QED-corrected precision phenomenology and PDF4LHC

2 December 2024

[PDF4LHC 2024, CERN]

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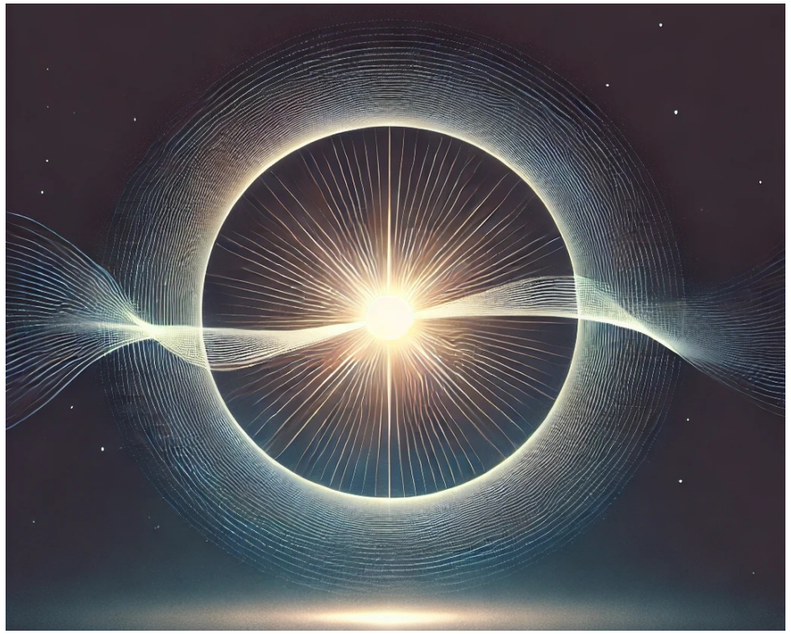

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an *update* on recent progress in electroweak phenomenology with QED corrections; ongoing investigations within PDF4LHC

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thanks to colleagues in CTEQ-TEA and PDF4LHC Working Groups

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recent progress in QED-corrected HEP phenomenology

- array of developments influencing precision in electroweak, HEP phenomenology

  → efforts to improve PDF working accuracy: multiple approximate N3LO, NNLO+ (QCD) methods

  [see talks: Bluemlein, Guzzi, Magni, Nadolsky]

  → new precision electroweak measurements and observables [see talks: ATLAS, CMS, LHCb]

  → novel uncertainty quantification, parameter inference techniques [see talks: today/tomorrow]

- the past ~2 years have seen all major PDF-fitting groups update their treatment of QED/EW

  (*i.e.*, with the LUXQED ansatz)

- this talk: ongoing PDF4LHC studies of QED-corrected precision Higgs/EW observables

  later results are *preliminary*.

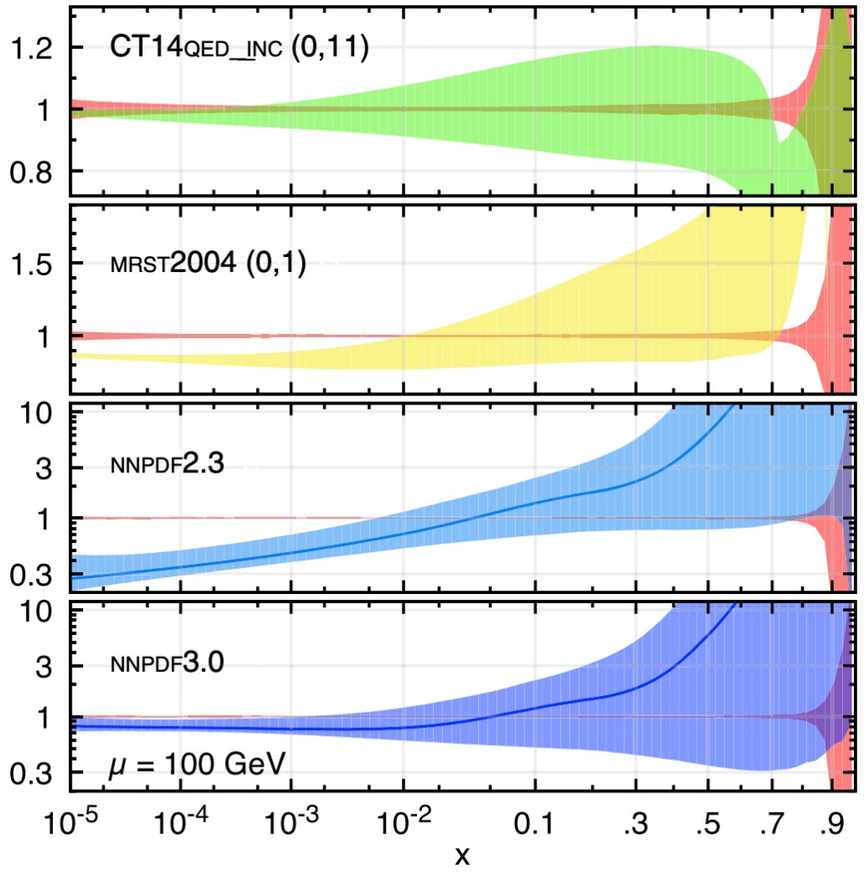
the LUX formalism

Manohar et al., PRL117, 242002 (2017)

