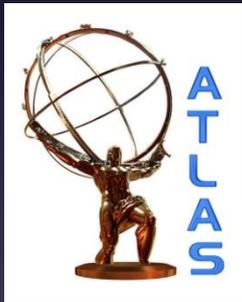


Probing perturbative QCD using electroweak bosons at ATLAS



Hugo Beauchemin
Tufts University



Introduction

Probing PDF with electroweak bosons

- V+X events, where $V = W, Z, \text{ or } \gamma$, allows to test pQCD and PDF in particular with hard colorless probes.
 - LHC measurements now challenge the precision on PDF, allowing for many of these measurements to improve the description and precision of PDF.
- At lowest order in α_s :
 - W/Z+X is highly sensitive to valence quarks PDF $q\bar{q}' \rightarrow W, q\bar{q} \rightarrow Z$
 - γ +X is more sensitive to gluon PDF $qg \rightarrow q\gamma$
 - Prompt photon production was dropped years ago from PDF fits but recent improvements in its description and large impact on gluon PDF brought new interests in these measurements at the LHC.
- Other QCD effects such as resummation of large logs and ISR parton shower modeling are also studied with inclusive V+X

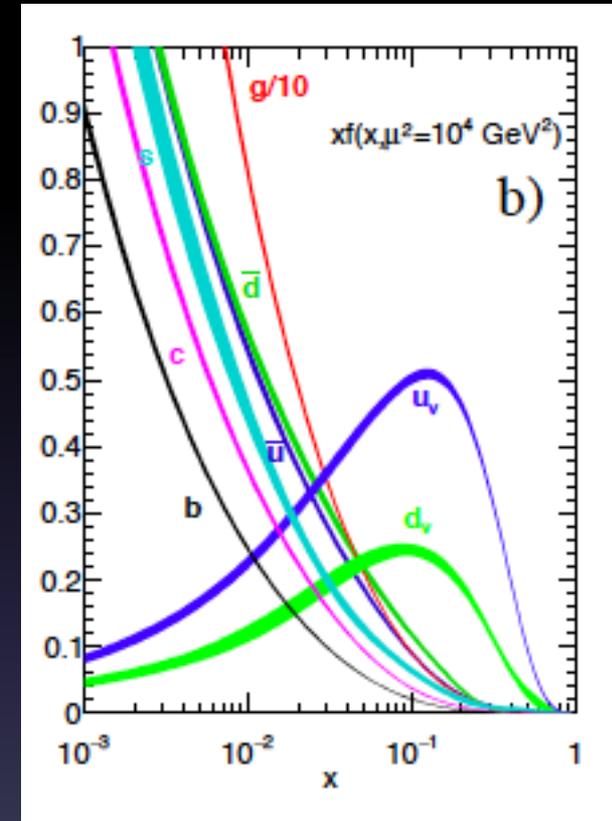
$$x = \left(\frac{M}{S}\right) e^y$$

- The range of x and Q^2 that can be probed depends on \sqrt{S} and rapidity y of electroweak bosons

- The main W production mechanism consists in a valence quarks scattering on a sea anti-quark so the W is preferentially boosted in the direction of the incoming valence quark.

- Higher probability of higher x
- High correlation between y_W and y_l .

- The difference between u_v and d_v yields an asymmetry between W^+ and W^- production which is function of y .



From PDG

- Measure differential cross sections as a function of y and for various \sqrt{S} pp collisions to provide complete information about PDF

Measuring ratios

- PDF extraction for LHC data are often limited by theory and experimental uncertainties on the measurement results used in the fit.
- One way to improve sensitivity to PDF is to measure ratios where correlations suppress many sources of uncertainties, if the PDF effect does not cancel.
- Many PDF measurements can benefit from such ratios:
 - W/Z : constraints s -quark distribution
 - W^+/W^- and charged Asymmetry (A_1) are sensitive to u_v and d_v .

ATLAS measurements: W,Z + X cross sections

- Inclusive W and A_{chg} at 8 TeV:

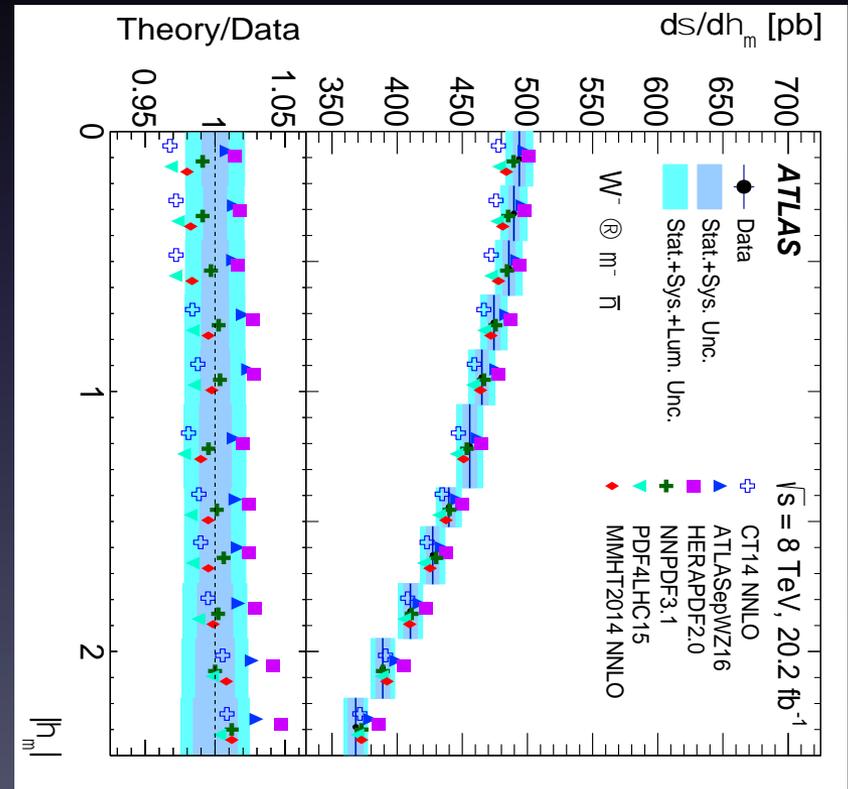
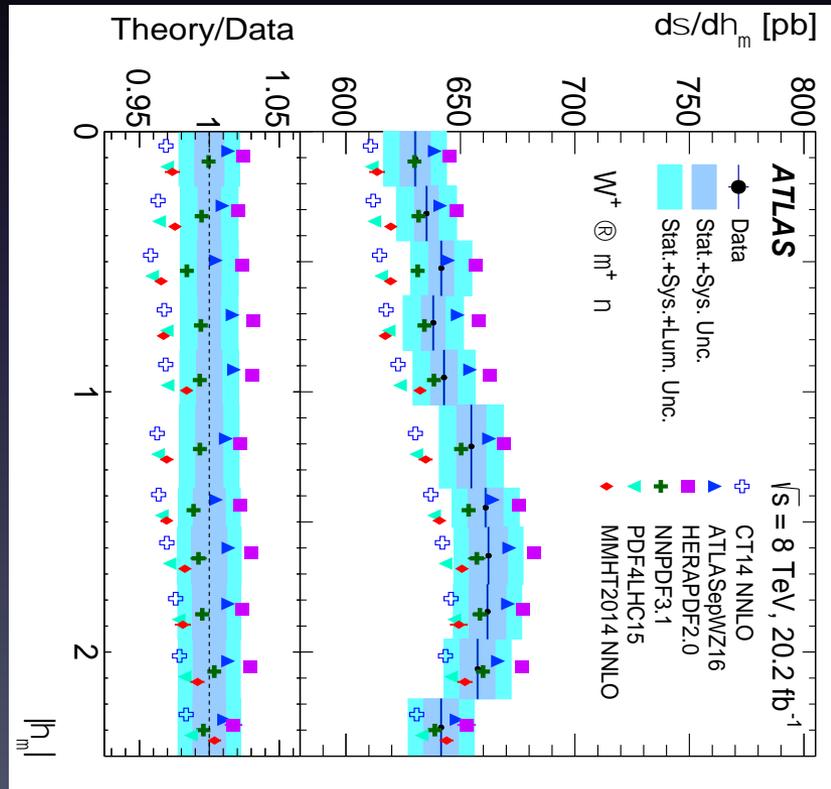
arXiv:1904.05631 [hep-ex]

- Inclusive W and Z at 5.04 TeV:

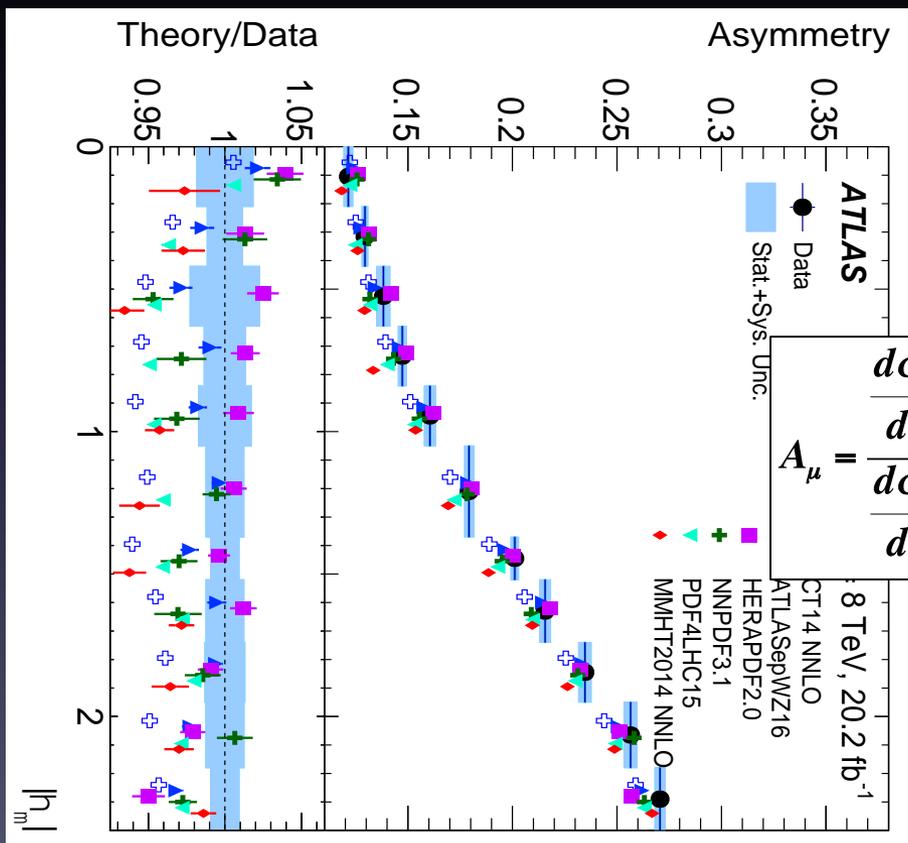
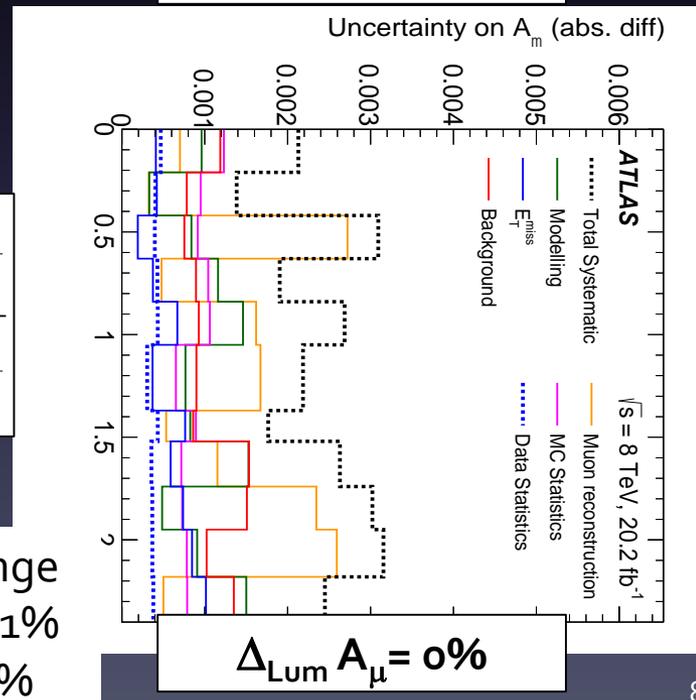
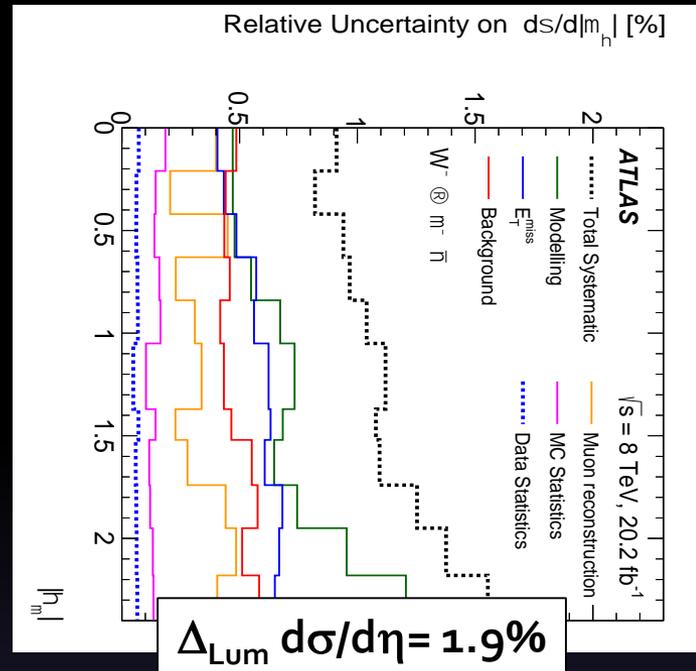
Eur. Phys. J. C 79 (2019) 128

