Center for Theoretical Physics

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Polarized jet anisotropy at the future EIC

Fanyi Zhao

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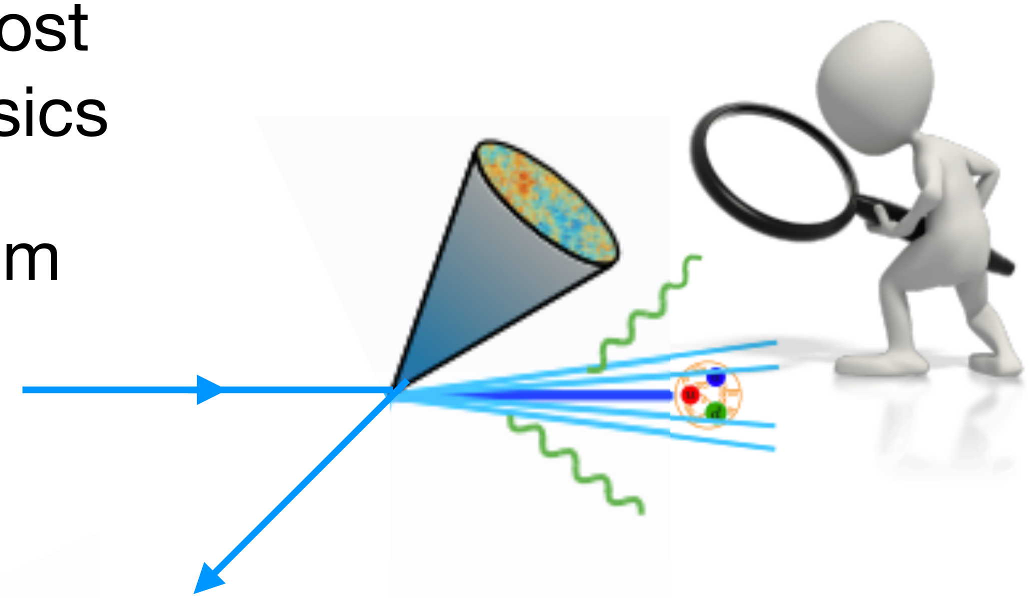
R. Esha, Z.-B. Kang, K. Lee, D. Shao and **FZ**, arXiv:2309.XXXX

Z.-B. Kang, H. Xing, Y. Zhou and **FZ**, arXiv:2309.XXXX

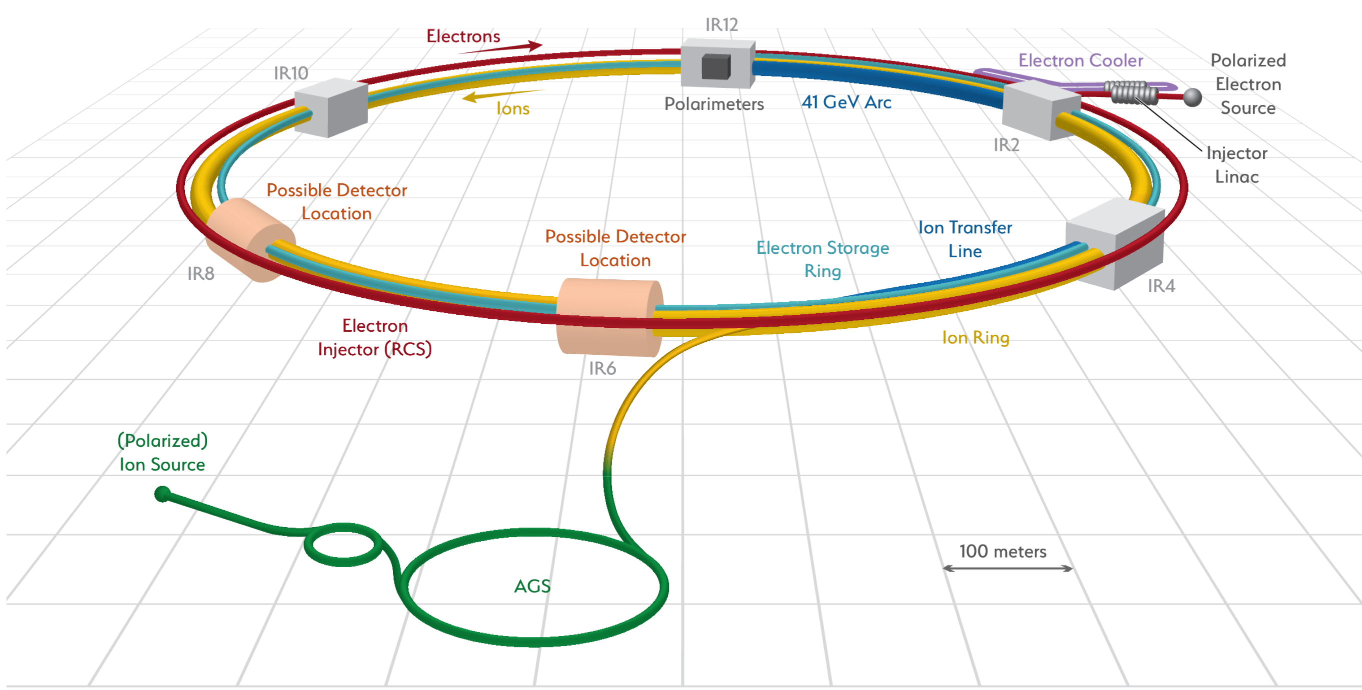
September 26th, 2023

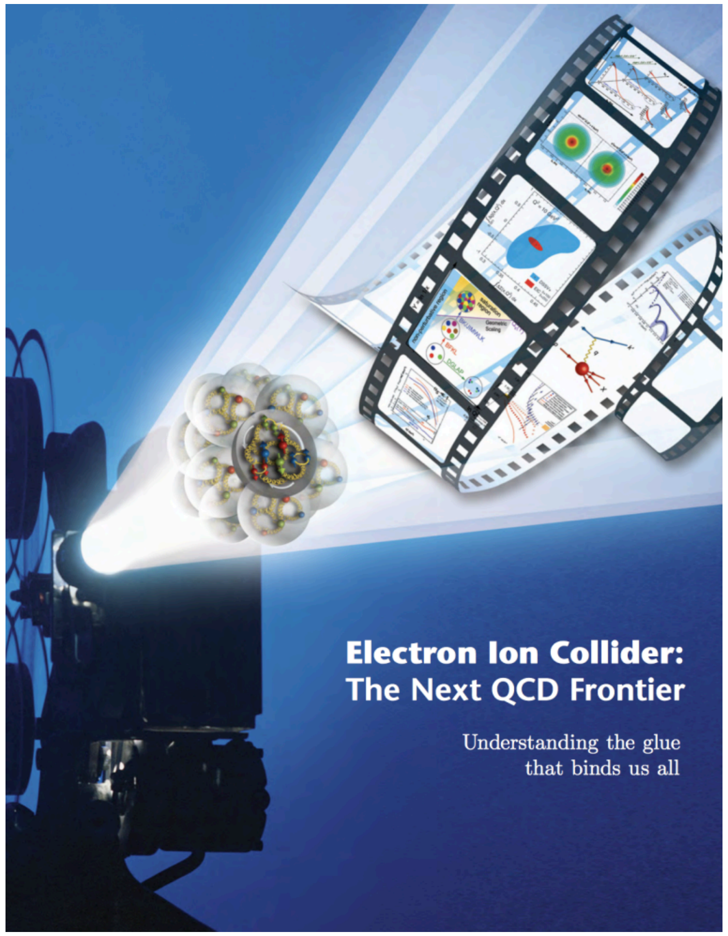
- 3D imaging of the nucleon: one of the most important research topics in hadron physics
- Back-to-back electron-jet production from *ep* collision ⇒ probe TMD PDFs



$$e(l) + p(P) \to e(l') + J_q(p_J) + X$$

Liu, Ringer, Vogelsang, Yuan PRL`18, PRD`20
Arratia, Kang, Prokudin, Ringer PRD`20
Kang, Lee, Shao, **Zhao**, JHEP`21

