Λ polarization across different small collision systems

e^+e^-, ep, pp, and pA

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arXiv: 2102.00658; 2108.07740; 2301.04096; 2307.02874; 2309.09487; 2403.06133; 2404.19202; 2410.20917; 2412.00394; 2504.00739; 2507.15387; 2511.06705.

Menu

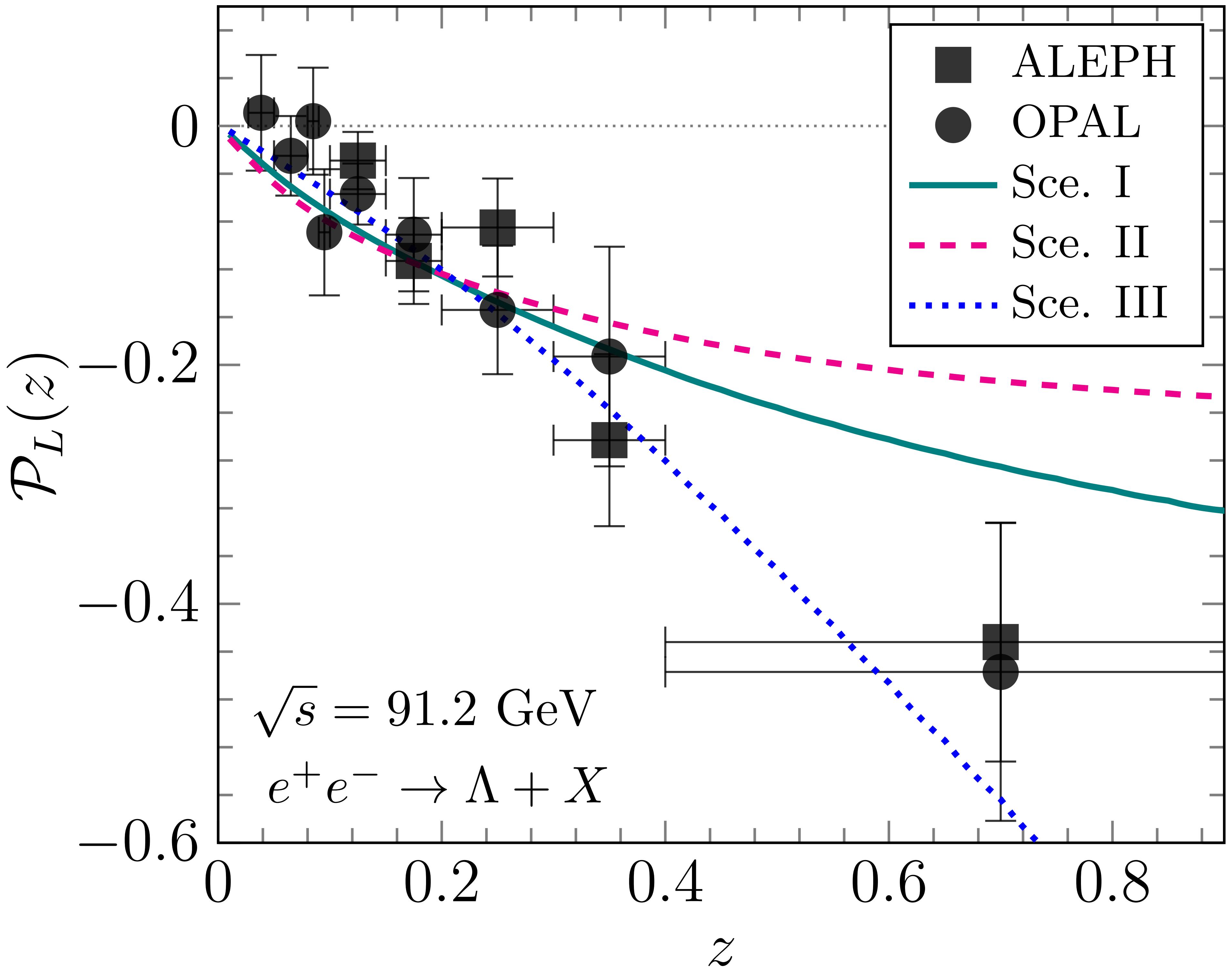
- Λ Helicity
- Spin Correlation
- Emerging Transverse Polarization

Introduction - Λ helicity

In the very beginning, Λ polarization is just a tool

In order to reach completely the vector and axial couplings of the neutral currents to quarks we propose to measure quark helicities from the polarizations of the leading baryons of the jets. Applications are given for $e^+e^- \to 2$ jets where large degrees of polarization are obtained from γ-Z interference.

NPB 162 (1980) 341



All 3 scenarios can describe LEP data

1: $g_{1L}(s) \gg g_{1L}(u) = g_{1L}(d) = 0$

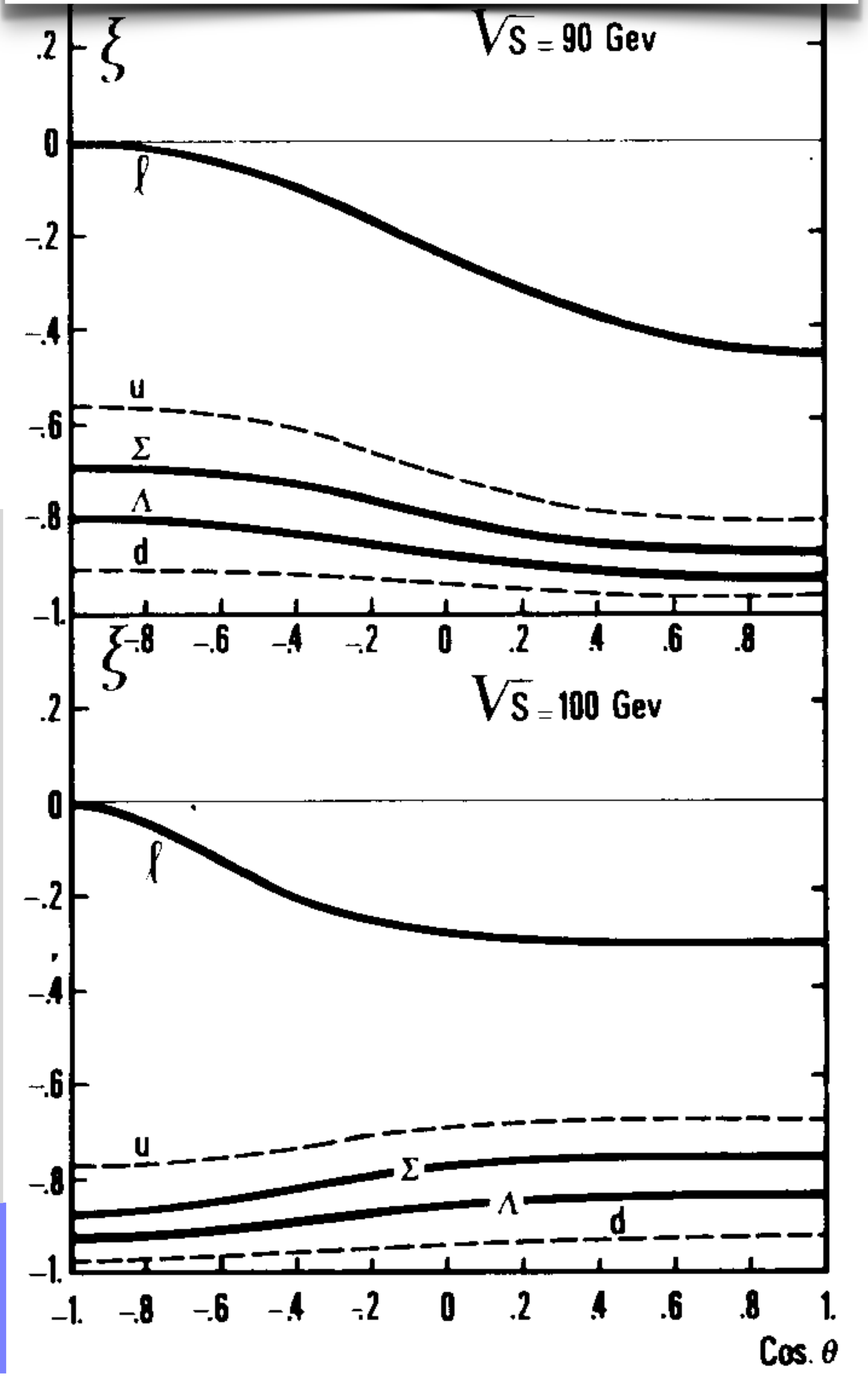
2: $g_{1L}(s) \gg 0,\ g_{1L}(u) = g_{1L}(d) < 0$

