# Magnetic Fields in Relativistic Heavy-Ion Collisions: Observables and Applications

Amaresh Jaiswal

NISER Bhubaneswar, Jatni, India

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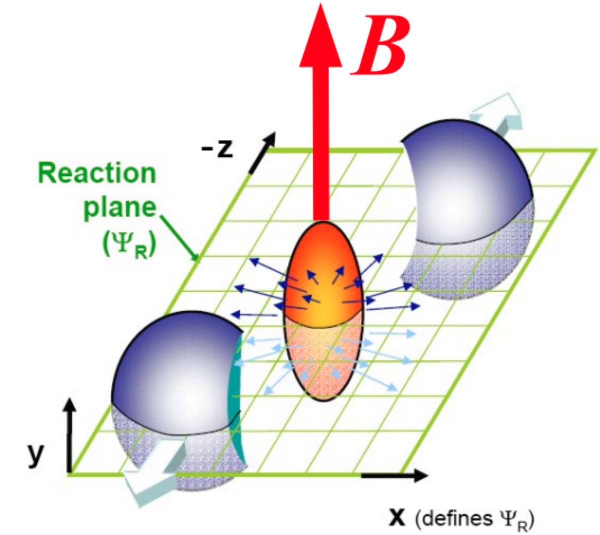
Theory of Hadronic Matter under Extreme Conditions

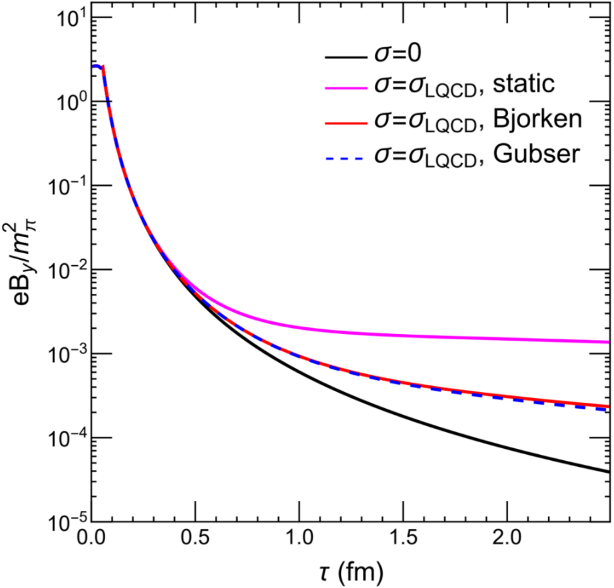
JINR Dubna

# Generation of magnetic field in heavy ion collisions

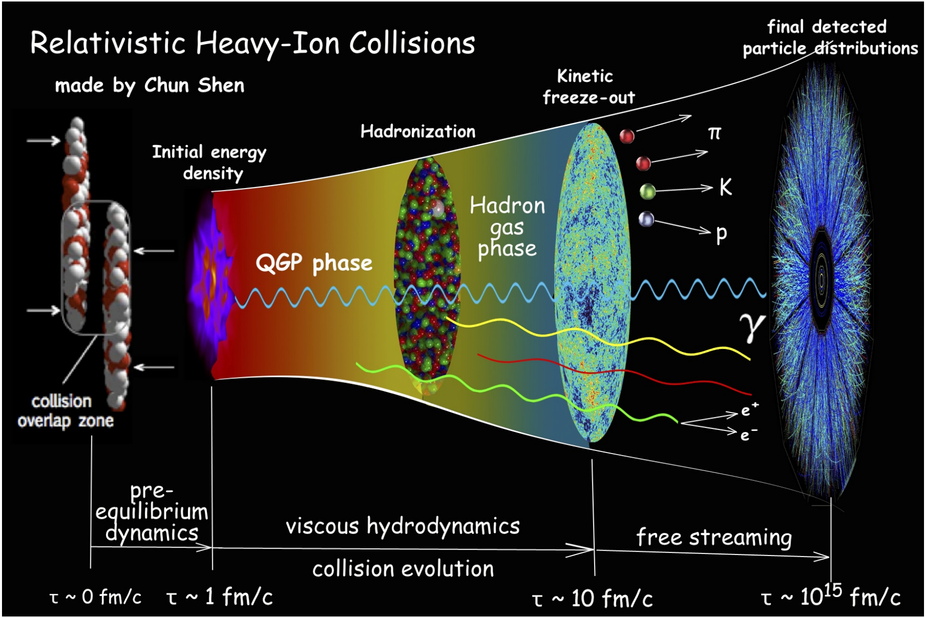



[Adapted from D. Kharzeev @ CPOD 2013.]

# Magnetic field time evolution




[A. Huang, D. She, S. Shi, M. Huang and J. Liao, Phys. Rev. C 107, 034901 (2023).]


Relativistic Heavy-Ion Collisions
made by Chun Shen
final detected particle distributions
Kinetic freeze-out
Hadronization
Initial energy density
Hadron gas phase
QGP phase
π
K
p
γ
e+
e−
collision overlap zone
pre-equilibrium dynamics
viscous hydrodynamics
free streaming
collision evolution
τ ~ 0 fm/c
τ ~ 1 fm/c
τ ~ 10 fm/c
τ ~ 10^15 fm/c

