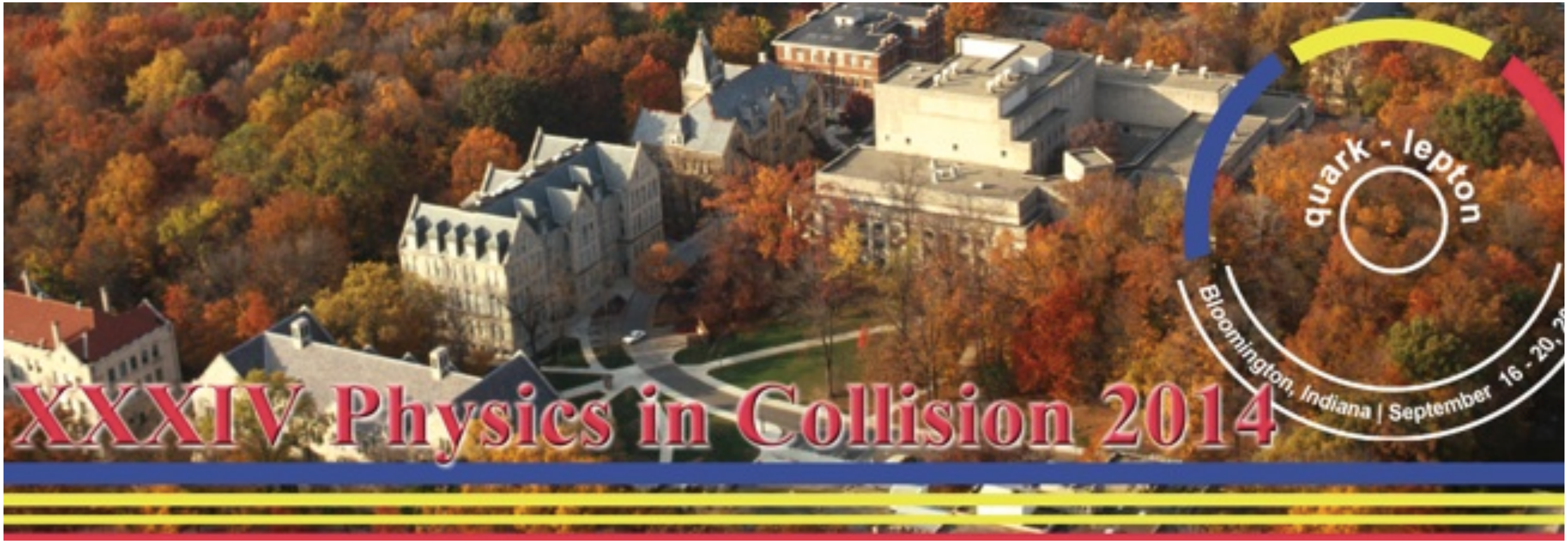
Structure Function Measurements and PDF Fits

Voica Radescu
DESY

- Importance of understanding the Proton Structure
- Recent Structure Function measurements from HERA
- Complementarity from LHC
- Summary



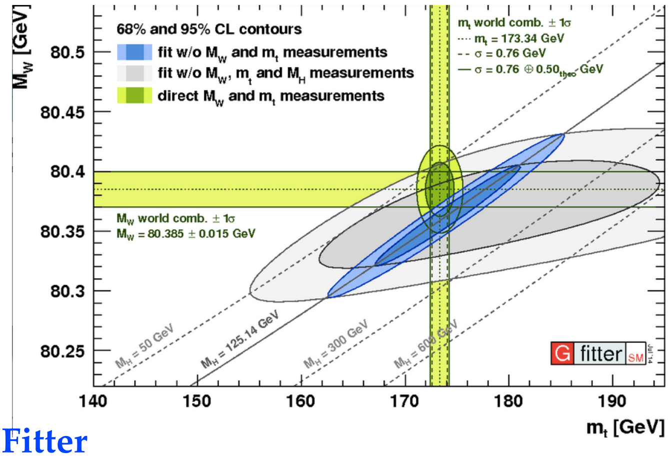
Why do we still need to care about PDFs?

- Discovery of new exciting physics relies on precise knowledge of proton structure.
- <u>Factorisation theorem:</u>
  - Cross section can be calculated by convoluting short distance partonic reactions (calculable in pQCD) with Parton Distribution Functions (PDFs):
  - PDFs cannot be calculated in perturbative QCD, however they are process independent (universal) and their evolution with the scale is predicted by pQCD

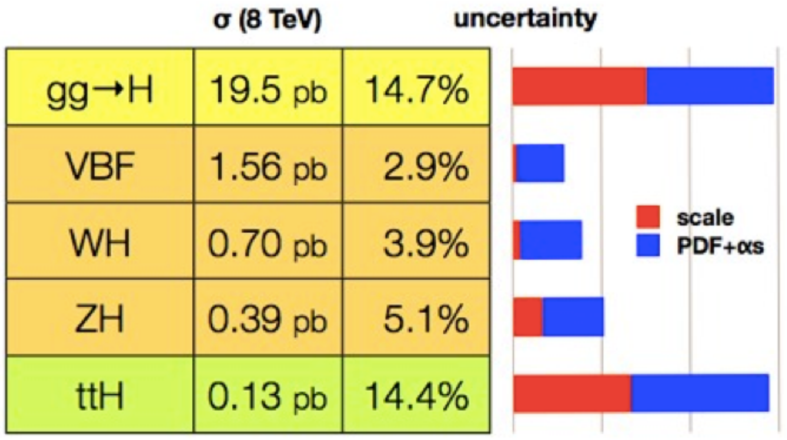
$$\mu^2 \frac{\partial f(x,\mu^2)}{\partial \mu^2} = \int_z^1 \frac{dz}{z} \frac{\alpha_s}{2\pi} P(z) f\left(\frac{x}{z},\mu^2\right)$$

LO - Dokshitzer; Gribov, Lipatov; Altarelli, Parisi, 1977
NLO - Floratos,Ross,Sachrajda; Floratos,Lacaze,Kounnas, Gonzalez-Arroyo,Lopez,Yndurain; Curci,Furmanski Petronzio, 1981
NNLO - Moch, Vermaseren, Vogt, 2004

- PDFs are one of the main theory uncertainties in Mw measurement
- precision of PDFs affect substantially theory predictions for SM and Beyond SM processes
- PDFs are one of main theory uncertainties in Higgs production.



GFitter



	σ (8 TeV)	uncertainty
gg→H	19.5 pb	14.7%
VBF	1.56 pb	2.9%
WH	0.70 pb	3.9%
ZH	0.39 pb	5.1%
ttH	0.13 pb	14.4%

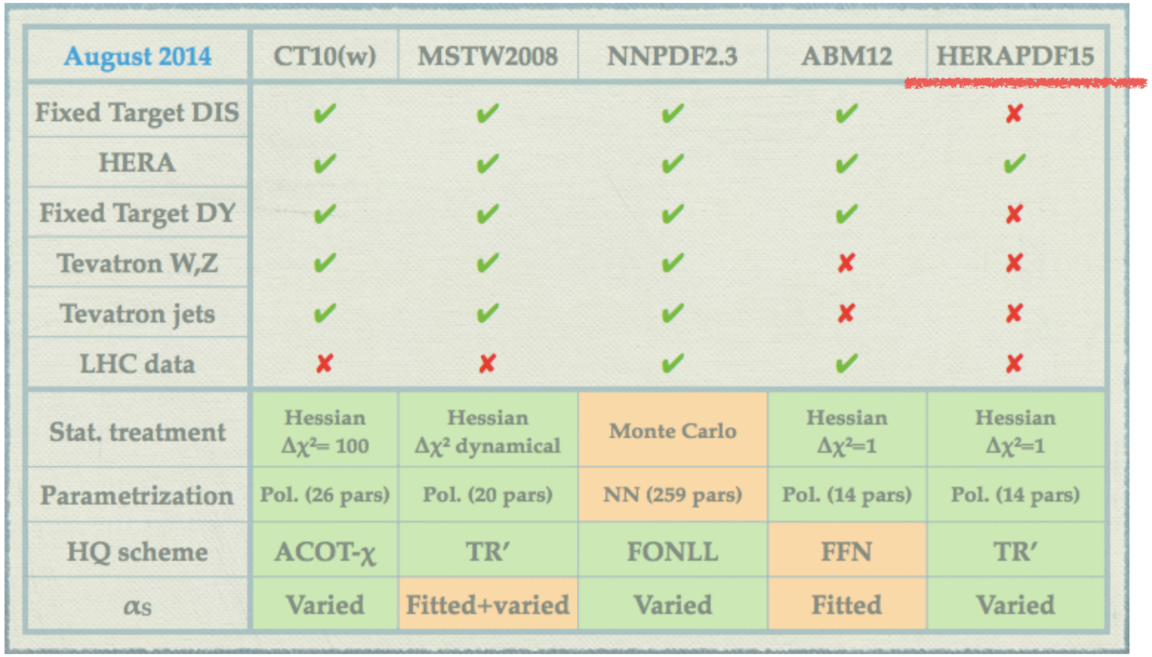
J. Campbell, ICHEP 2012

Current PDF sets in use

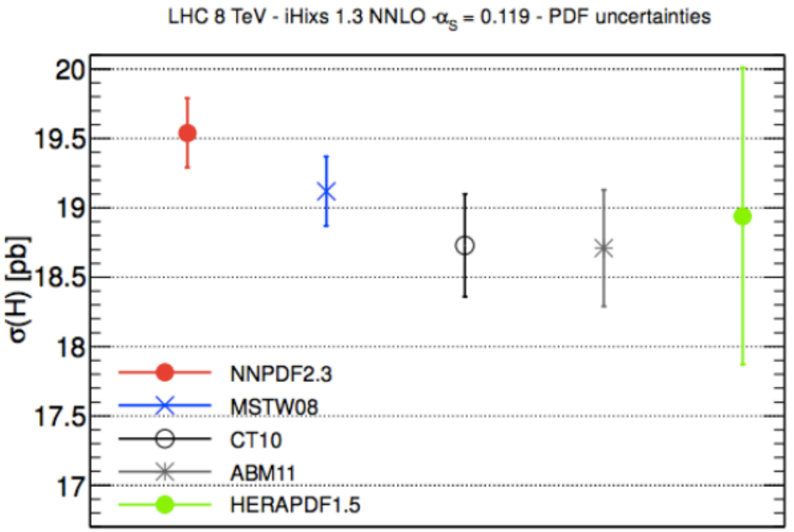
Tremendous efforts both in theory and data to better constrain PDFs:

- Data: targeted measurements, detailed information of sources of systematic uncertainties, addressing the importance of correlation information
- Theory: state of the art methods, advancement in computational powers that allowed for higher order calculations to be available

Active PDF groups:



August 2014	CT10(w)	MSTW2008	NNPDF2.3	ABM12	HERAPDF15
Fixed Target DIS	✓	✓	✓	✓	✗
HERA	✓	✓	✓	✓	✓
Fixed Target DY	✓	✓	✓	✓	✗
Tevatron W,Z	✓	✓	✓	✗	✗
Tevatron jets	✓	✓	✓	✗	✗
LHC data	✗	✗	✓	✓	✗
Stat. treatment	Hessian $\Delta\chi^2$= 100	Hessian $\Delta\chi^2$ dynamical	Monte Carlo	Hessian $\Delta\chi^2$=1	Hessian $\Delta\chi^2$=1
Parametrization	Pol. (26 pars)	Pol. (20 pars)	NN (259 pars)	Pol. (14 pars)	Pol. (14 pars)
HQ scheme	ACOT-χ	TR′	FONLL	FFN	TR′
α_S	Varied	Fitted+varied	Varied	Fitted	Varied

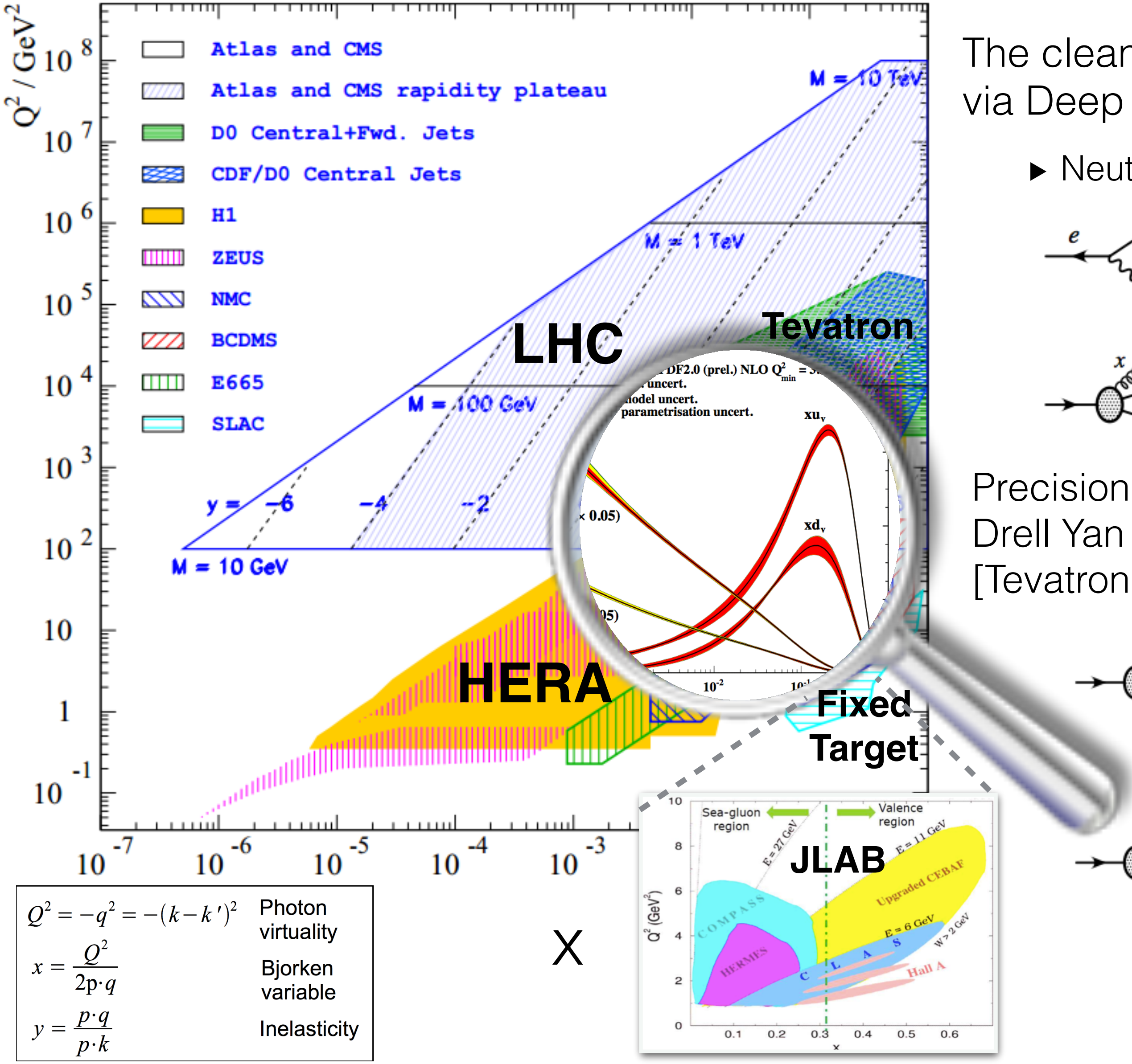


Dedicated studies to address this difference, PDF4LHC, http://arxiv.org/pdf/1405.1067.pdf

The analyses differ in many areas:

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

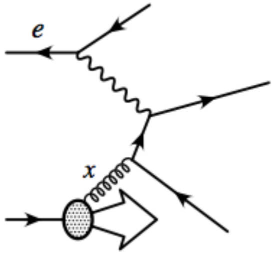
Proton Structure Measurements



$Q^2 = -q^2 = -(k-k')^2$	Photon virtuality
$x = \dfrac{Q^2}{2p\cdot q}$	Bjorken variable
$y = \dfrac{p\cdot q}{p\cdot k}$	Inelasticity

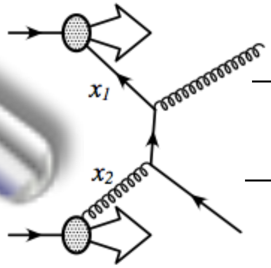
The cleanest way to probe Proton Structure is via Deep Inelastic Scattering:

- Neutrinos, muons, electrons



—> probes linear combination of quarks

Precision of PDFs can be complemented by the Drell Yan processes at the collider experiments - [Tevatron and LHC]



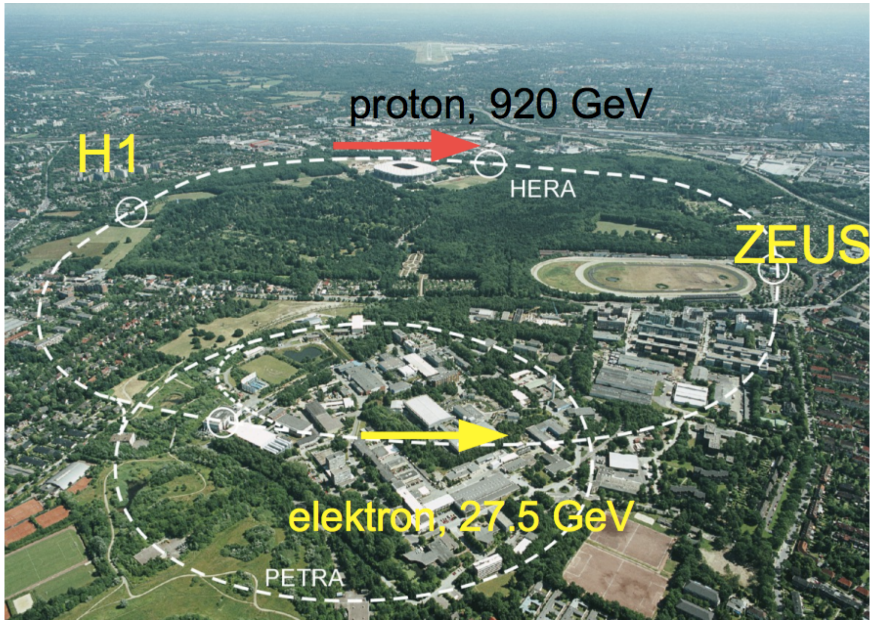
—> can provide flavour separation and more insight into gluons

—> probes bilinear combination of quarks

Different data constrain different parton combinations at different x, evolution with the scale is predicted by pQCD:

HERA ep collider (1992-2007) @ DESY

- HERA: unique lepton-proton collider
  - **Operational:**
    - **1992-2000 (HERA I)**
    - **2003-2007 (HERA II)**
  - **Ep=460-920 GeV, Ee = 27.6GeV**
- H1 and ZEUS collected 0.5/fb per experiment
- Rich Physics Program:
  - **proton structure, EW, QCD, diffraction, BSM searches,…**

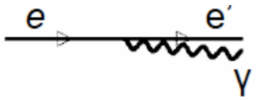


Kinematic variables

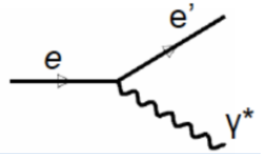
$Q^2 = -q^2 = -(k-k')^2$	Photon virtuality
$x = \dfrac{Q^2}{2p\cdot q}$	Bjorken variable
$y = \dfrac{p\cdot q}{p\cdot k}$	Inelasticity

Two kinematic regimes:

- **Photo-production (PHP)**: $Q^2 < 1\ \text{GeV}^2$

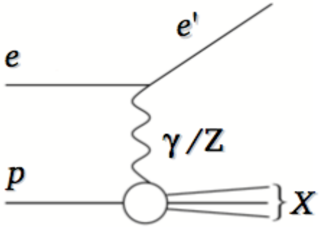


- **Deep Inelastic Scattering (DIS)**: $Q^2 > 1\ \text{GeV}^2$

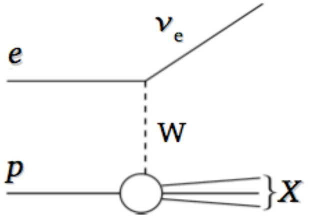


4 processes are available at HERA:

NC : $e\,p \rightarrow e'\,X$



CC : $e\,p \rightarrow \nu_e\,X$



Introducing Structure Functions

- Differential cross sections as function of x and Q2 can be decomposed as:

$$\frac{d\sigma^{\pm}_{NC}}{dxdQ^2} = \frac{2\pi\alpha^2}{x}\left[\frac{1}{Q^2}\right]^2\left[Y_+\tilde{F}_2 \mp Y_- x\tilde{F}_3 - y^2\tilde{F}_L\right]$$

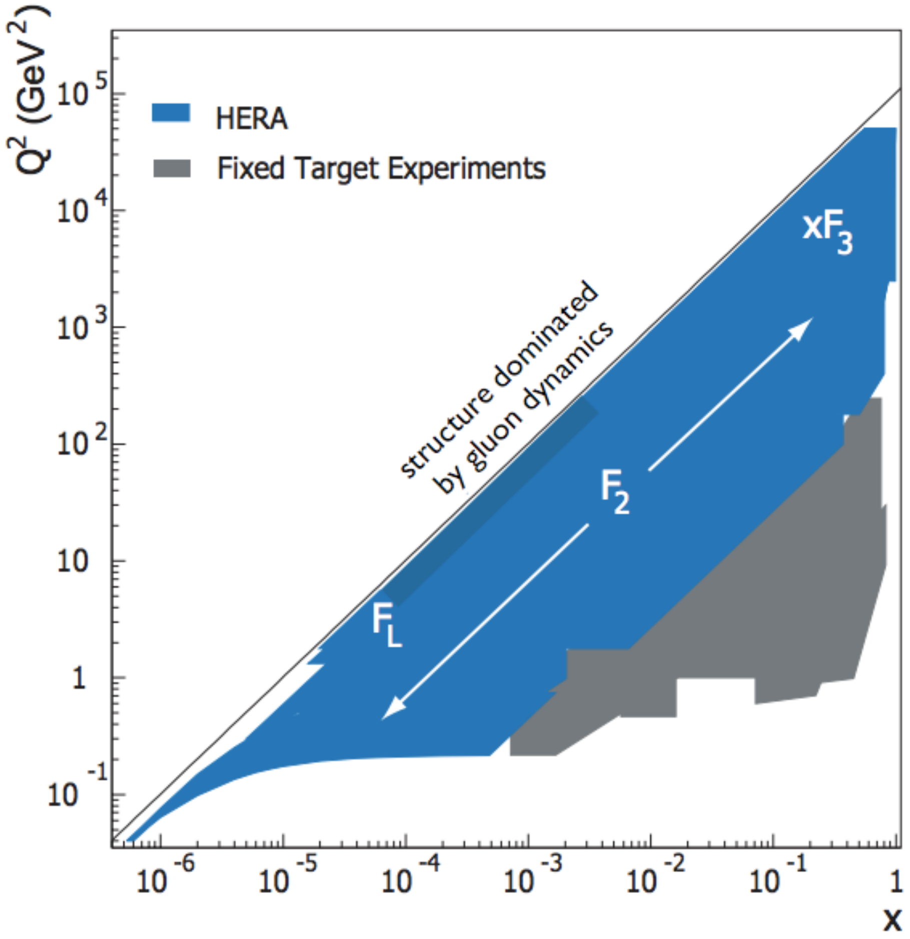
$$\frac{d\sigma^{\pm}_{CC}}{dxdQ^2} = \frac{G_F^2}{4\pi x}\left[\frac{M_W^2}{M_W^2+Q^2}\right]^2\left[Y_+\tilde{W}_2^{\pm} \mp Y_- x\tilde{W}_3^{\pm} - y^2\tilde{W}_L^{\pm}\right]$$

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

$$\tilde{F}_2 \propto \sum(xq_i + x\bar{q}_i)$$

$$x\tilde{F}_3 \propto \sum(xq_i - x\bar{q}_i)$$

$$\tilde{F}_L \propto \alpha_s \cdot xg(x,Q^2)$$



<u>NC Measurements</u>

- F2 dominates most of Q2 reach
- xF3 contributes in EW regime
- FL contributes only at highest y

<u>CC Measurements</u>

- W2 and xW3 contribute equally
- WL only at high y

New measurements from HERA

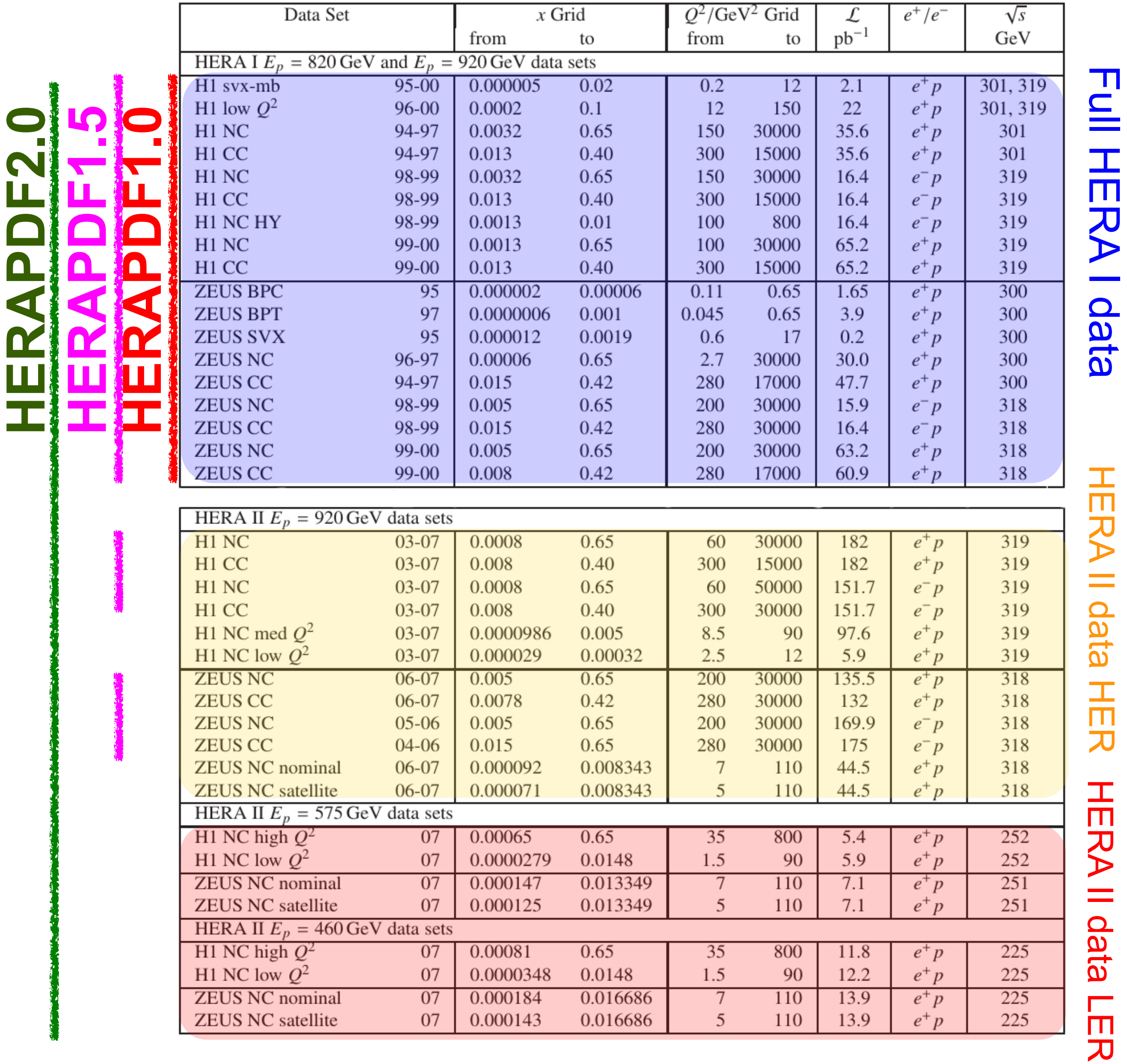
All inclusive individual DIS results from H1 and ZEUS are final and published!

