Strange quark-antiquark asymmetry of the nucleon sea from Lambda/anti-Lambda polarization

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Introduction

- Study of hadron spectrum leads to the hypothesis that hadrons are composed of quarks.
- Scaling phenomenon indicated by electron-nucleon deep inelastic(DIS) scattering leads to parton model.

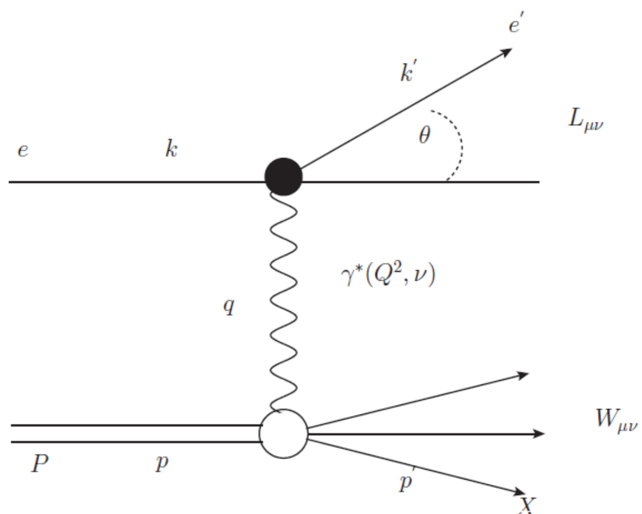


Figure : A sketch map for the *ep* deep inelastic scattering.

Parton distribution functions of nucleon

- **Introduced by Feynman (1969) in the parton model; interpreted as probability distributions**

- **PDFs are nonperturbative inputs in higher energy hadron processes**

  - **Determined via a global fit of experimental data**

  - **Calculated using various quark models**

- **Distributions for sea quarks are not well determined**

The sea content of the Nucleon

Two types of the nucleon sea quarks

- **extrinsic sea quark: perturbative contribution**
  - **Gluon splitting**

LO & NLO QCD evolution — **Quark-antiquark symmetry**

NNLO perturbative QCD evolution — **Quark-antiquark asymmetry**

S. Catani et. al PRL93 (2004) 152003)

- **intrinsic sea quark: nonperturbative contribution**
  - **Baryon-meson fluctuating model**
  - **Meson cloud model**
  - **Chiral quark model**
  - **……**

Quark-antiquark asymmetry

NuTeV anomaly

Other determinations and NuTeV result of $\sin^2 \theta_W$

World Average: 0.2227 ± 0.0004

D. Abbaneo et al., arXiv:hep-ex/0112021

NuTeV (2002): 0.2277 ± 0.0013(stat) ± 0.0009(syst)

➔ **Can be affected by strange antistrange asymmetry**

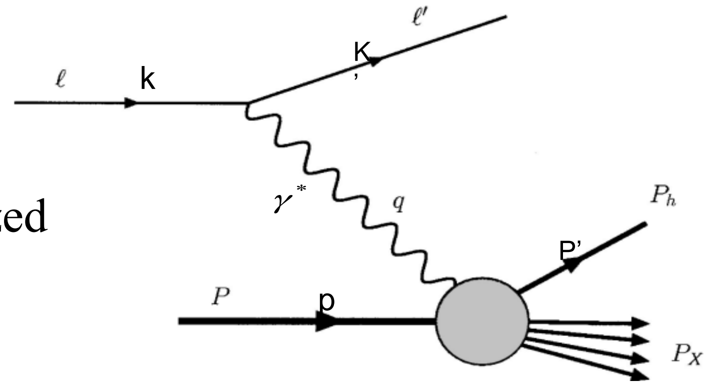
G. P. Zeller et al. [NuTeV Collaboration], PRL. 88, 091802 (2002)

The existence of intrinsic quark sea and strange-antistrange sea distribution are still under controversy!

Semi-inclusive deep-inelastic scattering : powerful microscope!

QCD factorization theory

Cross section of Final hadron can be factorized into: the parton distribution functions; the elementary lepton-parton scattering and the fragmentation functions.



$$l\,p \rightarrow l\,P_h X$$

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

lambda hyperon was suggested to be studied.

Why Λ-hyperon ?

