Polarized TMD FFs

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Y.Gao, K.B.Chen, **YKS**, S.Y.Wei, ArXiv: 2403.06133
Y.L.Pan, K.B.Chen, **YKS**, S.Y.Wei, PLB 850 (2024) 138509
K.B.Chen, Z.T.Liang, **YKS**, S.Y.Wei, PRD 105 (2022) 034027
K.B.Chen, Z.T.Liang, Y.L.Pan, **YKS**, S.Y.Wei, PLB 816 (2021) 136217

Outline

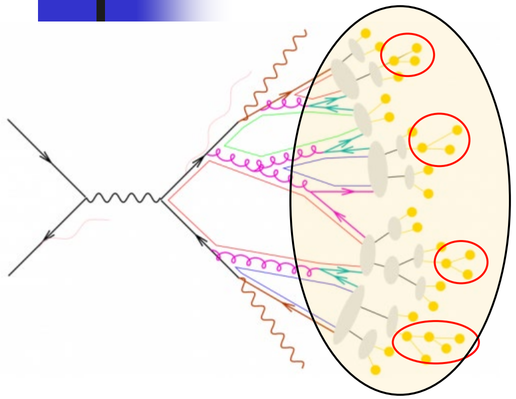
I. Introduction

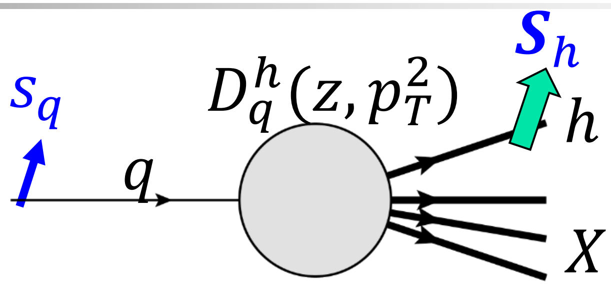
II. Transverse Λ polarization in e^+e^-, ep/eA and hadronic collisions ($D_{1T}^{\perp}$)

III. Longitudinal and transverse Λ polarization in e^+e^-, ep/eA collisions ($H_{1T}, H_{1T}^{\perp}, H_{1L}^{\perp}$)

IV. Weak decay contributions to FFs $\tilde{D}_{1L}, \tilde{G}_1$

V. Conclusion and outlook

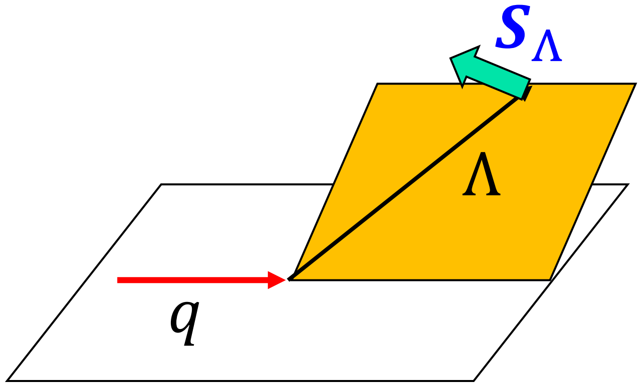




Polarized transverse-momentum-dependent fragmentation functions (**Polarized TMD FFs**)

TMD handbook
2304.03302

- For unpolarized reactions, without consider W/Z-exchange, **quarks are unpolarized**

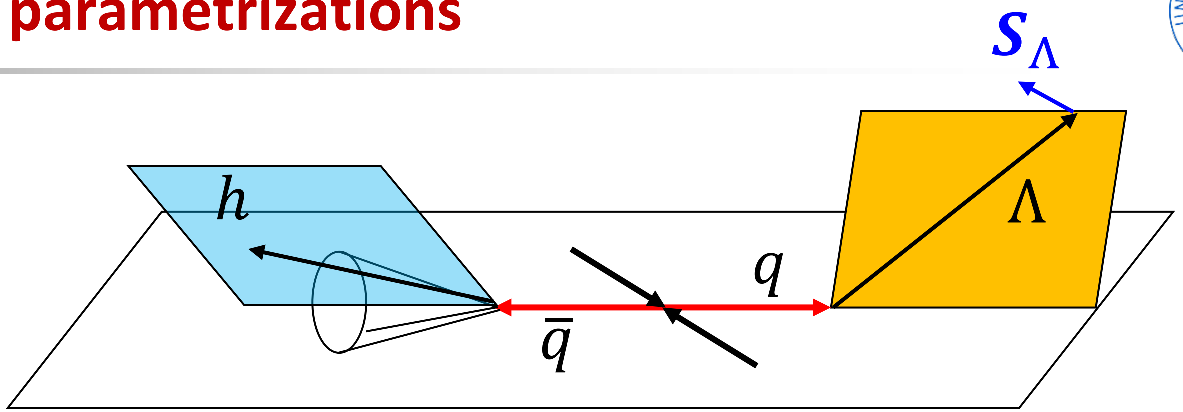


$$D_{1T}^{\perp}(z, p_T^2)$$
$$S_\Lambda \cdot (k \times p_\Lambda)$$

Leading Quark TMDFFs — Hadron Spin; Quark Spin

		Quark Polarization: Un-Polarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Unpolarized (or Spin 0) Hadrons		D_1 = Unpolarized		$H_1^{\perp}$ = Collins
Polarized Hadrons	L		G_1 = Helicity	$H_{1L}^{\perp}$ =
Polarized Hadrons	T	$D_{1T}^{\perp}$ = Polarizing FF	$G_{1T}^{\perp}$ =	H_1 = Transversity; $H_{1T}^{\perp}$ =

Belle data and parametrizations



- Belle collaboration PRL 122 (2019) 042001

1. Inclusive process in thrust frame

$$e^+e^- \to \Lambda(\bar{\Lambda})X$$

2. Semi-inclusive process

$$e^+e^- \to \Lambda(\bar{\Lambda})hX, \qquad h = \pi^\pm, K^\pm$$

- P_Λ for $\Lambda\pi^+$ and $\Lambda\pi^-$ are of opposite sign with $0.2 < z_\Lambda < 0.4$

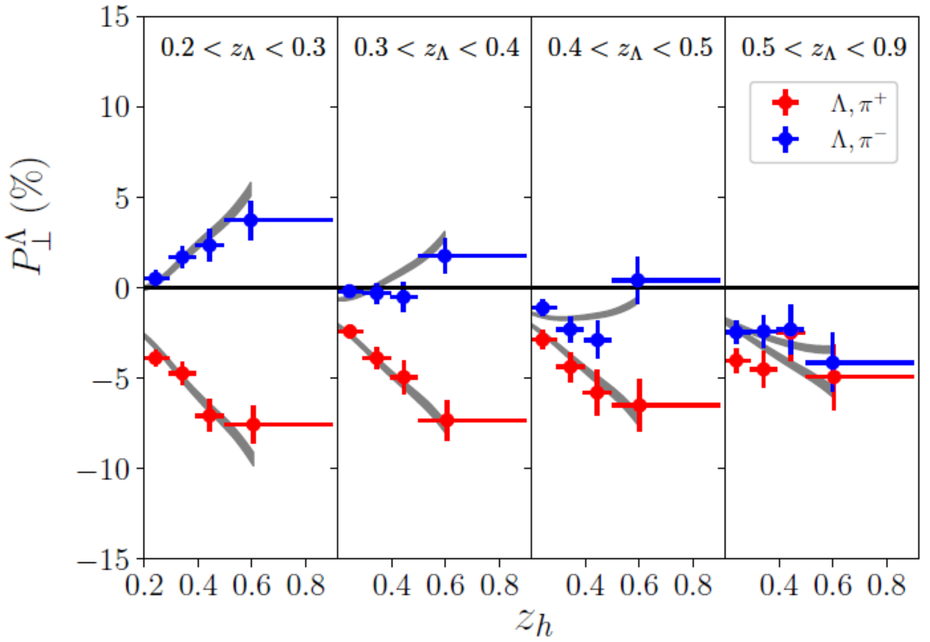
$$e^+e^- \to \Lambda(u\boldsymbol{d}s)\pi^+(u\bar{\boldsymbol{d}})X, \qquad e^+e^- \to \Lambda(\boldsymbol{u}ds)\pi^-(d\bar{\boldsymbol{u}})X$$

$$P_\Lambda \propto \sum_q e_q^2 D_{1T,q}^{\perp\Lambda} \quad \Longrightarrow \quad \boldsymbol{D_{1T,u}^{\perp\Lambda} \sim -D_{1T,d}^{\perp\Lambda}} \quad ???$$

- Parametrizations with $\boldsymbol{D_{1T,u}^{\perp\Lambda} \neq D_{1T,d}^{\perp\Lambda}}$

U.D'Alesio, F.Murgia, M.Zaccheddu (DMZ), PRD 102 (2020) 05400

D.Callos, Z.B.Kang, J.Terry (CKT), PRD 102 (2020) 096007



CKT

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Transverse Λ polarization in e^+e^--annihilations ($D_{1T}^{\perp}$)

- However, all q's carry same color charges, and

  (1) $m_u \sim m_d \sim$ several MeV (2) Λ is a isospin singlet with $I = 0$

Isospin symmetry should apply to D_q^Λ, i.e., $\boldsymbol{D_u^\Lambda = D_d^\Lambda}$

- Based on an **isospin symmetric** formalism, we fit the Belle data well using CLPSW parametrizations.

