通过虚光子极化和双轻子各向异性估计重离子碰撞中的磁场

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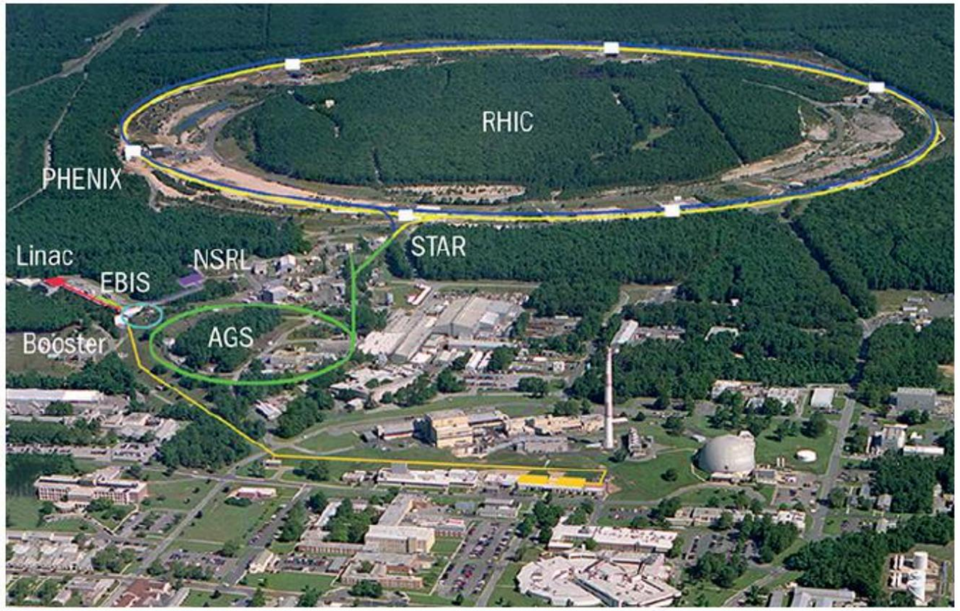
Based on: *Phys.Rev.D* 110 (2024) 5, 054024;

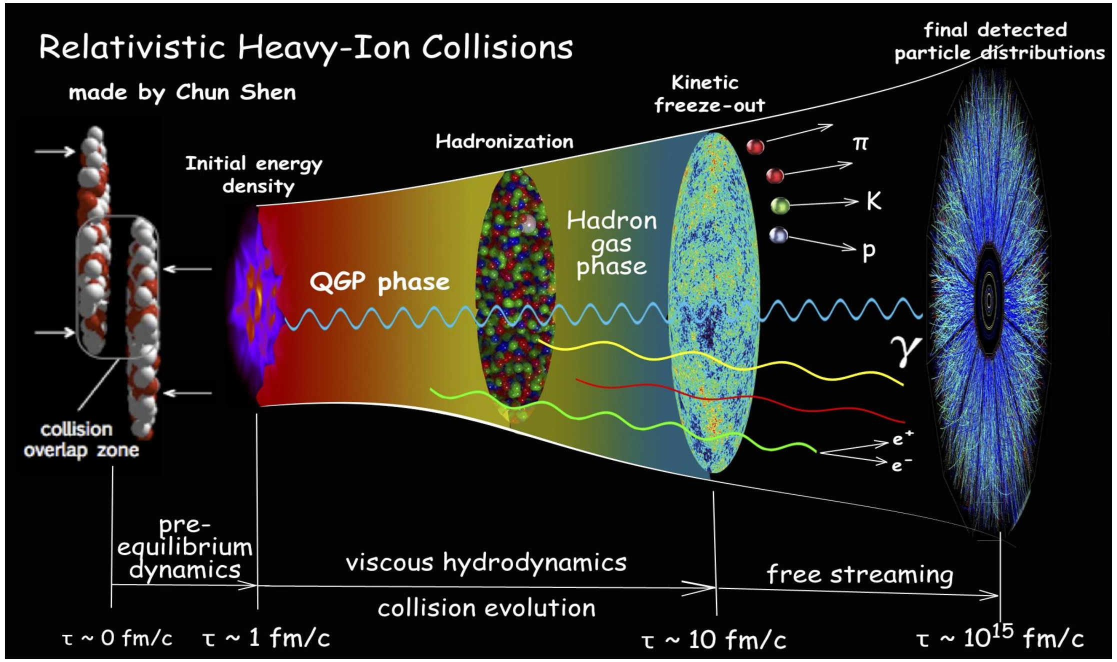
第二十届全国中高能核物理大会，2025年4月27日，上海

Outline

- Introduction： heavy-ion collision and magnetic fields
- Thermal dilepton production in magnetized QGP
  - Virtual photon polarization and dilepton anisotropy
  - Results in a weak magnetic field
  - Experimental report angular distributions of thermal dileptons
- Summary and outlook

Heavy-ion Collisions： a Little bang





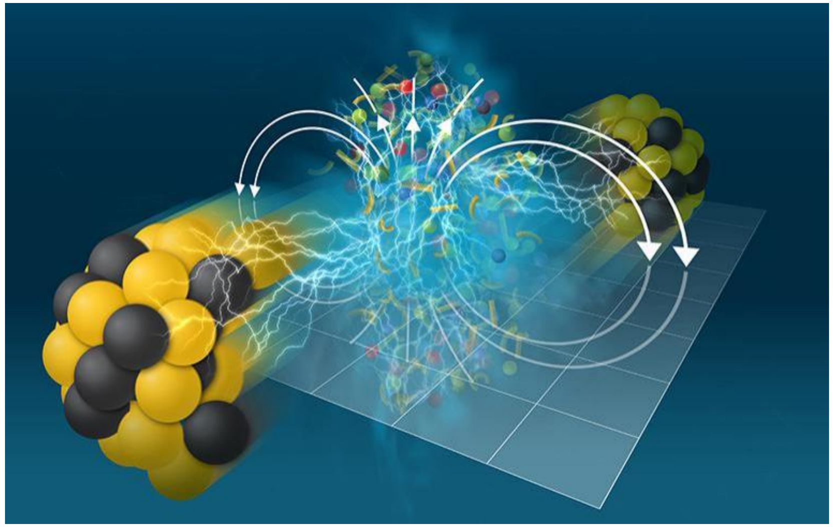
A demonstration sketch of HIC from Shen Chun

- Hadron Probe： p， K， π
- Electromagnetic Probe： γ， e^+e^-

Oral talk： April 26th Chi Yang

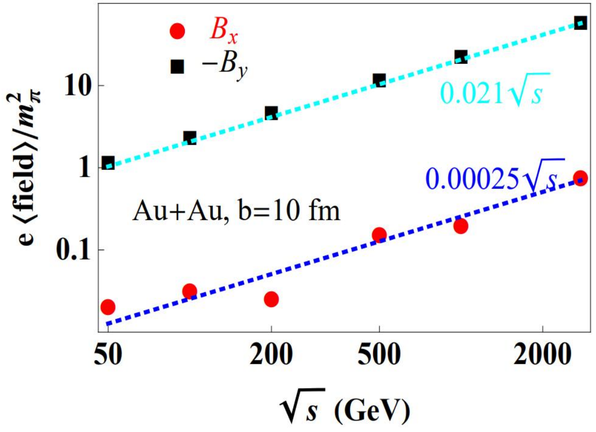
Magnetic Field in Heavy-ion Collisions

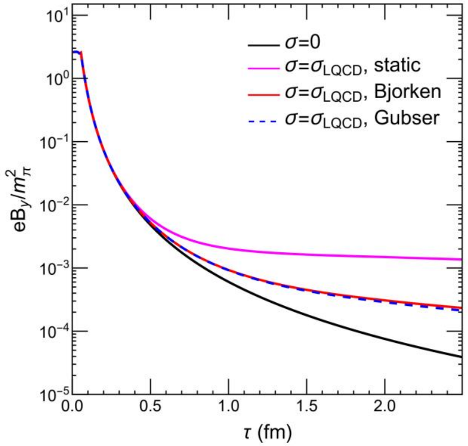
Non-central Collisions



T. Bowman and J. Abramowitz/Brookhaven National Laboratory

Magnitude of vorticity and magnet field





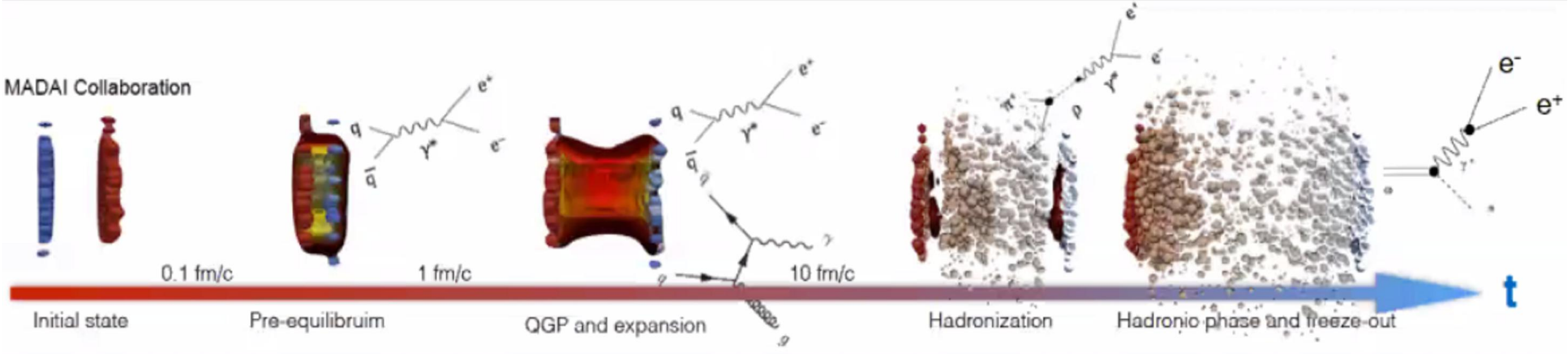
Deng W T, Huang X G.PRC2012; Anping Huang，PRC2023（April 26th）

