Probing Gluon Linear polarization via Energy Correlations

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Based on: Y. K. Song, S. Y. Wei, L. Yang, J. Zhou, PRL 136,131901(2026)

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Outline:

- Linear polarization of gluons
- Coherent effect and CCFM formalism
- Anisotropic EEC, a novel probe
- Summary

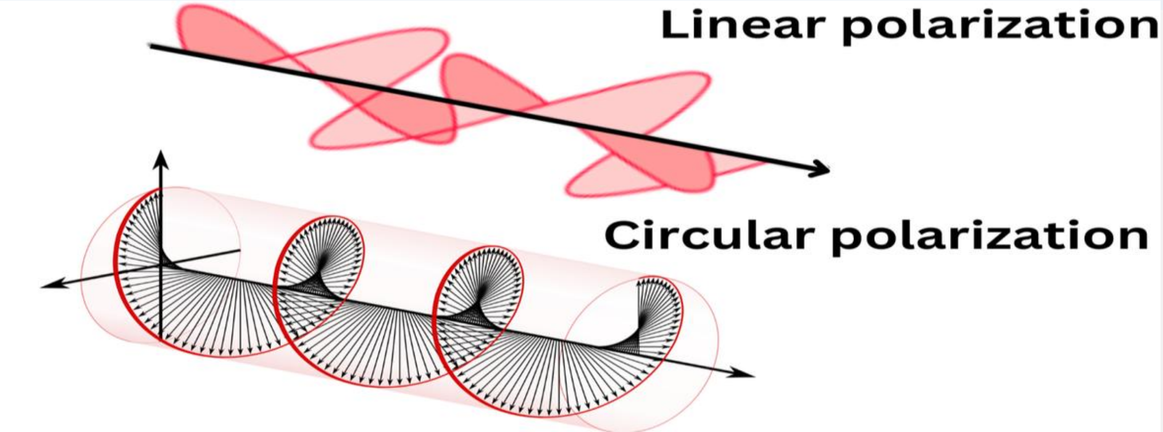
Gluon Linear Polarization: What Is It?

For a spin-1 gluon with momentum k, the polarization state is described by a 2×2 density matrix in the transverse plane:

$$\rho^{ij}(k) = \frac{1}{2}\left(\delta_\perp^{ij} f_1^g(x, k_\perp^2) + \left(\frac{k_\perp^i k_\perp^j}{k_\perp^2} - \frac{1}{2}\delta_\perp^{ij}\right) h_1^{\perp g}(x, k_\perp^2)\right)$$

- f_1^g — **unpolarized** gluon TMD
- $h_1^{\perp g}$ — **linearly polarized** gluon TMD

> **Striking fact:** In the dilute (small-x) limit, gluons exhibit 100% linear polarization — maximal entanglement between helicity and orbital angular momentum [Metz & Zhou '11, Bhattacharya et al. '24].



Collinear Gluon Radiation & Linear Polarization

Asymptotic limit ($P_\perp^2 \ll M_Z^2$):

$$\frac{d\sigma_U}{d\xi\, dy_Z\, d^2\vec{P}_\perp} = \sigma_0 \frac{\alpha_s}{2\pi} C_F \frac{1}{P_\perp^2} \frac{1+(1-\xi)^2}{\xi}$$

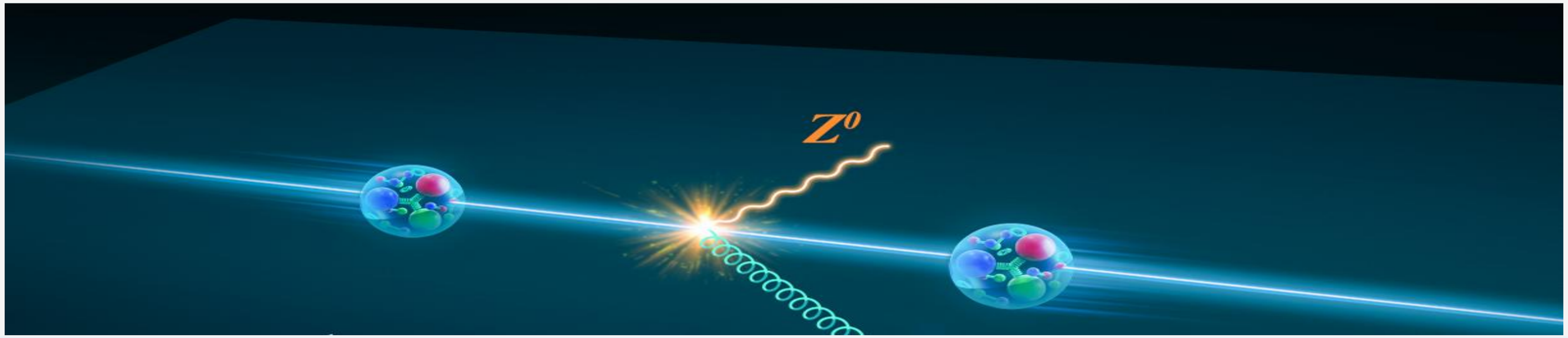
$$\frac{d\sigma_T}{d\xi\, dy_Z\, d^2\vec{P}_\perp} = \sigma_0 \frac{\alpha_s}{2\pi} C_F \frac{1}{P_\perp^2} \frac{2(1-\xi)}{\xi}$$

σ_U: unpolarized σ_T: linearly polarized

Exact result (full $q\bar{q} \to g + Z^0$):

$$P_g^T(\hat{s},\hat{t},\hat{u}) = \frac{2M_Z^2\hat{s}}{2M_Z^2\hat{s} + \hat{u}^2 + \hat{t}^2}$$

At $P_\perp = 10$ GeV: exact $\approx$ asymptotic
At $P_\perp = 30$ GeV: deviation $\lesssim 5\%$
At $P_\perp = 80$ GeV: visible but signal remains large

