Global polarization in HIC: past, present and future

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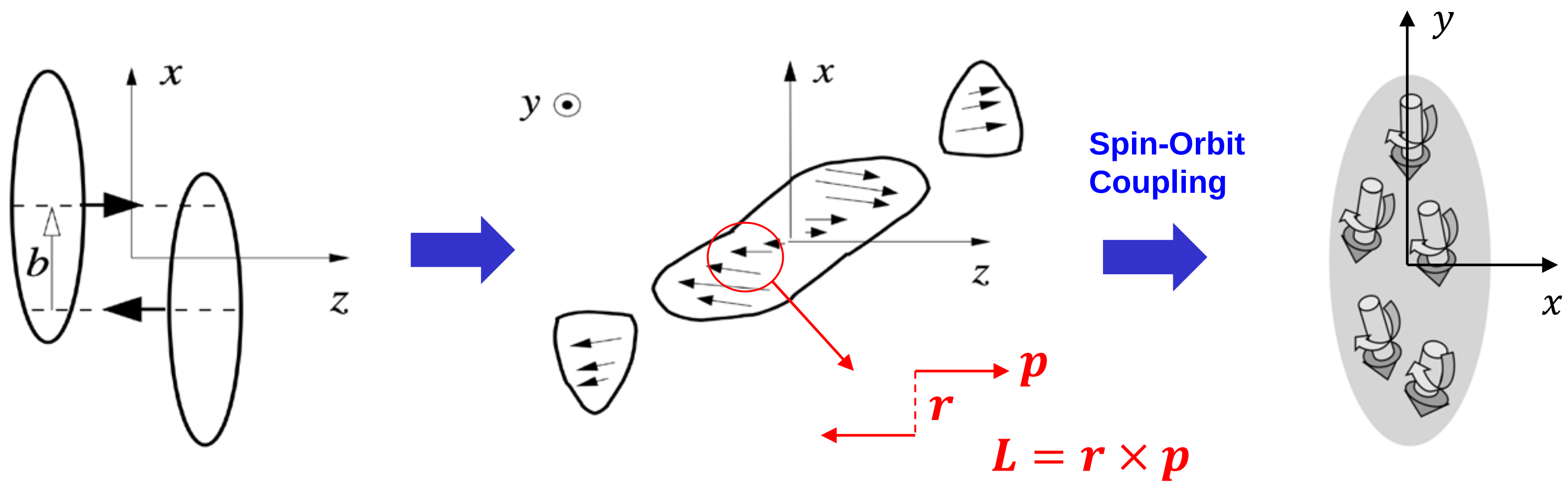
The 25th International Spin Symposium (SPIN 2023),
September 24-29, 2023, Duke University, Durham, NC

Outline

- Introduction to polarization phenomena in HIC
- Global polarization through spin-orbit coupling in particle scatterings [aspects of early works]
- Spin alignment of vector mesons through strong force field fluctuations [current works]
- Outlook [future works]

Plenary talks: QW, A. Tang (Sept. 29)
Parallel talks: Z. Liang, X. Bai, F. Li, D. Shen, G. Wilks (Sept. 26)

Global OAM and polarization in HIC

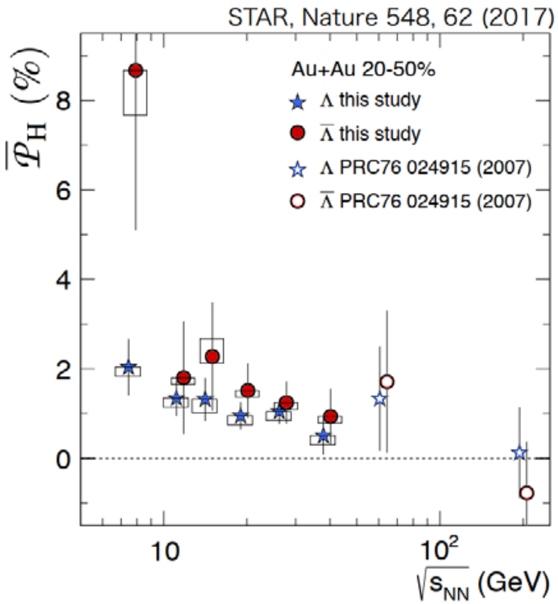


Materials

- **Barnett effect: rotation -> magnetization [Barnett, Phys Rev. 6, 239-270 (1915)]**
- **Einstein-de Haas effect: magnetization -> rotation [Einstein, de Haas, Experimental proof of the existence of Ampere's molecular currents, Verhandl. Deut. Phys. Ges. 17, 152–170 (1915)]**

HIC: Global OAM leads to global polarization of Λ hyperons through spin-orbit coupling

STAR: global polarization of Λ hyperon

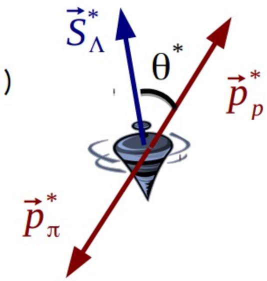


parity-violating decay of hyperons

In case of Λ's decay, daughter proton preferentially decays in the direction of Λ's spin (opposite for anti-Λ)

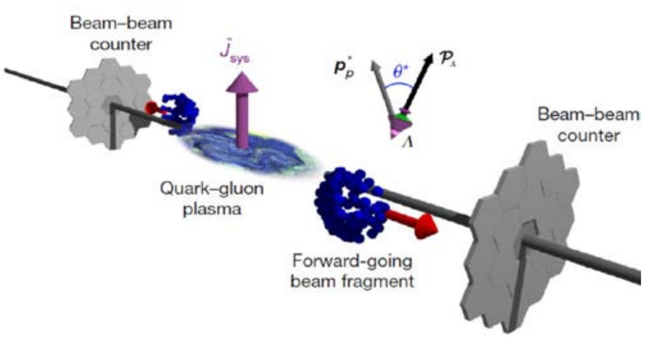
$$\frac{dN}{d\Omega^*} = \frac{1}{4\pi}(1 + \alpha \mathbf{P_\Lambda} \cdot \mathbf{p_p^*})$$

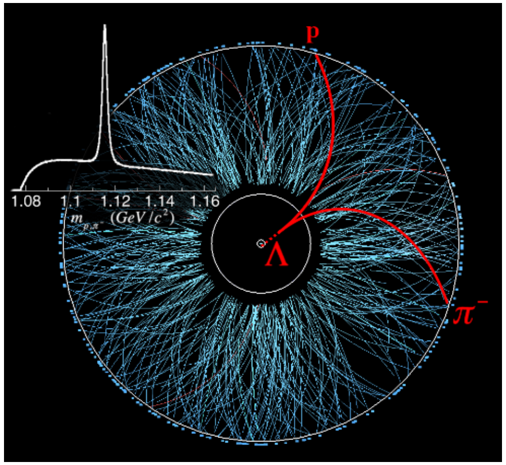
α: Λ decay parameter (=0.642±0.013)
P_Λ: Λ polarization
p_p^*: proton momentum in Λ rest frame



$\Lambda \rightarrow p + \pi^+$
(BR: 63.9%, c τ ~7.9 cm)

Updated by BES III, PRL129, 131801 (2022)





ω = (9 ± 1)x10²¹/s, the largest angular velocity that has ever been observed in any system

Theoretical models and proposals: early works on global polarization in HIC

Polarizations of Λ hyperons and vector mesons through spin-orbital coupling in HIC from global OAM

-- Liang and Wang, PRL 94,102301(2005), PRL 96, 039901(E) (2006) [nucl-th/0410079]

-- Liang and Wang, PLB 629, 20(2005) [nucl-th/0411101]

Polarized secondary particles in un-polarized high energy hadron-hadron collisions,

-- Voloshin, nucl-th/0410089 (the first unpublished paper following Liang-Wang's original work)

Polarization as probe to vorticity in HIC

-- Betz, Gyulassy, Torrieri, PRC 76, 044901(2007) [0708.0035]

Global quark polarization in non-central A+A collisions

-- Gao, Chen, Deng, Liang, QW, Wang, PRC 77, 044902(2008) [0710.2943]

Angular momentum conservation in HIC

-- Becattini, Piccinini, Rizzo, PRC 77, 024906 (2008) [0711.1253]

Some recent review articles on polarization in HIC

1. Global and local spin polarization in heavy ion collisions: a brief overview, [phenomenology]
   QW, Nucl. Phys. A 967, 225 (2017).

2. Relativistic hydrodynamics for spin-polarized fluids, [theory]
   Florkowski, Kumar, R. Ryblewski, Prog. Part. Nucl. Phys. 108, 103709 (2019).

3. Polarization and Vorticity in the Quark–Gluon Plasma, [phenomenology]
   Becattini, Lisa, Ann. Rev. Nucl. Part. Sci. 70, 395 (2020).

4. Vorticity and Spin Polarization in Heavy Ion Collisions: Transport Models, [phenomenology]
   Huang, Liao, QW, Xia, Lect. Notes Phys. 987, 281 (2021).

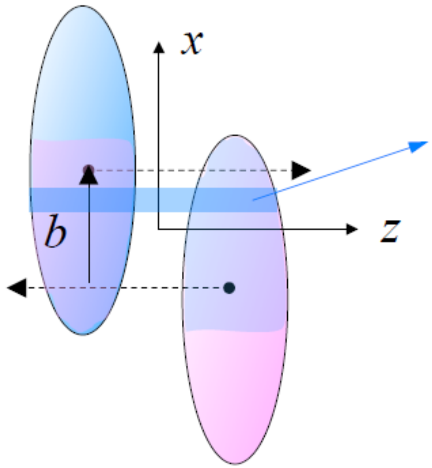
5. Global polarization effect and spin-orbit coupling in strong interaction, [phenomenology]
   Gao, Liang, QW, Wang, Lect. Notes Phys. 987, 195 (2021).