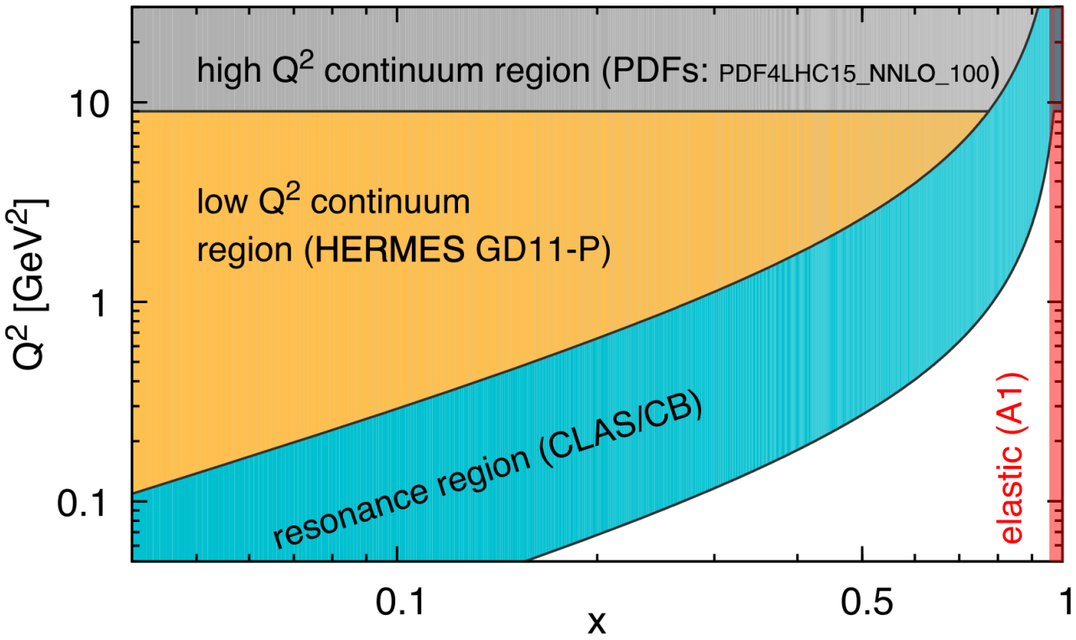
- significant leap: definition of auxiliary PDFs through *fictious* neutral-lepton scattering
  - → gives rise to explicit master formula for photon PDF, calculable from integrated proton structure functions:

$$x\gamma(x,\mu^2) = \frac{1}{2\pi\alpha(\mu^2)}\int_x^1 \frac{\mathrm{d}z}{z}\left\{\int_{x^2m_p^2/(1-z)}^{\mu^2}\frac{\mathrm{d}Q^2}{Q^2}\alpha_{\mathrm{ph}}(-Q^2)\left[\left(zp_{\gamma q}(z)+\frac{2x^2m_p^2}{Q^2}\right)F_2\left(\frac{x}{z},Q^2\right)\right.\right.$$

$$\left.\left.-z^2F_L\left(\frac{x}{z},Q^2\right)\right]-\alpha^2(\mu^2)z^2F_2\left(\frac{x}{z},\mu^2\right)\right\}+\mathcal{O}(\alpha^2,\alpha\alpha_s)$$