Typically several experiments provide their data in a similar kinematic phase space:

$$0.045 < Q^2 < 50000 \text{ GeV}^2$$

$$6\text{x}10^{-7} < x < 0.65$$

- Best precision achieved when data are combined
- Consistency check of the measurements in a model independent

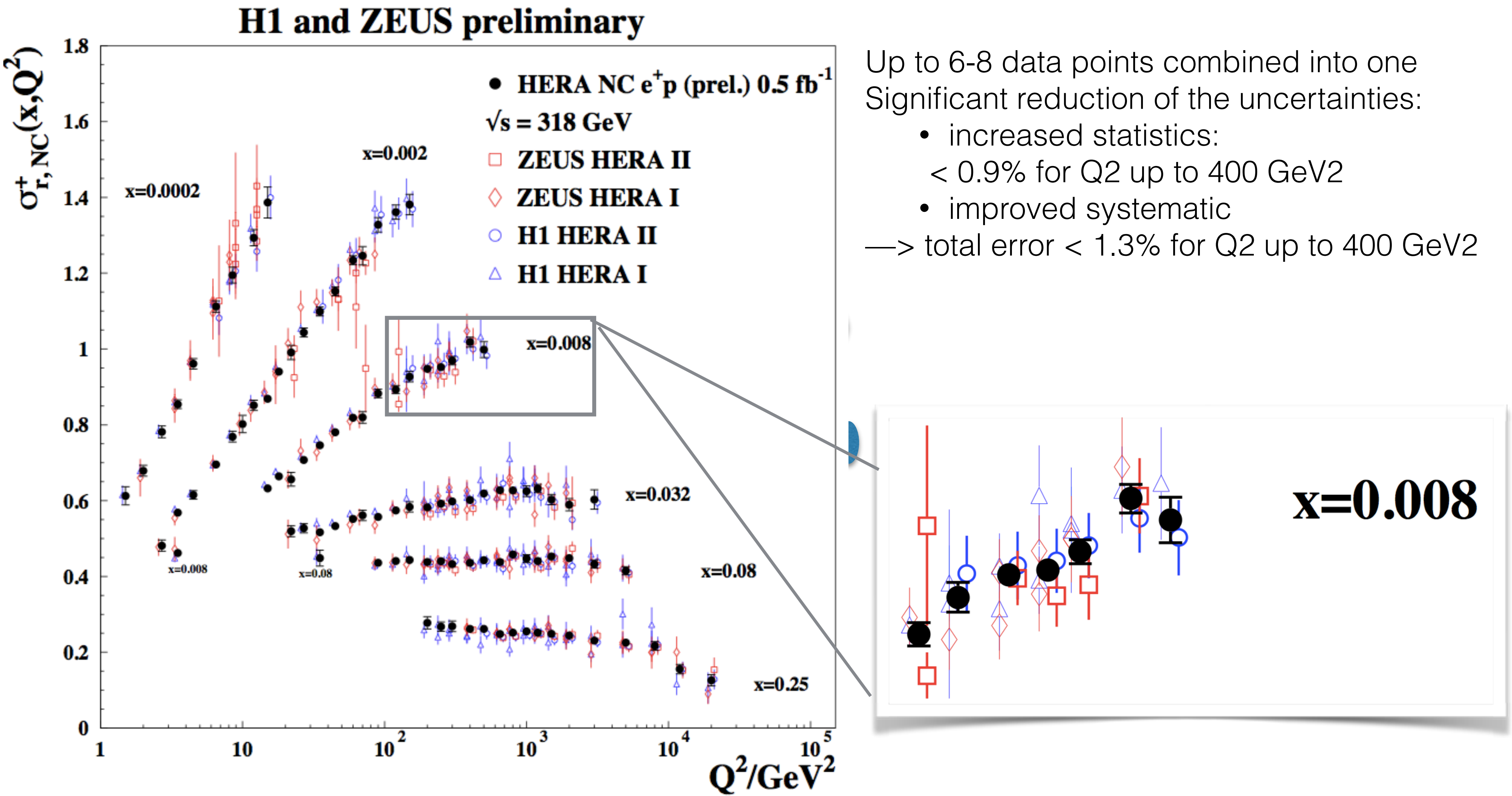


Data Set		x Grid		Q^2/GeV^2 Grid		$\mathcal{L}$	e^+/e^-	$\sqrt{s}$
		from	to	from	to	pb^{-1}		GeV
HERA I E_p = 820 GeV and E_p = 920 GeV data sets								
H1 svx-mb	95-00	0.000005	0.02	0.2	12	2.1	e^+p	301, 319
H1 low Q^2	96-00	0.0002	0.1	12	150	22	e^+p	301, 319
H1 NC	94-97	0.0032	0.65	150	30000	35.6	e^+p	301
H1 CC	94-97	0.013	0.40	300	15000	35.6	e^+p	301
H1 NC	98-99	0.0032	0.65	150	30000	16.4	e^-p	319
H1 CC	98-99	0.013	0.40	300	15000	16.4	e^-p	319
H1 NC HY	98-99	0.0013	0.01	100	800	16.4	e^-p	319
H1 NC	99-00	0.0013	0.65	100	30000	65.2	e^+p	319
H1 CC	99-00	0.013	0.40	300	15000	65.2	e^+p	319
ZEUS BPC	95	0.000002	0.00006	0.11	0.65	1.65	e^+p	300
ZEUS BPT	97	0.0000006	0.001	0.045	0.65	3.9	e^+p	300
ZEUS SVX	95	0.000012	0.0019	0.6	17	0.2	e^+p	300
ZEUS NC	96-97	0.00006	0.65	2.7	30000	30.0	e^+p	300
ZEUS CC	94-97	0.015	0.42	280	17000	47.7	e^+p	300
ZEUS NC	98-99	0.005	0.65	200	30000	15.9	e^-p	318
ZEUS CC	98-99	0.015	0.42	280	30000	16.4	e^-p	318
ZEUS NC	99-00	0.005	0.65	200	30000	63.2	e^+p	318
ZEUS CC	99-00	0.008	0.42	280	17000	60.9	e^+p	318
HERA II E_p = 920 GeV data sets								
H1 NC	03-07	0.0008	0.65	60	30000	182	e^+p	319
H1 CC	03-07	0.008	0.40	300	15000	182	e^+p	319
H1 NC	03-07	0.0008	0.65	60	50000	151.7	e^-p	319
H1 CC	03-07	0.008	0.40	300	30000	151.7	e^-p	319
H1 NC med Q^2	03-07	0.0000986	0.005	8.5	90	97.6	e^+p	319
H1 NC low Q^2	03-07	0.000029	0.00032	2.5	12	5.9	e^+p	319
ZEUS NC	06-07	0.005	0.65	200	30000	135.5	e^+p	318
ZEUS CC	06-07	0.0078	0.42	280	30000	132	e^+p	318
ZEUS NC	05-06	0.005	0.65	200	30000	169.9	e^-p	318
ZEUS CC	04-06	0.015	0.65	280	30000	175	e^-p	318
ZEUS NC nominal	06-07	0.000092	0.008343	7	110	44.5	e^+p	318
ZEUS NC satellite	06-07	0.000071	0.008343	5	110	44.5	e^+p	318
HERA II E_p = 575 GeV data sets								
H1 NC high Q^2	07	0.00065	0.65	35	800	5.4	e^+p	252
H1 NC low Q^2	07	0.0000279	0.0148	1.5	90	5.9	e^+p	252
ZEUS NC nominal	07	0.000147	0.013349	7	110	7.1	e^+p	251
ZEUS NC satellite	07	0.000125	0.013349	5	110	7.1	e^+p	251
HERA II E_p = 460 GeV data sets								
H1 NC high Q^2	07	0.00081	0.65	35	800	11.8	e^+p	225
H1 NC low Q^2	07	0.0000348	0.0148	1.5	90	12.2	e^+p	225
ZEUS NC nominal	07	0.000184	0.016686	7	110	13.9	e^+p	225
ZEUS NC satellite	07	0.000143	0.016686	5	110	13.9	e^+p	225

Towards final HERA data combination

H1prelim-14-041 and ZEUS-prel-14-005

- All individual measurements from H1 and ZEUS are published:
  - 41 data sets: 2927 data points are combined to 1307 averaged measurements with 162 sources of correlated systematic uncertainties.
  - Consistent data sets: total χ2/ndf = 1685/1620=1.04.



Up to 6-8 data points combined into one
Significant reduction of the uncertainties:

- increased statistics:
  < 0.9% for Q2 up to 400 GeV2
- improved systematic

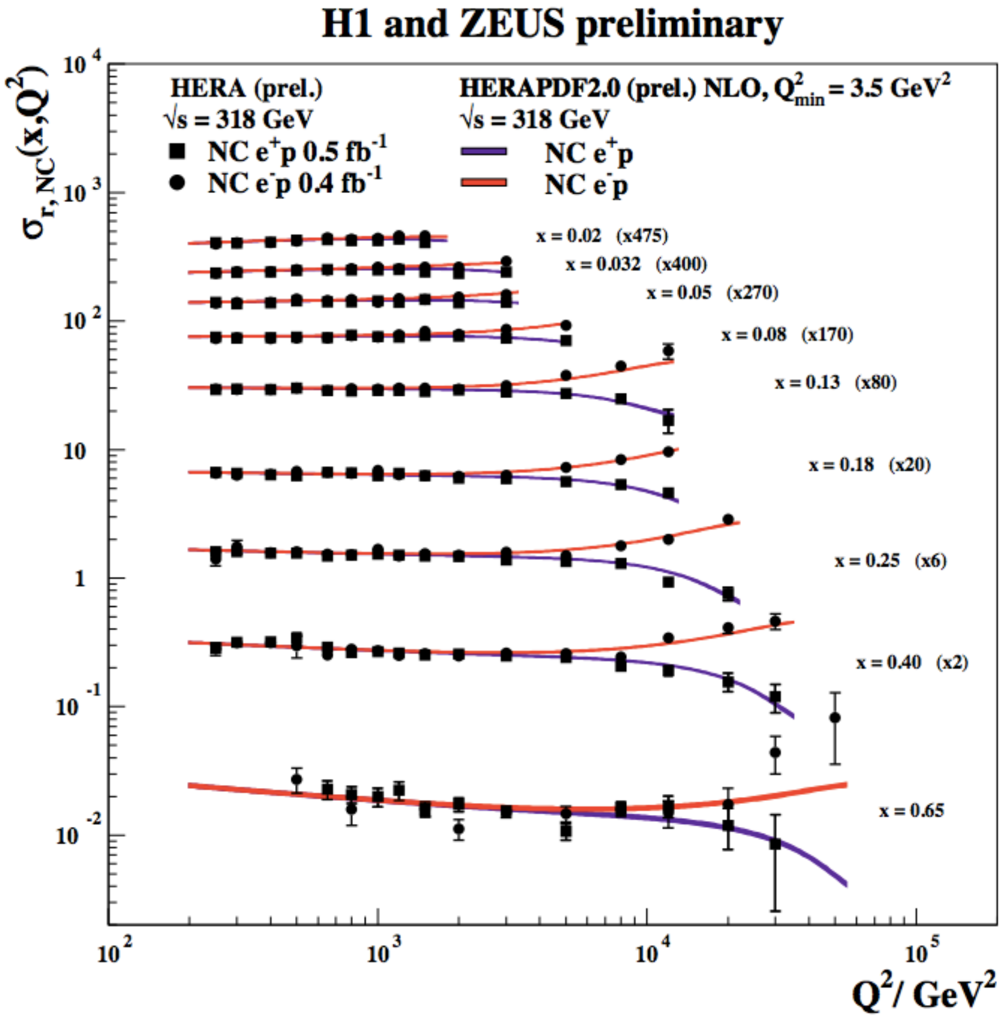
—> total error < 1.3% for Q2 up to 400 GeV2

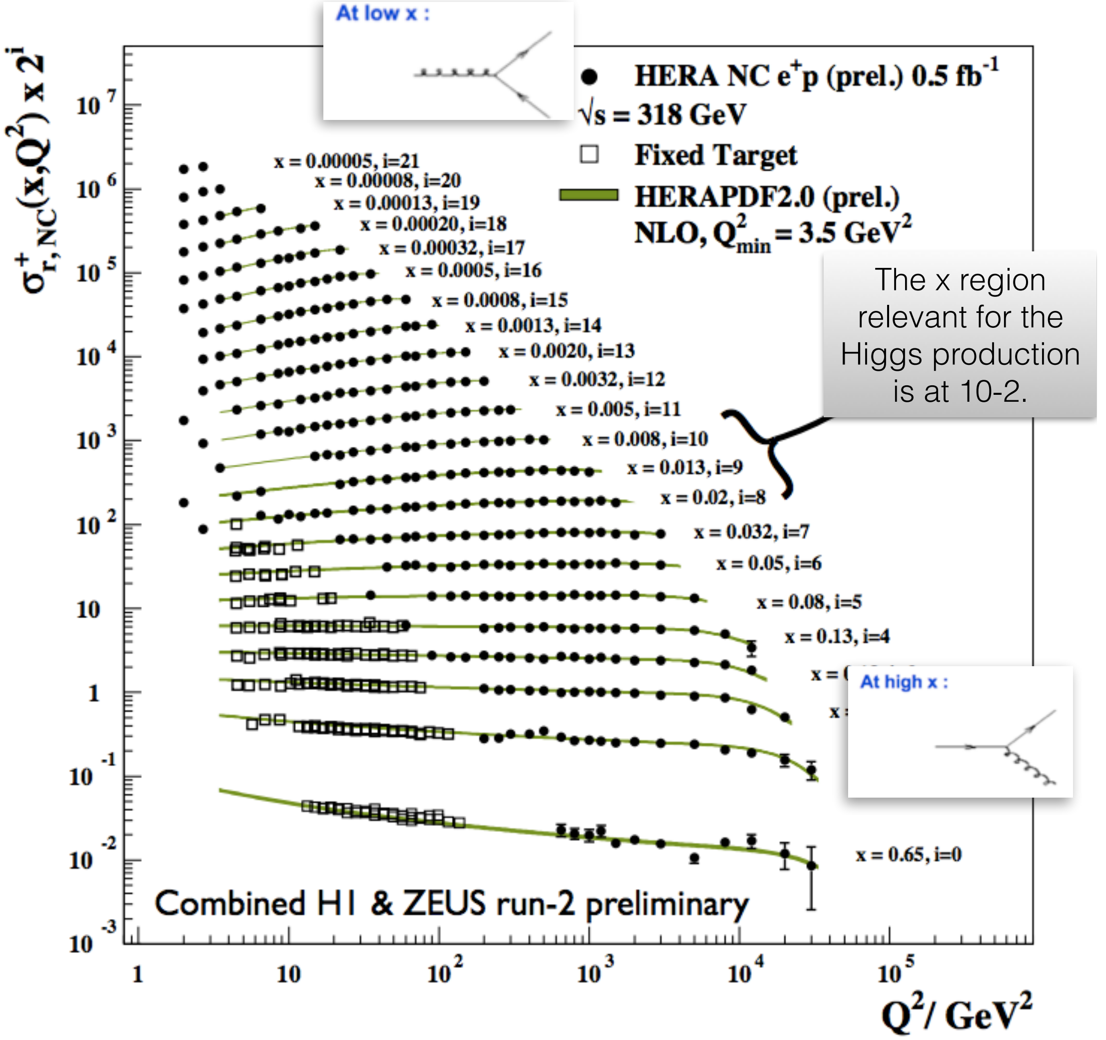
QCD scaling and EW effects

H1prelim-14-041 and ZEUS-prel-14-005

- EW effects clearly seen at high Q2:

QCD scaling violations nicely seen:





The x region relevant for the Higgs production is at 10-2.

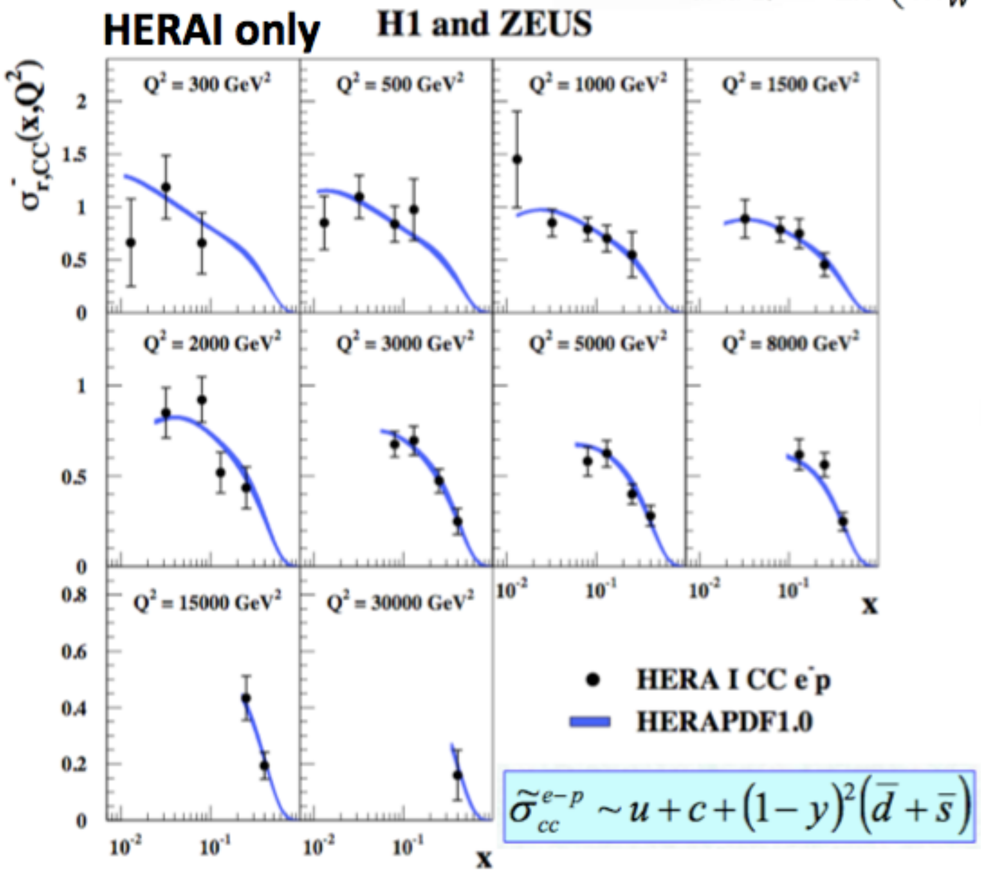
Charged Current Cross Section Measurements

H1prelim-14-041 and ZEUS-prel-14-005

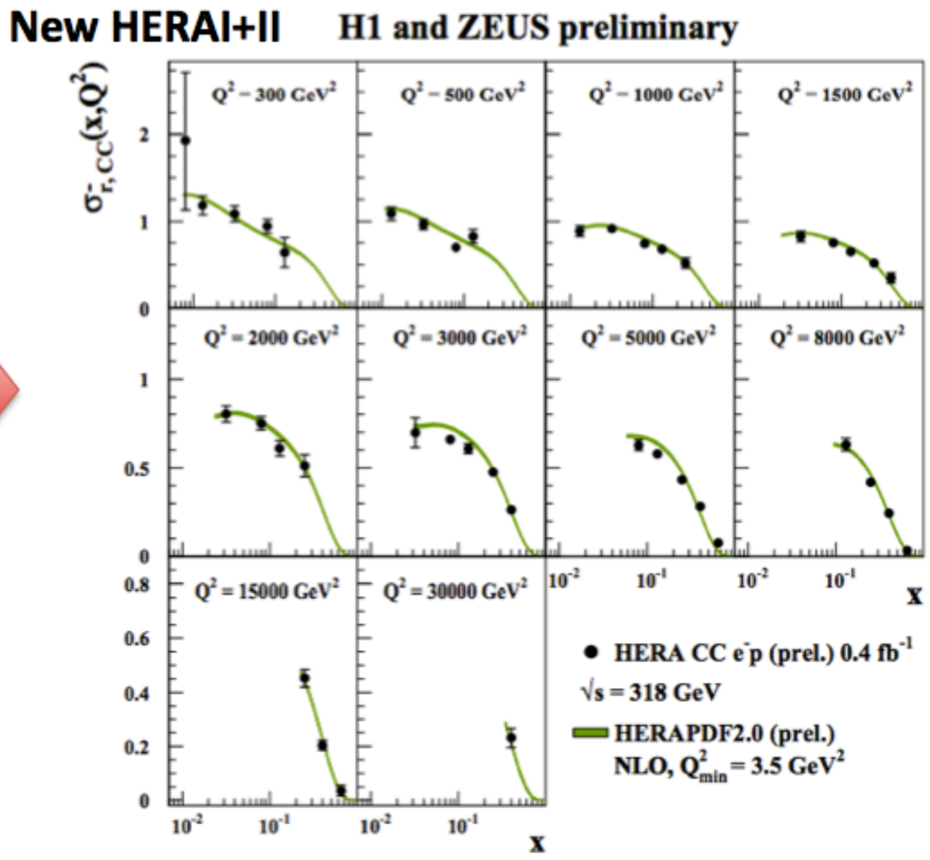
Charged Current: provides important flavour decomposition

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

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


HERAI only H1 and ZEUS

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


New HERAI+II H1 and ZEUS preliminary

Much more precise CC measurements after including new high Q² HERA II set!

