Quark to Λ and $\bar{\Lambda}$ longitudinal spin transfers in the current fragmentation region

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Introduction

The nonperturbative nature of QCD at low energy scale makes the detailed hadron structure hard to know

- the ”spin crisis”: quarks and anti-quarks contribute not more than 30% of the total nucleon spin
- the strange and anti-strange quark in the nucleon sea should be or not be symmetry in the nucleon sea.

Semi-inclusive deep inelastic scattering(SIDIS) process is important in dealing with some of these problems in experiment.

Use factorization theory, the nonperturbative part can be put into parton distribution functions and fragmentation functions.

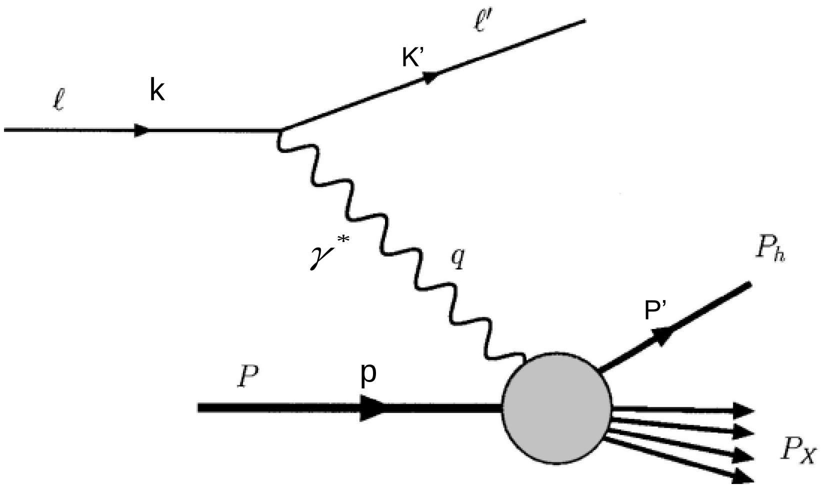

Figure1: A sketch map for the Semi-inclusive deep-inelastic scattering

The cross section of the final hadron can be expressed as a convolution of the parton distribution functions, the elementary lepton-parton scattering and the fragmentation functions.

The final hyperon plays an important role in the detection of nucleon structures.

Features of the Λ hyperon

- The Λ-hyperon has the "self-analyzing" property in polarization.

Two main decay ways:

$$\Lambda \rightarrow p + \pi^-, (\mathrm{BR} = (63.9 \pm 0.5)\%;$$
$$\Lambda \rightarrow n + \pi^0, (\mathrm{BR} = (35.8 \pm 0.5)\%.$$

In the Λ rest frame, the angle distribution of the produced proton is

$$\frac{\mathrm{d}N}{\mathrm{d}\Omega_p} \propto 1 + \alpha \vec{P}_\Lambda \cdot \hat{k}_p$$

- The polarization of the produced hadron

$$P_{L'} = P_b \cdot D(y) A^{\Lambda}_{LL'}, \qquad D(y) = \frac{1-(1-y)^2}{1+(1-y)^2},$$

