HERAPDF fits of the proton parton distribution functions (PDFs)

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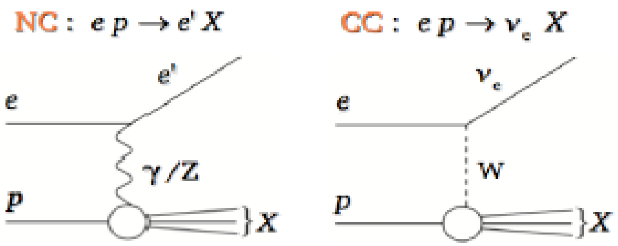
THE final inclusive combination
The HERAPDF2.0 today
The HERAPDF2.0 tomorrow
Beyond HERAPDF

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



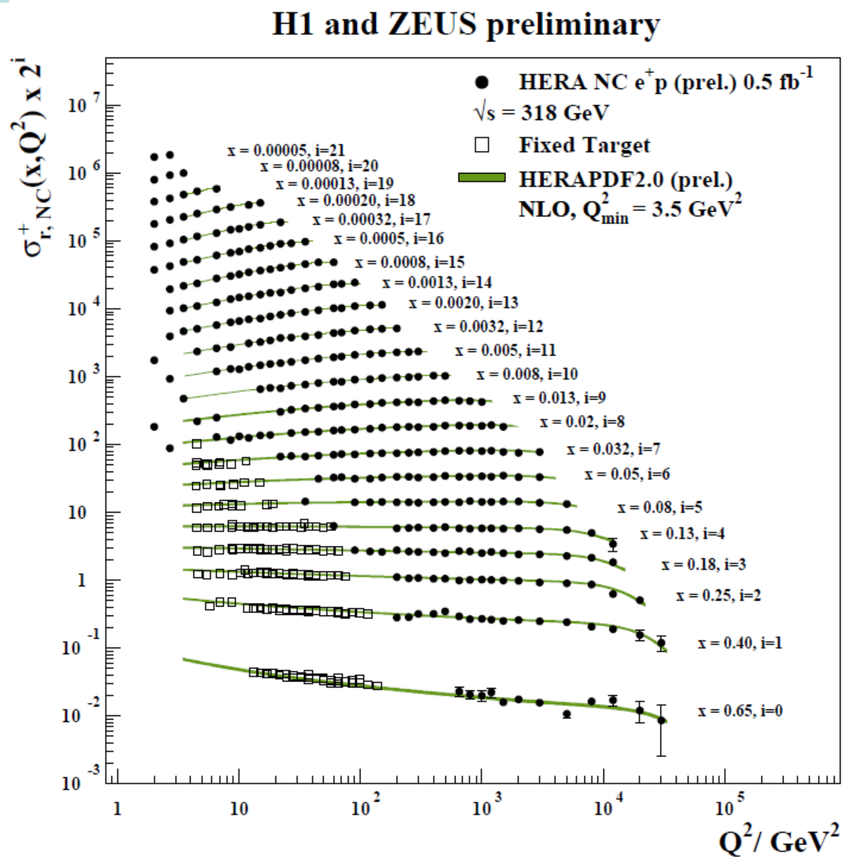
- Kinematic variables:

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

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

$F_2 \propto \sum_i e_i^2 (xq_i + x\bar{q}_i)$ — 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

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

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

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

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 $\chi 2$ tolerance $\Delta\chi 2 = 1$ 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

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

HERAPDF1.0 was based on the combination of HERA-I data

HERAPDF1.5 included preliminary HERA-II data

Now there is a new final combination of HERA-I and HERA-II data which will supersede the HERA-I combination
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.
The lower proton beam energies allow a measurement of F_L and thus give more information on the gluon.

A new PDF fit HERAPDF2.0 has been performed to these new final combined inclusive cross section data from HERA.

HERAPDF specifications: parametrisation and χ2 definition

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

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

QCD Sum rules constrain
Normalisation parameters: A_g, A_{u_v}, A_{d_v}
And the condition that:

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

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 →** 15/14 parameters at NLO//NNLO
- 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

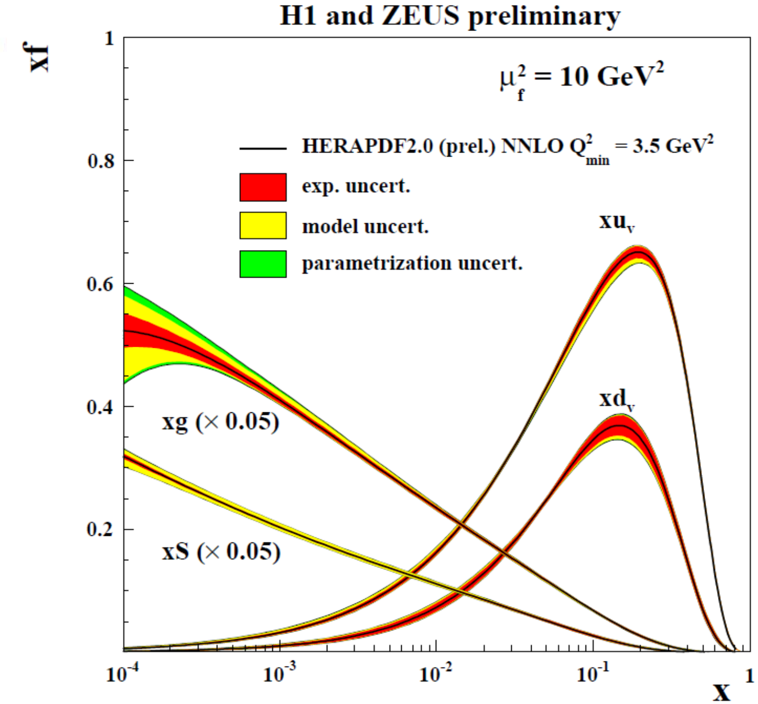
$\delta_{i,\mathrm{stat}}$, $\delta_{i,\mathrm{unc}}$ statistical and uncorrelated systematic uncertainty
γ_j^i correlated systematic uncertainties
b_j shifts

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

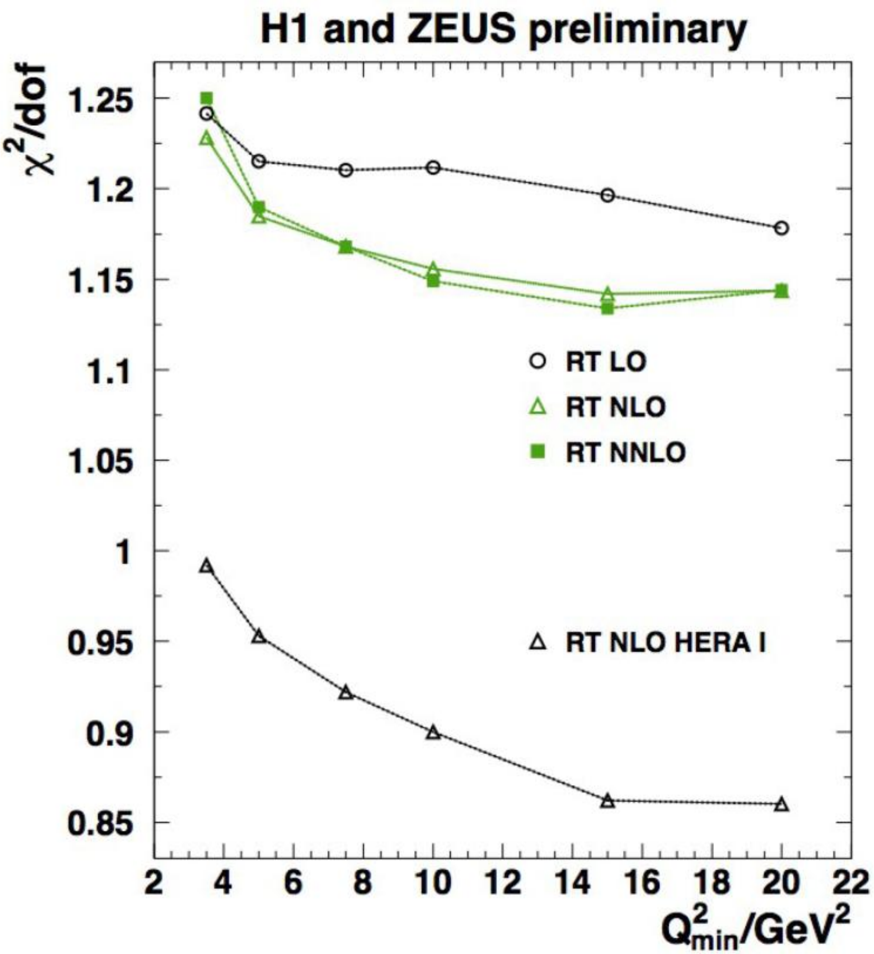
Variation	Standard Value	Lower Limit	Upper Limit
f_s	0.4	0.3	0.5
M_c^{opt}(NLO) [GeV]	1.47	1.41	1.53
M_c^{opt} (NNLO) [GeV]	1.44	1.38	1.50
M_b [GeV]	4.75	4.5	5.0
Q^2_{min} [GeV^2]	10.0	7.5	12.5
Q^2_{min} [GeV^2]	3.5	2.5	5.0
Q^2_0 [GeV^2]	1.9	1.6	2.2



- **Parametrisation:**
  - An envelope is formed from PDF fits using variants of parametrisation from
    - Scanning of 15/16 meter 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

