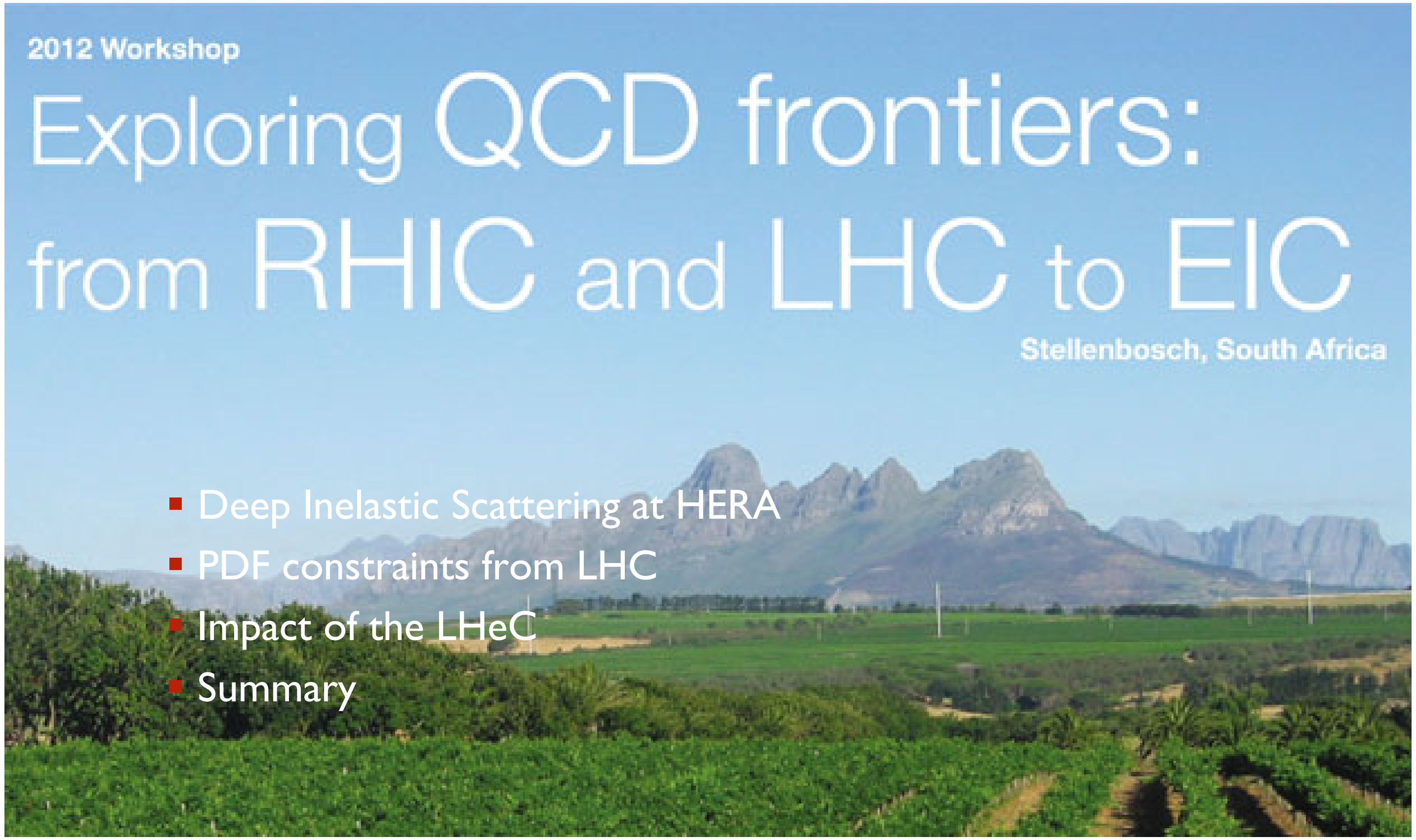
Precision Measurements of the Proton Structure from HERA, LHC and the impact of LHeC

Voica A. Radescu

DESY

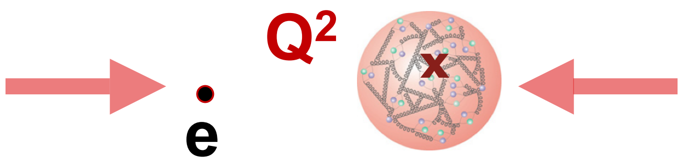


- Deep Inelastic Scattering at HERA
- PDF constraints from LHC
- Impact of the LHeC
- Summary

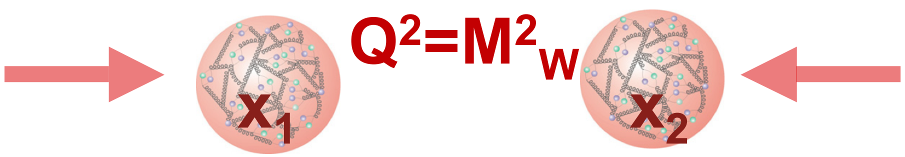
Proton Structure

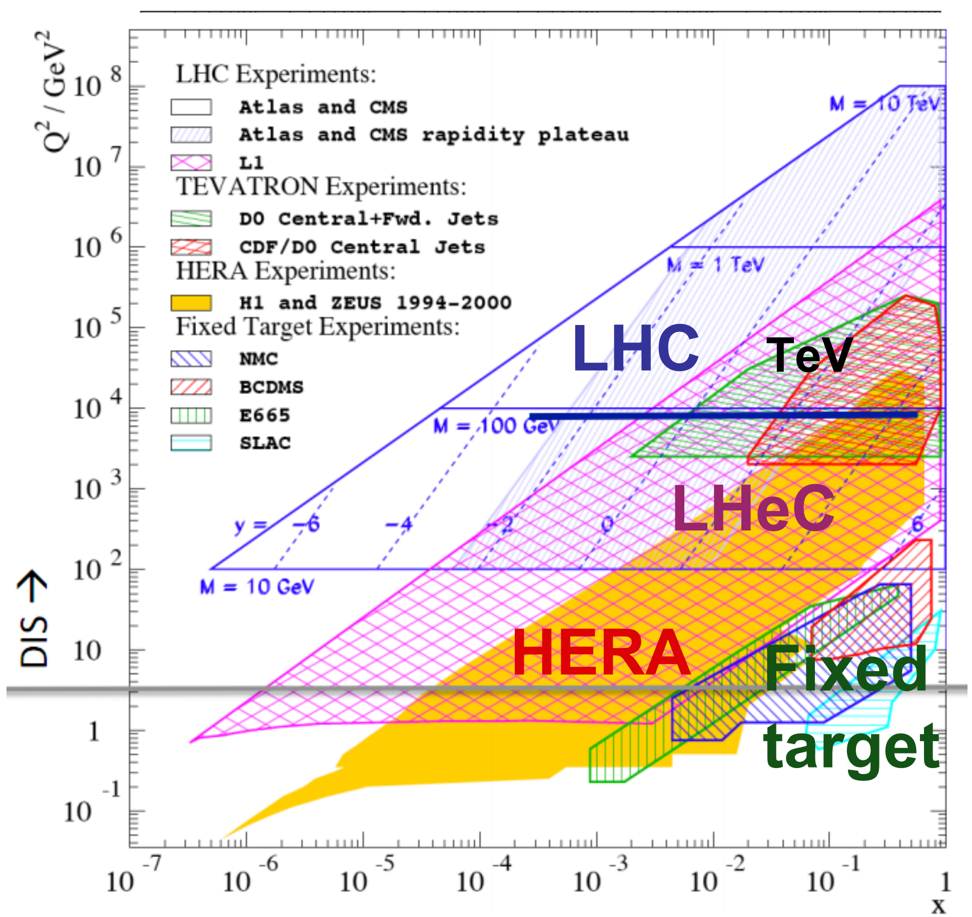
- Factorization theorem states that cross section can be calculated using universal partons x short distance calculable partonic reaction.

- Probing Proton Structure via Deep Inelastic Scattering using elementary particles such as:
  - Neutrinos, muons (fixed target experiments)
  - Electrons (fixed target and collider experiments)



- Knowledge on proton structure can be complemented by the collider experiments at Tevatron and LHC

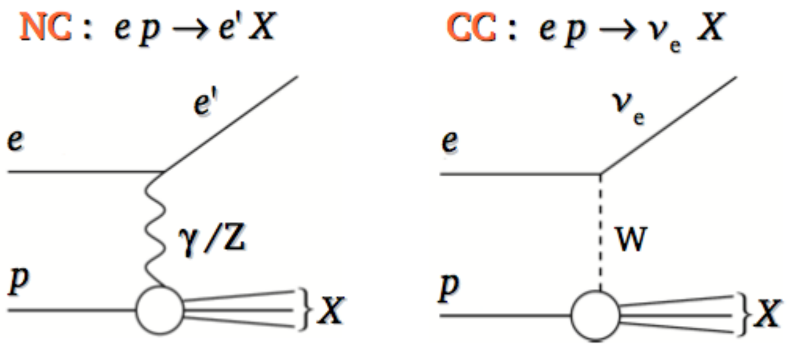




Persistent experimental effort over the last 40 years both by fixed-target and collider experiments around the world supported by the theoretical developments

Deep Inelastic Scattering

- DIS is best tool to probe structure of the proton:
  - Processes:



Kinematic variables:

$Q^2 = -q^2 = -(k-k')^2$ Virtuality of the exchanged boson

$x = \frac{Q^2}{2p \cdot q}$ Bjorken scaling parameter

$y = \frac{p \cdot q}{p \cdot k}$ Inelasticity parameter

$s = (k+p)^2 = \frac{Q^2}{xy}$ Invariant c.o.m.

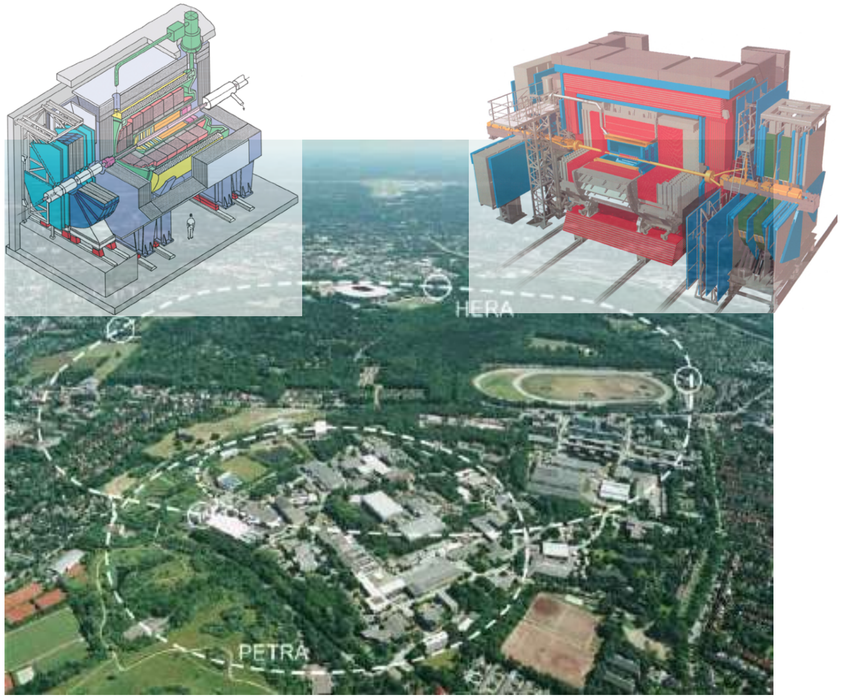
  - Double Differential cross sections:

$$\boxed{\sigma_r(x,Q^2) = \frac{d^2\sigma(e^{\pm}p)}{dxdQ^2}\frac{Q^4 x}{2\pi\alpha^2 Y_+} = F_2(x,Q^2) - \frac{y^2}{Y_+}F_L(x,Q^2) \mp \frac{Y_-}{Y_+}xF_3(x,Q^2)}$$

- F_2 dominates sensitive to all quarks
- xF_3 sensitive to valence quarks
- F_L sensitive to gluons

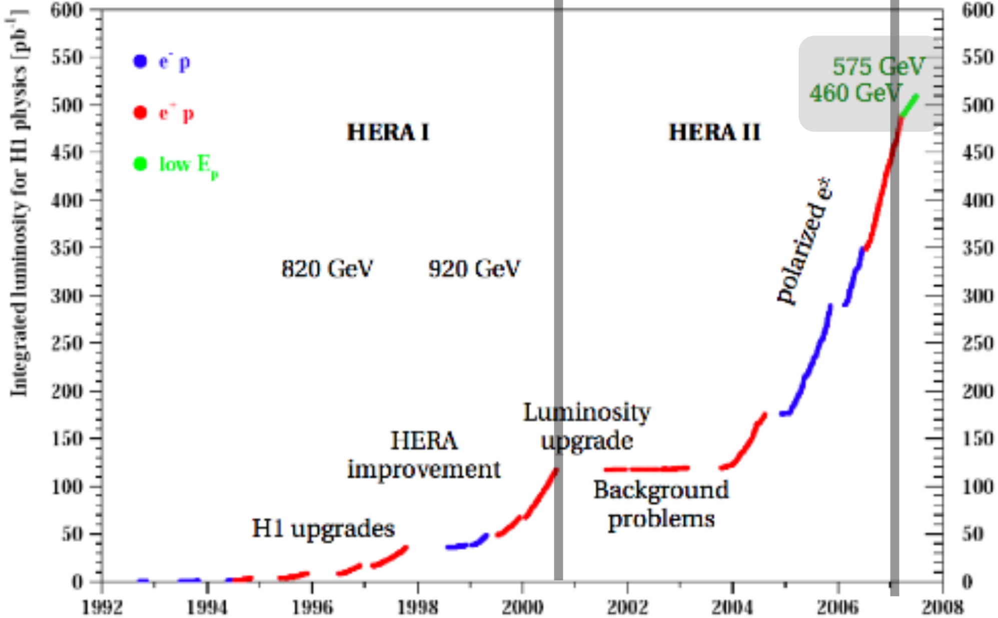
HERA

- World's first $e^{\pm}p$ accelerator and collider
  - located at DESY, Hamburg - Germany, in operation for 15 years (1992-2007)



HERAPDF1.5

HERAPDF1.0



- H1 and ZEUS collider experiments:
  - general purpose detectors
  - ~1fb^{-1} of integrated luminosity of physics data

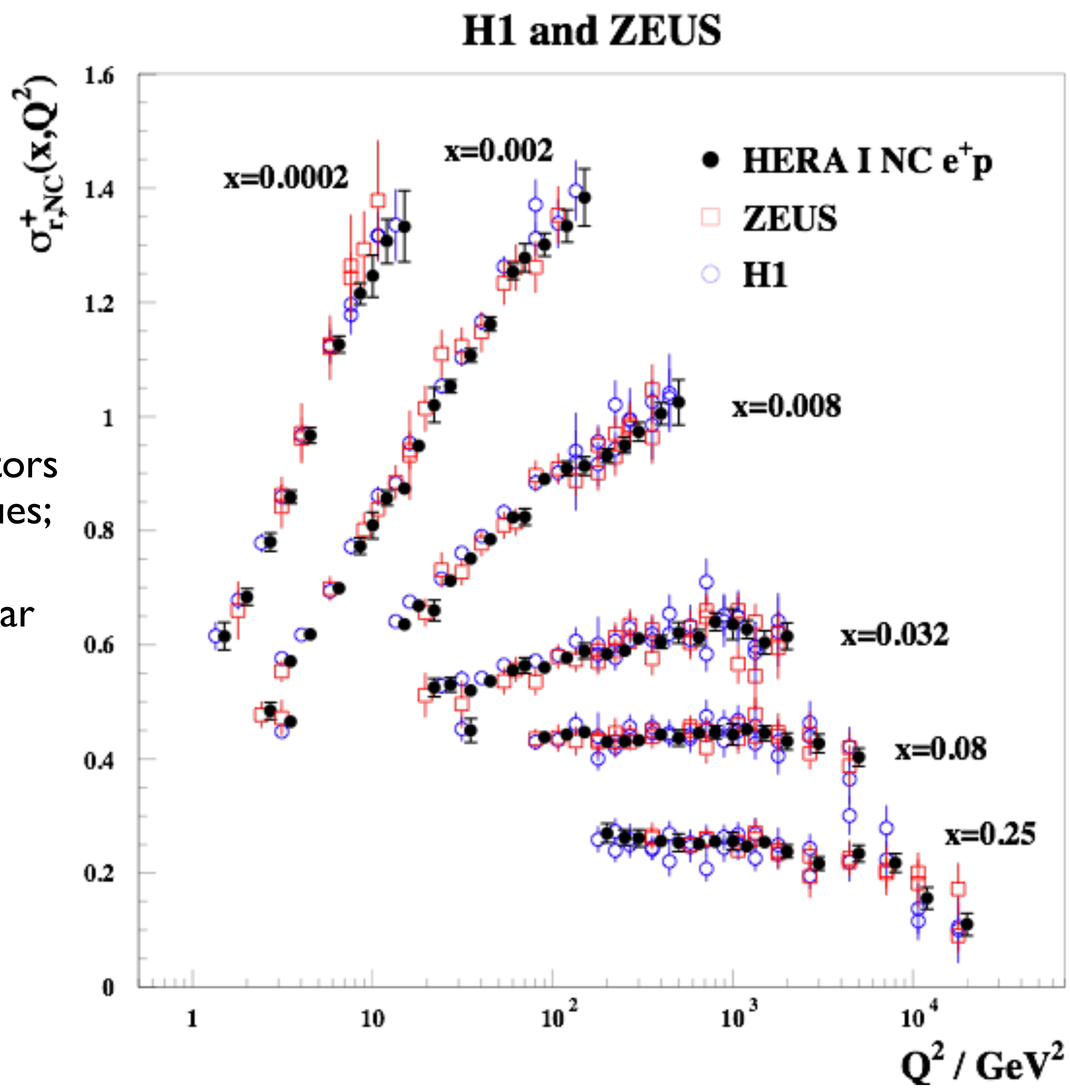
- Kinematics is determined with scattered electron or with HFS
  - high precision due to redundancy

Combination of the H1 and ZEUS Measurements

[JHEP01 (2010) 109]

- Ultimate precision is obtained by combining the H1 and ZEUS measurements

- The combination procedure is performed before QCD analysis using χ^2 minimisation
  - Improvement on Statistical precision:
    - H1 and ZEUS collected similar amounts of physics data.
  - Improvement of Systematic precision:
    - H1 and ZEUS are different detectors and use different analysis techniques;
    - The H1 and ZEUS cross sections have different sensitivities to similar sources of correlated systematic uncertainty.