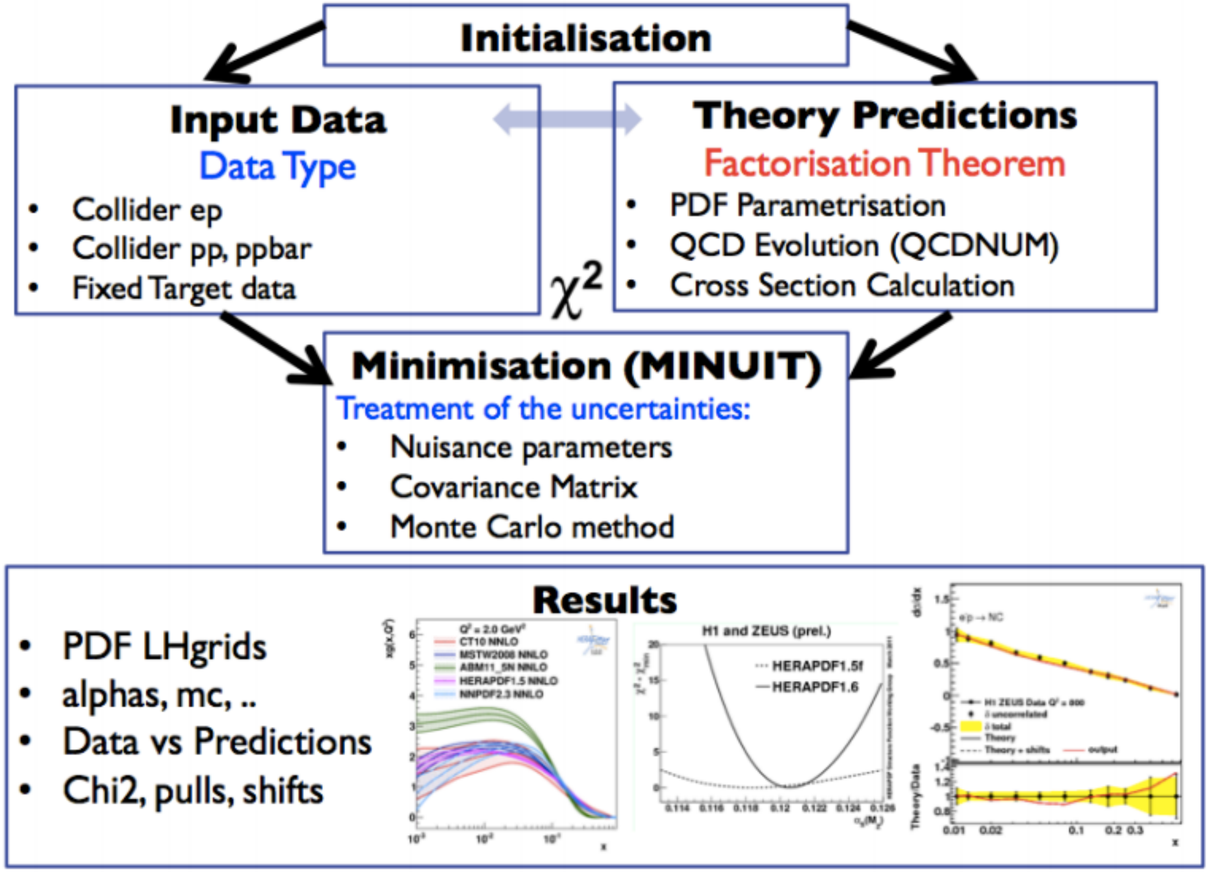
Extraction of PDFs through QCD fits

Typical measurements sensitive to PDFs are precise, with statistical uncertainties < 10%, so they follow normal distribution which allows the use of chi square minimisation for PDF extraction.

HERAFitter *www.herafitter.org*

Main Steps:

- Parametrise PDFs at starting scale
- Evolve to the scale corresponding to data point
- Calculate the cross section
- Compare with data via chi2
- Minimize chi2 with respect to PDF parameters



Initialisation

Input Data

Data Type

- Collider ep
- Collider pp, ppbar
- Fixed Target data

Theory Predictions

Factorisation Theorem

- PDF Parametrisation
- QCD Evolution (QCDNUM)
- Cross Section Calculation

χ^2

Minimisation (MINUIT)

Treatment of the uncertainties:

- Nuisance parameters
- Covariance Matrix
- Monte Carlo method

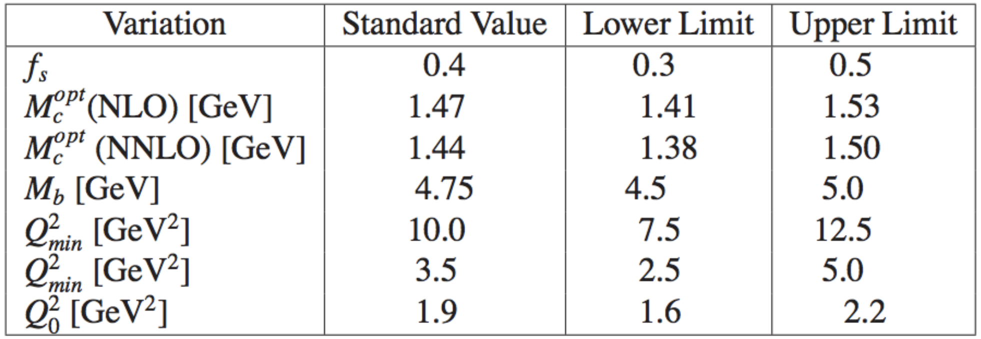
Results

- PDF LHgrids
- alphas, mc, ..
- Data vs Predictions
- Chi2, pulls, shifts

Modern understanding of PDFs

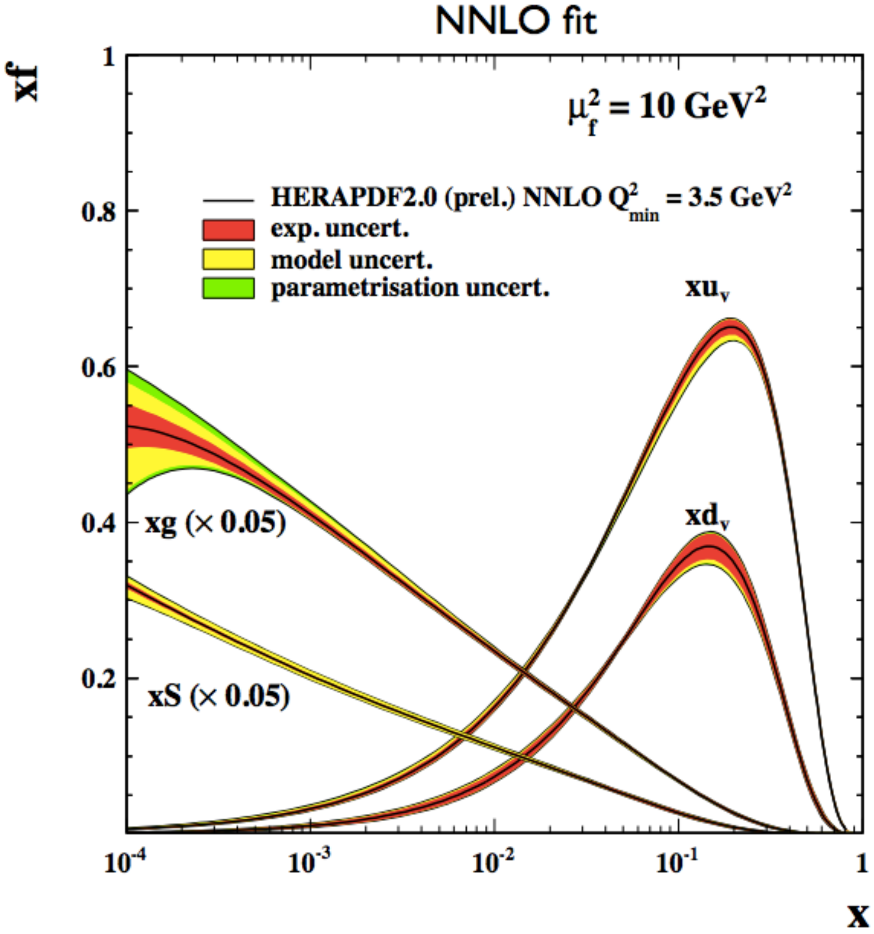
Uncertainties of three types considered:

- Experimental:
  - Hessian method used
  - Consistent data sets → use $\Delta\chi^2=1$
- Model:
  - variations of all assumed input parameters in the fit



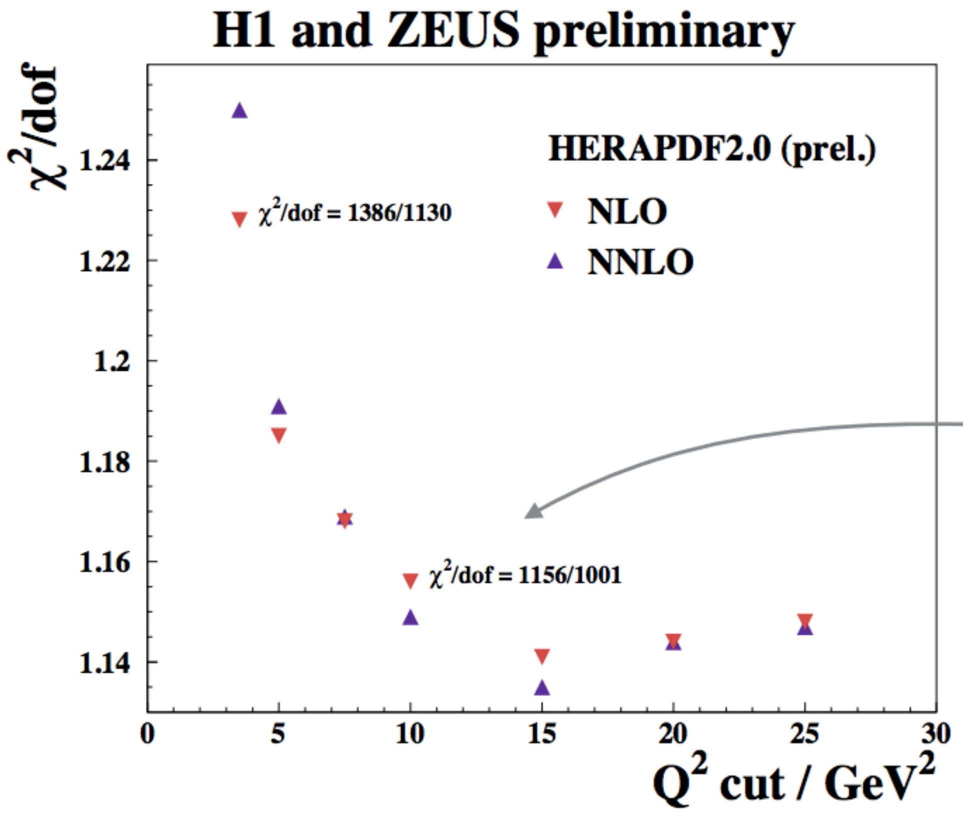
Variation	Standard Value	Lower Limit	Upper Limit
f_s	0.4	0.3	0.5
M_c^{opt}(NLO) [GeV]	1.47	1.41	1.53
M_c^{opt} (NNLO) [GeV]	1.44	1.38	1.50
M_b [GeV]	4.75	4.5	5.0
Q^2_{min} [GeV^2]	10.0	7.5	12.5
Q^2_{min} [GeV^2]	3.5	2.5	5.0
Q^2_0 [GeV^2]	1.9	1.6	2.2

- Parametrisation:
  - An envelope formed from PDF fits using variants of parametrisation form (extra parameter added)
  - Q_0^2 variation dominant parametrisation uncertainty



HERAPDF2.0 and Q2 cut dependence

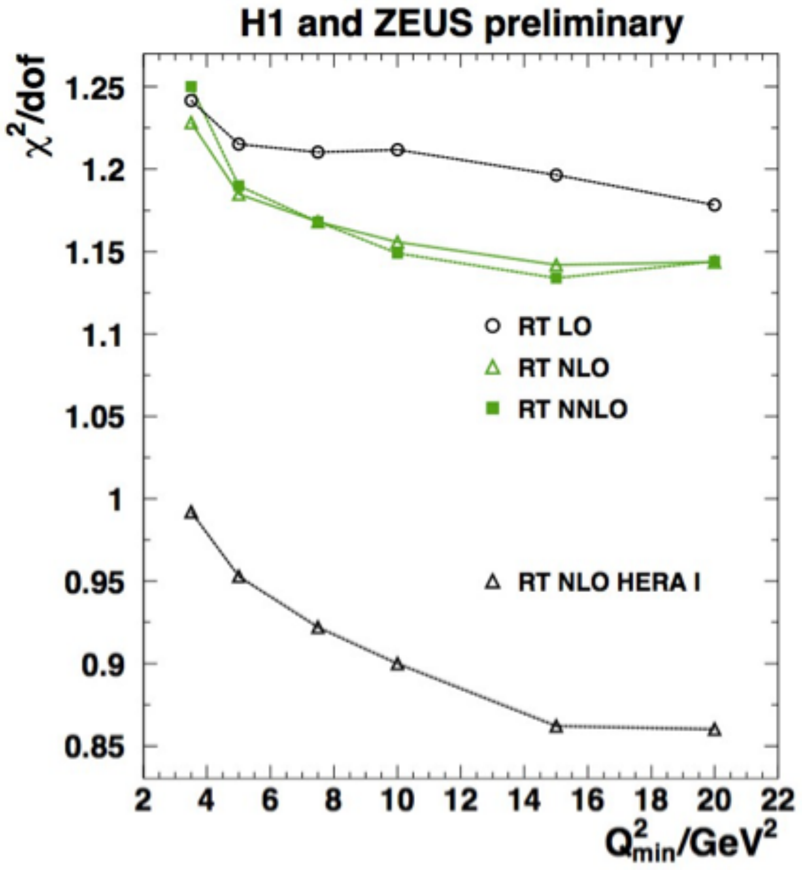
The Q^2 cut dependence on the fit is already included in the model variation for the HERAPDF sets, however usually we look at small range in cuts when assessing an uncertainty to Q^2_{min} choice.

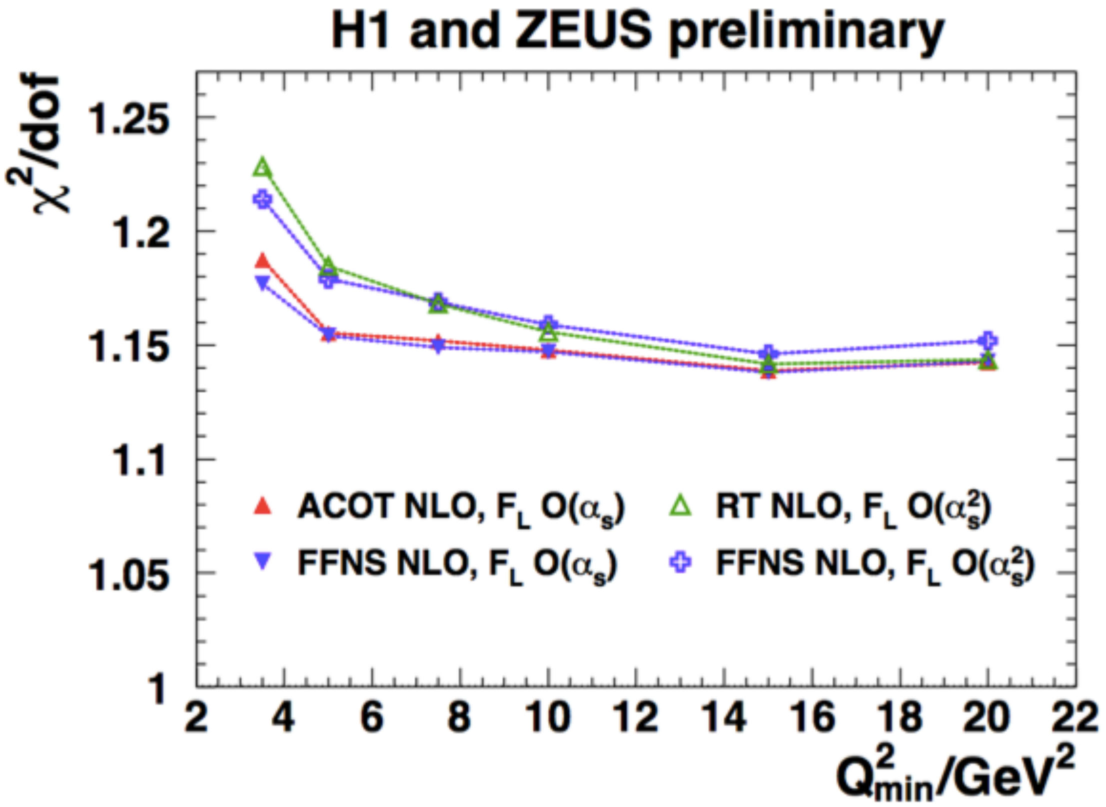


- Look at larger range and effect on χ2/ndf
- For Q2min = 3.5 GeV2
  - **χ2/ndf = 1385 / 1130 at NLO**
  - **χ2/ndf = 1414 / 1130 at NNLO**
- For Q2min = 10 GeV2
  - **χ2/ndf = 1156 / 1001 at NLO**
  - **χ2/ndf = 1150 / 1001 at NNLO**
- χ2 appears to saturate for Q2min = 10 GeV2
- Similar behaviour observed for HERA-I data
  - **Not so clear due to lower high Q2 precision for HERA-I Q2 min = 3.5 GeV2**
  - **χ2/ndf = 637 / 656 at NLO**

HERAPDF2.0 and Q2 cut dependence

The Q2 cut dependence on the fit is already included in the model variation for the HERAPDF sets, however usually we look at small range in cuts when assessing an uncertainty to Q^2_{min} choice.





Investigating:

- pQCD order dependence
- heavy flavour scheme dependence

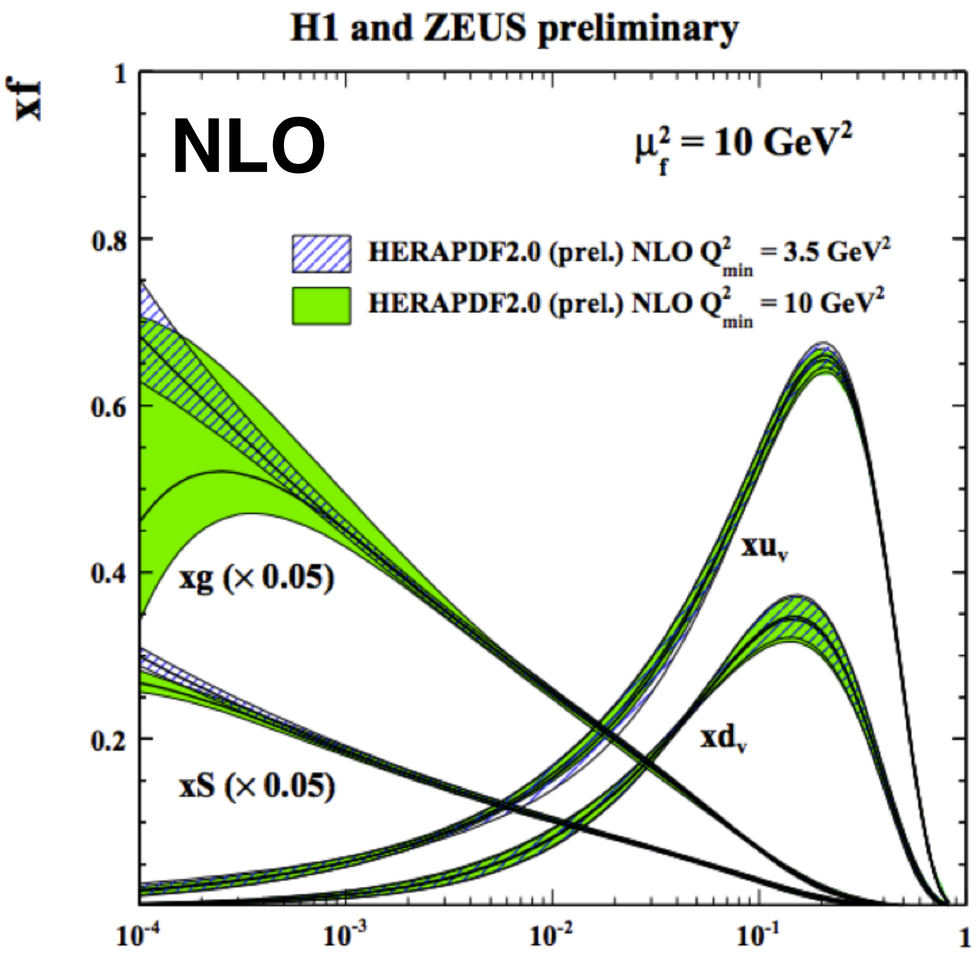
low Q2/low x remains an interesting region!

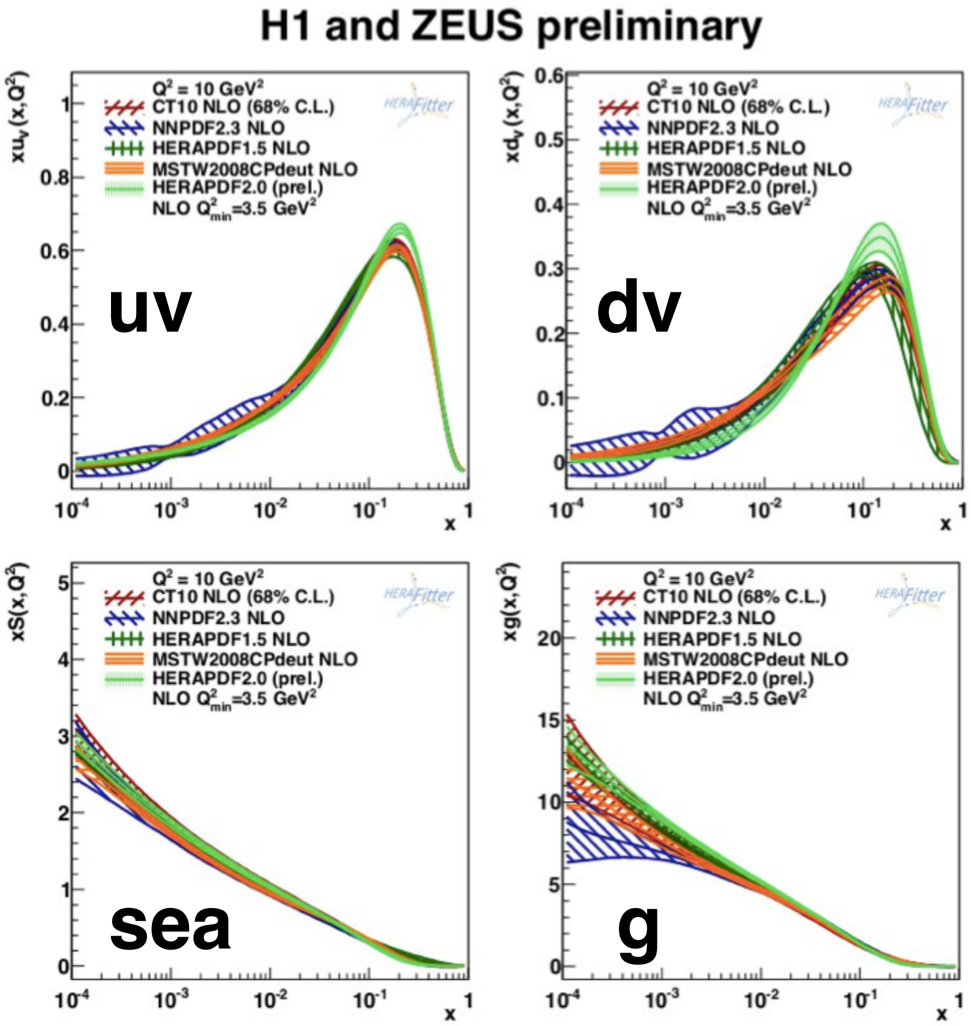
HERAPDF2.0 and Q2 cut dependence

The Q2 cut dependence on the fit is already included in the model variation for the HERAPDF sets, however usually we look at small range in cuts when assessing an uncertainty to Q^2_{min} choice.

