Studies of low *x* light sea/valence decomposition

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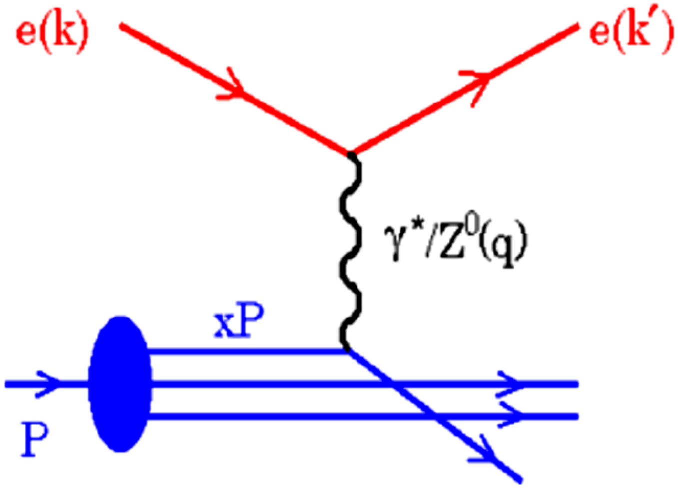
DIS 2011

ep scattering as a proton structure probe



Neutral current Deep Inelastic Scattering (DIS) cross section:

$$\frac{d^2\sigma^\pm}{dx dQ^2} = \frac{2\pi\alpha^2 Y_+}{Q^4 x}\sigma_r^\pm =$$

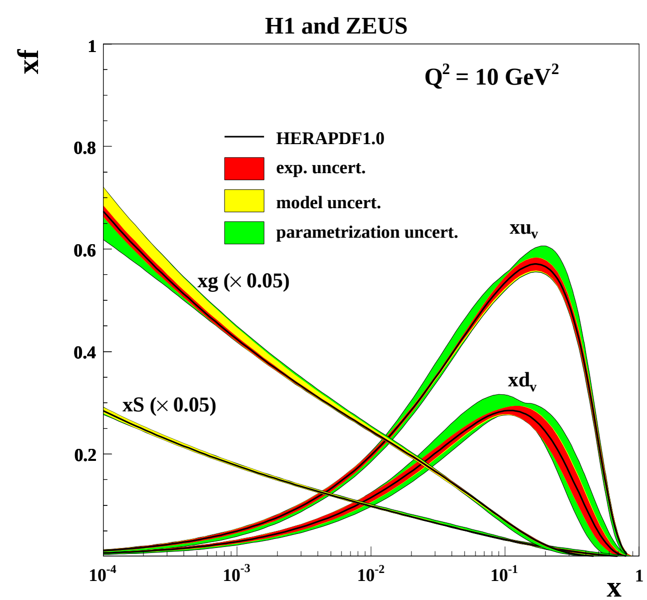
$$= \frac{2\pi\alpha^2 Y_+}{Q^4 x}\left[F_2(x,Q^2) - \frac{y^2}{Y_+}F_L(x,Q^2) \mp \frac{Y_-}{Y_+}xF_3\right]$$

where factors $Y_\pm = 1 \pm (1-y)^2$ and y^2 define polarisation of the exchanged boson and $y = Q^2/(S\,x)$.

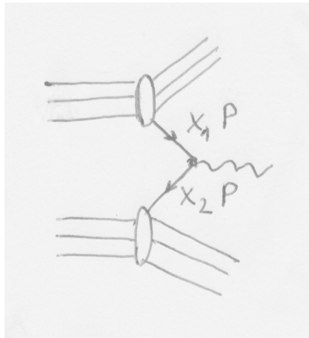
Kinematics is determined by boson virtuality Q^2 and Bjorken x.
At leading order:

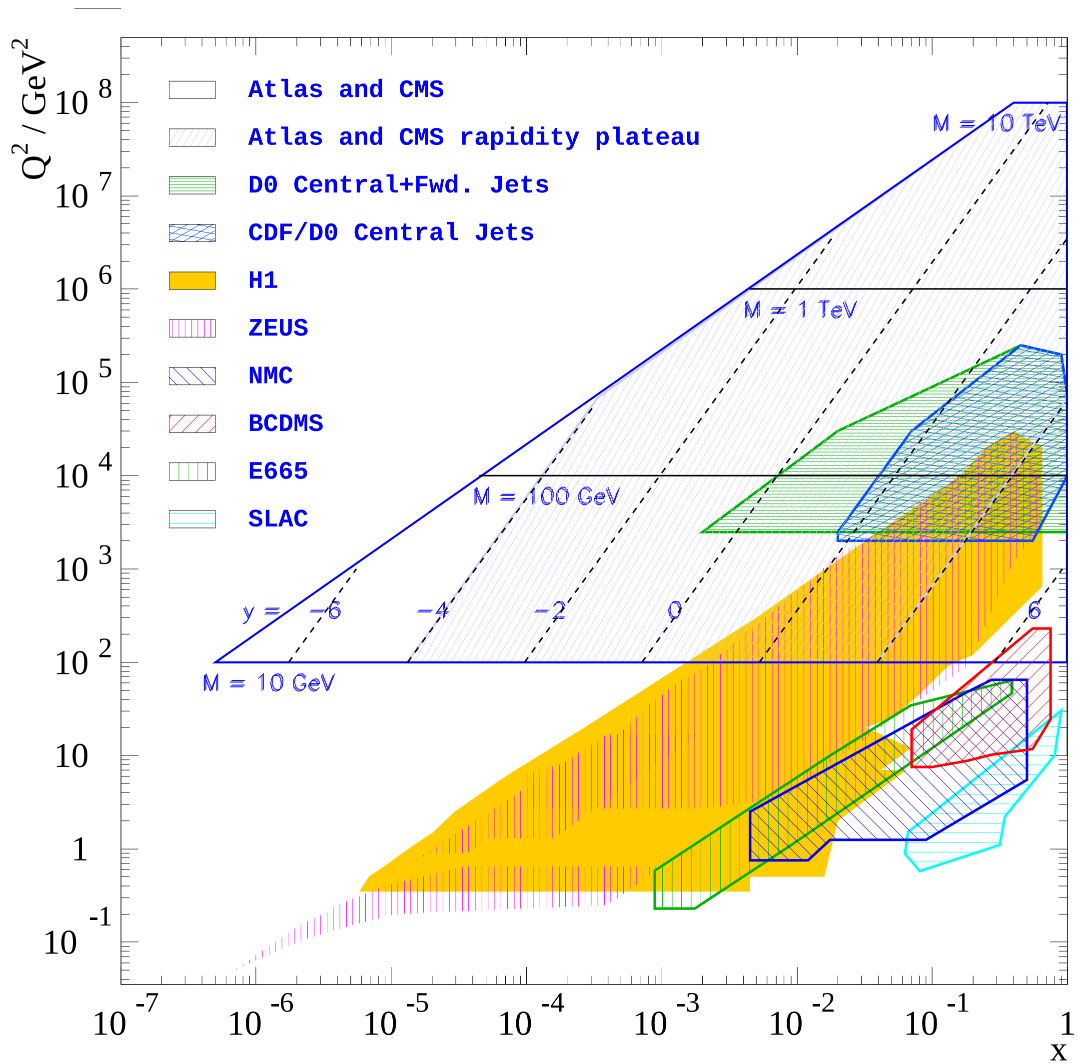
$$\begin{aligned} F_2 &= x\sum e_q^2(q(x)+\bar{q}(x)) \\ xF_3 &= x\sum 2e_q a_q(q(x)-\bar{q}(x)) \\ \sigma_{CC}^+ &\sim x(\bar{u}+\bar{c}) + x(1-y)^2(d+s) \\ \sigma_{CC}^- &\sim x(u+c) + x(1-y)^2(\bar{d}+\bar{s}) \end{aligned}$$

