Precision Measurements of the Proton Structure and physics at the LHC

Voica Radescu

Heidelberg Physikalisches Institut

Centre de Physique des Particules de Marseille

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- Analysis Methods
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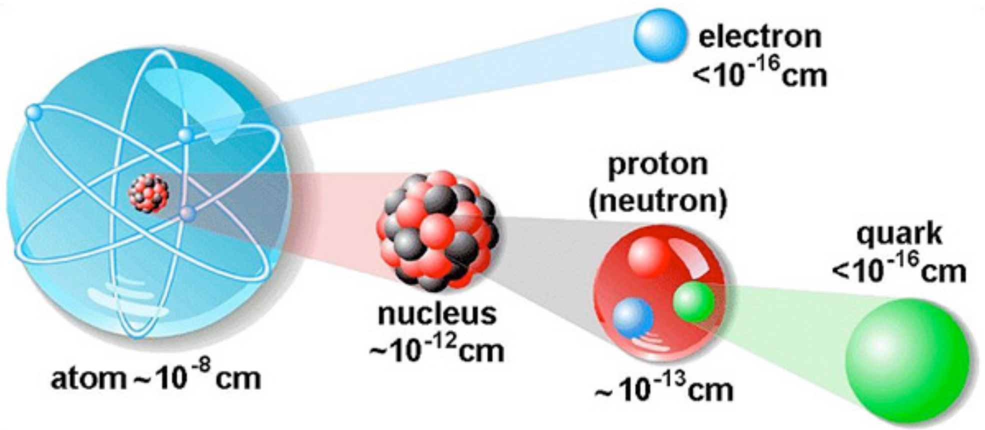
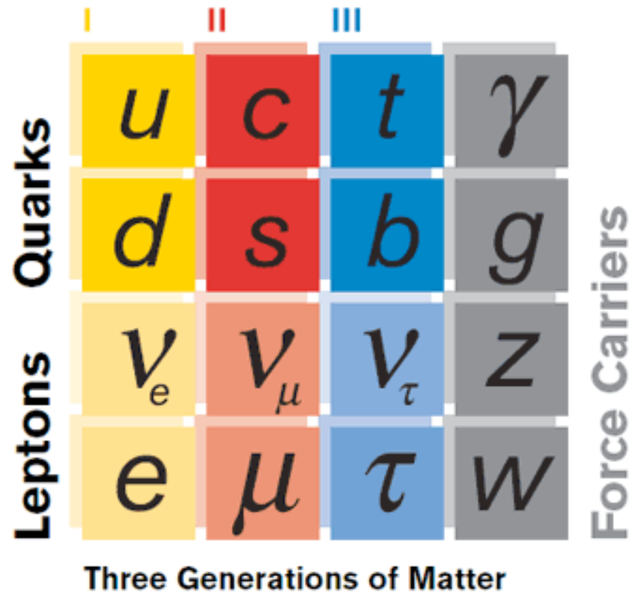
- Summary

Introduction

Buildings Blocks of the Standard Model



- Bosons
  - force carrier particles
- Fermions (quarks and leptons)
  - constituents of matter
  - Arranged in three generations of doublets in increasing mass:



- SM a triumph in particle physics, but there are still questions that remain unanswered.
- LHC provides a rich physics potential ranging from more precise measurements of SM parameters to the search of new physics phenomena.
  - Understanding the complex structure of the proton is important for interpretation of the LHC results.

Probing the Proton Structure

- Proton can be probed via elementary particles as:
  - neutrinos (fixed target experiments) - interact only weakly
  - electrons (fixed target and collider experiments) - interact electroweakly

- **Deep Inelastic Scattering (DIS)** is a tool to study the substructure of nucleon
  - scattering of a lepton off the quarks within the proton resulting into a hadronic shower and a lepton

- Kinematic Variables:
  - virtuality of exchanged boson

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

  - proton momentum fraction of the scattered quark (Bjorken scaling variable)

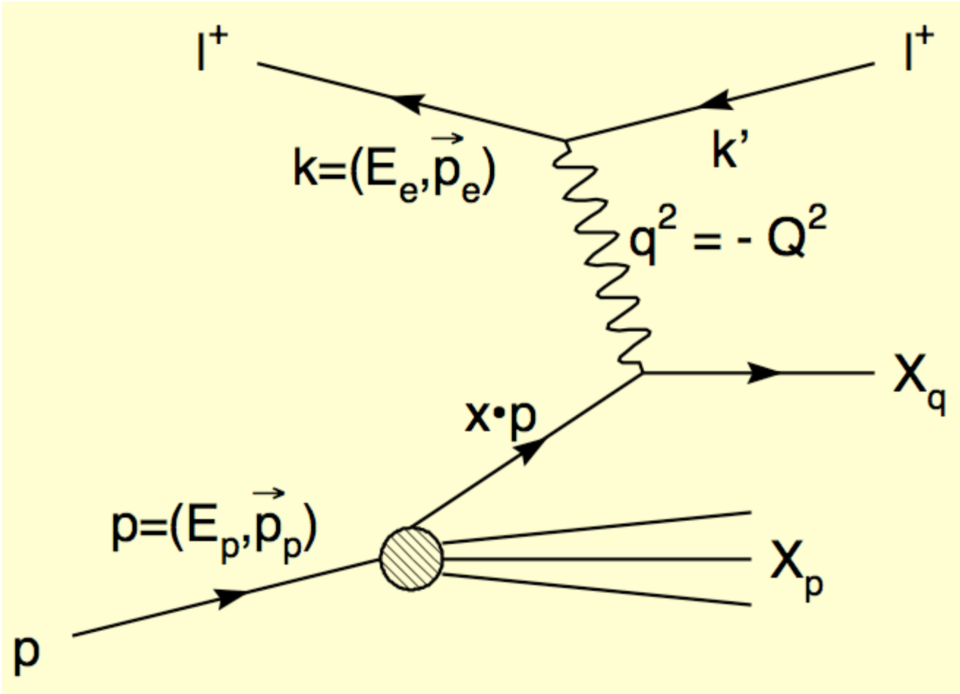
$$x = \frac{Q^2}{2p \cdot q}$$

  - inelasticity parameter:

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

  - invariant centre of mass energy:

$$s = (k + p)^2 = \frac{Q^2}{xy}$$



Cross Sections, Structure Functions, PDFs

- The proton is a dynamical object and its structure depends on the resolution (Q^2) of the observation:
  - higher the value of Q^2 more detail we examine

- General double differential cross-section for eN scattering:

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

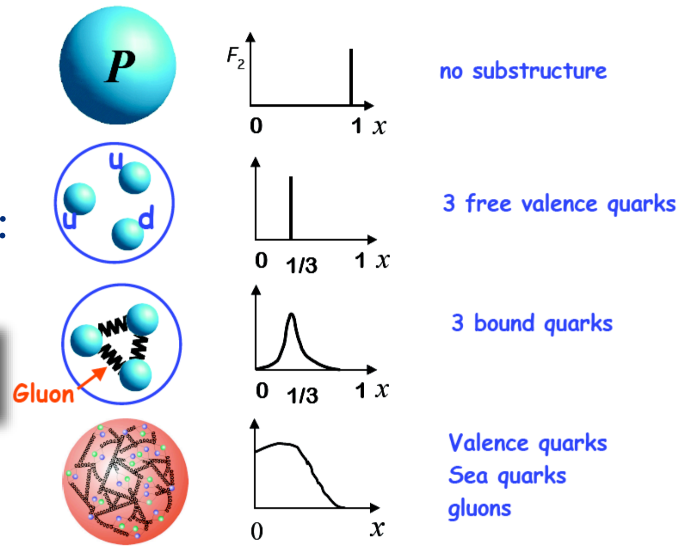
$$Y_{\pm} = 1 \pm (1-y^2)$$

  - F_2, F_L, xF_3 are structure functions (hadronic part) which are related to the momentum distributions of quarks within the nucleon:

    Parton Distribution Functions (PDFs):

    - valence quarks: carriers of proton charge
    - sea quarks and gluons: evolved by complex dynamics

- Can extract the structure functions experimentally by looking at the x,y,Q^2 dependence of the double differential cross-section



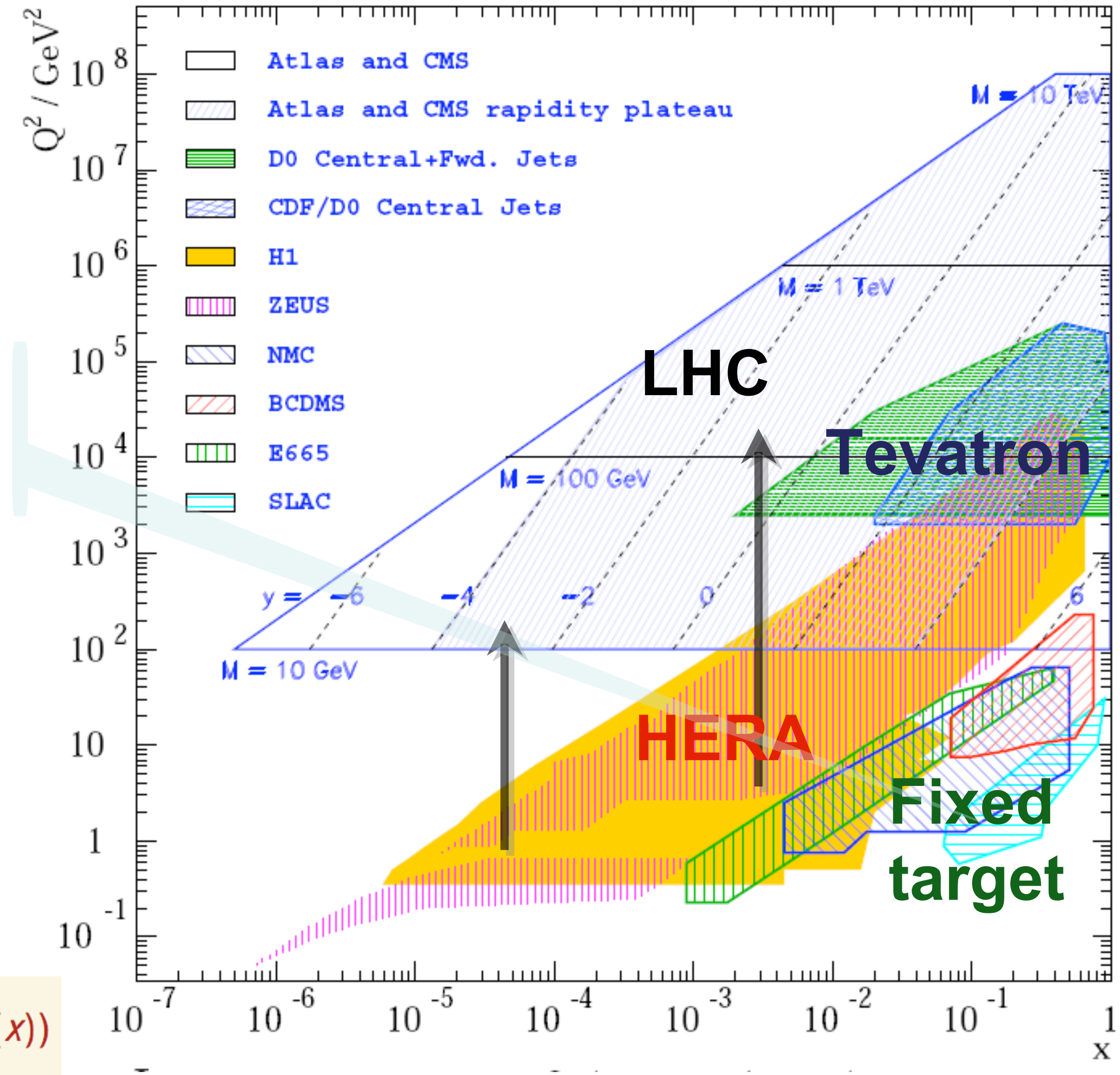
At Leading Order (LO):

$$F_2 = x\sum e_q^2\left(q(x)+\bar{q}(x)\right)$$
$$xF_3 = x\sum 2e_q a_q\left(q(x)-\bar{q}(x)\right)$$

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

Experimental Data on the Proton Structure

- Persistent experimental effort over the last 40 years both by fixed-target and collider experiments around the world supported by the theoretical developments
  - Large extension in kinematic space in x and Q^2 from the original SLAC measurements
  - Currently, HERA measurements dominate the kinematic plane and, hence, provides the best basis for LHC:
    - Main constraint on PDFs at low x comes from HERA measurements of proton F_2, dominated by gamma exchange



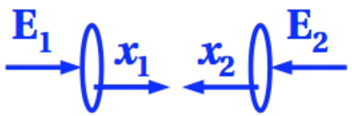
$$F_2 = \frac{4}{9}(xU(x) + x\bar{U}(x)) + \frac{1}{9}(xD(x) + x\bar{D}(x))$$

- U(x)=u(x)+c(x); D(x)=d(x)+s(x)

Probing the Proton Structure

- At the LHC: Drell Yan (DY)

Proton-proton collisions:



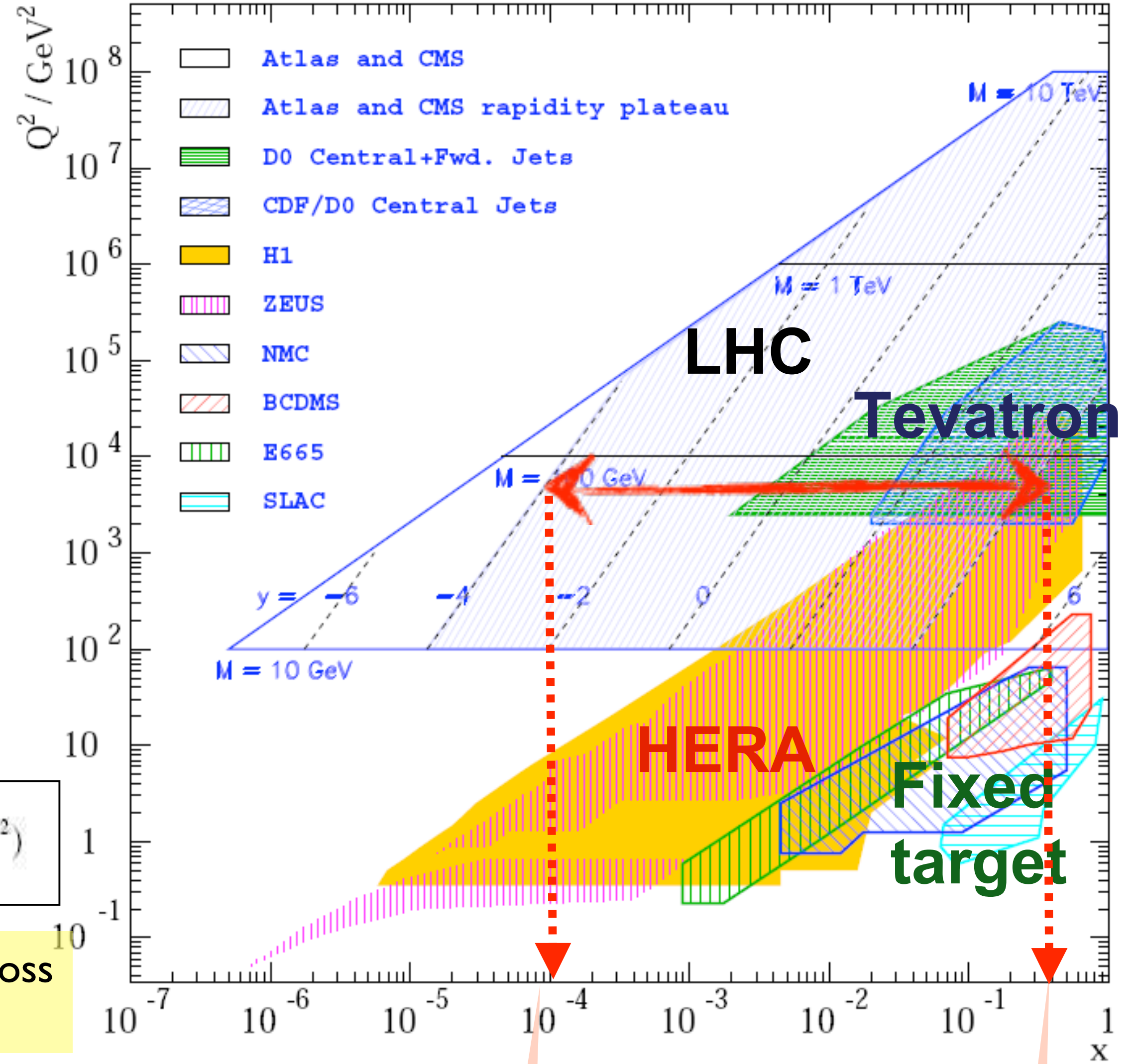
$$\text{rapidity } y = \frac{1}{2}\ln\frac{E+P_Z}{E-P_Z};$$

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

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

hadronic cross section

Partonic cross section

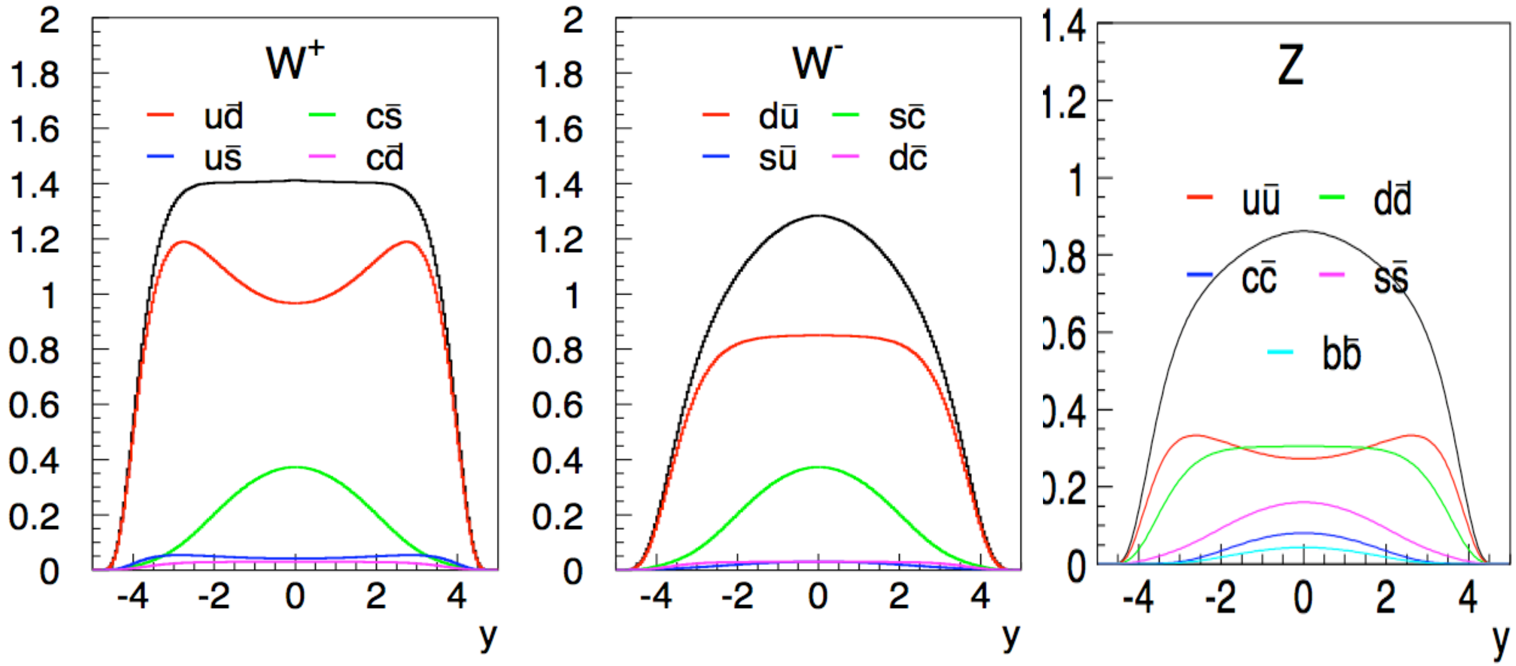


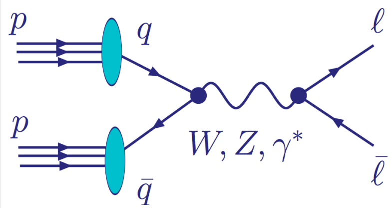
So, to predict Z or W production at LHC with a rapidity y=-4, it is needed:

$q(x_1=10^{-4},Q^2=M^2_{W,Z})$

$q(x_1=0.3,Q^2=M^2_{W,Z})$

Decomposition of W and Z at the LHC





Flavour decomposition:

For Ws:

- ud dominates for W
- u_{val} peaks at large rapidity
- sc important at mid y

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

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

For Z:

- all flavours contribute, even b is significant
- larger coupling to d compared to u

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

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

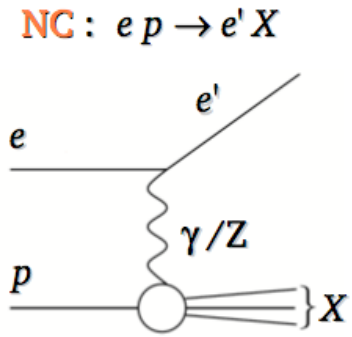
Experimental settings

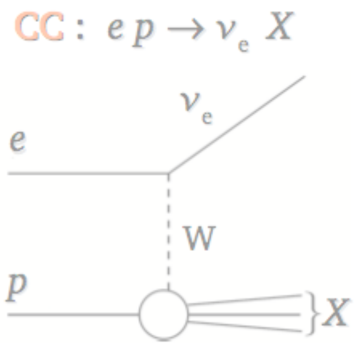
HERA

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

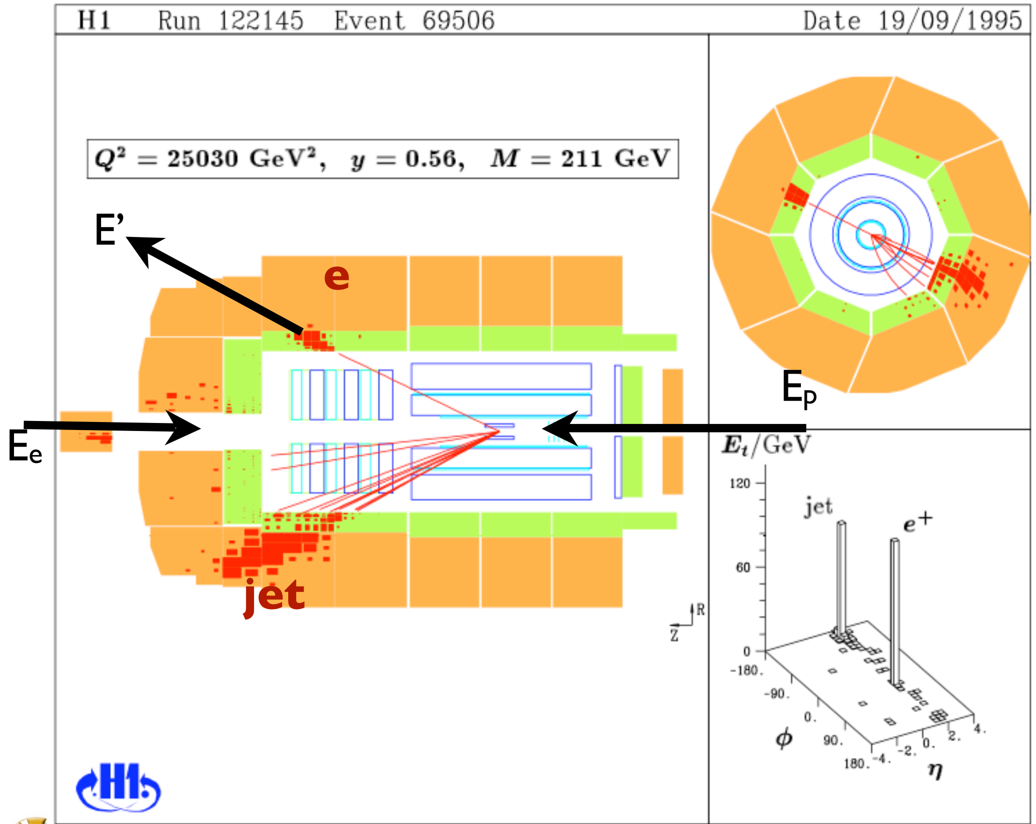
Detector and Kinematics at HERA: NC DIS

- <u>Processes:</u>
  - Neutral Current (NC): Intermediate boson is neutral (ϒ, Z)
  - Charged Current (CC): Intermediate boson is charged ($W^{\pm}$)