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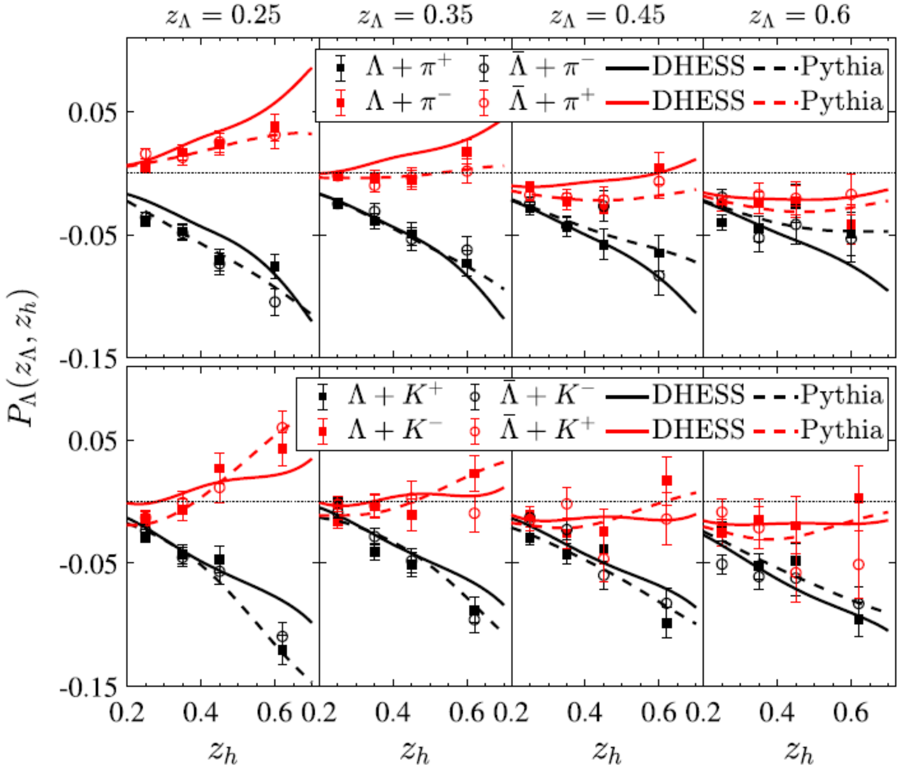
$$D_{1Tu}^{\perp\Lambda} = D_{1Td}^{\perp\Lambda},$$

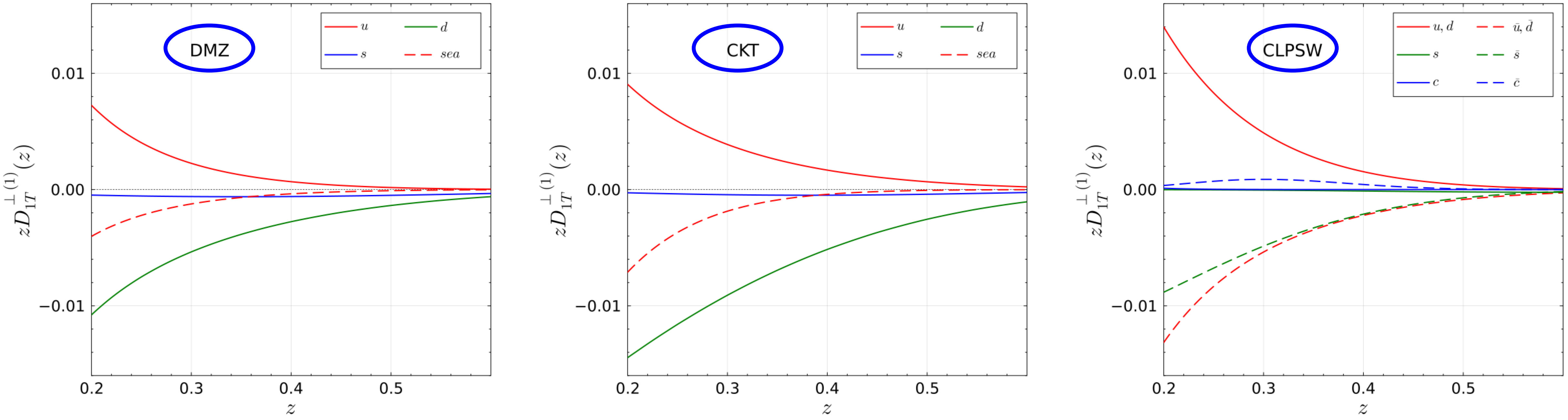
$$D_{1T\bar{u}}^{\perp\Lambda} = D_{1T\bar{d}}^{\perp\Lambda},$$

$$D_{1Ts}^{\perp\Lambda},\ D_{1T\bar{s}}^{\perp\Lambda},\ D_{1Tc}^{\perp\Lambda},\ D_{1T\bar{c}}^{\perp\Lambda}$$

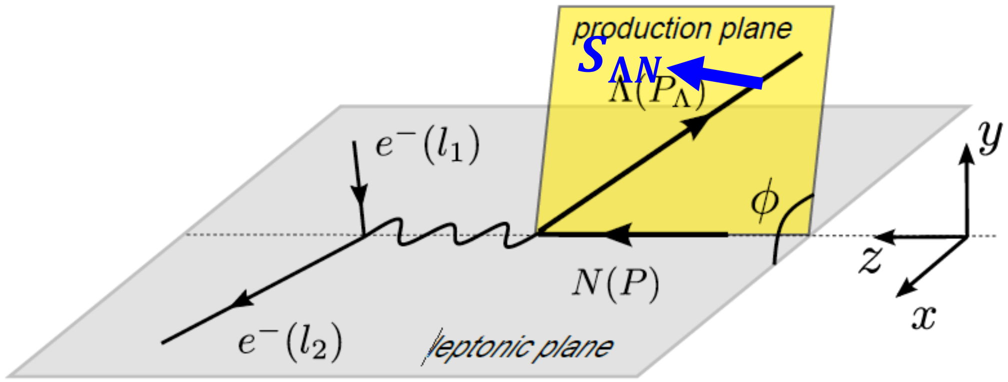


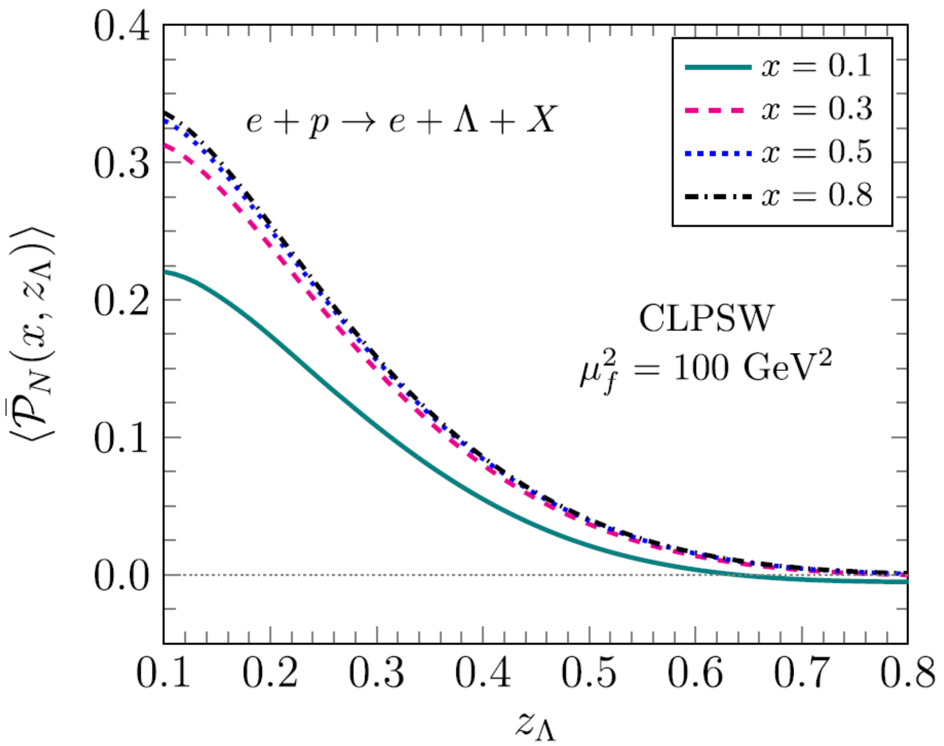
Comparison of different parametrizations

- Comparison of three parametrizations



How to decipher the flavor structure (Isospin symmetry) of the polarized FFs $\mathbf{D_{1T,q}^{\perp\Lambda}}$?





