Global and local spin polarization in heavy ion collisions

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Outline

- Introduction
- Theoretical models on particle polarization: [Spin-orbital coupling, Statistical-hydro, Kinetic]
- Experimental measurements of global polarization (recent STAR results)
- Prospect: correlation in Λ polarization as probe to the most vortical fluid
- Summary

Global OAM and Magnetic field in HIC

- **Huge global orbital angular momenta are produced**

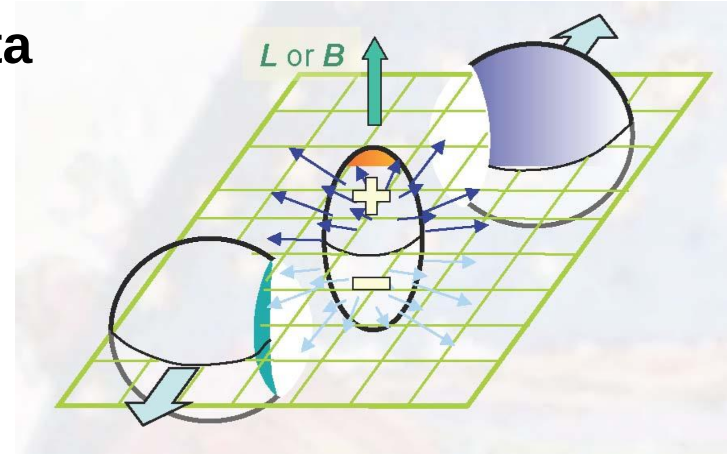
$$L \sim 10^5 \hbar$$

- **Very strong magnetic fields are produced**

$$B \sim m_\pi^2 \sim 10^{18}\ \mathrm{Gauss}$$

- **Can and how does orbital angular momentum be transferred to the matter created?**

- **Any way to measure angular momentum?**



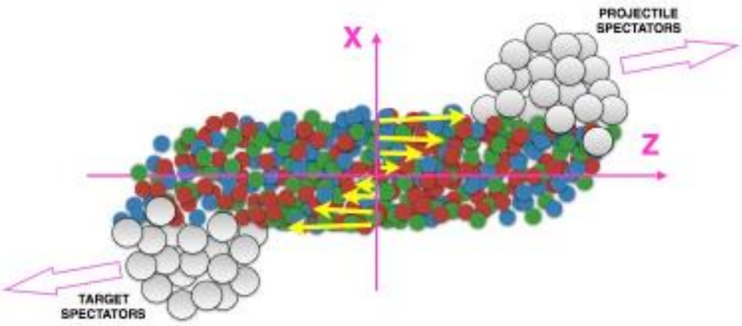


Figure taken from
Becattini et al, 1610.02506

Talks related to ω, B and L

- Parellel talks, Feb.7:
- Alexandru Florin Dobrin, Xu-Guang Huang, Prithwish Tribedy, Shuzhe Shi, Niklas Mueller, Liwen Wen, Isaac Upsal, Iurii Karpenko, Koichi Hattori, Long-gang Pang, Xingyu Guo
- Parellel talks, Feb.8:
- Dmitri Kharzeev, Balthazar Peroutka
- Plenary talks, Feb.9-10:
- Paul Sorensen, Qun Wang, Yuji Hirono

- 16 talks related to effects of vorticity, magnetic field and polarization, which can be classified into two themes

1. Chiral Effects such as CME, CVE, CMW and other relevant topics [theory and experiments] (Sorensen's talk)
2. global polarization and Vortical structure of fluids in HIC (theory and experiments)

Rotation vs Polarization

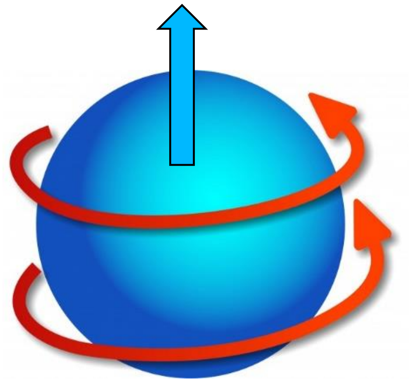
- **Barnett effect: rotation to polarization**

  uncharged object in rotation

  → spontaneous magnetization

  → polarization (spin-orbital coupling)

  [Barnett, Rev.Mod.Phys.7,129(1935)]



- **Einstein-de Haas Effect: polarization to rotation**

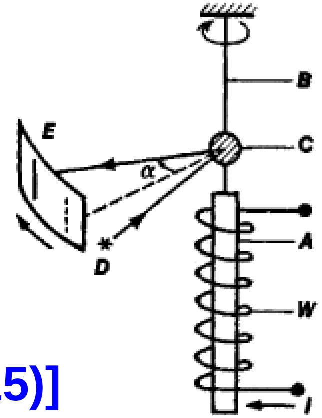
  magnetic field (impulse)

  → polarization of electrons

  → ΔL_electron

  → ΔL_mechanical = - ΔL_electron

[Einstein, de Haas, DPG Verhandlungen 17, 152(1915)]



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

With such correlation between rotation and polarization in materials, we expect the same phenomena in heavy ion collisions. Some early works along this line:

- **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**

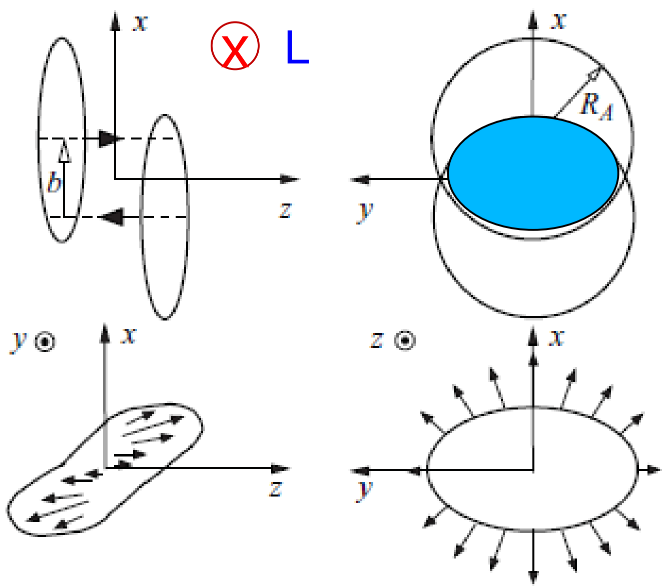
- **Polarization as probe to vorticity in HIC**
- **-- Betz, Gyulassy, Torrieri, PRC 76, 044901(2007) [0708.0035]**

