Centre de Physique des Particules de Marseille

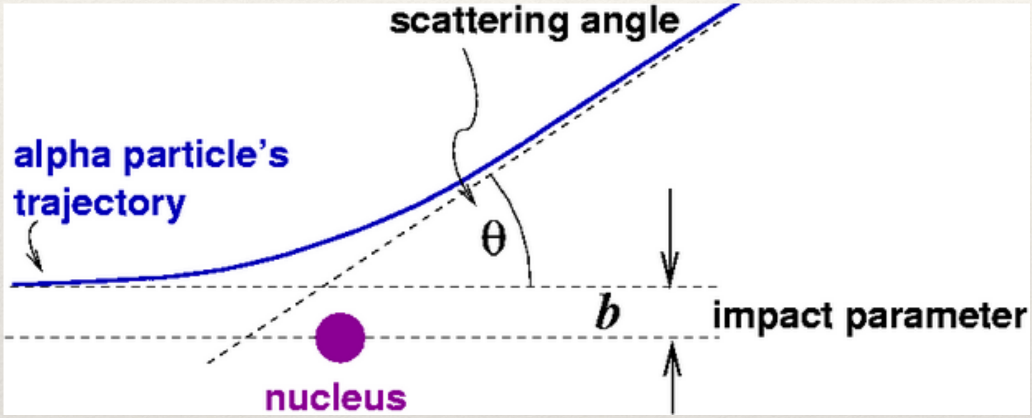
June 2015

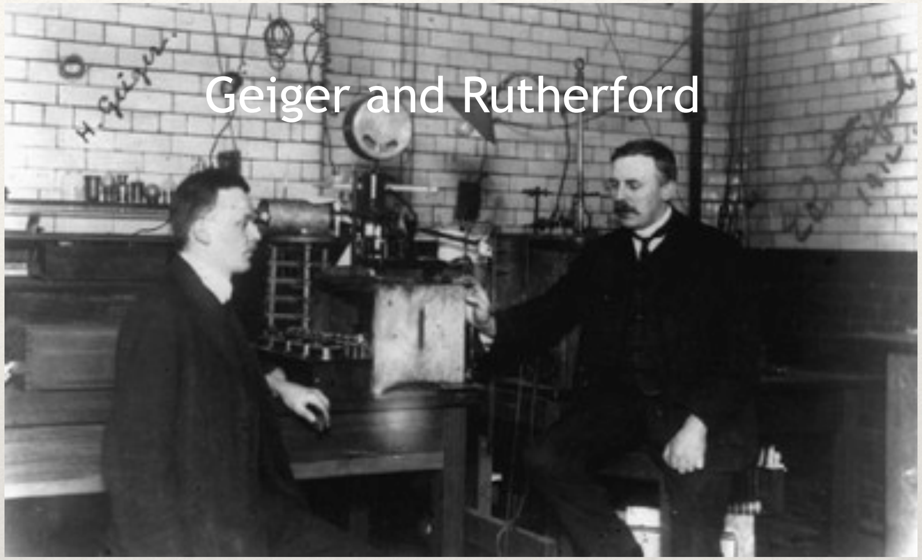
Precise measurements of the proton structure towards the new physics discoveries at the LHC

Voica Radescu
Physikalisches Institut Heidelberg

Early ideas …

Ideas for detecting quarks were formulated since
Rutherford's gold foil experiment 1909
(performed by Geiger and Marsden)

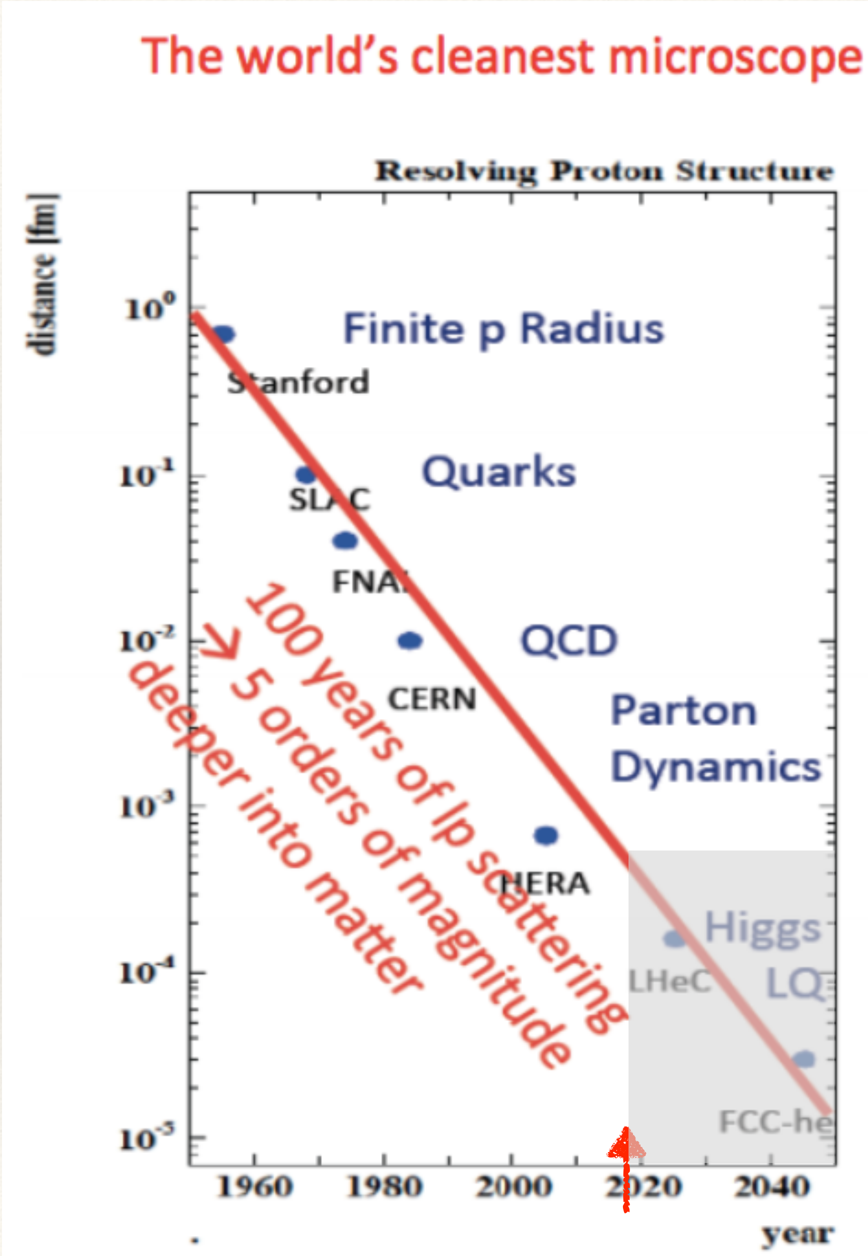


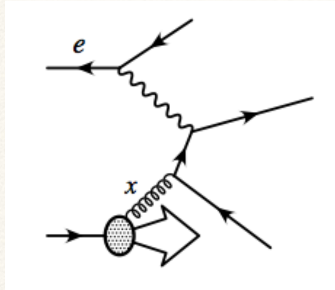


Rutherford's gold foil experiment set the scene for a century of ever-deeper and more precise resolution of the constituents of the atom, the nucleus and the nucleon.

To probe the interiors of target, point-like and easily produced particle needed to be used.

Probing the Proton Structure via DIS

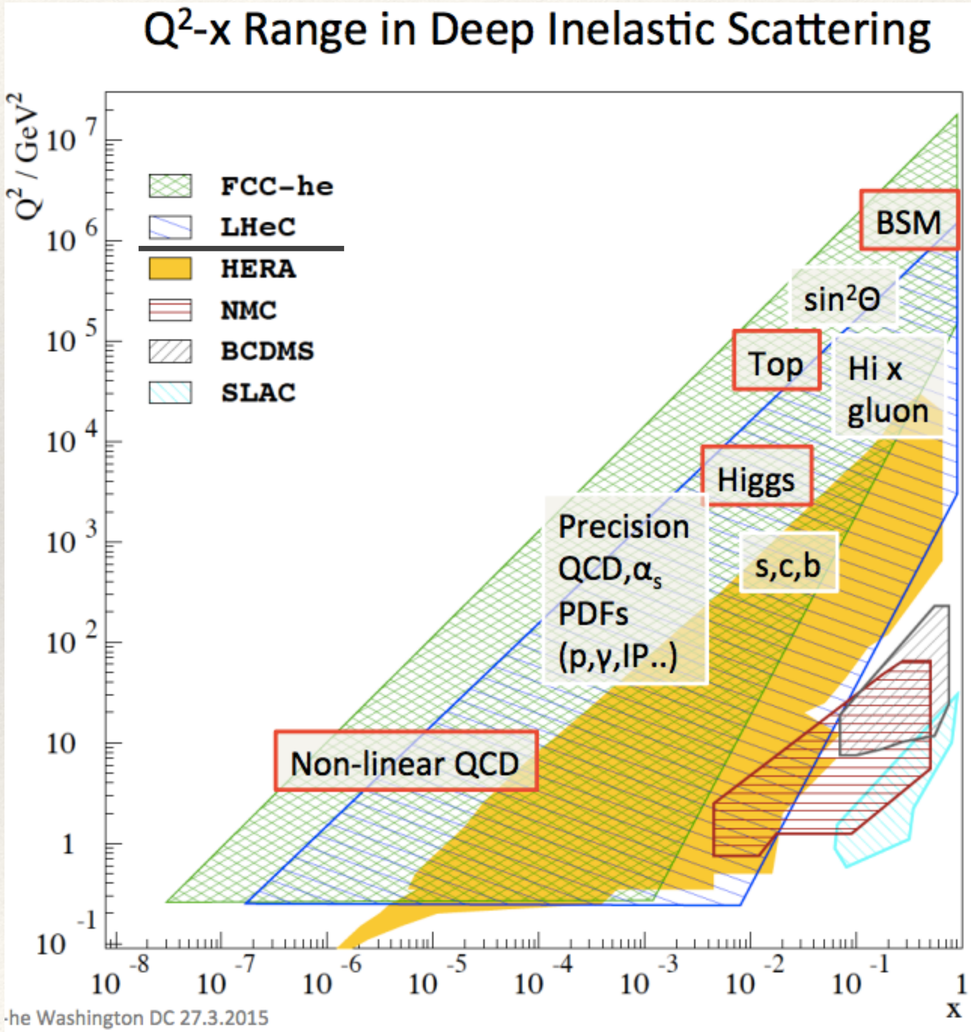




$Q^2 = -q^2 = -(k-k')^2$ Photon virtuality

$x = \dfrac{Q^2}{2\mathrm{p}\cdot q}$ Bjorken variable

$y = \dfrac{p\cdot q}{p\cdot k}$ Inelasticity



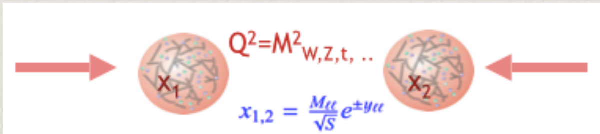
(taken from M. Klein's slides - LHeC workshop 2015)

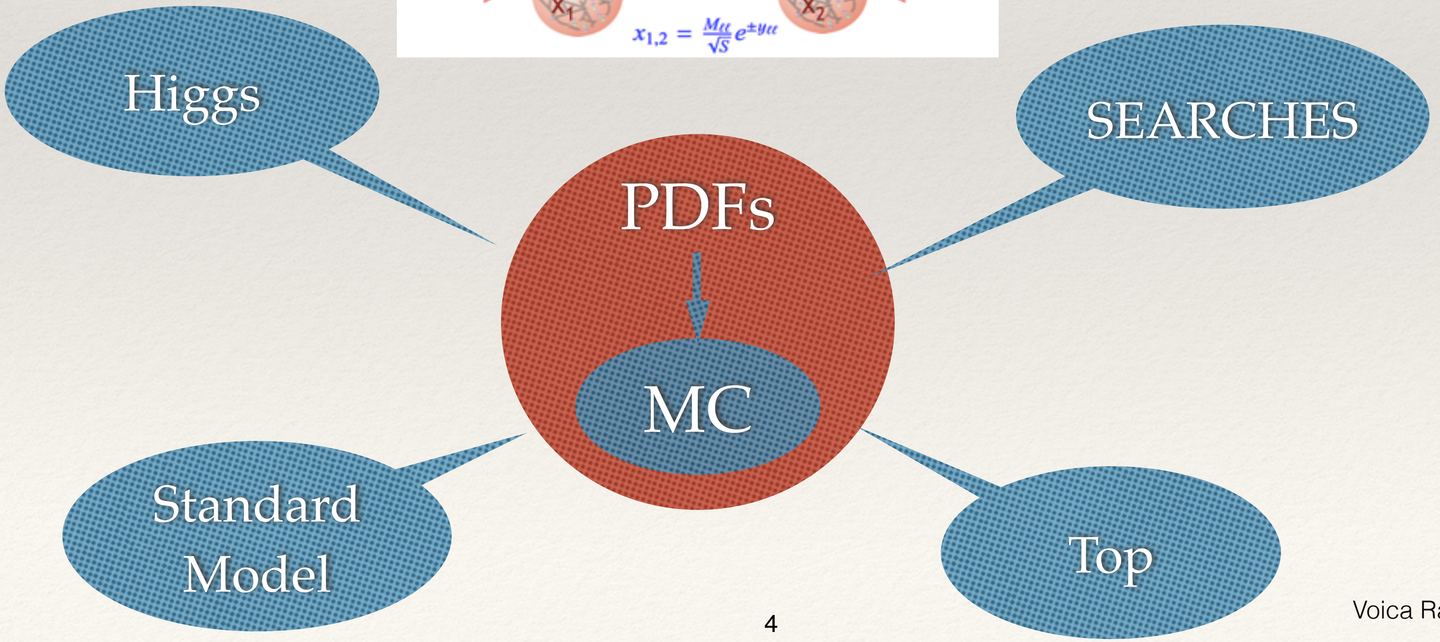
Why do we need precise PDFs?

- Discovery of new exciting physics relies on precise knowledge of proton structure.
  - PDFs are one of the main theory uncertainties in Mw, sinTheta measurements —> stress tests of SM
  - PDFs are one of main theory uncertainties in Higgs production
  - PDF uncertainties very large (>100%) for new heavy particle production
- **Factorisation theorem:**
  - Cross section can be calculated by convoluting short distance partonic reactions (calculable in pQCD) with PDFs:

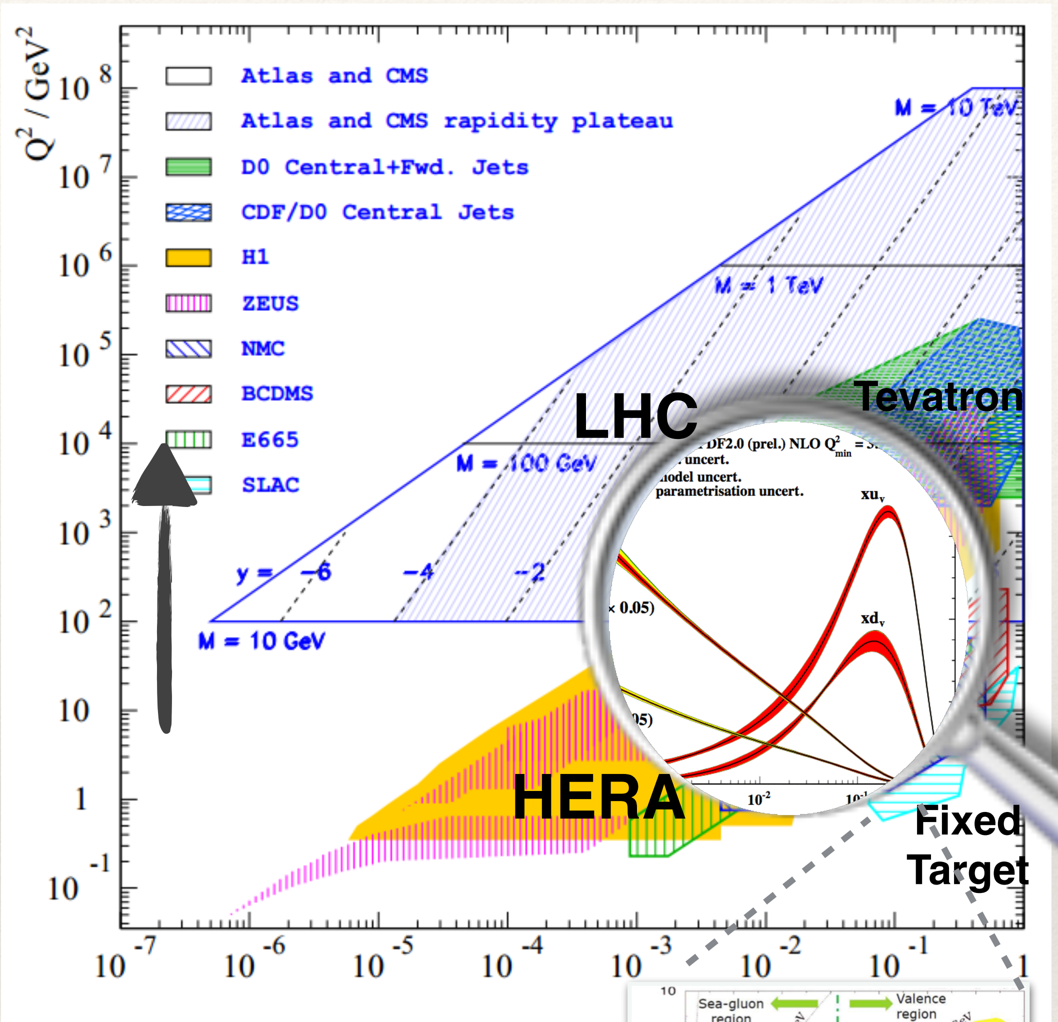
$$\mathrm{d}\sigma(\mathrm{h}_1\mathrm{h}_2 \to cd) = \int_0^1 \mathrm{d}x_1 \mathrm{d}x_2 \sum_{a,b} f_{a/\mathrm{h}_1}(x_1,\mu_F^2) f_{b/\mathrm{h}_2}(x_2,\mu_F^2) \mathrm{d}\hat{\sigma}^{(ab\to cd)}(Q^2,\mu_F^2)$$

  - PDFs cannot be calculated in perturbative QCD, however they are process independent (universal) and their evolution with the scale is predicted by pQCD:





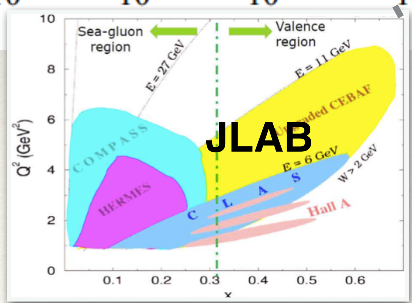
Today's data on proton structure



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

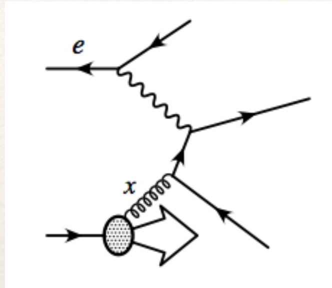
$$x = \frac{Q^2}{2p\cdot q}$$ Bjorken variable

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



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

- Neutrinos, muons, electrons

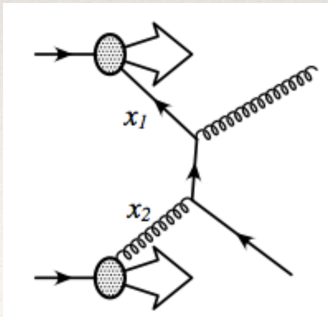


—> probes linear combination of quarks: sea quarks, gluon

HERA provides the basis of any PDFs

Precision of PDFs can be complemented by the Drell Yan [DY] processes at the collider experiments

$$\sigma_{hh\to X} = \boxed{f_{h\to a}} \otimes \hat{\sigma}_{ab\to X} \otimes \boxed{f_{h\to b}}$$

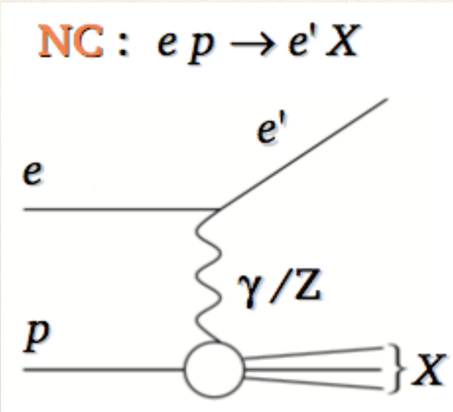


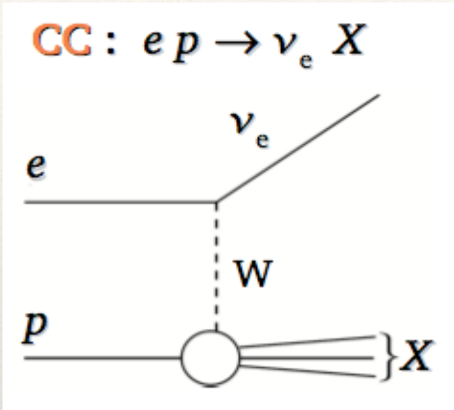
—> can provide flavour separation and more insight into gluons

—> probes bilinear combination of quarks

HERA ep collider (1992-2007) @ DESY

- H1 and ZEUS experiments at HERA collected ~1/fb of data
  - Ep=460/575/820/920 GeV and Ee=27.5 GeV
- 4 type of processes accessed at HERA: **Neutral Current and Charged Current ep**





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

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

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

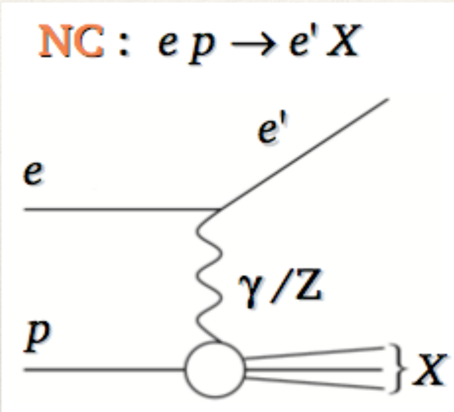
$$\tilde{F}_2 \propto \sum(xq_i + x\bar{q}_i)$$ dominant contribution (all Q2 plane)

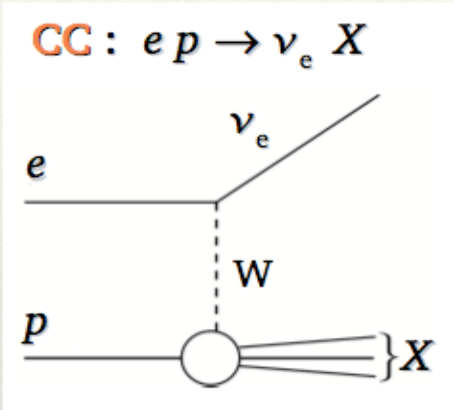
$$x\tilde{F}_3 \propto \sum(xq_i - x\bar{q}_i)$$ significant contributions at high Q2

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

HERA ep collider (1992-2007) @ DESY

- H1 and ZEUS experiments at HERA collected ~1/fb of data
  - Ep=460/575/820/920 GeV and Ee=27.5 GeV
- 4 type of processes accessed at HERA: **Neutral Current and Charged Current ep**

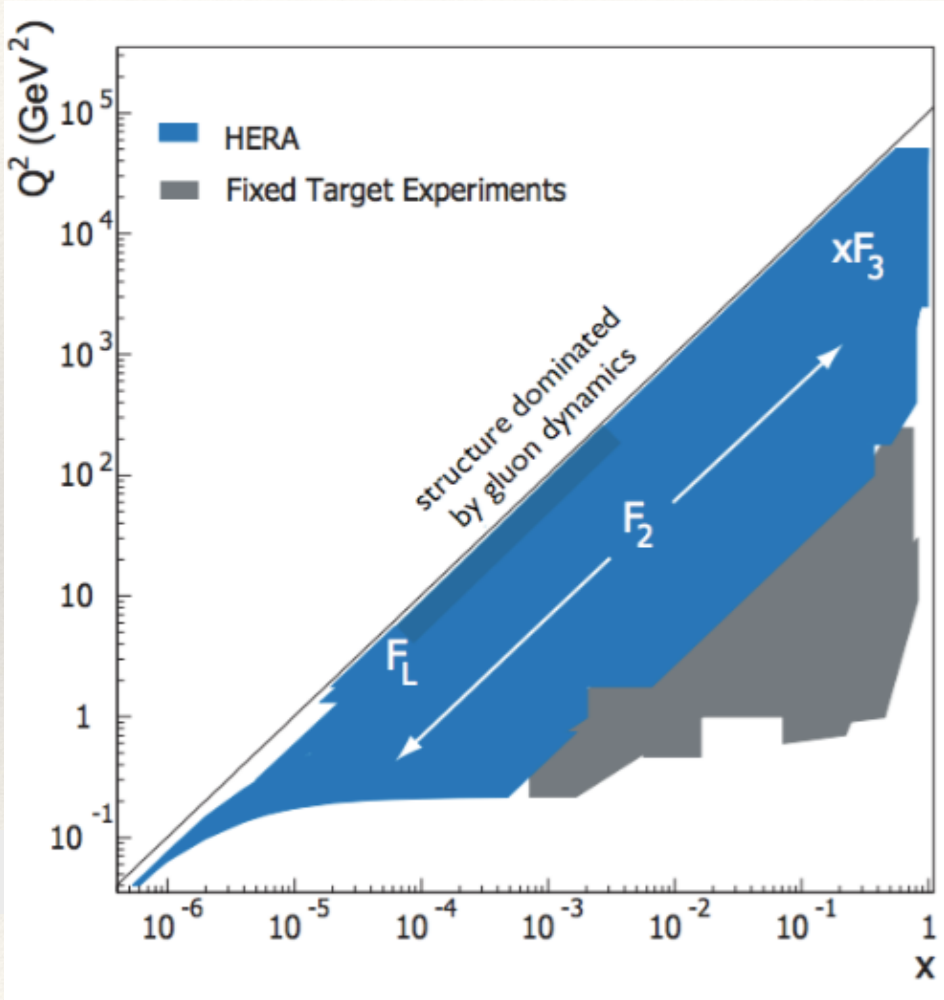




$$\frac{d\sigma^{\pm}_{NC}}{dxdQ^2} = \frac{2\pi\alpha^2}{x}\left[\frac{1}{Q^2}\right]^2\left[Y_+\tilde{F}_2 \mp Y_- x\tilde{F}_3 - y^2\tilde{F}_L\right]$$

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

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



$\tilde{F}_2 \propto \sum(xq_i + x\bar{q}_i)$ → dominant contribution (all Q2 plane)

$x\tilde{F}_3 \propto \sum(xq_i - x\bar{q}_i)$ → significant contributions at high Q2

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

HERA ep collider (1992-2007) @ DESY

Data Set		$x_{\rm Bj}$ Grid from	to	Q^2[GeV^2] Grid from	to	$\mathcal{L}$ pb^{-1}	e^+/e^-	$\sqrt{s}$ GeV
HERA I E_p = 820 GeV and E_p = 920 GeV data sets								
H1 svx-mb [2]	95-00	0.000005	0.02	0.2	12	2.1	e^+p	301, 319
H1 low Q^2 [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 [2] high/low Q^2	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 [1.5p]	03-07	0.0008	0.65	60	30000	182	e^+p	319
H1 CC [1.5p]	03-07	0.008	0.40	300	15000	182	e^+p	319
H1 NC [1.5p]	03-07	0.0008	0.65	60	50000	151.7	e^-p	319
H1 CC [1.5p]	03-07	0.008	0.40	300	30000	151.7	e^-p	319
H1 NC med Q^2 [*y.5]	03-07	0.0000986	0.005	8.5	90	97.6	e^+p	319
H1 NC low Q^2 [*y.5]	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 [1.5p]	06-07	0.0078	0.42	280	30000	132	e^+p	318
ZEUS NC [1.5]	05-06	0.005	0.65	200	30000	169.9	e^-p	318
ZEUS CC [1.5]	04-06	0.015	0.65	280	30000	175	e^-p	318
ZEUS NC nominal [*y]	06-07	0.000092	0.008343	7	110	44.5	e^+p	318
ZEUS NC satellite [*y]	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

- 41 data sets: 2927 data points are combined to1307 averaged measurements with 169 sources of correlated systematic uncertainties.

HERAPDF1.0

JHEP01 (2010) 109

HERAPDF1.5

HERAPDF2.0

[arxiv:1506.06042]

Combination of the H1 and ZEUS Measurements

FINAL HERA I+II inclusive data combination [arxiv:1506.06042]

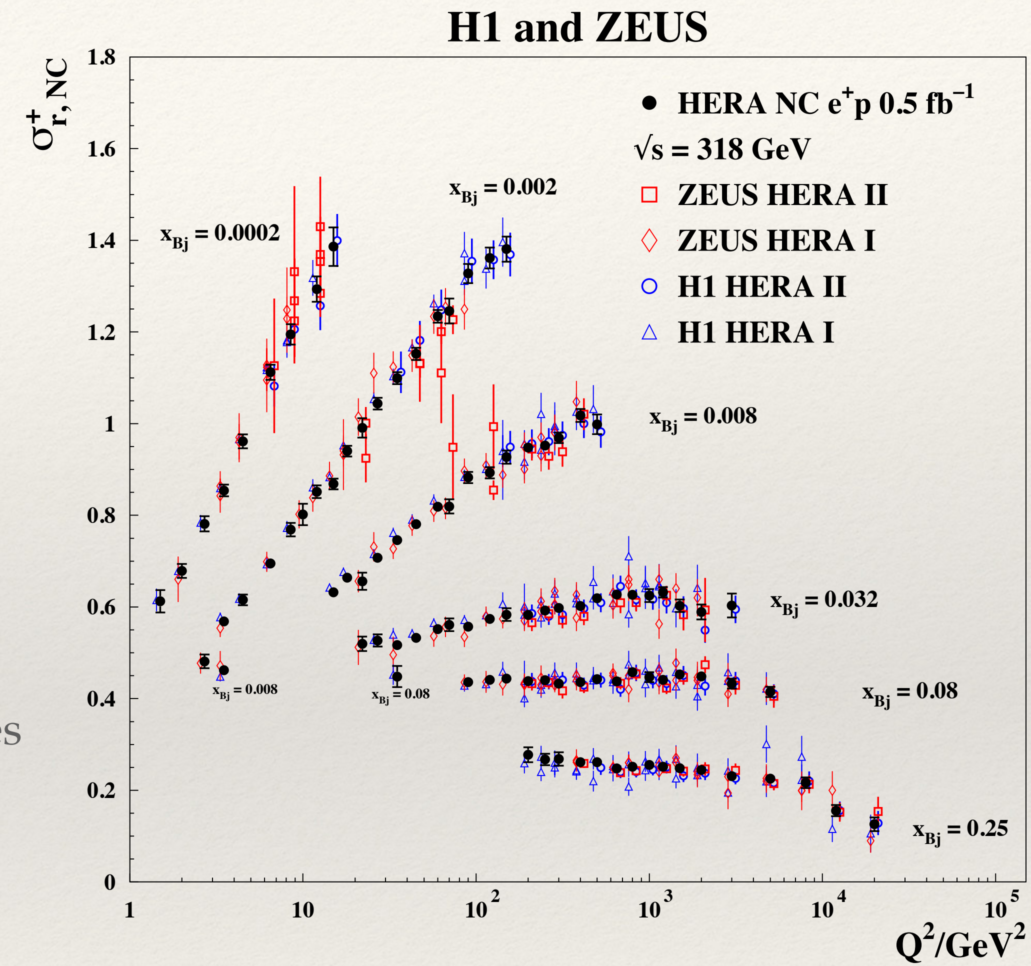
- Ultimate precision is obtained by combining the H1 and ZEUS measurements
- The combination procedure is performed before QCD analysis using χ^2 minimisation
  - χ^2 / dof =1687/1620

➢ Improvement on Statistical precision:

➢ 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.