$$\langle \bar{\mathcal{P}}_N(x, z_\Lambda) \rangle = \frac{\sqrt{\pi}\kappa_3(z_\Lambda)}{2z_\Lambda} \frac{\sum_q e_q^2 x f_{1q}(x) D_{1Tq}^{\perp\Lambda}(z_\Lambda)}{\sum_q e_q^2 x f_{1q}(x) D_{1q}^{\Lambda}(z_\Lambda)}$$

K.B.Chen, Z.T.Liang, **YKS**, S.Y.Wei, PRD 105 (2022) 034027

See also

Z.B.Kang, K.Lee, D.Y.Shao, F.Zhao, JHEP 11 (2021) 005

Z.B.Kang, J.Terry, A.Vossen, Q.H.Xu, J.L.Zhang, PRD 105 (2022) 094033

U.D'Alesio, L.Gamberg, F.Murgia, M.Zaccheddu, PRD 108 (2023) 094004

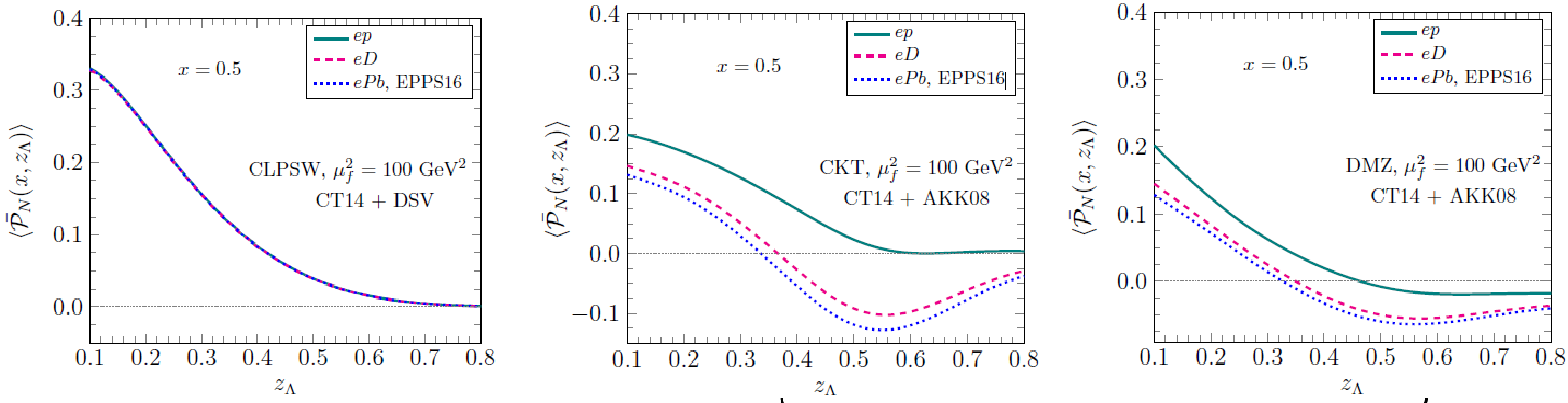
Z. Ji, X.Y.Zhao, A.Q.Guo, Q.H.Xu, J.L.Zhang, Nucl.Sci.Tech. 34 (2023) 155

Test of Isospin symmetry at the EIC with $\mathcal{P}_N$ for SIDIS

$$ep/eD/ePb \to e\Lambda X$$

Different u/d ratio→ $\begin{cases} \text{same } \mathcal{P}_N, & (D_{1u}^{\perp} = D_{1d}^{\perp}), \quad \text{CLPSW} \\ \text{different } \mathcal{P}_N, & (D_{1u}^{\perp} \neq D_{1d}^{\perp}), \quad \text{CKT, DMZ} \end{cases}$

EPPS16: Eskola, Paakkinen, Paukkunen, Salgado, Eur.Phys.J.C 77 (2017) 163



Isospin symmetric parametrization

Isospin symmetry violating parametrizations

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Transverse Λ production in hadronic collisions ($D_{1T}^{\perp}$)

- A wealth of data from hadronic collisions, e.g., $pp, p\bar{p}, pA, AA, \gamma A(UPC)$, ...
- Direct extension with $pp \to \Lambda h X$ suffer from violation of QCD factorization theorem

J. Collins, J.W.Qiu, PRD 75 (2007) 114014

- "Hadron inside jets" proposed to study TMD JFFs in hadronic collisions

F.Yuan, PRL 100 (2008) 032003

Z. B. Kang, X. Liu, F. Ringer and H. Xing, JHEP 11 (2017), 068

Z. B. Kang, K. Lee and F. Zhao, PLB 809 (2020), 135756

(1) Reconstruct jets from pp collisions

(2) Measure the p_T distribution of hadrons with respect to jet axis.

To explore the potential for flavor separation for $D_{1T,q}^{\perp\Lambda}$, we perform a detailed phenomenological analysis on various hadronic collisions

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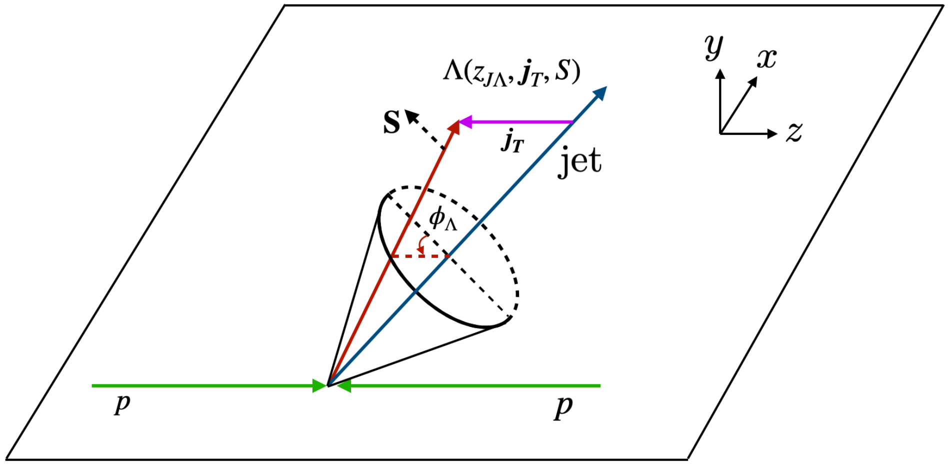


Figure from STAR

Λ inside jets in hadronic collisions

(1) $p + p \to j + X$, with jet reconstructed

$$\frac{d\sigma_{pp\to jX}}{dy\,d^2\boldsymbol{k}_T} = \sum_{abc} \int dy_2 x_1 f_a(x_1,\mu_f) x_2 f_b(x_2,\mu_f) \frac{1}{\pi} \frac{d\hat{\sigma}_{ab\to jc}}{d\hat{t}}$$