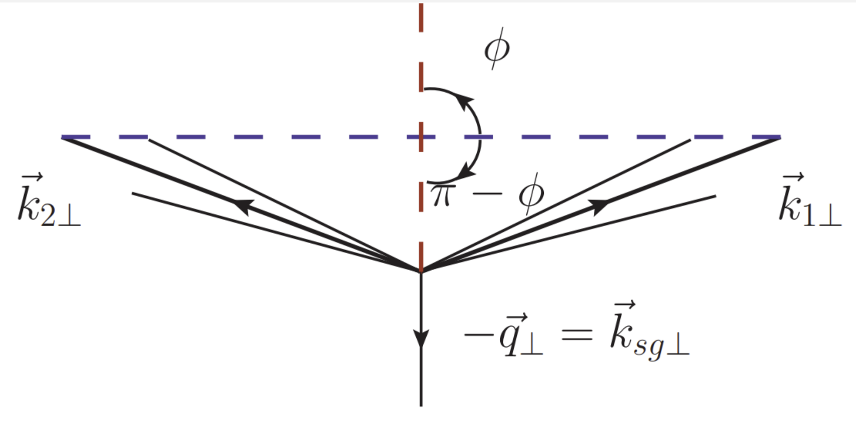


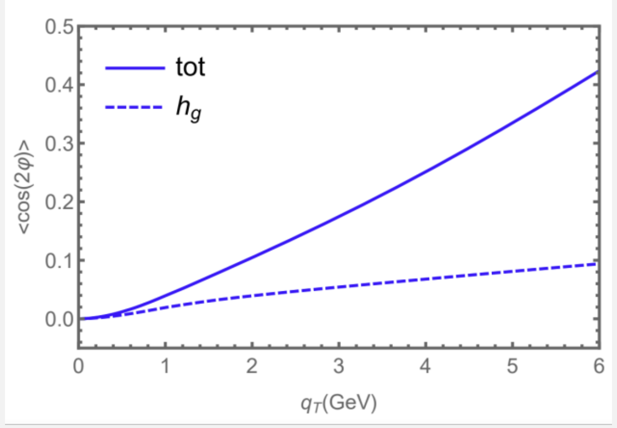
Asymptotic polarization degree: $P_g^T(\xi) = \dfrac{2(1-\xi)}{1+(1-\xi)^2}$ — up to $\sim 50\%$ for typical kinematics.

Validated at Tevatron $\sqrt{s} = 1.96$ TeV with forward jets ($y \in [1,3]$).

Tradition probes and Their limitations

- Based on TMD factorization: Cos 2phi in Di-jet production in ep, pp collisions



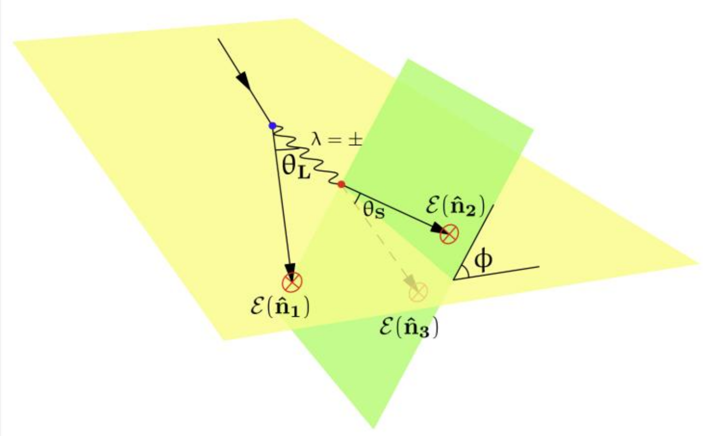


Hatta-Yuan-Xiao-ZJ, 2022

- ISR dilutes the asymmetry, FSR generate the same cos2phi asymmetries

- Three point energy correlations:

Chen, Moult, Zhu 2021:

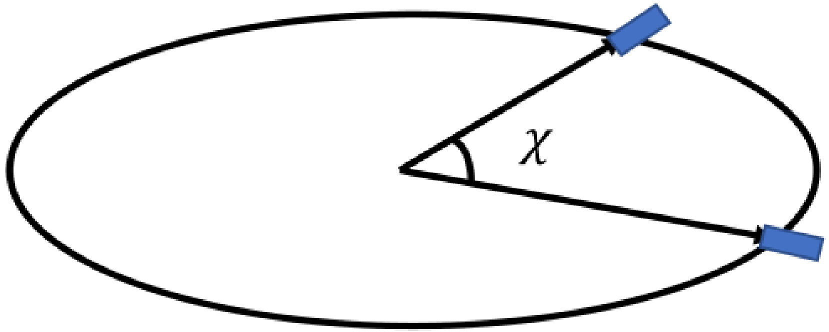


- Requiring complicate sub-jet structure analysis

Energy Correlators

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

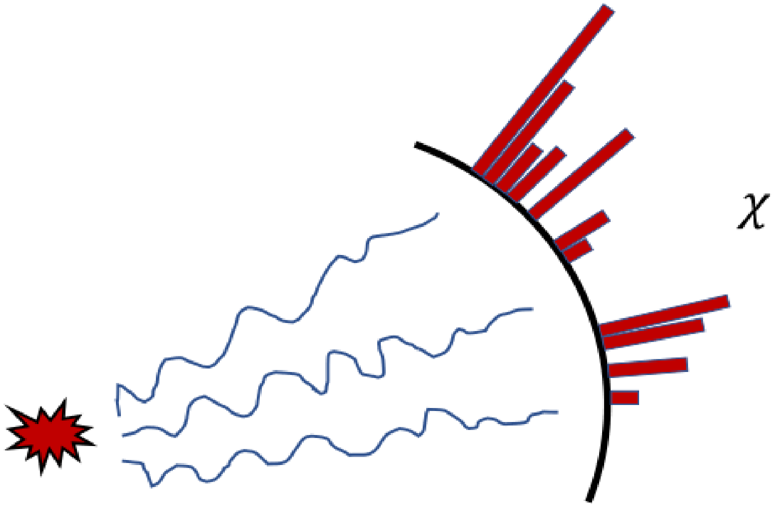
$$\mathrm{ENC}(\hat{n}) \sim \langle 0|J(x)\hat{\mathcal{E}}(\hat{n}_1)\cdots\hat{\mathcal{E}}(\hat{n}_k)J(0)|0\rangle$$