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



0.045 < Q^2 < 50000 GeV^2 6. 10^{-7} < x_{Bj} < 0.65

$$\sigma^{\pm}_{r,\mathrm{NC}} = \frac{d^2\sigma^{e^\pm p}_{\mathrm{NC}}}{dx_{\mathrm{Bj}}dQ^2}\cdot\frac{Q^4 x_{\mathrm{Bj}}}{2\pi\alpha^2 Y_+} = \tilde{F}_2 \mp \frac{Y_-}{Y_+}x\tilde{F}_3 - \frac{y^2}{Y_+}\tilde{F}_{\mathrm{L}}$$

Combination of data is now actively used at LHC for ex W, Z for muon and electron channels

Extraction of PDFs through QCD fits

- Extraction of PDFs relies on the factorisation: $\sigma = \hat{\sigma} \otimes \text{PDF}$

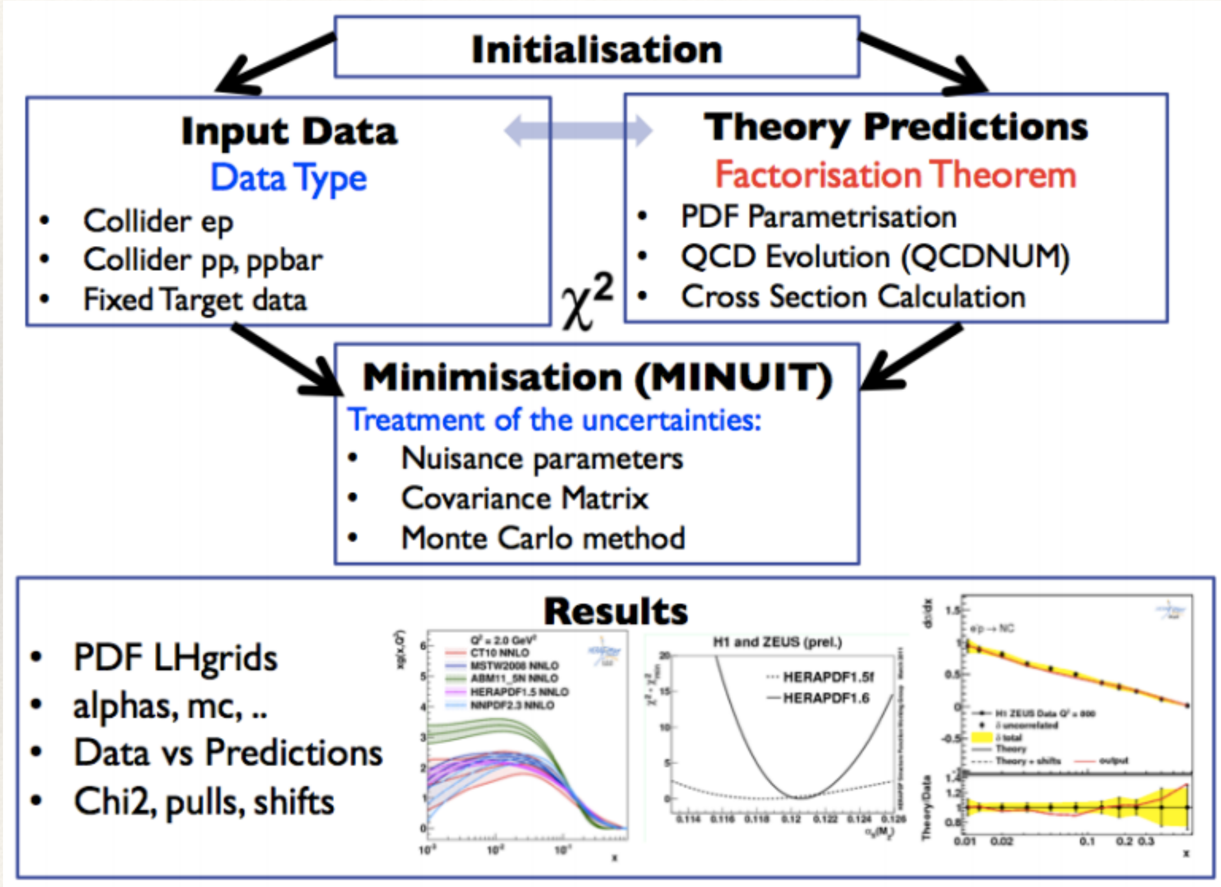
- Typical measurements sensitive to PDFs are precise, with statistical uncertainties < 10%, so they follow normal distribution —> use of χ^2 minimisation for PDF extraction.

Main Steps:

- Parametrise PDFs at a starting scale
- Evolve PDFs to the scale corresponding to data point
- Calculate the cross section
- Compare with data via χ^2
- Minimise χ^2 with respect to PDF parameters which takes about ~2000 iterations:

  —> it is crucial to have fast tools:

(i.e. fastNLO, APPLGRID)



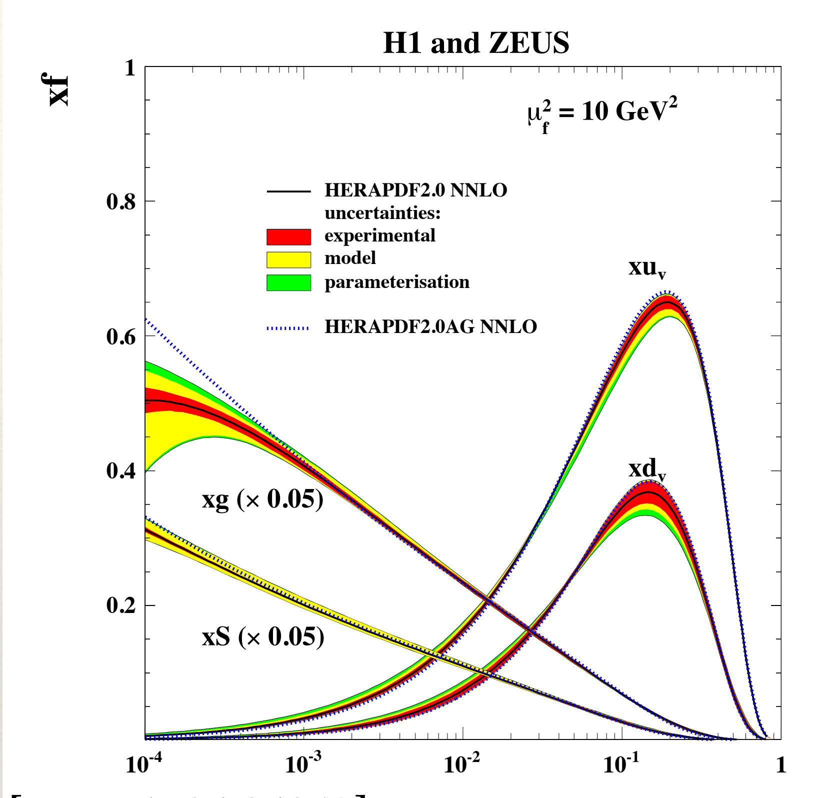
herafitter.org: open source QCD platform arxive:1503.05221

Modern understanding of PDFs

Different types of PDF uncertainties are considered:

- **Experimental:**
  - Hessian method used: MMHT, CT, …
    - Consistent data sets → use $\Delta\chi^2$=1
  - Monte Carlo Method: replicas of data(NNPDF)
- **Model:**
  - variations of all assumed input parameters in the fit

Variation	Standard Value	Lower Limit	Upper Limit
Q^2_{min} [GeV^2]	3.5	2.5	5.0
Q^2_{min} [GeV^2] HiQ2	10.0	7.5	12.5
M_c(NLO) [GeV]	1.47	1.41	1.53
M_c (NNLO) [GeV]	1.43	1.37	1.49
M_b [GeV]	4.5	4.25	4.75
f_s	0.4	0.3	0.5
$\alpha_s(M_Z^2)$	0.118	–	–
μ_{f_0} [GeV]	1.9	1.6	2.2

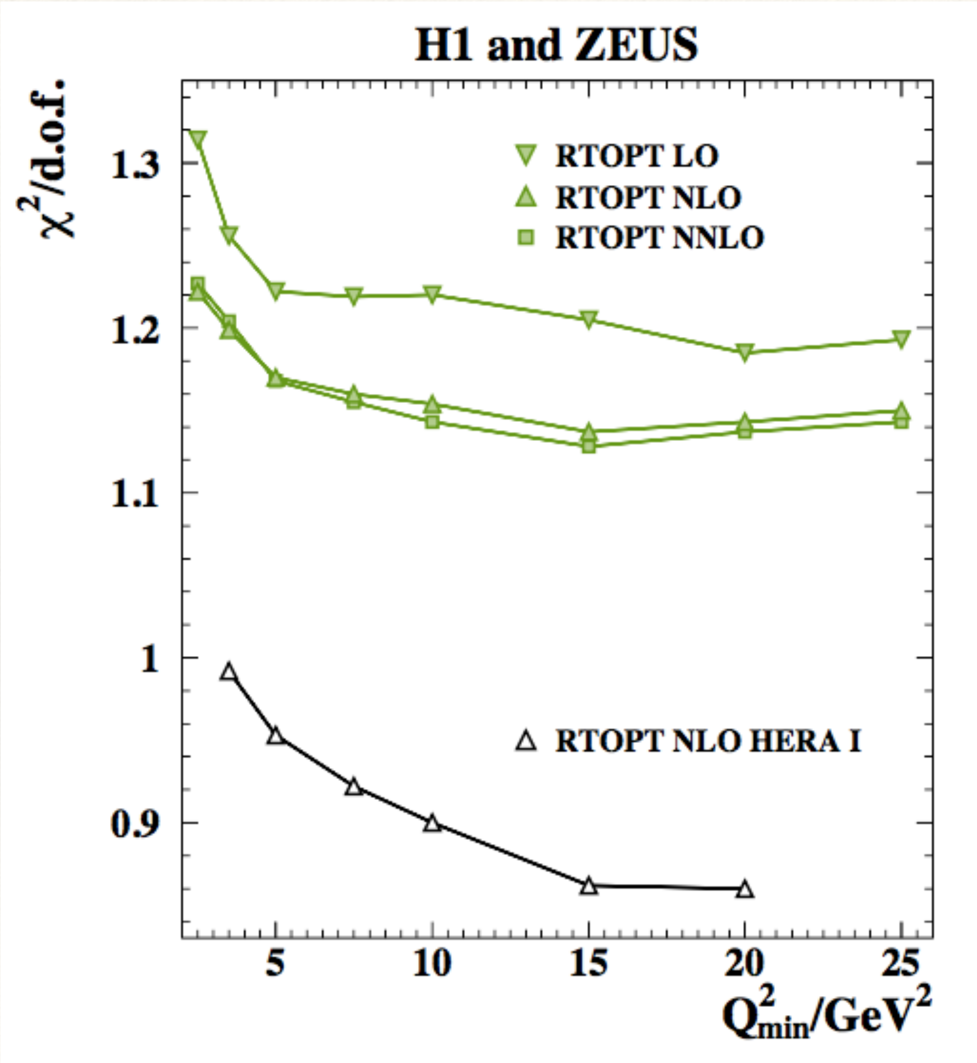


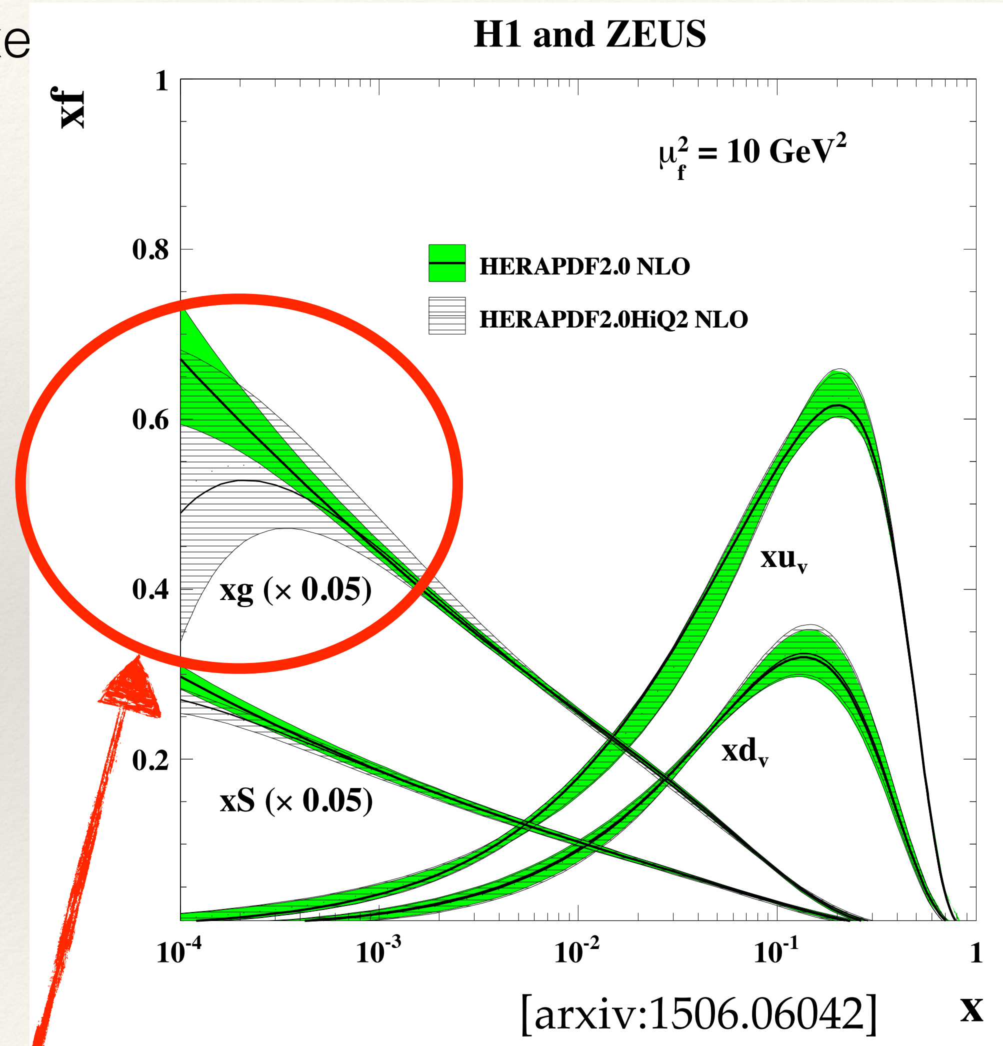
[arxiv:1506.06042]

- **Parametrisation:** only HERAPDF includes this as an additional uncertainty
  - NNPDFs use neural network approach based on data driven regularisation

Q2 cut dependence on PDFs

- HERA data provides a unique access to the low x, low Q2 region to investigate:
  - the validity of the DGLAP mechanism

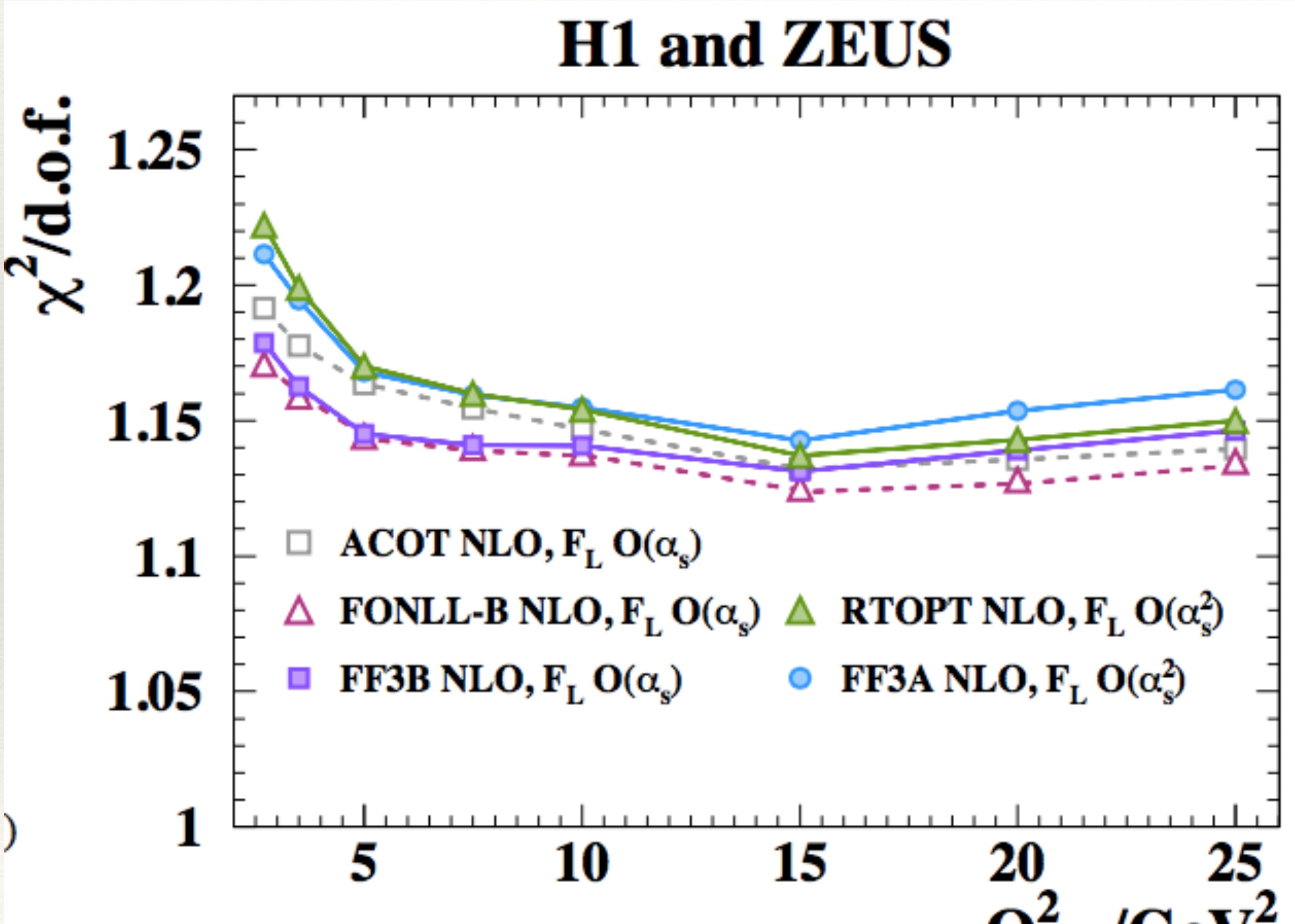




low Q2 data very important to constrain low x PDFs!`

Q2 cut dependence

- HERA data provides a unique access to the low x, low Q2 region to investigate:
  - the validity of the DGLAP mechanism
  - the various scheme dependence (fixed vs variable flavours)



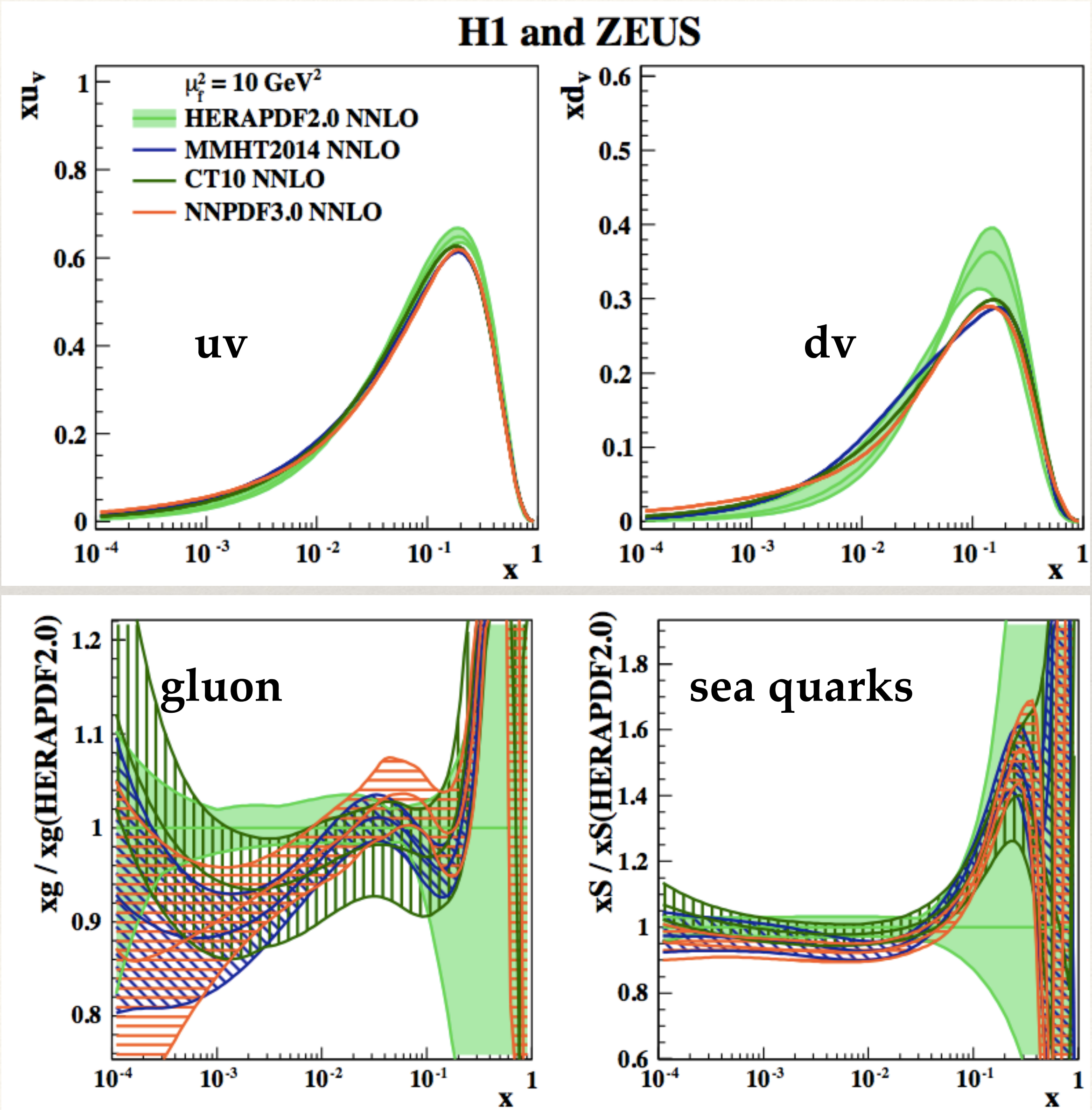
[arxiv:1506.06042]

ACOT as used by CT PDF sets
RT as used by MMHT
FONLL as used by NNPDF
FF3 as used by ABM

Low Q2 remains an interesting region to investigate (low x phenomenology)

HERAPDF2.0 vs other PDF sets

- HERAPDF sets are extracted solely from ep data and require no assumptions or corrections, hence provide an important cross check of PDF universality (process independence):



high x valence different:
new high- x data and use of proton target only

At NNLO gluon and Sea are both compatible with other PDFs

[arxiv:1506.06042]

PDF sets in use at the LHC

- Data: targeted measurements, detailed information of sources of systematic uncertainties, recently LHC data is being now included in the Global PDF sets
- Theory: state of the art methods, advancement in computational powers that allowed for higher order calculations to be available

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

Global proton PDF groups used at the LHC

- different treatment of heavy quarks
- inclusion of various data sets
- account for possible tensions
- different fit methodologies

- **List of latest PDF sets:**
  - NNPDF3.0
  - MMHT2014
  - CT14

    —> similar theory formalism
  - HERAPDF2.0 —> uses only HERA data
  - ABM12 —> based on Fixed Flavour scheme and free alphas
  - CJ12 —> addresses high x phenomenology (NLO)

Also ATLAS and CMS provide PDFs sets
to demonstrate the impact of new measurements

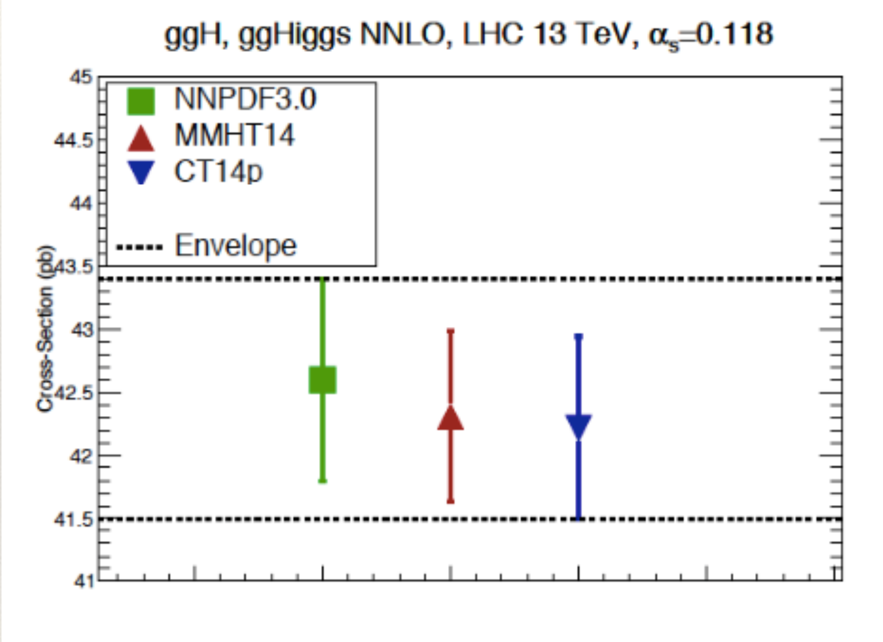
PDF sets in use at the LHC

- Data: targeted measurements, detailed information of sources of systematic uncertainties, recently LHC data is being now included in the Global PDF sets
- Theory: state of the art methods, advancement in computational powers that allowed for higher order calculations to be available

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

Global proton PDF groups used at the LHC

- different treatment of heavy quarks
- inclusion of various data sets
- account for possible tensions
- different fit methodologies



http://benasque.org

- **List of latest PDF sets:**
  - NNPDF3.0
  - MMHT2014
  - CT14

  —> similar theory formalism

  - HERAPDF2.0 —> uses only HERA data
  - ABM12 —> based on Fixed Flavour scheme and free alphas
  - CJ12 —> addresses high x phenomenology (NLO)

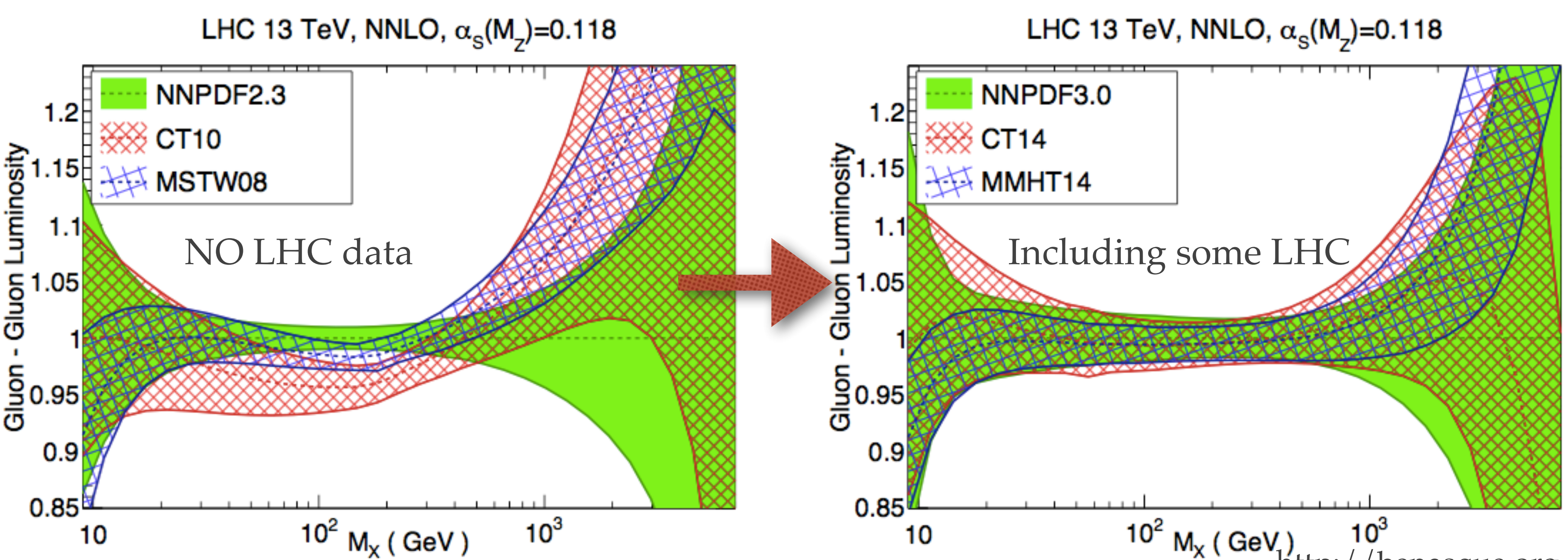
Also ATLAS and CMS provide PDFs sets
to demonstrate the impact of new measurements

PDF sets in use at the LHC

- Data: targeted measurements, detailed information of sources of systematic uncertainties, recently LHC data is being now included in the Global PDF sets
- Theory: state of the art methods, advancement in computational powers that allowed for higher order calculations to be available

