The 15th Workshop on QCD Phase Transition and Relativistic Heavy-Ion Physics (QPT 2023)

Decay contributions to the parity-odd fragmentation functions

Yu-kun Song, University of Jinan

In collaboration with Y.L.Pan, K.B.Chen and S.Y.Wei

2023/12/18

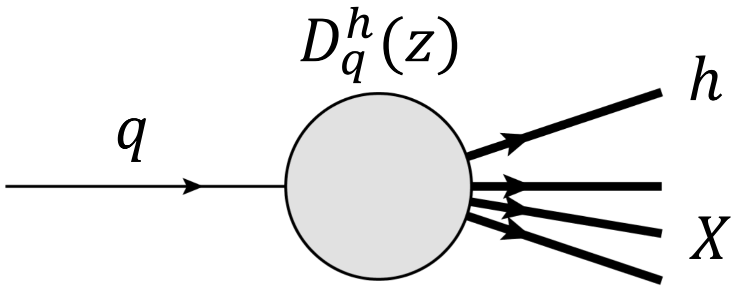
*Y.L.Pan, K.B.Chen, **YKS**, S.Y.Wei, ArXiv: 2311.04462*

Outline

- Introduction
- Formalism to calculate decay contributions to P-odd FFs
- Estimate of observables to P-odd FFs in e^+e^--annihilation
  - Spontaneous Λ polarization in $e^+e^- \to \Lambda X$
  - Modifications to the back-to-back di-hadron production in $e^+e^- \to h_1 h_2 X$
- Conclusions

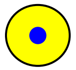
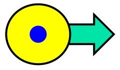
Introduction

- Fragmentation functions (FFs) can be labeled by quark and hadron helicity



$$D_{\lambda_q}^{\lambda_h}$$

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

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

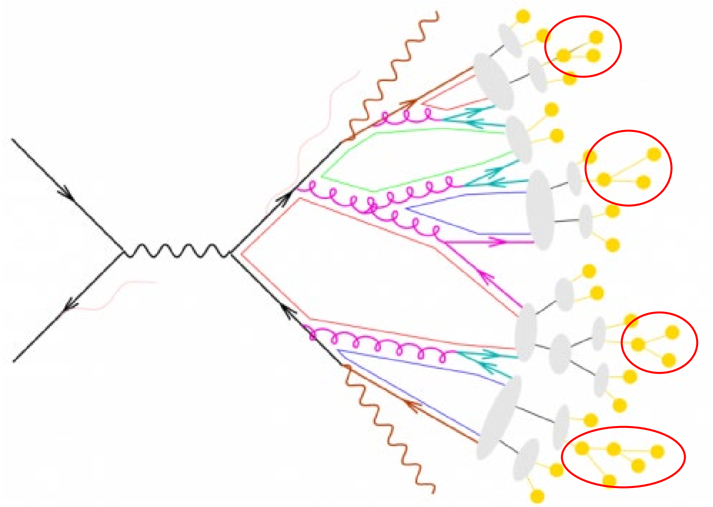
- Parity invariance in QCD $\Longrightarrow$ $D_+^+ = D_-^-$, $D_+^- = D_-^+$ $\Longrightarrow$ $\tilde{D}_{1L} = \tilde{G}_1 = 0$
- QCD θ-vacuum breaks parity invariance $\Longrightarrow$ non-zero parity-odd FFs *[Kang, Kharzeev 2011]*

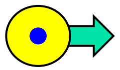
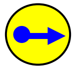
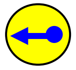
$$\mathcal{L} = \mathcal{L} + \frac{g^2}{32\pi^2}\theta(x,t)F_a^{\mu\nu}\tilde{F}_{\mu\nu}^a \quad \Longrightarrow \quad \Xi(z) \sim \gamma_\mu p^\mu\left(D_1 + \lambda_h \tilde{D}_{1L}\right) + \gamma_\mu\gamma_5 p^\mu\left(\lambda_h G_{1L} + \tilde{G}_1\right)$$

- The θ-parameter induce parity-odd FFs $\tilde{D}_{1L}, \tilde{G}_1$ with different signs in each event, hard to probe in exps.

Introduction

- Hadrons detected in exps may contain weak decay contributions, thus violating parity invariance.



