26th International Symposium on Spin Physics
A Century of Spin

SHANDONG UNIVERSITY

Suppression of Spin Transfer to Λ in Deep-Inelastic Scattering

Phys. Rev. Lett. 134, 231901

Xiaoyan Zhao (赵晓燕)

Shandong University

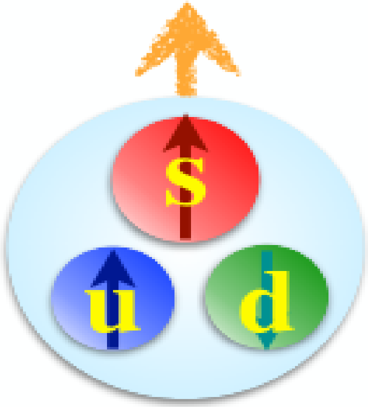
Collaborators: Tianbo Liu, Ya-jin Zhou, Zuo-tang Liang

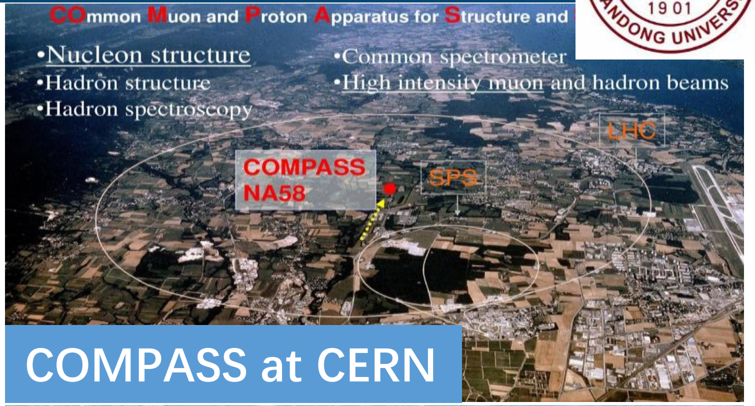
24 / 09 / 2025

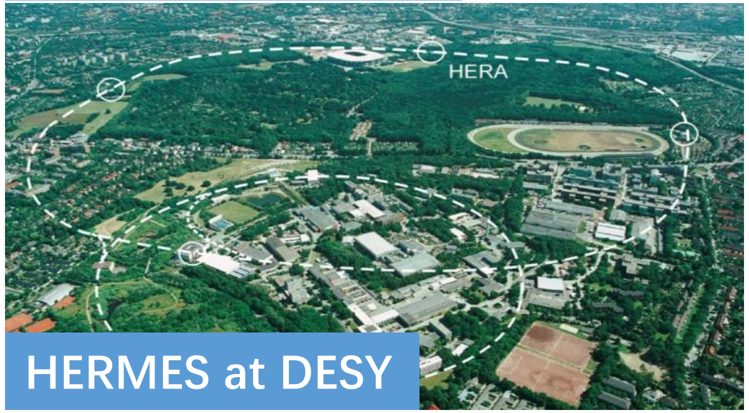
The structure of Λ hyperon

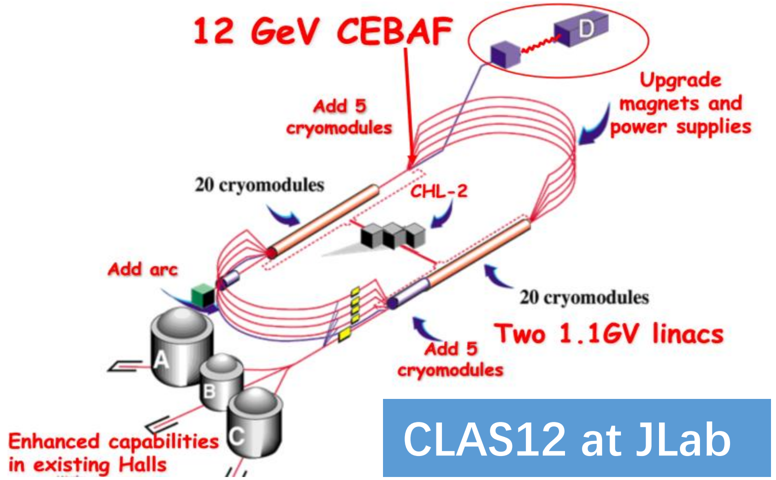
Λ valence component: $|uds\rangle$

s=1/2 , $M = 1.116$ GeV

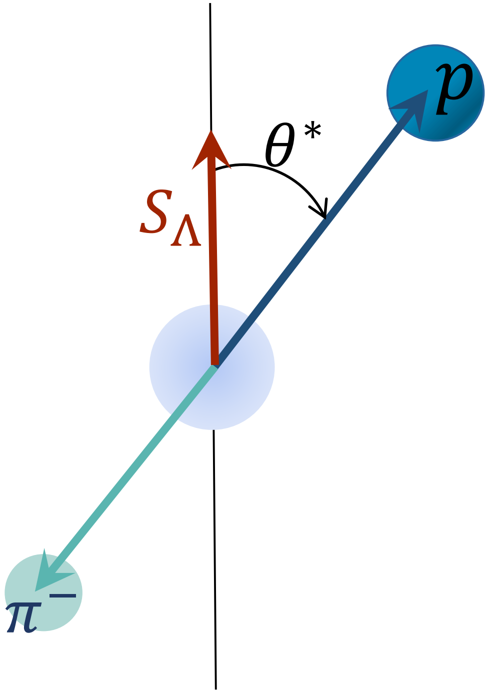








◆ Self-analyzing weak decay



Decay channel:

$$\Lambda \to p\pi^- \ (BR = (64.1 \pm 0.5)\%)$$

parity violation:

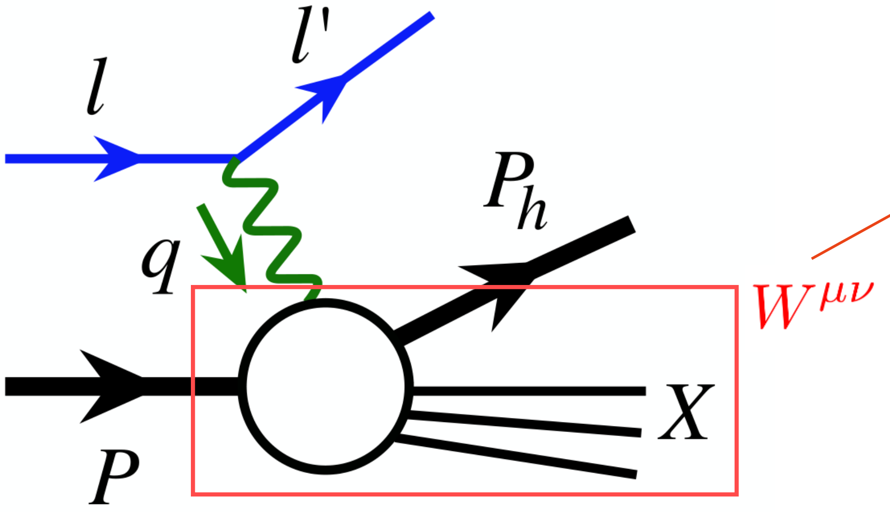
$$\frac{dN}{d\cos\theta^*} \propto \mathcal{A}(1 + \alpha_\Lambda P_\Lambda \cos\theta^*)$$

decay parameter: $\alpha_\Lambda = 0.764 \pm 0.009$ [BESIII]

See talks by Hai-Bo Li, Hongfei Shen

Semi-inclusive deep inelastic scattering

$$l(\ell) + N(P) \to l(\ell') + \Lambda(P_\Lambda) + X$$



$$\frac{d\sigma^{\mathrm{SIDIS}}}{dx\,dy\,dz_\Lambda d^2\boldsymbol{P}_{\Lambda\perp}} = \frac{\pi\alpha_{\mathrm{em}}^2}{2Q^4}\frac{y}{z_\Lambda}L_{\mu\nu}W^{\mu\nu}$$

in terms of structure functions

$$F_{AB}(x_B, z, P_{h\perp}, Q^2)$$

A : nucleon polarization

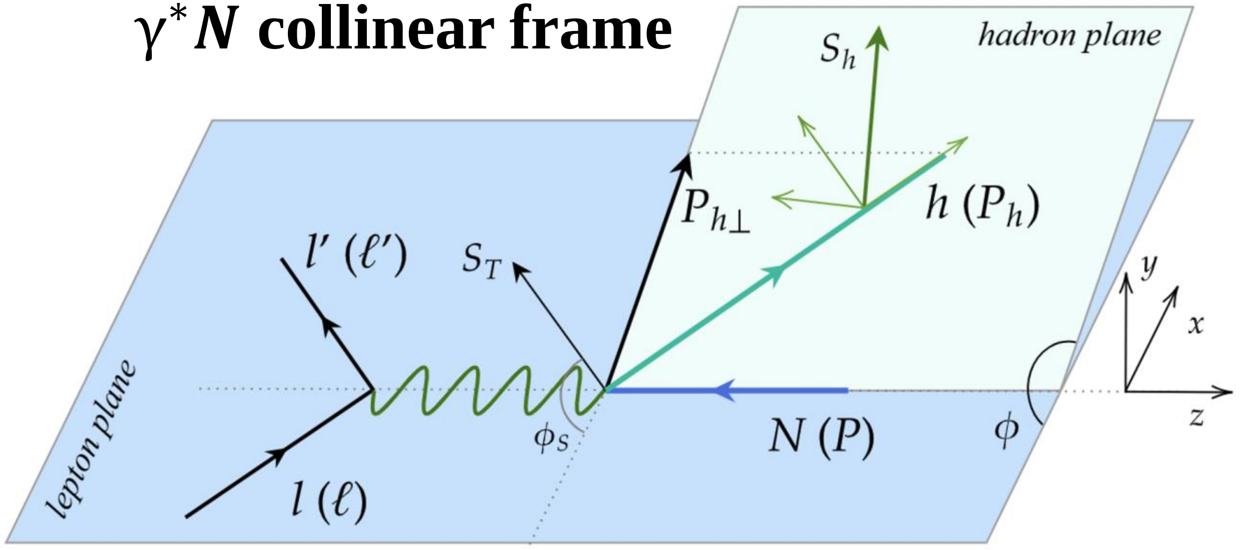
B : Λ polarization

$$\cos\phi_h = -\frac{g_\perp^{\mu\nu} l_\mu P_{h\nu}}{|l_\perp|\,|P_{h\perp}|}, \quad \sin\phi_h = -\frac{\epsilon_\perp^{\mu\nu} l_\mu P_{h\nu}}{|l_\perp|\,|P_{h\perp}|}.$$

$$\cos\phi_S = -\frac{g_\perp^{\mu\nu} l_\mu S_\nu}{|l_\perp|\,|S_T|}, \quad \sin\phi_S = -\frac{\epsilon_\perp^{\mu\nu} l_\mu S_\nu}{|l_\perp|\,|S_T|}.$$

$$\cos\phi_{S_h} = -\frac{g_{h\perp}^{\mu\nu} P_{h\mu} S_{h\nu}}{|P_{h\perp}|\,|S_{hT}|}, \quad \sin\phi_{S_h} = -\frac{\epsilon_{h\perp}^{\mu\nu} P_{h\mu} S_{h\nu}}{|P_{h\perp}|\,|S_{hT}|}.$$

$\gamma^* N$ collinear frame



Differential Cross Section

$$\frac{d\sigma}{dxdydzd^2P_{\Lambda\perp}} = \frac{4\pi\alpha_{em}^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)\{$$

Unpolarized P and Λ — 5

$$A(y)F_{UU}^{T} + B(y)F_{UU}^{L} + C(y)\cos\phi F_{UU}^{\cos\phi} + B(y)\cos 2\phi F_{UU}^{\cos 2\phi} + \lambda_e E(y)\sin\phi G_{UU}^{\sin\phi}$$

Polarized p Unpolarized Λ — 13

$$+\lambda C(y)\sin\phi F_{LU}^{\sin\phi} + \lambda B(y)\sin 2\phi F_{LU}^{\sin 2\phi} + \mathbf{S}_\perp A(y)\sin(\phi-\phi_S)F_{TU}^{T\sin(\phi-\phi_S)}$$

$$+\mathbf{S}_\perp B(y)\sin(\phi-\phi_S)F_{TU}^{L\sin(\phi-\phi_S)} + \mathbf{S}_\perp C(y)\sin(2\phi-\phi_S)F_{TU}^{\sin(2\phi-\phi_S)}$$

$$+\mathbf{S}_\perp C(y)\sin\phi_S F_{TU}^{\phi_S} + \mathbf{S}_\perp B(y)\sin(3\phi-\phi_S)F_{TU}^{\sin(3\phi-\phi_S)} + \mathbf{S}_\perp B(y)\sin(\phi+\phi_S)F_{TU}^{\sin(\phi+\phi_S)}$$

$$+\lambda_e\lambda D(y)G_{LU}^{T} + \lambda_e\lambda E(y)\cos\phi G_{LU}^{\cos\phi} + \lambda_e\mathbf{S}_\perp D(y)\cos(\phi-\phi_S)G_{TU}^{T\cos(\phi-\phi_S)}$$

$$+\lambda_e\mathbf{S}_\perp E(y)\cos\phi_S G_{TU}^{\cos\phi_S} + \lambda_e\mathbf{S}_\perp E(y)\cos(2\phi-\phi_S)G_{TU}^{\cos(2\phi-\phi_S)}$$

