Probing Polarized Fragmentation Functions in Unpolarized Collisions

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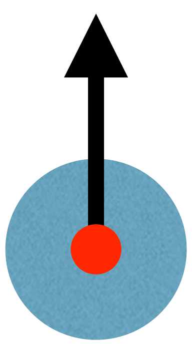
TMD factorization

partonic interaction, perturbative

$$\text{Cross Section} = \text{short distance} \otimes \text{long distance}$$

non-perturbative, universal

TMD PDFs: $\mathcal{FT}\langle p|\bar{\psi}(0)\psi(x^-,\vec{x}_\perp)|p\rangle$



$$\not{n}_+\left[f_1 - \frac{(\widehat{\boldsymbol{e}}_p \times \boldsymbol{k}_T)\cdot \boldsymbol{S}_\perp}{M} f_{1T}^\perp\right] + \gamma_5 \not{n}_+\left[\lambda g_{1L} + \frac{k_T\cdot S_\perp}{m} g_{1T}^\perp\right] + \frac{i[\not{k}_T,\not{n}_+]}{2m} h_1^\perp + \frac{1}{2}[\not{S}_\perp,\not{n}_+]\gamma_5 h_{1T} + \frac{[\not{k}_T,\not{n}_+]\gamma_5}{2m}\left[\lambda h_{1L}^\perp + \frac{k_T\cdot S_\perp}{m} h_{1T}^\perp\right]$$

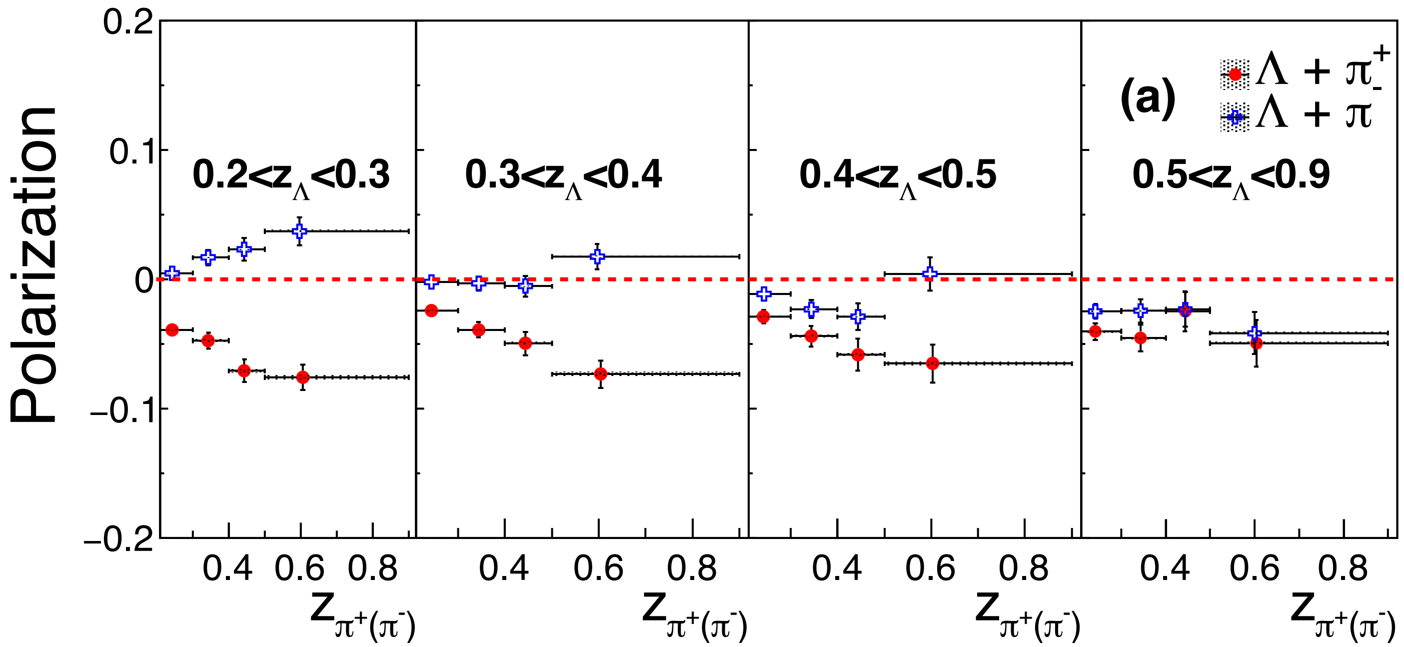
(x, k_{T})

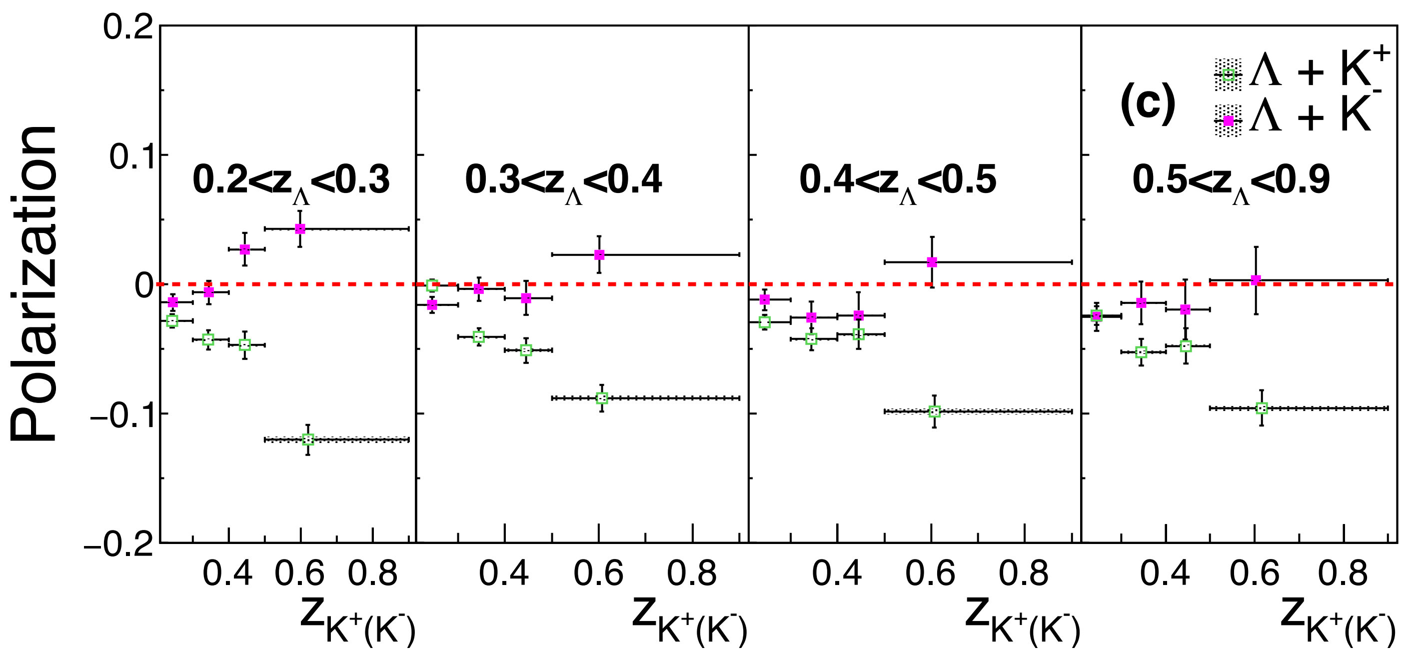
TMD FFs: $\mathcal{FT}\langle 0|\psi(0)|hX\rangle\langle hX|\bar{\psi}(x^-,\vec{x}_\perp)|0\rangle$