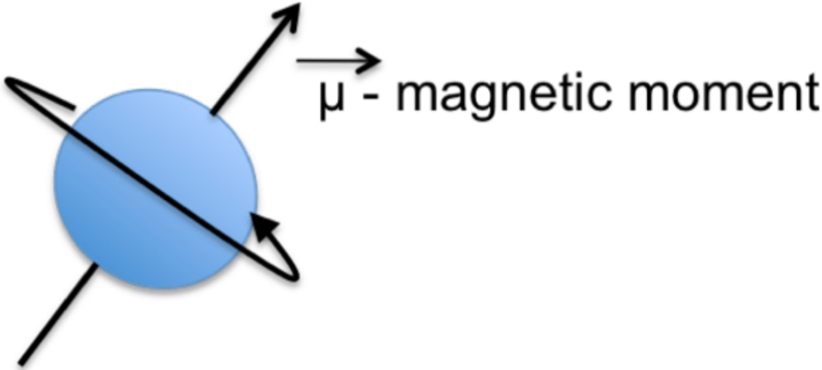
# Magnetic field and heavy quark spin polarization

[S. Dey and AJ, PLB 873 (2026) 140202]

# Heavy quarks in relativistic heavy-ion collisions

- Heavy quarks (charm and bottom) has long been recognized as an excellent probe of transport properties of QCD medium. [D. Banerjee, S. Datta, R. Gavai, and P. Majumdar, PRD 85 (2012) 014510; S. K. Das, S. Plumari, S. Chatterjee, et. al. PLB 768 (2017) 260-264; $\cdots$]
- Heavy quarks are primarily generated in the initial hard scatterings of partons.
- Clean probe of the early-stage properties of heavy-ion collisions.
- Strong transient magnetic fields produced which are significant only during the early stages of the collision.
- Polarized production of heavy quarks in strong field environment.
- Heavy quark polarization: signals of initial magnetic field.

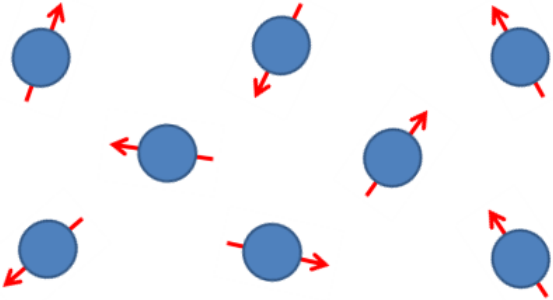
# Heavy quarks: charged, spin-1/2 particles




Interaction with magnetic field: $\mathcal{H} = -\vec{\mu} \cdot \vec{B}$

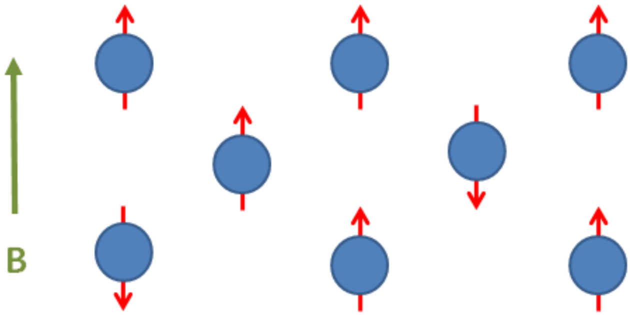
Magnetic moment and spin: $\vec{\mu} = \gamma \vec{s}$

# No external magnetic field



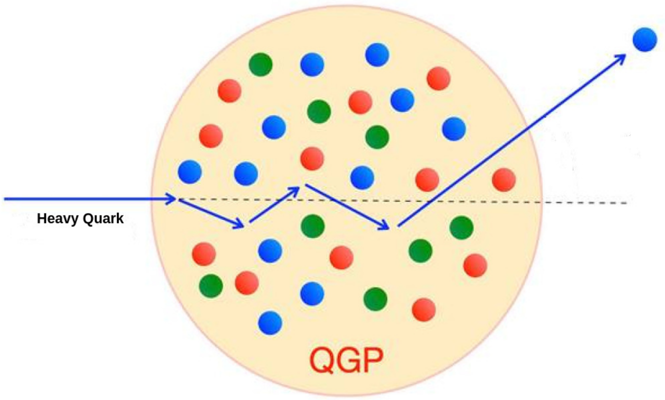
Un-aligned spins of heavy quarks.

# Heavy quarks in magnetic field



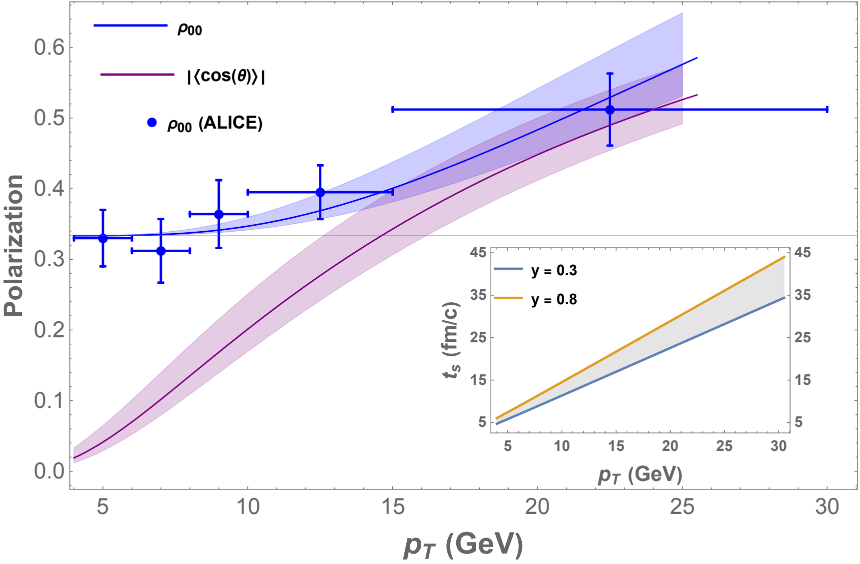

Aligned spins in presence of magnetic field due to polarized production of heavy quarks.

# Heavy quarks in QGP




Polarized heavy quarks propagates through QGP.

# Open heavy hadron polarization




Prediction: [S. Dey and AJ, 2502.20352], Observed: [ALICE, 2504.00714].