significant photon PDF uncertainty reductions

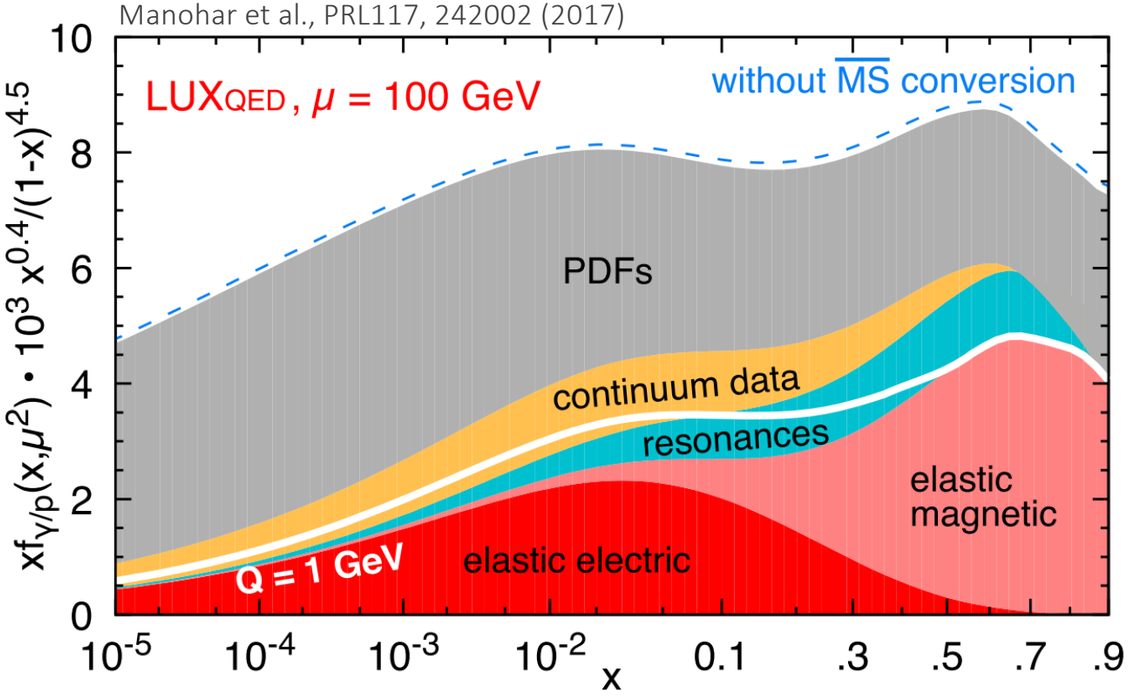


photon PDF uncertainties in LUX approach

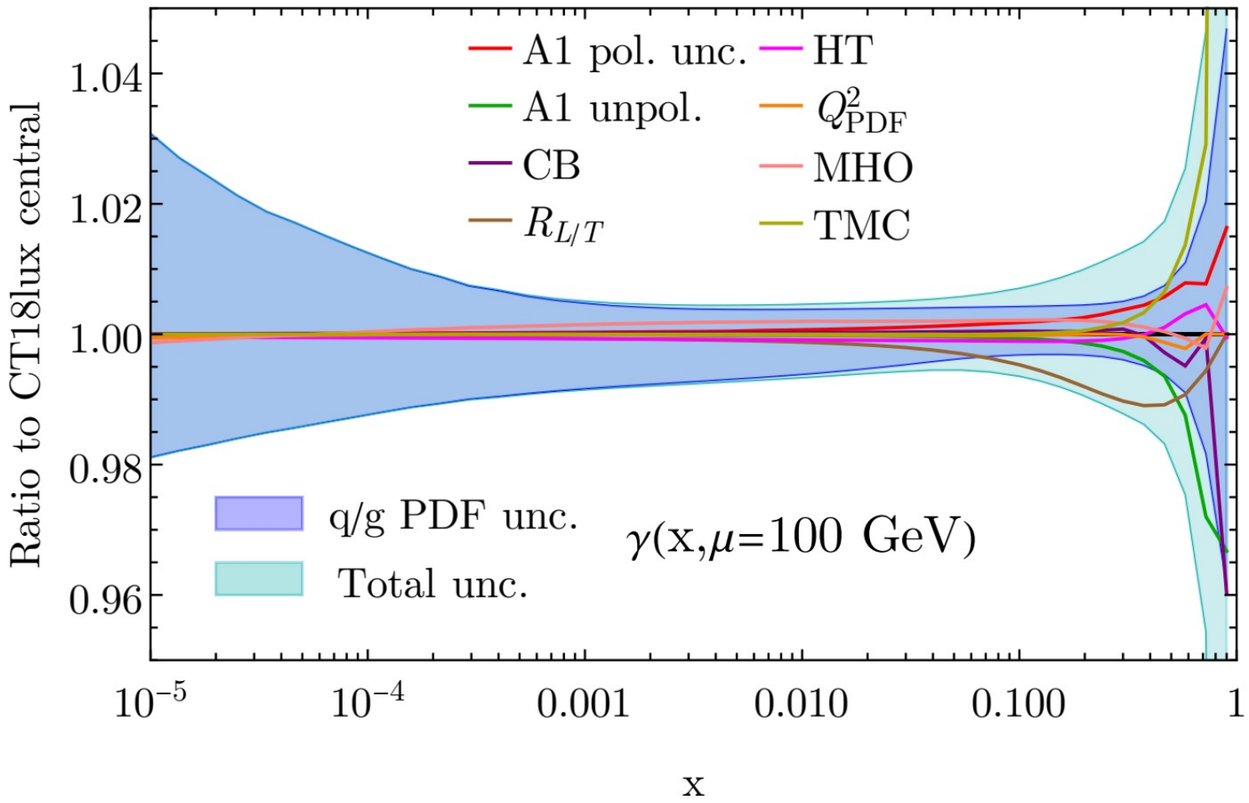
- LUX approach introduces an array of uncertainties from dynamics at low-Q^2

  → must be systematically quantified; typically included in error sets as, *e.g.*, distinct eigenvectors

Manohar et al., PRL117, 242002 (2017)



