Polarized jet anisotropy

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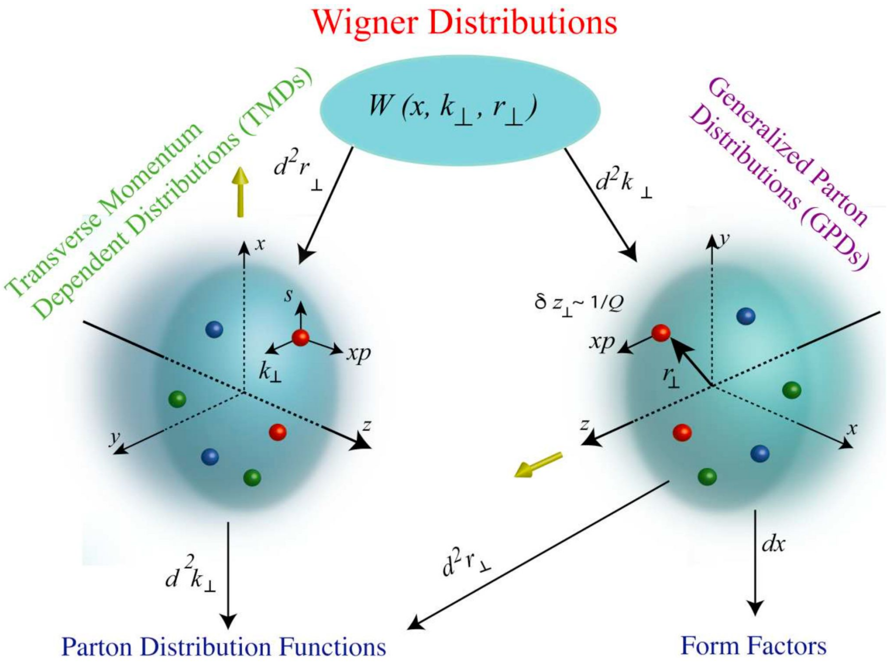
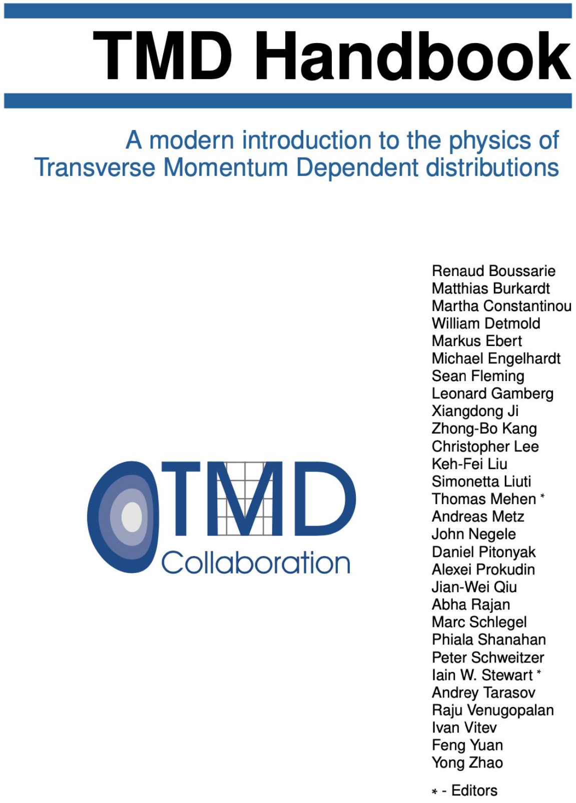
Motivation

- 3D imaging of nucleon: important topic in QCD
- Back-to-back electron-jet production in *ep* collision




TMD Handbook

A modern introduction to the physics of Transverse Momentum Dependent distributions

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* - Editors

Motivation

Traditionally, transverse spin asymmetry has also been called **left-right asymmetry**...

Spin asymmetries in hadronic reactions help unveil the unique correlation of partons inside the nucleon. SSAs are among the early experimental observations of spin asymmetries in high-energy hadron collisions (17, 18), where a beam of transversely polarized protons was scattered off unpolarized nucleons. These experiments (17, 18) showed that the charged pions are produced asymmetrically to the left or the right of the plane spanned by the momentum and spin directions of the initial polarized protons:

$$A_N = \frac{d\sigma(S_\perp) - d\sigma(-S_\perp)}{d\sigma(S_\perp) + d\sigma(-S_\perp)}. \qquad 1.$$

Therefore, this asymmetry is also called left–right asymmetry (**Figure 5**). Subsequent

Grosse-Perdekamp and Yuan: 1510.06783

See also STAR: 0801.2990, Huang, Kang, Vitev and Xing: 1511.06764
and Gamberg, Kang, Metz, Pitonyak and Prokudin: 1407.5078

Motivation

But, the azimuthal angle dependence has never been studied...

