Analysis of Isospin Symmetry for Fragmentation Functions

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Based on: *K.B. Chen, Z.T. Liang, Y.L. Pan, Y.K. Song and S.Y Wei, Phys. Lett. B816 (2021) 136217*

K.B. Chen, Z.T. Liang, Y.K. Song and S.Y. Wei, arXiv:2108.07740

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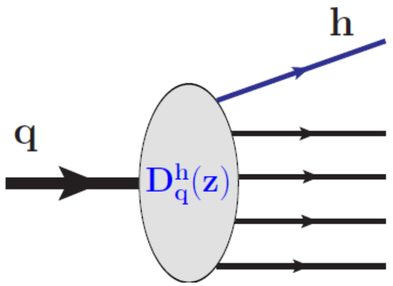
Motivation

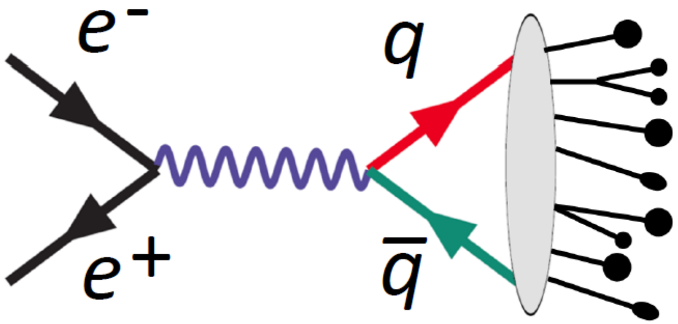
■ Fragmentation functions

Fragmentation functions (**FFs**)



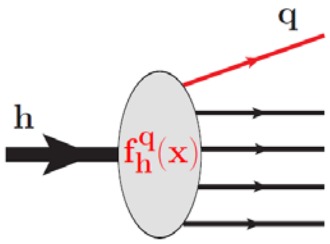
Hadronization mechanism

Hadron momentum distribution inside a parton jet



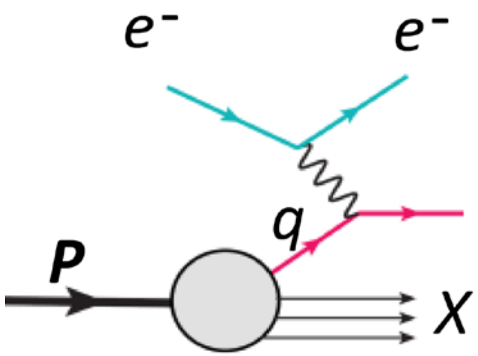
e^+e^- annihilation to hadrons

Parton distribution functions (**PDFs**)



Hadron structure

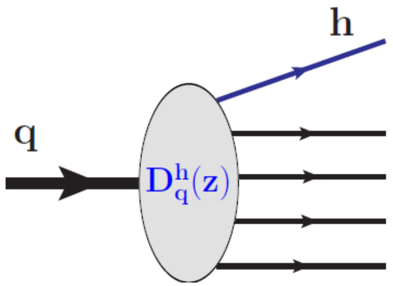
Parton momentum distribution inside a hadron



Lepton-nucleon deep inelastic scattering

Fragmentation functions

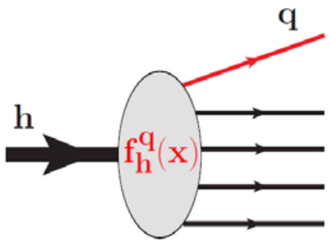
Fragmentation functions (**FFs**)



Hadronization mechanism

Hadron momentum distribution inside a parton jet

Parton distribution functions (**PDFs**)



Hadron structure

Parton momentum distribution inside a hadron

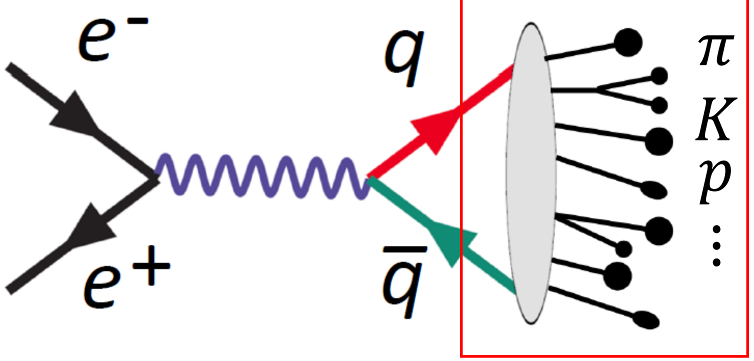
Why PDFs and FFs important?