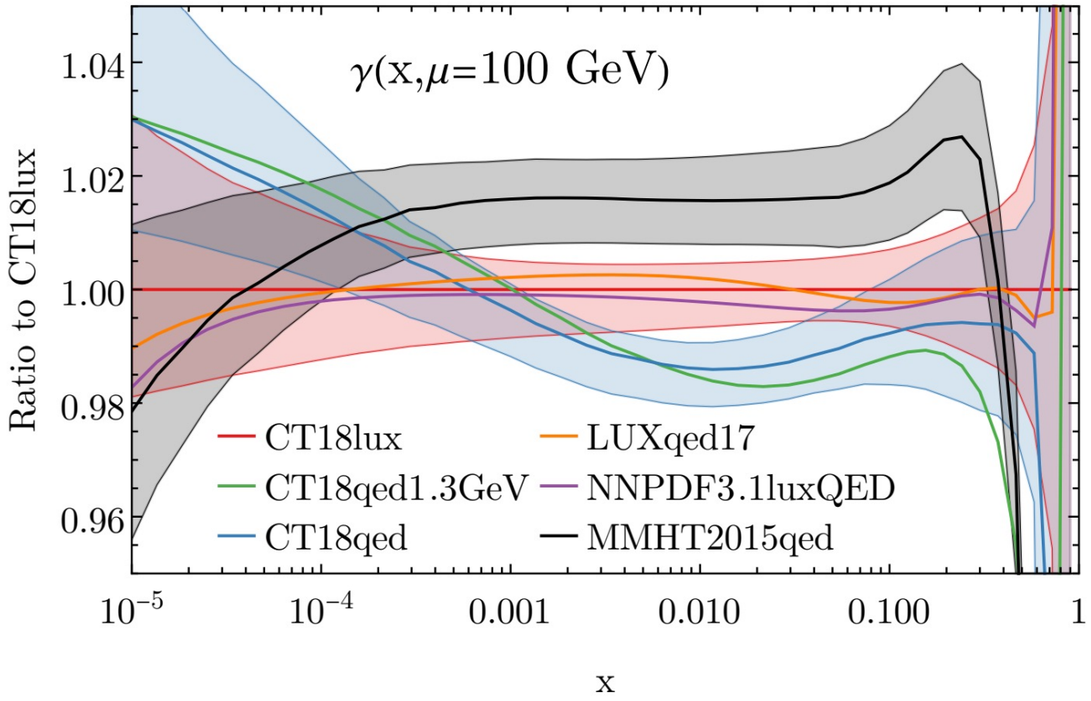
Xie et al. (CT18QED), PRD105 (2022) 5, 054006



- precision in high-x sensitive collider processes degraded by these low-Q^2 uncertainties

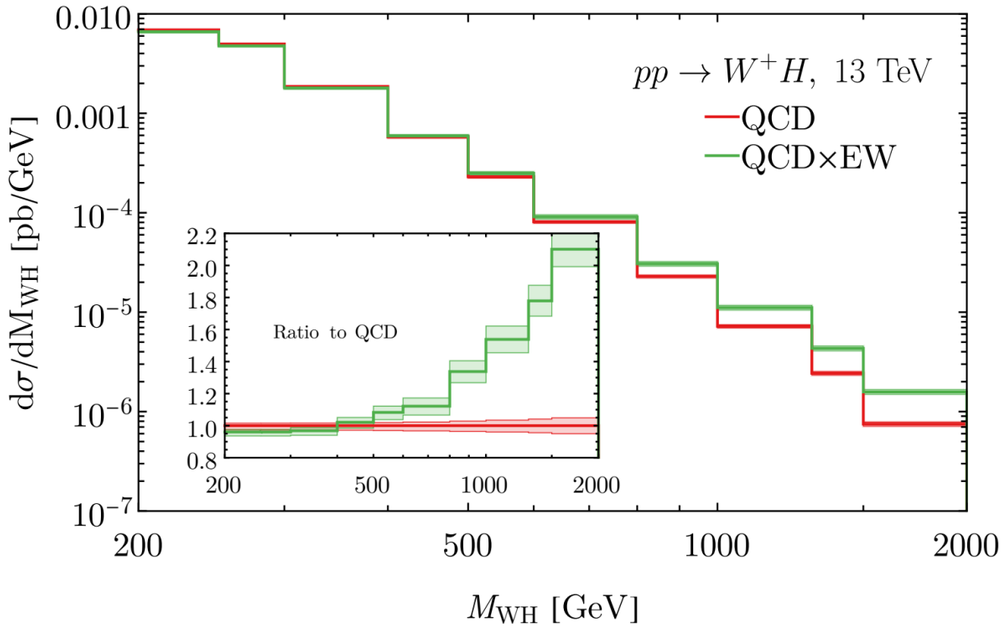
PDF analysis implementations: CT18QED

Xie et al. [CT18QED], PRD105 (2022) 5, 054006



- CT explored multiple scenarios for the inclusion of the photon PDF in fitting workflow
  - → at what scale to implement LUX formalism; how to integrate with QCD+QED evolution

- phenomenological studies: significant impact of photon-initiated channel on high-mass Higgs-strahlung
  - → enters first at NLO EW working accuracy
  - → connected to precision studies with higher-order QCD
  - → also: W^+W^-, high-mass DY, $\bar{t}t$, …

