



# Quark Asymmetries in Nucleons

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Problem: non-perturbative  $x$ -shape of parton distributions  $f_i(x, Q_0^2)$

- Conventional parameterizations of pdf's:
  - + good fit of data on structure functions etc
  - many parameters required
  - no understanding of non-PQCD dynamics
- Our model for pdf's:
  - ± reasonable fit to data
  - + few parameters
  - + insights into non-PQCD dynamics

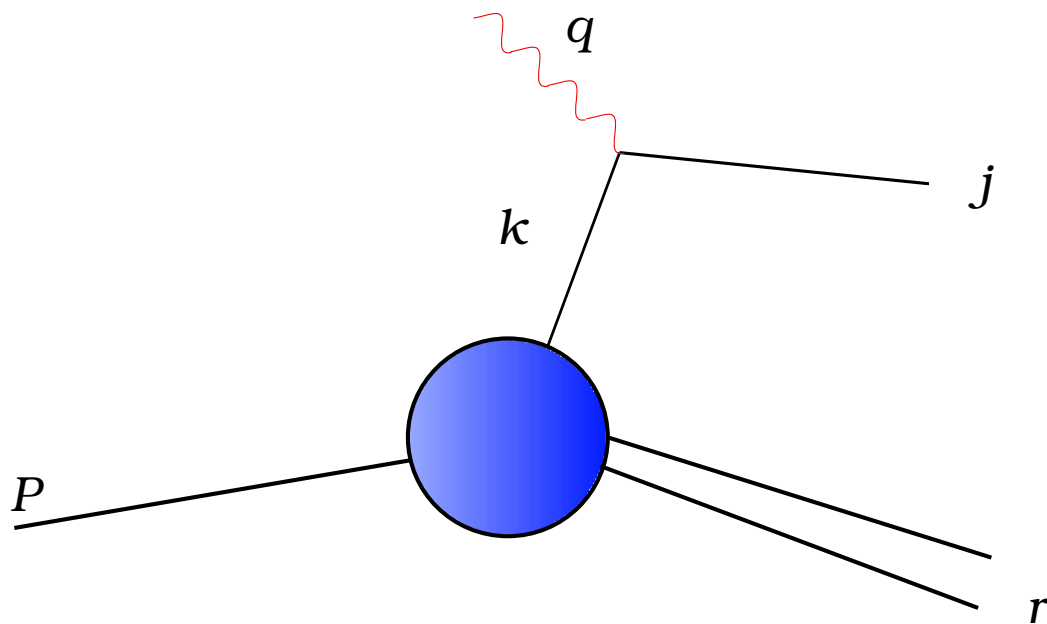
J.A. and G. Ingelman, hep-ph/0503099, 0407364, 0402248

# 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 (*cf.* intrinsic  $k_T$ ):



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

Kinematic constraints:

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

$$r^2 > 0$$

$\Rightarrow 0 \leq x \leq 1$  and  $f_i(x) \rightarrow 0$  as  $x \rightarrow 1$

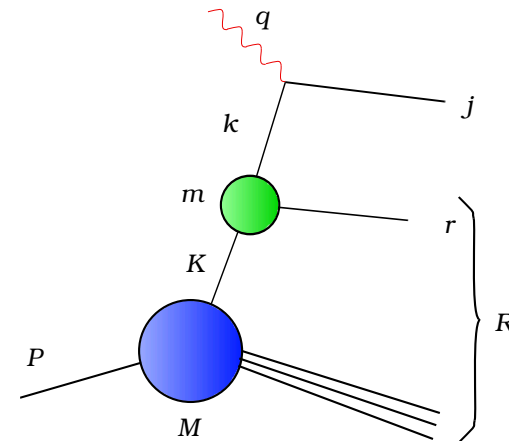
Monte Carlo-simulate to get  $x$  distribution.

# Our Model: Sea distributions

- **Hadronic quantum fluctuations:**

$$\begin{aligned}
 |p\rangle &= \alpha_0 |p_0\rangle + \alpha_{p\pi^0} |p_0\pi^0\rangle + \alpha_{n\pi^+} |n\pi^+\rangle \\
 &+ \dots + \alpha_{\Lambda K} |\Lambda K^+\rangle + \dots \\
 &+ \alpha_{\Lambda_C D} |\Lambda_C^+ \bar{D}^0\rangle + \dots
 \end{aligned}$$

- **Gaussian momentum distribution** of meson and baryon (in  $P$  rest frame)
- **Photon probes parton in meson or baryon**
- **Normalization: fit effective  $\alpha_{BM}^2$**  effectively including Clebsch-Gordan coefficients, unknown mass suppression and mixing of states