$$R_j(y,k_T) \equiv \frac{d\sigma_{pp\to jX}}{\sum_i d\sigma_{pp\to iX}}$$

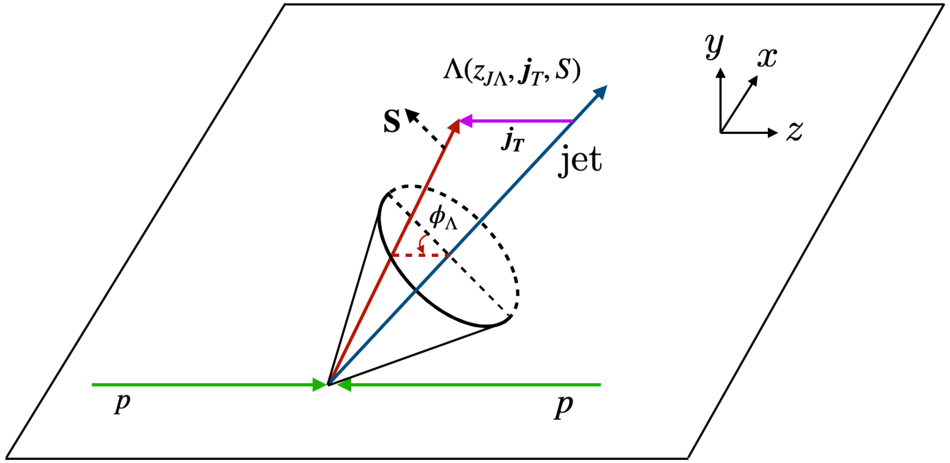


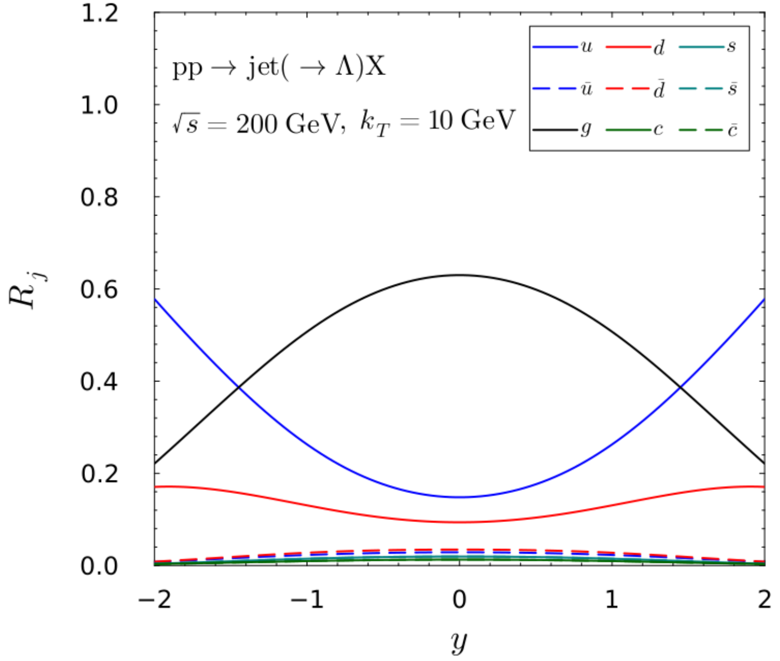
Figure from STAR

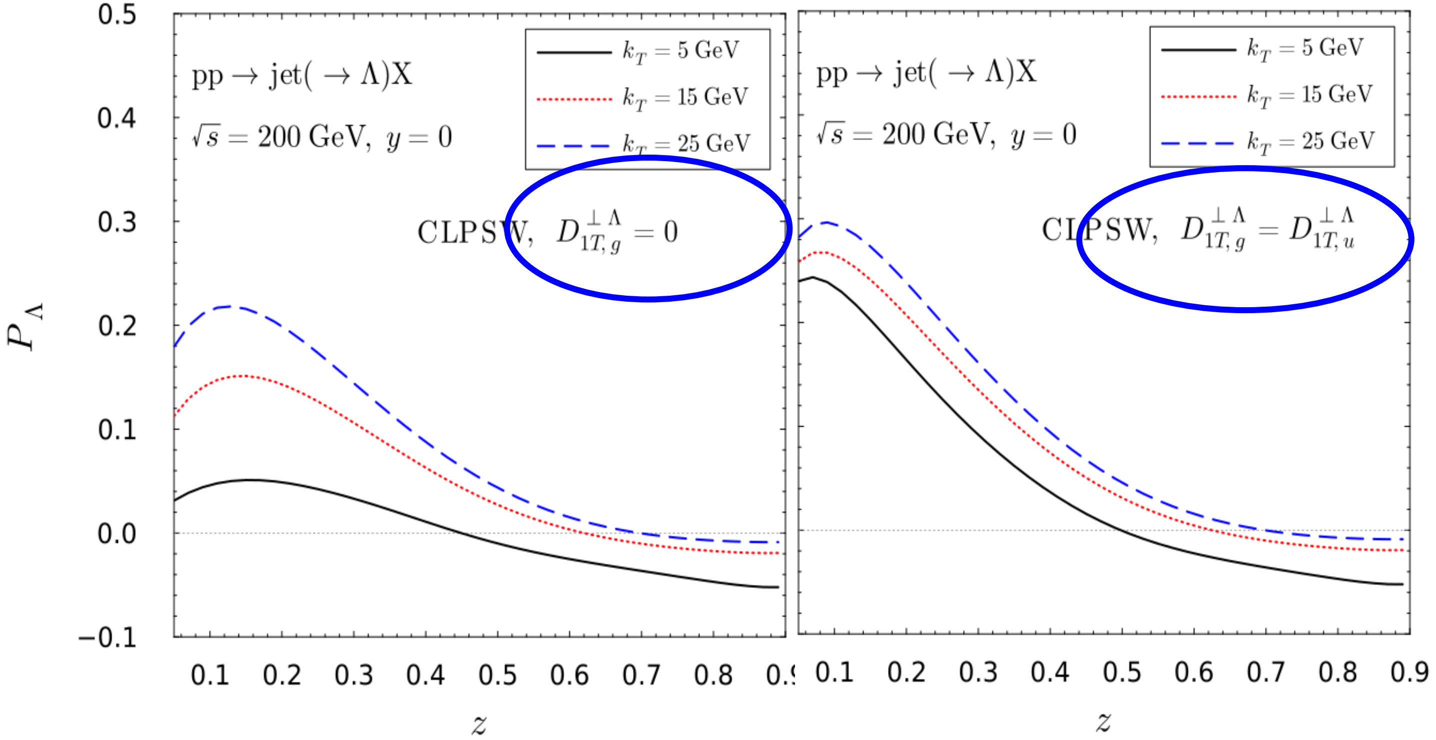
(2) $j \to \Lambda + X'$, described by TMD jet FFs

$$\frac{d\sigma_{pp\to j(\to\Lambda)X}}{dy\,d^2k_T\,dz\,d^2p_{\Lambda T}} = \sum_j \frac{d\sigma_{pp\to jX}}{dy\,d^2\boldsymbol{k}_T} \left(D_{1j}^{\Lambda}(z,p_{\Lambda T}) + \frac{\varepsilon_\perp^{\rho\sigma} p_{T\rho} S_{\Lambda T\sigma}}{zM} D_{1T,j}^{\perp\Lambda}(z,p_{\Lambda T}) \right)$$

$$P_\Lambda = \frac{\sqrt{\pi}\Delta_\Lambda}{2zM} \frac{\sum_j R_j(y,k_T) D_{1T,j}^{\perp\Lambda}(z)}{\sum_j R_j(y,k_T) D_{1,j}^{\Lambda}(z)}$$

- We have quite different quark/gluon production $R_j(y,k_T)$ in different reaction/kinematic regions, which provide the potential for deciphering the flavor structure.



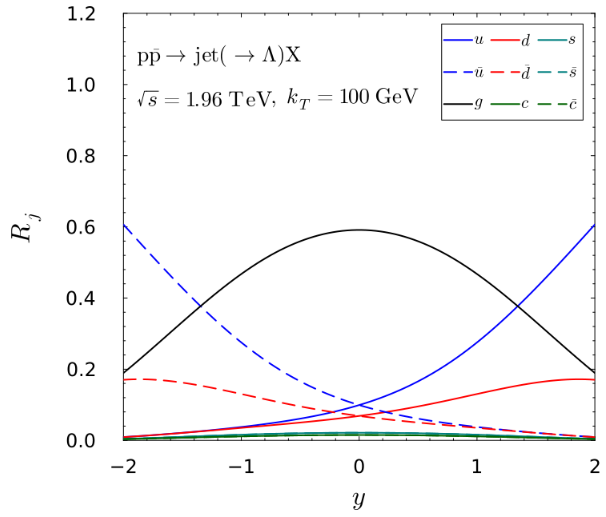


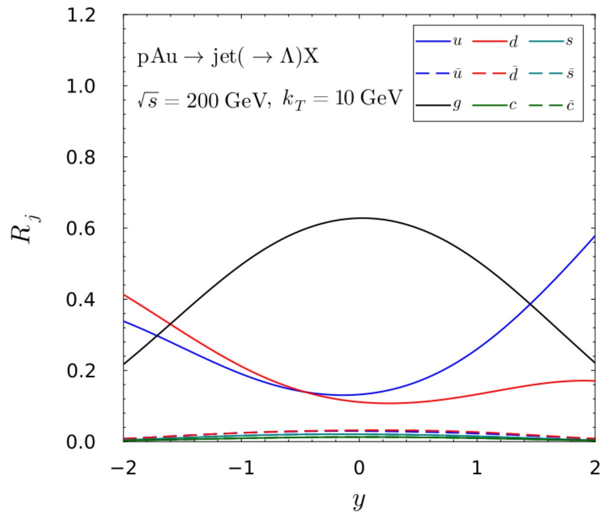
Ceontral rapidity & small k_T region, **gluon dominate**!

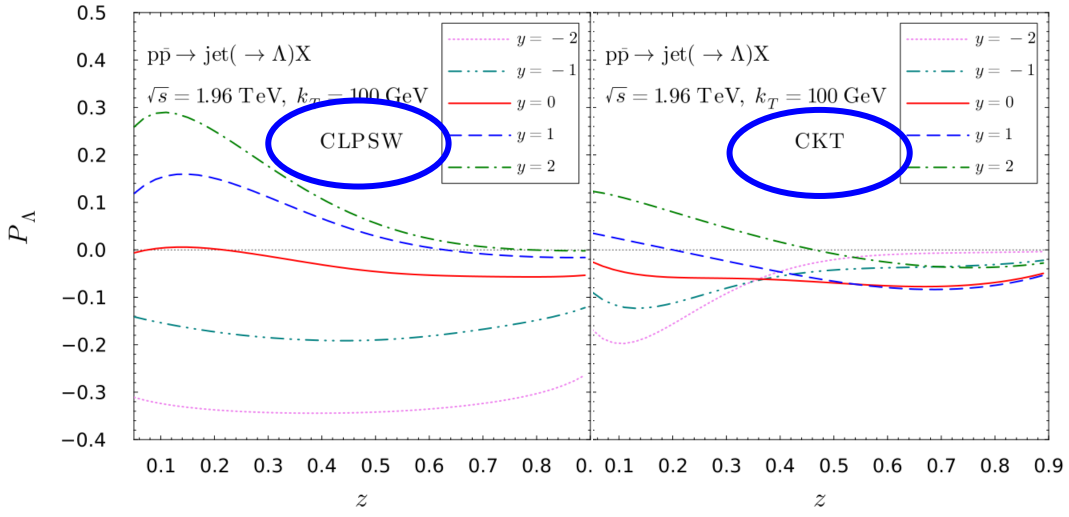
$\Longrightarrow$ a nice place to study the gluon polarized FF $\boldsymbol{D^{\perp\Lambda}_{1T,g}}$