PDFs with Q2 cut min @ 3.5 GeV2 and @10 GeV2 are shown

uncertainties are larger for Q2cut=10 GeV2 (more data is cut away) and impact mostly gluon PDF





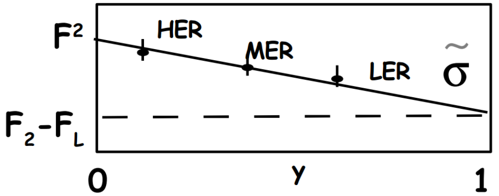
Longitudinal Structure Function

Longitudinal structure function FL is a pure QCD effect:

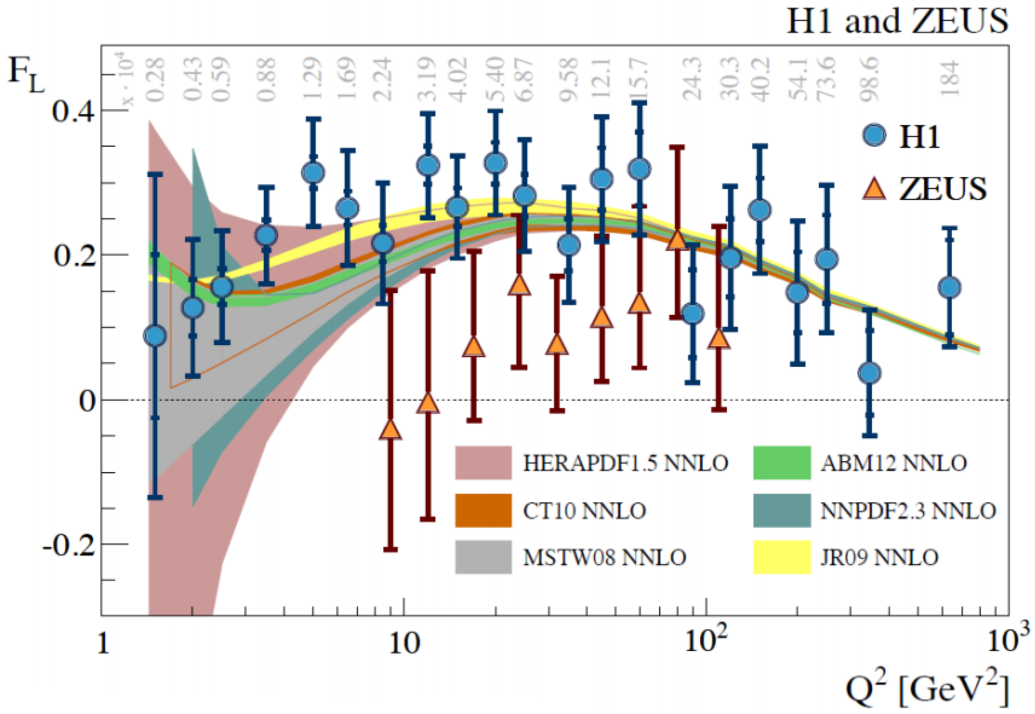
—> an independent way to probe sensitivity to gluon

$$F_L = \frac{\alpha_s}{4\pi} x^2 \int_x^1 \frac{dz}{z^3}\left[\frac{16}{3}\underbrace{F_2}_{\text{quarks radiating a gluon}} + 8\sum_q \underbrace{e_q^2\left(1-\frac{x}{z}\right)zg(z)}_{\text{gluons splitting into quarks}}\right]$$

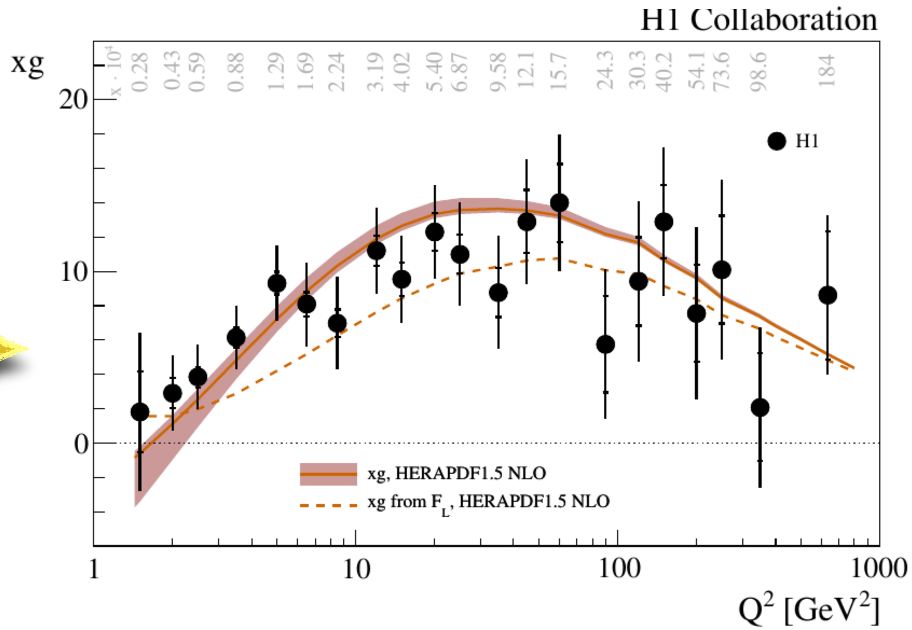
Direct measurement of FL at HERA required differential cross sections at same x and Q^2 but different y —> different beam energies: Ep= 460, 575, 920 GeV



$$\sigma_{NC}(x,Q^2,y) \propto F_2(x,Q^2) - \frac{y^2}{1+(1-y)^2}F_L(x,Q^2)$$



$$xg(x,Q^2) \approx 1.77\frac{3\pi}{2\alpha_S(Q^2)}F_L(ax,Q^2)$$



Eur. Phys. J. C 74 (2014) 2814 [arXiv:1312.4821]

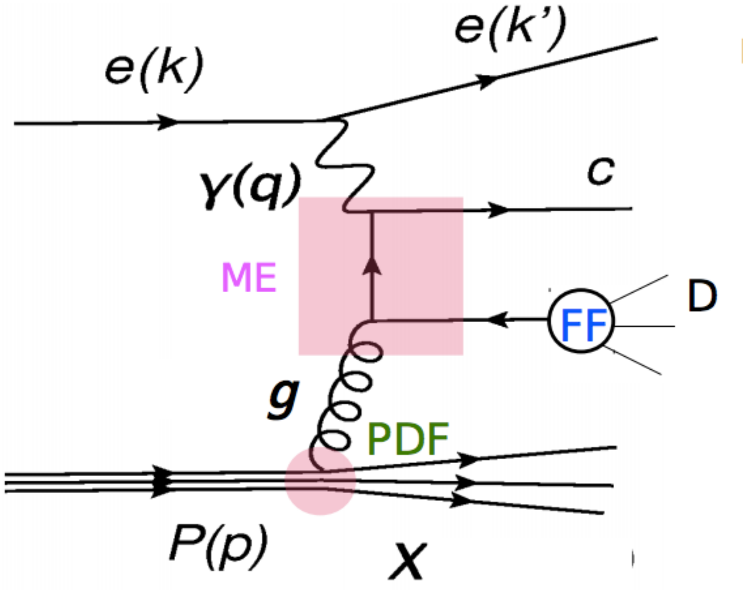
DESY-14-053, submitted to Phys. Lett. B [arXiv:1404.6376]

Heavy Flavour Production at HERA

- Heavy Flavour (HF) production: multi-hard scales pose a challenge for pQCD
  - m_c, m_b, p_T, Q^2 —> several calculations (schemes) exist
    - Zero-Mass Variable Flavour Number Scheme (ZMVFNS) — massless scheme
    - Fixed Flavour Number Scheme (FFNS) — massive scheme
    - General-Mass Variable Flavour Number Scheme (GM-VFNS) — matched scheme
- Main process of heavy quark production at HERA is Boson Gluon Fusion

- Measurements of heavy quarks:
  - are sensitive to the gluon PDF
  - are sensitive to the masses of the heavy quarks
  - are sensitive to the fragmentation process of heavy flavour hardons

- Measurements allow for tests of pQCD:

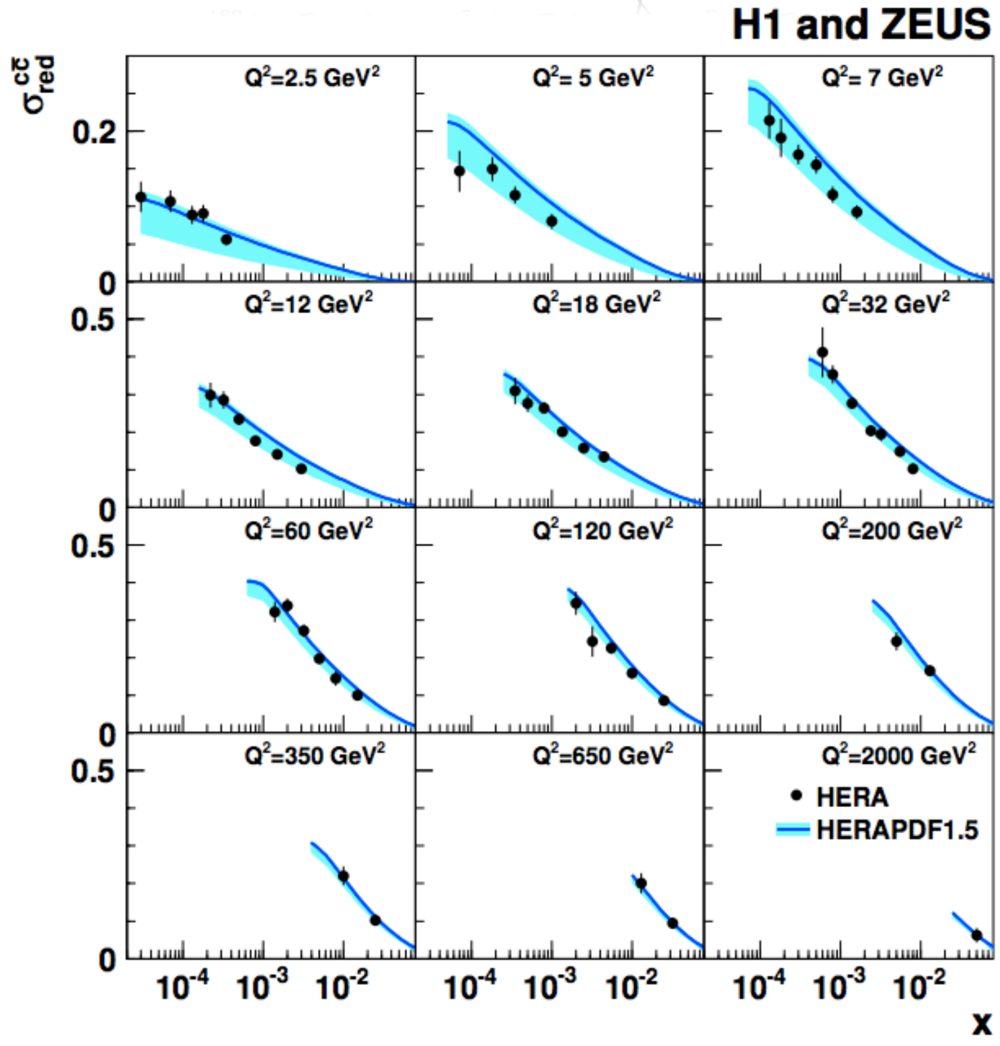


F2 charm Structure Function

EPJC 73 (2013) 2311

- Rates at HERA in DIS regime σ(b) : σ(c) ≈ O(1%) : O(20%) of σ_{TOT}
- Charm data combination is performed at charm cross sections level:
  - **they are obtained from xsec in visible phase space and extrapolated to full space**

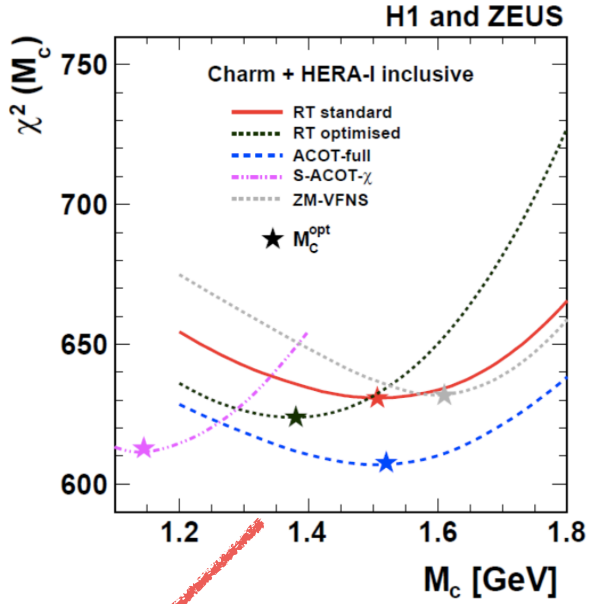
$$\sigma_{red}^{c\bar{c}}(x,Q^2,s) = F_2^{c\bar{c}}(x,Q^2) - \frac{y^2}{Y_+} F_L^{c\bar{c}}(x,Q^2)$$

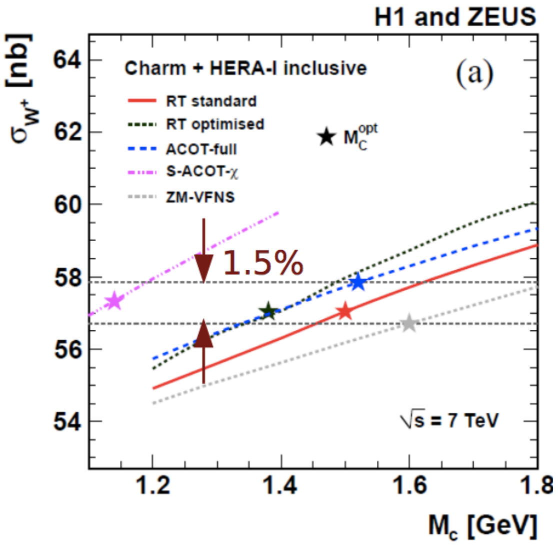


QCD Fits

HERA I+charm

Different calculation schemes prefer different Mc





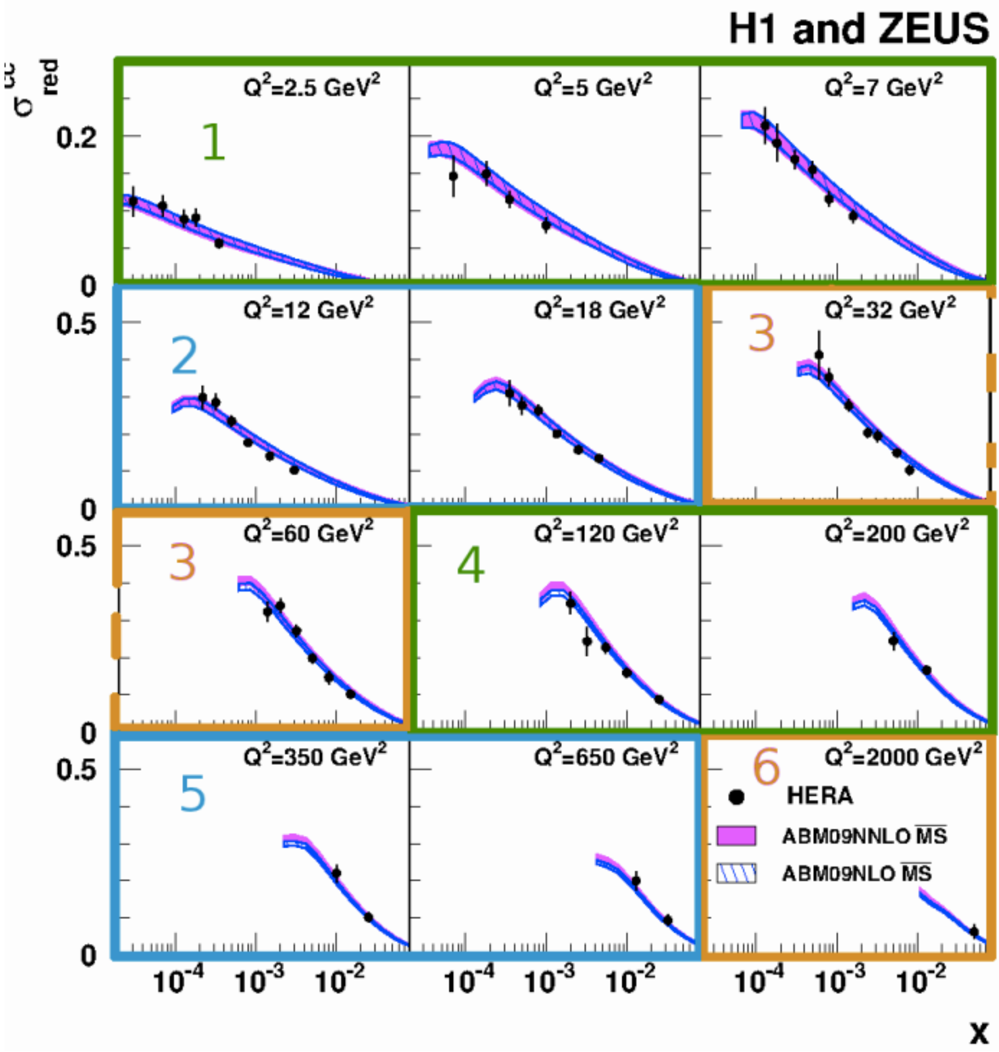
measurements help reduce uncertainties of predictions for the LHC

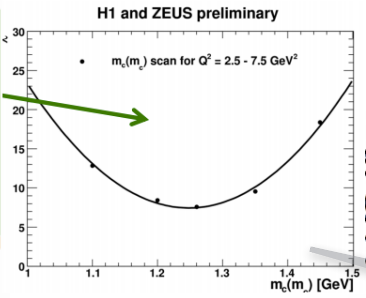
New Measurement of Charm Mass Running

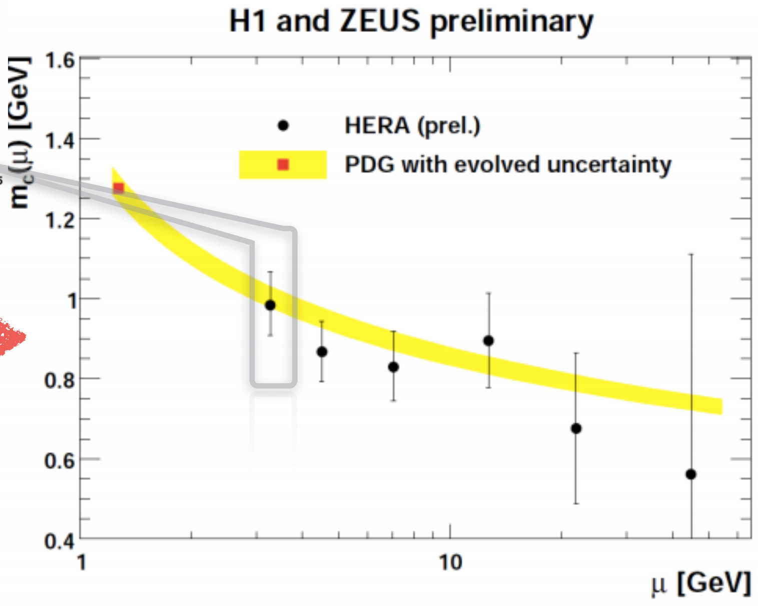
H1-prelim-14-071 ZEUS-prel-14-006 and S. Moch

The running of the charm mass in the $\overline{\text{MS}}$ scheme is measured for the first time from the same HERA combined charm data:

- Extract $m_c(m_c)$ in 6 separate kinematic regions
- Translate back to $m_c(\mu)$ [with $\mu=\sqrt{Q^2+4m_c^2}$] using OpenQCDrad [S.Alekhin's code].





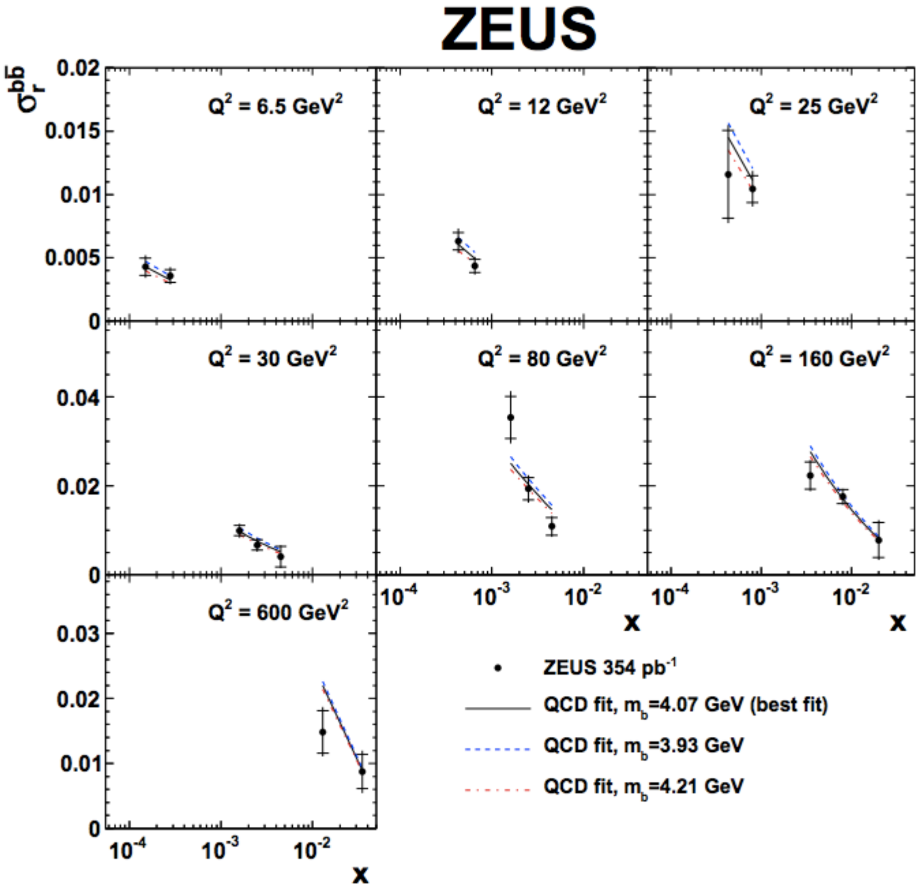


The scale dependence of the mass is consistent with QCD expectations

Running beauty mass $m_b(m_b)$ from F2 beauty

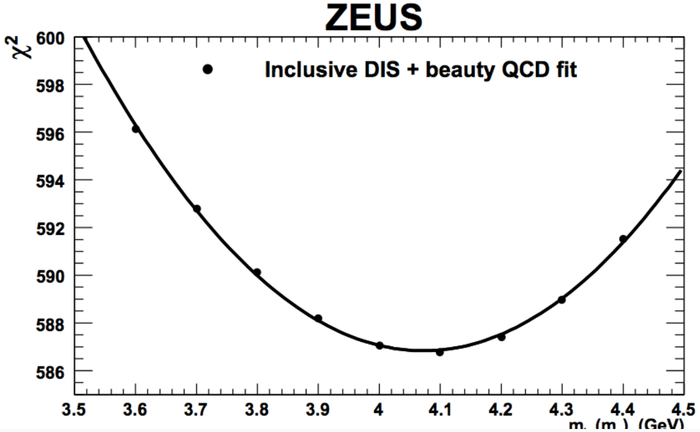
DESY-14-083 arXiv:1405.6915

- The value of the running beauty mass is obtained in a similar manner as for $m_c(m_c)$:
  - chi2 scan method from QCD fits in FFN scheme to the combined HERA I inclusive data + beauty measurements, beauty-quark mass is defined in the MS scheme.