- Neutral Current event sample in H1 detector



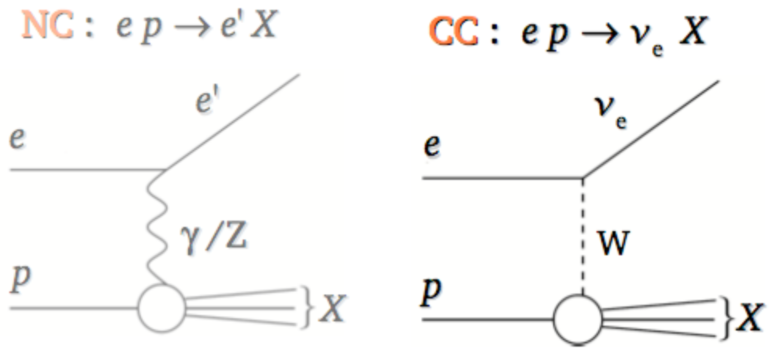
The invariant kinematic variables in terms of measurable variables in the lab frame:

$$s = 4E_eE_p$$
$$Q^2 = E_eE'(1+\cos\theta_e)$$
$$y = 1 - \frac{E'}{E_e}\frac{1}{2}(1-\cos\theta_e)$$
$$x = \frac{Q^2}{sy}$$

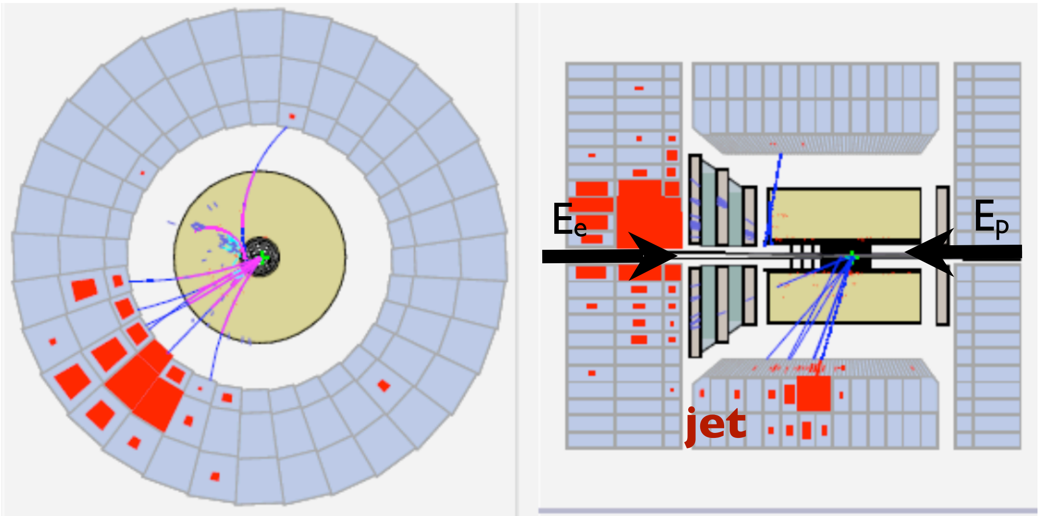
- Determination of the Event Kinematics:
  - using lepton information (E_e, E', θ_e)
  - using hadronic final state particles
  - using both lepton and hadronic final state variables

Detector and Kinematics at HERA: CC DIS

- Processes:
  - Neutral Current (NC): Intermediate boson is neutral (ϒ, Z)
  - Charged Current (CC): Intermediate boson is charged ($W^{\pm}$)



- Charged Current event sample in ZEUS detector
  - Neutrino signature: missing transverse momentum



The invariant kinematic variables in terms of measurable variables in the lab frame:

$$s = 4E_e E_p$$

$$Q^2 = \frac{p_t^2}{1-y}$$

$$y = \frac{\sum(E-P_Z)}{2E_e}$$

$$x = \frac{Q^2}{sy}$$

- Determination of the Event Kinematics:
  - using lepton information (E_e,E',θ_e)
  - using hadronic final state particles
  - using both lepton and hadronic final state variables

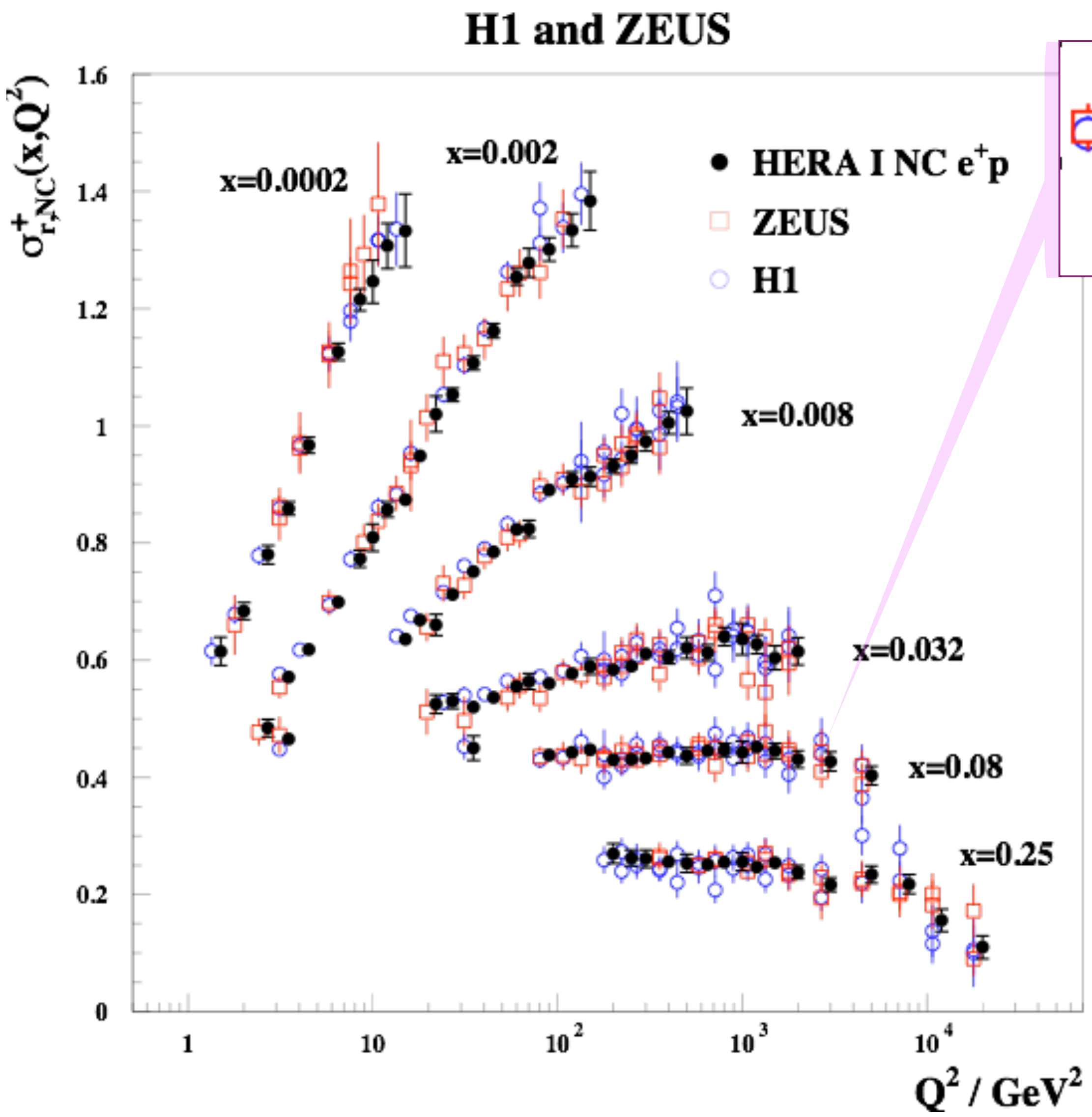
Combination of the H1 and ZEUS Measurements

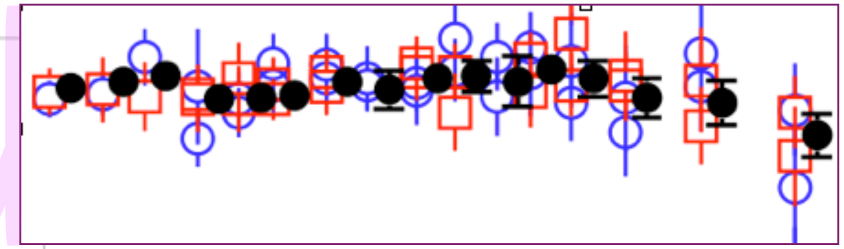
[JHEP01 (2010) 109]

- 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]



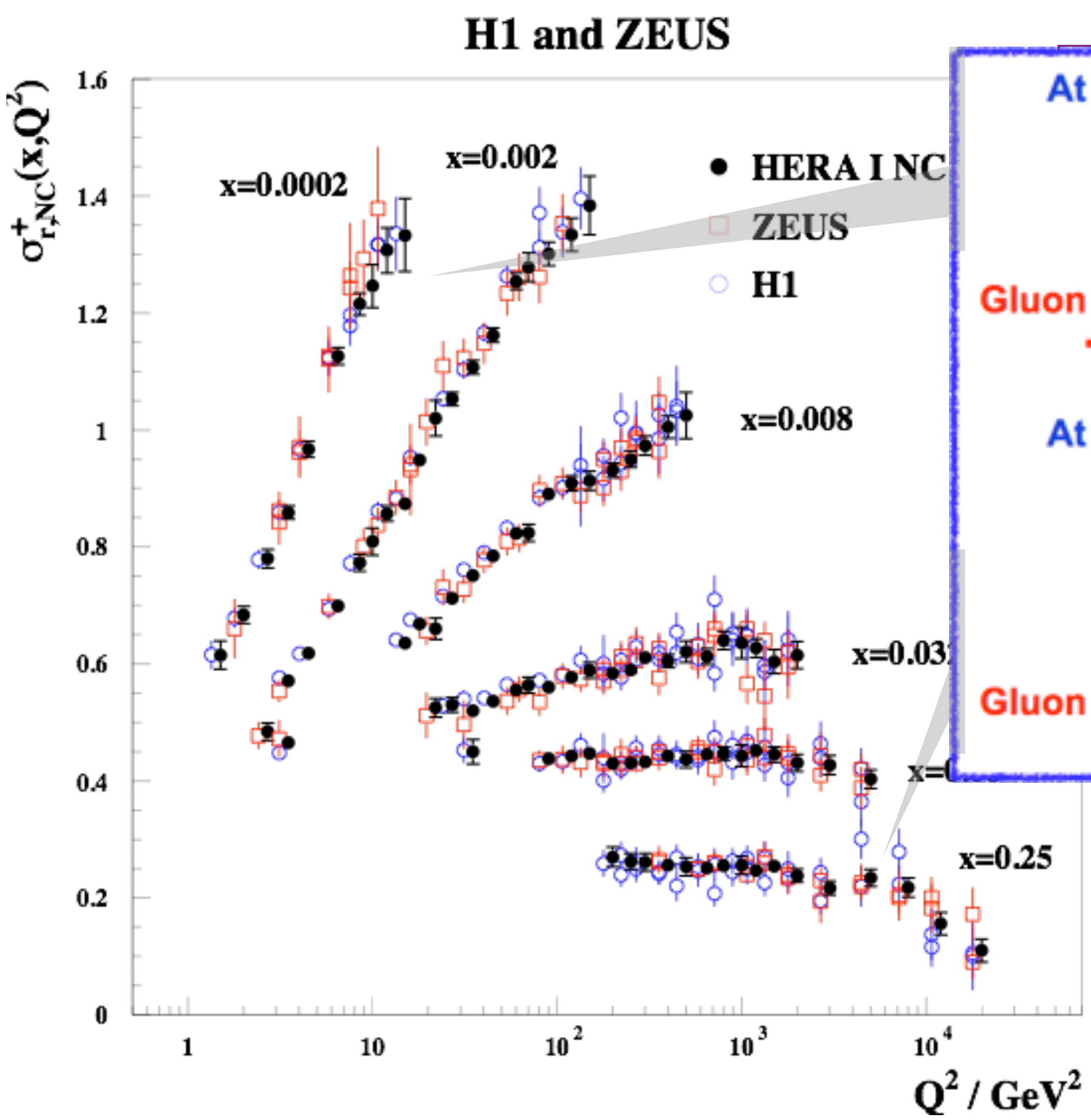


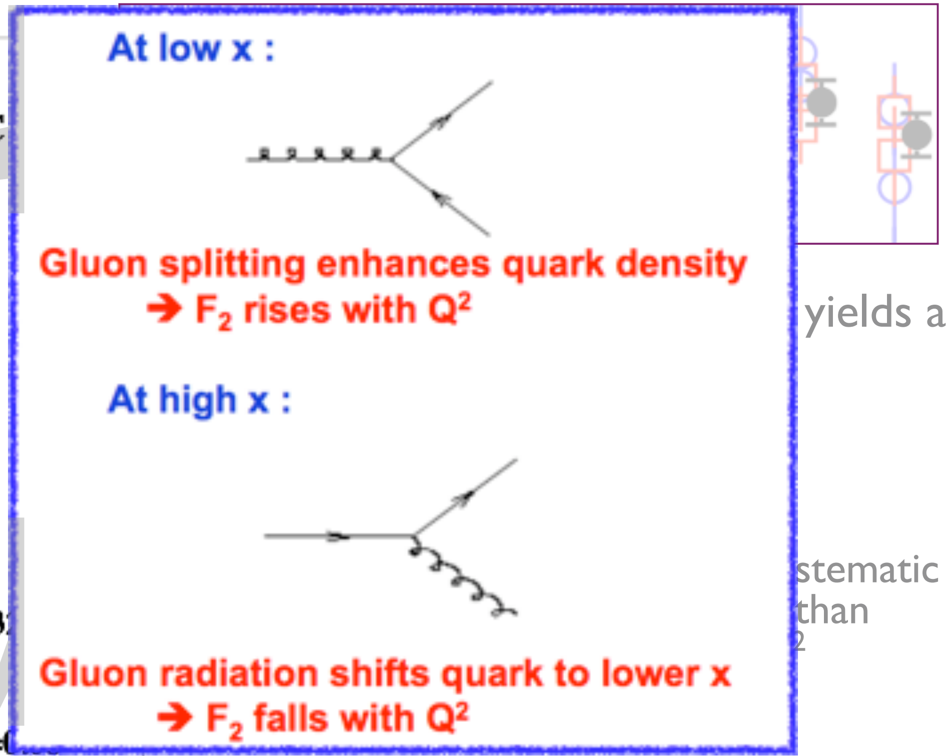
The combination procedure yields a consistent data set:

- 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!

Results of Combining H1 and ZEUS Data

[JHEP01 (2010) 109]





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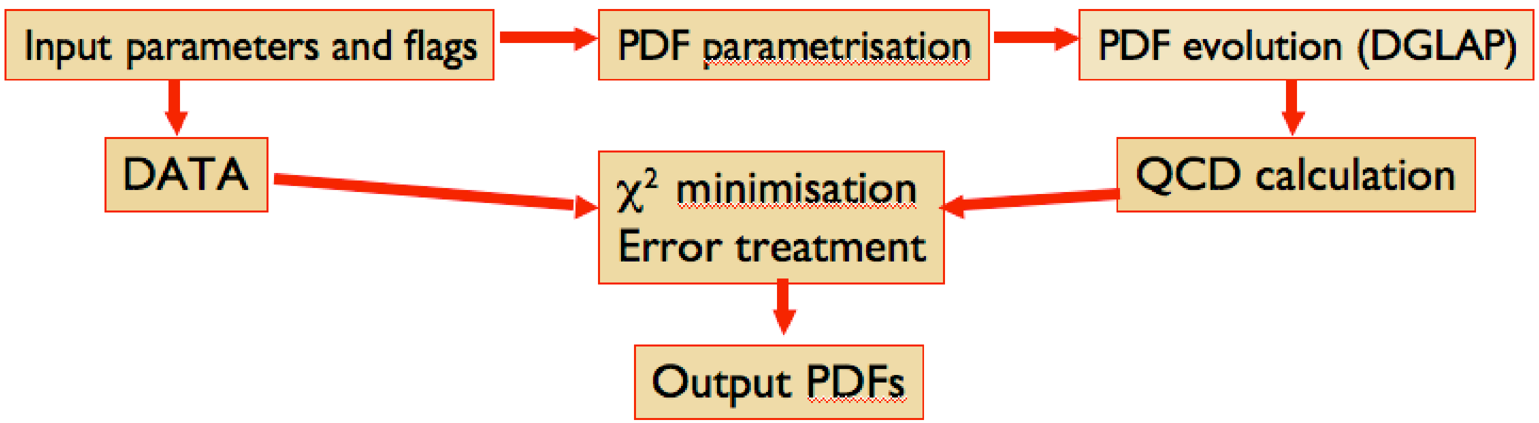
- After combination, the systematic errors are of same precision as the statistical errors, reaching 1% total precision!

Schematics of PDF extractions

- Theoretical basis:
  - Factorisation Theorem:
    - short and long distances processes are separable and PDFs are universal
  - Asymptotic Freedom:
    - hard scattering is weak at short distance and hence perturbatively calculable

⇨Structure Functions (F_i) are a convolution of PDFs (f_a) with hard scattering coefficient functions (ω_i^a)



- 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

PDF Fit Analysis Group

- Various data sets have constraining powers on PDFs:
  - Fixed Target experiments - high x
  - HERA (ep collider) - low x
  - Tevatron (ppbar collider) - high x
  - LHC (pp collider)

- Now LHAPDF V5.8.5 (released 2nd February 2011).

	MSTW08	CT10	NNPDF2.1	HERAPDF1.0/1.5	ABKM09	GJR08/JR09
HERA DIS	✔	✔	✔	✔	✔	✔
Fixed-target DIS	✔	✔	✔	✗	✔	✔
Fixed-target DY	✔	✔	✔	✗	✔	✔
Tevatron W,Z	✔	✔	✔	✗	✗	✗
Tevatron jets	✔	✔	✔	✗	✗	✔
GM-VFNS	✔	✔	✔	✔	✗	✗
NNLO	✔	✗	✗	✔	✔	✔

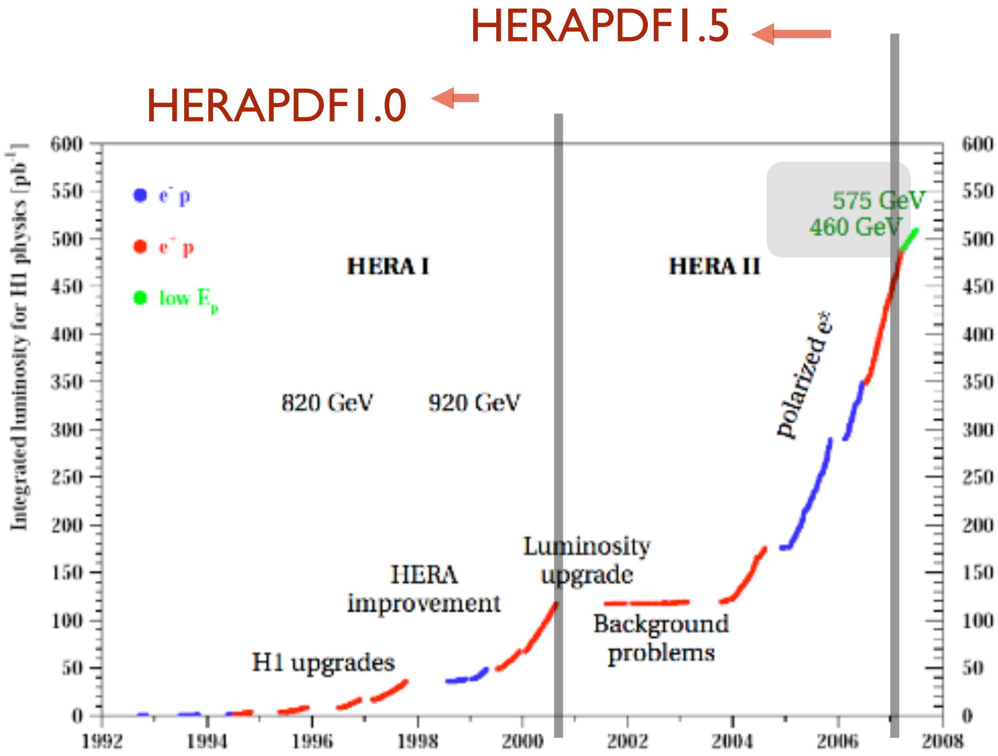
From G.Watt, PDF4LHC March 2011

- Following Fit groups are active:
  - CTEQ (Coordinated Theoretical-Experimental Project on QCD)
  - MSTW(Martin, Stirling, Thorne, Watt)
  - NNPDF(Neural Net PDF group)
  - ABKM/ABM (Alechin, Bluemlein, Klein, Moch)
  - GJR/JR (Glueck, JimenezDelgado, Reya)
  - **HERAPDF (H1 and ZEUS)**
    - Different data sets
    - Deifferent parametrisations
    - Different arrangements of the perturbative series
    - Different input values for alphas, charm masses
    - Different treatment for heavy quark

- The PDF sets from the above group can all be used for predictions and the remaining differences still needs to be studied and understood.