- Insights into the properties of strong interaction
- Inputs for describing high energy reactions
- Prerequisite for doing new physics researches
- …… …

Fragmentation functions and isospin symmetry

- ✓ Fragmentation processes are dominated by strong interactions
- ✓ Isospin symmetry is a fundamental property of strong interactions

QCD dominated



FFs respect isospin symmetry:

equal under the exchange of $u \leftrightarrow d$.

$$D_{1u}^{\pi^+(u\bar{d})}(z) \xlongequal{u\leftrightarrow d} D_{1d}^{\pi^-(d\bar{u})}(z), \quad D_{1u}^{K^+(u\bar{s})}(z) \xlongequal{u\leftrightarrow d} D_{1d}^{K^0(d\bar{s})}(z)$$

$$D_{1u}^{p(uud)}(z) \xlongequal{u\leftrightarrow d} D_{1d}^{n(udd)}(z), \quad D_{1u}^{\Lambda(uds)}(z) \xlongequal{u\leftrightarrow d} D_{1d}^{\Lambda(uds)}(z)$$

$$D_{1u}^{\Xi^0(uss)}(z) \xlongequal{u\leftrightarrow d} D_{1d}^{\Xi^-(dss)}(z), \quad D_{1u}^{\Omega^-(sss)}(z) \xlongequal{u\leftrightarrow d} D_{1d}^{\Omega^-(sss)}(z)$$

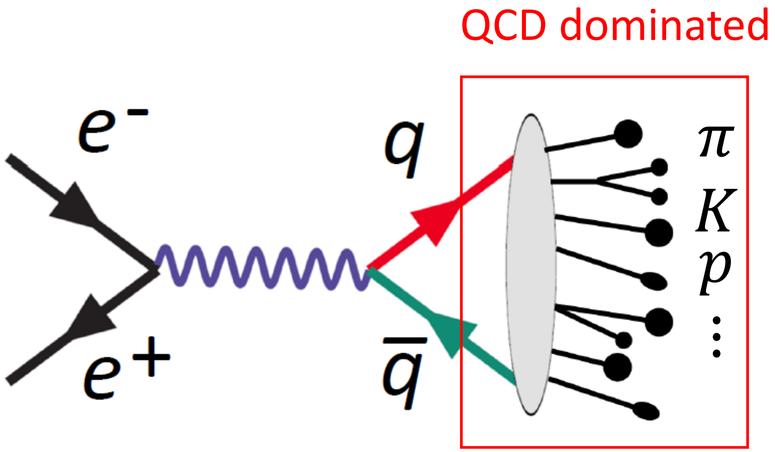
$\cdots\cdots$

Motivation

■ **Fragmentation functions and isospin symmetry**

✓ Fragmentation processes are dominated by strong interactions

✓ Isospin symmetry is a fundamental property of strong interactions



FFs respect isospin symmetry:
equal under the exchange of $u \leftrightarrow d$.

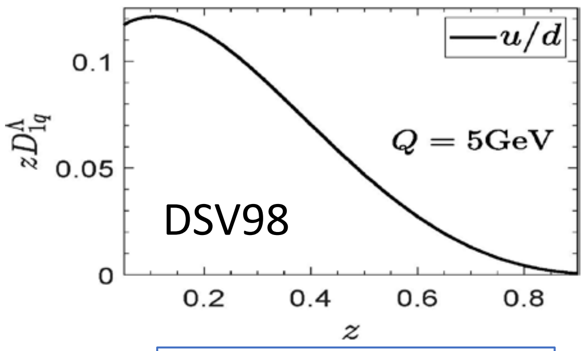
But:

Hadron electroweak decays **violate isospin symmetry**

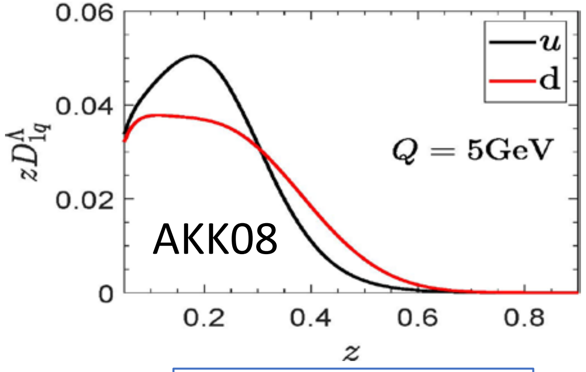
Isospin symmetry for FFs **can be violated!!**