Experiment measurement of Λ and $\bar{\Lambda}$ spin transfers

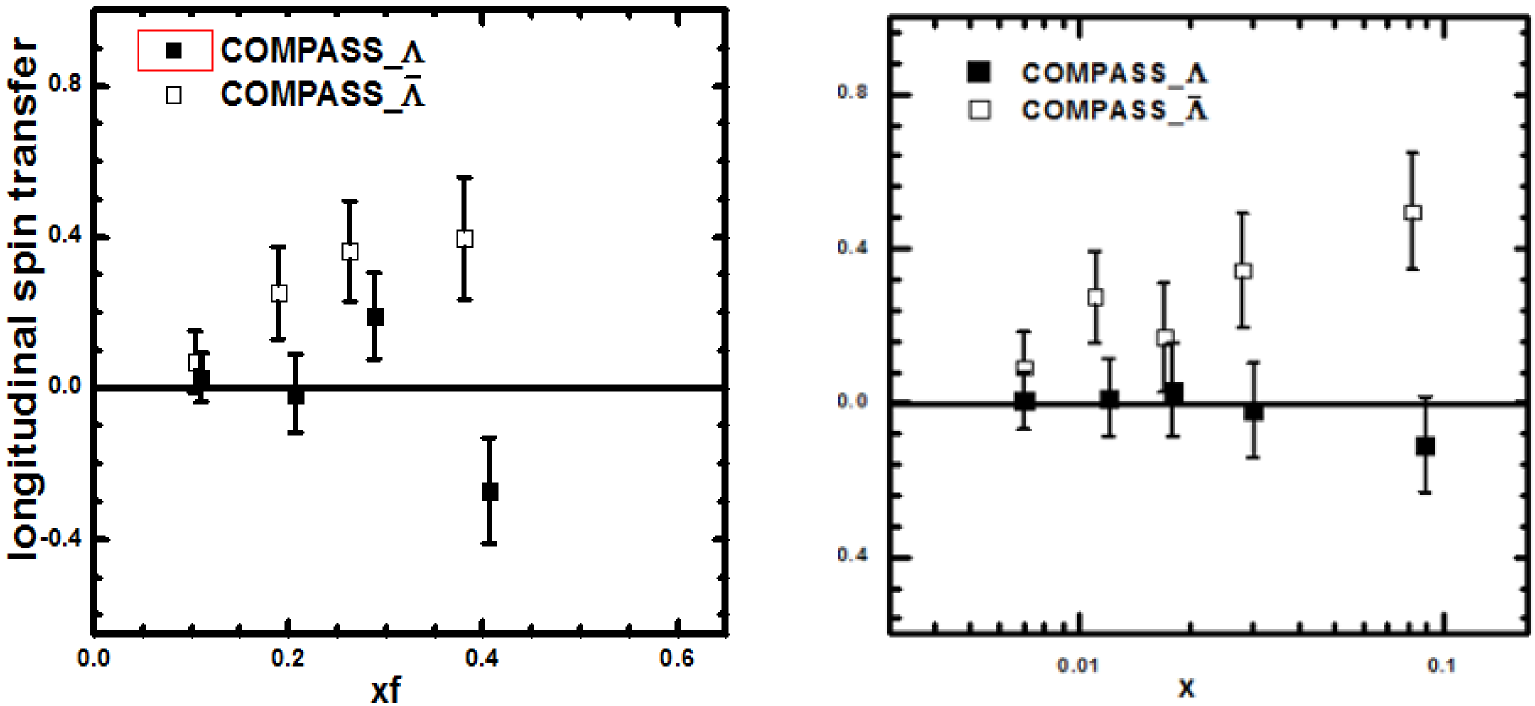

Figure2: Longitudinal spin transfer of Λ and $\bar{\Lambda}$ hyperon versus x_F and x variables at COMPASS experiment

M. Alekseev *et al.* (COMPASS Collaboration), Eur. Phys. J. C 64, 171 (2009).

The observable longitudinal spin transfers for Λ and $\bar{\Lambda}$

For a general SIDIS process $\ell p \to \ell P_h X$ the differential cross section is

$$\frac{d\sigma}{dx\,dy\,dz\,d^2\vec{P}_{h\perp}} = \frac{\pi\alpha_{em}^2}{2Q^4}\frac{y}{z}L_{\mu\nu}W^{\mu\nu}.$$

Three Lorentz invariants

$$x = \frac{Q^2}{2P\cdot q}, \quad y = \frac{P\cdot q}{P\cdot\ell}, \quad z = \frac{P\cdot P_h}{P\cdot q}$$

The differential cross section for the production of the unpolarized hadron h

$$\frac{d\sigma}{dx\,dy\,dz} = \frac{4\pi\alpha_{em}^2 S}{Q^4}\sum_q e_q^2 x\frac{1+(1-y)^2}{2}f_q(x,Q^2)D_q(z,Q^2),$$

The observable longitudinal spin transfers for Λ and $\bar{\Lambda}$

For polarized electron beam hit on an unpolarized proton target process, the helicity asymmetry cross section is

$$A(x,y,z) = \frac{d\sigma_{\Uparrow} - d\sigma_{\Downarrow}}{d\sigma_{\Uparrow} + d\sigma_{\Downarrow}}$$
$$= \frac{\frac{4\pi\alpha_{\rm em}^2 S}{Q^4}\sum_a e_a^2 xy(1-y/2) f_a(x,Q^2)\Delta D_a(z,Q^2)}{\frac{4\pi\alpha_{\rm em}^2 S}{Q^4}\sum_a e_a^2 x \frac{1+(1-y)^2}{2} f_a(x,Q^2) D_a(z,Q^2)},$$

