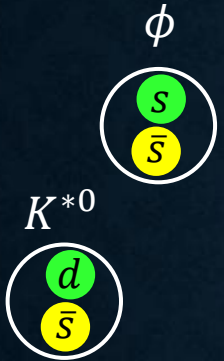
spin polarization distribution for quarks/antiquarks along the y direction (\sim parallel to \mathbf{J} and \mathbf{B})

$$P_{q/\bar{q}}^y(t, \mathbf{x}, \mathbf{p}_{q/\bar{q}}) = \frac{1}{2} \omega_y \pm \frac{1}{2m_q} (\boldsymbol{\varepsilon} \times \mathbf{p}_{q/\bar{q}})_y \pm \frac{Q_q}{2m_q T} B_y \pm \frac{Q_q}{2m_q^2 T} (\mathbf{E} \times \mathbf{p}_{q/\bar{q}})_y \pm \frac{g_V}{2m_q T} B_y^V \pm \frac{g_V}{2m_q^2 T} (\mathbf{E}^V \times \mathbf{p}_{q/\bar{q}})_y$$

Like the em field, **effective mesonic fields can polarize particles** but with large magnitude due to the strong interaction



VECTOR MESON SPIN ALIGNMENT



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

$$\rho_{00}^y(\sqrt{s_{NN}})$$

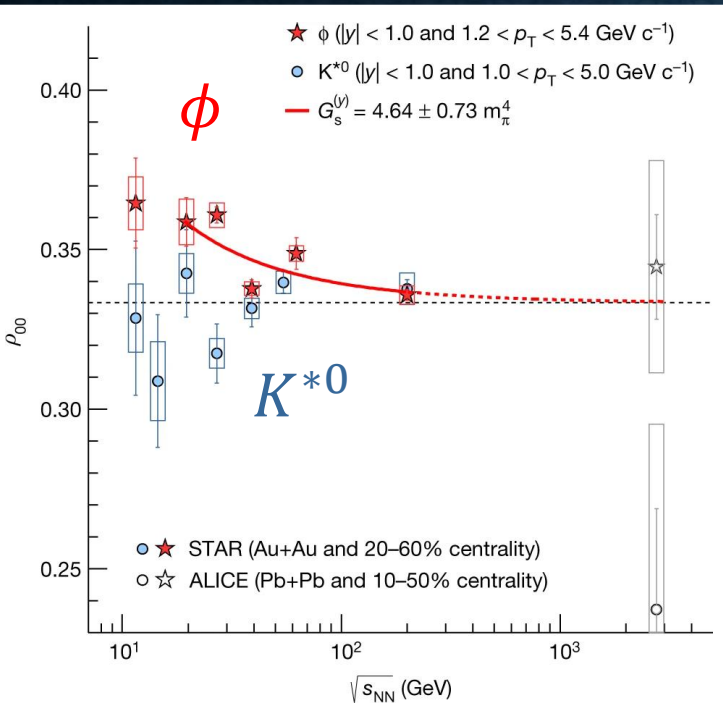
nonrelativistic quark coalescence model

$$\rho_{00}^\phi(t, \mathbf{x}) \approx \frac{1}{3} - \frac{4}{9} \int \frac{d^3\mathbf{p}}{(2\pi)^3} P_s^y(\mathbf{p}) P_{\bar{s}}^y(-\mathbf{p}) |\psi_\phi(\mathbf{p})|^2$$

polarized quarks

COALESCENCE

polarized hadrons



$$\rho_{00}^\phi \approx \frac{1}{3} + c_\Lambda + c_\varepsilon + c_E + c_\phi$$

$$c_\Lambda \equiv -\frac{4}{9} \langle P_\Lambda^y P_\Lambda^y \rangle = -\frac{1}{9} \langle \omega_y^2 \rangle + \frac{Q_s^2}{9m_s^2 T_{\text{eff}}^2} \langle B_y^2 \rangle$$

$$c_\varepsilon \equiv \frac{1}{27m_s^2} \langle \mathbf{p}^2 \rangle_\phi \langle \varepsilon_z^2 + \varepsilon_x^2 \rangle \quad c_E \equiv -\frac{e^2}{243m_s^4 T_{\text{eff}}^2} \langle \mathbf{p}^2 \rangle_\phi \langle E_z^2 + E_x^2 \rangle$$

$$c_\phi \equiv \frac{g_\phi^2}{27m_s^2 T_{\text{eff}}^2} \left[3 \langle B_{\phi,y}^2 \rangle - \frac{\langle \mathbf{p}^2 \rangle_\phi}{m_s^2} \langle E_{\phi,z}^2 + E_{\phi,x}^2 \rangle \right]$$

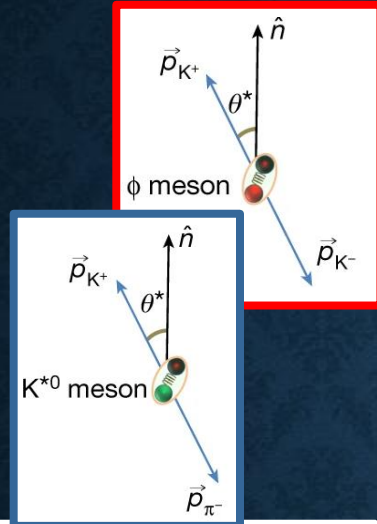
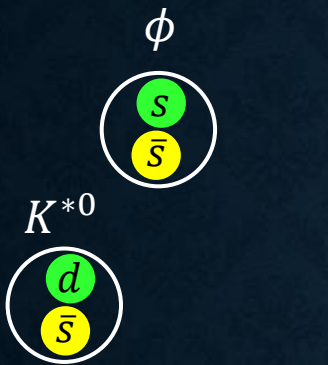
$c_\Lambda, c_\varepsilon, c_E \sim 10^{-3} - 10^{-5}$ are negligibly small compared to $1/3$

the ϕ -meson effective field in c_ϕ may explain the large positive deviation of ρ_{00} from $1/3$

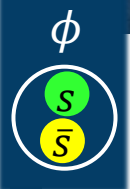
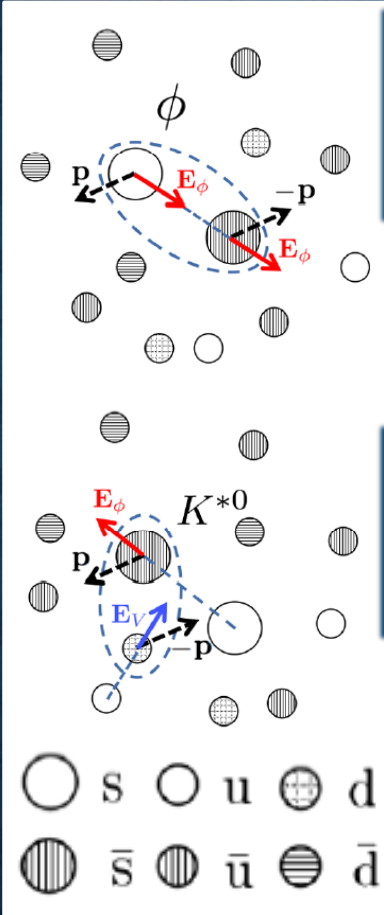
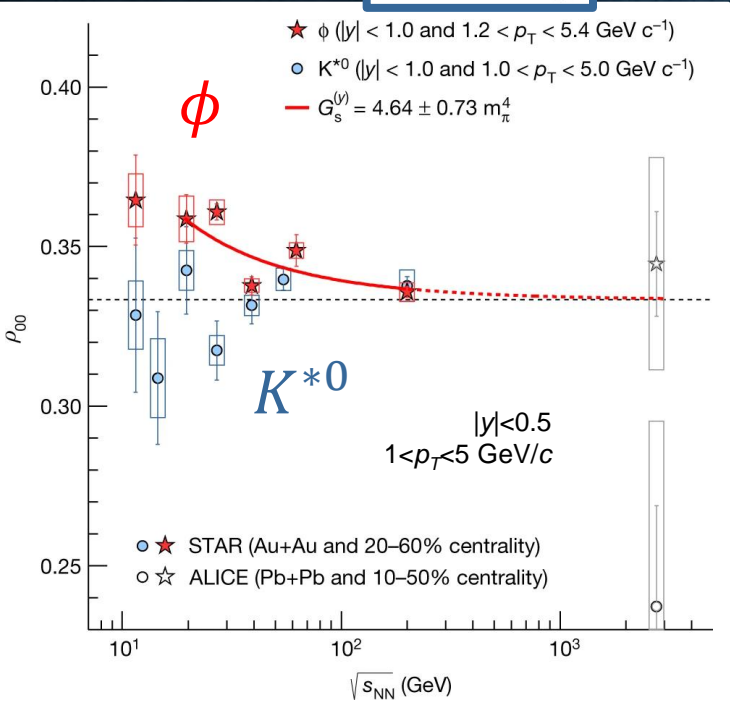
X.-L. Sheng, LO and Q. Wang,

Phys. Rev. D 101, 096005 (2020) [Phys. Rev. D 105, 099903 (2022)]

WHY ONLY ϕ MESON?



