# Proton structure and PDFs from HERA

**Pavel Belov**, DESY
(on behalf of the H1 and ZEUS Collaborations)

ISMD, Kielce
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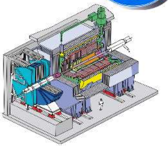
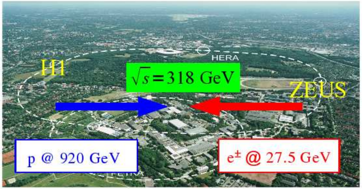
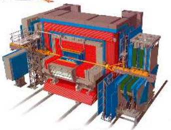
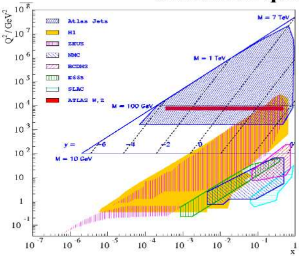
## HERA collider (Hamburg, Germany)





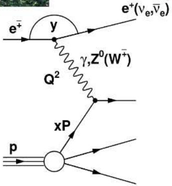
**Kinematic quantities of DIS:**




Photon virtuality: $Q^2$

Inelasticity: $y$

Bjorken Variable: $x$




- Periods of operation:
  HERAI: 1992-2000
  HERAII: 2003-2007
- Integrated luminosity:
  ~ 0.5 fb$^{-1}$ per exp.

## Probe of proton structure

**Neutral Current** DIS cross section can be written via structure functions $F_2$, $xF_3$, $F_L$:

$$\frac{d^2\sigma^{\pm}_{NC}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[Y_+F_2 \mp Y_-xF_3 - y^2F_L\right]$$

where $Y_\pm = 1 \pm (1-y)^2$

**Proton structure functions:**

$\mathbf{F_2}$ - dominant, sensitive to sea quarks

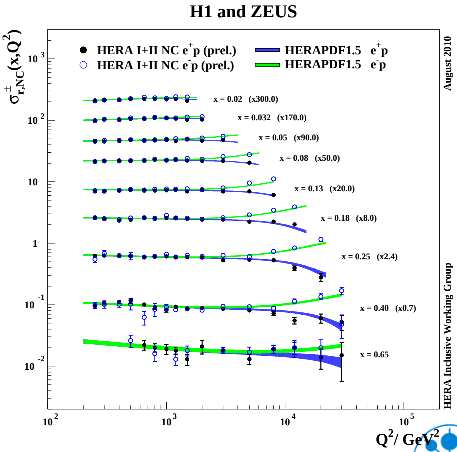
$\mathbf{xF_3}$ - sensitive to valence quarks, essential at high $Q^2$

$\mathbf{F_L}$ - sensitive to gluon, essential at high $y$

At the leading order:

$$F_2 = x\sum e_q^2[q(x) + \bar{q}(x)]$$

$$xF_3 = x\sum 2e_q a_q[q(x) - \bar{q}(x)]$$

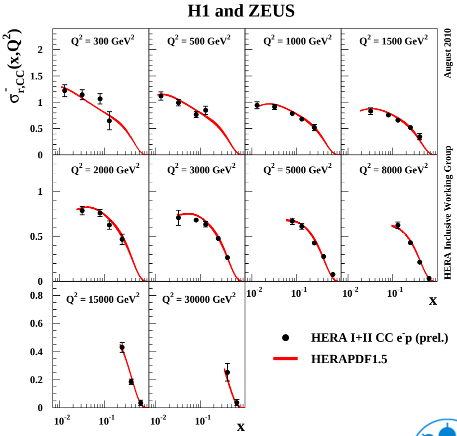


## Probe of proton structure

At LO, **Charge Current** DIS $e^+p$ and $e^-p$ cross sections are sensitive to different quark densities:

$$\sigma^+_{CC} \sim x[\bar{u}+\bar{c}] + x(1-y)^2[d+s]$$

$$\sigma^-_{CC} \sim x[u+c] + x(1-y)^2[\bar{d}+\bar{s}]$$



## Input Data into HERAPDF fits

**Input data:**

- HERAPDF1.0 (NLO)
  - combined CC/NC HERA-I inclusive data [JHEP01(2010) 109]
- **HERAPDF1.5** (NLO,NNLO)

  the currently recommended set, available at LHAPDF
  - + combined CC/NC High $Q^2$ HERA-II inclusive data [prelim]

