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Quark Asymmetries in Nucleons

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Dep. of Radiation Sciences, 4/2 2005

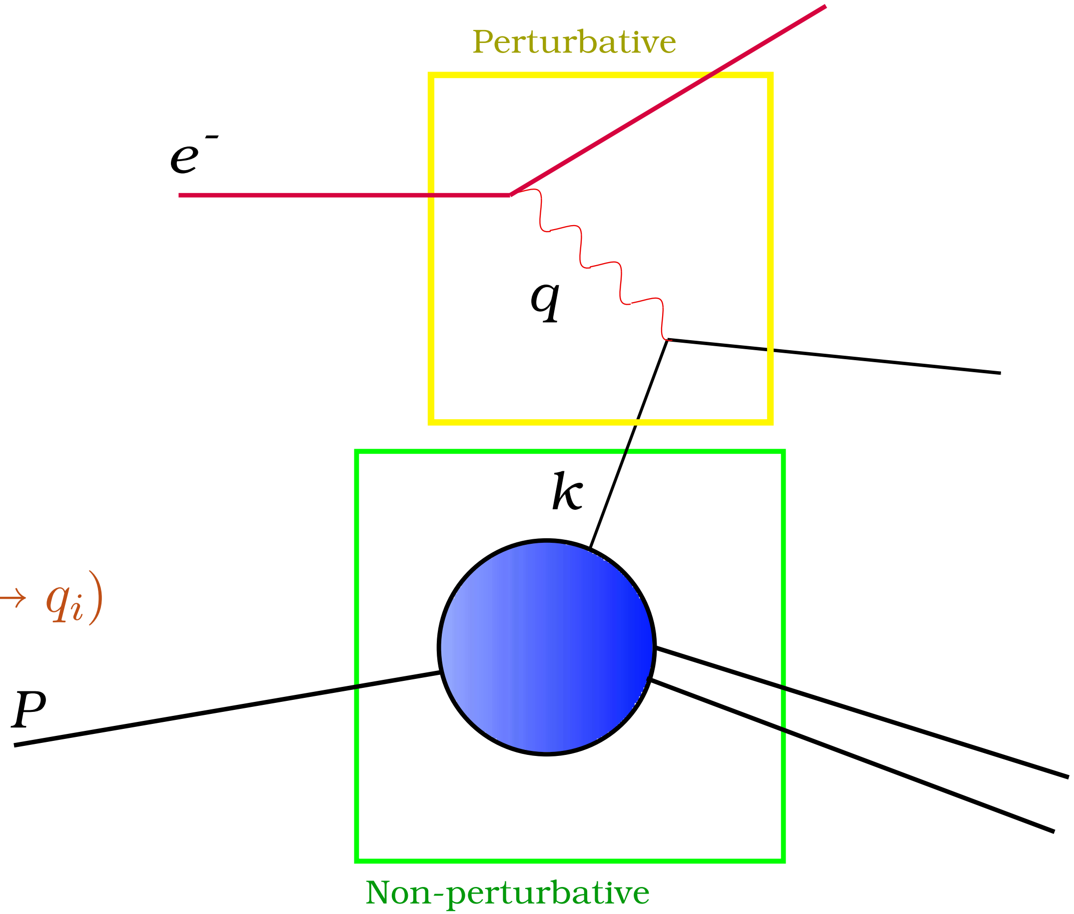
Parton distributions in hadrons

The cross-section for hadronic interactions can be factorized into

- A "hard" (perturbative) parton scattering
- A parton probability (parton distribution)

$$d\sigma(\gamma p \to X) = \sum_i f_i(k, Q^2)\, d\sigma(\gamma q_i \to q_i)$$

$$Q^2 = -q^2,\ k \leftrightarrow x_{\mathrm{Bjorken}}$$



Parton distributions in hadrons, cont.

- Q^2 dependence of parton distributions $f_i(x, Q^2)$ given by the DGLAP (Altarelli-Parisi) evolution in perturbative QCD

- Starting distributions $f_i(x, Q_0^2)$ non-perturbative and non-calculable

  $\hookrightarrow$ Usually parametrizations of arbitrary functions chosen to describe data

- Valence (u_v, d_v), gluon and sea ($q\bar{q}$) distributions

- Sea first believed to be symmetric ($\bar{d} = \bar{u} = s = \bar{s}$)

  $\hookrightarrow$ Soon $s, \bar{s} = \frac{1}{2}\frac{\bar{d} + \bar{u}}{2}$ due to $SU(3)$ violation

  $\hookrightarrow$ Also $\bar{d} > \bar{u}$ (Gottfried sum rule violation)

