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# Quark Asymmetries in Nucleons

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J.A. and Gunnar Ingelman, hep-ph/0503099

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# Parton distributions in hadrons

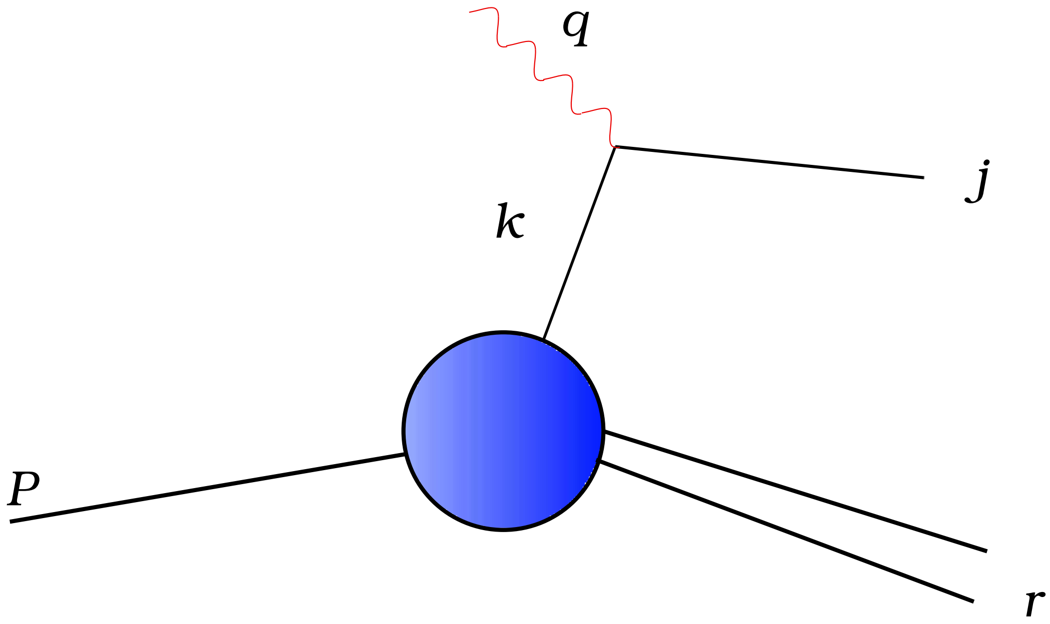
- Factorization theorems of QCD separate soft and hard dynamics
- $Q^2$ dependence of parton distributions $f_i(x, Q^2)$ given by the DGLAP (Altarelli-Parisi) evolution in perturbative QCD
- Starting distributions $f_i(x, Q_0^2)$ non-perturbative and non-calculable
  $\hookrightarrow$ Usually parametrizations 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 $s, \bar{s} \approx \frac{1}{2}\frac{\bar{d} + \bar{u}}{2}$ 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
  $\hookrightarrow$ Insights into non-perturbative QCD dynamics

# Our Model: Valence distributions

In hadron rest frame:

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

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:

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

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

Monte Carlo-simulate to get $x$ distribution.

# Analytical expressions

Integrating over $k_\perp^2$ and $k_-$:

$$f_i(x) = N(\tilde{\sigma}_i, \tilde{x}_i) \left\{ \left[1 + \mathrm{erf}\left(\frac{1-\tilde{x}_i}{2\tilde{\sigma}_i}\right)\right] \exp\left[-\frac{(x-\tilde{x}_i)^2}{4\tilde{\sigma}_i^2}\right] - \left[1 + \mathrm{erf}\left(\frac{x-\tilde{x}_i}{2\tilde{\sigma}_i}\right)\right] \exp\left[-\frac{(1-\tilde{x}_i)^2}{4\tilde{\sigma}_i^2}\right] \right\}$$

where $\tilde{\sigma}_i \equiv \sigma_i/M$, $\tilde{x}_i \equiv m_i/M$

Approximately

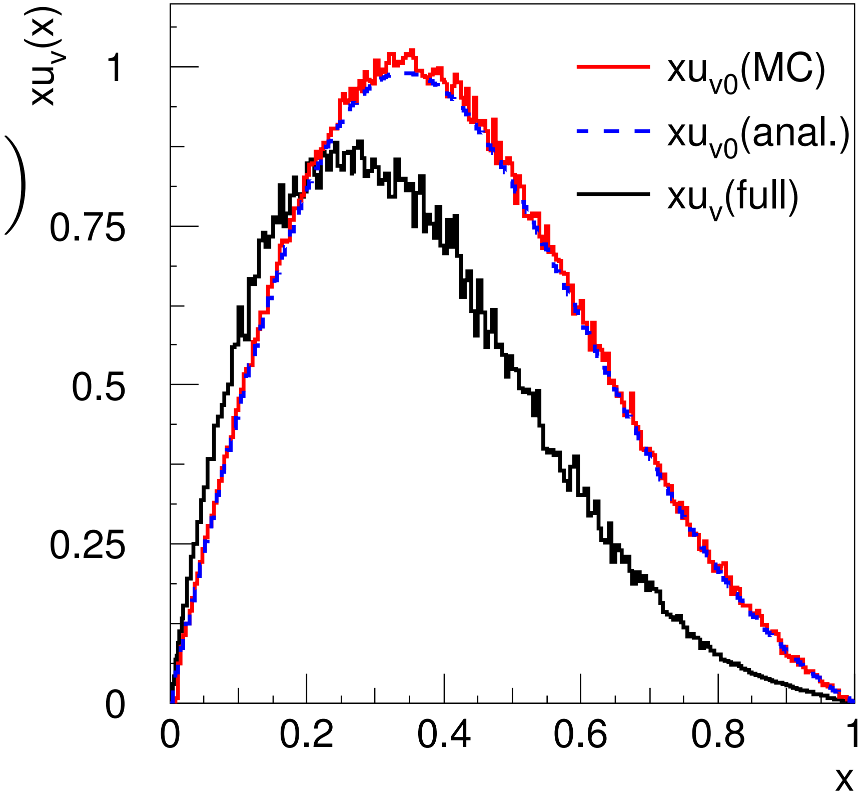
$$f_i(x) = N(\tilde{\sigma}_i, \tilde{x}_i) \left[1 - \exp\left(\frac{1-x}{2\tilde{\sigma}_i^2}\right)\right] \exp\left(-\frac{(x-\tilde{x}_i)^2}{4\tilde{\sigma}_i^2}\right)$$

