Transverse Spin Correlation and Anisotropic EEC

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Lei Yang, Yu-Kun Song, Shu-Yi Wei, Phys.Rev.D 111 (2025) 5, 054035

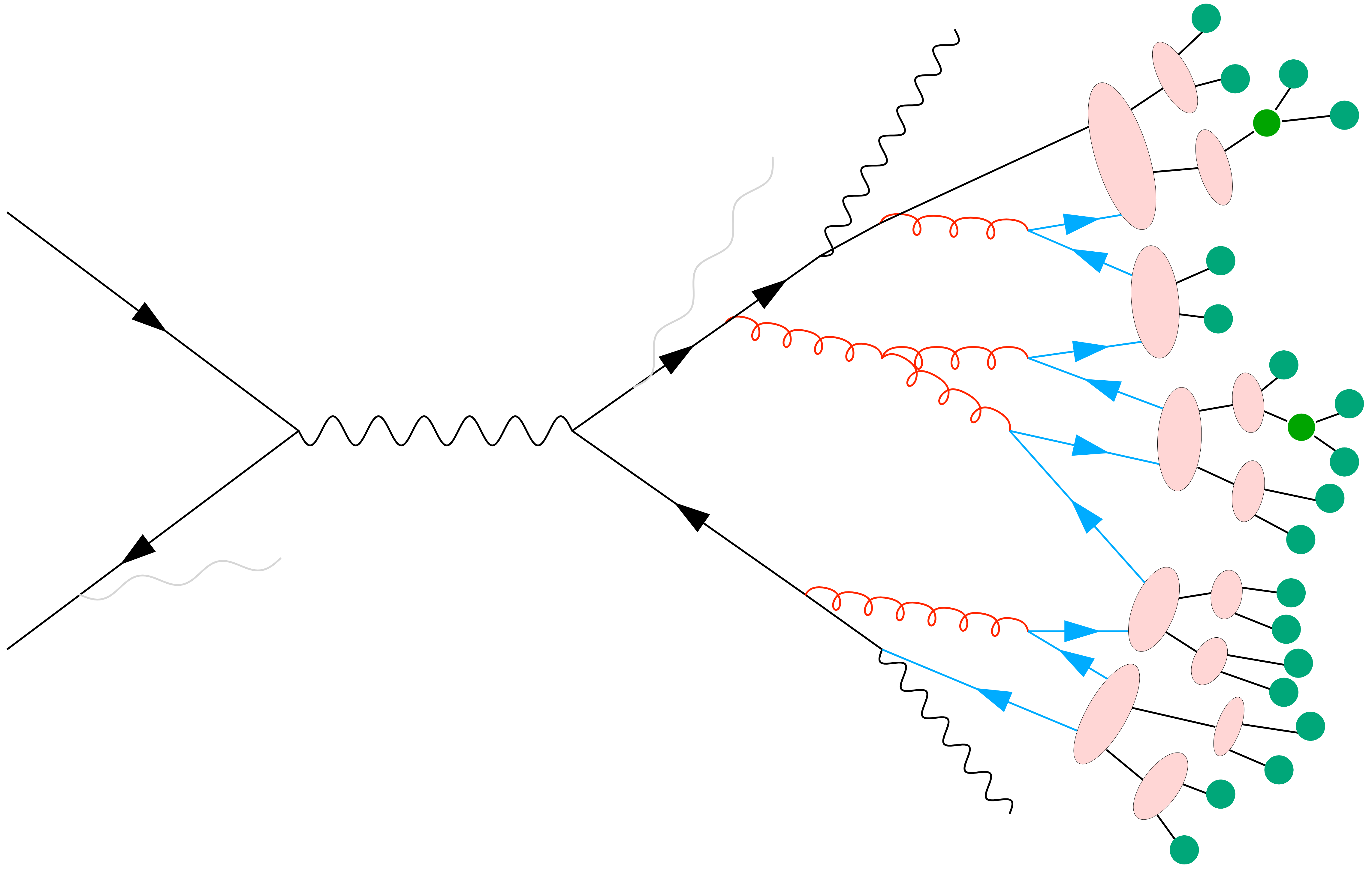
Yu-Kun Song, Shu-Yi Wei, Lei Yang, Jian Zhou, Phys.Rev.Lett. 136 (2026) 13, 131901

May 16 2026

Contents

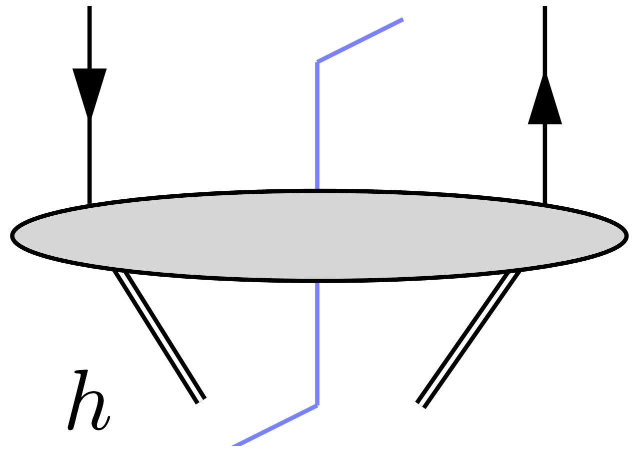
Background & Motivation

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



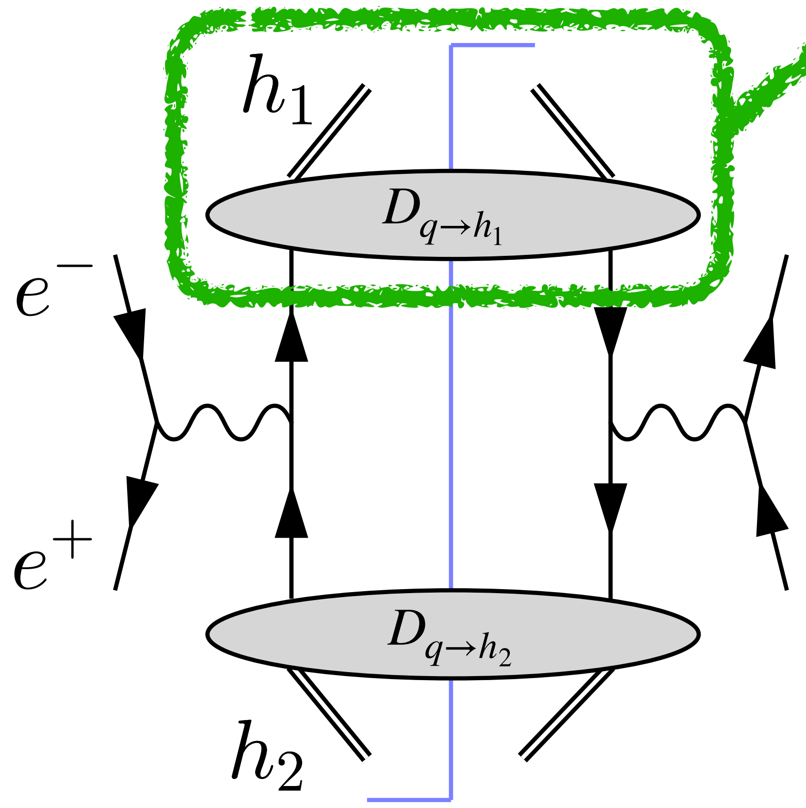
$\mu \sim \Lambda_{\text{QCD}} \sim 200$ GeV $\leftrightarrow$ $\alpha_s \sim 1$

Background & Motivation



QCD Factorization

- e^+e^- Annihilation



$$\frac{1}{4z}\int dp^+ \sum_X \frac{1}{(2\pi)^4}\int d^4\xi\, e^{ip\cdot\xi}\langle 0|\psi_i(\xi)|P_h,X\rangle\langle P_h,X|\bar\psi_j(0)|0\rangle\Big|_{p^-=P_h^-/z,\,p_T}$$

$$=\frac{1}{4}\Big[D_1 \not n_+ + D_{1T}^\perp \frac{\epsilon_{\mu\nu\rho\sigma}\gamma^\mu n_+^\nu p_T^\rho S_{hT}^\sigma}{M_h} - \lambda G_{1L}\not n_+\gamma_5 - G_{1T}\frac{(p_T\cdot S_T)}{M_h}\not n_+\gamma_5$$

$$- H_{1T}\, i\sigma_{\mu\nu}\gamma_5 S_{hT}^\mu n_+^\nu - \lambda H_{1L}^\perp \frac{i\sigma_{\mu\nu}\gamma_5 p_T^\mu n_+^\nu}{M_h} - H_{1T}^\perp\frac{(p_T\cdot S_T)}{M_h}\frac{i\sigma_{\mu\nu}\gamma_5 p_T^\mu n_+^\nu}{M_h} + H_1^\perp \frac{\sigma_{\mu\nu}p_T^\mu n_+^\nu}{M_h}\Big]$$

$$\frac{d\sigma_{e^+e^-}}{d\mathcal{P}.\mathcal{S}.} \propto \sum_q e_q^2\, D_{q\to h_1}\otimes D_{\bar q\to h_2}\otimes \hat\sigma_H^{e^+e^-\to q\bar q}$$