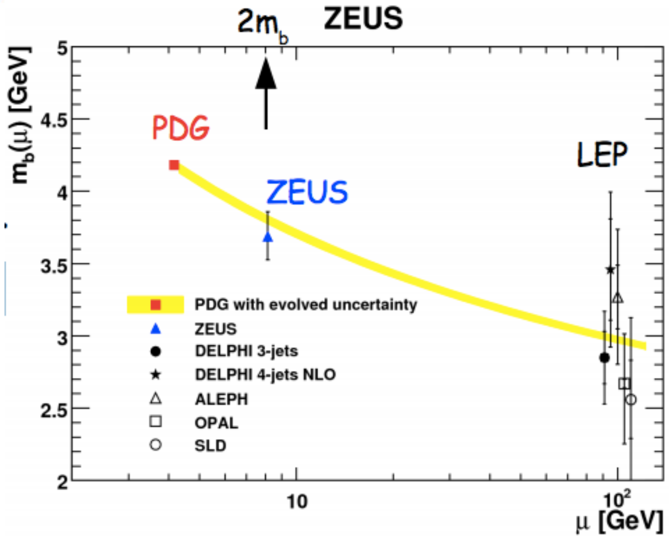
QCD Fits

HERA I+beauty



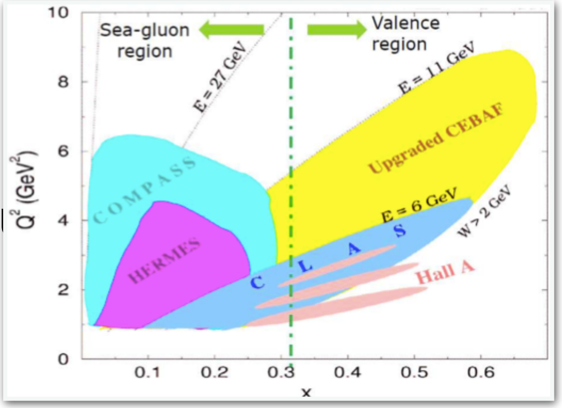
$$m_b(m_b) = 4.07 \pm 0.14\,(\text{fit})^{+0.01}_{-0.07}\,(\text{mod.})^{+0.05}_{-0.00}\,(\text{param.})^{+0.08}_{-0.05}\,(\text{theo.})\,\text{GeV}$$

$$m_b(m_b) \;=\; (4.18 \pm 0.03)\,\text{GeV}$$ —>PDG2012

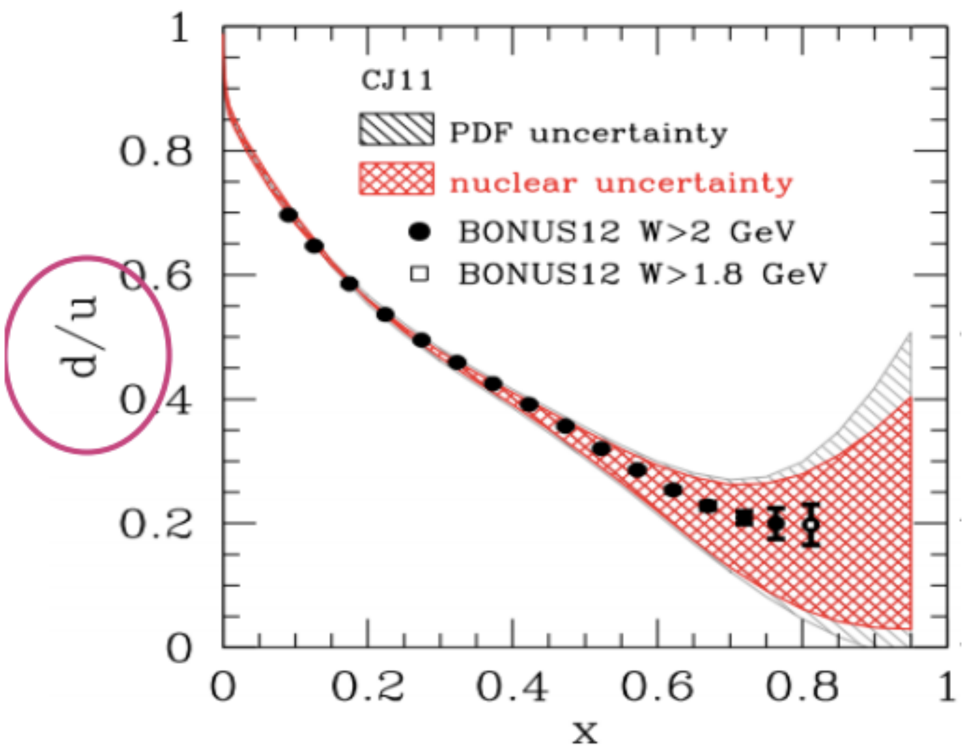


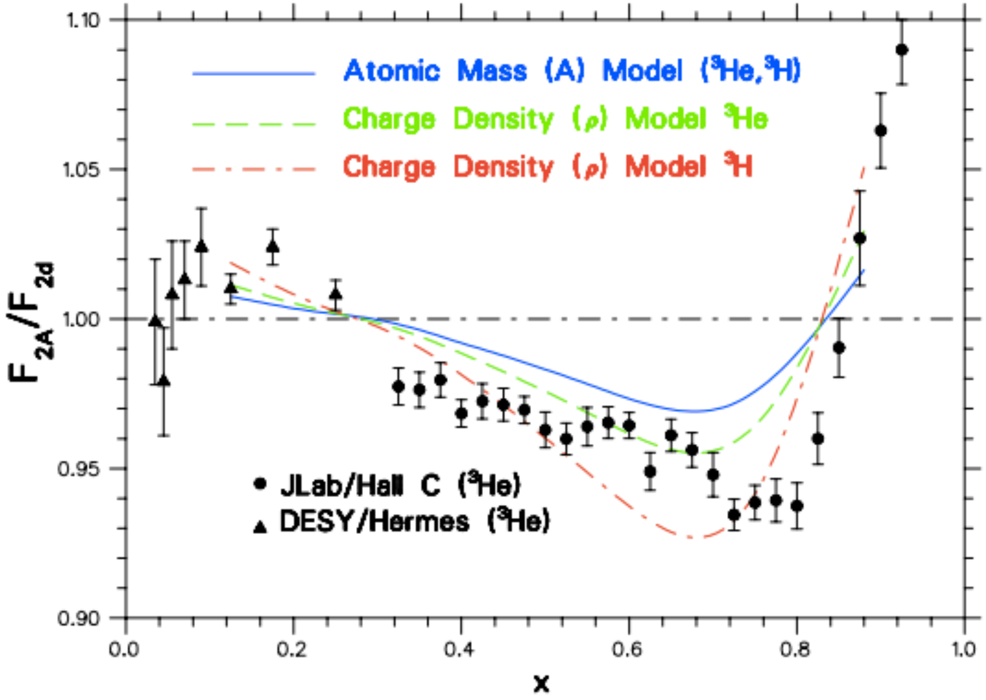
The extracted $\overline{\text{MS}}$ beauty-quark mass is in agreement with PDG average and LEP results.

Structure Functions at high x

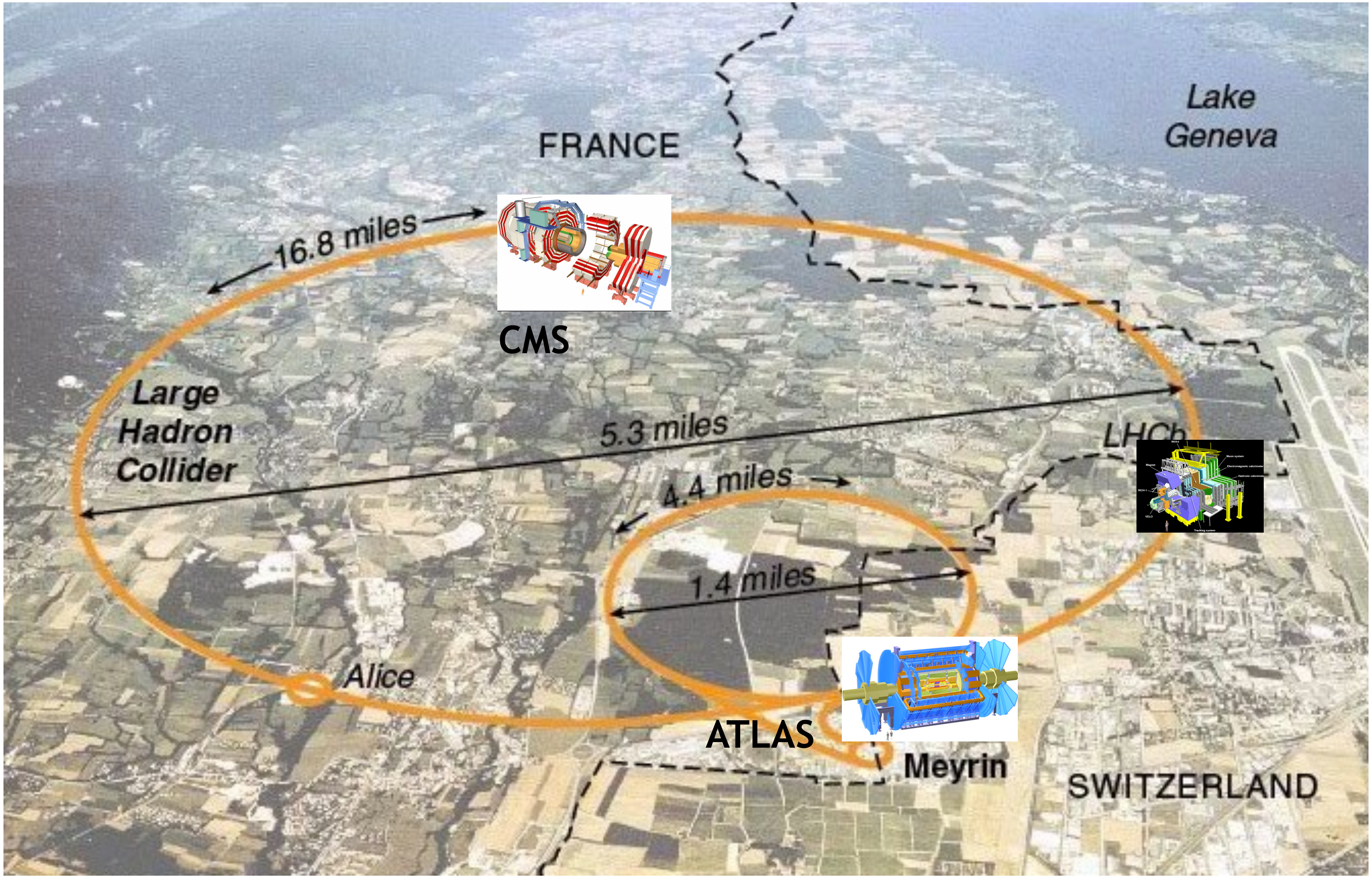


- PDF precision at high x is crucial for new physics frontiers.
- JLAB has an intense program on polarised and unpolarised stru functions.
    - better handle of higher twist effects, nuclear medium corrections
    - Measurements of the neutron structure proton
        - provides handle of d/u at high x: $\frac{F_2^n}{F_2^p} = \frac{u+u+4(d+d)+s+s}{4(u+u)+d+d+s+s} \Longrightarrow \frac{d}{u} \approx \frac{4\,F_{2n}/F_{2p}-1}{4-F_{2n}/F_{2p}}$
        - at BONUS12: Measurements that emulate a quasi-free neutron target to measure F2n
    - MARATHON: use mirror nuclei of 3H and 3He to study nuclear effect dependence



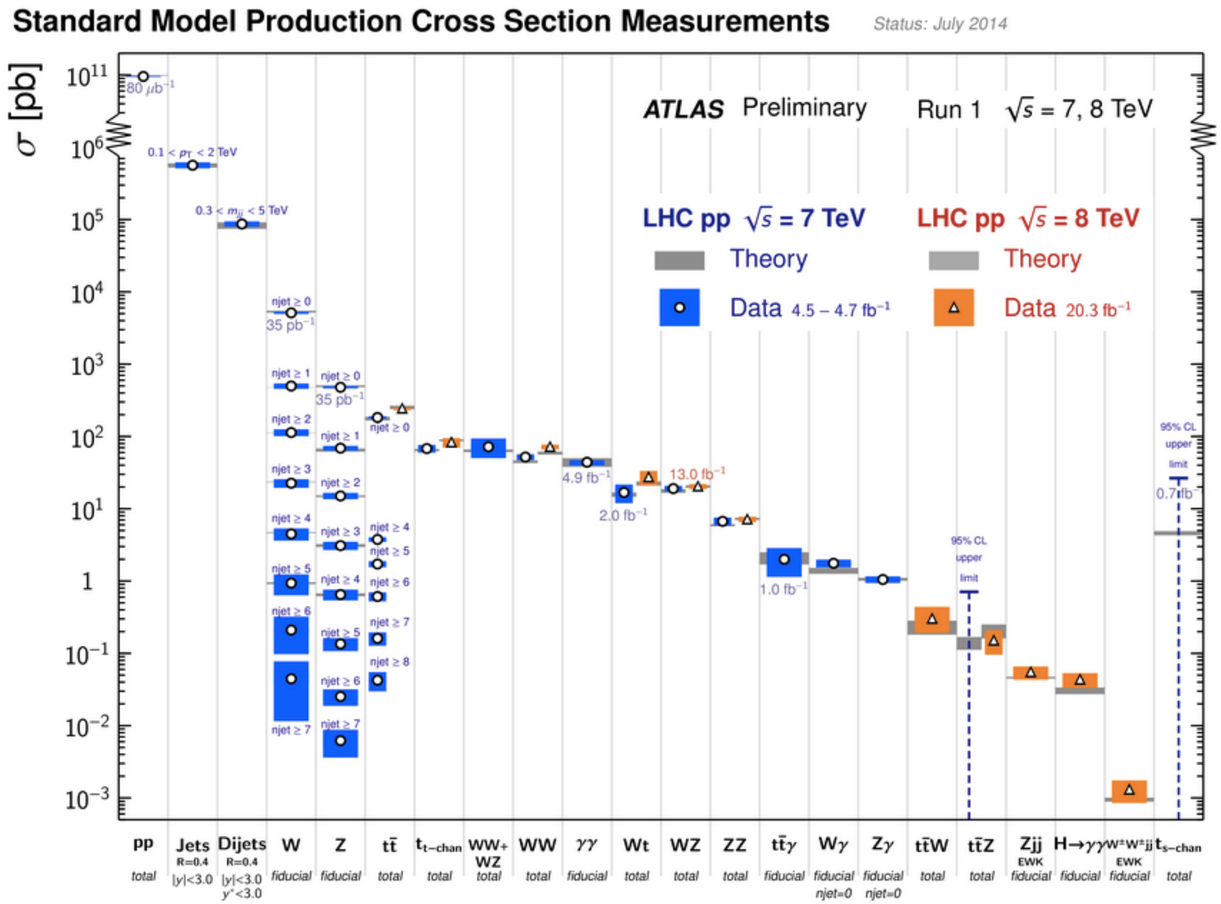


What can LHC do for PDFs?



LHC measurements from RUN1

- Successful run in 2010 - 2012 at the LHC confirmed and tested SM



LHC can provide with its multitude of new measurements:

• PDF discrimination by confronting theory with data
• PDF improvement by using LHC data in QCD fit

1. W and Z production
2. W+c production
3. Drell-Yan: low and high invariant mass
4. Inclusive Jet, Di-Jet and Tri-jet production
5. Prompt Photon + Jets
6. Top, ttbar

Flavour decomposition at LHC (EW bosons)

Additional constraints on PDFs come from DY and jet data at the LHC probe a bi-linear combination of quarks

$$x_1 = \frac{M}{\sqrt{s}} e^{+y}$$

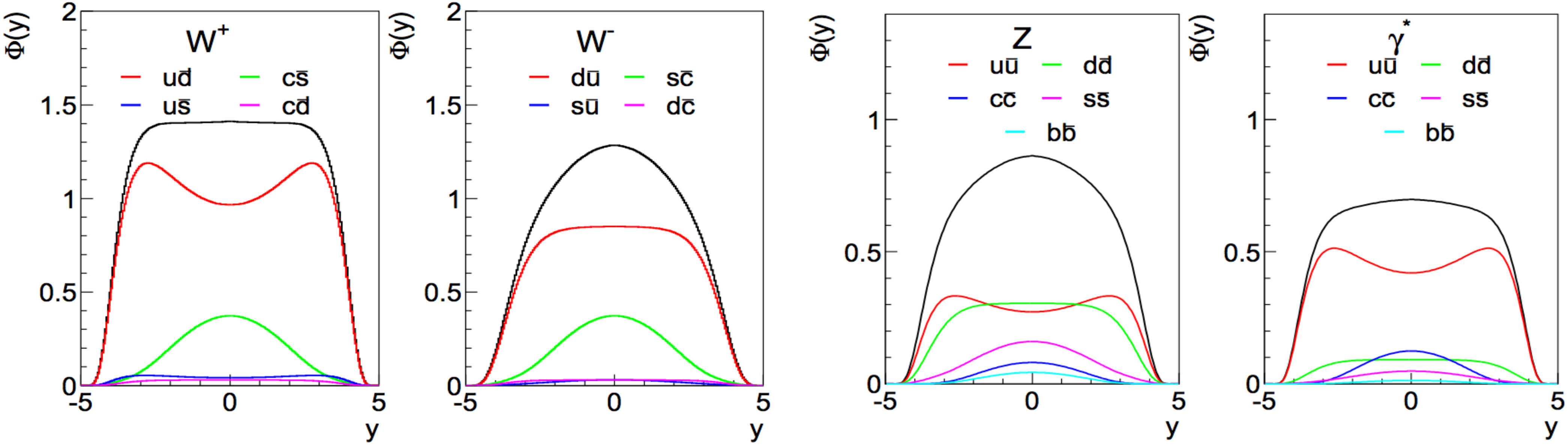
$$x_2 = \frac{M}{\sqrt{s}} e^{-y}$$

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

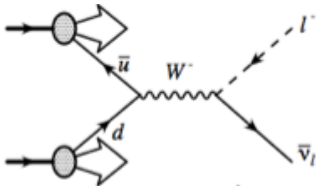
$$W^- \quad \sim 0.95(d\bar{u} + s\bar{c}) + 0.05(d\bar{c} + s\bar{u})$$

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

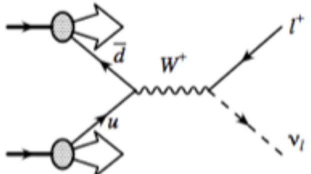
$$\gamma^* \quad \sim 0.44(u\bar{u} + c\bar{c}) + 0.11(d\bar{d} + s\bar{s} + b\bar{b})$$



Measurements of W, Z production differentially in y_Z and η_ℓ provide information on light sea decomposition



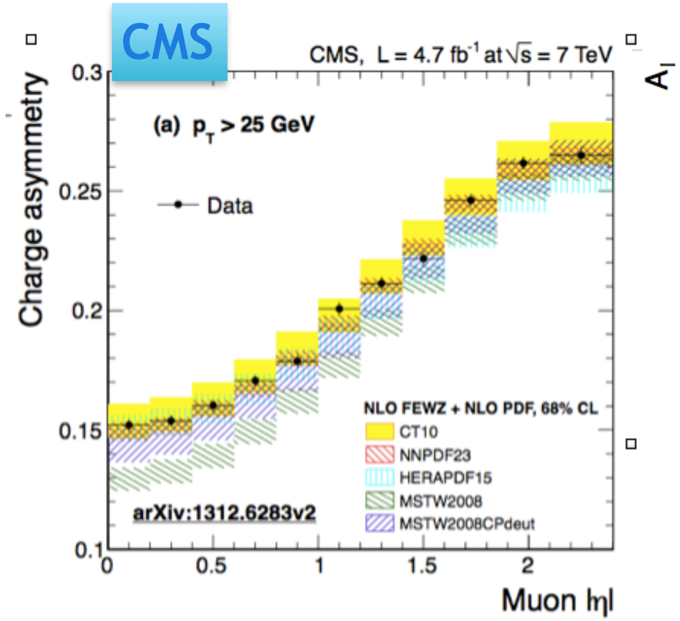
W charge asymmetry



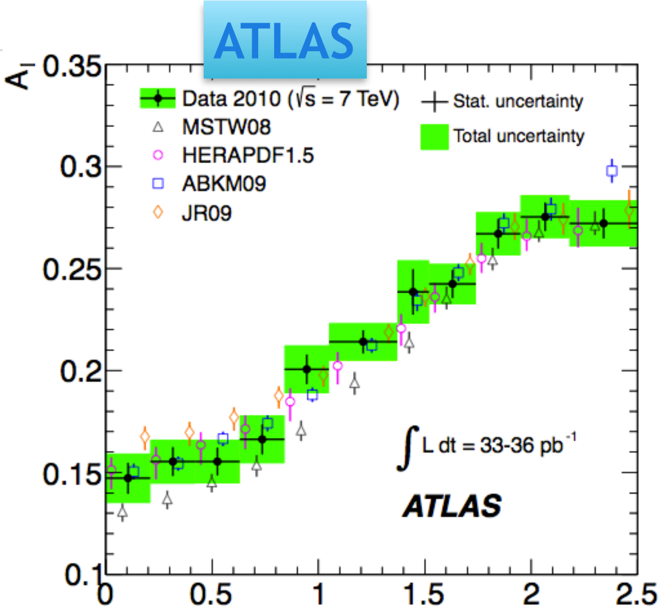
- The interplay between the flavour asymmetries can be enhanced via ratio measurements:
  - W-asymmetry measurement
    - sensitive to uv, dv

$$\mathcal{A}_W^l = \frac{d\sigma_{W^+}/d\eta_{l^+} - d\sigma_{W^-}/d\eta_{l^-}}{d\sigma_{W^+}/d\eta_{l^+} + d\sigma_{W^-}/d\eta_{l^-}} \qquad \mathcal{A}_W \approx \frac{u_v - d_v}{u + d}$$

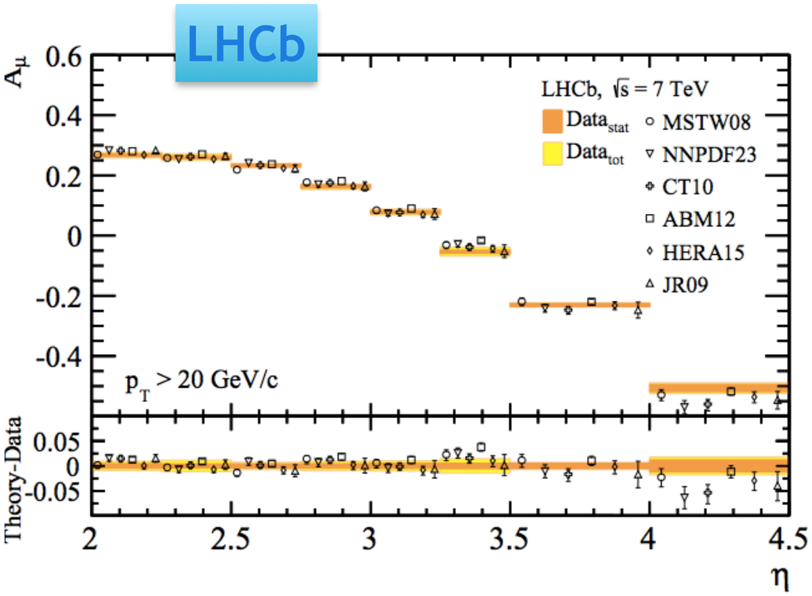
CMS



ATLAS

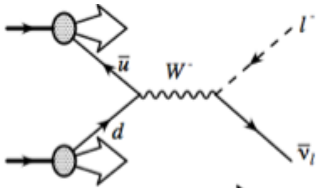


LHCb

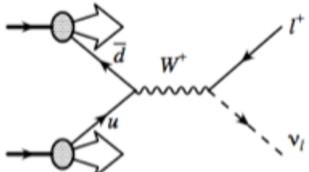


- CMS measures directly the electron asymmetry data from 2011
- ATLAS differential measurements of W^+ and W^- (combined muon and electron) based on 2010 data translated into charge asymmetry Al:
  - proper treatment of correlations are accounted for.
- LHCb extends the measurement to forward region

Selection criteria are optimized for each experiment—> a challenge for data combination



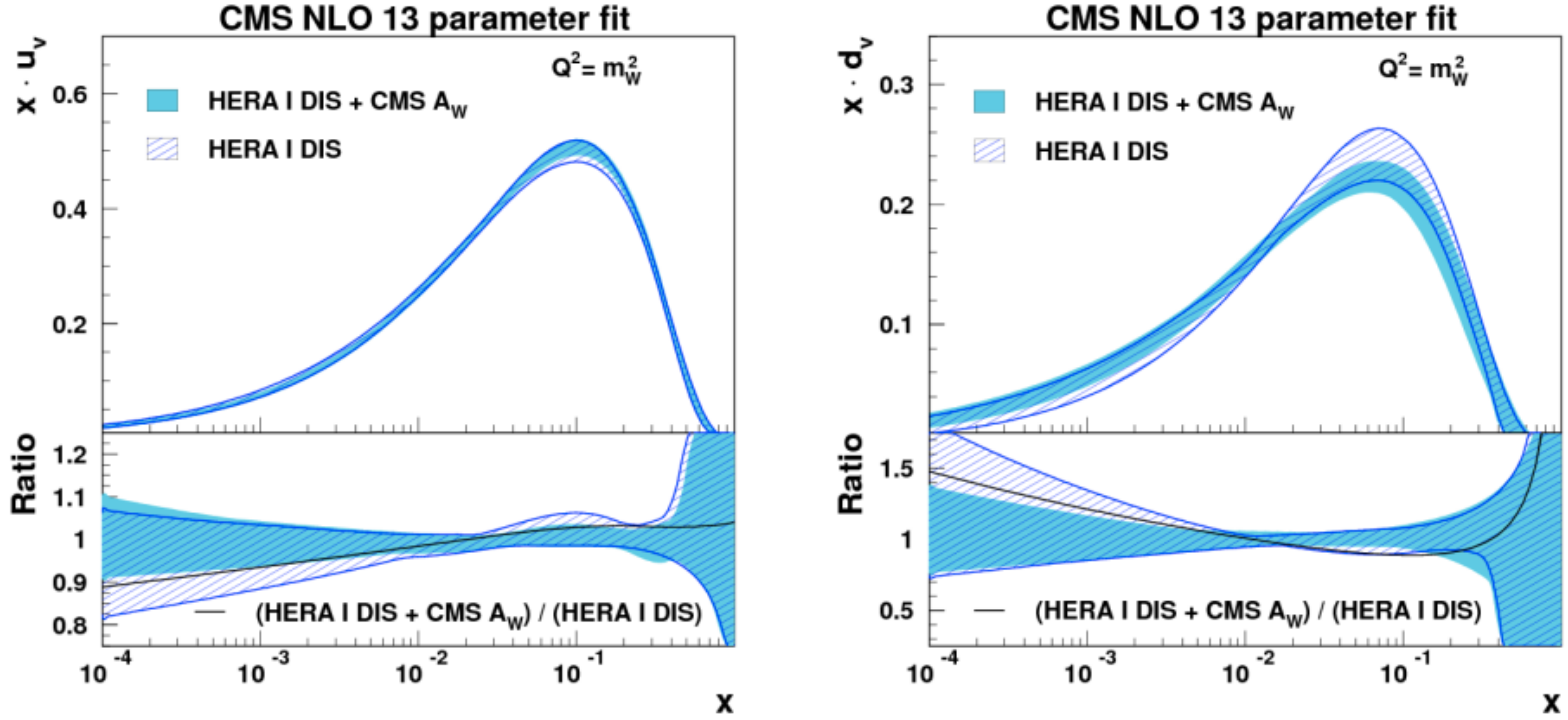
W charge asymmetry



- The interplay between the flavour asymmetries can be enhanced via ratio measurements:
  - W-asymmetry measurement
    - sensitive to uv, dv

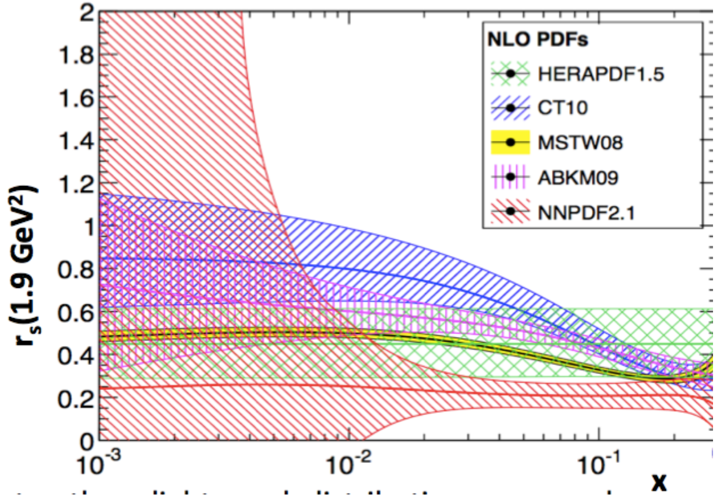
$$\mathcal{A}^l_{\rm W} = \frac{d\sigma_{W^+}/d\eta_{l^+} - d\sigma_{W^-}/d\eta_{l^-}}{d\sigma_{W^+}/d\eta_{l^+} + d\sigma_{W^-}/d\eta_{l^-}} \qquad \mathcal{A}_{\rm W} \approx \frac{u_v - d_v}{u + d}$$

The largest effect is on the $\mathrm{u_{valance}}$ and $\mathrm{d_{valance}}$ PDFs $(0.001 < x < 0.1)$.