# Magnetic field in HQ rest frame

- Lorentz transform initial electromagnetic field to HQ rest frame

$$\boldsymbol{B} = \gamma_v \left(\boldsymbol{B}_{\mathbf{Lab}} - \boldsymbol{E}_{\mathbf{Lab}} \times \boldsymbol{v}\right) + (1-\gamma_v)\left(\frac{\boldsymbol{B}_{\mathbf{Lab}} \cdot \boldsymbol{v}}{|\boldsymbol{v}|^2}\right)\boldsymbol{v}.$$

- $\gamma_v \equiv E/m_Q$ – Lorentz gamma factor ; $\boldsymbol{v} = \boldsymbol{p}/E$ – velocity of HQ.
- $\boldsymbol{E}_{\mathbf{Lab}}$ and $\boldsymbol{B}_{\mathbf{Lab}}$: laboratory-frame electric and magnetic fields.
- For a given $p_T$, the magnetic field component along the $y$-direction in the heavy quark's rest frame increases with rapidity.
- Direction of the magnetic field in the heavy-quark rest frame generally differs from that in the laboratory frame.
- Ensemble average of magnetic field experienced by the HQ:

$$\langle \mathbf{B} \rangle = \int \frac{d^2\Omega_v}{4\pi} f_Q(\theta_v, \phi_v)\left[\gamma_v(\boldsymbol{B}_{\mathbf{Lab}} - \boldsymbol{E}_{\mathbf{Lab}} \times \boldsymbol{v}) + (1-\gamma_v)\left(\frac{\boldsymbol{B}_{\mathbf{Lab}} \cdot \boldsymbol{v}}{|\boldsymbol{v}|^2}\right)\boldsymbol{v}\right].$$

- Assuming isotropic velocity distribution, $\langle \mathbf{B} \rangle = \dfrac{1}{3}(1+2\gamma_v)\boldsymbol{B}_{\mathbf{Lab}}$ .

# Rotational Brownian motion

- Random rotational motion (orientation and angular velocity) of a microscopic particle due to thermal fluctuations caused by collisions with surrounding medium particles.
- Rotational Brownian motion problem: first considered by Debye.
- For classical spins, the Langevin equation corresponds to the stochastic Landau–Lifshitz-Gilbert equation

$$\frac{d\mathbf{s}}{d\tau} = \mathbf{s} \times \left[\tilde{\mathbf{B}} + \boldsymbol{\xi}(\tau)\right] - \lambda\, \mathbf{s} \times \left(\mathbf{s} \times \tilde{\mathbf{B}}\right)$$

- Here $\tilde{\mathbf{B}} \equiv \gamma \mathbf{B} = -\frac{\partial \mathcal{H}}{\partial \mathbf{s}}$ and $\gamma$ is the gyromagnetic ratio $\boldsymbol{\mu} = \gamma\, \mathbf{s}$.
- $\mathbf{s} \times \tilde{\mathbf{B}}$ represents precession dynamics of the system.
- $\boldsymbol{\xi}(\tau)$ is the random torque on the particle by the medium.
- $\lambda$ is the damping coefficient.

# Langevin and Fokker-Planck equations

- Generalized multivariate Langevin equation

$$\frac{dy_i}{d\tau} = A_i(y,\tau) + C_{ik}(y,\tau)\,\xi_k(\tau).$$

- Reduces to Landau–Lifshitz-Gilbert equation with $s_i = y_i$ and

$$A_i = \epsilon_{ijk} s_j \tilde{B}_k + \lambda\,(s^2\delta_{ik} - s_i s_k)\tilde{B}_k, \qquad C_{ik} = \epsilon_{ijk} s_j.$$

- Assume statistical properties of white noise for the random torque

$$\langle \xi_k(\tau) \rangle = 0, \qquad \langle \xi_k(\tau_1)\,\xi_l(\tau_2) \rangle = 2\,D\,\delta_{kl}\,\delta(\tau_1 - \tau_2).$$

- Using the Kramers–Moyal expansion, one arrives at the Fokker–Planck equation

$$\frac{\partial \mathcal{P}}{\partial \tau} = -\frac{\partial}{\partial y_i}\left[A_i(y,\tau) + D C_{jk}(y,\tau)\frac{\partial C_{ik}(y,\tau)}{\partial y_j}\right]\mathcal{P} + D\frac{\partial^2}{\partial y_i \partial y_j}[C_{ik}(y,\tau)C_{jk}(y,\tau)\mathcal{P}]$$

# Fokker-Planck equation for spin

- Fokker–Planck equation corresponding to the stochastic Landau–Lifshitz-Gilbert equation

$$\frac{\partial \mathcal{P}}{\partial \tau} = -\frac{\partial}{\partial s_i}\Big[\epsilon_{ijk}\, s_j \tilde{B}_k + \lambda(s^2\delta_{ik} - s_i\, s_k)\tilde{B}_k - 2Ds_i\Big]\mathcal{P} + D\,\frac{\partial^2}{\partial s_i\,\partial s_j}\big[s^2\delta_{ij} - s_i s_j\big]\mathcal{P}$$

- Assuming that the field $\tilde{\mathbf{B}}$ is independent of particle spin $\mathbf{s}$

$$\frac{\partial \mathcal{P}}{\partial \tau} = D\,\frac{\partial}{\partial \mathbf{s}} \cdot \left[\mathbf{s} \times \left(\mathbf{s} \times \left(\frac{\lambda}{D}\tilde{\mathbf{B}} - \frac{\partial}{\partial \mathbf{s}}\right)\right)\right]\mathcal{P}$$

- To find: Probability of a spin-polarized particle having an instantaneous orientation in the direction $(\theta, \phi)$.
- Consider a sphere in spin-space of fixed radius $s$, i.e., $\mathbf{s} = (s, \theta, \phi)$: each point on the sphere represents a different spin orientation.

$$\tau_s \frac{\partial \mathcal{P}}{\partial \tau} = \frac{1}{\sin\theta}\frac{\partial}{\partial \theta}\left[\sin\theta\left(\frac{\lambda}{D}\frac{\partial \mathcal{H}}{\partial \theta}\mathcal{P} + \frac{\partial \mathcal{P}}{\partial \theta}\right)\right], \qquad \tau_s \equiv \frac{1}{D}.$$

- Here, $\mathcal{H} = -\boldsymbol{\mu}\cdot\boldsymbol{B} = -\boldsymbol{s}\cdot\tilde{\boldsymbol{B}}$.