Global proton PDF groups used at the LHC

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



http://benasque.org

The difference reduced, however still very large uncertainties at high Masses

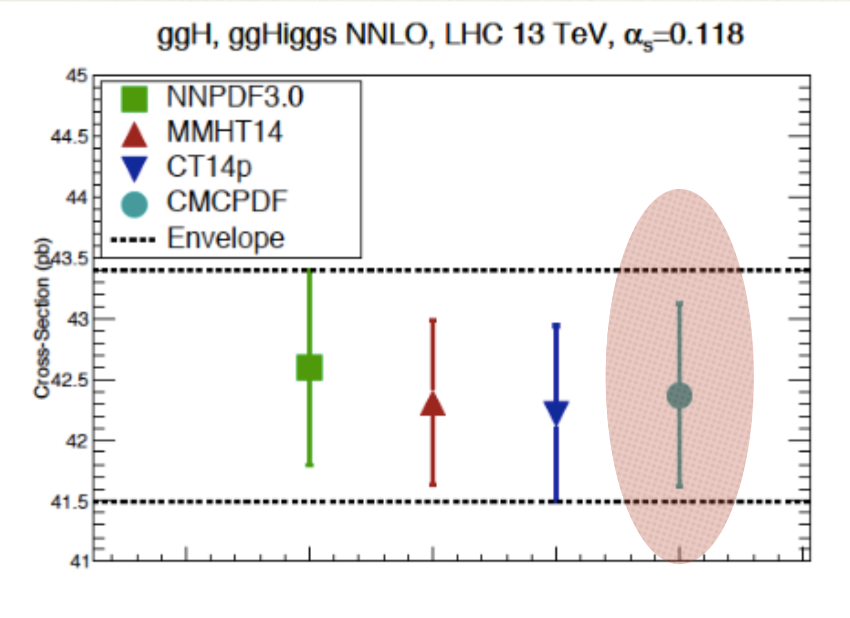
Combined (averaged) PDFs

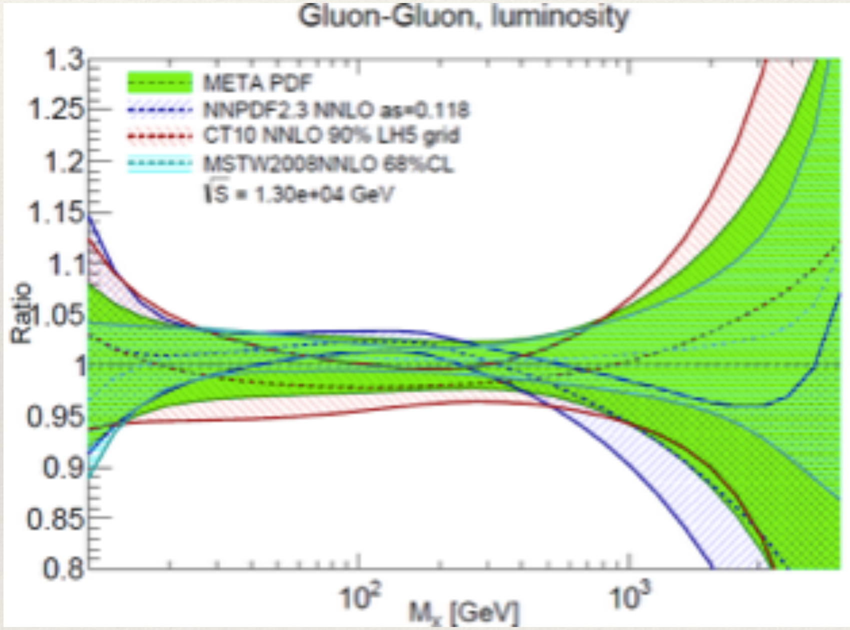
http://benasque.org/2015lhc/cgi-bin/talks/allprint.pl

To simplify the life of analysers, instead of building an envelope of 3-5 PDF sets with their uncertainties, a proposal is to provide already an averaged PDFs set to account for differences in PDFs and their uncertainties (especially for searches and Higgs physics)

-> METAPDF set: based on the meta data from various PDF fitting groups

-> CMC set: compressed PDFs using MC replicas





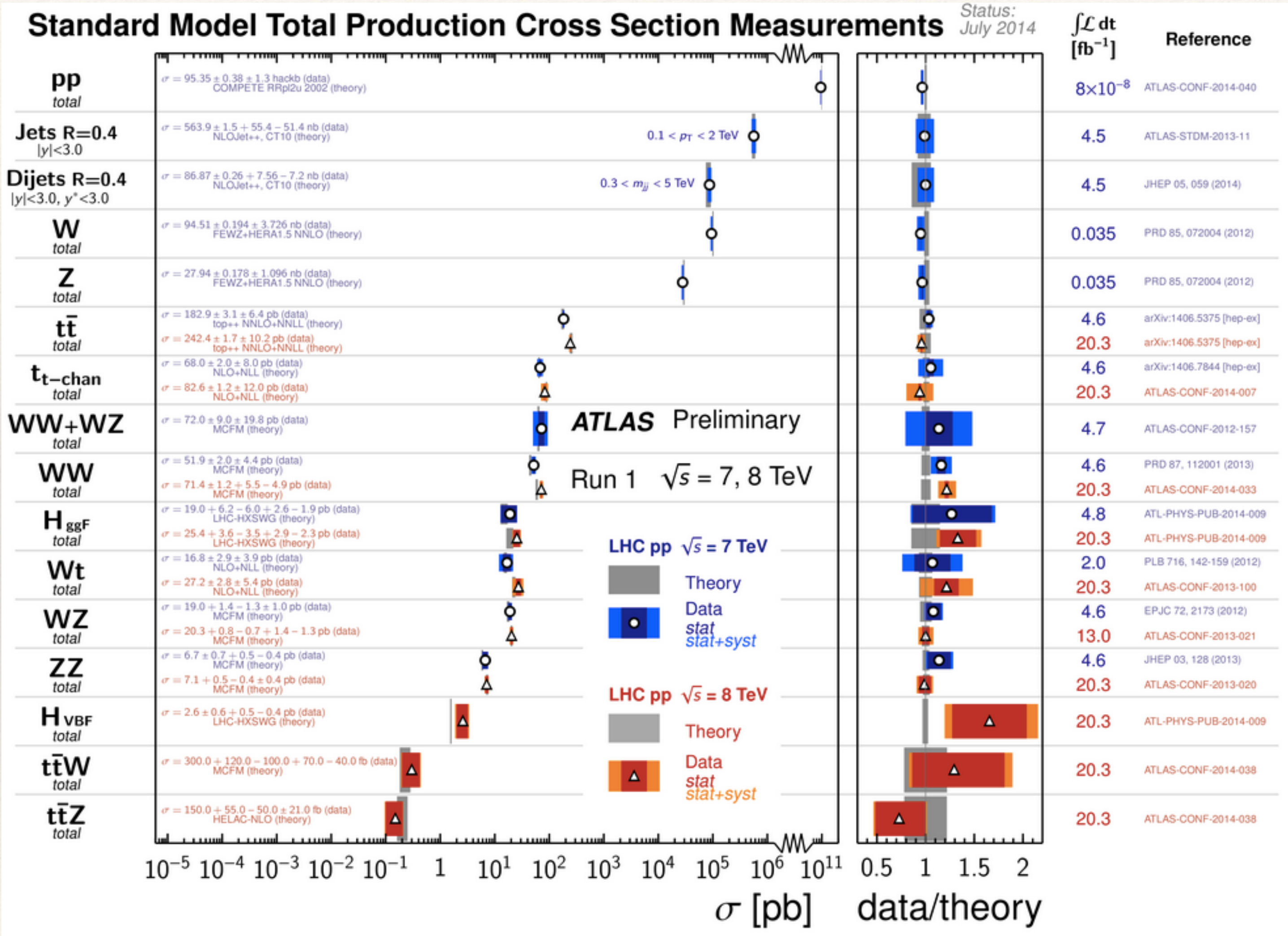
S. Carazza et al: arXiv:1505.06736

P. Nadolski, J. Gao

For any analysis where PDF systematics are important, one should not use combined sets, but use individual sets: to understand what drives PDF uncertainties, and to learn how to reduce them!

The LHC measurements from Run1

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

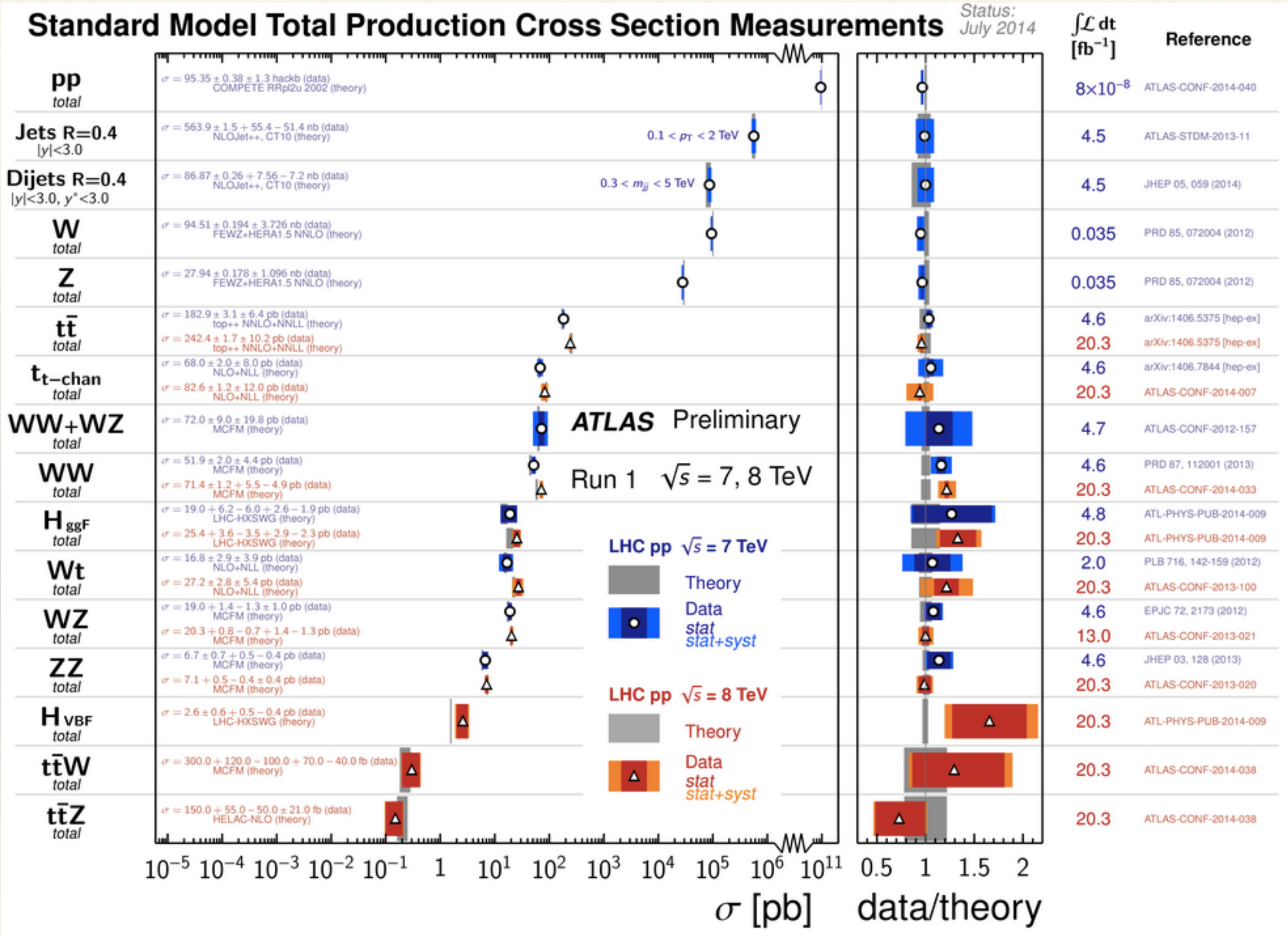


- 0.05 / fb (7 TeV, 2010)
- 4.6 / fb (7 TeV, 2011)
- 20.3 / fb (8 TeV, 2012)

- Remarkable agreement with SM predictions

The LHC measurements from Run1

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



– 0.05 / fb (7 TeV, 2010)
– 4.6 / fb (7 TeV, 2011)
– 20.3 / fb (8 TeV, 2012)

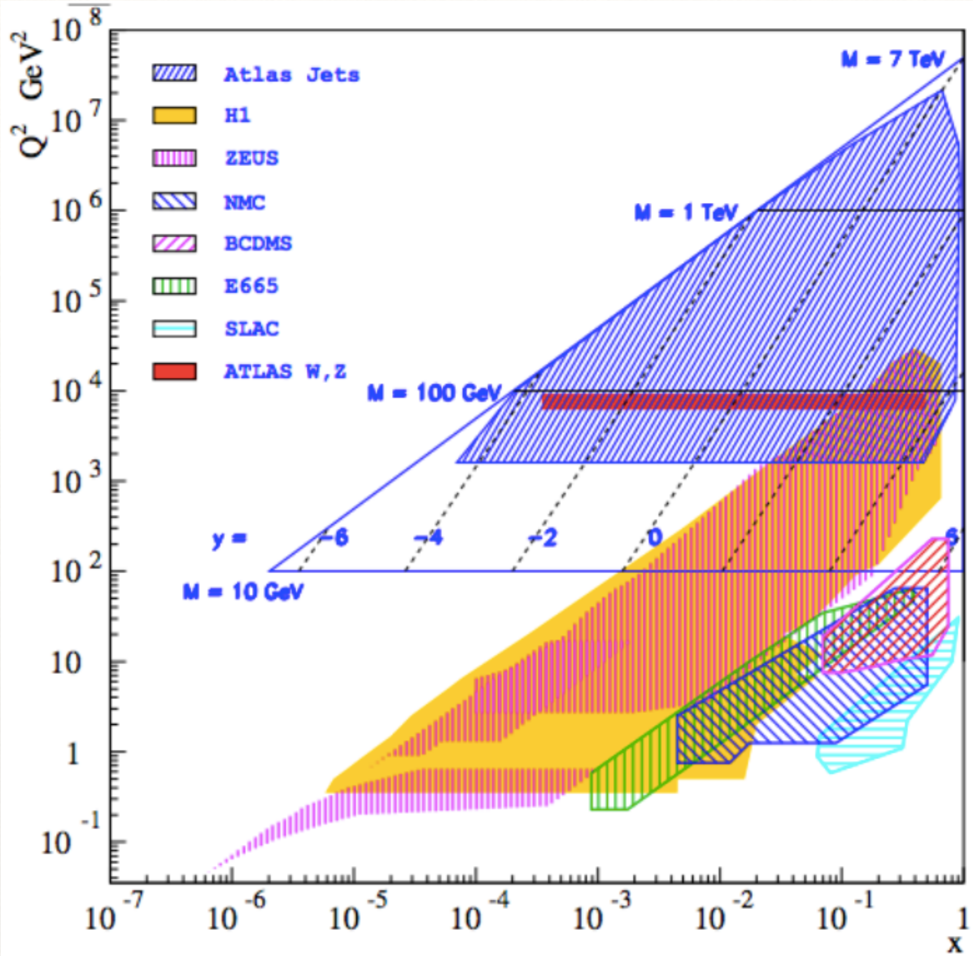
- **PDF discrimination** by confronting theory with data
- **PDF improvement** by using LHC data

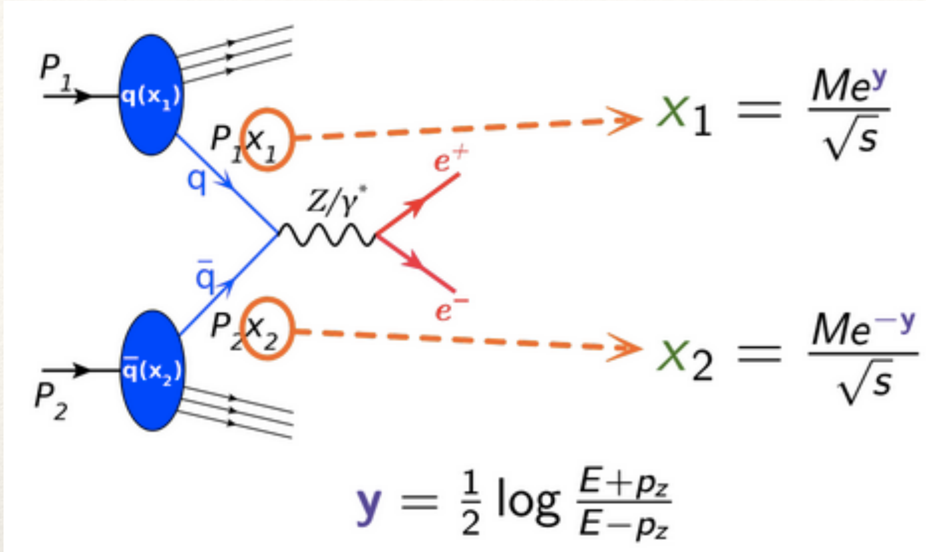
- Remarkable agreement with SM predictions

Much of theory error is from PDFs —> it is crucial to improve our knowledge on PDFs

ATLAS

The LHC measurements from Run1 for PDFs



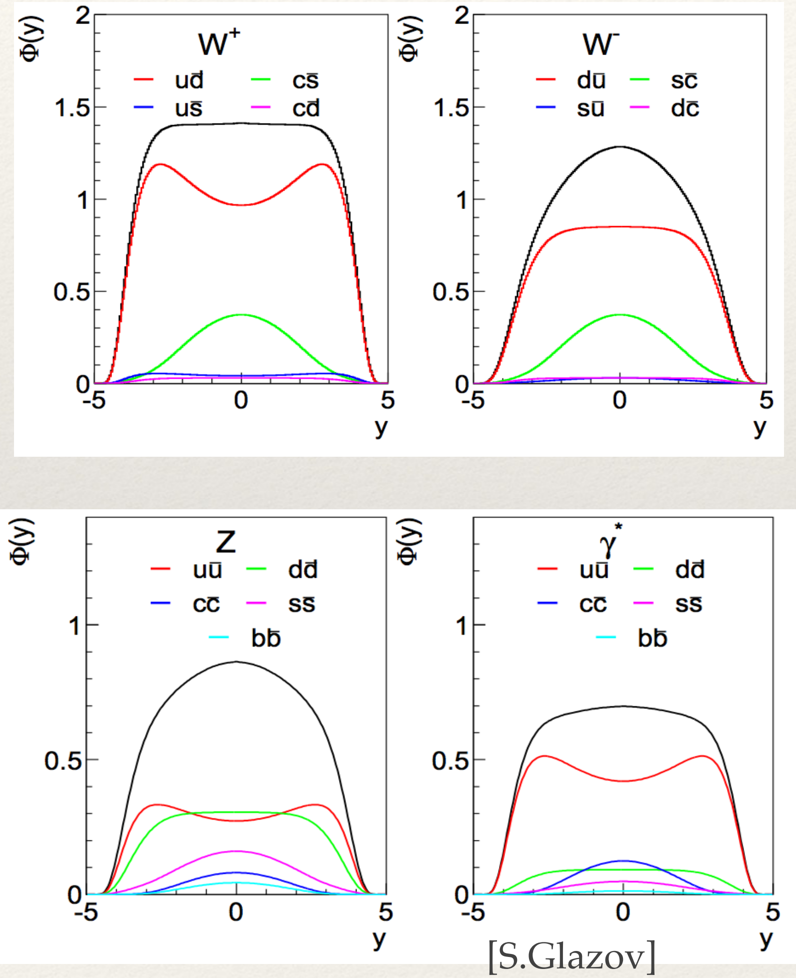


- Low and high x are linked together at the LHC

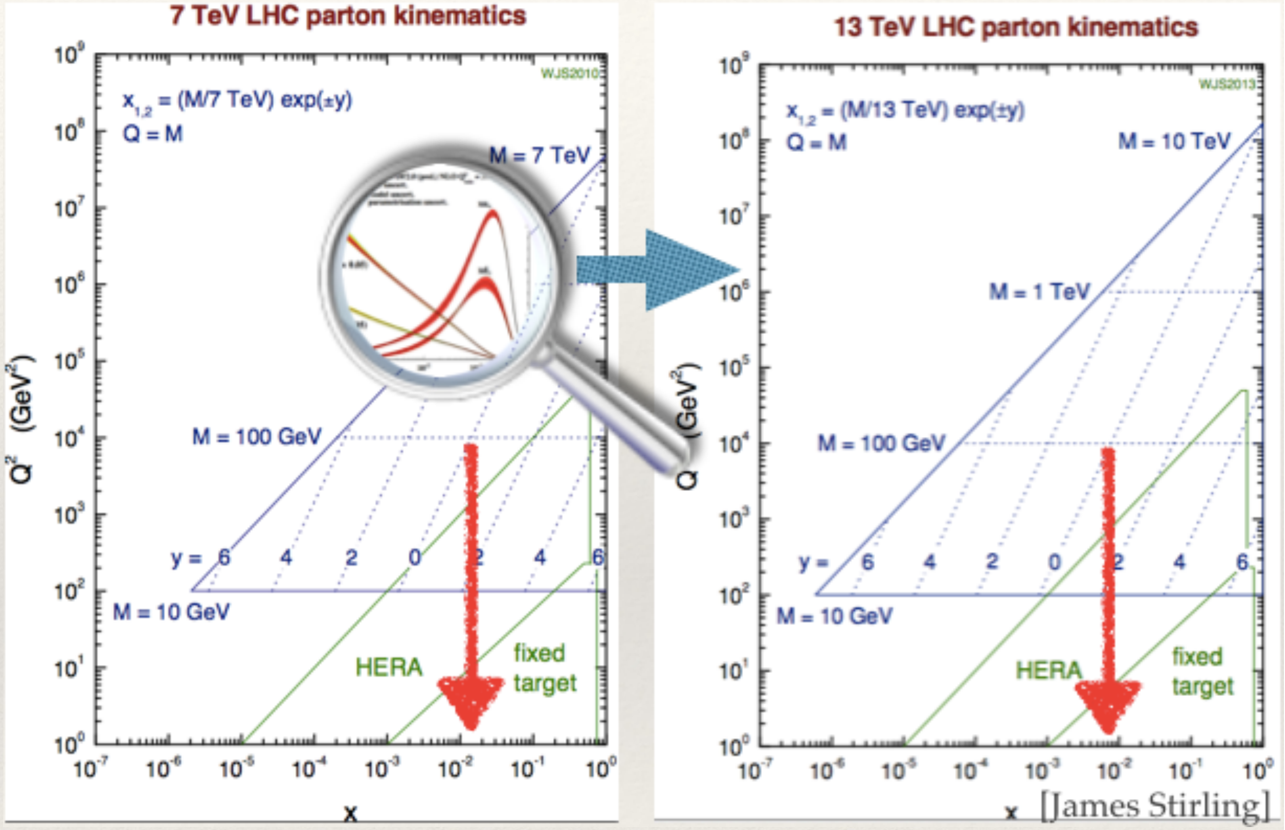
1. W and Z production —> valence, light sea quarks
2. W+c production —> strange
3. Drell-Yan: low and high invariant mass —> sea quarks at high-x, test evolution formalism at low x
4. Inclusive Jet, Di-Jet and Tri-jet production —> gluon and alphas
5. Prompt Photon + Jets —> gluon
6. Top, ttbar —> gluon and alphas
7. W,Z +jets or ZpT —> gluon

Flavour decomposition at LHC (EW bosons)

- Inclusive cross sections of W and Z are well understood theoretically at NNLO
    - exploit different PDF flavour sensitivity:



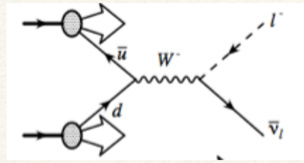
[S.Glazov]

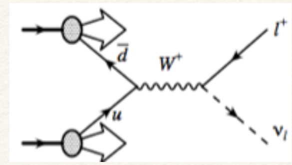


[James Stirling]

- At the LHC, we can access PDFs at 7, 8, and now 13 TeV
    - access to a different kinematic region in x which provides different PDF sensitivit

W charge asymmetry

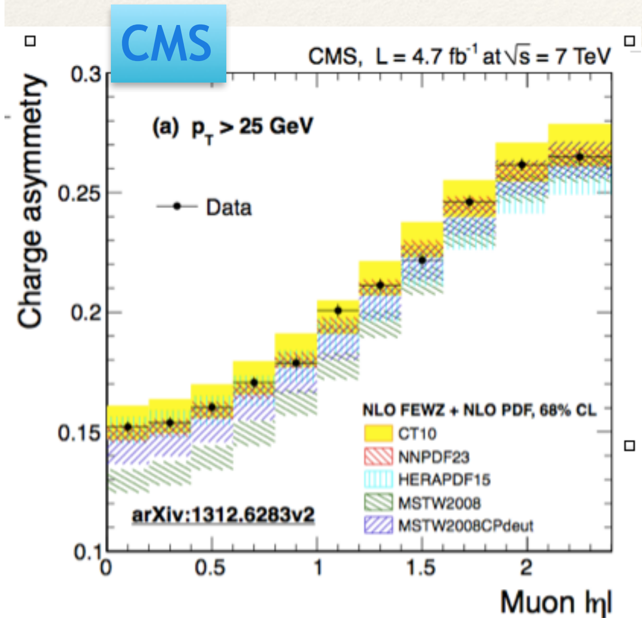




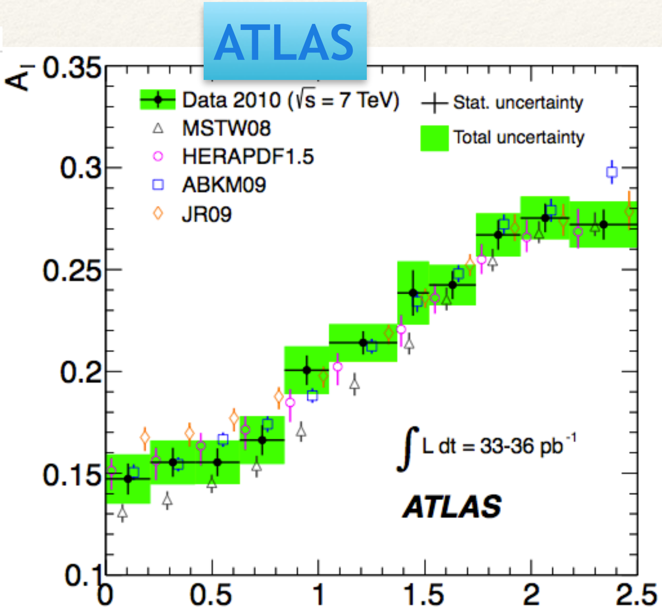
- The interplay between the flavour asymmetries can be enhanced via ratio measurements:
  - W-asymmetry measurement
    - sensitive to uv, dv

$$A_W^l = \frac{d\sigma_{W^+}/d\eta_{l^+} - d\sigma_{W^-}/d\eta_{l^-}}{d\sigma_{W^+}/d\eta_{l^+} + d\sigma_{W^-}/d\eta_{l^-}}$$

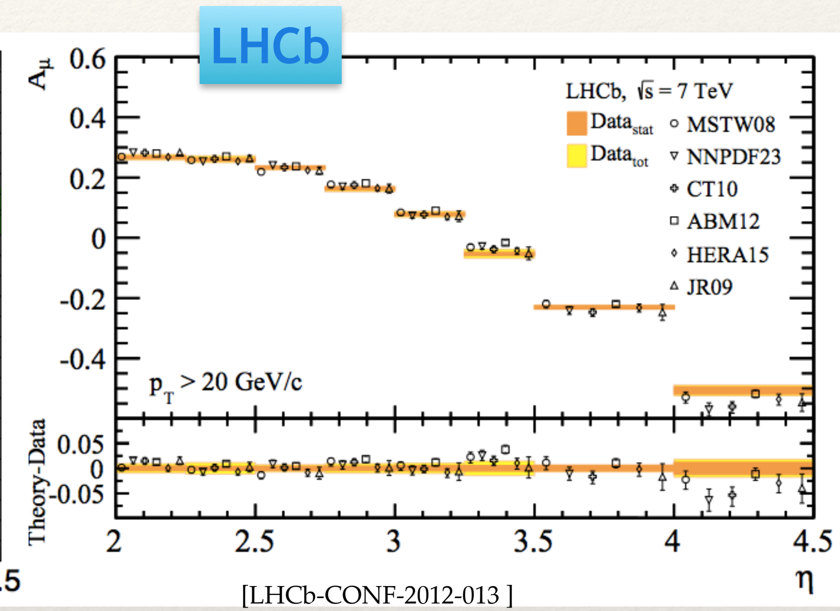
$$A_W \approx \frac{u_v - d_v}{u + d}$$



PRD 90 (2014) 034004



Phys Rev D 85 (2012) 072004

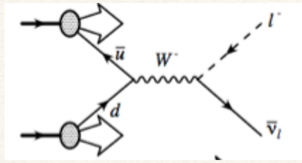


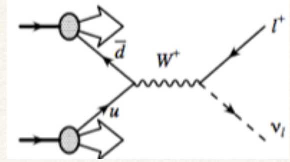
[LHCb-CONF-2012-013]