Long distance **Short distance**

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

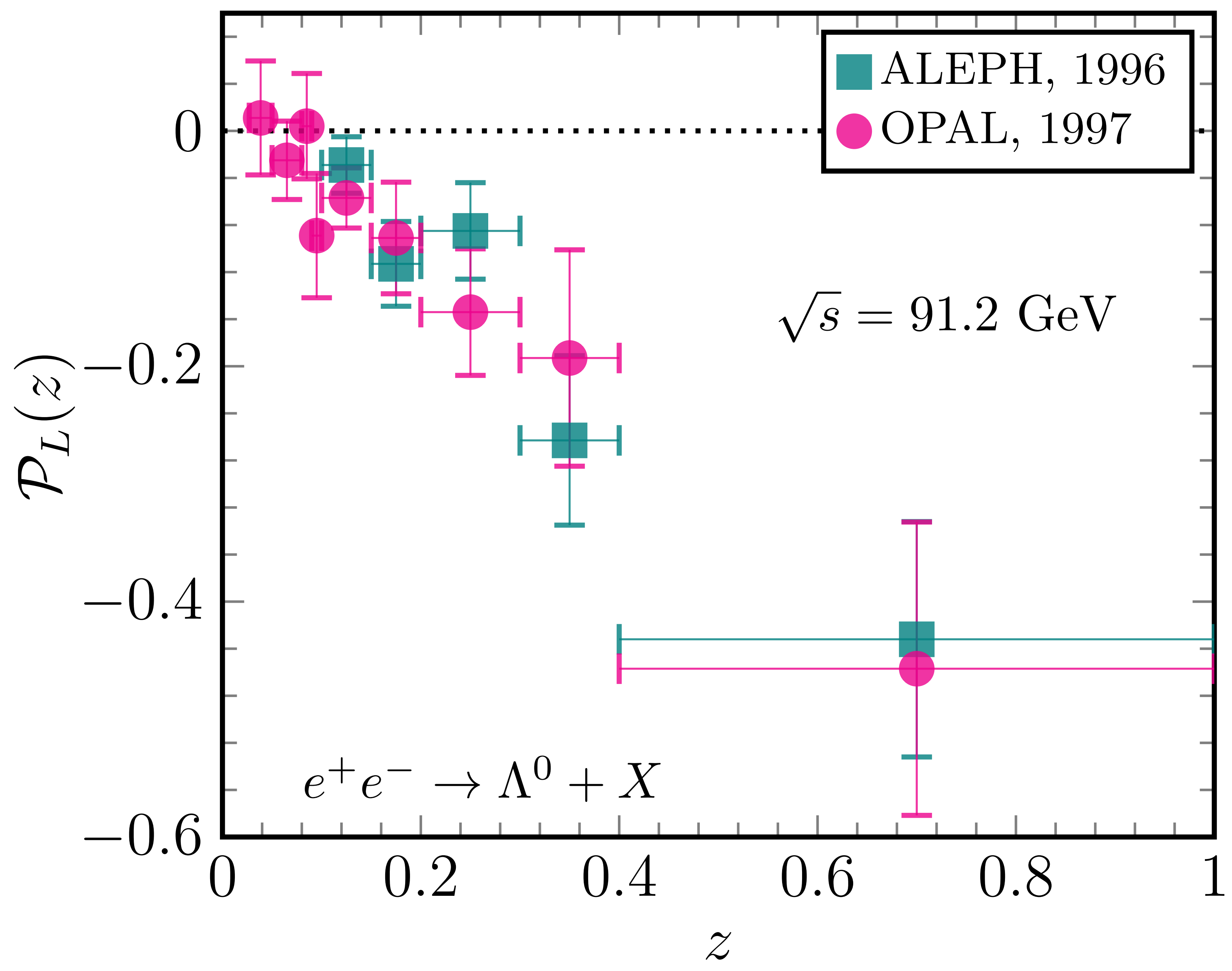
Background & Motivation

Buskulic, D.; et al. Measurement of Lambda polarization from Z decays. Phys. Lett. B 1996, 374, 319-330.
Ackerstaff, K.; et al. Polarization and forward-Backward asymmetry of Lambda baryons in hadronic ZO decays. Eur. Phys. J. C 1998, 2, 49-59.
Kai-Bao Chen, Tianbo Liu, Yu-Kun Song, Shu-Yi Wei. Particles 6 (2023) 2, 515-545

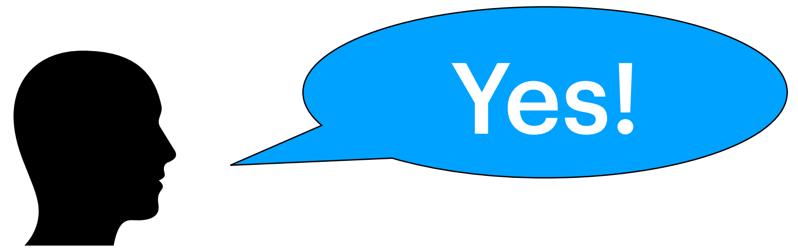
QCD Factorization

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

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



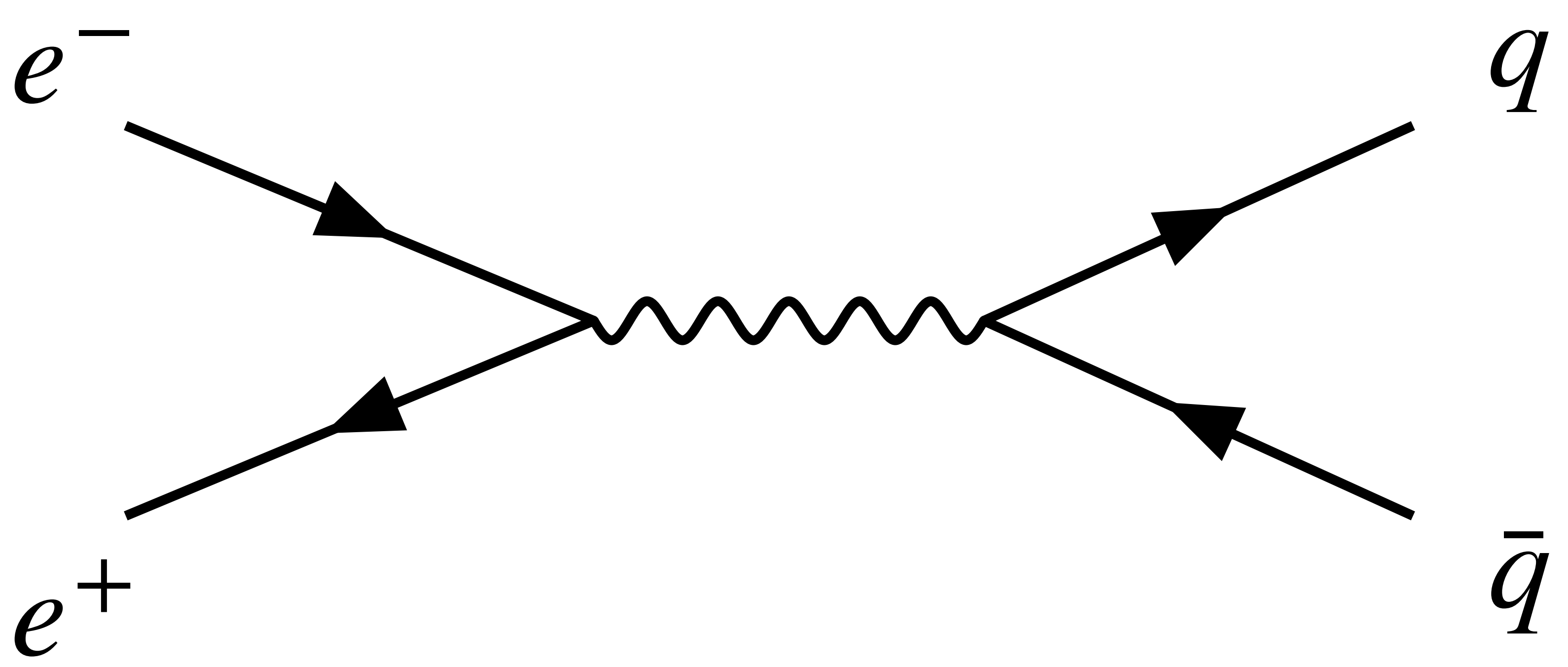
The preparation of polarized beams/target is relatively difficult → **Can we study the FFs of spin transfer in unpolarized beam collisions?**



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



$\bar{u}\gamma^\mu u = \bar{u}_L\gamma^\mu u_L + \bar{u}_R\gamma^\mu u_R$ Unpolarized

- **Unpolarized beam collisions**
- **Helicity conservation**

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

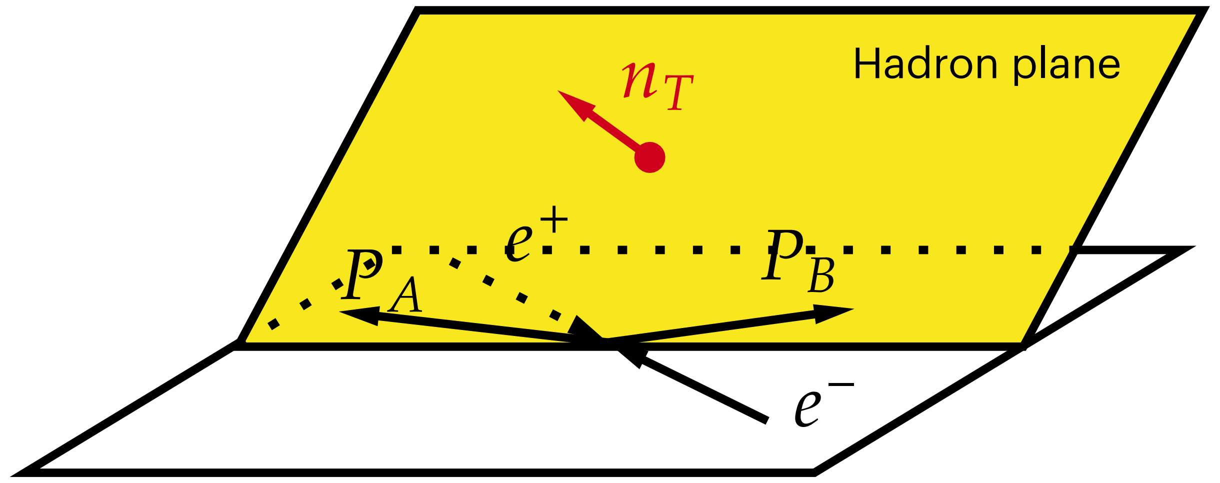
  A novel probe to the spin-dependence fragmentation functions

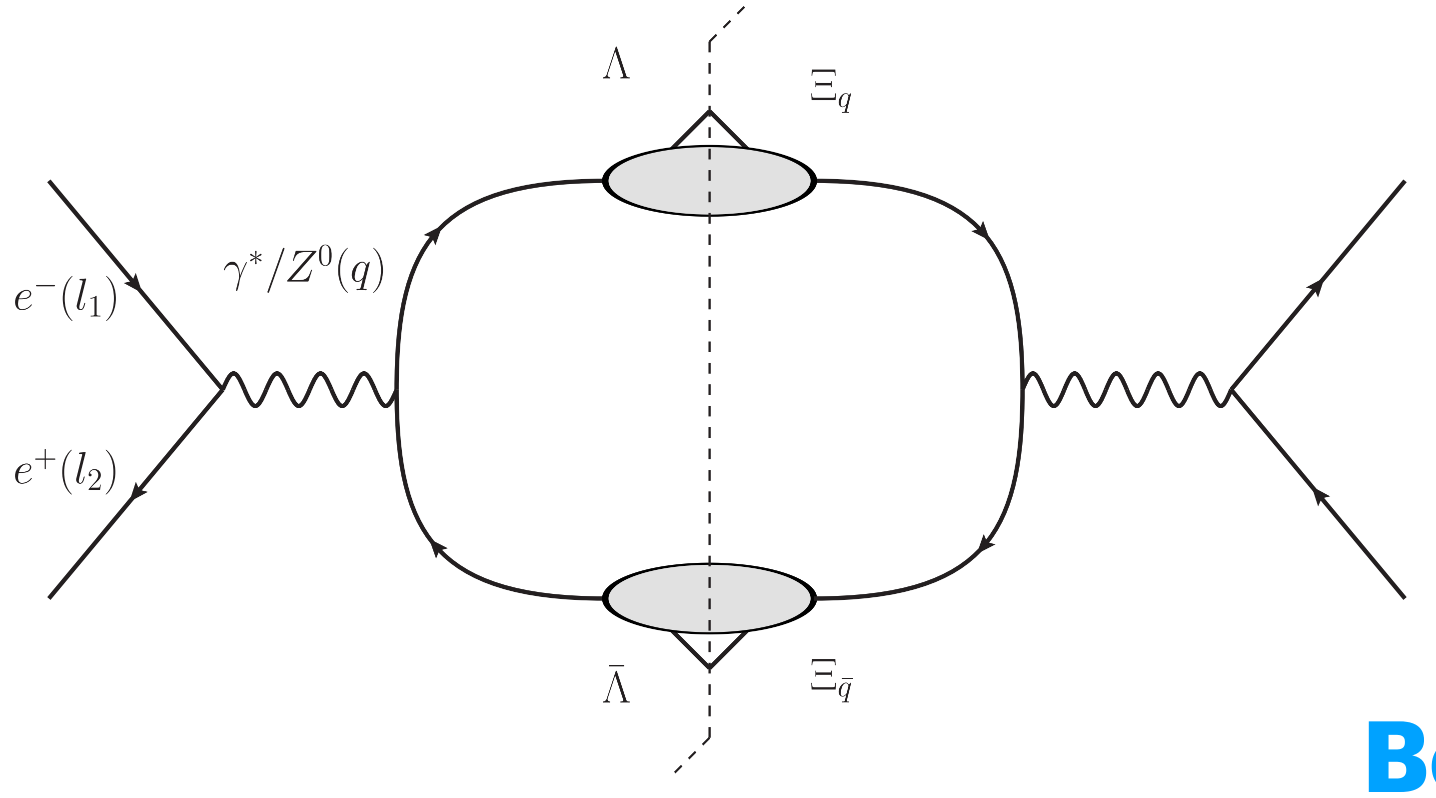
We will focus on the transverse spin transfer H_{1T}

