



The Strange Quark-Antiquark Asymmetry of the Nucleon

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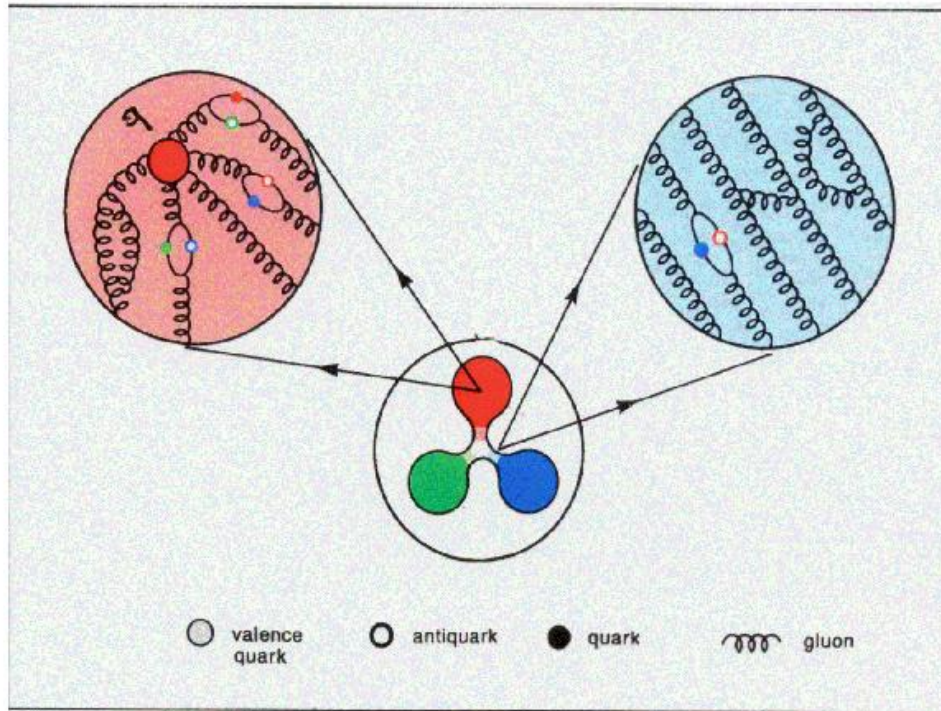
2025强子物理与有效场论前沿讲习班

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Outline

- The nucleon s - $\bar{s}$ asymmetry as a non-perturbative effect inside the nucleon sea.
- The nucleon strangeness asymmetry versus NuTeV anomaly
- Influence of Heavy Quark Recombination to the Measurement of the Nucleon Strangeness Asymmetry
- New Support from Lambda and anti-Lambda Spin Transfer

Nucleons: Building Block of Matter



- Nucleon anomalous magnetic moment (***Stern, Nobel Prize 1943***)
- Electromagnetic form factor from electron scattering (***Hofstadter, Nobel Prize 1961***)
- Deep-in-elastic scattering, quark underlying structure of the nucleon (***Freedman, Kendell, Feldman, Nobel Prize 1990***)

Understanding the underlying nucleon structure from quantum chromodynamics is essential

The Strange-Antistrange Asymmetry

The strange quark and antiquark distributions are symmetric at leading-orders of perturbative QCD

$$s(x) = \bar{s}(x)$$

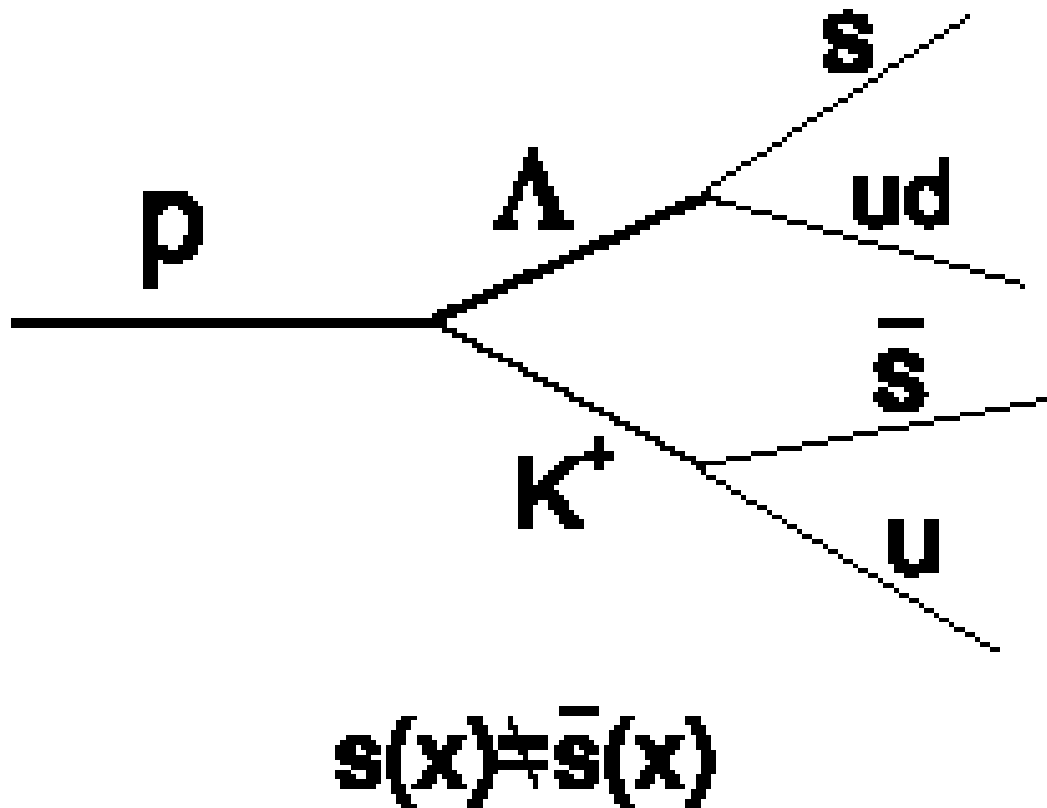
However, it has been argued that there is strange-antistrange distribution asymmetry in pQCD evolution at three-loops from non-vanishing up and down quark valence densities.

S.Catani et al. PRL93(2004)152003

Strange-Antistrange Asymmetry *from Non-Perturbative Sources*

- **Meson Cloud Model** $s(x) < \bar{s}(x)$ at large x
A.I. Signal and A.W. Thomas, PLB191(87)205
- **Chiral Field** $s(x) > \bar{s}(x)$ at large x
M. Burkardt and J. Warr, PRD45(92)958
- **Baryon-Meson Fluctuation** $s(x) > \bar{s}(x)$ at large x
S.J. Brodsky and B.-Q. Ma, PLB381(96)317

Mechanism for s-sbar asymmetry



Strange-Antistrange Asymmetry in phenomenological analyses

- **V. Barone et al. Global Analysis, EPJC12(00)243**

$$\int x[s(x) - \bar{s}(x)]dx \approx 0.002$$

- **NuTeV dimuon analysis, hep-ex/0405037, PRL99(07)192001**

$$\int x[s(x) - \bar{s}(x)]dx \approx -0.0013 \rightarrow 0.00196$$

- **CTEQ Global Analysis, F. Olness et. al (hep-ph/0312323),**

$$\int x[s(x) - \bar{s}(x)]dx \approx -0.001 \rightarrow 0.004$$

With large uncertainties

Weinberg (weak) Angle from Neutrino DIS: NuTeV Anomaly

- NuTeV Collaboration reported result, [PRL88\(02\)091802](#)

$$\sin^2 \theta_w = 0.2277 \pm 0.0013(\text{stat}) \pm 0.0009(\text{syst})$$

- Other electroweak processes

$$\sin^2 \theta_w = 0.2227 \pm 0.0004$$

- The three standard deviations could be an indication of **new physics beyond standard model** if it cannot be explained in conventional physics

- **The Paschos-Wolfenstein relation**

$$R^- = \frac{\sigma_{NC}^{\nu N} - \sigma_{NC}^{\bar{\nu} N}}{\sigma_{CC}^{\nu N} - \sigma_{CC}^{\bar{\nu} N}} = \frac{1}{2} - \sin^2 \theta_w$$

- **The assumptions for the P-W relationship**

a isoscalar target

b charge symmetry or isospin symmetry between p and n

$$u^p(x) = d^n(x) \quad d^p(x) = u^n(x)$$

$$\bar{u}^p(x) = \bar{d}^n(x) \quad \bar{d}^p(x) = \bar{u}^n(x)$$

c symmetric strange and antistrange distributions

$$s^p(x) = \bar{s}^p(x) = s^n(x) = \bar{s}^n(x)$$

- **The modified P-W relation**

$$R_N^- = \frac{\sigma_{NC}^{\nu N} - \sigma_{NC}^{\bar{\nu} N}}{\sigma_{CC}^{\nu N} - \sigma_{CC}^{\bar{\nu} N}} = R^- + \delta R_s^-.$$

$$\delta R_s^- = -\left(-1 + \frac{7}{3} \sin^2 \theta_w\right) \frac{S^-}{Q_V + 3S^-},$$

$$Q_V \equiv \int_0^1 x[u_V(x) + d_V(x)]dx \text{ and } S^- \equiv \int_0^1 x[s(x) - \bar{s}(x)]dx.$$