Input Data from HERA into the HERAPDF fits

- Combined HERA I inclusive data
  [JHEP01(2010) 109]
  - HERAPDF1.0
  - In other PDF sets: NNPDF2.0(1), CT10(w), ABKM
- Combined HERA I+high Q^2 HERA II Data
  [prelim]:
  - Accurate measurements in high Q^2 region which are sensitive to the valence distributions.
  - HERAPDF1.5
- Low Energy Data HERA II [prelim]:
  - Accurate measurement in $Q^2 \geq 2.5$ GeV^2 range, sensitive to structure function F_L:
    - Investigate the low Q^2 region;
    - Test sensitivity to different heavy flavour treatments;
- Combined Charm F_2 data [prelim]:
  - Provides constraints on charm mass
- Jet data [prelim]:
  - HERAPDF1.6
  - Determination of strong coupling



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

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

QCD Analysis Framework

- QCD Fit settings:
  - NLO (and NNLO) DGLAP evolution equations QCDNUM package [M. Botje]
  - 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

- central fit with 10 free parameters
- χ^2/dof=574/582

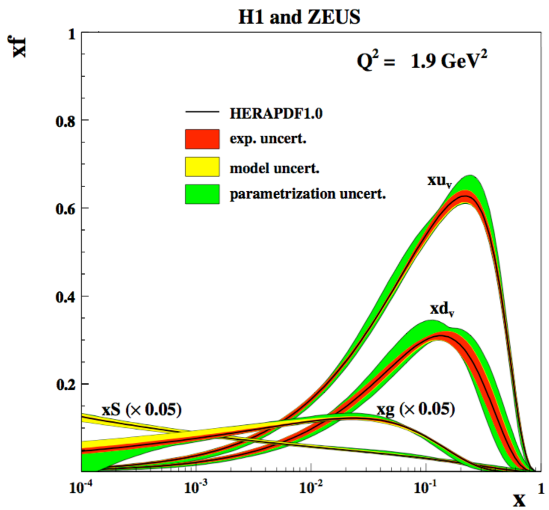
Scheme	TRVFNS
Evolution	QCDNUM17
Order	NLO
Q_0^2	1.9 GeV^2
$f_s = s/D$	0.31
Renorm. scale	Q^2
Factor. scale	Q^2
Q^2_{min}	3.5 GeV^2
$\alpha_S(M_Z)$	0.1176
M_c	1.4 GeV
M_b	4.75 GeV

Sources of PDF uncertainties at HERA

- **Experimental Uncertainties:**
  - Consistent data sets → use $\Delta\chi^2 = 1$
  - Cross checked with Monte Carlo method [PDF4LHC Interim Report arXiv:1101:0536]

- **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
  - Studies using Chebyshev Polynomials [A. Glazov, S. Moch, VR PLB27193]

Benchmarking Exercises within HERA framework

Monte Carlo Method

[benchmark exercise with NNPDF - PDF4LHC Interim Report arXiv:1101:0536]

- Method consists in preparing replicas of data sets allowing the central values of the cross sections to fluctuate within their systematic and statistical uncertainties taking into account all point to point correlations

  - Shift central values randomly within the uncorrelated errors assuming Gauss distribution of the errors:

$$\sigma_i = \sigma_i(1 + \delta_i^{uncorr} RAND_i)$$

  - Shift central values with the same probability of the corresponding correlated systematic shift assuming Gauss distribution of the errors:

$$\sigma_i = \sigma_i(1 + \delta_i^{uncorr} RAND_i + \sum_j^{N_{sys}} \delta_{ij}^{corr} RAND_j)$$

- Preparation of the data is repeated for N times (N>100)
  - For each MC replica, NLO QCD fit is performed to extract the N PDF sets

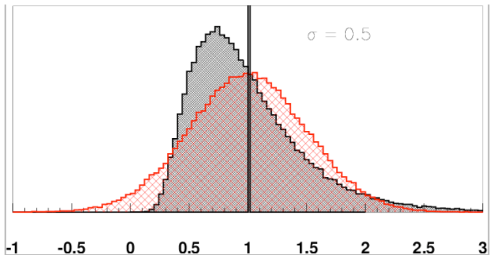
- Errors on the PDFs are estimated from the RMS of the spread of the N curves corresponding to the N individual extracted PDFs

Results of the MC method

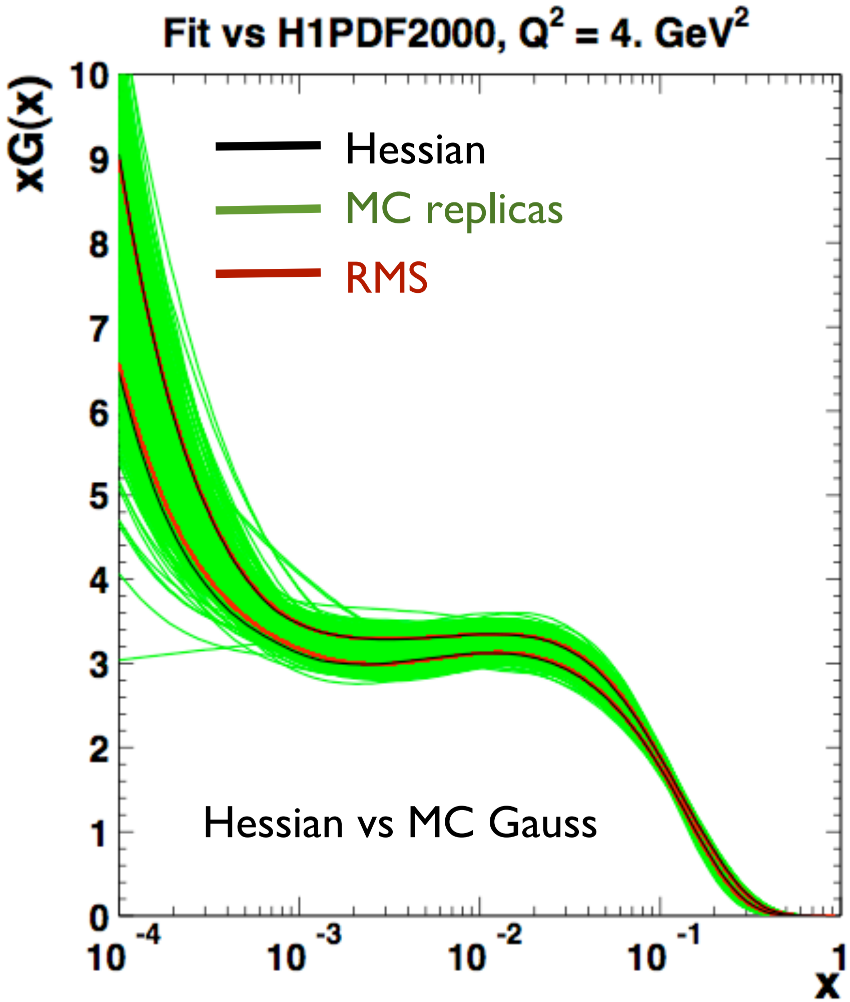
- Standard error estimation of PDFs relies on the assumption that all errors follow Gauss statistics

- MC method can provide an independent cross check of it
  - Hessian Method and MC method give the same results in the linear error propagation approximation

- MC method allows to test various assumptions for error distributions
  - some systematic uncertainties follow Log-Normal distribution (i.e., lumi, detector acceptance, ...)



  - does this affect the PDF uncertainty?
    - Similar results to Gauss distributions when using Log-Normal assumptions



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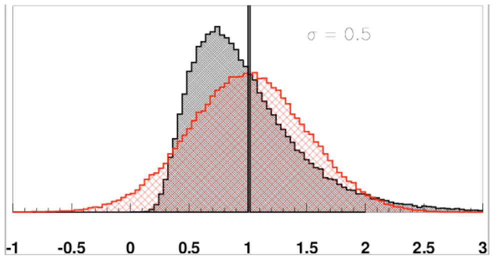

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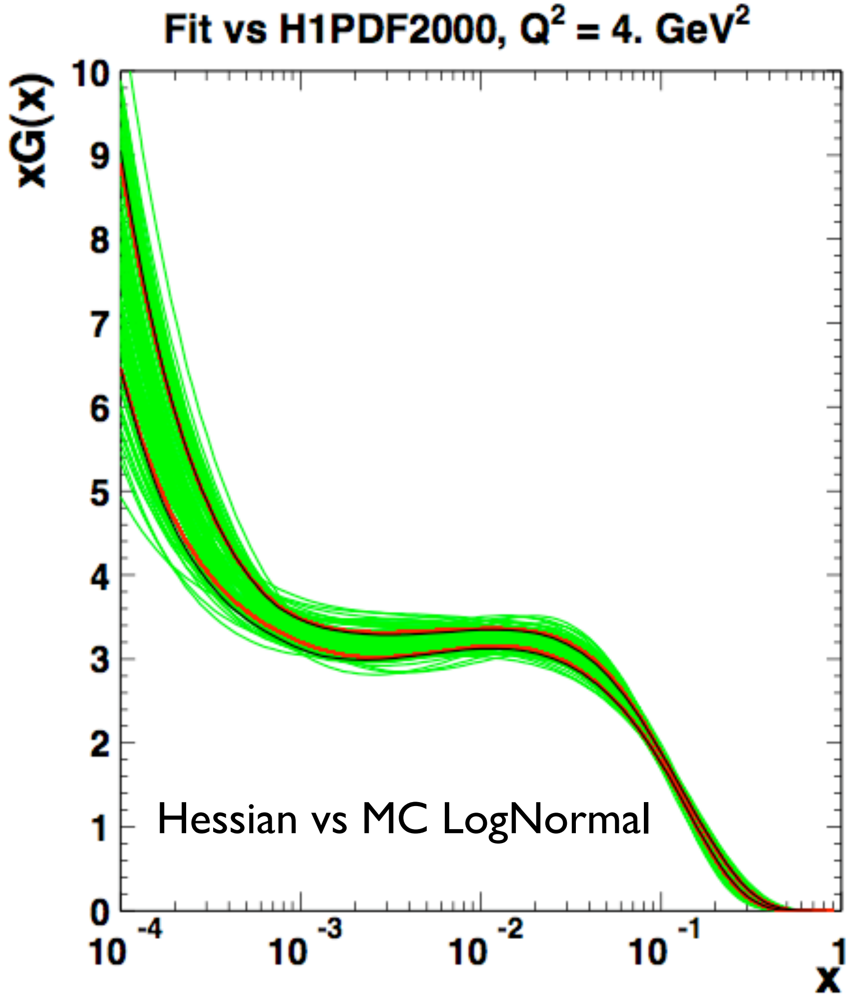


Study of the Parametrisation Biases

[A. Glazov, S. Moch, VR PLB27193]

- Standard Method:

$$xf(x) = Ax^B(1-x)^C(1+\epsilon\sqrt{x}+Dx+Ex^2).$$

  - Describes the shape of PDFs with few input parameters.
    - The variants considered mostly affect the high x region

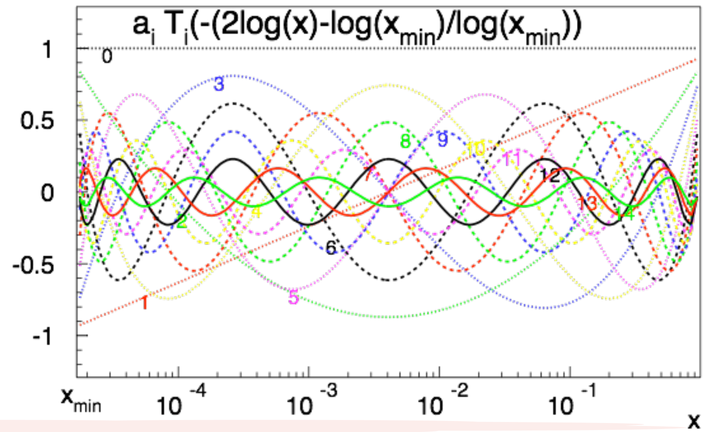
- A method, mathematically more robust to study parametrisation biases, is to use orthogonal polynomials to parametrise PDFs : Chebyshev Polynomials of Ist kind

  - Orthogonally defined in the [-1,1] interval and given by the recurrence relation:

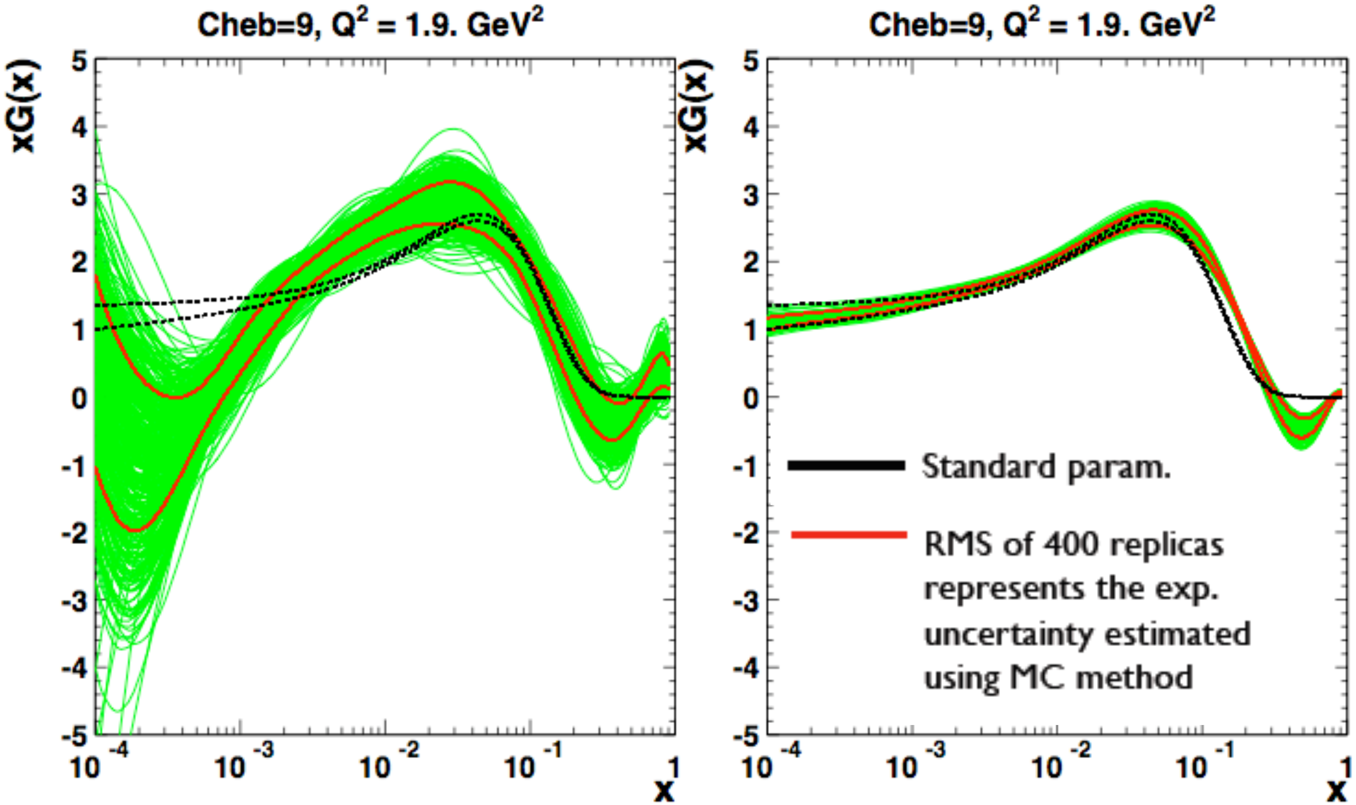
$$T_{n+1}(x) = 2xT_n(x) - T_{n-1}(x)$$

    - To approximate PDFs, change variable $x \rightarrow \dfrac{-(2\log x - \log x_{min})}{\log x_{min}}$ such that [log(x_{min}),0] interval is mapped to [-1,1]
    - This allows to approximate PDF with few parameters

  - Momentum Sum Rule leads to simple finite integrals



Study of adding explicit smoothness prior

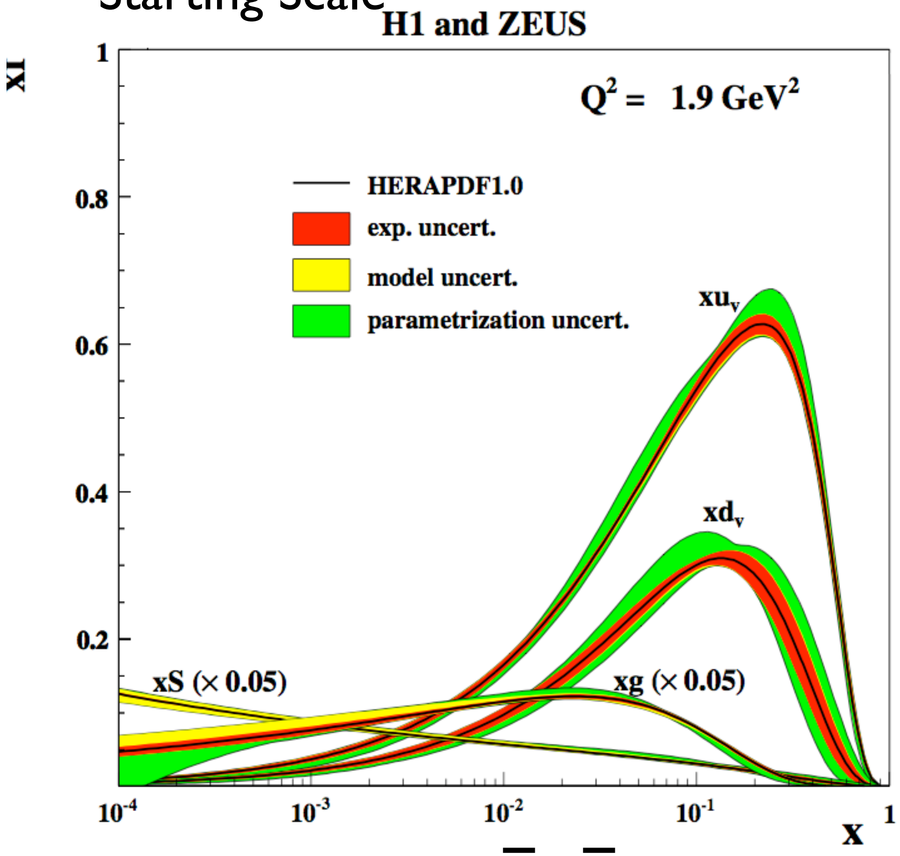


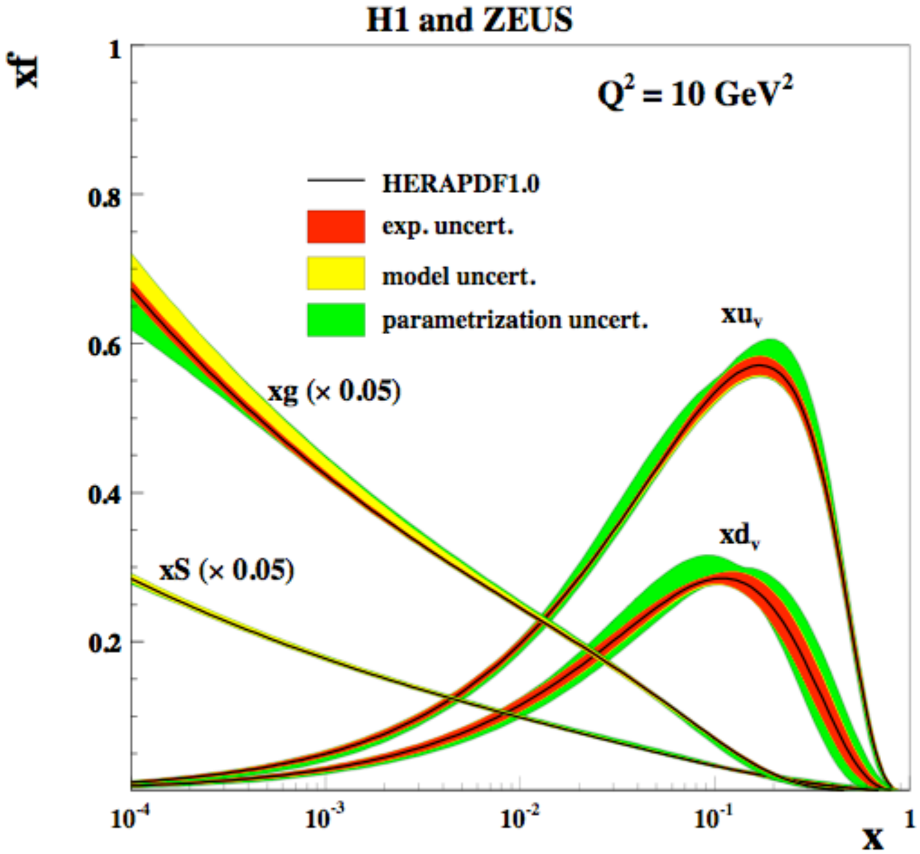
- The uncertainty of the fit is generally small in the kinematic range of bulk data
- However, in the region outside data sensitivity uncertainties are large.
- Parameterisation uncertainty can be reduced with additional theory input:
  - The regularization with a smoothness prior, which disfavors resonant structures for large values of *W* allows to significantly reduce uncertainty also for the low x region
  - Further studies are required.

HERA Fits to the Combined HERA I Inclusive data: HERAPDF1.0

HERAPDF1.0 at NLO

- Starting Scale 10 GeV²





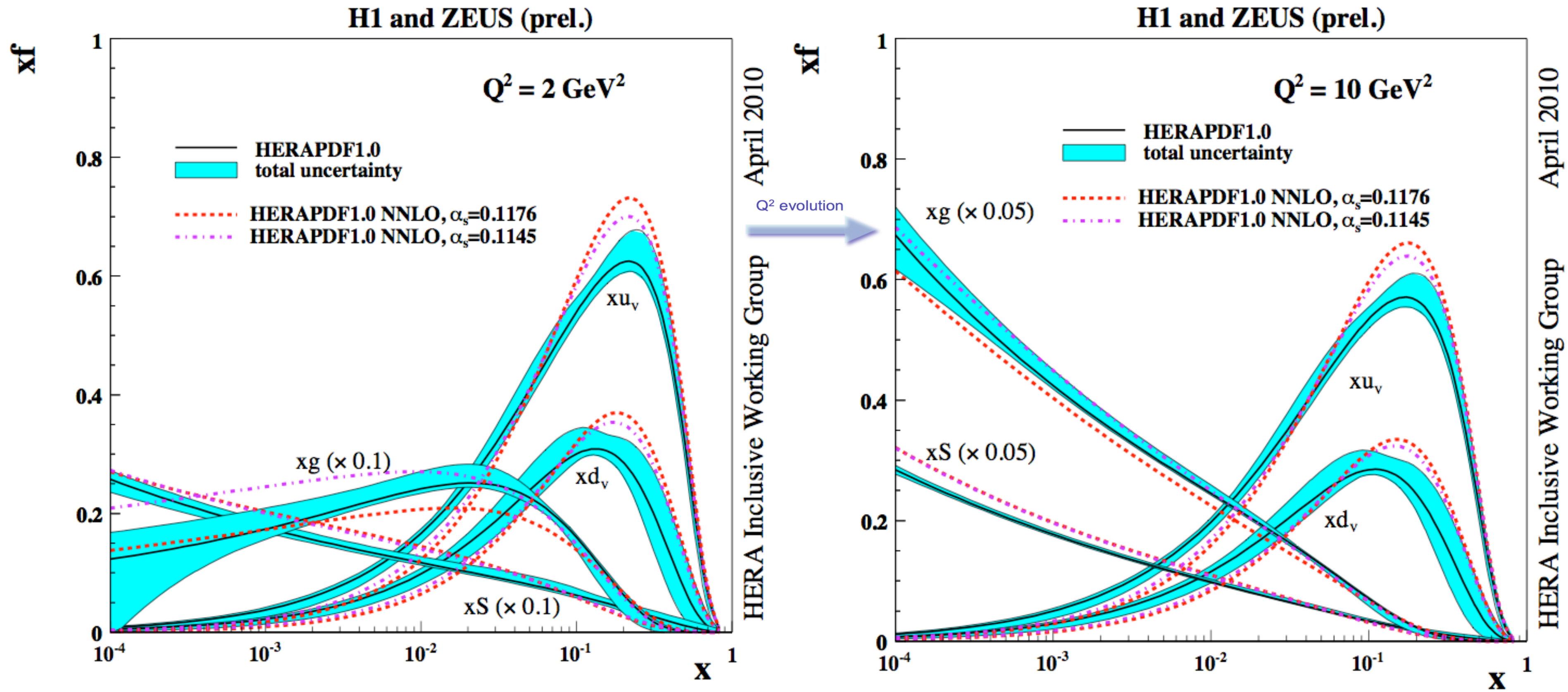
xg, xu_v, xd_v, xS ($xS = x\overline{U} + x\overline{D}$)

- 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)

HERAPDF1.0 @ 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

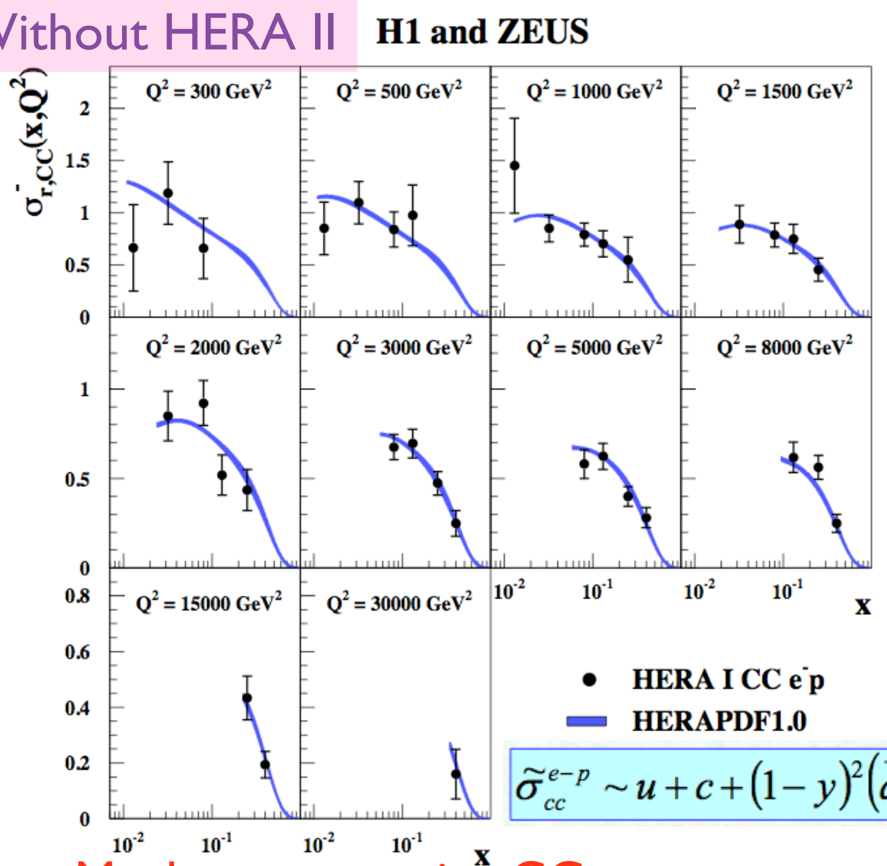
- Using the same settings as for HERAPDF1.0, NNLO fit does not improve fit results.
- Lhapdf grid files available at: https://www.desy.de/h1zeus/combined_results/index.php?do=proton_structure

