# *The impact of Z transverse momentum data of PDF determinations*

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Mostly based on:
R. Boughezal, AG, F. Petriello & M. Ubiali, arXiv:1705.00343

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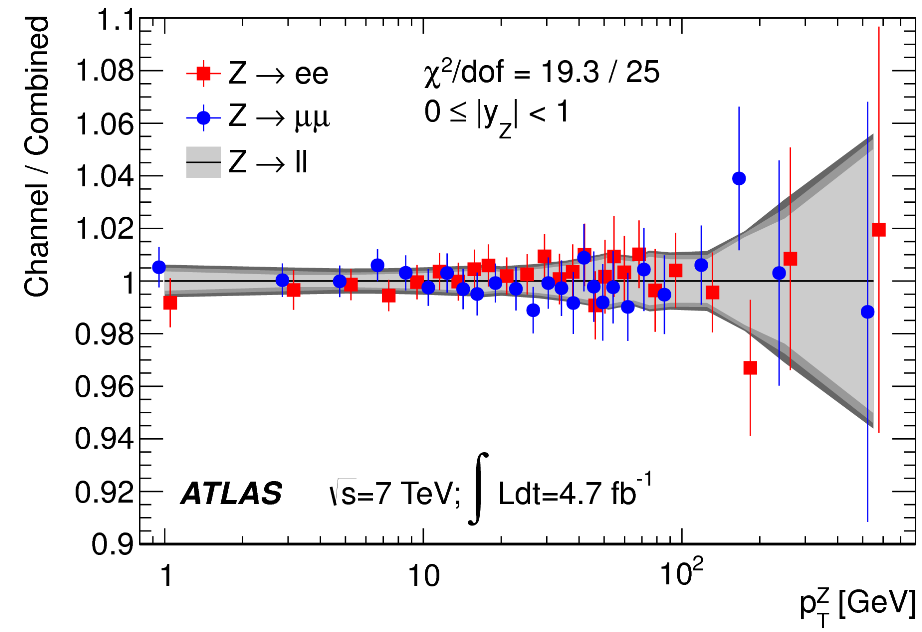
# *Outline*

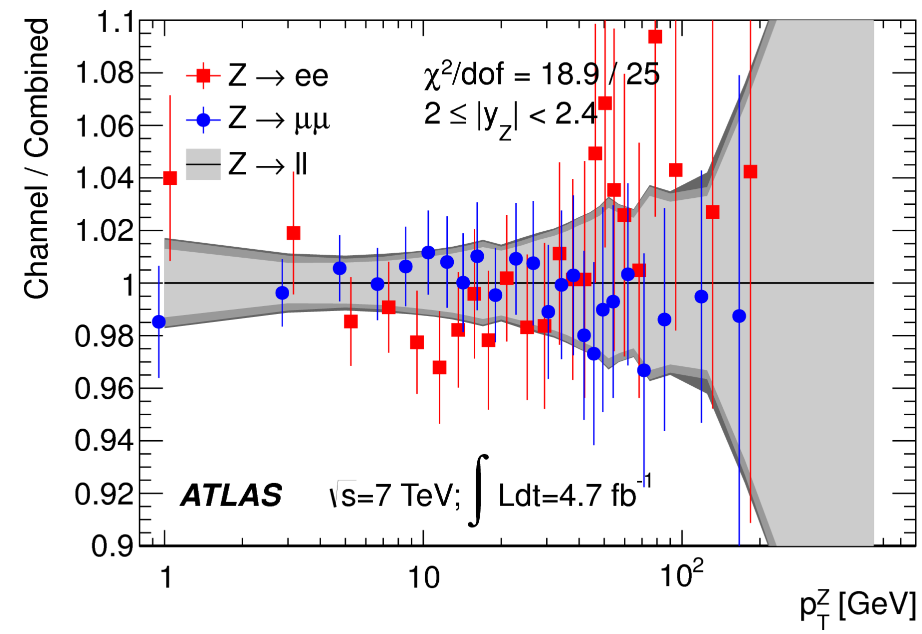
- Z transverse momentum measurements at the LHC
- Theoretical computation & Fitting framework
- DIS + Zpt fits
- Global fits
- Recent developments
- Outlook

# *Zpt measurements at the LHC - ATLAS 7 TeV*

- Based on the **7 TeV dataset** (4.7 $fb^{-1}$)
- Z transverse momentum distribution, **normalised** to the fiducial cross-section.
- **Three** rapidity bins in the **Z peak** region:
  - 0.0 < |yZ| < 1.0
    1.0 < |yZ| < 2.0
    2.0 < |yZ| < 2.4
- **Luminosity** uncertainty **cancels, dominated** by **correlated systematic** uncertainties (~1%) up to $p_t$~150 GeV (not true for the last rapidity bin)
- **64(39)** data points ($p_T$ > 30 GeV)

[ATLAS Collaboration, arXiv:1406.3360]

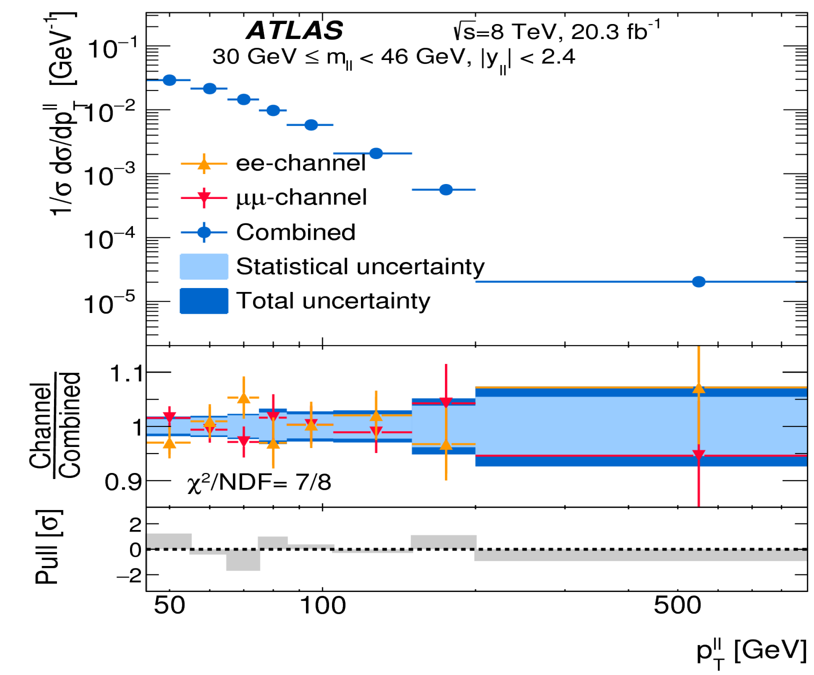


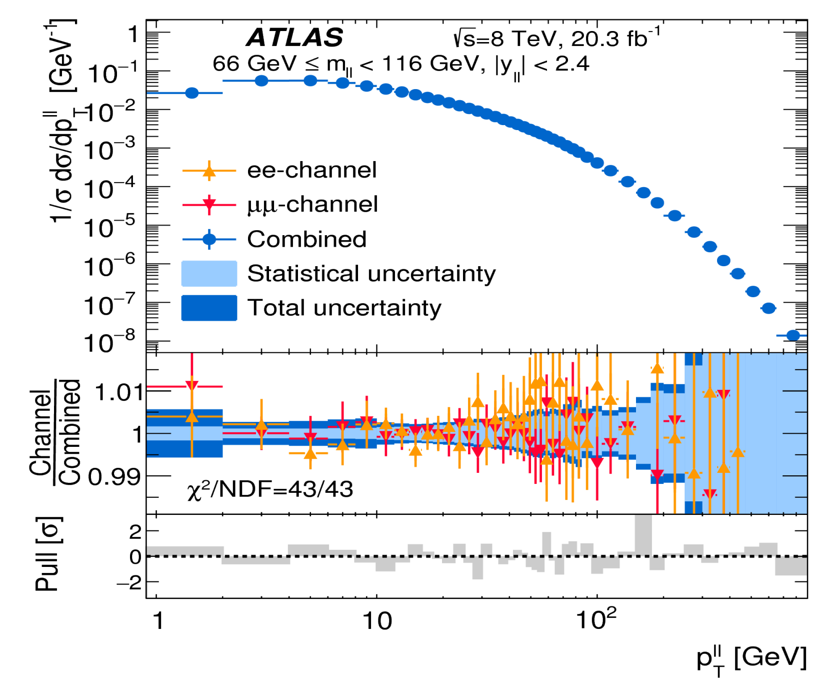



# *Zpt measurements at the LHC - ATLAS 8 TeV*

[ATLAS Collaboration, arXiv:1512.02192]

