xFitter Meeting in Oxford, UK

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The photon PDF from high-mass Drell Yan data at the LHC

F. Giuli (on the behalf of the analysis team)

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20/03/2017

Oxford Physics

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xFitter

High Energy Physics – Phenomenology

The photon PDF from high-mass Drell Yan data at the LHC

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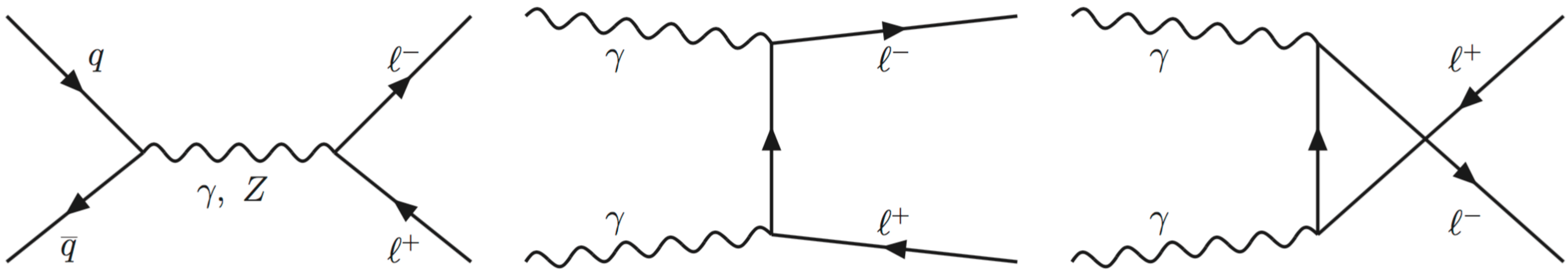
(Submitted on 30 Jan 2017)

- Theory motivations
- ATLAS analysis at 8 TeV review
- Theory inputs
- Fit results
- Comparison of the fit with modern PDF sets
- Robustness and perturbative stability checks
- Concluding remarks

arXiv:1701.08553v1

Theoretical motivations

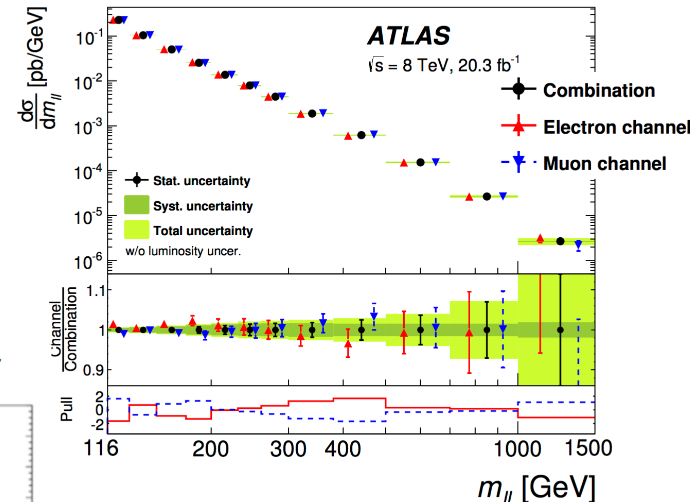
- Interpretation of the LHC data requires theoretical calculations that include not only QCD corrections, but also the EW effects for the TeV region.
- DY data at LHC can provide direct sensitivity to photon PDF: from $q\bar{q}$ *s*-channel scattering, from $\gamma\,\gamma$ *t*- and *u*- channels scattering mediated by a lepton



- An important ingredient of the EW corrections is the photon PDF of the proton:
  - Historically, the first set was MRST2004 QED: photon taken from a model and tested on direct photon production at HERA
  - NNPDF2.3 QED provided a first model independent determination from fits to DY LHC data
  - More photon PDFs followed: CT, NNPDF
  - A new approach from LUXqed: photon PDF calculated from inclusive structure functions (% level precision); similarly HKR16

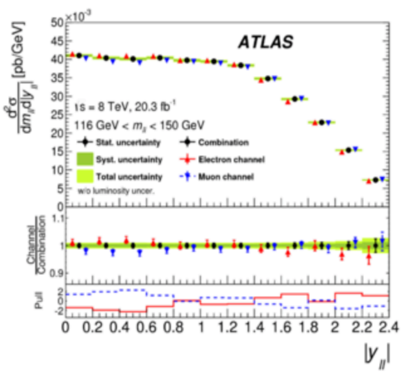
Input dataset

- ATLAS high mass Drell Yan at 8 TeV (published in June '16) arXiv:1606.01736
- 1D (dilepton mass distribution)
- 2D in mass and rapidity bins distribution
  - 48 data points
  - this is expected to provide most sensitivity to PDFs

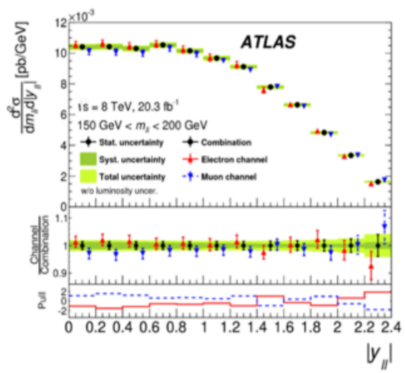


- Quite precise data! (less of 5% unc. up to 700 GeV)