3: $g_{1L}(s) = g_{1L}(u) = g_{1L}(d)$

DSV: hep-ph/9711387

Chen, Yang, Liang, Zhou: 1609.07001

How to Measure Quark Helicities in $e^+e^- \to$ Hadrons

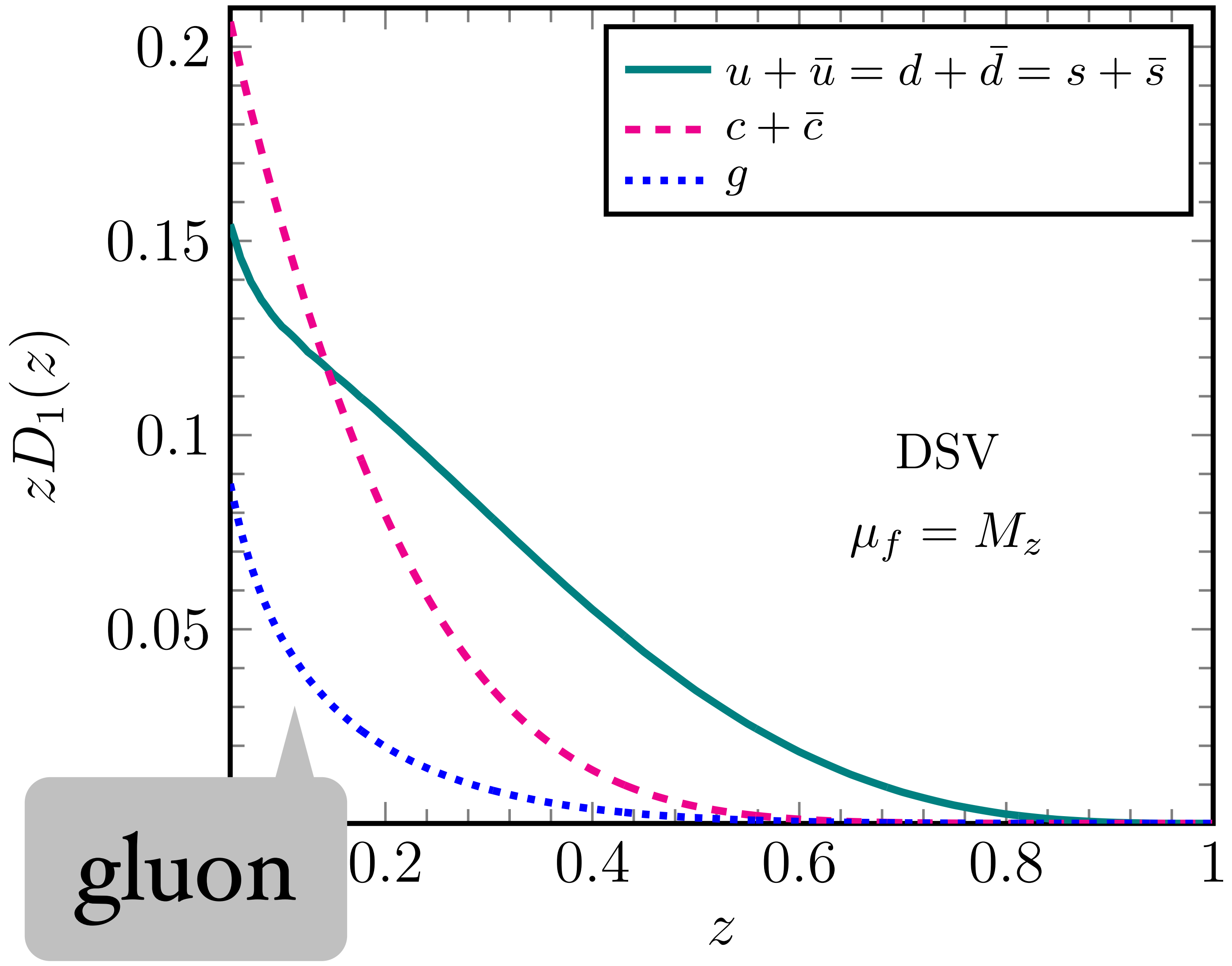


Introduction - Λ helicity

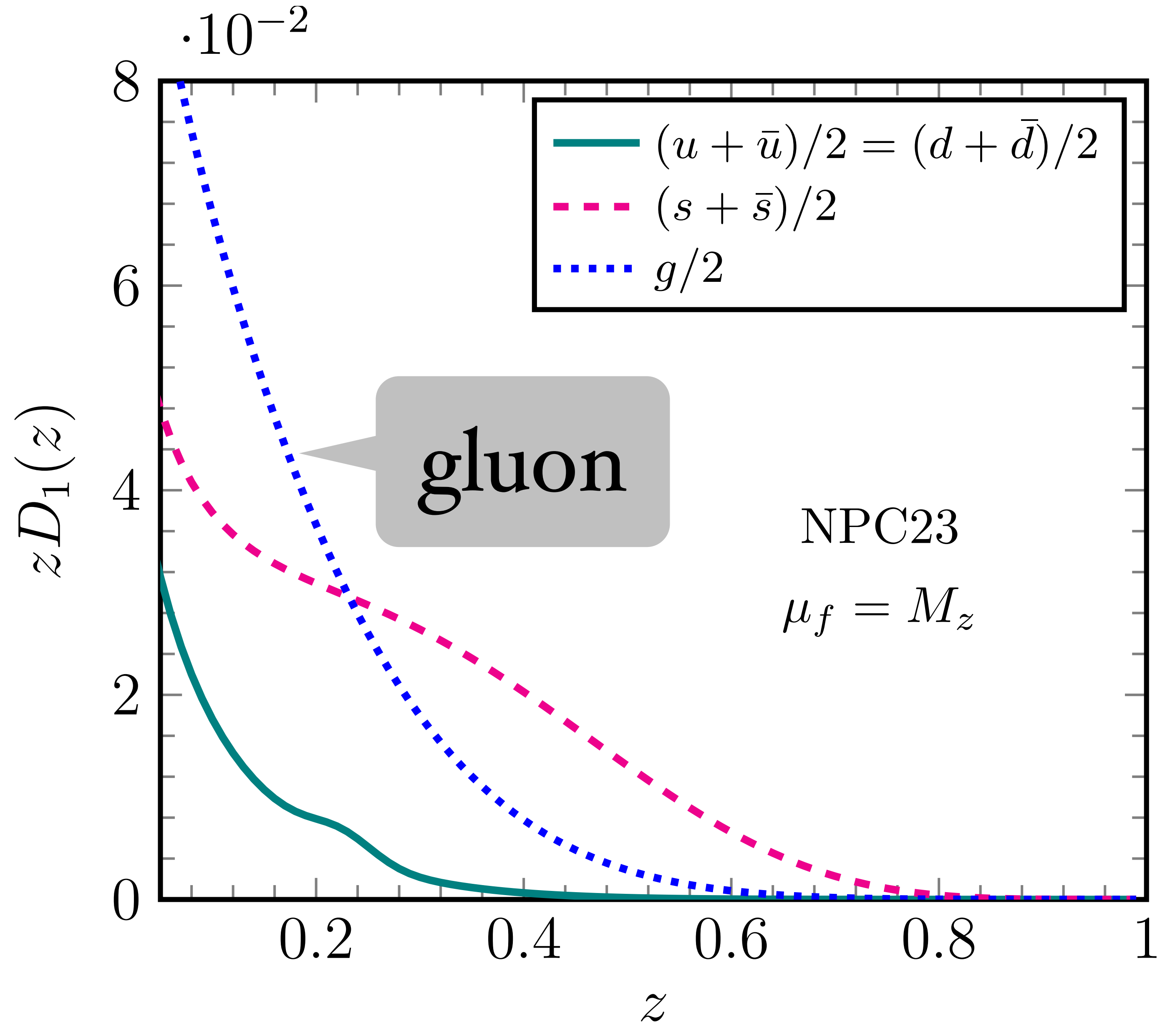
More experimental data are required

Gluon fragmentation function is largely unknown

DSV: w/o *pp* data

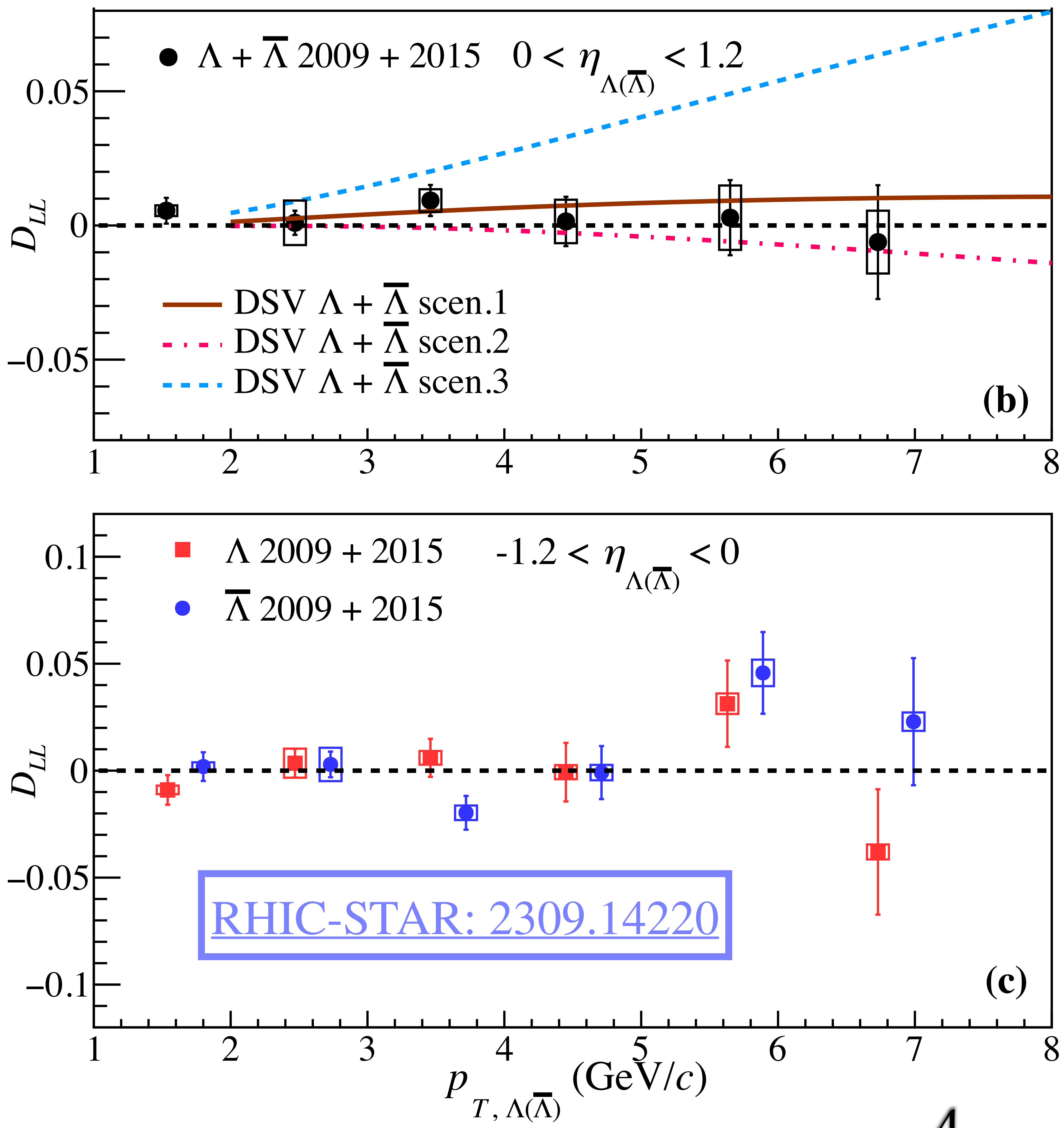


NPC23: w/ *pp* data



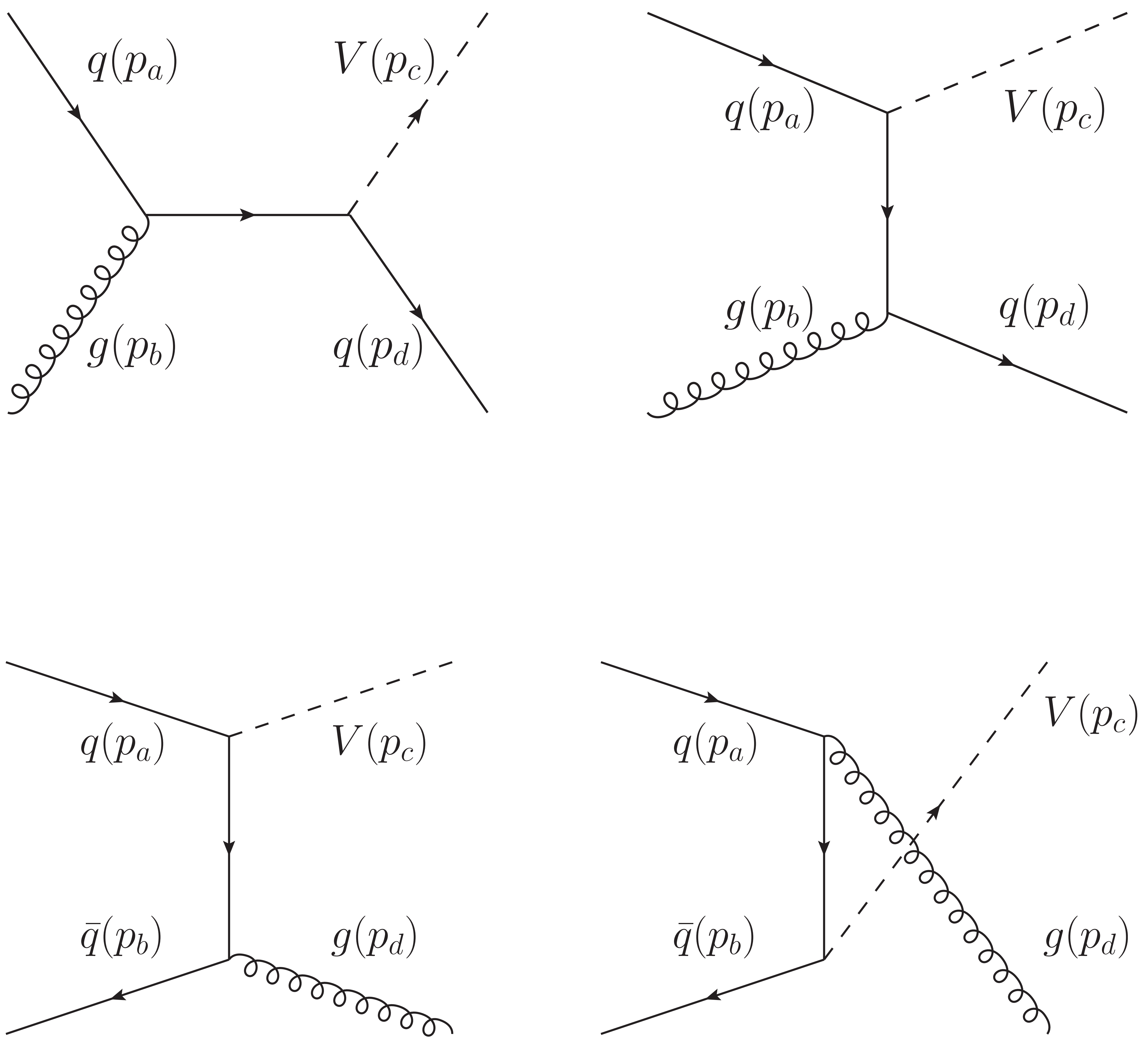
J. Gao, C. Liu, M. Li, X. Shen, H. Xing, Y. Zhao and Y. Zhou: 2503.21311

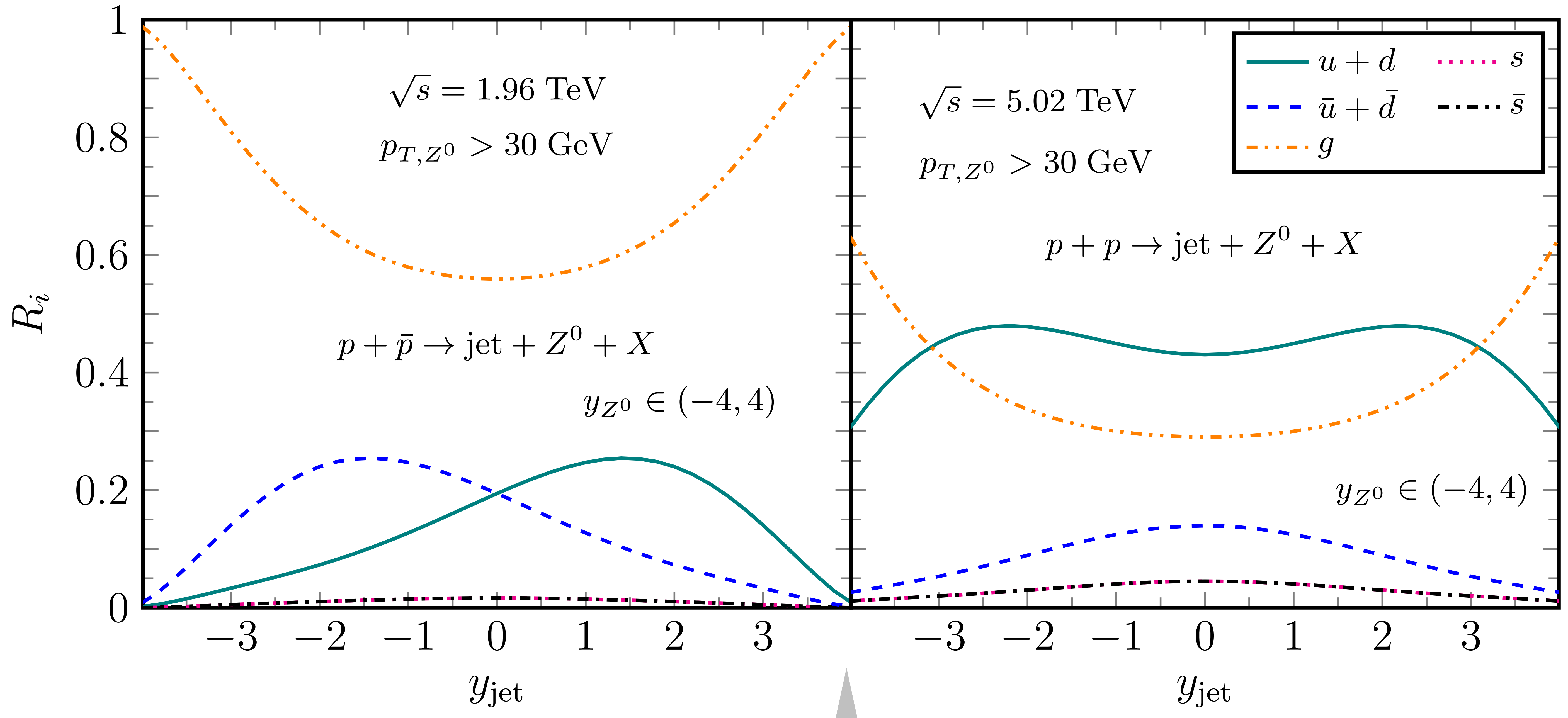
Polarized *pp* Collider



Z^0-tagged Λ production in unpolarized *pp* collisions

W.H. Yao, X. Li, H. Dong, S.Y. Wei, 2511.06705



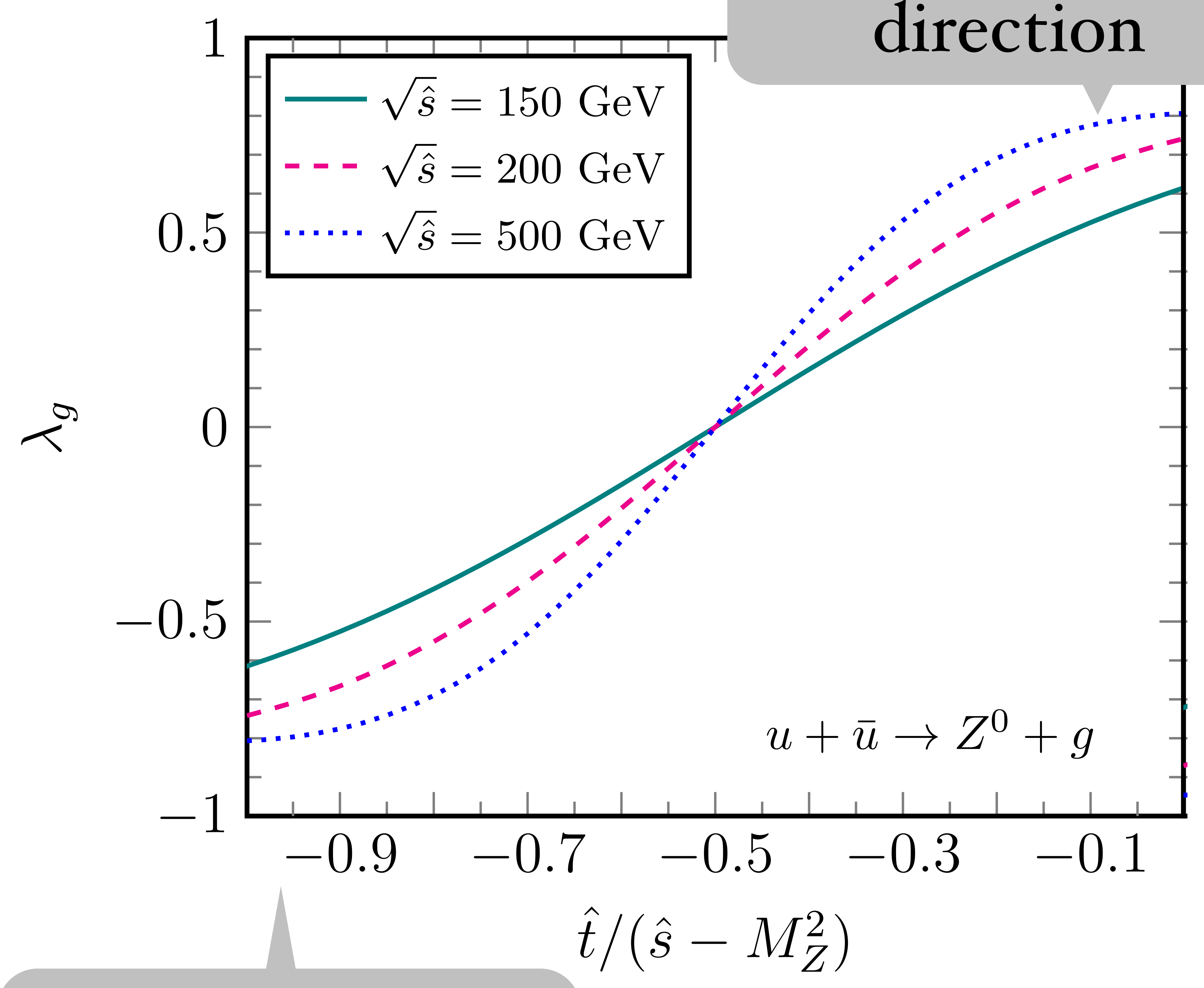


flavor prism of partons in
$p\bar{p}$ and pp collisions

Z^0-tagged Λ production in unpolarized *pp* collisions

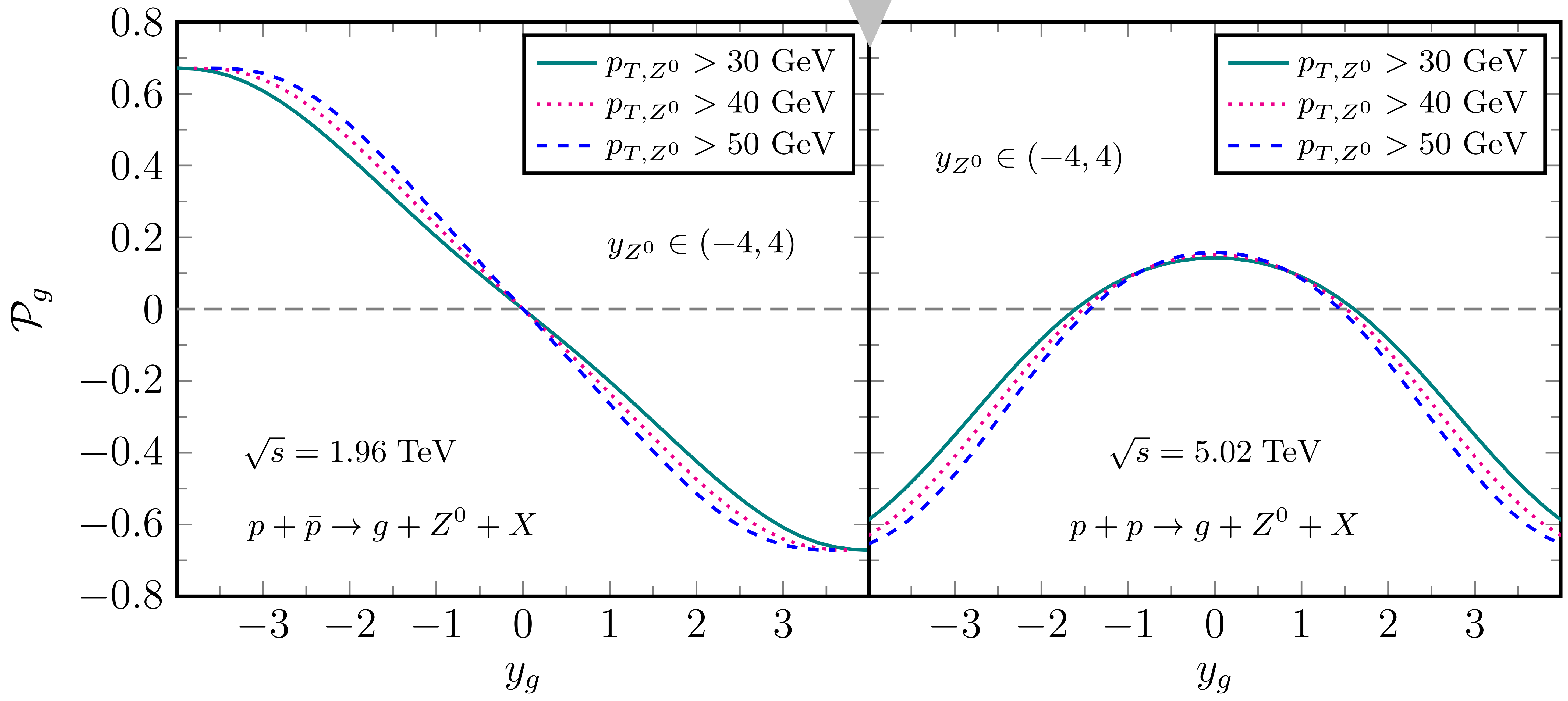
W.H. Yao, X. Li, H. Dong, S.Y. Wei, 2511.06705