$$x_H = K_+ / (K + K_{\text{partner}})_+$$

$$x_p = k_+ / K_+$$

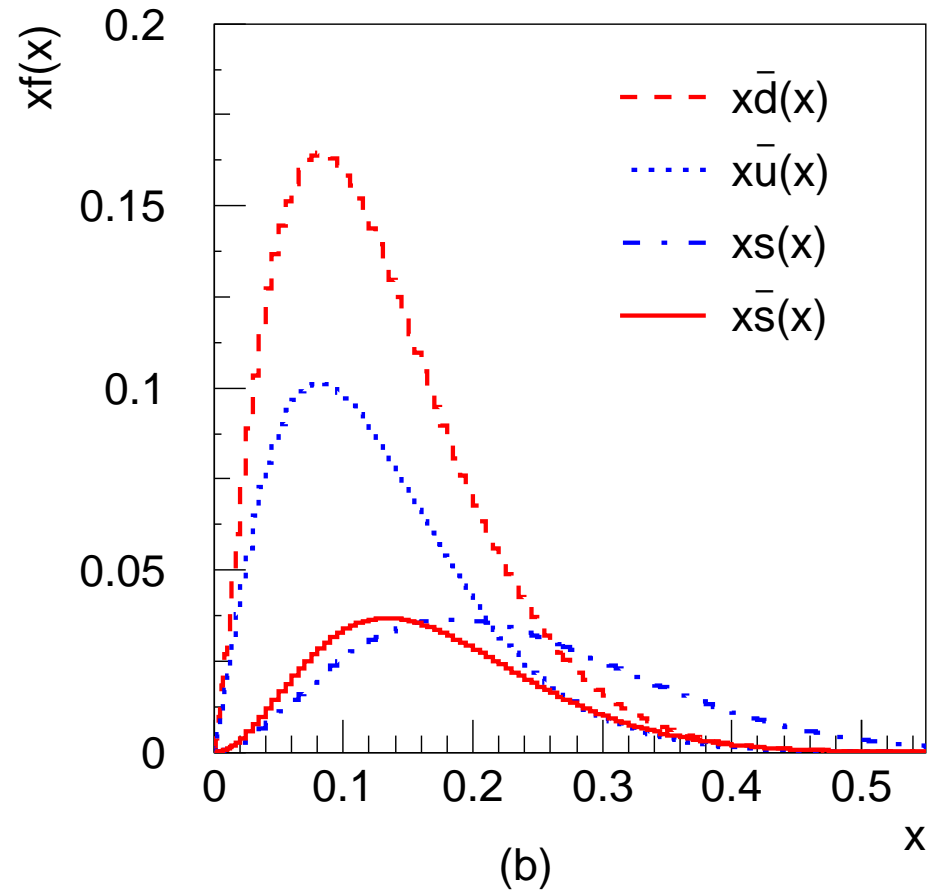
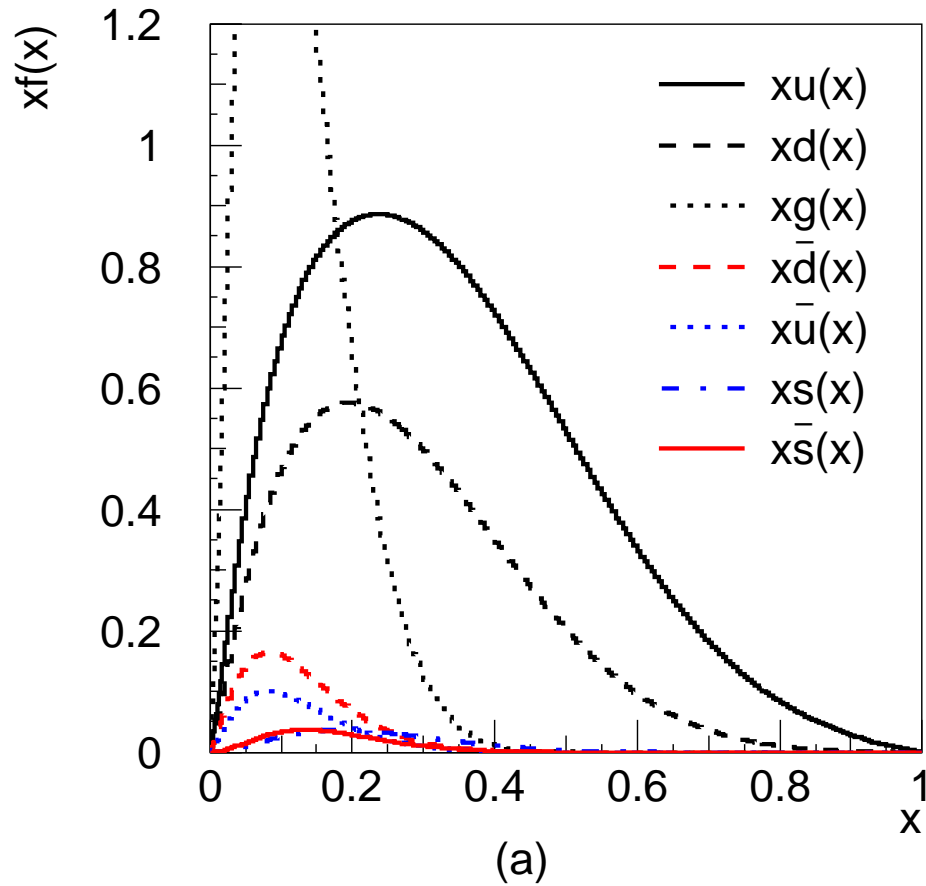
$$x = x_H \cdot x_p$$

Kinematic constraints:

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

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

# Resulting distributions



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

# Parameters and experimental data

Parameters:

$$\begin{aligned}\sigma_u &= 230 \text{ MeV} & \sigma_d &= 170 \text{ MeV} & \sigma_g &= 77 \text{ MeV} & \sigma_H &= 100 \text{ MeV} \\ \alpha_{p\pi^0}^2 &= 0.45 & \alpha_{n\pi^+}^2 &= 0.14 & \alpha_{\Lambda K}^2 &= 0.05 \\ Q_0 &= 0.75 \text{ GeV}\end{aligned}$$

DGLAP evolution:

QCDNUM16: NLO evolution in  $\overline{MS}$  scheme

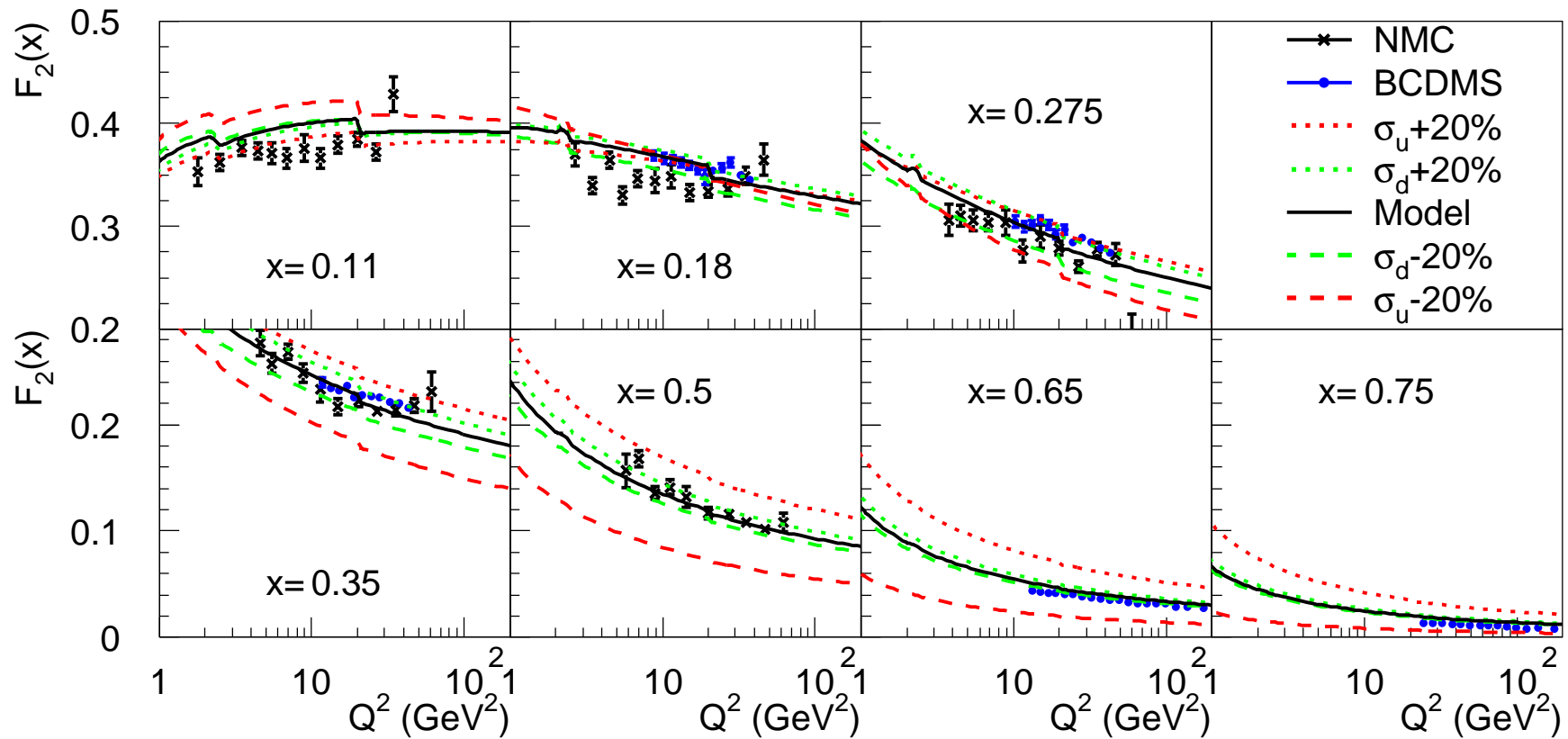
Experimental data sets (to fix the free parameters):