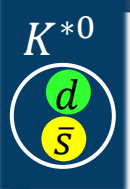
$$\rho_{00}^y(\sqrt{s_{NN}})$$



neglecting EM fields

$$\rho_{00}^\phi \approx \frac{1}{3} - \frac{1}{9} \langle \omega_y^2 \rangle + \frac{\langle \mathbf{p}_b^2 \rangle_\phi}{27m_s^2} \langle \varepsilon_z^2 + \varepsilon_x^2 \rangle$$

$$+ \frac{g_\phi^2}{27m_s^2 T_{\text{eff}}^2} \left[3 \langle (B_y^\phi)^2 \rangle - \frac{\langle \mathbf{p}_b^2 \rangle_\phi}{m_s^2} \langle (E_z^\phi)^2 + (E_x^\phi)^2 \rangle \right]$$

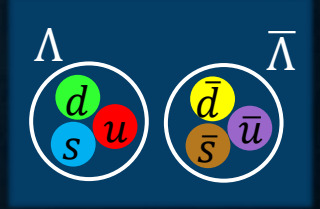


$$\rho_{00}^{K^{*0}} \approx \frac{1}{3} - \frac{1}{9} \langle \omega_y^2 \rangle + \frac{\langle \mathbf{p}_b^2 \rangle_{K^*}}{27m_s m_d} \langle \varepsilon_z^2 + \varepsilon_x^2 \rangle$$

$$+ \frac{g_\phi g_V}{27m_s m_d T_{\text{eff}}^2} \left[3 \langle B_y^\phi B_y^V \rangle - \frac{\langle \mathbf{p}_b^2 \rangle_{K^*}}{m_s m_d} \langle E_z^\phi E_z^V + E_x^\phi E_x^V \rangle \right]$$

negligible assuming that different fields do not have large correlation in space

contribution on hyperon polarization proportional to the fluctuation of the ϕ -meson field that is on average negligible



X.-L. Sheng, LO and Q. Wang, PRD 101, 096005 (2020) [PRD 105, 099903 (2022)]

STAR Collaboration, Nature 614, 244 (2023)

X.-L. Sheng, Q. Wang, and X.-N. Wang, Phys. Rev. D 102, 056013 (2020)

SPIN BOLTZMANN EQUATION FOR VECTOR MESONS

nonrelativistic quark coalescence model
cannot account for spin dynamics



spin Boltzmann equation for the
vector meson's matrix-valued
spin-dependent distributions (MVSD)

QUANTUM
RELATIVISTIC
TRANSPORT
THEORY FOR
SPIN DYNAMICS

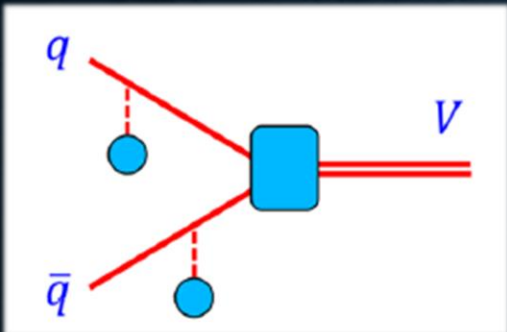
$$k \cdot \partial_x f_{\lambda_1 \lambda_2}^V(x, \mathbf{k}) = \frac{1}{8} [\epsilon_\mu^*(\lambda_1, \mathbf{k}) \epsilon_\nu(\lambda_2, \mathbf{k}) C_{\text{coal}}^{\mu\nu}(x, \mathbf{k}) - C_{\text{diss}}(\mathbf{k}) f_{\lambda_1 \lambda_2}^V(x, \mathbf{k})]$$

3x3 Hermitian matrix in spin space

COALESCENCE

DISSOCIATION
independent from the
quark/antiquark MVSDs

$q\bar{q}V$ vertices



$$C_{\text{coal}}^{\mu\nu}(x, \mathbf{k}) = \int \frac{d^3 \mathbf{p}'}{(2\pi\hbar)^2} \frac{1}{E_{\mathbf{p}'}^{\bar{q}} E_{\mathbf{k}-\mathbf{p}'}^q} \delta(E_{\mathbf{k}}^V - E_{\mathbf{p}'}^{\bar{q}} - E_{\mathbf{k}-\mathbf{p}'}^q) \\ \times \text{Tr} \{ \Gamma^\nu (p' \cdot \gamma - m_{\bar{q}}) [1 + \gamma_5 \gamma \cdot P^{\bar{q}}(x, \mathbf{p}')] \\ \times \Gamma^\mu [(k - p') \cdot \gamma + m_q] [1 + \gamma_5 \gamma \cdot P^q(x, \mathbf{k} - \mathbf{p}')] \} \\ \times f_{\bar{q}}(x, \mathbf{p}') f_q(x, \mathbf{k} - \mathbf{p}')$$

polarization distribution
for quark/antiquark

unpolarized distribution for quark/antiquark

SPIN DENSITY MATRIX FOR VECTOR MESONS

solution of the spin Boltzmann equation

Δt : vector meson formation time
 $f_{\lambda_1\lambda_2}^V$ assumed = 0 at initial time

$$f_{\lambda_1\lambda_2}^V(x, \mathbf{k}) \sim \frac{1}{C_{\text{diss}}(\mathbf{k})} [1 - e^{-C_{\text{diss}}(\mathbf{k})\Delta t}] \epsilon_{\mu}^*(\lambda_1, \mathbf{k}) \epsilon_{\nu}(\lambda_2, \mathbf{k}) C_{\text{coal}}^{\mu\nu}(x, \mathbf{k})$$

MVSD can be parameterized as
 spin-independent distribution function
 (unpolarized)

+

normalized spin density matrix
 (polarization part)

$$\rho_{\lambda_1\lambda_2}^V(x, \mathbf{k}) = \frac{\epsilon_{\mu}^*(\lambda_1, \mathbf{k}) \epsilon_{\nu}(\lambda_2, \mathbf{k}) C_{\text{coal}}^{\mu\nu}(x, \mathbf{k})}{\sum_{\lambda=0, \pm 1} \epsilon_{\mu}^*(\lambda, \mathbf{k}) \epsilon_{\nu}(\lambda, \mathbf{k}) C_{\text{coal}}^{\mu\nu}(x, \mathbf{k})}$$

spin density matrix for vector mesons

$C_{\text{coal}}^{\mu\nu}$ include the polarization phase space
 distributions for quark/antiquark $P_{q/\bar{q}}^{\mu}(x, p)$



similar to the process in the
 nonrelativistic coalescence model

SPIN ALIGNMENT OF ϕ MESONS



polarization distributions of strange/antistrange quarks appearing in ϕ mesons spin density matrix

$$P_{s/\bar{s}}^\mu(x, \mathbf{p}) = \frac{1}{4m_s} \epsilon^{\mu\nu\rho\sigma} \left(\omega_{\rho\sigma}^{\text{th}} \pm \frac{g_\phi}{(u \cdot p)T} F_{\rho\sigma}^\phi \right) p_\nu$$

$$\rho_{00}^\phi(x, \mathbf{k}) \approx \frac{1}{3} + C_1 \left[\frac{1}{3} \boldsymbol{\omega}' \cdot \boldsymbol{\omega}' - (\boldsymbol{\epsilon}_0 \cdot \boldsymbol{\omega}')^2 \right] + C_2 \left[\frac{1}{3} \boldsymbol{\varepsilon}' \cdot \boldsymbol{\varepsilon}' - (\boldsymbol{\epsilon}_0 \cdot \boldsymbol{\varepsilon}')^2 \right] - \frac{4g_\phi^2}{m_\phi^2 T_h^2} C_1 \left[\frac{1}{3} \mathbf{B}'_\phi \cdot \mathbf{B}'_\phi - (\boldsymbol{\epsilon}_0 \cdot \mathbf{B}'_\phi)^2 \right] - \frac{4g_\phi^2}{m_\phi^2 T_h^2} C_2 \left[\frac{1}{3} \mathbf{E}'_\phi \cdot \mathbf{E}'_\phi - (\boldsymbol{\epsilon}_0 \cdot \mathbf{E}'_\phi)^2 \right]$$

vorticity fields

ϕ -meson fields

neglecting EM fields

the 00 element of the spin density matrix for ϕ meson in its rest frame

$$C_1 = \frac{8m_s^4 + 16m_s^2 m_\phi^2 + 3m_\phi^4}{120m_s^2(m_\phi^2 + 2m_s^2)}$$

$$C_2 = \frac{8m_s^4 - 14m_s^2 m_\phi^2 + 3m_\phi^4}{120m_s^2(m_\phi^2 + 2m_s^2)}$$

For quarkonium vector mesons like ϕ meson

- cancellation of all mixed terms of two different field components
- only short-distance correlations between same field components

ρ_{00}^ϕ measures local fluctuations of vortical and mesonic fields during hadronization

SPIN ALIGNMENT OF ϕ MESONS



in terms of lab-frame fields and taking the y -axis as spin quantization direction (**out-of-plane**)

$$\rho_{00}^{\phi}(x, \mathbf{k}) \approx \frac{1}{3} + \frac{1}{3} \sum_{i=1,2,3} \left\{ I_{B_i}(\mathbf{k}) \left[\omega_i^2 - \left(\frac{2}{m_{\phi}} \right)^2 \left(\frac{g_{\phi} B_i^{\phi}(x)}{T_h} \right)^2 \right] + I_{E_i}(\mathbf{k}) \left[\varepsilon_i^2 - \left(\frac{2}{m_{\phi}} \right)^2 \left(\frac{g_{\phi} E_i^{\phi}(x)}{T_h} \right)^2 \right] \right\}$$

factorization of space-time and momentum dependence
in the squares of field components and their coefficients

$$\rho_{00}^{\phi}(x, \mathbf{k}) \approx \frac{1}{3} - \frac{1}{3} \left(\frac{2}{m_{\phi}} \right)^2 \sum_{i=1,2,3} \left\{ \langle I_{B_i}(\mathbf{k}) \rangle_{\mathbf{k}} \left\langle \left(\frac{g_{\phi} B_i^{\phi}(x)}{T_h} \right)^2 \right\rangle_x + \langle I_{E_i}(\mathbf{k}) \rangle_{\mathbf{k}} \left\langle \left(\frac{g_{\phi} E_i^{\phi}(x)}{T_h} \right)^2 \right\rangle_x \right\}$$

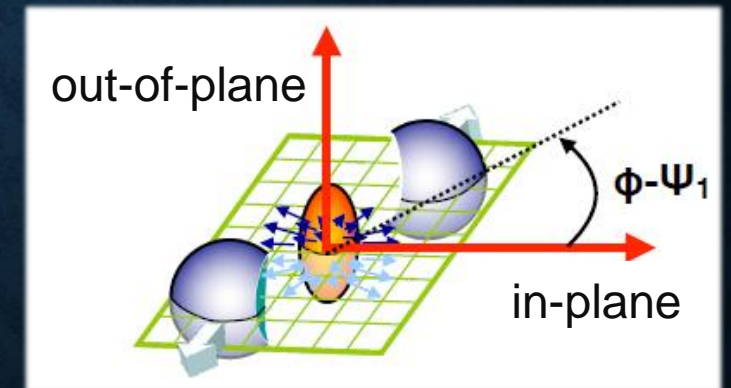
considering only
the ϕ -meson field

transverse fields

$$\left\langle \left(\frac{g_{\phi} B_{x,y}^{\phi}}{T_h} \right)^2 \right\rangle_x = \left\langle \left(\frac{g_{\phi} E_{x,y}^{\phi}}{T_h} \right)^2 \right\rangle_x \equiv F_T^2$$

longitudinal fields

$$\left\langle \left(\frac{g_{\phi} B_z^{\phi}}{T_h} \right)^2 \right\rangle_x = \left\langle \left(\frac{g_{\phi} E_z^{\phi}}{T_h} \right)^2 \right\rangle_x \equiv F_z^2$$