$\widetilde{D}_{1L}$	$\widetilde{G}_1$
	 − 

For example, weak interaction vertex

$$\gamma^{\mu}(1-\gamma_5) \implies q_L \implies \widetilde{D}_{1L} \neq 0$$

- 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.**

Formalism to calculate decay contributions to P-odd FFs

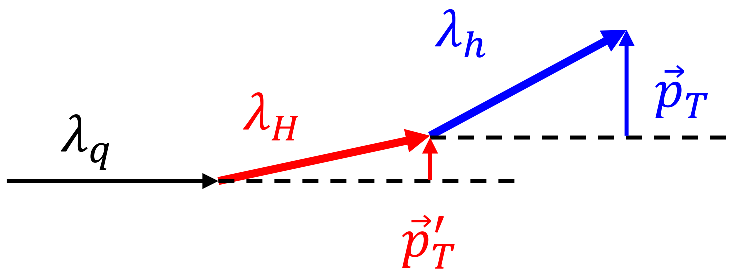
$$D_q^h = D_q^{h,\text{dir}} + \sum_H D_q^{h,H}$$

- $D_1^{h,\text{dir}}$: directly produced part, dominated by QCD, free of parity violation
- $D_1^{h,H}$: decay contribution from parent hadron H, might contain parity violation effects

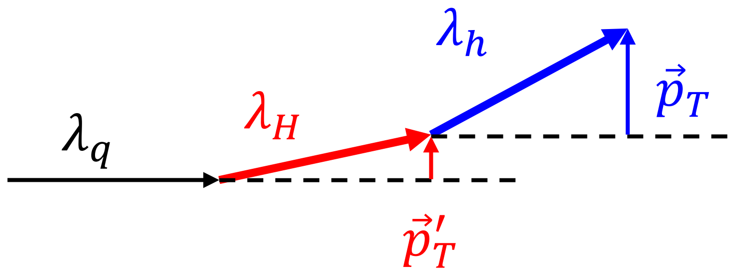
$$H \to h + X$$

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

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



Formalism to calculate decay contributions to P-odd FFs



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

- $\frac{1}{2} \to \frac{1}{2} + 0 \;\; (\Xi \to \Lambda\pi, \ldots)$

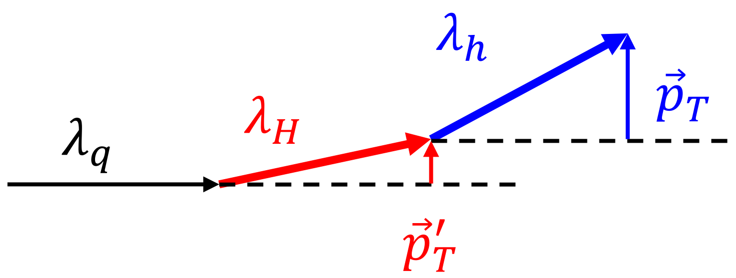
$$\frac{dN(\lambda_h,\lambda_H)}{dzd^2p_T} = \frac{1}{8\pi}\frac{2M_H}{z|\vec{p}_h^{\,*}|}\delta[(p_H-p_h)^2-M_X^2][\,1+\gamma\lambda_H\lambda_h\boldsymbol{\omega_i}\cdot\boldsymbol{\omega_f}+(1-\gamma)\lambda_H\lambda_h(\boldsymbol{\omega_i}\cdot\hat{\boldsymbol{p}}_{\boldsymbol{h}}^*)(\boldsymbol{\omega_f}\cdot\hat{\boldsymbol{p}}_{\boldsymbol{h}}^*)$$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

- $\frac{3}{2} \to \frac{1}{2} + 0 \;\; (\Omega \to \Lambda K, \ldots,$ unpolarized parent hadron)

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

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

Formalism to calculate decay contributions to P-odd FFs



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

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

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

where the kernel functions are given by

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

- However, for most hyperons there are no parametrizations.

$$D_{1q}^H,\ G_{1L,q}^H = ?$$

Numeric results of $\widetilde{D}_{1L}$ for Λ hyperon

Assumptions: $D_{1,q}^{H,\text{dir}} = \lambda_s^{n_s'}\left(n_q^H D_B^{\text{val}} + D_B^{\text{sea}}\right)$

where $\lambda_s = \frac{1}{3}$ is the strangeness suppression factor.