Examples of Λ FFs

- Unpolarized Λ FFs

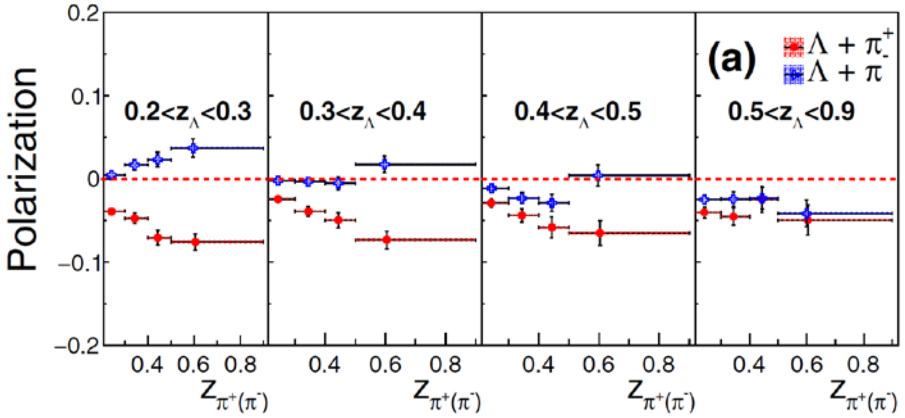


Isospin symmetric



Isospin violating

- Belle data on Λ transverse polarization



Y. Guan et al. (Belle Collaboration), PRL 122, 042001 (2019)

$$e^+e^- \rightarrow \Lambda(uds)\pi^+(u\bar{d}) + X$$

$$u \leftrightarrow d$$

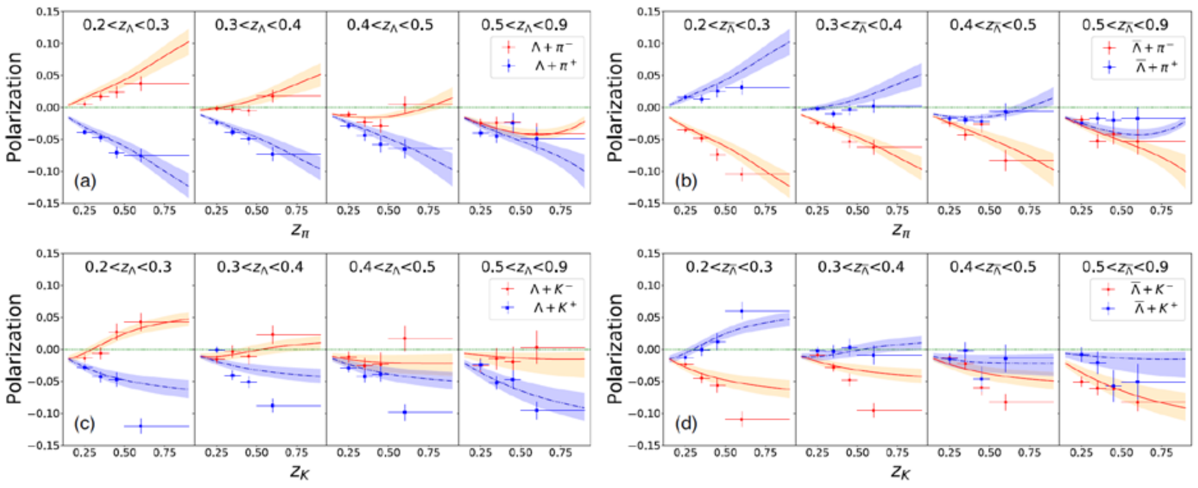
$$e^+e^- \rightarrow \Lambda(uds)\pi^-(d\bar{u}) + X$$

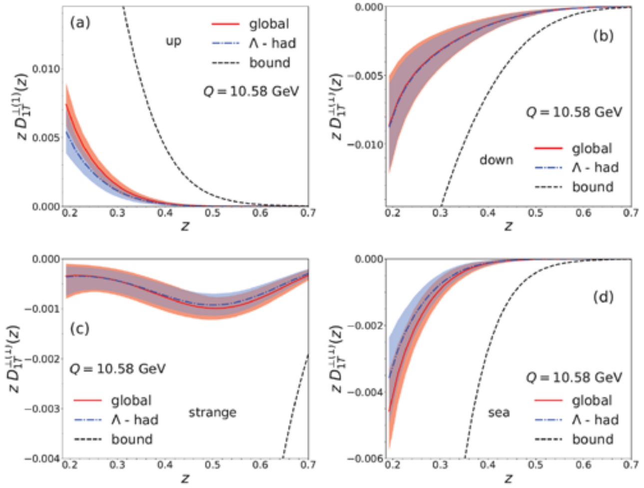
Isospin violation for polarized Λ FFs??