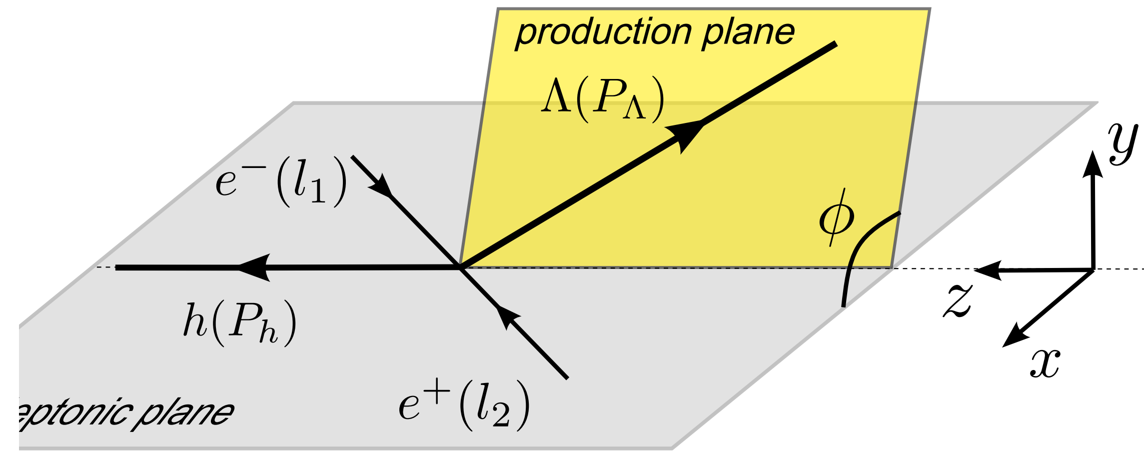
$$\not{n}_-\left[D_1 + \frac{(\widehat{\boldsymbol{e}}_j \times \boldsymbol{p}_T)\cdot \boldsymbol{S}_\perp}{zM} D_{1T}^\perp\right] + \gamma_5 \not{n}_-\left[\lambda G_{1L} + \frac{p_T\cdot S_\perp}{zM} G_{1T}^\perp\right] + \frac{i[\not{p}_T,\not{n}_-]}{2M} H_1^\perp + \frac{1}{2}[\not{S}_\perp,\not{n}_-]\gamma_5 H_{1T} + \frac{[\not{p}_T,\not{n}_-]\gamma_5}{2M}\left[\lambda H_{1L}^\perp + \frac{p_T\cdot S_\perp}{M} H_{1T}^\perp\right]$$

(z, p_{T})