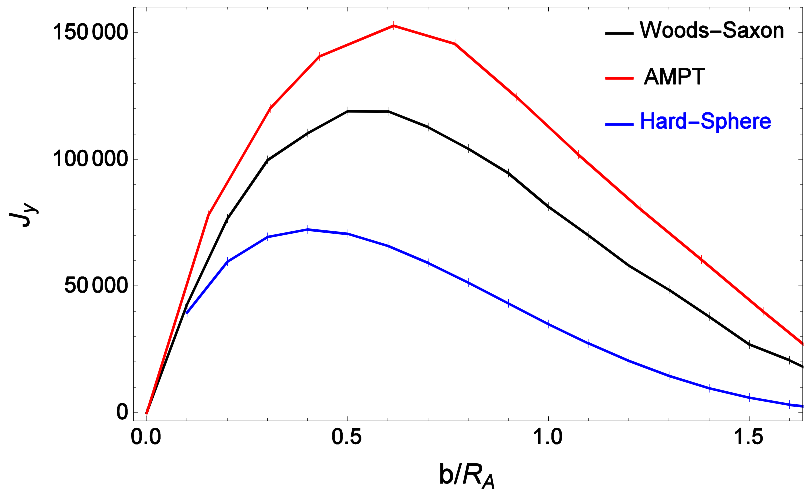
- **Angular momentum conservation in HIC**
- **-- Becattini, Piccinini, Rizzo, PRC 77, 024906 (2008) [0711.1253]**

Spin-orbital coupling model

Global OAM in HIC

- **Non-central collisions produce global orbital angular momentum**

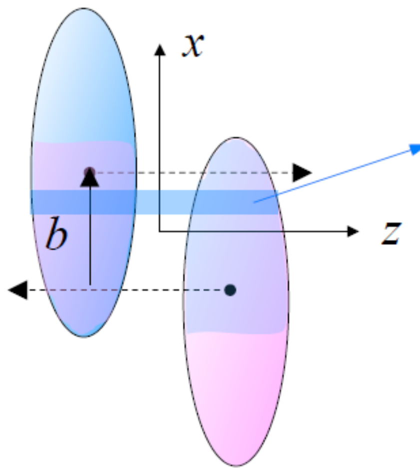




$$L_y = -p_{\text{in}} \int x dx \left(\frac{dN^P_{\text{part}}}{dx} - \frac{dN^T_{\text{part}}}{dx} \right)$$

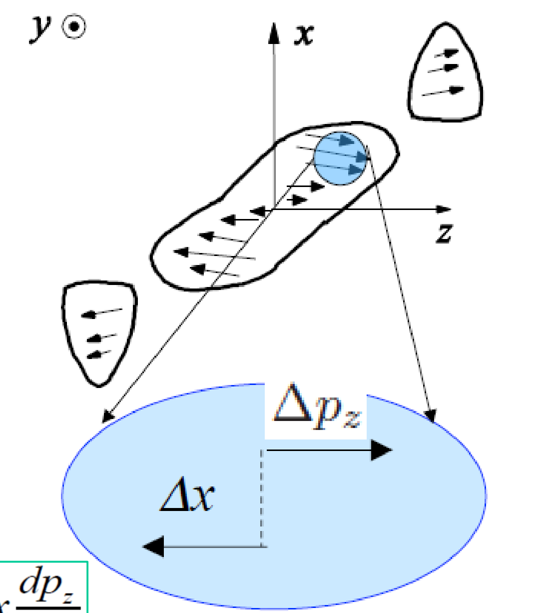
Liang & Wang, PRL 94, 102301(2005); PLB 629, 20(2005); Gao, Chen, Deng, Liang, QW, Wang, PRC 77, 044902(2008); Huang, Huovinen, Wang,PRC 84,054910(2011); Jiang, Lin, Liao, PRC 94,044910(2016); Deng,Huang, PRC 93,064907(2016); many others ……

Global OAM in HIC



$$\frac{dN^{P,T}_{part}}{dx}$$

Number of participant nucleons per unit x in projectile or target



Collective longitudinal momentum per produced parton

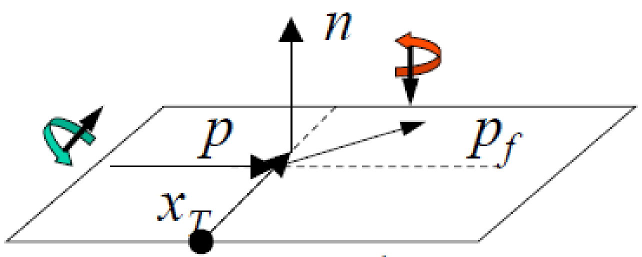
$$p_z(x,b) = \frac{\sqrt{s}}{2c(s)} \frac{\frac{dN^P_{\rm part}}{dx} - \frac{dN^T_{\rm part}}{dx}}{\frac{dN^P_{\rm part}}{dx} + \frac{dN^T_{\rm part}}{dx}}$$

$$\boxed{\Delta p_z = \Delta x \frac{dp_z}{dx}}$$

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

Liang & Wang (2005); Gao, et al. (2008); Betz, Gyulassy, Torrieri (2007); Becattini, Piccinini, Rizzo (2008); Jiang, Lin, Liao (2016); Deng, Huang (2016); many others ……

Quark scatterings in potential



- Quark scatterings at small angle in static potential with screening mass
- Unpolarized and polarized cross sections