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

Two main decay ways:

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

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

K. A. Olive et al. [PDG], CPC, 090001 (2014).

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

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

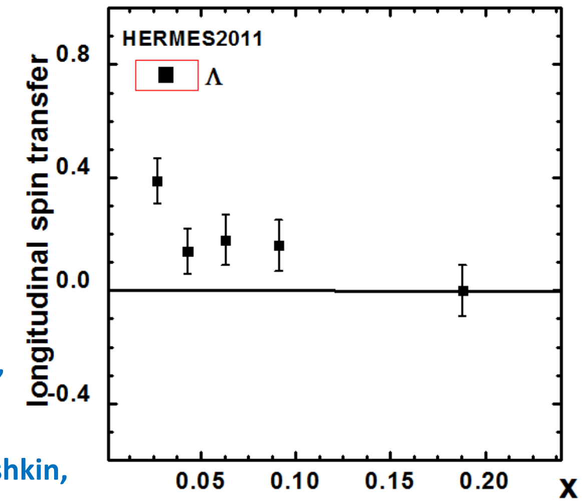
The polarization of the produced hadron

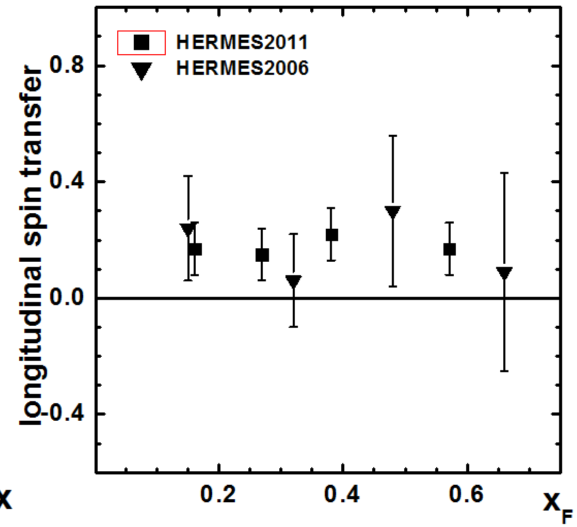
$$P_{L'} = P_b \cdot D(y) A^{\Lambda}_{LL'}, \qquad D(y) = \frac{1-(1-y)^2}{1+(1-y)^2},$$

R. L. Jaffe, PRD 54, R6581 (1996).

Experimental progress in lambda/lambdabar production

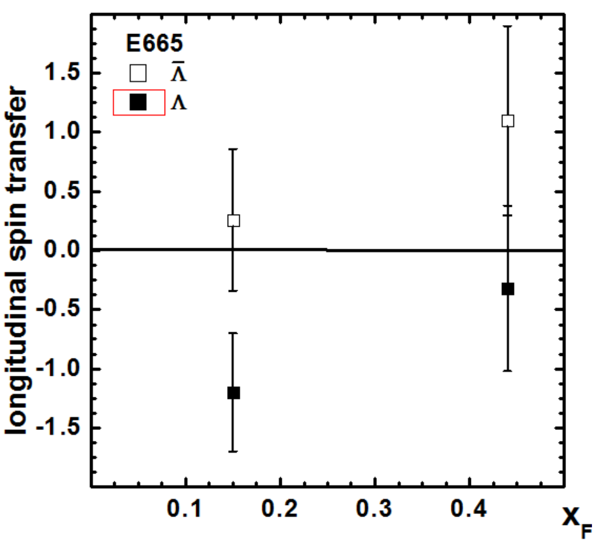
- Fermilab: E665
- DESY: HERMES
- CERN: COMPASS