The probabilities for meson-baryon fluctuation

- General case

$$P_{(K^+\Lambda)} = 3\% - 6\%$$

Brodsky & Ma, PLB381(96)317

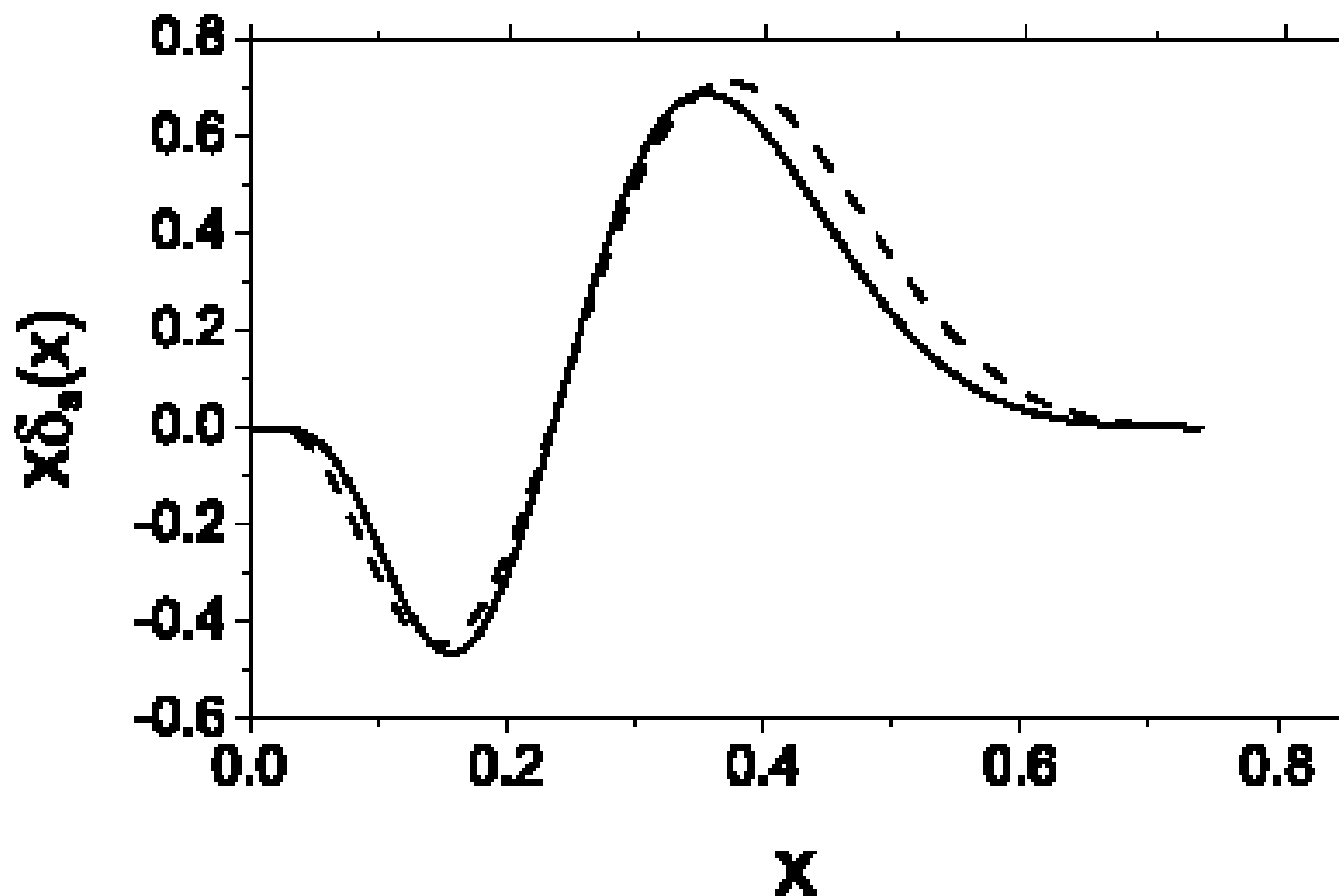
Ma, Schmidt, Yang, EPJA12(01)353

- Our estimate for

$$P_{(K^+\Lambda)} = 4\% - 10\%$$

- The distributions for $x \delta_s(x)$

with $\delta_s(x) = s(x) - \bar{s}(x)$



The results for S^-

$$Q_V \equiv \int_0^1 x[u_V(x) + d_V(x)]dx \text{ and } S^- \equiv \int_0^1 x[s(x) - \bar{s}(x)]dx.$$

- For Gaussian wave function

$$0.0042 < S^- < 0.0106$$
$$\psi_{\text{Gaussian}}(\mathcal{M}^2) = A_{\text{Gaussian}} \exp(-\mathcal{M}^2/2\alpha^2) ,$$
$$\psi_{\text{Power}}(\mathcal{M}^2) = A_{\text{Power}} (1 + \mathcal{M}^2/\alpha^2)^{-p} ,$$

- For power law wave function

$$0.0035 < S^- < 0.0087$$

However, we have also very large Q_V (around a factor of 3 larger) in our model calculation, so the ratio of S^-/Q_V is reasonable

The results in the baryon-meson fluctuation model

- For Gaussian wave function

$$0.0017 < \delta R_s^- < 0.0041$$

the discrepancy from 0.005 to 0.0033(0.0009)

- For power law wave function

$$0.0014 < \delta R_s^- < 0.0034$$

the discrepancy from 0.005 to 0.0036(0.0016)

Remove the discrepancy 30%-80%

between NuTeV and other values of Weinberg angle

The Effective Chiral Quark Model

- Established by Weinberg, and developed by Manohar and Georgi, has been widely adopted by the hadron physics society as an effective theory of QCD at low energy scale.
- Applied to explain the Gottfried sum rule violation by Eichten, Hinchliffe and Quigg, PRD 45 (92) 2269.
- Applied to explain the proton spin puzzle by Cheng and Li, PRL 74 (95) 2872.

The Effective Chiral Quark Model

$$|U\rangle = Z^{\frac{1}{2}} |u_0\rangle + a_\pi |u\pi^0\rangle + \frac{a_\pi}{\sqrt{2}} |d\pi^+\rangle + a_K |sK^+\rangle + \frac{a_\eta}{\sqrt{6}} |u\eta\rangle$$

$$|D\rangle = Z^{\frac{1}{2}} |d_0\rangle + a_\pi |d\pi^0\rangle + \frac{a_\pi}{\sqrt{2}} |d\pi^-\rangle + a_K |sK^0\rangle + \frac{a_\eta}{\sqrt{6}} |d\eta\rangle$$

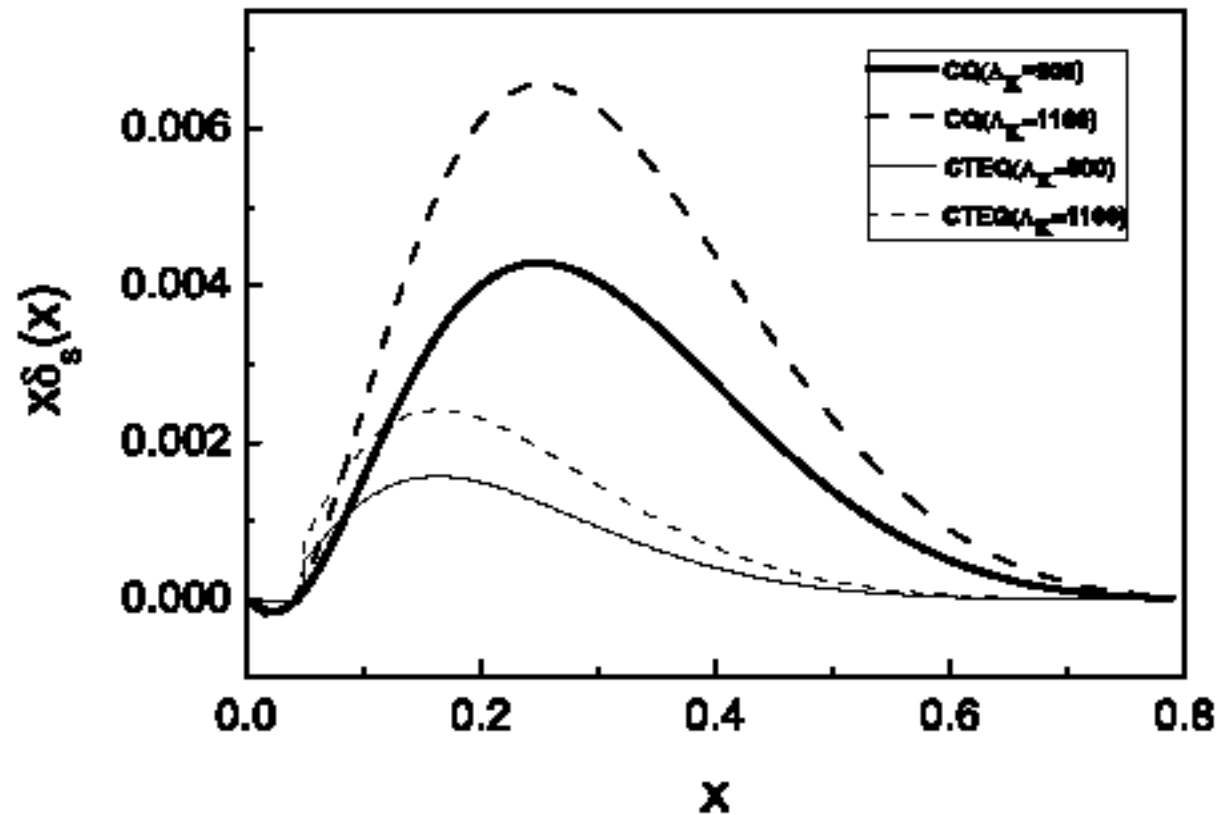
$$\begin{aligned} \underline{U} &= \underline{u_0} + \frac{\pi_0}{\underline{u_0} \quad \underline{u} \quad \underline{u_0}} + \frac{\pi^+}{\underline{u_0} \quad \underline{d} \quad \underline{u_0}} + \frac{K^+}{\underline{u_0} \quad \underline{s} \quad \underline{u_0}} + \frac{\eta}{\underline{u_0} \quad \underline{u} \quad \underline{u_0}} \\ \underline{D} &= \underline{d_0} + \frac{\pi^-}{\underline{d_0} \quad \underline{u} \quad \underline{d_0}} + \frac{\pi^0}{\underline{d_0} \quad \underline{d} \quad \underline{d_0}} + \frac{K^0}{\underline{d_0} \quad \underline{s} \quad \underline{d_0}} + \frac{\eta}{\underline{d_0} \quad \underline{d} \quad \underline{d_0}} \end{aligned}$$