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

Simultaneous fit to all data sets

# Fixed-target DIS data

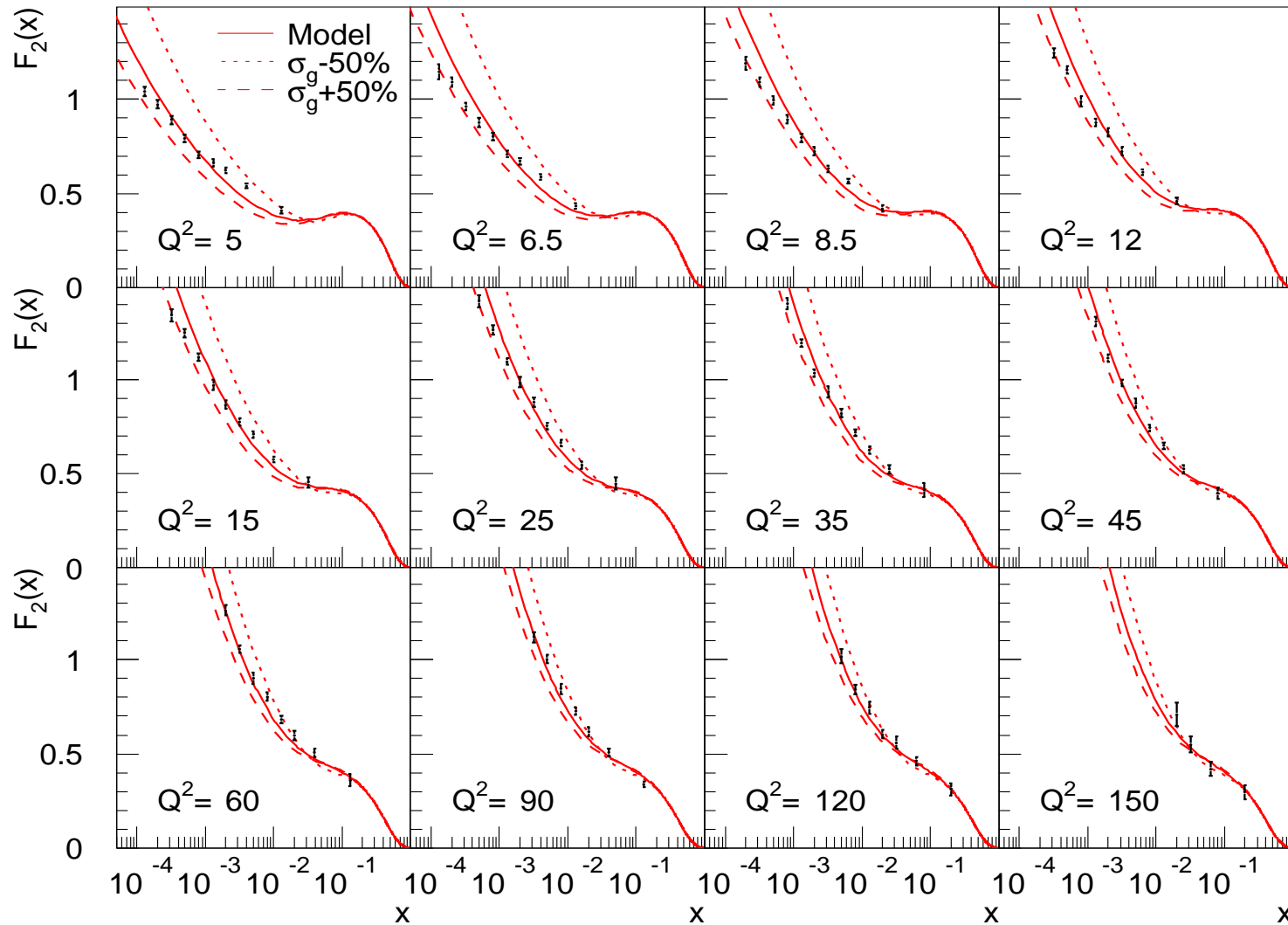
NMC and BCDMS  $F_2$  data fixes large- $x$  valence distributions ( $\sigma_u, \sigma_d$ )



Harder constraints on  $u$  distribution than on  $d$  distribution

# HERA DIS data

H1 small- $x$   $F_2$  data fixes gluon distribution ( $\sigma_g$ ) and starting scale  $Q_0$



