Spin Correlations

Shu-Yi Wei 魏树一 (Shandong University)
shuyi@sdu.edu.cn

H.C. Zhang, S.Y. Wei; PLB 839, 137821 (2023)
X.W. Li, Z.X. Chen, S. Cao, S.Y. Wei, PRD 109, 014035 (2024)
Z.X. Chen, H. Dong, S.Y. Wei, PRD 110, 056040 (2024)
L. Yang, Y.K. Song, S.Y. Wei, PRD 111, 054035 (2025)
F. Huang, T. Liu, Y.K. Song, S.Y. Wei, PLB 862, 139346 (2025)

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- Spin correlation of back-to-back dihadron
- Helicity correlation of neighboring dihadron
- Summary

Introduction

QCD factorization

partonic interaction, perturbative

Cross Section = short distance $\otimes$ long distance

non-perturbative, universal

Fragmentation Functions: quarks $(k, \lambda_q, \boldsymbol{S}_{T,q}) \to$ hadrons $(p = zk, \lambda_h, \boldsymbol{S}_{T,h})$

$$\mathscr{D}_q^h(z; \lambda_q, \lambda_h; \boldsymbol{S}_{Tq}, \boldsymbol{S}_{Th}) = D_{1,q}^h(z) + \lambda_q \lambda_h G_{1L,q}^h(z) + \boldsymbol{S}_{T,q} \cdot \boldsymbol{S}_{T,h} H_{1T}(z)$$

$$\mathscr{D}_g^h(z; \lambda_g, \lambda_h; \boldsymbol{S}_{Th}) = D_{1,g}^h(z) + \lambda_g \lambda_h G_{1L,g}^h(z)$$

QCD dominant process: Parity Symmetry.

QCD factorization

Baryons

Quarks	Unpolarized	L	T
Unpolarized	D_1		
L		G_{1L}	
T			H_{1T}

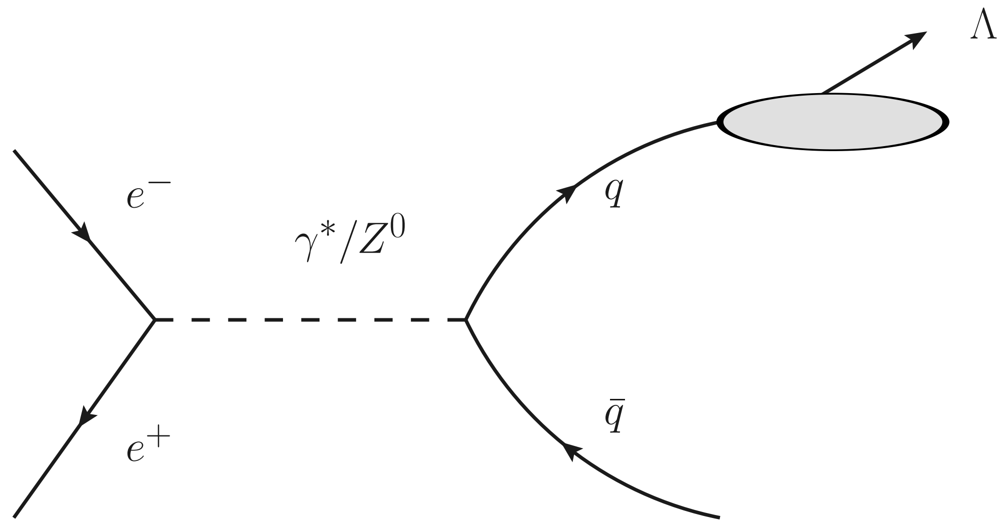
quark only

polarized beams or weak interaction

☑ **G_{1L}, aka, the longitudinal spin transfer**

Number density of longitudinally polarized hadrons produced from longitudinally polarized quarks.

Single Inclusive Λ Production in e⁺e⁻ Annihilation Experiment



Final state quarks gain polarization through weak interaction

spin transfer

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

quark polarization

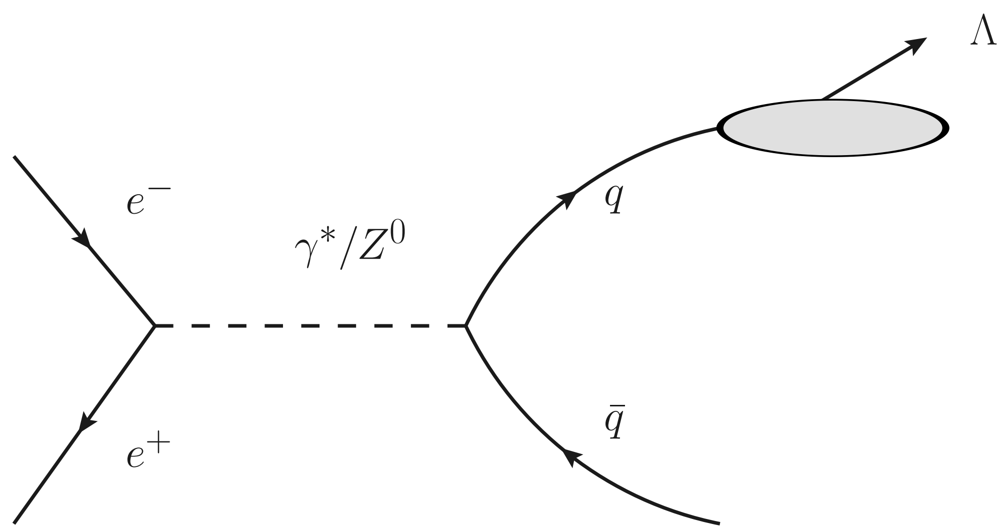
γ^* Z^0

$$\frac{d\sigma}{dPS} = \sigma_0 \left[D_{1q}^{\Lambda}(z) + \lambda_q \lambda_\Lambda G_{1Lq}^{\Lambda}(z) \right]$$

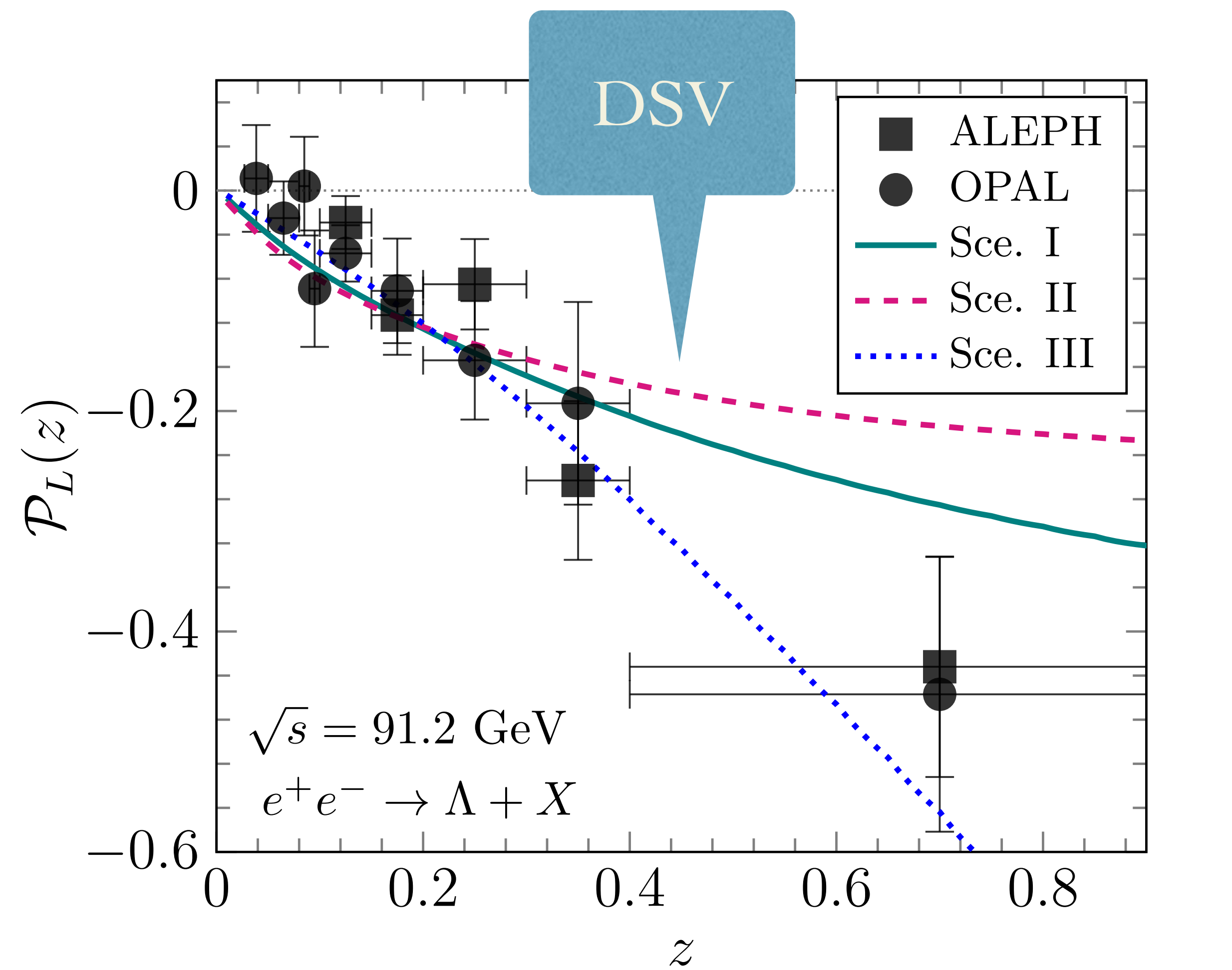
Belle Energy

LEP Energy

Single Inclusive Λ Production in e⁺e⁻ Annihilation Experiment



Final state quarks gain polarization through weak interaction



spin transfer

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

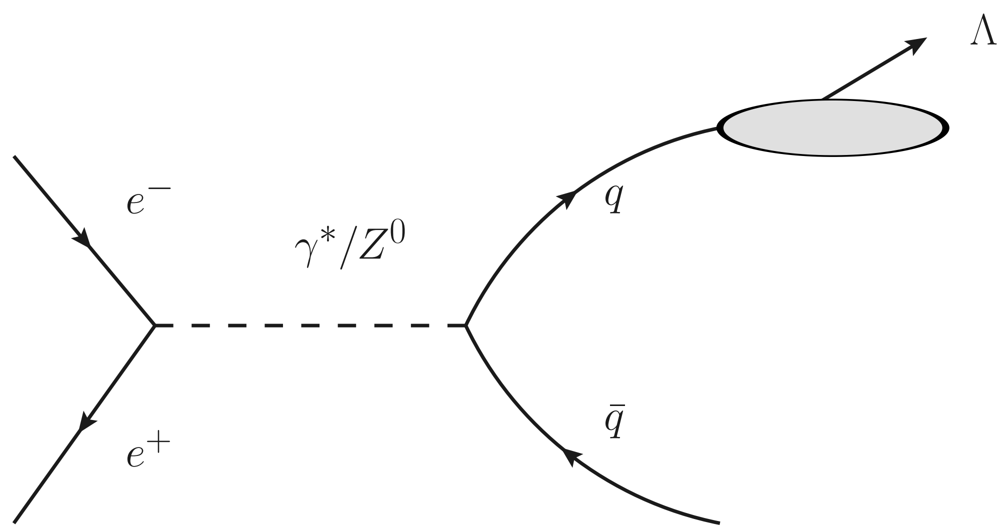
quark polarization

DSV: Phys.Rev.D 57 (1998) 5811

See also: Chen, Yang, Liang, Zhou, PRD 95, 034009 (2017)

Introduction

Single Inclusive Λ Production in e⁺e⁻ Annihilation Experiment



Final state quarks gain polarization through weak interaction

γ^* Z^0

$$\frac{d\sigma}{dPS} = \sigma_0 \left[D_{1q}^{\Lambda}(z) + \lambda_q \lambda_\Lambda G_{1Lq}^{\Lambda}(z) \right]$$