$xg(x)$ — from F_2 scaling violation, jets and F_L



HERA and LHC kinematics



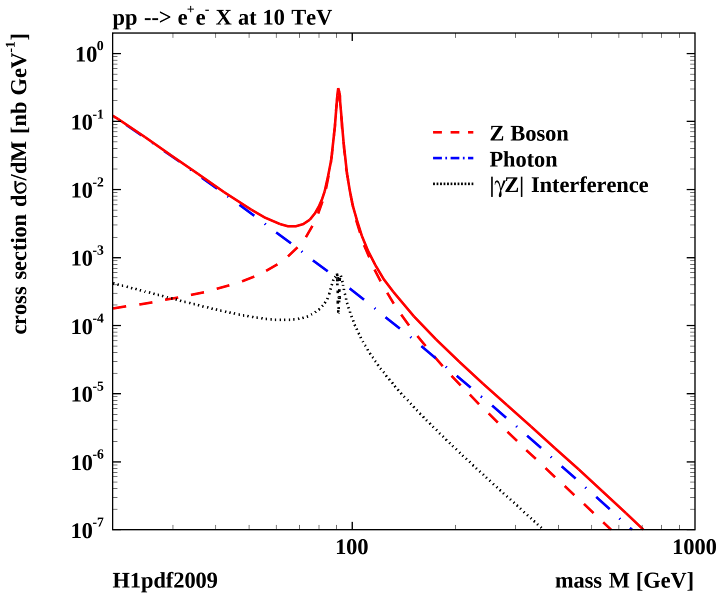


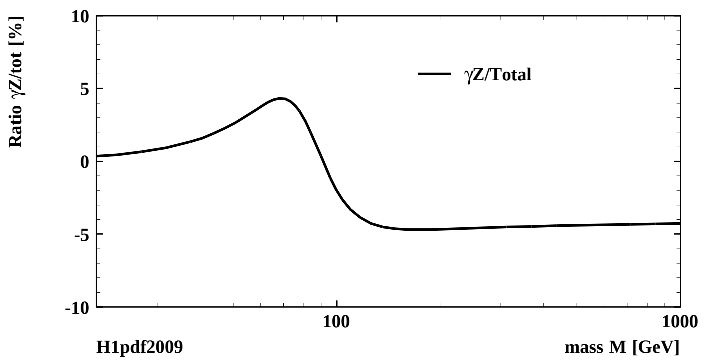
x_1, x_2 are momentum fractions.

Factorization theorem states that cross section can be calculated using universal partons × short distance calculable partonic reaction.

$$x_{1,2} = \frac{M}{\sqrt{S}} \exp(\pm y)$$

Neutral Current Processes at the LHC





Double differential cross section:

$$\frac{d\sigma^2}{dMdy} = \frac{4\pi\alpha^2(M)}{9} \cdot M \cdot P(M) \cdot \Phi(y, M^2).$$

Propagator for γ exchange:

$$P_\gamma(M) = \frac{1}{M^4} ,$$

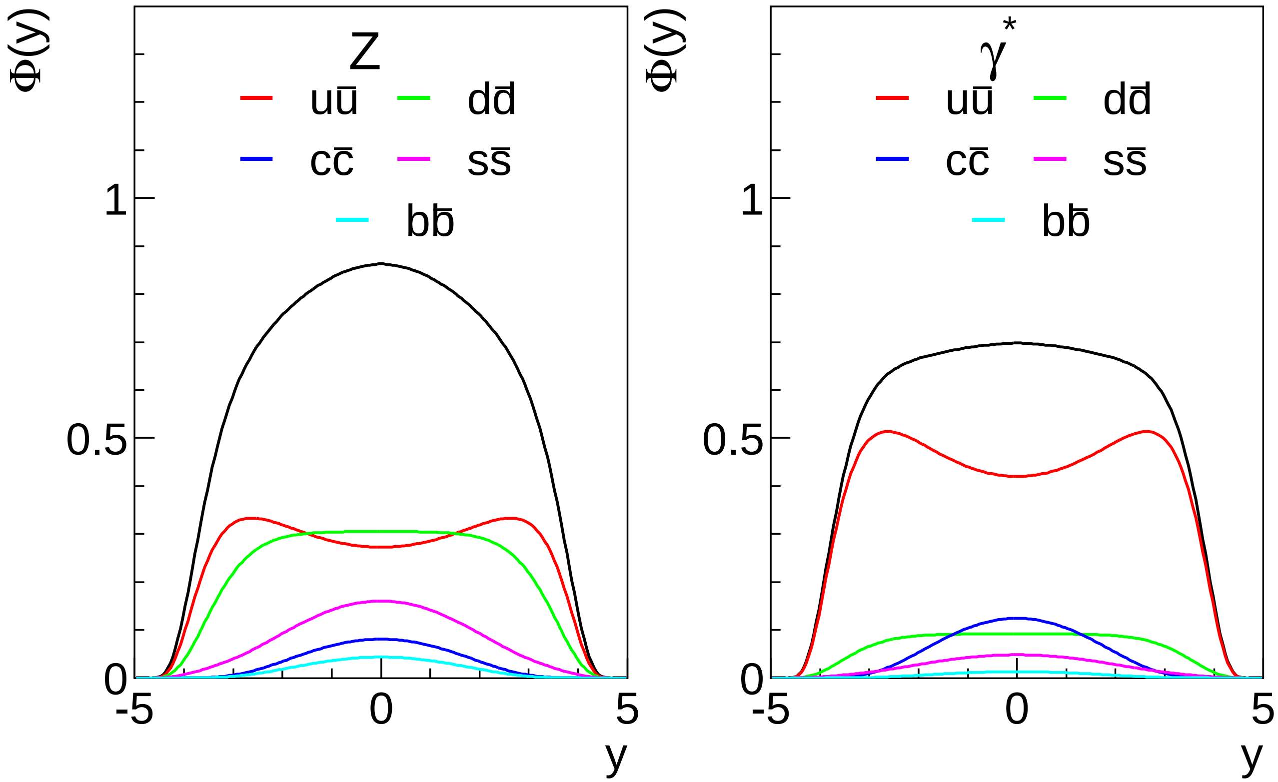
pure Z exchange:

$$P_Z(M) = \frac{k_Z^2(v_e^2 + a_e^2)}{\left(M^2 - M_Z^2\right)^2 + \Gamma_Z^2 M_Z^2} ,$$

where $k_Z = (4\sin^2\theta_W \cos^2\theta_W)^{-1}$, and γZ interference:

$$P_{\gamma Z}(M) = \frac{k_Z v_e(M^2 - M_Z^2)}{M^2\left[\left(M^2 - M_Z^2\right)^2 + \Gamma_Z^2 M_Z^2\right]} ,$$

Z and low mass DY production flavour decomposition



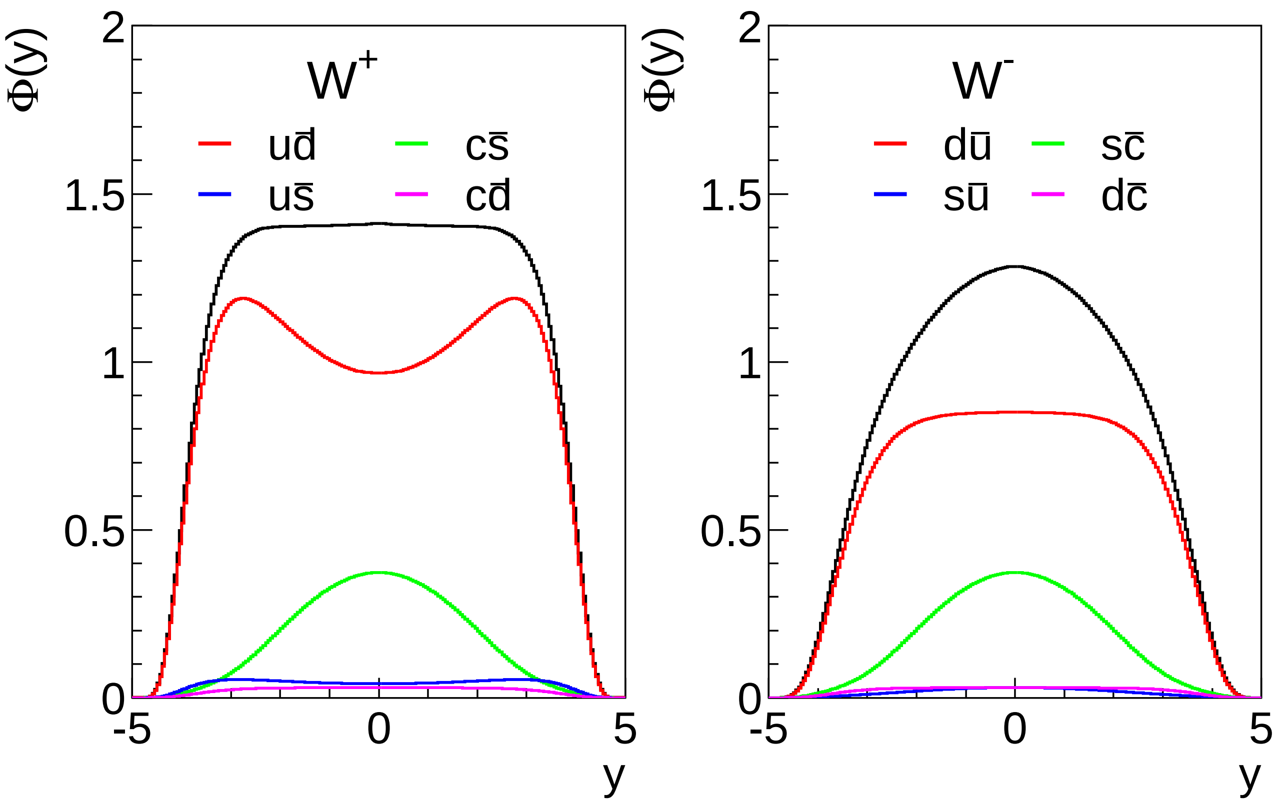
Z vs γ^* are sensitive to U/D ratio:

$$Z \quad \sim 0.29(u\bar{u} + c\bar{c}) + 0.37(d\bar{d} + s\bar{s} + b\bar{b})$$

$$\gamma^* \quad \sim 0.44(u\bar{u} + c\bar{c}) + 0.11(d\bar{d} + s\bar{s} + b\bar{b})$$

Contribution from $\gamma - Z$ interference is small.

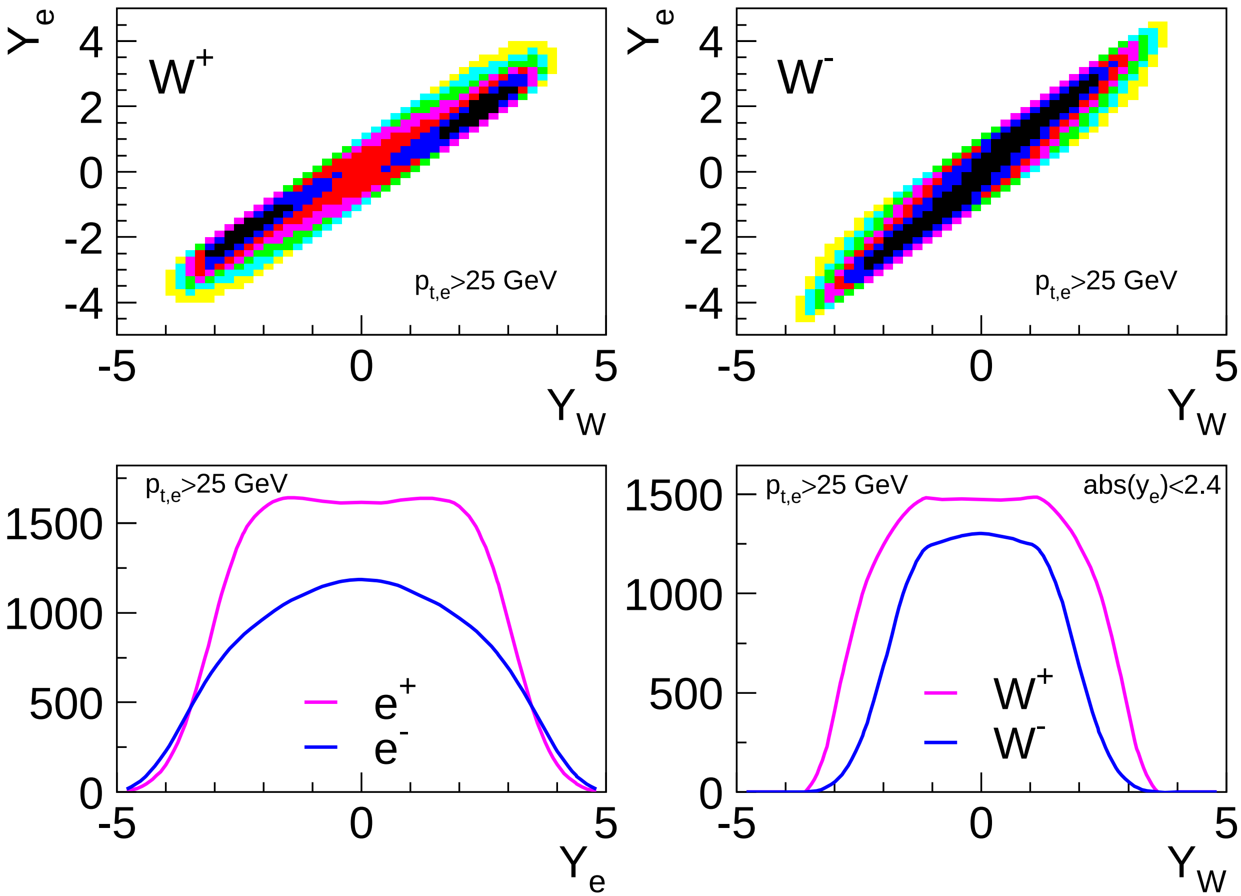
W^+ and W^- production flavour decomposition



W^+ (W^-) production is sensitive to $u\bar{d}$ ($d\bar{u}$) as well as $c\bar{s}$ ($s\bar{c}$) flavour combinations and to lesser extend to Cabbibo suppressed pairs:

$$W^+ \quad \sim 0.95(u\bar{d} + c\bar{s}) + 0.05(u\bar{s} + c\bar{d})$$
$$W^- \quad \sim 0.95(d\bar{u} + s\bar{c}) + 0.05(d\bar{c} + s\bar{u})$$

W decays



For $W^{\pm}$ production the observables are lepton p_t and η. V-A structure of the decay modifies rapidity distribution of the lepton vs the boson. W^+ production accesses higher y for a given η_e range.

(plots based on LO `MCFM`, HERAPDF1.0)