- To fix $D_B^{\text{val}}, D_B^{\text{sea}}$ we take DSV parametrization for $\Lambda(\text{uds})$
  de Florian, Stratmann, Vogelsang, 1998

$$D_u^{\Lambda,\text{dir}} = \lambda_s\left(D_B^{\text{val}} + D_B^{\text{sea}}\right) = \frac{1+z}{2} D_{1u}^{\Lambda/\bar{\Lambda}}\Big|_{\text{DSV}}$$

$$D_{\bar{u}}^{\Lambda,\text{dir}} = \lambda_s D_B^{\text{sea}} = \frac{1-z}{2} D_{1u}^{\Lambda/\bar{\Lambda}}\Big|_{\text{DSV}}$$

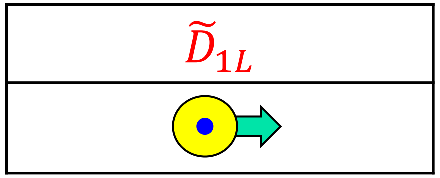
All FFs of spin-1/2 hadrons can be given in this form.

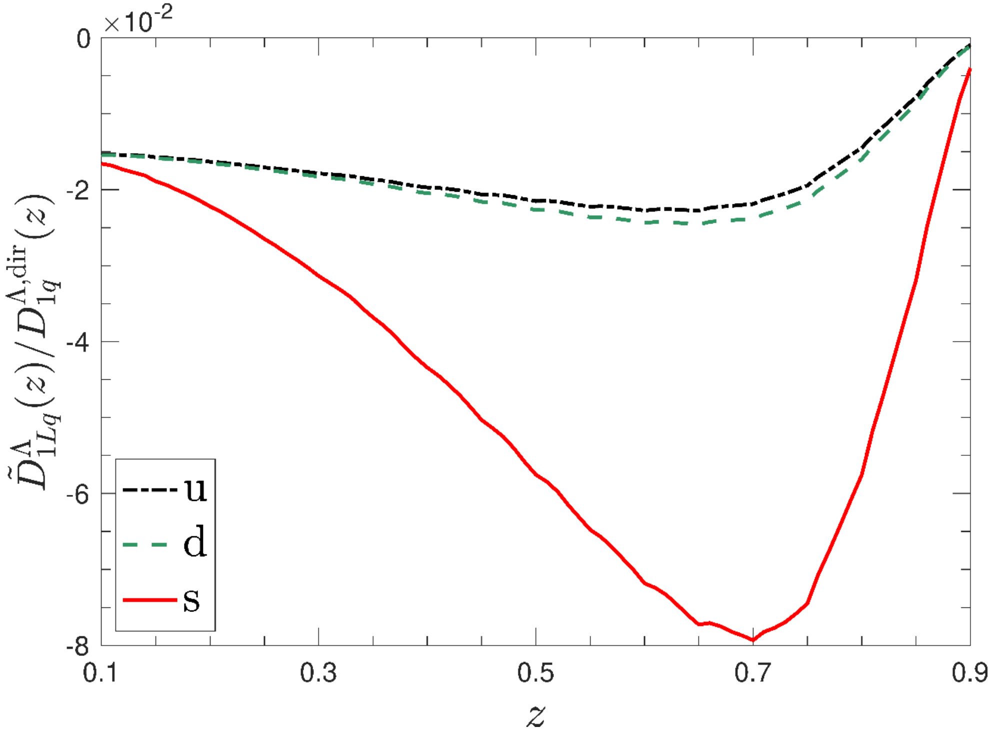
- Spin-3/2 hadrons assigned $\kappa = \frac{1}{3}$ suppression factor, e.g.

$$\Xi^0(uss):\quad D_u^{\Xi^0,\text{dir}} = \lambda_s^2\left(D_B^{\text{val}} + D_B^{\text{sea}}\right)$$

$$\Xi^-(dss):\quad D_u^{\Xi^-,\text{dir}} = \lambda_s^2 D_B^{\text{sea}}$$

$$\Omega^-(sss):\quad D_u^{\Omega^-,\text{dir}} = \lambda_s^3 \kappa D_B^{\text{sea}}$$