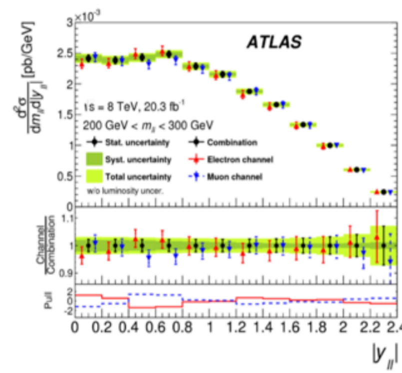
116 GeV < m < 150 GeV



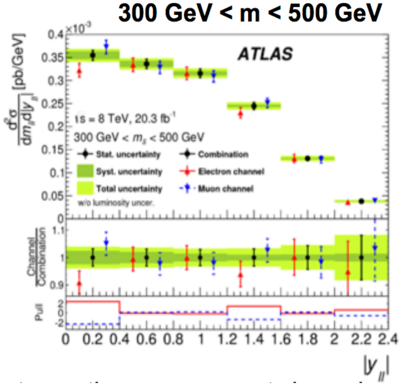
150 GeV < m < 200 GeV



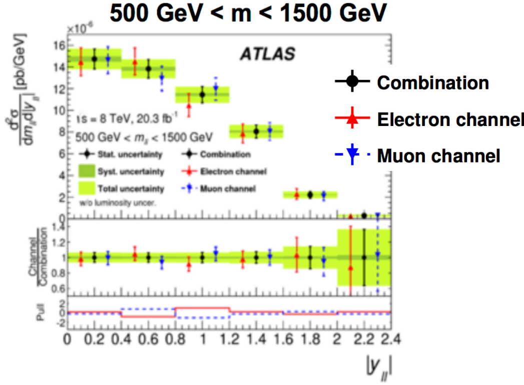
200 GeV < m < 300 GeV



300 GeV < m < 500 GeV



500 GeV < m < 1500 GeV

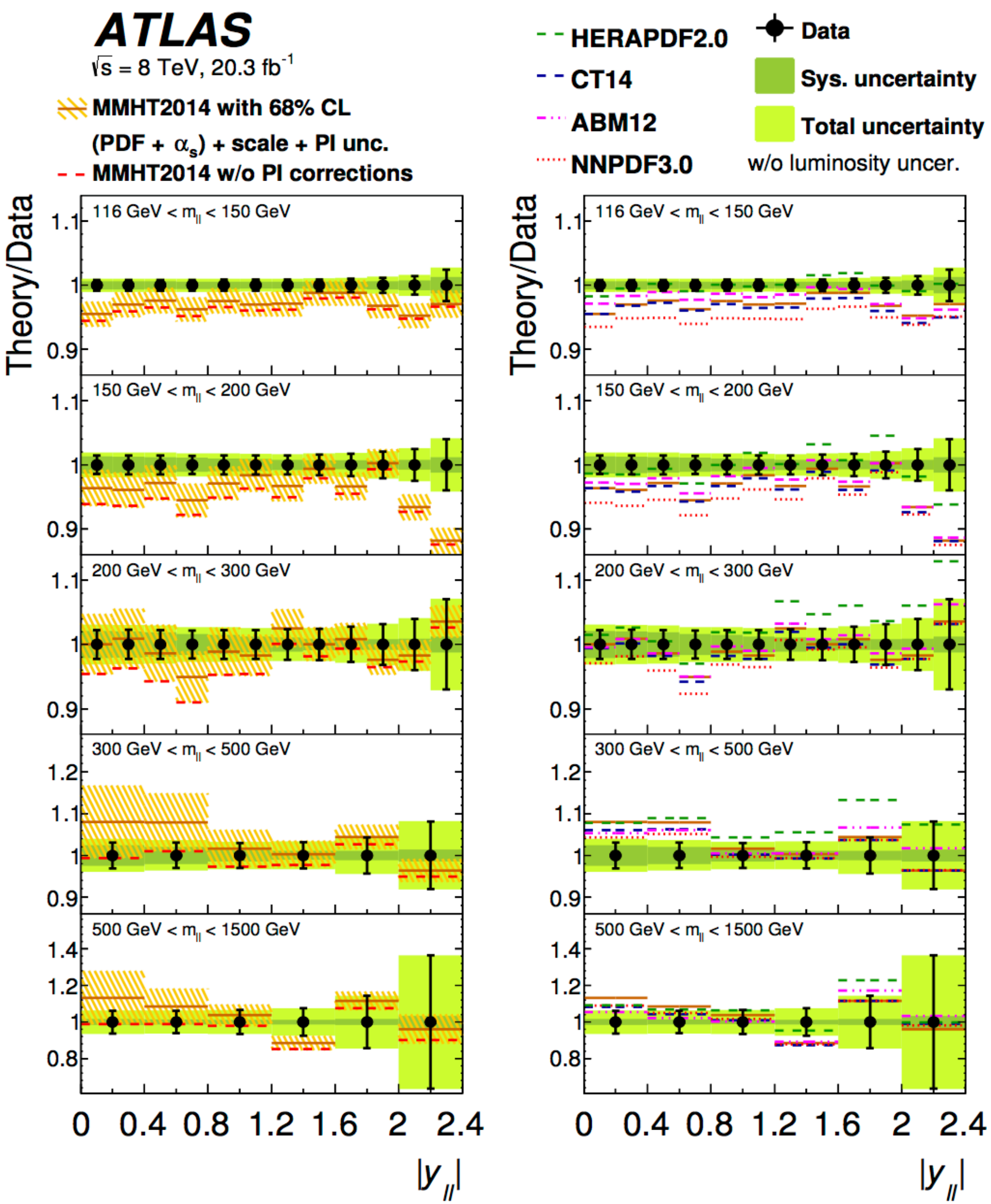


$$\frac{d^2\sigma}{dm_{ll}d|y_{ll}|}$$

- Also 2D in mass and Δη bins distribution

- Inclusive HERA I+II used as the base (7 data sets) – for full PDF coverage

Theory comparison



$$\frac{d^2\sigma}{dm_{ll}\,d|y_{ll}|}$$ **data/theory ratio**

- Really precise data!
- Photon-induced (PI) contribution increases with m_{ll} and decreasing $|y_{ll}|$
- PDF uncertainties calculated for each PDF scaled to 68% CL
- Compatibility of data to predictions with other PDFs test with χ^2 function

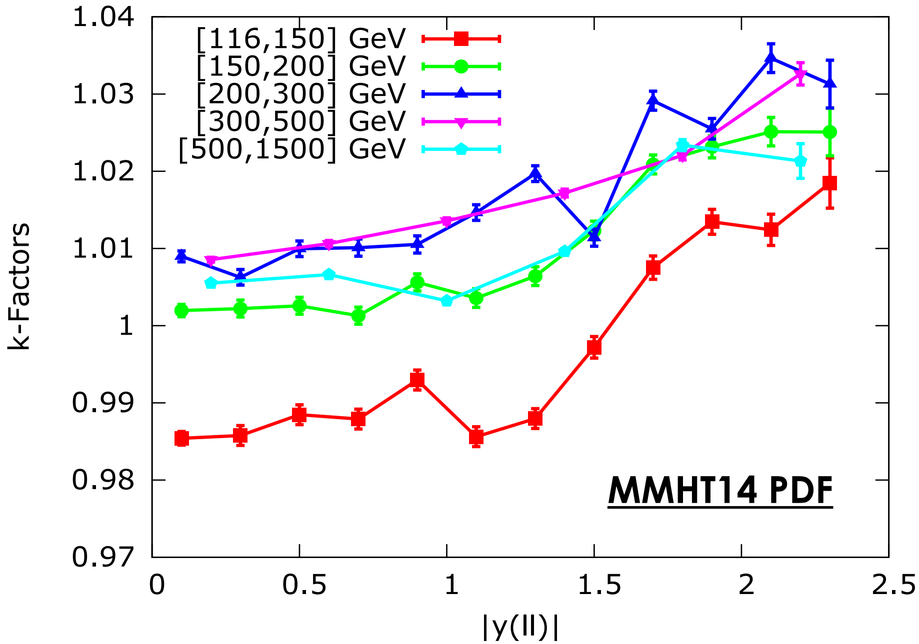
	$m_{\ell\ell}$	$\lvert y_{\ell\ell}\rvert$	$\lvert\Delta\eta_{\ell\ell}\rvert$
MMHT2014	18.2/12	59.3/48	62.8/47
CT14	16.0/12	51.0/48	61.3/47
NNPDF3.0	20.0/12	57.6/48	62.1/47
HERAPDF2.0	15.1/12	55.5/48	60.8/47
ABM12	14.1/12	57.9/48	53.5/47

Data in good agreement with SM predictions

Theory inputs

- **Fit Settings**:
- PDF evolution computed with APFEL program:
  - Accurate up to NNLO in QCD + NLO in QED
  - Includes relevant mixed QCD + QED correction
- HERA cross section: using FONLL-C HF scheme
- LHC hmDY cross sections calculated via Madgraph5_aMC@NLO which includes PI diagrams
  - Interfaced to APPLGRID via aMCfast
  - Tailored version of APPLGRID used to account for photon contributions
- NNLO QCD + NLO QED predictions obtained using FEWZ3.1 (dynamical scales are used se to m_{ll})

$$k_F(m_{ll}, |y_{ll}|) \equiv \frac{NNLO\ QCD + NLO\ EW}{NLO\ QCD + LO\ EW}$$



Determined by the technique of saturation of the χ^2

$$xu_v(x) = A_{u_v} x^{B_{u_v}} (1-x)^{C_{u_v}} (1 + E_{u_v} x^2),$$
$$xd_v(x) = A_{d_v} x^{B_{d_v}} (1-x)^{C_{d_v}},$$
$$x\bar{U}(x) = A_{\bar{U}} x^{B_{\bar{U}}} (1-x)^{C_{\bar{U}}},$$
$$x\bar{D}(x) = A_{\bar{D}} x^{B_{\bar{D}}} (1-x)^{C_{\bar{D}}},$$
$$xg(x) = A_g x^{B_g} (1-x)^{C_g} (1 + E_g x^2),$$
$$x\gamma(x) = A_\gamma x^{B_\gamma} (1-x)^{C_\gamma} (1 + D_\gamma x + E_\gamma x^2)$$

PDF parameterisation

(the number of parameters is increased one by one until the χ^2 does not improve further)

Theory inputs

- **Fit Settings**:
- PDF evolution computed with APFEL program:
  - Accurate up to NNLO in QCD, NLO in QED
  - Includes relevant mixed QCD+QED correction
- HERA cross section: using FONLL-C HF scheme
- LHC hmDY cross sections calculated via Madgraph5_aMC@NLO which includes PI diagrams
  - Interfaced to APPLGRID via aMCfast
  - Tailored version of APPLGRID used to account for photon contributions
- NNLO QCD + NLO QED predictions obtained using FEWZ3.1 (dynamical scales are used se to m_{ll})
- Chi2 definition: from H1 paper (arXiv:1206.7007)
- $Q_0^2 = 7.5$ GeV^2 (also Q^2 cut on data)
- $r_s = \frac{s+\bar{s}}{2\bar{d}} = 1.0$ (ATLAS W,Z data)
- $M_c = 1.41$ GeV
- $M_b = 4.5$ GeV
- Experimental uncertainties: MC vs. Hessian

$$k_F(m_{ll}, |y_{ll}|) \equiv \frac{NNLO\ QCD + NLO\ EW}{NLO\ QCD + LO\ EW}$$

Determined by the technique of saturation of the χ^2

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

PDF parameterisation

$$\chi^2 = \sum_i \frac{\left[\mu_i - m_i\left(1 - \sum_j \gamma_j^i b_j\right)\right]^2}{\delta_{i,\mathrm{unc}}^2 m_i^2 + \delta_{i,\mathrm{stat}}^2 \mu_i m_i \left(1 - \sum_j \gamma_j^i b_j\right)} + \sum_j b_j^2 + \sum_i \ln \frac{\delta_{i,\mathrm{unc}}^2 m_i^2 + \delta_{i,\mathrm{stat}}^2 \mu_i m_i}{\delta_{i,\mathrm{unc}}^2 \mu_i^2 + \delta_{i,\mathrm{stat}}^2 \mu_i^2},$$