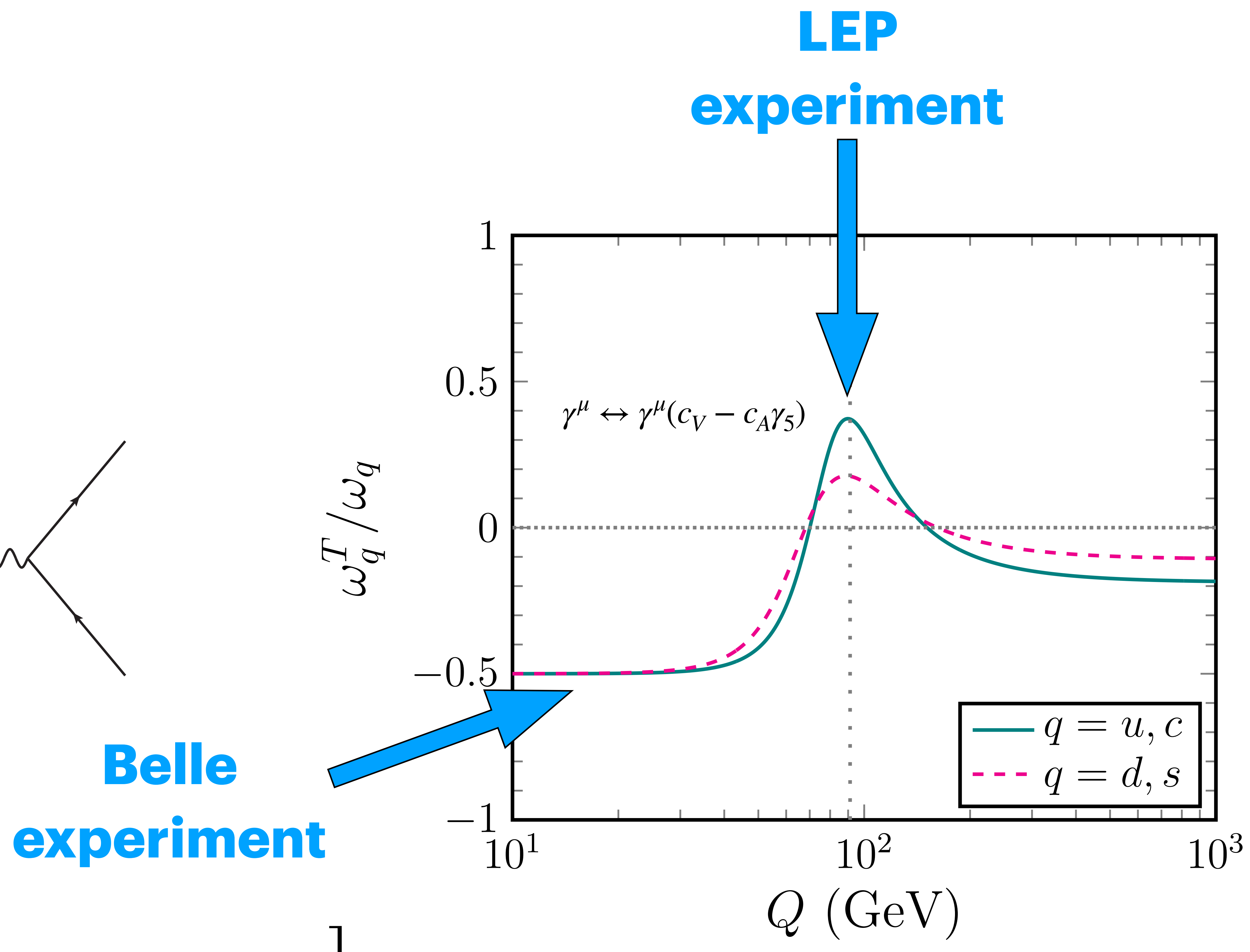
Back-to-back Di-hadron Spin Correlations