- Based on the **8 TeV dataset** (20.3 fb$^{-1}$)
- Both **absolute** and **normalised** data available with full correlation information
- **Six** lepton pair **invariant mass bins**:
  - $12 < |m_{ll}| < 20$ GeV, $0 < |y_Z| < 2.4$
    $20 < |m_{ll}| < 30$ GeV, $0 < |y_Z| < 2.4$
    $30 < |m_{ll}| < 46$ GeV, $0 < |y_Z| < 2.4$
    $46 < |m_{ll}| < 66$ GeV, $0 < |y_Z| < 2.4$
  - $66 < |m_{ll}| < 116$ GeV, **6 rapidity bins**
  - $16 < |m_{ll}| < 150$ GeV, $0 < |y_Z| < 2.4$
- **Dominated** by **correlated systematic** uncertainties (~1%) up to $p_T$~200 GeV
- **184(94)** data points ($p_T > 30$ GeV)

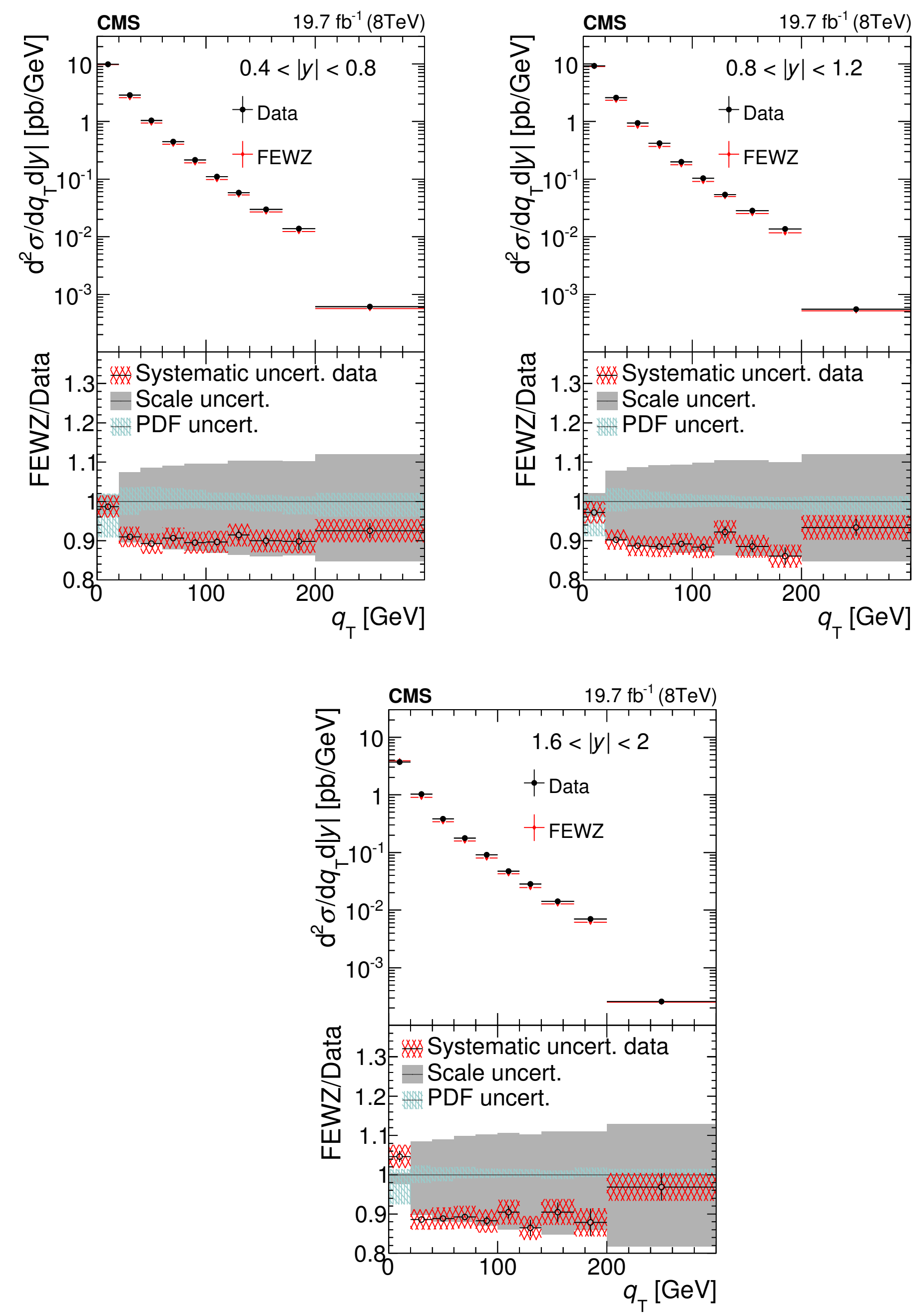


# *Zpt measurements at the LHC - CMS 8 TeV*

[CMS Collaboration, arXiv:1504.03511]

- Based on the **8 TeV dataset** (19.7 $fb^{-1}$)
- Both **absolute** and **normalised** data available with full correlation information
- **Five rapidity bins** in the **Z peak** region:
  - $0.0 < |y_Z| < 0.4$
    $0.4 < |y_Z| < 0.8$
    $0.8 < |y_Z| < 1.2$
    $1.2 < |y_Z| < 1.6$
    $1.6 < |y_Z| < 2.0$
- **Dominated** by **correlated systematic** uncertainties (~1%) up to $p_T$~200 GeV
- **50(28)** data points ($p_T$ > 30 GeV)



# *Zpt@NNLO - Theoretical computation*

- **NNLO** predictions for **Z transverse momentum** available thanks to the recent computation of **Z+jet** at **NNLO**

[**Boughezal et al., arXiv:1512.01291**
Gehrmann-De Ridder et al, arXiv:1605.04295
Gehrmann-De Ridder et al., arXiv1610.01843]

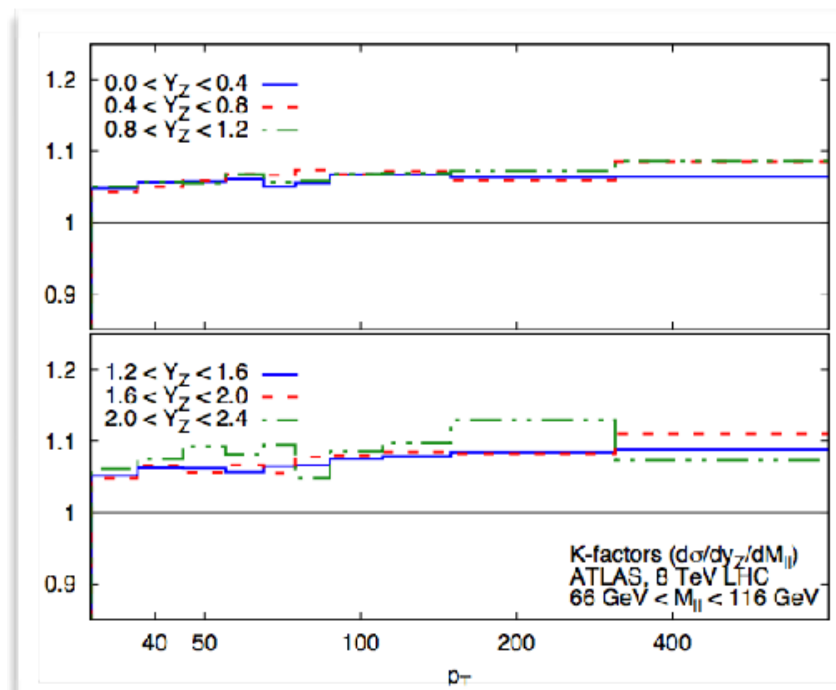
- **Renormalisation** and **factorisation** scales set to