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

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

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

screening mass

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

Polarization vector OAM Spin-Orbital coupling

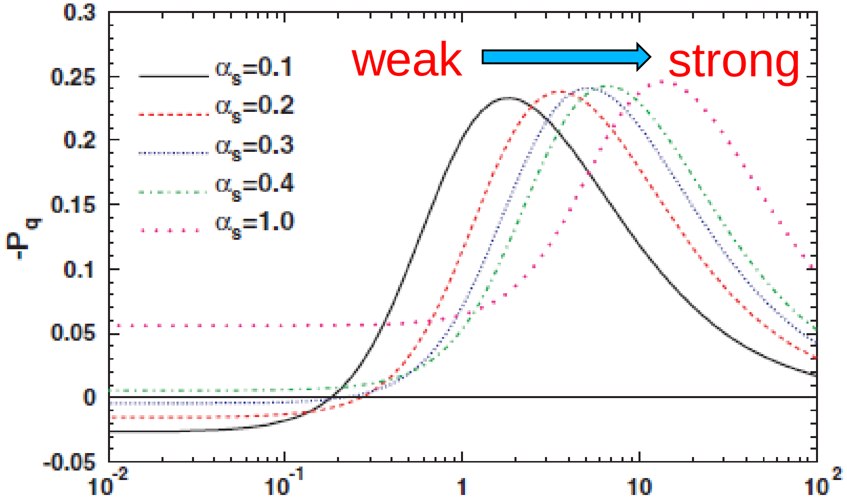
- Polarization for small angle scattering and $m_q \gg p, \mu$

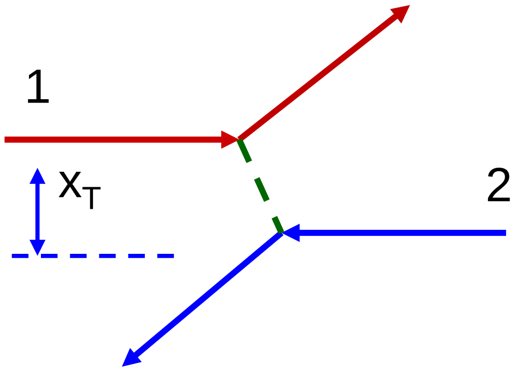
$$P_q \approx -\pi\frac{\mu p}{4m_q^2} \sim -\frac{\Delta E_{LS}}{E_0}$$

Liang, Wang, PRL 94, 102301(2005)

Quark-quark scattering

- **Beyond small angle approximation with HTL gluon progagator**





$\sqrt{\hat{s}}/T$ → **Local OAM or vorticity** → $L \sim \langle x \rangle p \sim \frac{p}{\mu} \sim \beta\omega$

Quark polarization as functions of the square root of parton-parton scattering energy over T [≈ local OAM or vorticity] which increases with α_S

Liang, Wang, PRL 94, 102301(2005); PLB 629, 20(2005);
Gao, Chen, Deng, Liang, QW, Wang, PRC 77, 044902(2008)

Statistical-hydro model

Rotation effect in non-inertial frame

- A particle of mass m moves in a non-inertial rotating frame in potential U(r)

speed in r-frame

angular velocity of r-frame

$$L = \frac{1}{2}m(\mathbf{v}_r + \boldsymbol{\omega}\times\mathbf{r})^2 - U(r)$$

assume no relative velocity between inertial and non-inertial rotating frame

$$\mathbf{p} = \frac{\partial L}{\partial \mathbf{v}_r} = m(\mathbf{v}_r + \boldsymbol{\omega}\times\mathbf{r})$$

canonical momentum

$$H = \mathbf{p}\cdot\mathbf{v}_r - L = H_0 - \boldsymbol{\omega}\cdot\mathbf{J}$$

angular momentum

Hamiltonian in inertial frame

$$H_0 = \frac{1}{2m}\mathbf{p}^2 + U(r)$$

$$\hat{\rho}_{\mathrm{GE}} = \frac{1}{Z}\exp\left(-\beta\hat{H}_0 + \beta\boldsymbol{\omega}\cdot\mathbf{J} + \beta\mu\hat{Q}\right)$$

Global equilibrium density operator

Covariant form of quantum statistical physics (local equilibrium)

- To obtain covariant form in local equilibrium, we use principle of maximal entropy with conservation of total energy-momentum and particle number,

$$\boxed{d\Sigma_\mu = d\Sigma n_\mu}$$

space-like hyper-surface
n^μ is time-like vector

$$\hat{\rho}_{\mathrm{LE}} = \frac{1}{Z}\exp\left[\int_\Sigma d\Sigma_\mu \left(-\hat{T}^{\mu\nu}\beta_\nu + \zeta \hat{j}^\mu\right)\right]$$

Zubarev (1979);
Weert (1982);
Becattini et al. (2012-2015);
Hayat, et al. (2015);
Floerchinger (2016)

- Given n^μ, one can determine β^μ and ζ by

$$n_\mu \left\langle \hat{T}^{\mu\nu}(x)\right\rangle_{\mathrm{LE}}(\beta^\alpha,\zeta) = n_\mu T^{\mu\nu}(x), \quad n_\mu \left\langle \hat{j}^\mu(x)\right\rangle_{\mathrm{LE}}(\beta^\alpha,\zeta) = n_\mu j^\mu(x)$$

Energy condition

Particle number condition

- where statistical average is defined by $\boxed{\left\langle \hat{O}(x)\right\rangle_{\mathrm{TE}} = \mathrm{Tr}\left[\hat{\rho}_{\mathrm{TE}}\hat{O}(x)\right]}$

Global equilibrium and stationary conditions

- **Stationary conditions**

Becattini (2012); Becattini, Bucciantini, Grossi, Tinti (2015) Becattini, Grossi (2015)

$$\partial_\mu \beta_\nu + \partial_\nu \beta_\mu = 0, \qquad \partial_\mu \zeta = 0$$