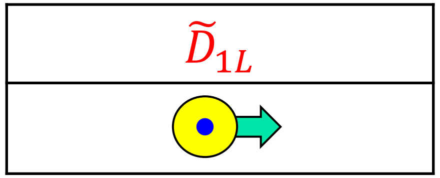


The magnitude of $\widetilde{D}_{1L}$ are negative and of a few percent of D_1

Observables-1: Spontaneous Λ polarizations in e^+e^- annihilation

$$e^+e^- \to \gamma^*/Z^0 \to \Lambda X$$

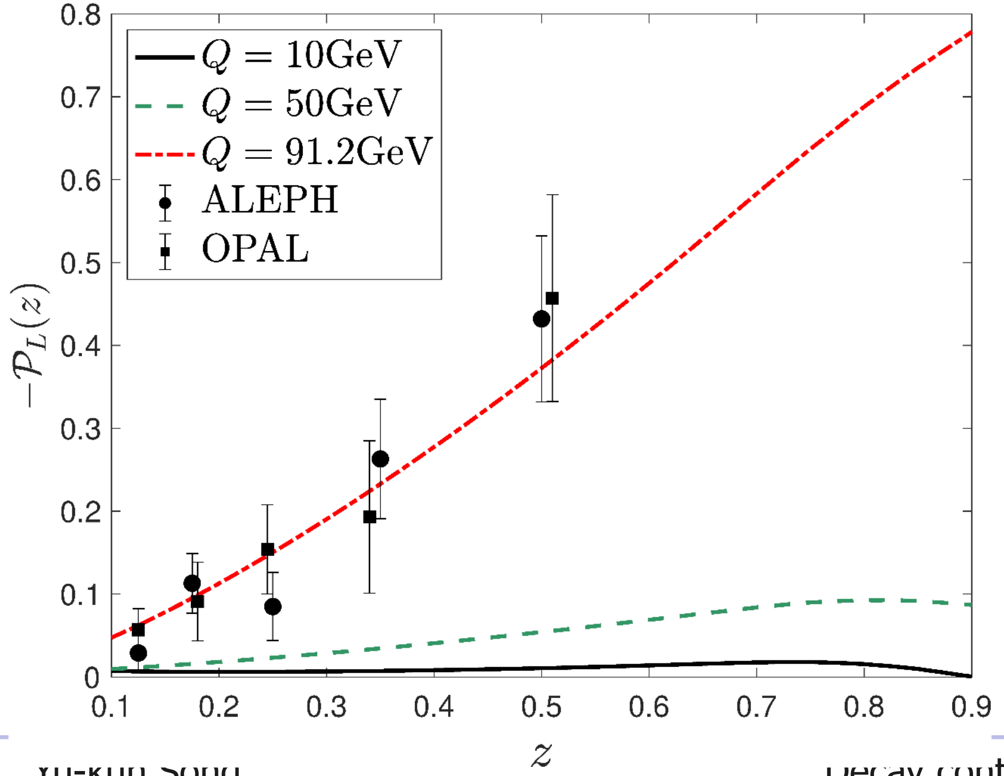
Spontaneous $\boldsymbol{\Lambda}$ polarizations