Electron-position Annihilation

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



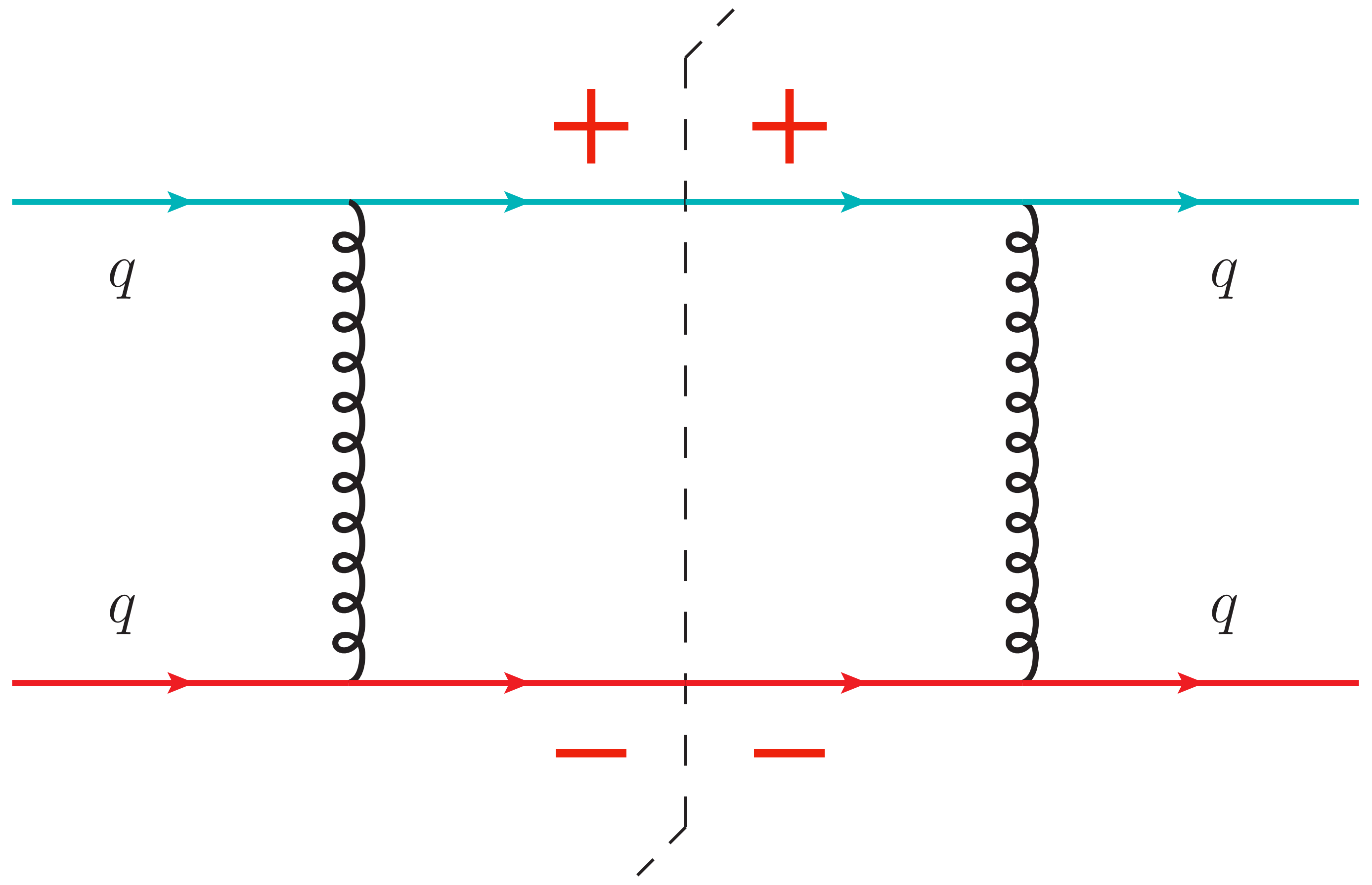


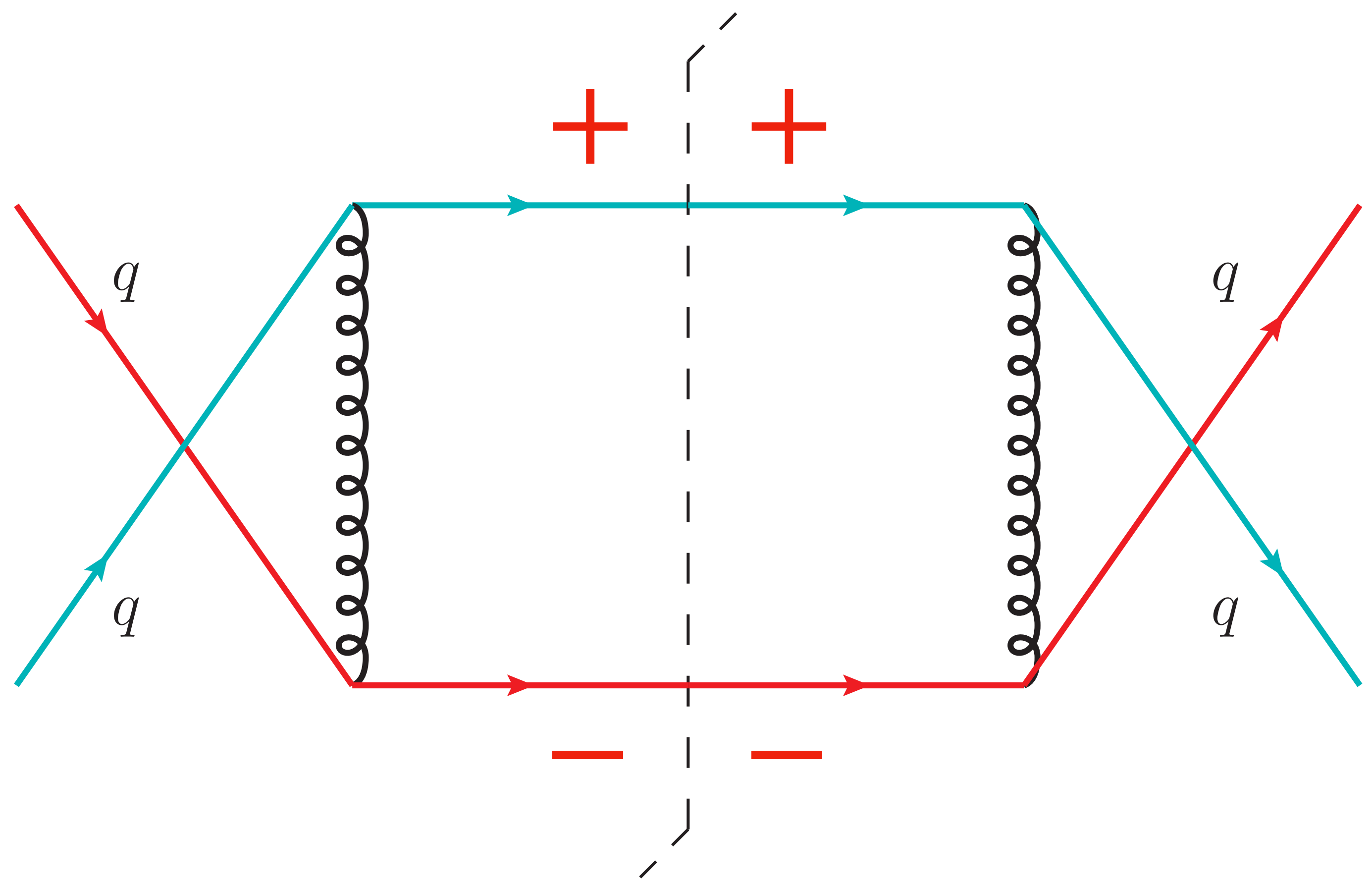


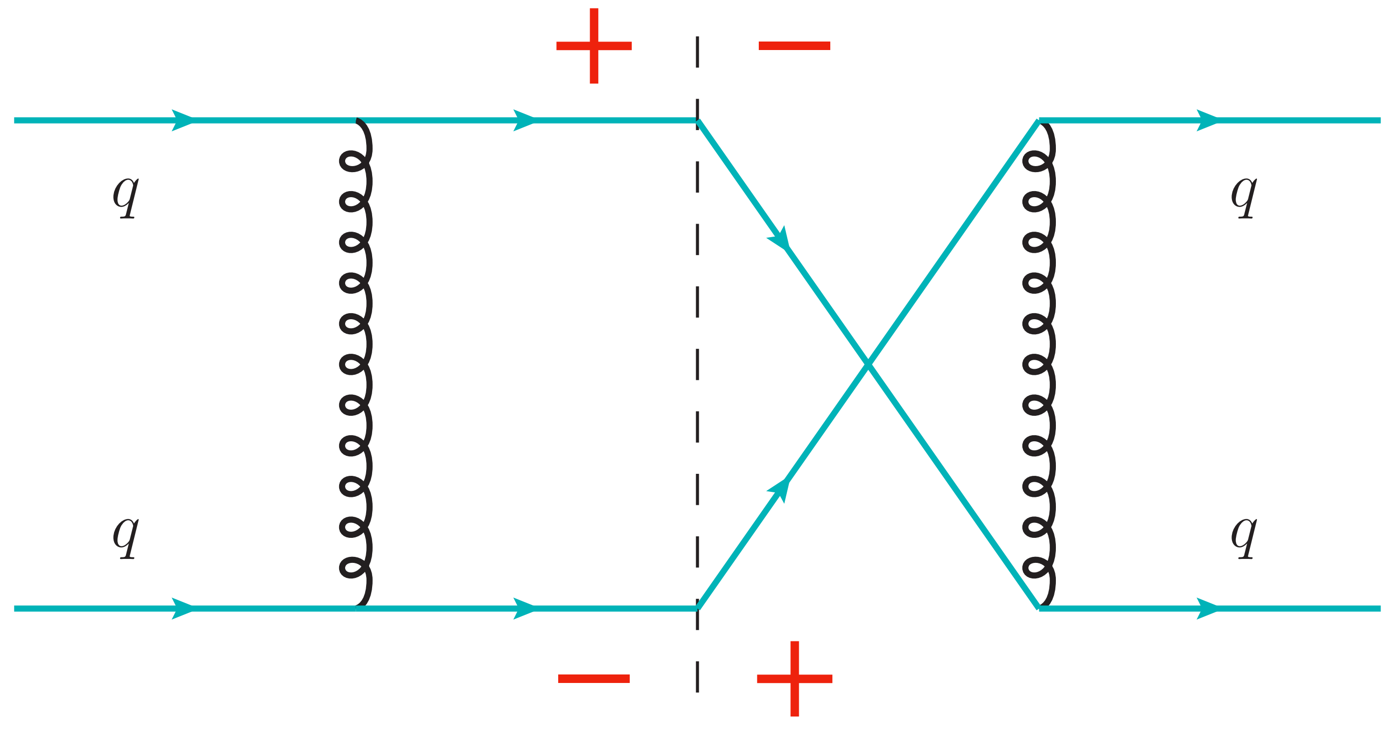
$$\frac{d\sigma}{dy dz_1 dz_2} = \frac{2\pi N_c \alpha_e^2}{Q^2} \sum_q \left[\omega_q(y) D_{1,q}(z_1) D_{1,\bar{q}}(z_2) + (\mathbf{S}_{T1} \cdot \mathbf{S}_{T2}) \omega_q^T(y) H_{1T,q}(z_1) H_{1T,\bar{q}}(z_2)\right]$$

Back-to-back Di-hadron Spin Correlations

Unpolarized Proton-proton Collisions





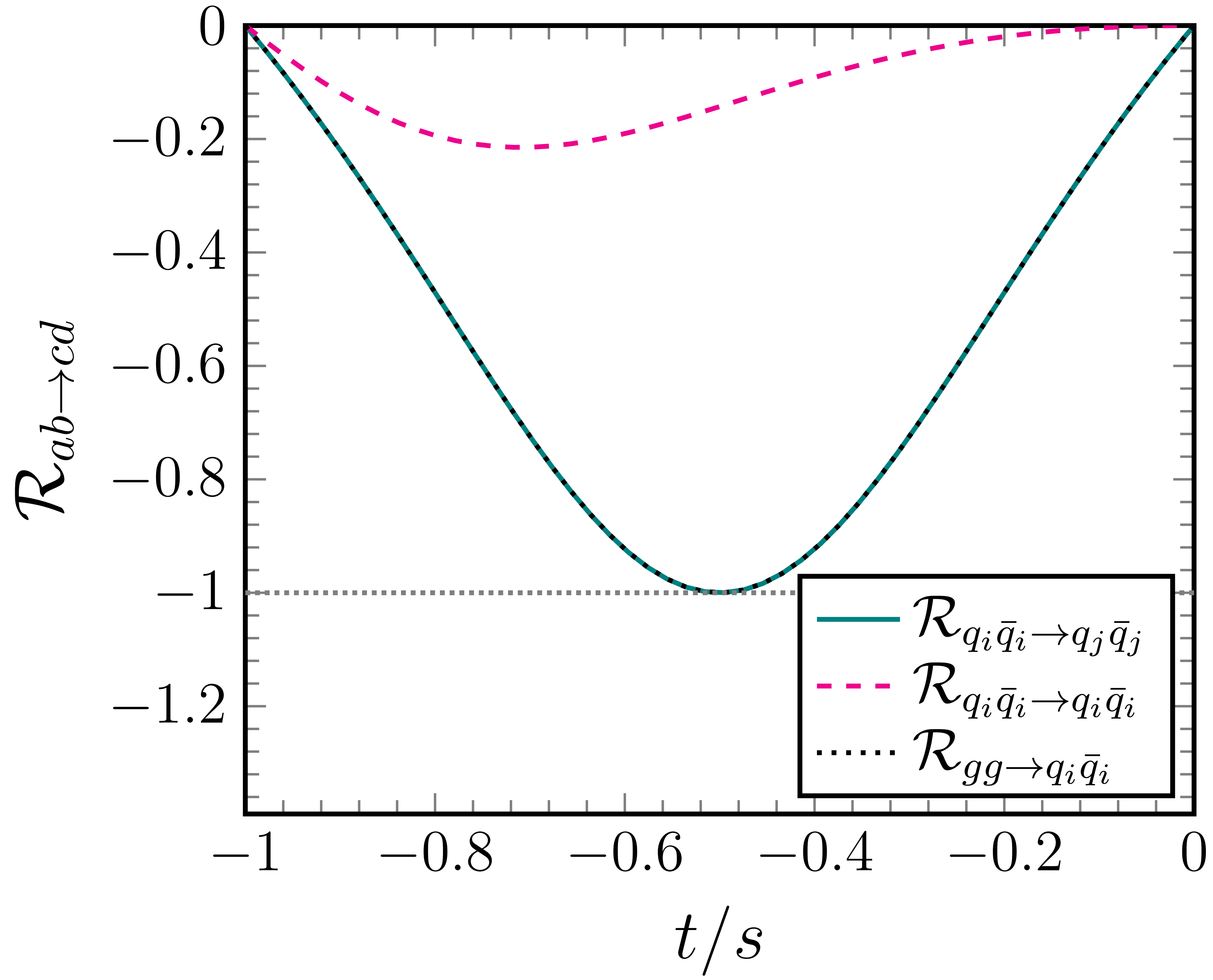


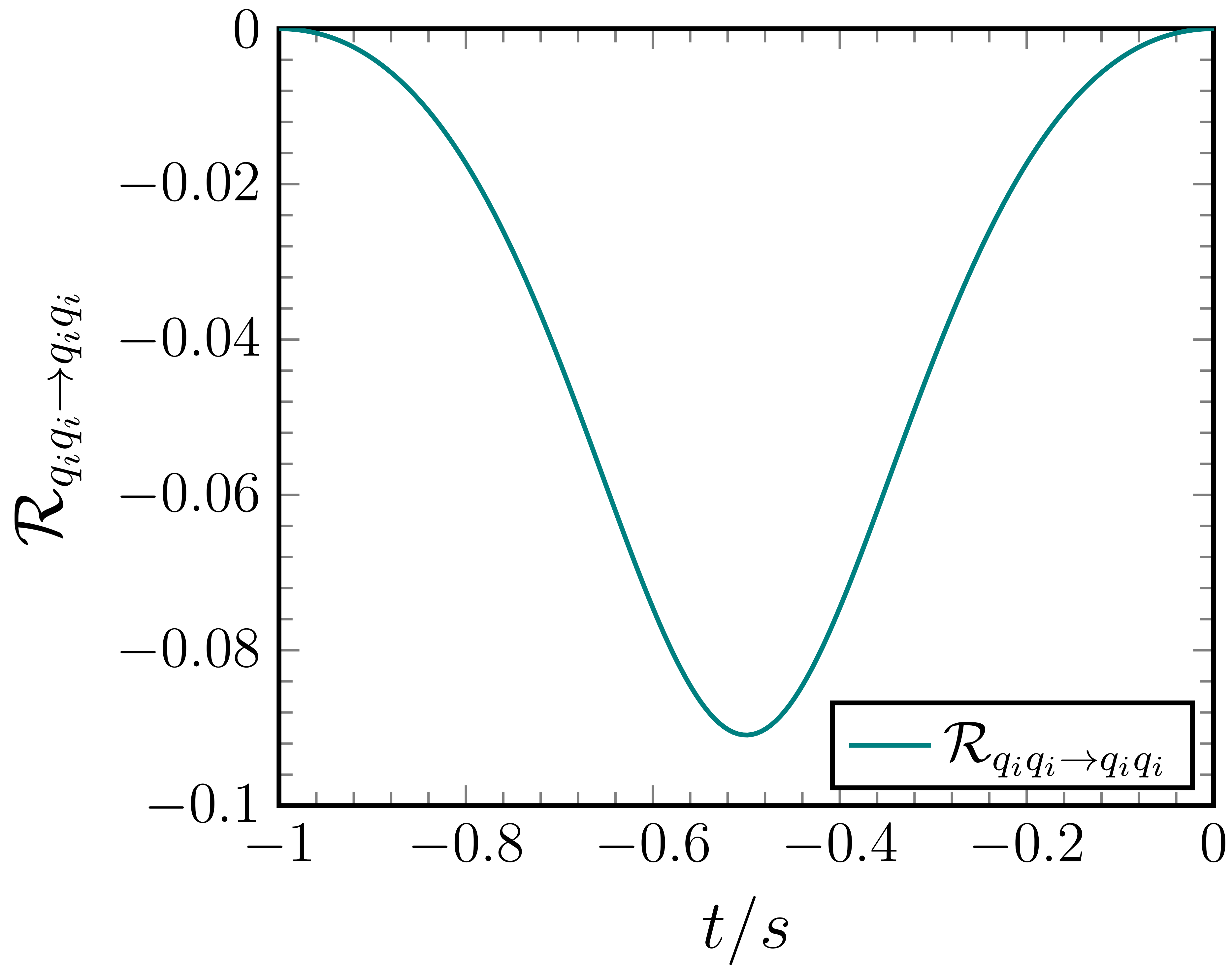
Transverse spin correlation requires a helicity flip