Motivation

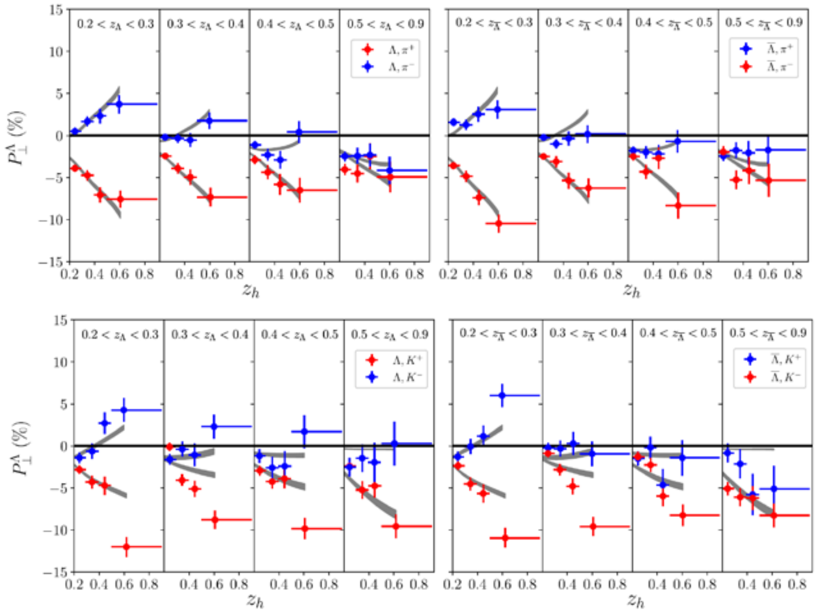
Fittings

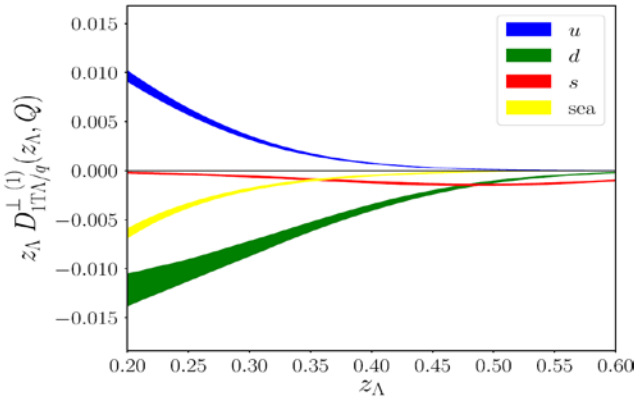
D‘Alesio, Murgia, Zaccheddu, PRD 102, 054001





Callos, Kang, Terry, PRD 102, 096007





Both fittings have large isospin symmetry violation for $D_{1Tq}^{\perp\Lambda}$

Motivation

- To what extent the isospin symmetry violation can be accommodated in FFs if it's held in QCD?

- Do the Belle data really mean that there is a large isospin symmetry violation of Λ FFs?

Isospin symmetry of fragmentation functions

Isospin symmetry of fragmentation functions

The formalism

- **Unpolarized FFs:** $D_{1q}^{h}(z) = D_{1q}^{h,\mathrm{dir}}(z) + D_{1q}^{h,\mathrm{dec}}(z)$

$$= D_{1q}^{h,\mathrm{dir}}(z) + \sum_{h_j} Br(h,h_j) \int dz' \, K_{h,h_j}(z,z') D_{1q}^{h_j}(z')$$

direct fragmentation decay contributions

- ✓ Direct FFs: $D_{1q}^{h,\mathrm{dir}}(z)$ are isospin symmetric
- ✓ Decay contributions, consider: $J^P = 0^-$(pseudo-scalar) and 1^-(vector) mesons,

  $J^P = \frac{1}{2}^+$(octet) and $\frac{3}{2}^+$(decuplet) baryons.
- ✓ Higher excited resonance states (very small production rates, mostly strong decay) are included into the direct FFs effectively.
- ✓ Isospin violation may arise from EW-decays, determined by the branch ratio $Br(h,h_j)$.