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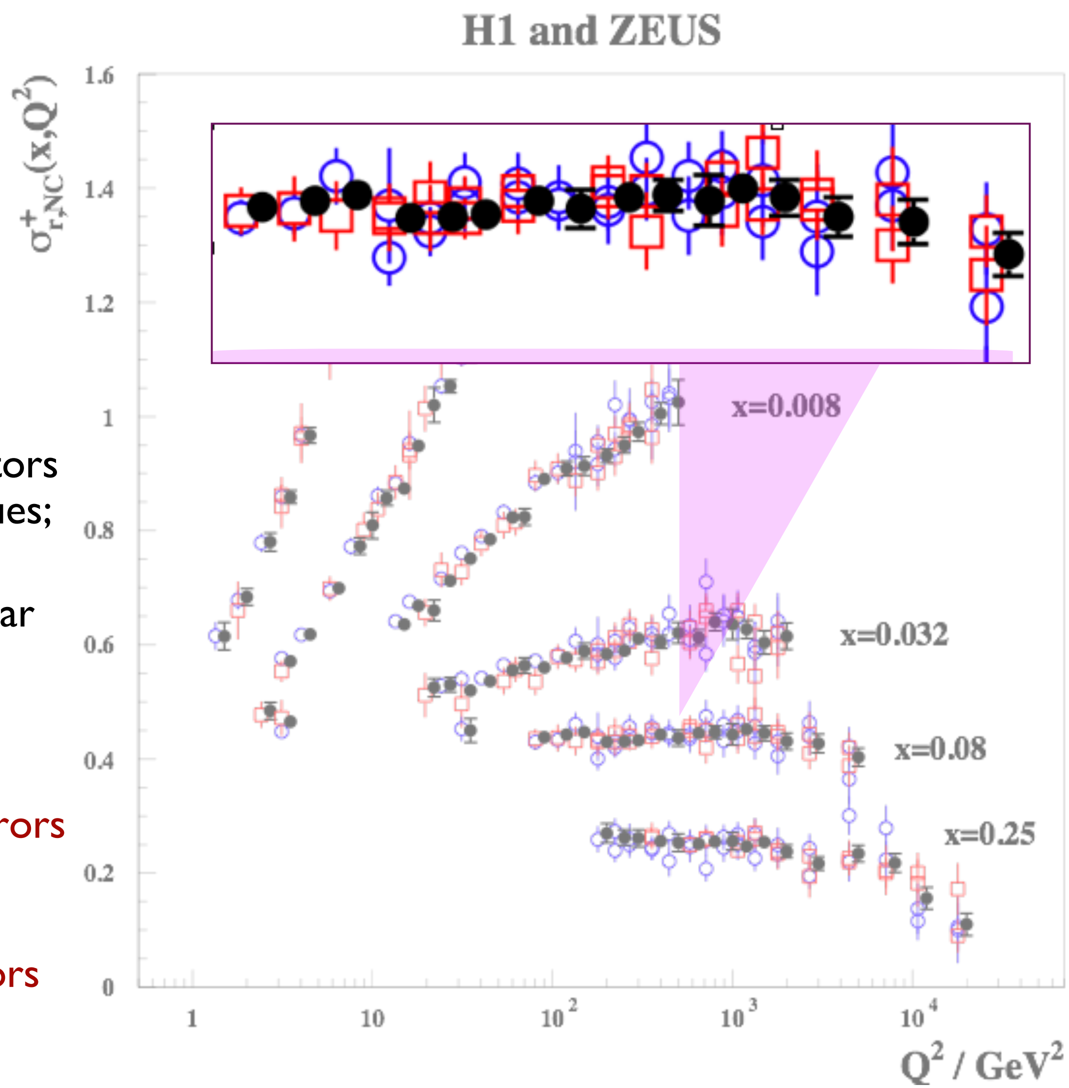
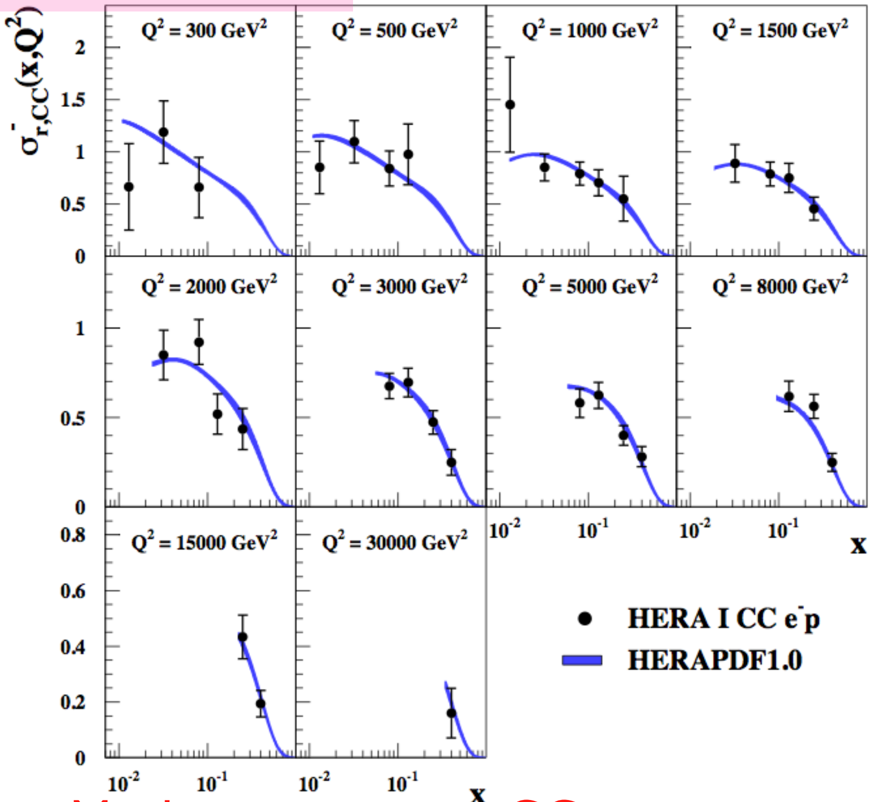


- Before combination, the systematic errors are ~3 times larger than statistical for Q^2<100 GeV^2

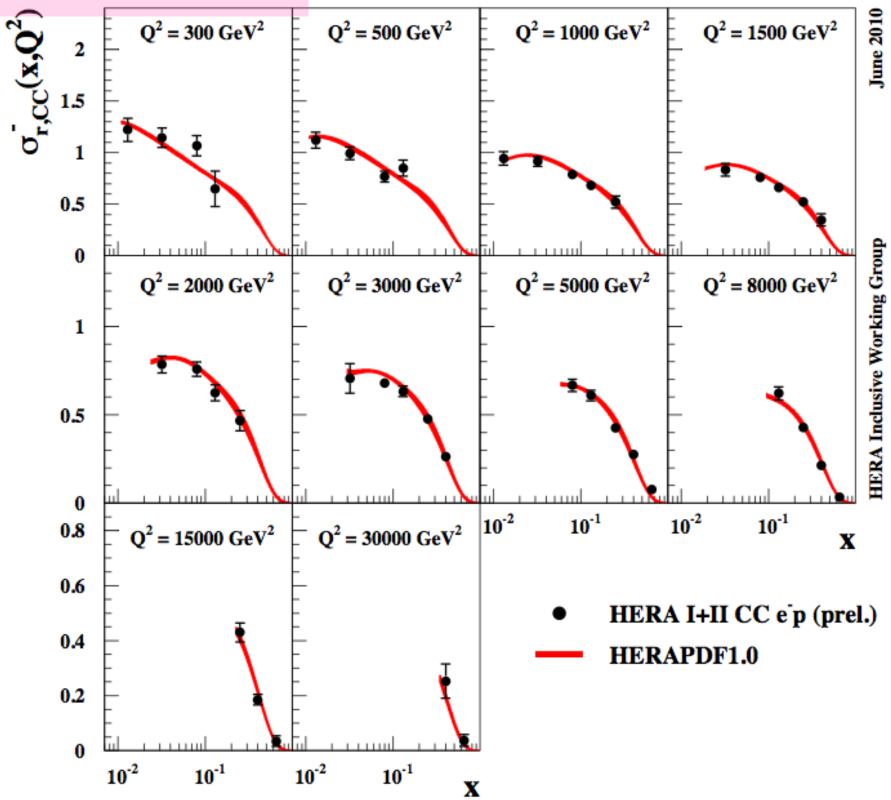
- After combination, the systematic errors are of same precision as the statistical errors, reaching 1% total precision!

Combining HERA I and II Inclusive data

Without HERA II



With HERA II



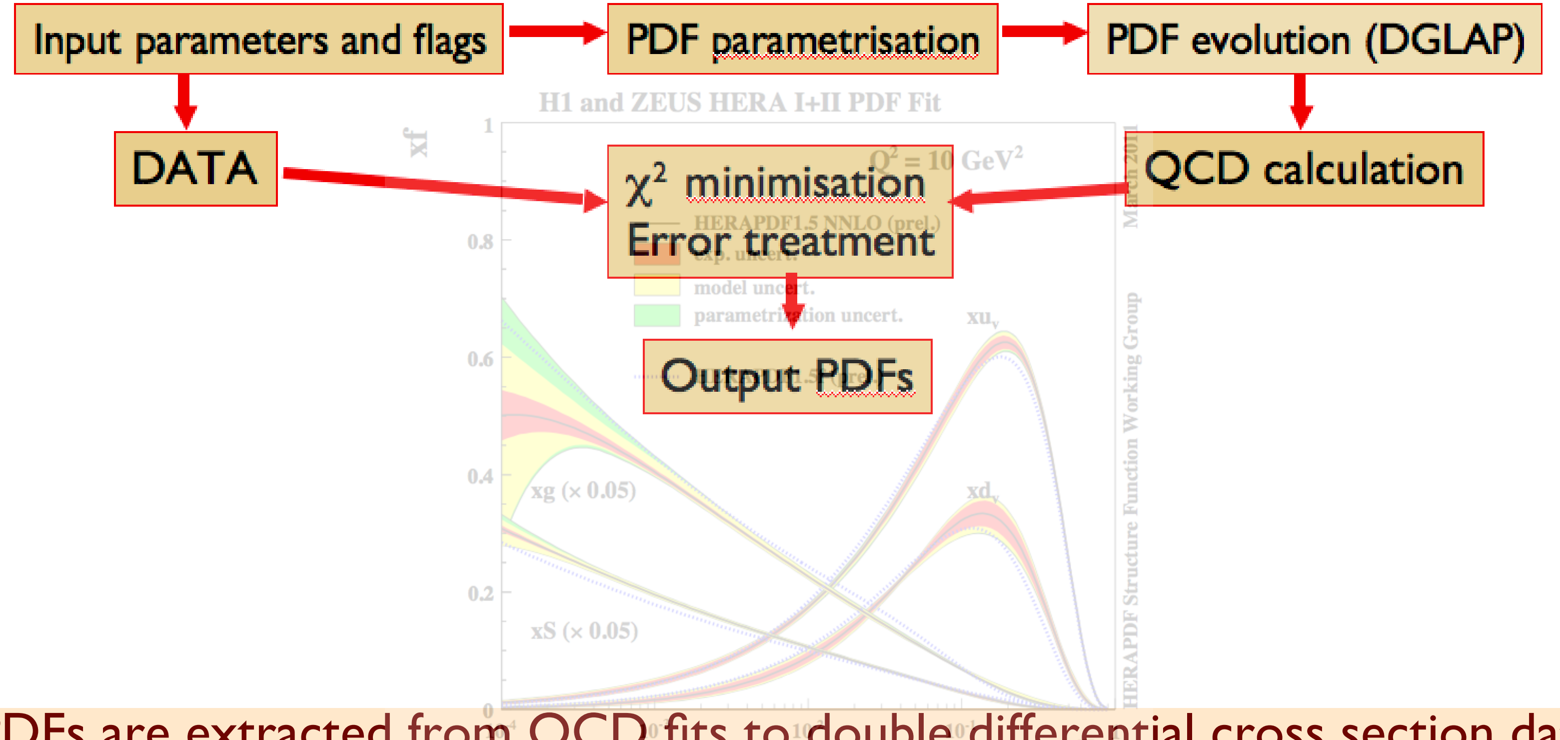
Much more precise CC measurements after including new high Q^2 HERA II set

HERA CC data give flavour information:

- e^+p CC process sensitive to d_v at high x
- e^-p CC process sensitive to u_v at high x

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

Schematics of PDF extractions



- PDFs are extracted from QCD fits to double differential cross section data:
  - Parametrise PDFs at a starting scale by smooth functions with sufficient parameters;
  - Evolve PDFs to other scales by the evolution equations (DGLAP)
  - Compute cross sections for DIS (or other processes) at NLO (NNLO)
  - Calculate χ^2 measure of agreement between data and theory model
  - Obtain the best estimate of the PDFs by varying the free parameters to minimize χ^2

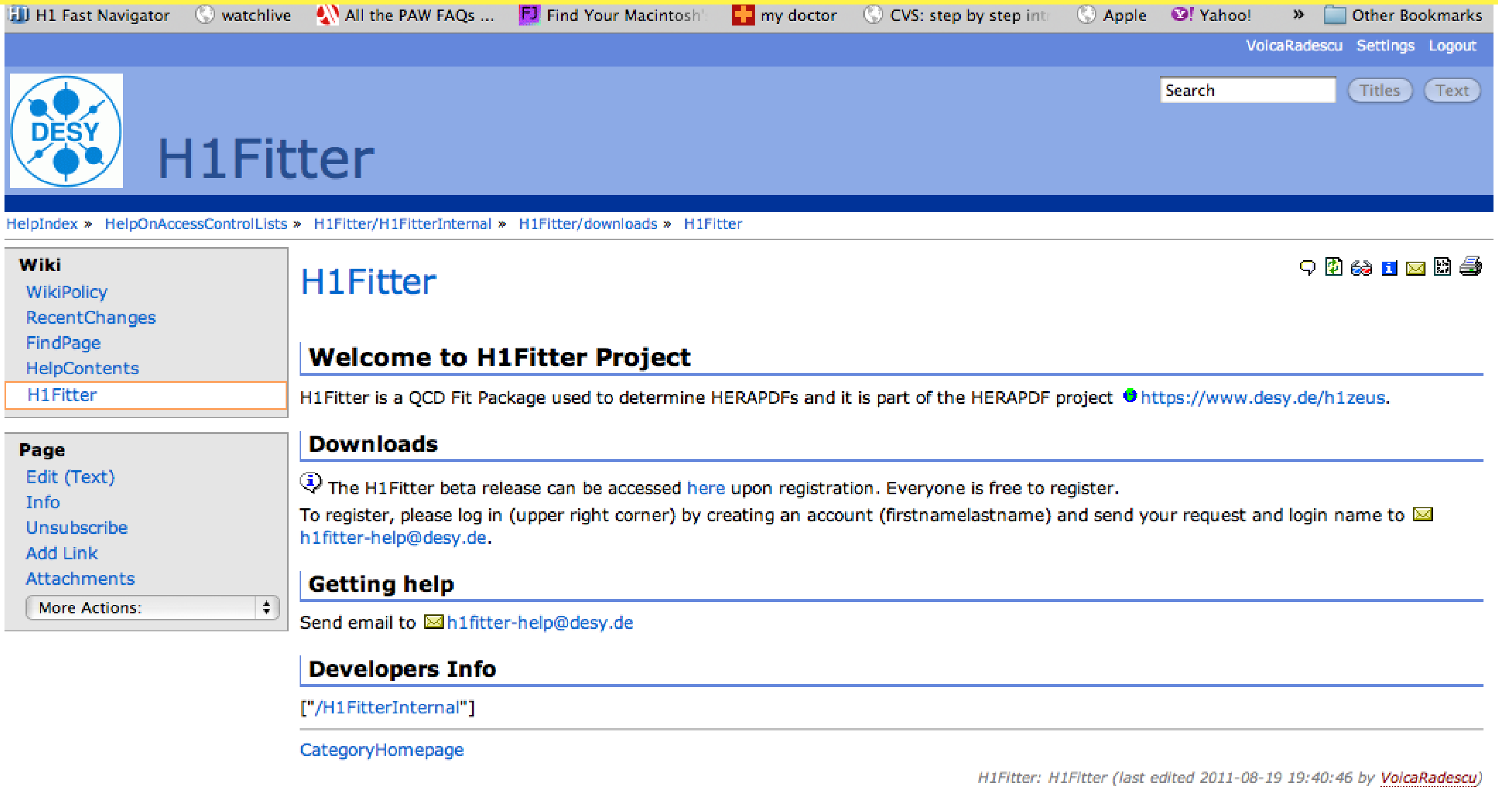
HERAFitter Open Source QCD Fit package

A common initiative of H1 and ZEUS:

▿ HERAFitter is a set of PDF fitting tools jointly developed by the H1 and ZEUS collaborations for determination of the parton density functions.

▿ The current distribution contains a BETA-version of the first code released within the HERAFitter package, the H1fitter program.

- **HERAFitter package available online at http://projects.hepforge.org/herafitter/**



PDF determination at HERA

- HERA PDFs are determined from QCD Fits to solely HERA data
  - NLO (and NNLO) DGLAP evolution equations, RT-VFNS (as for MSTW08)
    - Other schemes were investigated as well: RT (optimal), ACOT (full and χ), FFNS

- The QCD settings are optimised for HERA measurements of proton structure functions

$$\boxed{F_2(x,Q^2) = \frac{4}{9}(xU + x\overline{U}) + \frac{1}{9}(xD + x\overline{D})}$$

  - PDF parametrised at the starting scale Q_0^2:

$$xg, xu_{val}, xd_{val}, x\bar{U} = x\bar{u}(+x\bar{c}), x\bar{D} = x\bar{d} + x\bar{s}(+x\bar{b})$$

  - Simple Functional form: $xq_i(x) = A_i x^{B_i}(1-x)^{C_i} P_i(x)$

- A - normalisation
- B - low x behaviour
- C - high x behaviour
- D,E - medium x tuning

  - Where Pi(x) are polynomials in powers of x and only terms that bring significant improvement to the fit quality are retained

  - QCD sum rules:

$$\int_0^1 dx \cdot (xu_v + xd_v + x\bar{U} + x\bar{D} + xg) = 1$$

$$\int_0^1 dx \cdot 2u_v = 2 \qquad \int_0^1 dx \cdot d_v = 1$$

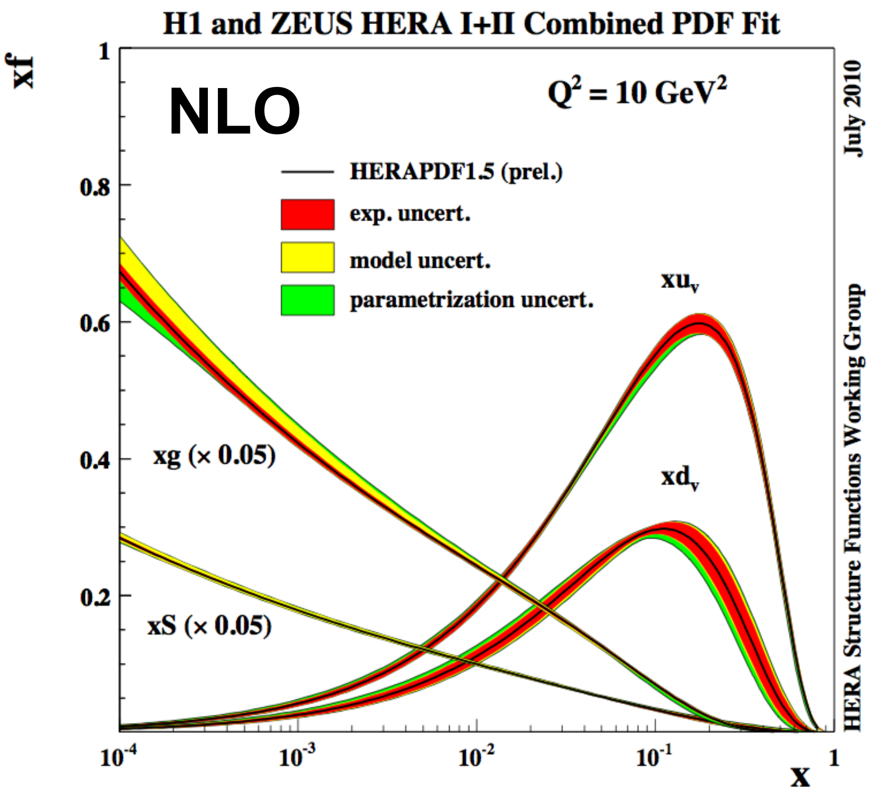
Additional Constraints:

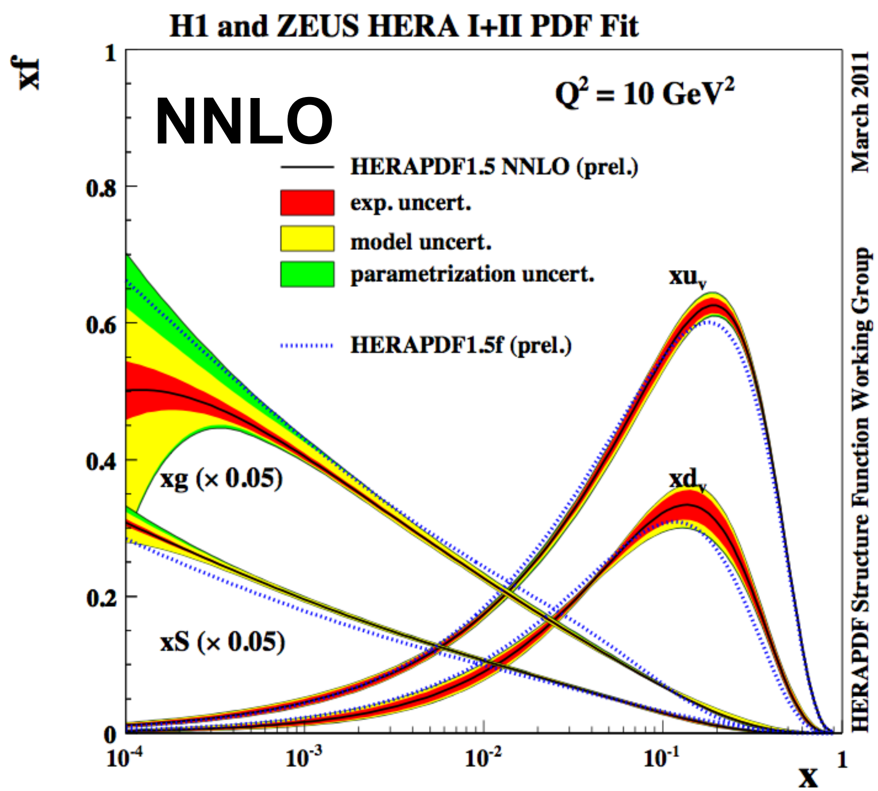
$x\bar{s} = f_s x\bar{D}$ strange sea is a fixed fraction f_s of $\bar{D}$ at Q_0^2