Results

- **After minimisation 1283.80 1083 1.185** (χ^2/ #degrees of freedom)

HMDY 8 TeV

Dataset 1 8.96(-0.01) 12 HMDY rap 116-150
Dataset 2 15.36(+0.00) 12 HMDY rap 150 200
Dataset 3 13.81(-0.21) 12 HMDY rap 200 300
Dataset 4 4.82(+0.02) 6 HMDY rap 300 500
Dataset 5 3.96(+0.07) 6 HMDY rap 500 1500
Correlated Chi2 1.16547881441444461
Log penalty Chi2 -0.11984831500646678

χ^2/#points = 47.96/48

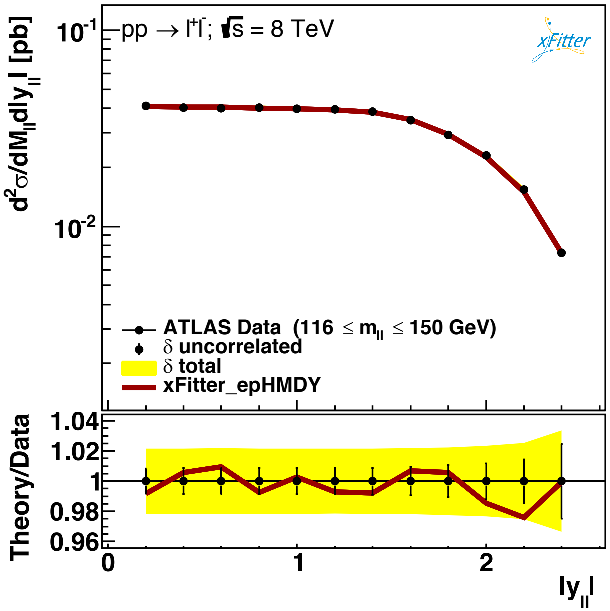
(data described well)

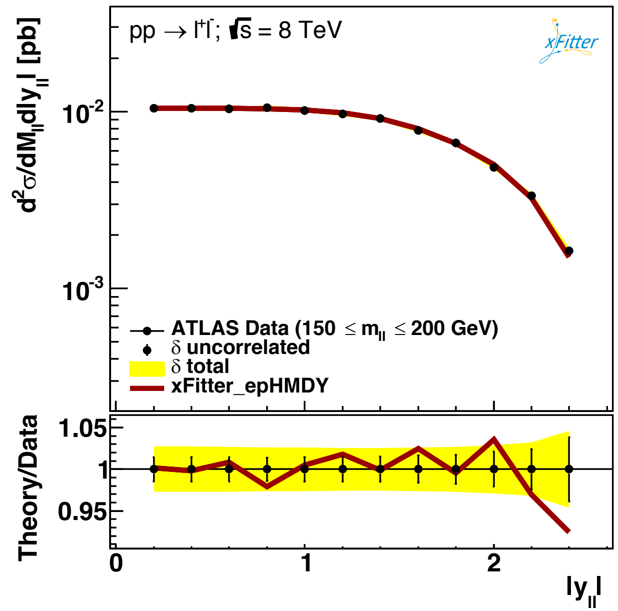
HERAI+II

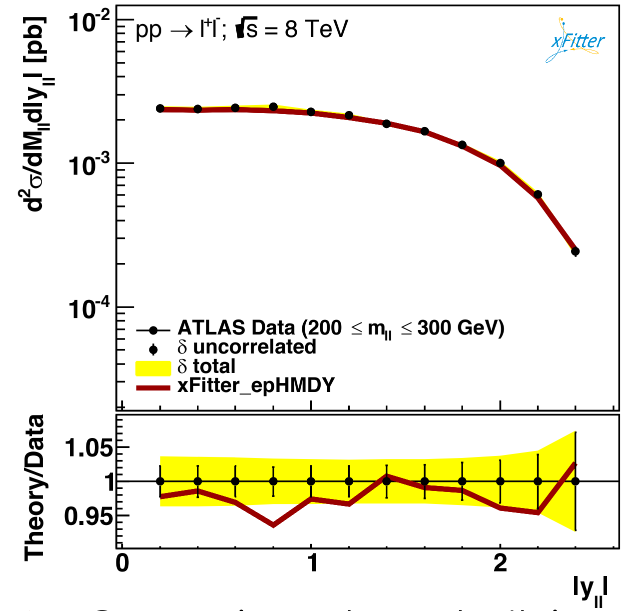
Dataset 1 218.79(-1.59) 159 HERA1+2 NCem
Dataset 2 383.22(+2.13) 332 HERA1+2 NCep 920
Dataset 3 60.49(-0.81) 63 HERA1+2 NCep 820
Dataset 4 197.41(+2.98) 234 HERA1+2 NCep 575
Dataset 5 207.41(-1.55) 187 HERA1+2 NCep 460
Dataset 6 54.61(-2.21) 42 HERA1+2 CCem
Dataset 7 48.52(+0.00) 39 HERA1+2 CCep
Correlated Chi2 66.4488724391
Log penalty Chi2 -1.0519009775

