HERAPDF fits of the proton parton distribution functions (PDFs)

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The previous generation of HERAPDF, HERAPDF1.5 has been issued at LO and is available in LHAPDF

A new preliminary PDF fit HERAPDF2.0 has been performed to the new final combined inclusive cross section data from HERA.
This comprises Neutral and Charged Current e-p scattering data using electron and positron beams at ~27 GeV and proton beam energies: 920, 820,575, 460 GeV

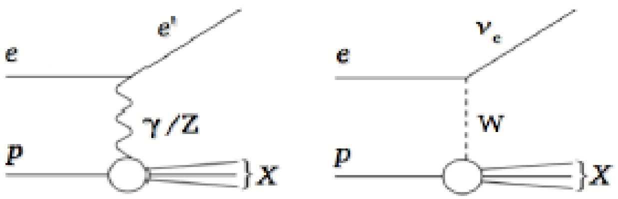
Fits have been performed at LO, NLO and NNLO in perturbative QCD

PDF precision is improved , particularly at high-x

The effect of the minimum Q^2 of data allowed in the fit is studied.

Deep Inelastic Scattering (DIS) is the best tool to probe proton structure

NC : $e\,p \to e'X$ CC : $e\,p \to \nu_e\,X$



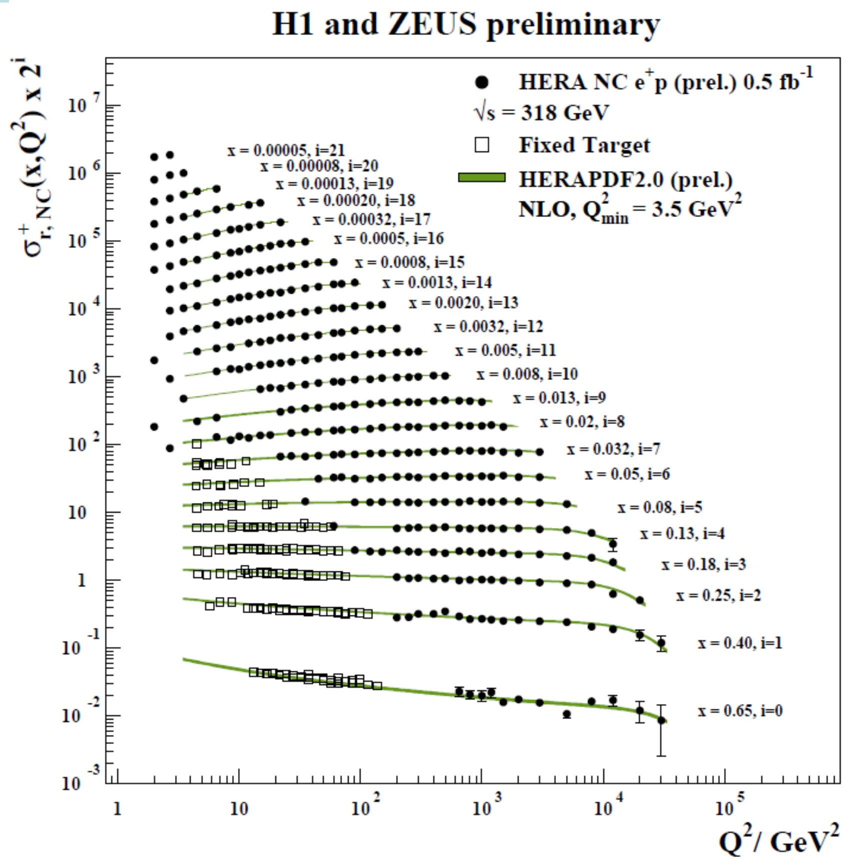
- Kinematic variables:

$Q^2 = -q^2 = -(k-k')^2$ 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.



Neutral current:

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

$F_2 \propto \sum_i e_i^2 (xq_i + x\bar{q}_i)$ — quark distributions, gluon from scaling violation

$xF_3 \propto \sum_i (xq_i - x\bar{q}_i)$ — valence quarks

$F_L \propto \alpha_s \times g$ — gluon at NLO

Charged current:

LO expressions

$$\frac{d^2\sigma^{-}_{CC}}{dxdQ^2} = \frac{G_F^2}{2\pi}\frac{M_W^2}{M_W^2+Q^2}\left(u+c+(1-y^2)(\bar{d}+\bar{s})\right)$$

$$\frac{d^2\sigma^{-}_{CC}}{dxdQ^2} = \frac{G_F^2}{2\pi}\frac{M_W^2}{M_W^2+Q^2}\left(\bar{u}+\bar{c}+(1-y^2)(d+s)\right)$$

flavour decomposition

Gluon from the scaling violations: DGLAP equations tell us how the partons evolve

$$\frac{dq(x,Q^2)}{d\ln Q^2} = \frac{\alpha_s}{2\pi}\int_x^1 \frac{dy}{y}\left[P_{qq}\left(\frac{x}{y}\right)q(y,Q^2) + P_{qg}\left(\frac{x}{y}\right)g(y,Q^2)\right]$$

$$\frac{dg(x,Q^2)}{d\ln Q^2} = \frac{\alpha_s}{2\pi}\int_x^1 \frac{dy}{y}\left[P_{gq}\left(\frac{x}{y}\right)q(y,Q^2) + P_{gg}\left(\frac{x}{y}\right)g(y,Q^2)\right]$$

The HERAPDF approach uses only HERA data

Some of the debates about the best way of estimating PDF uncertainties concern the use of many different data sets with varying levels of consistency.

The combination of the HERA data yields a very accurate and consistent data set for 4 different processes: e+p and e-p Neutral and Charged Current reactions.

The use of the single consistent data set allows the usage of the conventional $\chi2$ tolerance $\Delta\chi2 = 1$ when setting 68%CL experimental errors

NOTE the use of a pure proton target means d-valence is extracted without need for heavy target/deuterium corrections or strong iso-spin assumptions these are the only PDFs for which this is true

Furthermore, the kinematic coverage at low-x ensures that these are the most crucial data when extrapolating predictions from W, Z and Higgs cross-sections to the LHC

HERAPDF evaluates model uncertainties and parametrisation uncertainties in addition to experimental uncertainties

HERAPDF specifications: parametrisation and χ2 definition

- PDFs are parametrised at the starting scale Q_0^2=1.9 GeV^2 as follows:

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

QCD Sum rules constrain Normalisation parameters: A_g, A_{u_v}, A_{d_v}

And the condition that:

$$x\bar{u} \rightarrow x\bar{d} \text{ as } x \rightarrow 0.$$

relate $A_{\bar{U}}$ to $A_{\bar{D}}$, and with $x\bar{s} = f_s x\bar{D}$

  - **Due to increased precision of data, more flexibility in functional form is allowed → 15 free parameters**

- PDFs are evolved via evolution equations (DGLAP) to NLO and NNLO (alphas(MZ)=0.118)[QCDNUM]
- Thorne-Roberts GM-VFNS for heavy quark coefficient functions – as used in MSTW
- Chi2 definition used in the minimisation [MINUIT] accounts for correlated uncertainties:

$$\chi^2 = \sum_i \frac{\left[\mu_i - m_i\left(1 - \sum_j \gamma_j^i b_j\right)\right]^2}{\delta_{i,\mathrm{unc}}^2 m_i^2 + \delta_{i,\mathrm{stat}}^2 \mu_i m_i\left(1 - \sum_j \gamma_j^i b_j\right)} + \sum_j b_j^2 + \sum_i \ln\frac{\delta_{i,\mathrm{unc}}^2 m_i^2 + \delta_{i,\mathrm{stat}}^2 \mu_i m_i}{\delta_{i,\mathrm{unc}}^2 \mu_i^2 + \delta_{i,\mathrm{stat}}^2 \mu_i^2}$$

m_i is the theoretical prediction

μ_i is the measured cross section

$\delta_{i,\mathrm{stat}}$, $\delta_{i,\mathrm{unc}}$ statistical and uncorrelated systematic uncertainty

γ_j^i correlated systematic uncertainties

b_j shifts

HERAPDF specifications: sources of uncertainty

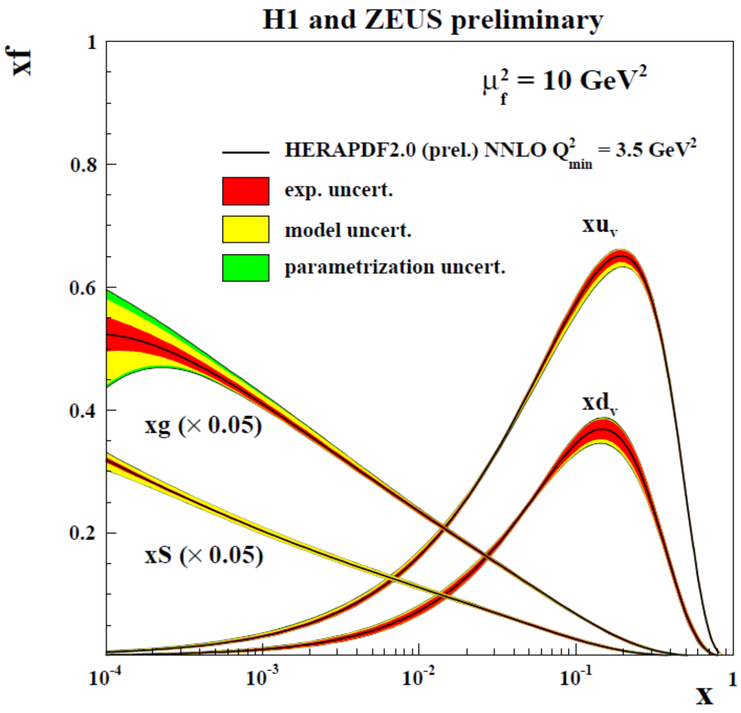
Experimental:

- Hessian method is used to evaluate experimental uncertainties
- Consistent data sets → use $\Delta\chi^2=1$

Model:

- Following variations have been considered

Variation	Standard Value	Lower Limit	Upper Limit
f_s	0.4	0.3	0.5
M_c^{opt}(NLO) [GeV]	1.47	1.41	1.53
M_c^{opt} (NNLO) [GeV]	1.44	1.38	1.50
M_b [GeV]	4.75	4.5	5.0
Q^2_{min} [GeV^2]	10.0	7.5	12.5
Q^2_{min} [GeV^2]	3.5	2.5	5.0
Q^2_0 [GeV^2]	1.9	1.6	2.2



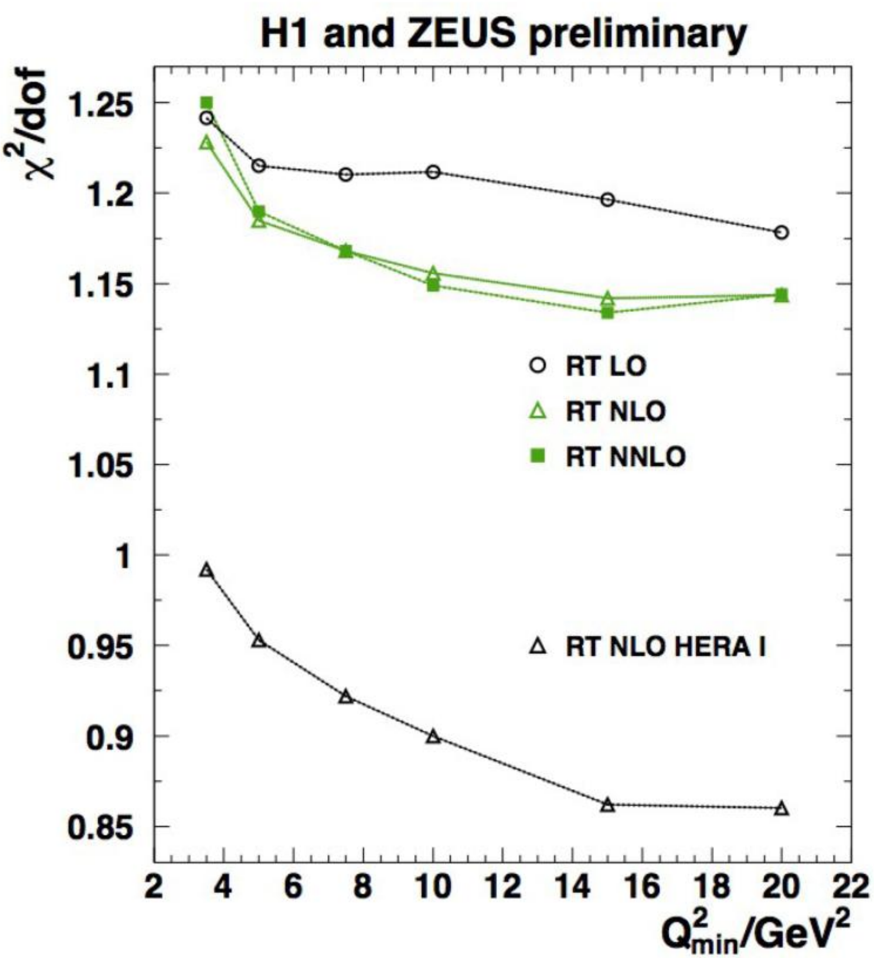
Parametrisation:

- An envelope is formed from PDF fits using variants of parametrisation from
  - Scanning of 16 parameter space with D or E as extra parameters of $(1 + Dx + Ex^2)$
  - Q_0^2 variation → dominant parametrisation uncertainty

•Values of M_c^{opt} and its uncertainties from scanning χ2 for fits including HERA charm combination data

•Value of f_s from considering ATLAS result AND neutrino di-muon results

HERAPDF specifications: minimum value of Q^2



A minimum value of Q^2 for data allowed in the fit is imposed to ensure that pQCD is applicable. For HERAPDF the usual value is $Q^2 > 3.5$ GeV^2 but consider the variation of χ2 with this cut

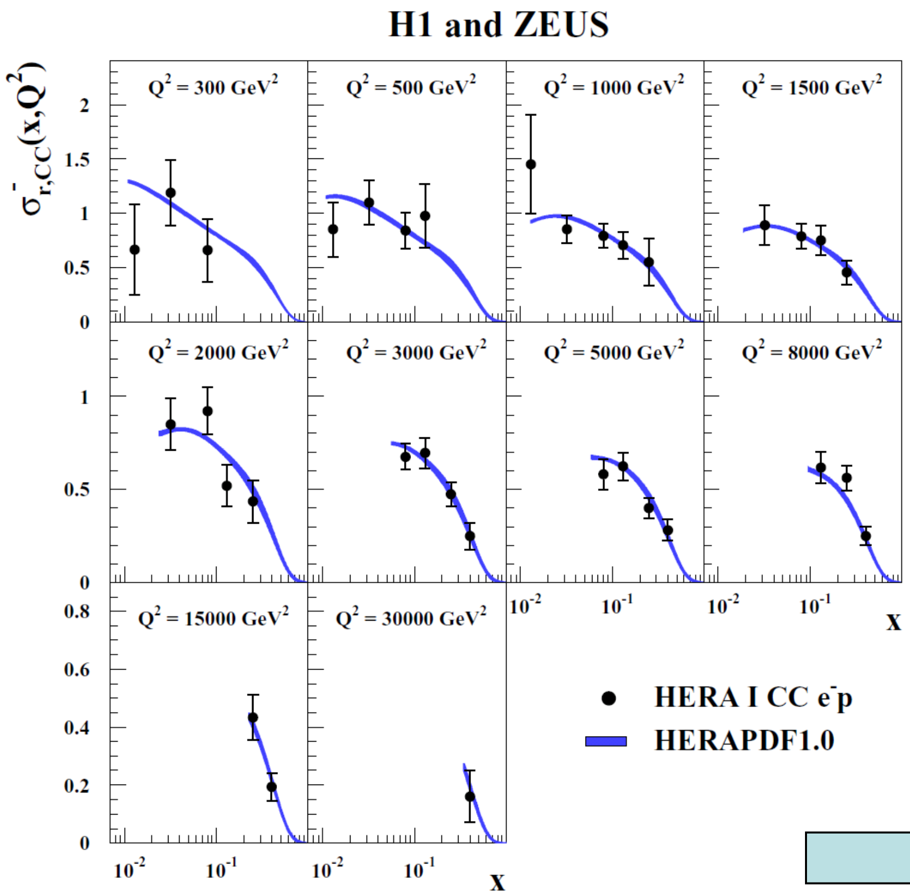
- The χ2 decreases with increase of Q^2 minimum until $Q^2_{min} \sim 10$ GeV^2
- NLO is obviously better than LO but NNLO is not significantly better than NLO
- This is independent of heavy flavour scheme (see backup)
- The same effect was observed in HERA-1 data