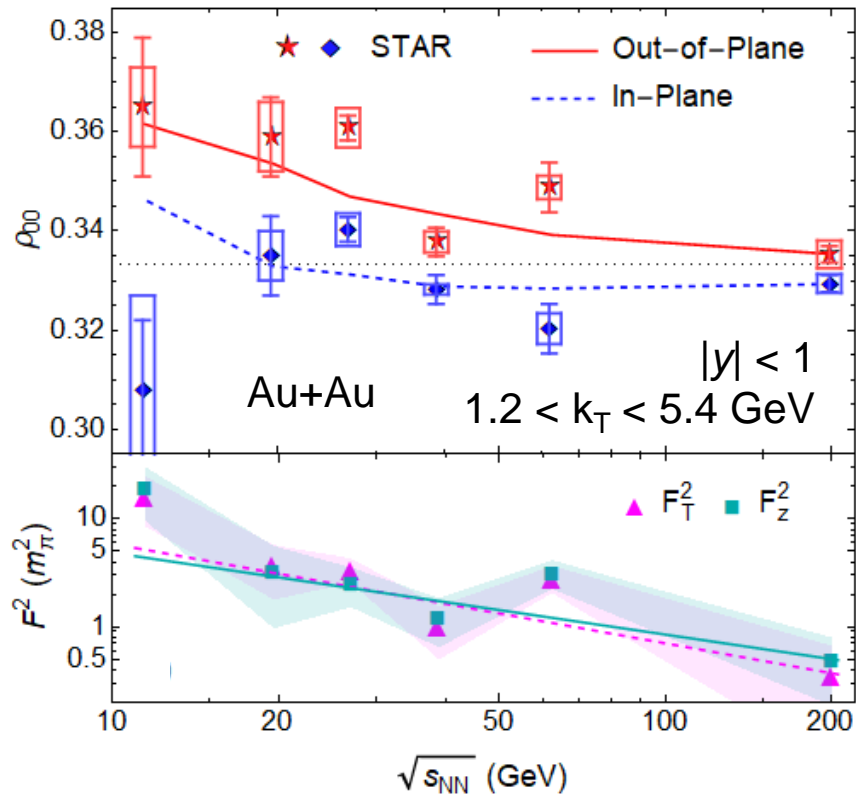


SPIN ALIGNMENT OF ϕ MESONS



Exp. data: STAR Coll.,
Nature 614, 244 (2023)

$$\rho_{00}^{x,y}(\sqrt{s_{NN}})$$

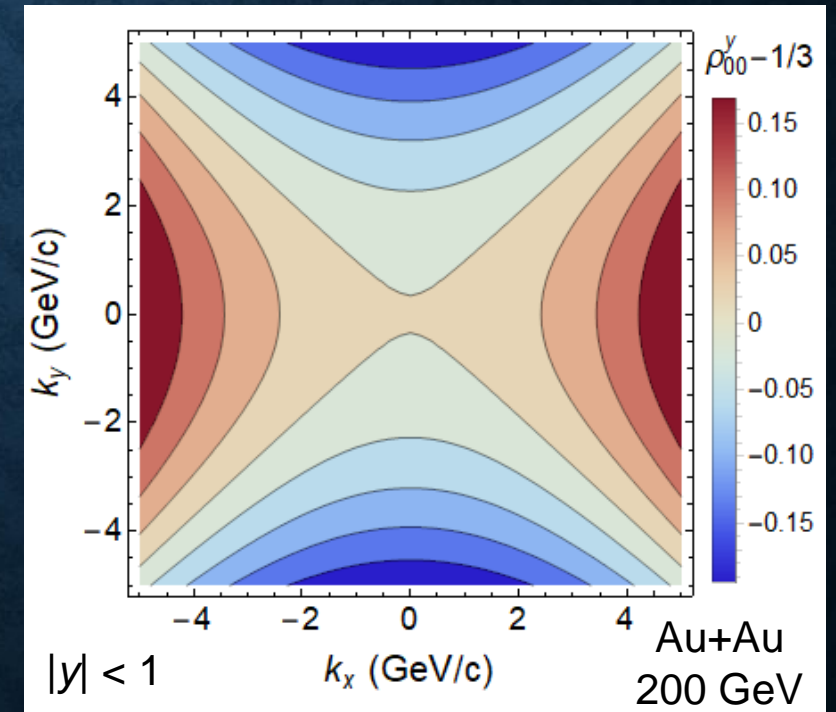


fit the exp. data for ρ_{00} vs collision energy

extract the field fluctuation parameters

determine ρ_{00} vs k_T and ϕ

$$\rho_{00}^y - 1/3(k_x, k_y)$$



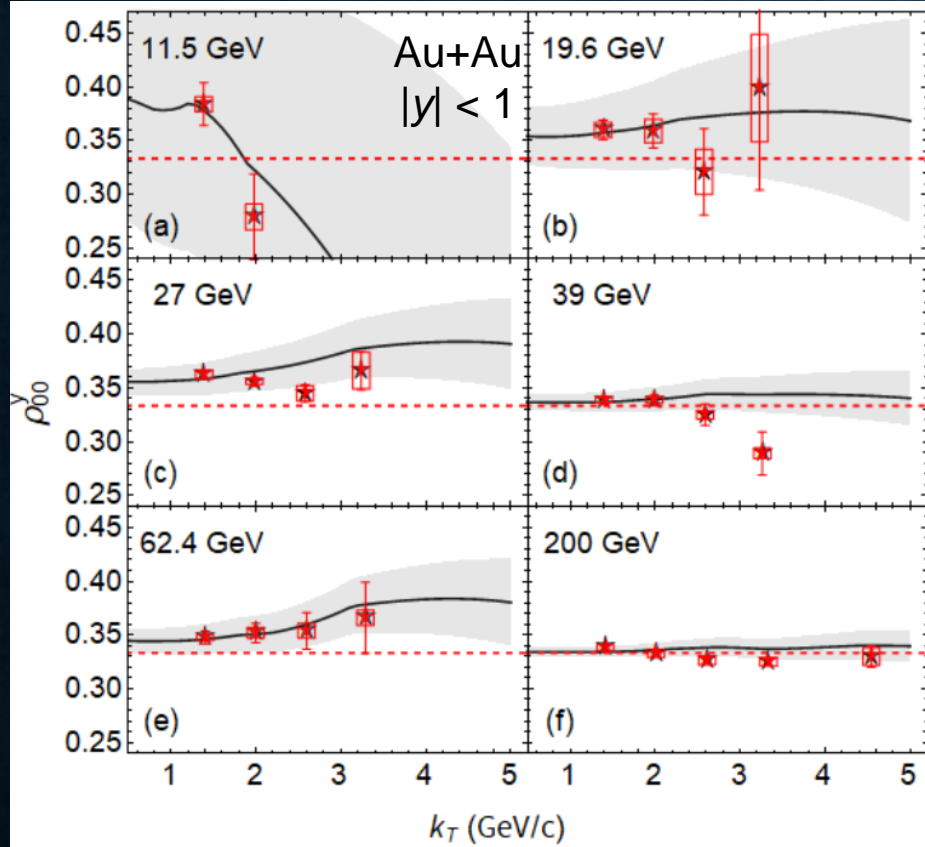
- ❖ out-of-plane: $\rho_{00}^y > 1/3$ for all energies
- ❖ in-plane: $\rho_{00}^x \leq 1/3$ for $\sqrt{s_{NN}} \geq 20$ GeV
- ❖ difference between ρ_{00}^y and ρ_{00}^x driven by the momentum anisotropy via the elliptic flow $v_2(k_T)$

SPIN ALIGNMENT OF ϕ MESONS



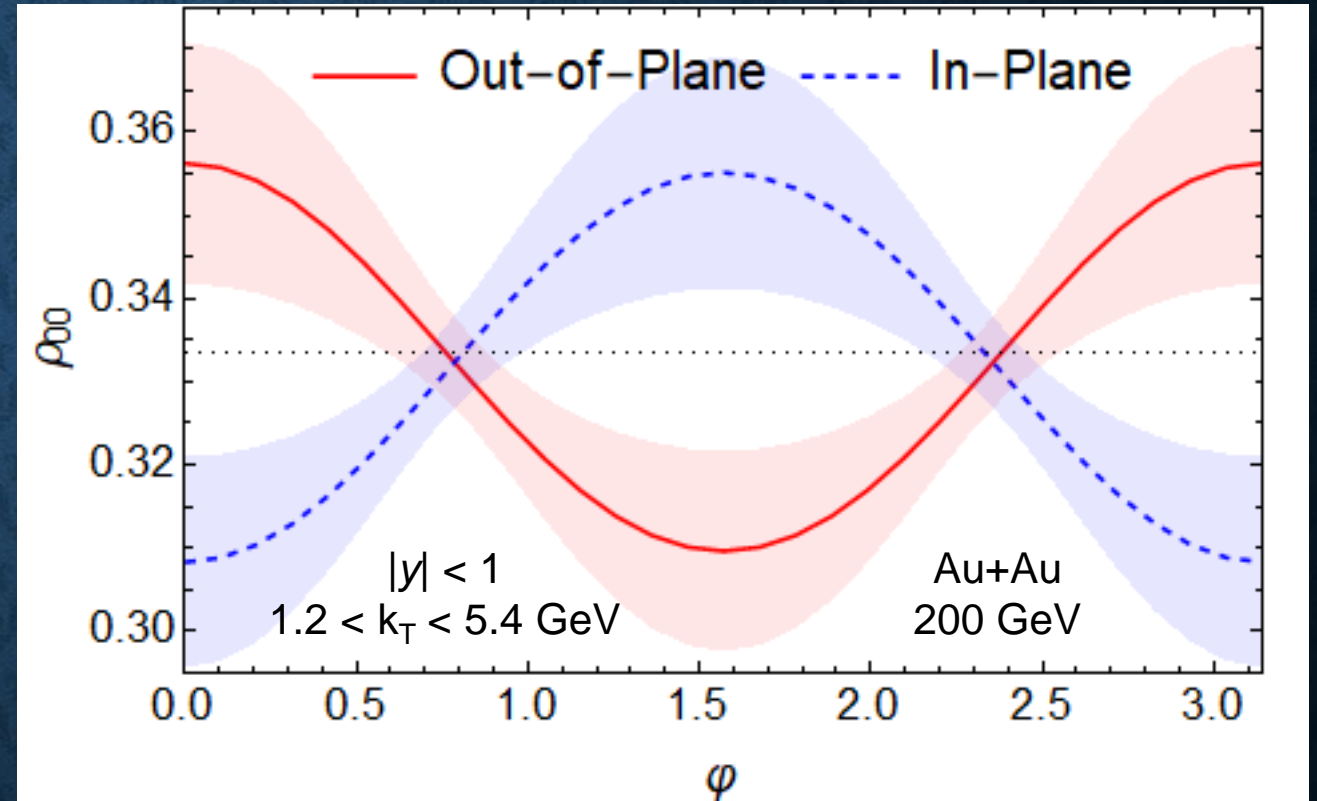
Exp. data: STAR Coll.,
Nature 614, 244 (2023)

$$\rho_{00}^y(k_T)$$



- ❖ nearly constant at $k_T < 2$ GeV
- ❖ at low k_T it is significantly larger than $1/3$ at lower energies

$$\rho_{00}^{x,y}(\varphi)$$



- ❖ modulation of $\rho_{00}^{x,y}$ with the azimuthal angle
- ❖ **can be tested in future experiments!**