6. Spin and polarization: a new direction in relativistic heavy ion physics, [theory+phenom.]
   Becattini, Rept. Prog. Phys. 85, No.12, 122301 (2022)

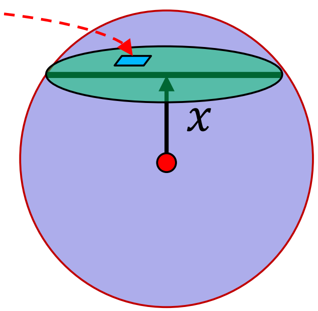
7. Foundations and applications of quantum kinetic theory, [theory]
   Hidaka, Pu, QW, Yang, Prog. Part. Nucl. Phys. 127, 103989 (2022).

8. Spin and chiral effects in high energy heavy ion collisions (in Chinese), [theory+phenom.]
   QW, Liang, Ma (editors), Acta Phys. Sin. 72, No. 7 & 11 (2023)

Global OAM in HIC



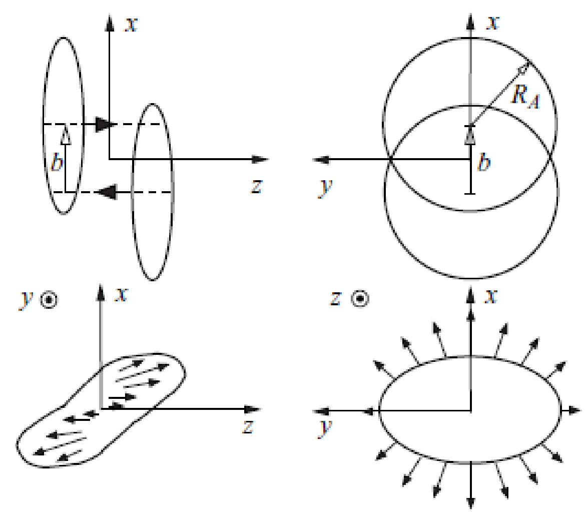
$$\frac{dN_{part}^{P,T}}{dx} = \int dy\, dz\, \rho_A^{P,T}(x, y, z, b)$$



Number of participant nucleons per unit x in projectile or target

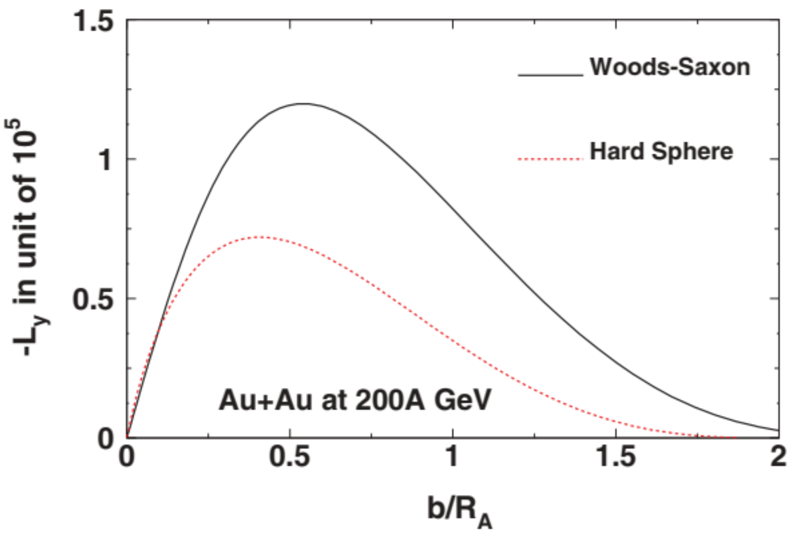
Collective longitudinal momentum per produced parton

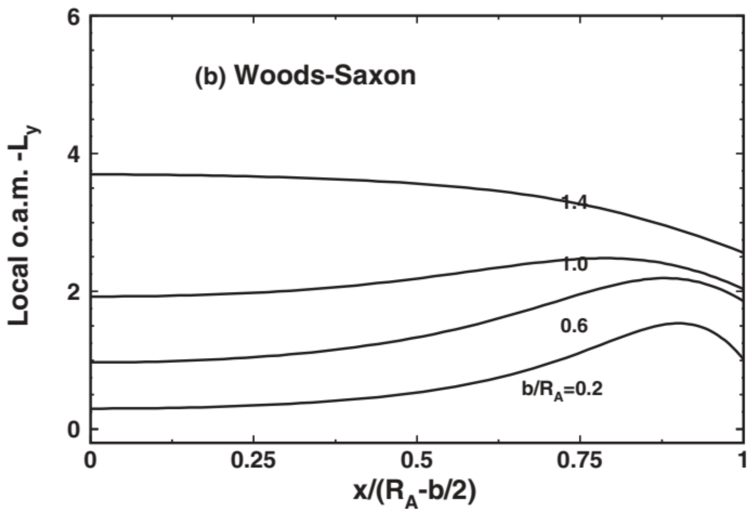
$$p_z(x,b) = \frac{\sqrt{s}}{2c(s)} \frac{\frac{dN_{\rm part}^{P}}{dx} - \frac{dN_{\rm part}^{T}}{dx}}{\frac{dN_{\rm part}^{P}}{dx} + \frac{dN_{\rm part}^{T}}{dx}}$$



Liang, Wang PRL (2005); Gao, Chen, Deng, et al. PRC (2008)

Global and local OAM





Global OAM in y-direction

$$L_y = -p_{\text{in}} \int x dx \left(\frac{dN^P_{\text{part}}}{dx} - \frac{dN^T_{\text{part}}}{dx} \right)$$

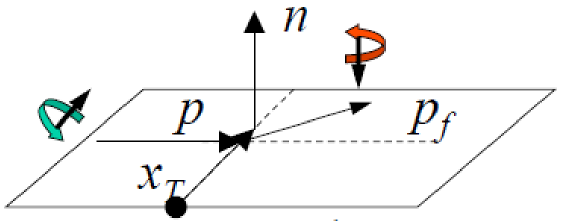
Local OAM in y-direction

$$\begin{aligned} L_y &= -\Delta x \Delta p_z \\ &= -(\Delta x)^2 \frac{dp_z}{dx} \sim \beta \omega_y \end{aligned}$$

Liang, Wang PRL (2005); Gao, Chen, Deng, et al. PRC (2008)

Quark polarization in potential scatterings

- **Quark scatterings at small angle in static potential at impact parameter x_T**
- **Unpolarized and polarized cross sections**



$$A^0(q_T) = \frac{1}{q_T^2 + \mu^2}$$

screening mass

$$\boxed{\mu \sim T\sqrt{\alpha_S}}$$

$$\frac{d\sigma}{d^2\vec{x}_T} = \frac{d\sigma_+}{d^2\vec{x}_T} + \frac{d\sigma_-}{d^2\vec{x}_T} = 4C_T\alpha_s^2 K_0(\mu x_T)$$

$$\frac{d\Delta\sigma}{d^2\vec{x}_T} = \frac{d\sigma_+}{d^2\vec{x}_T} - \frac{d\sigma_-}{d^2\vec{x}_T} \propto \boxed{\vec{n}\cdot(\underline{\vec{x}_T \times \vec{p}})}$$

Spin quantization direction **OAM** **Spin-orbit coupling**

- **Polarization for small angle scattering and** $m_q \gg p, \mu$

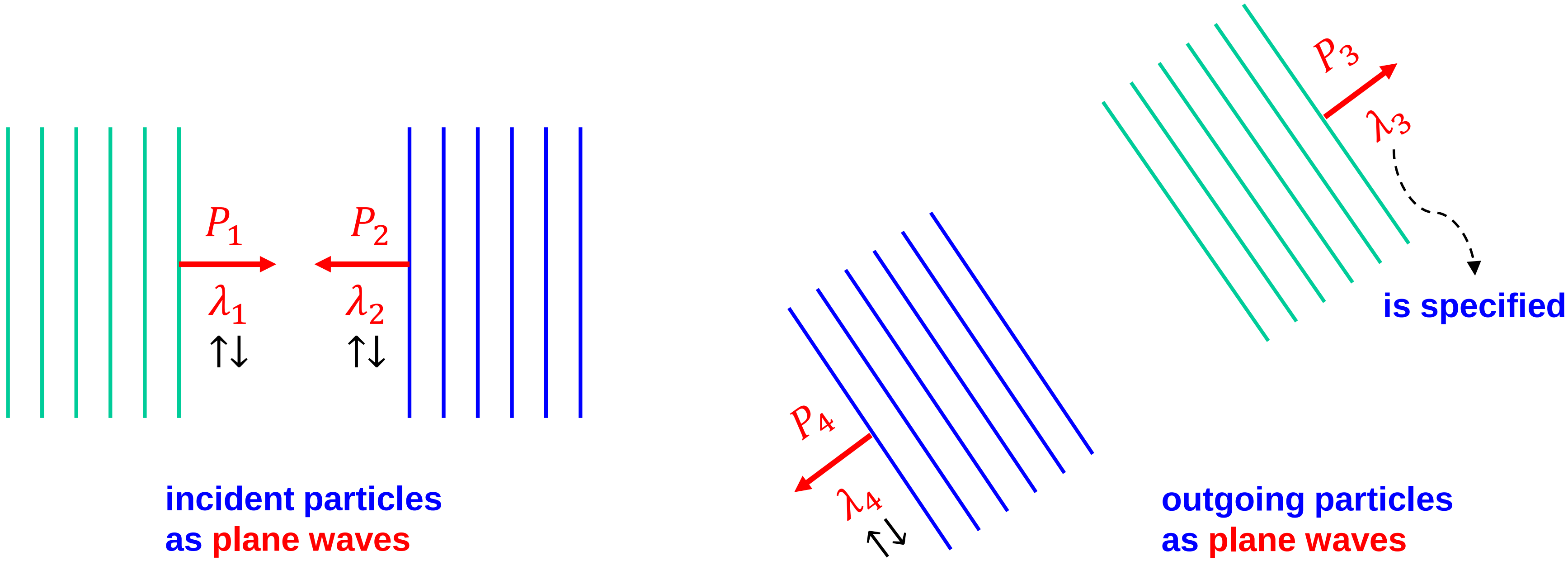
$$P_q \approx -\pi\frac{\mu p}{4m_q^2} \sim -\frac{\Delta E_{LS}}{E_0}$$