Belle Energy

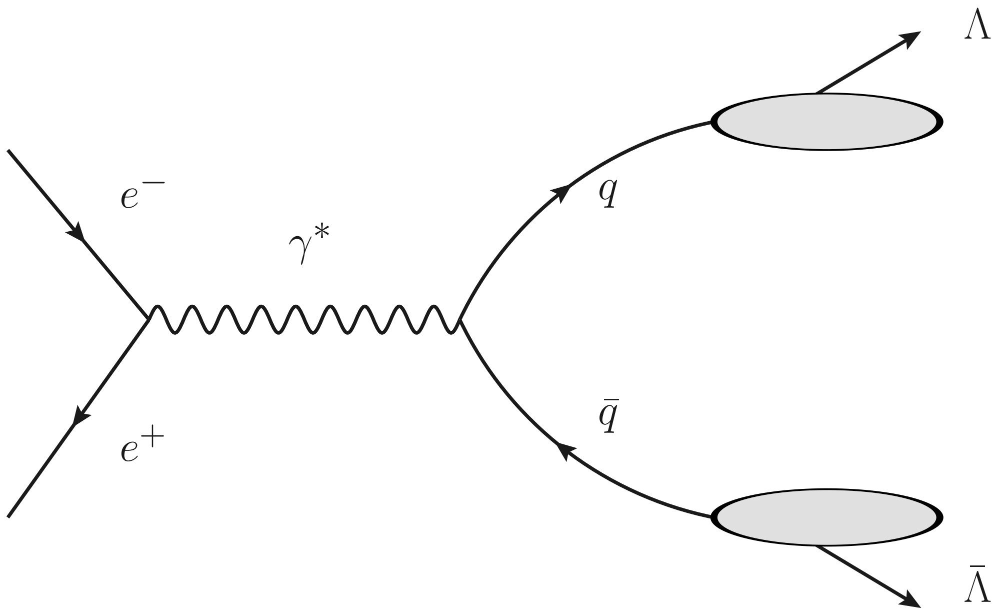
LEP Energy

spin transfer

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

quark polarization

$\Lambda\bar{\Lambda}$-pair Production in e+e- Annihilation Experiment



Belle Energy

$$\frac{d\sigma}{dPS} = \sigma_0 \left[D_{1q}^{\Lambda}(z_1) D_{1\bar{q}}^{\bar{\Lambda}}(z_2) - \lambda_\Lambda \lambda_{\bar{\Lambda}} G_{1Lq}^{\Lambda}(z_1) G_{1L\bar{q}}^{\bar{\Lambda}}(z_2) \right]$$

☑ **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-dependent fragmentation functions

☑ **Entangled states**

$$\frac{1}{\sqrt{2}} |A^\uparrow B^\downarrow \pm A^\downarrow B^\uparrow\rangle$$

$$\frac{1}{\sqrt{2}} |A^\uparrow B^\uparrow \pm A^\downarrow B^\downarrow\rangle$$

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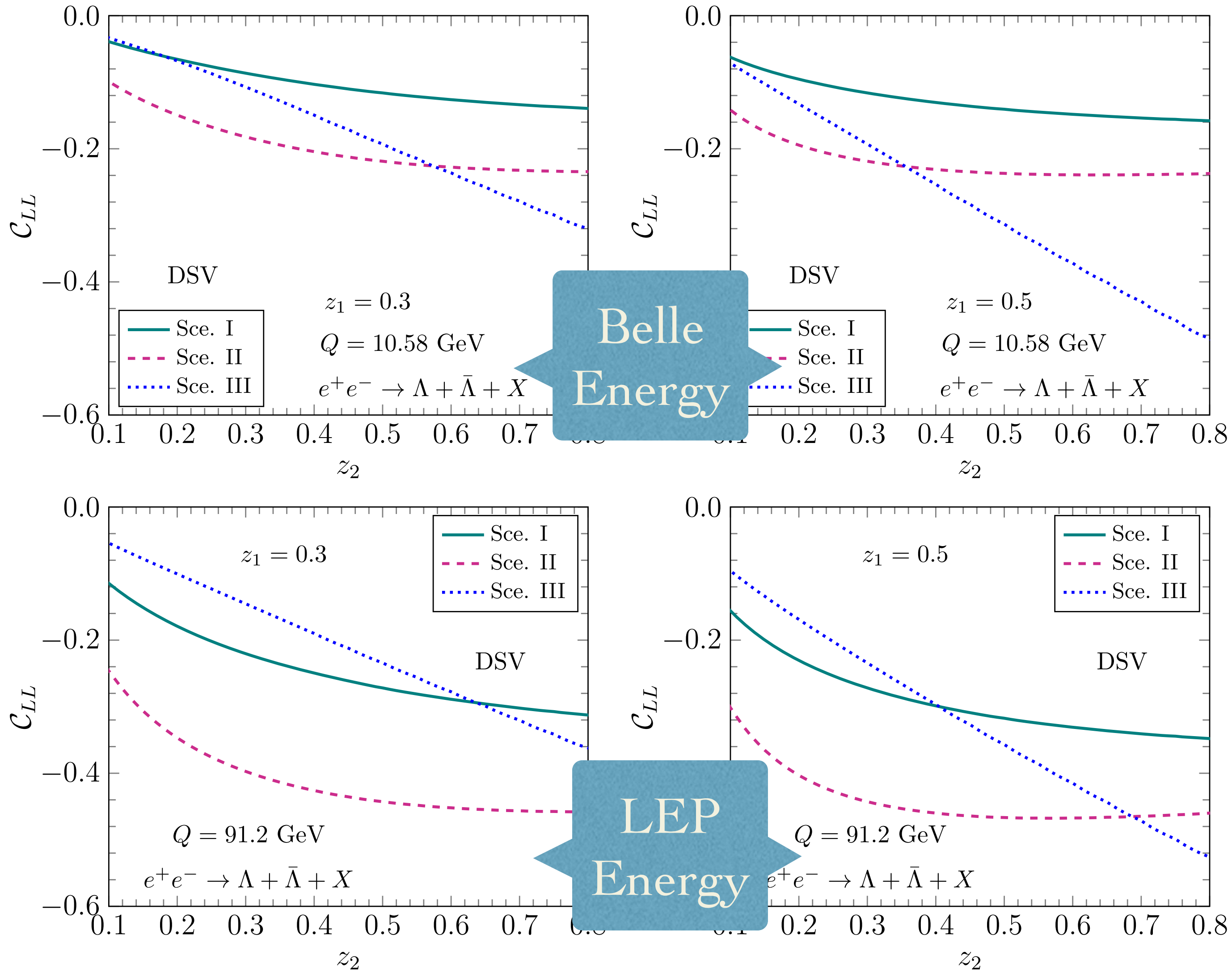
see also Nucl. Phys. B 445 (1995) 380.

Helicity Correlation of $\Lambda\bar{\Lambda}$-pair

$$C_{LL} = \frac{\text{same signs} - \text{opposite signs}}{\text{total cross section}} = -\frac{\sum_q \sigma_0 G_{1Lq}^{\Lambda}(z_1) G_{1L\bar{q}}^{\bar{\Lambda}}(z_2)}{\sum_q \sigma_0 D_{1q}^{\Lambda}(z_1) D_{1\bar{q}}^{\bar{\Lambda}}(z_2)} \propto \langle \cos\theta_1^* \cos\theta_2^* \rangle$$



- ☑ The helicity correlation at the Belle energy has a similar magnitude with that at the LEP energy.
- ☑ It is now possible to extract the longitudinal spin transfer at Belle experiment.

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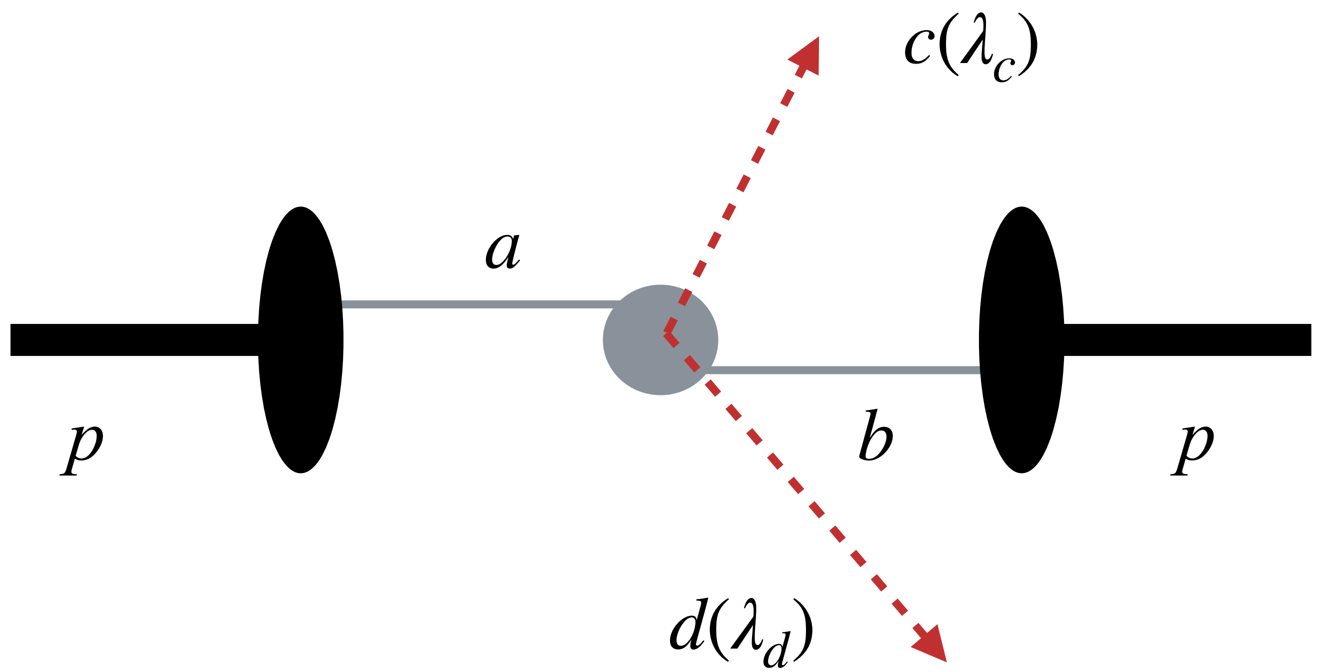
Applying to the unpolarized pp collisions

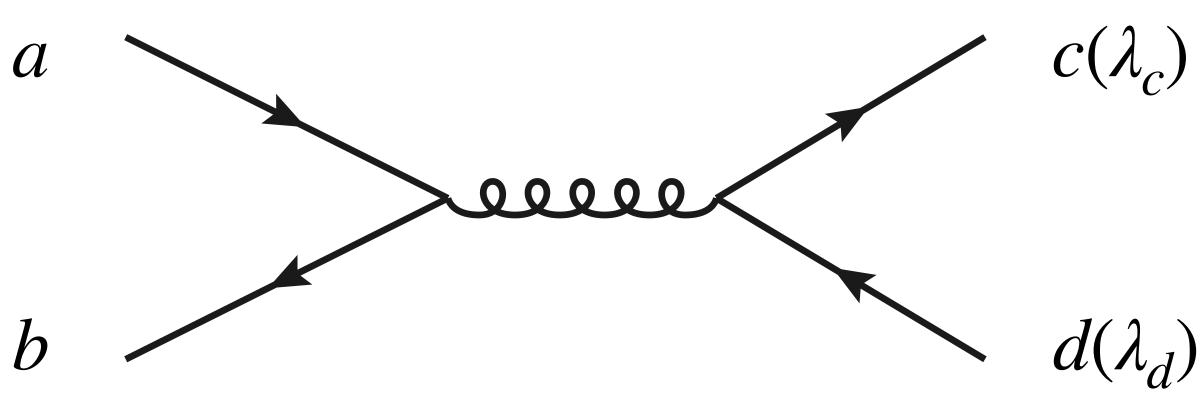


$$a + b \to c(\lambda_c) + d(\lambda_d)$$

☑ **Are λ_c and λ_d correlated?**

Yes!

