Spin polarization and spin alignment in heavy-ion collisions

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SEZIONE DI FIRENZE

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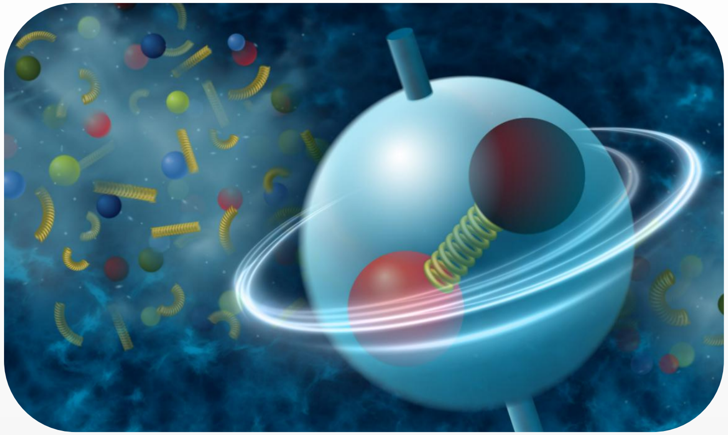

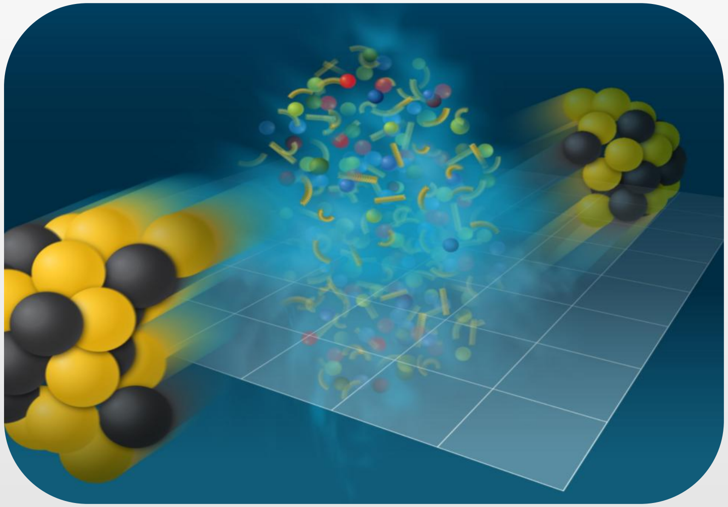

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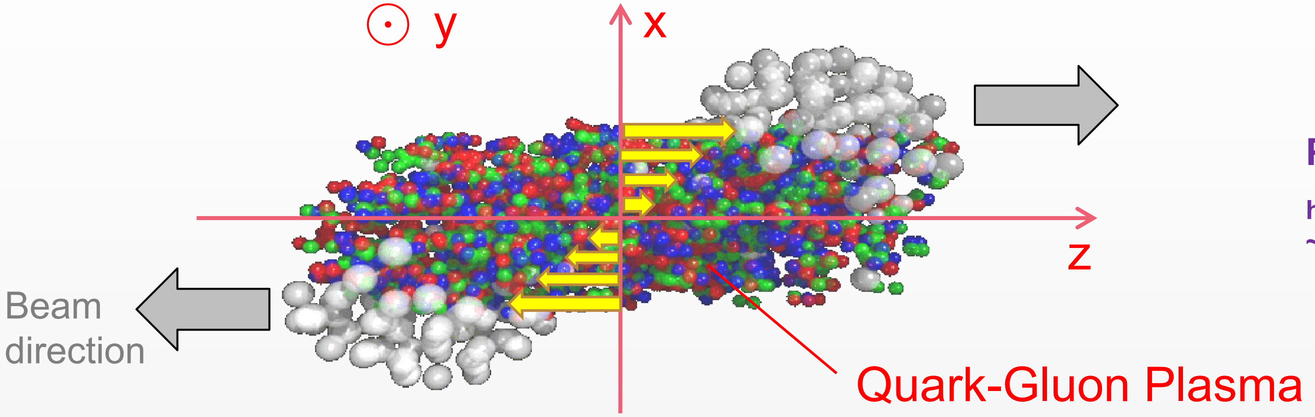
Outline

- Introduction
- Spin polarization for quarks and baryons
- Spin alignment for vector mesons
- Summary

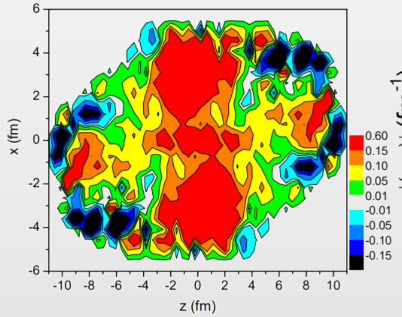
Relativistic heavy-ion collisions



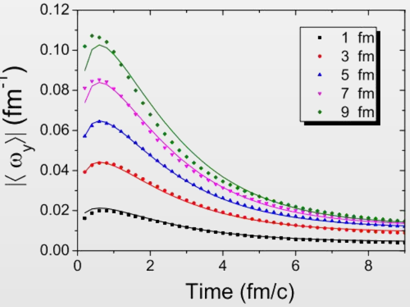
Picture for UrQMD model

https://itp.uni-frankfurt.de/~bleicher/index.html?content=urqmd

Vorticity fields $\omega \sim 10^{21} s^{-1}$

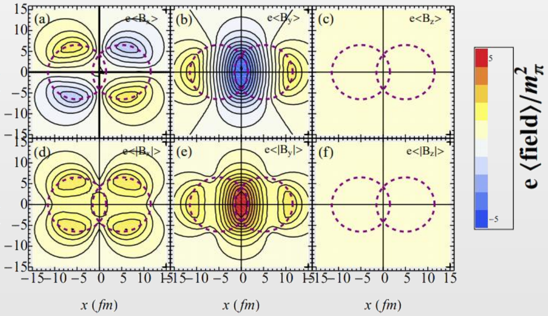


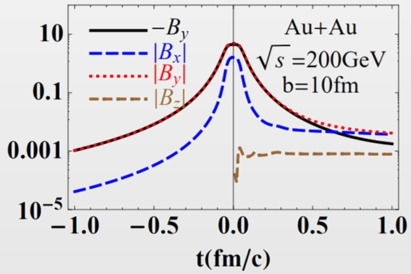
F. Becattini, L. Csernai, D.J. Wang, PRC 88, 034905 (2013); PRC 93, 069901 (2016)



