Symmetry breaking and determination of parton distribution functions of the nucleon

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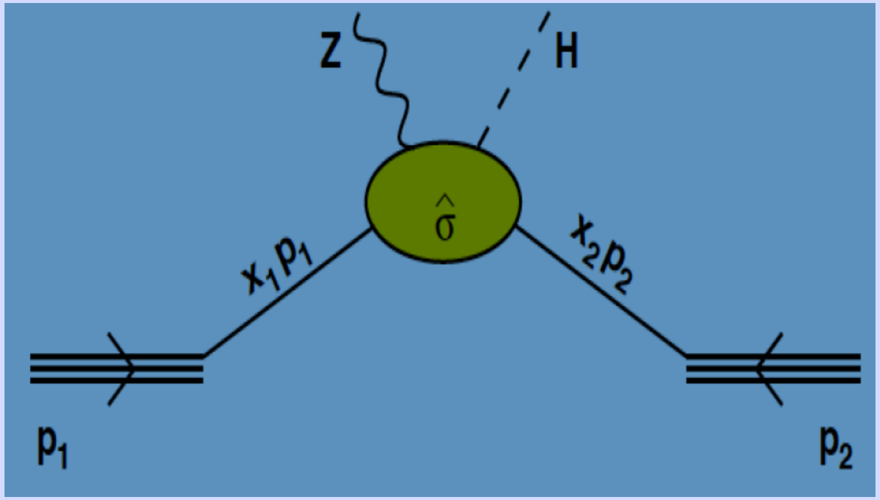
1. Symmetries in the PDFs
   - flavour symmetry, quark-antiquark symmetry
   - charge symmetry
2. Symmetry breaking in the meson cloud model
3. Strange distributions of the nucleon
4. Summary

1. Introduction

- Parton distribution functions are non-perturbative inputs in higher-energy hardon processes.



QCD factorization theorem

$$\sigma = \int dx_1\, dx_2 f_{q/p}(x_1, \mu^2)\hat{\sigma}(x_1 p_1, x_2 p_2, \mu^2) f_{q/p}(x_2, \mu^2)$$

Total X-section is factorized into a hard part, $\hat{\sigma}(x_1 p_1, x_2 p_2, \mu^2)$, and soft parts, $f_{q/p}(x_1, \mu^2)$, and $f_{q/p}(x_2, \mu^2)$.

- PDFs are key ingredients for Tevatron and LHC phenomenology, e.g. Higgs electroweak couplings.

- Introduced by Feynman (1969) in the parton model; interpreted as probability distributions
- Universal distributions containing long-distance structure of hadrons; related to parton model distributions at leading order, but with logarithmic scaling violations

$q(x,Q^2) = q^{\uparrow}(x,Q^2) + q^{\downarrow}(x,Q^2)$ unpolarized PDFs

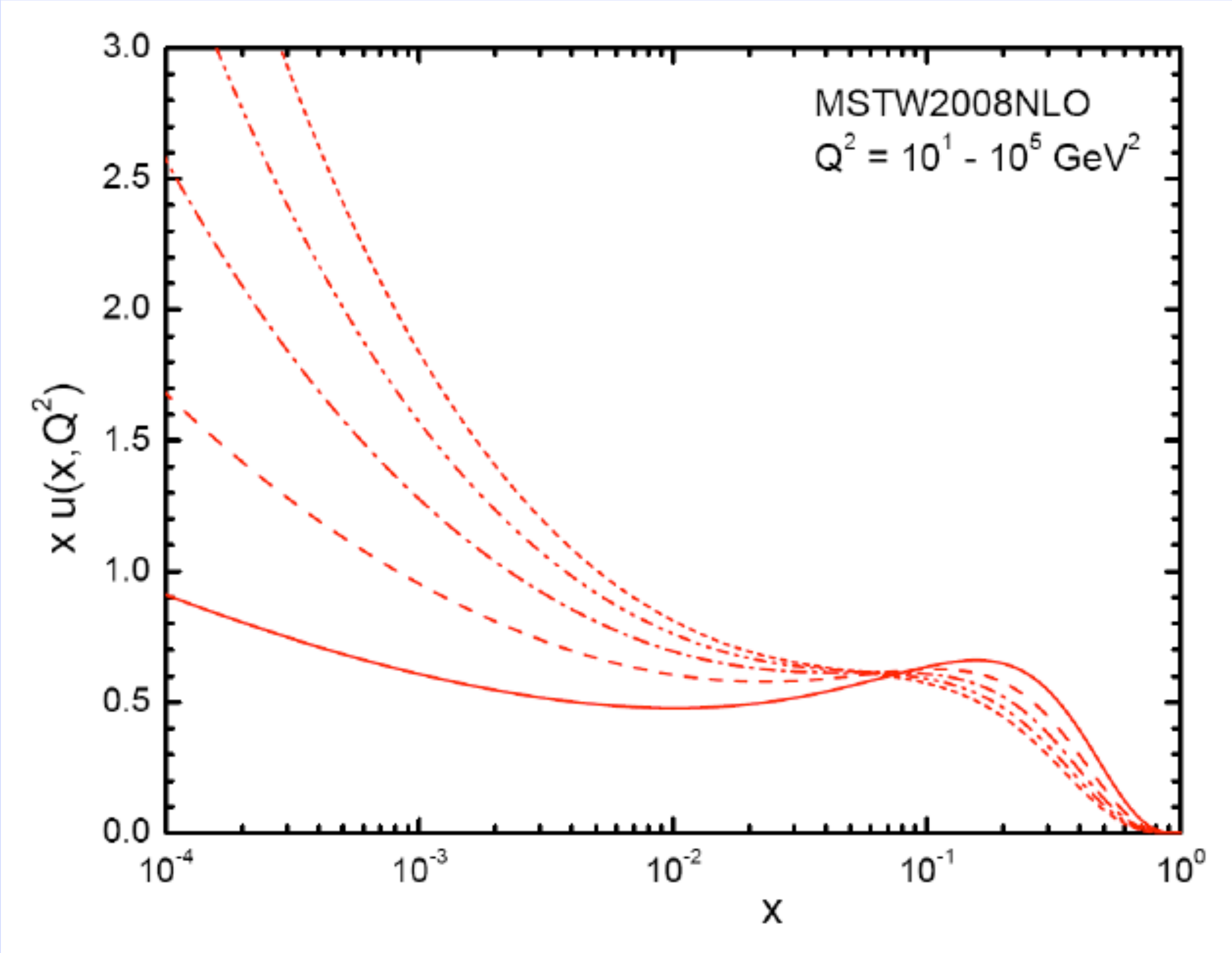
$\Delta q(x,Q^2) = q^{\uparrow}(x,Q^2) - q^{\downarrow}(x,Q^2)$ longitudinally ploarized PDFs and transversely polarized PDFs

$q^{\uparrow}(x,Q^2), q^{\downarrow}(x,Q^2)$:

number densities of quarks whose spin orientation is parallel and antiparallel to the longitudinal spin direction of the nucleon

x: the fractional parton momentum

- Q^2-dependence is determined by the DGLAP eq.



- NuTeV anomaly

Neutrino-nucleon deep inelastic processes and the measurement of $\sin^2\theta_W$

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

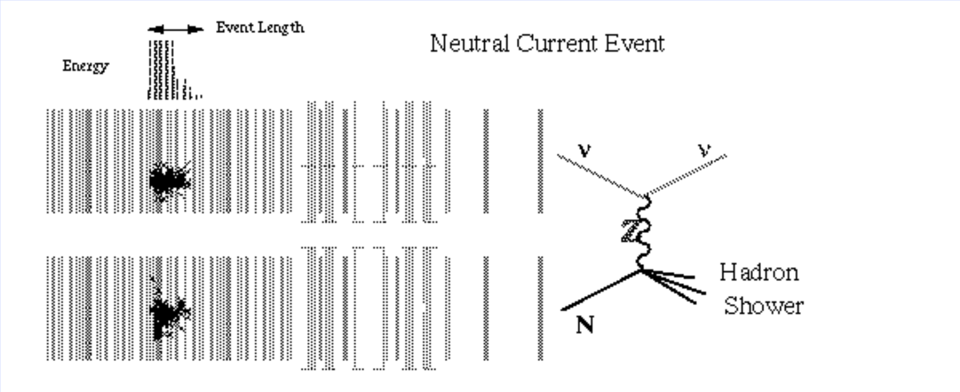
World Average: 0.2227 ± 0.0004

2% difference ➔ 3σ discrepancy →

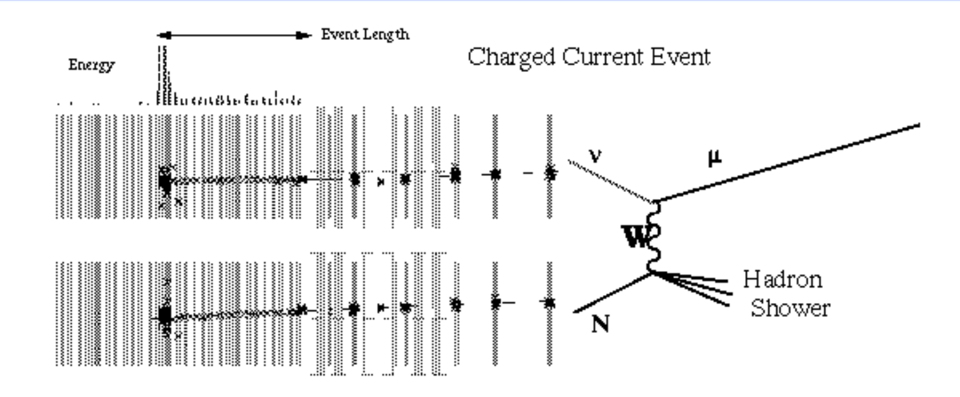
The probability that it is consistent with the expected result is only about 1 in 400

The NuTeV Experiment

- Two processes occur



Neutral current process:
- A neutrino collides with a nucleon and stays a neutrino.
- Z is exchanged
- See nothing leaving



Charged current process:
- A neutrino collides with a nucleon and turns into a muon.
- W is exchanged
- See muons leaving

- QCD corrections to the Paschos-Wolfenstein ratio

$$R^{-} = \frac{\sigma_{NC}^{\nu} - \sigma_{NC}^{\bar{\nu}}}{\sigma_{CC}^{\nu} - \sigma_{CC}^{\bar{\nu}}} = \frac{1}{2} - \sin^2\theta_W + 1.3\left[\frac{1}{2}\left(\langle \delta u\rangle - \langle \delta d\rangle\right) - \left(\langle s\rangle - \langle \bar{s}\rangle\right)\right]$$

$\delta u = u^p - d^n; \quad \delta d = d^p - u^n$ Charge symmetry breaking

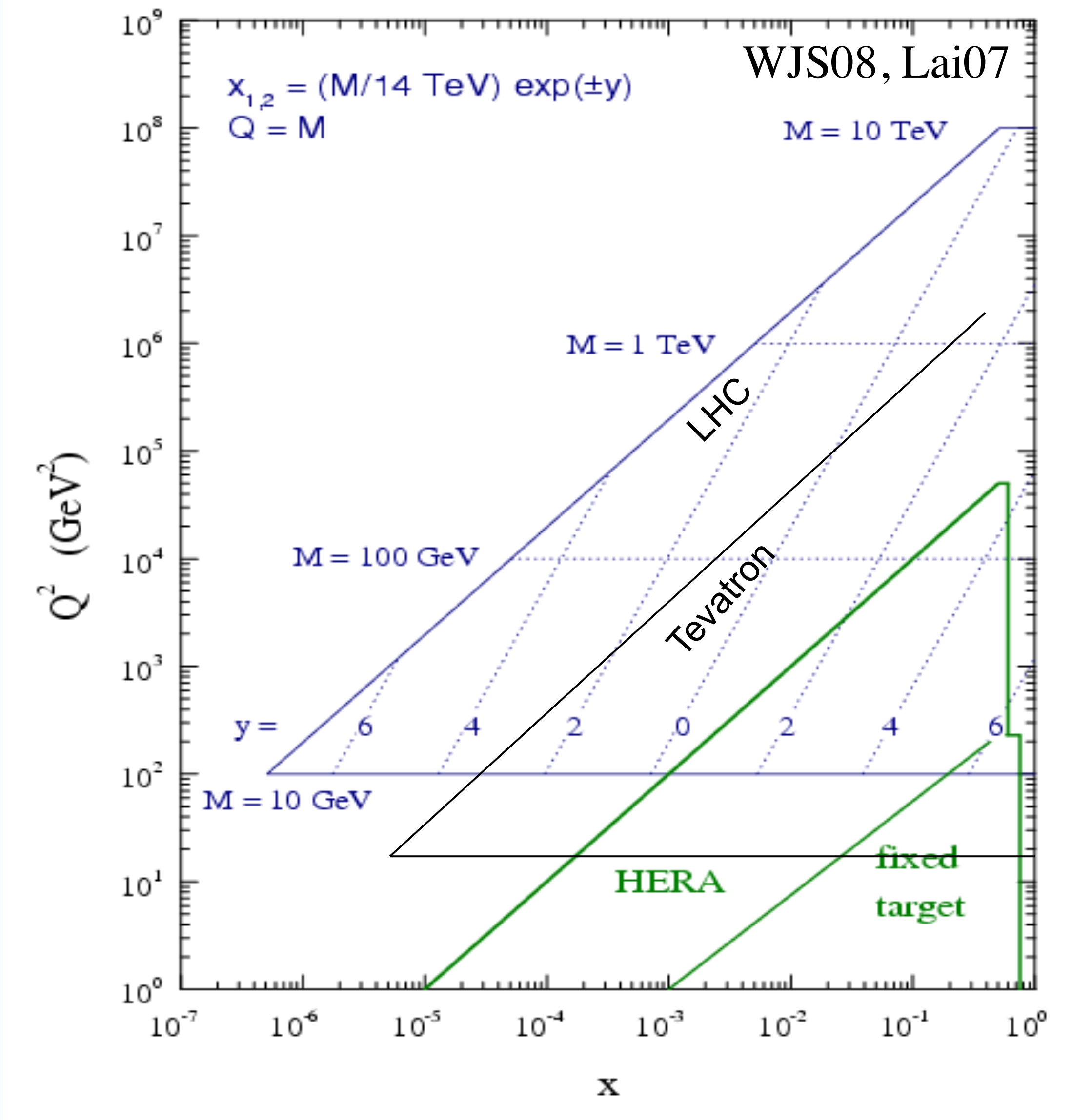
$\langle s\rangle = \int_0^1 dx\, x\, s(x); \quad \langle \bar{s}\rangle = \int_0^1 dx\, x\, \bar{s}(x)$ s-sbar asymmetry