"s-channel diagrams": just like e^+e^- annihilation, maximum correlation



$$g + g \to q + \bar{q}$$

$$q_i + \bar{q}_i \to q_j + \bar{q}_j$$

$$q + \bar{q} \to g + g$$

negative correlation

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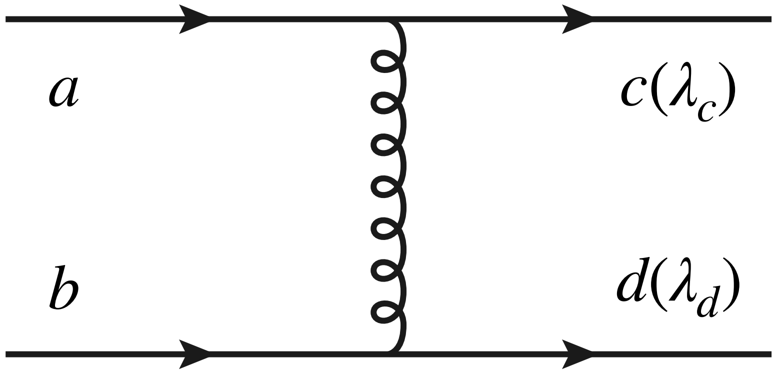
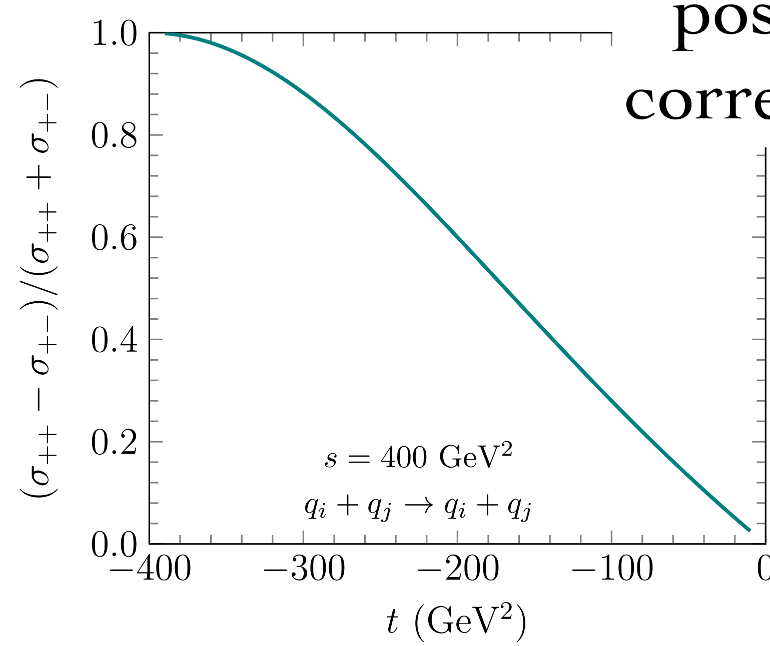
Helicity correlation of B2B dihadron

"t-channel diagrams": prefer same-sign correlation



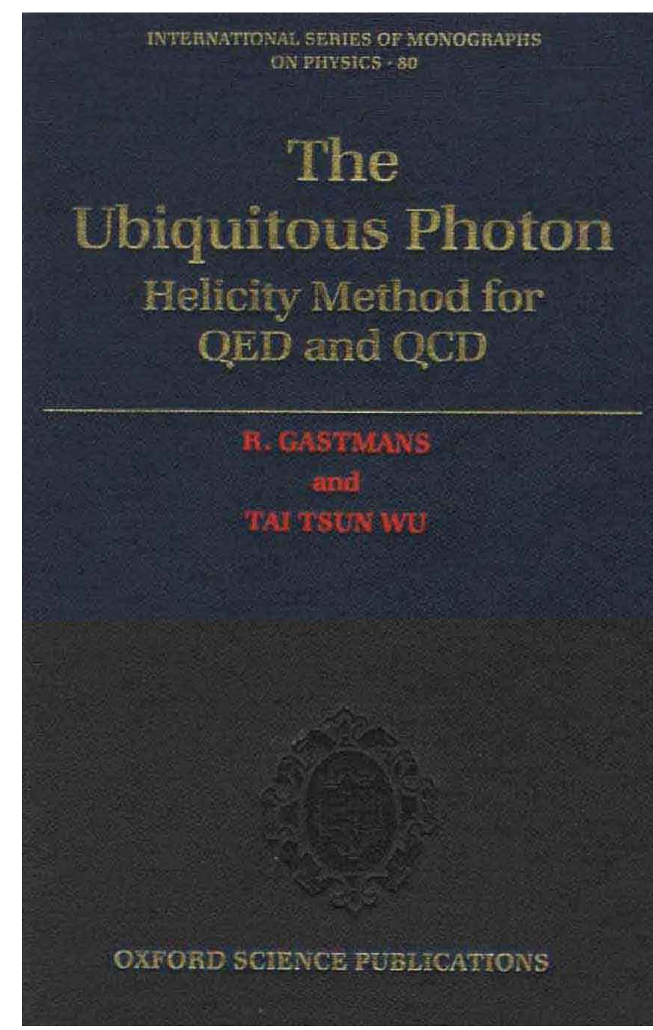


positive correlation

$$q + g \to q + g$$
$$q_i + q_j \to q_i + q_j$$
$$g + g \to g + g$$
$$q_i + q_i \to q_i + q_i$$
$$q_i + \bar{q}_i \to q_i + \bar{q}_i$$

To summarize

- "s-channel": $\sigma_{+-} = \sigma_{-+} > \sigma_{++} = \sigma_{--} = 0$
- "t-channel": $\sigma_{++} = \sigma_{--} > \sigma_{+-} = \sigma_{-+} > 0$
- Probe polarized FF in unpolarized pp collisions
- Explore the circularly polarized gluon FF



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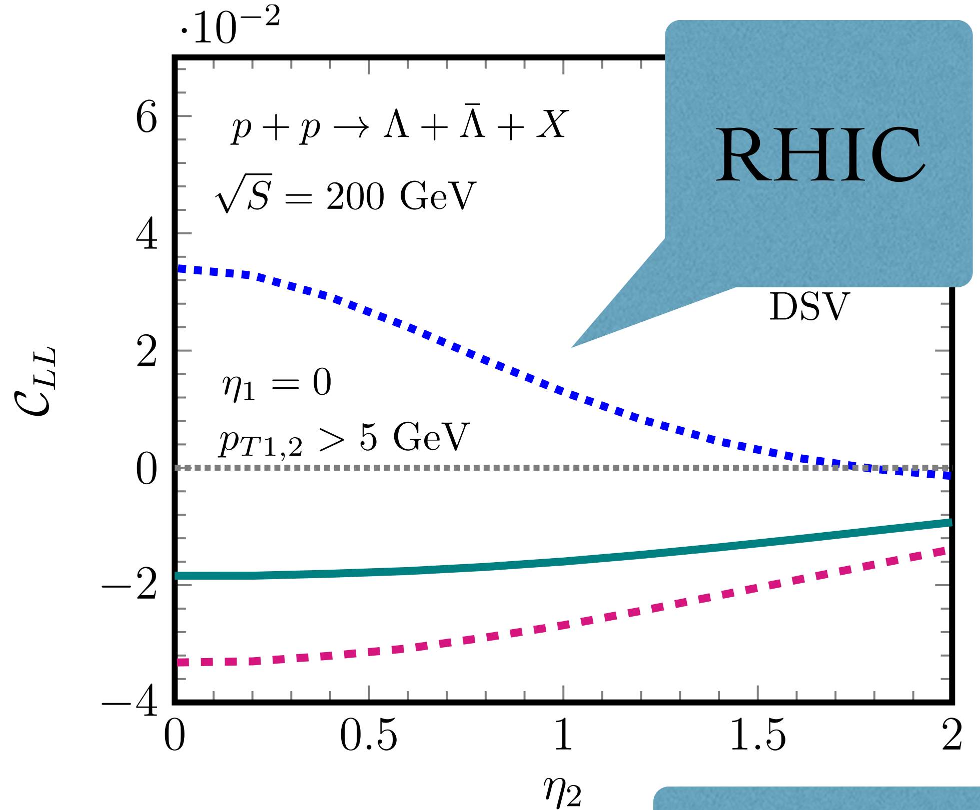
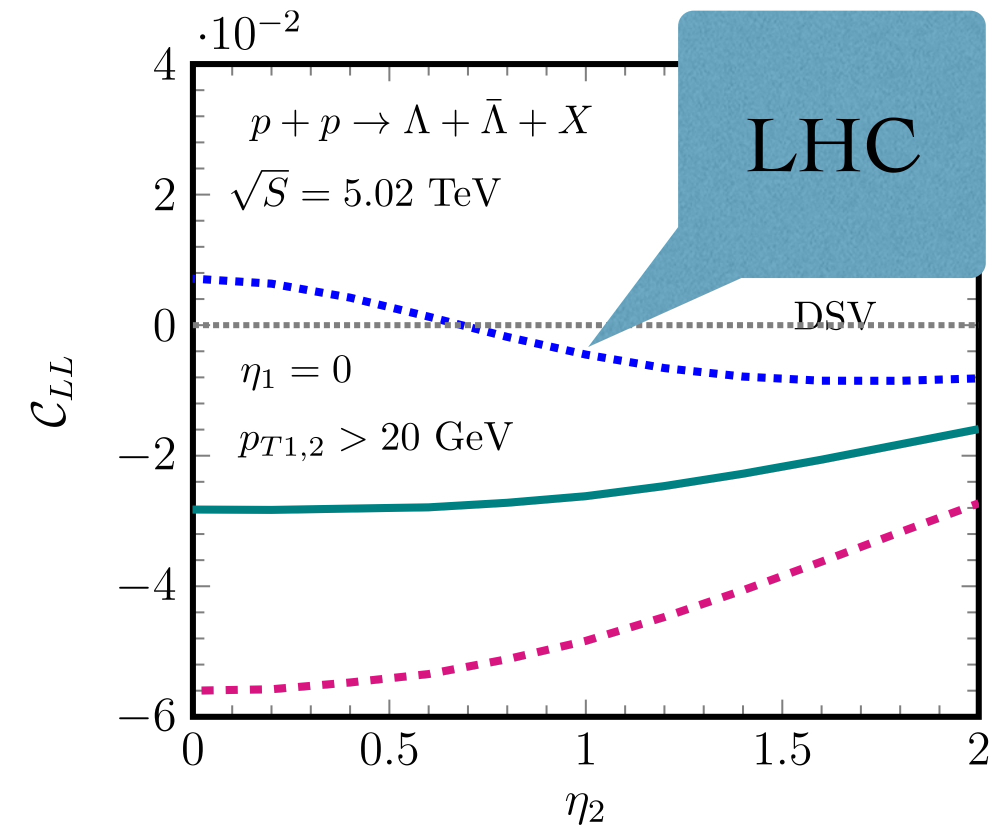
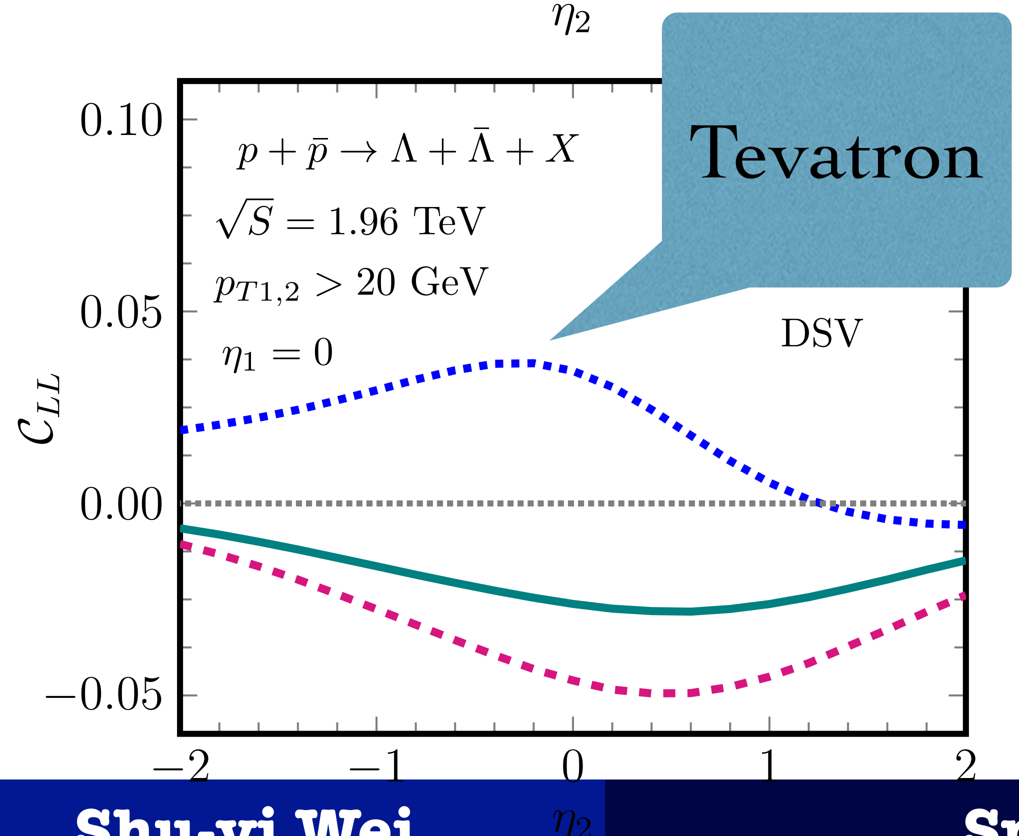
Helicity correlation of B2B dihadron

Polarization Correlation in unpolarized pp collisions







- ☑ Smaller, but none-zero
- ☑ Distinguish different scenarios
- ☑ Avoid contamination of polarized PDF
- ☑ Probe gluon spin transfer

