Polarization as a signature of local parity violation in hot QCD matter

Based on

F.Becattini, M.Buzzegoli, A.P., G. Prokhorov, 2020

arXiV:2009.13449

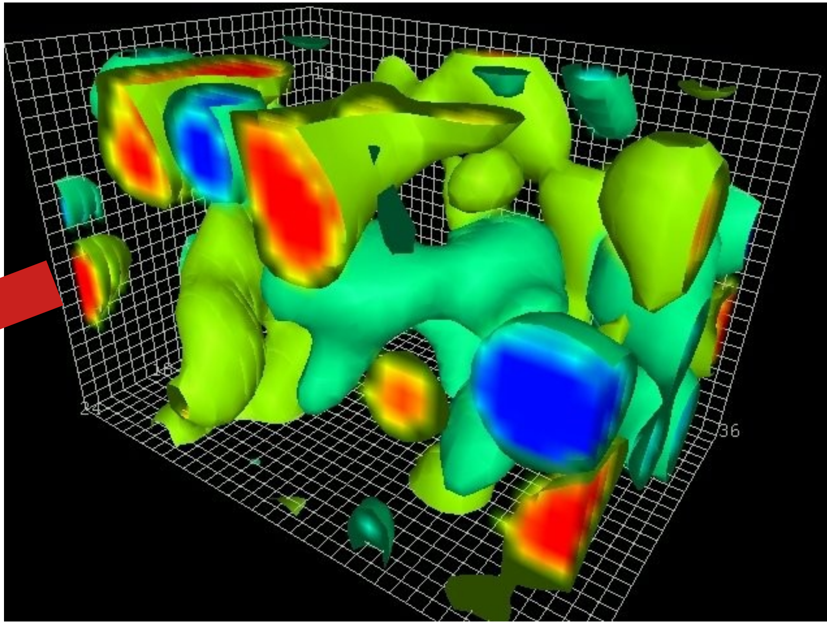
Na7 Workshop
Crete 2021

Andrea Palermo

Motivations

Topological gauge configurations give rise to a fluctuating axial chemical potential: **local parity breaking!**

$$\mu_A \neq 0 \qquad \langle\langle \mu_A \rangle\rangle = 0$$



D. Leinweber

Experimental observable: chiral magnetic effect

Drawbacks: magnetic field, difficult background, not observed even in isobar collisions (under discussion) (STAR,arXiv:2109.00131, 2021)

Using linear response theory we show that **the axial chemical potential contributes to polarization**.

Spin vector

In the presence of an **axial chemical potential** (Becattini, Buzzegoli, A.P. Prokhorov, arXiv:2009.13449, 2020)

$$S^\mu_{tot}(p) = S^\mu_{\text{hyd}}(p) + S^\mu_\chi(p)$$

$$S^\mu_\chi(p) = \frac{g_h}{2} \frac{\int_\Sigma \mathrm{d}\Sigma \cdot p\, \zeta_A n_F\,(1-n_F)}{\int_\Sigma \mathrm{d}\Sigma \cdot p\, n_F} \frac{\varepsilon p^\mu - m^2 \hat{t}^\mu}{m\varepsilon}$$

$$\zeta_A = \frac{\mu_A}{T}$$

Independent of the magnetic field

Over many events:

$$\langle\langle S^\mu \rangle\rangle = \langle\langle S^\mu_{\text{hyd}} \rangle\rangle + \cancel{\langle\langle S_\chi \rangle\rangle}$$

$$\langle\langle \zeta_A \rangle\rangle = 0 \qquad \langle\langle \zeta_A^2 \rangle\rangle \neq 0$$

Detectable:
helicity-helicity correlators

Calculating polarization

Given a density matrix $\widehat{\rho}$, we compute Wigner function of Dirac fermions (particle component)

$$W_+(x,p)_{AB} = \theta(p^0)\theta(p^2)\frac{1}{(2\pi)^4}\int \mathrm{d}^4y \; \mathrm{e}^{-ip\cdot y}\mathrm{Tr}(\widehat{\rho} : \bar{\Psi}_B(x+y/2)\Psi_A(x-y/2) :)$$