Why strange-antistrange asymmetry in the chiral quark model?

$$\begin{aligned}
 \underline{U} &= \underline{u_0} + \frac{\pi_0}{u_0 \ u \ u_0} + \frac{\pi^+}{u_0 \ d \ u_0} + \frac{K^+}{u_0 \ s \ u_0} + \frac{\eta}{u_0 \ u \ u_0} \\
 \underline{D} &= \underline{d_0} + \frac{\pi^-}{d_0 \ u \ d_0} + \frac{\pi^0}{d_0 \ d \ d_0} + \frac{K^0}{d_0 \ s \ d_0} + \frac{\eta}{d_0 \ d \ d_0}
 \end{aligned}$$

The distributions for

$$x\delta_s(x) = x(s(x) - \bar{s}(x))$$



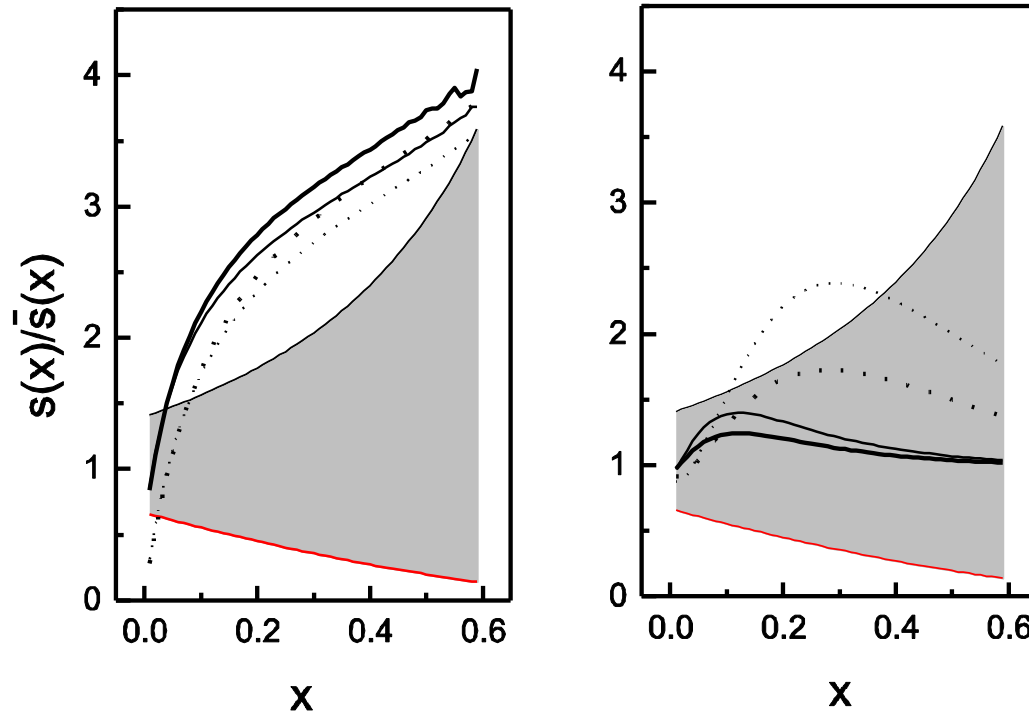
The results for different inputs within the effective chiral quark model

Λ_k	Z	Q_v	S^-	δR_s^-
900	0.74888	0.86376	0.00558	0.00297
1000	0.73996	0.85484	0.007183	0.00384
1100	0.73063	0.84551	0.00879	0.00473

Λ_k	Z	Q_v	S^-	δR_s^-
900	0.74888	0.37089	0.00252	0.00312
1000	0.73996	0.36686	0.00322	0.00402
1100	0.73063	0.36247	0.00398	0.00498

- The results can remove the deviation at least 60%

The comparison for $s(x)/\bar{s}(x)$ between the model calculation and experiment data



The shadowing area is the range of NuTeV Collaboration, the left side is the result of the chiral quark model only, and the right side is with an additional symmetric strange sea contribution.

Several works with similar conclusion

- **Ding-Ma, 30-80% correction**

PLB590 (2004) 216

- **Alwall-Ingelman, 30% correction**

PRD70 (2004) 111505(R)

- **Ding-Xu-Ma, 60-100% correction**

PLB607 (2005) 101, PRD71 (2005) 094014

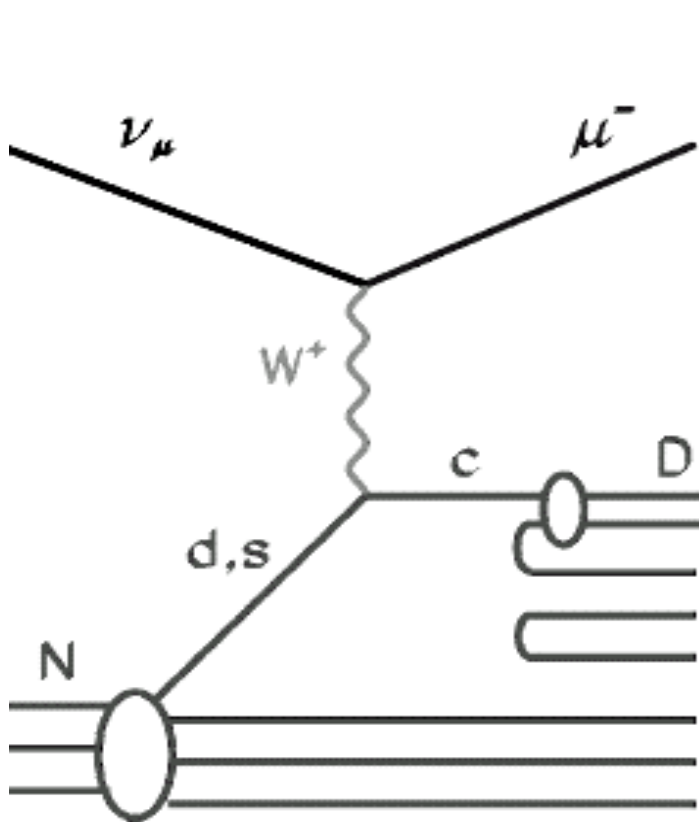
- **Wakamatsu, 70-110% correction**

PRD71 (2005) 057504

NuTeV anomaly **versus** s - $\bar{s}$ asymmetry

- The effect due to strange-antistrange asymmetry might be important to explain the NuTeV anomaly **or** the NuTeV anomaly could be served as an evidence for the s - $\bar{s}$ asymmetry.
- The calculated s - $\bar{s}$ asymmetry are compatible with the data by including some additional symmetric strange quark contribution.
- Reliable precision measurements are needed to make a crucial test of s - $\bar{s}$ asymmetry.