CONCLUSIONS

- ✓ The directed flow of light and heavy mesons is a probe of vortical and EM fields in large and small systems
- ✓ the thermal vorticity gives the dominant contribution to the global polarization of Λ hyperons, the magnetic field induces a splitting of Λ and $\bar{\Lambda}$ particles
- ✓ thermal vorticity and EM fields at freeze-out cannot explain the significant positive deviation from $1/3$ of ρ_{00} for ϕ meson observed at lower energies
- ✓ the dominant source of the ϕ -meson spin alignment may be the local fluctuations of an effective ϕ -meson field that polarizes the s and \bar{s} quarks
- ✓ we derived a relativistic quantum transport theory for spin dynamics describing ρ_{00} as phase-space distribution function
- ✓ we extracted the strength of ϕ -meson field fluctuations from exp. data of ϕ -meson global spin alignment and predicted its transverse momentum and azimuthal angle dependence



Further explore the connection between particle spin polarization and local correlation of strong force fields

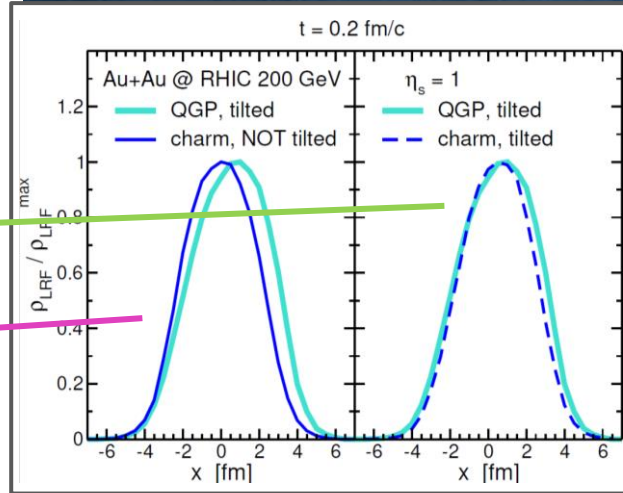
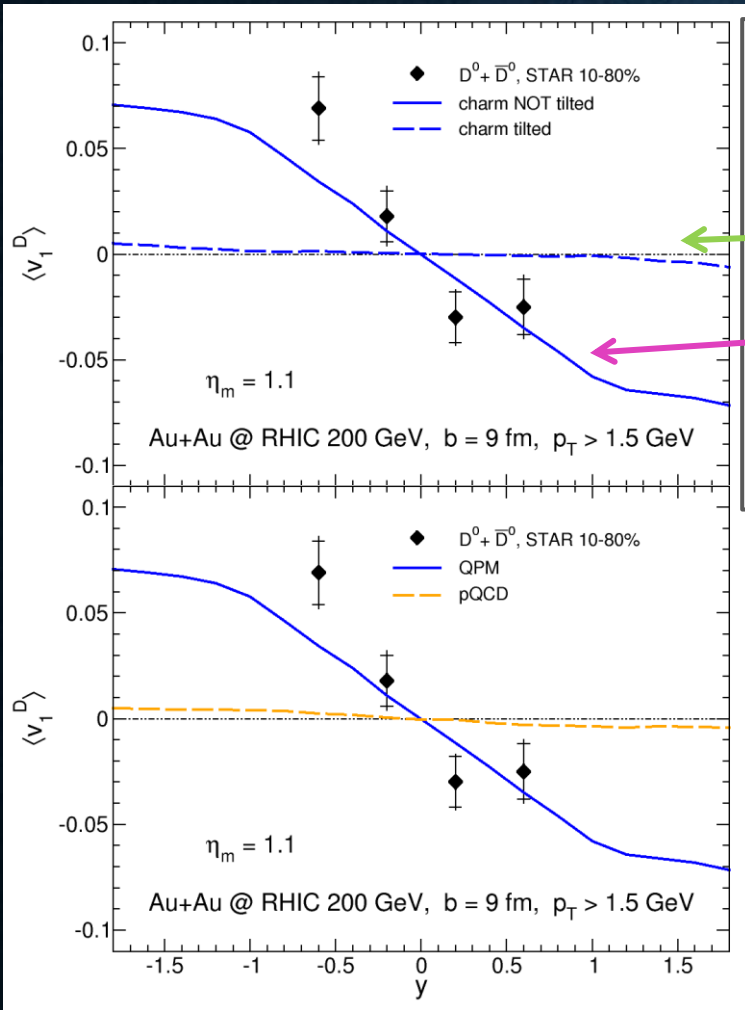
- open a potential new avenue for studying the behaviour of strong interaction

The End

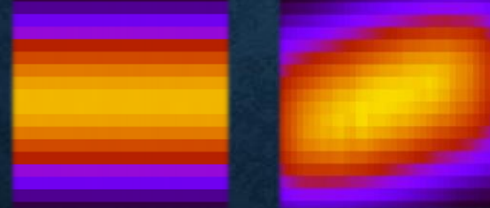
DIRECTED FLOW MAGNITUDE OF D MESONS

origin of the large directed flow of HQs different from the one of light particles

$$\langle v_1^D \rangle(y)$$



CHARM NOT TILTED CHARM TILTED

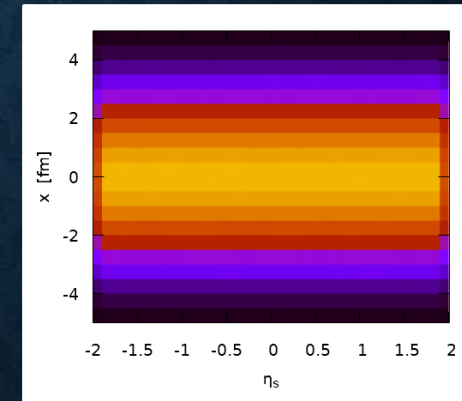


QGP tilted in both cases

$$v_1(HQs) \gg v_1(QGP)$$

longitudinal asymmetry leads to pressure push of the bulk on the HQs

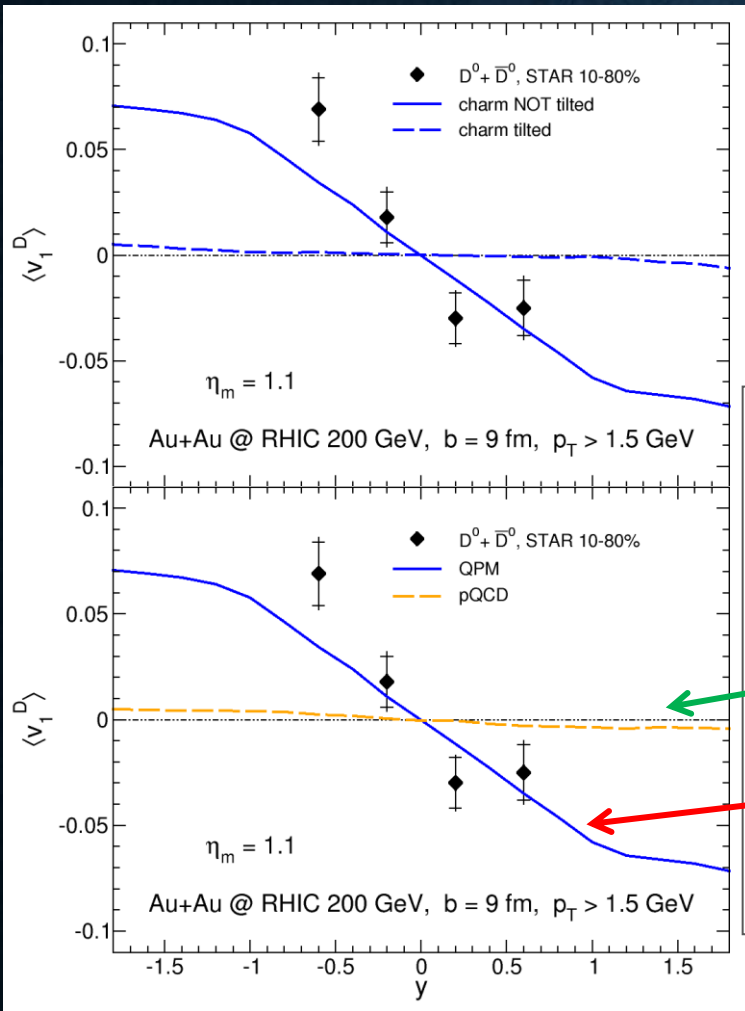
HQ production points symmetric in the forward-backward hemispheres