Liang, Wang, PRL 94, 102301(2005)

- **With initial polarization P_i, the final polarization P_f after one scattering is** $P_f = P_i - \frac{(1-P_i^2)\pi\mu p}{2E(E+m) - P_i\pi\mu p}.$

Huang, Huovinen, Wang, PRC84, 054910(2011)

Collisions of particles as plane waves



incident particles
as plane waves

outgoing particles
as plane waves

Particle collisions as plane waves:
since there is no favored position for particles, so the OAM vanishing

$$\langle \hat{\boldsymbol{x}} \times \hat{\boldsymbol{p}} \rangle = \mathbf{0} \quad \Longrightarrow \quad \left(\frac{d\sigma}{d\Omega}\right)_{\lambda_3=\uparrow} = \left(\frac{d\sigma}{d\Omega}\right)_{\lambda_3=\downarrow}$$

Quark-quark scattering at fixed impact parameter

We consider quark-quark scattering of spin-momentum states

$$q_1(P_1,\lambda_1)+q_2(P_2,\lambda_2)\rightarrow q_1(P_3,\lambda_3)+q_2(P_4,\lambda_4)$$

where $P_i=(E_i,\vec{p}_i)$ and λ_i denote spin states. The difference cross section (λ_3 is specified)

$c_{qq}=2/9$ (color factor)

$$d\sigma_{\lambda_3}=\frac{c_{qq}}{4F}\sum_{\lambda_1\lambda_2\lambda_4}\mathcal{M}(Q)\mathcal{M}^*(Q)(2\pi)^4\delta^{(4)}(P_1+P_2-P_3-P_4)\frac{d^3\vec{p}_3}{(2\pi)^3 2E_3}\frac{d^3\vec{p}_4}{(2\pi)^3 2E_4}$$

fixed

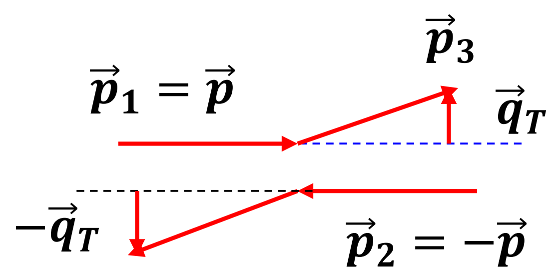
sum over ↑↓

$Q=P_3-P_1=P_2-P_4$
(momentum transfer)

$F=4\sqrt{(P_1\cdot P_2)^2-m_1^2m_2^2}$ (flux factor)

Integrate $\vec{p}_4$ and $p_{3z}^{\pm}=\pm\sqrt{p^2-q_T^2}$

to remove $\delta^{(4)}(P_1+P_2-P_3-P_4)$



Quark-quark scattering at fixed impact parameter

We obtain $d\sigma_{\lambda_3}$ for scattered quark with spin state λ_3

$$d\sigma_{\lambda_3} = \frac{c_{qq}}{16F} \sum_{\lambda_1\lambda_2\lambda_4} \sum_{i=+,-} \frac{1}{(E_1+E_2)|p^i_{3z}|} \mathcal{M}(Q_i)\mathcal{M}^*(Q_i) \frac{d^2\vec{q}_T}{(2\pi)^2}$$

for small angle scattering, only $i=+$ is relevant

Jacobian

momentum transfer in small angle scattering

Then we can introduce impact parameter $\vec{x}_T = (x_T, \phi)$

$$d\sigma_{\lambda_3} = \frac{c_{qq}}{16F} \sum_{\lambda_1\lambda_2\lambda_4} \int d^2\vec{x}_T \int \frac{d^2\vec{q}_T}{(2\pi)^2} \frac{d^2\vec{k}_T}{(2\pi)^2} \frac{1}{(E_1+E_2)|p^i_{3z}|} e^{i(\vec{k}_T-\vec{q}_T)\cdot\vec{x}_T} \frac{\mathcal{M}(\vec{q}_T)\mathcal{M}^*(\vec{k}_T)}{\Lambda(\vec{q}_T)\Lambda^*(\vec{k}_T)}$$

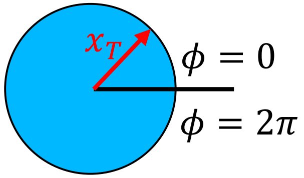
$\Rightarrow d^2\sigma_{\lambda_3}/d^2\vec{x}_T$

$\boxed{1}$

$$\Lambda(\vec{q}_T)\Lambda^*(\vec{k}_T) = \sqrt{(E_1+E_2)|p^+_{3z}(q_T)|}$$

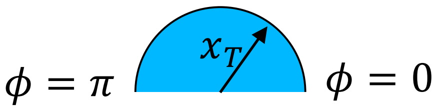
If we integrate over $\vec{x}_T$ in whole space we obtain

$$\sigma_{\lambda_3} = \int_0^\infty dx_T\, x_T \int_0^{2\pi} d\phi \frac{d^2\sigma_{\lambda_3}}{d^2\vec{x}_T} \Longrightarrow \sigma_\uparrow = \sigma_\downarrow$$



Quark-quark scattering at fixed impact parameter

If we integrate over $\vec{x}_T$ in half-space we obtain



$$\boldsymbol{\sigma_{\lambda_3} = \int_0^\infty dx_T\, x_T \int_0^{\color{red}\pi} d\phi \frac{d^2\sigma_{\lambda_3}}{d^2\vec{x}_T}} \Longrightarrow {\color{red}\boldsymbol{\sigma_\uparrow \neq \sigma_\downarrow}}$$

The differential cross section for spin-independent and spin-dependent part

$$\frac{d^2\sigma_{\lambda_3}}{d^2\vec{x}_T} = \frac{d^2\sigma}{d^2\vec{x}_T} + \lambda_3 \frac{d^2\Delta\sigma}{d^2\vec{x}_T}$$

$$\frac{d^2\sigma}{d^2\vec{x}_T} = \frac{1}{2}\left(\frac{d^2\sigma_\uparrow}{d^2\vec{x}_T} + \frac{d^2\sigma_\downarrow}{d^2\vec{x}_T}\right) = F(x_T)$$

$$\frac{d^2\Delta\sigma}{d^2\vec{x}_T} = \frac{1}{2}\left(\frac{d^2\sigma_\uparrow}{d^2\vec{x}_T} - \frac{d^2\sigma_\downarrow}{d^2\vec{x}_T}\right) = \underbrace{\vec{n}\cdot(\vec{x}_T \times \vec{p})}_{\text{spin-orbit coupling}}\Delta F(x_T)$$

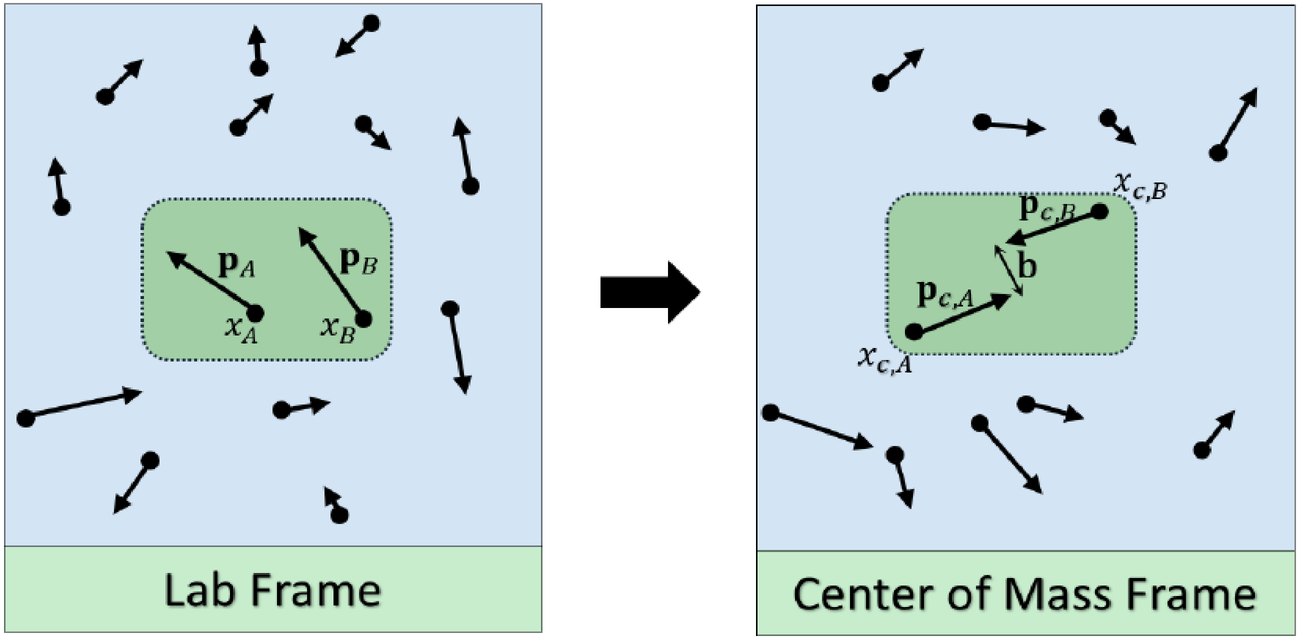
$$\boxed{\begin{aligned}\Delta\sigma &= \int_0^\infty dx_T x_T \int_0^\pi d\phi \frac{d^2\Delta\sigma}{d^2\vec{x}_T}\\ \sigma &= \int_0^\infty dx_T x_T \int_0^{2\pi} d\phi \frac{d^2\Delta\sigma}{d^2\vec{x}_T}\end{aligned}}$$