Strangeness Measurement via dimuon events by CCFR and NuTeV



$$\nu_\mu + \overset{50\%}{\uparrow} \textcolor{red}{S}(\textcolor{teal}{d}) \rightarrow \mu^- + \textcolor{red}{c}$$

$$\bar{\nu}_\mu + \overset{90\%}{\uparrow} \textcolor{red}{\bar{S}}(\textcolor{teal}{\bar{d}}) \rightarrow \mu^+ + \textcolor{red}{\bar{c}}$$

• Different charged dimuon signal:

$$c \rightarrow \mu^+ \quad \bar{c} \rightarrow \mu^-$$

Dimuon measurement of strangeness asymmetry:

$$\frac{d^2\sigma_{\nu_\mu N \rightarrow \mu^- \mu^+ X}}{d\xi dy} - \frac{d^2\sigma_{\bar{\nu}_\mu N \rightarrow \mu^+ \mu^- X}}{d\xi dy} = \frac{G_F^2 S}{\pi r_w^2} f_c B_c \\ \times \left\{ \xi[s(\xi) - \bar{s}(\xi)]|V_{cs}|^2 + \frac{1}{2}\xi[d_v(\xi) + u_v(\xi)]|V_{cd}|^2 \right\},$$

$$\xi = x(1 + m_c^2/Q^2) \qquad y = \nu/E_\nu$$

$$f_c \equiv 1 - m_c^2/2ME_\nu\xi, \qquad r_w \equiv 1 + Q^2/M_W^2$$

Strangeness asymmetry: $S^-(\xi) \equiv \xi[s(\xi) - \bar{s}(\xi)]$

Early analysis shows no indication of strangeness asymmetry.

•Mason, hep-ex/0405037

•CCFR & NuTeV LO fit: $S^- = -0.0027 \pm 0.0013$

•NuTeV LO fit: $S^- = -0.0003 \pm 0.0011$

•NuTeV NLO fit: $S^- = -0.0011 \pm 0.0014$

Later NLO analysis of NuTeV data with improved method shows support of positive S^-

$$S^- = +0.00196 \pm 0.00046(stat) \pm 0.00045(syst) \pm 0.00128(external)$$

•Mason, FERMILAB-THESIS-2006-01,

•NuTeV, PRL99(07)192001

Influence of Heavy Quark Recombination

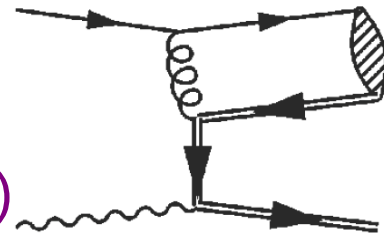
- Heavy Quark Recombination

Heavy quark recombination combines a heavy quark with a light anti-quark of small relative momentum, e.g. ($c\bar{q}$), and then hadronize into a D meson.

- Can explain the following issues through simple QCD picture

A. Charm photoproduction asymmetry

Braaten, Jia, Mehen, PRD66,012003(2002)



B. Leading particle effect in pi-N scattering

Braaten, Jia, Mehen, PRL89,122002(2002)

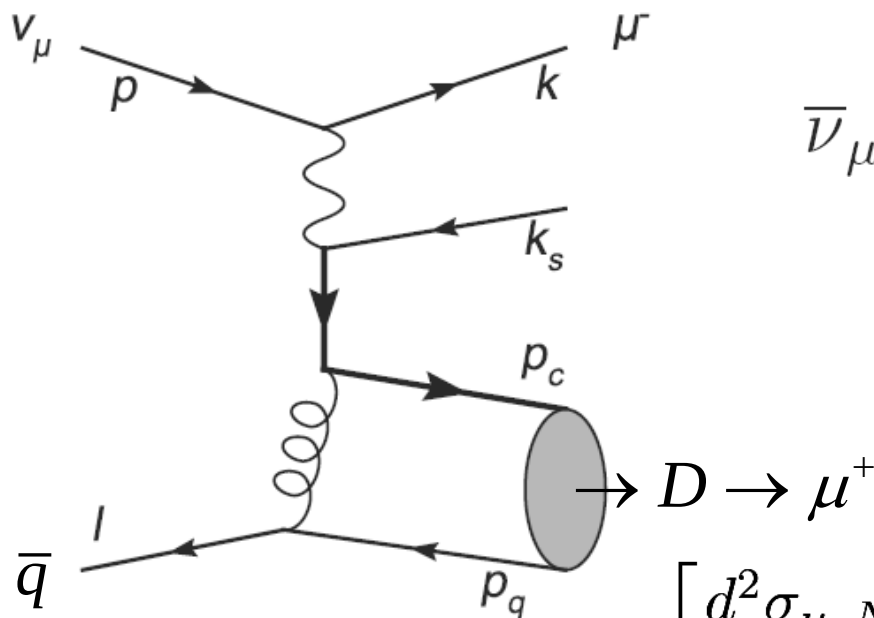
Influence on Strangeness Asymmetry Measurement

Heavy Quark Recombination

$$\nu_\mu + \bar{q} \rightarrow \mu^- + \bar{s}(\bar{d}) + D(c\bar{q})$$

$$\bar{\nu}_\mu + q \rightarrow \mu^+ + s(d) + \bar{D}(\bar{c}q)$$

HR has an additional contribution



$$q = u, d$$

$$D: {}^1S_0, {}^3S_1$$

$$\left[\frac{d^2\sigma_{\nu_\mu N \rightarrow \mu^- \mu^+ X}}{d\xi dy} - \frac{d^2\sigma_{\bar{\nu}_\mu N \rightarrow \mu^+ \mu^- X}}{d\xi dy} \right]_{HR}$$

$$= \sum_{q,D} \int dx [\bar{q}(x) - q(x)] \frac{d^2\hat{\sigma}_{D(c\bar{q})}}{d\xi dy} B_{D(c\bar{q})},$$

Influence on Strangeness Asymmetry Measurement

$$S_{\text{real}}^{-}(\xi) = S_{\text{analy}}^{-}(\xi) + \delta S_{\text{HR}}^{-}(\xi).$$

$$\begin{aligned} \delta S_{\text{HR}}^{-}(\xi) &\approx \frac{\pi r_w^2}{G_F^2 S f_c B_c |V_{cs}|^2} \\ &\times \sum_{q,D} \int dx [q(x) - \bar{q}(x)] \frac{d^2 \hat{\sigma}_{D(c\bar{q})}}{d\xi dy} \cdot B_{D(c\bar{q})} \end{aligned}$$

$$\delta S_{\text{HR}}^{-}(\xi) > 0 \qquad S_{\text{real}}^{-} \equiv \int d\xi S_{\text{real}}^{-}(\xi)$$