Unpolarized p Polarized Λ — 13

$$+\lambda_h C(y)\sin\phi F_{UL}^{\sin\phi} + \lambda_h B(y)\sin 2\phi F_{UL}^{\sin 2\phi} + \mathbf{S}_{h\perp}\sin\phi_{Sh}B(y)F_{UT}^{L} + \mathbf{S}_{h\perp}\sin\phi_{Sh}A(y)F_{UT}^{T}$$

$$+\mathbf{S}_{h\perp}B(y)\sin(2\phi+\phi_{Sh})F_{UT}^{\sin(2\phi+\phi_{Sh})} + \mathbf{S}_{h\perp}B(y)\sin(2\phi-\phi_{Sh})F_{UT}^{\sin(2\phi-\phi_{Sh})}$$

$$+\mathbf{S}_{h\perp}C(y)\sin(\phi+\phi_{Sh})F_{UT}^{\sin(\phi+\phi_{Sh})} + \mathbf{S}_{h\perp}C(y)\sin(\phi-\phi_{Sh})F_{UT}^{\sin(\phi-\phi_{Sh})}$$

$$+\lambda_e\lambda_h D(y)G_{UL}^{T} + \lambda_e\mathbf{S}_{h\perp}\cos\phi_{Sh}D(y)G_{UT}^{T} + \lambda_e\lambda_h E(y)\cos\phi G_{UL}^{\cos\phi}$$

$$+\lambda_e\mathbf{S}_{h\perp}E(y)\cos(\phi-\phi_{Sh})G_{UT}^{\cos(\phi-\phi_{Sh})} + \lambda_e\mathbf{S}_{h\perp}E(y)\cos(\phi+\phi_{Sh})G_{UT}^{\cos(\phi+\phi_{Sh})}$$

F_{AB} : unpolarized lepton, G_{AB} : polarized lepton,
U: unpolarized, L: longitudinal, T: transvers

$$A(y) = \frac{y^2}{4}(2+\gamma^2) - y + 1$$

$$B(y) = 1 - y - \frac{1}{4}\gamma^2 y^2$$

......

Differential Cross Section

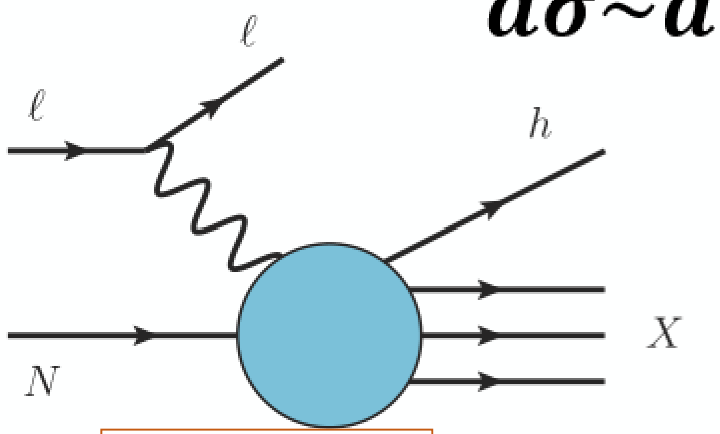
$$
\begin{aligned}
&+\lambda\lambda_h A(y)F_{LL}^{T} + \lambda\lambda_h B(y)F_{LL}^{L} + \lambda\lambda_h C(y)\cos\phi F_{LL}^{T\cos\phi} + \lambda\lambda_h B(y)\cos 2\phi F_{LL}^{T\cos 2\phi} + \lambda\mathbf{S}_{h\perp}\cos\phi_{Sh} A(y)F_{LT}^{T}\\
&+\lambda\mathbf{S}_{h\perp}\cos\phi_{Sh} B(y)F_{LT}^{L} + \lambda\mathbf{S}_{h\perp}C(y)\cos(\phi-\phi_{Sh})F_{LT}^{\cos(\phi-\phi_{Sh})} + \lambda\mathbf{S}_{h\perp}B(y)\cos(2\phi-\phi_{Sh})F_{LT}^{\cos(2\phi-\phi_{Sh})}\\
&+\lambda\mathbf{S}_{h\perp}C(y)\cos(\phi+\phi_{Sh})F_{LT}^{\cos(\phi+\phi_{Sh})} + \lambda\mathbf{S}_{h\perp}B(y)\cos(2\phi+\phi_{Sh})F_{LT}^{\cos(2\phi+\phi_{Sh})}\\
&+\mathbf{S}_{\perp}\lambda_h C(y)\cos\phi_S F_{TL}^{\phi_S} + \mathbf{S}_{\perp}\lambda_h A(y)\cos(\phi-\phi_S)\,F_{TL}^{T\cos(\phi-\phi_S)} + \mathbf{S}_{\perp}\lambda_h B(y)\cos(\phi-\phi_S)\,F_{TL}^{L\cos(\phi-\phi_S)}\\
&+\mathbf{S}_{\perp}\lambda_h C(y)\cos(2\phi-\phi_S)\,F_{TL}^{\cos(2\phi-\phi_S)} + \mathbf{S}_{\perp}\lambda_h B(y)\cos(\phi+\phi_S)\,F_{TL}^{\cos(\phi+\phi_S)} + \mathbf{S}_{\perp}\lambda_h B(y)\cos(3\phi-\phi_S)\,F_{TL}^{\cos(3\phi-\phi_S)}\\
&+\lambda_e\mathbf{S}_{\perp}\lambda_h E(y)\sin\phi_S G_{TL}^{\sin\phi_S} + \lambda_e\mathbf{S}_{\perp}\lambda_h E(y)\sin(2\phi-\phi_S)\,G_{TL}^{\sin(2\phi-\phi_S)} + \lambda_e\mathbf{S}_{\perp}\lambda_h D(y)\sin(\phi-\phi_S)\,G_{TL}^{T\sin(\phi-\phi_S)}\\
&+\lambda_e\lambda\lambda_h E(y)\sin\phi G_{LL}^{\sin\phi} + \lambda_e\lambda\mathbf{S}_{h\perp}E(y)\left[\sin(\phi+\phi_{Sh})G_{LT}^{\sin(\phi+\phi_{Sh})} + \sin(\phi-\phi_{Sh})G_{LT}^{\sin(\phi-\phi_{Sh})}\right] + \lambda_e\lambda\mathbf{S}_{h\perp}\sin\phi_{Sh}D(y)G_{LT}^{T}\\
&+\lambda_e\mathbf{S}_{\perp}\mathbf{S}_{h\perp}D(y)\left[\sin(\phi-\phi_S+\phi_{Sh})\,G_{TT}^{T\sin(\phi-\phi_S+\phi_{Sh})} + \sin(\phi-\phi_S-\phi_{Sh})\,G_{TT}^{T\sin(\phi-\phi_S-\phi_{Sh})}\right]\\
&+\lambda_e\mathbf{S}_{\perp}\mathbf{S}_{h\perp}E(y)\left[\sin(\phi_S+\phi_{Sh})\,G_{TT}^{\sin(\phi_S+\phi_{Sh})} + \sin(\phi_S-\phi_{Sh})\,G_{TT}^{\sin(\phi_S-\phi_{Sh})}\right.\\
&\qquad\left.+\sin(2\phi-\phi_S-\phi_{Sh})\,G_{TT}^{\sin(2\phi-\phi_S-\phi_{Sh})} + \sin(2\phi-\phi_S+\phi_{Sh})\,G_{TT}^{\sin(2\phi-\phi_S+\phi_{Sh})}\right]\\
&+\mathbf{S}_{\perp}\mathbf{S}_{h\perp}\cos(\phi-\phi_S-\phi_{Sh})\,A(y)F_{TT}^{T\cos(\phi-\phi_S-\phi_{Sh})} + \mathbf{S}_{\perp}\mathbf{S}_{h\perp}B(y)\sin(\phi-\phi_S-\phi_{Sh})\,F_{TT}^{L\sin(\phi-\phi_S-\phi_{Sh})}\\
&+\mathbf{S}_{\perp}\mathbf{S}_{h\perp}B(y)\cos(3\phi-\phi_S-\phi_{Sh})\,F_{TT}^{\cos(3\phi-\phi_S-\phi_{Sh})} + \mathbf{S}_{\perp}\mathbf{S}_{h\perp}B(y)\cos(\phi+\phi_S-\phi_{Sh})\,F_{TT}^{\cos(\phi+\phi_S-\phi_{Sh})}\\
&+\mathbf{S}_{\perp}\mathbf{S}_{h\perp}C(y)\cos(2\phi-\phi_S-\phi_{Sh})\,F_{TT}^{\cos(2\phi-\phi_S-\phi_{Sh})} + \mathbf{S}_{\perp}\mathbf{S}_{h\perp}C(y)\cos(\phi_S-\phi_{Sh})F_{TT}^{\cos(\phi_S-\phi_{Sh})}\\
&+\mathbf{S}_{\perp}\mathbf{S}_{h\perp}\cos(\phi-\phi_S+\phi_{Sh})\,A(y)F_{TT}^{T\cos(\phi-\phi_S+\phi_{Sh})} + \mathbf{S}_{\perp}\mathbf{S}_{h\perp}B(y)\sin(\phi-\phi_S+\phi_{Sh})\,F_{TT}^{L\sin(\phi-\phi_S+\phi_{Sh})}\\
&+\mathbf{S}_{\perp}\mathbf{S}_{h\perp}B(y)\cos(3\phi-\phi_S+\phi_{Sh})\,F_{TT}^{\cos(3\phi-\phi_S+\phi_{Sh})} + \mathbf{S}_{\perp}\mathbf{S}_{h\perp}B(y)\cos(\phi+\phi_S+\phi_{Sh})\,F_{TT}^{\cos(\phi+\phi_S+\phi_{Sh})}\\
&+\mathbf{S}_{\perp}\mathbf{S}_{h\perp}C(y)\cos(2\phi-\phi_S+\phi_{Sh})\,F_{TT}^{\cos(2\phi-\phi_S+\phi_{Sh})} + \mathbf{S}_{\perp}\mathbf{S}_{h\perp}C(y)\cos(\phi_S+\phi_{Sh})F_{TT}^{\cos(\phi_S+\phi_{Sh})}
\end{aligned}
$$

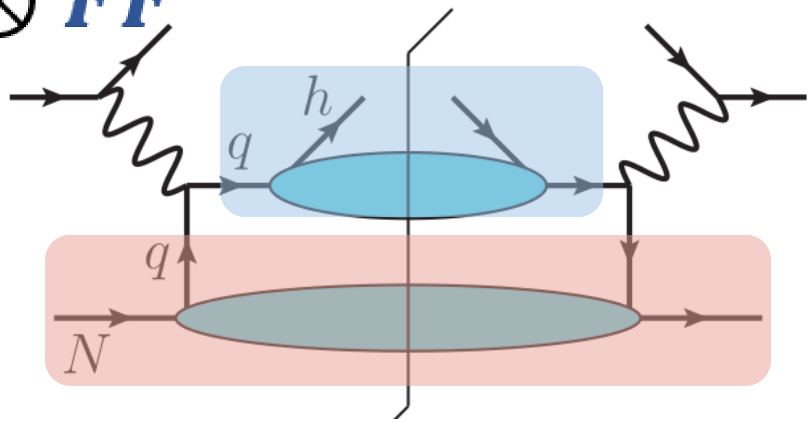
41

Polarized p
Polarized Λ

Current Fragmentation

$$d\sigma \sim d\hat{\sigma} \otimes PDF \otimes FF$$





$$F_{U,U}^{T} = \mathscr{C}\left[f_1 D_1\right]$$
$$F_{U,U}^{\cos 2\phi_h} = \mathscr{C}\left[-w_2 h_1^{\perp} H_1^{\perp}\right]$$
$$F_{U,L}^{\sin 2\phi_h} = \mathscr{C}\left[w_2 h_1^{\perp} H_{1L}^{\perp}\right]$$
$$F_{U,T}^{T\sin\phi_{hT}T} = \mathscr{C}\left[\bar{w}_1 f_1 D_{1T}^{\perp}\right]$$
$$F_{U,T}^{\sin(2\phi_h+\phi_h T)} = \mathscr{C}\left[-w_1 h_1^{\perp} H_{1T}\right]$$
$$F_{U,T}^{\sin(2\phi_h-\phi_{hT})} = \mathscr{C}\left[-\bar{w}_3 h_1^{\perp} H_{1T}^{\perp}\right]$$
$$F_{L,U}^{\sin 2\phi_h} = \mathscr{C}\left[-w_2 h_{1L}^{\perp} H_1^{\perp}\right]$$
$$F_{L,L}^{T} = \mathscr{C}\left[g_{1L} G_{1L}\right]$$
$$F_{L,L}^{\cos 2\phi_h} = \mathscr{C}\left[-w_2 h_{1L}^{\perp} H_{1L}^{\perp}\right]$$