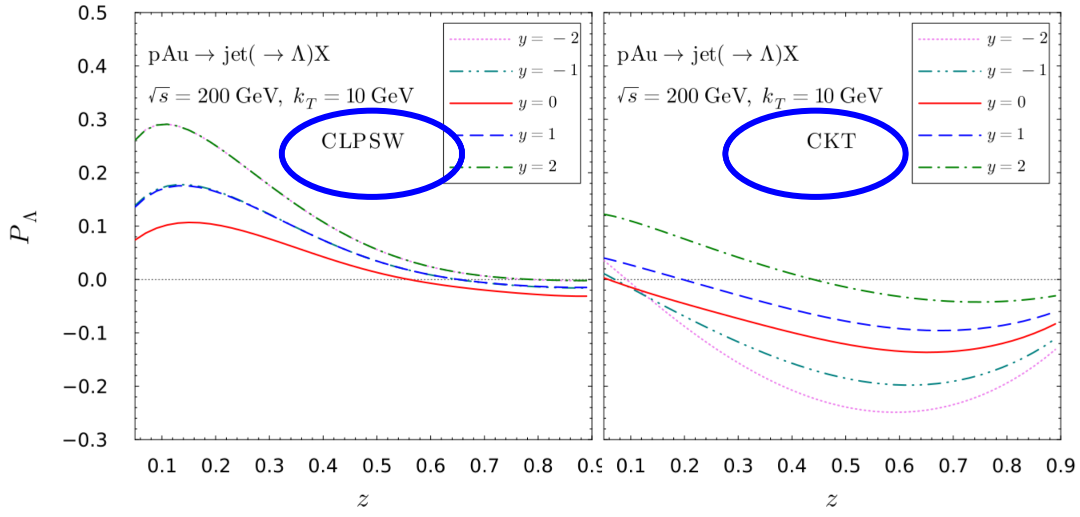
CT18 PDF, DSV FF D_1^Λ, CLPSW $D_{1T}^\perp$

$p\bar{p}$ and pA





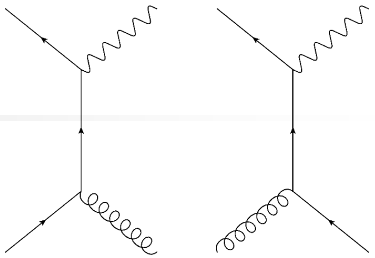




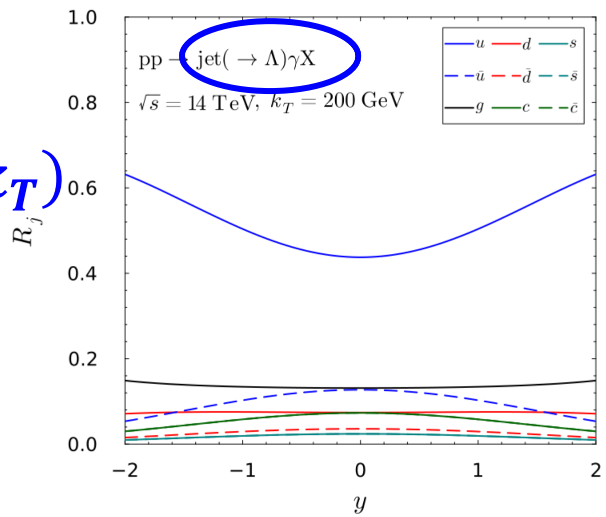
$p\bar{p}$: Forward rapidity region, **u quark dominate**;
backward rapidity region, **$\bar{u}$ quark dominate**

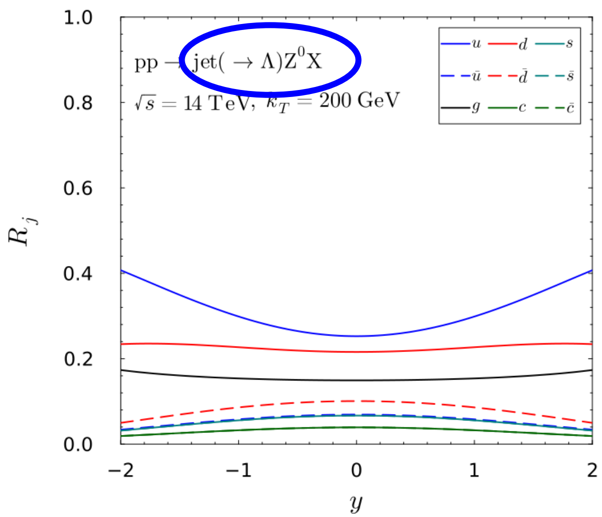
pA: Forward rapidity region, **u quark dominate**;
backward rapidity region, **$u + d$ quark dominate**

γ/Z^0-associated Λ production



$R_j(y, k_T)$





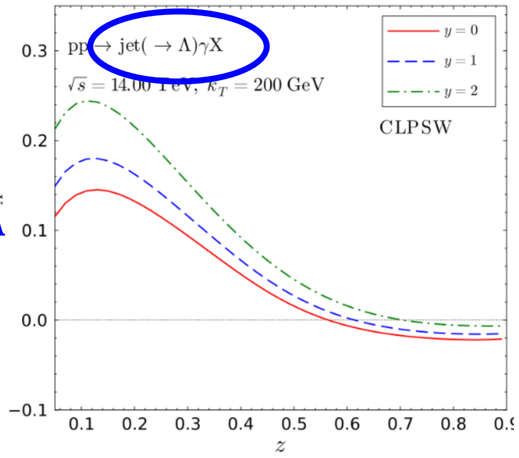
- Quarks dominate over gluons
- u dominate in γ-associated process, while $u \sim d$ in Z-associated process

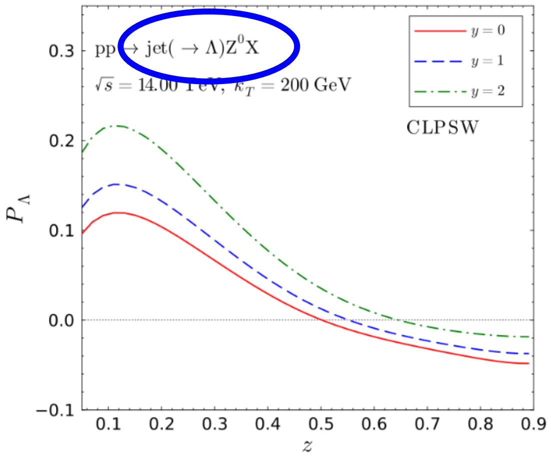
$\Longrightarrow$ a complementary place to study the difference between $D_{1T,u}^{\perp\Lambda}$ and $D_{1T,\bar{u}}^{\perp\Lambda}$

$D_{1T,u}^{\perp\Lambda} = D_{1T,d}^{\perp\Lambda}$

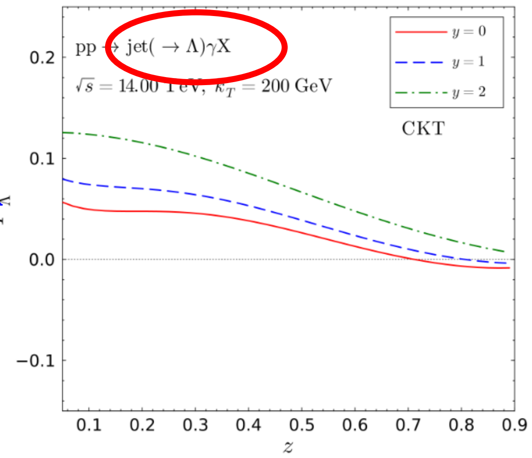
$D_{1T,u}^{\perp\Lambda} \sim -D_{1T,d}^{\perp\Lambda}$