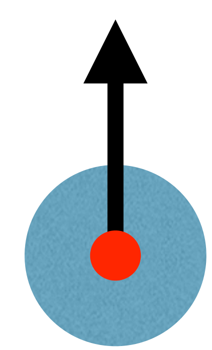
Transverse Polarization of Λ







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

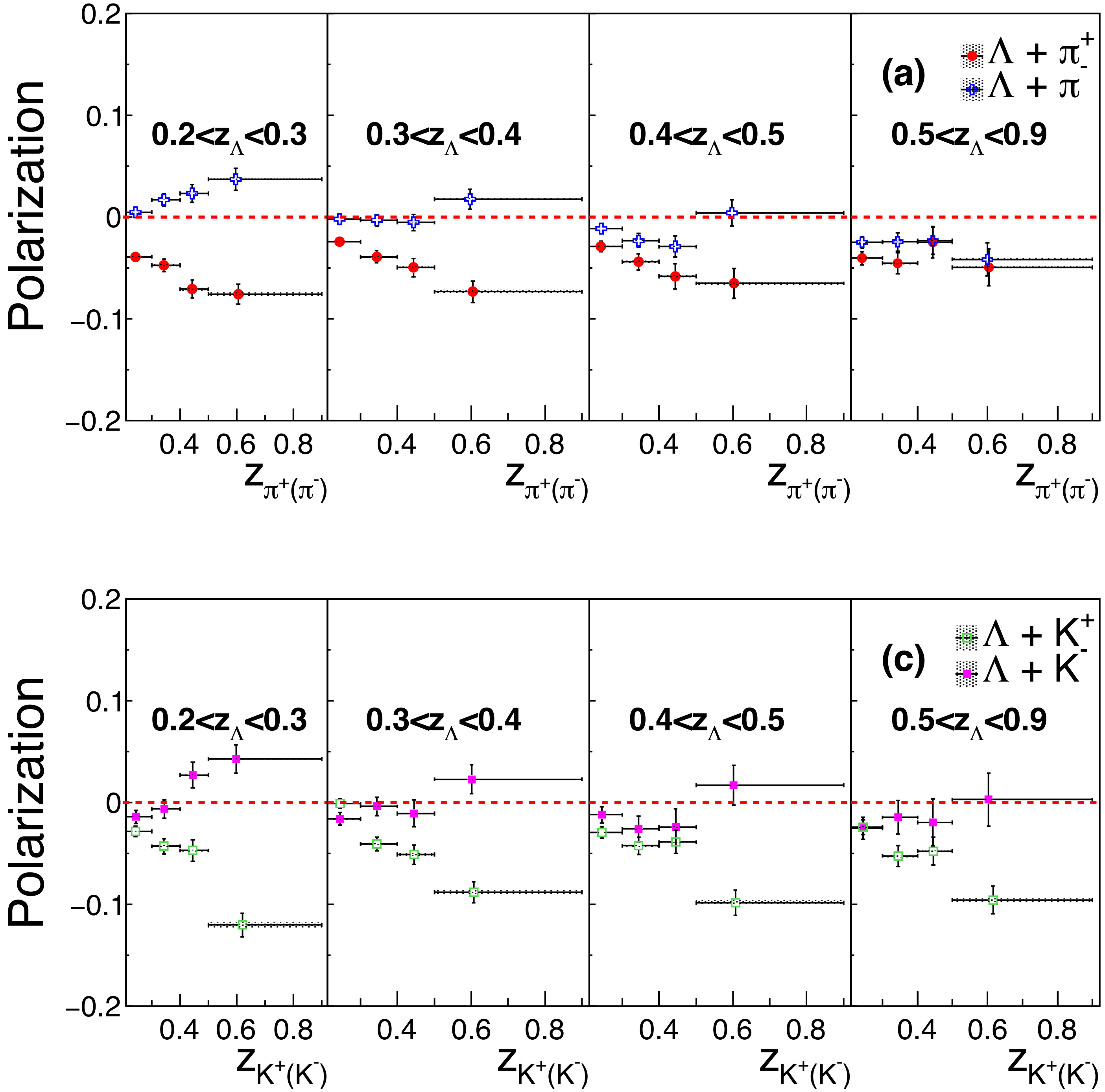


in analogue to
Sivers function
in TMD PDFs

[Belle], PRL122, 2019

Introduction

Transverse Polarization of Λ



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

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

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

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

