Global polarization in heavy ion collisions

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Outline

- Introduction
- Microscopic picture for quark polarization: spin-orbit coupling
- Statistic-hydro model for hadron polarization
- Wigner function approach to spin polarization
- Vorticity and Λ polarization in transport model
- Correlation in Λ polarization as probe to the most vortical fluid
- Summary

Two Casimir invariants of Poincare group

- **Mass of a particle from four-momentum**

$$
\begin{aligned}
\hat{P}^{\mu} &= \underline{\hat{T}^{0\mu}} \\
\hat{P}^{\mu}\hat{P}_{\mu} &= m^{2}
\end{aligned}
$$

Angular Momentum is related to momentum: $J^{\mu\rho} = x^{\mu}P^{\rho} - x^{\rho}P^{\mu} + S^{\mu\rho}$

- **Spin of a particle from Pauli-Lubanski pseudovector**

$$
\begin{aligned}
\hat{S}^{\mu} &= -\frac{1}{2m}\epsilon^{\mu\nu\rho\sigma}\underline{\hat{J}_{\nu\rho}}\hat{P}_{\sigma} \\
\hat{S}^{\mu}\hat{S}_{\mu} &= -S(S+1)
\end{aligned}
$$

$$\hat{S}^{\mu}\hat{P}_{\mu} = 0, \; \left[\hat{S}^{\mu}, \hat{P}^{\nu}\right] = 0$$

- **Insertion between physical state (e.g. nucleon) gives expectation value (Xiangdong Ji, 1994,1996)**

$$\langle N|\hat{P}^{\mu}|N\rangle = P_{N}^{\mu} \qquad \langle N|\hat{S}^{\mu}|N\rangle = S_{N}^{\mu}$$

Global spin polarization: a different story

- **Instead of taking expectation value between a nucleon state, we take expectation value between thermalized states of quark/nuclear mattter described by global equilibrium density operator**

$$\boldsymbol{S^{\mu} = \sum_i \langle i | \exp(-\beta E_i) \hat{S}^{\mu} | i \rangle = \mathrm{Tr}(\hat{\rho}_{GE} \hat{S}^{\mu})}$$

Thermalized states of quark/nuclear matter

Global equilibrium density operator

Global OAM and Magnetic field in HIC

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

$$\mathrm{L} \sim 10^5 \hbar$$

- **Very strong magnetic fields are produced**

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

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

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

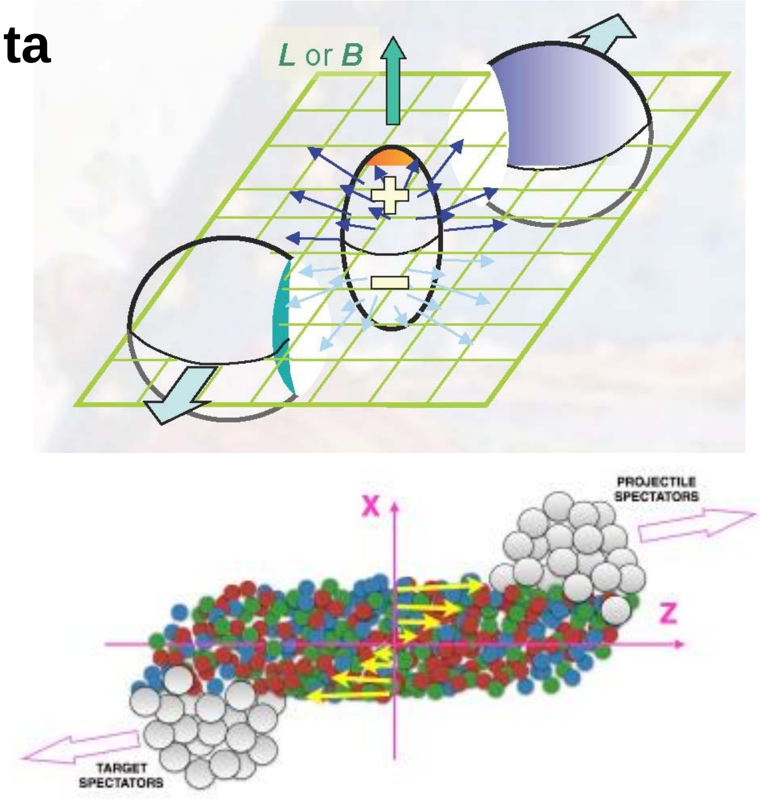


Figure taken from Becattini et al, 1610.02506

Rotation vs Polarization

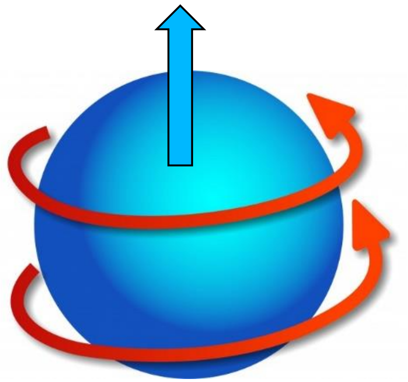
- **Barnett effect: rotation to polarization**

  uncharged object in rotation

  → spontaneous magnetization

  → polarization (spin-orbital coupling)

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



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

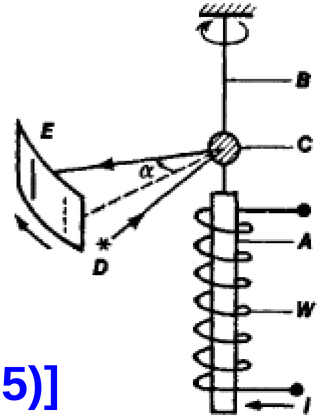
  magnetic field (impulse)

  → 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]**

Polarization of Λ hyperon

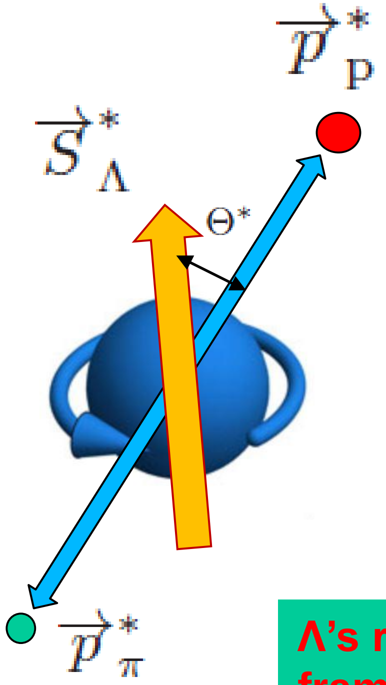
- Λ is '**self-analyzing**' in weak decay $\Lambda \to \mathrm{p} + \pi^-$ which breaks parity (proton emission preferentially along Λ spin in Λ's rest frame)

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

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

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

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

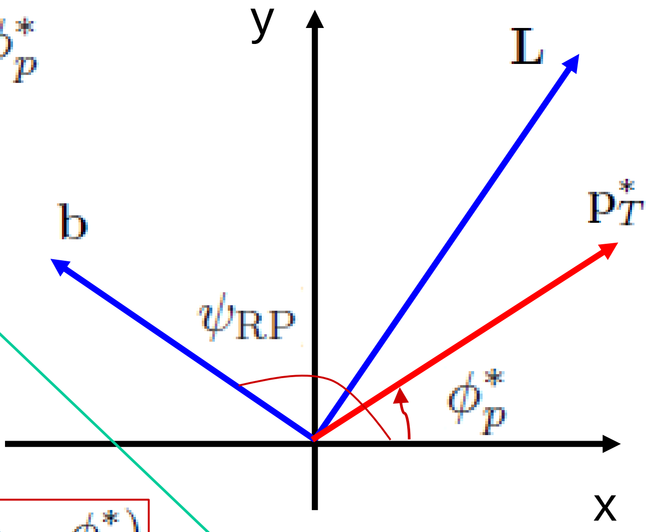
Measurement of Λ polarization

- **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**

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

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

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



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

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

Azimuthal angle of event plane determined by direct flow

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

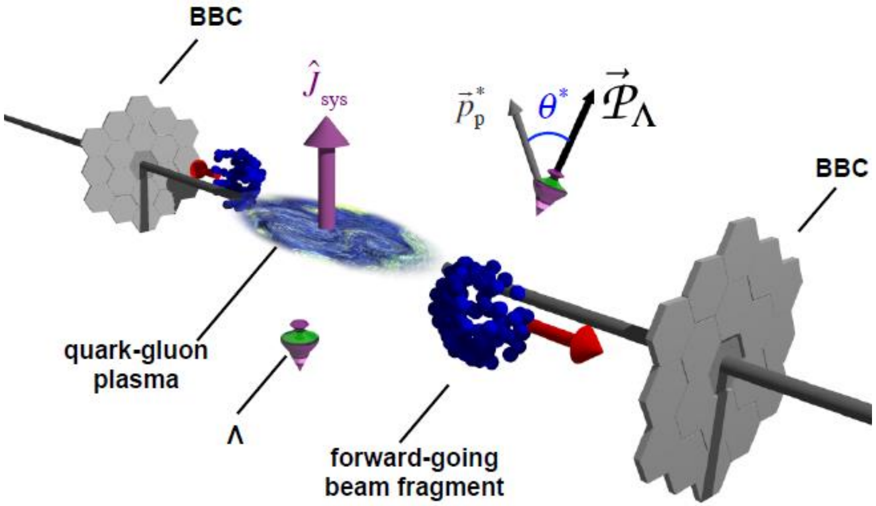
Reaction plane resolution from direct flow