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

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

Sterman, 1975
Bashman, *et.al.* 1978

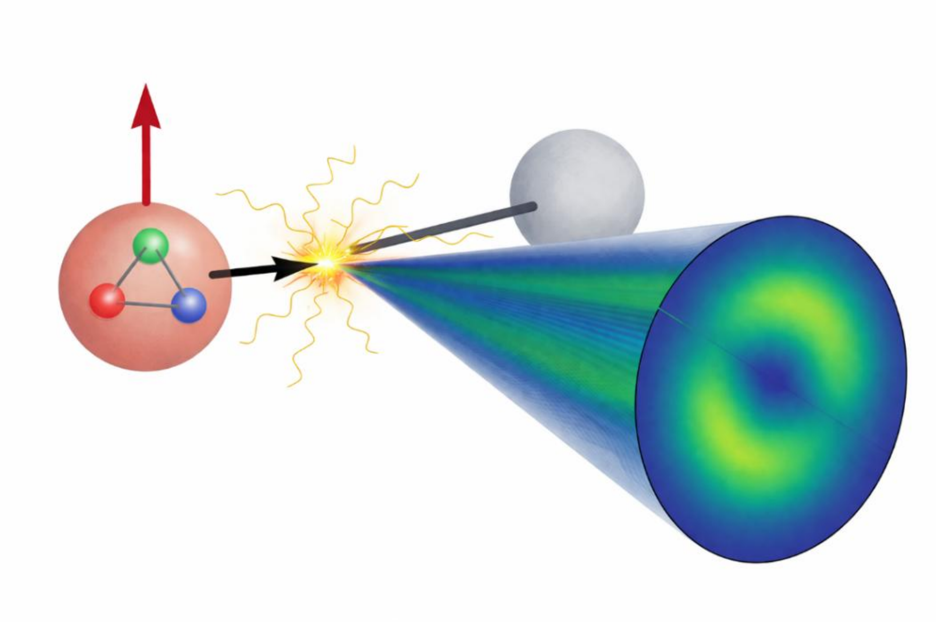


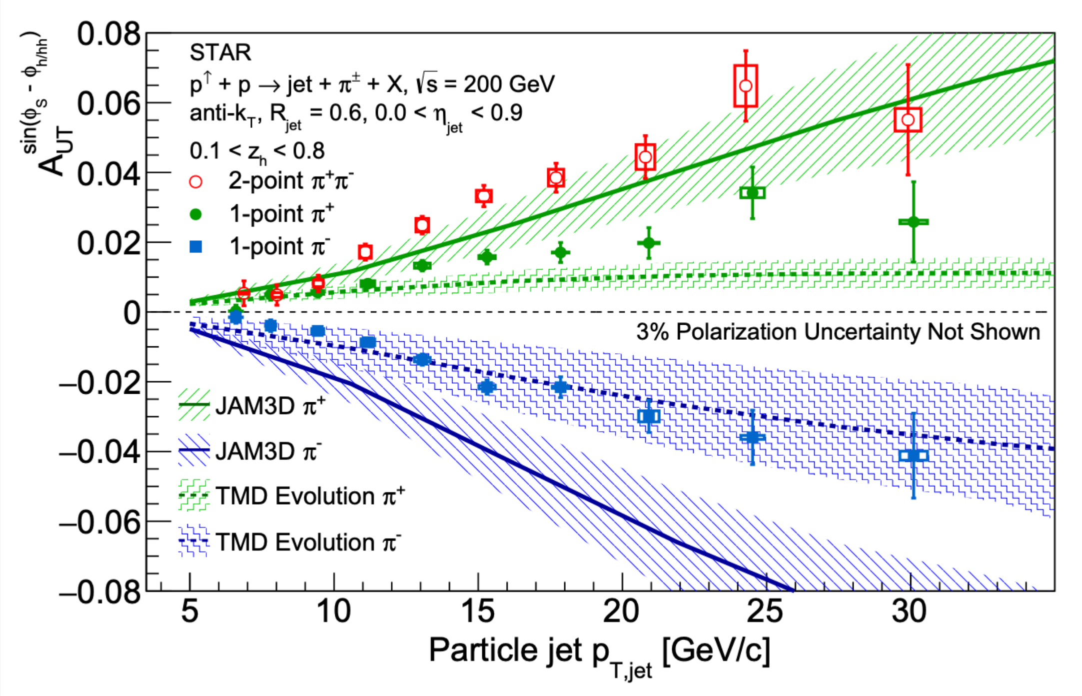
- Easy to implement and nature
- Energy weight suppresses the soft contamination
- Governed by DGLAP, not sensitive to soft gluon radiations
- Infrared-collinear safe, perturbatively

Sterman: "Energy flow became the focus of calculability"