⋮

$$F_{T,U}^{T\sin(\phi_h-\phi_T)} = \mathscr{C}\left[w_1 f_{1T}^{\perp} D_1\right]$$
$$F_{T,U}^{\sin(\phi_h+\phi_T)} = \mathscr{C}\left[\bar{w}_1 h_{1T} H_1^{\perp}\right]$$
$$F_{T,U}^{\sin(3\phi_h-\phi_T)} = \mathscr{C}\left[w_3 h_{1T}^{\perp} H_1^{\perp}\right]$$
$$F_{T,L}^{T\cos(\phi_h-\phi_T)} = \mathscr{C}\left[-w_1 g_{1T} G_{1L}\right]$$
$$F_{T,L}^{\cos(\phi_h+\phi_T)} = \mathscr{C}\left[\bar{w}_1 h_{1T} H_{1L}^{\perp}\right]$$
$$F_{T,}^{\cos(3\phi_h-\phi_T)} = \mathscr{C}\left[w_3 h_{1T}^{\perp} H_{1L}^{\perp}\right]$$
$$F_{T,T}^{\cos(\phi_h+\phi_h+\phi_T)} = \mathscr{C}\left[-h_{1T} H_{1T}\right]$$
$$F_{T,T}^{\cos(\phi_h-\phi_h+\phi_T)} = \mathscr{C}\left[-\bar{w}_4 h_{1T} H_{1T}^{\perp}\right]$$

⋮

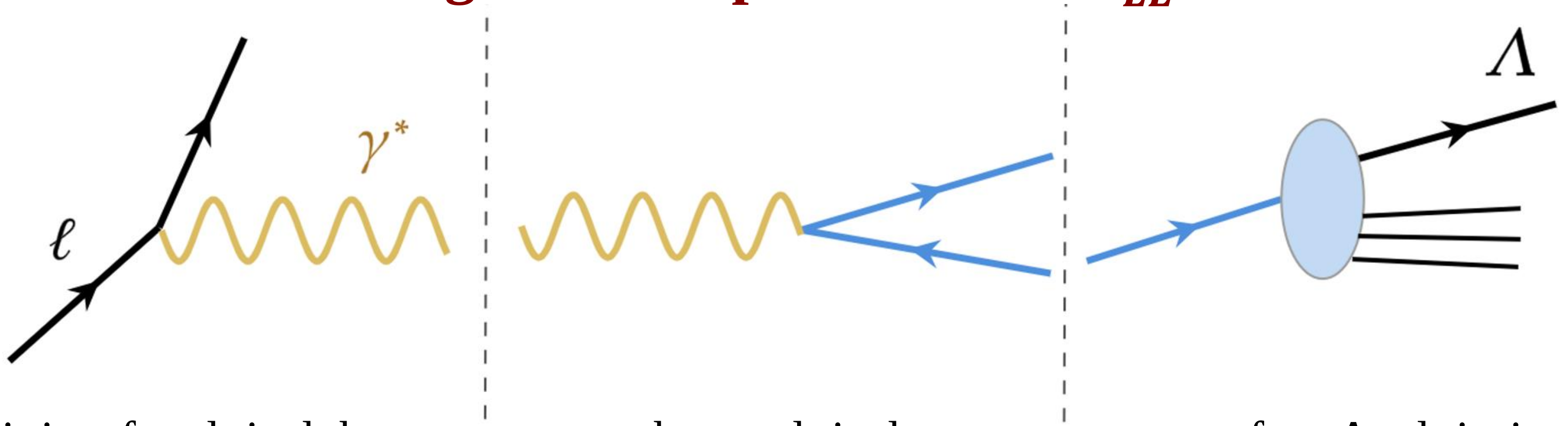
$$G_{U,L} = \mathscr{C}\left[f_1 G_{1L}\right]$$
$$G_{U,T}^{\cos\phi_{hT}} = \mathscr{C}\left[-\bar{w}_1 f_1 G_{1T}^{\perp}\right]$$
$$G_{L,U}^{\perp} = \mathscr{C}\left[g_{1L} D_1\right]$$
$$G_{L,T}^{\sin\phi_{hT}} = \mathscr{C}\left[\bar{w}_1 g_{1L} D_{1T}^{\perp}\right]$$
$$G_{T,U}^{\cos(\phi_h-\phi_T)} = \mathscr{C}\left[-w_1 g_{1T}^{\perp} D_1\right]$$
$$G_{T,L}^{\sin(\phi_h-\phi_T)} = \mathscr{C}\left[w_1 f_{1T}^{\perp} G_{1L}\right]$$
$$G_{T,T}^{\sin(\phi_h-\phi_{hT}-\phi_T)} = \mathscr{C}\left[-\frac{w_2}{2}\left(f_{1T}^{\perp} G_{1T}^{\perp} - g_{1T}^{\perp} D_{1T}^{\perp}\right)\right]$$
$$G_{T,T}^{\sin(\phi_h+\phi_{hT}-\phi_T)} = \mathscr{C}\left[\frac{w_2'}{2}\left(f_{1T}^{\perp} G_{1T}^{\perp} + g_{1T}^{\perp} D_{1T}^{\perp}\right)\right]$$

32

Spin Transfer

Spin asymmetry : $A = \frac{d\sigma(\uparrow) - d\sigma(\downarrow)}{d\sigma(\uparrow) + d\sigma(\downarrow)}$ ⇒ $A = \frac{F_{XY}^{\omega(\phi_h,\phi_s)}}{F_{UU}}$

- **Illustration of the longitudinal Spin Transfer D_{LL}^{Λ}**



emission of a polarized photon | quark gets polarized | transfer to **Λ** polarization

$$D_{LL}^{\Lambda} = \frac{G_{U,L}(x, Q^2, z)}{F_{U,U}(x, Q^2, z)}$$

$$G_{U,L} \sim f_1(x) \otimes G_1(z)$$

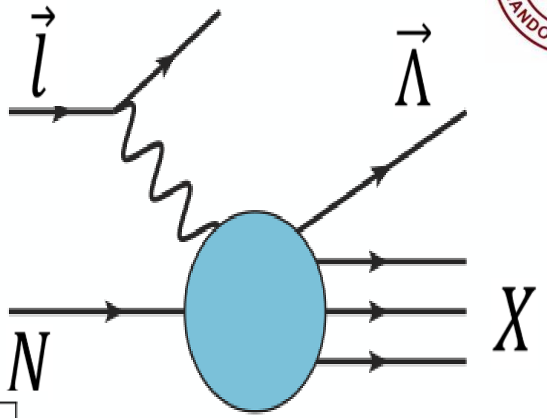
$$F_{U,L} \sim f_1(x) \otimes D_1(z)$$

Longitudinal Spin Transfer D_{LL}

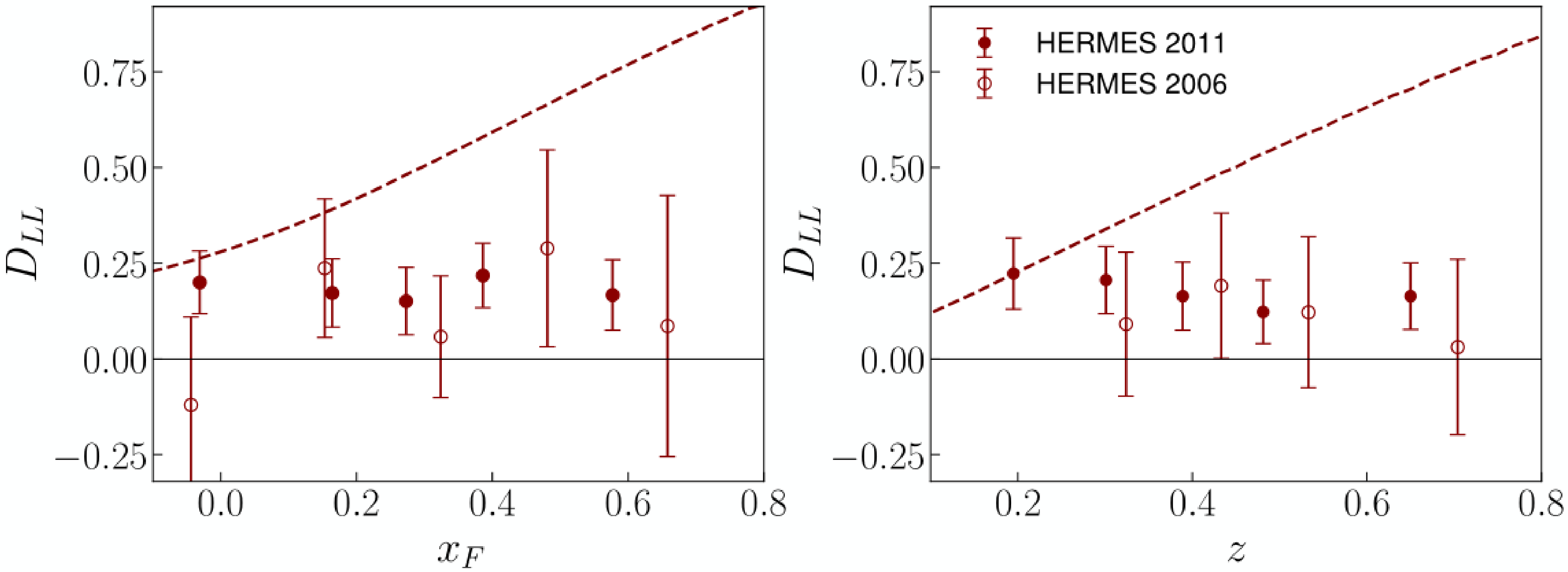
$$D_{LL}^{\Lambda} = \frac{G_{U,L}\left(x, Q^2, z\right)}{F_{U,U}\left(x, Q^2, z\right)}$$

$$G_{U,L} \sim f_1(x) \otimes G_1(z)$$

$$F_{U,L} \sim f_1(x) \otimes D_1(z)$$



Theory curves based on JR14 PDF parametrization and DSV FFs parametrization.



The tension between data and theory with the current fragmentation mechanism.

Kinematic Regions

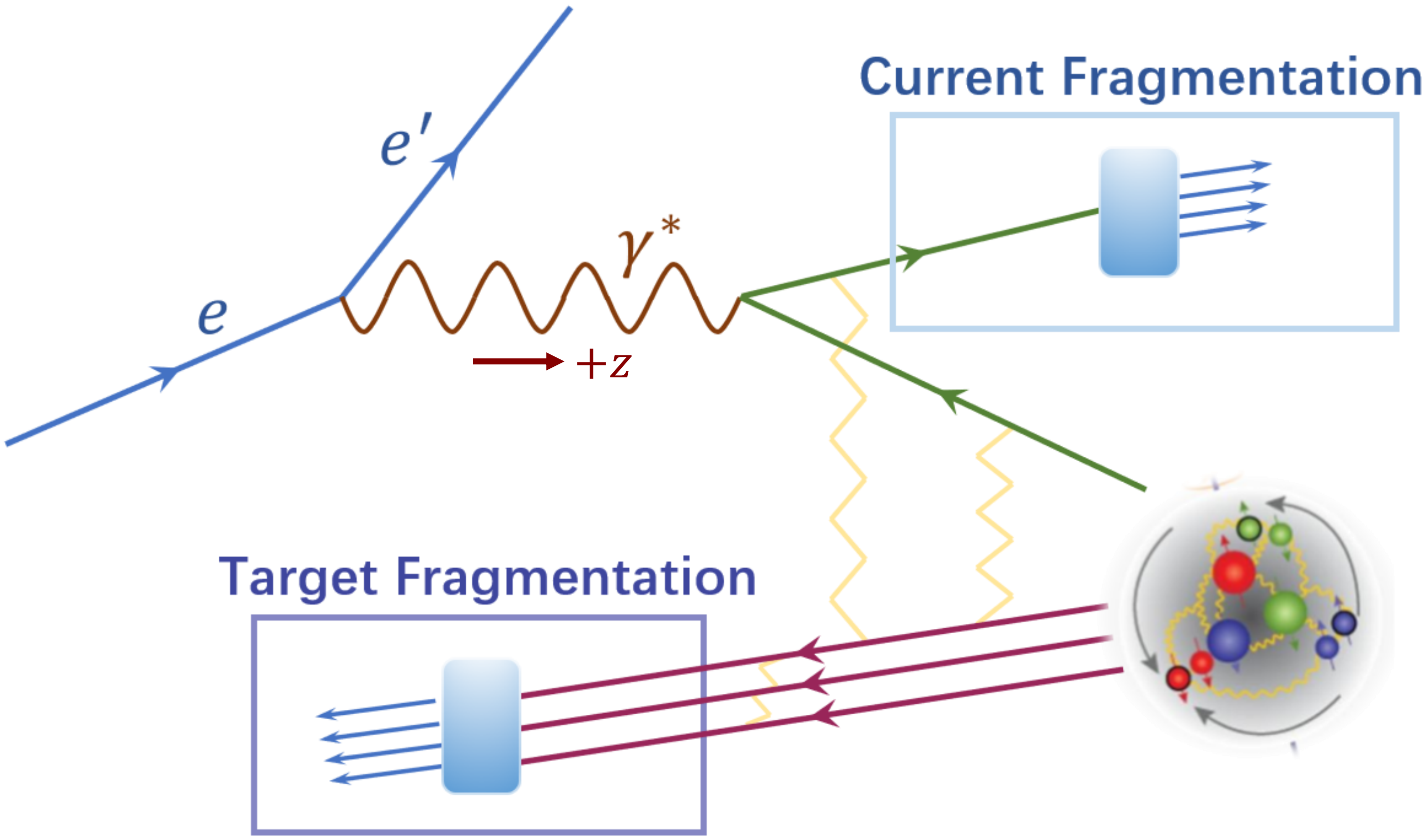
The Λ production in SIDIS process :