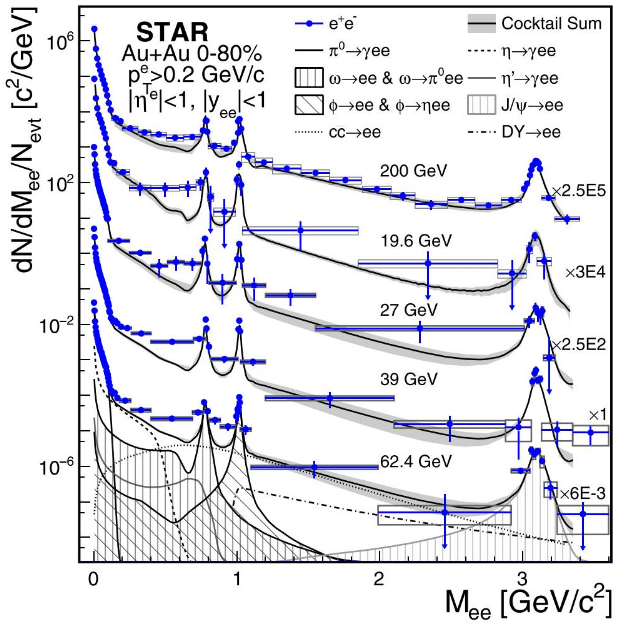
Magnet field related phenomena

- Generated from the relativistic motion of nucleus (spectators).
- From fluctuations of nucleons inside nucleus -- finite in central (small) collision.

- Chiral Magnetic Effect(CME)
- Magnetic Catalysis
- $\Lambda/\overline{\Lambda}$ polarization splitting
- Photon and dilepton production in magnetic field

Dilepton production in Heavy-ion Collisions





STAR, PRC2023

Source of dilepton in HIC

- Pre-equilibrium stage Drell-Yan process
- Dalitz decays of vector mesons
- Decays of heavy quarkonium
- Ultra peripheral collision
- Thermal dilepton production

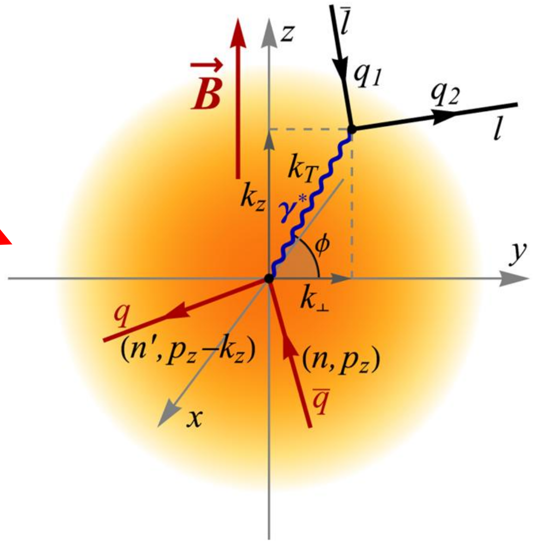
Thermal Dilepton Production in magnetized QGP

Thermal production per volume

Magnetic effects

$$\frac{dR}{d^4q \times d^4x} = \frac{e^4}{q^4}\int \frac{d^3\mathbf{l}}{(2\pi)^3 2E_{\mathbf{l}}}\frac{d^3\bar{\mathbf{l}}}{(2\pi)^3 2E_{\bar{\mathbf{l}}}} W^{\mu\nu}(q) L_{\mu\nu}(l,\bar{l}) \times \delta^{(4)}(q-l-\bar{l})$$

$$q^\mu = (M_T \cosh y\,, q_T \cos\phi_\gamma\,, q_T \sin\phi_\gamma\,, M_T \sinh y)$$



Production rate in virtual photon rest frame

$$\frac{dR}{d^4q d\Omega_\ell} = \frac{\alpha^2}{32\pi^4}\frac{1}{M^4}\sqrt{1-4m_\ell^2/M^2}\, W_{\mu\nu}L^{\mu\nu}$$

April 26th， 16： 10， Xinyang Wang
April 27th， 14： 30， Pengfei Zhuang

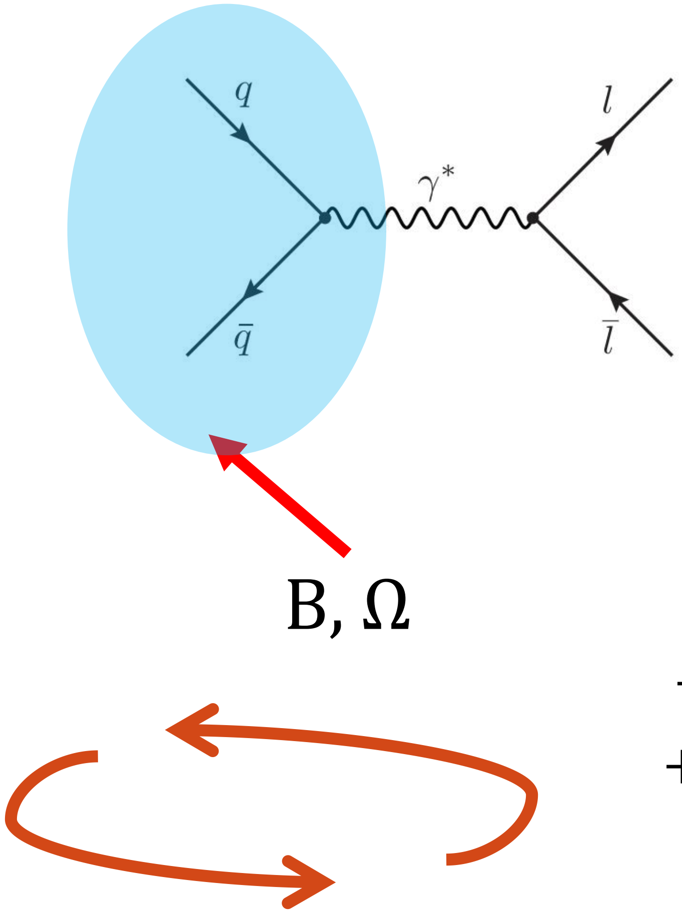
$\Omega_l = (\theta_l, \phi_l)$

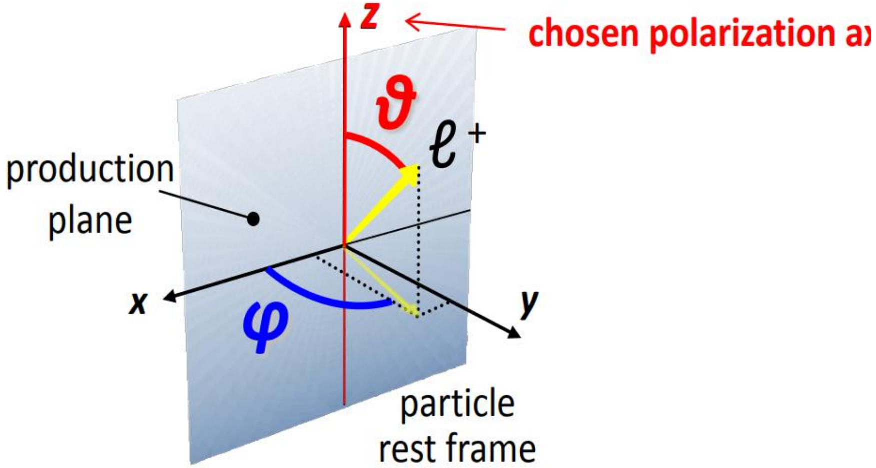
Dilepton Anisotropy

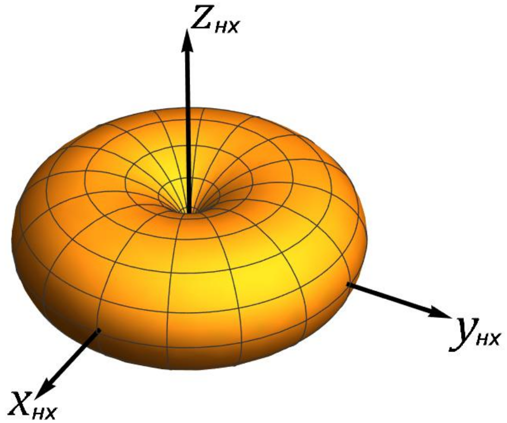
- Total momenta q^μ， $\frac{dR}{d^4q} = \frac{dR}{dq_t M dM dy d\phi_\gamma}$ Ellipticity v_2
- Angle between $\vec{q}$ and $\vec{l}$, $\frac{dR}{d\Omega_\ell}$ is determined by Virtual Photon Polarization

Virtual Photon Polarization And Dilepton Anisotropy

Magnetic field、Vorticity → Dilepton Anisotropy ← Virtual Photon Polarization，$\lambda_\theta < 0$







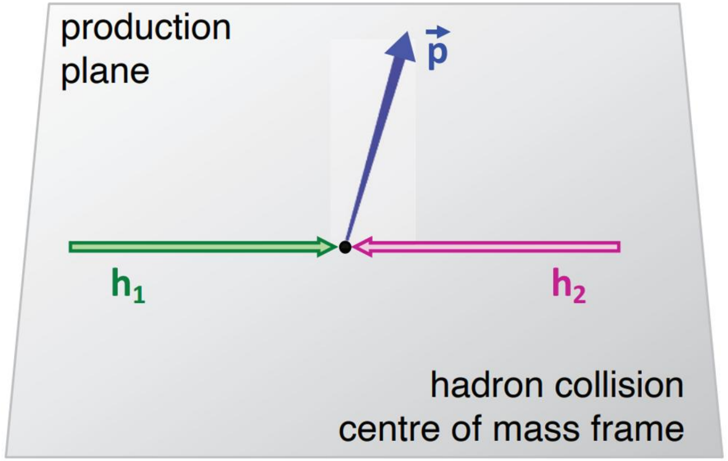
$$\frac{dR}{d^4q d\Omega_\ell} = N(1 + \lambda_\theta \cos^2\theta_\ell + \lambda_\phi \sin^2\theta_\ell \cos 2\phi_\ell + \lambda_{\theta\phi} \sin 2\theta_\ell \cos\phi_\ell + \lambda_\phi^\perp \sin^2\theta_\ell \sin 2\phi_\ell + \lambda_{\theta\phi}^\perp \sin 2\theta_\ell \sin\phi_\ell),$$

