Re-Visit of the Strange-Antistrange Asymmetry of the Nucleon

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Outline

- The nucleon s-sbar 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 from COMPASS Data

The Strange-Antistrange Asymmetry

The strange quark and antiquark distributions are

symmetric at leading-orders of perturbative QCD

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

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

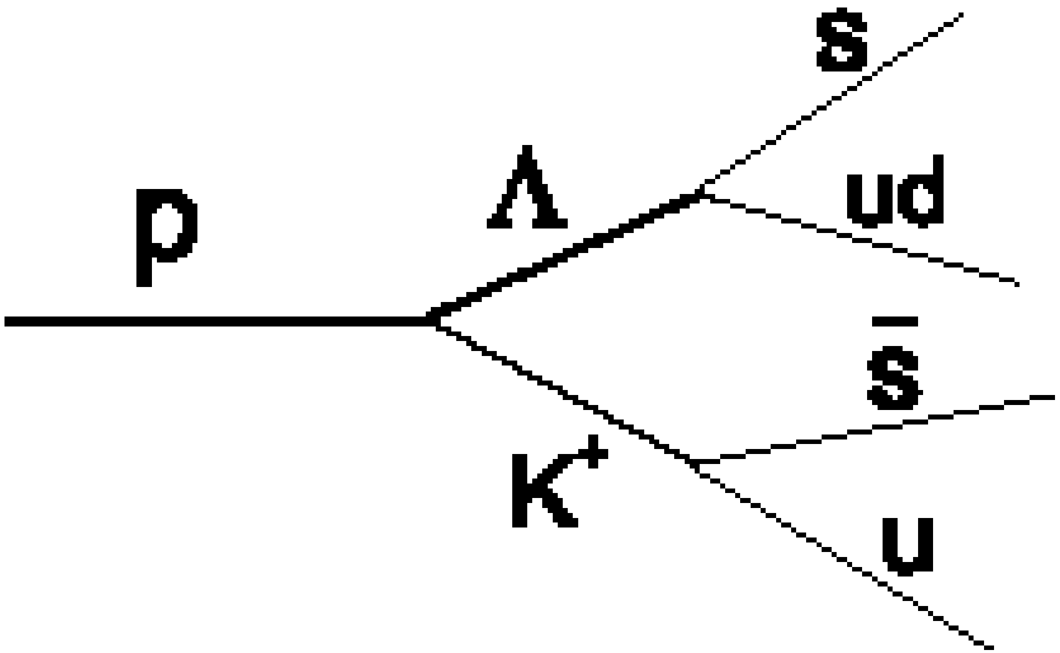
- **Chiral Field** $s(x) > \bar{s}(x)$ at large x

  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



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

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 Anamoly

- **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**

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

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

$Q_V \equiv \int_0^1 x[u_V(x) + d_V(x)]\mathrm{d}x$ and $S^- \equiv \int_0^1 x[s(x) - \overline{s}(x)]\mathrm{d}x.$

The probabilities for meson-baryon fluctuation

- **General case**

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

Brodsky & Ma, PLB381(96)317

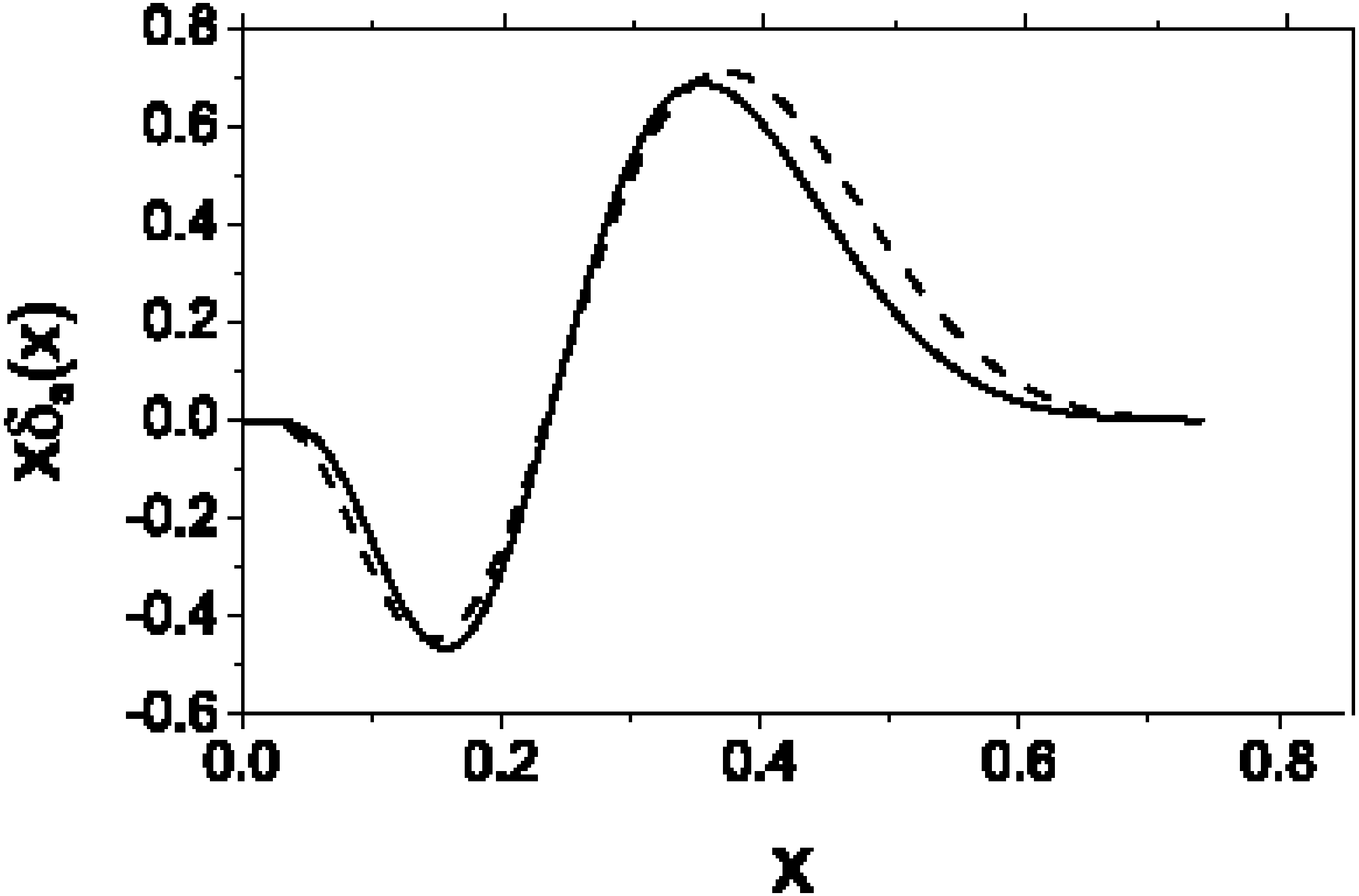
Ma, Schmidt, Yang, EPJA12(01)353

- **Our case**

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

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

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



The results for S^-

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

- 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 Qv (around a factor of 3 larger) in our model calculation, so the ratio of S^-/Qv is reasonable

Ding-Ma, PLB590 (2004) 216

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

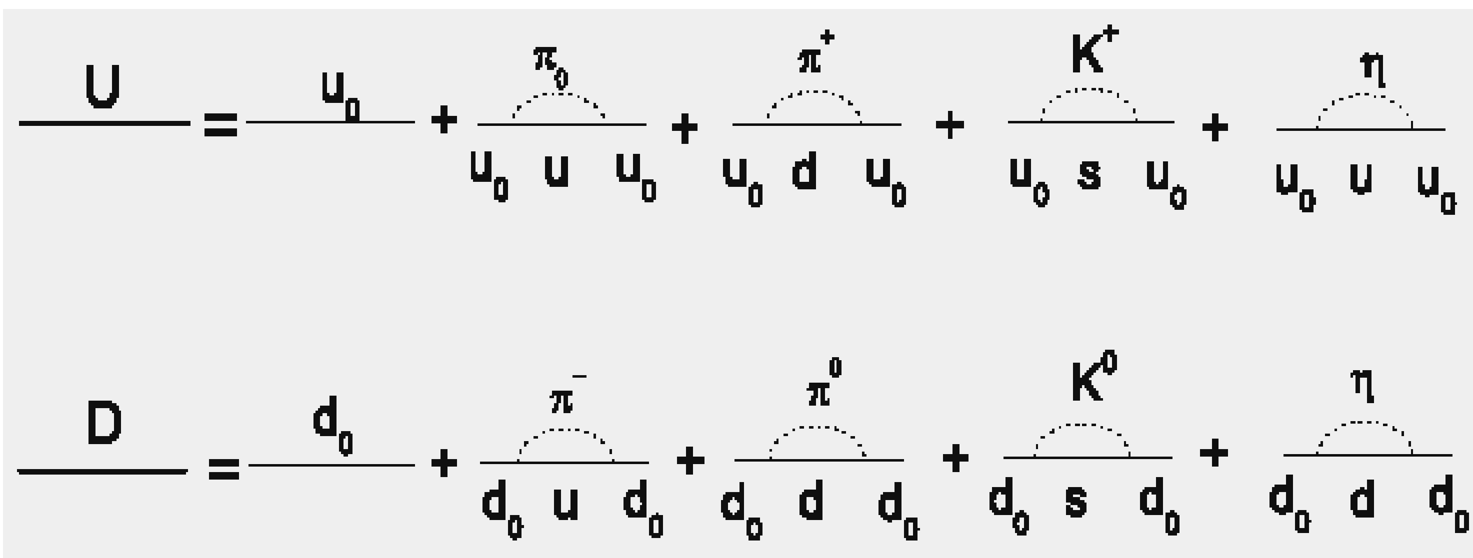
The Effective Chiral Quark Model

- 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.