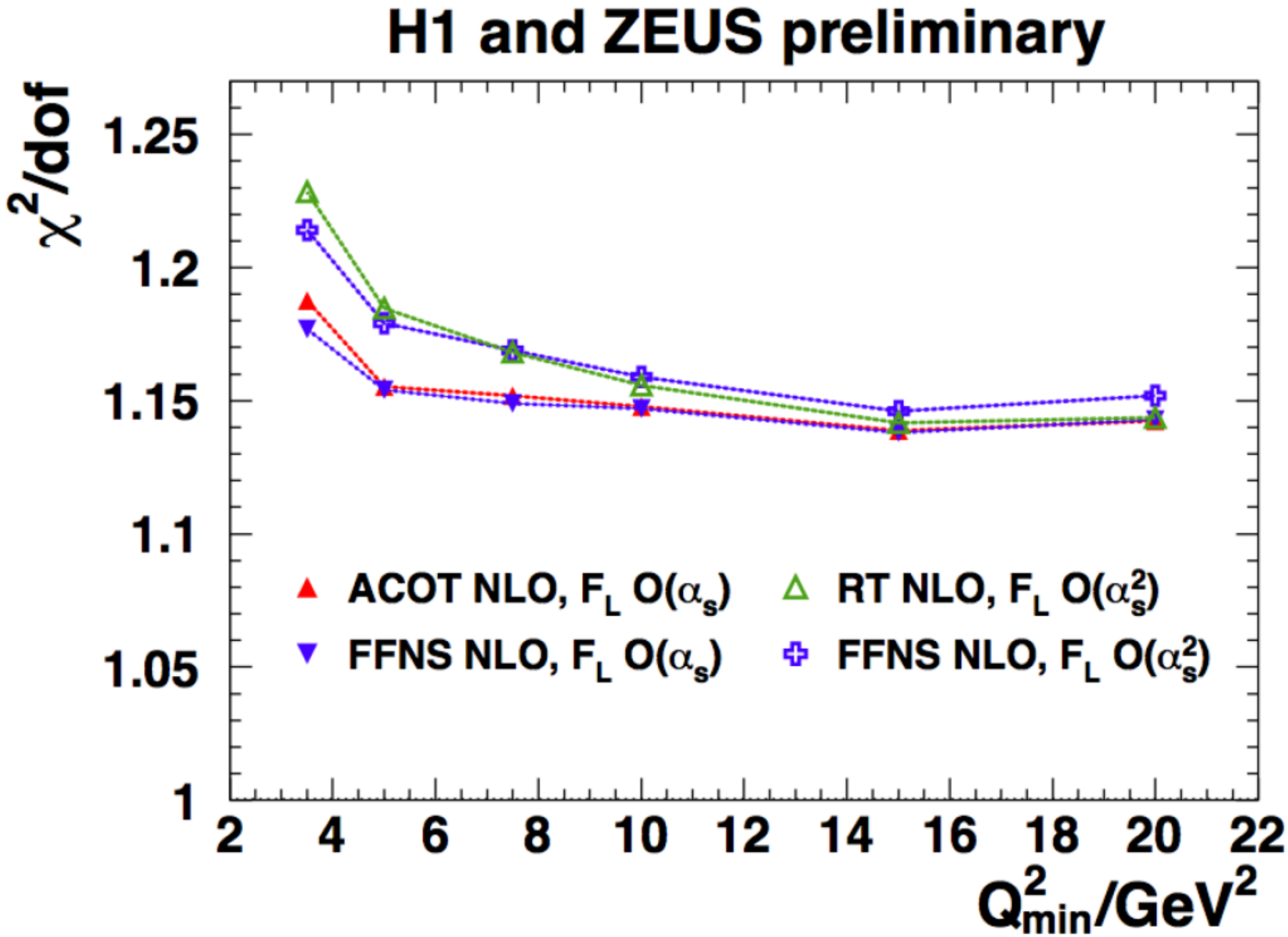
- The χ2 decreases with increase of Q^2 minimum until $Q^2_{min} \sim 10$ GeV^2
- The same effect was observed in HERA-1 data

- NLO is obviously better than LO but NNLO is not significantly better than NLO
- This is independent of heavy flavour scheme (see next slide)
- See also comparison to data in back-up

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

Further remarks on dependence on Q^2_{min}

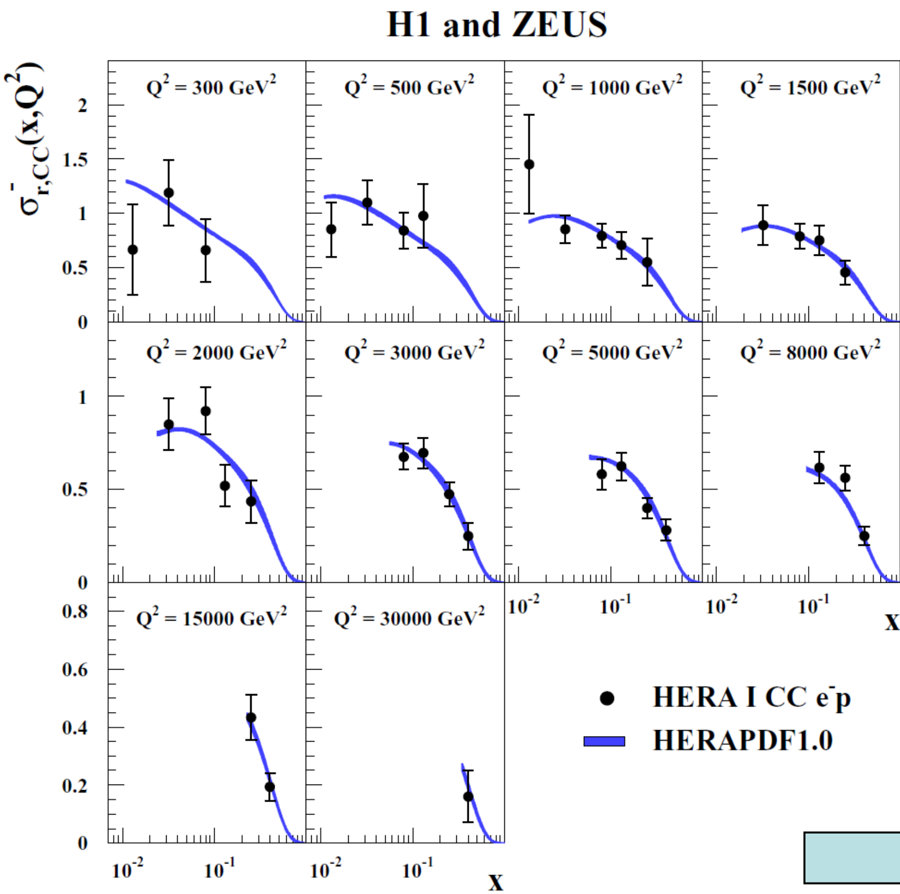


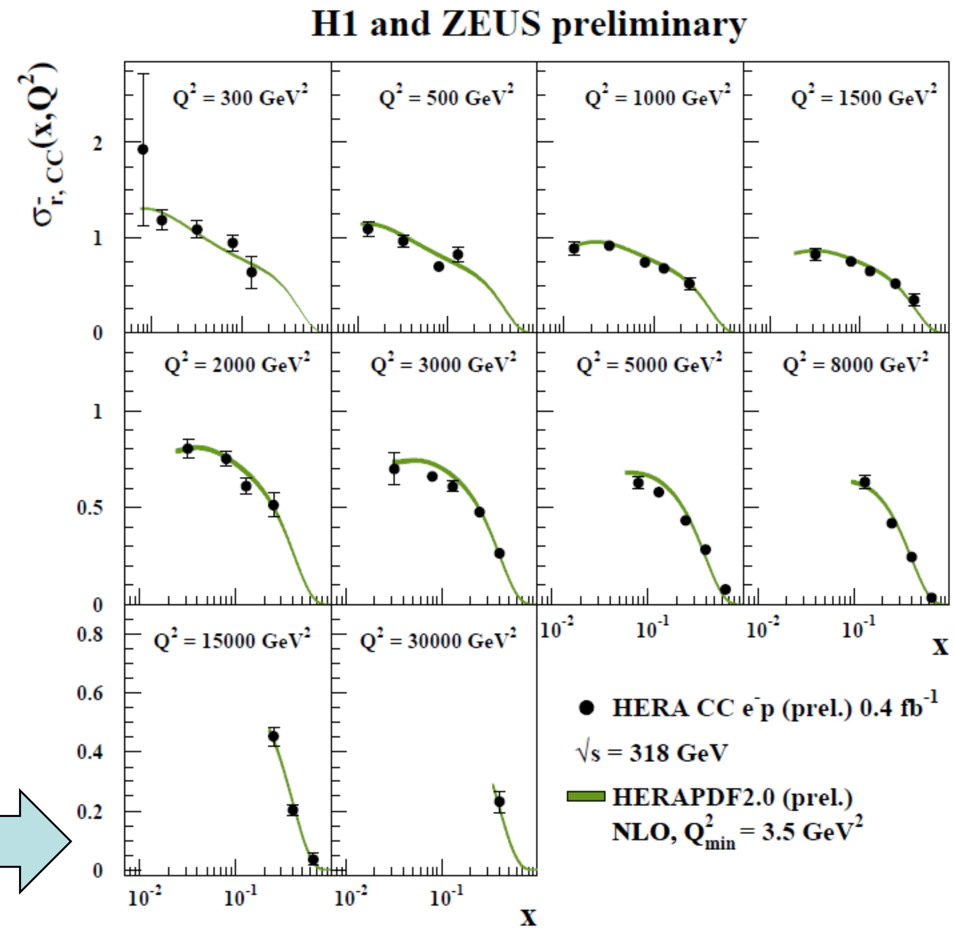
Treating F_L to order α_s - the same order as F_2 - yields better χ^2 than treating F_L to order α_s^2 - the same number of loops (1 loop)

Almost independent of heavy flavor scheme

HERAPDF2.0: new data and new QCD fit

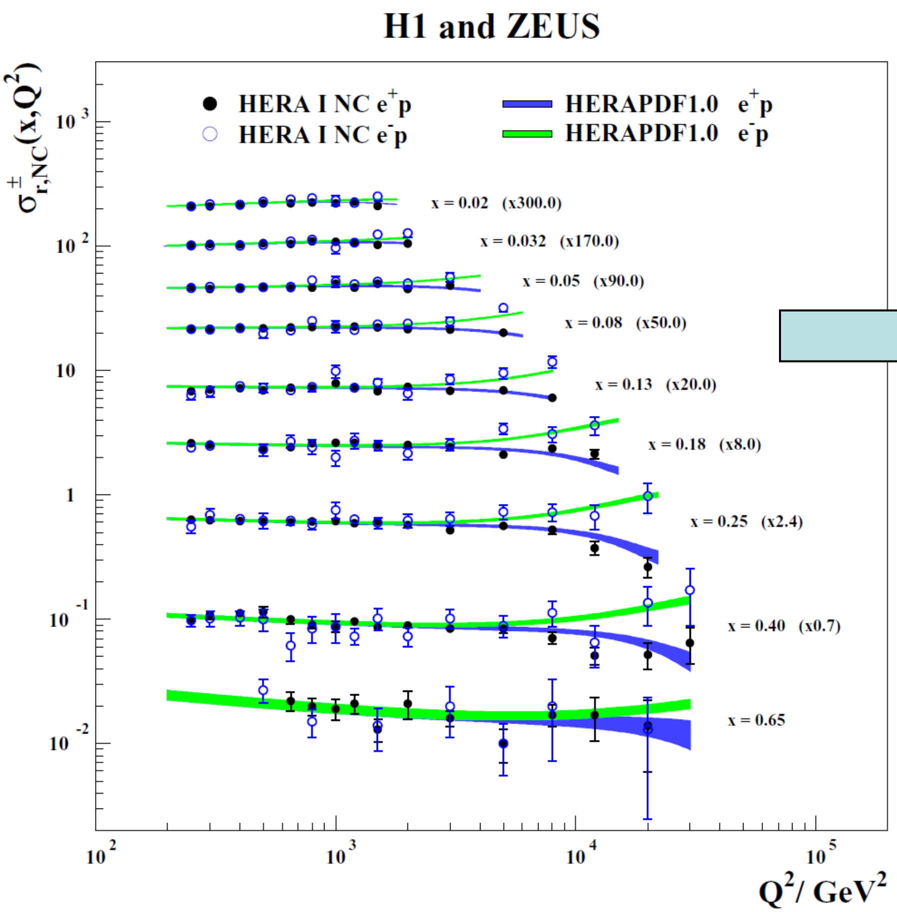
The fit quality is similar for NLO and NNLO. The NLO Q^2>3.5 GeV^2 fit is illustrated