$$\Downarrow$$

$$\boxed{P_q = \frac{\Delta\sigma}{\sigma}}$$

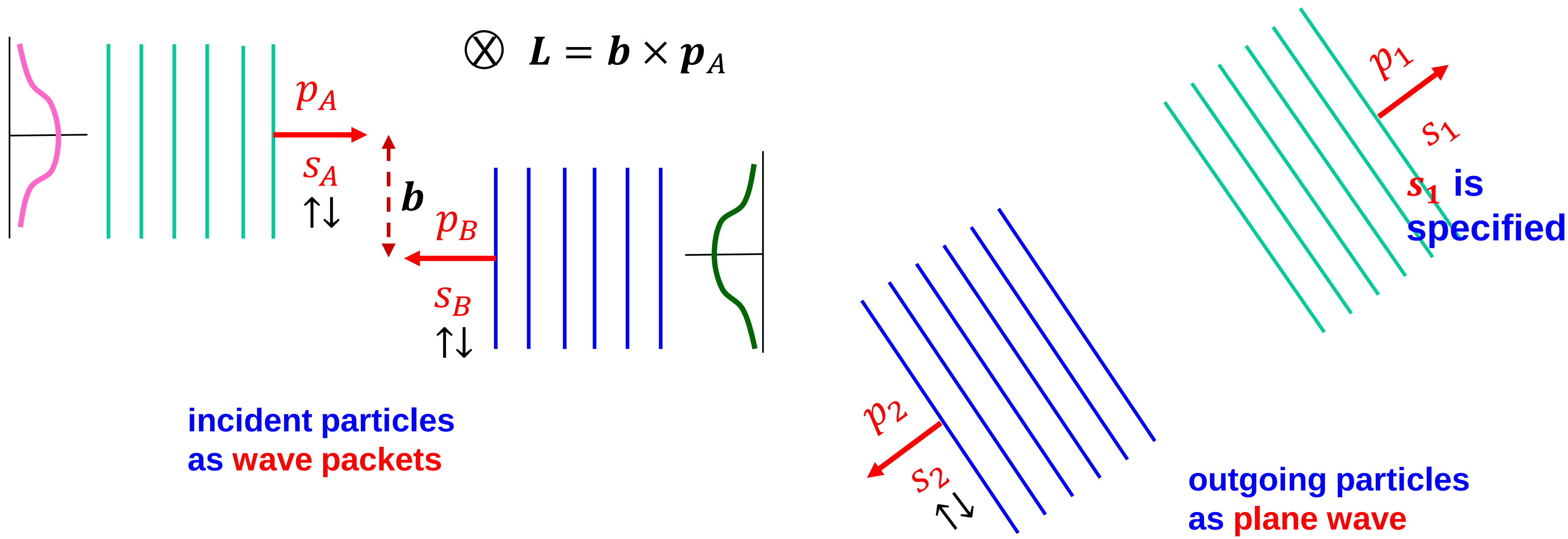
Gao, Chen, Deng, et al. PRC (2008)

Ensemble average in thermal QGP for global polarization through spin-orbit couplings in parton scatterings



Zhang, Fang, QW, Wang, Phys. Rev. C 100, 064904 (2019)

Collisions of particles as wave packets



Particle collisions as wave packets: there is a transverse distance between two wave packets (impact parameter) giving non-vanishing OAM and then the polarization of one final particle

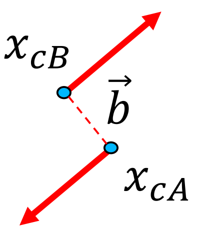
$$\boldsymbol{L} = \boldsymbol{b} \times \boldsymbol{p}_A \quad \Longrightarrow \quad \left(\frac{d\sigma}{d\Omega}\right)_{s_1=\uparrow} \neq \left(\frac{d\sigma}{d\Omega}\right)_{s_1=\downarrow}$$

Collisions of particles at different space-time points

- **Two incident particles at** $x_A = (t_A, \mathbf{x}_A)$ **and** $x_B = (t_B, \mathbf{x}_B)$ **in the lab frame**

$$t_A = t_B \xrightarrow{\boxed{\mathbf{x}_A \neq \mathbf{x}_B}} t_{c,A} \neq t_{c,B}$$

$$t_A \neq t_B \xrightarrow[\boxed{\mathbf{x}_{c,A} \neq \mathbf{x}_{c,B}}]{} t_{c,A} = t_{c,B}$$



CM frame

- **We impose the causality condition in CM frame for scattering of particles at two different space-time points (the time interval and longitudinal distance of two space-time points should be small enough for scattering to take place)**

$$\Delta t_c = t_{c,A} - t_{c,B} = 0$$
$$\Delta x_{c,L} = \hat{\mathbf{p}}_{c,A} \cdot (\mathbf{x}_{c,A} - \mathbf{x}_{c,B}) = 0$$

CM frame: collision take places at the same time but displaced by the impact parameter

From spin-orbit coupling to spin-vorticity coupling: ensemble average

- **Quark polarization rate per unit volume: 10D + 6D integration**

$$
\begin{aligned}
\frac{d^4\mathbf{P}_{AB\to 12}(X)}{dX^4} &= \frac{\pi}{(2\pi)^4}\frac{\partial(\beta u_\rho)}{\partial X^\nu}\int \boxed{\frac{d^3p_A}{(2\pi)^3 2E_A}\frac{d^3p_B}{(2\pi)^3 2E_B}} \\
&\quad \times |v_{c,A}-v_{c,B}|\boxed{[\Lambda^{-1}]^\nu_{\ j}}\mathrm{e}_{c,i}\epsilon_{ikh}\hat{\mathbf{p}}^h_{c,A} \\
&\quad \times f_A(X,p_A)\, f_B(X,p_B)\,(p^\rho_A - p^\rho_B)\boxed{\Theta_{jk}(\mathbf{p}_{c,A})} \\
&\equiv \frac{\partial(\beta u_\rho)}{\partial X^\nu}\boxed{\mathbf{W}^{\rho\nu}}
\end{aligned}
$$

6D integral

Lorentz boost

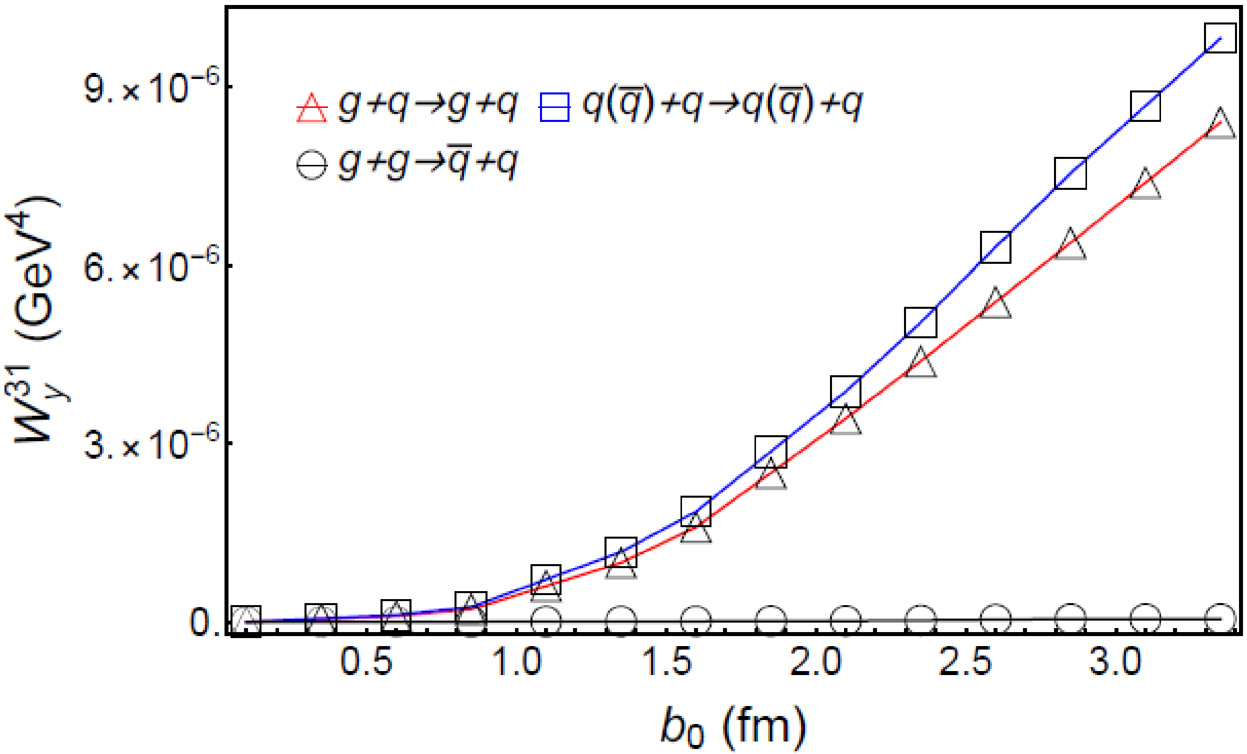
10D integral

16D integral !!