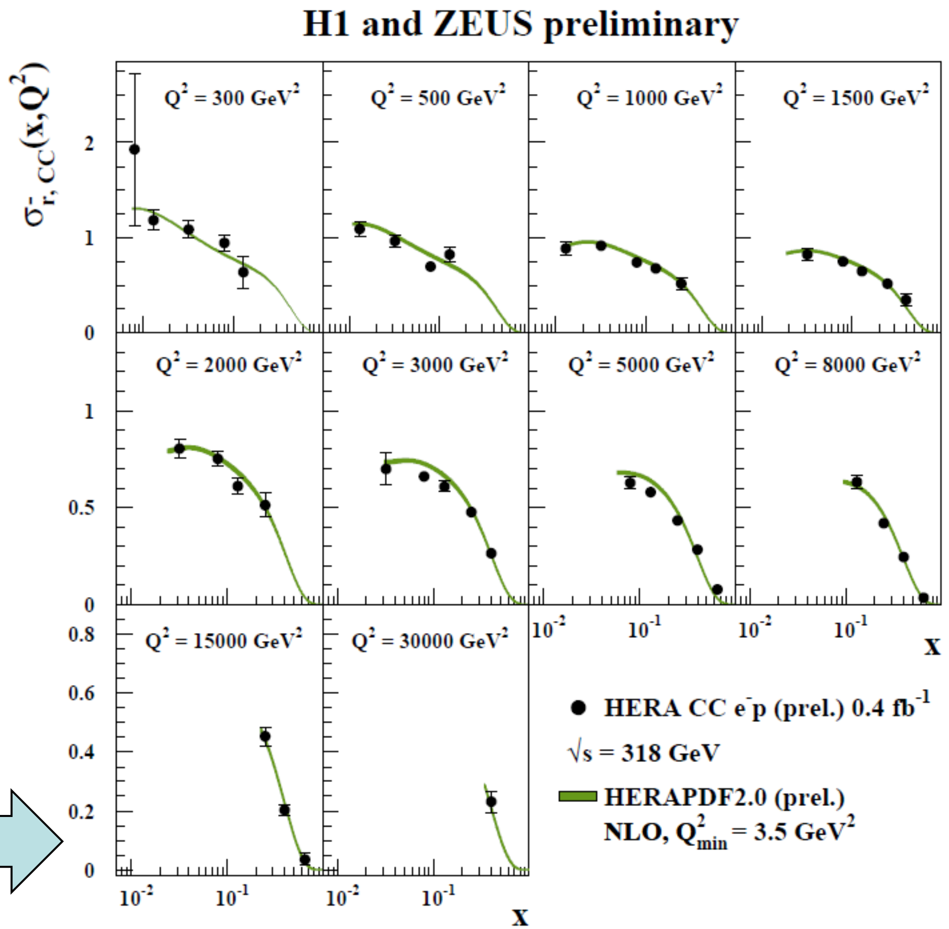
Fits for two Q^2 cuts will be presented: $Q^2 > 3.5$ and $Q^2 > 10$ GeV^2

Note that HERA kinematics is such that cutting out low Q^2 also cuts the lowest x values

HERAPDF2.0: new data and new QCD fit

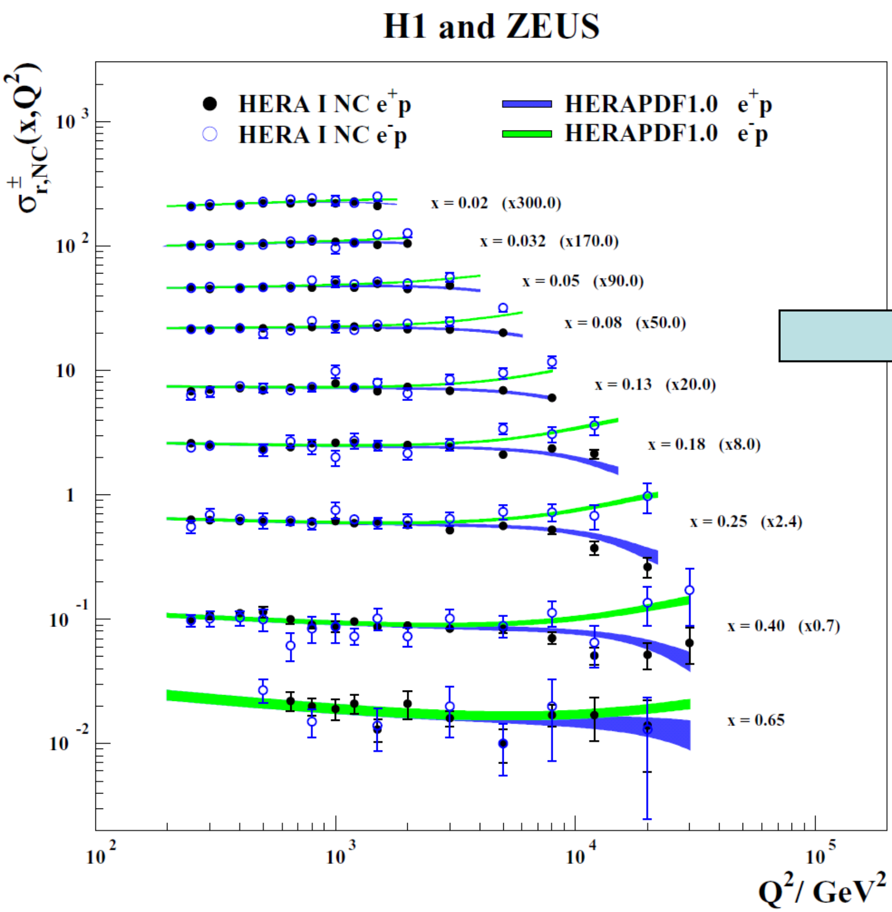
The fit quality is similar for NLO and NNLO. The NLO Q^2>3.5 GeV^2 fit is illustrated

