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# 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:
  - $\pm$ reasonable fit to data
  - $+$ few parameters
  - $+$ insights into non-PQCD dynamics

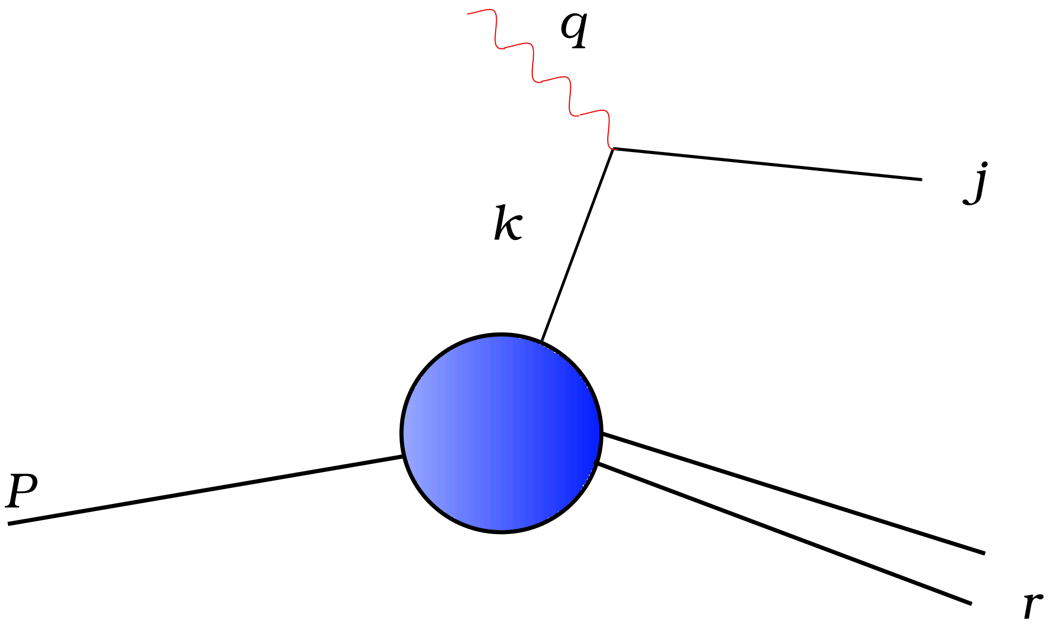
J.A. and G. Ingelman, hep-ph/0503099, 0407364, 0402248

# Our Model: Valence distributions

In hadron rest frame:

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

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

$\Rightarrow 0 \le x \le 1$ and $f_i(x) \to 0$ as $x \to 1$

Monte Carlo-simulate to get $x$ distribution.

# Our Model: Sea distributions

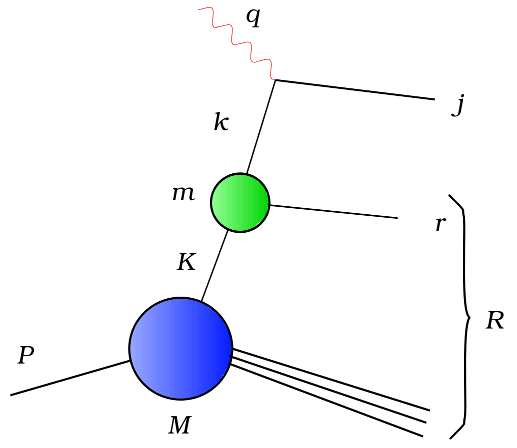
- Hadronic quantum fluctuations:

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

- Gaussian momentum distribution of meson and baryon (in $P$ rest frame)

- Photon probes parton in meson or baryon

- Normalization: fit effective $\alpha^2_{BM}$ effectively including Clebsch-Gordan coefficients, unknown mass suppression and mixing of states