Note: for $x \gtrsim 0.9$ $f_i(x) \sim (1-x)^1$

BUT for $0.3 \lesssim x \lesssim 0.9$:

$xu(x) \sim x(1-x)^{2.8}$ (*cf.* counting rules)

$x \lesssim 0.7$: Shape modified by hadronic fluctuations

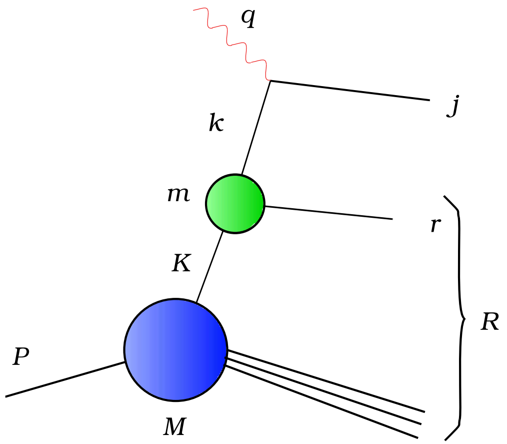


# Our Model: Sea distributions

- Hadronic quantum fluctuations:

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

- 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



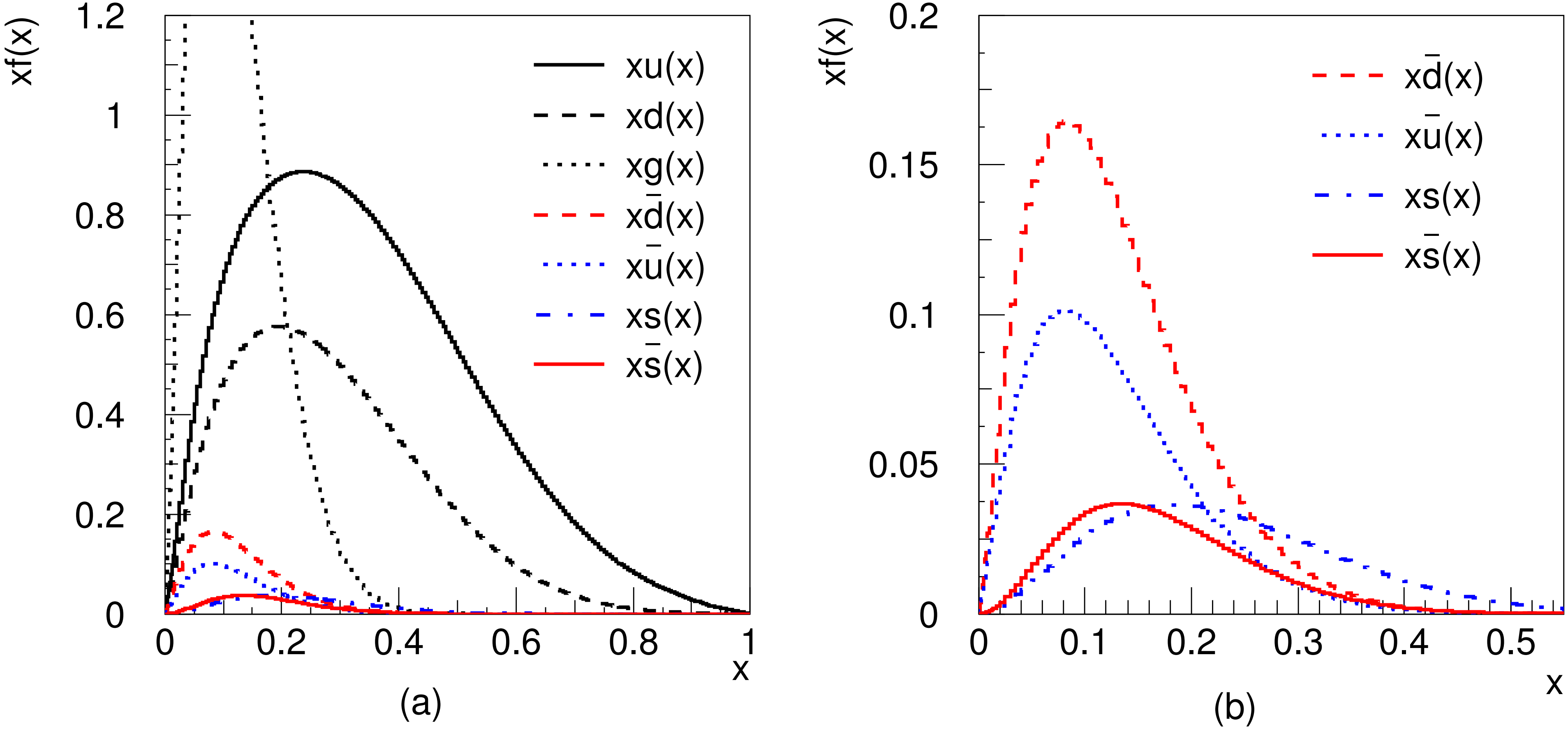

$$x_H = K_+/(K + K_{\text{partner}})_+$$
$$x_p = k_+/K_+$$
$$x = x_H \cdot x_p$$

Kinematic constraints:

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

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

# Resulting distributions




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

# Parameters and experimental data

Parameters:

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

DGLAP evolution:

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

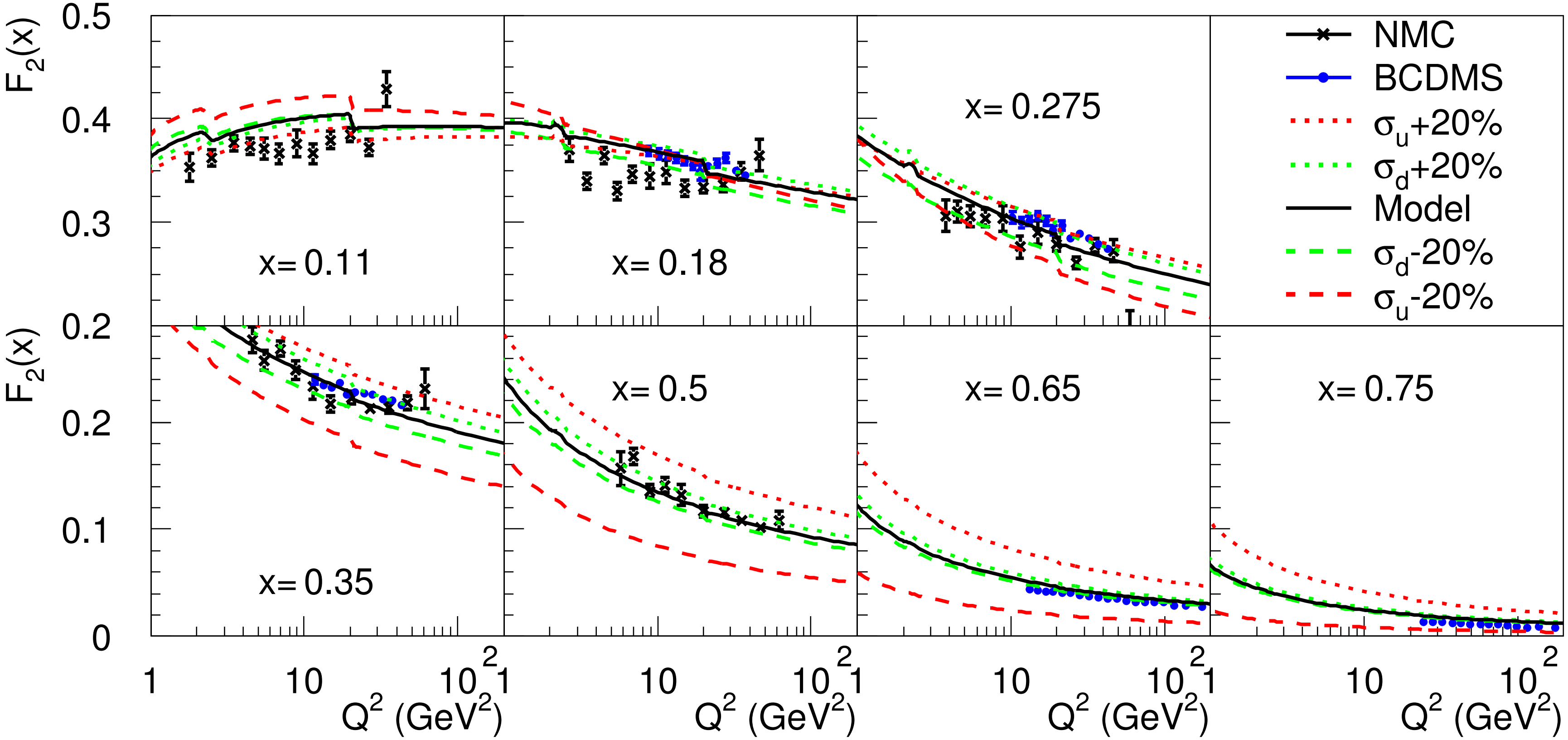
Experimental data sets (to fix the free parameters):

- 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

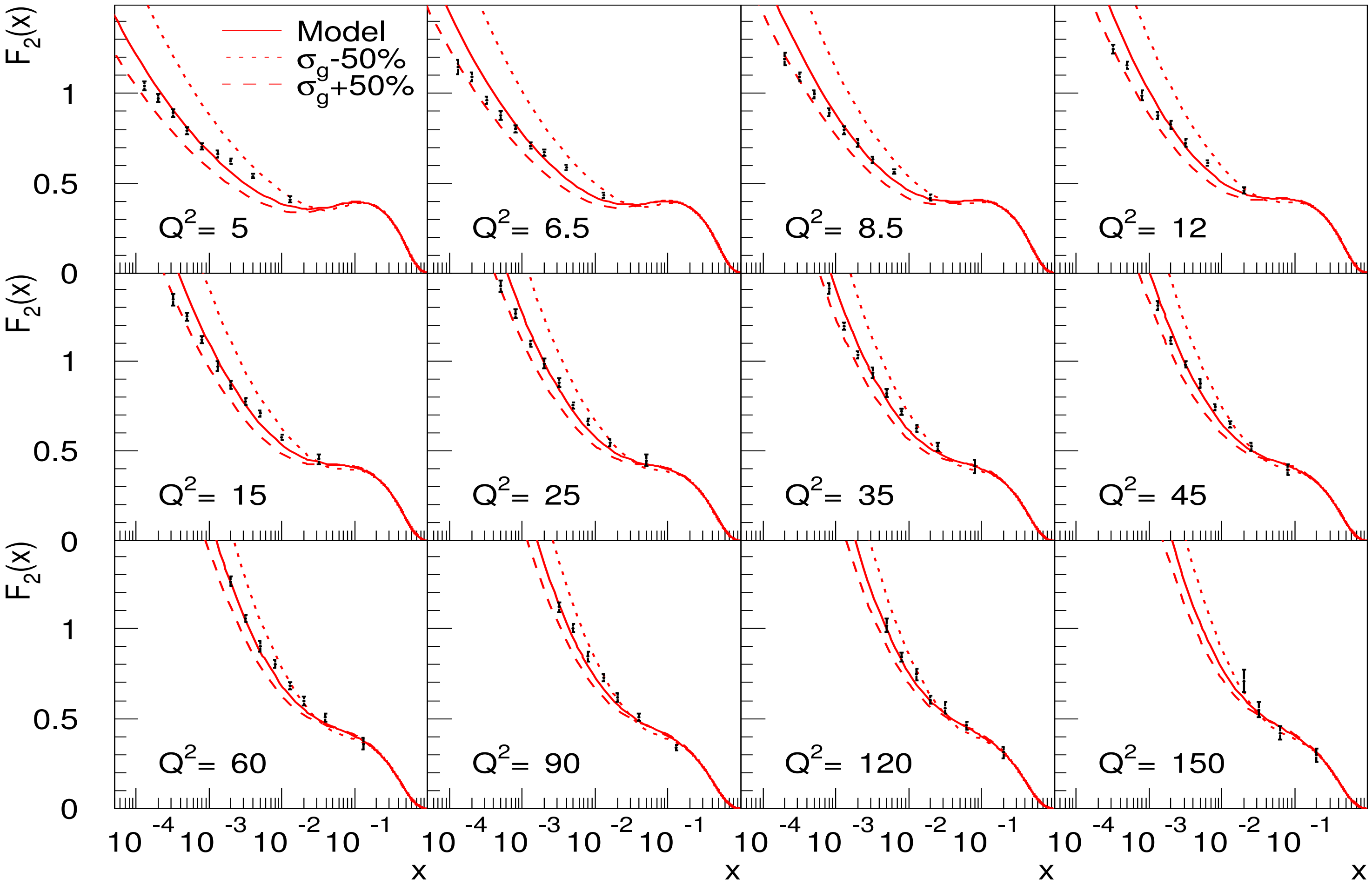
NMC and BCDMS $F_2$ data fixes large-$x$ valence distributions $(\sigma_u,\ \sigma_d)$