The spin vector reads

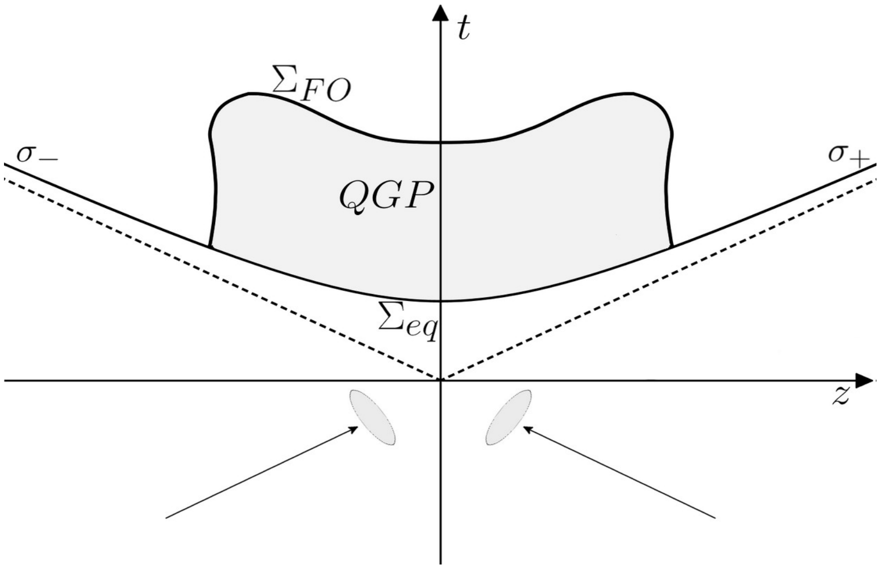
$$S^\mu(p) = \frac{1}{2}\frac{\int_\Sigma \mathrm{d}\Sigma \cdot p \, \mathrm{tr}\left[\gamma^\mu\gamma^5 W_+(x,p)\right]}{\int_\Sigma \mathrm{d}\Sigma \cdot p \, \mathrm{tr}\left[W_+(x,p)\right]}$$

In heavy ion collisions Σ is the **freeze-out hypersurface**.

Zubarev's density operator

$$\widehat{\rho} = \frac{1}{Z} \exp\left[-\int_{\Sigma_{\rm eq}} {\rm d}\Sigma_\mu \left(\widehat{T}^{\mu\nu}\beta_\nu - \zeta_A \widehat{j}^\mu_A \right) \right]$$

$$\beta^\mu = \frac{u^\mu}{T} \qquad \zeta_A = \frac{\mu_A}{T}$$



Using the Gauss theorem

Dissipation

$$\int_{\Sigma_{\rm eq}} {\rm d}\Sigma_\mu \left(\widehat{T}^{\mu\nu}\beta_\nu - \zeta_A \widehat{j}^\mu_A \right) = \int_{\Sigma_{FO}} {\rm d}\Sigma_\mu \left(\widehat{T}^{\mu\nu}\beta_\nu - \zeta_A \widehat{j}^\mu_A \right) + \int_\Omega {\rm d}\Omega \left(\widehat{T}^{\mu\nu}\partial_\mu\beta_\nu - \widehat{j}^\mu_A \partial_\mu \zeta_A - \zeta_A \partial_\mu \widehat{j}^\mu_A \right)$$

If we neglect dissipation (supposedly small)

$$\widehat{\rho} \simeq \widehat{\rho}_{LE} = \frac{1}{Z_{LE}} \exp\left[-\int_{\Sigma_{FO}} {\rm d}\Sigma_\mu \left(\widehat{T}^{\mu\nu}\beta_\nu - \zeta_A \widehat{j}^\mu_A \right) \right]$$

The Wigner function is the expectation value of a Wigner operator.

$$\widehat{W}_+(x,p)_{AB} = \theta(p^0)\theta(p^2)\frac{1}{(2\pi)^4}\int \mathrm{d}^4y\, \mathrm{e}^{-ip\cdot y} : \bar{\Psi}_B(x+y/2)\Psi_A(x-y/2) :$$

$$W_+(x,p)_{AB} = \mathrm{Tr}(\widehat{\rho}\,\widehat{W}_+(x,p)_{AB})$$

We use the **hydrodynamic approximation**: thermodynamic quantities vary slowly with respect to microscopic correlation lengths.