$$F_{UT}^{\sin(\phi_q-\phi_S)} \propto H(Q)\mathcal{J}_q(p_T R) \times f_{1T,q/p}^{\perp}(x,\boldsymbol{k}_T) \otimes \boxed{S_{\text{global}}(\boldsymbol{k}_{\text{g},\perp})S_{\text{cs}}(\boldsymbol{k}_{\text{sc},\perp},R)}$$

Azimuthal angle ϕ dependence!

$$S_{\text{global}}(\boldsymbol{b},\mu) = 1 + \frac{\alpha_s}{2\pi}C_F\left[\frac{1}{\epsilon^2} + \frac{1}{\epsilon}\ln\left(\frac{\mu^2}{\mu_b^2}\right) + \frac{1}{2}\ln^2\left(\frac{\mu^2}{\mu_b^2}\right) + 2\left(y_J + \ln(-2i\cos(\phi_{bJ}))\right)\left(\frac{1}{\epsilon} + \ln\left(\frac{\mu^2}{\mu_b^2}\right)\right) - \frac{\pi^2}{12}\right]$$

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

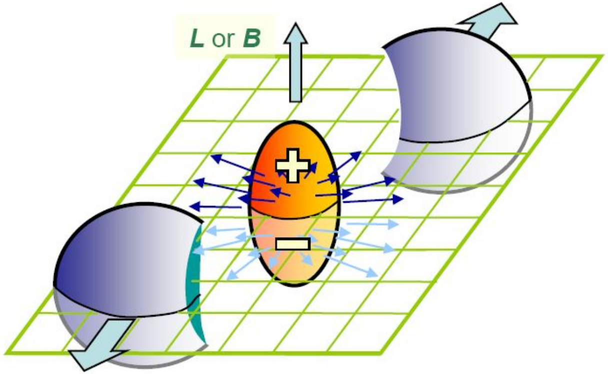
Buffing, Kang, Lee and Liu: 1812.07549
Kang, Lee, Shao and Zhao: 2106.15624

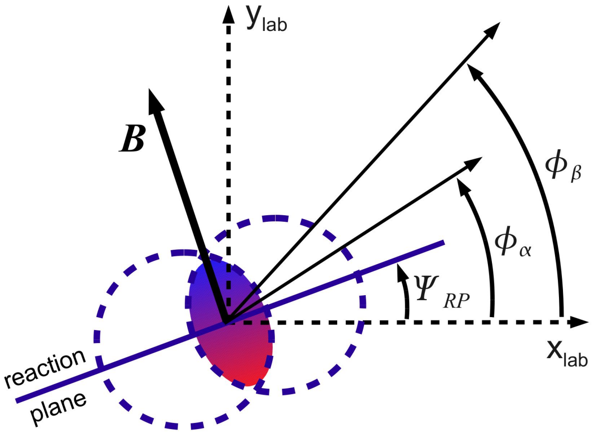
Motivation

Anisotropic flow expansions in heavy-ion collisions:

$$\Delta\phi \equiv \phi_\alpha - \Psi_{\mathrm{RP}}$$

$$\frac{\mathrm{d}N_\alpha}{\mathrm{d}\phi_\alpha} \propto 1 + 2v_{1,\alpha}\cos(\Delta\phi) + 2v_{2,\alpha}\cos(2\Delta\phi) + \cdots$$