$B_{Ubar} = B_{Dbar}$
sea = 2 x (Ubar +Dbar)
Ubar = Dbar at x=0

HERAPDF1.5

- **HERAPDF1.5:** most precise DIS data, **recommended PDF**
  - **HERAPDF** sets are based **only** on combined H1 and ZEUS HERA I+II data with well understood systematics
  - eigenvectors available in LHAPDF allows for specific studies (i.e. model variations)

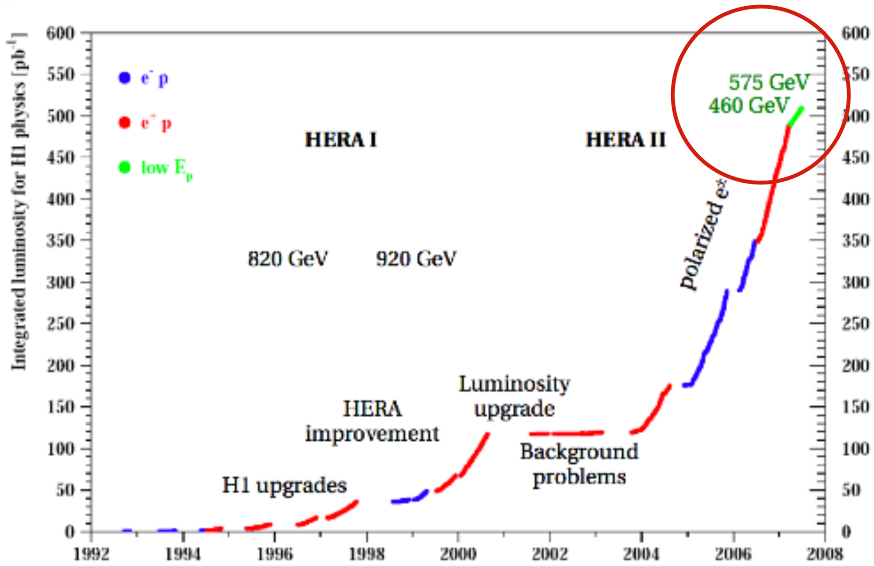


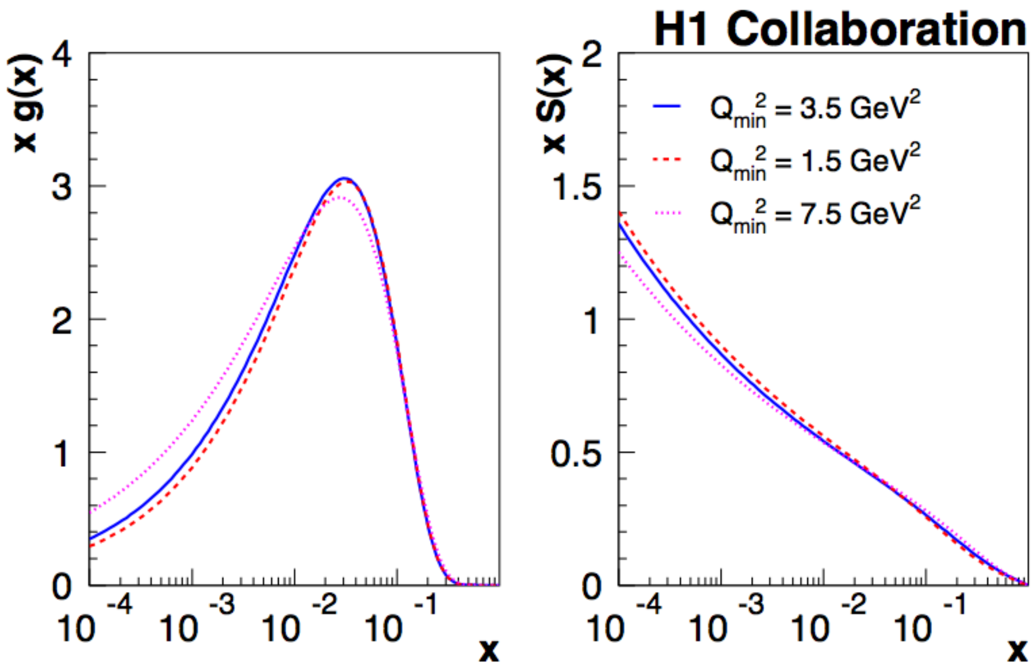


- Observe a possible turn over of gluon at low x

F_L from Low Energy Run at HERA

- Accurate measurement in Q^2>1.5 GeV^2 range from HERA II low energy runs sensitive to structure function F_L are included in the QCD analysis on top of the HERA I data:
  - Observe sensitivity to the Q2 cut applied which triggers further explorations of DGLAP validity at low Q2.





Gluon becomes larger while the sea decreases at low x

Q^2 cut dependence study

Eur.Phys.J.C71 (2011)

- Stability of the fit to inclusion of low Q^2 data is studied by varying the Q^2_{min} cut

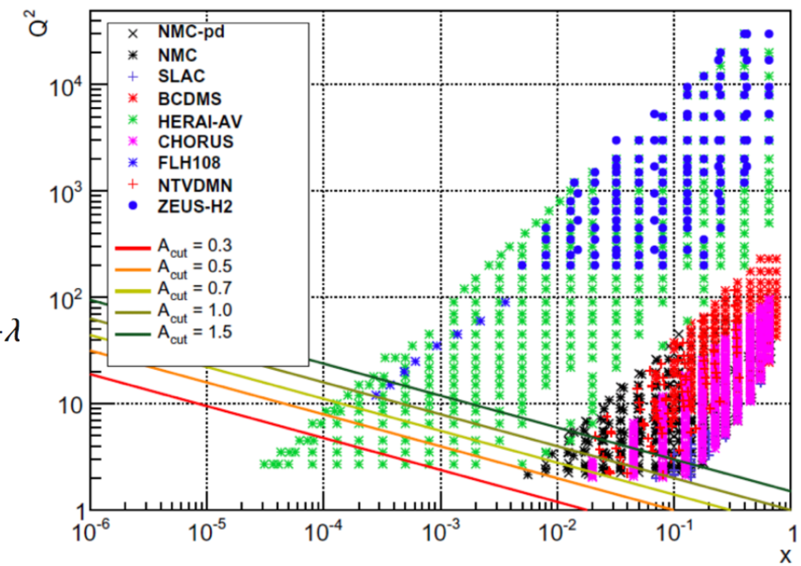
Q^2_{min} / GeV^2	1.5	2	2.5	3.5	5	7.5
$\chi^2 / n_{\mathrm{dof}}$	824.8/834	777.9/818	748.7/801	715.2/781	677.6/759	626.9/712

→ fit has more difficulties to describe data at the lowest Q^2 values

- Change of Q^2 cut from 1.5 to 7.5 GeV^2 leads to increase of the gluon

- An alternative to the Q^2_{min} variation is a saturaton inspired cut on data [F. Caola, DIS2010]: $Q^2 \geq A_S\, x^{-\lambda}$
  - With different values of parameters As and lamda=0.3

→ fit quality improves with the increase of A_S

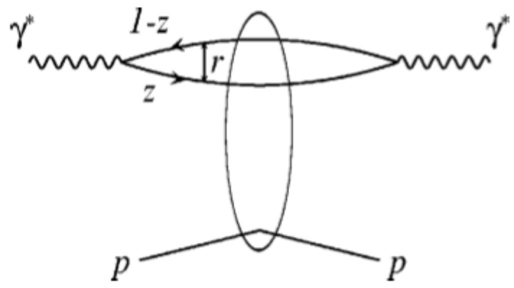


A_S	0.2	0.3	0.5	0.7	1.0	1.5
$\chi^2 / n_{\mathrm{dof}}$	709.5/777	696.1/762	643.1/734	617.3/709	594.4/690	554.1/654

Low x phenomenology with Dipole Models

Eur.Phys.J.C71 (2011)

- At low x and Q^2 the virtual photon-proton scattering can be described using the color dipole model:
    - Fluctuation of the photon into a quark-antiquark pair (dipole) interacting with proton
    - Dipole has built-in saturation assumption
- Following models have been considered:



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

- GBW dipole model:

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

Fitting parameters: σ_0, λ, x_0.

- IIM (CGC) dipole model:

$$\sigma(x,r^2) = \sigma_0 \begin{cases} N_0 \quad (\tau^2)^{\gamma_s + \frac{\ln(\tau)}{\kappa\lambda \ln(x)}} & \text{if } \tau \le 1 \\ \left(1 - \exp[-a\ln^2(2b\ \tau)]\right) & \text{if } \tau > 1 \end{cases}$$

$$\tau = r/2R_0(x)$$

Fitting parameters: σ_0, λ, x_0.

- B-SAT dipole model:

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

$$xg(x,Q_0^2) = A_g x^{-\lambda_g}(1-x)^{5.6}$$

$$\mu^2 = \frac{C}{r^2} + \mu_0^2$$

Fitting parameters: A_g, λ_g, Q_0.
Fixed parameters: $\sigma_0 = 23.8$(mb), $C = 1.0$, $\mu_0^2 = 4.0$.

Model Comparisons: DGLAP vs Dipole

Eur.Phys.J.C71 (2011)

- To facilitate comparisons with dipole models, fits are performed in the same kinematic domain:
  - X<0.01 [where Dipole is applicable]
  - Q^2>3.5 GeV^2 [where DGLAP is valid]
- DGLAP fits:
  - However, for x<0.01 region valence quark cannot be determined in this range when DGLAP fits are performed ➔ fix valence parameters to values obtained from the fits to the full kinematic range

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

Data not yet precise enough to discern among models

Model Comparisons: DGLAP vs Dipole

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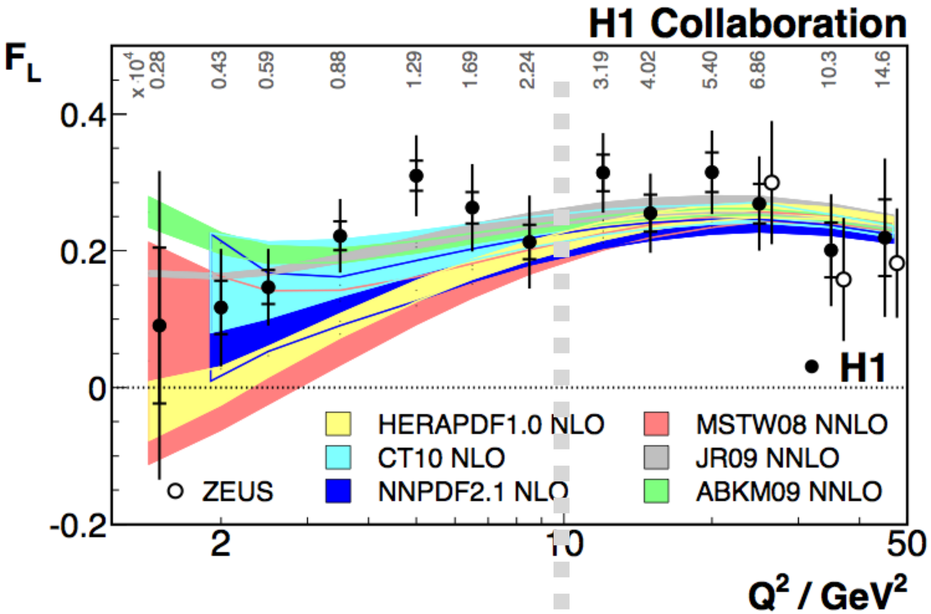
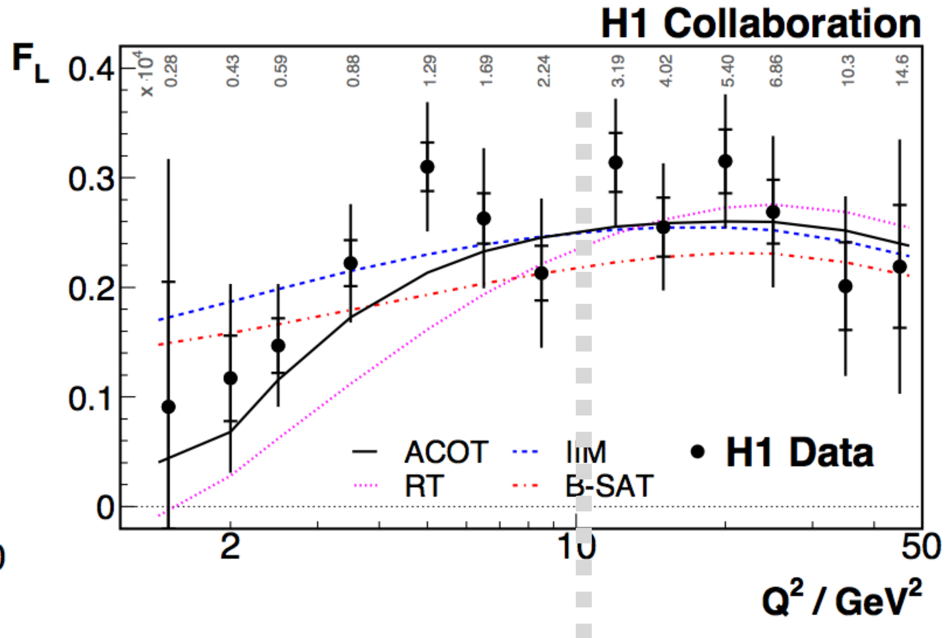
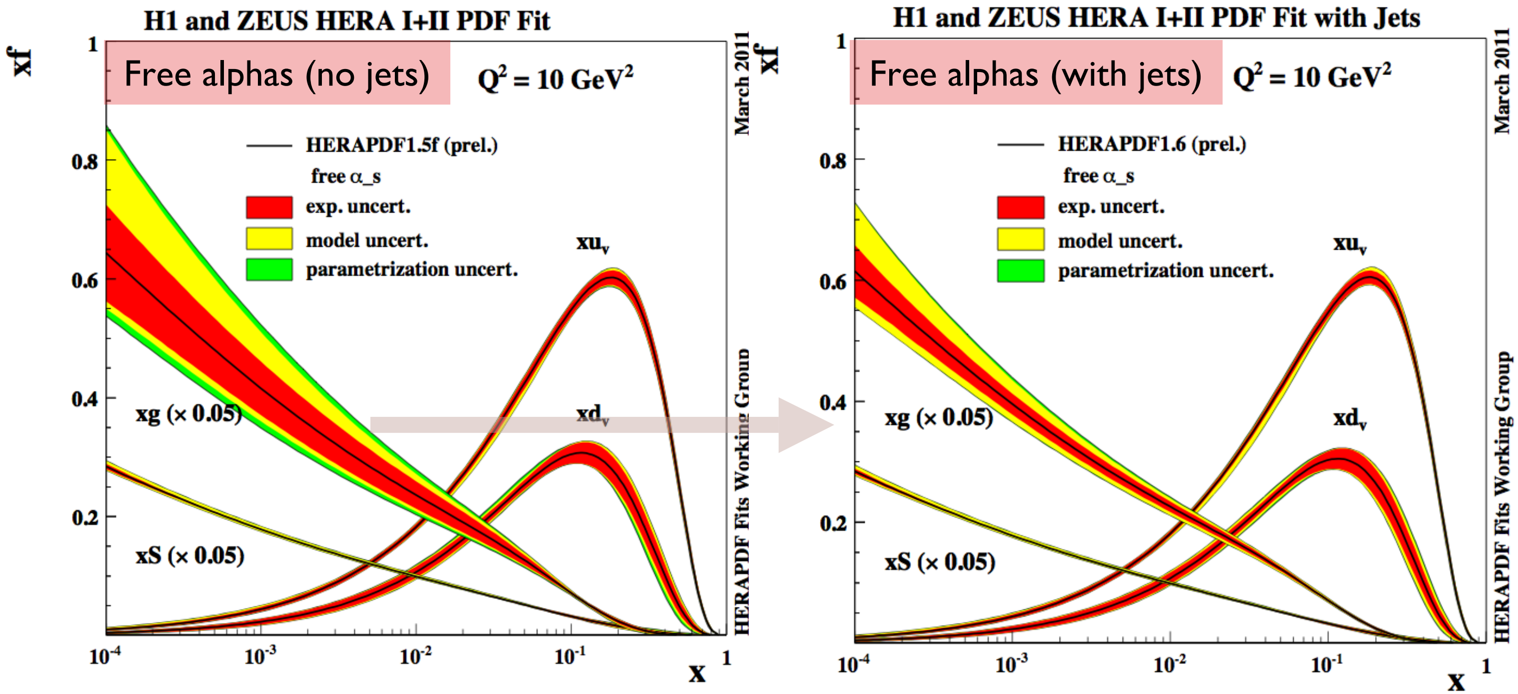




Low Q2 region remains interesting to be investigated!