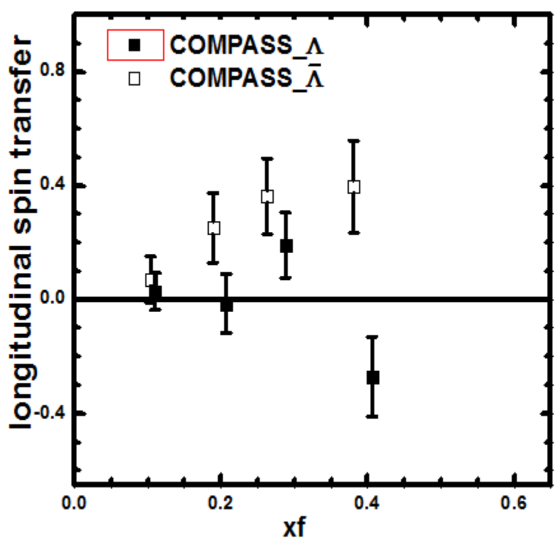


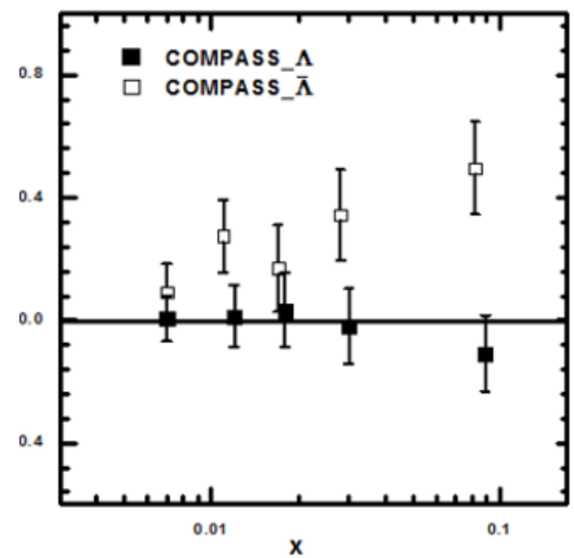


A. Airapetian et al. [HERMES Collaboration], Phys.Rev. D 74, 072004 (2006)

S. Belostotski, D. Veretennikov and Y. Naryshkin, J. Phys. Conf. Ser. 295, 012114 (2011).







M. R. Adams et al. [E665 Collaboration], EPJC 17, 263 (2000)

M. Alekseev et al. [COMPASS Collaboration], EPJ C 64, 171 (2009).

Longitudinal spin transfer of Lambda

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

$$A(x,y,z) = \frac{\mathrm{d}\sigma_{\Uparrow} - \mathrm{d}\sigma_{\Downarrow}}{\mathrm{d}\sigma_{\Uparrow} + \mathrm{d}\sigma_{\Downarrow}}$$

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

Longitudinal spin transfer of Lambda

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

Relation between x, y, z,and x_F

$$z = \frac{x_F}{2}\sqrt{\frac{4M^2x}{Sy}+1} + \left(\frac{M^2}{Sy}+\frac{1}{2}\right)\sqrt{\frac{4(M_h^2+P_{h\perp}^2)}{M^2+Sy-Sxy}+x_F^2},$$

Inputs of parton distribution functions

Nonstrange distribution functions in nucleon are from the CTEQ(CT14)

S. Dulat et al., PRD, 93, 033006 (2016)

Strange distribution functions:

Baryon-meson fluctuation model $\mathrm{p}(\mathrm{uuds}\bar{s}) = K^{+}(\mathrm{u}\bar{s}) + \Lambda(\mathrm{uds})$

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

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

The probabilities

$$f_{\Lambda/K^+\Lambda}(\mathrm{y}) = \int_{-\infty}^{+\infty} dk_\perp \left| A_D \exp\left[-\frac{1}{8\alpha_D^2}\left(\frac{m_\Lambda^2 + k_\perp^2}{y} + \frac{m_{k^+}^2 + k_\perp^2}{1-y}\right)\right]\right|^2$$

$$q_{s/\Lambda}(\mathrm{x/\,y}) = \int_{-\infty}^{+\infty} dk_\perp \left| A_D \exp\left[-\frac{1}{8\alpha_D^2}\left(\frac{m_s^2 + k_\perp^2}{x/y} + \frac{m_D^2 + k_\perp^2}{1-x/y}\right)\right]\right|^2$$

S. J. Brodsky and B.-Q. Ma, PLB 381, 317 (1996)

Input of the strange sea PDFs

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

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

Quark to lambda fragmentations

Lambda production

✓Direct quark fragments

✓Intermediate heavier hyperon decay process

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

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

Y. Chi and B.-Q. Ma, PLB 726, 737 (2013).

Weight coefficients and the polarization parameters

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

C. Adolph et al. [COMPASS Collaboration], EPJC 73, 2581 (2013).

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

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

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

V.N. Gribov and L.N. Lipatov, PLB 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 (scalar or vector diquark).