# $W^\pm$ asymmetry data

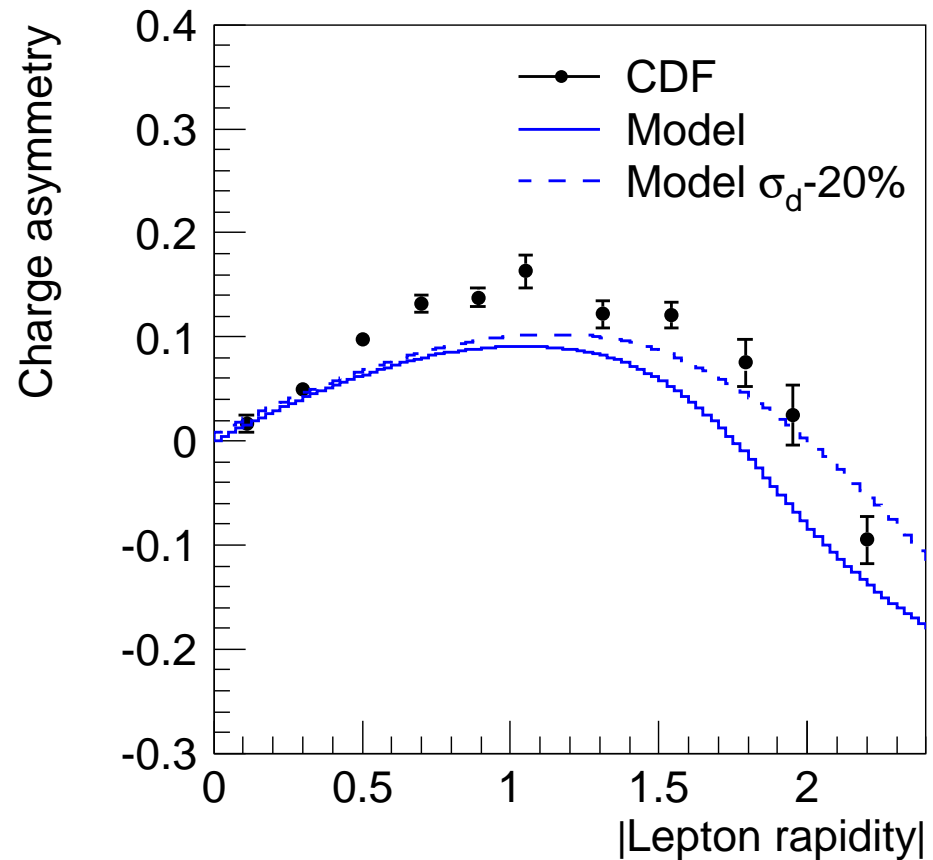
In  $p\bar{p}$ -collisions at Tevatron:

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

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  $\sigma_u$  and  $\sigma_d$  (due to Pauli exclusion?)



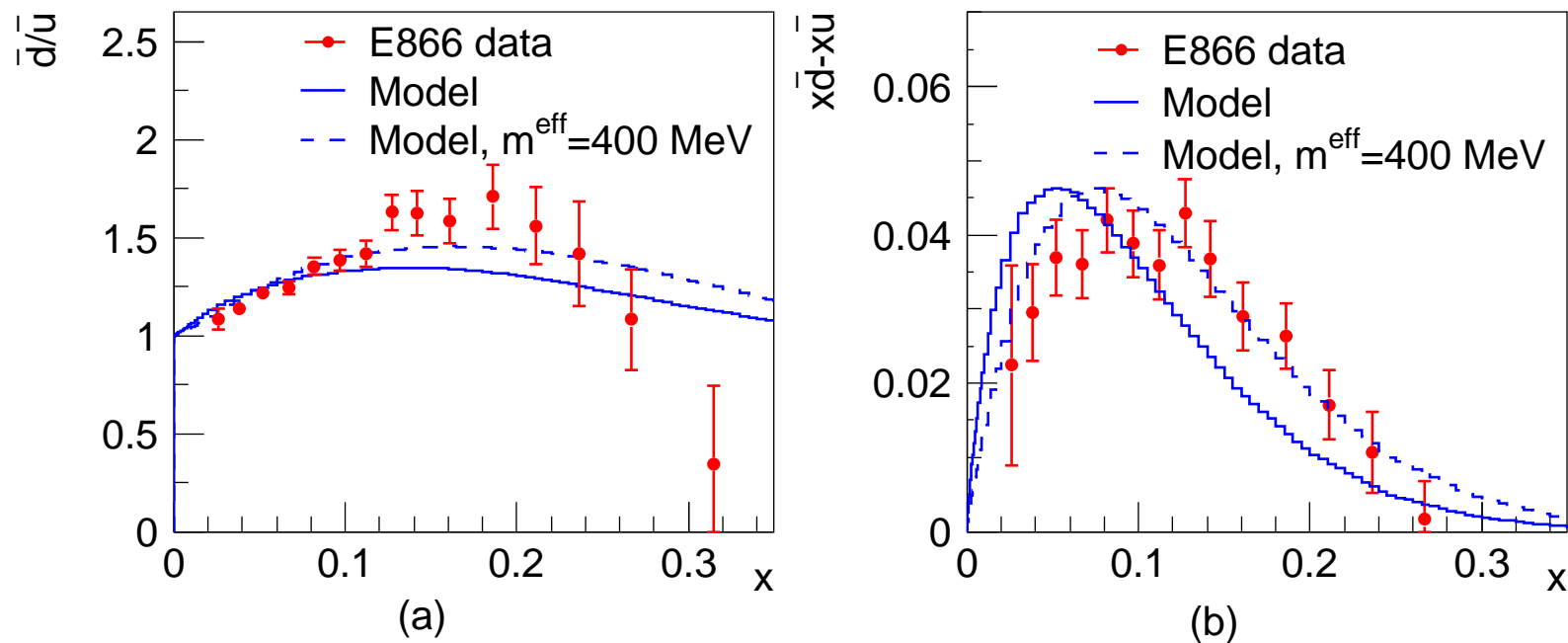


# The $\bar{d} - \bar{u}$ asymmetry

Pert. QCD  $g \rightarrow q\bar{q}$  gives  $\bar{d} - \bar{u}$  symmetry, but no symmetry forbids  $d\bar{d} \neq u\bar{u}$

Fluctuations  $p \rightarrow p\pi^0$ ,  $p \rightarrow n\pi^+$ , but only  $p \rightarrow \Delta^{++}\pi^- \Rightarrow$  excess of  $\bar{d}$  over  $\bar{u}$

Fitted parameters to Drell-Yan data in  $pp$  and  $pd$  scattering:  $\alpha_{p\pi^0}^2$  and  $\alpha_{n\pi^+}^2$

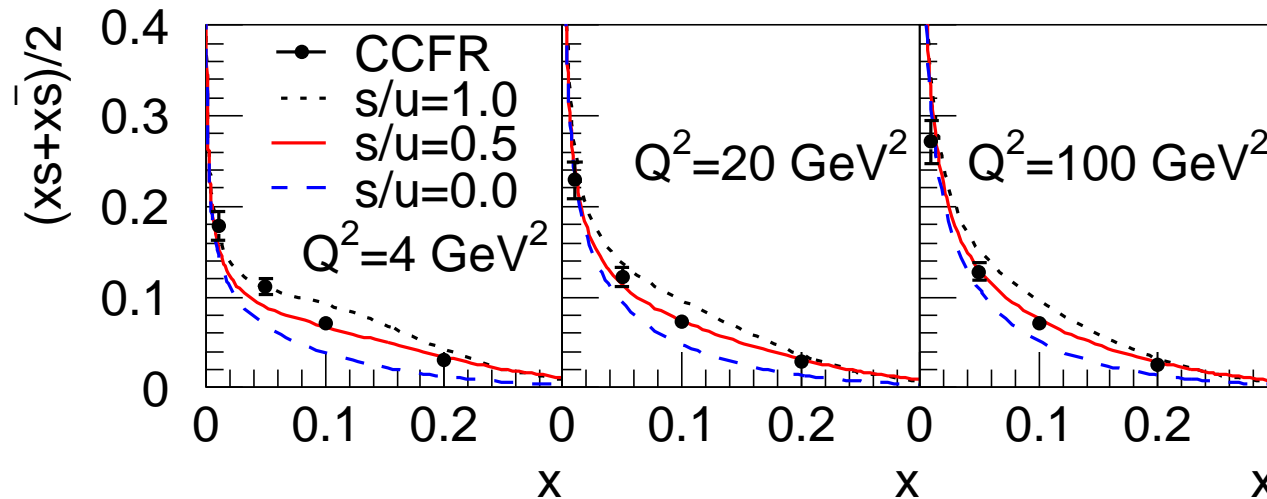


Note: Position of peak better described with effective pion mass  $m^{\text{eff}} \approx 400$  MeV may account for heavier mesons, *e.g.*  $|N\rho\rangle$ , or generic meson states?