$$e^- P \rightarrow e^- \Lambda X$$

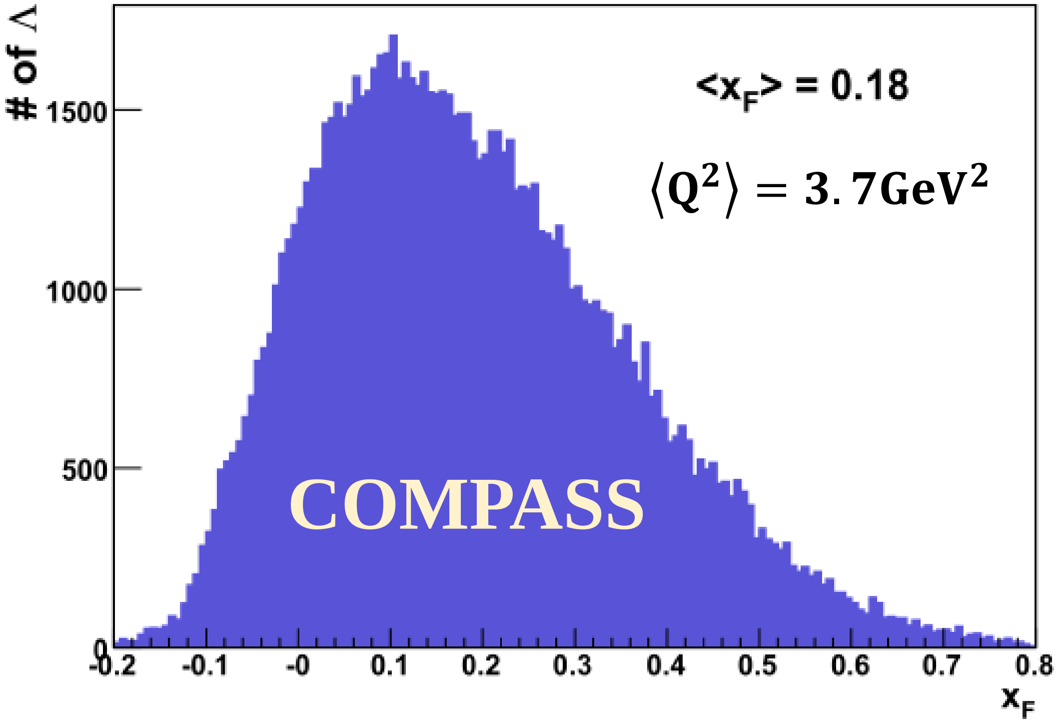
- Current Fragmentation (CF)
- Target Fragmentation (TF)

$$x_F = \frac{2P_{\Lambda L}}{W}$$

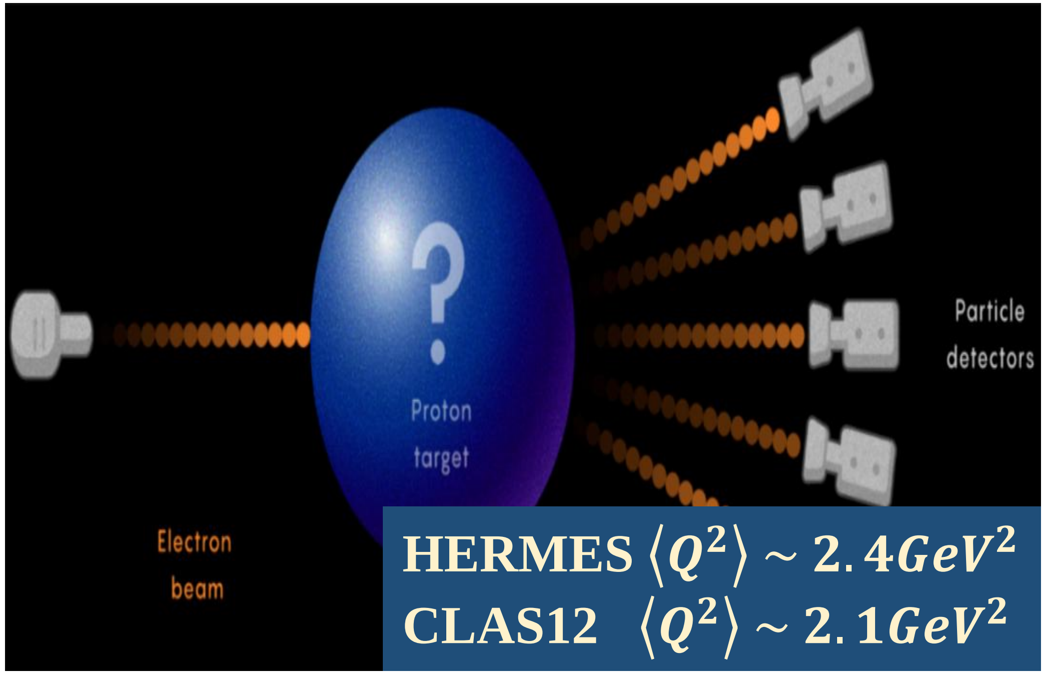
In $\gamma^* N$ center-of-mass frame,
$P_{\Lambda L}$ is the projection of the Λ momentum onto the direction of the γ^*momentum,
W is invariant mass.



Λ Events Distribution



In photon-nucleon frame, with photon moving forward.

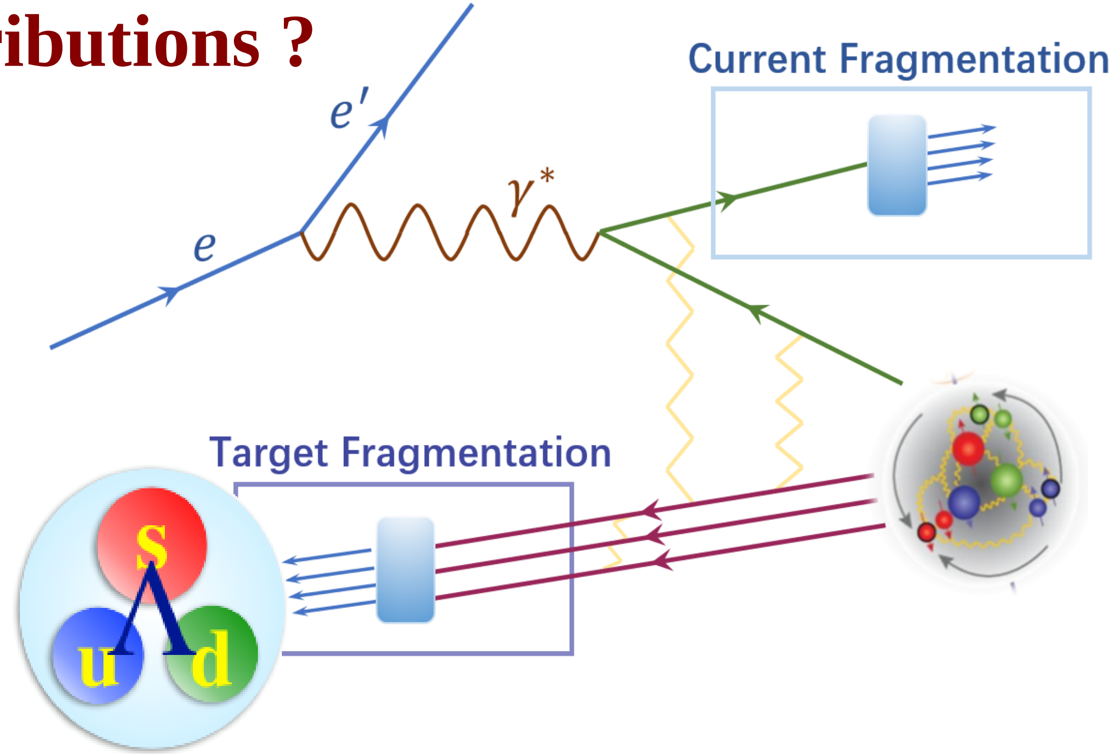


HERMES $\langle Q^2 \rangle \sim 2.4GeV^2$

CLAS12 $\langle Q^2 \rangle \sim 2.1GeV^2$

No clear separation between current region and target region!

Whether TF can compete with CF contributions ?



- **Quark densities in the nucleon**

  $u, d > \bar{u}, \bar{d} > s, \bar{s}$

- **Current fragmentation:**

  favored channels: u, d, s

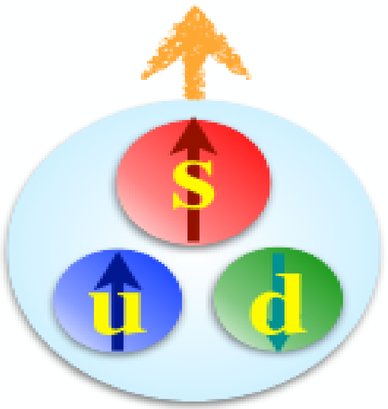
- **In the target nucleon remnant:**
  - ud, us, ds pairs have a better chance to produce Λ than u, d, s
  - considering quark densities in the nucleon, ud pair is expected the dominant channel

The influence of TF

What is the expected effect of TF on spin transfer measurements ?

- **Spin-flavor wave function**

$$\Lambda^{\uparrow} = \frac{1}{\sqrt{3}}(ud)_{0,0}s^{\uparrow} + \frac{1}{\sqrt{12}}(us)_{0,0}d^{\uparrow} - \frac{1}{\sqrt{12}}(ds)_{0,0}u^{\uparrow} + \frac{1}{2}\left(\sqrt{\frac{2}{3}}(us)_{1,1}d^{\downarrow} - \sqrt{\frac{1}{3}}(us)_{1,0}d^{\uparrow}\right) - \frac{1}{2}\left(\sqrt{\frac{2}{3}}(ds)_{1,1}u^{\downarrow} - \sqrt{\frac{1}{3}}(ds)_{1,0}u^{\uparrow}\right)$$

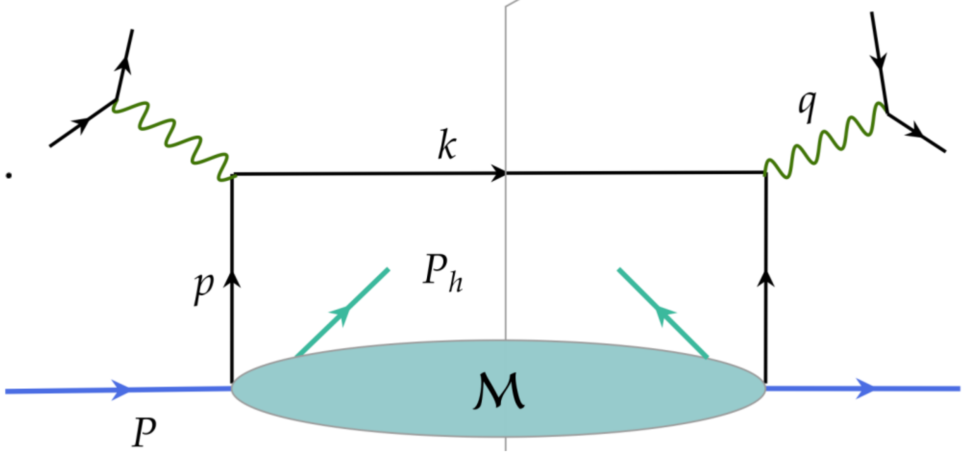


- **In the target nucleon remnant**
  - ud pair in an isoscalar state is more likely to produce Λ and will be **unpolarized**
  - the target remnant is not directly polarized by the virtual photon

Expect: the target fragmentation will **suppress** the overall measured D_{LL}

Target Fragmentation

$$W^{\mu\nu} = \sum_a e_a^2 \int \frac{\mathrm{d}^4 k}{(2\pi)^4}\, 2\pi\, \delta[(k+q)^2]\, \mathrm{Tr}\, [\mathcal{M}\gamma^\mu(\not{k}+\not{q})\gamma^\nu]\ .$$



◆ The correlation function $\mathcal{M}$

$$\mathcal{M}_{ij}(k;P,S;P_\Lambda,S_\Lambda) = \sum_X \int \frac{d^3\mathbf{P}_X}{(2\pi)^3 2E_X} \int \frac{d^4\xi}{(2\pi)^4} e^{ik\xi} \langle P,S|\overline{\Psi}_j(0)|P_\Lambda,S_\Lambda;X\rangle \langle P_\Lambda,S_\Lambda;X|\Psi_i(\xi)|P,S\rangle$$

decompose it on a basis of Dirac structures: $\mathcal{M} = \frac{1}{2}\left(\mathcal{S}I + \mathcal{V}_\mu\gamma^\mu + \mathcal{A}_\mu\gamma^\mu\gamma_5 + i\mathcal{P}\gamma_5 + i\mathcal{T}_{\mu\nu}\sigma^{\mu\nu}\gamma_5\right)$

$\mathcal{M}_{ij}(k;P,S;P_\Lambda,S_\Lambda)$

Dirac Struture: $1, \gamma^\mu, \gamma^\mu\gamma_5, \gamma_5, \sigma^{\mu\nu}\gamma_5$