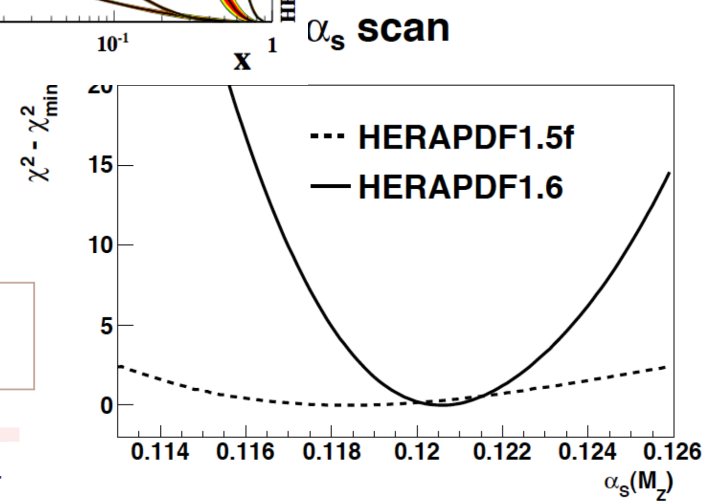
Alphas from HERA

- Addition of the HERA Jet cross section data (NLOJet++/fastNLO) into the fits allows to constrain simultaneously alphas and gluon
- Comparison of the PDFs with free alphas fit with and without Jet data



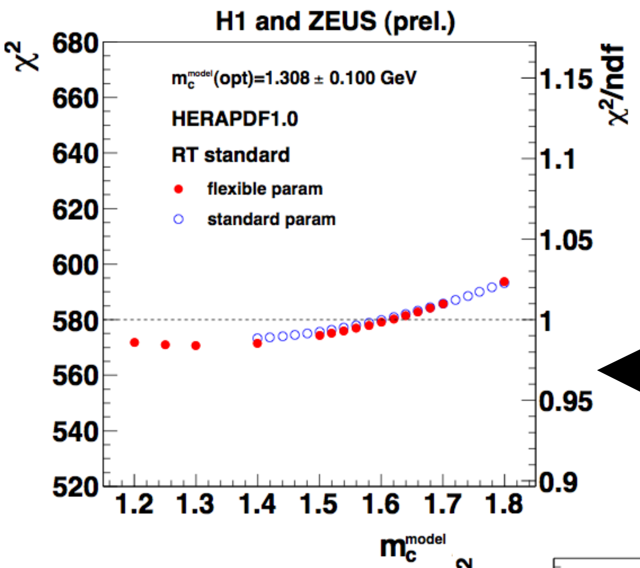
- HERA data prefer larger value for strong coupling:

$$\alpha_s = 0.1202 \pm 0.0013\,(\exp) \pm 0.0007\,(mod) \pm 0.0012\,(had)^{+0.0045}_{-0.0036}\,(th)$$

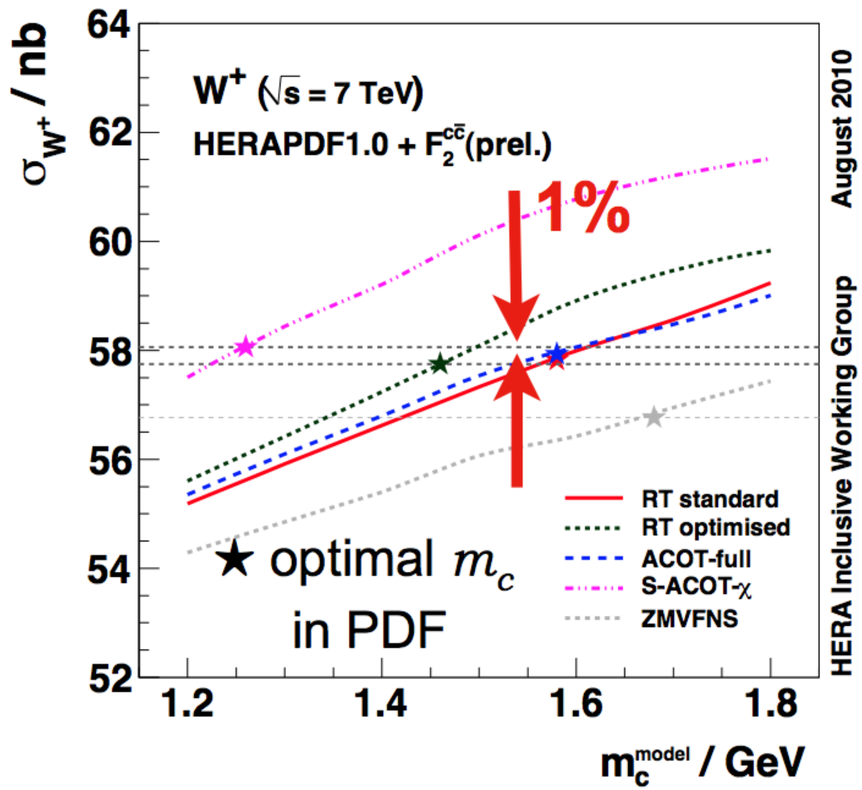


Effect of the charm data

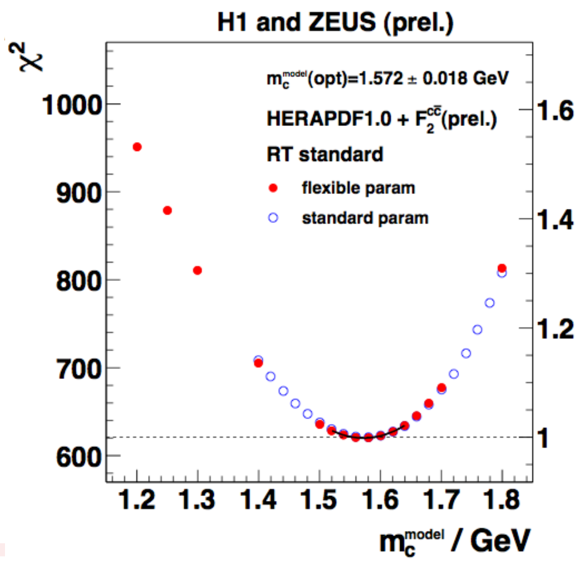
- Addition of the HERA combined F_2 charm data can help reduce model uncertainty of m_c(1.35-1.65):
  - Inclusive data show low sensitivity, addition of the charm data have strong constraining power



without charm data



Including charm data



- 11% error due to different schemes
- Uncertainty on σW prediction due to HF treatment in PDFs reduced to 1 %

A summary of PDF sets

- Table shows a summary of the current status of available PDFs

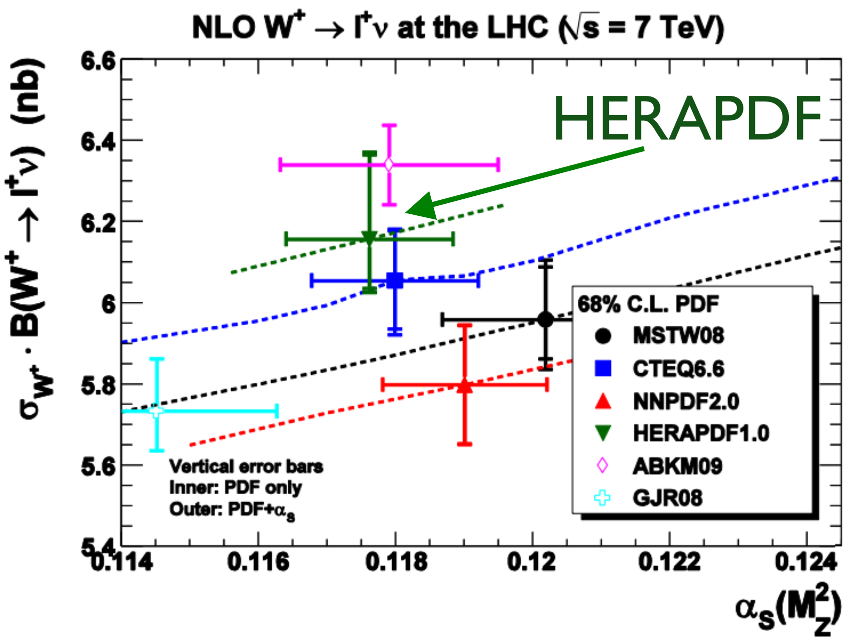
	MSTW08	CTEQ6.6/CT10	NNPDF2.0/2.1	HERAPDF1.0/1.5	ABKM09/ABM11	GJR08/JR09
PDF order	LO, NLO, NNLO	LO, NLO, NNLO	LO, NLO, NNLO	NLO, NNLO	NLO, NNLO	NLO, NNLO
HERA DIS	✔ (old)	✔ (old/new)	✔ (new)	✔ (new/newest)	✔ (new)	✔ (new)
Fixed target DIS	✔	✔	✔	-	✔	✔
Fixed target DY	✔	✔	✔	-	✔	✔
Tevatron W, Z	✔	✔	✔	-	-	-
Tevatron jets	✔	✔	✔	-	✔	✔
HF Scheme	RTGMVF	SACOT GMVFN	FONLL GMVFN	RT GMVFN	BMSN FFNS	FFNS
Alphas (NLO)	0.120	0.118(f)	0.119	0.1176(f)	0.1179	0.1145
Alphas (NNLO)	0.1171	0.118(f)	0.1174	0.1176(f)	0.1147	0.1124

The analyses differ in many areas:

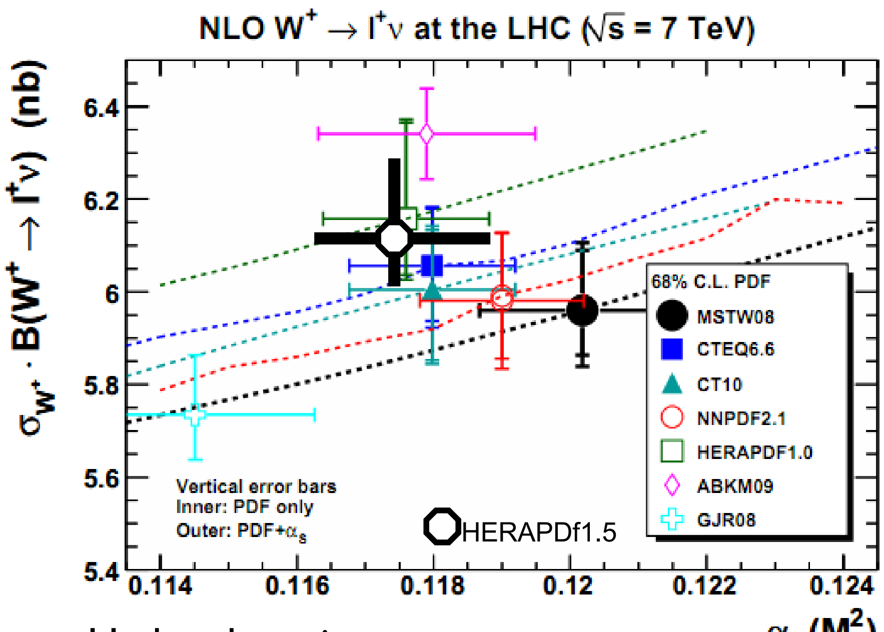
- different treatment of heavy quarks
- inclusion of various data sets and account for possible tensions
- different alphas assumption

Level of PDF agreement

- Overall disagreement in W, Z cross sections was found ~8%



(Plots from G. Watt -68%CL)

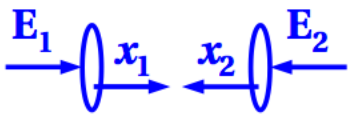


Updated version

Probing the Proton Structure at LHC

- At the LHC: Drell Yan (DY)

Proton-proton collisions:



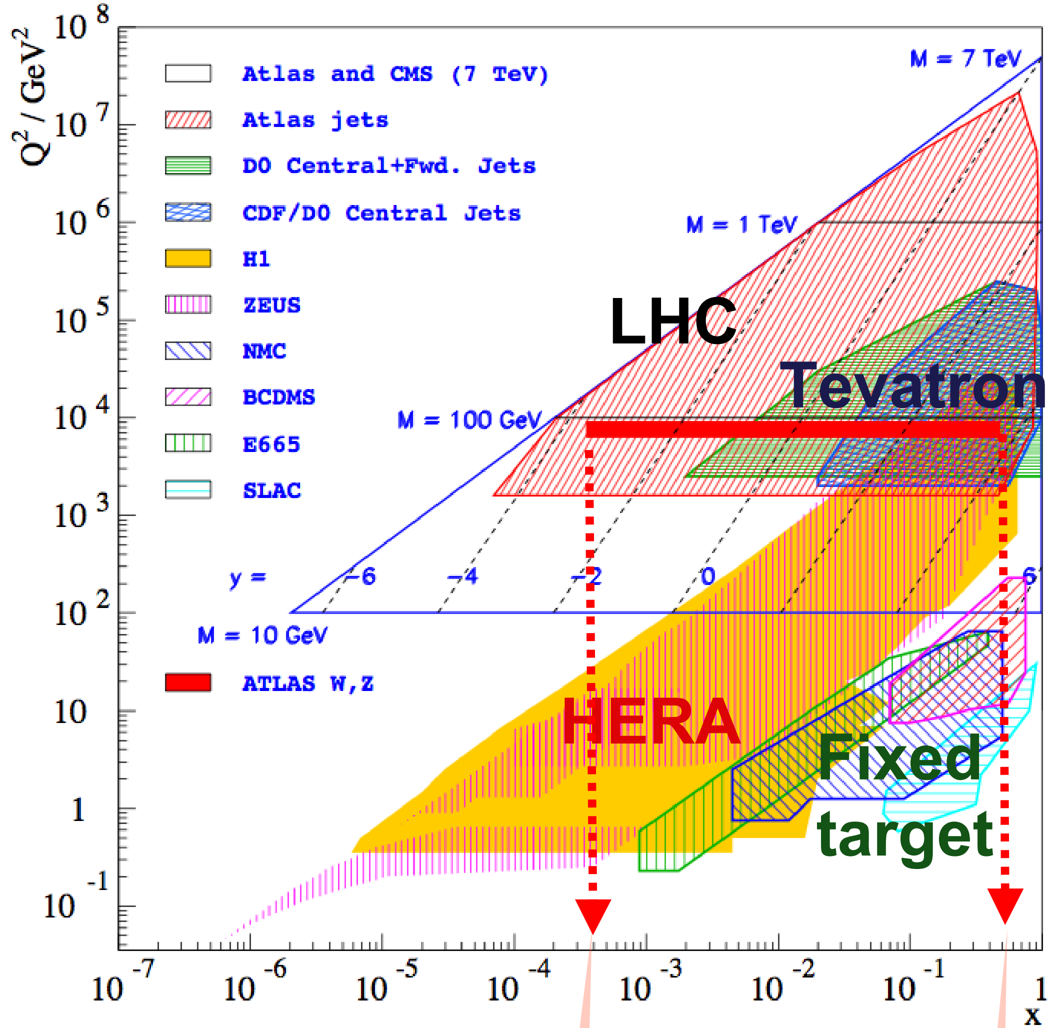
$$\text{rapidity } y = \frac{1}{2}\ln\frac{E+P_Z}{E-P_Z};$$

$$x_1 = \frac{M}{\sqrt{s}}e^{y};\ x_2 = \frac{M}{\sqrt{s}}e^{-y};$$

$$\sigma_X(Q^2) = \sum_{a,b}\int_0^1 dx_1 dx_2 f_a(x_1,Q^2) f_2(x_2,Q^2)\hat{\sigma}_{ab\to X}(x_1,x_2,Q^2)$$

hadronic cross section

Partonic cross section

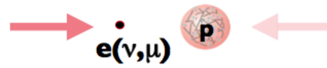


$q(x_1, Q^2 = M^2_{W,Z})$ $q(x_2, Q^2 = M^2_{W,Z})$

So, to predict Z or W production at LHC with a rapidity y=-4, it is needed:

PDF Constraints from LHC

- Main information on proton structure comes from DIS data at HERA:



  - probes linear combination of quarks:
    - CC: provides constraints on valence quarks
    - NC: $F_2 \sim 0.44x(u+\bar{u}+c+\bar{c})+0.11x(d+\bar{d}+s+\bar{s}+b+\bar{b})$

➔ No flavour decomposition of the sea distribution [S=2(ubar+dbar+sbar)]

- Additional constrain come from DY and jet data at the LHC

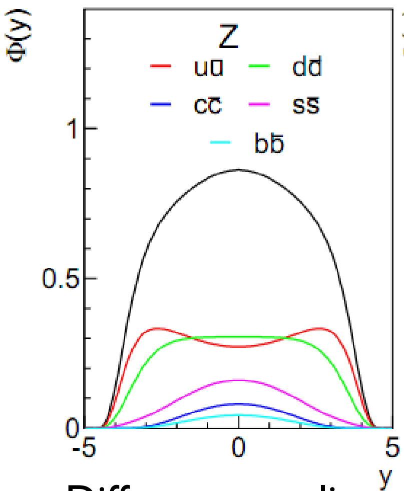
  - probe a bi-linear combination of quarks

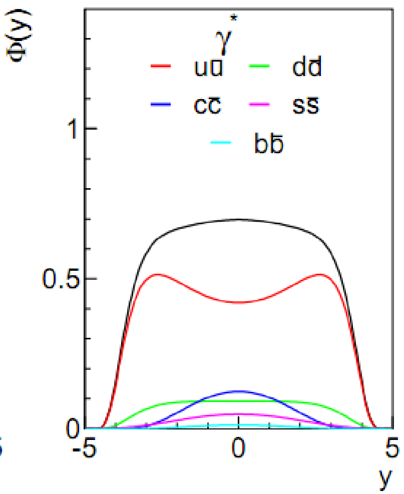
$$Z \quad \sim 0.29(u\bar{u}+c\bar{c})+0.37(d\bar{d}+s\bar{s}+b\bar{b})$$

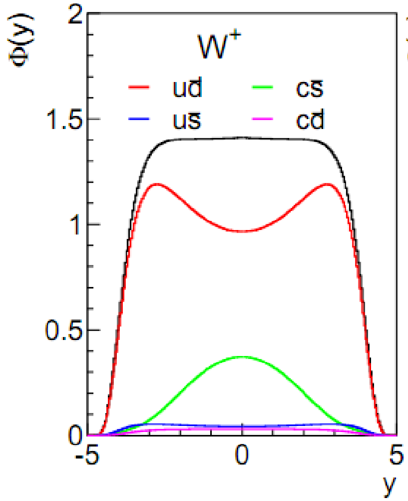
$$\gamma^* \quad \sim 0.44(u\bar{u}+c\bar{c})+0.11(d\bar{d}+s\bar{s}+b\bar{b})$$

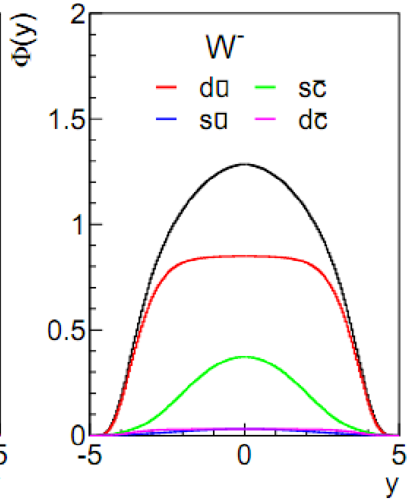
$$W^+ \quad \sim 0.95(u\bar{d}+c\bar{s})+0.05(u\bar{s}+c\bar{d})$$

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









  - Different couplings:
    - Z production more sensitive to **d** vs **u** quarks and more sensitive to **s** than W production

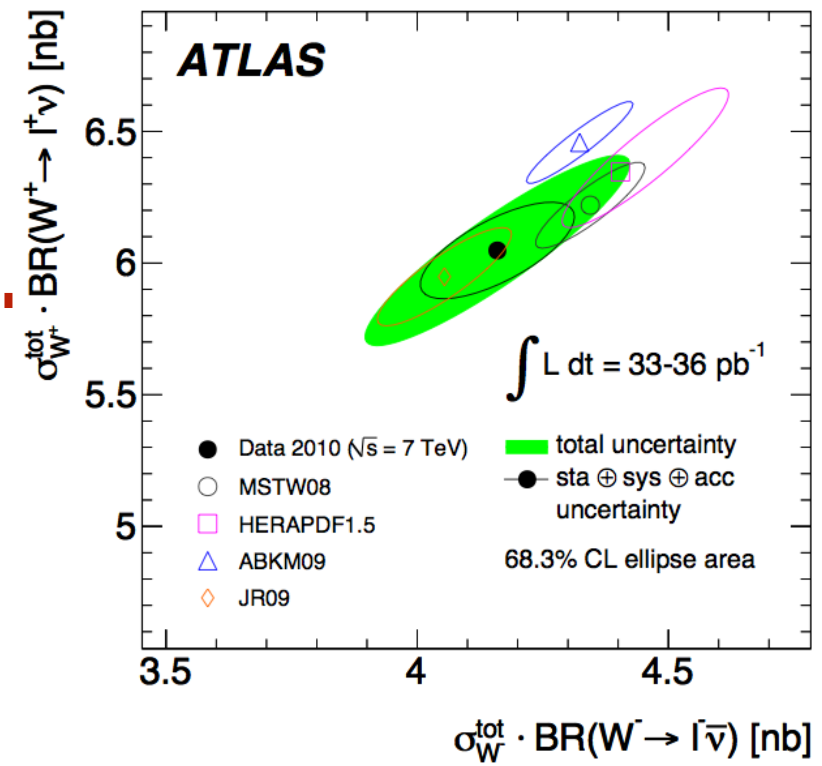
➔ LHC data can provide complementary information:
flavour decomposition of the quark sea

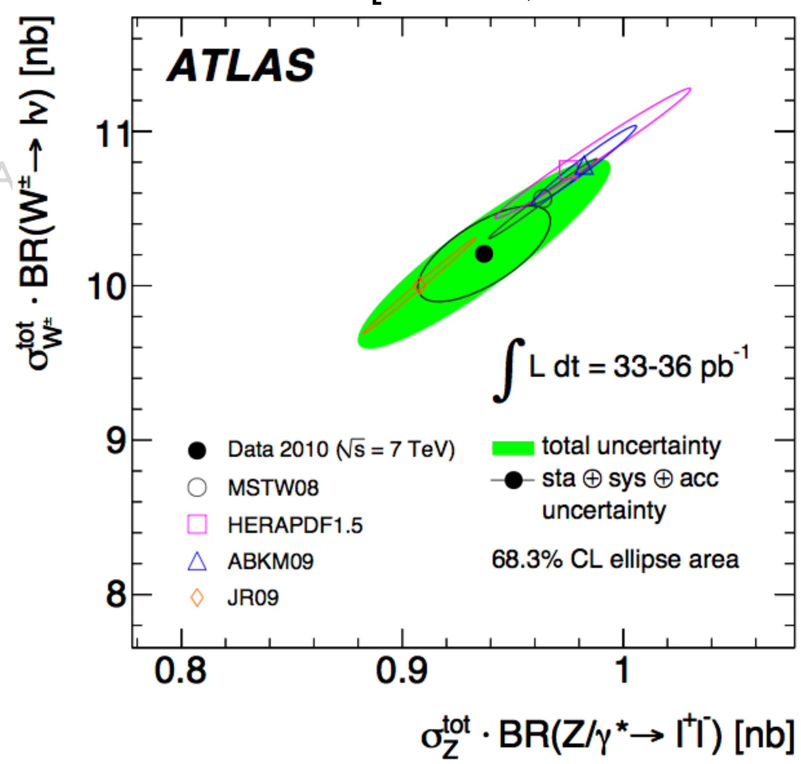
Measurements at the LHC relevant to PDFs

