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SPIN ALIGNMENT OF VECTOR MESONS IN HEAVY-ION COLLISIONS

Lucia Oliva

Collaborators

Xin-Li Sheng, Qun Wang

Zuo-Tang Liang, Xin-Nian Wang

INFN CATANIA
Istituto Nazionale di Fisica Nucleare
Sezione di Catania

UNIVERSITÀ degli STUDI di CATANIA

DIPARTIMENTO DI FISICA E ASTRONOMIA "ETTORE MAJORANA"

INTENSE FIELDS IN HEAVY-ION COLLISIONS

vorticity

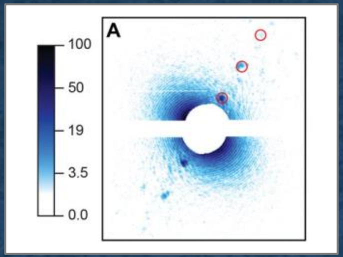
ω

tornado cores

~ 10^{-1} s^{-1}

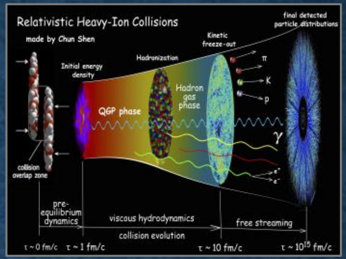
Jupiter's spot

~ 10^{-4} s^{-1}



He nanodroplets

~ 10^{7} s^{-1}



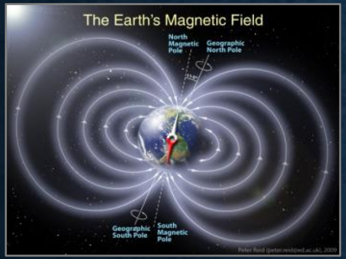
urHICs

~ 10^{22}–10^{23} s^{-1}

HUGE ANGULAR MOMENTUM GENERATING A STRONG **VORTICITY**

magnetic field

B



Earth's field

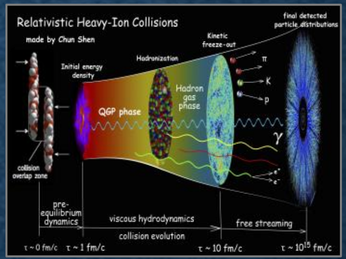
~ 1 G

laboratory

~ 10^{6} G

magnetars

~ 10^{14}–10^{15} G



urHICs

~ 10^{18}–10^{19} 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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~ $10^{-1}\ s^{-1}$

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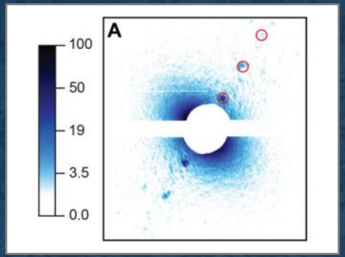
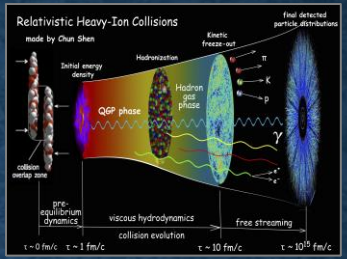
~ $10^{-4}\ s^{-1}$



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



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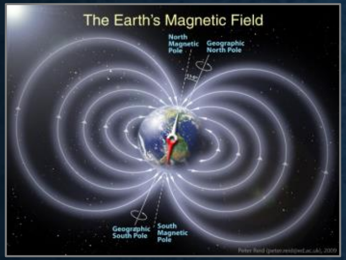

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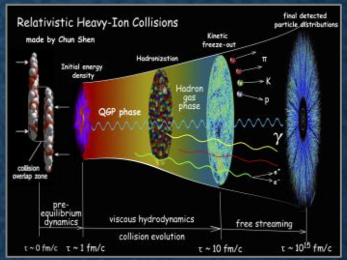


urHICs
~ 10^{18}–10^{19} G

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

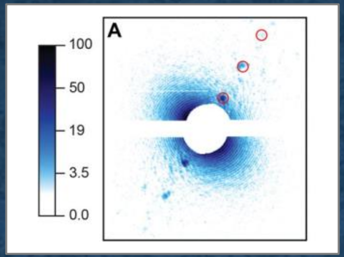
ω

tornado cores

$\sim 10^{-1}\ s^{-1}$

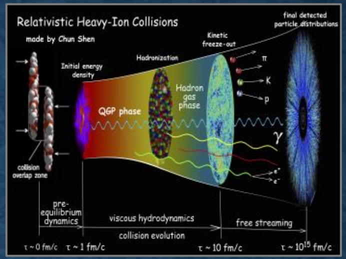
Jupiter's spot

$\sim 10^{-4}\ s^{-1}$



He nanodroplets

$\sim 10^{7}\ s^{-1}$



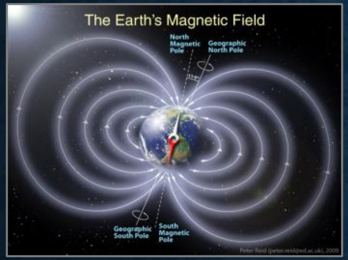
urHICs

$\sim \mathbf{10^{22}–10^{23}\ s^{-1}}$

HUGE ANGULAR MOMENTUM GENERATING A STRONG **VORTICITY**

magnetic field

B



Earth's field

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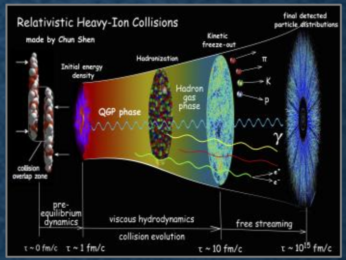
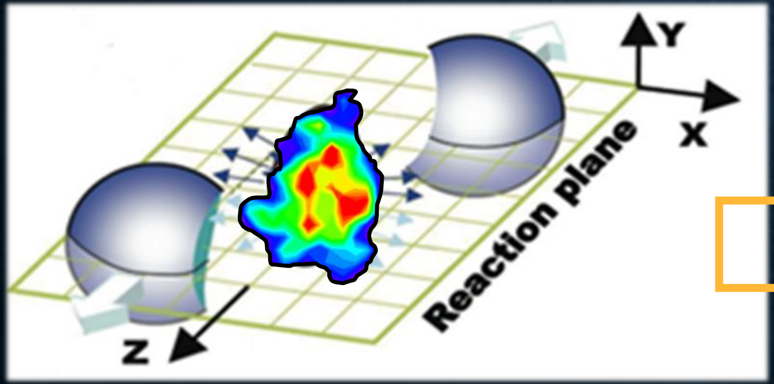


urHICs

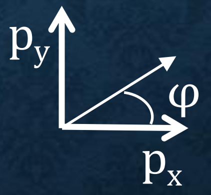
$\sim \mathbf{10^{18}–10^{19}}$ **G**

INTENSE **ELECTRIC** AND **MAGNETIC FIELDS**

How to probe them?



anisotropic azimuthal particle distributions



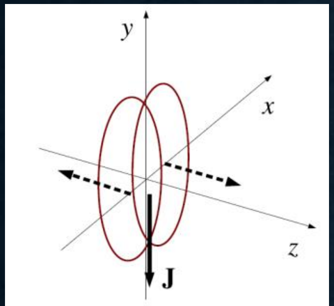
$$\frac{dN}{d\varphi} \propto 1 + \sum_n 2\, v_n \cos[n\varphi]$$

DIRECTED FLOW v_1

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

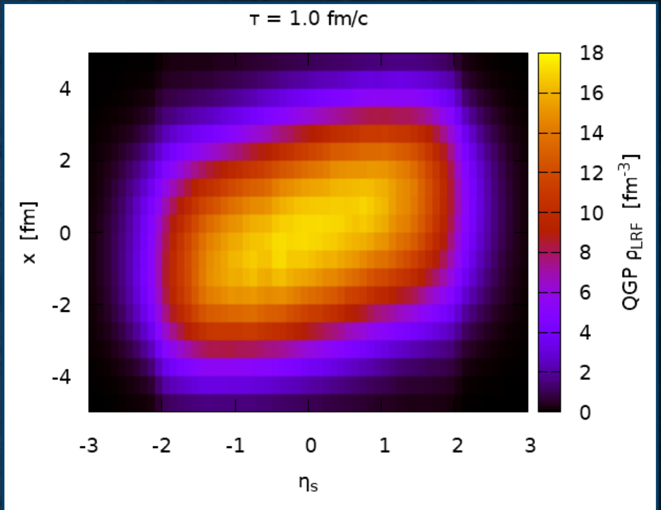
collective sidewards particle deflection

THE VORTICAL QUARK-GLUON PLASMA



Huge **orbital angular momentum** of the colliding system
- in ultra-relatvistic HICs **$J \approx 10^5 - 10^6\ \hbar$**
- mainly perpendicular to the reaction plane
- partly transferred to the plasma