# The strange sea

Lightest strange fluctuation  $p \rightarrow \Lambda K^+$ :

Normalization  $\alpha_{\Lambda K}^2$  given by comparison to CCFR  $\nu_\mu N \rightarrow \mu + c + X$  data



$(s + \bar{s})/(\bar{u} + \bar{d}) \approx 0.5$  as

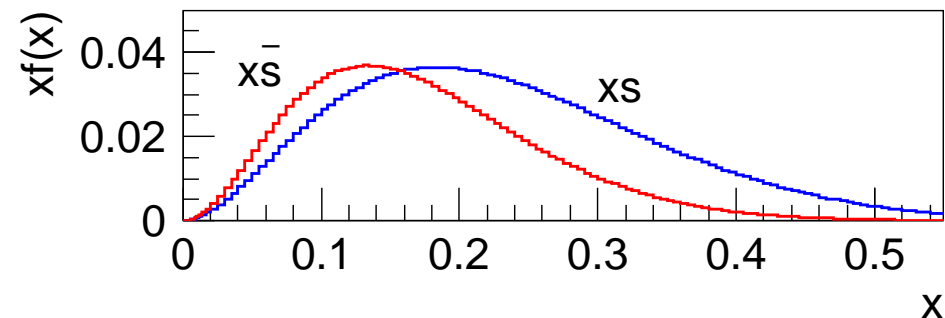
- pdf parameterizations

- hadronization models

Lund  $\frac{P(s\bar{s})}{P(u\bar{u}+d\bar{d})/2} \simeq \frac{1}{3}$

Norm  $\sim 1/\Delta M_{BM}$   
(Cf. OFPT  $1/\Delta E^2$ )

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



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

# Strange sea asymmetry and the NuTeV anomaly

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

NuTeV obtains  $\sin^2 \theta_W^{\text{NuTeV}} = 0.2277 \pm 0.0016$ ,  $3\sigma$  deviation from previous fits of Standard Model  $\sin^2 \theta_W^{\text{SM}} = 0.2227 \pm 0.0004$ , *i.e.* an anomaly!

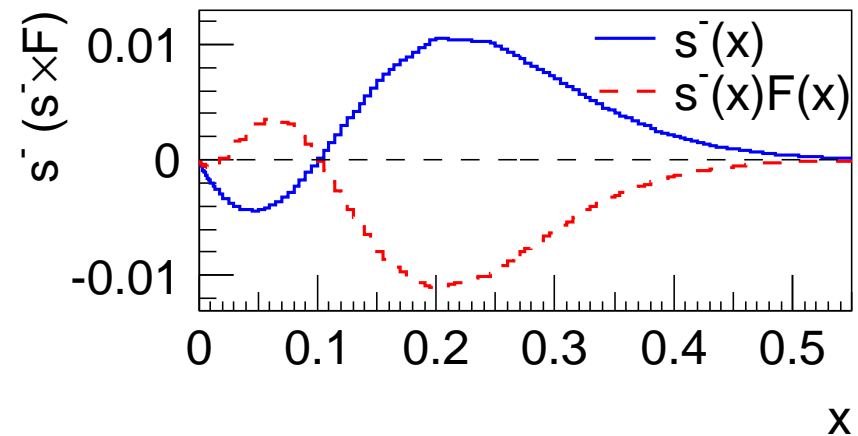
**But**, if  $x s(x) \neq x \bar{s}(x)$  since  $\nu s \rightarrow \mu^- c$  and  $\bar{\nu} \bar{s} \rightarrow \mu^+ \bar{c}$  then give different  $\sigma$ 's

$\Rightarrow$  shift  $\Delta \sin^2 \theta_W = \int_0^1 dx [x s(x) - x \bar{s}(x)] F(x)$  ( $F(x)$  is NuTeV folding function)

**Our model:**  $0.0010 \leq S^- = \int_0^1 dx [x s(x) - x \bar{s}(x)] \leq 0.0023$  (varying details,  $\sigma_d$ )

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

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



No significant indication for physics beyond the Standard Model

# Intrinsic charm

Intrinsic charm component from  $|\Lambda_{CD}\rangle$  and other charmed fluctuations.

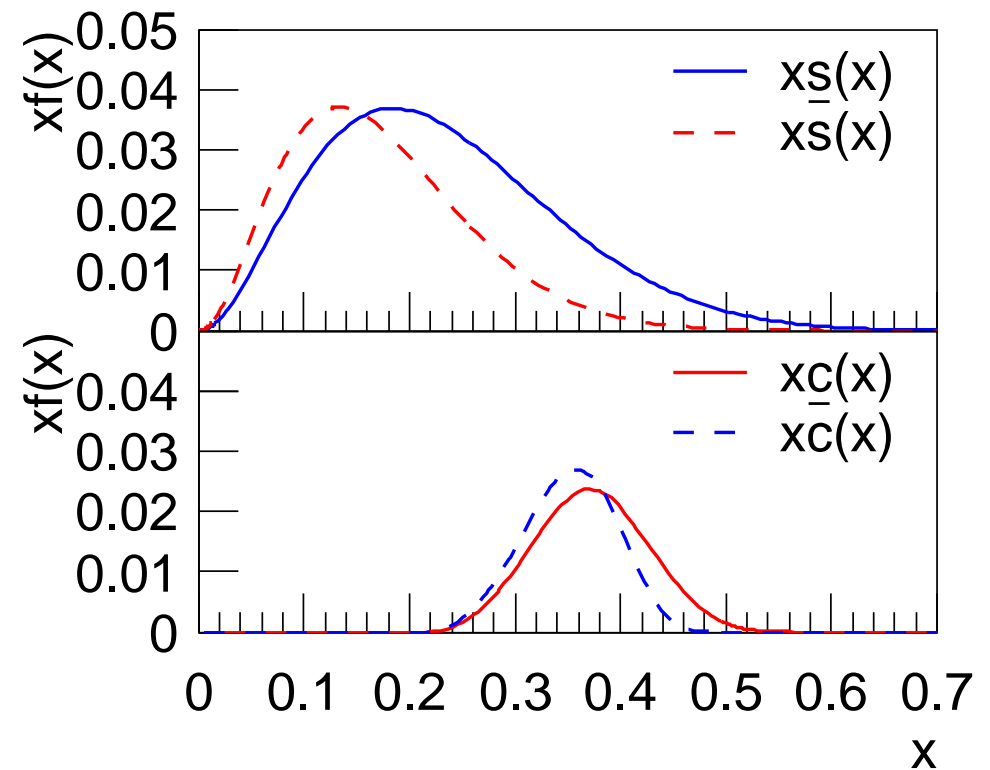
**Just for fun:** Assume normalization as  $1/\Delta M_{BM}$  (as suggested by strange sea data)