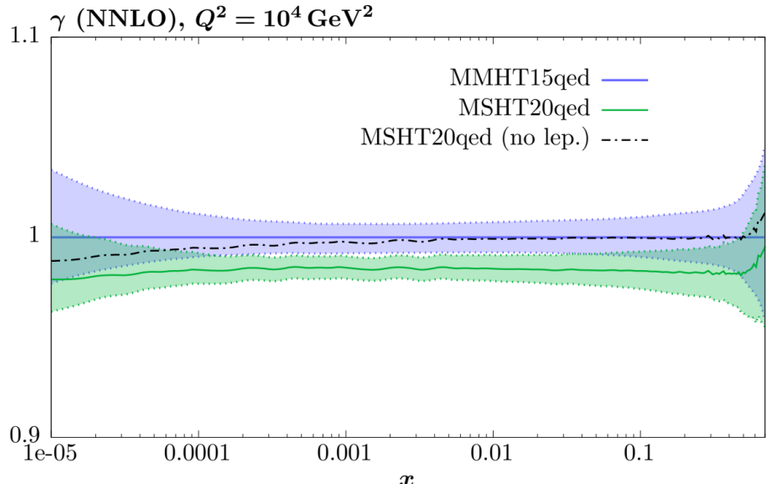


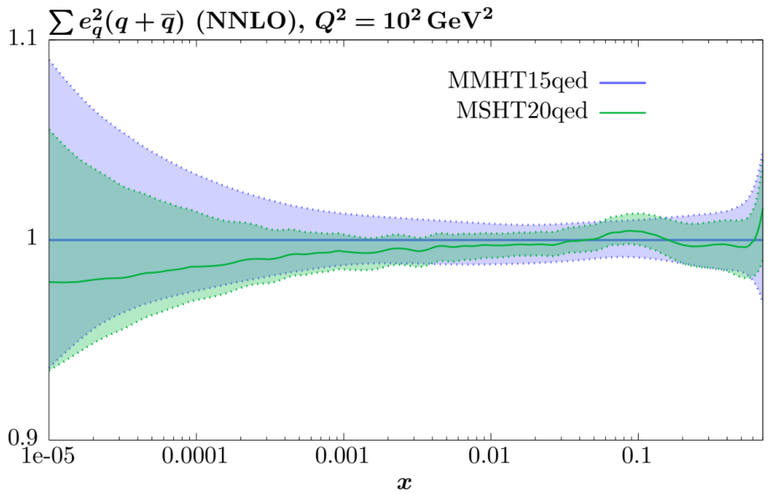
MSHT20 QED

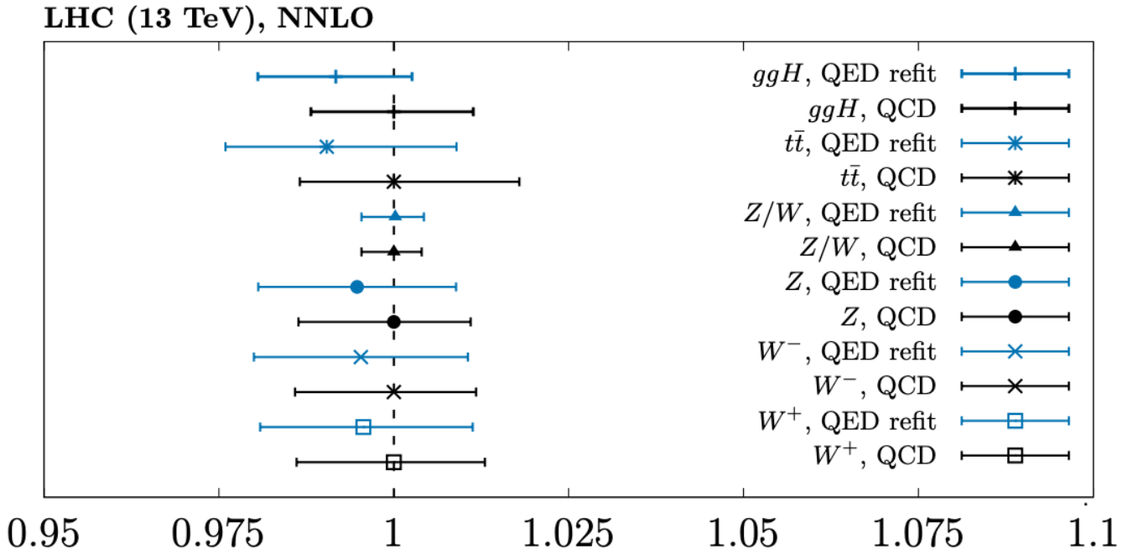
Cridge et al. [MSHT20QED], EPJC82 (2022) 1, 90

- MSHT incorporated LUX-based PDF refits subsequent to the MSHT20 PDF main release

  → quantified (in)elastic photon decomposition; phenomenological studies, charge-symmetry violation, …







- PDF refits in presence of QED corrections, photon PDF: notable (but within uncertainties) shifts in key LHC channels