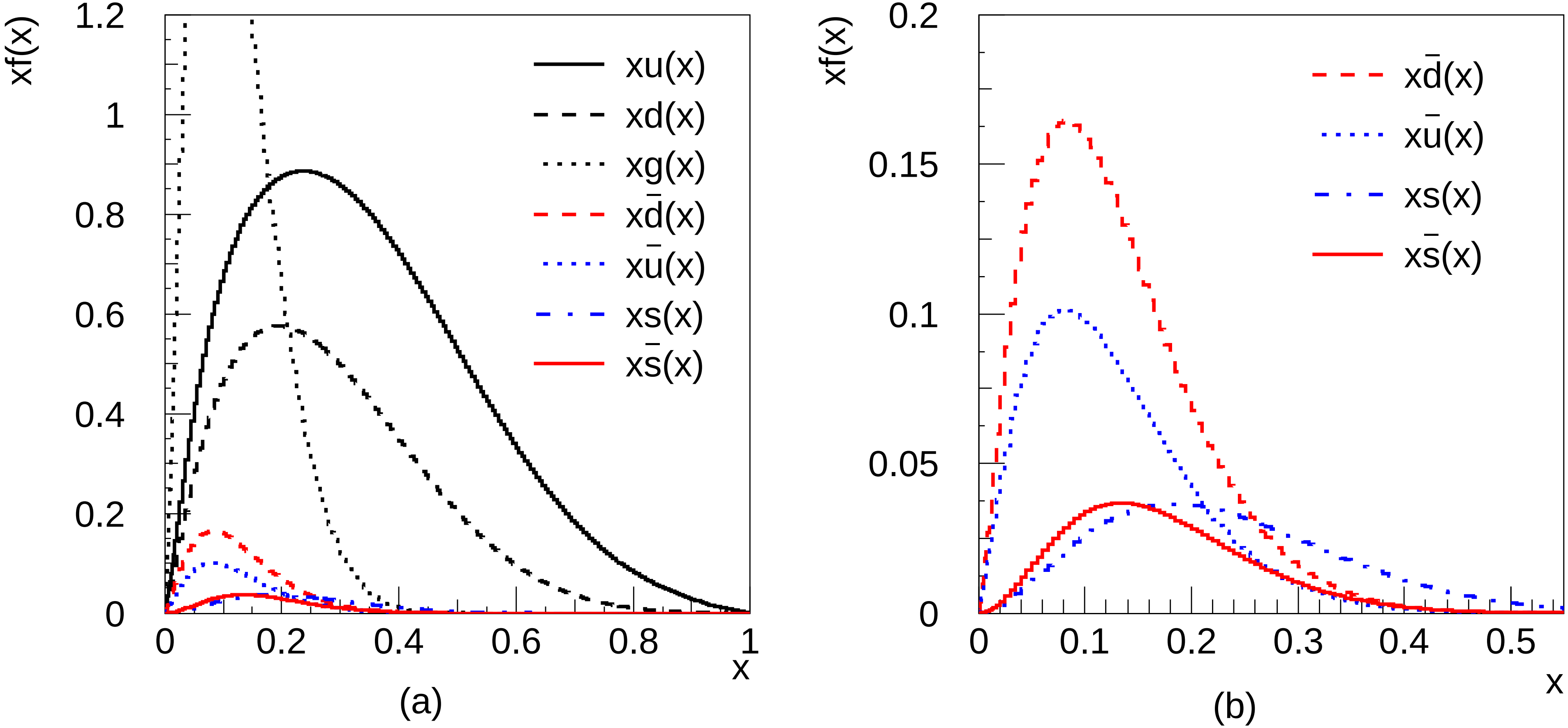

$$\begin{aligned} x_H &= K_+/(K + K_{\text{partner}})_+ \\ x_p &= k_+/K_+ \\ x &= x_H \cdot x_p \end{aligned}$$

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:

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

DGLAP evolution:

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

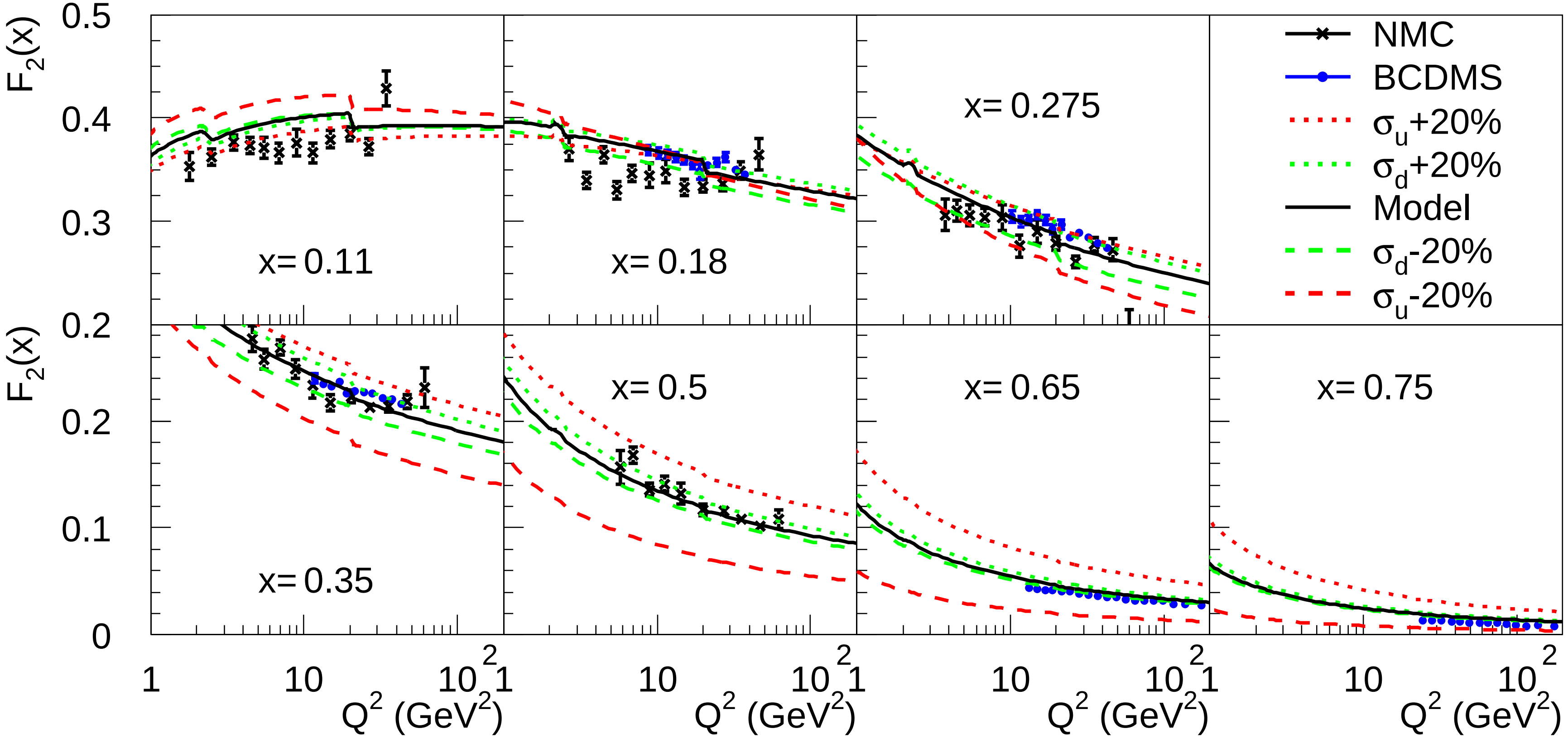
Experimental data sets (to fix the free parameters):