$$\Rightarrow \alpha_{\Lambda_{CD}}^2 \approx \alpha_{\Lambda_K}^2/5$$

*Cf.* S.J. Brodsky, et al.,  
Phys. Lett. B 93, 451 (1980)

Might explain EMC data: excess of charm at  $x > 0.3$   
(and other experiments observing charmed states at large  $x$ )

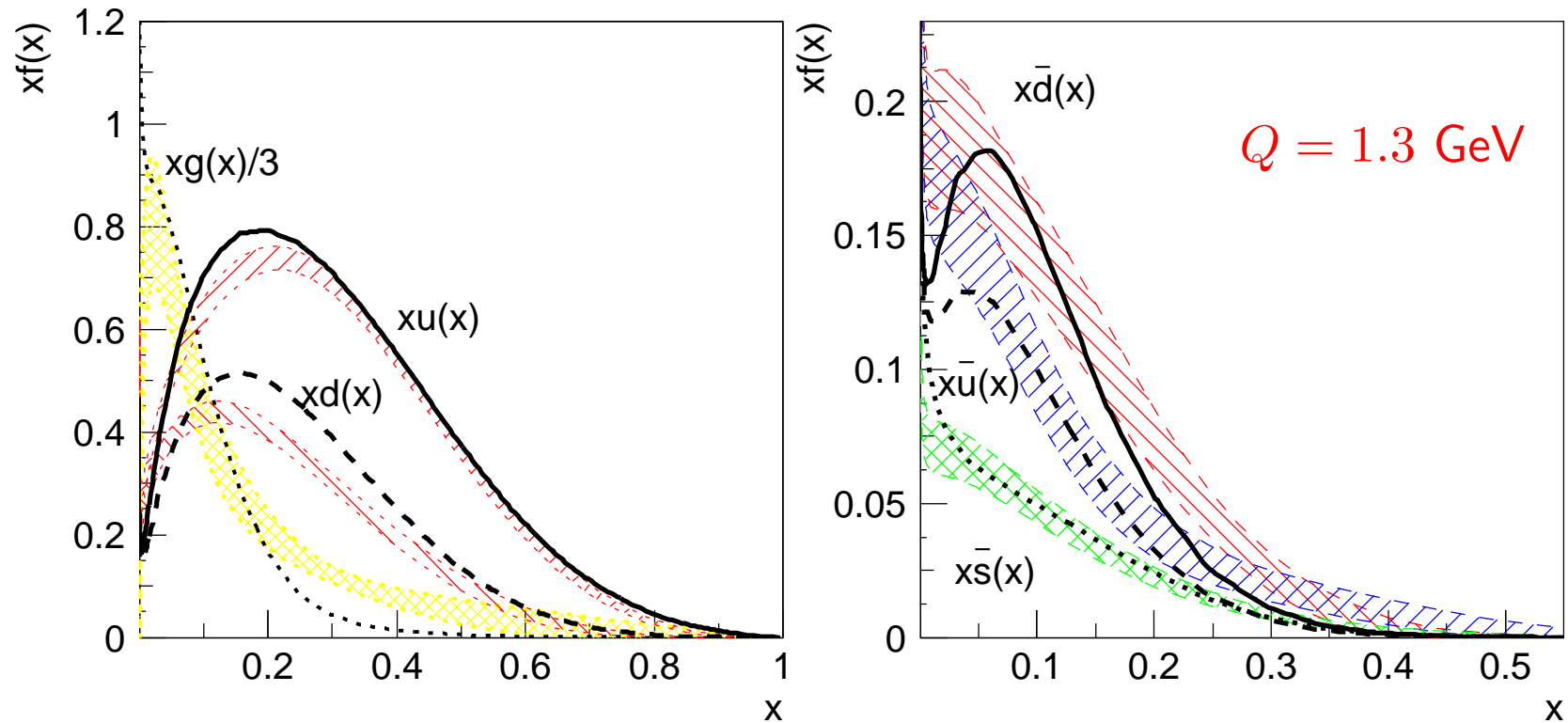
Also B hadron fluctuations might be interesting to look at.



## Comparison with CTEQ6M distributions

CTEQ: “arbitrary” parameterization, 20 shape parameters (+ normalization)