- **Numerical challenge !!!** **We have developed ZMCintegral-3.0, a Monte Carlo integration package that runs on multi-GPUs** **[Wu, Zhang, Pang, QW, Comp. Phys. Comm. (2020) (1902.07916)]**
- **Another challenge:** **there are more than 5000 terms in polarized amplitude squared for 2-to-2 parton scatterings**

$$
I_M^{q_a q_b \to q_a q_b}(s_2) = \sum_{s_A, s_B, s_1}\sum_{i,j,k,l}\mathcal{M}\left(\{s_A,k_A;s_B,k_B\}\to\{s_1,p_1;s_2,p_2\}\right)\mathcal{M}^*\left(\{s_A,k'_A;s_B,k'_B\}\to\{s_1,p_1;s_2,p_2\}\right)
$$

Numerical results for quark polarization



The cutoff b_0 is of the order of hydro length scale $1/\partial u(x)$ and larger than interaction scale $1/m_D$: $b_0 \sim \frac{1}{\partial u(x)} > \frac{1}{m_D}$

$$\frac{d^4 \mathrm{P}_{AB\to 12}(X)}{dX^4} = 2W\nabla_X \times (\beta \mathbf{u})$$

Zhang, Fang, QW, et al., PRC 100, 064904 (2019)

Polarization from different sources in QKT with Wigner functions (without collisions)

Axial vector component of WF (spin vector) has many contributions

$$\mathcal{J}_5^\mu = \mathcal{J}^\mu_{\text{thermal}} + \mathcal{J}^\mu_{\text{shear}} + \mathcal{J}^\mu_{\text{accT}} + \mathcal{J}^\mu_{\text{chemical}} + \mathcal{J}^\mu_{\text{EB}},$$

Becattini, et al, (2021)
Fu, Liu, et al., (2021)

Thermal vorticity

$$\mathcal{J}^\mu_{\text{thermal}} = a\frac{1}{2}\epsilon^{\mu\nu\alpha\beta}p_\nu\partial_\alpha\frac{u_\beta}{T},$$

Shear viscous tensor

$$\mathcal{J}^\mu_{\text{shear}} = -a\frac{1}{(u\cdot p)T}\underline{\epsilon^{\mu\nu\alpha\beta}p_\alpha u_\beta p^\sigma\partial_{<\sigma}u_{\nu>}}$$

Fluid acceleration

$$\mathcal{J}^\mu_{\text{accT}} = -a\frac{1}{2T}\epsilon^{\mu\nu\alpha\beta}p_\nu u_\alpha(Du_\beta - \frac{1}{T}\partial_\beta T).$$

Gradient of chemical potential

$$\mathcal{J}^\mu_{\text{chemical}} = a\frac{1}{(u\cdot p)}\epsilon^{\mu\nu\alpha\beta}p_\alpha u_\beta\partial_\nu\frac{\mu}{T},$$

Electromagnetic fields

$$\mathcal{J}^\mu_{\text{EB}} = a\frac{1}{(u\cdot p)T}\epsilon^{\mu\nu\alpha\beta}p_\alpha u_\beta E_\nu + a\frac{B^\mu}{T},$$

Hidaka, Pu, Yang (2018); Yi, Pu, Yang (2021)

QKT for massive fermions in Wigner functions

- **Wigner function (4x4 matrix) for spin 1/2 massive fermions**

$$W_{\alpha\beta}(x,p) = \int d^4y \exp\left(\frac{i}{\hbar}p\cdot y\right)\left\langle\overline{\psi}_\beta\left(x-\frac{y}{2}\right)\psi_\alpha\left(x+\frac{y}{2}\right)\right\rangle$$

Heinz (1983); Vasak-Gyulassy-Elze (1987); Zhuang-Heinz (1996); Iancu-Blaizot (2001); QW-Redlich-Stoecker-Greiner (2002)

- **Wigner function decomposition in 16 generators of Clifford algebra**

spin 4-vector

$$W = \frac{1}{4}\left[\mathscr{F} + i\gamma^5\mathscr{P} + \gamma^\mu\mathscr{V}_\mu + \gamma^5\gamma^\mu\mathscr{A}_\mu + \frac{1}{2}\sigma^{\mu\nu}\mathscr{S}_{\mu\nu}\right]$$

scalar p-scalar vector axial-vector tensor

$$j^\mu = \int d^4p\mathscr{V}^\mu, \qquad j_5^\mu = \int d^4p\mathscr{A}^\mu, \qquad T^{\mu\nu} = \int d^4p p^\mu\mathscr{V}^\nu$$

Recent reviews:
Hidaka-Pu-QW-Yang, PPNP (2022)
Gao-Liang-QW, IJMPA (2021)

Vasak-Gyulassy-Elze, Ann. Phys. 173, 462 (1987);
Elze-Gyulassy-Vasak, Nucl. Phys. B 276, 706 (1986);

Spin DOF: Matrix Valued Spin Dependent Distributions (MVSD)

Relativistic MVSD for fermion in QFT

$$p^\mu \equiv \frac{1}{2}(p_1^\mu + p_2^\mu) \qquad q^\mu \equiv p_1^\mu - p_2^\mu$$

$$f_{rs}(x,p) \equiv \int \frac{d^4q}{2(2\pi)^3} \exp\left(-\frac{i}{\hbar} q\cdot x\right) \delta(\underline{p\cdot q}) \left\langle a^\dagger(\underline{s,\mathbf{p}_2}) a(\underline{r,\mathbf{p}_1})\right\rangle$$

Relativistic MVSD can be parameterized in un-polarized distributions and Spin Density Matrix (polarization part)

$$f_{rs}^{(+)}(x,\mathbf{p}) = \frac{1}{2}\underline{f_q(x,\mathbf{p})}\left[\delta_{rs} - \underline{P_\mu^q(x,\mathbf{p})}\,\underline{n_j^{(+)\mu}(\mathbf{p})}\tau_{rs}^j\right],$$

$$f_{rs}^{(-)}(x,-\mathbf{p}) = \frac{1}{2}\underline{f_{\overline{q}}(x,-\mathbf{p})}\left[\delta_{rs} - \underline{P_\mu^{\overline{q}}(x,-\mathbf{p})}\,\underline{n_j^{(-)\mu}(\mathbf{p})}\tau_{rs}^j\right],$$

Pauli matrices in spin space (rs-space)

un-polarized dist.

spin polarization dist.

Four-vectors of three basis directions in rest frame of q and $\overline{q}$ (one is the spin quantization direction)

MVSD:
Becattini et al. (2013)
Sheng, Weickgenannt, et al. (2021)
Sheng, QW, Rischke (2022)

Spin Boltzmann equation for massive fermions

- **At leading order spin Boltzmann equation (SBE) with local collision terms**

$$\begin{aligned}\frac{1}{E_p}p\cdot\partial_x \mathrm{tr}\left[f^{(0)}(x,p)\right] &= \mathscr{C}_{\mathrm{scalar}}\left[f^{(0)}\right]\\ \frac{1}{E_p}p\cdot\partial_x \mathrm{tr}\left[n_j^{(+)\mu}\tau_j f^{(0)}(x,p)\right] &= \mathscr{C}_{\mathrm{pol}}\left[f^{(0)}\right]\end{aligned} \Longrightarrow \boldsymbol{f_{rs}^{(0)}(x,p)}$$

- **At next-to-leading order, SBE describes how $\boldsymbol{f^{(1)}(x,p)}$ evolves for given $\boldsymbol{f^{(0)}(x,p)}$ with space-time derivatives of $\boldsymbol{f^{(0)}(x,p)}$ [non-local terms]**

determined by leading order SBE

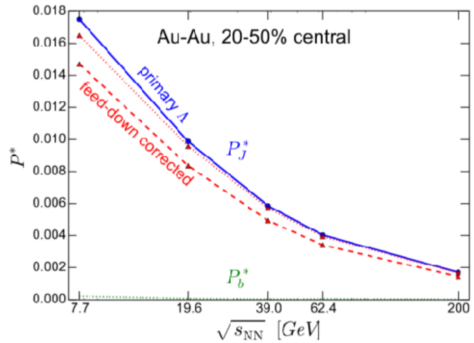
$$\begin{aligned}\frac{1}{E_p}p\cdot\partial_x \mathrm{tr}\left[f^{(1)}(x,p)\right] &= \mathscr{C}_{\mathrm{scalar}}\left[\underline{f^{(0)},\partial_x f^{(0)}}, f^{(1)}\right]\\ \frac{1}{E_p}p\cdot\partial_x \mathrm{tr}\left[n_j^{(+)\mu}\tau_j f^{(1)}(x,p)\right] &= \mathscr{C}_{\mathrm{pol}}\left[\underline{f^{(0)},\partial_x f^{(0)}}, f^{(1)}\right] \longrightarrow \boxed{\partial_\mu u_\nu,\ \partial_\mu T,\ \partial_\mu \mu_B}\end{aligned}$$

Convenient for simulation !

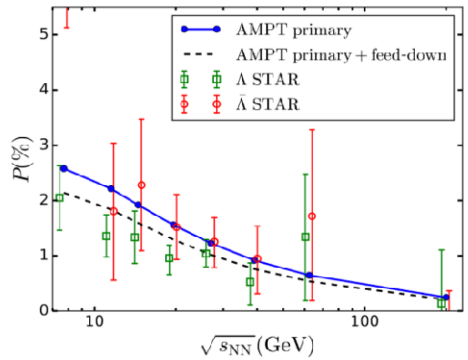
Sheng, Speranza, Rischke, QW, Weickgenannt (2021)

spin transport for massive fermions from WF or KB equation was also studied in: Yang, Hattori, Hidaka (2020); Gao, Liang (2021); Wang, Zhuang (2021)

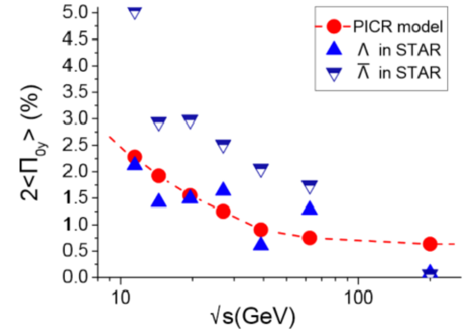
Theoretical model calculations for global polarization of Λ hyperon



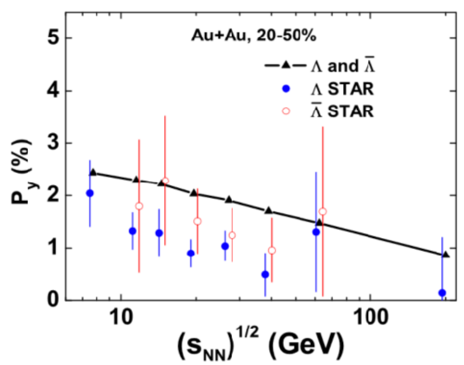
Karpenko, Becattini, EPJC(2017)