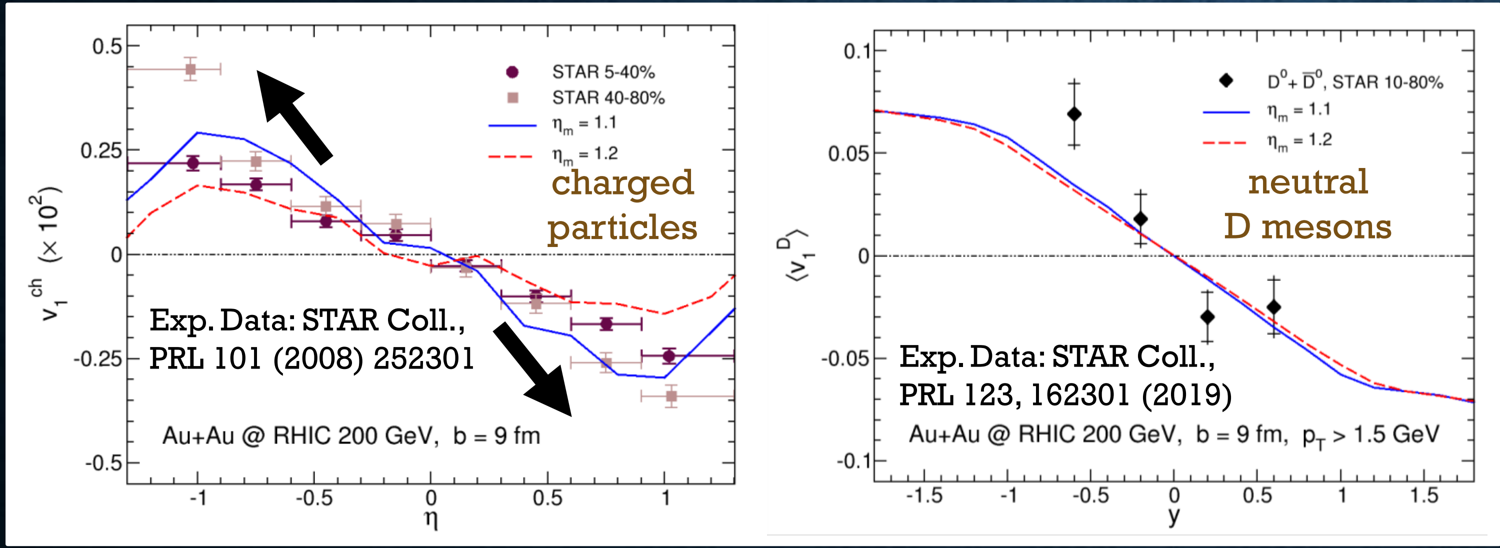
TILTED FIREBALL



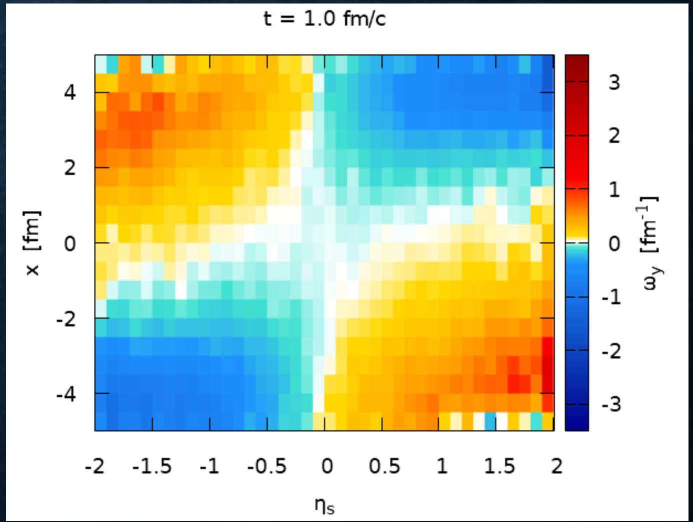
⇩

asymmetry in local participant density
from forward and backward going nuclei

P. Bozek and I. Wyskiel, Phys. Rev. C 81, 054902 (2010)



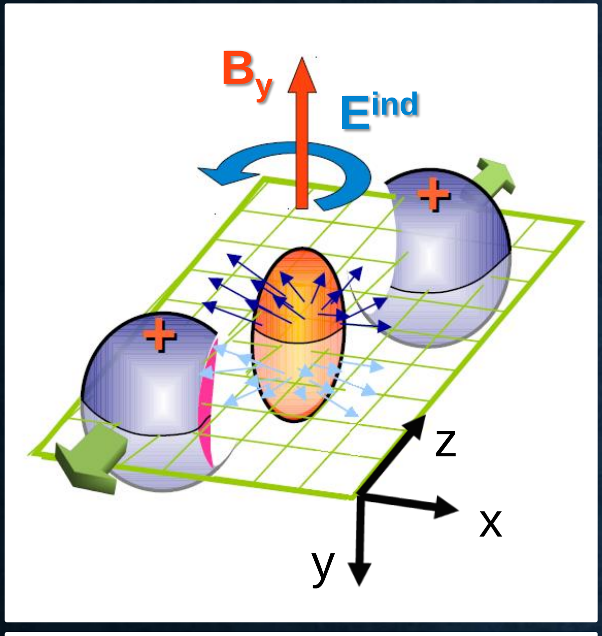
negative slope of $v_1(\eta)$

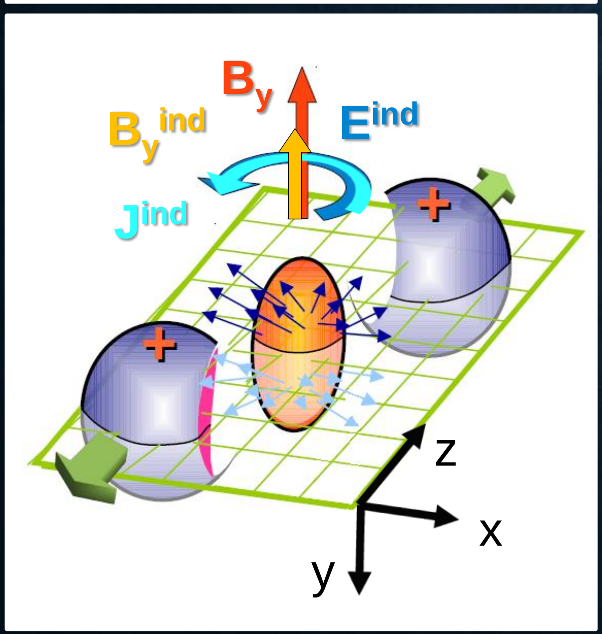


huge vorticity ω_y

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

ELECTROMAGNETIC (EM) FIELDS





Huge **magnetic field** in the overlap area

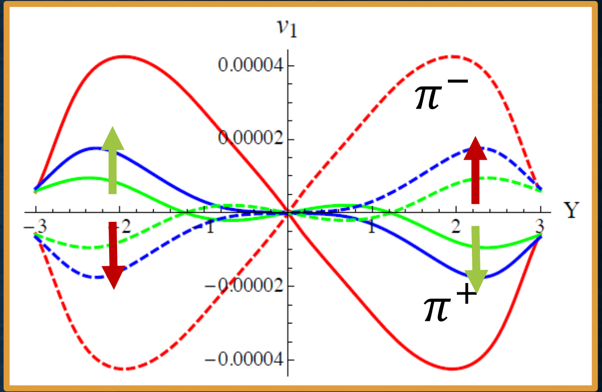
- in uRHICs up to **eB ≈ 5-50 m_π^2**
- mainly perpendicular to the reaction plane
- intense Faraday-induced electric field
- charged currents induced in the conducting QGP sustain the magnetic field

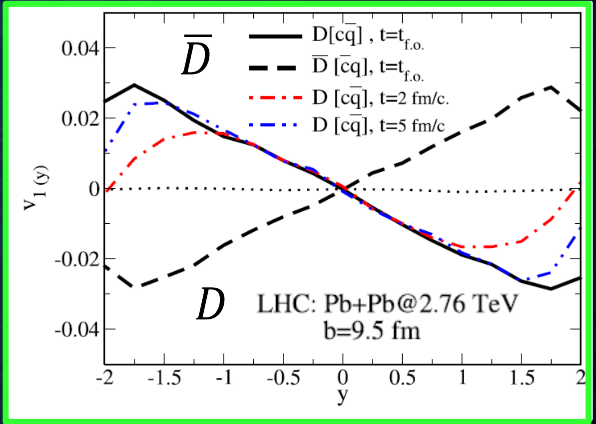
splitting in the v_1 of particles with same mass and opposite charge

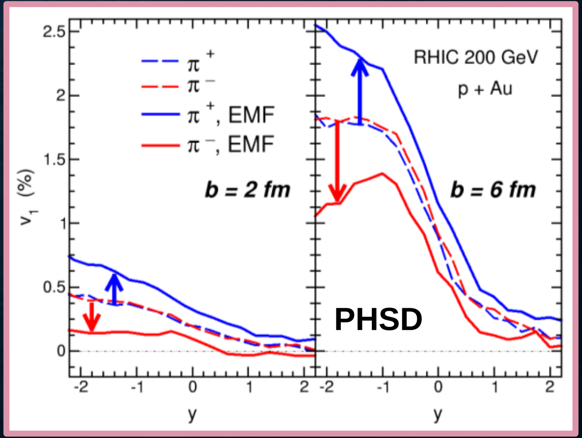
- Δv_1 of light hadrons in AA: $O(10^{-4}$–$10^{-3})$
  Gursoy et al., Phys. Rev. C 89, 054905 (2014)
- Δv_1 of heavy mesons in AA: $O(10^{-2})$
  Das et al., Phys. Lett. B 768, 260 (2017)
- Δv_1 of light mesons in pA: $O(10^{-2})$
  Oliva et al., Phys. Rev. C 101, 014917 (2020)

reviews

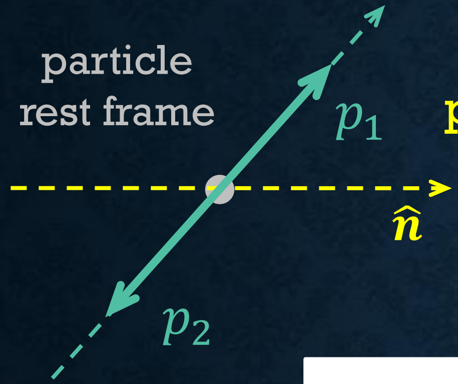
Oliva, Eur. Phys. J. A 56, 255 (2020)
Dubla, Gursoy and Snellings, Mod. Phys. Lett. A 35, 2050324 (2020)





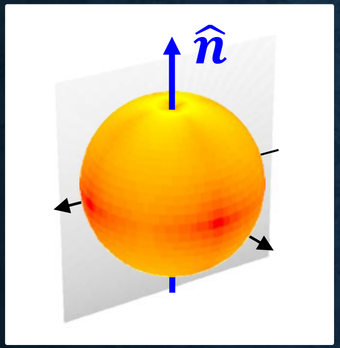


SPIN POLARIZATION

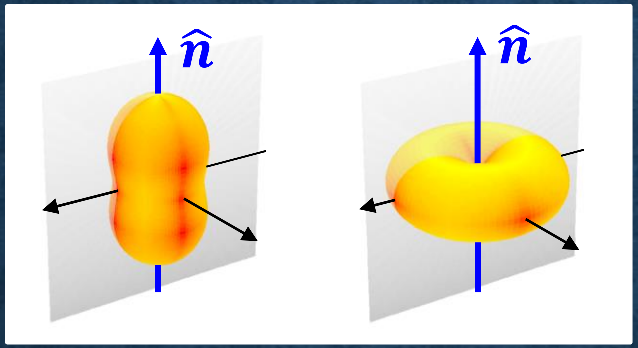


Spin polarization is the degree of alignment of the particle spin with a given direction (quantization axis)

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



spherically symmetric
$\Longrightarrow$ unpolarized production



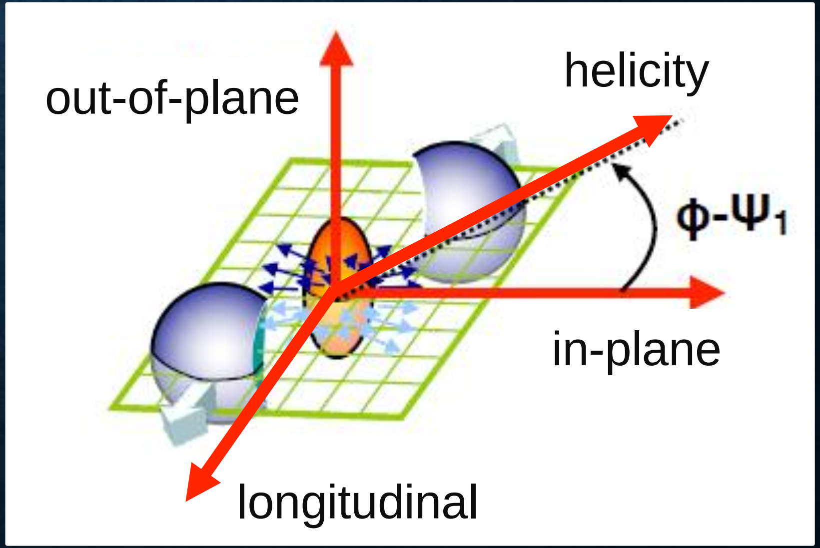
anisotropic distribution
$\Longrightarrow$ polarized production

Picture credit: P. Faccioli

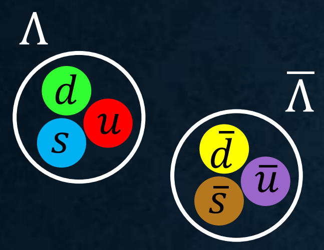
"Spin Family (Bosons and Fermions)" sculptures by Julian Voss-Andreae (2009)

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)
- …

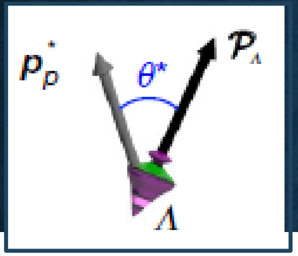


HYPERON POLARIZATION



Λ hyperon is a spin-1/2 particle
decaying through weak interaction
$\Lambda \rightarrow p + \pi^-$ (BR ~ 64%)
$\Longrightarrow$ measure POLARIZATION

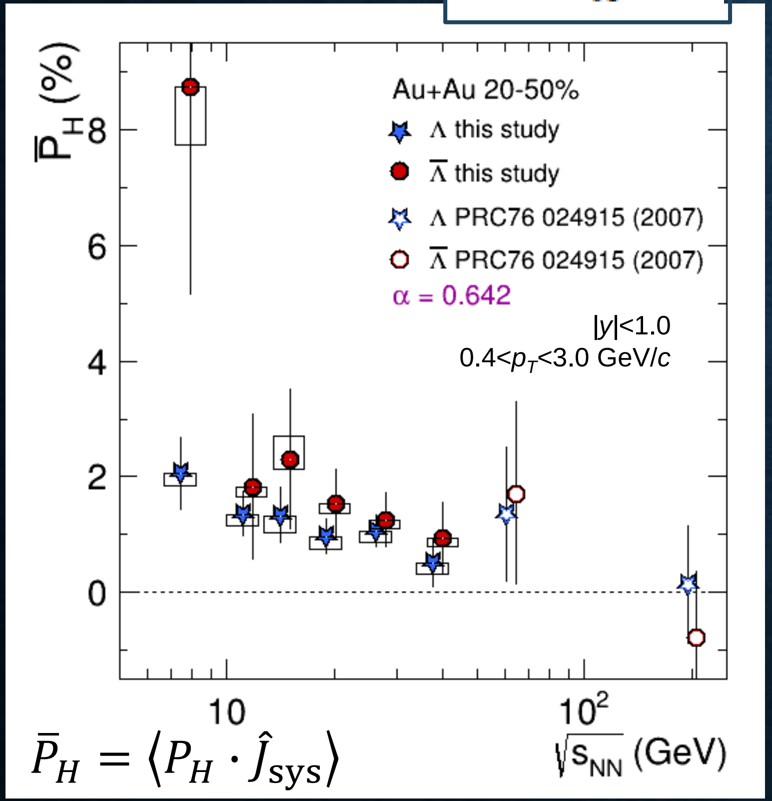
parity-violating weak decays:
daughter proton preferentially
emitted in the direction of Λ spin



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

P_H : hyperon polarization
α_H : hyperon decay parameter

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



$\bar{P}_H = \langle P_H \cdot \hat{J}_{sys} \rangle$

STAR Coll., Nature 548, 62 (2017)

μ_Λ : magnetic moment of Λ hyperon
T : temperature at thermal equilibrium

F. Becattini, Iu. Karpenko, M.A. Lisa, I. Upsal, S. Voloshin,
Phys. Rev. C 95, 054902 (2017)

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

thermal approach

thermal vorticity

magnetic field

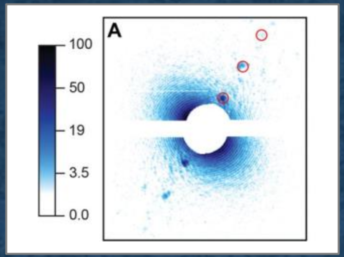
CONVENTIONAL SOURCES OF SPIN POLARIZATION

VORTICITY AND MAGNETIC FIELD

vorticity
ω

tornado cores
~ $10^{-1}\ s^{-1}$

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



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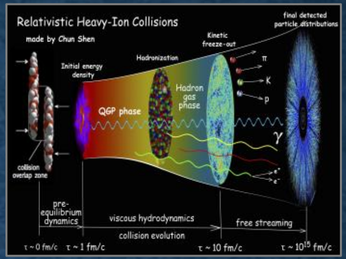

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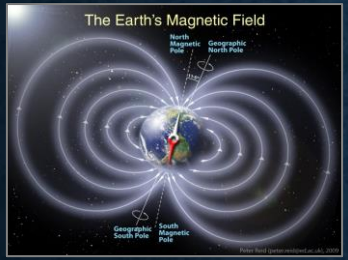

