

Transverse Spin Correlation and Anisotropic EEC

Lei Yang



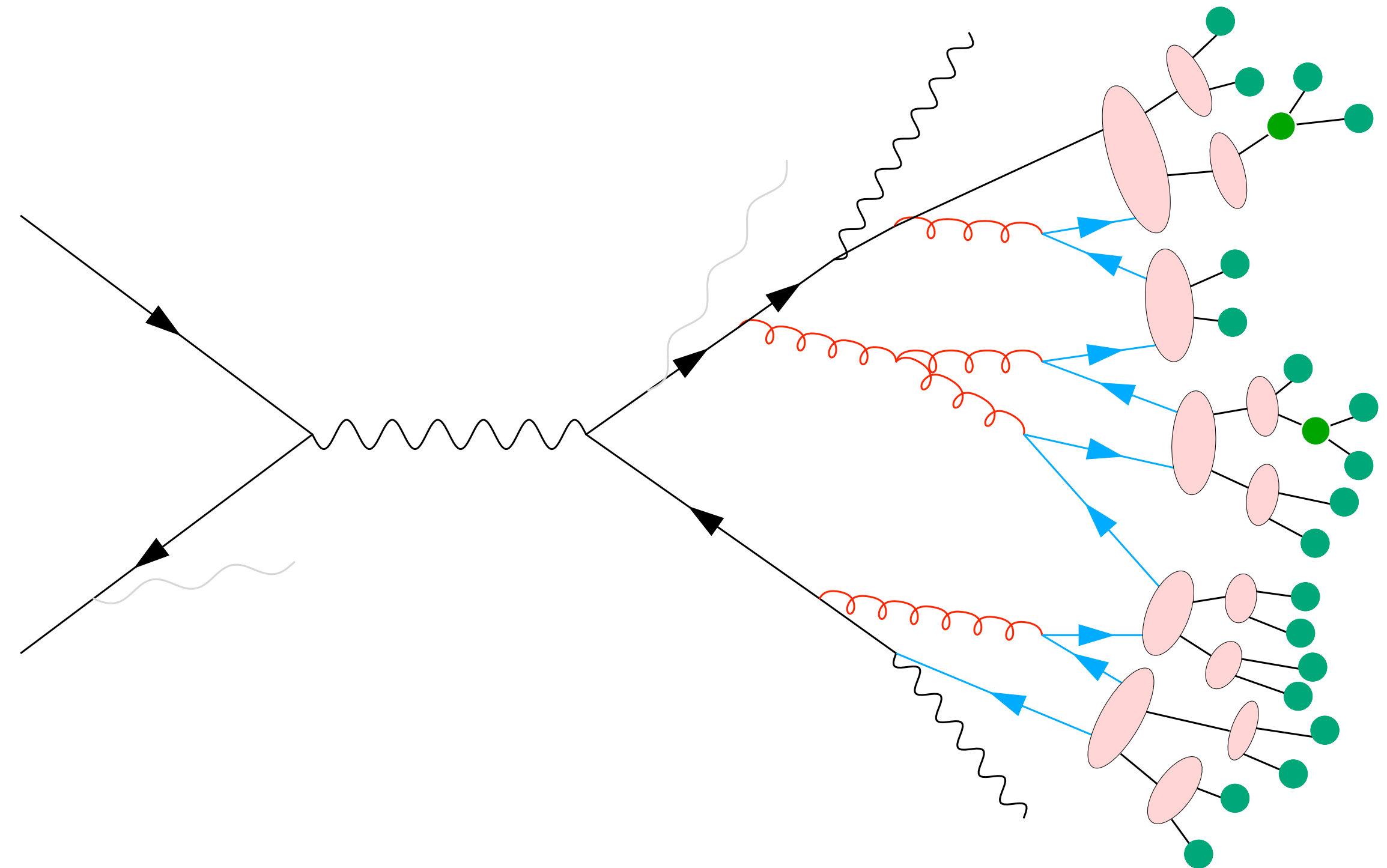
Lei Yang, Yu-Kun Song, Shu-Yi Wei, Phys.Rev.D 111 (2025) 5, 054035
Yu-Kun Song, Shu-Yi Wei, Lei Yang, Jian Zhou, Phys.Rev.Lett. 136 (2026) 13, 131901

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Background & Motivation

- ❖ **Hadronization** is the non-perturbative process where partons evolve into hadrons
- ❖ Only detected final-state hadrons

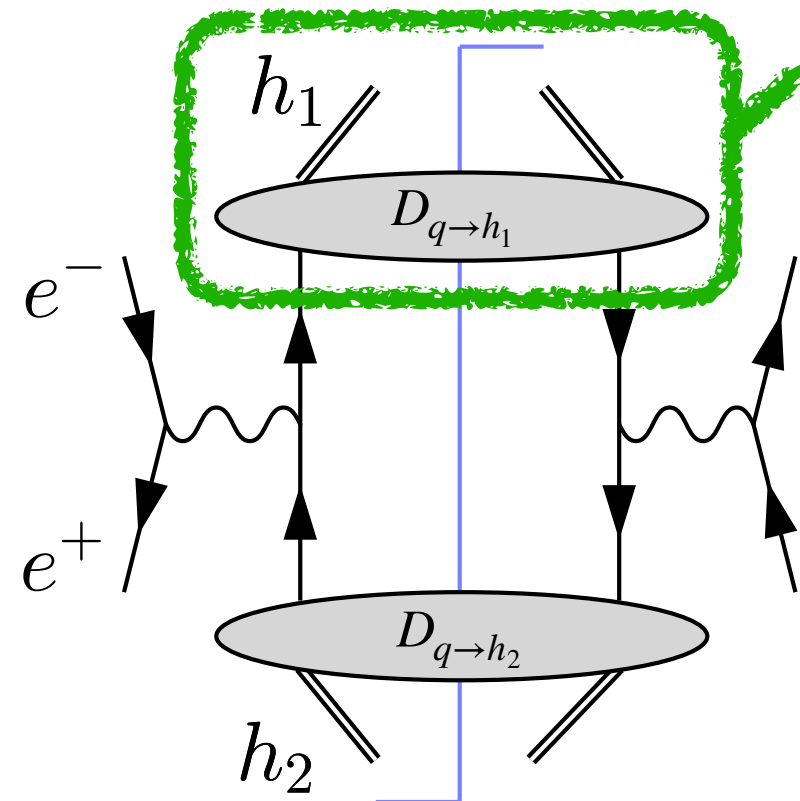


$$\mu \sim \Lambda_{\text{QCD}} \sim 200 \text{ GeV} \quad \leftrightarrow \quad \alpha_s \sim 1$$

Background & Motivation

QCD Factorization

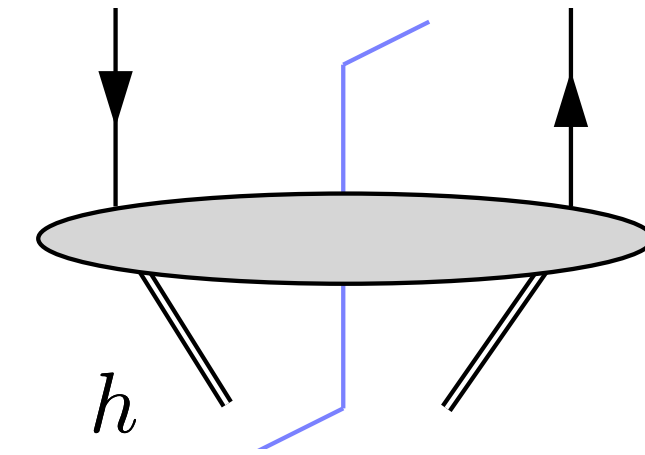
❖ e^+e^- Annihilation



$$\frac{d\sigma_{e^+e^-}}{d\mathcal{P} \cdot \mathcal{S}} \propto \sum_q e_q^2 D_{q \rightarrow h_1} \otimes D_{\bar{q} \rightarrow h_2} \otimes \hat{\sigma}_H^{e^+e^- \rightarrow q\bar{q}}$$

Long distance

Short distance



$$\begin{aligned} & \frac{1}{4z} \int dp^+ \sum_X \frac{1}{(2\pi)^4} \int d^4\xi e^{ip \cdot \xi} \langle 0 | \psi_i(\xi) | P_h, X \rangle \langle P_h, X | \bar{\psi}_j(0) | 0 \rangle \Big|_{p^- = P_h^-/z, p_T} \\ &= \frac{1}{4} \left[D_1 h_+ + D_{1T}^\perp \frac{\epsilon_{\mu\nu\rho\sigma} \gamma^\mu n_+^\nu p_T^\rho S_{hT}^\sigma}{M_h} - \lambda G_{1L} h_+ \gamma_5 - G_{1T} \frac{(p_T \cdot S_T)}{M_h} h_+ \gamma_5 \right. \\ & \quad \left. - H_{1T} i\sigma_{\mu\nu} \gamma_5 S_{hT}^\mu n_+^\nu - \lambda H_{1L}^\perp \frac{i\sigma_{\mu\nu} \gamma_5 p_T^\mu n_+^\nu}{M_h} - H_{1T}^\perp \frac{(p_T \cdot S_T)}{M_h} \frac{i\sigma_{\mu\nu} \gamma_5 p_T^\mu n_+^\nu}{M_h} + H_1^\perp \frac{\sigma_{\mu\nu} p_T^\mu n_+^\nu}{M_h} \right] \end{aligned}$$

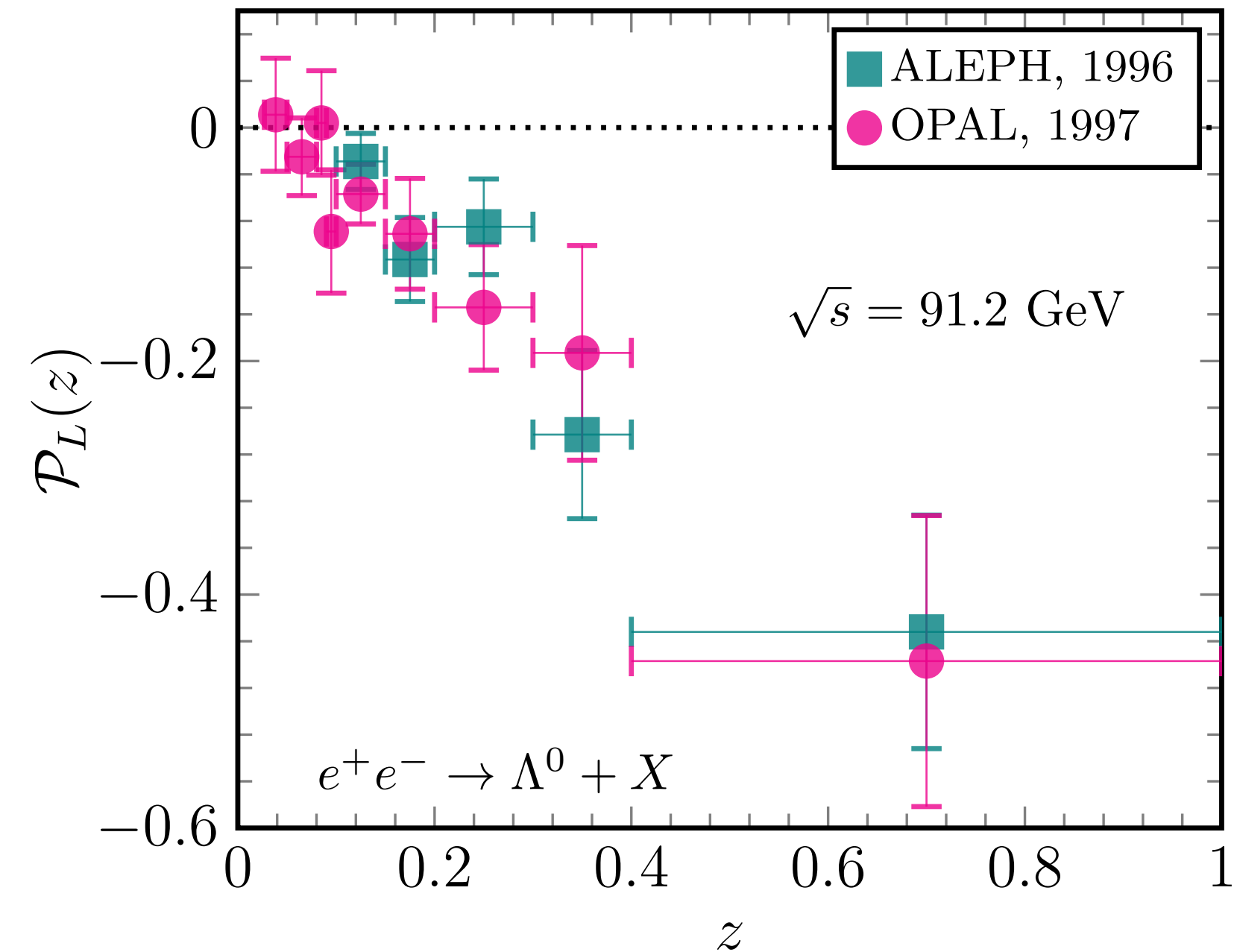
TMD FFs	Quark Polarization		
	Un-polarized (U)	Longi-polarized (L)	Trans-polarized (T)
Unpolarized Hadronss	D_1		$H_{1T}^\perp$
Polarized Hadronss		G_{1L}	$H_{1L}^\perp$
	$D_{1T}^\perp$	$G_{1T}^\perp$	$H_1, H_{1T}^\perp$