    *increase of statistics, sensitive to valence quarks*
- HERAPDF1.6 (NLO)
  - + inclusive H1 and ZEUS Jet data [EPJC 65, 363 (2010), EPJC 67, 1 (2010), PLB 547, 164 (2002) PLB 649, 12 (2007)]

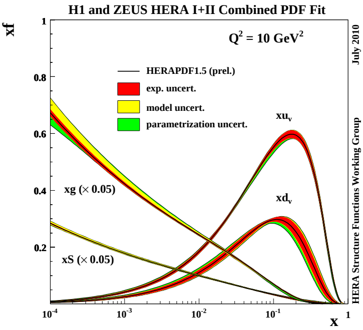
    *determination of $\alpha_S$*
- HERAPDF1.7 (NLO)
  - + combined charm $F_2$ data [prelim]

    *constrains on charm mass*
  - + combined low energy run data [prelim]

    *sensitive to $F_L$*

## QCD Fit settings

The extracted PDFs



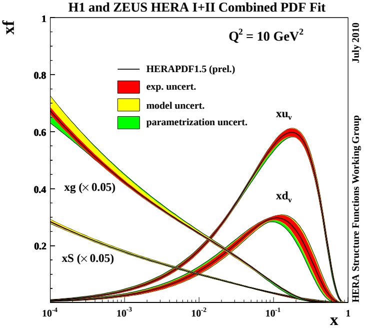

**Fit settings:**

- Fitted distributions: $xg, xu_v, xd_v, x\overline{U} = x\bar{u}, x\overline{D} = x\bar{d} + x\bar{s}$
- The simple functional form

$$xf(x) = Ax^B(1-x)^C(1+Dx+Ex^2)$$

  A – normalization
  B – low-$x$ behaviour, C – high-$x$ behaviour
  D,E – medium behaviour
- starting scale $Q_0^2 = 1.9GeV^2$ below the charm mass threshold
- NLO and NNLO DGLAP fit with heavy flavour schemes (RT, ACOT)
- fit is performed for $Q^2 \geqslant Q^2_{min} = 3.5GeV^2$
- factorization and renormalization scales = $Q^2$
- fixed $\alpha_s(M_Z) = 0.1176$

## PDF uncertainties




$$xf(x) = A x^{B} (1-x)^{C} (1 + Dx + Ex^{2})$$

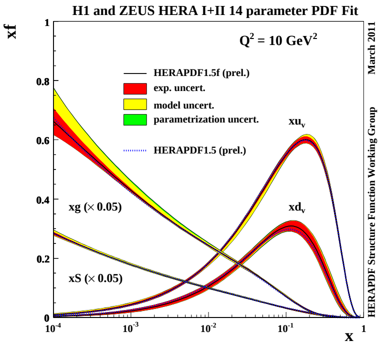
**PDF uncertainties:**

$$\Delta\chi^2 = 1$$

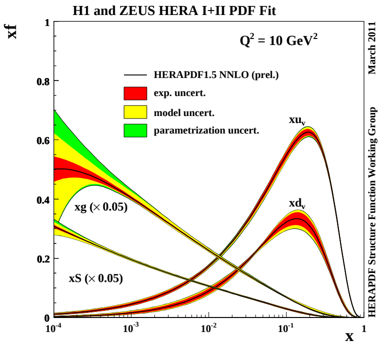
- Correlations of the sys uncertainties are properly taken into account
- Experimental, model and parametrization uncertainties:
  - model uncertainties obtained by variation $Q^2_{min}$, $m_c$, $m_b$, $f_s$
  - parametrization uncertainties are estimated by including additional parameters into the functional form and variation of $Q_0^2$