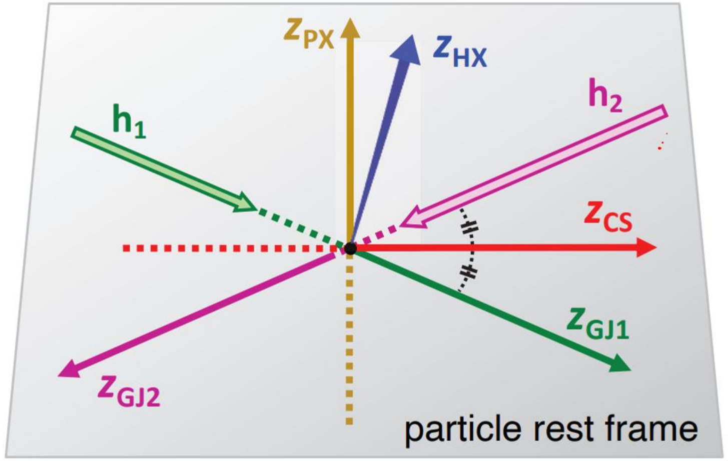
$$\lambda_\theta = \frac{\rho^{\gamma^*}_{-1,-1} + \rho^{\gamma^*}_{1,1} - 2\rho^{\gamma^*}_{0,0}}{\rho^{\gamma^*}_{-1,-1} + \rho^{\gamma^*}_{1,1} + 2\rho^{\gamma^*}_{0,0}}$$

$$\lambda_{\theta\phi} = \sqrt{2}\frac{\mathrm{Re}\left(\rho^{\gamma^*}_{0,1} - \rho^{\gamma^*}_{-1,0}\right)}{\rho^{\gamma^*}_{-1,-1} + \rho^{\gamma^*}_{1,1} + 2\rho^{\gamma^*}_{0,0}}$$

$$\lambda_\phi = 2\frac{\mathrm{Re}\left(\rho^{\gamma^*}_{-1,1}\right)}{\rho^{\gamma^*}_{-1,-1} + \rho^{\gamma^*}_{1,1} + 2\rho^{\gamma^*}_{0,0}}$$

Polarization axes





- helicity (HX) frame: the quantization axis is taken along the flight direction of the Vector particle itself.

$$\hat{z} = -\frac{\mathbf{h}_1 + \mathbf{h}_2}{|\mathbf{h}_1 + \mathbf{h}_2|}, \qquad \hat{y} = \frac{\mathbf{h}_1 \times \mathbf{h}_2}{|\mathbf{h}_1 \times \mathbf{h}_2|},$$

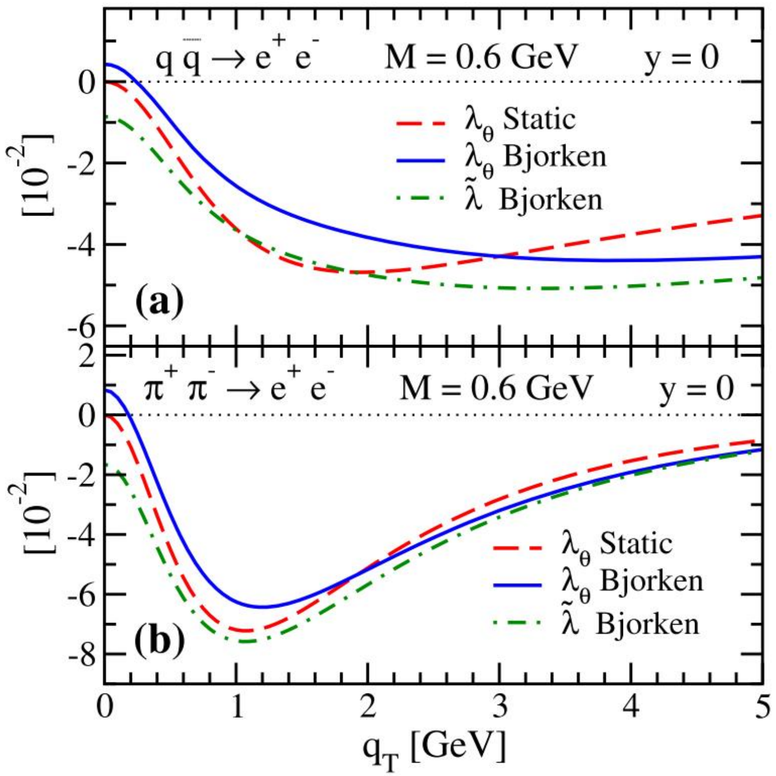
- Gottfried–Jackson (GJ) frame: the z axis is "simply" the direction of the momentum of one of the two colliding hadrons;
- The Collins–Soper (CS) frame : obtained by geometrically averaging the two beam directions;
- perpendicular helicity (PX) frame: If we take the other bisector, we obtain the PX frame

Aim:

Calculate $W^{\mu\nu} = \frac{1}{16\pi^2}\int_{-1}^{1} \mathrm{d}\cos\theta \int_0^{2\pi} \mathrm{d}\phi \sqrt{1 - \frac{4m_q^2}{M^2}}\, f_q(p,\theta,\phi) f_{\bar{q}}(p,\pi-\theta,\phi+\pi) w^{\mu\nu}$ in HX frame

Thermal Dilepton VS Magnetic field

- Virtual Photon Polarization in HICs
  (1702.05906Gordon Baym,1802.02479 Enrico Speranza, 2309.03189 Florian Seck, Maurice Coquet 2309.00555)
- Strong magnetic field region ($eB \sim 1 - 10 m_\pi^2$)
  - One loop polarization function and spectral function(1812.10380Chowdhury Aminul Islam)
  - Dilepton production enhancement
    (2109.00019 2310.11869 Aritra Das,1808.05176Snigdha Ghosh, 1601.04887N. Sadooghi)
  - Ellipticity of Dilepton emission
    (2205.00276Xinyang Wang,Igor A. Shovkovy 2311.17632Rajkumar Mondal)
  - Virtual photon polarization (less attention)
- Weak magnetic field region ($eB \sim 0.01 - 0.1 m_\pi^2$)
  - Distribution function
  - Dilepton production enhancement
  - Virtual photon polarization(our motivation)



$q\bar{q} \to \gamma^*$ Process with weak EM Field

Quark distribution functions

$$f_q \sim n_{\rm eq} + f_{\rm EM}$$

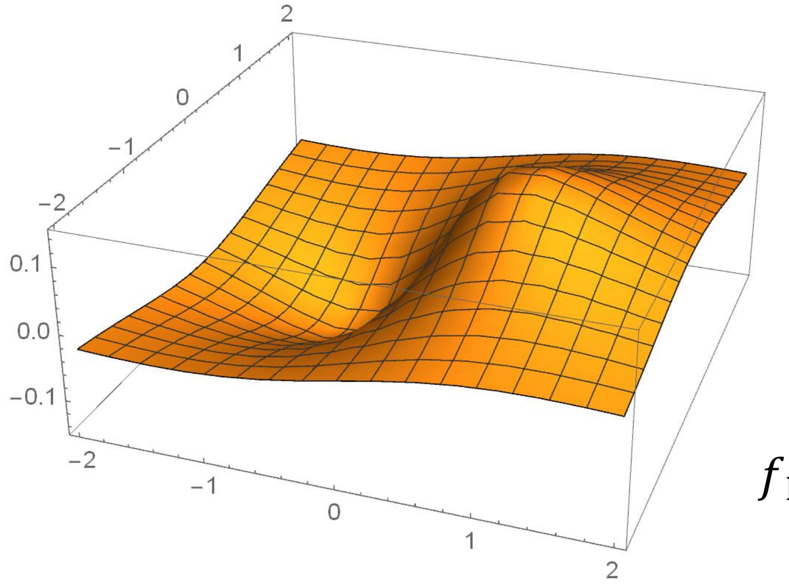
$$f_{\rm EM} = \frac{c}{8\alpha_{\rm EM}} \frac{\sigma_{\rm el} n_{\rm eq}(1-n_{\rm eq})}{T^3 p\cdot u} eQ_f F^{\mu\nu} p_\mu u_\nu$$

From Boltzmann equation, see 2311.03929

$$p^\mu \partial_\mu f + qF^{\mu\nu} p_\mu \frac{\partial}{\partial p^\nu} f = C[f] \sim \frac{f - n_{\rm eq}}{\tau_R}$$

Static fluid have no magnet effect

$$f_{\rm EM} = \frac{c}{8\alpha_{\rm EM}} \frac{\sigma_{\rm el} n_{\rm eq}(1-n_{\rm eq})}{T^3 p\cdot u} eQ_f B_y (p_x u_z - p_z u_x)$$