Background & Motivation

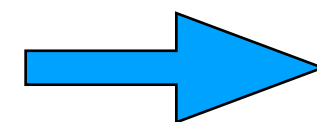
QCD Factorization

- ❖ How to study polarized FFs?
 - polarized targets
 - polarized beams

$$\mathcal{P}_L^\Lambda = \lambda_q \frac{G_{1L,q}^\Lambda}{D_{1,q}^\Lambda}$$



The preparation of polarized beams/target is relatively difficult



Can we study the FFs of spin transfer in unpolarized beam collisions?

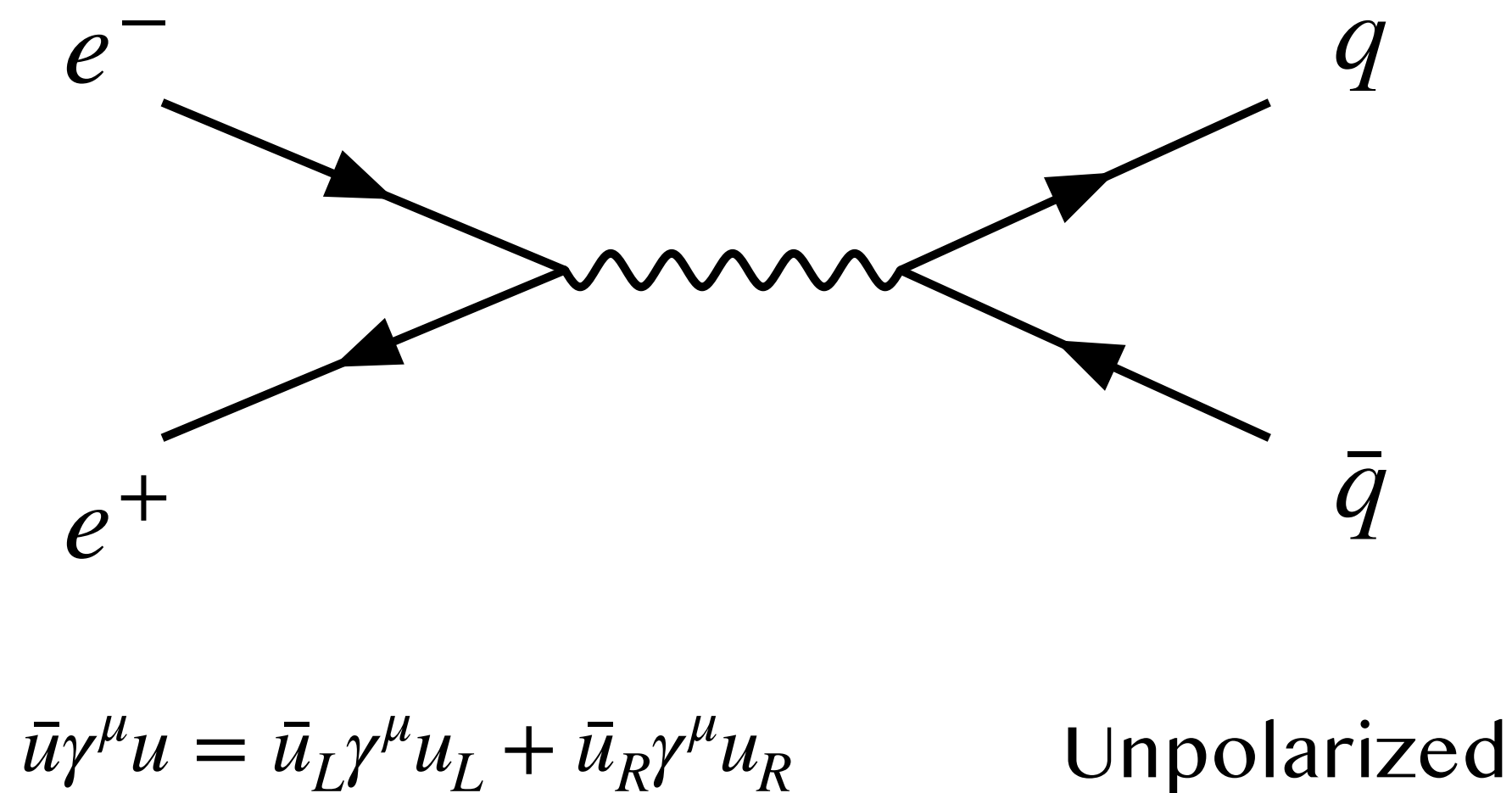


Yes!

Background & Motivation

Extracting Polarization information from unpolarized collisions

Kun Chen, Gary R. Goldstein, R. L. Jaffe, and
Xiangdong Ji. Nucl.Phys.B 445 (1995) 380-398



❖ Unpolarized beam collisions

❖ Helicity conservation

q and $\bar{q}$ are on the same fermion line.
They must have opposite helicities

❖ Helicity correlation

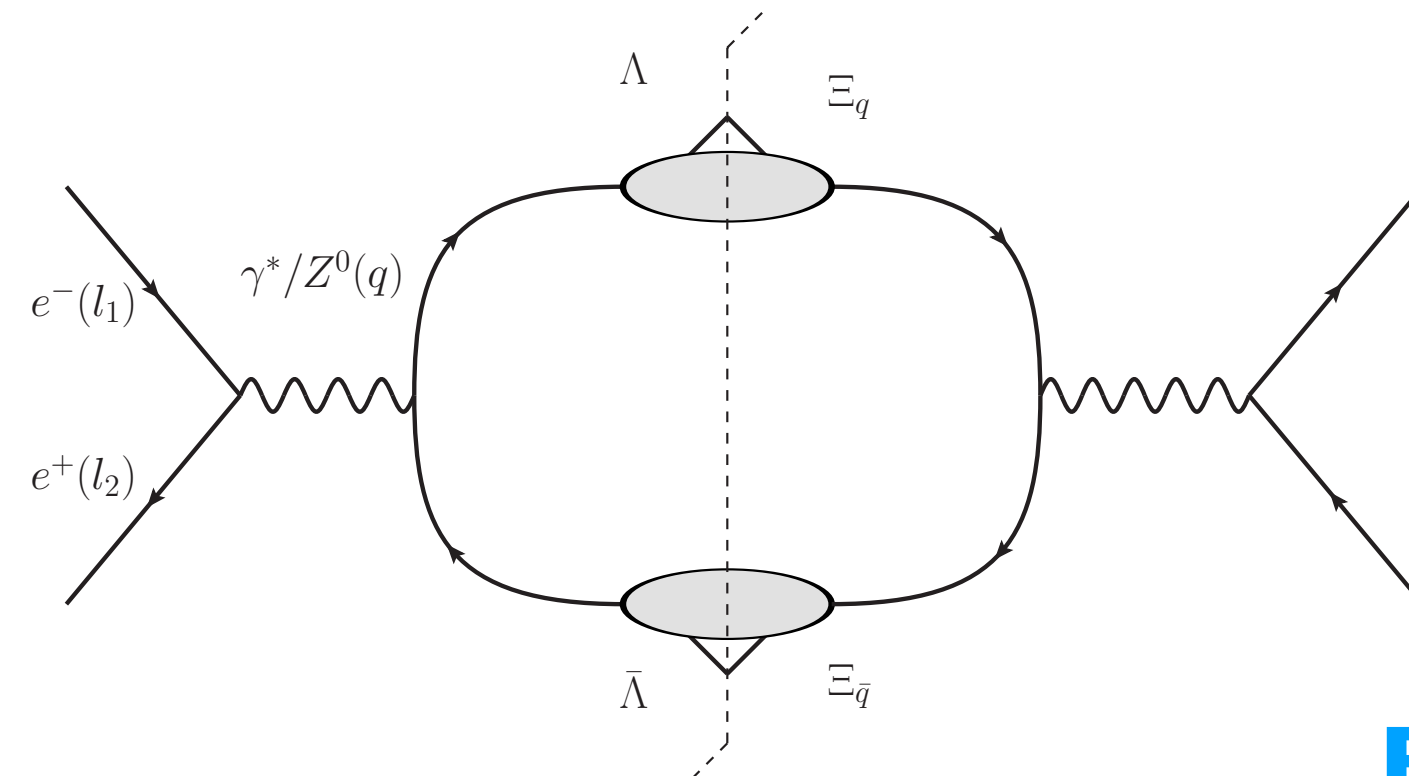
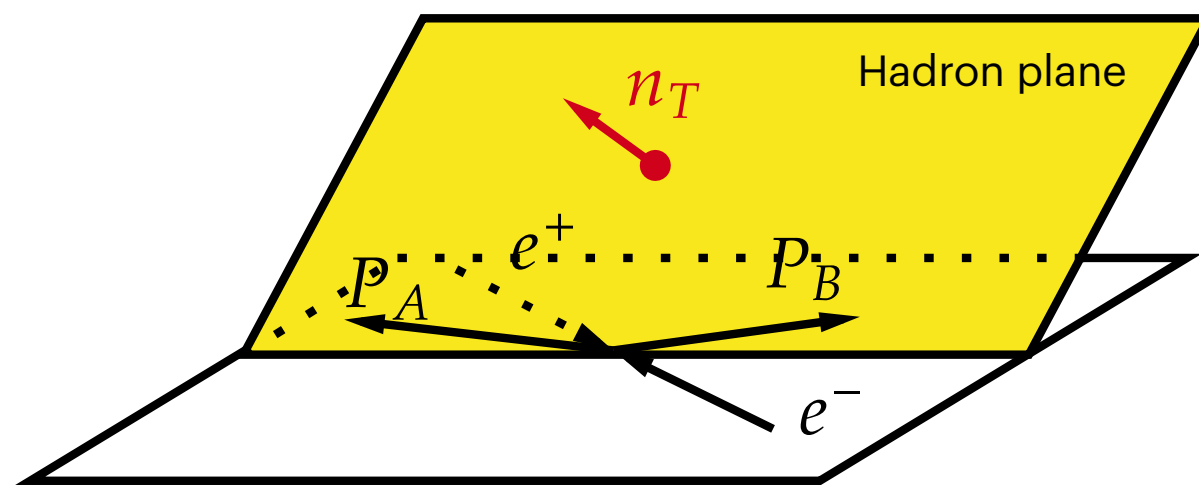
A novel probe to the spin-dependence
fragmentation functions