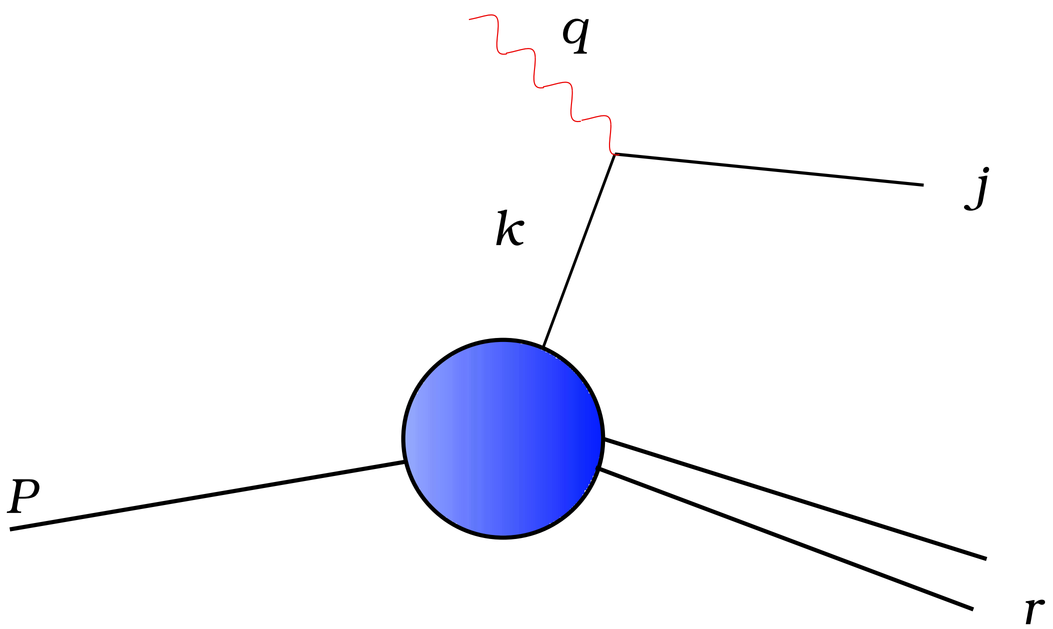
- We have a physically motivated model for the starting distributions

Our Model: Valence distributions

In hadron rest frame:

- Parton momenta spherically symmetric
- Typical momentum from Heisenberg uncertainty: $\langle k \rangle \sim \Delta p = \hbar / \Delta x \sim 200 \text{ MeV}$

Gaussian momentum fluctuations $(k^\mu \in N(0, \sigma_i))$ of partons:



Use z-boost invariant $x = \dfrac{k_+}{P_+} = \dfrac{E_k + k_z}{E_P + P_z}$

Kinematic constraints:

$$0 < j^2 < W^2 = (P+q)^2$$
$$r^2 > 0$$

$\Longrightarrow 0 \leq x \leq 1$ and $f_i(x) \to 0$ as $x \to 1$

Monte Carlo-simulate to get x distribution.

Hadronic fluctuations

- At low Q^2, the proton is viewed as consisting of a sum of several quantum states (fluctuations):

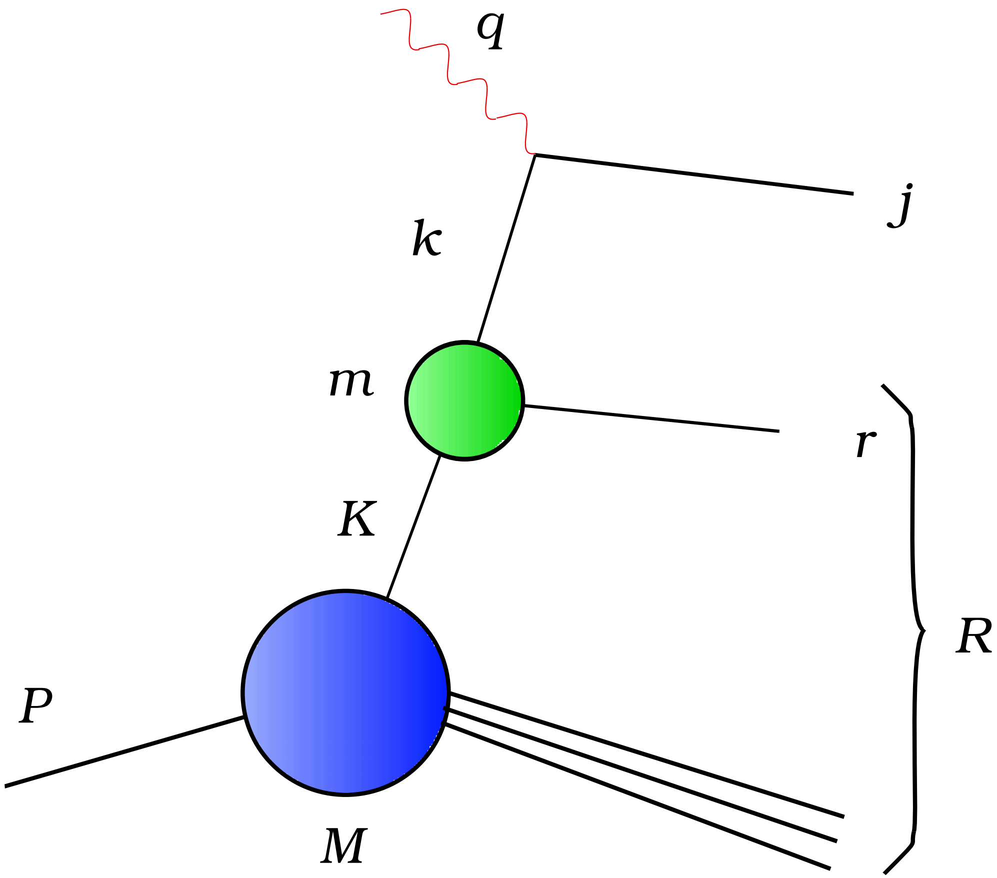
$$|p\rangle = \alpha_0|p_0\rangle + \alpha_{p\pi^0}|p_0\pi^0\rangle + \alpha_{n\pi^+}|n\pi^+\rangle + \ldots + \alpha_{\Lambda K}|\Lambda K^+\rangle + \ldots$$

- Gaussian momentum distribution of fluctuation hadrons (meson and baryon) in the rest frame of the proton.

- The photon (probe) interacts with parton in the meson or baryon.

- Normalization given by Clebsch-Gordan coefficients, mass suppression and mixing of different meson-baryon states with same quark content – here just fit effective α^2_{MB}.