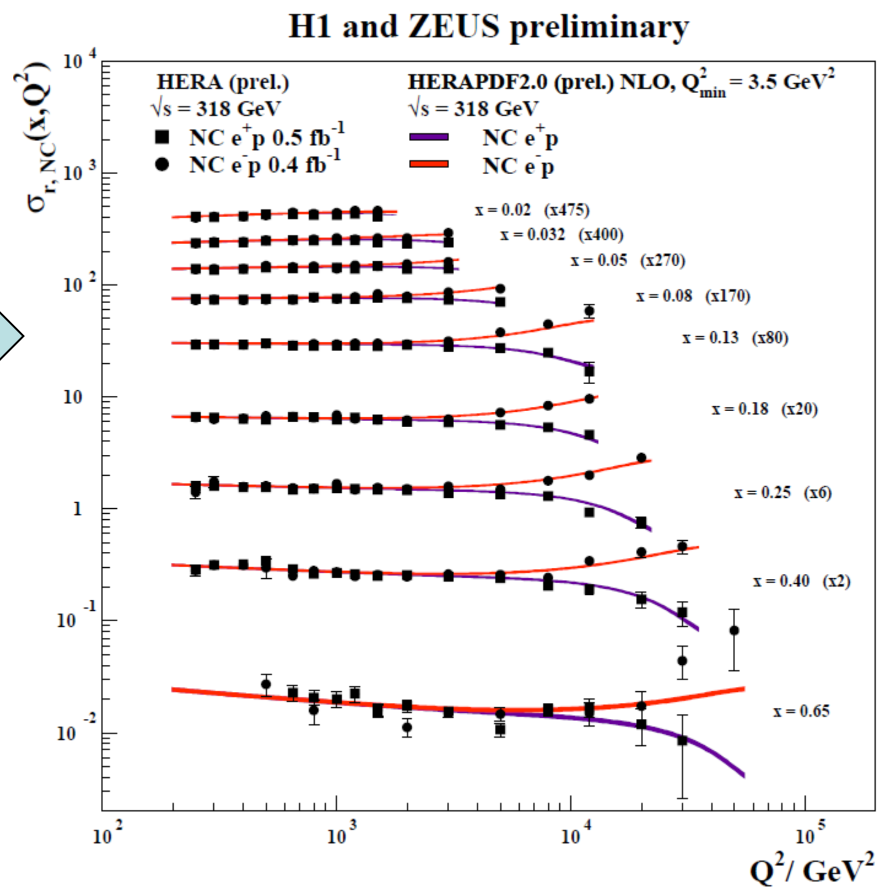




Improvement since HERAPDF1.0

HERAPDF2.0: new data and new QCD fit

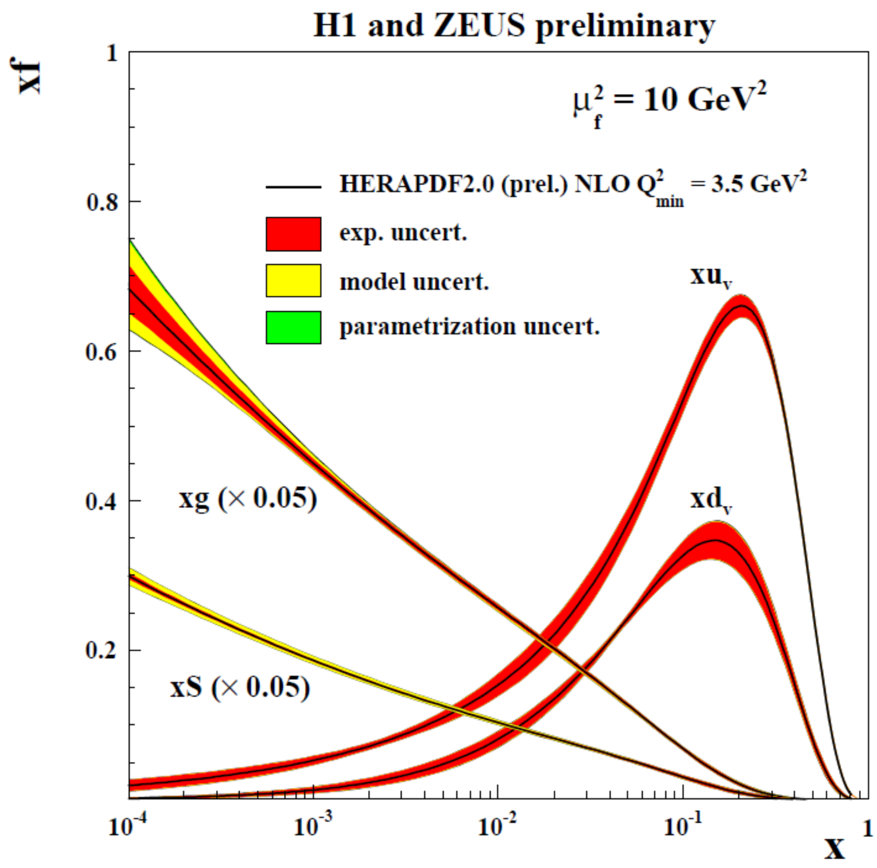




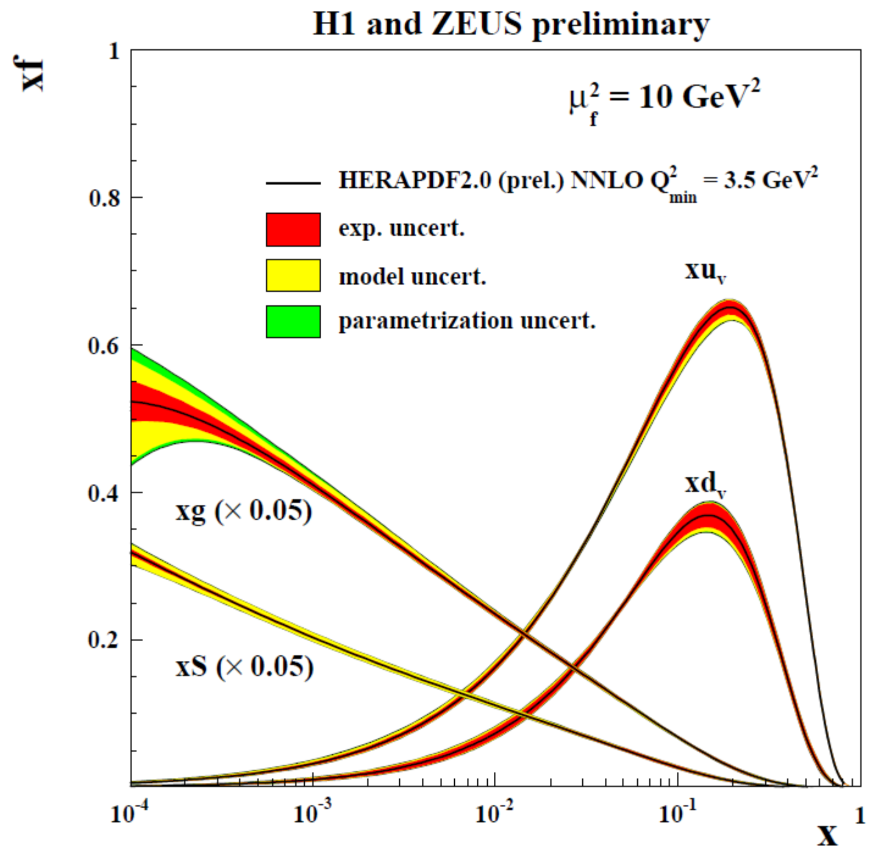
Improvement since HERAPDF1.0

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

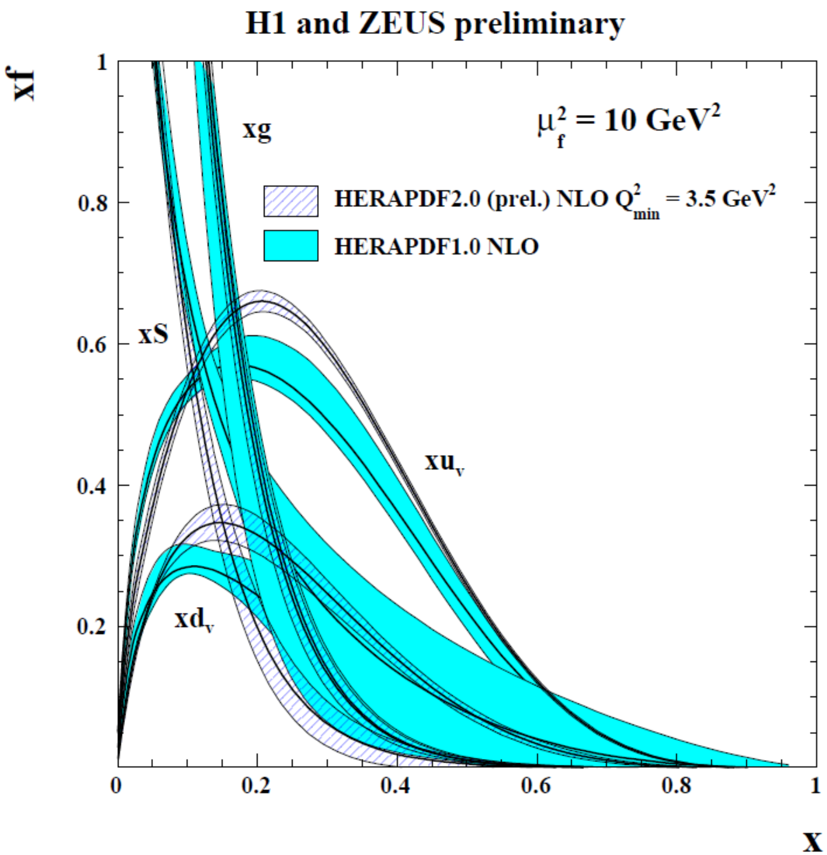
NLO

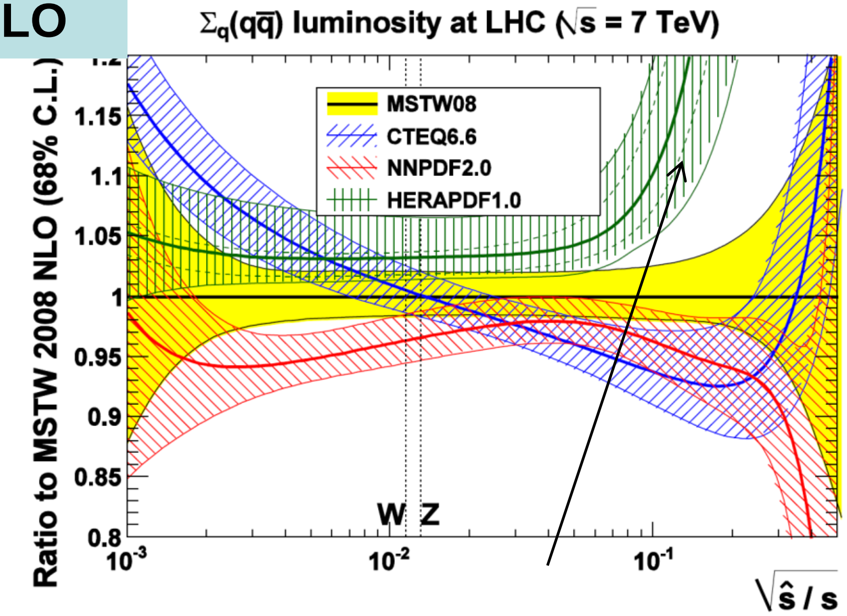


NNLO



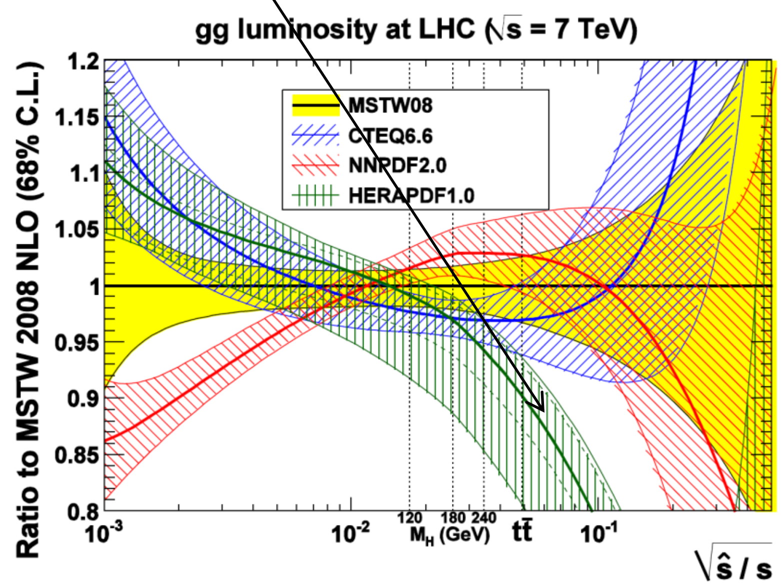
Compare HERAPDF2.0 to HERAPDF1.0 at NLO





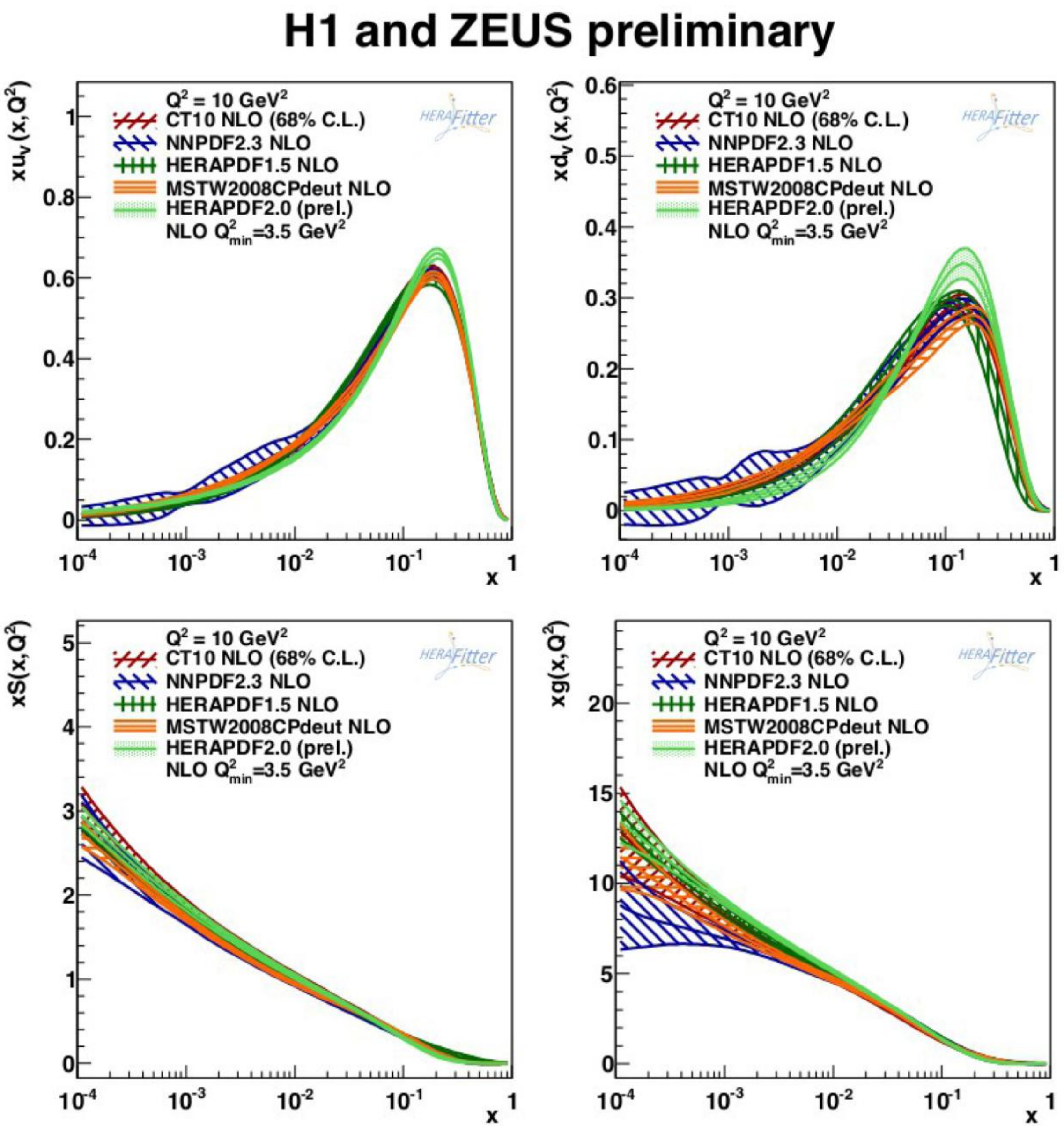