We will focus on the transverse spin transfer H_{1T}

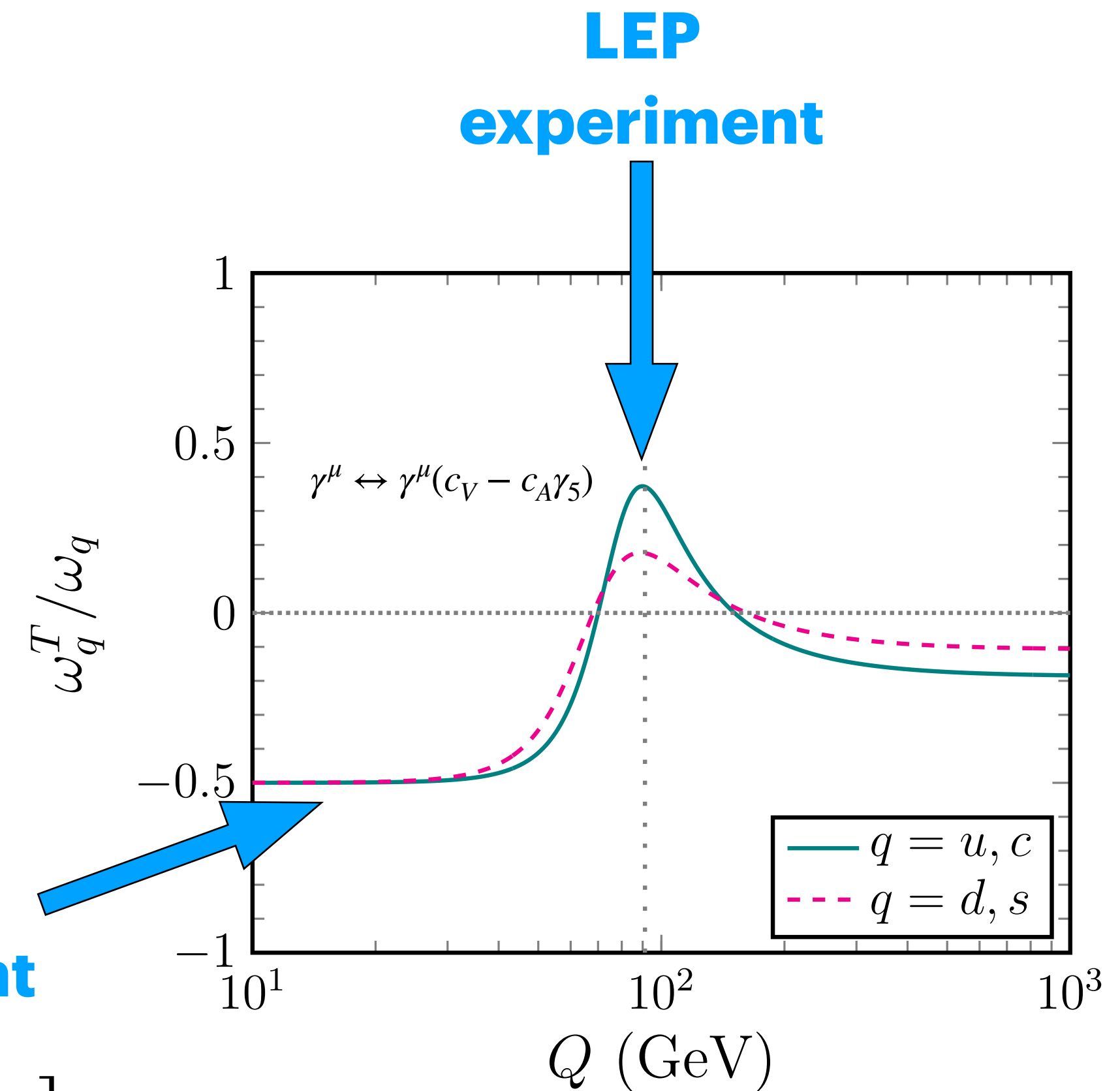
Back-to-back Di-hadron Spin Correlations

Electron-positron Annihilation

$$\mathcal{C}_{TT} = \frac{\mathcal{P}(\mathbf{n}_T, \mathbf{n}_T) + \mathcal{P}(-\mathbf{n}_T, -\mathbf{n}_T) - \mathcal{P}(\mathbf{n}_T, -\mathbf{n}_T) - \mathcal{P}(-\mathbf{n}_T, \mathbf{n}_T)}{\mathcal{P}(\mathbf{n}_T, \mathbf{n}_T) + \mathcal{P}(-\mathbf{n}_T, -\mathbf{n}_T) + \mathcal{P}(\mathbf{n}_T, -\mathbf{n}_T) + \mathcal{P}(-\mathbf{n}_T, \mathbf{n}_T)}$$



**Belle
experiment**



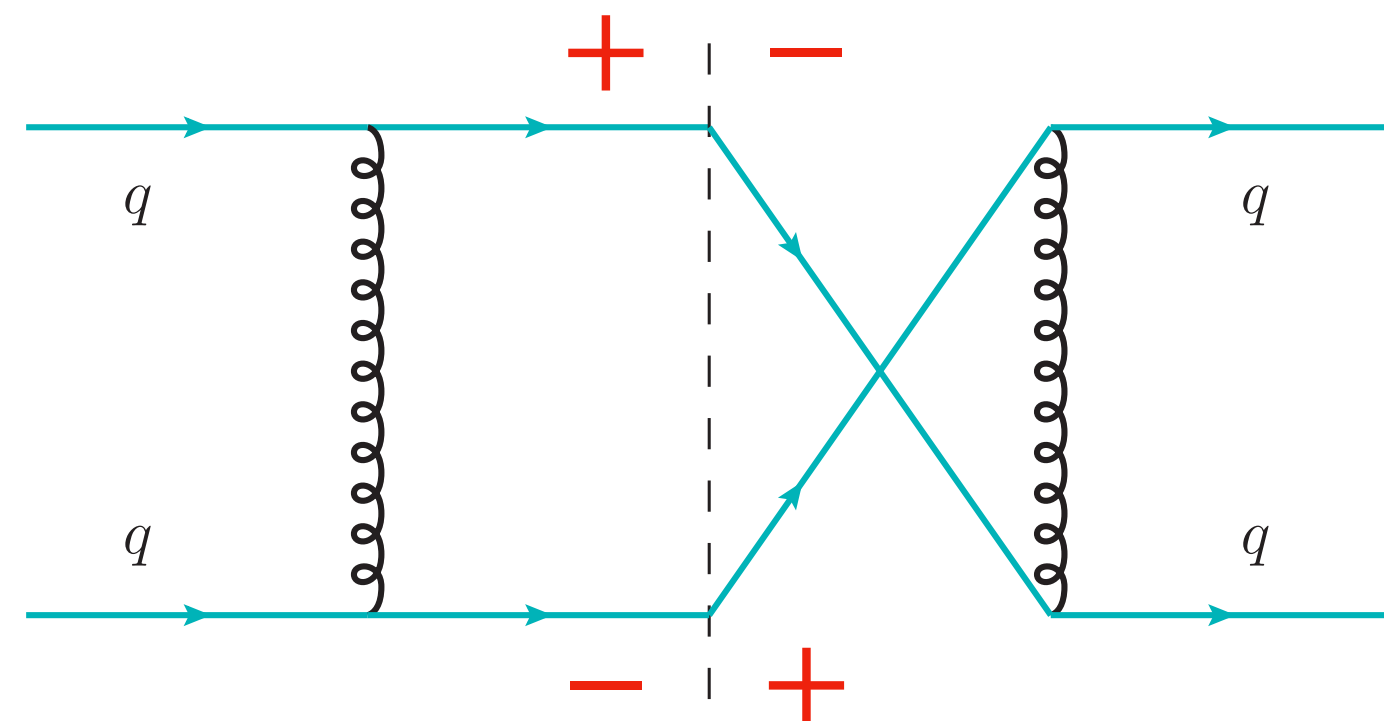
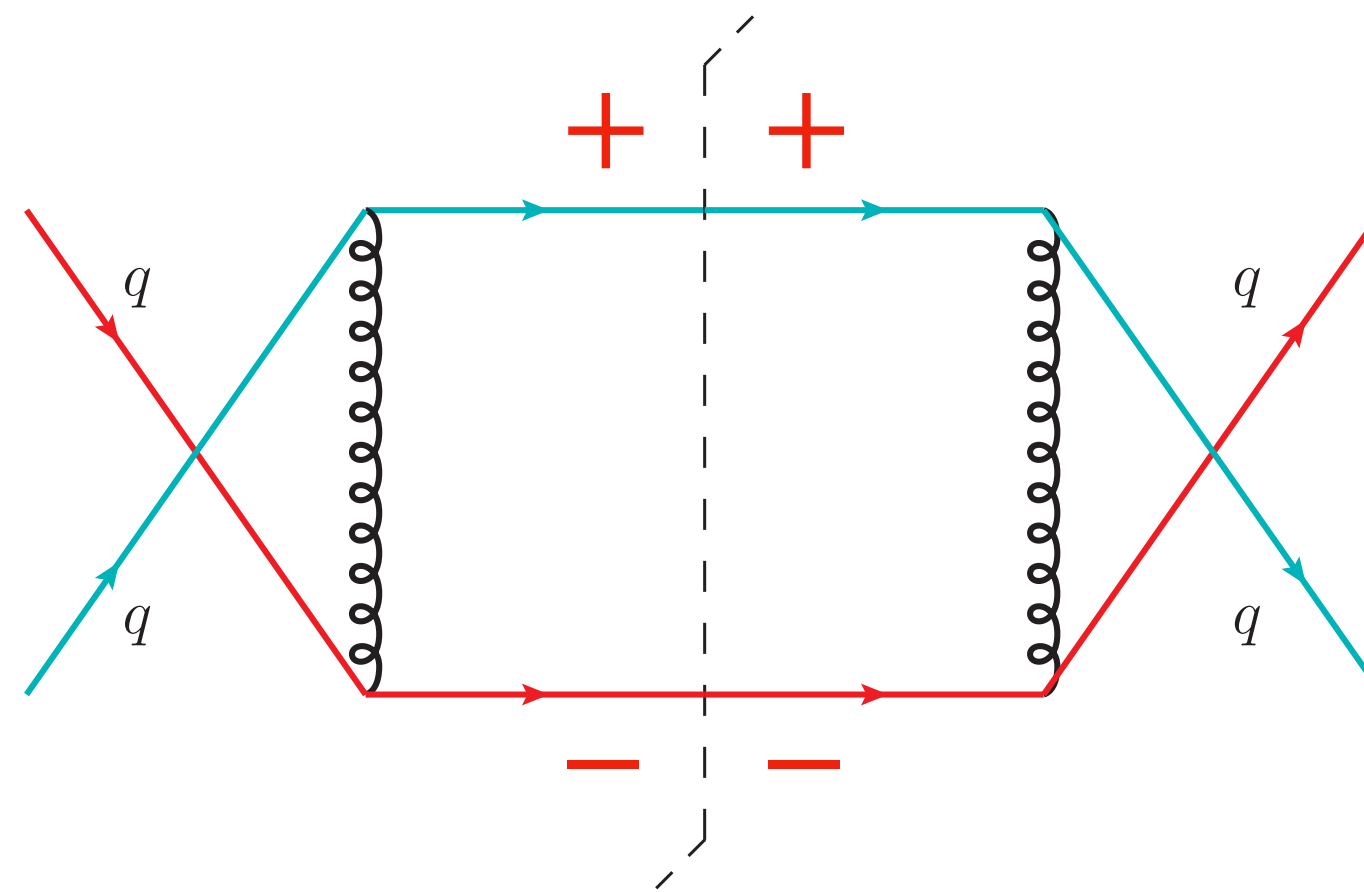
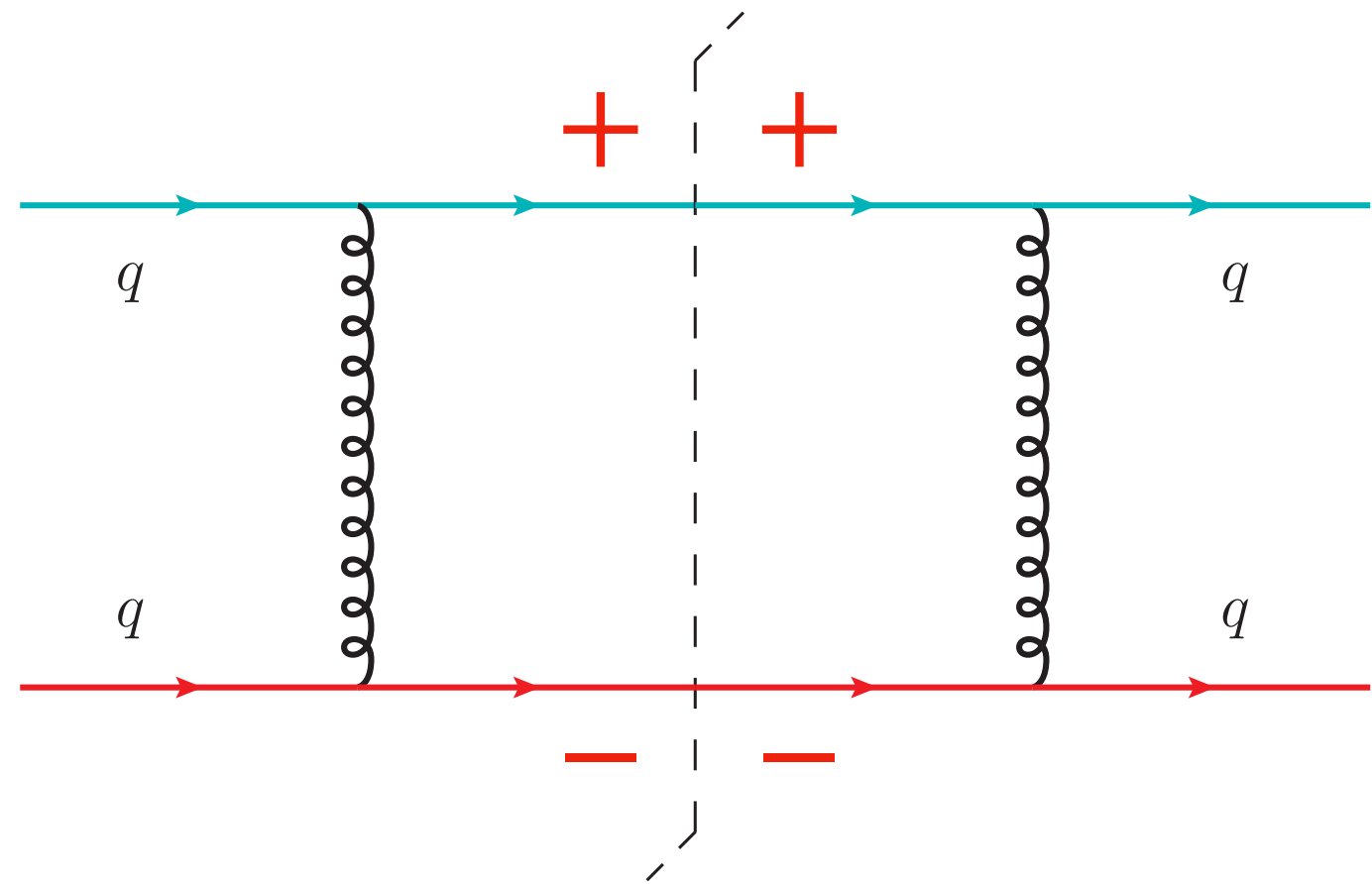
$$\frac{d\sigma}{dydz_1dz_2} = \frac{2\pi N_c \alpha_e^2}{Q^2} \sum_q \left[\omega_q(y) D_{1,q}(z_1) D_{1,\bar{q}}(z_2) + (\mathbf{S}_{T1} \cdot \mathbf{S}_{T2}) \omega_q^T(y) H_{1T,q}(z_1) H_{1T,\bar{q}}(z_2) \right]$$