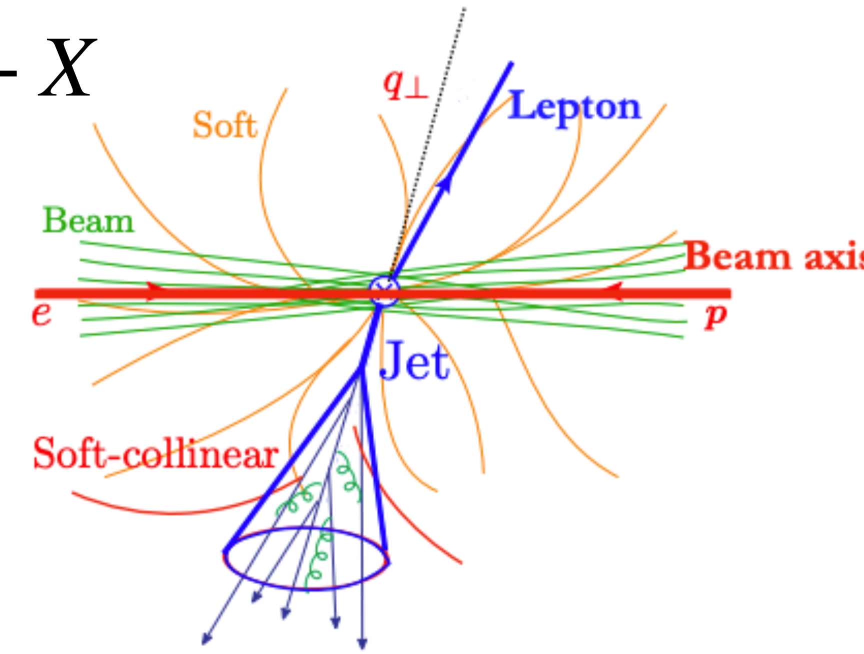




Motivation

- Back-to-back electron-jet production from *ep* collision,

$$e(l) + p(P) \to e(l') + J_q(p_J) + X$$



$$q_T = |\boldsymbol{l}'_T + \boldsymbol{p}_T|\,,$$

p_T : jet transverse momentum

Liu, Ringer, Vogelsang, Yuan PRL `18, PRD`20
Arratia, Kang, Prokudin, Ringer PRD `20
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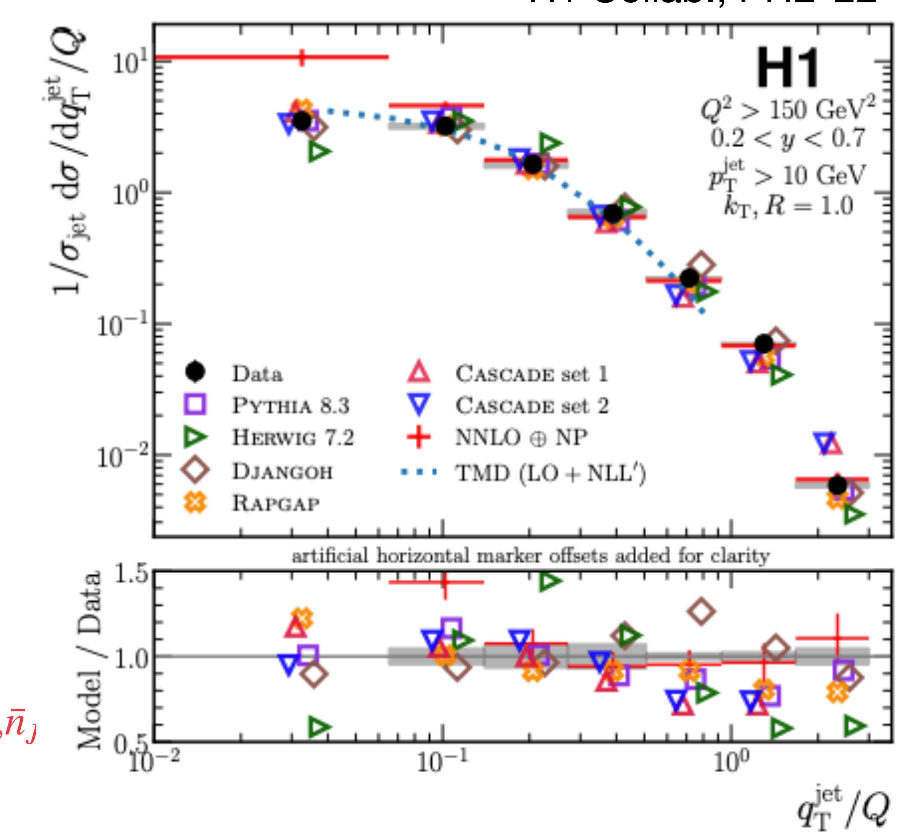
Unpolarized:

H1 Collab., PRL `22



$$\frac{d\sigma^{ep\to e+\text{jet}+X}}{dp_T dq_T} = f_1(x,\ k_{c,\perp}) \otimes S_{\text{global}}(k_{gs,\perp}) \otimes S_{sc}(k_{sc,\perp})$$

$$\times H(Q)\, J_c(p_T R)$$

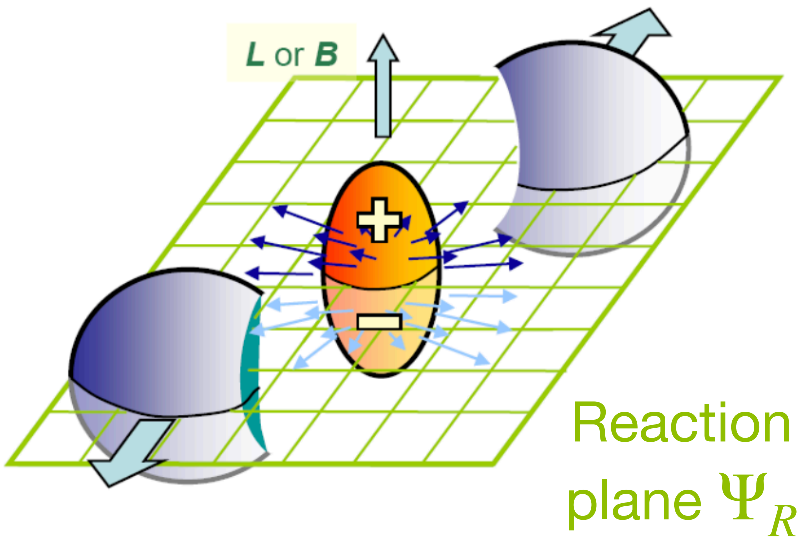
Relevant modes ($\lambda = q_T/p_T$):

n-collinear: $k_c \sim p_T(\lambda^2, 1, \lambda)_{n,\bar{n}}$ $(+,-,\perp)$ n_J-collinear: $k_J \sim p_T(R^2, 1, R)_{n_J,\bar{n}_J}$

global soft: $k_{gs} \sim p_T(\lambda, \lambda, \lambda)$ Soft-collinear: $k_{sc} \sim p_T R(\lambda R, \lambda/R, \lambda)_{n_J,\bar{n}_J}$