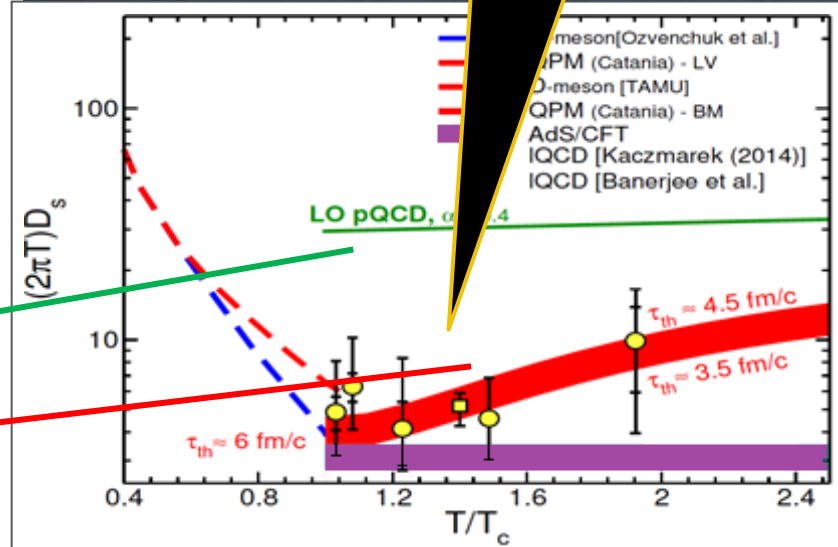
DIRECTED FLOW MAGNITUDE OF D MESONS

origin of the large directed flow of HQs different from the one of light particles

$$\langle v_1^D \rangle(y)$$



non-perturbative behaviour of QGP



V. Greco, Nucl. Phys. A 967, 200 (2017)

$$v_1(HQs) \gg v_1(QGP)$$

longitudinal asymmetry leads to pressure push of the bulk on the HQs effective because the HQ interaction in QGP is largely non-perturbative

in agreement with
S. Chatterjee and P. Bozek,
Phys. Rev. Lett. 120, 192301 (2018)
A. Beraudo et al., JHEP 05, 279 (2021)

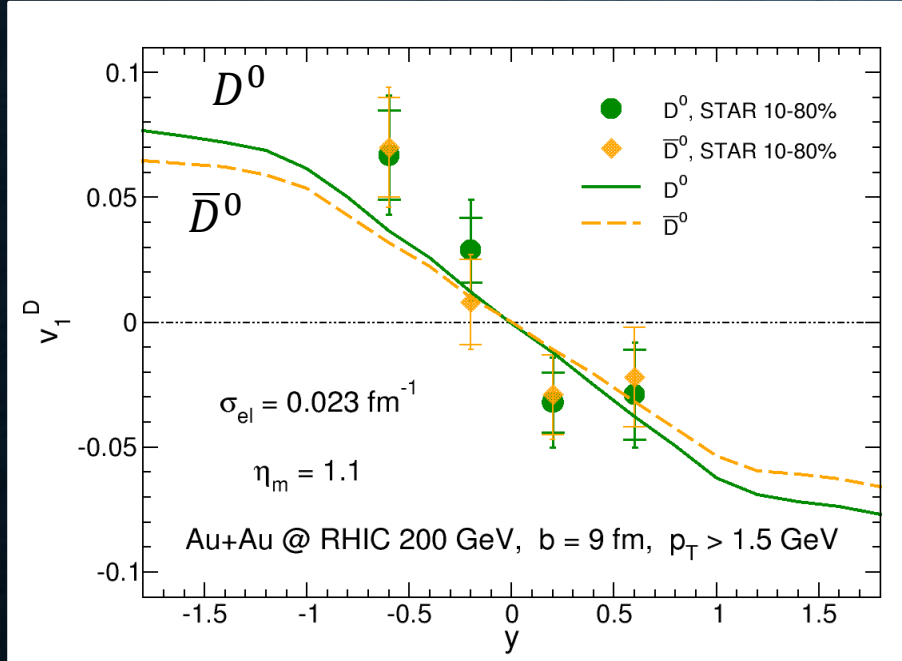
$2\pi T D_s \approx 3 - 6$
QGP diffuses charm quarks like an almost perfect fluid

DIRECTED FLOW SPLITTING OF D MESONS

The EM fields induce a large splitting in the v_1 of HQs

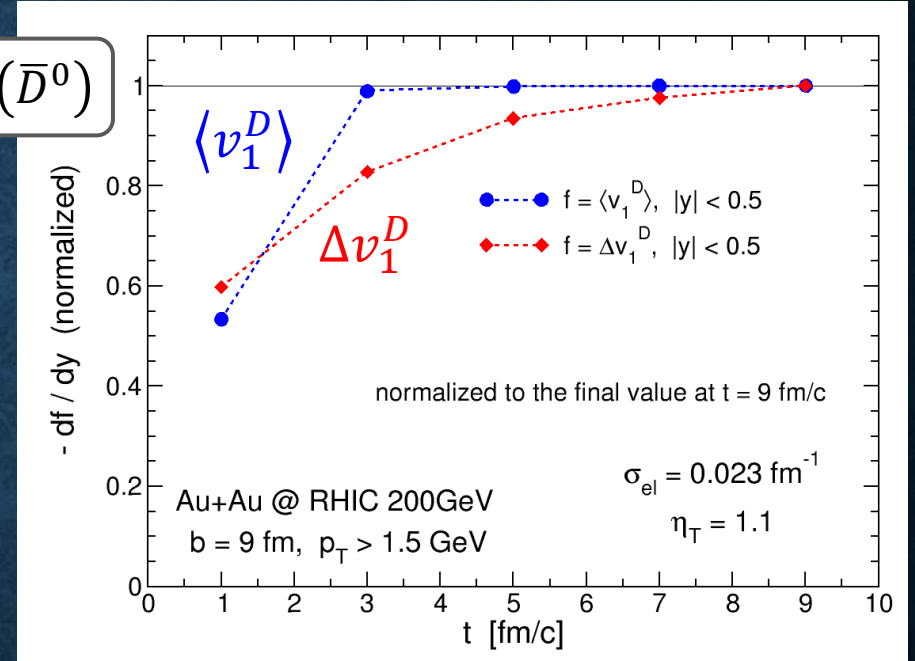
S.K. Das et al., Phys. Lett. B 768, 260 (2017)

$v_1^D(y)$



$$\Delta v_1^D = v_1(D^0) - v_1(\bar{D}^0)$$

SLOPE TIME EVOLUTION



L. Oliva, S. Plumari and V. Greco, JHEP 05, 034 (2021)

Δv_1 of D mesons is ~ 10 times larger than that of light hadrons in agreement with STAR exp. data (still consistent with zero)

STAR Coll., PRL. 123 (2019) 162301



At LHC energy Δv_1^D has opposite sign and magnitude ~ 40 times larger than models

ALICE Coll., Phys. Rev. Lett. 125, 022301 (2020)

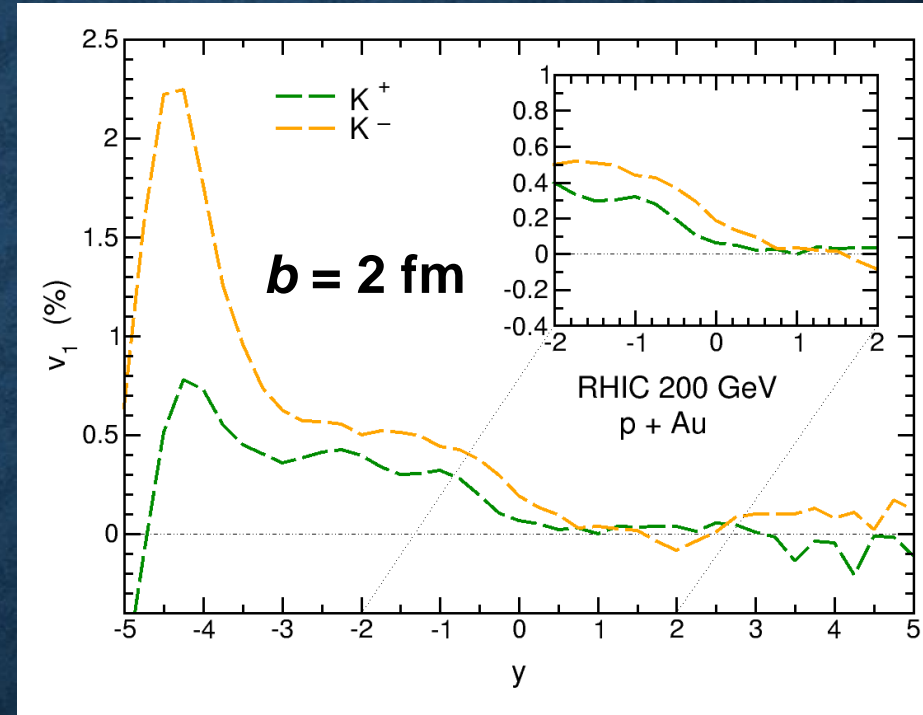
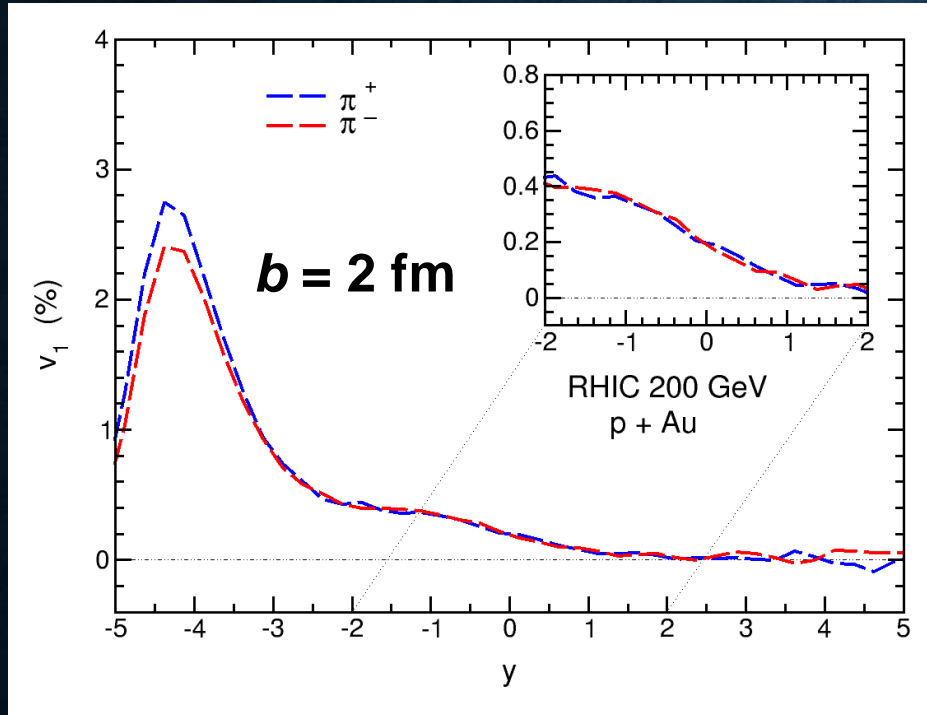
v_1^D more sensitive to the early QGP evolution when T is higher, while v_2^D probes more $T \sim T_c$

if the v_1 splitting of neutral D mesons is of EM origin it is a proof of QGP formation

DIRECTED FLOW IN pA

LO, P. Moreau, V. Voronyuk and E. Bratkovskaya, Phys. Rev. C 101, 014917 (2020) [📄](#)