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

Azimuthal angle of daughter proton in Λ rest frame

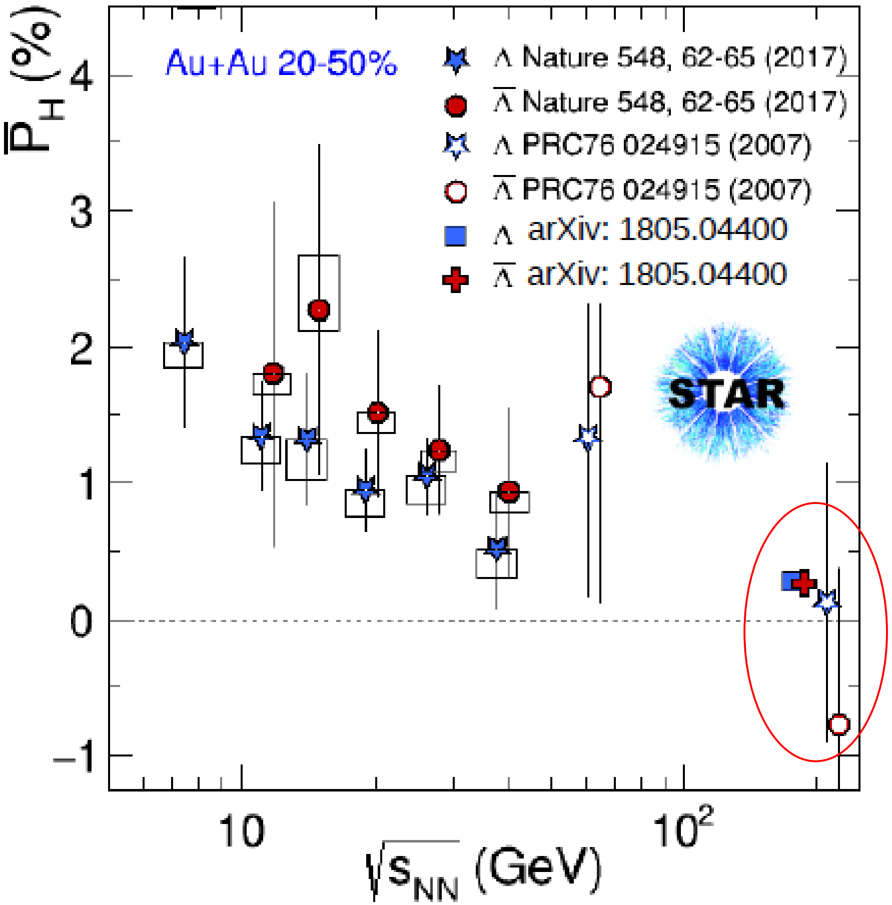
Decay constant

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



STAR, PRC 76,024915 (2007); 1701.06657

STAR results for global Λ polarization



STAR collab., Nature, 548, 62(2017); arXiv: 1701.06657.

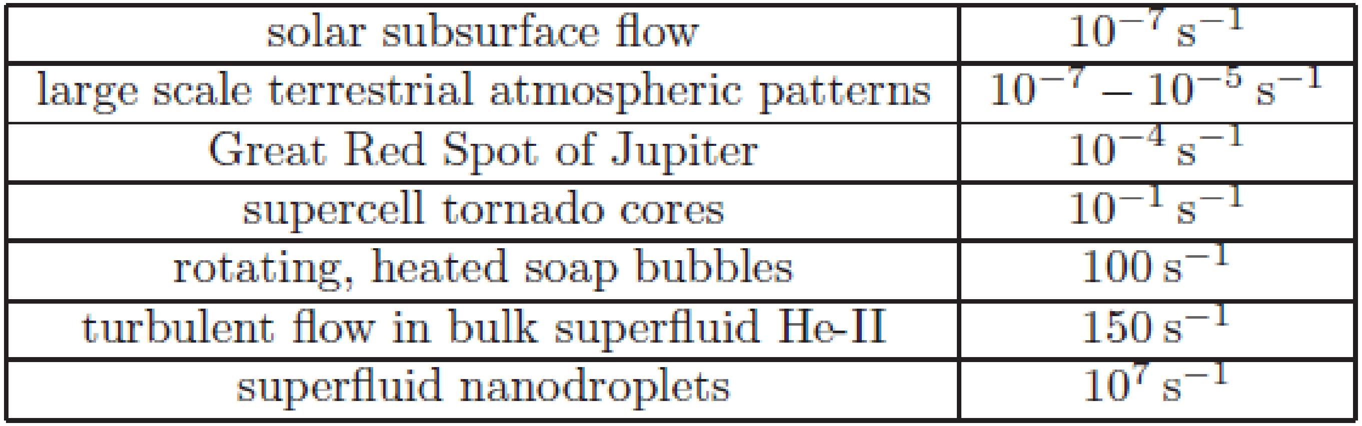
Largest vorticity ever observed

- **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.,Nature, 548, 62(2017);
Becattini et al., PRC95,054902(2017);
Pang et al., PRC 94, 024904(2016);
Many others, ……

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

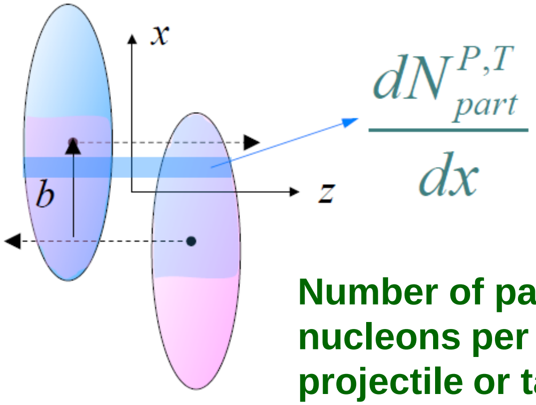


solar subsurface flow	$10^{-7}\ \mathrm{s}^{-1}$
large scale terrestrial atmospheric patterns	$10^{-7} - 10^{-5}\ \mathrm{s}^{-1}$
Great Red Spot of Jupiter	$10^{-4}\ \mathrm{s}^{-1}$
supercell tornado cores	$10^{-1}\ \mathrm{s}^{-1}$
rotating, heated soap bubbles	$100\ \mathrm{s}^{-1}$
turbulent flow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

Spin-orbit coupling as microscopic picture for global polarization

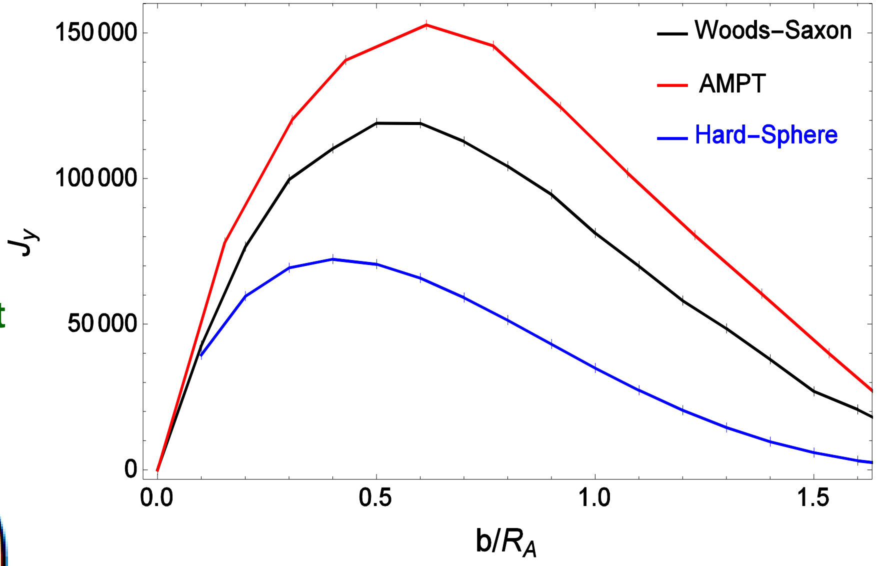
Global OAM in HIC

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



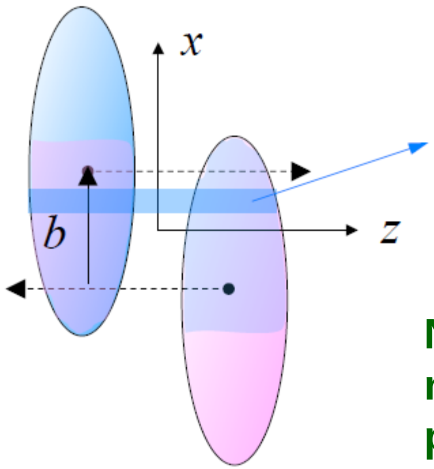
Number of participant nucleons per unit x in projectile or target