*Many more results with W, Z or γ in inclusive or exclusive final states can be found in:
<https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults>

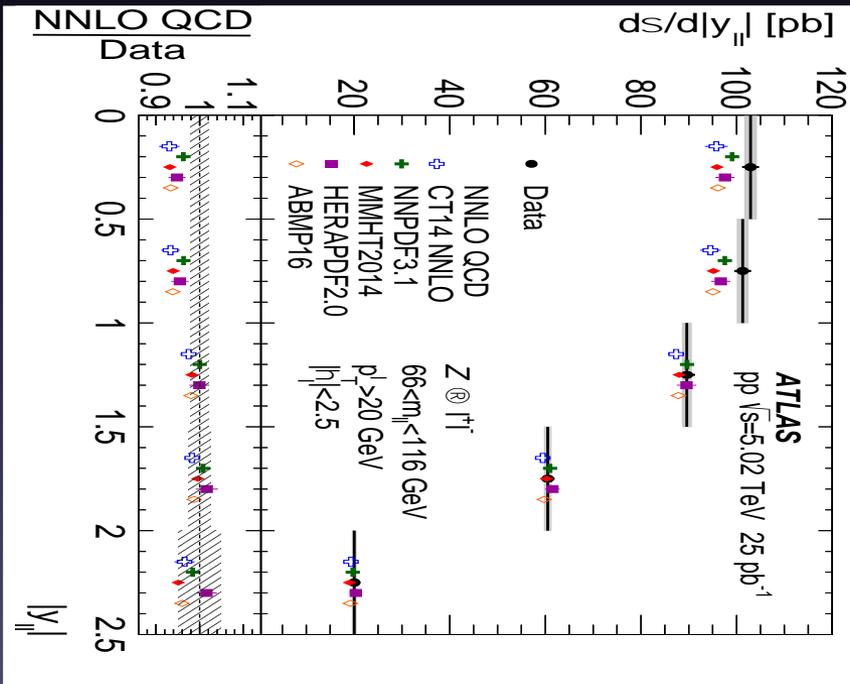
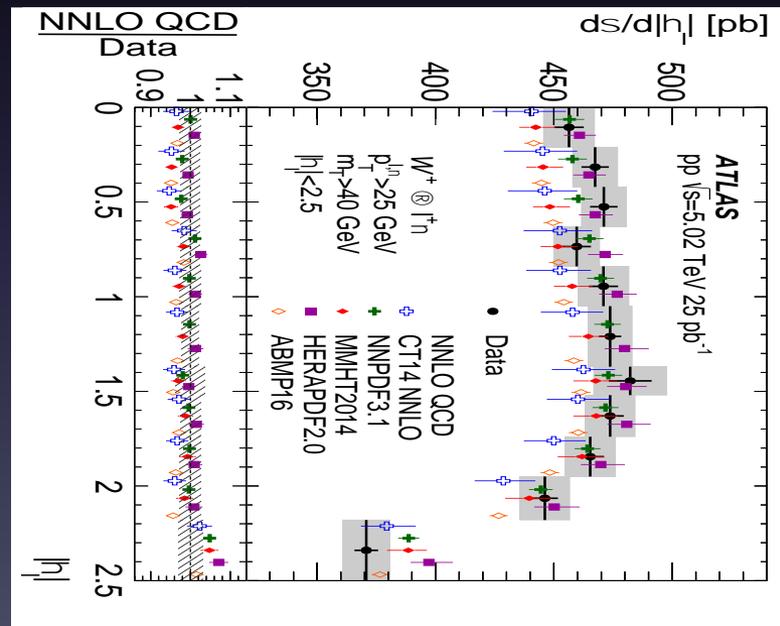
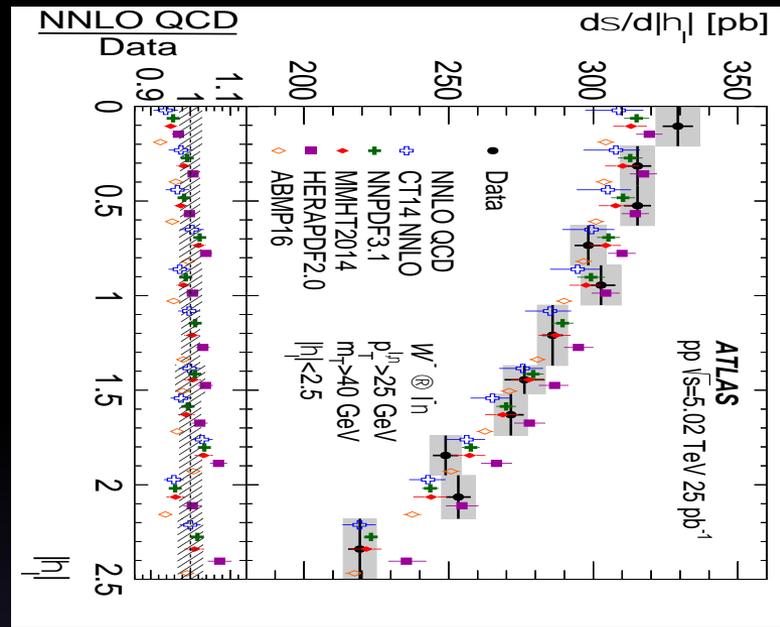
- Higher rate of W^+ than W^- at larger η_μ .
 - Expected due larger u_ν than d_ν at high x .
- Stronger discrimination power for W^+
 - predictions more widespread for similar uncertainty
- Data favor PDF sets that included 7 TeV ATLAS W/Z data in fit
 - Independent of these results; confirm previous impact of W data