- 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

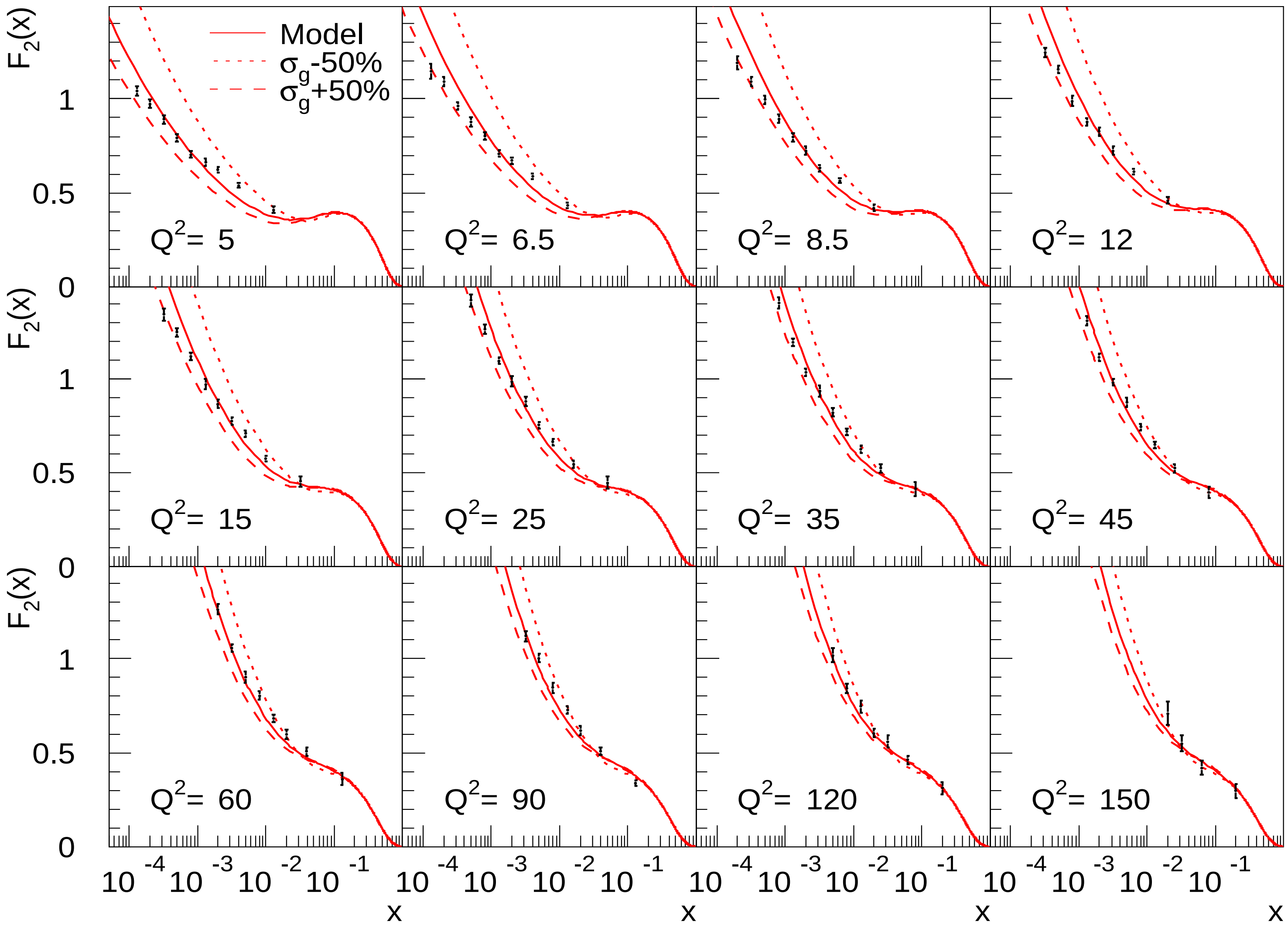
NMC and BCDMS $F_2$ data fixes large-$x$ valence distributions $(\sigma_u,\ \sigma_d)$




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

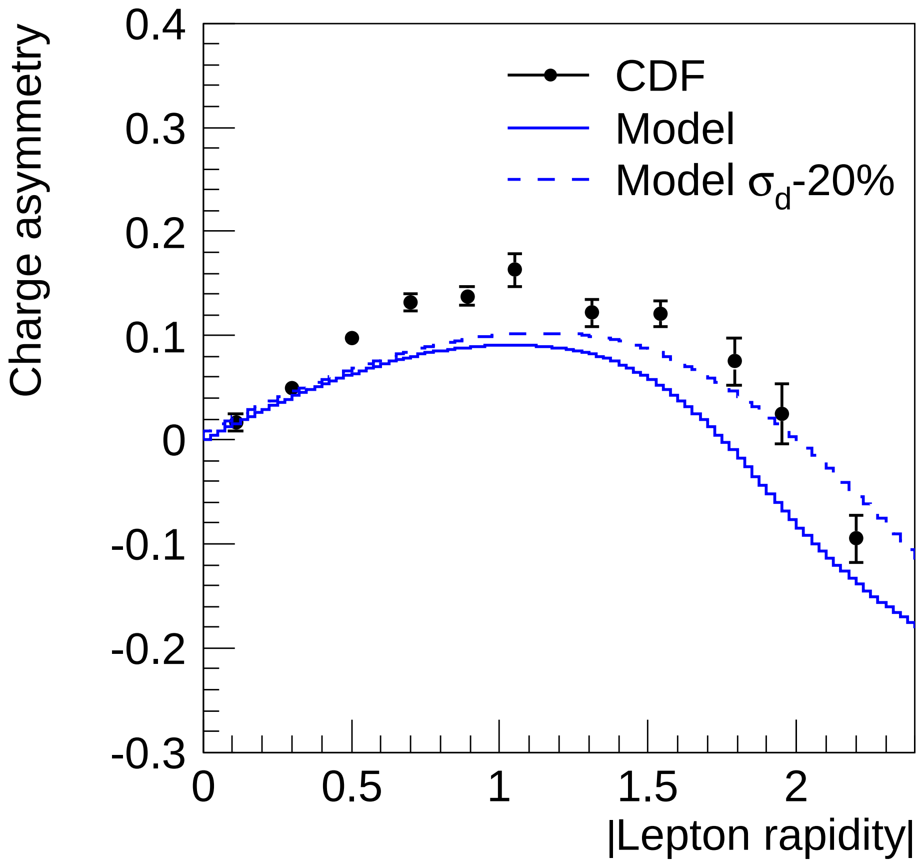
In $p\bar{p}$-collisions at Tevatron:

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

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?)

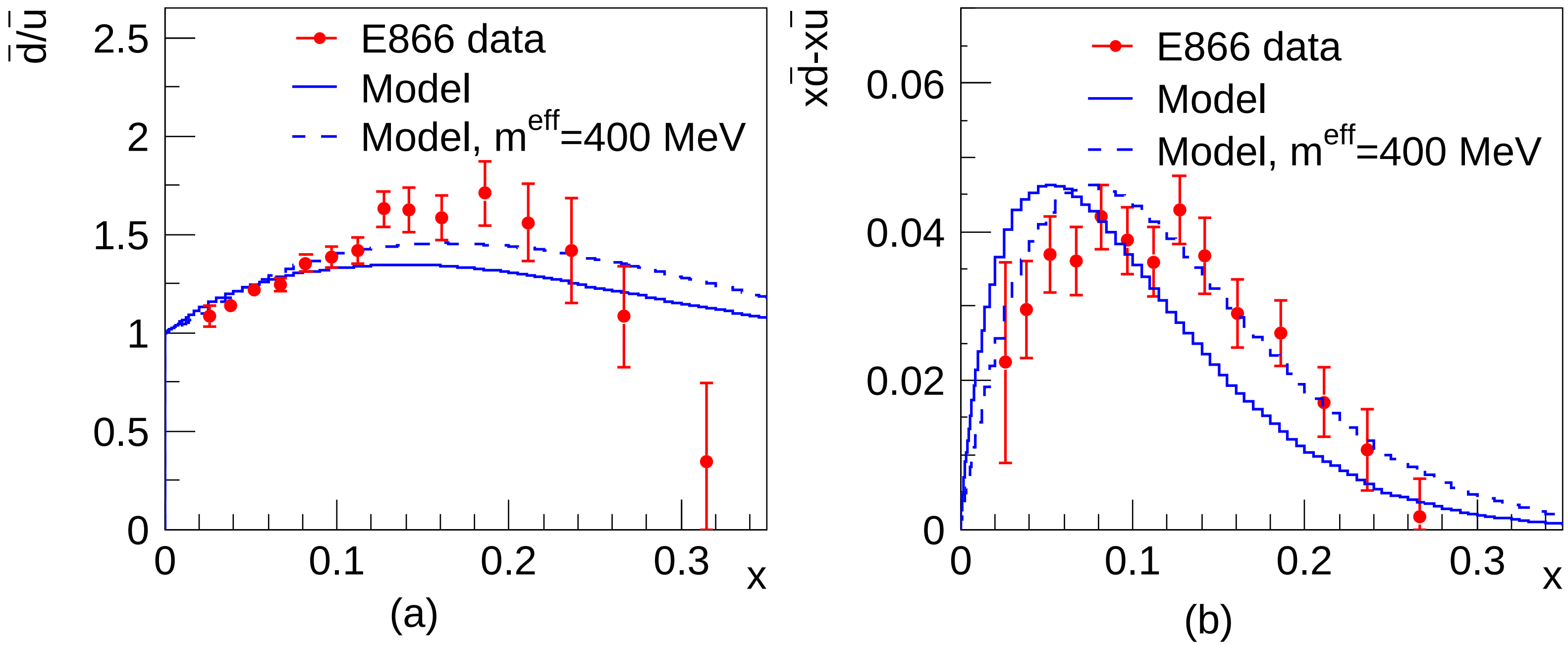


# The $\bar{d}$ - $\bar{u}$ asymmetry

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

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

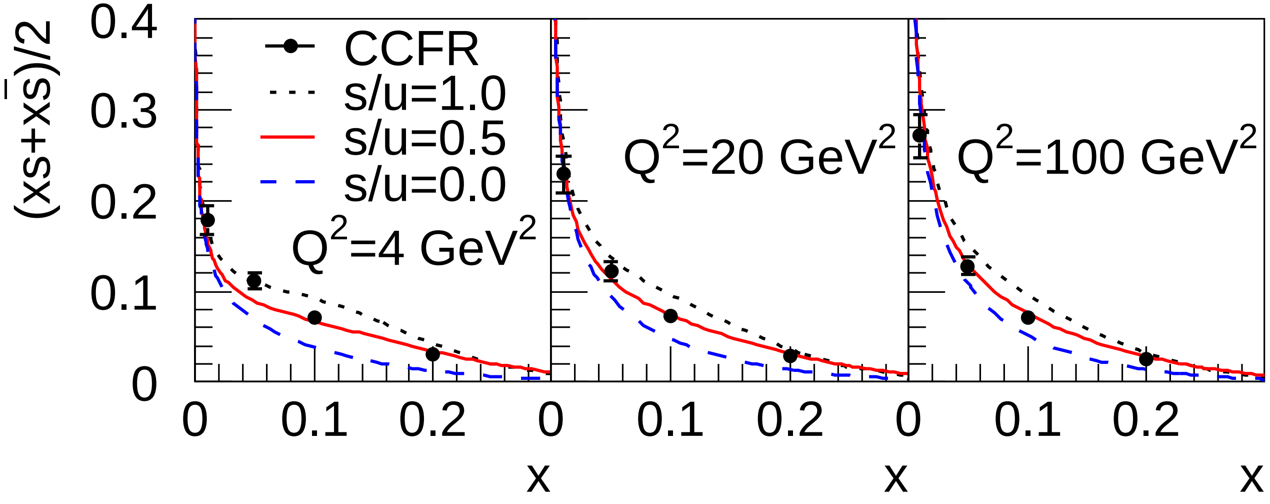
Fitted parameters to Drell-Yan data in $pp$ and $pd$ scattering: $\alpha^2_{p\pi^0}$ and $\alpha^2_{n\pi^+}$