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



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

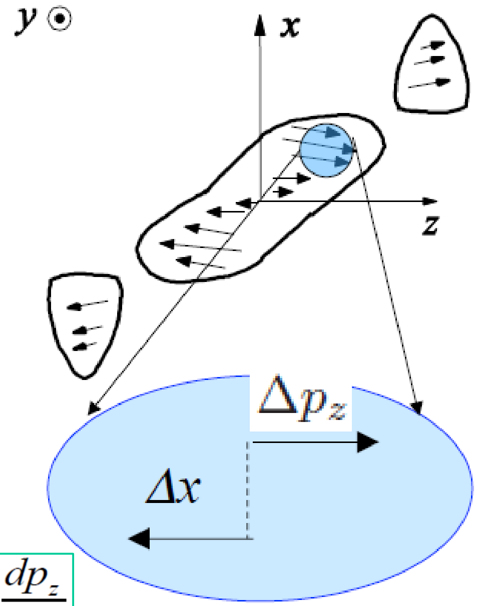


$$\frac{dN^{P,T}_{part}}{dx}$$

Number of participant nucleons per unit x in projectile or target

Collective longitudinal momentum per produced parton

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



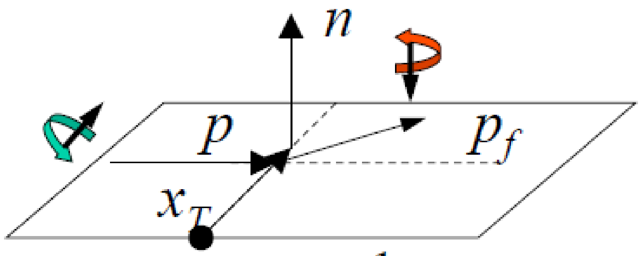
$$\boxed{\Delta p_z = \Delta x \frac{dp_z}{dx}}$$

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

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**



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

screening mass

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

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

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

Polarization vector **OAM** **Spin-Orbit coupling**

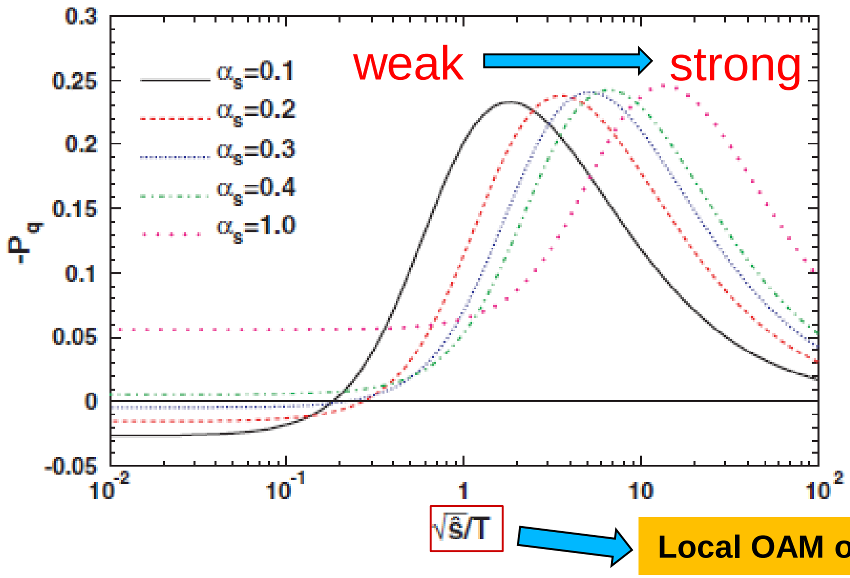
- **Polarization for small angle scattering and** $m_q \gg p, \mu$

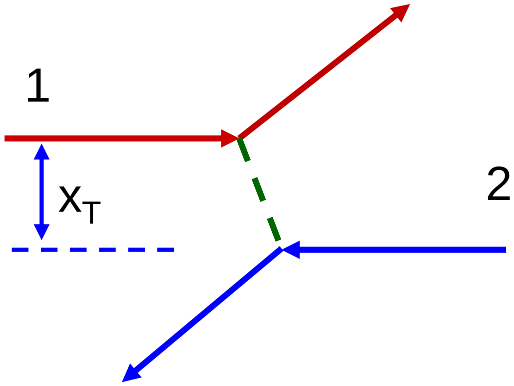
$$P_q \approx -\pi \frac{\mu p}{4m_q^2} \sim -\frac{\Delta E_{LS}}{E_0}$$

Liang, Wang, PRL 94, 102301(2005)

Quark-quark scattering

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





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

$$
\begin{aligned}
L &= \frac{1}{2}m(\mathbf{v}_r + \boldsymbol{\omega}\times\mathbf{r})^2 - U(r) \\
\mathbf{p} &= \frac{\partial L}{\partial \mathbf{v}_r} = m(\mathbf{v}_r + \boldsymbol{\omega}\times\mathbf{r}) \\
H &= \mathbf{p}\cdot\mathbf{v}_r - L = H_0 - \boldsymbol{\omega}\cdot\mathbf{J}
\end{aligned}
$$

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

canonical momentum

angular momentum

Hamiltonian in inertial frame

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

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

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,**

space-like hyper-surface

n^{μ} is time-like vector

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

$$\hat{\rho}_{\mathrm{LE}}=\frac{1}{Z}\exp\left[\int d\Sigma_{\mu}\left(\hat{T}^{\mu\nu}\beta_{\nu}-\frac{1}{2}\omega_{\alpha\beta}\hat{J}^{\mu,\alpha\beta}-\zeta\hat{N}^{\mu}\right)\right]$$

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

- **Given n^{μ}, one can determine β^{μ} , $\omega_{\alpha\beta}$ and ζ by**

$$\begin{aligned}n_{\mu}\mathrm{Tr}(\hat{\rho}\hat{T}^{\mu\nu})&=n_{\mu}T^{\mu\nu}\\ n_{\mu}\mathrm{Tr}(\hat{\rho}\hat{J}^{\mu,\alpha\beta})&=n_{\mu}J^{\mu,\alpha\beta}\\ n_{\mu}\mathrm{Tr}(\hat{\rho}\hat{N}^{\mu})&=n_{\mu}N^{\mu}\end{aligned}$$

Energy-momentum conservation

Angular momentum conservation

Charge conservation

$$\boxed{n_{\mu}\mathrm{Tr}(\hat{\rho}\hat{S}^{\mu,\alpha\beta})=n_{\mu}S^{\mu,\alpha\beta}}$$

For symmetric $T^{\mu\nu}=T^{\nu\mu}$

$$\boxed{\partial_{\mu}\hat{S}^{\mu,\alpha\beta}=\hat{T}^{\beta\alpha}-\hat{T}^{\alpha\beta}=0}$$

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

Killing vector solution ⇨

$$\beta^\mu = \underline{b^\mu} + \underline{\varpi^{\mu\nu}} x_\nu$$

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

Thermal vorticity tensor

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

Density operator at global equilibrium

$$\hat{\rho}_{\mathrm{GE}} = \frac{1}{Z} \exp\left(\beta'_\mu \underline{\hat{P}^\mu} - \frac{1}{2} \omega_{\alpha\beta} \underline{\hat{S}^{\alpha\beta}} - \zeta \underline{\hat{N}^\mu} \right)$$

four-momentum operator

Spin tensor

Particle number

$$\boxed{\beta'_\mu = b_\mu + (\omega_{\mu\nu} + \varpi_{\mu\nu}) x^\nu}$$

Spin and polarization

Spin (Pauli-Lubanski) pseudovector

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

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

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

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

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); Yang, Fang, QW, Wang, PRC97,034917(2018).

$$\begin{aligned} \mathscr{M}^{\mu\alpha\beta}(x,p) &\equiv \frac{1}{2}\mathrm{Tr}\left[\{\gamma^{\mu}, S^{\alpha\beta}\}W(x,p)\right] \\ &= -\frac{1}{2}\epsilon^{\mu\alpha\beta\rho}\mathscr{A}_{\rho}(x,p), \end{aligned}$$

- **For αβ=ij (space indices)**

Pauli matrices

$$\mathscr{M}^{ij}(x,p) = \frac{1}{2}\epsilon^{ijk}\mathscr{A}^{k}(x,p) \Longrightarrow \begin{aligned} A^{i}(x) &= \psi^{\dagger}(x)\Sigma_{i}\psi(x) \\ &= \int d^{4}p\mathscr{A}^{i}(x,p) \end{aligned}$$

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

$$\begin{aligned} \Pi^{\mu}(x) &\sim \frac{1}{2}\int d^{4}p\underline{\mathscr{A}^{\mu}(x,p)} \\ &\sim \frac{1}{2}\int d^{4}p\frac{|p_{0}|}{\underline{m}}\mathscr{A}^{\mu}(x,p) \end{aligned}$$