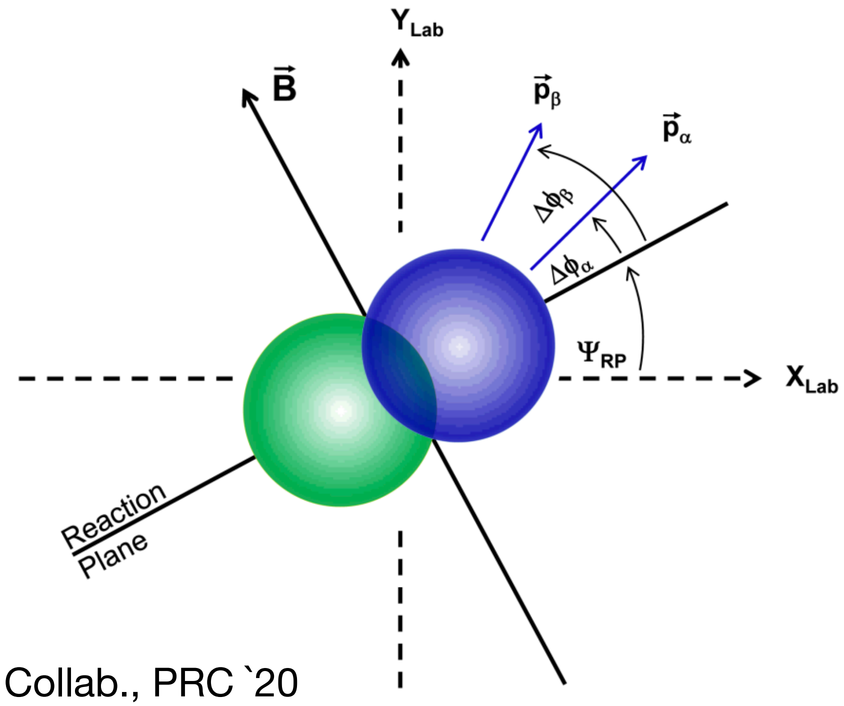
- Anisotropic flow expansions in heavy-ion collisions,

$$E\frac{d^3N}{d^3\mathbf{p}} = \frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}\left(1 + 2\sum_{n=1}^{\infty} v_n \cos\left[n\left(\varphi - \Psi_{RP}\right)\right]\right), \quad v_n\left(p_t, y\right) = \langle\cos[n(\varphi - \Psi_{RP})]\rangle$$



STAR Collab., PRC `20

v_1 : directed flow
v_2 : elliptic flow
v_3 : triangular flow
v_4 : quadrapole flow …



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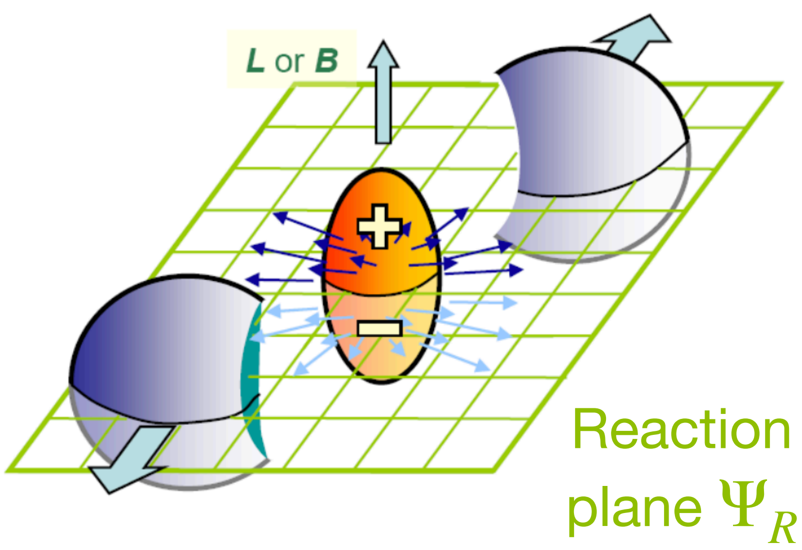

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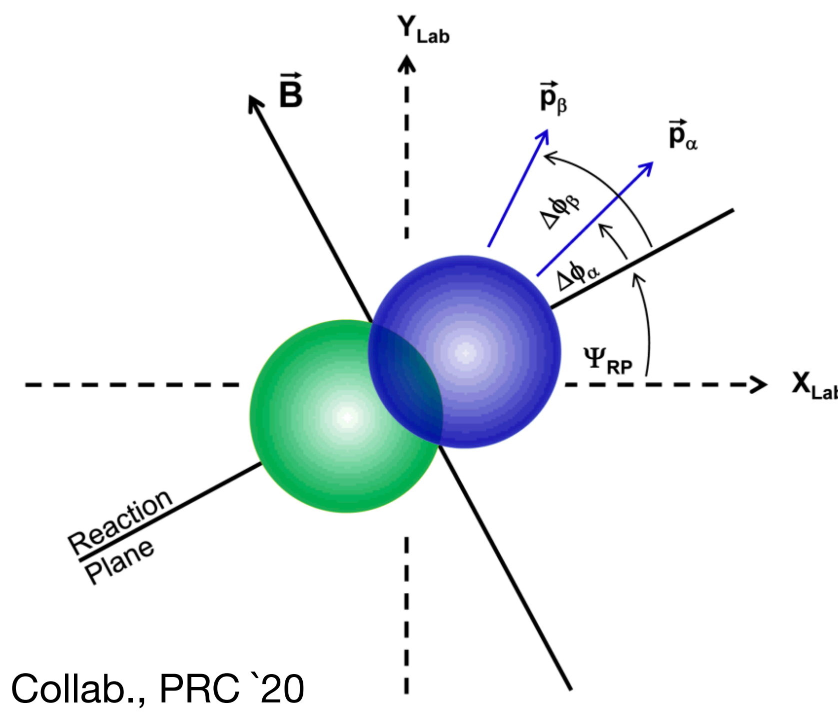


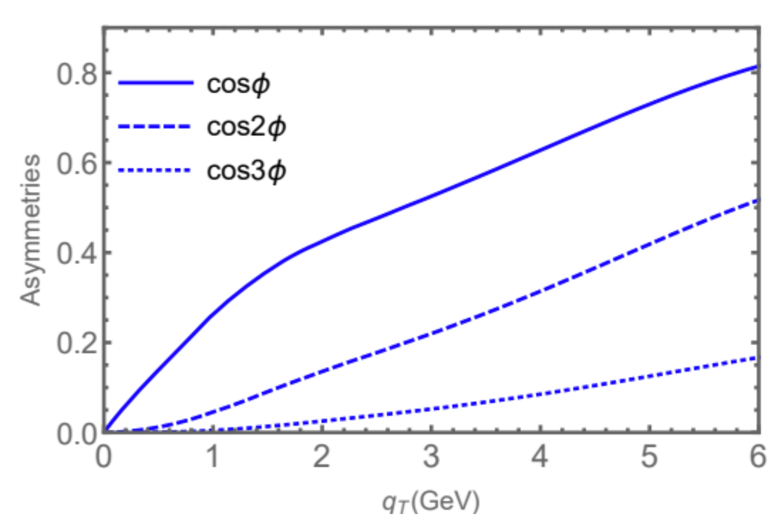
STAR Collab., PRC `20

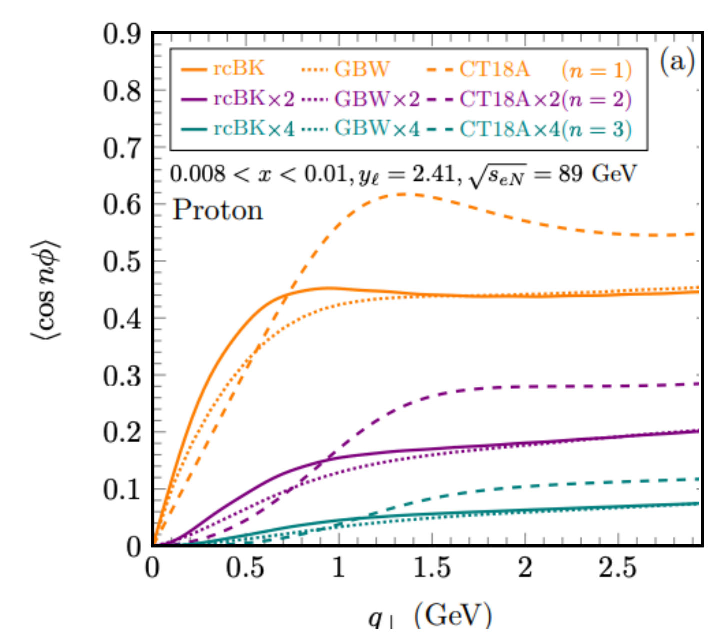
- Azimuthal anisotropy in unpolarized *ep* collisions,