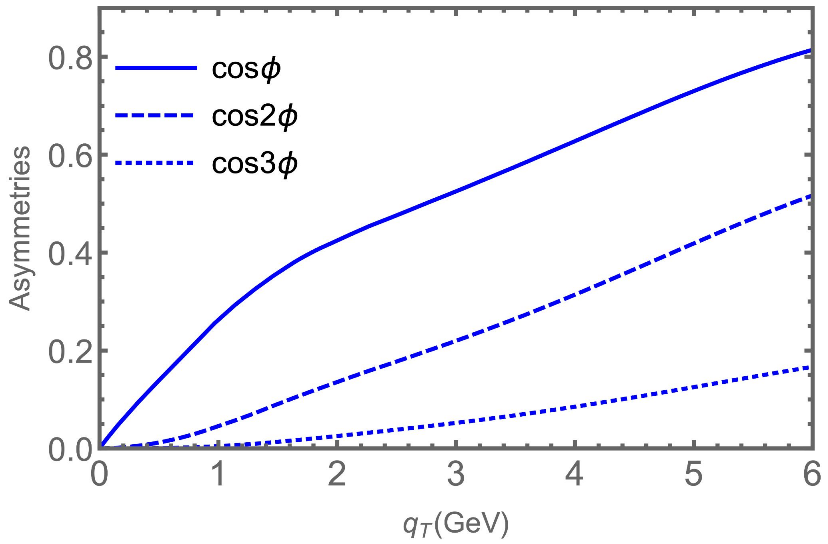


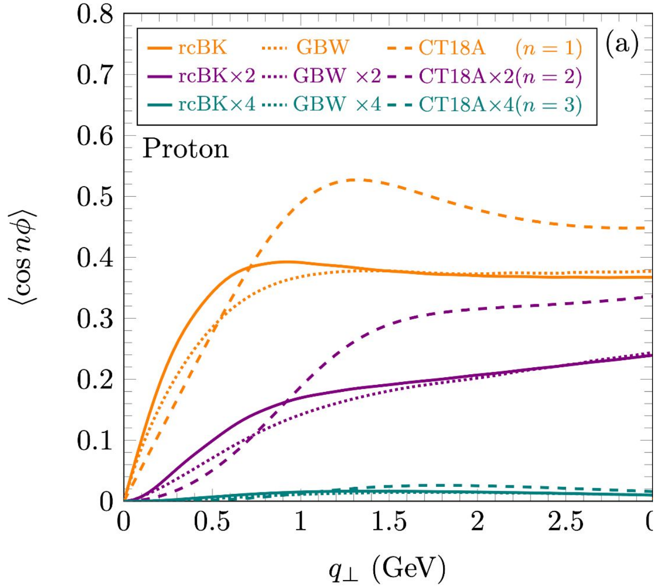
Feng, Voloshin and Wang: 2502.09742

STAR: 0909.1717 & 0909.1739

Motivation

Anisotropic flow expansions in unpolarized *ep* collision:





Hatta, Xiao, Yuan and Zhou: [2106.05307]

Polarized?

Tong, Xiao and Zhang: [2310.20662]

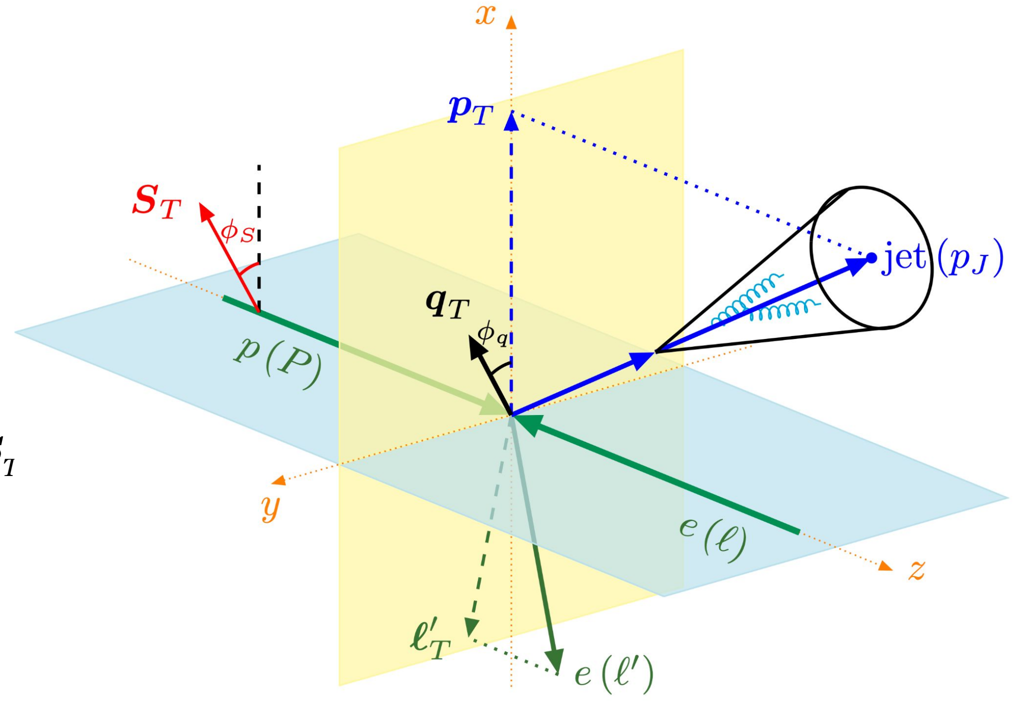
Back-to-back electron-jet production

$$e\,(\ell, \lambda_e) + p\,(P, S) \to e\,(\ell') + \text{jet}\,(p_J) + X$$

- $\boldsymbol{p}_T$: jet transverse momentum
- $\boldsymbol{q}_T$: transverse momentum imbalance,

  $\boldsymbol{q}_T = \boldsymbol{l'}_T + \boldsymbol{p}_T$
- $\boldsymbol{b}$: conjugate variable of $\boldsymbol{q}_T$
- ϕ_S, ϕ_J, ϕ_q and ϕ_b: azimuthal angle of $\boldsymbol{S}_T$