## NLO vs NNLO

**NLO** HERAPDF1.5 flexible




**NNLO** HERAPDF1.5 flexible

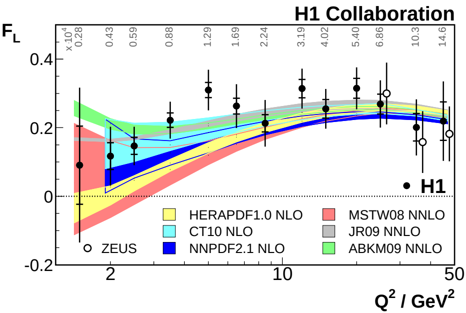



Both fits have flexible gluon parametrization

$$xg(x) = A_g x^{B_g} (1-x)^{C_g} - A'_g x^{B'_g} (1-x)^{25}$$

- NNLO fit demands fewer gluon at low-$x$
  low-$x$ needs to be considered precisely

## H1: Measurement of the Structure function $F_L$




The following data are used:

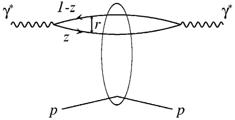
- HERA-II $E_p = 920$ GeV sample: the improved accuracy at high $y$ by factor of 2 comparing to HERA-I data
- HERA-II reduced proton energy run for $E_p = 460, 575$ GeV

- The low-$x$ ($x \lesssim 0.002$) measurements of the structure function $F_L$ are extended to $Q^2 \gtrsim 1.5$ GeV$^2$
- Within uncertainties, all predictions describe data reasonably well

EPJC 71, 1579 (2011)

## Dipole models

$x < 0.01$




– gluon dominance is assumed
– valence contribution is ignored, however this contribution is substantial reaching 10% for $x \sim 0.01$.

Factorization:

$$\sigma_{T,L}(x,Q^2) = \int d^2\mathbf{r} \int_0^1 dz |\Psi_{T,L}(z,\mathbf{r})|^2 \sigma(x,r^2)$$

GBW (Golec-Biernat, Wüsthoff) dipole model:

$$\sigma(x,r^2) = \sigma_0 \left(1 - e^{\left[-\frac{r^2}{4R_0^2(x)}\right]}\right), \quad R_0^2(x) = \left(\frac{x}{x_0}\right)^{\lambda}$$

CGC (Iancu, Itakura, Munier) dipole model:
approximate solution BFKL eq. produces $\sigma(x,r^2)$

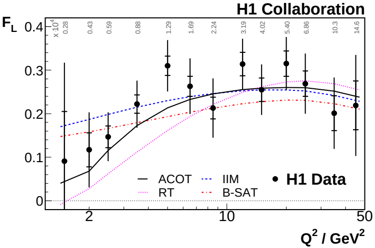
B-SAT (Kowalski, Motyka, Watt) dipole model:

$$\sigma(x,r^2) = \sigma_0 \left(1 - \exp\left[-\frac{\pi r^2 \alpha_s(\mu^2) xg(x,\mu^2)}{3\sigma_0}\right]\right)$$

$$xg(x,Q_0^2) = A_g x^{-\lambda_g}(1-x)^{C_g}$$

## Dipole models

- DGLAP: RT scheme, ACOT scheme
- Describe the data by the DGLAP and Dipole models in the kinematic region $x < 0.01$ and $Q^2 > 3.5$ GeV$^2$.
  IIM dipole model leads to the best $\chi^2$.
- Estimate the valence quark contribution using DGLAP.