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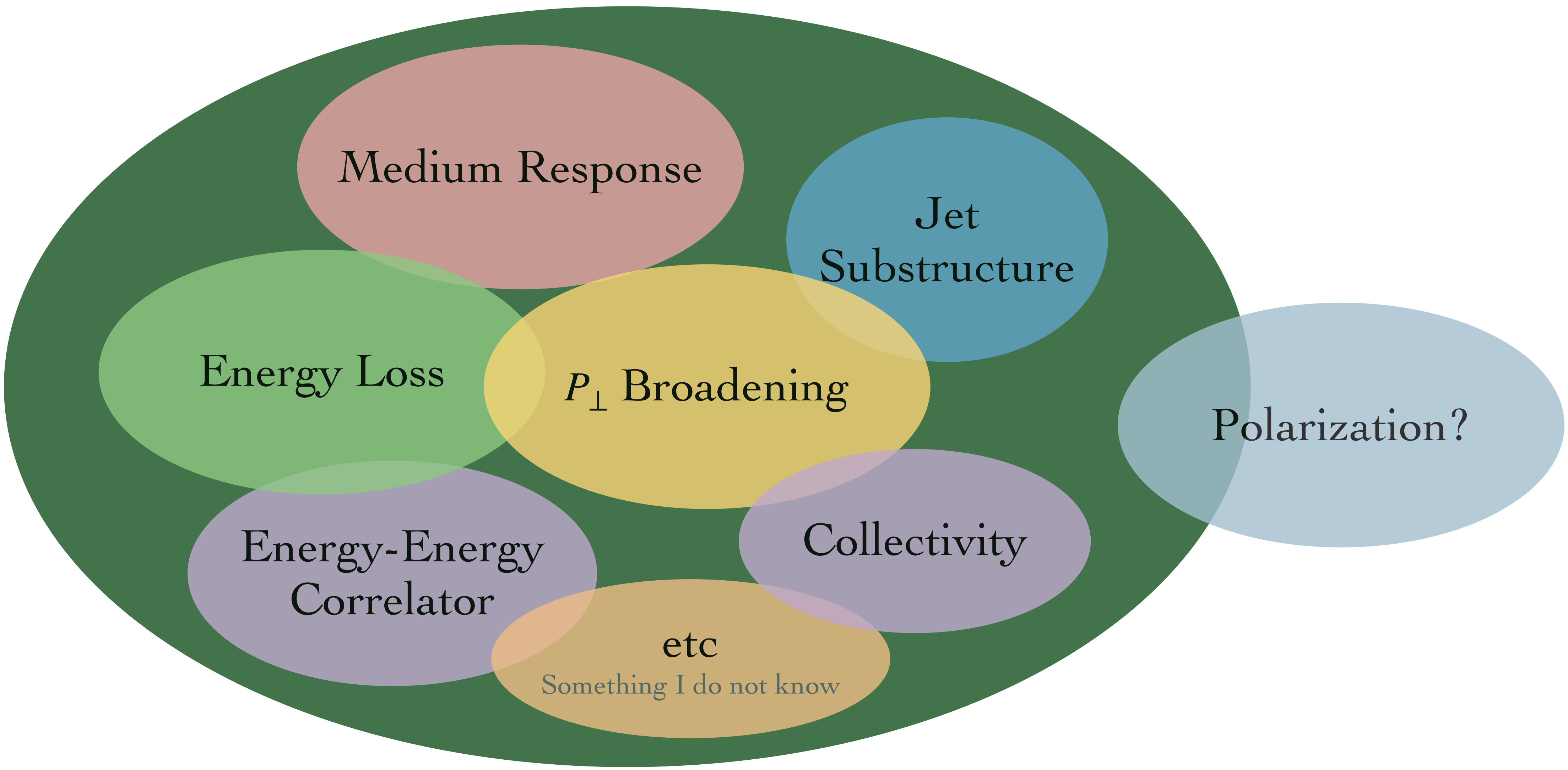
Keywords of Jet Quenching



Helicity correlation of B2B dihadron

Helicity Correlation in central and peripheral AA collisions

$$\text{A toy model: } \left.\frac{d\sigma}{d\text{PS}}\right|_{AA} = \text{Energy Loss} \otimes \left.\frac{d\sigma}{d\text{PS}}\right|_{pp}$$

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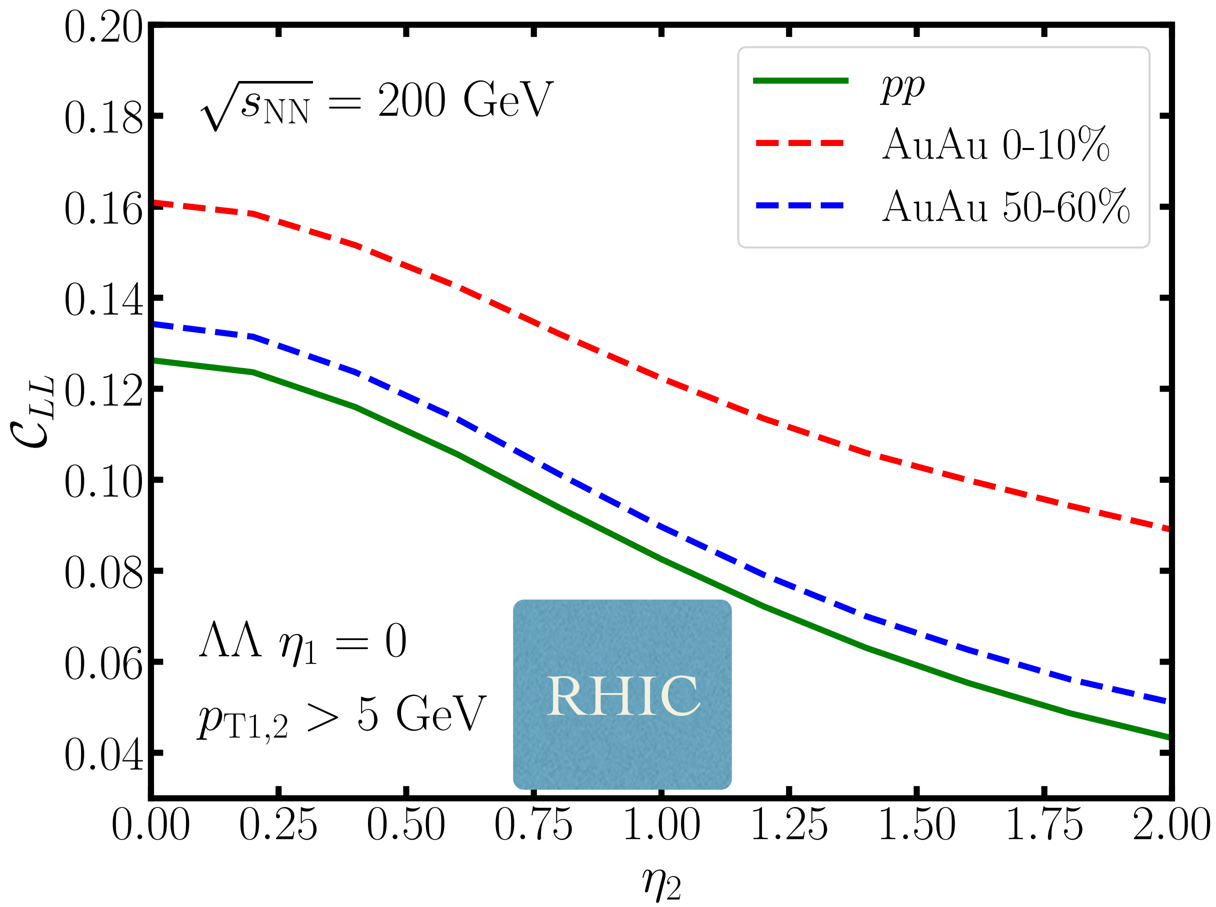
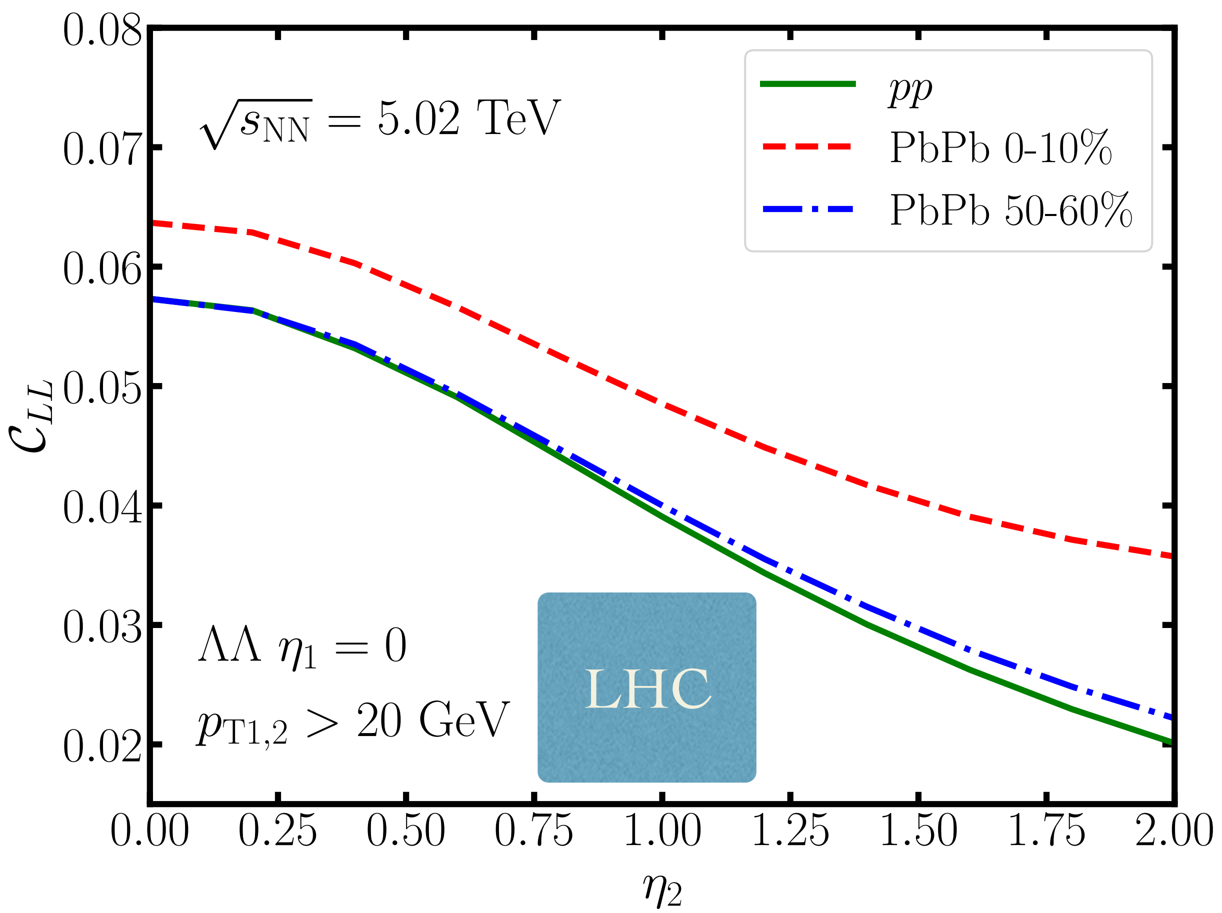


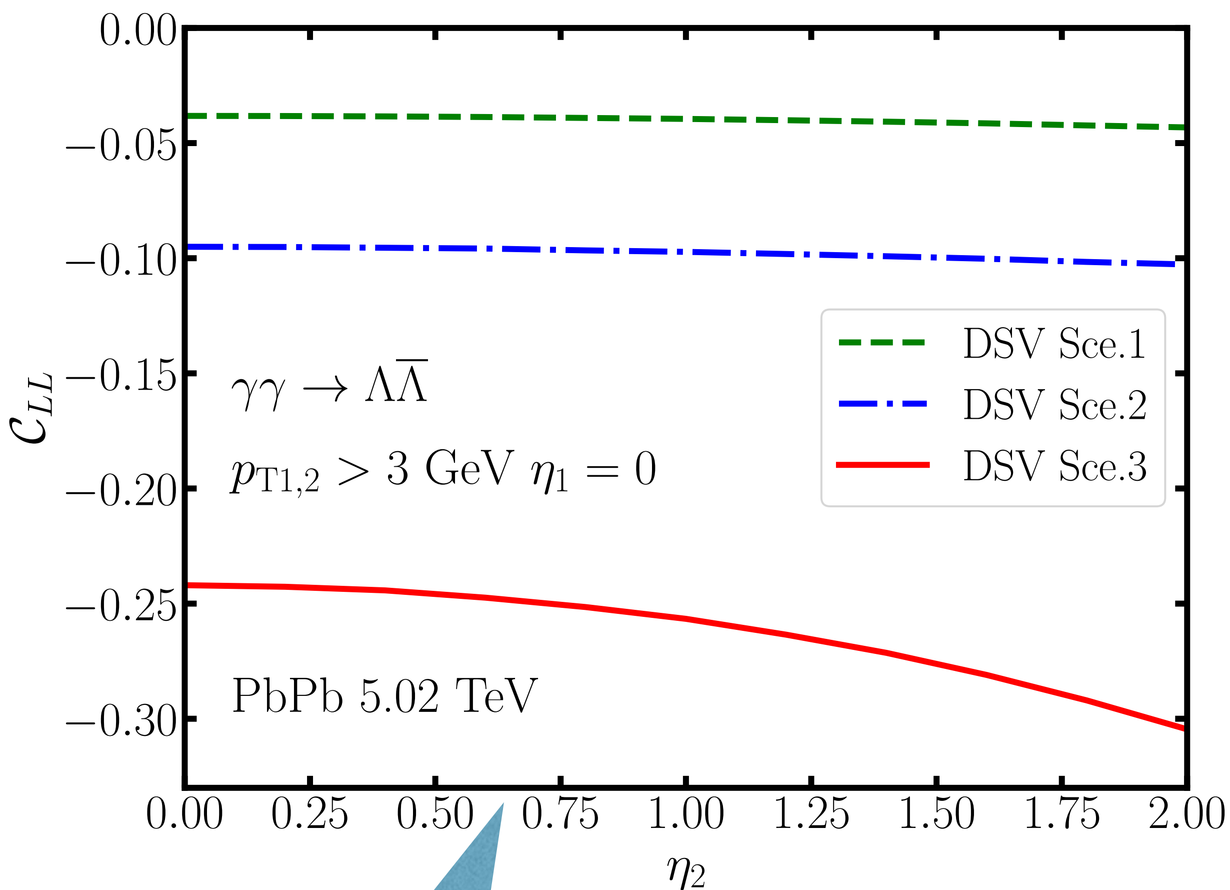
Clear Enhancement in central AA collisions