The unpolarized and polarized quark distribution functions

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

where

B.-Q. Ma, I. Schmidt, J. Soffer, and J.-J. Yang, PRD 65, 034004 (2002).

$$a_D(x) \propto \int \left[\mathrm{d}^2\mathbf{k}_\perp\right] |\varphi(x,\mathbf{k}_\perp)|^2, \quad \tilde{a}_D(x) = \int \left[\mathrm{d}^2\mathbf{k}_\perp\right] W_D(x,\mathbf{k}_\perp)|\varphi(x,\mathbf{k}_\perp)|^2 \quad (D = S/V)$$

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

Brodsky-Huang-Lepage prescription

$$\varphi(x,\mathbf{k}_\perp) = A_D \exp\left[-\frac{1}{8\alpha_D^2}\left(\frac{m_q^2+\mathbf{k}_\perp^2}{x} + \frac{m_D^2+\mathbf{k}_\perp^2}{1-x}\right)\right]$$

S. J. Brodsky, T. Huang, and G. P. Lepage, Conf. Proc. C 810816, 143 (1981)

PDFs of the baryons in the light-cone SU(6) qrark-diquark model

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
$\Sigma^+(1385)$	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	$\frac{2}{3}\tilde{a}_V/\frac{2}{9}\tilde{a}_V$	330	950	
(dds)	s	$\frac{1}{3}a_V$	Δs	$\frac{1}{3}\tilde{a}_V/\frac{1}{9}\tilde{a}_V$	480	800	

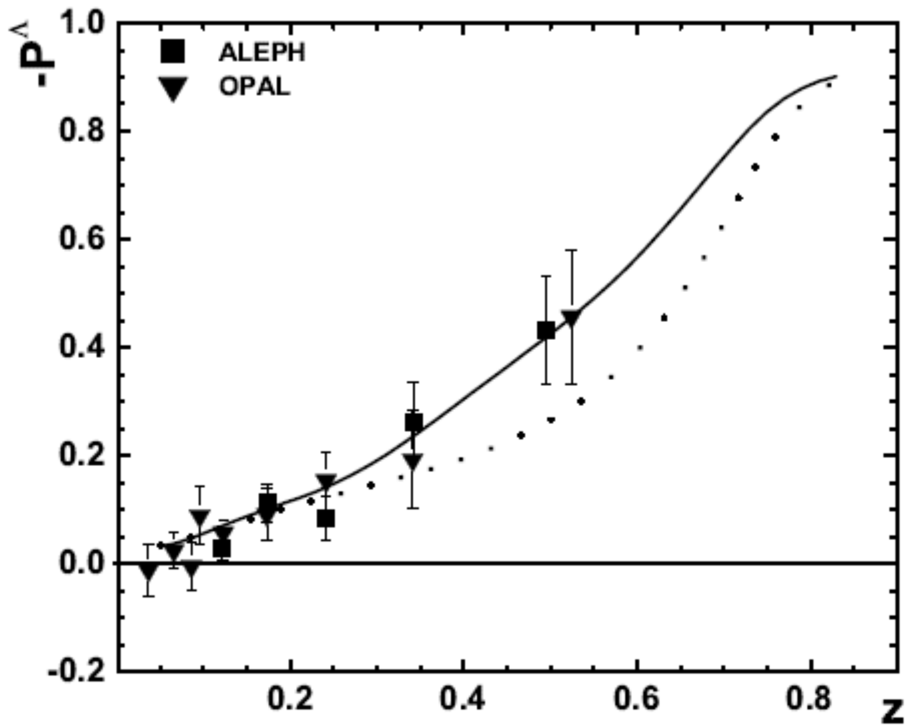
Lambda produced from s quark fragments should be larger than that from the u or d quark.

- If Λ originates from the primarily *u* quark, a ssbar and a ddbar pair have to be created in order to provide the constituent quarks.
- if Λ produced from initial s quark, the creation of only uubar and ddbar pairs are required