Our model: physically motivated, 4 shape parameters with reasonable values



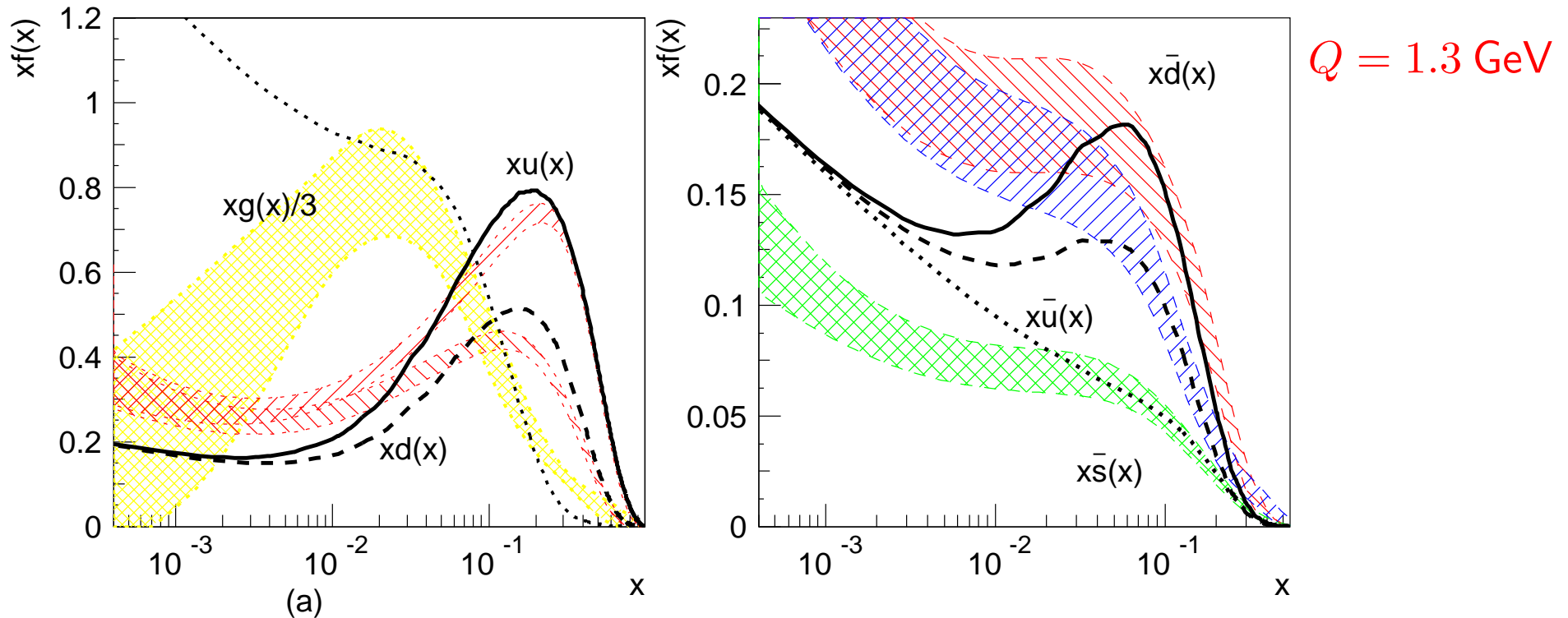
For  $x \gtrsim 10^{-2}$

- valence and sea quarks agree with CTEQ
- gluon lower than CTEQ at large  $x$

## Comparison with CTEQ6M cont.

CTEQ:  $xq(x) \rightarrow x^{-0.3}$  for  $x \rightarrow 0$  at  $Q_0 = 1.3$  GeV with  $xg(x) \rightarrow 0$

Our model:  $xf(x) \rightarrow 0$  for  $x \rightarrow 0$  at  $Q_0 = 0.75$  GeV  $\Rightarrow$  low- $x$  sea from  $g$  splitting



For  $x \lesssim 10^{-2}$ : Gluon larger than CTEQ, but  $u\bar{u}$  and  $d\bar{d}$  sea lower than CTEQ

Large  $xg(x, Q_0^2)$  and low  $Q_0^2$  needed to give low- $x$  quark sea via DGLAP

$\Rightarrow$  Need for additional source of  $q\bar{q}$  without accompanying gluons !?

## Possible source of $q\bar{q}$ : GVDM in $ep$ at low $Q^2$

Quantum fluctuations of photon:

$$|\gamma\rangle = C_0|\gamma_0\rangle + \sum_V \frac{e}{f_V}|V\rangle + \int_{m_0} dm_V(\dots)|V\rangle$$

i.e. photon  $\rightarrow$  vector mesons  $V = \rho^0, \omega, \phi \dots$  + continuum

followed by  $Vp \rightarrow X$  with soft hadronic cross-section

$$\sigma_{T,L}^{\text{GVDM}} = P(\gamma \rightarrow V)\sigma_{Vp}; \sigma_{Vp} = A_V s^\epsilon + B_V s^{-\eta}; \epsilon \approx 0.08$$

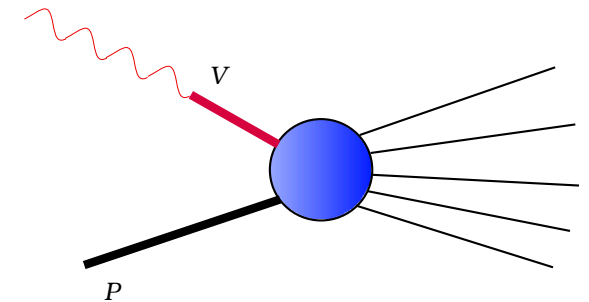
$$s_{\gamma p} = Q^2 \frac{1-x}{x} + m_p^2 \approx Q^2/x \text{ at small-}x$$

$$\Rightarrow F_2^{\text{GVDM}}(x, Q^2) = \frac{(1-x)Q^2}{4\pi^2\alpha} \left\{ \sum_V r_V \left( \frac{m_V^2}{Q^2+m_V^2} \right)^2 \left( 1 + \xi \frac{Q^2}{m_V^2} \right) + r_C \frac{m_0^2}{Q^2+m_0^2} \right\} A \left( \frac{Q^2}{x} \right)^\epsilon$$

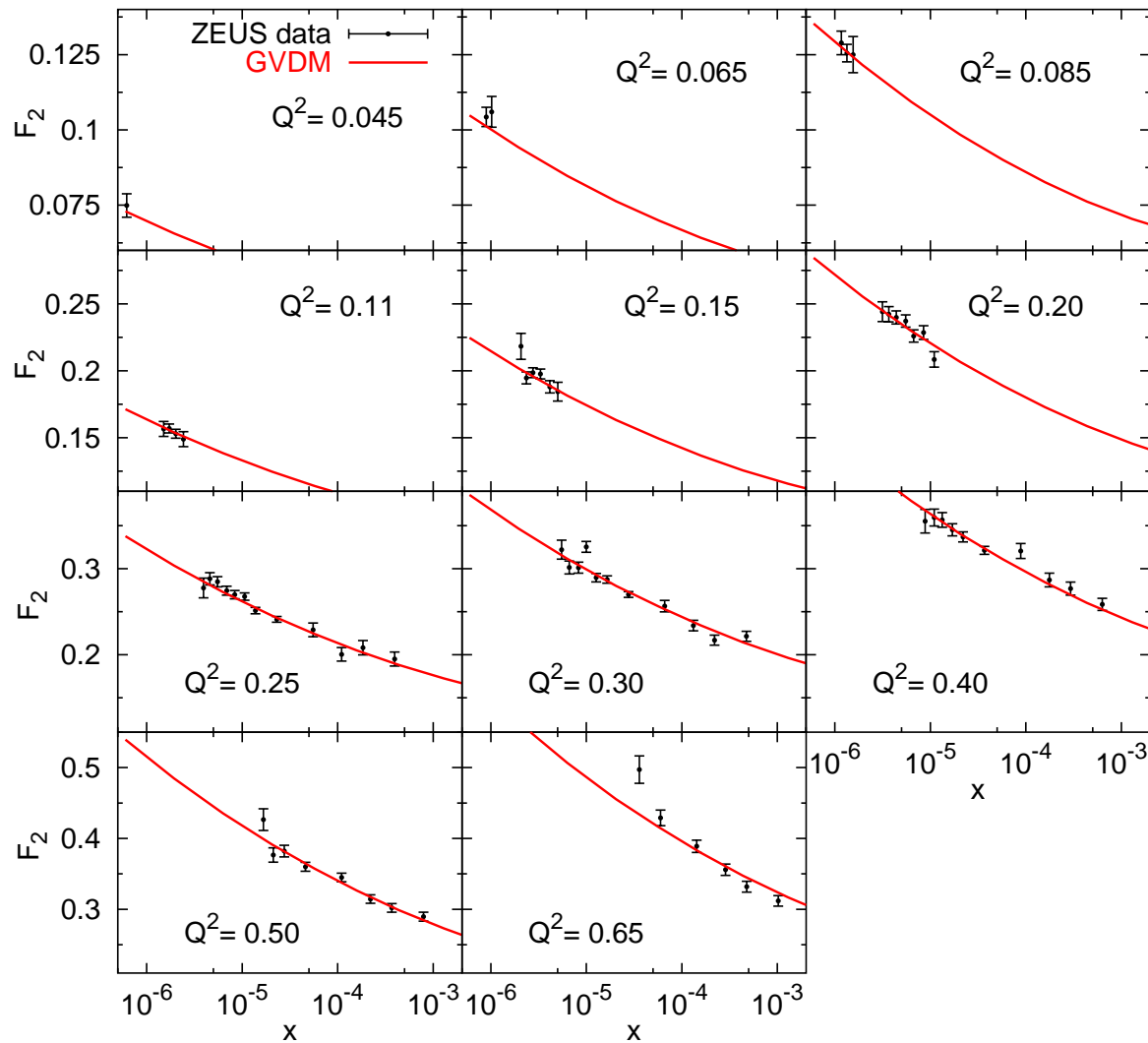
More complex  $Q^2$ -dependence from  $\sigma_L$  and continuum than simple VDM

