Parton Distributions from HERA

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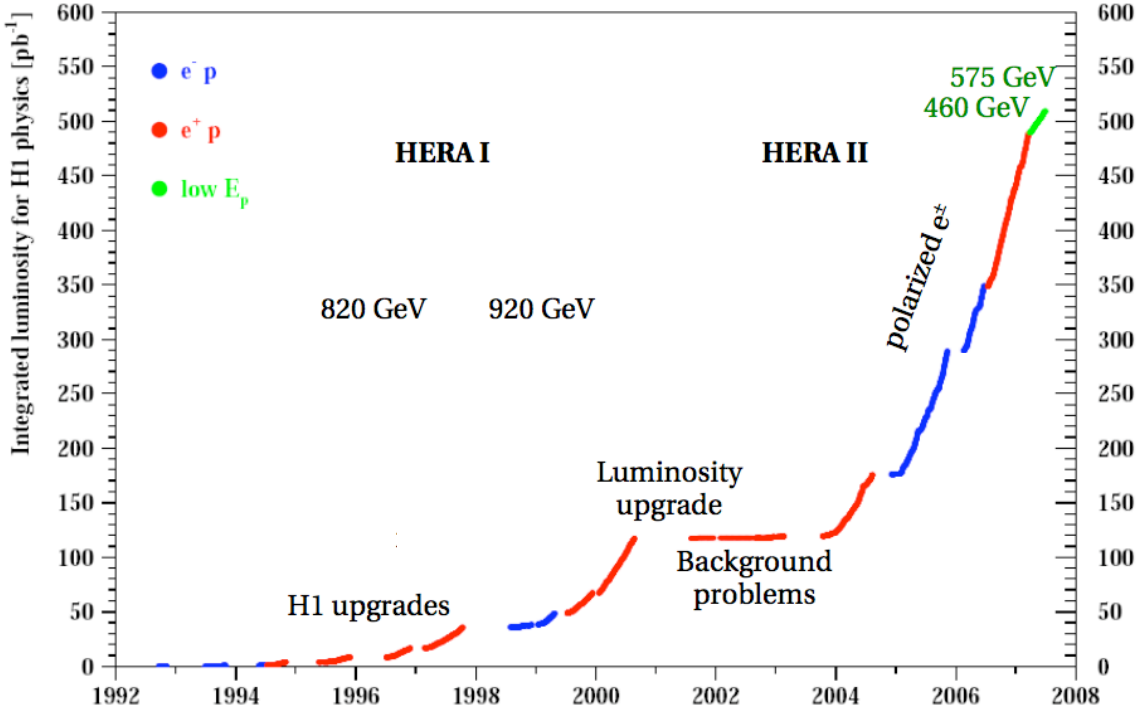
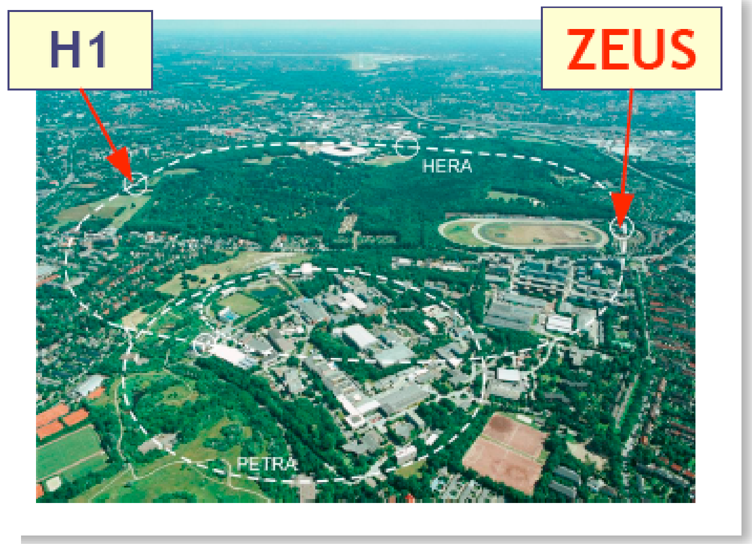
Outline:

- H1 and ZEUS at the HERA collider
- Data Combination
- QCD Analysis
- Results and Comparisons
- Summary

HERA at DESY

- HERA is world's only $e^{\pm}p$ collider
  - located at DESY, Hamburg - Germany
  - In operation for 15 years (1992-2007)
  - H1 and ZEUS collider experiments
    - General purpose detectors



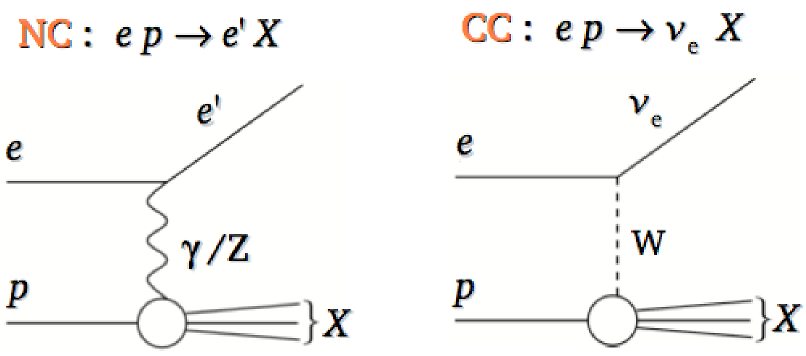


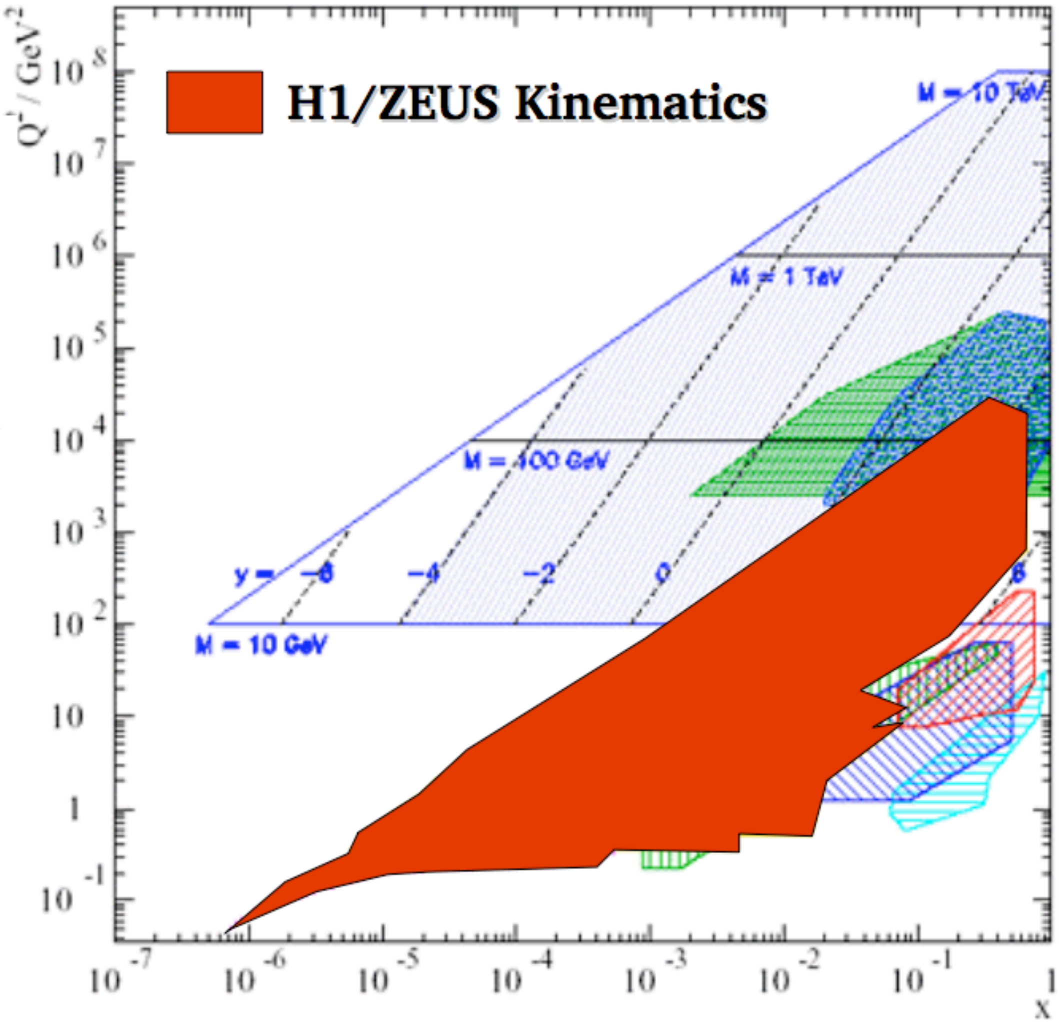
HERA-I	1992-2000	Ep=820,920 GeV
HERA-II	2003-2007	Ep=920, 460,575 GeV

Registered ~1fb^{-1} of integrated luminosity of physics data.

H1 and ZEUS kinematics

- HERA provides unique opportunity to study the structure of proton via DIS processes:





- Kinematic variables:
  - Virtuality of exchanged boson:

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

  - Bjorken scaling variable:

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

H1 and ZEUS kinematics span over 6 orders of magnitude in x and Q^2!

PDF determination at HERA

- General double differential cross section:

$$\frac{d^2\sigma^{\pm}_{NC}}{dx\,dQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[Y_+\tilde{F}_2 \mp Y_- x\tilde{F}_3 - y^2\tilde{F}_L\right] \equiv \frac{2\pi\alpha^2}{xQ^4} Y_+ \tilde{\sigma}^{\pm}_{NC}$$

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

  - F_2, F_L and xF_3 are the structure functions which are related to the momentum distributions of quarks and gluon inside the nucleon.
  - At Leading Order:

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

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

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

  - Also, HERA CC data give flavour information

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

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

→Sensitive to d_v at high x

→Sensitive to u_v at high x

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Combination of the H1 and ZEUS Measurements

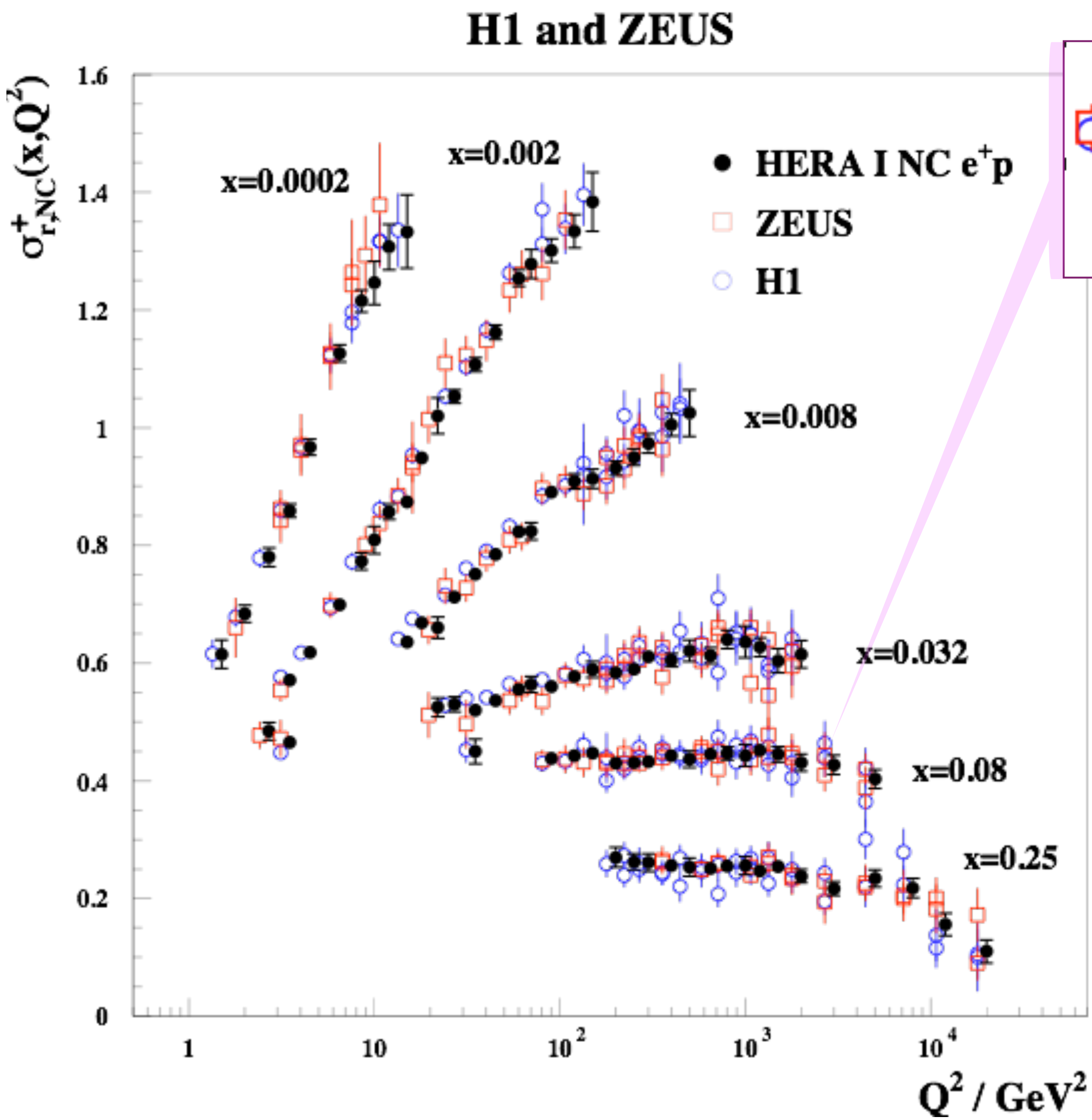
[JHEP01 (2010) 109]

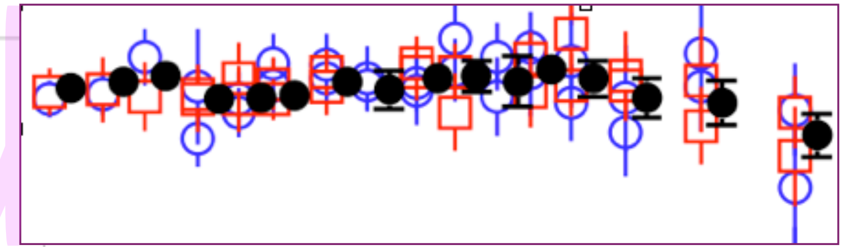
- Ultimate precision is obtained by combining the H1 and ZEUS measurements
- The combination procedure is performed before QCD analysis using χ^2 minimisation

  - 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.