From Xiaohui's slides

The application of EEC in spin physics





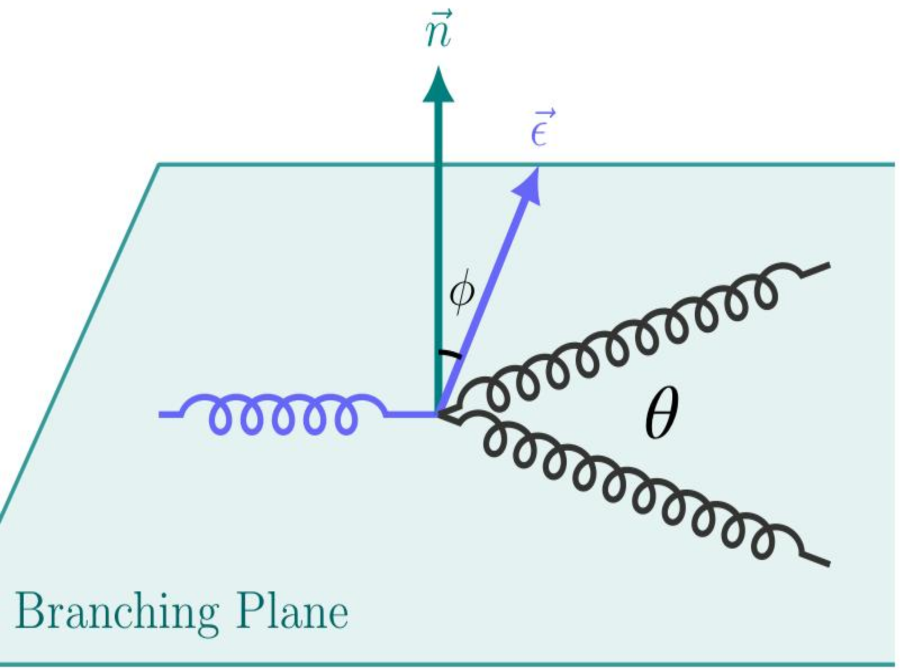
See, Zhongbo's talk

Gao, Kang, Li, Shao, PRL 136 (2026) 151902

- **Transversity distribution h_1^q is a fundamental, yet less known, parton distribution.**
- **Its chiral-odd nature prevents access via inclusive DIS**
- **Nucleon tensor charge δq is essential for BSM search, Lattice QCD benchmarks**
- **We introduce the one-point energy correlator (OPEC) to probe the nucleon transversity**

Branching of a Linearly Polarized Gluon

Anisotropic EEC becomes a novel probe of gluon linear polarization



Since the linear polarization of the parent gluon specifies a transverse direction, the parton branchings are no longer isotropic.

isotropic term

anisotropic term

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

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

EEC and Jet Functions : DGLAP formalism

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

Unpolarized Jet Function $J_i(\ln \kappa)$ follows the DGLAP evolution equation

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

Polarized Jet Function $J_{g,T}(\ln \kappa)$

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

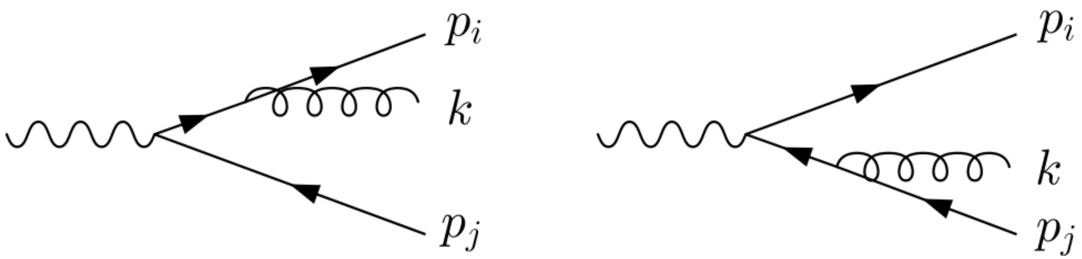
Diagonal Equation

Goes beyond the DGLAP formalism

Coherent Effect & Angular Ordering

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

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



CCFM evolution equation:

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

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

Evolution of the jet function

DGLAP

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

CCFM

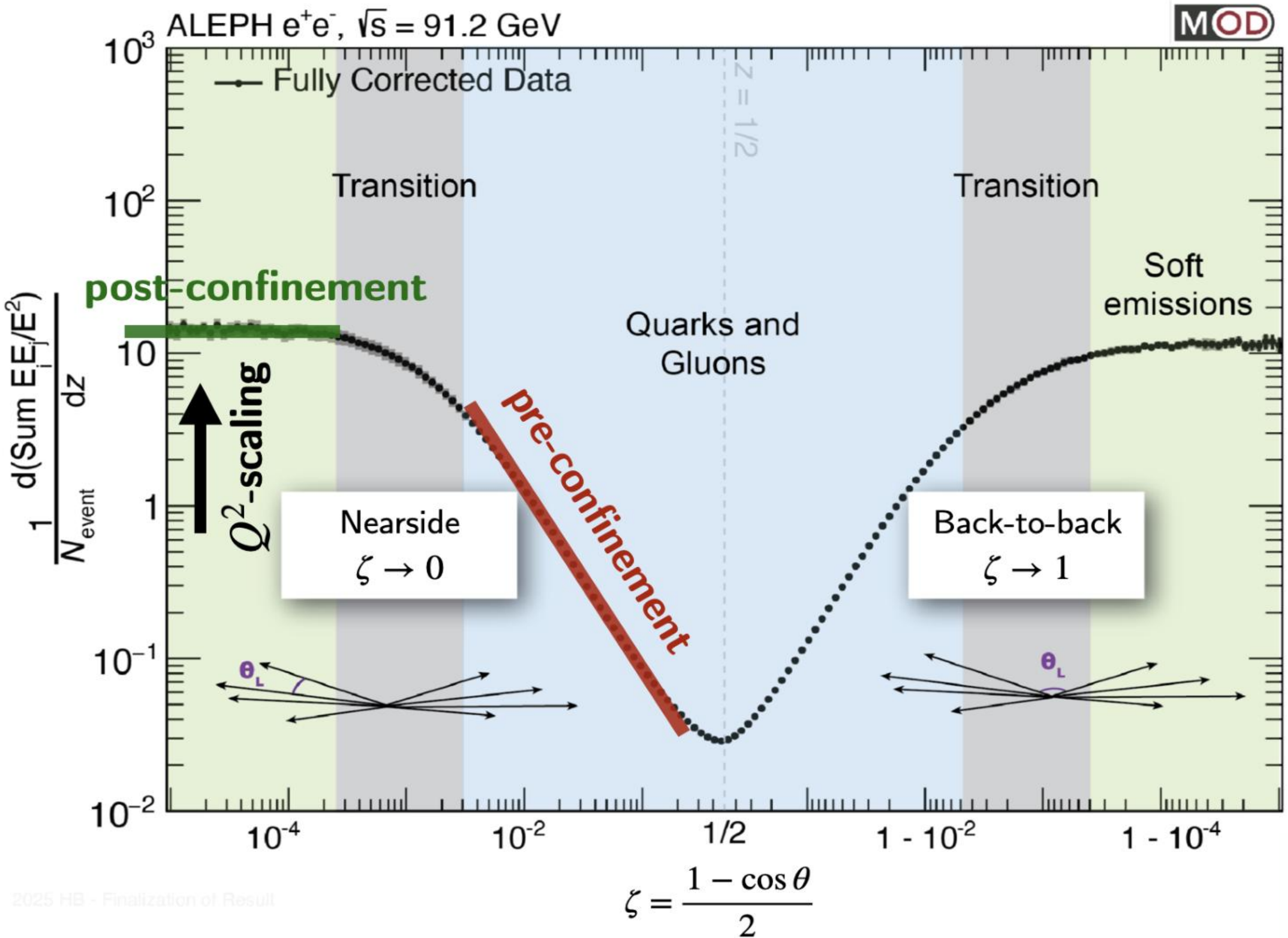
$$\frac{\partial}{\partial \ln\mu^2} \frac{J_g(\ln\kappa)}{\Delta_s(\mu^2)} = \frac{\alpha_s}{2\pi} \frac{1}{\Delta_s(\mu^2)} \int_{\Lambda/\mu}^{1-\Lambda/\mu} dy y^2 \left[\tilde{P}_{gg}(y) J_g(\ln\kappa) + \tilde{P}_{gq}(y) J_q(\ln\kappa)\right]$$