Non-relativistic limit

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 $(\partial_x)^i$:

$$\mathscr{A}^\mu = \mathrm{Tr}[\gamma^\mu\gamma^5 W]$$

$$\mathscr{A}^\mu_{(0)}(x,p) = m\left[\theta(p_0)\underline{n^\mu(\mathbf{p},\mathbf{n})} - \theta(-p_0)\underline{n^\mu(-\mathbf{p},-\mathbf{n})}\right]\delta(p^2-m^2)\underline{A}$$

$$\mathscr{A}^\alpha_{(1)}(x,p) = -\frac{1}{2}\hbar\beta\tilde{\Omega}^{\alpha\sigma}p_\sigma\frac{d\underline{V}}{d(\beta p_0)}\delta(p^2-m^2) - Q\hbar\tilde{F}^{\alpha\lambda}p_\lambda\underline{V}\frac{\delta(p^2-m^2)}{p^2-m^2}$$

where A and V are related to distribution functions

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

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

- Spin (pseudo-)vector in Lab frame

$$\underline{n^\mu(\mathbf{p},\mathbf{n})} = \underline{\Lambda^\mu_{\ \nu}(-\mathbf{v}_p)}\underline{n^\nu(0,\mathbf{n})} = \left(\frac{\mathbf{n}\cdot\mathbf{p}}{m}, \mathbf{n} + \frac{(\mathbf{n}\cdot\mathbf{p})\mathbf{p}}{m(m+E_p)}\right)$$

Spin in Lab frame

Lorentz boost from cms to Lab frame

Spin in cms frame

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

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);
Yang, Fang, QW, Wang, PRC97,034917(2018)

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

susceptiblility

+/- → 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

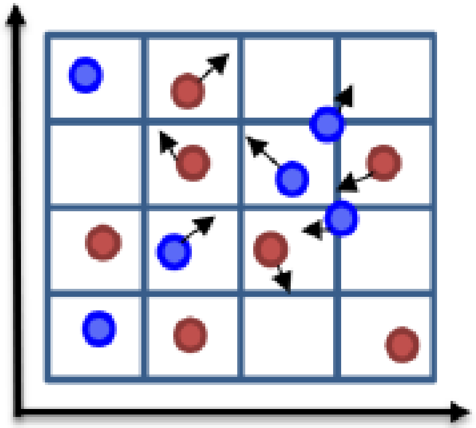
Global Λ polarization from transport models

Fluid velocity and vorticity from AMPT

- **Velocity:**

(a) average in cell

$$\mathbf{v}(t,\mathbf{x}) = \frac{\sum_i \mathbf{p}_i}{\sum_i E_i}$$



(b) Other method: Gaussian smearing

$$\mathbf{v}(t,\mathbf{x}) = \frac{\sum_i \mathbf{p}_i G(\mathbf{x}_i - \mathbf{x})}{\sum_i E_i G(\mathbf{x}_i - \mathbf{x})}$$

Other methods:
Oliinychenko, Petersen 2016
Deng, Huang 2016

(c) Sum is over particles and events

(d) 10^5 events at each energy in BES range

- **Vorticity: finite-difference method**

Vorticity from AMPT:
Jiang, Lin, Liao, 2016

Vorticity fields from AMPT

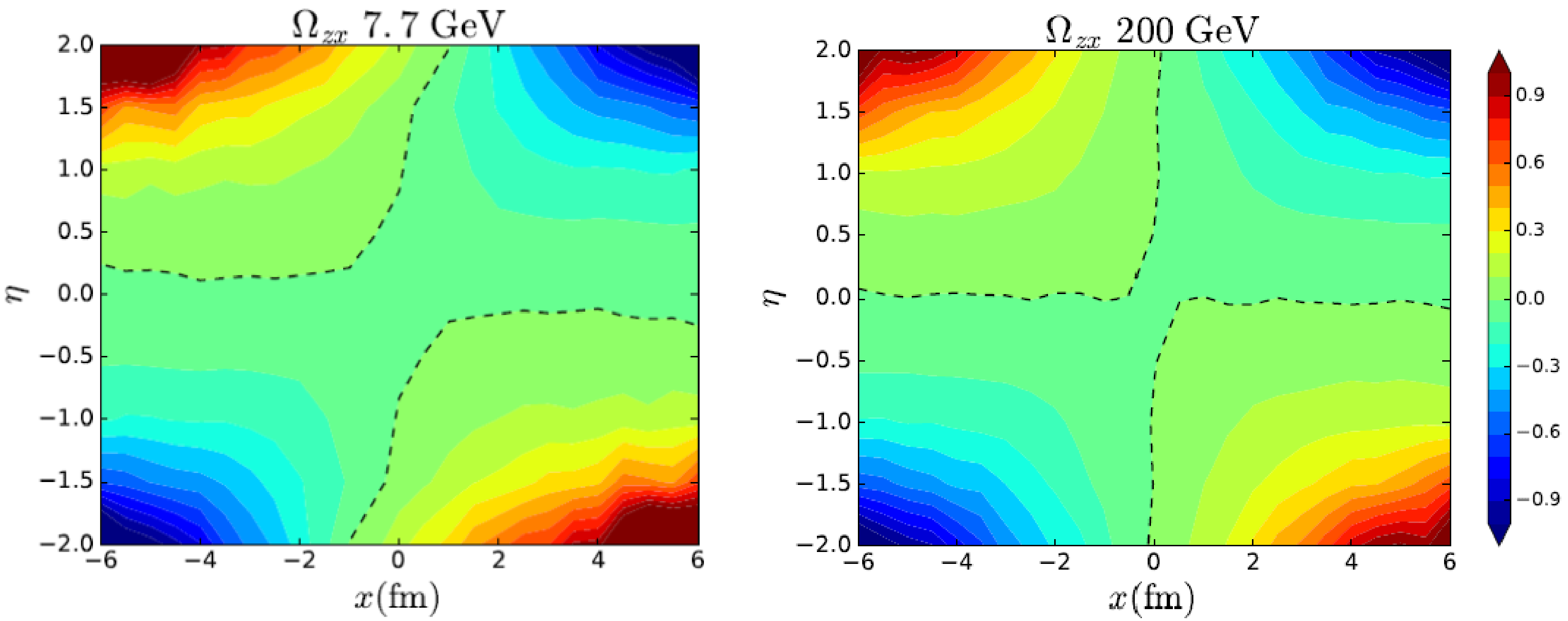
Vorticity field on reaction plane:

(a) Nearly odd function of x and η;

(b) Less odd-symmetric at lower energy

Li, Pang, QW, Xia, PRC96,054908(2017)

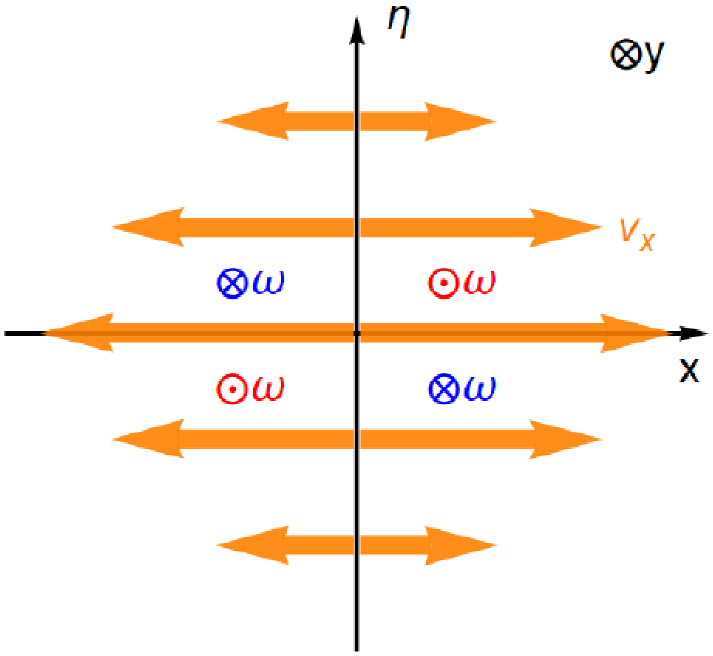
$$\langle \mathbf{S}^* \rangle \sim \int d^4x f_\Lambda(x) \Omega_{zx}(x)$$



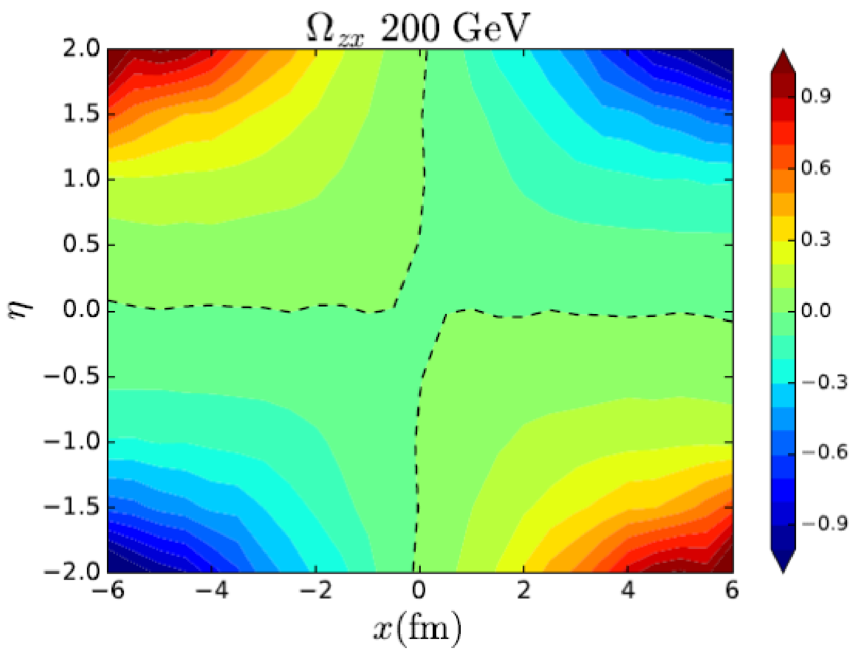
Vorticity fields in reaction plane

The odd-symmetry can be understood by the radial flow.