Results of Combining H1 and ZEUS Data

[JHEP01 (2010) 109]





The combination procedure yields a consistent data set:

- χ^2/dof=637/656

- 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!

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QCD Analysis Framework

- Data Sets:
  - HERA I combined data [JHEP01 (2010) 109]
    - NC e^-, CC e^-, CC e^+ (Q^2>100 GeV^2)
    - NC e^+ (Q^2>0.045 GeV^2)
  - Combined HERA I+high Q^2 HERA II data [prelim.]

→HERAPDF1.0

- QCD Fit settings:
  - NLO (and NNLO) DGLAP evolution equations
  - RT-VFNS (as for MSTW08)
    - Other schemes were investigated as well: RT (optimal), ACOT (full and χ), FFNS
  - PDF parametrised at the starting scale Q_0^2:

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

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

  - Apply fermion and momentum sum rules
  - The optimum number of parameters chosen by saturation of the χ^2
    - central fit with 10 free parameters
    - χ^2/dof=574/582

Scheme	TRVFNS
Evolution	QCDNUM17.02
Order	NLO
Q_0^2	1.9 GeV^2
$f_s = s/D$	0.31
Renorm. scale	Q^2
Factor. scale	Q^2
Q^2_{min}	3.5 GeV^2
$\alpha_S(M_Z)$	0.1176
M_c	1.4 GeV
M_b	4.75 GeV

QCD Analysis Framework

- **Data Sets:**
  - HERA I combined data [JHEP01 (2010) 109] → HERAPDF1.0
    - NC e⁻, CC e⁻, CC e⁺ (Q^2>100 GeV^2)
    - NC e⁺ (Q^2>0.045 GeV^2)
  - Combined HERA I+high Q^2 HERA II data [prelim.] → HERAPDF1.5

- **QCD Fit settings:**
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Sources of PDF uncertainties at HERA

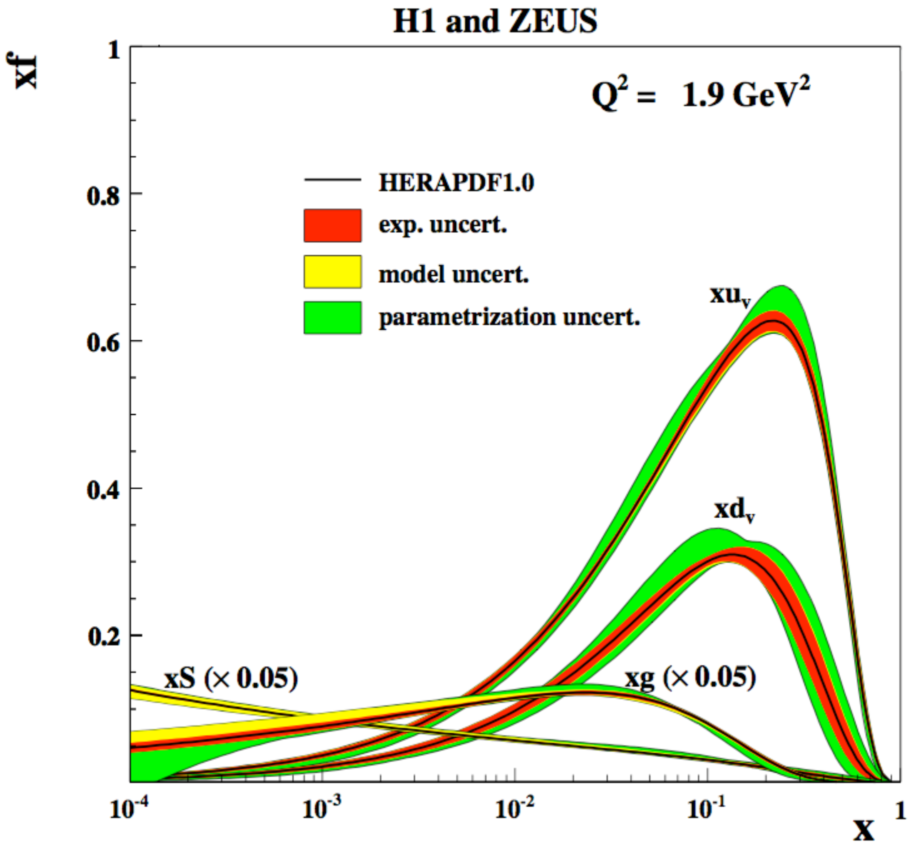
- **Experimental Uncertainties:**
  - Consistent data sets → use $\Delta\chi^2 = 1$
- **Model Uncertainties:**
  - following variations have been considered

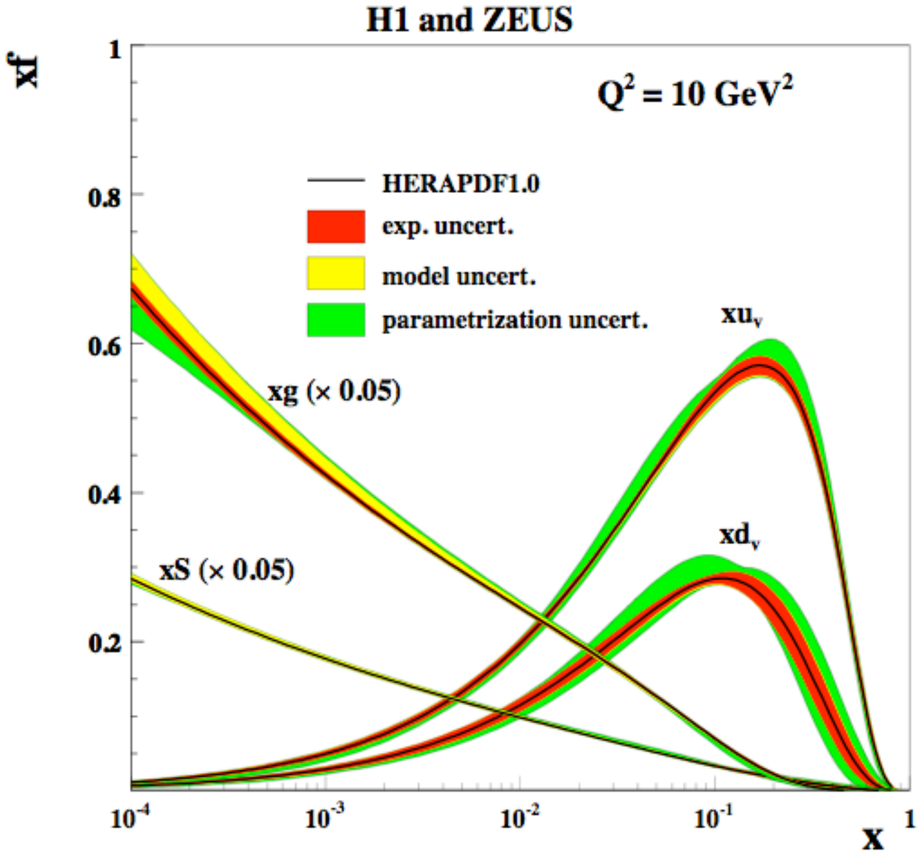
Variation	Standard Value	Lower Limit	Upper Limit
f_s	0.31	0.23	0.38
m_c [GeV]	1.4	1.35	1.65
m_b [GeV]	4.75	4.3	5.0
Q^2_{min} [GeV^2]	3.5	2.5	5.0

- **Parametrisation Uncertainties:**
  - An envelope formed from PDF fits using other variants of parametrisation form at the starting scale (especially sensitive to the higher x region):
    - Scanning of 11 parameter space
    - Q_0^2 variation and a more flexible gluon parametrisation

HERAPDF1.0 at NLO

- Starting Scale 10 GeV^2





xg, xu_v, xd_v, xS ($xS=x\bar{U}+x\bar{D}$)

- Observe valence like shape of the gluon at the starting scale.
- Parametrisation uncertainty dominates.

- HERAPDF1.0 set available in LHAPDF since v5.8.1 (Dec 2009)

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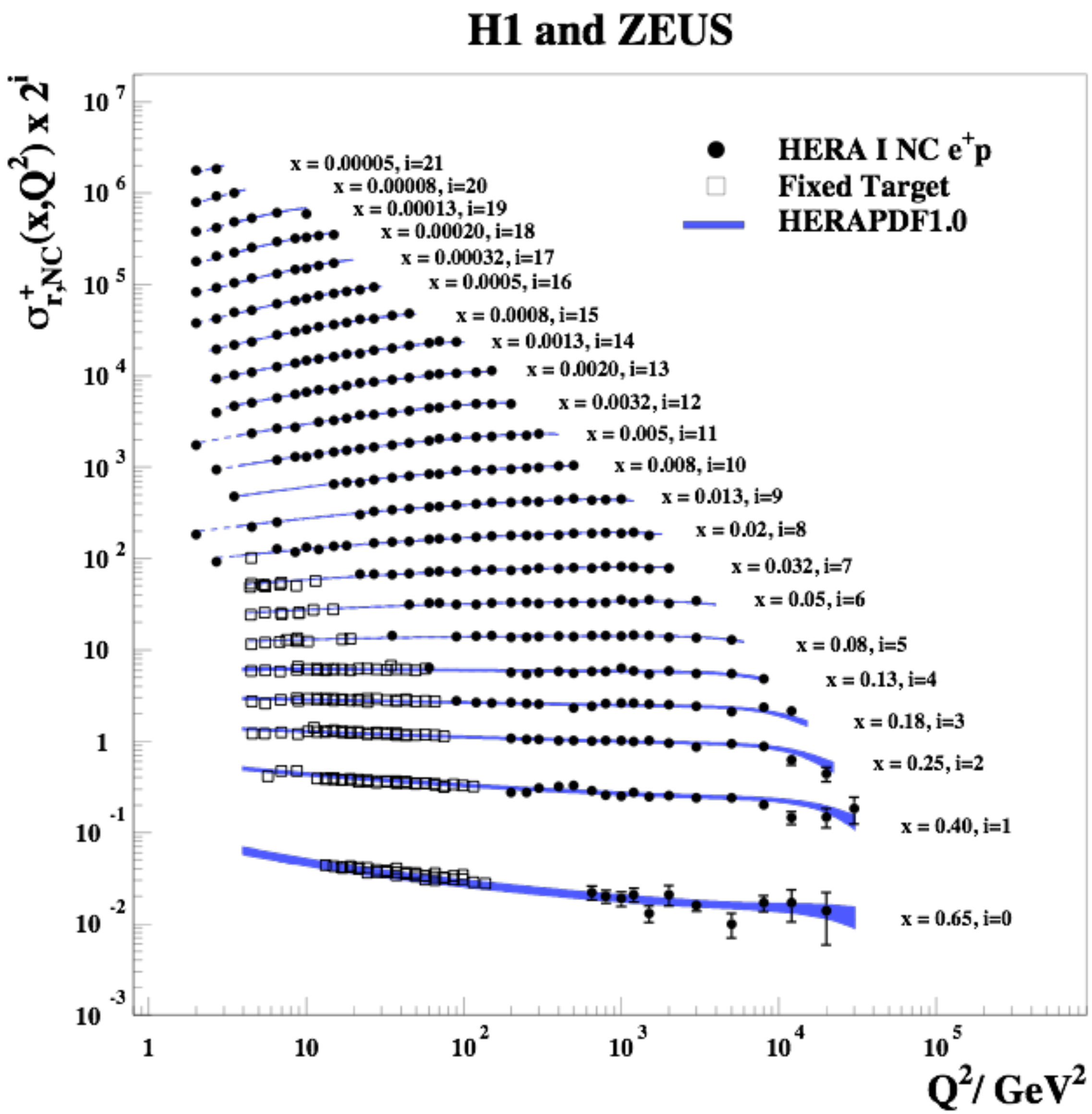
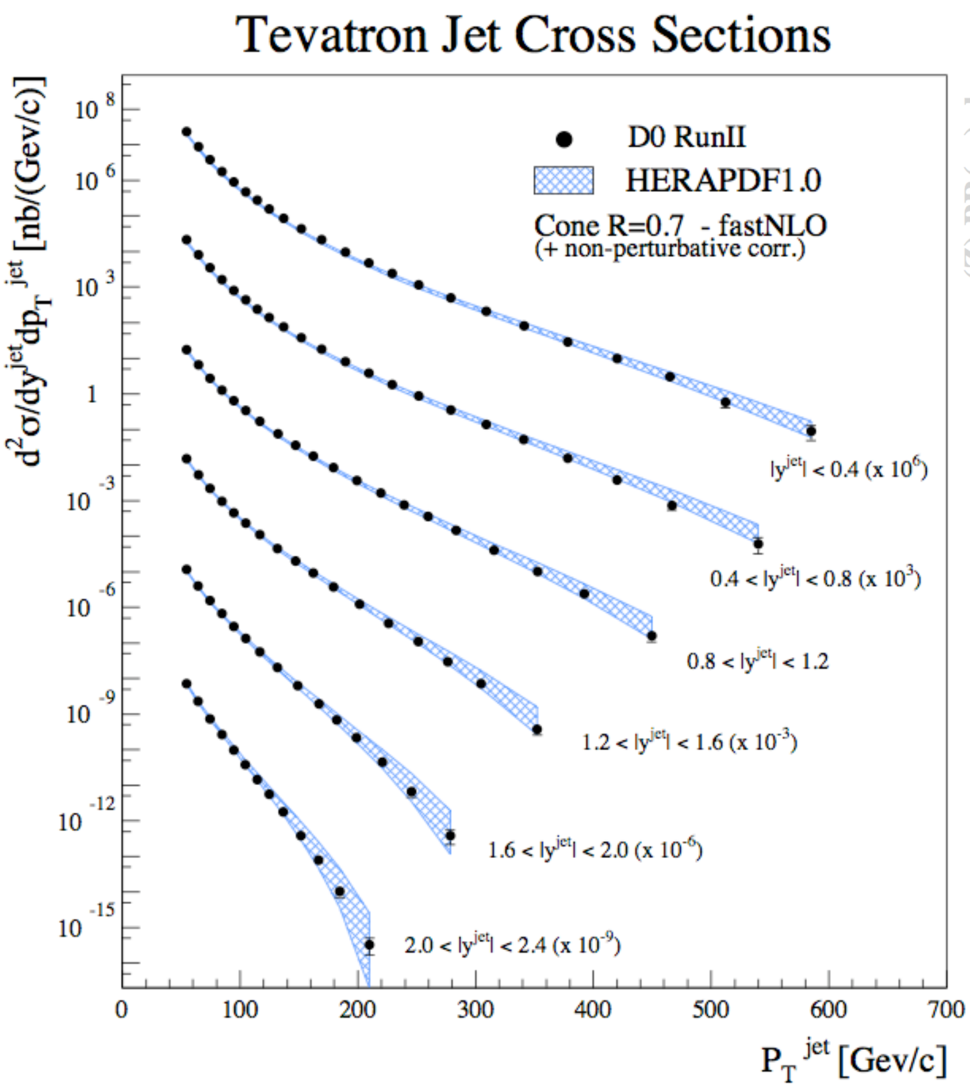
HERAPDF1.0 vs NC DIS Data