# Heavy quark polarization

- Assume all heavy quarks are initially spin polarized along $\theta = \theta_0$ direction, i.e., for the initial cond. $\mathcal{P}(\theta, 0) = \frac{1}{2\pi}\delta(\cos\theta - \cos\theta_0)$.
- Considering $B(\tau) = B_0\, e^{-\tau/\tau_B}$, vector polarization (baryons) is

$$\langle\cos\theta\rangle = \cos\theta_0 e^{-\frac{2\tau}{\tau_s}} - \frac{2\alpha\tau_B}{3} e^{-\frac{2\tau}{\tau_s}} \left[\frac{1-\exp\left[-\frac{(\tau_s - 2\tau_B)\tau}{\tau_s\tau_B}\right]}{\tau_s - 2\tau_B} - \frac{1-\exp\left[-\frac{(4\tau_B + \tau_s)\tau}{\tau_s\tau_B}\right]}{4\tau_B + \tau_s}\right]$$

- Tensor polarization (vector mesons) is

$$\langle\cos^2\theta\rangle = \frac{1}{3} + \frac{2}{3} e^{-\frac{6\tau}{\tau_s}} + \frac{2\alpha\tau_B}{5} e^{-\frac{6\tau}{\tau_s}} \left[\frac{1}{(\tau_s - 4\tau_B)}\left(1-\exp\left[-\frac{(\tau_s - 4\tau_B)\tau}{\tau_s\tau_B}\right]\right) - \frac{1}{(\tau_s + 6\tau_B)}\left(1-\exp\left[-\frac{(\tau_s + 6\tau_B)\tau}{\tau_s\tau_B}\right]\right)\right]\cos\theta_0$$

- So far classical treatment. Similar results at leading order by considering transition between two spin states [arXiv:2605.06461].

# Heavy baryon and meson polarization

- For baryons, the angular distribution of one of the decay daughter

$$\frac{dN}{d\cos\theta^*} = \frac{1}{2}\Big(1 + \alpha_B|\vec{P}_B|\cos\theta^*\Big)$$

- $\alpha_B$ is decay parameter. Using this distribution, one gets

$$\langle\cos\theta^*\rangle = \int \cos\theta^* \frac{dN}{d\cos\theta^*} d\cos\theta^* \implies |\vec{P}_B| = \frac{3}{\alpha_B}\langle\cos\theta^*\rangle$$

- Similarly, for mesons, the angular distribution is

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

- $\rho_{00}$ is element of spin density matrix; unpolarized $\implies \rho_{00} = 1/3$.
- Using this distribution, one gets

$$\langle\cos^2\theta^*\rangle = \int \cos^2\theta^* \frac{dN}{d\cos\theta^*} d\cos\theta^* \implies \Delta\rho_{00} = \frac{5}{2}\Big[\langle\cos^2\theta^*\rangle - \frac{1}{3}\Big]$$

- Here $\Delta\rho_{00} \equiv \rho_{00} - 1/3$

# Ensemble average of angular anisotropy

- Consider leading terms in the polarization

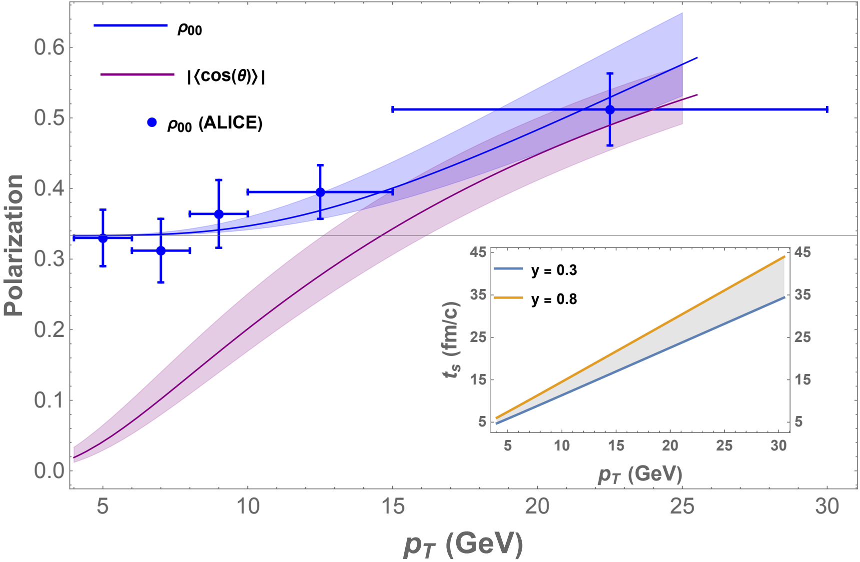
$$\langle \cos\theta \rangle = \cos\theta_0\, e^{-2\tau/\tau_s}, \qquad \langle \cos^2\theta \rangle = \frac{1}{3} + \frac{2}{3}\, e^{-6\tau/\tau_s}.$$