Y. Jiang, Z.-W. Lin, J. Liao, PRC 94, 044910 (2016); PRC 95,049904 (2017)

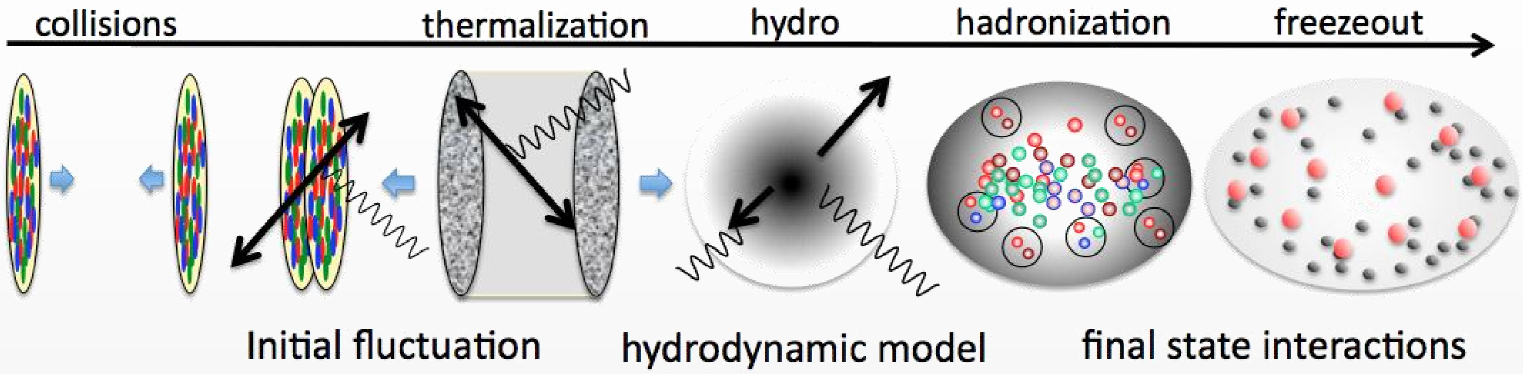
Magnetic fields $B \sim 10^{18}$ Gauss





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

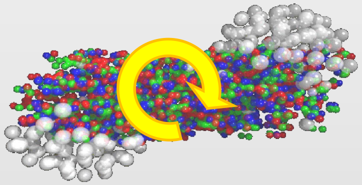
Relativistic heavy-ion collisions



Quarks and gluons

Baryons and mesons

Initial orbital angular momentum



Vorticity field

Magnetic field

Polarized quark/gluon

Spin polarization for spin-1/2 or spin-3/2 baryons, Λ, Σ^0, Δ^{++}, Ω^-, ...

Spin alignment for vector mesons, ϕ, K^{*0}, ρ^0, ...

gain insights into

Spin polarization/alignment

- Spin polarization for spin-1/2 quarks/baryons is average of spin

⇨ measure through weak decays

$$\Lambda \rightarrow p + \pi^-$$

$$\Xi^- \rightarrow \Lambda + \pi^-$$

$$P = \frac{f_{+\frac{1}{2}} - f_{-\frac{1}{2}}}{f_{+\frac{1}{2}} + f_{-\frac{1}{2}}}$$

$P = 0$ if spin does not have a preferred direction

- Spin polarization for spin-1 vector mesons

⇨ can not measure

$$P = \frac{f_{+1} - f_{-1}}{f_{+1} + f_0 + f_{-1}}$$

- Spin alignment for spin-1 vector mesons is 00-element ρ_{00} of its normalized spin density matrix

⇨ measure through p-wave strong decays

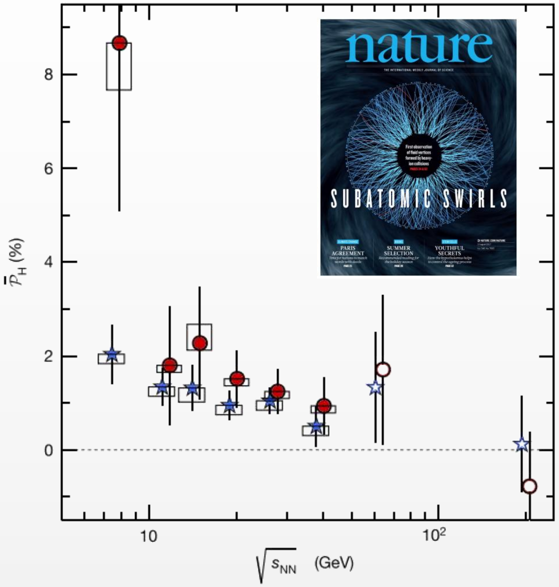
$$\phi \rightarrow K^+ + K^-$$

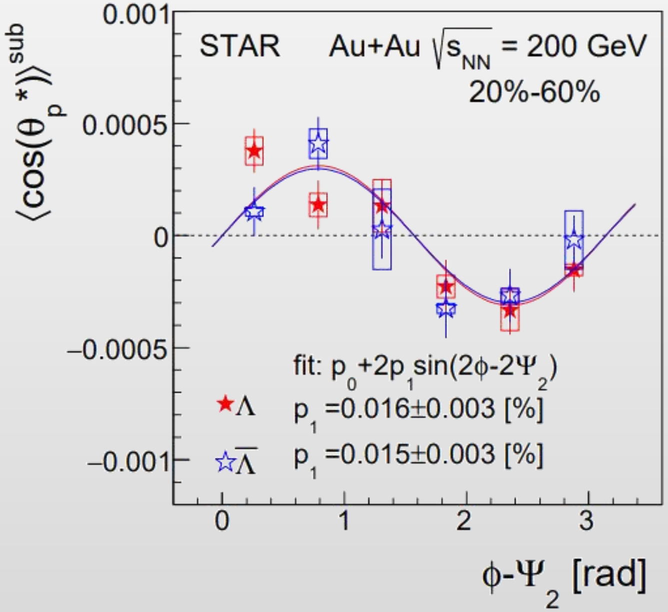
$$K^{*0} \rightarrow K^+ + \pi^-$$

$$\rho_{00} = \frac{f_0}{f_{+1} + f_0 + f_{-1}}$$

$\rho_{00} = 1/3$ if spin does not have a preferred direction

Λ's spin polarization





Λ's spin polarizations along direction of global angular momentum / beam direction

STAR, Nature 548, 62 (2017)
PRL 123, 132301 (2019)

$$\Lambda \rightarrow p + \pi^-$$

Parity-violating weak decay

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

Angular distribution of decay products

Λ's decay constant

Λ's spin polarization

polar angle of proton's momentum w.r.t. polarization direction

Λ's spin polarization

- Cooper-Frye formula for spin polarization (for quarks and spin-1/2 baryons)

F. Becattini, V. Chandra, L. Del Zanna and E. Grossi, Annals Phys. 338, 32 (2013)

F. Becattini, M. Buzzegoli and A. Palermo, PLB 820, 136519. (2021)

S. Y. F. Liu and Y. Yin, JHEP 07 (2021), 188

F. Becattini, Rept. Prog. Phys. 85, 122301 (2022)

$$S^\mu(p) = -\frac{1}{8m}\epsilon^{\mu\nu\rho\sigma}p_\sigma \frac{\int d\Sigma_\lambda p^\lambda n_F(1-n_F)\left(\varpi_{\nu\rho} + 2\hat{t}_\nu \xi_{\rho\tau}p^\tau/\varepsilon\right)}{\int d\Sigma_\lambda p^\lambda n_F}$$

Thermal vorticity tensor

$$\varpi_{\mu\nu} \equiv -\frac{1}{2}(\partial_\mu\beta_\nu - \partial_\nu\beta_\mu)$$