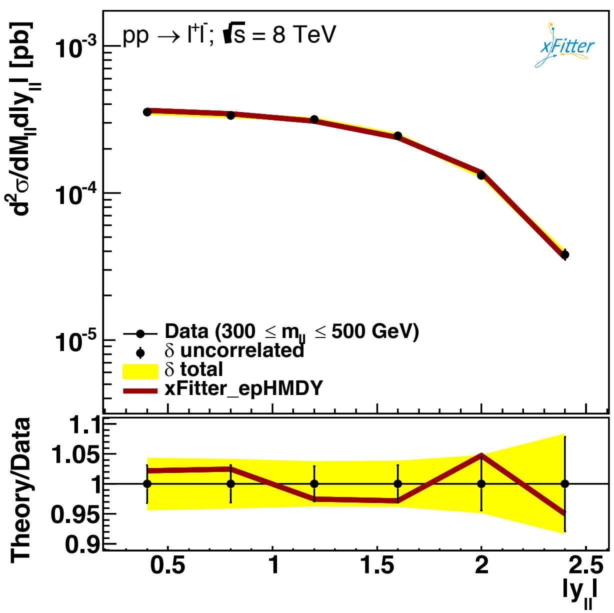
χ^2 /#points =1235.85/1056

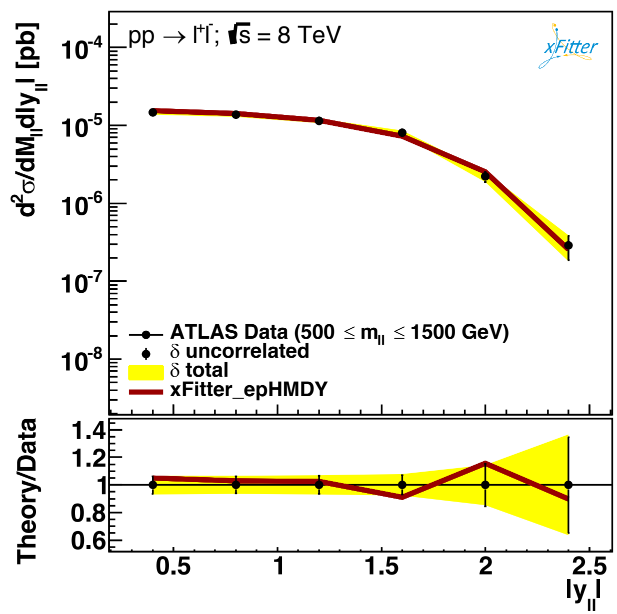
Data Vs Theory





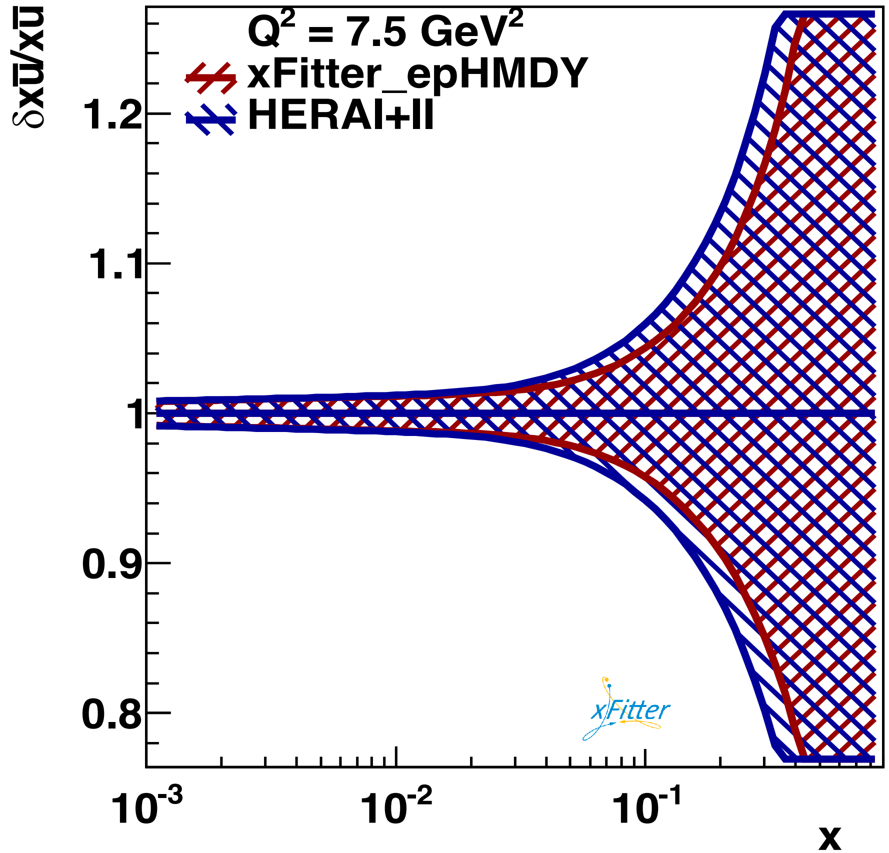


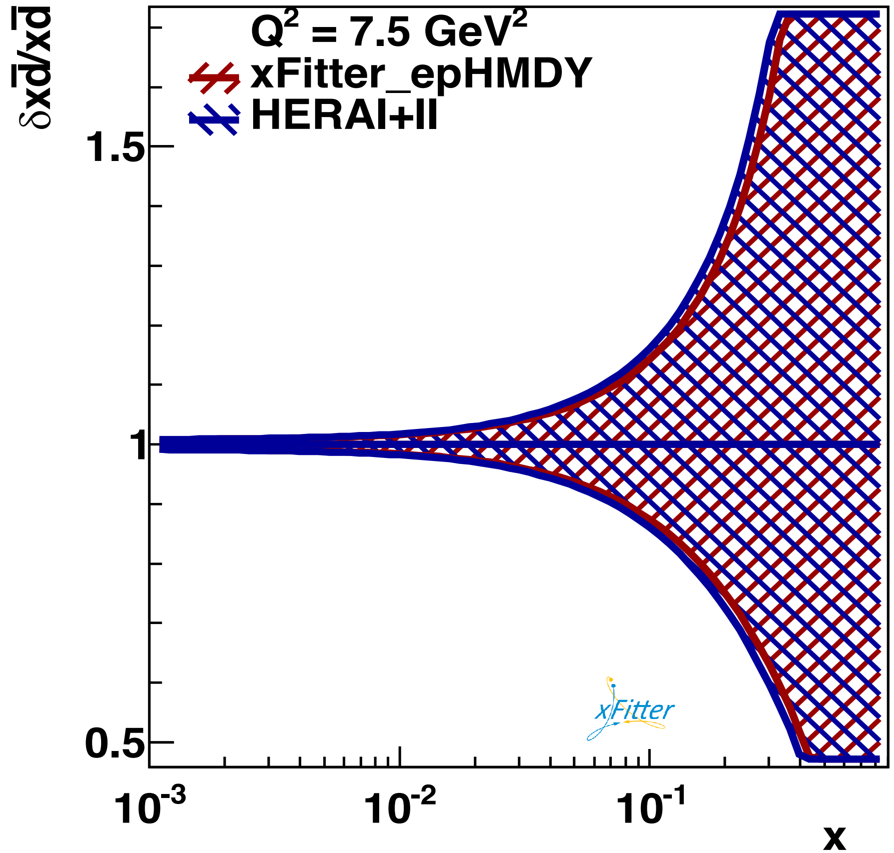




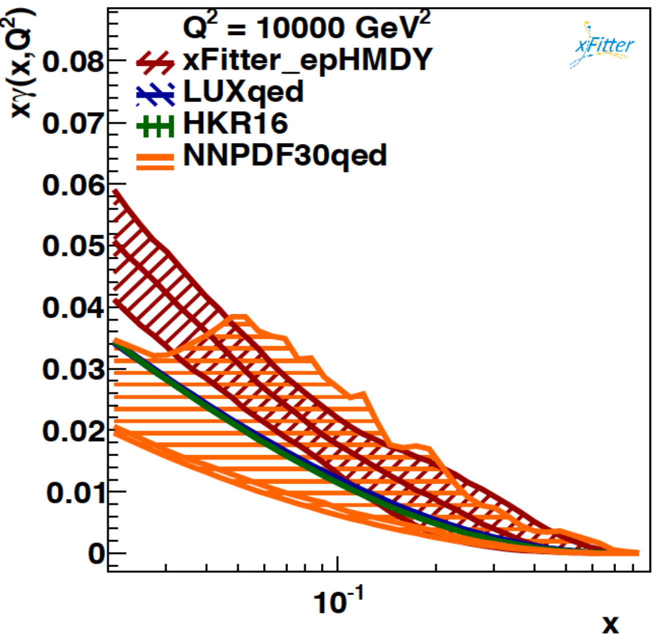
- Comparisons shown both in an absolute scale and as ratios to the central value of the experimental data
- Error bars on data correspond to statistical uncertainties
- Yellow bands indicate the size of the correlated systematic uncertainties
- **Good agreement between ATLAS data and NNLO theory predictions**