Hadronic fluctuations, contd.



Definitions:

$$x_H = \frac{K_+}{(K + K_{\rm partner})_+}$$

$$x_i = \frac{k_+}{K_+}$$

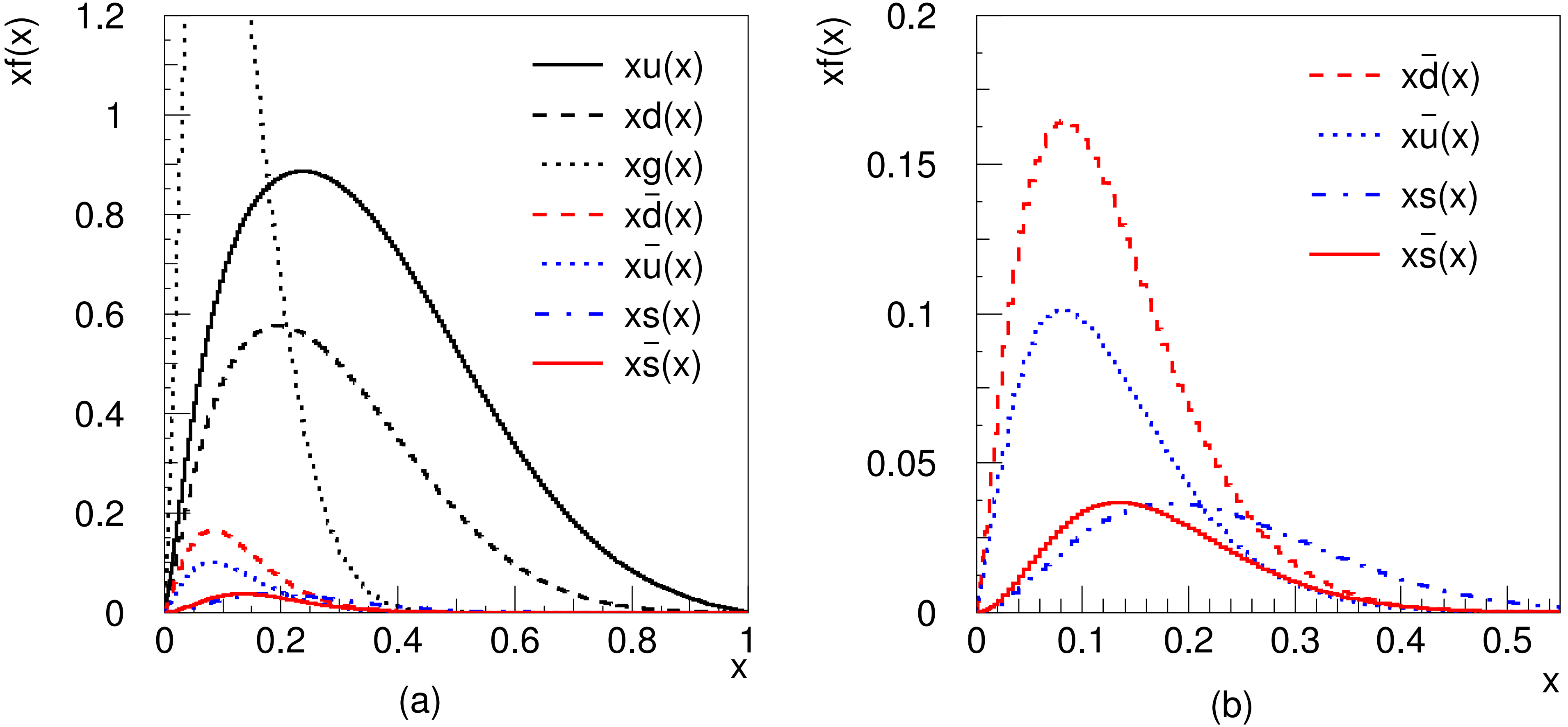
$$x = x_H \cdot x_i$$

Kinematic constraints:

$$0 < j^2 < W_H^2 = (K+q)^2$$

$$r^2 > 0\,,\; R^2 > 0$$

Resulting distributions



Shapes agree well with parametrizations (as will be shown below)

Parameters and experimental data

Parameters:

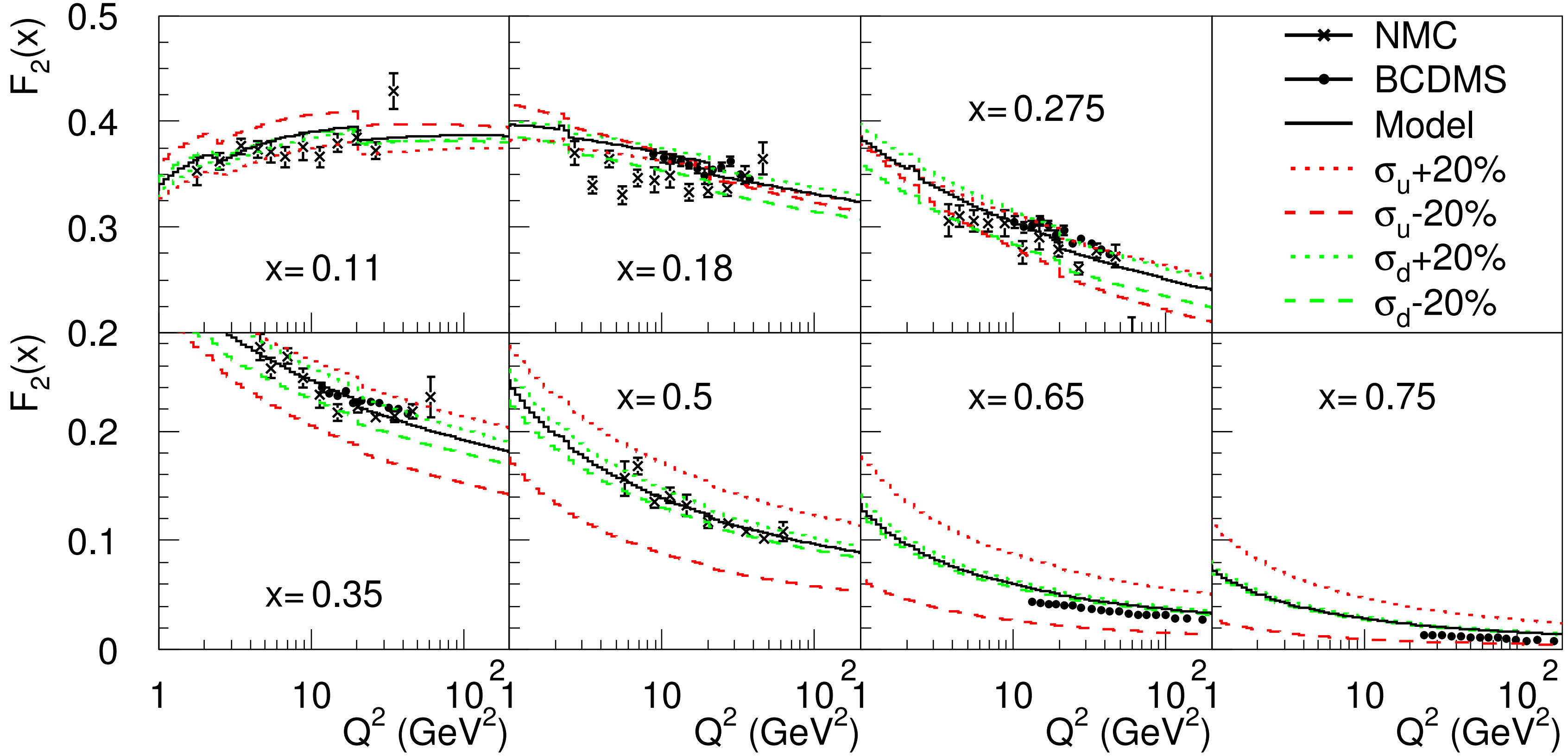
$$\sigma_u = 230 \text{ MeV} \quad \sigma_d = 170 \text{ MeV} \quad \sigma_g = 77 \text{ MeV}$$
$$Q_0 = 0.75 \text{ GeV} \quad \sigma_H = 100 \text{ MeV}$$
$$\alpha^2_{p\pi^0} = 0.45 \quad \alpha^2_{n\pi^+} = 0.14 \quad \alpha^2_{\Lambda K} = 0.05$$

Experimental data sets:

- Fixed-target F_2 data
- HERA F_2 data
- $W^{\pm}$ charge asymmetry data
- $\bar{d}/\bar{u}$-asymmetry data
- Strange sea data