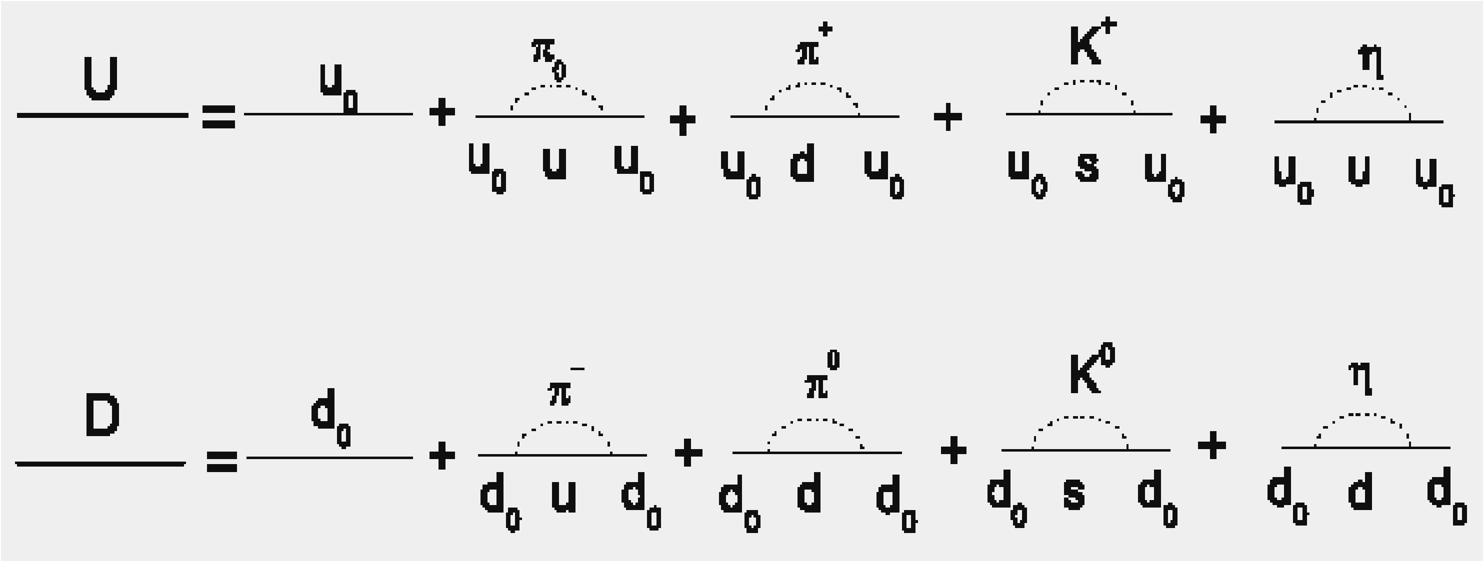
The Effective Chiral Quark Model

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

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

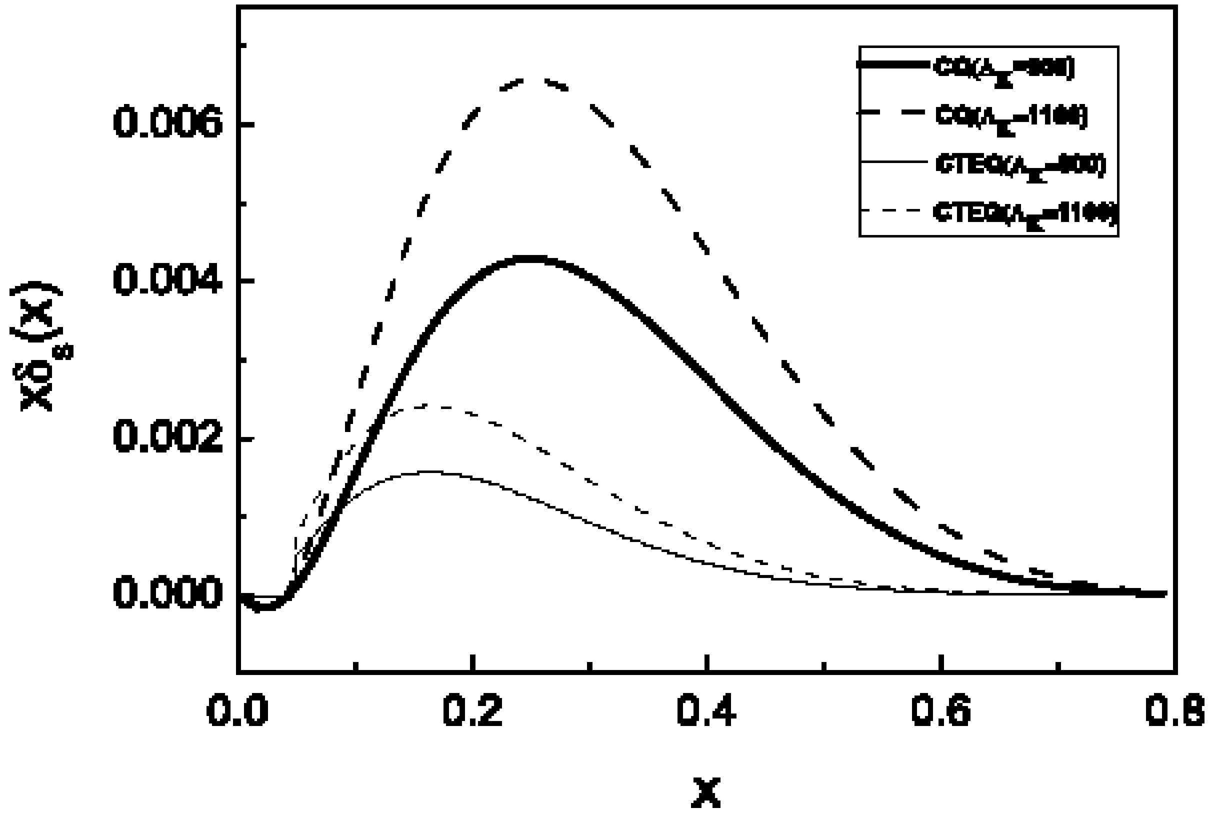


Why strange-antistrange asymmetry in the chiral quark model?



The distributions for

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



Y.Ding, R.-G.Xu, B.-Q.Ma, PLB607(2005)101

The results for different inputs within the effective chiral quark model

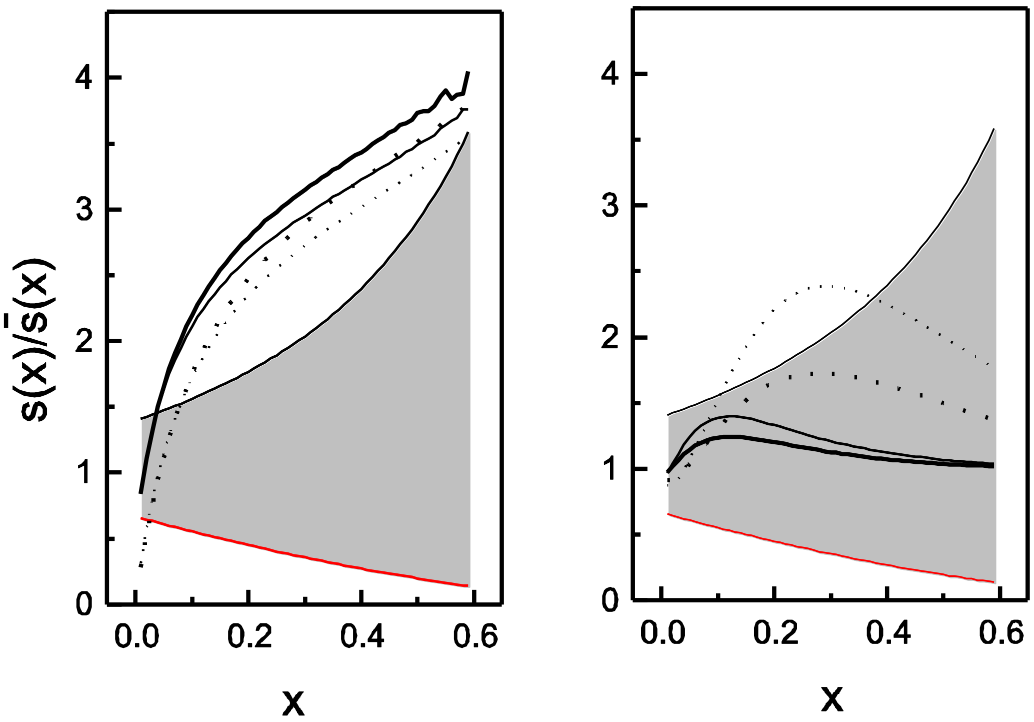
Λ_k	Z	Q_v	S^-	δR_s^-
900	0.74888	0.86376	0.00558	0.00297
1000	0.73996	0.85484	0.007183	0.00384
1100	0.73063	0.84551	0.00879	0.00473