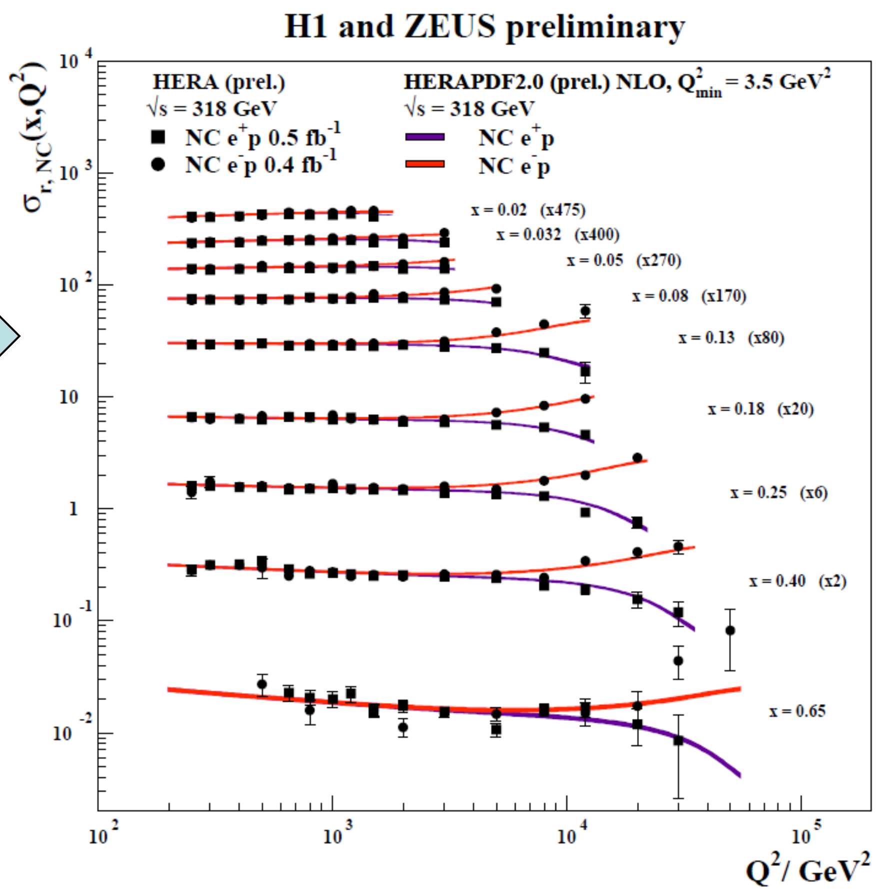




Improvement since HERAPDF1.0

HERAPDF2.0: new data and new QCD fit

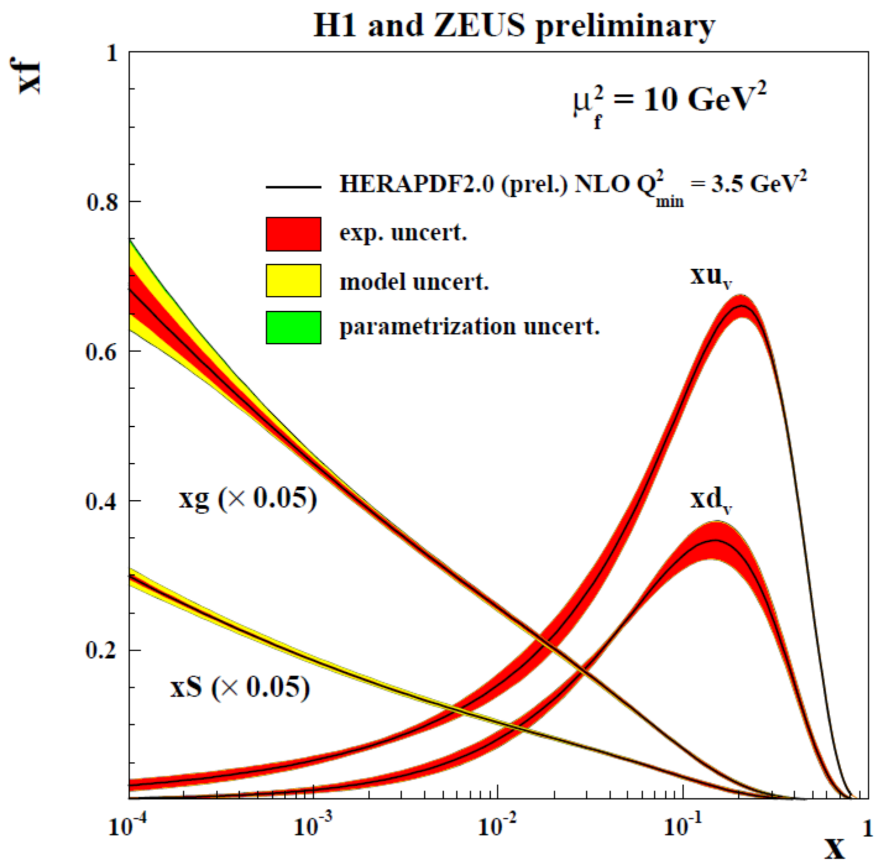




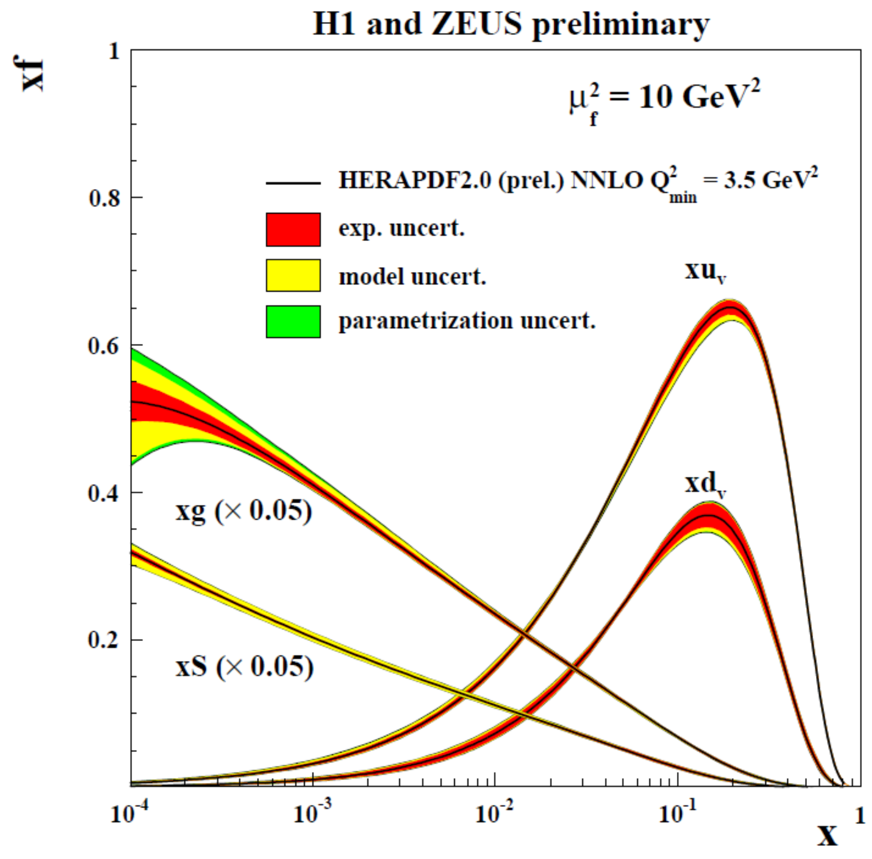
Improvement since HERAPDF1.0

HERAPDF2.0: NLO and NNLO fits Q^2>3.5 GeV^2

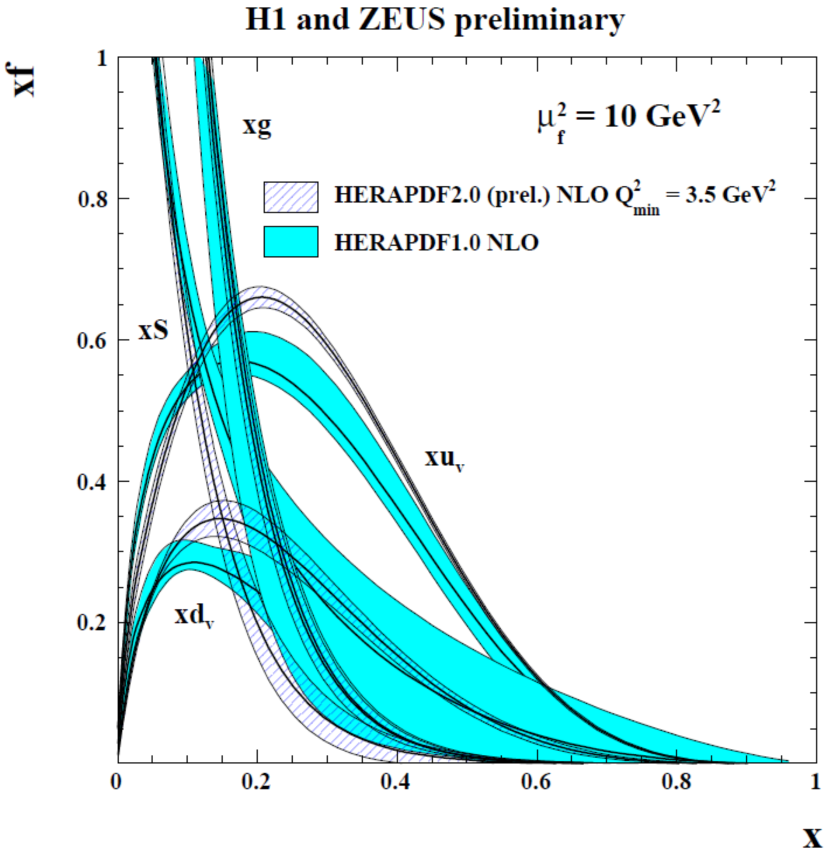
NLO

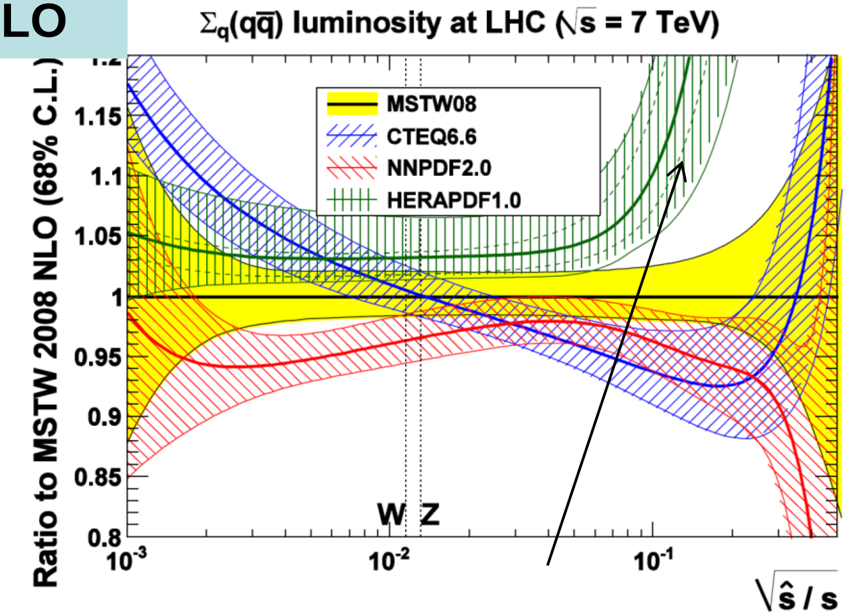


NNLO



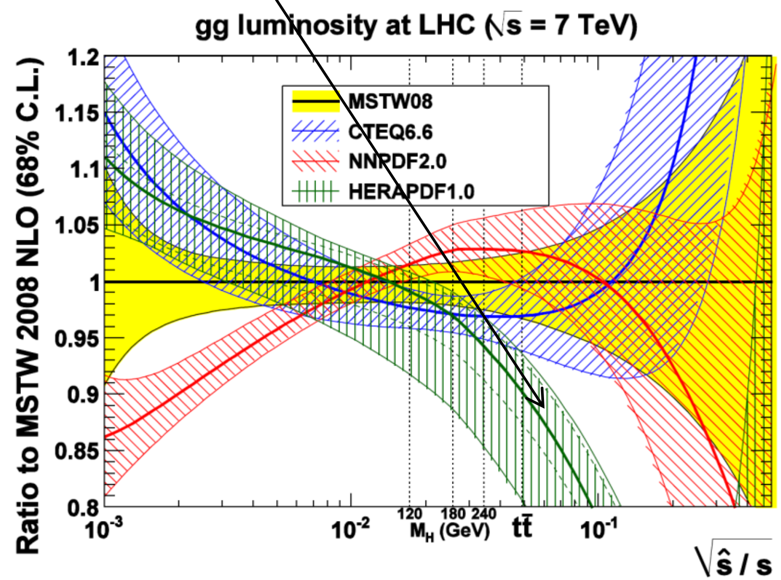
Compare HERAPDF2.0 to HERAPDF1.0 at NLO





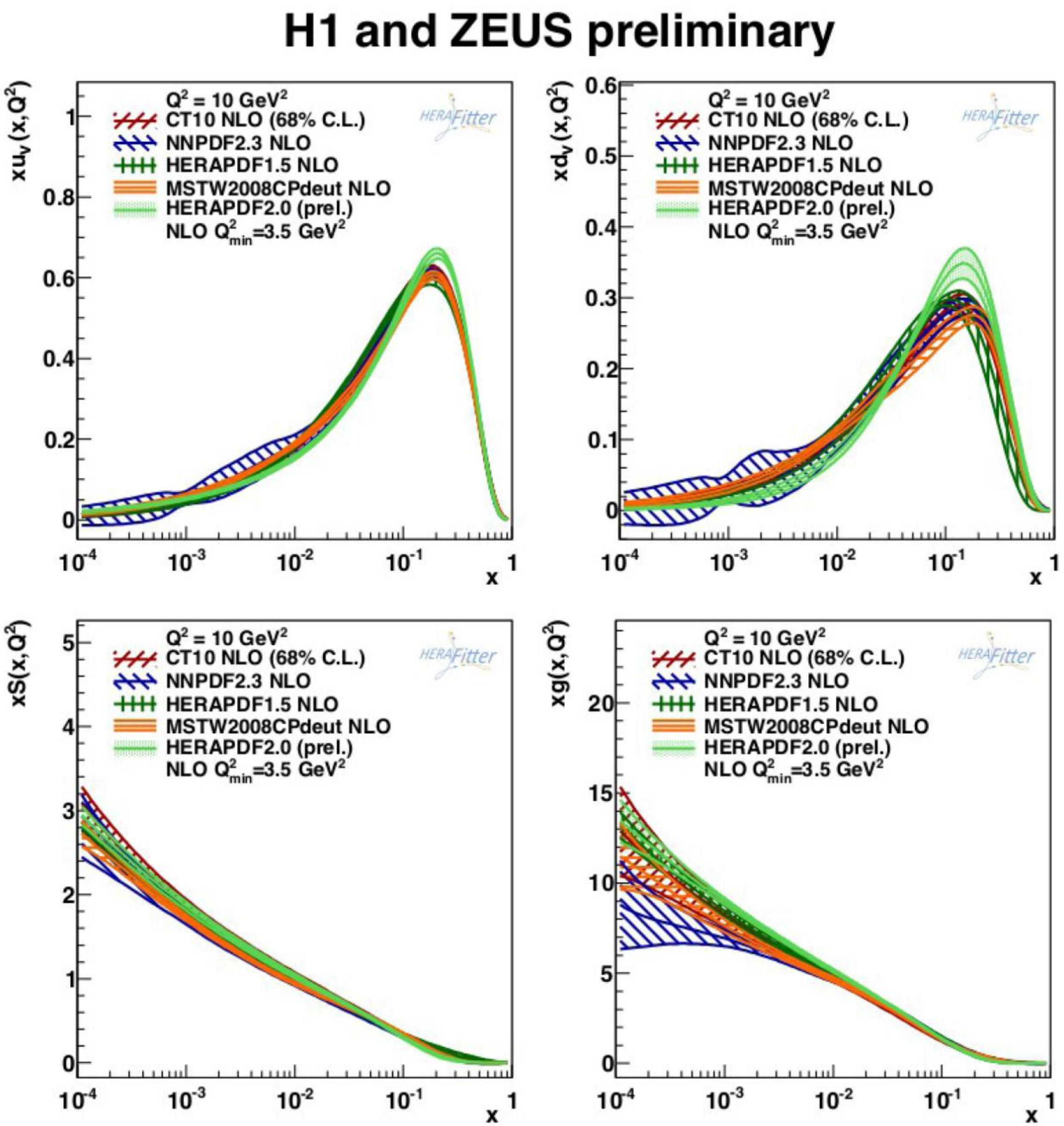
So the q-qbar luminosity at high-x comes down