$$\mu_R = \mu_F = \sqrt{(p_T^Z)^2 + M_{ll}^2}$$

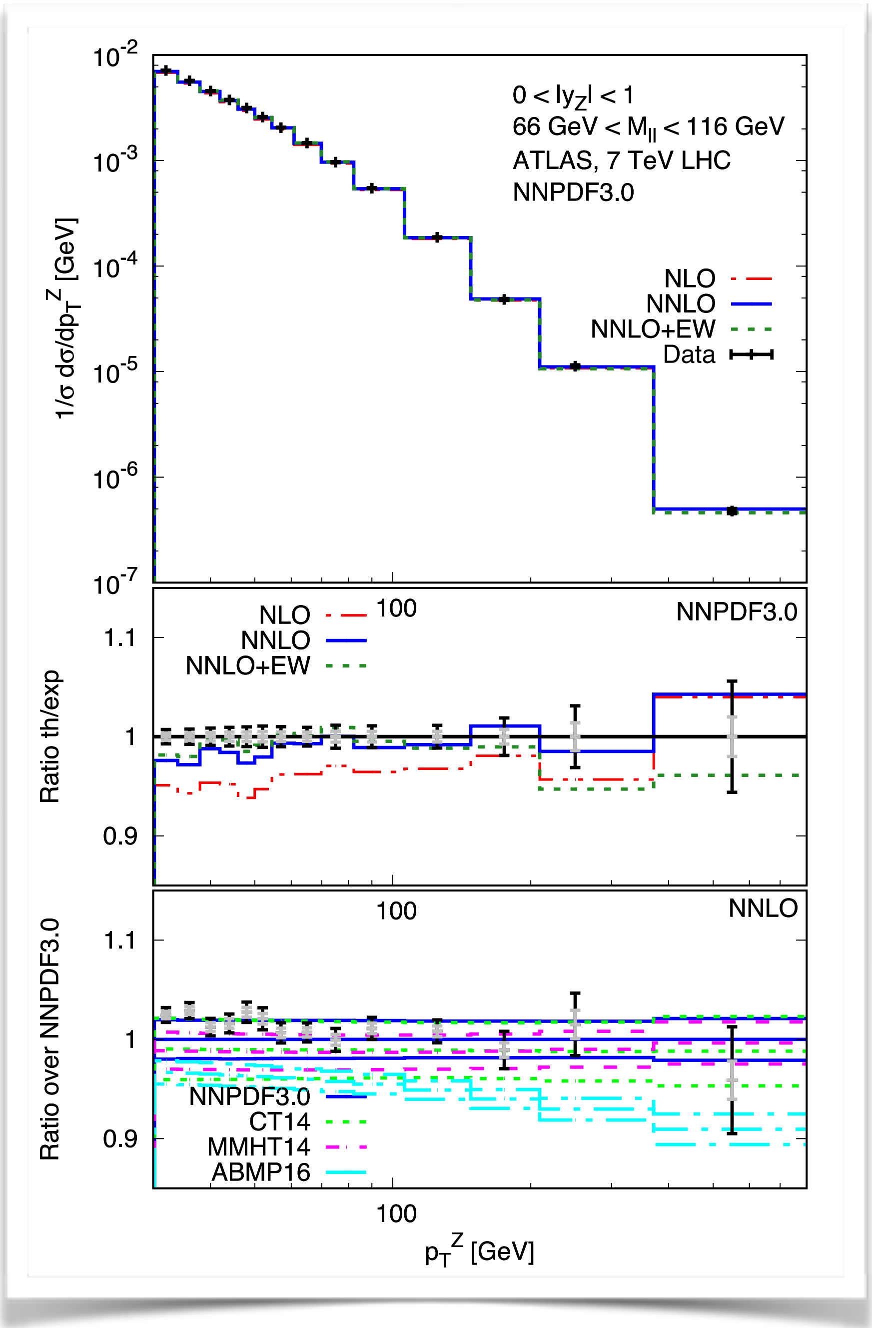
- **NNLO/NLO** QCD **K factor** as large as **5-10%**, depending on **kinematic region** ($m_{ll}$, $p_T$, $y_Z$)

- **EW corrections** become **important** (~1%) for **large transverse momentum** ($p_T$>150 GeV)

[Denner et al., arXiv:1103.0914
Hollik et al., arXiv:1504.07574
Kallweit et al., arXiv:1511.08692]



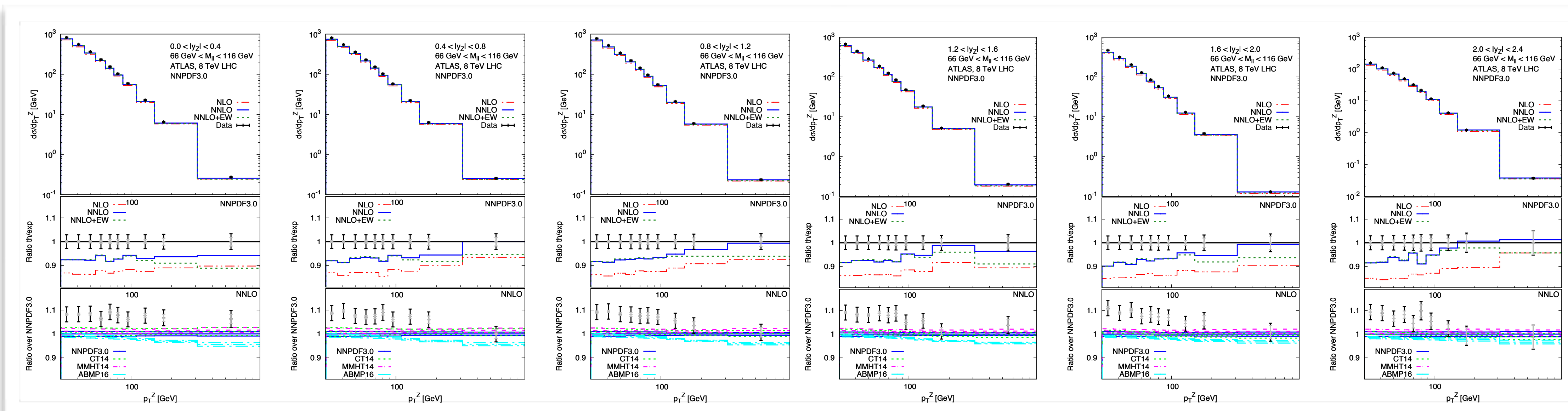
# *Data/Theory comparison - ATLAS 7 TeV*




| Bin | Order | $N_{\rm dat}$ | $\chi^2_{\rm d.o.f.}$ (NN30) | $\chi^2_{\rm d.o.f.}$(CT14) | $\chi^2_{\rm d.o.f.}$ (MMHT14) | $\chi^2_{\rm d.o.f.}$(ABMP16) |
|---|---|---|---|---|---|---|
| $0.0 < y_Z < 1.0$ | NLO | 14 | 10 | 21 | 9.2 | n.a. |
| | NNLO | 14 | 2.2 | 3.8 | 4.3 | 11 |
| | NNLO+EW | 14 | 1.3 | 2.3 | 2.6 | 9.1 |
| $1.0 < y_Z < 2.0$ | NLO | 14 | 13 | 18 | 12 | n.a. |
| | NNLO | 14 | 5.6 | 8.2 | 9.3 | 15. |
| | NNLO+EW | 14 | 3.9 | 6.0 | 6.8 | 12. |
| $2.0 < y_Z < 2.4$ | NLO | 14 | 7.0 | 7.1 | 6.0 | n.a. |
| | NNLO | 14 | 7.0 | 8.2 | 8.7 | 11. |
| | NNLO+EW | 14 | 5.9 | 7.1 | 7.5 | 9.5 |
| All bins | NLO | 42 | 9.9 | 15 | 9.1 | n.a. |
| | NNLO | 42 | 4.9 | 6.7 | 7.4 | 13. |
| | NNLO+EW | 42 | 3.7 | 5.2 | 5.6 | 12. |