HERA Fits to the Combined HERA I+II Inclusive data: HERAPDF1.5

Combining HERA I and II Inclusive data

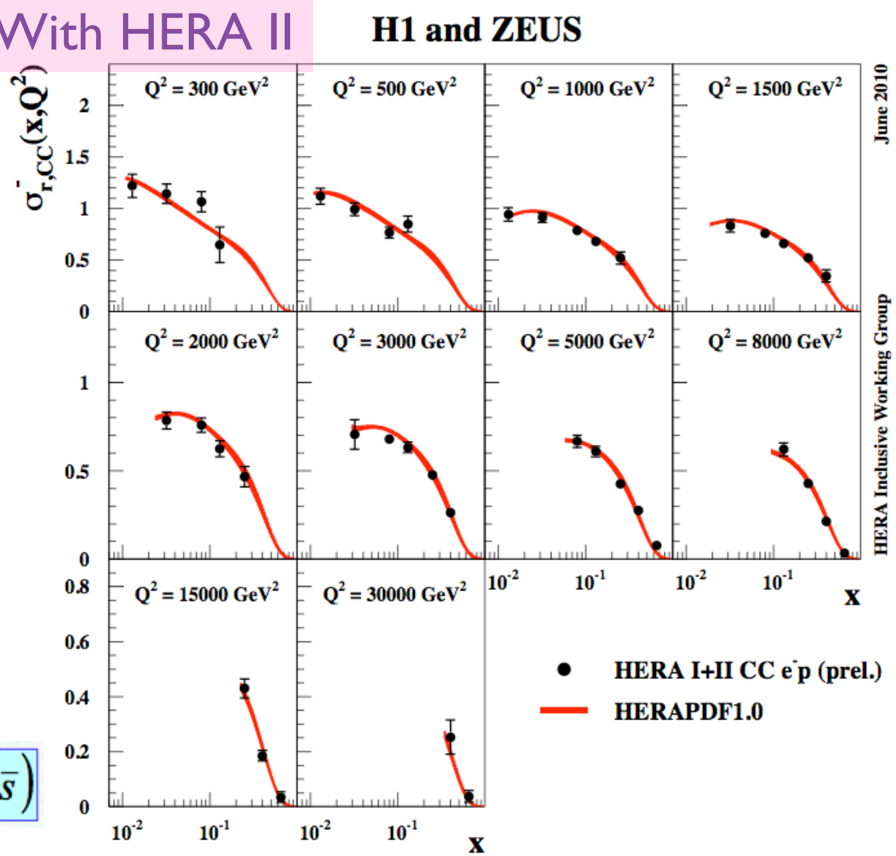
- New HERA II preliminary data available for HERAPDF fits
  - More precise measurements in the high Q^2 and high x regions (especially NC e^-p and CC $e^\pm p$)
  - ➔ could constrain better PDFs at high x
- HERA I and HERA II are combined using same averaging procedure as described before:
  - 674 unique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

Without HERA II



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

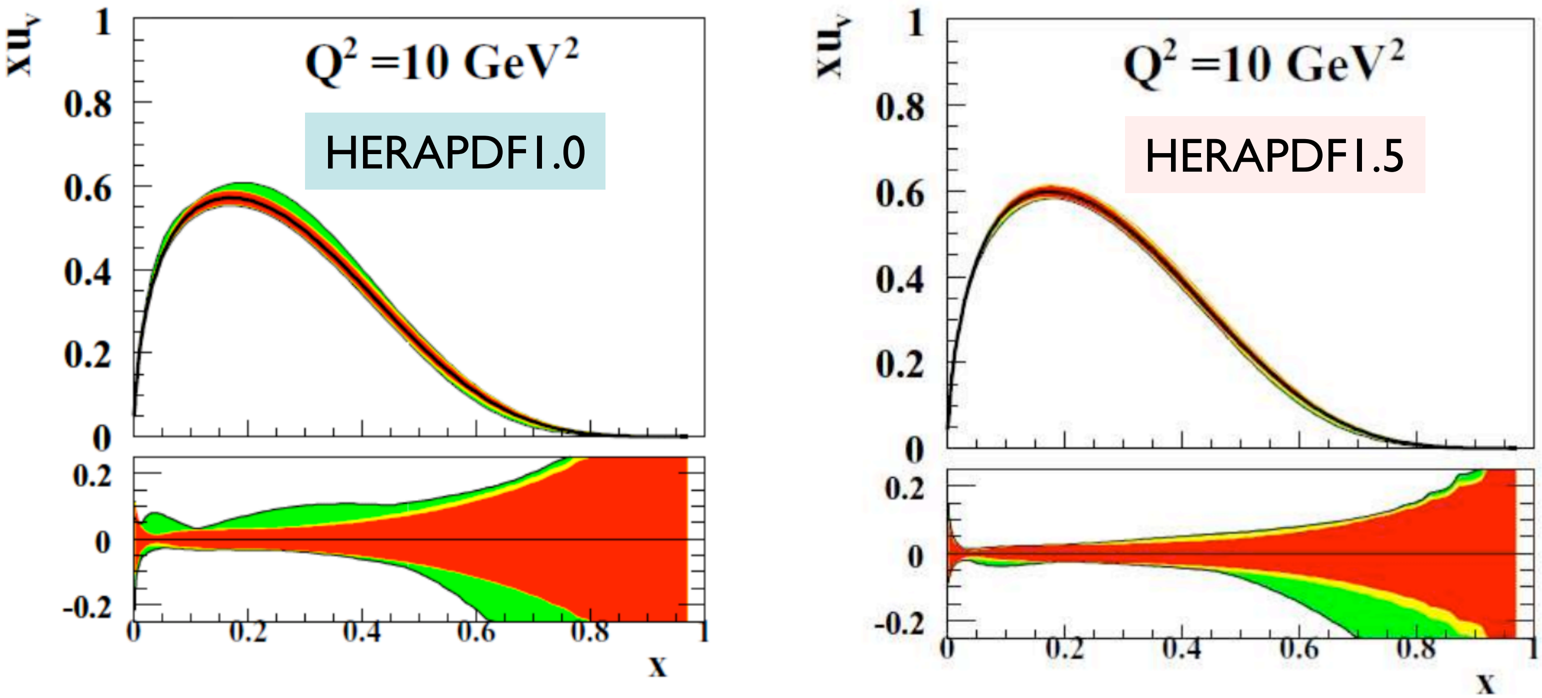
With HERA II



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

Fits to New Combined HERA data: HERAPDF1.5

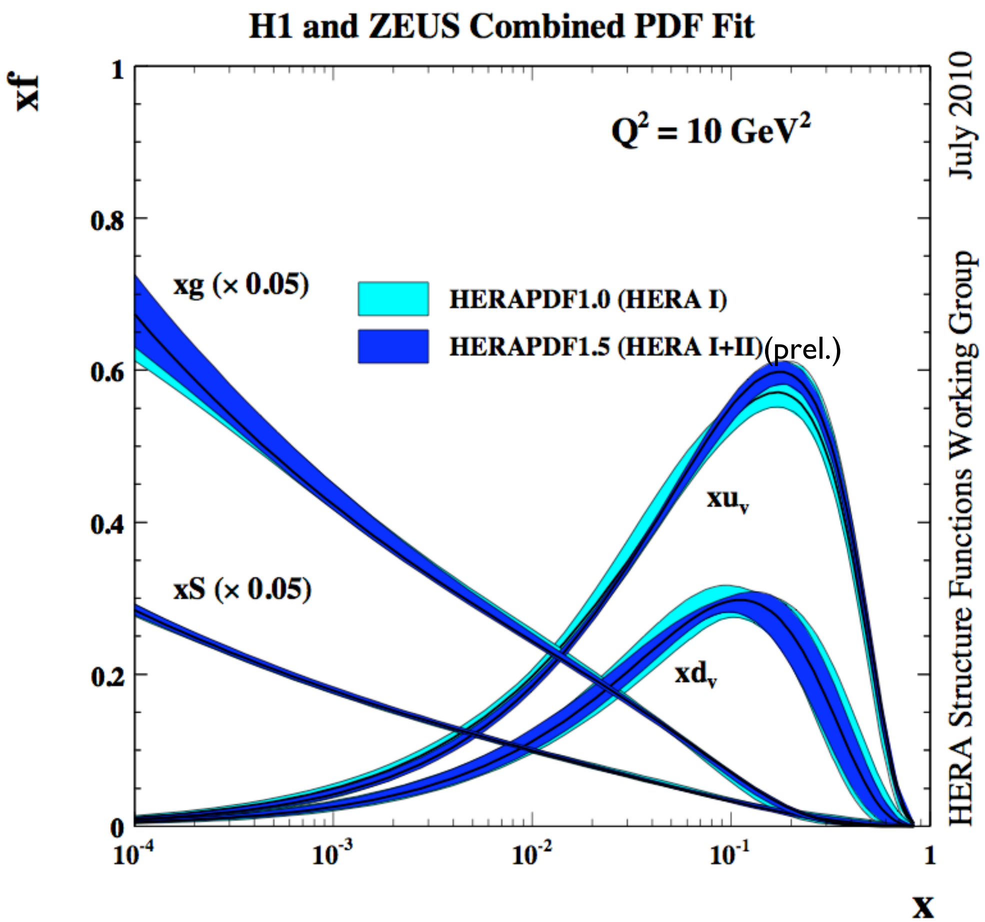
- Propagate new data through QCD fit analysis to produce a new set of HERAPDFs: HERAPDF1.5
  - For preliminary studies use same settings as for HERAPDF1.0
  - Parametrisation uncertainty will be further investigated for final release.



⇒Experimental uncertainty reduced
⇒Parametrisation uncertainty reduced

HERAPDF1.5 vs HERAPDF1.0

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

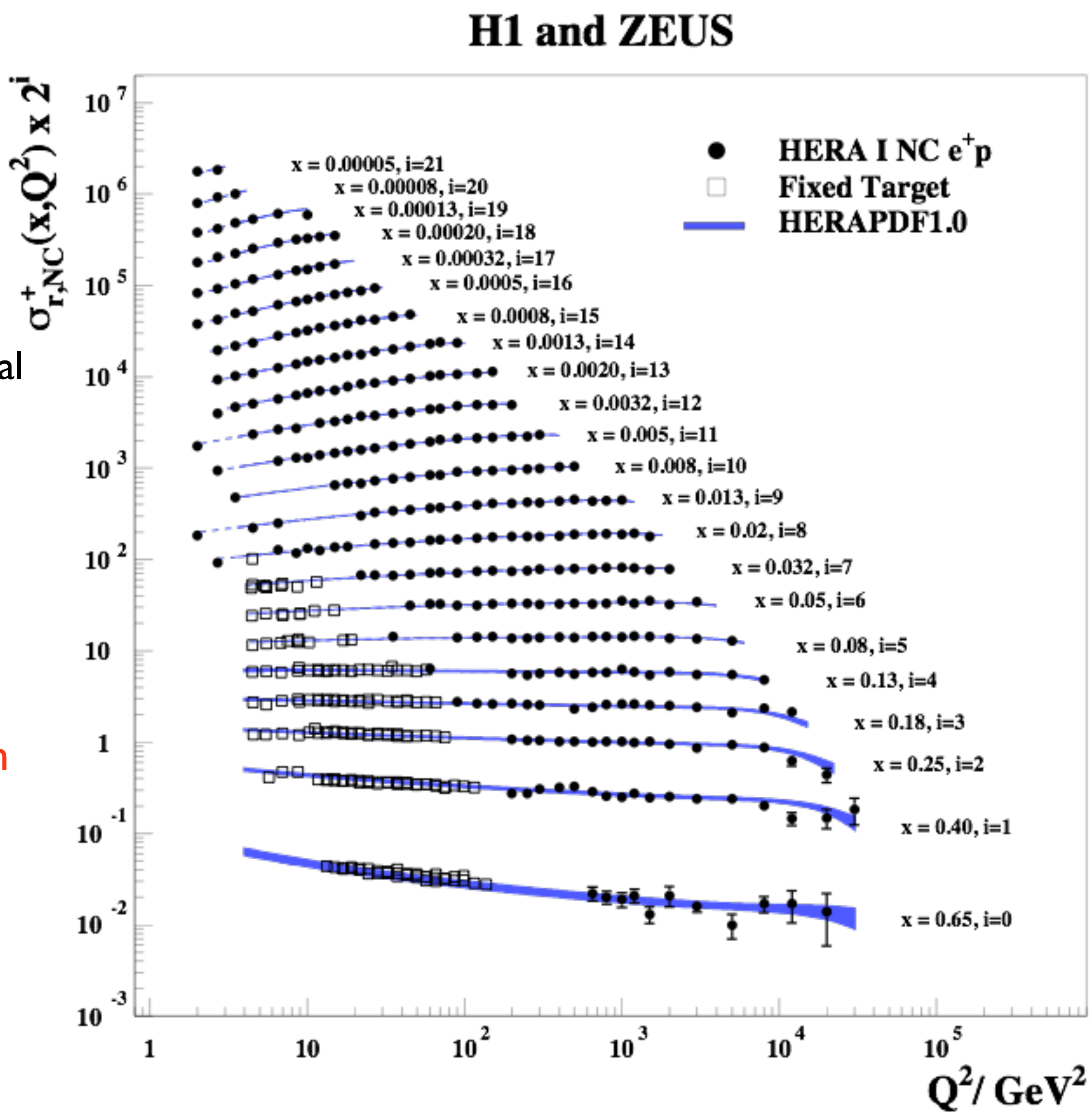


- Inclusion of the HERA II data reduces the uncertainties on PDFs in the high x region especially visible on the valence distributions!
  - See HERAPDF1.5(prel) vs HERAPDF1.0

Fixed Target, Tevatron, LHC data
vs
Predictions based on HERAPDFs

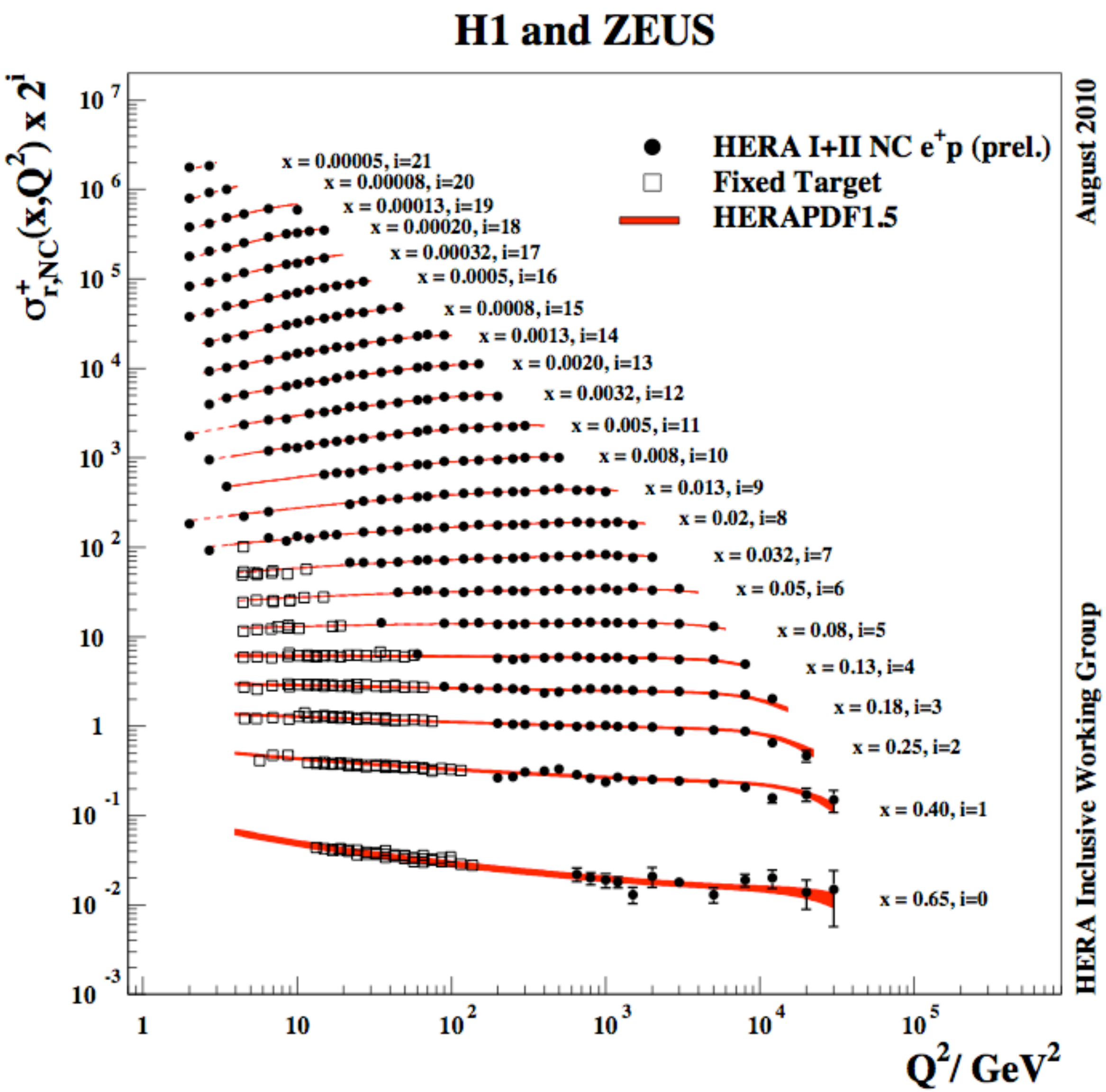
HERAPDF1.0 vs DIS Data

- 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
- HERAPDF1.0 fit describes our data well
- Extrapolation of the HERAPDF1.0 fit agrees well with fixed target data
  - (SLAC and BCDMS)

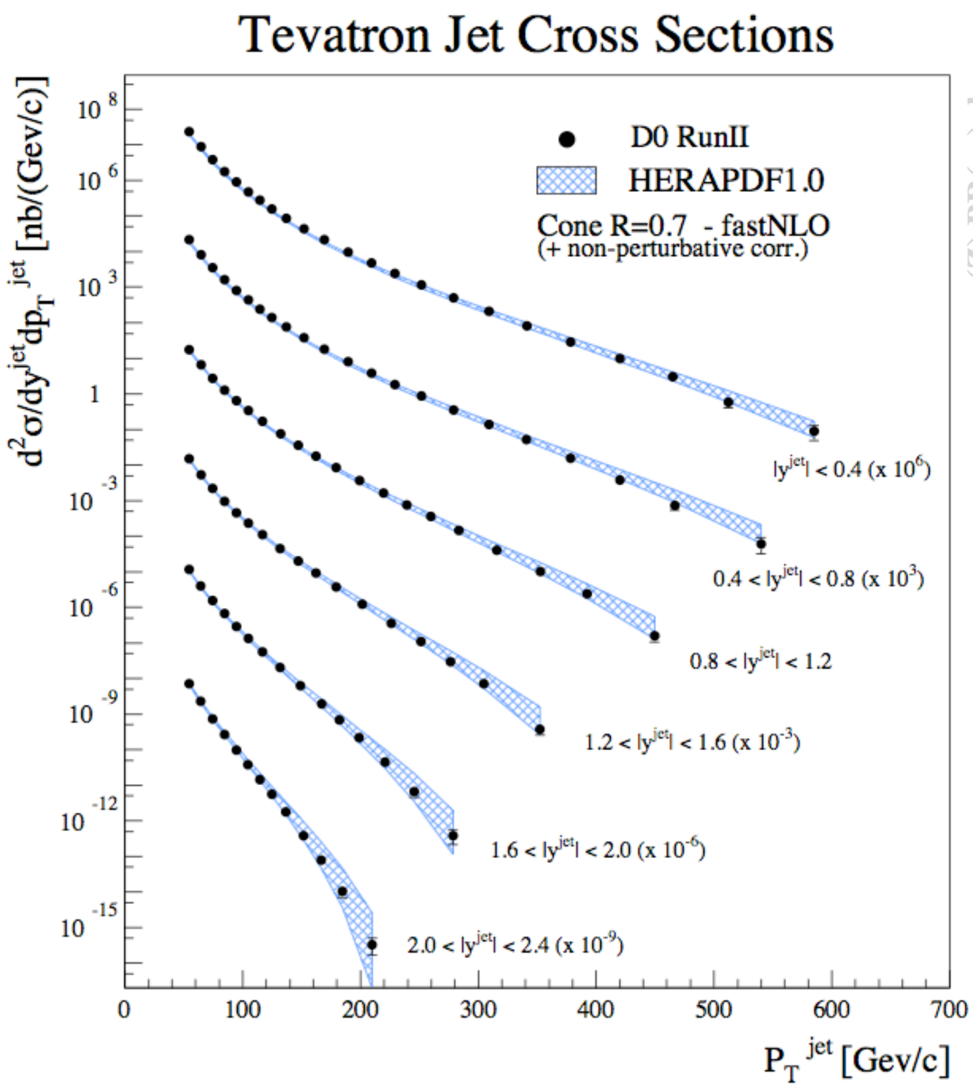


HERAPDF1.5 vs DIS Data

- Plots show the extended kinematic range of the HERA I(and II) data as compared to the fixed target measurements:
  - Data points include experimental errors
  - Fit line includes total error
- HERAPDF1.0 and HERAPDF1.5 fits describe our data well!
- Extrapolation of the HERAPDF1.0 and HERAPDF1.5 fits agree well with fixed target data:
  - SLAC and BCDMS