- The asymmetry ratio results largely improve the precision and provide complementary information on PDF
- Stronger support of ATLASepWZ16, but also consistent discrepancy between W^+ and W^- for HERAPDF



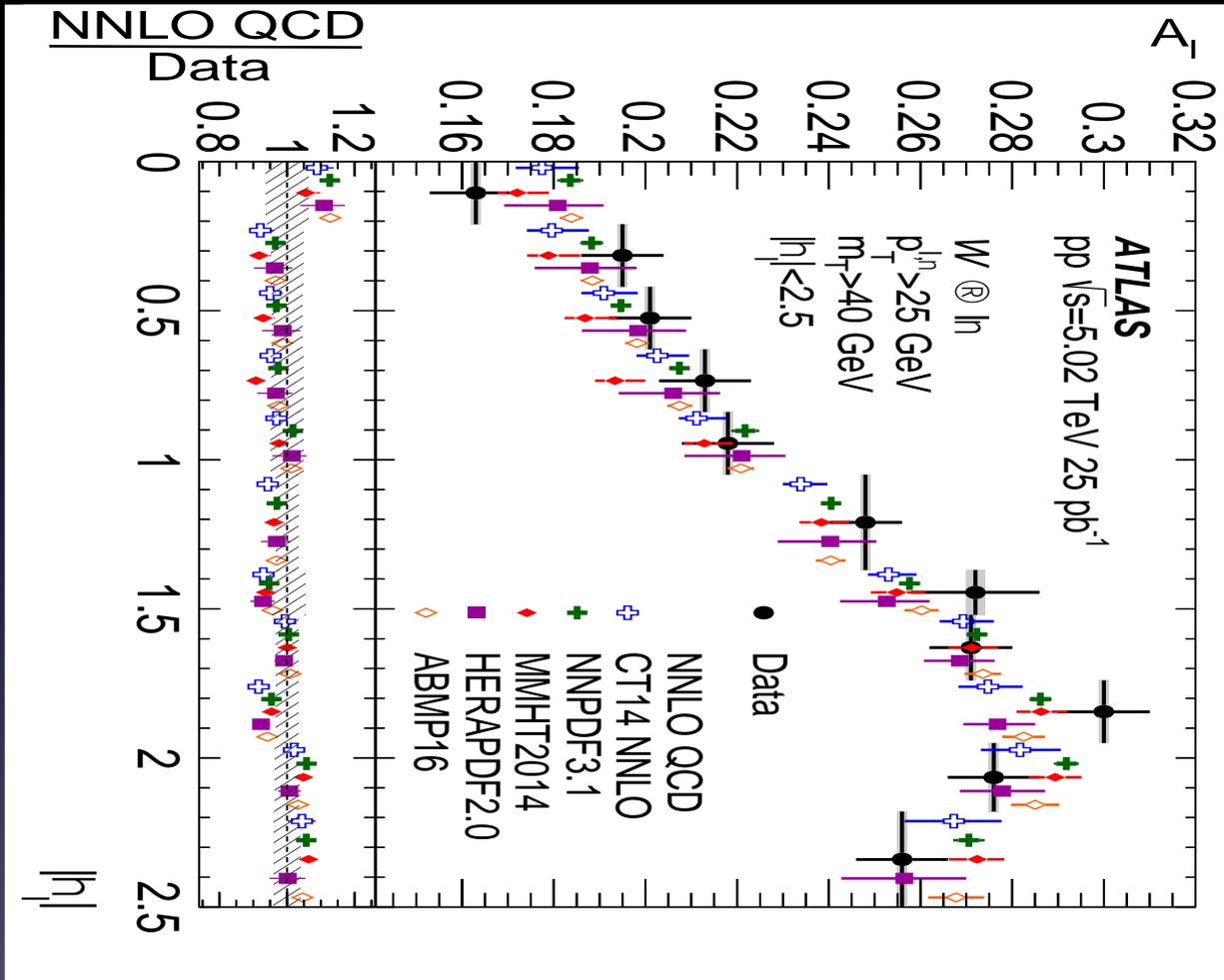
- General agreement with each PDF sets for 5 TeV W/Z data
 - Significant tension with all sets at very low η_{\perp} (low x) for W^- and Z
- Cannot disentangle any PDF sets except ABMP and CT14 in W^+
 - Nevertheless help improving Δ_{PDF}