[…]=−0.0038 is needed to explain the NuTeV anomaly

- No well established experimental evidence for these symmetry breakings
- Models to break these symmetries are known, e.g. the Meson Cloud Model

- The LHC will measure the PDFs in as yet unexplored kinematic regions of small x and high Q^2.

- Understanding the PDFs are important to the discovery of New Physics at the LHC.

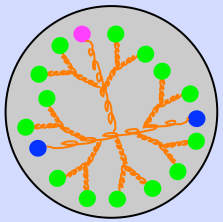


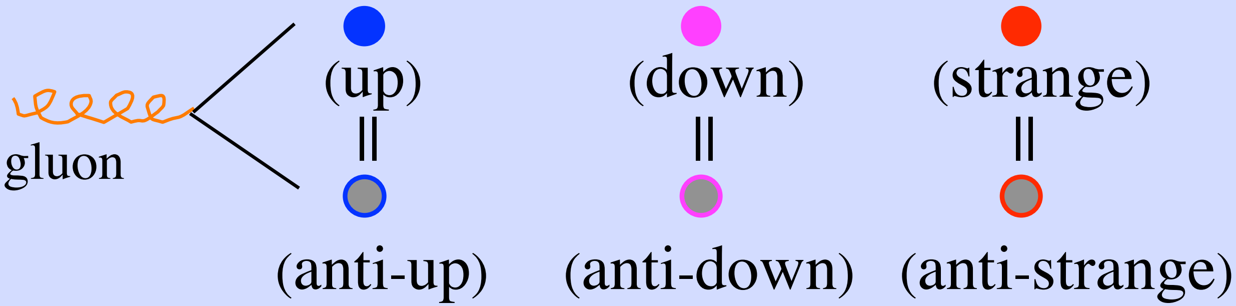
- Determination of the PDFs of the Nucleon
  - Determined via a global fit of experimental data
    - Certain function forms are assumed at an initial scale (but not in neutral network methods)
    - QCD evolution equations give PDFs at different scales
    - Comparing theoretical calculations with experimental measurements for various processes
  - Can be calculated using various quark models
- Distributions for the sea quarks are not well determined

Sea quarks: $\bar{u}, \bar{d}, s, \bar{s}, c, \bar{c}, b, \bar{b}$

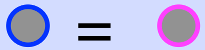
- Generation of the nucleon sea

Perturbative mechanism for the nucleon sea



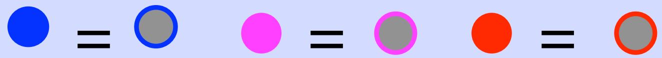


Flavour symmetry



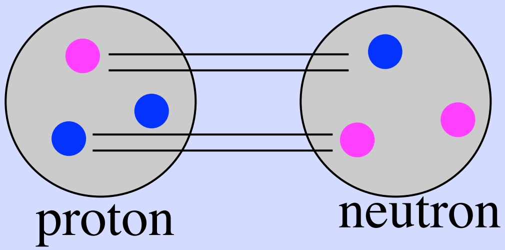
$(\bar{u} = \bar{d})$

Quark-antiquark symmetry



$(q = \bar{q})$

Charge symmetry



$$\begin{pmatrix} d^p = u^n \\ u^p = d^n \end{pmatrix}$$

Non-perturbative mechanism for the nucleon sea

→ Meson cloud model $\left|\pi^+ n\right\rangle > \left|\pi^- \Delta^{++}\right\rangle$

→ Pauli blocking

→ Chiral perturbation theory

$$u \to d\,\pi^+, \quad d \to u\pi^-$$

→ Chiral quark-soliton model

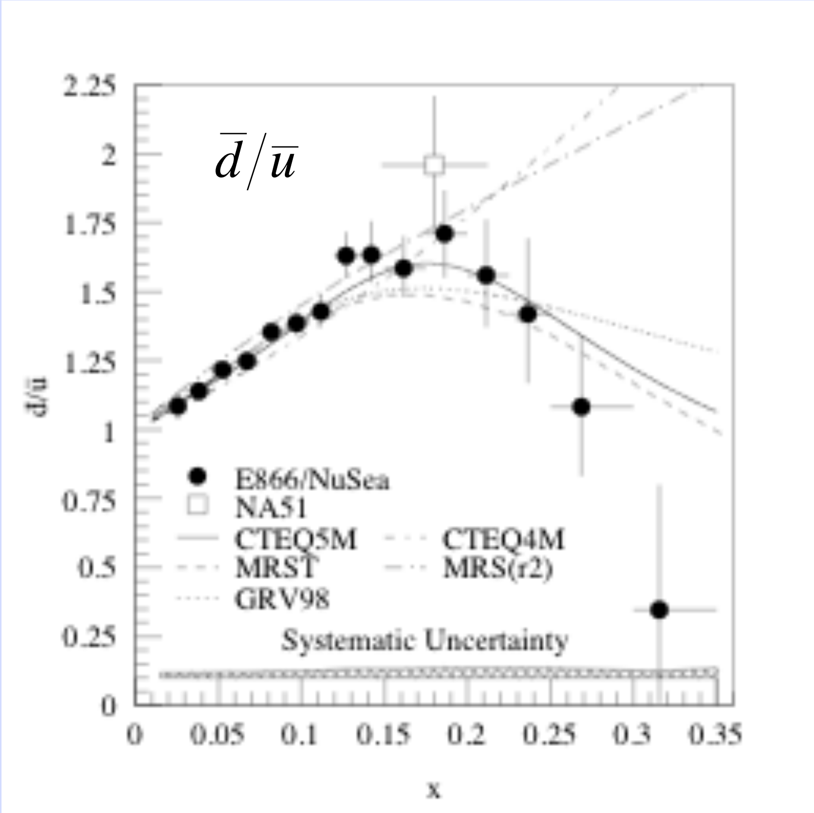
$$\bar{d} - \bar{u} = N_c f(xN_c)$$

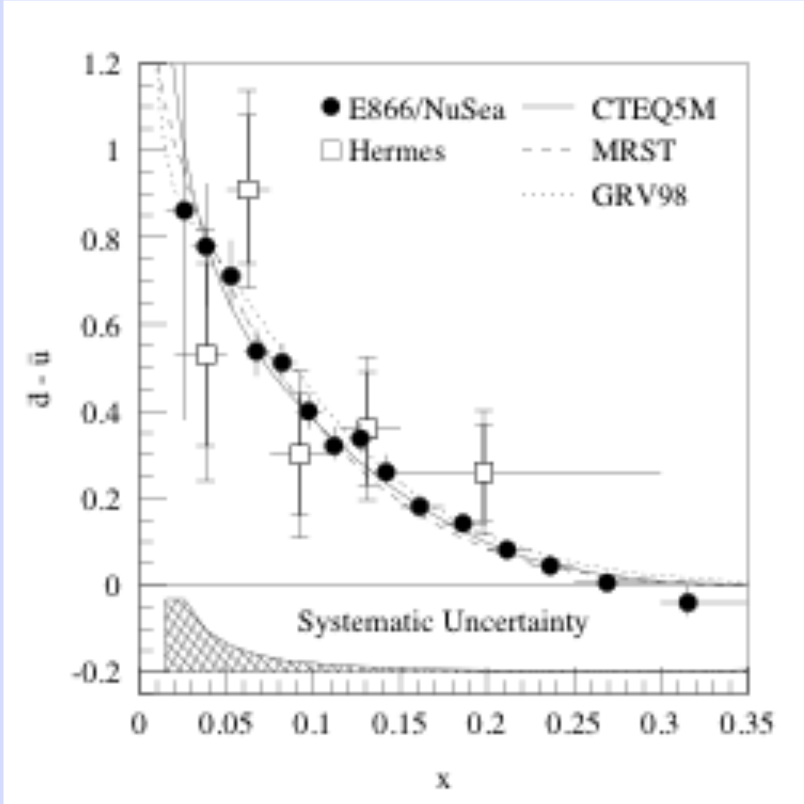
→ Instanton model

→ Isospin breaking

Break symmetries!

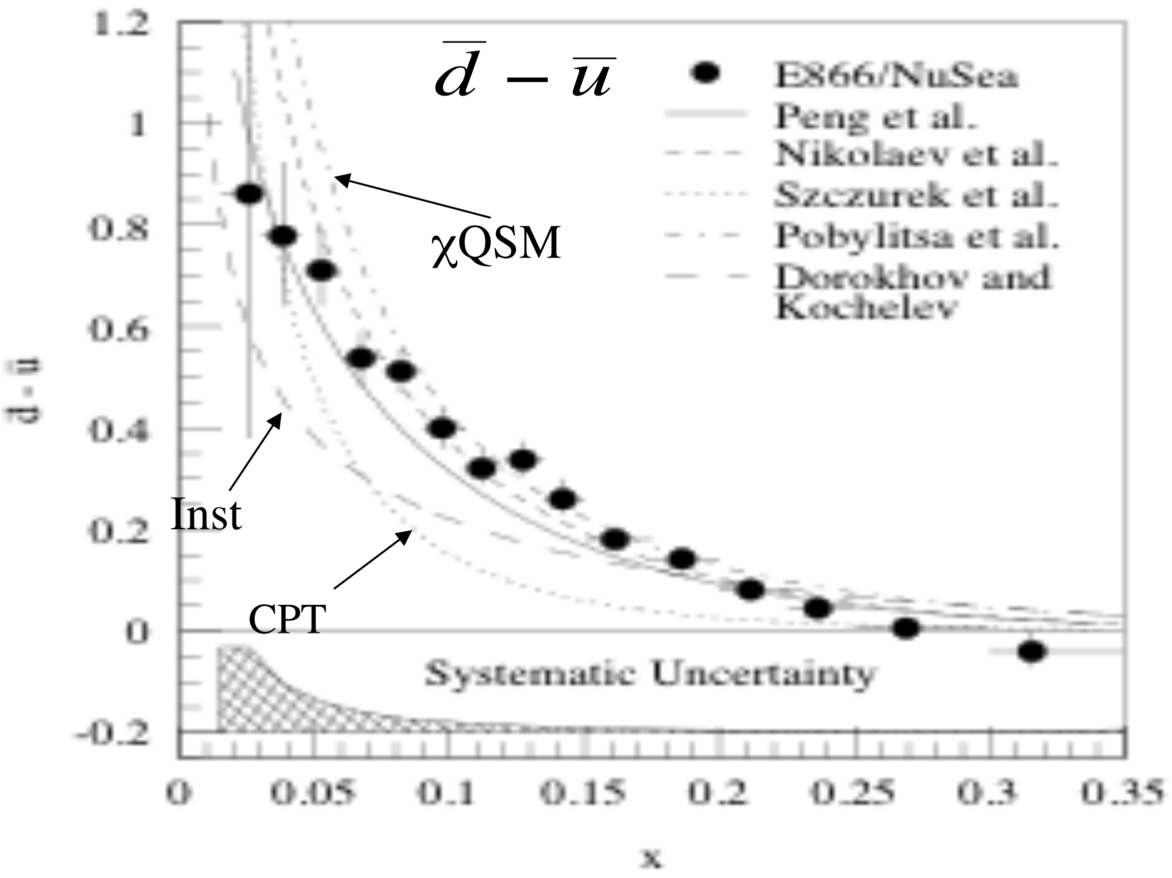
SU(2) flavour asymmetry in the unpolarized nucleon sea