- One can show: $\dfrac{\langle \cos\theta^* \rangle}{\langle \cos\theta \rangle} = C_B, \ \dfrac{\langle \cos^2\theta^* \rangle - 1/3}{\langle \cos^2\theta \rangle - 1/3} = C_M$ [arXiv:2605.12554].

$$\implies |\vec{P}_B| = \frac{3\cos\theta_0}{\alpha_B}\, C_B\ e^{-2\tau/\tau_s}, \quad \Delta\rho_{00} = \frac{5}{3}\, C_M\, e^{-6\tau/\tau_s}$$

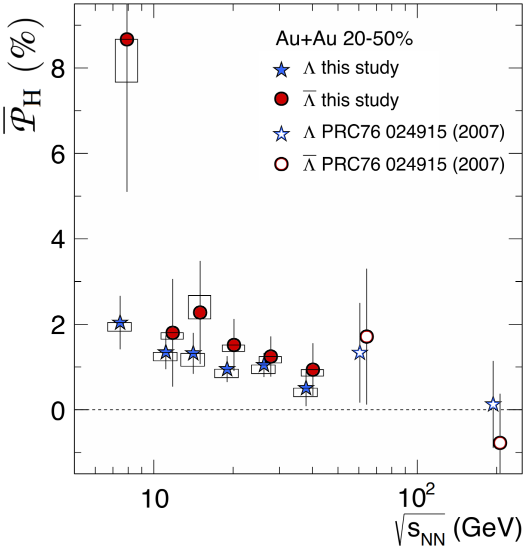
- Here $\tau_s$: spin relaxation time. Treated as a fit parameter.
- Initially $\theta_0 = 0, \pi$ depending on charge of the quark.
- Baryon, anti-baryon: opposite sign; meson, anti-meson: same sign
- Quarkonium pol. small: heavy quark and anti-quark opp. pol.
- Static uniform fireball of constant temperature, $\tau = \frac{(R/\gamma_v)}{v_T}$.
- In the mid-rapidity region, $v_T = \frac{p_T}{E}$ and $\gamma_v = \frac{E}{m_Q}$.

# Open heavy hadron polarization




Heavy quarks polarized along initial magnetic field direction.

# Light quark polarization due to angular momentum

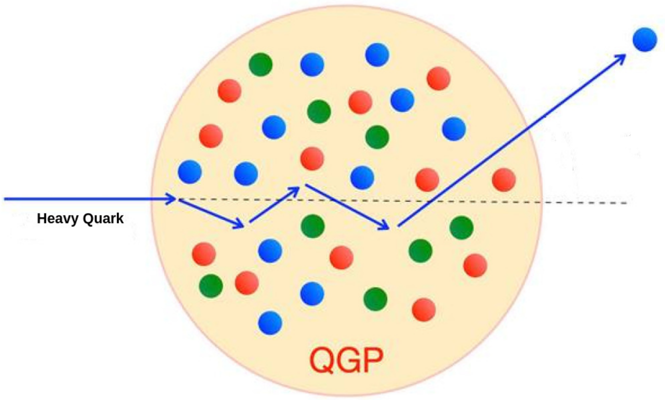



[STAR collaboration, Nature 548 (2017) 62-65]

# Polarization harmonics for fireball geometry

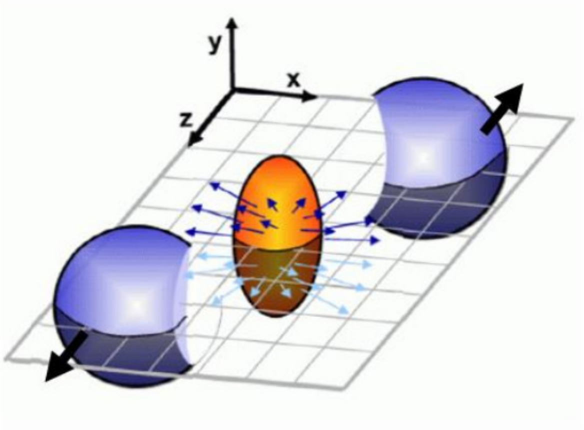
[AJ, arXiv:2601.22882]

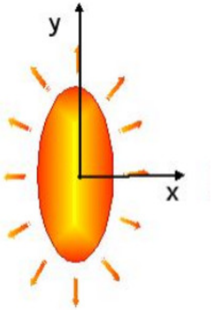
# Heavy quarks in QGP




Polarized heavy quarks propagates through QGP.

# Heavy quarks in QGP




Propagation through anisotropic QGP.

# Fireball geometry and path length

- Average path length can be written as a Fourier series,

$$\langle L(\phi)\rangle = L_0 \left[1 + \sum_{n=2}^{\infty} 2\,\ell_n \cos n(\phi - \Psi_n)\right]$$

- Transverse geometry whose boundary is parametrized as

$$R(\varphi) = R_0 \left[1 + \sum_{n=2}^{\infty} a_n \cos n(\varphi - \Phi_n)\right], \quad |a_n| \ll 1$$

- For convex geometries with weak anisotropies, one has

$$\frac{\delta\langle L(\phi)\rangle}{L_0} \approx \frac{\delta R(\phi)}{R_0} \implies 2\,\ell_n = a_n$$

- Initial state in HICs are characterized by

$$\epsilon_n\, e^{in\Phi_n} \equiv -\frac{\langle r^n\, e^{in\varphi}\rangle}{\langle r^n\rangle}, \qquad n \geq 2$$

- For weakly deformed & smooth transverse profile, $\ell_n = -\dfrac{\epsilon_n}{2\,(n+2)}$

# Heavy hadron polarization

- Solution for Fokker-Planck equation obtained earlier

$$\langle \cos\theta \rangle = \cos\theta_0 \, e^{-2\tau/\tau_s}, \qquad \langle \cos^2\theta \rangle = \frac{1}{3} + \frac{2}{3}\, e^{-6\tau/\tau_s}.$$