- A successful 2010 and 2011 years: rediscovery of the SM:
  - sufficient lumi to measure precisely W, Z production

- Inclusive measurements:
  - W, Z total cross sections:
    - W^+, W^-, $W^+ + W^-$, Z for electron and muon decay channels

[PRD2011, arXiv:1109.5141v3]





- Large correlations between uncertainties due to the common lumi uncertainty

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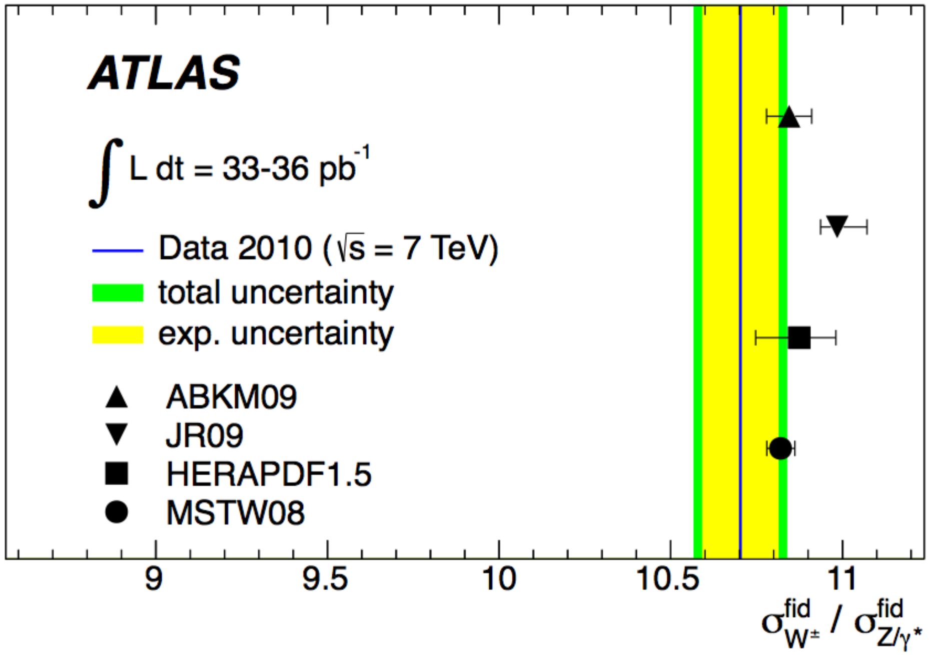

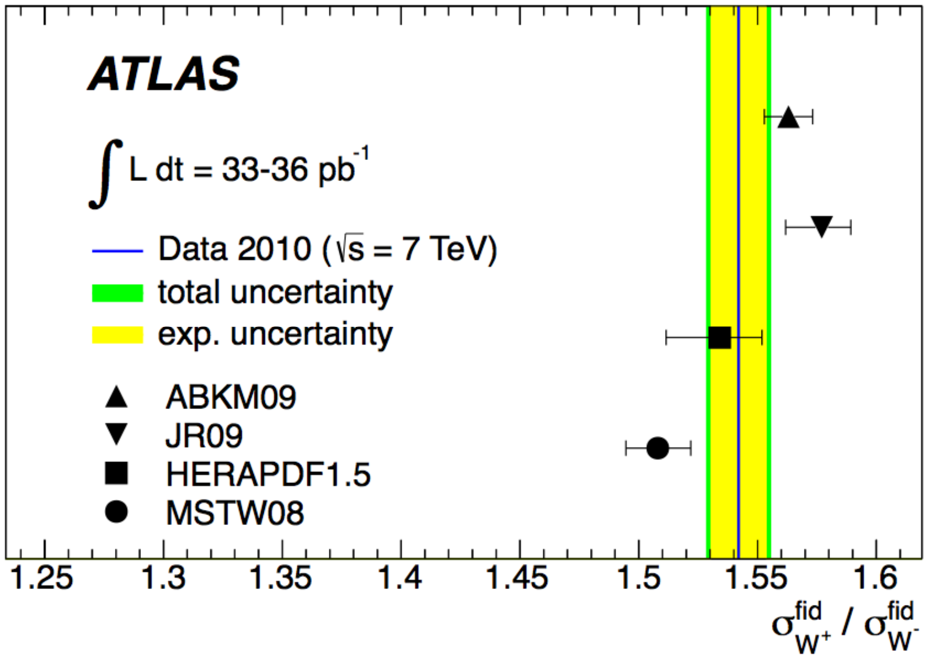

- Uncertainties due to lumi is cancelled, hence reduced uncertainties

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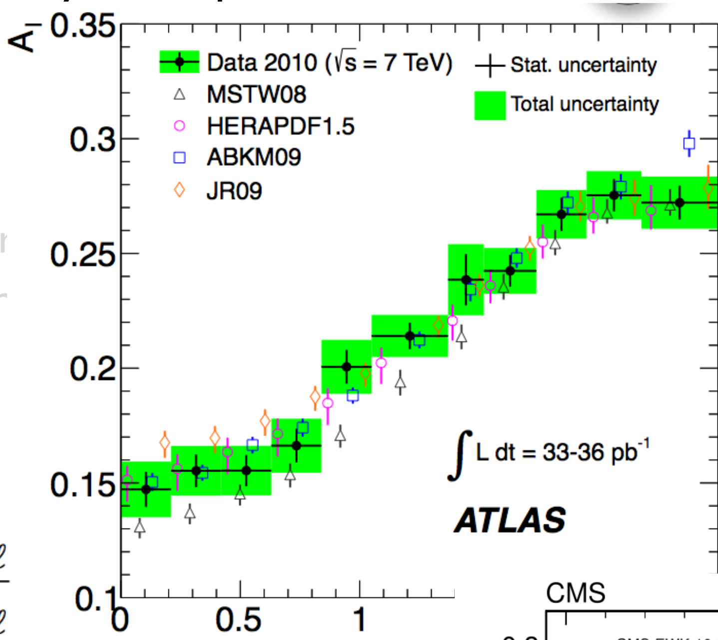
arXiv:1109.5141v3



- Inclusive measurements:
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    - W^+, W^-, $W^+ + W^-$, Z for electr
  - Ratios of W and Z cross section
    - W^+/Z and W-/Z
  - Lepton charge asymmetry
    - (measured in fiducial volume)

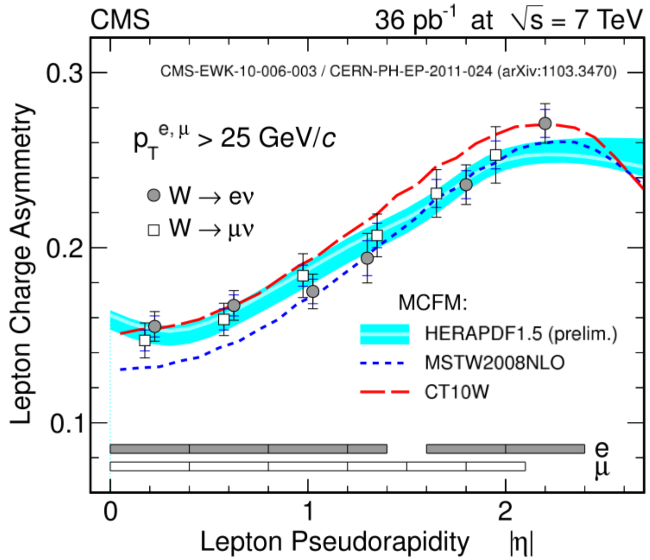
$$A_\ell(\eta_\ell) = \frac{d\sigma_{W+}/d\eta_\ell - d\sigma_{W-}/d\eta_\ell}{d\sigma_{W+}/d\eta_\ell + d\sigma_{W-}/d\eta_\ell}$$

- Assuming $\bar{u} \approx \bar{d}$, $W^\pm$ asymmetry is given by

$$\mathcal{A} \approx \frac{u_v - d_v}{u + d}$$

- Large spread in theory predictions is due to differences in dv/uv at low x.

arXiv:1103.3470



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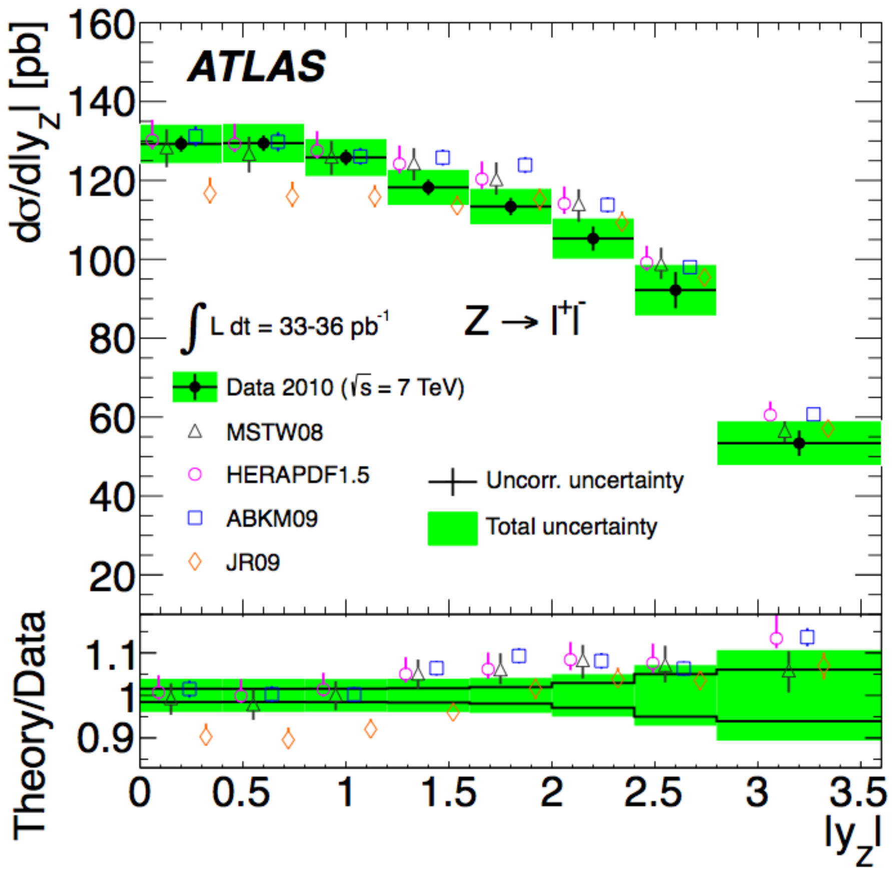
    - (measured in fiducial volume)
  - Z rapidity distribution

    Z production is more sensitive to *d*-quarks compared to *F2* from HERA

    y=0 corresponds to $x_{1,2}$~0.01
    y=3 to x_1=0.3, x_2=6x10^{-4}.

arXiv:1109.5141v3



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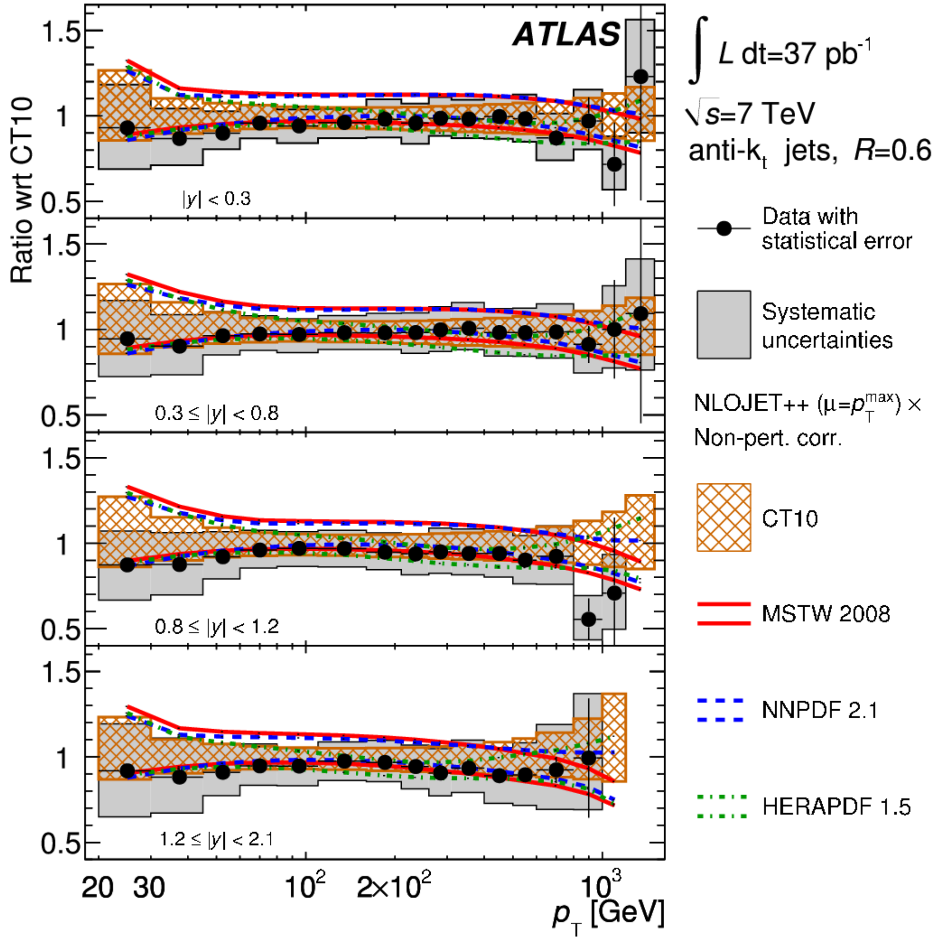
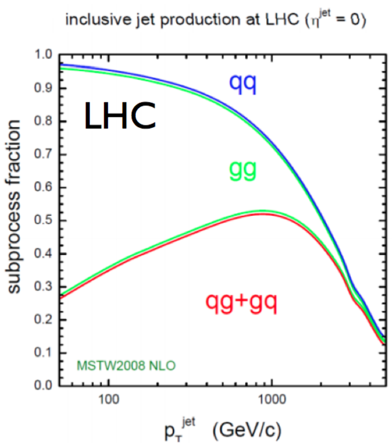
  - Lepton charge asymmetry
    - (measured in fiducial volume)
  - Z rapidity distribution
  - Inclusive jets:
    - Sensitive to gluon at high x





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    - (measured in fiducial volume)
  - Z rapidity distribution
  - Inclusive jets
- Beyond inclusive measurements:
  - W, Z + jets:
    - sensitive to higher order QCD effects
    - Sensitive to PDFs
  - Diboson production
    - W+gamma, Z+gamma
    - W^+W^-
    - Rapid increase of accumulated luminosity should allow for improved accuracy

Motivation for LHeC

- What HERA could/did not do:

Test of the isospin symmetry (u-d) with eD	no deuterons
Investigation of the q-g dynamics in nuclei	no time for eA
Verification of saturation prediction at low x	too low c.o.m energy
Measurement of the strange quark distribution	too low Luminosity
Discovery of Higgs in WW fusion in CC	too low cross section
Study of top quark distribution in the proton	too low c.o.m energy
Precise measurement of FL	too short running time with low energy runs
Resolving d/u question at large Bjorken x	too low Luminosity
Determination of gluon distribution at hi/lo x	too small range
High precision measurement of α_s	overall not precise enough

HEP needs a TeV energy scale machine with 100 times higher luminosity than HERA to develop DIS physics further and to complement the physics at the LHC. The Large Hadron Collider p and A beams offer a unique opportunity to build a second ep and first eA collider at the energy frontier.

(M. Klein)

The Large Hadron Electron Collider at CERN

http://cern.ch/lhec

LHeC Study Group

J. Abelleira Fernandez[10,15], C.Adolphsen[39], S.Alekhin[40,11], A.N.Akai[01], H.Aksakal[30], P.Allport[17], J.L.Albacete[37], V.Andreev[25], R.B.Appleby[23], N.Armesto[38], G.Azuelos[26], M.Bai[47], D.Barber[11], J.Bartels[12], J.Behr[11], O.Behnke[11], S.Belyaev[10], I.BenZvi[47], N.Bernard[16], S.Bertolucci[10], S.Bettoni[10], S.Biswal[32], J.Bluemlein[11], H.Boettcher[11], H.Braun[48], S.Brodsky[39], A.Bogacz[28], C.Bracco[10], O.Bruening[10], E.Bulyak[08], A.Bunyatian[11], H.Burkhardt[10], I.T.Cakir[54], O.Cakir[53], R.Calaga[47], E.Ciapala[10], R.Ciftci[01], A.K.Ciftci[01], B.A.Cole[29], J.C.Collins[46], J.Dainton[17], A.De.Roeck[10], D.d'Enterria[10], A.Dudarev[10], A.Eide[43], E.Eroglu[45], K.J.Eskola[14], L.Favart[06], M.Fitterer[10], S.Forte[24], P.Gambino[42], T.Gehrmann[50], C.Glasman[22], R.Godbole[27], B.Goddard[10], T.Greenshaw[17], A.Guffanti[09], V. Guzey[28], C.Gwenlan[34], T.Han[36], Y.Hao[47], F.Haug[10], W.Herr[10], B.Holzer[10], M.Ishitsuka[41], M.Jacquet[33], B.Jeanneret[10], J.M.Jimenez[10], H.Jung[11], J.M.Jowett[10], H.Karadeniz[54], D.Kayran[47], F.Kocac[45], A.Kilic[45], K.Kimura[41], M.Klein[17], U.Klein[17], T.Kluge[17], G.Kramer[12], M.Korostelev[23], A.Kosmicki[10], P.Kostka[11], H.Kowalski[11], D.Kuchler[10], M.Kuze[41], T.Lappi[14], P.Laycock[17], E.Levichev[31], S.Levonian[11], V.N.Litvinenko[47], A.Lombardi[10], C.Marquet[10], B.Mellado[07], K.H.Mess[10], S.Moch[11], I.I.Morozov[31], Y.Muttoni[10], S.Myers[10], S.Nandi[26], P.R.Newman[03], T.Omori[44], J.Osborne[10], Y.Papaphilippou[10], E.Paoloni[35], C.Pascaud[33], H.Paukkunen[38], E.Perez[10], T.Pieloni[15], E.Pilicer[45], A.Polini[04], V.Ptitsyn[47], Y.Pupkov[31], V.Radescu[13], S.Raychaudhuri[27], L.Rinolfi[10], R.Rohini[27], J.Rojo[24], S.Russenschuck[10], C.A.Salgado[38], K.Sampei[41], E.Sauvan[19], M.Sahin[01], U.Schneekloth[11], A.N.Skrinsky[31], T.Schoerner Sadenius[11], D.Schulte[10], H.Spiesberger[21], A.M.Stasto[46], M.Strikman[46], M.Sullivan[39], B.Surrow[05], S.Sultansoy[01], Y.P.Sun[39], W.Smith[20], I.Tapan[45], P.Taels[02], E.Tassi[52], H.Ten.Kate[10], J.Terron[22], H.Thiesen[10], L.Thompson[23], K.Tokushuku[44], R.Tomas.Garcia[10], D.Tommasini[10], D.Trbojevic[47], N.Tsoupas[47], J.Tuckmantel[10], S.Turkoz[53], K.Tywoniuk[18], G.Unel[10], J.Urakawa[44], P.VanMechelen[02], A.Variola[37], R.Veness[10], A.Vivoli[10], P.Vobly[31], R.Wallny[51], G.Watt[10], G.Weiglein[12], C.Weiss[28], U.A.Wiedemann[10], U.Wienands[39], F.Willeke[47], V.Yakimenko[47], A.F.Zarnecki[49], F.Zimmermann[10], F.Zomer[33]

About 150 Experimentalists and Theorists from 50 Institutes

Tentative **list of those who contributed to the CDR**

Supported by
CERN, ECFA, NuPECC

Kinematic range of LHeC

LHeC scenario: (Lumi $e^{+/-}p$ = 50 fb^{-1})