Li, Pang, QW, Xia, RC96,054908(2017)

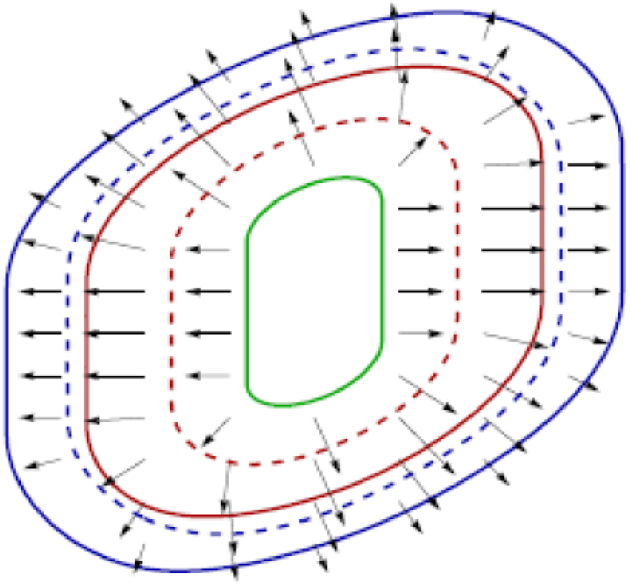


$$\Omega_{zx} = \partial_z u^x - \partial_x u^z$$

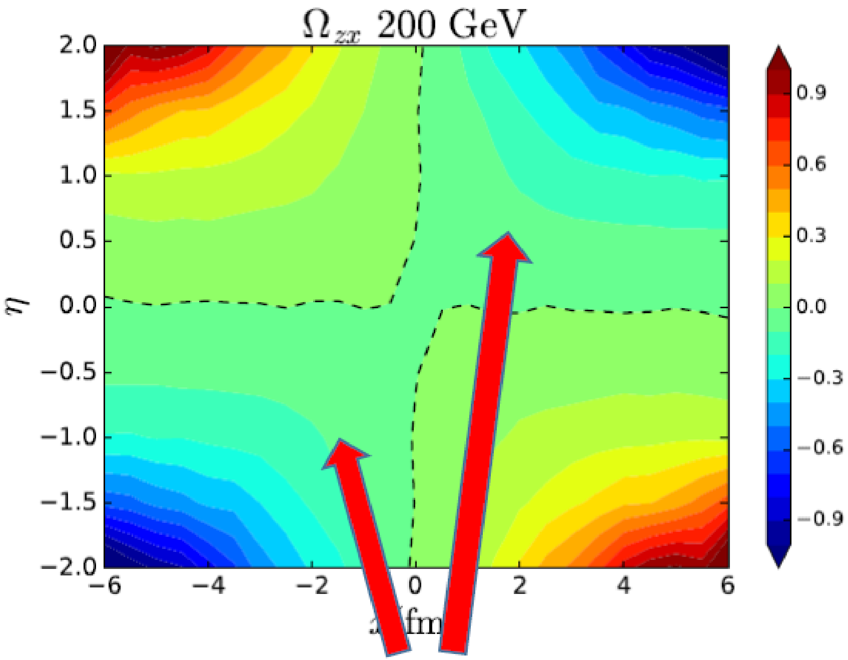


Vorticity fields and matter distribution

Due to global OAM, fireball or matter distribution is tilted



Bozek, Wyskiel 2010



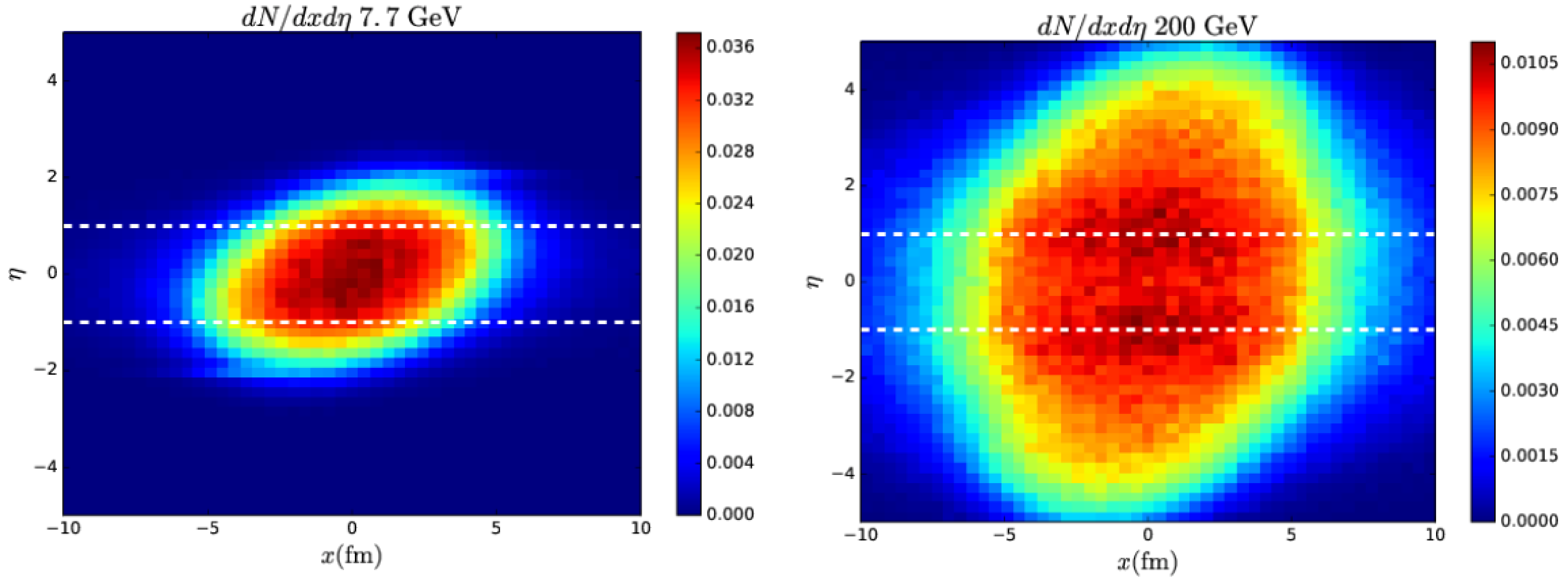
More matter here!

Li, Pang, QW, Xia, PRC96,054908(2017)

Number distribution of Λ

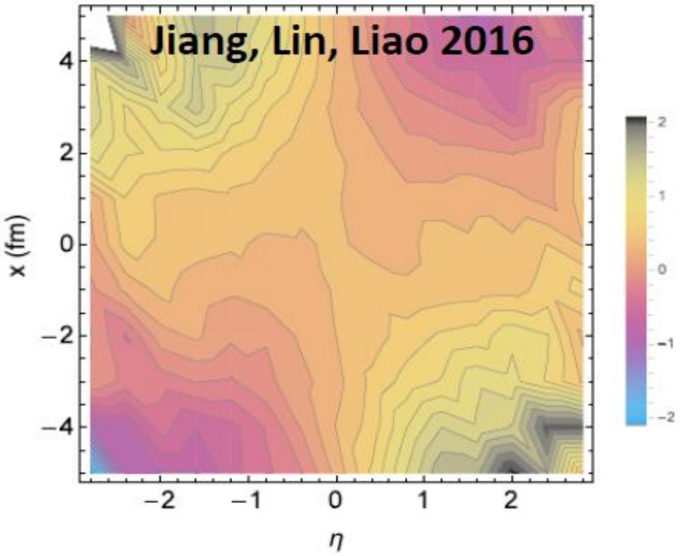
More tilted at 7.7 GeV

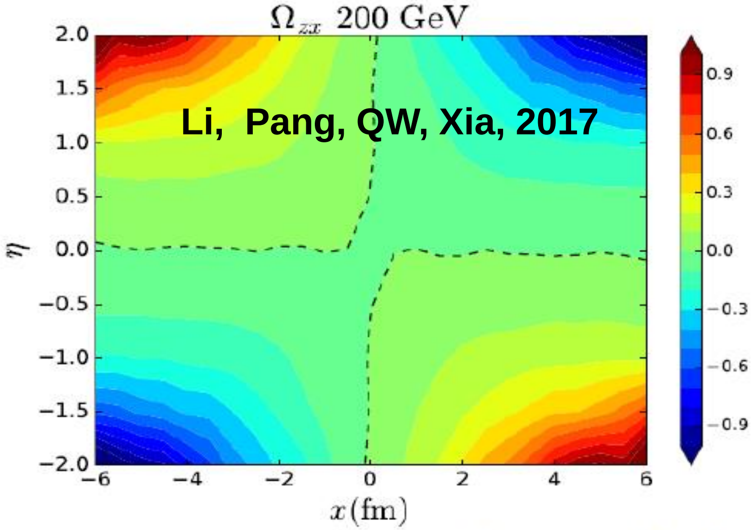
More symmetric at 200 GeV due to rapid expansion in beam direction