Killing equation

Thermal vorticity tensor

Killing vector solution ⇒ $\beta^\mu = \underline{b^\mu} + \underline{\varpi^{\mu\nu}} x_\nu$

$$\varpi^{\mu\nu} = -\frac{1}{2}(\partial^\mu \beta^\nu - \partial^\nu \beta^\mu)$$

$$b^\mu = \frac{1}{T} u^\mu$$

Total particle number

Density operator at global equilibrium

$$\hat{\rho}_{\mathrm{GE}} = \frac{1}{Z} \exp\left[-\beta u_\nu \underline{\hat{P}^\nu} + \frac{1}{2} \underline{\hat{J}^{\nu\rho}} \varpi_{\nu\rho} + \zeta \underline{\hat{Q}} \right]$$

4-momentum vector operator

Total angular momentum tensor (OAM+spin)

Spin and polarization

- **Spin (Pauli-Lubanski) pseudo-vector**

$$\hat{S}^\mu = -\frac{1}{2m}\epsilon^{\mu\nu\rho\sigma}\hat{J}^{\mathrm{S}}_{\nu\rho}\hat{P}_\sigma$$
$$S^\mu = \mathrm{Tr}(\hat{\rho}_{\mathrm{GE}}\hat{S}^\mu)$$
$$\Pi^\mu = \frac{1}{S}S^\mu$$

$$\boxed{\begin{array}{l}[\hat{S}^\mu,\hat{P}^\nu]=0, \quad \hat{S}^\mu\hat{P}_\mu=0\\ \hat{S}^\mu\hat{S}_\mu=-S(S+1)\end{array}}$$

properties of spin vector

phase space spin density for spin ½-fermions

$$\boxed{S^\mu(x,p) = -\frac{1}{8m}[1-n_F(x,p)]\epsilon^{\mu\rho\sigma\tau}p_\tau\varpi_{\rho\sigma}}$$

particle number at freezeout

$$\boxed{N = \int\frac{d^3p}{E_p}\int d\Sigma_\lambda p^\lambda n_F(x,p)}$$

spin at freezeout hypersurface

$$\boxed{S^\mu = \frac{1}{N}\int\frac{d^3p}{E_p}\int d\Sigma_\lambda p^\lambda n_F(x,p)S^\mu(x,p)}$$

Becattini, et al., 1610.02506;
Karpenko, Becattini, 1610.04717

Kinetic model with Wigner function

- **To describe polarization for massive spin ½ fermions, we have to explicitly know their momentum p, therefore we need to know information in phase space (t,x,p), that's why we use kinetic approach**
- **Classical kinetic approach: f(t,x,p)**
- **Quantum kinetic approach: W(t,x,p)**

Wigner functions for fermions in background EM field

- **The Wigner function for spin 1/2 fermions in constant EM field satisfies EOM, which can be solved perturbatively in $(F_{\mu\nu})^i$ and $(\partial_x)^i$.**
- **Wigner function can be decomposed in 16 generators of Clifford algebra**

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

4x4 matrix | scalar | p-scalar | vector | axial-vector | tensor

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

Heinz, Phys.Rev.Lett. 51, 351 (1983);
Vasak, Gyulassy and Elze, Annals Phys. 173, 462 (1987);
Elze, Gyulassy and Vasak, Nucl. Phys. B 276, 706(1986).

Spin tensor component

- **Spin tensor component of Wigner function**

Fang, Pang, QW, Wang, PRC 94,024904(2016); QW, et al, work in progress

$$\mathscr{M}^{\alpha\beta}(x,p) \equiv \frac{1}{2}\mathrm{Tr}\left[\gamma_0\sigma^{\alpha\beta}W(x,p)\right] = \frac{1}{2}\left[-\epsilon^{0\alpha\beta\rho}\mathscr{A}_\rho + ig^{\alpha 0}\mathscr{V}^\beta - ig^{\beta 0}\mathscr{V}^\alpha\right]$$

- **For αβ=ij (space indices)**

$$\mathscr{M}^{ij}(x,p) = \frac{1}{2}\epsilon^{ijk}\mathscr{A}^k(x,p) \Longrightarrow$$

$$A^i(x) = \psi^\dagger(x)\Sigma_i\psi(x) = \int d^4p\mathscr{A}^i(x,p)$$

Pauli matrices

- **We can regard axial vector as spin vector (up to ½)**

$$\Pi^\mu(x) \sim \frac{1}{2}\int d^4p\mathscr{A}^\mu(x,p)$$

Non-relativistic limit

$$\sim \frac{1}{2}\int d^4p\frac{|p_0|}{m}\mathscr{A}^\mu(x,p)$$

To match Pauli-Lubanski pseudo-vector

Axial vector component of Wigner function for massive fermions

- **Axial vector component: zero (i=0) and first (i=1) order in $(F_{\mu\nu})^i$ and $(\partial_x)^i$:**

$$\begin{aligned}
\mathscr{A}^{\mu} &= \mathrm{Tr}[\gamma^{\mu}\gamma^{5}W] \\
\mathscr{A}^{\mu}_{(0)}(x,p) &= m\left[\theta(p_0)n^{\mu}(\mathbf{p},\mathbf{n}) - \theta(-p_0)n^{\mu}(-\mathbf{p},-\mathbf{n})\right]\delta(p^2-m^2)A \\
\mathscr{A}^{\alpha}_{(1)}(x,p) &= -\frac{1}{2}\hbar\beta\tilde{\Omega}^{\alpha\sigma}p_{\sigma}\frac{dV}{d(\beta p_0)}\delta(p^2-m^2) - Q\hbar\tilde{F}^{\alpha\lambda}p_{\lambda}V\frac{\delta(p^2-m^2)}{p^2-m^2}
\end{aligned}$$

where A and V are related to distribution functions

$$\tilde{F}^{\alpha\lambda} = \frac{1}{2}\epsilon^{\alpha\lambda\rho\sigma}F_{\rho\sigma}$$

$$\tilde{\Omega}^{\alpha\lambda} = \frac{1}{2}\epsilon^{\alpha\lambda\rho\sigma}\Omega_{\rho\sigma}$$

$$\Omega_{\rho\sigma} = \frac{1}{2}(\partial_{\rho}u_{\sigma} - \partial_{\sigma}u_{\rho})$$