$f_{\rm EM}(p_x, p_y, p_z = 1)$

Spin Density Operator of Virtual Photon

$$\rho^{\gamma^*}_{\lambda\lambda'} = (\epsilon^\mu(\lambda))^* W_{\mu\nu} \epsilon^\nu(\lambda') \qquad W^{\mu\nu} = \langle w^{\mu\nu} \rangle$$

$$w^{\mu\nu} = 2C_q(-q^2 g^{\mu\nu} + q^\mu q^\nu - \Delta p^\mu \Delta p^\nu)$$

Dilepton rate with the weak EM Field

$$\frac{dR}{d^4q \times d^4x} = 4N_c \sum_f \int \frac{d^3p_1}{(2\pi)^3} \frac{d^3p_2}{(2\pi)^3} \delta^{(4)}(q - p_1 - p_2) \times f_{q_f}(\mathbf{p}_1) f_{\bar{q}_f}(\mathbf{p}_2) \sigma_{q_f\bar{q}_f}(M) v_{12}$$

Anisotropic Coefficient λ_θ in Bjorken Flow

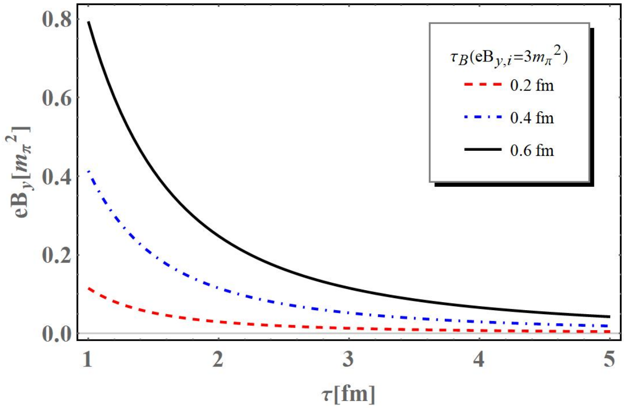
Bjorken flow $u^\mu = (\cosh\eta, 0, 0, \sinh\eta)$ $\tau = \sqrt{t^2 - z^2}$ $\eta = 1/2 \ln\frac{t+z}{t-z}$

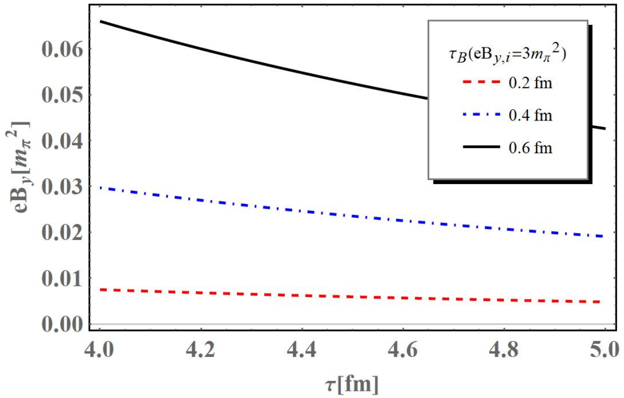
Temperature $T = T(\tau,\eta) = T_i\left(\frac{\tau}{\tau_0}\right)^{\frac{1}{3}}$

We set $T_i = 300\text{MeV}$, $\tau_i = 1\text{fm}$, $\tau_f = 5\text{fm}$

Magnetic field evolution: $B_y(\tau) = \frac{B_{y,i}}{1 + (\frac{\tau}{\tau_B})^2}$

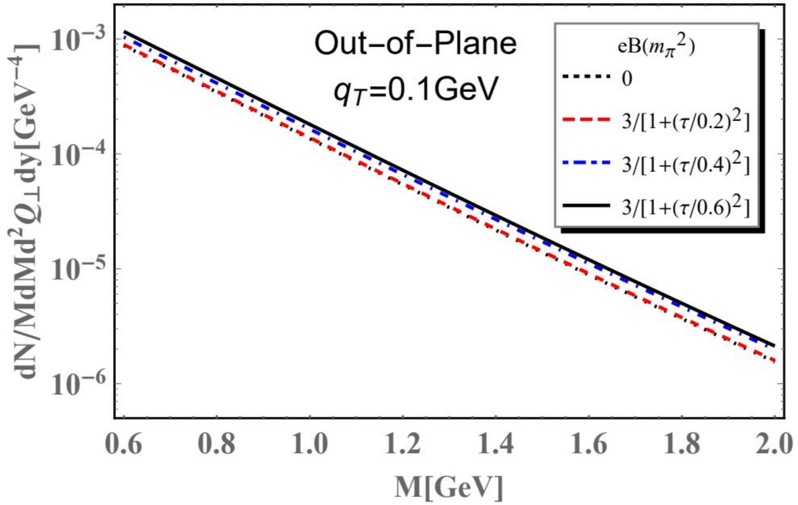
$$f_{EM} = \frac{c}{8\alpha_{EM}} \frac{\sigma_{el} n_{eq}(1 - n_{eq})}{T^3 p \cdot u} e Q_f B_y p_x u_z$$





Integration over the time evolution:

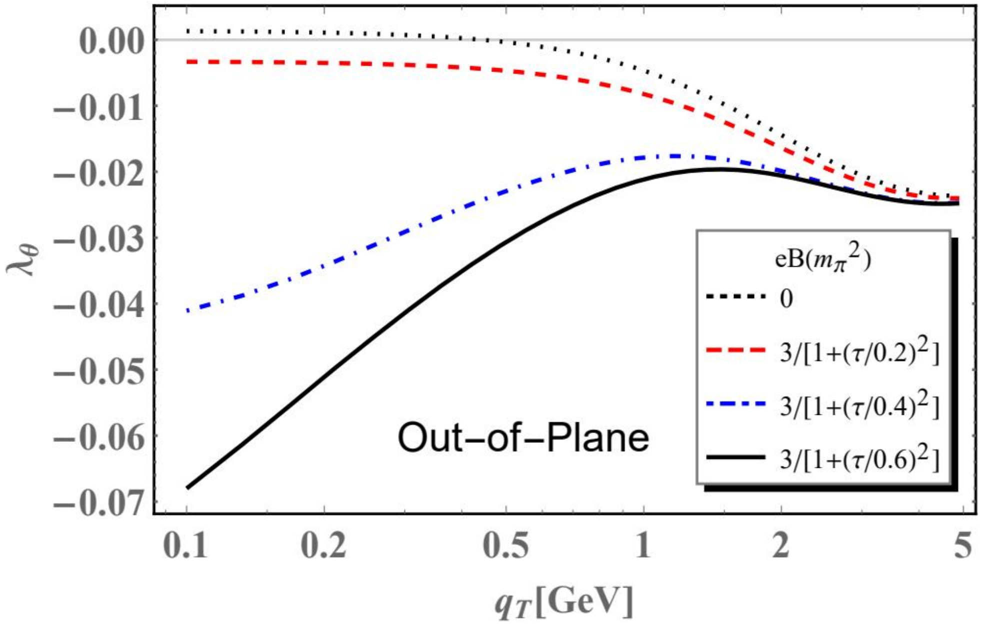
$$\frac{dN}{q_T dq_T d\phi_\gamma M dM dy} = \pi R_A^2 \int_{\tau_i}^{\tau_f} d\tau\tau \int_{-\infty}^{\infty} d\eta \left(\frac{dR}{d^4x d^4q}\right)$$

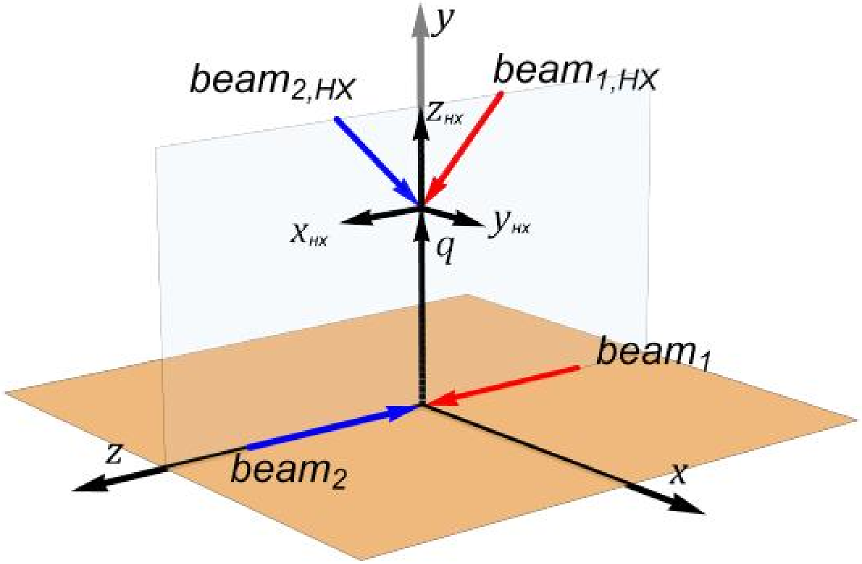


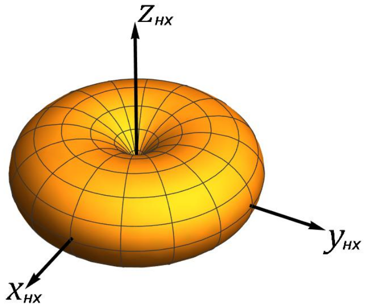
Anisotropic Coefficient λ_θ in Bjorken Flow

Integration of space time

$$\lambda_\theta^{\text{Bjorken}}(B_{y,i}, M, q_T, \phi_\gamma, y) = \frac{\pi R_A^2 \int_{\tau_i}^{\tau_f} d\tau\tau \int_{-\infty}^{\infty} d\eta R^{\text{Cell}}(\tau,\eta)\lambda_\theta(\tau,\eta)}{\pi R_A^2 \int_{\tau_i}^{\tau_f} d\tau\tau \int_{-\infty}^{\infty} d\eta \left(\frac{dR}{d^4x d^4q}\right)}$$