- ☑ Much larger luminosity
- ☑ Jet Quenching + Polarization



Helicity correlation of B2B dihadron

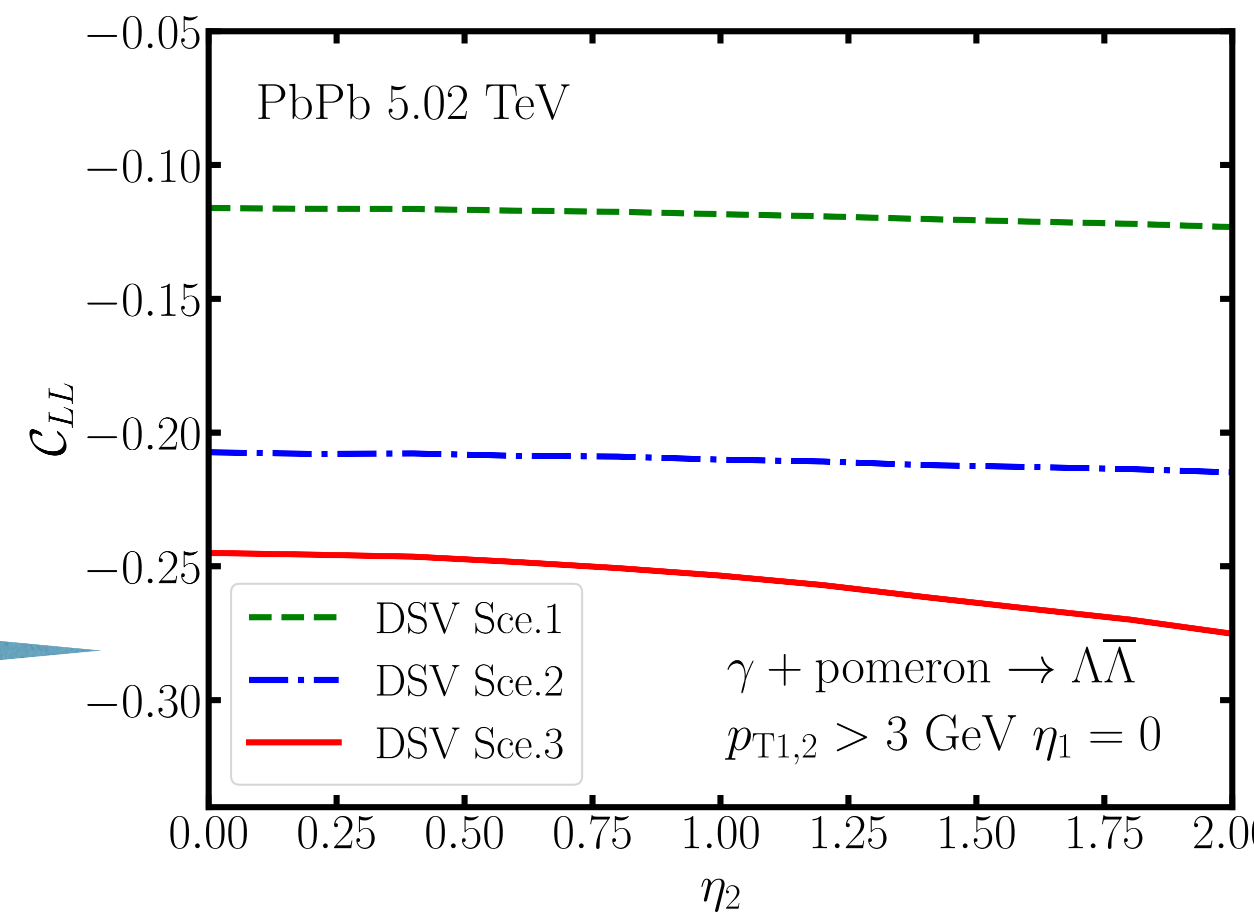
Helicity Correlation in ultra-peripheral AA collisions



$\gamma + \gamma$

- ☑ Much larger luminosity
- ☑ Pomeron + Polarization

$\gamma + \mathbb{P}$



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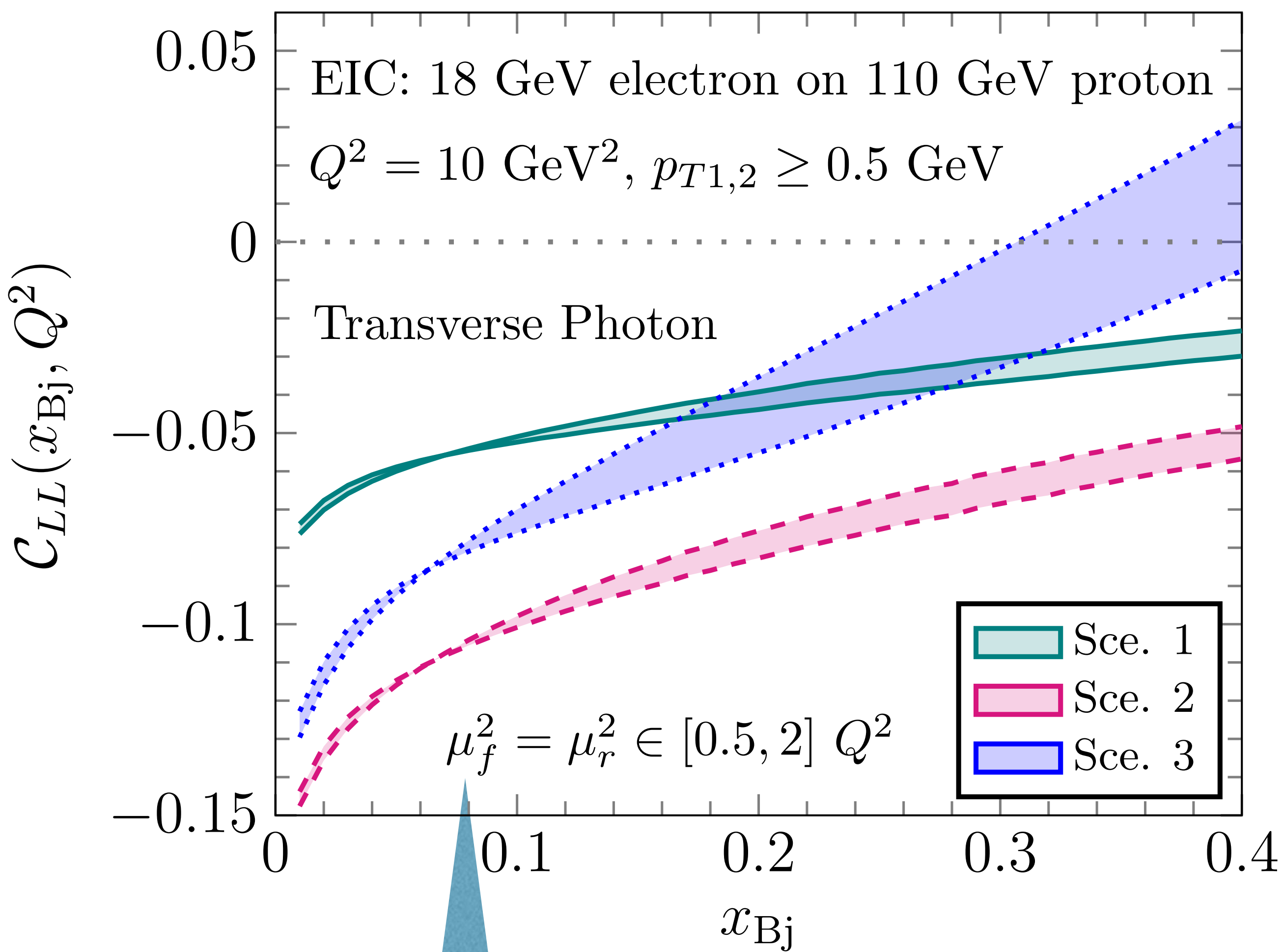
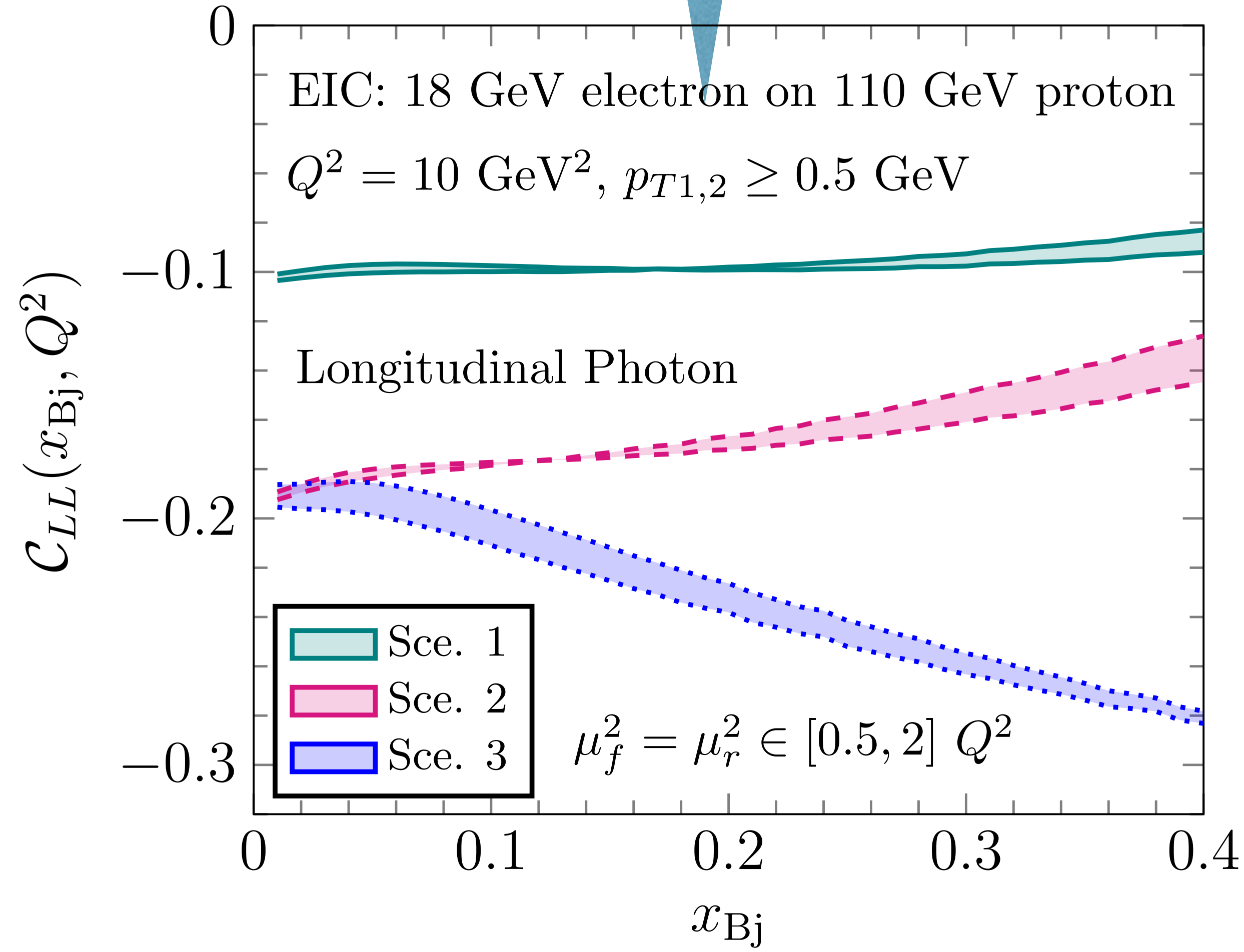
Helicity correlation of B2B dihadron