antiquark-going direction



quark-going direction

gluon helicity in different kinematic regions

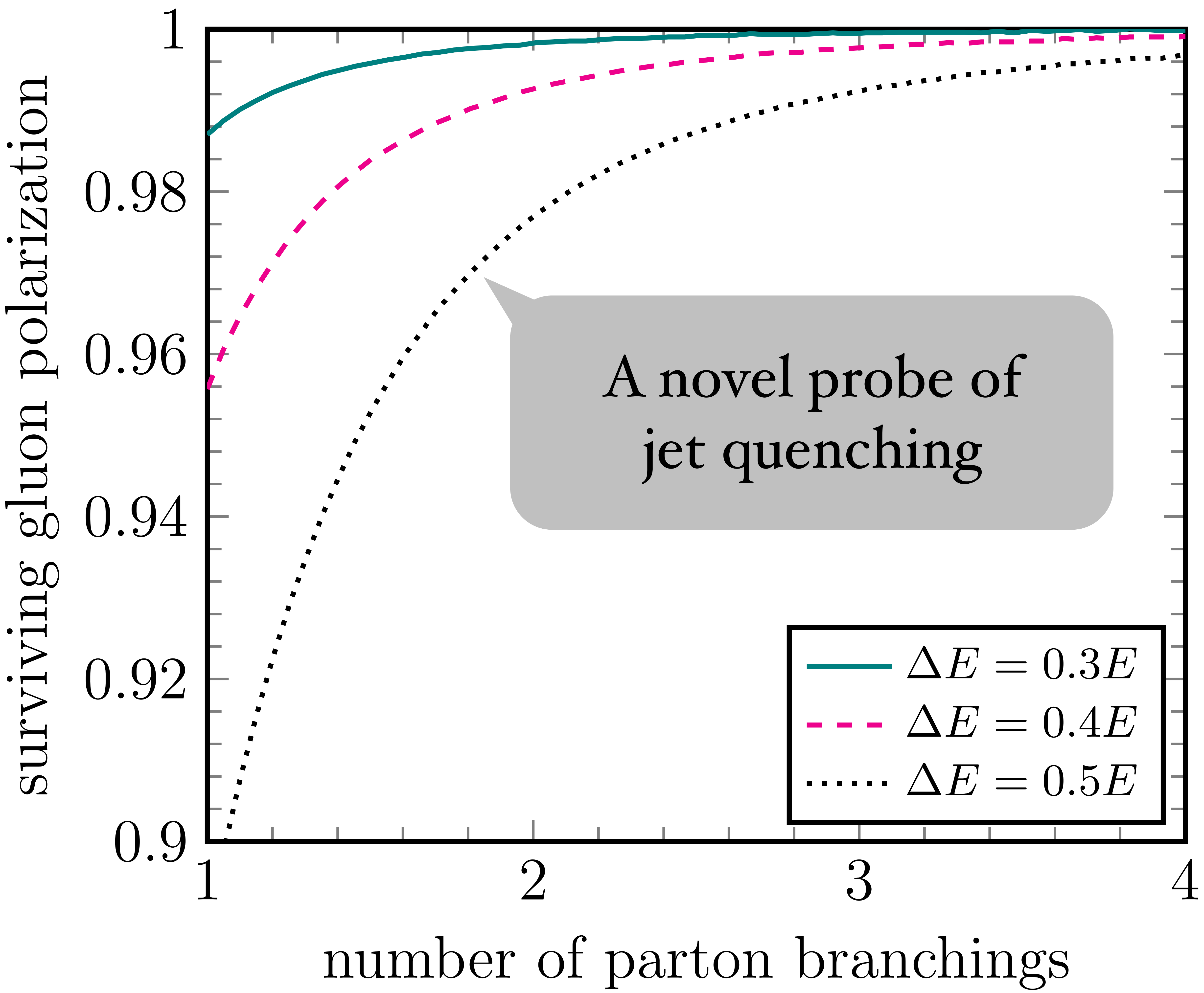


forward rapidity: $x_1 \gg x_2$

Introduction - Λ helicity

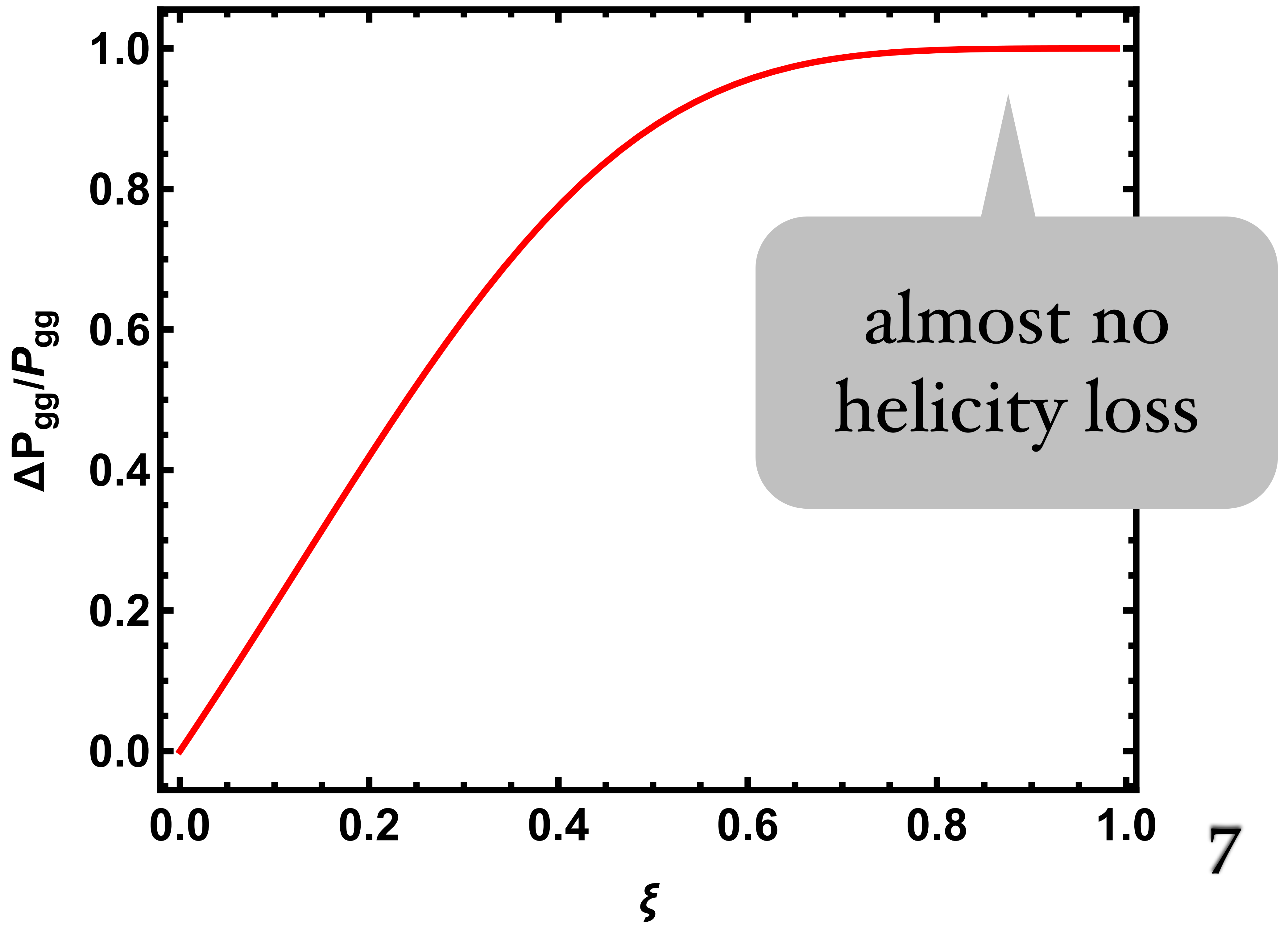
Z^0-tagged Λ production in unpolarized AA collisions

W.H. Yao, X. Li, H. Dong, S.Y. Wei, 2511.06705



$$P_{gg}(\xi) = 2N_c\left(\frac{1-\xi}{\xi} + \xi(1-\xi) + \frac{\xi}{(1-\xi)_+}\right) + \frac{11N_c - 2n_f}{6}\delta(1-\xi),$$

$$\Delta_L P_{gg}(\xi) = N_c\left(\frac{1+\xi^4-(1-\xi)^3}{\xi} + \frac{1+\xi^4}{(1-\xi)_+}\right) + \frac{11N_c - 2n_f}{6}\delta(1-\xi).$$



Menu

- Λ Helicity
- Spin Correlation
- Emerging Transverse Polarization

Spin Correlation

Spin Correlation in e^+e^- annihilation

$e^+ + e^- \to \gamma^* \to q + \bar{q}$

Single Inclusive

Parity Symmetry

$\boldsymbol{P}_q = \boldsymbol{P}_{\bar{q}} = 0$

helicity conservation

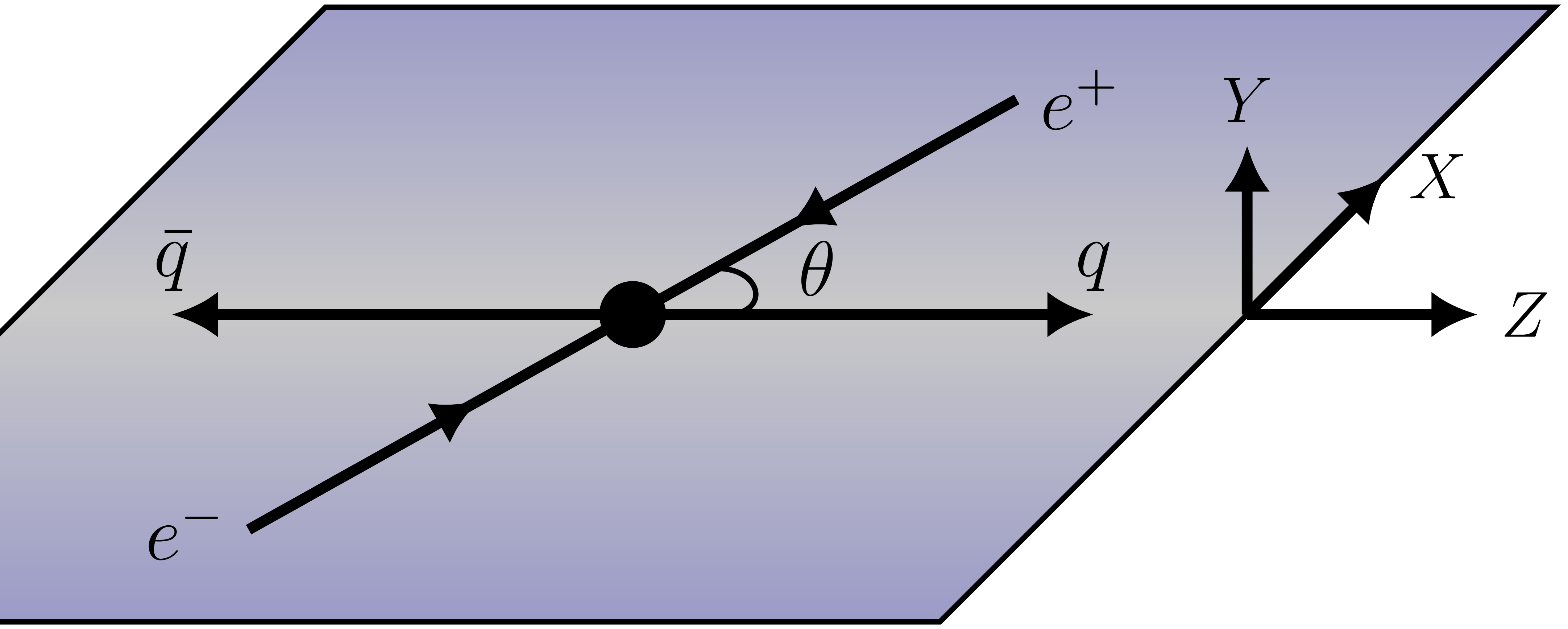
$q\bar{q}$ Pair Production

$$C_{ZZ} = +1$$

$$C_{XX} = +\frac{\sin^2\theta}{1+\cos^2\theta}$$

$$C_{YY} = -\frac{\sin^2\theta}{1+\cos^2\theta}$$

Wigner D-matrix



final state $q \otimes \bar{q}$ system

=

two qubits

K. Chen, G.R. Goldstein, R.L. Jaffe, X. Ji, 9410337; H. Zhang, S.Y. Wei, 2301.04096;
L. Yang, Y.K. Song, S.Y. Wei, 2410.20917; S.J. Lin, M.J. Liu, D.Y. Shao, S.Y. Wei, 2507.15387.

Spin Correlation

Spin Correlation in e^+e^- annihilation

Bell state: $|\Psi\rangle = \frac{1}{\sqrt{2}}\left[\,|++\rangle + |--\rangle\,\right]$

None of these two particles is individually polarized

$$\boldsymbol{P}_q = \langle\Psi|\boldsymbol{\sigma}_q \otimes I|\Psi\rangle = 0$$

$$\boldsymbol{P}_{\bar{q}} = \langle\Psi|I \otimes \boldsymbol{\sigma}_{\bar{q}}|\Psi\rangle = 0$$

Spin Correlations reach unity

$$C_{ZZ} = \langle\Psi|\sigma_Z \otimes \sigma_z|\Psi\rangle = +1$$

$$C_{XX} = \langle\Psi|\sigma_x \otimes \sigma_x|\Psi\rangle = +1$$

$$C_{YY} = \langle\Psi|\sigma_y \otimes \sigma_y|\Psi\rangle = -1$$

Conclusion

At $\theta = \pi/2$,
the b2b $q\bar{q}$ pair forms
a Bell state:
$(|++\rangle + |--\rangle)/\sqrt{2}$
with maximal entanglement.

Useful relations:

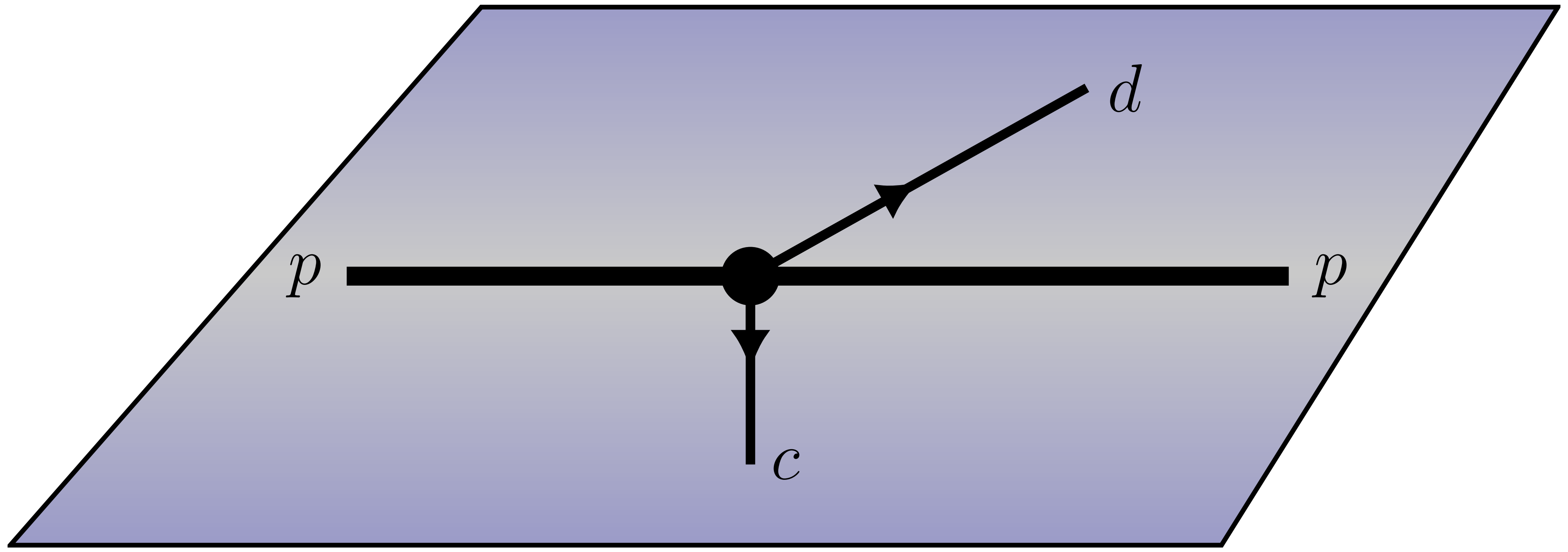
$\sigma_z|+\rangle = +1|+\rangle$, $\sigma_x|+\rangle = +1|-\rangle$, $\sigma_y|+\rangle = +i|-\rangle$
$\sigma_z|-\rangle = -1|-\rangle$, $\sigma_x|-\rangle = +1|+\rangle$, $\sigma_y|-\rangle = -i|+\rangle$

See also: *K. Cheng, B. Yan*, 2501.03321;
S.J. Lin, M.J. Liu, D.Y. Shao, S.Y. Wei, 2507.15387

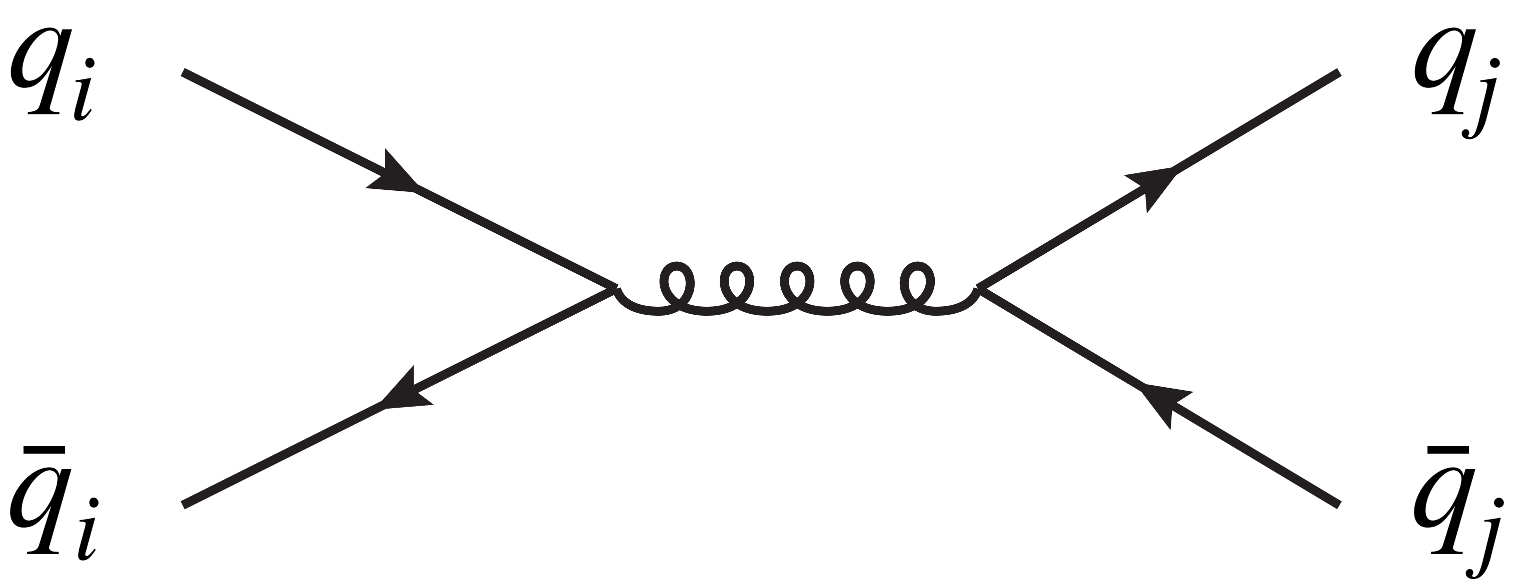
K. Chen, G.R. Goldstein, R.L. Jaffe, X. Ji, 9410337; *H. Zhang, S.Y. Wei*, 2301.04096;
L. Yang, Y.K. Song, S.Y. Wei, 2410.20917; *S.J. Lin, M.J. Liu, D.Y. Shao, S.Y. Wei*, 2507.15387.