Garvey&Peng, Prog.Part.Nucl.Phys. 47 (2001) 203-243

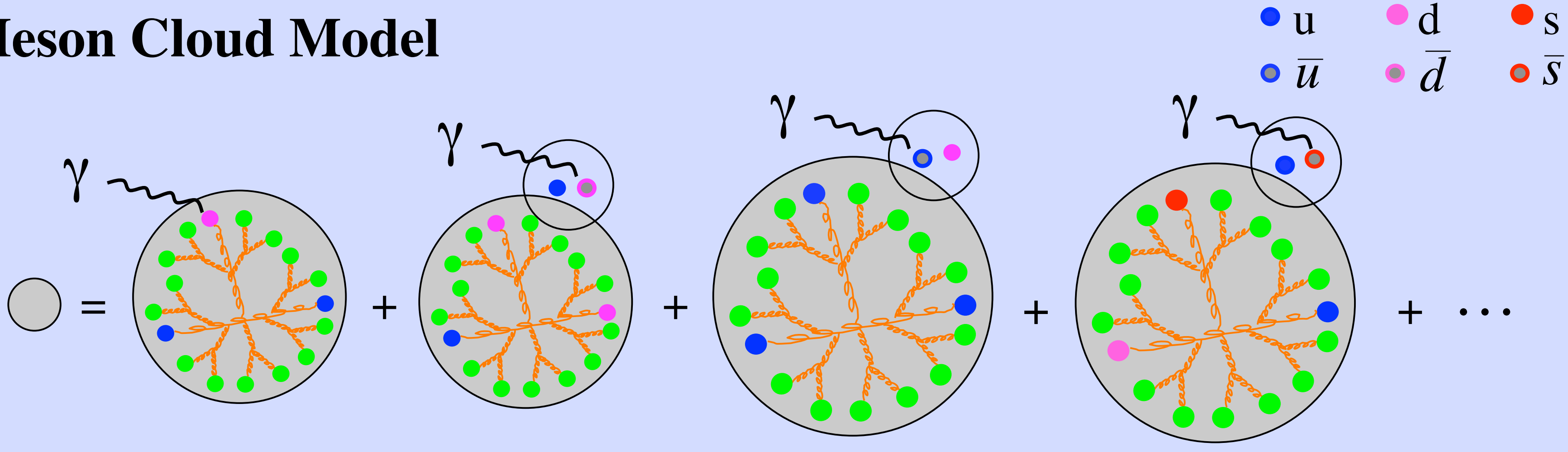
SU(2) flavour asymmetry in the unpolarized nucleon sea



Data from Phys. Rev. D64 (2001) 052002

2. Symmetry breaking in the meson cloud model

Meson Cloud Model



$$\left|p\right\rangle_{phys} = \left|p\right\rangle_{bare} + \left|n\pi^{+}\right\rangle + \left|\Delta^{++}\pi^{-}\right\rangle + \left|\Lambda K^{+}\right\rangle + \cdots$$

-- Fock state expansion of proton's wave function

- The photons may 'see' the anti-quarks in the mesons.
- Observed PDFs:

$$q_{phys} = q_{bare} + \delta q \quad \text{with } \delta q = \int_x^1 \frac{dy}{y} f_{BM}(y)\, q^{B(M)}\left(\frac{x}{y}\right)$$

• Each NBM vertex is described by an effective Lagrangian

$$e.g. \quad L = i\, g_{NN\pi} \overline{N} \gamma_5 \pi N \quad \text{for the } NN\pi \text{ vertex}$$

• f is calculated using time-order perturbative theory (TOPT) in the infinite momentum frame

$$f_{BM}(y) = \sum_{\lambda\lambda'} \int_0^\infty dk_\perp^2 \left| \phi_{BM}^{\lambda\lambda'}(y, k_\perp^2) \right|^2, \quad \phi_{BM}^{\lambda\lambda'}(y, k_\perp^2) \propto V_{IMF}(y, k_\perp^2)\, G(y, k_\perp^2)$$

↑ Phenomenological form factor

• Prescriptions for $q^{B(M)}$

→ Bag model calculations

→ Ansatz based on lattice calculations $\int_0^1 \Delta V_\rho(x) dx = 0.6 \int_0^1 V_\rho(x) dx$

$$\rightarrow \Delta V_\rho = 0.6\, V_\rho = 0.6\, V_\pi$$

→ SU(3) symmetry $s^\Lambda = s^\Sigma = \frac{1}{2} u^N$

Mechanism for symmetry breaking:

Probabilities are different;

PDFs of meson and baryon are different.

$$q_{phys} = q_{bare} + \delta q \quad \text{with } \delta q = \int_x^1 \frac{dy}{y} f_{BM}(y)\, q^{B(M)}\left(\frac{x}{y}\right)$$

Possible symmetry breakings:

1. Flavor symmetry breaking
2. Quark-antiquark symmetry breaking
3. Charge symmetry breaking

Flavor symmetry breaking

- SU(2) flavour asymmetry in the unpolarized nucleon sea is well established.

$$\mathrm{Prob}(p \rightarrow n\,\pi^{+}(u\bar{d})) > \mathrm{Prob}(p \rightarrow \Delta\,\pi^{0}(\bar{u}\,d)) \Rightarrow \bar{d} > \bar{u}$$

Flavor symmetry breaking

- Possible SU(2) flavour asymmetry in the polarized nucleon sea?
- The extent of SU(3) flavour symmetry breaking

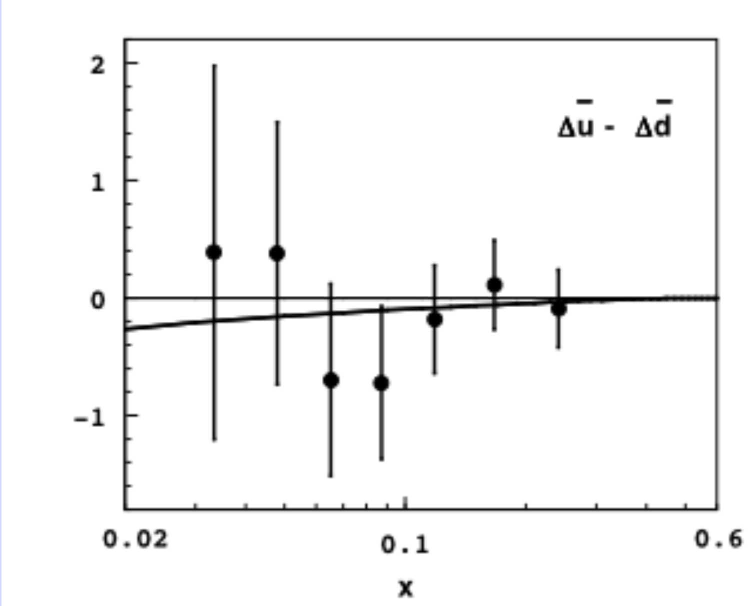
Common practice in most global QCD analyses of PDFs is

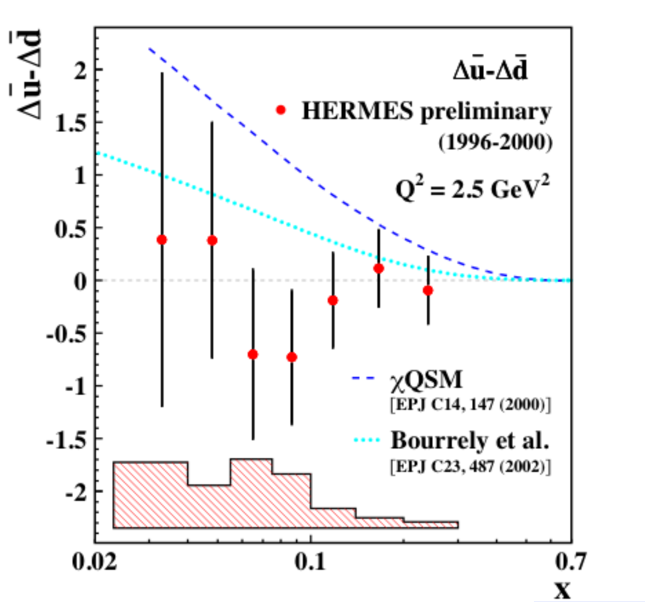
$$s(x)+\bar{s}(x)=r\left[\bar{u}(x)+\bar{d}(x)\right] \text{ with } r=0.50 \text{ (CTEQ6.5M)}$$

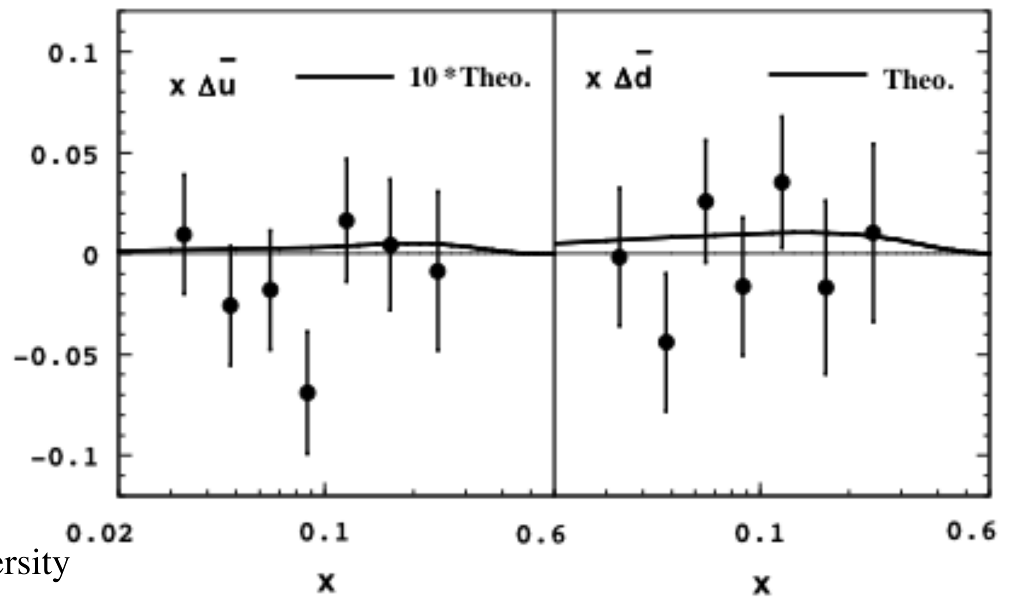
while $r=1.0$ under SU(3) symmetry and $q-\bar{q}$ symmetry.

Direct experimental evidence for the value of r is very weak.