So the q-qbar luminosity at high-x comes down

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



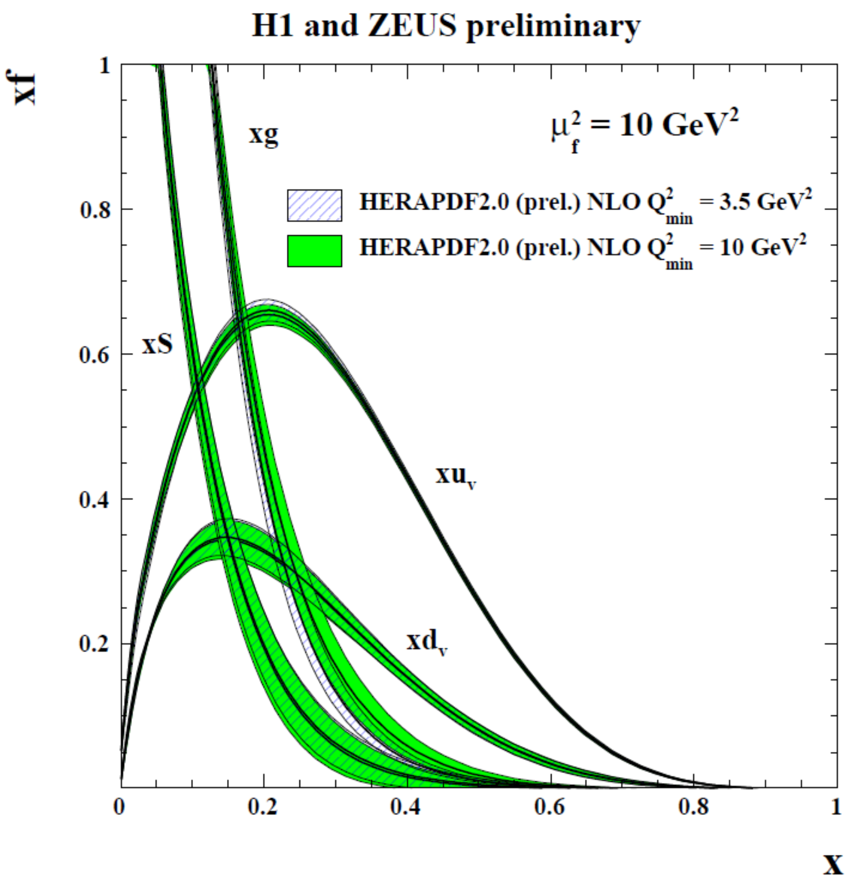
- HERAPDF1.0 had a rather hard high-x sea, harder than the gluon (within large uncertainties).This is no longer the case and uncertainties are much reduced
- HERAPDF1.0 had a soft high-x gluon this moves to the top of its previous error band
- Valence shapes have changed due to much more data at high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

