Recent Precision Measurements of the Proton Structure at HERA

ICNFP 2013

Ringailė Plačakytė

on behalf of the H1 and ZEUS collaborations

- Introduction
- HERA structure function data
- HERAFitter project
- Summary

Introduction: Proton Structure

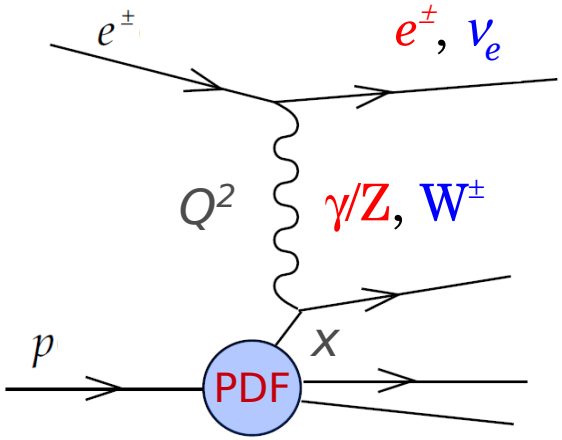
The proton is made up of point like constituents (partons)

→ probability for a parton to carry a fraction x of proton momentum:
Parton Distribution Functions (PDFs)

QCD factorisation: hardronic cross section is a convolution of the PDFs and perturbatively calculable hard-scattering coefficients:

$$\sigma \approx \hat{\sigma} \otimes \text{PDF}$$

Deep Inelastic Scattering (DIS):
unique opportunity to study the structure of the proton



Neutral Current (NC): $ep \to eX$
Charged Current (CC): $ep \to \nu X$

Kinematics:

Q^2 - virtuality of exchanged boson

x – Bjorken scaling variable

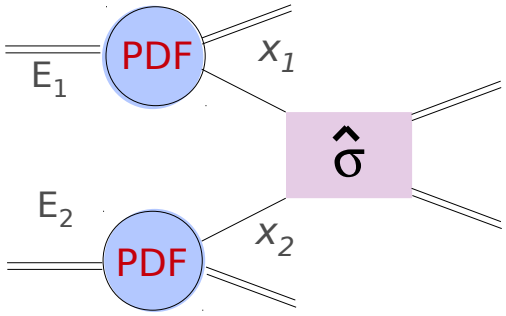
y – inelasticity

$Q^2 = sxy$ ($\sqrt{s}$ centre-of-mass energy)

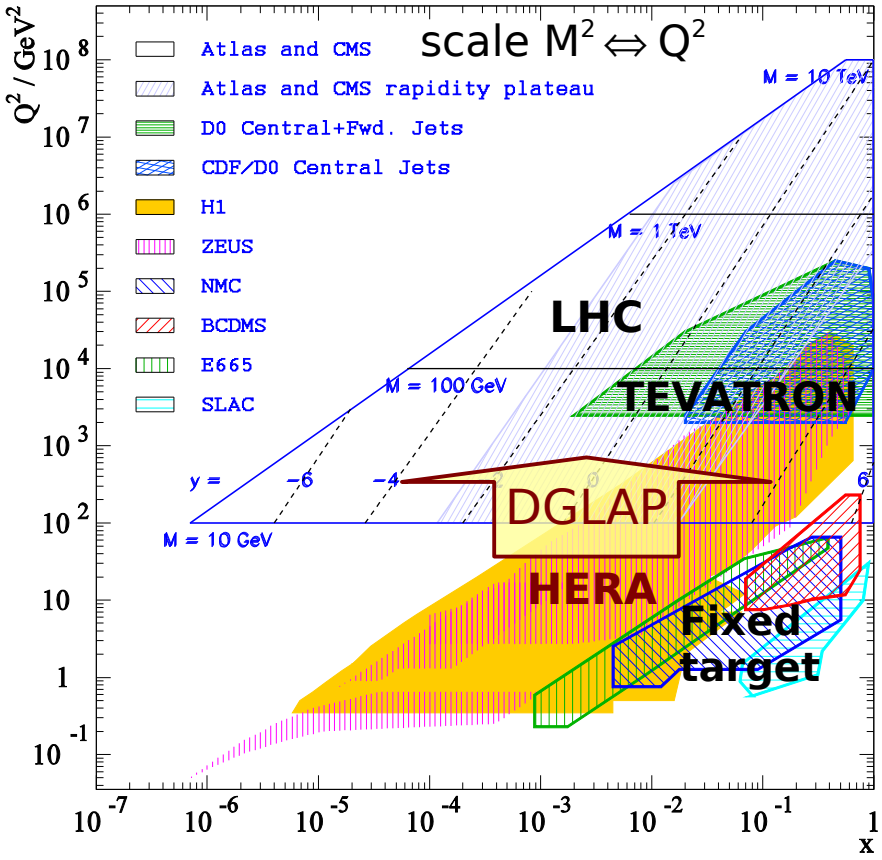
Introduction: Proton Structure

PDFs are intrinsic property of nucleon, i.e. assumed to be process independent

→ same PDFs can be used to predict *pp* collisions

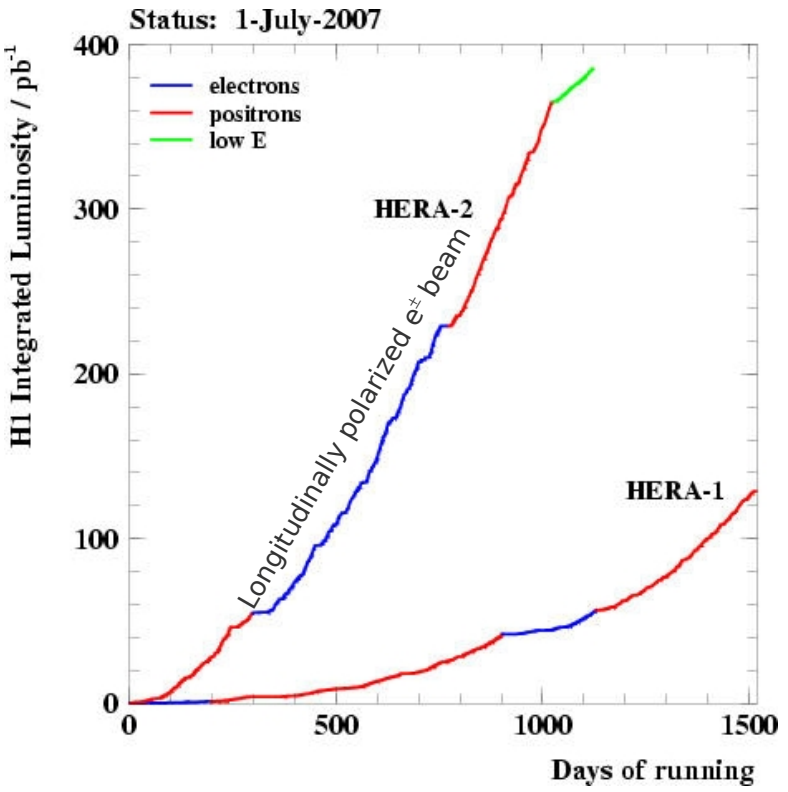


HERA covers the *x* range of the LHC evolution in Q^2 via DGLAP



HERA Collider

HERA was the worlds only $e^{\pm}p$ collider



- $e^{\pm}$(27.5 GeV), p(460-920 GeV)
  $\sqrt{s}$ = 225-318 GeV

- Two collider experiments: H1 and ZEUS
- ~0.5 fb^{-1} of luminosity recorded by each experiment

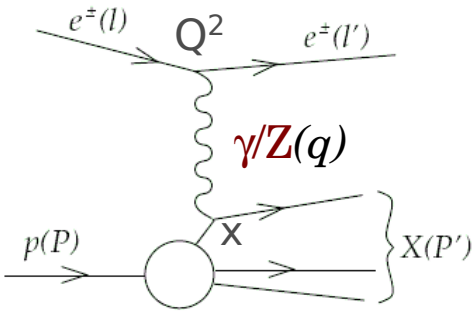
1994-2000: HERA I data

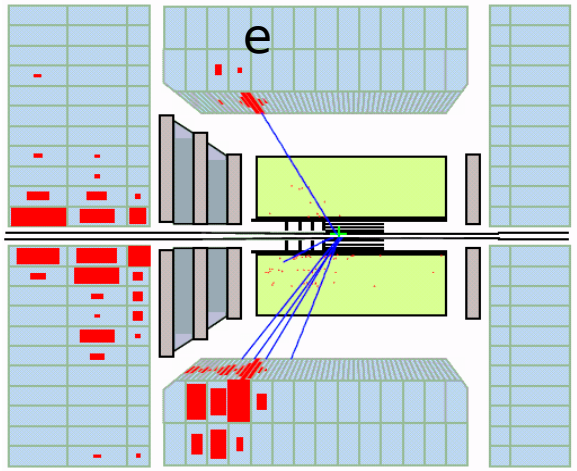
2003-2007: HERA II data
with longitudinal $e^{\pm}$ polarisation:

$$P = N_R - N_L / N_R + N_L$$

Neutral Current DIS Cross section

Neutral current DIS cross section:





$$\frac{d^2\sigma_{NC}^{e^{\pm}p}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[Y_+\tilde{F}_2^{\pm} \mp Y_- x\tilde{F}_3^{\pm} - y^2\tilde{F}_L^{\pm}\right]$$

dominant contribution

important at high Q^2

sizable at high y

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

$$k = \frac{1}{4\sin^2\theta_w\cos^2\theta_w}\frac{Q^2}{Q^2+M_Z^2}$$

LO: $F_2 \approx x\sum e^2_q(q+\bar{q})$ (in NLO $(\alpha_s\, g)$ appear)