$\Lambda \sim 0.5$ GeV is an IR parameter, implementing the coherent AO

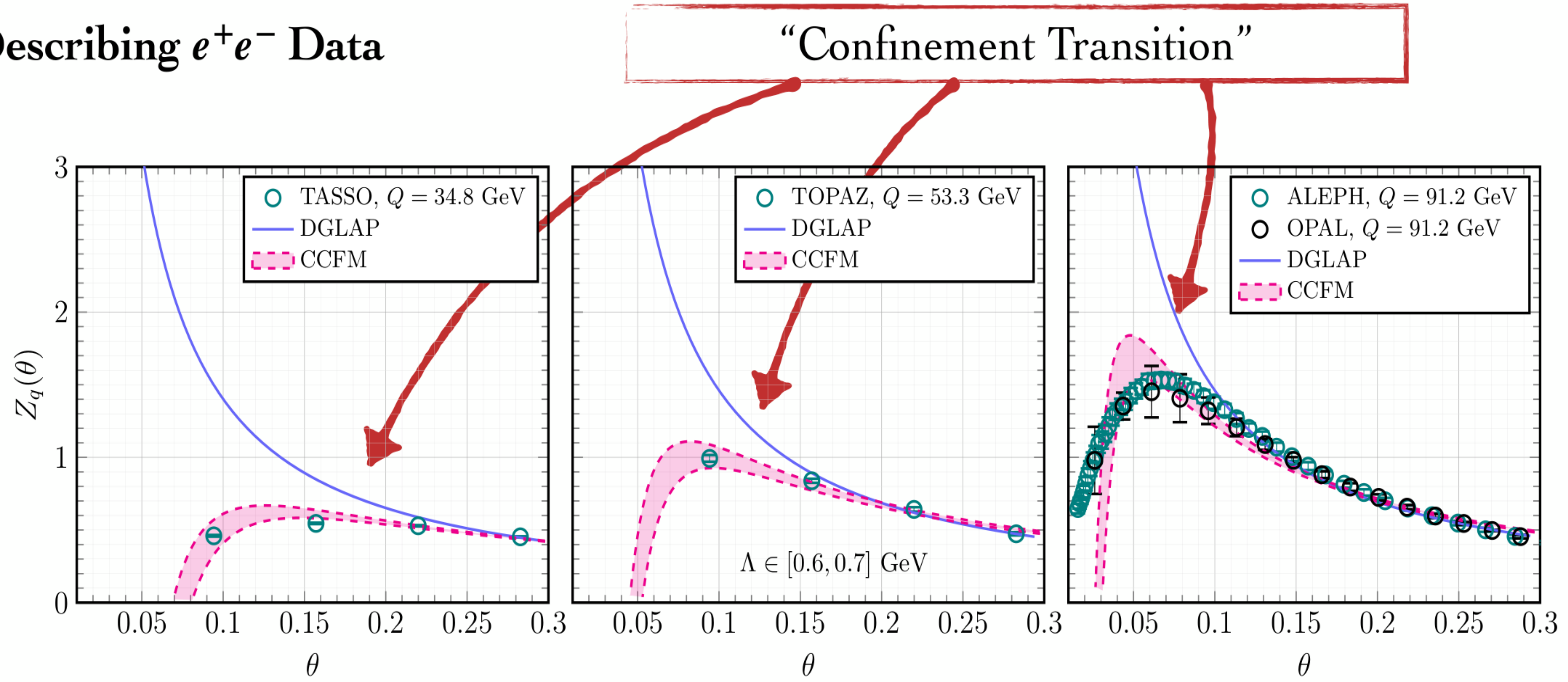
Post-confinement and pre-confinement

Describing e^+e^- Data

C.H. Chang, H. Chen, X. Liu,
D. Simmons-Duffin, F. Yuan,
H.X. Zhu, PRL136, 081903 (2026).



Describing e^+e^- Data



The unphysical increase is effectively tamed in the CCFM by incorporating coherence effects, alongside an IR cutoff

CCFM vs DGLAP: Detailed Comparison I — Formalism

Aspect	DGLAP	CCFM
Ordering variable	Virtuality $k_\perp^2/z(1-z)$	Angle $\theta = \mu/E$ (angular ordering)
Splitting functions	Regularized ($+$-prescription)	Unregularized, singular terms only
IR behavior $(\theta \to 0)$	Power-law divergence $\sim 1/\theta$	Finite plateau — regulated by Λ
Sudakov factor	Implicit in $+$-prescription	Explicit multiplicative $\Delta_s(\mu^2)$
y**-dependence in log**	$\ln(y^2\kappa)$ — y appears inside log	$\ln\kappa$ only — angular ordering eliminates y-dependence
Non-perturbative modeling	Needs external hadronization model	Λ cutoff mimics confinement scale naturally

Key takeaway: CCFM provides a unified description bridging perturbative and non-perturbative regimes without additional model dependence.