Strange quark from W, Z measurements at LHC

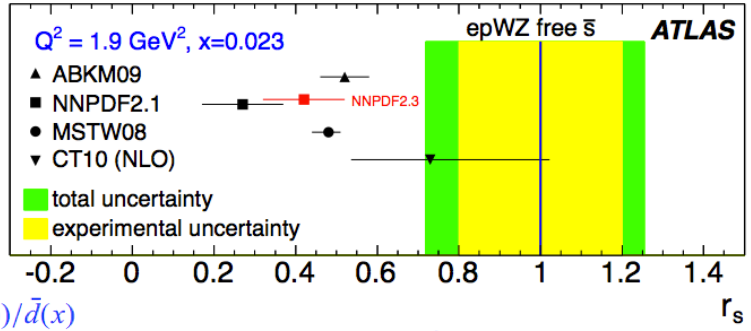
G.Watt



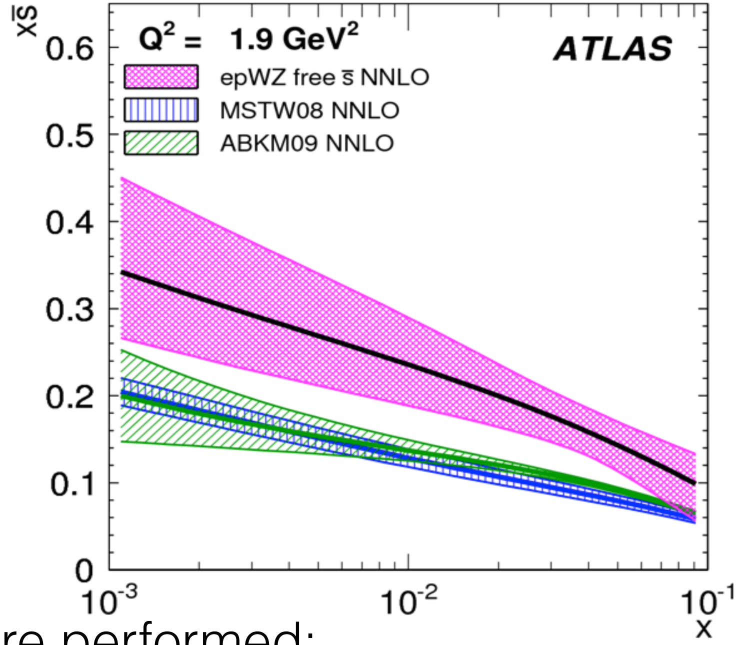
- Strange quark is not so well constrained:
  - Neutrino dimuon data provides constraints:
    - prefers rather strongly suppressed strange
    - nuclear target
- in 2010, at LHC the EW boson data was used to constrain strange quark through a QCD fit analysis

$$xs(x) \quad = \quad A_{\bar{s}} x^{B_s} (1-x)^{C_s}$$

- Impact comes from Z, W+, W- help constrain normalisation
- a rather enhanced strange distribution is found —>



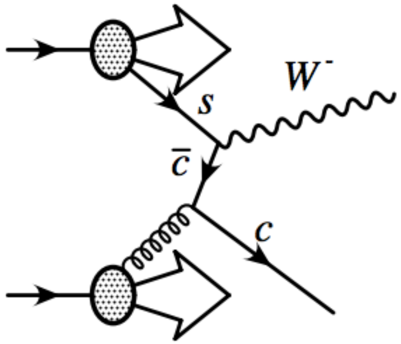
$r_s(x) = 0.5(s(x) + \bar{s}(x))/\bar{d}(x)$



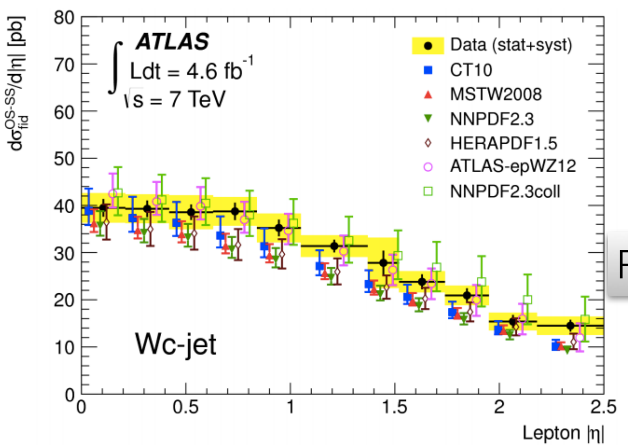
Since then, new measurements and QCD analyses were performed:

- W+charm from ATLAS and CMS
- QCD fits to W asymmetry + W+charm data @ CMS
- ongoing efforts to combine the measurements

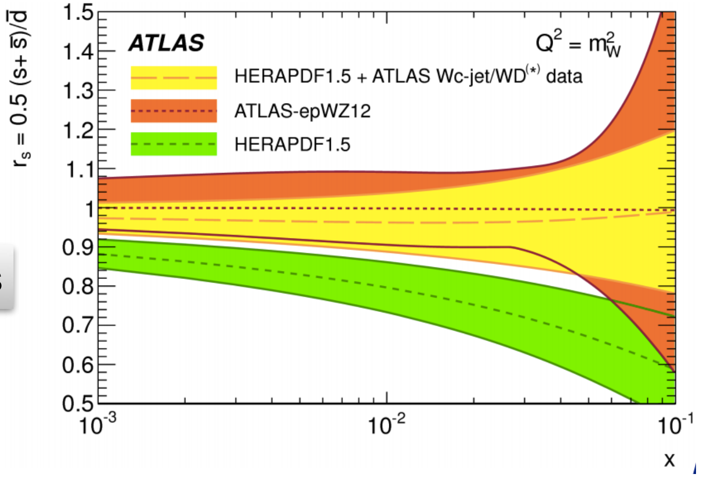
W+c sensitivity to strange



- W + charm data is directly sensitive to the strange quark density
- Both ATLAS and CMS have performed dedicated measurements:
  - Measure fully reconstructed D* mesons or soft leptons within a jet
    - ATLAS @ particle level [arXiv:1402.6263v1]

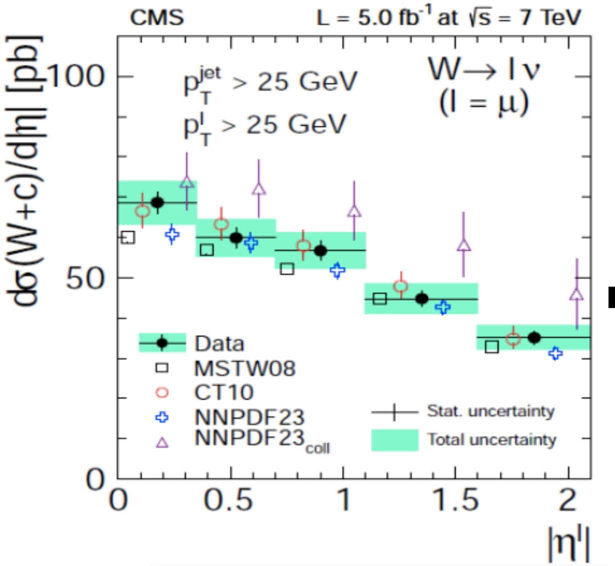


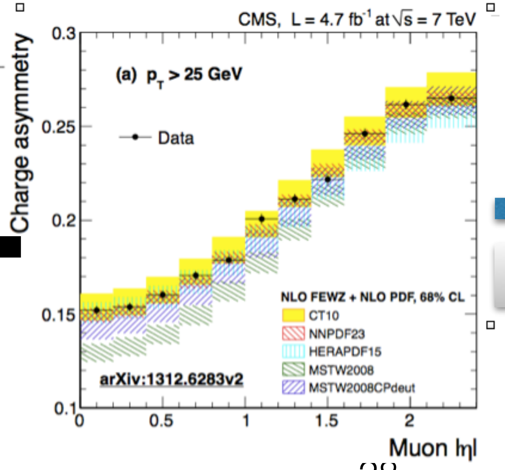
PDF eigenvector analysis



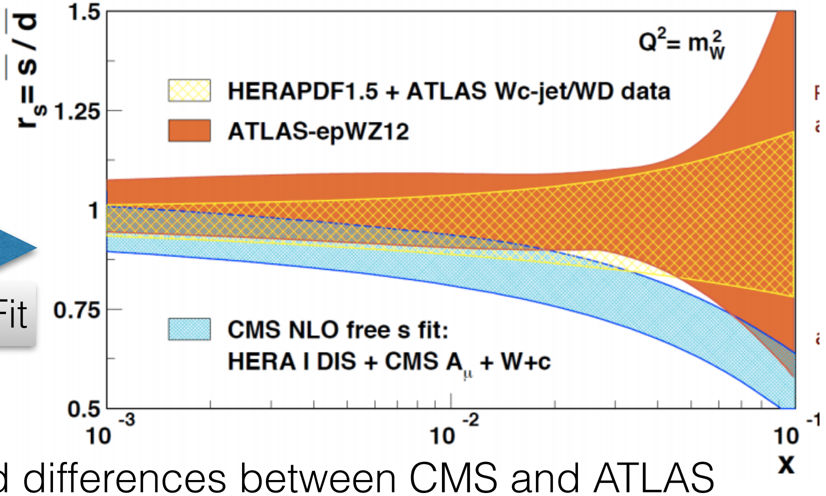
consistent with previous ATLAS result

- CMS @parton level [arXiv:1310.1138]





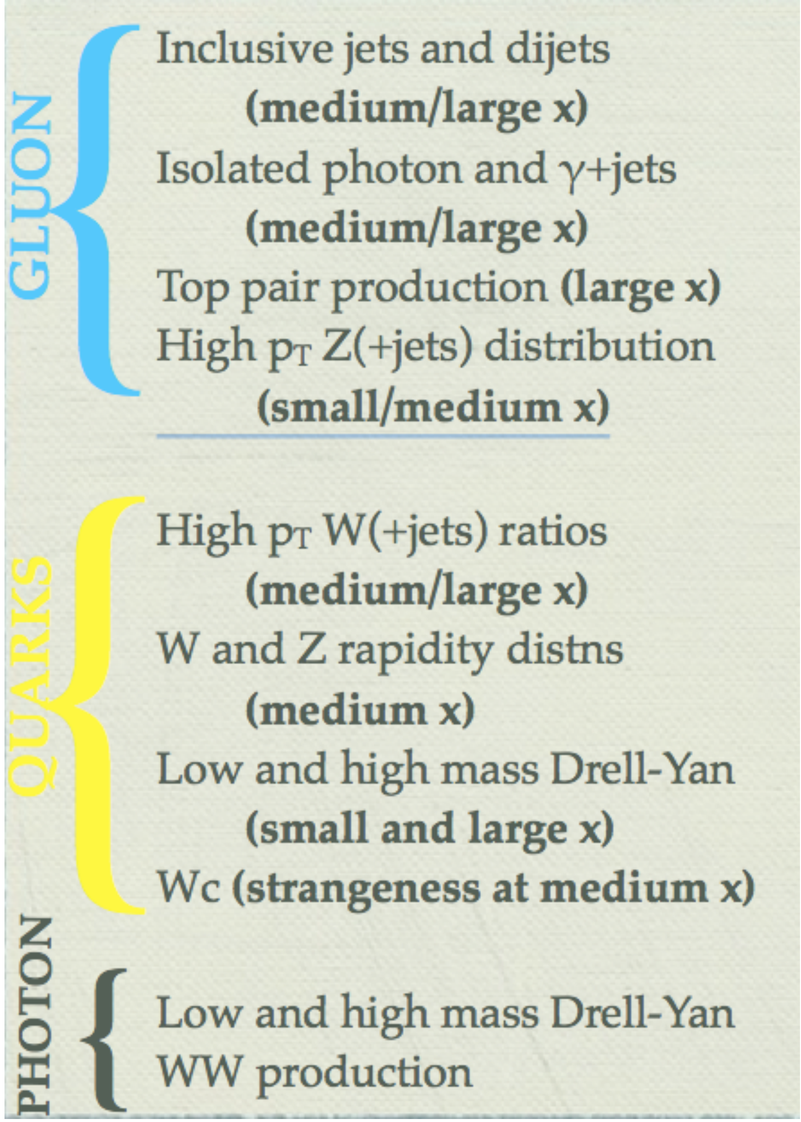
QCD Fit



mild differences between CMS and ATLAS

Impact of LHC data on PDFs

- Abundant LHC data with possible novel constraints on PDFs are investigated:



GLUON

Inclusive jets and dijets **(medium/large x)**

Isolated photon and γ+jets **(medium/large x)**

Top pair production **(large x)**

High p_T Z(+jets) distribution **(small/medium x)**

QUARKS

High p_T W(+jets) ratios **(medium/large x)**

W and Z rapidity distns **(medium x)**

Low and high mass Drell-Yan **(small and large x)**

Wc **(strangeness at medium x)**

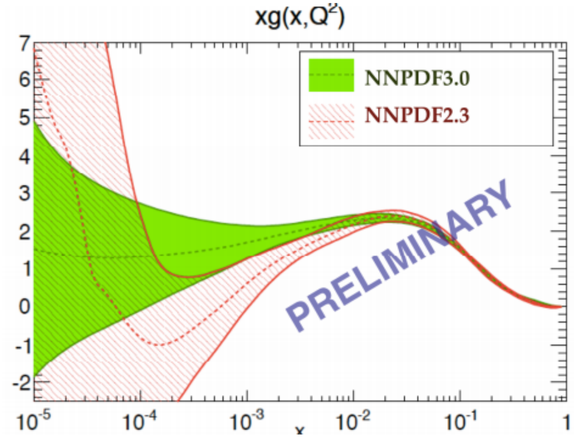
PHOTON

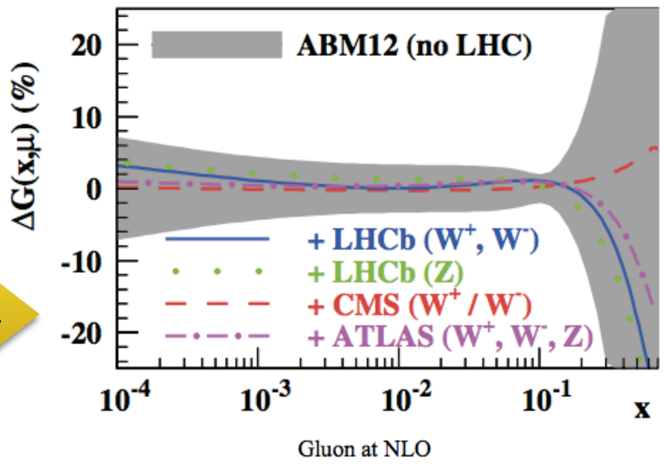
Low and high mass Drell-Yan

WW production

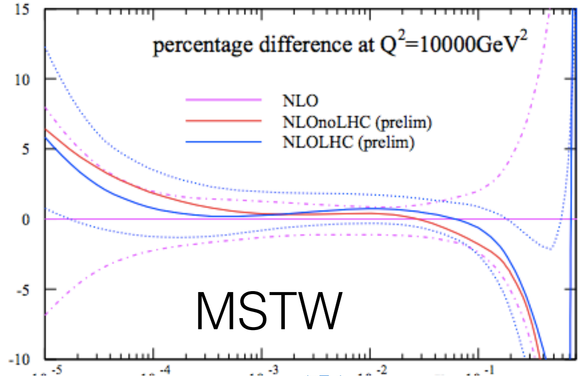
Intense activity of global PDF groups to include these measurements in the new PDF releases in time for Run2 data.

PDF4LHC, QCD@LHC, 2014





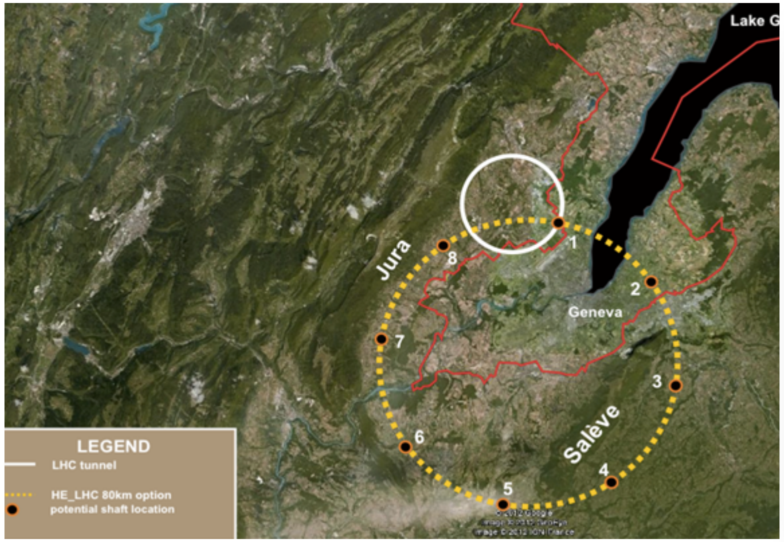
NNPDF3.0 is in LHAPDF, announced updates from: MSTW, HERA, CT, ABM



[see M. Kuze, S. Lee, J. Stupak]

Future prospects for better PDFs?

Future Circular Collider project: ee, eh, hh (100 TeV proton)



ISSN 0954-3899

Journal of Physics G

Nuclear and Particle Physics

Volume 39 Number 7 July 2012 Article 075001

A Large Hadron Electron Collider at CERN

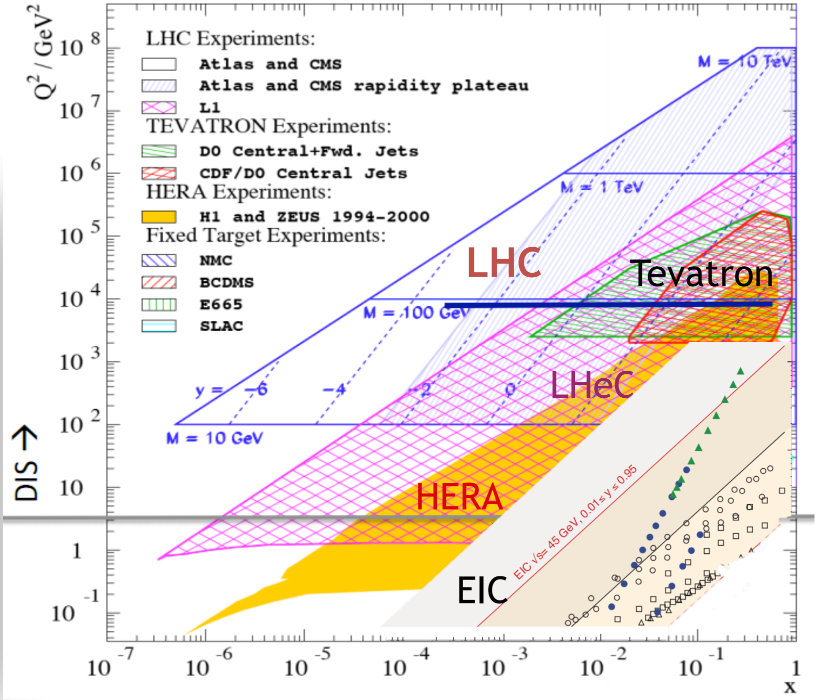
Report on the Physics and Design Concepts for Machine and Detector

LHeC Study Group

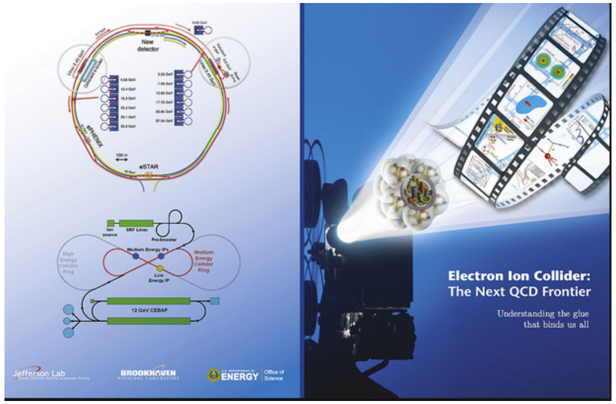
arXiv:1206.2913

iopscience.org/jphysg

IOP Publishing



EIC project (JLAB, Brookhaven)



Electron Ion Collider:
The Next QCD Frontier

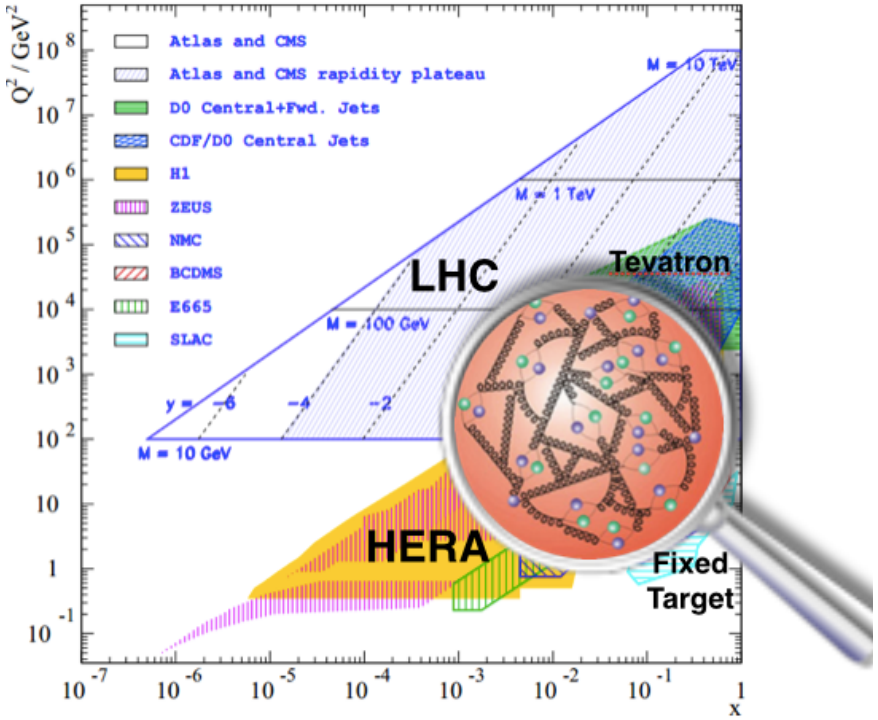
Understanding the glue that binds us all

Jefferson Lab

BROOKHAVEN

ENERGY

Summary



Many Thanks!

PDFs are very important as they still limit our knowledge of cross sections whether SM or BSM.