  jet, $\boldsymbol{q}_T$ and $\boldsymbol{b}$



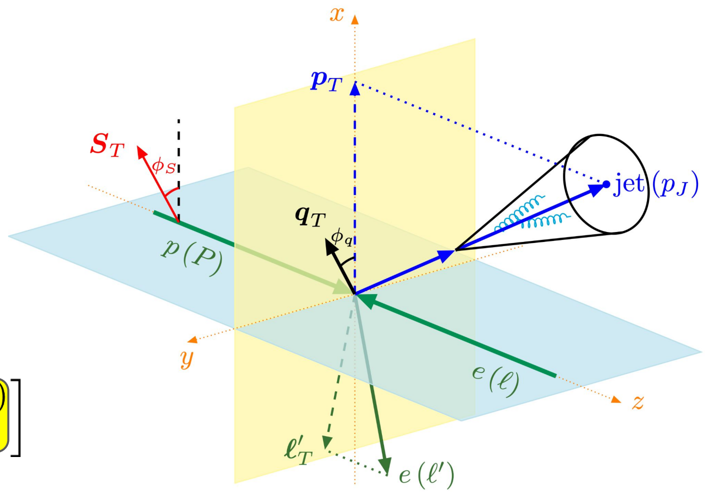
Back-to-back electron-jet production

$$e\,(\ell, \lambda_e) + p\,(P, S) \to e\,(\ell') + \text{jet}\,(p_J) + X$$

With longitudinally polarized electron beam

and transversely polarized proton beam:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\phi_q\,\mathrm{d}\mathcal{PS}} = \overset{f_1}{F_{UU}} + \lambda_e\lambda_p \overset{g_{1L}}{F_{LL}} + S_T\Big[\sin(\phi_q - \phi_S) \times \underset{f_{1T}^{\perp}}{\boxed{F_{UT}^{\sin(\phi_q-\phi_S)}}} + \lambda_e \cos(\phi_q - \phi_S) \underset{g_{1T}}{\boxed{F_{LT}^{\cos(\phi_q-\phi_S)}}}\Big]$$



Back-to-back electron-jet production

Sivers polarized jet anisotropy:

$$F_{UT}^{\sin(\phi_q-\phi_S)} = \sum_{n=0}^{\infty} \boxed{A_n^{\text{Sivers}}} \cos(n\phi_{qJ})$$

anisotropic Fourier coefficients

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

Back-to-back electron-jet production

Worm-gear polarized jet anisotropy:

$$F_{LT}^{\cos(\phi_q-\phi_S)} = \sum_{n=0}^{\infty} \boxed{A_n^{\text{worm-gear}}} \cos(n\phi_{qJ})$$

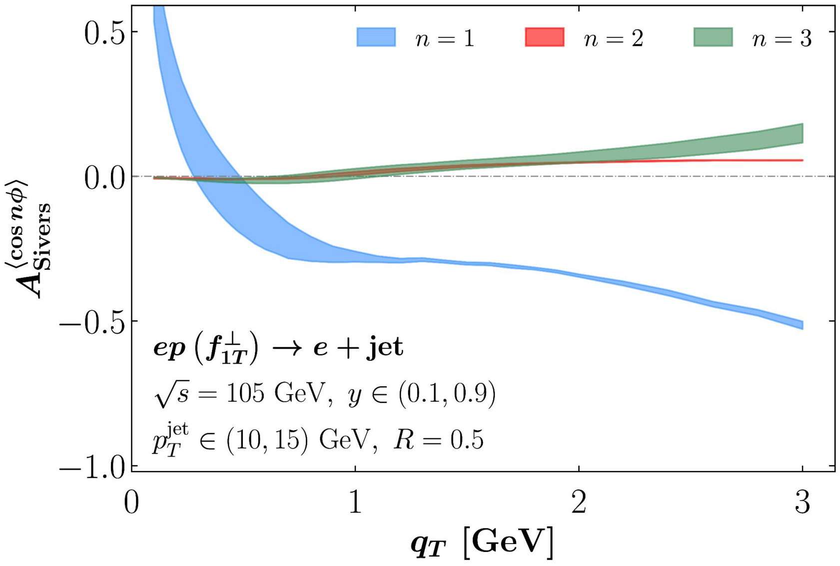
anisotropic Fourier coefficients

$$\begin{aligned} A_n^{\text{worm-gear}} \equiv\ & \hat{\sigma}_L H(Q,\mu) \sum_q e_q^2 \mathcal{J}_q(p_T R,\mu) \int \frac{b^2\,\mathrm{d}b}{2\pi} xM \\ & \times \tilde{g}_{1T,q/p}^{(1)}(x,b^2,\mu,\zeta) i^n \left(\frac{1}{2}\right)^{\delta_{0n}} \\ & \times \left(J_{n-1}(q_T b) - J_{n+1}(q_T b)\right) \\ & \times \int \frac{\mathrm{d}\phi_{bJ}}{2\pi} \cos(n\phi_{bJ}) S_{\text{global}}(\boldsymbol{b},\mu,\nu) S_{\text{cs}}(\boldsymbol{b},R,\mu), \end{aligned}$$