$1.0\% < \Delta_{\text{sys}} < 2.0\%$, $1.7\% < \Delta_{\text{stat}} < 4.5\%$

$1.9\% < \Delta_{\text{sys}} < 3.1\%$, $1.3 < \Delta_{\text{stat}} < \Delta_{\text{lum}} = 1.9\%$

- Even with improved precision and combination of W^+ and W^- in a ratio, conclusions stay the same.
 - Still useful to improve the precision when included in fits

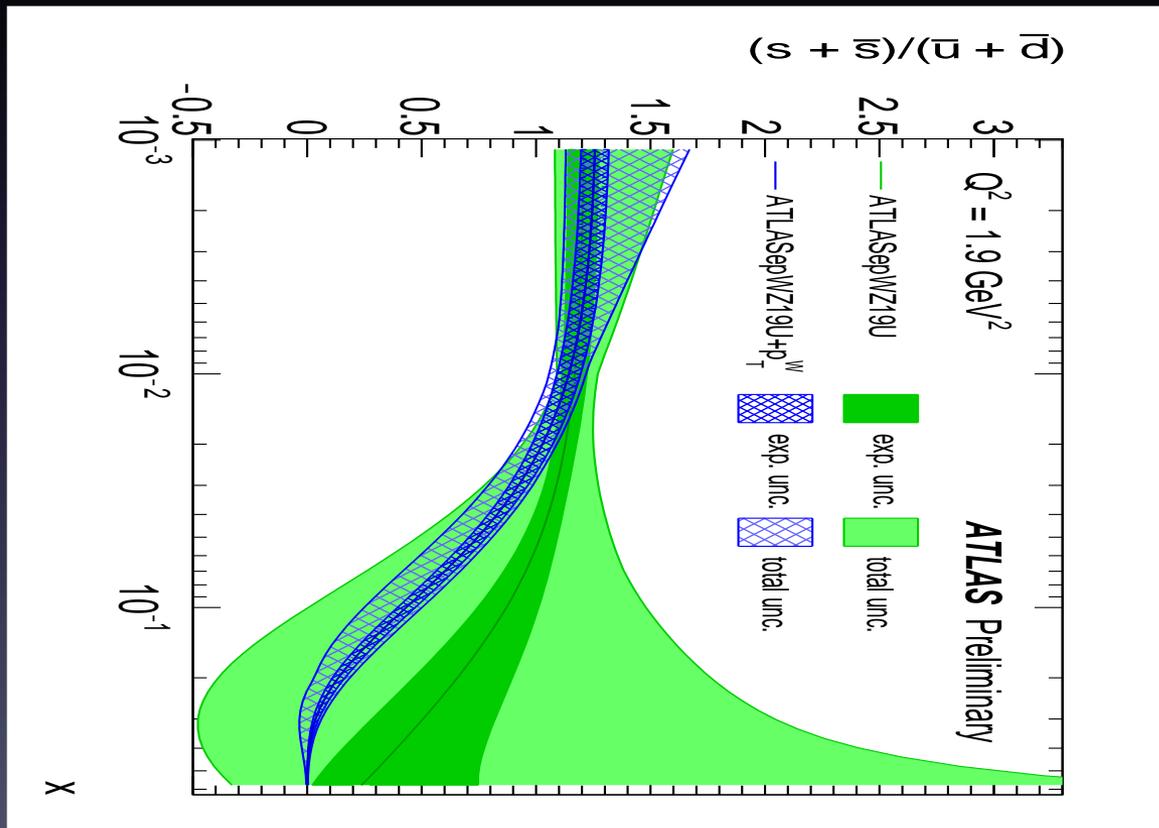


$$\Delta_{\text{sys}} \sim 0.7\%, \quad 3.3\% < \Delta_{\text{stat}} < 6.0\%, \quad \Delta_{\text{lum}} = 0\%$$

- To show an example:

How R_s is improved when W +jets 8 TeV ATLAS data are included in PDF fit

- Very low scale: $Q^2 = 1.9 \text{ GeV}^2$
- Use the p_T^W observable measured in W +jets events