$\frac{1}{2}(1-\cos^2\theta_\ell)$

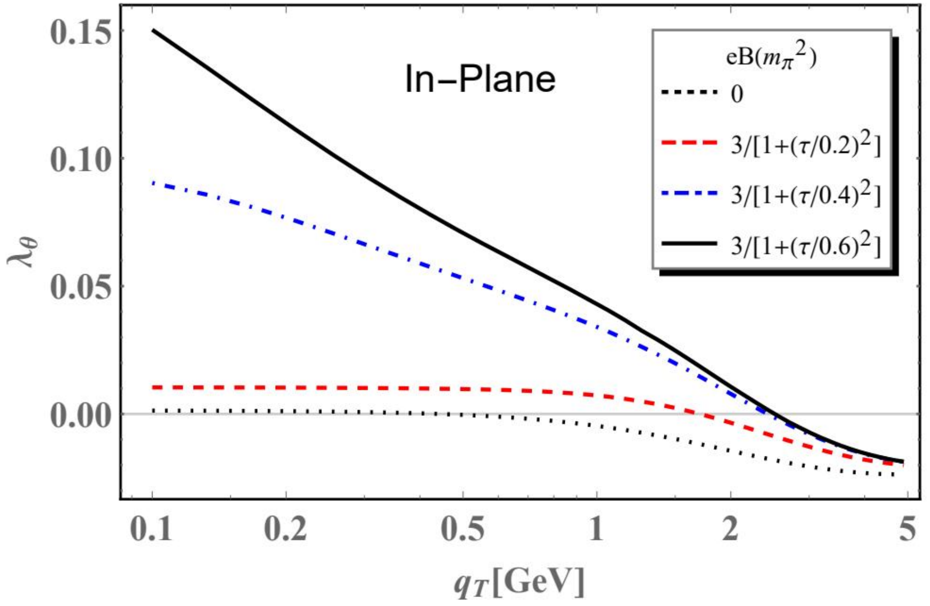
Longitudinal polarization $\lambda_\theta < 0$

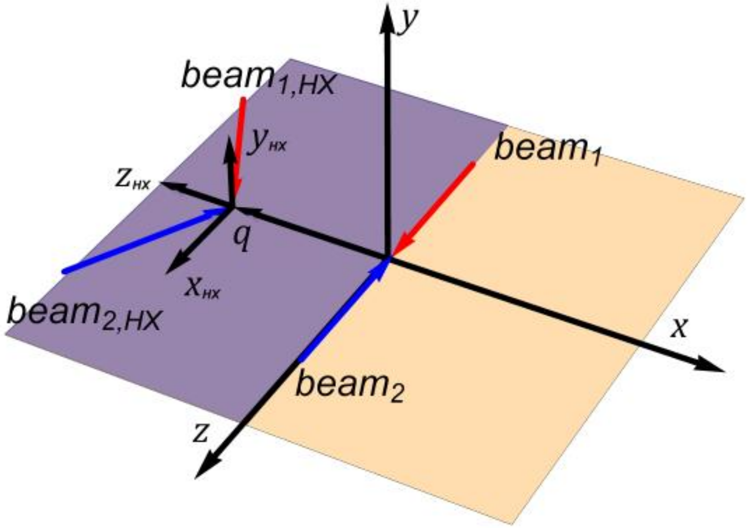
$f_{\text{EM}} \propto B_y p_x u_z$

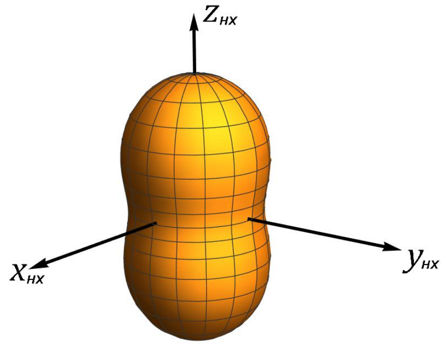
Anisotropic Coefficient λ_θ in Bjorken Flow

Integration of space time

$$\lambda_\theta^{\text{Bjorken}}(B_{y,i}, M, q_T, \phi_\gamma, y) = \frac{\pi R_A^2 \int_{\tau_i}^{\tau_f} d\tau\tau \int_{-\infty}^{\infty} d\eta R^{\text{Cell}}(\tau,\eta)\lambda_\theta(\tau,\eta)}{\pi R_A^2 \int_{\tau_i}^{\tau_f} d\tau\tau \int_{-\infty}^{\infty} d\eta \left(\frac{dR}{d^4x d^4q}\right)}$$







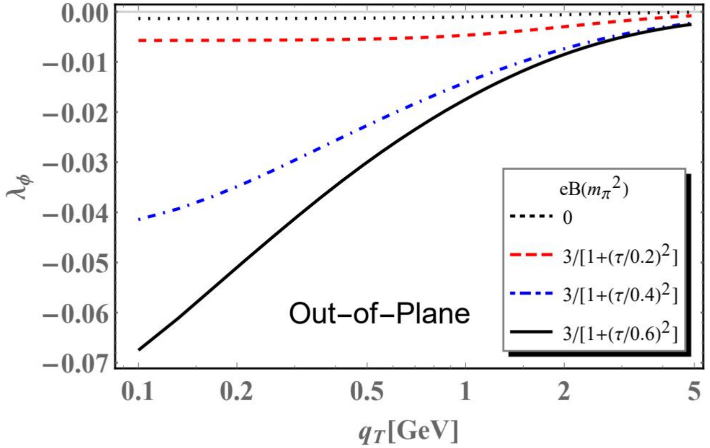
$\frac{1}{2}(1+\cos^2\theta_\ell)$

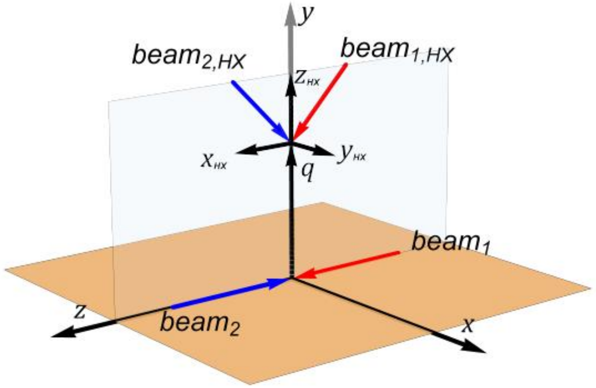
Transverse polarization $\lambda_\theta > 0$

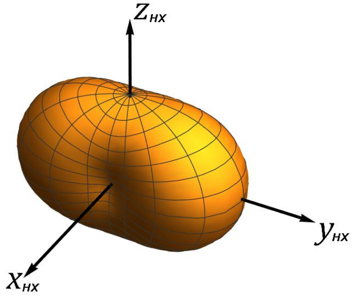
$f_{\text{EM}} \propto B_y p_x u_z$

Anisotropic Coefficient λ_ϕ in Bjorken Flow

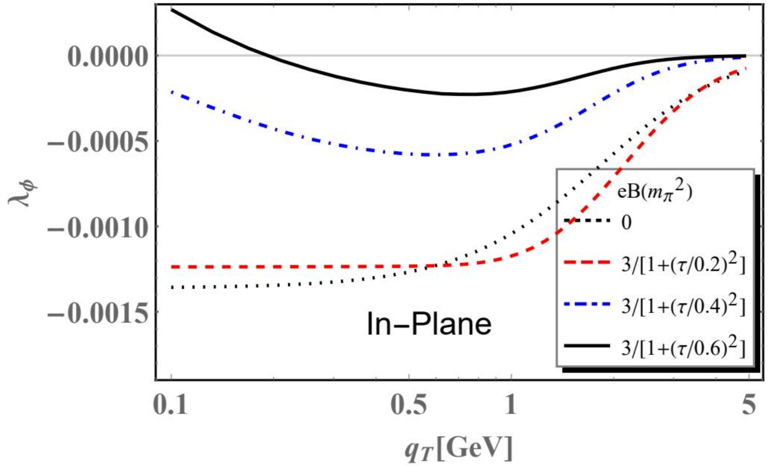
- The common parameters: $\frac{\sigma}{T} = 2, M = 2GeV, y = 0;$
- In the vicinity of $q_T = 0GeV$, λ_ϕ is significant;
- For $q_T \rightarrow 0GeV$, quarks and antiquarks have anti-parallel momenta (tend to y_{HX}， $f_{\mathrm{EM}} \propto B_y p_x u_z$); According to time reversal， momenta of lepton tend to y_{HX} as well;