Thermal shear tensor

$$\xi_{\mu\nu} \equiv \frac{1}{2}(\partial_\nu\beta_\rho + \partial_\rho\beta_\nu)$$

$$\beta_\mu = \frac{u_\mu}{T}$$

- Non-relativistic limit

$$\mathbf{S}^* \propto \frac{\hbar}{k_B T}2\gamma\left(\boldsymbol{\omega}^* - (\boldsymbol{\omega}^*\cdot\mathbf{u}^*)\mathbf{u}^*/\gamma^2c^2\right) + \frac{\hbar}{k_B T}\mathbf{A}^*\times\mathbf{u}/c^2 + \frac{2\hbar}{k_B T^2}\mathbf{u}^*\times\boldsymbol{\nabla}T$$

Voticity induced polarization (Barnett effect)

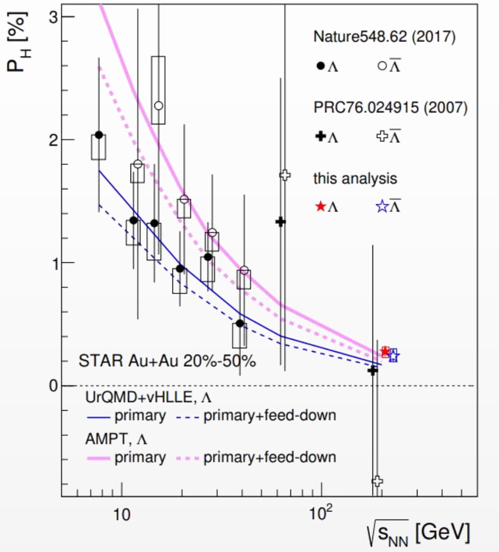
Acceleration induced polarization (Thomas precession)

Spin Nernst effect

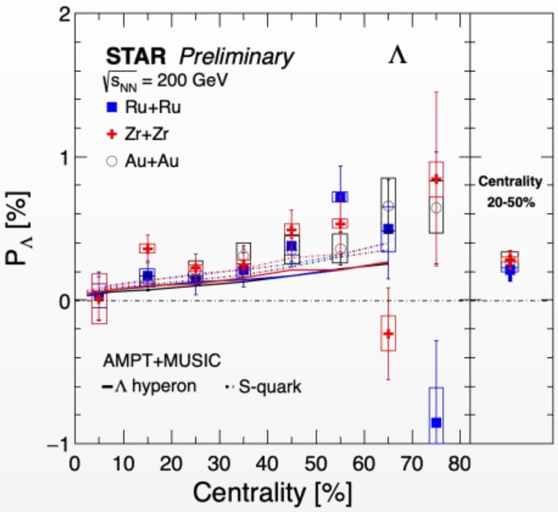
S. J. Barnett, Phys. Rev. 6 (1915) 239.

P. Sheng, Y. Sakuraba, Y.-C. Lau, S. Takahashi, S. Mitani, M. Hayashi, Sci. Adv. 3, 11 (2017)

Λ's spin polarization



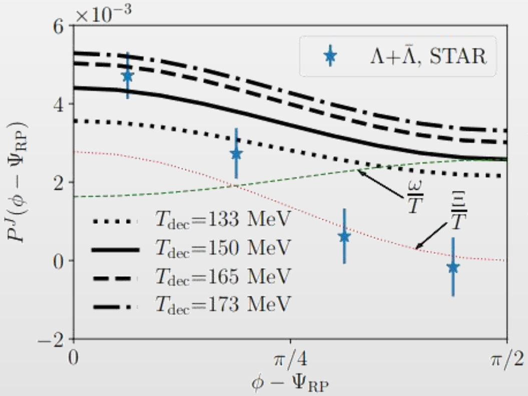
F. Becattini, Rept. Prog. Phys. 85, 122301 (2022)

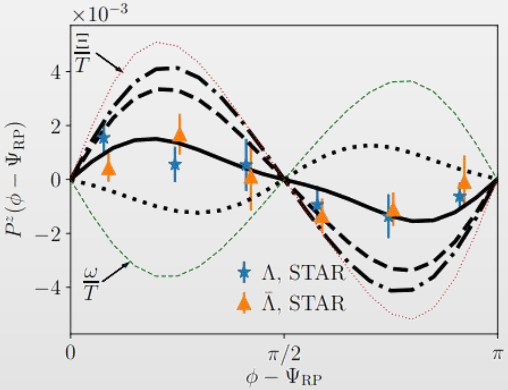


X. Gou's talk in QM2023

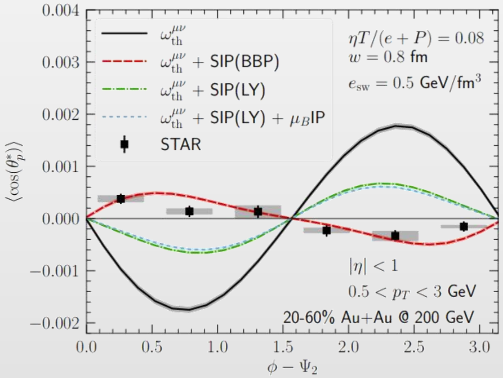
- Thermal vorticity / shear explain experiment results well for P_Λ and $P_{\bar{\Lambda}}$
- Tiny difference between P_Λ and $P_{\bar{\Lambda}}$ ➡ negligible contribution from magnetic field