- Spin polarization of baryons:

$$|\vec{P}_B| = \frac{3}{\alpha_B}\, C_B \, \langle \cos\theta \rangle = \frac{3\cos\theta_0}{\alpha_B}\, C_B \; e^{-2\tau/\tau_s}$$

- Spin alignment of vector mesons:

$$\Delta\rho_{00} \equiv \rho_{00} - 1/3 = \frac{5}{2}\, C_M \left[ \langle \cos^2\theta \rangle - \frac{1}{3} \right] = \frac{5}{3}\, C_M \, e^{-6\tau/\tau_s}$$

- Spin polarization/alignment can be written in the generic form as

$$P\,(\boldsymbol{p}) = A\, e^{-\alpha\,\tau/\tau_s}$$

- Here, $\alpha = 2$: baryons; $\alpha = 6$: mesons. Two unknowns: $A$ and $\tau_s$.

# Polarization harmonics

- Duration for which the heavy quark undergoes Brownian motion:

$$\tau = \frac{[\langle L(\phi)\rangle\, m_Q]}{|\boldsymbol{p}|}, \qquad |\boldsymbol{p}| = \sqrt{p_T^2 \cosh^2 y + m_Q^2\, \sinh^2 y}$$

- Substituting in $P\,(\boldsymbol{p}) = A\, e^{-\alpha\, \tau/\tau_s}$, one obtains

$$P\,(p_T,\, \phi,\, y) = A \exp\!\left(-\frac{\alpha\, m_Q\, L_0}{|\boldsymbol{p}|\tau_s}\right) \left[1 + \sum_{n=2}^{\infty} 2\, p_n \cos n\,(\phi - \Psi_n)\right]$$

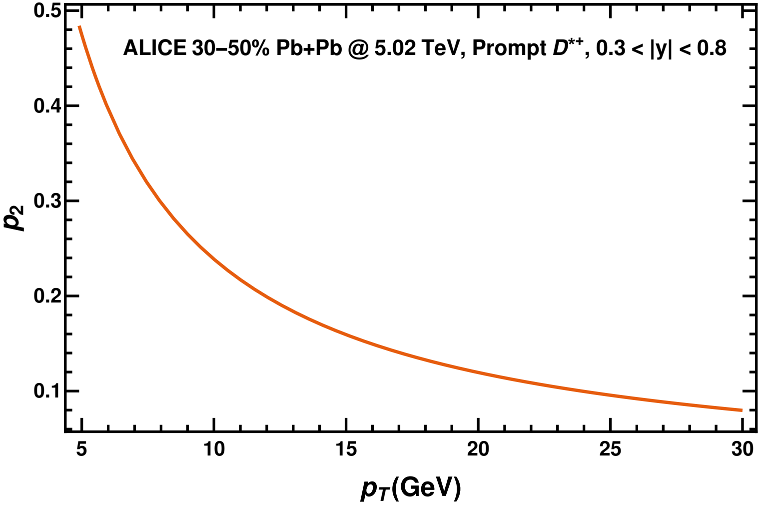
- The polarization harmonics are

$$p_n\,(p_T, y) = \frac{\alpha\, m_Q\, L_0\, \epsilon_n}{2\,(n+2)\,|\boldsymbol{p}|\,\tau_s}$$

- Differential polarization:

$$\frac{dP}{d^2p_T\, dy} = \left.\frac{dN}{d^2p_T\, dy}\right|_{\rm prompt} \times P\,(p_T,\, \phi,\, y)$$

# Elliptic polarization harmonic




$L_0 = 10$ fm, $\tau_s = 1.31$ fm, $\alpha = 6$ for mesons, $m_Q = 1.27$ GeV, $y = 0.55$ for rapidity, $\epsilon_2 = 0.38$ from M-C Glauber.

# Numerical estimates

- Fixed-Order + Next-to-Leading Logarithm parametrization [Liu, Plumari, Das, Greco, Ruggieri, PRC 102 (2020) 044902]:

$$\left.\frac{dN}{d^2p_T\,dy}\right|_{\rm prompt} = \frac{a_0}{m_Q^2\left[1 + a_3\left(\frac{p_T}{m_Q}\right)^{a_1}\right]^{a_2}}$$

- The parameters are: $a_0 = 32.71558$, $a_1 = 1.95061$, $a_2 = 3.13695$, and $a_3 = 0.11981$.
- Use the fit parameters from earlier work, $L_0 = 10$ fm and $\tau_s = 1.31$ fm, $\alpha = 6$ for mesons, $\epsilon_2 = 0.38$ from Monte Carlo Glauber, charm-quark mass $m_Q = 1.27$ GeV, and $y = 0.55$.
- $p_T$ averaged elliptic polarization harmonic:

$$\langle p_2\rangle = \frac{\int p_T\,dp_T\,d\phi\,\cos\left[2(\phi - \Psi_2)\right]\frac{dP}{d^2p_T\,dy}}{\int p_T\,dp_T\,d\phi\,\frac{dP}{d^2p_T\,dy}}$$

- The value is significant: $\langle p_2\rangle \simeq 0.17$. Need for measurement!