- 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

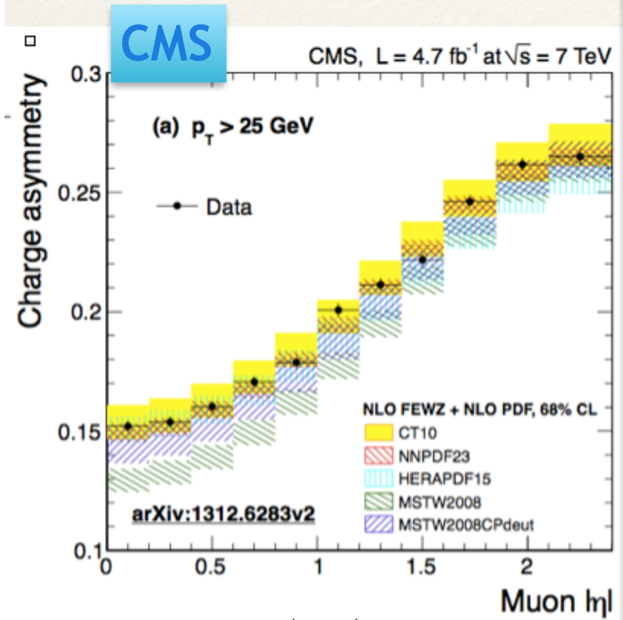




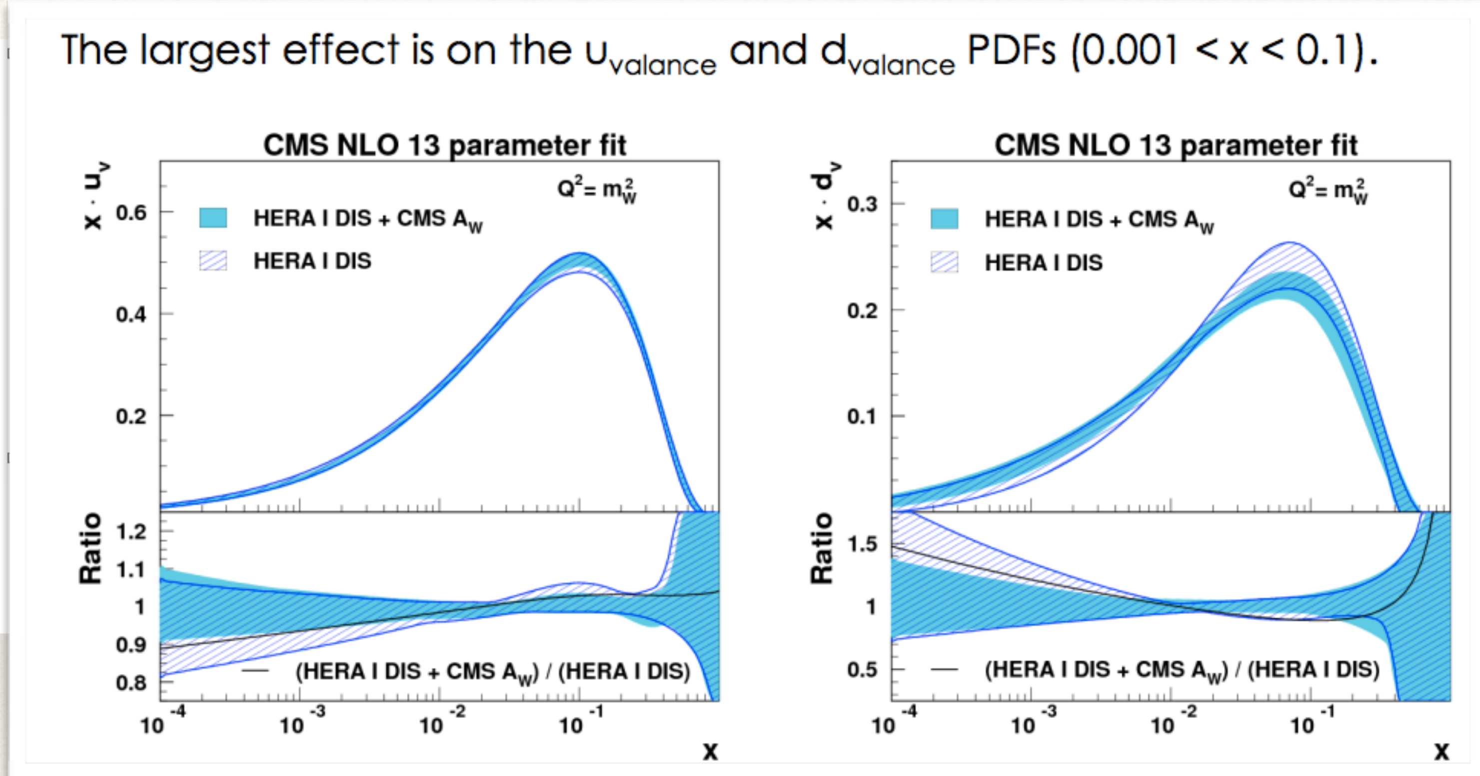
- The interplay between the flavour asymmetries can be enhanced via ratio measurements:
  - W-asymmetry measurement
    - sensitive to uv, dv

$$\mathcal{A}^l_W = \frac{d\sigma_{W^+}/d\eta_{l^+} - d\sigma_{W^-}/d\eta_{l^-}}{d\sigma_{W^+}/d\eta_{l^+} + d\sigma_{W^-}/d\eta_{l^-}}$$

$$\mathcal{A}_W \approx \frac{u_v - d_v}{u + d}$$



PRD 90 (2014) 034004

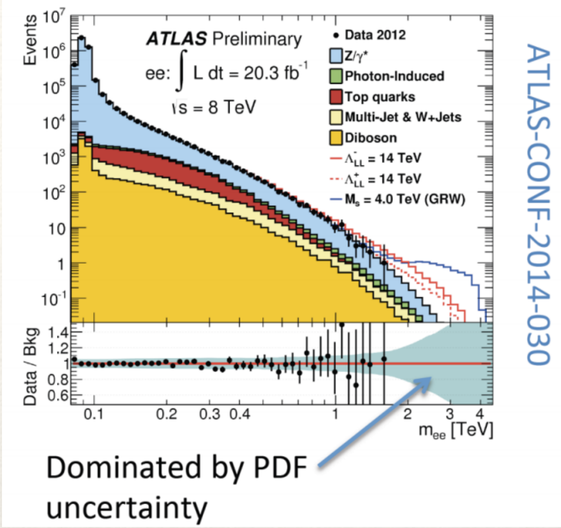


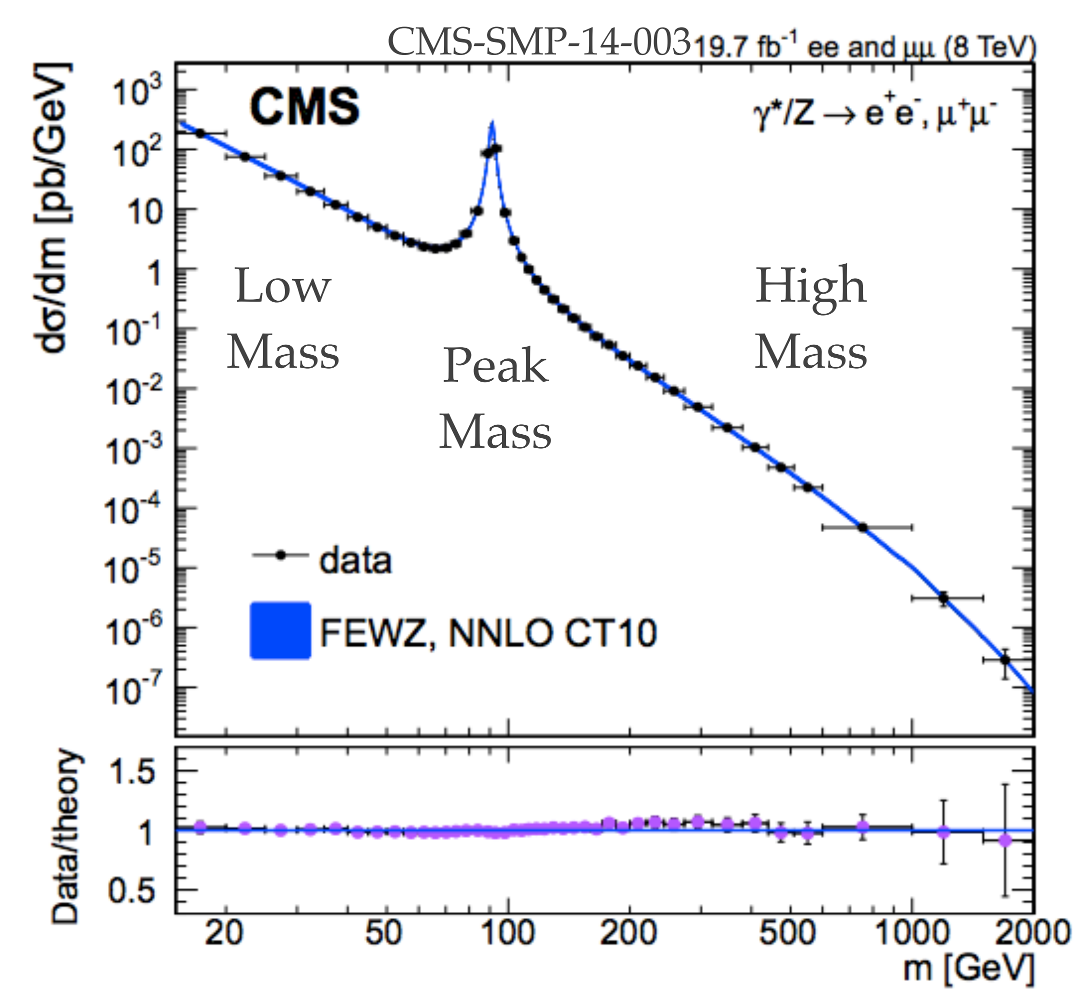
(JHEP 1001 -109)

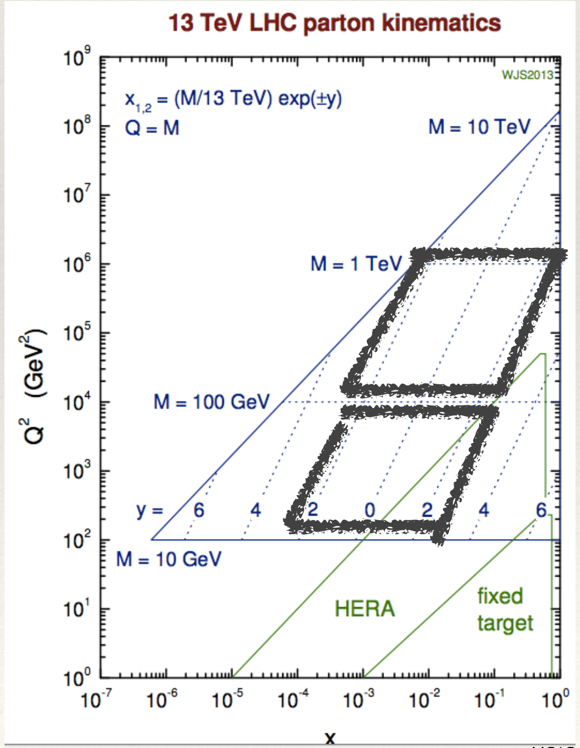
- A PDF fit of these CMS muon asymmetry data together with the combined HERA-I inclusive deep inelastic scattering (DIS) data shows the potential of the LHC data to constrain valence quarks

Neutral Current Drell Yan di-lepton measurements

- Drell Yan Mass Spectra data are sensitive to new physics at high-scale and can give information on sea quark PDFs.
  - High Mass: sensitive to sea quarks at high x
  - Low Mass: sensitive to low x region (test of DGLAP?)



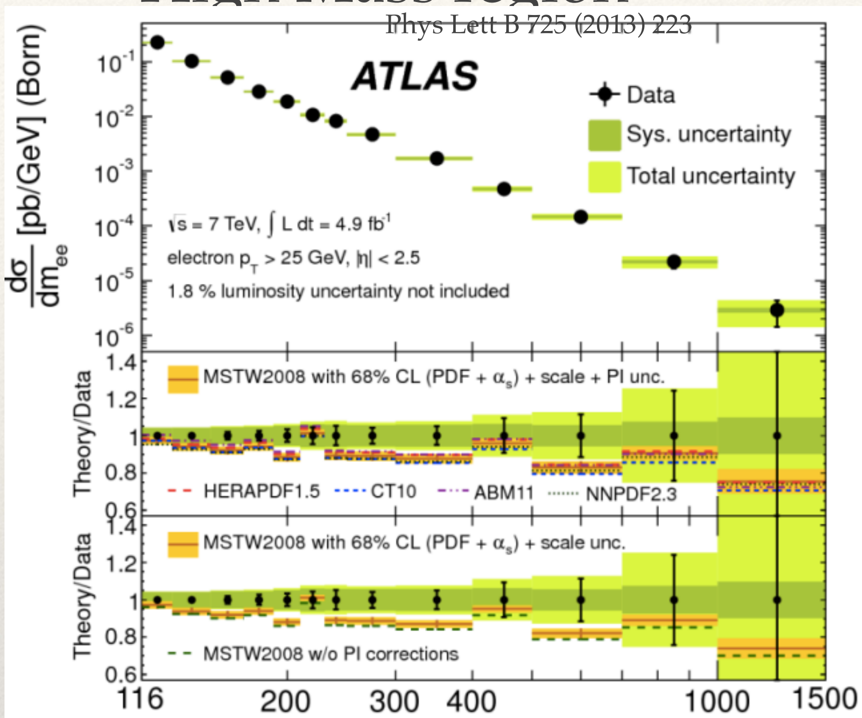




Z Differential Cross Section (off resonance region)

- High Mass region

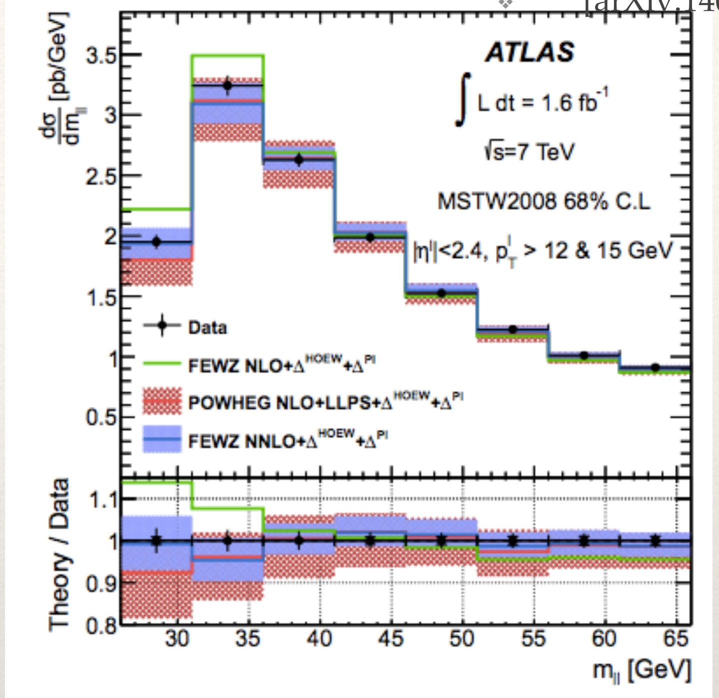
Phys Lett B 725 (2013) 223



ATLAS: $116<M_{ee}<1500$

Low Mass Region

[arXiv:1404.1212]



ATLAS: $20<M_{ll}<65$

Data is confronted with NNLO predictions corrected for NLO EW effects

- Currently predictions based on various PDFs give a good description
- for HM DY: the photon induced piece brings up to 4% effect at high mll

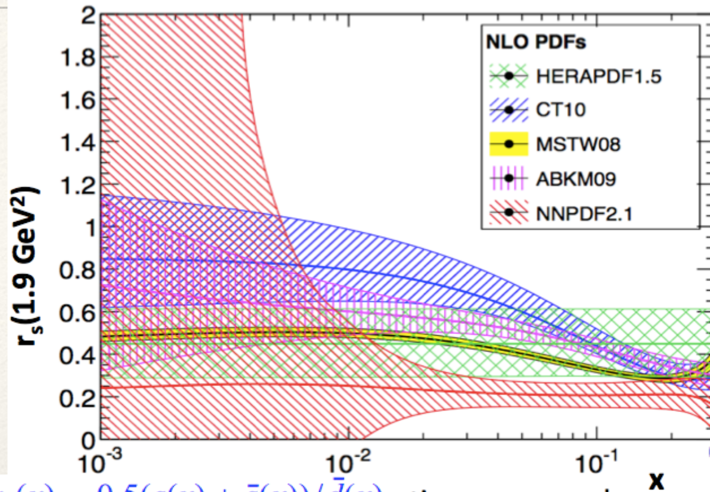
  —> can be used for extracting QED PDF
- for LM DY: highest order calculations must be used to describe data

13 TeV data can bring considerable improvement in the statistical uncertainty compared to Run 1

- **can extend the measurement up to 3 TeV in di-lepton mass —> important coverage in x for PDFs**

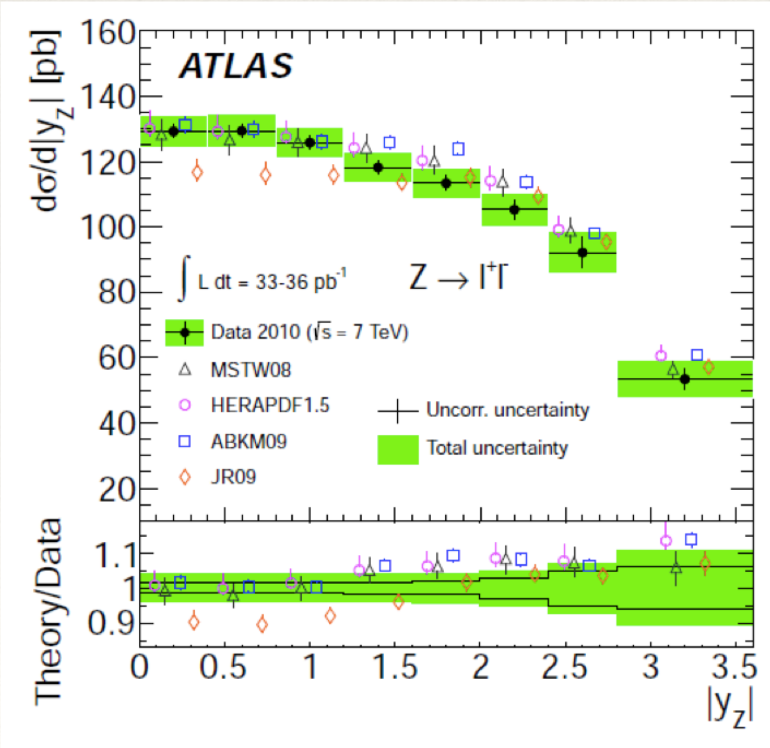
Strange quark from W, Z measurements at LHC

- Strange quark is not so well constrained —>
  - Neutrino dimuon data provides constraints:
    - prefers rather strongly suppressed strange (s/d)
- In 2010, at LHC the EW boson data was used to constrain strange quark through a QCD fit analysis
  - Impact comes mainly from Z rapidity distribution:



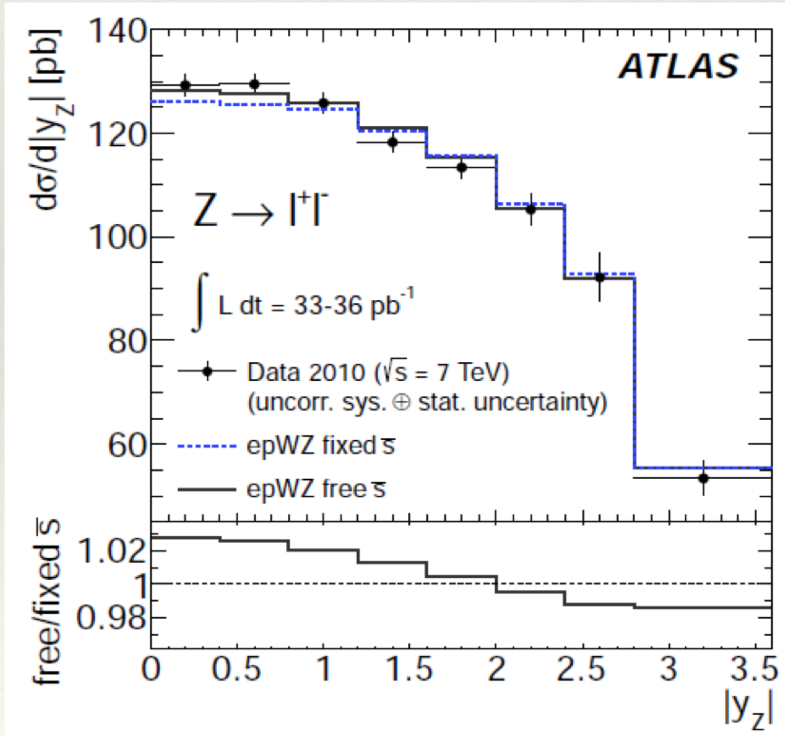
$r_s(x) = 0.5(s(x) + \bar{s}(x))/\bar{d}(x)$

G.Watt



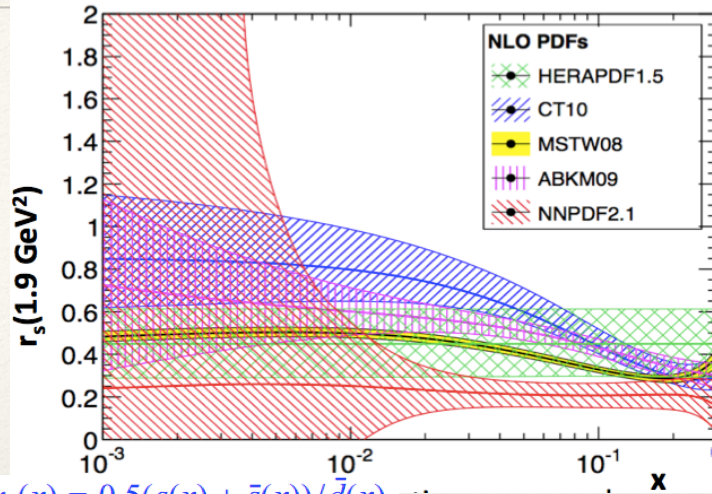
—> discrimination among PDFs

enhanced strange <— is preferred by data

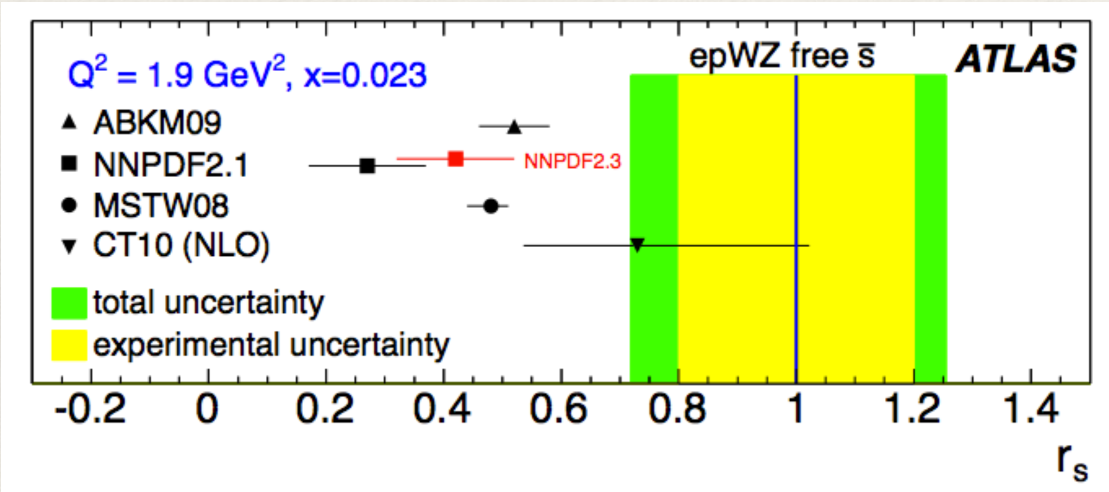


Strange quark from W, Z measurements at LHC

- Strange quark is not so well constrained —>
  - Neutrino dimuon data provides constraints:
    - prefers rather strongly suppressed strange (s/d)
- In 2010, at LHC the EW boson data was used to constrain strange quark through a QCD fit analysis
  - Impact comes mainly from Z rapidity distribution:



G.Watt



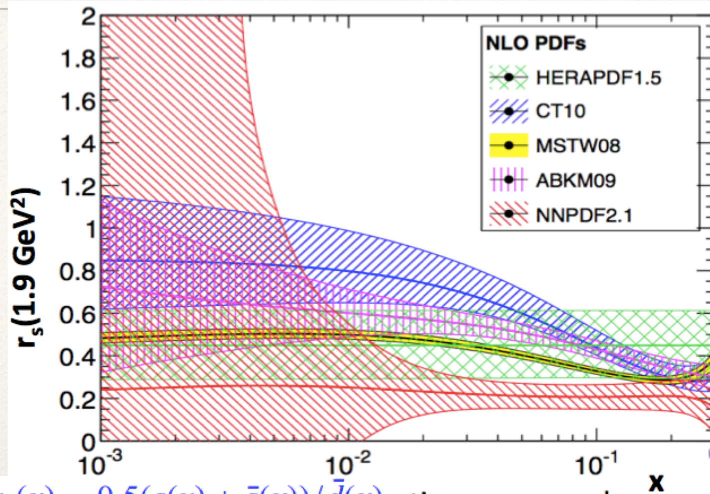
Phys Rev Lett 109 (2012) 012001

Since then, new measurements and QCD analyses were performed:

- W+charm from ATLAS and CMS
- QCD fits to W asymmetry + W+charm data @ CMS

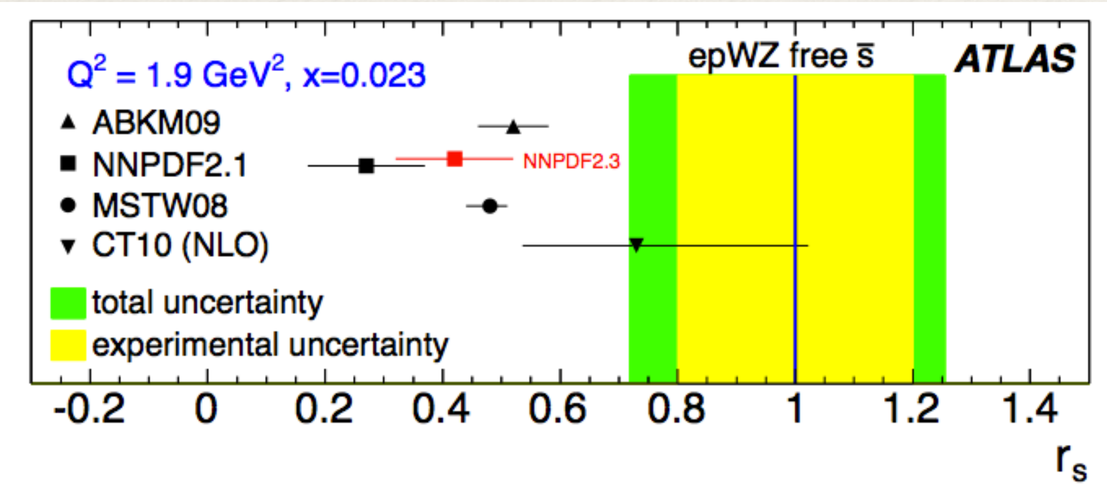
Strange quark from W, Z measurements at LHC

- Strange quark is not so well constrained —>
  - Neutrino dimuon data provides constraints:
    - prefers rather strongly suppressed strange (s/d)
- In 2010, at LHC the EW boson data was used to constrain strange quark through a QCD fit analysis
  - Impact comes mainly from Z rapidity distribution:

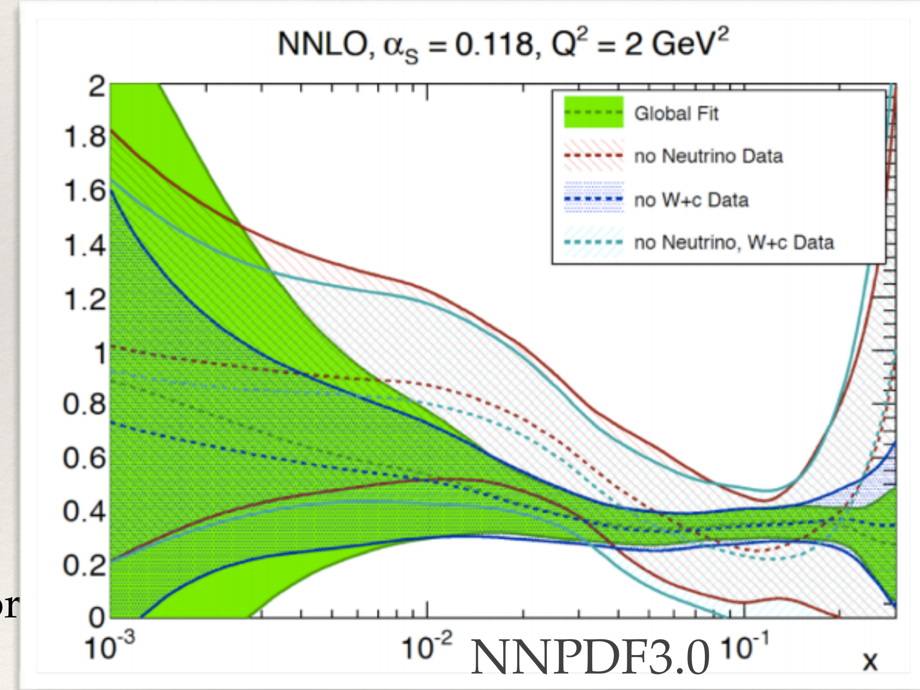


$r_s(x) = 0.5(s(x) + \bar{s}(x))/\bar{d}(x)$

G.Watt



Phys Rev Lett 109 (2012) 012001



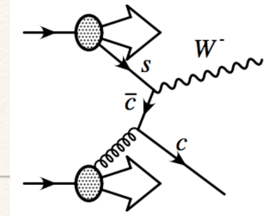
NNPDF3.0

rs=(s+sb)/(ub+db)

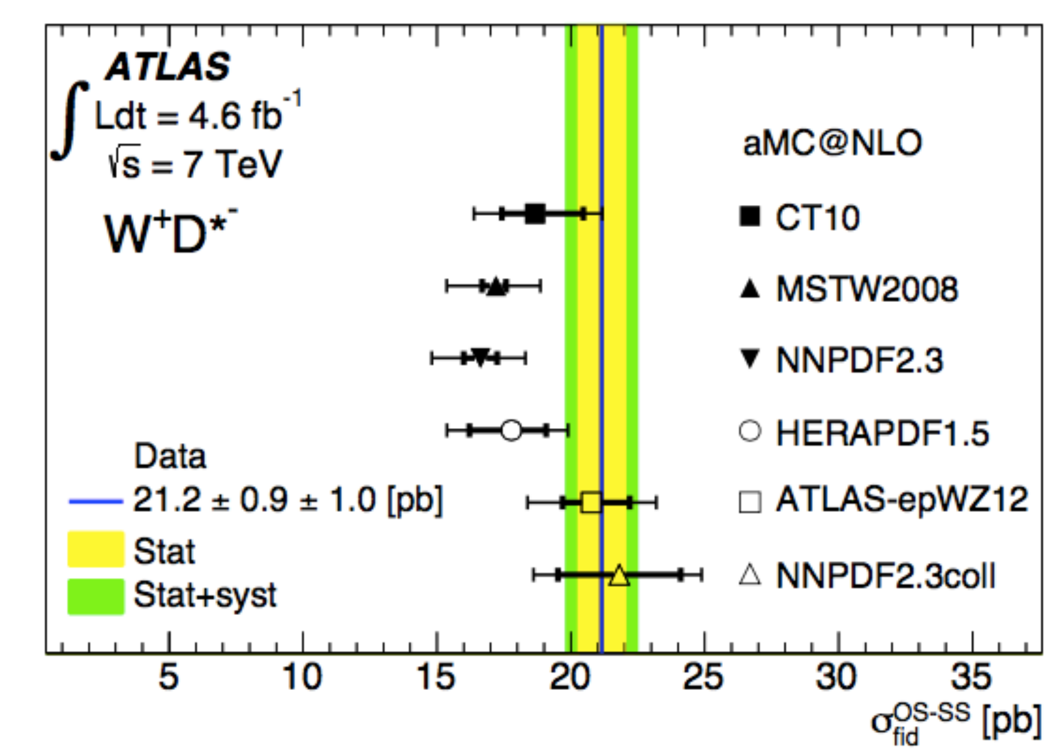
Since then, new measurements and QCD analyses were perfor

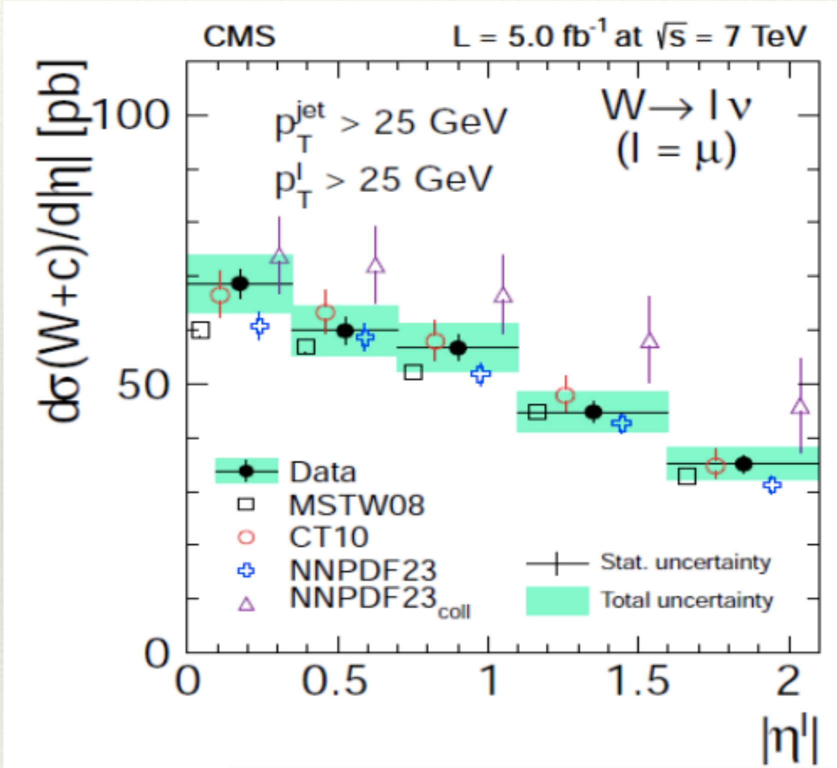
- W+charm from ATLAS and CMS
- QCD fits to W asymmetry + W+charm data @ CMS