Ep=7TeV, Ee=50 GeV, Pol=±0.4

- Kinematic region:
  - $2 < Q^2 < 500\,000$ GeV^2
  - $0.000002 < x < 0.8$

Typical uncertainties:

- Statistical <1%

  it ranges from 0.1% (low Q^2) to 45% (highest x, Q^2 CC)
- Uncorrelated systematic: 0.7 %
- Correlated systematic: typically 1-3 % (for CC high x up to 9%)

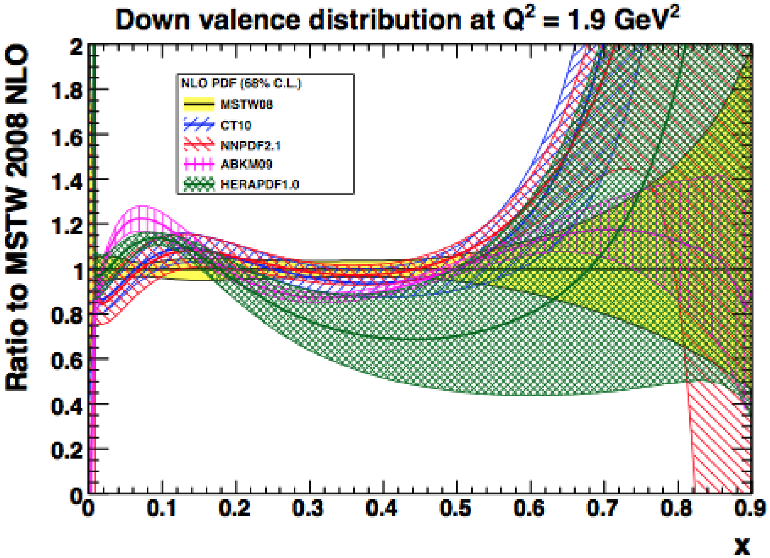
- To evaluate the impact of LHeC, the following data sets have been used under the same QCD settings as for HERAPDF (same machinery):
  - LHeC data: NC e^+p, NC, e^-p, CC e^+p, CC e^-p postive and negative polarisations P=±0.4
  - Published HERA I
    - NC, CC $e^{\pm}p$ data, P=0
    - Kinematics of HERA data: $0.65>x>10^{-4}$, $30\,000 > Q^2 > 3.5$ GeV^2
  - Fixed target data from BCDMS
  - Extrapolated LHC precision assuming the same y range
    - stat 0.5%, uncor 0.5%, total 1%
  - Uncertainties are estimated using Hessian method cross checked against MC method

Valence distribution

- Current knowledge is limited at high x:
  - Lumi barrier
  - challenging systematic
  - nuclear effects

- LHeC could improve the knowledge of the valence at high x to 5% precision

NOW



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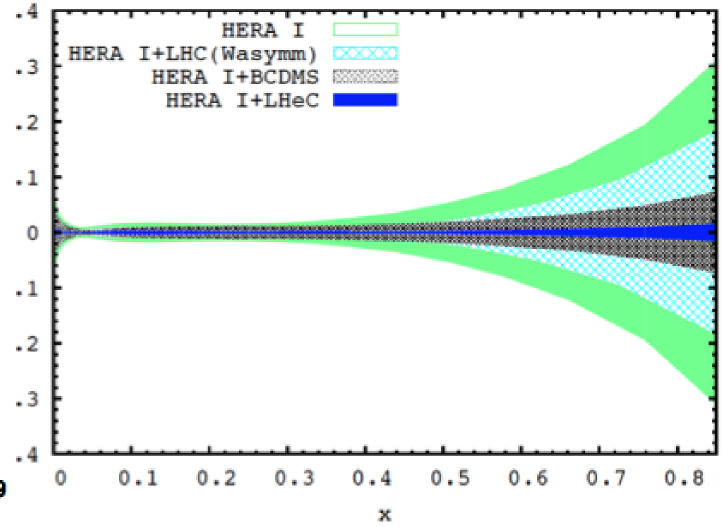
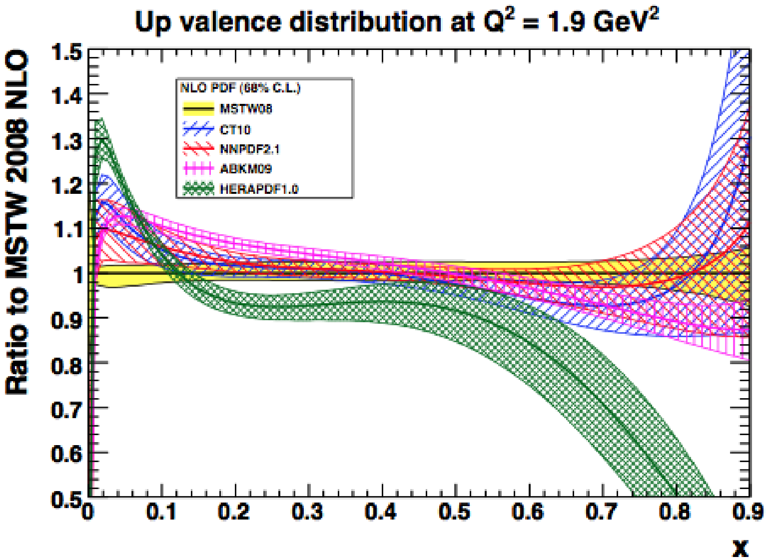
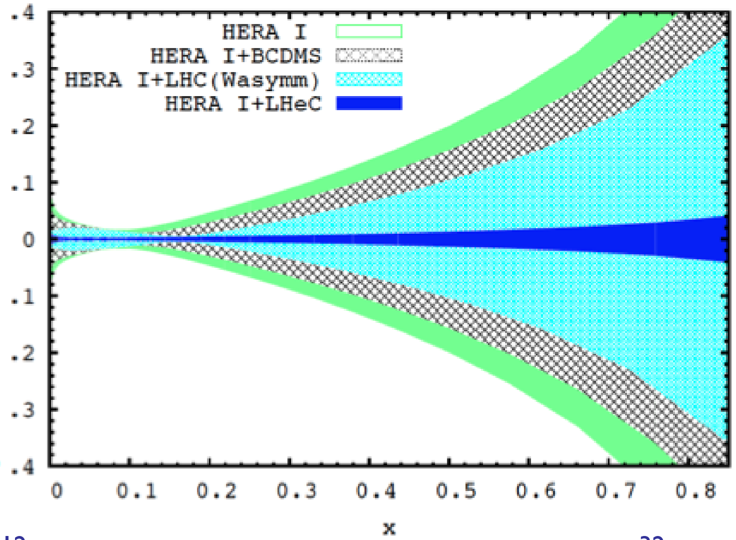
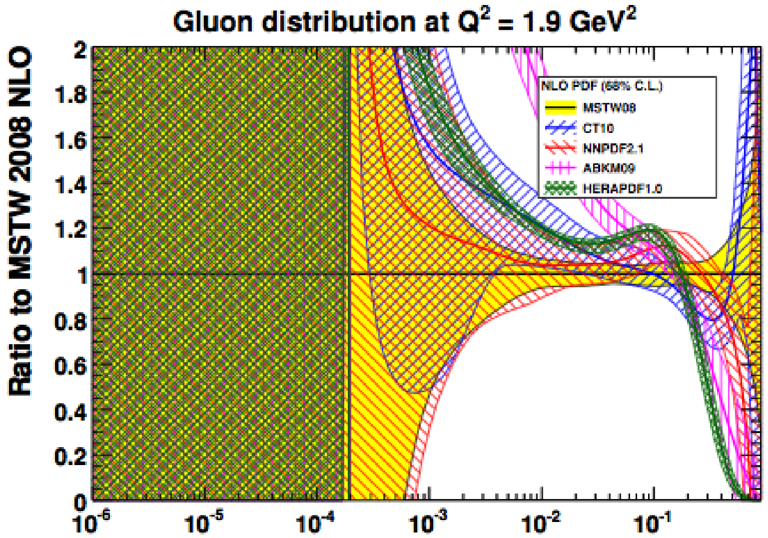


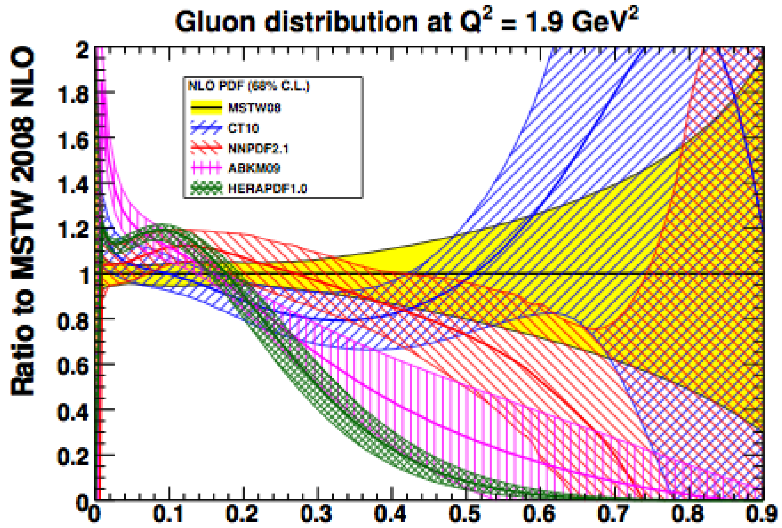




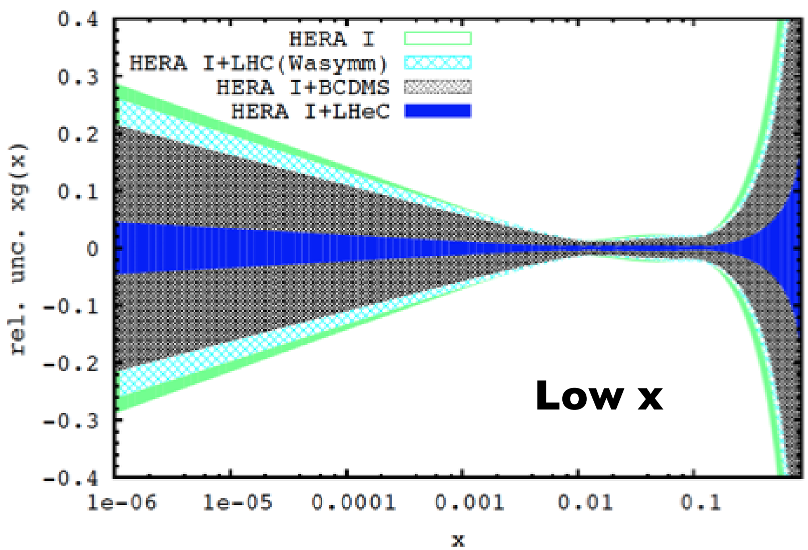
Gluon Distribution

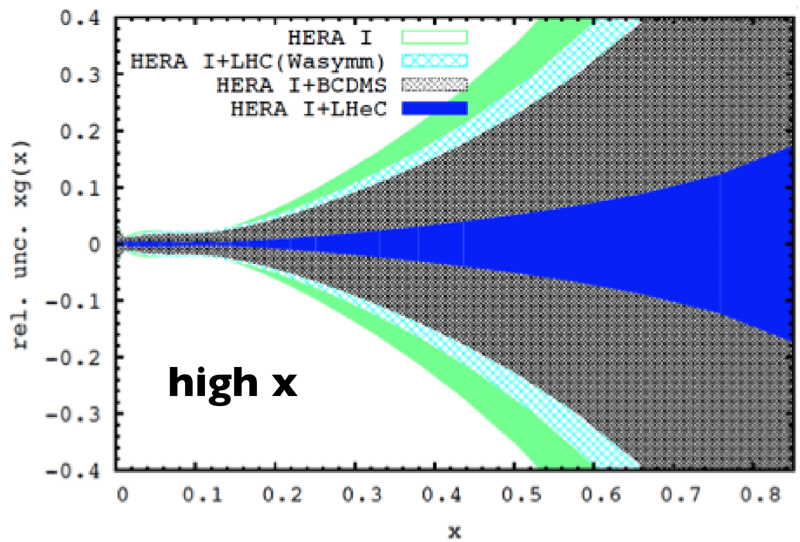
NOW





Then





Amazing precision over extended kinematic range, from low to high x enable for accurate determination of alphas from DIS

Alpha strong from DIS

- The precise knowledge of $\alpha_s(M_Z^2)$ is of instrumental importance for the correct prediction of the electroweak gauge boson production cross sections and the Higgs boson cross section at Tevatron and the LHC
- The strong coupling α_s exhibits the largest uncertainty out of SM couplings, which is currently of the size of ~ 1%.

case	cut [Q^2 in GeV^2]	relative precision in %
HERA only (14p)	$Q^2 > 3.5$	1.94
HERA+jets (14p)	$Q^2 > 3.5$	0.82
LHeC only (14p)	$Q^2 > 3.5$	0.15
LHeC only (10p)	$Q^2 > 3.5$	0.17
LHeC only (14p)	$Q^2 > 20.$	0.25
LHeC+HERA (10p)	$Q^2 > 3.5$	0.11
LHeC+HERA (10p)	$Q^2 > 7.0$	0.20
LHeC+HERA (10p)	$Q^2 > 10.$	0.26

LHeC promises per mille accuracy on alphas!

Summary

- HERA data is the main ingredient for determination of the PDFs
  - Combination of the H1 and ZEUS data brings ultimate precision for PDFs.
  - *FL* measurement down to Q2 = 1.5 GeV2 as a new input for low *x* phenomenological analyses
  - Fit to inclusive + DIS-jet data provides determination of strong coupling with consistent treatment of PDF uncertainties.
  - Charm data constrain heavy flavour models parameter and reduce PDF uncertainties for the LHC predictions
- HERAPDF fits provide basis for QCD analysis with a consistent and high accuracy input data having well understood systematic uncertainties.
- LHC data can provide complementary PDF constraints:
  - Very successful operation of the LHC allows for precision physics measurements
  - data precision is comparable to the PDF uncertainties and requires NNLO calculations.
- The LHeC has the potential to constrain the full set of PDFs and strong coupling due to its kinematic range, huge luminosity, availability of electron and positron beams, as of proton and deuteron beams.

Electron Beam -Two Options

$$L = \frac{N_p \gamma}{4\pi e \varepsilon_{pn}} \cdot \frac{I_e}{\sqrt{\beta_{px}\beta_{py}}}$$

$$N_p = 1.7 \cdot 10^{11}, \varepsilon_p = 3.8\mu m, \beta_{px(y)} = 1.8(0.5)m, \gamma = \frac{E_p}{M_p}$$

$$L = 8.2 \cdot 10^{32} cm^{-2}s^{-1} \cdot \frac{N_p 10^{-11}}{1.7} \cdot \frac{m}{\sqrt{\beta_{px}\beta_{py}}} \cdot \frac{I_e}{50mA}$$

$$I_e = 0.35mA \cdot P[MW] \cdot (100/E_e[GeV])^4$$

Ring-Ring

Power Limit of 100 MW wall plug

"ultimate" LHC proton beam

60 GeV $e^{\pm}$ beam

→L = 2 10^{33} $cm^{-2}s^{-1}$ → O(100) fb^{-1}

LINAC Ring

Pulsed, **60 GeV**: ~10^{32}

High luminosity:

Energy recovery: $P=P_0/(1-\eta)$

β^*=0.1m

[5 times smaller than LHC by reduced l*, only one p squeezed and IR quads as for HL-LHC]

L = 10^{33} $cm^{-2}s^{-1}$ → O(100) fb^{-1}

$$L = \frac{1}{4\pi} \cdot \frac{N_p}{\varepsilon_p} \cdot \frac{1}{\beta^*} \cdot \gamma \cdot \frac{I_e}{e}$$

$$N_p = 1.7 \cdot 10^{11}, \varepsilon_p = 3.8\mu m, \beta^* = 0.2m, \gamma = 7000/0.94$$

$$L = 8 \cdot 10^{31} cm^{-2}s^{-1} \cdot \frac{N_p 10^{-11}}{1.7} \cdot \frac{0.2}{\beta^*/m} \cdot \frac{I_e/mA}{1}$$

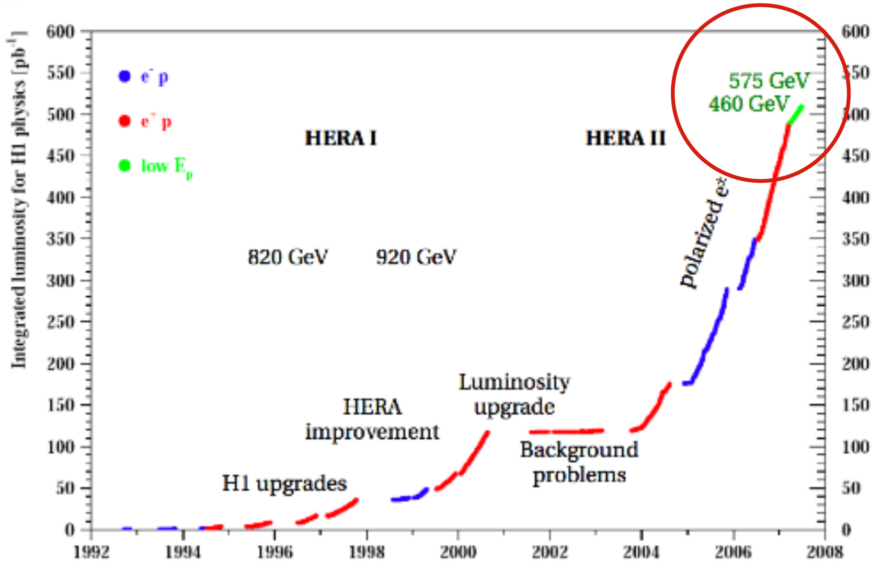
$$I_e = mA \frac{P/MW}{E_e/GeV}$$

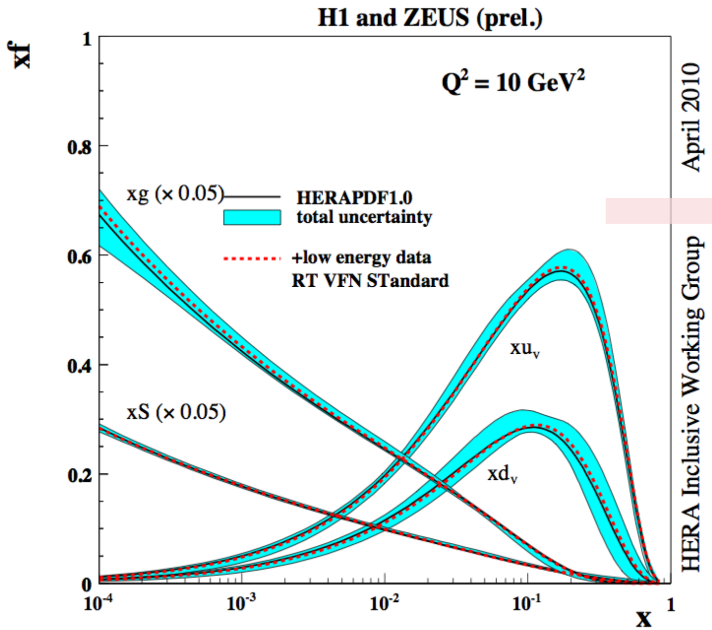
Synchronous ep and pp operation (small ep tuneshifts)

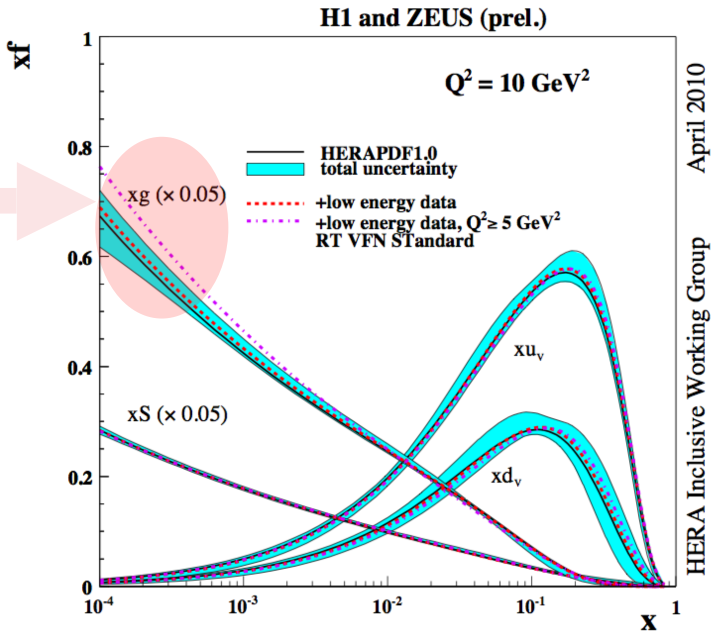
The LHC p beams provide 100 times HERA's luminosity

FL from Low Energy Run at HERA

- Accurate measurement in $Q^2>1.5$ GeV^2 range, sensitive to structure function F_L are included in the QCD analysis on top of the HERA I data using DGLAP
  - Observe sensitivity to the Q2 cut applied which triggers further explorations of DGLAP validity at low Q2.