Removing the depolarization factor D(y) from the asymmetry cross section

$$A(x,y,z) = \frac{\frac{Sx}{Q^4}\sum_q e_q^2 f_q^p(x,Q^2)\Delta D_q^h(z,Q^2)}{\frac{Sx}{Q^4}\sum_q e_q^2 f_q^p(x,Q^2) D_q^h(z,Q^2)}.$$

Consider intermediate hyperon decay process

$$\begin{aligned} D_{\Lambda}^{q(\bar{q})}(z,Q^2) &= a_1 D_{q(\bar{q})\Lambda}(z,Q^2) + a_2 D_{\Sigma^0}^{q(\bar{q})}(z',Q^2) \\ &+ a_3 D_{\Sigma^*}^{q(\bar{q})}(z',Q^2) + a_4 D_{\Xi}^{q(\bar{q})}(z',Q^2), \end{aligned}$$

Modeling quark fragmentation functions

$$\begin{aligned}\Delta D_{\Lambda}^{q}(z,Q^2) &= a_1\Delta D_{q\Lambda}(z,Q^2)+a_2\Delta D_{\Sigma^0}^{q}(z',Q^2)\alpha_{\Sigma^0\Lambda}\\ &+ a_3\Delta D_{\Sigma^*}^{q}(z',Q^2)\alpha_{\Sigma^*\Lambda}\\ &+ a_4\Delta D_{\Xi}^{q}(z',Q^2)\alpha_{\Xi\Lambda},\end{aligned}$$

The production weight coefficients and the polarization parameters

$$a_1=0.4,\quad a_2=0.2,\quad a_3=0.3,\quad a_4=0.1,$$

$$\begin{aligned}\alpha_{\Sigma^0\Lambda} &= -0.333, \quad \alpha_{\Sigma^*(\frac{3}{2},\frac{3}{2})\Lambda}=1.0,\\ \alpha_{\Sigma^*(\frac{3}{2},\frac{1}{2})\Lambda} &= 0.333, \quad \alpha_{\Xi^0\Lambda}=-0.406,\\ \alpha_{\Xi^-\Lambda} &= -0.458.\end{aligned}$$

R. Gatto, Phys. Rev. 109, 610 (1958).
Beringer et al. [Particle Data Group], Phys. Rev. D 86, 010001 (2012).

Gribov - Lipatov phenomenological relation:

$$D_q^h(z)\sim z f_h^q(z).$$

Y. Chi and B.-Q. Ma, Phys. Lett. B **726**, 737 (2013).

V.N. Gribov and L.N. Lipatov, Phys. Lett. B **37**, 78 (1971).

Light-cone SU(6) quark-spectator-diquark model

If any one of the quark is probed, the remaining two quarks in the nucleon can be treated as a quasi-particle spectator which can be described by two quark wave functions with spin 0 or 1 (scalar or vector diquark).

Commonly, the unpolarized and polarized quark distribution functions can be expressed as

$$q(x) = c_q^S a_S(x) + c_q^V a_V(x), \quad \Delta q(x) = \tilde{c}_q^S \tilde{a}_S(x) + \tilde{c}_q^V \tilde{a}_V(x).$$

where

$$a_D(x) \propto \int [\mathrm{d}^2\mathbf{k}_\perp] |\varphi(\mathrm{x}, \mathbf{k}_\perp)|^2$$

$$\tilde{a}_D(x) = \int [\mathrm{d}^2\mathbf{k}_\perp] \, W_D(x, \mathbf{k}_\perp) |\varphi_D(x, \mathbf{k}_\perp)|^2, \qquad (D = S \ \text{or} \ V),$$

$$W_D(x, \mathbf{k}_\perp) = \frac{(k^+ + m_q)^2 - \mathbf{k}_\perp^2}{(k^+ + m_q)^2 + \mathbf{k}_\perp^2},$$ with $k^+ = x\mathcal{M}$ and $\mathcal{M}^2 = \frac{m_q^2 + \mathbf{k}_\perp^2}{x} + \frac{m_D^2 + \mathbf{k}_\perp^2}{1-x}$.

B.-Q. Ma, I. Schmidt, J. Soffer, and J.-J. Yang, Phys. Rev. D **65**, 034004 (2002).