We can Taylor expand β about x.

$$\beta_\mu(y) \simeq \beta_\mu(x) + \partial_\nu\beta_\mu(x)(y-x)^\nu$$

$$\widehat{\rho}_{LE} \simeq \frac{1}{Z}\exp\left[-\beta(x)\cdot\widehat{P} + \partial_\nu\beta_\mu(x)\int \mathrm{d}\Sigma_\alpha \widehat{T}^{\alpha\mu}(y-x)^\mu + \int \mathrm{d}\Sigma_\mu \zeta_A(y)\widehat{j}^\mu_A(y)\right]$$

Hydrodynamic polarization

The density operator is approximated in **linear response theory.** The gradients of temperature yield the known results.

$$\mathrm{e}^{\widehat{A}+\widehat{B}} = \mathrm{e}^{\widehat{A}} + \int_0^1 \mathrm{d}z\, \mathrm{e}^{z\widehat{A}}\, \widehat{B}\, \mathrm{e}^{-z\widehat{A}}\, \mathrm{e}^{\widehat{A}} + \cdots$$

$$\widehat{A} = -\beta(x) \cdot \widehat{P}, \quad \widehat{B} = \int_\Sigma \mathrm{d}\Sigma_\rho(y) \zeta_A(y) \widehat{j}^\rho_A(y)$$

The Wigner function reads:

$$\langle \widehat{W}_+(x,p) \rangle \simeq W_+(x,p)|_{\mu_A=0} + \Delta W_+(x,p)$$

$$\Delta W_+(x,p) = \int_\Sigma \mathrm{d}\Sigma_\rho \zeta_A \int_0^1 \mathrm{d}z \langle \widehat{W}_+(x,p) \widehat{j}^\rho_A(y + iz\beta) \rangle_{c,\beta(x)} \qquad \langle \bullet \rangle_{\beta(x)} = \frac{1}{Z} \mathrm{Tr}(e^{-\beta(x)\cdot\widehat{P}} \bullet)$$

The correction to the Wigner function induces polarization

$$S^{\mu}_{tot} = S^{\mu}_{\text{hyd}} + S^{\mu}_{\chi}$$

$$S^{\mu}_{\chi}(p) = \frac{1}{2}\frac{\int_{\Sigma} \mathrm{d}\Sigma \cdot p \,\mathrm{tr}\left[\gamma^{\mu}\gamma^{5}\Delta W_{+}(x,p)\right]}{\int_{\Sigma} \mathrm{d}\Sigma \cdot p \,\mathrm{tr}\left[W_{+}(x,p)|_{\zeta_A=0}\right]}$$

After some calculations (for details, see the paper):

$$S^{\mu}_{\chi}(p) = \frac{g_h}{2}\frac{\int_{\Sigma} \mathrm{d}\Sigma \cdot p\, \zeta_A n_F \left(1-n_F\right)}{\int_{\Sigma} \mathrm{d}\Sigma \cdot p\, n_F}\frac{\varepsilon p^{\mu} - m^2 \hat{t}^{\mu}}{m\varepsilon}$$

Polarization By Axial imbalance!

Helicity and local parity violations

Back boosting to the rest frame of the particle:

$$\boldsymbol{S}_{0,\chi}(p) = \frac{g_h}{2}\frac{|\boldsymbol{p}|}{\varepsilon}\frac{\int_\Sigma \mathrm{d}\Sigma \cdot p\, \zeta_A n_F\,(1-n_F)}{\int_\Sigma \mathrm{d}\Sigma \cdot p\; n_F}\hat{\boldsymbol{p}} \equiv h_\chi(p)\hat{\boldsymbol{p}}$$

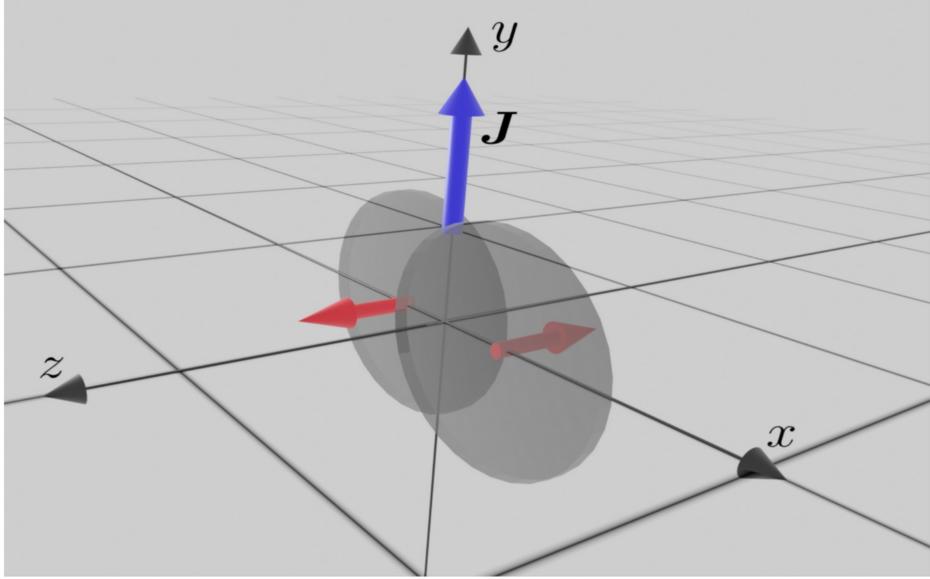
We define the helicity: $h_\chi(p) \equiv \boldsymbol{S}_{0,\chi}(p)\cdot\hat{\boldsymbol{p}}$