SU(2) flavour asymmetry in the polarized nucleon sea

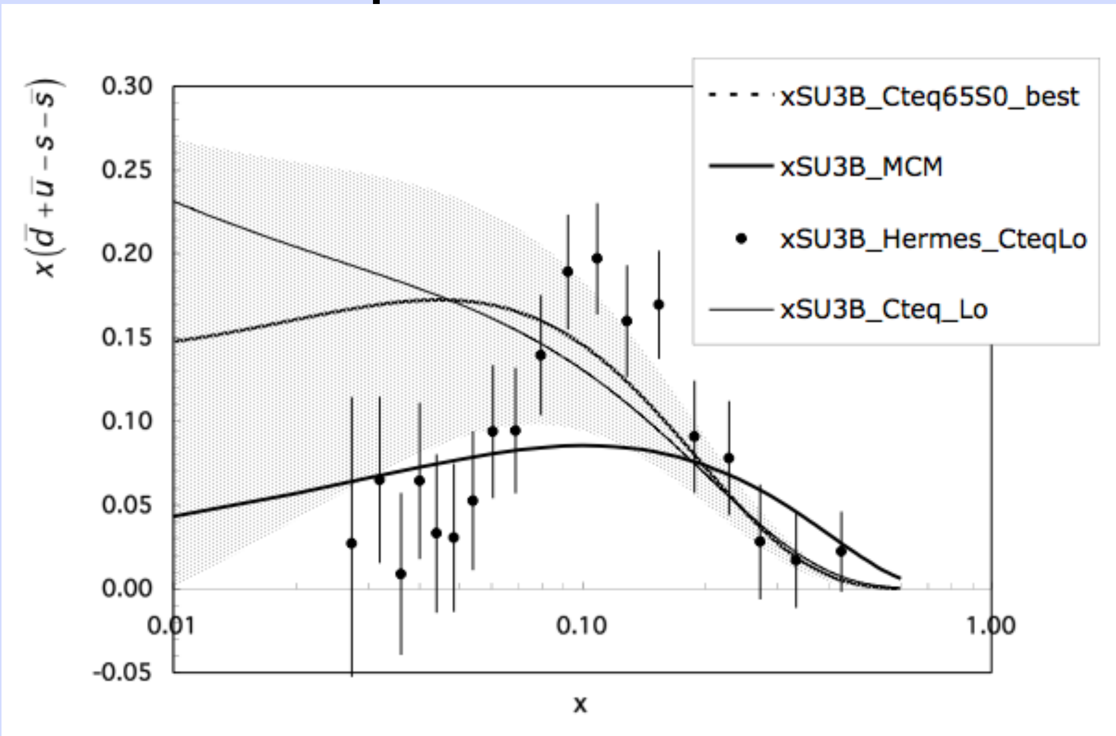






SU(3) flavour asymmetry in the unpolarized nucleon sea

$$x\Delta(x) = x\left[\bar{d}(x) + \bar{u}(x) - s(x) - \bar{s}(x)\right]$$



H. Chen, FGC, A.I. Signal, JPG37(2010)105006

Early refs. e.g., S. Kumano, PRD43(1991)59

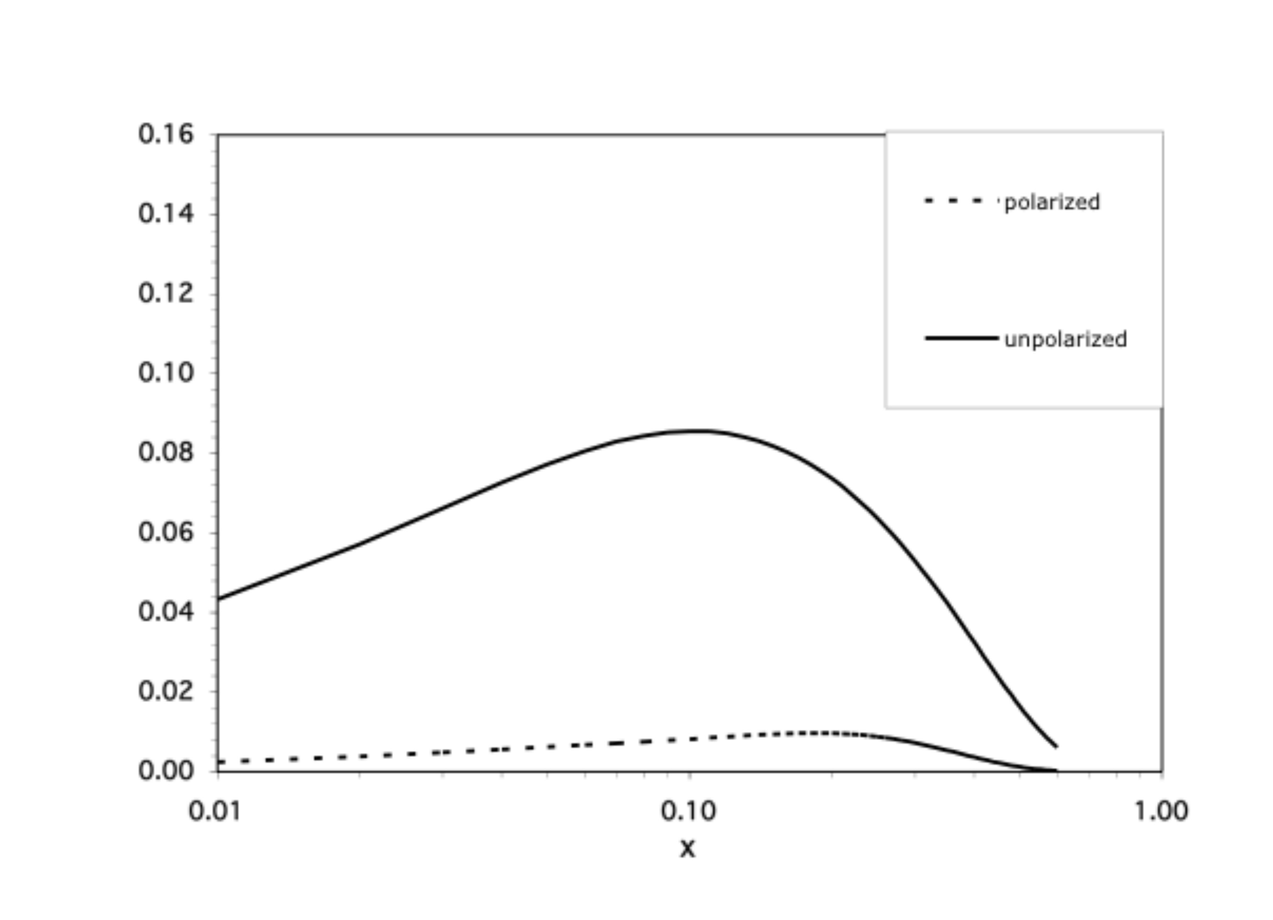
CTEQ65S [JHEP 0704 : 089,2007] :

$s(x) + \bar{s}(x)$ has different shape from $\bar{d}(x) + \bar{u}(x)$

HERMES[PLB666(2008)446 also arXiv : 0803.2993] :

a measurement of $s(x) + \bar{s}(x)$ and $\Delta s(x) + \Delta\bar{s}(x)$

SU(3) flavour asymmetry in the polarized nucleon sea



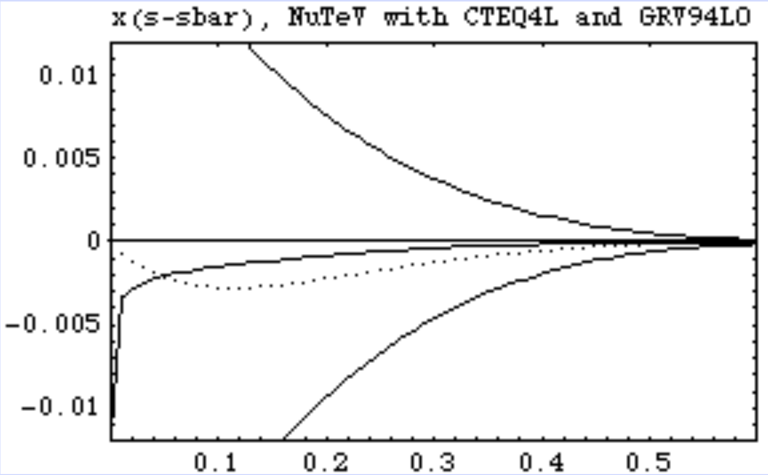
Strange-antistrange asymmetry: unpolarized nucleon sea

- No net strangeness: $\int_0^1 dx\, s(x) = \int_0^1 dx\, \bar{s}(x)$
- CCFR (Z. Phys. C65 (1995) 189)

$$x\, s = \kappa \frac{\bar{u}+\bar{d}}{2}(1-x)^{\alpha}, \quad x\, \bar{s} = \bar{\kappa} \frac{\bar{u}+\bar{d}}{2}(1-x)^{\bar{\alpha}}$$

$\Rightarrow$ No evidence for $s(x) \neq \bar{s}(x)$

- NuTeV (PRD 64 (2001) 112006)

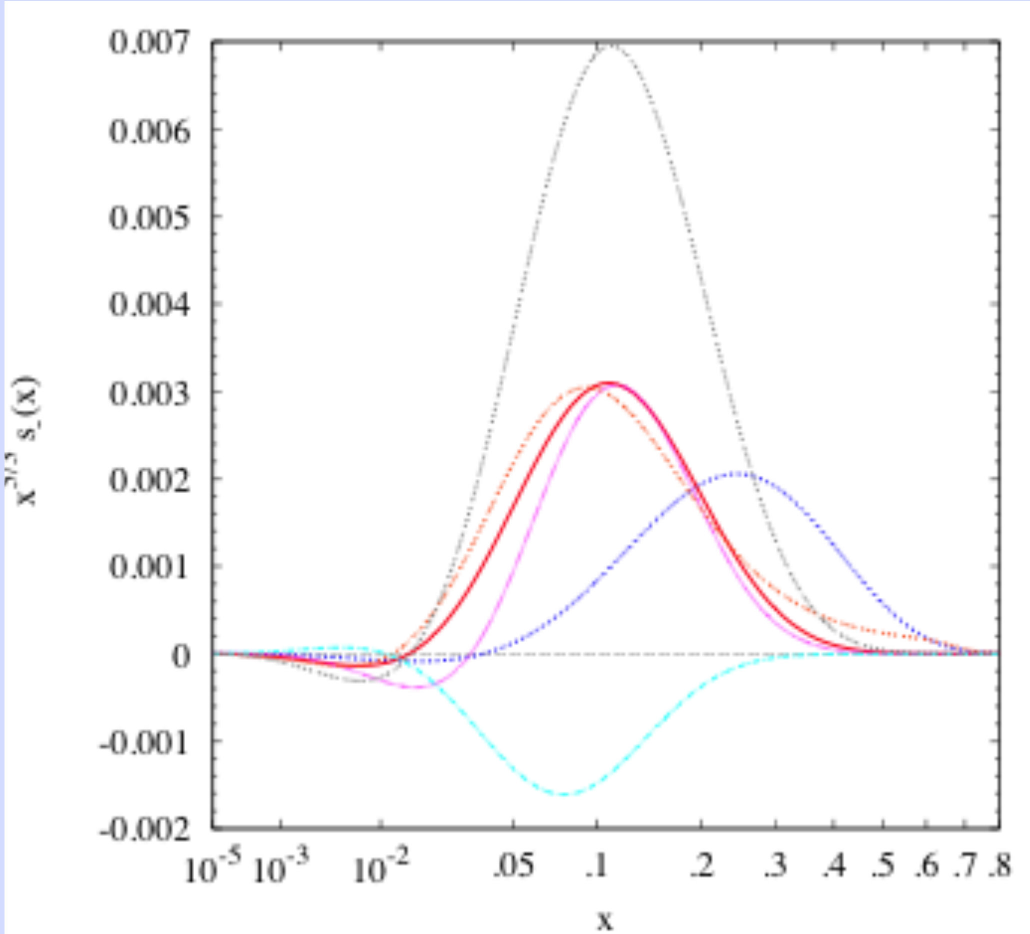


o CTEQ4L: $\langle s \rangle - \langle \bar{s} \rangle = -0.0004$

o GRV94LO: $\langle s \rangle - \langle \bar{s} \rangle = -0.0008$

• H. L. Lai et. al (CTEQ6.5S), JHEP 0704:089 (2007)

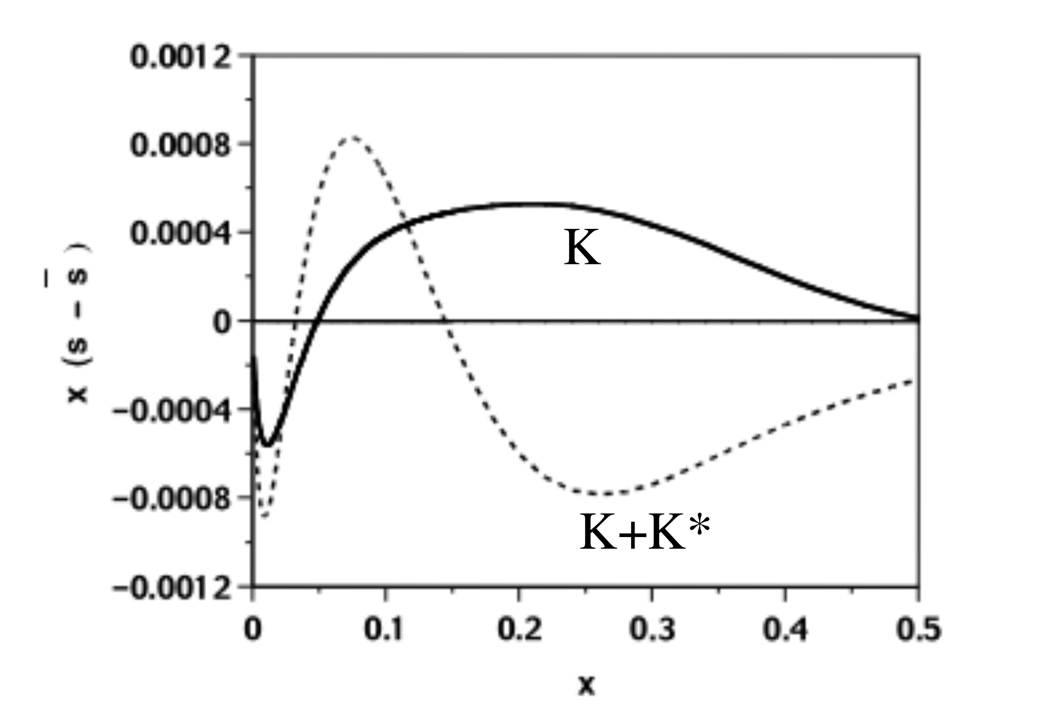
$$s_{-}(x,Q_0) = s_{+}(x,Q_0)\frac{2}{\pi}\tan^{-1}\left[cx^a(1-\tfrac{x}{b})e^{dx+ex^2}\right]$$