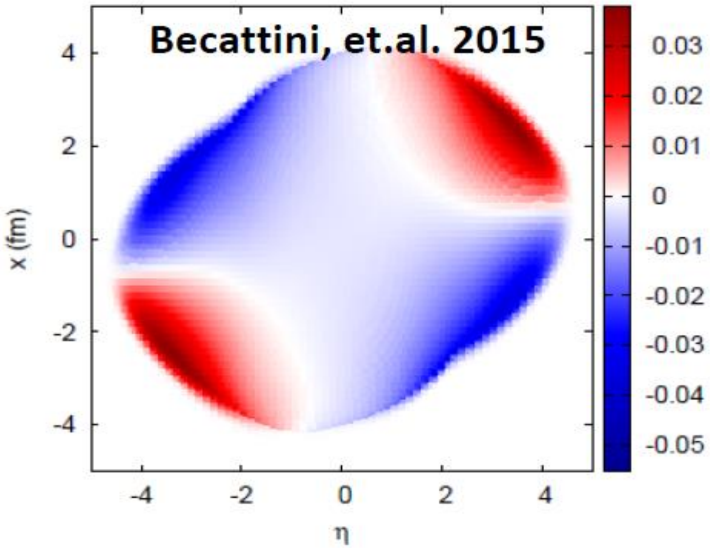


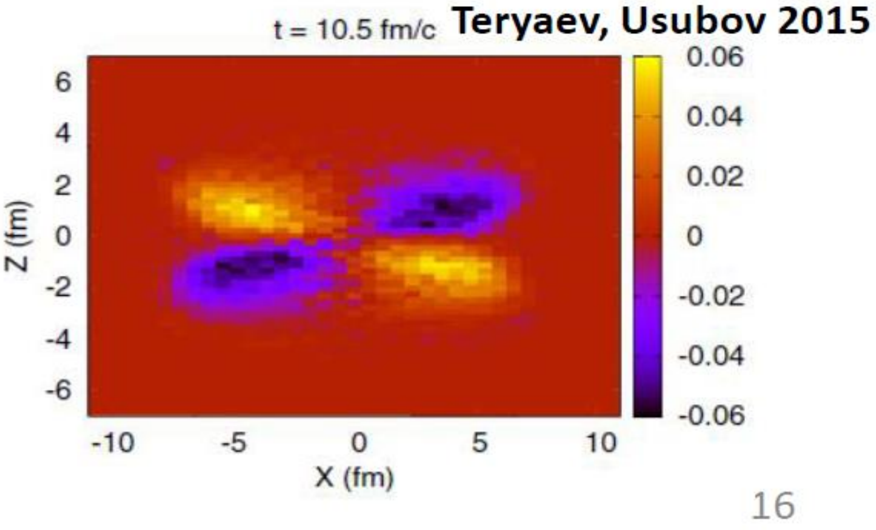
Li, Pang, QW, Xia, PRC96,054908(2017)

Vorticity fields from other methods







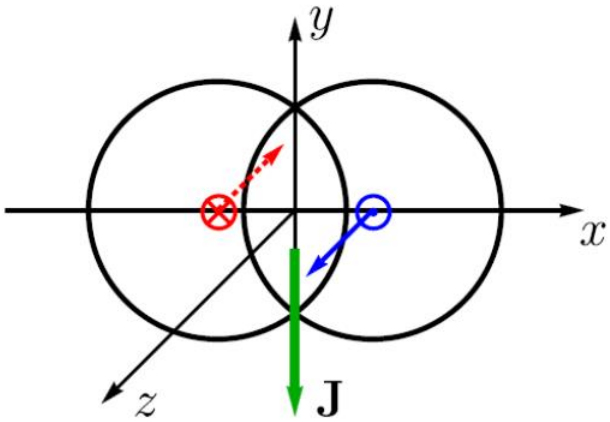


Global polarization of Λ from AMPT

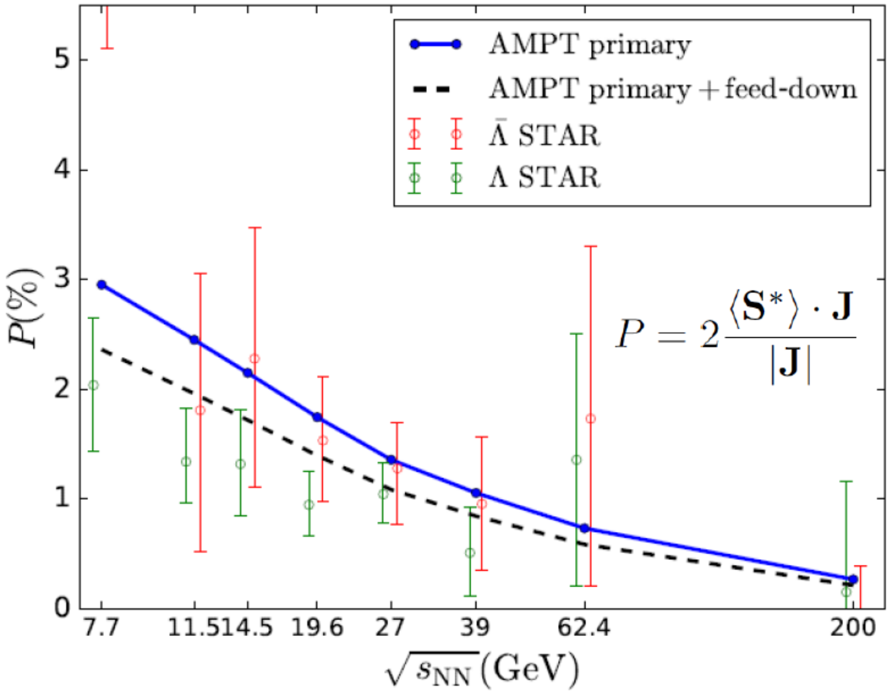
- **Polarization of Λ: average over events with |η|<1**

$$\langle \mathbf{S}^* \rangle = \frac{1}{N} \sum_{i=1}^{N} \mathbf{S}^*(x,p)$$

$$P = 2\frac{\langle \mathbf{S}^* \rangle \cdot \mathbf{J}}{|\mathbf{J}|}$$



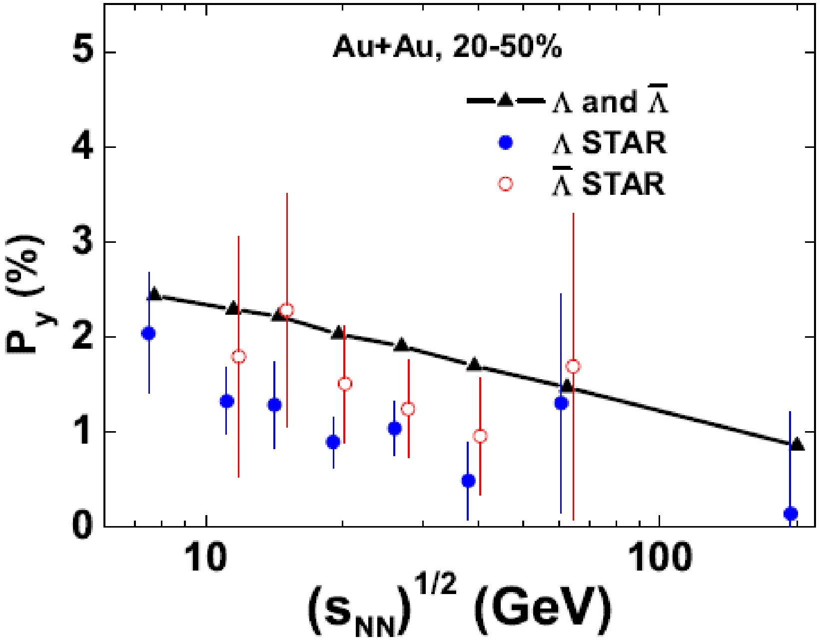
Au+Au, 20%-50%, with feed-down



Li, Pang, QW, Xia, PRC96,054908(2017)

Global polarization of Λ from Chiral Kinetic approach

- Chiral kinetic approach+ AMPT model
- Spin polarizations of quarks and antiquarks
- Quarks and antiquarks are converted to hadrons via the coalescence Model