Over many events, the axial chemical potential averages to zero

$$\langle\langle\zeta_A\rangle\rangle = 0 \Rightarrow \langle\langle h_\chi(p)\rangle\rangle = 0$$

Geometrical symmetries in heavy ion collisions (**model independent**):

- Parity
- Rotation of π around global angular momentum



Local parity violation: parity is not a symmetry of the density operator.

Parity is a symmetry of ρ **No parity violation:** helicity is a pseudoscalar $h_P(-\boldsymbol{p}) = -h_P(\boldsymbol{p})$	**Parity is not a symmetry of ρ** **Parity violation**: helicity is a scalar $h_S(-\boldsymbol{p}) = h_S(\boldsymbol{p})$

In general:

$$h(p) = h_P(p) + h_S(p)$$

Consider particles at midrapidity: $p_z = 0$, $\boldsymbol{p} = (p_T, \phi)$

Rotational and parity symmetries imply

$$h_P(p_T, \phi) = \sum_k P_k(p_T) \sin[(2k+1)\phi]$$

$$h_S(p_T, \phi) = \sum_k S_k(p_T) \cos[2k\phi]$$

Contribution of the leading harmonics:

$$h(p) \simeq S_0(p_T) + P_0(p_T) \sin\phi + \dots$$

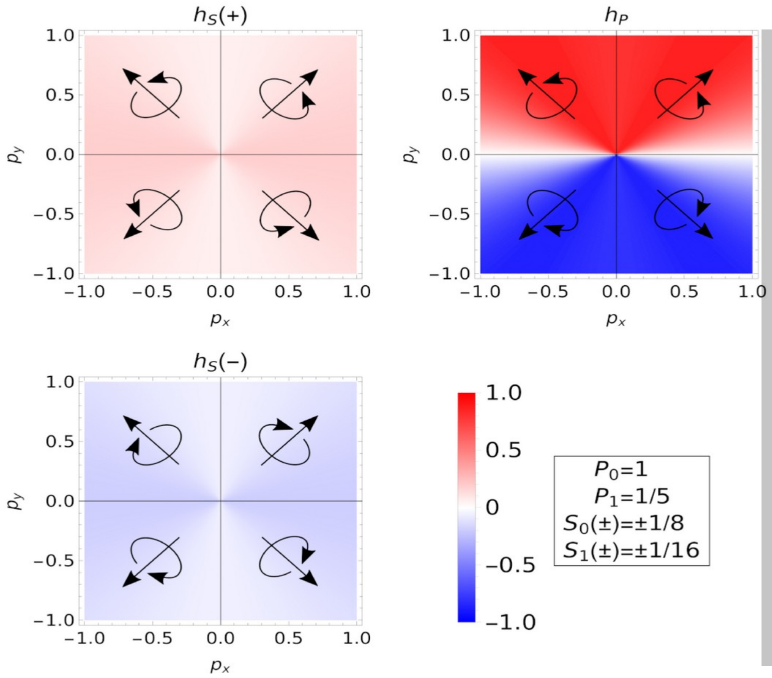
We have to devise a suitable observable to highlight scalar components of the helicity

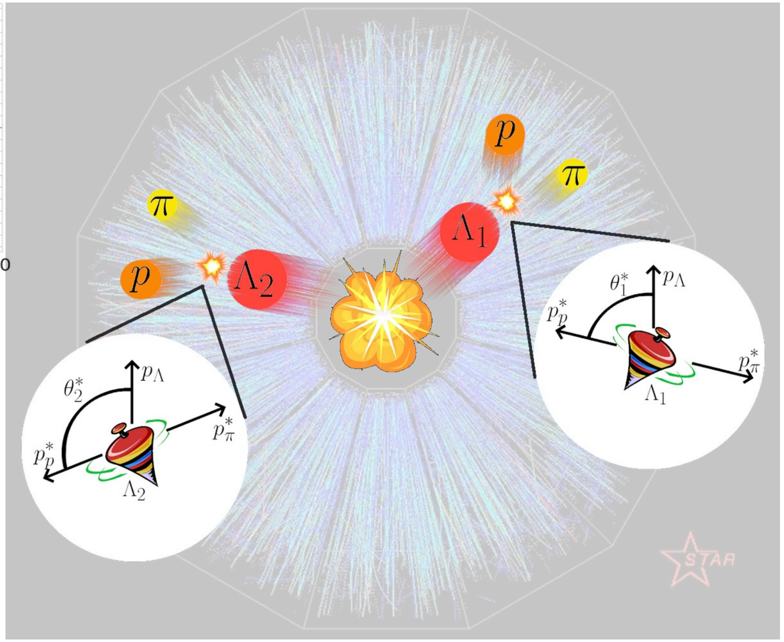
$$\langle\langle S_0 \rangle\rangle = 0 \qquad \langle\langle S_0^2 \rangle\rangle \neq 0$$