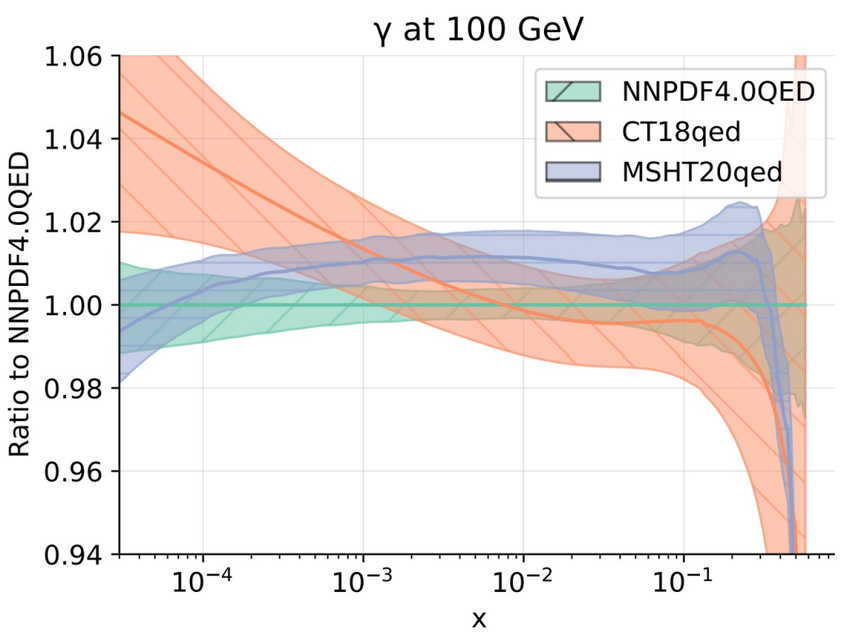
  → interplay with aN3LO (2312.07665, 2411.05373) [see talks: Thorne, Magni]

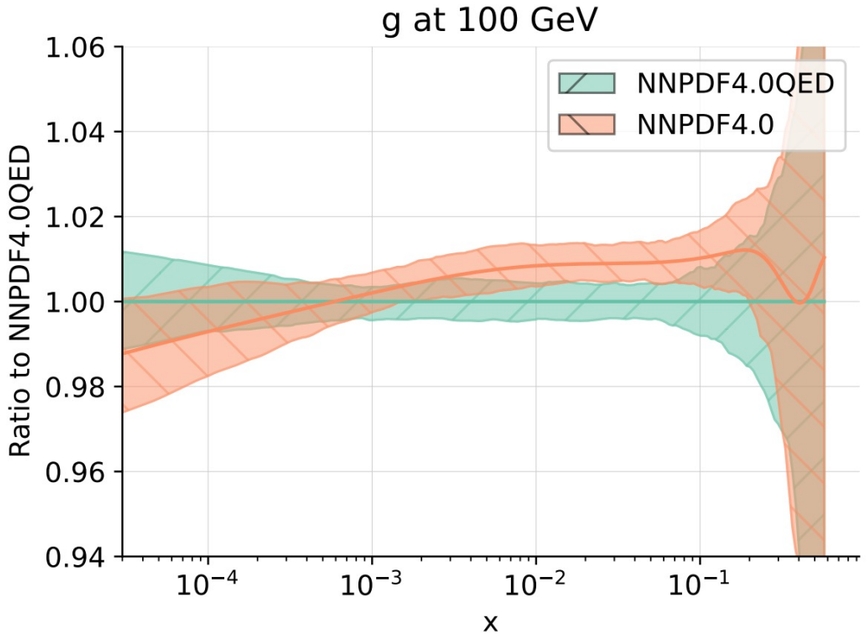
QED in NNPDF4.0

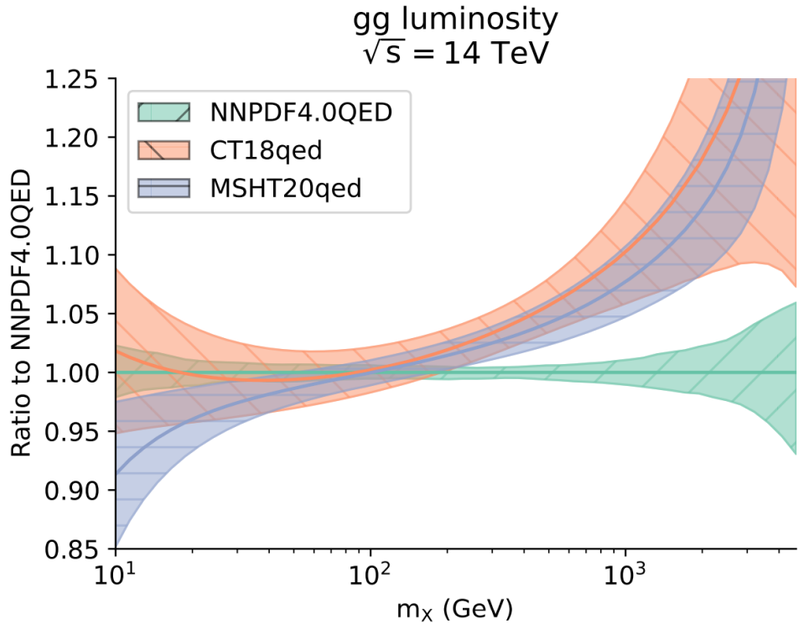
Ball et al. [NNPDF4.0QED], EPJC84 (2024) 5, 540