**NNLO** (and **EW**) corrections are **crucial** (and often not enough) to **describe well** data over the whole kinematic range

# Data/Theory comparison - ATLAS 8 TeV

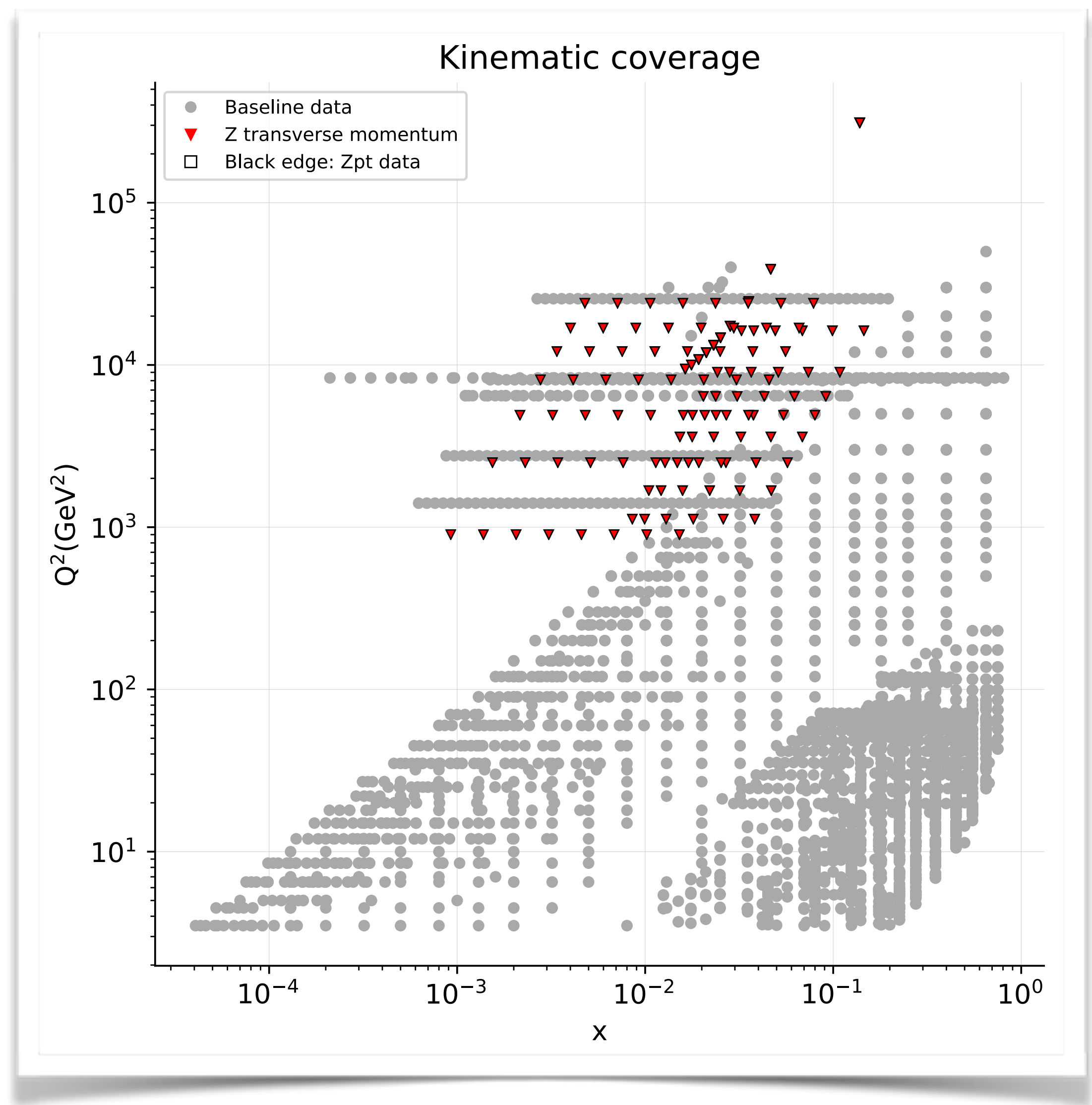



| Bin | Order | $N_{\rm dat}$ | $\chi^2_{\rm d.o.f.}$ (NN30) | $\chi^2_{\rm d.o.f.}$ (CT14) | $\chi^2_{\rm d.o.f.}$ (MMHT14) | $\chi^2_{\rm d.o.f.}$ (ABMP16) |
|---|---|---|---|---|---|---|
| $0.0 < y_Z < 0.4$ | NLO | 10 | 4.0 | 3.2 | 2.4 | n.a. |
| | NNLO | 10 | 2.7 | 2.7 | 2.6 | 2.7 |
| | NNLO+EW | 10 | 3.4 | 3.2 | 3.1 | 5.4 |
| $0.4 < y_Z < 0.8$ | NLO | 10 | 5.6 | 4.6 | 3.8 | n.a. |
| | NNLO | 10 | 5.4 | 5.2 | 5.3 | 3.3 |
| | NNLO+EW | 10 | 4.0 | 3.9 | 3.7 | 3.8 |
| $0.8 < y_Z < 1.2$ | NLO | 10 | 5.8 | 3.8 | 3.0 | n.a. |
| | NNLO | 10 | 4.7 | 4.0 | 4.3 | 2.1 |
| | NNLO+EW | 10 | 2.3 | 2.0 | 1.9 | 1.7 |
| $1.2 < y_Z < 1.6$ | NLO | 10 | 4.5 | 3.2 | 2.5 | n.a. |
| | NNLO | 10 | 5.1 | 4.0 | 4.6 | 3.0 |
| | NNLO+EW | 10 | 3.3 | 2.6 | 2.7 | 2.5 |
| $1.6 < y_Z < 2.0$ | NLO | 10 | 4.4 | 3.2 | 2.4 | n.a. |
| | NNLO | 10 | 5.4 | 4.3 | 5.0 | 3.7 |
| | NNLO+EW | 10 | 3.9 | 3.2 | 3.4 | 3.0 |
| $2.0 < y_Z < 2.4$ | NLO | 10 | 4.1 | 3.2 | 2.4 | n.a. |
| | NNLO | 10 | 3.4 | 3.1 | 3.3 | 3.2 |
| | NNLO+EW | 10 | 2.6 | 2.3 | 2.4 | 2.5 |

**Uncertainties** are dominated by **correlated systematics.**

# *Fitting framework*

- Based on the **NNPDF3.0** PDF determination **framework**
  - **Charm** is perturbatively generated
  - **Heavy quark masses** values match the Higgs XS WG values
  - **No inclusive jet data** (NNLO QCD corrections not available)
- Additional **statistical uncertainty** added to account for **numerical uncertainty** (MC integration) in **NNLO predictions**
- **HERA+Z $p_T$** fits to perform detailed studies and decide on final setup
- **Global fit** with optimal settings