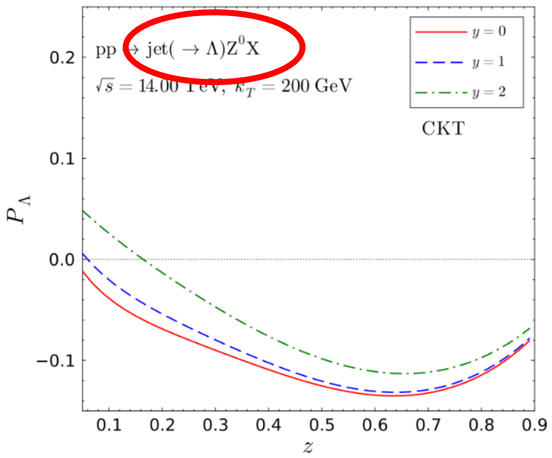
P_Λ





P_Λ





CLPSW

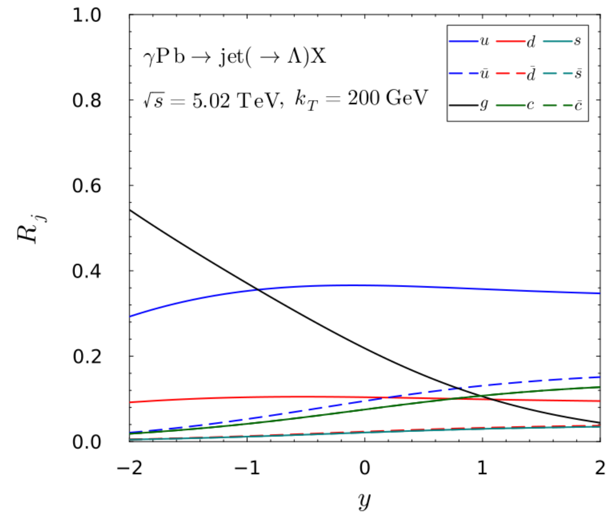
CKT

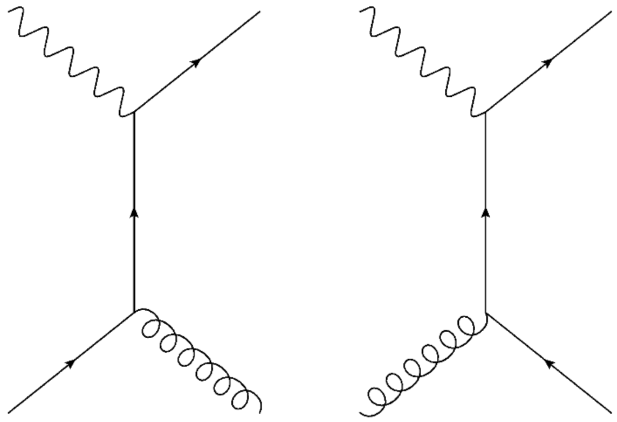
Λ production in UPC

- Highly energetic nucleus $\Longleftrightarrow$ quarks and gluons inside the nucleus
  + quasi-real photons surrounding the nucleus
- Equivalent Photon approximation (EPA)

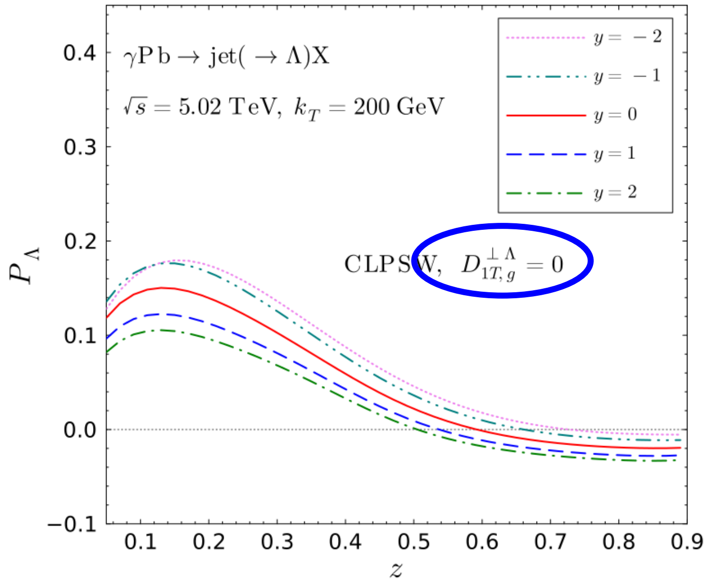
$$x f_\gamma(x) = \frac{2Z^2\alpha}{\pi}\left[\zeta K_0(\zeta)K_1(\zeta) - \frac{\zeta^2}{2}\left(K_1^2(\zeta) - K_0^2(\zeta)\right)\right]$$

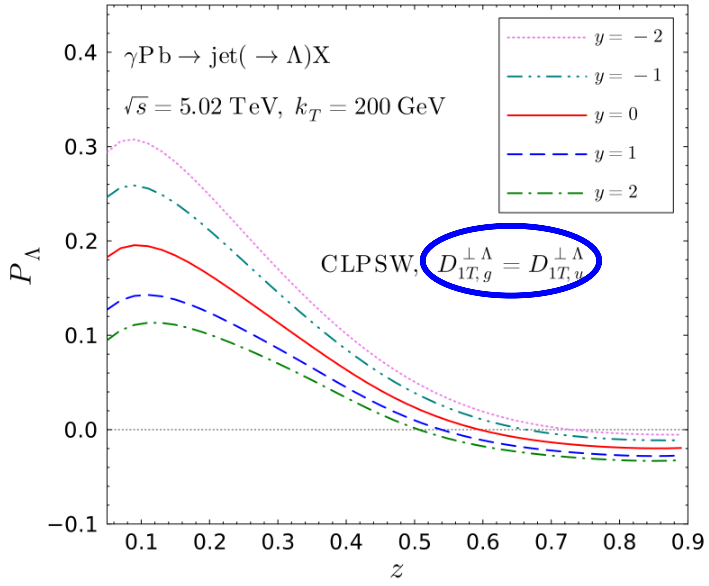
$R_j(y, k_T)$





P_Λ





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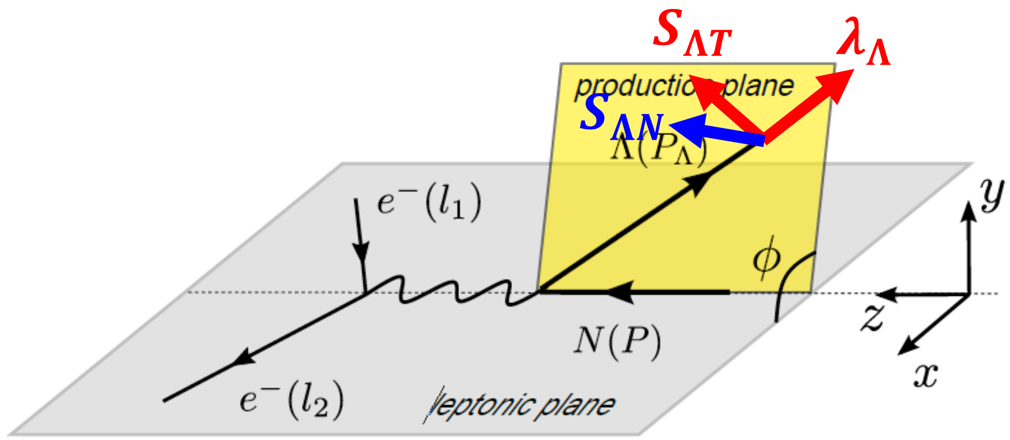

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Polarized Hadrons	L		G_1 = − Helicity	$H_{1L}^{\perp}$ = −
Polarized Hadrons	T	$D_{1T}^{\perp}$ = − Polarizing FF	$G_{1T}^{\perp}$ = −	H_1 = − Transversity; $H_{1T}^{\perp}$ = −

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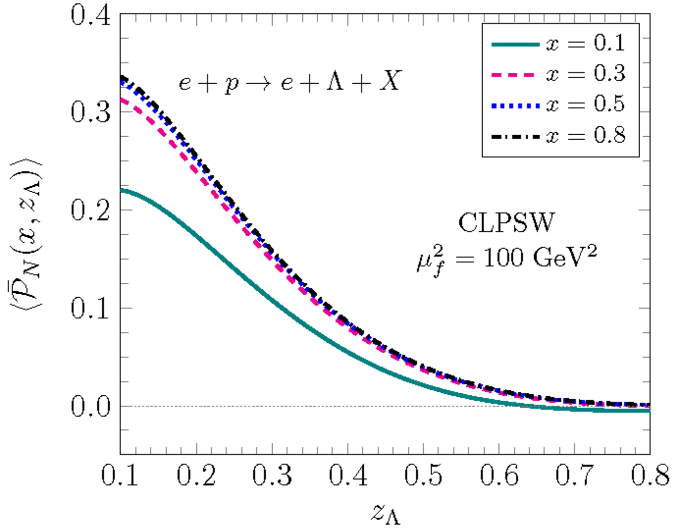
$S_\Lambda \cdot (k \times p_\Lambda)$ ← $D_{1T}^{\perp}$

$H_{1L}^{\perp}$ → $(s_{qT} \cdot p_{\Lambda T})(S_\Lambda \cdot p_\Lambda)$

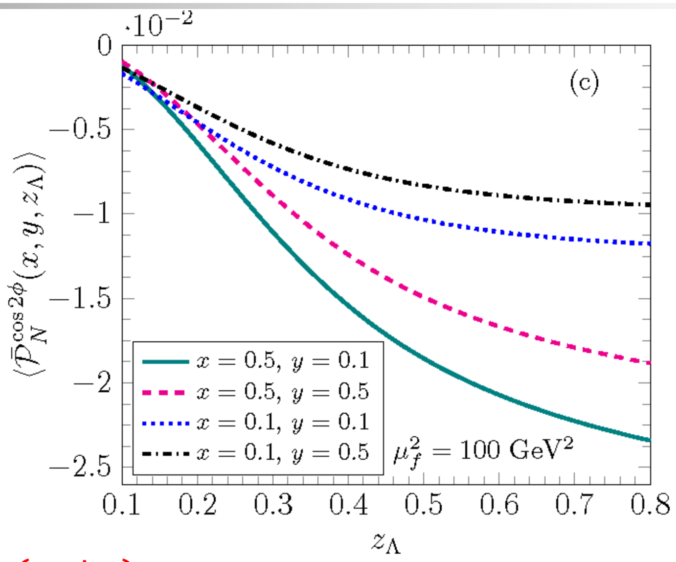
H_1 → $s_{qT} \cdot S_{\Lambda T}$

$H_{1T}^{\perp}$ → $(s_{qT} \cdot p_{\Lambda T})(S_{\Lambda T} \cdot p_{\Lambda T})$