And the g-g luminosity a high-x goes up



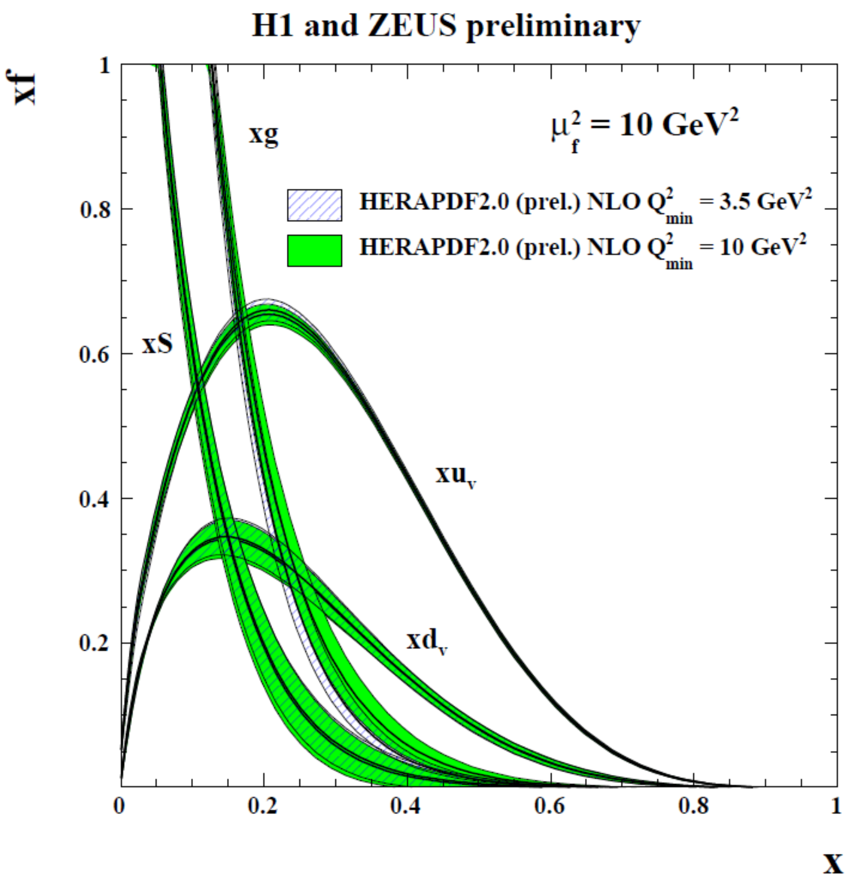
- HERAPDF1.0 had a rather hard high-x sea, harder than the gluon (within large uncertainties).This is no longer the case and uncertainties are much reduced
- HERAPDF1.0 had a soft high-x gluon this moves to the top of its previous error band
- Valence shapes have changed due to much more data at high x

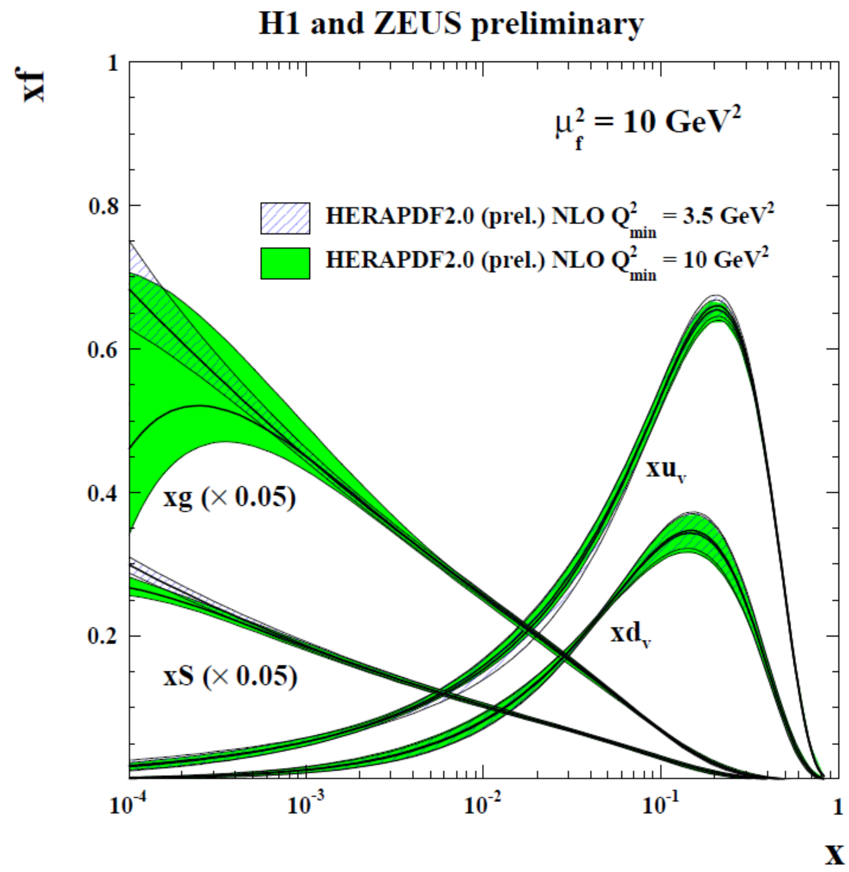
Compare HERAPDF2.0 to other PDFs at NLO



HERAPDF gets d-valence directly from the proton, not from assuming
d in proton = u in neutron