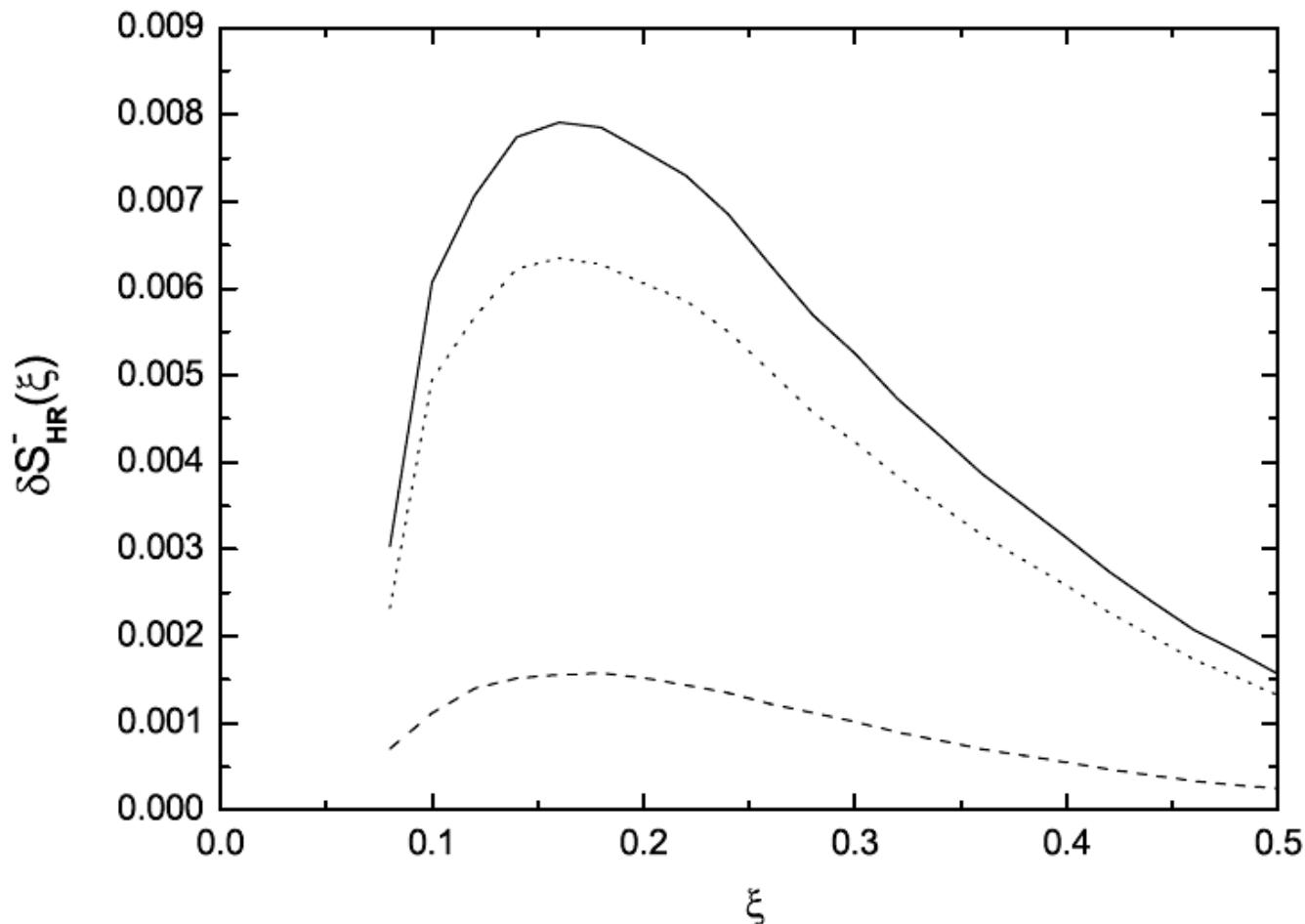


FIG. 2: $\delta S_{\text{HR}}^-(\xi)$ for $E_\nu = 160$ GeV, $Q^2 = 20$ GeV and $\rho_{\text{sm}} = 0.15$. The dashed curve is the contribution from 1S_0 state; the dotted curve is the contribution from 3S_1 state; and the solid curve is their sum, the $\delta S_{\text{HR}}^-(\xi)$.

$$\delta S_{\text{HR}}^- \approx 0.0023 \quad \text{for} \quad \rho_{\text{sm}} = 0.15.$$

$$S_{\text{real}}^- = S_{\text{analy}}^- + \delta S_{\text{HR}}^-$$

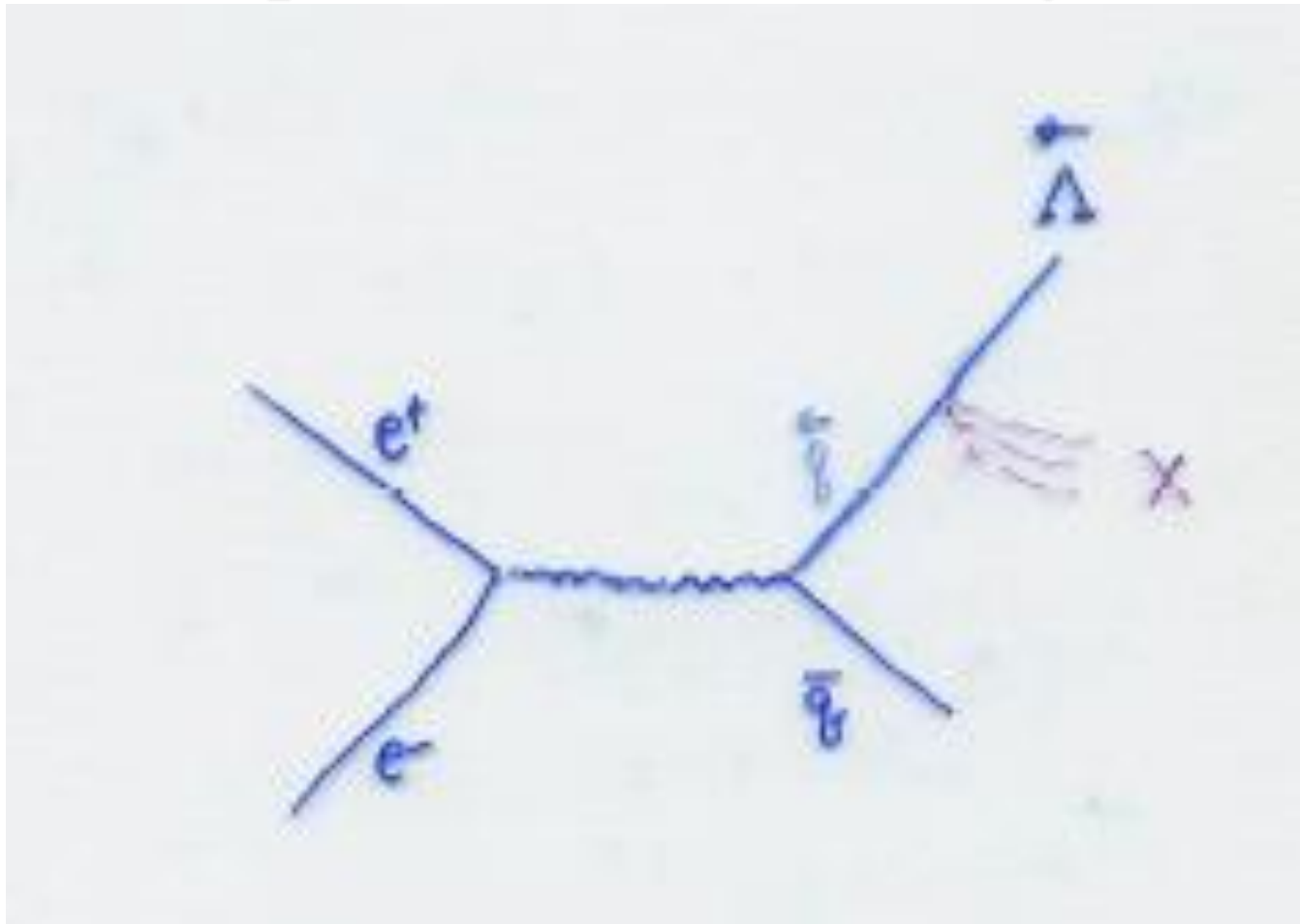
•**NuTeV NLO fit:** •Mason, FERMILAB-THESIS-2006-01

$$S^- = +0.00196 \pm 0.00046(\text{stat}) \pm 0.00045(\text{syst}) \pm 0.00128(\text{external})$$

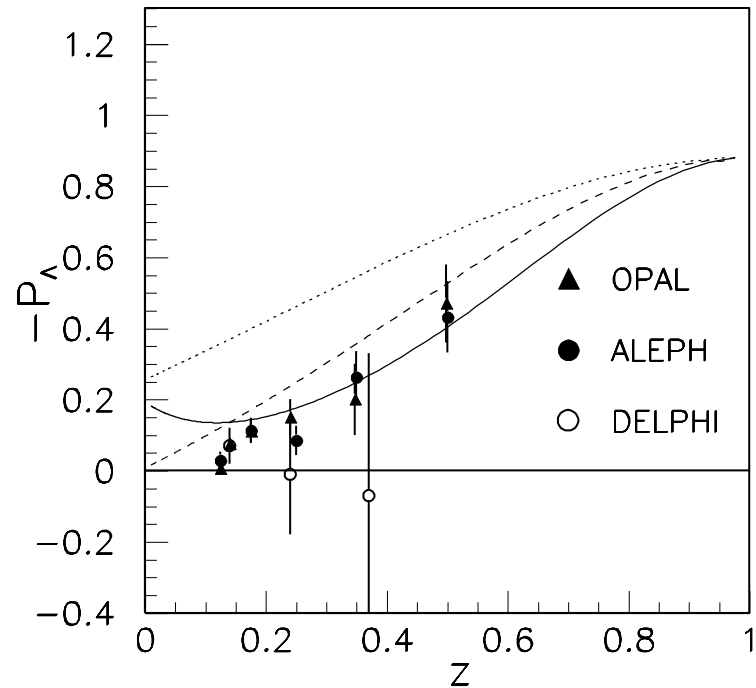
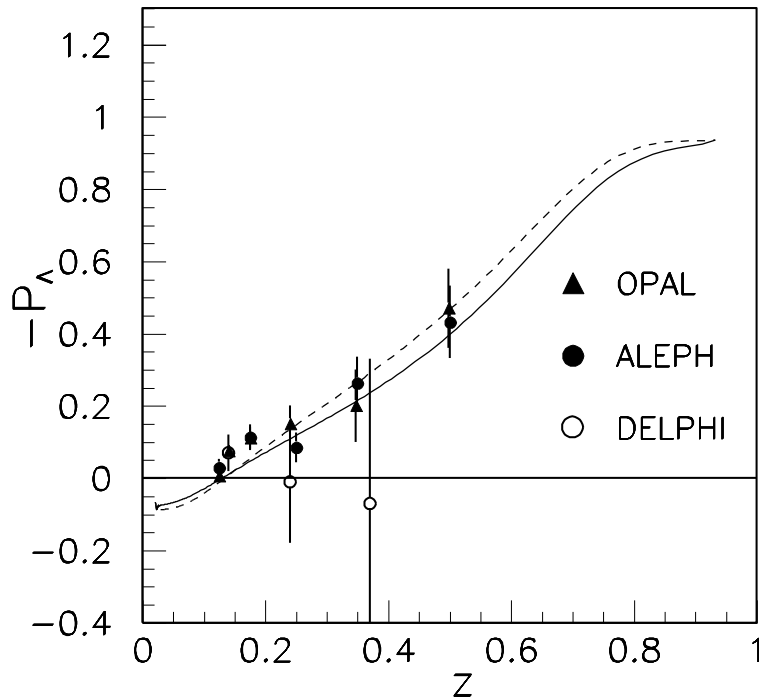
the central value of the realistic strangeness asymmetry should be $S_{\text{real}}^- \approx 0.0043$.