# Quantum spin dynamics of heavy quarks

[S. Jaiswal, S. Dey and AJ, arXiv:2605.06461]

# Quantum spin dynamics

- The spin density matrix of heavy quarks:

$$\rho(\tau, \mathbf{x}, \mathbf{p}) = \frac{1}{2}\left[\mathbf{1} + \boldsymbol{\mathcal{P}}(\tau, \mathbf{x}, \mathbf{p}) \cdot \boldsymbol{\sigma}\right]$$

- Magnetic field as the source of the initial spin polarization.
- Choose the quantization axis along the direction of the initial magnetic field and diagonalize the density matrix in this basis:

$$\rho(\tau) = \begin{pmatrix} P_\uparrow(\tau) & 0 \\ 0 & P_\downarrow(\tau) \end{pmatrix}, \quad P_\uparrow(\tau) = \frac{1 + \mathcal{P}(\tau)}{2}, \quad P_\downarrow(\tau) = \frac{1 - \mathcal{P}(\tau)}{2}$$

- Normalization: $P_\uparrow + P_\downarrow = 1$, define polarization: $\mathcal{P} = P_\uparrow - P_\downarrow$.
- Medium interactions can induce spin flip transitions between two states. Transition rate equations:

$$\frac{dP_\uparrow}{d\tau} = -\Gamma_{\uparrow\to\downarrow} P_\uparrow + \Gamma_{\downarrow\to\uparrow} P_\downarrow \quad , \qquad \frac{dP_\downarrow}{d\tau} = -\Gamma_{\downarrow\to\uparrow} P_\downarrow + \Gamma_{\uparrow\to\downarrow} P_\uparrow$$

- Evolution equation for the spin polarization:

$$\frac{d\mathcal{P}}{d\tau} = -\left(\Gamma_{\uparrow\to\downarrow} + \Gamma_{\downarrow\to\uparrow}\right)\mathcal{P} + \left(\Gamma_{\downarrow\to\uparrow} - \Gamma_{\uparrow\to\downarrow}\right)$$

# Spin polarization evolution equation

- Spin-relaxation time and eq. polarization and evolution equation:

$$\tau_s \equiv \frac{1}{\Gamma_{\uparrow\to\downarrow} + \Gamma_{\downarrow\to\uparrow}}, \qquad \mathcal{P}_{\rm eq} \equiv \frac{\Gamma_{\downarrow\to\uparrow} - \Gamma_{\uparrow\to\downarrow}}{\Gamma_{\uparrow\to\downarrow} + \Gamma_{\downarrow\to\uparrow}}, \qquad \frac{d\mathcal{P}}{d\tau} = -\frac{\mathcal{P} - \mathcal{P}_{\rm eq}}{\tau_s}$$

- For constant transition rates, the solution is:

$$\mathcal{P}(\tau) = \mathcal{P}_{\rm eq} + (\mathcal{P}_0 - \mathcal{P}_{\rm eq})\, e^{-(\tau-\tau_0)/\tau_s}$$

- If two rates are equal, i.e., $\Gamma_{\uparrow\to\downarrow} = \Gamma_{\downarrow\to\uparrow} \equiv \Gamma_s$, then $\mathcal{P}_{\rm eq} = 0$ and

$$\mathcal{P}(\tau) = \mathcal{P}_0\, e^{-(\tau-\tau_0)/\tau_s}$$

- Open heavy mesons formed via coalescence/fragmentation:

$$\rho_{00}^{\rm coal} = \frac{1 - \mathcal{P}_Q \mathcal{P}_q}{3 + \mathcal{P}_Q \mathcal{P}_q}, \qquad \rho_{00}^{\rm frag} = \frac{1 + \beta \mathcal{P}_Q^2}{3 - \beta \mathcal{P}_Q^2}$$

[Z.-T. Liang, X.-N. Wang, Phys. Lett. B 629 (2005) 20-26]

- For very high energy, $\sqrt{s_{\rm NN}} = 5.02$ TeV, $\mathcal{P}_q \simeq 0$. Frag. dominant.

# Spin alignment and polarization harmonics

- For vector mesons, spin-alignment signal is $\Delta\rho_{00} = \rho_{00}^{\rm frag} - 1/3$

$$\Delta\rho_{00}(\phi, p_T, y) = \Delta\rho_{00}^{(0)}(p_T, y)\left[1 + 2\sum_{n=2}^{\infty} p_n^{D^{*+}}(p_T, y)\cos n(\phi - \Psi_n)\right]$$

- Here,

$$\Delta\rho_{00}^{(0)}(p_T, y) = \frac{4X(p_T, y)}{3[3 - X(p_T, y)]}\,, \quad X(p_T, y) \equiv A\exp\left[-2\kappa\frac{m_c}{|\mathbf{p}|}\right]$$

- Polarization harmonics coefficient:

$$p_n^{D^{*+}}(p_T, y) = \frac{6}{3 - X(p_T, y)}\frac{\kappa}{2}\frac{m_c}{|\mathbf{p}|}\frac{\epsilon_n}{n+2}$$

- Qulitatively similar features as the classical stochastic treatment.
- Open heavy-flavor spin observables are clean probes of early-time dynamics: initial magnetic field and geometric anisotropies.
- Dedicated measurements of open-charm hadrons polarization and polarization harmonics are needed.

# Possible directions to be explored

- Fireball assumed to be static with constant average temperature.
- More realistic space-time evolution of the fireball and external magnetic field necessary.
- Incorporate momentum drag and diffusion in the framework.
- Linear response formulation for spin diffusion and drag.
- Calculation of spin relaxation time $\tau_s = 1/D$ for heavy quarks.
- Lattice QCD results for $B - B$ correlators may be helpful.
- Derivation of an Einstein-Stokes-like relation between the spin diffusion and dissipative parameters in spin hydrodynamics.
- Derivation of rotational Fokker-Planck equation from Kinetic theory with non-local collision terms.
- Evlauation of spin transition rates $\Gamma_s$ from microscopic theory.
- New area to study non-equilibrium spin dynamics in HIC.