Lei Yang

Transverse Spin Correlation and Anisotropic EEC

Back-to-back Di-hadron Spin Correlations

Unpolarized Proton-proton Collisions

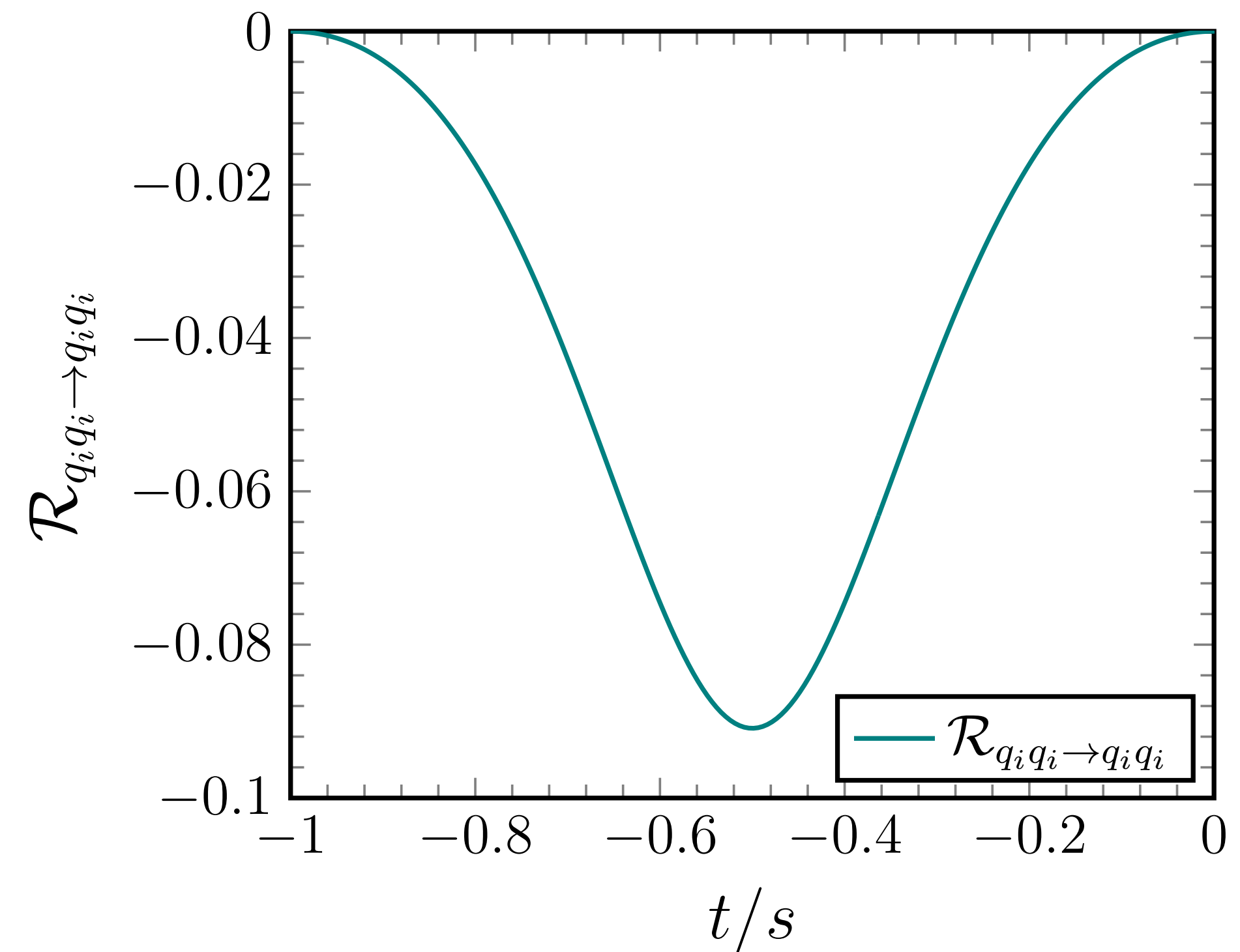
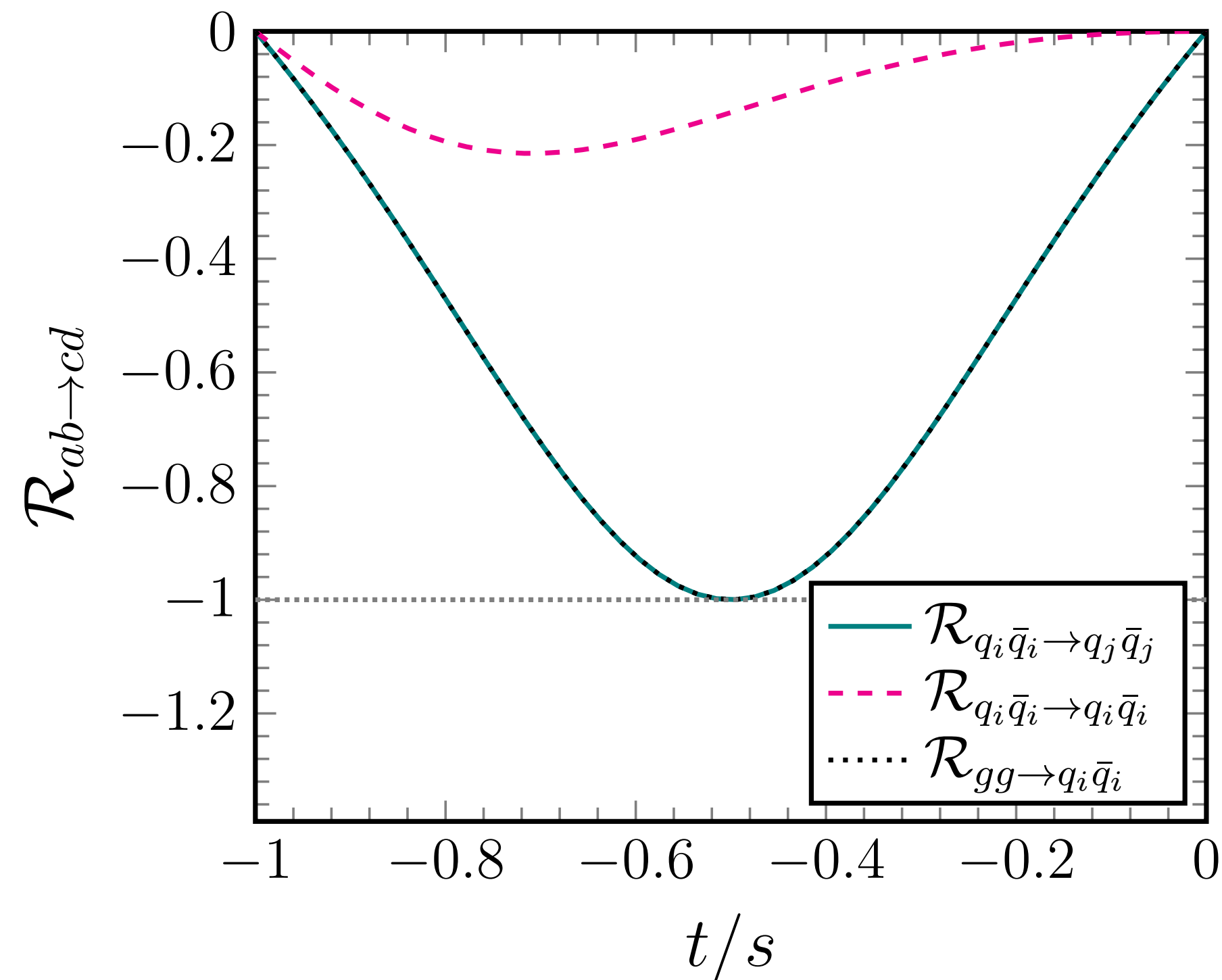


Transverse spin correlation
requires a helicity flip

Back-to-back Di-hadron Spin Correlations

Unpolarized Proton-proton Collisions

Partonic transverse spin correlation: $\mathcal{R} = \frac{d\sigma^T/dt}{d\sigma^U/dt}$



How to probe gluon linearly polarization?