Hatta, Xiao, Yuan, Zhou PRL `21

Tong, Xiao, Zhang PRL `22

Esha, Kang, Lee, Shao, **Zhao**, `23





Polarized jet anisotropy

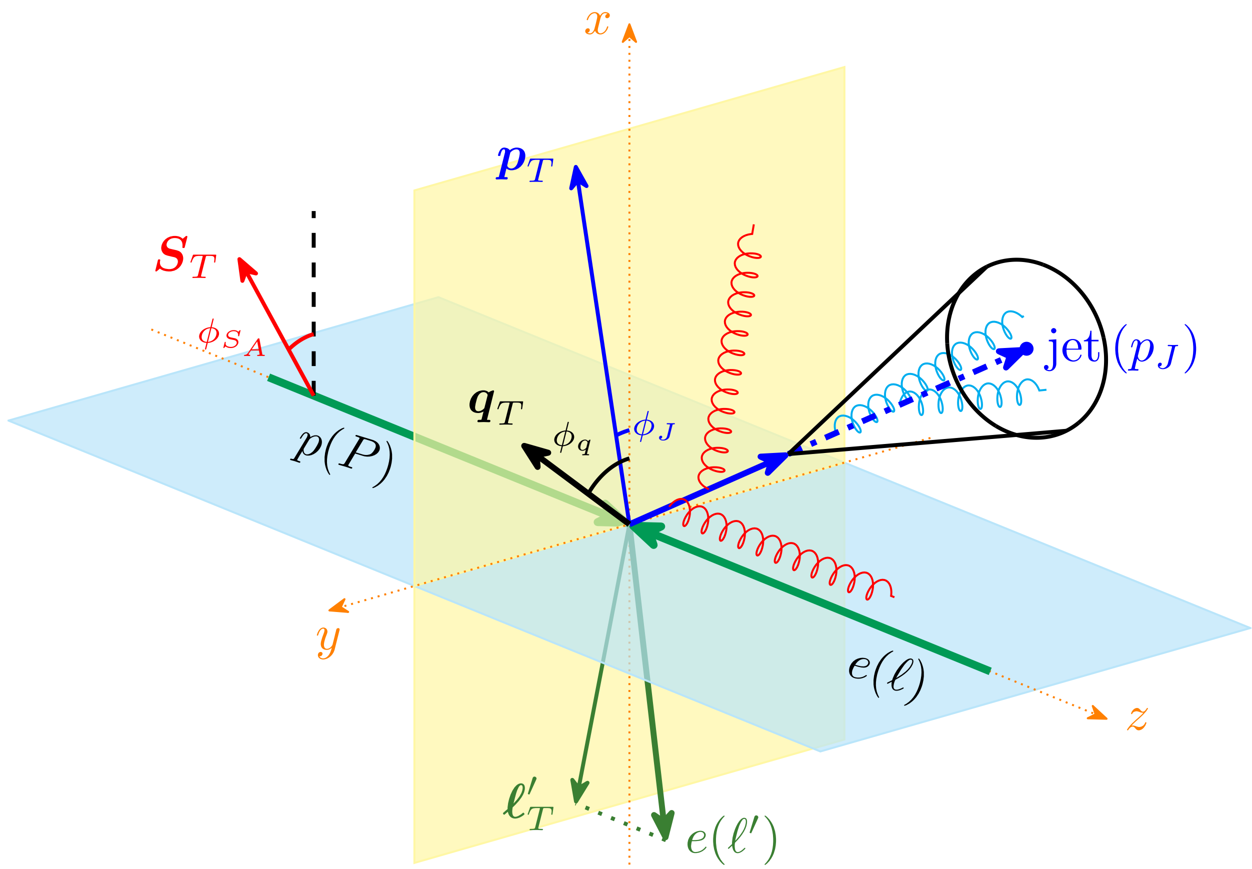
- Back-to-back electron-jet production from *ep* collision,

$$e(l, \lambda_e) + p(P, S) \to e(l') + J_q(p_J) + X$$

Kang, Lee, Shao, **Zhao**, JHEP `21

$$\frac{d\sigma}{d^2\boldsymbol{p}_T dy_J d\phi_J d^2\boldsymbol{q}_T} = F_{UU} + \lambda_p \lambda_e F_{LL} + S_T\left[\sin(\phi_q - \phi_S) F_{UT}^{\sin(\phi_q - \phi_S)} + \lambda_e \cos(\phi_q - \phi_S) F_{LT}^{\cos(\phi_q - \phi_S)}\right]$$

$\sim f_1$ $\quad \sim g_1$ $\quad \sim f_{1T}^{\perp}$ $\quad \sim g_{1T}$



$F_{AB} : AB = UU, LL, UT, LT$

A : electron polarization $\quad \lambda_e$

B : proton polarization $\quad \lambda_p,\ S_T$

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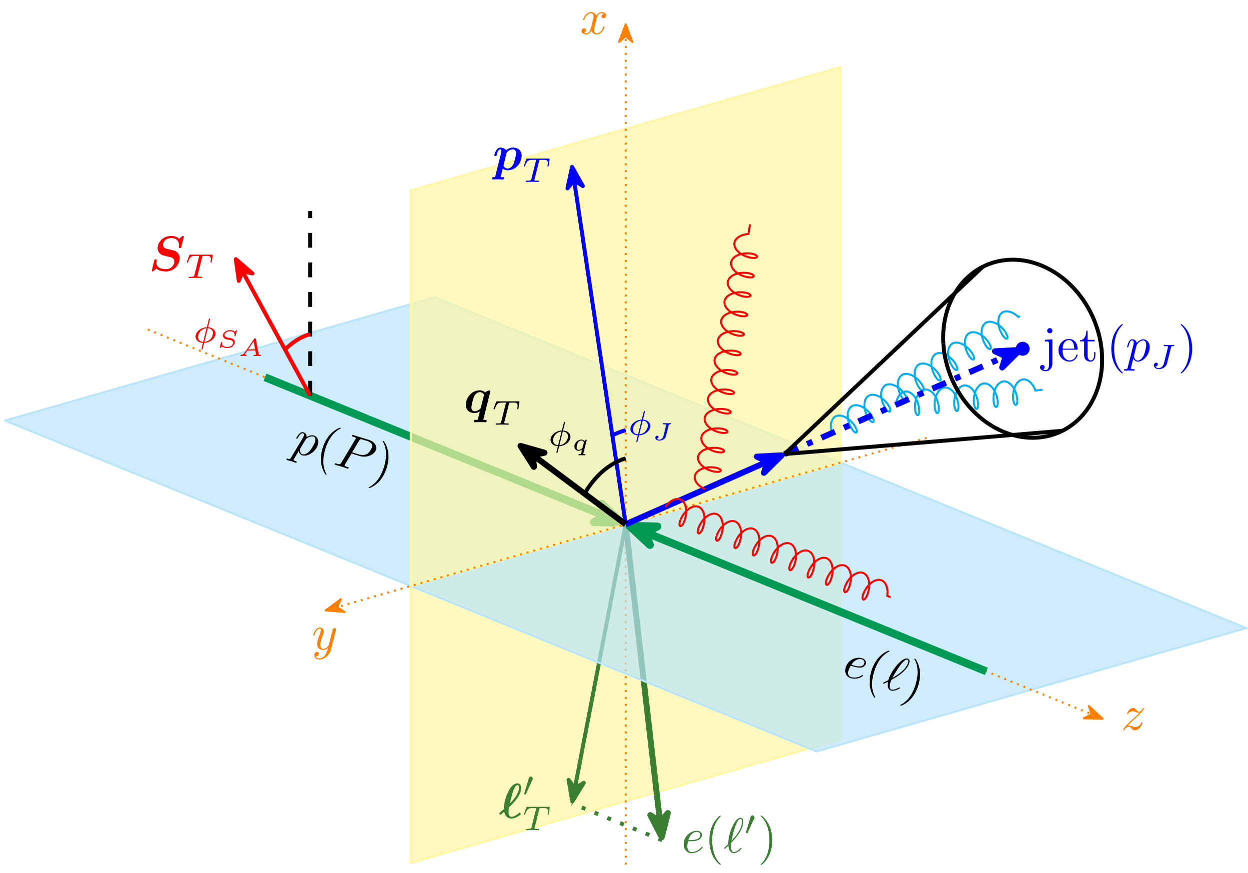
$$= \frac{d\sigma}{2\pi d^2\boldsymbol{p}_T dy_J q_T dq_T}\left[1 + 2\sum_{n=1}^{\infty}\sum_{AB} v_{AB}^n \cos(n(\phi_q - \phi_J))\right]$$