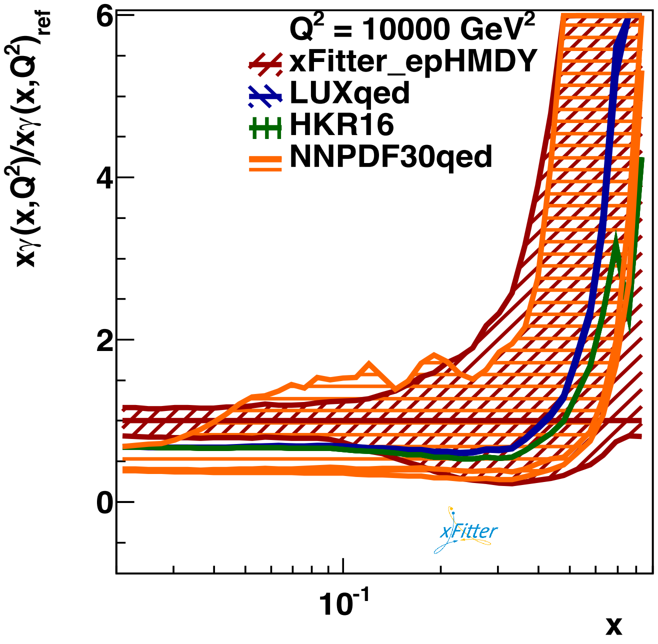
Impact on the antiquark PDFs



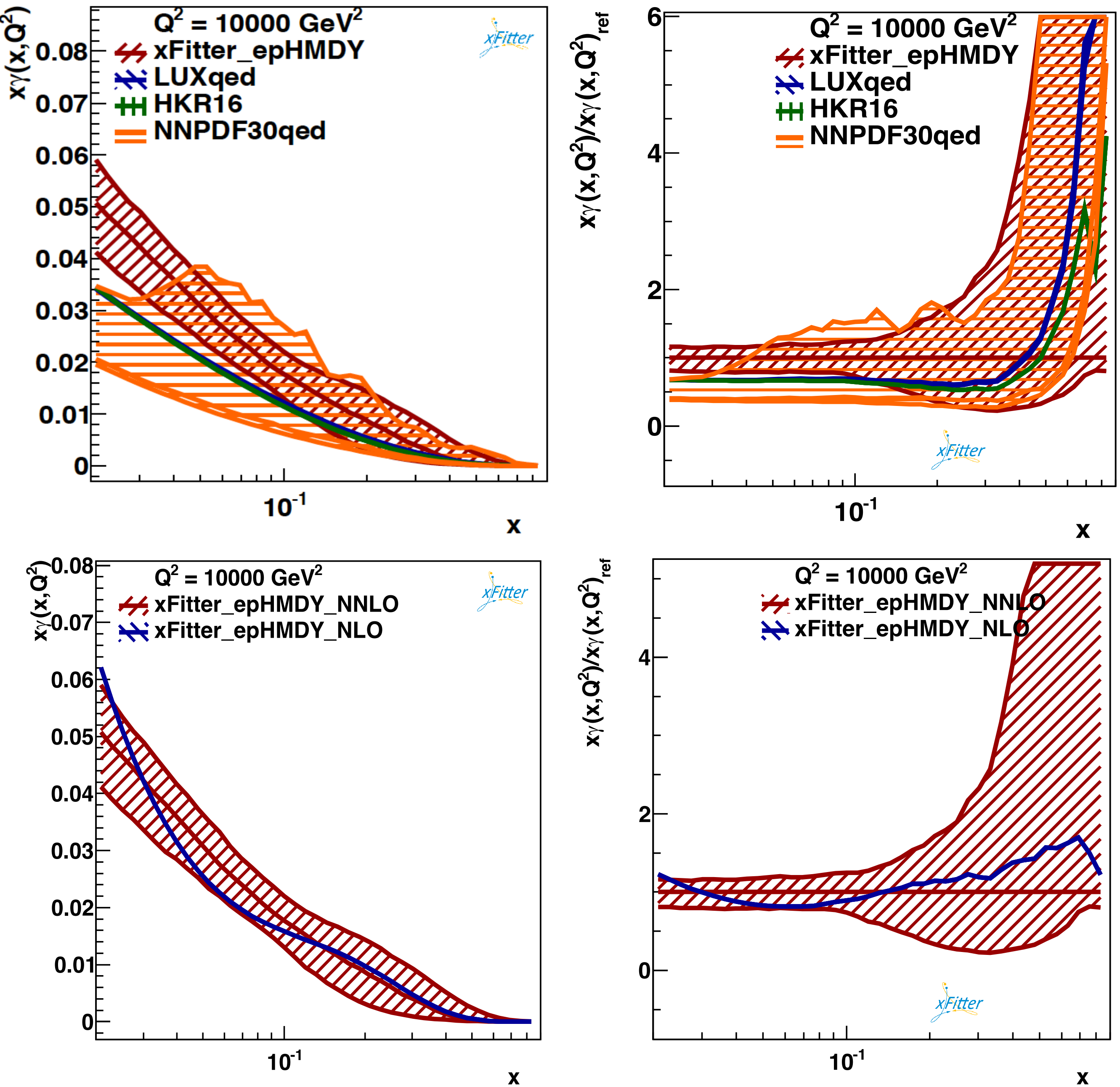


The impact in the medium and large-x antiquark distributions from the high mass DY data are rather moderate





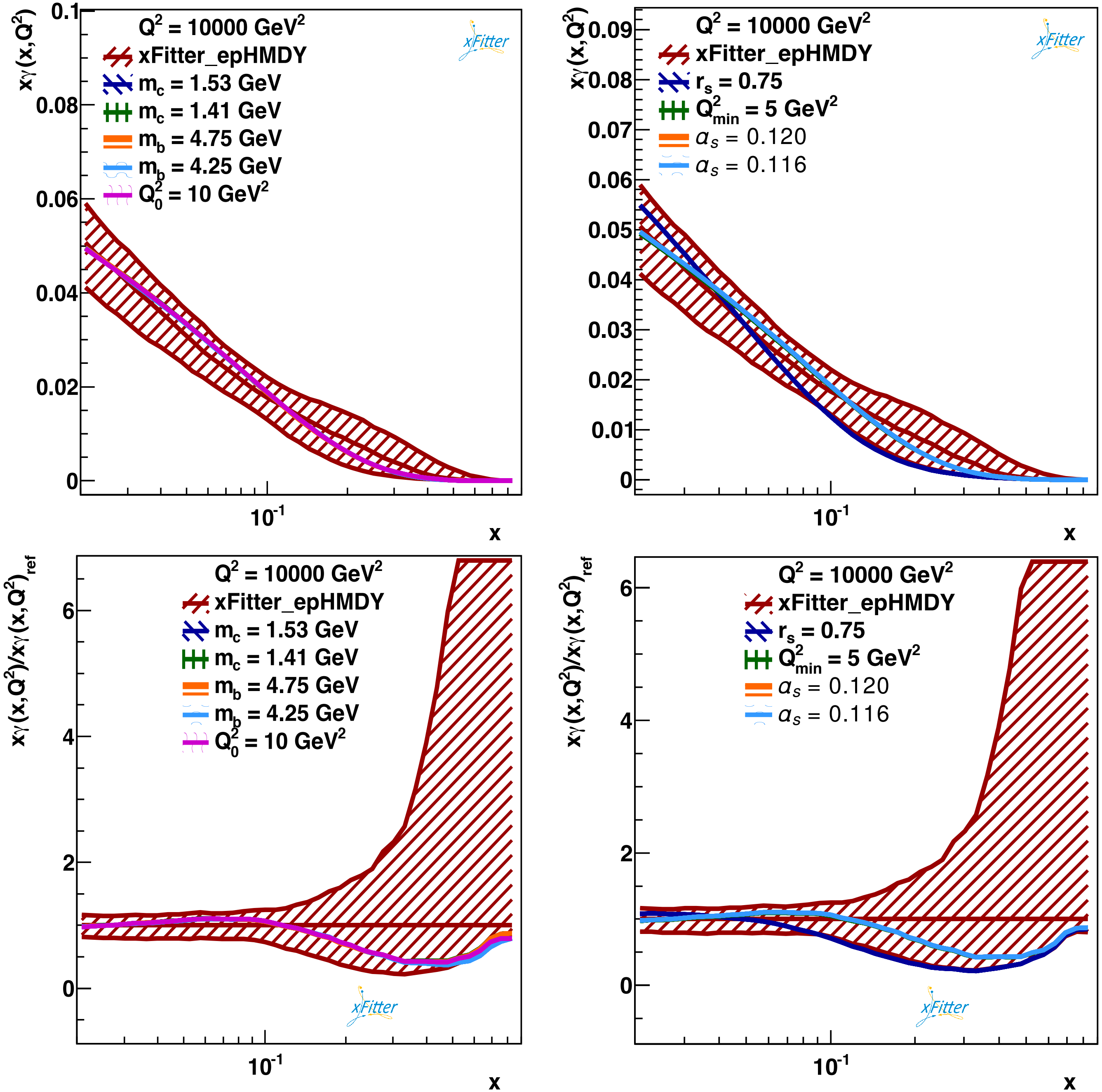
- $x\gamma(x, Q^2)$ compared to LUXqed, HKR16 and NNPDF30qed
- Only experimental uncertainties at 68% confidence level (CL)
- $0.02 \leq x \leq 0.9$ (beyond that region very limited sensitivity)
- For $x \geq 0.1$, photon PDF determinations consistent; for smaller x values, in agreement at the 2σ level
- For $0.04 \leq x \leq 0.2$ smaller PDF uncertainties as compared to those from NNPDF30qed
- Uncertainties ~30% for $x \leq 0.1$
- Limited sensitivity of the ATLAS data to the photon PDF doesn't allow obtaining a determination of $x\gamma$ with uncertainties competitive with those of LUXqed and HKR16



Comparison between **NLO vs NNLO** photon PDF

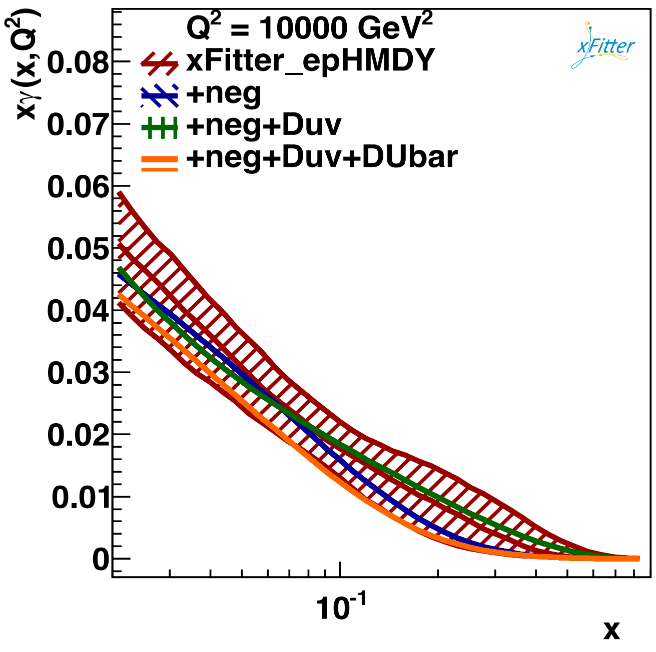
To quantify perturbative stability of photon PDF determination (QED part of the calculation identical in both cases)