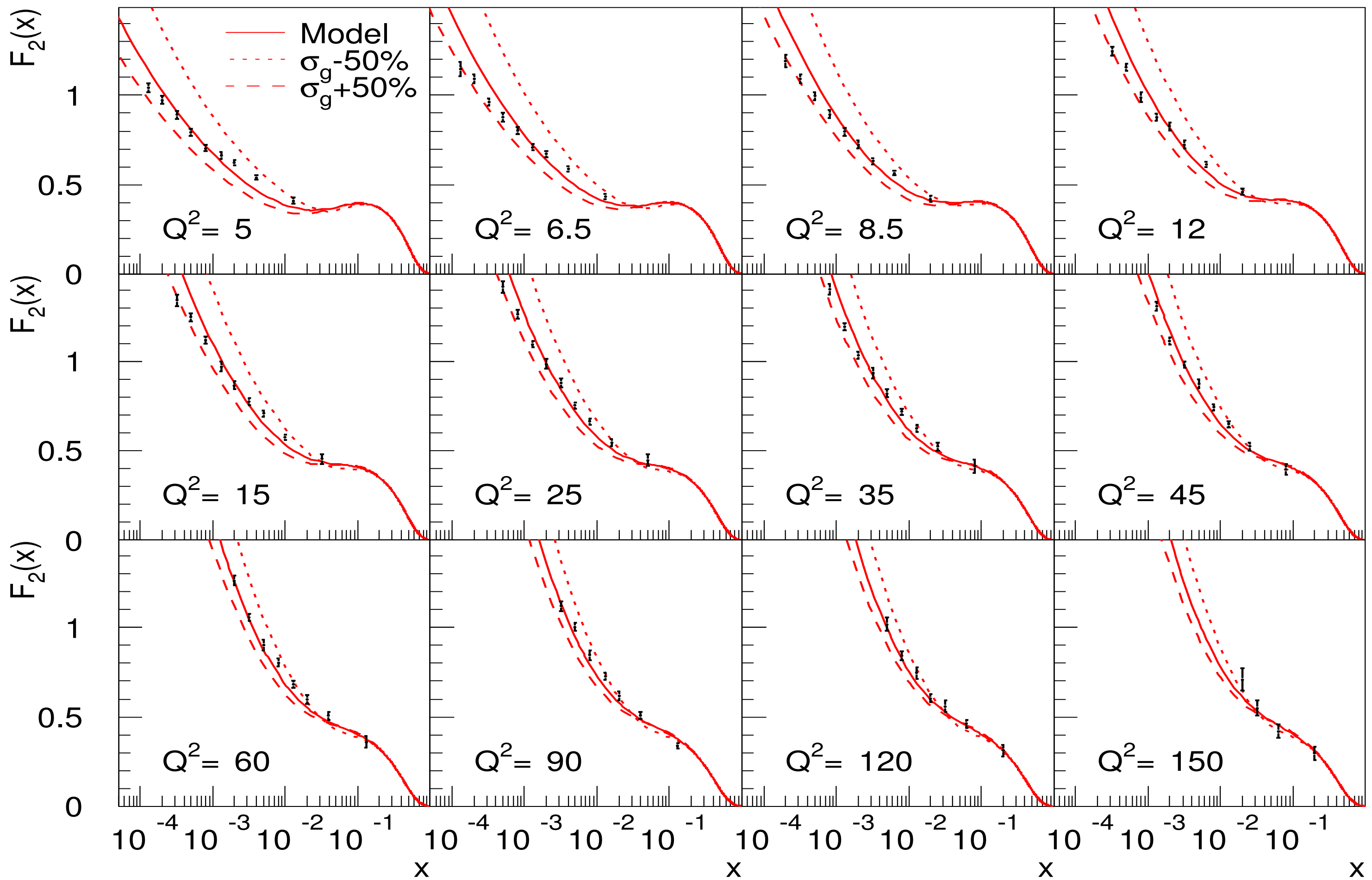
Fixed-target DIS data

NMC and BCDMS F_2 data to fix large-x valence distributions ($\sigma_u,\ \sigma_d$)



HERA DIS data

HERA small-x F_2 data to fix gluon distribution (σ_g) and starting scale Q_0



$W^{\pm}$ asymmetry data

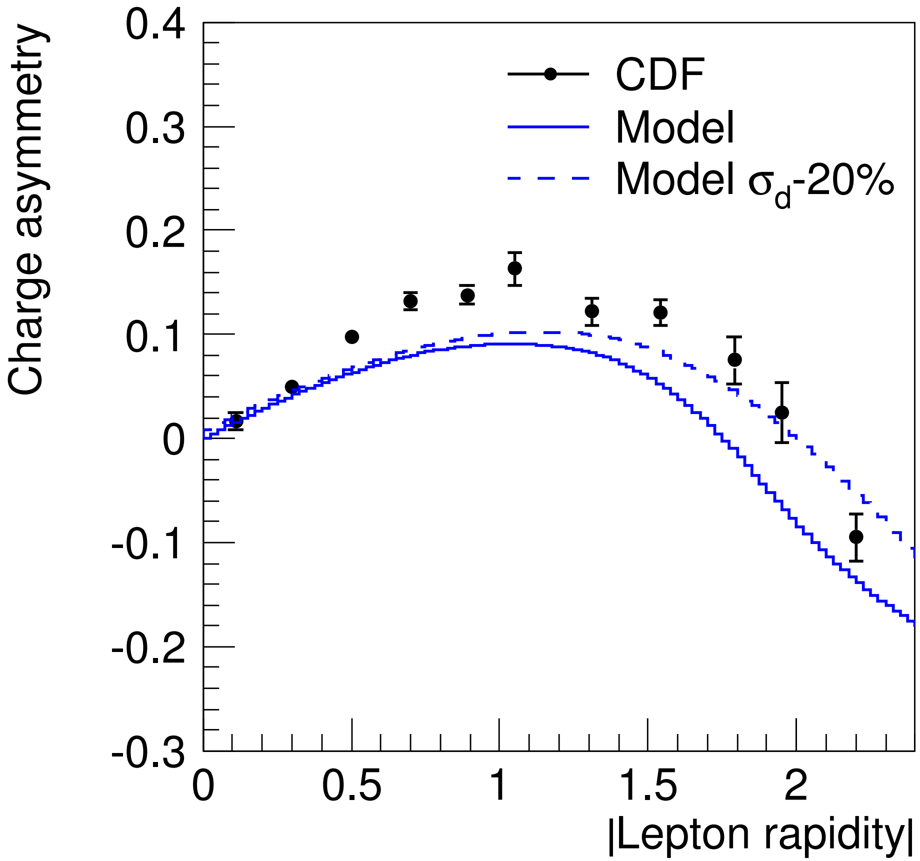
In $p\bar{p}$-collisions at Tevatron:

$$\left.\begin{array}{l} u\bar{d} \to W^+ \to l^+\nu_l \\ d\bar{u} \to W^- \to l^-\bar{\nu}_l \end{array}\right\} \Longrightarrow$$

charged lepton forward-backward asymmetry if different u and d spectrum:

$$A(y_l) = \frac{d\sigma^+/dy_l - d\sigma^-/dy_l}{d\sigma^+/dy_l + d\sigma^-/dy_l}$$

In our model: Different Gaussian widths σ_u and σ_d (due to Pauli exclusion?)