Longitudinal and transverse Λ polarization in ep/eA collision ($H_{1T}, H_{1T}^{\perp}, H_{1L}^{\perp}$)

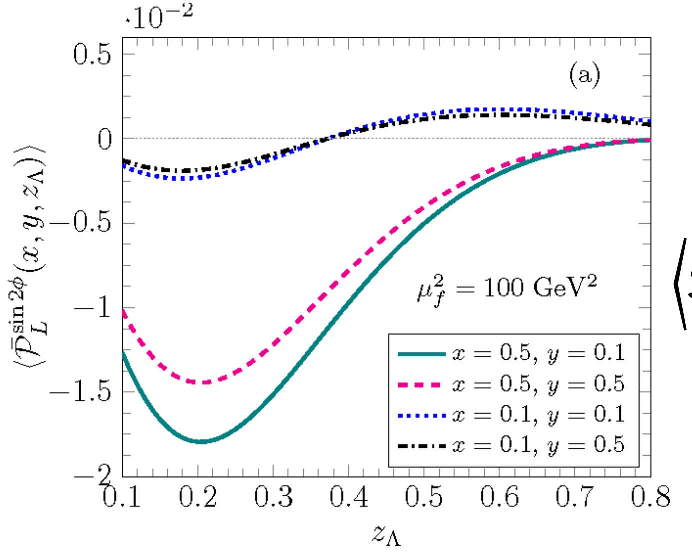


$$\langle \bar{\mathcal{P}}_N \rangle \propto \frac{f_{1q} D_{1T}^{\perp}}{f_1 D_1}$$

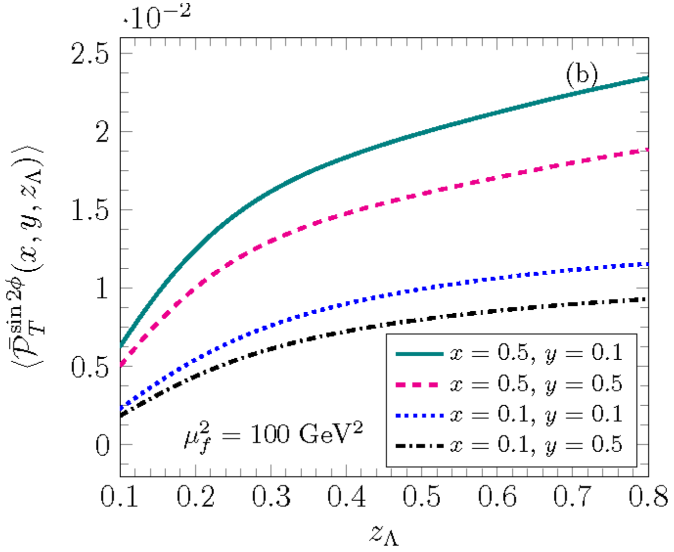


$$\left\langle \bar{\mathcal{P}}_N^{\cos 2\phi} \right\rangle \propto \frac{h_1^{\perp}(-H_{1T} + \kappa_5 H_{1T}^{\perp})}{f_1 D_1}$$

Assuming $H_{1L}^{\perp} \sim H_{1T}^{\perp} \sim \left(D_{1T}^{\perp}\right)/z$ and $H_{1T} \sim G_{1L}$



$$\left\langle \bar{\mathcal{P}}_L^{\sin 2\phi} \right\rangle \propto \frac{h_1^{\perp} H_{1L}^{\perp}}{f_1 D_1}$$



$$\left\langle \bar{\mathcal{P}}_T^{\sin 2\phi} \right\rangle \propto \frac{h_1^{\perp}(-H_{1T} + \kappa_4 H_{1T}^{\perp})}{f_1 D_1}$$

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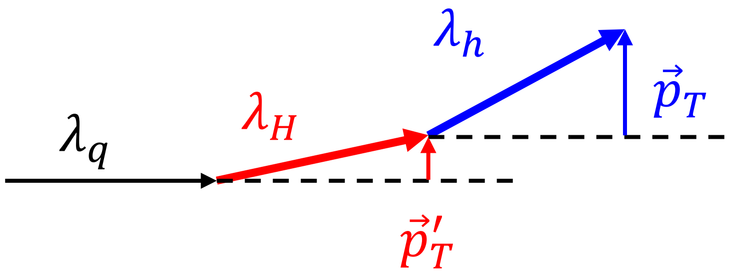
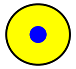
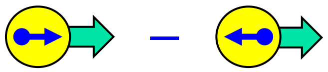
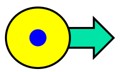
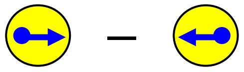
$q \to H + X$

$\quad \hookrightarrow h + X'$



$D_{\lambda_q}^{\lambda_h}$ $\quad D_+^+, D_-^+, D_-^-, D_+^- \to$

$$\begin{cases} D_1 = \frac{1}{2}(D_+^+ + D_+^- + D_-^+ + D_-^-) \\ G_{1L} = \frac{1}{2}(D_+^+ - D_+^- - D_-^+ + D_-^-) \\ \tilde{D}_{1L} = \frac{1}{2}(D_+^+ - D_+^- + D_-^+ - D_-^-) \\ \tilde{G}_1 = \frac{1}{2}(D_+^+ + D_+^- - D_-^+ - D_-^-) \end{cases}$$

D_1	G_{1L}	$\tilde{D}_{1L}$	$\tilde{G}_1$
			

$\tilde{D}_{1L}$: Difference of absolute values of hadron polarizations

$\tilde{G}_1$: Difference of number of hadrons

} in jets initiated by helicity + and – quarks

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Weak decay contributions to TMD FFs $\widetilde{D}_{1L}, \widetilde{G}_1$

- QCD θ−vacuum breaks parity invariance $\Longrightarrow$ non−zero parity−odd FFs *[Kang, Kharzeev 2011]*

$$\mathcal{L} = \mathcal{L} + \frac{g^2}{32\pi^2}\theta(x,t)F_a^{\mu\nu}\tilde{F}_{\mu\nu}^a \quad \Longrightarrow \quad \Xi(z) \sim \gamma_\mu p^\mu\left(D_1 + \lambda_h \widetilde{D}_{1L}\right) + \gamma_\mu\gamma_5 p^\mu\left(\lambda_h G_{1L} + \widetilde{G}_1\right)$$

- The θ−parameter induce parity−odd FFs $\widetilde{D}_{1L}, \widetilde{G}_1$ with different signs in each event, hard to probe in exps.
- Hadrons detected in exps may contain weak decay contributions, thus violating parity invariance.
- It is not an easy task to subtract all decay contributions, leaving room for P-odd FFs
- **We perform a detailed calculation of weak decay contributions to P-odd FFs, and estimate the magnitudes of their observables in exps.**

$$D_q^{h,H}(\lambda_q, \lambda_h; z, p_T) = \sum_{\lambda_H}\int dz' d^2p_T' \frac{dN(\lambda_h, \lambda_H)}{dz d^2 p_T} D_q^H(\lambda_q, \lambda_H; z', p_T')$$

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Weak decay contributions to TMD FFs $\widetilde{D}_{1L}, \widetilde{G}_1$

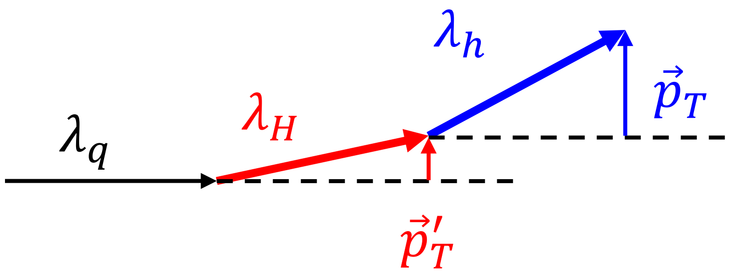
$$D_q^h = D_q^{h,\mathrm{dir}} + \sum_H D_q^{h,H}$$

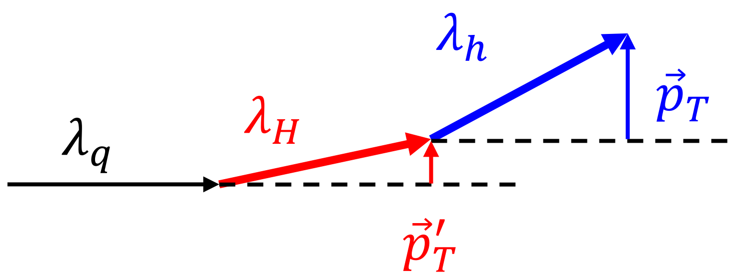
- $D_1^{h,\mathrm{dir}}$: directly produced part, free of parity violation
- $D_1^{h,H}$: decay contribution from parent hadron H

$$H \to h + X$$

Where X can be a single particle (2-body decay) or several particles (3-body decays etc.)

$$D_q^{h,H}(\lambda_q, \lambda_h; z, p_T) = \sum_{\lambda_H} \int dz' d^2 p'_T \frac{dN(\lambda_h, \lambda_H)}{dz d^2 p_T} D_q^H(\lambda_q, \lambda_H; z', p'_T)$$





$\frac{dN(\lambda_h,\lambda_H)}{dzd^2p_T}$ contain information of weak interactions. We calculate them via helicity amplitudes.