CCFM vs DGLAP: Detailed Comparison II — Phenomenology

Observable	DGLAP prediction	CCFM prediction
EEC shape at small θ	Unphysical rise $\propto 1/\theta$	Plateau, consistent with e^+e^- data
Confinement transition	Not captured; needs power corrections	Naturally captured via Λ cutoff
Energy dependence of plateau	Cannot predict	Plateau height grows with E_g — matches data trend
$\cos 2\phi$ **analyzing power**	Similar magnitude to CCFM at moderate θ	Robust to Λ variation; stable in ratio
Free parameters	$\alpha_s(M_Z)$ (1 param)	$\alpha_s(M_Z)$, Λ (2 params)

Note: The additional Λ parameter in CCFM is *physically motivated* (confinement scale) and can be fixed by fitting e^+e^- EEC data. It is not a free "tuning knob."

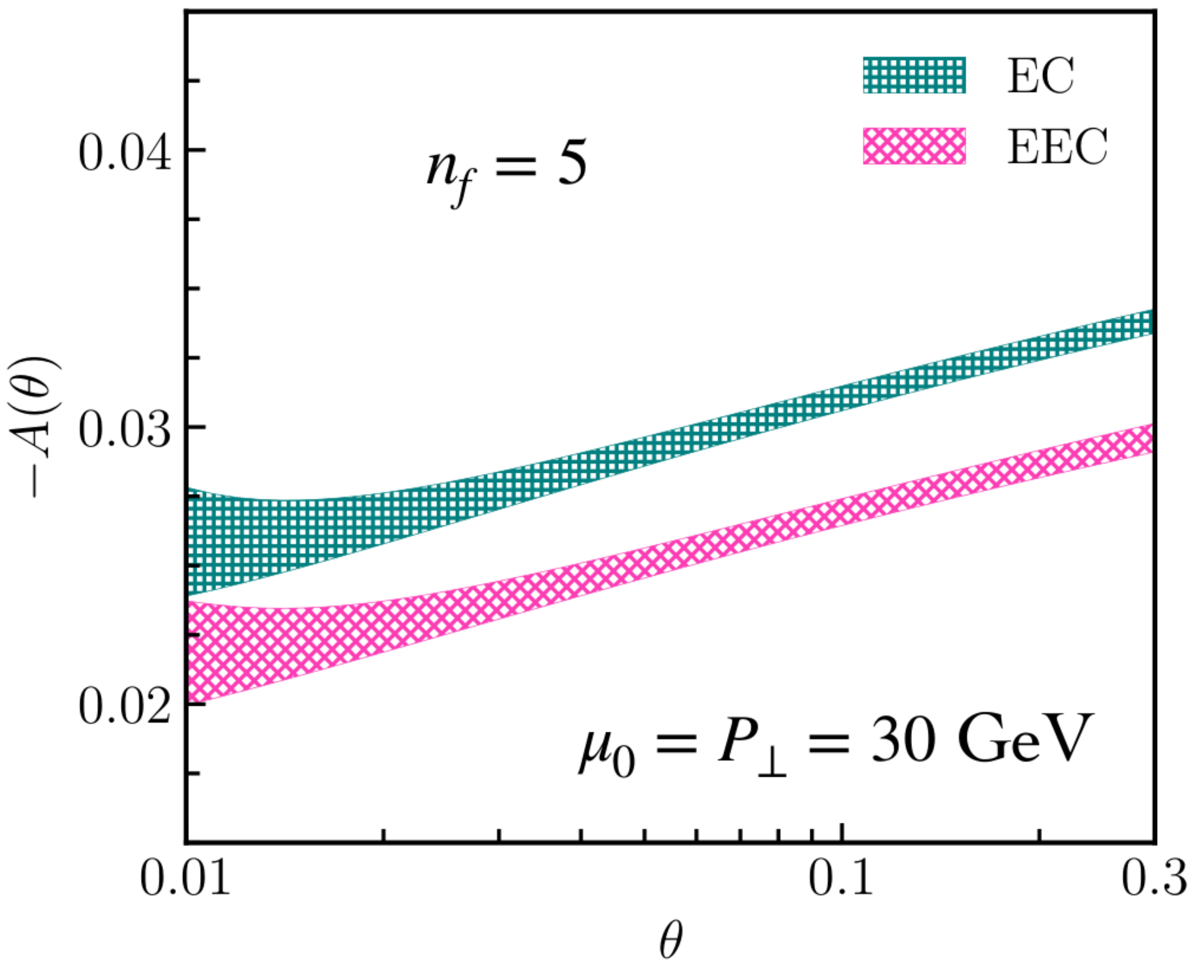
Analyzing Power $A(\theta)$

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

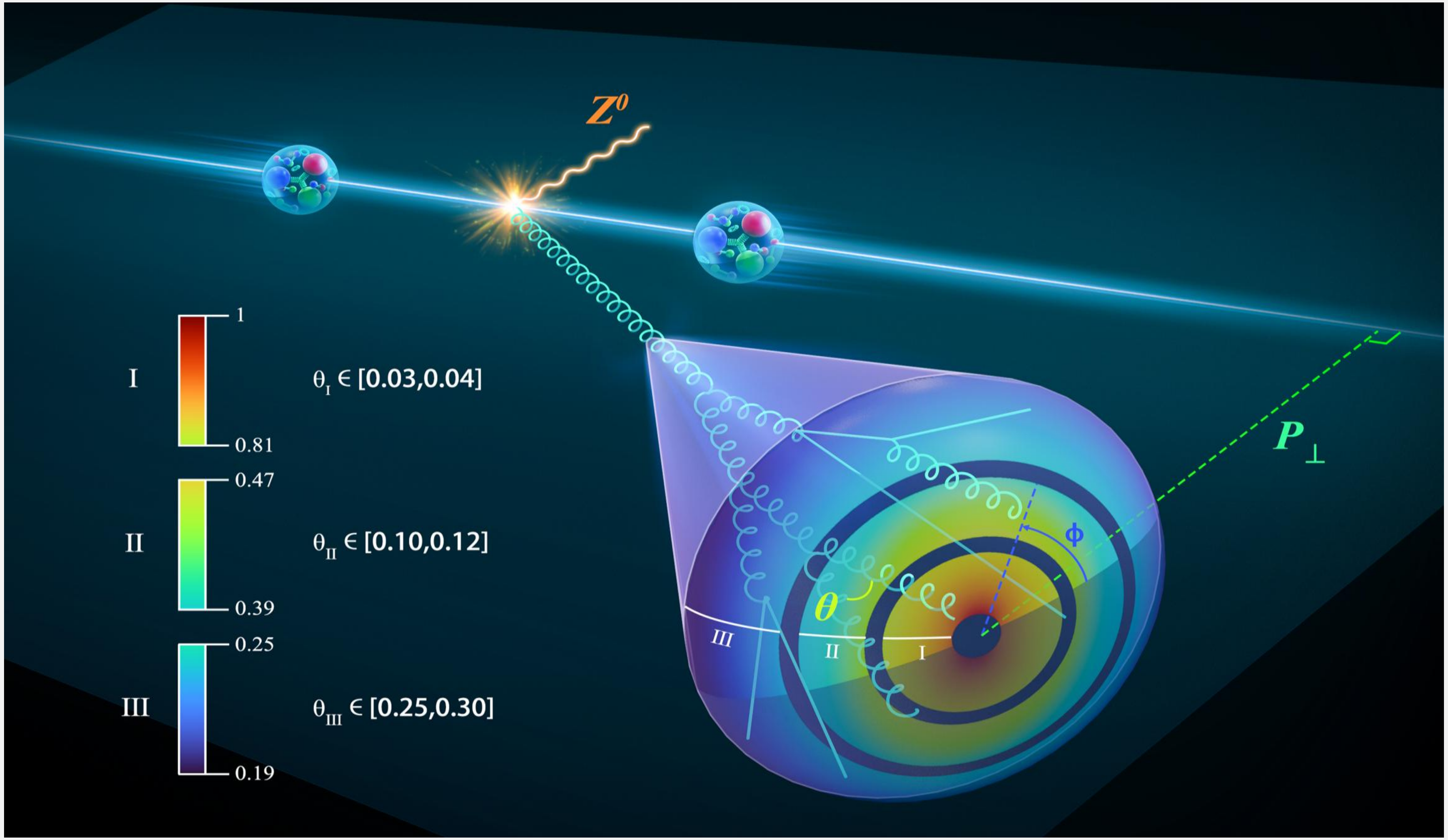
Partial cancellation between $g \to gg$ and $g \to q\bar{q}$ branchings

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

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



Z^0+gluon jet production at LHC



- The polarization vector of emitted gluon aligns with the P_\perp

Heavy-Flavor Tagging: Enhancing the Signal

The problem: Partial cancellation between $g \to gg$ and $g \to q\bar{q}$ channels dilutes the inclusive $\cos 2\phi$ asymmetry.

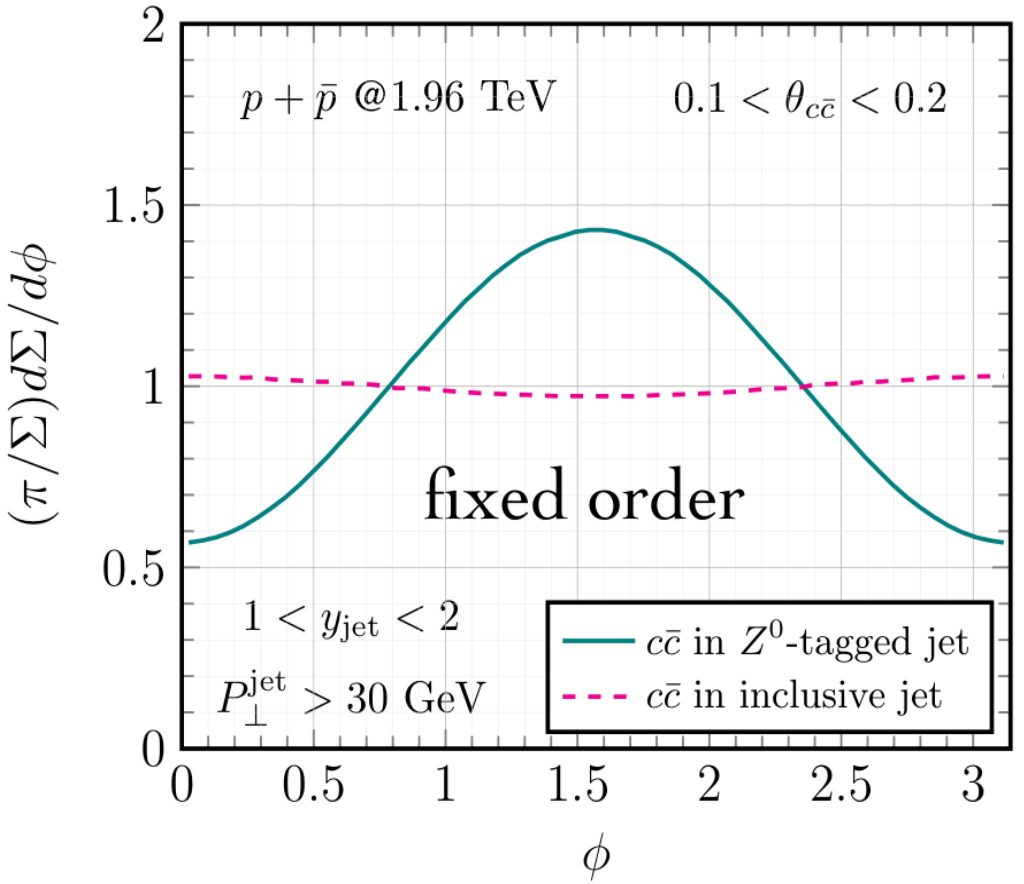
The solution: **Heavy-flavor tagging** isolates a single splitting channel.