- Plots show the extended kinematic range of the HERA I data as compared to the fixed target measurements:
    - Data points include experimental errors
    - Fit line includes total error
- HERA data extends to x=0.65 for Q^2>500 GeV^2, clean high x probe at high W
- HERAPDF1.0 fit describes HERA data well
- Extrapolation of the HERAPDF1.0 fit agrees well with fixed target data
    - (SLAC and BCDMS)!



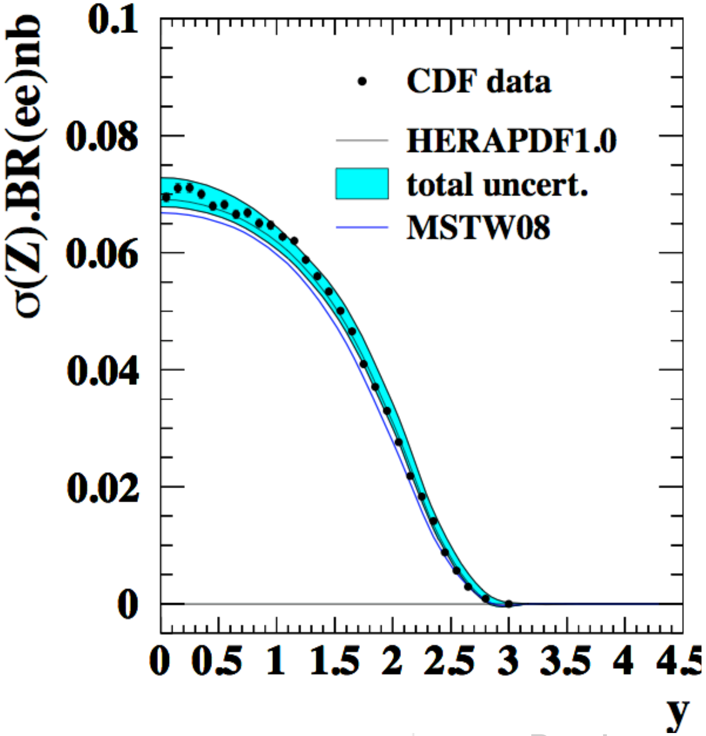
HERAPDF1.0 vs Tevatron Data

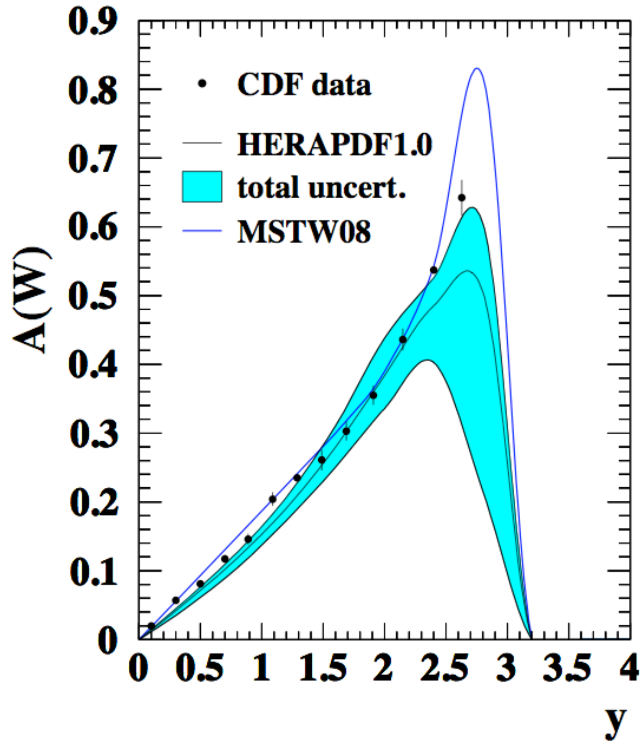


- Predictions for high-E_T jet cross-sections with full uncertainties compared to the D0 data
- DIS data from HERA predicts Tevatron jets production from ppbar process.
- Z and W at Tevatron are well predicted by HERAPDF1.0

- Hence, there is a universal description of partonic processes and all can be described with: HERA input, SM couplings and pQCD evolution!

HERAPDF1.0 vs Tevatron Data





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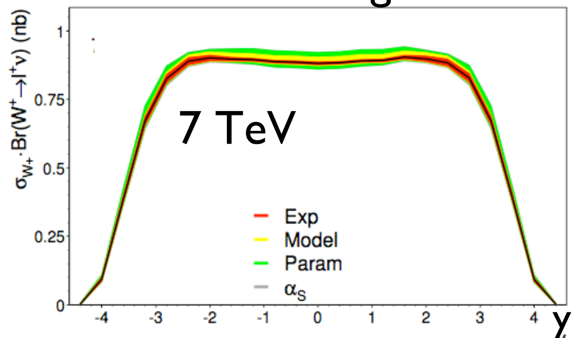
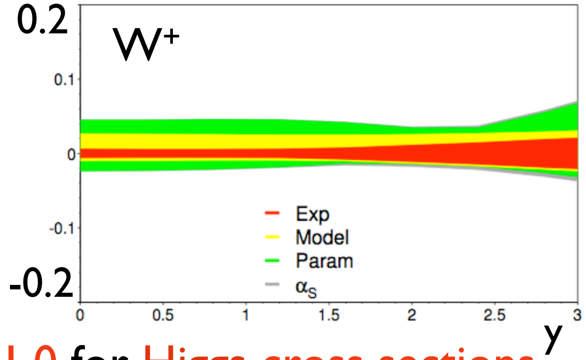
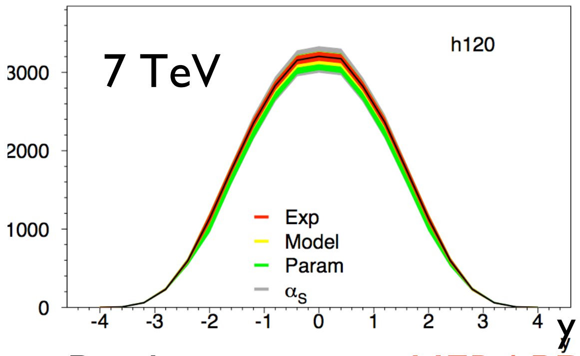
LHC predictions based on HERAPDF1.0

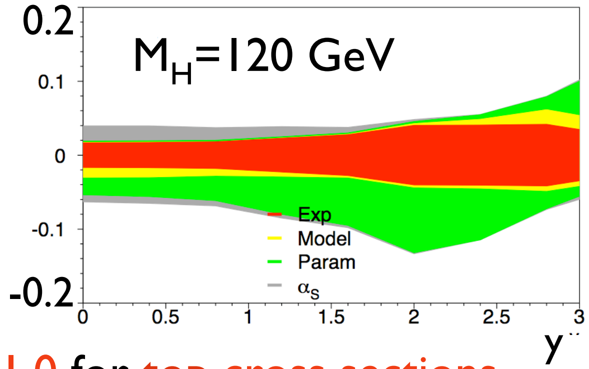
- Predictions using HERAPDF1.0 for W cross sections.



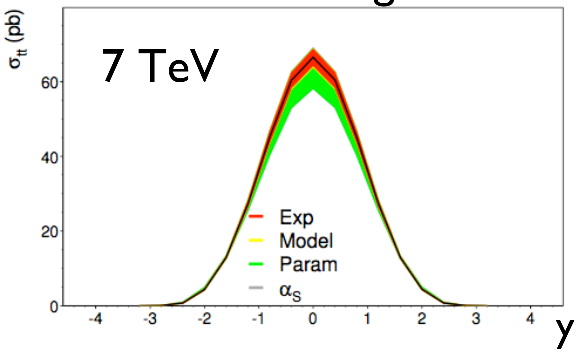


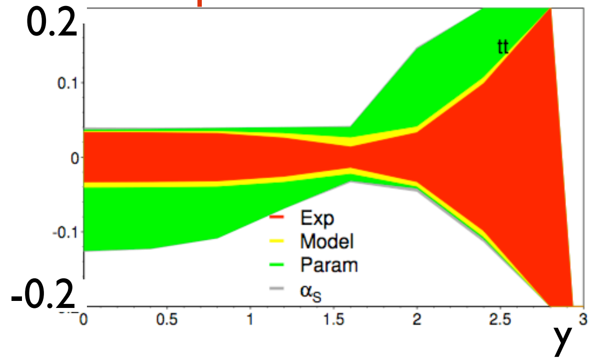
- Predictions using HERAPDF1.0 for Higgs cross sections.





- Predictions using HERAPDF1.0 for top cross sections.