❑ NNPDF included LUX photon PDFs in the larger setting of NNPDF4.0 [see talks: Magni, Rojo, Stegman]

→ extends NNPDF3.1QED determination by implementing QCD+QED evolution within EKO framework







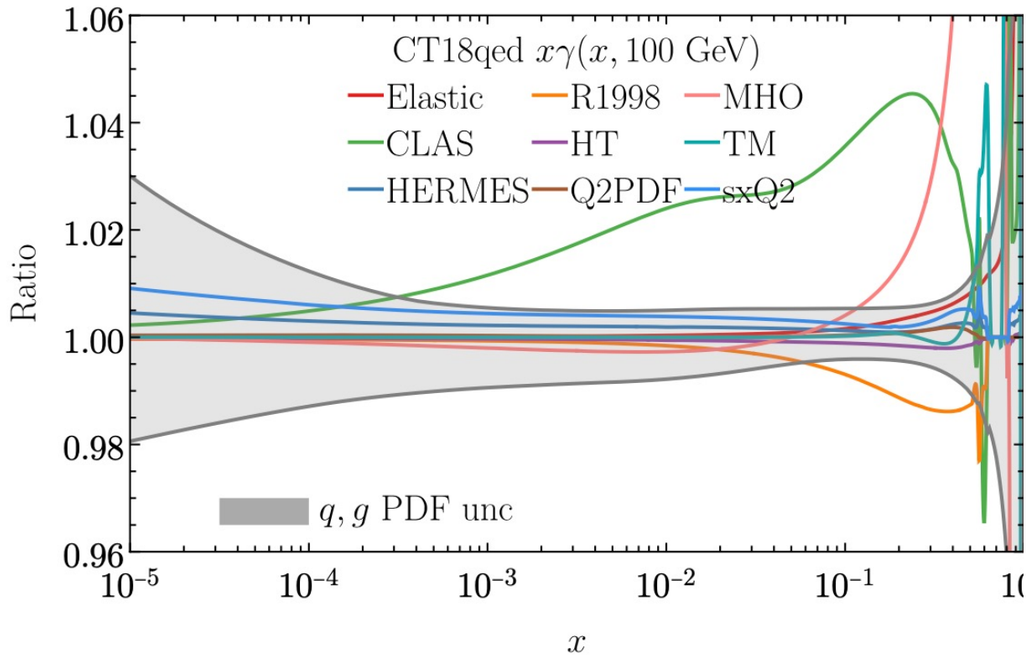
→ general statistical agreement for photon PDF among fitting groups; QED refits may impact other flavors

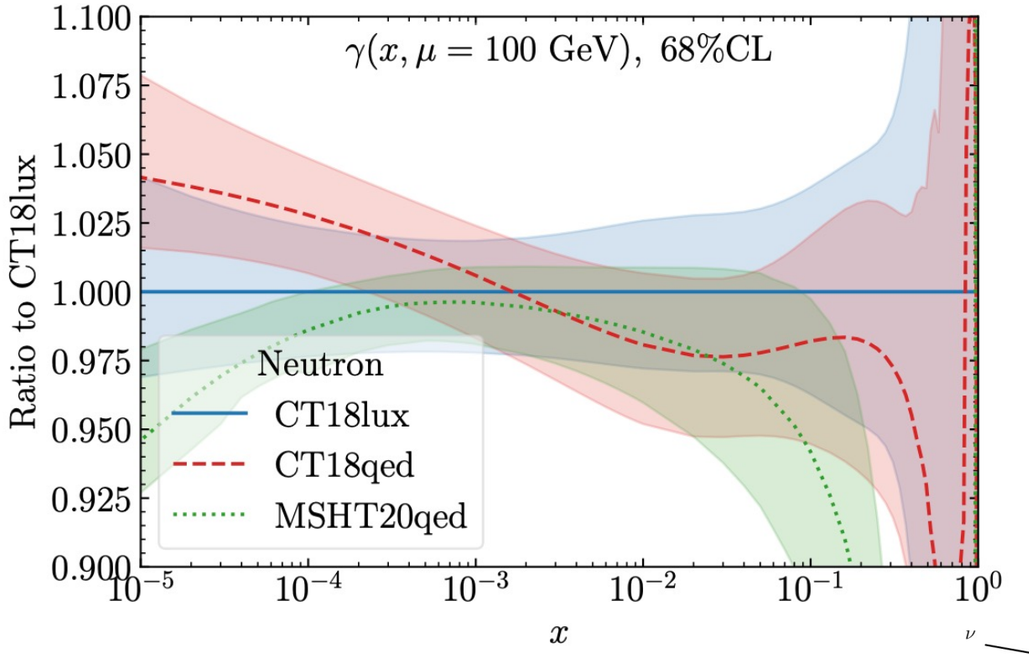
→ small but non-negligible QED impacts on key LHC channels; e.g., ~2% impact(s) on Higgs cross section

how bright is the neutron?