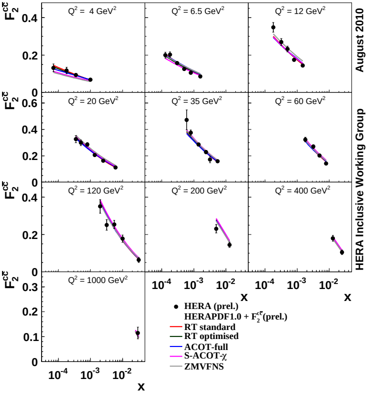



$Q^2 \geqslant 10$ GeV$^2$: agreement
$Q^2 < 10$ GeV$^2$: RT and ACOT predict lower $F_L$

| Fit | GBW | IIM | B-SAT | ACOT (NLO) | RT (NLO) |
|---|---|---|---|---|---|
| Dipole | 559.7/252 | 259.4/252 | 261.7/252 | | |
| +DGLAP$_{\text{valence}}$ | 739.5/252 | 287.6/252 | 371.4/252 | 248.3/249 | 288.8/249 |

Table: Quality of fits in terms of $\chi^2/N_{dof}$ for GBW, IIM and B-SAT dipole model as well as ACOT and RT DGLAP schemes for various fit conditions.

## The charm contribution $F_2^c$ into the proton structure function




**The inclusive structure function**

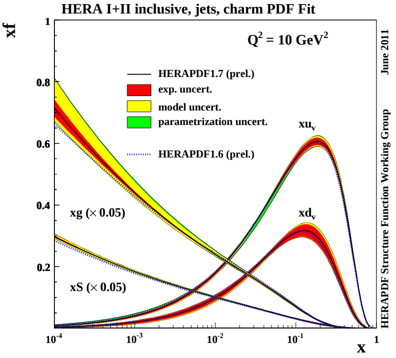
$$F_2 \sim \frac{4}{9}(U + \overline{U}) + \frac{1}{9}(D + \overline{D}),$$

where $U = u + c$ and $D = d + s + b$.

- for $Q^2 \gg m_c^2$ the charm contribution reaches 30% at low-$x$
- The treatment of the charm mass threshold is challenging
- Charm data prodive information about separation of $x\overline{U}$ into $x\bar{u}$ and $x\bar{c}$
- In HERAPDF the uncertainties due to heavy flavour modeling are estimated by varying of $m_c$

Precision of 5–10% is achieved for combined HERA measurements of charm contribution $F_2^c$

## NLO HERAPDF1.7

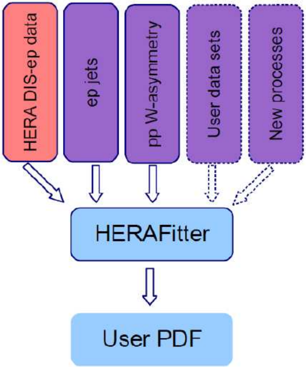



### HERAPDF1.7 includes

- HERA inclusive data
- combined low energy run data
- published jet data
- preliminary combined charm data

- The PDFs are strongly constrained and consistent with previous HERAPDFs
- We are underway to HERAPDF2.0

# HERAFitter package




http://herafitter.hepforge.org/

is the open source QCD Fit Package used to determine the PDFs

- different data can be analysed: DIS *ep*, Drell-Yan *pp*, $p\bar{p}$ and jet data.
- the package is based on MINUIT minimization
- theory predictions can be calculated by
  - VFNS from R. Thorne
  - ACOT from F. Olness
  - QCDNUM from M. Botje
  - APPLGRID code
  - FastNLO code
  - Dipole models
- PDF parametrizations: **HERA**, CTEQ, Chebyshev
- estimation of uncertainties: Hessian method, MC method

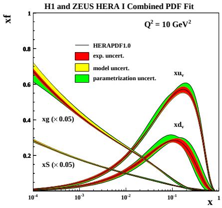
# Summary

- The HERA data strongly constrain the parton density functions
- HERAPDF is a series of PDF sets released by the H1 and ZEUS collaborations. **HERAPDF1.5** is the currently recommended set
- The low energy data allowed to obtain measurements of $F_L$ extended to $Q^2 \geqslant 1.5$ GeV$^2$
- The dipole models describe the data at low $x$, the IIM dipole model is the best
- The charm contribution to $F_2$ is measured with accuracy about 10%
- The publicly available `HERAFitter` package is a powerful tool for determination of PDFs using different data http://herafitter.hepforge.org/