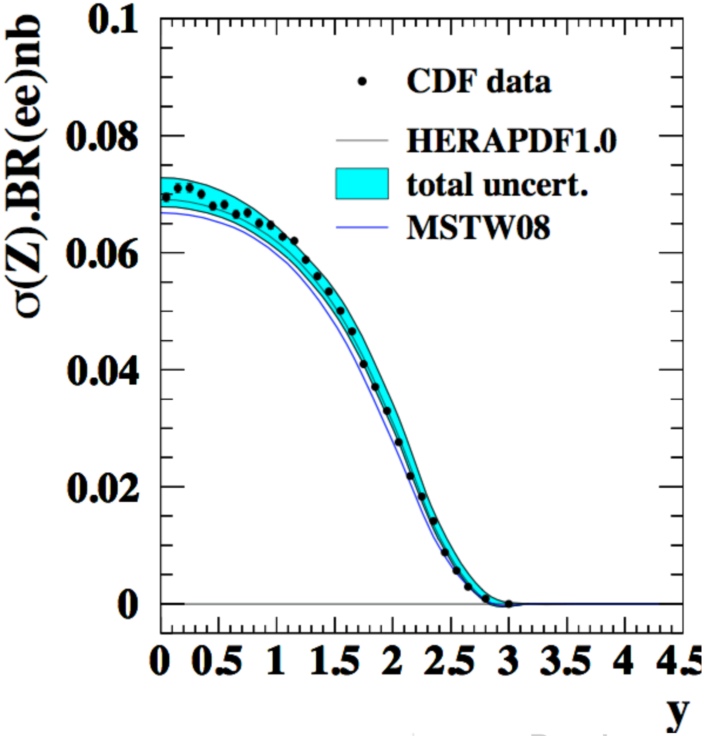


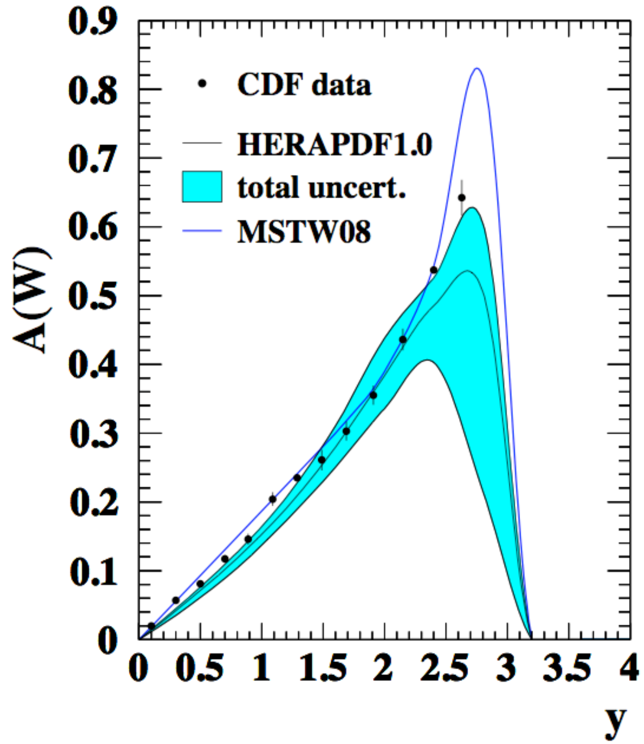
HERAPDF1.0 vs Tevatron Data



- 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

HERAPDF1.0 vs Tevatron Data





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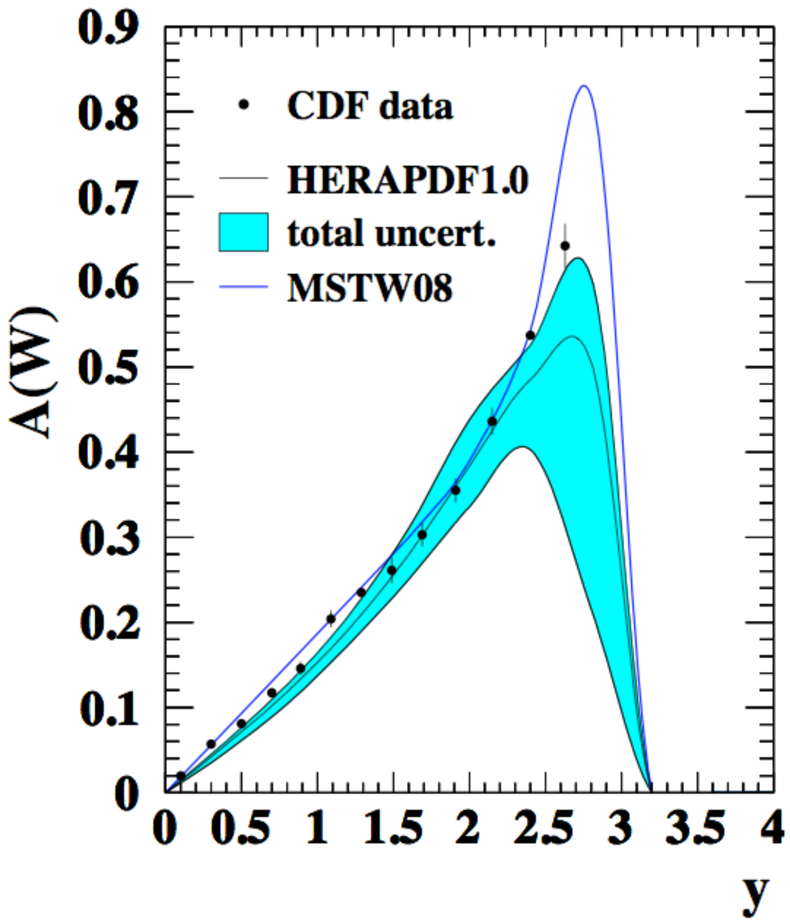
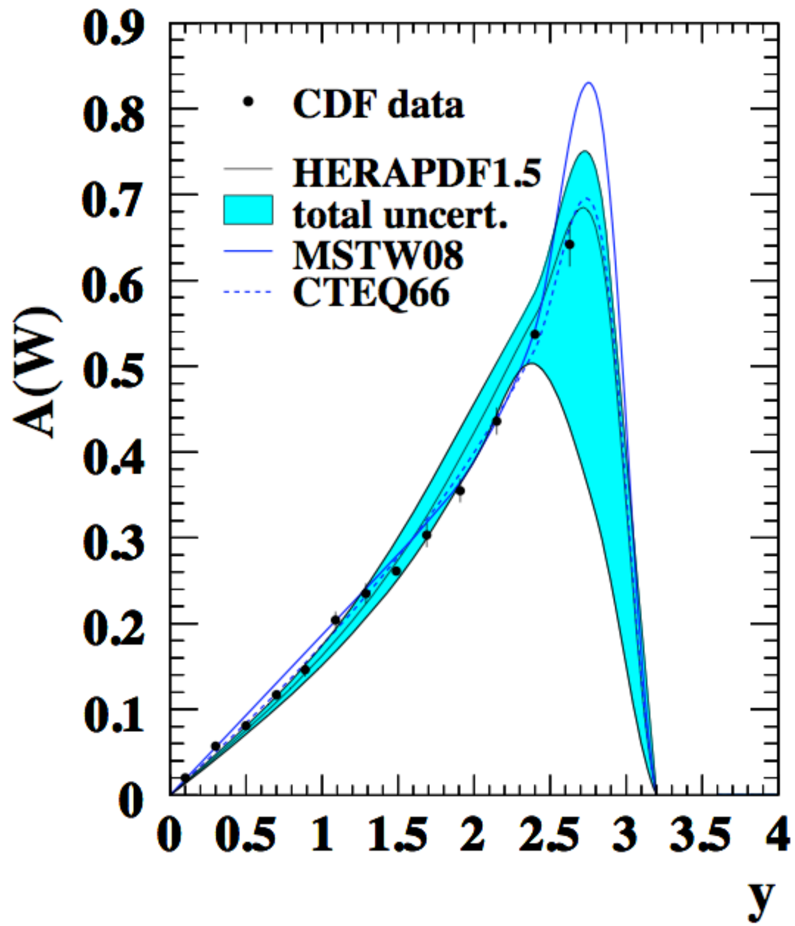
- DIS data from HERA predicts Tevatron jets production from ppbar process.
- Z and W at Tevatron are well predicted by HERAPDF1.0

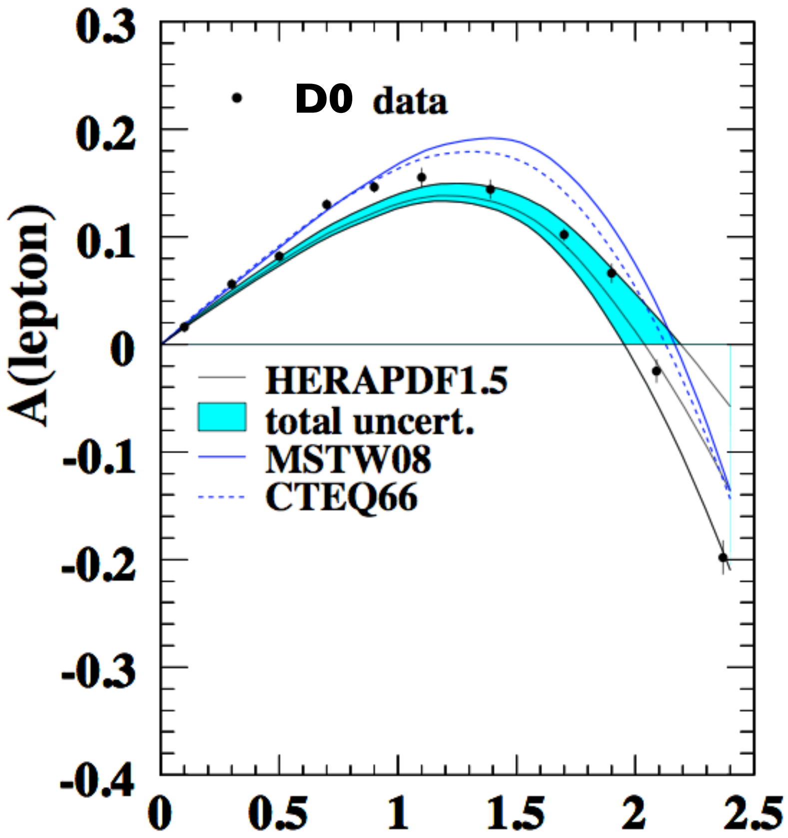
Comparison of HERAPDF1.5 to Tevatron W asymmetry

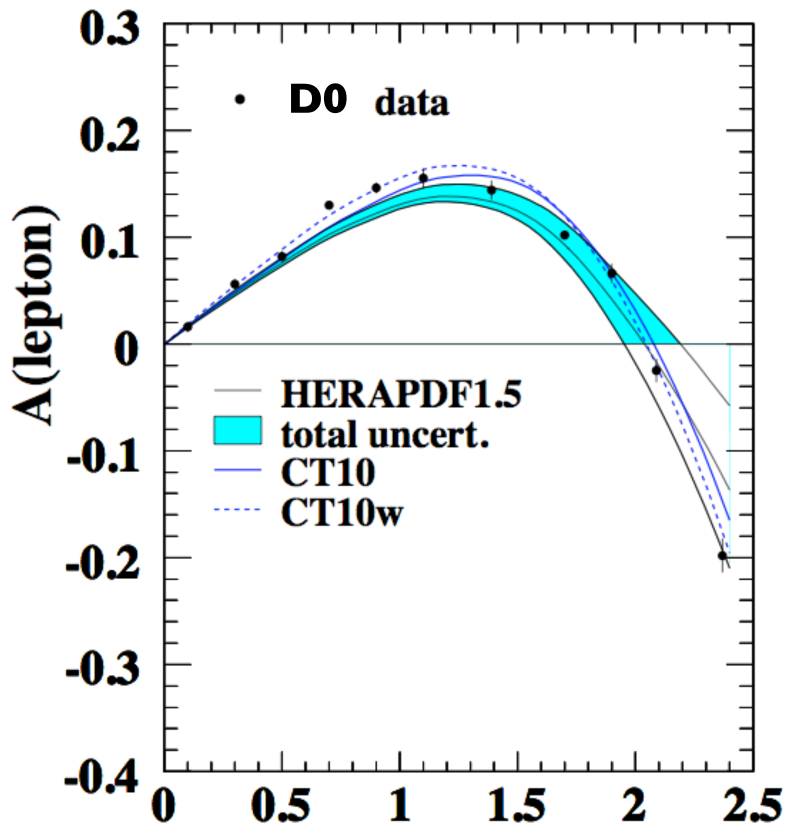




- HERAPDF1.5 results in even a better agreement than HERAPDF1.0 with the CDF data for the W asymmetry, even if this data is not included in the HERA fits.

D0 Lepton Asymmetry

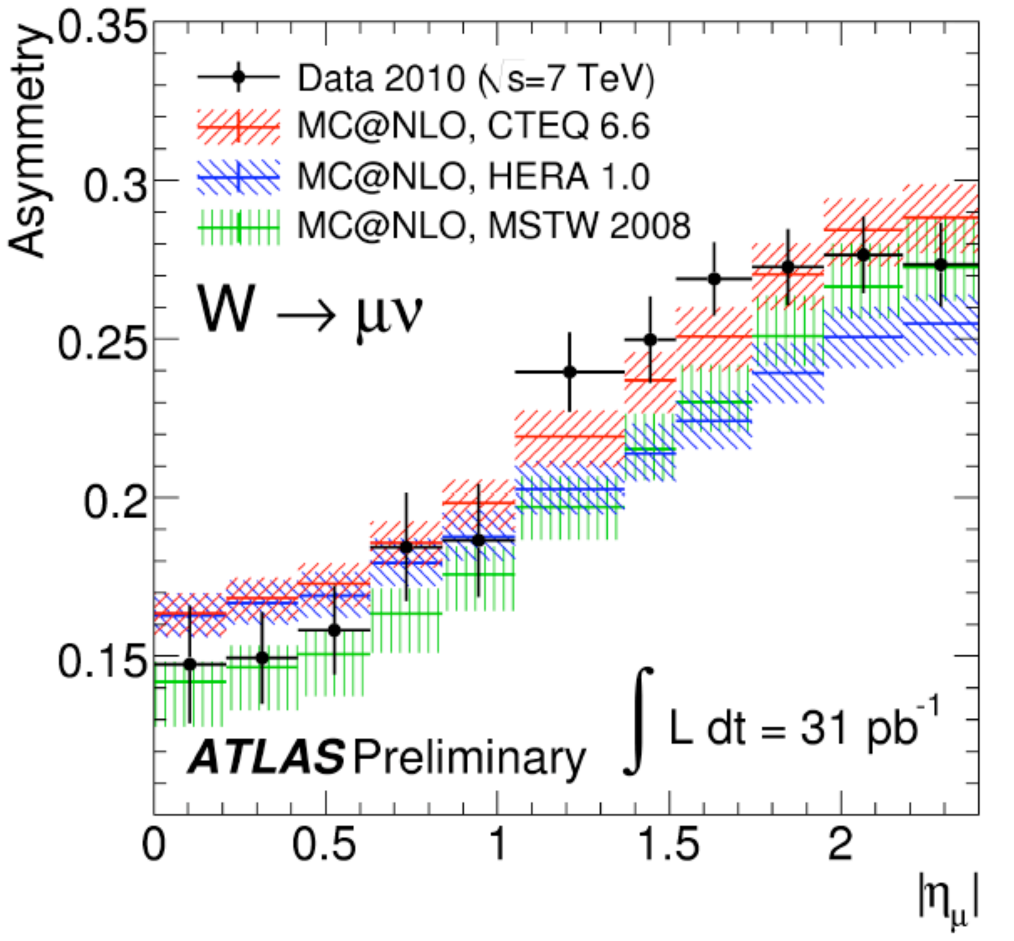




- HERAPDF1.5 provides a reasonable agreement even with the D0 lepton asymmetry, for which the global fits have difficulties.

  - Hence, there is a universal description of partonic processes and all can be described with ep data.

Predictions for W and lepton asymmetries at LHC



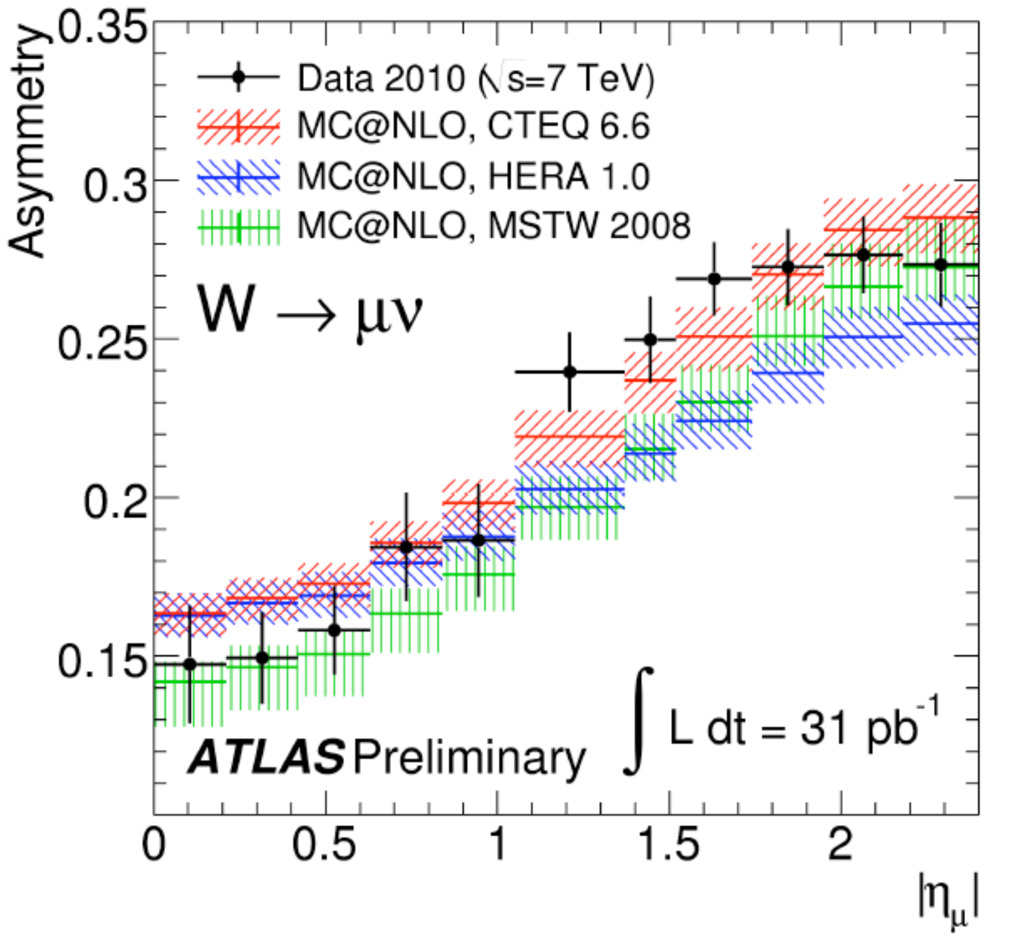
$$A_{\pm}(y_W) = \frac{d\sigma/dy_W(W^+) - d\sigma/dy_W(W^-)}{d\sigma/dy_W(W^+) + d\sigma/dy_W(W^-)}$$

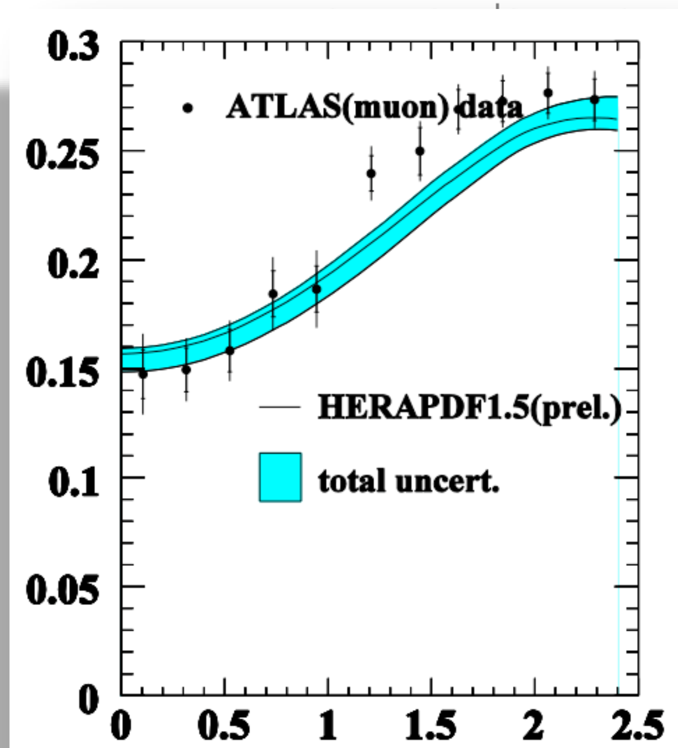
$$\approx \frac{u(x_1)\bar{d}(x_2) - d(x_1)\bar{u}(x_2)}{u(x_1)\bar{d}(x_2) + d(x_1)\bar{u}(x_2)} \approx \frac{u(x_1) - d(x_1)}{u(x_1) + d(x_1)}$$

- W asymmetry is sensitive to differences between u and d
- Difference in u and d quarks can be better measured by all experiments at the LHC

- Muon Lepton asymmetry from ATLAS compared to various predictions:
  - HERAPDF is providing a competitive prediction although uses only ep data

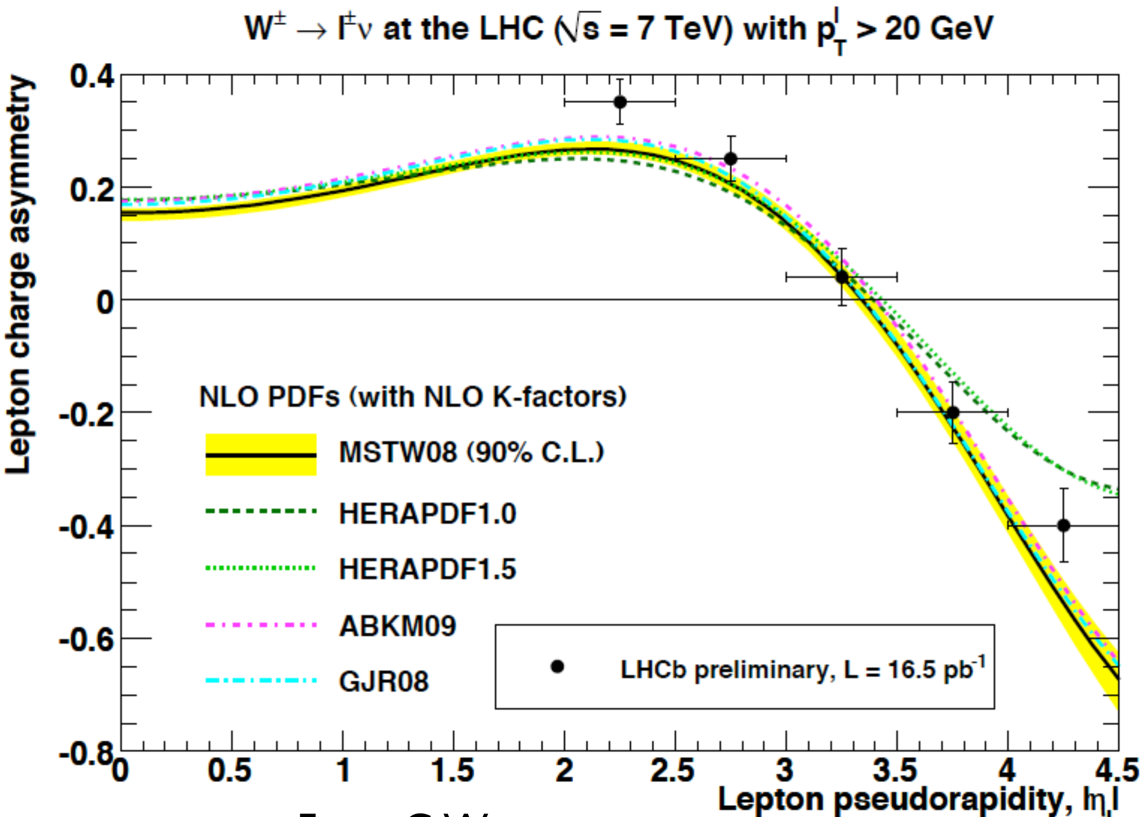
LHC predictions for W and lepton asymmetries



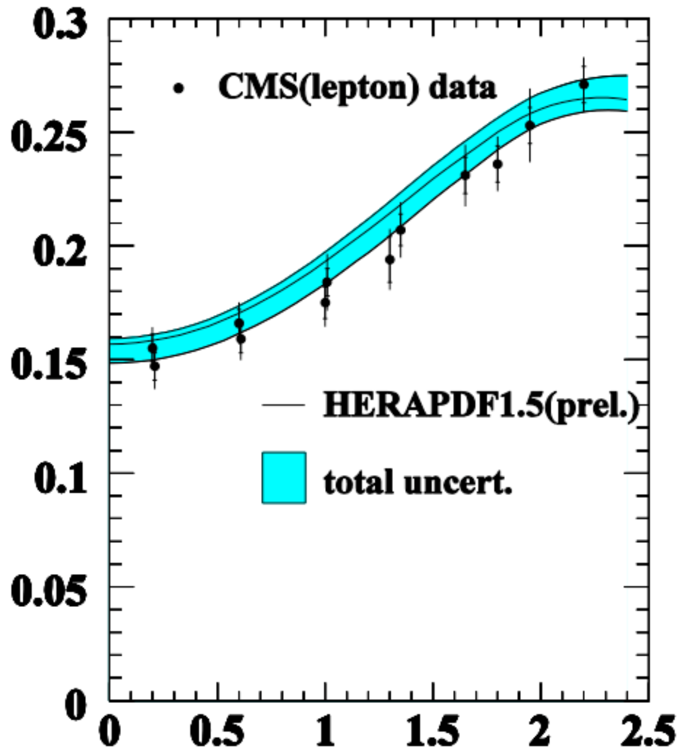


- The uncertainties are reduced for the HERAPDF1.5 predictions as compared to HERAPDF1.0:
  - Due to the new precise measurements from HERA II
  - Better constrain at high x for HERAPDF1.5 translates into better constrain at high rapidity