Earth's field
~ 1 G

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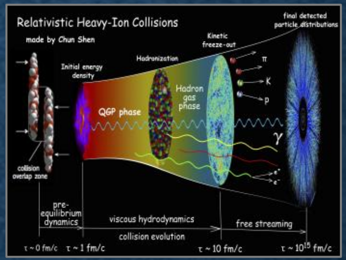

urHICs
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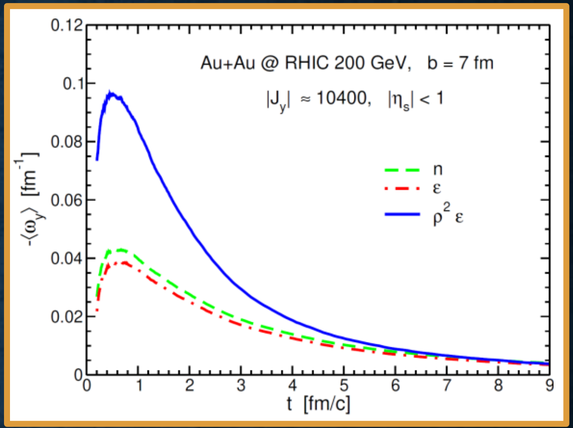
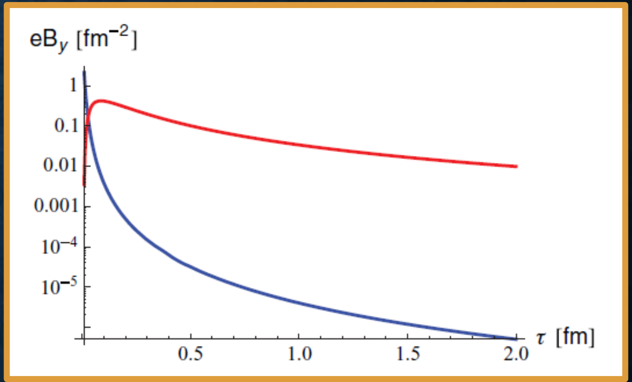


LO, S. Plumari and V. Greco, JHEP 05, 034 (2021)



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

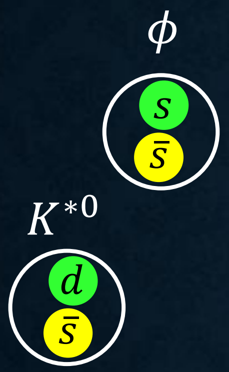
Estimates **at freeze-out** from $\Lambda - \bar{\Lambda}$ polarization based on **thermal approach**

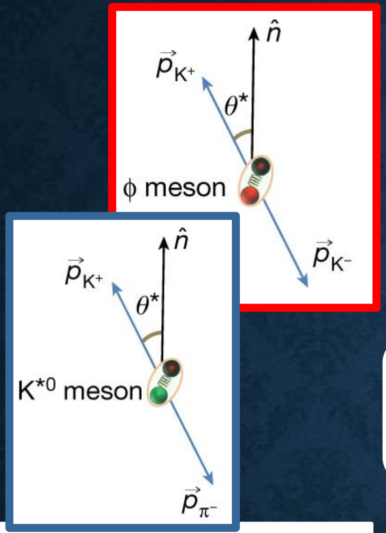
$$\omega \approx (P_\Lambda + P_{\bar{\Lambda}}) k_B T/\hbar \sim 0.02 - 0.09\ \mathrm{fm}^{-1} \sim 0.6 - 2.7 \times 10^{22}\ \mathrm{s}^{-1}$$

$$B \approx (P_\Lambda - P_{\bar{\Lambda}}) T/2\mu_\Lambda \sim 2 \times 10^{15}\ \mathrm{G} \rightarrow eB \sim 5 \times 10^{-3}\ \mathrm{fm}^{-2} \sim 10^{-2}\ m_\pi^2$$

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

VECTOR MESON SPIN ALIGNMENT





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

$\phi \rightarrow K^+ + K^-$ (BR ~49%)

$K^{*0} \rightarrow K^+ + \pi^-$ (BR ~100%)

$\Longrightarrow$ measure SPIN ALIGNMENT

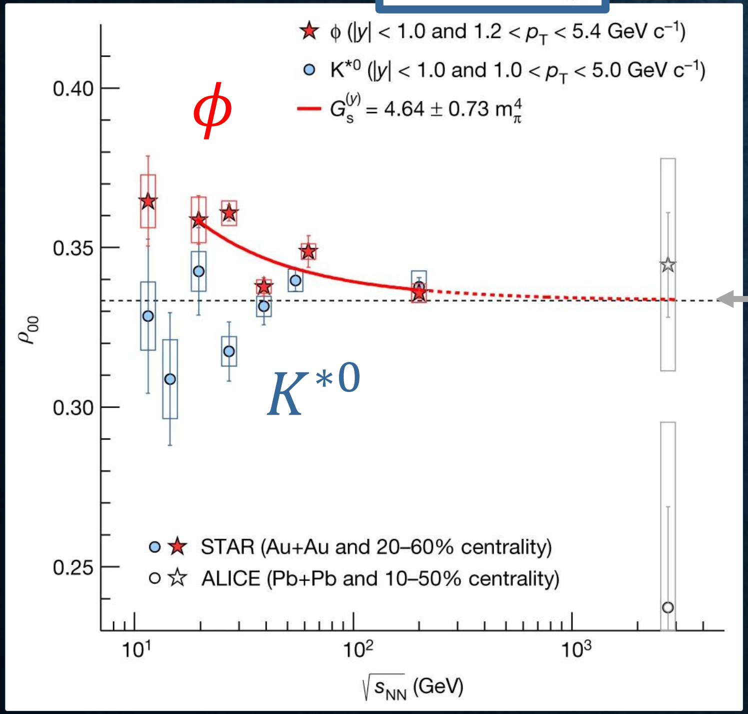
parity-conserving strong decays: direction of the polarization cannot be determined

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

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

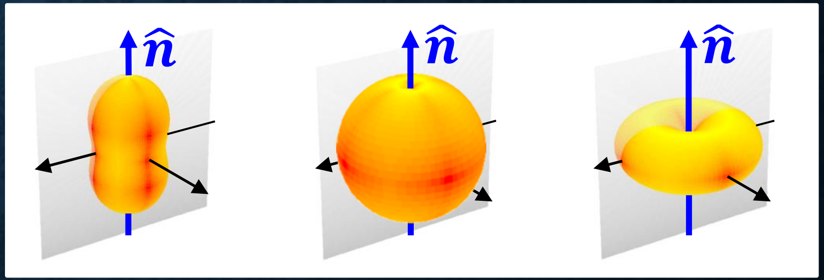
$\rho^y_{00}(\sqrt{s_{NN}})$



STAR Coll., Nature 614, 244 (2023)

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



$\rho_{00} > 1/3$	$\rho_{00} = 1/3$	$\rho_{00} < 1/3$
$S_V \perp \hat{n}$		$S_V \parallel \hat{n}$
$\lvert 1,0\rangle$		$\lvert 1,\pm 1\rangle$

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 plane[26], 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 known[2] 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 indicates[2] 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 GeV c^{-1} (ref. [12]). Helicity polarization gives a negative contribution at all centralities[27]. Locally fluctuating axial charge currents induced by possible local charge violation gives rise to the expectation[29] of $\rho_{00}(K^{*0}) < \rho_{00}(\phi) < 1/3$. 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 $\bar{s}$ quarks[2–6], 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

STAR Collaboration, Nature 614, 244 (2023)

2. X.-L. Sheng, LO & Q. Wang, *Phys. Rev. D* 101, 096005 (2020)
3. X.-L. Sheng, LO & 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, LO, Z.-T. Liang, Q. Wang & X.-N. Wang, 2205.15689
6. X.-L. Sheng, LO, 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

SPIN POLARIZATION OF QUARKS

spin polarization vector for massive fermion/antifermion

$$P^{\mu}_{\pm}(x,p) = \frac{1}{4m}\epsilon^{\mu\nu\varrho\sigma}\left(\omega^{\rm th}_{\varrho\sigma} \pm \frac{Q}{(u\cdot p)T}F^{\rm em}_{\varrho\sigma} \pm \frac{g_V}{(u\cdot p)T}F^{\rm V}_{\varrho\sigma}\right)p_\nu\left[1 - f_{\rm FD}\left(E_p \mp \mu\right)\right]$$

thermal vorticity tensor

electromagnetic field strength tensor

vector meson field strength tensor

$$\omega^{\rm th}_{\varrho\sigma} = \frac{1}{2}\left(\partial_\varrho(\beta u_\sigma) - \partial_\sigma(\beta u_\varrho)\right)$$

"electric" $\varepsilon = -\frac{1}{2}\left(\partial_t(\beta \mathbf{u}) + \nabla(\beta u^0)\right)$

"magnetic" $\boldsymbol{\omega} = \frac{1}{2}\nabla \times (\beta \mathbf{u})$

$$F^{\rm em,V}_{\varrho\sigma} = \partial_\varrho A^{\rm em,V}_\sigma - \partial_\sigma A^{\rm em,V}_\varrho$$

"electric" $\mathbf{E}^{\rm em,V}_i = \mathbf{E}^i_{\rm em,V} = F^{i0}_{\rm em,V}$

"magnetic" $\mathbf{B}^{\rm em,V}_i = \mathbf{B}^i_{\rm em,V} = -\frac{1}{2}\epsilon_{ijk}F^{jk}_{\rm em,V}$

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

$$P^y_{q/\bar{q}}(t,\mathbf{x},\mathbf{p}_{q/\bar{q}}) = \frac{1}{2}\omega_y \pm \frac{1}{2m_q}\left(\boldsymbol{\varepsilon}\times\mathbf{p}_{q/\bar{q}}\right)_y \pm \frac{Q_q}{2m_qT}B_y \pm \frac{Q_q}{2m_q^2T}\left(\mathbf{E}\times\mathbf{p}_{q/\bar{q}}\right)_y \pm \frac{g_V}{2m_qT}B^V_y \pm \frac{g_V}{2m_q^2T}\left(\mathbf{E}^V\times\mathbf{p}_{q/\bar{q}}\right)_y$$

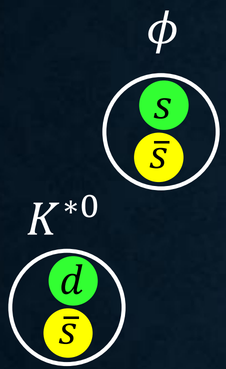
Like the em field, effective mesonic fields can polarize particles but with large magnitude due to the strong interaction

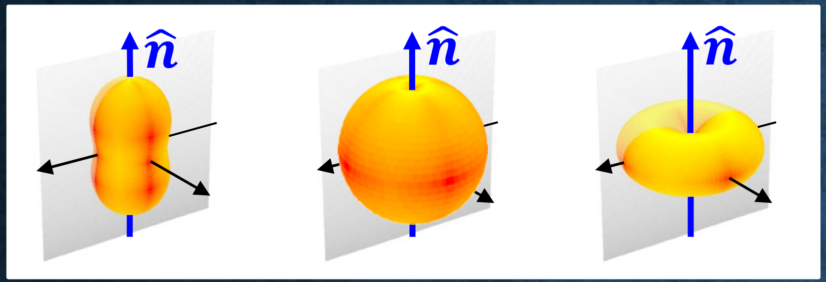
ϕ

K^{*0}

X.-L. Sheng, LO and Q. Wang, Phys. Rev. D 101, 096005 (2020) [Phys. Rev. D 105, 099903 (2022)]
X.-L. Sheng, Q. Wang and X.-N. Wang, Phys. Rev. D 102, 056013 (2020)

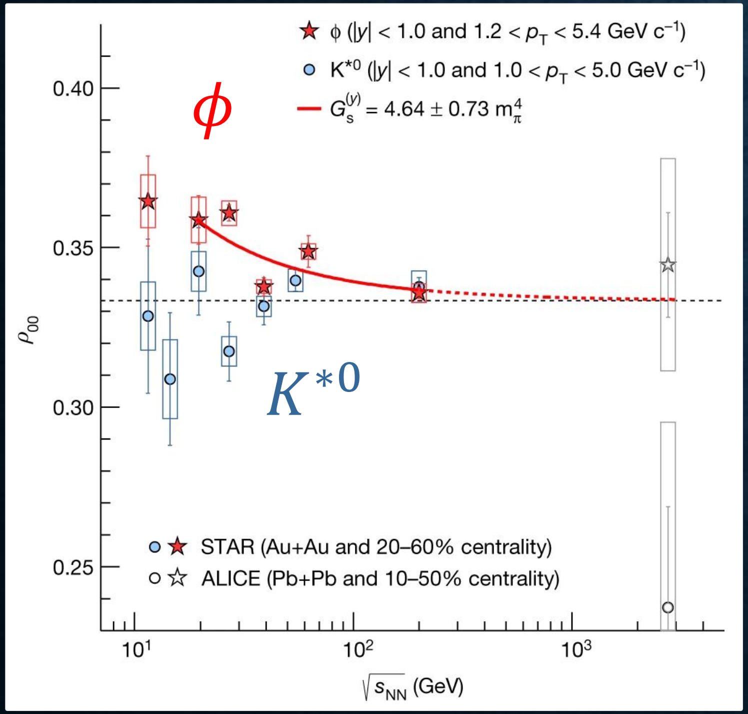
VECTOR MESON SPIN ALIGNMENT





$\rho_{00} > 1/3$ $S_V \perp \hat{n}$ $\rho_{00} = 1/3$ $\rho_{00} < 1/3$ $S_V \parallel \hat{n}$

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



STAR Coll., Nature 614, 244 (2023)

nonrelativistic quark coalescence model

$$\rho^{\phi}_{00}(t,\mathbf{x}) \approx \frac{1}{3} - \frac{4}{9}\int \frac{d^3\mathbf{p}}{(2\pi)^3} P^y_s(\mathbf{p}) P^y_{\bar{s}}(-\mathbf{p}) \left|\psi_\phi(\mathbf{p})\right|^2$$

polarized quarks → COALESCENCE → polarized hadrons

$$\rho^{\phi}_{00} \approx \frac{1}{3} + c_\Lambda + c_\varepsilon + c_E + c_\phi \qquad c_\Lambda \equiv -(4/9)\left\langle P^y_{\bar{\Lambda}} P^y_{\Lambda}\right\rangle = -\frac{1}{9}\left\langle \omega_y^2\right\rangle + \frac{Q_s^2}{9 m_s^2 T_{\text{eff}}^2}\left\langle B_y^2\right\rangle$$