$$v_{AB}^n(p_T, y_J, \lambda_e, S, \phi_S, \phi_q)$$

$$AB = UU, LL, UT, LT$$

A : electron polarization

B : proton polarization

q_T : transverse momentum imbalance

$$\boldsymbol{q}_T = \boldsymbol{l}'_T + \boldsymbol{p}_T$$

p_T : jet transverse momentum

y_J : jet rapidity

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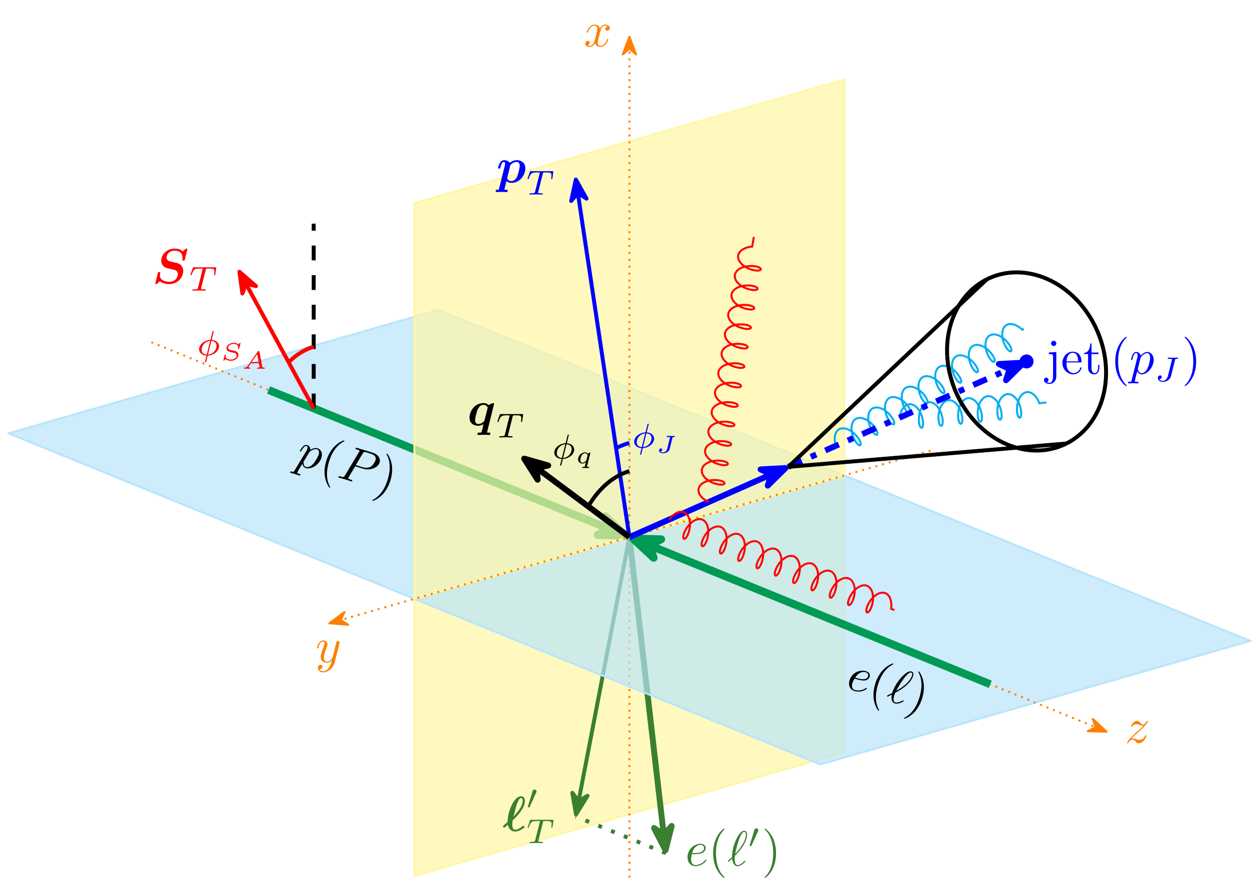