Spin Correlation

Spin Correlation in *pp* collision



Type I: $q_i + \bar{q}_i \to q_j + \bar{q}_j$ and $g + g \to q_i + \bar{q}_i$



$$C_{LL} = -1$$

Not C_{ZZ}

$$C_{TT} = -\frac{\sin^2\theta}{1+\cos^2\theta}$$

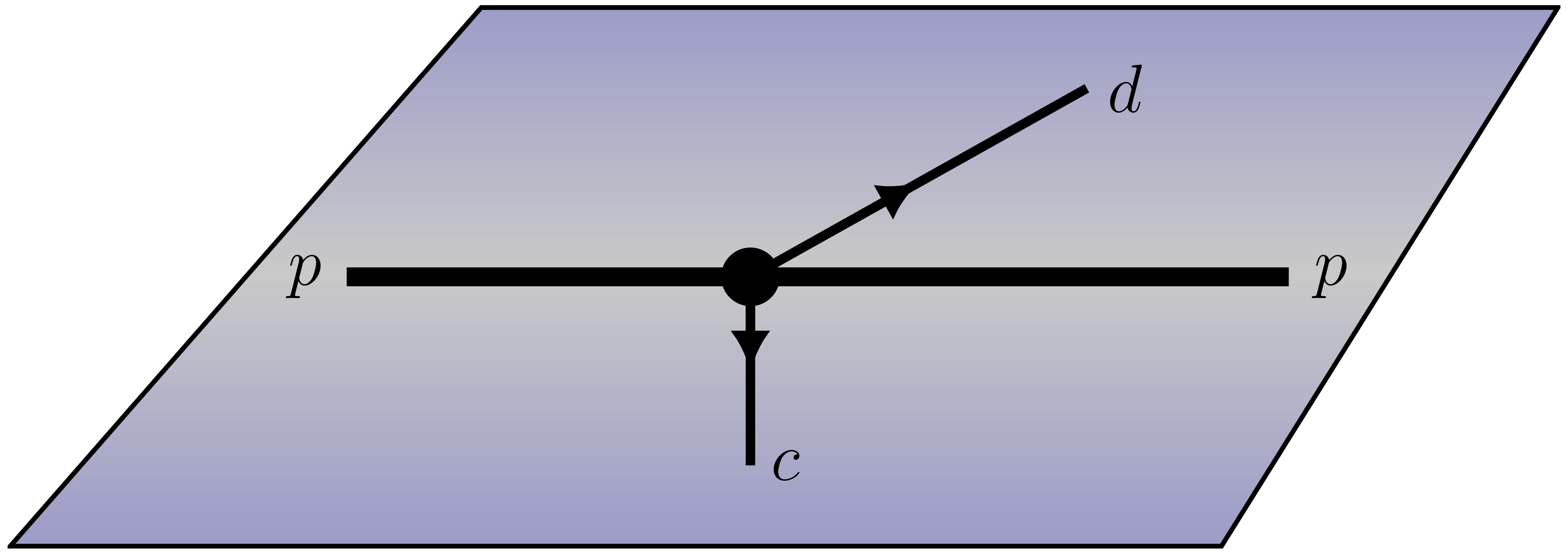
Akin to C_{YY}

Just like the e^+e^- annihilation, the final state $q\bar{q}$ pair also form a Bell state with maximal entanglement at $\theta = \pi/2$, (i.e., $\hat{t} = \hat{u} = -\hat{s}/2$)

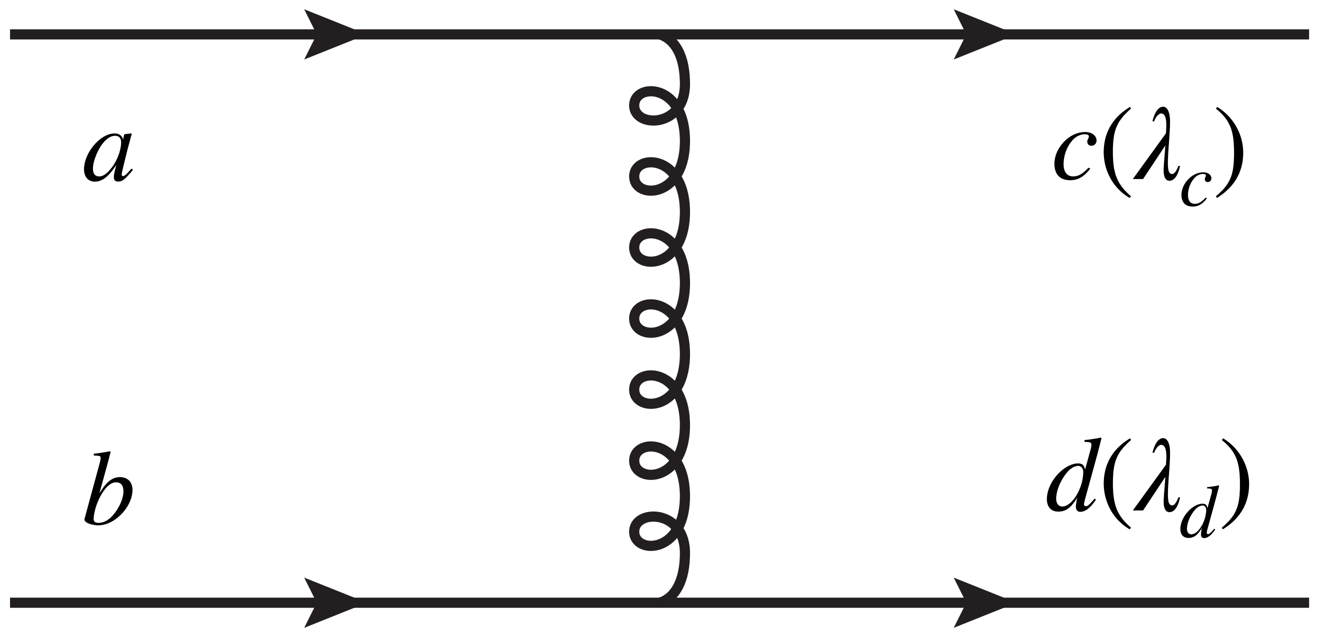
H. Zhang, S.Y. Wei, 2301.04096; *L. Yang, Y.K. Song, S.Y. Wei*, 2410.20917.

Spin Correlation

Spin Correlation in *pp* collision



Type II: $q_i + q_j \to q_i + q_j$



$$C_{LL} = \frac{\hat{s}^2 - \hat{u}^2}{\hat{s}^2 + \hat{u}^2} > 0$$

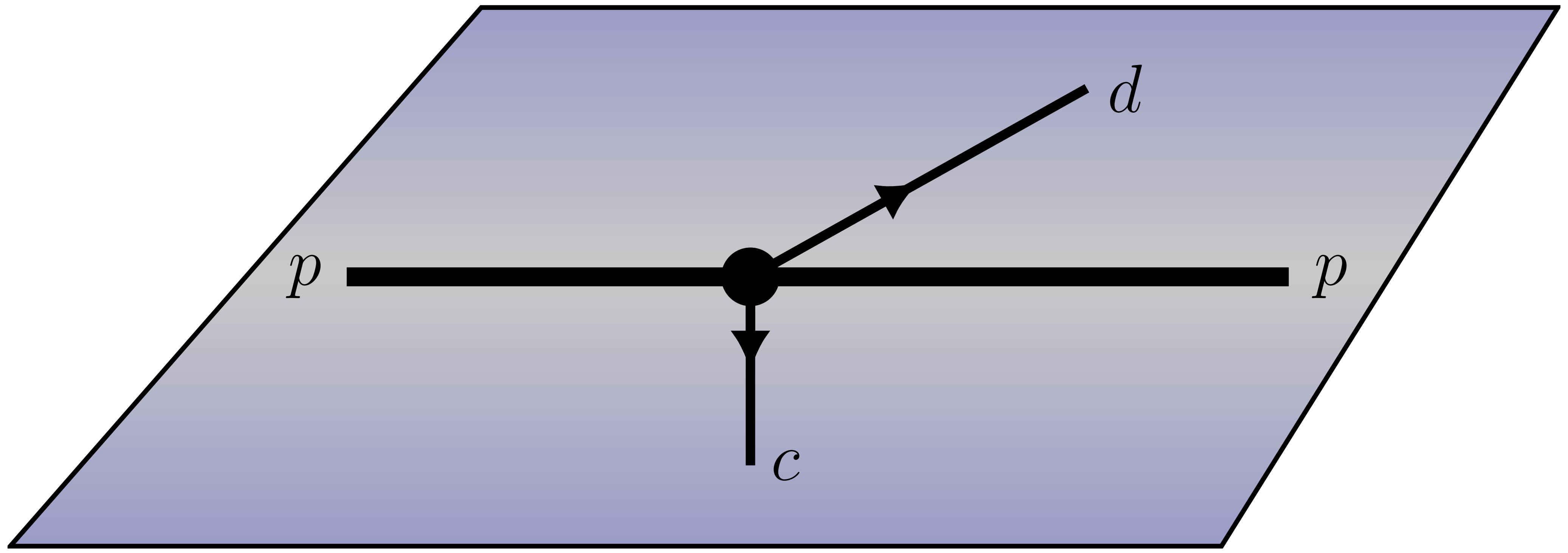
$$C_{TT} = 0$$

Chiral-odd

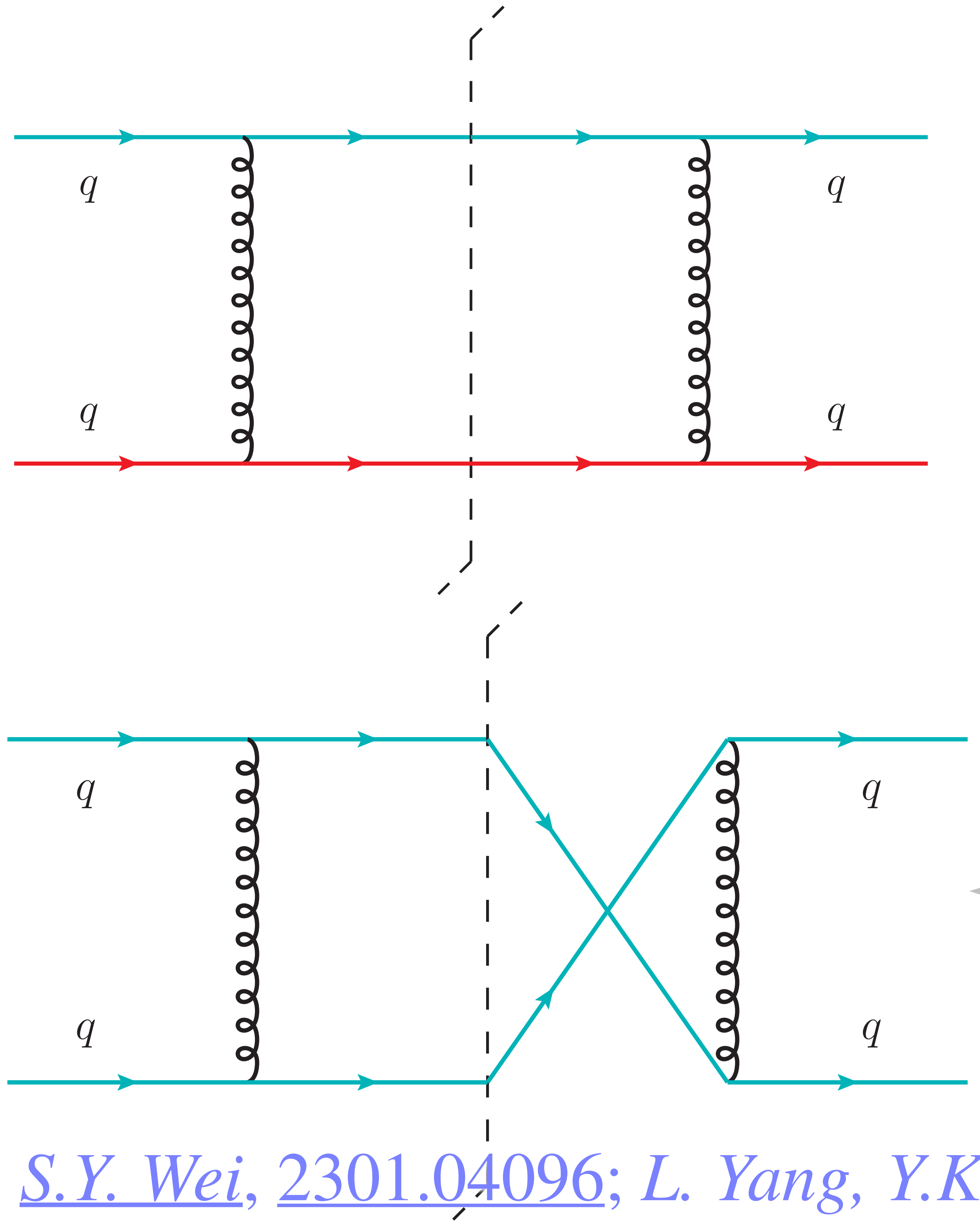
Transverse spin correlation vanishes, since the final state quarks are disconnected.