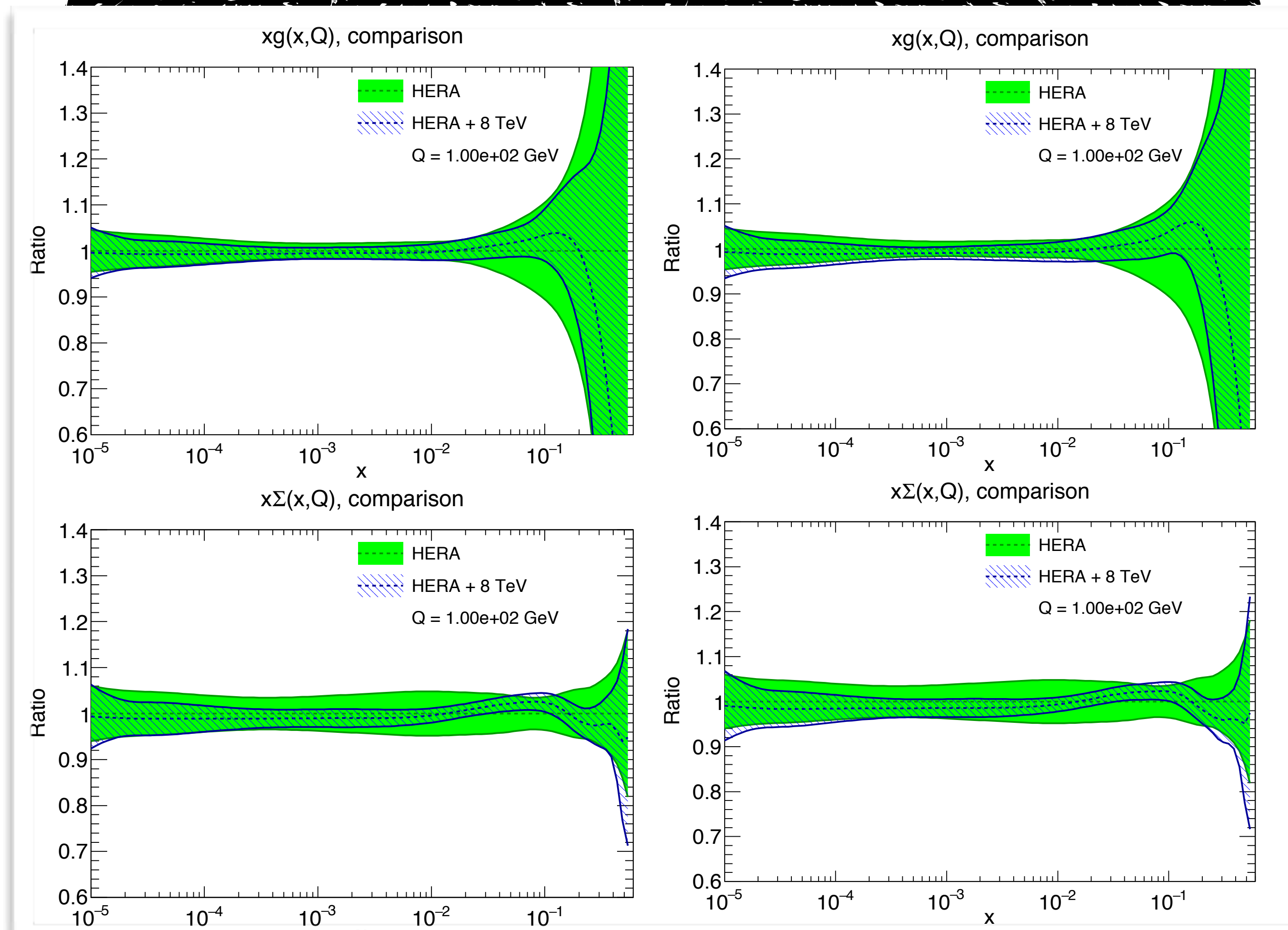


# *HERA + Z $p_T$ 8 TeV data*

| fit id | extra Δ | $\chi^2_{\rm ATLAS7tev}$ | $\chi^2_{\rm ATLAS8tev,m}$ | $\chi^2_{\rm ATLAS8tev,y}$ | $\chi^2_{\rm CMS8tev}$ | $\chi^2_{\rm tot}$ |
|---|---|---|---|---|---|---|
| (a) | 1% | (21.8) | (1.00) | (1.56) | (1.55) | 1.168 |
| (b) | 1% | (19.6) | 0.91 | 0.70 | (1.61) | 1.146 |
| (c) | 1% | (16.2) | (1.04) | (1.56) | 1.21 | 1.176 |
| (d) | 1% | (18.0) | 0.90 | 0.77 | 1.42 | 1.156 |
| (a) | 0.5% | (27.6) | (1.10) | (2.83) | (2.46) | 1.168 |
| (e) | 0.5% | (23.0) | 0.99 | 1.05 | (3.01) | 1.168 |
| (f) | 0.5% | (20.5) | (1.13) | (3.15) | 1.91 | 1.198 |
| (g) | 0.5% | (21.4) | 0.99 | 1.29 | 2.44 | 1.207 |
| (a) | no | (30.6) | (1.15) | (4.65) | (3.46) | 1.168 |
| (h) | no | (25.5) | 1.02 | 1.66 | (4.79) | 1.193 |
| (i) | no | (19.5) | (1.28) | (5.44) | 2.51 | 1.225 |
| (j) | no | (24.5) | 1.03 | 2.09 | 3.59 | 1.251 |

**Inclusion** of **8 TeV data** in the fit **improves description** of **these data** but **does not improve** description of **7 TeV ones**

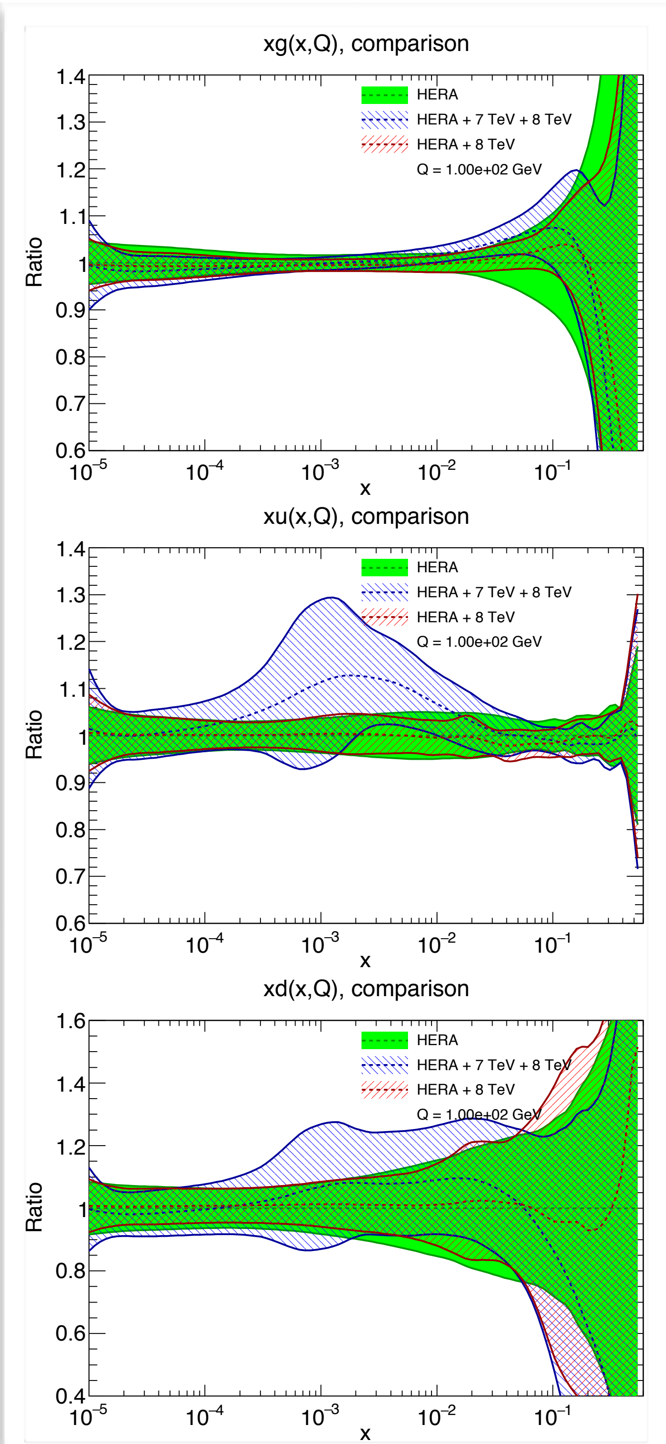
Value of **extra uncertainty** on **theoretical predictions** has **marginal** impact on derived **PDF uncertainties**