Helicity Correlation at future EIC



Transverse photon

Longitudinal photon



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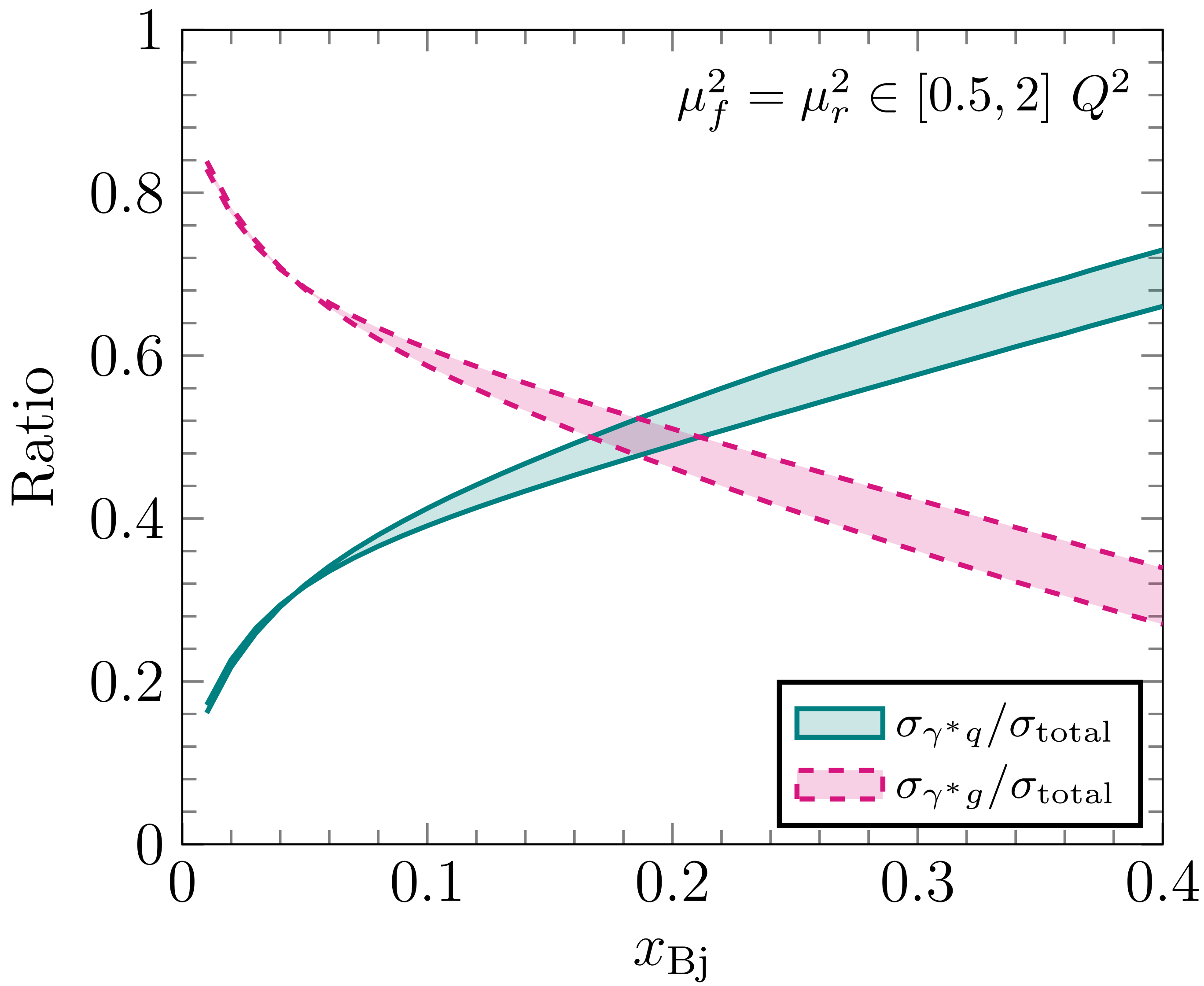
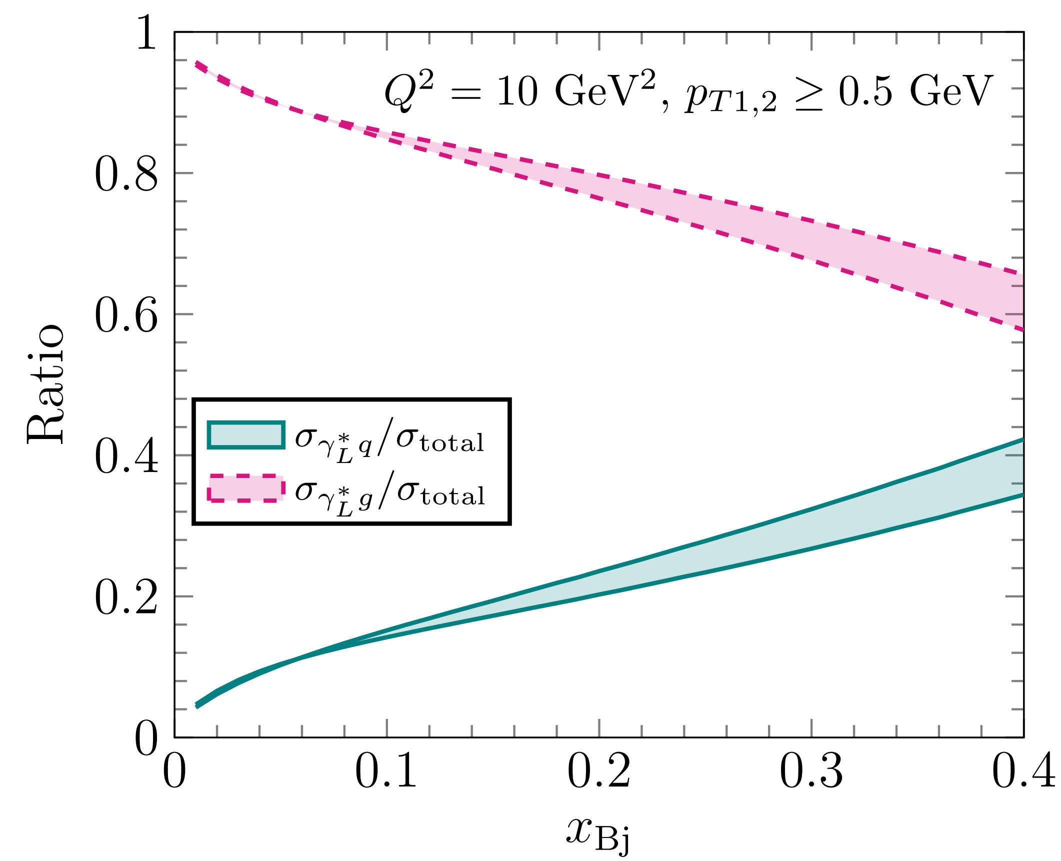
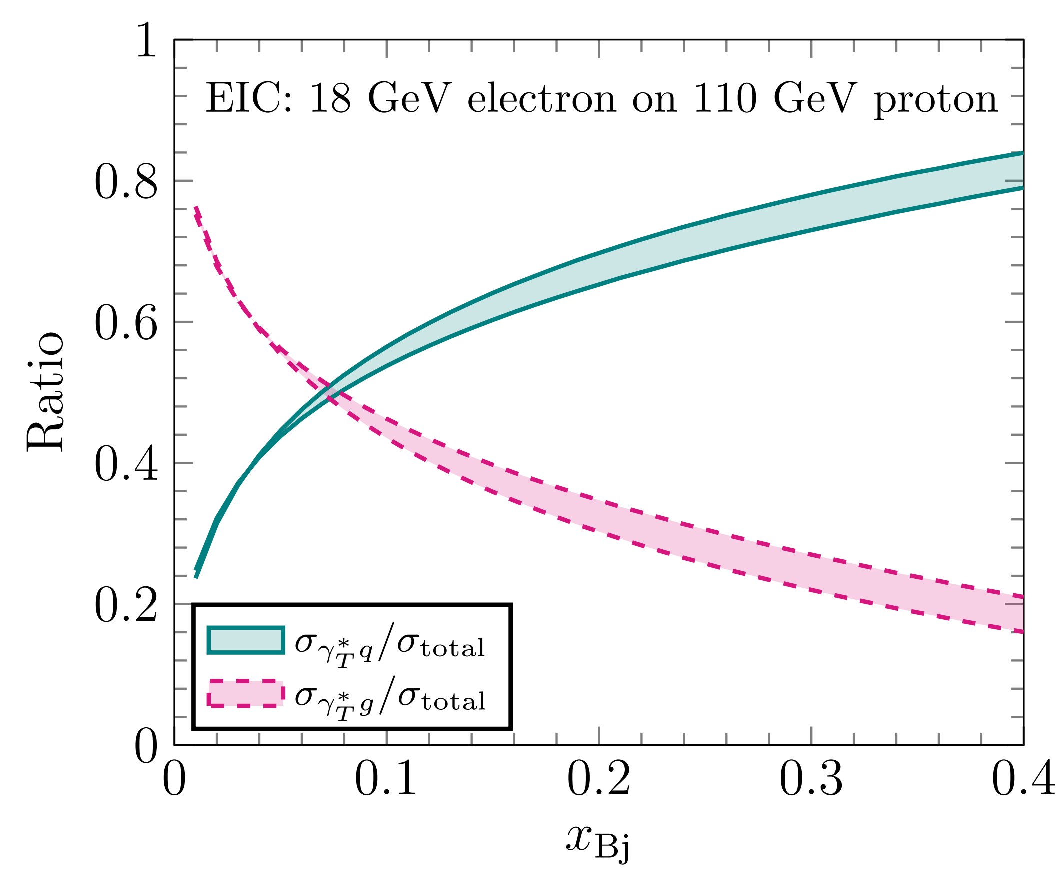
Helicity correlation of B2B dihadron