LHC predictions: for LHCb and CMS W asymmetry data



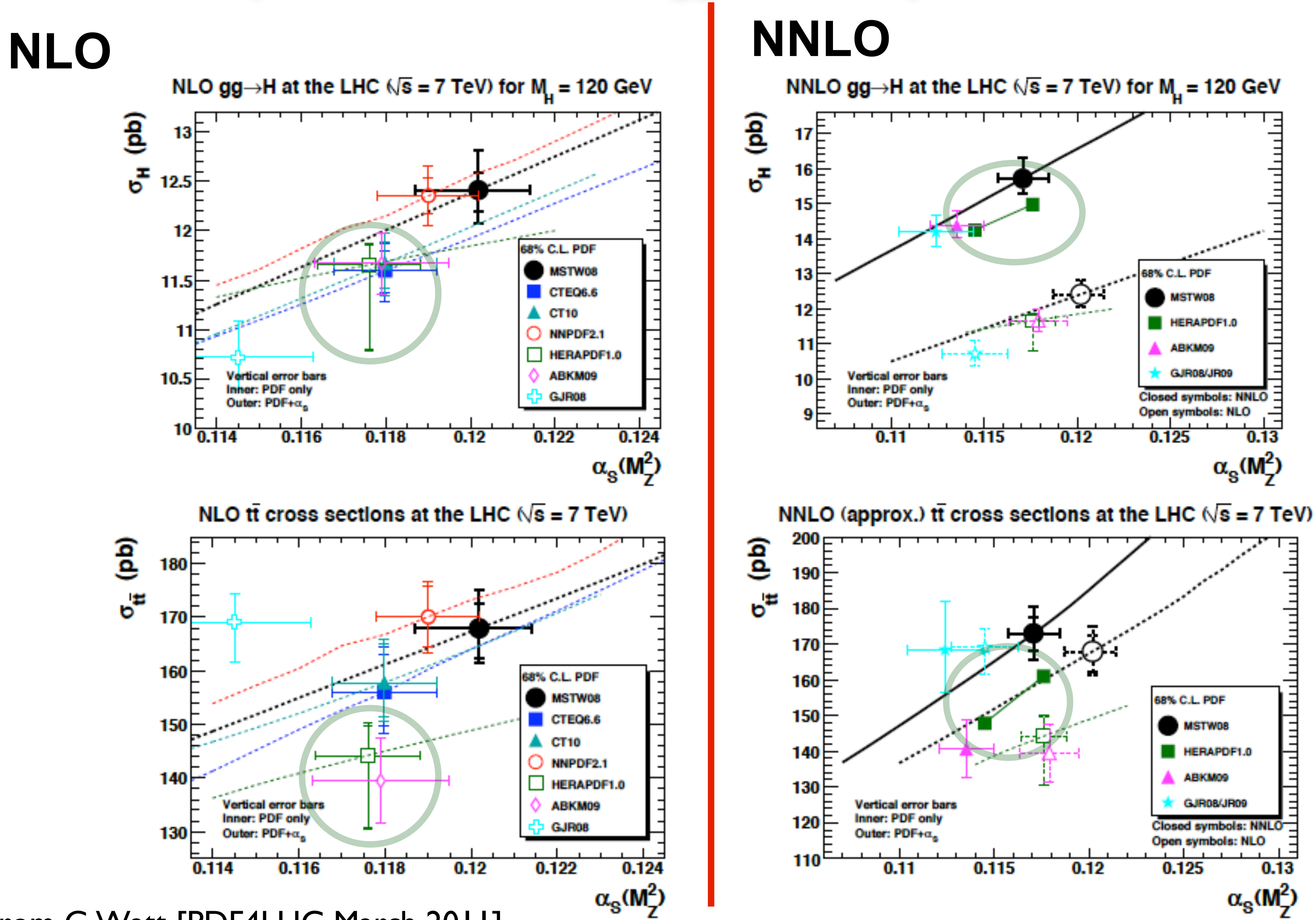
From G.Watt



From M.Cooper-Sarkar

HERAPDF provide reasonable predictions for LHCb and CMS data too

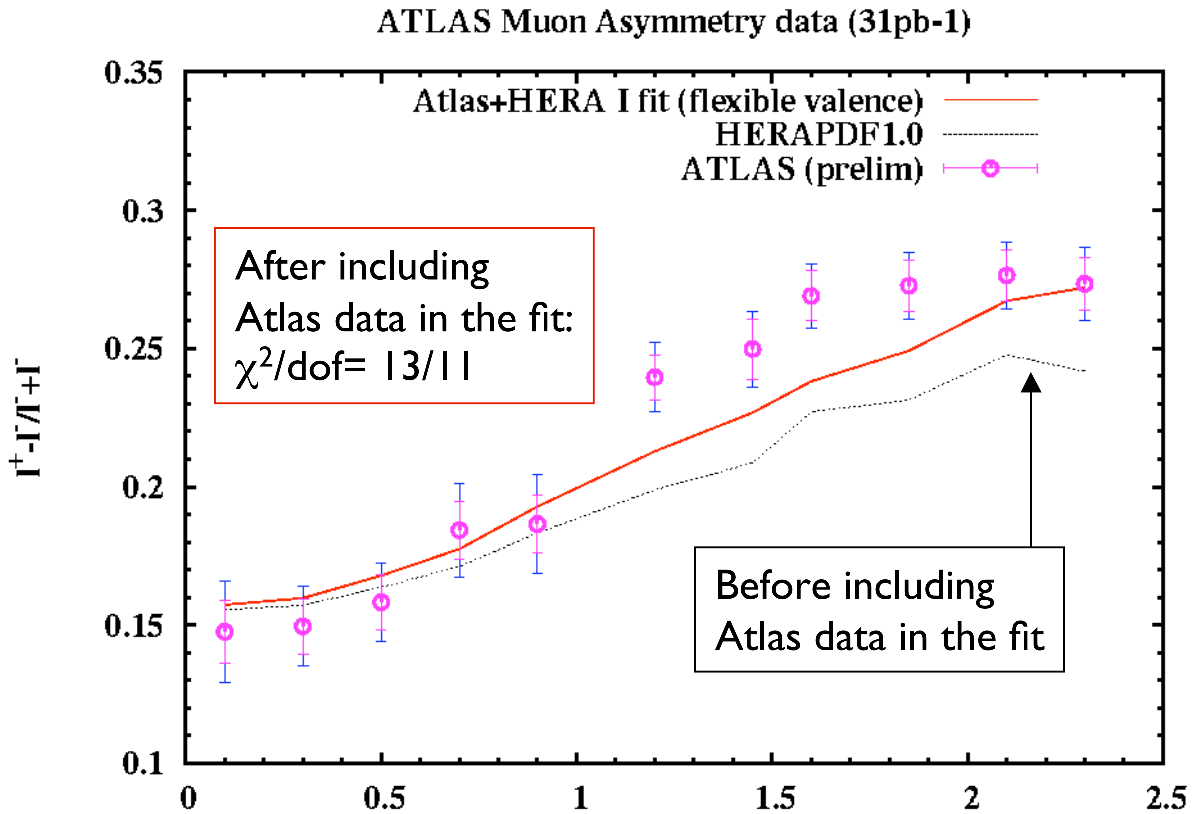
LHC predictions for Higgs and top cross sections



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

Summary

- HERA data provides precise PDFs for the LHC
- New preliminary combined HERA-II improves accuracy at high x
- Studies within HERAPDF framework check robustness of the estimations for the experimental, model and parametrisation uncertainties
  - More studies are available based on low energy data, charm data, jet data (see backup)

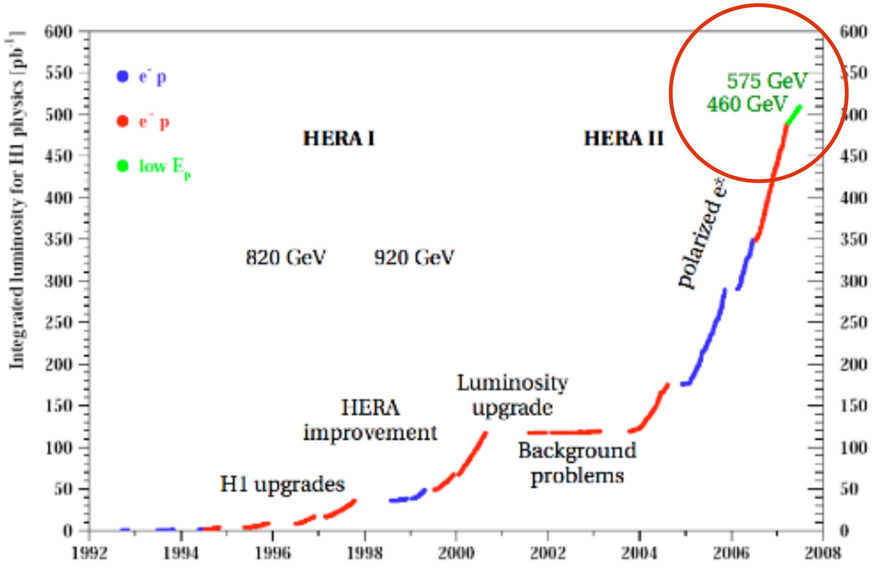
- HERAPDF predicts measurements from Fixed Target and Tevatron experiments well.

- HERA data are confronted with the first results from the LHC:
  - Quantitative test of the Standard Models: predictions from ep scattering are in good agreement with observation at pp machine.
  - Results for Z rapidity, accurate jet measurements are expected soon from the LHC.

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

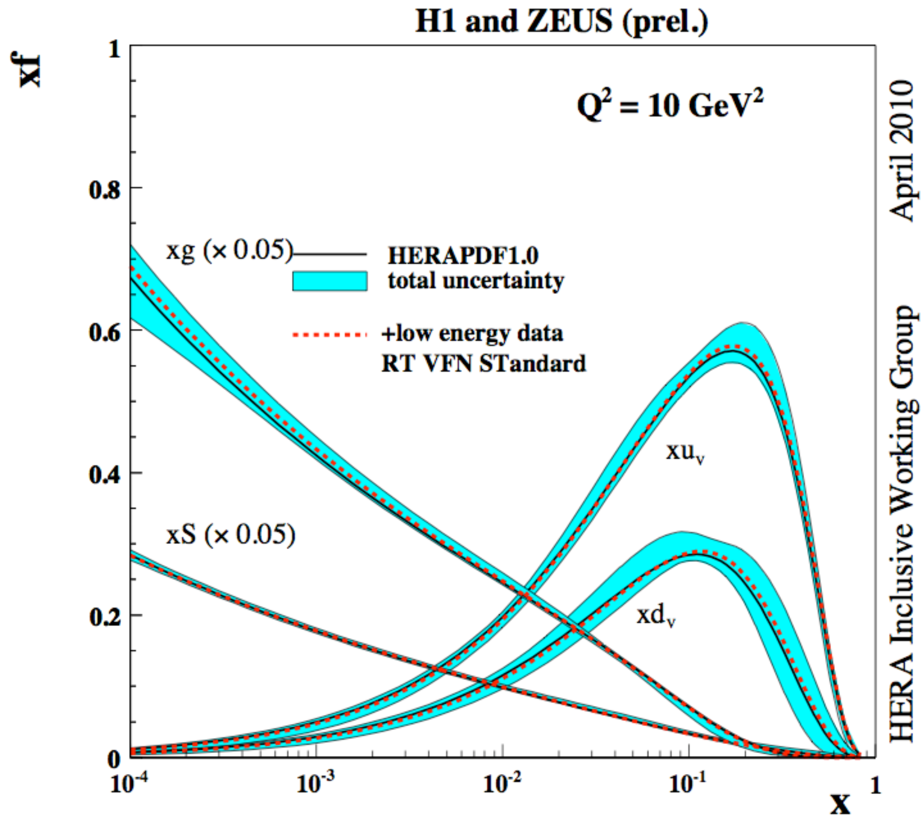
Extra
HERAPDF including Low Energy Data

HERAPDF including Low Energy data



- Preliminary HERA Combined Low Energy data available!

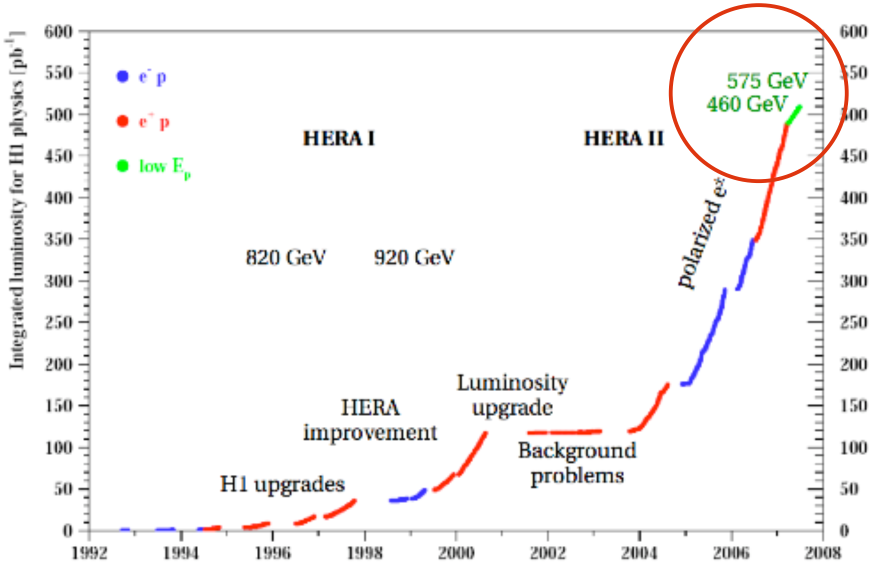
- New accurate measurement in $Q^2>2.5$ GeV^2 range, sensitive to structure function F_L are included in the QCD analysis on top of the HERA I data➔



- 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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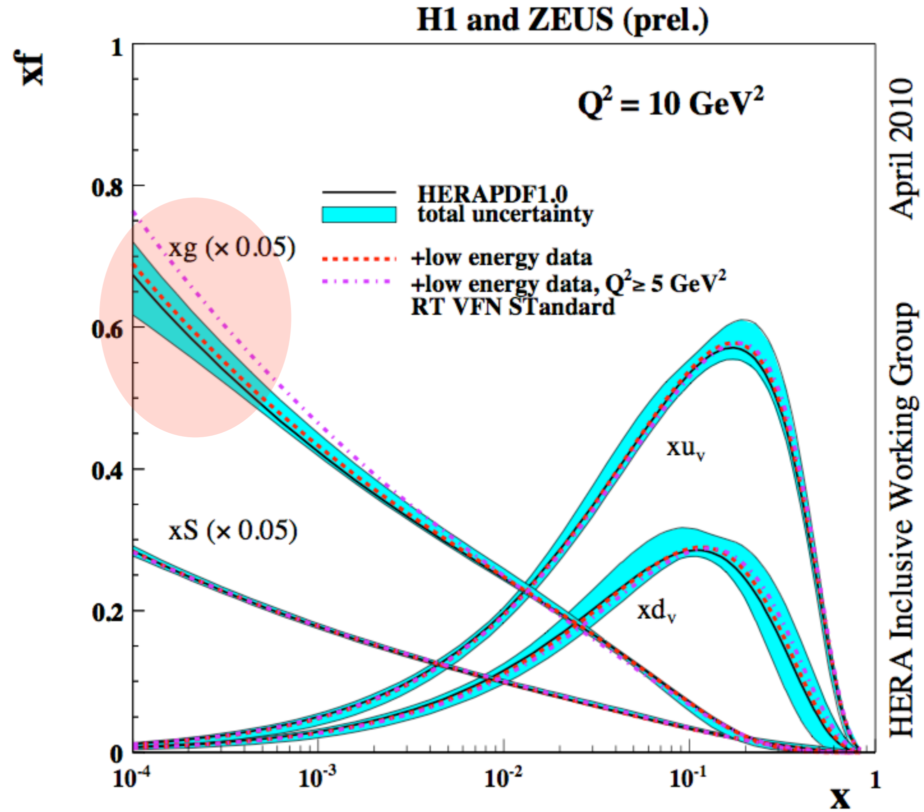
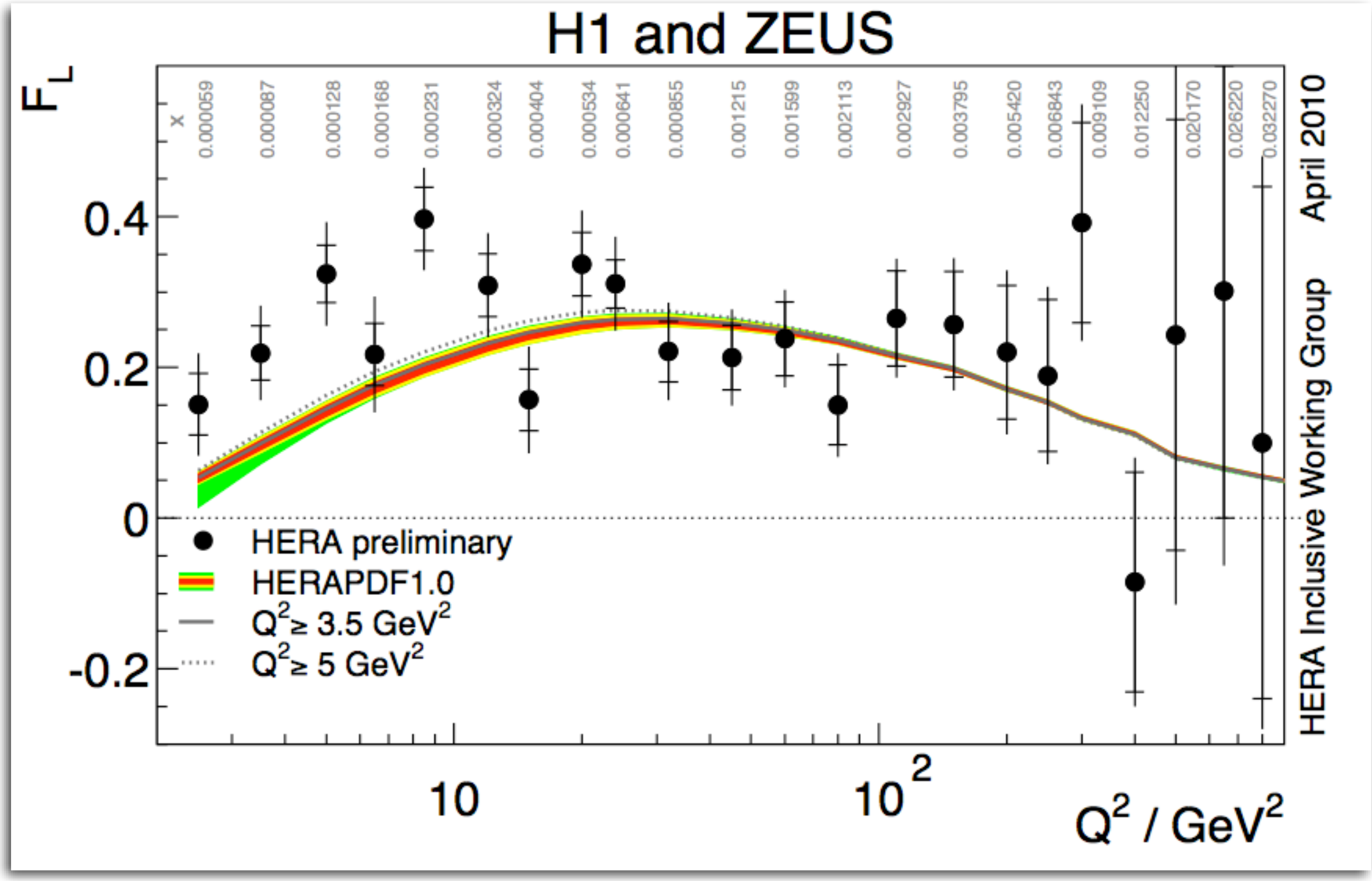


- However, The $Q^2 \geq 5$ GeV^2 cut brings large improvement in χ^2 [818/806 → 698/771] and it yields different shapes for gluon and sea PDFs.
  - for HERAPDF1.0, Q^2 cut variation is included in the model uncertainty, but it had smaller effect.

HERA F_L data vs F_L predictions

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

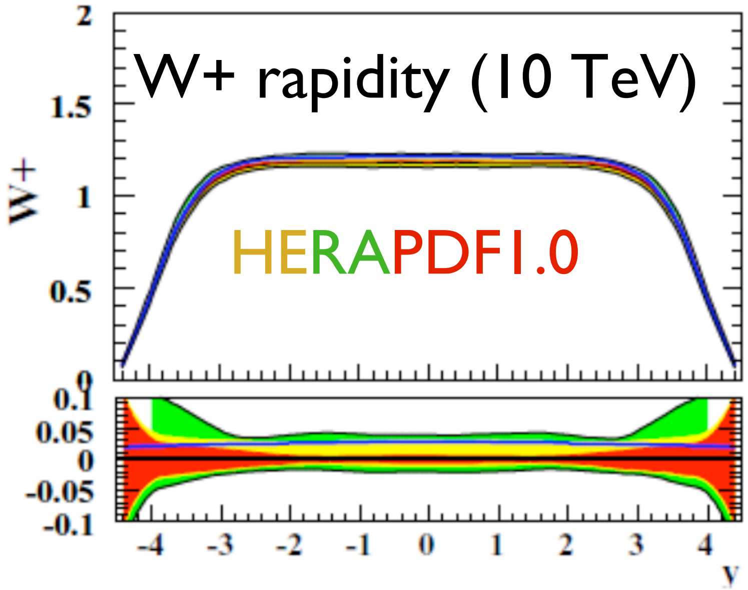


Low Q^2 region remains very interesting for further QCD tests!

Extra

HERAPDF including Charm Data

Impact of charm data on the LHC predictions

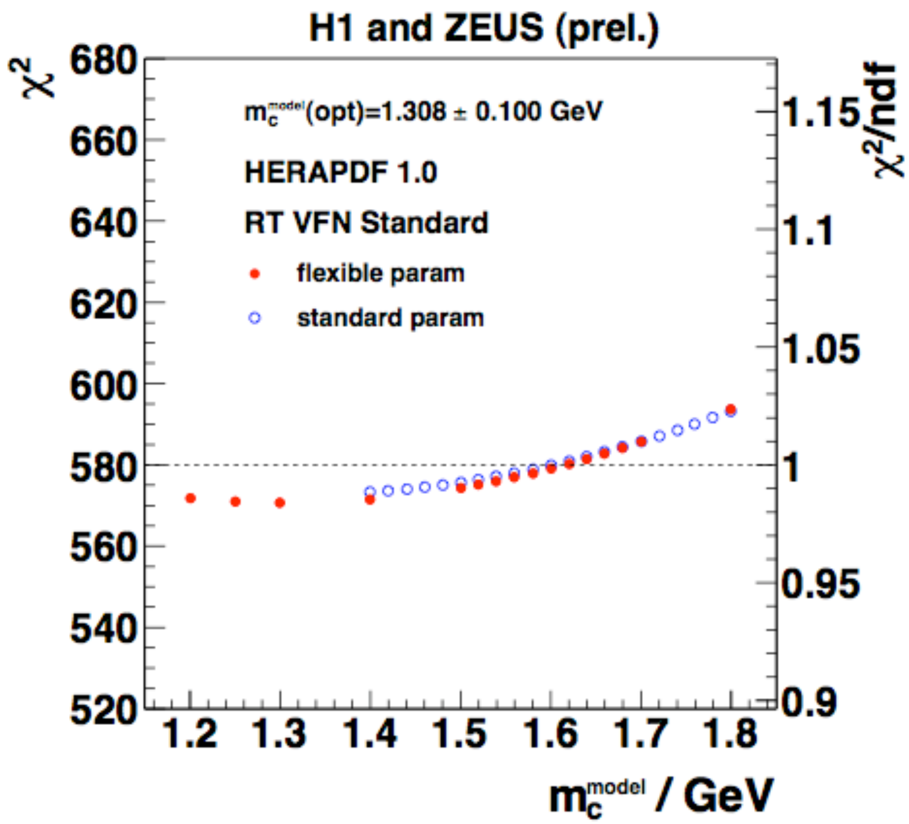


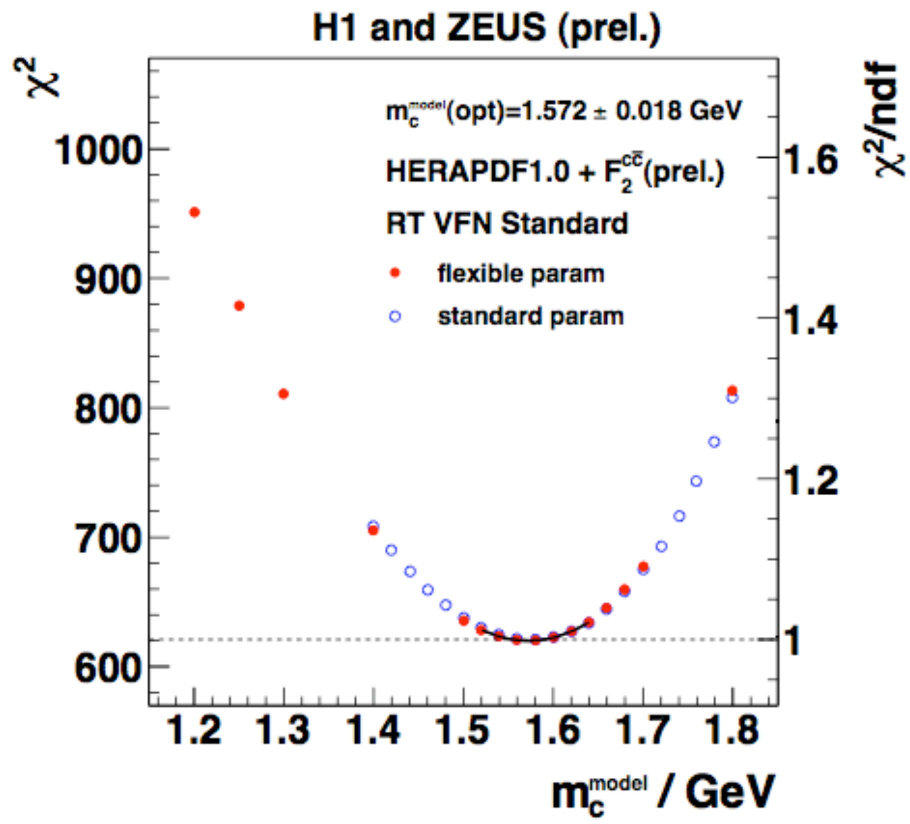
- In HERAPDF1.0, uncertainties due to heavy flavour modeling is estimated by varying $m_{c,b}$
- Predictions rise with the increased value for m_c: m_c=1.4 →1.65 GeV by 3%