The $\bar{d}$ - $\bar{u}$ asymmetry

Perturbatively: $g \to q\bar{q}$ symmetric between $d\bar{d}$ and $u\bar{u}$ (DGLAP evolution)

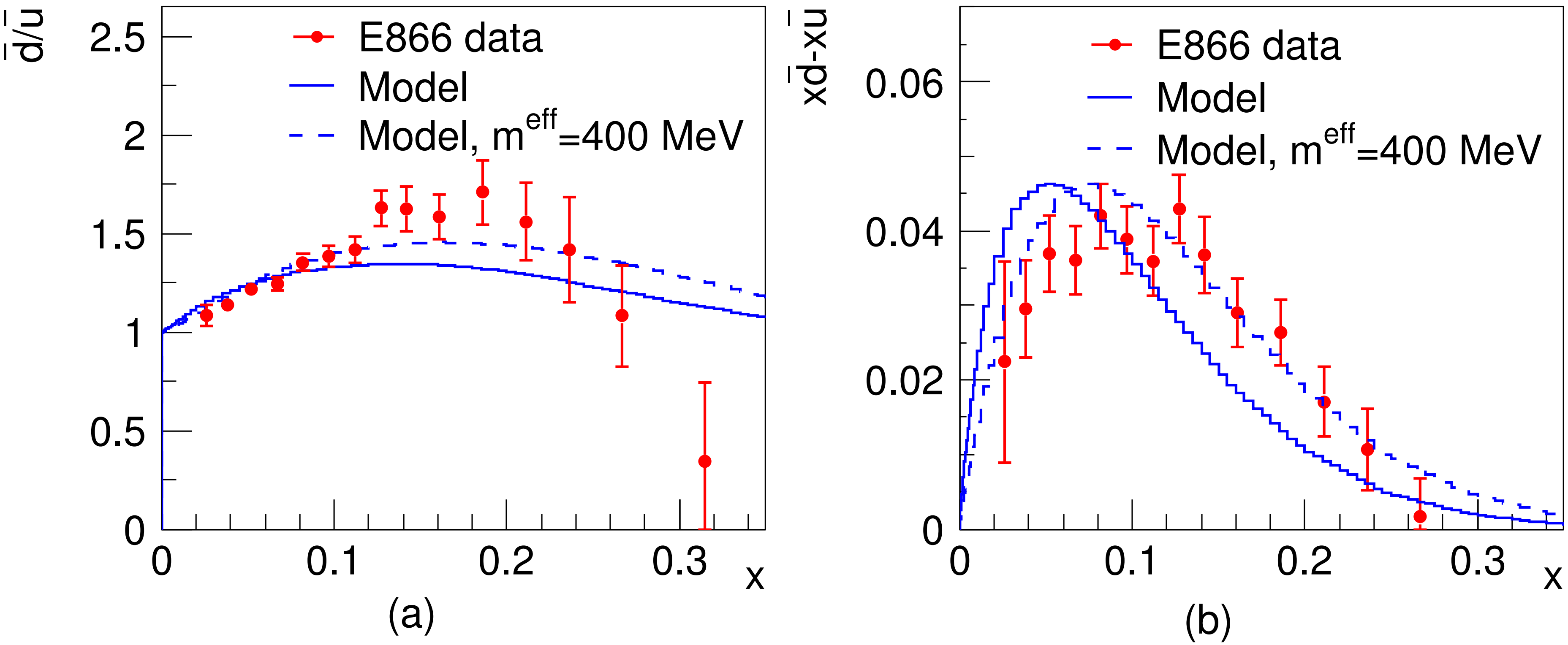
Non-perturbative start distributions: No symmetry law to forbid $d\bar{d} \neq u\bar{u}$

$\bar{d}/\bar{u}$ **measured experimentally** by comparing Drell-Yan lepton production in pp and pd collisions.

$\bar{d} - \bar{u}$ **obtained** from $\bar{d}/\bar{u}$ by assuming shape for $\bar{d} + \bar{u}$ – shows "directly" non-perturbative distributions.

In our model: Fluctuations $p \to p\pi^0$, $p \to n\pi^+$, but no $p \to N\pi^-$ component $\Longrightarrow$ Excess of $\bar{d}$ over $\bar{u}$.

The $\bar{d}$ - $\bar{u}$ asymmetry (cont.)



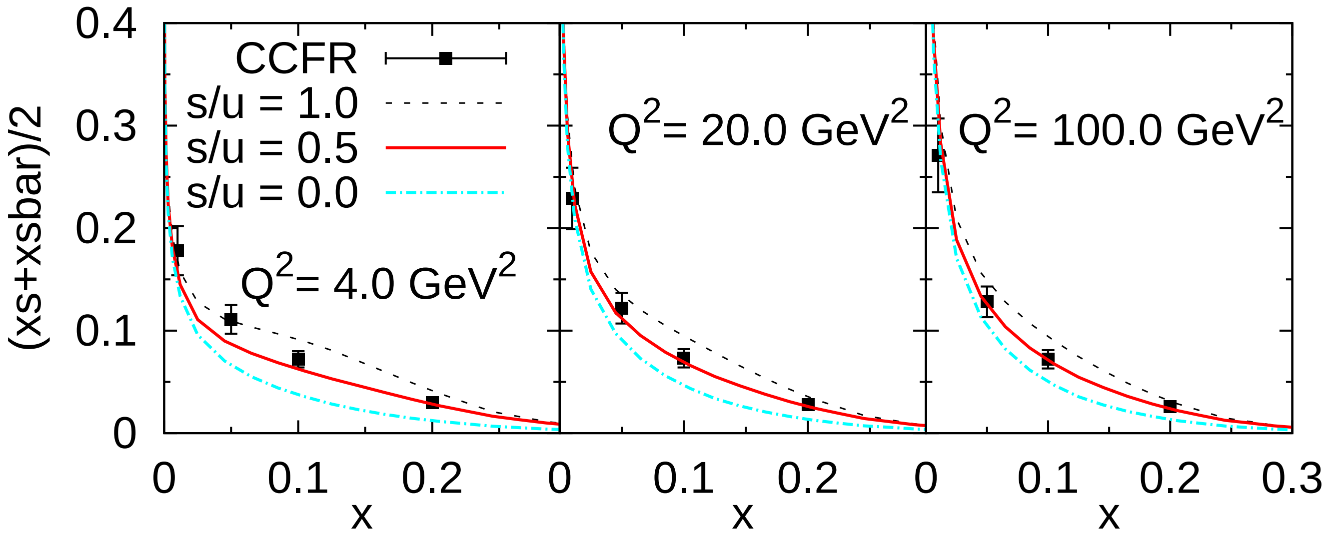
Fitted parameters: $\alpha^2_{p\pi^0}$ and $\alpha^2_{n\pi^+}$

Interesting observation:

Position of peak better described with "effective pion mass" $m^{\mathrm{eff}} \approx 400\ \mathrm{MeV}$.