Polarized jet anisotropy: Sivers

$$R_{UT}^{\langle\cos(n\phi)\rangle} \equiv \int_0^{2\pi} \frac{\mathrm{d}\phi_{qJ}}{2\pi} \cos^2(n\phi_{qJ}) R_{UT}^n$$

$$R_{UT}^n \equiv A_n^{\text{Sivers}} / A_0^{\text{Sivers}}$$

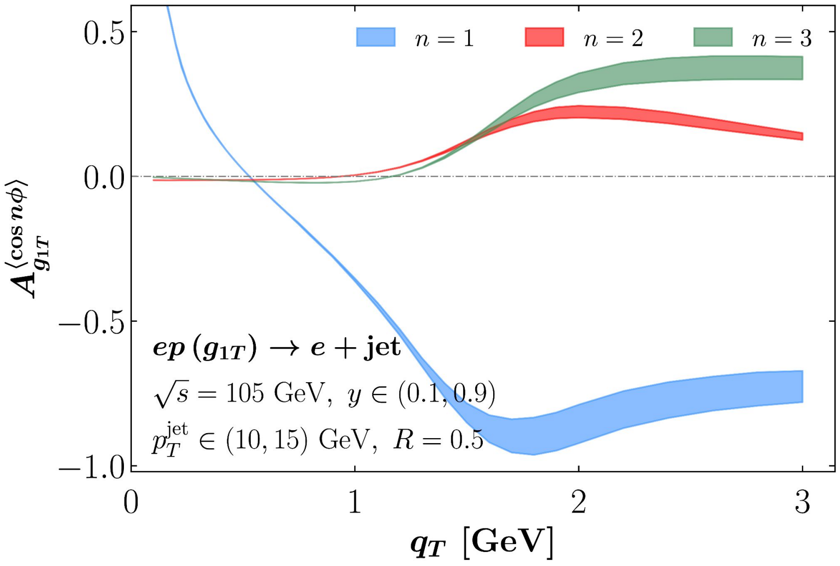


Anisotropic flows: produced by angular dependence in global and collinear soft functions

Polarized jet anisotropy: worm-gear

$$R_{LT}^{\langle\cos(n\phi)\rangle} \equiv \int_0^{2\pi} \frac{\mathrm{d}\phi_{qJ}}{2\pi} \cos^2(n\phi_{qJ}) R_{LT}^n$$

$$R_{LT}^n \equiv A_n^{\text{worm-gear}} / A_0^{\text{worm-gear}}$$



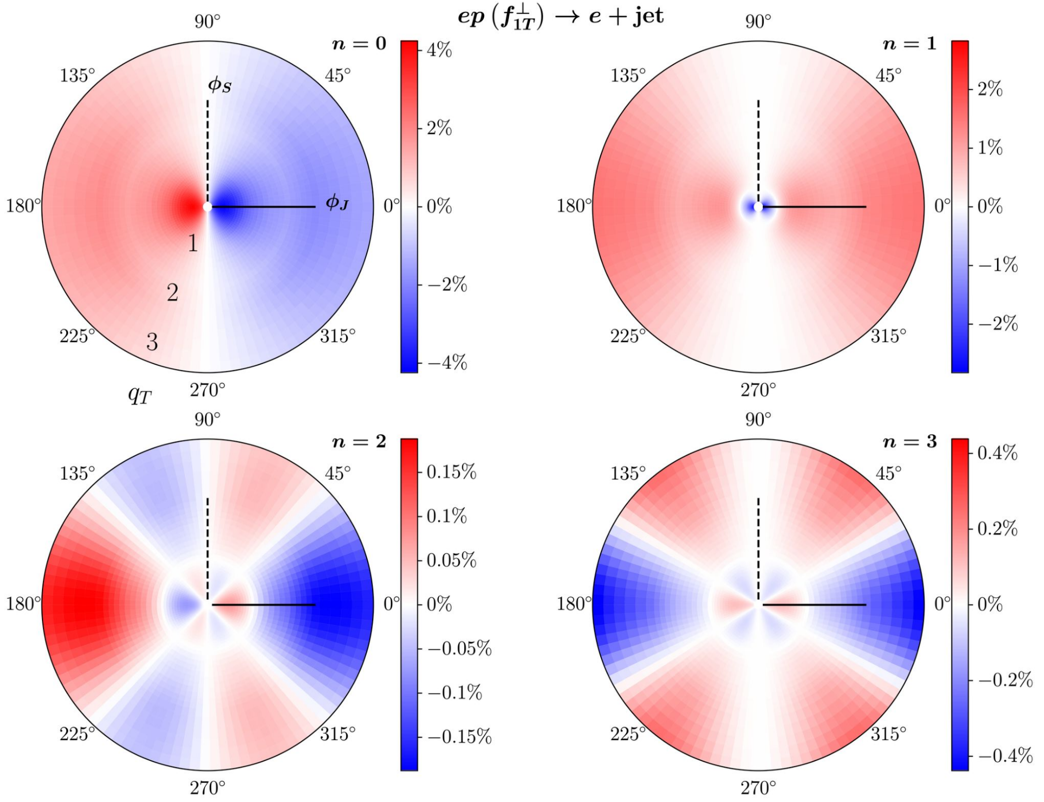
Anisotropic flows: produced by angular dependence in global and collinear soft functions

Polarized jet anisotropy: Sivers

We can also map the anisotropy in the azimuthal plane of q_T:

$$\sin(\phi_q - \phi_S)\cos(n\phi_{qJ}) \times A_n^{\text{Sivers}} / A_0^{\text{unp.}}$$