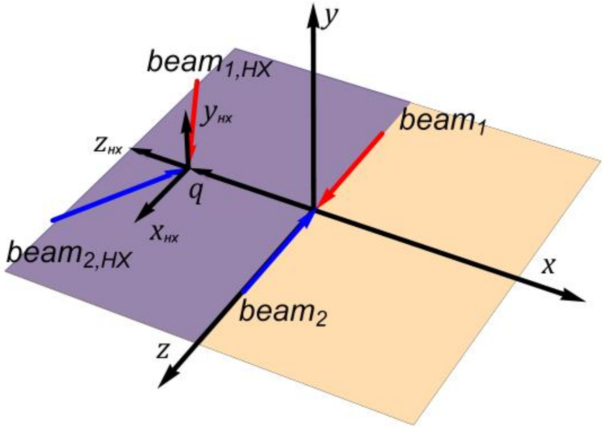


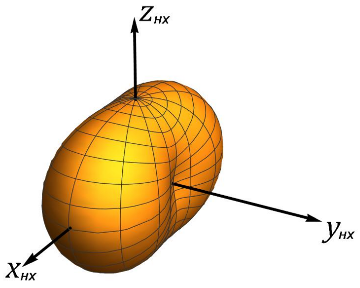




$1 - 1/2 \sin^2 \theta_\ell \cos 2\, \phi_\ell$



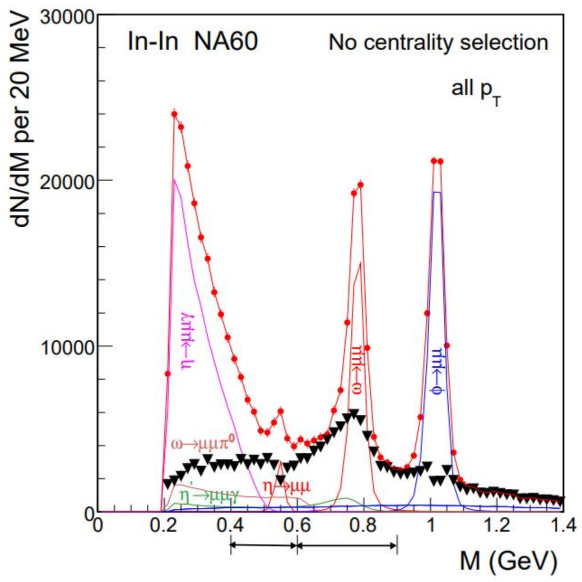




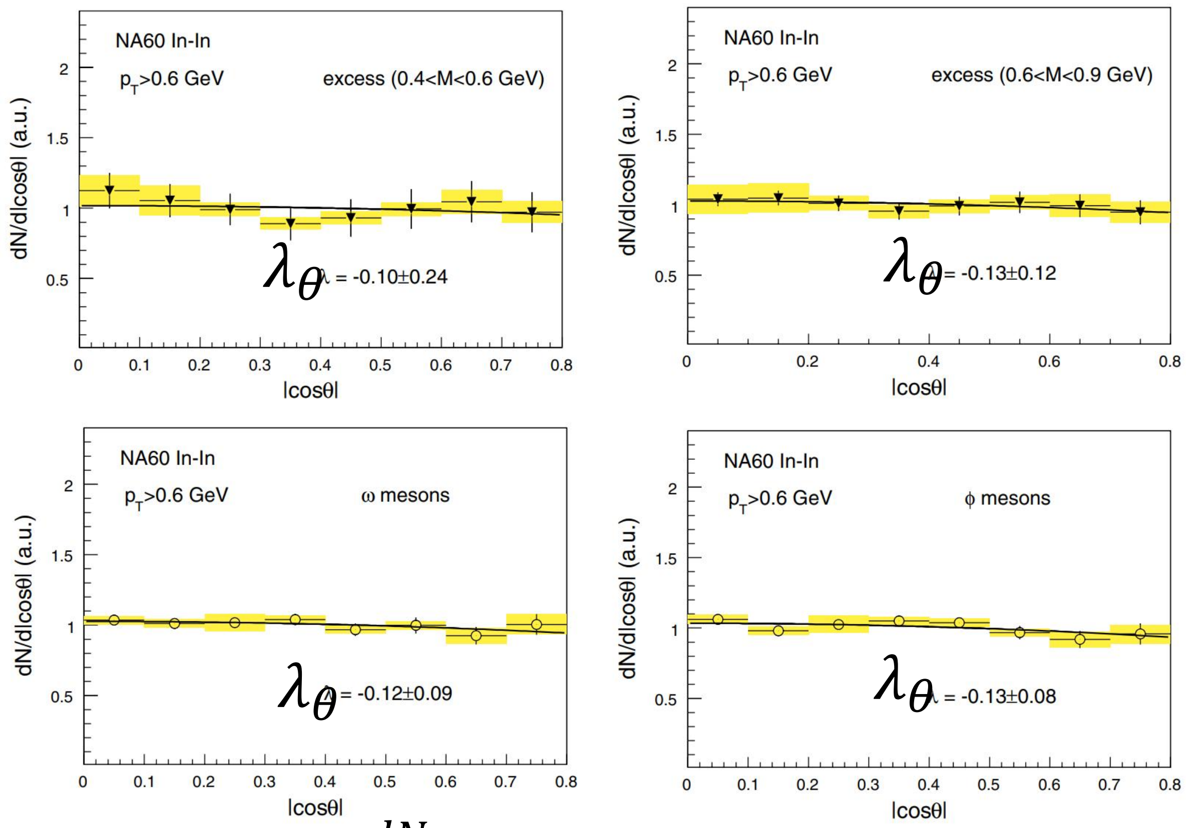
$1 + 1/2 \sin^2 \theta_\ell \cos 2\, \phi_\ell$

Angular distributions of thermal dileptons in nuclear collision

- Results in Collins–Soper (CS) frame;
- The centrality-integrated net mass spectrum after background subtraction ;
- neutral meson decays,η, ω, ϕ, the excess dimuons are isolated by subtracting them from the total (except for the ρ)



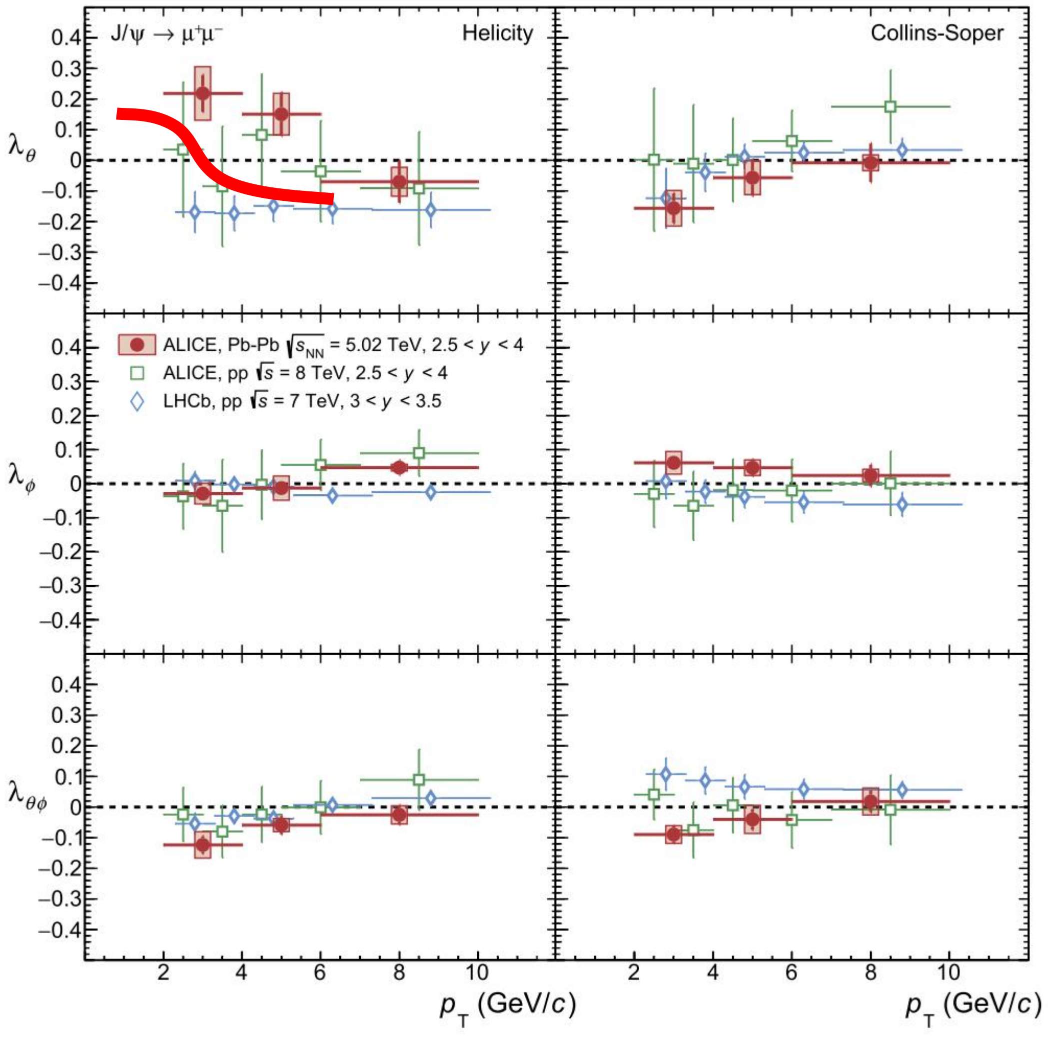
Anisotropic Coefficient λ_θ



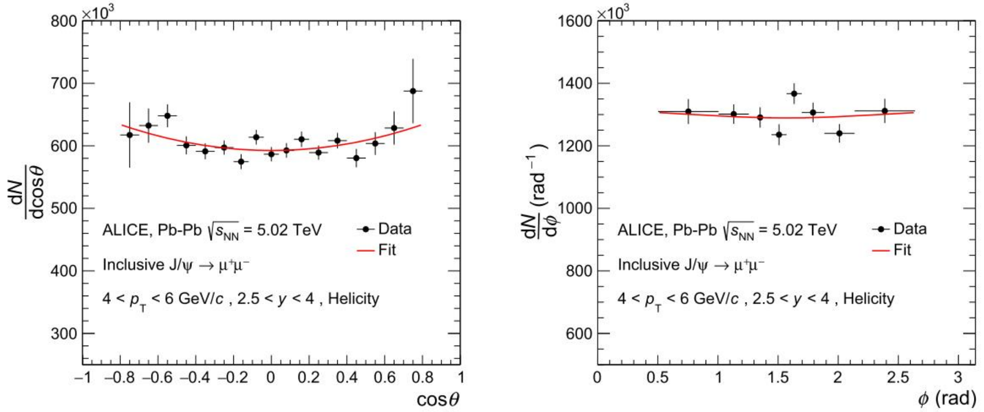
$$\frac{dN}{d\cos\theta} = A_0(1 + \lambda_\theta \cos^2\theta)$$

(NA60 Collaboration) , Phys. Rev. Lett.102, 222301 (2009),

Quarkonium Polarization In Nuclear Collisions At The LHC



Phys.Lett.B 815 (2021) 136146



- Pb–Pb collisions;
- A slight transverse polarization at low p_T ($\sim 2.1\sigma$);
- The sign of λ_θ have a transition;

Posters：
38.Tianyang Li ;42.Jiayun Xiang;
62. Zhishun Chen;78Haoyu Liang;
127.Baoshan Xi； 185.Guowei Yan.