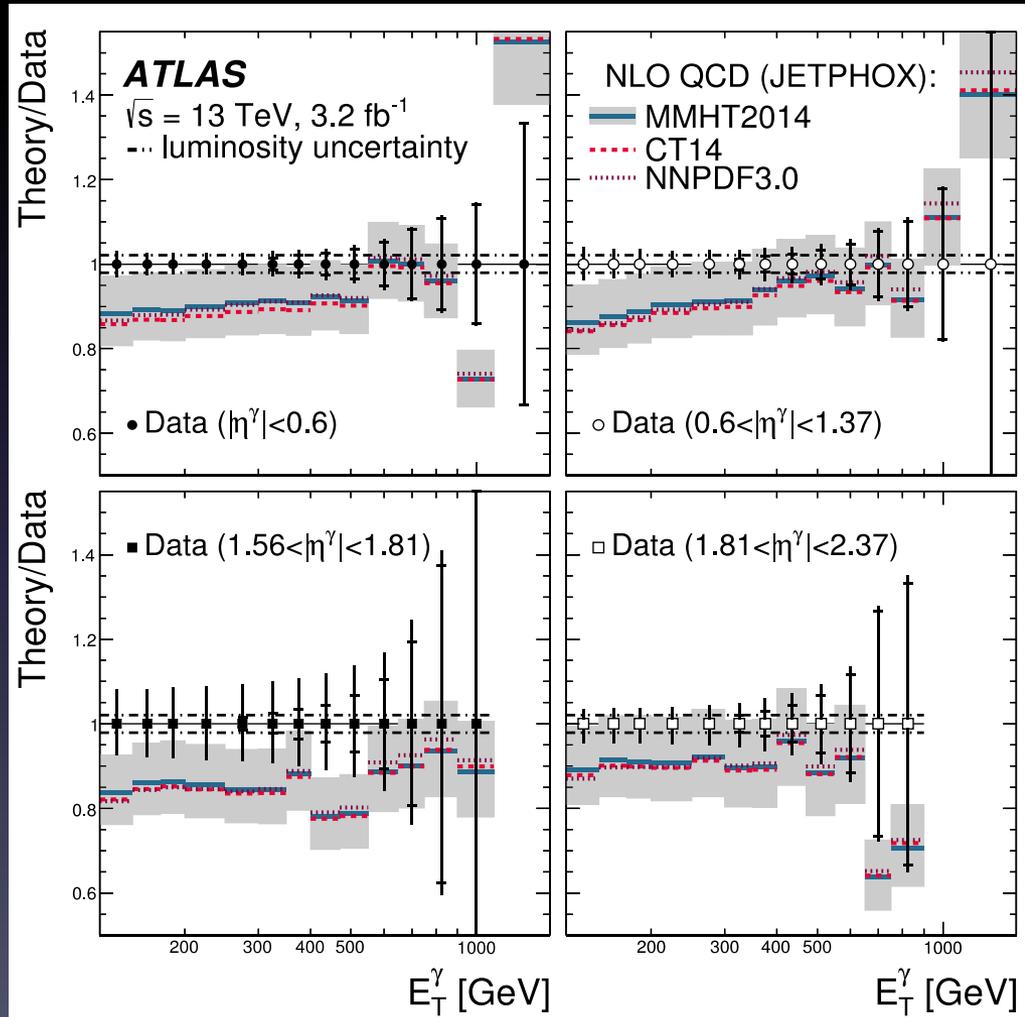


ATLAS photon + X measurements

- Inclusive isolated photon ratios

[arXiv:1901.10075](https://arxiv.org/abs/1901.10075) [hep-ex]

- Differential $\gamma+X$ cross section results as a function of E_T^γ and η_γ suffer from too large scale uncertainty to conclude anything about PDF.
 - Some data excess over NLO predictions from JETPHOX



Phys. Lett. B 770 (2017) 473

Similar tension
at all η

Uncertainties on σ_{tot} :

- $\Delta_{\text{sys}} \sim 3.4\%$
- $\Delta_{\text{stat}} \sim 0.4\%$
- $\Delta_{\text{lum}} \sim 1.9\%$