H. Zhang, S.Y. Wei, 2301.04096; L. Yang, Y.K. Song, S.Y. Wei, 2410.20917.

Spin Correlation in *pp* collision



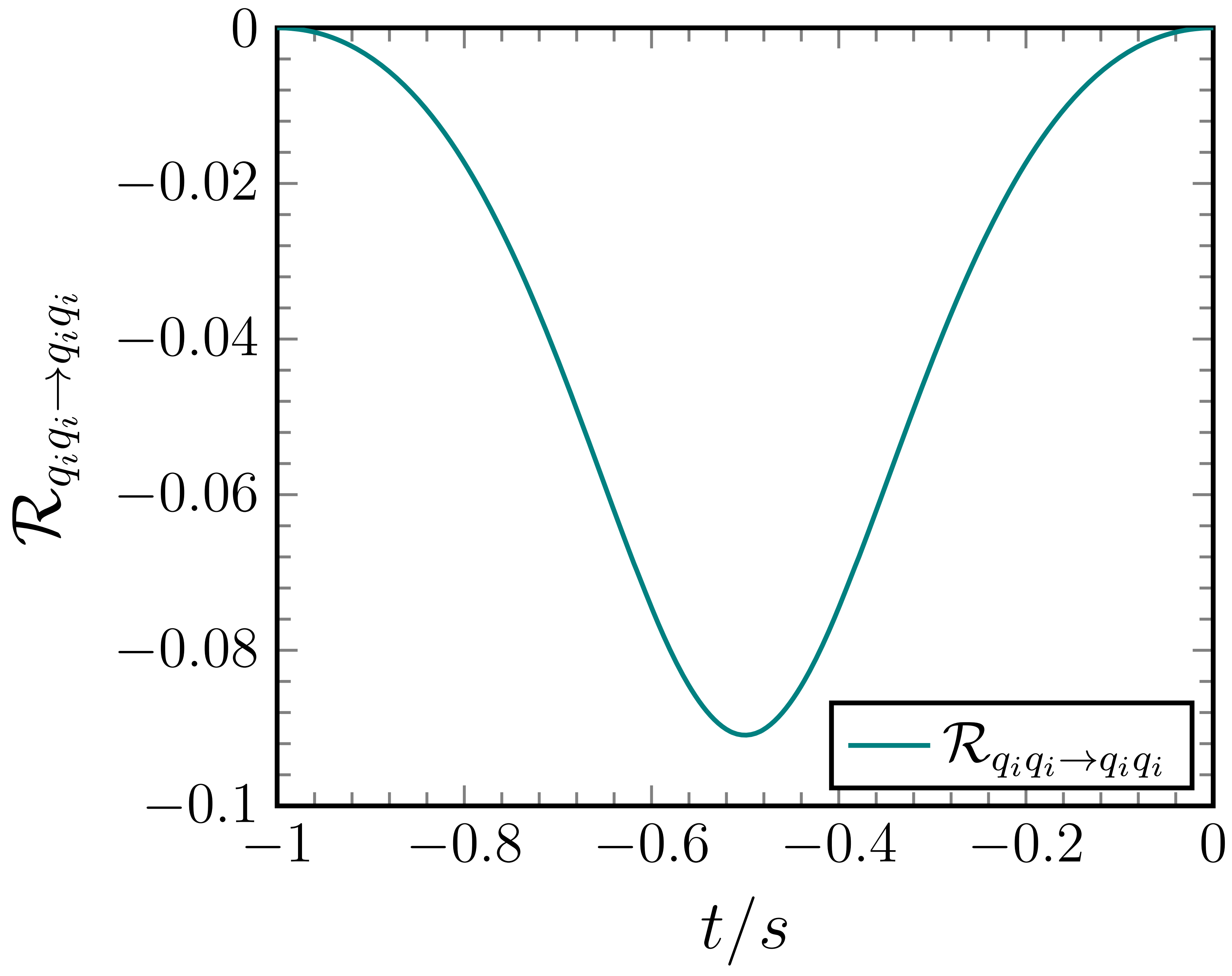
Type III: $q_i + q_i \to q_i + q_i$



$C_{LL} > 0$

$C_{TT} < 0$

Interference Effect



H. Zhang, S.Y. Wei, 2301.04096; *L. Yang, Y.K. Song, S.Y. Wei*, 2410.20917.

Spin Correlation

Spin Correlation in *ep* collision

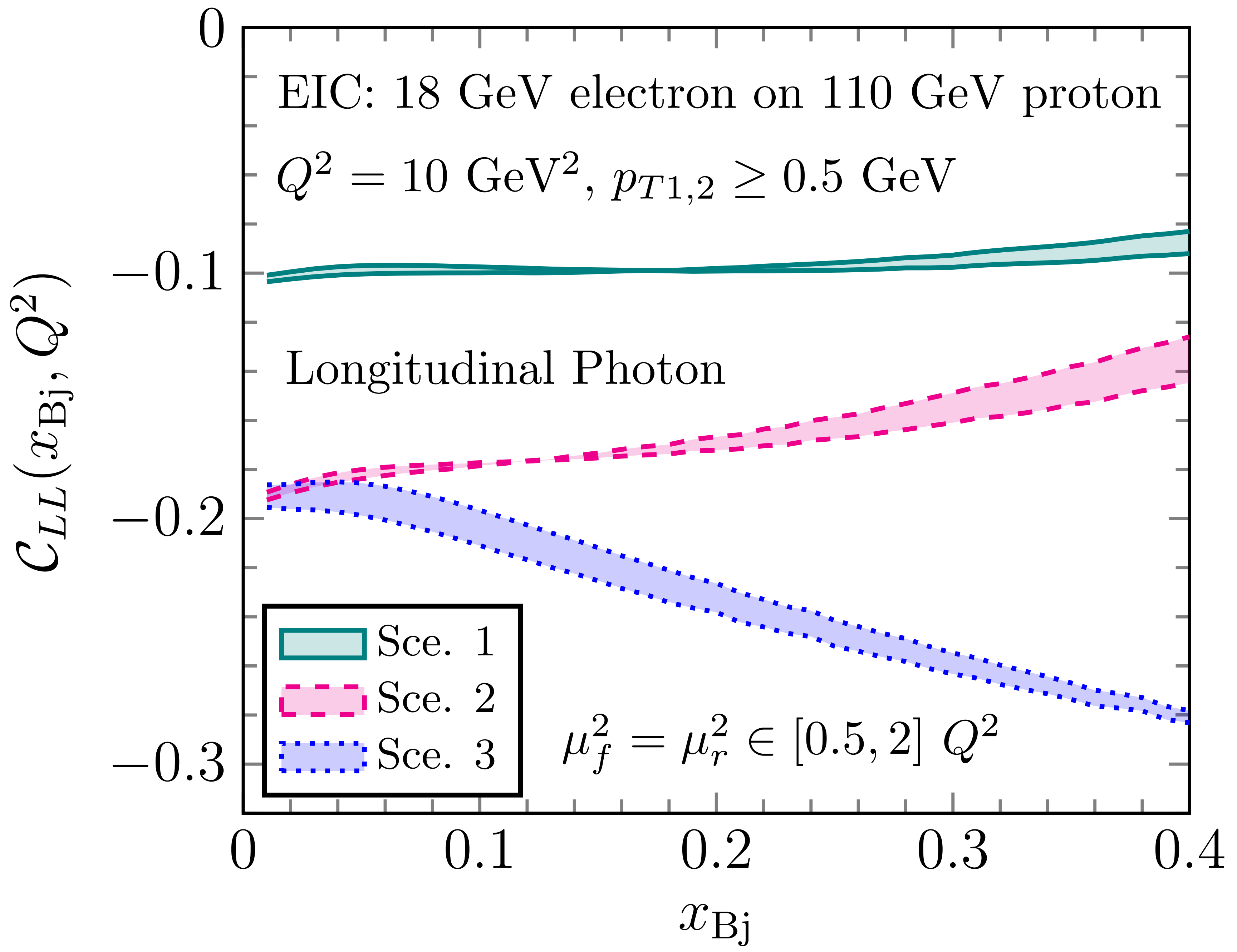
Longitudinal Photon γ_L^* is interesting

$\gamma_L^* + g \to q + \bar{q}$: $C_{LL} = -1$, $C_{TT} = +1$;

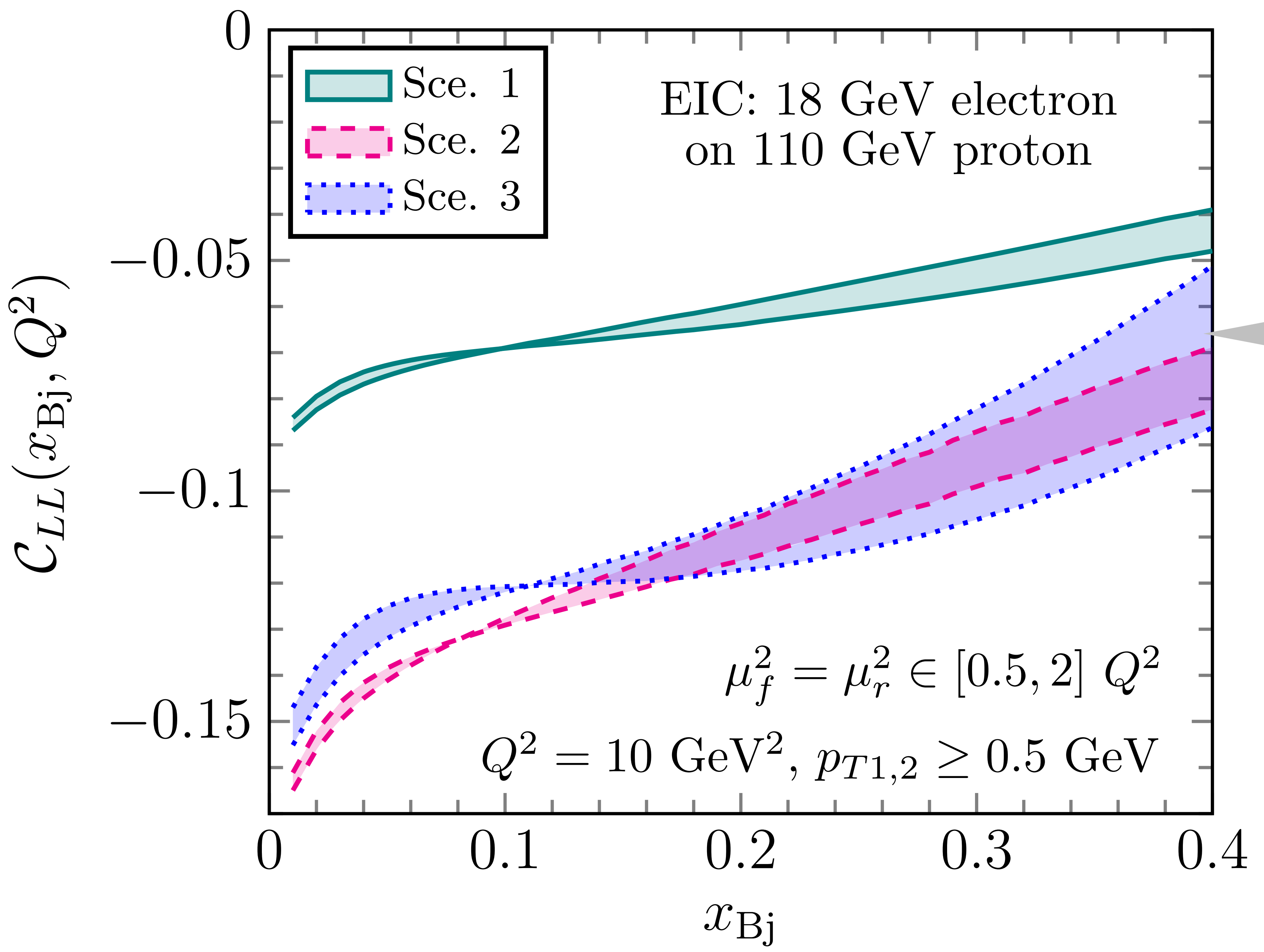
$\gamma_L^* + q \to g + q$: $C_{LL} = -1$, $C_{TT} = 0$

kinematics invariant

Z.X. Chen, H. Dong, S.Y. Wei, 2404.19202;
L. Yang, Y.K. Song, S.Y. Wei, 2410.20917.



vanish at the $Q^2 \to 0$ limit



longitudinal + transverse photons

Helicity correlation of b2b $\Lambda\bar{\Lambda}$ pair at EIC using DSV

See W. Qi, Z. Guo, B.W. Xiao, 2506.12889 for near threshold production

Spin Correlation in *ep* collision

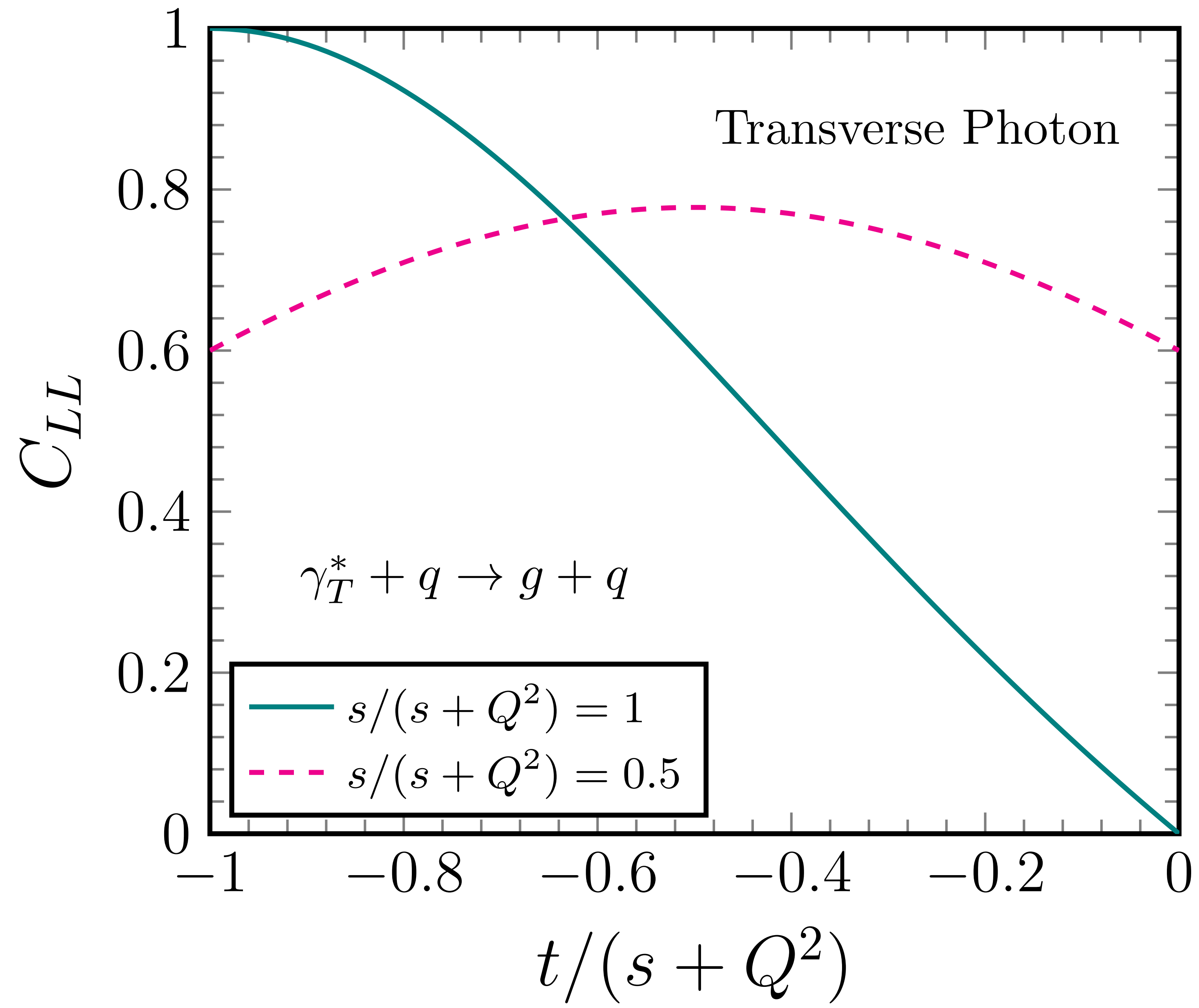
Transverse Photon γ_T^*

$\gamma_T^* + g \to q + \bar{q}$ $C_{LL} = -1$ due to helicity conservation

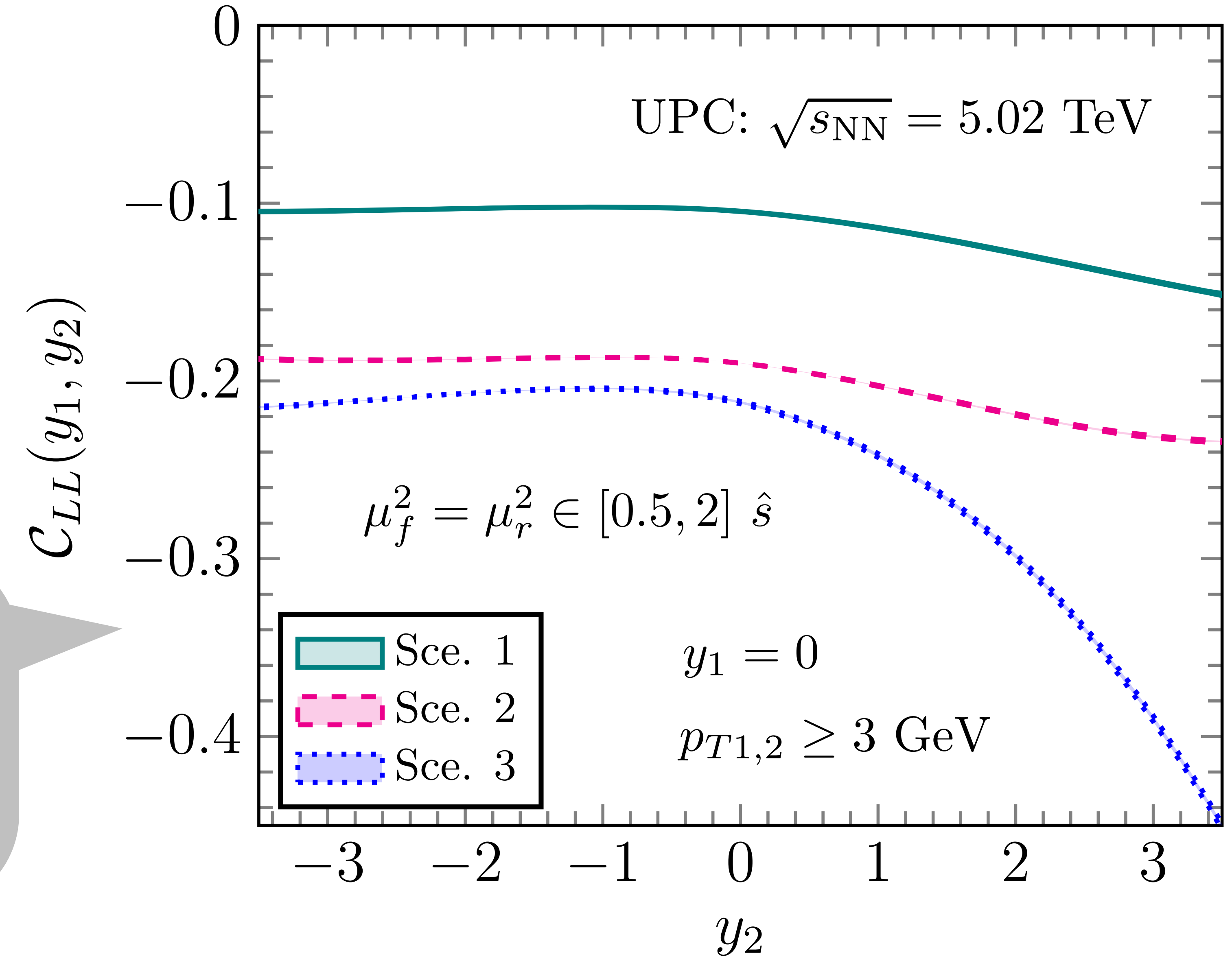
$\gamma_T^* + q \to g + q$

$$C_{LL} = \frac{(s+Q^2)^2\left[(s+Q^2)^2 - (u+Q^2)^2\right] - 2Q^2sut}{(s+Q^2)^2\left[(s+Q^2)^2 + (u+Q^2)^2\right] + 2Q^2sut}$$

Z.X. Chen, H. Dong, S.Y. Wei, 2404.19202;