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

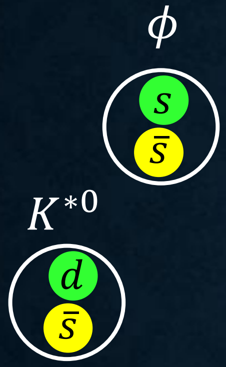
$$c_\phi \equiv \frac{g_\phi^2}{27 m_s^2 T_{\text{eff}}^2}\left[3\left\langle B^2_{\phi,y}\right\rangle - \frac{\left\langle \mathbf{p}^2\right\rangle_\phi}{m_s^2}\left\langle E^2_{\phi,z} + E^2_{\phi,x}\right\rangle\right]$$

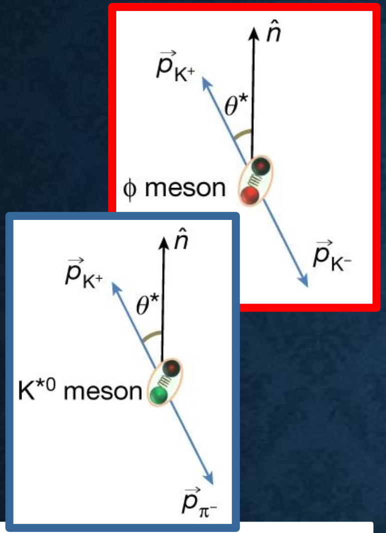
$c_\Lambda, c_\varepsilon, c_E \sim 10^{-3} - 10^{-5}$ are negligibly small compared to 1/3

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

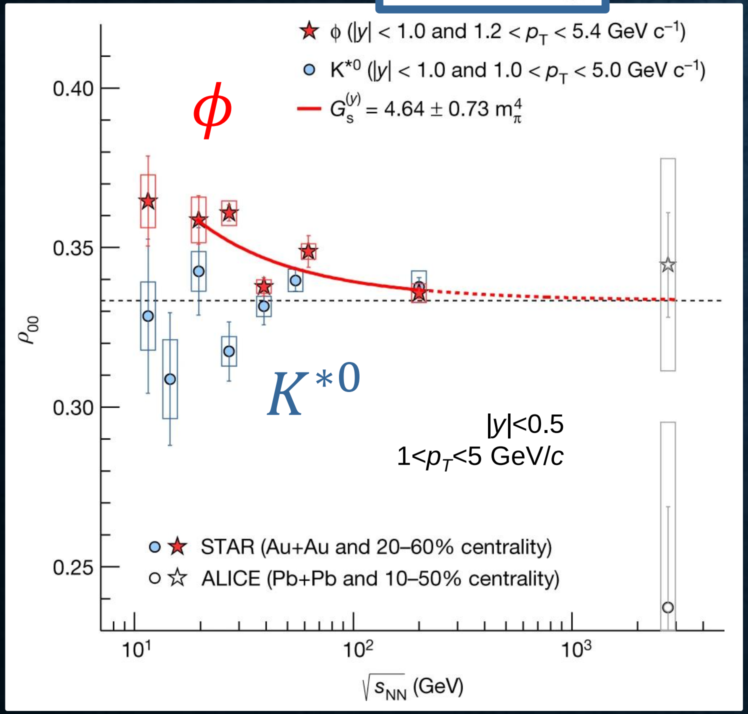
X.-L. Sheng, LO and Q. Wang,
Phys. Rev. D 101, 096005 (2020) [Phys. Rev. D 105, 099903 (2022)]

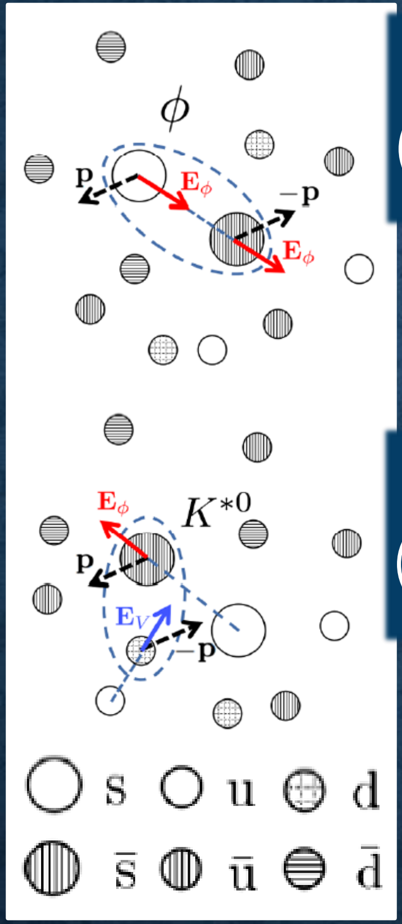
WHY ONLY ϕ MESON?



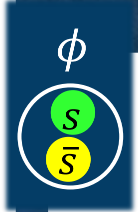


$\rho_{00}^{y}(\sqrt{s_{NN}})$

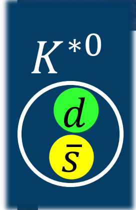




neglecting EM fields



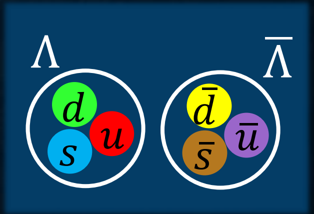
$$\rho_{00}^{\phi} \approx \frac{1}{3} - \frac{1}{9}\langle \omega_y^2 \rangle + \frac{\langle \boldsymbol{p}_b^2 \rangle_\phi}{27 m_s^2} \langle \varepsilon_z^2 + \varepsilon_x^2 \rangle + \frac{g_\phi^2}{27 m_s^2 T_{\text{eff}}^2} \left[3 \left\langle \left(B_y^\phi\right)^2 \right\rangle - \frac{\langle \boldsymbol{p}_b^2 \rangle_\phi}{m_s^2} \left\langle \left(E_z^\phi\right)^2 + \left(E_x^\phi\right)^2 \right\rangle \right]$$



$$\rho_{00}^{K^{*0}} \approx \frac{1}{3} - \frac{1}{9}\langle \omega_y^2 \rangle + \frac{\langle \boldsymbol{p}_b^2 \rangle_{K^*}}{27 m_s m_d} \langle \varepsilon_z^2 + \varepsilon_x^2 \rangle + \frac{g_\phi g_V}{27 m_s m_d T_{\text{eff}}^2} \left[3 \left\langle B_y^\phi B_y^V \right\rangle - \frac{\langle \boldsymbol{p}_b^2 \rangle_{K^*}}{m_s m_d} \left\langle E_z^\phi E_z^V + E_x^\phi E_x^V \right\rangle \right]$$

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

$$k\cdot\partial_x f^V_{\lambda_1\lambda_2}(x,\mathbf{k}) = \frac{1}{8}\left[\epsilon^*_\mu(\lambda_1,\mathbf{k})\epsilon_\nu(\lambda_2,\mathbf{k})\mathcal{C}^{\mu\nu}_{\rm coal}(x,\mathbf{k}) - \mathcal{C}_{\rm diss}(\mathbf{k}) f^V_{\lambda_1\lambda_2}(x,\mathbf{k})\right]$$

3×3 Hermitian matrix in spin space

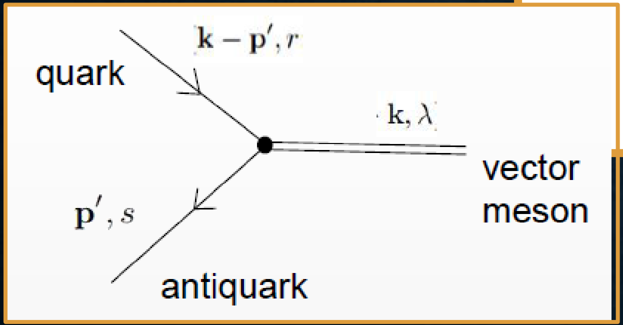
COALESCENCE

DISSOCIATION independent from the quark/antiquark MVSDs

$$\mathcal{C}^{\mu\nu}_{\rm coal}(x,\mathbf{k}) = \int \frac{d^3\mathbf{p}'}{(2\pi\hbar)^2}\frac{1}{E^{\bar q}_{\mathbf{p}'}E^q_{\mathbf{k}-\mathbf{p}'}}\delta\left(E^V_{\mathbf{k}} - E^{\bar q}_{\mathbf{p}'} - E^q_{\mathbf{k}-\mathbf{p}'}\right)$$
$$\times \mathrm{Tr}\left\{\Gamma^\nu(p'\cdot\gamma - m_{\bar q})\left[1+\gamma_5\gamma\cdot P^{\bar q}(x,\mathbf{p}')\right]\right.$$
$$\left.\times\Gamma^\mu\left[(k-p')\cdot\gamma + m_q\right]\left[1+\gamma_5\gamma\cdot P^q(x,\mathbf{k}-\mathbf{p}')\right]\right\}$$
$$\times f_{\bar q}(x,\mathbf{p}')f_q(x,\mathbf{k}-\mathbf{p}')$$

polarization distribution for quark/antiquark

$q\bar q V$ vertices



unpolarized distribution for quark/antiquark

X.-L- Sheng, LO, Z.-T. Liang, Q. Wang Q and X.-N. Wang, Phys. Rev. Lett. 131, 042304 (2023) ; 2206.05868

SPIN DENSITY MATRIX FOR VECTOR MESONS

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

solution of the spin Boltzmann equation

$$f^V_{\lambda_1\lambda_2}(x,\mathbf{k}) \sim \frac{1}{\mathcal{C}_{\rm diss}(\mathbf{k})}\left[1-e^{-\mathcal{C}_{\rm diss}(\mathbf{k})\Delta t}\right]\epsilon^*_\mu(\lambda_1,\mathbf{k})\epsilon_\nu(\lambda_2,\mathbf{k})\mathcal{C}^{\mu\nu}_{\rm coal}(x,\mathbf{k})$$

MVSD can be parameterized as

spin-independent distribution function
(unpolarized)
+
normalized spin density matrix
(polarization part)

$$\rho^V_{\lambda_1\lambda_2}(x,\mathbf{k}) = \frac{\epsilon^*_\mu(\lambda_1,\mathbf{k})\epsilon_\nu(\lambda_2,\mathbf{k})\mathcal{C}^{\mu\nu}_{\rm coal}(x,\mathbf{k})}{\sum_{\lambda=0,\pm1}\epsilon^*_\mu(\lambda,\mathbf{k})\epsilon_\nu(\lambda,\mathbf{k})\mathcal{C}^{\mu\nu}_{\rm coal}(x,\mathbf{k})}$$

spin density matrix for vector mesons

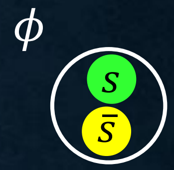
$\mathcal{C}^{\mu\nu}_{\rm coal}$ include the polarization phase space distributions for quark/antiquark $P^\mu_{q/\bar{q}}(x,p)$

polarized quarks → COALESCENCE → polarized hadrons

similar to the process in the nonrelativistic coalescence model

X.-L- Sheng, LO, Z.-T. Liang, Q. Wang Q and X.-N. Wang, Phys. Rev. Lett. 131, 042304 (2023) ; 2206.05868

SPIN ALIGNMENT OF ϕ MESONS



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

$$P^{\mu}_{s/\bar{s}}(x,\mathbf{p}) = \frac{1}{4m_s}\epsilon^{\mu\nu\varrho\sigma}\left(\omega^{\text{th}}_{\varrho\sigma} \pm \frac{g_\phi}{(u\cdot p)T}F^{\phi}_{\varrho\sigma}\right)p_\nu$$

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

vorticity fields

ϕ-meson fields

neglecting EM fields

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

$$C_1 = \frac{8m_s^4 + 16m_s^2 m_\phi^2 + 3m_\phi^4}{120 m_s^2(m_\phi^2 + 2m_s^2)}$$
$$C_2 = \frac{8m_s^4 - 14m_s^2 m_\phi^2 + 3m_\phi^4}{120 m_s^2(m_\phi^2 + 2m_s^2)}$$

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

X.-L- Sheng, LO, Z.-T. Liang, Q. Wang Q and X.-N. Wang, Phys. Rev. Lett. 131, 042304 (2023) ; 2206.05868

SPIN ALIGNMENT OF ϕ MESONS

ϕ s $\bar{s}$

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

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

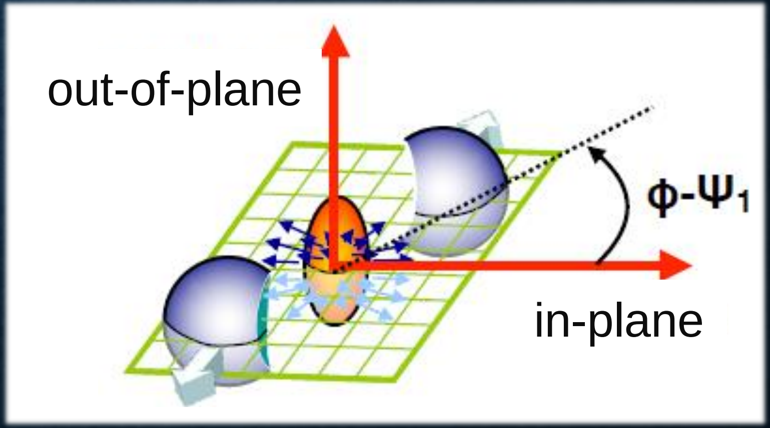
factorization of space-time and momentum dependence
in the squares of field components and their coefficients

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

considering only
the ϕ-meson field

transverse fields $\left\langle\left(g_\phi B_{x,y}^\phi/T_{\mathrm{h}}\right)^2\right\rangle_x = \left\langle\left(g_\phi E_{x,y}^\phi/T_{\mathrm{h}}\right)^2\right\rangle_x \equiv F_T^2$

longitudinal fields $\left\langle\left(g_\phi B_z^\phi/T_{\mathrm{h}}\right)^2\right\rangle_x = \left\langle\left(g_\phi E_z^\phi/T_{\mathrm{h}}\right)^2\right\rangle_x \equiv F_z^2$