$xF_3 \approx x\sum 2e_q a_q(q-\bar{q})$

PDFs

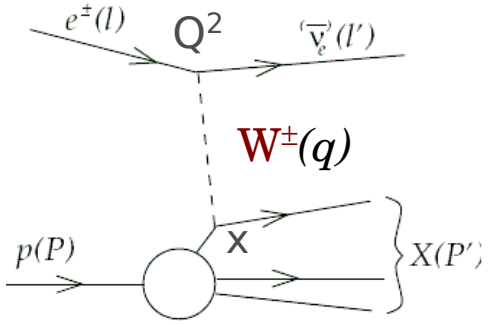
polarisation dependence due to γZ interference and Z terms

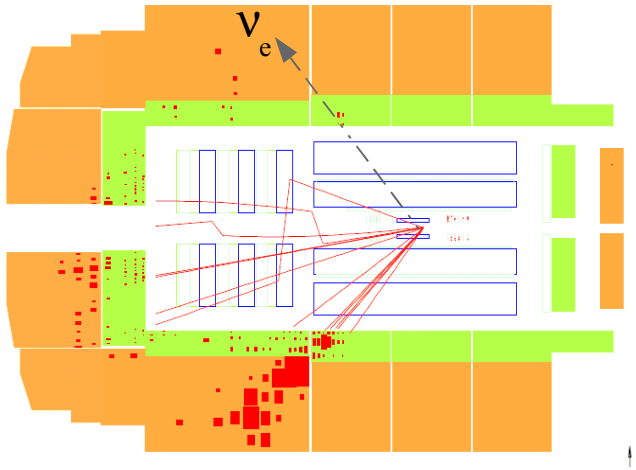
$$\tilde{F}_2^{\pm} = F_2 + k(-v_e \mp P_e a_e)F_2^{\gamma Z} + k^2\left(v_e^2 + a_e^2 \pm 2P_e v_e a_e\right)F_2^Z$$

$$x\tilde{F}_3^{\pm} = k(-a_e \mp P_e v_e)xF_3^{\gamma Z} + k^2\left(2v_e a_e \pm P_e(v_e^2 + a_e^2)\right)xF_3^Z$$

Charged Current DIS Cross section

Charged current DIS cross section:





$$\frac{d^2\sigma_{CC}^{e^{\pm}p}}{dxdQ^2} = (1 \pm P_e)\frac{G_F^2}{2\pi x}\left(\frac{M_W^2}{Q^2 + M_W^2}\right)^2 \tilde{\sigma}_{CC}^{e^{\pm}p}$$

$\rightarrow$ linear polarisation dependence

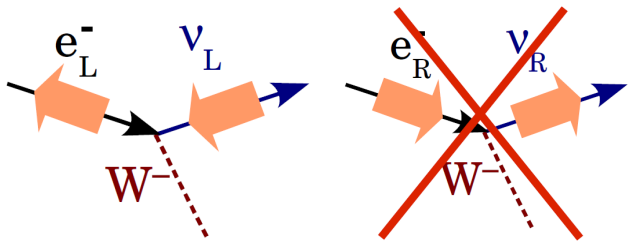
In SM weak interaction acts only on left-handed particles (right-handed anti-particles)

at LO e^+/e^- sensitive to different quark densities:

$$\tilde{\sigma}_{CC}^{e^+p} = x[\overline{u} + \overline{c}] + (1-y)^2 x[d + s]$$

$$\tilde{\sigma}_{CC}^{e^-p} = x[u + c] + (1-y)^2 x[\overline{d} + \overline{s}]$$

PDFs



HERA Structure Function Data

Inclusive HERA I and II data

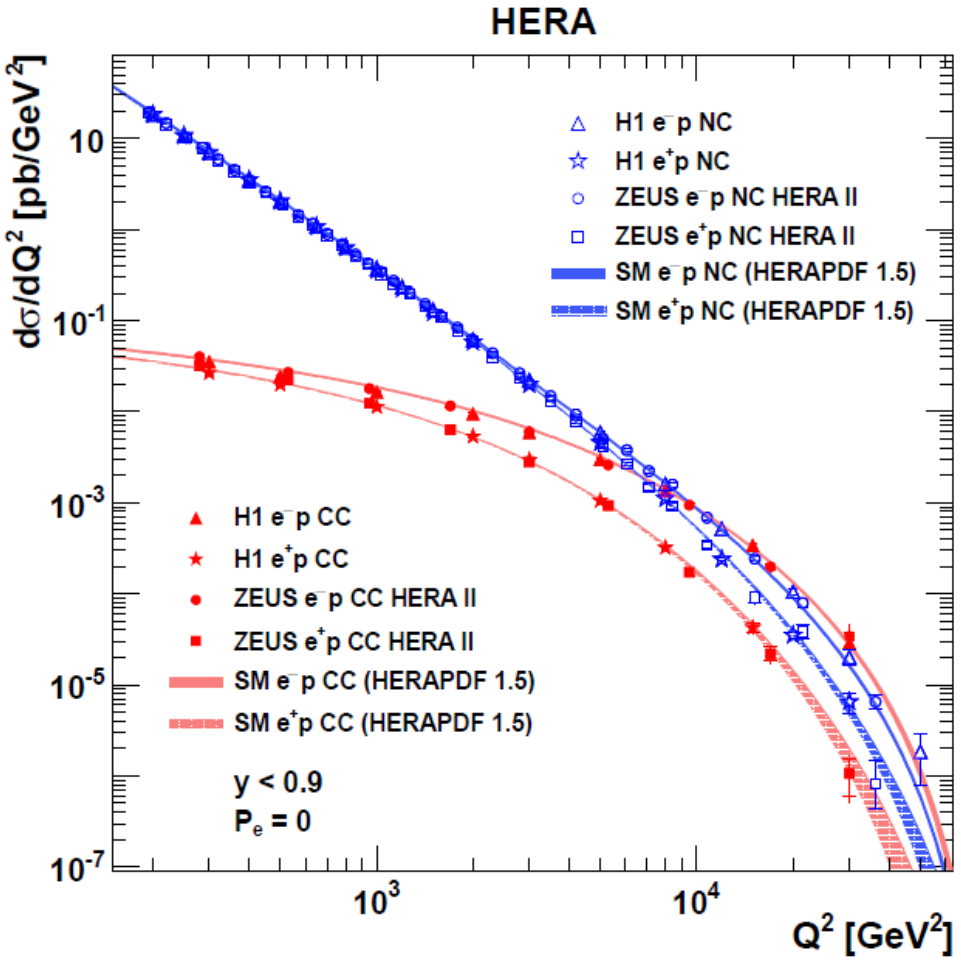
with typical precision:
NC: ~1.5%
CC: ~4%

neutral (γ/Z)
charged ($W^{\pm}$)
currents cross sections
at $Q^2 \gtrsim M^2_{Z/W}$ scale
are similar:

EW unification

good agreement with
the SM (HERAPDF 1.5)

