

Spin polarization and magnetic field in relativistic heavy ion collisions

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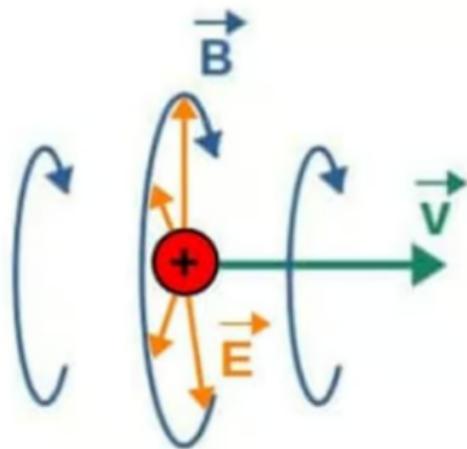
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Moving charges create a magnetic field

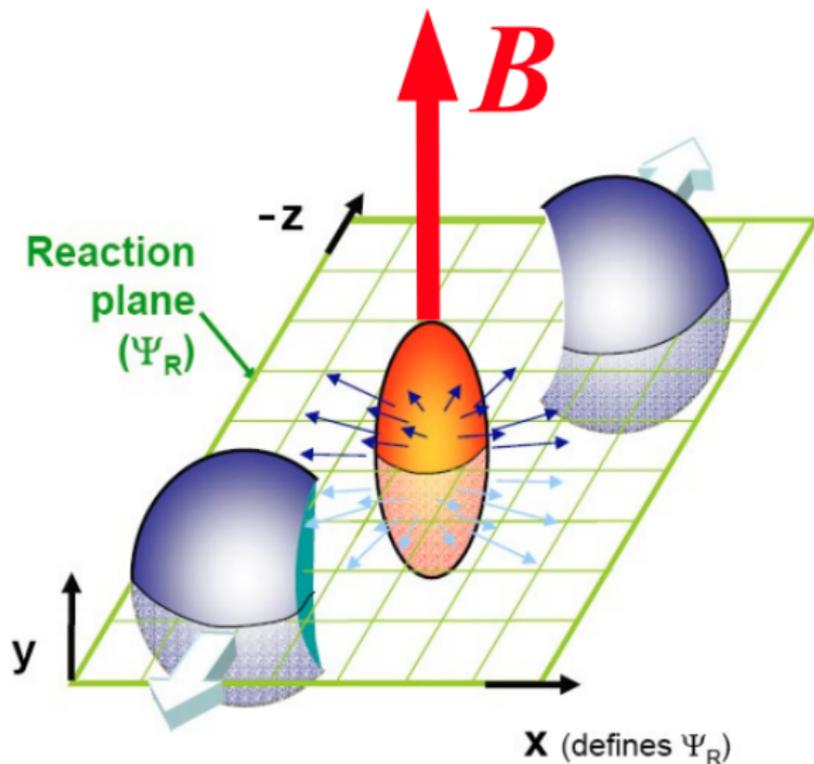


A moving charged particle generates magnetic field due to its motion.

Biot – Savart law :

$$\mathbf{B}(t, \mathbf{r}) = \frac{\mu_0 q}{4\pi} \frac{\mathbf{v} \times \hat{\mathbf{R}}}{R^2}, \quad \mathbf{R} \equiv \mathbf{r} - \mathbf{r}_0$$

Generation of magnetic field in heavy ion collisions



[Adapted from D. Kharzeev @ CPOD 2013.]