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%

Y.Ding, R.-G.Xu, B.-Q.Ma, PRD71(2005) 094014

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

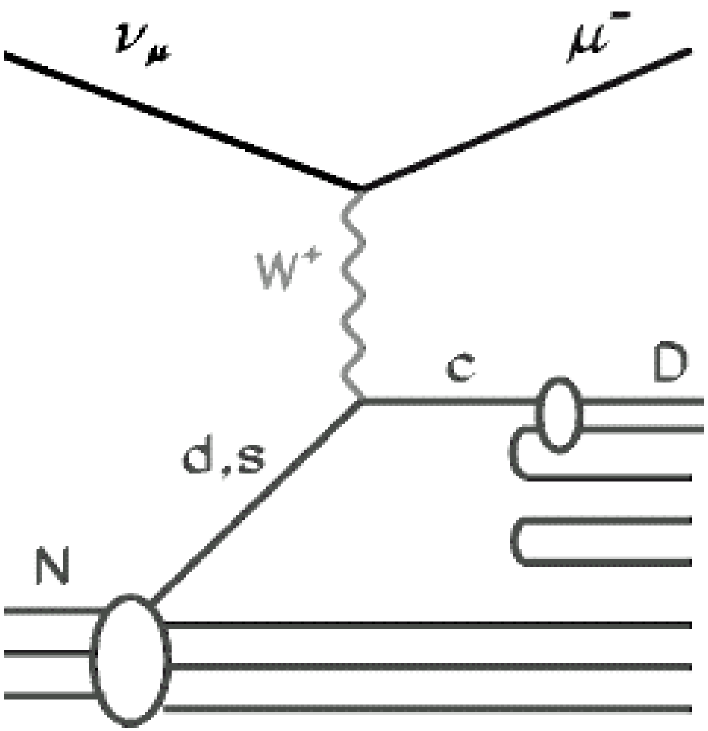
- **Wakamatsu, 70-110% correction**

  PRD71 (2005) 057504

NuTeV anomaly versus s-sbar asymmetry

- The effect due to strange-antistrange asymmetry might be important to explain the NuTeV anomoly **or** the NuTeV anomaly could be served as an evidence for the s-sbar asymmetry.
- The calculated s-sbar 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-sbar asymmetry.

Strangeness Measurment
via dimuon events by CCFR and NuTeV



50%

$$\nu_\mu + s(d) \rightarrow \mu^- + c$$

90%

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

• **Different charged dimuon signal:**

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

Dimuon measurement of strangeness asymmetry:

$$\frac{d^2\sigma_{\nu_\mu N\to\mu^-\mu^+X}}{d\xi dy} - \frac{d^2\sigma_{\overline{\nu}_\mu N\to\mu^+\mu^-X}}{d\xi dy} = \frac{G_F^2 S}{\pi r_w^2} f_c B_c$$

$$\times \left\{ \xi[s(\xi) - \overline{s}(\xi)]|V_{cs}|^2 + \frac{1}{2}\xi[d_v(\xi) + u_v(\xi)]|V_{cd}|^2 \right\};$$

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

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

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

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

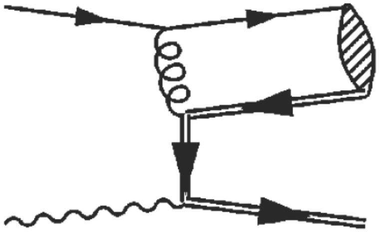
Influence of Heavy Quark Recombination

- 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)

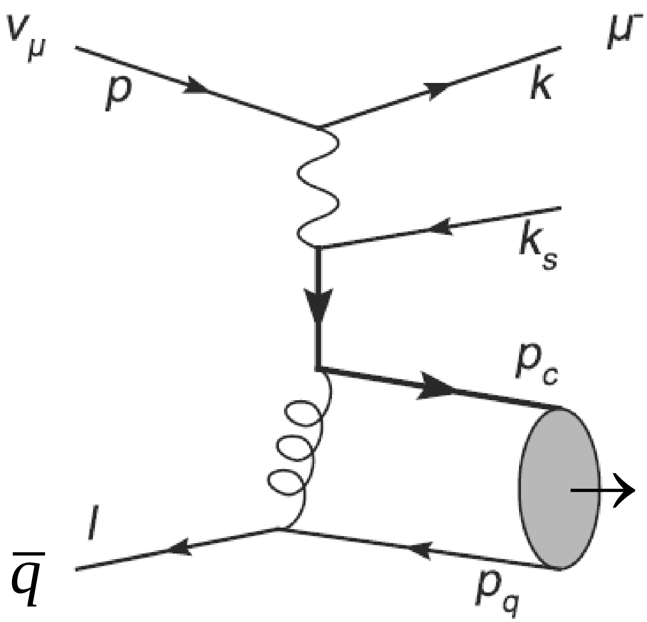
B. Leading particle effect in pi-N scattering
Braaten, Jia, Mehen,PRL89,122002(2002)

Influence on Strangeness Asymmetry Measurement

Heavy Quark Rocombination

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

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



$$\rightarrow D \rightarrow \mu^+$$

HR has an additional contribution

$$q = u, d$$

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

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

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

Influence on Strangeness Asymmetry Measurement

$$S^{-}_{\rm real}(\xi) = S^{-}_{\rm analy}(\xi) + \delta S^{-}_{\rm HR}(\xi)$$

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

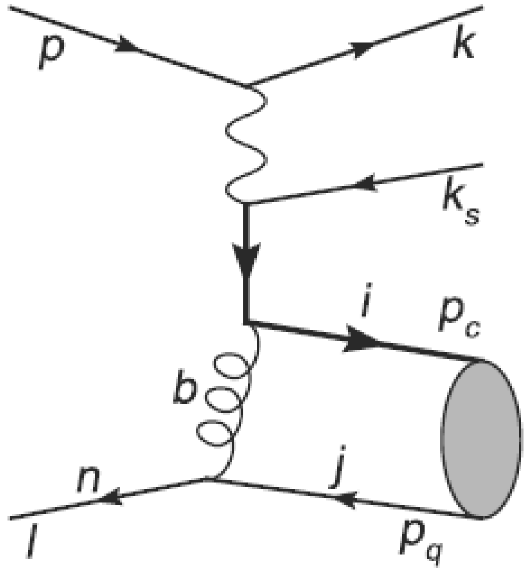
$$\delta S^{-}_{\rm HR}(\xi) > 0$$

$$S^{-}_{\rm real} \equiv \int d\xi S^{-}_{\rm real}(\xi)$$

Calculation on HR Contribution

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

color singlet ${}^1S_0$

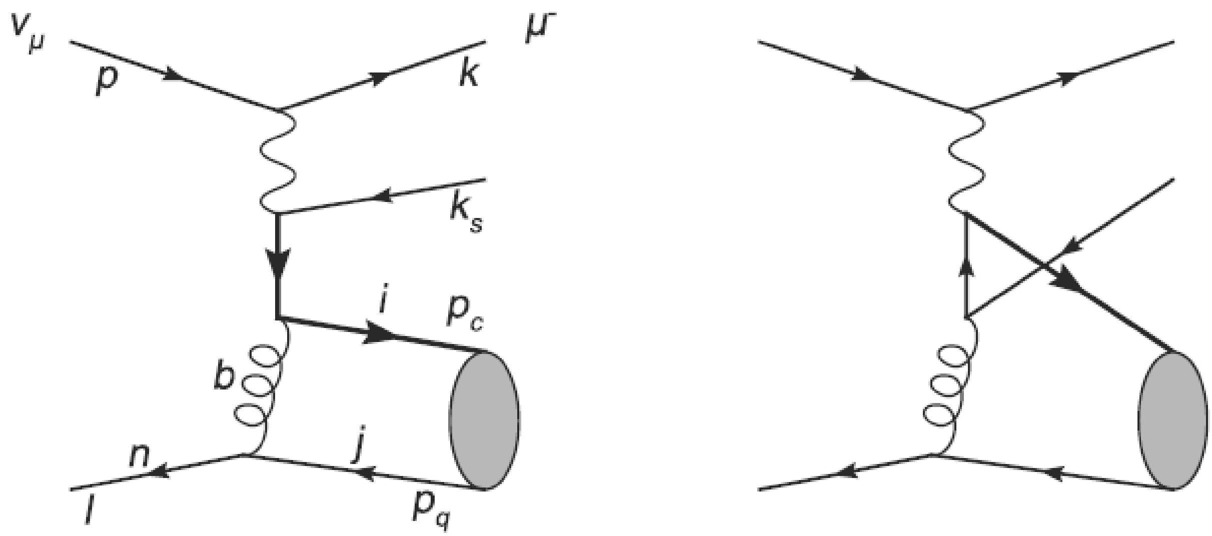


$$v_j(p_q)\overline{u}_i(p_c) \to x_q \frac{\delta_{ij}}{N_c} m_c f_+ (\not{p}_c - m_c)\gamma_5 .$$

For color octet $\delta_{ij} \to \sqrt{6} T^a_{ij}$

For ${}^3S_1$ state $\gamma_5 \to \not{\epsilon}$

Then set $p_q = x_q p_c$ and take the limit $x_q \to 0$



color singlet $^1S_0$

$$M_{in} = \frac{16\pi G_F \alpha_s m_c \delta_{in} f_+}{9\sqrt{2} r_w (2l \cdot p_c)} L^\mu \overline{u}(l)\gamma^\nu (\not{p}_c - m_c)\gamma_5$$

$$\times[\gamma_\nu \frac{\not{p} - \not{k} - \not{k}_s + m_c}{(p-k-k_s)^2 - m_c^2}\gamma_\mu(1-\gamma_5)$$

$$+\gamma_\mu(1-\gamma_5)\frac{\not{l} - \not{k}_s}{(l-k_s)^2}\gamma_\nu]v(k_s),$$