arXiv:1208:6138 NEW
EPJC 70 (2010) 945
JHEP 1209:061 (2012) NEW
EPJC 62 (2009) 625
EPJC 61 (2009) 223



High Q^2 NC Cross Sections

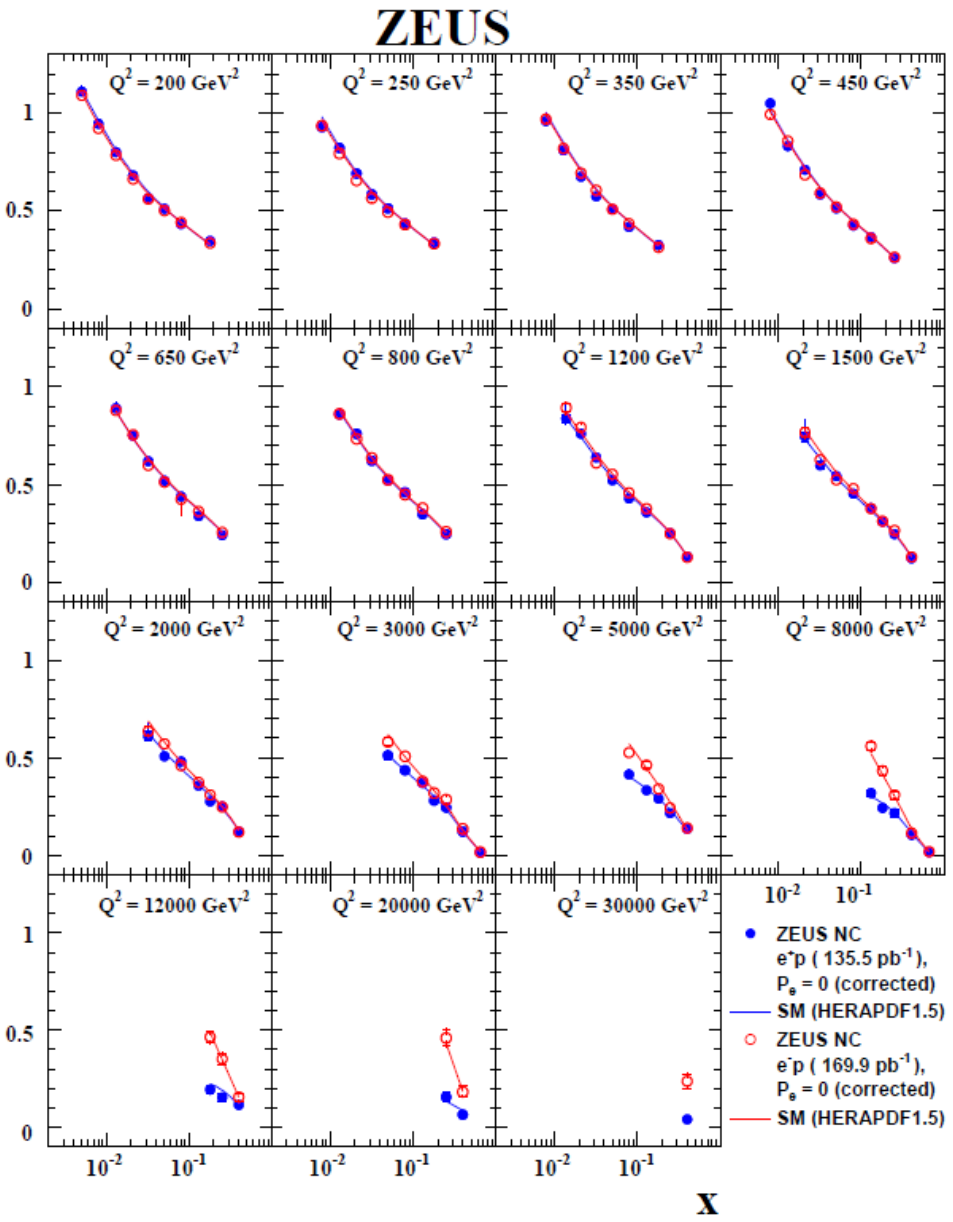
ZEUS: high Q^2 NC HERA II data

→ good agreement with the SM (HERAPDF1.5)

At high Q^2 difference between e^- and e^+: xF_3 (sensitive to valence PDFs)

$$\tilde{\sigma}^{\pm} = \frac{d^2\sigma_{NC}^{e^{\pm}p}}{dxdQ^2}\frac{xQ^4}{2\pi\alpha^2}\frac{1}{Y_+} = \tilde{F}_2 \mp \frac{Y_-}{Y_+}x\tilde{F}_3 - \frac{y^2}{Y_+}\tilde{F}_L$$