$$-0.001 < \langle x \rangle_{s_-} < 0.005$$

Large experimental uncertainties

Strange-antistrange asymmetry: unpolarized nucleon sea



$p \to \Lambda K; \Sigma K; \Lambda K^*; \Sigma K^*$

$p \to \Lambda K^*; \Sigma K^*$

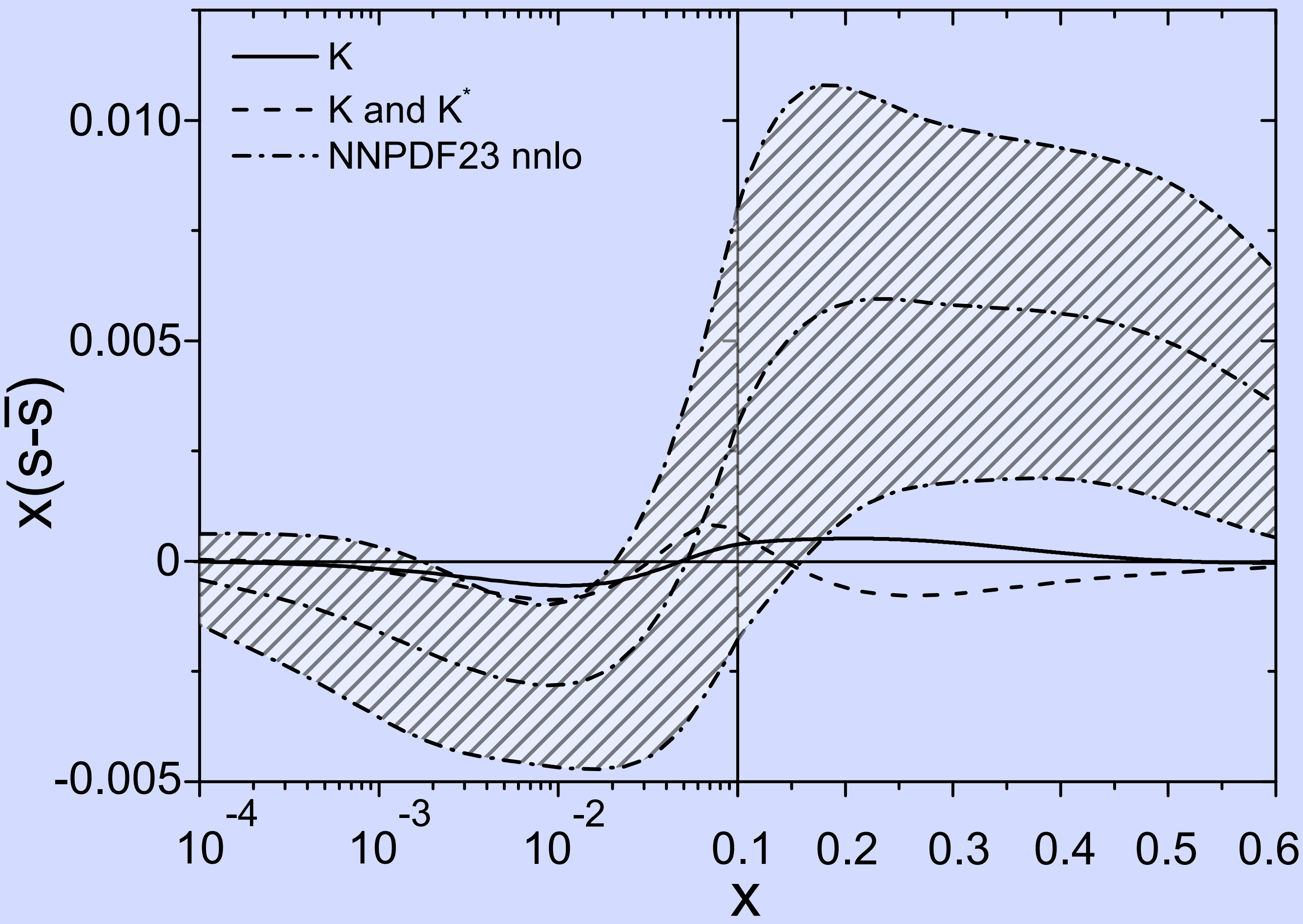
is expected to be suppressed.

$\langle s \rangle - \langle \bar{s} \rangle = 0.00014$ including only K

$\langle s \rangle - \langle \bar{s} \rangle = -0.00014$ including K+K*

- Contributions from fluctuations involving K* are important.

Comparison with global fit results

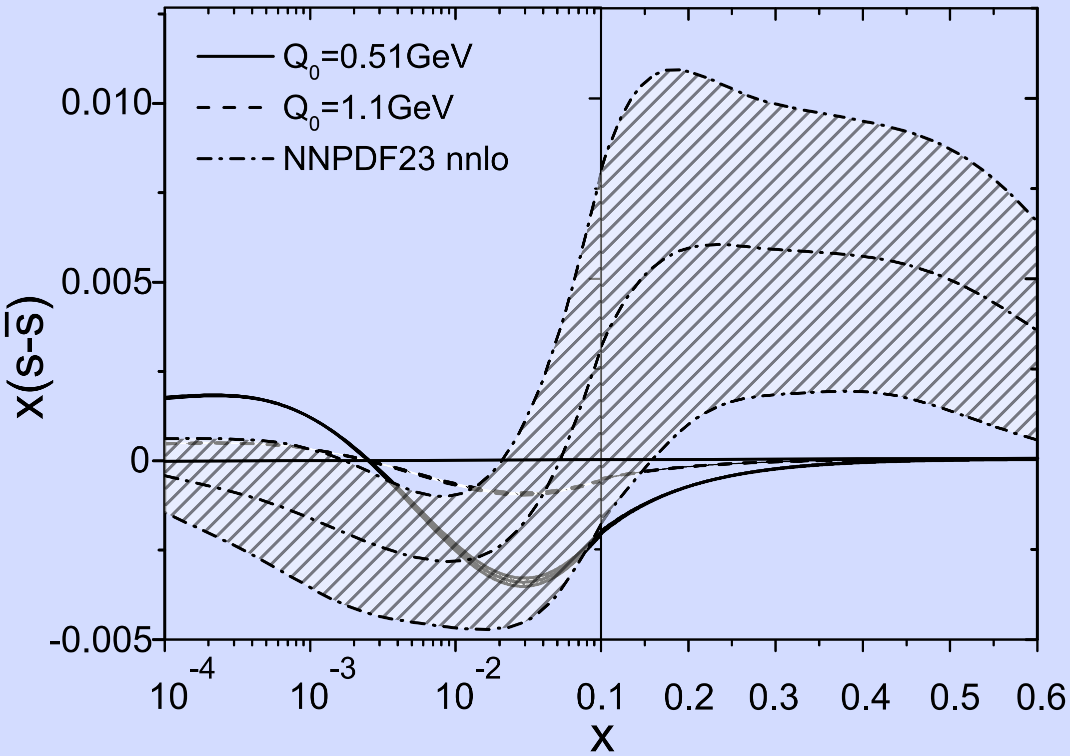


Non-pert.
contribution

Perturbative vs. non-perturbative contributions

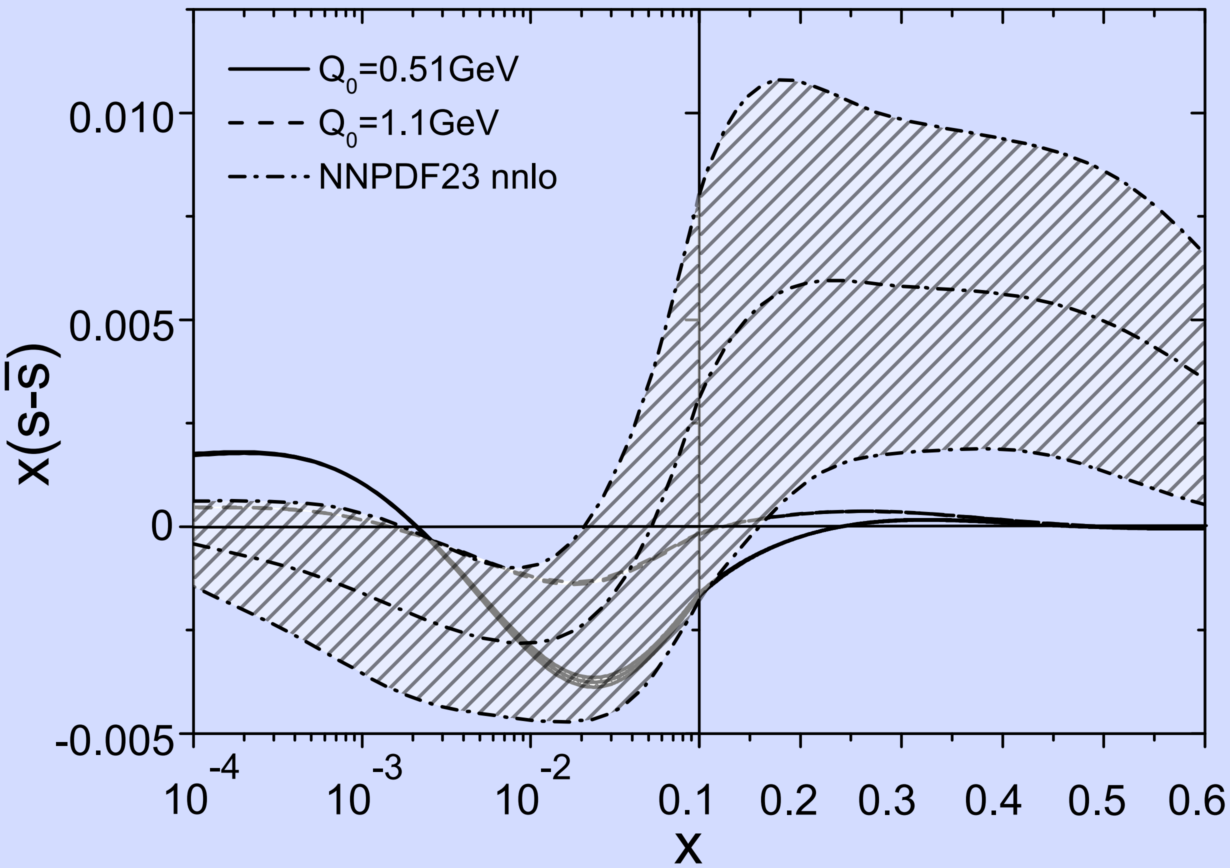
- NNLO effects
- Splitting functions for q and qbar are different at NNLO

$$(s-\bar{s})(x,Q^2) \propto \int_x^1 \frac{dz}{z} P_{ns}^{(2)}\left(\frac{x}{z}\right)\left(u^v + d^v\right)(x,Q^2)$$