$\rho_1 = f_+^2 \qquad \rho_8 = (f_+^8)^2$ will appear in cross sections

For $^1S_0$ state

$$d\hat{\sigma}_{D(c\overline{q})} = d\hat{\sigma}[c\overline{q}(^1S_0)_1] \cdot \rho_1 + d\hat{\sigma}[c\overline{q}(^1S_0)_8] \cdot \rho_8$$

$$d\hat{\sigma}_{D(c\overline{q})} = d\hat{\sigma}[c\overline{q}(^1S_0)_1] \cdot \rho_{\text{eff}}[c\overline{q}(^1S_0) \to D(c\overline{q})],$$

with $\rho_{\text{eff}} = \rho_1 + \rho_8/8.$

For $^3S_1$ state

$$d\hat{\sigma}_{D^*(c\overline{q})} = d\hat{\sigma}[c\overline{q}(^3S_1)_1] \cdot \rho_{\text{eff}}[c\overline{q}(^3S_1) \to D^*(c\overline{q})]$$

such transitions as $c\overline{q}(^1S_0) \to D^*(c\overline{q})$ and $c\overline{u} \to D^+(c\overline{d})$ are neglected

Calculation on HR Contribution

heavy quark spin symmetry implies

$$\rho_{\rm eff}[c\bar{q}(^1S_0) \to D(c\bar{q})] = \rho_{\rm eff}[c\bar{q}(^3S_1) \to D^*(c\bar{q})],$$

flavor symmetry indicates

$$\rho_{\rm eff}[c\bar{u}(^1S_0) \to D^0] = \rho_{\rm eff}[c\bar{d}(^1S_0) \to D^+]$$

Thus, only one parameter is left:

$$\begin{aligned}\rho_{\rm sm} &\equiv \rho_{\rm eff}[c\bar{d}(^1S_0) \to D^+] = \rho_{\rm eff}[c\bar{d}(^3S_1) \to D^{*+}] \\ &= \rho_{\rm eff}[c\bar{u}(^1S_0) \to D^0] = \rho_{\rm eff}[c\bar{u}(^3S_1) \to D^{*0}].\end{aligned}$$

sm=spin-matched, sf=spin-flipped

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

$$\delta S^-_{\rm HR}(\xi) \approx \frac{\pi r_w^2}{G_F^2 S f_c |V_{cs}|^2 B_c} \int dx [u_v(x) + d_v(x)] \times \left[\frac{d\hat{\sigma}[c\overline{q}(^1S_0)_1]}{d\xi dy} b_1 + \frac{d\hat{\sigma}[c\overline{q}(^3S_1)_1]}{d\xi dy} b_2 \right] \cdot \rho_{\rm sm},$$

where $b_1 = (B_{D^+} + B_{D^0})/2$ and $b_2 = (B_{D^{*+}} + B_{D^{*0}})/2$

经过振幅平方，初态自旋颜色平均，末态求和，再相空间变换，积分，可以计算 $\delta S^-_{\rm HR}(\xi)$

P.Gao&B.-Q.Ma, PRD77(08)054002.

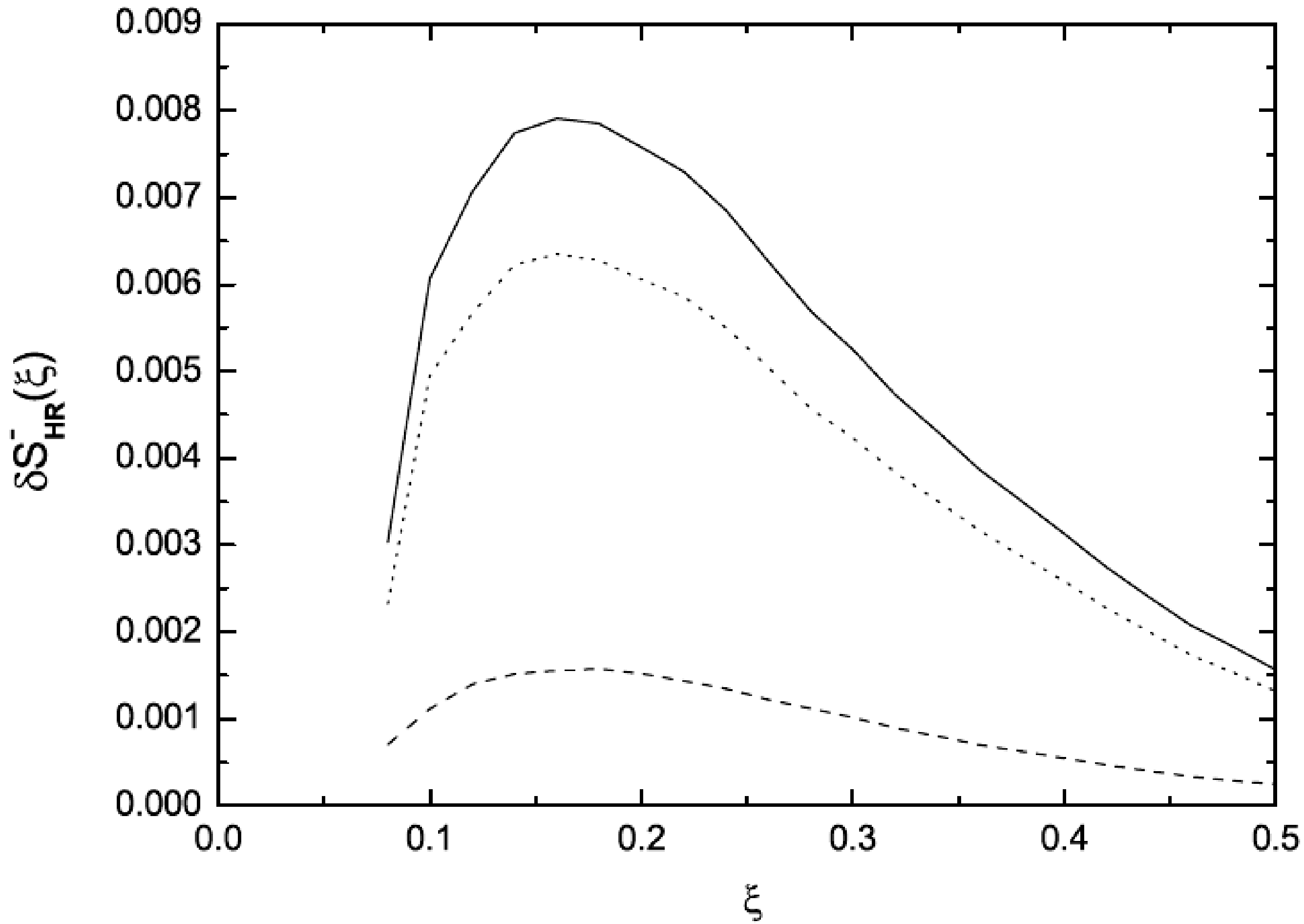


FIG. 2: $\delta S^-_{\rm HR}(\xi)$ for $E_\nu = 160$ GeV, $Q^2 = 20$ GeV and $\rho_{\rm sm} = 0.15$. The dashed curve is the contribution from ${}^1S_0$ state; the dotted curve is the contribution from ${}^3S_1$ state; and the solid curve is their sum, the $\delta S^-_{\rm HR}(\xi)$.

$$\delta S^-_{\rm HR} \approx 0.0023 \qquad \text{for} \qquad \rho_{\rm sm} = 0.15$$

$$S^-_{\rm real} = S^-_{\rm analy} + \delta S^-_{\rm HR}$$

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

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

the central value of the realistic strangeness asymmetry should be $S^-_{\rm real} \approx 0.0043$.

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

NuTeV central value $\sin^2\theta_W^{\text{(on shell)}} = 0.2277$

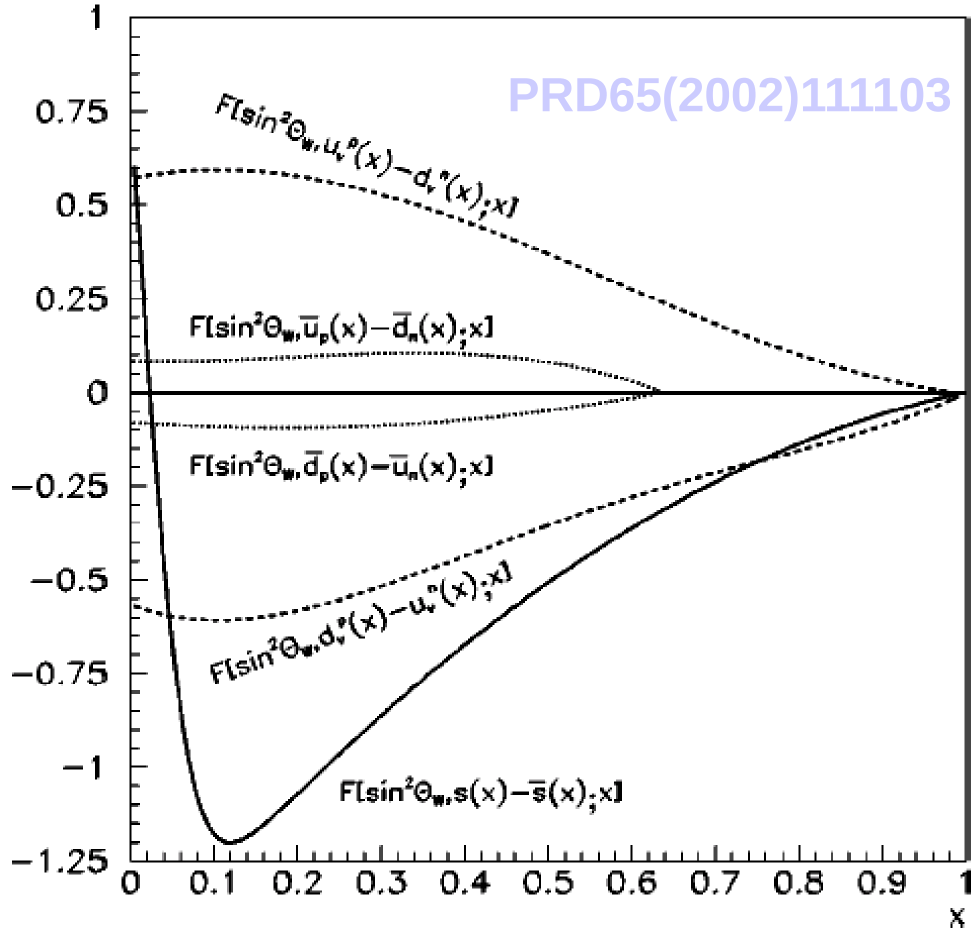
3 standard deviations above the expected value of 0.2227 ± 0.0004

nonzero $S^-(\xi)$ to the result of $\sin\theta_w$ is most sensitive in the range $\xi = 0.06 - 0.3$