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



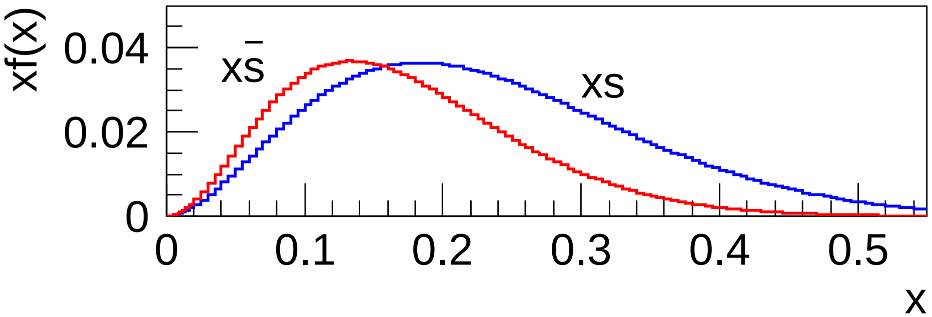

$(s + \bar{s})/(\bar{u} + \bar{d}) \approx 0.5$ as

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

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

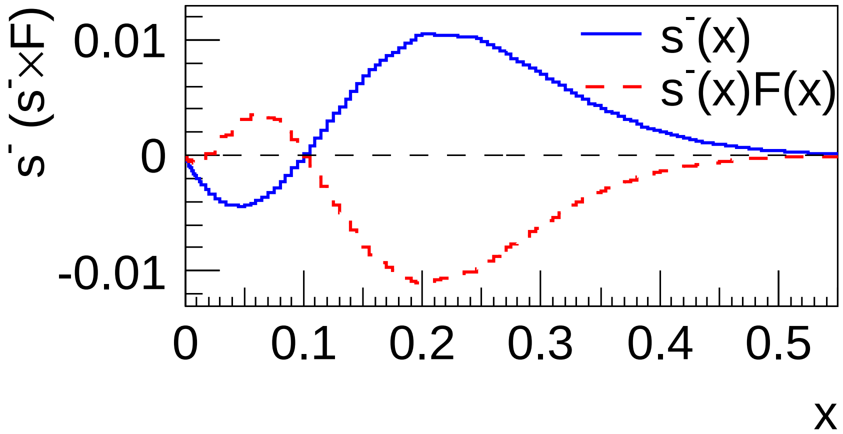
But, if $xs(x) \neq x\bar{s}(x)$ since $\nu s \to \mu^- c$ and $\bar{\nu}\bar{s} \to \mu^+ \bar{c}$ then give different $\sigma$'s

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

Our model: $0.0010 \leq S^- = \int_0^1 dx[xs(x) - x\bar{s}(x)] \leq 0.0023$ (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 $|\Lambda_C D\rangle$ and other charmed fluctuations.

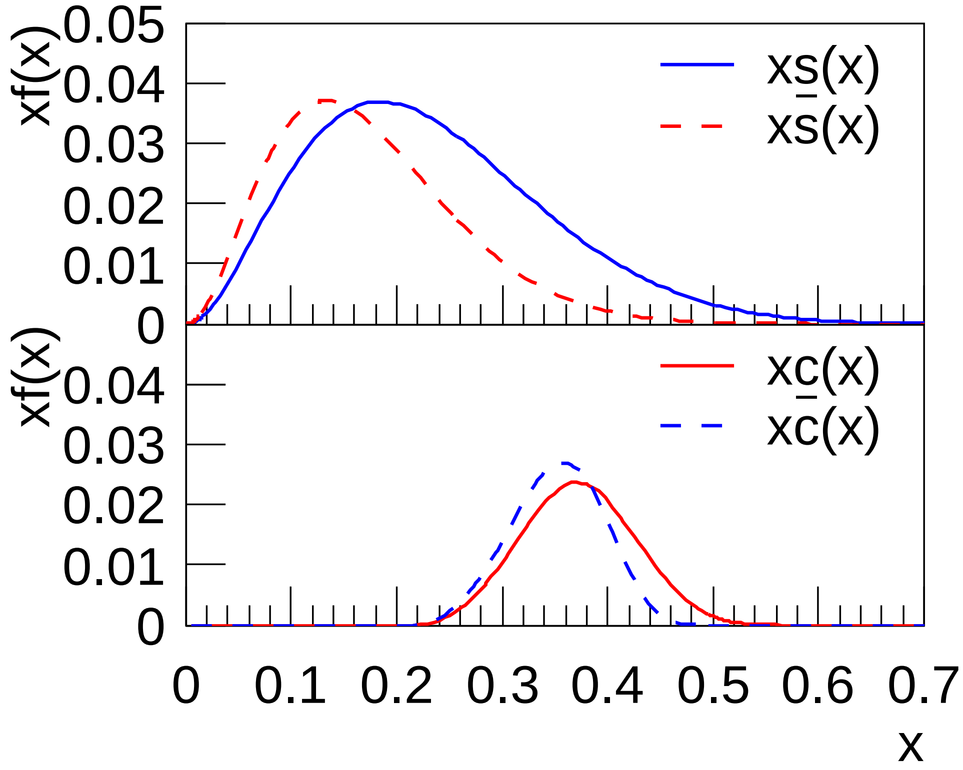
Just for fun: Assume normalization as $1/\Delta M_{BM}$ (as suggested by strange sea data)