$$
\begin{aligned}
D_d^\Lambda(x,Q^2) &= D_u^\Lambda(x,Q^2) = \left(\frac{D_u^\Lambda(x)}{D_{u+\bar{u}}^\Lambda(x)}\right)^{\text{th}} D_{u+\bar{u}}^\Lambda(x,Q^2)^{\text{AKK}},\\
D_{\bar{d}}^\Lambda(x,Q^2) &= D_{\bar{u}}^\Lambda(x,Q^2) = \left(\frac{D_{\bar{u}}^\Lambda(x)}{D_{u+\bar{u}}^\Lambda(x)}\right)^{\text{th}} D_{u+\bar{u}}^\Lambda(x,Q^2)^{\text{AKK}},\\
\Delta D_d^\Lambda(x,Q^2) &= \Delta D_u^\Lambda(x,Q^2) = \left(\frac{\Delta D_u^\Lambda(x)}{D_{u+\bar{u}}^\Lambda(x)}\right)^{\text{th}} D_{u+\bar{u}}^\Lambda(x,Q^2)^{\text{AKK}},\\
D_s^\Lambda(x,Q^2) &= \left(\frac{D_s^\Lambda(x)}{D_{s+\bar{s}}^\Lambda(x)}\right)^{\text{th}} D_{s+\bar{s}}^\Lambda(x,Q^2)^{\text{AKK}},\\
D_{\bar{s}}^\Lambda(x,Q^2) &= \left(\frac{D_{\bar{s}}^\Lambda(x)}{D_{s+\bar{s}}^\Lambda(x)}\right)^{\text{th}} D_{s+\bar{s}}^\Lambda(x,Q^2)^{\text{AKK}},\\
\Delta D_s^\Lambda(x,Q^2) &= \left(\frac{\Delta D_s^\Lambda(x)}{D_{s+\bar{s}}^\Lambda(x)}\right)^{\text{th}} D_{s+\bar{s}}^\Lambda(x,Q^2)^{\text{AKK}}.
\end{aligned}
$$

S. Albino, B. A. Kniehl and G. Kramer, NPB 803, 42 (2008)

z dependence of Λ hyperon in e^+e^- annihilation process



D. Buskulic et al. [ALEPH Collaboration], PLB 374, 319 (1996).

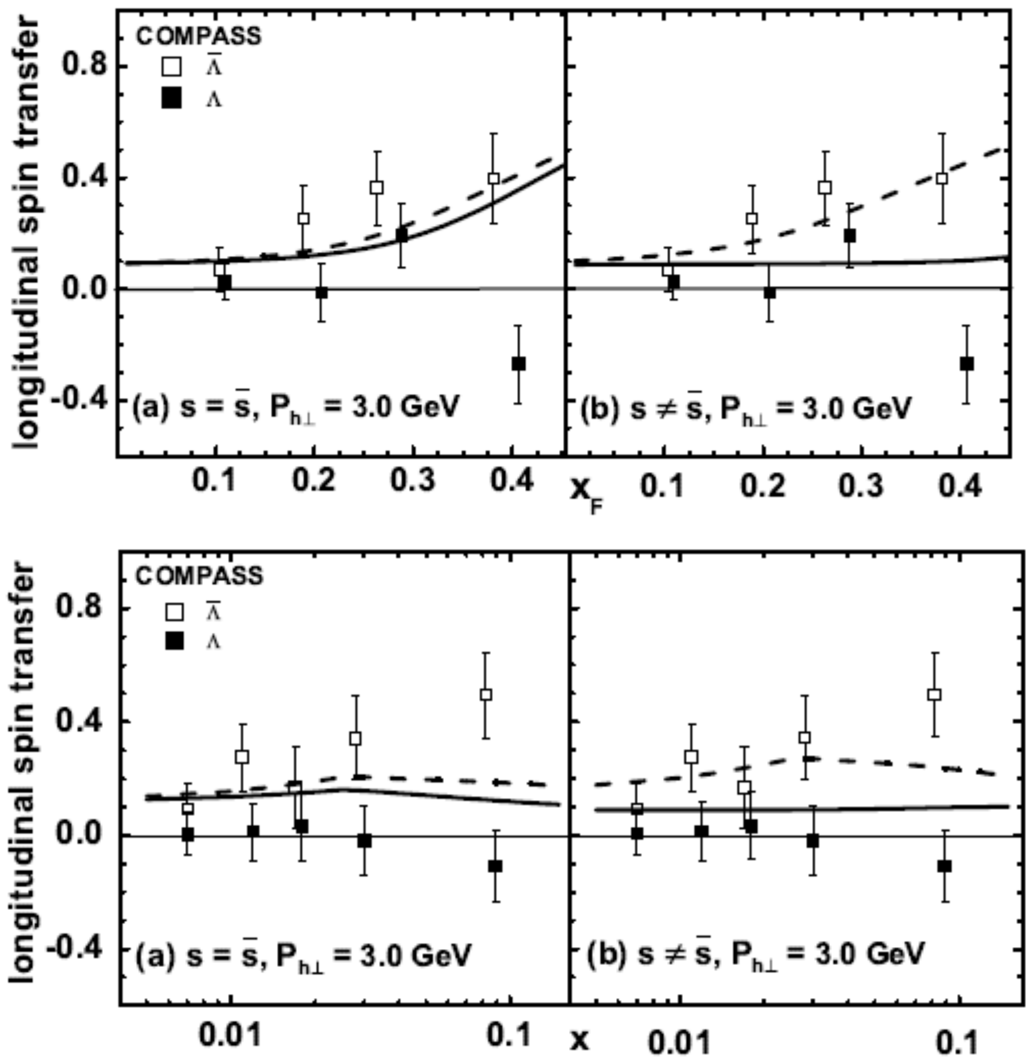
K. Ackerstaff et al. [OPAL Collaboration], EPJC 2, 49 (1998)