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

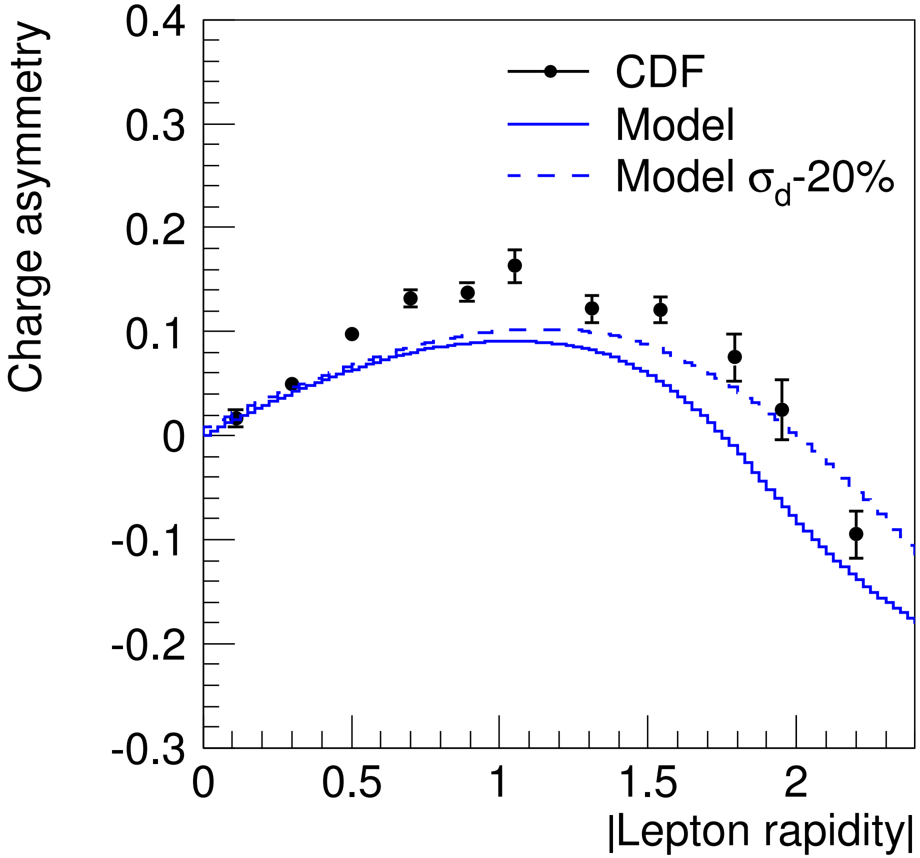
In $p\bar{p}$-collisions at Tevatron:

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

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?)