$$\Rightarrow \alpha^2_{\Lambda_C D} \approx \alpha^2_{\Lambda K}/5$$

*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 $x$)

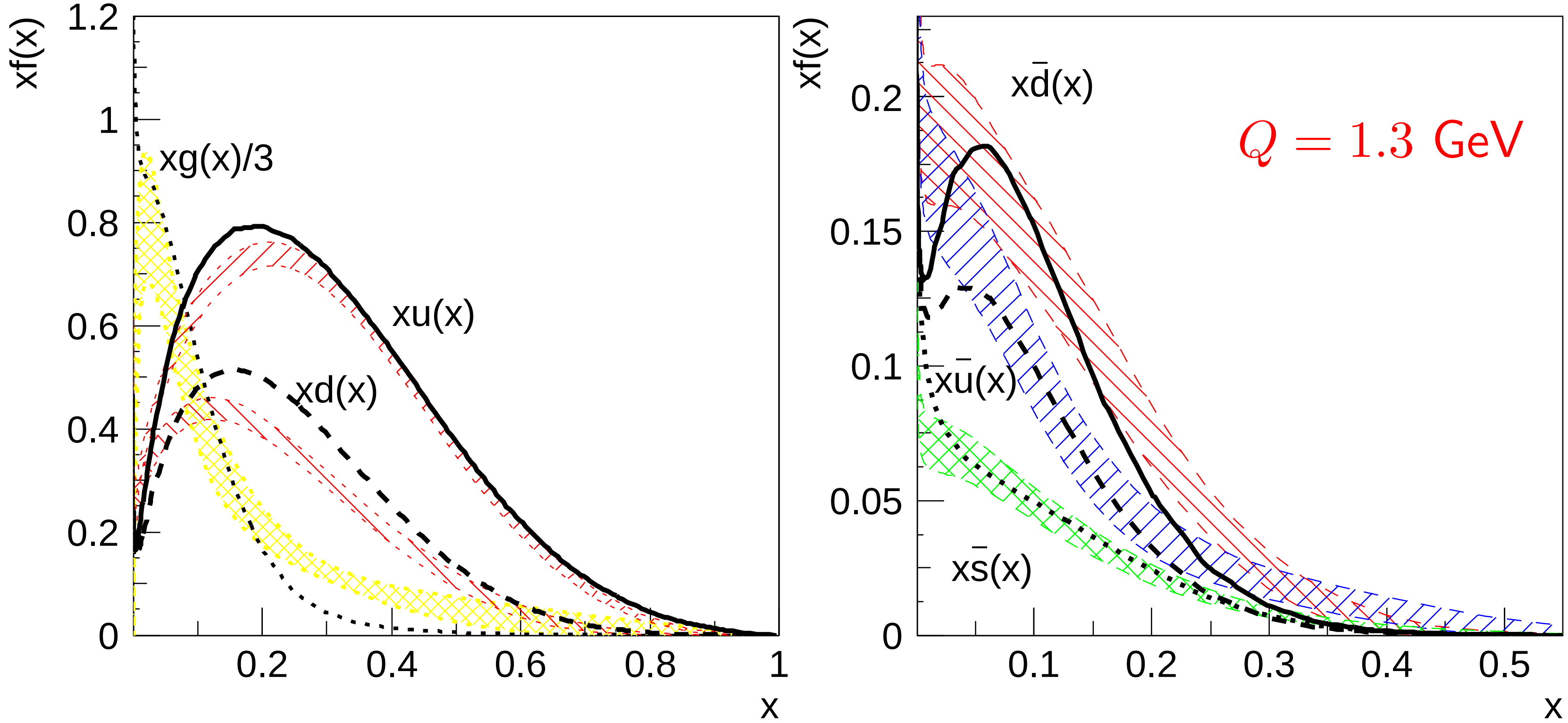
Also B hadron fluctuations might be interesting to look at.