Such value of the strangeness asymmetry can explain the NuTeV anomaly to a large extent.

Spin structure of Lambda from Lambda polarization in Z^0 decay



Diquark model and pQCD results



B.-Q. Ma, I. Schmidt, J.-J. Yang, Phys. Rev. D 61 (2000) 034017

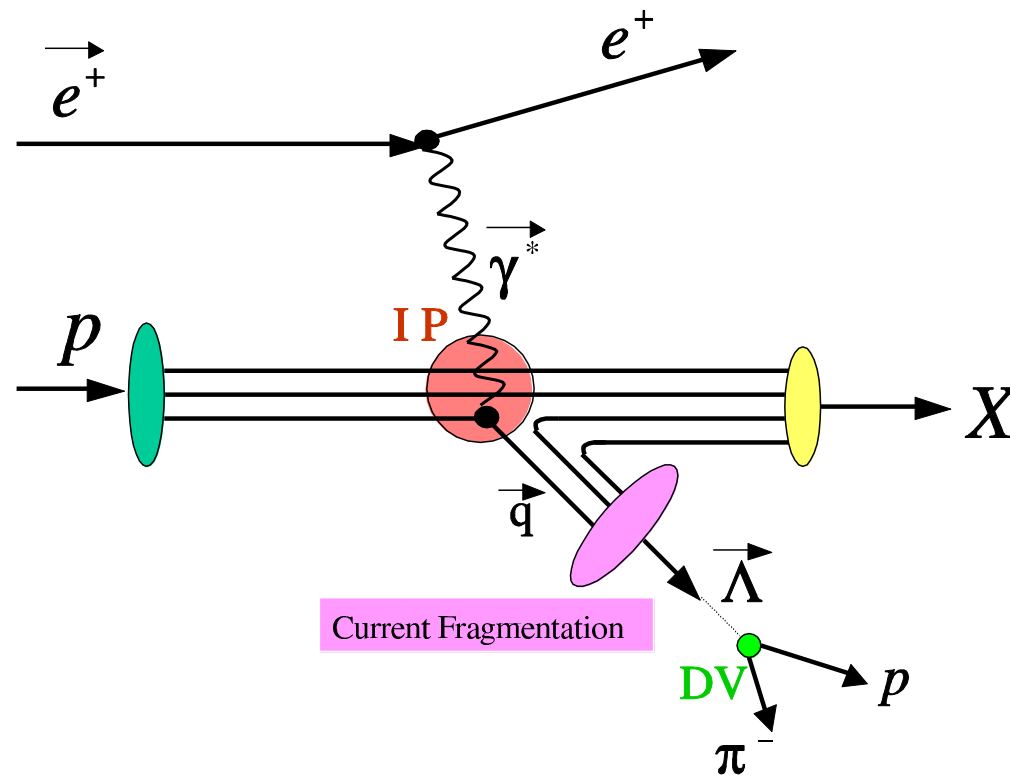
Flavor separation of fragmentation functions

B.-Q. Ma, J. Soffer, PRL 82 (1999) 2250

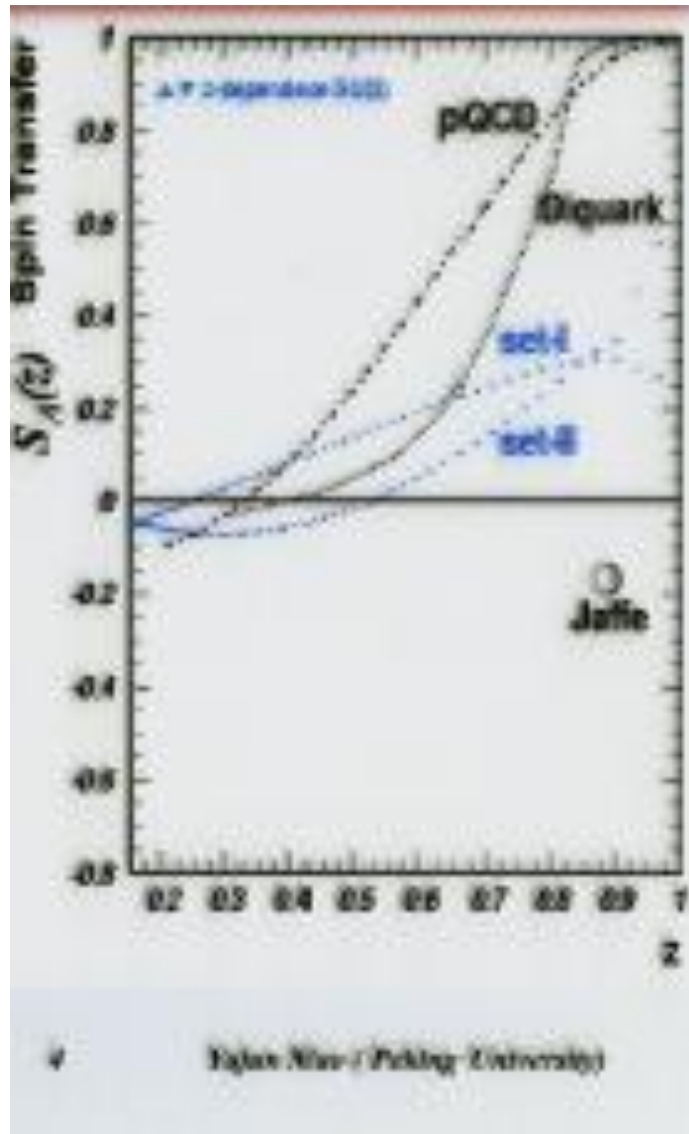
Complete flavor separation of
 $D_q^{\Lambda}(z)$, $\Delta D_q^{\Lambda}(z)$, $D_q^{\bar{\Lambda}}(z)$, $\Delta D_q^{\bar{\Lambda}}(z)$

- $\nu N \rightarrow \mu^- \vec{\Lambda} X$
- $\bar{\nu} N \rightarrow \mu^+ \vec{\Lambda} X$
- $\nu N \rightarrow \mu^- \vec{\bar{\Lambda}} X$
- $\bar{\nu} N \rightarrow \mu^+ \vec{\bar{\Lambda}} X$