- **Spin (pseudo-)vector in Lab frame**

$$\underbrace{n^{\mu}(\mathbf{p},\mathbf{n})}_{\text{Spin in Lab frame}} = \underbrace{\Lambda^{\mu}_{\ \nu}(-\mathbf{v}_p)}_{\text{Lorentz boost from cms to Lab frame}}\underbrace{n^{\nu}(0,\mathbf{n})}_{\text{Spin in cms frame}} = \left(\frac{\mathbf{n}\cdot\mathbf{p}}{m}, \mathbf{n} + \frac{(\mathbf{n}\cdot\mathbf{p})\mathbf{p}}{m(m+E_p)}\right)$$

Spin in Lab frame

Lorentz boost from cms to Lab frame

Spin in cms frame

Fang, Pang, QW, Wang, PRC 94,024904(2016);
Fang, Pang, QW, Wang, PRD 95, 014032(2017)

Polarization (spin) vector

- **Polarization at zeroth order is vanishing if we assume that the chemical potential for spin-up and spin-down fermions are equal.**
- **Polarization vector at the first order**

Fang, Pang, QW, Wang, PRC(2016);
Aristova, Frenklakh, Gorsky, Kharzeev, JHEP(2016);
QW, et al, work in progress

$$\Pi^{\alpha}_{(1)} \approx \frac{1}{2m}\hbar\beta\int\frac{d^3p}{(2\pi)^3}\left\{[E_p\omega^{\alpha}+QB^{\alpha}]\boxed{\frac{e^{\beta(E_p-\mu)}}{[e^{\beta(E_p-\mu)}+1]^2}} + [E_p\omega^{\alpha}-QB^{\alpha}]\boxed{\frac{e^{\beta(E_p+\mu)}}{[e^{\beta(E_p+\mu)}+1]^2}}\right\}$$

susceptiblility

+/- $\rightarrow$ particle/antiparticle

- **Polarization at freezeout**

$$E_p\frac{d\Pi^{\alpha}(p)}{d^3p} \approx \frac{\hbar}{2m}\beta\int d\Sigma_{\lambda}p^{\lambda}\left(\tilde{\Omega}^{\alpha\sigma}p_{\sigma}\pm Q\tilde{F}^{\alpha\sigma}u_{\sigma}\right)\underline{f^{\pm}_{\mathrm{FD}}(x,p)\left[1-f^{\pm}_{\mathrm{FD}}(x,p)\right]}$$

vorticity **magnetic field** **susceptiblility**

Experimental measurements of global polarization by Λ's weak decay

- **Related talks:**
- **Isaac Upsal's talk on Feb.7, Global polarization of Lambda hyperons in Au+Au Collisions at RHIC BES**
- **Iurii Karpenko's talk on Feb.7, Vorticity in the QGP liquid and Lambda polarization at the RHIC Beam Energy Scan**

Polarization of Λ hyperon

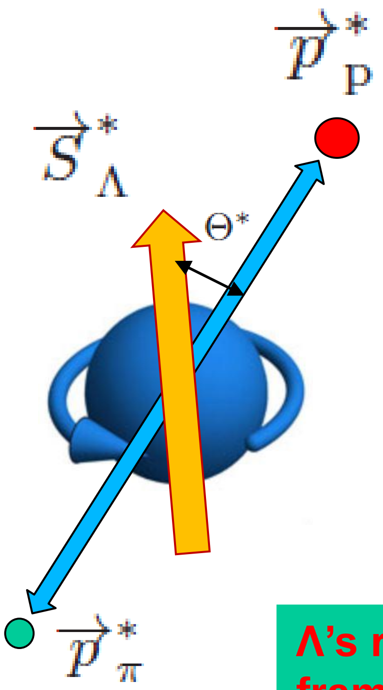
- Λ is '**self-analyzing**' in weak decay $\Lambda \rightarrow \mathrm{p} + \pi^-$ which breaks parity (proton emission preferentially along Λ spin in Λ's rest frame)

$$\frac{d\sigma}{d\Omega^*} = \frac{1}{4\pi}\left(1 + \alpha_H \vec{\Pi}_\Lambda \cdot \hat{\mathrm{p}}^*_{\mathrm{p}}\right)$$

$$= \frac{1}{4\pi}\left(1 + \alpha_H \Pi_\Lambda \cos\Theta^*\right)$$

Decay constant

Polarization vector $\vec{\Pi}_\Lambda = \Pi_\Lambda \hat{\mathrm{S}}^*_\Lambda, \qquad (\Pi_\Lambda \in [0,1])$



Λ's rest frame

- Λ polarization can be determined by event average of proton momentum direction in Λ's rest frame

$$\Pi_\Lambda = \frac{3}{\alpha_H}\langle\cos\Theta^*\rangle_{\mathrm{ev}}$$

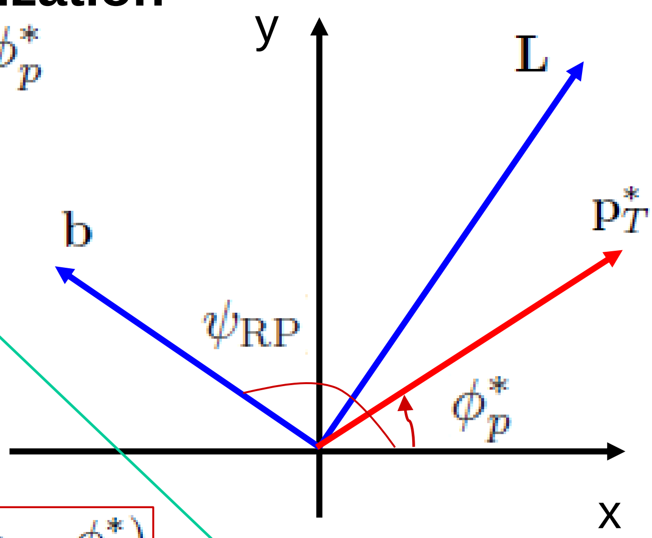
Measurement of Λ polarization

- **If $\vec{\Pi}_\Lambda \parallel \mathrm{L}$, then $\Theta^* = \theta^* = \hat{\mathrm{p}}^*_\mathrm{p} \cdot \hat{\mathrm{L}}$, Λ polarization can be measured in a simpler way by ϕ^*_p**