S^- of the order 0.005 large enough to explain NuTeV anomaly

$\delta S^-_{\text{HR}} \approx 0.0023$

alone can provide nearly half



The functionals describing the shift in the NuTeV $\sin^2\theta_W$

Some uncertainties

$\rho_{\rm sm} = 0.15$, From charm photoproduction asymmetry

at least 30% uncertainty due to finite heavy quark mass, SU(3) breaking and $1/N_c$ corrections

should be multiplied by a K factor if NLO corrections in photo-gluon fusion are incorporated

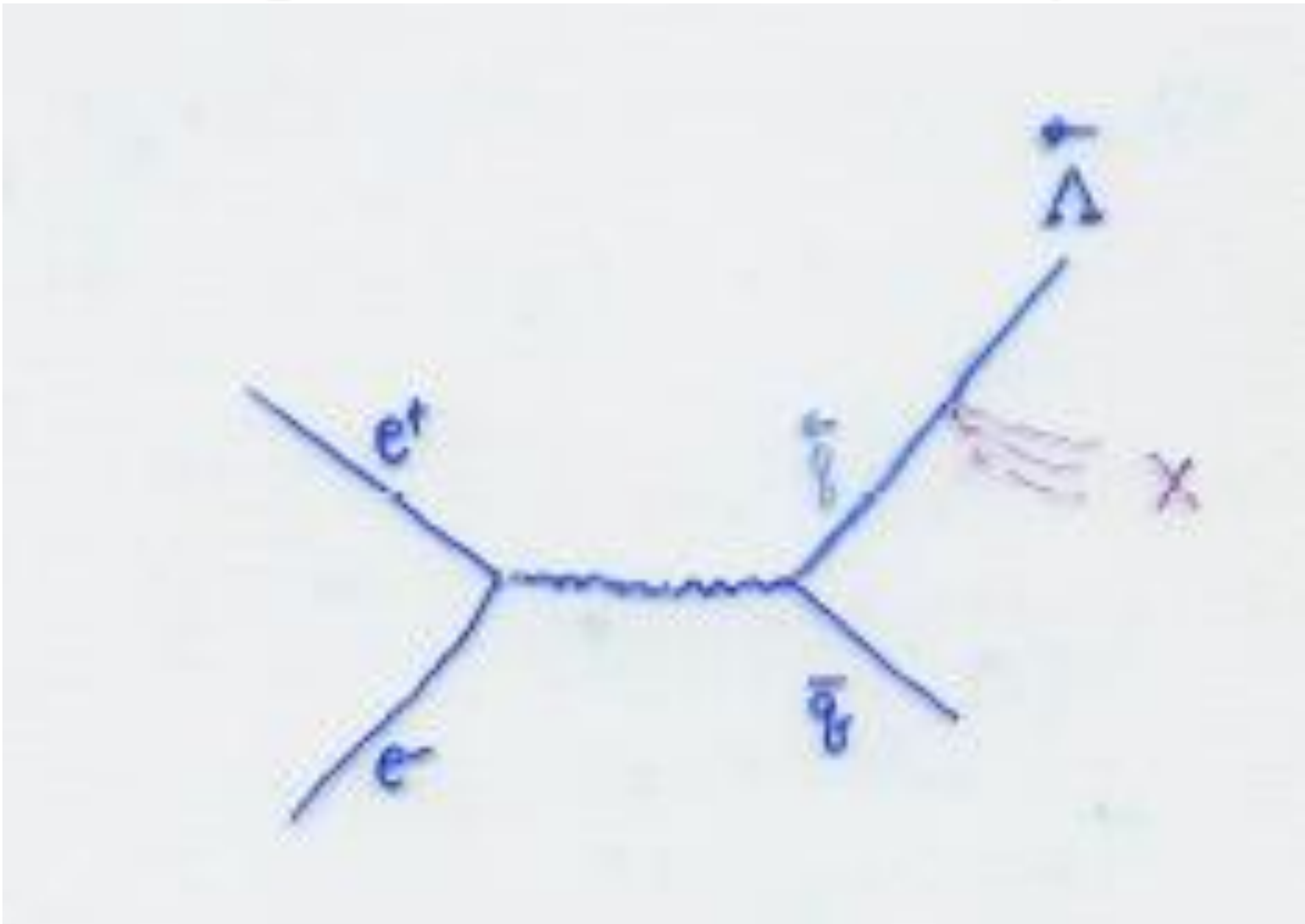
$\rho_{\rm sm}$ could well be as large as 0.3. $\delta S^-_{\rm HR} \approx 0.0046$

This alone is enough to explain the NuTeV anomaly

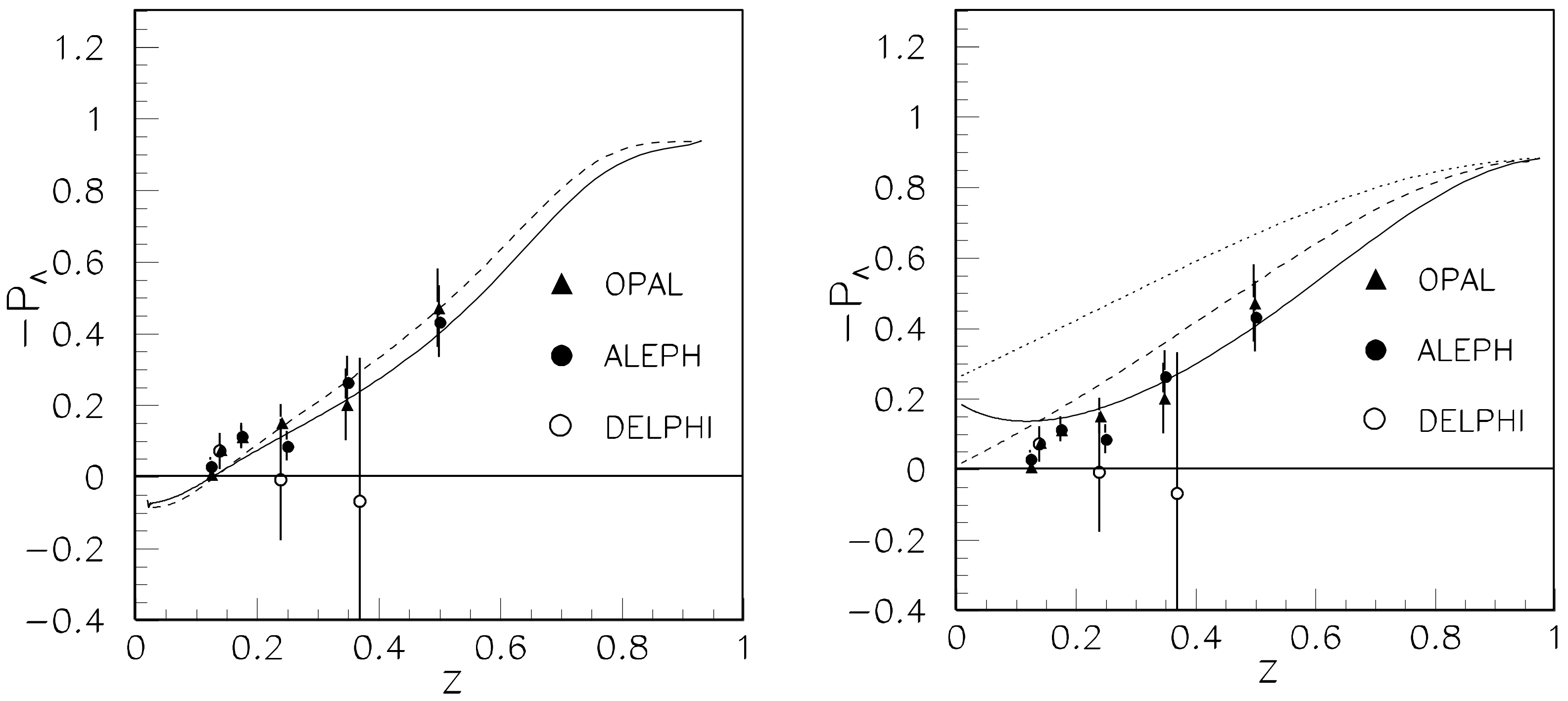
$\rho_{\rm sm}$ could also be smaller than 0.15, $\rho_1 = 0.06$ from the leading particle effect, if take $\rho_{\rm sm} = 0.06$, we get $\delta S^-_{\rm HR} \approx 0.0009$.