Five Vectors: $k^\mu, P^\mu, P_\Lambda^\mu, S^\mu, S_\Lambda^\mu.$

the most general decomposition of $\mathcal{M}$

Fracture Functions

$$F_{UU}^{T} = \sum_q e_q^2 x_B \left|\frac{\partial\zeta}{\partial z}\right| M_U^U(x,\zeta,\boldsymbol{P}_{h\perp}^2)$$

$$F_{LL}^{T} = \sum_q e_q^2 x_B \left|\frac{\partial\zeta}{\partial z}\right| M_L^L(x,\zeta,\boldsymbol{P}_{h\perp}^2)$$

$$F_{TT}^{\cos(\phi_S-\phi_{S_h})} = \sum_q e_q^2 x_B \left|\frac{\partial\zeta}{\partial z}\right| \left[M_T^T(x,\zeta,\boldsymbol{P}_{h\perp}^2) + \frac{P_{h\perp}^2}{m_h^2} M_T^{Th}(x,\zeta,\boldsymbol{P}_{h\perp}^2)\right]$$

$$F_{TT}^{T\cos(2\phi-\phi_S-\phi_{S_h})} = \sum_q e_q^2 x_B \left|\frac{\partial\zeta}{\partial z}\right| \frac{P_{h\perp}^2}{m_h^2} M_T^{Th}(x,\zeta,\boldsymbol{P}_{h\perp}^2)$$

$$F_{TU}^{T\sin(\phi-\phi_S)} = -\sum_q e_q^2 x_B \left|\frac{\partial\zeta}{\partial z}\right| \frac{P_{h\perp}}{m_h} M_T^{Uh}(x,\zeta,\boldsymbol{P}_{h\perp}^2)$$

$$F_{UT}^{T\sin(\phi-\phi_{S_h})} = -\sum_q e_q^2 x_B \left|\frac{\partial\zeta}{\partial z}\right| \frac{P_{h\perp}}{m_h} M_U^{Th}(x,\zeta,\boldsymbol{P}_{h\perp}^2)$$

$$F_{LT}^{\cos(\phi-\phi_S)} = \sum_q e_q^2 x_B \left|\frac{\partial\zeta}{\partial z}\right| \frac{P_{h\perp}}{m_h} M_L^{Th}(x,\zeta,\boldsymbol{P}_{h\perp}^2)$$

$$F_{TL}^{\cos(\phi-\phi_{S_h})} = \sum_q e_q^2 x_B \left|\frac{\partial\zeta}{\partial z}\right| \frac{P_{h\perp}}{m_h} M_T^{Lh}(x,\zeta,\boldsymbol{P}_{h\perp}^2)$$

$$G_{LU}^{T} = \sum_q e_q^2 x_B \left|\frac{\partial\zeta}{\partial z}\right| \Delta M_L^U(x,\zeta,\boldsymbol{P}_{h\perp}^2)$$

$$G_{UL}^{T} = \sum_q e_q^2 x_B \left|\frac{\partial\zeta}{\partial z}\right| \Delta M_U^L(x,\zeta,\boldsymbol{P}_{h\perp}^2)$$

$$G_{TU}^{\cos(\phi-\phi_S)} = \sum_q e_q^2 x_B \left|\frac{\partial\zeta}{\partial z}\right| \frac{P_{h\perp}}{m_h} \Delta M_T^{Uh}(x,\zeta,\boldsymbol{P}_{h\perp}^2)$$

$$G_{UT}^{\cos(\phi-\phi_{S_h})} = \sum_q e_q^2 x_B \left|\frac{\partial\zeta}{\partial z}\right| \frac{P_{h\perp}}{m_h} \Delta M_U^{Th}(x,\zeta,\boldsymbol{P}_{h\perp}^2)$$

$$G_{LT}^{T\sin(\phi_\Lambda-\phi_{S_\Lambda})} = -\sum_q e_q^2 x_B \left|\frac{\partial\zeta}{\partial z}\right| \frac{P_{h\perp}}{m_h} \Delta M_L^{Th}(x,\zeta,\boldsymbol{P}_{h\perp}^2)$$

$$G_{TL}^{T\sin(\phi_\Lambda-\phi_S)} = -\sum_q e_q^2 x_B \left|\frac{\partial\zeta}{\partial z}\right| \frac{P_{h\perp}}{m_h} \Delta M_T^{Lh}(x,\zeta,\boldsymbol{P}_{h\perp}^2)$$

$$G_{TT}^{\sin(\phi_S-\phi_{S_h})} = -\sum_q e_q^2 x_B \left|\frac{\partial\zeta}{\partial z}\right| \left[\Delta M_T^T(x,\zeta,\boldsymbol{P}_{h\perp}^2) + \frac{P_{h\perp}^2}{m_h^2} \Delta M_T^{Th}(x,\zeta,\boldsymbol{P}_{h\perp}^2)\right]$$

$$G_{TT}^{\sin(2\phi-\phi_S-\phi_{S_h})} = -\sum_q e_q^2 x_B \left|\frac{\partial\zeta}{\partial z}\right| \frac{P_{h\perp}^2}{m_h^2} \Delta M_T^{Th}(x,\zeta,\boldsymbol{P}_{h\perp}^2)$$

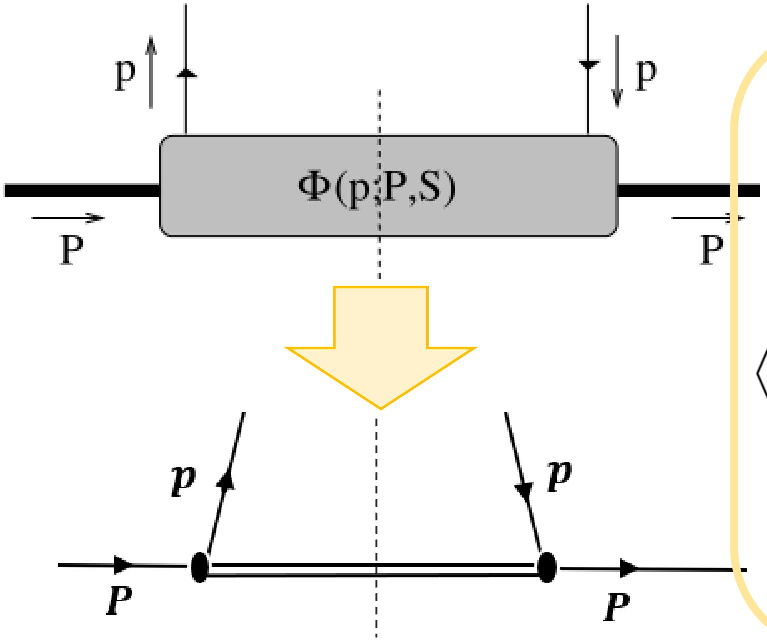
16

M_X^Y X: nucleon polarization, Y: Λ polarization

ΔM: longitudinally polarized quark

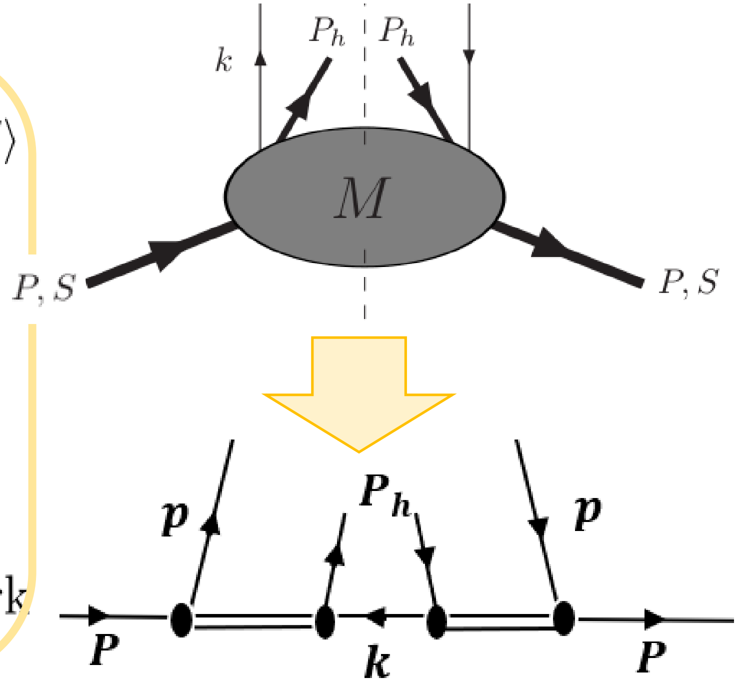
Quark- Diquark Model

R. P. Feynman, "Photon Hadron Interactions," New York 1972-01-01.



$$\Phi^R_{ij} = \sum_X \int \frac{d^3\mathbf{P}_X}{(2\pi)^3 2P^0_X} \langle P,S|\bar{\psi}_j(0)|X\rangle \langle X|\psi_i(0)|P,S\rangle$$
$$* (2\pi)^4 \delta(P - p - P_X)$$

$$\langle P,S|\bar{\psi}(0)|X\rangle = \begin{cases} \bar{U}(P,S)\Upsilon_s \frac{i}{\not{p}-m_q}, & \text{scalar diquark} \\ \bar{U}(P,S)\Upsilon^\mu_a \frac{i}{\not{p}-m_q}\epsilon_\mu, & \text{axial-vector diquark} \end{cases}$$



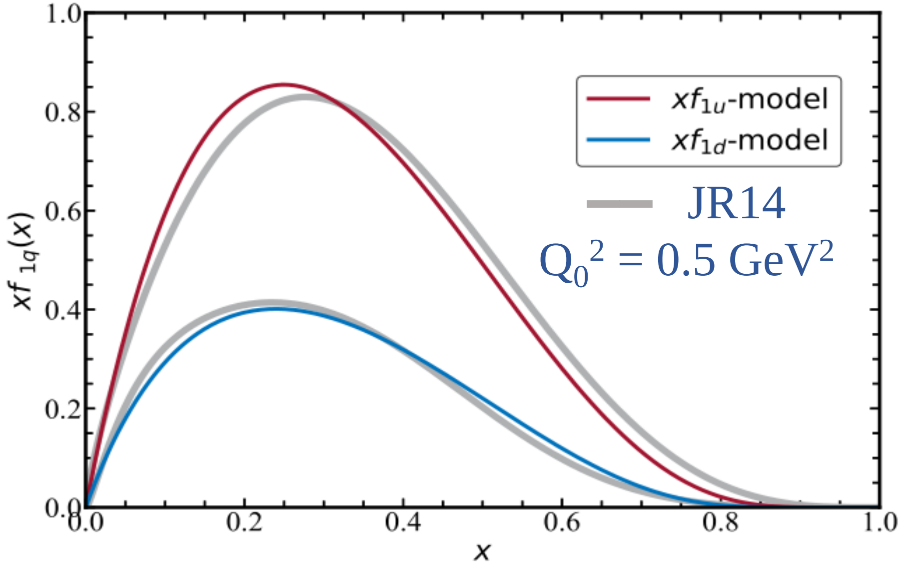
Parton distribution function

Target fragmentation

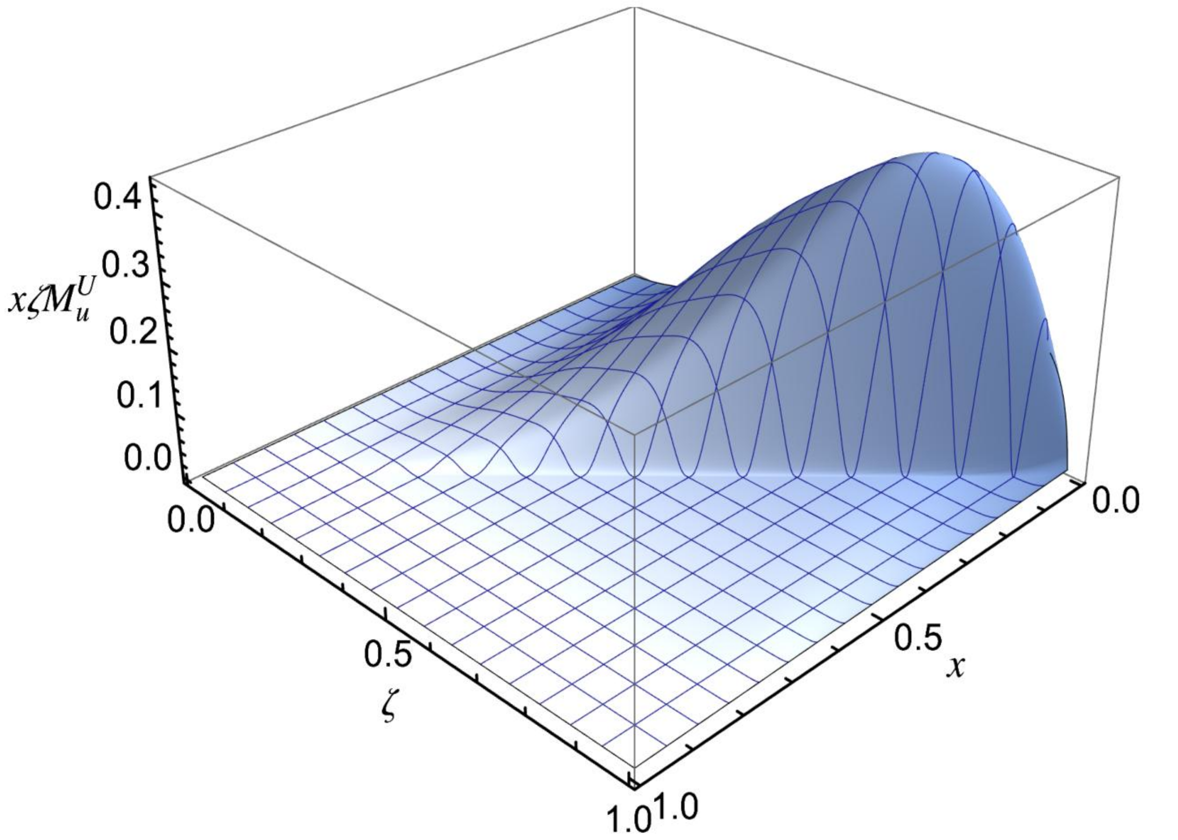
$$M^U_u = \frac{3g^2_{sN}g^2_{s\Lambda}x^2\left[(m_u + xM)^2 + \boldsymbol{p}^2_\perp\right]}{4(2\pi)^6\zeta^2(1-\zeta-x)^2(p^2 - m^2_u)^2}$$
$$\times \frac{\left[(1-x-\zeta)M_\Lambda - \zeta m_s\right]^2 + \left[(1-x)\boldsymbol{P}_{\Lambda\perp} + \zeta\boldsymbol{p}_\perp\right]^2}{\left[x(1-x)M^2 - xM^2_s - (1-x)p^2 - \boldsymbol{p}^2_\perp\right]^2},$$