$$\frac{dN}{d\phi^*_p} = \int_0^\pi d\theta^*_p \sin\theta^*_p \frac{dN}{d\Omega^*}(\cos\theta^*)$$
$$= \frac{1}{2\pi} + \frac{1}{8}\alpha_H \Pi_\Lambda \sin(\psi_\mathrm{RP} - \phi^*_p)$$

$$\cos\theta^* = \sin\theta^*_p \sin(\psi_\mathrm{RP} - \phi^*_p)$$

$$\Pi_\Lambda = \frac{8}{\pi\alpha_H}\left\langle \sin(\psi_\mathrm{RP} - \phi^*_p)\right\rangle_\mathrm{ev}$$



$$\hat{\mathrm{p}}^*_\mathrm{p} = (\theta^*_\mathrm{p}, \phi^*_\mathrm{p})$$

STAR, PRC 76,024915 (2007)
(Erratum for wrong sign)

Corrections for event plane

Reaction plane can be estimated by event plane → needs corrections by reaction plane resolution

Reaction plane resolution from direct flow

$$R_{\mathrm{EP}}^{(1)} = \left\langle \cos(\psi_{\mathrm{RP}} - \psi_{\mathrm{EP}}^{(1)}) \right\rangle$$

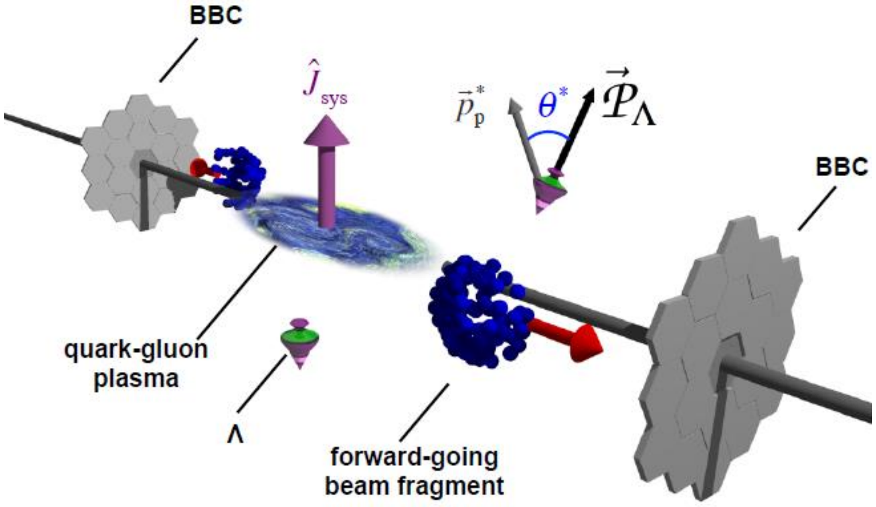
Azimuthal angle of event plane determined by direct flow

$$\Pi_\Lambda = \frac{8}{\pi \alpha_H} \frac{1}{R_{\mathrm{EP}}^{(1)}} \left\langle \sin(\phi_p^* - \psi_{\mathrm{EP}}^{(1)}) \right\rangle_{\mathrm{ev}}$$

Azimuthal angle of daughter proton in Λ rest frame

Decay constant

$$\alpha_\Lambda = -\alpha_{\bar{\Lambda}} = 0.642 \pm 0.013$$



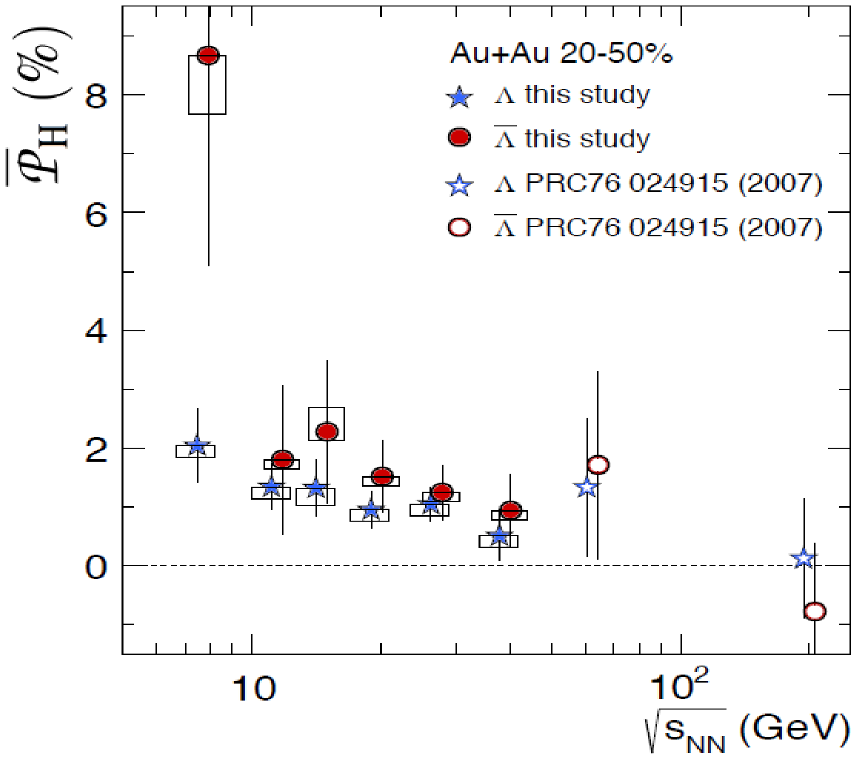
STAR, PRC 76,024915 (2007); 1701.06657

STAR data for Λ polarization

- At each energy, a positive polarization for Λ and $\overline{\Lambda}$ at 1.1-3.6σ level. The polarizations decrease with energies. On average over all data,

$$\mathscr{P}_{\Lambda} = (1.08 \pm 0.15)\%$$
$$\mathscr{P}_{\bar{\Lambda}} = (1.38 \pm 0.30)\%$$

- Systematic uncertainties are smaller than statistical ones and are mainly from estimated combinatoric background of proton-pion pairs.
- Other small systematic uncertainties in the overall scale: a) Λ decay parameter α_H (2%); b) the reaction-plane resolution (2%); c) detector efficiency corrections (3.5%)
- The data contain both primary and those feed-down contributions from heavier particles. The effect of feed-down is about 20% difference between the polarization of primary and all hyperons.