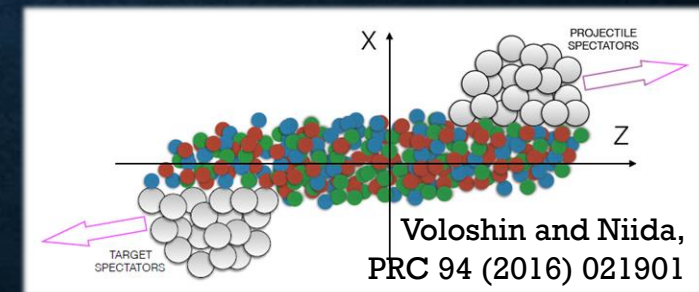
$$v_1(y) = \langle \cos[\varphi(y)] \rangle$$



different v_1 for kaons also without EMF
due to baryon transport to midrapidity

more contributions to K^+ ($\bar{s}u$) with respect to
 K^- ($s\bar{u}$) from quarks of the initial colliding nuclei

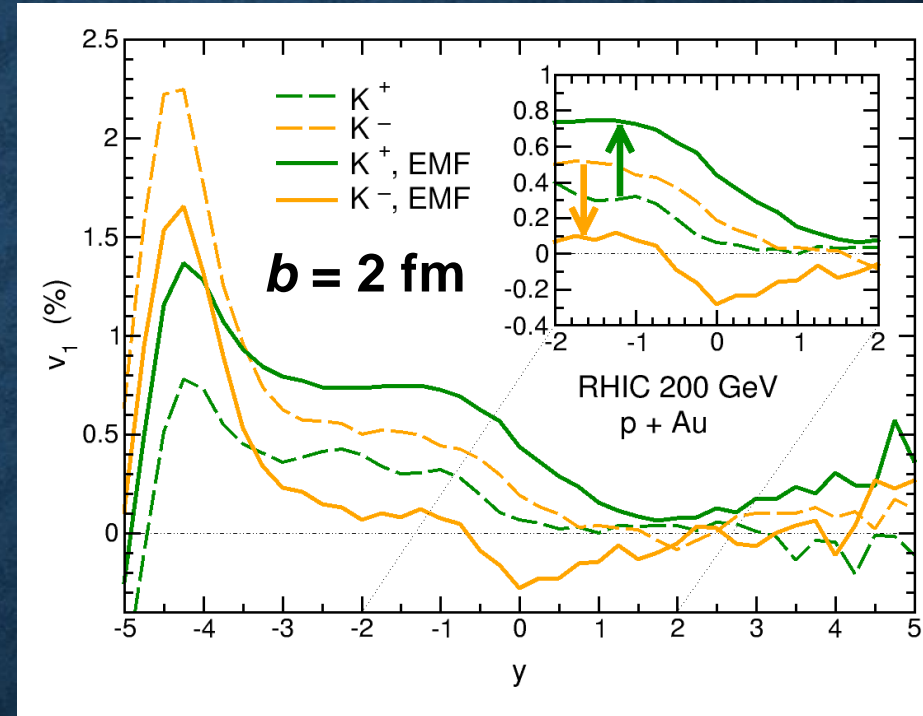
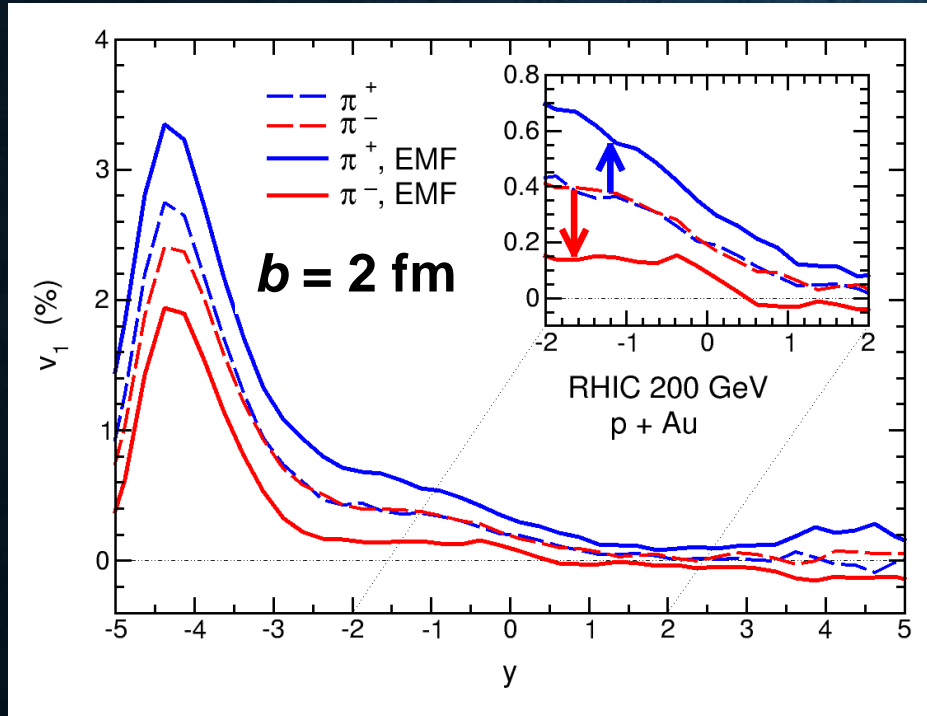
STAR Coll., PRL 120 (2018) 062301



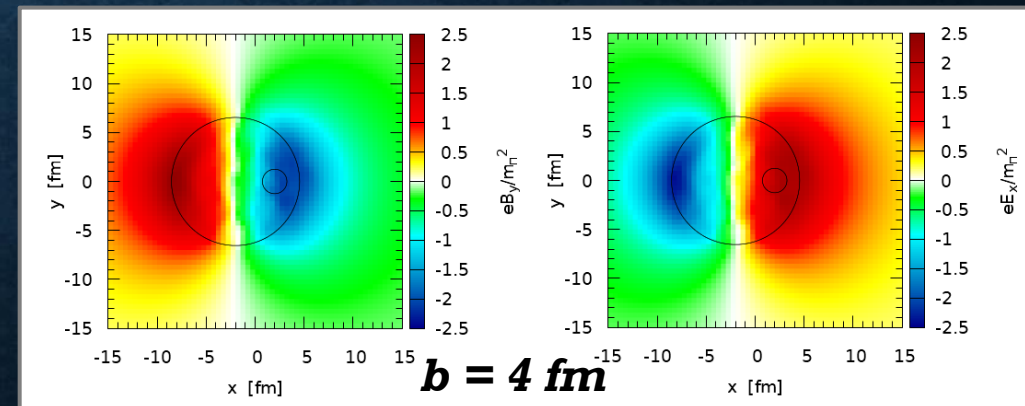
DIRECTED FLOW IN pA

LO, P. Moreau, V. Voronyuk and E. Bratkovskaya, Phys. Rev. C 101, 014917 (2020) [📄](#)

$$v_1(y) = \langle \cos[\varphi(y)] \rangle$$



Splitting of charged pions and kaons induced by the electromagnetic field

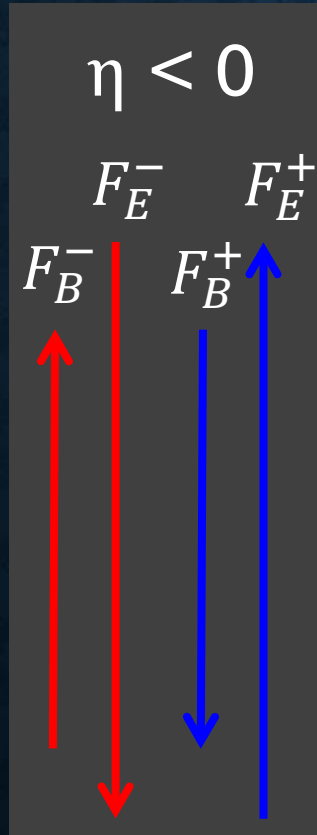


EM FIELDS AND DIRECTED FLOW IN AA

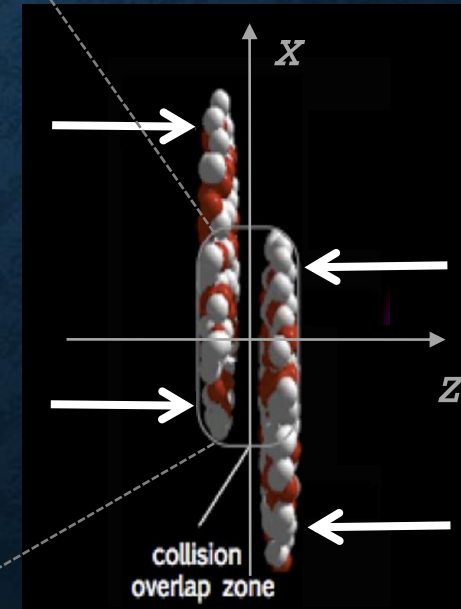
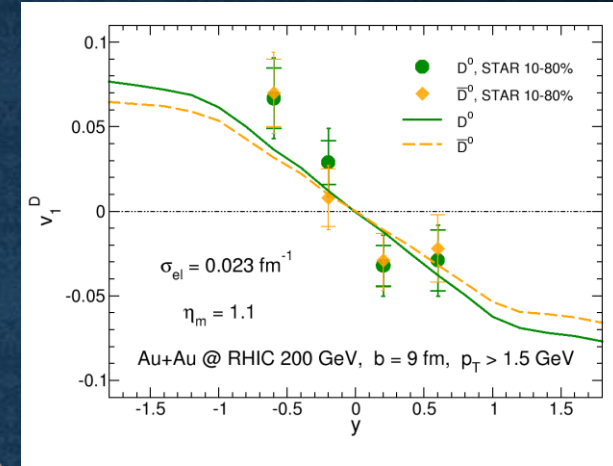
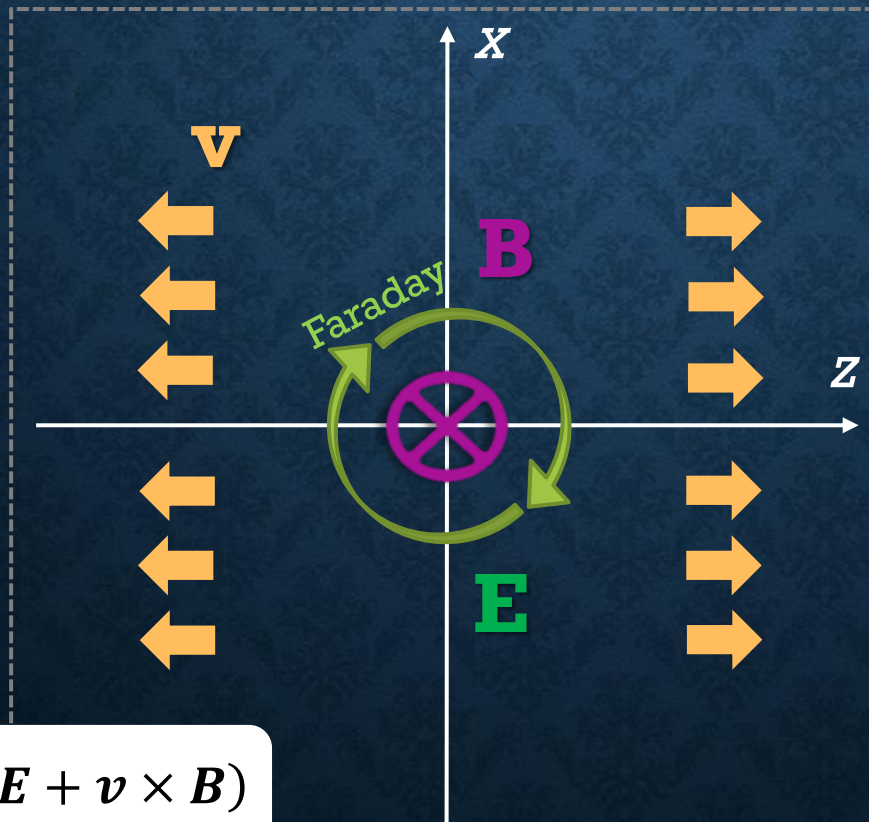
rapidity dependence of the DIRECTED FLOW