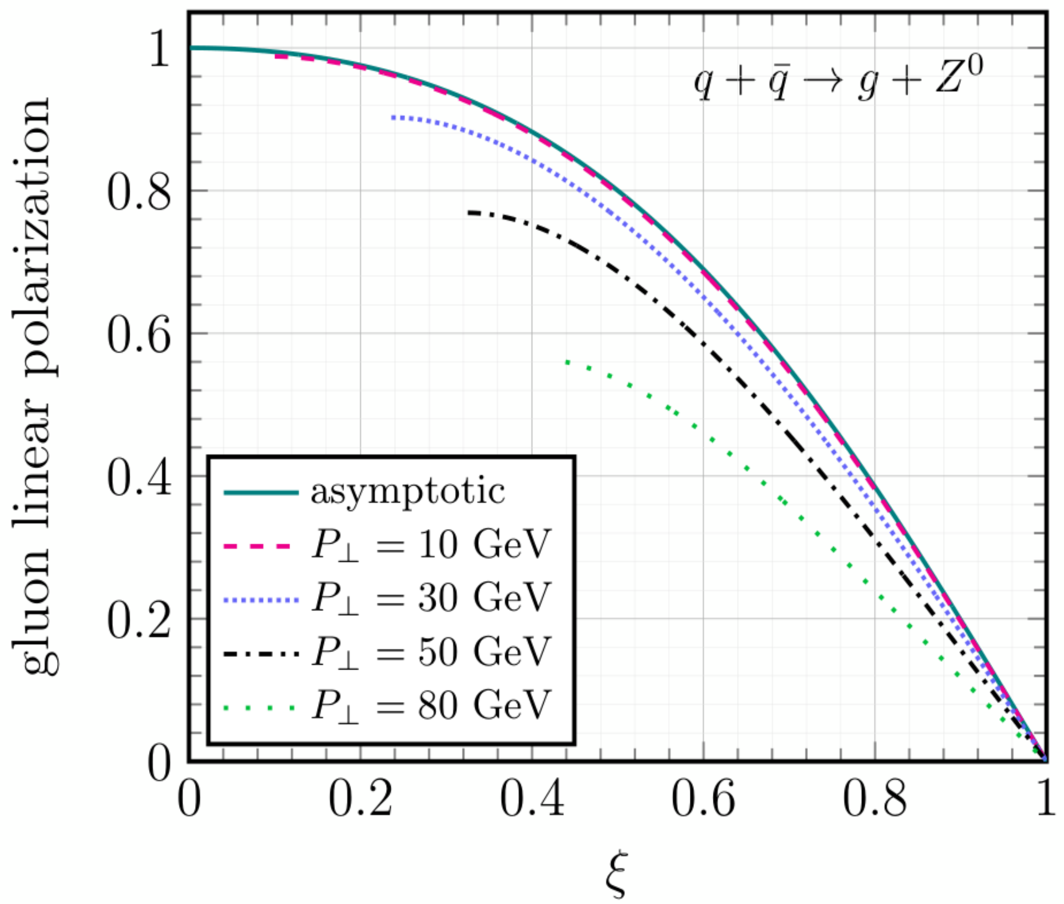
$g \to b\bar{b}$ or $g \to c\bar{c}$ tagging:

- Eliminates $g \to gg$ contribution entirely
- No cancellation — full polarization signal preserved
- CMS has demonstrated technique [CMS '25]
- First direct observation of spin correlations in gluon splittings

Theory status: Current resummation formalism is *massless*. Extension to massive quarks (charm, bottom) with track functions is future work. Fixed-order calculations already show dramatic enhancement.

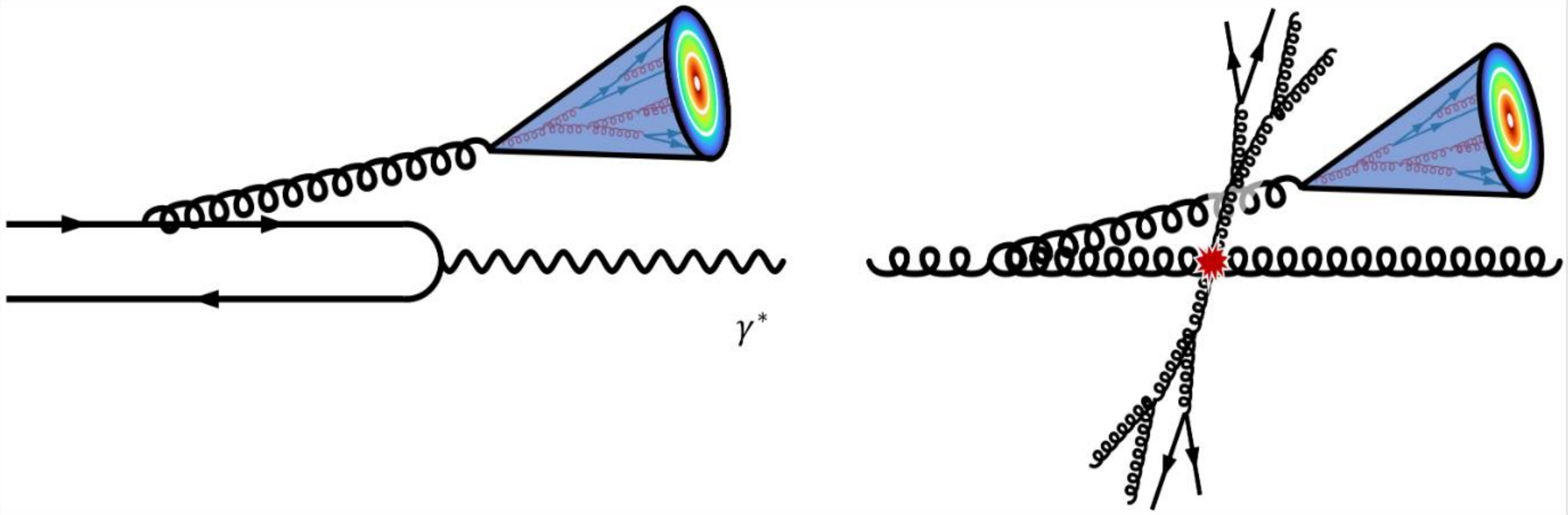
Realistic Configuration: $Z^0 + (g \to c\bar{c})$ production v.s. inclusive $(g \to c\bar{c})$ production





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

Extension to Other Hard Processes



DIS ($ep \to e' + \text{jet} + X$)

- Cleaner initial state than pp
- Photon Q^2 provides hard scale
- Forward jet tags ISR gluon
- Ideal for EIC

Mid-rapidity di-jet in pp

- Higher cross section than Z+jet
- Requires careful treatment of underlying event
- Can use γ+jet as control channel
- Accessible at LHC and RHIC

Conclusion

- Collinear gluons are automatically linearly polarized in high energy collisions.
- 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.

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