- HERA has finalised its separate measurements relevant to PDFs and ongoing efforts on combining final measurements to reach its ultimate precision:
    - PDFs, mc, mb, alphas …
- JLAB has a dedicated program on improving PDFs at high x
- Standard Model LHC measurements can themselves contribute to PDF discrimination and PDF improvement:

… Many more valuable measurements are already available, but not covered in this talk …

- More precision measurements from LHC to come from Run I and in future from Run 2
- Intense activity of PDF groups to include constraining information in new releases
- Future Facilities to further push our limits are being considered …

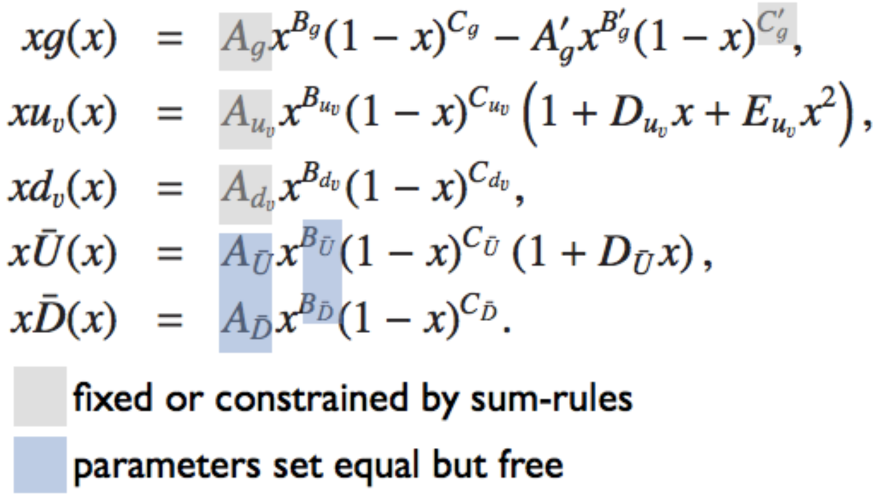
Extra Material

not necessarily useful

QCD Settings for HERAPDF2.0

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

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



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

▨ fixed or constrained by sum-rules

🟦 parameters set equal but free

NC structure functions

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

$$xF_3 \sim xu_v + xd_v$$

CC structure functions

$$W_2^- = x(U + \overline{D}), \qquad W_2^+ = x(\overline{U} + D)$$

$$xW_3^- = x(U - \overline{D}), \qquad xW_3^+ = x(D - \overline{U})$$

Due to increased precision of data, more flexibility in functional form is allowed —> 15 free parameters

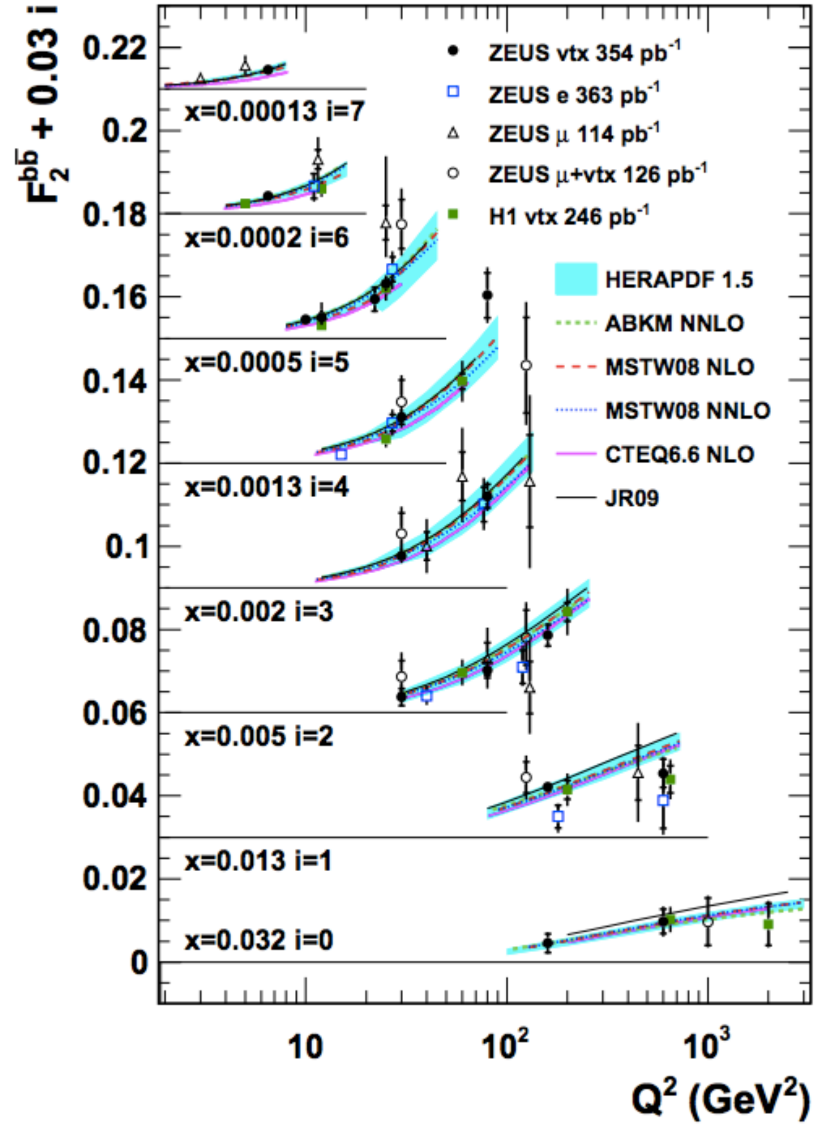
- PDFs are evolved via evolution equations (DGLAP) to NLO and NNLO (as(MZ)=0.118)
- Thorne-Roberts GM-VFNS for heavy quark coefficient functions – as used in MSTW
- Chi2 definition used in the minimisation [MINUIT] accounts for correlated uncertainties:

$$\chi^2_{tot}(\mathbf{m},\mathbf{b}) = \sum_i \frac{[\mu^i - m^i(1-\sum_j \gamma^i_j b_j)]^2}{\delta^2_{i,stat}\mu^i m^i(1-\sum_j \gamma^i_j b_j) + (\delta_{i,unc}m^i)^2} + \sum_j b_j^2 + \sum_i \ln \frac{\delta^2_{i,unc}m_i^2 + \delta^2_{i,stat}\mu^i m^i}{\delta^2_{i,unc}\mu_i^2 + \delta^2_{i,stat}\mu_i^2}$$

New Beauty in DIS from LifeTime-Tagging

DESY-14-083 arXiv:1405.6915

- Inclusive jet cross sections in beauty and charm events are used to:
  - **The good agreement of the data and NLO calculations in the visible phase (given by the heavy quark tagging) allow to extrapolate to the full phase space and to measure F2bb (and identical F2cc) :**



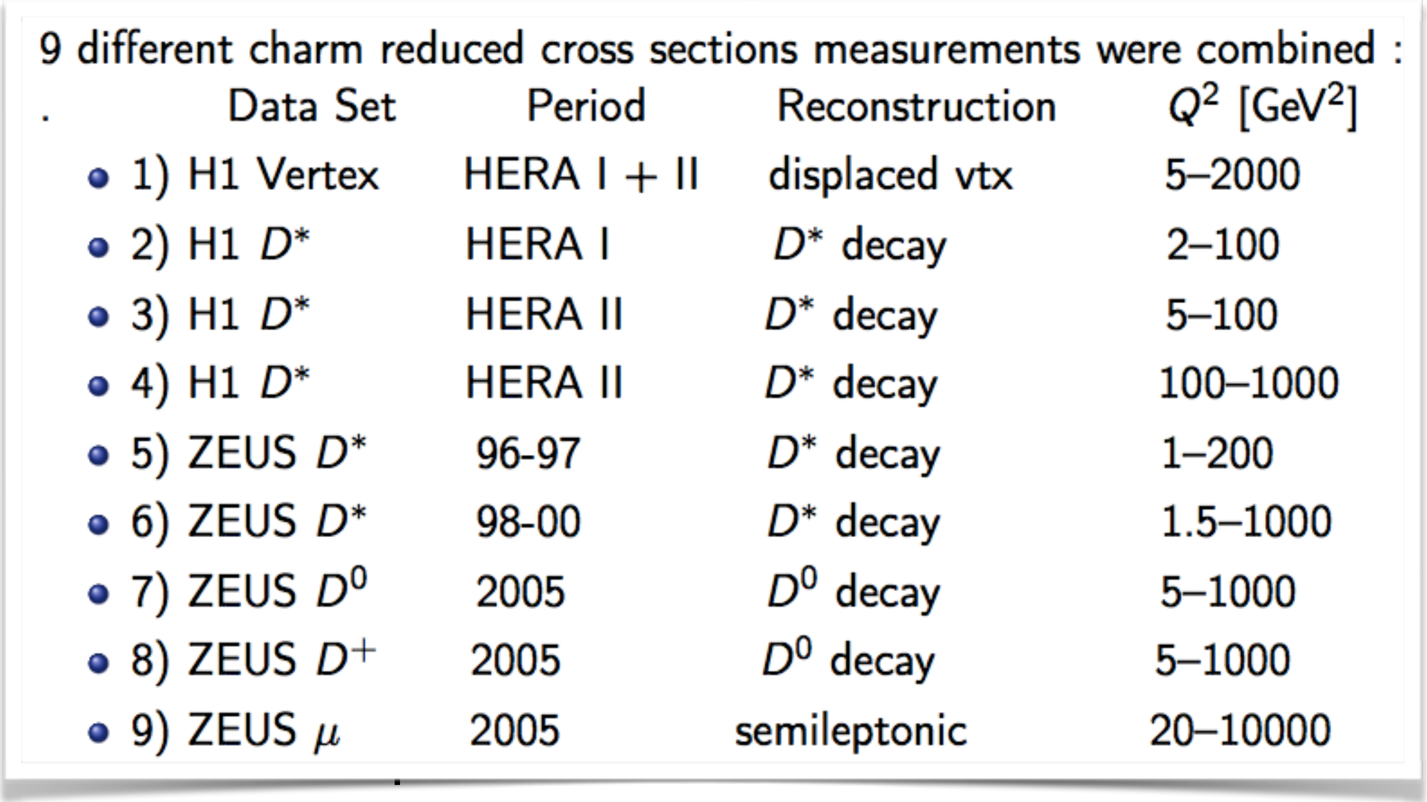
$$\frac{d\sigma^{b\bar{b}}}{dxdQ^2}=\frac{2\pi\alpha^2}{xQ^4}\cdot[(1+(1-y)^2)\cdot F_2^{b\bar{b}}-y^2\cdot F_L^{b\bar{b}}]$$

- The new measurement is the most precise determination of F_2b from ZEUS
- Data are in good agreement and well described by fixed-order (massive) and variable-flavour (mixed) NLO and NNLO QCD calculations

HERA Charm Data Combination

EPJC 73 (2013) 2311

- Best precision achieved when measurements are combined:
  - **Charm Data Combination: chi2/ndof = 62/103**
    - **155 data points from 9 different measurements of H1 and ZEUS were combined into 52 points**
    - **efforts in accounting for correlations of systematic uncertainties between data sets**



9 different charm reduced cross sections measurements were combined :

Data Set	Period	Reconstruction	Q^2 [GeV^2]
1) H1 Vertex	HERA I + II	displaced vtx	5–2000
2) H1 D^*	HERA I	D^* decay	2–100
3) H1 D^*	HERA II	D^* decay	5–100
4) H1 D^*	HERA II	D^* decay	100–1000
5) ZEUS D^*	96-97	D^* decay	1–200
6) ZEUS D^*	98-00	D^* decay	1.5–1000
7) ZEUS D^0	2005	D^0 decay	5–1000
8) ZEUS D^+	2005	D^0 decay	5–1000
9) ZEUS μ	2005	semileptonic	20–10000

- Data combination is performed at the reduced charm cross sections level (as in DIS):
  - **they are obtained from xsec in visible phase space and extrapolated to full space**

$$\frac{d^2\sigma^{c\bar{c}}}{dx\,dQ^2} = \frac{2\pi\alpha_{em}^2}{xQ^4} Y_+ \sigma_{red}^{c\bar{c}}(x,Q^2,s)$$

$$\sigma_{red}^{c\bar{c}}(x,Q^2,s) = F_2^{c\bar{c}}(x,Q^2) - \frac{y^2}{Y_+} F_L^{c\bar{c}}(x,Q^2)$$

$$\sigma_{red}^{c\bar{c}}(x,Q^2) = \left(\sigma_{vis} - \sigma_{vis}^{beauty}\right)\left(\frac{\sigma_{red,HVQDIS}^{c\bar{c}}}{\sigma_{vis,HVQDIS}}\right)$$

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EPJC 73 (2013) 2311

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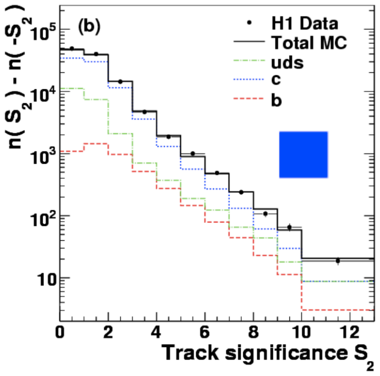
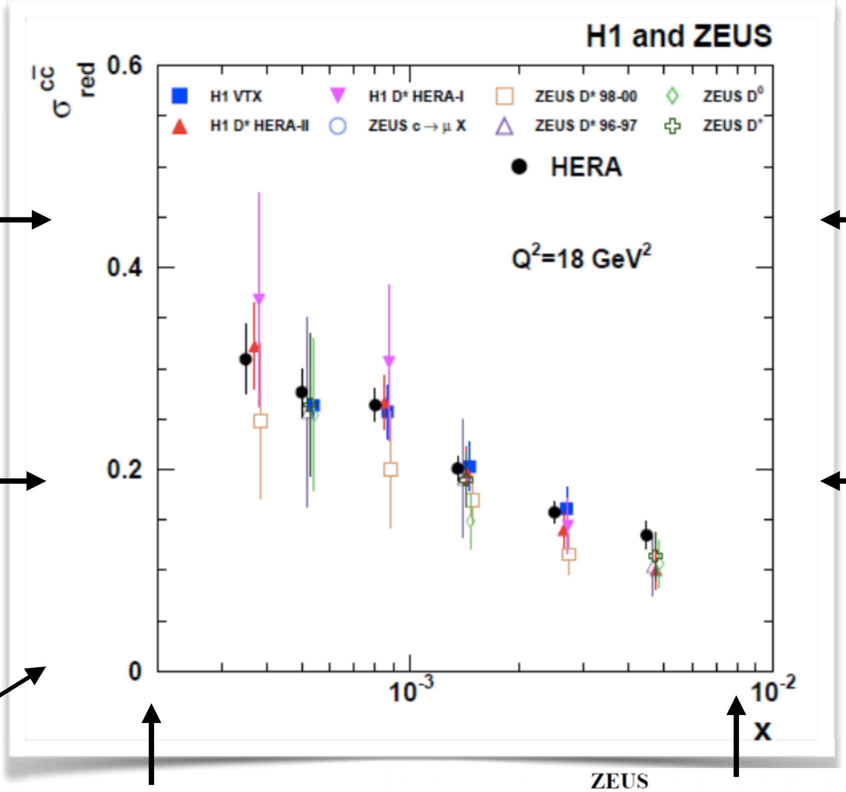
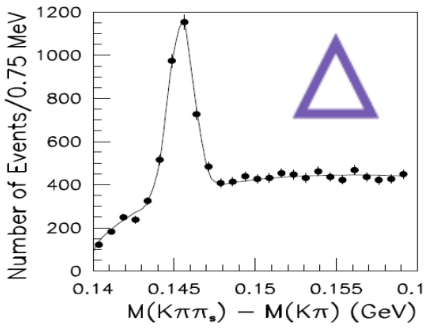
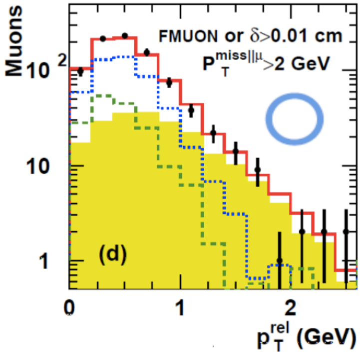
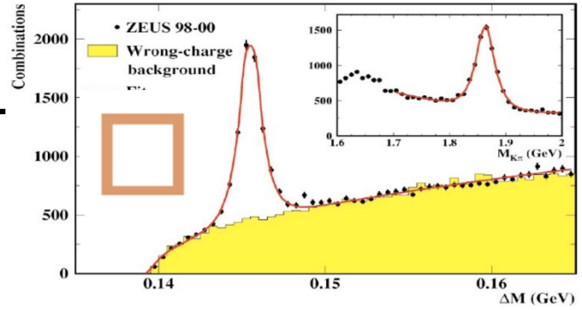
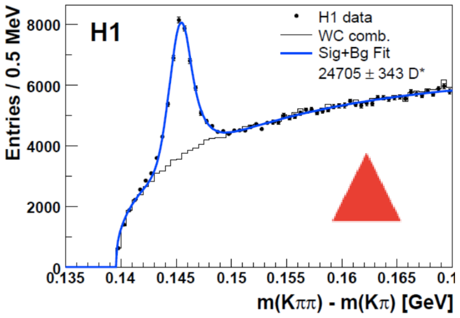


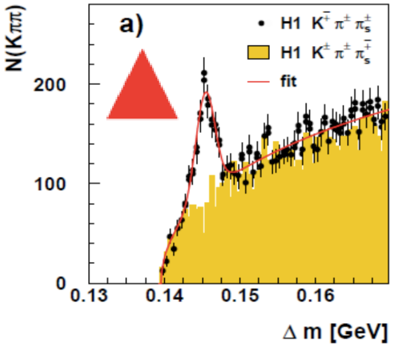


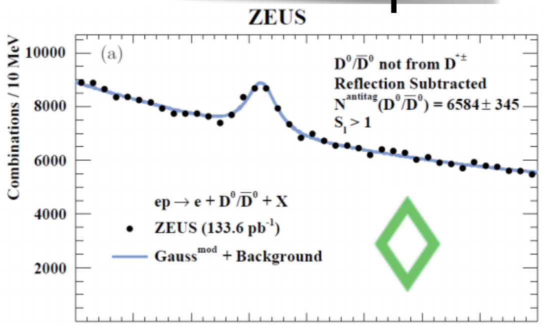


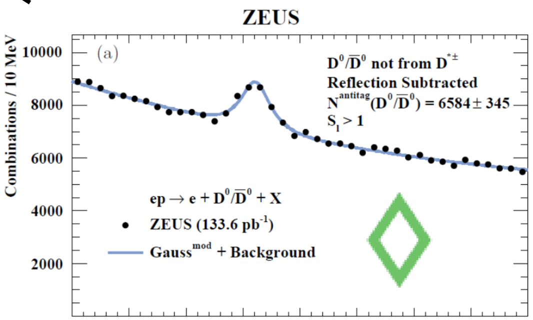










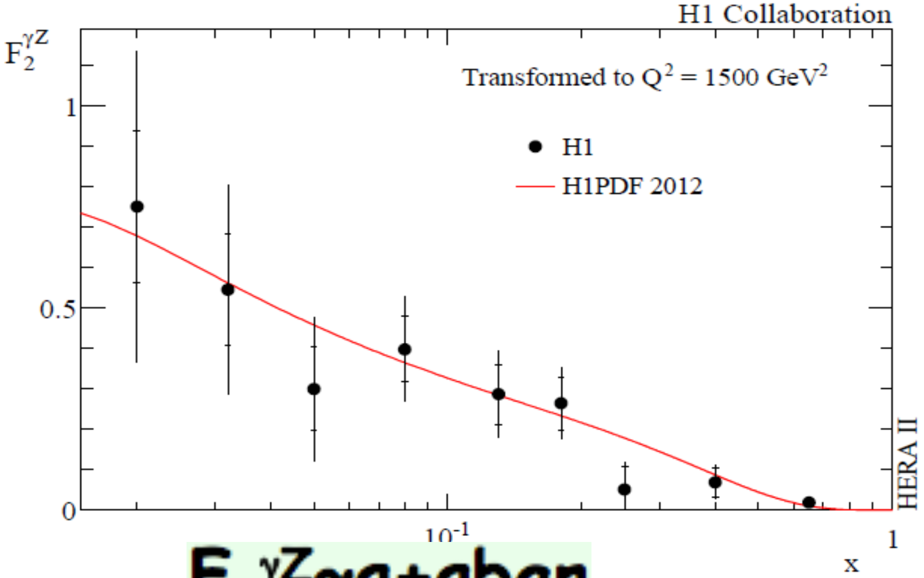


Measurements of Asymmetries from HERA

- Explore polarisation asymmetry to extract $F_2^{\gamma Z}$
- Explore charge asymmetry to extract $xF_3^{\gamma Z}$ (improved measurement from HERA I+II)

$$\tilde{F}_2^{\pm} \approx F_2 - (v_e \pm P_e a_e)\kappa \frac{Q^2}{Q^2 + M_Z^2} F_2^{\gamma Z}$$

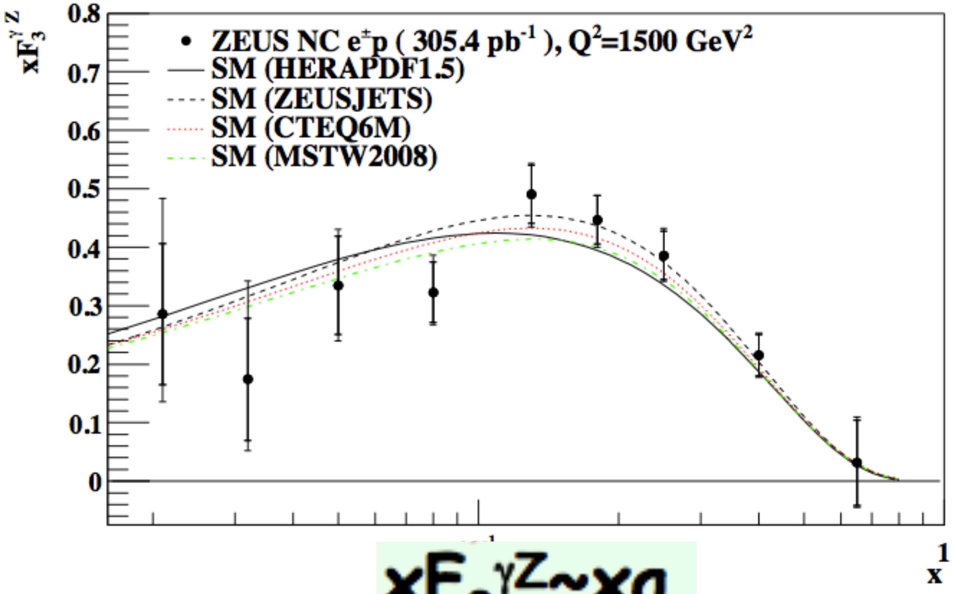
JHEP 1209:061 (2012)



$F_2^{\gamma Z}$~q+qbar

$$\sigma_r^{\pm} = \tilde{F}_2^{\pm} \mp \frac{1-(1-y)^2}{1+(1+y)^2} x\tilde{F}_3 - \frac{y^2}{1+(1-y)^2} \tilde{F}_L$$

arXiv:1208:6138



$xF_3^{\gamma Z}$~xq_v

The shape of the distribution reflects their parton sensitivity

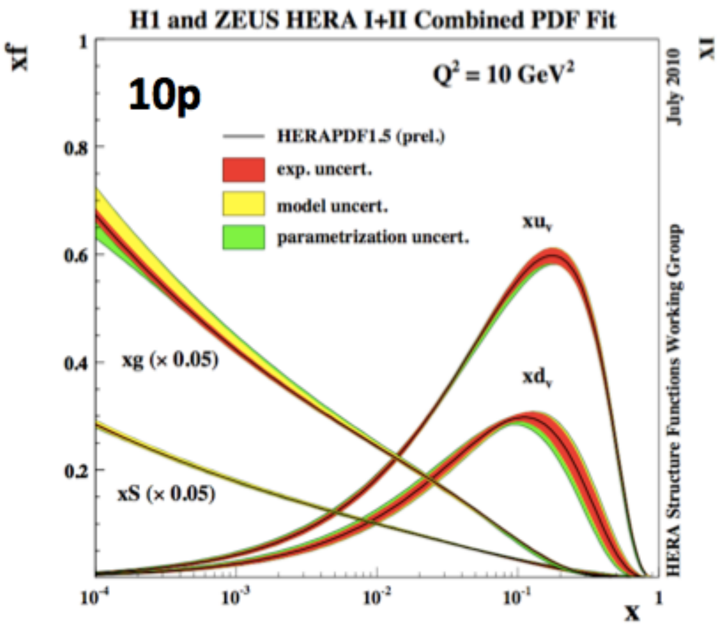
Extraction of PDFs through QCD fits

Typical measurements sensitive to PDFs are precise, with statistical uncertainties < 10%, so they follow normal distribution which allows the use of chi square minimisation for PDF extraction.