Back-to-back Di-hadron Spin Correlations

Unpolarized Proton-proton Collisions

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





How to probe gluon linearly polarization?

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

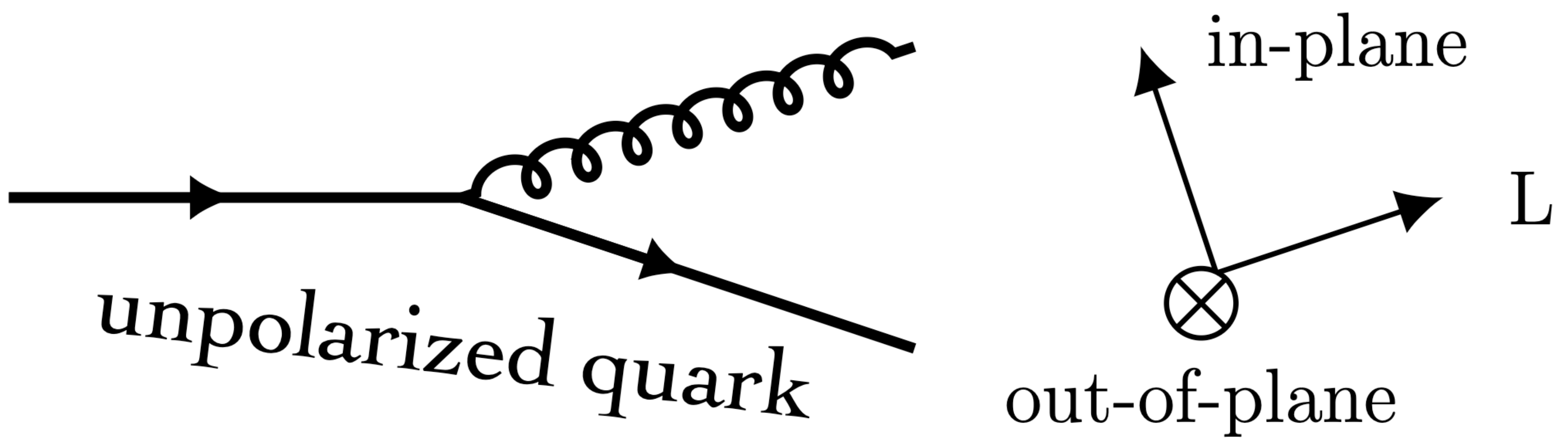
- Quark hadronization: $D(q \to \Lambda) = D_{1,q}^{\Lambda}(z) + \lambda_q \lambda_\Lambda G_{1L,q}^{\Lambda}(z) + \mathbf{S}_{T,q} \cdot \mathbf{S}_{T,\Lambda} H_{1T,q}^{\Lambda}(z)$
- Gluon hadronization: $D(g \to \Lambda) = D_{1,g}^{\Lambda}(z) + \lambda_g \lambda_\Lambda G_{1L,g}^{\Lambda}(z)$

Solution: Anisotropic

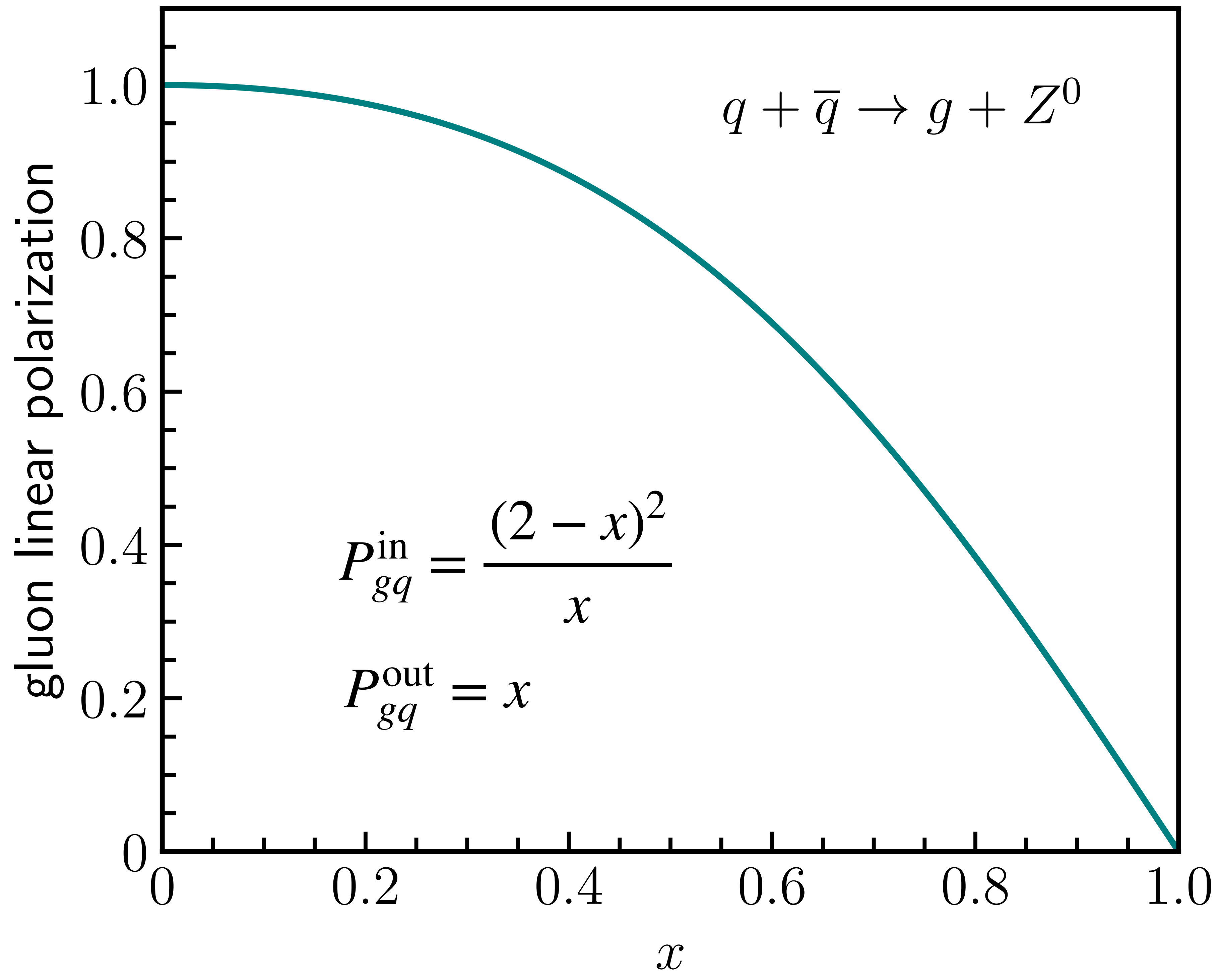
Probing Gluon Linearly Polarization with EEC

Why Linearly Polarized Gluon?

- Small-x limit: ~100% linear polarization



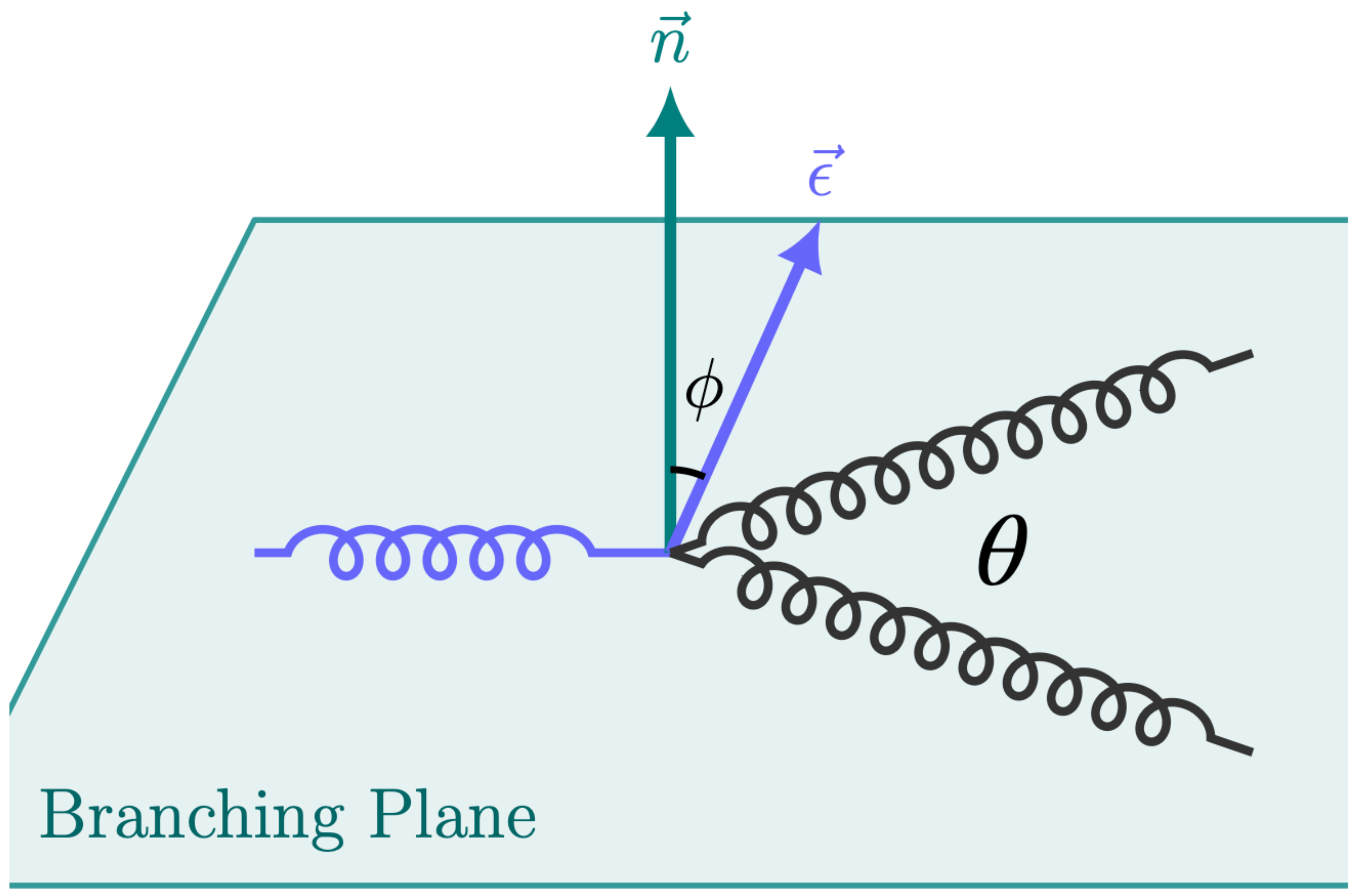
See, e.g., R.K. Ellis, et al, QCD and Collider Physics