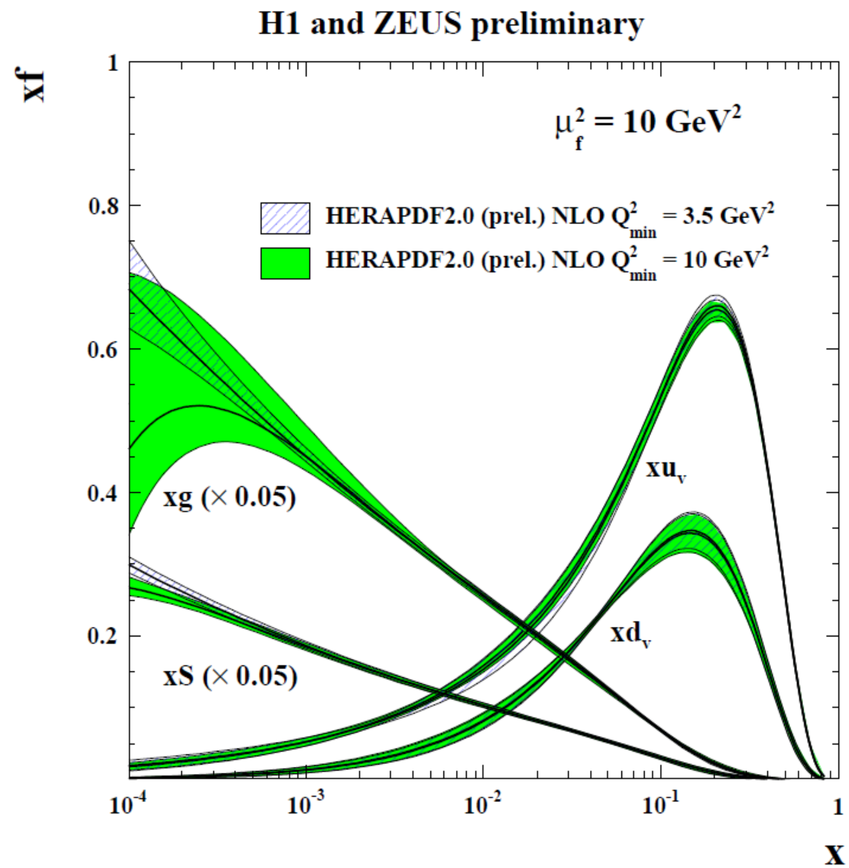
Compare HERAPDF2.0 to other PDFs at NLO



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

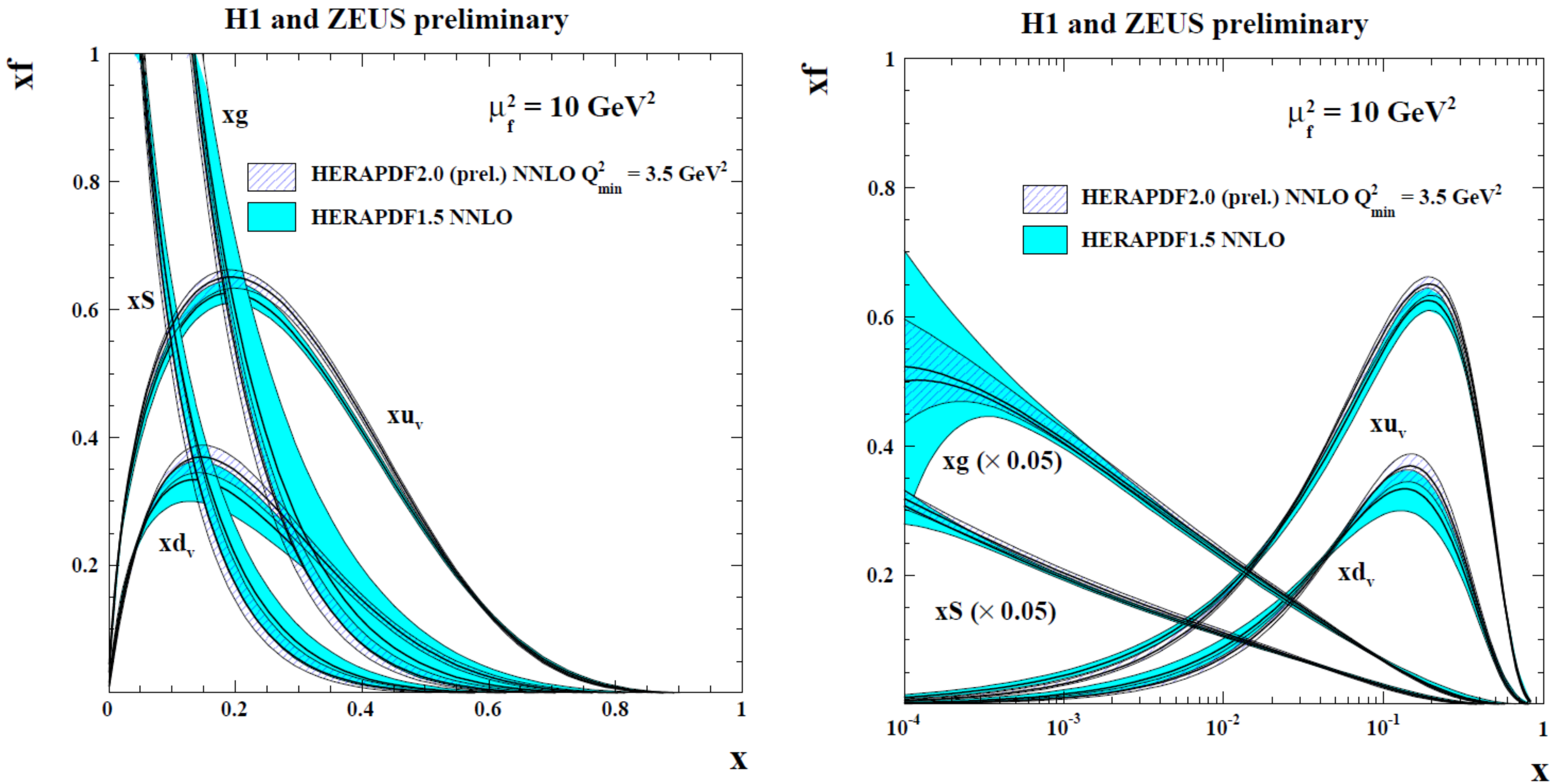
Compare HERAPDF2.0 with Q2>10GeV^2 to the standard fit at NLO



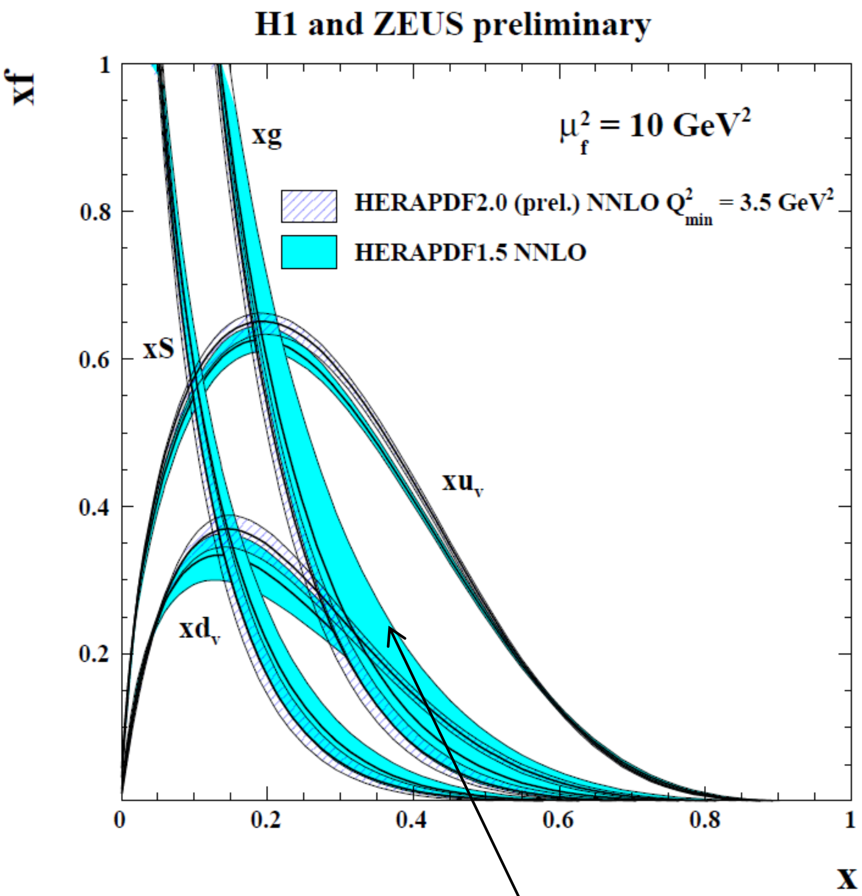


Fits are compatible
There is greater uncertainty at low-x for Sea and glue there is some small change of gluon and sea shape at low-x.
At large x gluon and sea and valence are all similar
There is no bias at high scale due to the inclusion of the lower Q^2, lower x data within the kinematic region of the LHC