**Thank you so much for your attention!**

# Backup

NLO HERAPDF1.0




A – normalization
B – low-$x$ behaviour
C – high-$x$ behaviour
D,E – additional

Parametrized PDFs at the starting scale
$xg, xu_v, xd_v, x\overline{U} = x\bar{u}, x\overline{D} = x\bar{d} + x\bar{s},$

Parametrization

$$\begin{aligned} xg(x) &= A_g x^{B_g} (1-x)^{C_g} - A'_g x^{B'_g} (1-x)^{25} \\ xu_v(x) &= A_{u_v} x^{B_{u_v}} (1-x)^{C_{u_v}} (1 + D_{u_v} x + E_{u_v} x^2) \\ xd_v(x) &= A_{d_v} x^{B_{d_v}} (1-x)^{C_{d_v}} \\ x\overline{U}(x) &= A_{\overline{U}} x^{B_{\overline{U}}} (1-x)^{C_{\overline{U}}} \\ x\overline{D}(x) &= A_{\overline{D}} x^{B_{\overline{D}}} (1-x)^{C_{\overline{D}}} \end{aligned}$$

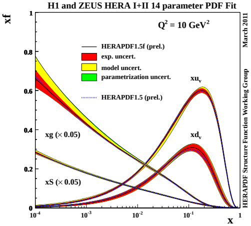
*Additional constraints:* $A_g, A_{u_v}, A_{d_v}$ are from sumrules
$A_{\overline{U}} = A_{\overline{D}}(1-f_s), B_{\overline{U}} = B_{\overline{D}}, \to x\bar{u} \to x\bar{d}$ for low-$x$

Parametrization choices for each HERAPDF set:

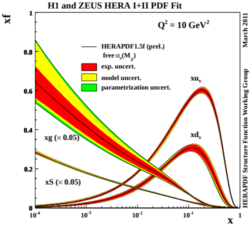
| HERAPDF | $D_{u_v}$ | $E_{u_v}$ | $A'_g$ | $B'_g$ | $B_{u_v}$ | $\sum$ par |
|---|---|---|---|---|---|---|
| 1.0 | 0 | free | 0 | 0 | $B_{u_v} = B_{d_v}$ | 10 |
| 1.5 | 0 | free | 0 | 0 | $B_{u_v} = B_{d_v}$ | 10 |
| 1.6 | free | free | free | free | free | 14 |
| 1.7 | 0 | free | free | free | free | 13 |

**Note:** flexible gluon parametrization is used when $A'_g$ and $B'_g$ are free

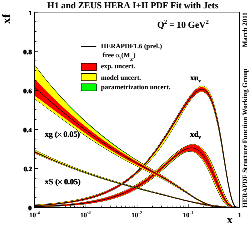
**HERAPDF1.6** includes inclusive **jet data** and combined inclusive HERA-I and HERA-II data




fix $\alpha_s$, no jets

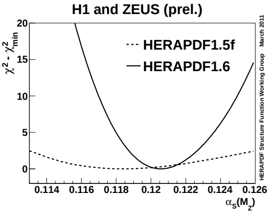



free $\alpha_s$, no jets



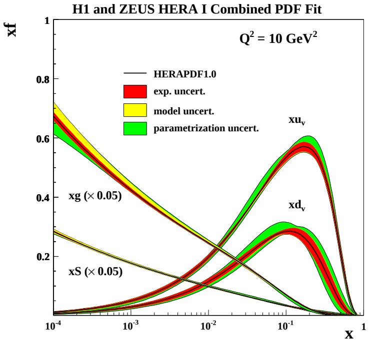

free $\alpha_s$, + jets

- free $\alpha_s$ increases gluon uncertainty at low $x$ due to large gluon-$\alpha_s$ correlation
- inclusion of jet data makes it possible to significantly reduce the correlation and, consiquently, the gluon uncertainties
- $\alpha_s(M_Z) = 0.1202 \pm 0.0013(exp) \pm 0.0007(mod/param) \pm 0.0012(had)$