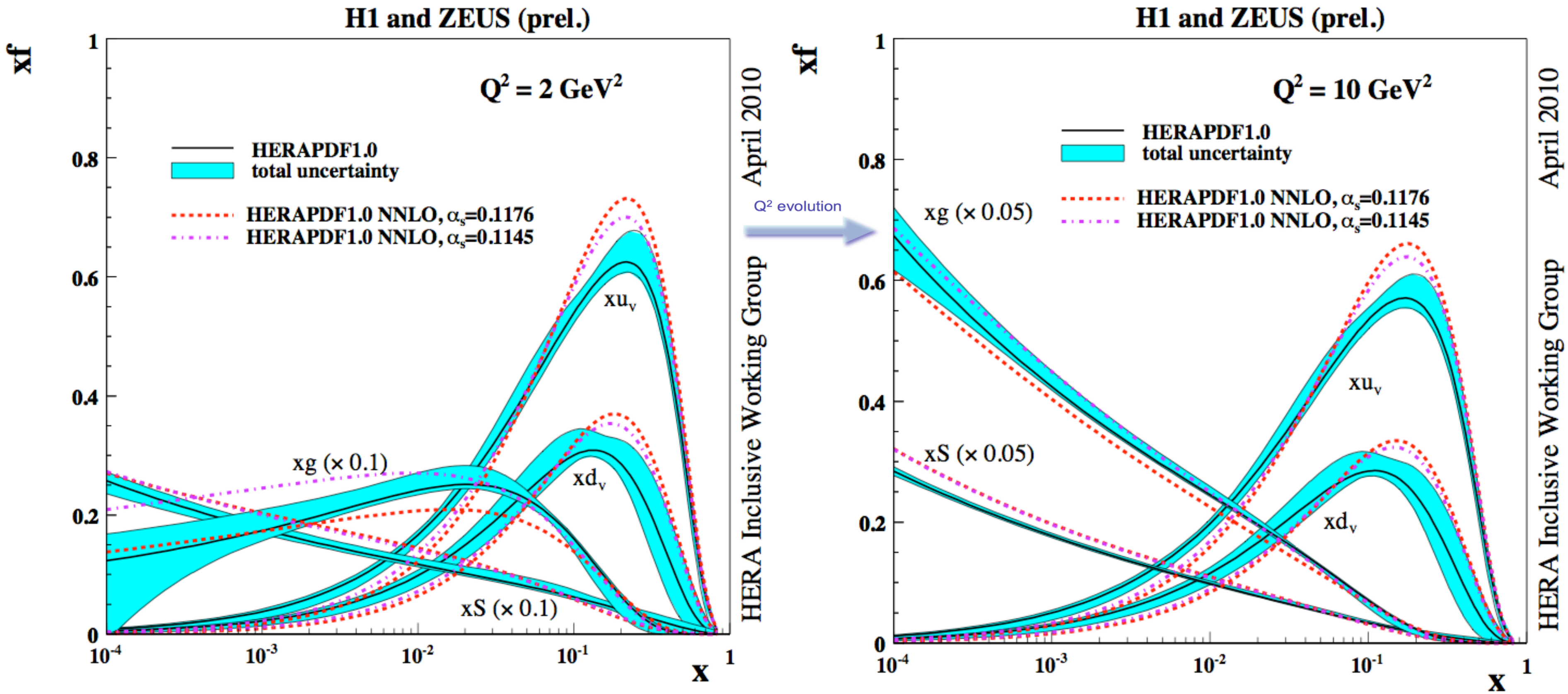
Uncertainties:

- Experimental
- Model
- Parametrisation
- α_S variation

Exciting new times ahead to actually compare the predictions to real measurements from the LHC!

HERAPDF fits at NNLO

- Fits performed to HERA I data (as used for HERAPDF1.0) at NNLO using RT-VFNS:
  - α_S(Mz) at NNLO = 0.1176 and α_S(Mz) at NNLO = 0.1145



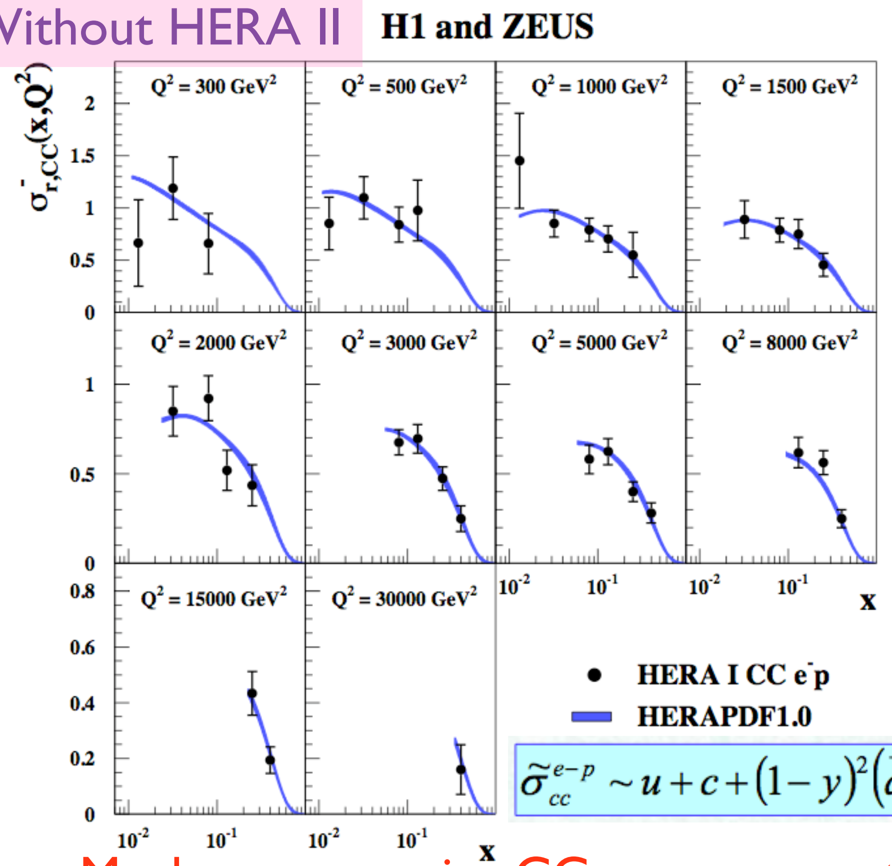
scheme	NNLO α_S(Mz)=0.1145	NNLO α_S(Mz)=0.1176	NLO α_S(Mz)=0.1176
All χ^2/dof	623.7/582	638.3/582	574.4/582

- Using the same settings as for HERAPDF1.0 NNLO fit does not improve fit results.
- Lhapdf grid files available at:
  - https://www.desy.de/h1zeus/combined_results/index.php?do=proton_structure

Combining HERA I and II Inclusive data

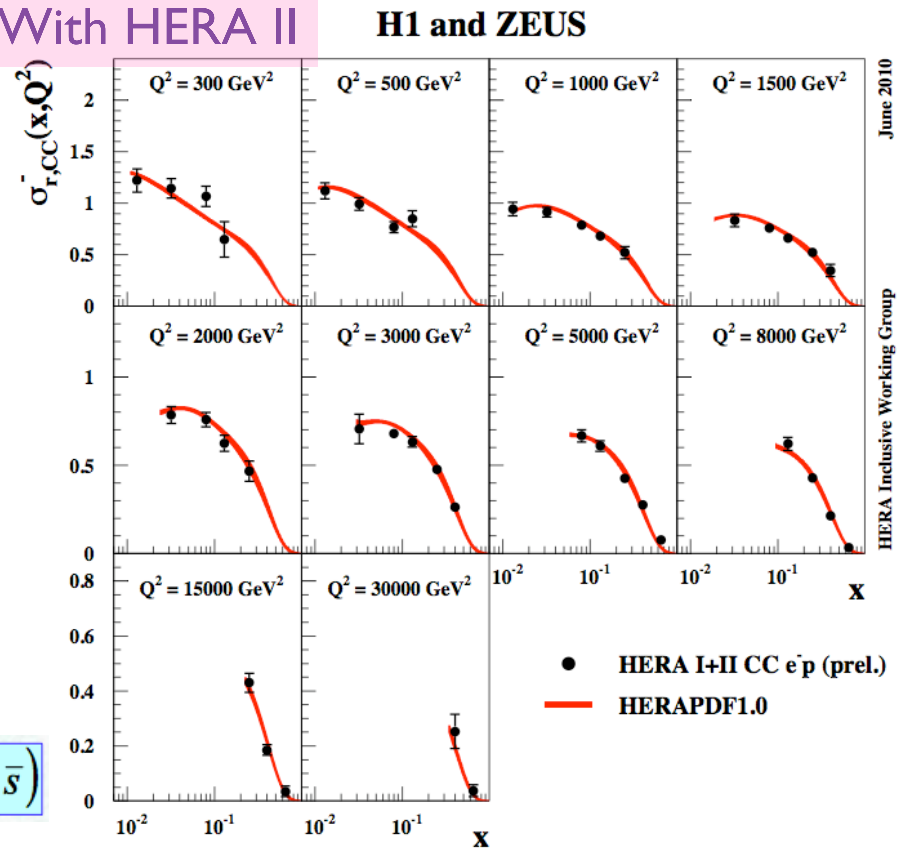
- New HERA II preliminary data available!
  - More precise measurements in the high Q^2 and high x regions (especially NC e^-p and CC $e^{\pm}p$)
  - ➔ could constrain better PDFs at high x
- HERA I and HERA II are combined using same averaging procedure as described before:
  - 674 unique cross sections points with 134 sources of systematic uncertainties

Without HERA II



$$\tilde{\sigma}^{e^-p}_{cc} \sim u + c + (1-y)^2(\bar{d} + \bar{s})$$

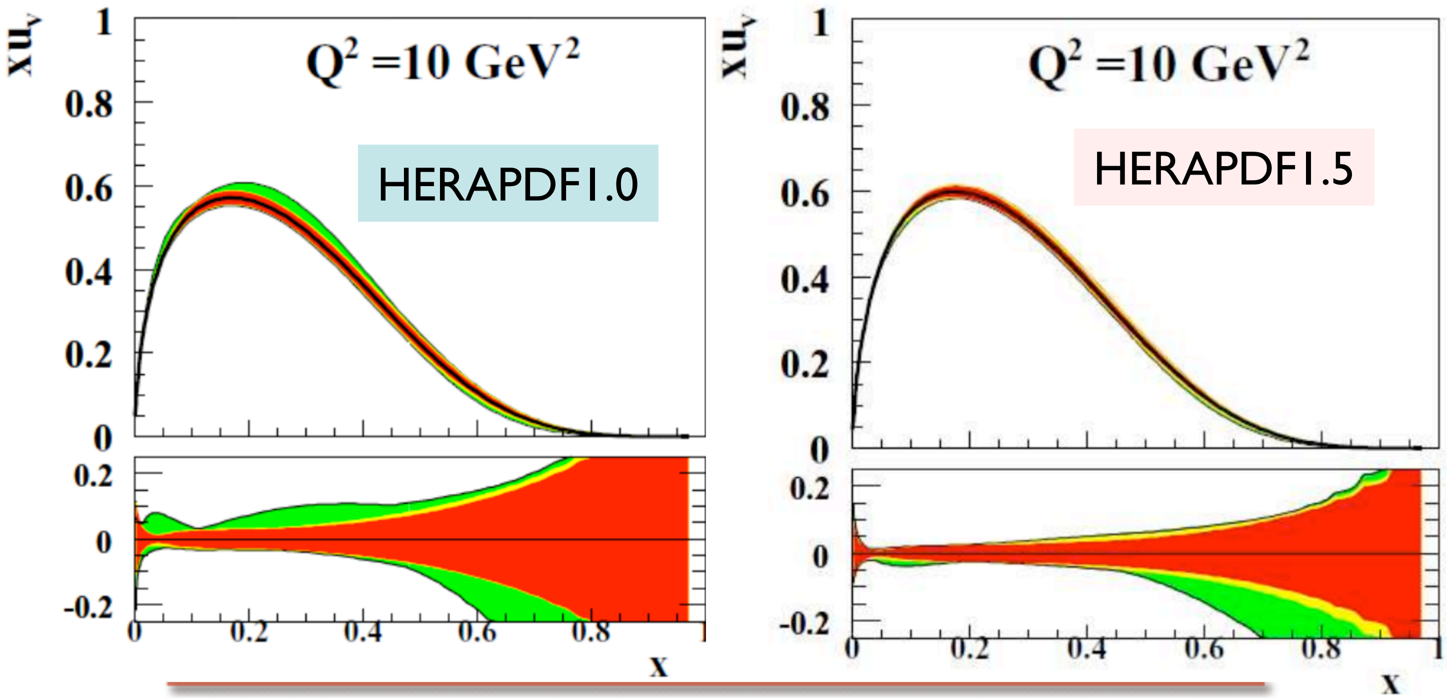
With HERA II



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

Fits to New Combined HERA data: HERAPDF1.5

- Propagate new data through QCD fit analysis to produce a new set of HERAPDFs: HERAPDF1.5
  - For preliminary studies use same settings as for HERAPDF1.0
  - Parametrisation uncertainty will be further investigated for final release.