The gluon linear polarization cannot be inherited by Λ hyperons in the collinear factorization

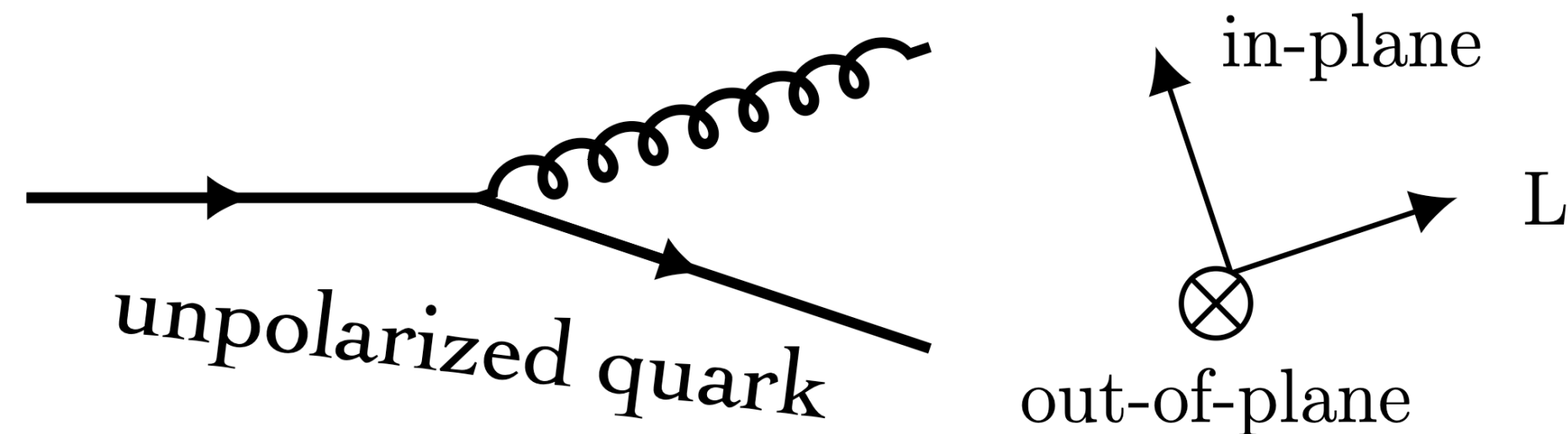
- ❖ Quark hadronization: $D(q \rightarrow \Lambda) = D_{1,q}^\Lambda(z) + \lambda_q \lambda_\Lambda G_{1L,q}^\Lambda(z) + \mathbf{S}_{T,q} \cdot \mathbf{S}_{T,\Lambda} H_{1T,q}^\Lambda(z)$
- ❖ Gluon hadronization: $D(g \rightarrow \Lambda) = D_{1,g}^\Lambda(z) + \lambda_g \lambda_\Lambda G_{1L,g}^\Lambda(z)$

Solution: Anisotropic

Probing Gluon Linearly Polarization with EEC

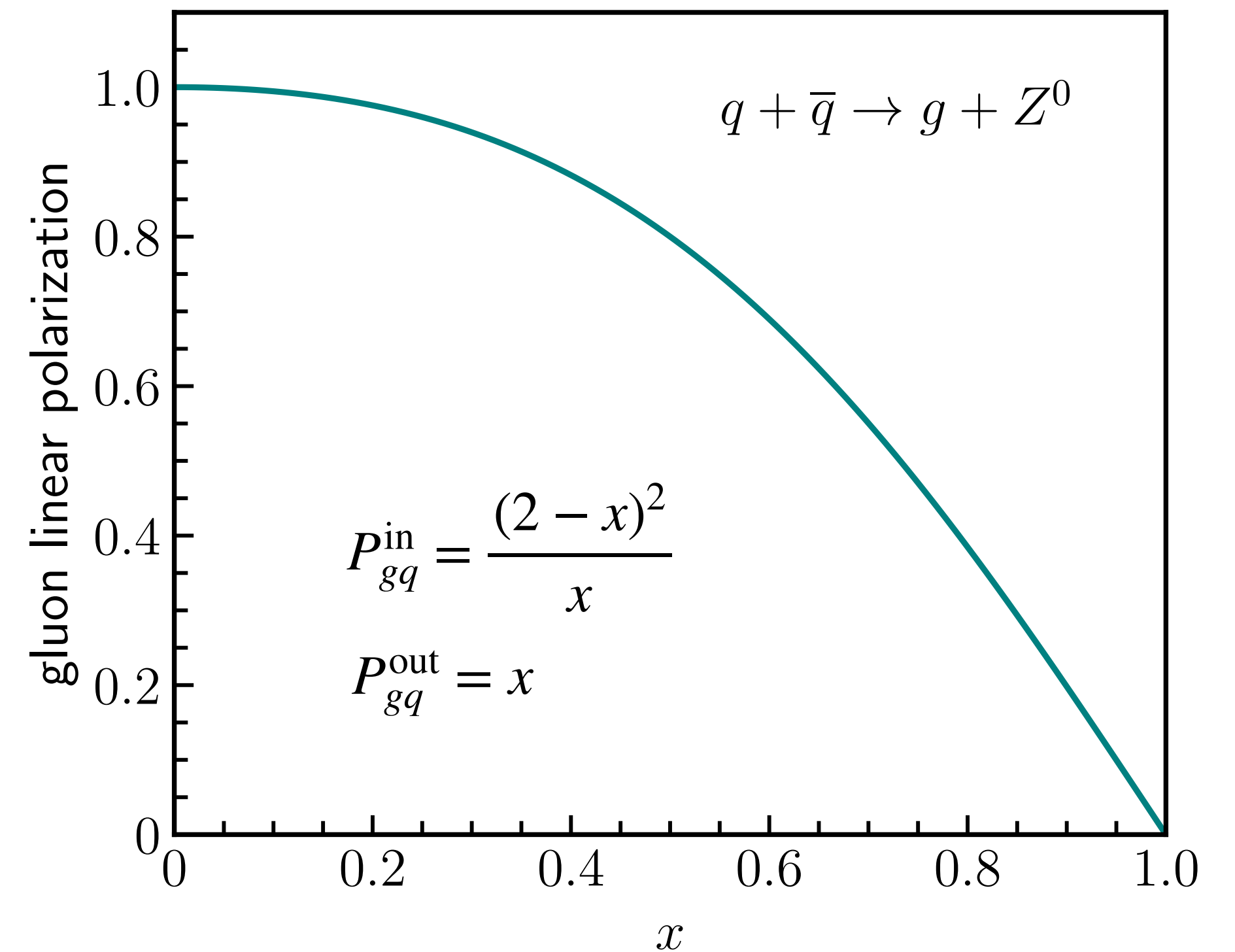
Why Linearly Polarized Gluon?

- ❖ Small-x limit: ~100% linear polarization



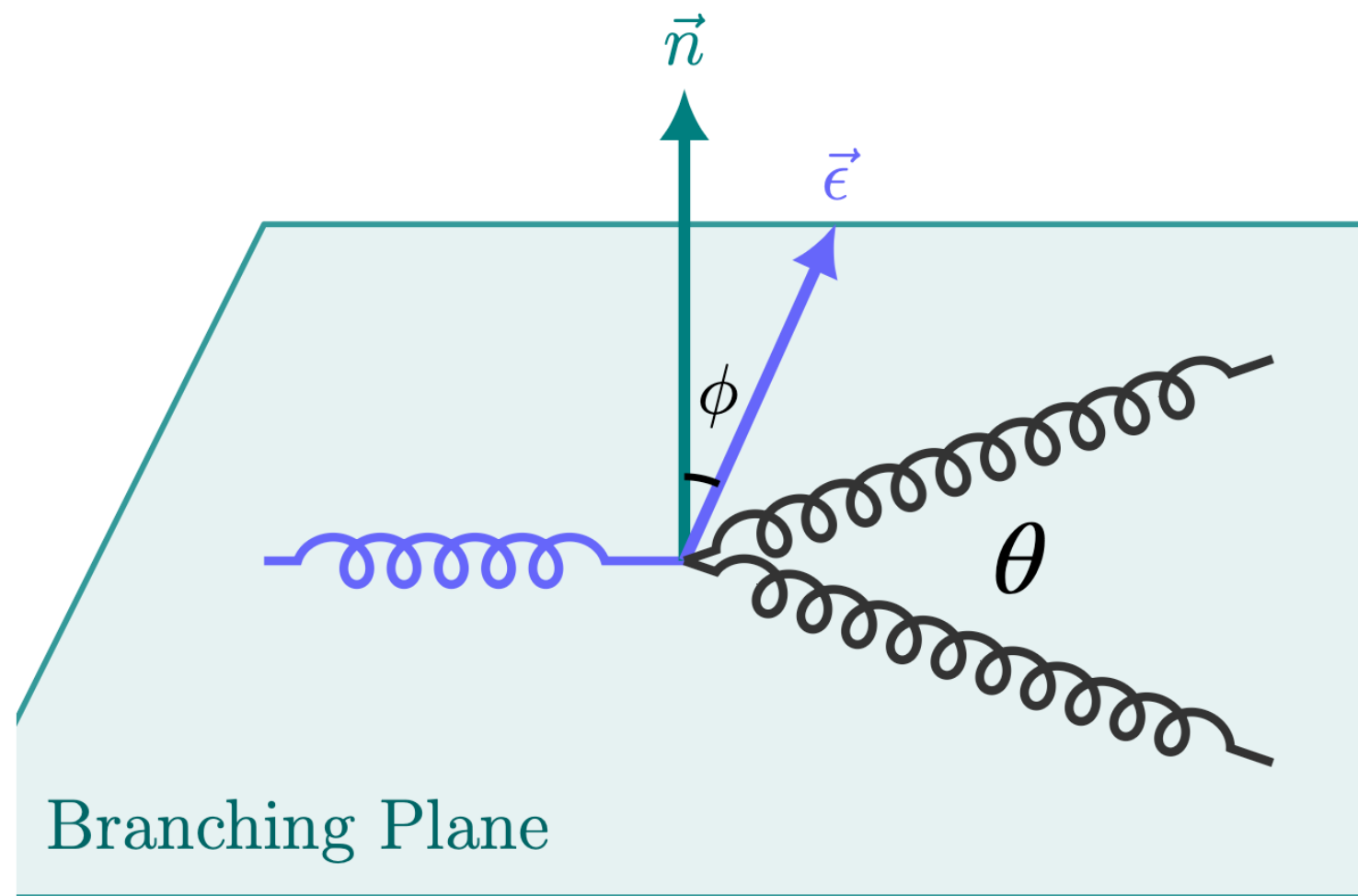
- ❖ Challenge: directly measuring linear polarized gluon

See, e.g., R.K. Ellis, et al, QCD and Collider Physics



Probing Gluon Linearly Polarization with EEC

Branching Plane



Since the linear polarization of the parent gluon specifies a transverse direction, the parton branching is no longer isotropic

Isotropic term

Anisotropic term

$$P_{g \rightarrow gg}(x, \phi) = 2N_c \left[\frac{1-x}{x} + \frac{x}{1-x} + x(1-x) + x(1-x)\cos 2\phi \right]$$

$$P_{g \rightarrow q\bar{q}}(x, \phi) = \frac{1}{2} \left[x^2 + (1-x)^2 - 2x(1-x)\cos 2\phi \right]$$

Anisotropic
EEC: a novel probe

Probing Gluon Linearly Polarization with EEC

Energy Correlators

Energy Flow $\mathcal{E}(\hat{n}) |X\rangle = \sum_{k \in X} k^0 \delta^{(2)}(\Omega_n - \Omega_k) |X\rangle$

Two-point correlation $EEC = \frac{1}{\sigma} \sum_{i,j} \int d\sigma \frac{E_i E_j}{Q^2} \delta(\chi - \theta_{ij})$