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:1402.6263] CMS @parton level [arXiv:1310.1138]

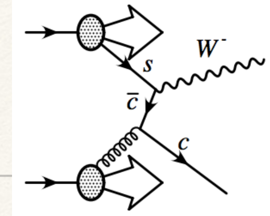




—>consistent with ATLAS-epWZ12
(PDF set from ATLAS Z, W inclusive)

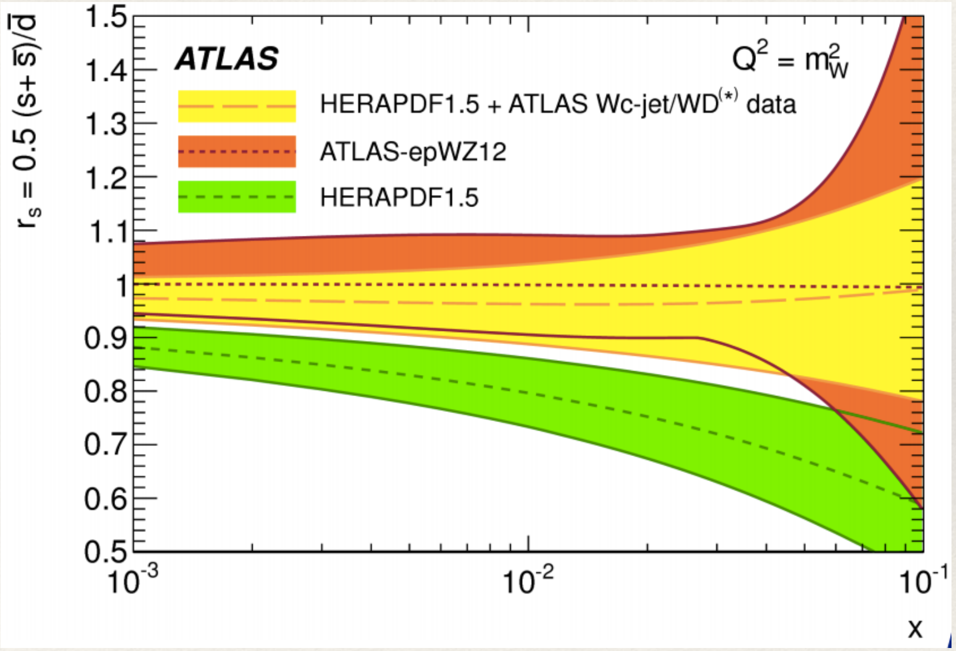
—>consistent with CT10

W+c sensitivity to strange



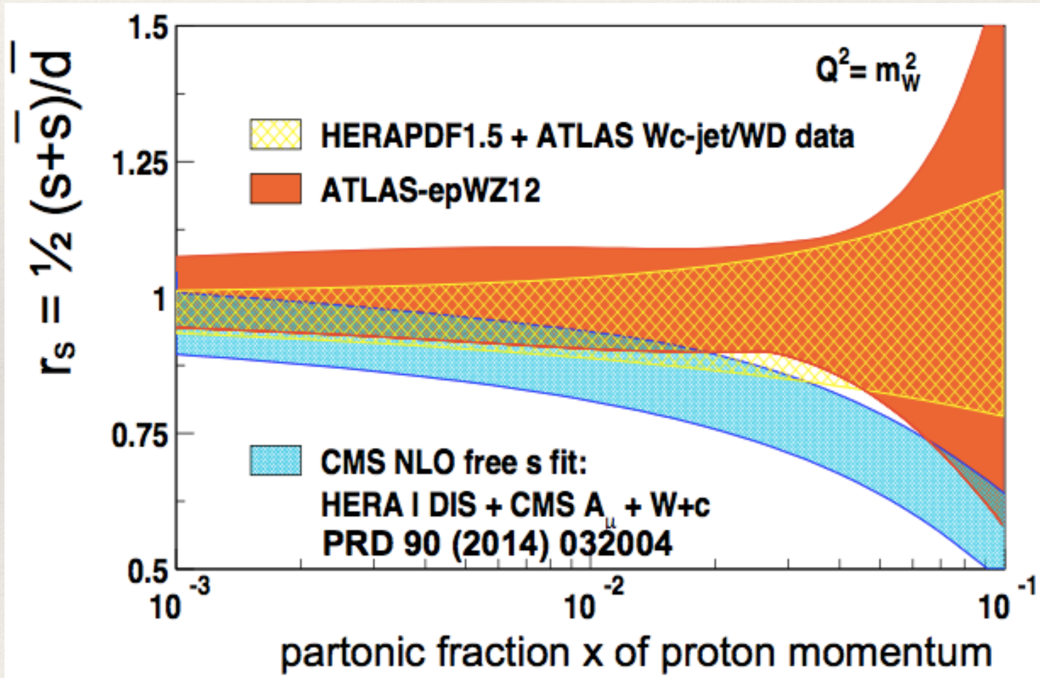
- W + charm data is directly sensitive to the strange quark density
- Both ATLAS and CMS have performed dedicated measurements:
  - Measure fully reconstructed D* mesons or soft leptons within a jet
    - ATLAS @ particle level [arXiv:1402.6263v1] CMS @parton level [arXiv:1310.1138]

PDF eigenvector analysis



—> consistent with previous ATLAS result

QCD Fit

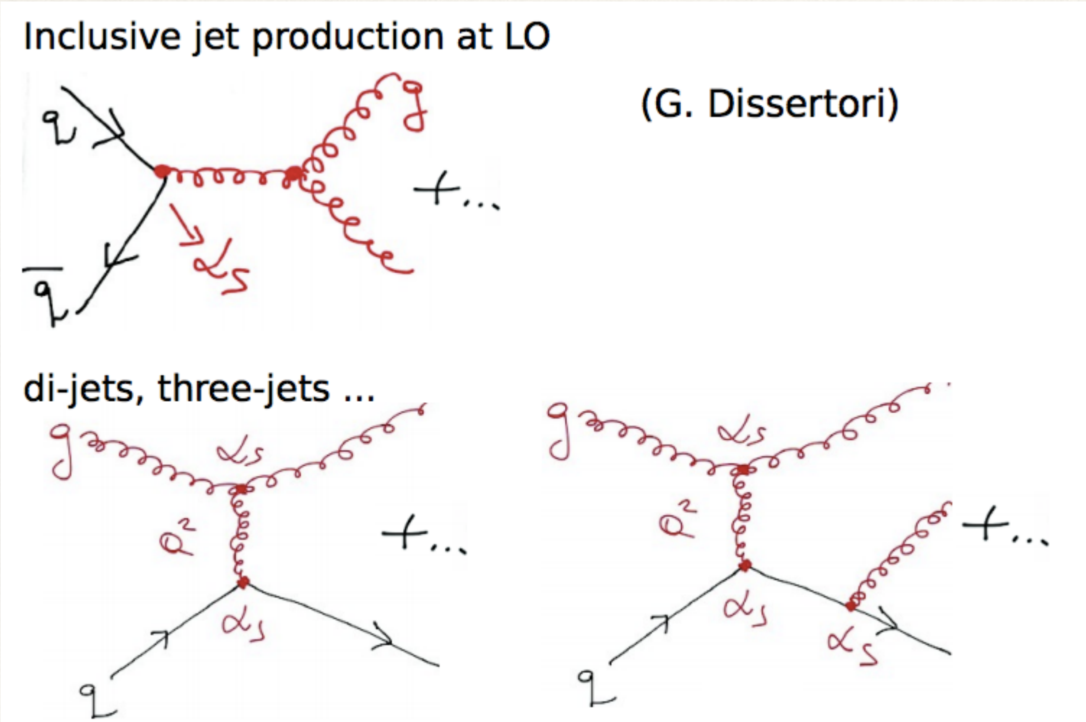


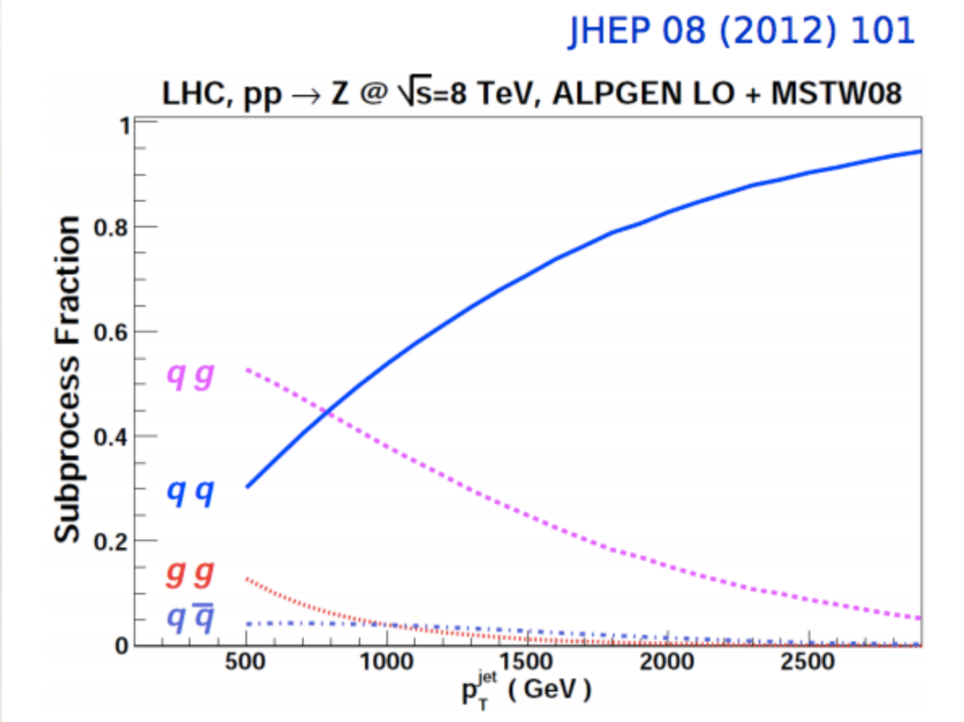
—> mild differences between CMS and ATLAS

Jet Production at the LHC

- Jet production at the highest scales may reveal new physics and the reliability of the predictions depends on how well we know the high-x gluon PDF

- Jet production at LHC provides information about hard QCD, PDFs , strong coupling:
  —> PDFs and alphas depend on scale of the process (Pt of the jet)

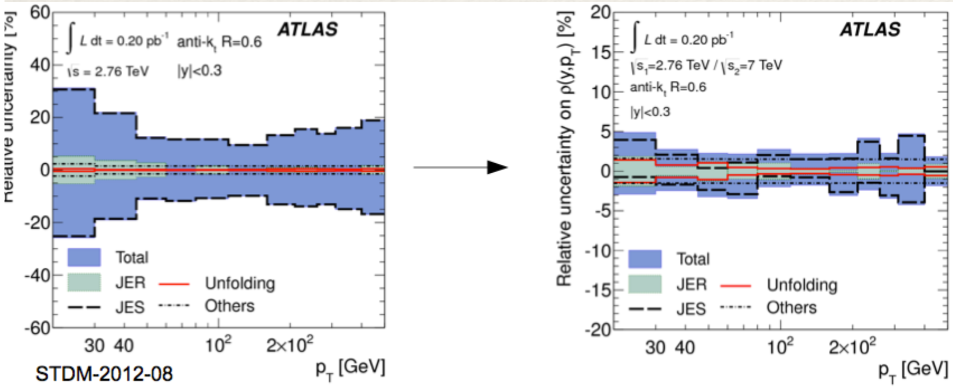




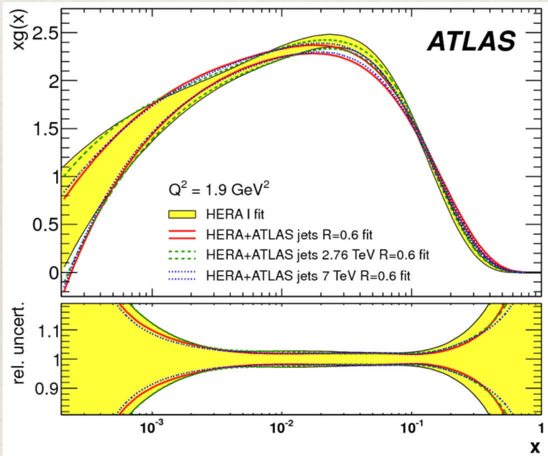
Inclusive Jet Production at the LHC

- To enhance the impact of jet data, it's smart to consider ratios:
  - the major experimental systematic - the Jet Energy Scale - cancels out (i.e. 2.76 vs 7 TeV data)

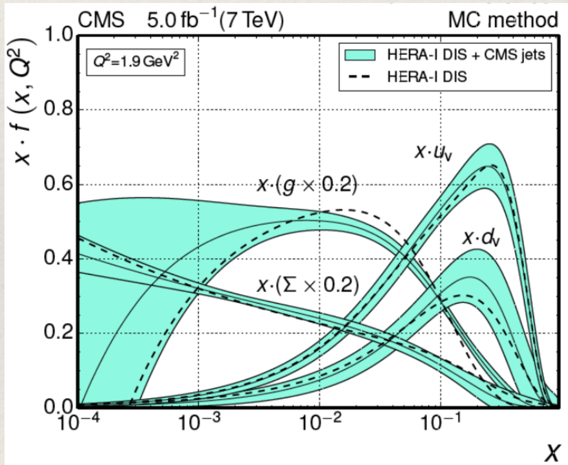
- The impact of the LHC 7 TeV inclusive jet data on proton PDFs was investigated by including the jet cross section measurement in a combined fit with the HERA-I inclusive DIS cross sections.



EPJC (2013) 73 2509



arXiv:1410.6765



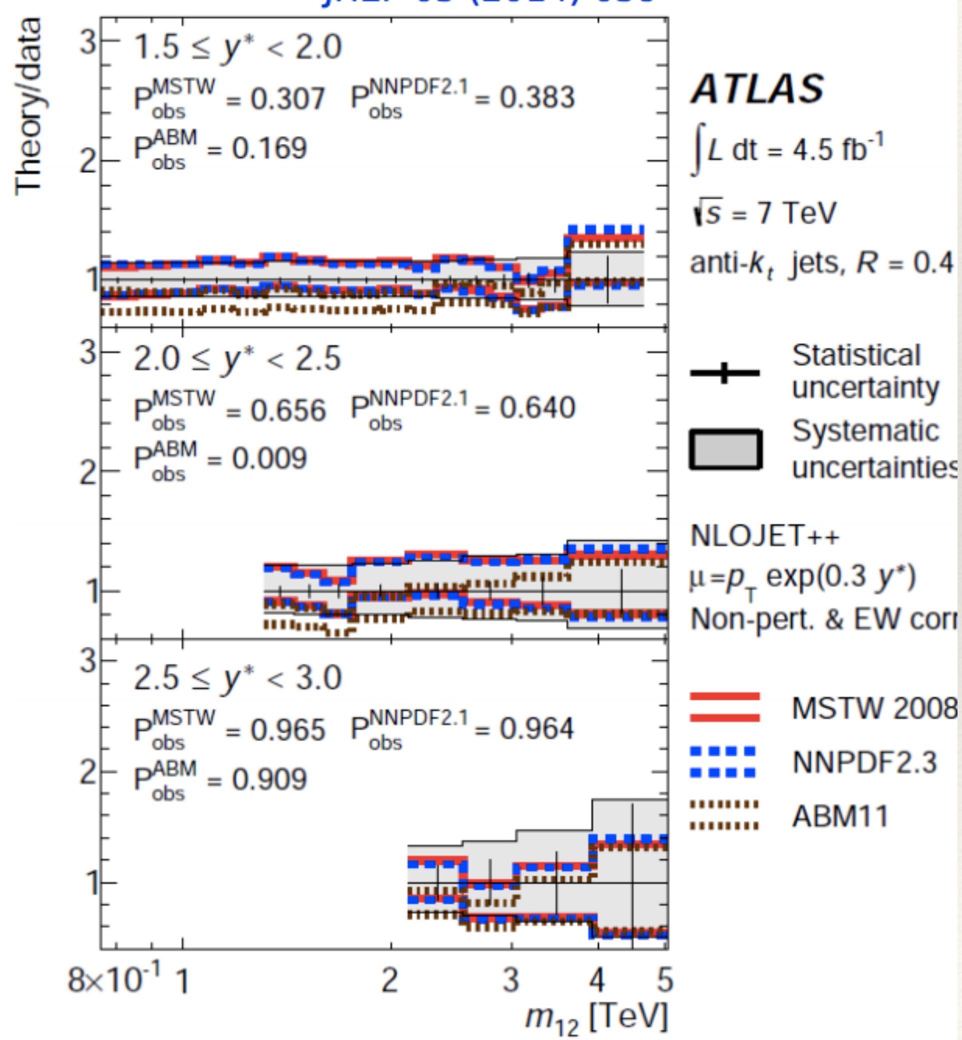
- jet data can help to improve gluon in high-x region
- Data can be used in extracting strong coupling, however one limitation is that jet calculations are still only available to NLO and there is thus still a substantial scale dependence on predictions

$$\alpha_S(M_Z) = 0.1185 \pm 0.0019(\text{exp}) \pm 0.0028(\text{PDF})\,^{+0.0055}_{-0.0022}(\text{scale})$$

Di-Jet, Tri-Jet Production at the LHC

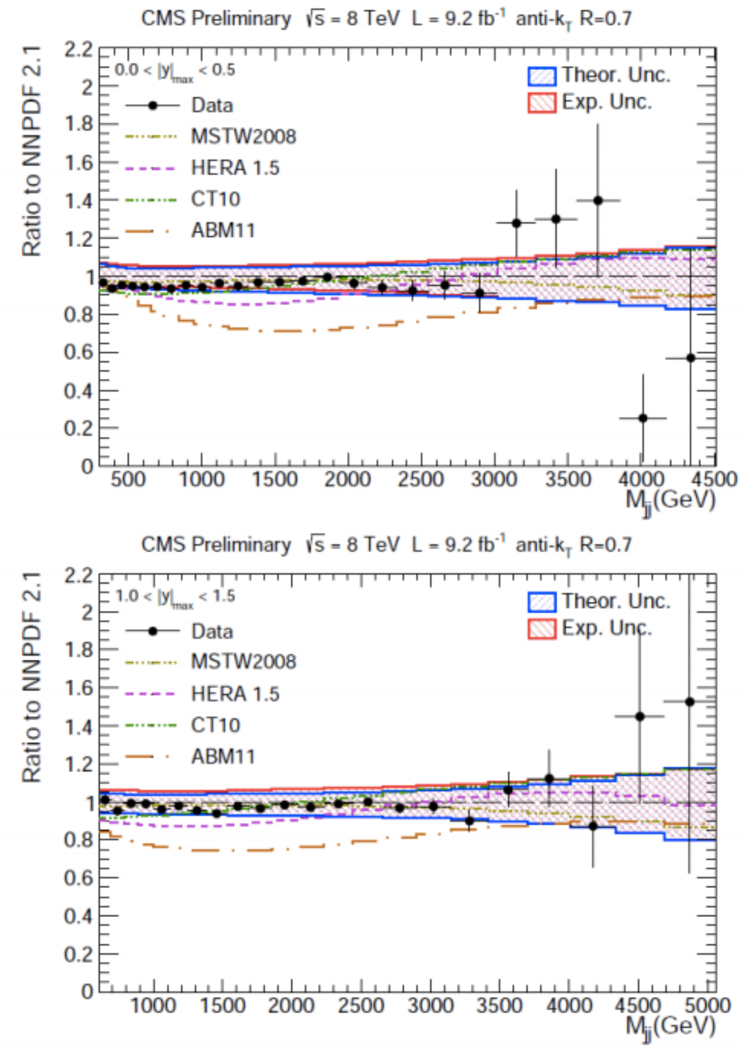
- More data on jets from 2011 7 TeV running (4.5/fb of data) from CMS and ATLAS
- A detailed statistical analysis is performed when comparing data to theory
  -> lowest probability found for ABM

JHEP 05 (2014) 059

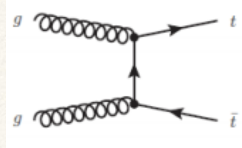


Different rapidity and mass ranges are considered.

CMS PAS SMP 14-002

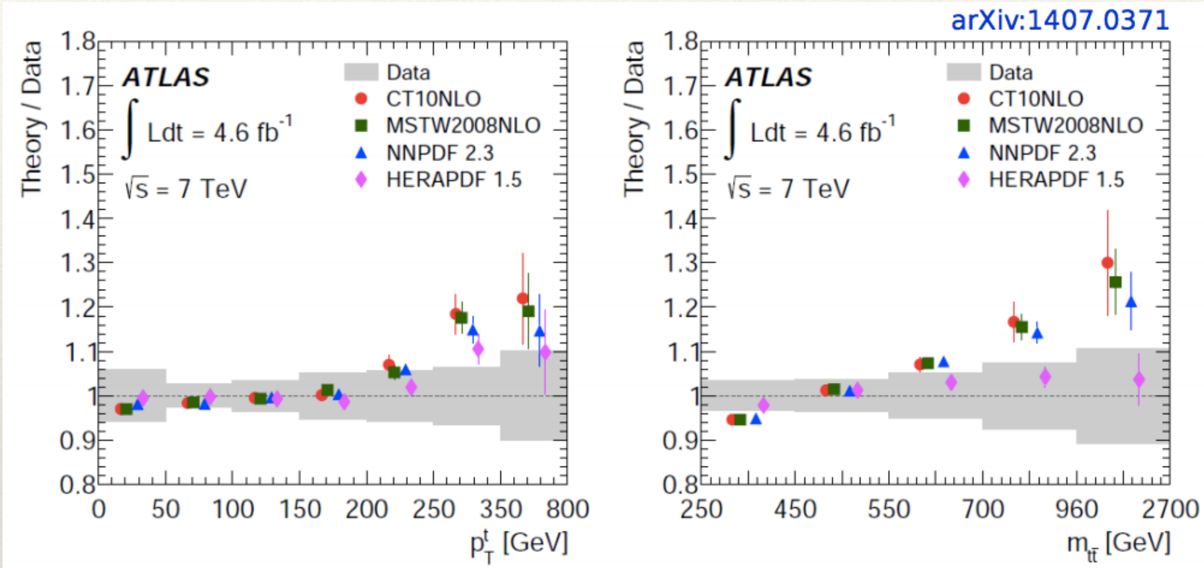


Sensitivity to PDFs from Top Production

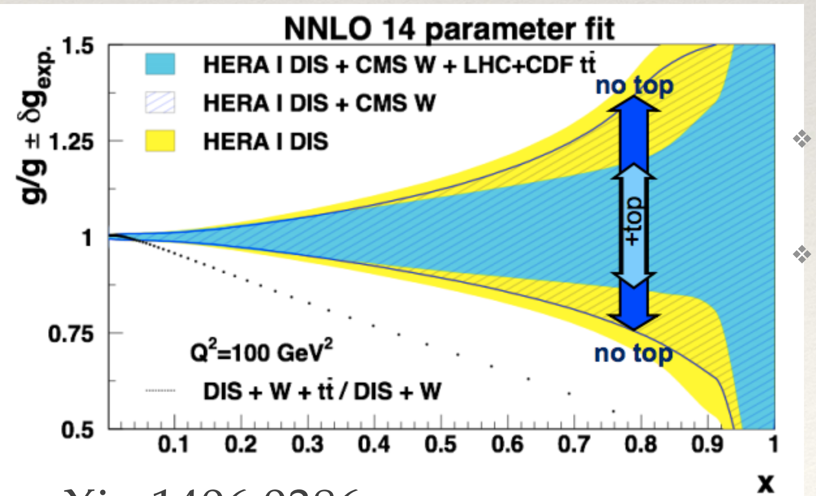


- Top-quark pair production at the LHC probes high-x gluon ($x \approx 0.1$):
  —> there is a strong correlation between g(x), αs and the top-quark mass mt
- Precise measurements of the total and differential (normalised and absolute) cross section of ttbar pair production can constrain and de-correlate αs, gluon, mt

  - compared with theory (NLO) using different PDFs



  - NNLO theory calculations are becoming available …

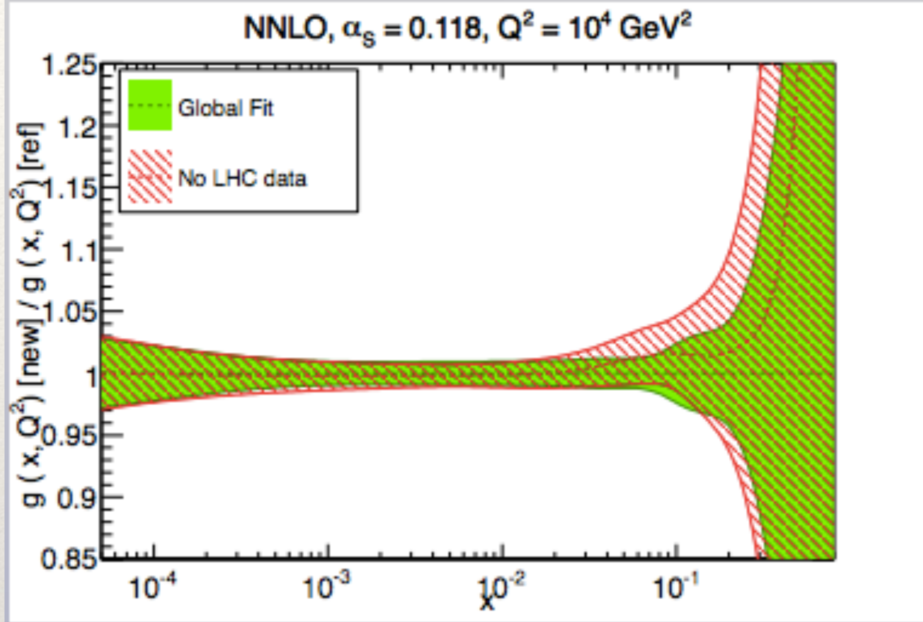


arXiv:1406.0386

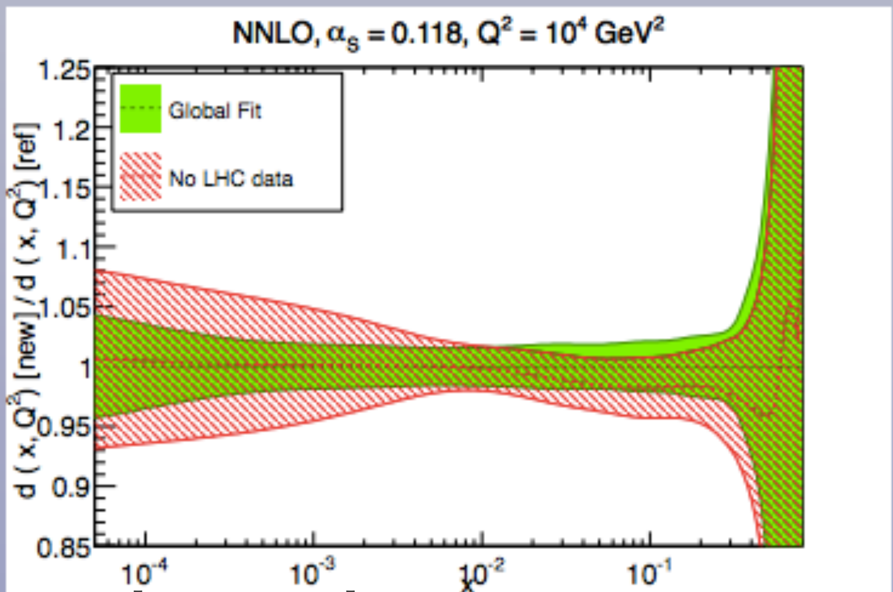
- QCD analysis with ATLAS and CMS ttbar data (together with HERA, Tevatron and W production data at LHC)
- moderate improvement of the uncertainty on the gluon distribution for $x > 0.1$ and significant change of the shape of the gluon distribution observed

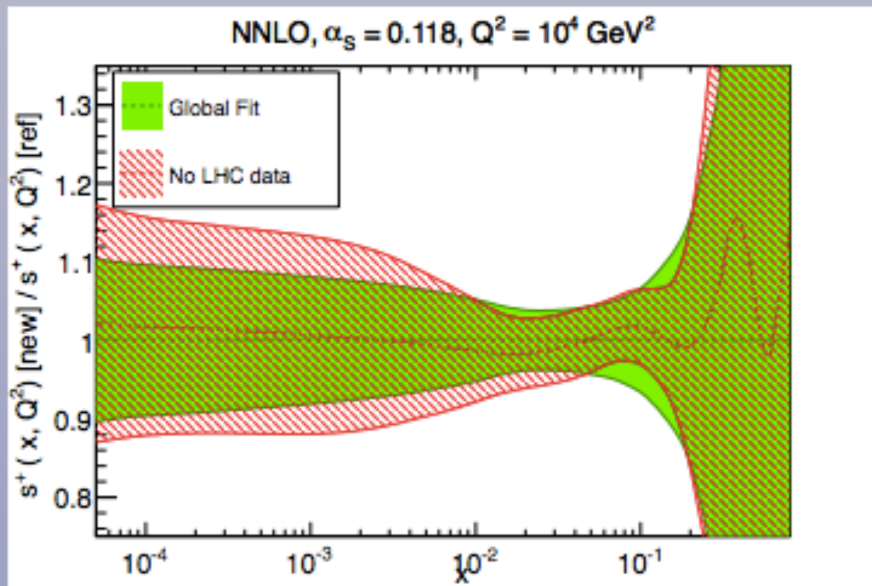
Impact of LHC data on PDFs

- Abundant LHC data with constraints on PDFs are investigated:



- Compare global NNPDF3.0 fit with a fit **without LHC data**
- PDF uncertainties on **large-x gluon** reduced due to **top quark and jet data**
- PDF uncertainties on **light quarks** reduced from the **Drell-Yan** and **W+charm data**
- The **description of all new LHC data**, already good in NNPDF2.3, is further improved in NNPDF3.0



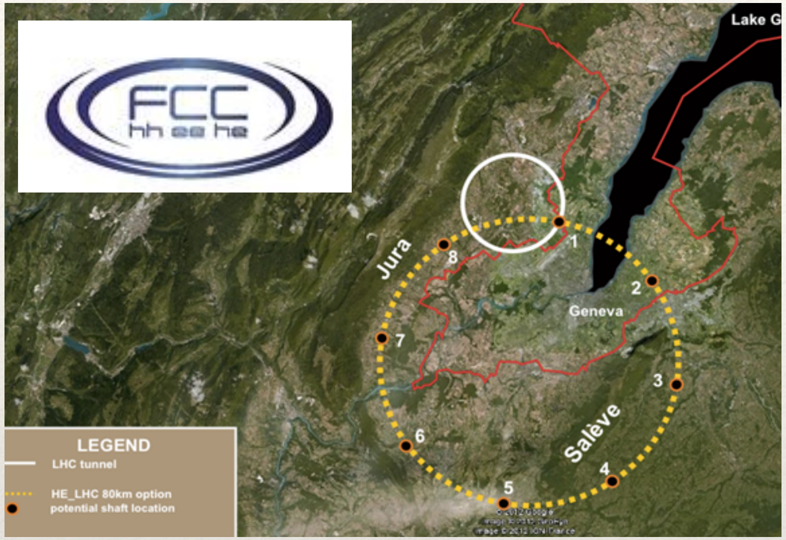


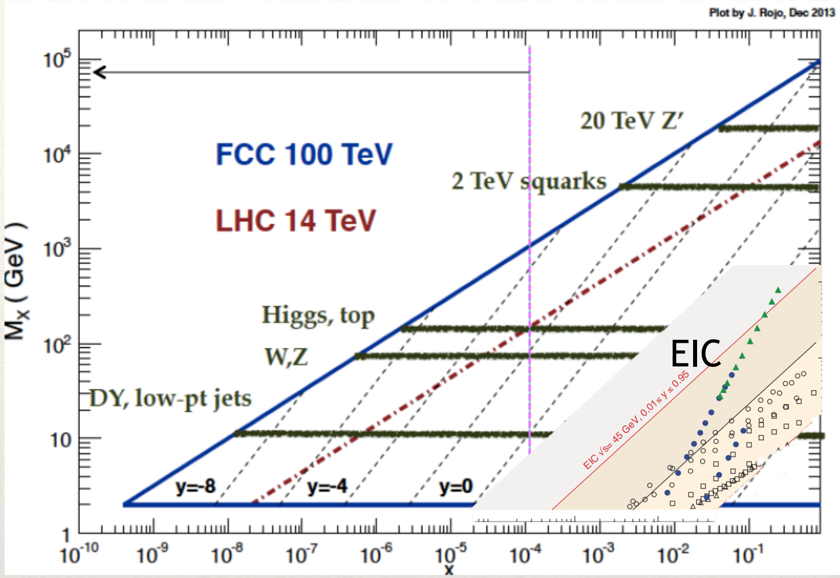
J. Rojo [NNPDF3.0]

Future proposals for better PDFs?