Helicity Correlation at future EIC







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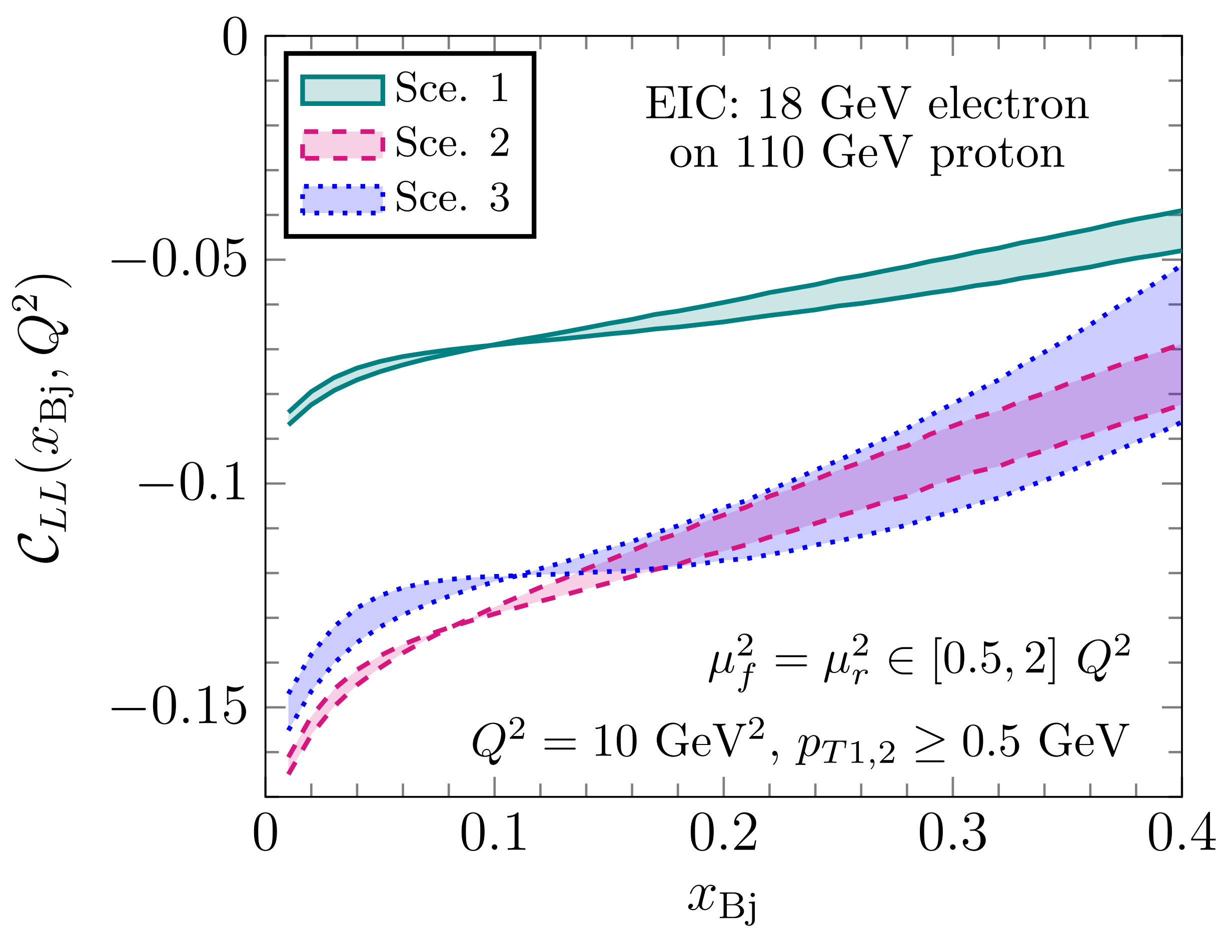
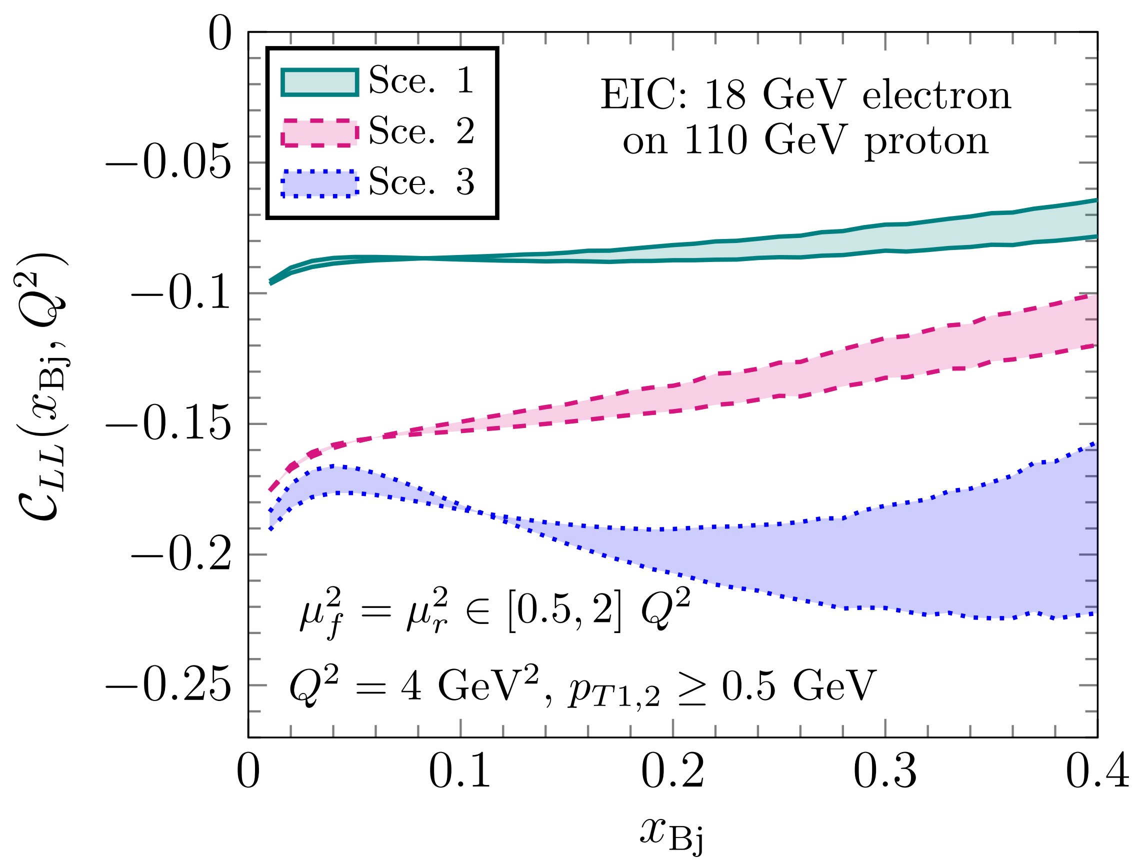
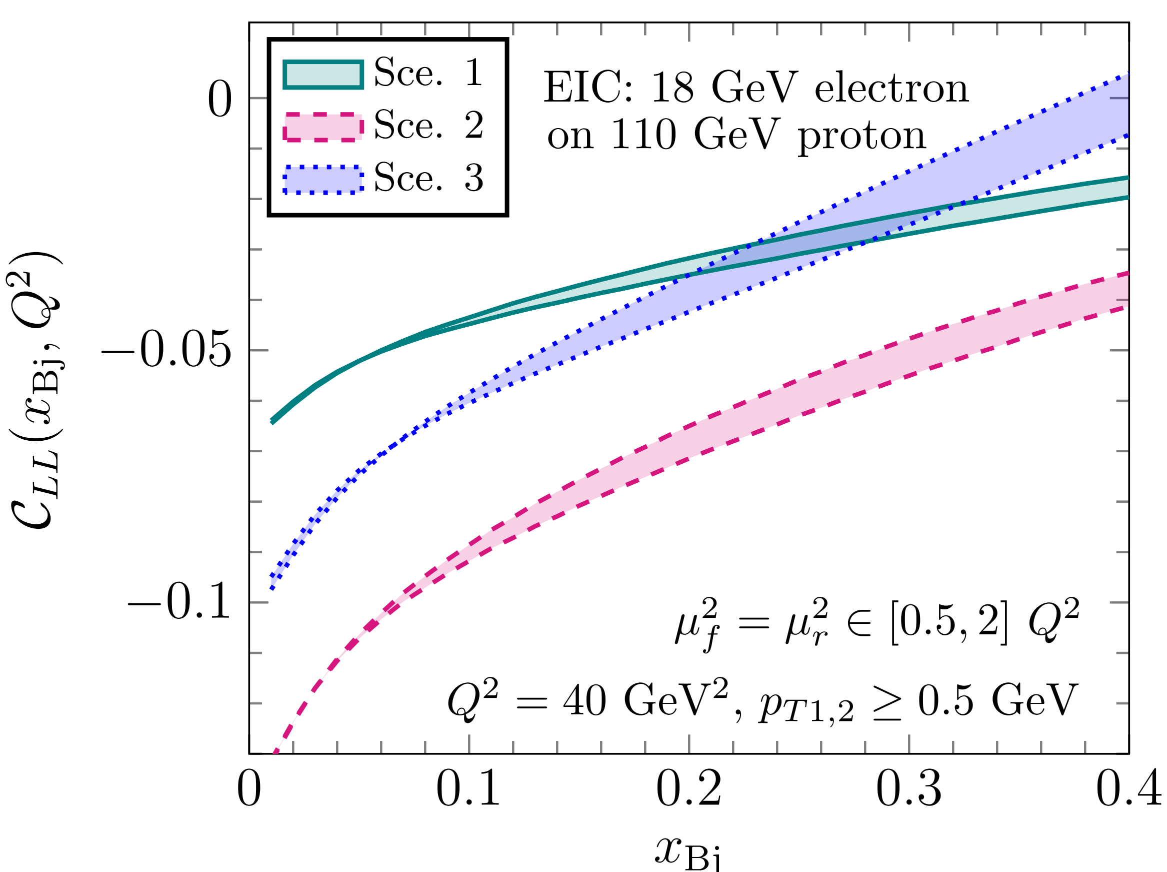
Helicity Correlation at future EIC







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Transverse spin correlation of B2B dihadron

QCD factorization

Baryons

Quarks	Unpolarized	L	T
Unpolarized	D_1		
L		G_{1L}	
T			H_{1T}

quark only

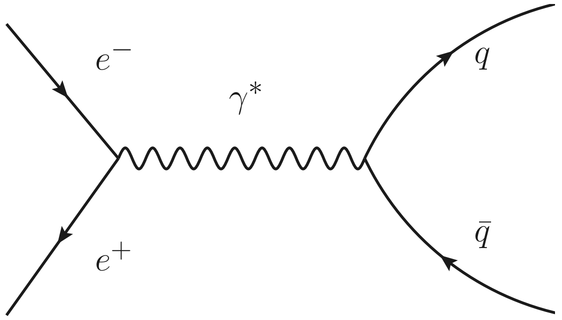
Chiral-odd fragmentation function

☑ **H_{1T}, aka, the transverse spin transfer**

Number density of transversely polarized hadrons produced from transversely polarized quarks.

Transverse spin correlation of B2B dihadron

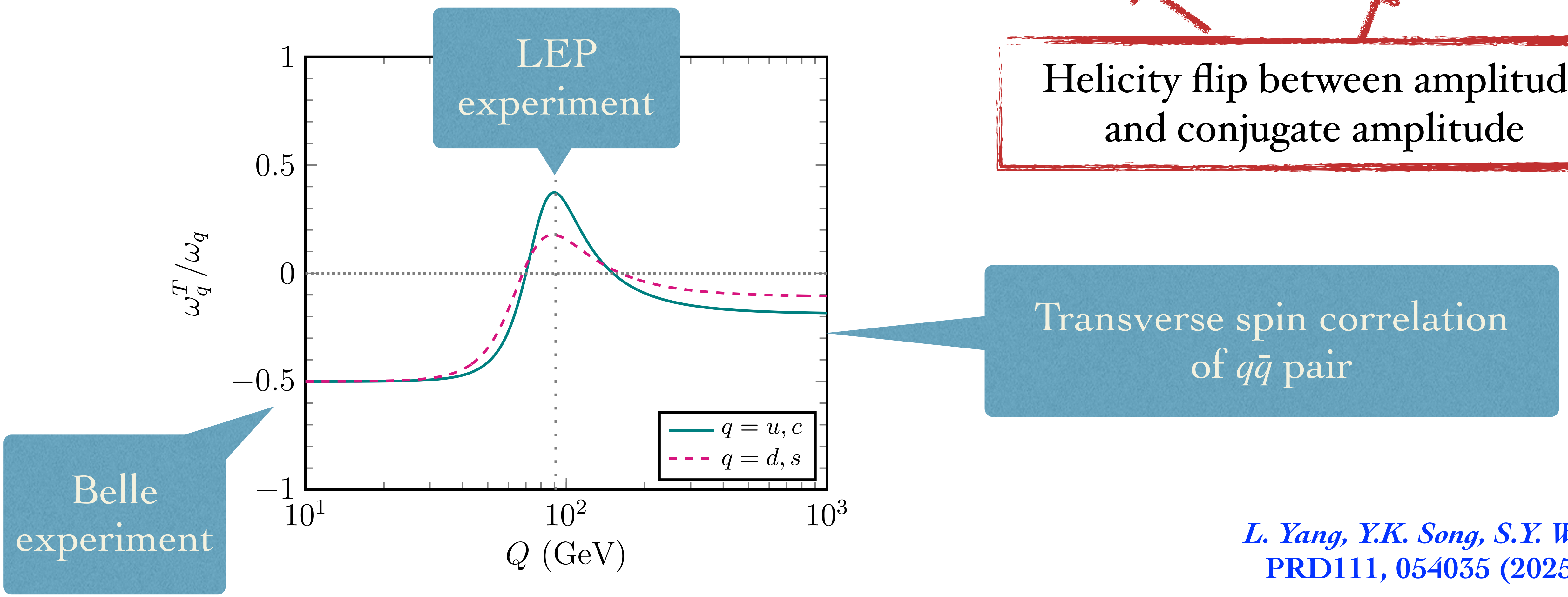
Electron-position annihilation



helicity correlation of $q\bar{q}$: $|M(\lambda_q = +1, \lambda_{\bar{q}} = -1)|^2 + |M(\lambda_q = -1, \lambda_{\bar{q}} = +1)|^2$

transverse spin correlation of $q\bar{q}$: $2\text{Re}\left[M(\lambda_q = +1, \lambda_{\bar{q}} = -1)M^*(\lambda_q = -1, \lambda_{\bar{q}} = +1)\right]$

Helicity flip between amplitude and conjugate amplitude



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Transverse spin correlation of B2B dihadron