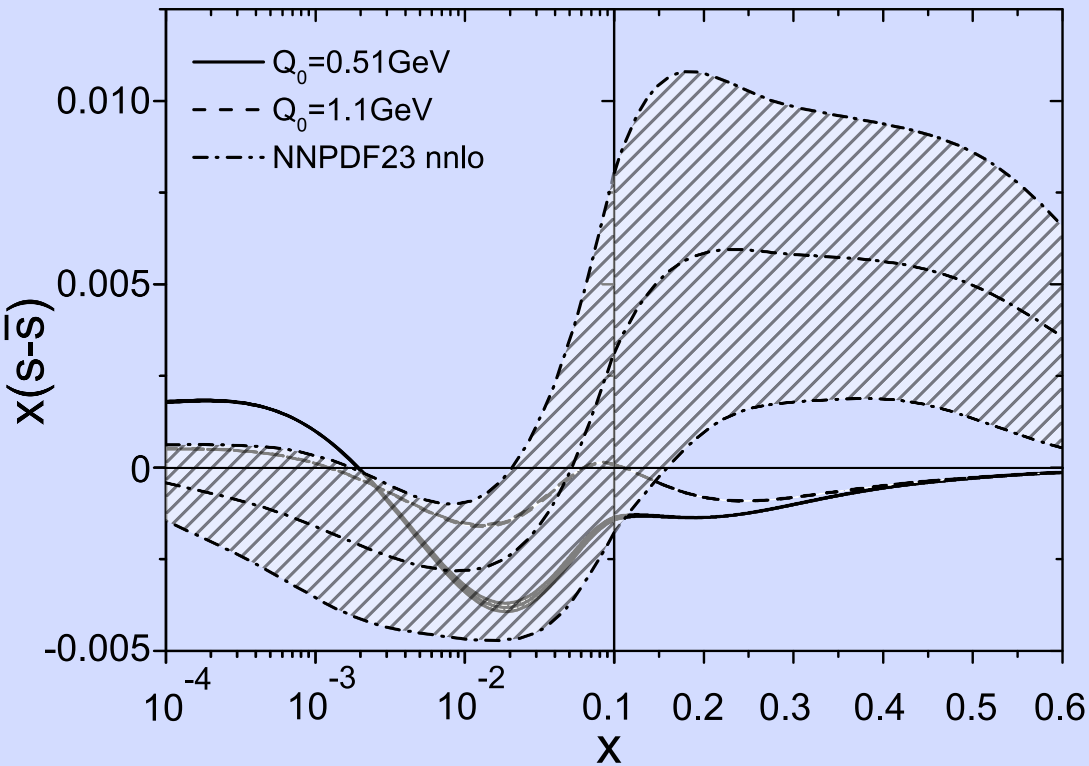
Perturbative contribution

Perturbative vs. non-perturbative contributions



Pert + Non-pert. K-mesons

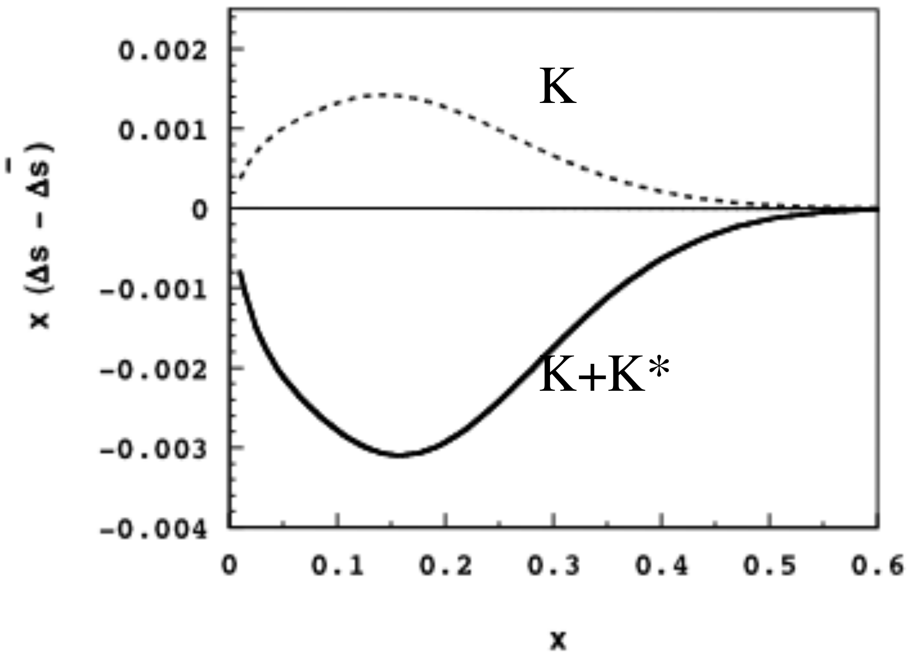
Perturbative vs. non-perturbative contributions

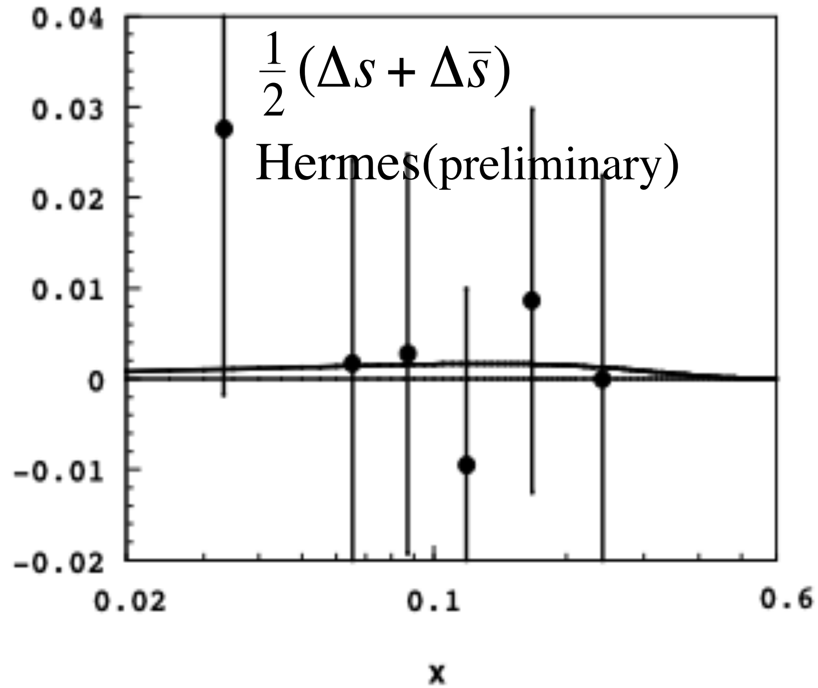


Pert + Non-pert. K + K* mesons

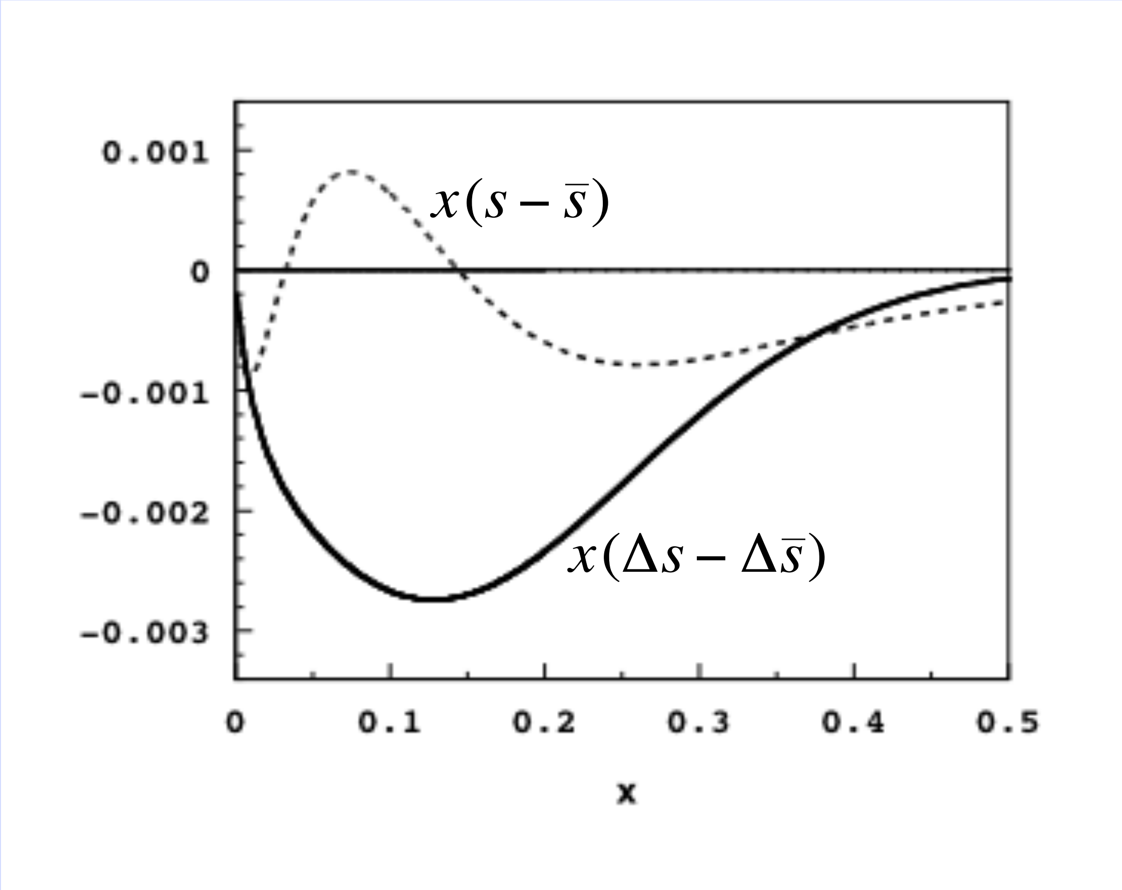
- Best region to detect the asymmetry 0.02<x<0.03.
- Multiple nodes having implications for parameterizations of the asymmetry in global analysis.

Strange-antistrange asymmetry: polarized nucleon sea





- Strange-antistrange symmetry is broken in the polarized nucleon sea.



- Strange-antistrange asymmetry is more significant in the polarized nucleon sea than that in the unpolarized nucleon sea.

Charge symmetry breaking in the PDFs

- Definitions

$$\delta u_V = u_V^p - d_V^n; \quad \delta d_V = d_V^p - u_V^n;$$

$$\delta \bar{u} = \bar{u}_V - \bar{d}_V; \ \delta \bar{d} = \bar{d}_V - \bar{u}_V; \ \delta s = s^p - s^n; \ \delta \bar{s} = \bar{s}^p - \bar{s}^n$$

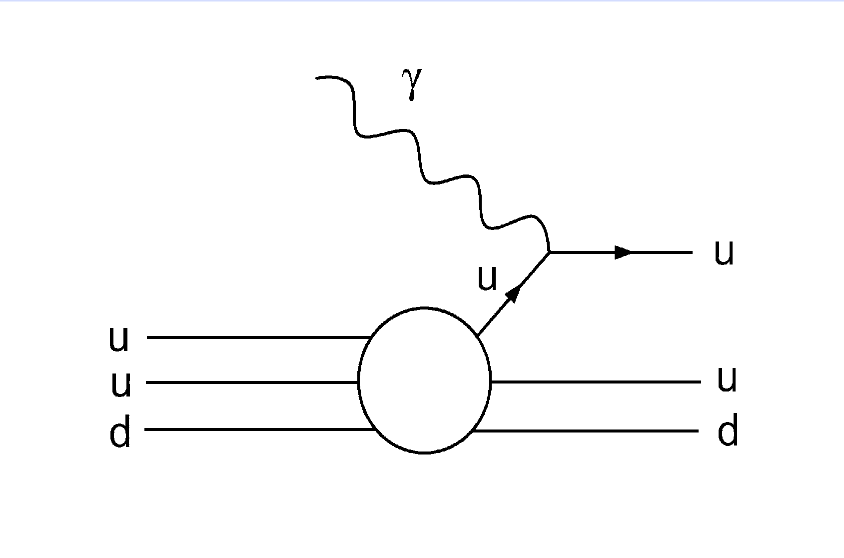
- CS is universally assumed in the quark phenomenology

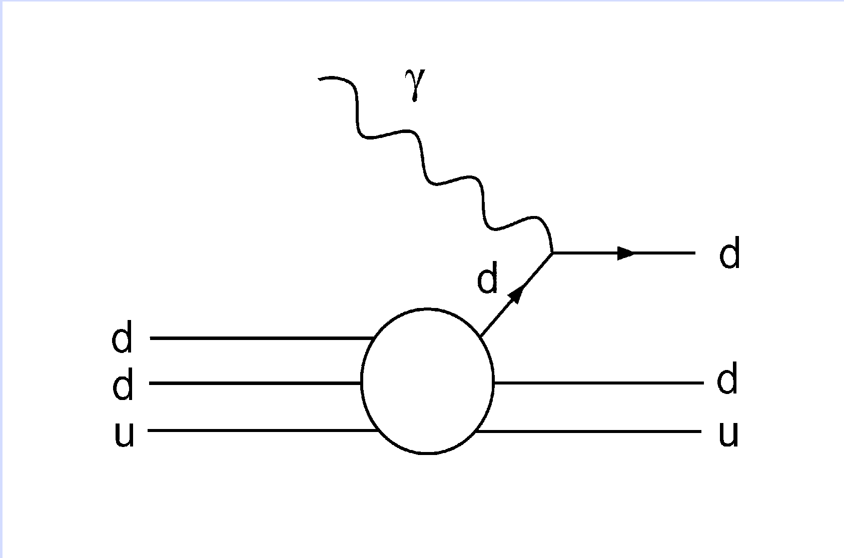
- Nuclear physics: 1%

- EW interaction: $\dfrac{m_d - m_u}{M} = \dfrac{3 \sim 5\,MeV}{0.5 \sim 1GeV} < 1\%$

- Quark model calculations:

  EW interaction; mass differences of the struck quark; mass differences of the di-quark; quark wavefunction





(Ref: Prog. Par. Nucl 41 (1998) 41; Londegran and Thomas)

- MCM calculation for the charge symmetry breaking

$$d^p = d^p_{bare} + d^p_{per.} + d^p_{non}; \quad u^n = u^n_{bare} + u^n_{per.} + u^n_{non};$$

$$\bar{d}^p = \bar{d}^p_{per.} + \bar{d}^p_{non}; \quad \bar{u}^n = \bar{u}^n_{per.} + \bar{u}^n_{non};$$

$$\Downarrow d^p_{per.} = \bar{d}^p_{per.};$$

$$d^p_V = d^p_{bare} + d^p_{non} - \bar{d}^p_{non}; \quad u^n_V = u^n_{bare} + u^n_{non} - \bar{u}^n_{non};$$

$$\delta d_V = \left[d^p_{bare} - u^n_{bare} \right] + \left[\left(d^p_{non} - \bar{d}^p_{non} \right) - \left(u^n_{non} - \bar{u}^n_{non} \right) \right];$$

$\Uparrow$ Calculated with quark models

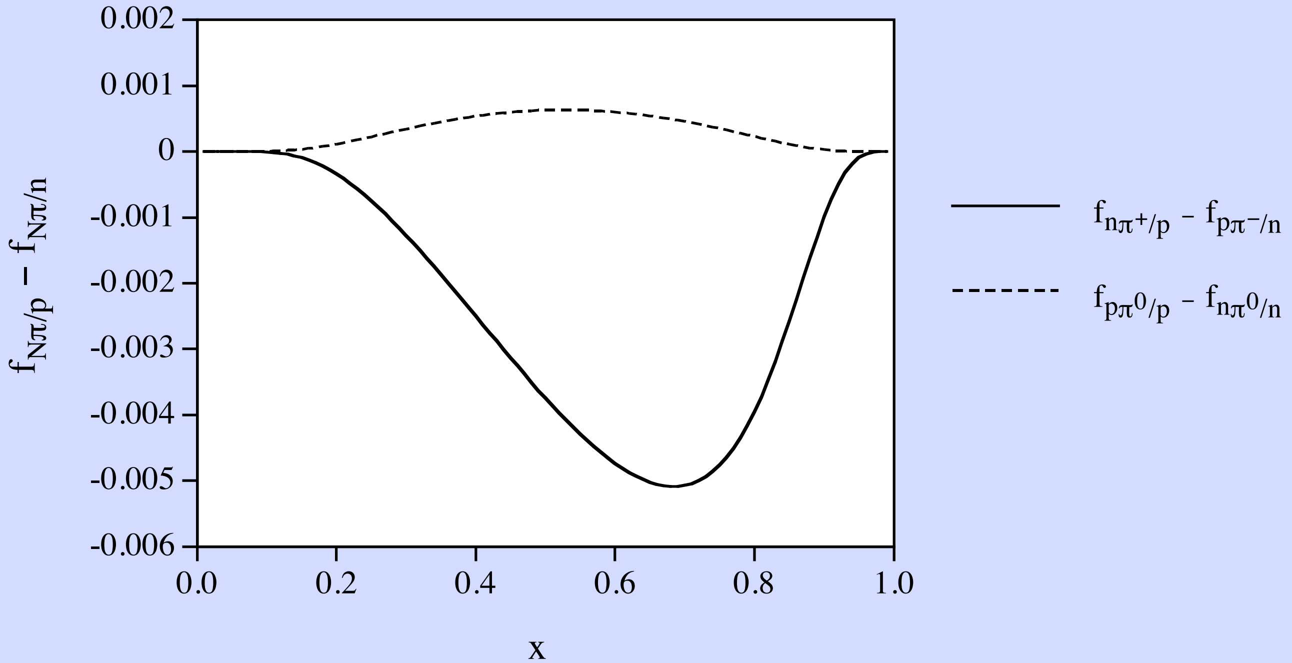
$\Uparrow$ Calculated with the Meson cloud model

- MCM calculation for the charge symmetry breaking

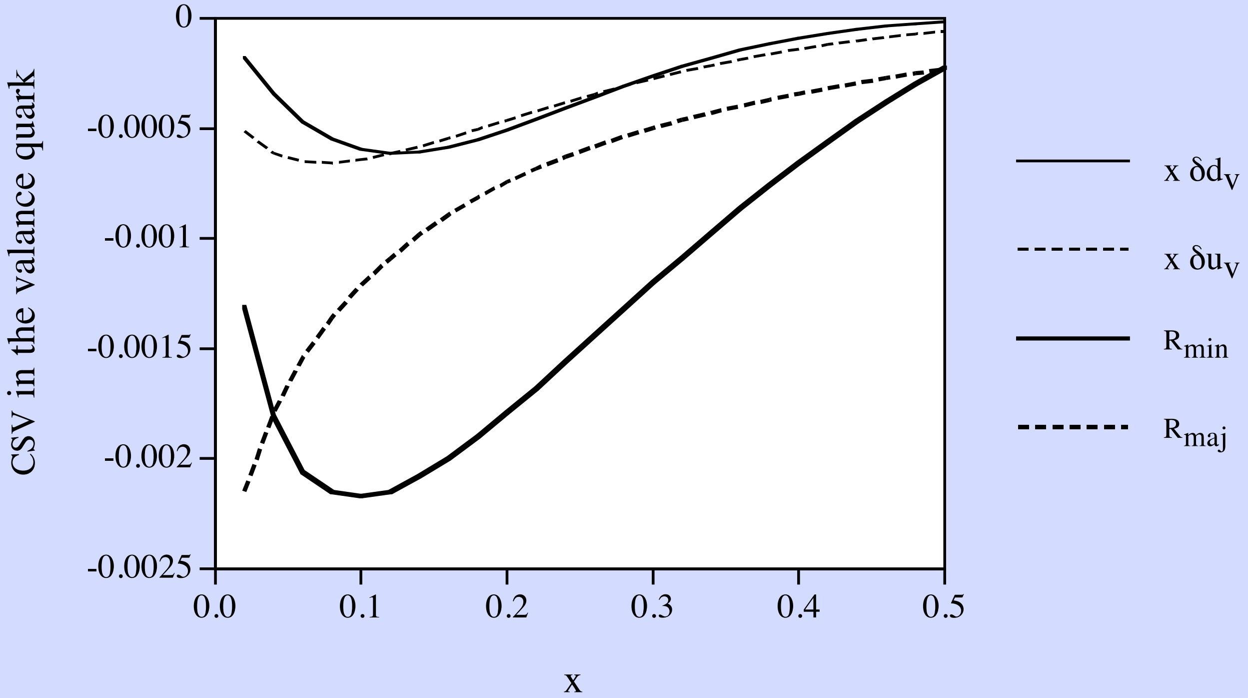
  Fluctuations considered include:

$$p \rightarrow n\,\pi^{+}; \qquad n \rightarrow p\,\pi^{-};$$
$$p \rightarrow \Delta^{0}\,\pi^{+}; \qquad n \rightarrow \Delta^{+}\,\pi^{-};$$
$$p \rightarrow \Lambda\,K^{+}; \qquad n \rightarrow \Lambda\,K^{o}$$

$$m_p - m_n = -1.3\,MeV,$$
$$m_{\pi^{\pm}} - m_{\pi^0} = 4.6\,MeV,\ etc$$



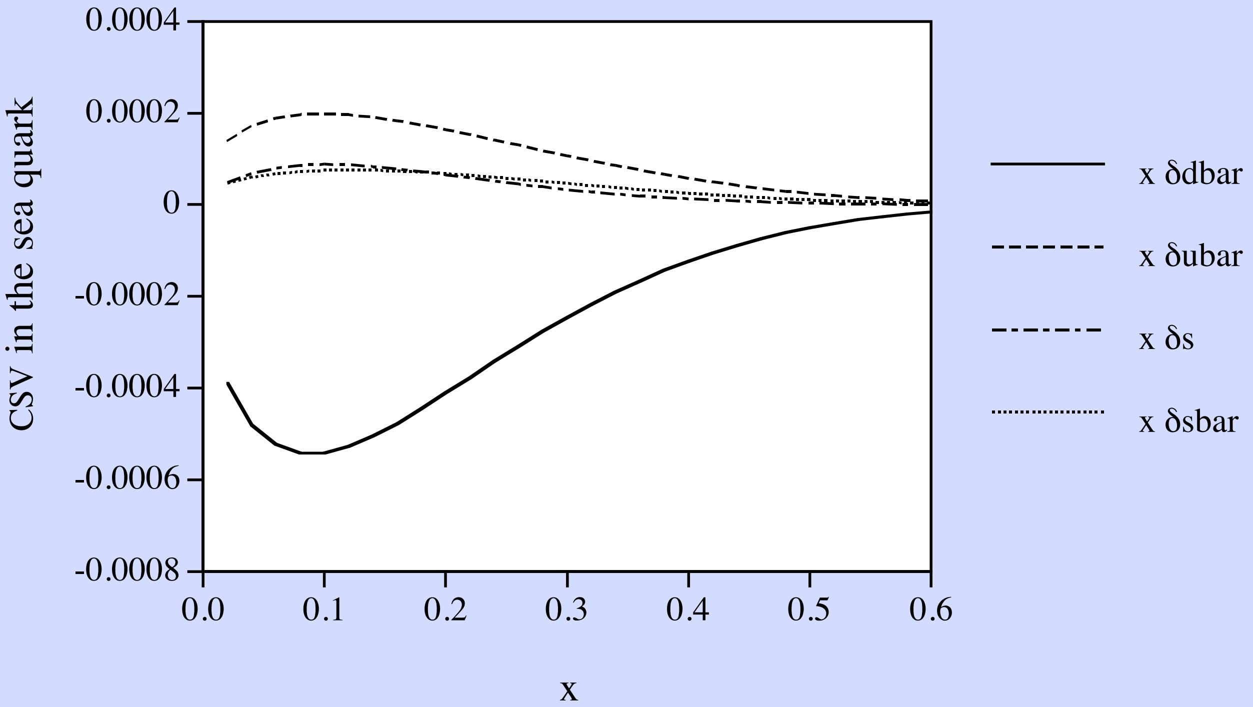
Charge symmetry breaking in the valence quarks



$$\delta u_V = u_V^p - d_V^n, \quad \delta d_V = d_V^p - u_V^n;$$

$$R_{\min} = {\delta d_V}\big/{d_V}, \quad R_{\mathrm{maj}} = {\delta u_V}\big/{u_V}$$

Charge symmetry breaking in the sea quarks



$$\delta\bar{u} = \bar{u}_V - \bar{d}_V;\ \ \delta\bar{d} = \bar{d}_V - \bar{u}_V;\ \ \delta s = s^p - s^n;\ \ \delta\bar{s} = \bar{s}^p - \bar{s}^n$$

Meson cloud contributions to the CSV are slightly smaller than that calculated with quark models.

3. Strange sea distributions

Strange sea distributions are not well determined compared with the valence distributions and light quark sea.