- The reason for this large sensitivity is that *x* of the central W, *Z* production at the LHC is measured at HERA around the charm threshold where the contribution of F_2^c to the total inclusive F_2 is significant (up to 30%).
  - The increase in m_c leads to the suppression of xcbar in the sea distribution which is compensated by the increase of xubar.
- Recent preliminary combined H1 and ZEUS data has a precision up to 5-10% and kinematic range of $2<Q^2<1000$ GeV^2.
- The accuracy of data should allow to reduce the ambiguity in separation of Ubar type quark into xubar and xcbar contributions
  - Ubar=ubar+cbar which is fixed by F_2 data

Impact of inclusion of the charm data in the fits

- In QCD fits without charm data similar and smaller optimal m_c are preferred for each scheme
- Strong preference for a particular m_c once charm data is included
  - Study performed for RT, ACOT, ZMVFNS schemes





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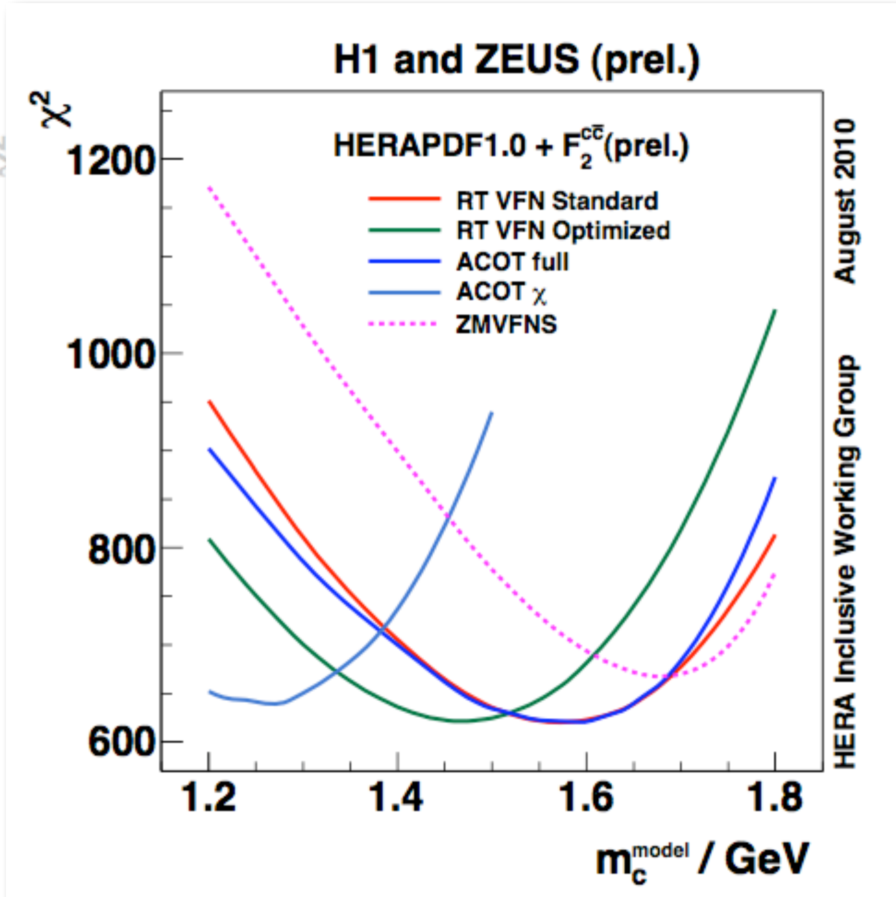


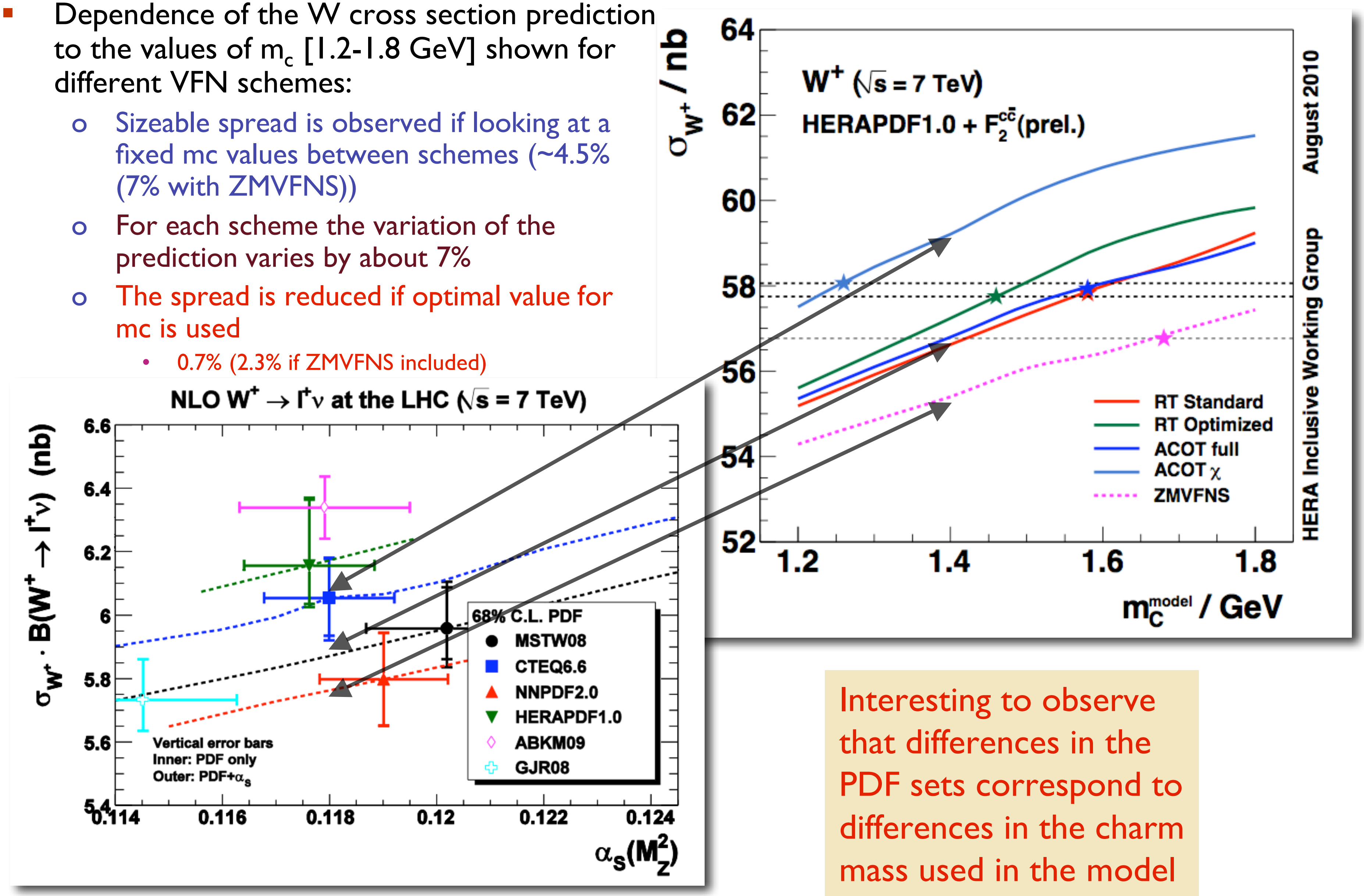
- Comparisons of the χ^2 minima of HERA I + charm data using different VFN schemes shown in different colors

- 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]

Propagate PDFs to W LHC predictions

- Dependence of the W cross section prediction to the values of m_c [1.2-1.8 GeV] shown for different VFN schemes:
  - Sizeable spread is observed if looking at a fixed mc values between schemes (~4.5% (7% with ZMVFNS))
  - For each scheme the variation of the prediction varies by about 7%
  - The spread is reduced if optimal value for mc is used
    - 0.7% (2.3% if ZMVFNS included)



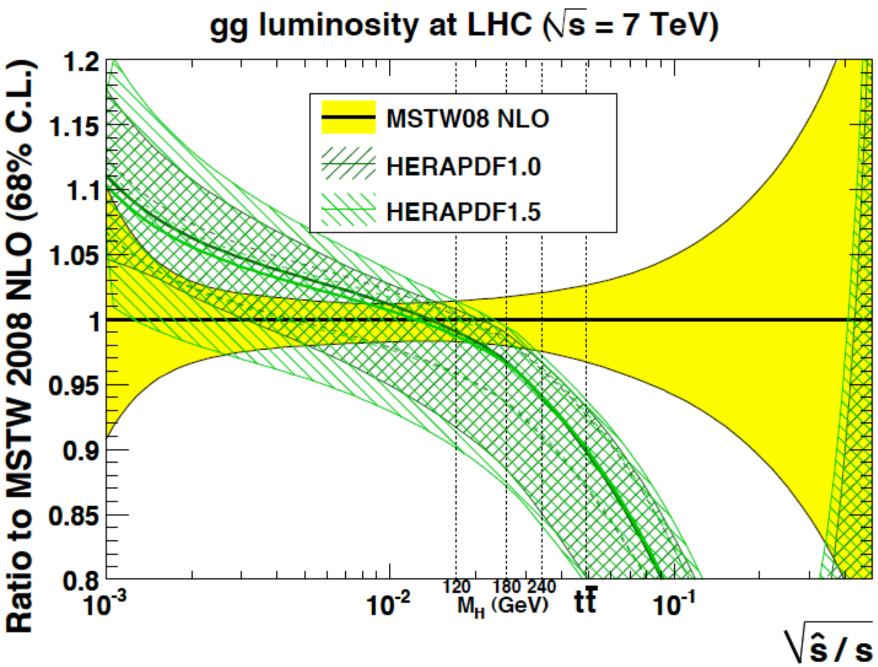
Interesting to observe that differences in the PDF sets correspond to differences in the charm mass used in the model

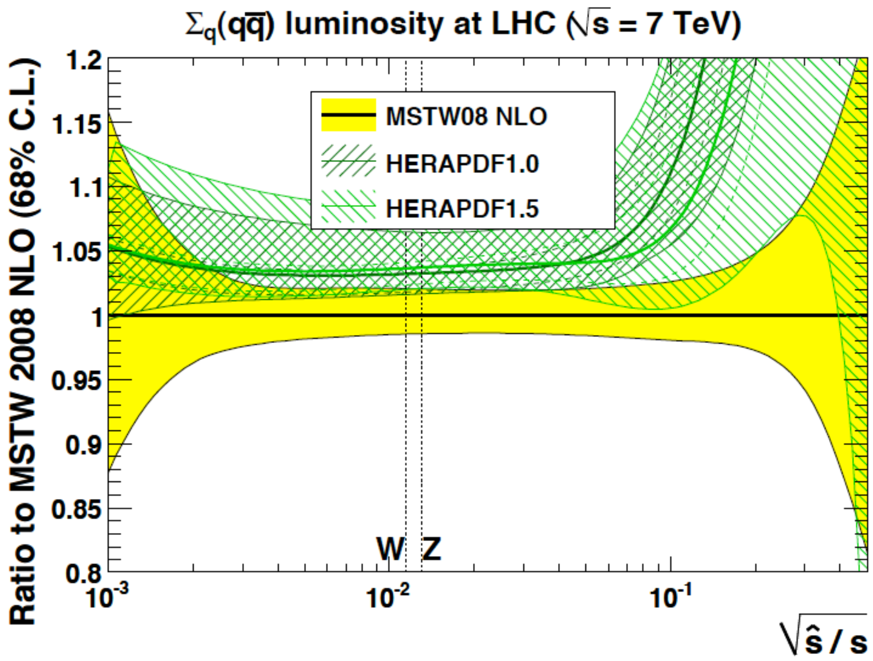
Extra

HERAPDF including Jet Data:

HERAPDF1.6

Predictions on the latest data from the LHC

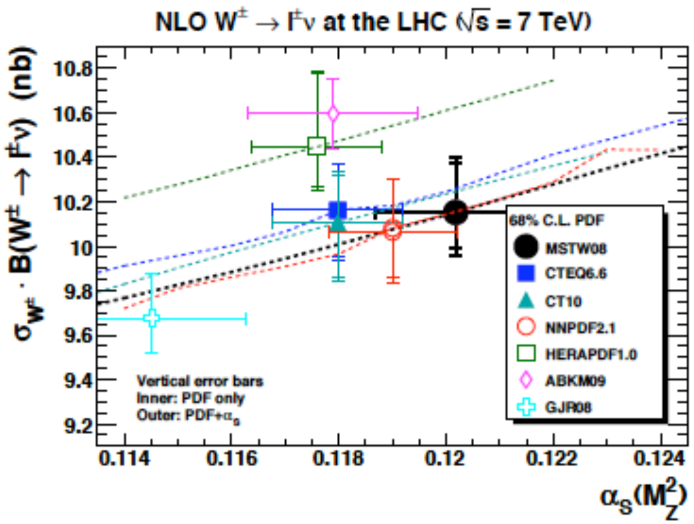


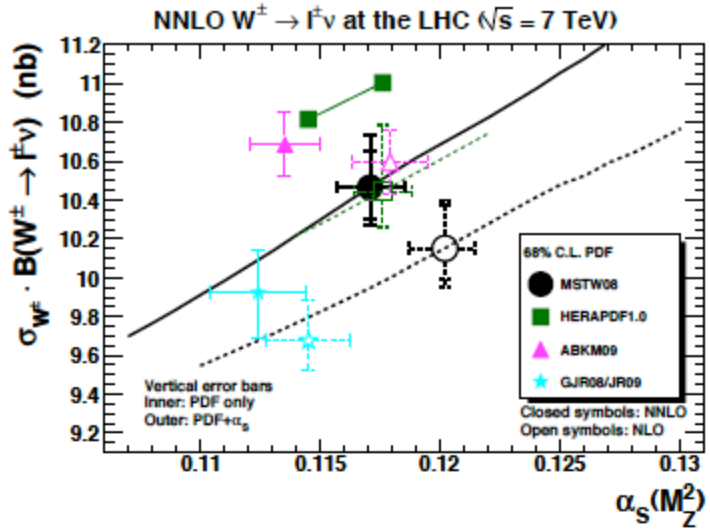


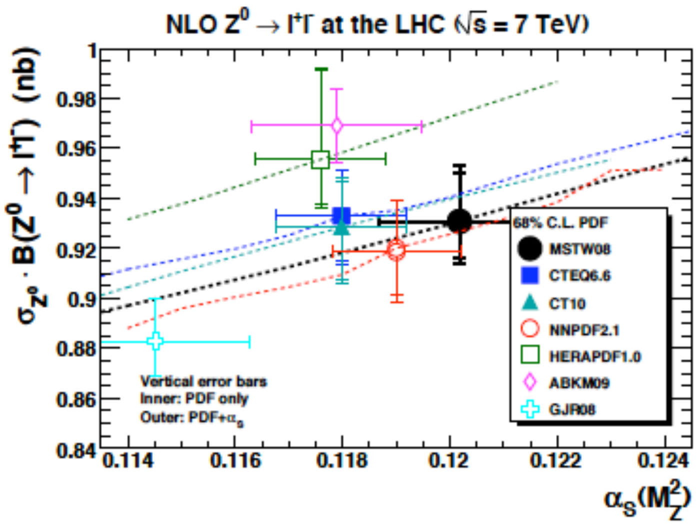
- The coming results from the LHC starts to discriminate among various predictions
  - Hence, they are important inputs to constrain the PDFs

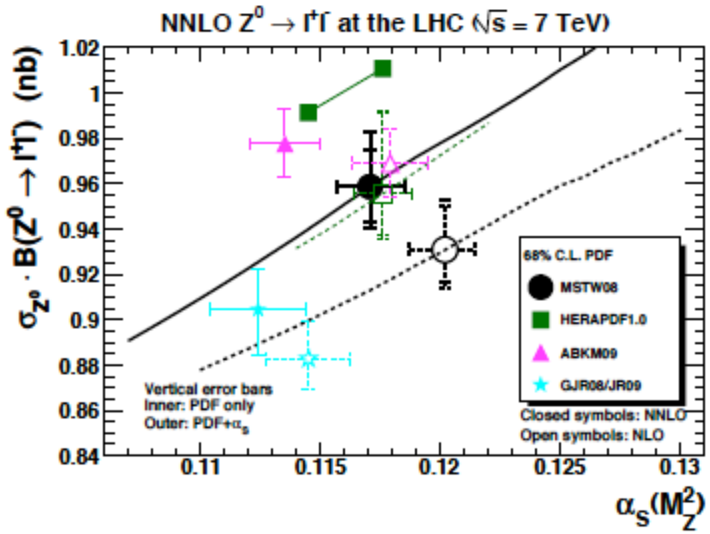
LHC predictions

- NLO and NNLO W and Z total corss sections versus strong coupling (courtesy G. Watt):