$Q^2 \to 0$ limit



Helicity correlation of b2b $\Lambda\bar{\Lambda}$ pair at UPC

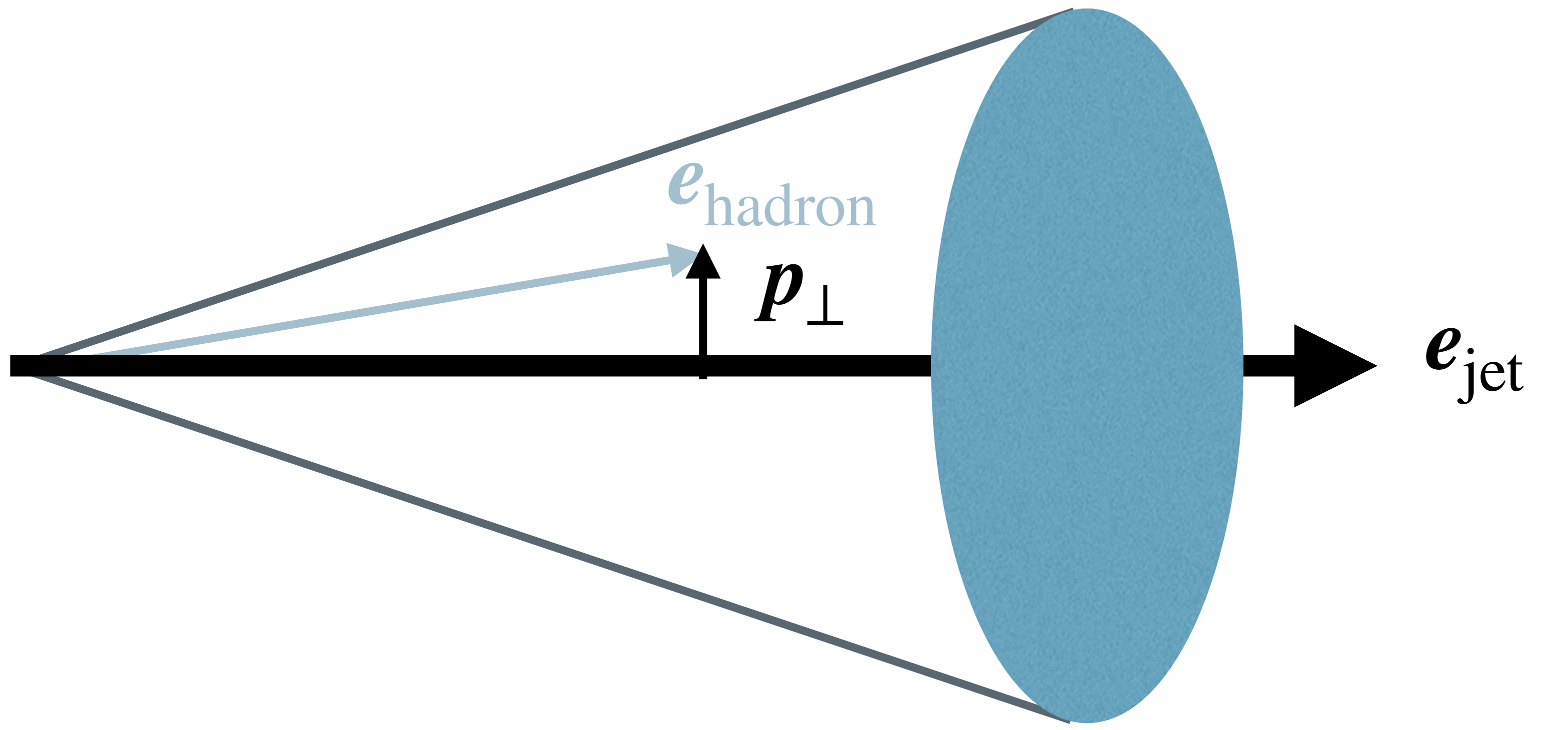
Menu

- Λ Helicity
- Spin Correlation
- Emerging Transverse Polarization

Emerging Transverse Polarization

Hadron-in-Jet: TMD factorization

$$p_\perp \ll E_{\text{hadron}} \sim E_{\text{jet}}$$



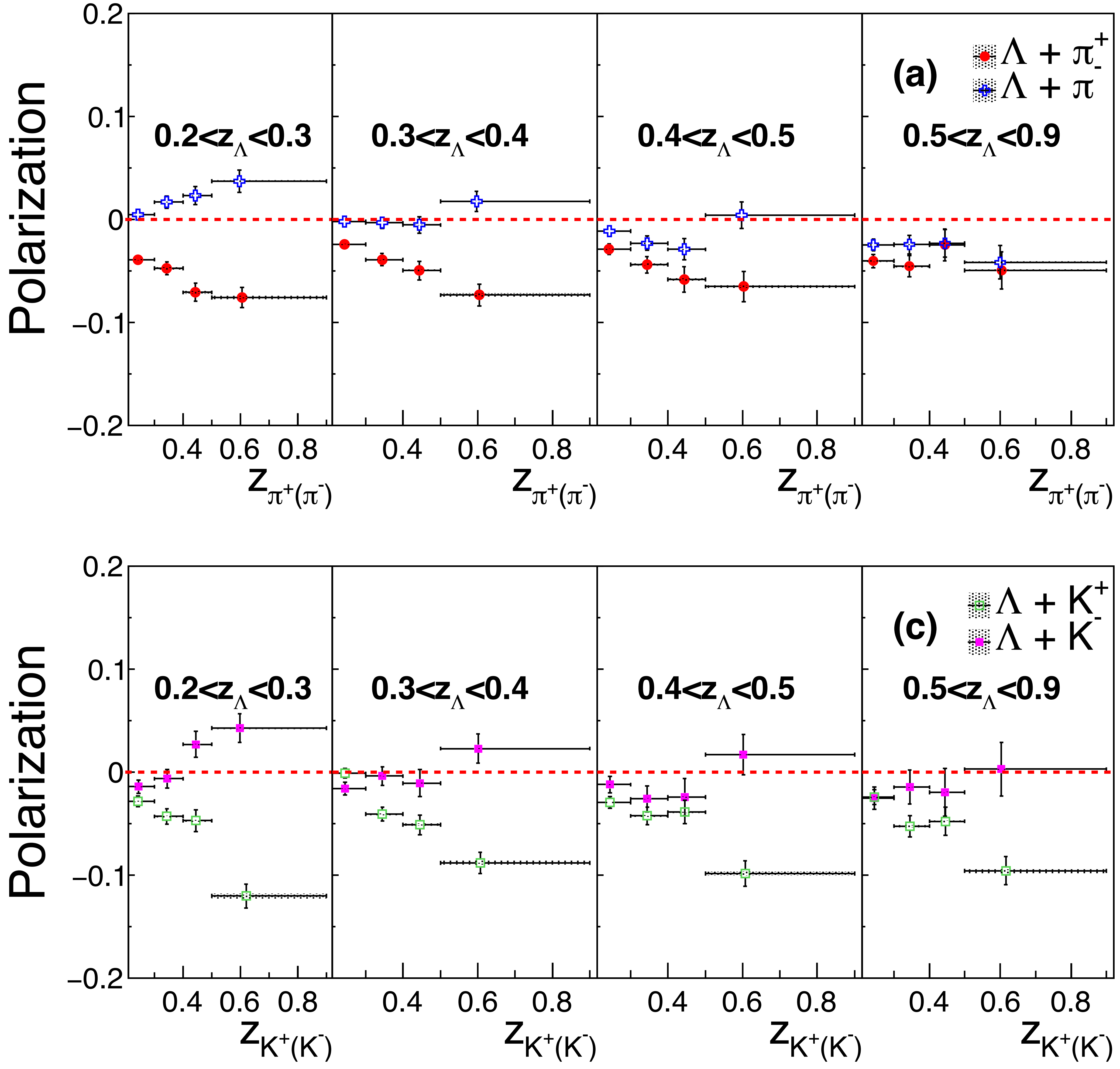
Baryons

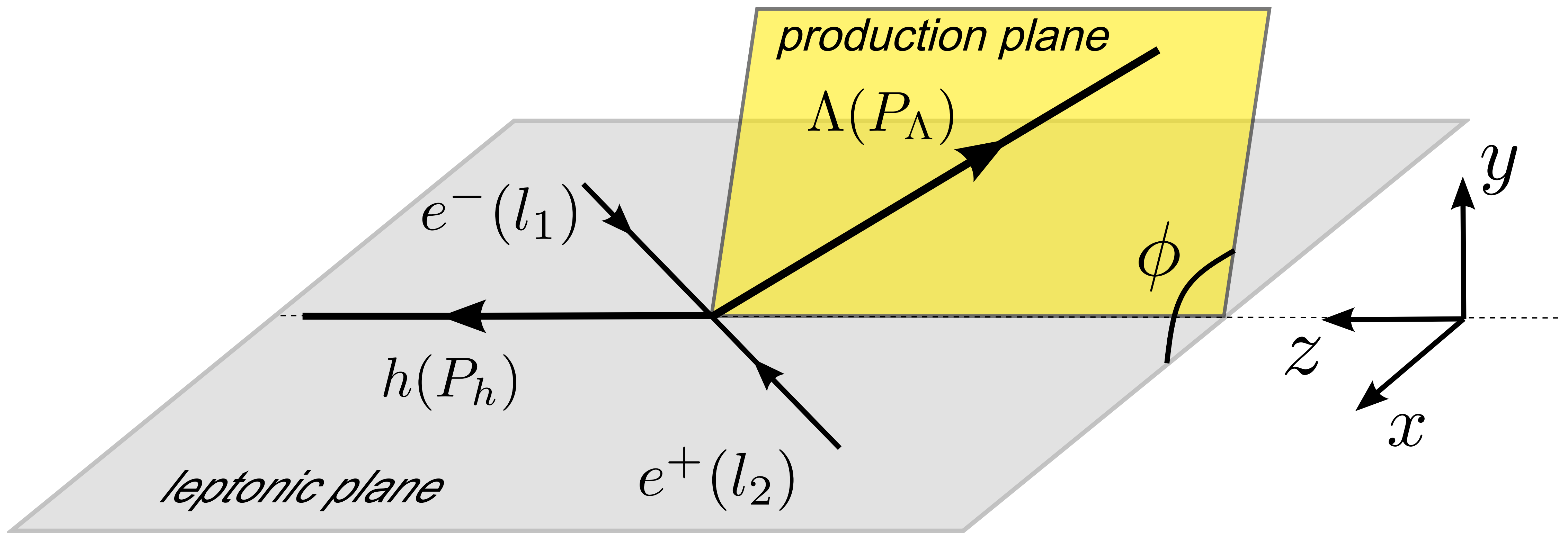
Quarks	Unpolarized	L	T
Unpolarized	D_1		$D_{1T}^\perp$
L		G_{1L}	$G_{1T}^\perp$
T	H_1	H_{1L}	$H_{1T}, H_{1T}^\perp$

$\boldsymbol{D_{1T}^\perp}$: Producing Transversely polarized hadron from unpolarized quark

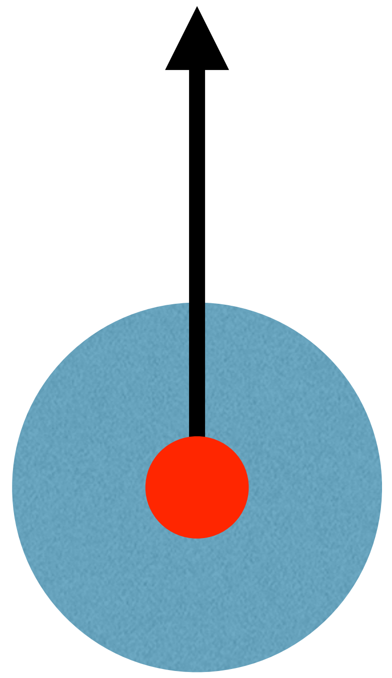
Emerging Transverse Polarization

Transverse Polarization in e^+e^-





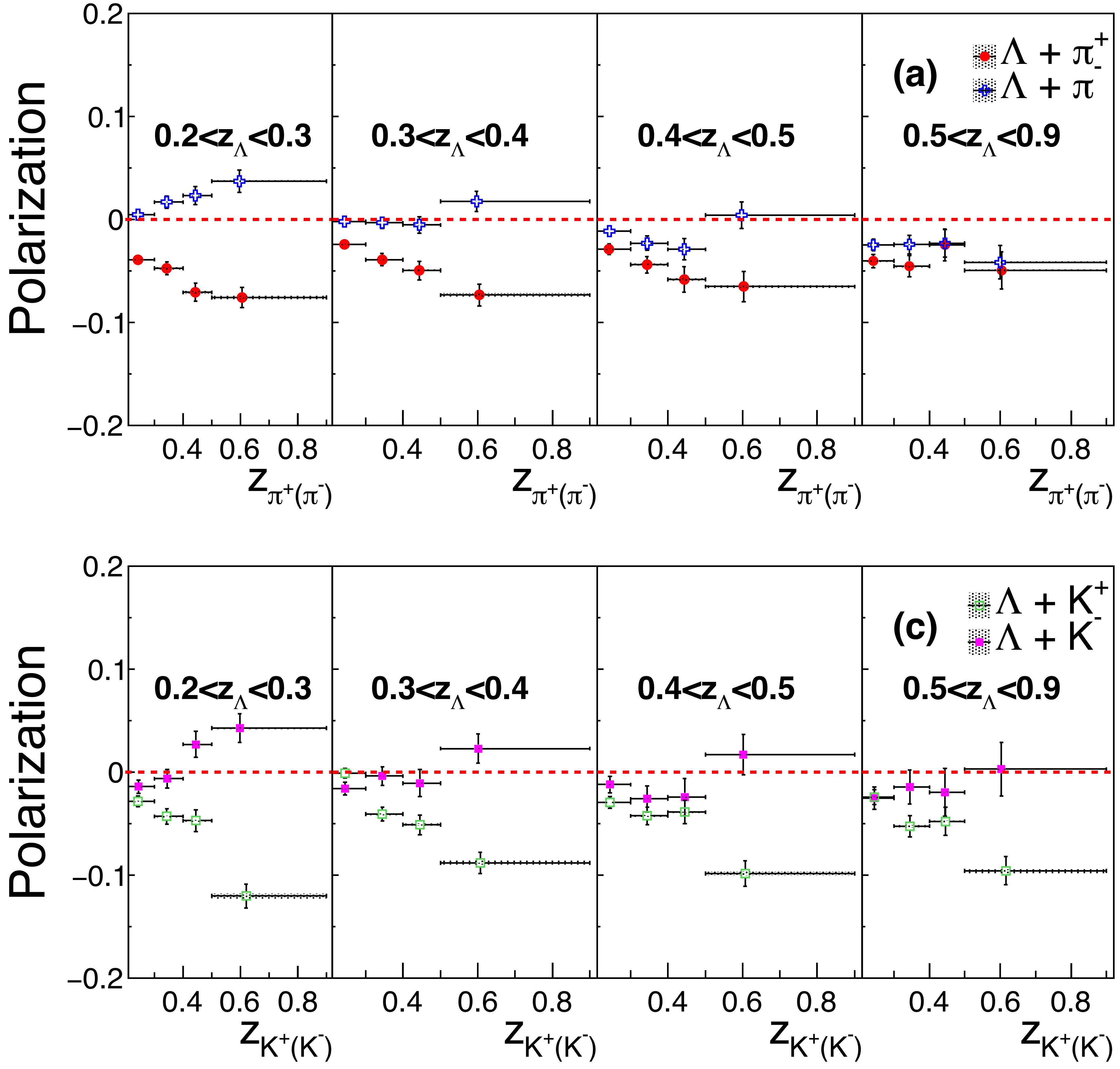
$$\left[D_{1q}^{\Lambda}(z_\Lambda, p_T) + \frac{(\hat{e}_j \times \boldsymbol{p}_T)\cdot \boldsymbol{S}_{\Lambda\perp}}{z_\Lambda M_\Lambda} D_{1Tq}^{\perp\Lambda}(z_\Lambda, p_T)\right]$$