Moving nuclei with relativistic velocities

Using Lienard-Wiechert potentials [K. Tuchin, AHEP (2013) 490495]:

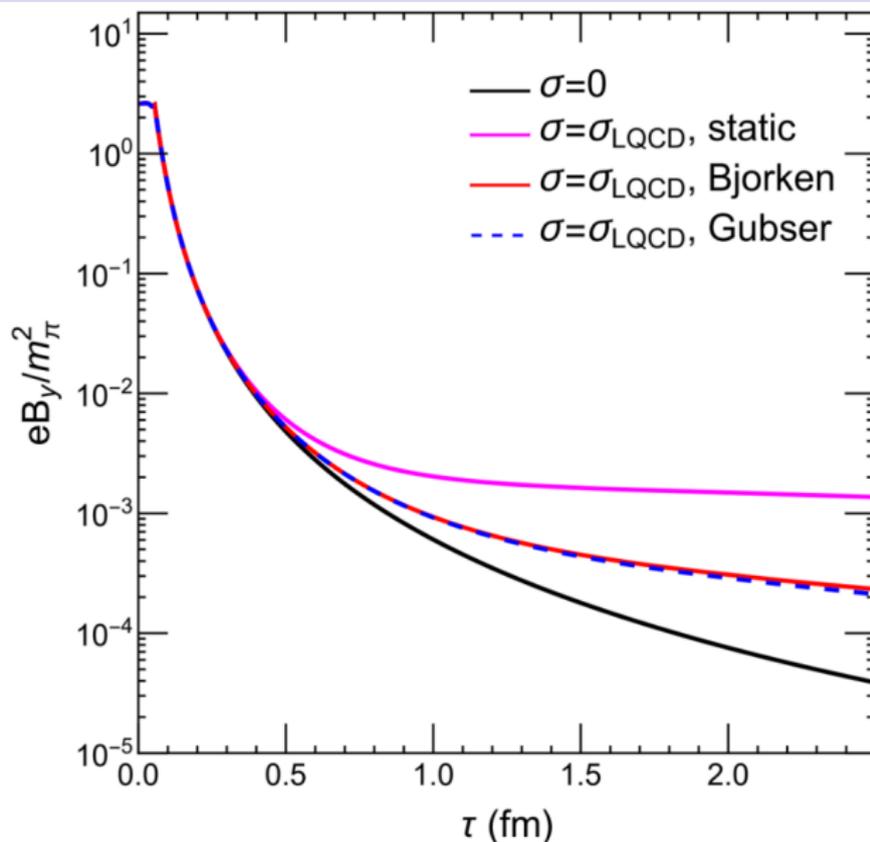
$$e\mathbf{E}(t, \mathbf{r}) = \alpha_{\text{em}} \sum_a \frac{(1 - v_a^2) \mathbf{R}_a}{R_a^3 [1 - (\mathbf{R}_a \times \mathbf{v}_a)^2 / R_a^2]^{3/2}},$$

$$e\mathbf{B}(t, \mathbf{r}) = \alpha_{\text{em}} \sum_a \frac{(1 - v_a^2) (\mathbf{v}_a \times \mathbf{R}_a)}{R_a^3 [1 - (\mathbf{R}_a \times \mathbf{v}_a)^2 / R_a^2]^{3/2}},$$

where $\mathbf{R}_a \equiv \mathbf{r} - \mathbf{r}_a$.

- Magnetic field due to motion of charges relative to an observer.
- Interplay between \mathbf{E} and \mathbf{B} in different reference frames.
- $\mathbf{B} \sim 10^{14}$ Tesla produced in relativistic heavy-ion collisions.