$$\mathbf{S}^* \propto \frac{1}{T}\mu_{\rm m}\mathbf{B}^*$$



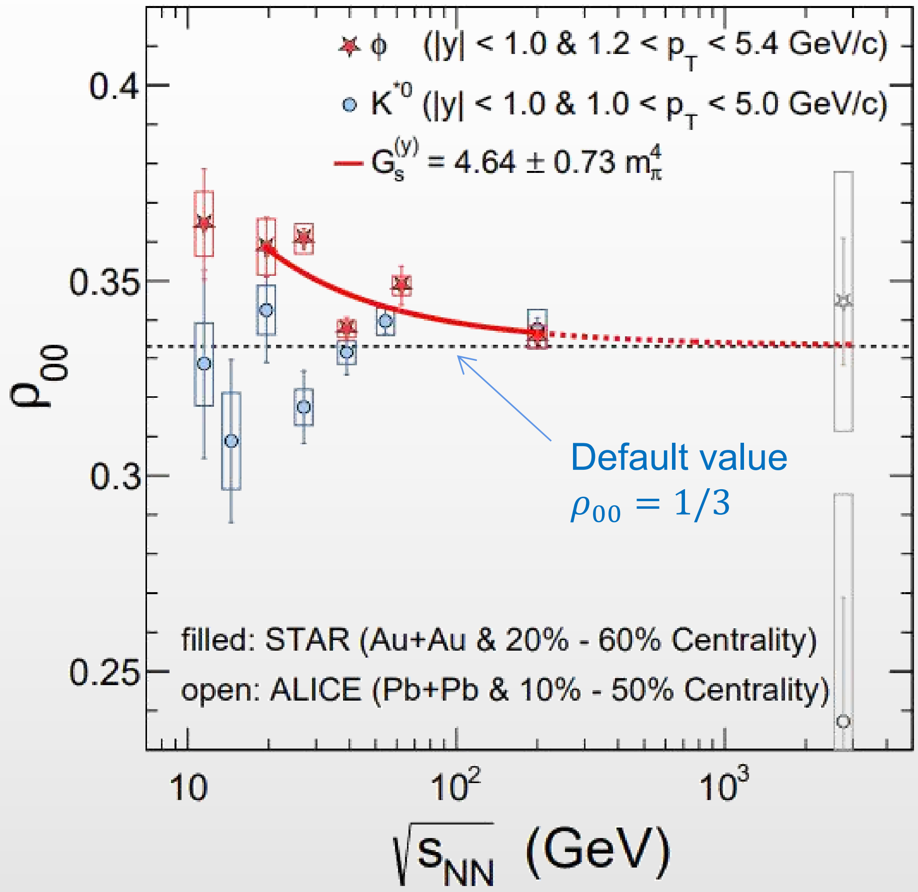


F. Becattini, M. Buzzegoli, G. Inghirami, I. Karpenko, A. Palermo, PRL 127, 272302 (2021)



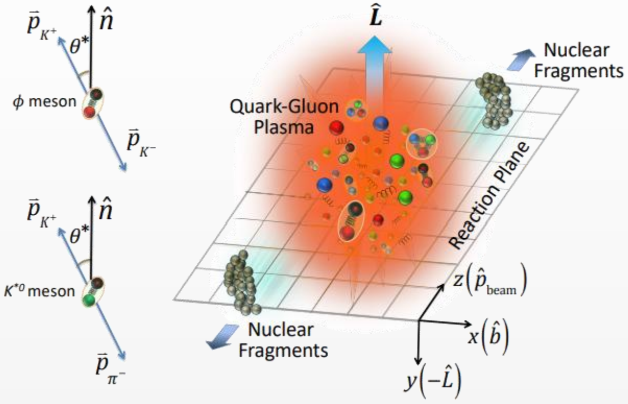
S. Alzhrani, S. Ryu, C. Shen, PRC 106, 014905 (2022)

Global spin alignment



Default value
$\rho_{00} = 1/3$

STAR, Nature 614, 244 (2023)



ϕ and K^{*0} mesons' spin alignment along direction of global angular momentum

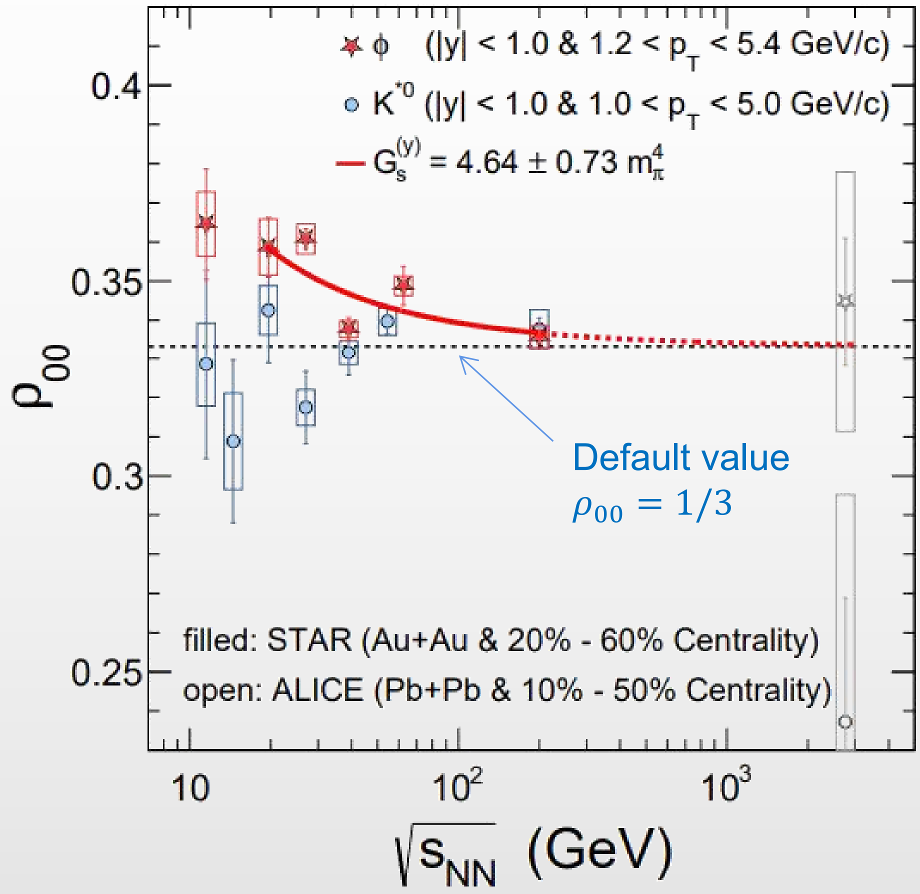
$$\phi \rightarrow K^{+} + K^{-}$$

$$K^{*0} \rightarrow K^{+} + \pi^{-}$$

p-wave
strong decay

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

Global spin alignment

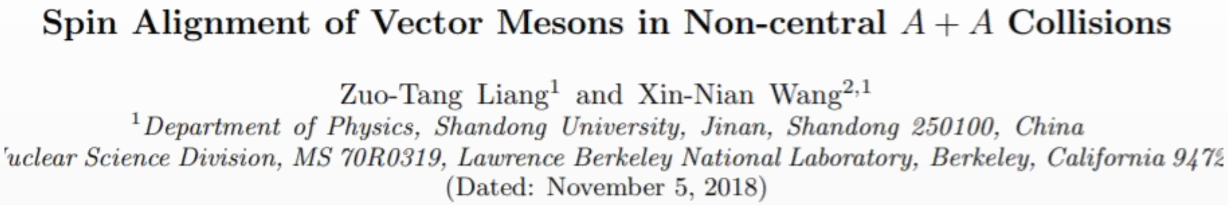


Default value
$\rho_{00} = 1/3$

STAR, Nature 614, 244 (2023)

Vorticity field?
Magnetic field?

Relation to quark polarization



Spin Alignment of Vector Mesons in Non-central $A+A$ Collisions

Zuo-Tang Liang[1] and Xin-Nian Wang[2,1]
[1]*Department of Physics, Shandong University, Jinan, Shandong 250100, China*
uclear Science Division, MS 70R0319, Lawrence Berkeley National Laboratory, Berkeley, California 947
(Dated: November 5, 2018)

PLB 629, 20 (2005).