- Challenge: directly measuring linear polarized gluon

Probing Gluon Linearly Polarization with EEC

Branching Plane



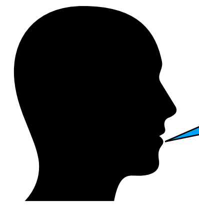
Since the linear polarization of the parent gluon specifies a transverse direction, the parton branching is no longer isotropic

Isotropic term

Anisotropic term

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

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



Anisotropic EEC: a novel probe

Probing Gluon Linearly Polarization with EEC

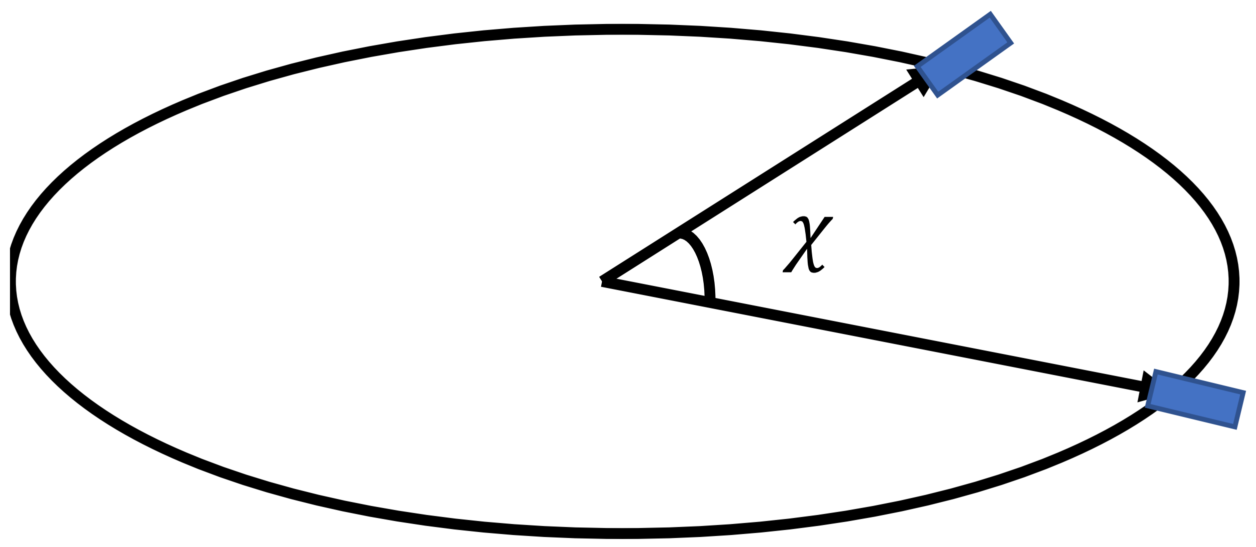
Energy Correlators

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

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

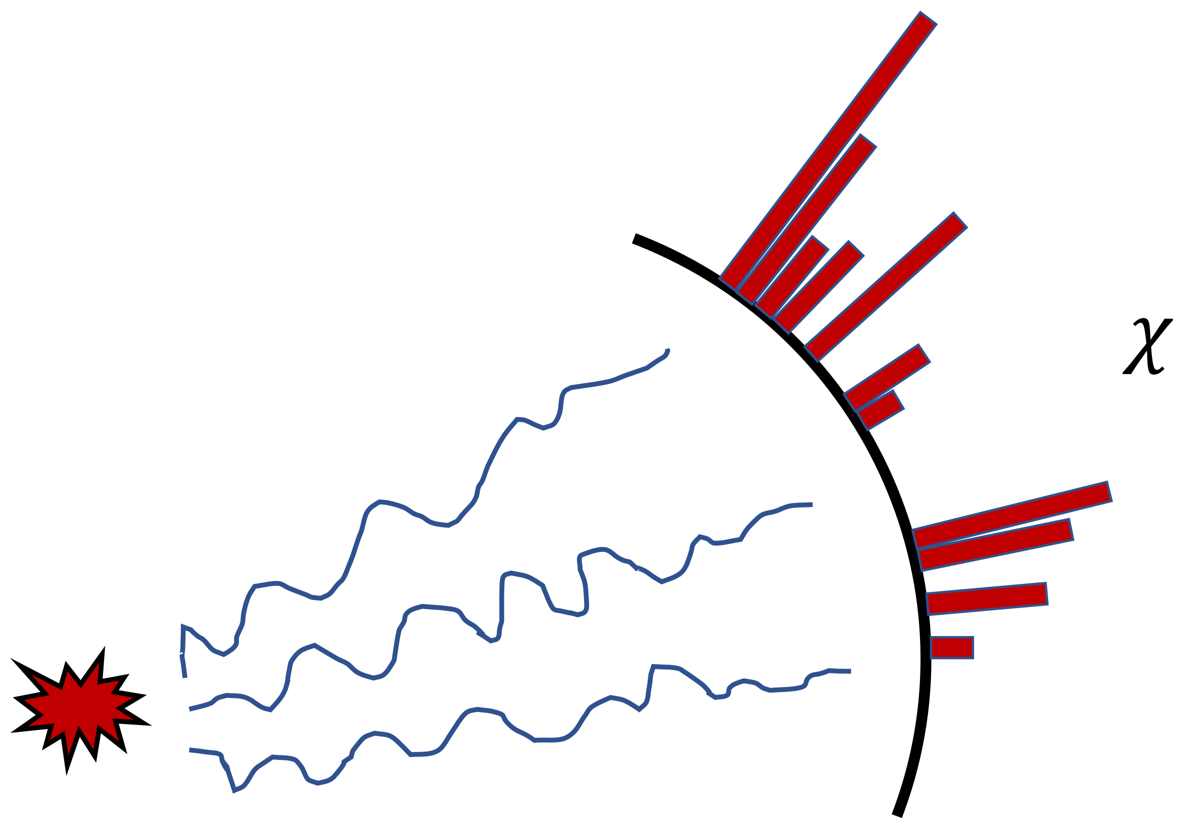
Energy Flow $$\mathcal{E}(\hat{n})|X\rangle = \sum_{k\in X} k^0 \delta^{(2)}(\Omega_n - \Omega_k)|X\rangle$$

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



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



Probing Gluon Linearly Polarization with EEC

EEC and Jet Function

- θ-integrated EEC

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

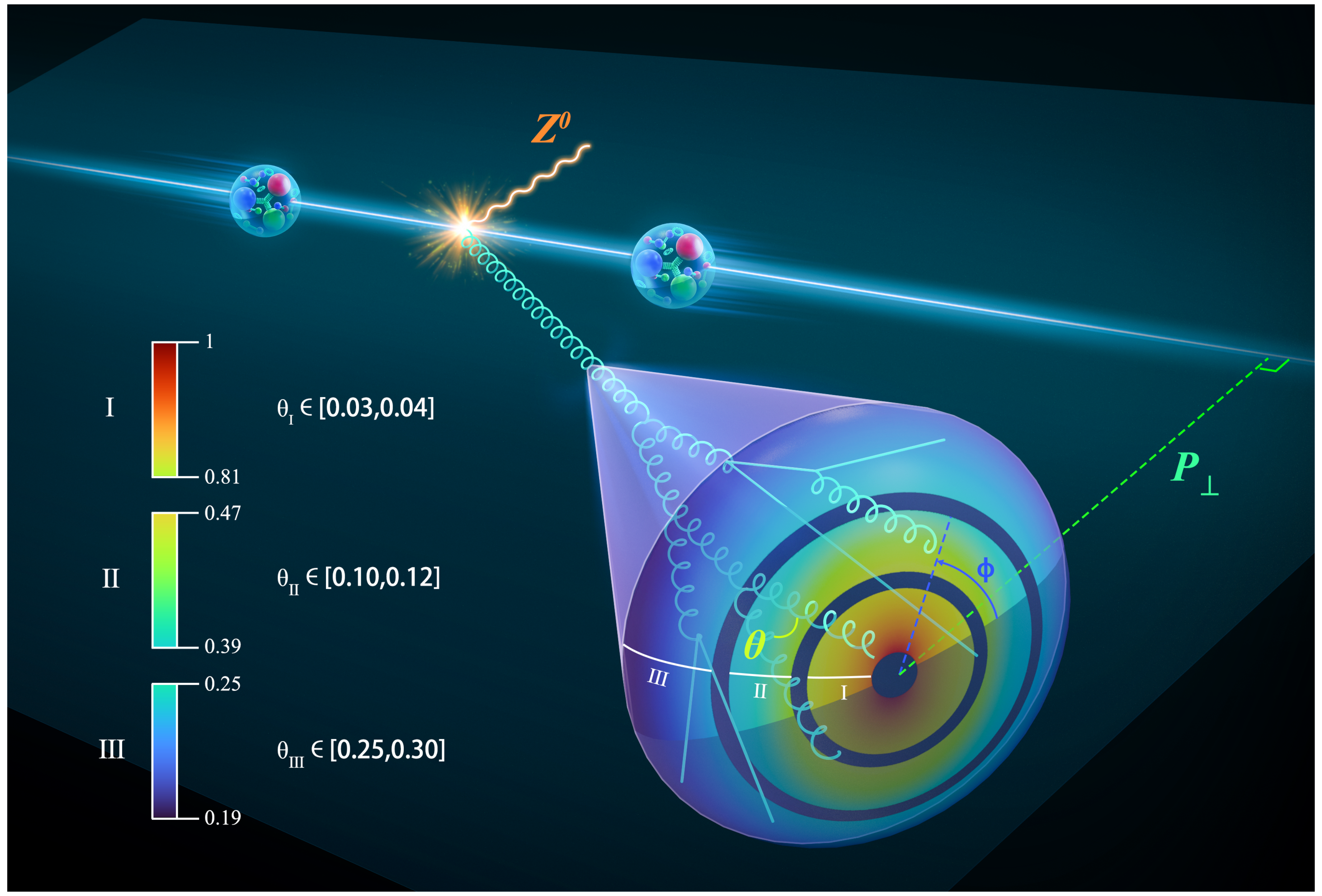
$$\langle \mathrm{EEC} \rangle = \sum_{i=q,g} \int \mathrm{d}x x^2 H_i(x,\mu) J_i(\ln x^2 \kappa), \qquad \kappa = (\theta E_g)^2/\mu^2$$