- $\phi_J = 0$
- $\phi_S = \pi/2$



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- $\phi_J = 0$
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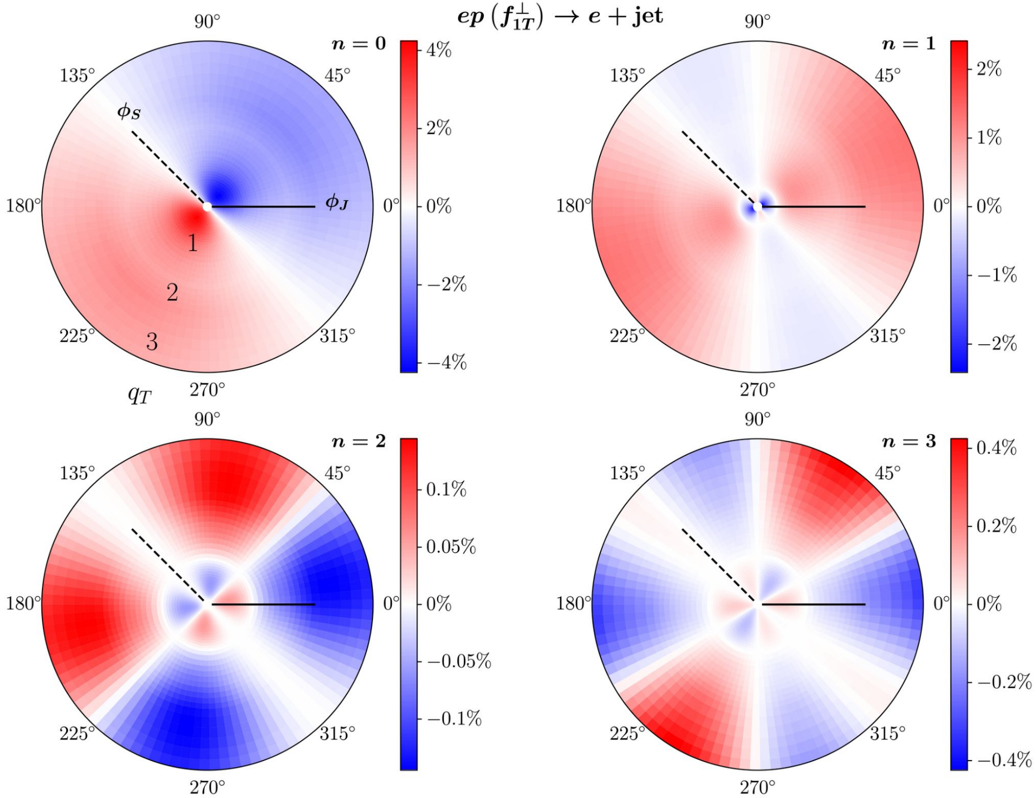

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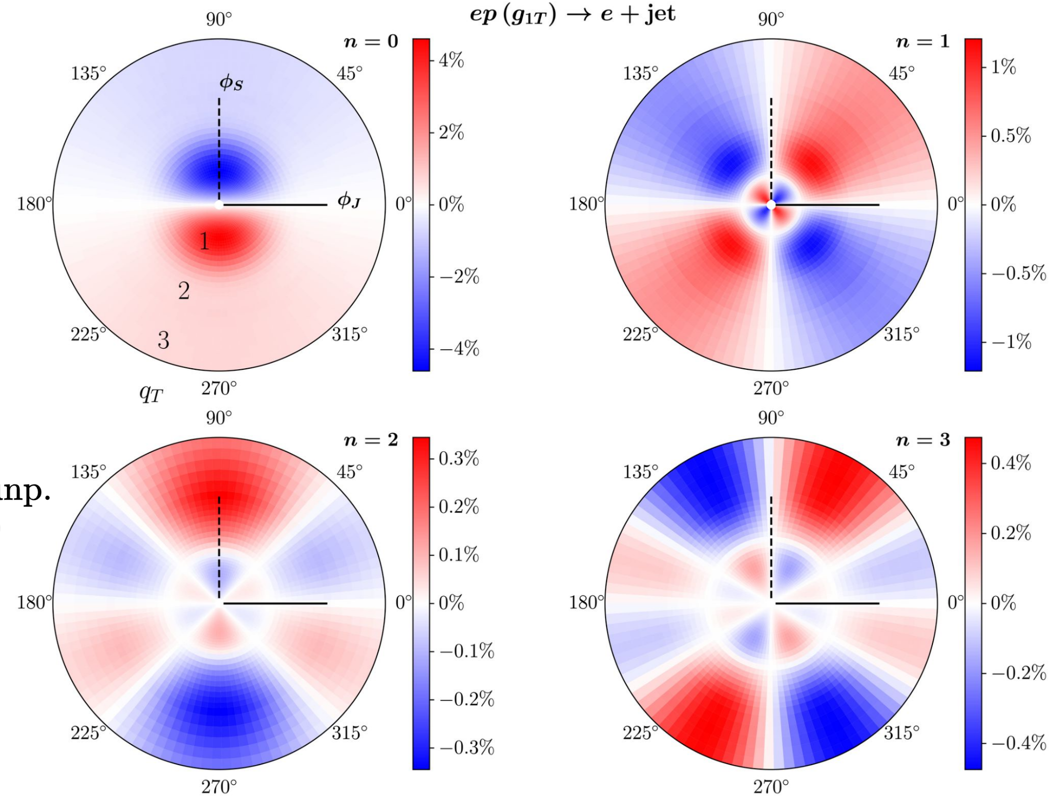