CTEQ6.5S [H. L. Lai et. al, JHEP 0704:089 (2007)]

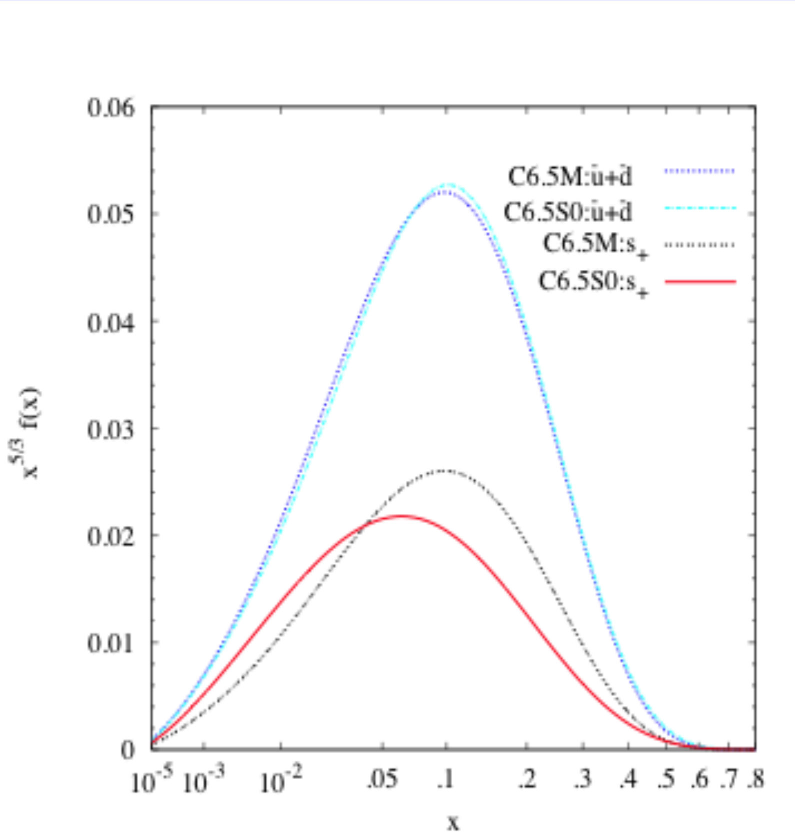
$$s_{\pm}(x,Q_0) = s(x,Q_0) \pm \bar{s}(x,Q_0)$$

$$s_{+}(x,Q_0) = A_0 x^{A_1} (1-x)^{A_2}$$

$A_1^{s_+} = A_1^{(\bar{u}+\bar{d})_+}$ is assumed

A_0 is related to suppression factor

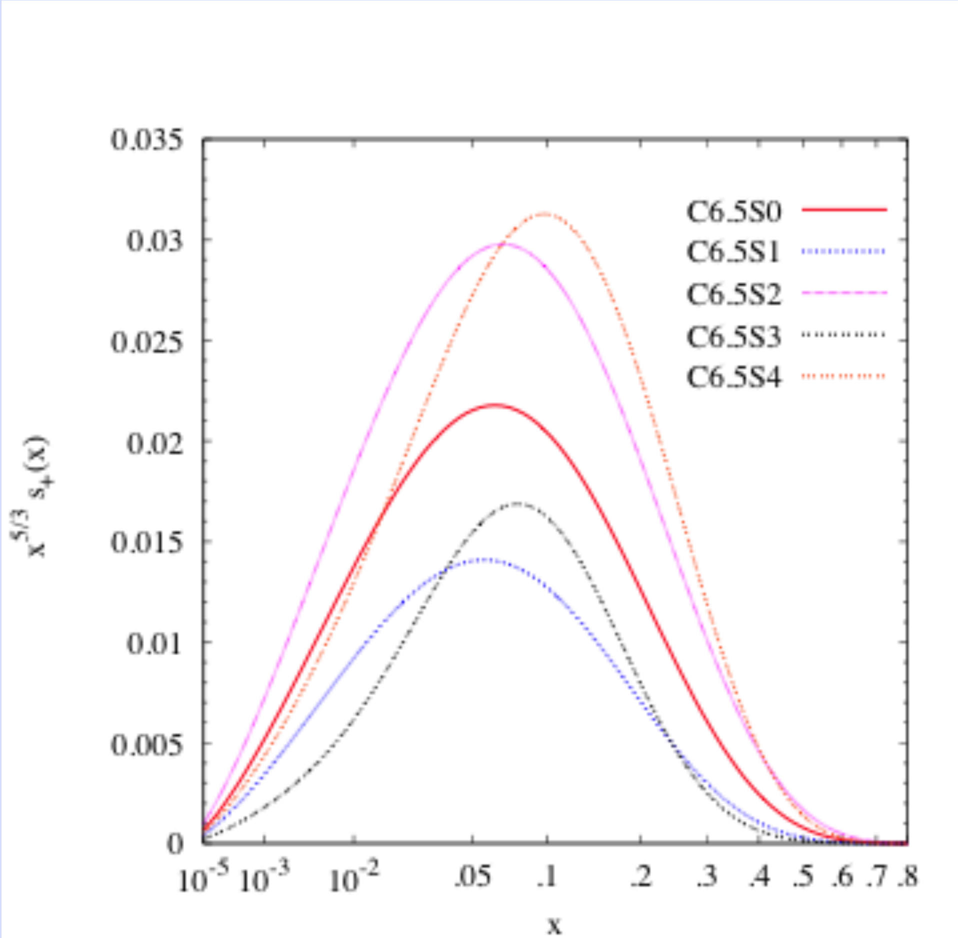
$$r = \frac{\langle x \rangle_{s+}}{\langle x \rangle_{\bar{u}(x)+\bar{d}(x)}}$$



Light sea is almost unchanged while $s_+(x)$ becomes smaller and softer compared to CTEQ6.5M.

$r = 0.44$ (CTEQ6.5S$_0$) vs. 0.50 (CTEQ6.5M)

- Allowed range for s_+(x)

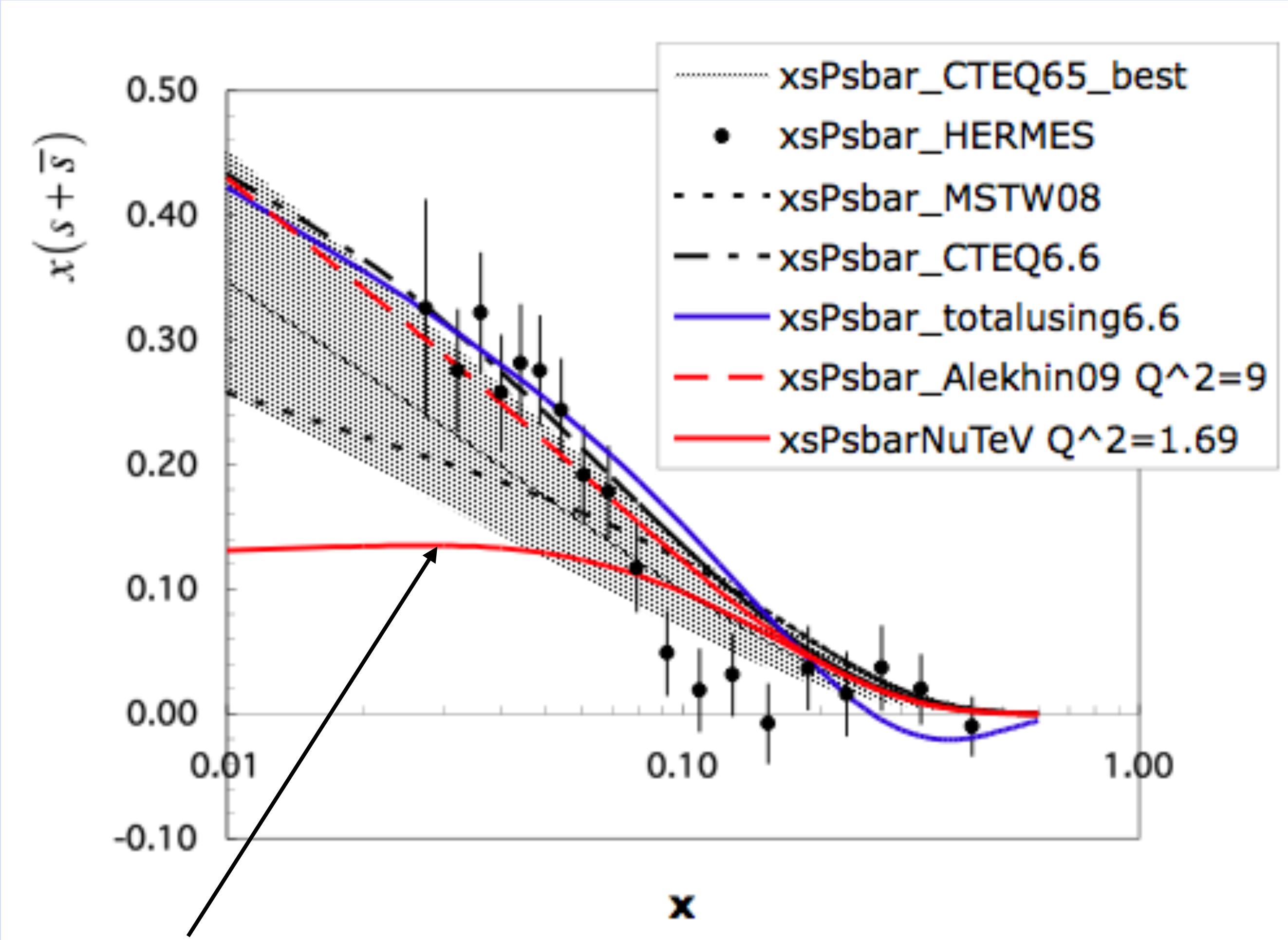


Monentum fraction

$0.018 < \langle x \rangle < 0.040$;

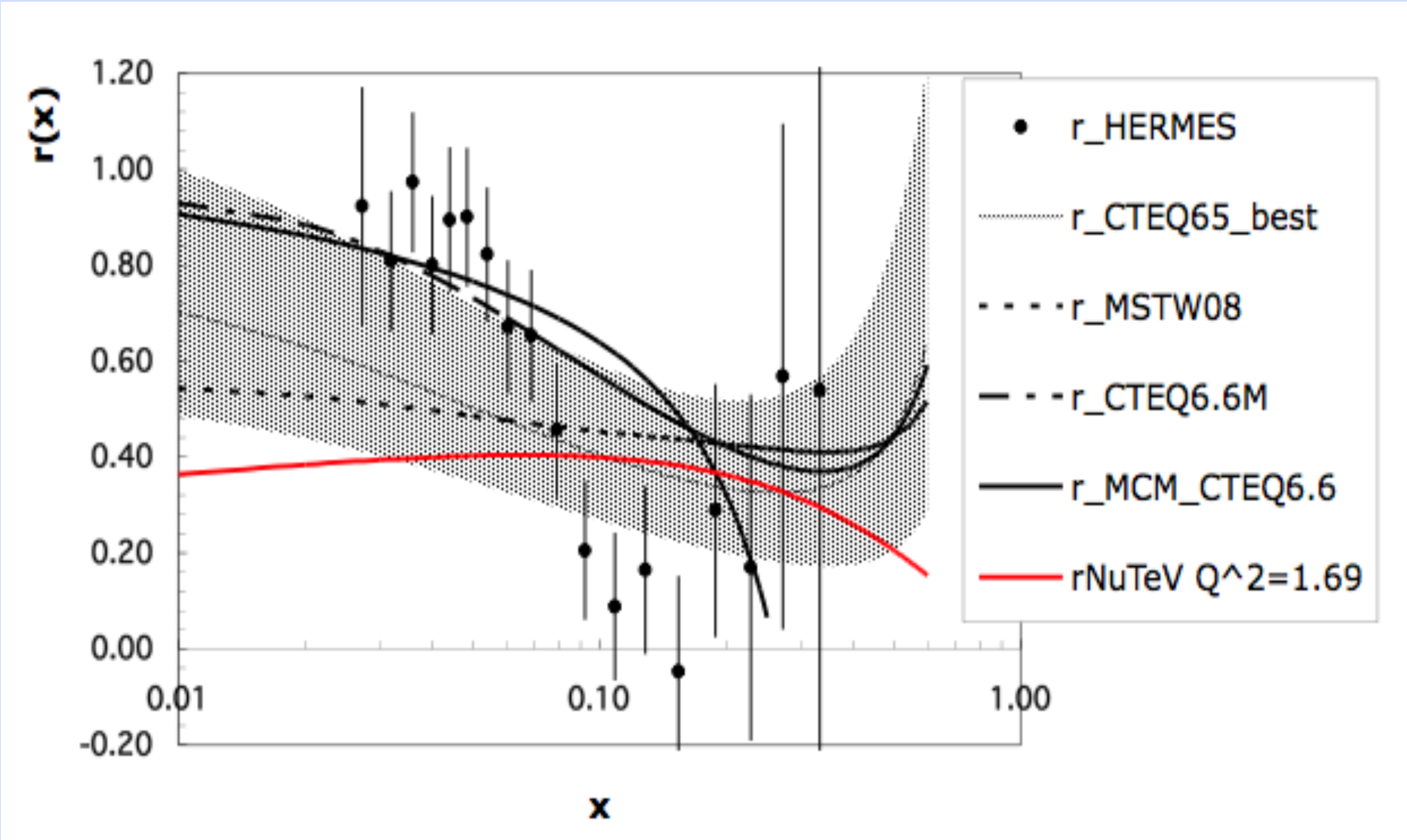
Different parameterizations

$$xs_{+}(x) = \left[\bar{d}(x) + \bar{u}(x)\right]_{\mathrm{Fit}} - x\Delta(x)_{\mathrm{MCM}}$$



NLO analysis of NuTeV data PRL99(2007)192001

The suppression factor $r(x) = \dfrac{s(x) + \bar{s}(x)}{\bar{d}(x) + \bar{u}(x)}$



4. Summary

- Non-pert. QCD models for the nucleon structure can make reliable predictions for the symmetry breaking effects.
- Possible strange-antistrange asymmetry is of great interest. The asymmetry may have multiple nodes.
- Strange sea distributions are not well constrained.
- Combining the MCM calculations for the $SU(3)_f$ breaking effect with global analysis results for the light quark sea, we estimated the total strange sea distributions. The calculations agree with HERMES results, but not with the NLO analysis of NuTeV dimuon data.