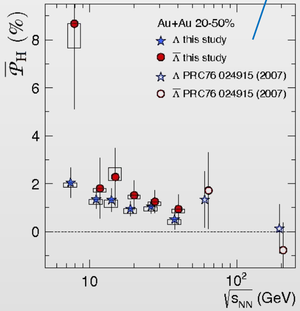
- Spin alignment of vector meson is determined by spin polarizations of constitute quark/antiquark

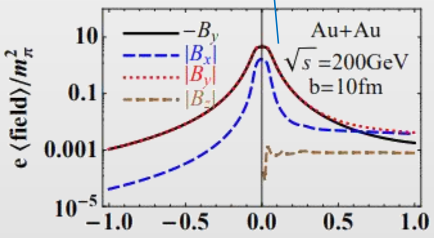
$$\boxed{\rho_{00}^{V\,(\mathrm{rec})} = \frac{1-P_q P_{\bar{q}}}{3+P_q P_{\bar{q}}} \approx \frac{1}{3} - \frac{4}{9} P_q P_{\bar{q}}}$$

$$\langle P_{q/\bar{q}} \rangle \approx \frac{1}{2}\langle \omega_y \rangle \pm \frac{Q_s}{2m_s T}\langle B_y \rangle \Longrightarrow \rho_{00}^{\phi} \approx \frac{1}{3} - \underbrace{\frac{1}{9}\langle \omega_y \rangle^2}_{4\times10^{-5}} + \underbrace{\frac{Q_s^2}{9m_s^2 T^2}\langle B_y \rangle^2}_{1\times10^{-5}}$$

$\lesssim 0.02$

$\lesssim 0.1 m_\pi^2$





➢ Contributions from vorticity and magnetic are negligible

Spin alignment

$$\rho_{00} \approx \frac{1}{3} + \overbrace{c_{\text{hydro}} + c_{\text{EM}} + c_F + c_A + c_h}^{\text{Cannot explain large positive deviation from 1/3}} + c_{\text{strong}}$$

Hydrodynamic gradient (vorticity, acceleraction, shear tensor)[1-9]

Electromagnetic fields [3,4,9]

Fragmentation [1]

Turbulent color field [10]

Helicity polarization [11]

Strong force (ϕ meson fields, gluon fields) [4,12,13]

[1] Z.-T. Liang, X.-N. Wang, PLB 629, 20 (2005)

[2] F. Becattini, L. Csernai, D.-J. Wang, PRC 88, 034905 (2013)

[3] Y.-G. Yang, R.-H. Fang, Q. Wang, X.-N. Wang, PRC 97, 034917 (2018)

[4] XLS, L. Oliva, Q. Wang, PRD 101, 096005 (2020)

[5] X.-L. Xia, H. Li, X.-G. Huang, H.-Z. Huang, PLB 817, 136325 (2021)

[6] F. Li, S. Liu, arXiv: 2206.11890

[7] D. Wagner, N. Weickgenannt, E. Speranza, PRR 5, 013187 (2023)

[8] M. Wei, M. Huang, arXiv:2303.01897

[9] XLS, S.-Y. Yang, Y.-L. Zou, D. Hou, arXiv:2209.01872

[10] B. Muller, D.-L. Yang, PRD 105, 1 (2022).

[11] J.-H. Gao, PRD 104, 076016 (2021)

[12] XLS, L. Oliva, Z.-T. Liang, Q. Wang, X.-N. Wang, PRL 131, 042304 (2023); arXiv: 2206.05868

[13] A. Kumar, B. Muller, D.-L. Yang, arXiv: 2304.04181

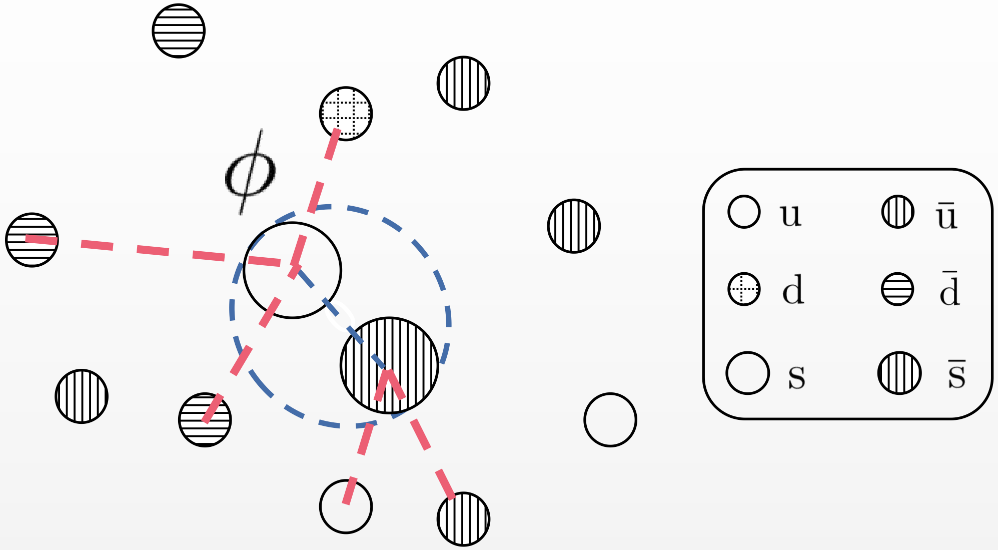
Strong force

- Strong force is a fundamental interaction that acts between quarks.

- At high temperatures, strong force is mediated by gluons.
(Quantum Chromodynamics)

- At low temperatures, strong force is mediated by mesons, proposed by Yukawa in 1935.

H. Yukawa, Proc. Phys. Math. Soc. Jap. 17, 48 (1935)



- Effective Lagrangian for a quark-meson model with scalar and vector fields.

$$\mathcal{L}_{\mathrm{eff}}(x) = \overline{\psi}(x)\left[i\partial\cdot\gamma - (m_0 + g_\sigma \sigma) - g_V \gamma\cdot V\right]\psi(x) + \frac{1}{2}\left(\partial_\mu\sigma\partial^\mu\sigma - m_\sigma^2\sigma^2\right) + \frac{1}{2}m_V^2 V_\mu V^\mu - \frac{1}{4}V^{\mu\nu}V_{\mu\nu}$$

strong interactions between $s/\bar{s}$ quarks are mediated by vector ϕ field

Short wave-length: quantum fields (particles)

Long wave-length: classical fields

Spin alignmnet

- Polarizations of strange quark/antiquark induced by vector ϕ field

$$P^{\mu}_{s/\bar{s}} = \pm \frac{g_{\phi}}{4 m_s E_p T} \epsilon^{\mu\nu\rho\sigma} p_{\nu} F^{\phi}_{\rho\sigma}$$

Coupling constant

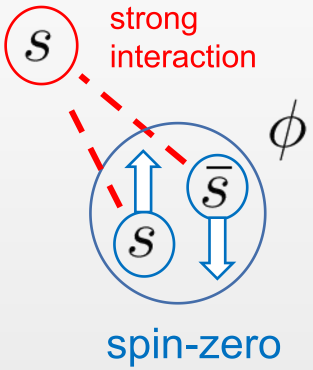
$$\frac{g_{\phi}^2}{4\pi} \sim \mathcal{O}(1) \gg \frac{e^2}{4\pi}$$