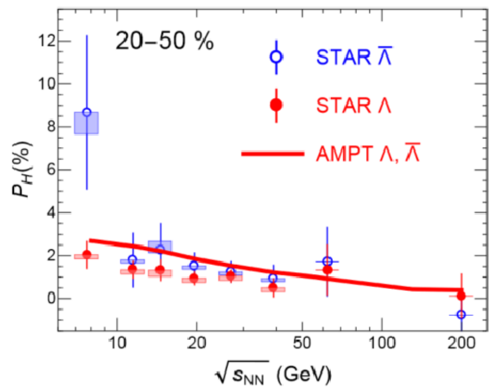
Li, Pang, Wang, Xia PRC(2017)



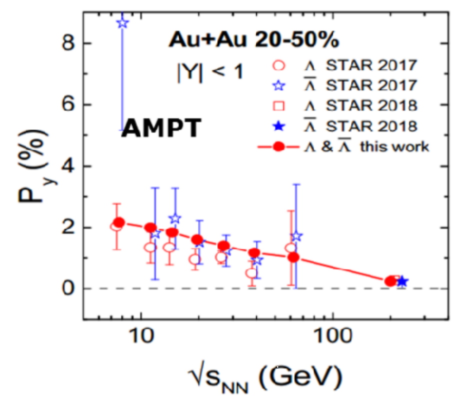
Xie, Wang, Csernai, PRC(2017)



Sun, Ko, PRC(2017)

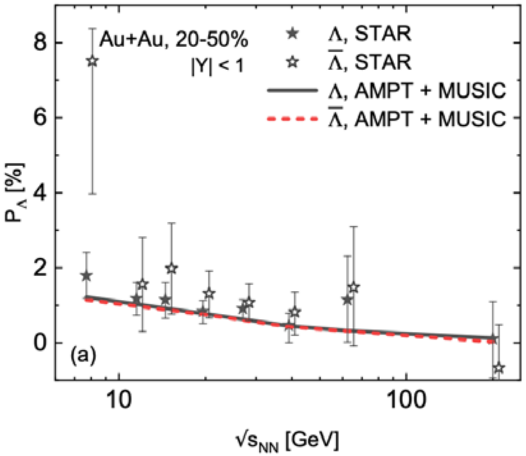


Shi, Li, Liao, PLB(2018)

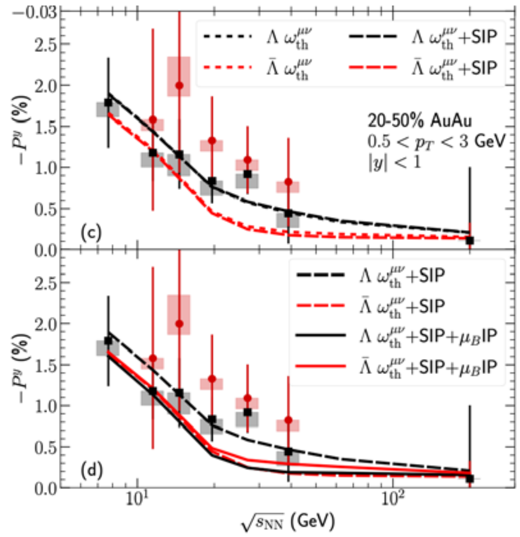


Wei, Deng, Huang, PRC(2019)

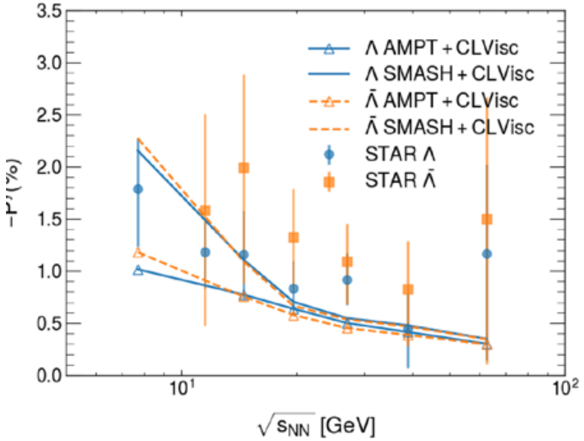
Theoretical model calculations for global polarization of Λ hyperon



Fu, Xu, Huang, Song (2021)



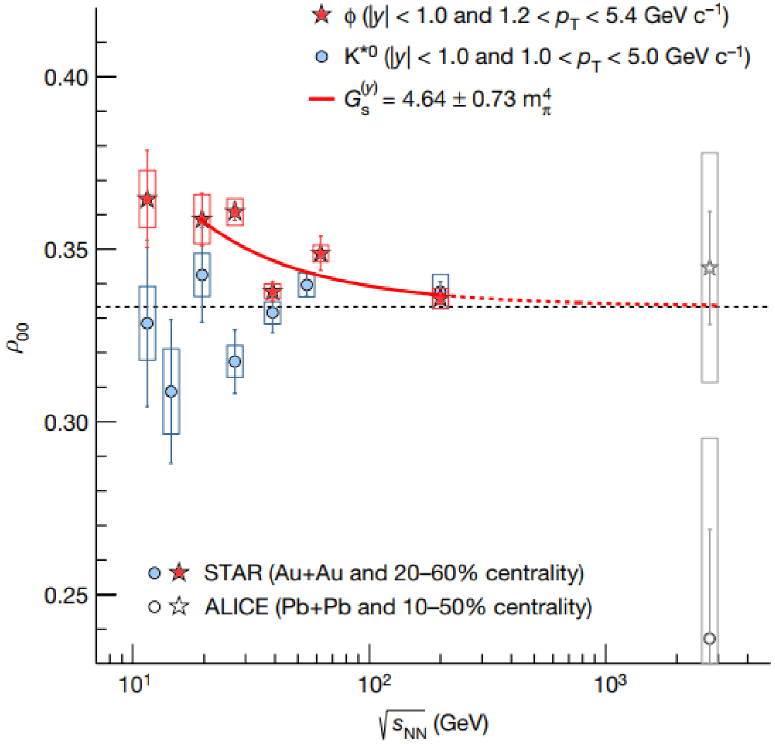
Ryu, Jupic, Shen (2021)



Wu, Yi, Qin, Pu (2022)

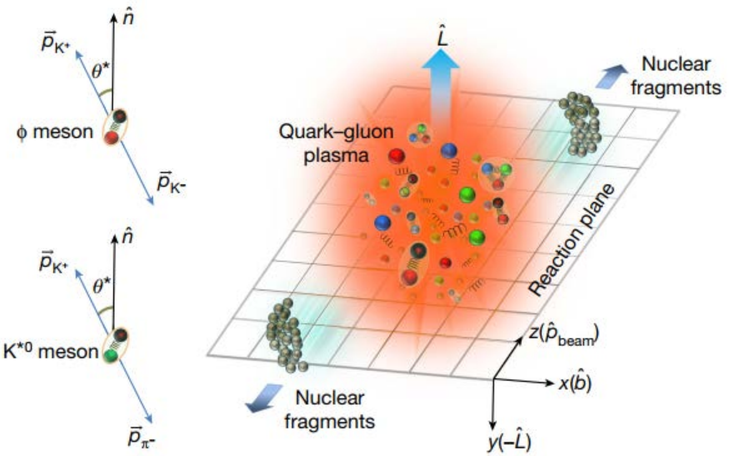
STAR: global spin alignments of vector mesons

STAR Collab., Nature 614, 244 (2023)



NR-QCM with local correlation or fluctuation of strong force fields

Experiments: AiHong Tang's talk



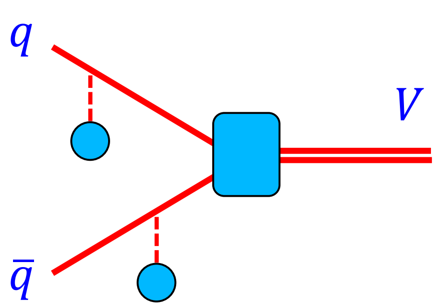
$$\frac{dN}{d\cos\theta} = \frac{3}{4}\left[1 - \rho_{00} + (3\rho_{00} - 1)\cos^2\theta\right]$$

Theory predictions:
Sheng, Oliva, QW (2020);
Sheng, Oliva, et al., (2022)

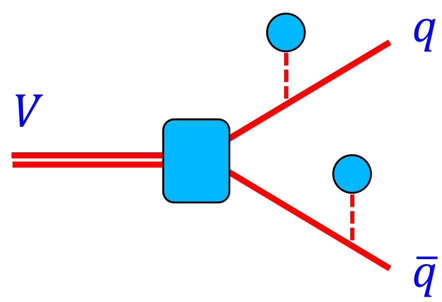
Relativistic Spin Kinetic Equation (RSKE) for vector mesons in quark coalescence model

Sheng, Oliva, et al., 2206.05868, 2205.15689

Review on QKE and SKE based on Wigner functions:
Hidaka, Pu, et al., Prog. Part. Nucl. Phys. 127 (2022) 103989



Quark coalescence to V-meson



V-meson dissociation to quarks

Quark coalescence model:
Greco, Ko, Levai (2003);
Fries, Mueller et al (2003);
Yang, Hwa (2003).