- Unpolarized jet function J_i follows the DGLAP evolution equation

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

- Polarized jet function $J_{g,T}$

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



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

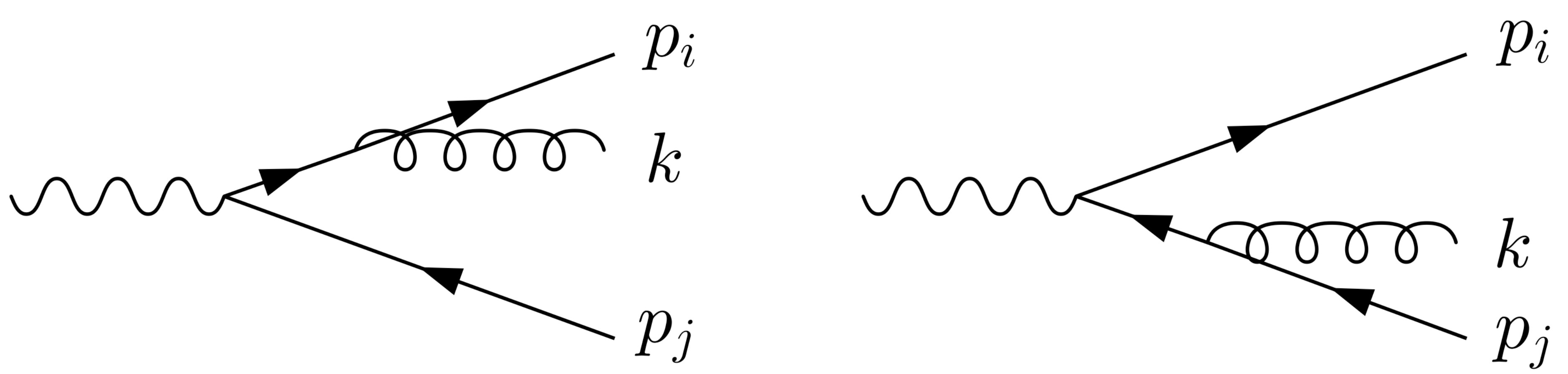
Probing Gluon Linearly Polarization with EEC

Angular Ordering & CCFM

- Angular ordering:

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

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



- Evolution of jet function:

DGLAP

CCFM

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

- CCFM evolution equation:

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

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

Probing Gluon Linearly Polarization with EEC

EEC Phenomenology analysis

- Scaling behavior

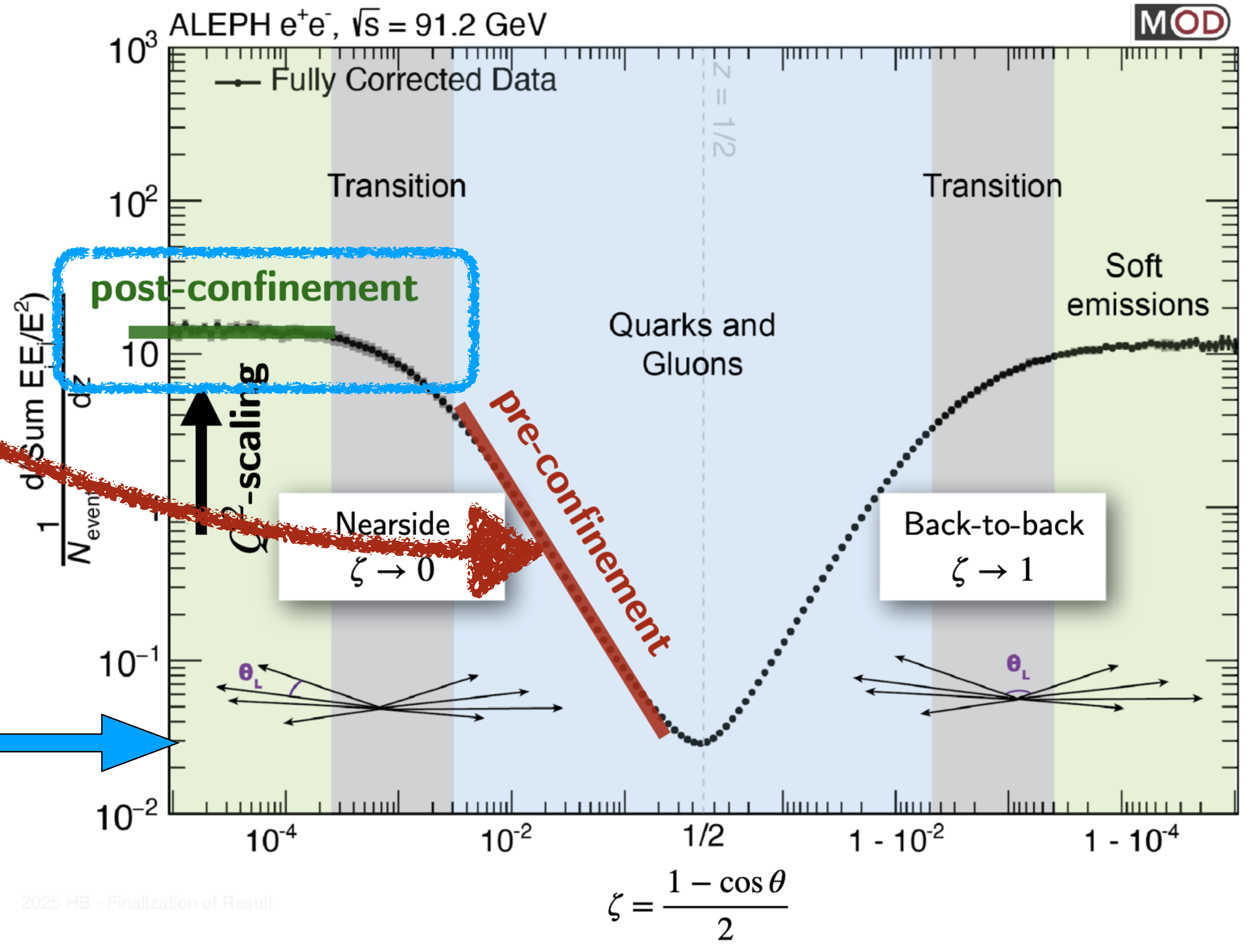
$$\langle \mathcal{E}(n_1)\mathcal{E}(n_2)\rangle \sim \frac{1}{\theta^{1-\gamma(N=2)}}$$

Anomolous diamention

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

Chen et.al., 2020

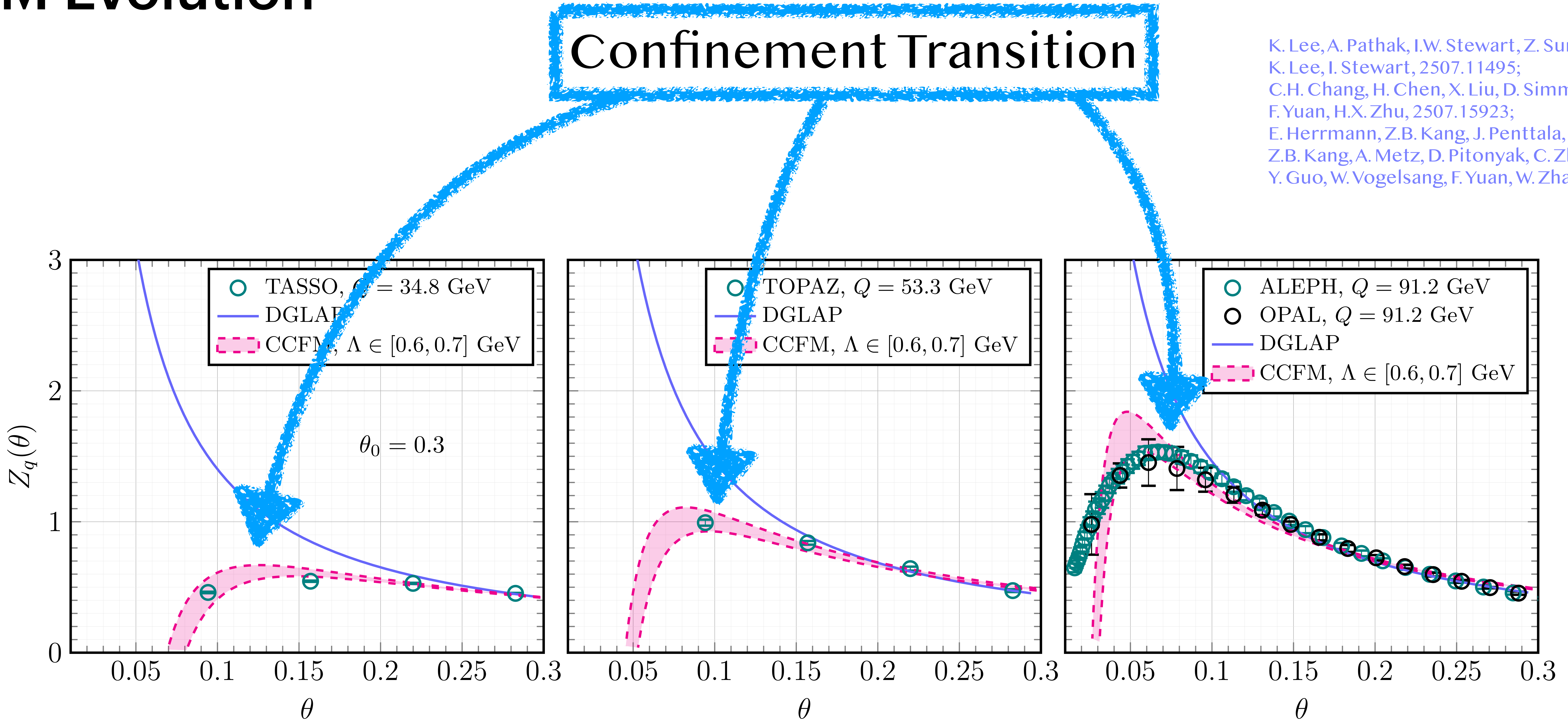
C.H. Chang, H. Chen, X. Liu, D. Simmons-Duffin, F. Yuan, H.X. Zhu, PRL 136, 081903 (2026)