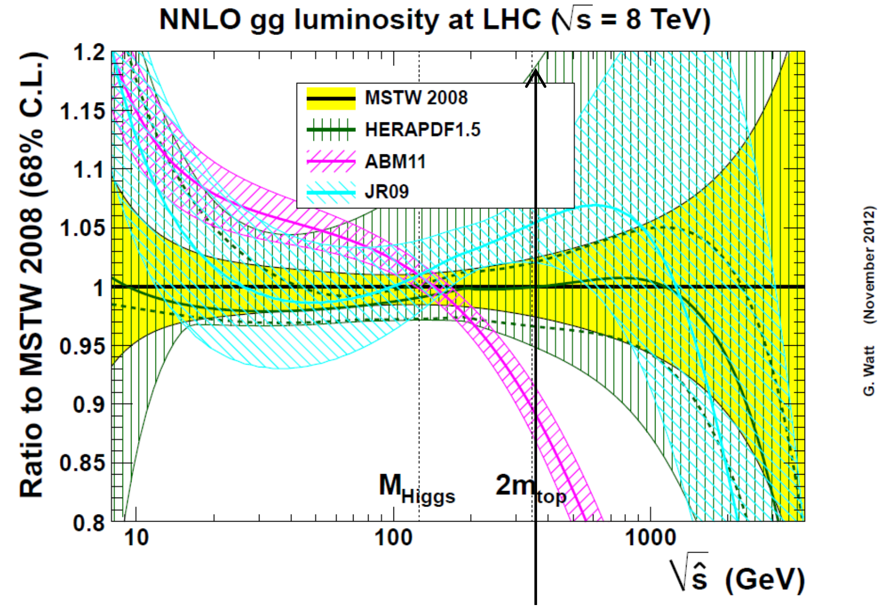
Compare HERAPDF2.0 to HERAPDF1.5 at NNLO



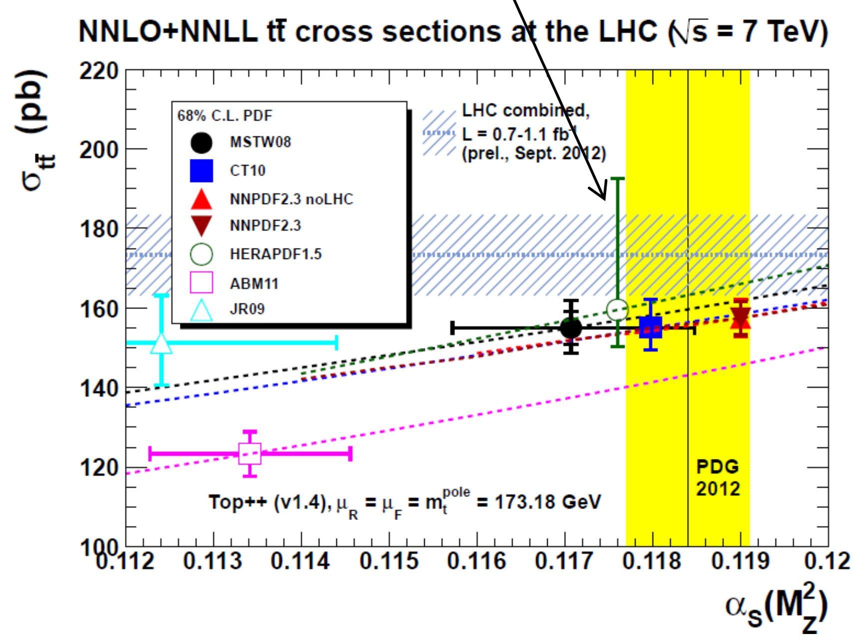
Reduction in gluon uncertainty both at low-x and high-x.
A lot of this reduction is because the model variation due to variation of Q^2 cut is not as dramatic now that we have more data.



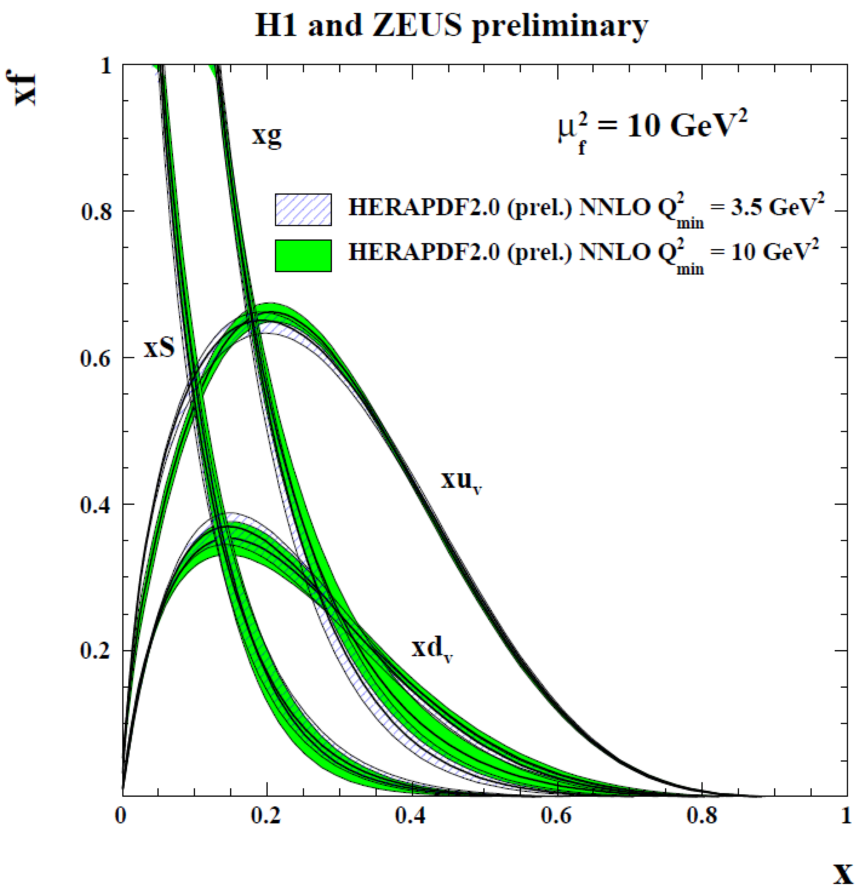
This uncertainty on the gluon decreases and it moves to the lower end of its previous error band

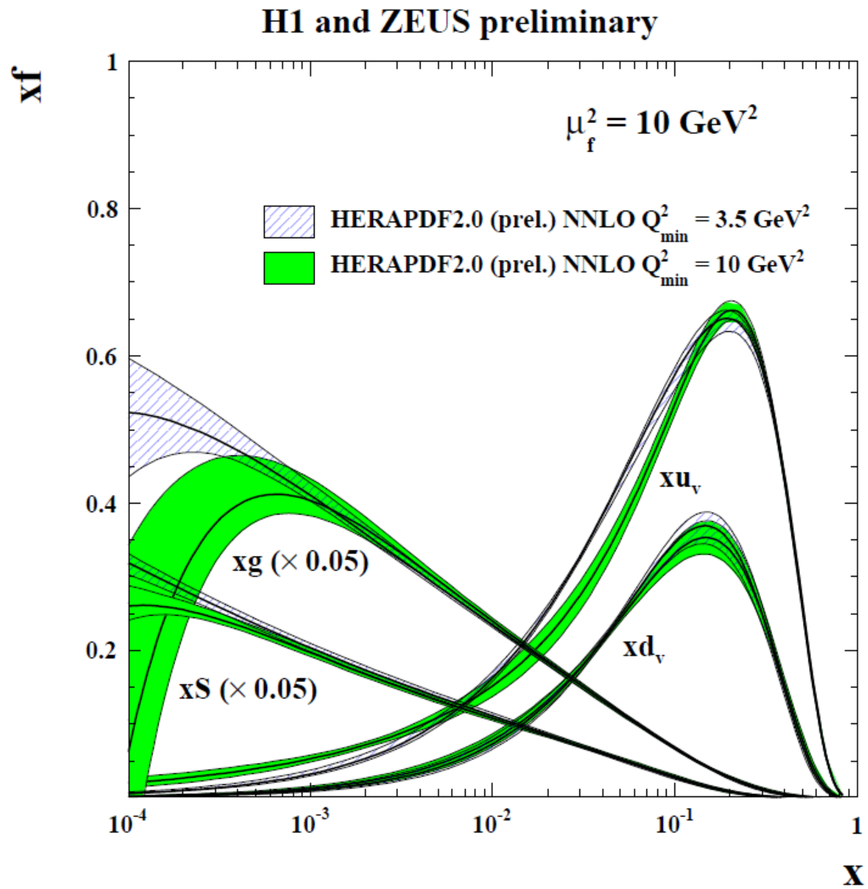


So this uncertainty on the g–g luminosity will also decrease



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
There is still no bias from including the lower Q2, lower x data in the fits if we move to LHC scales
For the ATLAS,CMS kinematic regimes.
However at very low-x – and moderate Q2 as in LHCb --the NNLOfit for Q2min=10 cannot be used--- does this indicate a breakdown of DGLAP at low x?– beyond our scope

What is coming?

Not just the final version of this but extended studies.

- An LO version of HERAPDF2.0 (LO HERAPDF1.5 already exists)
- Combined xF3 and EW unification plots

- Study of various alternative parametrisations
- Consideration of the shape of strangeness
- Use of MC as well as hessian uncertainties

- Use of charm data in the fit- already used to restrict the range of the parameter M_c^{opt}

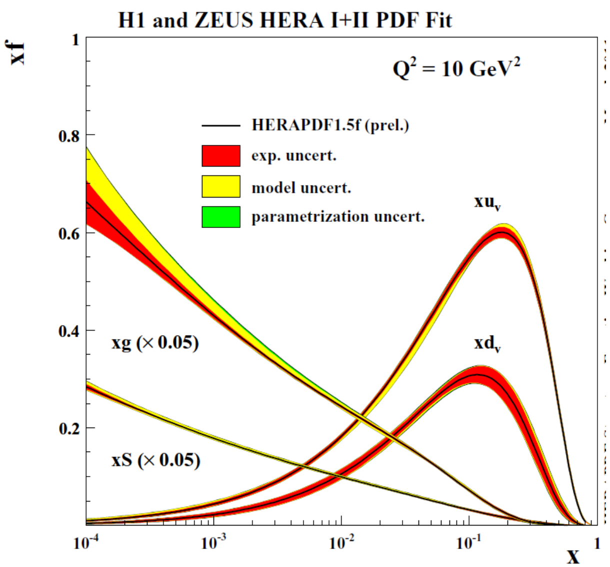
- Use of beauty data - used to restrict the range of the parameter M_b^{opt}

- Use of HERA jet in the fit data – to improve the high x gluon PDF and to make a simultaneous $\alpha_S(M_Z)$ and PDF fit →