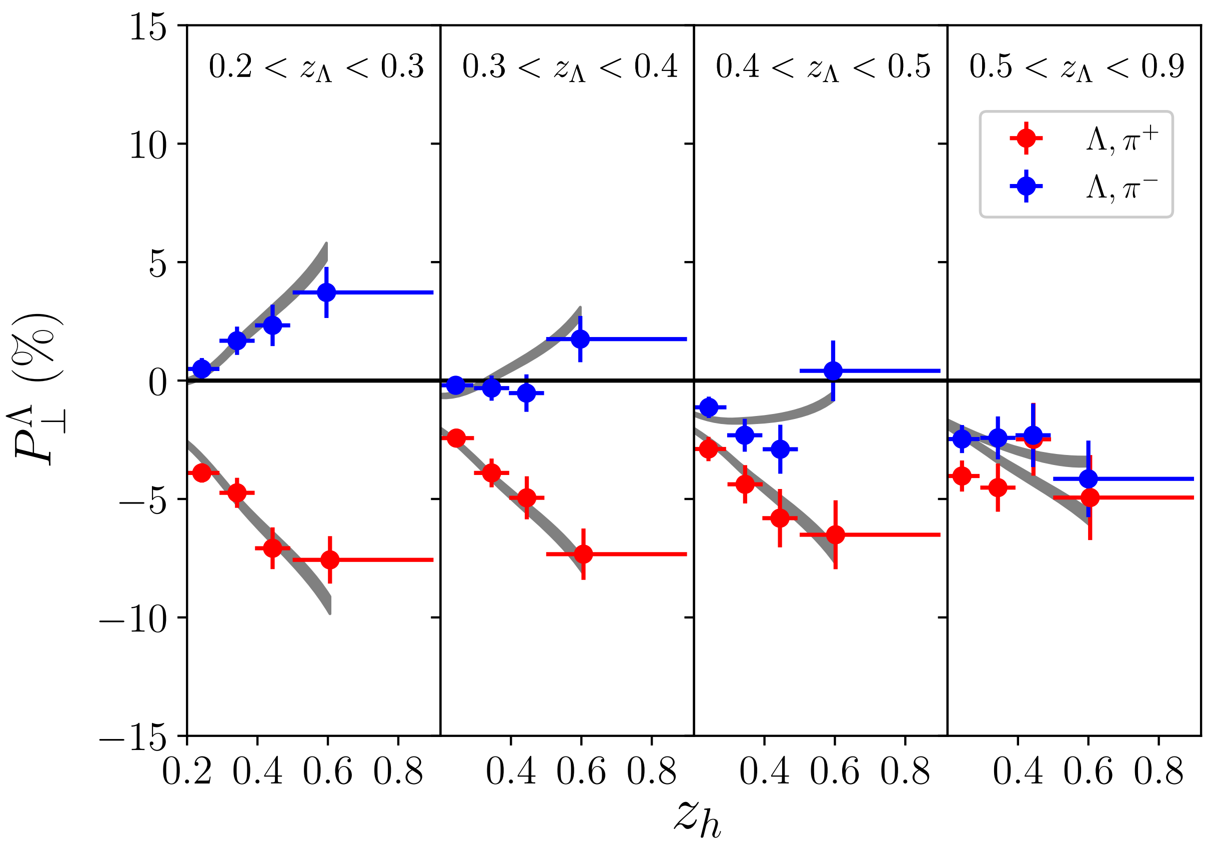
$K^+ : u\bar{s}; \quad s \to \Lambda$

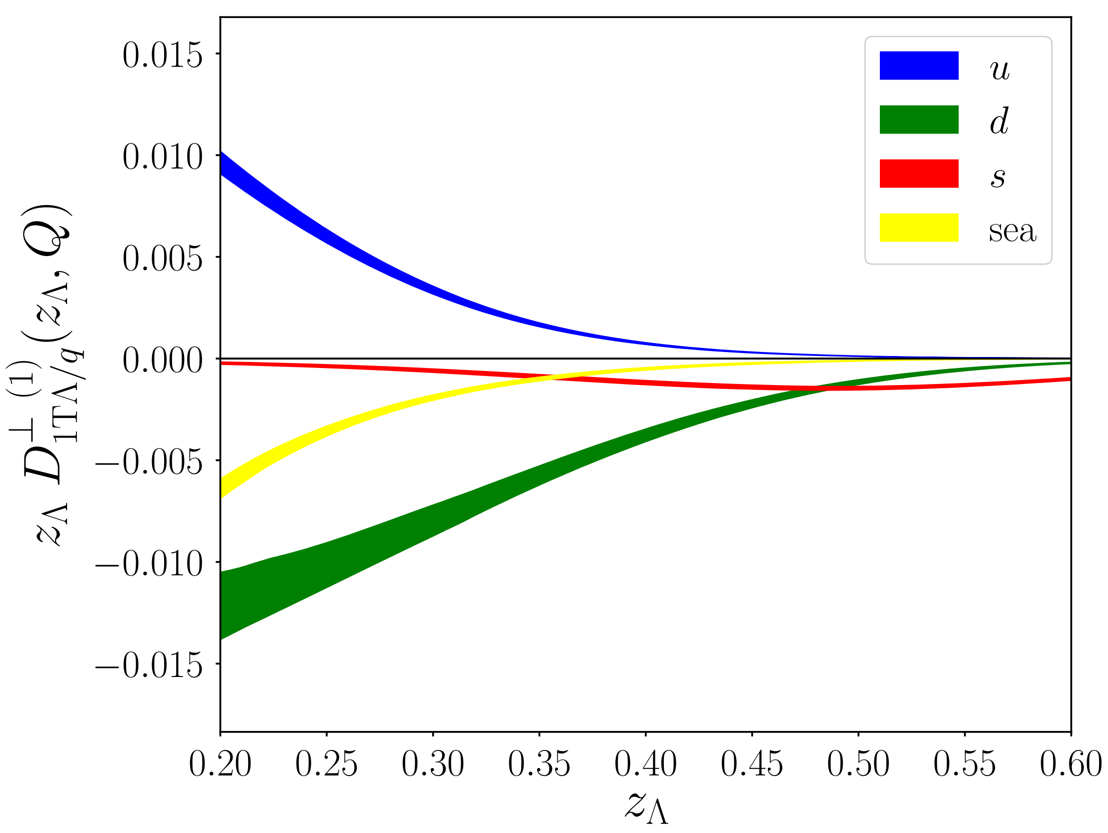
$K^- : \bar{u}s; \quad u \to \Lambda$

[Belle], PRL122, 2019

Transverse Polarization of Λ   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)

Isospin Symmetry Robust symmetry in QCD

$u \leftrightarrow d$

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

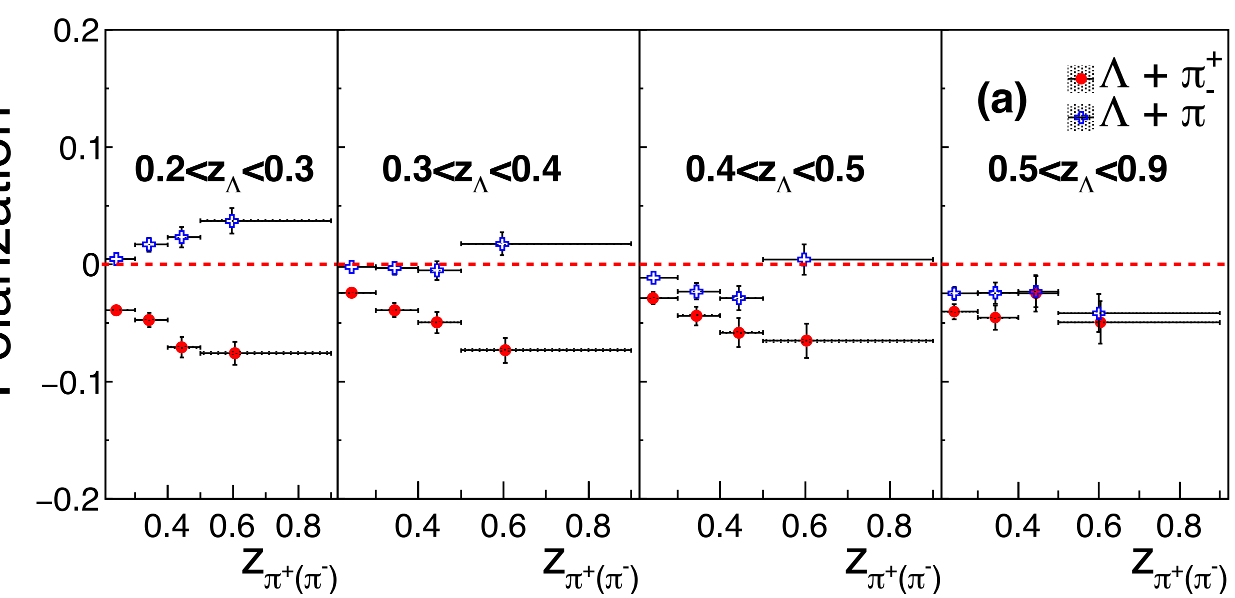
Example: proton (uud) $\leftrightarrow$ neutron (udd)