Helicity-helicity correlators

Correlation between helicities in the same event, $\Delta\phi$ apart.

$$\langle h_1 h_2(\Delta\phi)\rangle = \frac{1}{N}\int \mathrm{d}^2\mathbf{p}_{T1}\mathrm{d}^2\mathbf{p}_{T2}\,\delta(\phi_2-\phi_1-\Delta\phi)\,h_1(\mathbf{p}_{T1})\,h_2(\mathbf{p}_{T2})\,n(\mathbf{p}_{T1},\mathbf{p}_{T2})$$





Correlator at large angle reveal parity violations!

Parity violation:

$$\langle h_1 h_2(\pi)\rangle > 0$$

No parity violation:

$$\langle h_1 h_2(\pi)\rangle < 0$$

Using the leading harmonics ($\bar{S}_0, \bar{P}_0$ averaged over transverse momentum).

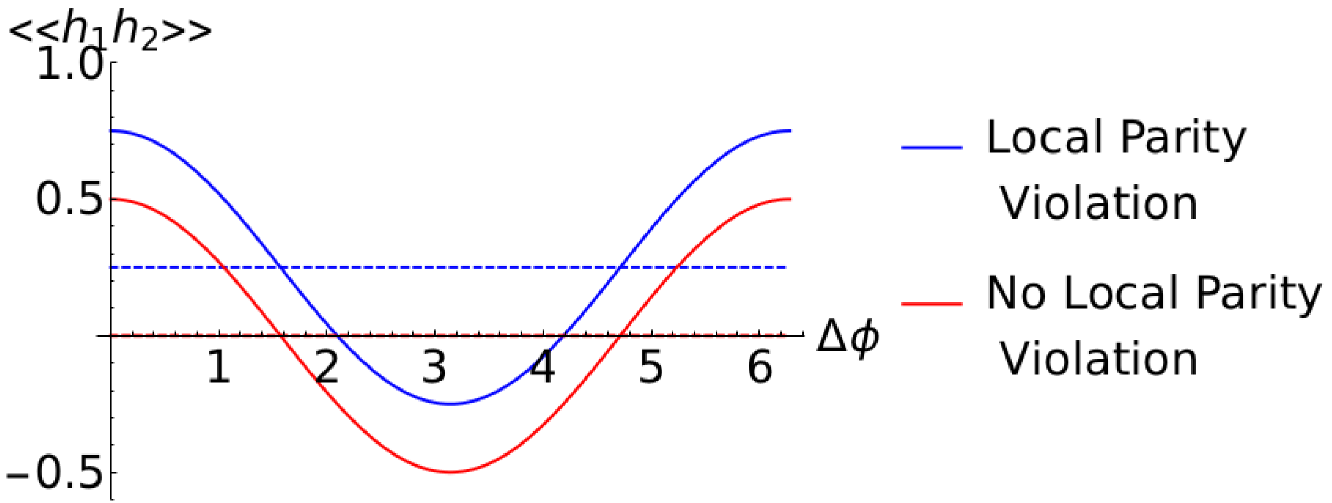
$$\langle h_1 h_2(\Delta\phi)\rangle = \bar{S}_0^2 + \frac{1}{2}\bar{P}_0^2 \cos\Delta\phi$$

Constant term in the correlator reveals local parity breaking

$$\frac{1}{\pi}\int_0^{\pi} \mathrm{d}\Delta\phi \, \langle h_1 h_2(\Delta\phi)\rangle = \bar{S}_0^2 \geq 0$$

This observable:

- **Avoids** the identification of the reaction plane.
- **Independent** of the magnetic field.



Conclusions

- **Local parity violations** can be detected by measuring **polarization**.
- We connected the **mean spin vector to the axial chemical potential**.
- Suitable observable: **helicity-helicity correlator**.
- **Independent of the magnetic field.**

Scan for more details!
arXiv:2009.13449

Thank you for the attention!