Table 1: Quark distribution function of octet baryons

Baryon	q		Δq		m_q (MeV)	m_V (MeV)	m_S (MeV)
p	u	$\frac{1}{6}a_V + \frac{1}{2}a_S$	Δu	$-\frac{1}{18}\tilde{a}_V + \frac{1}{2}\tilde{a}_S$	330	800	600
(uud)	d	$\frac{1}{3}a_V$	Δd	$-\frac{1}{9}\tilde{a}_V$	330	800	600
n	u	$\frac{1}{3}a_V$	Δu	$-\frac{1}{9}\tilde{a}_V$	330	800	600
(udd)	d	$\frac{1}{6}a_V + \frac{1}{2}a_S$	Δd	$-\frac{1}{18}\tilde{a}_V + \frac{1}{2}\tilde{a}_S$	330	800	600
Σ^+	u	$\frac{1}{6}a_V + \frac{1}{2}a_S$	Δu	$-\frac{1}{18}\tilde{a}_V + \frac{1}{2}\tilde{a}_S$	330	950	750
(uus)	s	$\frac{1}{3}a_V$	Δs	$-\frac{1}{9}\tilde{a}_V$	480	800	600
Σ^0	u	$\frac{1}{12}a_V + \frac{1}{4}a_S$	Δu	$-\frac{1}{36}\tilde{a}_V + \frac{1}{4}\tilde{a}_S$	330	950	750
(uds)	d	$\frac{1}{12}a_V + \frac{1}{4}a_S$	Δd	$-\frac{1}{36}\tilde{a}_V + \frac{1}{4}\tilde{a}_S$	330	950	750
	s	$\frac{1}{3}a_V$	Δs	$-\frac{1}{9}\tilde{a}_V$	480	800	600
Σ^-	d	$\frac{1}{6}a_V + \frac{1}{2}a_S$	Δd	$-\frac{1}{18}\tilde{a}_V + \frac{1}{2}\tilde{a}_S$	330	950	750
(dds)	s	$\frac{1}{3}a_V$	Δs	$-\frac{1}{9}\tilde{a}_V$	480	800	600
Λ^0	u	$\frac{1}{4}a_V + \frac{1}{12}a_S$	Δu	$-\frac{1}{12}\tilde{a}_V + \frac{1}{12}\tilde{a}_S$	330	950	750
(uds)	d	$\frac{1}{4}a_V + \frac{1}{12}a_S$	Δd	$-\frac{1}{12}\tilde{a}_V + \frac{1}{12}\tilde{a}_S$	330	950	750
	s	$\frac{1}{3}a_S$	Δs	$\frac{1}{3}\tilde{a}_S$	480	800	600
Ξ^-	d	$\frac{1}{3}a_V$	Δd	$-\frac{1}{9}\tilde{a}_V$	330	1100	900
(dss)	s	$\frac{1}{6}a_V + \frac{1}{2}a_S$	Δs	$-\frac{1}{18}\tilde{a}_V + \frac{1}{2}\tilde{a}_S$	480	950	750
Ξ^0	u	$\frac{1}{3}a_V$	Δu	$-\frac{1}{9}\tilde{a}_V$	330	1100	900
(uss)	s	$\frac{1}{6}a_V + \frac{1}{2}a_S$	Δs	$-\frac{1}{18}\tilde{a}_V + \frac{1}{2}\tilde{a}_S$	480	950	750

B.-Q. Ma, I. Schmidt, J.-J. Yang, Nucl. Phys. B **574**, 331 (2000).

Table 2: Quark distribution function of ∑(1385)

Baryon	q		Δq	(3/2,3/2)	(3/2,1/2)	m_q (MeV)	m_V (MeV)
$\Sigma^+(1385)$	u	$\frac{2}{3}a_V$	Δu	$\frac{2}{3}\tilde{a}_V$	$\frac{2}{9}\tilde{a}_V$	330	950
(uus)	s	$\frac{1}{3}a_V$	Δs	$\frac{1}{3}\tilde{a}_V$	$\frac{1}{9}\tilde{a}_V$	480	800
$\Sigma^0(1385)$	u	$\frac{1}{3}a_V$	Δu	$\frac{1}{3}\tilde{a}_V$	$\frac{1}{9}\tilde{a}_V$	330	950
(uds)	d	$\frac{1}{3}a_V$	Δd	$\frac{1}{3}\tilde{a}_V$	$\frac{1}{9}\tilde{a}_V$	330	950
	s	$\frac{1}{3}a_V$	Δs	$\frac{1}{3}\tilde{a}_V$	$\frac{1}{9}\tilde{a}_V$	480	800
$\Sigma^-(1385)$	d	$\frac{2}{3}a_V$	Δd	$\frac{2}{3}\tilde{a}_V$	$\frac{1}{9}\tilde{a}_V$	330	950
(dds)	s	$\frac{1}{3}a_V$	Δs	$\frac{1}{3}\tilde{a}_V$	$\frac{1}{9}\tilde{a}_V$	480	800