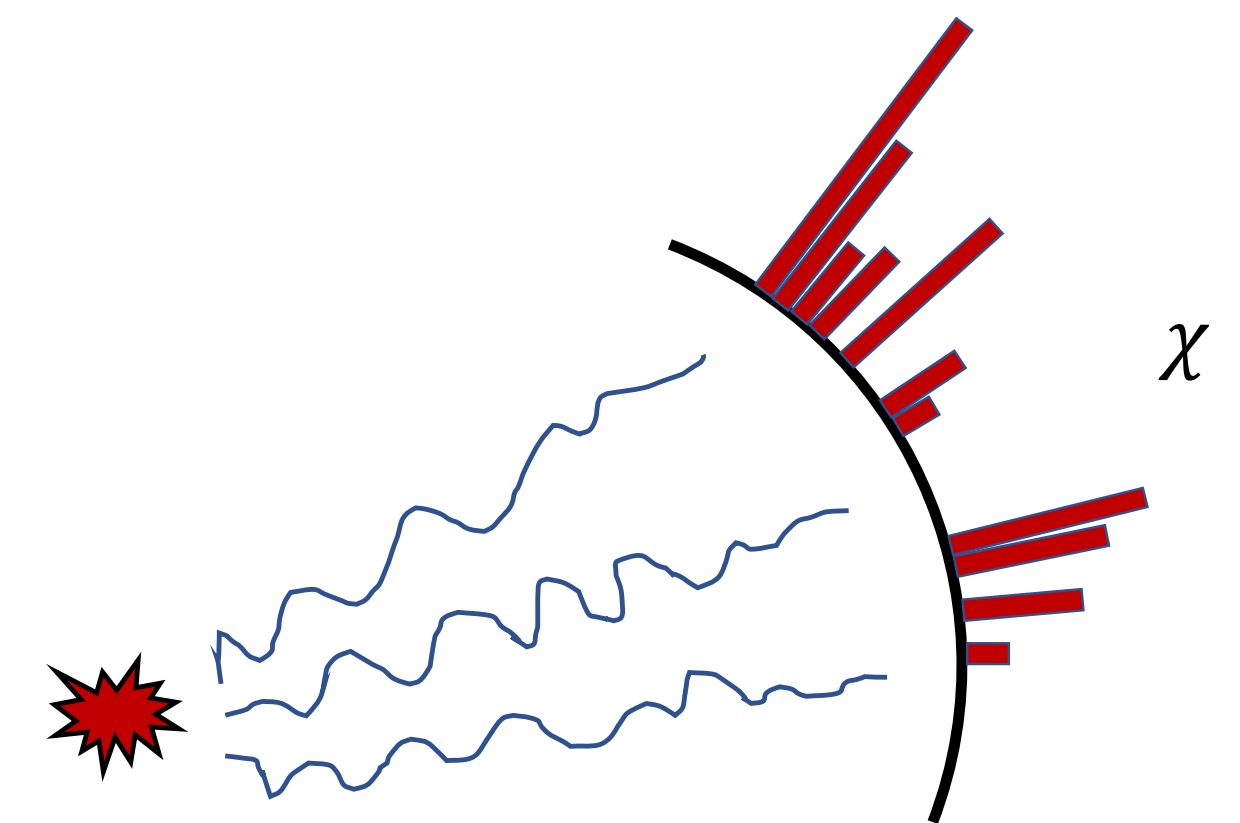
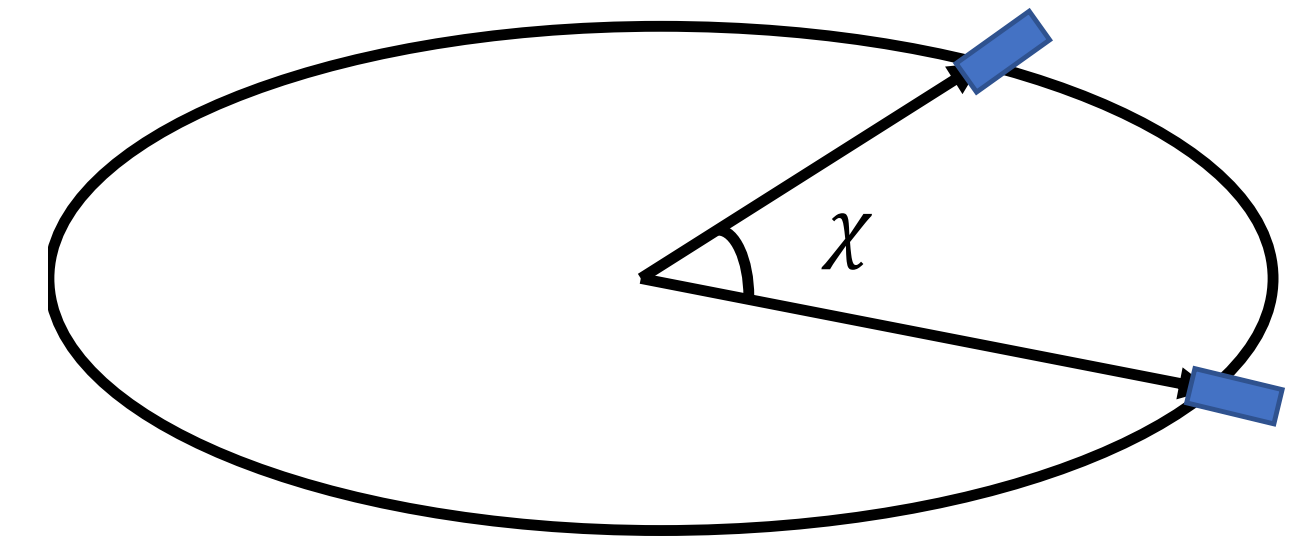
Sterman, 1975
Bashman, et.al., 1978

- ❖ Easy to implement and nature
- ❖ Energy weight suppresses the soft contamination
- ❖ Governed by DGLAP, not sensitive to soft gluon radiations
- ❖ Infrared-collinear safe, perturbatively

$$EC(\hat{n}) \sim \langle 0 | J(0) \hat{\mathcal{E}}(\hat{n}) J(0) | 0 \rangle$$



$$ENC(\hat{n}) \sim \langle 0 | J(0) \hat{\mathcal{E}}(\hat{n}_1) \cdots \hat{\mathcal{E}}(\hat{n}_k) J(0) | 0 \rangle$$



Probing Gluon Linearly Polarization with EEC

EEC and Jet Function

❖ θ -integrated EEC

L. J. Dixon, I. Mout, and H. X. Zhu,
Phys. Rev. D 100, 014009 (2019), 1905.01310

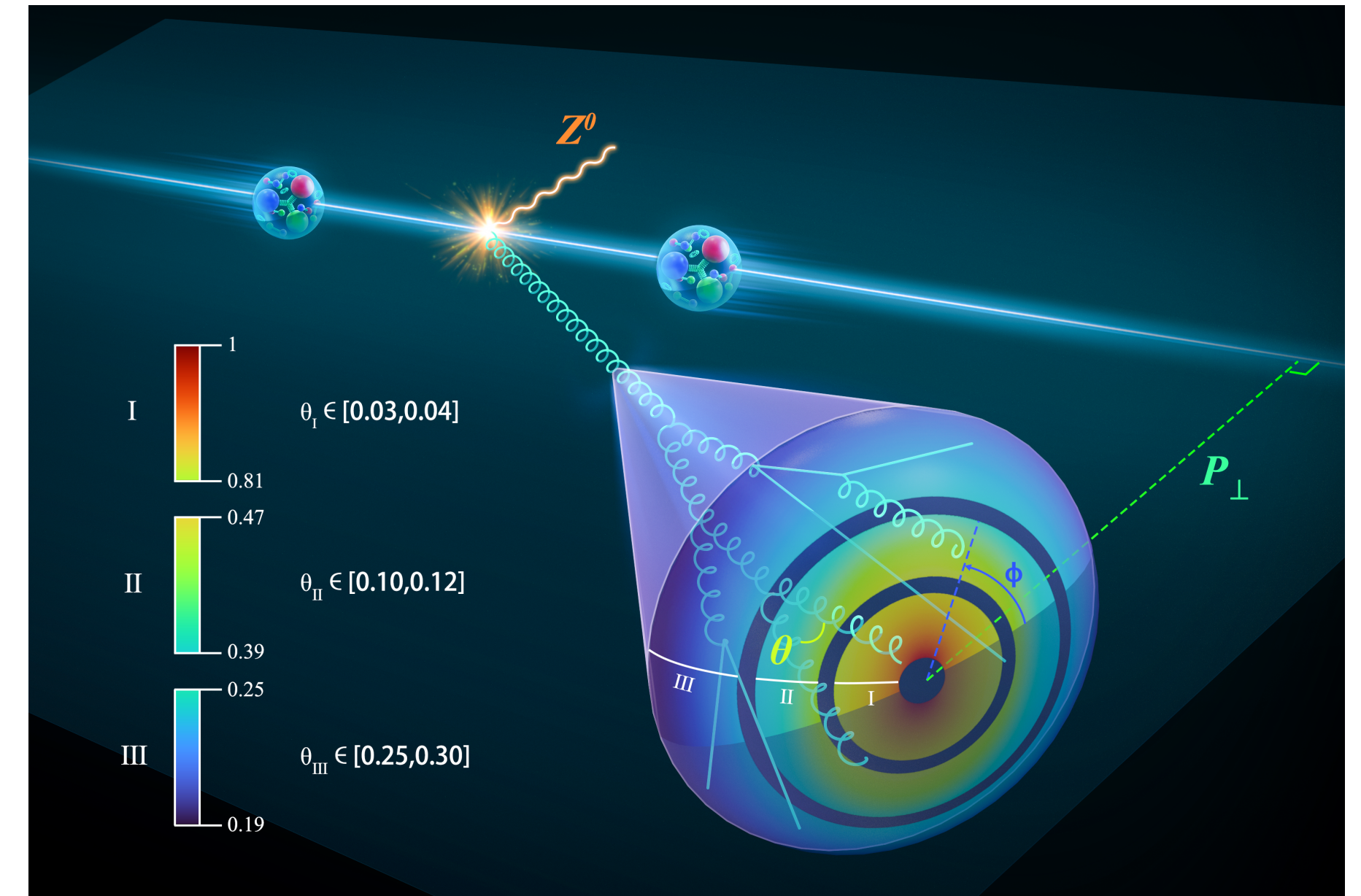
$$\langle \text{EEC} \rangle = \sum_{i=q,g} \int dx x^2 H_i(x, \mu) J_i(\ln x^2 \kappa), \quad \kappa = (\theta E_g)^2 / \mu^2$$

❖ Unpolarized jet function J_i follows the DGLAP evolution equation

$$\frac{\partial J_i(\ln \kappa)}{\partial \ln \mu^2} = \frac{\alpha_s^2}{2\pi} \sum_j \int_0^1 dy y^2 P_{ij}(y) J_j[\ln(y^2 \kappa)]$$

❖ Polarized jet function $J_{g,T}$

$$\frac{\partial J_{g,T}(\ln \kappa)}{\partial \ln \mu^2} = \frac{\alpha_s^2}{2\pi} \sum_j \int_0^1 dy y^2 P_{gg}^T(y) J_{g,T}[\ln(y^2 \kappa)]$$



It is not consider the quantum coherence effect of large-angle soft gluon radiation