Isospin symmetry of fragmentation functions

- **Ξ production:** $\delta D_{1q}^{\Xi}(z) \stackrel{\text{def}}{=} D_{1u}^{\Xi^0}(z) - D_{1d}^{\Xi^-}(z)$

$D_{1u}^{\Xi^0,\text{dir}}(z) = D_{1d}^{\Xi^-,\text{dir}}(z)$ $\quad D_{1u}^{\Xi^0,\Xi^*}(z) = D_{1d}^{\Xi^-,\Xi^*}(z)$

$D_{1q}^{\Xi^i}(z) = D_{1q}^{\Xi^i,\text{dir}}(z) + D_{1q}^{\Xi^i,\Xi^*}(z) + D_{1q}^{\Xi^i,\Omega^-}(z)$ $\quad D_{1u}^{\Omega^-}(z) = D_{1d}^{\Omega^-}(z)$

Ω^- decays to Ξ^0 and Ξ^- unequally: $\begin{cases} Br(\Omega^- \to \Xi^0\pi^-) = (23.6 \pm 0.7)\% \\ Br(\Omega^- \to \Xi^-\pi^0) = (8.6 \pm 0.4)\% \end{cases}$ ➡ $\delta Br(\Xi, \Omega^-) = (15.0 \pm 1.1)\%$

$$\delta D_{1q}^{\Xi}(z) = \delta D_{1q}^{\Xi,\Omega^-} = \delta Br(\Xi, \Omega^-) \int dz' K_{\Xi,\Omega^-}(z,z') D_{1u}^{\Omega^-}(z') \le \text{ a few percent}$$

➡ *Tiny isospin violation for Ξ FFs, i.e.,* $D_{1u}^{\Xi^0}(z) \approx D_{1d}^{\Xi^-}(z)$

- **Λ production:** $\delta D_{1q}^{\Lambda}(z) \stackrel{\text{def}}{=} D_{1u}^{\Lambda}(z) - D_{1d}^{\Lambda}(z)$

$$D_{1q}^{\Lambda}(z) = D_{1q}^{\Lambda,\text{dir}}(z) + D_{1q}^{\Lambda,\Omega^-}(z) + D_{1q}^{\Lambda,\Sigma^*}(z) + D_{1q}^{\Lambda,\Xi}(z) + D_{1q}^{\Lambda,\Sigma^0}(z)$$

➡ *No isospin violation for Λ FFs, i.e.,* $D_{1u}^{\Lambda}(z) = D_{1d}^{\Lambda}(z)$

Notice: Ξ^0 and Ξ^- added together gives no isospin violation for Λ FFs via $\Xi \to \Lambda\pi$ (branch ratio 100%).

Isospin symmetry of fragmentation functions

- **Polarized FFs:** $\Delta D_{1q}^{h,\mathrm{dec}}(z) = \sum_{h_j} Br\left(h, h_j\right) \int dz' \, K_{h,h_j}(z, z') t_D^{h,h_j}(z) \Delta D_{1q}^{h_j}(z')$

polarization transfer factor

The difference of t_D^{Λ,Ξ^0} and t_D^{Λ,Ξ^-} is very small through the weak decay of $\Xi \to \Lambda\pi$,

leads to very tiny isospin violation for polarized Λ FFs.

★ **Conclusion:**

No isospin violation for unpolarized Λ FFs, only tiny violation for polarized.

Isospin symmetry should be kept in the parameterizations of Λ FFs.

Can we describe the Belle data under the constraint of isospin symmetric Λ FFs?

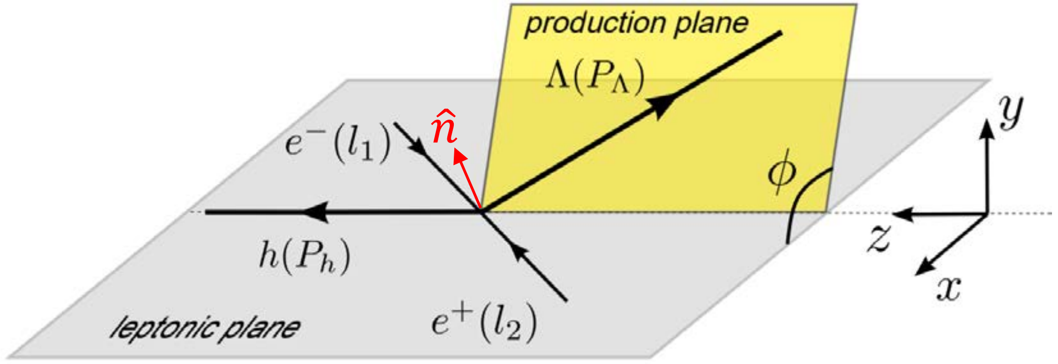
Fit to Belle Λ polarization data

- Motivation
- Isospin symmetry of fragmentation functions
- **Fit to Belle Λ polarization data**
- Summary