# Comparison with CTEQ6M distributions

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

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



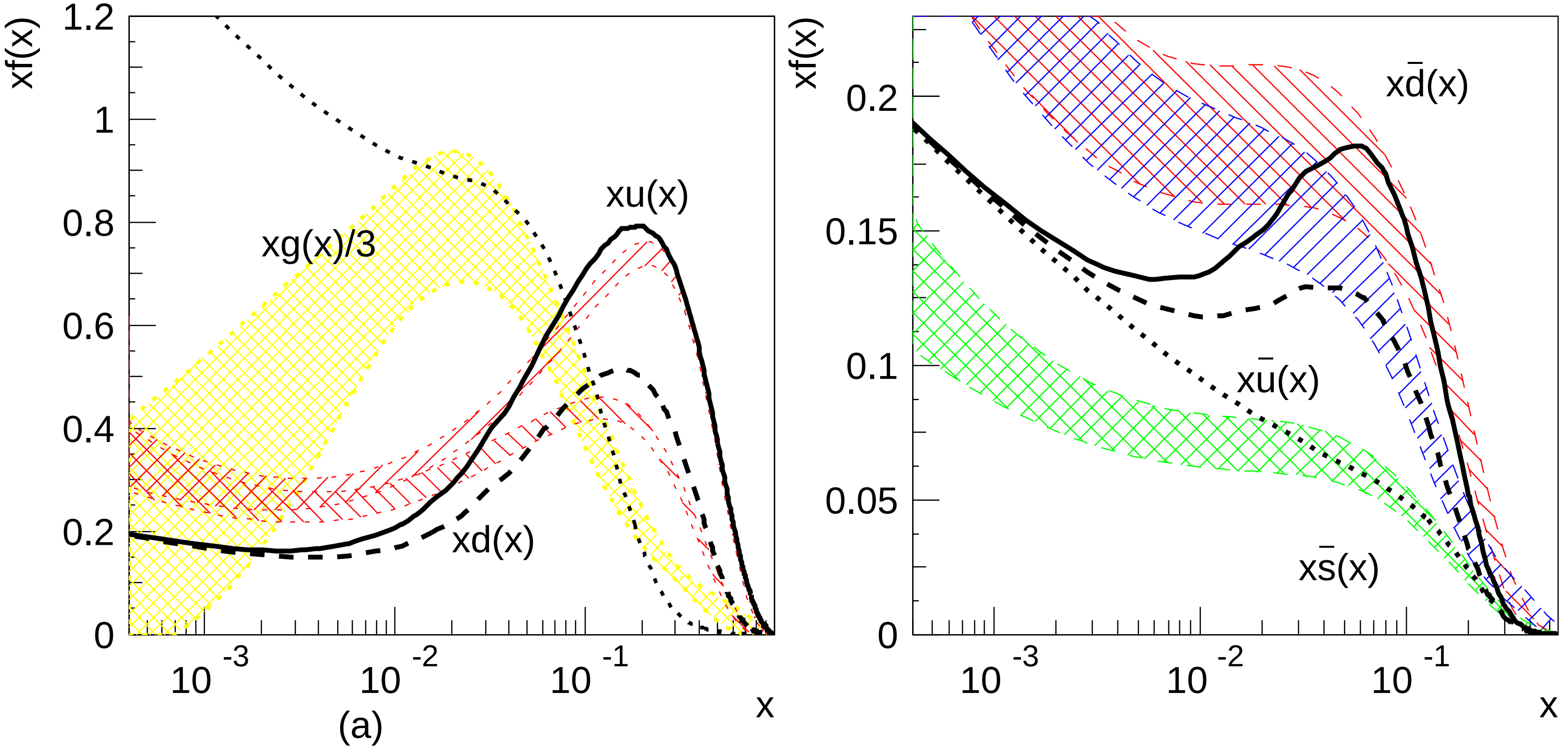

For $x \gtrsim 10^{-2}$

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

# Comparison with CTEQ6M cont.

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

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




$Q = 1.3$ GeV

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 !?

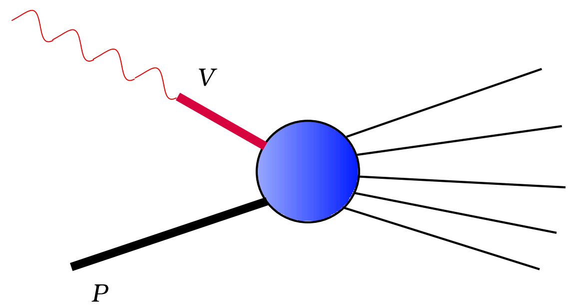
# Possible source of $q\bar{q}$: GVDM in $ep$ at low $Q^2$

Quantum fluctuations of photon:

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

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

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




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

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

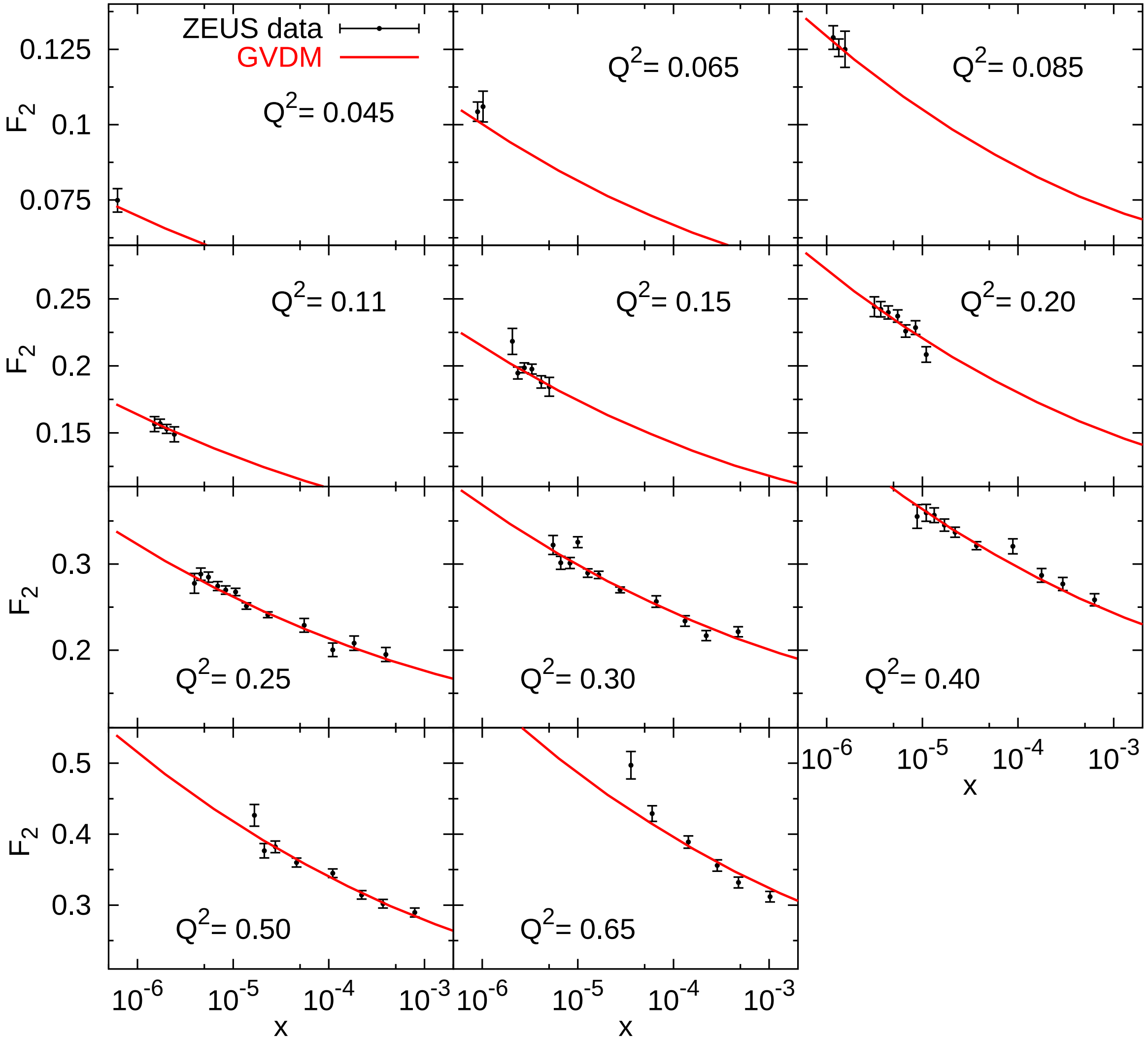
$$\Rightarrow F_2^{\mathrm{GVDM}}(x, Q^2) = \frac{(1-x)Q^2}{4\pi^2\alpha} \left\{ \sum_V r_V \left(\frac{m_V^2}{Q^2+m_V^2}\right)^2 \left(1 + \xi \frac{Q^2}{m_V^2}\right) + r_C \frac{m_0^2}{Q^2+m_0^2} \right\} A \left(\frac{Q^2}{x}\right)^{\epsilon}$$

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

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

$m_0 \approx 1$ 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

$\epsilon = 0.091$

$m_0 = 1.5$ GeV

$A = 71\,\mu$b

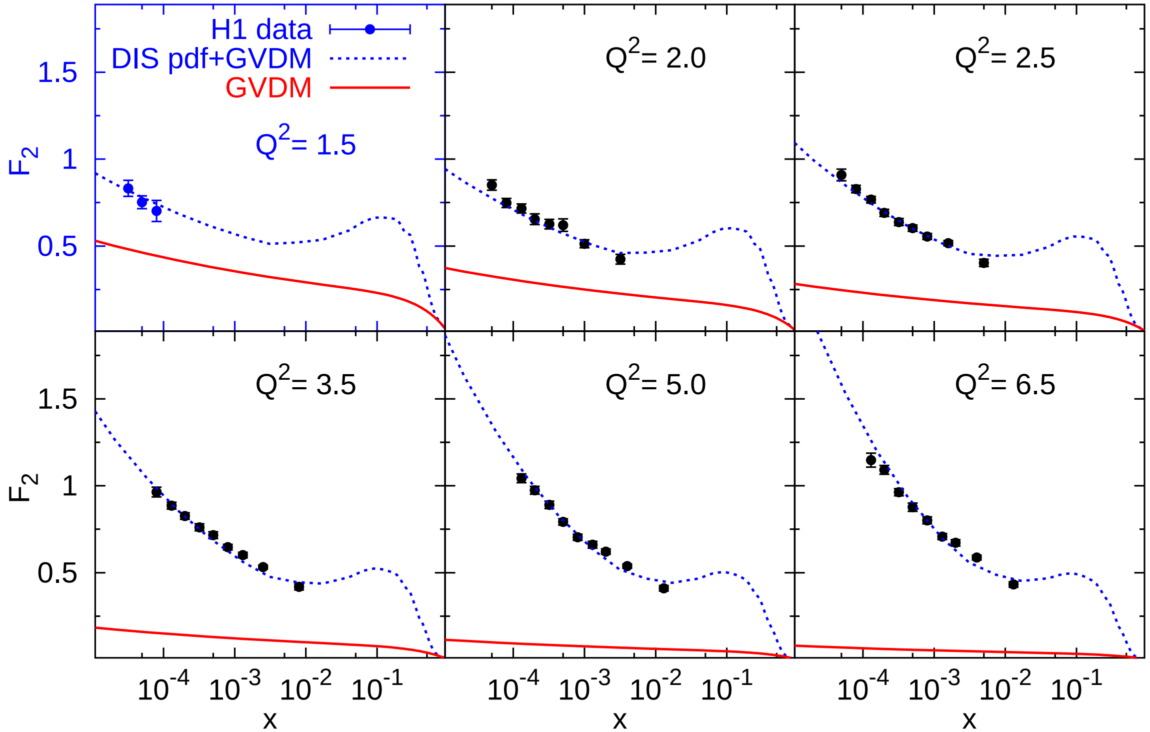
$\xi = 0.34$

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
  $\hookrightarrow$ Gaussian momenta OK $\rightarrow$ 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
  $\hookrightarrow$ Meson-baryon fluctuations explain non-perturbative sea
- $s - \bar{s}$ asymmetry sufficient to reduce the NuTeV anomaly below $2\sigma$
  $\hookrightarrow$ No strong hint of new physics
- Prediction of intrinsic charm in nucleons due to charmed fluctuations