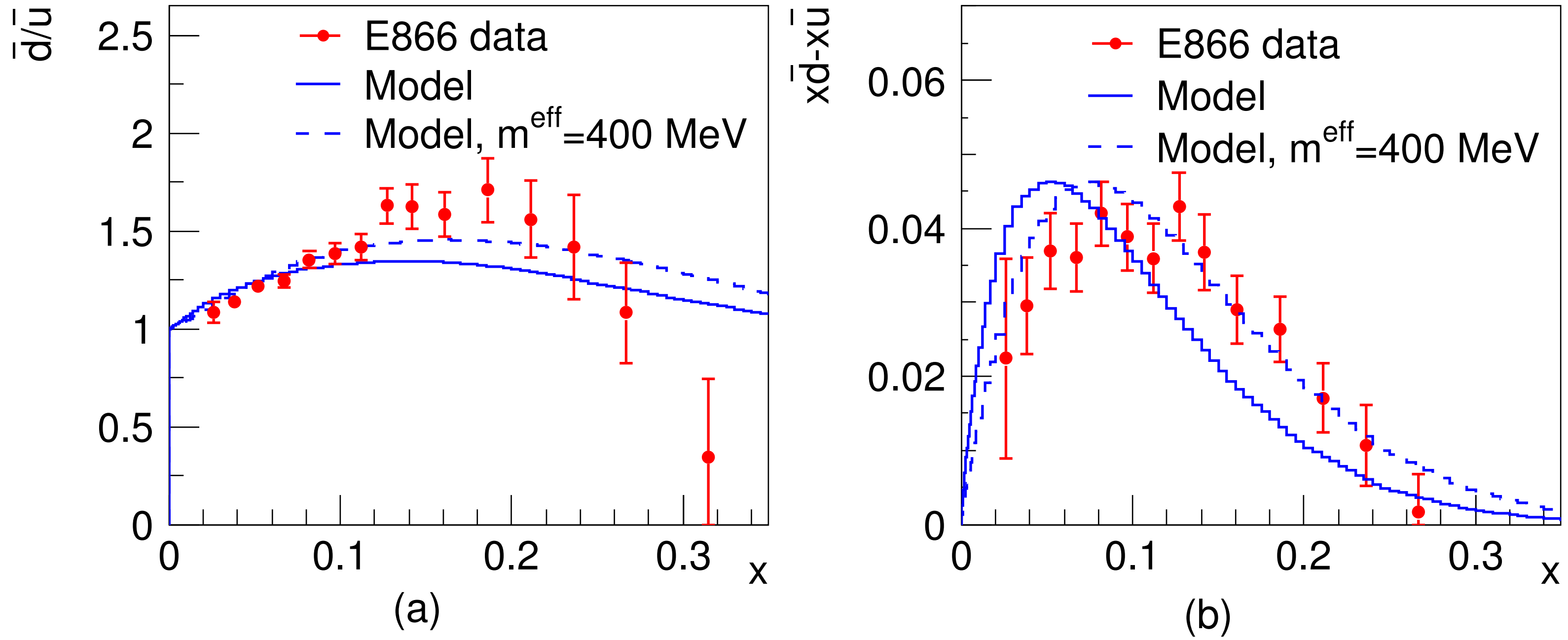


# The $\bar{d}$ - $\bar{u}$ asymmetry

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 $\alpha^2_{n\pi^+}$



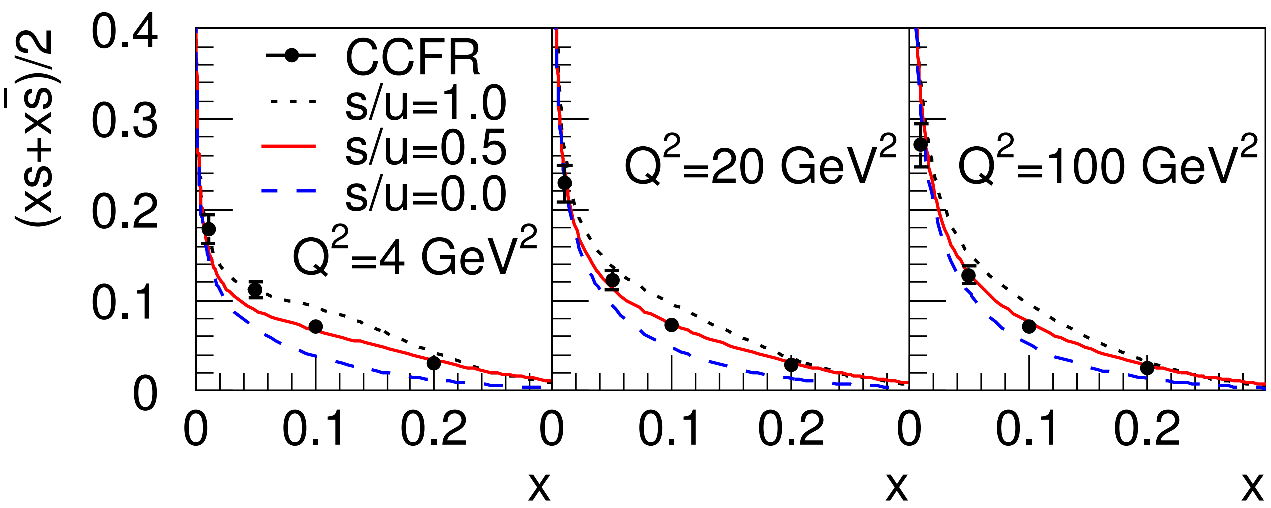

Note: Position of peak better described with effective pion mass $m^{\text{eff}} \approx 400$ MeV may account for heavier mesons, $e.g.$ $|N\rho\rangle$, or generic meson states?

# The strange sea

Lightest strange fluctuation $p \to \Lambda K^+$

Heavier fluctuations ($|\Sigma K\rangle$, $|\Lambda K^*\rangle$) effectively included by fit

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 parameterisations
- hadronisation models: Lund $\frac{P(s\bar{s})}{P(u\bar{u}+d\bar{d})/2} \simeq \frac{1}{3}$

Norm $\sim 1/\Delta M_{BM}$ (not $1/\Delta E^2_{BM}$, as in OFPT)

# Asymmetry of the strange sea

Remember:

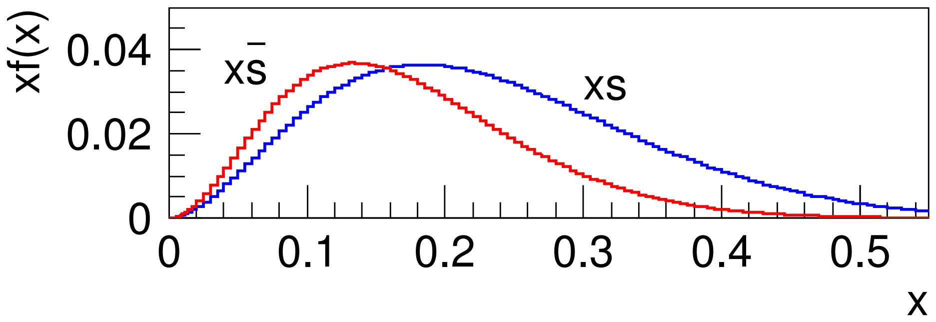
$$x = x_H \cdot x_p$$

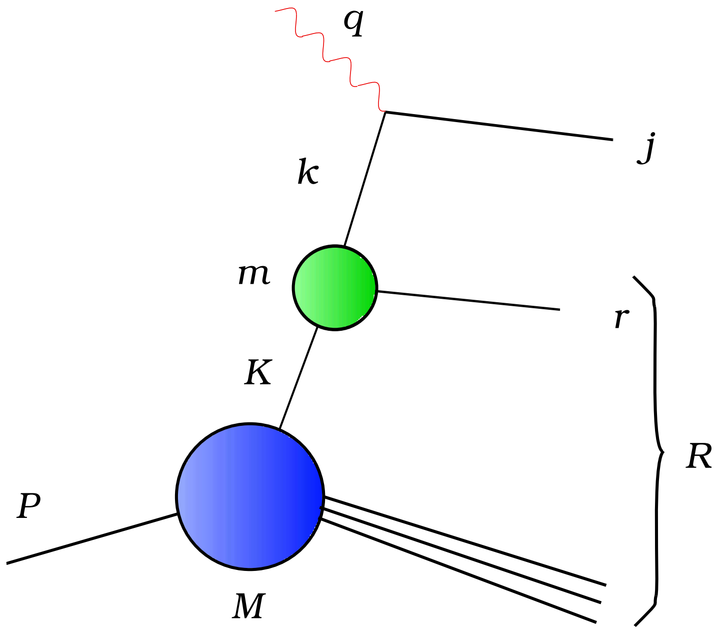
$$x_H = K_+/(K + K_{\text{partner}})_+$$
$$\approx M_H/(M_{\text{meson}} + M_{\text{baryon}})$$