⇒Experimental uncertainty reduced
⇒Parametrisation uncertainty reduced

- "HERAPDF1.0"

SET	Data	points	RT	ACOT
TOT	χ^2	582(dof)	574	560

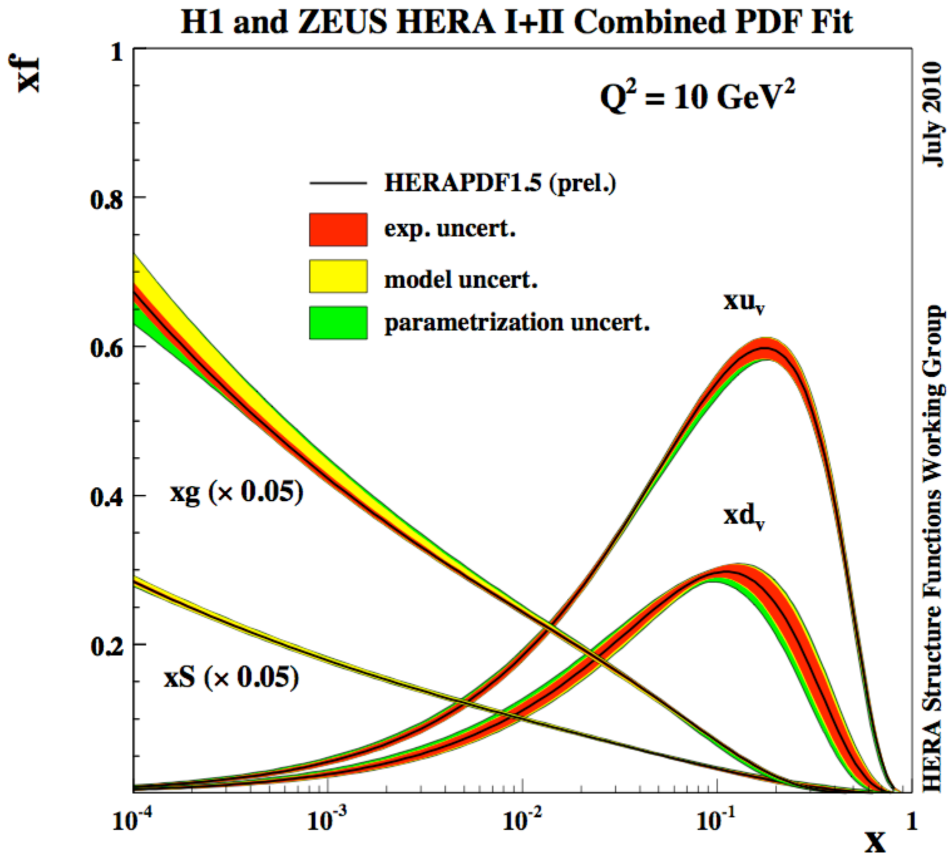
- "HERAPDF1.5"

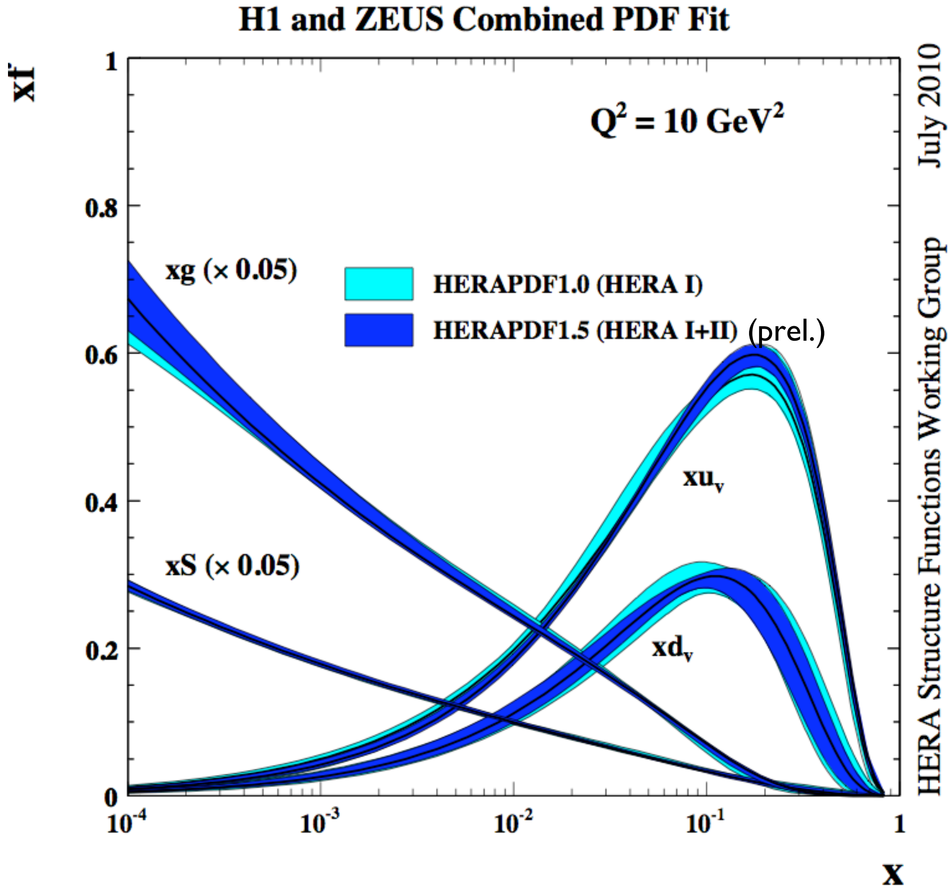
SET	Data	points	RT	ACOT
TOT	χ^2	664(dof)	761.8	754.6

The χ^2 increased due to the precision of data (especially CC)

HERAPDF1.5 vs HERAPDF1.0

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

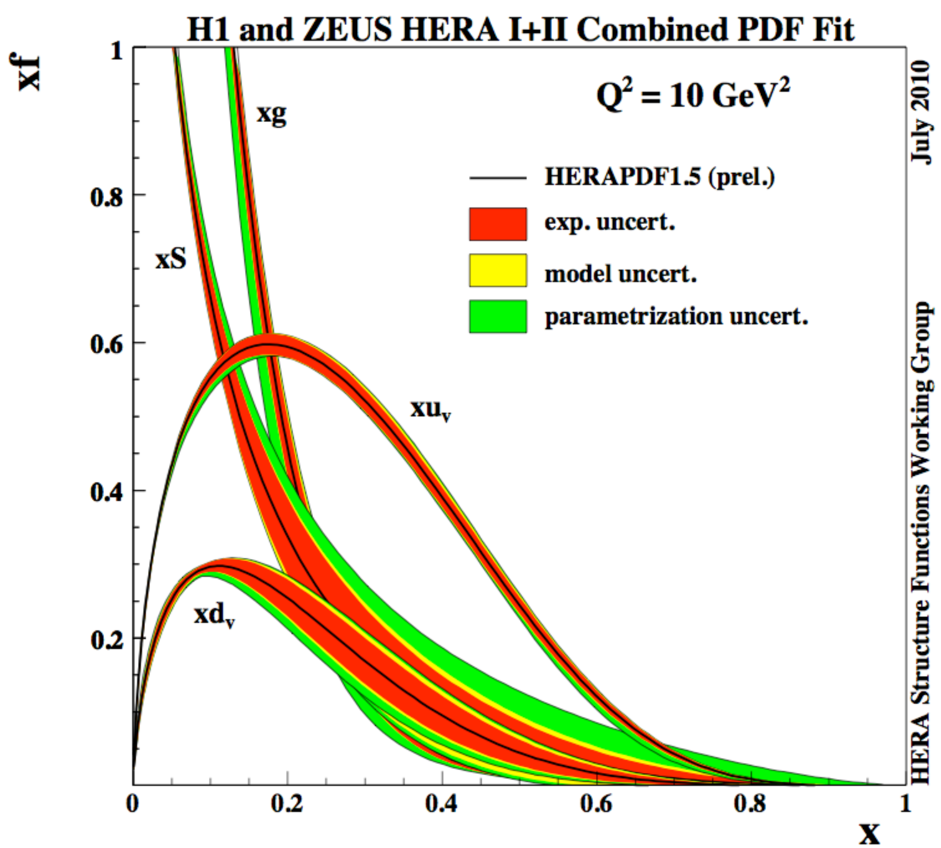


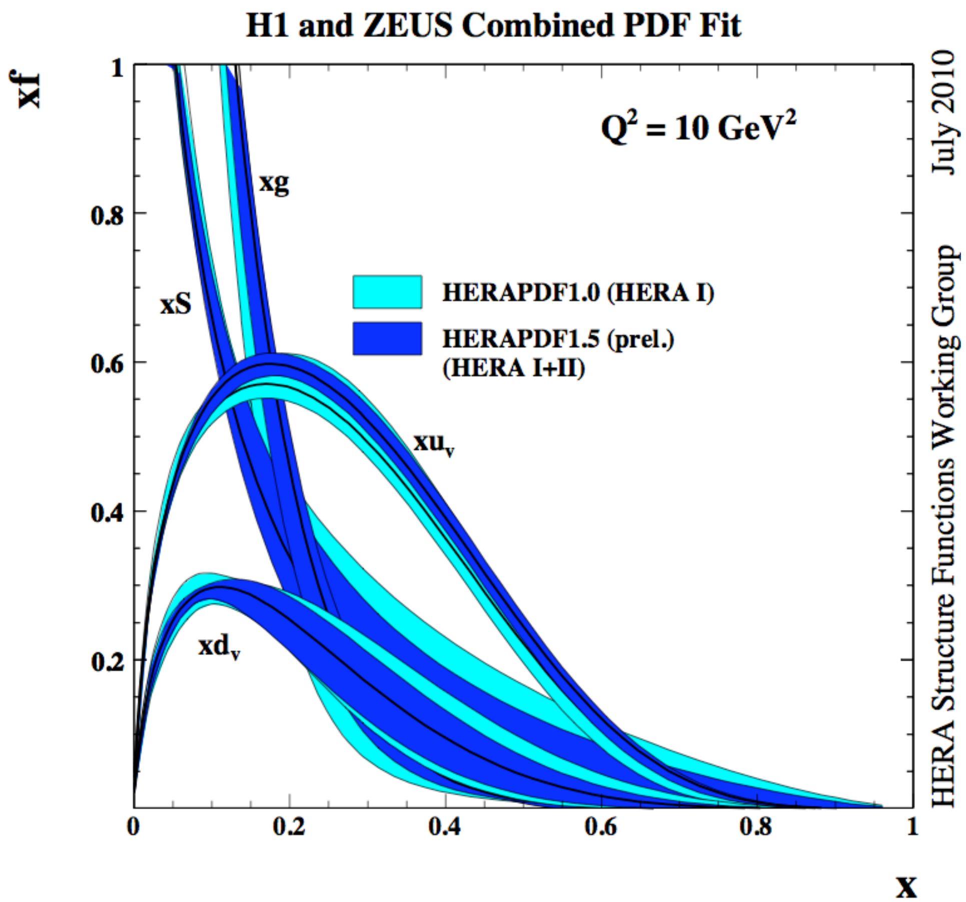


- Inclusion of the HERA II data reduces the uncertainties on PDFs in the high x region especially visible on the valence distributions!
  - See HERAPDF1.5(prel) vs HERAPDF1.0

HERAPDF1.5 vs HERAPDF1.0

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





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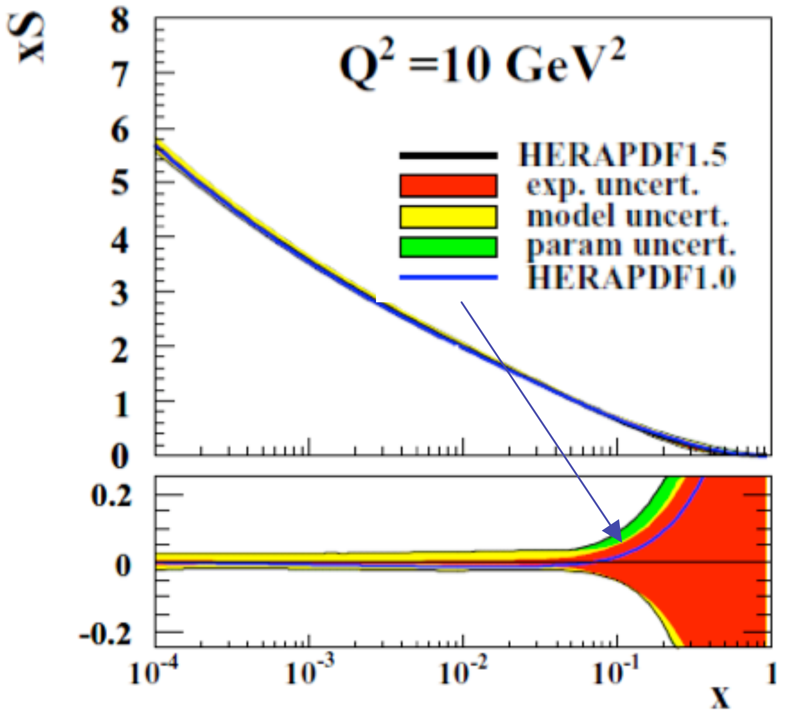
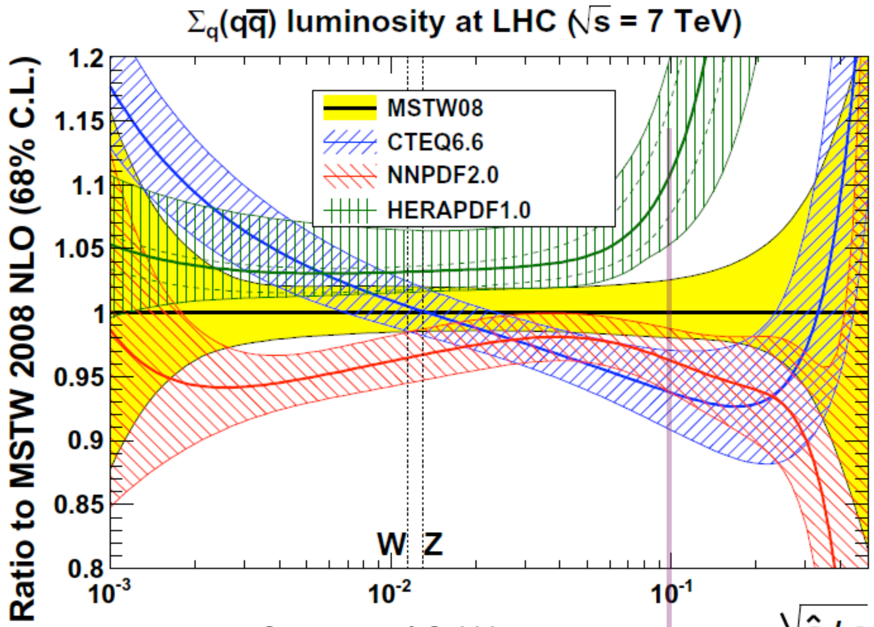
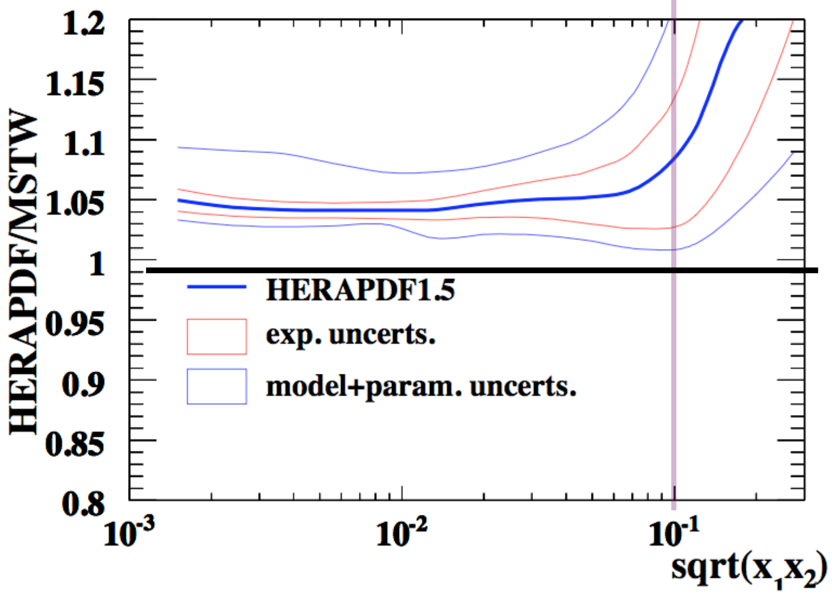
Impact on the LHC