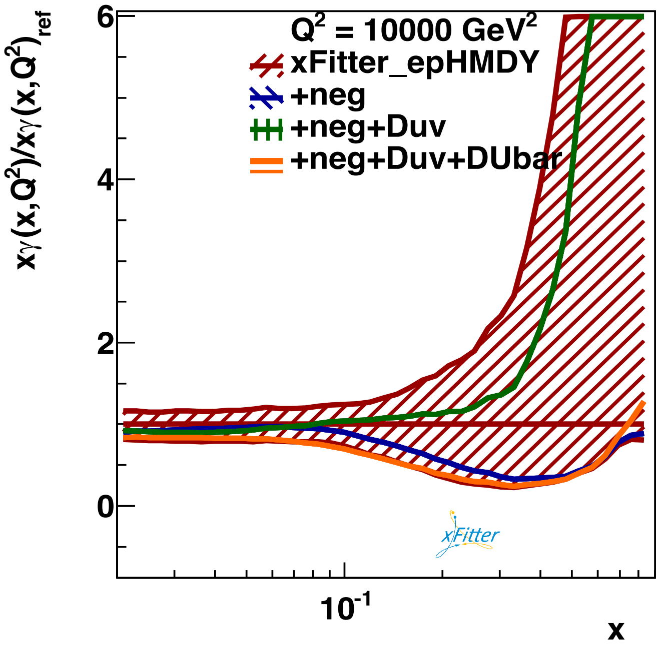
The fit exhibits a reasonable perturbative stability, since the central value of the NLO fit is always contained in the 1σ PDF uncertainty band (only exp. unc.)



- Here, **NNLO Hessian** results for nine model variations:
  - α_s = 0.116
  - α_s = 0.120
  - r_s = 0.75
  - Q^2 cut = 5 GeV^2
  - m_b down = 4.25 GeV
  - m_b up = 4.75 GeV
  - m_c down = 1.41 GeV
  - m_c up = 1.53 GeV
  - Q_0^2 cut = 10 GeV^2
- NNLO hessian fits with median ± 68% C.L.
- No changes in the chi2
- All the central fit are inside the MC error bands (some of them not visible)

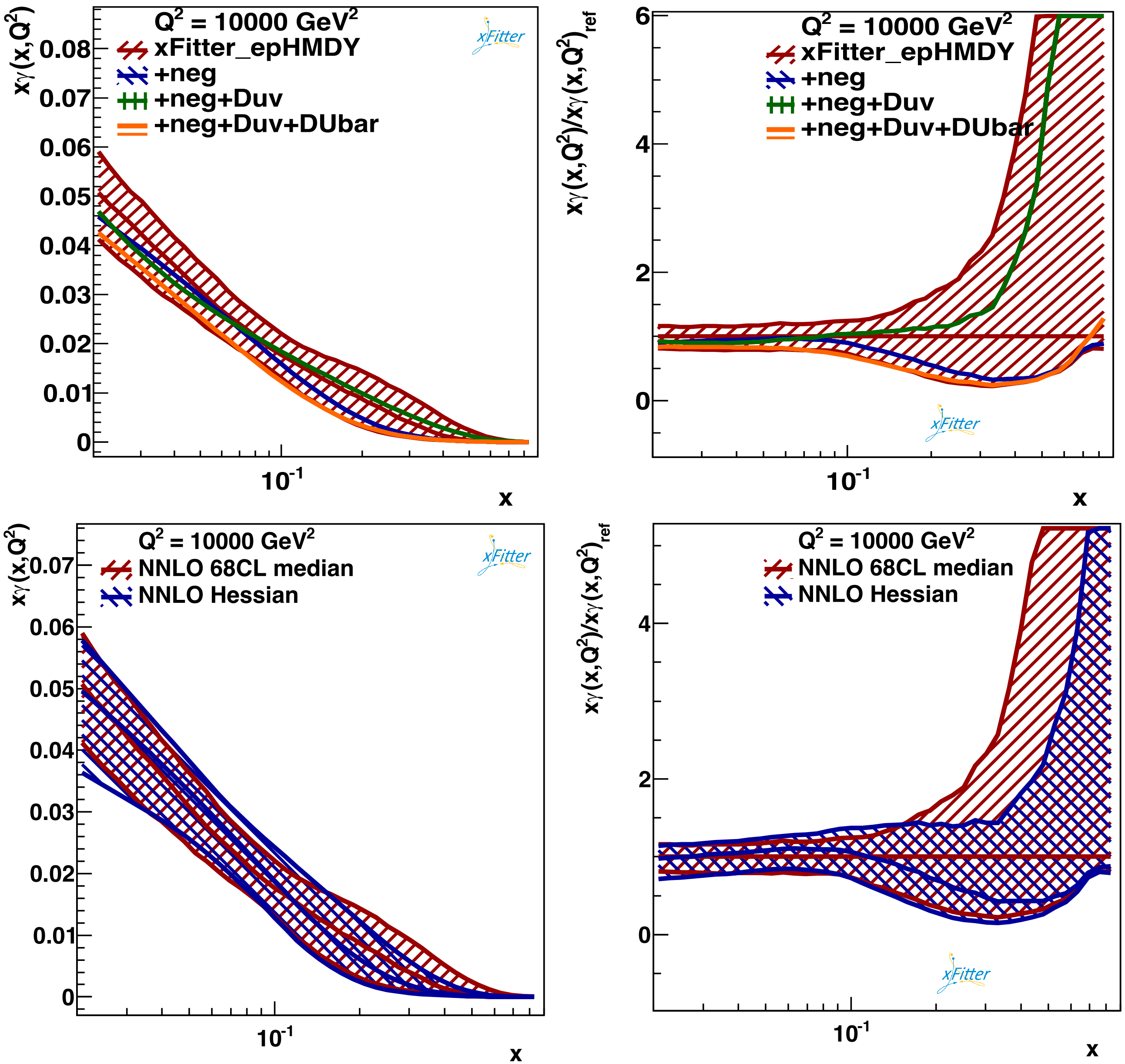
$$r_s = (s + \bar{s})/2\bar{d}$$





- Here, I'm showing the **NNLO Hessian results** for parameterisation variations:
  - +neg
  - +neg+Duv
  - +neg+Duv+DUbar
- NNLO hessian fits with median ± 68% C.L.
- All the central fit are inside the MC error bands

Median ± 68% CL vs Hessian (asym)



- Bands = experimental uncertainties only
- Reasonable agreement between the two methods
- Central values with different fitting techniques similar to each other
- MC uncertainties larger than Hessian ones (expecially for $x \gtrsim 0.2$, indicating deviations with respect to the Gaussian behaviour of the photon PDF)