The solid curve corresponds to the theoretical calculation with AKK parametrization input.

The dotted curve is result without AKK parametrization input.

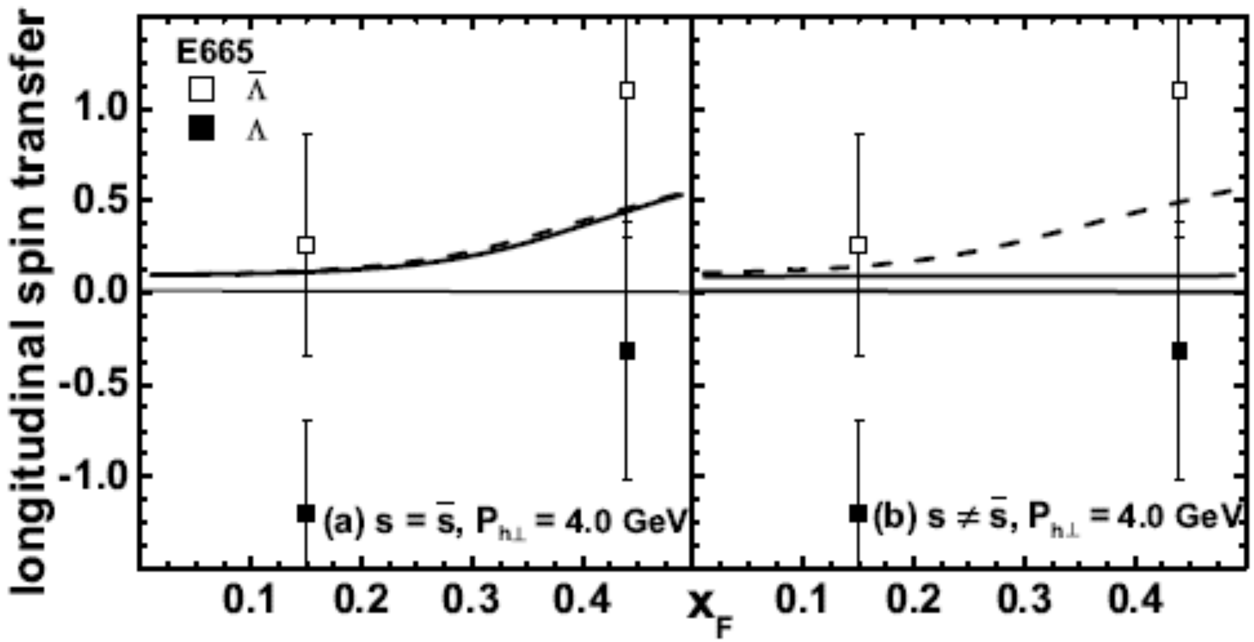
COMPASS Collaboraation

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



M. Alekseev et al. [COMPASS Collaboration], EPJ C 64, 171 (2009).

x_F dependence of Λ and anti-Λ longitudinal spin transfers at E665

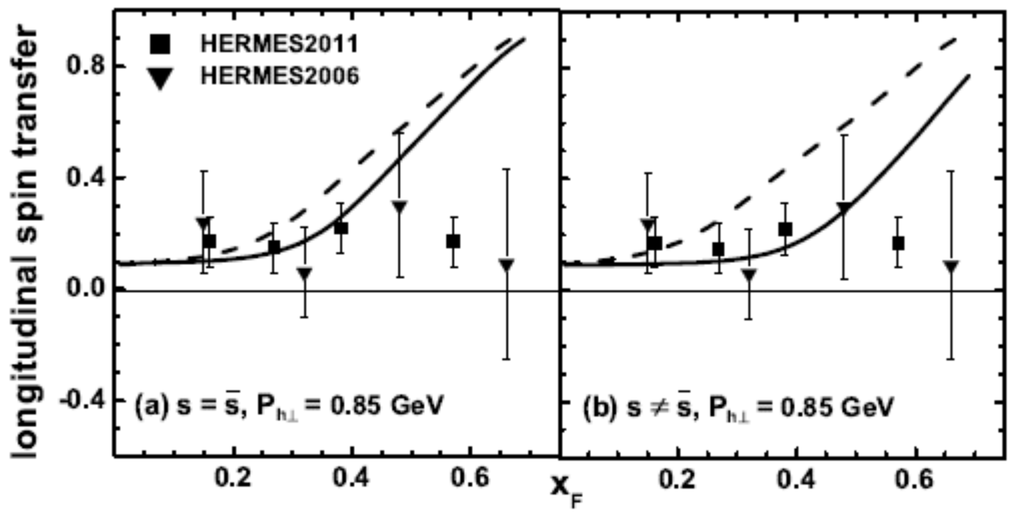


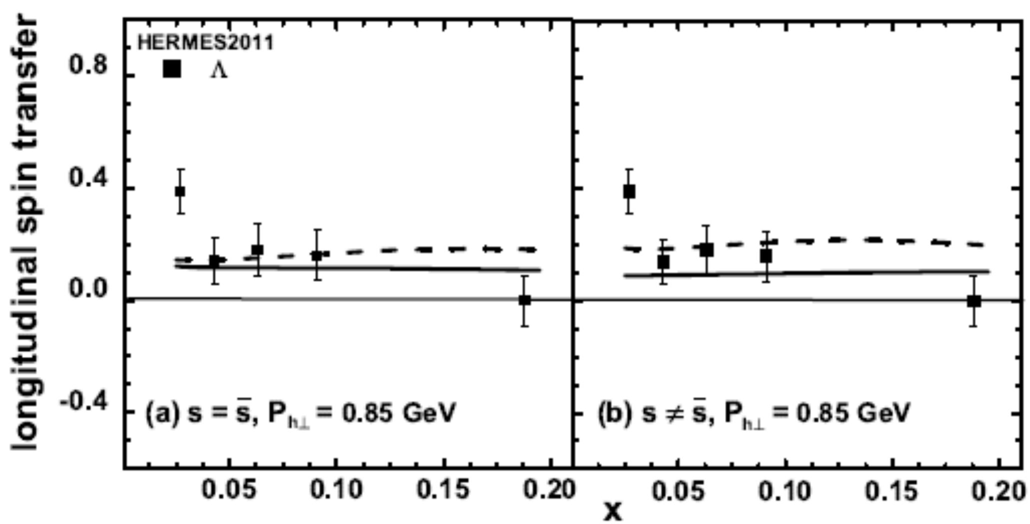
The solid and dashed curves correspond to Λ and anti-Λ hyperons.

M. R. Adams et al. [E665 Collaboration], EPJC 17, 263 (2000)

HERMES Collaboration

$$0.8\,GeV^2 < Q^2 < 24\,GeV^2,\ W^2 > 4\,GeV^2,\ 0.05 < y < 0.9$$





A. Airapetian et al. [HERMES Collaboration], Phys.Rev. D 74, 072004 (2006)

S. Belostotski, D. Veretennikov and Y. Naryshkin, J. Phys. Conf. Ser. 295, 012114 (2011).

Conclusion

◆The asymmetric nucleon strange sea distribution input gives a better description of the experimental data.

◆The analysis on the polarization of Λ/anti-Λ can open a new window to probe the nucleon strange sea properties.

◆We suggest future experiments to analyze the polarization of Λ/anti-Λ for providing more information on the nucleon strange sea content.