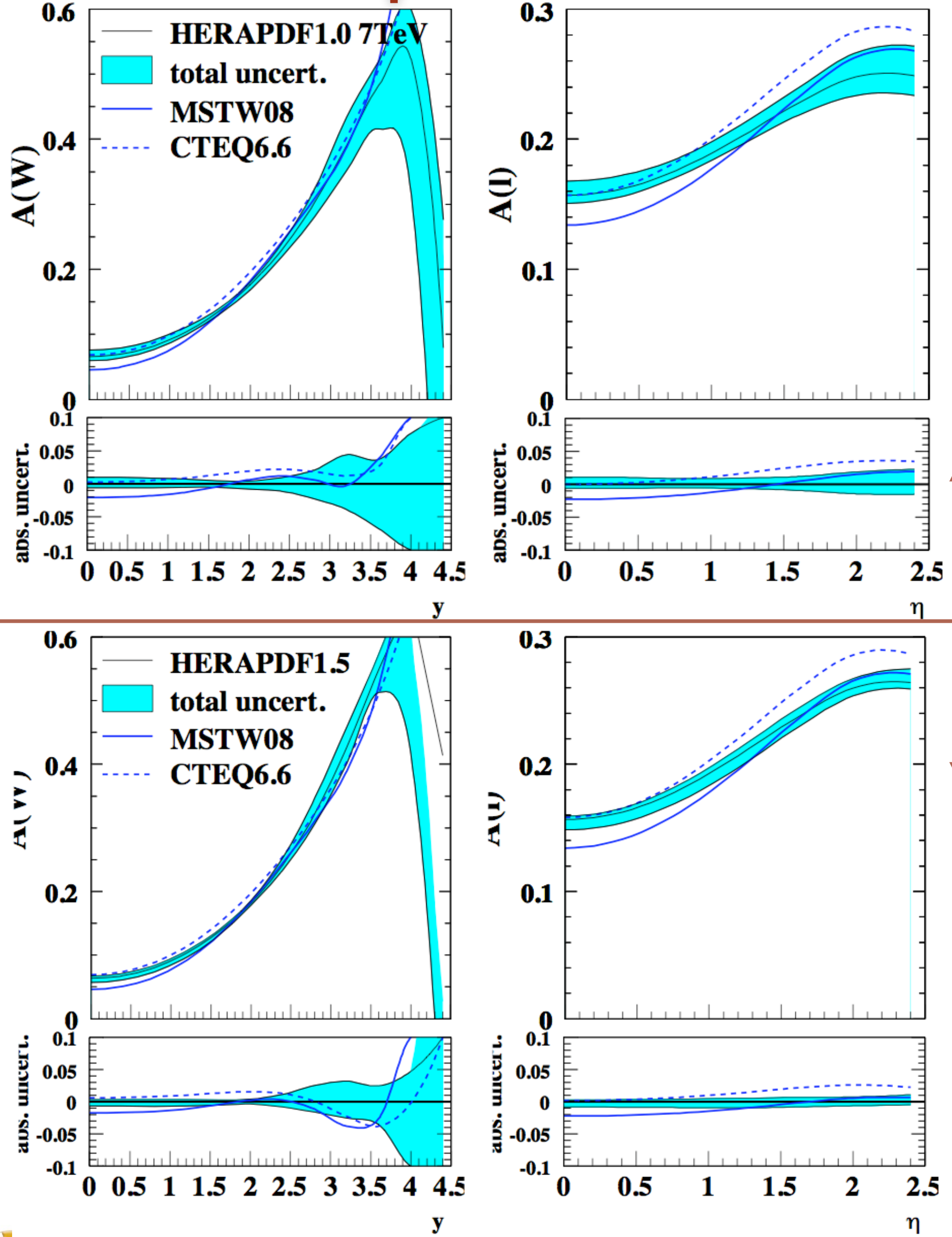


Courtesy of G. Watts



- HERAPDF1.0 is high at the large scale because sea is hard at high x.
- HERAPDF1.5 has a softer sea.

LHC predictions for W and lepton asymmtries



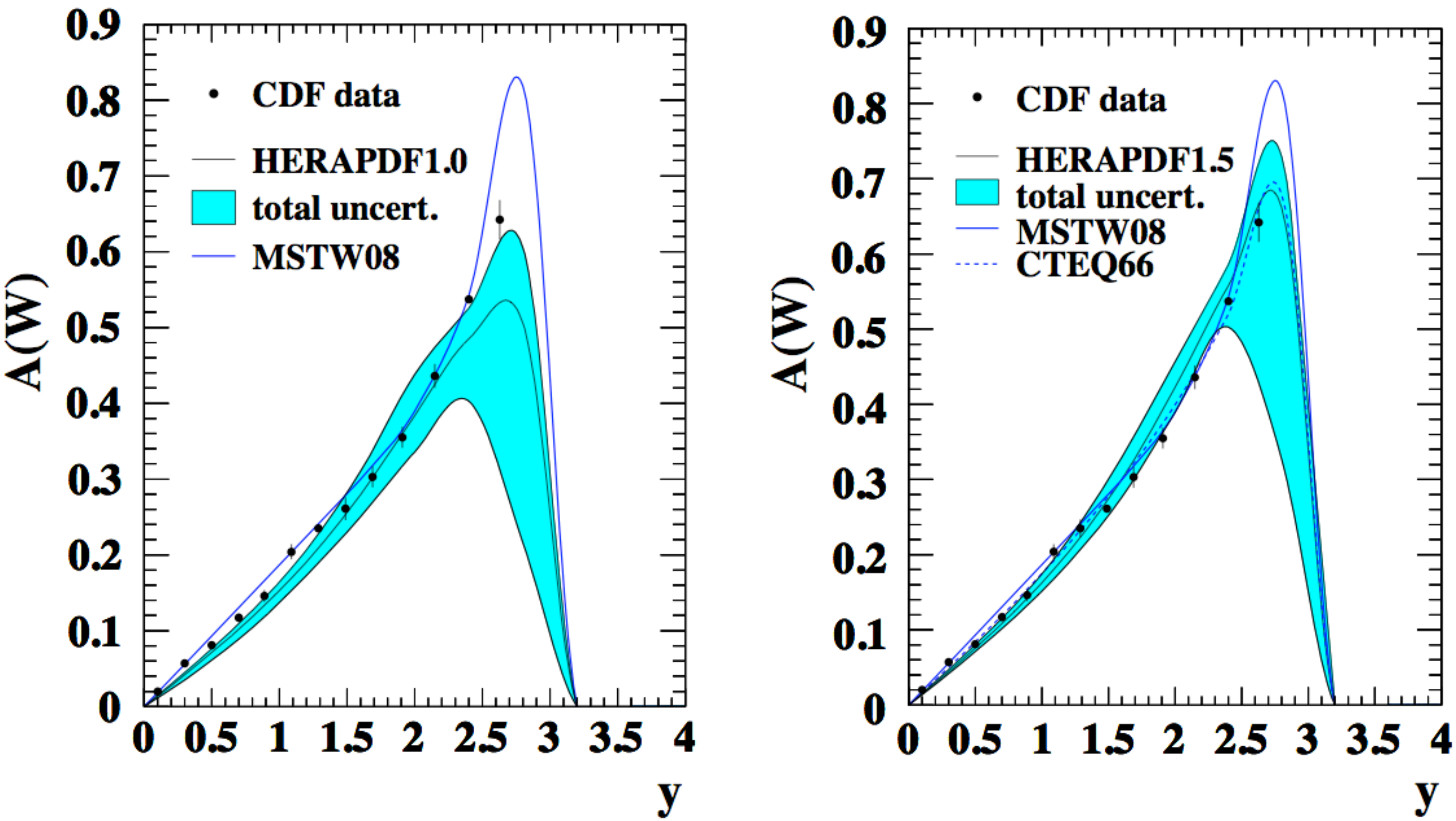
Impact of inclusion of HERA II data:

- ➔ The uncertainties are reduced for the predictions using HERAPDF1.5 compared to HERAPDF1.0