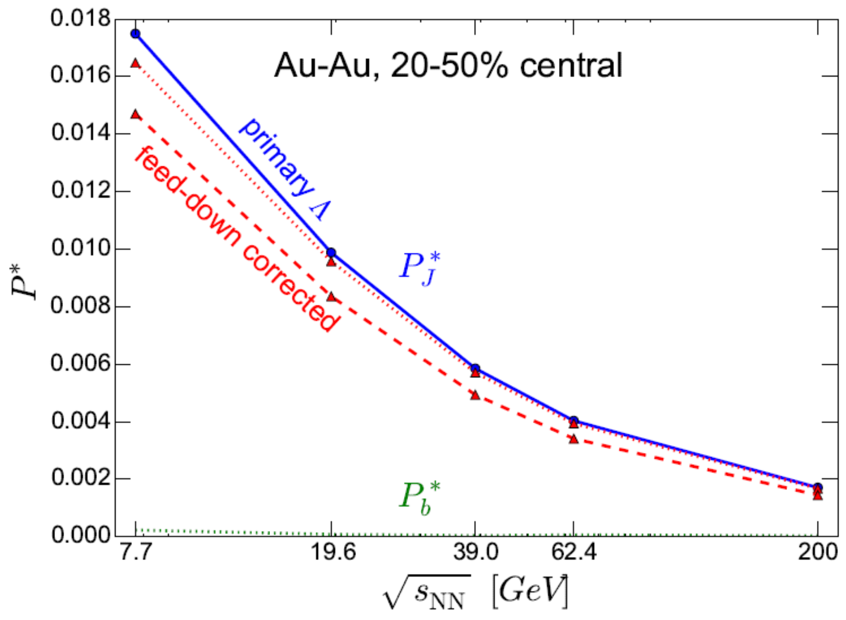


Sun, Ko, PRC96, 024906(2017)

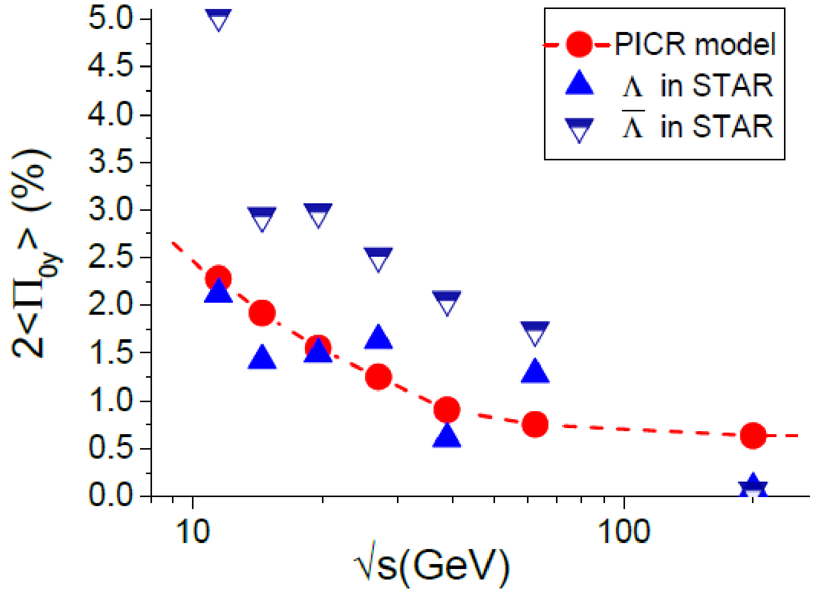
Chiral kinetic approach:

Son, Yamamoto, PRL 109 (2012) 181602;
Stephanov, Yin, PRL 109 (2012) 162001;
Chen, Pu, QW, Wang, PRL 110 (2013) 262301;
Mueller, Venugopalan, PRD 96 (2017) 016023.

Global polarization of Λ from other methods



Karpenko, Becattini, EPJC 77,213(2017)
UrQMD + vHLLE hydro



Xie,Wang,Csernai,PRC 95,031901(2017)
PICR hydro

Other approach:
Aristova, Frenklakh, Gorsky, Kharzeev, JHEP 1610, 029 (2016)

Circular vorticity

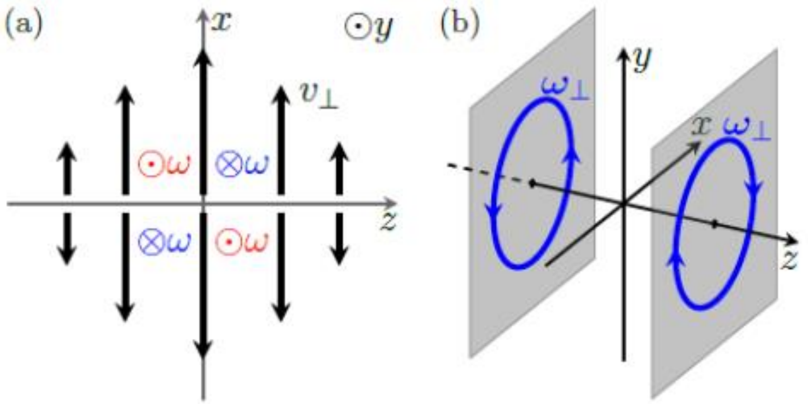


FIG. 2. Left: Schematic illustration of the quadrupole pattern of ω_y generated from $\partial_z v_\perp$ in the reaction plane, where the vorticity is along the $-y$ direction ($\otimes$) in the $xz > 0$ quadrants and the y direction ($\odot$) in the $xz < 0$ quadrants. Right: A three dimensional view of the circular structure of the transverse vorticity $\omega_\perp = (\omega_x, \omega_y)$.

Xia, Li, Tang, Wang, PRC (2018)

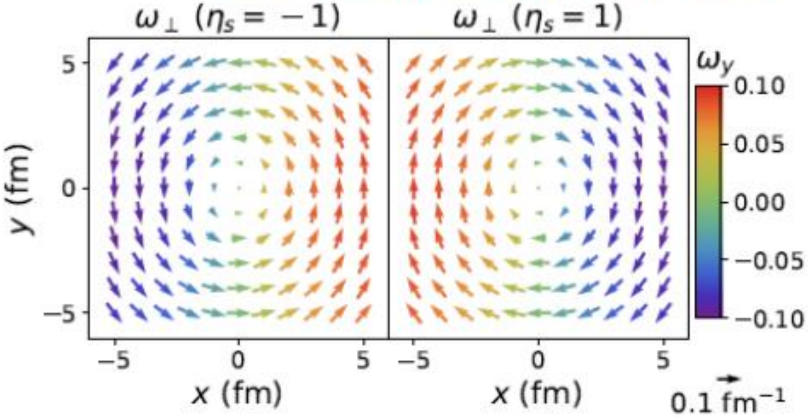
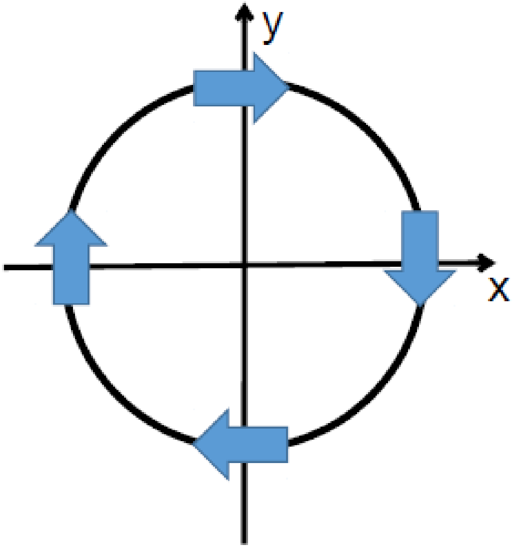
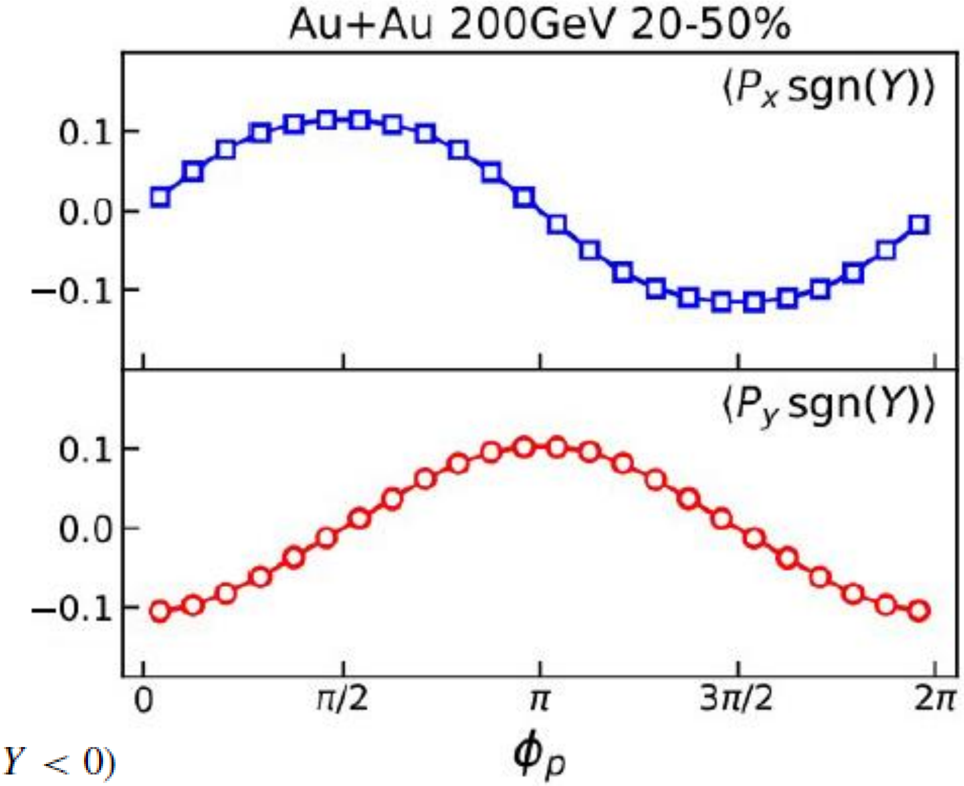


FIG. 3. The distribution of the transverse vorticity $\omega_\perp = (\omega_x, \omega_y)$ in the transverse plane at longitudinal positions $\eta_s = -1$ (left) and $\eta_s = 1$ (right) at time $t = 5$ fm/c in 20-30% central Au+Au collisions at $\sqrt{s_{\rm NN}} = 200$ GeV. The color represents the value of the component ω_y.