Fit to Belle Λ polarization data

Λ transverse polarization in $e^+e^- \to \Lambda h X$

w.r.t. the normal direction of the production plane ($\hat{n}$)



$$P_\Lambda(z_\Lambda, z_h, p_{\Lambda\perp}) = \frac{\mathcal{C}\left[wD_{1Tq}^{\perp\Lambda} D_{1\bar{q}}^{h}\right] + (q \leftrightarrow \bar{q})}{\mathcal{C}\left[D_{1q}^{\Lambda} D_{1\bar{q}}^{h}\right] + (q \leftrightarrow \bar{q})}$$

$$\mathcal{C}\left[wD_{1Tq}^{\perp\Lambda} D_{1\bar{q}}^{h}\right] \equiv \sum_q e_q^2 \int d^2p_T d^2p_{hT} \delta^2\left(\frac{z_\Lambda}{z_h} p_{hT} + p_T - p_{\Lambda\perp}\right) wD_{1Tq}^{\perp\Lambda}(z_\Lambda, p_T) D_{1\bar{q}}^{h}(z_h, p_{hT}), \qquad w = \frac{\vec{p}_{\Lambda\perp} \cdot \vec{p}_T}{z_\Lambda M_\Lambda |\vec{p}_{\Lambda\perp}|}$$

Gaussian ansatz:

$$D_{1Tq}^{\perp\Lambda}(z_\Lambda, p_T) = D_{1Tq}^{\perp\Lambda}(z_\Lambda) \frac{1}{\pi\Delta^2} \exp(-p_T^2/\Delta^2)$$

$$D_{1Tq}^{\perp\Lambda}(z_\Lambda) = N_{Tq} \frac{(\alpha_q + \beta_q - 1)^{\alpha_q + \beta_q - 1}}{(\alpha_q - 1)^{\alpha_q - 1} \beta_q^{\beta_q}} \times z_\Lambda^{\alpha_q} (1 - z_\Lambda)^{\beta_q} D_{1q}^{\Lambda}(z_\Lambda)$$

$\Rightarrow$

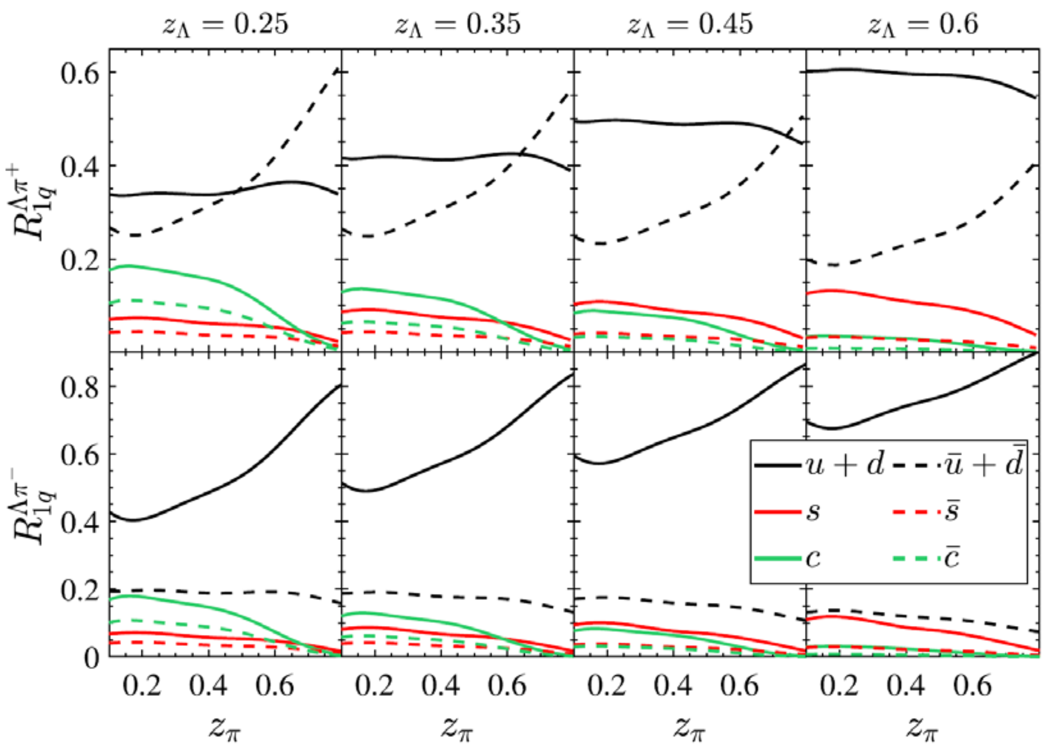
$p_{\Lambda\perp}$ integrated Λ transverse polarization:

$$\boxed{P_\Lambda(z_\Lambda, z_h) = \frac{\sqrt{\pi}\, z_h \Delta / 2 z_\Lambda M_\Lambda}{\sqrt{z_h^2 + z_\Lambda^2 \Delta_h^2/\Delta^2}} \sum_q \left[R_{1q}^{\Lambda h}(z_\Lambda, z_h) \frac{D_{1Tq}^{\perp\Lambda}(z_\Lambda)}{D_{1q}^{\Lambda}(z_\Lambda)} + (q \leftrightarrow \bar{q})\right]}$$

relative weight: $$R_{1q}^{\Lambda h}(z_\Lambda, z_h) = \frac{e_q^2 D_{1q}^{\Lambda}(z_\Lambda) D_{1\bar{q}}^{h}(z_h)}{\sum_f e_f^2 D_{1q}^{\Lambda}(z_\Lambda) D_{1\bar{q}}^{h}(z_h) + (f \leftrightarrow \bar{f})}$$

Fit to Belle Λ polarization data

$R_{1q}^{\Lambda\pi}$ calculated using DSV and DHESS FFs



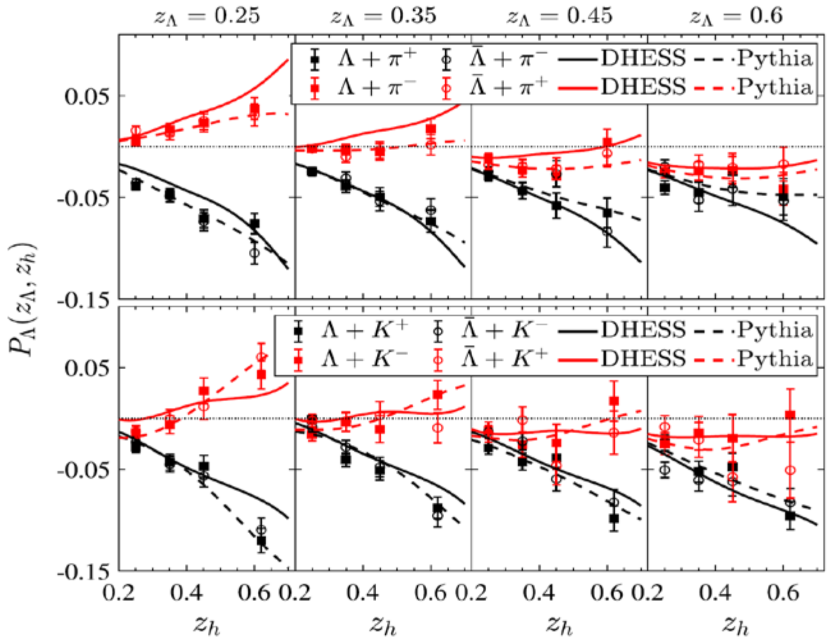
parameterization schemes:

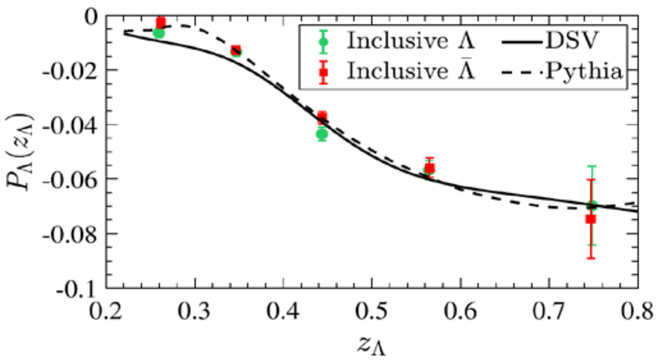
- Keep isospin symmetry, i.e., $u = d$ and $\bar{u} = \bar{d}$
- s contributes differently from u, d
- $c, \bar{c}$ not negligible and different from light flavors

Six groups of parameters for $D_{1Tq}^{\perp\Lambda}(z_\Lambda)$,
$q = (u/d), s, c, (\bar{u}/\bar{d}), \bar{s}, \bar{c}$