STAR collab., 1701.06657

Global polarization Λ hyperons

- **STAR data at low energies**

  $P \approx$ 1-8% from 7.7 to 62.4 GeV

  $\Delta P(\bar{\Lambda} - \Lambda) \approx$ 0.03% - 0.2%

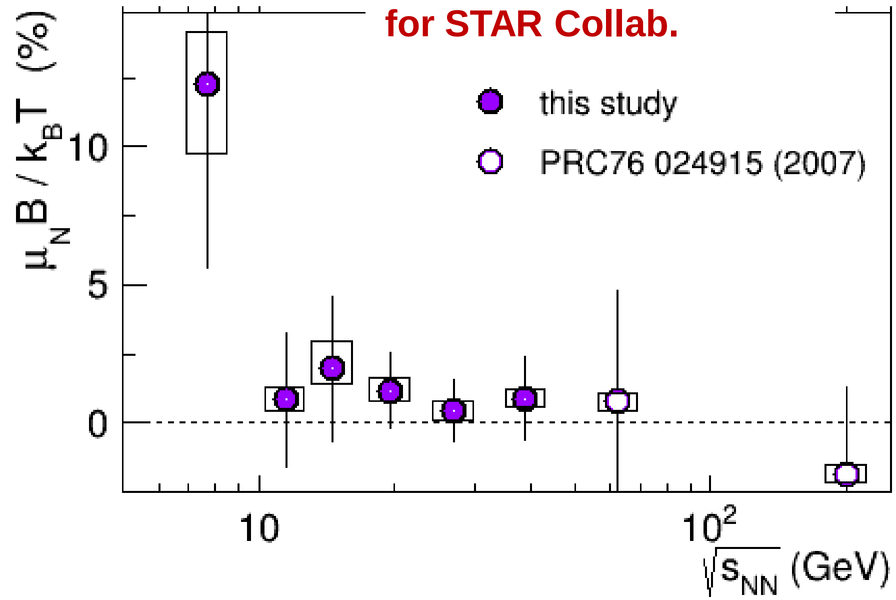
- **P_Λ is anti-parallel to B due to negative magnetic moment**
- **Magnetic field that leads to**

$$\Delta P \sim \frac{1}{2}\beta\frac{B^\alpha}{m_\Lambda} \times \sum_{e=\pm} \boxed{\frac{\int d^3p f_{\mathrm{FD}}^e(1-f_{\mathrm{FD}}^e)}{\int d^3p f_{\mathrm{FD}}^e}} \quad \approx O(1)$$

$$\sim \beta\frac{B^\alpha}{m_\Lambda} \Longrightarrow B \sim T m_\Lambda \Delta P \sim \boxed{(0.1 \sim 0.01)m_\pi^2}$$

too large for low energy HIC in freezeout scenario.

Coutesy of Isaac Upsal for STAR Collab.



[Pang et al. 2016; Becattini et al. 2016 Shuryak 2016]

- **From vorticity, there is more Pauli blocking effect for fermions than anti-fermions in lower energy HIC**

Largest vorticity ever observed

- **The fluid vorticity may be estimated from the data using the hydrodynamic relation with a systematic uncertainty of a factor of 2, mostly due to uncertainties in the temperature**

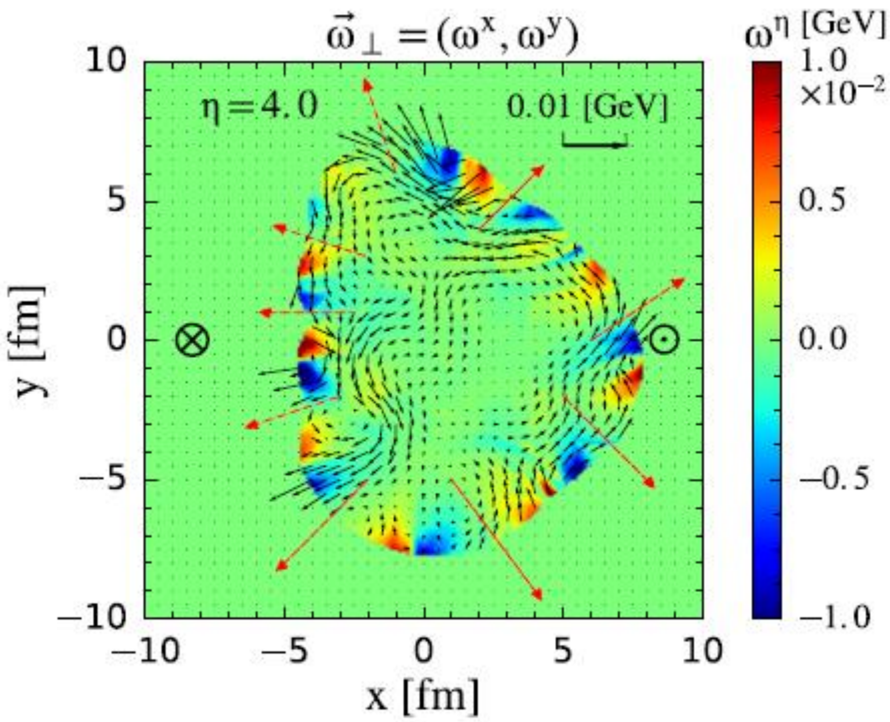
$$\boxed{\begin{aligned}\omega &\sim k_B T(\mathscr{P}_\Lambda + \mathscr{P}_{\bar{\Lambda}})/\hbar \\ &\approx (9 \pm 1) \times 10^{21}\ \mathrm{s}^{-1}\end{aligned}}$$