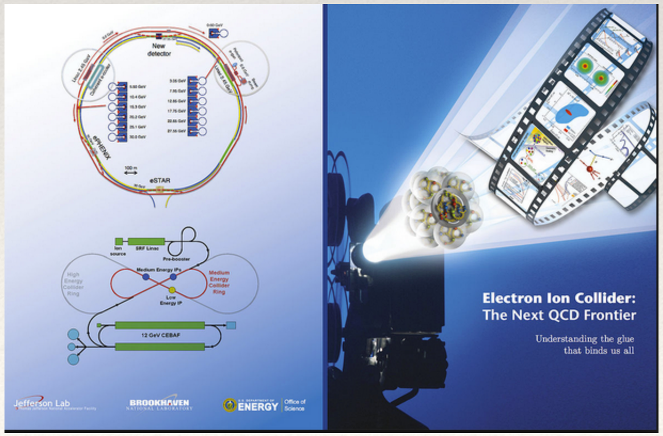
- Future Circular Collider project: ee, eh, hh (100 TeV proton)

https://espace2013.cern.ch/fcc/Pages/default.aspx

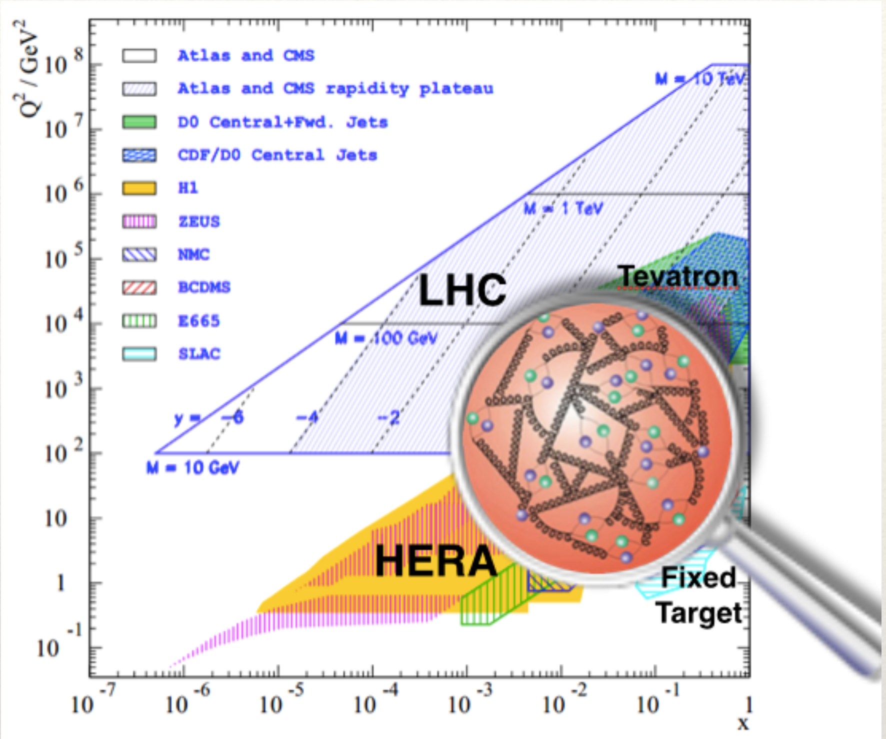




- EIC project (JLAB/Brookhaven) and LHeC (CERN)



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 has combined them into final measurements to reach its ultimate precision:
  - PDFs, mc, mb, alphas …
- 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 soon from Run 2:
  - The Run 2 is expected to impact PDFs by accessing a different kinematic region
- Future Facilities to further push our limits are being considered

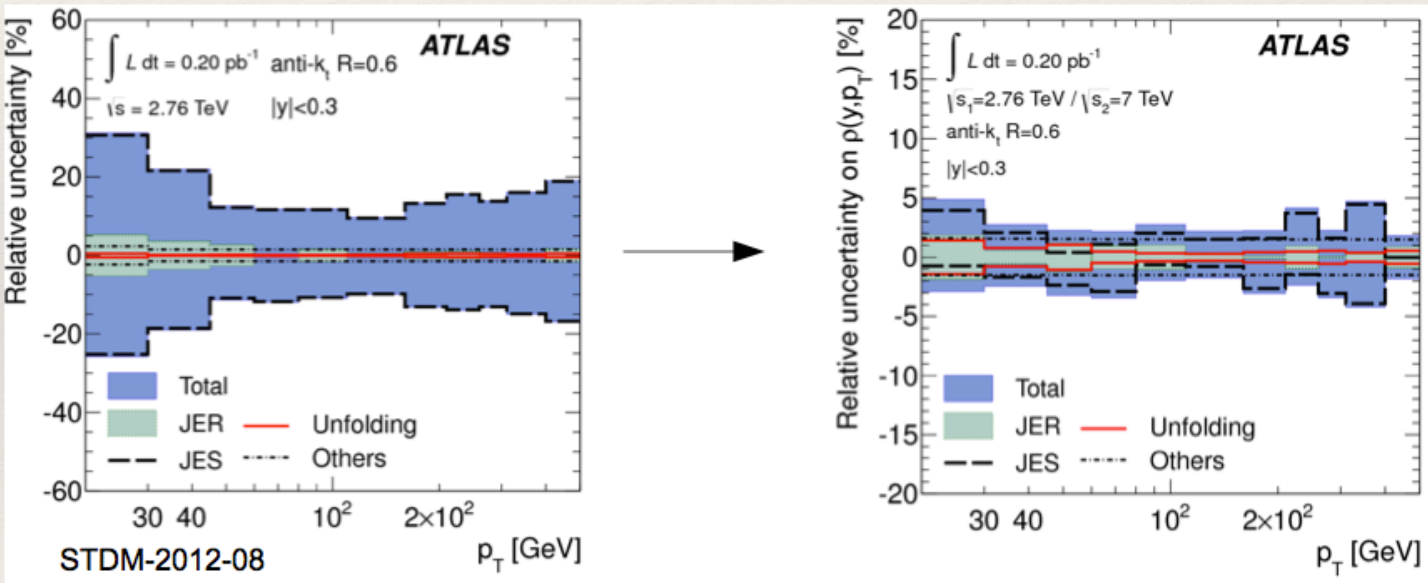
Many Thanks!

back-up slides

not necessarily useful …

Jet measurements from Run 2

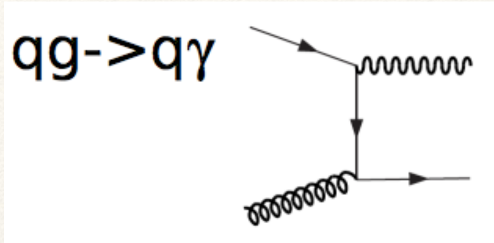
- Precise understanding of systematic uncertainties is essential if we want to use inclusive jet measurements in the PDF fits
- Jet measurements of 2015 bring a new kinematic reach with jet p_T up to 3.5 TeV, interesting to observe if it will help to further constrain PDFs
- Exploiting ratio measurements to better control the dominant JES uncertainty, as done for 2010 data:



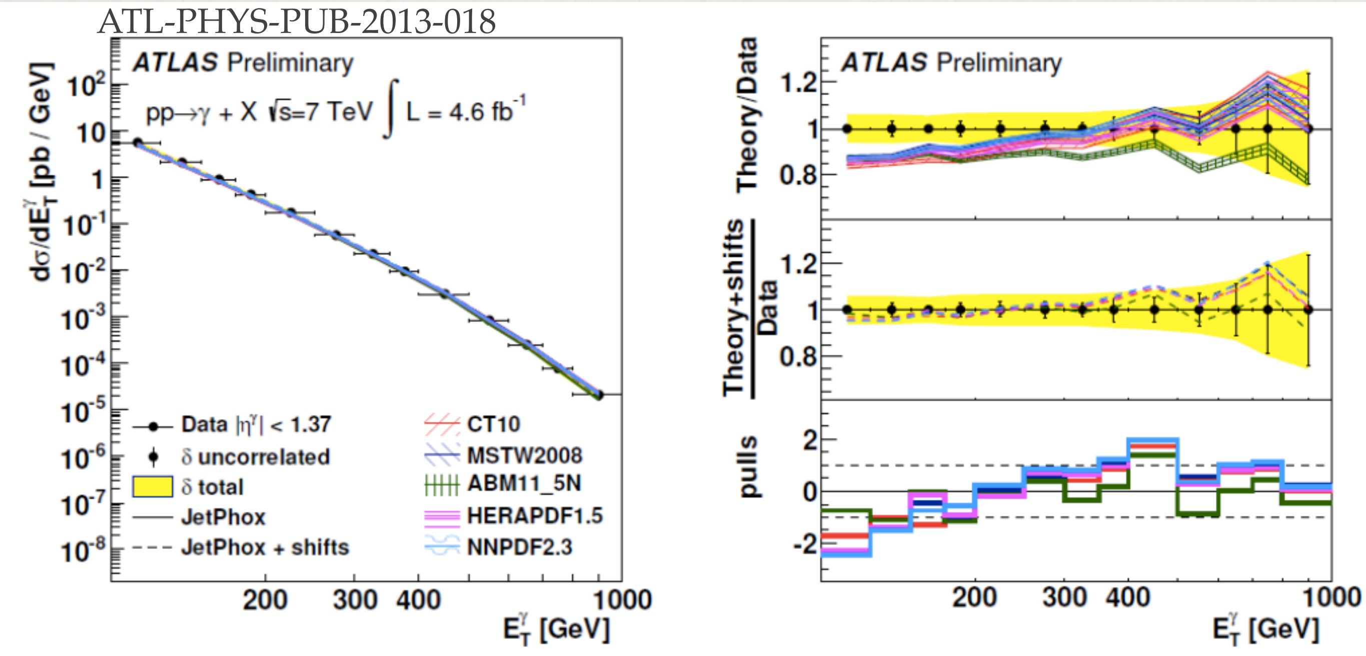
- Other measurements:
  - Dijet invariant mass,
  - multijet measurements, etc..

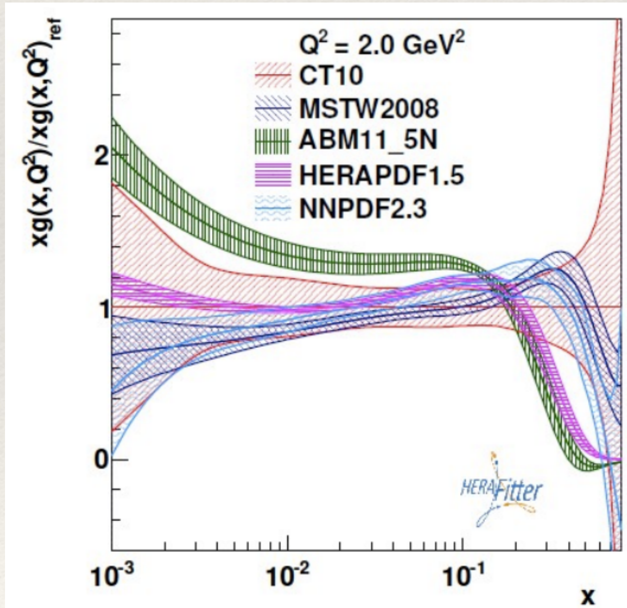
Prompt Photon production at LHC

- Prompt photon data at LHC is sensitive to gluon content at high x
  - Dominantly via Compton-like process



- ATLAS study of the inclusive photon data sensitivity to parton distributions
  - data show potential to improve gluon distribution
  - currently limited by scale uncertainty



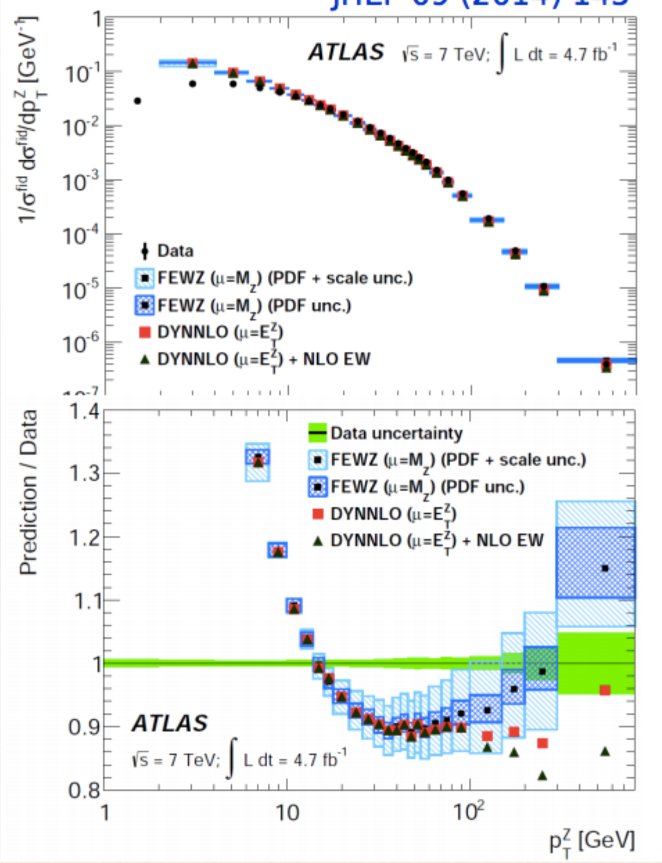


- large differences observed with theory (NLO) using different PDFs

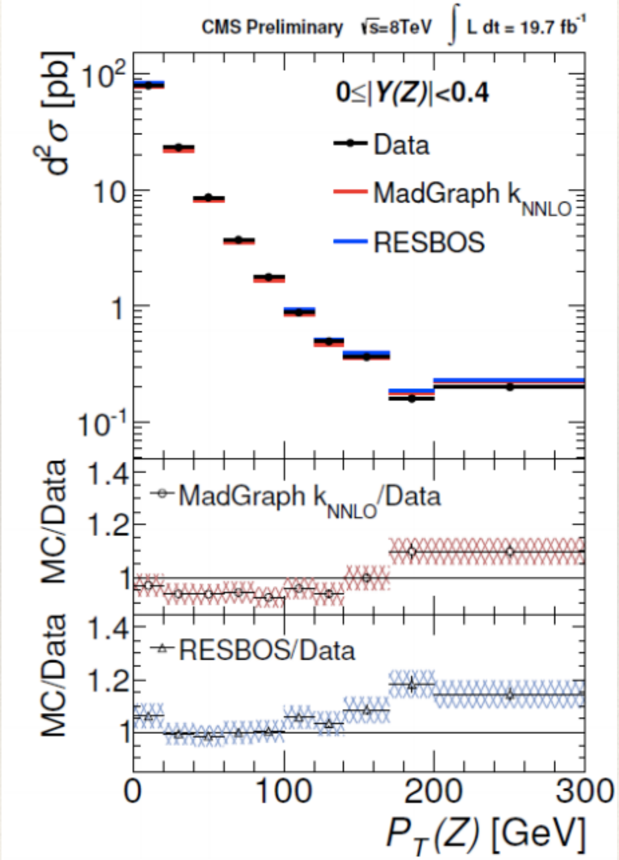
Vector boson Pt spectrum at the LHC

- ATLAS and CMS both studied the Pt spectrum in rapidity bins
  - low Pt region: dominated by the emission of soft partons (resummation and shower models, fixed order calculations don't work)
  - high Pt region: quark-gluon scattering (PDFs)

JHEP 09 (2014) 145



CMS PAS SMP 13-013

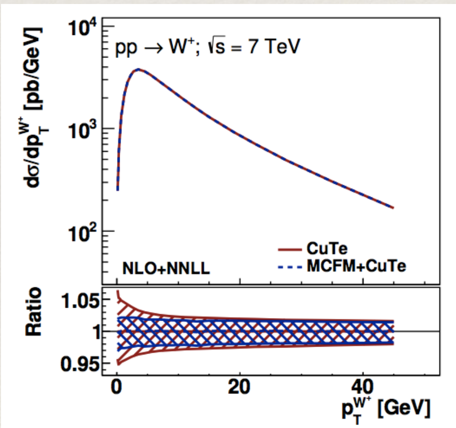


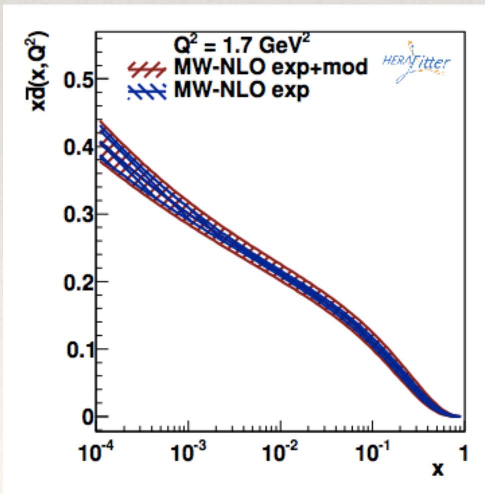
  - sensitive data for W mass measurement, PDFs at high x
  - currently, limited by precision in theory (needs NNLO and EW corrections)

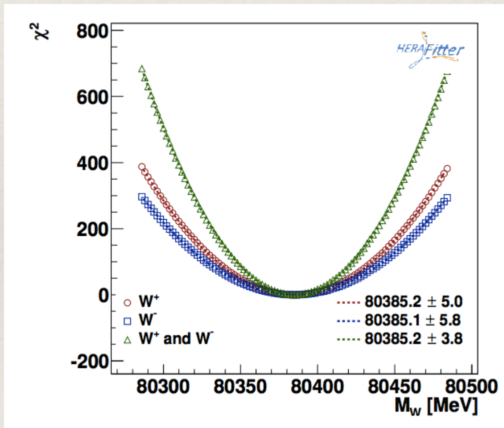
Studies of theoretical uncertainties of Mw mass at the LHC

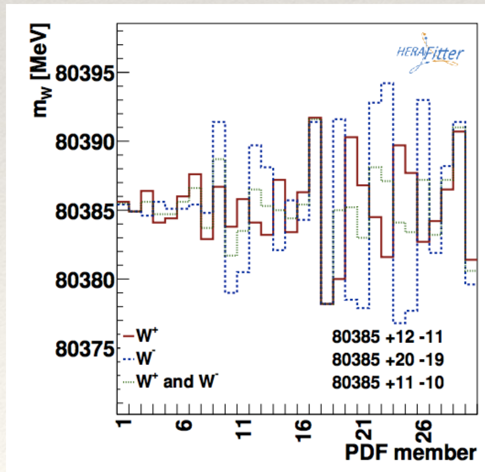
ATL-PHYS-PUB-2014-015

- The measurement of the mass of the W boson provides a stringent test of the SM
- At the LHC, the best experimental precision on Mw might be achieved from the pT distribution of the charged electron/muon from leptonic decay of W:
- A quantitative study of the theoretical uncertainties due to the incomplete knowledge of the quark PDF, and to the uncertainties on the modelling of the low-pT region of W/Z bosons, was performed using HERAFitter platform.
  - Theoretical predictions is based on MCFM and CuTe (interfaced to APPLGRID)
  - A PDF set is generated using simply HERA I data to study the model variations (mc, strange) and propagated via chi2 profiling method to study the effect of PDF uncertainties





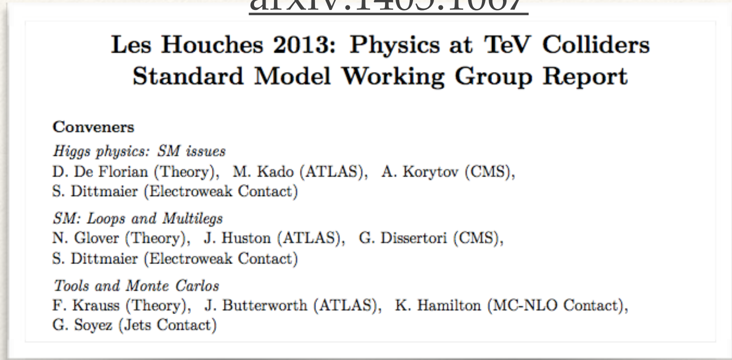




ggH benchmark studies

- Efforts in reducing the PDF uncertainties arising from discrepancy between PDF groups:
  - Benchmark comparisons of NNLO neutral current DIS cross sections (Exercise on HERA-I only data)

arxiv:1405.1067



Les Houches 2013: Physics at TeV Colliders
Standard Model Working Group Report

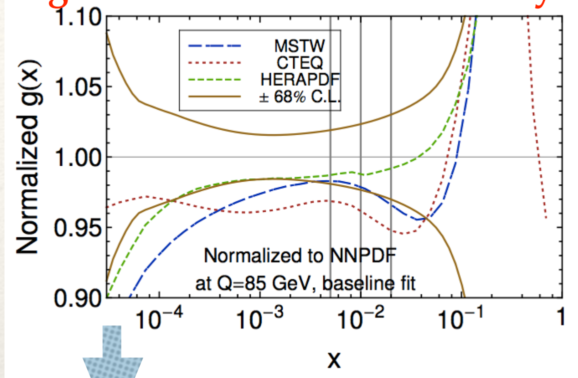
Conveners

Higgs physics: SM issues
D. De Florian (Theory), M. Kado (ATLAS), A. Korytov (CMS),
S. Dittmaier (Electroweak Contact)

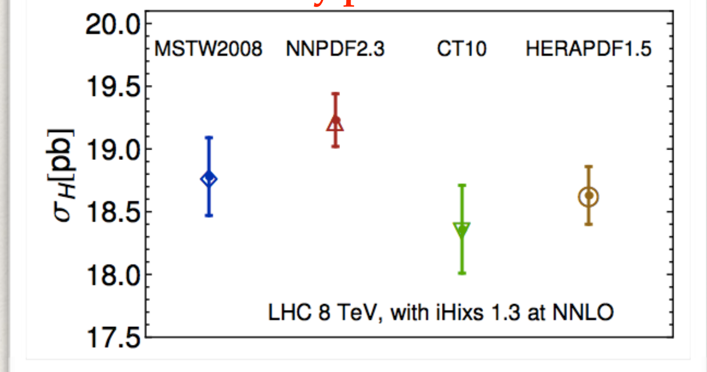
SM: Loops and Multilegs
N. Glover (Theory), J. Huston (ATLAS), G. Dissertori (CMS),
S. Dittmaier (Electroweak Contact)

Tools and Monte Carlos
F. Krauss (Theory), J. Butterworth (ATLAS), K. Hamilton (MC-NLO Contact),
G. Soyez (Jets Contact)

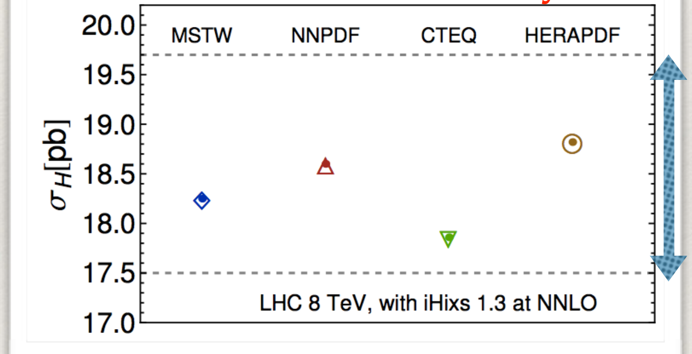
gluon PDF from HERA-I only fits



based on recently published NNLO PDFs.



based on HERA-I only fits



PDF uncert

  - predictions from MSTW, CT, NNPDF and HERAPDF all consistent within PDF uncertainties
  - however the tendency among NNPDF, MSTW and CT is maintained
- **Next step:**
  - continue this exercise by adding additional experimental data sets into the PDF fits sequentially:
  - benchmarking the theoretical predictions used by each group for the different observables -
  - **==> HERAFitter will continue to participate in these studies.**

HERAFitter Program at glance

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

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

Experimental Data	Process	Reaction	Theory schemes calculations
HERA, Fixed Target	DIS NC	$ep \to eX$ $\mu p \to \mu X$	TR′, ACOT, ZM (QCDNUM), FFN (OPENQCDRAD, QCDNUM), TMD (uPDFevolv)
HERA	DIS CC	$ep \to \nu_e X$	ACOT, ZM (QCDNUM), FFN (OPENQCDRAD)
	DIS jets	$ep \to e$ jets$X$	NLOJet++ (fastNLO)
	DIS heavy quarks	$ep \to ec\bar{c}X$, $ep \to eb\bar{b}X$	TR′, ACOT, ZM (QCDNUM), FFN (OPENQCDRAD, QCDNUM)
Tevatron, LHC	Drell-Yan	$pp(\bar{p}) \to l\bar{l}X$, $pp(\bar{p}) \to l\nu X$	MCFM (APPLGRID)
	top pair	$pp(\bar{p}) \to t\bar{t}X$	MCFM (APPLGRID), HATHOR, DiffTop
	single top	$pp(\bar{p}) \to tl\nu X$, $pp(\bar{p}) \to tX$, $pp(\bar{p}) \to tWX$	MCFM (APPLGRID)
	jets	$pp(\bar{p}) \to$ jets$X$	NLOJet++ (APPLGRID), NLOJet++ (fastNLO)
LHC	DY heavy quarks	$pp \to VhX$	MCFM (APPLGRID)

Longitudinal Structure Function

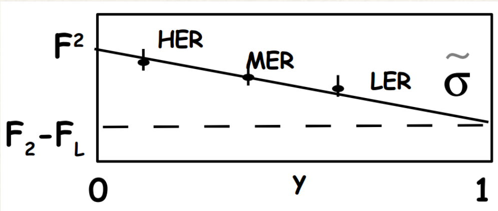
Longitudinal structure function FL is a pure QCD effect:

—> an independent way to probe sensitivity to gluon

$$F_L = \frac{\alpha_s}{4\pi} x^2 \int_x^1 \frac{dz}{z^3}\left[\frac{16}{3} F_2 + 8\sum_q e_q^2 \left(1-\frac{x}{z}\right) z g(z)\right]$$

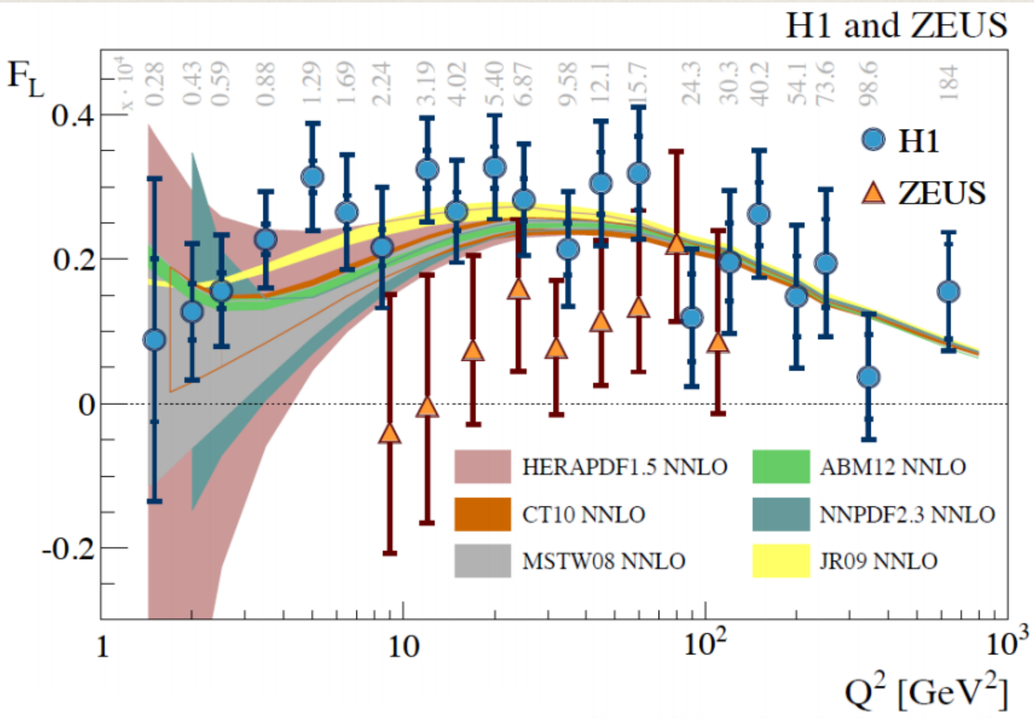
quarks radiating a gluon — gluons splitting into quarks