$v_{AB}^n(p_T, y_J, \lambda_e, S, \phi_S, \phi_q)$

ϕ_q : azimuthal angle of transverse momentum imbalance

ϕ_J : azimuthal angle of jet transverse momentum

ϕ_S : azimuthal angle of initial proton transverse spin

v_{AB}^n : anisotropic Fourier coefficients

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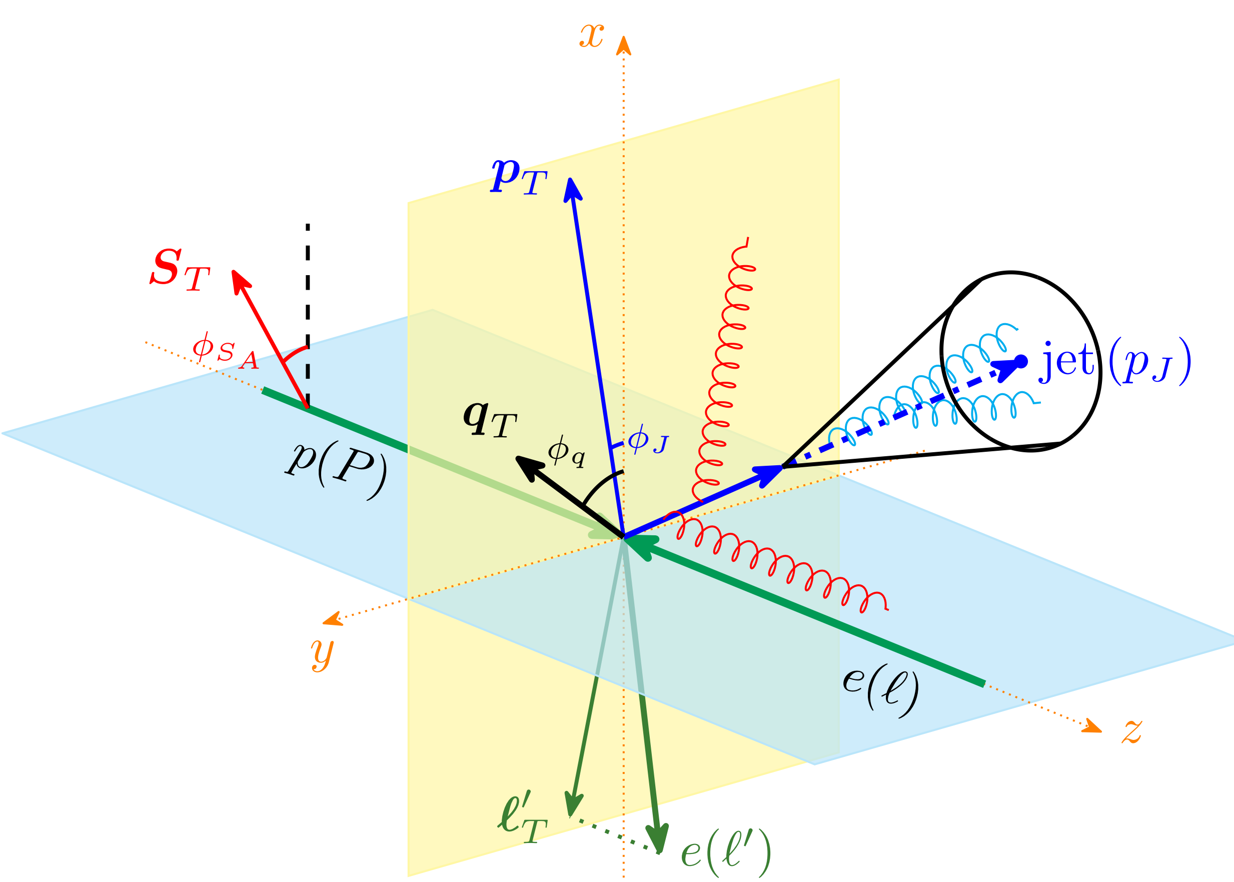


$v_{AB}^n(p_T, y_J, \lambda_e, S, \phi_S, \phi_q)$

ϕ_q : azimuthal angle of transverse momentum imbalance

ϕ_J : azimuthal angle of jet transverse momentum

ϕ_S : azimuthal angle of initial proton transverse spin

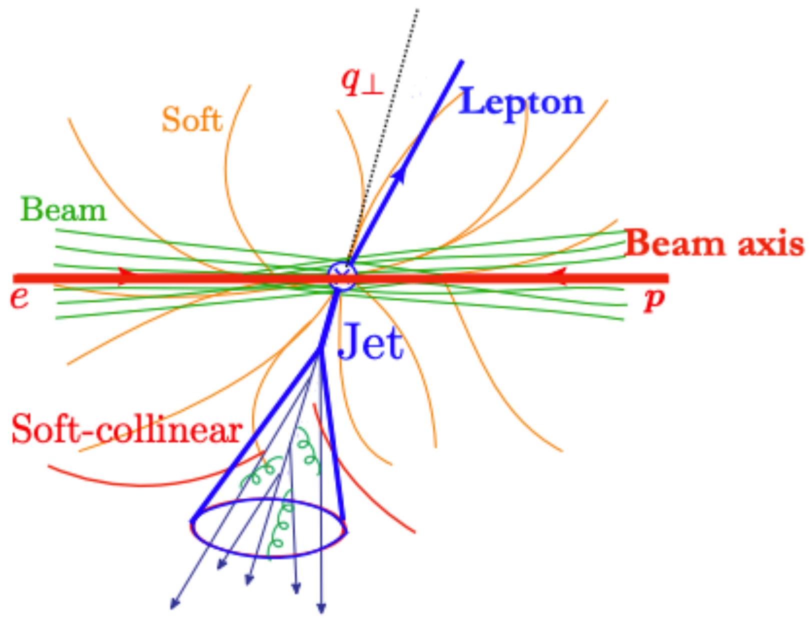
v_{AB}^n : anisotropic Fourier coefficients

Polarized jet anisotropy

- E.g. $F_{UT}^{\sin(\phi_q-\phi_S)}$:

$$F_{UT}^{\sin(\phi_q-\phi_S)} = \hat{\sigma}_0 H(Q,\mu)\sum_q e_q^2 \mathscr{J}_q(p_T R,\mu)\int \frac{b\mathrm{d}b}{2\pi} e^{-i\boldsymbol{q}_T\cdot\boldsymbol{b}} x\tilde{f}_{1T}^{\perp,q,(1)}\left(x,b^2,\mu,\zeta\right)$$

$$\times \int \frac{\mathrm{d}\phi_{bq}}{2\pi} ib\cos(\phi_{bq}) M S_{\mathrm{global}}(\boldsymbol{b},\mu) S_{cs}(\boldsymbol{b},R,\mu)$$



$$ib\cos(\phi_{bq}) e^{-ibq_T\cos(\phi_{bq})}$$

$$= -b\left(-J_1 + \sum_{n=1}^{\infty} -i^n\left(J_{n-1}-J_{n+1}\right)\cos(n\phi_{bq})\right)$$

Jacobi-Anger identity

$$F_{UT}^{\sin(\phi_q-\phi_S)} = \sum_{n=0}^{\infty} A_n^{\mathrm{Sivers}}$$

$$A_n^{\mathrm{Sivers}} \equiv \hat{\sigma}_0 H(Q,\mu)\sum_q e_q^2 \mathscr{J}_q(p_T R,\mu)\int \frac{b^2\mathrm{d}b}{2\pi} xM\tilde{f}_{1T}^{\perp\, q,(1)}\left(x,b^2,\mu,\zeta\right)(-i)^n\left(\frac{1}{2}\right)^{\delta_{0n}}\left(J_{n+1}(q_T b) - J_{n-1}(q_T b)\right)$$

$$\times \int \frac{\mathrm{d}\phi_{bJ}}{2\pi}\cos(n(\phi_{bJ}-\phi_{qJ})) S_{\mathrm{global}}(\boldsymbol{b},\mu) S_{cs}(\boldsymbol{b},R,\mu)$$