Compare HERAPDF2.0 with Q2>10GeV^2 to the standard fit at NLO



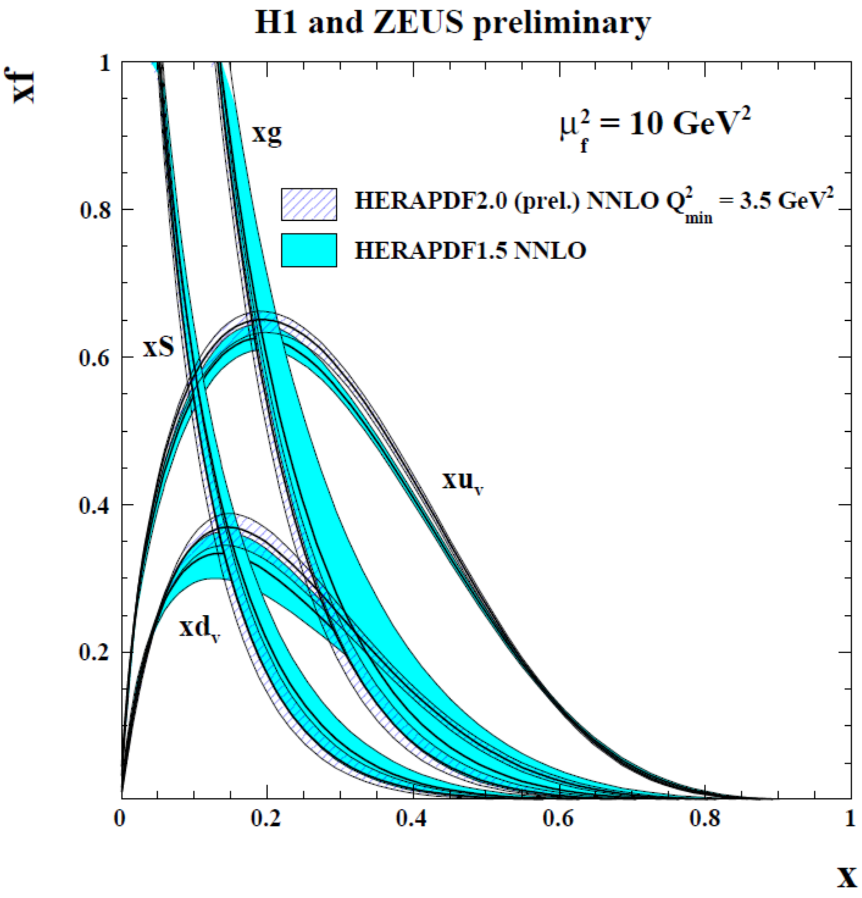


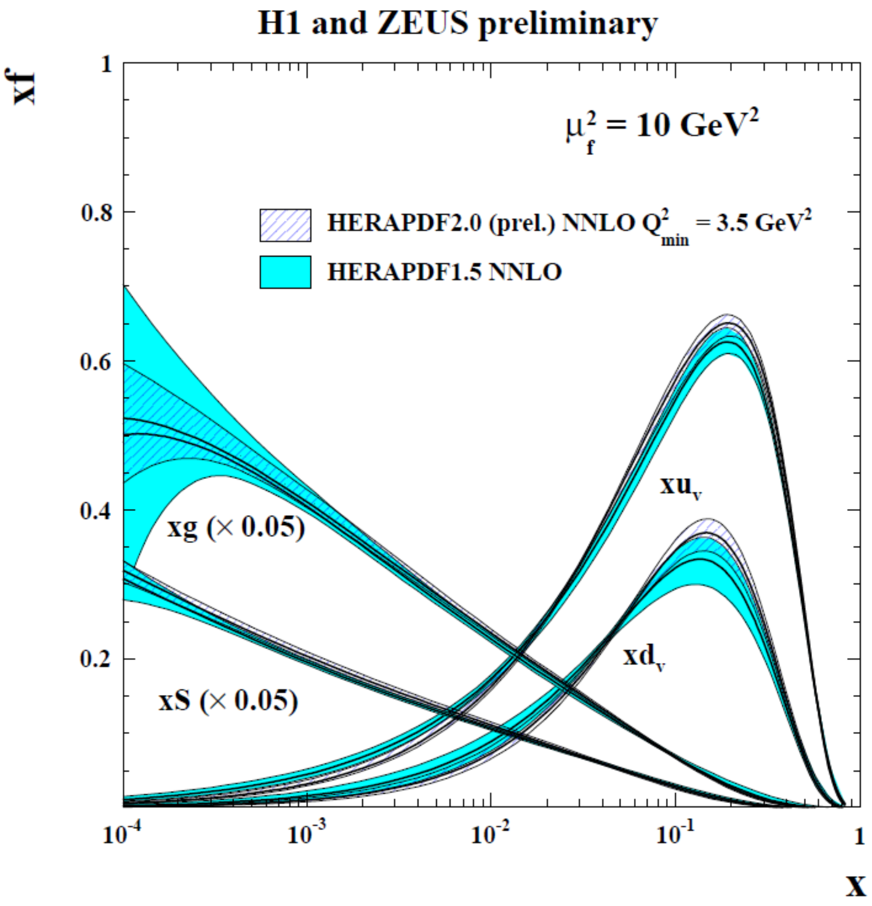
Fits are compatible

There is greater uncertainty at low-x for Sea and glue there is some small change of gluon and sea shape at low-x.

At large x gluon and sea and valence are all similar

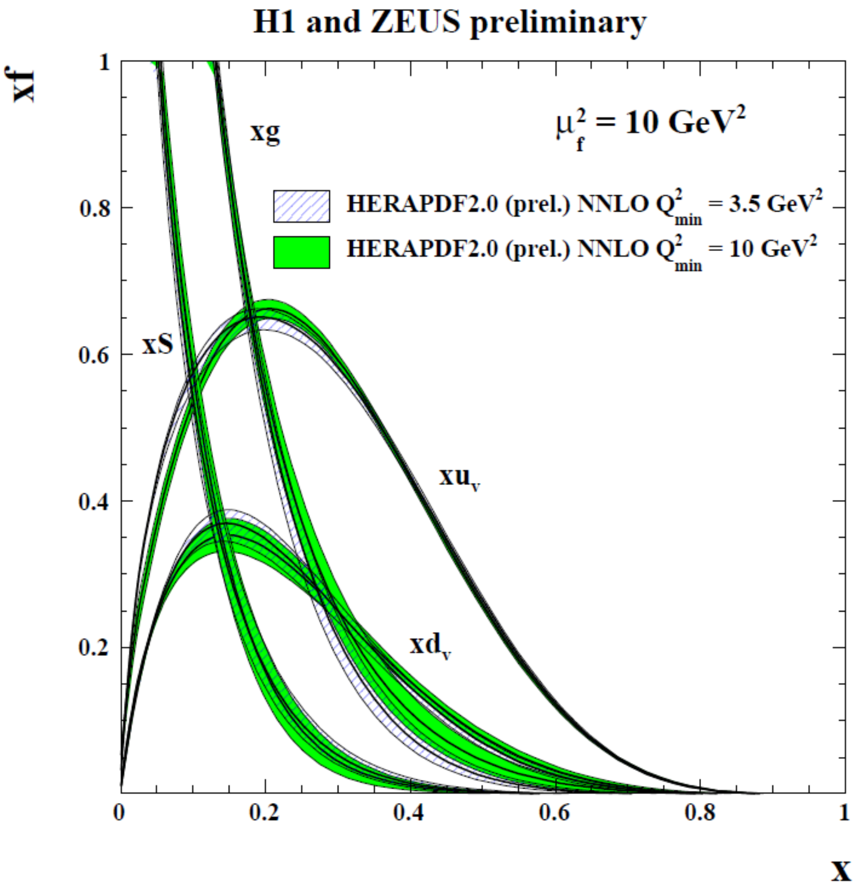
Compare HERAPDF2.0 to HERAPDF1.5 at NNLO