Magnetic field time evolution



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

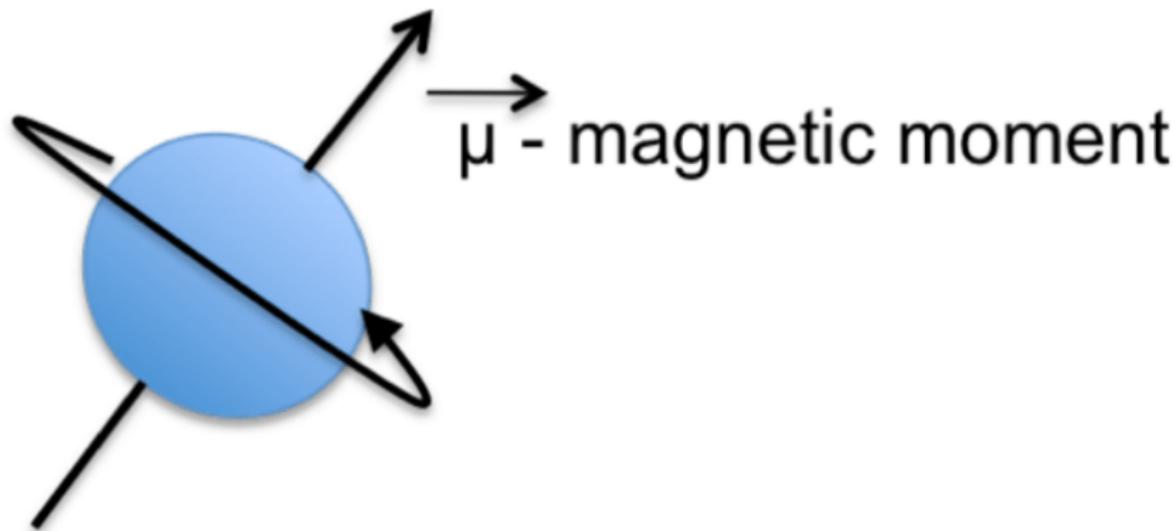
Signature of magnetic field in HIC

[S. Dey and AJ, arXiv:2502.20352]

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; ...]
- 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.
- Heavy quarks: ideal for observable signals of initial magnetic field.
- Our proposal:
 - Strong magnetic fields induce spin polarization of heavy quarks.
 - These induced spin polarization of heavy quarks can be observed in the polarization of open heavy-flavor hadrons.
 - Transverse momentum dependence of open heavy-flavor hadron polarization: distinctive signal for initial strong magnetic field.

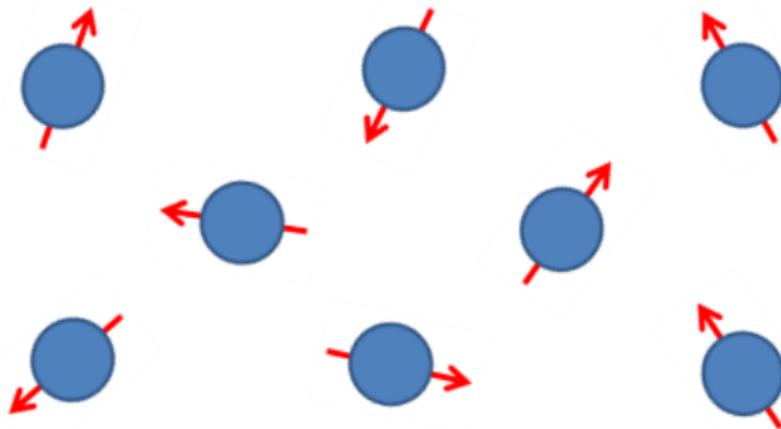
Heavy quarks: charged, spin-1/2 particles



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

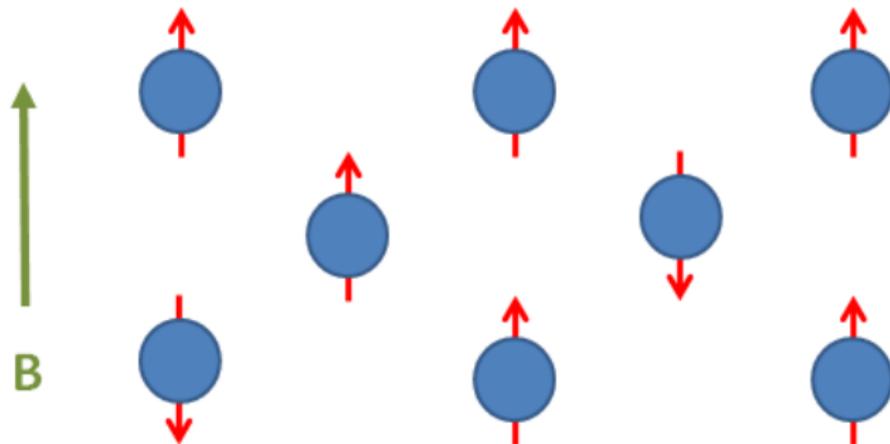
Magnetic moment and spin: $\vec{\mu} = \gamma \vec{s}$

No external magnetic field



Un-aligned spins of heavy quarks.