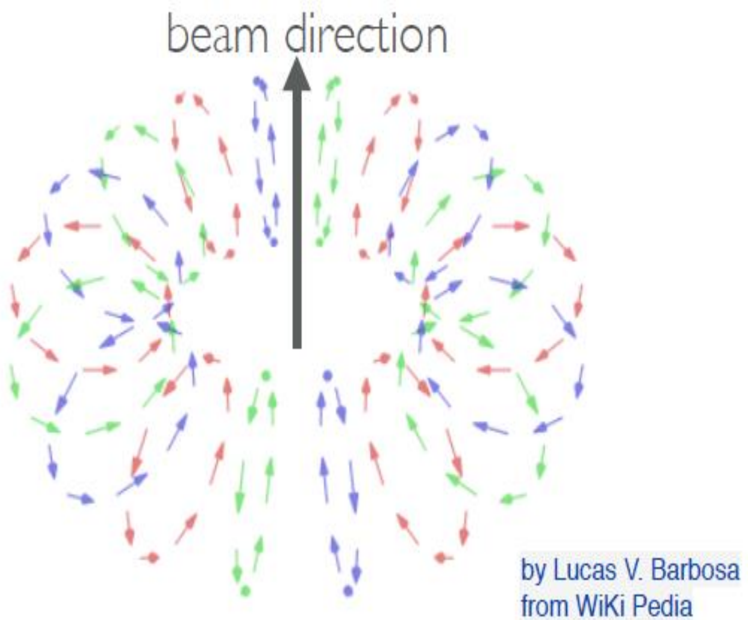
STAR Collab., 1701.06657;
Becattini et al., 1610.02506;
Pang et al., PRC 94, 024904(2016);
Aristova, Frenklakh, Gorsky, Kharzeev, JHEP(2016);

- **This far surpasses the vorticity of all other known fluids**

solar subsurface flow	$10^{-7}\ \mathrm{s}^{-1}$
large scale terrestrial atmospheric patterns	$10^{-7} - 10^{-5}\ \mathrm{s}^{-1}$
Great Red Spot of Jupiter	$10^{-4}\ \mathrm{s}^{-1}$
supercell tornado cores	$10^{-1}\ \mathrm{s}^{-1}$
rotating, heated soap bubbles	$100\ \mathrm{s}^{-1}$
turbulent flow in bulk superfluid He-II	$150\ \mathrm{s}^{-1}$
superfluid nanodroplets	$10^{7}\ \mathrm{s}^{-1}$

Prospect: Turbulence and vortices in high energy HIC



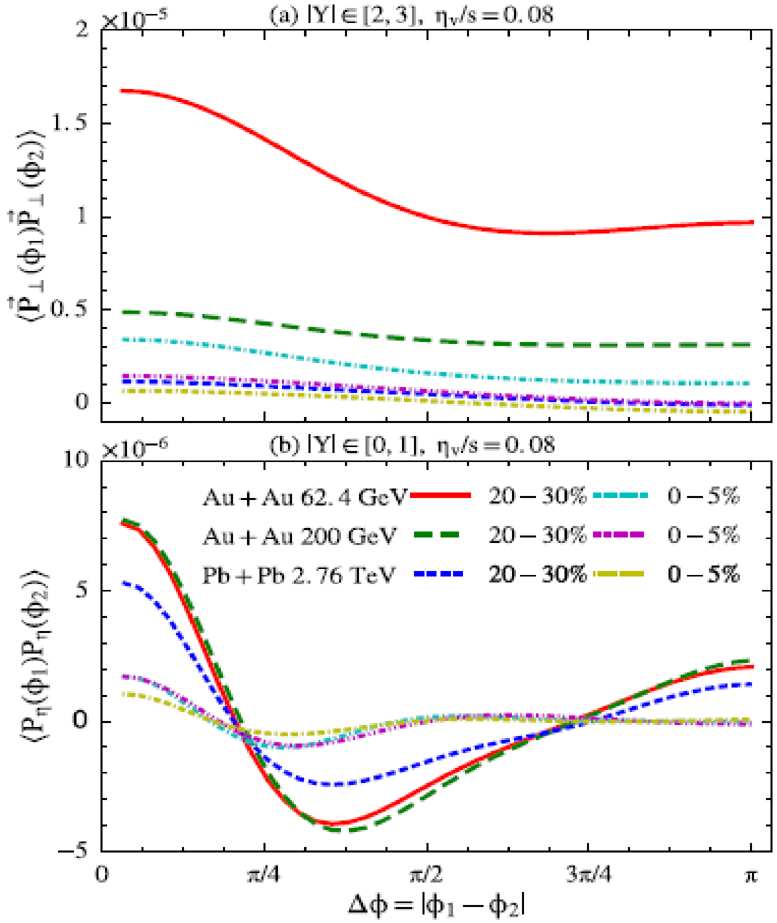


Spin-spin correlation of Λ can probe the vortical structure of sQGP

Pang, Petersen, QW, Wang, PRL 117, 192301 (2016)

Prospect: correlation in Λ Polarization as probe to vortical fluid

- **(a) The offset of transverse spin correlation indicates that global polarization are stronger at lower beam energies and peripheral collisions.**
- **(b)** $\cos(\Delta\phi)$ **azimuthal distribution in transverse spin correlation is due to circular structure of ω along beam direction.**
- **(c) Longitudinal spin correlation (pair structure) is due to transverse energetic particles. The beam energy dependence for longitudinal spin is weak.**



Pang, Petersen, QW, Wang, PRL 117, 192301 (2016)

Summary

- **Λ polarization provides a measurement of global angular momentum in HIC**
- **STAR data in Beam Energy Scan program show a clear non-vanishing global polarization for Λ**
- **There are a few theoretical models for hadron polarization: microscopic spin-orbital coupling model, statistical-hydro models, kinetic approach etc.**
- **"Discovery of global Λ polarization opens new directions in the study of the hottest, least viscous – and now, most vortical – fluid ever produced in the laboratory." --- from STAR Collab., 1701.06657**

It is just the beginning, stay tuned !