HERAPDF1.0

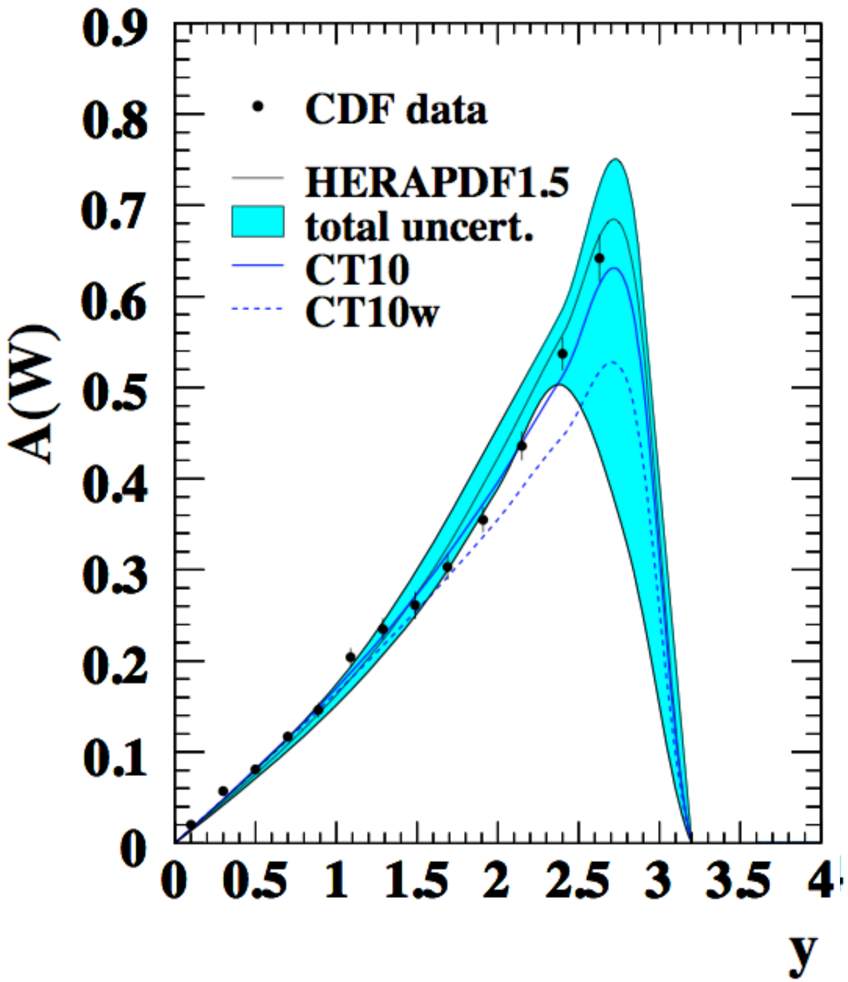
HERAPDF1.5

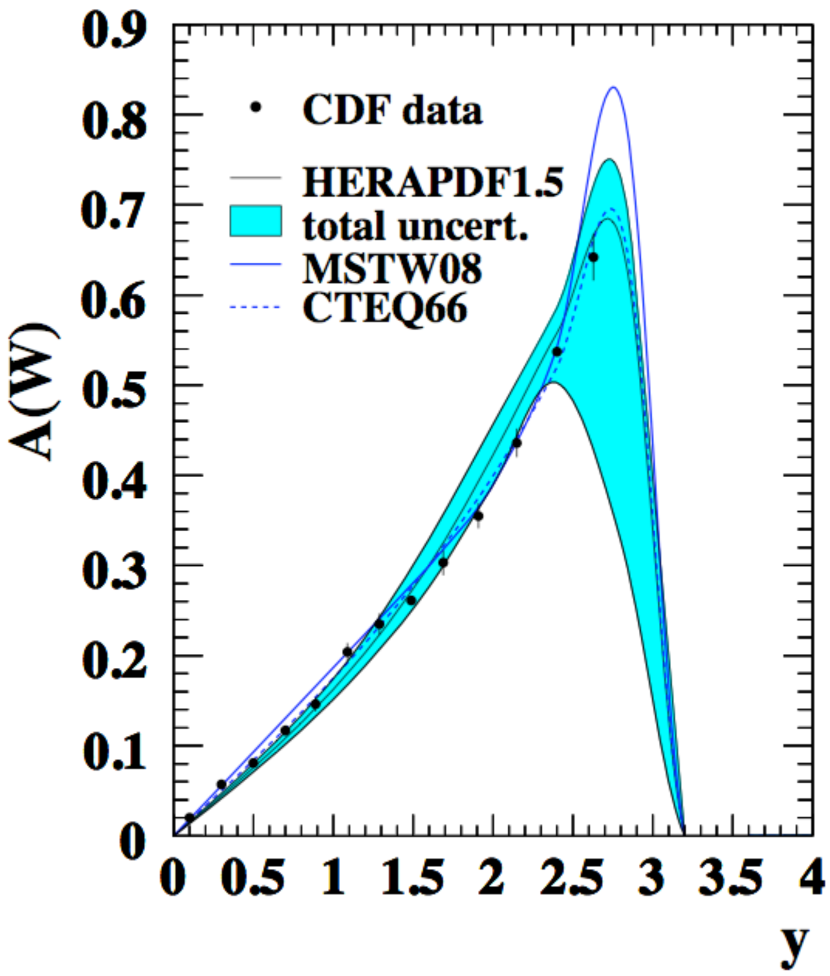
Comparison to Tevatron W asymmetry



- HERAPDF1.5 results in a better agreement than HERAPDF1.0 with the CDF data for the W asymmetry, even if this data is not included in the HERA fits.

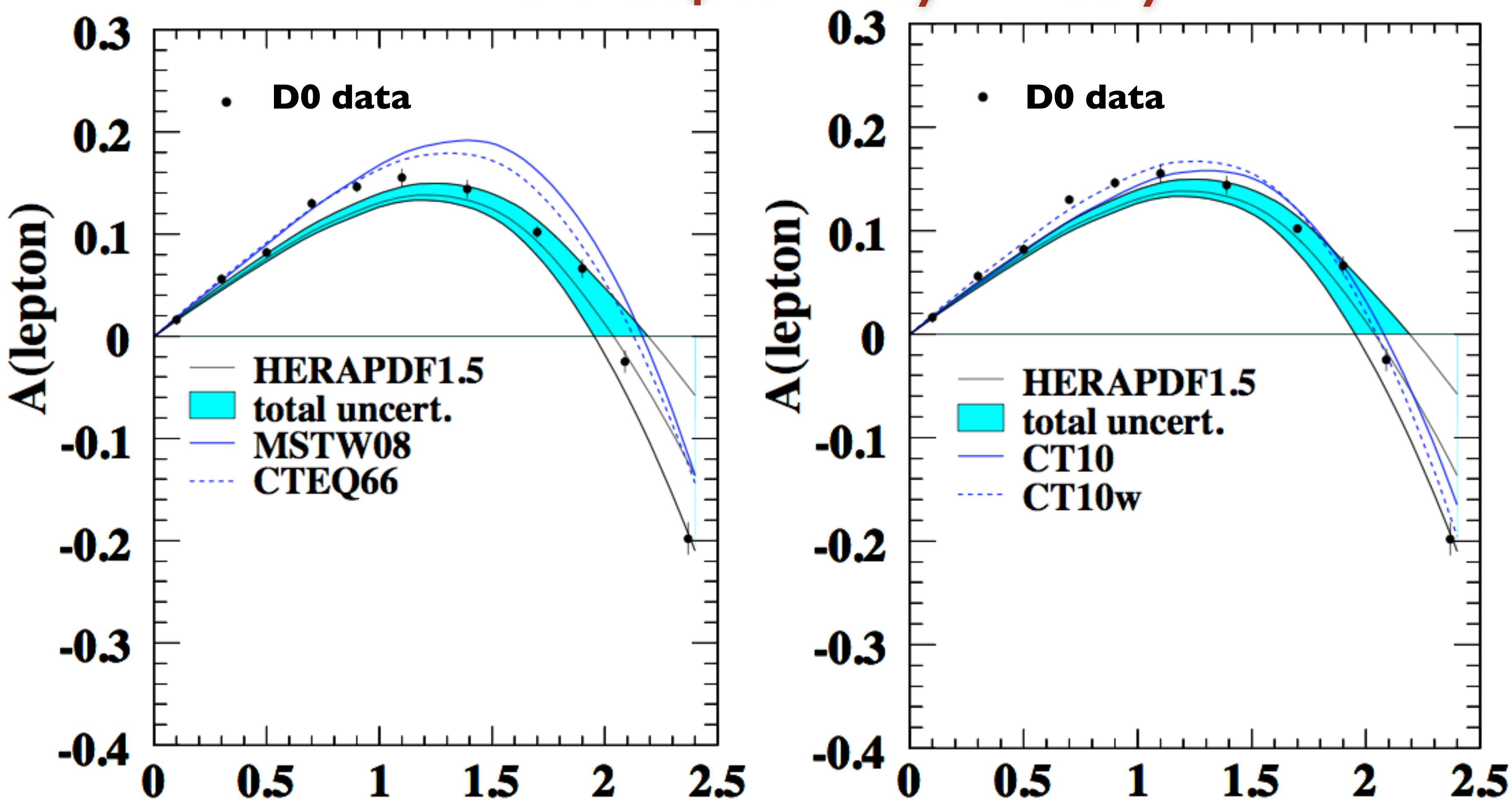
Comparison to Tevatron W asymmetry





- HERAPDF1.5 compared to Global PDF sets

D0 Lepton Asymmetry



- HERAPDF1.5 provides a reasonable agreement even with the D0 lepton asymmetry, for which the global fits have difficulties.
  - HERA ep data do not require assumptions on isospin symmetry and heavy target corrections

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Summary

- HERA provides accurate determination of the proton structure and can predict related Standard Model processes:
  - HERA ep data do not require assumptions on isospin symmetry and heavy target corrections

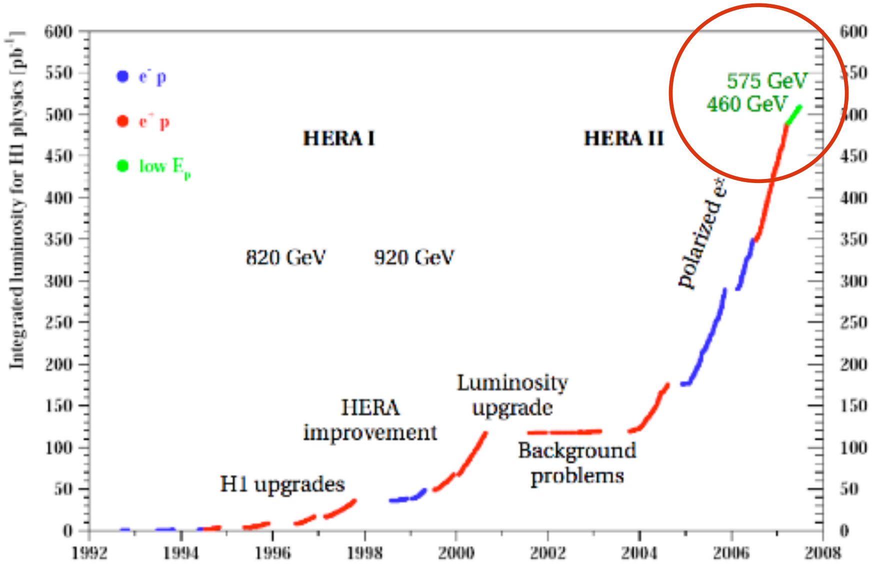
- New preliminary measurements from HERA II included in the QCD Analysis
  - Precise new measurements at high Q^2 with constraining power in the high x region
    HERAPDF1.5 [prelim]
  - Provides more precise predictions for LHC than HERAPDF1.0
  - Provides good predictions for the W and lepton asymmetries measured at Tevatron

▿ LHAPDF grid files for HERAPDF1.5 with the full uncertainties can be found at:

https://www.desy.de/h1zeus/combined_results/index.php?do=proton_structure

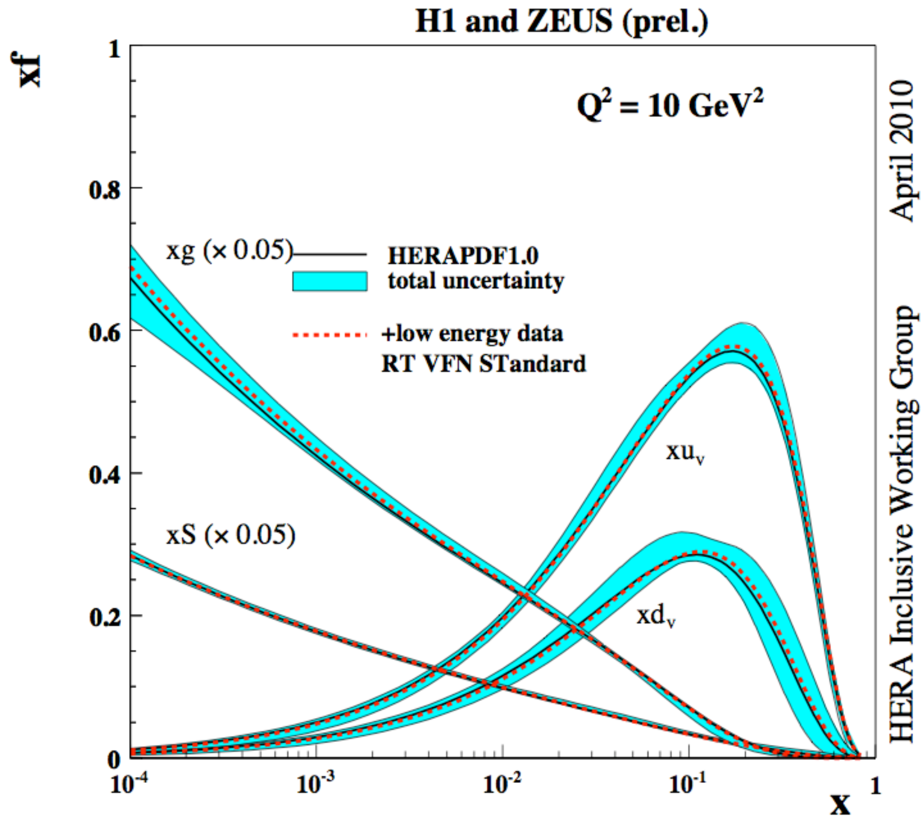
Backup

HERAPDF including Low Energy data



- Preliminary HERA Combined Low Energy data available!