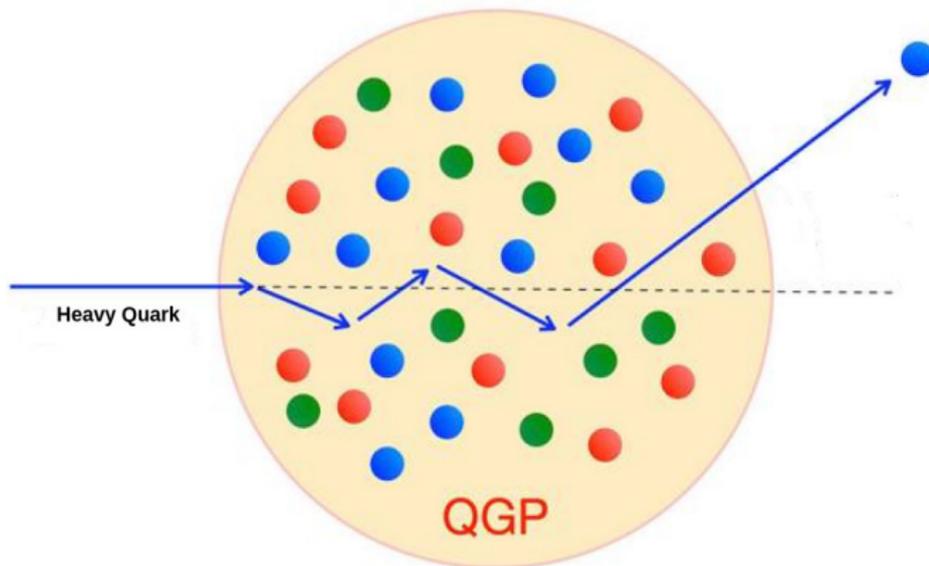
Heavy quarks in magnetic field



Aligned spins in presence of magnetic field.