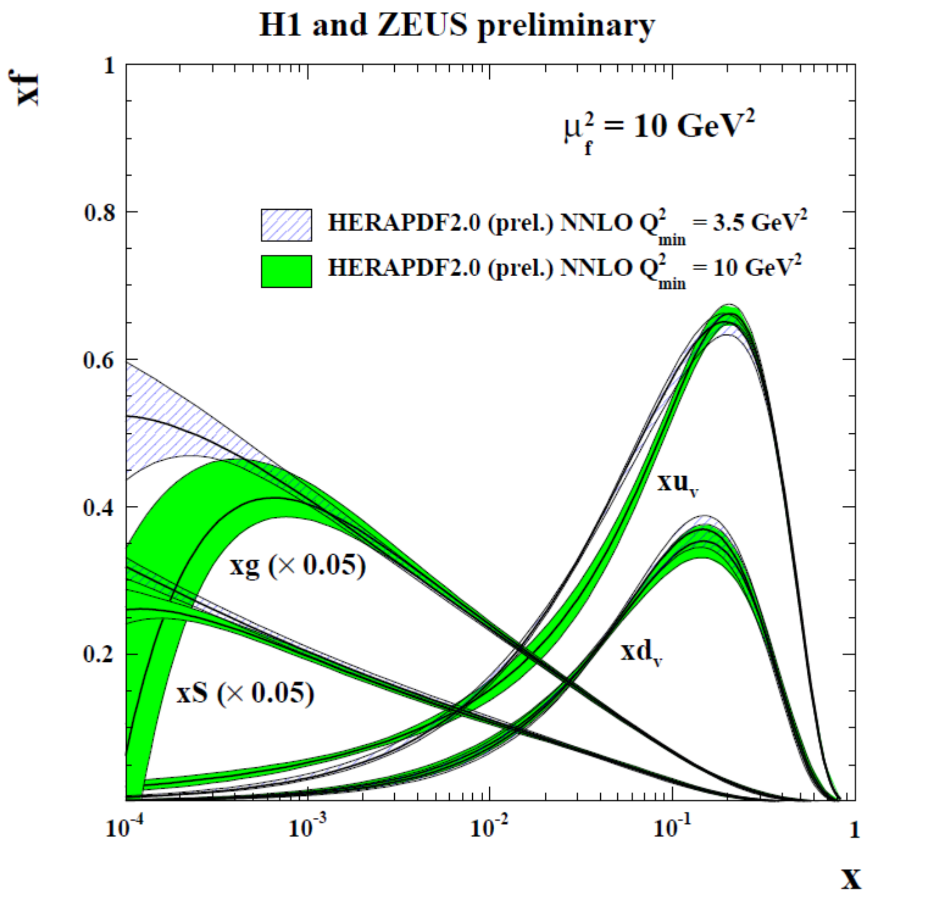




Reduction in gluon uncertainty both at low-x and high-x.
A lot of this reduction is because the model variation due to variation of Q^2 cut is not as dramatic now that we have more data.

Compare HERAPDF2.0 with Q2>10GeV² to the standard fit at NNLO





Fits are VERY compatible at high-x ---like in NLO case
BUT the difference in shape for low-x Sea and gluon– has now become pronounced- fits are no longer compatible,

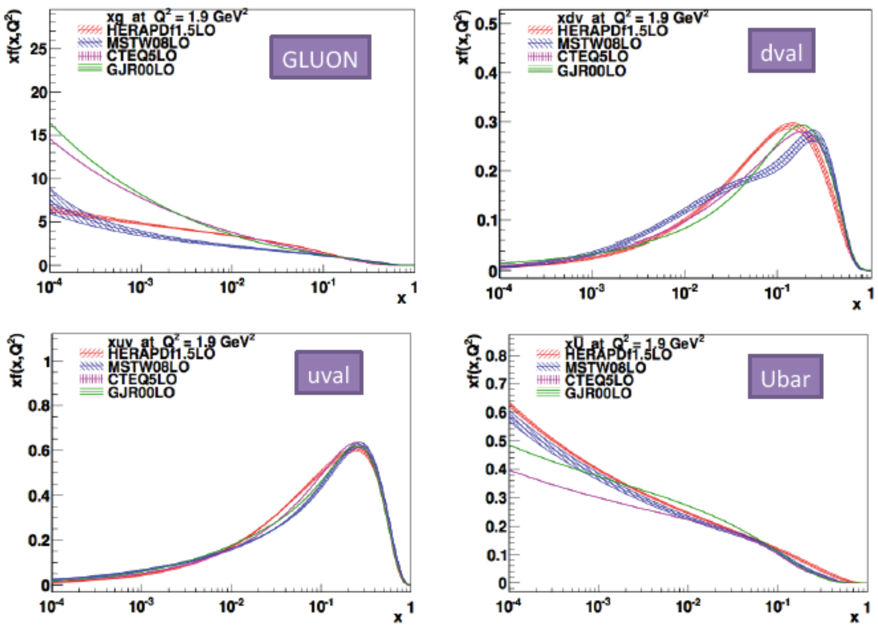
HERAPDF1.5LO fit

The previous generation of HERAPDF, HERAPDF1.5 has been issued at LO and is available in LHAPDF

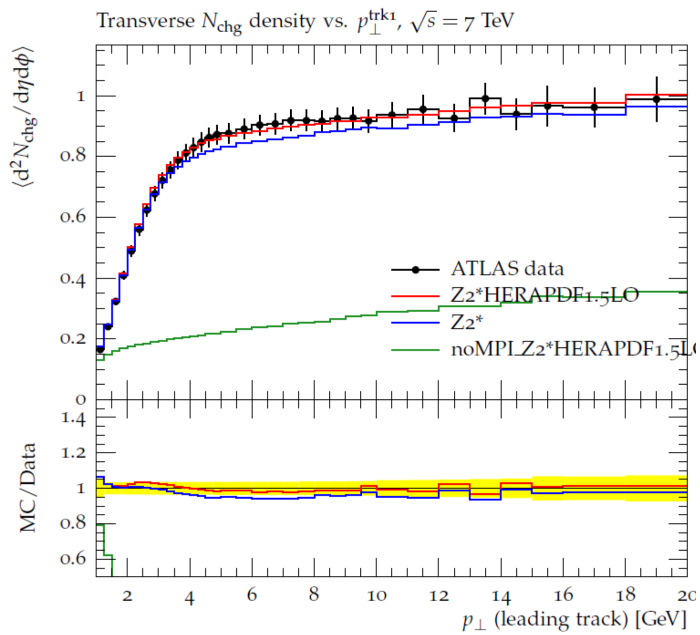
PDFs at LO are used for the simulation of parton showers, underlying event, minimum bias and pile-up at the LHC.

The LHC at 13 or 14TeV will extend kinematic coverage to lower values of Bjorken x

The HERAPDF has a special emphasis on low x because it fits only HERA data



Comparison to other LO PDFs



Example of the use of HERAPDF1.5LO in tuning to the underlying event

Summary

•The previous generation of HERAPDF, HERAPDF1.5 has been issued at LO and is available in LHAPDF

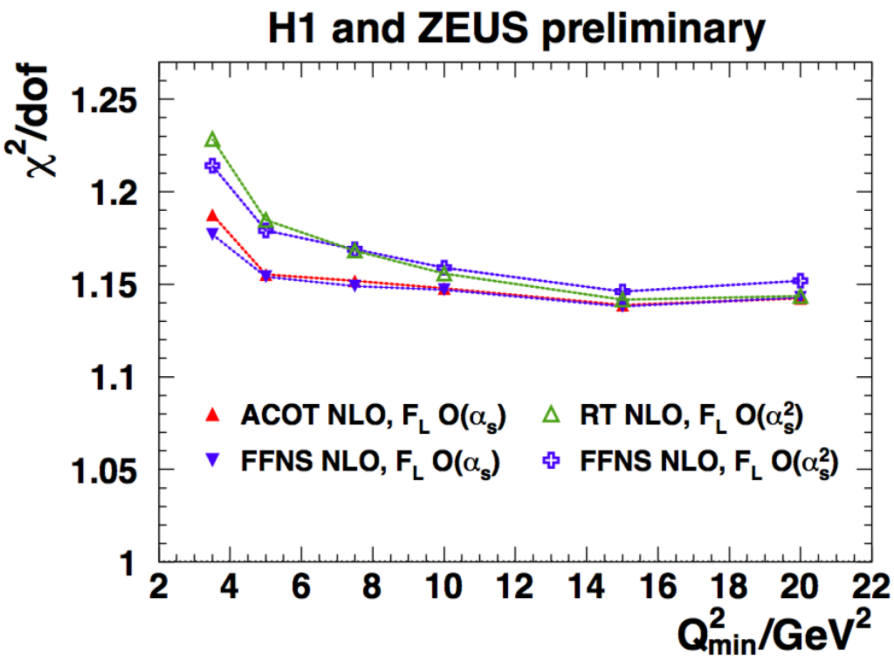
•A new PDF fit HERAPDF2.0 has been performed to the new final combined inclusive cross section data from HERA –I+HERA-II and low energy running.

•Fits have been performed at LO, NLO and NNLO in perturbative QCD

•PDF precision is improved at high-x for NLO and NNLO fits, and at low-x for the NNLO fit

•The effects of the minimum Q^2 of data allowed in the fit is studied. This is important for the NNLO fit at low-x.