Spin density matrix element for vector mesons

The fusion (coalescence) collision kernel $C^{\mu\nu}_{coal}$ can be evaluated in the rest frame of ϕ meson, which gives ρ^{ϕ}_{00}

$$\rho_{00}(x,\underline{\mathbf{0}}) \approx \frac{1}{3} + C_1\left[\frac{1}{3}\boldsymbol{\omega}'\cdot\boldsymbol{\omega}' - (\boldsymbol{\epsilon}_0\cdot\boldsymbol{\omega}')^2\right] + C_2\left[\frac{1}{3}\boldsymbol{\varepsilon}'\cdot\boldsymbol{\varepsilon}' - (\boldsymbol{\epsilon}_0\cdot\boldsymbol{\varepsilon}')^2\right] - \frac{4g_\phi^2}{m_\phi^2 T_{\mathrm{eff}}^2}C_1\left[\frac{1}{3}\mathbf{B}'_\phi\cdot\mathbf{B}'_\phi - \underline{(\boldsymbol{\epsilon}_0}\cdot\mathbf{B}'_\phi)^2\right] - \frac{4g_\phi^2}{m_\phi^2 T_{\mathrm{eff}}^2}C_2\left[\frac{1}{3}\mathbf{E}'_\phi\cdot\mathbf{E}'_\phi - \underline{(\boldsymbol{\epsilon}_0}\cdot\mathbf{E}'_\phi)^2\right],$$

rest frame of ϕ meson

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

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

All fields with prime are defined in the rest frame of ϕ meson

spin quantization direction

Features: (1) Perfect factorization of x and p dependence; (2) Perfect cancellation for mixing terms (protected by symmetry): all fields appear in squares, i.e. ρ^{ϕ}_{00} measures fluctuations of fields. Surprising results!

Lorentz transformation for ϕ fields

We can express ρ_{00}^{ϕ} in terms of ϕ fields in the lab frame and obtain the dependence on momenta of ϕ mesons through Lorentz transformation

$$\mathbf{B}'_{\phi} = \gamma \mathbf{B}_{\phi} - \gamma \mathbf{v} \times \mathbf{E}_{\phi} + (1-\gamma)\frac{\mathbf{v}\cdot\mathbf{B}_{\phi}}{v^2}\mathbf{v},$$

$$\mathbf{E}'_{\phi} = \gamma \mathbf{E}_{\phi} + \gamma \mathbf{v} \times \mathbf{B}_{\phi} + (1-\gamma)\frac{\mathbf{v}\cdot\mathbf{E}_{\phi}}{v^2}\mathbf{v},$$

where $\gamma = E_{\mathbf{k}}^{\phi}/m_{\phi}$ **and** $\mathbf{v} = \mathbf{k}/E_{\mathbf{k}}^{\phi}$

Then we obtain factorization form of $\left\langle \rho_{00}^{\phi} \right\rangle$ in terms of lab-frame fields

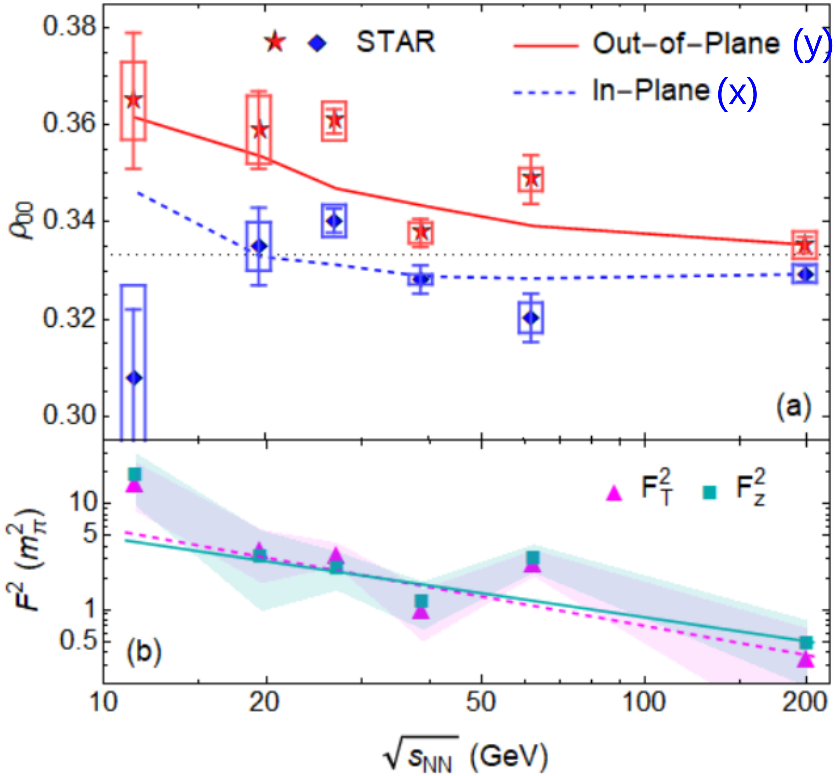
$$\left\langle \overline{\rho}_{00}^{\phi}(x,\mathbf{p}) \right\rangle_{x,\mathbf{p}} \approx \frac{1}{3} + \frac{1}{3}\sum_{i=1,2,3} \langle I_{B,i}(\mathbf{p})\rangle \frac{1}{m_{\phi}^2}\left[\langle \boldsymbol{\omega}_i^2\rangle - \frac{4g_{\phi}^2}{m_{\phi}^2 T_{\text{eff}}^2}\left\langle (\mathbf{B}_i^{\phi})^2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

space-time average

momentum average

three basis directions in lab frame

STAR data on ρ_{00}^{y} and ρ_{00}^{x}

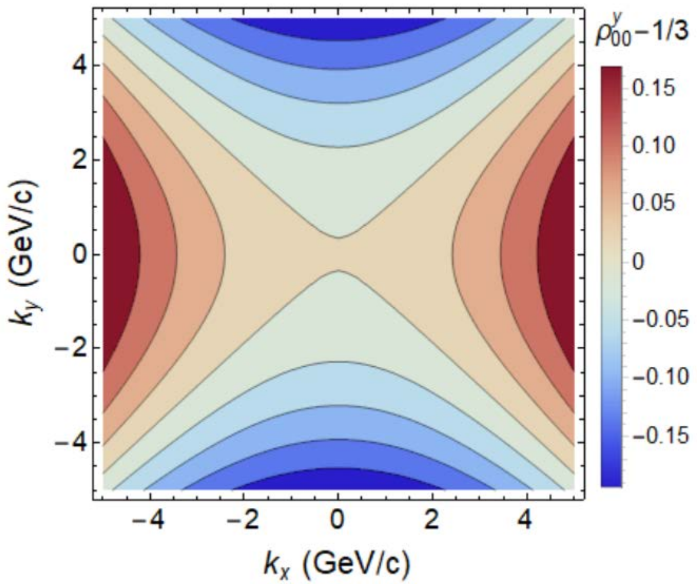


$$F_T^2 \equiv \langle E_{x,y}^2 \rangle = \langle B_{x,y}^2 \rangle, \quad F_z^2 \equiv \langle E_z^2 \rangle = \langle B_z^2 \rangle$$

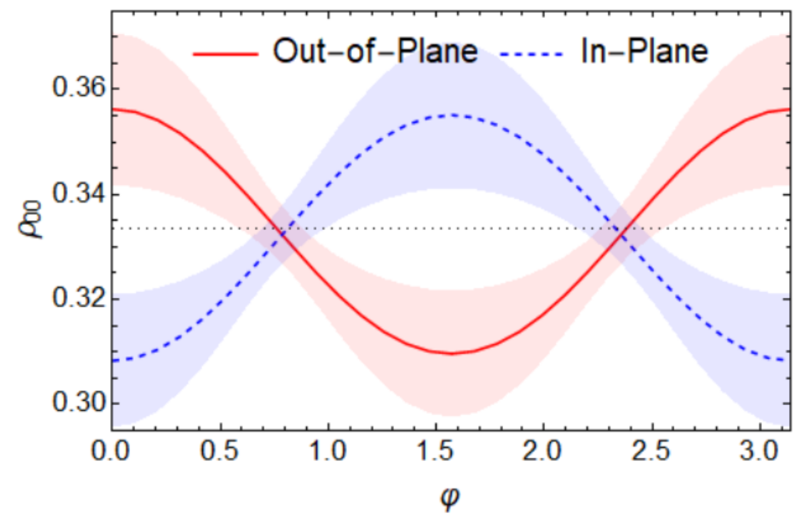
(a) The STAR's data on phi meson's ρ_{00}^{y} (out-of-plane, red stars) and ρ_{00}^{x} (in-plane, blue diamonds) in 0-80% Au+Au collisions as functions of collision energies. The red-solid line and blue-dashed line are calculated with values of F_T^2 and F_z^2 from fitted curves in (b).

(b) Values of F_T^2 (magenta triangles) and F_z^2 (cyan squares) with shaded error bands extracted from the STAR's data on the phi meson's ρ_{00}^{y} and ρ_{00}^{x} in (c). The magenta-dashed line (cyan-solid line) is a fit to the extracted F_T^2 (F_z^2) as a function of $\sqrt{s_{NN}}$ (see the text).

Prediction on ρ_{00}^{y} and ρ_{00}^{x}

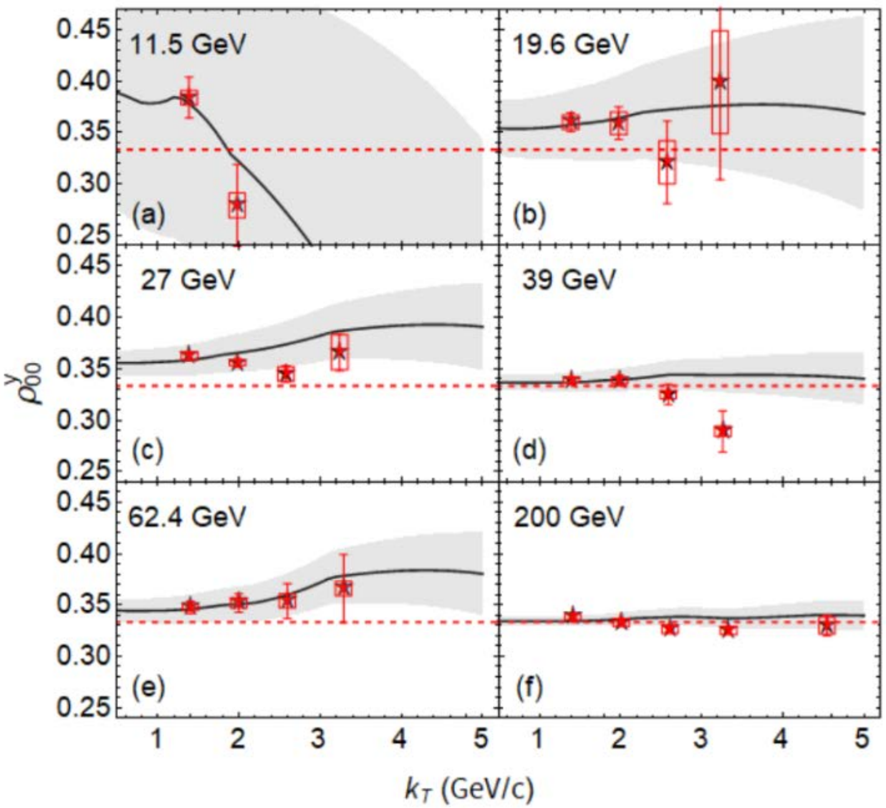


Contour plot of $\rho_{00}^{y} - 1/3$ for ϕ mesons as a function of k_x and k_y in 0-80% Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV.