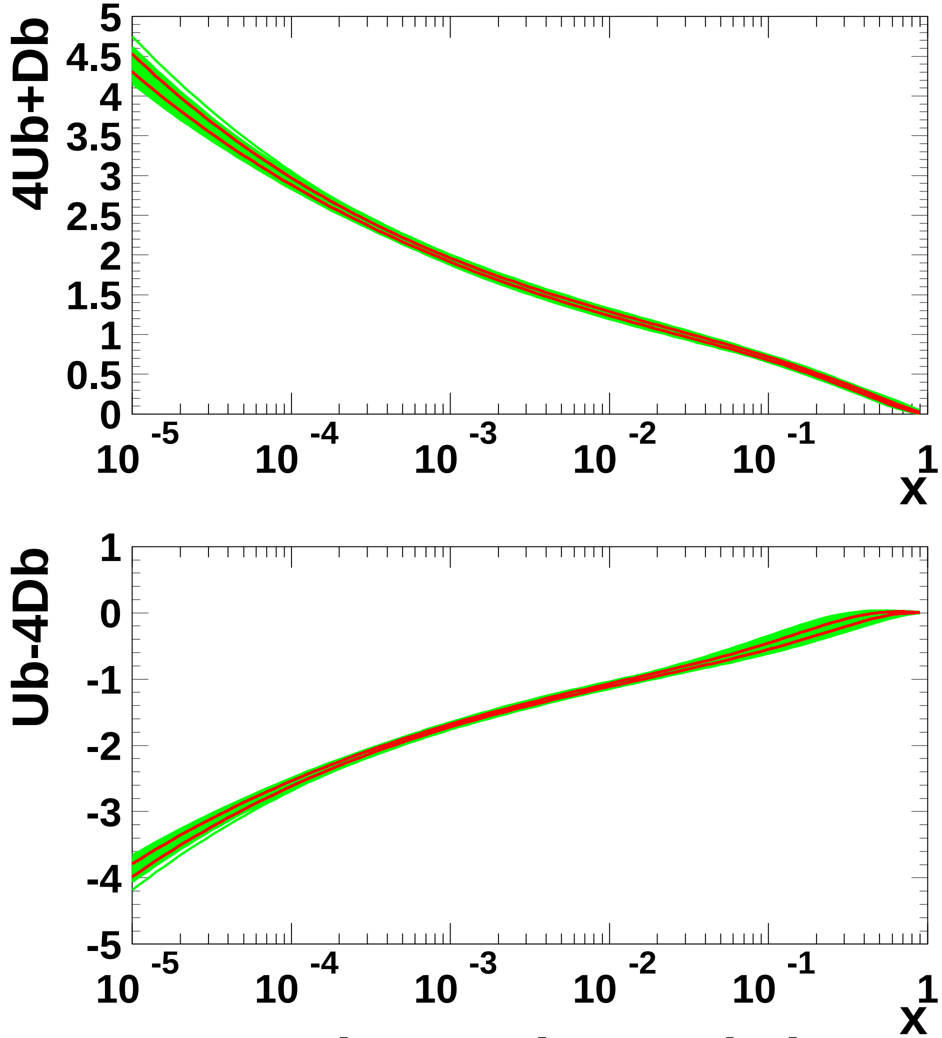
HERAPDF1.0 Fit Settings

- Input: combined HERA-I data for $e^{\pm}p$ NC and CC scattering. Well understood experimental errors and minimal theoretical uncertainties: pure ep data far from low W region, no jets.
- (N)NLO evolution, RT-VFNS for charm and bottom, $\alpha_S = 0.1176$.
- Evolution starting scale $Q^2 = 1.9$ GeV^2, below $m_c^{\mathrm{model}} = 1.4$ GeV. Start fitting data at $Q^2_{min} = 3.5$ GeV^2.
- Fitted PDFs are xg, xu_v, $xd_v(x)$, $x\bar{U}$, $x\bar{D}$ where $x\bar{U} = x\bar{u}$ and $x\bar{D} = x\bar{d} + x\bar{s}$ at the starting scale. For the strange, $x\bar{s} = f_s x\bar{D}$ with $f_s = 0.31$ is assumed.
- Standard parameterisation form

$$xf(x) = Ax^B(1-x)^C(1+\epsilon\sqrt{x} + Dx + Ex^2)$$

  with only significant ϵ, D and E terms kept.
- A_g, A_{u_v}, A_{d_v} fixed by sum rules. <u>Extra constraints</u> for small x behaviour of d and u-type quarks: $B_{u_v} = B_{d_v}$, $B_{\bar{U}} = B_{\bar{D}}$, $A_{\bar{U}} = A_{\bar{D}}(1 - f_s)$

Decomposition of U and D



Low x behaviour of d and u is assumed to be the same. Forced in HERAPDF1.0 fit by requiring

$$B_{\bar{U}} = B_{\bar{D}}$$

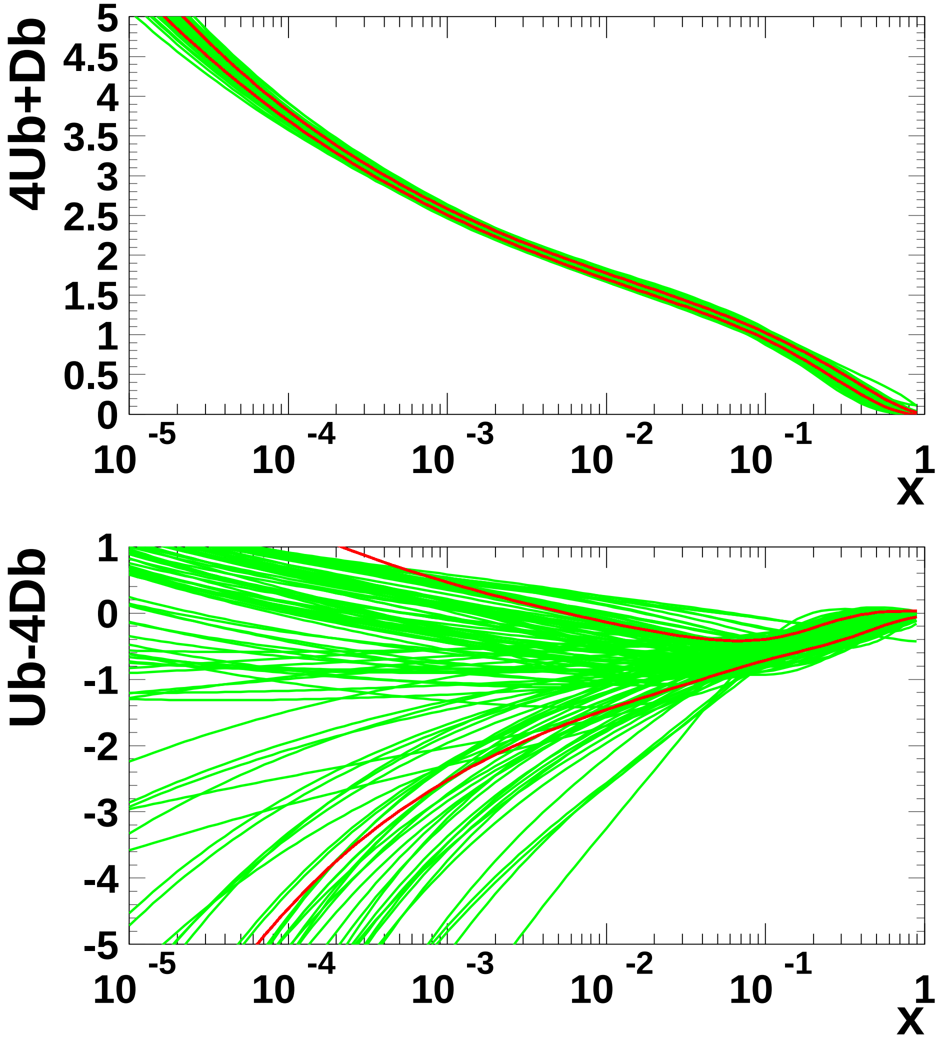
and

$$A_{\bar{U}} = A_{\bar{D}}(1 - f_s)$$

This imposes constraint on other linear combinations of $\overline{U}, \overline{D}$ vs $4\overline{U} + \overline{D}$.

Uncertainties are determined MC method, green lines: individual replicas, red: RMS.