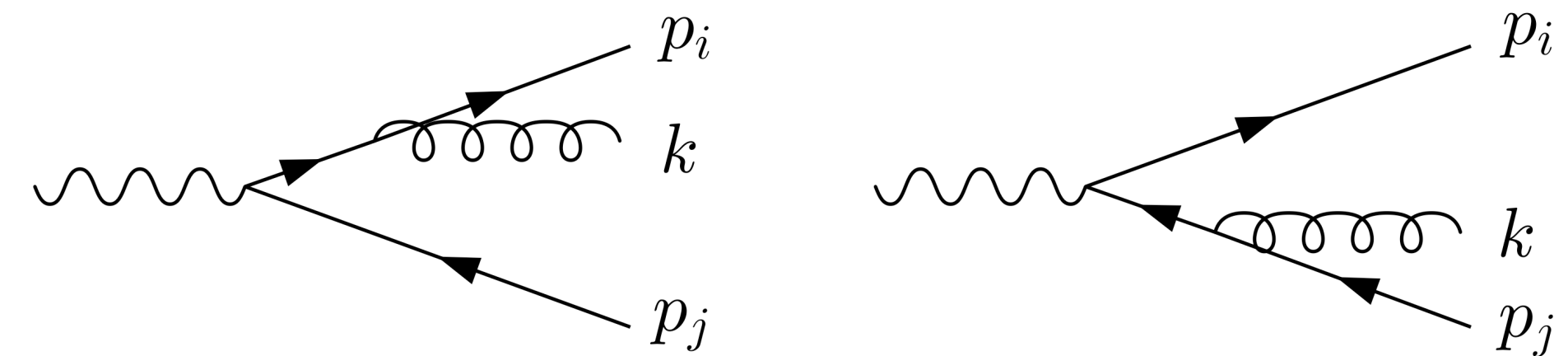
Probing Gluon Linearly Polarization with EEC

Angular Ordering & CCFM

❖ Angular ordering:

$$\langle W_{ij}^{(i)} \rangle_\phi = \int_0^{2\pi} \frac{d\phi_{ik}}{2\pi} W_{ij}^{(i)} = \frac{1}{E_k^2 (1 - \cos \theta_{ik})} \Theta(\theta_{ij} - \theta_{ik})$$

See, e.g., R.K. Ellis, et al, QCD and Collider Physics



❖ Evolution of jet function:

DGLAP

CCFM

$$\frac{\partial J_i(\ln \kappa)}{\partial \ln \mu^2} = \frac{\alpha_s}{2\pi} \sum_j \int_0^1 dy y^2 P_{ij}(y) J_j [\ln(y^2 \kappa)] \quad \longrightarrow \quad \frac{\partial}{\partial \ln \mu^2} \frac{J_g(\ln \kappa)}{\Delta_s(\mu^2)} = \frac{\alpha_s}{2\pi} \frac{1}{\Delta_s(\mu^2)} \int_{\Lambda/\mu}^{1-\Lambda/\mu} dy y^2 \left[\tilde{P}_{gg}(y) J_g(\ln \kappa) + \tilde{P}_{gq}(y) J_q(\ln \kappa) \right]$$

❖ CCFM evolution equation:

$$\mathcal{A}(x, k, p) = \bar{\alpha}_s \int_x^1 \frac{dz}{z} \int \frac{d^2 q}{\pi q^2} \theta(p - zq) \Delta_{\text{ns}}(k, z, q) \mathcal{A}\left(\frac{x}{z}, k', q\right)$$

Ciafaloni, NPB 1988; Catani, Fiorani, Marchesini, NPB 1990.

Probing Gluon Linearly Polarization with EEC

EEC Phenomenology analysis

❖ Scaling behavior

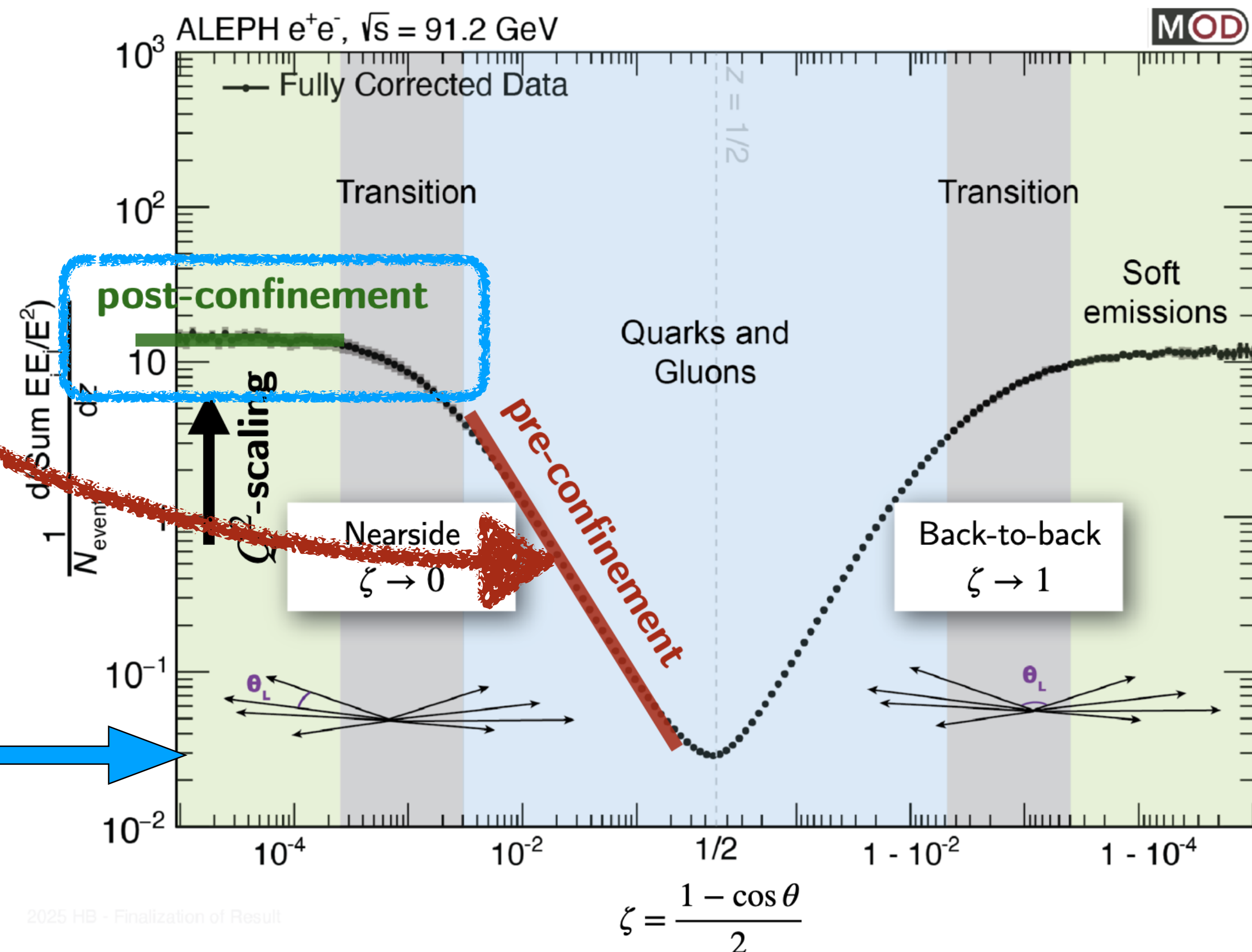
$$\langle \mathcal{E}(n_1) \mathcal{E}(n_2) \rangle \sim \frac{1}{\theta^{1-\gamma(N=2)}}$$

Anomalous dimension

$$\gamma(N) = \int_0^1 z^N P_{ij}(z) dz$$

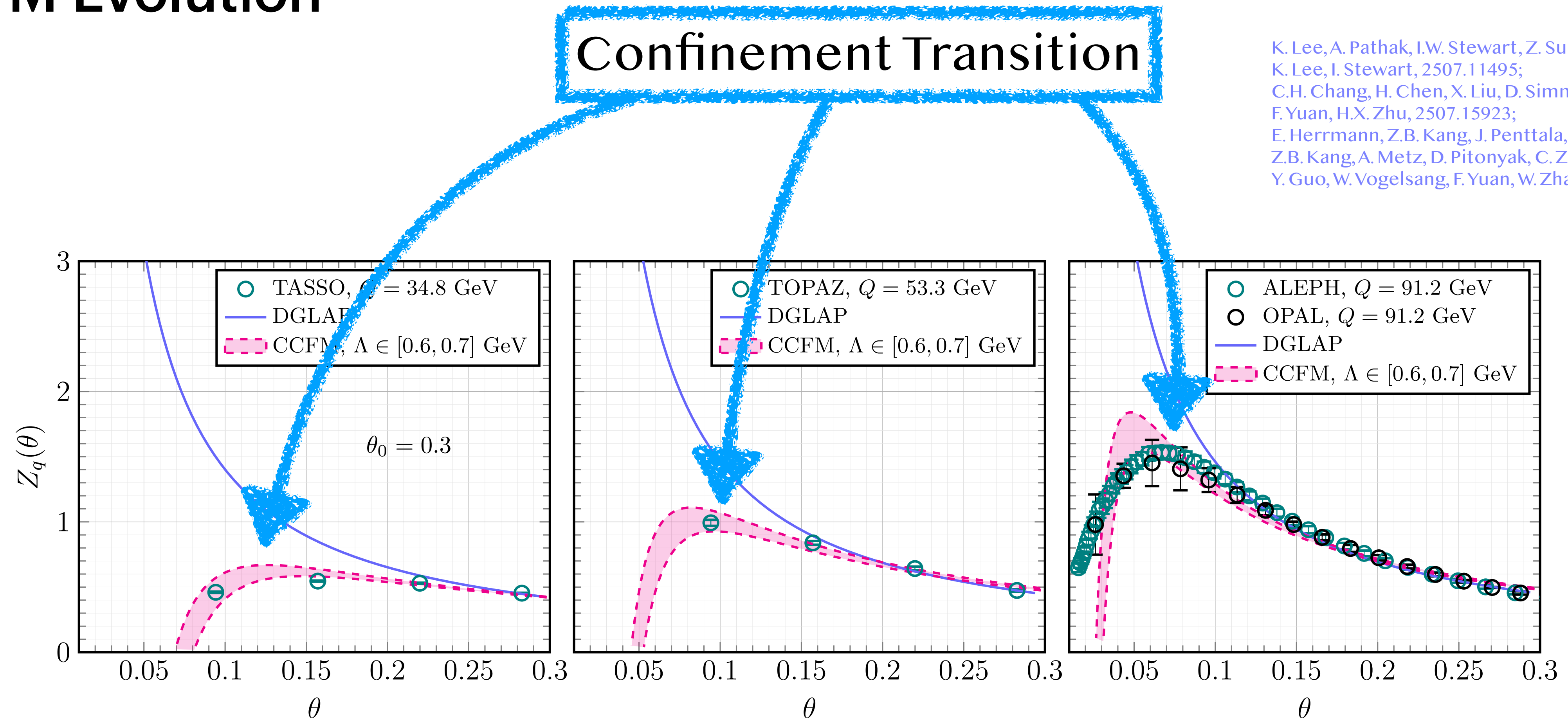
Chen et.al., 2020

C.H. Chang, H. Chen, X. Liu, D. Simmons-Duffin, F. Yuan, H.X. Zhu, PRL 136, 081903 (2026)



Probing Gluon Linearly Polarization with EEC

CCFM Evolution



K. Lee, A. Pathak, I.W. Stewart, Z. Sun, 2405.19396;
K. Lee, I. Stewart, 2507.11495;
C.H. Chang, H. Chen, X. Liu, D. Simmons-Duffin,
F. Yuan, H.X. Zhu, 2507.15923;
E. Herrmann, Z.B. Kang, J. Penttala, C. Zhang, 2507.17704;
Z.B. Kang, A. Metz, D. Pitonyak, C. Zhang, 2507.17444;
Y. Guo, W. Vogelsang, F. Yuan, W. Zhao, 2512.15896.