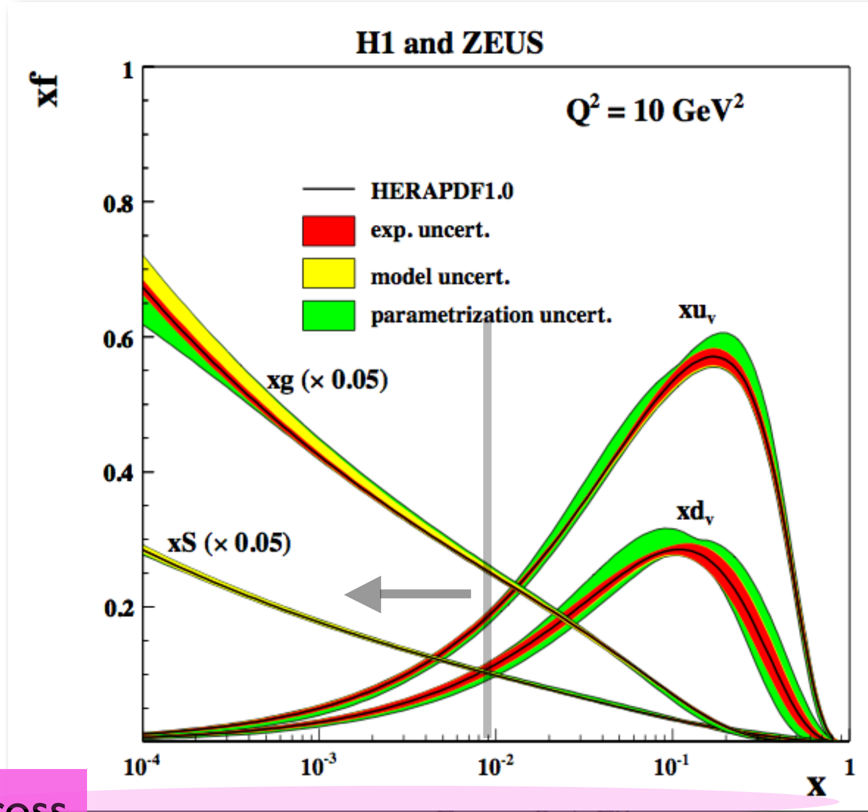




Prelim 2010

Dipole Model Fits

- At low x and Q^2 the virtual photon-proton scattering can be described using the color dipole model:
  - Fluctuation of the photon into a quark-antiquark pair (dipole) interacting with proton
- Following models have been considered:



- GBW dipole model:

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

Fitting parameters: σ_0, λ, x_0.

- IIM (CGC) dipole model:

Contribution of the valence to the ep scattering cross section is sizeable for the whole HERA kinematics: for x in 0.0001 to 0.01 contribution varies 5-15%

Fitting parameters: A_g, λ_g, Q_0.

Fixed parameters: $\sigma_0 = 23.8$(mb), $C = 1.0$, $\mu_0^2 = 4.0$.

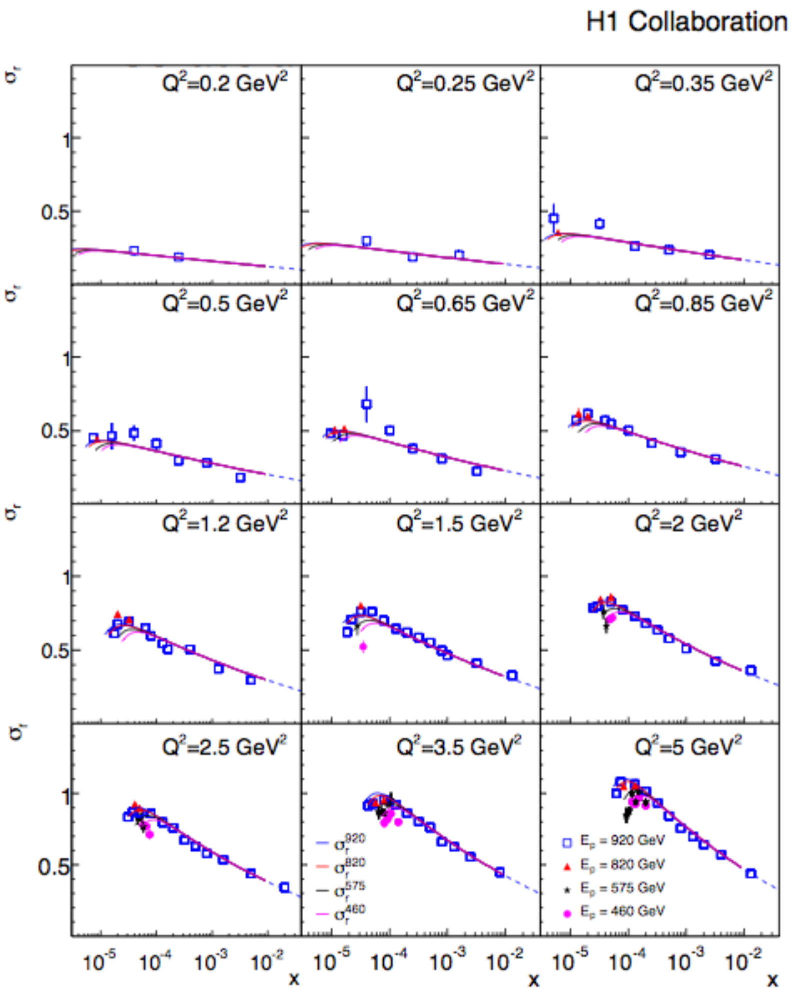
$\tau = r/2R_0(x)$

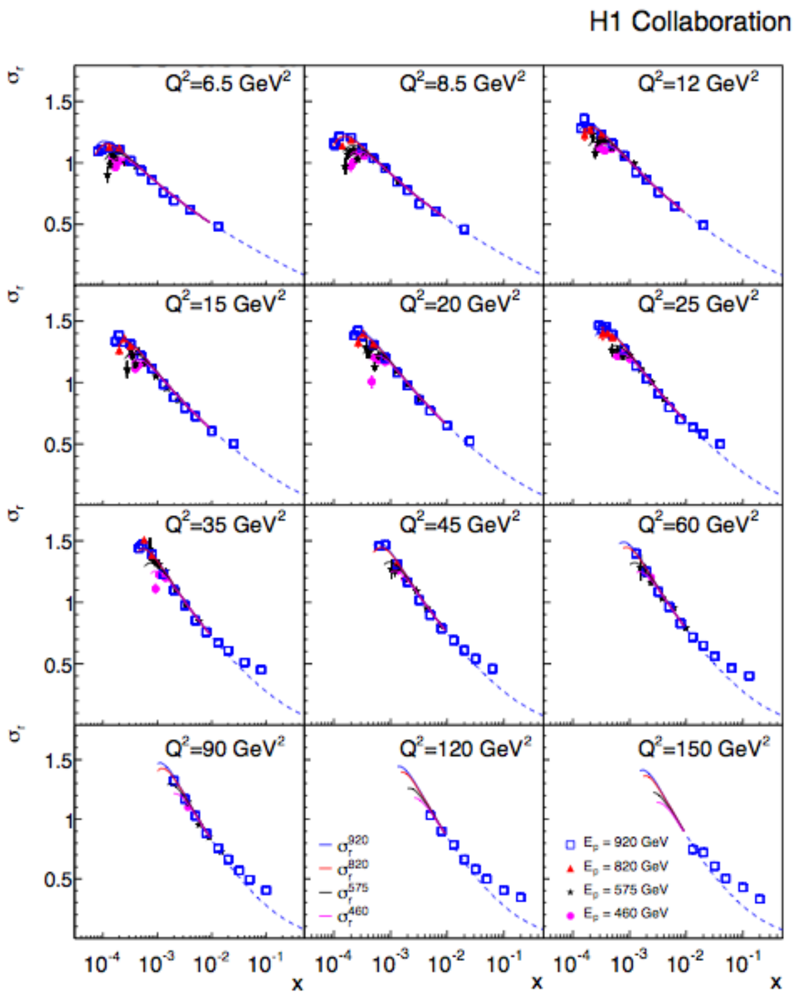
Fitting parameters: σ_0, λ, x_0.

- Dipole models are applicable for x<0.01 where the gluon and sea dominate. All models neglect valence contributions, However…

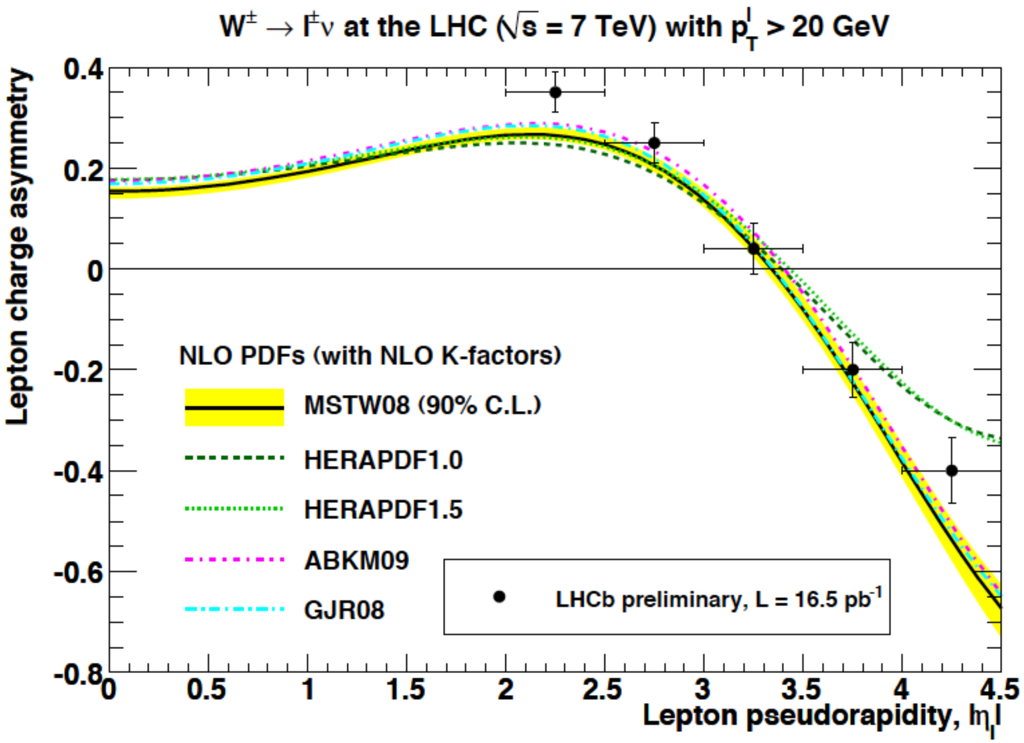
Standard Dipole Model Fit Results

- GBW model yields very bad description of data with χ^2/ndf=719/352
- B-SAT model yields slightly improved description of data with χ^2/ndf=425/352
- IM model yields a reasonable description of data with χ^2/ndf=398/352

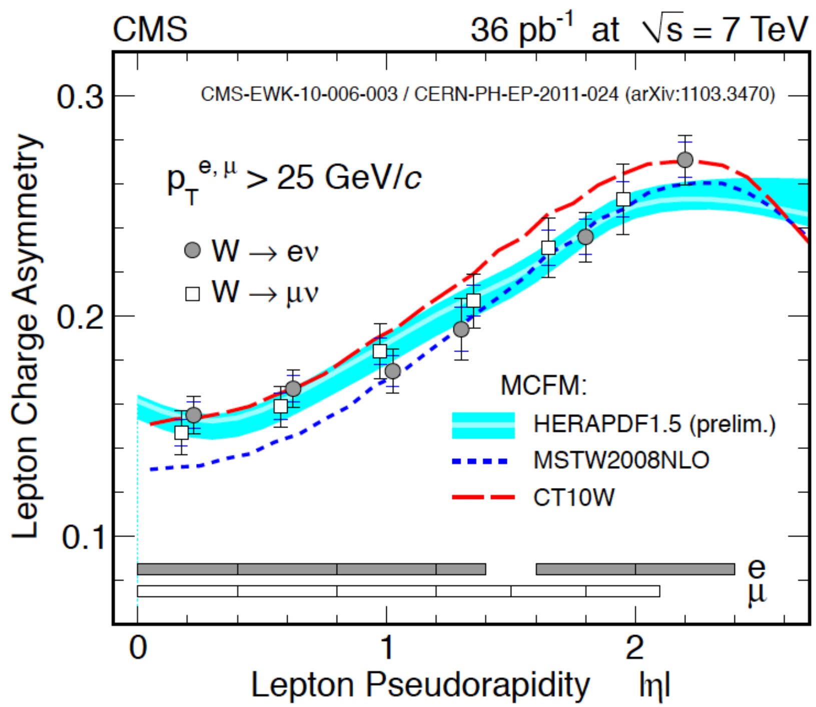




LHC predictions: for LHCb and CMS W asymmetry data

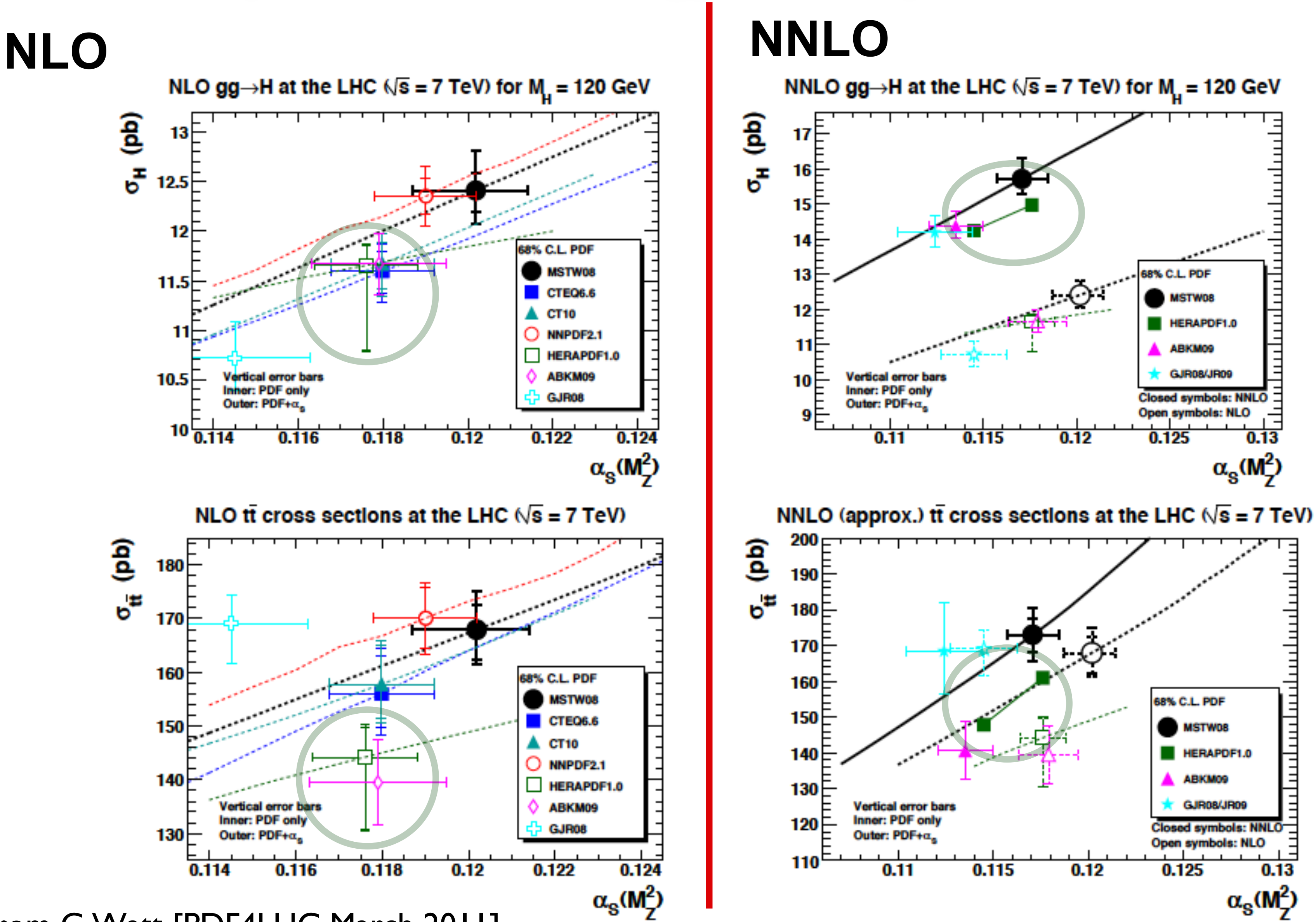


From G.Watt



HERAPDF provide reasonable predictions for LHCb and CMS data too

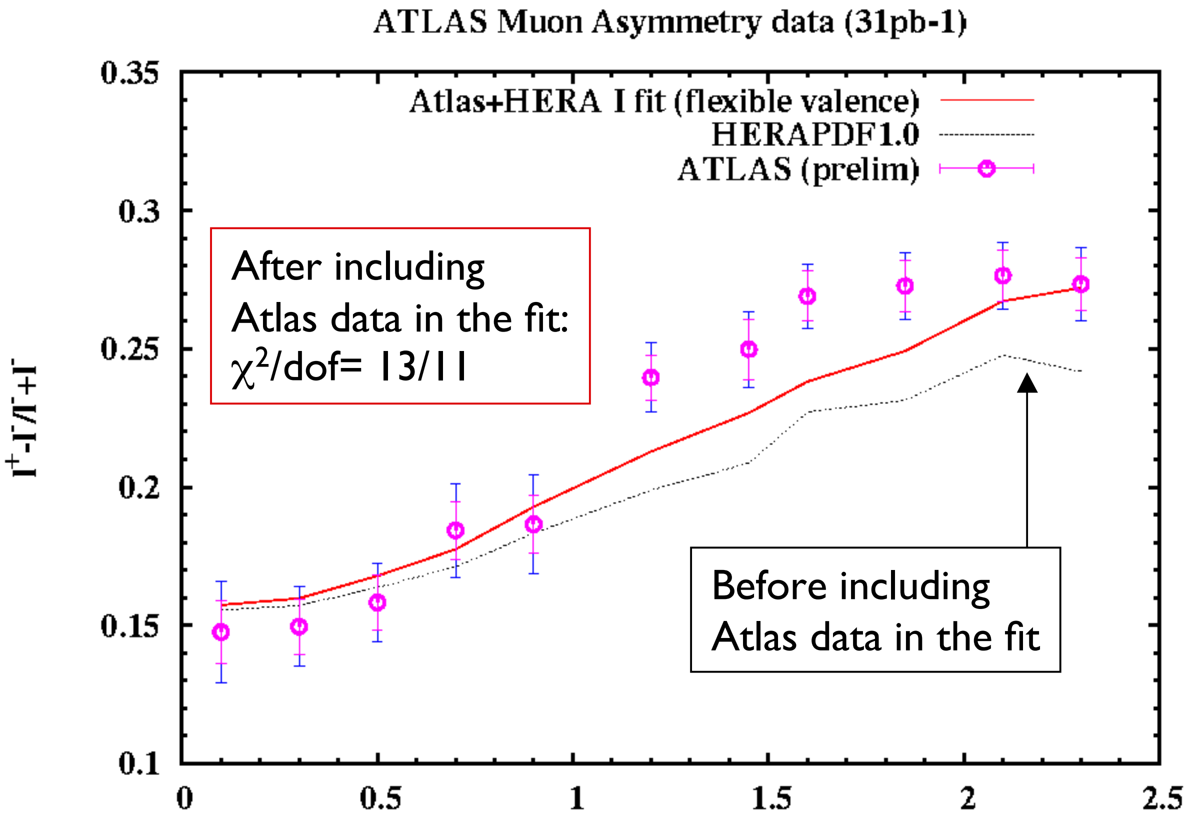
LHC predictions for Higgs and top cross sections