$$x\tilde{F}_3 = \frac{Y_+}{2Y_-}[\tilde{\sigma}^- - \tilde{\sigma}^+]$$

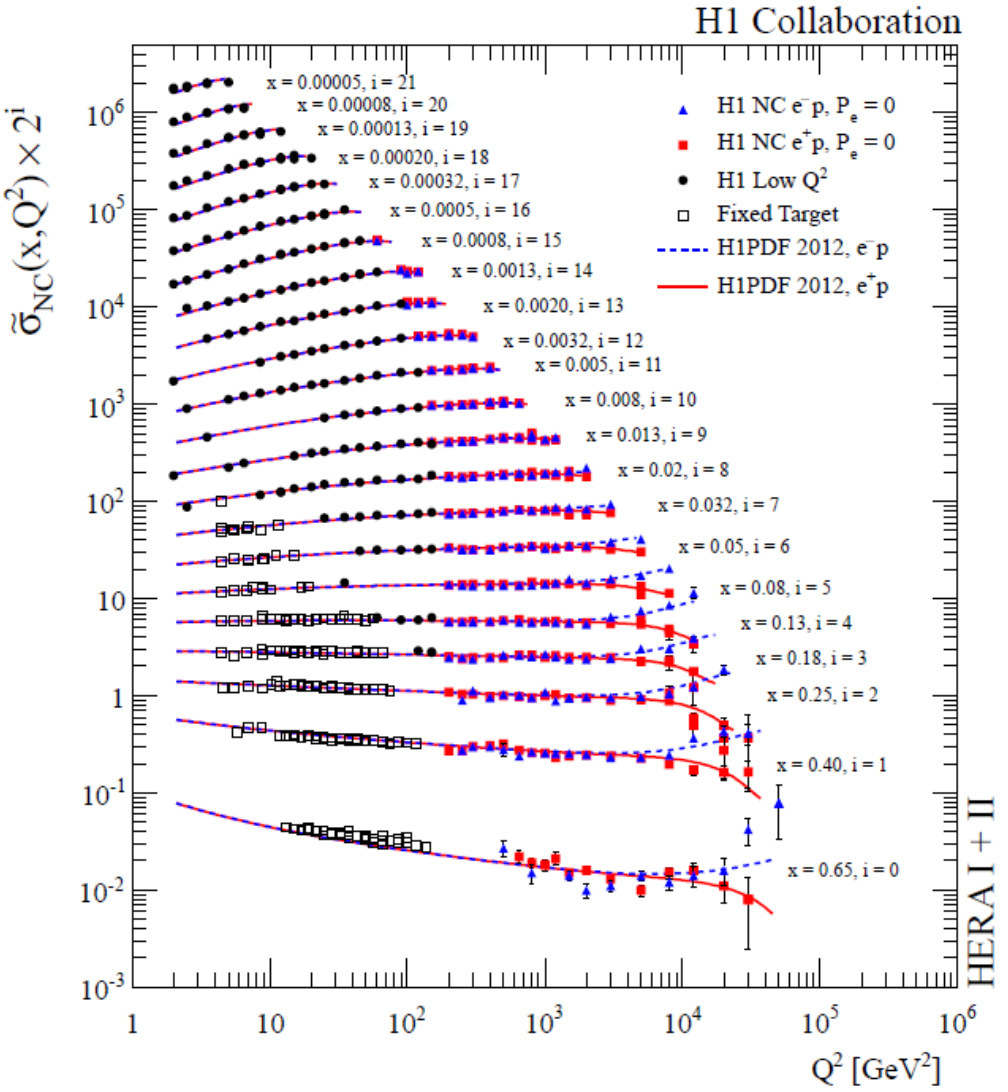


High Q^2 NC Cross Sections

H1: combination of high Q^2 HERA I and HERA II data

H1 precision 1.5% for $Q^2 < 500$ GeV^2

→ factor 2 reduction in error vs HERA I



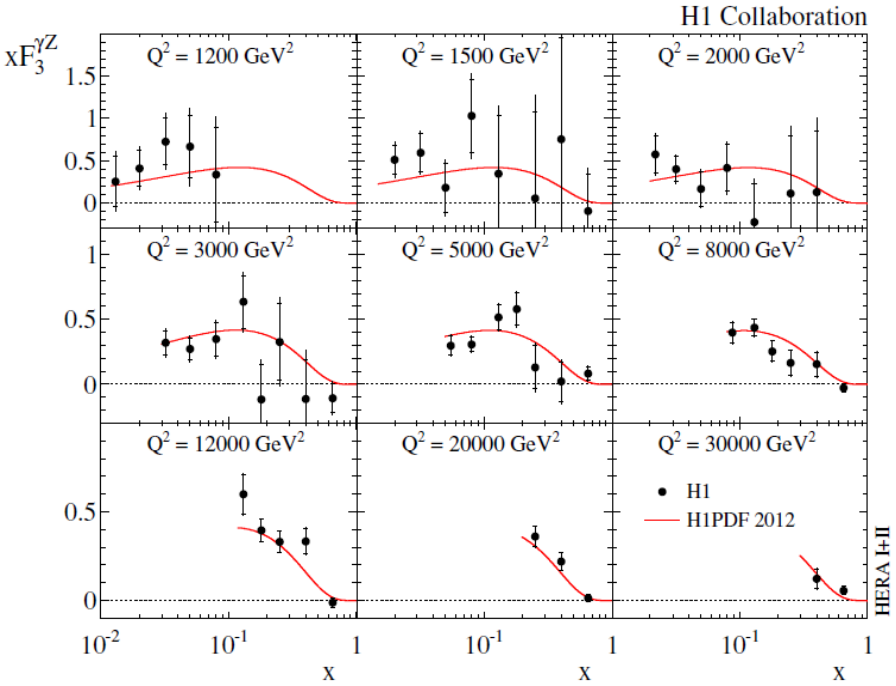
High Q^2 NC Cross Sections

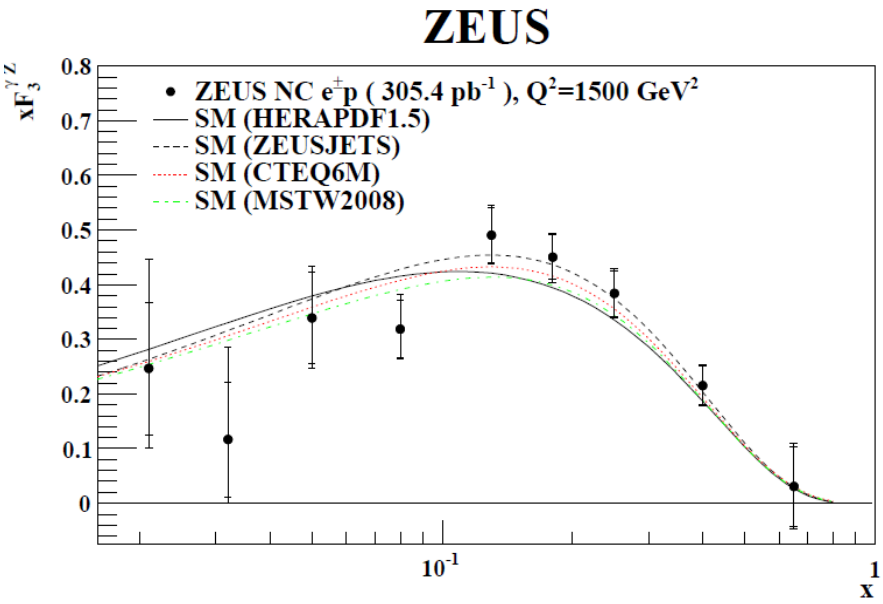
Structure function xF_3

$$x\tilde{F}_3 = \frac{Y_+}{2Y_-}[\tilde{\sigma}^- - \tilde{\sigma}^+]$$

dominant contribution from $xF_3^{\gamma Z}$

$$x\tilde{F}_3^{\gamma Z} \simeq x\tilde{F}_3 \frac{(Q^2 + M_Z^2)}{\alpha^2 \kappa Q^2}$$





$xF_3^{\gamma Z} \sim xq_{val}$

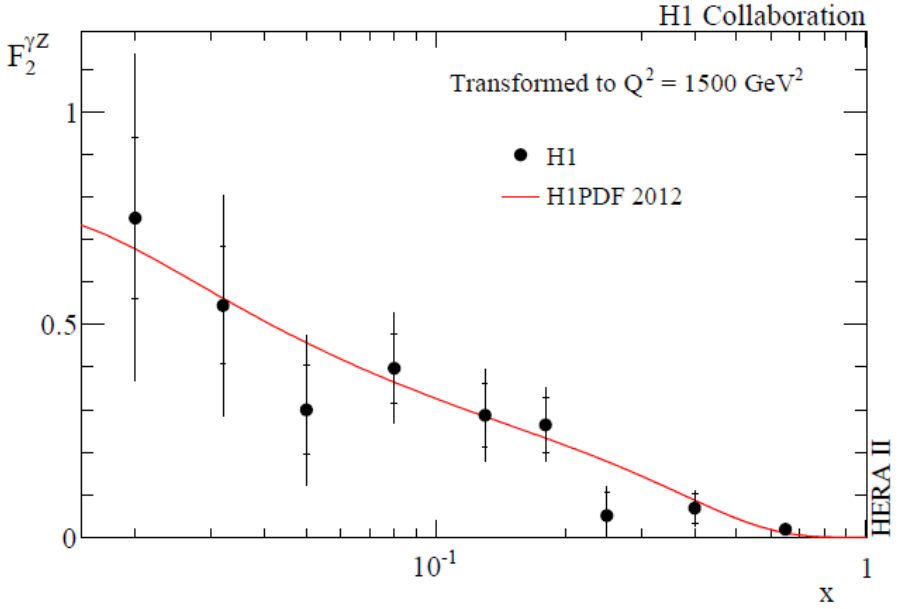
High Q^2 NC Cross Sections

Measuring the difference in NC polarised cross sections $F_2^{\gamma Z}$ can be accessed:

$$\frac{\sigma^{\pm}(P_L^{\pm}) - \sigma^{\pm}(P_R^{\pm})}{P_L^{\pm} - P_R^{\pm}} = \frac{\kappa Q^2}{Q^2 + M_Z^2}\left[\mp a_e F_2^{\gamma Z} + \frac{Y_-}{Y_+} v_e x F_3^{\gamma Z} - \frac{Y_-}{Y_+}\frac{\kappa Q^2}{Q^2 + M_Z^2}(v_e^2 + a_e^2) x F_3^Z\right]$$

$F_2^{\gamma Z}$ measurement is only possible because of e^+ and e^-, L and R data

First measurement of $F_2^{\gamma Z}$



$F_2^{\gamma Z} \sim q + \bar{q}$

Polarisation Asymmetry in NC

The charge dependent polarisation asymmetries in neutral currents
→ direct measure of EW effects

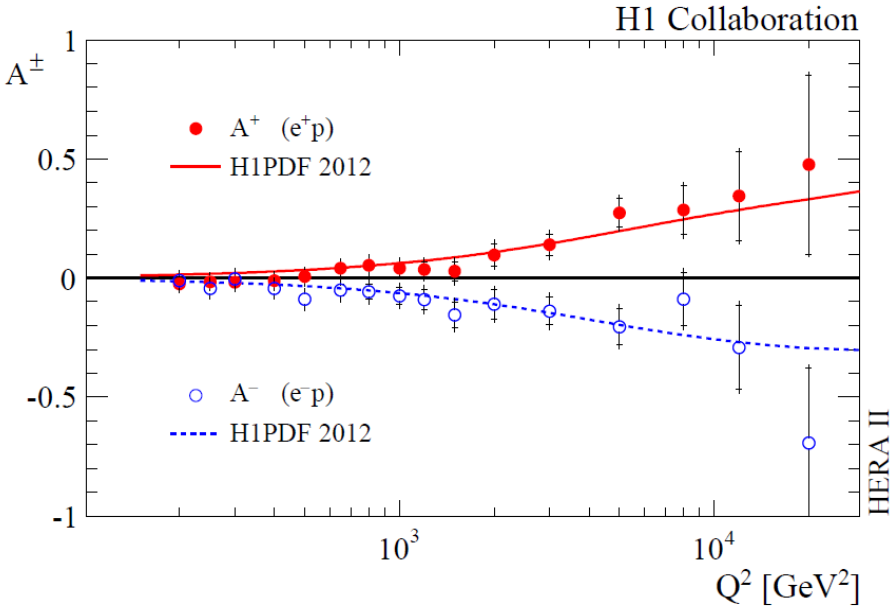
neglecting Z term generalised structure function F_2 is expressed:

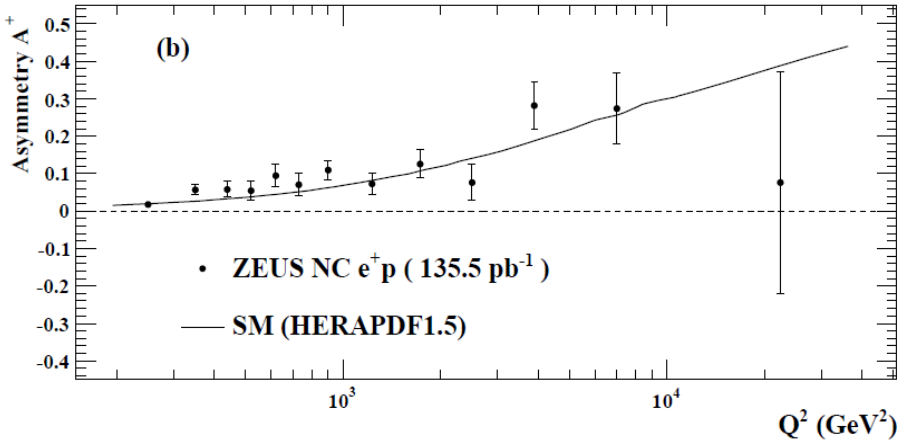
$$\tilde{F}_2^{\pm} \approx F_2 + k(-v_e \mp P_e a_e) F_2^{\gamma Z}$$

at LO: $F_2^{\gamma Z} = x \sum 2 e_q v_q (q + \overline{q})$

Polarisation asymmetry A
is proportional to $a_e v_q$ combination:

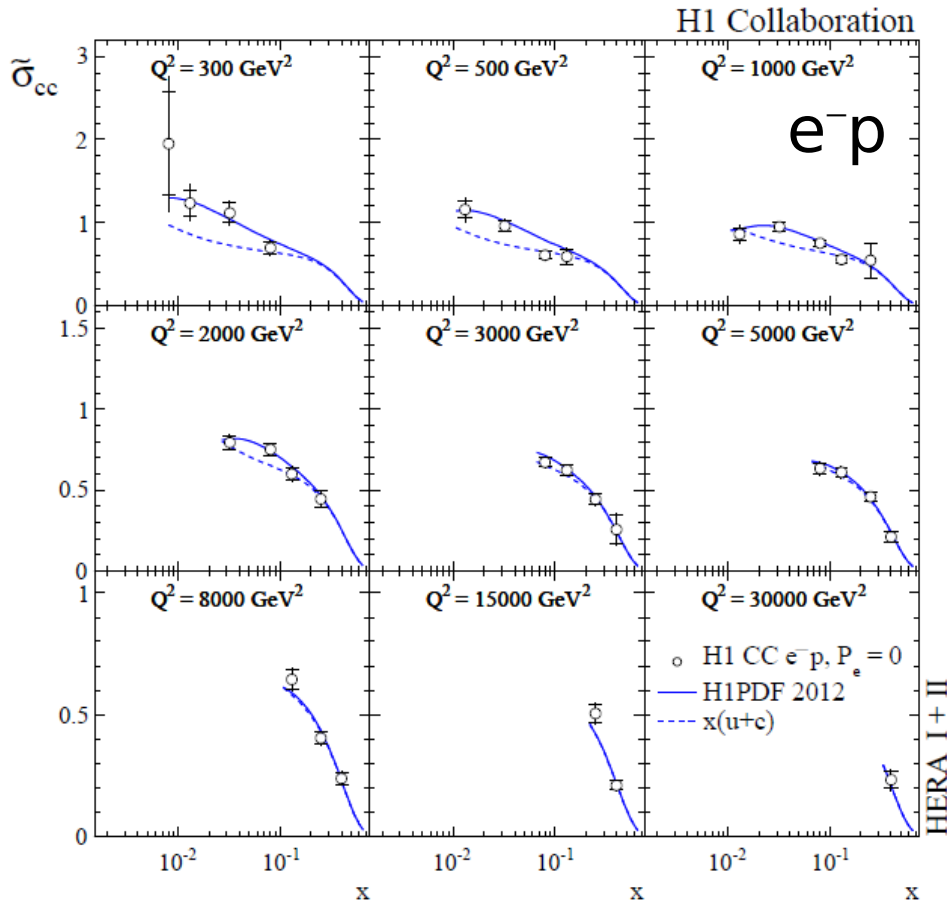
$$A^{\pm} = \frac{2}{P_R - P_L} \frac{\sigma^{\pm}(P_R) - \sigma^{\pm}(P_L)}{\sigma^{\pm}(P_R) + \sigma^{\pm}(P_L)} \simeq \mp k a_e \frac{F_2^{\gamma Z}}{F_2}$$

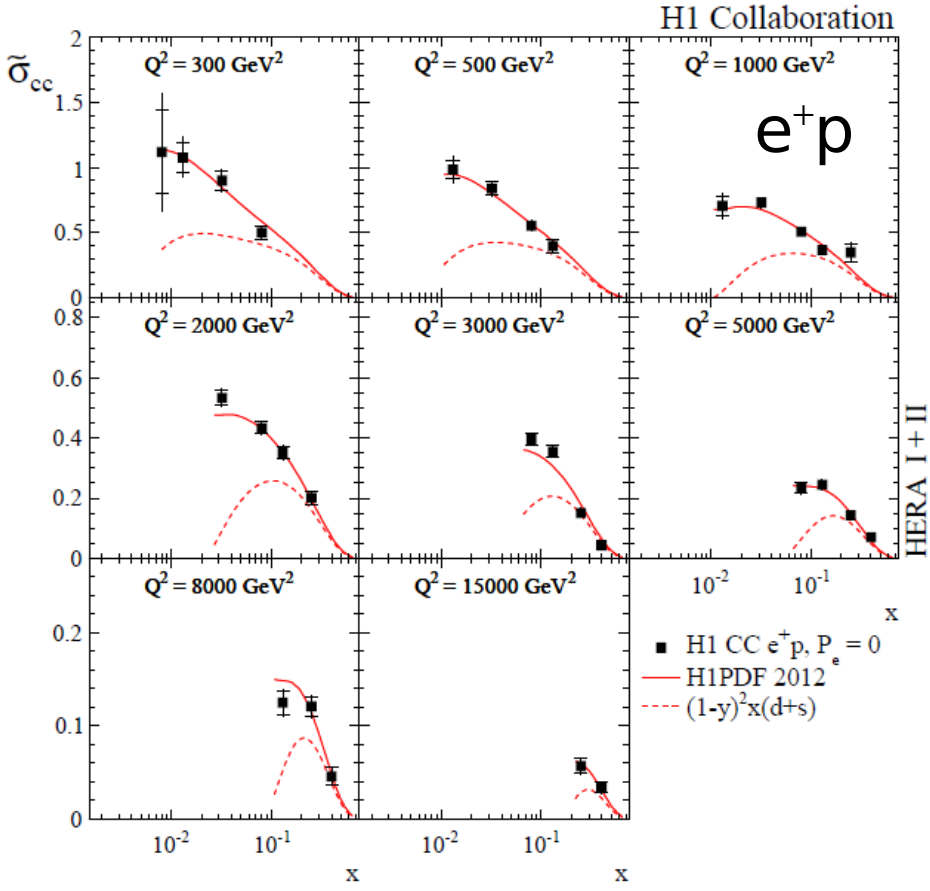




→ direct measurement of the parity violation

Highlights from High Q^2 CC Measurement





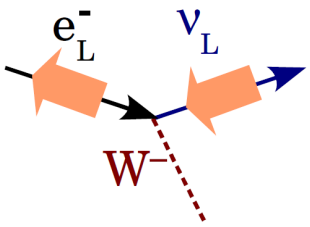
HERA CC e^+/e^- measurements:

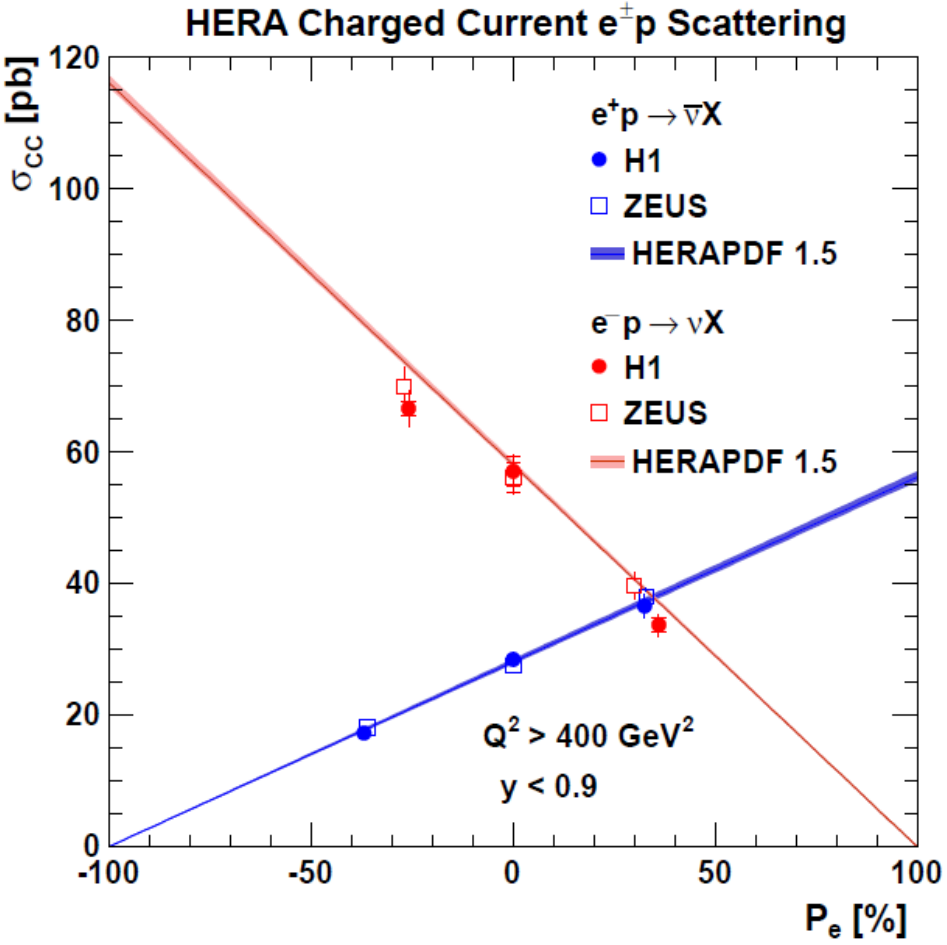
→ sensitivity to quark flavour

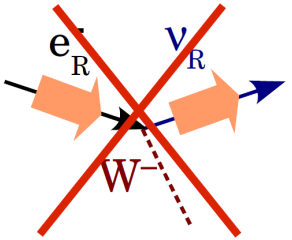
→ improvement in precision: $e^+(e^-)p$ factor of 3(10) luminosity vs HERA I