HERA fits without $d = u$ assumption



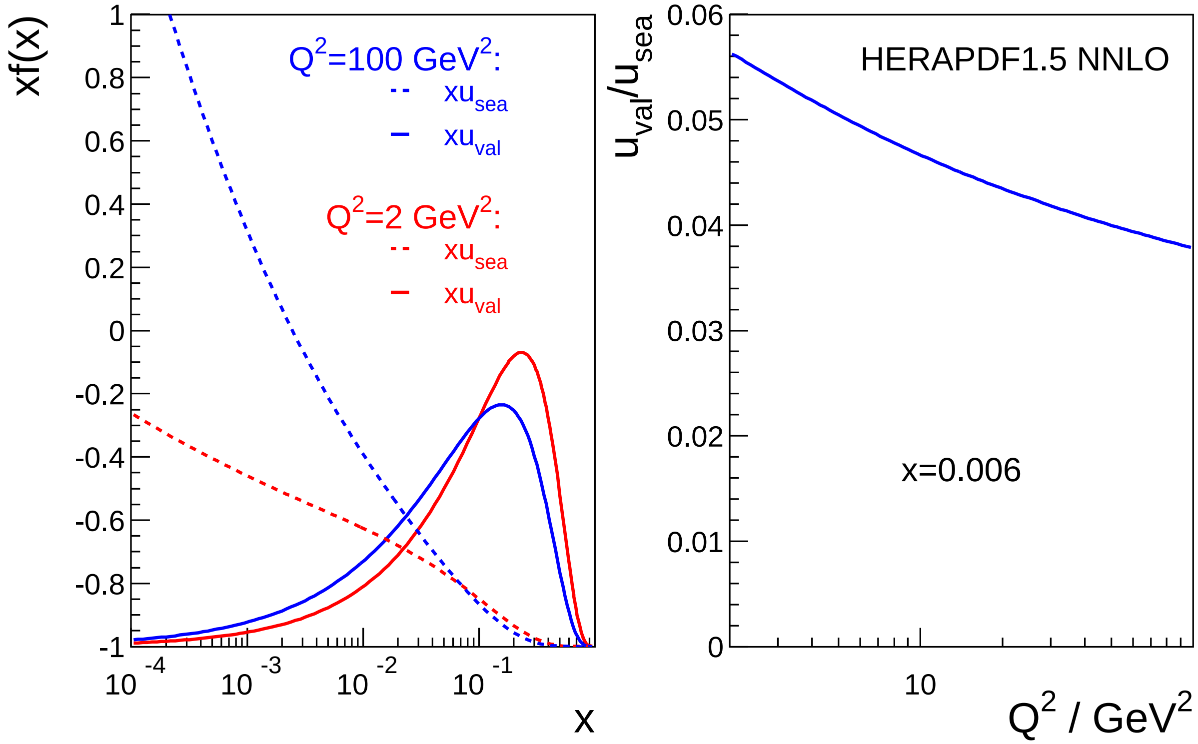
Unconstrained fit preserves narrow $4\bar{U} + \bar{D}$ but orthogonal combination $\bar{U} - 4\bar{D}$ has very large spread. The only significant constraint comes from the positivity of the PDFs, $\bar{D} > 0, \bar{U} > 0$, which is built in the parameterisation.

Valence/sea quarks: existing sources of information

- Neutrino scattering data: limited to high x, heavy target corrections.
- CC data from HERA: $x > 0.01$.
- xF_3 structure function from HERA: limit-ted precision, high x.
- Quark counting sum rules: integrated constrain.
- pp and $p\bar{b}$ W lepton asymmetry.

Valence and sea quarks show different Q^2 evolution. Can existing HERA combined data provide constraints on valence distributions?

Sea and Valence Evolution at low x



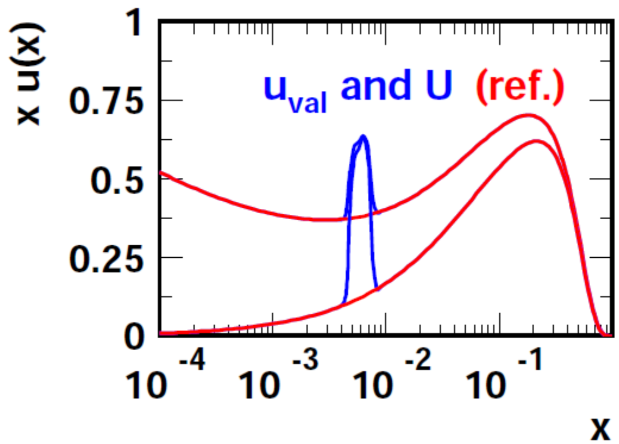
- Valence and sea quarks evolve differently: coupled sea/gluon evolution for the sea and softening due to gluon radiation for the valence.
- Difference in the evolution corresponds to $\sim$ 1% in valence fraction for Q^2 running from 2 GeV^2 to 100 GeV^2 for $x = 0.006$.
- Data precision reaches $\sim$ 1%, can we use this as a constraint ?

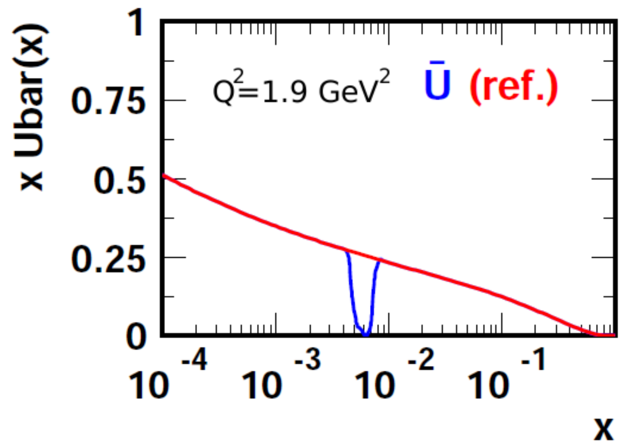
Test Setup

Consider following variations of the light quark densities at the starting scale $Q^2 = 1.9$ GeV^2, locally for $0.0047 < x < 0.0070$:

$$\begin{aligned} u'_v &= u_v(1-A), \\ d'_v &= d_v(1-B), \\ \bar{U}' &= \bar{U} + S/4\,\bar{U} + 1/2\,A\,u_v, \\ \bar{D}' &= \bar{D} - S\,\bar{U} + 1/2\,B\,d_v, \end{aligned}$$

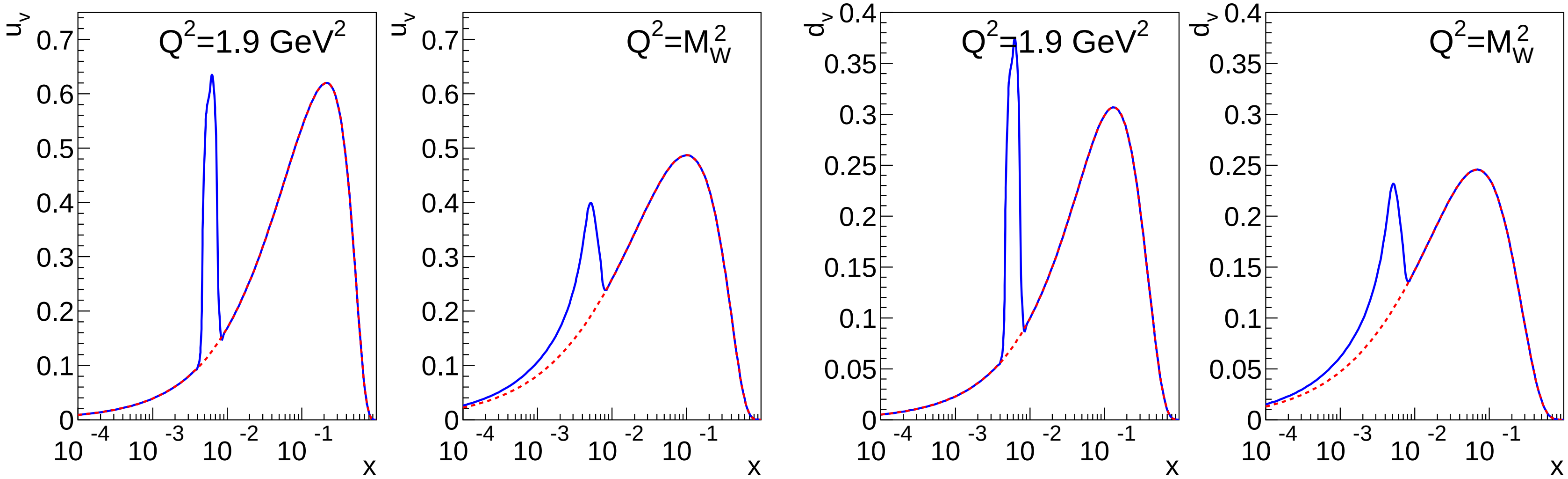
where A, B and S are free parameters. Ignore quark counting and momentum sum rules.