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

isospin singlet

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

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



☑ QED hard interaction

☑ QCD hadronization

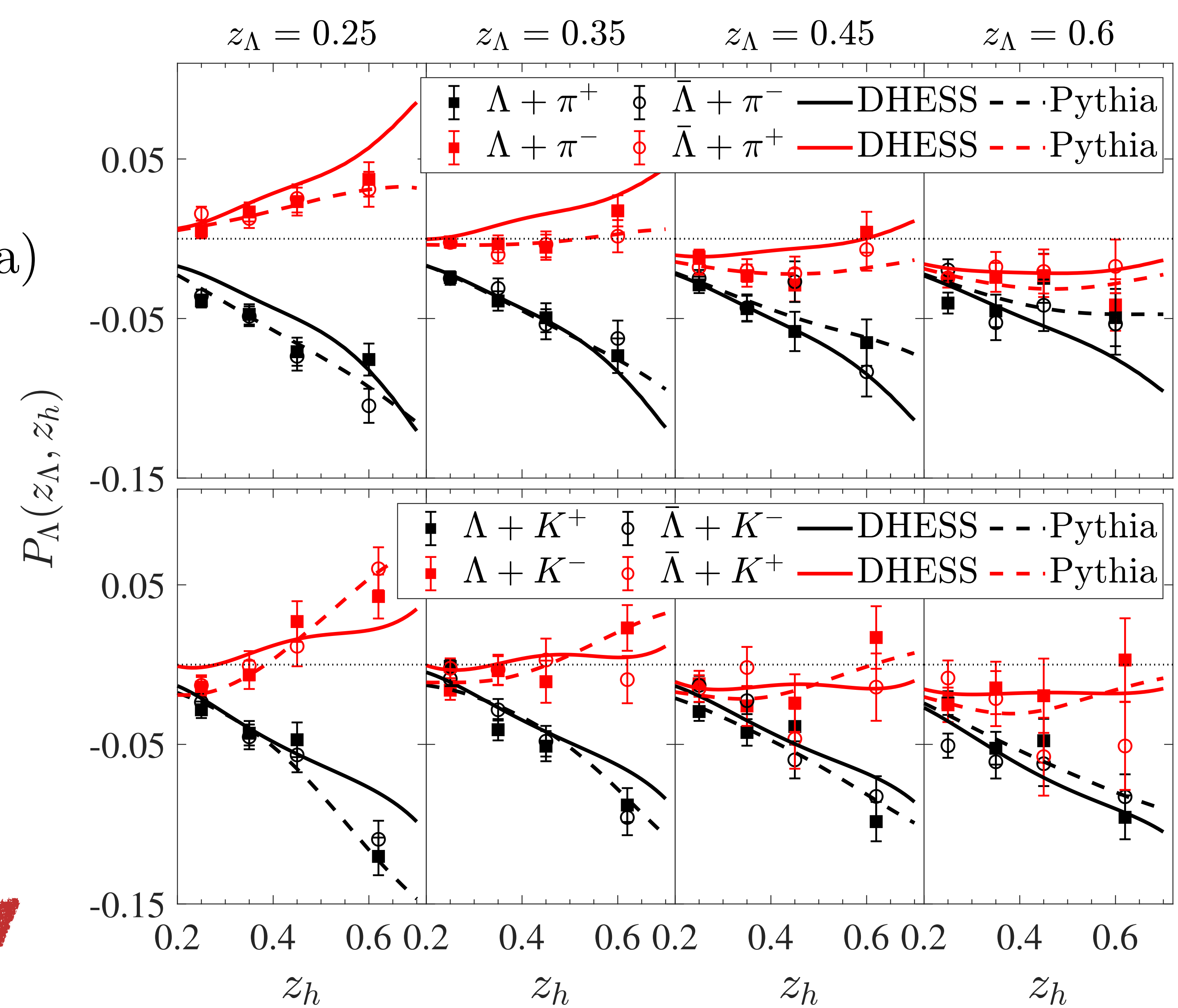
differentiating valance quarks
from sea quarks

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

paradigm
shift

enforcing isospin symmetry

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

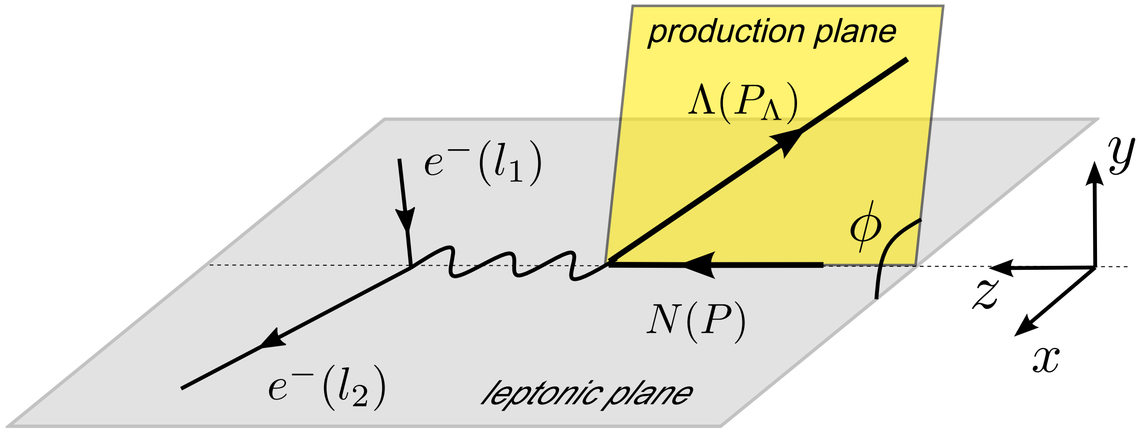


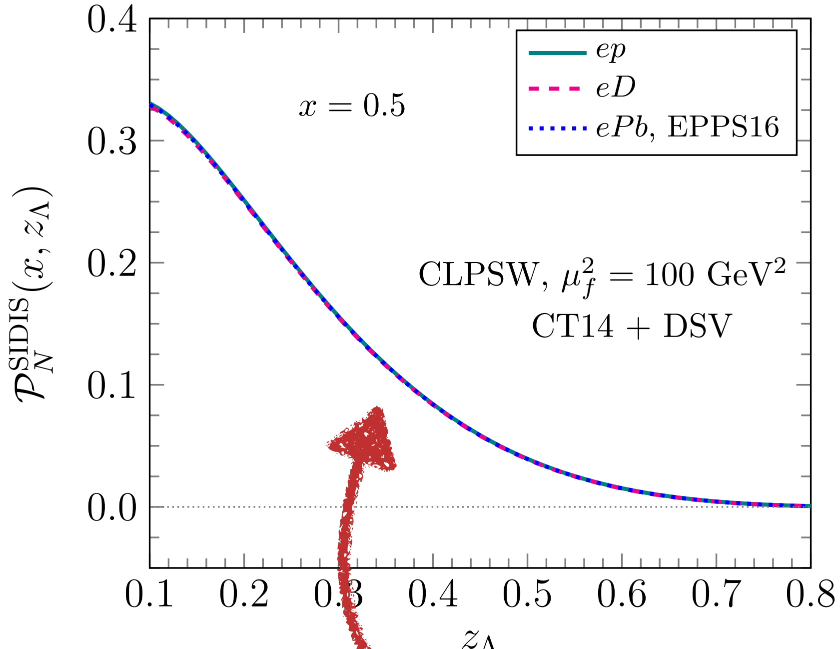
Belle data does not endorse isospin symmetry breaking.