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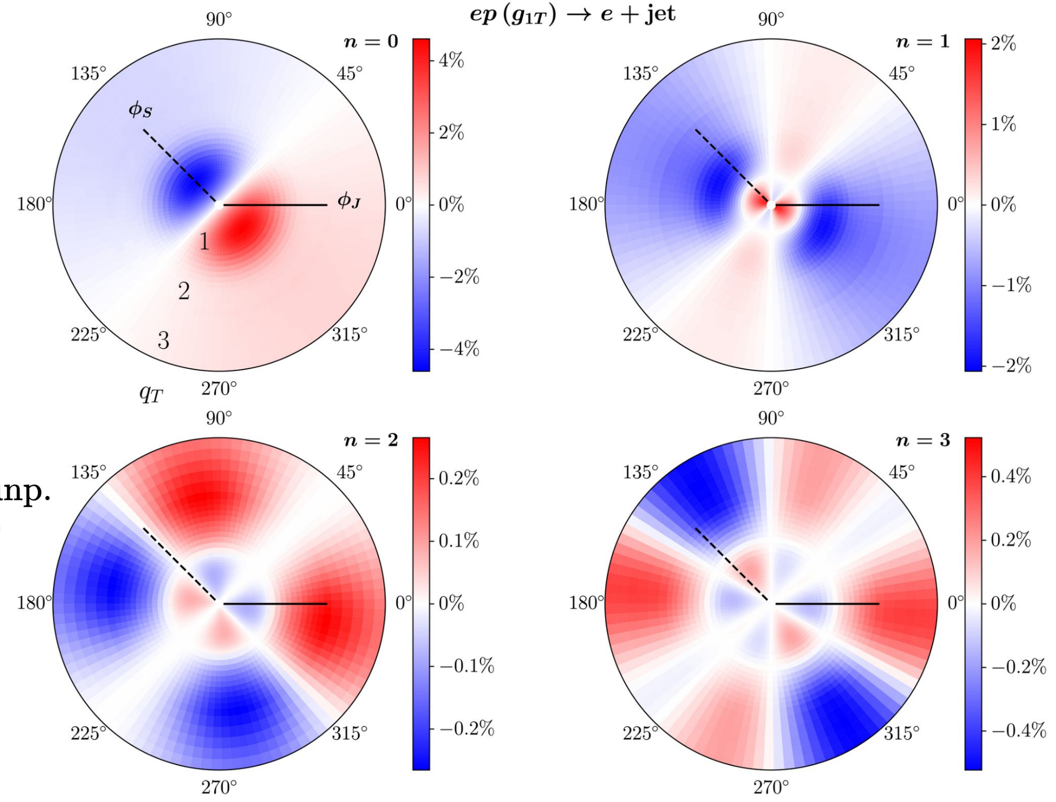
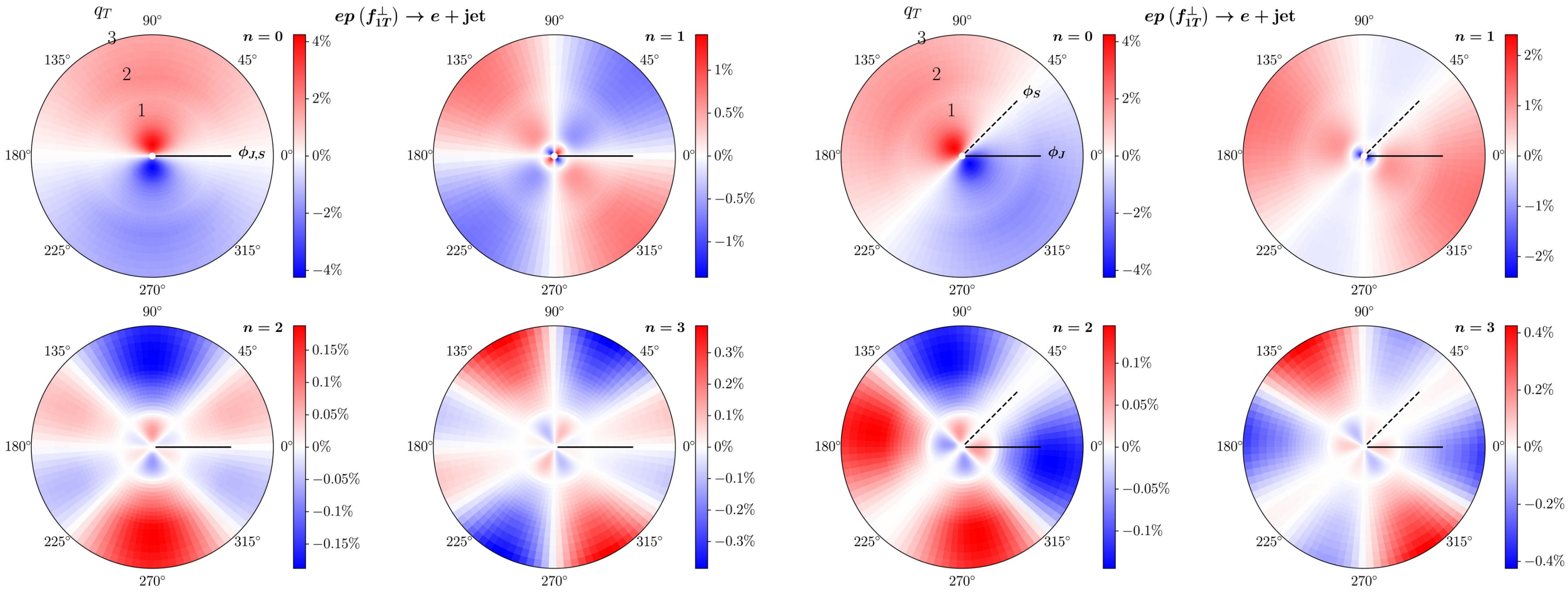