- Spin alignment for ϕ meson, measured along direction of $\boldsymbol{\epsilon}_0$

$$\begin{aligned} \rho_{00} \approx \; & \frac{1}{3} - \frac{4 g_{\phi}^2}{m_{\phi}^2 T_h^2} C_1 \left[\frac{1}{3} \mathbf{B}'_{\phi} \cdot \mathbf{B}'_{\phi} - (\boldsymbol{\epsilon}_0 \cdot \mathbf{B}'_{\phi})^2 \right] \\ & - \frac{4 g_{\phi}^2}{m_{\phi}^2 T_h^2} C_2 \left[\frac{1}{3} \mathbf{E}'_{\phi} \cdot \mathbf{E}'_{\phi} - (\boldsymbol{\epsilon}_0 \cdot \mathbf{E}'_{\phi})^2 \right] \end{aligned}$$

Temperature when ϕ meson is produced

Magnetic-like and electric-like components of vector ϕ field



XLS, L.Oliva, Q.Wang, PRD 101, 096005 (2020);

XLS, L.Oliva, Z.-T.Liang, Q.Wang, X.-N.Wang, PRL 131, 042304 (2023); arXiv: 2206.05868.

$$\begin{aligned} C_1 &= \frac{8 m_s^4 + 16 m_s^2 m_{\phi}^2 + 3 m_{\phi}^4}{120 m_s^2 (m_{\phi}^2 + 2 m_s^2)}, \\ C_2 &= \frac{8 m_s^4 - 14 m_s^2 m_{\phi}^2 + 3 m_{\phi}^4}{120 m_s^2 (m_{\phi}^2 + 2 m_s^2)}. \end{aligned}$$

Fluctuation induced alignment

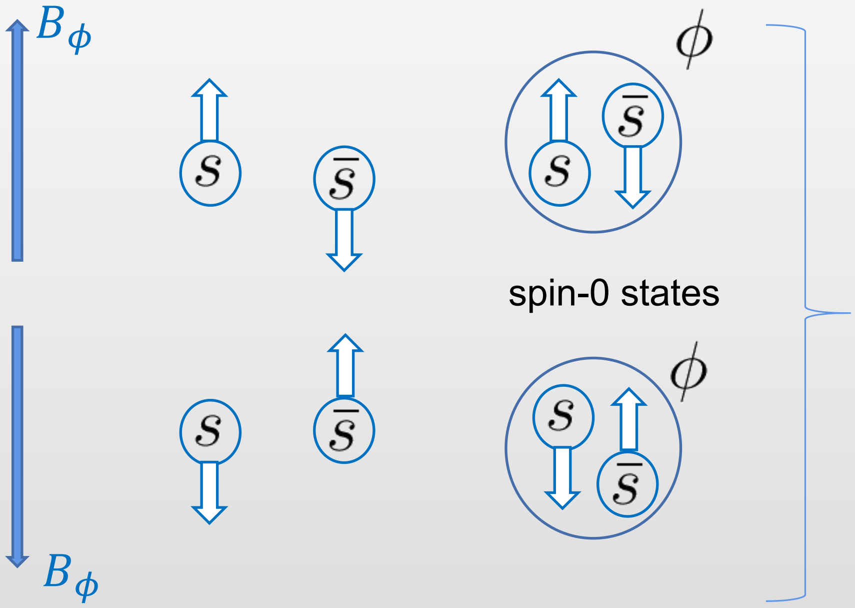
- Spin alignment of ϕ meson, measured along direction of $\boldsymbol{\epsilon}_0$

$$\begin{aligned}\rho_{00} \approx \frac{1}{3} & - \frac{4g_\phi^2}{m_\phi^2 T_h^2} C_1 \left[\frac{1}{3} \mathbf{B}'_\phi \cdot \mathbf{B}'_\phi - (\boldsymbol{\epsilon}_0 \cdot \mathbf{B}'_\phi)^2 \right] \\ & - \frac{4g_\phi^2}{m_\phi^2 T_h^2} C_2 \left[\frac{1}{3} \mathbf{E}'_\phi \cdot \mathbf{E}'_\phi - (\boldsymbol{\epsilon}_0 \cdot \mathbf{E}'_\phi)^2 \right]\end{aligned}$$

- All fields appear in squares
  ➡ spin alignment measures anisotropy of fluctuations

e.g., spin alignment along *y*-direction

$$\propto (B'_{\phi,y})^2 - \frac{(B'_{\phi,x})^2 + (B'_{\phi,z})^2}{2}$$



$$\langle B_\phi \rangle = 0, \quad \langle (B_\phi)^2 \rangle \neq 0$$

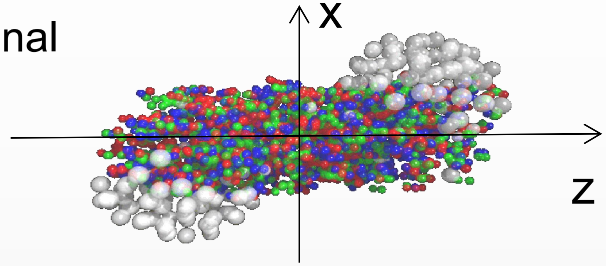
$$\rho_{00} > 1/3$$

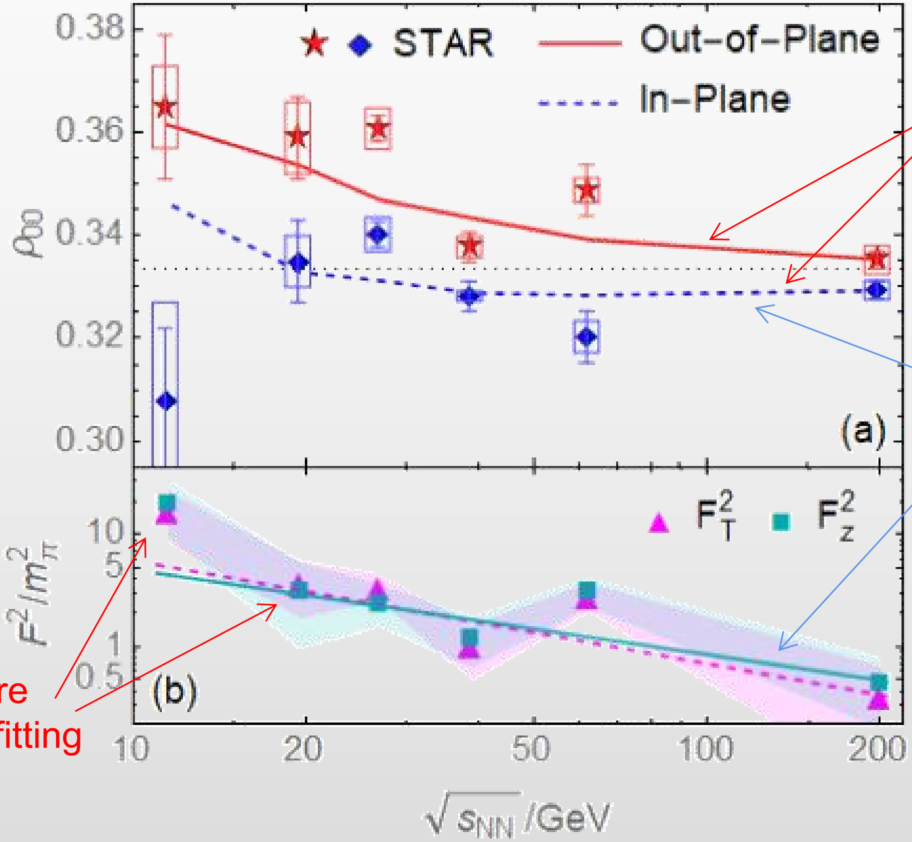
Fitting experiment datas

- Taking fluctuations of transverse and longitudinal fields as two independent parameters.