Model Results

Model parameters tuned to
match proton unpolarized PDF



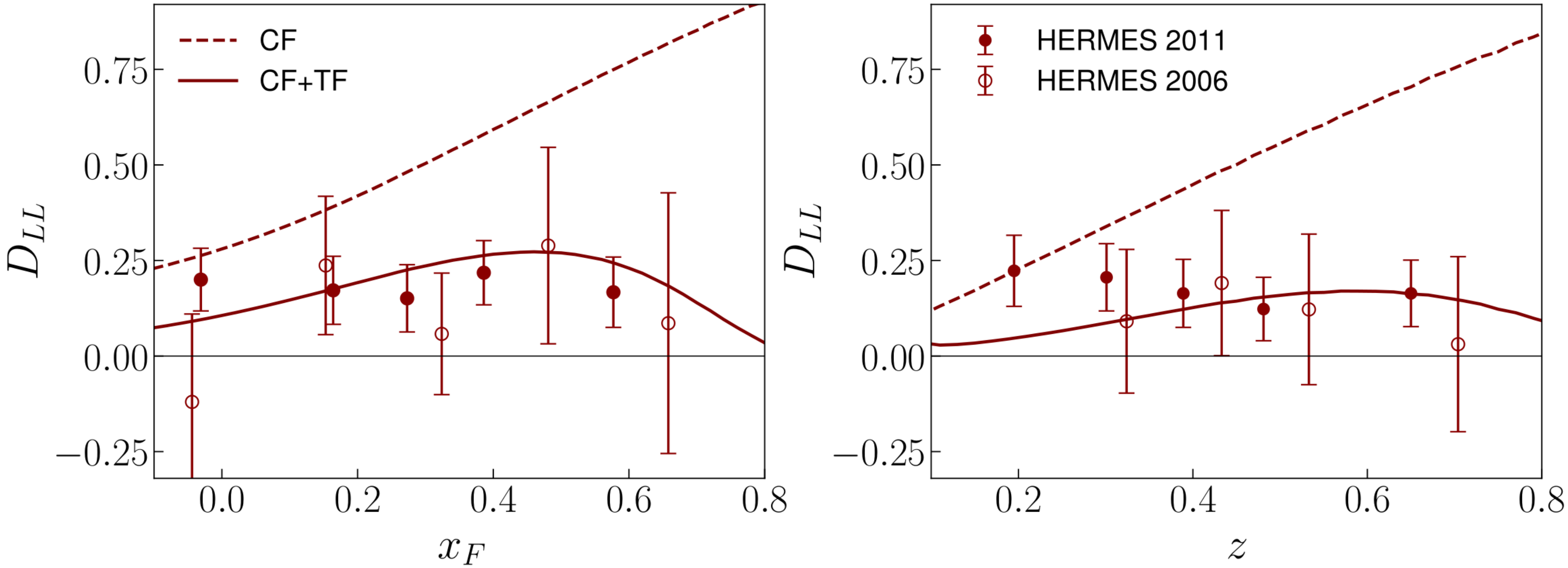
$$m = 0.3GeV,$$
$$M_s = 1.2GeV,\ \ M_a = 1.3GeV$$
$$\lambda_s = 2.9GeV,\ \ \lambda_a = 1.8GeV$$



Model result of fracture function

◆ Compare with HERMES data at $\langle Q^2 \rangle = 2.4\ GeV^2$

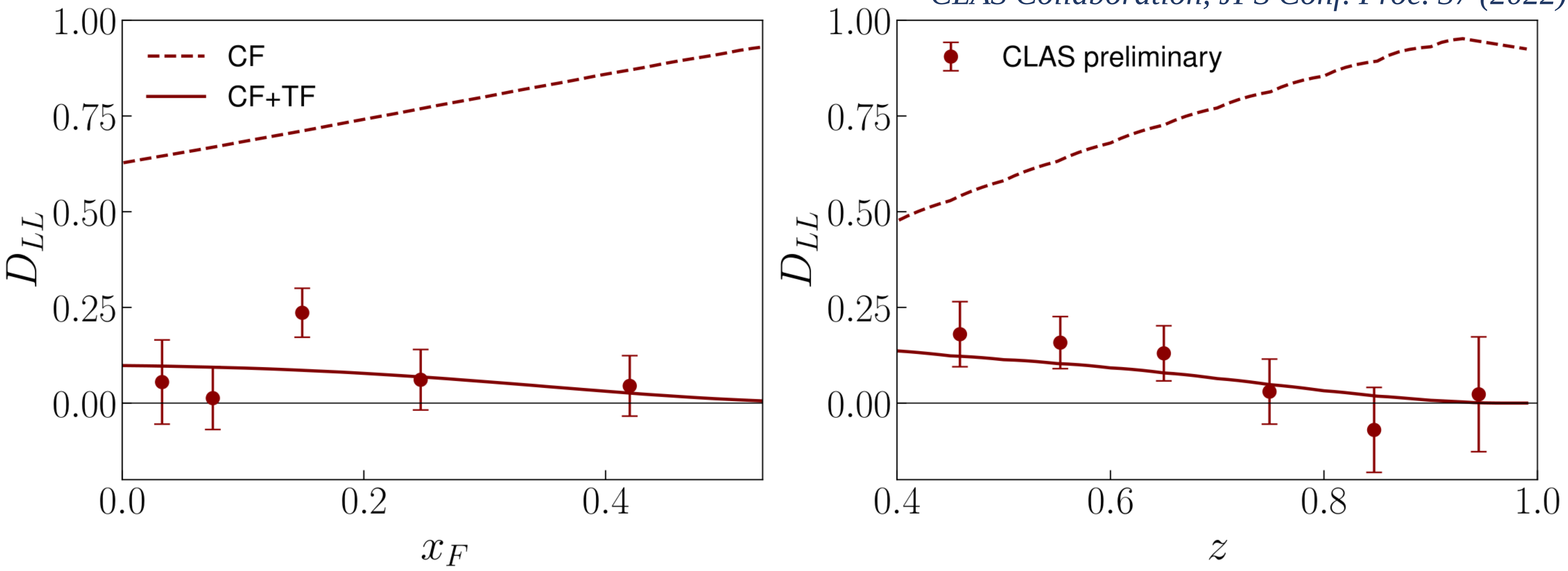
HERMES Collaboration, Phys. Rev. D 74 (2006) 072004; J. Phys. Conf. Ser. 295 (2011) 012114.



- Longitudinal spin transfer D_{LL} to Λ is significantly **suppressed** by target fragmentation (TF) contributions, even at large x_F or z.
- Including only the leading TF channel can describe the data well.

◆ Compare with JLab-CLAS data $\langle Q^2\rangle = 2.13\ \mathrm{GeV}^2$

CLAS Collaboration, JPS Conf. Proc. 37 (2022) 020304.

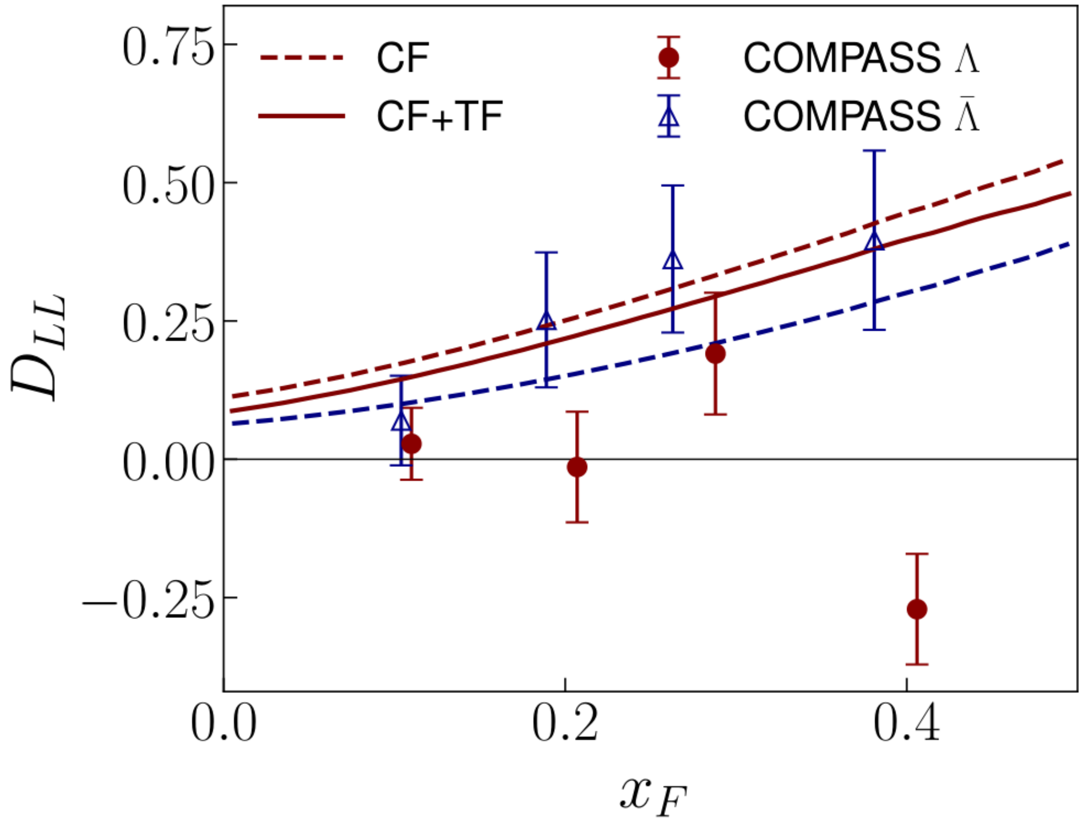


See the talk by Anselm

- **At lower energies**, the suppression effect becomes more significant.
- Including only the leading TF channel can describe the data well.

◆ Compare with COMPASS data $\langle Q^2 \rangle = 3.7\ \text{GeV}^2$

COMPASS Collaboration, Eur. Phys. J. C 64 (2009) 171.

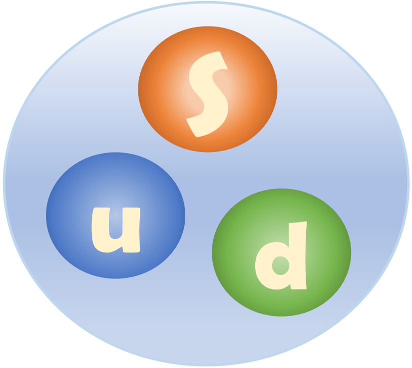


- The suppression effect reduces **at higher energies**, as expected.
- Including the leading TF channel alleviates the tension, but still deviates from the data. Need a detailed analysis including more channels.
- For $\bar{\Lambda}$ production, target fragmentation cannot compete with current fragmentation. Only current fragmentation can describe the $\bar{\Lambda}$ data.