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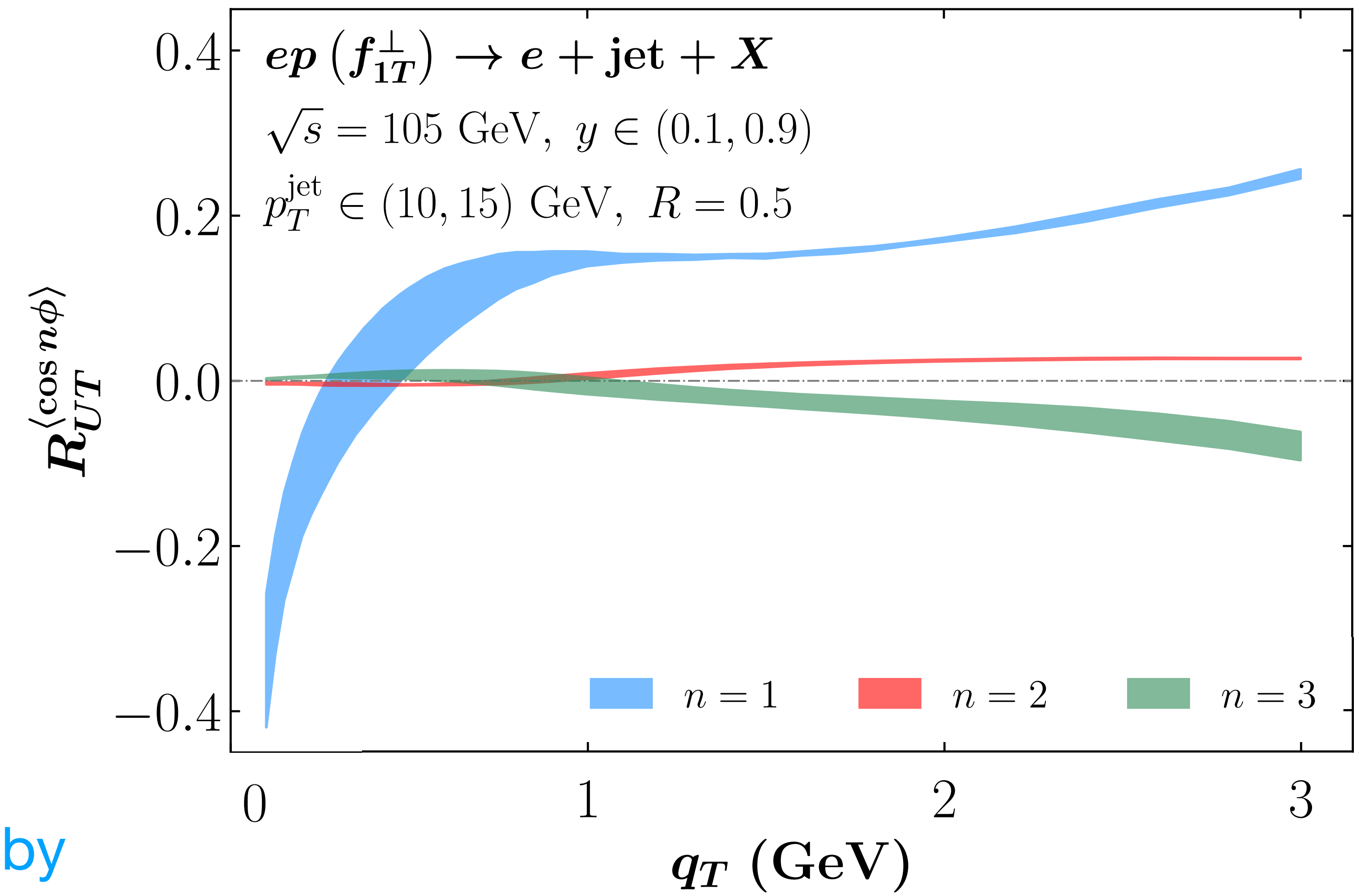
$$R_{UT}^{\langle\cos(n\phi)\rangle} = \frac{\int A_n^{\text{Sivers}} \cos(n\phi)\frac{d\phi}{2\pi}}{\int A_0^{\text{Sivers}}\frac{d\phi}{2\pi}},$$

$$\phi = \phi_{qJ}$$



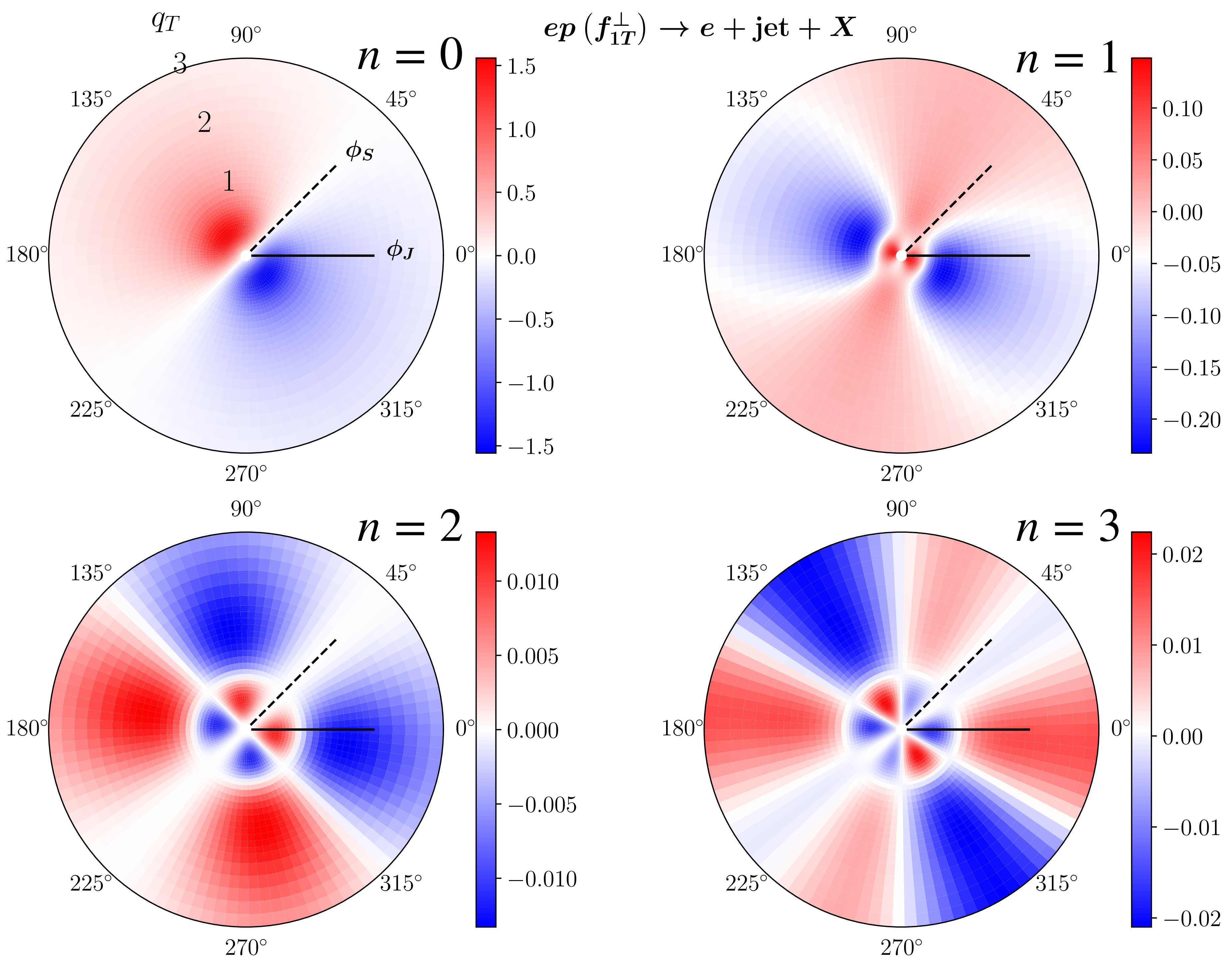
Anisotropic flows produced by global and collinear soft functions

$$A_n^{\text{Sivers}} \equiv \hat{\sigma}_0 H(Q,\mu) \sum_q e_q^2 \mathcal{J}_q(p_T R,\mu) \int \frac{b^2 \mathrm{d}b}{2\pi} x M \tilde{f}_{1T}^{\perp\, q,(1)}\left(x, b^2, \mu, \zeta\right)(-i)^n \left(\frac{1}{2}\right)^{\delta_{0n}} \left(J_{n+1}(q_T b) - J_{n-1}(q_T b)\right)$$
$$\times \int \frac{\mathrm{d}\phi_{bJ}}{2\pi} \cos(n(\phi_{bJ}-\phi_{qJ})) S_{\text{global}}(\boldsymbol{b},\mu) S_{cs}(\boldsymbol{b},R,\mu)$$

Polarized jet anisotropy

- E.g. $F_{UT}^{\sin(\phi_q - \phi_S)}$: $\phi_S = \frac{\pi}{4}$, $\phi_J = 0$

Rich spin structure!