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

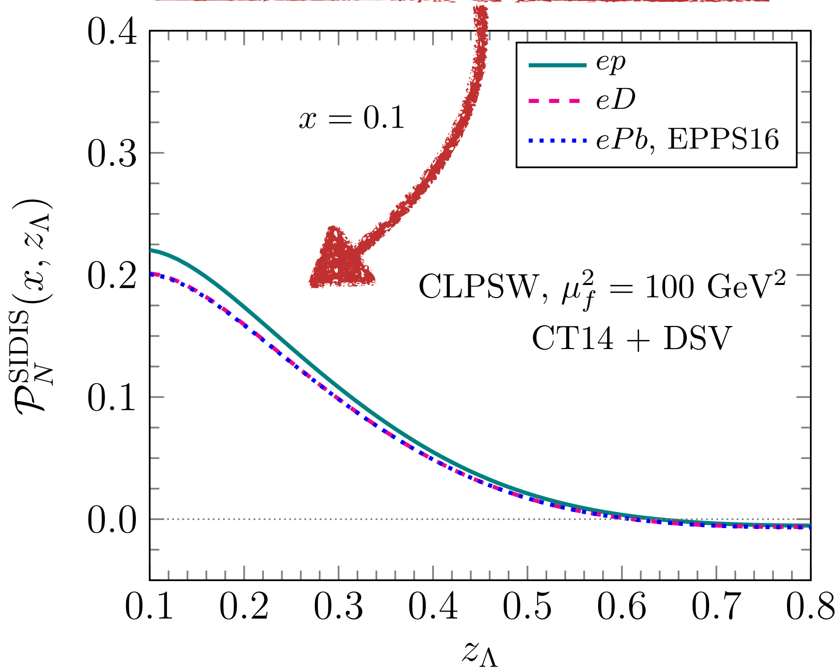
Isospin Symmetry

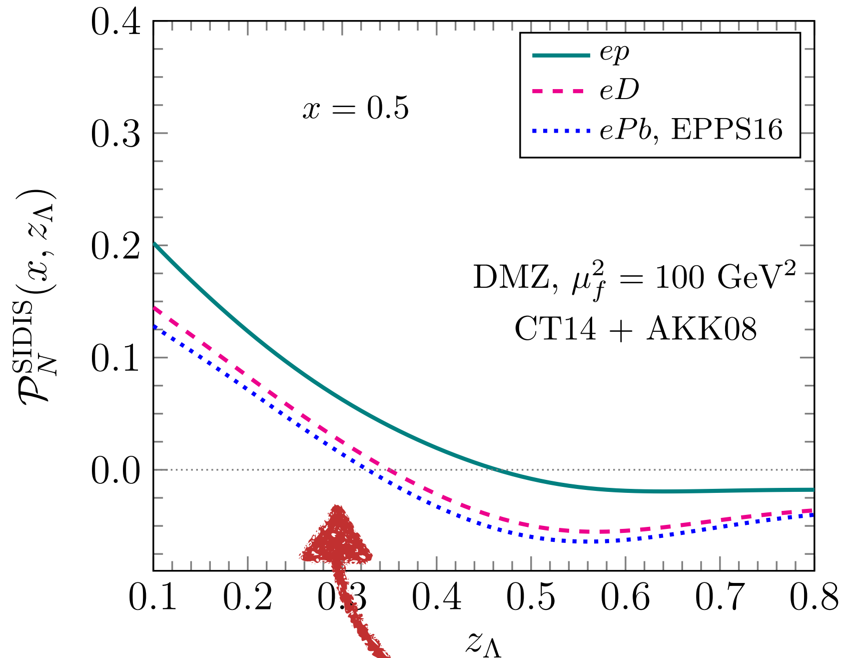
Testing Isospin Symmetry at EIC/EicC

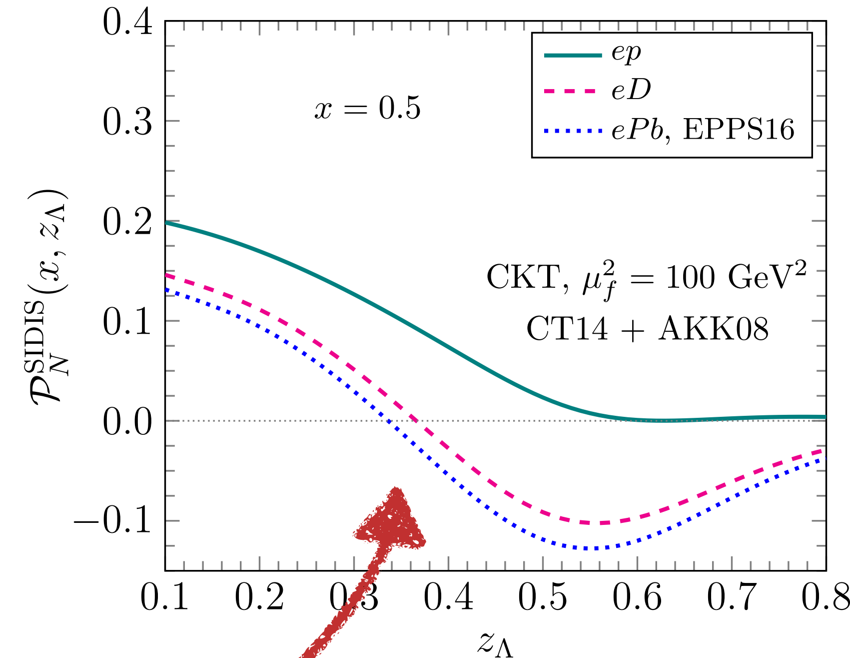




isospin symmetric







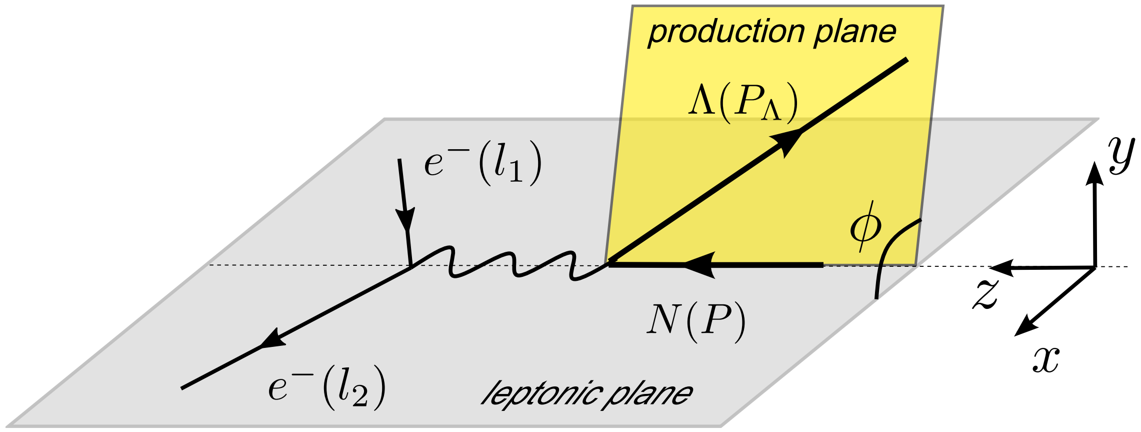
isospin-symmetry-violated parameterizations

Chen, Liang, Song, Wei, PRD(2022)

Hyperon Polarizations in unpolarized SIDIS

Kinematic Analysis

$$\sigma \propto L_{\mu\nu} W^{\mu\nu}(q, P, P_\Lambda, \vec{S}_\Lambda)$$



$$\begin{aligned}\frac{d\sigma^{\rm SIDIS}}{dx dy dz_\Lambda d^2 \boldsymbol{P}_{\Lambda\perp}} = & \frac{2\pi\alpha_{\rm em}^2}{xyQ^2}\Big\{A(y)F_{UU}^T + B(y)F_{UU}^L \\ & + C(y)\cos\phi F_{UU}^{\cos\phi} + B(y)\cos 2\phi F_{UU}^{\cos 2\phi} \\ & + \lambda_\Lambda \Big[C(y)\sin\phi F_{UL}^{\sin\phi} + B(y)\sin 2\phi F_{UL}^{\sin 2\phi}\Big] \\ & + S_{\Lambda T}\Big[C(y)\sin\phi F_{UT}^{\sin\phi} + B(y)\sin 2\phi F_{UT}^{\sin 2\phi}\Big] \\ & + S_{\Lambda N}\Big[A(y)F_{UT}^T + B(y)F_{UT}^L + C(y)\cos\phi F_{UT}^{\cos\phi} + B(y)\cos 2\phi F_{UT}^{\cos 2\phi}\Big]\Big\}\end{aligned}$$

azimuthal asymmetries

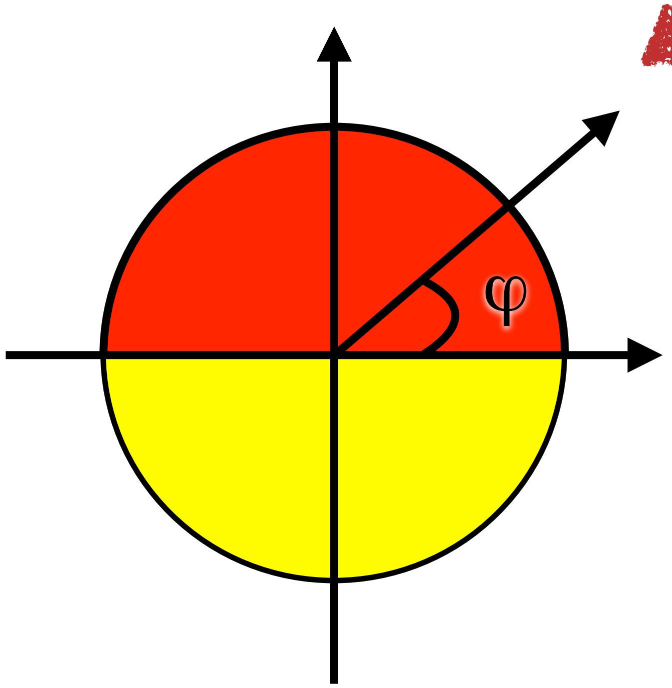
longitudinal polarization

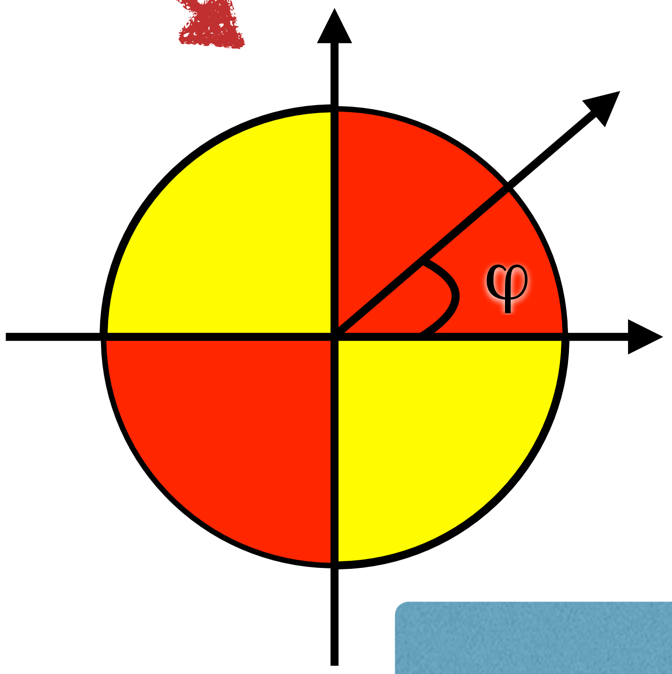
transverse polarizations

Arnold, Metz, Schlegel, PRD (2009)
Pitonyak, Schlegel, Metz, PRD (2014)
Chen, Yang, Wei, Liang, PRD (2016)
...