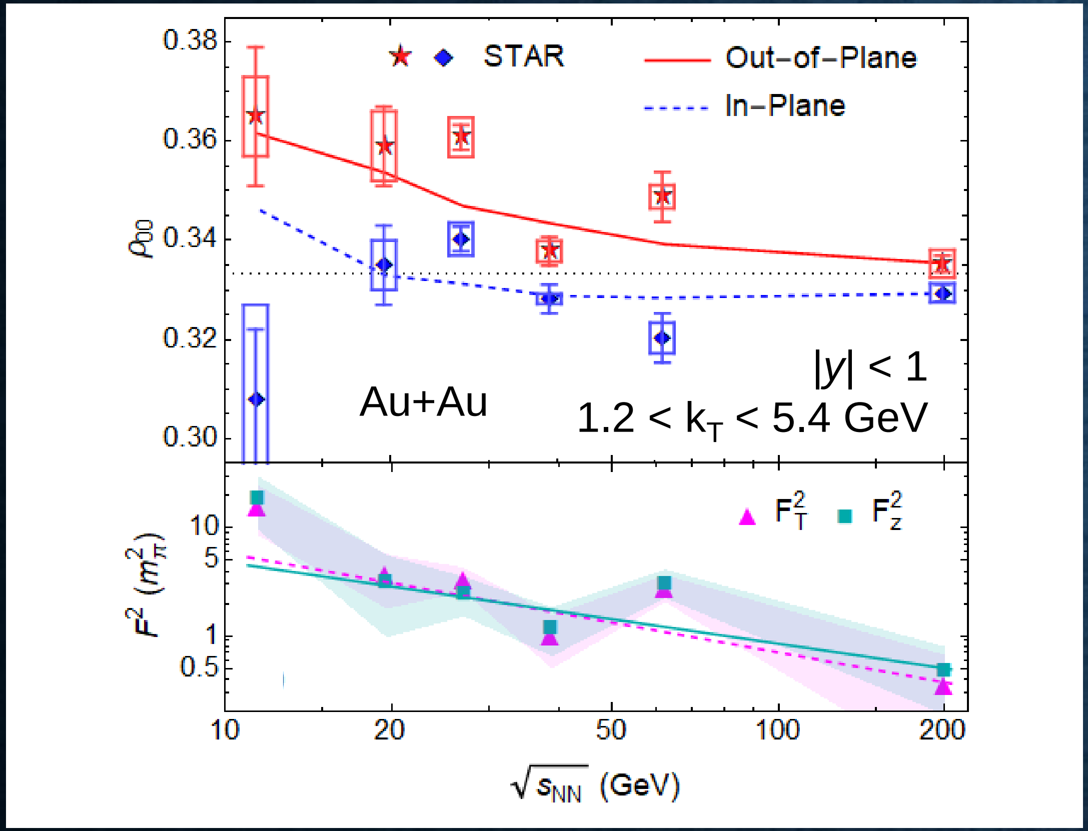


X.-L- Sheng, LO, Z.-T. Liang, Q. Wang Q and X.-N. Wang, Phys. Rev. Lett. 131, 042304 (2023) ; 2206.05868

SPIN ALIGNMENT OF ϕ MESONS

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

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

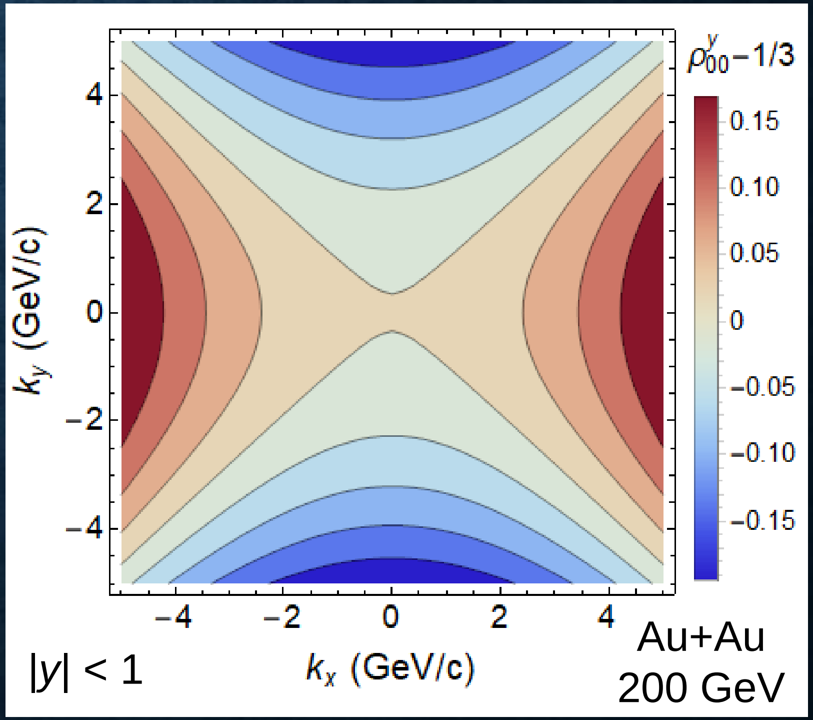


fit the exp. data for ρ_{00} vs collision energy

extract the field fluctuation parameters

determine ρ_{00} vs k_T and φ

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



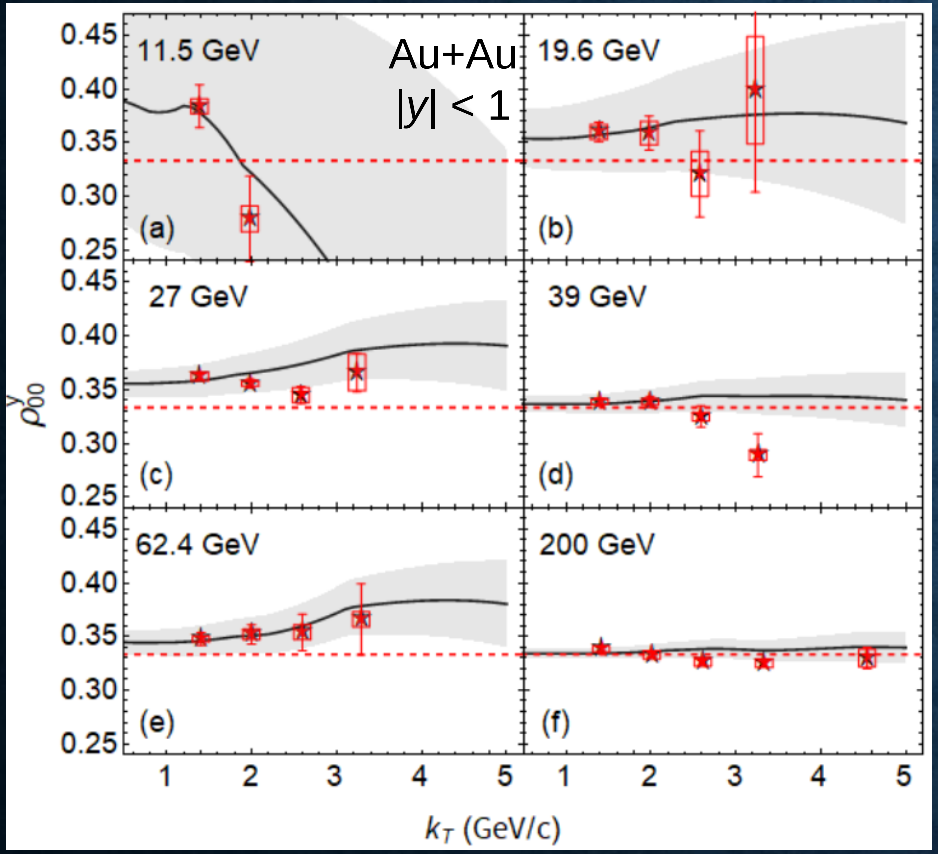
- out-of-plane: $\rho_{00}^{y} > 1/3$ for all energies
  in-plane: $\rho_{00}^{x} \lesssim 1/3$ for $\sqrt{s_{NN}} \gtrsim 20$ GeV
- difference between ρ_{00}^{y} and ρ_{00}^{x} driven by the momentum anisotropy via the elliptic flow $v_2(k_T)$

X.-L- Sheng, LO, Z.-T. Liang, Q. Wang Q and X.-N. Wang, Phys. Rev. Lett. 131, 042304 (2023)

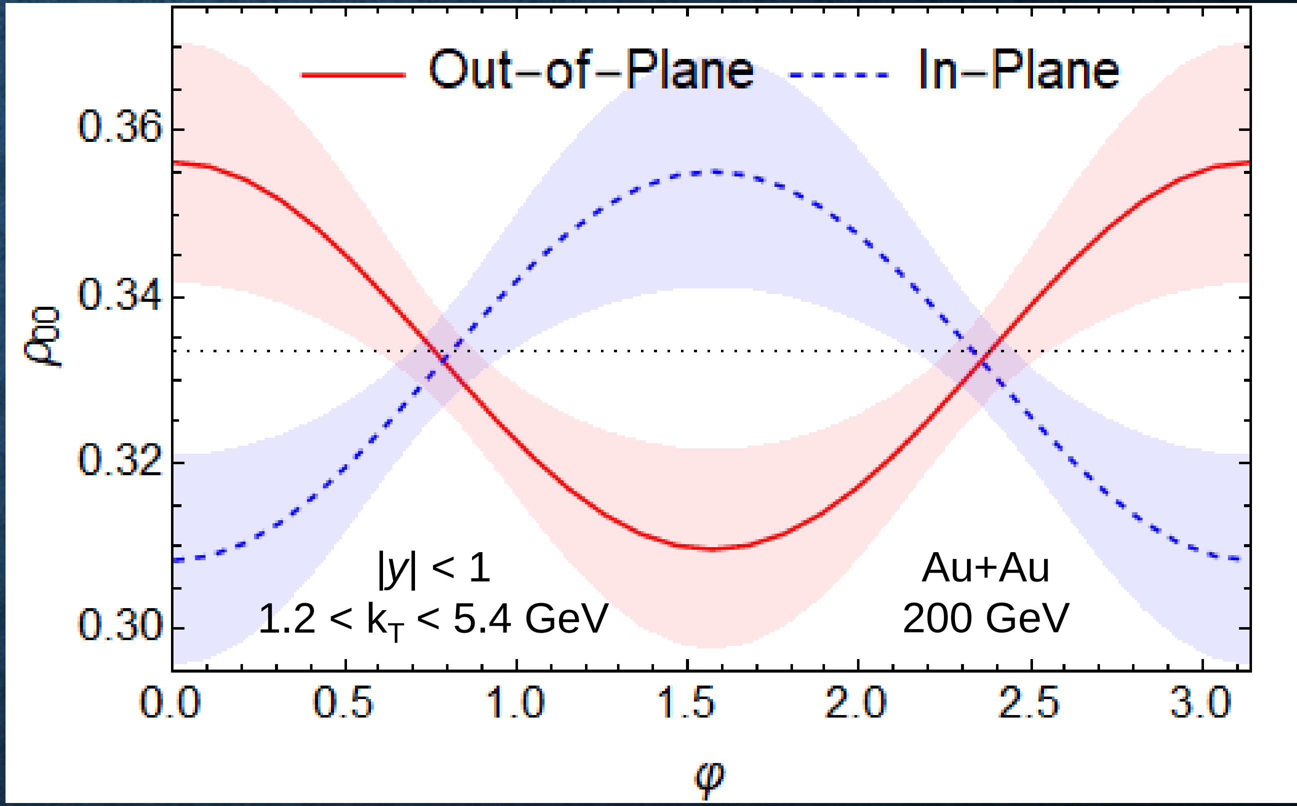
SPIN ALIGNMENT OF ϕ MESONS

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

$\rho^{y}_{00}(k_T)$



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



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

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

X.-L- Sheng, LO, Z.-T. Liang, Q. Wang Q and X.-N. Wang, Phys. Rev. Lett. 131, 042304 (2023)

CONCLUSIONS

✓ The directed flow of light and heavy mesons is a probe of vortical and EM fields in large and small systems

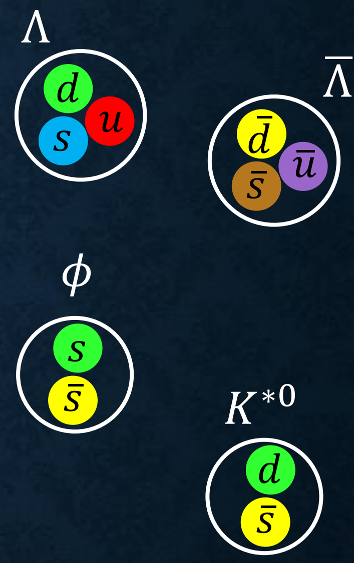
✓ the thermal vorticity gives the dominant contribution to the polarization of Λ hyperons, the magnetic field induces a splitting of Λ and $\overline{\Lambda}$ particles

✓ 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

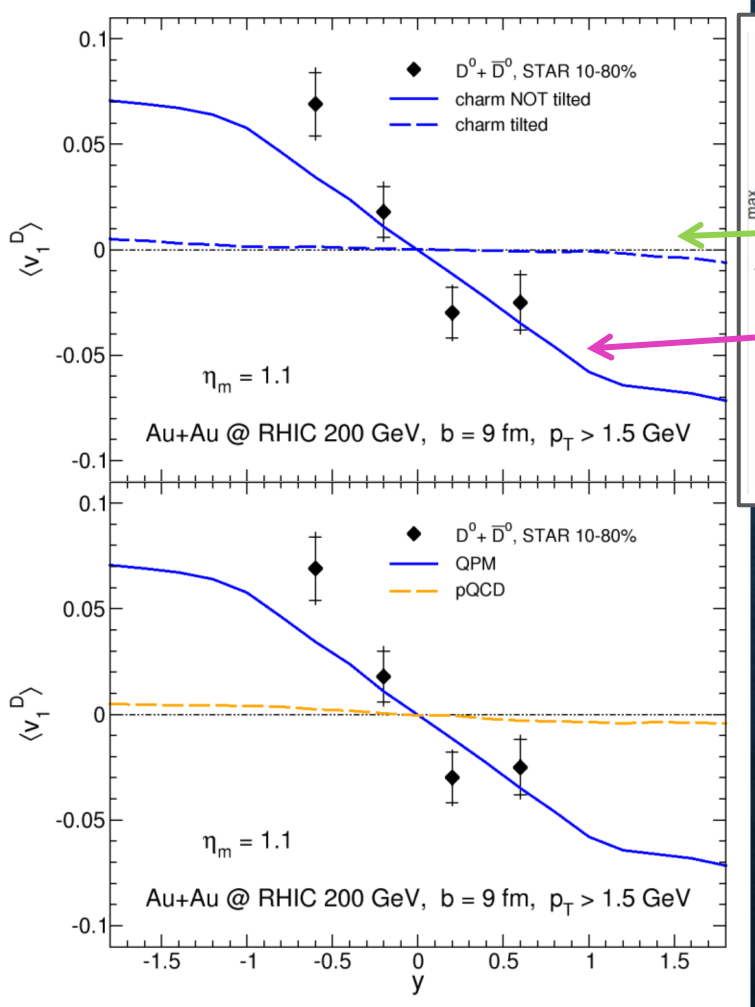
Thank you for your attention!