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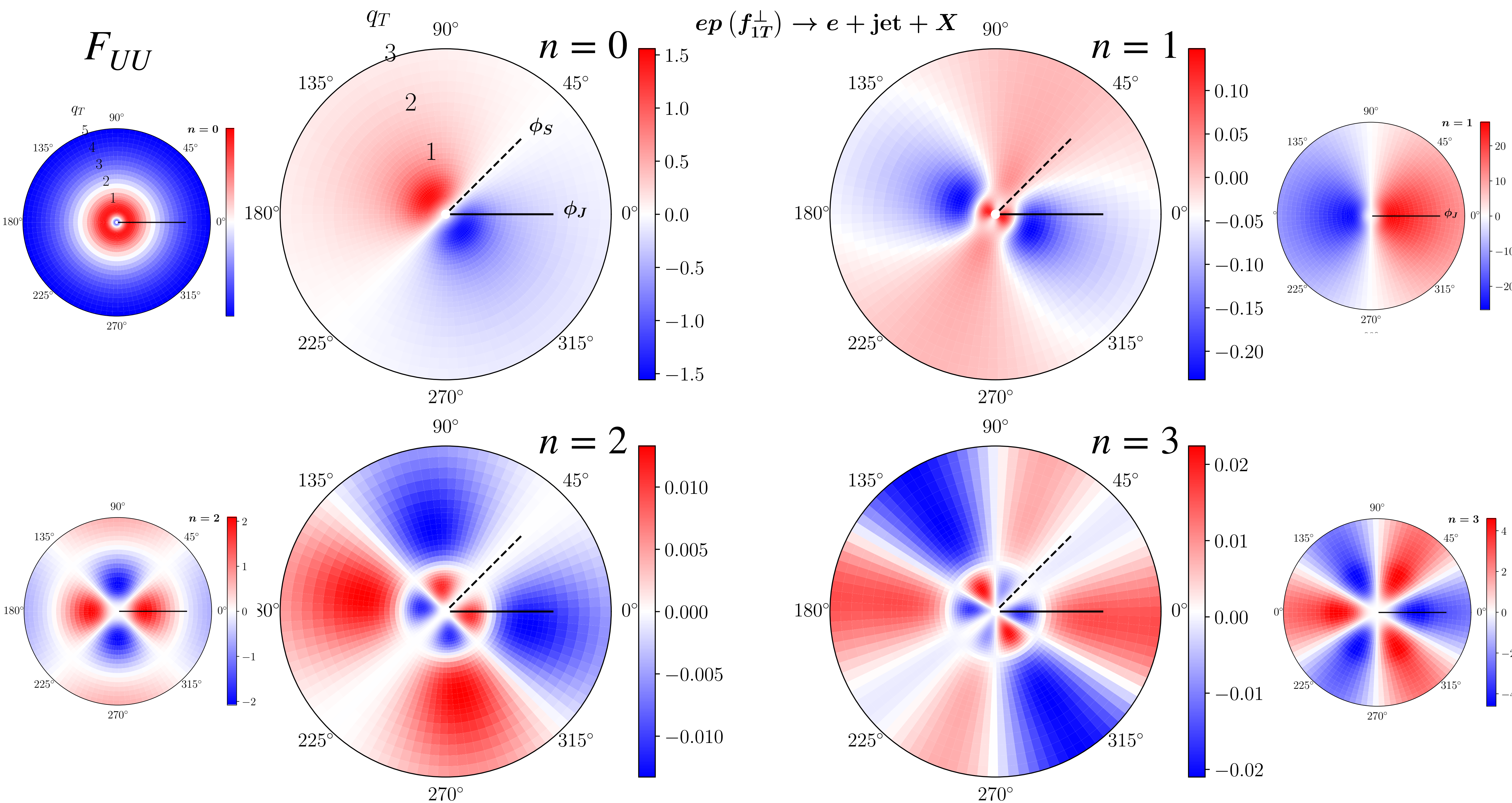

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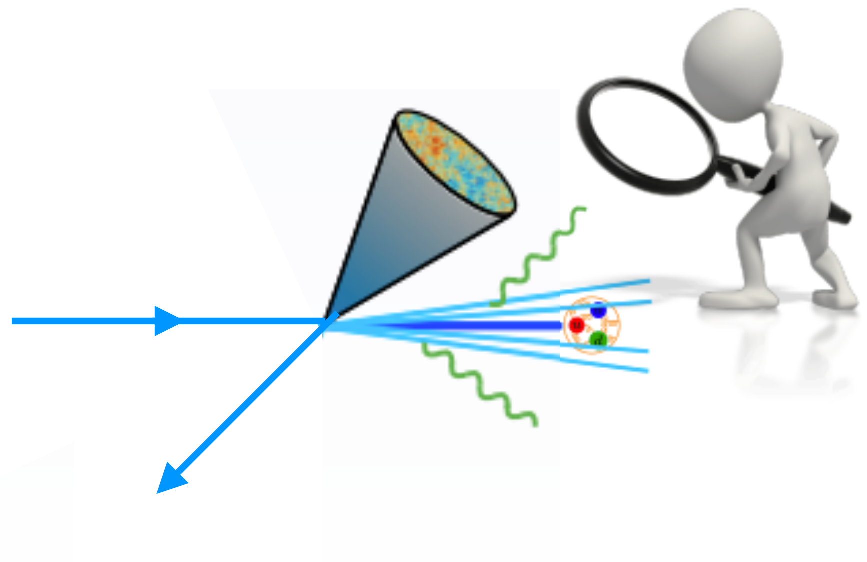
Summary



- We study back-to-back polarized lepton-jet production in polarized ep collisions. In this work, we study the azimuthal anisotropy with azimuthal angle dependence on ϕ_q, ϕ_J and ϕ_S
- Soft gluon radiation would lead to even more rich dynamics with nontrivial and novel features in polarized scattering: how soft gluon radiation would distort the azimuthal asymmetric pictures in the transverse plane related to the Sivers function
- The polarized jet anisotropy observables have measurable magnitudes and can be a valuable tool in exploring spin structures, polarized TMD PDFs in the lepton-jet correlations in future EIC.

Backup

Polarized jet anisotropy

- The global soft function: soft radiation that has no phase space restriction and does not resolve the jet cone.

$$S_{\text{global}}(\boldsymbol{b},\mu,\nu) = 1 + \frac{\alpha_s}{2\pi}C_F\left\{\left[-\frac{2}{\eta} + \ln\frac{\mu^2}{\nu^2} + 2y_J + 2\ln(-2i\cos(\phi_{bJ}))\right]\left(\frac{1}{\epsilon} + \ln\frac{\mu^2}{\mu_b^2}\right) + \frac{2}{\epsilon^2} + \frac{1}{\epsilon}\ln\frac{\mu^2}{\mu_b^2} - \frac{\pi^2}{6}\right\}$$

- The collinear-soft function: soft radiation which is only sensitive to the jet direction and resolves the jet cone

$$S_{cs}(\boldsymbol{b},R,\mu) = 1 - \frac{\alpha_s}{2\pi}C_F\left[\frac{1}{\epsilon^2} + \frac{2}{\epsilon}\ln\left(\frac{-2i\cos(\phi_{bJ})\mu}{\mu_b R}\right) + 2\ln^2\left(\frac{-2i\cos(\phi_{bJ})\mu}{\mu_b R}\right) + \frac{\pi^2}{4}\right]$$

$\mu_b = 2e^{-\gamma_E}/b$, $\phi_{bJ} \equiv \phi_b - \phi_J$ with ϕ_b and ϕ_J are the azimuthal angles of the vector $\boldsymbol{b}$ and jet transverse momentum $\boldsymbol{p}_T$

Polarized jet anisotropy