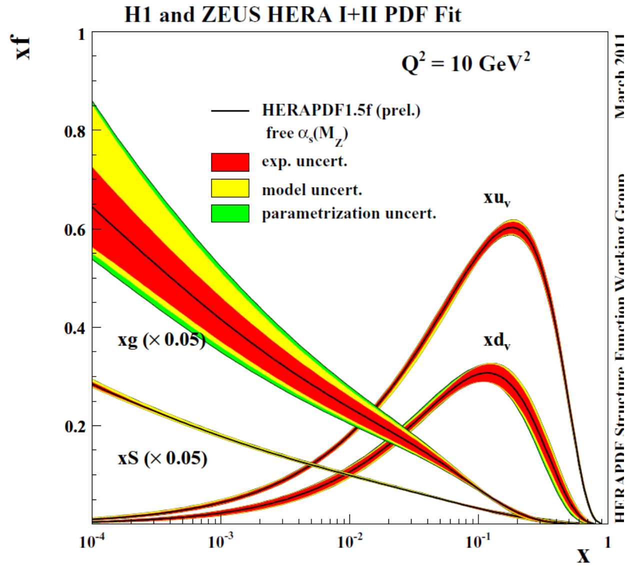
- FFN fits as well as GMVFN fits

This is all to be in the paper which is forthcoming (as well as the data of course) .
It is now in 2nd circulation through the collaboration.
We expect the final reading and sending to the DESY directorate for sign-off on March 17th

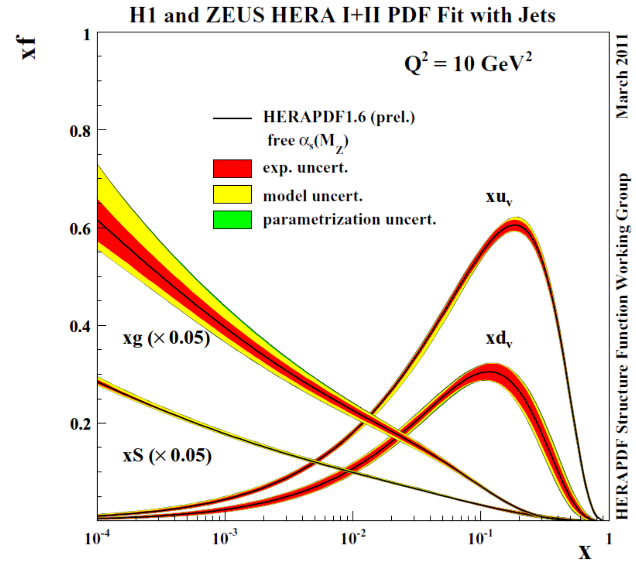
This is not new it is HERAPDF1.5 +jets, just to illustrate the main point



Take the usual fit

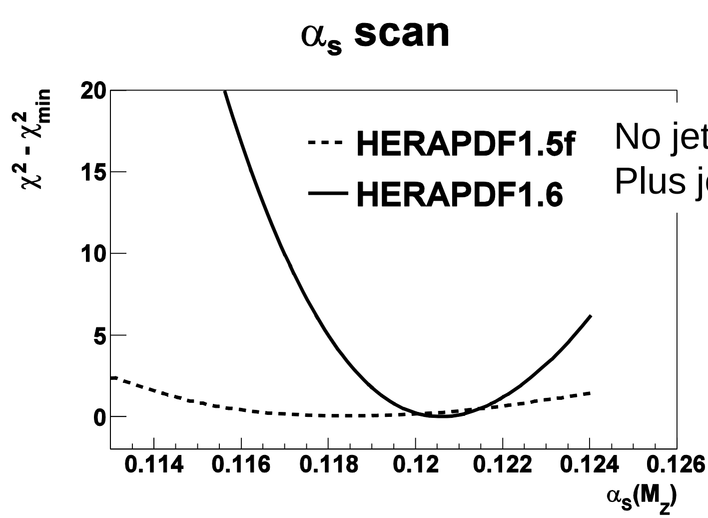


And free $\alpha_S(M_Z)$



But now add HERA jet data

And look at what happens to your ability to determine $\alpha_S(M_Z)$



No jets
Plus jets

What then?

- Well HERA has not quite finished. There are further charm data, not in the charm combination paper, and there are beauty data which could be combined.
- We plan a further heavy flavour combination paper which could have a 'HERAPDF2.1' extension

- A simultaneous fit to PDFs and contact interaction terms in under study

- So far we just combined unpolarised data. We plan to combine it preserving the polarisation and do simultaneous electroweak and PDF fits for the NC couplings

→

And beyond HERA

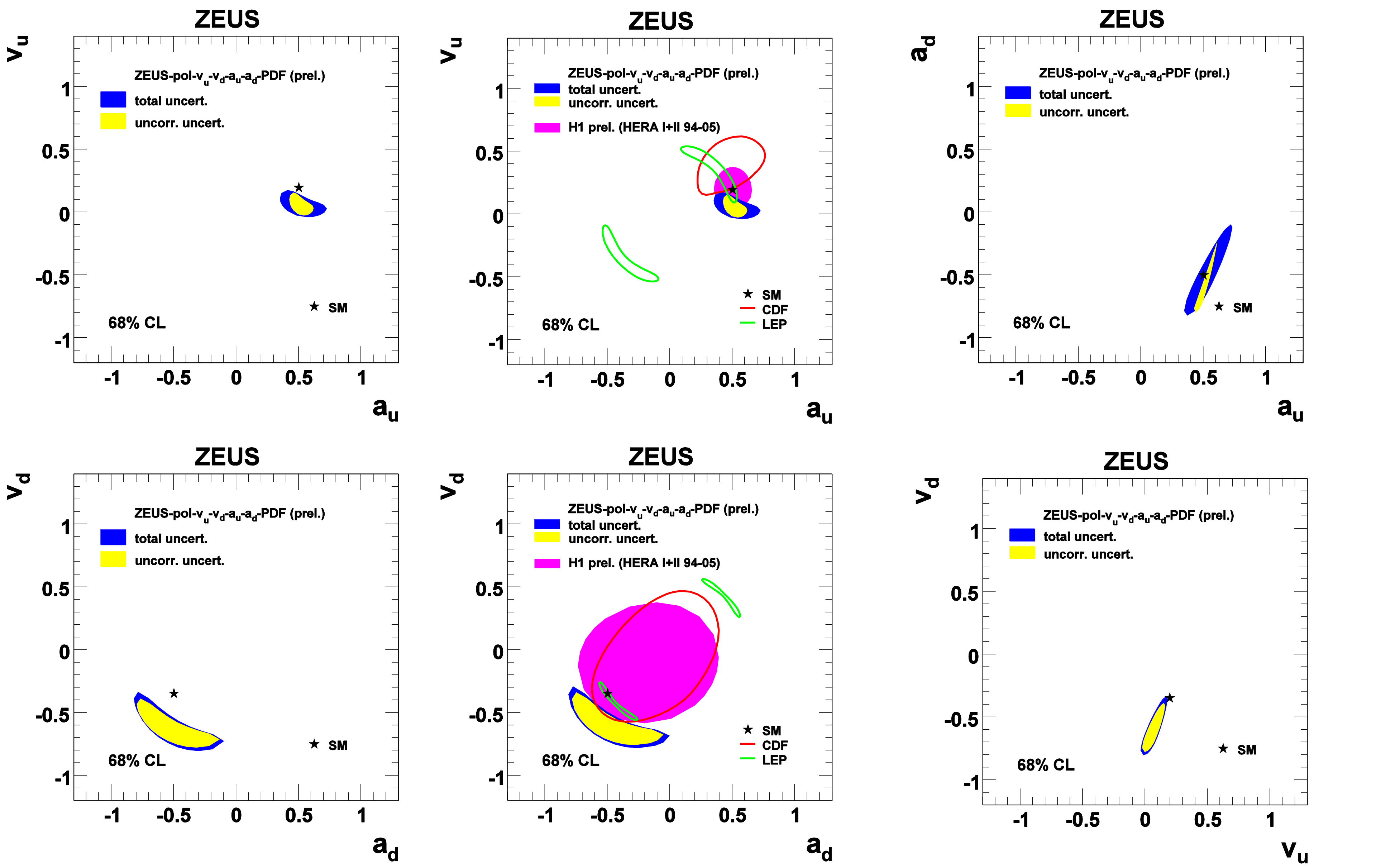
- The move to use HERAPDF2.0 rather than 1.0 as the basis for the ATLAS and CMS PDF fits using the HERAFitter framework arXiv1410.4412

→

- Extend the HERAFitter framework to many more processes ….

- Examples of the use of HERA+ATLAS/CMS data using HERAFItter are in many other talks at this workshop ,plus the PROSA group

au/vu ad/vd au/ad vu/vd contours from a previous ZEUS analysis



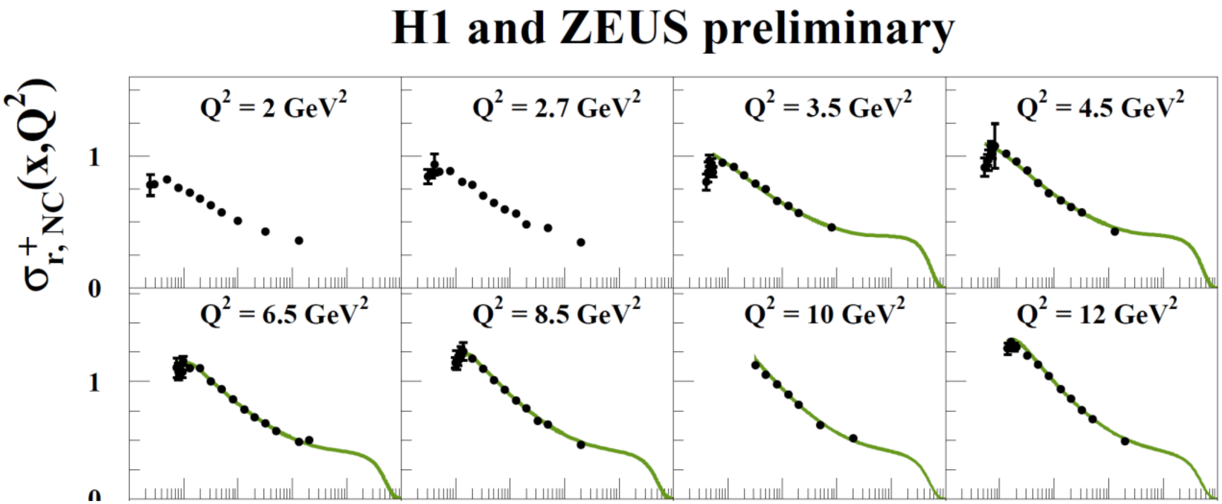
HERAFitter Program at glance

- HERAFitter code is a combination of C++ and Fortran 77 libraries with minimal dependencies and modular structure with interface to external packages:
  - QCDNUM for evolution of PDFs
- DIS inclusive processes in ep and fixed target
  - Different schemes of heavy quark treatment
    - VFNS, FFNS:
      - OPENQCDRAD (ABM)
      - TR' (MSTW)
      - ACOT (CT)
  - Diffractive PDFs
  - Dipole Models
  - Unintegrated PDFs (TMDs)
- Jet production (ep, pp, ppbar)
  - FastNLO and APPLGRID techniques
- Drell-Yan processes (pp, ppbar)
  - LO calculation x NLO k-factors
  - APPLGRID technique
- Top pair production
  - total inclusive ttbar cross sections (HATHOR)
  - differential (DiffTop approx NNLO via fastNLO grids)