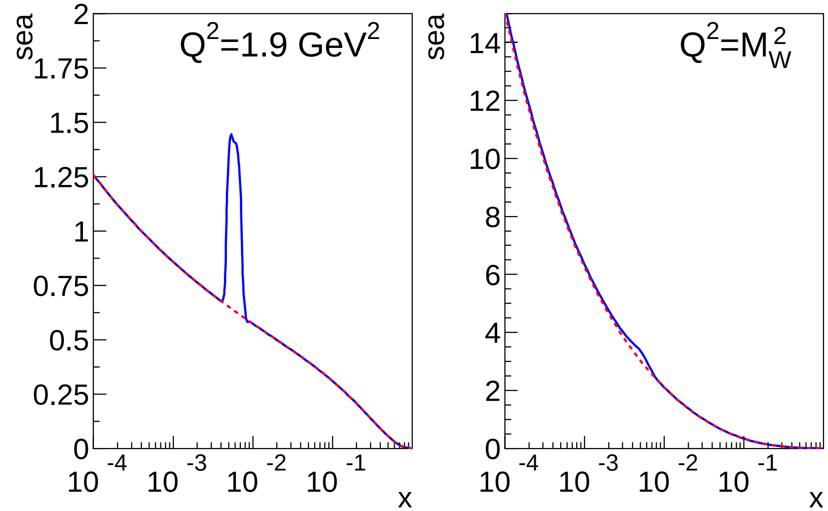
Same χ^2 for the reference and $A = -4$ solution, no constraints from HERA on A, B.

Effect of Evolution

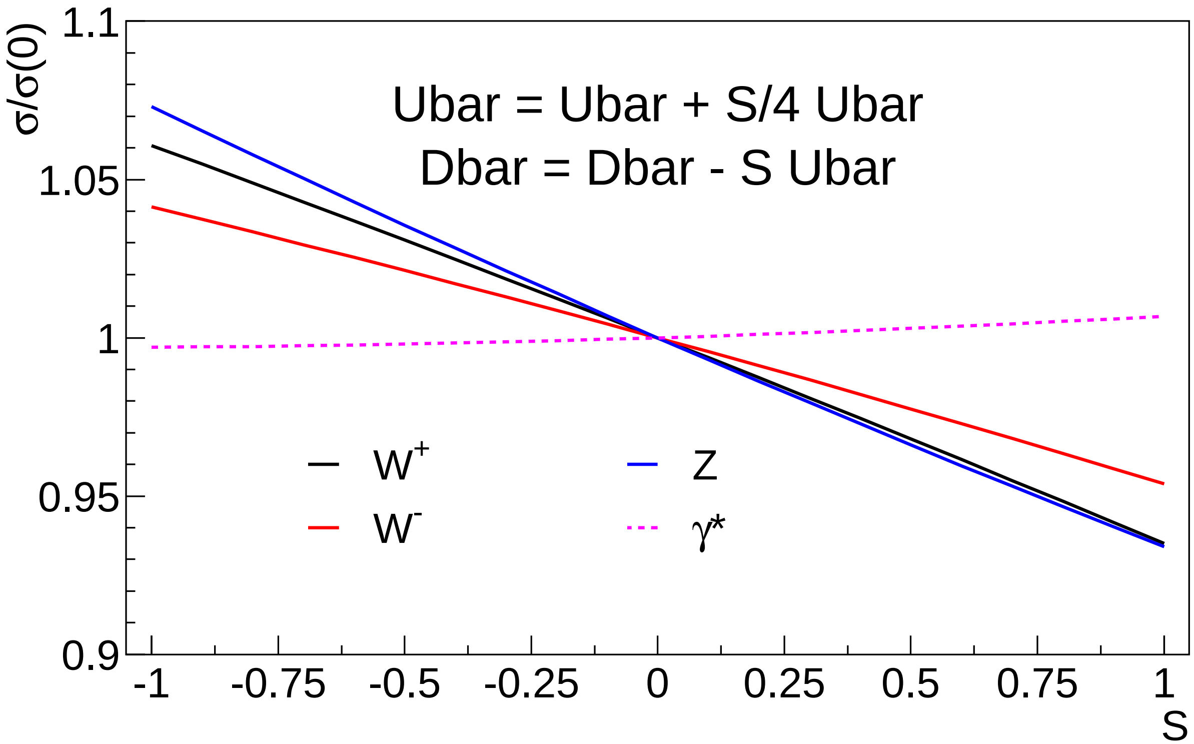


Setting $A = B = -4$ and $S = -4$ leads to large variation of valence quarks and sea which is washed out for large scales.

The washing out effect is the biggest for the sea.

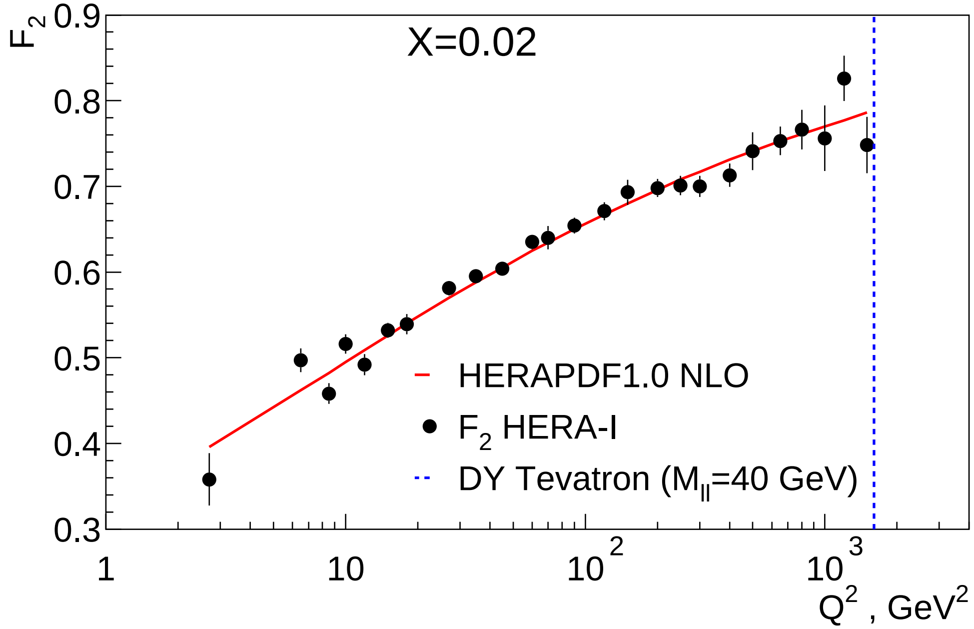


Dependence of $W^{\pm}$, Z, and γ^* production on A, B, S



- Consider central production of $W^{\pm}$, Z and γ for different A, B, S for LHC at $s = 14$ TeV. For simplicity, consider same $Q^2 = M_W^2$ and ignore heavy quark contribution.
- γ^* production has PDF decomposition very similar to F_2, shows little dependence on S. Ratio $\sigma_Z/\sigma_{\gamma^*}$ is a good observable to fix S.