Parameters 'known' from GVDM:  $r_V = \frac{4\pi\alpha}{f_V^2} \frac{A_V}{A}$ ,  $r_C = 1 - \sum_V r_V$

$m_0 \approx 1 \text{ GeV}$ ,  $r_{V=\rho,\omega,\phi,C} = 0.67, 0.062, 0.059, 0.21$ ;  $\xi \approx 0.25$



# HERA $F_2$ at low $Q^2$



ZEUS 1997 data

GVDM model fits well

$$\chi^2 = 87 / (70 - 4) = 1.3$$

with parameter values

$$\epsilon = 0.091$$

$$m_0 = 1.5 \text{ GeV}$$

$$A = 71 \mu\text{b}$$

$$\xi = 0.34$$

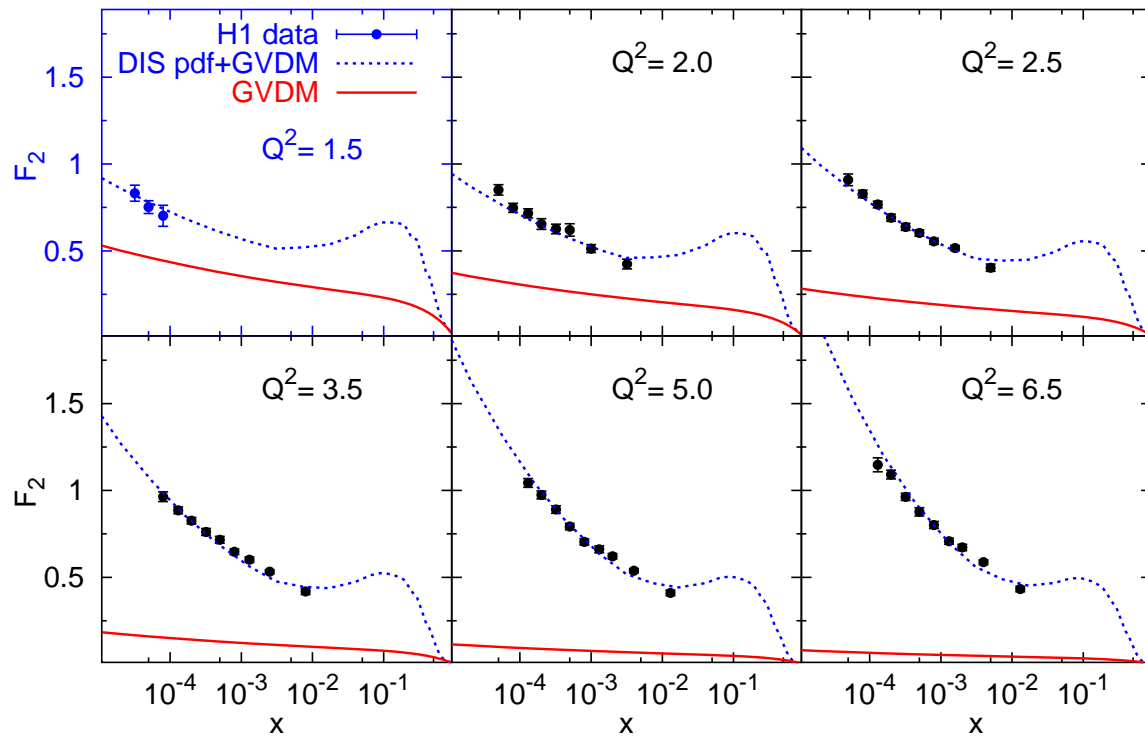
as expected

For higher  $Q^2$  and  $x$  need parton densities – how to combine?



# HERA $F_2$ at intermediate $Q^2$

Simplest solution: Use GVDM scale-down factor (form factor) for higher  $Q^2$



GVDM  $\times \left(\frac{Q_0^2}{Q^2}\right)^a$  with  $a = 1.8$   
 for  $Q^2 > Q_0^2 = 1.26$  (fitted)  
 $\rightarrow$  GVDM negligible for  $Q^2 \gtrsim 3$

Adding parton densities,  
 here Alwall-Edin-Ingelman model,  
 gives good description of data  
 without negative gluon density

# Summary

- Our physically motivated model, based on Gaussian momentum fluctuations, gives the  $x$ -shape of parton distribution functions in hadrons  $f_i(x, Q_0^2)$
- Sea quark distributions from hadronic quantum fluctuations, *e.g.*  $|N\pi\rangle$ ,  $|\Lambda K\rangle$
- Nice description of large- $x$  valence quark data  
↳ Gaussian momenta OK → statistical description of non-perturbative dynamics
- Large- $x$  valence and sea quark behavior  $\sim$  CTEQ, but small- $x$  and gluon differs!?
- $\bar{u} - \bar{d}$  asymmetry in agreement with data  
↳ Meson-baryon fluctuations explain non-perturbative sea
- $s - \bar{s}$  asymmetry sufficient to reduce the NuTeV anomaly below  $2\sigma$   
↳ No strong hint of new physics
- Prediction of intrinsic charm in nucleons due to charmed fluctuations