- $s$ quark in (heavier) baryon $\Lambda$

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

$\Downarrow$




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

*Cf.* Brodsky and Ma, Phys. Lett. B **381**, 317 (1996)

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

But, if $xs(x) \neq x\bar{s}(x)$: $\nu s \to \mu^- c$ and $\bar{\nu}\bar{s} \to \mu^+ \bar{c}$ 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)

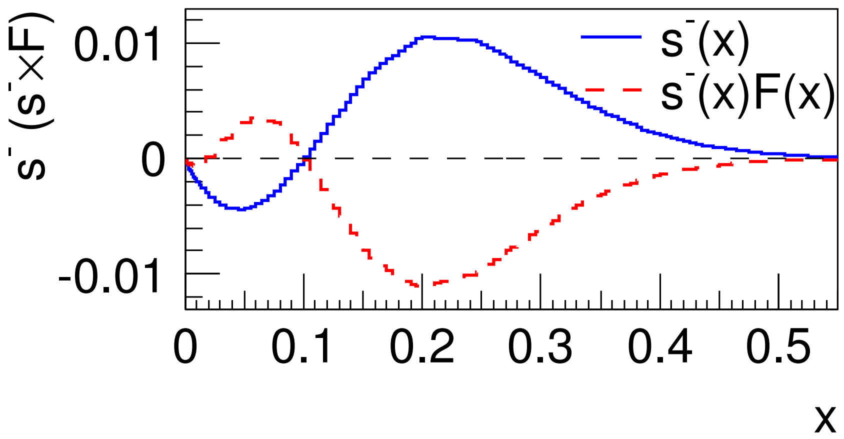
Our model: $0.0010 \leq S^- = \int_0^1 dx[xs(x) - x\bar{s}(x)] \leq 0.0023$ (varying details, $\sigma_d$)

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

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

*Cf.* CTEQ data analysis with similar result (Olness et al., hep-ph/0312323)

*Cf.* perturbative asymmetry opposite but small, hep-ph/0404240

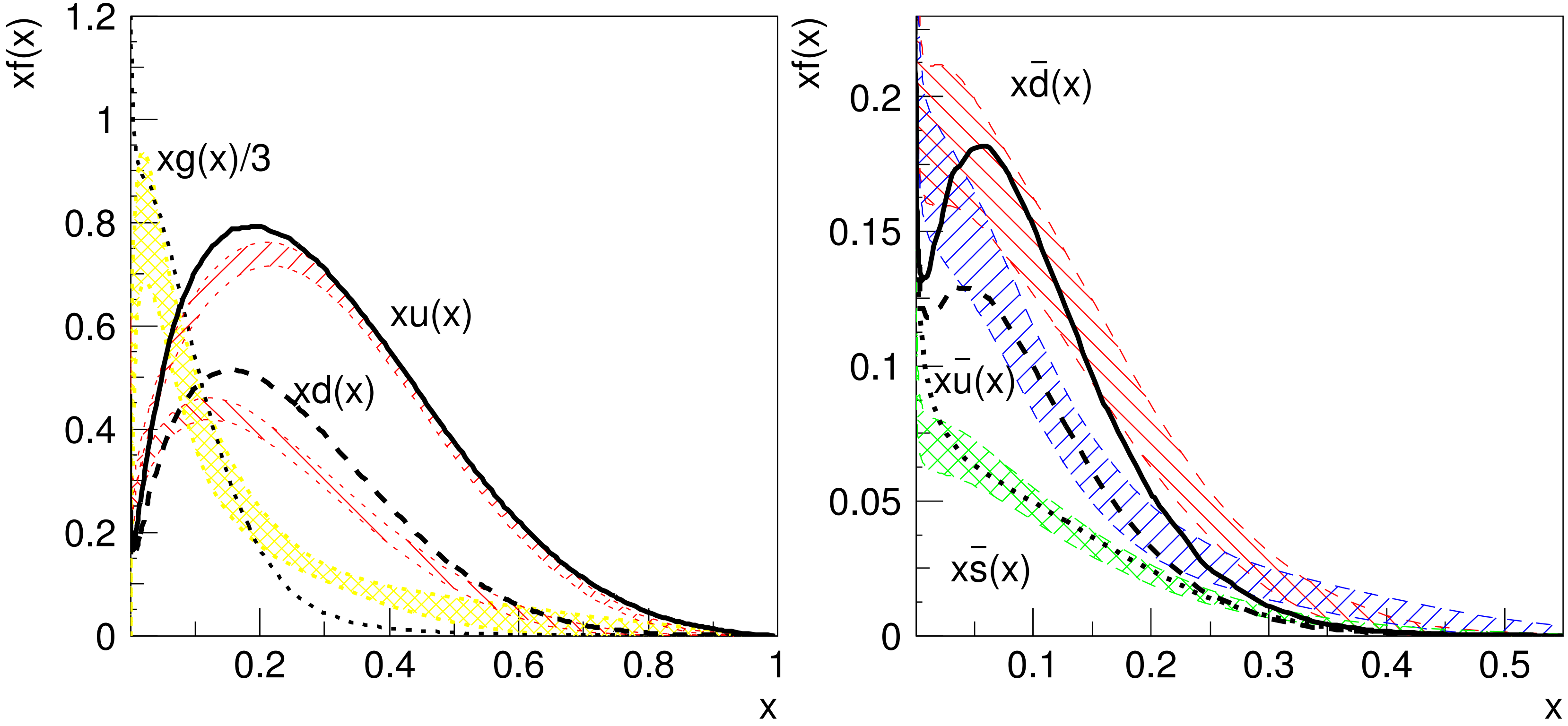



No significant indication for physics beyond the Standard Model !