collective sideways deflection of particles

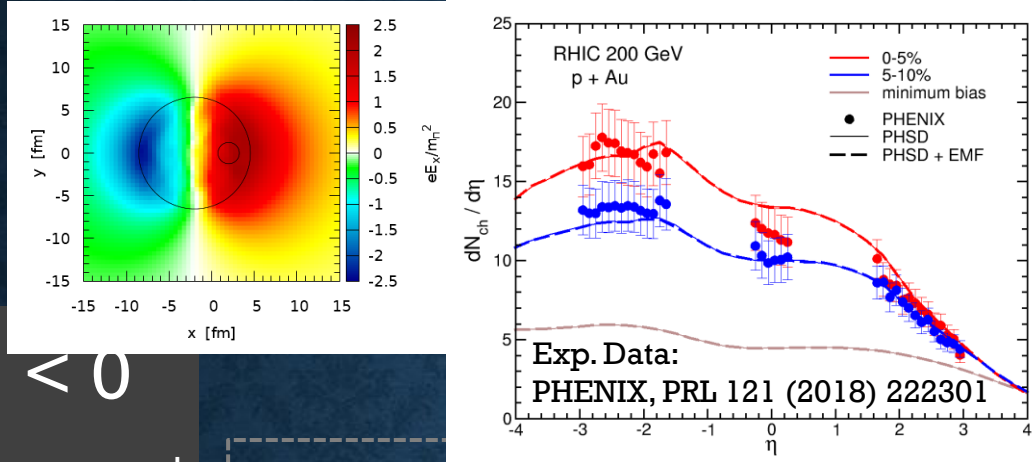
$$v_1 = \langle \cos\varphi \rangle = \langle p_x/p_T \rangle$$



$$F_{\text{Lorentz}} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$$



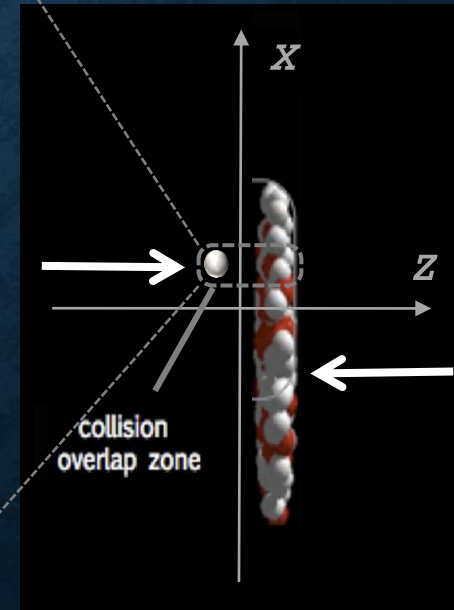
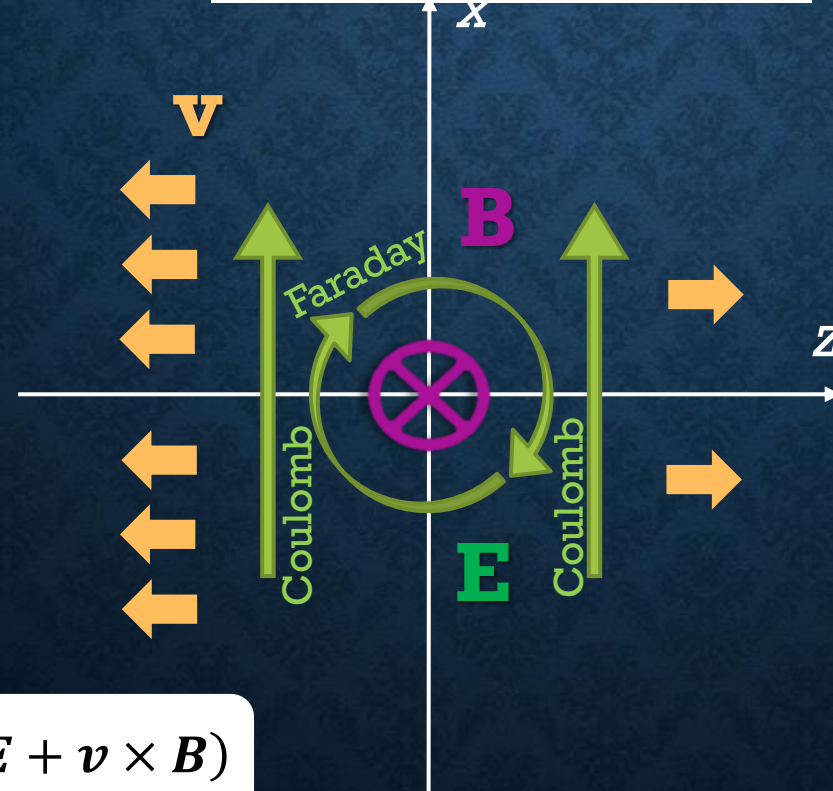
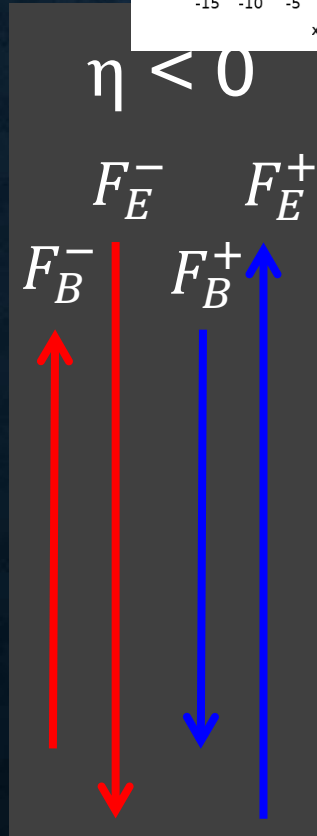
EM FIELDS AND DIRECTED FLOW IN pA



Asymmetry in charged particle and electric field profiles in p+Au

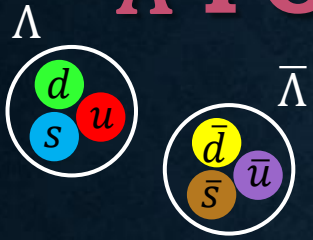
- enhanced particle production in the Au-going direction
- electric field directed from the heavy ion to the proton

LO, P. Moreau, V. Voronyuk and E. Bratkovskaya, Phys. Rev. C 101, 014917 (2020)



$$F_{Lorentz} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$$

Λ POLARIZATION IN COALESCENCE MODEL



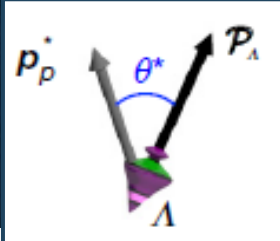
Λ hyperon is a spin-1/2 particle decaying through weak interaction

$$\Lambda \rightarrow p + \pi^- \quad (\text{BR} \sim 64\%)$$

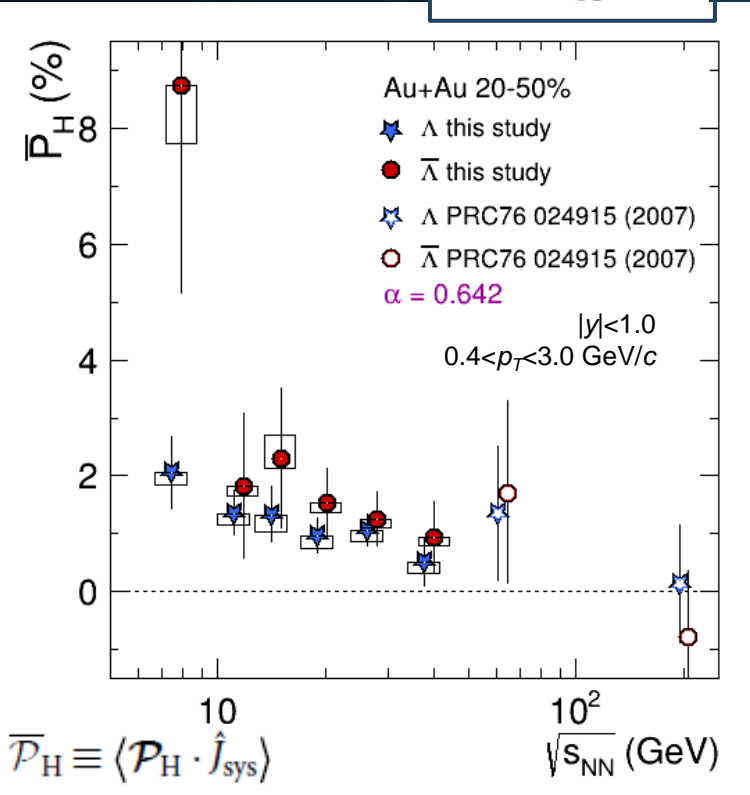
⇒ measure **POLARIZATION**

$$\frac{dN}{d \cos \theta^*} = \frac{1}{2} (1 + \alpha_H |P_H| \cos \theta^*)$$

$$\begin{aligned} \mathbf{p}_1 &= \frac{1}{3} \mathbf{p} + \frac{1}{2} \mathbf{r} + \mathbf{q} \\ \mathbf{p}_2 &= \frac{1}{3} \mathbf{p} + \frac{1}{2} \mathbf{r} - \mathbf{q} \\ \mathbf{p}_3 &= \frac{1}{3} \mathbf{p} - \mathbf{r} \end{aligned}$$



$$P_H(\sqrt{s_{NN}})$$



Y.-G. Yang, R.-H. Fang, Q. Wang and X.-N. Wang, Phys. Rev. C 97, 034917 (2018)