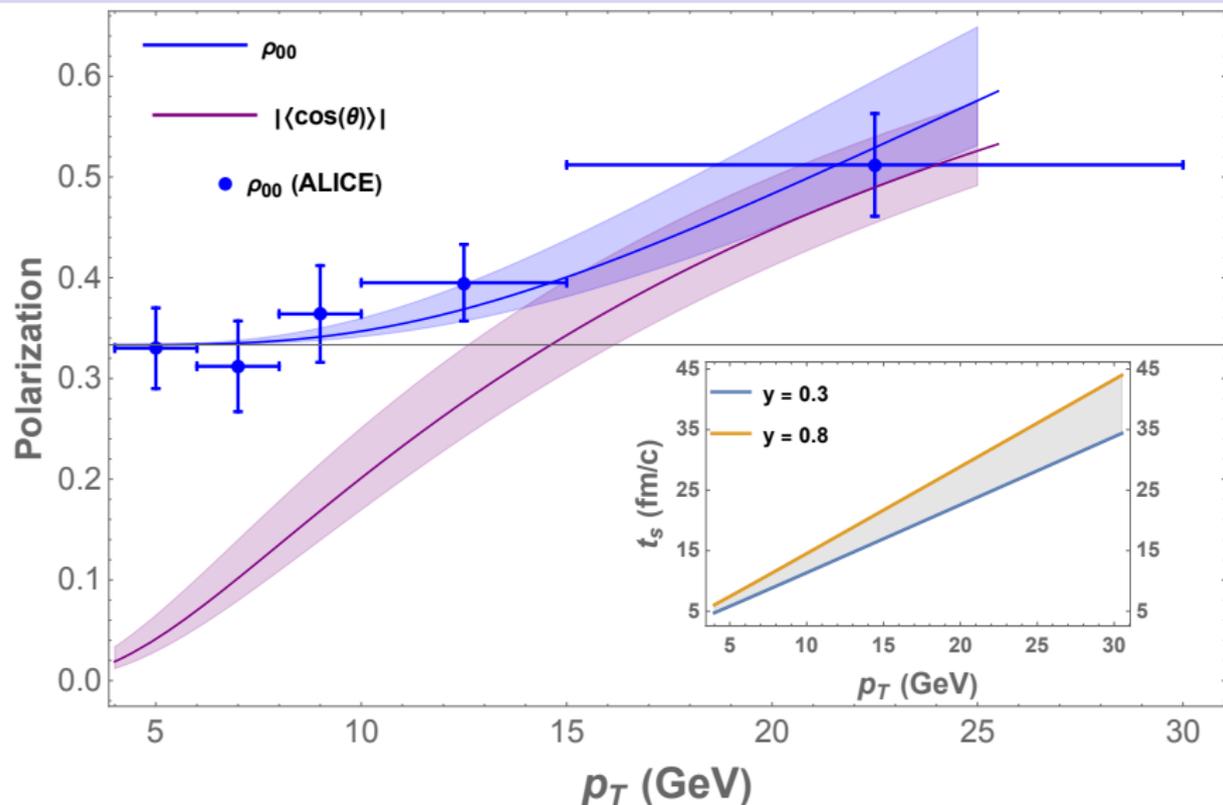
Spin-polarization of heavy quarks.

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].

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

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

- Here $\tilde{\mathbf{B}} \equiv \gamma \mathbf{B} = -\frac{\partial \mathcal{H}}{\partial \mathbf{s}}$ and γ 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.
- λ 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

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

- Assume statistical properties of white noise for the random torque

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

- 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

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

- 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 (θ, ϕ) .
- 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.
- Choose z -axis to be along $\tilde{\mathbf{B}}$.

Fokker-Planck equation for spin (angular variables)

- Since we have an axially symmetric Hamiltonian

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

- Here, $\mathcal{H} = -\boldsymbol{\mu} \cdot \mathbf{B} = -s \cdot \tilde{\mathbf{B}}$.
- For spatially homogeneous and time varying magnetic field \mathbf{B} ,

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

- This equation can be written in shorthand notation as

$$\tau_s \partial_\tau \mathcal{P}(\theta, \tau) = \mathcal{L}_\theta(\tau) \mathcal{P}(\theta, \tau) \quad \Longrightarrow \quad \tau_s \partial_\tau |\mathcal{P}, \tau\rangle = \hat{\mathcal{L}}(\tau) |\mathcal{P}, \tau\rangle.$$

- The generic solution has the structure

$$|\mathcal{P}, \tau\rangle = \exp \left[\frac{1}{\tau_s} \int_0^\tau d\tau' \hat{\mathcal{L}}(\tau') \right] |\mathcal{P}, 0\rangle.$$

Solution using perturbation theory

- Considering the time dependence of the magnetic field to be of the form $B(t) = B_0 \phi(\tau)$

$$\hat{\mathcal{L}}(\tau) = \hat{\mathcal{L}}^0 + \alpha \hat{\mathcal{L}}'(\tau), \quad \hat{\mathcal{L}}^0 = \frac{1}{\sin \theta} \frac{\partial}{\partial \theta} \left(\sin \theta \frac{\partial}{\partial \theta} \right), \quad \mathcal{L}'(\tau) = \frac{\phi(\tau)}{\sin \theta} \frac{\partial}{\partial \theta} \sin^2 \theta.$$