0%

1%

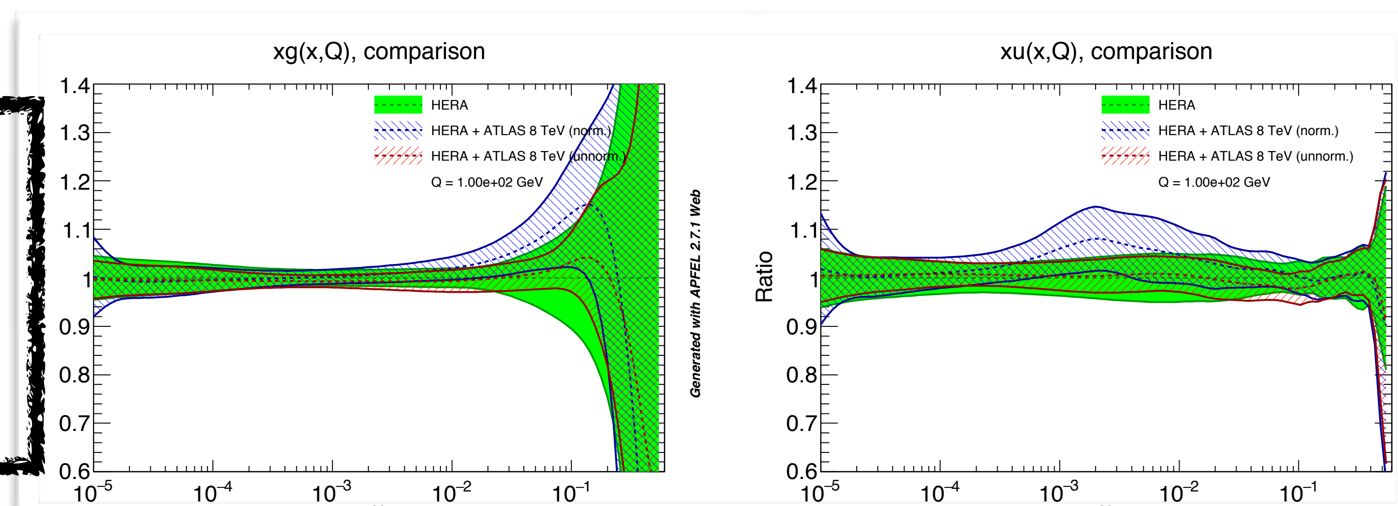
# *The case of Z $p_T$ 7 TeV data*




| fit id | extra $\Delta$ | $\chi^2_{\mathrm{ATLAS7tev}}$ | $\chi^2_{\mathrm{ATLAS8tev,m}}$ | $\chi^2_{\mathrm{ATLAS8tev,y}}$ | $\chi^2_{\mathrm{CMS8tev}}$ | $\chi^2_{\mathrm{tot}}$ |
|---|---|---|---|---|---|---|
| (a) | 1% | (21.8) | (1.00) | (1.56) | (1.55) | 1.168 |
| (k) | 1% | 1.39 | (1.39) | (2.04) | (1.41) | 1.176 |
| (l) | 1% | 1.64 | 1.05 | 1.17 | 1.27 | 1.171 |
| (a) | 0.5% | (27.6) | (1.10) | (2.83) | (2.46) | 1.168 |
| (m) | 0.5% | 1.58 | (1.54) | (3.36) | (2.11) | 1.186 |
| (n) | 0.5% | 2.13 | 1.18 | 1.98 | 2.21 | 1.253 |
| (a) | no | (30.6) | (1.15) | (4.65) | (3.46) | 1.168 |
| (o) | no | 1.74 | (1.69) | (4.79) | (3.06) | 1.185 |
| (p) | no | 2.35 | 1.24 | 2.81 | 3.19 | 1.301 |

Proper inclusion of **normalised data** with cuts only possible if corresponding **covariance matrix** is available

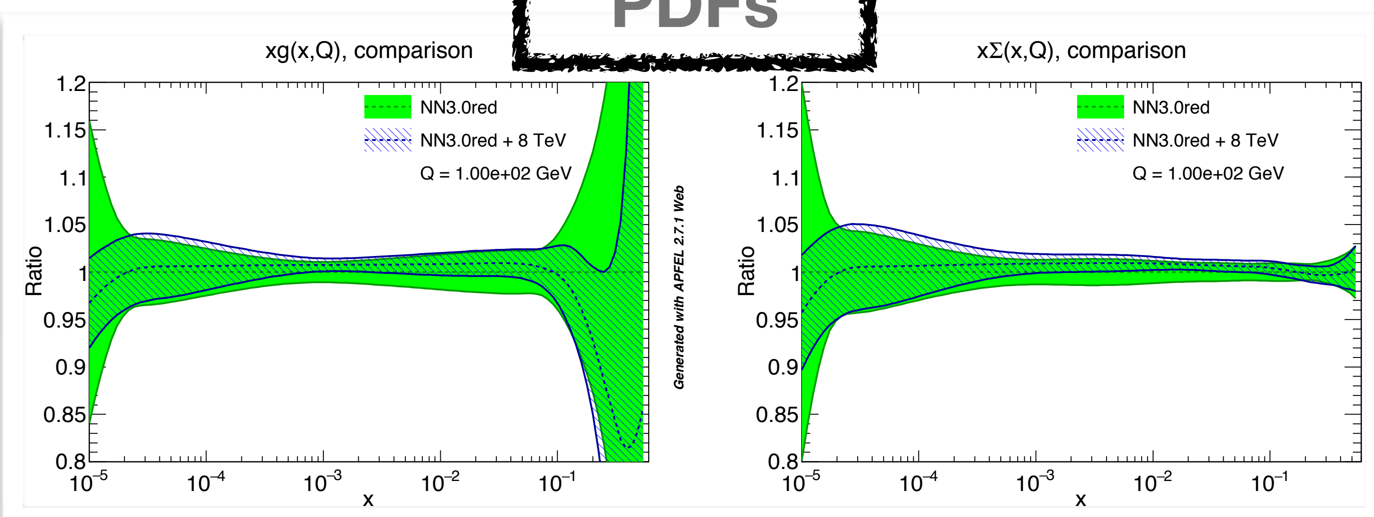
Norm. vs. Abs. 8 TeV



# *ZpT data in a global fit*

| fit | $\chi^2_{\rm ATLAS7tev}$ | $\chi^2_{\rm ATLAS8tev,mdist}$ | $\chi^2_{\rm ATLAS8tev,ydist}$ | $\chi^2_{\rm CMS8tev}$ | $\chi^2_{\rm tot}$ |
|---|---|---|---|---|---|
| NN30red | (6.93) | (0.98) | (1.06) | (1.41) | 1.17677 |
| NN30red + 8 TeV | (7.87) | 0.96 | 0.88 | 1.32 | 1.17690 |