Σ hyperon

- Spin-flavor wave function of *Σ* hyperon

$$\Sigma^{0\uparrow} = \frac{1}{2}(us)_{0,0}d^{\uparrow} + \frac{1}{2}(ds)_{0,0}u^{\uparrow} + \frac{1}{\sqrt{3}}\left(\sqrt{\frac{2}{3}}(ud)_{1,1}s^{\downarrow} - \sqrt{\frac{1}{3}}(ud)_{1,0}s^{\uparrow}\right)$$
$$-\frac{1}{\sqrt{12}}\left(\sqrt{\frac{2}{3}}(us)_{1,1}d^{\downarrow} - \sqrt{\frac{1}{3}}(us)_{1,0}d^{\uparrow}\right) - \frac{1}{\sqrt{12}}\left(\sqrt{\frac{2}{3}}(ds)_{1,1}u^{\downarrow} - \sqrt{\frac{1}{3}}(ds)_{1,0}u^{\uparrow}\right)$$

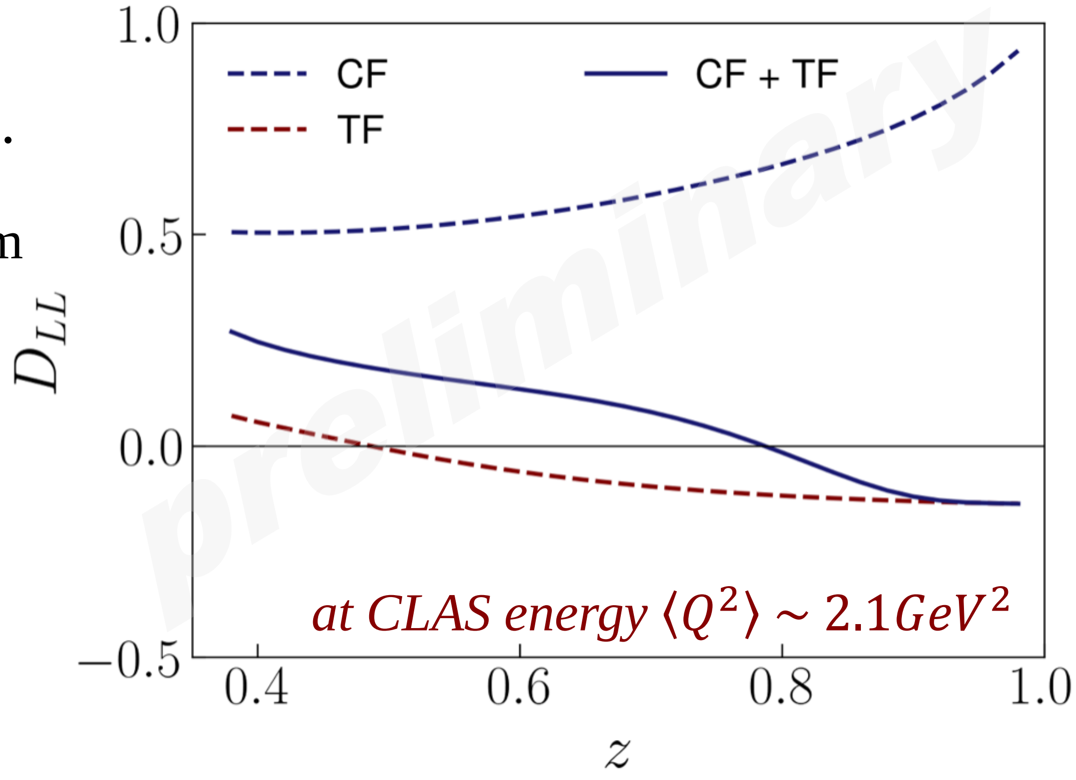


- In the target nucleon remnant, the *ud* pair in a vector state can produce a **polarized Σ** hyperon.

- Spin transfer to Σ along virtual photon γ^* momentum in Σ rest frame

$$D_{LL}^{\Sigma(CF)} \propto \frac{f_1(x)G_{1L}(z)}{f_1(x)D_1(z)}$$

$$D_{LL}^{\Sigma(TF)} \propto \frac{\Delta M_U^L(x,z)}{M_U^U(x,z)}$$



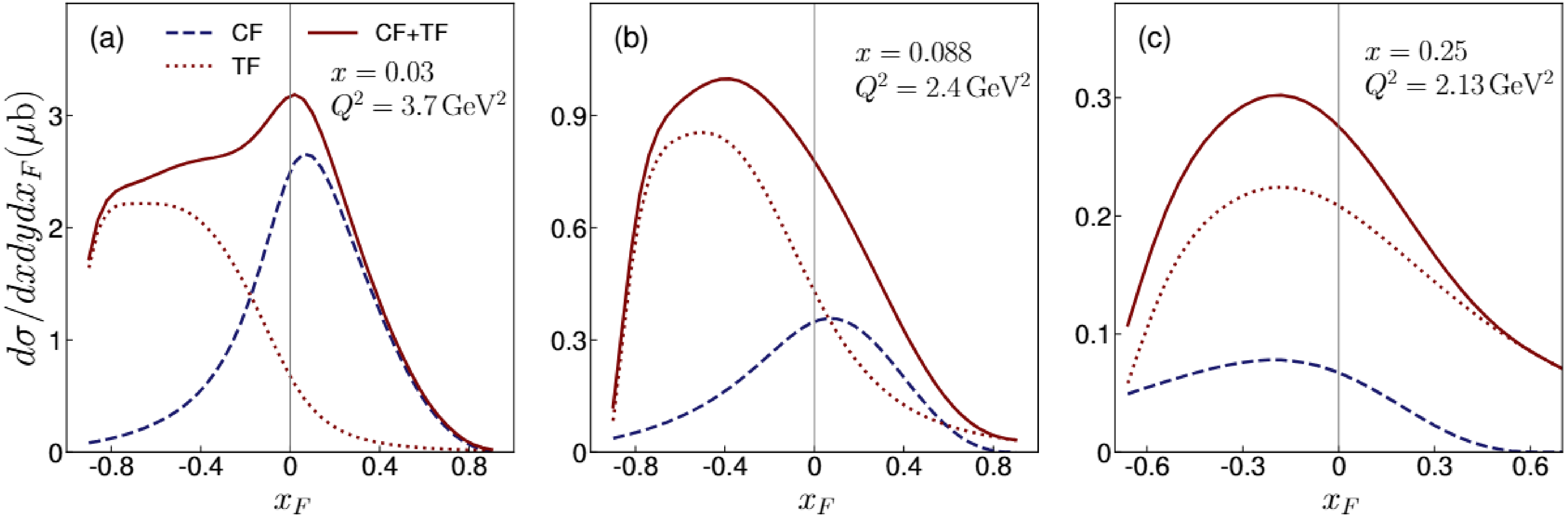
Summary

- Λ polarization can be measured through its self-analyzing weak decay, making it an ideal candidate for studying hadronization and spin effects in high-energy scattering.
- At existing fixed-target SIDIS experiments, one cannot clearly separate the current and target fragmentation regions of Λ production events.
- **Target fragmentation** is important to understanding spin-related observables.
- **Longitudinal Spin Transfer** serves as a sensitive observable to identify the origin of the produced Λ in the SIDIS process.
- Global analysis of fragmentation functions, including SIDIS data, should carefully consider the target fragmentation effects.
- Future experiments at EIC, HIAF, and other facilities may help to clarify this issue.

Thank you!

Back up

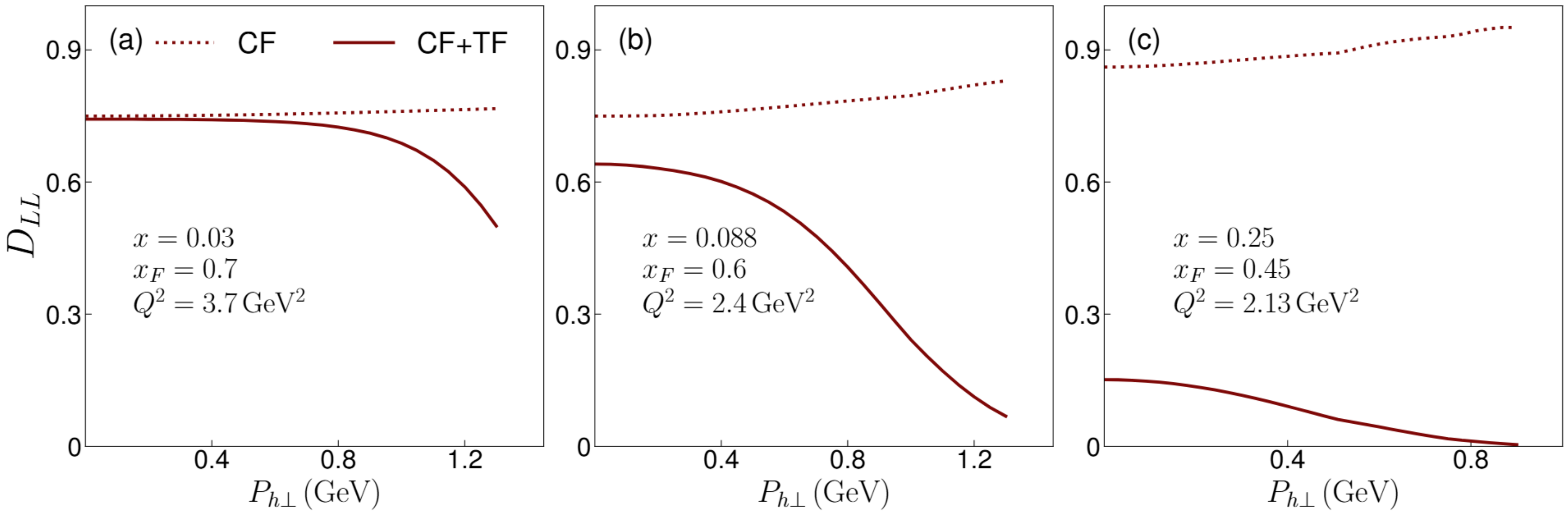
Unpolarized cross sections including CF and TF contributions at different energies



Dashed curves represent the CF contributions, dotted curves represent the TF contributions, and solid curves are the sum of CF and TF.

As one can observe, the TF contribution is significant in low x_F regions, and its overall fraction increases at lower energies. This observation aligns with the findings from early neutrino experiments. The calculation results further confirm the situation that no rapidity gap exists between CF and TF at these fixed target experiments.

Longitudinal Spin Transfer D_{LL} as a function of $P_{h\perp}$

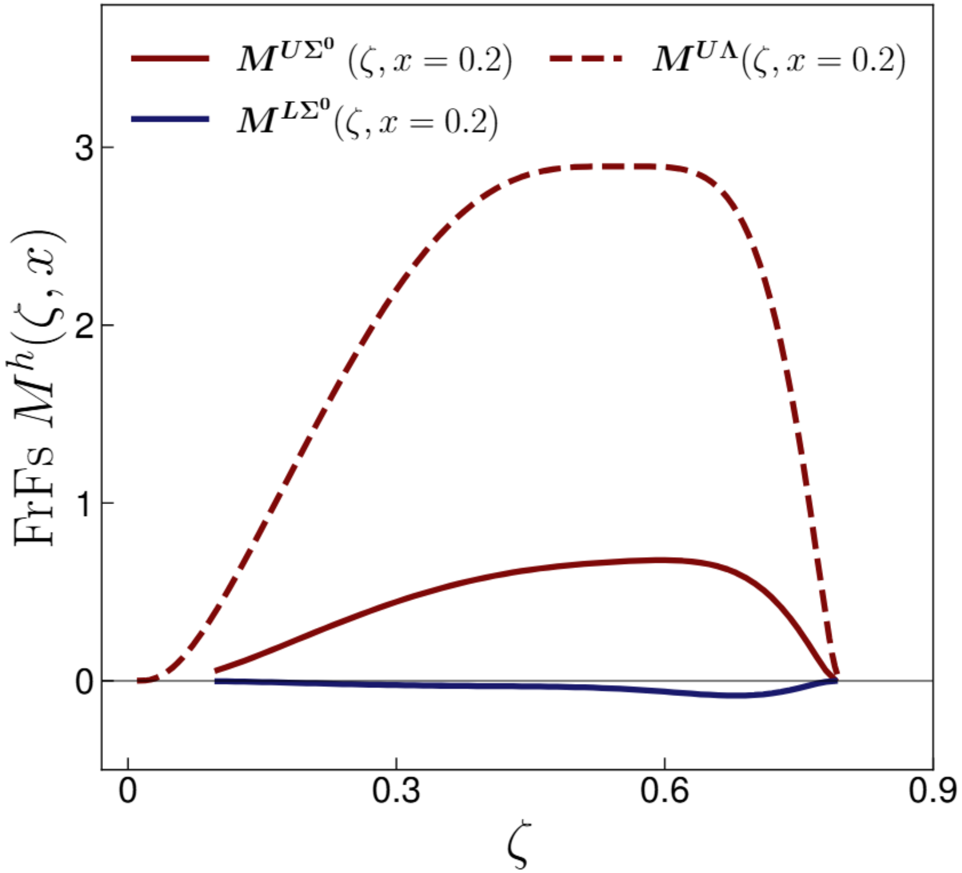


In the CF, large $\boldsymbol{x_F}$ corresponds large $\boldsymbol{z}$, and the struck quark needs at least two pairs of quarks to form a Λ, which leads to the fall-off behavior of FF at large $\boldsymbol{z}$ in powers of ***(1-z)***. As the $\boldsymbol{z}$ increases, the $\mathbf{P_{h\perp}}$ broadening is suppressed, consistent with observations in TMD studies. So the CF contribution at large $\boldsymbol{x_F}$ rapidly drops with increasing $\mathbf{P_{h\perp}}$.

In the TF, large $\boldsymbol{x_F}$ corresponds to small $\boldsymbol{\zeta}$, meaning the generated Λ carries only a small momentum fraction of the target remnant, leaving relatively more phase space for transverse momentum. Hence, the TF contribution decreases slowly with increasing $\mathbf{P_{h\perp}}$ in this region.

Therefore, the spin transfer suppression effect by TF at the large $\boldsymbol{x_F}$ region becomes more pronounced with increasing $\mathbf{P_{h\perp}}$.

Fracture functions of Σ^0 as a function of ζ



With the same setup of model parameters, the unpolarized fracture function $\boldsymbol{M^{U\Sigma}}$, is found smaller than that of Λ, and the longitudinally polarized fracture function $\boldsymbol{M^{L\Sigma}}$, is negative.
If further considering the spin transfer from Σ to Λ with the decay parameter $\alpha_{\Sigma\Lambda} = -0.333$, its contribution to the Λ polarization is negligible.