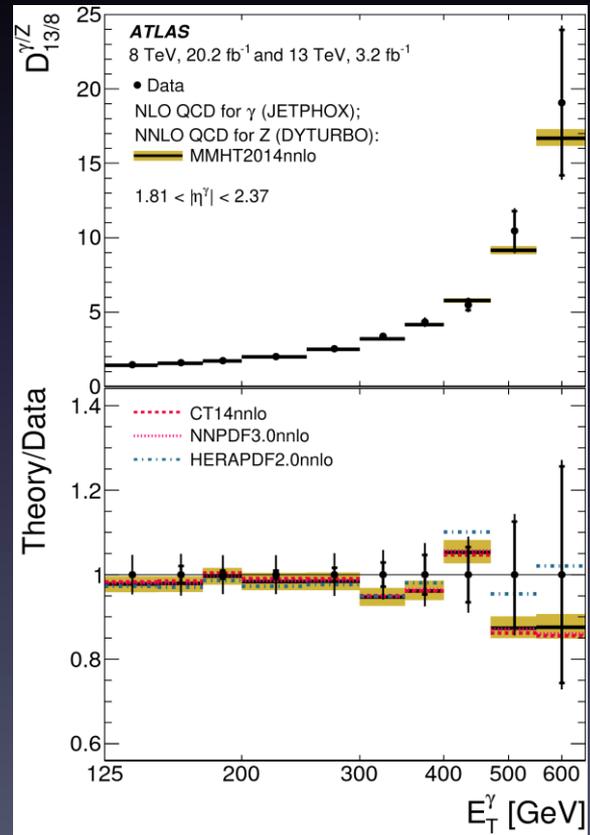
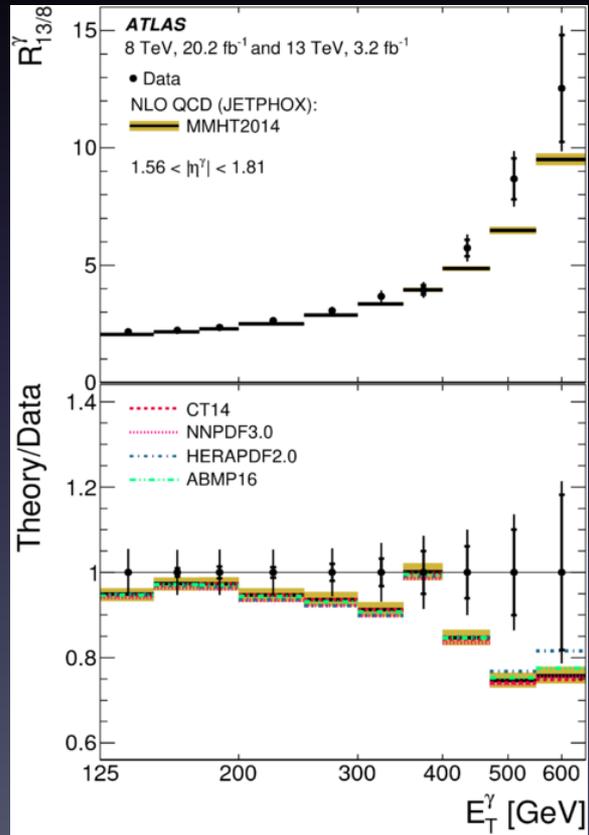
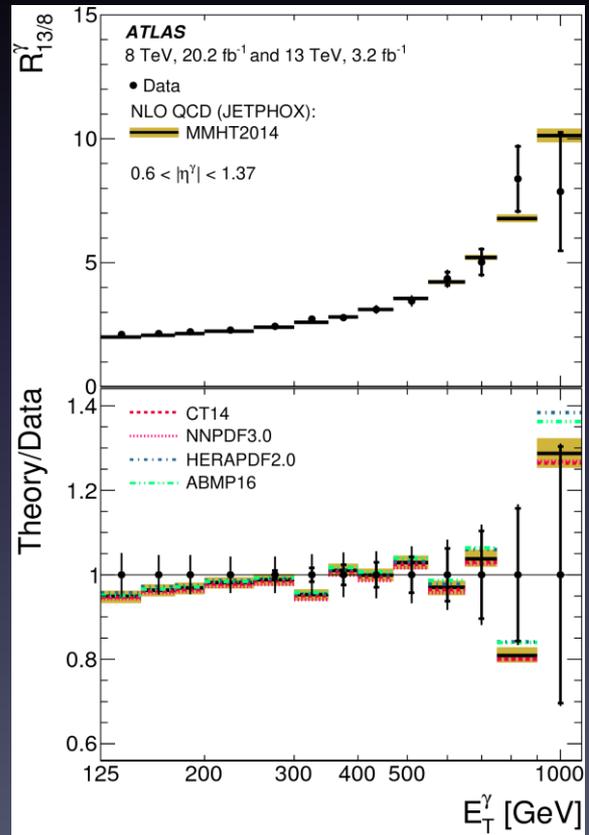
Much smaller than scale
uncertainty on predictions.

Inclusive γ cross section ratios

- Measure the ratio $R_{13/8}^\gamma$ as a function of different observables to gain sensitivity to PDF and other pQCD effects in photon production measurements.
 - Predictions obtained at NLO
- The distribution of this ratio can further be normalized on the $R_{13/8}^Z$ measured value obtained by ATLAS
 - Cancel luminosity uncertainty
 - $R_{13/8}^Z$ (meas.) = 1.537 ± 0.001 (stat.) ± 0.010 (syst.) ± 0.044 (lumi.)
 - Agreed with predictions calculated at NNLO
- Scale uncertainties:
 - Assumed correlated in $R_{13/8}^\gamma$ but not in $D_{13/8}^{\gamma/Z}$
 - Theo uncert: 10-15% (absolute diff. cross section) \rightarrow 2% ($R_{13/8}^\gamma$)
 - Exp syst: <5% for all range

- Generally good description of data by NLO predictions
 - Some hint of tensions for $E_T^\gamma \sim 125$ GeV
 - Just for smaller γ rapidity regions
 - Some tension for large E_T^γ
 - Not very consistent between η_γ regions, and very large uncertainties
 - Near perfect agreement for forward photon