Spin Transfer to Λ in Semi-Inclusive DIS

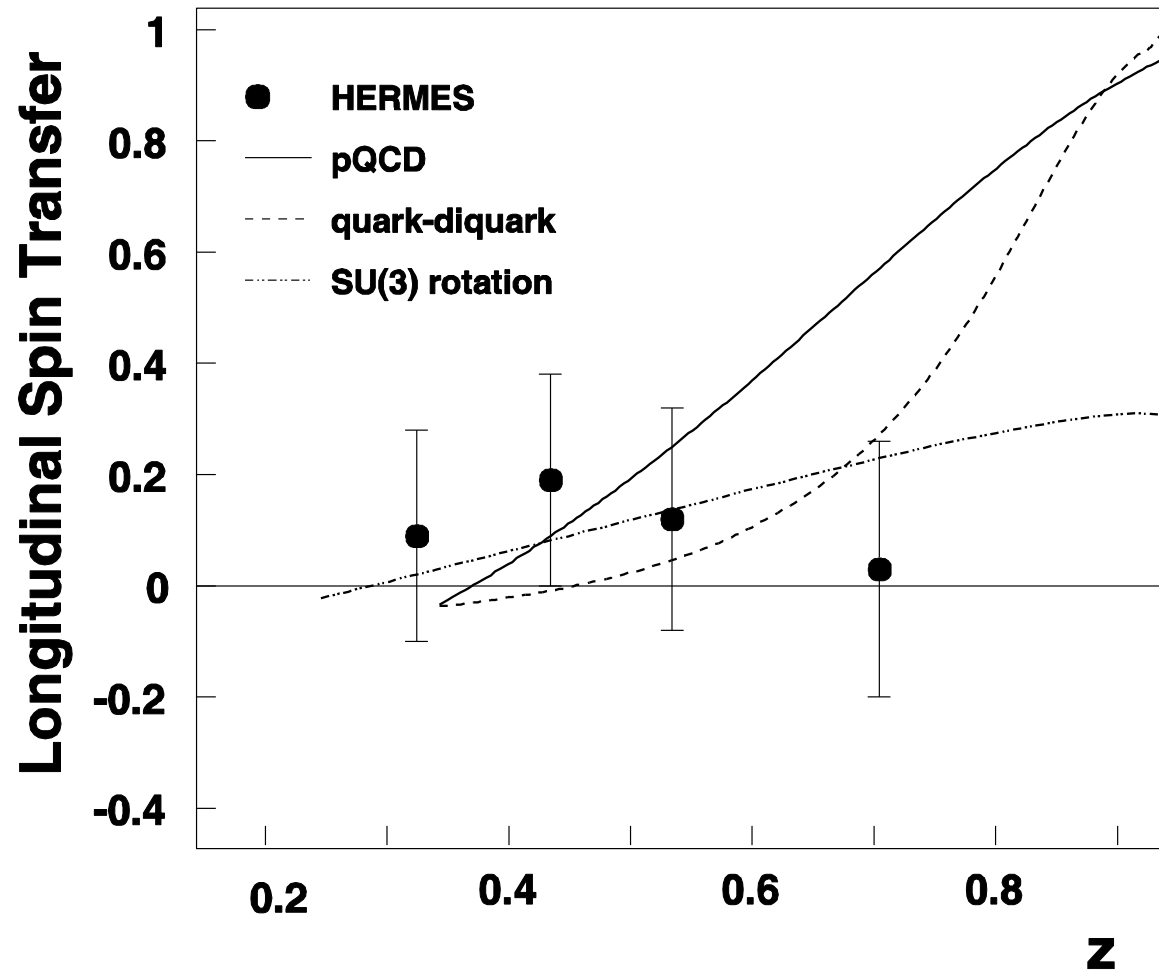


Different predictions



B.-Q. Ma, I. Schmidt, J.-J. Yang,
Phys. Lett. B 477 (2000) 107

Comparison with data



Parametrization of Λ fragmentation functions

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

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

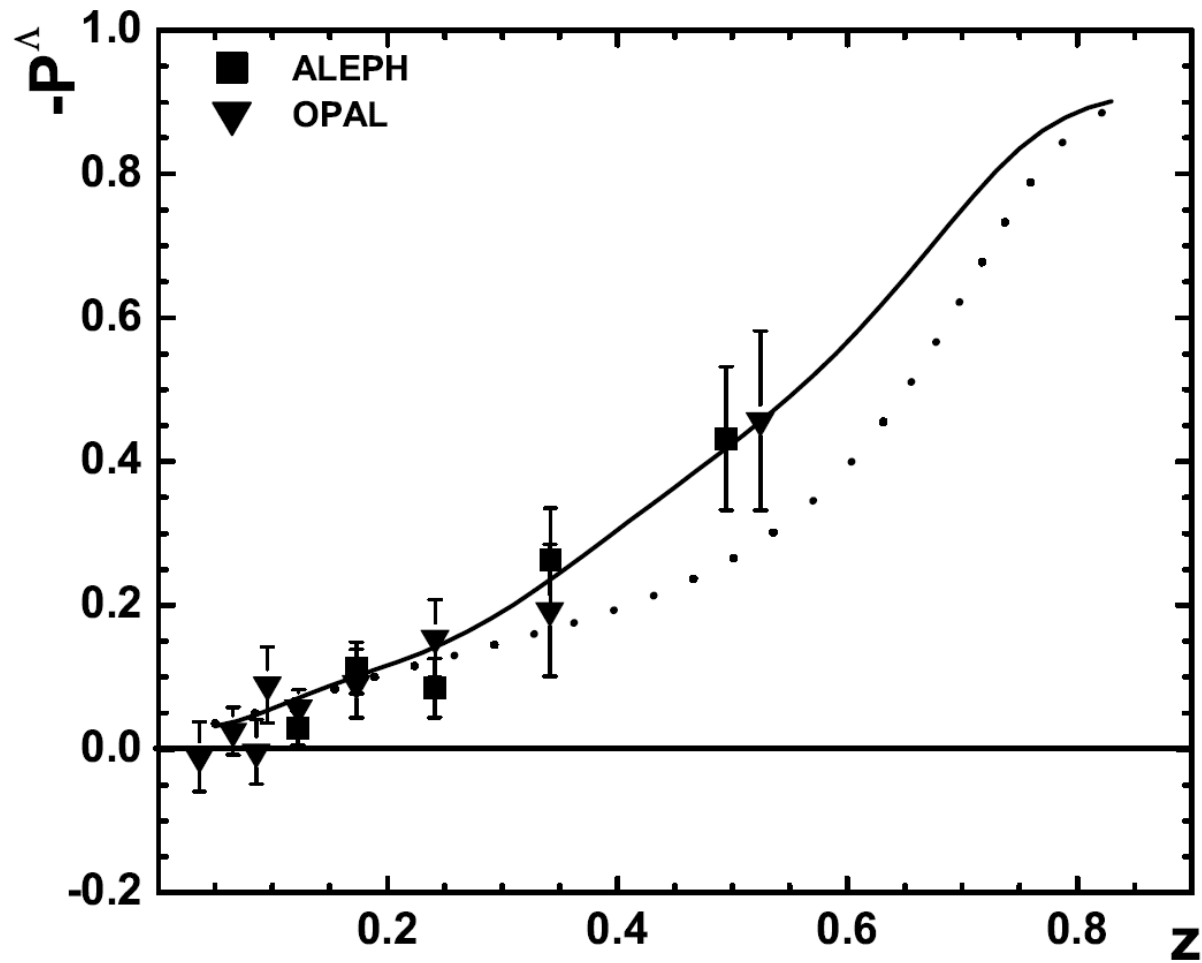
$$\begin{aligned} \Delta D_d^\Lambda(x, Q^2) &= \Delta D_u^\Lambda(x, Q^2) \\ &= \left(\frac{\Delta D_u^\Lambda(x)}{D_{u+\bar{u}}^\Lambda(x)} \right)^{\text{th}} D_{u+\bar{u}}^\Lambda(x, Q^2)^{\text{AKK}}, \end{aligned}$$

$$D_s^\Lambda(x, Q^2) = \left(\frac{D_s^\Lambda(x)}{D_{s+\bar{s}}^\Lambda(x)} \right)^{\text{th}} D_{s+\bar{s}}^\Lambda(x, Q^2)^{\text{AKK}},$$

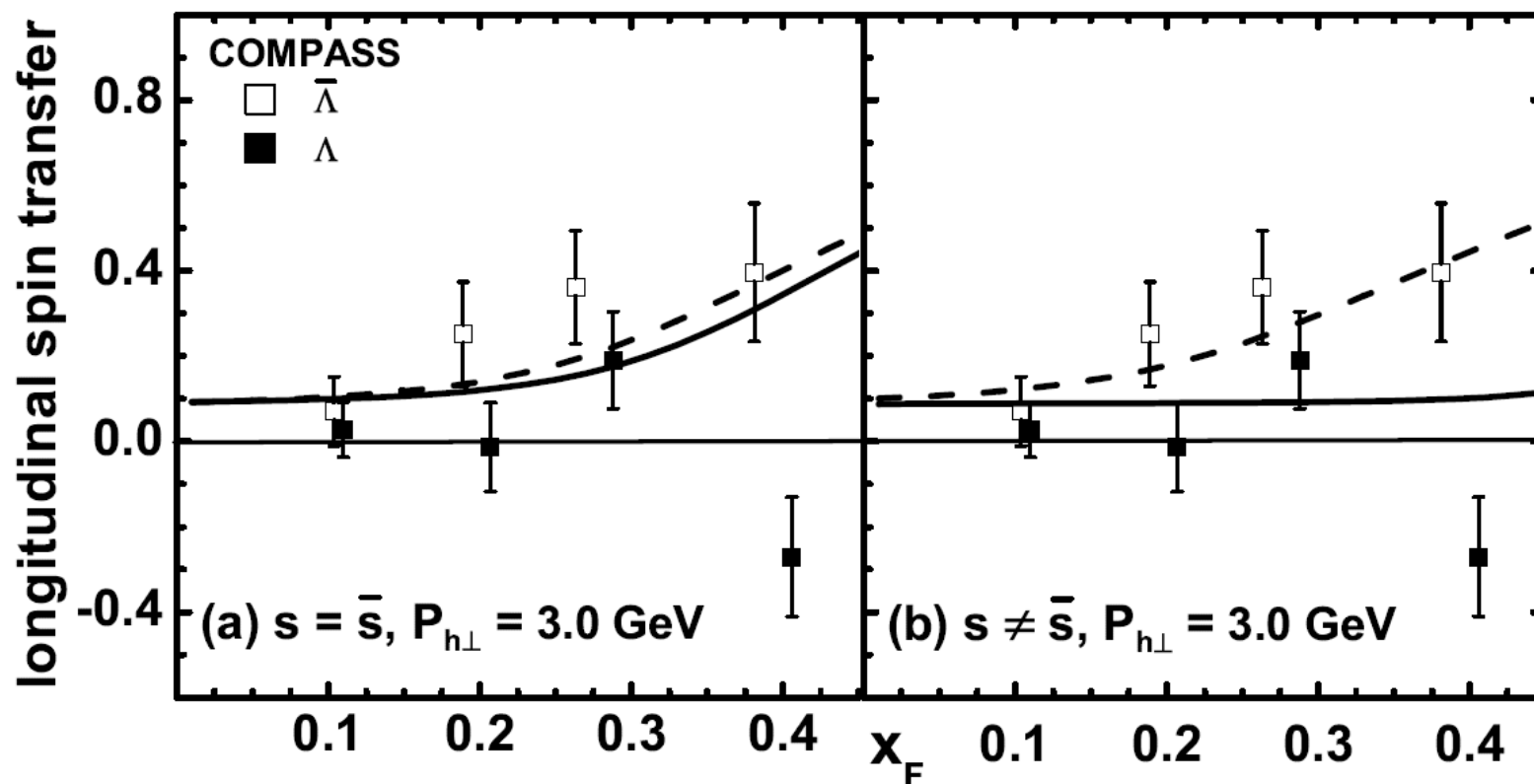
$$D_{\bar{s}}^\Lambda(x, Q^2) = \left(\frac{D_{\bar{s}}^\Lambda(x)}{D_{s+\bar{s}}^\Lambda(x)} \right)^{\text{th}} D_{s+\bar{s}}^\Lambda(x, Q^2)^{\text{AKK}},$$

$$\Delta D_s^\Lambda(x, Q^2) = \left(\frac{\Delta D_s^\Lambda(x)}{D_{s+\bar{s}}^\Lambda(x)} \right)^{\text{th}} D_{s+\bar{s}}^\Lambda(x, Q^2)^{\text{AKK}}.$$