Circular vorticity

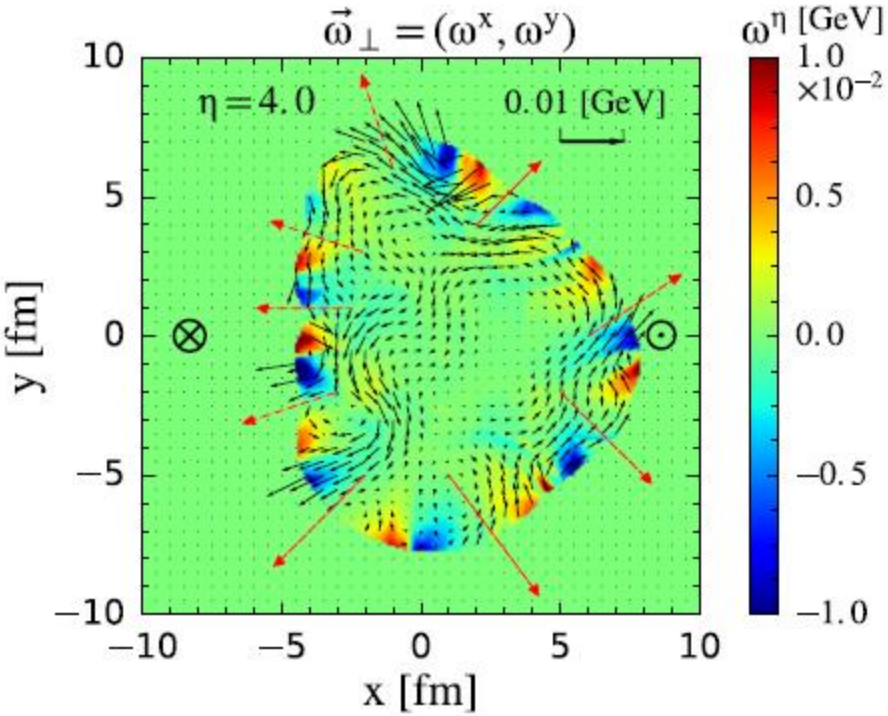


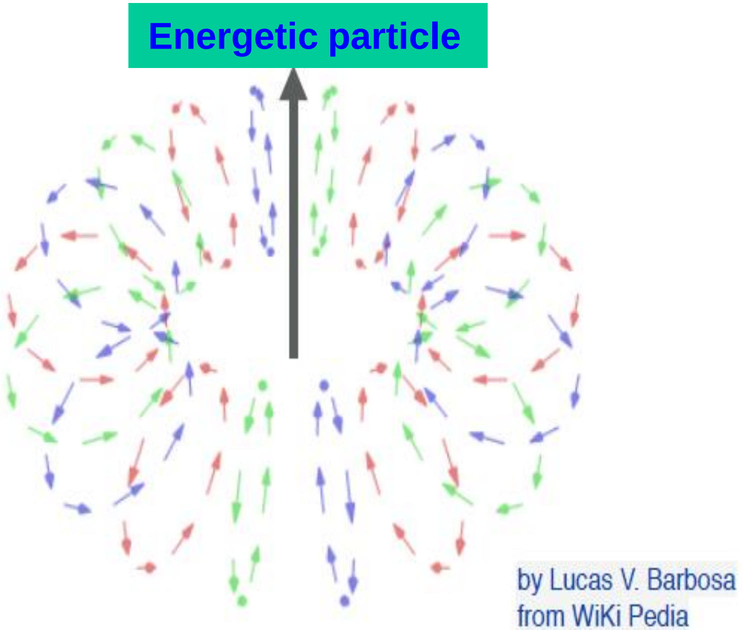


$$\langle P_x \mathrm{sgn}(Y)\rangle = \frac{P_x(\phi_p, Y > 0) - P_x(\phi_p, Y < 0)}{2}$$

$$\langle P_y \mathrm{sgn}(Y)\rangle = \frac{P_y(\phi_p, Y > 0) - P_y(\phi_p, Y < 0)}{2}$$

Turbulence and vortices in high energy HIC



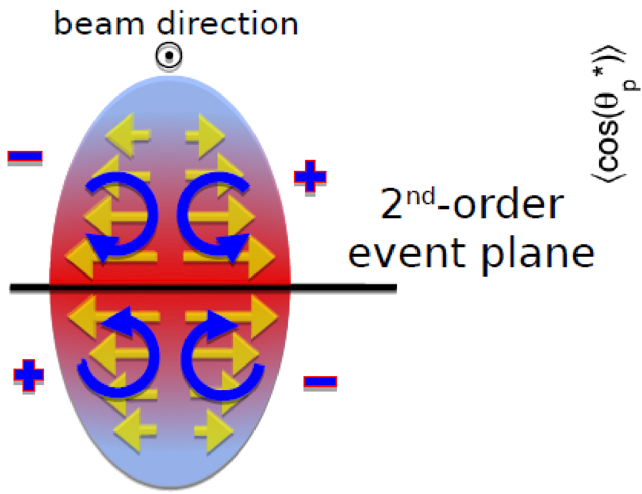


by Lucas V. Barbosa
from WiKi Pedia

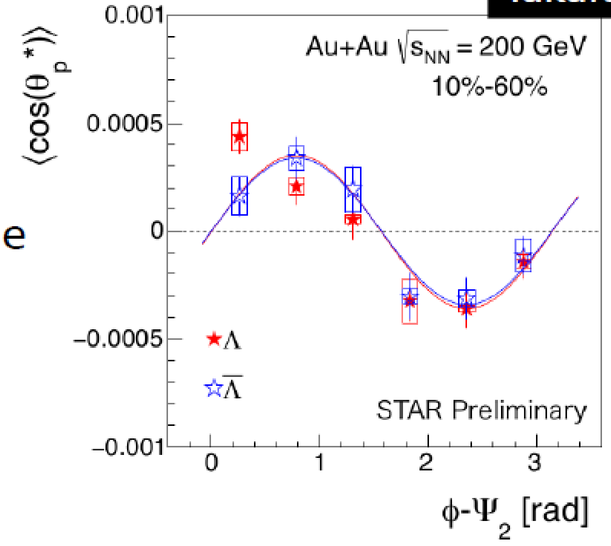
Spin-spin correlation of Λ can probe the vortical structure of sQGP

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

Polarization along the beam direction



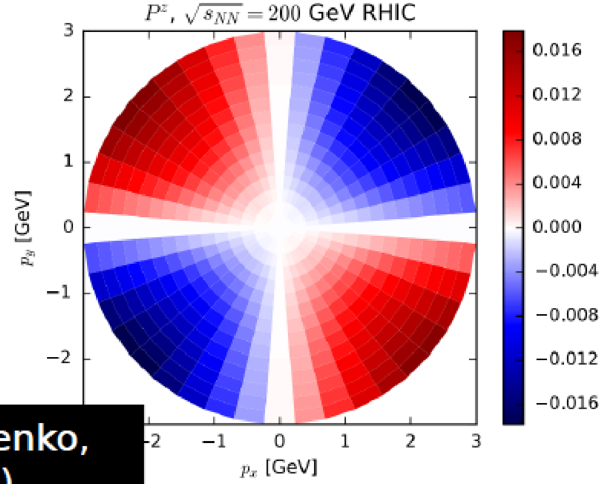
Takafumi Niida, talk @ QM18



- Clear signal at 200 GeV
- Signal qualitatively disagrees with hydro model

- Local velocity gradients due to elliptic flow may produce vorticity along beam direction
- This is a brand new area to look!
- Look for sinusoidal polarization structure projected onto the beam direction

From Isaac Upsal, ATHIC2018



S. Voloshin, EPJ Web Conf. 17 (2018) 10700

F. Becattini and I. Karpenko, PRL.120.012302 (2018)

Summary

- **Λ polarization provides a way of measuring vortical structure of sQGP**
- **STAR data in Beam Energy Scan program show a clear non-vanishing global polarization for Λ**
- **Theoretical models for hadron polarizations: microscopic spin-orbital coupling model, statistical-hydro models, Wigner function approach, quark coalescence model, transport model, 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., Nature, 548, 62-65 (2017)**