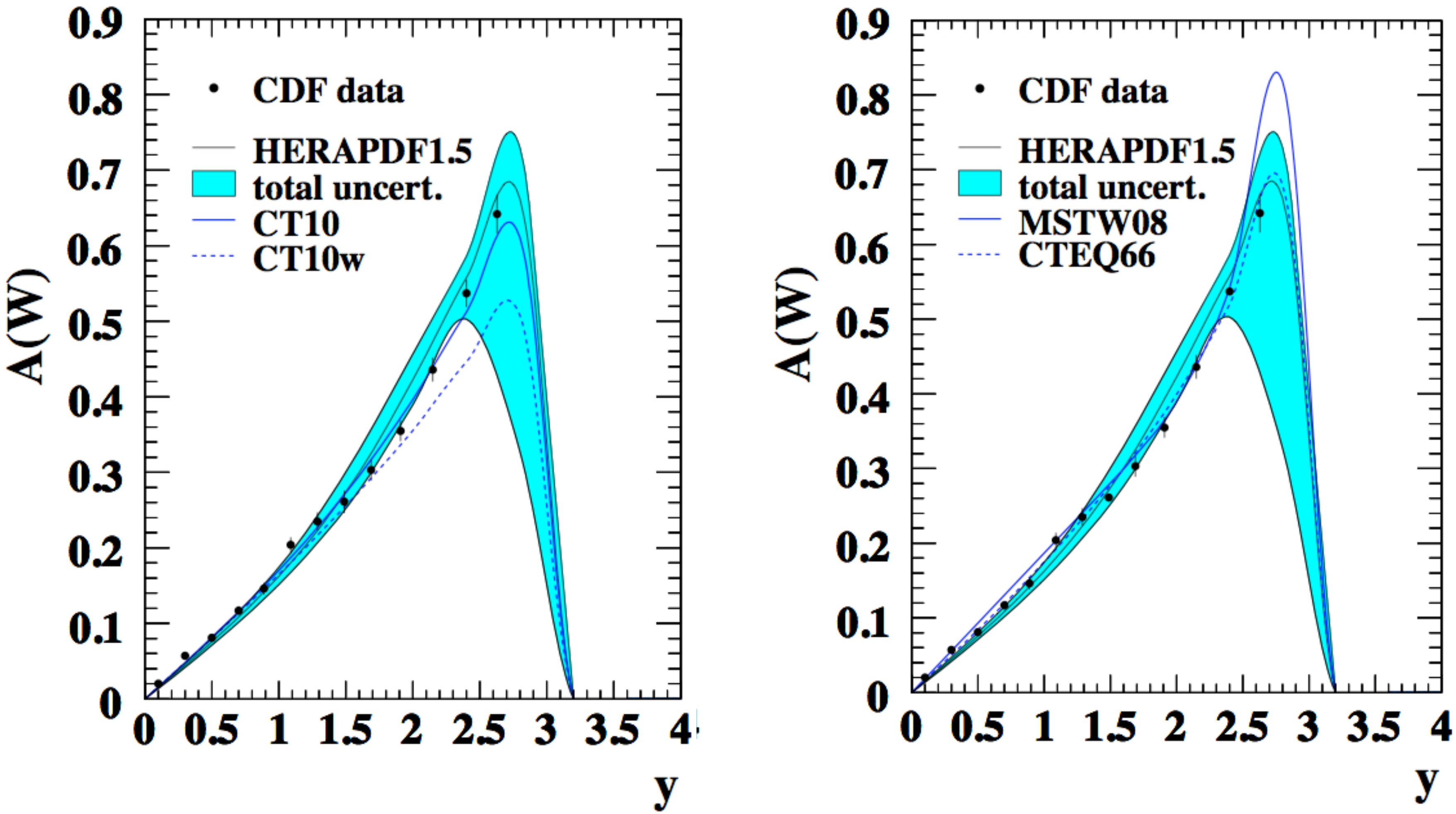






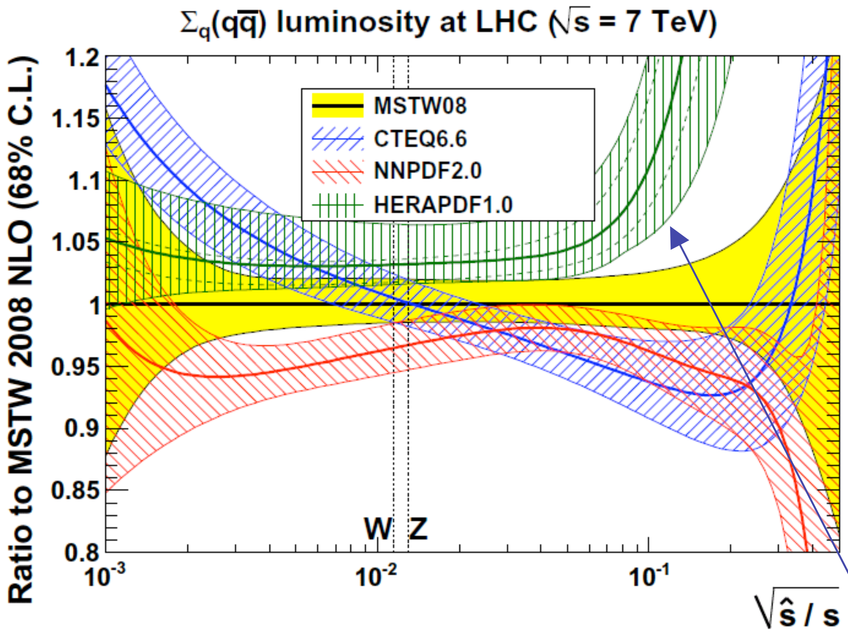


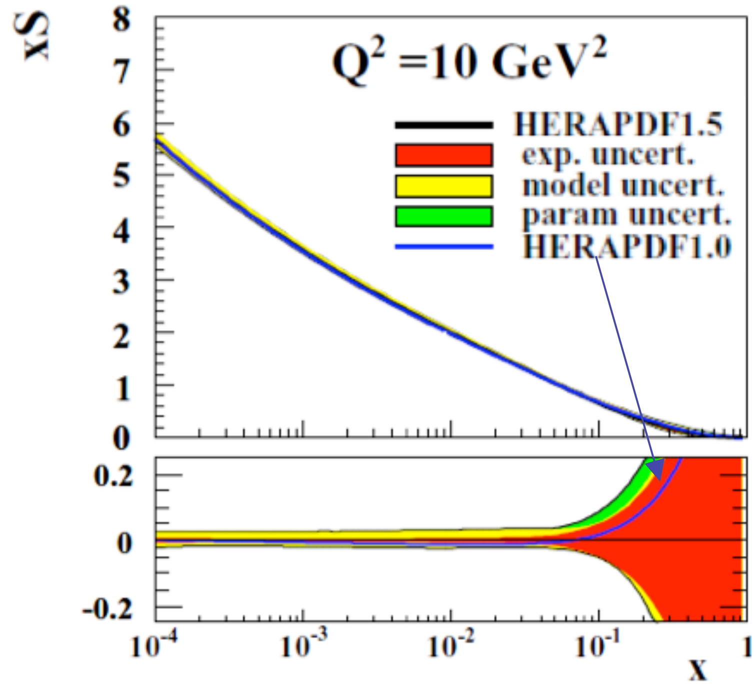
Comparison to Tevatron W asymmetry

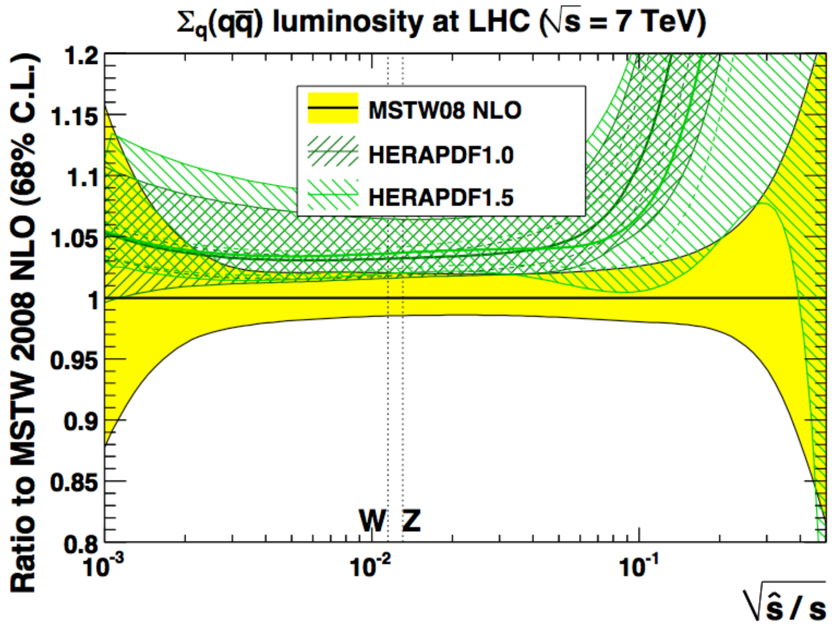


- HERAPDF1.5 compared to Global PDF sets

Impact on the LHC predictions





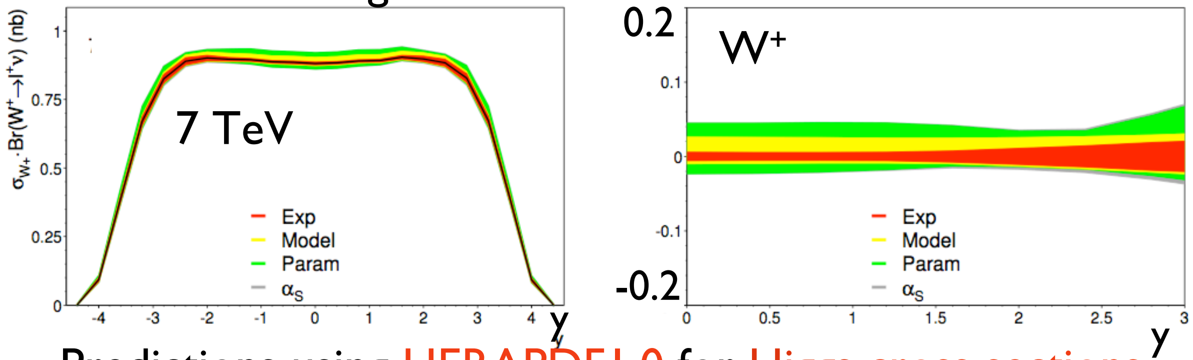


- HERAPDF1.0 is high at the large scale because Sea is hard at high x
- HERAPDF1.5 has a softer Sea, hence in a better agreement with other PDF sets

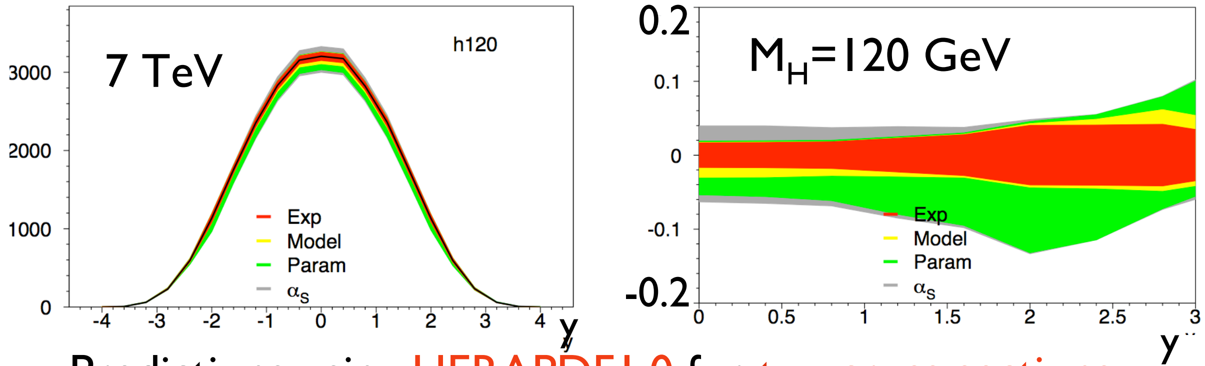
(plots courtesy of G.Watt)

LHC predictions based on HERAPDF1.0

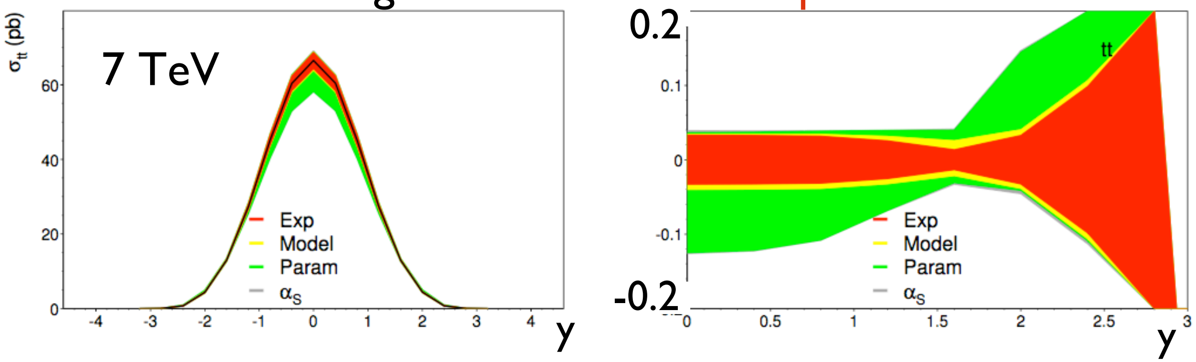
- Predictions using HERAPDF1.0 for W cross sections.



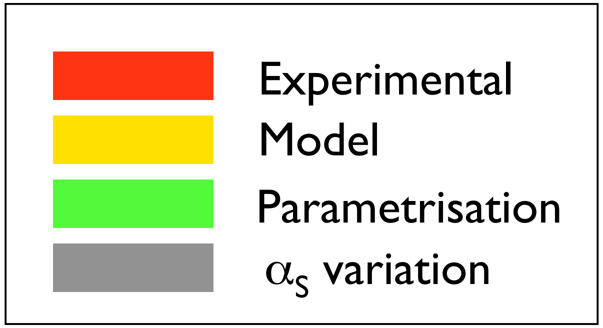
- Predictions using HERAPDF1.0 for Higgs cross sections.



- Predictions using HERAPDF1.0 for top cross sections.

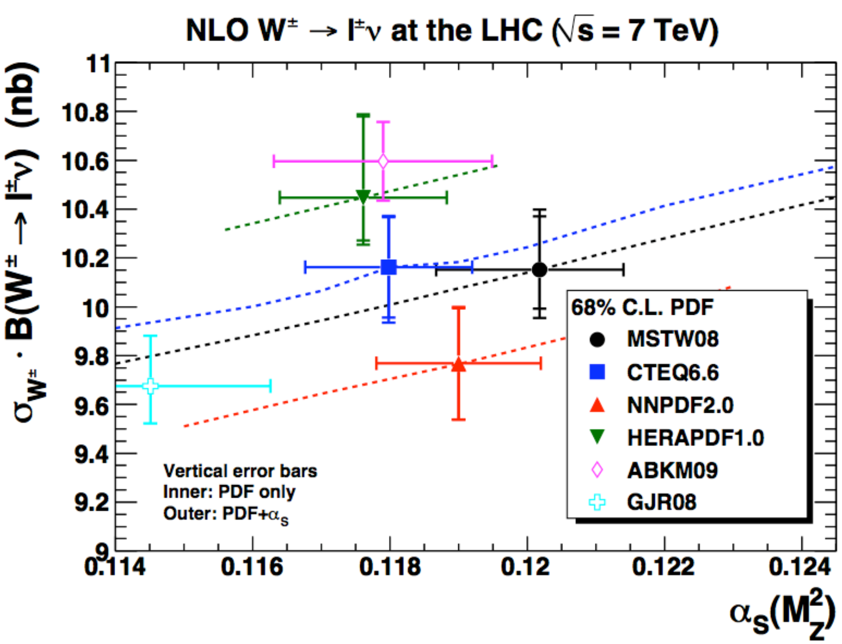


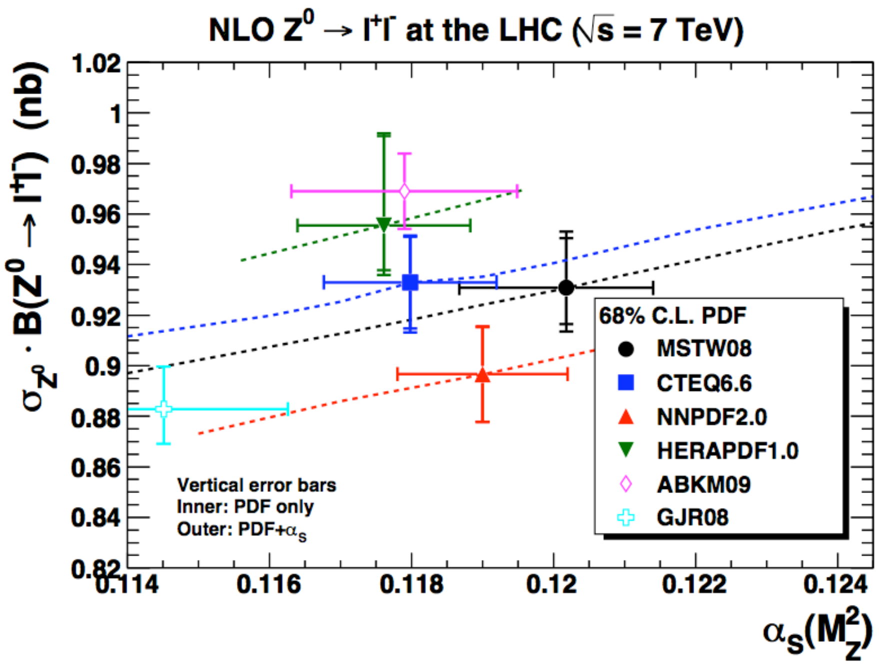
Uncertainties:



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

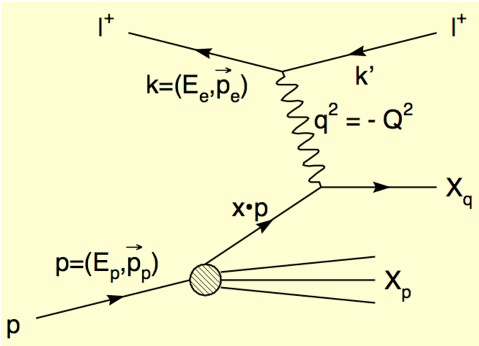
LHC Predictions based on older sets





Probing the Proton Structure

- Deep Inelastic Scattering (DIS)



- Kinematic Variables
  - Virtuality of exchanged boson

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

  - Proton momentum fraction of the scattered quark (Bjorken variable)

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

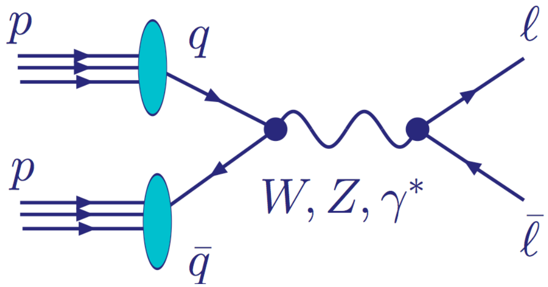
  - Inelasticity parameter

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

  - Invariant centre of mass energy

    $$s = (k+p)^2 = \frac{Q^2}{xy}$$

- Drell Yann (DY)



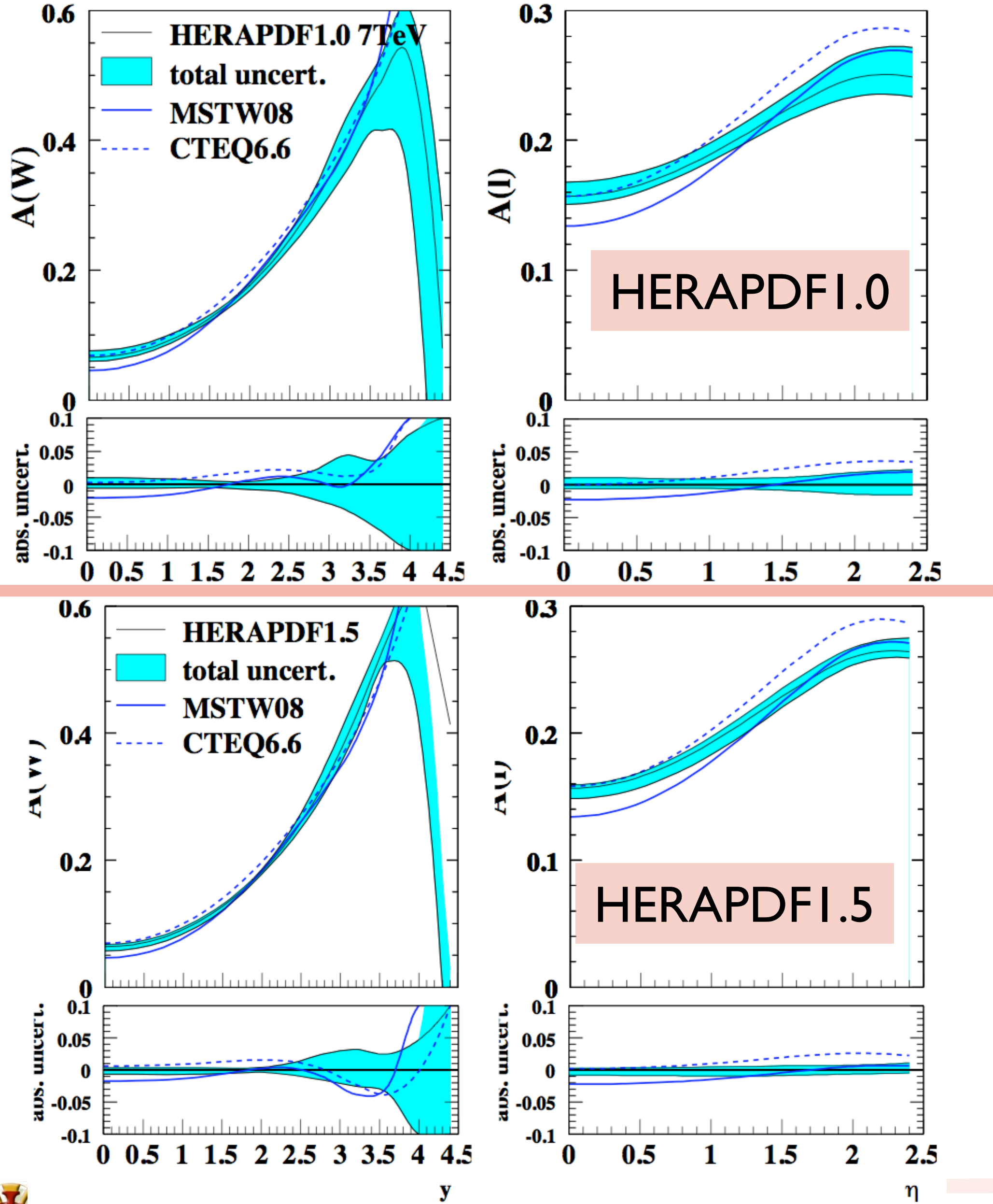
- Kinematic Variables
  - $Q^2=M^2_{Z,W}$
  - rapidity y

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

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

  - $s=4E_p^{\ 2}$

LHC predictions for W and lepton asymmetries



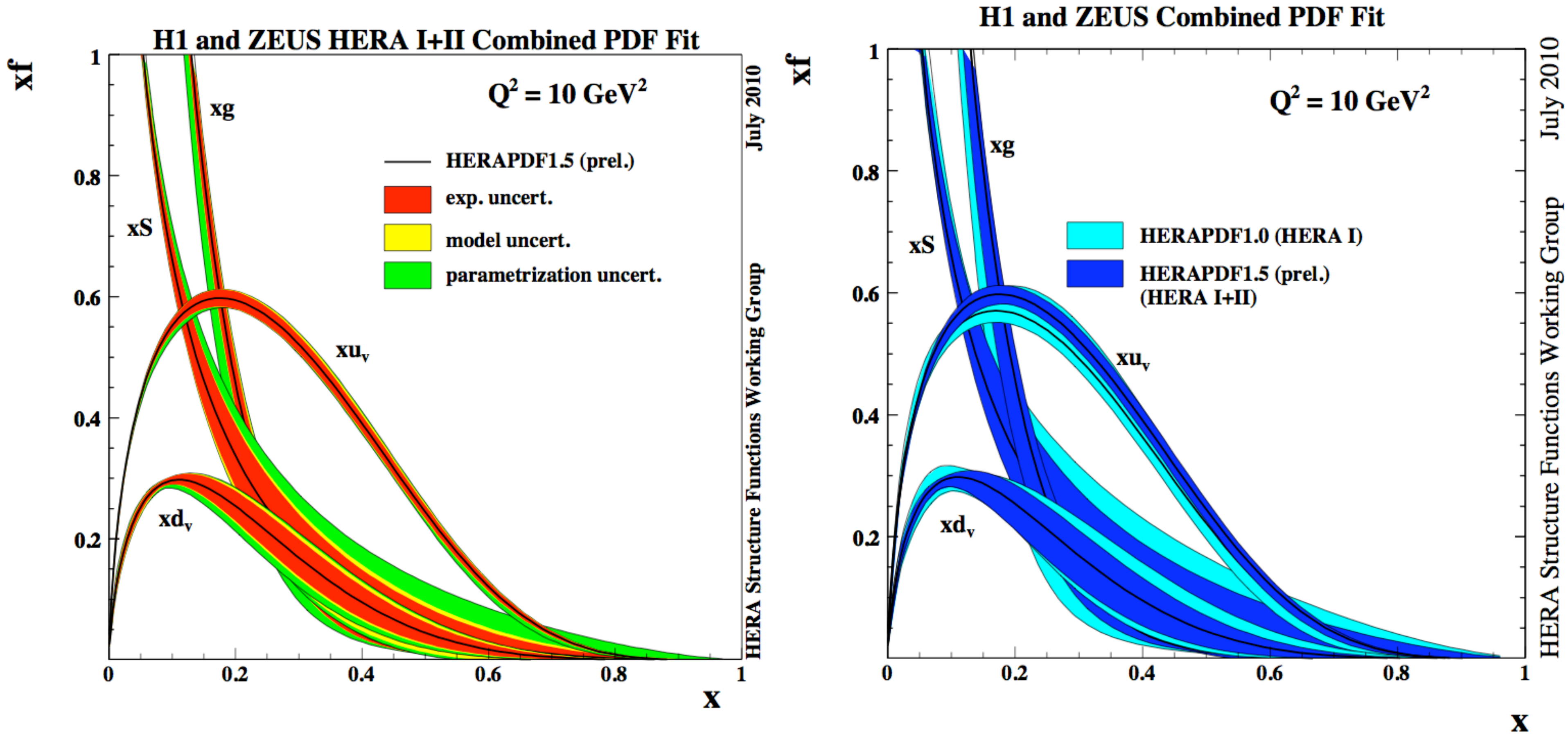
$$A_{\pm}(y_W) = \frac{d\sigma/dy_W(W^+) - d\sigma/dy_W(W^-)}{d\sigma/dy_W(W^+) + d\sigma/dy_W(W^-)}$$

$$\approx \frac{u(x_1)\bar{d}(x_2) - d(x_1)\bar{u}(x_2)}{u(x_1)\bar{d}(x_2) + d(x_1)\bar{u}(x_2)} \approx \frac{u(x_1) - d(x_1)}{u(x_1) + d(x_1)}$$

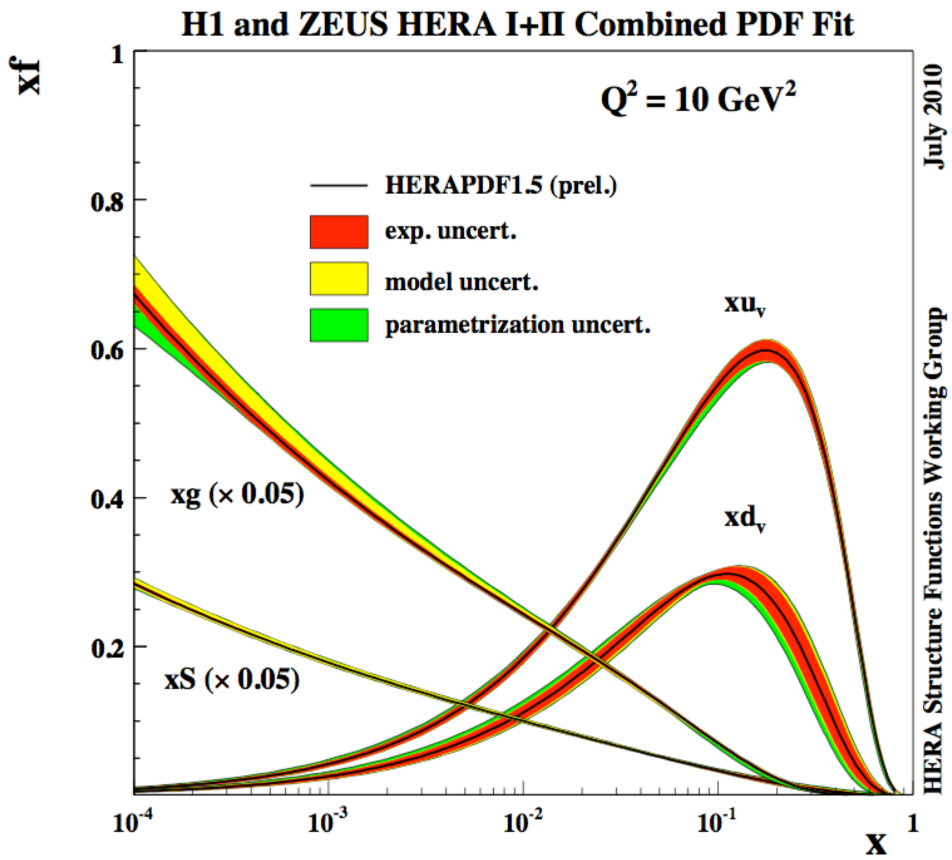
- W asymmetry is sensitive to differences between u and d
- Difference in u and d quarks can be better measured by all experiments at the LHC
- The uncertainties are reduced for the HERAPDF1.5 predictions as compared to HERAPDF1.0:
  - Due to the new precise measurements from HERA II
  - Better constrain at high x for HERAPDF1.5 translates into better constrain at high rapidity

HERAPDF1.5 vs HERAPDF1.0

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


H1 and ZEUS HERA I+II Combined PDF Fit
xf
$Q^2 = 10\ GeV^2$
HERAPDF1.5 (prel.)
exp. uncert.
model uncert.
parametrization uncert.
xu_v
xd_v
xg (× 0.05)
xS (× 0.05)
1
0.8
0.6
0.4
0.2
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
x
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HERA Structure Functions Working Group