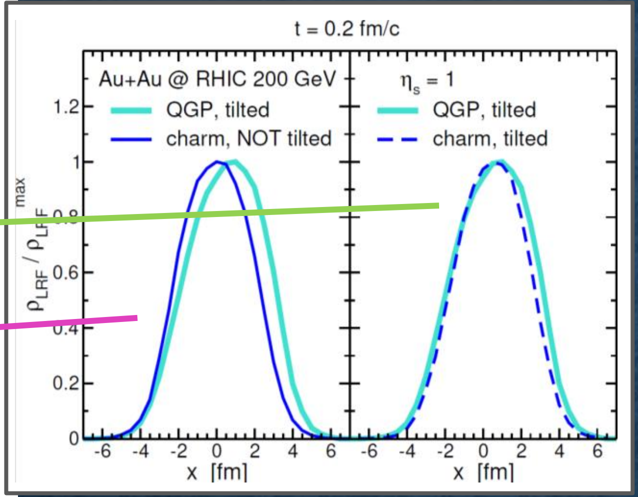
lucia.oliva@dfa.unict.it

DIRECTED FLOW MAGNITUDE OF *D* MESONS

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

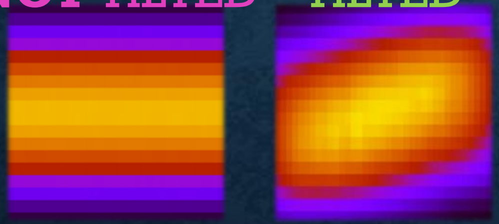
$\langle v_1^D \rangle(y)$





CHARM NOT TILTED

CHARM TILTED

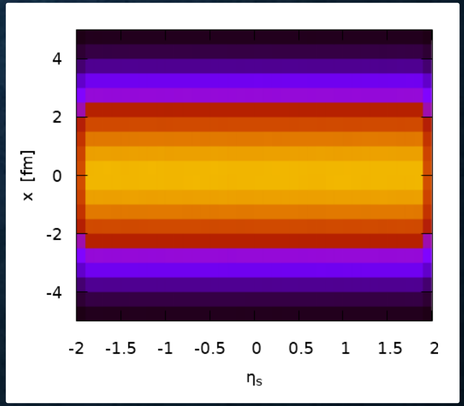


QGP tilted in both cases

v_1 (HQs) ≫ v_1 (QGP)

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

HQ production points symmetric in the forward-backward hemispheres

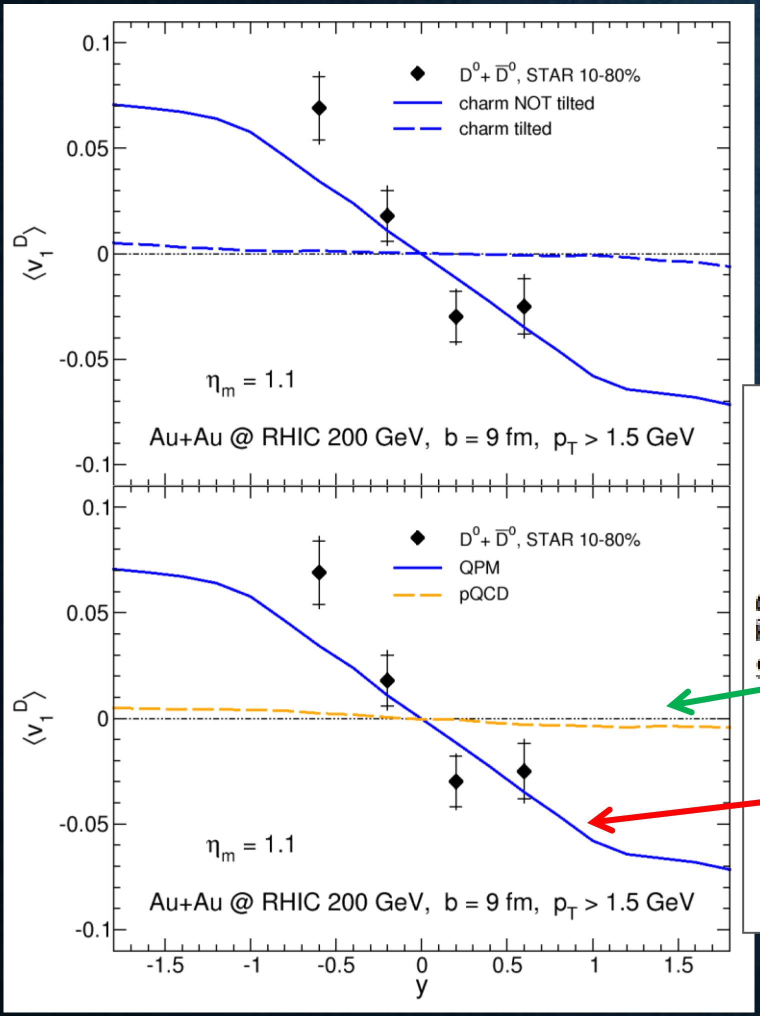


LO, S. Plumari and V. Greco, JHEP 05, 034 (2021)

DIRECTED FLOW MAGNITUDE OF *D* MESONS

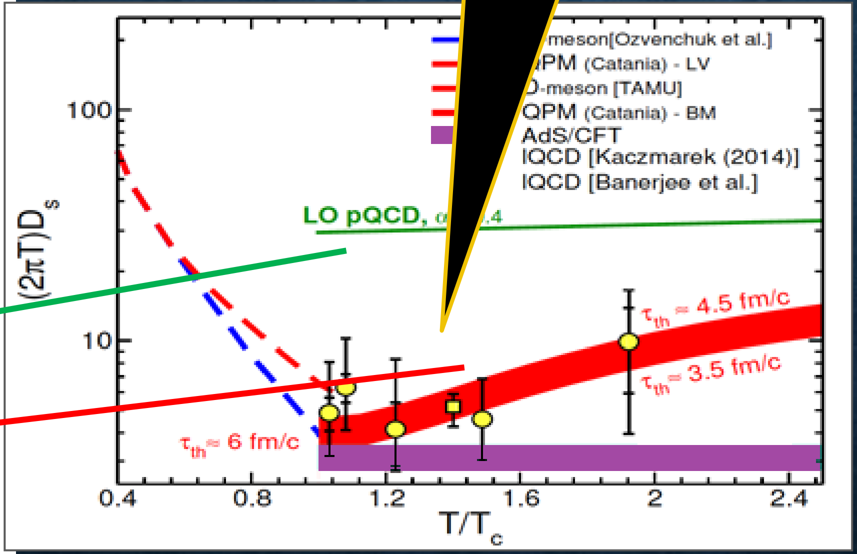
origin of the large directed flow of HQs different from the one of light particles

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



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

non-perturbative behaviour of QGP



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

v_1 (HQs) ≫ 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)

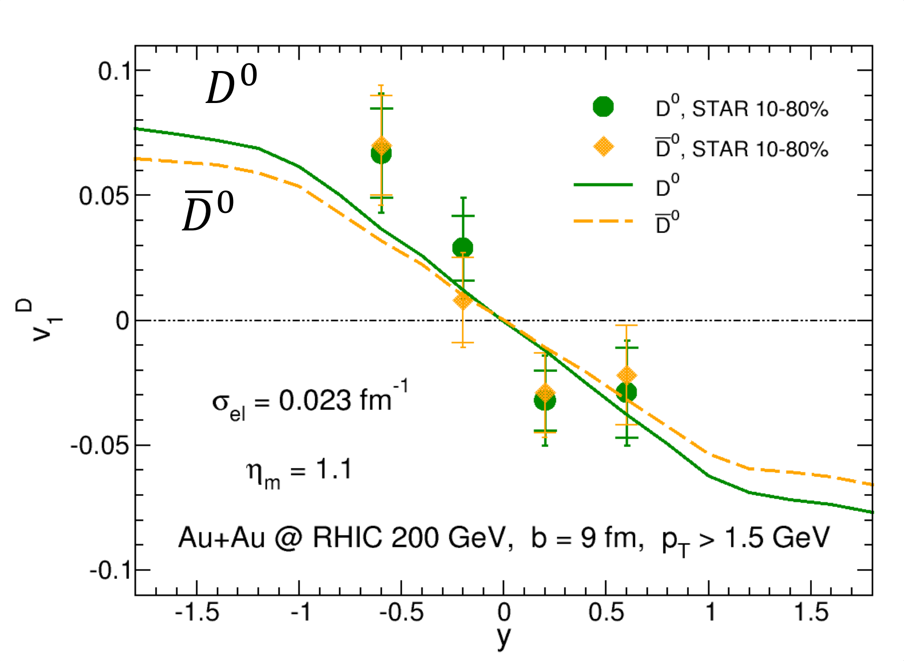
$2\pi T D_s \approx 3 - 6$
QGP diffuses charm quarks like an almost perfect fluid

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)

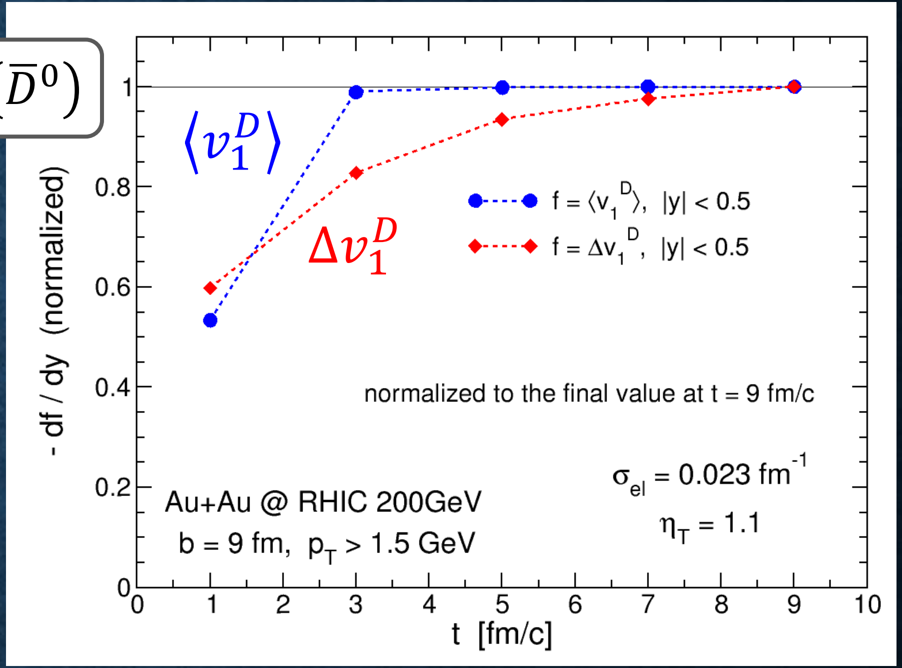
$v_1^D(y)$



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

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

SLOPE TIME EVOLUTION



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

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

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

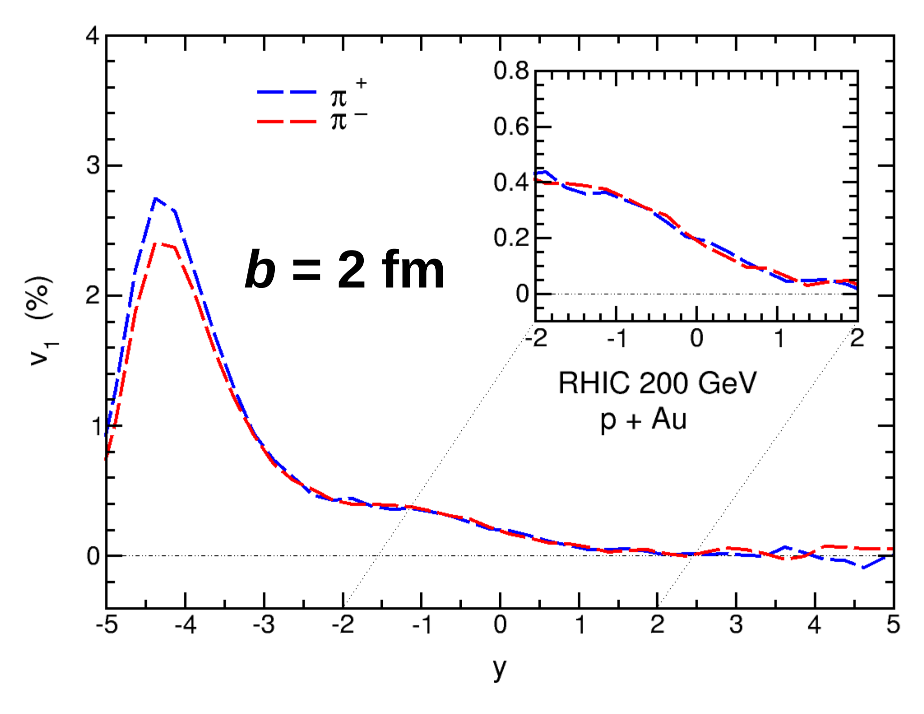
ALICE Coll., Phys. Rev. Lett. 125, 022301 (2020)