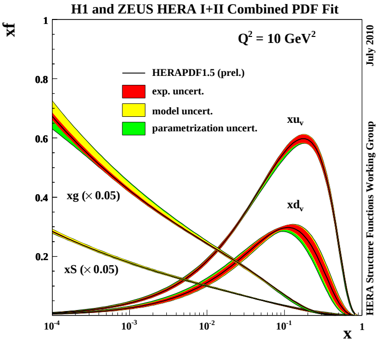


## HERAPDF1.0 ⟶ HERAPDF1.5

NLO HERAPDF**1.0**




NLO HERAPDF**1.5**



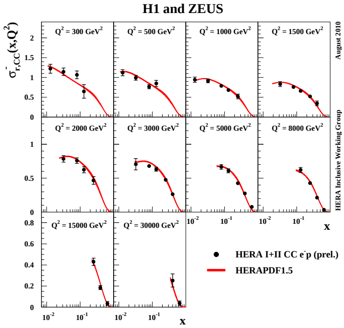

In addition to the HERA-I DIS data, HERAPDF1.5 includes High $Q^2$ HERA-II data. It increases the statistics:

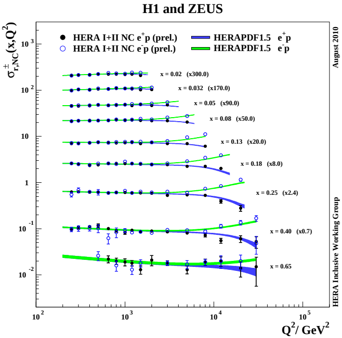
– by 2.5 times for $e^+p$

– by about 10 times for $e^-p$

For HERAPDF1.5 **the precision of the valence distributions at high $x$ is improved**

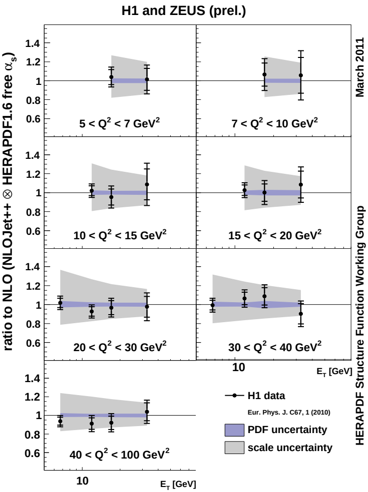
## HERAPDF1.0 → HERAPDF1.5

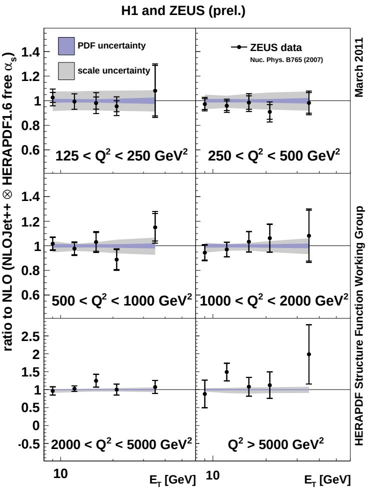



- Combination of HERA-I and HERA-II data collected by H1 and ZEUS, for CC and NC processes (missing only NC $e^+p$ from ZEUS, which comes next!)
- 674 combined data points with 134 sources of systematic uncertainty
- Significantly more precise $e^{\pm}p$ CC and $e^{\pm}p$ NC data compared to HERA-I combination
- NLO HERAPDF1.5 fit: good agreement between DGLAP predictions and data

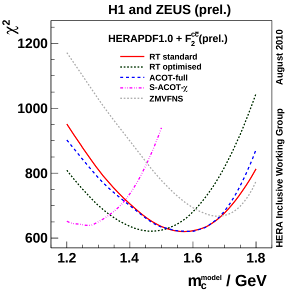
## HERAPDF1.0 → HERAPDF1.5

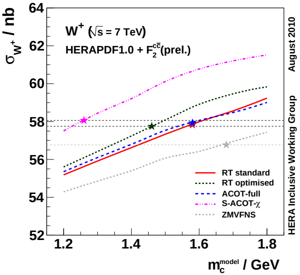



- Fit combined inclusive HERA I+II data and add to this fit published inclusive jet samples from H1 and ZEUS
- Good description of the jet cross sections: HERAPDF1.6 set