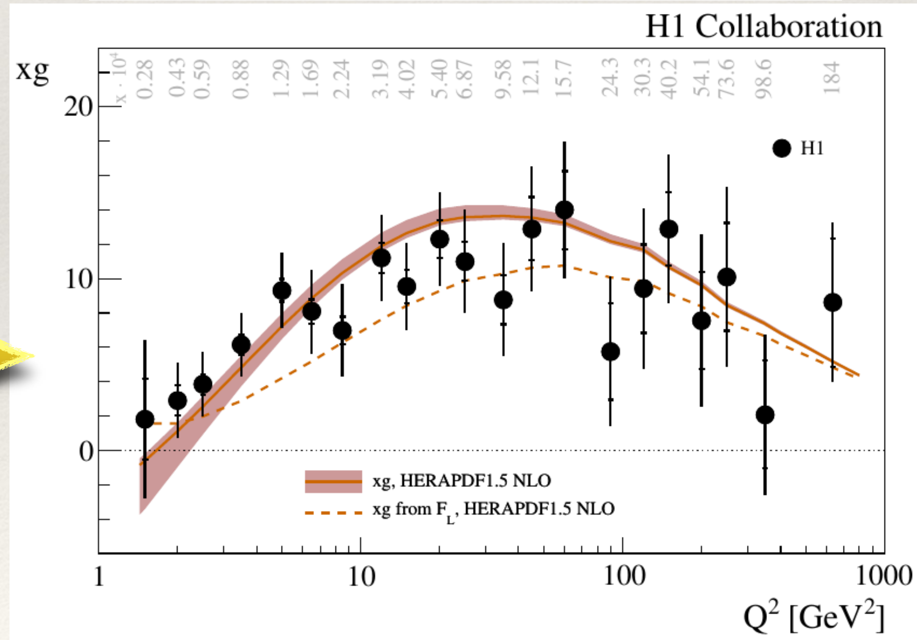
Direct measurement of FL at HERA required differential cross sections at same x and Q^2 but different y —> different beam energies: Ep= 460, 575, 920 GeV



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

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





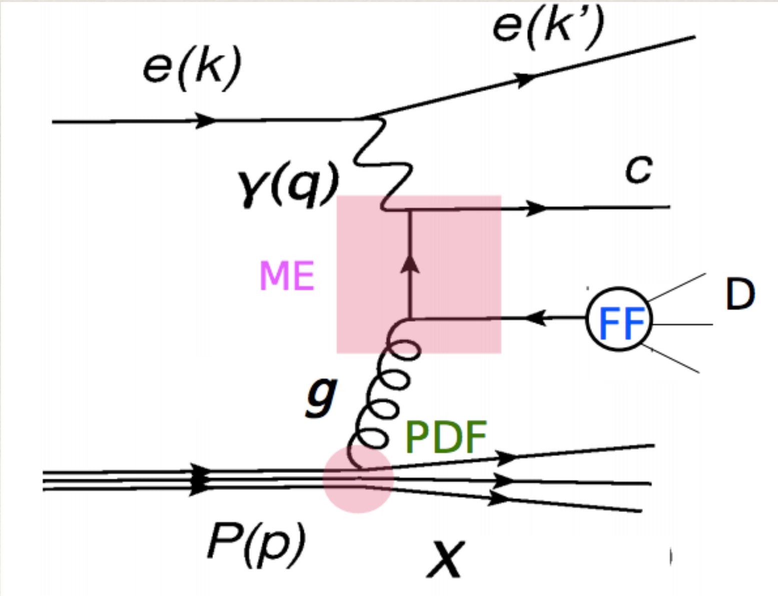
Eur. Phys. J. C 74 (2014) 2814 [arXiv:1312.4821]

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



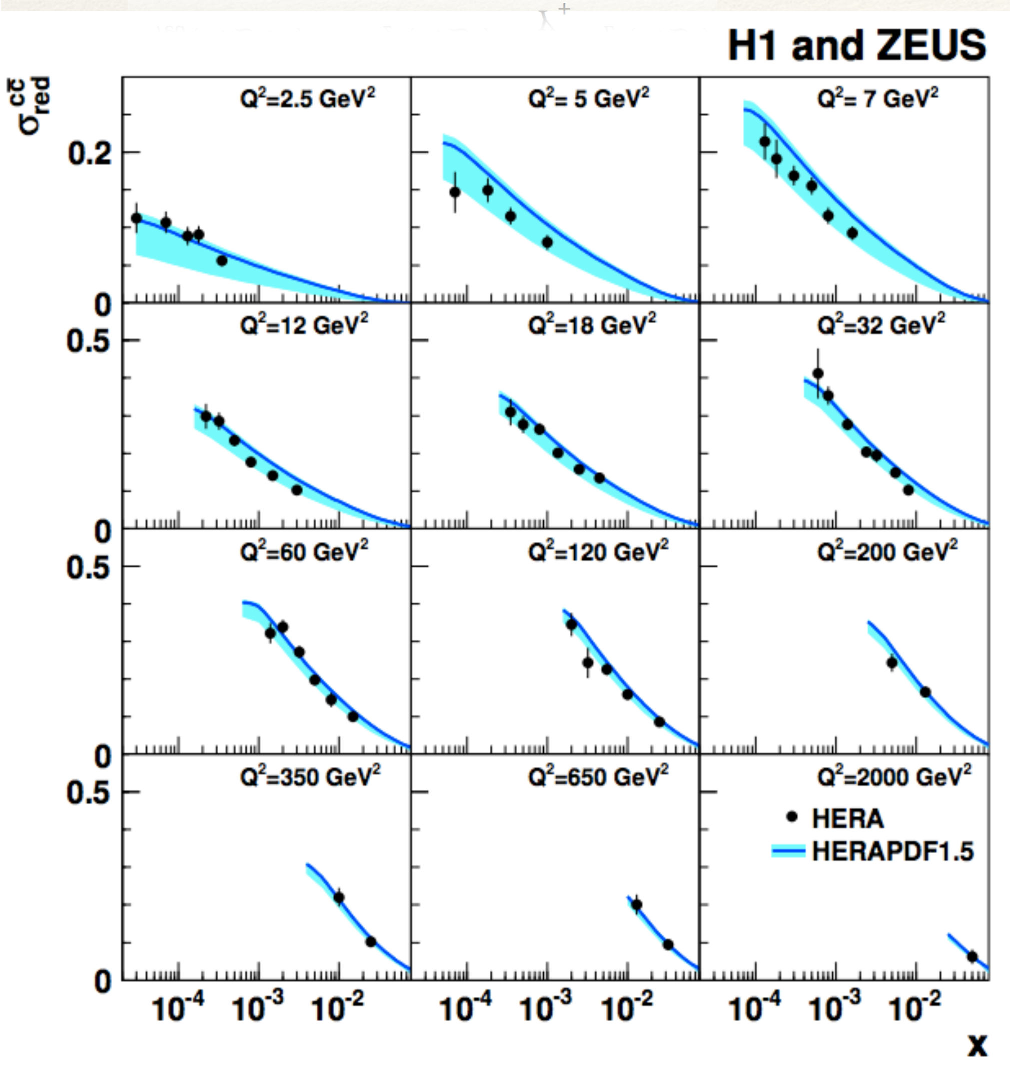
- Measurements of heavy quarks:
  - are sensitive to the gluon PDF
  - are sensitive to the masses of the heavy quarks
  - are sensitive to the fragmentation process of heavy flavour hardons

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

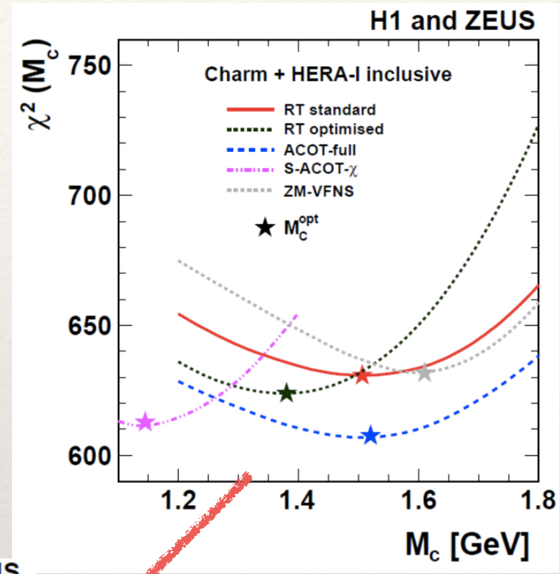
$$\sigma_{red}^{c\bar{c}}(x,Q^2,s) = F_2^{c\bar{c}}(x,Q^2) - \frac{y^2}{Y_+}F_L^{c\bar{c}}(x,Q^2)$$

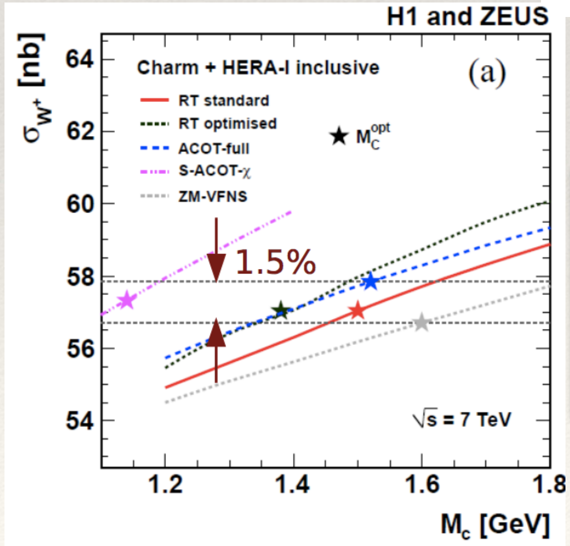


QCD Fits

HERA I+charm

Different calculation schemes prefer different Mc





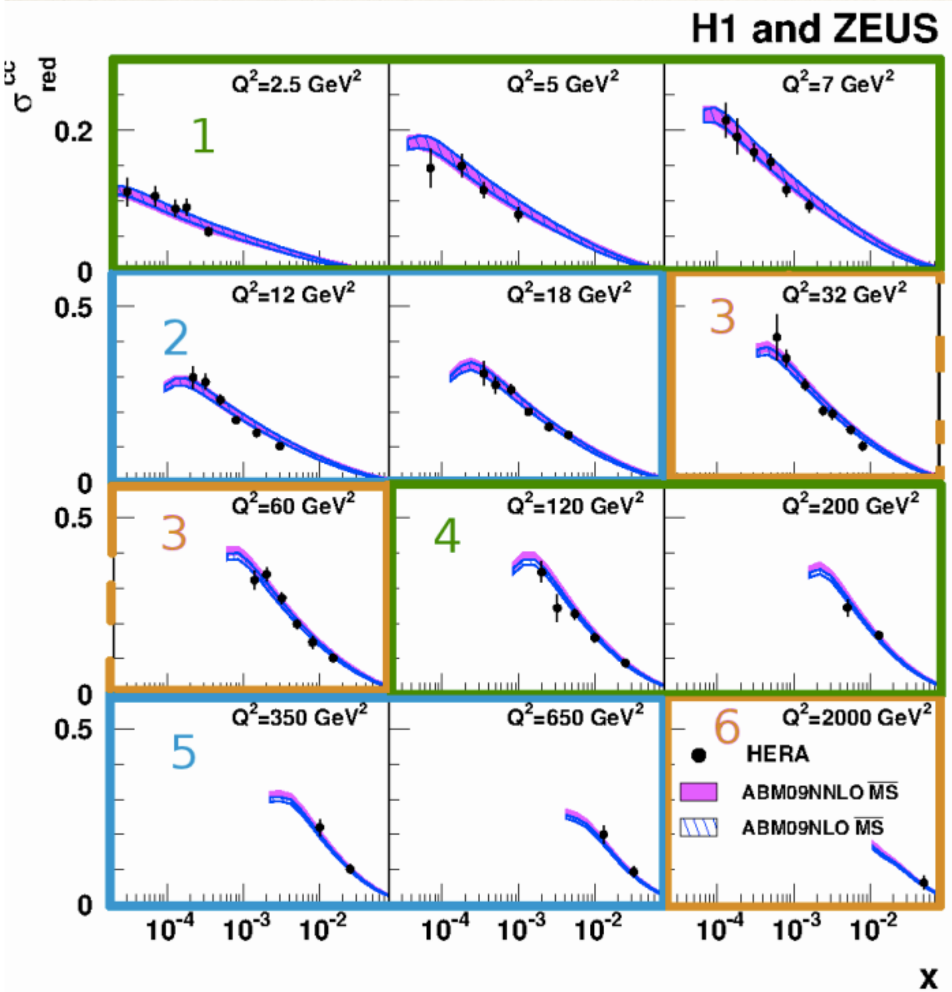
measurements help reduce uncertainties of predictions for the LHC

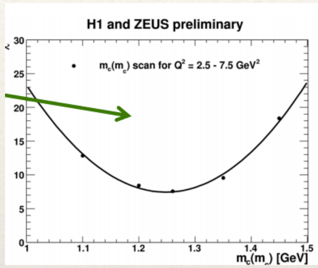
New Measurement of Charm Mass Running

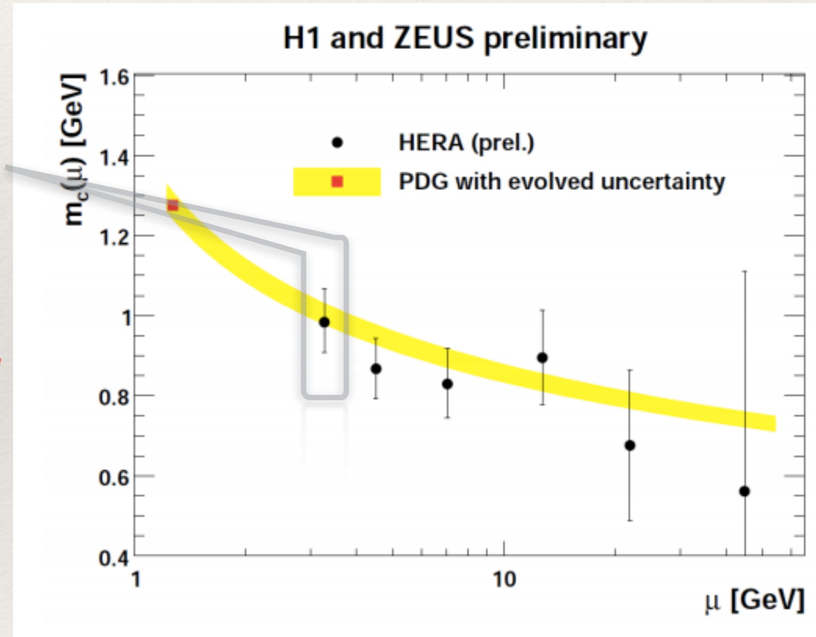
H1-prelim-14-071 ZEUS-prel-14-006 and S. Moch

The running of the charm mass in the $\overline{\mathrm{MS}}$ 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].



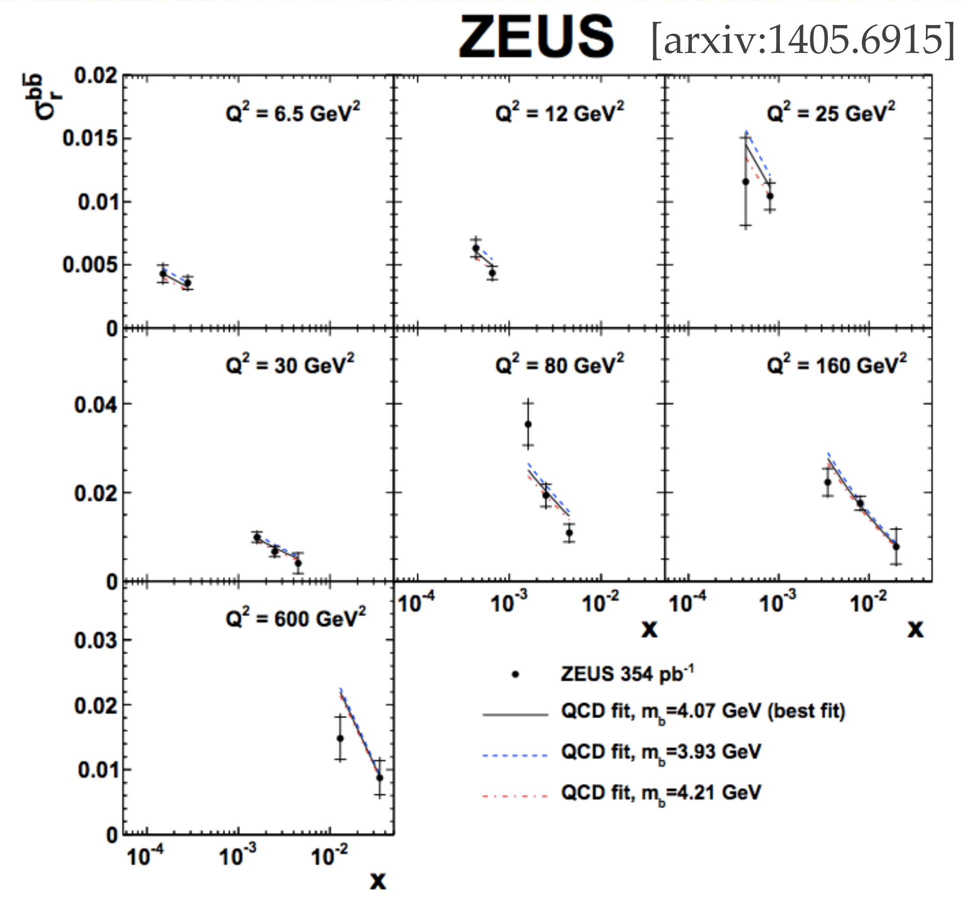




The scale dependence of the mass is consistent with QCD expectations

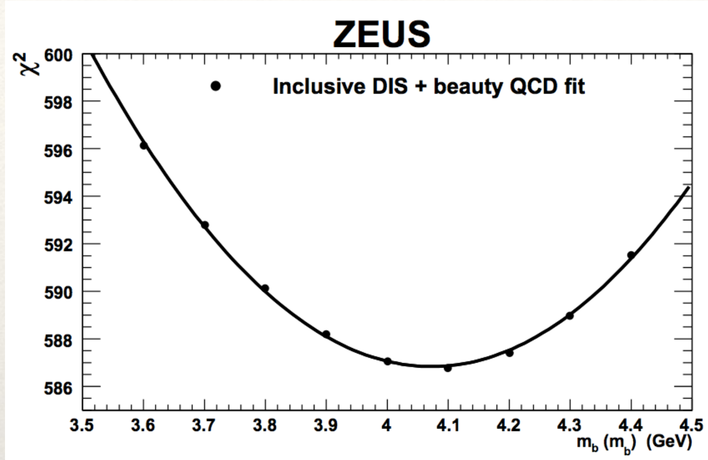
Running beauty mass from F2b

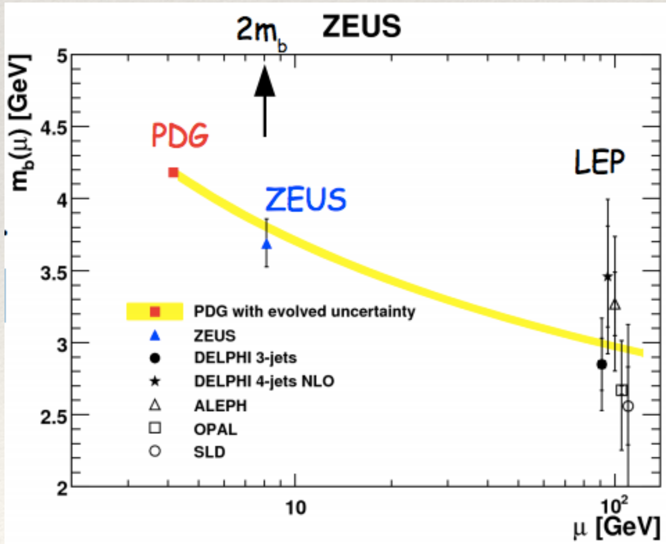
- The value of the running beauty mass is obtained using HERAFitter (via OPENQCDRAD):
  - chi2 scan method from QCD fits in FFN scheme to the combined HERA I inclusive data + beauty measurements, beauty-quark mass is defined in the $\overline{\text{MS}}$ scheme.



QCD Fits

HERA I+beauty





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

Transverse Momentum Distributions

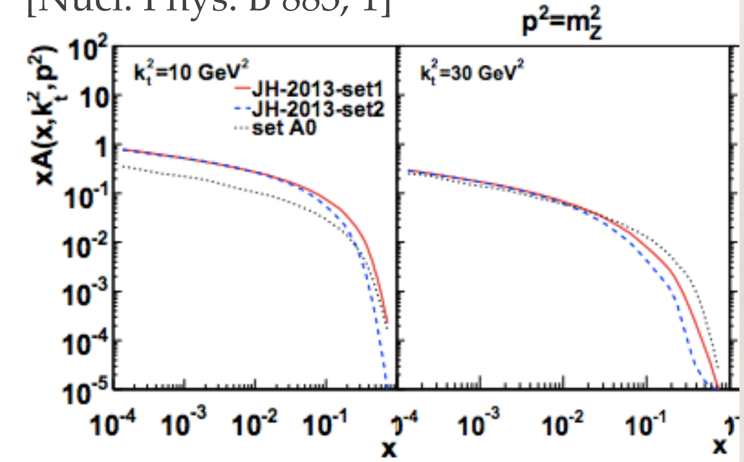
- QCD applications to multiple-scale scattering problems and complex final-state observables require in general formulations of factorisation which involve transverse-momentum dependent (TMD) - or known also as unintegrated PDFs.

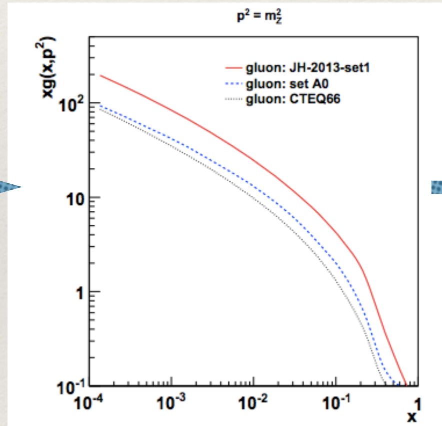
$$\sigma_j(x, Q^2) = \int_x^1 dz \int d^2k_t \; \hat{\sigma}_j(x, Q^2, z, k_t) \; \mathcal{A}(z, k_t, \mu)$$

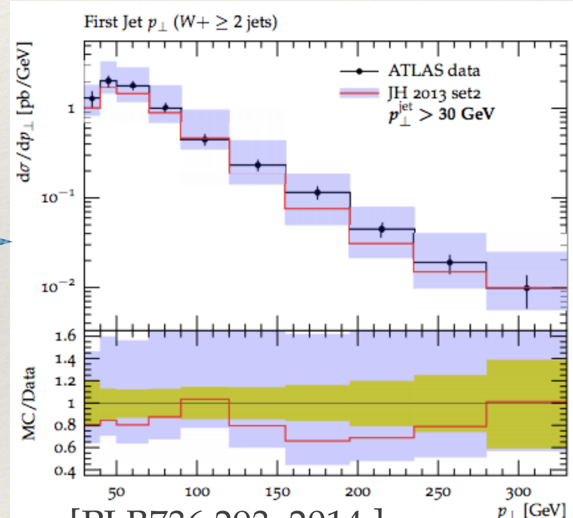
$\longrightarrow$ a convolution in both longitudinal and transverse momenta of TMD with off-shell partonic matrix elements

- Fits to combined measurements of proton's structure functions from HERA using transverse momentum dependent QCD factorisation and CCFM evolution is performed using HERAFitter platform

[Nucl. Phys. B 883, 1]







[PLB736:293, 2014.]

- The extracted gluon TMD with experimental and theory uncertainty [JH-2013-set1] is then used as prediction to vector boson+jet production process at the LHC [Phys. Rev. D 85 (2012) 092002.]
  - This process is important both for SM physics and for new physics searches at the LHC
  - Results compare well with the measurements of jet multiplicities and transverse momentum spectra within the pdf uncertainties

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

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

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

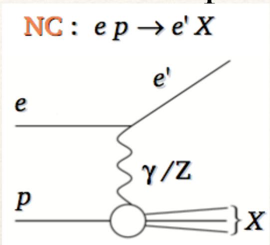
Due to increased precision of data, more flexibility in functional form is allowed —> 15 free parameters

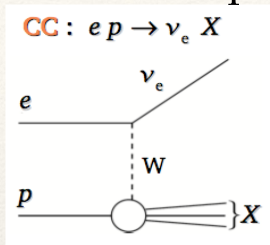
- PDFs are evolved via evolution equations (DGLAP) to NLO and NNLO (as(MZ)=0.118)
- Thorne-Roberts GM-VFNS for heavy quark coefficient functions – as used in MSTW
- Chi2 definition used in the minimisation [MINUIT] accounts for correlated uncertainties:

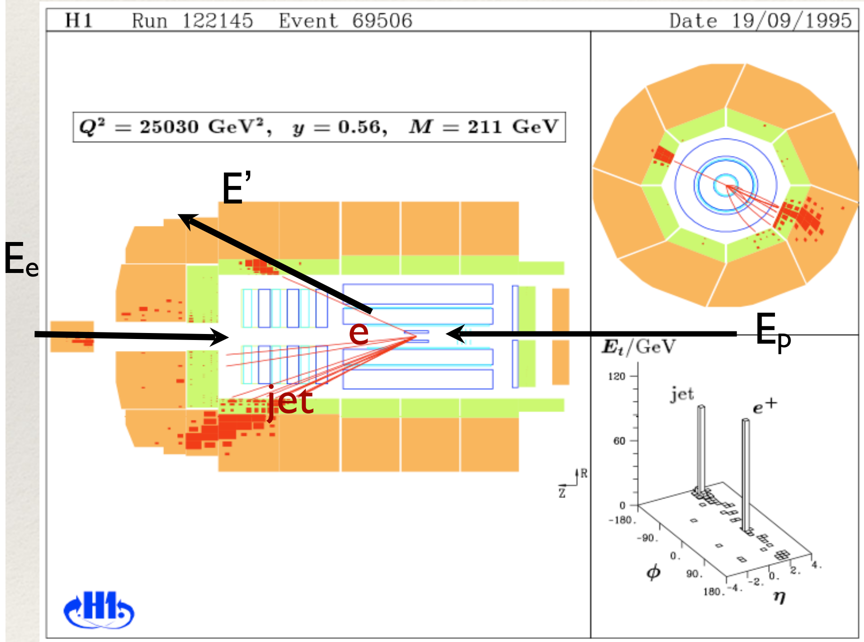
$$\chi^2_{tot}(\mathbf{m},\mathbf{b}) = \sum_i \frac{[\mu^i - m^i(1-\sum_j \gamma^i_j b_j)]^2}{\delta^2_{i,stat}\mu^i m^i(1-\sum_j \gamma^i_j b_j) + (\delta_{i,unc} m^i)^2} + \sum_j b_j^2 + \sum_i \ln \frac{\delta^2_{i,unc} m_i^2 + \delta^2_{i,stat}\mu^i m^i}{\delta^2_{i,unc}\mu_i^2 + \delta^2_{i,stat}\mu_i^2}$$

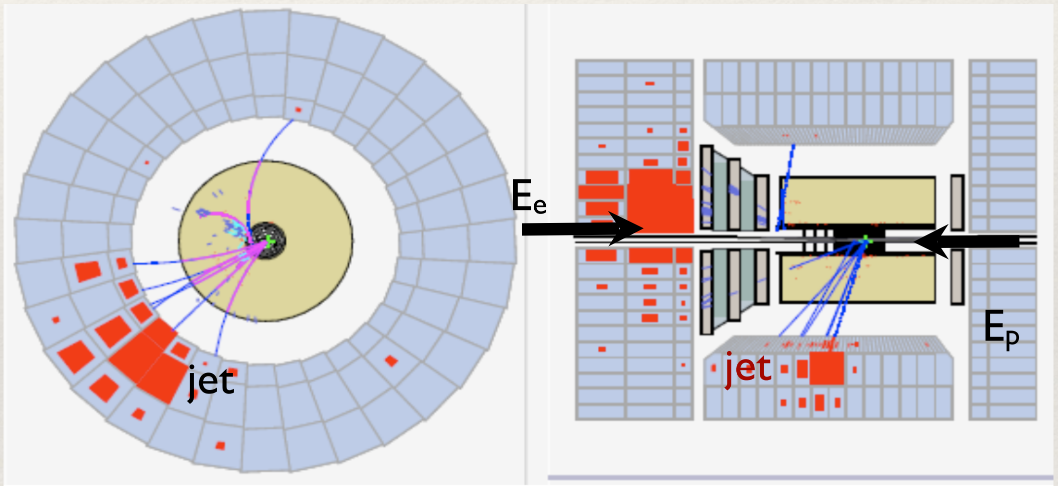
HERA ep collider (1992-2007) @ DESY

- H1 and ZEUS experiments at HERA collected ~1/fb of data
  - Ep=460/575/820/920 GeV and Ee=27.5 GeV
- **Neutral Current** event sample in H1 detector
- **Charged Current** event sample in ZEUS detector









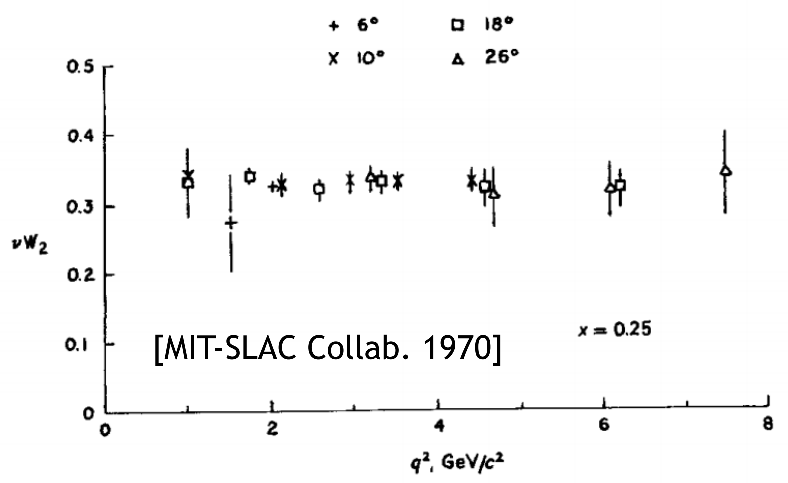
Determination of the Event Kinematics:

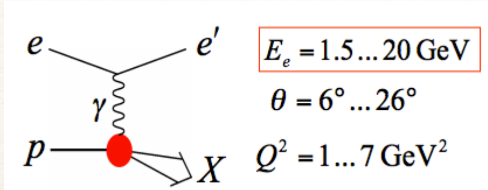
- using lepton information (E_e',θ_e)
- **using hadronic final state particles**
- using both lepton and hadronic final state variables

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

Parton Distribution Functions

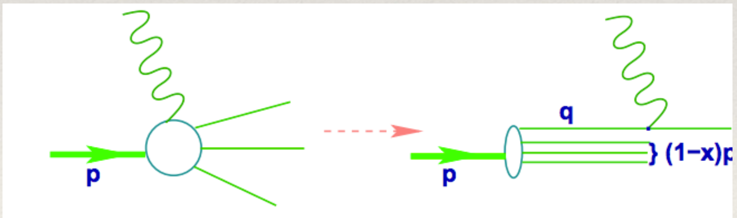
- Parton Model was introduced by Feynman (1969) to explain the Bjorken scaling:





Concept of Scaling:
if proton is made up from point-like particles, then the cross section becomes approximately independent on the scale;
[as we know, later with higher resolving power scaling violations were proven]

- inelastic scattering with nucleon is viewed as elastic scattering between lepton and a point-like constituent of the target – **partons** (non-interacting) – explicitly assumed to be spin-1/2 particles