High Q^2 CC Cross Sections

Final measurement of polarisation dependence of CC cross sections from H1 and ZEUS







excludes limits on M_W^R below 214 (e^-) and 194 (e^+) at 95% CL

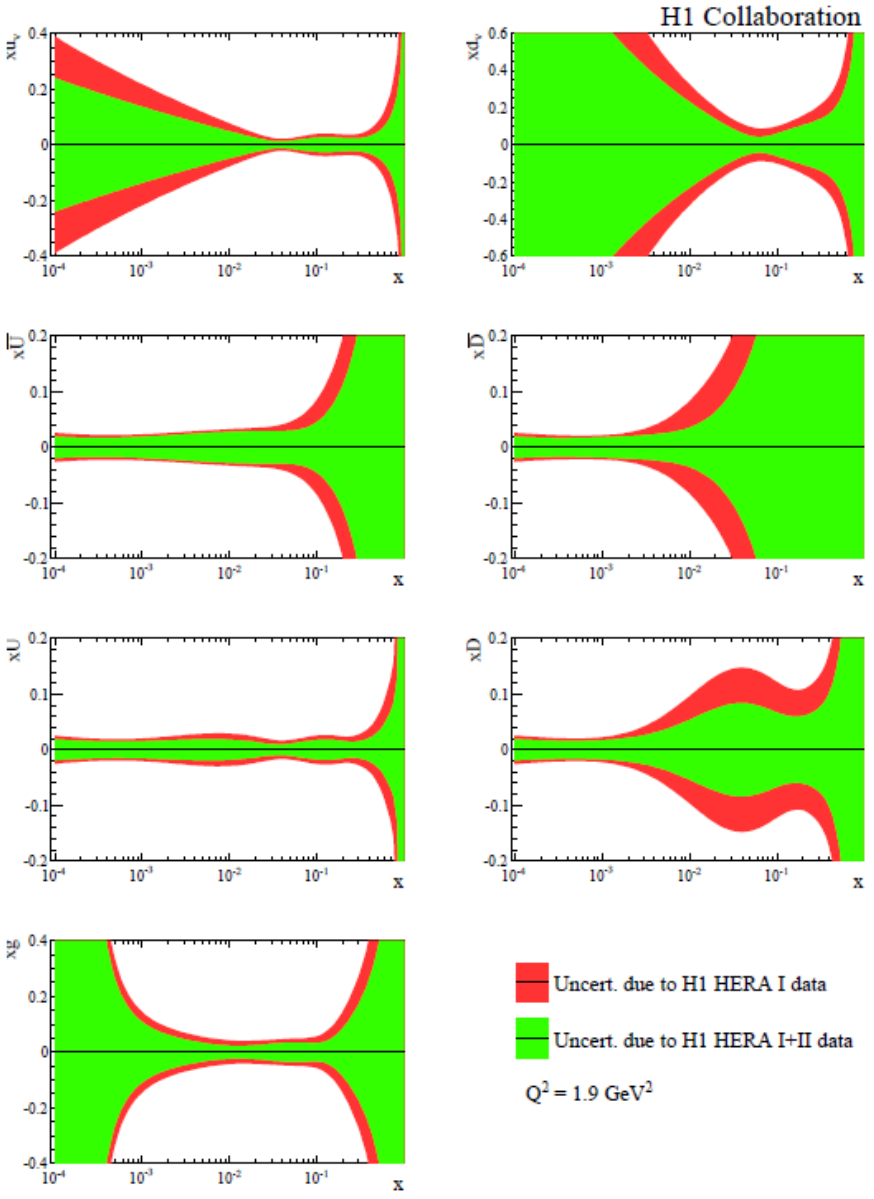
Results are consistent with the SM

H1PDF2012: QCD fit to final H1 NC, CC data

QCD analysis of final H1 NC,CC data

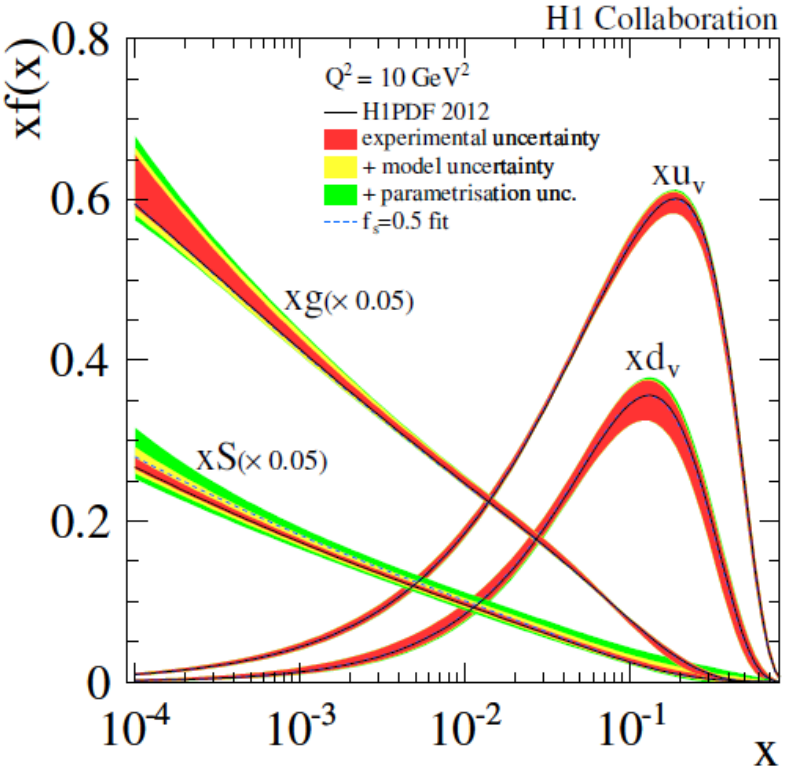
→ performed using HERAFitter

→ improvement in precision for all PDFs in full x range in particular for down-type quarks xD

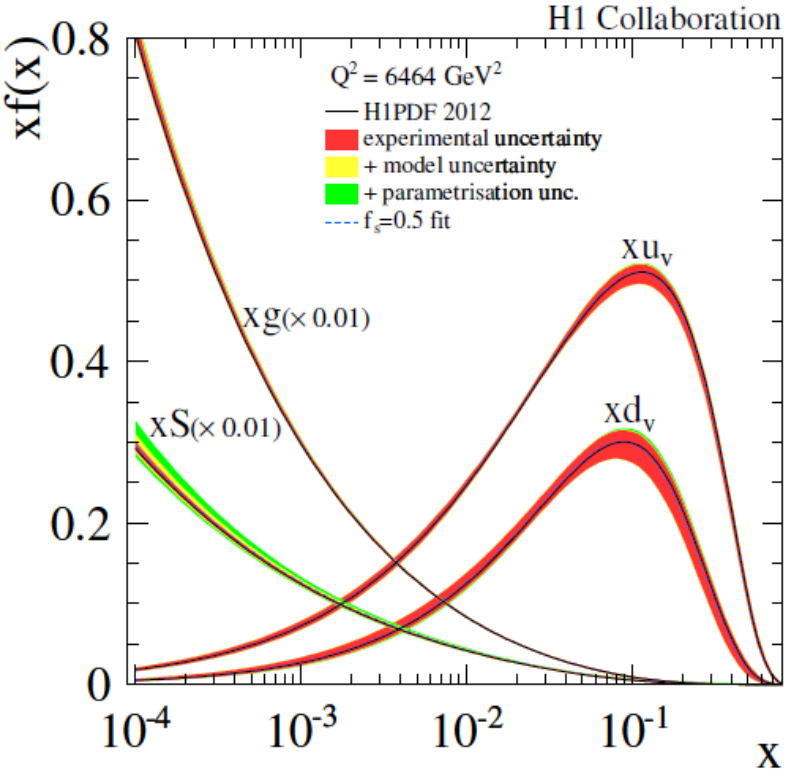


H1PDF2012: QCD fit to final H1 NC, CC data

$Q^2 = 10\ \mathrm{GeV}^2$



$Q^2 = M_W^2$



Currently combination of final published H1 and ZEUS inclusive data is ongoing → input to HERAPDF2.0

HERAFitter Project

HERAFitter project is an open source QCD fit framework ready to extract PDFs and assess the impact of new data

→ open source, everyone is free to download and use it

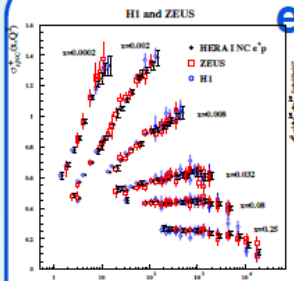
→ developers: H1 and ZEUS, ATLAS, CMS, LHCb, active support by theory groups

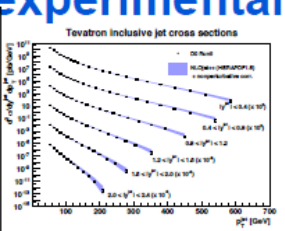
HERAFitter-0.1.0: Sept 2011, HERAFitter-0.2.0: May 2012, HERAFitter-0.3.1: March 2013

www.herafitter.org

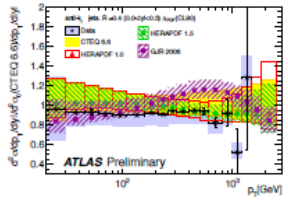
HERAFitter: Structure

experimental input





experiments:
HERA, Tevatron,
LHC, fixed target



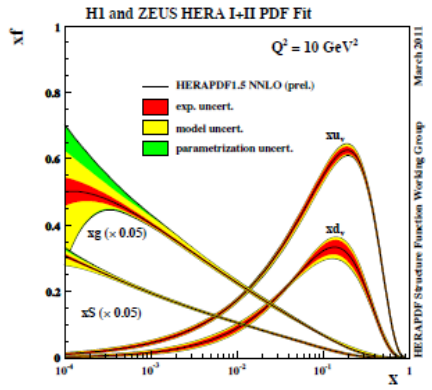
processes:
NC, CC DIS, jets, diffraction,
heavy quarks (c,b,t)
Drell-Yan, W production

theoretical calculations/tools

Heavy quark schemes:	MSTW, CTEQ, ABM
Jets, W, Z production:	fastNLO, Applgrid
Top production	NNLO (Hathor)
QCD Evolution	DGLAP (QCDNUM)
	k_T factorisation
Alternative tools	NNPDF reweighting
Other models	Dipole model

+ Different error treatment models
+ Tools for data combination (HERAaverager)

HERAFitter



PDF or DPDF,...