Fit to Belle Λ polarization data

Fitting results





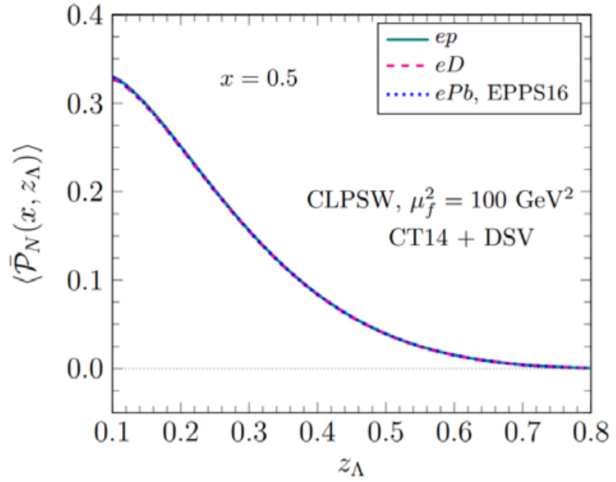
parameter	u, d	s	c	$\bar u, \bar d$	$\bar s$	$\bar c$
$\frac{\Delta}{M_\Lambda} N_{Tq}$	0.391 0.245	−0.391 −0.148	0.0278 0.108	−0.456 −0.231	−0.430 0.523	0.401 −0.324
α_q	1.38 2.41	6.91 1.54	1.43 5.14	1.00 1.86	2.64 1.74	11.6 1.02
β_q	3.98 7.69	0.646 0.551	14.3 15.0	0.0319 2.35	2.77 14.9	14.9 2.41

The Belle data can be well described using polarized Λ FFs with isospin symmetry.

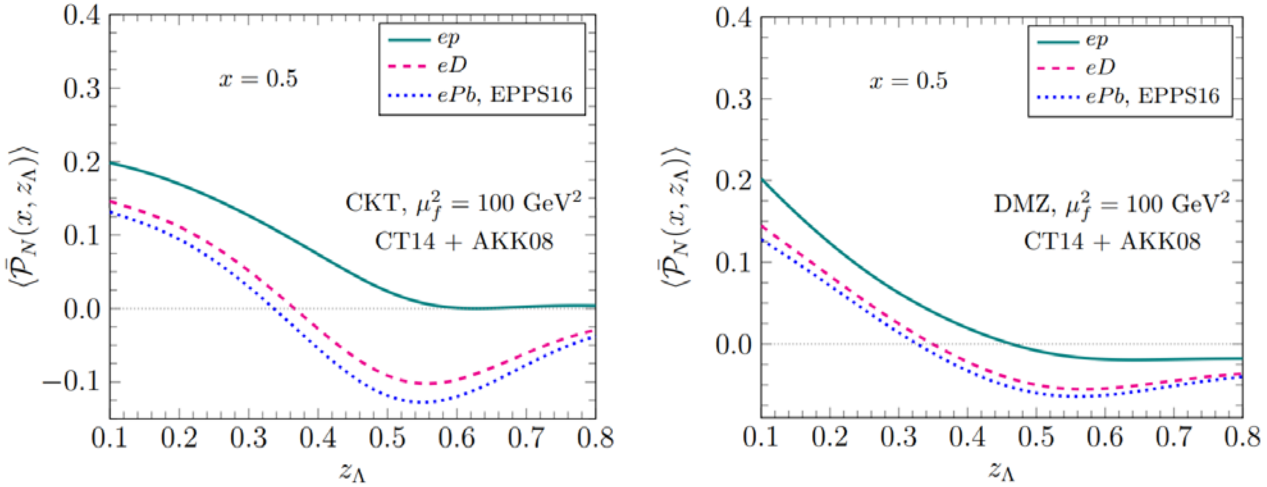
Current e^+e^- data cannot distinguish different scenarios of isospin symmetry or violation.

Checking isospin symmetry in SIDIS off nucleus

Using isospin symmetric parameterizations for polarized Λ FFs



Using isospin violating parameterizations for polarized Λ FFs



Chen, Liang, Song and Wei, arXiv:2108.07740

A clean test!

Summary

- Motivation
- Isospin symmetry of fragmentation functions
- Fit to Belle Λ polarization data
- **Summary**

Summary

- We make a systematic analysis of isospin symmetry for FFs by considering hadron decay contributions.
- There is no isospin violation for unpolarized Λ FFs, tiny violation for polarized.
- The Belle Λ polarization data can be well described under isospin symmetric Λ polarized FFs. There is no need to introduce large isospin violation at current stage.
- The isospin symmetry can be clearly checked at EIC with SIDIS off different nucleus.

Thank you for your attention!