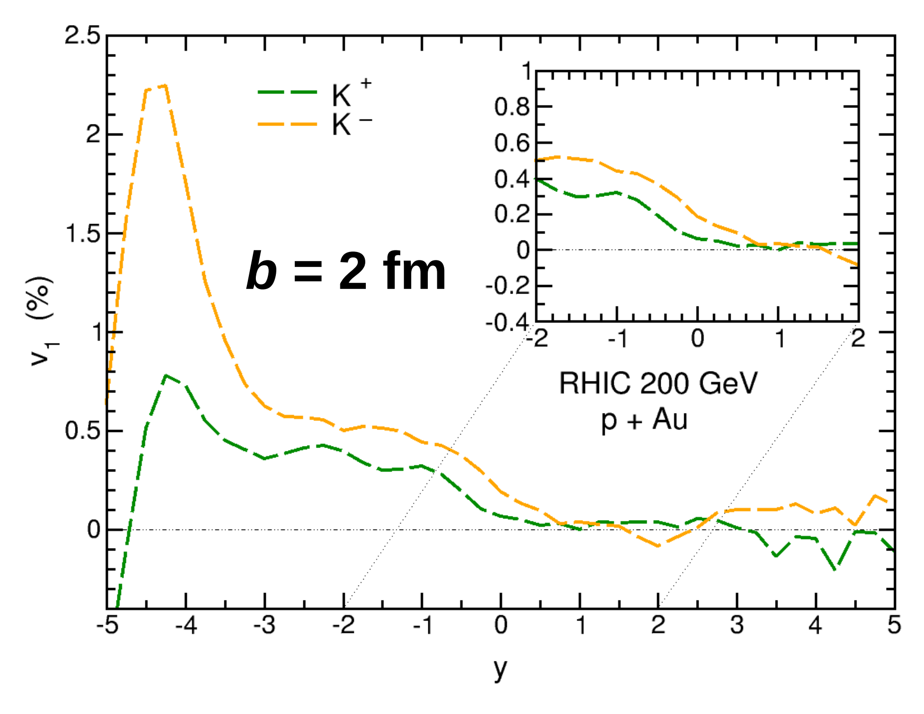
if the v_1 splitting of neutral *D* mesons is of EM origin it is a proof of QGP formation

DIRECTED FLOW IN pA

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

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

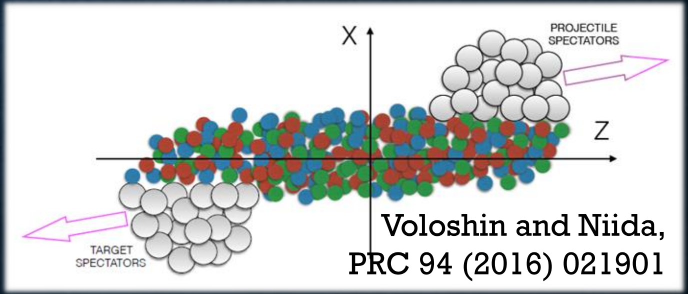




different v_1 for kaons also without EMF
due to baryon transport to midrapidity

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

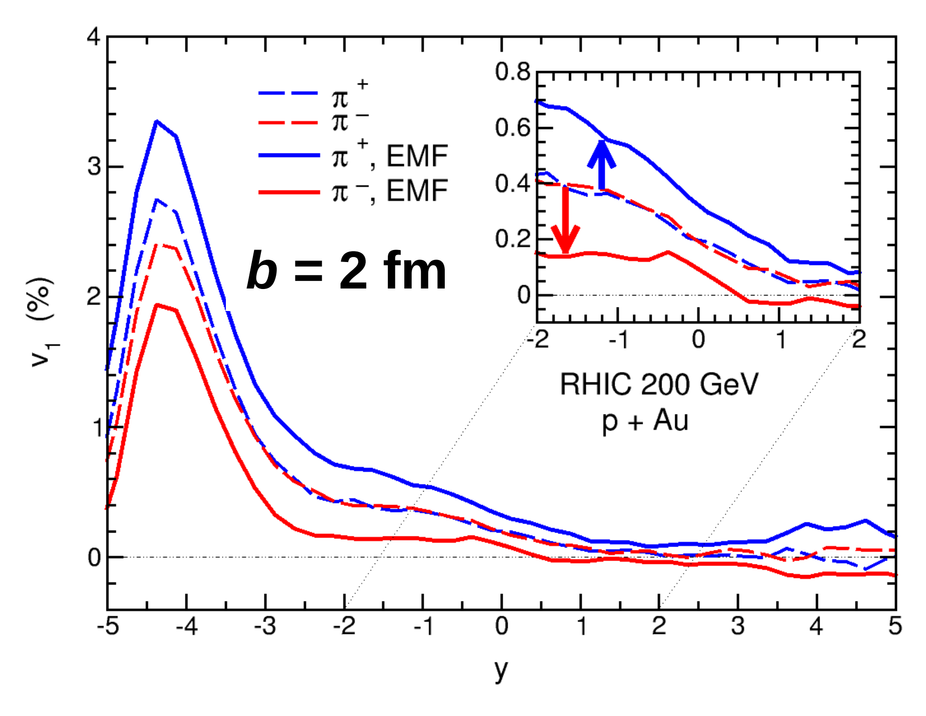


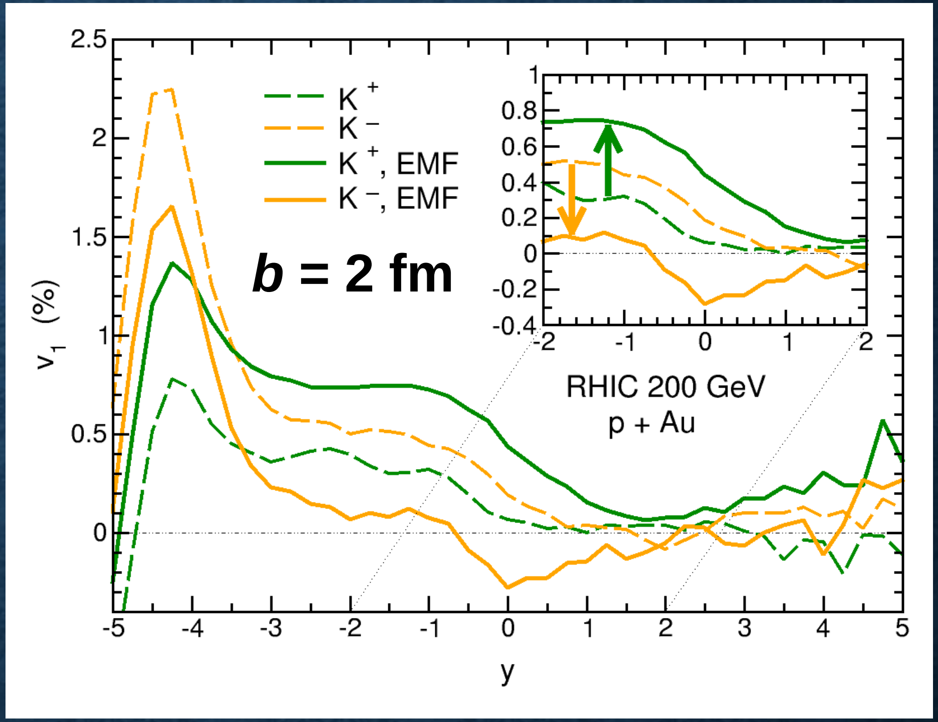
Voloshin and Niida, PRC 94 (2016) 021901

DIRECTED FLOW IN pA

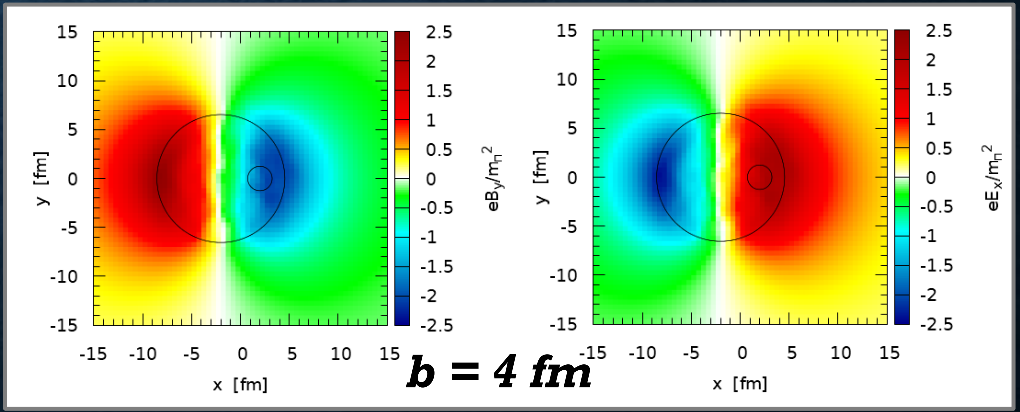
LO, P. Moreau, V. Voronyuk and E. Bratkovskaya, Phys. Rev. C 101, 014917 (2020)

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





Splitting of charged pions and kaons induced by the electromagnetic field

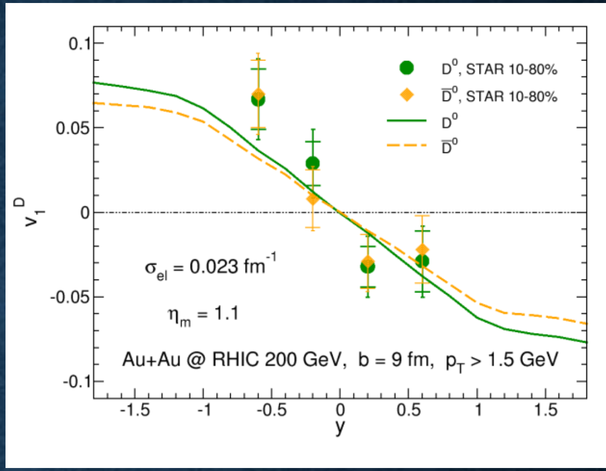


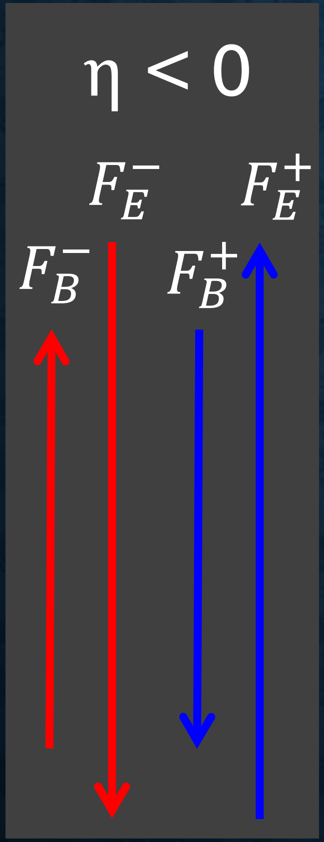
EM FIELDS AND DIRECTED FLOW IN AA

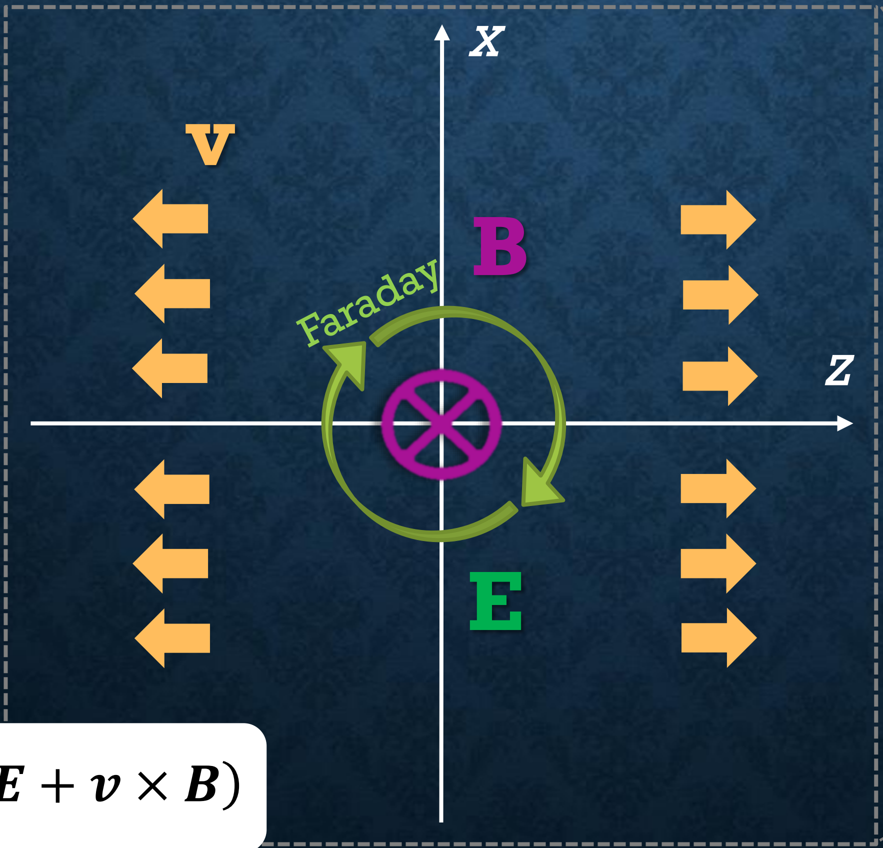
rapidity dependence of the DIRECTED FLOW