Structure Function as PDFs⊗FFs

$$F_{U,U}^{T} = \mathscr{C}\left[f_1 D_1\right]$$
$$F_{U,U}^{\cos 2\phi_h} = \mathscr{C}\left[-w_2 h_1^{\perp} H_1^{\perp}\right]$$
$$F_{U,L}^{\sin 2\phi_h} = \mathscr{C}\left[w_2 h_1^{\perp} H_{1L}^{\perp}\right]$$
$$F_{U,T}^{T\sin\phi_{hT}T} = \mathscr{C}\left[\bar{w}_1 f_1 D_{1T}^{\perp}\right]$$
$$F_{U,T}^{\sin(2\phi_h+\phi_h T)} = \mathscr{C}\left[-w_1 h_1^{\perp} H_{1T}\right]$$
$$F_{U,T}^{\sin(2\phi_h-\phi_{hT})} = \mathscr{C}\left[-\bar{w}_3 h_1^{\perp} H_{1T}^{\perp}\right]$$
$$F_{L,U}^{\sin 2\phi_h} = \mathscr{C}\left[-w_2 h_{1L}^{\perp} H_1^{\perp}\right]$$
$$F_{L,L}^{T} = \mathscr{C}\left[g_{1L} G_{1L}\right]$$
$$F_{L,L}^{\cos 2\phi_h} = \mathscr{C}\left[-w_2 h_{1L}^{\perp} H_{1L}^{\perp}\right]$$
$$F_{L,T}^{T}\cos\phi_{hT} = \mathscr{C}\left[-\bar{w}_1 g_{1L} G_{1T}^{\perp}\right]$$
$$F_{L,T}^{\cos(2\phi_h+\phi_h T)}] = \mathscr{C}\left[w_1 h_{1L}^{\perp} H_{1T}\right]$$
$$F_{L,T}^{\cos(2\phi_h-\phi_h T)} = \mathscr{C}\left[\bar{w}_3 h_{1L}^{\perp} H_{1T}^{\perp}\right]$$

$$F_{T,U}^{T\sin(\phi_h-\phi_T)} = \mathscr{C}\left[w_1 f_{1T}^{\perp} D_1\right]$$
$$F_{T,U}^{\sin(\phi_h+\phi_T)} = \mathscr{C}\left[\bar{w}_1 h_{1T} H_1^{\perp}\right]$$
$$F_{T,U}^{\sin(3\phi_h-\phi_T)} = \mathscr{C}\left[w_3 h_{1T}^{\perp} H_1^{\perp}\right]$$
$$F_{T,L}^{T\cos(\phi_h-\phi_T)} = \mathscr{C}\left[-w_1 g_{1T} G_{1L}\right]$$
$$F_{T,L}^{\cos(\phi_h+\phi_T)} = \mathscr{C}\left[\bar{w}_1 h_{1T} H_{1L}^{\perp}\right]$$
$$F_{T,}^{\cos(3\phi_h-\phi_T)} = \mathscr{C}\left[w_3 h_{1T}^{\perp} H_{1L}^{\perp}\right]$$
$$F_{T,T}^{\cos(\phi_h+\phi_h+\phi_T)} = \mathscr{C}\left[-h_{1T} H_{1T}\right]$$
$$F_{T,T}^{\cos(\phi_h-\phi_h+\phi_T)} = \mathscr{C}\left[-\bar{w}_4 h_{1T} H_{1T}^{\perp}\right]$$
$$F_{T,T}^{\cos(3\phi_h+\phi_h-\phi_T)} = \mathscr{C}\left[-w_4 h_{1T}^{\perp} H_{1T}\right]$$
$$F_{T,T}^{\cos(3\phi_h-\phi_h-\phi_T)} = \mathscr{C}\left[w_5 h_{1T}^{\perp} H_{1T}^{\perp}\right]$$
$$F_{T,T}^{T\cos(\phi_h-\phi_h-\phi_T)} = \mathscr{C}\left[\frac{w_2}{2}\left(f_{1T}^{\perp} D_{1T}^{\perp} + g_{1T}^{\perp} G_{1T}^{\perp}\right)\right]$$
$$F_{T,T}^{T\cos(\phi_h+\phi_h-\phi_T)} = \mathscr{C}\left[\frac{w_2'}{2}\left(f_{1T}^{\perp} D_{1T}^{\perp} - g_{1T}^{\perp} G_{1T}^{\perp}\right)\right]$$

$$G_{U,L} = \mathscr{C}\left[f_1 G_{1L}\right]$$
$$G_{U,T}^{\cos\phi_{hT}} = \mathscr{C}\left[-\bar{w}_1 f_1 G_{1T}^{\perp}\right]$$
$$G_{L,U}^{\perp} = \mathscr{C}\left[g_{1L} D_1\right]$$
$$G_{L,T}^{\sin\phi_{hT}} = \mathscr{C}\left[\bar{w}_1 g_{1L} D_{1T}^{\perp}\right]$$
$$G_{T,U}^{\cos(\phi_h-\phi_T)} = \mathscr{C}\left[-w_1 g_{1T}^{\perp} D_1\right]$$
$$G_{T,L}^{\sin(\phi_h-\phi_T)} = \mathscr{C}\left[w_1 f_{1T}^{\perp} G_{1L}\right]$$
$$G_{T,T}^{\sin(\phi_h-\phi_{hT}-\phi_T)} = \mathscr{C}\left[-\frac{w_2}{2}\left(f_{1T}^{\perp} G_{1T}^{\perp} - g_{1T}^{\perp} D_{1T}^{\perp}\right)\right]$$
$$G_{T,T}^{\sin(\phi_h+\phi_{hT}-\phi_T)} = \mathscr{C}\left[\frac{w_2'}{2}\left(f_{1T}^{\perp} G_{1T}^{\perp} + g_{1T}^{\perp} D_{1T}^{\perp}\right)\right]$$

32

Differential Cross Section

$$\frac{d\sigma^{(\mathrm{TF})}}{dx\,dy\,d\zeta\,d^2\mathbf{P}_{hT}} = \frac{4\pi\alpha^2}{yQ^2}\sum_a e_a^2 \Big\{ (\frac{y^2}{2} - y + 1)\left[M_U^U + \lambda\lambda_h M_L^L + |S_\perp||S_{h\perp}|\cos(\phi_S - \phi_{S_h})\, M_T^T \right.$$

$$+ |S_\perp||S_{h\perp}|\frac{\mathbf{P}_{h\perp}^2}{M_h^2}\left(\cos(2\phi - \phi_S - \phi_{S_h}) + \cos(\phi_S - \phi_{S_h})\right) M_T^{Th}$$

$$- |S_\perp|\frac{\mathbf{P}_{h\perp}}{M_h}\sin(\phi - \phi_S)\, M_T^{Uh} - |S_{h\perp}|\frac{\mathbf{P}_{h\perp}}{M_h}\sin(\phi - \phi_{S_h})\, M_U^{Th}$$

$$\left. + \lambda|S_{h\perp}|\frac{\mathbf{P}_{h\perp}}{M_h}\cos(\phi - \phi_{S_h})\, M_L^{Th} + \lambda_h|S_\perp|\frac{\mathbf{P}_{h\perp}}{M_h}\cos(\phi - \phi_S)\, M_T^{Lh} \right]$$

$$+ \lambda_e y(1 - \frac{y}{2})\left[\lambda\Delta M_L^U + \lambda_h\Delta M_U^L - |S_\perp||S_{h\perp}|\sin(\phi_S - \phi_{S_h})\Delta M_T^T \right.$$

$$- |S_\perp||S_{h\perp}|\frac{\mathbf{P}_{h\perp}^2}{M_h^2}\left(\sin(2\phi_h - \phi_S - \phi_{S_h}) + \sin(\phi_S - \phi_{S_h})\right)\Delta M_T^{Th}$$

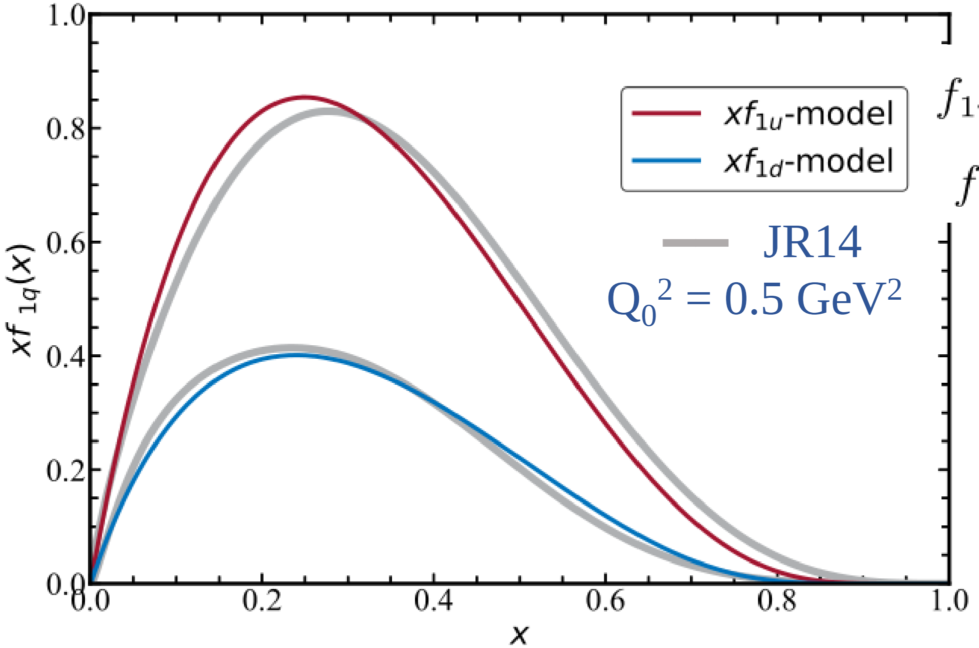
$$+ |S_\perp|\frac{\mathbf{P}_{h\perp}}{M_h}\cos(\phi - \phi_S)\,\Delta M_T^{Uh} + |S_{h\perp}|\frac{\mathbf{P}_{h\perp}}{M_h}cos(\phi - \phi_{S_h})\,\Delta M_U^{Th}$$

$$\left. - \lambda|S_{h\perp}|\frac{\mathbf{P}_{h\perp}}{M_h}\sin(\phi - \phi_{S_h})\,\Delta M_L^{Th} - \lambda_h|S_\perp|\frac{\mathbf{P}_{h\perp}}{M_h}\sin(\phi - \phi_S)\,\Delta M_T^{Lh} \right]\Big\},$$

We choose the scalar and vector vertices to be

$$\mathcal{Y}_s = i g_s(p^2)\mathbf{1}, \qquad \mathcal{Y}_a^{\mu} = i\frac{g_a(p^2)}{\sqrt{2}}\gamma^{\mu}\gamma_5,$$

$$g_X(p^2) = \begin{cases} g_X^{\text{p.l.}} & \text{pointlike,} \\ g_X^{\text{dip}} \frac{p^2-m^2}{|p^2-\Lambda_X^2|^2} & \text{dipolar,} \\ g_X^{\text{exp}} e^{(p^2-m^2)/\Lambda_X^2} & \text{exponential,} \end{cases}$$



Unpolarized PDF $f_1(x)$ vs x for u quark (red line) and d quark (blue line). The gray band from the parametrizations of JR14, and the curves represent the best fit obtained with our spectator model. *Eur. Phys. J. C75 (2015) 3, 132*

$$f_{1u} = \frac{3}{2}f_1^s + \frac{1}{2}f_1^a$$

$$f_{1d} = f_1^a$$

$$m = 0.3\ \text{GeV},$$
$$M_s = 1.2\ \text{GeV}, \Lambda_s = 2.3\ \text{GeV},$$
$$M_a = 1.3\ \text{GeV}, \Lambda_a = 1.6\ \text{GeV},$$
$$g_s = 14.98, \qquad g_a = 15.33.$$

◆ Longitudinal Spin Transfer $D_{LL}(x)$

$$\sigma = \sigma^{CFR} + \sigma^{TFR}$$

$$\zeta = \frac{2x_B(M_h^2 + \boldsymbol{P}_{h\perp}^2)}{z_h Q^2 + \sqrt{z_h^2 Q^4 - 4x_B^2 M^2 (M_h^2 + \boldsymbol{P}_{h\perp}^2)}}$$

ζ is the momentum fraction of the nucleon carried by the final-state Λ

$$x_F = \frac{z_\Lambda}{\frac{x_B M^2}{Q^2} + (1 - x_B)} \left[\left(1 + \frac{Q^2}{2x_B M^2}\right) \sqrt{1 - \frac{4x_B^2 M^2 (M_h^2 + \mathbf{P}_{h\perp}^2)}{z_\Lambda^2 Q^4}} - \sqrt{\frac{Q^4}{4x_B^2 M^4} + \frac{Q^2}{M^2}} \right]$$

$$D_{LL}^{\Lambda}(x, z, Q^2) = \frac{\sum_q e_q^2 z^2 f_{1q}(x_B, Q^2) G_{1Lq}^{\Lambda}(z_\Lambda, Q^2)}{\sum_q e_q^2 \left[z^2 f_{1q}(x_B, Q^2) D_{1q}^{\Lambda}(z_\Lambda, Q^2) + \frac{\zeta}{z} M_q^{\Lambda}(x_B, \zeta, Q^2) \right]}.$$

$$p^\uparrow = \frac{1}{\sqrt{2}}(ud)_{0,0}u^\uparrow$$
$$+ \frac{1}{\sqrt{3}}\left(\sqrt{\frac{2}{3}}(uu)_{1,1}d^\downarrow - \sqrt{\frac{1}{3}}(uu)_{1,0}d^\uparrow\right) - \frac{1}{\sqrt{6}}\left(\sqrt{\frac{2}{3}}(ud)_{1,1}u^\downarrow - \sqrt{\frac{1}{3}}(ud)_{1,0}u^\uparrow\right)$$