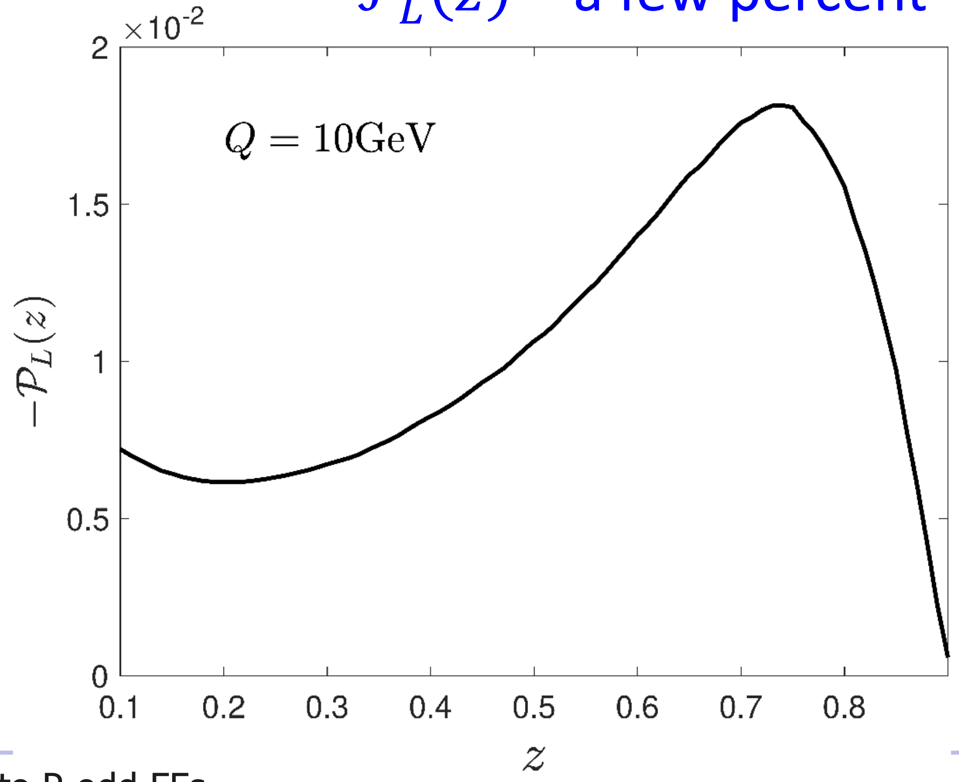


$$\mathcal{P}_L(z) = \frac{\sum_q \left[\Delta\omega_q G_{1L,q}(z) + \omega_q \widetilde{D}_{1L,q}(z)\right]}{\sum_q \omega_q D_{1,q}(z)}$$

- ω_q is the weight to produce unpolarized quarks
- $\Delta\omega_q$ is the weight to produce polarized quarks (through Z-exchange)

$\mathcal{P}_L(z)$~ a few percent



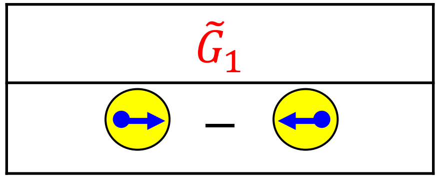


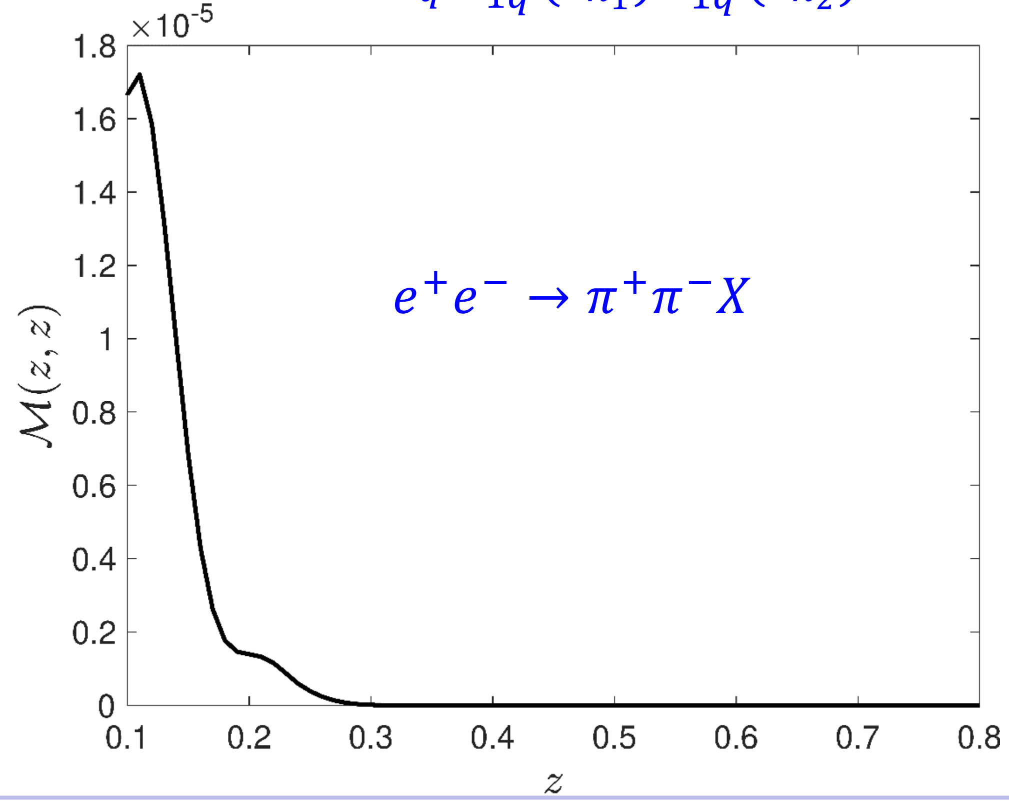
Observables-2: Modifications to di-hadron production

$$\frac{d\sigma(e^+e^- \to h_1 h_2 X)}{dz_{h_1} dz_{h_2}} = \frac{4\pi\alpha_{em}^2}{Q^2} \sum_q \left[D_{1q}^{h_1}(z_{h_1}) D_{1\bar{q}}^{h_2}(z_{h_2}) - \tilde{G}_{1q}^{h_1}(z_{h_1}) \tilde{G}_{1\bar{q}}^{h_2}(z_{h_2}) \right],$$