This $\delta S^-_{\rm HR}$ alone is not enough to explain NuTeV anomaly, however, could still shift the measured value S^- to a entirely positive range.

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

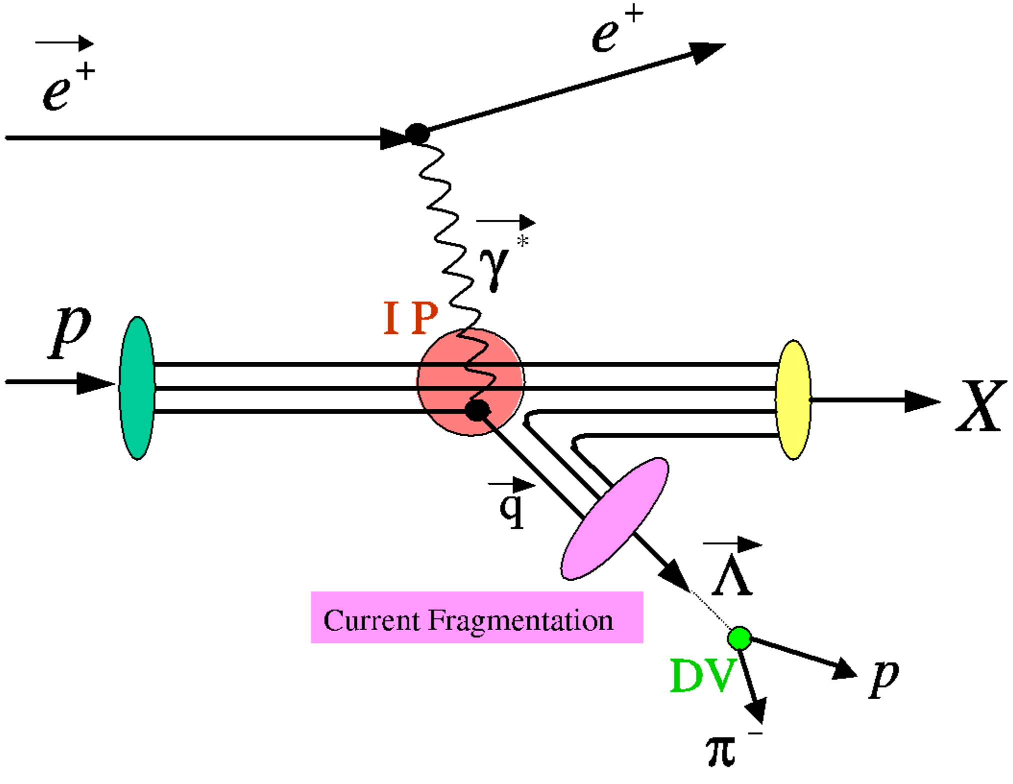


Diquark model and pQCD results

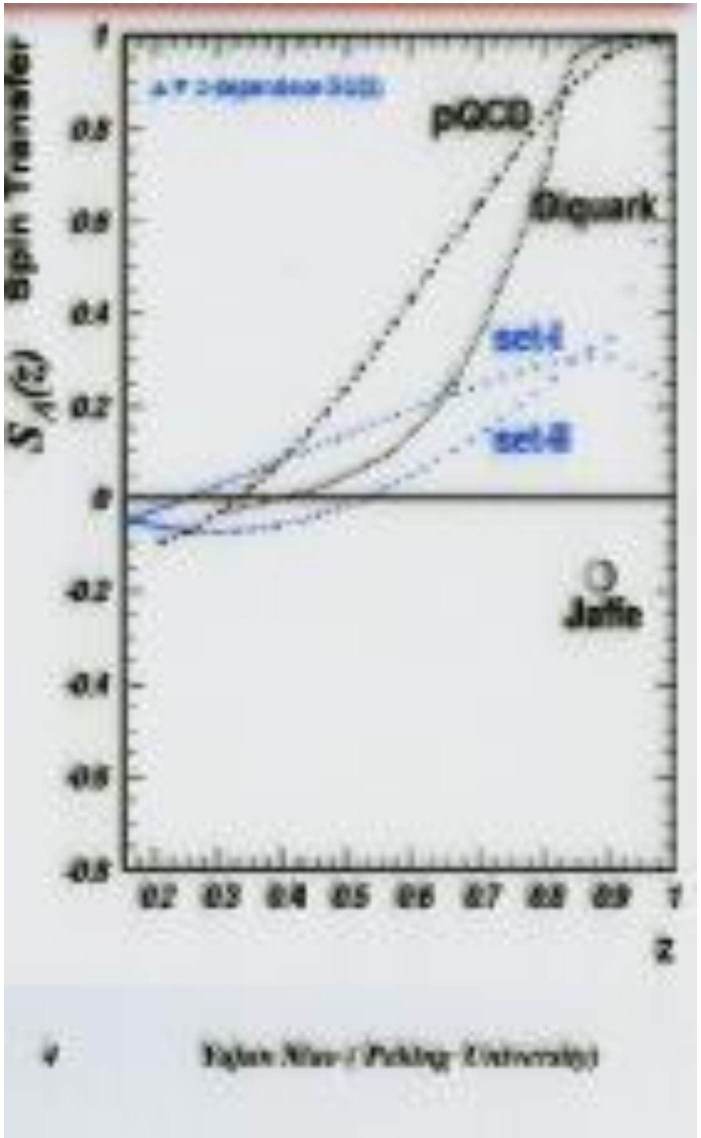


B.-Q. Ma, I. Schmidt, J.-J. Yang, Phys. Rev. D 61 (2000) 034017