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

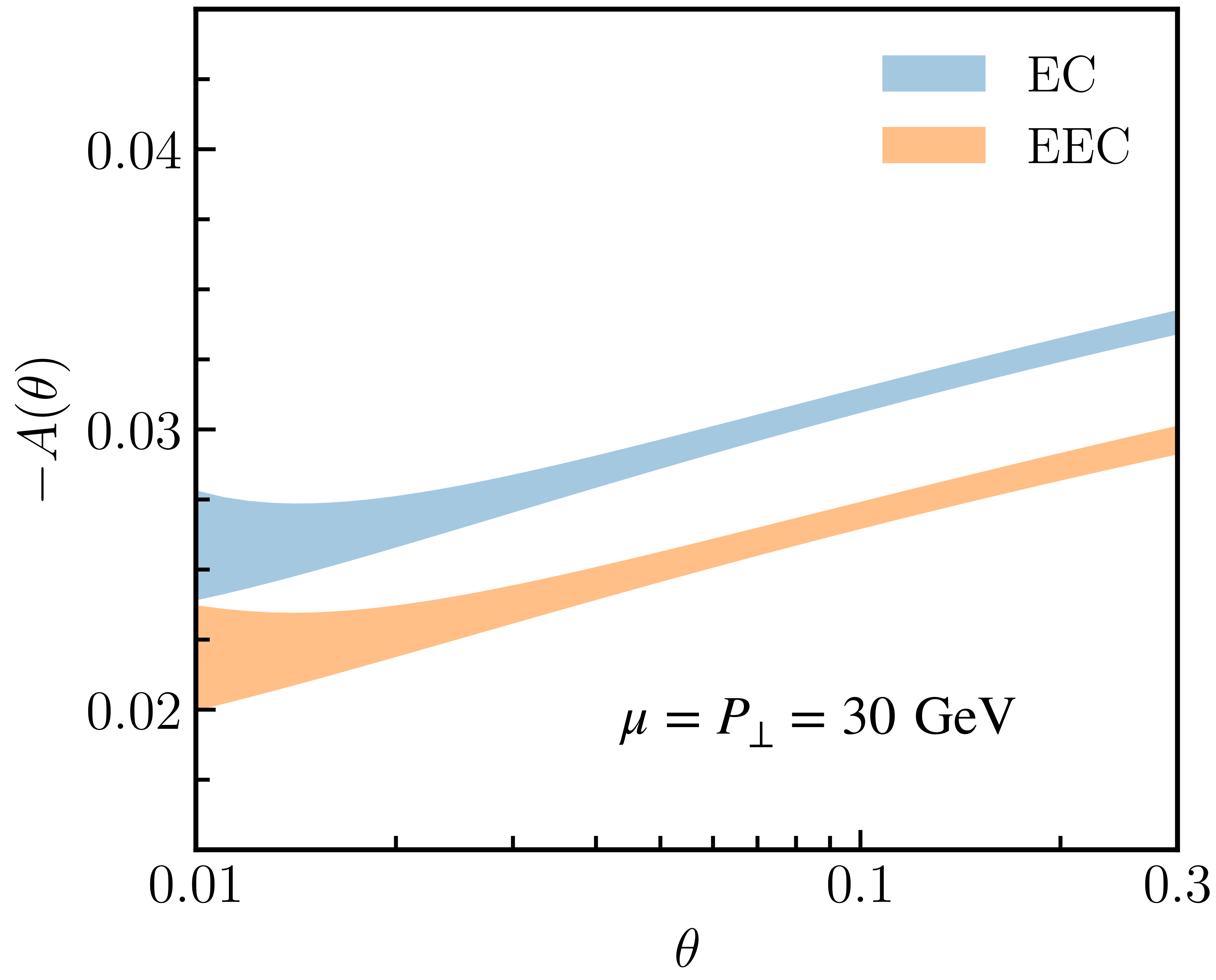
Analyzing Power $A(\theta)$

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

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

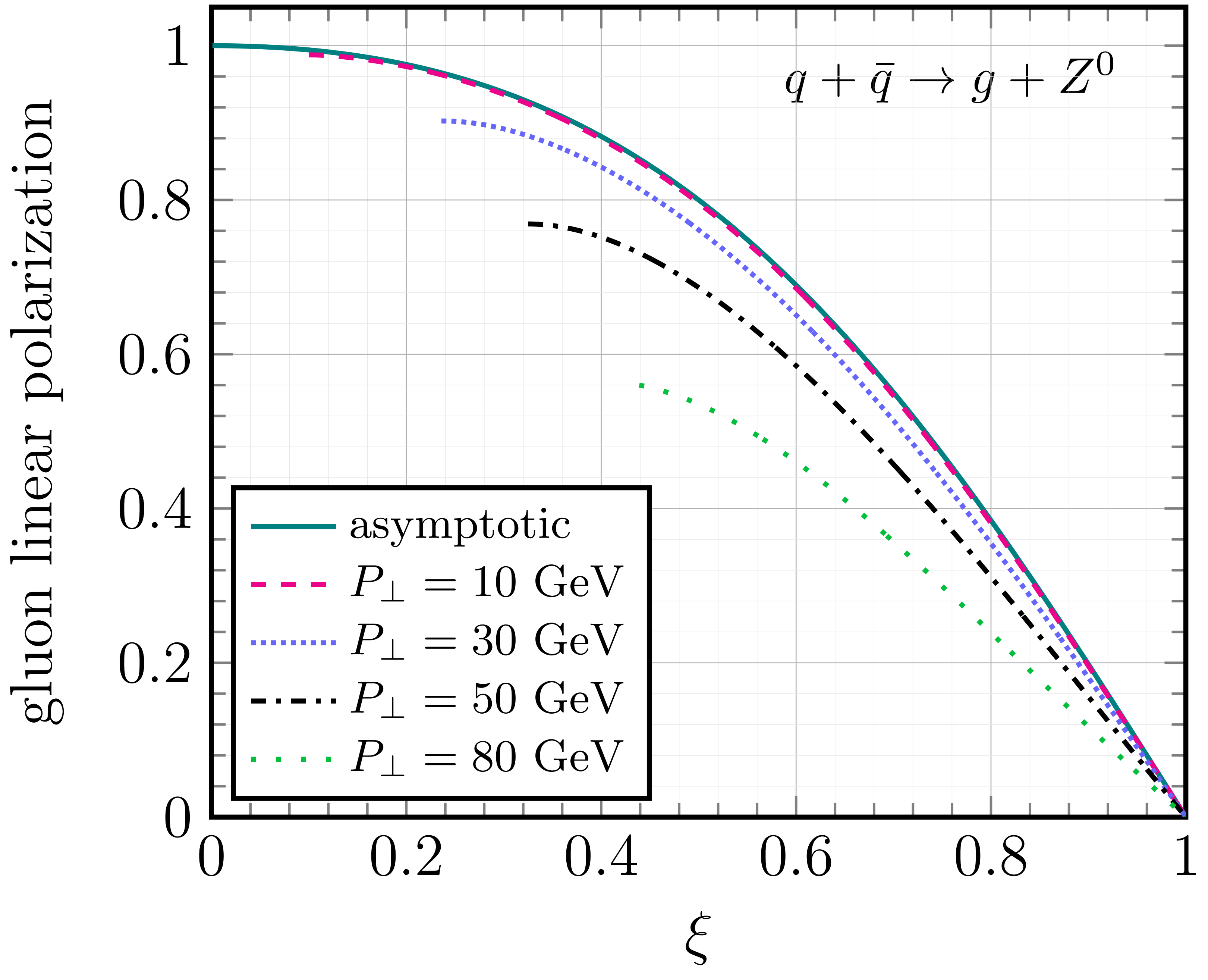
$$P^{2\phi}_{gg}(y) = 2N_c y(1-y)$$

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

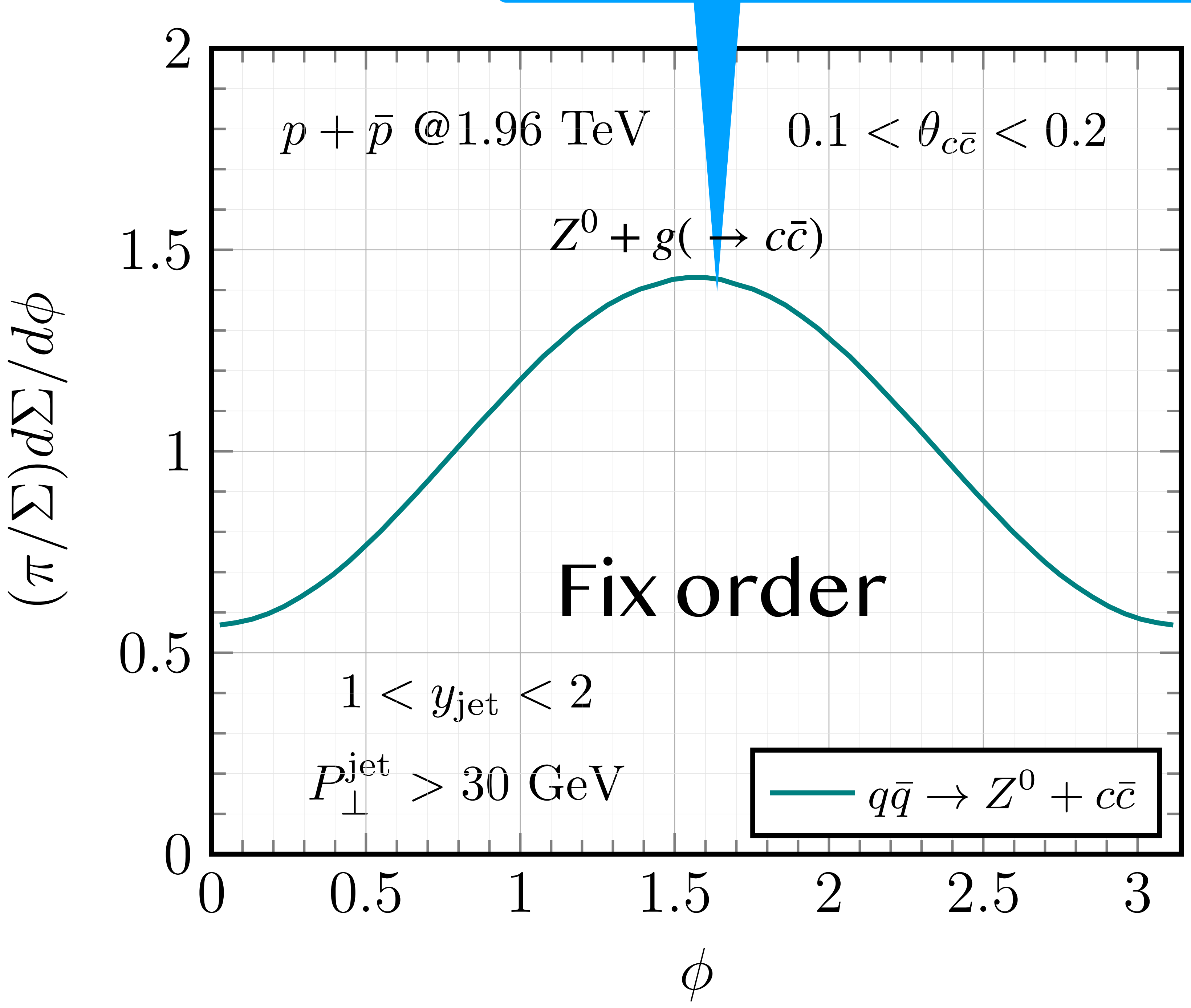


Probing Gluon Linearly Polarization with EEC

Anisotropic EEC — heavy flavor tagging



The $\cos 2\phi$ modulation reaching approximately 40 %



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!