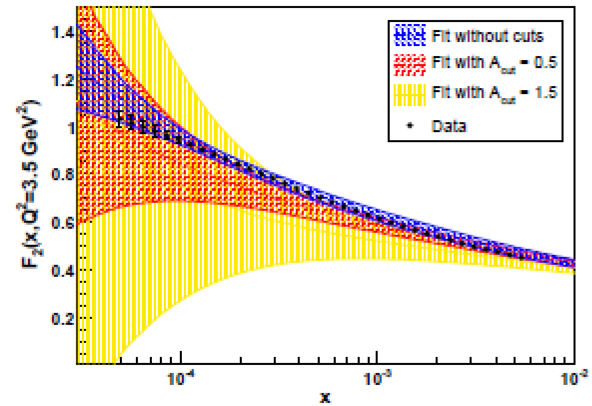
```
--enable-openmp          enable openmp support
--enable-trapFPE         Stop of floating point errors (default=no)
--enable-checkBounds     add -fbounds-check flag for compilation (default=no)
--enable-nnpdfWeight     use NNPDF weighting (default=no)
--enable-lhapdf          use lhapdf (default=no)
--enable-applgrid        use applgrid for fast pdf convolutions (default=no)
--enable-genetic         use genetic for general minimia search (defaults=no)
--enable-hathor          use hathor for ttbar cross section predictions
                         (default=no)
--enable-updf            use uPDF evolution (default=no)
--enable-doc             Build documentation (default=no)
```

Experimental Data	Process	Reaction	Theory schemes calculations
HERA, Fixed Target	DIS NC	$ep \to eX$ $\mu p \to \mu X$	TR', ACOT, ZM (QCDNUM), FFN (OPENQCDRAD, QCDNUM), TMD (uPDFevolv)
HERA	DIS CC	$ep \to \nu_e X$	ACOT, ZM (QCDNUM), FFN (OPENQCDRAD)
	DIS jets	$ep \to e\,\text{jets}X$	NLOJet++ (fastNLO)
	DIS heavy quarks	$ep \to ec\bar{c}X$, $ep \to eb\bar{b}X$	TR', ACOT, ZM (QCDNUM), FFN (OPENQCDRAD, QCDNUM)
Tevatron, LHC	Drell-Yan	$pp(\bar{p}) \to l\bar{l}X$, $pp(\bar{p}) \to l\nu X$	MCFM (APPLGRID)
	top pair	$pp(\bar{p}) \to t\bar{t}X$	MCFM (APPLGRID), HATHOR, DiffTop
	single top	$pp(\bar{p}) \to tl\nu X$, $pp(\bar{p}) \to tX$, $pp(\bar{p}) \to tWX$	MCFM (APPLGRID)
	jets	$pp(\bar{p}) \to \text{jets}X$	NLOJet++ (APPLGRID), NLOJet++ (fastNLO)
LHC	DY heavy quarks	$pp \to VhX$	MCFM (APPLGRID)

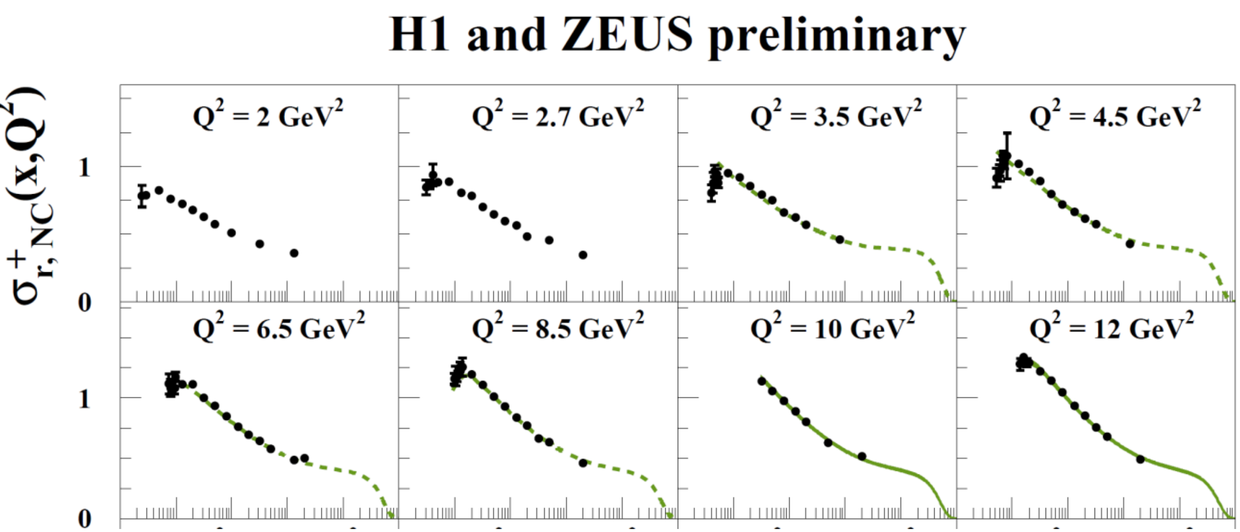
Back-up



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

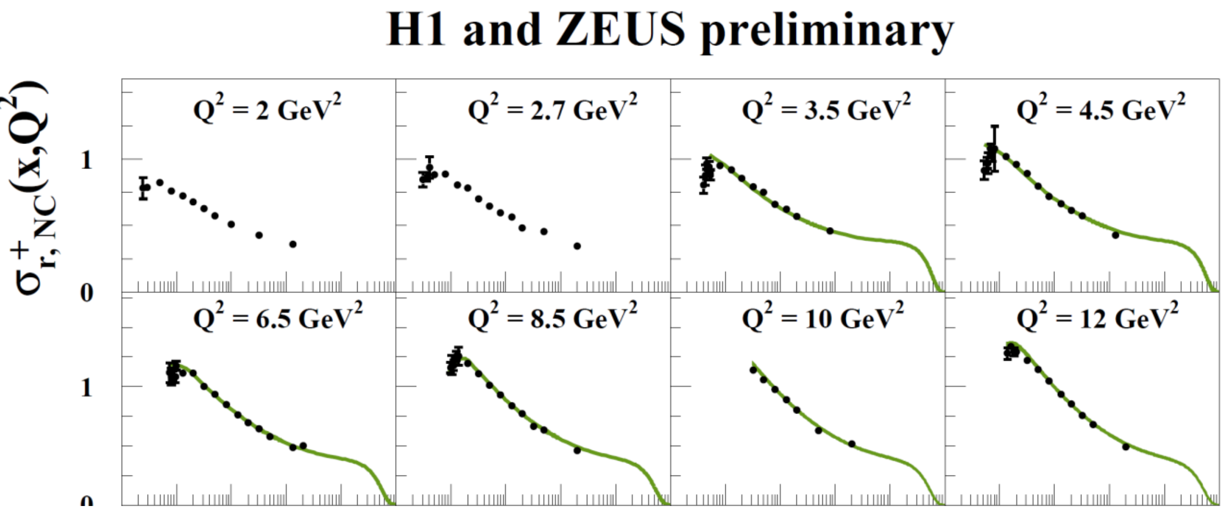


Reminds us of this?

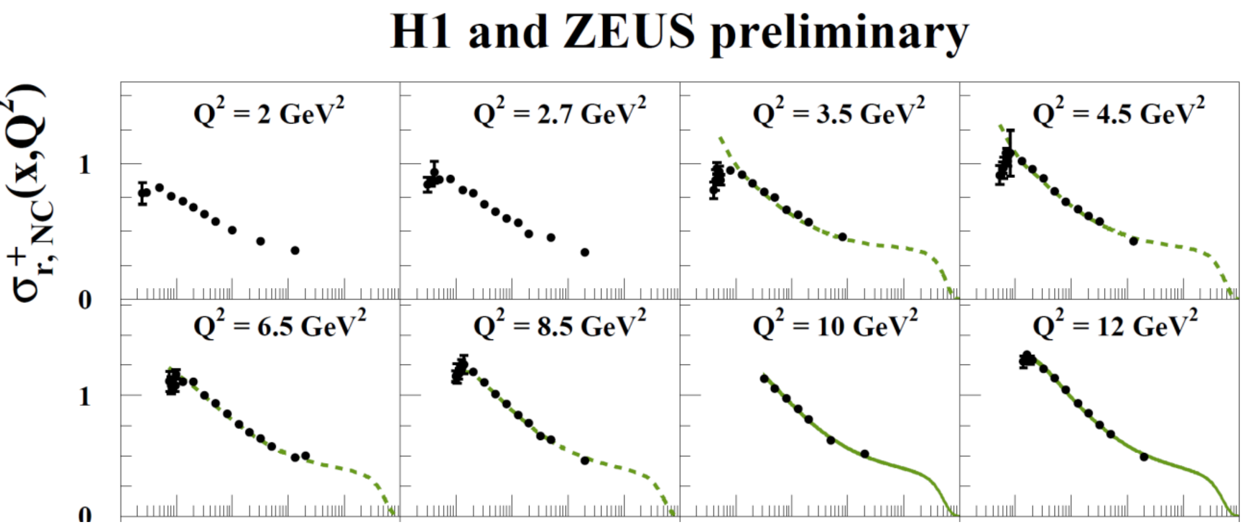


NLO
$Q^2 > 10\ GeV^2$

These are the comparisons of the fit to the NCe+p data at low Q^2
The fit with Q^2>10 misses the lower Q2 data in a systematic matter – worse at low-x and low Q2--- (not just at high-y)



NNLO
$Q^2 > 3.5$ GeV^2



NNLO
$Q^2 > 10$ GeV^2

Going to higher orders does not improve the fit at low-Q2, low-x