# Application of magnetic field in HIC

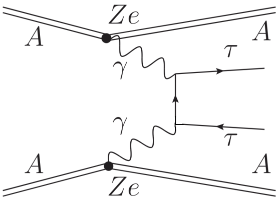
[AJ, Phys.Lett.B 876 (2026) 140383]

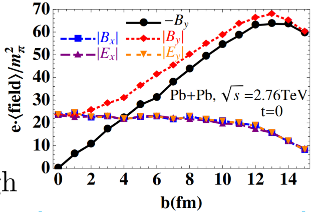
# Tau leptons in heavy ion collisions

- Observation of $CP$ violation in any decay of leptons: indication of physics beyond the Standard Model.
- Hint to the origin of matter–antimatter asymmetry in universe.
- $\tau$-lepton: particularly sensitive probe for BSM physics.
- Polarized $\tau$ decay from polarized beam in $e^+e^-$ colliders proposed for capturing $CP$ violation signals [Y. S. Tsai, PRD 1994; PLB 1996].
- Heaviest lepton, mass: 1.777 GeV, lifetime: $2.9 \times 10^{-13}$ s.
- Produced early in heavy ion collisions due to large mass.
- Should witness the strong magnetic field; similar to heavy quarks.
- Decays outside fireball but before reaching the detectors.
- Neutrinos in final state; too much background in HIC.

# Ultraperipheral heavy ion collisions

- Ultraperipheral heavy-ion collisions (UPCs): $b > 2R$.
- Clean environment for investigating photon-induced processes.
- In UPCs, $\tau^+\tau^-$ pairs are produced exclusively via $\gamma\gamma$ fusion [ATLAS, CMS].
- Energy of $\tau$ leptons could be obtained using zero-degree calorimeter data.
- Use collinear approximation.
- In UPCs, the spectator nuclei generate strong magnetic fields.
- Spin polarization of $\tau$-lepton pairs through alignment of their magnetic moments.




[Deng & Huang, 1201.5108]

- Anisotropic emission patterns of the decay products.
- Polarization asymmetry between $\tau^\mp$: probe for $CP$ violation.

# Magnetic field and $\tau$ polarization

- Lorentz-transformed magnetic field in the $\tau$ rest frame

$$\boldsymbol{B} = \gamma \left( \boldsymbol{B}_{\mathbf{Lab}} - \boldsymbol{E}_{\mathbf{Lab}} \times \boldsymbol{v} \right) + (1-\gamma) \left( \frac{\boldsymbol{B}_{\mathbf{Lab}} \cdot \boldsymbol{v}}{\beta^2} \right) \boldsymbol{v}$$

- $\tau$ polarization vector aligned along the magnetic field

$$\boldsymbol{P}_\tau = P_\tau \, \hat{\boldsymbol{B}}$$

- We adopt *helicity frame*: the spin quantization axis along $\tau$ momentum direction in its rest frame.
- Relevant component of the polarization vector is

$$P_\tau^{\rm hel} \equiv \boldsymbol{P}_\tau \cdot \hat{\boldsymbol{v}} = P_\tau \, \frac{|\boldsymbol{B}_{\mathbf{Lab}}|}{|\boldsymbol{B}|} \cos\psi$$

- Assuming electric field $\boldsymbol{E}_{\mathbf{Lab}}$ produced in UPCs is small

$$P_\tau^{\rm hel} = P_\tau \, \frac{\cos\psi}{\sqrt{\cos^2\psi + \gamma^2 \sin^2\psi}}$$

- For isotropic $\tau$ momenta, $P_\tau^{\rm hel} = 0$; consider "half"-ensemble.

# Pion decay mode: $\tau \to \pi\,\nu_\tau$

- Normalized angular distribution for decay in $\tau$ rest frame is

$$\frac{1}{\Gamma_\tau}\frac{\mathrm{d}\Gamma_\pi}{\mathrm{d}\cos\theta_\pi} = \frac{1}{2}B_\pi\left(1 + P_\tau^{\mathrm{hel}}\cos\theta_\pi\right)$$

- Express the above equation in the form

$$\frac{1}{\Gamma_\tau}\frac{\mathrm{d}\Gamma_\pi}{\mathrm{d}\cos\theta_\pi}\left(\tau^\mp \to \pi^\mp\nu_\tau\right) = \frac{1}{2}B_\pi\left(1 + \alpha\,P_\tau^\mp\cos\theta_\pi\right)$$

- Here, $\alpha \equiv (|\boldsymbol{B}_{\mathbf{Lab}}|/|\boldsymbol{B}|)\cos\psi$ and $P_\tau^\mp$ is the polarization of $\tau^\mp$.
- In terms of pion energy fraction with collinear approximation,

$$\cos\theta_\pi = 2z_\pi - 1, \qquad \text{where } z_\pi \equiv E_\pi/E_\tau$$

- "half"-ensemble average over $\tau$ with complimentary $\psi$ ranges

$$P_\tau^\mp = 3\,\frac{\langle 2z_\pi - 1\rangle_{\pi^\mp}}{B_\pi\,\langle\alpha\rangle_{\tau^\mp}}$$

- We propose the observable: $\Delta_\pi \equiv 1 - \left|\frac{P_\tau^-}{P_\tau^+}\right| = 1 - \left|\frac{\langle 2z_\pi - 1\rangle_{\pi^-}}{\langle 2z_\pi - 1\rangle_{\pi^+}}\right|$

# UPCs as arena for BSM physics

- Novel application of electromagnetic fields generated in HICs.
- Polarized $\tau$ decay: new avenue to test fundamental symmetries.
- Leverages the unique strong-field environment of UPCs, not attainable in conventional collider experiments.
- Physics case for Zero Degree Calorimeter (ZDC) upgrades.
- Detailed analysis of higher-order QED and QCD corrections in $\gamma\gamma \to \tau^+\tau^-$ required.
- Feasibility of reconstructing $\tau$ polarization challenging due to limited production rates.
- More data for $\tau$ events in UPCs required to increase statistics for accurate measurements.
- Heavy ion collision experiments still have enormous potential for exciting physics.

# Thank you!