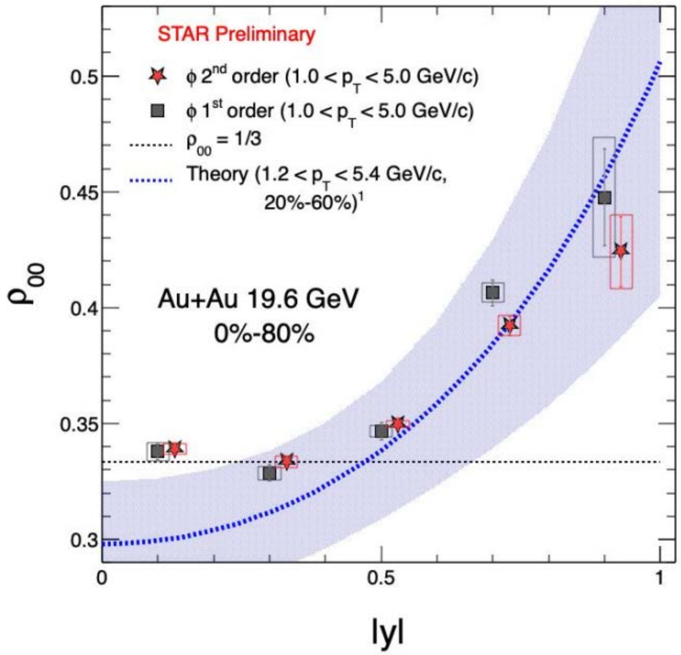
Calculated ρ_{00}^{y} (out-of-plane) and ρ_{00}^{x} (in plane) of ϕ mesons as functions of the azimuthal angle φ in 0-80% Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Shaded error bands are from the extracted parameters F_T^2 and F_z^2.

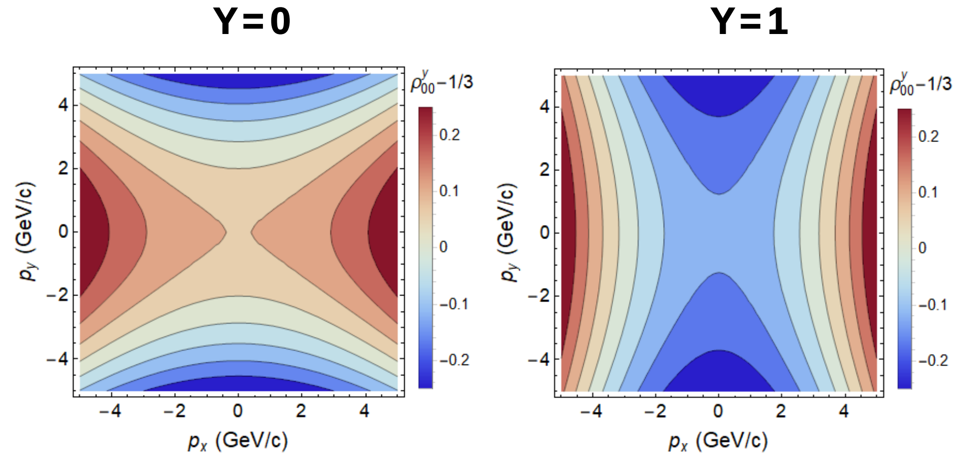
Transverse momentum spectra of ρ_{00}^{y}



Calculated ρ_{00}^{y} (solid line) of ϕ mesons as functions of transverse momenta in 0-80% Au+Au collisions at different colliding energies in comparison with STAR data. Shaded error bands are from the extracted parameters F_T^2 and F_z^2 .

STAR's new measurements and our prediction on rapidity dependence of ρ^{y}_{00}





$$\langle\rho^{y}_{00}\rangle - \frac{1}{3} \propto \frac{1}{2}p_T^2\left[3\cos(2\varphi)-1\right] + \sqrt{m_\phi^2+p_T^2}\,\sinh^2 Y$$

Sheng, Pu, QW, 2308.14038

Vector fields in Chiral quark model

Nuclear Physics B234 (1984) 189–212

Citations: 2272 (till September 22, 2023)

Fernandez, Valcarce, Straub, Faessler (1993)
Zhang, et al, (1997); Li, Ye, Lu (1997); Zhao, Li, Bennhold (1998)

CHIRAL QUARKS AND THE NON-RELATIVISTIC QUARK MODEL*

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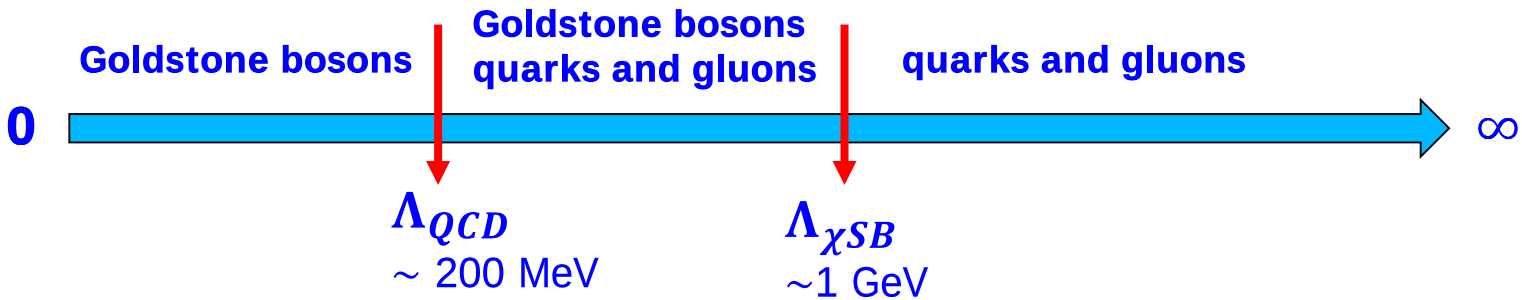
Received 18 July 1983

We study some of the consequences of an effective lagrangian for quarks, gluons and goldstone bosons in the region between the chiral symmetry breaking and confinement scales. This provides an understanding of many of the successes of the non-relativistic quark model. It also suggests a resolution to the puzzle of the hyperon non-leptonic decays.

Vector fields in Chiral quark model

- **Scale for strong interaction in dynamical process**



- **SU(3) Goldstone bosons by 3×3 matrix Σ and ξ,**

$$\Sigma = \exp\left(i\frac{2\chi}{f}\right) = \exp\left(i\frac{\chi}{f}\right)\exp\left(i\frac{\chi}{f}\right) = \xi\xi$$

$$\chi = \frac{1}{\sqrt{2}}\begin{pmatrix} \frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & \pi^+ & K^+ \\ \pi^- & -\frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & K^0 \\ K^- & \overline{K}^0 & -\frac{2}{\sqrt{6}}\eta \end{pmatrix}$$

$f = $ **93 MeV**

Vector field in Chiral quark model

- **Σ and ξ transform under $SU_L(3) \times SU_R(3)$ as**

$$\Sigma \to L\Sigma R^\dagger, \qquad \xi \to L\xi U^\dagger = U\xi R^\dagger$$

- **A set of color and flavor triplet quarks** $\psi = \begin{pmatrix} u \\ d \\ s \end{pmatrix}, \qquad \psi = U\psi$

- **Lagrangian is invariant under $SU_L(3) \times SU_R(3)$ transformation**

$$\begin{aligned} \mathcal{L} &= \overline{\psi}\left[i\gamma_\mu\left(\partial^\mu + igG^\mu\right) + \underline{g_V\gamma_\mu V^\mu}\right]\psi + g_A\overline{\psi}\gamma_\mu V^\mu\psi \\ &+\frac{1}{4}f^2\mathrm{Tr}\left(\partial^\mu\Sigma^\dagger\partial_\mu\Sigma\right) - \frac{1}{2}\mathrm{Tr}F_{\mu\nu}F^{\mu\nu} \end{aligned}$$

3x3 matrix

$$\boxed{V^\mu = \frac{1}{2}\left(\xi^\dagger\partial^\mu\xi + \xi\partial^\mu\xi^\dagger\right)}$$

$$A^\mu = \frac{1}{2}i\left(\xi^\dagger\partial^\mu\xi - \xi\partial^\mu\xi^\dagger\right)$$

Effective vector fields induced by currents Goldstone boson fields

Take-home message

Take-home message

- **P_Λ measures the fields (net mean field), ρ_{00}^{ϕ} measures field squared (field correlation or fluctuation).**
- **The vector field is induced by current of pseudo-Goldstone boson during the hadronization**

Questions for answers in the future

Global polarization:

- **We really need a comprehensive simulation solving the spin Boltzmann equation or spin hydro which includes non-equilibrium effects**

Spin alignment of vector mesons:

- **Any connection with QCD sum rules and QCD vacuum properties? Any connection with quark or gluon condensates (trace anomaly)?**
- **Implication for J/Psi polarization (gluon fields)?**
- **Any connection with effects from glasma fields? (Kuma, Mueller, Yang, 2023)**
- **Other contributions from hydro quantities [Li, Liu (2022); Wagner, Weickgenannt, Speranza (2022)]**