- Here $\alpha \equiv \mu B_0 \lambda / D$. Solve perturbatively assuming $\alpha \ll 1$.

$$\alpha \equiv \frac{\mu \gamma_v B_{\text{Lab}} \lambda}{D} = \frac{g s q \gamma_v B_{\text{Lab}}}{2 m_Q T} = \frac{(f e) \gamma_v B_{\text{Lab}}}{2 m_Q T}$$

- $g \approx 2$ is the g-factor, $\gamma_v \equiv E/m_Q$, the charge $q = f e$, where f is $2/3$ and $-1/3$ for charm and bottom quarks, respectively.
- For $e B_{\text{Lab}} \lesssim 0.1 m_\pi^2$ and $T = 300$ MeV, we obtain $\alpha = 0.034$ for charm and $\alpha = -0.007$ for bottom quarks with $E \simeq 50$ GeV .

Ensemble average of angular anisotropy

- Since α is small, we find dominant contributions to be

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

- Here τ_s is spin relaxation time. Supposedly large but not well constrained. Could be treated as a fit parameter.
- Initially $\theta_0 = 0, \pi$ depending on charge of the quark.
- Open heavy baryon and anti-baryon have opposite polarization.
- Open heavy vector mesons and its anti-particle, 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 $\gamma_v = \frac{E}{m_Q}$.

Heavy baryon and meson polarization

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

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

- α_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

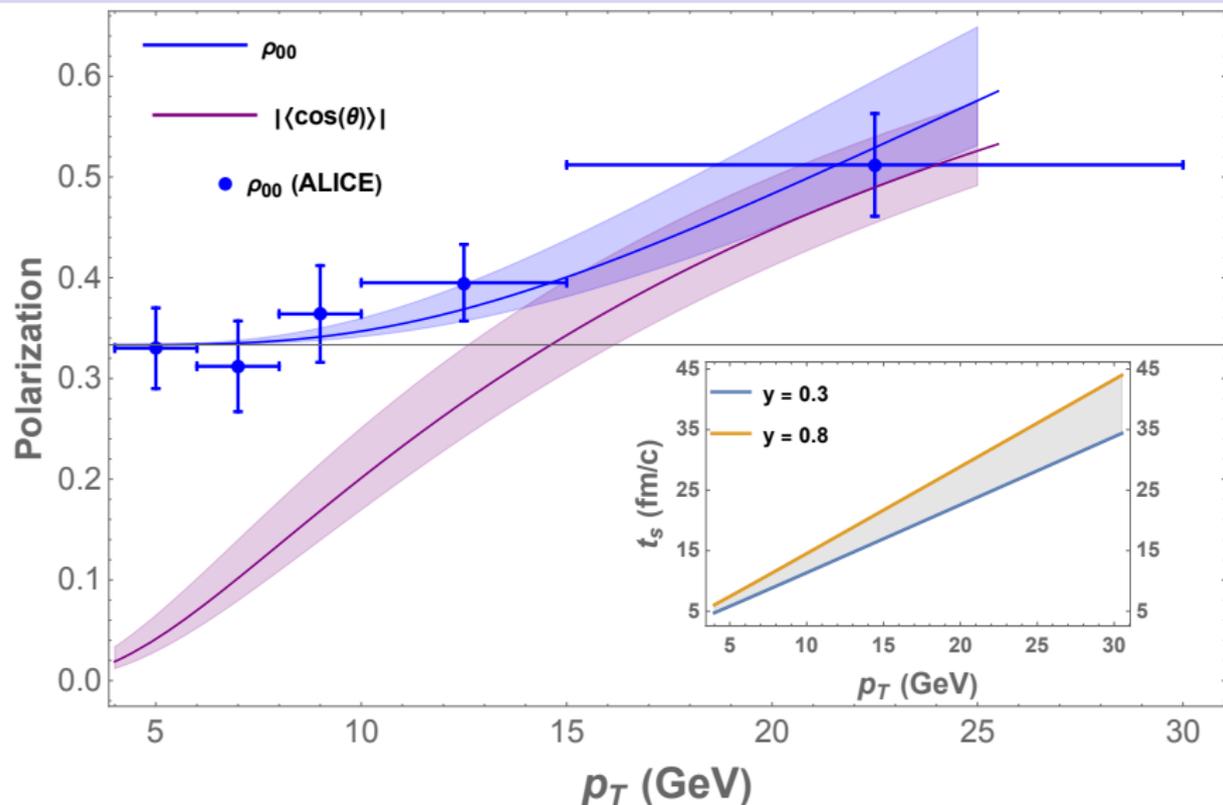
$$\frac{dN}{d\cos\theta} = \frac{3}{4} \left[1 - \rho_{00} + (3\rho_{00} - 1) \cos^2\theta \right]$$