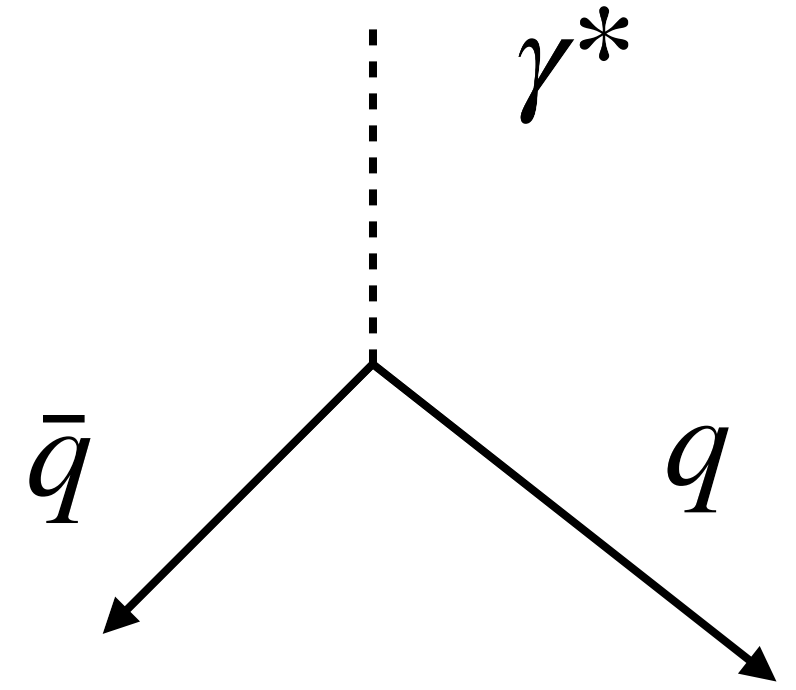


in analogue to Sivers function in TMD PDFs

[Belle], PRL122, 2019

Transverse Polarization in e^+e^-





$$\pi^+ : u\bar{d}; \qquad d \to \Lambda$$

$$\pi^- : \bar{u}d; \qquad u \to \Lambda$$

$$D_{1T}^{\perp}(u) \neq D_{1T}^{\perp}(d)$$

$$D_{1T}^{\perp}(u) \neq D_{1T}^{\perp}(s)$$

$$K^+ : u\bar{s}; \qquad s \to \Lambda$$

$$K^- : \bar{u}s; \qquad u \to \Lambda$$

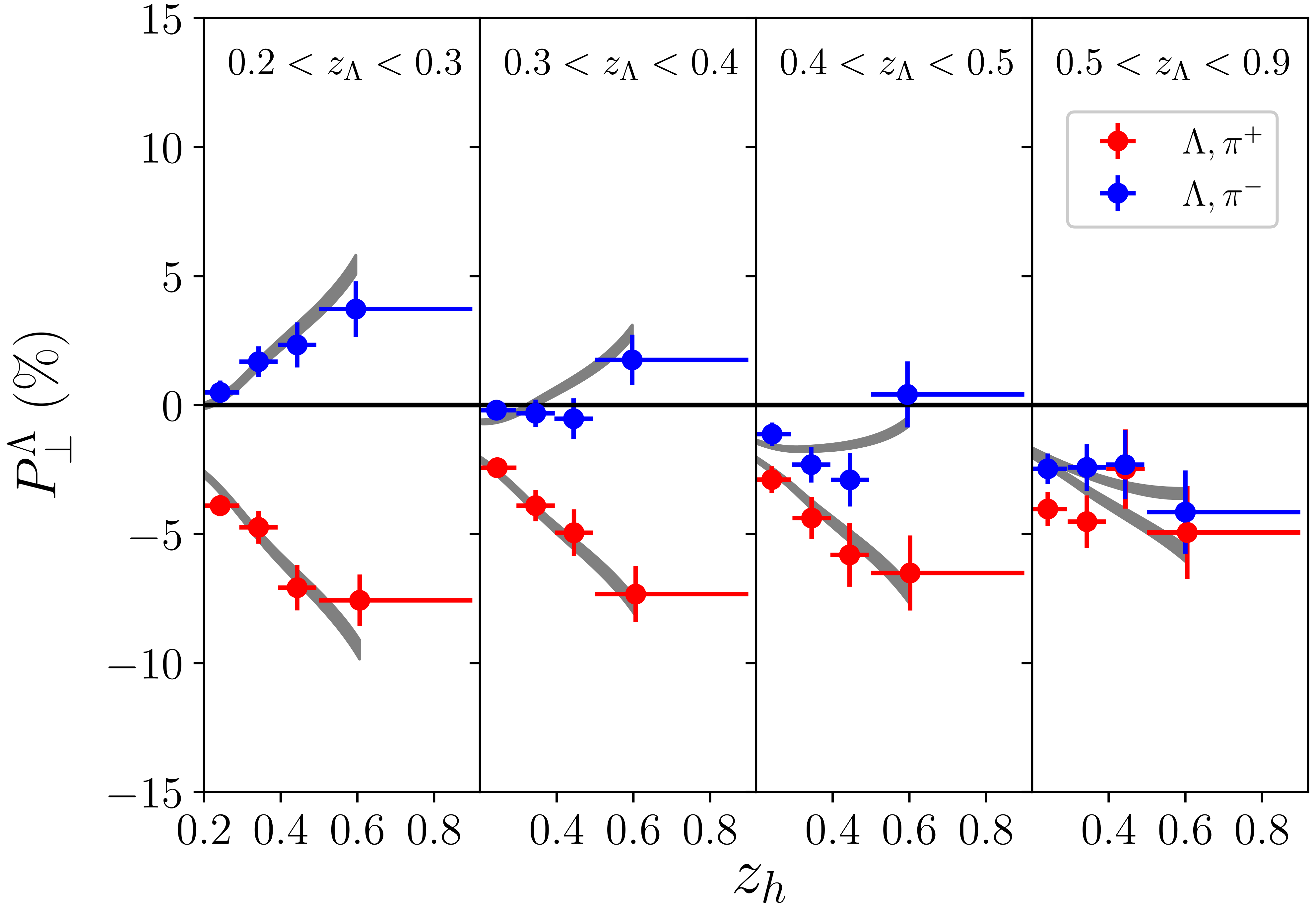
[Belle], PRL122, 2019

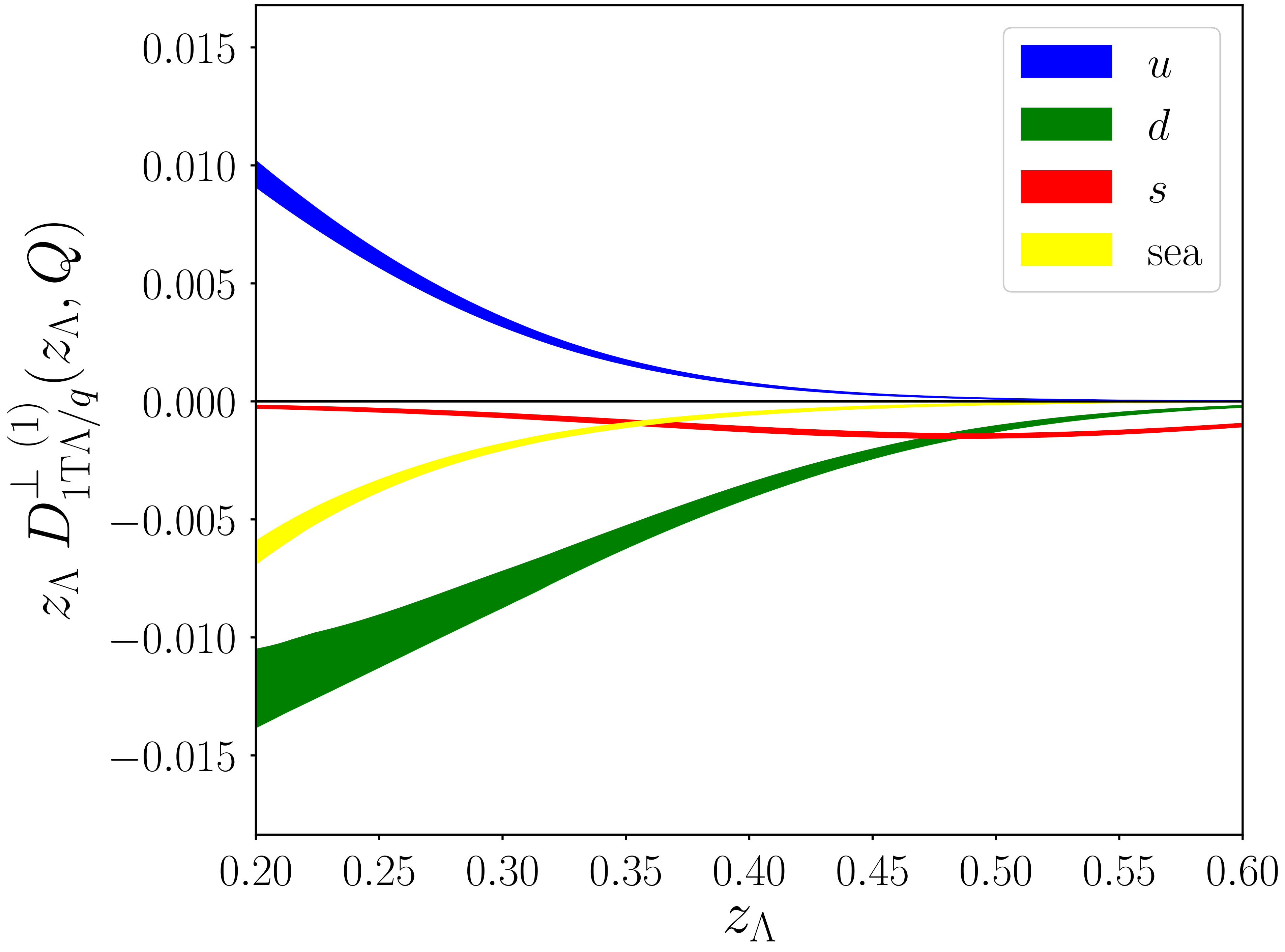
Emerging Transverse Polarization

Transverse Polarization in e^+e^-

differentiate valance quarks from sea quarks

$$D_{1T}^{\perp}(u) \neq D_{1T}^{\perp}(d) \neq D_{1T}^{\perp}(s) \neq D_{1T}^{\perp}(\text{sea})$$





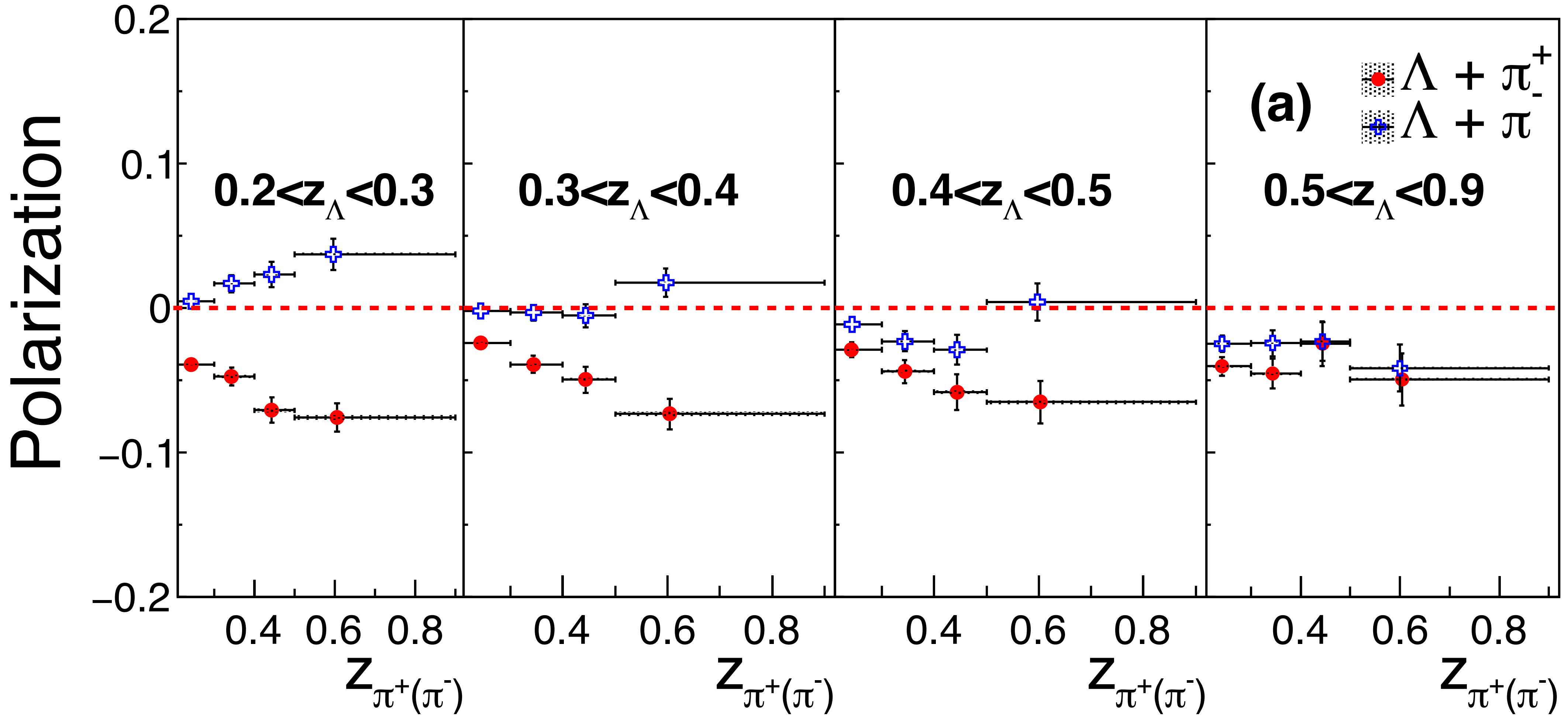
Strong violation of isospin symmetry

Callos, Kang, Terry, PRD 102 (2020)

D'Alesio, Murgia, Zaccheddu, PRD 102 (2020)

Emerging Transverse Polarization

Isospin Symmetry



isospin singlet

Robust symmetry in QCD

$$u \leftrightarrow d$$
$$\bar{u} \leftrightarrow \bar{d}$$

proton (uud) ↔ neutron (udd)

$$f^u_{\text{proton}}(x) = f^d_{\text{neutron}}(x)$$
$$f^d_{\text{proton}}(x) = f^u_{\text{neutron}}(x)$$

Lambda ↔ Lambda $\quad \frac{1}{\sqrt{2}}(u^\uparrow d^\downarrow - u^\downarrow d^\uparrow)s^\uparrow$

$$D_{1T}^{\perp,u\to\Lambda}(z,p_T) = D_{1T}^{\perp,d\to\Lambda}(z,p_T)$$

Emerging Transverse Polarization

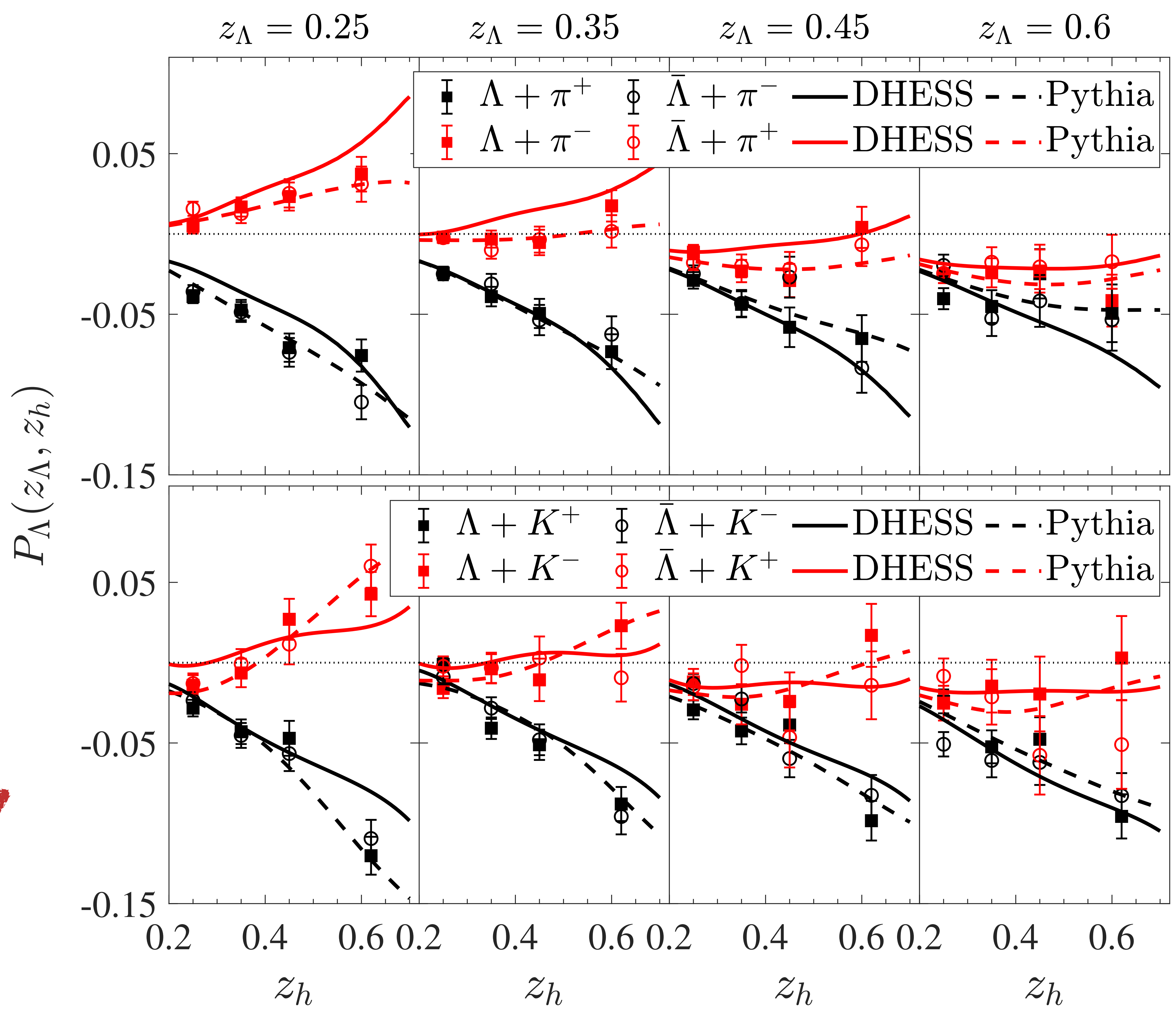
differentiate valance quarks
from sea quarks

$$D_{1T}^{\perp}(u) \neq D_{1T}^{\perp}(d) \neq D_{1T}^{\perp}(s) \neq D_{1T}^{\perp}(\text{sea})$$

paradigm
shift

enforce isospin symmetry

$$D_{1T}^{\perp}(u) = D_{1T}^{\perp}(d)$$
$$D_{1T}^{\perp}(\bar{u}) = D_{1T}^{\perp}(\bar{d})$$

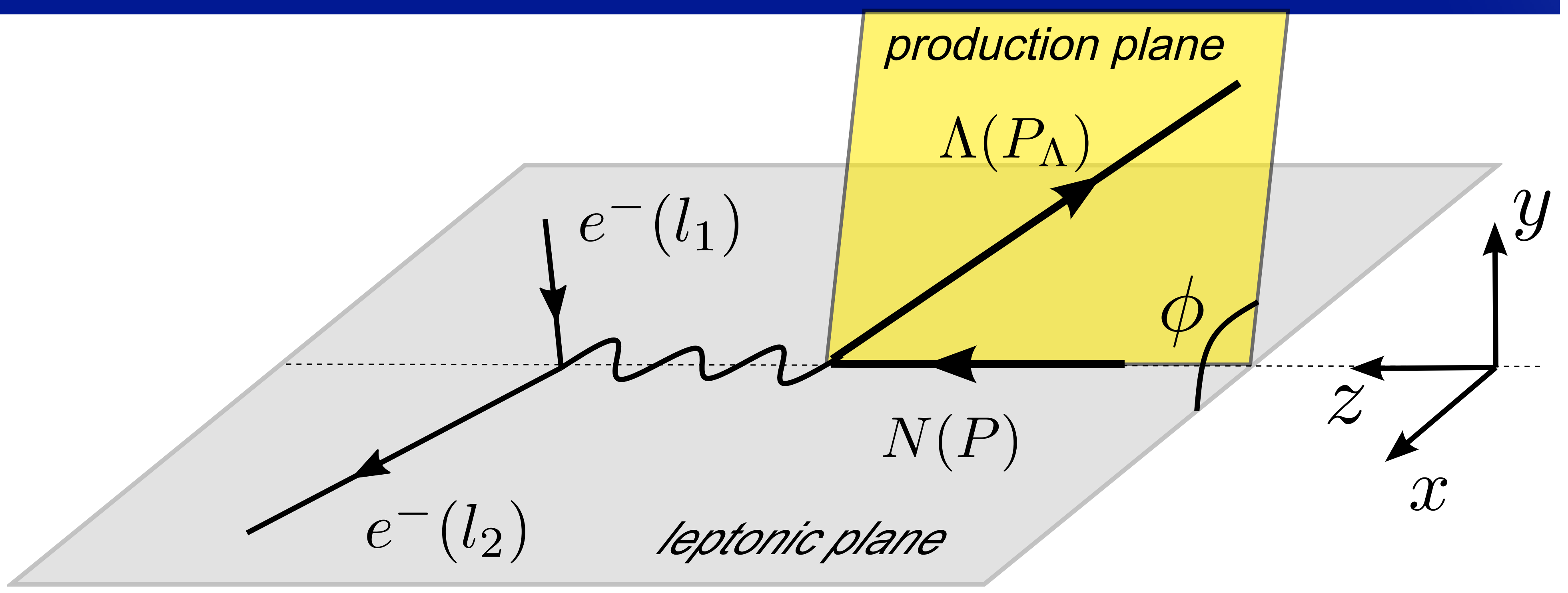


Belle data does not endorse isospin symmetry breaking.