Spin Transfer to Λ in Semi-Inclusive DIS

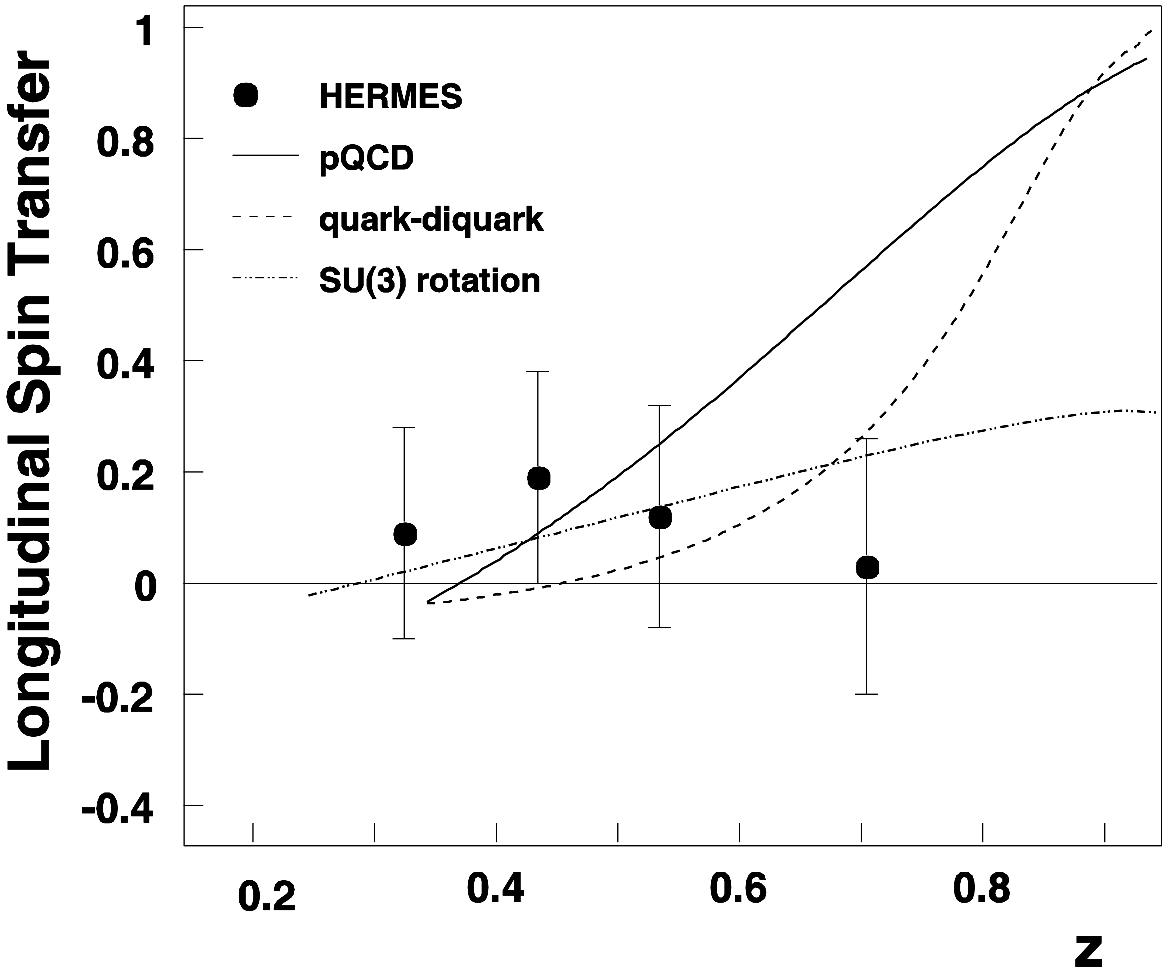


Different predictions

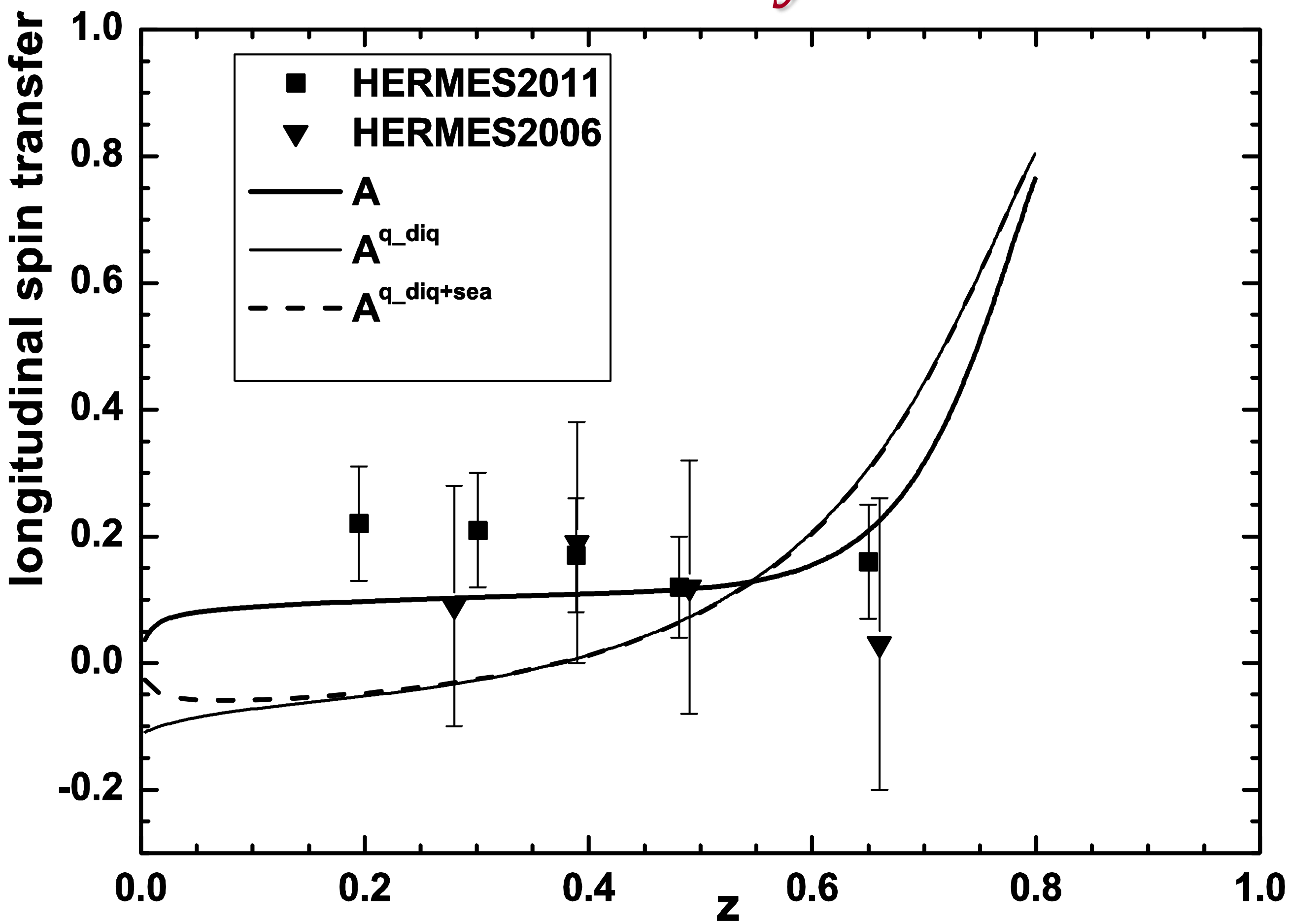


B.-Q. Ma, I. Schmidt, J.-J. Yang,
Phys. Lett. B 477 (2000) 107

Comparison with data

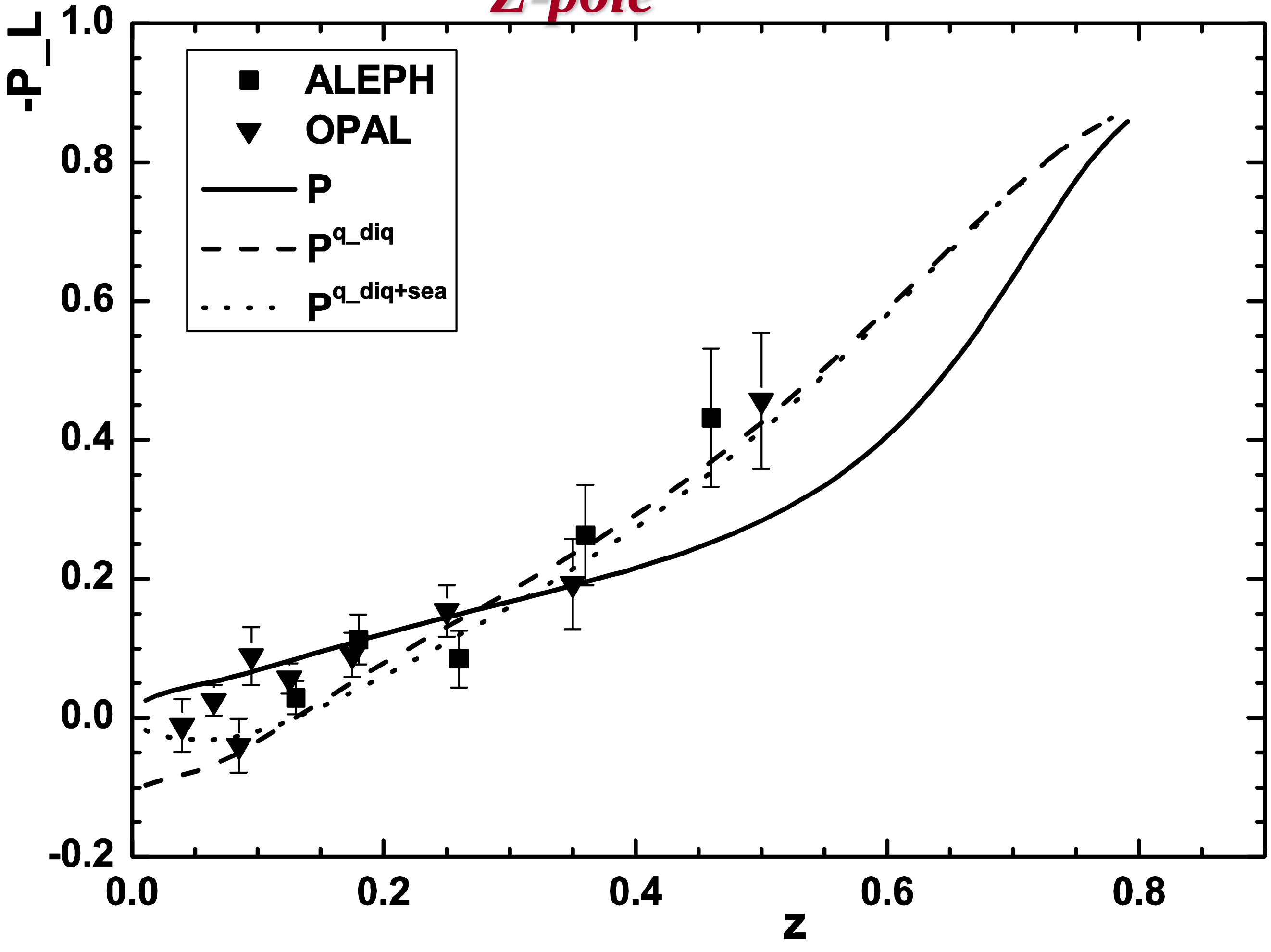


New results including both unfavored and indirect decays: SIDIS



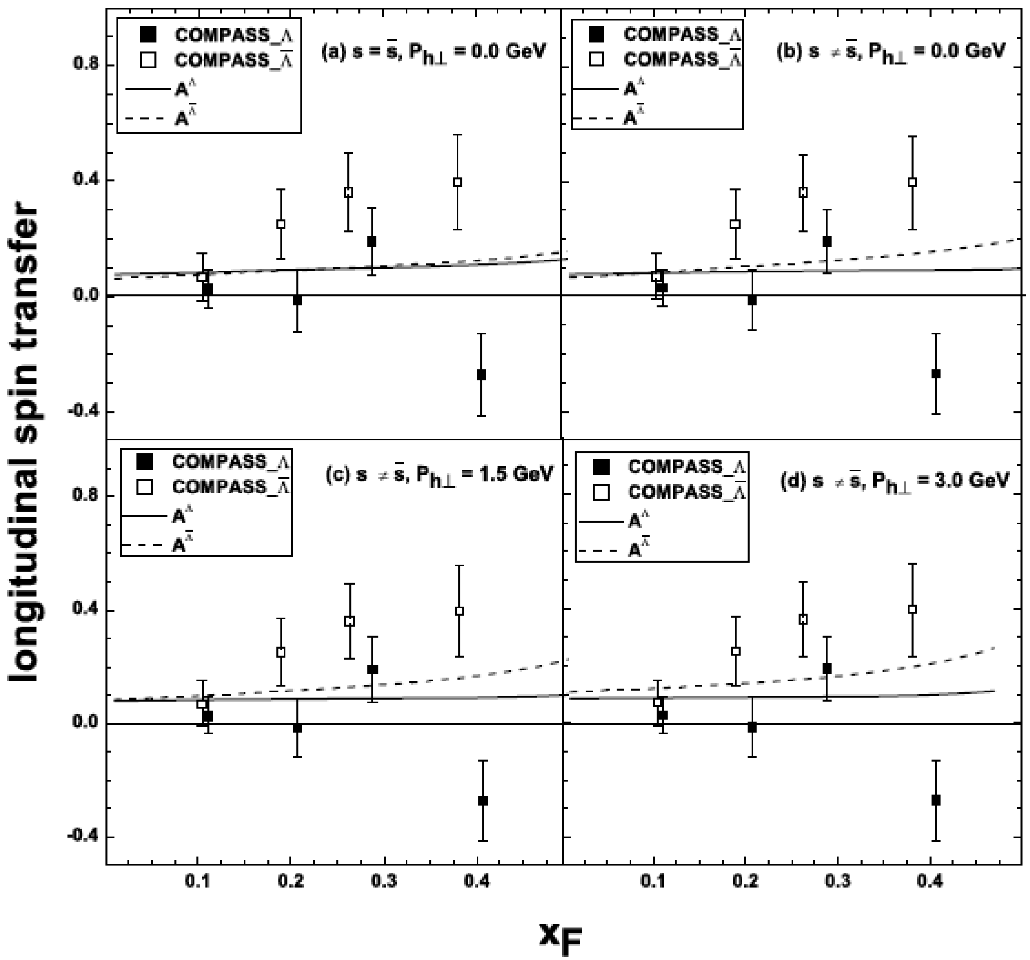
Y.Chi, B.-Q. Ma, Phys.Lett.B 726 (2013) 737