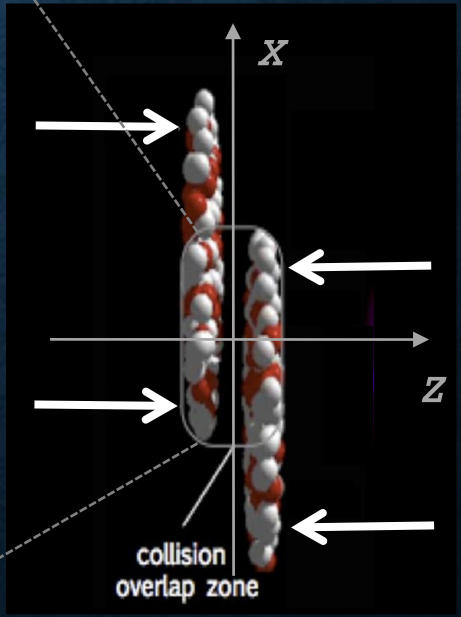
collective sidewards deflection of particles

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



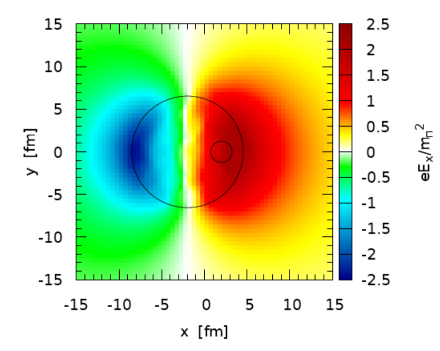


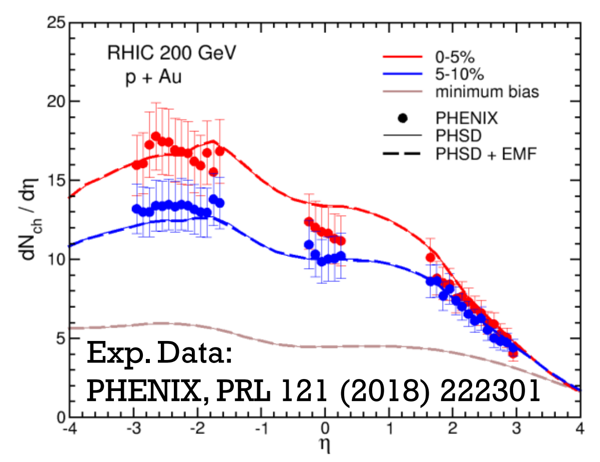


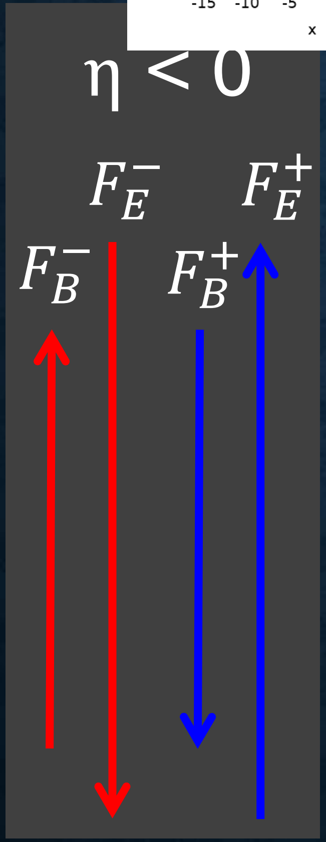


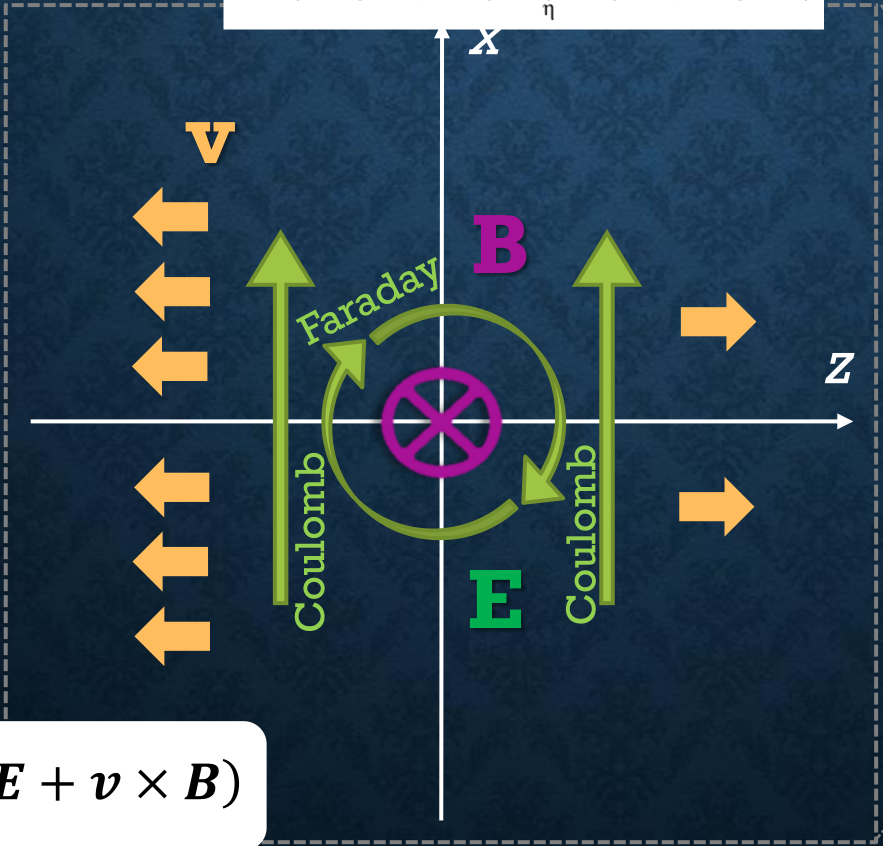
$$\boldsymbol{F}_{\boldsymbol{Lorentz}} = q(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B})$$

EM FIELDS AND DIRECTED FLOW IN pA

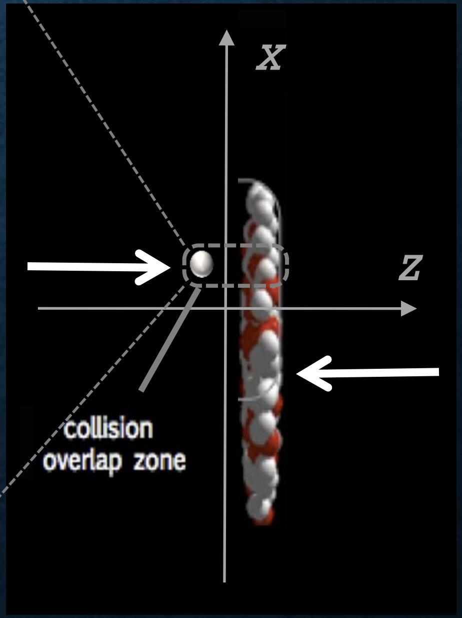








$$F_{Lorentz} = q(E + v \times B)$$

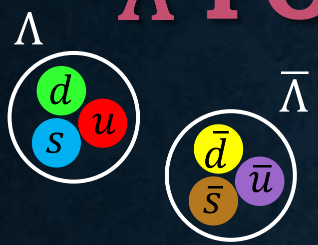


Asymmetry in charged particle and electric field profiles in p+Au

- 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)

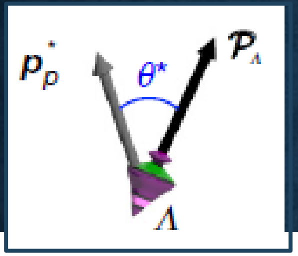
Λ POLARIZATION IN COALESCENCE MODEL



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

$\Lambda \rightarrow p + \pi^-$ (BR ~ 64%)

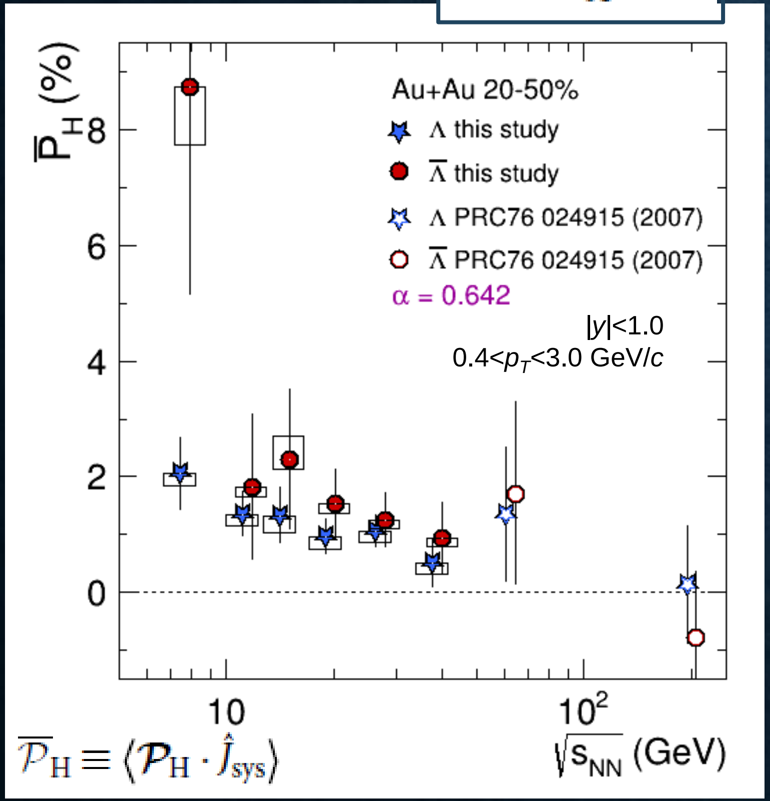
$\Longrightarrow$ measure **POLARIZATION**



$$\frac{\mathrm{d}N}{\mathrm{d}\cos\theta^*} = \frac{1}{2}\left(1 + \alpha_H |P_H| \cos\theta^*\right)$$

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

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



STAR Collaboration, Nature 548, 62 (2017)

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

$$P^y_{\Lambda/\bar{\Lambda}}(t,\mathbf{x}) = \frac{1}{3}\int \frac{d^3\mathbf{r}}{(2\pi)^3}\frac{d^3\mathbf{q}}{(2\pi)^3}\left|\psi_{\Lambda/\bar{\Lambda}}(\mathbf{q},\mathbf{r})\right|^2 \times \left[P^y_{s/\bar{s}}(t,\mathbf{x},\mathbf{p}_1) + P^y_{s/\bar{s}}(t,\mathbf{x},\mathbf{p}_2) + P^y_{s/\bar{s}}(t,\mathbf{x},\mathbf{p}_3)\right]$$

$$= \frac{1}{2}\omega_y \pm \frac{Q_s}{2m_s T}B_y = \frac{1}{2}\omega_y \mp \frac{1}{6m_s T}eB_y$$

thermal vorticity — magnetic field

CONVENTIONAL SOURCES OF SPIN POLARIZATION

EFFECTIVE VECTOR MESON FIELDS

QUARK-MESON MODEL

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

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)

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

vector meson field strength tensor

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

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

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

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

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 $\overline{\Lambda}$ 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)]

VECTOR MESON SPIN ALIGNMENT

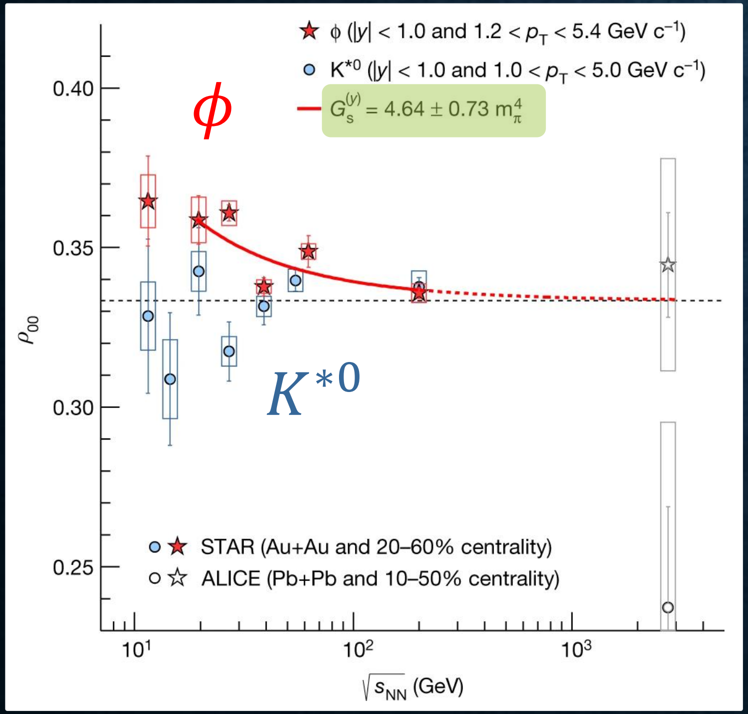
ϕ

K^{*0}

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)

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



STAR Collaboration, Nature 614, 244 (2023)

$$\rho^{\phi}_{00}(t,\mathbf{x}) \approx \frac{1}{3} - \frac{4}{9}\int \frac{d^3\mathbf{p}}{(2\pi)^3}\,|\psi_\phi(\mathbf{p})|^2 \times \left\{ P^y_s(\mathbf{p})P^y_{\bar{s}}(-\mathbf{p}) - \frac{1}{2}\left[P^x_s(\mathbf{p})P^x_{\bar{s}}(-\mathbf{p}) + P^z_s(\mathbf{p})P^z_{\bar{s}}(-\mathbf{p})\right]\right\}$$

$$\rho^{\phi}_{00} \approx \frac{1}{3} + c_\Lambda + c_\varepsilon + c_E + c_\phi \qquad c_\phi = \frac{G_s^{(y)}}{27 m_s^2 T_{\text{eff}}^2}$$

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

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

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

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

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

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

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

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

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

X.-L- Sheng, L. Oliva, Z.-T. Liang, Q. Wang Q and X.-N. Wang, 2205.15689