Y. Chi, X. Du and B.-Q. Ma, Phys. Rev. D **90**, 074003 (2014).

Inputs of the quark fragmentation functions

- Use CTEQ parameterization as an input

$$u_v^p(x) = u_v^{\rm ctq}(x),$$

$$d_v^\Lambda(x) = u_v^\Lambda(x) = \frac{u_v^{\Lambda,\rm th}(x)}{u_v^{p,\rm th}(x)} * u_v^{\rm ctq}(x),$$

$$s_v^\Lambda(x) = \frac{s_v^{\Lambda,\rm th}(x)}{u_v^{p,\rm th}(x)} * u_v^{\rm ctq}(x),$$

$$\Delta d_v^\Lambda(x) = \Delta u_v^\Lambda(x) = \frac{\Delta u_v^{\Lambda,\rm th}(x)}{u_v^{p,\rm th}(x)} * u_v^{\rm ctq}(x),$$

$$\Delta s_v^\Lambda(x) = \frac{\Delta s_v^{\Lambda,\rm th}(x)}{u_v^{p,\rm th}(x)} * u_v^{\rm ctq}(x),$$

- For sea quark distribution functions, use SU(3) symmetry

$$d_s^\Lambda(x) = u_s^\Lambda(x) = \overline{u}^\Lambda(x) = \frac{1}{2}(\overline{u}^{\rm ctq}(x) + \overline{d}^{\rm ctq}(x))$$

$$s_s^\Lambda(x) = \overline{s}^\Lambda(x) = \overline{d}^{\rm ctq}(x),$$

Gribov - Lipatov phenomenological relation: $D_q^h(z) \sim z f_h^q(z).$

Y. Chi and B.-Q. Ma, Phys. Lett. B **726**, 737 (2013).
V.N. Gribov and L.N. Lipatov, Phys. Lett. B **37**, 78 (1971).

Inputs of quark distribution functions

- Nonstrange distribution functions in the proton are from the CTEQ parameterization.
- For the strange and antistrange sea quark distribution in the proton

In the baryon-meson fluctuation model

$$s(x) = \int_x^1 \frac{\mathrm{d}y}{y} f_{\Lambda/K^+\Lambda}(y) q_{s/\Lambda}\left(\frac{x}{y}\right),$$
$$\bar{s}(x) = \int_x^1 \frac{\mathrm{d}y}{y} f_{K^+/K^+\Lambda}(y) q_{\bar{s}/K^+}\left(\frac{x}{y}\right).$$

Use the model as an effective modification to the whole strange sea, the strange sea PDFs read

$$s^P(x) = \frac{2s^{\mathrm{th}}}{s^{\mathrm{th}} + \bar{s}^{\mathrm{th}}} s^{\mathrm{ctq}},$$
$$\bar{s}^P(x) = \frac{2\bar{s}^{\mathrm{th}}}{s^{\mathrm{th}} + \bar{s}^{\mathrm{th}}} s^{\mathrm{ctq}}.$$

S. J. Brodsky and B.-Q. Ma, Phys. Lett. B **381**, 317 (1996)

Nucleon strange $s\bar{s}$ asymmetry to the Λ / $\bar{\Lambda}$ fragmentation

Exact relation between x_F , x, y, z variables

$$x_F = \frac{Syz}{M\,[M^2 + Sy(1-x)]}\left[\left(M + \frac{Sy}{2M}\right)\times\sqrt{1 - \frac{[4M^2(M_h^2 + P_{h\perp}^2)]}{(Syz)^2}} - \sqrt{\frac{S^2y^2}{4M^2} + Sxy}\right]$$

The COMPASS experimental cuts for 2004 run

$$1\ \mathrm{GeV}^2 < Q^2 < 50\ \mathrm{GeV}^2, 0.005 < x < 0.65,$$
$$0.2 < y < 0.9, 0.05 < x_F < 0.5$$