Unpolarized pp Collisions

$g + g \to q + \bar{q}$

$q_i + \bar{q}_i \to q_j + \bar{q}_j$

$q_i + \bar{q}_i \to q_i + \bar{q}_i$

negative correlation

$q_i + q_i \to q_i + q_i$

small correlation

$q_i + q_j \to q_i + q_j$

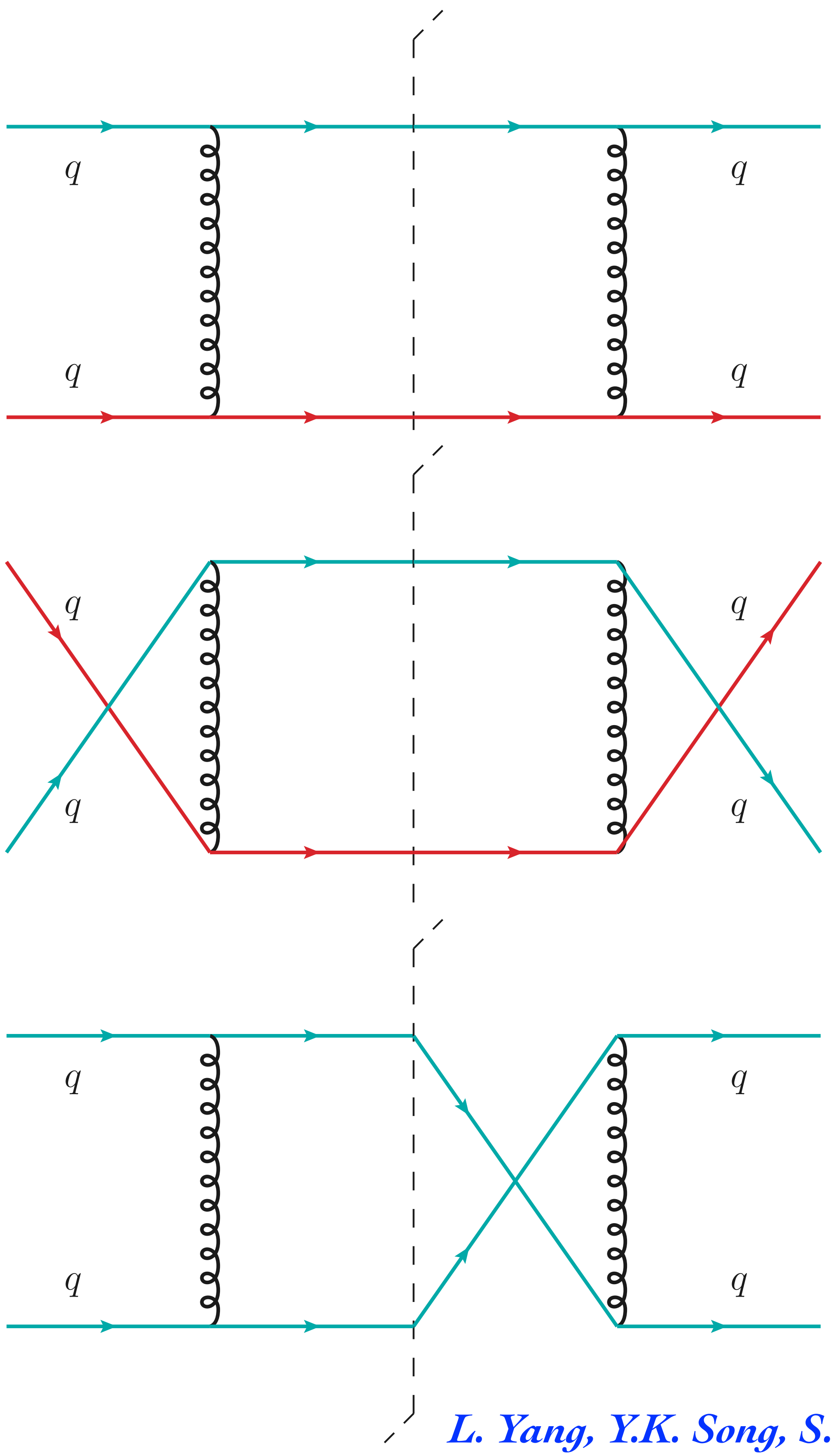
no correlation

$q + g \to q + g$

$q + \bar{q} \to g + g$

$g + g \to g + g$

gluon channels does not contribute



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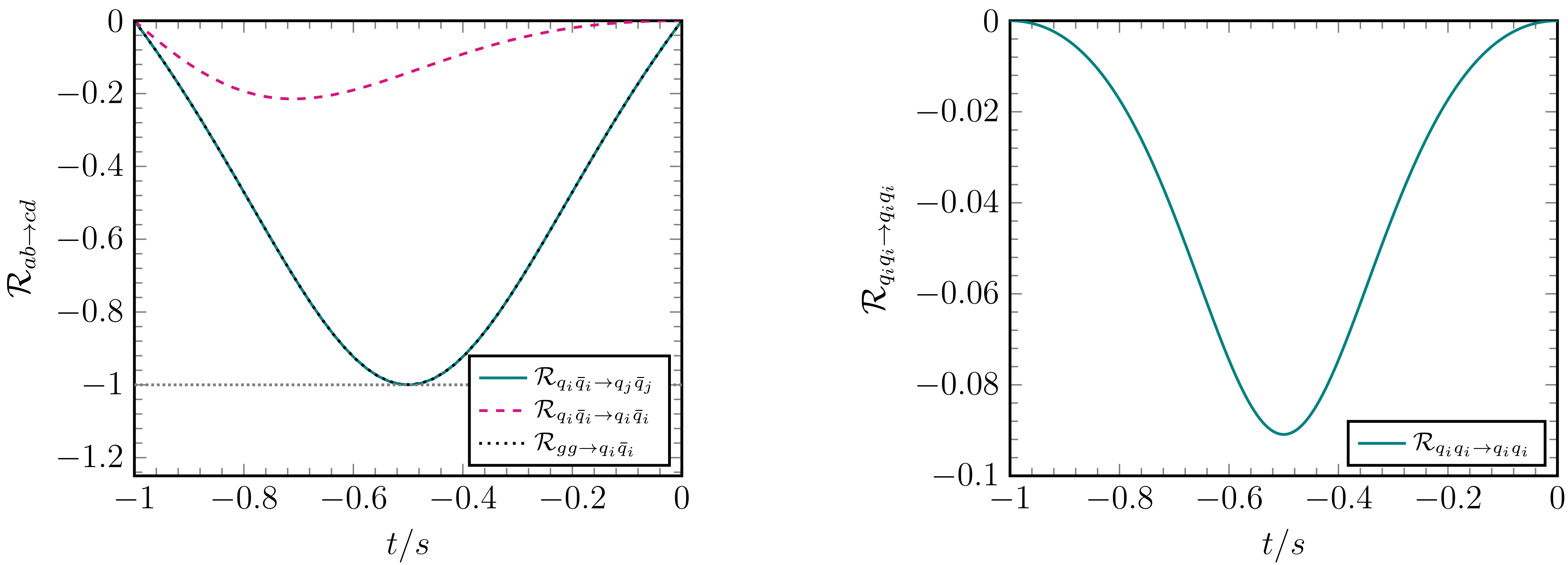
Unpolarized pp Collisions

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



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Helicity correlation of neighboring dihadron

Dihadron Fragmentation Function

$$\mathscr{D}^{h_1h_2}(z_1, z_2, \lambda_1, \lambda_2, \mu_f^2) = D_1^{h_1h_2}(z_1, z_2, \mu_f^2) + \lambda_1\lambda_2 D_{1LL}^{h_1h_2}(z_1, z_2, \mu_f^2) + \boldsymbol{S}_{T1} \cdot \boldsymbol{S}_{T2} D_{1TT}^{h_1h_2}(z_1, z_2)$$

$$\hat{P}_{jk\leftarrow i}^{LL/U}(\xi) = \frac{1}{2}\sum_{\lambda_i}\left[\hat{P}_{jk\leftarrow i}(\xi, \lambda_i, +, +) + \hat{P}_{jk\leftarrow i}(\xi, \lambda_i, -, -) - \hat{P}_{jk\leftarrow i}(\xi, \lambda_i, +, -) - \hat{P}_{jk\leftarrow i}(\xi, \lambda_i, -, +)\right]$$

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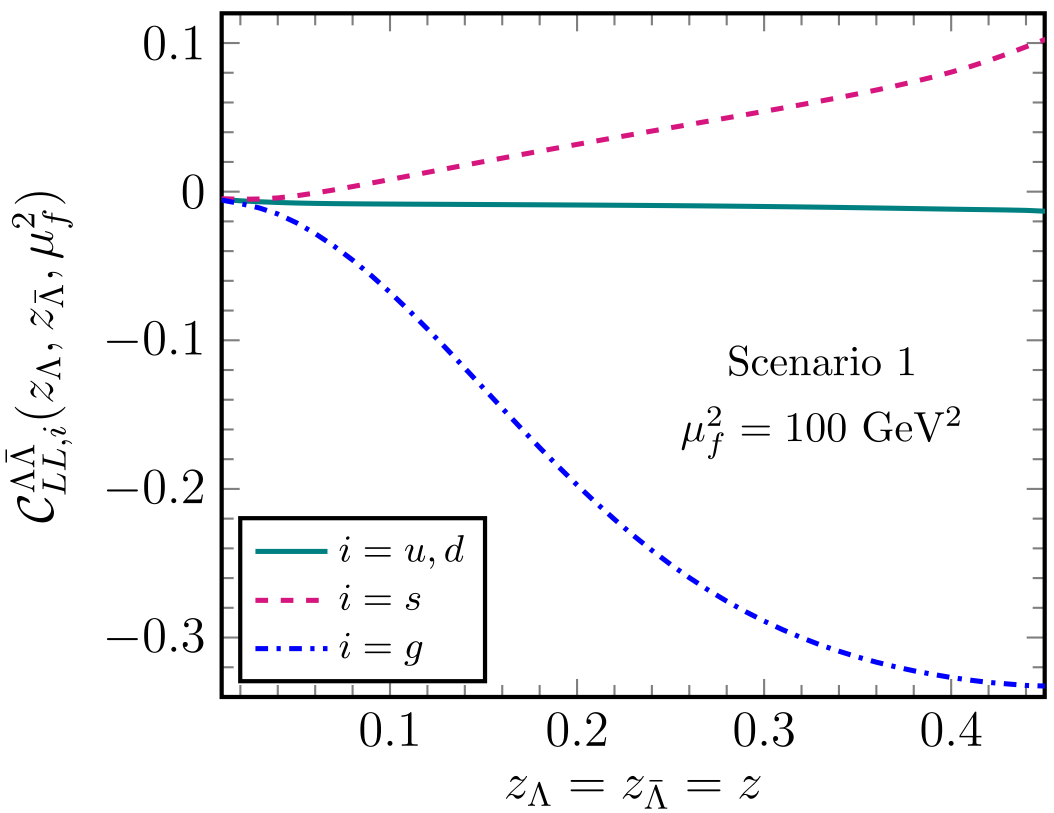
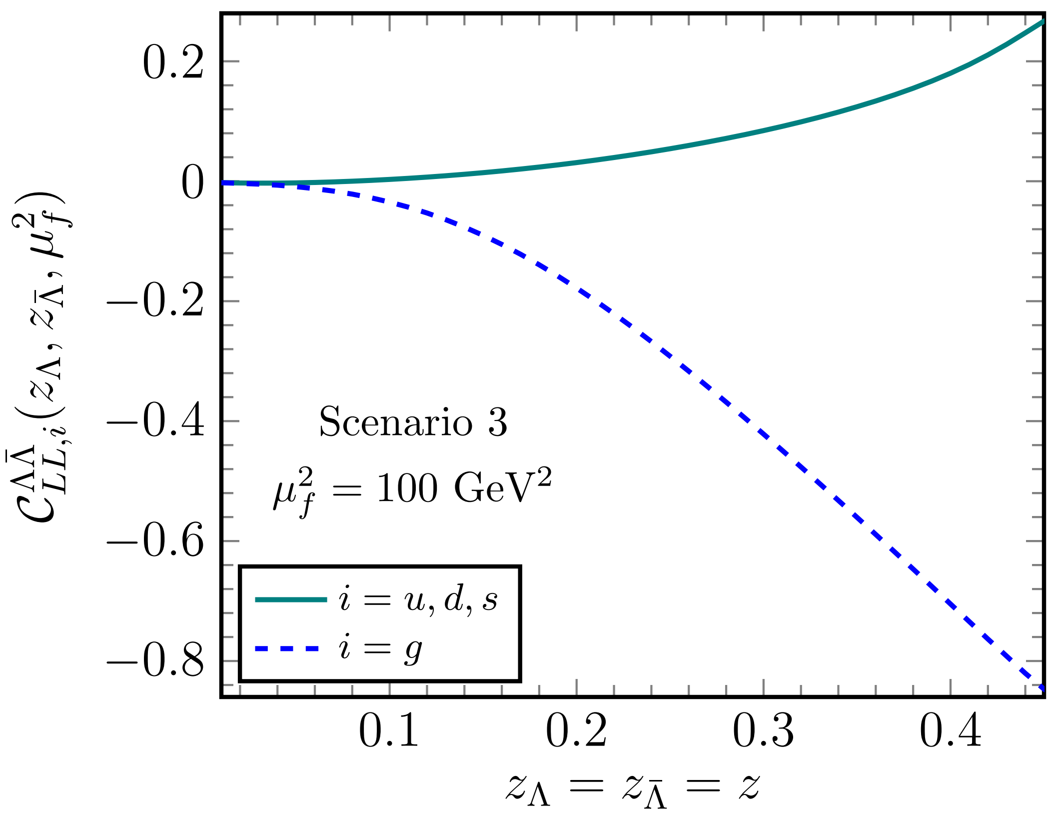
Helicity correlation of neighboring dihadron

Dihadron Fragmentation Function





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Summary

- ☑ Spin correlations emerge in unpolarized collisions.
- ☑ The unpolarized colliders are also capable of investigating the hadronization of polarized parons.

Thanks for your attention!

The End