Back-up



Treating F_L to order α_s – the same order as F_2 – yields better χ^2 than treating F_L to order α_s^2 – the same number of loops (1 loop)

Almost independent of heavy flavor scheme

For Q^2_{min}= 3.5 GeV^2

Chi2/dof (NLO) = 1386/1130

Chi2/dof(NNLO)= 1414/1130

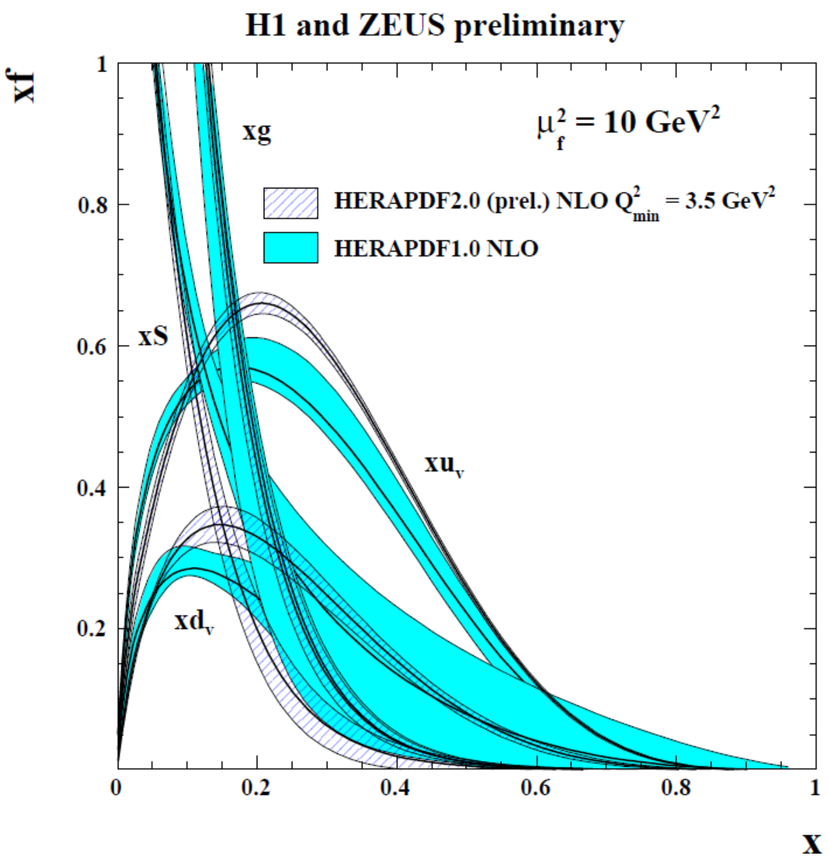
For Q^2_{min}= 10 GeV^2

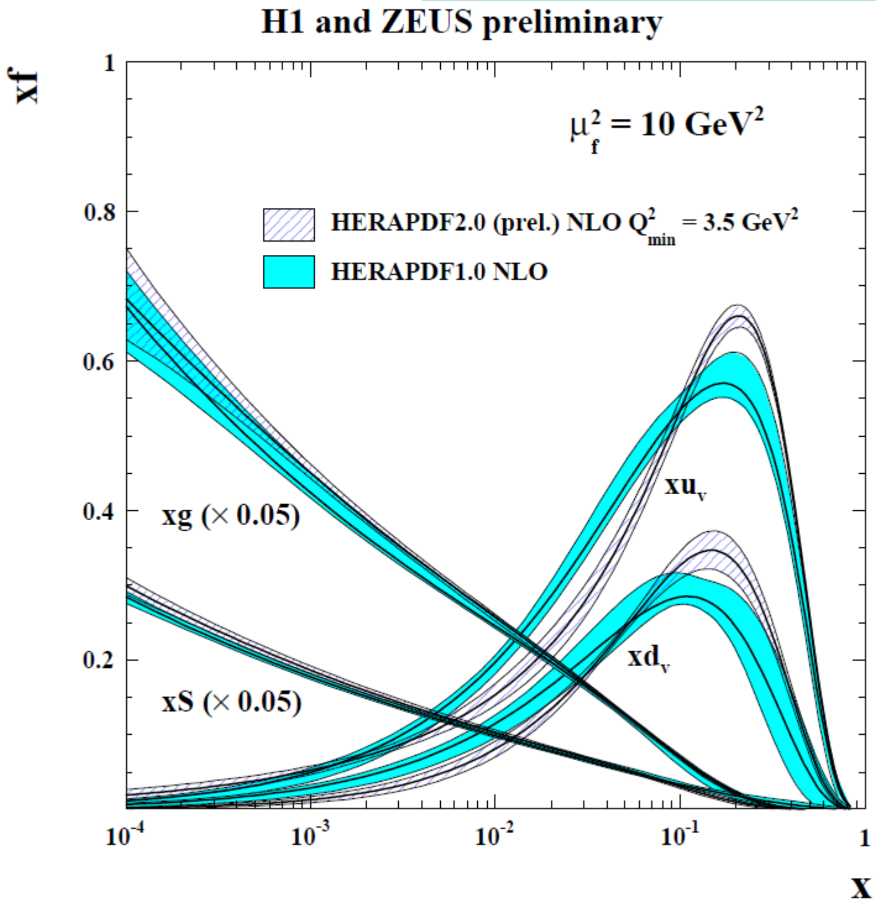
Chi2/dof (NLO) = 1156/1001

Chi2/dof(NNLO)= 1150/1001

Now make the same comparison by overlaying

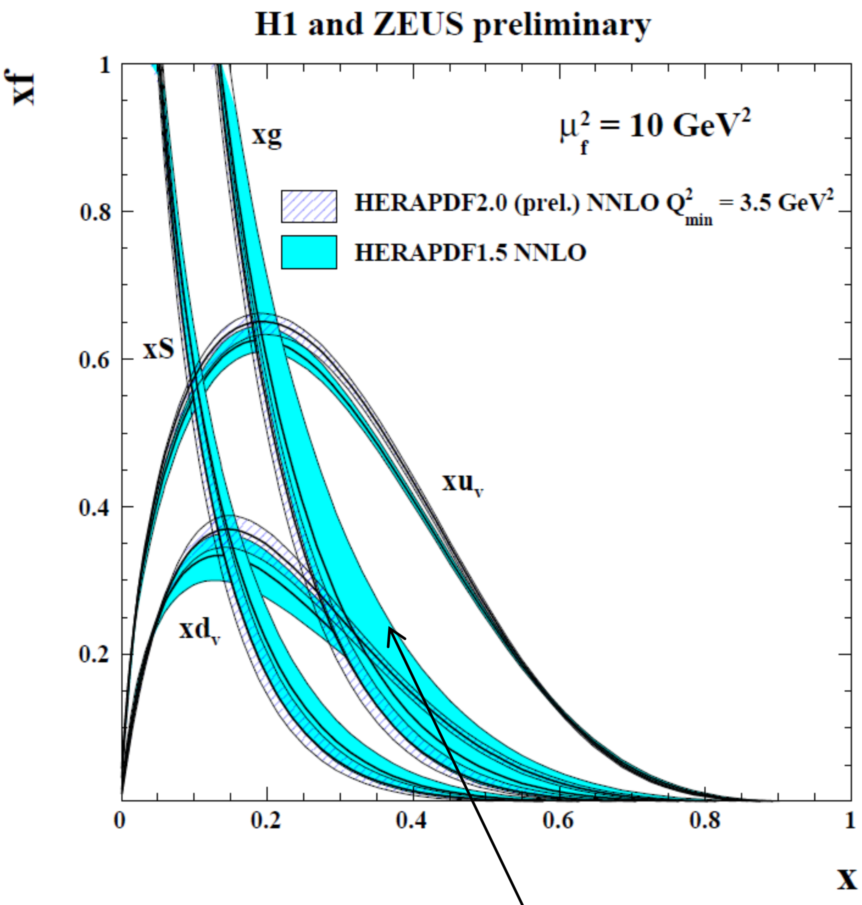
NLO
$Q^2 > 3.5\ GeV^2$

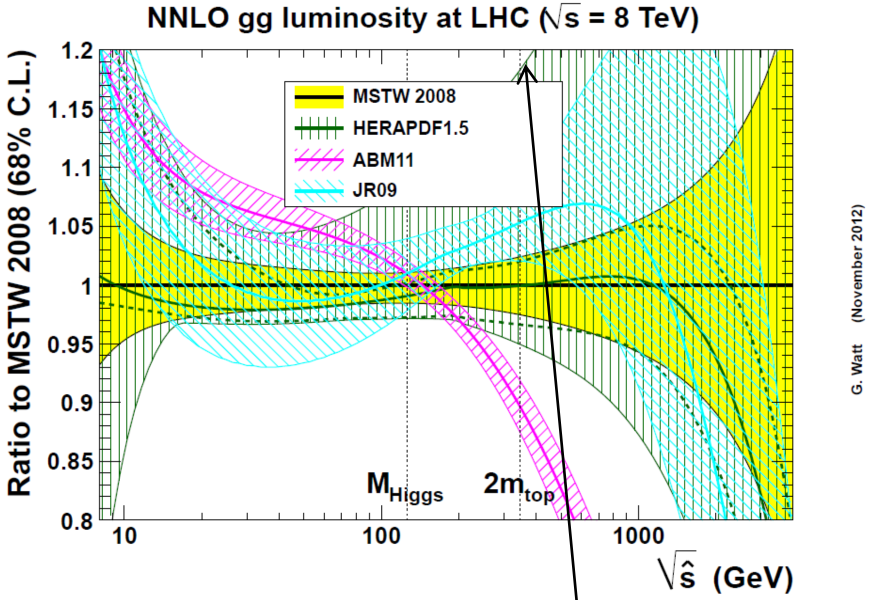




These figures have all the model/param variations included in the blue bands

- HERAPDF1.0 had a rather hard high-x sea, harder than the gluon (within large uncertainties).This is no longer the case and uncertainties are reduced
- The valence shapes are also somewhat different- new high-x data in the fit





This uncertainty on the gluon decreases

So this uncertainty on the g–g luminosity will also decrease