$$\left\langle (g_\phi \mathbf{B}^\phi_{x,y}/T_\mathrm{h})^2 \right\rangle = \left\langle (g_\phi \mathbf{E}^\phi_{x,y}/T_\mathrm{h})^2 \right\rangle \equiv F_T^2$$

$$\left\langle (g_\phi \mathbf{B}^\phi_{z}/T_\mathrm{h})^2 \right\rangle = \left\langle (g_\phi \mathbf{E}^\phi_{z}/T_\mathrm{h})^2 \right\rangle \equiv F_z^2$$





Difference induced by v_2

Energy-dependent parameters fitted by

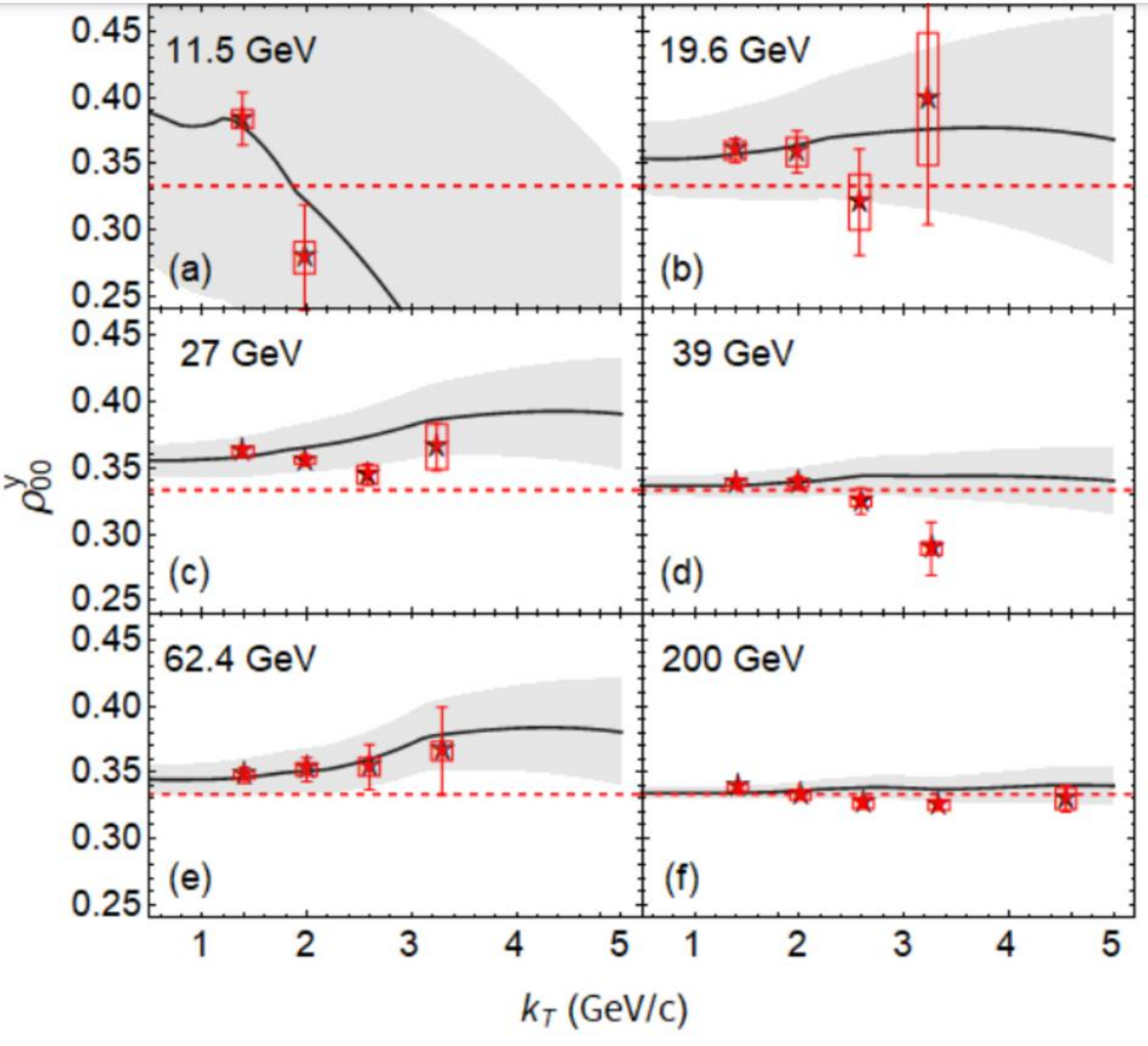
$$\ln(F_T^2/m_\pi^2) = 3.90 - 0.924 \ln \sqrt{s_{\mathrm{NN}}}$$
$$\ln(F_z^2/m_\pi^2) = 3.33 - 0.760 \ln \sqrt{s_{\mathrm{NN}}}$$

STAR, Nature 614, 244 (2023)

XLS, L.Oliva, Z.-T.Liang, Q.Wang, X.-N.Wang, PRL 131, 042304 (2023)

Parameters are evaluated by fitting STAR data

k_T dependence



XLS, L.Oliva, Z.-T.Liang, Q.Wang, X.-N.Wang, PRL 131, 042304 (2023)

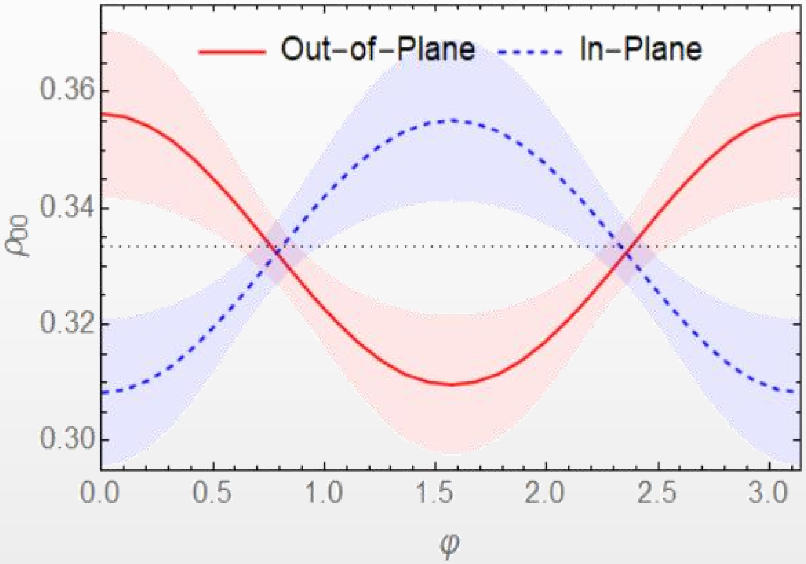
Calculated ρ_{00}^{y} as functions of ϕ meson's transverse momentum, in comparison with STAR data for Au+Au collisions in 0-80% centrality region.