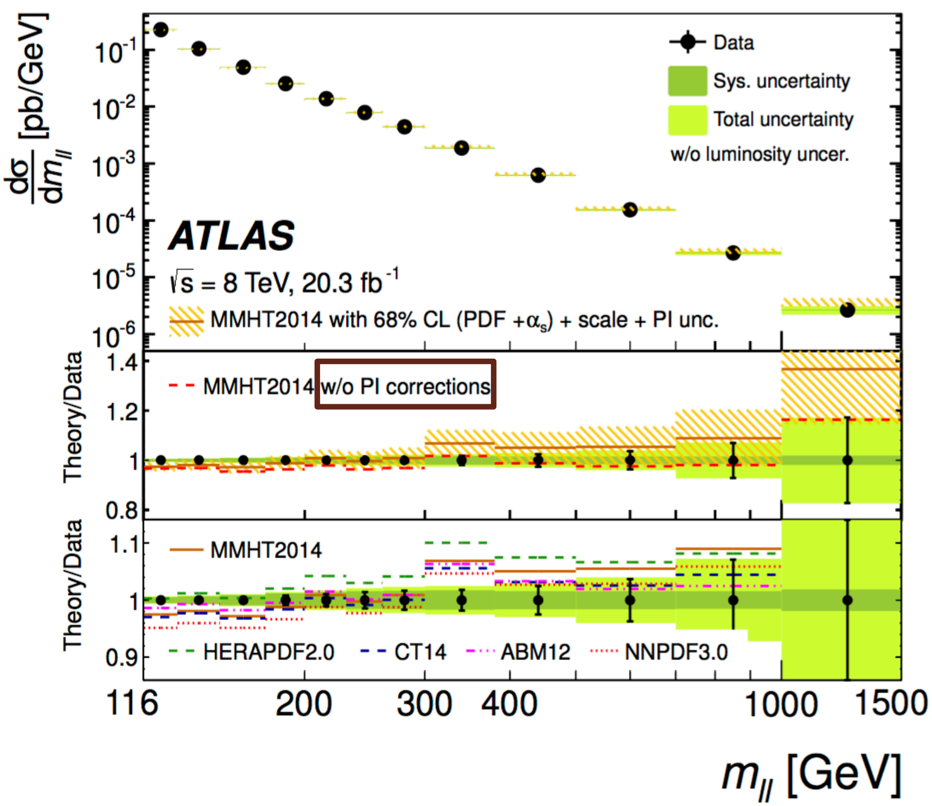
Summary

- New technical developments:
  - Full NLO QED corrections to the DGLAP evolution and DIS structure functions were implemented
  - Possibility to fit more than standard 12 PDFs
  - Extension of the APPLGRID to aMCfast for the presence of the photon-initiated channels
- Determination of $x\gamma(x)$ with uncertainties at the 30% level for $0.02 \leq x \leq 0.1$, then they increase for higher values of x
- Robustness of the fit and his perturbative stability shown
- Our results in agreement with LUXqed and HKR16 within uncertainties
- Direct determination of the photon PDF from hadron collider data is still far from being competitive with these calculations, based instead on precise measurements of the inclusive DIS structure functions of the proton
- This analysis provides further evidence that the information on the photon PDF provided by the most sensitive LHC data available so far is fully consistent with these two independent calculations
- Paper on the arXiv! **arXiv:1701.08553v1**
- Results of this study available upon request in the LHAPDF6 format

Backup Slides

Theory comparison

- The measured cross sections are compared to theoretical predictions using a selection of recent PDF sets (HERAPDF2.0, CT14, ABM12, NNPDF30)
- Theory = NNLO pQCD ⊗ NLO EW + LO PI; pQCD uses MMHT14 NNLO PDF set
- LO PI uses NNPDF23qed for photon PDF ± 68% of replicas; $\alpha_s = 0.118 \pm 0.001$
- Scale error: envelope of μ_F and μ_R varied by factors of 2

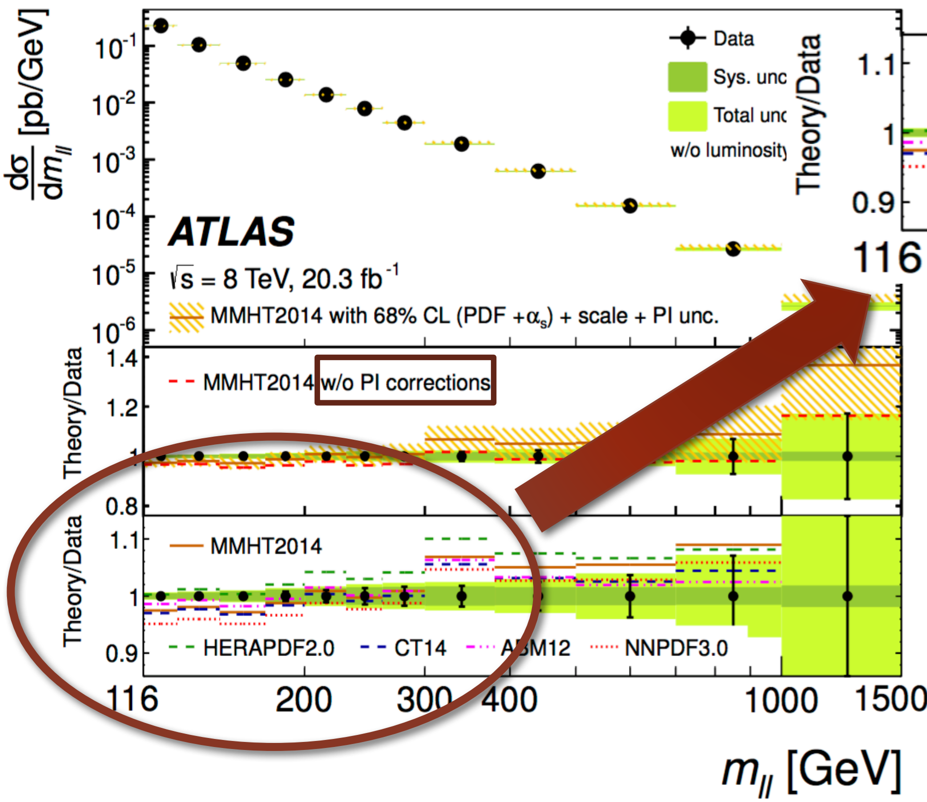


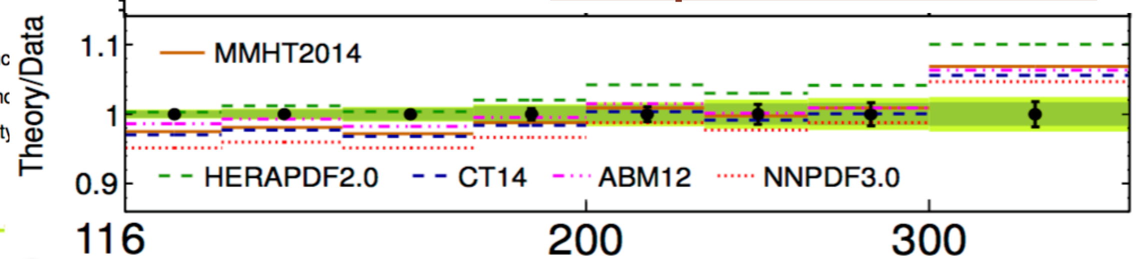
- Theory uncertainties are larger than data uncertainties → potential for PDF constraints
- Theory generally in agreement with data
- Photon induced contribution reaches 15% at large m
- Where PI contribution is large, theory uncertainty dominated by the PI piece
- Else PDF uncertainty dominates theory precision

Theory comparison

- The measured cross sections are compared to theoretical predictions using a selection of recent PDF sets (HERAPDF2.0, CT14, ABM12, NNPDF30)
- Theory = NNLO pQCD ⊗ NLO EW + LO PI; pQCD uses MMHT14 NNLO PDF set
- LO PI uses NNPDF23qed for photon PDF ± 68% of replicas; $\alpha_s = 0.118 \pm 0.001$
- Scale error: envelope of μ_F and μ_R varied by factors of 2

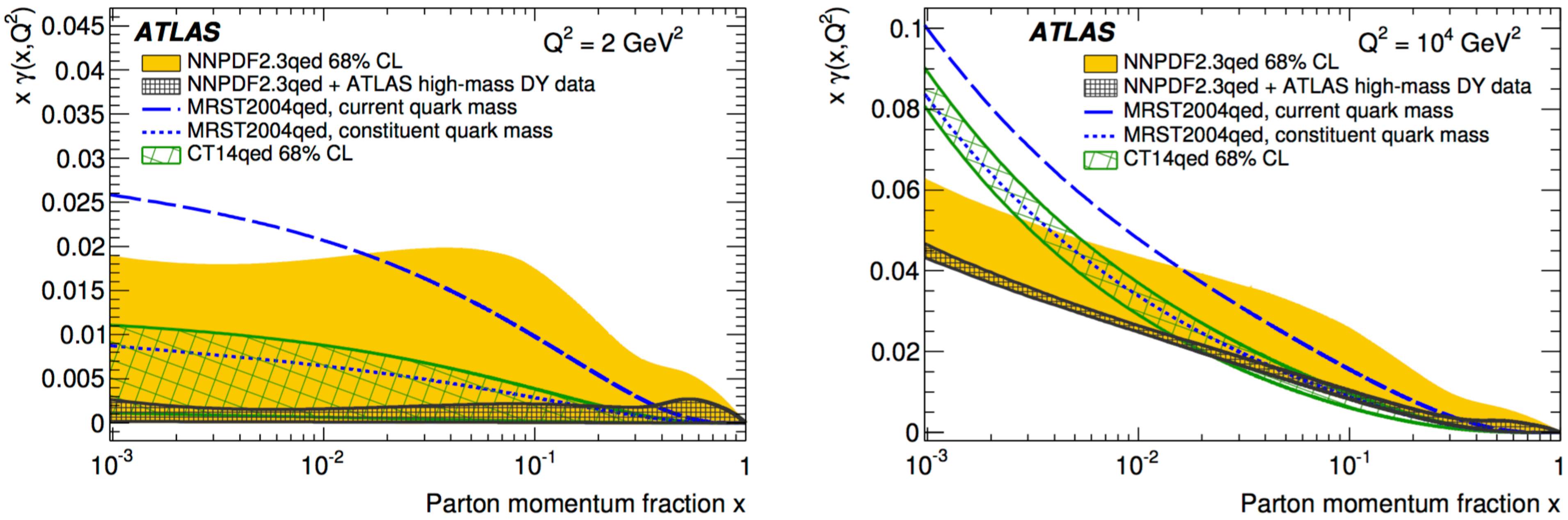
0.6% precision reached





At low m_{ll} observe large spread of predictions from different PDFs compared to experimental accuracy → **large potential to constrain PDFs!**