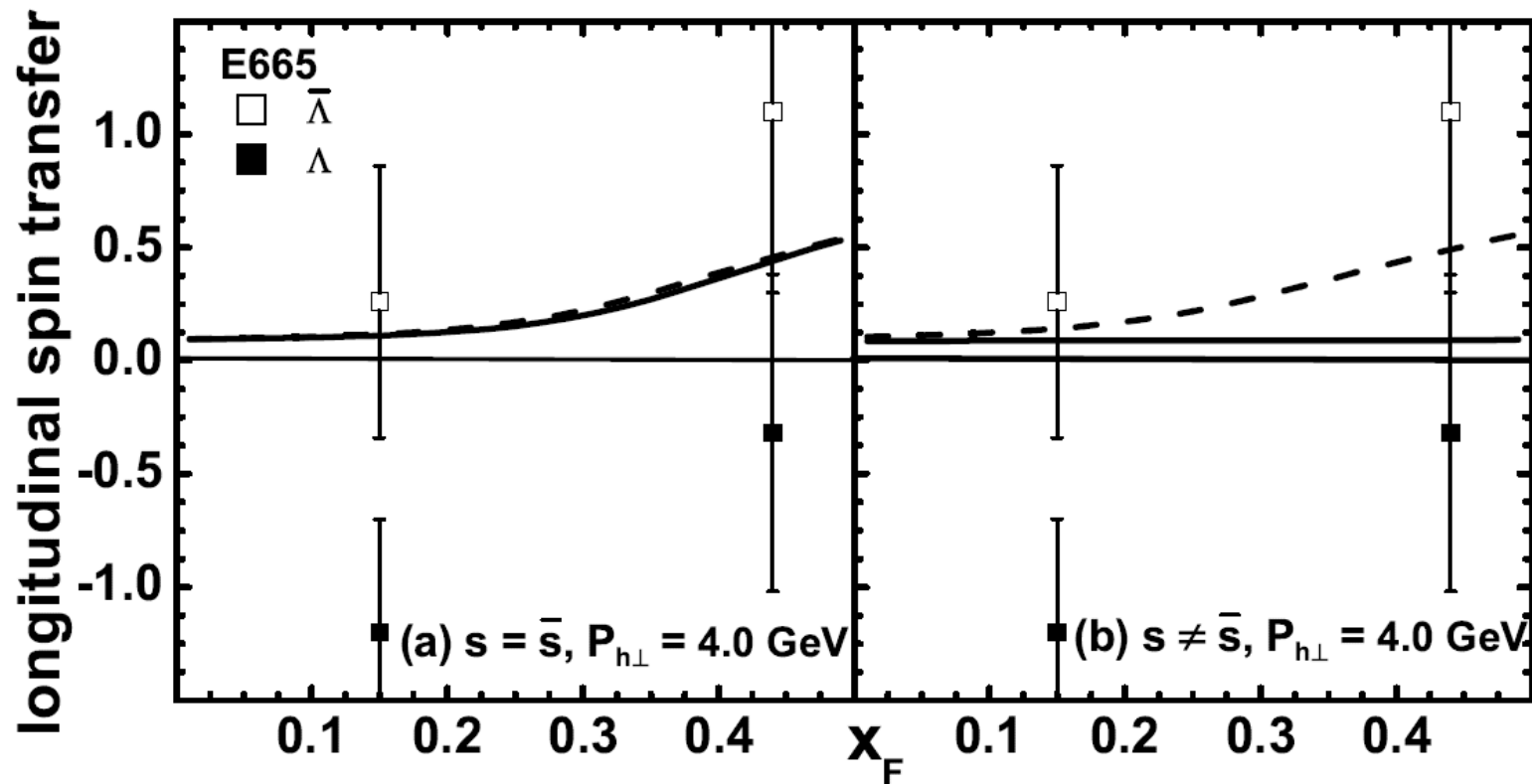
Results with new parametrization: Z-pole



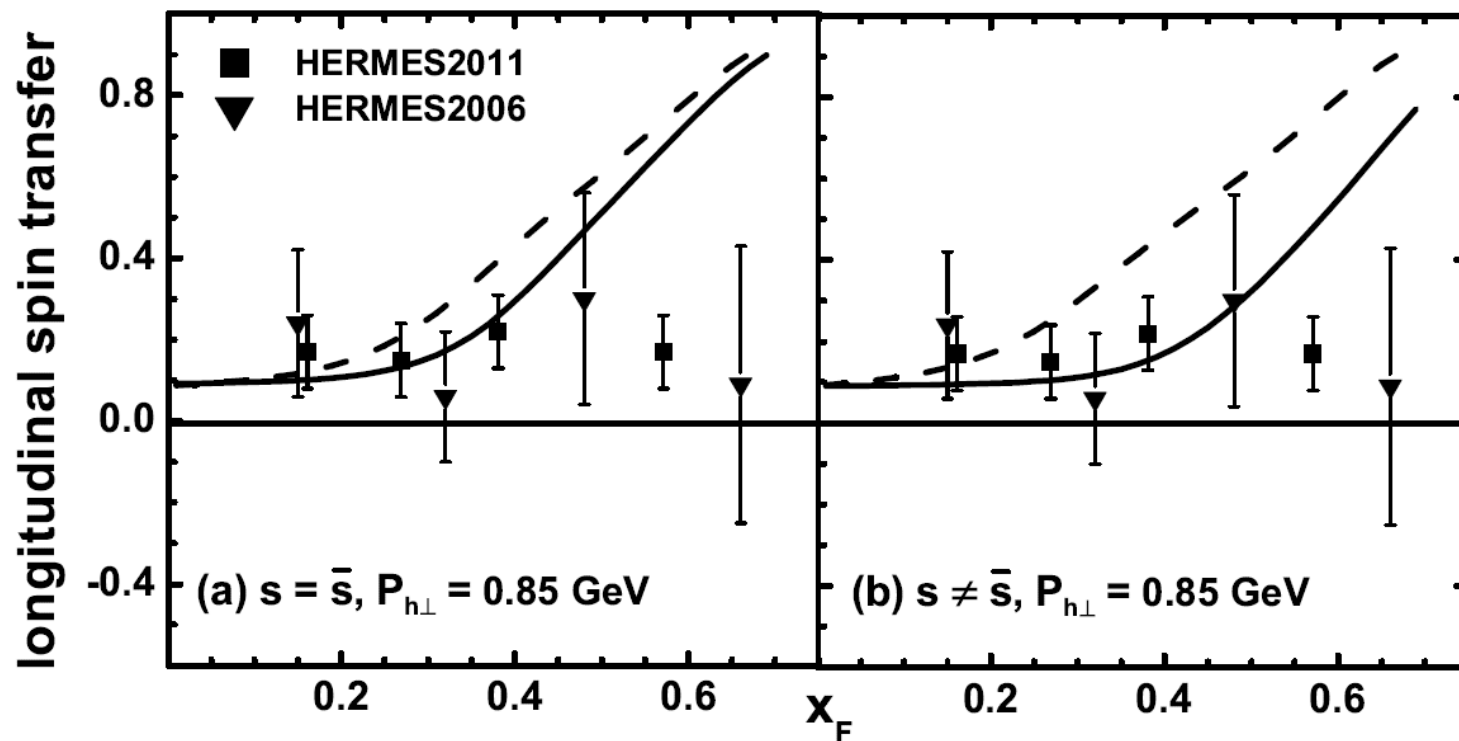
Difference between Lambda and anti-Lambda spin transfers with the COMPASS data



Difference between Lambda and anti-Lambda spin transfers with s - $\bar{s}$ asymmetry for E665



Difference between Lambda and anti-Lambda spin transfers with s - $\bar{s}$ asymmetry for HERMES



Summary

Our studies show that the nucleon strangeness asymmetry might be positive and could be large enough to explain a number of experimental observations:

- **The NuTeV anomaly.**
- **With heavy quark recombination to give a sizable influence on the measurement of the nucleon strangeness asymmetry in CCFR and NuTeV dimuon measurements.**
- **The difference between Lambda and anti-Lambda spin transfers.**