Probing Gluon Linearly Polarization with EEC

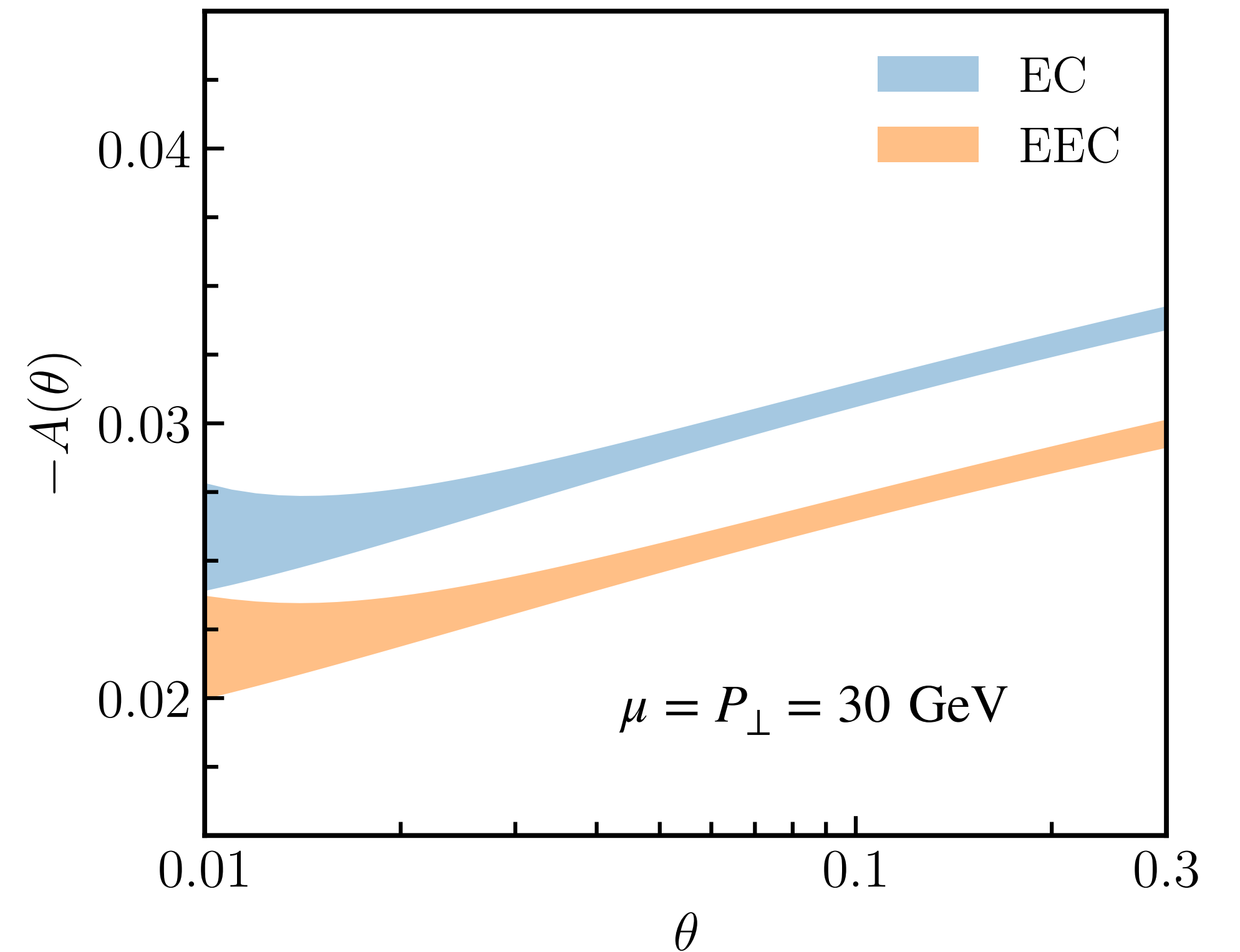
Analyzing Power $A(\theta)$

$$A(\theta) \equiv \frac{\int dy y(1-y) [P_{gg}^{2\phi} + 2n_f P_{qg}^{2\phi}] J_{g,T}}{\int dy y(1-y) \left\{ [\tilde{P}_{gg} + 2n_f \tilde{P}_{qg}] J_g + [\tilde{P}_{qq} + \tilde{P}_{gq}] J_q \right\}}$$

Partial cancellation between
 $g \rightarrow gg$ and $g \rightarrow q\bar{q}$ branching

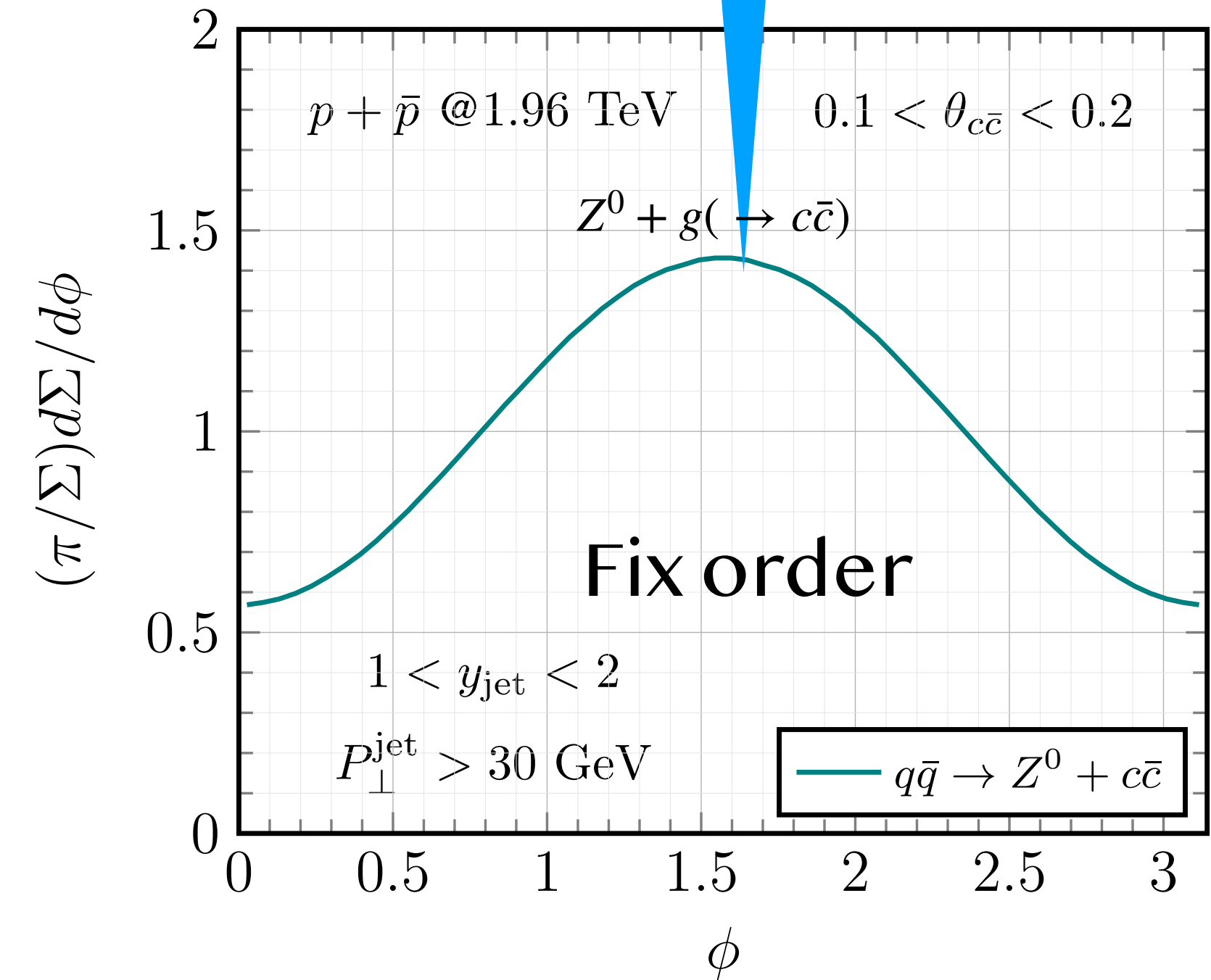
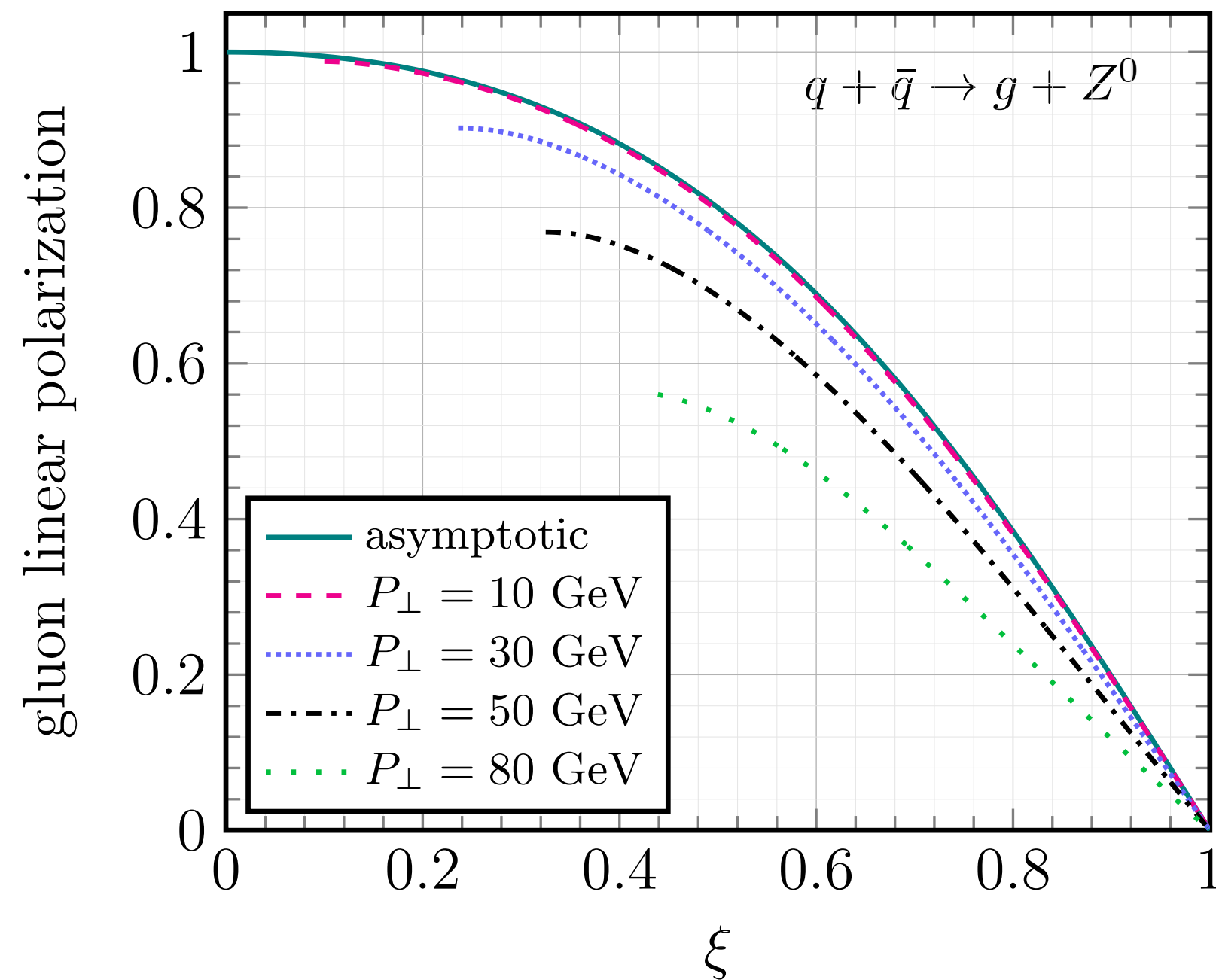
$$P_{gg}^{2\phi}(y) = 2N_c y(1-y)$$

$$P_{qg}^{2\phi}(y) = -y(1-y)$$



Probing Gluon Linearly Polarization with EEC

Anisotropic EEC — heavy flavor tagging



In Z^0 -tagged process, gluon can be consider as collinear radiated by the quark when $P_\perp \ll M_Z$, generating a sizable linear polarization.

Conclusion

- ❖ The transverse polarized FFs can be probed by means of transverse spin correlations
- ❖ The anisotropic EEC is a novel probe
- ❖ Coherent effect is naturally encoded in the CCFM equation, providing a smooth transition into the non-perturbative regime

Thank you!