Photon PDF



- Assess impact of new data on photon PDF → use Bayesian reweighting of NNPDF replicas
- Each replica receives a weight according to χ^2 function (poorly fitting replicas receive a small weight; replicas fitting the data well receive a large weight)
- New PDF central value is estimated from mean of weighted replicas
- New PDF uncertainty determined from 68% CL
- **Original NNPDF uncertainty dramatically reduced in reweighting**

APPLGRID settings

- The APPLGRIDs are produced using aMCfast (v01-03-00 and MG5_aMC@NLO v2.4.3 – **latest tag available**) technology and then transferred to xFitter for fitting

- Because photon PDF is a new addition to the lhapdf format type, a mapping of the indices is needed to assure that that the photon PDF contribution is actually accounted for:
  - use of the adjusted applgrid for photon PDF (thanks to V. Bertone / S. Carrazza)
  - use of the modern interface to LHAPDF (v6.1.6)
  - use of a dedicated branch of xFitter that is linked to the adjusted applgrid (PI_apfel_for_lhaGridQED)

- Validation procedure then is performed using:
  - standalone reader of the applgrids (thanks to V. Bertone)
  - xfitter reader of the predictions

Following suggestion made by Sasha during last meeting: increment the number of points in the grids and play a bit with Q^2_{min} and Q^2_{max} … So I modified the following piece of code in my analyses:

```
*
*     Grid parameters
*
      appl_Q2min   = (lower mass bin edge – 5 GeV)^2d0
      appl_Q2max   = (higher mass bin edge + 5 GeV)^2d0
      appl_xmin    = 1d-5
      appl_xmax    = 1d0
      appl_nQ2     = 10     (for QCD 1D distribution and for all LO PI = 70)
      appl_Q2order = 3
      appl_nx      = 30     (for QCD 1D distribution and for all LO PI = 50)
      appl_xorder  = 3
```

I'm also optimising the cut on m_{ll} at the generation level (lower mass bin edge – 5 GeV) and I'm using dynamical scales, set to the invariant mass of the lepton pair: in setscale.f

```
elseif(dynamical_scale_choice.eq.0) then

        temp_scale_id='Mll' ! use a meaningful
string
        tmp=dsqrt(2d0*dot(pp(0,3),pp(0,4)))
```

LO PI contribution to total xsection

m_{ll} [GeV]	$\lvert y_{ll}\rvert$	QED/QCD
116 – 150	0.0 – 0.2	0.0252
116 – 150	0.2 – 0.4	0.0252
116 – 150	0.4 – 0.6	0.0250
116 – 150	0.6 – 0.8	0.0245
116 – 150	0.8 – 1.0	0.0241
116 – 150	1.0 – 1.2	0.0234
116 – 150	1.2 – 1.4	0.0227
116 – 150	1.4 – 1.6	0.0214
116 – 150	1.6 – 1.8	0.0184
116 – 150	1.8 – 2.0	0.0160
116 – 150	2.0 – 2.2	0.0138
116 – 150	2.2 – 2.4	0.0127
150 – 200	0.0 – 0.2	0.0524
150 – 200	0.2 – 0.4	0.0520
150 – 200	0.4 – 0.6	0.0507
150 – 200	0.6 – 0.8	0.0491
150 – 200	0.8 – 1.0	0.0473
150 – 200	1.0 – 1.2	0.0442
150 – 200	1.2 – 1.4	0.0380
150 – 200	1.4 – 1.6	0.0315
150 – 200	1.6 – 1.8	0.0263
150 – 200	1.8 – 2.0	0.0223
150 – 200	2.0 – 2.2	0.0188
150 – 200	2.2 – 2.4	0.0174

As expected:

- LO PI contribution increases when m_{ll} increases
- LO PI contribution decreases when $\lvert y_{lll}\rvert$ increases
- LO PI contribution reached ~12% of the total σ in the last invariant mass bin

m_{ll} [GeV]	$\lvert y_{ll}\rvert$	QED/QCD
200 – 300	0.0 – 0.2	0.0837
200 – 300	0.2 – 0.4	0.0822
200 – 300	0.4 – 0.6	0.0793
200 – 300	0.6 – 0.8	0.0737
200 – 300	0.8 – 1.0	0.0643
200 – 300	1.0 – 1.2	0.0525
200 – 300	1.2 – 1.4	0.0421
200 – 300	1.4 – 1.6	0.0339
200 – 300	1.6 – 1.8	0.0279
200 – 300	1.8 – 2.0	0.0231
200 – 300	2.0 – 2.2	0.0202
200 – 300	2.2 – 2.4	0.0178
500 – 1500	0.0 – 0.4	0.1184
500 – 1500	0.4 – 0.8	0.0910
500 – 1500	0.8 – 1.2	0.0580
500 – 1500	1.2 – 1.6	0.0362
500 – 1500	1.6 – 2.0	0.0239
500 – 1500	2.0 – 2.4	0.0182
500 – 1500	0.0 – 0.4	0.1216
500 – 1500	0.4 – 0.8	0.0816
500 – 1500	0.8 – 1.2	0.0493
500 – 1500	1.2 – 1.6	0.0308
500 – 1500	1.6 – 2.0	0.0221
500 – 1500	2.0 – 2.4	0.0250

Parameterisation variation

Starting point →10p from HERA + Euv: **1340.22/1088** (1.230) - χ^2 / #degrees of freedom

	Dg	Eg	neg	Duv	Euv	Ddv	Edv	DUbar	EUbar	DDbar	EDbar	Dph	Eph
-	1311.27	1316.13	1312.98	1314.41	-	1309.50	1302.23	1313.55	1308.85	1313.82	1313.37	**1285.24**	X
+ Dph	1287.42	1289.77	1285.26	1287.24	-	1287.29	1287.33	1283.40	**1280.64**	1287.43	1285.53	-	**1283.30**
+ Eph	1283.30	1278.25	**1274.66**	1282.51	-	1280.41	1283.19	1277.93	1276.51	1283.32	1281.80	-	-
+ neg	1274.64	1274.39	-	**1267.91**	-	1274.49	1274.63	1272.20	1269.05	1274.42	1271.23	-	-
+ Duv	1267.92	1267.65	-	-	-	1267.79	1267.78	**1253.34**	1260.77	1267.89	1265.36	-	-
+ DUbar	1253.32	1253.10	-	-	-	1253.12	1253.23	-	1253.29	1253.30	**1250.33**	-	-
+EDbar	1250.32	1250.23	-	-	-	1249.81	1250.04	-	1250.28	**1244.87**	-	-	-

- Euv + Dph + Eph is our central fit (**NNLO**)
- We include the solutions +neg, +Duv, +DUbar (4th, 5th and 6th line) as parameterisation variation
- +DDbar solution didn't converge so we cannot take it into account
- Beyond +neg,Duv,DUbar no really significant decrease of the χ^2
- More checks on parameterisation scan in backup slides…

Extra checks on the parameterisation scan

- **NNLO fit with +Euv+Dph+Eph our baseline…** Are we sure that is the best solution?

- I performed a reversed parameterisation scan:

  - 16p:
    After minimisation 1283.80 1088 1.180

  - 15p (no Eph):
    After minimisation 1287.30 1089 1.182

  - 15p (no Dph):
    After minimisation 1286.58 1089 1.181

  - 15p (no Euv):
    After minimisation 1359.14 1089 1.25

- The impact of Dph, Eph on the chi2 is marginal but there's an improvement so it justifies our choice to have 13p+Euv+Dph_Eph as central fit