Modification factor

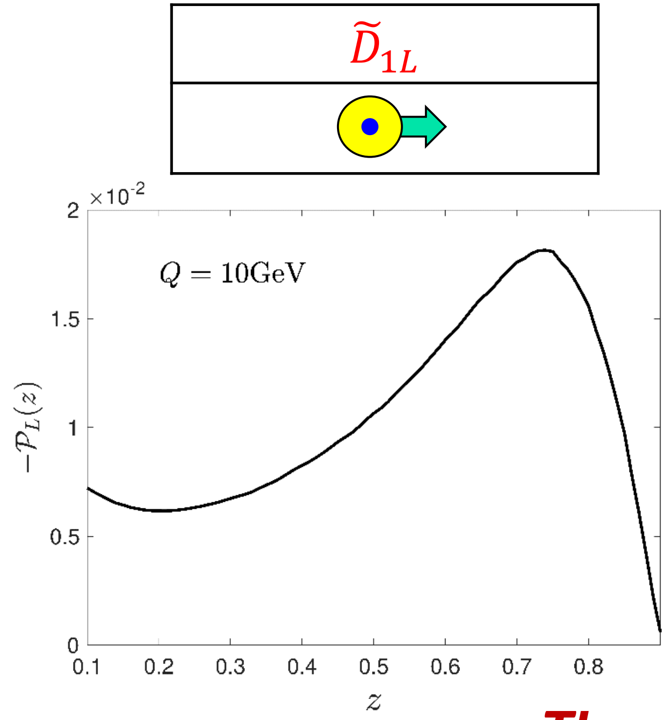
$$\mathcal{M}(z_{h_1}, z_{h_2}) \equiv \frac{\sum_q \tilde{G}_{1q}^{h_1}(z_{h_1}) \tilde{G}_{1\bar{q}}^{h_2}(z_{h_2})}{\sum_q D_{1q}^{h_1}(z_{h_1}) D_{1\bar{q}}^{h_2}(z_{h_2})}$$

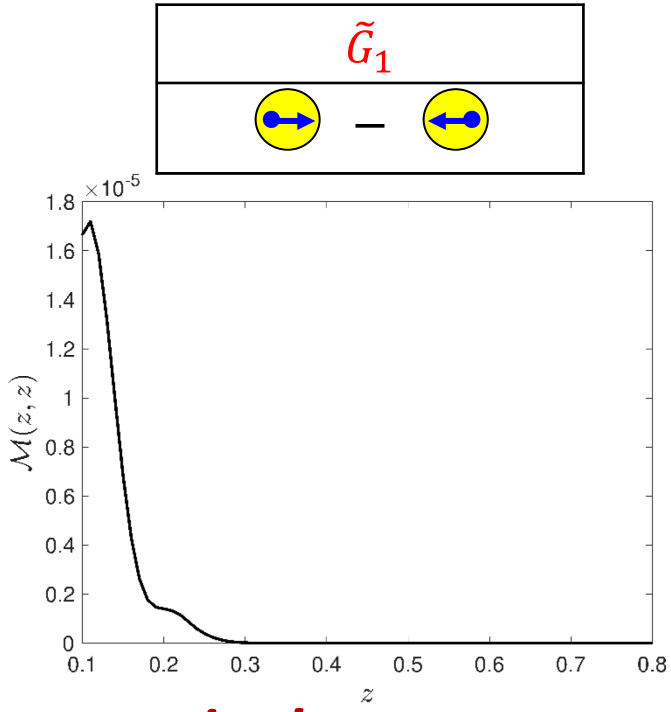




Conclusions

- We calculated weak decays contributions to P-odd FFs, giving non-zero results
- Rough estimates show that P-odd FF $\widetilde{D}_{1L}/D_1 \sim$ a few percent, and the observables for P-odd FFs are
  - **Spontaneous Λ polarization in $e^+e^- \to h^\uparrow X$**
  - **Modifications to the di-hadron cross sections in $e^+e^- \to h_1 h_2 X$**





Thanks for you attention!