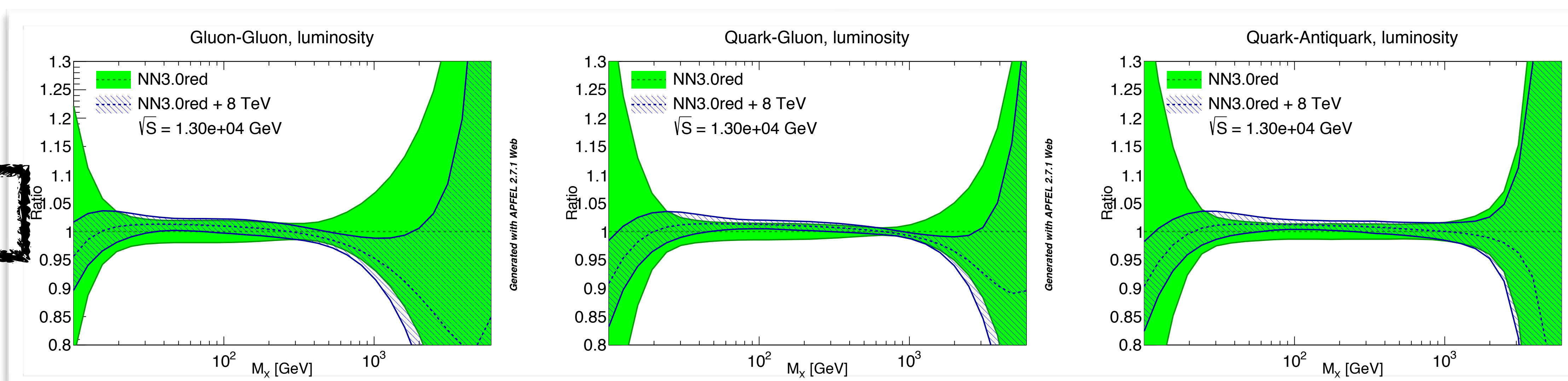
**PDFs**




**Higgs XS**

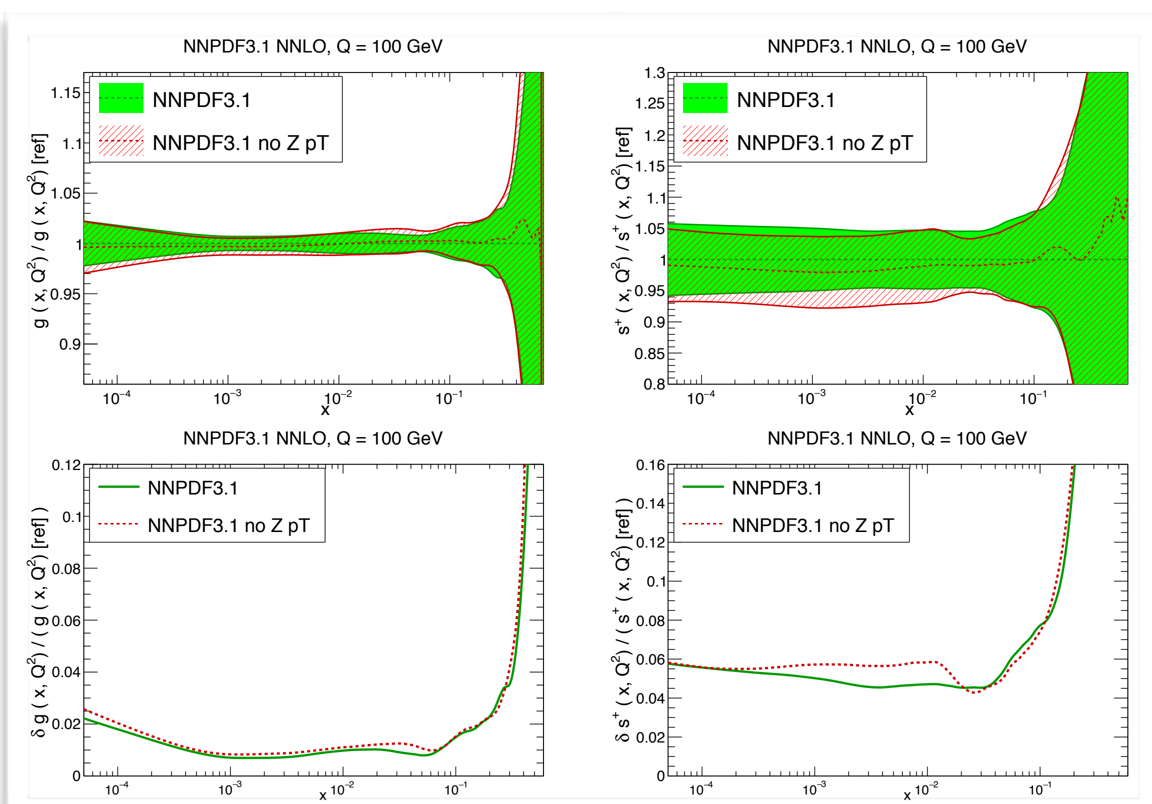
| | Before $p_T^Z$ data | After $p_T^Z$ data |
|---|---|---|
| $\sigma_{gg\to H}$ [pb] | $48.22 \pm 0.89$ (1.8%) | $48.61 \pm 0.61$ (1.3%) |
| $\sigma_{\rm VBF}$ [pb] | $3.92 \pm 0.06$ (1.5%) | $3.96 \pm 0.04$ (1.0%) |

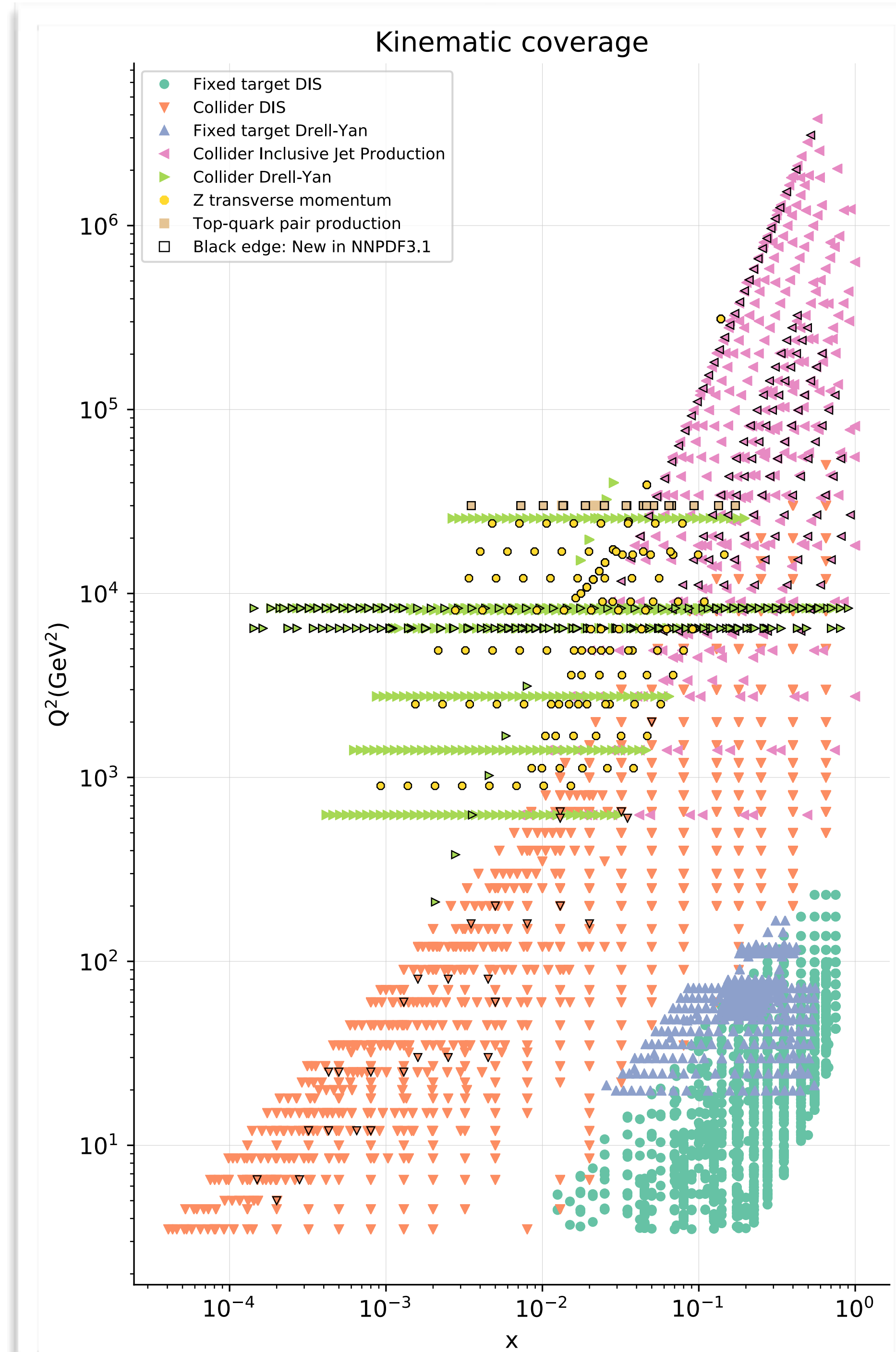
**Lumis**



# *Recent developments: NNPDF3.1*

- **Extended dataset**, in particular
  - **Top differential** distributions
  - More **inclusive jet data**
  - **ATLAS W/Z**, full 7 TeV dataset
- **Charm** PDF is **fitted**