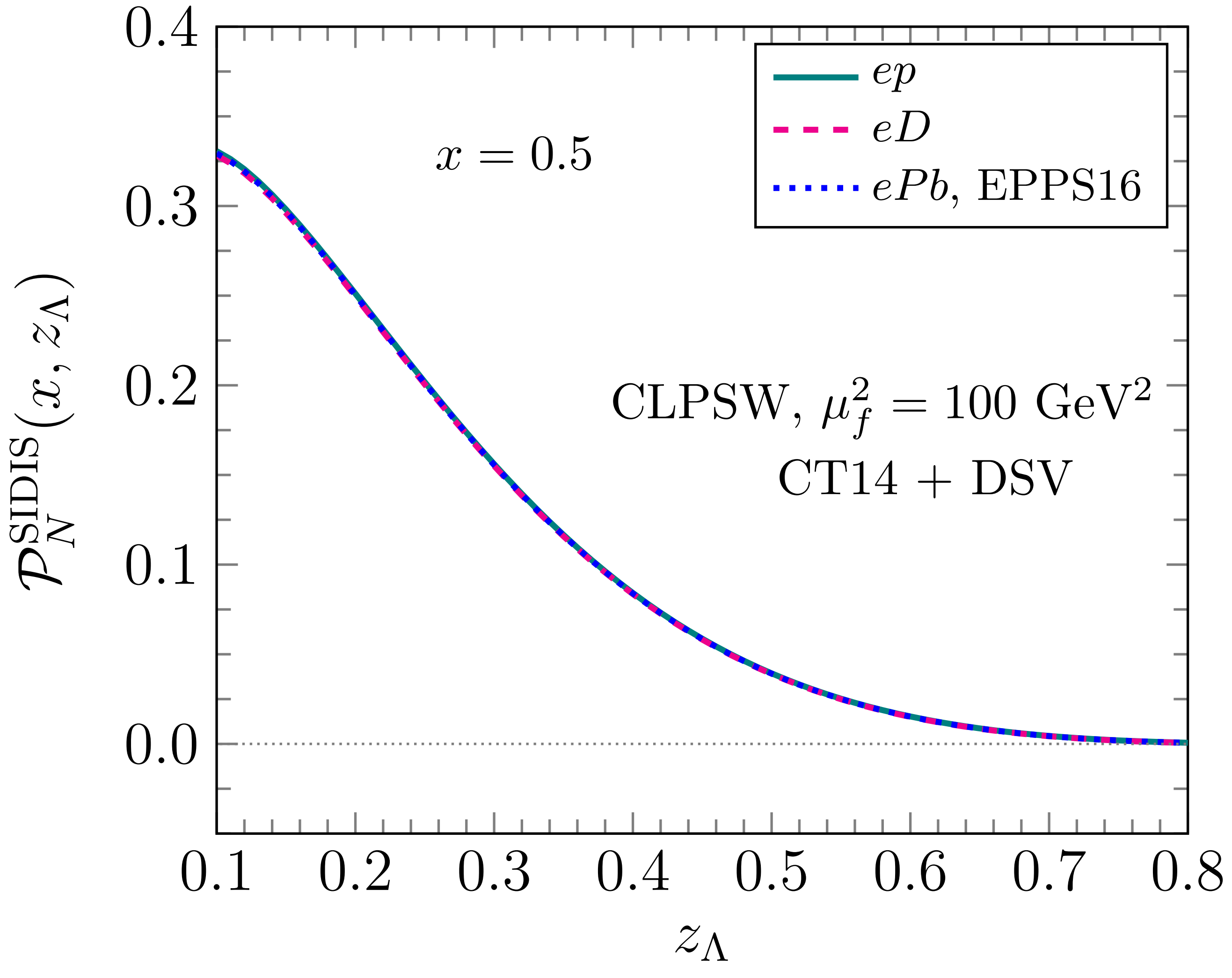
Chen, Liang, Pan, Song, Wei, PLB816 (2021)

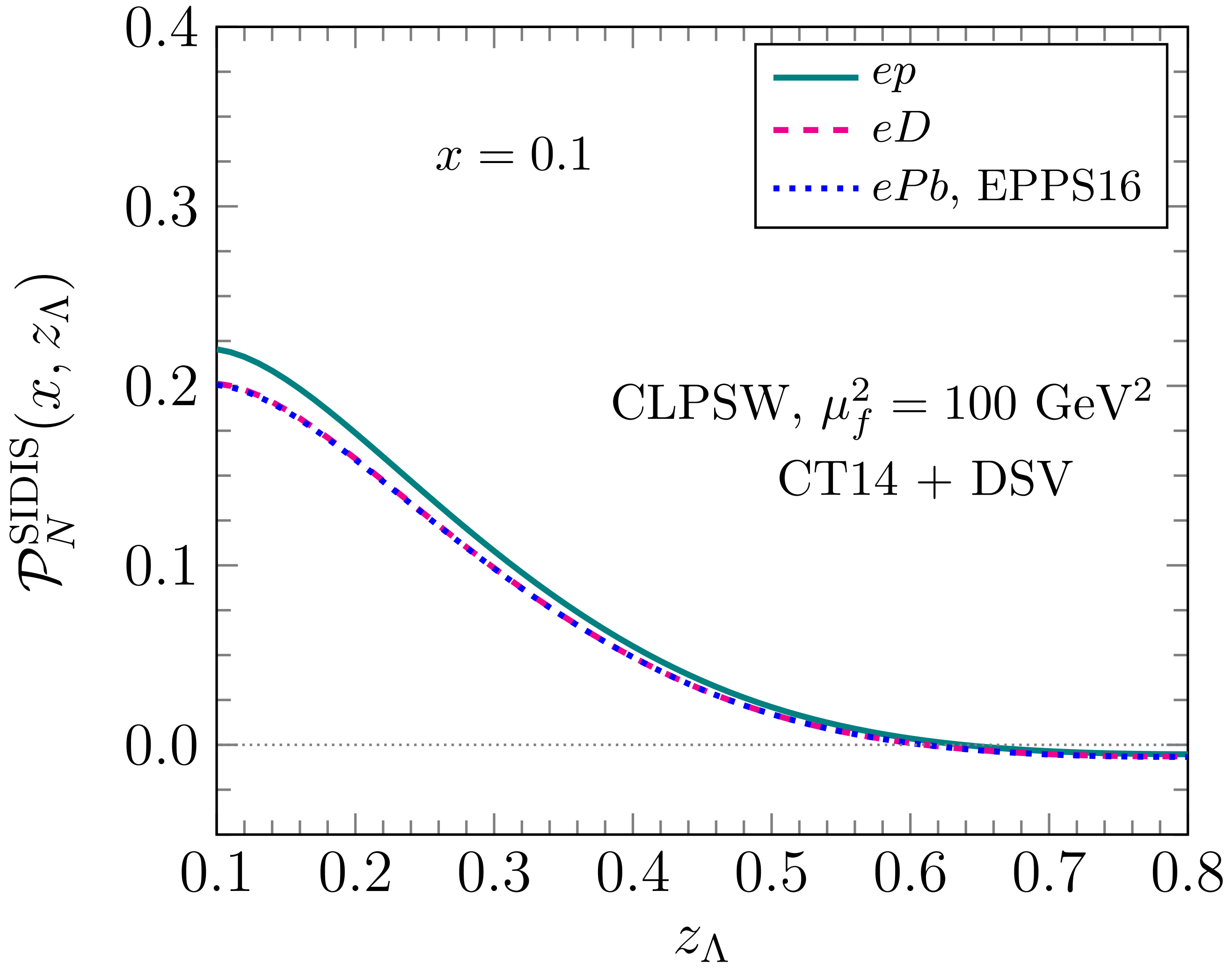
Emerging Transverse Polarization

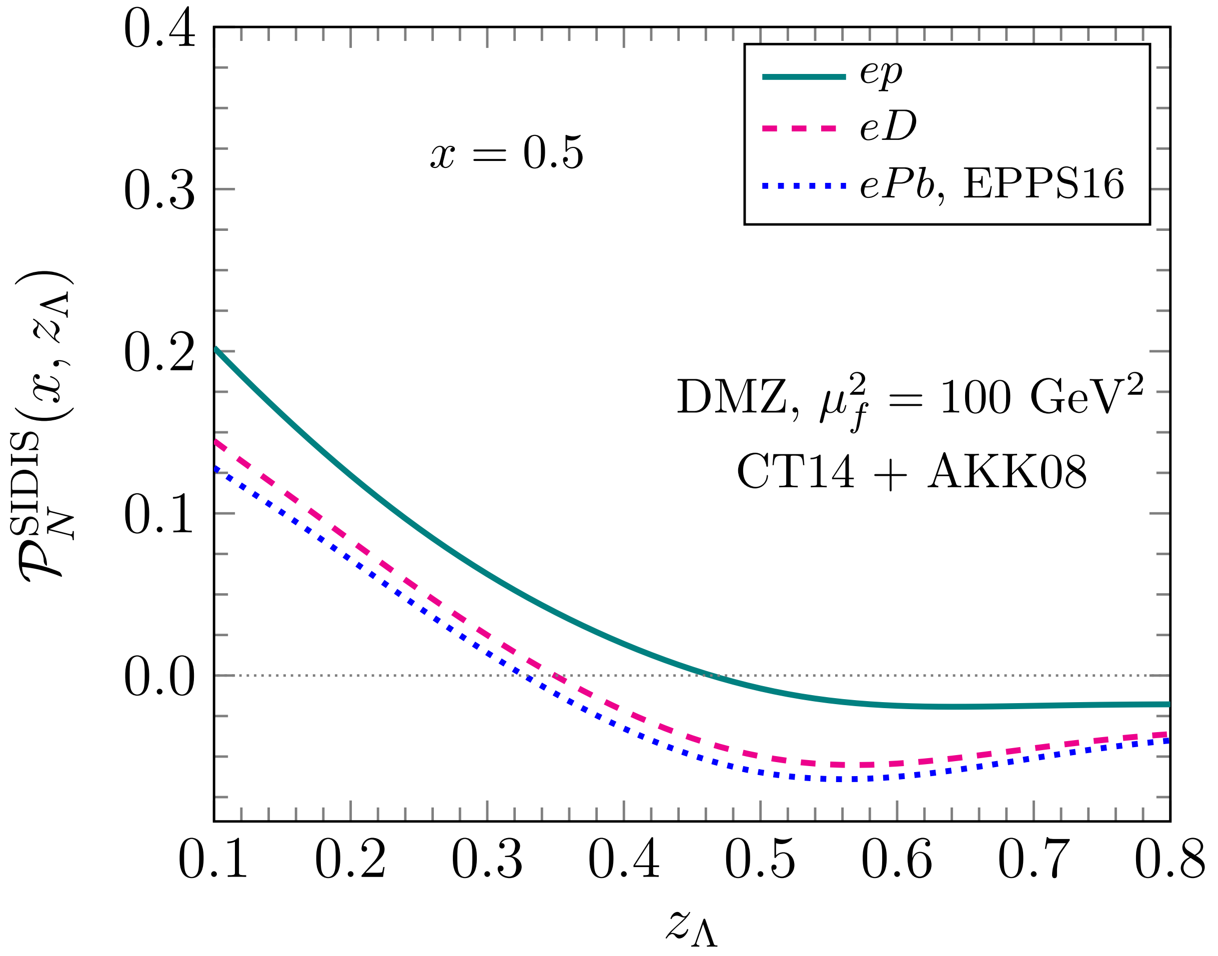
Transverse Polarization in *ep* vs *eA*

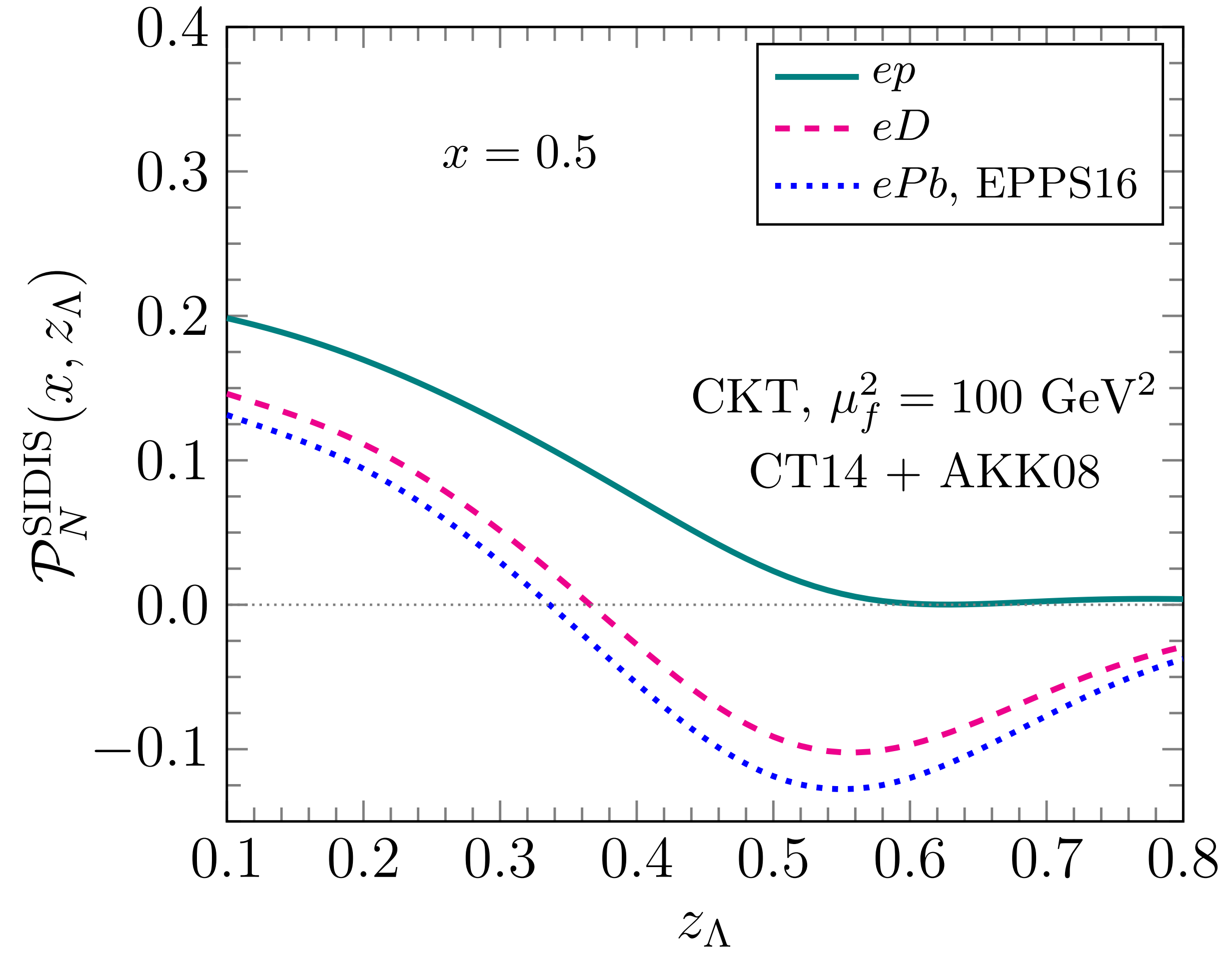


isospin symmetric









isospin-symmetry-violated parameterizations

[Chen, Liang, Song, Wei, 2021]

Conclusion

- Unpolarized High Energy Collisions are capable of investing Polarized hadronization.
- It offers important information on the hadronization from a unique perspective.

Thank you very much for your attention!