$\alpha_S(M_Z), m_c, m_b, m_t, f_s, ..$

Theory predictions

Benchmarking

Comparison of schemes

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HERAFitter: Usage

https://www.herafitter.org/HERAFitter/HERAFitter/results

"Determination of the strange quark density of the proton from ATLAS measurements of the W → lν and Z → ll cross sections"
Phys.Rev.Lett. 109 (2012) 012001

"Measurement of the inclusive jet cross section in pp collisions at √s = 2.76 TeV and comparison to the inclusive jet cross section at √s = 7 TeV using the ATLAS detector"
arXiv:1304:4739

"Measurement of the high-mass Drell-Yan differential cross-section in pp collisions at √s = 7 TeV with the ATLAS detector"
arXiv:1304:4192

In CMS several analyses are using HERAFitter for PDF constraints
→ jets, DY, W+charm data

"Combination and QCD Analysis of Charm Production Cross Section Measurements in Deep Inelastic ep Scattering at HERA"
Eur. Phys. J. C73 (2013) 2311

"Inclusive Deep Inelastic Scattering at High Q2 with Longitudinally Polarised Lepton Beams at HERA"
JHEP 1209 (2012) 061

LHeC impact studies J.Phys.G39 (2012)

Theory: updates of ACOT scheme module (with CTEQ group)
inclusion of photon PDF in QCDNUM (publication is planned)

Summary

HERA provides unique determinations of the proton structure

→ final HERA II neutral and charged current data published

→ H1-ZEUS combination and HERAPDF2.0 determination ongoing

www.h1.desy.de www-zeus.desy.de

www.desy.de/h1zeus/combined_results/index.php

HERAFitter

multi-functional QCD framework well integrated into the high energy community (both, experimental and theory)

→ open to everyone and anyone can contribute

→ well integrated in the LHC analyses

www.herafitter.org

Back-up slides

HERA Structure Function Data

HERA I inclusive data

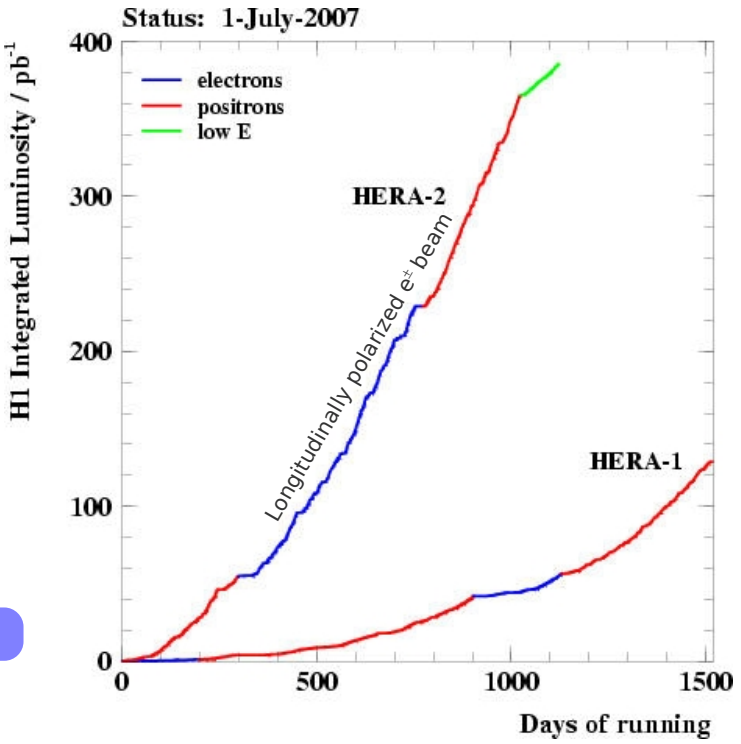
→ combination of H1 and ZEUS sets

JHEP 1001:109 (2010)

HERA II inclusive data

→ combination of preliminary H1 and ZEUS sets

→ new published data



- full HERA II NC and CC data JHEP 1209:061 (2012)
- increase of integrated luminosity by factor of 3(10) for e+(e-)p sets
- significantly improved systematic uncertainties
- integrated luminosity determined with elastic QED Compton events

Eur.Phys. J. C72 (2012), 2163

- last e+p NC period EPJC 12 08 066

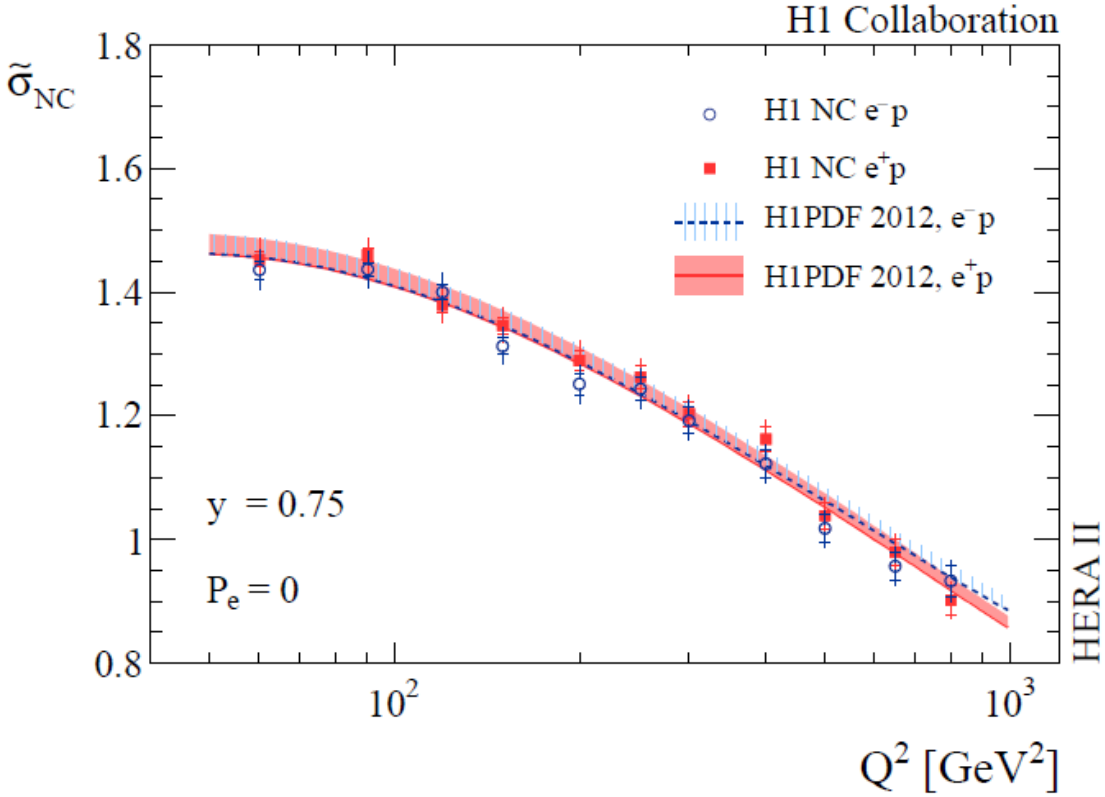
→ currently in process of combination (H1 and ZEUS, HERA I and II)

NC High y Cross Sections

The measurement of neutral current cross sections in high y region ($0.63 < y < 0.9$)

→ sensitive to F_L structure function measurement

→ good agreement with the SM (H1PDF 2012)



Deep Inelastic Scattering (DIS)