New results including both unfavored and indirect decays: Z-pole



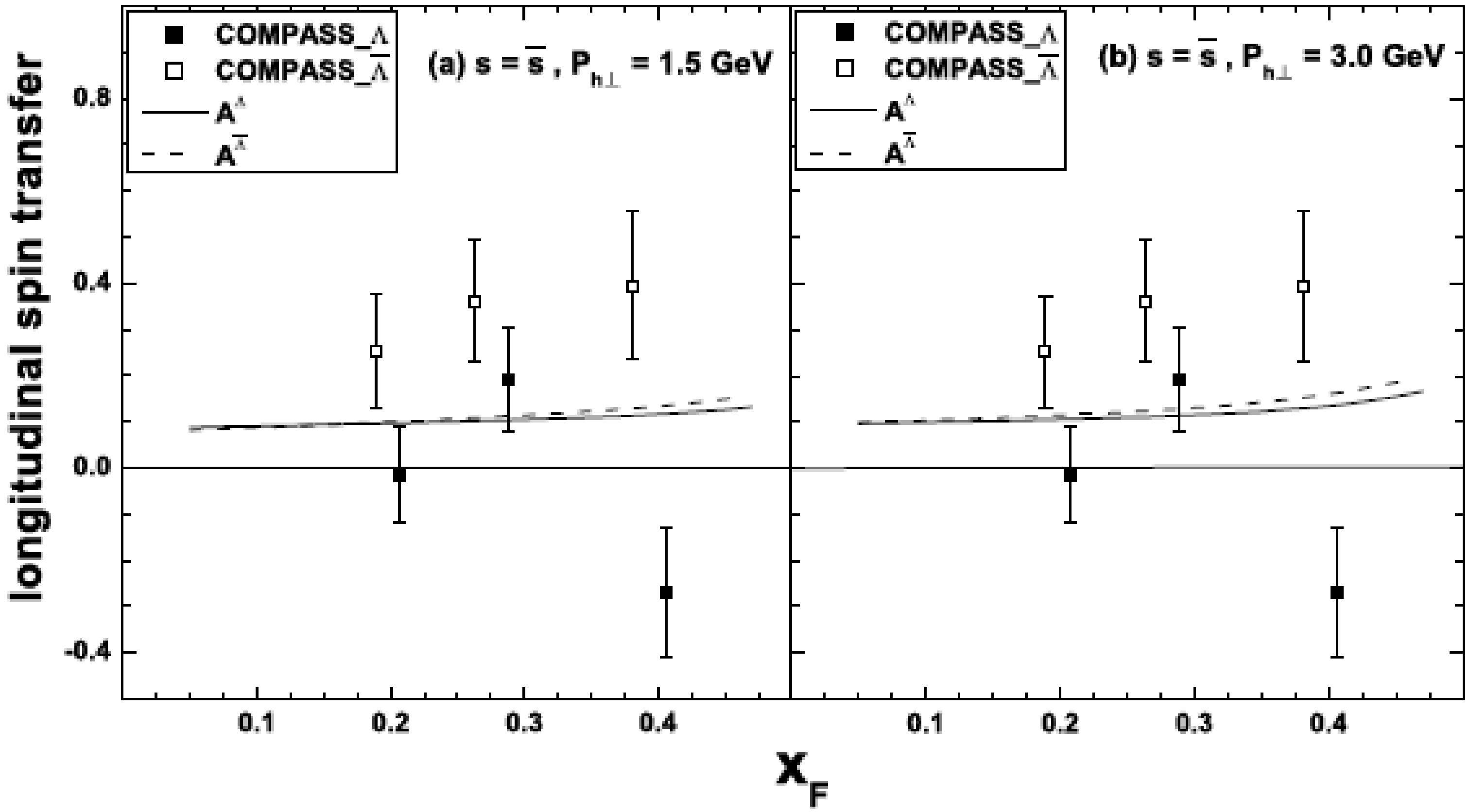
Y.Chi, B.-Q. Ma, Phys.Lett.B 726 (2013) 737

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



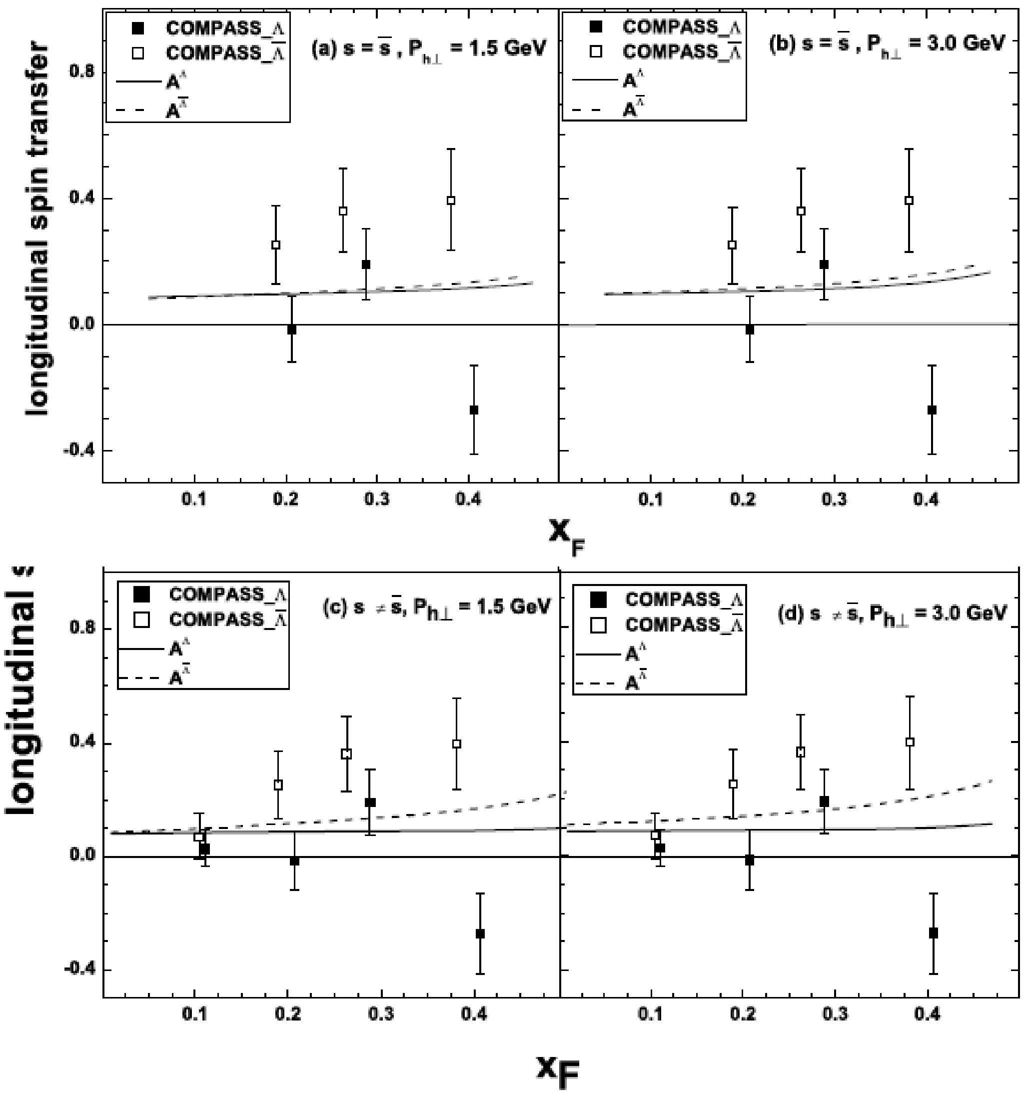
Y.Chi, X.Du, B.-Q. Ma, to appear

Difference between Lambda and anti-Lambda spin transfers without s-sbar asymmetry



Y.Chi, X.Du, B.-Q. Ma, to appear

Difference between Lambda and anti-Lambda spin transfers with s-sbar asymmetry



Y.Chi, X.Du, B.-Q. Ma, to appear

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.