From G.Watt [PDF4LHC March 2011]

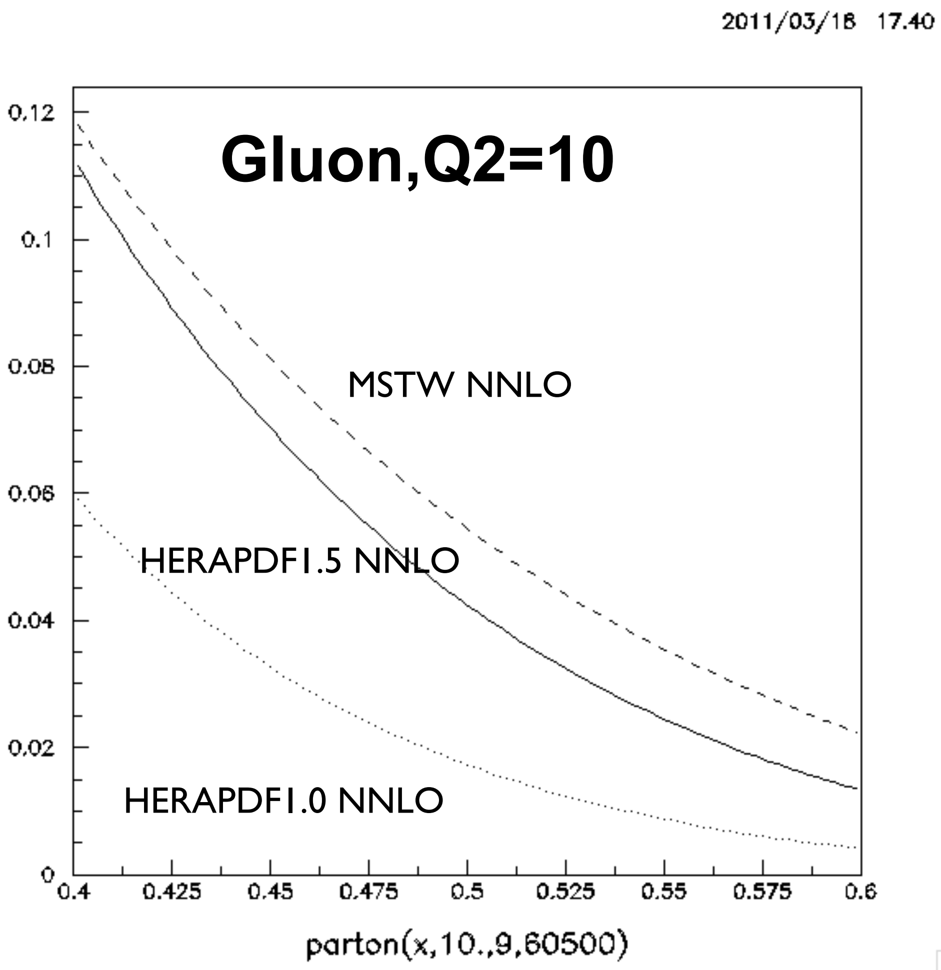
Fitting LHC data

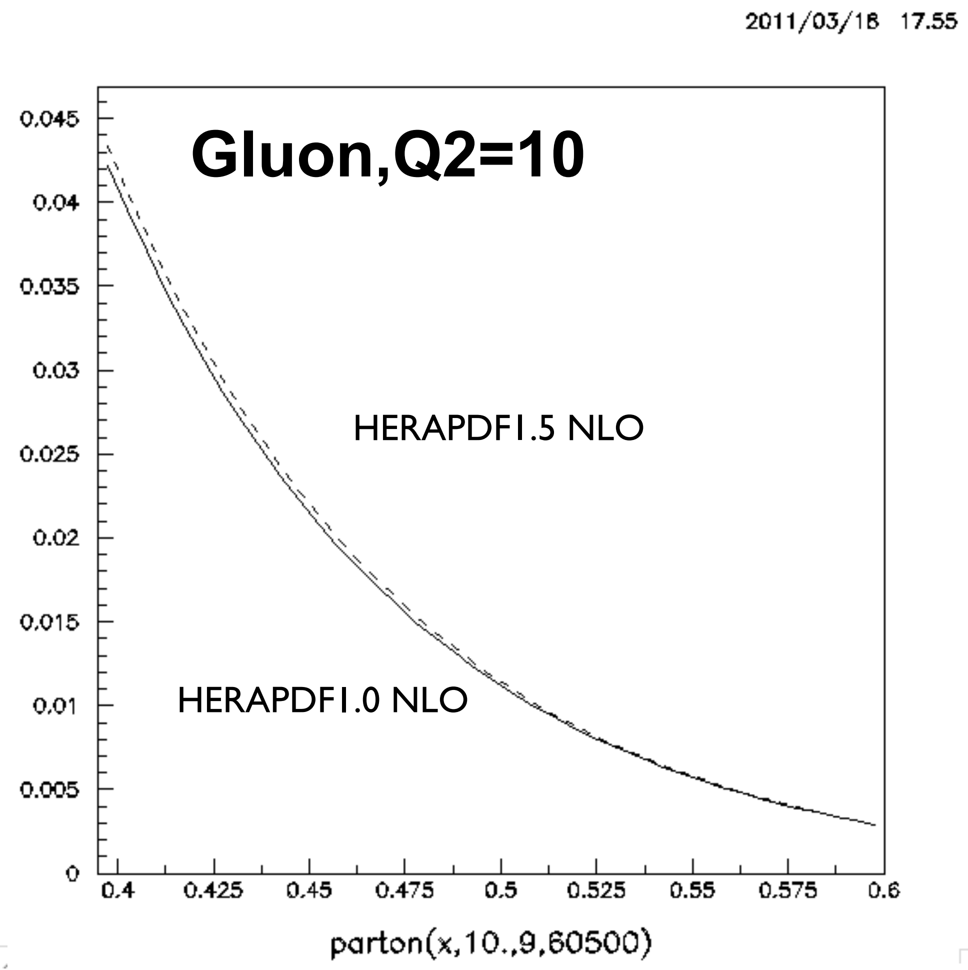
- Fitting machinery exists:
  - DIS processes at NLO and NNLO calculations
  - DY process at LO + kfactors from external sources (MCFM)
- First impact studies performed on ATLAS muon asymmetry data.

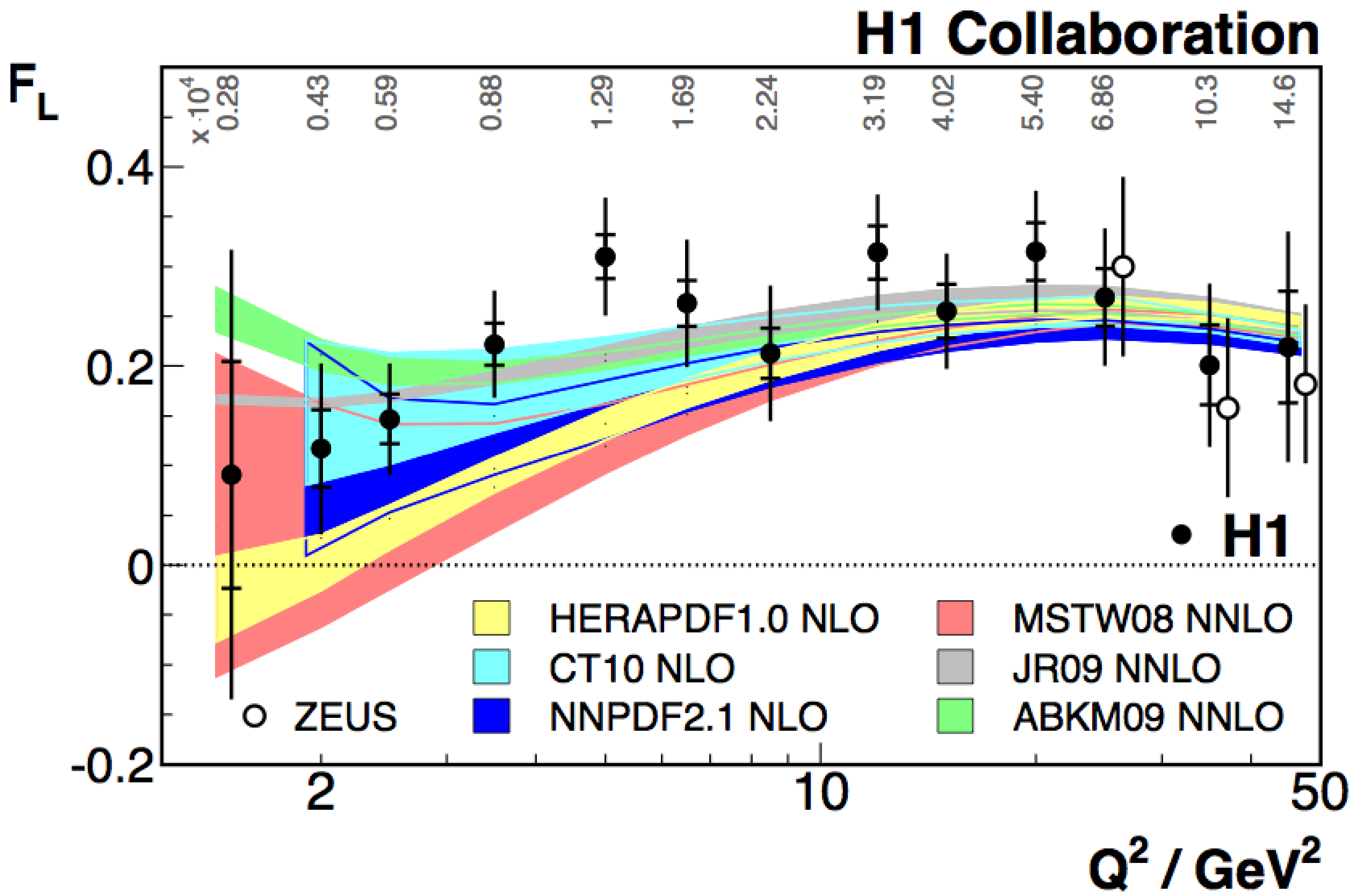


- Soon more data will be available for fits in ATLAS:
  - W, Z cross sections
  - Z rapidity distributions

comparisons



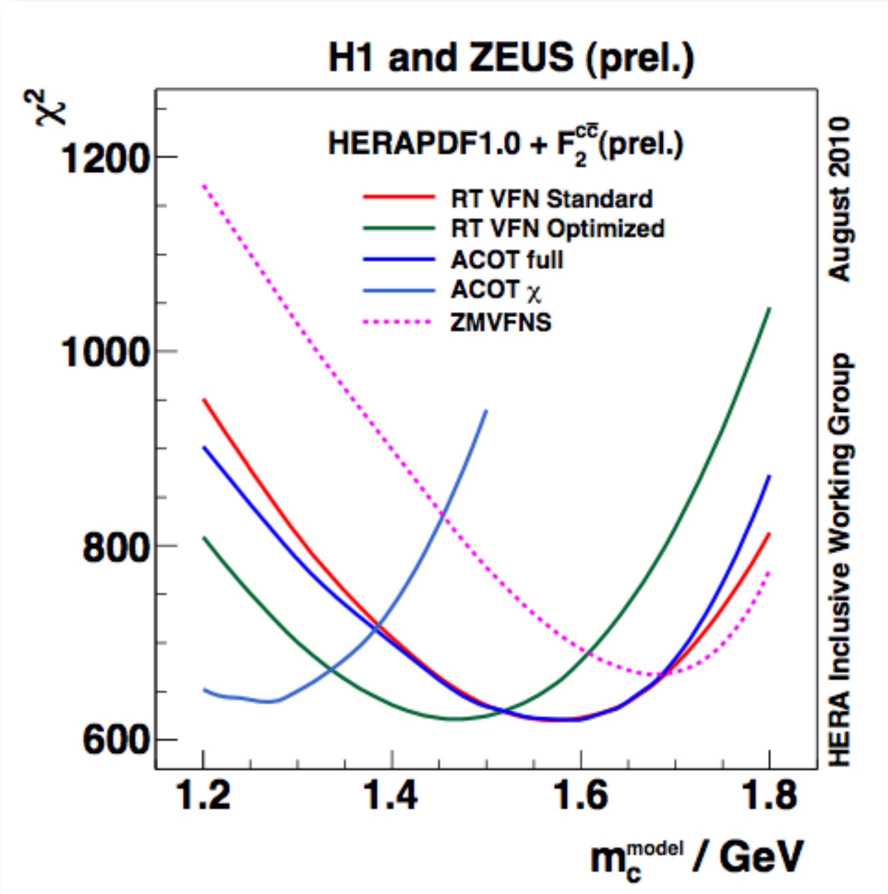




H1 Collaboration
F_L
x·10^4
0.28
0.43
0.59
0.88
1.29
1.69
2.24
3.19
4.02
5.40
6.86
10.3
14.6
0.4
0.2
0
-0.2
2
10
50
Q^2 / GeV^2
H1
ZEUS
HERAPDF1.0 NLO
CT10 NLO
NNPDF2.1 NLO
MSTW08 NNLO
JR09 NNLO
ABKM09 NNLO

Effects of inclusion of the HERA charm data

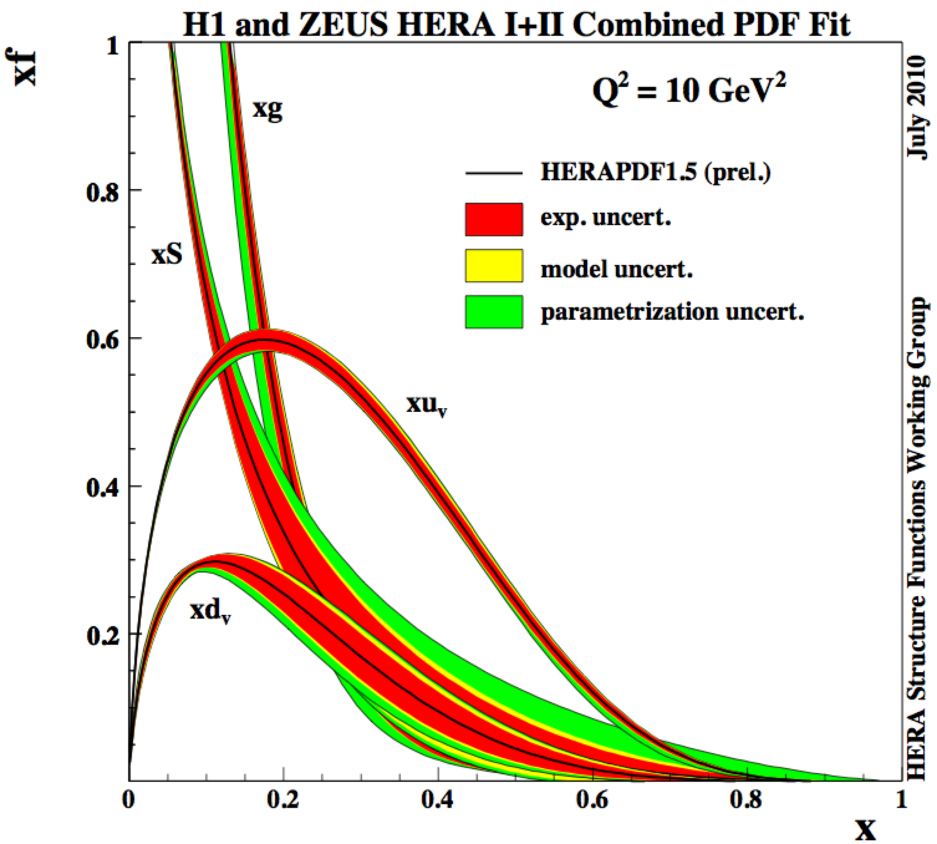
- QCD fits without charm data have only small sensitivity to the value of the charm mass
- However, there is a strong preference for a particular m_c once charm data is included
  - Study performed for RT, ACOT, ZMVFNS schemes

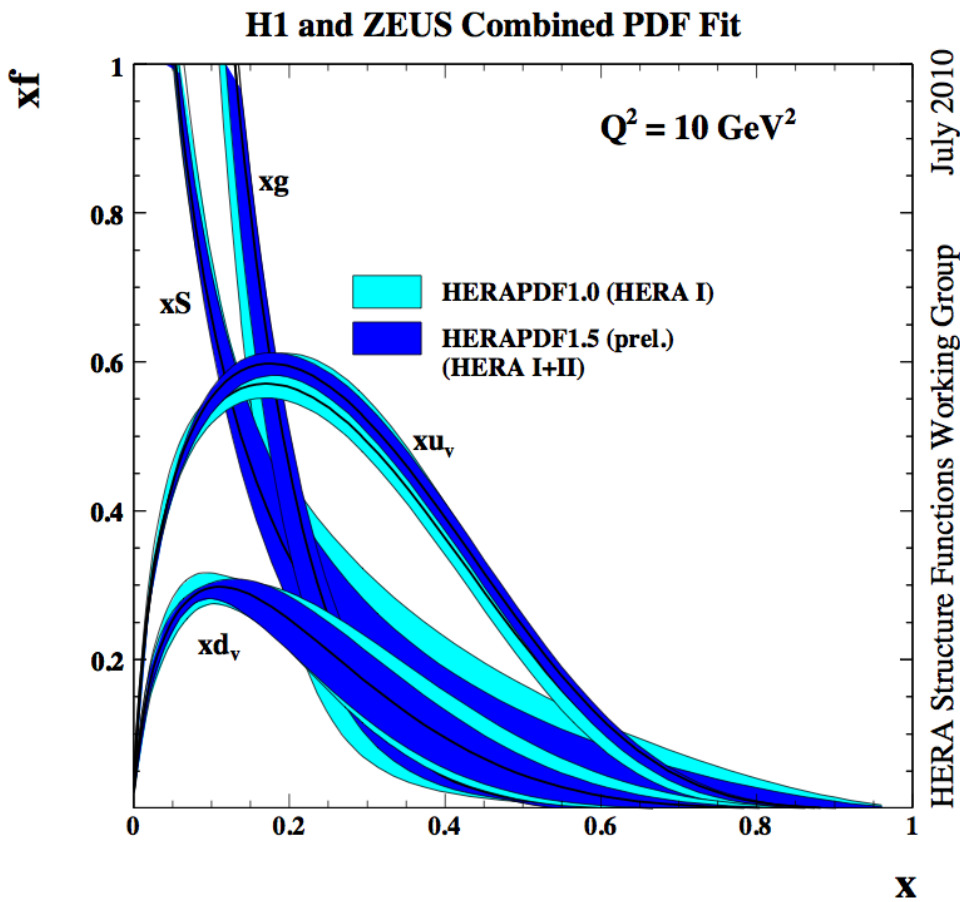


- Comparisons of the χ^2 minima of HERA I + charm data using different schemes that account for quark masses (shown in different colors)
- Observe sizeable spread in optimal values of mc: 1.25 - 1.68 GeV
  - RT Standard:
    - m_c=1.57 GeV [for MSTW08: 1.4 GeV]
  - RT Optimised:
    - m_c=1.47 GeV
  - ACOTχ
    - m_c=1.25 GeV [for CTEQ: 1.3 GeV]
  - ACOT full
    - m_c=1.58 GeV
  - ZMVFNS
    - m_c=1.68 GeV [for NNPDF: 1.4 GeV]
- Each scheme describes data well at the corresponding χ^2 minimum

HERAPDF1.5 vs HERAPDF1.0

- xg, xu_v, xd_v, xS ($xS = x\bar{U} + x\bar{D}$) at the scale $Q_0^2 = 10\ \mathrm{GeV}^2$





- Inclusion of the HERA II data reduces the uncertainties on PDFs in the high x region especially visible on the valence distributions!
  - See HERAPDF1.5(prel) vs HERAPDF1.0

HERAPDF1.7 (NLO)

- Data Sets:
  - Combined HERA I+II data (prelim)
  - Combined HERA Charm data (prelim)
  - Combined HERA II low energy data
  - Separate H1 and ZEUS jet data

- Adjustments of the settings:
  - Use extended parametrisation
  - Use RT optimised version with its prefered value of mc=1.5 GeV
    - From the studies based using charm data
  - Raise the value of strong coupling from 0.1176 to 0.1190
    - From the studies using jet data