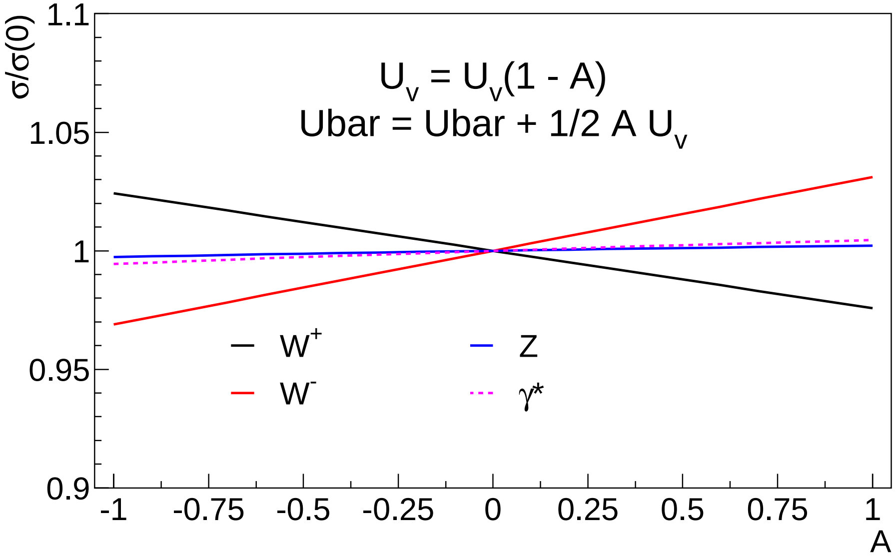
DY at Tevatron

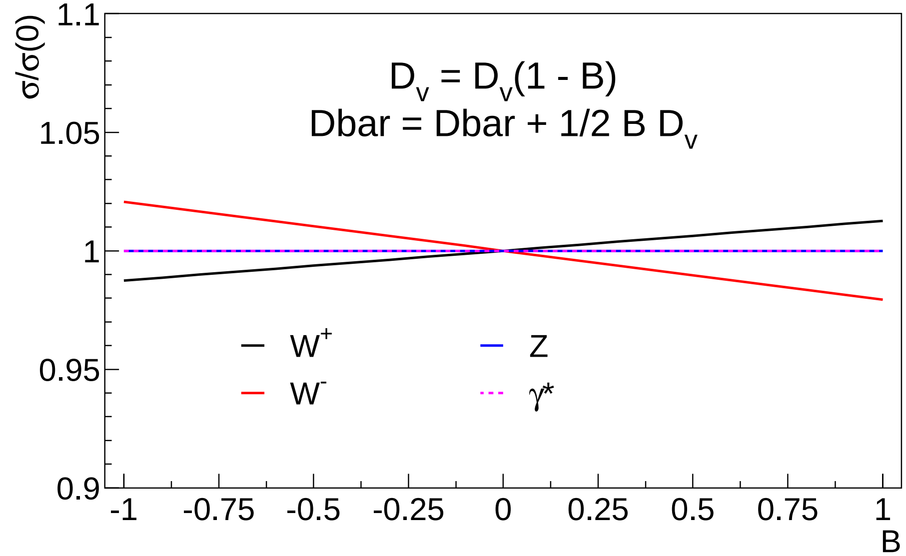


- For central $p\bar{p} \to X + \gamma^* \to \ell\ell$ production at leading order, the partonic structure is "the same" as for $F_2(x = M_{\ell\ell}/S, Q^2 = M^2_{\ell\ell})$ with $q(x, Q^2) \to q^2(x, Q^2)$. Therefore, uncertainties due to PDF decomposition cancel to large extend.
- Numerically, $M_{\ell\ell} = 40$ GeV corresponds at Tevatron to $x = 0.02, Q^2 = 1600$ GeV^2, right above HERA data points.

$\to$ Since DIS and DY processes are know to NNLO, this provides excellent normalisation point (aka "standard candle") for the Tevatron experiments.

Dependence of $W^{\pm}$, Z, and γ^* production on A, B

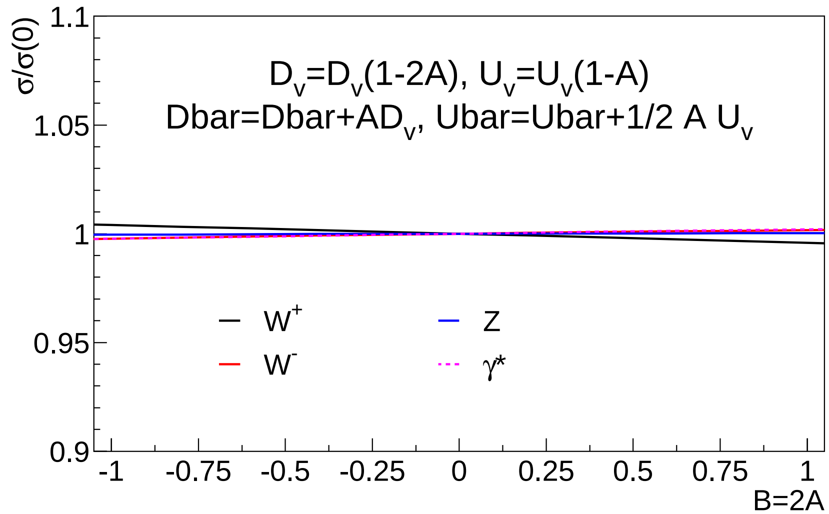




- Simultaneous variation in opposite direction of the valence and sea quarks leaves Z, γ^* production virtually invariant.
- Rate of production of $W^{\pm}$ changes in opposite direction, providing good constraint on u_v/d_v ratio.

But ...

Dependence of $W^{\pm}$, Z, and γ^* production on A, $B = 2A$



Variation $u_v \to u_v(1-A)$, $d_v \to d_v(1-2A)$ (and corresponding changes in $\bar{u}, \bar{d}$) leaves rates of all processes virtually invariant. This follows from light quark symmetries for the central HERAPDF fit. For light quark contribution since $d_{sea} = \bar{d}$ and $u_{sea} = \bar{u}$:

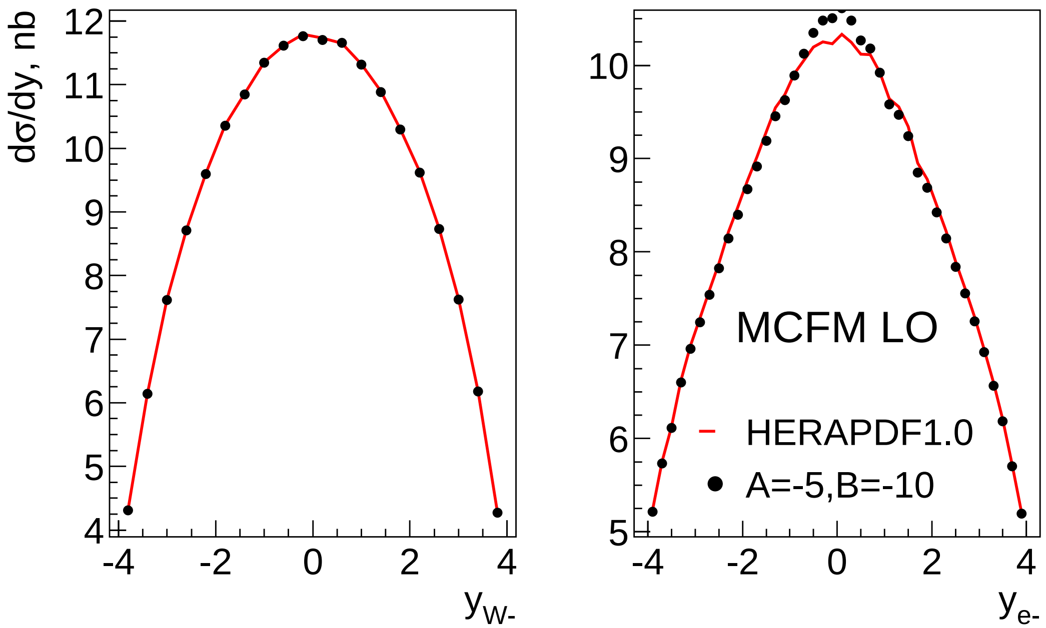
$$\sigma_{W^+} \sim (\bar{u} + u_v)\bar{d}, \qquad \sigma_{W^-} \sim (\bar{d} + d_v)\bar{u},$$

and neglecting A^2 and $d_v u_v$ terms, productions rates after the variation are

$$\begin{aligned}
\sigma'_{W^+} &\sim (\bar{u} + u_v - 0.5Au_v)(\bar{d} + Ad_v) \approx \sigma_{W^+} + 0.5Au_v(\bar{u} - \bar{d}) + A\bar{u}(d_v - 0.5u_v) \\
\sigma'_{W^-} &\sim (\bar{d} + d_v - Ad_v)(\bar{u} + 0.5Au_v) \approx \sigma_{W^-} + Ad_v(\bar{d} - \bar{u}) + 0.5A\bar{d}(u_v - 2d_v)
\end{aligned}$$

Since $\bar{u} \approx \bar{d}$ and $u_v \approx 2d_v$, they remain constant.

Effect on lepton rapidity distribution



- Consider variation $A = -5$, $B = -10$. Propagate through `H1Fitter`, generate LHAGRID files.
- Run MCFM (LO) for $W^{\pm}$ production using original and modified PDFs.