# Comparison with CTEQ6M distributions

CTEQ: “arbitrary” parametrization, 20 shape parameters (+ normalisation)

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




$Q = 1.1$ GeV

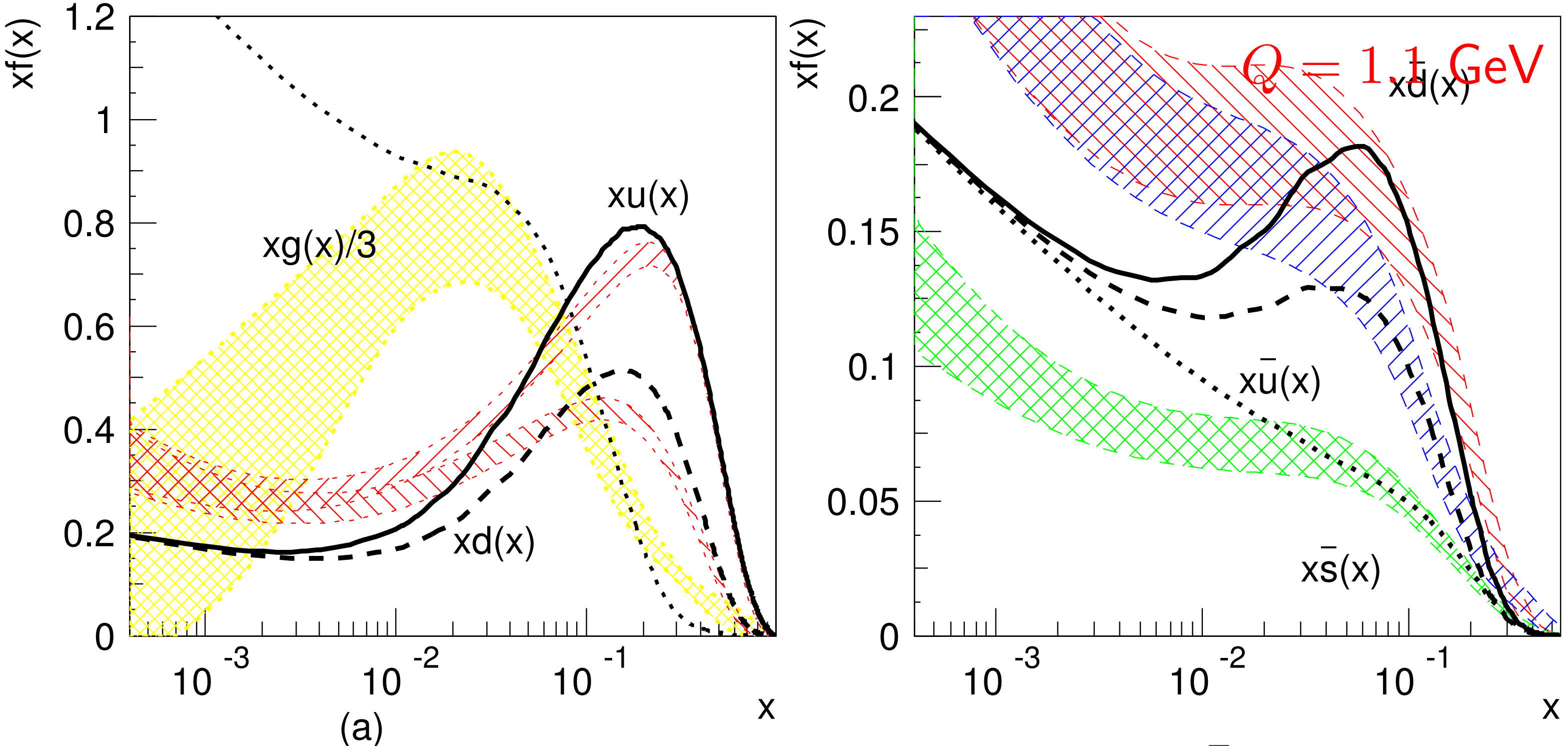
For $x \gtrsim 10^{-2}$

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

# Comparison with CTEQ6M cont.

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

Our model: $xf(x) \to 0$ for $x \to 0$ at $Q_0 = 0.75$ 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 souce of $q\bar{q}$ without accompanying gluons !?

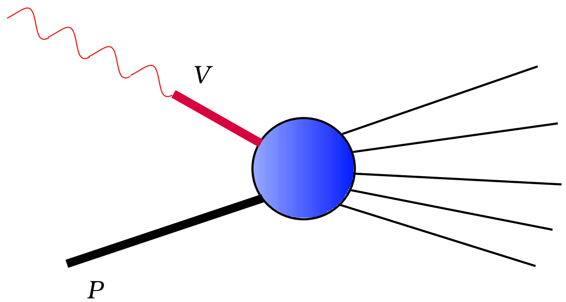
# Possible source of $q\bar{q}$: GVDM in $ep$ at low $Q^2$