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

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

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

Open heavy hadron polarization [S. Dey and AJ, 2502.20352]



Unambiguous signature of initial strong magnetic field.

Application of magnetic field in HIC

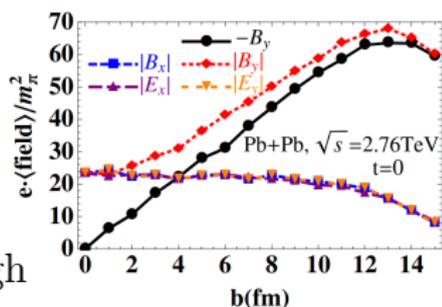
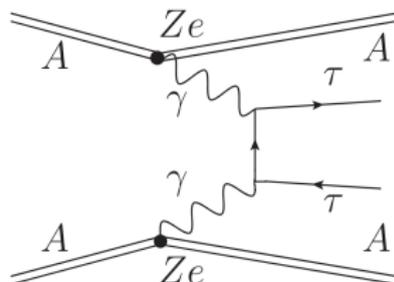
[AJ, [arXiv:2509.02228](https://arxiv.org/abs/2509.02228)]

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.
- τ -lepton: particularly sensitive probe for BSM physics.
- Polarized τ 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: 2.9×10^{-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.

Ultrapерipheral heavy ion collisions

- Ultrapерipheral 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.
- Energy of τ leptons could be obtained using zero-degree calorimeter data.
- Use collinear approximation.
- In UPCs, the spectator nuclei generate strong magnetic fields.
- Spin polarization of τ -lepton pairs through alignment of their magnetic moments.
- Anisotropic emission patterns of the decay products.
- Polarization asymmetry between τ^\mp : probe for CP violation.



[Deng & Huang, 1201.5108]

Magnetic field and τ polarization

- Lorentz-transformed magnetic field in the τ rest frame

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

- τ polarization vector aligned along the magnetic field

$$\mathbf{P}_\tau = P_\tau \hat{\mathbf{B}}$$

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

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

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

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

- For isotropic τ momenta, $P_\tau^{\text{hel}} = 0$; consider “half”-ensemble.

Pion decay mode: $\tau \rightarrow \pi \nu_\tau$

- Normalized angular distribution for decay in τ rest frame is

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

- Express the above equation in the form

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

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

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

- “half”-ensemble average over τ with complimentary ψ 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

- Similar analysis for τ decay to leptons ($\tau \rightarrow \ell \bar{\nu}_\ell \nu_\tau$) and vector mesons ($\tau \rightarrow v \nu_\tau$).
- Novel application of electromagnetic fields generated in HICs.
- Polarized τ decay: new avenue to test fundamental symmetries.
- Detailed analysis of higher-order QED and QCD corrections in $\gamma\gamma \rightarrow \tau^+ \tau^-$ required.
- Feasibility of reconstructing τ polarization challenging due to limited production rates.
- More data for τ events in UPCs required to increase statistics for accurate measurements.
- Heavy ion collision experiments still have enormous potential for exciting new physics.

Thank you!