Summary

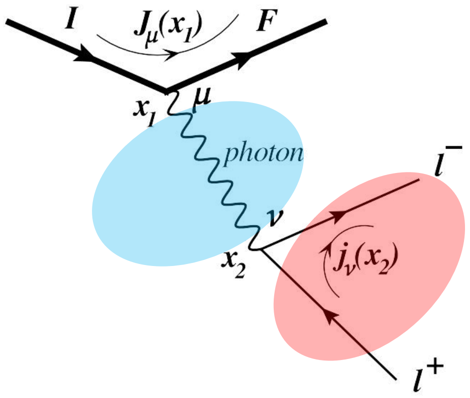
- Conclusions
  - In a Bjorken flow, a weak magnetic field induced virtual photon polarization;
  - Anisotropic Coefficient $\lambda_\theta, \lambda_\phi$ depend on the reference frame; Helicity frame relate to azimuthal angle of virtual photon ϕ_γ
  - In the vicinity of $q_T = 0GeV$, magnetic effects is more significant;
  - For $\phi_\gamma = 0$, π, a sign of λ_θ has a transition at transverse momentum $q_{T,\mathrm{C}}$;
- Outlook
  - A realistic fluid with vorticity; Construct a quantities for practical measurement;
  - In a rotating medium, Elliptic flow v_2 of the dilepton production is induced by rotation(*Phys.Rev.D* 105 (2022) 5, 054014);How about the Virtual Photon Polarization in a rotating medium?

18

BACKUP

Dilepton production in a rotating medium

Thermal Dilepton production



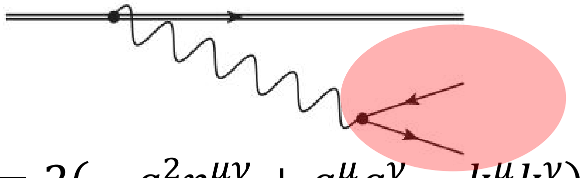
Dilepton rate is related to the Lepton tensor and the photon tensor

$$dR_{\bar{l}l} = 2\pi e^2 e^{-\beta\omega} L_{\mu\nu}(p_1, p_2)\rho^{\mu\nu}(\omega, \mathbf{q}) \frac{d^3\mathbf{p}_1}{(2\pi)^3 E_1}\frac{d^3\mathbf{p}_2}{(2\pi)^3 E_2}$$

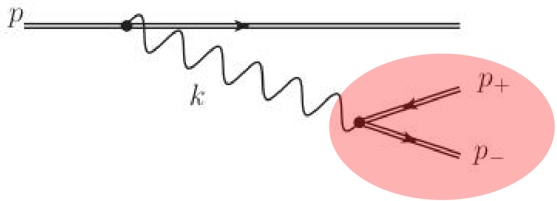
Combined with Lepton tensor for plane wave

$$\frac{dR_{l\bar{l}}}{d^4q} = \frac{\alpha}{12\pi^4}\frac{n_B(\omega)}{q^2}\left(1+\frac{2m_l^2}{q^2}\right)\left(1-\frac{4m_l^2}{q^2}\right)^{1/2} \mathrm{Im}\left[\Pi_\mu^\mu(\omega, \mathbf{k})\right]$$

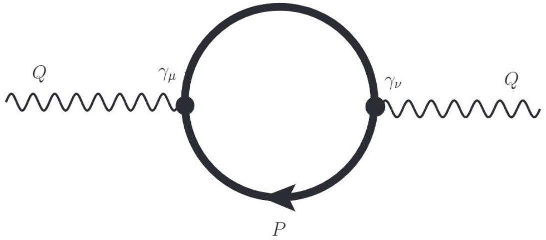
Lepton tensor for plane wave



$$L^{\mu\nu} = 2(-q^2\eta^{\mu\nu} + q^\mu q^\nu - k^\mu k^\nu)$$



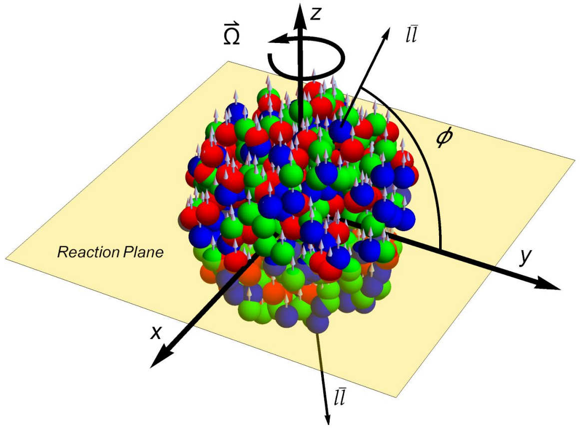
$$L^{\mu\nu} = ?$$

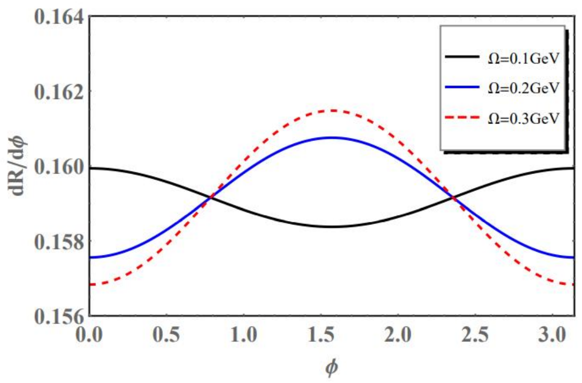


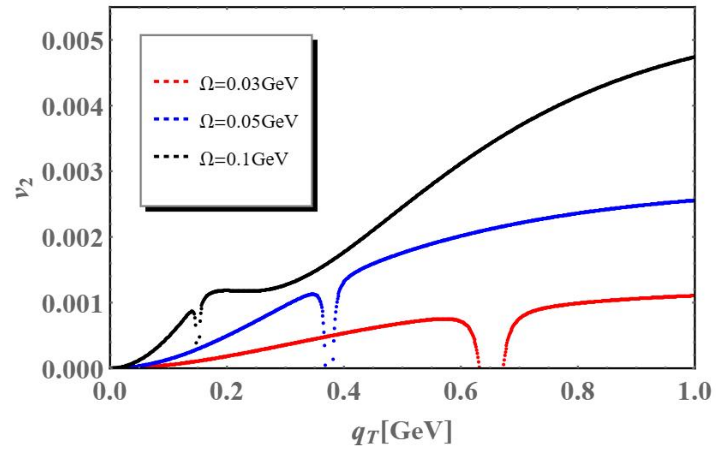
$$\Pi^{\mu\nu}(q;\Omega) = -i\int d^4\tilde{r}\,\mathrm{Tr}_{sfc}[i\gamma^\mu S(0;\tilde{r};\Omega)i\gamma^\nu S(\tilde{r};0;\Omega)]e^{iq\cdot\tilde{r}}$$

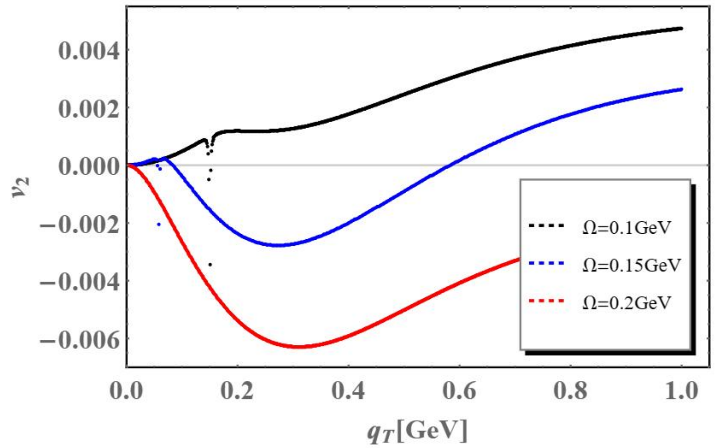
Ellipticity of Dilepton emission in a rotating QCD medium

Angular distribution for momentum q





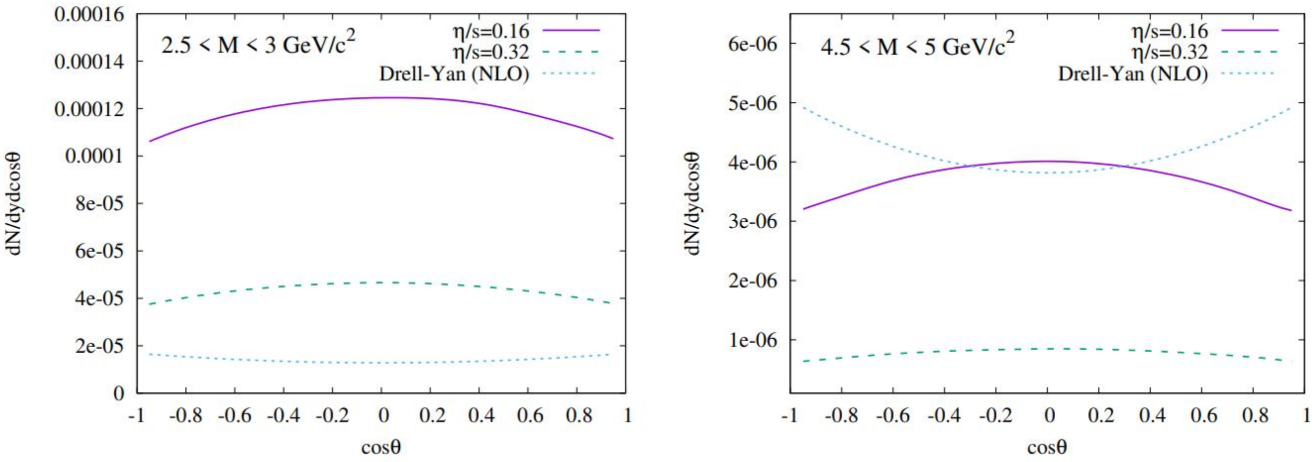




$$E\frac{\mathrm{d}^3R}{\mathrm{d}^3\mathbf{q}} = \frac{1}{2\pi}\frac{\mathrm{d}^2R}{q_T\mathrm{d}q_T\mathrm{d}y}\left(1 + 2\sum_{n=1}^{\infty} v_n\cos\left[n(\phi - \Psi_{\mathrm{RP}})\right]\right)$$

- In low angular velocity region, positive elliptical flow v_2 is induced;
- In high angular velocity region, negative elliptical flow v_2 is induced .