## HERAPDF1.0 → HERAPDF1.5




**Tune the HF schemes to charm data using $m_c^{model}$ as an input parameter**

- charm data makes $\chi^2$ to be sensitive to value of $m_c^{model}$
- different optimal values are obtained

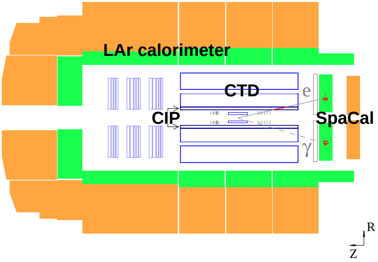
| Scheme | $RT_{st}$ | $RT_{opt}$ | $ACOT_{\chi}$ | $ACOT_{full}$ | ZMVFNS |
|---|---|---|---|---|---|
| $m_c^{opt}$ GeV | 1.58 | 1.46 | 1.26 | 1.58 | 1.68 |

### $W^+$ production cross section at the LHC

- the difference between schemes reaches 7%
- at the full interval $1.2 < m_c^{model} < 1.8$ GeV the change of prediction is also about 7%
- the spread is 0.7% for optimal value of $m_c^{model}$

# Radiative photon production in QED Compton process:

$$ep \longrightarrow e\gamma p$$




Advantages:

- insensibility to details of the beam optics
- clear detection in the H1 main detector

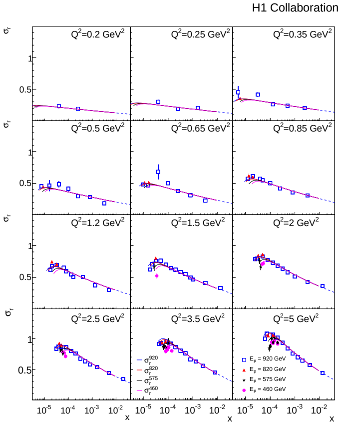
Disadvantages:

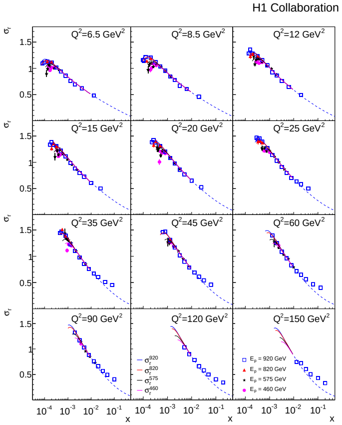
- smallness of the cross section
- necessity to control background

The integrated luminosity in the years 2003 to 2007:

$$\mathcal{L} = 351.6\text{pb}^{-1} \pm 0.8\%(\text{stat}) \pm 2.1\%(\text{syst})$$

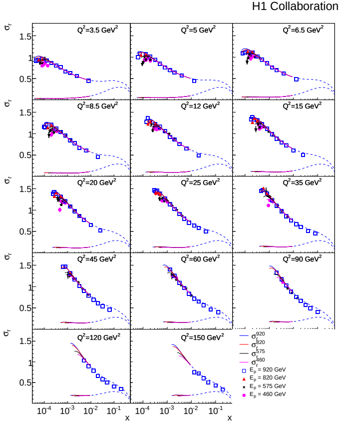
## HERAPDF1.0 → HERAPDF1.5




IIM fit: $\chi^2/n_{dof} = 397.6/352$ (plots in paper draft)

## HERAPDF1.0 → HERAPDF1.5




- Data for $x > 0.01$ are not included in the fit
- Description of the data is much improved at high $x$ due to the addition of the valuence contribution.
- Overall $\chi^2$ in the fitted region is not improved.
- Plot from the paper