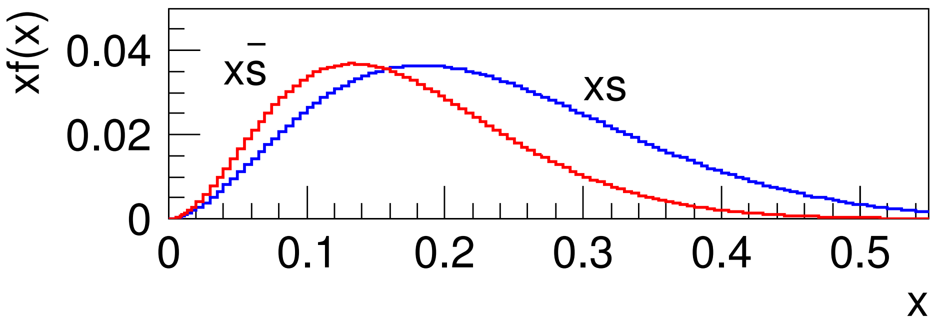
The strange sea

Lightest strange fluctuation $p \to \Lambda K^+$:
Normalization $\alpha^2_{\Lambda K}$ given by comparison to CCFR $\nu_\mu N \to \mu + c + X$ data



- s quark in (heavier) baryon Λ
- $\bar{s}$ quark in (lighter) meson K^+

$\Longrightarrow$



s distribution harder than $\bar{s}$ distribution

Strange sea asymmetry and the NuTeV anomaly

The NuTeV experiment: ratio of neutral to charged current interactions in $\nu_\mu N$ and $\bar{\nu}_\mu N$ scattering

$$R^- = \frac{\sigma(\nu_\mu N \to \nu_\mu X) - \sigma(\bar{\nu}_\mu N \to \bar{\nu}_\mu X)}{\sigma(\nu_\mu N \to \mu^- X) - \sigma(\bar{\nu}_\mu N \to \mu^+ X)}$$
$$= g_L^2 - g_R^2 = \frac{1}{2} - \sin^2\theta_W$$

Result: $\sin^2\theta_W$ (mixing parameter for the weak and EM interactions) which differs by 3σ from previous fits:

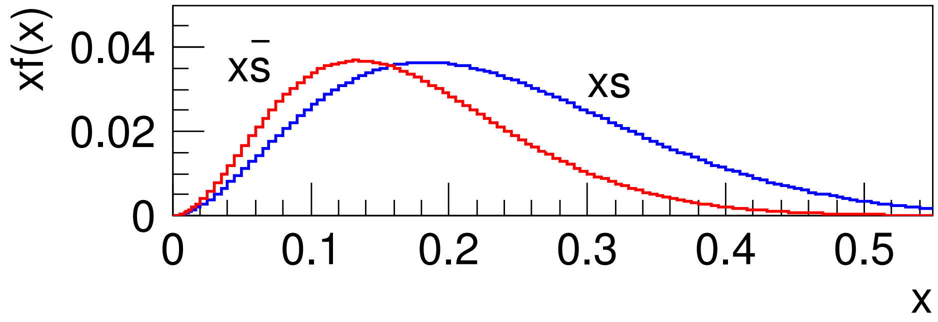
$$\sin^2\theta_W^{\mathrm{NuTeV}} = 0.2277 \pm 0.0016 \text{ while } \sin^2\theta_W^{\mathrm{SM}} = 0.2227 \pm 0.0004$$

Note: If $S^- = \int_0^1 [xs(x) - x\bar{s}(x)]dx \neq 0$, the NuTeV result is shifted since ν and $\bar{\nu}$ interact differently with s and $\bar{s}$

The NuTeV anomaly (cont)

In our model: $0.0010 \leq S^- = \int_0^1 [xs(x) - x\bar{s}(x)]dx \leq 0.0023$

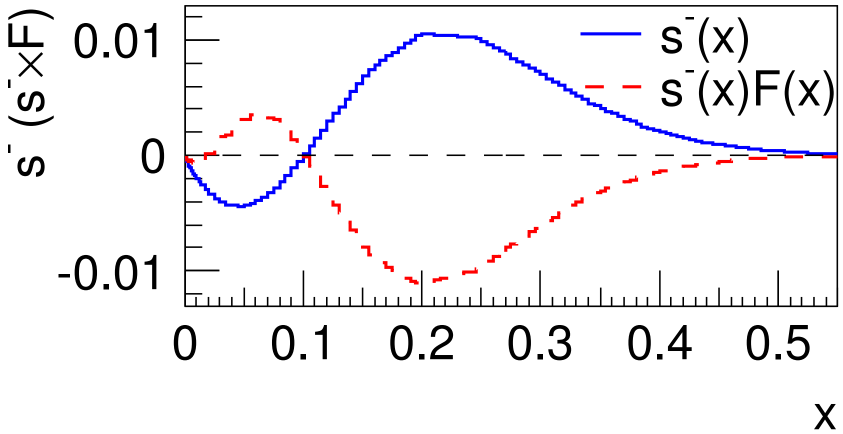
(with different details such as σ_d).