• Normalizing on $R_{13/8}^Z$ doesn't change the results



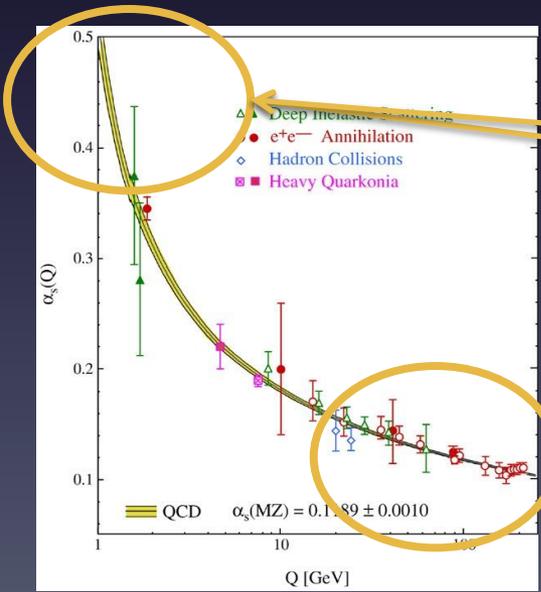
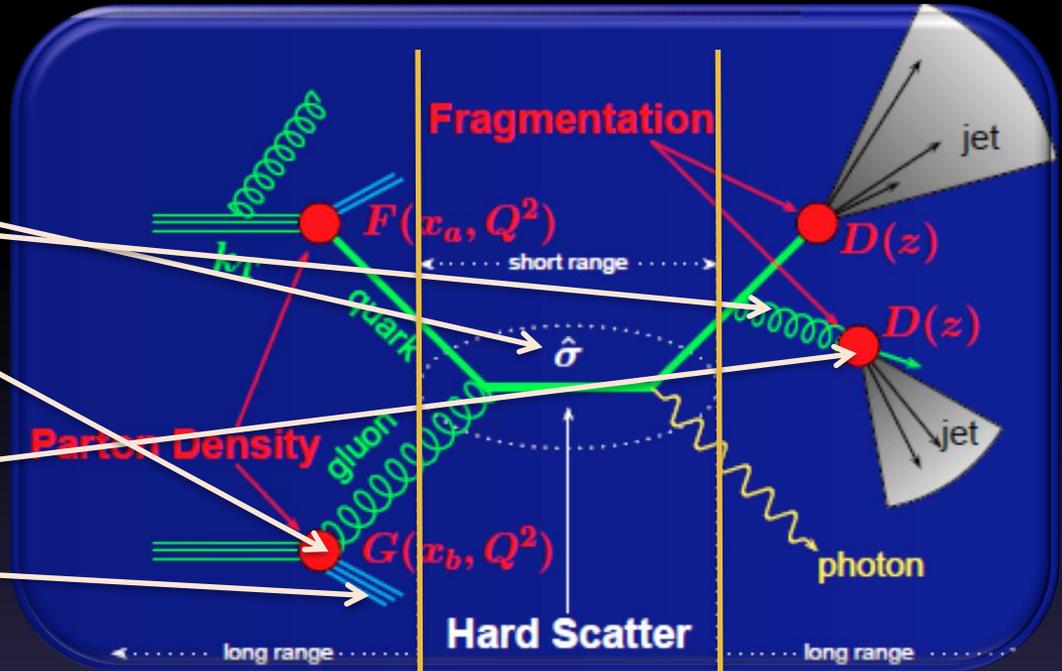
Conclusion

- ATLAS performed comprehensive studies of PDF and other pQCD effects in inclusive electroweak boson production
 - Sensitive to various NNLO PDF predictions
- 8TeV W^+ , W^- and charge asymmetry:
 - Favor PDFs that already include W/Z 7 TeV ATLAS data in their fits
 - The A_1 asymmetry shows that HERAPDF yields a reasonable agreement with no hadron collider data at all included in their fit
 - Excellent precision will improve PDF uncertainties
- From $\gamma+X$:
 - Cannot conclude much from differential cross section results other than NLO predictions are in tensions with data
 - Ratio improves the precision, but without distinguishing the various PDF set tested.

Back-up slides

The strong interaction intervenes in various ways and at various scales in every single event at the LHC

- Matrix element of interest $(\hat{\sigma})$
- Gluon emission (ISR/FSR)
- Proton structure (F, G)
- Fragmentation and hadronization $(D(z))$
- Underlying event



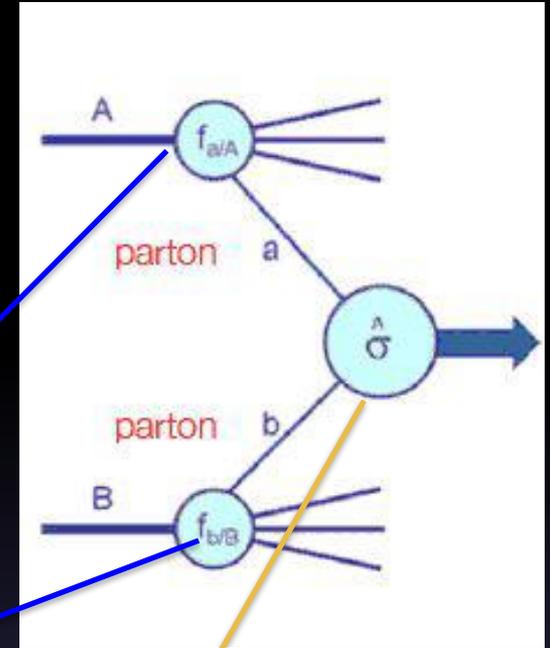
Long distance physics Short distance physics Long distance physics

Require a mix of theoretical predictions and data measurements to model these effects

Factorization theorem:

The probabilities for short-distance and long-distance processes factorize

The long-distance factors are universal and can be empirically obtained from ancillary measurements. **Idea behind PDF "industry"**



$$d\sigma(P_1, P_2) = \sum_{i,j,k} \int dx_1 dx_2 dz f_i(x_1, \mu_F) f_j(x_2, \mu_F) D_{k \rightarrow H}(z, \mu_F) \times d\tilde{\sigma}_{ij \rightarrow k+X}(p_1 = x_1 P_1, p_2 = x_2 P_2, p_k = P/z, \alpha_S(\mu_R), Q^2, \mu_R, \mu_F)$$

Evolution equations (e.g. DGLAP), analogous to β -functions for α_S , account for transition from one scale to the other

- PDFs are not uniquely defined. Different sets make different choices of:
 - Data included in the fits, uncertainty correlations, fitting techniques, and $\Delta\chi^2$ tolerance
 - e.g. HERAPDF only use HERA data and some DIS fixed target scattering on low mass nuclei data, while others include pp data
 - PDF phenomenological parametrization, and theory methods
 - e.g. choice of $P(x;A_3)$ in : $F(x, Q_0) = A_1 x^{A_1} (1-x)^{A_2} P(x; \vec{A}_3)$
 - Constraints to reduce the number of parameters to fit
 - e.g. HERAPDF uses $r_s=1.0$, while MMHT let s and $sbar$ float
 - Physics parameter values
 - e.g. Q_0^2 , $m_{c,f}$, $\alpha_{s,f}$, $\mu_R/\mu_{F,f}$ etc.
- The results to be presented compare data to different NNLO PDF sets:
 - NNPDF3.1, CT14nnlo, MMHT14nnlo68cl, ABMP16, HERAPDF2.0