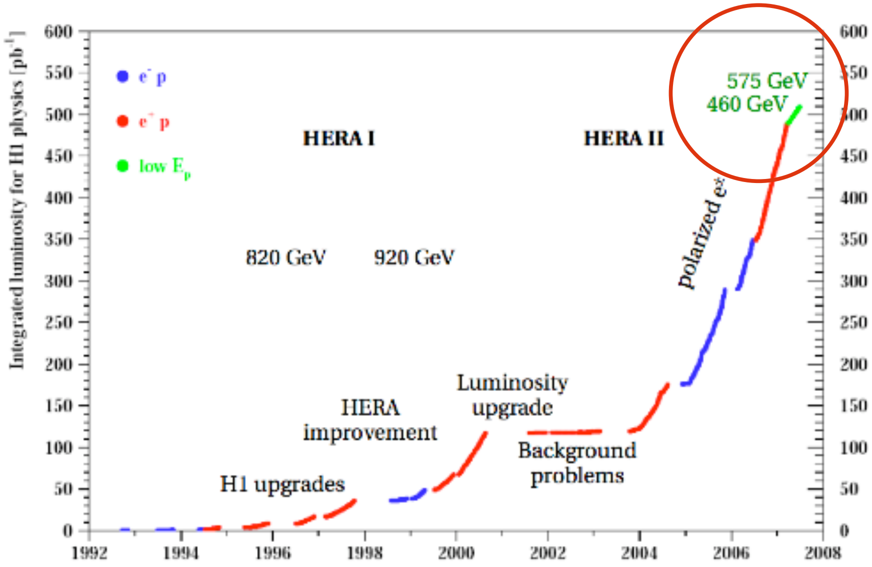
- New accurate measurement in Q^2>2.5 GeV^2 range, sensitive to structure function F_L are included in the QCD analysis on top of the HERA I data➔



- PDFs from the new fit agree very well with HERAPDF1.0

Data sets	HERAPDF1.0	+ Low Energy data
Total χ^2/dof	574/582	818/806

HERAPDF including Low Energy data



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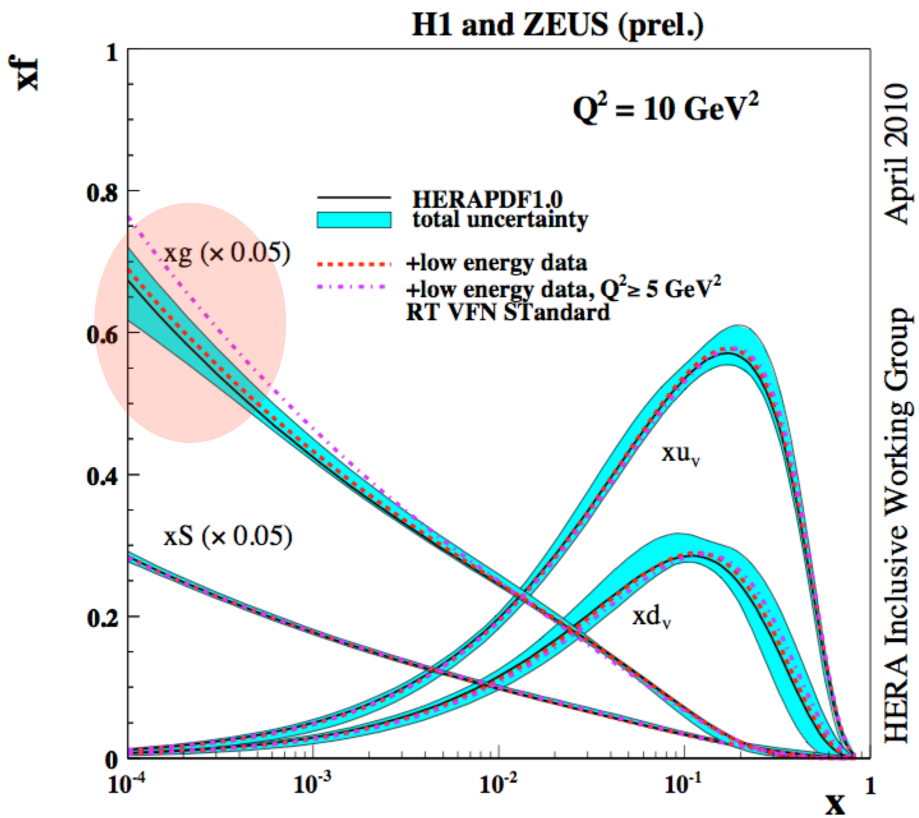
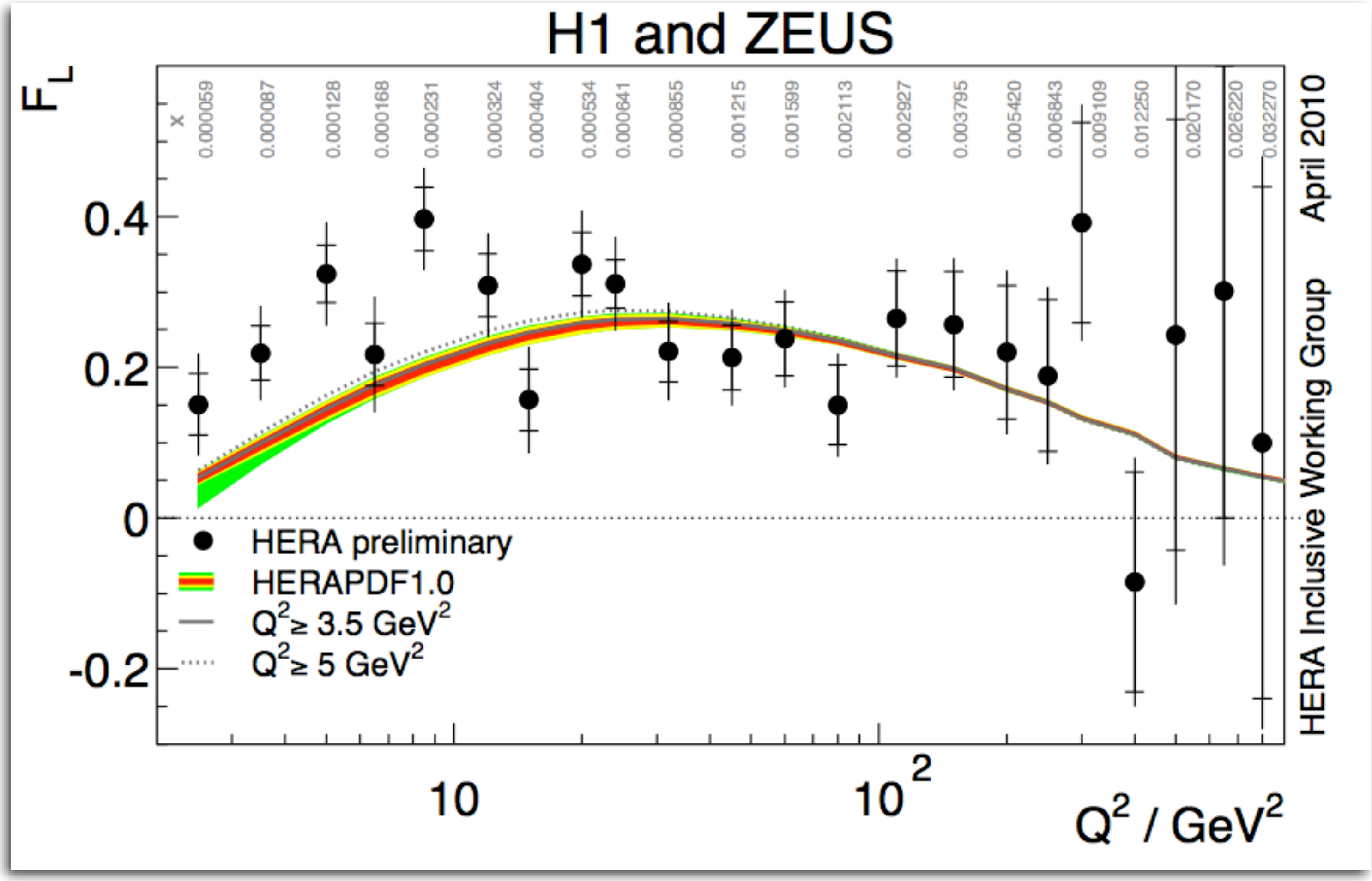
- New accurate measurement in Q^2>2.5 GeV^2 range, sensitive to structure function F_L are included in the QCD analysis on top of the HERA I data➔



- However, The $Q^2 \geq 5$ GeV^2 cut brings large improvement in χ^2 [818/806 → 698/771] and it yields different shapes for gluon and sea PDFs.
  - for HERAPDF1.0, Q^2 cut variation is included in the model uncertainty, but it had smaller effect.

HERA F_L data vs F_L predictions

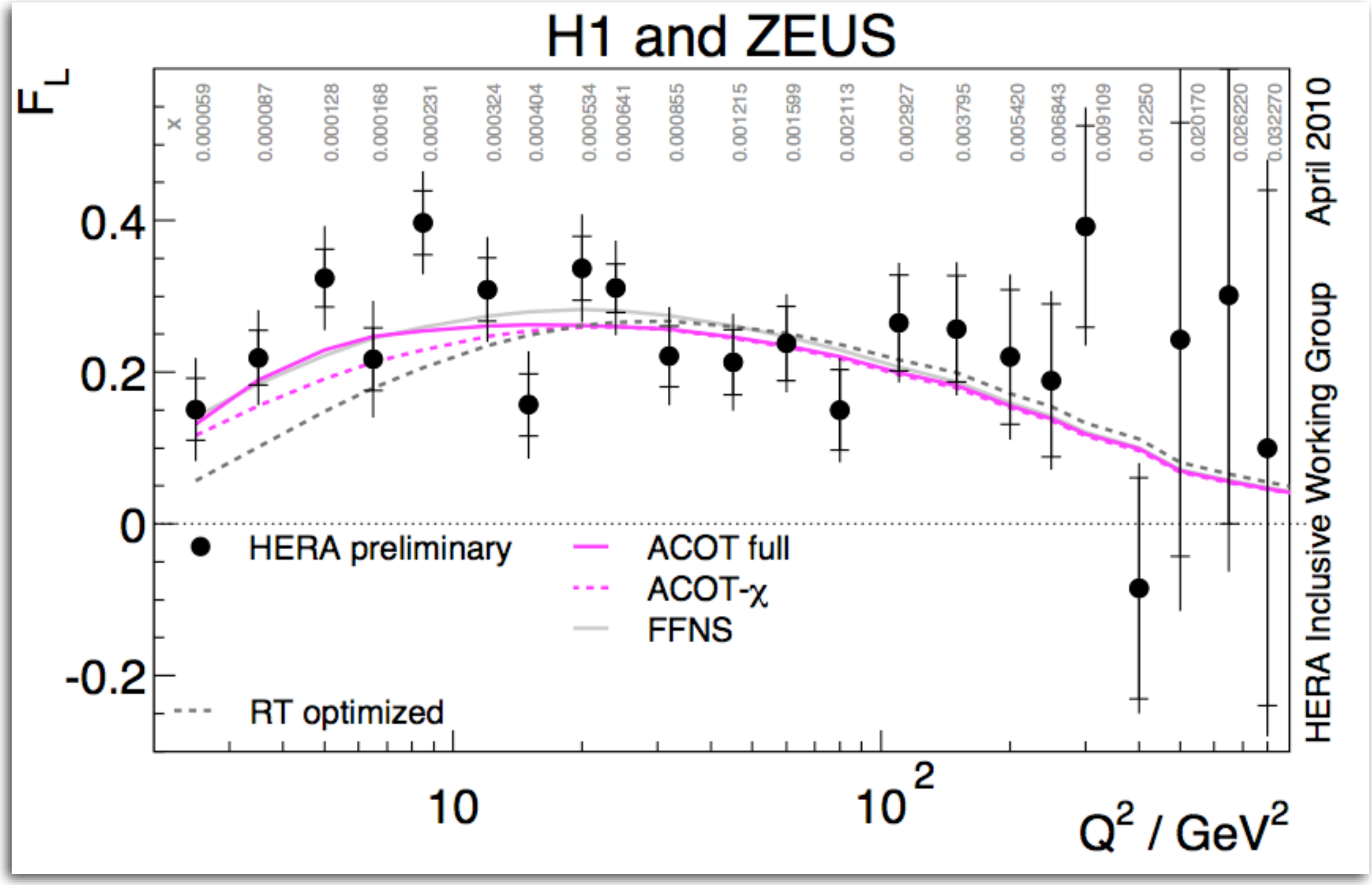
The lines are F_L predictions using combined HERA I and low energy data.



Low Q^2 region remains very interesting for further QCD tests!

HERA F_L data vs F_L predictions

The lines are F_L predictions using combined HERA I and low energy data.



Various Heavy Flavour schemes: best ACOT(full) and FFNS

More on PDF parametrisation at HERA

- PDFs that are parametrised at a starting scale Q_0^2=1.9 GeV^2 (below M_c^2) are:

$$xg, xu_v, xd_v, x\bar{U} = x\bar{u}, x\bar{D} = x\bar{d} + x\bar{s}$$

- A standard functional parametrisation form is used:

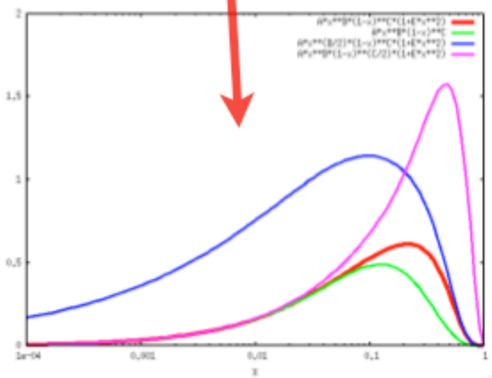
$$xf(x, Q_0^2) = Ax^B(1-x)^C(1 + Dx + Ex^2)$$

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

  - It describes the shape of PDFs with few input parameters
    - The number of parameters are chosen by saturation of the χ^2

  - The parametrisation for the best fit (central fit):

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



  - The number of free parameters is reduced by the physics constraints such as:
    - normalisation parameters A_g, A_{uv}, A_{dv} by the quark number and momentum sum-rules
    - B parameters so that there is one for sea and another one for valence distributions
    - Ensure that $x\bar{u} \to x\bar{d}$ as $x \to 0$.

  - The best fit results in 10 free parameters