STAR, Nature 614, 244 (2023)

Shaded error bands from uncetainties of extracted parameters F_T^2 and F_z^2.

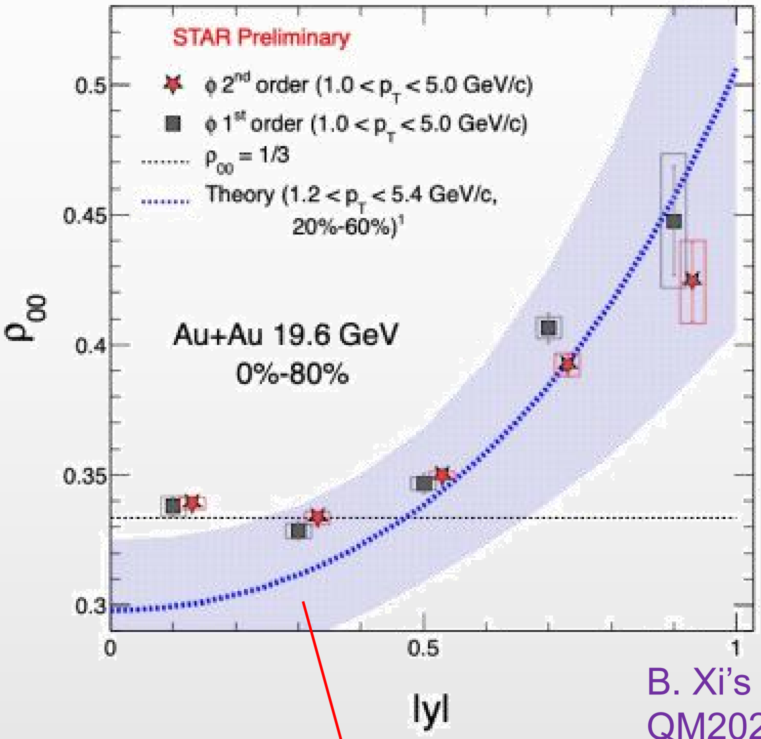
Model predictions

- Predictions for azimuthal angle dependence and rapidity dependence



Au-Au collisions at 200 GeV/A

$1.2 < k_T < 5.4$ GeV



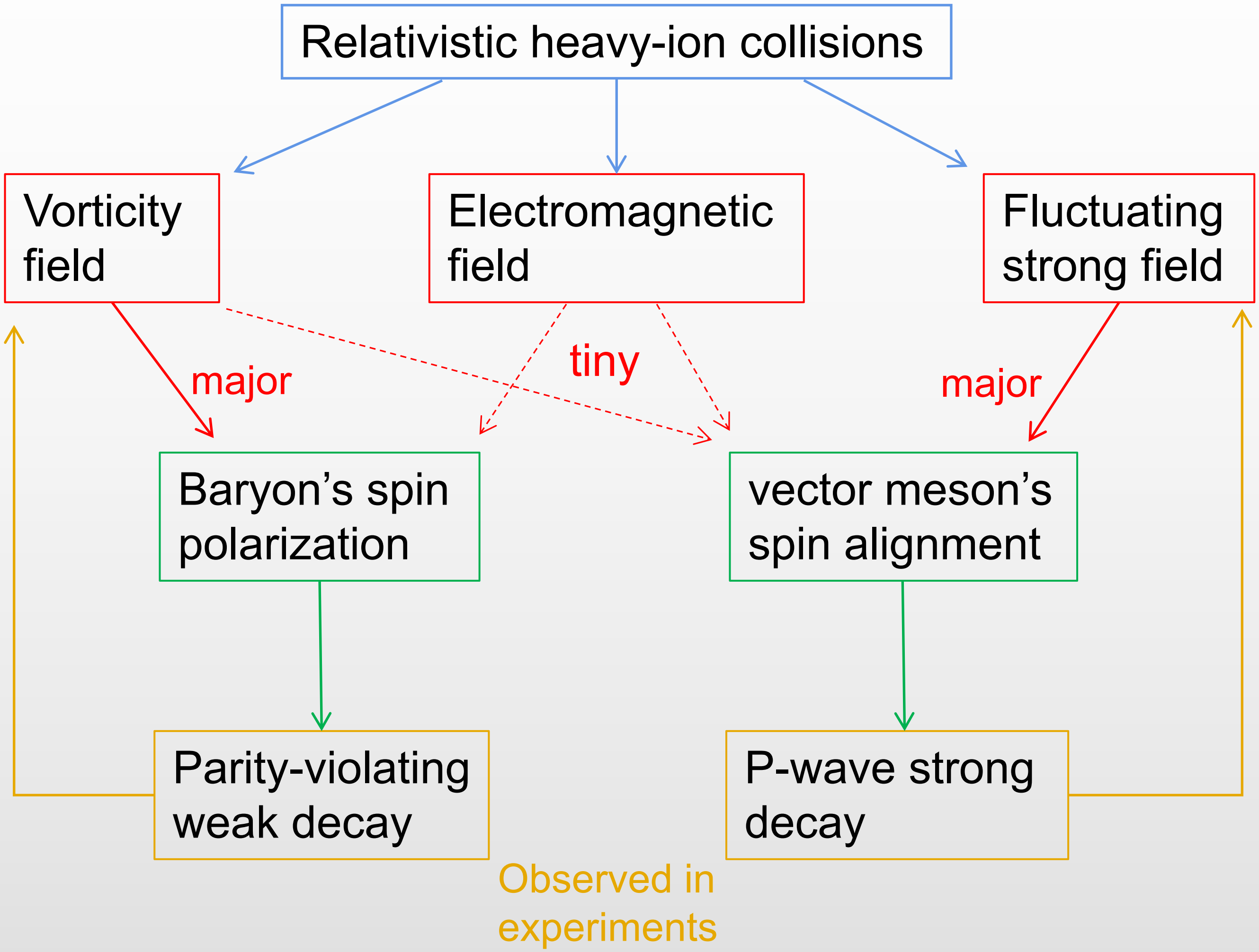
our prediction

B. Xi's talk in QM2023

XLS, L.Oliva, Z.-T.Liang, Q.Wang, X.-N.Wang, PRL 131, 042304 (2023)

XLS, S. Pu, Q. Wang, arXiv: 2308.14038

Summary



Relativistic heavy-ion collisions

Vorticity field

Electromagnetic field

Fluctuating strong field

major

tiny

major

Baryon's spin polarization

vector meson's spin alignment

Parity-violating weak decay

P-wave strong decay

Observed in experiments

Thank you!