Longitudinal Polarization

$$\mathcal{P}_L(x,y,z_\Lambda,\boldsymbol{P}_{\Lambda\perp}) = \frac{1}{\mathcal{F}_{UU}^{\text{tot}}}\left\{C(y)\sin\phi F_{UL}^{\sin\phi} + B(y)\sin 2\phi F_{UL}^{\sin 2\phi}\right\}$$





$$\langle\mathcal{P}_L\rangle_{\text{I+II}} = \frac{2}{\pi}\frac{C(y)F_{UL}^{\sin\phi}}{A(y)F_{UU}^T + B(y)F_{UU}^L} = 0$$

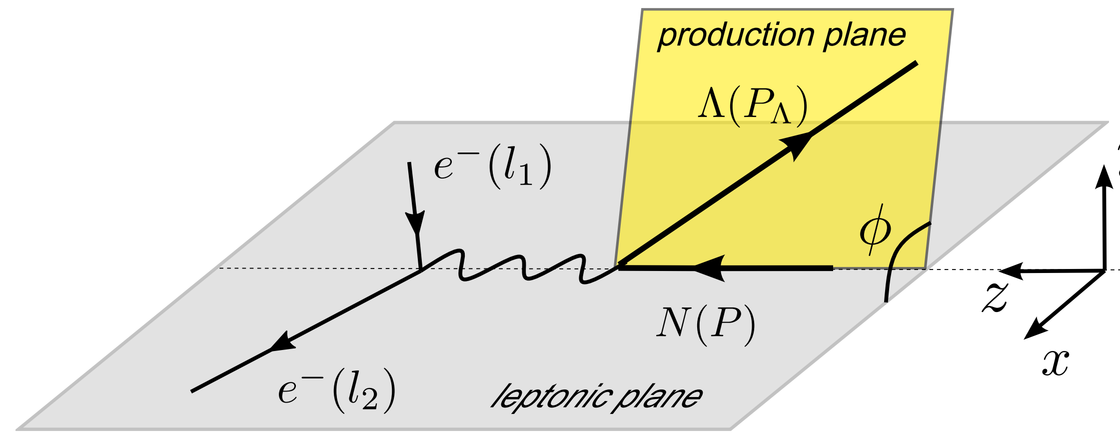
LO

leading twist

$$\langle\mathcal{P}_L\rangle_{\text{I+III}} = \frac{2}{\pi}\frac{B(y)F_{UL}^{\sin 2\phi}}{A(y)F_{UU}^T + B(y)F_{UU}^L} = \frac{2}{\pi}\frac{B(y)\mathcal{I}[w_2 h_1^\perp H_{1L}^{\perp\Lambda}]}{A(y)\mathcal{I}[f_1 D_1^\Lambda]}$$

Boer-Mulders function

Hyperon Polarizations in unpolarized SIDIS



Unpolarized Proton

$f_{1q}(x, k_\perp)$

$h_{1q}^\perp(x, k_\perp)$

Unpolarized Quark

Transversely Polarized Quark

$D_{1q}(z, p_T)$

Total Cross Section

$D_{1Tq}^\perp(z, p_T)$

Transverse P_N

$H_{1q}^\perp(z, p_T)$

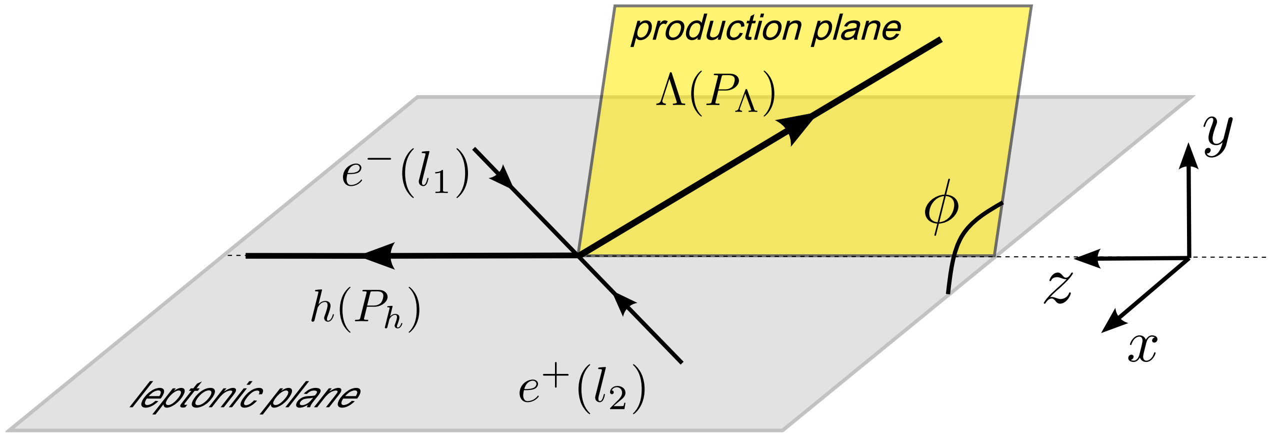
Azimuthal Asymmetry

$H_{1Lq}^\perp(z, p_T)$

Longitudinal P_L

$H_{1Tq}(z, p_T), \ H_{1Tq}^\perp(z, p_T)$

Transverse P_N, P_T



Longitudinal Polarization

$$\mathcal{P}_L(y, z_h, z_\Lambda, \boldsymbol{P}_{\Lambda\perp}) = \frac{1}{\mathcal{F}_{UU}^{\rm tot}}\Big\{\mathcal{C}(y)\sin\phi F_{UL}^{\sin\phi} + \mathcal{B}(y)\sin 2\phi F_{UL}^{\sin 2\phi}\Big\}$$

collins function

$$\langle\mathcal{P}_L\rangle_{\rm I+II} = \frac{2}{\pi}\frac{\mathcal{C}(y)F_{UL}^{\sin\phi}}{\mathcal{A}(y)F_{UU}^{T} + \mathcal{B}(y)F_{UU}^{L}} \xrightarrow[\text{leading twist}]{\text{LO}} = 0$$

$$\langle\mathcal{P}_L\rangle_{\rm I+III} = \frac{2}{\pi}\frac{\mathcal{B}(y)F_{UL}^{\sin 2\phi}}{\mathcal{A}(y)F_{UU}^{T} + \mathcal{B}(y)F_{UU}^{L}} = \frac{2}{\pi}\frac{\mathcal{B}(y)\mathcal{I}[\tilde{w}_2 H_1^{\perp h} H_{1L}^{\perp\Lambda}]}{\mathcal{A}(y)\mathcal{I}[D_1^h D_1^\Lambda]}$$

Summary

- ☑ Belle data does not signal the onset of isospin symmetry violation in polarized FFs.
- ☑ The isospin symmetry can be ultimately tested at the future EIC.
- ☑ Polarized FFs can be probed in unpolarized collisions.

Thanks for your attention!

The End