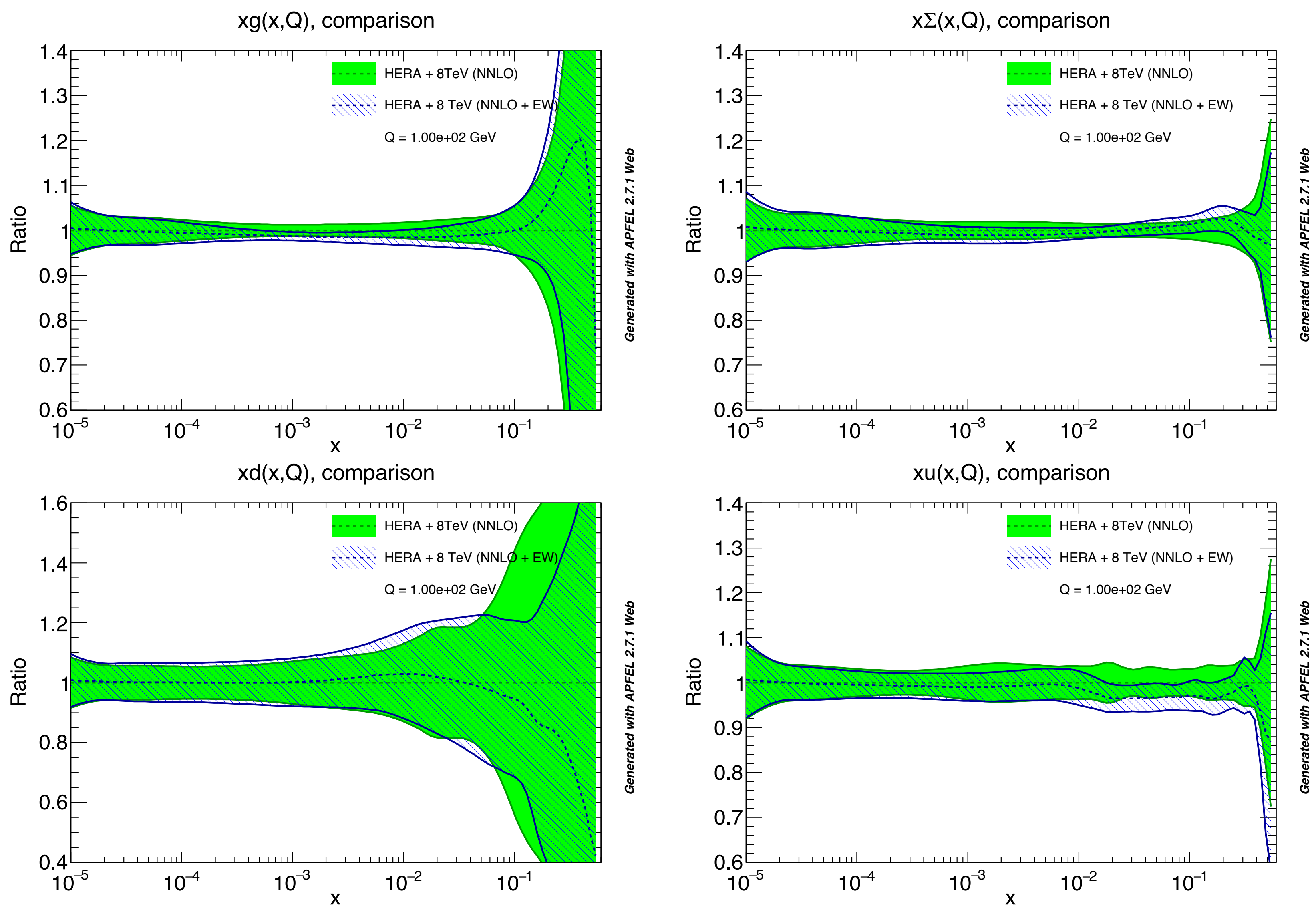
# *Conclusions*

- **Z transverse momentum** measurements provide valuable **constraints on PDFs**, in particular the **gluon** in the *x* range relevant for **Higgs production** in gluon fusion
- Recent computation of **NNLO QCD** corrections to ***Z+jet*** allow consistent inclusion of **Z $p_T$ measurements** in **NNLO PDF determinations**
- Recent **ATLAS** and **CMS** (**8 TeV**) measurements are in **good agreement** with other **data included in global PDF fits**
- Inclusion of **normalised measurements** with **cuts** can be **problematic** if corresponding covariance matrix is not publicly available
- **High precision** of measurements (extremely small **statistical uncertainties**) require us to think about **uncertainties on theoretical computations**
- Use of **low-$p_T$** data requires a lot of thinking about **theoretical predictions** and their **accuracy**

## *Extra Slides*

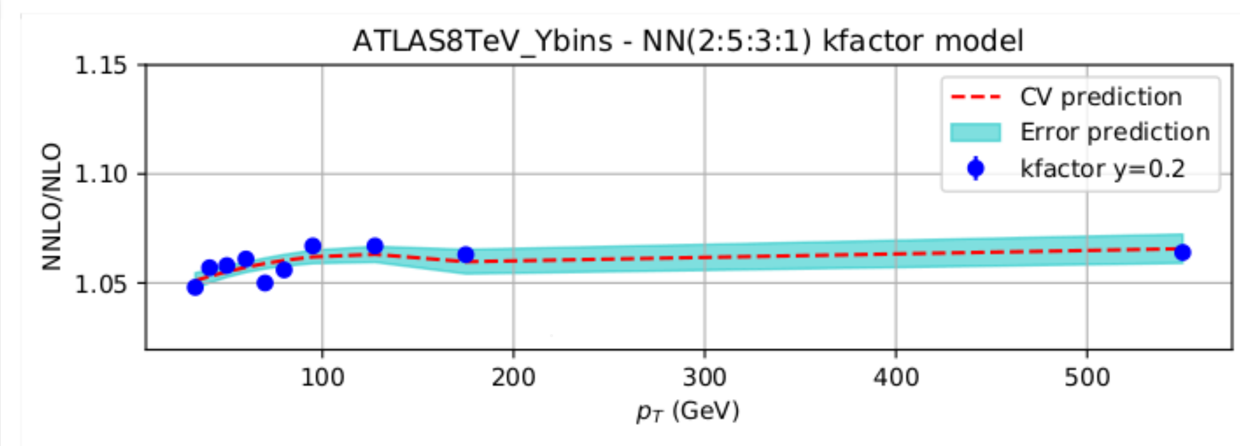
# *Electroweak corrections*

| fit id | extra Δ | Theory | $\chi^2_{\mathrm{ATLAS7tev}}$ | $\chi^2_{\mathrm{ATLAS8tev,m}}$ | $\chi^2_{\mathrm{ATLAS8tev,y}}$ | $\chi^2_{\mathrm{CMS8tev}}$ | $\chi^2_{\mathrm{tot}}$ |
|---|---|---|---|---|---|---|---|
| (e) | 1% | NNLO | (18) | 0.90 | 0.77 | 1.42 | 1.156 |
| (q) | 1% | NNLO+EW | (16) | 1.00 | 0.87 | 1.72 | 1.182 |



# *Uncertainties on theoretical predictions*

- **NNLO predictions** for *Z+jet* are affected by **non-negligible** Monte Carlo integration **uncertainties**
- The **size of uncertainties** can be **estimated** by **comparing** the **fluctuations** to the results of an **interpolation** based on a **smooth** function (neural network)




HERA + 8 TeV ZpT data fits

| Extra $\Delta$ | $\chi^2$ ATLAS 7 TeV | $\chi^2$ ATLAS 8 TeV (M) | $\chi^2$ ATLAS 8 TeV (Y) | $\chi^2$ CMS 8 TeV (Y) |
|---|---|---|---|---|
| 1% | (18) | 0.90 | 0.77 | 1.42 |
| No | (25) | 1.03 | 2.09 | 3.59 |

Studied the impact of introducing an uncertainty on theoretical predictions of 0%, 0.5% and 1%