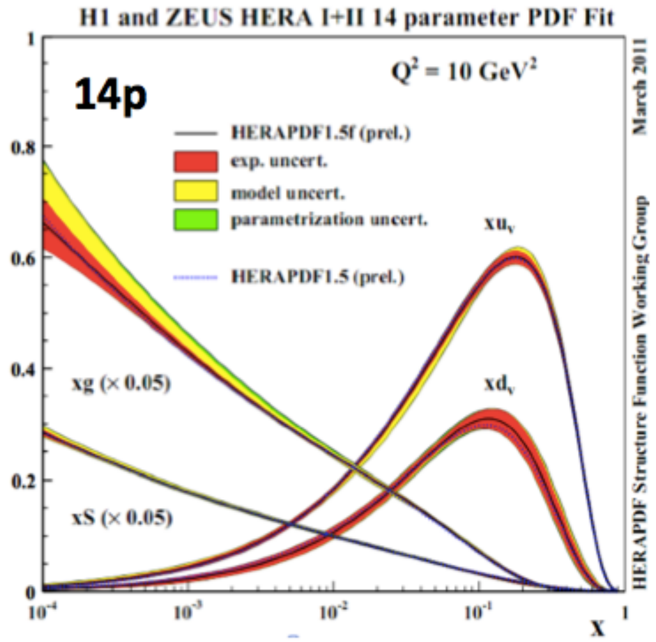
Flow diagram of a PDF extraction:

Review of HERAPDF sets:

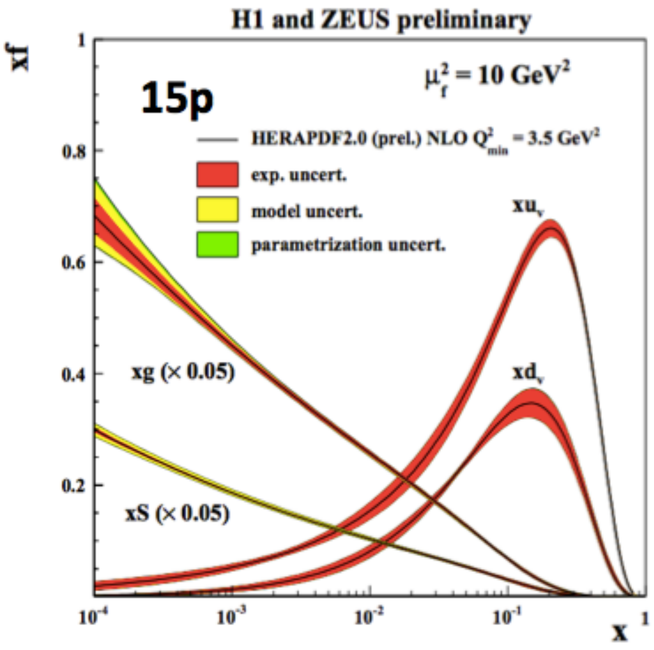
HERAPDF1.5-NLO(10p) → **HERAPDF1.5-NLOf(14p)** → **HERAPDF2.0-NLO (15p)**



We started with similar settings as used for HERAPDF1.0 (10 free parameters)



preliminary HERA II data
Required additional flexibility
(14 free parameters)



New HERAI+II combiation
(15 free parameters)

Running charm mass $m_c(m_c)$

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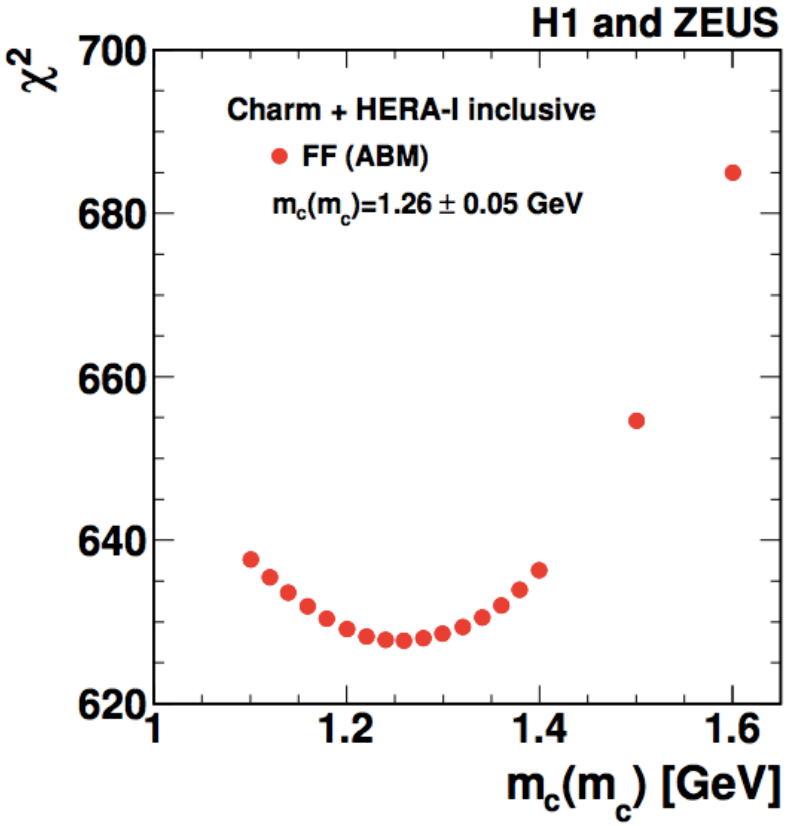
- Charm combination can also be used in a NLO QCD analysis in FFN scheme to determine the running of charm-quark mass mc(mc) in MS:

$$m_c(m_c) = 1.26 \pm 0.05_{\mathrm{exp}} \pm 0.03_{\mathrm{mod}} \pm 0.02_{\mathrm{param}} \pm 0.02_{\alpha_s}\ \mathrm{GeV}$$

  - **which is in agreement with the world average extraction:**

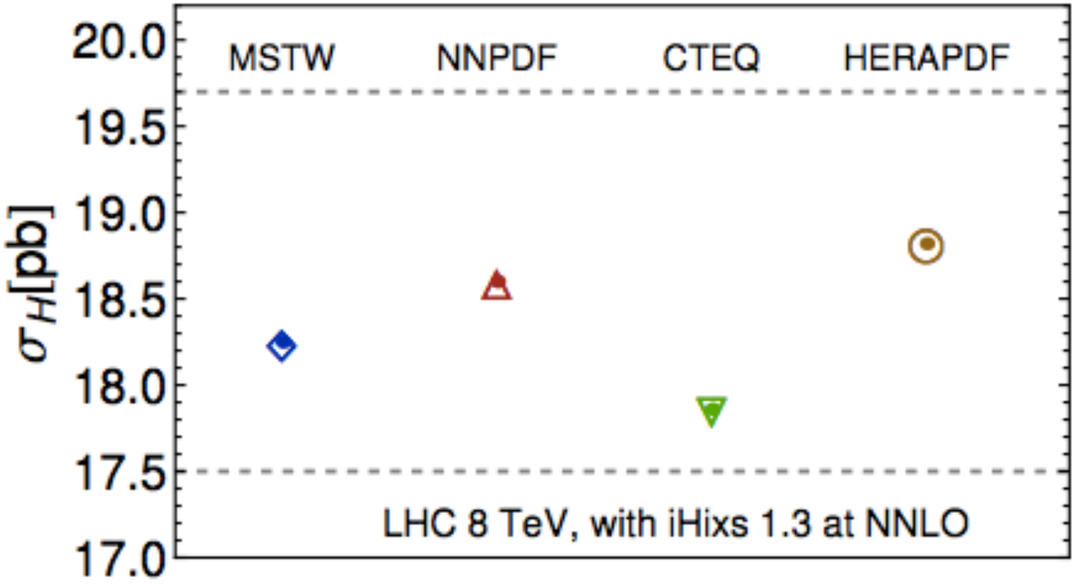
$$m_c(m_c) = 1.275 \pm 0.025\ \mathrm{GeV}$$



- This has triggered the question:

—> how about measuring the running of m_c?

ggH studies


MSTW
NNPDF
CTEQ
HERAPDF
σ_H[pb]
20.0
19.5
19.0
18.5
18.0
17.5
17.0
LHC 8 TeV, with iHixs 1.3 at NNLO

Review of HERAPDF sets:

PDFs at HERA are determined from QCD Fits to solely HERA data

HERAPDF1.0:
- Combined NC and CC HERA-I data
- NLO set, RT scheme —> available in LHAPDF

HERAPDF1.5(prel.) -> recommended so far:
- Include additional NC and CC HERA-II data
- LO, NLO, NNLO sets —> available in LHAPDF

HERAPDF1.6 (prel., not public)
- Include additional NC inclusive jet data 5 < Q2 < 15000
- αs = 0.1202 ± 0.0013 (exp) ± 0.004 (scales) free in fit
- NLO

HERAPDF1.7 (prel. not public)
- Include F2cc data 4 < Q2 < 1000
- Include combined cross section points Ep=575/460 GeV
- NLO

HERAPDF2.0(prel)

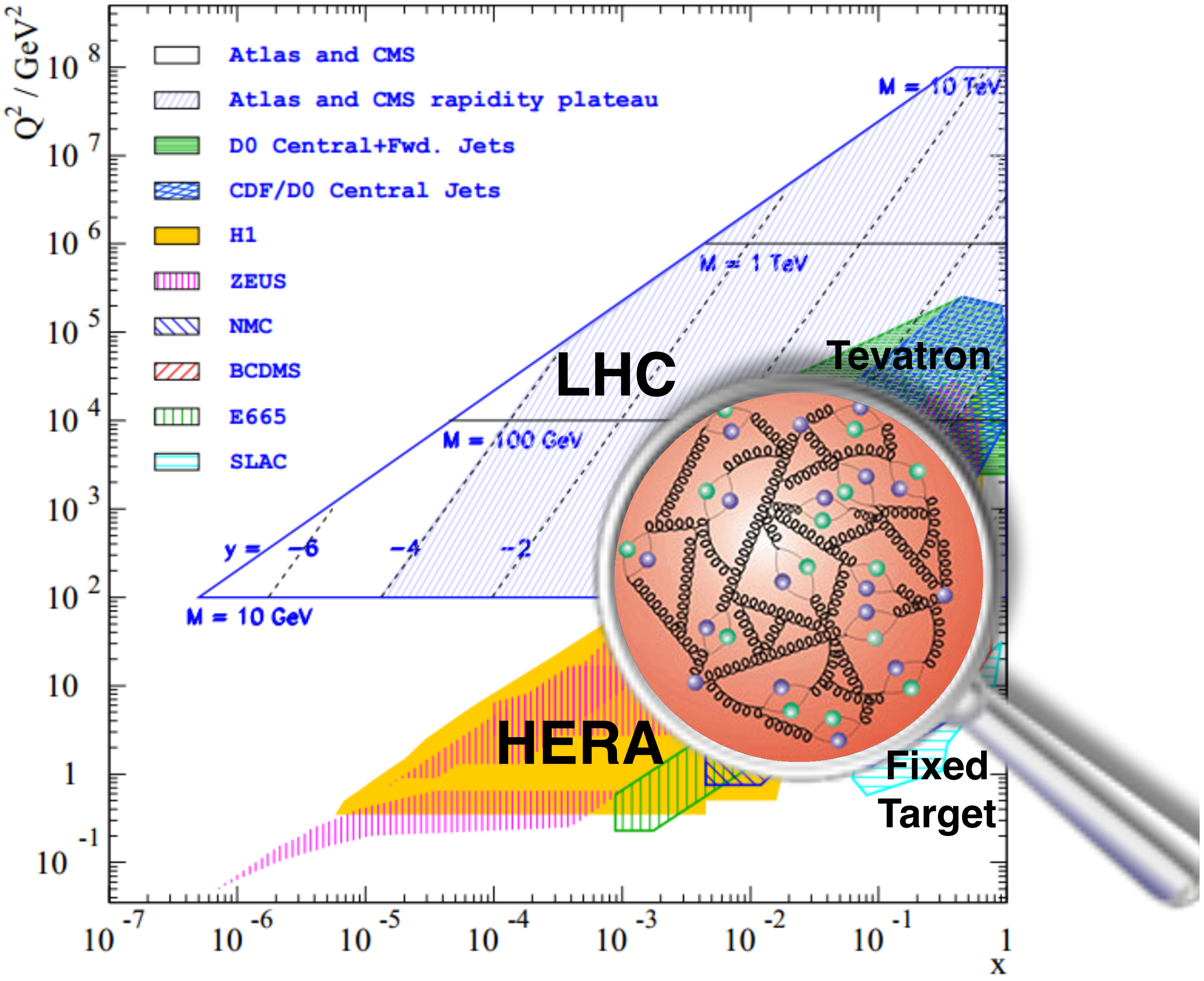
Summary

PDFs are very important as they still limit our knowledge of cross sections whether SM or BSM.

- HERA has finalised its separate measurements relevant to PDFs and ongoing efforts on combining final measurements to reach its ultimate precision:
    - PDFs, mc, mb, alphas …
- JLAB has a dedicated program on improving PDFs at high x
- Standard Model LHC measurements can themselves contribute to PDF discrimination and PDF improvement:

… Many more valuable measurements are already available, but not covered in this talk …

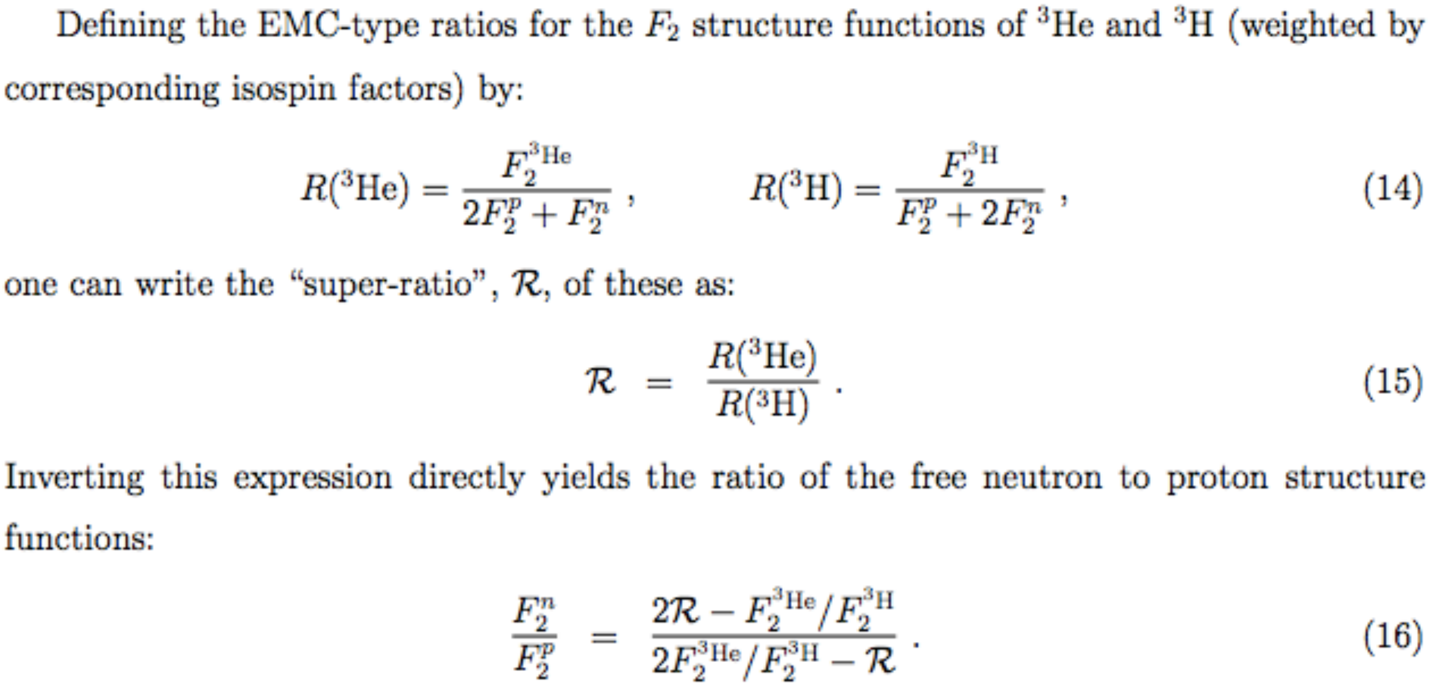
- More precision measurements from LHC to come from Run I and in future from Run 2
- Intense activity of PDF groups to include constraining information in new releases
- Future Facilities to further push our limits are being considered …



Many Thanks!

testing EMC effect

- Marathon's idea:



Defining the EMC-type ratios for the F_2 structure functions of ^{3}He and ^{3}H (weighted by corresponding isospin factors) by:

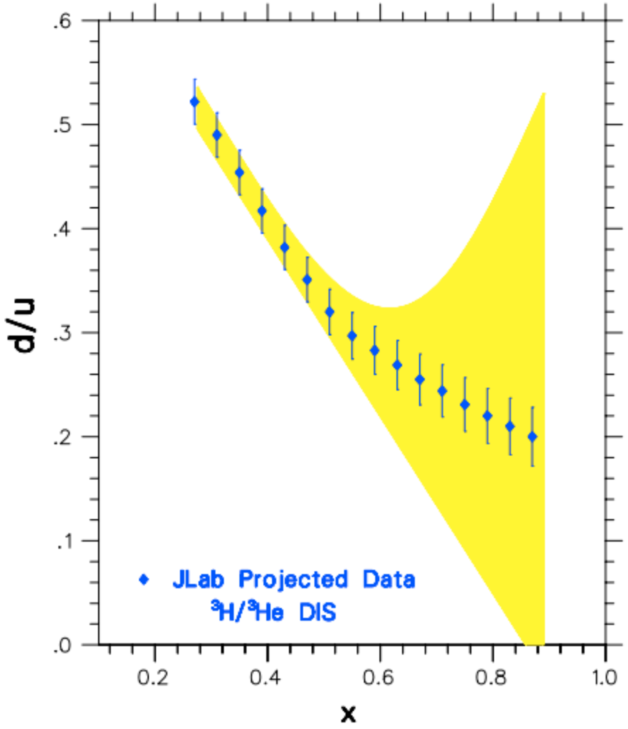
$$R(^3\mathrm{He}) = \frac{F_2^{^3\mathrm{He}}}{2F_2^p + F_2^n}, \qquad R(^3\mathrm{H}) = \frac{F_2^{^3\mathrm{H}}}{F_2^p + 2F_2^n}, \tag{14}$$

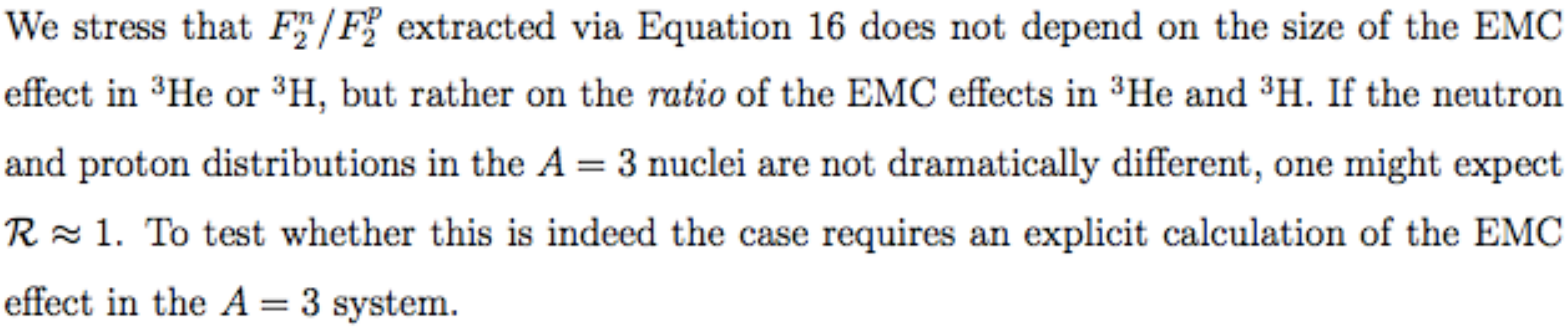
one can write the "super-ratio", $\mathcal{R}$, of these as:

$$\mathcal{R} = \frac{R(^3\mathrm{He})}{R(^3\mathrm{H})}. \tag{15}$$

Inverting this expression directly yields the ratio of the free neutron to proton structure functions:

$$\frac{F_2^n}{F_2^p} = \frac{2\mathcal{R} - F_2^{^3\mathrm{He}}/F_2^{^3\mathrm{H}}}{2F_2^{^3\mathrm{He}}/F_2^{^3\mathrm{H}} - \mathcal{R}}. \tag{16}$$

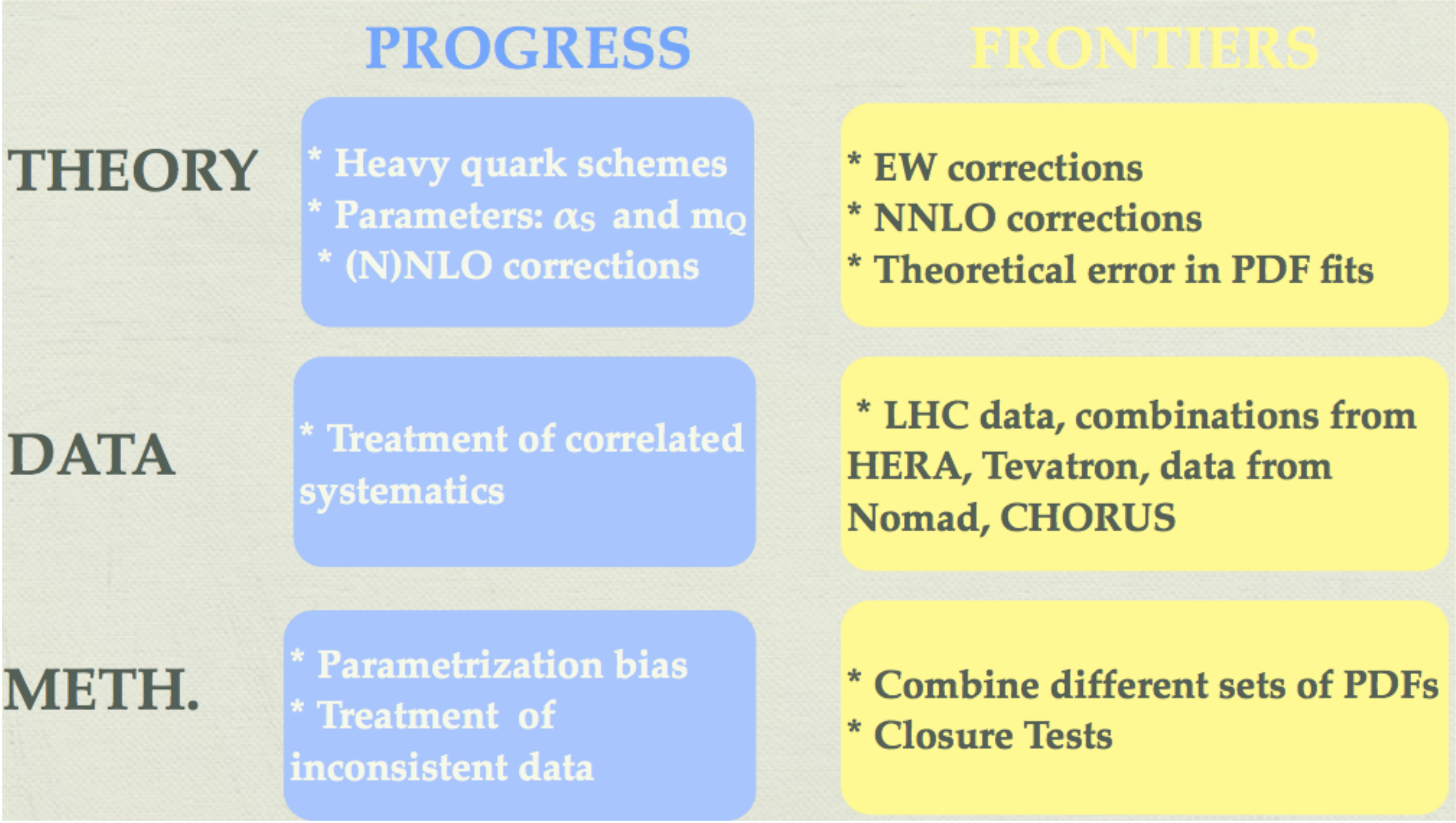




We stress that F_2^n/F_2^p extracted via Equation 16 does not depend on the size of the EMC effect in ^{3}He or ^{3}H, but rather on the *ratio* of the EMC effects in ^{3}He and ^{3}H. If the neutron and proton distributions in the $A = 3$ nuclei are not dramatically different, one might expect $\mathcal{R} \approx 1$. To test whether this is indeed the case requires an explicit calculation of the EMC effect in the $A = 3$ system.

a schematic view of the progress

- Snapshot from M. Ubiali:



	PROGRESS	FRONTIERS
THEORY	* Heavy quark schemes * Parameters: α_S and m_Q * (N)NLO corrections	* EW corrections * NNLO corrections * Theoretical error in PDF fits
DATA	* Treatment of correlated systematics	* LHC data, combinations from HERA, Tevatron, data from Nomad, CHORUS
METH.	* Parametrization bias * Treatment of inconsistent data	* Combine different sets of PDFs * Closure Tests