Y. Chi, X. Du and B.-Q. Ma, Phys. Rev. D **90**, 074003 (2014).

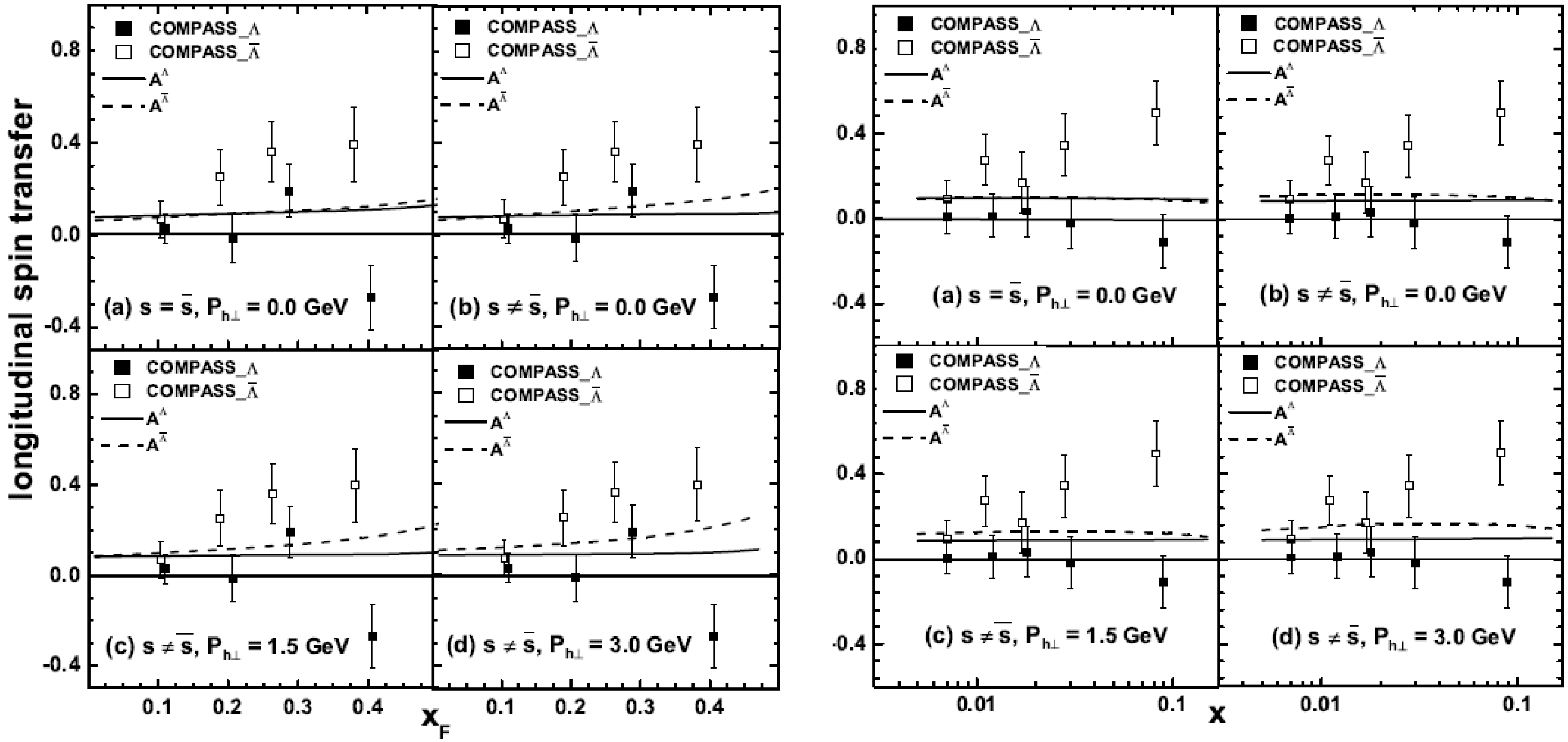

Figure3: x_F and x-dependent longitudinal spin transfer in polarized SIDIS process. Inputs of the proton strange sea asymmetry and the $P_{h\perp}$ nonzero values are considered step by step.

Conclusion

- The $s\bar{s}$ asymmetry gives more proper trend to the difference between the Λ and $\bar{\Lambda}$ longitudinal spin transfer.

- The large z region is more sensitive to the asymmetric nucleon strange sea input, and this sensitivity can give better explanations to the experimental data.

- We suggest new and precise experimental measurement of the Λ and $\bar{\Lambda}$ production in the large z region.