$\chi^2/n_{dof} = 287.6/252$ compared to $\chi^2/n_{dof} = 259.4/252$ without DGLAP valence contribution

| | IIM fit | | IIM+DGLAP$_{\mathrm{valence}}$ fit | |
|---|---|---|---|---|
| **Parameter** | **Value** | **Uncertainty** | **Value** | **Uncertainty** |
| $R_{\mathrm{IIM}}$ (fm) | 0.593 | 0.004 | 0.665 | 0.010 |
| $\lambda$ | 0.258 | 0.002 | 0.288 | 0.004 |
| $x_0$ | $0.59 \times 10^{-4}$ | $0.03 \times 10^{-4}$ | $0.13 \times 10^{-4}$ | $0.02 \times 10^{-4}$ |

Table: Parameters and total uncertainties of the IIM dipole and IIM+DGLAP$_{\mathrm{valence}}$ fits performed for $Q^2 \geqslant 3.5$ GeV$^2$.

| | B-SAT fit | | B-SAT+DGLAP$_{\mathrm{valence}}$ fit | |
|---|---|---|---|---|
| **Parameter** | **Value** | **Uncertainty** | **Value** | **Uncertainty** |
| $A_g$ | 2.35 | 0.04 | 1.64 | 0.03 |
| $\lambda_g$ | 0.072 | 0.006 | 0.098 | 0.006 |
| $Q_0^2$ (GeV$^2$) | 2.02 | 0.10 | 1.49 | 0.06 |

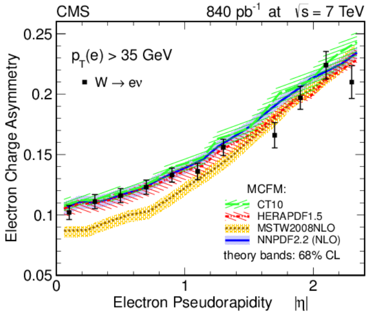
Table: Parameters and total uncertainties of the B-SAT dipole and B-SAT+DGLAP$_{\mathrm{valence}}$ fits performed for $Q^2 \geqslant 3.5$ GeV$^2$.

| Fit Conditions | GBW | IIM | $\chi^2/n_{dof}$ B-SAT | ACOT | RT |
|---|---|---|---|---|---|
| Nominal fit | 718.8/352 | 397.6/352 | 424.9/352 | 715.2/781 | 764.5/781 |
| $Q^2 \geqslant 3.5$ GeV$^2$ | 559.7/252 | 259.4/252 | 261.7/252 | | |
| DGLAP$_{\text{valence}}$ | 739.5/252 | 287.6/252 | 371.4/252 | 248.3/249 | 288.8/249 |

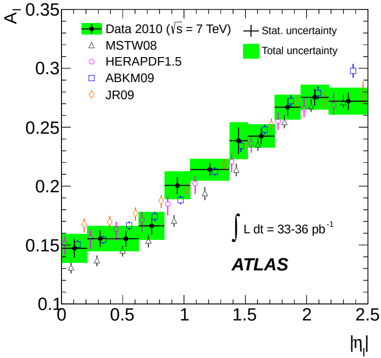
Table: Quality of fits in terms of $\chi^2/n_{dof}$ for GBW, IIM and B-SAT dipole model as well as ACOT and RT DGLAP schemes for various fit conditions described in the H1 paper.

- ACOT and RT DGLAP fits are discussed in the H1 paper
- ”Nominal fits” for the dipole models are performed for $x < 0.01$ while for the DGLAP fits at $Q^2_{min} \geqslant 3.5$ GeV$^2$.
- DGLAP$_{\text{valence}}$ fits are performed in a common phase space for the Dipole and DGLAP models.

## HERAPDF1.0 ⟶ HERAPDF1.5




Comparison of the measured $e$ charge asymmetry to the predictions of different PDF models for electron $p_T > 35$ GeV.




Measured $W$ charge asymmetry as a function of lepton pseudorapidity $|\eta_l|$ compared with theoretical predictions calculated to NNLO.