- $\frac{1}{2} \to \frac{1}{2} + 0$

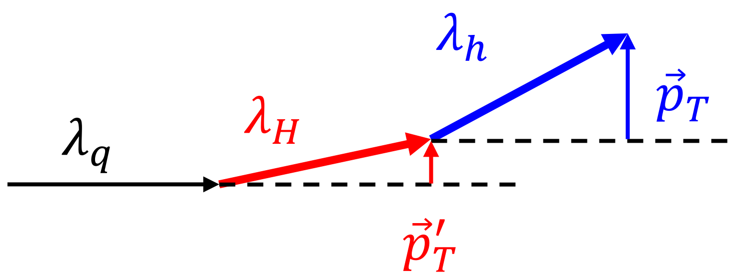
$$\frac{dN(\lambda_h,\lambda_H)}{dzd^2p_T} = \frac{1}{8\pi}\frac{2M_H}{z|\vec{p}_h^*|}\delta[(p_H-p_h)^2-M_X^2][\,1+\gamma\lambda_H\lambda_h\boldsymbol{\omega_i}\cdot\boldsymbol{\omega_f}+(1-\gamma)\lambda_H\lambda_h(\boldsymbol{\omega_i}\cdot\hat{\boldsymbol{p}}_h^*)(\boldsymbol{\omega_f}\cdot\hat{\boldsymbol{p}}_h^*)$$
$$+\alpha\left(\lambda_H\boldsymbol{\omega_i}\cdot\hat{\boldsymbol{p}}_h^*+\lambda_h\boldsymbol{\omega_f}\cdot\hat{\boldsymbol{p}}_h^*\right)+\beta\lambda_H\lambda_h\hat{\boldsymbol{p}}_h^*\cdot\left(\boldsymbol{\omega_i}\times\boldsymbol{\omega_f}\right)]$$

- $\frac{3}{2} \to \frac{1}{2} + 0$

$$\frac{dN(\lambda_h,\lambda_H)}{dzd^2p_T} = \frac{1}{8\pi}\frac{2M_H}{z|\vec{p}_h^*|}\delta[(p_H-p_h)^2-M_X^2]\left[1+\alpha\lambda_h\boldsymbol{\omega_f}\cdot\hat{\boldsymbol{p}}_h^*\right]$$

- For strong decays $\alpha=\beta=0, \gamma=\pm 1$

Weak decay contributions to TMD FFs $\widetilde{D}_{1L}, \widetilde{G}_1$



- By inserting $\frac{dN(\lambda_h,\lambda_H)}{dz d^2 p_T}$ into the decay contributions to P-odd FFs, we finally obtain

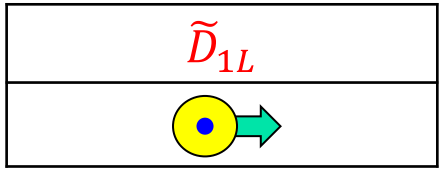
$$\widetilde{D}_{1L}^{h,H}(z) = \frac{M_H}{2|\boldsymbol{p}_h^*|}\int \frac{dz'}{z'} d^2 p_T' D_{1q}^H(z', p_T') K_{U\to L}$$

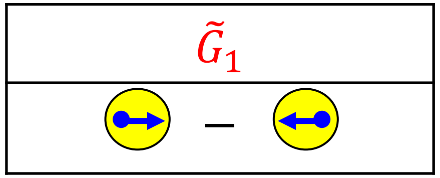
$$\widetilde{G}_1^{h,H}(z) = \frac{M_H}{2|\boldsymbol{p}_h^*|}\int \frac{dz'}{z'} d^2 p_T' G_{1L,q}^H(z', p_T') K_{L\to U}$$

where the kernel functions are given by

$$K_{U\to L} = \alpha \frac{M_H E_h E_h^* - E_H m_h^2}{M_H |\boldsymbol{p}_h||\boldsymbol{p}_h^*|}, \qquad K_{L\to U} = \alpha \frac{M_H E_h - E_H E_h^*}{|\boldsymbol{p}_H||\boldsymbol{p}_h^*|}$$

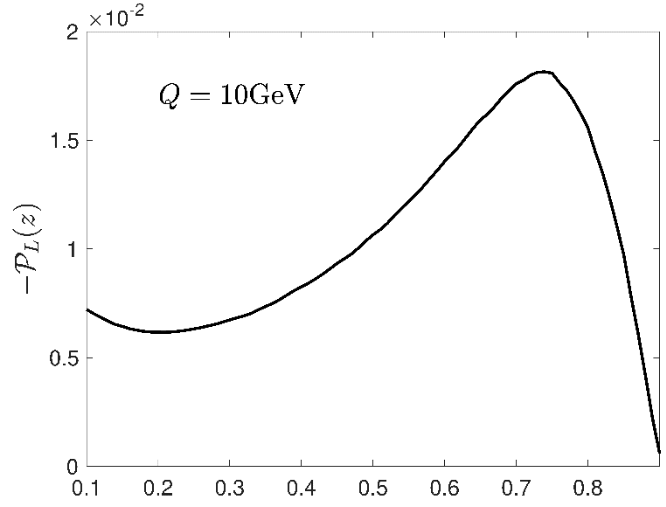
1. Spontaneous **Λ** polarizations in $e^+e^- \to \gamma^*/Z^0 \to \Lambda X$
2. Modifications to the di-hadron cross sections in $e^+e^- \to h_1 h_2 X$

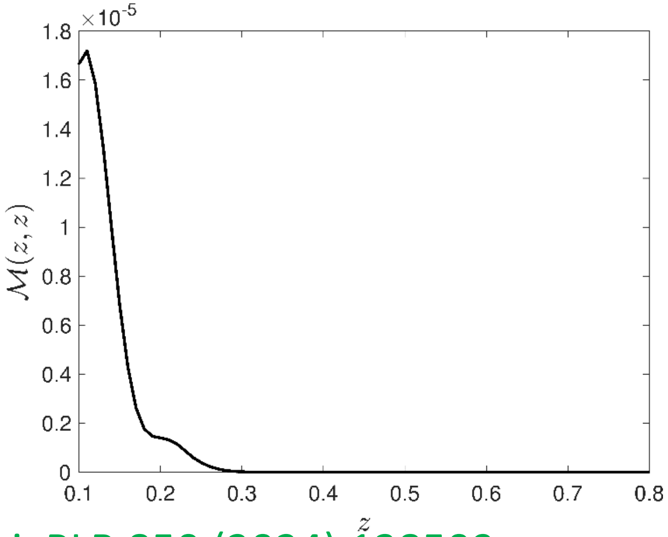




$$\mathcal{P}_L(z) = \frac{\sum_q \left[\Delta\omega_q G_{1L,q}(z) + \omega_q \widetilde{D}_{1L,q}(z)\right]}{\sum_q \omega_q D_{1,q}(z)}$$

$$\mathcal{M}(z_{h_1}, z_{h_2}) \equiv \frac{\sum_q \widetilde{G}_{1q}^{h_1}(z_{h_1}) \widetilde{G}_{1\bar{q}}^{h_2}(z_{h_2})}{\sum_q D_{1q}^{h_1}(z_{h_1}) D_{1\bar{q}}^{h_2}(z_{h_2})}$$





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Conclusions and outlook

- $D_{1T}^{\perp}$: Belle data, three group of parametrizations, Flavor structure (isospin symmetry)
  - ep/eA
  - Hadronic collisions

  $D_{1T,g}^{\perp\Lambda}$ in pp collisions, and in γA collisions (UPC)

  $D_{1T,u}^{\perp\Lambda}$ v. s. $D_{1T,\bar{u}}^{\perp\Lambda}$ in $p\bar{p}$ collision

  $D_{1T,u}^{\perp\Lambda}$ v. s. $D_{1T,d}^{\perp\Lambda}$ in pA collisions, and in γ/Z^0-associated process (Isospin symmetry)
- $H_{1T}, H_{1T}^{\perp}, H_{1L}^{\perp}$: rough estimates in e^+e^-, ep/eA collisions
- $\widetilde{D}_{1L}, \widetilde{G}_1$: non-negligible magnitudes, probable to measure in exp.

A garden with a wealth of polarized TMD FFs unexplored, calling for experimental efforts from e^+e^--annihilation, EIC, hadron collider et al.

Thanks for you attention!