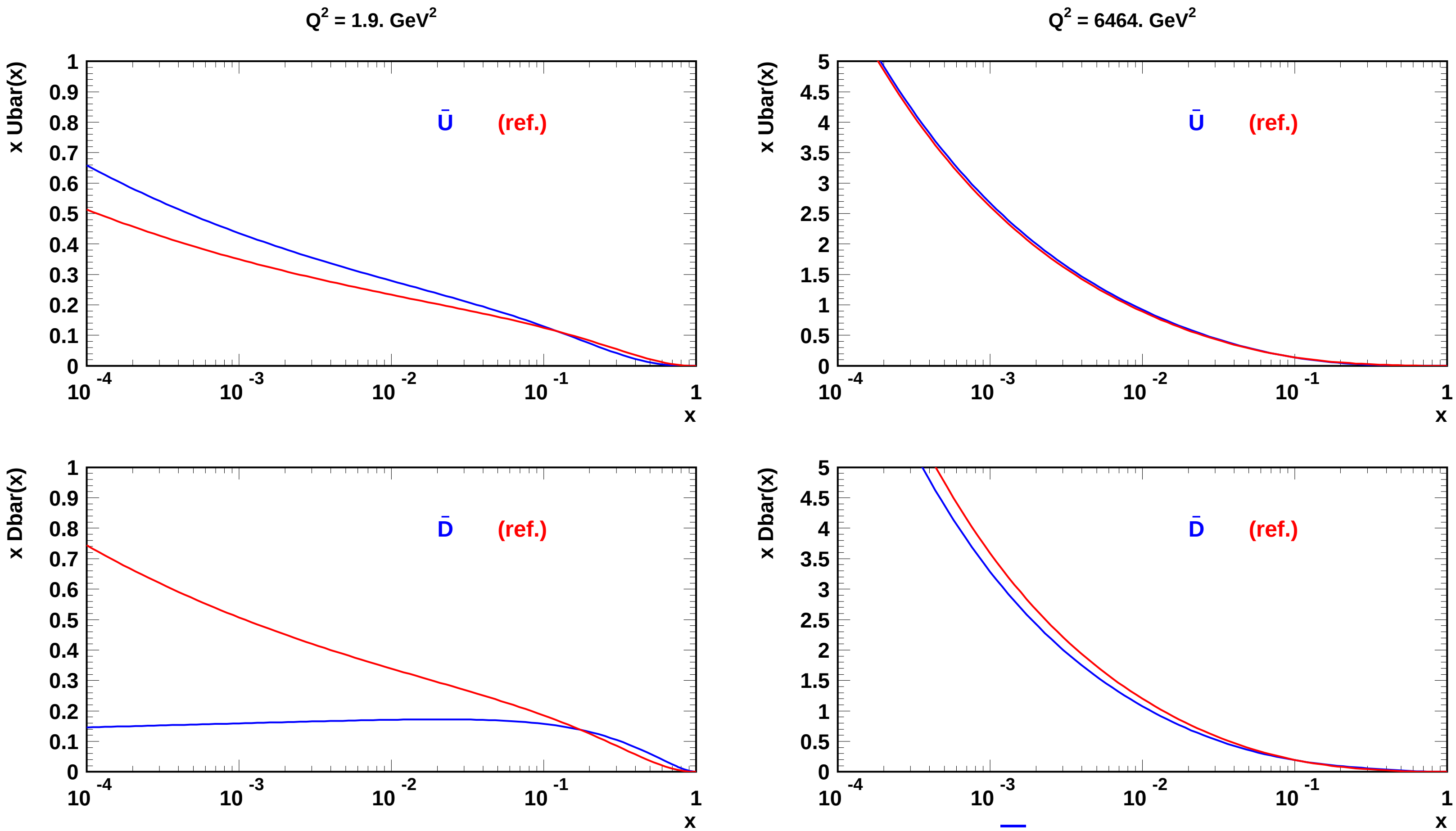
$\rightarrow$ $\mathrm{d}\sigma/\mathrm{d}y_{W^-}$ distribution remains invariant, while $\mathrm{d}\sigma/\mathrm{d}\eta_{e^-}$ is modified!

Summary and Outlook

- HERA data provides accurate input for the sea at low x. However, data have little sensitivity to variations of light flavors as well as valence-sea quark separation.
- Adding LHC allows to fix $\bar{u}/\bar{d}$ separation, good observable for that is NC DY processes, γ^* vs Z production.
- Tevatron measurement of NC DY for $M_{\ell\ell} \sim 40$ GeV is complimentary to HERA F_2 measurement, can provide reference cross section for the Tevatron measurements.
- W^+, W^- production controls u_v and d_v densities. However, variation $u_v \to u_v(1-A)$, $d_v \to d_v(1-2A)$ with a corresponding change of sea quarks is hard to fix.
- Next steps: extend to strange sea density, study effects of PDF uncertainties on W polarisation $\rightarrow$ PDF uncertainties on M_W.

Extras

$\bar{U}$ and $\bar{D}$ densities in the unconstrained fit

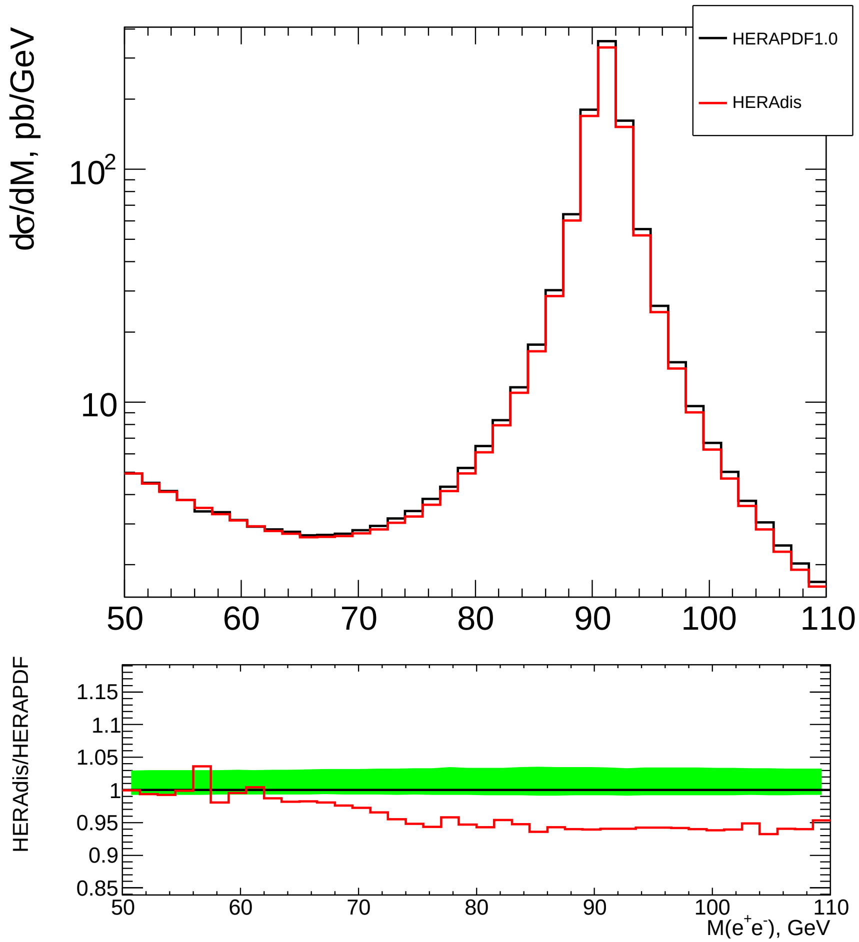


Central unconstrained fit prefers solution with low $\bar{D}$ and increased $\bar{U}$. The difference is dramatic at the starting scale, but it remains sizable at the M_W scale too.

LHAPDF grid file for the unconstrained fit:

`https://www.desy.de/h1zeus/combined_results/proton_structure/Fits/HERAPDF1.0u.LHgrid.gz`

Low mass DY vs Z for U over D decomposition



Since γ^* exchange has the same sensitivity to the quark flavours as the measurement of F_2 at HERA, unconstrained fit agrees with HERAPDF1.0 at low $M_{e^+e^-}$, but sizable lower at $M_{e^+e^-} = M_Z$.

based on NLO MCFM

To separate $\bar{U}$ and $\bar{D}$ for the same (Q^2, x) region a good observable is the ratio of $d\sigma/dy$ for Z production at $\sqrt{s} = 7$ TeV and DY for $M_{\ell^+\ell^-} = M_Z/2$ at $\sqrt{s} = 14$ TeV at the LHC.