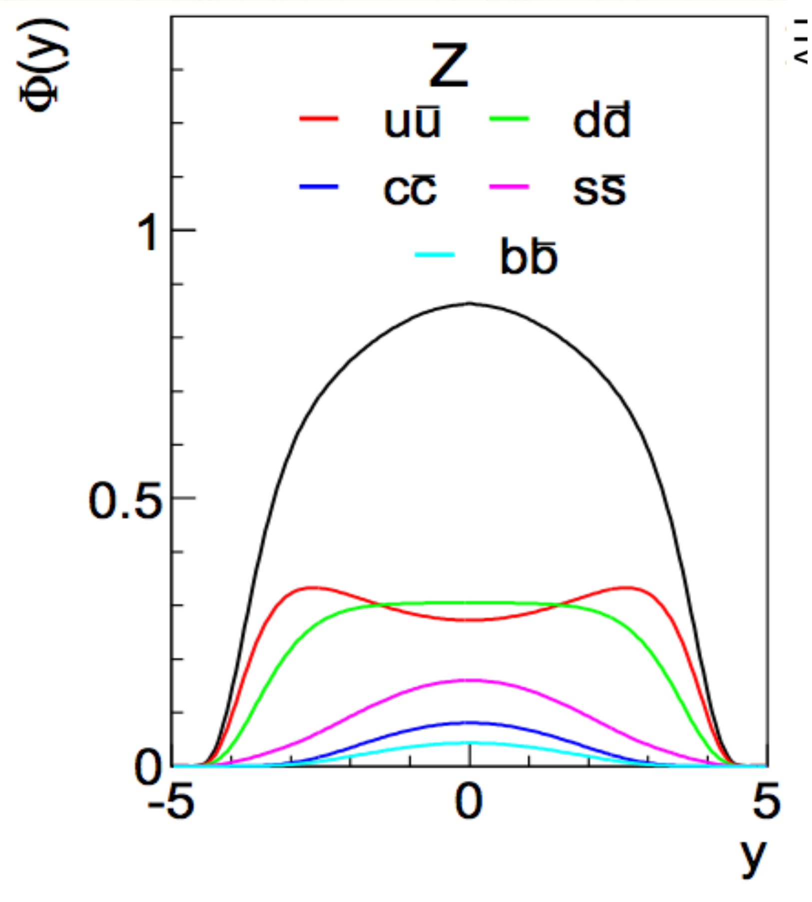


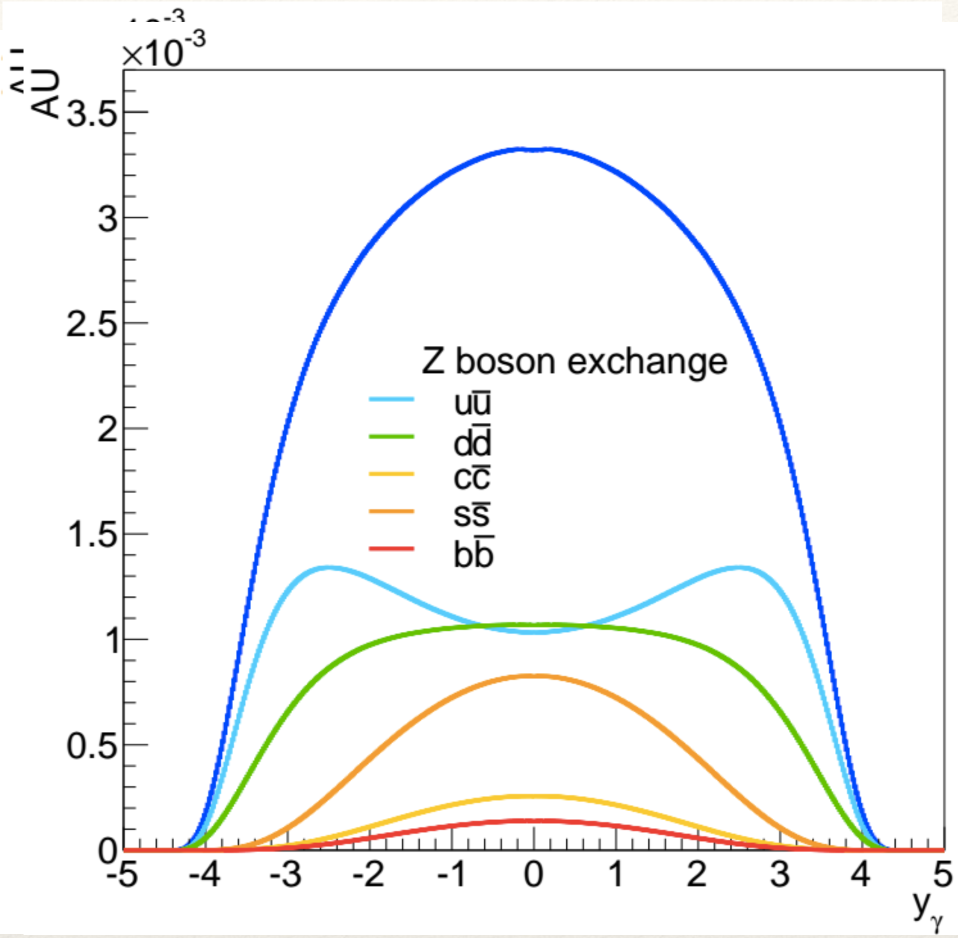
- Parton Distribution Functions (PDFs): Each parton carries the fraction x with a probability q(x)

$$\left(\frac{d\sigma}{dxdQ^2}\right)_{ep\to eX} = \sum_i \int dx e_i^2 q_i(x) \left(\frac{d\sigma}{dxdQ^2}\right)_{eq_i\to eq_i}.$$

Enhanced Strange

- CT10 vs ATLAS_epWZ





DIS Cross Sections

- Differential cross section is experimentally measured: theory meets the experiment

- Factorisable nature of interaction: Inclusive scattering cross section is a product of leptonic and hadronic tensors times propagator characteristic of the exchanged particle:

$$\frac{d^2\sigma}{dxdQ^2} = \frac{2\pi\alpha^2}{Q^4 x}\sum_j \eta_j L_j^{\mu\nu} W_j^{\mu\nu}$$

For NC: j=γ, Z, γZ
For CC: j=W+, W-

$$\eta_\gamma = 1; \qquad \eta_{\gamma Z} = \left(\frac{G_F M_Z^2}{2\sqrt{2}\pi\alpha}\right)\left(\frac{Q^2}{Q^2+M_Z^2}\right); \qquad \eta_Z = \eta_{\gamma Z}^2;$$

$$\eta_W = \frac{1}{2}\left(\frac{G_F M_W^2}{4\pi\alpha}\frac{Q^2}{Q^2+M_W^2}\right)^2,$$

Leptonic tensor: related to the coupling of the lepton with the exchanged boson

- contains the electromagnetic or the weak couplings
- can be calculated exactly in the standard electroweak U(1) × SU(2) theory.

Hadronic tensor: related to the interaction of the exchanged boson with proton

- can't be calculated, but only be reduced to a sum of structure functions:

~m_{lepton}

$$W^{\alpha\beta} = -g^{\alpha\beta}W_1 + \frac{p^\alpha p^\beta}{M^2}W_2 - \frac{i\epsilon^{\alpha\beta\gamma\delta}p_\gamma q_\delta}{2M^2}W_3 + \boxed{\frac{q^\alpha q^\beta}{M^2}W_4 + \frac{p^\alpha q^\beta + p^\beta q^\alpha}{M^2}W_5 + \frac{i(p^\alpha q^\beta - p^\beta q^\alpha)}{2M^2}W_6}$$

$$\frac{d^2\sigma}{dxdQ^2} = A^i\left\{(1-y-\frac{x^2y^2M^2}{Q^2})F_2^i + y^2 x F_1^i \mp (y-\frac{y^2}{2})xF_3^i\right\}$$

A^i: process dependent

Extraction of PDFs through QCD fits

- Extraction of PDFs relies on the factorisation: $\sigma = \hat{\sigma} \otimes \mathrm{PDF}$

- Typical measurements sensitive to PDFs are precise, with statistical uncertainties < 10%, so they follow normal distribution —> use of χ^2 minimisation for PDF extraction.

Main Steps:

- **Parametrise PDFs at a starting scale**

HERAPDF style has standard polynomial form: $xf_j(x) = A_j x^{B_j}(1-x)^{C_j} P_j(x)$

where $P_j(x) = (1 + \epsilon\sqrt{x} + Dx + Ex^2)$ for HERA PDF style, or
$P_j(x) = e^{a_3 x}(1 + e^{a_4}x + e^{a_5}x^2)$ for CTEQ PDF style

A: overall normalisation
B: small x behavior
C: x→ 1 shape

Bi Log-Normal Distribution style: $xf_j(x) = a_j x^{p_j - b_j \log(x)}(1-x)^{q_j - d_j \log(1-x)}$

Chebyshev is a flexible parametrisation (polynomials with argument log(x)) which can be employed for the gluon and sea distributions
(see A. Glazov, S. Moch, and V. Radescu, Phys. Lett. B 1149 695, 238 (2011), [arXiv:1009.6170])

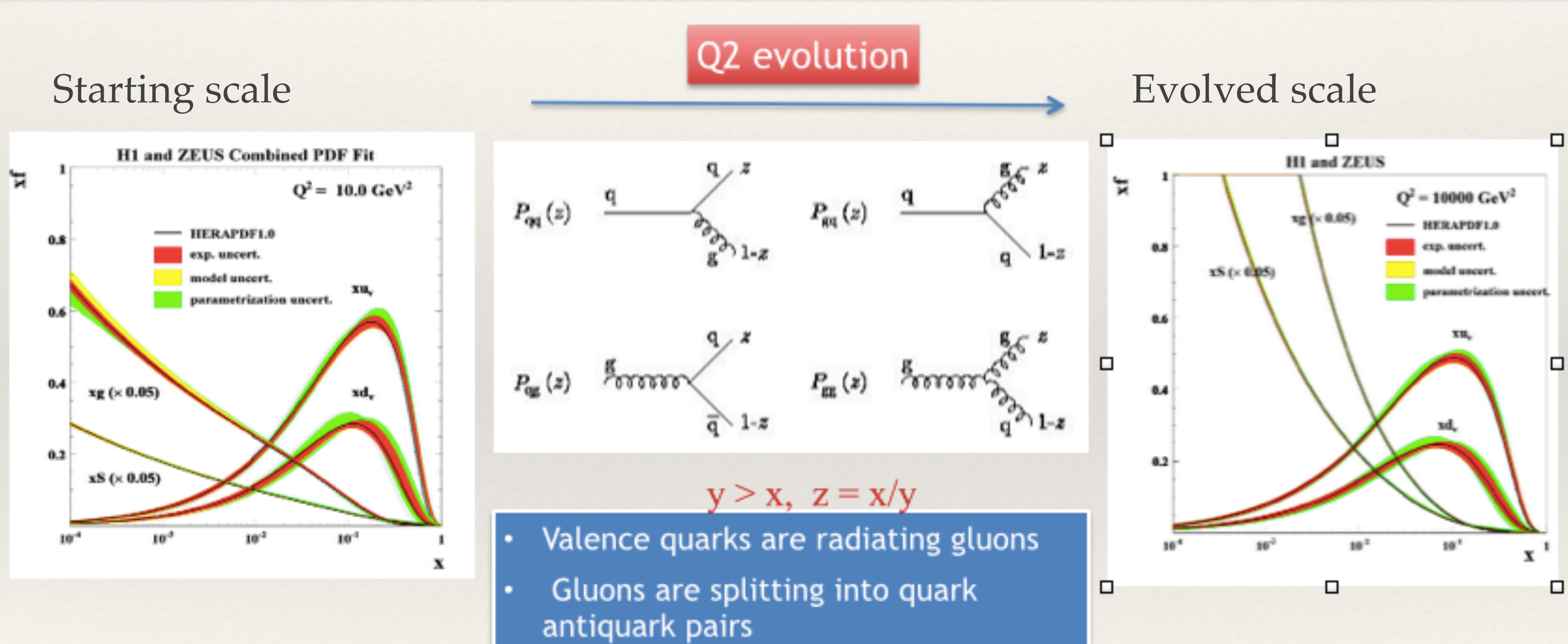
Extraction of PDFs through QCD fits

- Extraction of PDFs relies on the factorisation: $\sigma = \hat{\sigma} \otimes \mathrm{PDF}$

- Typical measurements sensitive to PDFs are precise, with statistical uncertainties < 10%, so they follow normal distribution —> use of χ^2 minimisation for PDF extraction.

Main Steps:

- Parametrise PDFs at a starting scale
- **Evolve PDFs to the scale corresponding to data point**



Extraction of PDFs through QCD fits

- Extraction of PDFs relies on the factorisation: $\sigma = \hat{\sigma} \otimes \mathrm{PDF}$

- Typical measurements sensitive to PDFs are precise, with statistical uncertainties < 10%, so they follow normal distribution —> use of χ^2 minimisation for PDF extraction.

Main Steps:

- Parametrise PDFs at a starting scale
- Evolve PDFs to the scale corresponding to data point
- **Calculate the cross section**
- Compare with data via χ^2
- Minimise χ^2 wrt PDF parameters

DY integration code:

Simple LO cross section formulae: DY NC: $pp \to Z/\gamma \to e^+e^-$

$$\frac{d\sigma^2_\gamma}{dMdycos\theta^*} = N_c C^2_{q\bar{q}} \frac{8\alpha^2}{3M^3}\tau \times \sum_q e_q^2 f_q(x_1, M) f_{\bar{q}}(x_2, M) F_{q\bar{q}}(1+\cos^2\theta^*, \cos\theta^*)$$

DY CC: $pp \to W^\pm \to e^\pm \nu$

$$\frac{d\sigma^3_{W\pm}}{dMdycos\theta^*} = \frac{\pi\alpha^2}{48 s_W^4} M\tau \frac{(1-cos\theta^*)^2}{(M^2 - M_W^2)^2 + \Gamma_W^2 M_W^2} \times \sum_{qq'} V_{qq'} f_q(x_1, M) f_{q'}(x_2, M)$$

Theory:
necessary to have fast tools
(APPLGRID, FASTNLO)

Extraction of PDFs through QCD fits

- Extraction of PDFs relies on the factorisation: $\sigma = \hat{\sigma} \otimes \text{PDF}$

- Typical measurements sensitive to PDFs are precise, with statistical uncertainties < 10%, so they follow normal distribution —> use of χ^2 minimisation for PDF extraction.

Main Steps:

- Parametrise PDFs at a starting scale
- Evolve PDFs to the scale corresponding to data point
- Calculate the cross section
- **Compare with data via χ^2**
- **Minimise χ^2 wrt PDF parameters**

Covariance Matrix Representation:

$$\chi^2(m) = \sum_{i,k}(m_i - \mu_i)C^{-1}_{ik}(m_k - \mu_k)$$

*is C^{-1}_{ik}(**stat**), C^{-1}_{ik}(**syst**) or C^{-1}_{ik}(**tot**)$=C^{-1}_{ik}$(**stat**)$+C^{-1}_{ik}$(**syst**)*

Mixed form representation:

$$\chi^2_{\text{exp}}(\boldsymbol{m}, \boldsymbol{b}) = \sum_{ij}\left(m^i - \sum_l \Gamma^i_l(m^i)b_l - \mu^i\right)C^{-1}{}_{ij}(m^i, m^j)\left(m^j - \sum_l \Gamma^j_l(m^j)b_l - \mu^j\right) + \sum_l b_l^2$$

$\chi^2_{min}/N_{D.F} \approx 1$ if model is consistent with the data.

Nuisance parameter case:

$$\chi^2(m,b) = \sum_i \frac{\left[\underbrace{\mu_i}_{\text{data}} - \underbrace{m_i}_{\text{theory}}\left(1 - \sum_j \gamma^i_j b_j\right)\right]^2}{\delta^2_{i,\text{unc}} m_i^2 + \delta^2_{i,\text{stat}}\,\mu_i m_i\left(1 - \sum_j \gamma^i_j b_j\right)} + \sum_j b_j^2 + \text{log penalty}$$

$\delta_{i,\text{stat}}$ $\delta_{i,\text{uncor}}$ are relative statistical and uncor related systematic uncertainties of the measurement *i*

γ^i_j quantifies the sensitivity of the measurement to the correlated systematic source *j*

b_j nuisance parameter

→ for more details see e.g. HERAPDF1.9, JHEP 1001, 109 (2010)

Extraction of PDFs through QCD fits

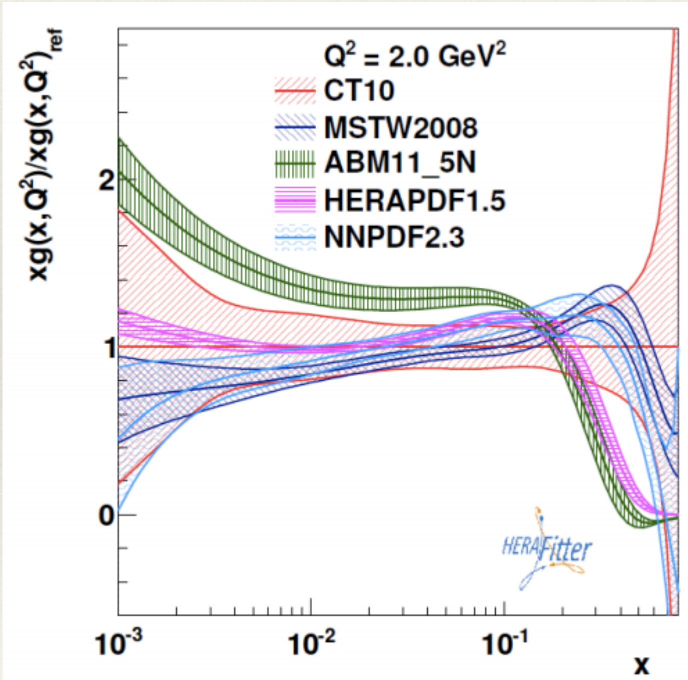
- Extraction of PDFs relies on the factorisation: $\sigma = \hat{\sigma} \otimes \mathrm{PDF}$

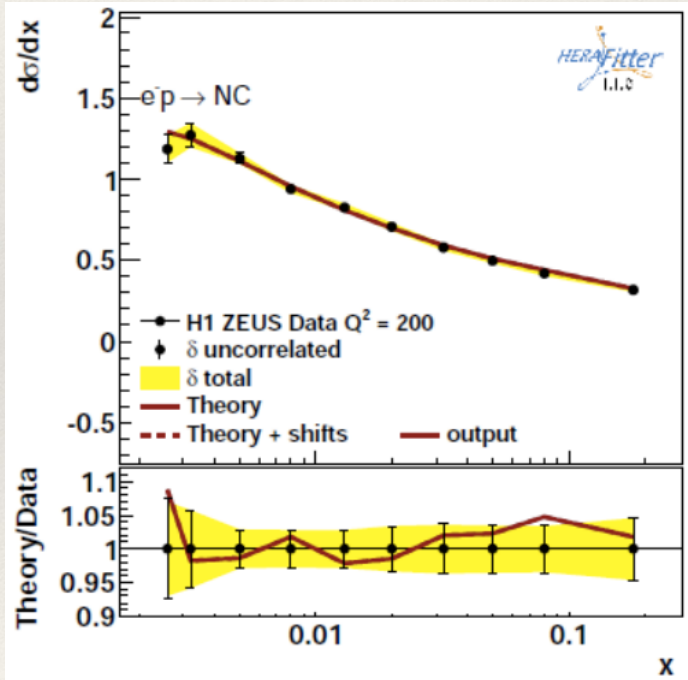
- Typical measurements sensitive to PDFs are precise, with statistical uncertainties < 10%, so they follow normal distribution —> use of χ^2 minimisation for PDF extraction.

Main Steps:

www.herafitter.org

- Parametrise PDFs at a starting scale
- Evolve PDFs to the scale corresponding to data point
- Calculate the cross section
- Compare with data via χ^2
- Minimise χ^2 wrt PDF parameters
- **extract PDFs, and build predictions based on PDFs**





DIS Cross Sections

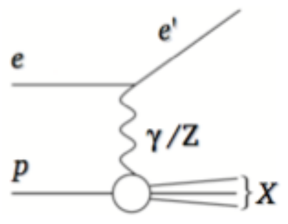
General Form for the Differential cross section:

$$\boxed{\frac{d^2\sigma}{dx dQ^2} = A^i\left\{(1-y-\frac{x^2y^2M^2}{Q^2})F_2^i + y^2xF_1^i \mp (y-\frac{y^2}{2})xF_3^i\right\}}$$

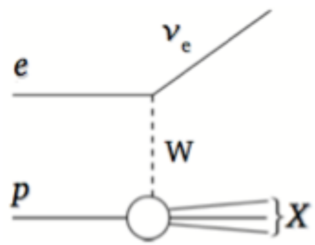
$$xF_3 \sim \sum(xq_i - x\bar{q}_i)$$
$$F_L \sim \alpha_S g$$
$$F_2 \sim \sum e_i^2(xq_i + x\bar{q}_i)$$

A^i: process dependent

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



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



NC:

$$\boxed{\frac{d^2\sigma^{\pm}_{NC}}{dx dQ^2} = \frac{2\pi\alpha^2}{x}\left[\frac{1}{Q^2}\right]^2 \phi^{\pm}_{NC}(x,Q^2)}$$

$$\phi_{NC} = Y_+\tilde{F}_2^{\pm}(x,Q^2) - y^2\tilde{F}_L^{\pm}(x,Q^2) \mp Y_- x\tilde{F}_3^{\pm}(x,Q^2),$$

$$\tilde{F}_2^{\pm} = F_2 - (v_e \pm P_e a_e)\kappa_Z F_2^{\gamma Z} + (v_e^2 + a_e^2 \pm 2P_e v_e a_e)\kappa_Z^2 F_2^Z, \quad \kappa_Z(Q^2) = \frac{1}{4\sin^2(\theta_W)\cos^2(\theta_W)}\frac{Q^2}{Q^2+M_Z^2}$$

$$x\tilde{F}_3^{\pm} = -(a_e \pm P_e v_e)\kappa_Z xF_3^{\gamma Z} + (2v_e a_e \pm P_e(v_e^2 + a_e^2))\kappa_Z^2 xF_3^Z,$$

CC:

$$\boxed{\frac{d^2\sigma^{\pm}_{CC}}{dx dQ^2} = (1 \pm P_e)\frac{G_F^2}{2\pi x}\left[\frac{M_W^2}{Q^2+M_W^2}\right]^2 \phi^{\pm}_{CC}(x,Q^2).}$$

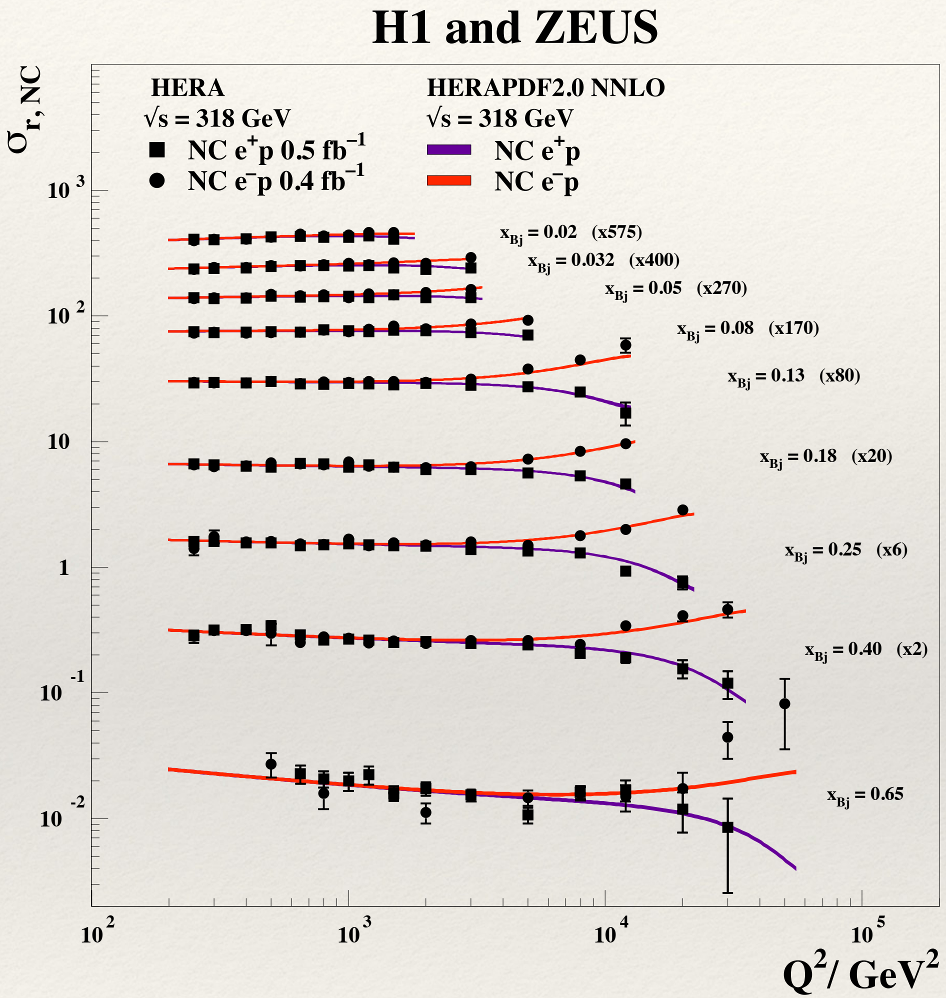
At LO

$$e^+: \quad \phi^+_{CC} = x[(\bar{u}(x) + \bar{c}(x)) + (1-y)^2(d(x) + s(x))].$$

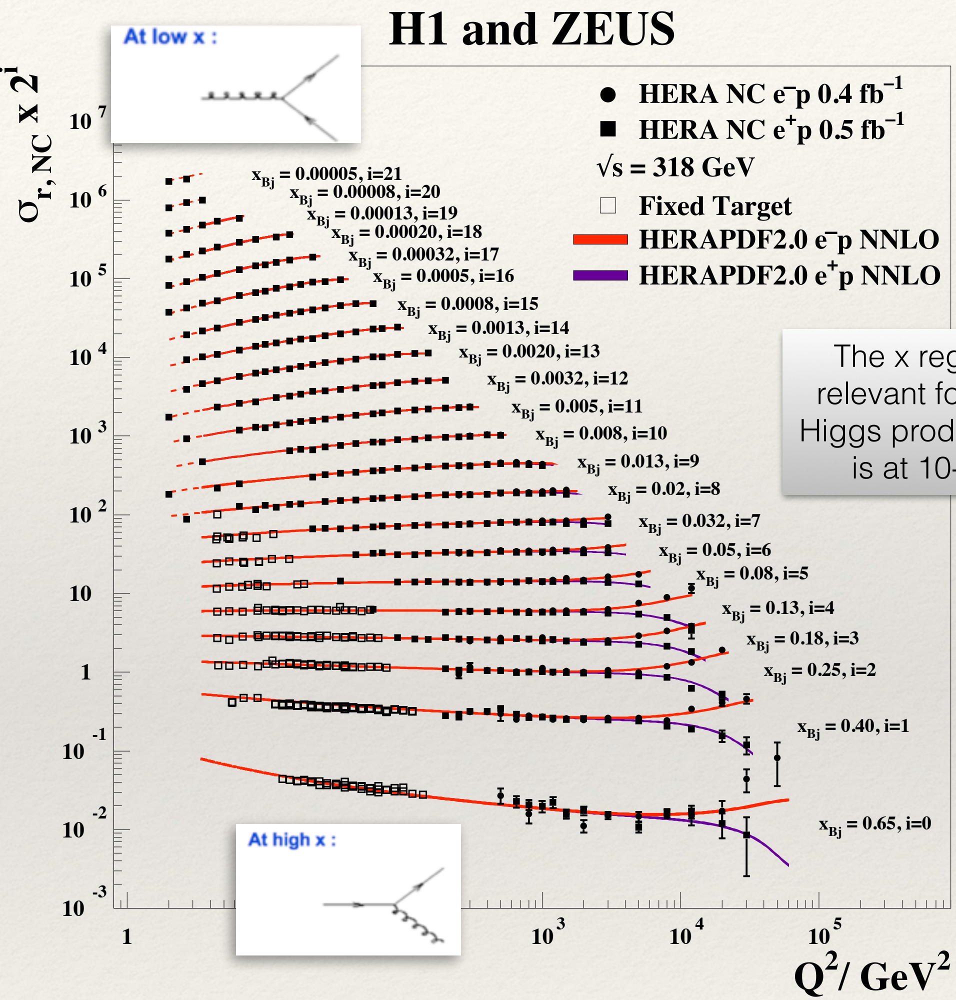
$$e^-: \quad \phi^-_{CC} = x[(u(x) + c(x)) + (1-y)^2(\bar{d}(x) + \bar{s}(x))]$$

QCD scaling and EW effects

- EW effects clearly seen at high Q2:



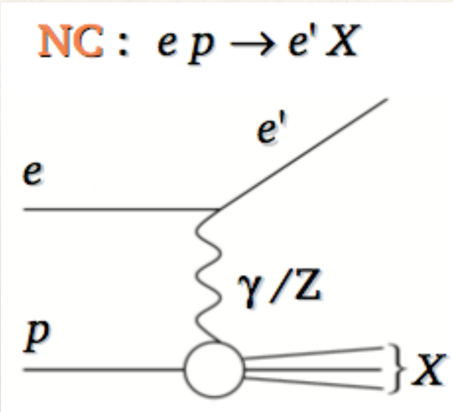
QCD scaling violations nicely seen:

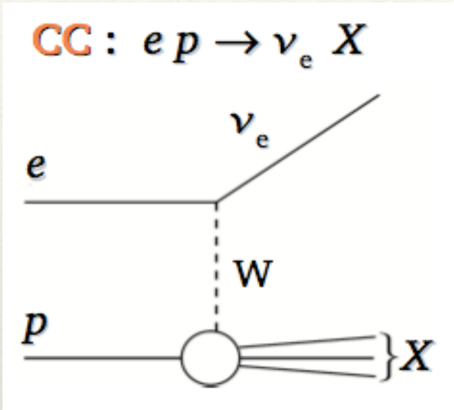


The x region relevant for the Higgs production is at 10-2.

HERA ep collider (1992-2007) @ DESY

- H1 and ZEUS experiments at HERA collected ~1/fb of data
  - Ep=460/575/820/920 GeV and Ee=27.5 GeV
- 4 type of processes accessed at HERA: **Neutral Current and Charged Current ep**





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

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

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

$\tilde{F}_2 \propto \sum(xq_i + x\bar{q}_i)$ → dominant contribution (all Q2 plane)

$x\tilde{F}_3 \propto \sum(xq_i - x\bar{q}_i)$ → significant contributions at high Q2

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

Determination of the Event Kinematics:

- using lepton information (E_e', θ_e)
- using hadronic final state particles
- using both lepton and hadronic final state variables

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

Modern understanding of PDFs

Different types of PDF uncertainties are considered:

- **Experimental:**
  - Hessian method used: MSTW, CT, ABM, JR, HERAPDF, CJ..
    - Consistent data sets → use $\Delta\chi^2$=1 (HERAPDF, ABM, ..) or larger tolerance (MMHT, CT)
  - Monte Carlo Method: replicas of data (NNPDF)

- 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 [A.Glazov and VR, HERA-LHC proceedings, arXiV:0901.2504, page 41-42]

  - 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