Virtual Photon Polarization



Dilepton polarization as a signature of plasma anisotropy

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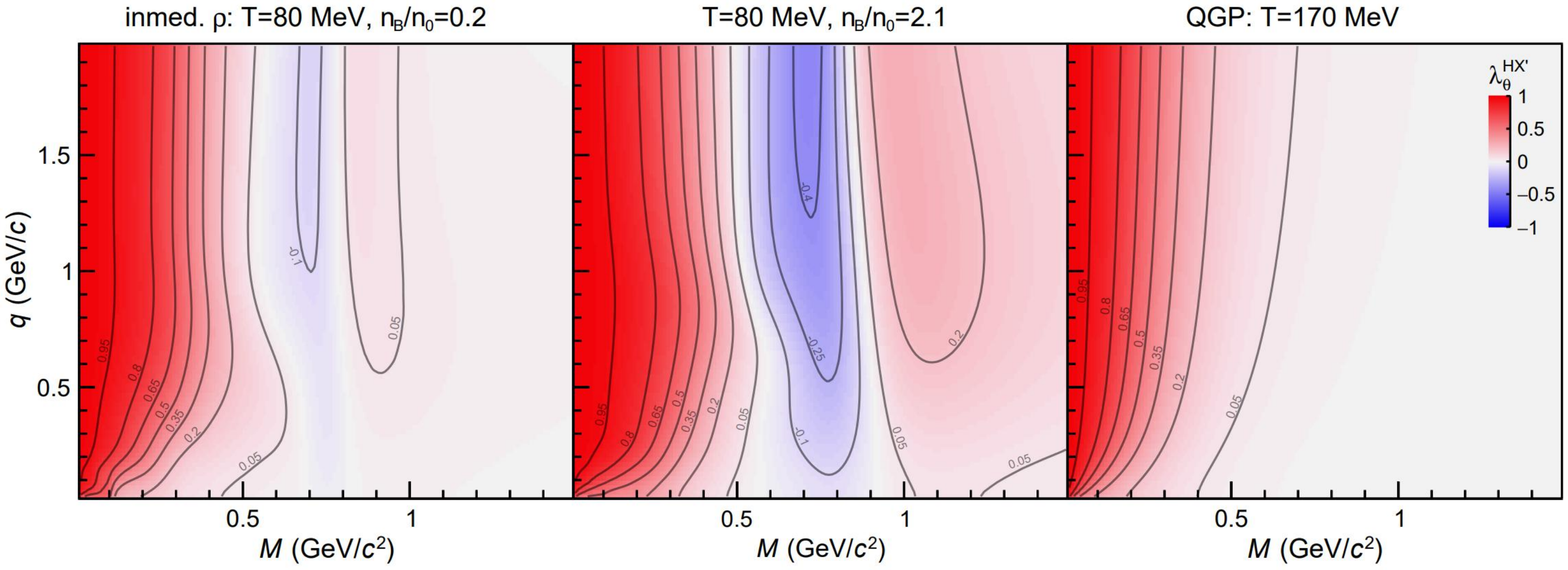
(Dated: September 4, 2023)

2309.00555.pdf (arxiv.org)

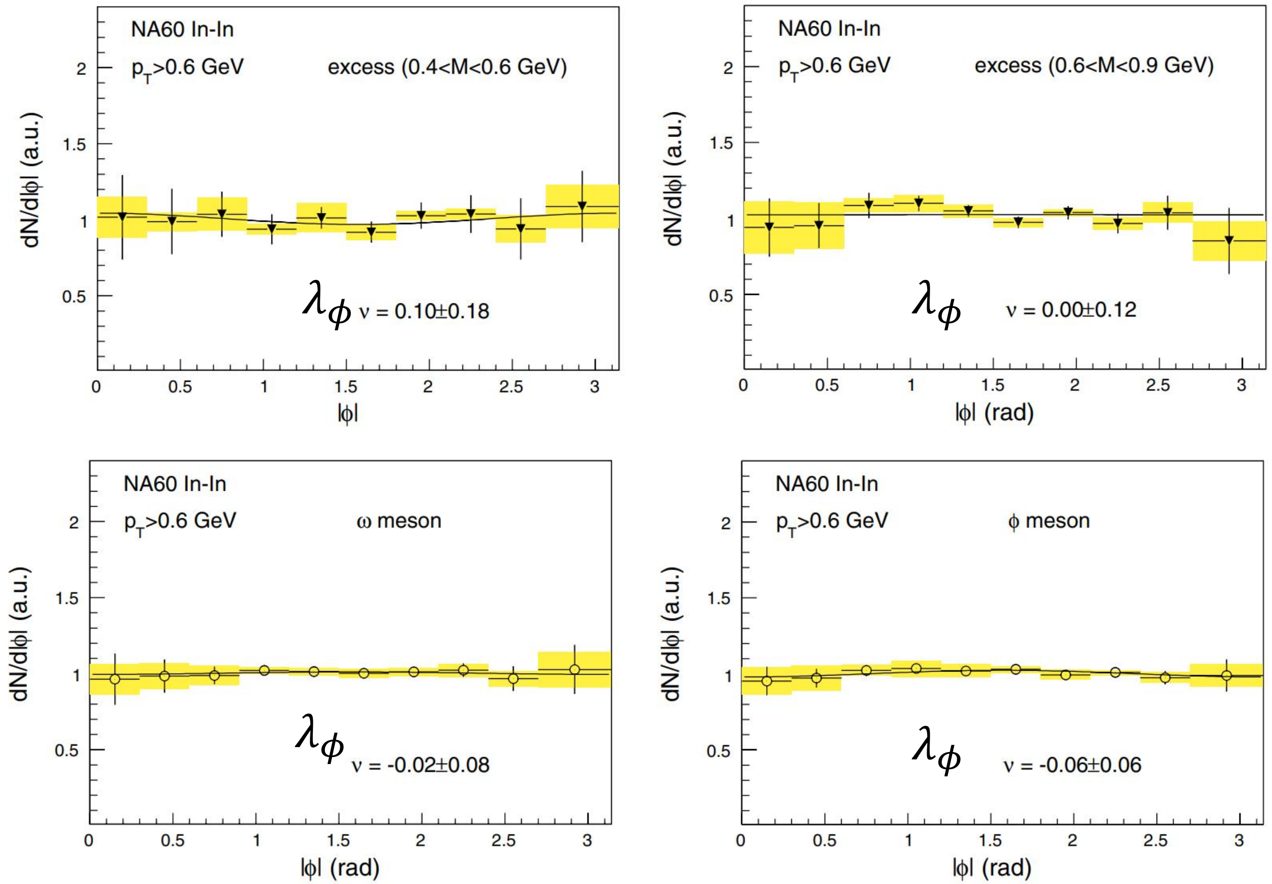


2309.03189.pdf (arxiv.org)

Angular distributions of thermal dileptons in nuclear collision

Anisotropic Coefficient λ_ϕ

- Results in Collins–Soper (CS) frame
- Azimuth angle distributions of excess dileptons and of the vector mesons ω, ϕ
- Notice: $3.2 < y < 4.2(+0.3 < y_{cm} <+ 1.3)$



$$\frac{dN}{d\phi} = A_1\left(1 + \frac{\lambda_\theta}{3} + \frac{\lambda_\phi}{3}\cos 2\phi\right)$$

(NA60 Collaboration) , Phys. Rev. Lett.102, 222301 (2009)

Quantities in helicity frame

$$(p_1^\mu)_{\rm HX} = \begin{pmatrix} \frac{M}{2} \\ \frac{1}{2}\sqrt{M^2 - 4m_q^2}\sin\theta_{\rm HX} \times \cos\phi_{\rm HX} \\ \frac{1}{2}\sqrt{M^2 - 4m_q^2}\sin\theta_{\rm HX} \times \sin\phi_{\rm HX} \\ \frac{1}{2}\sqrt{M^2 - 4m_q^2}\cos\theta_{\rm HX} \end{pmatrix}.$$

$$\begin{aligned}(u \cdot p_1)_{\rm HX} =& \frac{p}{qM}\left(q^2 u_t - q_x u_x \omega - q_y u_y \omega - q_z u_z \omega\right)\cos\theta \\ &+ \frac{1}{q} p(\cos\phi_\gamma q_z u_x - q_t u_z + \sin\phi_\gamma q_z u_y)\cos\phi\sin\theta \\ &- \frac{1}{2}(q_x u_x + q_y u_y + q_z u_z - u_t \omega) - p(\sin\phi_\gamma u_x - \cos\phi_\gamma u_y)\sin\theta\sin\phi,\end{aligned}$$

$$\begin{aligned}(F^{\mu\nu} p_{1,\mu} u_\nu)_{\rm HX} =& \frac{1}{qM} B_y \left[p(-q_z u_x + q_t \cos\phi_\gamma u_z)\omega\cos\theta - p(q_t u_x + \cos\phi_\gamma q_z u_z) M \cos\phi\sin\theta\right] \\ &+ \frac{1}{2} B_y \left[(-q_z u_x + q_x u_z) + 2p\sin\phi_\gamma u_z \sin\theta\sin\phi\right]\end{aligned}$$