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




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

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

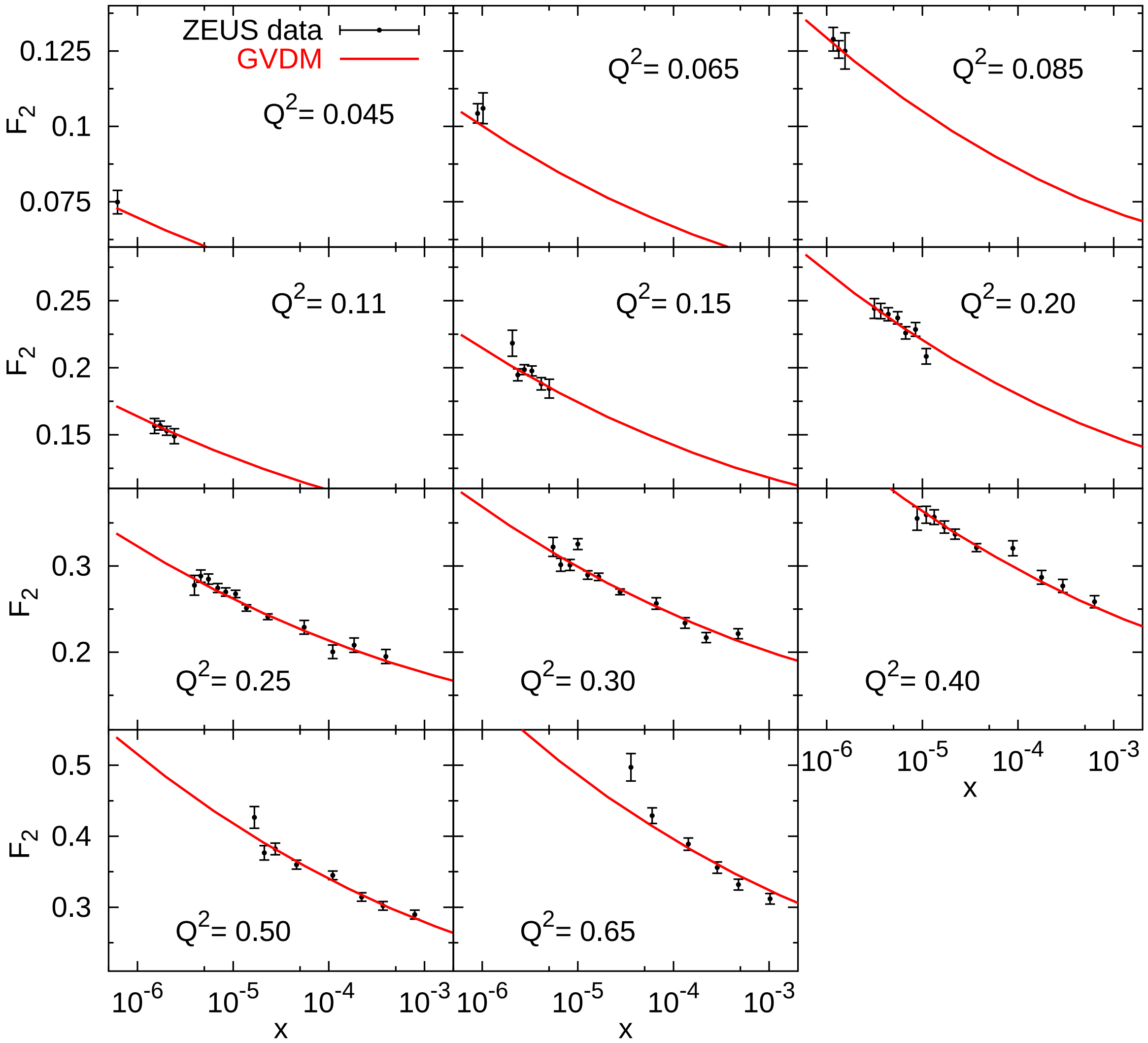
$$\Rightarrow F_2^{\mathrm{GVDM}}(x, Q^2) = \frac{(1-x)Q^2}{4\pi^2\alpha} \left\{ \sum_V r_V \left(\frac{m_V^2}{Q^2+m_V^2}\right)^2 \left(1 + \xi \frac{Q^2}{m_V^2}\right) + r_C \frac{m_0^2}{Q^2+m_0^2} \right\} A \left(\frac{Q^2}{x}\right)^{\epsilon}$$

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

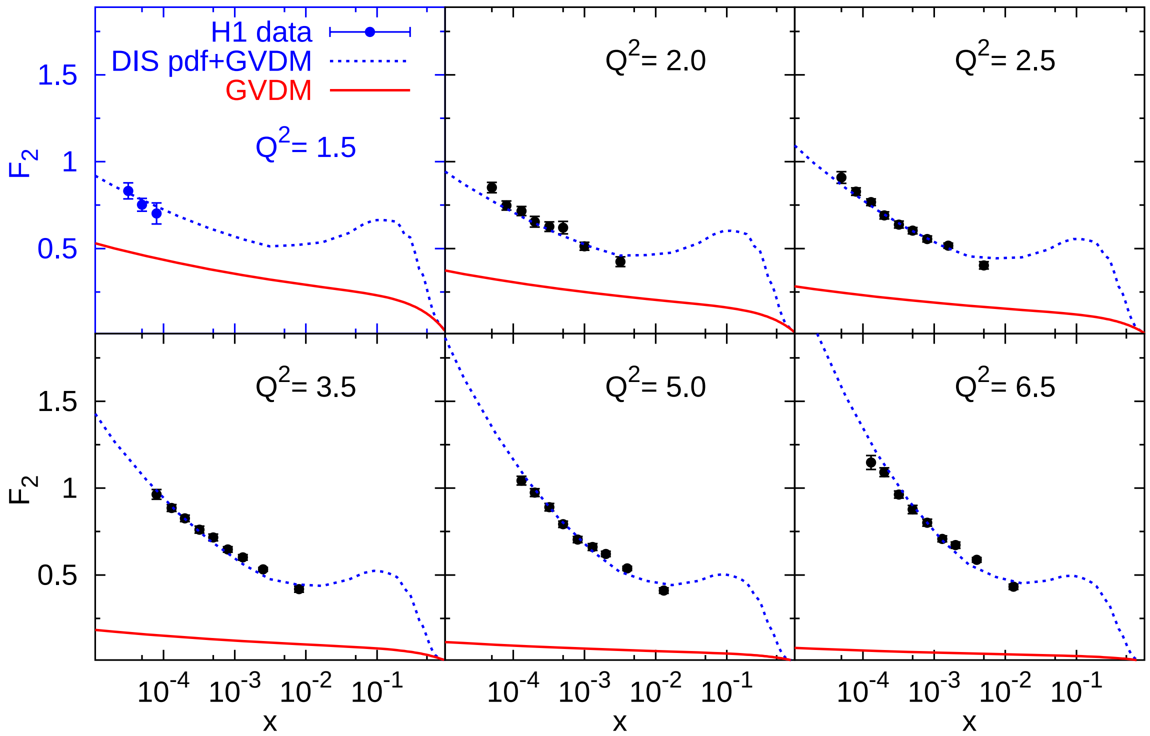
$\xi = 0.34$

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
- $\bar{u} - \bar{d}$ 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 hint of new physics
- Valence and sea quarks $\sim$ CTEQ, but gluon differs !?