To calculate shift in $\sin^2\theta_W$:

$\Delta \sin^2\theta_W = \int_0^1 dx(xs(x) - x\bar{s}(x))F(x)$

($F(x)$ folding function from NuTeV)



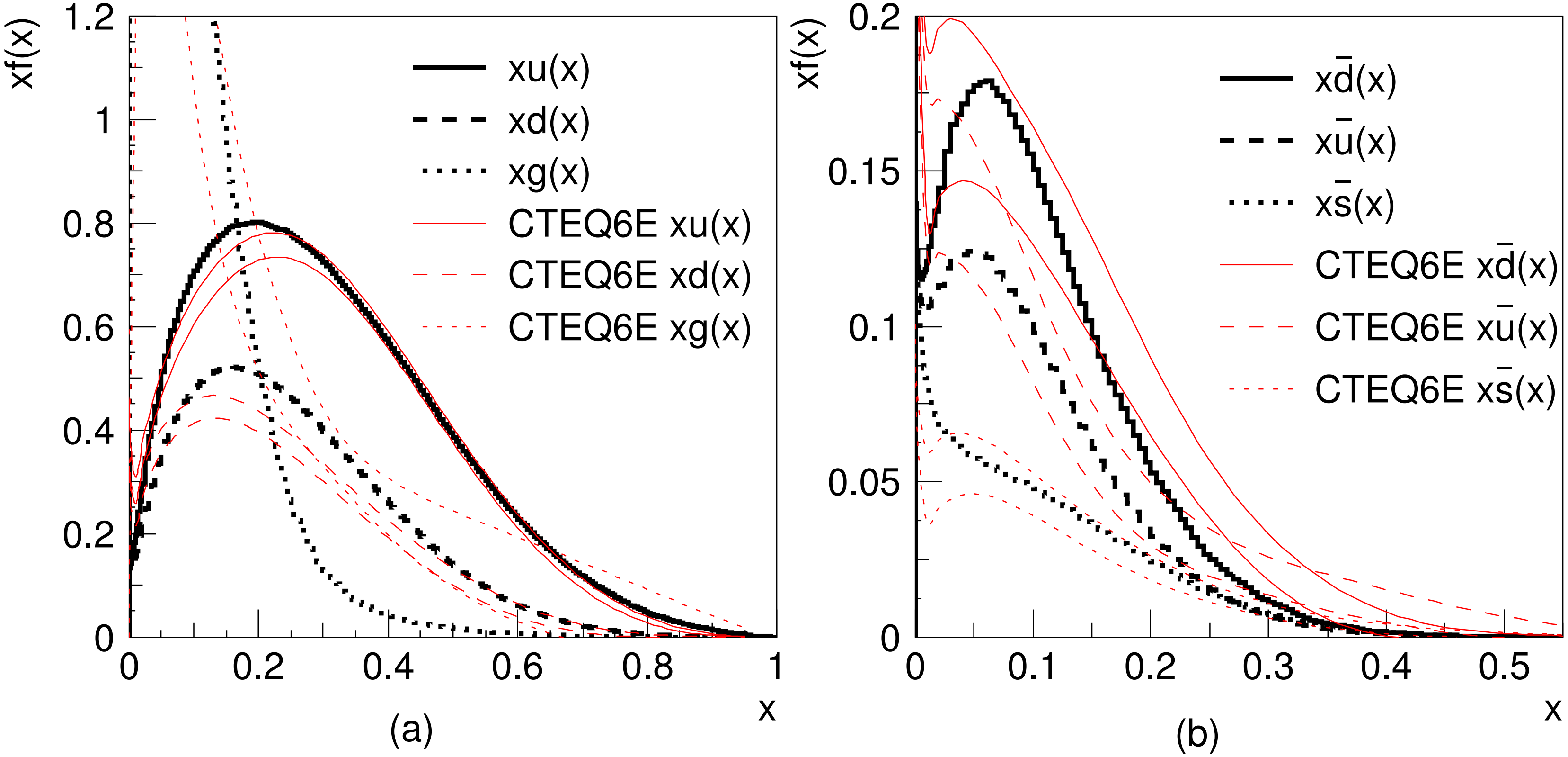
With our model:

$-0.0024 \leq \Delta \sin^2\theta_W \leq -0.00097$

$i.e.$ discrepancy reduced to $1.6 - 2.4\sigma$.

No longer need for explanation beyond the Standard Model.

Comparison with CTEQ distributions



- Very nice agreement for valence quarks
- Nice agreement for sea quarks
- Problem with gluons? Might be discussed...

CTEQ: "arbitrary" parametrization
> 20 parameters

Our model: Physically motivated
8 parameters

Conclusions

- Our physically motivated model based on Gaussian momentum fluctuation gives the x-shape of parton distribution functions in hadrons

- We describe sea quark distributions by hadronic fluctuations of the hadron

- The model gives a nice description of large-x valence quark data
  $\hookrightarrow$ Indicates that Gaussian momentum distributions OK

- We get a $\bar{u} - \bar{d}$ asymmetry in agreement with data
  $\hookrightarrow$ Meson-baryon fluctuations explain non-perturbative sea

- The model predicts an $s - \bar{s}$ asymmetry sufficient to reduce the NuTeV anomaly below 2σ
  $\hookrightarrow$ No hint of new physics

Comparison with CTEQ distributions (cont)