Summary

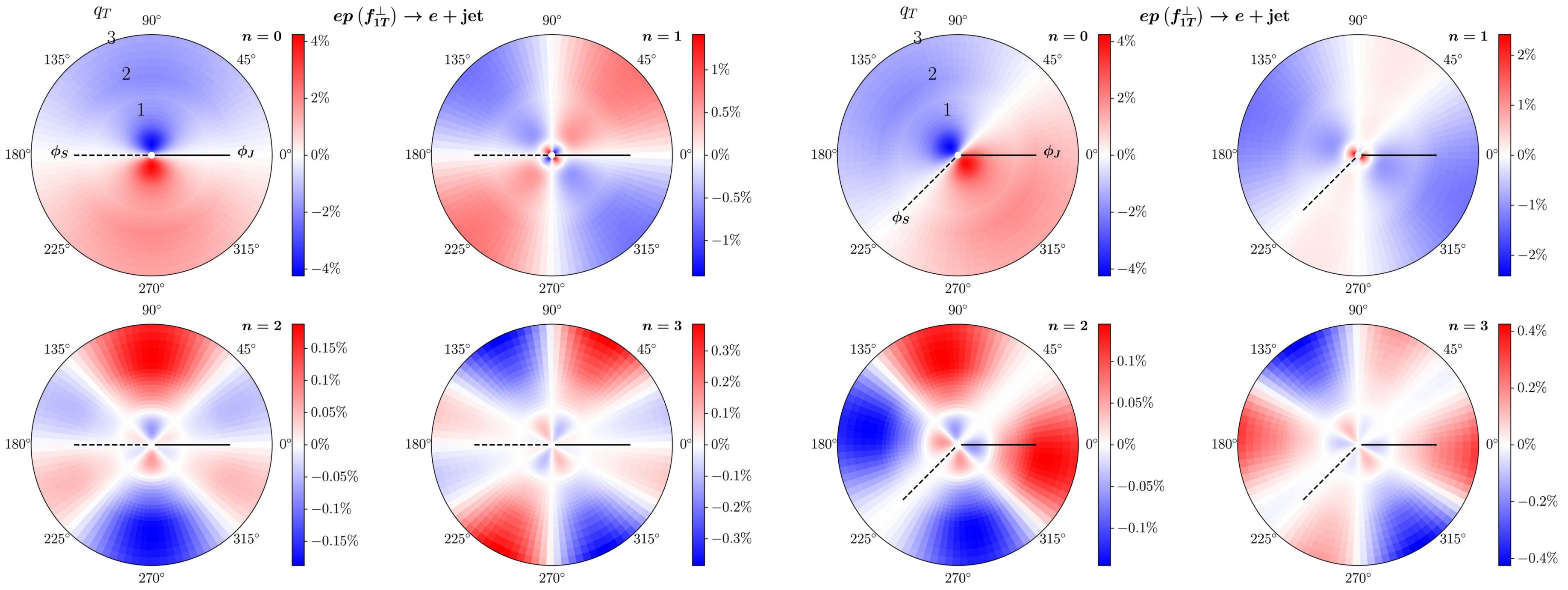
- Back-to-back electron-jet production is studied in polarized *ep* collisions
- Azimuthal angle dependence in soft function can lead to counter-intuitive (a)symmetry patterns
- Polarized jet anisotropy observables are measurable at EIC kinematics

Thank you for your attention!

Polarized jet anisotropy: Sivers



Polarized jet anisotropy: Sivers



Polarized jet anisotropy: Sivers