X.-L. Sheng, LO and Q. Wang,

Phys. Rev. D 101, 096005 (2020); Phys. Rev. D 105, 099903 (2022)

nonrelativistic
quark
coalescence
model

$$\begin{aligned} P_{\Lambda/\bar{\Lambda}}^y(t, \mathbf{x}) &= \frac{1}{3} \int \frac{d^3 \mathbf{r}}{(2\pi)^3} \frac{d^3 \mathbf{q}}{(2\pi)^3} |\psi_{\Lambda/\bar{\Lambda}}(\mathbf{q}, \mathbf{r})|^2 \\ &\times \left[P_{s/\bar{s}}^y(t, \mathbf{x}, \mathbf{p}_1) + P_{s/\bar{s}}^y(t, \mathbf{x}, \mathbf{p}_2) + P_{s/\bar{s}}^y(t, \mathbf{x}, \mathbf{p}_3) \right] \\ &= \frac{1}{2} \omega_y \pm \frac{Q_s}{2m_s T} B_y = \frac{1}{2} \omega_y \mp \frac{1}{6m_s T} eB_y \end{aligned}$$

thermal vorticity magnetic field

CONVENTIONAL SOURCES OF SPIN POLARIZATION

EFFECTIVE VECTOR MESON FIELDS

QUARK-MESON MODEL

$$\mathcal{L} = \bar{\Psi}(i\gamma^\mu \partial_\mu - g_V \gamma^\mu V_\mu)\Psi$$

effective vector meson fields

$$V = \frac{1}{\sqrt{2}} \begin{pmatrix} \frac{\omega+\rho}{\sqrt{2}} & 0 & 0 \\ 0 & \frac{\omega-\rho}{\sqrt{2}} & 0 \\ 0 & 0 & \phi \end{pmatrix}$$

A. Manohar and H. Georgi,
Nucl. Phys. B 234, 189 (1984)

A. Zacchi, R. Stiele and J. Schaffner-Bielich,
Phys. Rev. D92, 045022 (2015)

$$F_{\mu\nu}^\phi = \partial_\mu \phi_\nu - \partial_\nu \phi_\mu$$

vector meson field
strength tensor



$$\phi^\mu \approx -\frac{g_\phi}{m_\phi^2} J_s^\mu$$

effective ϕ -meson field
(from field-current identity)

M. Gell-Mann and F. Zachariasen,
Phys. Rev. 124, 953 (1961)



$$J_s^\mu(t, \mathbf{x}) = (\rho_s, \mathbf{J}_s)$$

current density of net
strangeness number

Effective mesonic fields can polarize particles like the electromagnetic field but with large magnitude due to the strong interaction

➤ may contribute to the splitting in polarization between Λ and $\bar{\Lambda}$ hyperons
L. Csernai, J. Kapusta and T. Welle, Phys. Rev. C 99, 021901 (2019)

➤ can explain the spin alignment of ϕ meson

X.-L. Sheng, LO and Q. Wang, Phys. Rev. D 101, 096005 (2020) [Phys. Rev. D 105, 099903 (2022)] [\[1\]](#)

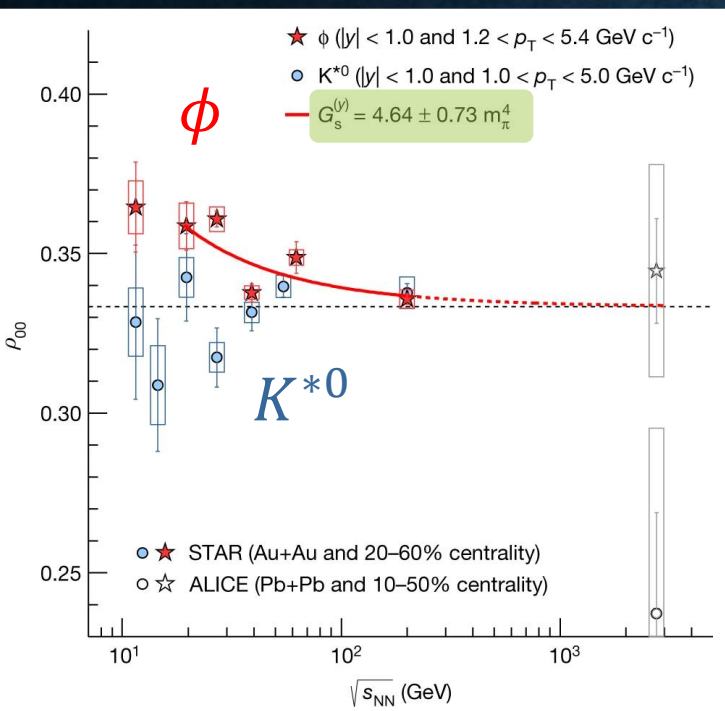
VECTOR MESON SPIN ALIGNMENT

Previous results with the nonrelativistic spin density matrix approach has been derived assuming that the polarization of s and \bar{s} quarks is only along the y direction

Relaxing this condition, the polarization of s and \bar{s} quarks can be along all directions (spin quantization direction still in the y direction)



$$\rho_{00}^y(\sqrt{s_{NN}})$$



$$\rho_{00}^\phi(t, \mathbf{x}) \approx \frac{1}{3} - \frac{4}{9} \int \frac{d^3\mathbf{p}}{(2\pi)^3} |\psi_\phi(\mathbf{p})|^2 \times \left\{ P_s^y(\mathbf{p})P_{\bar{s}}^y(-\mathbf{p}) - \frac{1}{2} [P_s^x(\mathbf{p})P_{\bar{s}}^x(-\mathbf{p}) + P_s^z(\mathbf{p})P_{\bar{s}}^z(-\mathbf{p})] \right\}$$

$$\rho_{00}^\phi \approx \frac{1}{3} + c_\Lambda + c_\epsilon + c_E + c_\phi \quad c_\phi = \frac{G_s^{(y)}}{27m_s^2 T_{\text{eff}}^2}$$

$$G_s^{(y)} = g_\phi^2 \left[3 \left\langle (B_y^\phi)^2 \right\rangle + \frac{\langle \mathbf{p}_b^2 \rangle_\phi}{m_s^2} \left\langle (E_y^\phi)^2 \right\rangle - \frac{3}{2} \left\langle (B_x^\phi)^2 + (B_z^\phi)^2 \right\rangle - \frac{\langle \mathbf{p}_b^2 \rangle_\phi}{2m_s^2} \left\langle (E_x^\phi)^2 + (E_z^\phi)^2 \right\rangle \right]$$

X.-L. Sheng, LO and Q. Wang,

Phys. Rev. D 101, 096005 (2020); Phys. Rev. D 105, 099903 (2022)

see arXiv: 1910.13684

SPIN ALIGNMENT OF ϕ MESONS

ρ_{00}^ϕ in terms of lab-frame fields taking the y -axis as spin quantization direction

$$\bar{\rho}_{00}^\phi(x, \mathbf{p}) \approx \frac{1}{3} + \frac{1}{3} \sum_{i=1,2,3} I_{B,i}(\mathbf{p}) \left[\omega_i^2 - \frac{4g_\phi^2}{m_\phi^2 T_{\text{eff}}^2} (\mathbf{B}_i^\phi)^2 \right] + \frac{1}{3} \sum_{i=1,2,3} I_{E,i}(\mathbf{p}) \left[\varepsilon_i^2 - \frac{4g_\phi^2}{m_\phi^2 T_{\text{eff}}^2} (\mathbf{E}_i^\phi)^2 \right]$$

$$I_{B,x}(\mathbf{p}) = C_1 \left[(E_{\mathbf{p}}^\phi)^2 - \left(1 + \frac{p_y^2}{(m_\phi + E_{\mathbf{p}}^\phi)^2} \right) p_x^2 \right] + C_2 (p_y^2 - 2p_z^2),$$

$$I_{E,x}(\mathbf{p}) = C_1 (p_y^2 - 2p_z^2) + C_2 \left[(E_{\mathbf{p}}^\phi)^2 - \left(1 + \frac{p_y^2}{(m_\phi + E_{\mathbf{p}}^\phi)^2} \right) p_x^2 \right],$$

$$I_{B,y}(\mathbf{p}) = C_1 \left[6 \frac{E_{\mathbf{p}}^\phi}{m_\phi + E_{\mathbf{p}}^\phi} p_y^2 - 2(E_{\mathbf{p}}^\phi)^2 - p_y^2 - \frac{p_y^4}{(m_\phi + E_{\mathbf{p}}^\phi)^2} \right] + C_2 (p_x^2 + p_z^2),$$

$$I_{E,y}(\mathbf{p}) = C_1 (p_x^2 + p_z^2) + C_2 \left[6 \frac{E_{\mathbf{p}}^\phi}{m_\phi + E_{\mathbf{p}}^\phi} p_y^2 - 2(E_{\mathbf{p}}^\phi)^2 - p_y^2 - \frac{p_y^4}{(m_\phi + E_{\mathbf{p}}^\phi)^2} \right]$$

$$I_{B,z}(\mathbf{p}) = C_1 \left[(E_{\mathbf{p}}^\phi)^2 - \left(1 + \frac{p_y^2}{(m_\phi + E_{\mathbf{p}}^\phi)^2} \right) p_z^2 \right] + C_2 (p_y^2 - 2p_x^2),$$

$$I_{E,z}(\mathbf{p}) = C_1 (p_y^2 - 2p_x^2) + C_2 \left[(E_{\mathbf{p}}^\phi)^2 - \left(1 + \frac{p_y^2}{(m_\phi + E_{\mathbf{p}}^\phi)^2} \right) p_z^2 \right].$$