Structure function factorisation:

each structure function can be written as a convolution of a hard-scattering coefficient C and non-perturbative parton distributions:

$$F_2^V(x,Q^2) = \sum_{i=q,\bar{q},g} \int_x^1 dz \times C_2^{V,i}\left(\frac{x}{z}, Q^2, \mu_F, \mu_R, \alpha_S\right) \times f_i(z, \mu_F, \mu_R)$$

determined using measured cross section

calculable in perturbative QCD

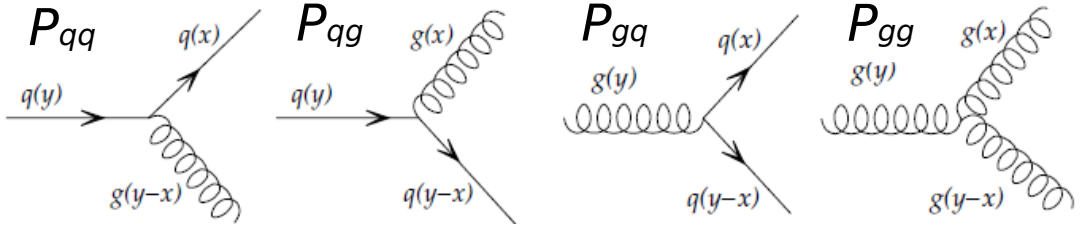
PDFs

PDF scale dependence is calculable in perturbative QCD (DGLAP evolution):

$$\frac{\partial q(x,Q^2)}{\partial ln Q^2} \propto \int_x^1 \frac{dz}{z}\left[q(z,Q^2)P_{qq}\left(\frac{x}{z}\right) + g(z,Q^2)P_{qg}\left(\frac{x}{z}\right)\right]$$

$$\frac{\partial g(x,Q^2)}{\partial ln Q^2} \propto \int_x^1 \frac{dz}{z}\left[q(z,Q^2)P_{gq}\left(\frac{x}{z}\right) + g(z,Q^2)P_{gg}\left(\frac{x}{z}\right)\right]$$

Probability via splitting functions:



PDF Determination

Experimentally measured $\sigma(x,Q^2) \rightarrow F_2(x,Q^2)$

Q^2 dependence of F_2 is given in pQCD (DGLAP evolution equations)

x-dependence of PDFs is not calculable in pQCD

- parametrise PDFs at the starting scale Q^2_0
- evolve PDFs using DGLAP equations to $Q^2 > Q^2_0$
- construct structure functions from PDFs and coefficient functions: predictions for every data point in (x, Q^2) – plane
- χ^2-fit to the experimental data

HERAPDF strategy and settings

DGLAP at NLO → QCD predictions

PDFs parametrised (at starting scale Q^2_0) using standard parametrisation form:

$$
\begin{aligned}
xg(x) &= A_g x^{B_g}(1-x)^{C_g}, \\
xu_v(x) &= A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}\left(1+E_{u_v}x^2\right), \\
xd_v(x) &= A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}}, \\
x\bar{U}(x) &= A_{\bar{U}} x^{B_{\bar{U}}}(1-x)^{C_{\bar{U}}}, \\
x\bar{D}(x) &= A_{\bar{D}} x^{B_{\bar{D}}}(1-x)^{C_{\bar{D}}}.
\end{aligned}
$$

A: overall normalisation

B: small x behavior

C: x→1 shape

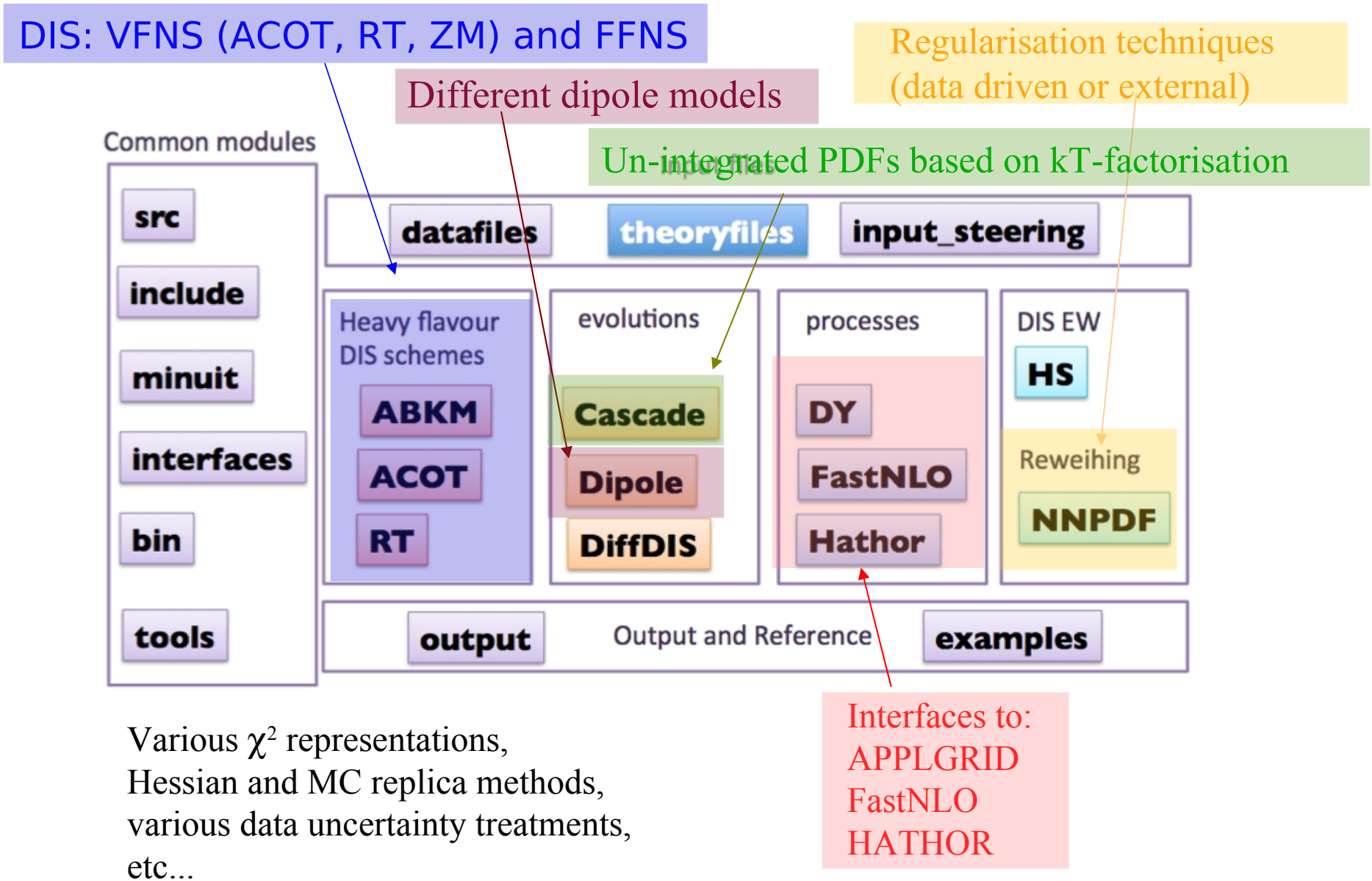
The optimal number of parameters chosen by saturation of the χ^2
- central fit with:
  10 free parameters for HERA I data
  13 for HERA I+II data

xg, xu_v, xd_v, $x\bar{U}$, $x\bar{D}$
where $x\bar{U}=x\bar{u}$ and $x\bar{D}=x\bar{d}+x\bar{s}$ at the starting scale ($x\bar{s}=f_s x\bar{D}$ with $f_s=0.31$)

A_g, A_{uv}, A_{dv} are fixed by sum rules

extra constrains for small x behavior of d- and u-type quarks:
$B_{uv}=B_{dv}$, $B_{\bar{U}}=B_{\bar{D}}$, $A_{\bar{U}}=A_{\bar{D}}(1-f_s)$ for $\bar{u}=\bar{d}$ as $x\to 0$

HERAFitter: Functionality



Various χ^2 representations,
Hessian and MC replica methods,
various data uncertainty treatments,
etc...

HERAFitter: Download

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Releases of the HERAFitter QCD analysis package

- Versioning convention: **i.j.k** with
  - **i** - stable release
  - **j** - beta release
  - **k** - bug fixes.
- The release notes can be found in this attachment: HERAFitter_release_notes.pdf.

Date	Version	Files	Remarks
06/2013	0.3.1	herafitter-0.3.1.tgz	fix release includes manual-0.3.1.pdf and decoupled theoryfiles.tgz
03/2013	0.3.0	herafitter-0.3.0.tgz	release includes manual-0.3.1.pdf and decoupled theoryfiles.tgz
07/2012	0.2.1	herafitter-0.2.1.tgz	fix release for 0.2.0
05/2012	0.2.0	herafitter-0.2.0.tgz	added functionality for LHC users
09/2011	0.1.0	herafitter-0.1.0.tgz	first release

Releases
(publicly accessible)

Documentation

- From 0.3.0 on a manual is provided together with an example directory.
- The **README** file (accessible via the package) gives an explanation for a quick start.

Web access to SVN

- For users with a valid DESY account, the SVN repository is accessible on the web at https://svnsrv.desy.de/k5viewvc/h1fitter .
- For users without DESY account, the SVN repository is accessible on the web at https://svnsrv.desy.de/basviewvc/h1fitter/ with herafitter-user@desy.de account and PDFfits password.

Doxygen Documentation

- The doxygen documentation is located here

Documentation:
manual,
release notes,
README,
DOXYGEN

Links to external packages

External packages that could be run with HERAFitter via configuration flags can be accessed for convenience HERE .

External packages

HERAverager data combination package

Information can be accessed here https://wiki-zeuthen.desy.de/HERAverager.

Subscription

We encourage users to subscribe to mailing list for news and updates related to the HERAFitter webpage. (average rate of e-mails is once a month), please contact herafitter-help@desy.de (or by creating a user account to this wiki we get a notification)