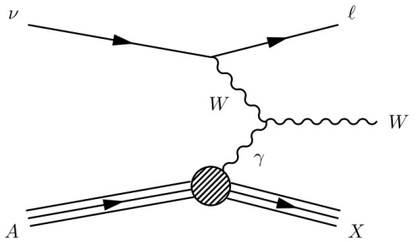
Xie et al., JHEP04 (2024) 022

- recent follow-on calculation in spirit of proton analysis; parallels proton-LUX implementation
  - → counterpart to MSHT-family calculations Cridge et al. [MSHT20QED], EPJC82 (2022) 1, 90
  - → low-Q^2 information on neutron SF (especially resonance-region) limited: driver of uncertainty





- EW pheno implications: *e.g.*, TeV-scale (and beyond) neutrino-nuclear scattering



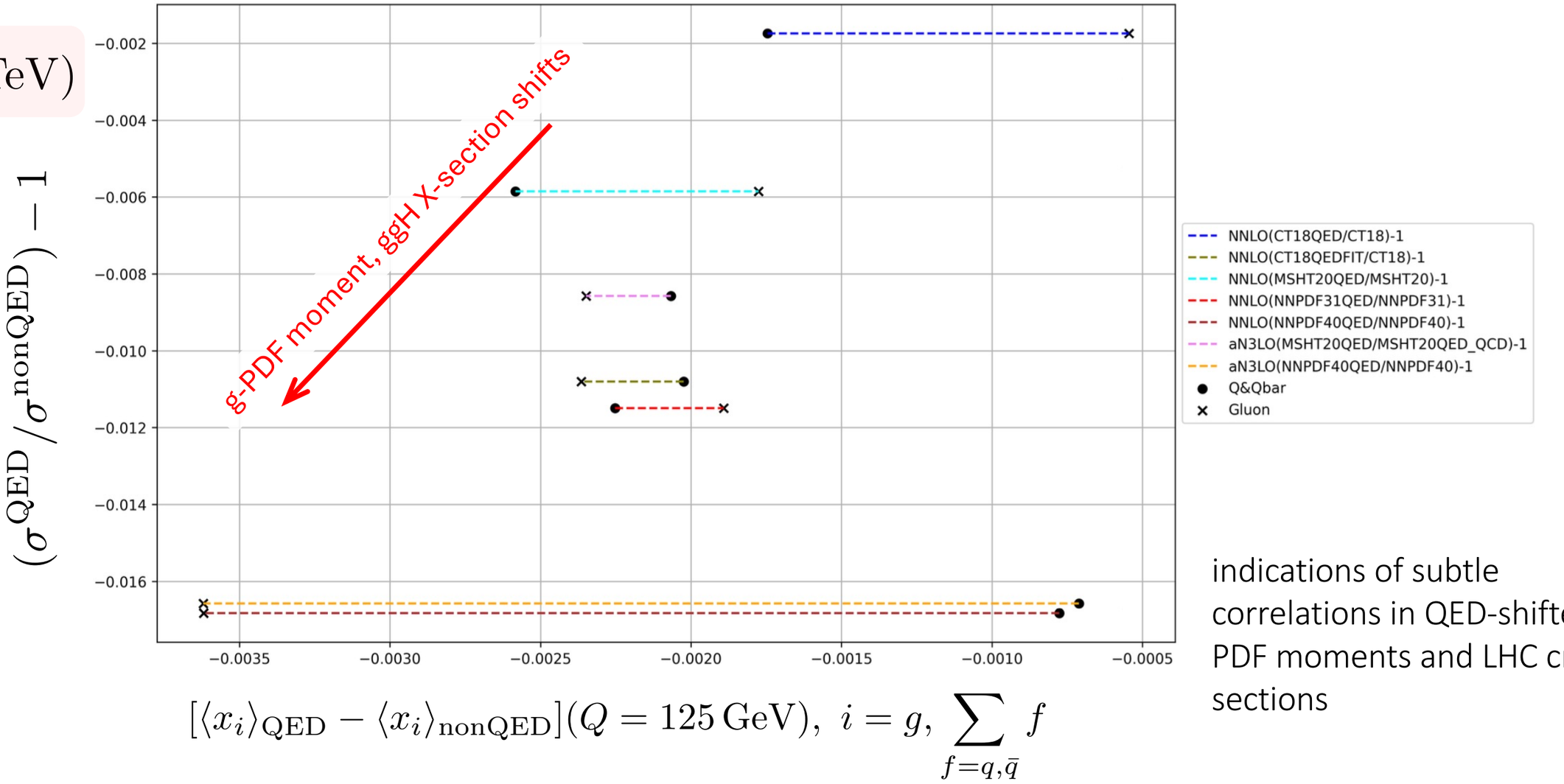
→ - various analysis developments; **practical implications for Higgs precision?**

QED-corrected total Higgs cross sections

$gg \to H$

- various total cross sections available at N3LO in `n3loxs`; calculations by Max Ponce

$\sigma^{gg\to H}(14\ \text{TeV})$



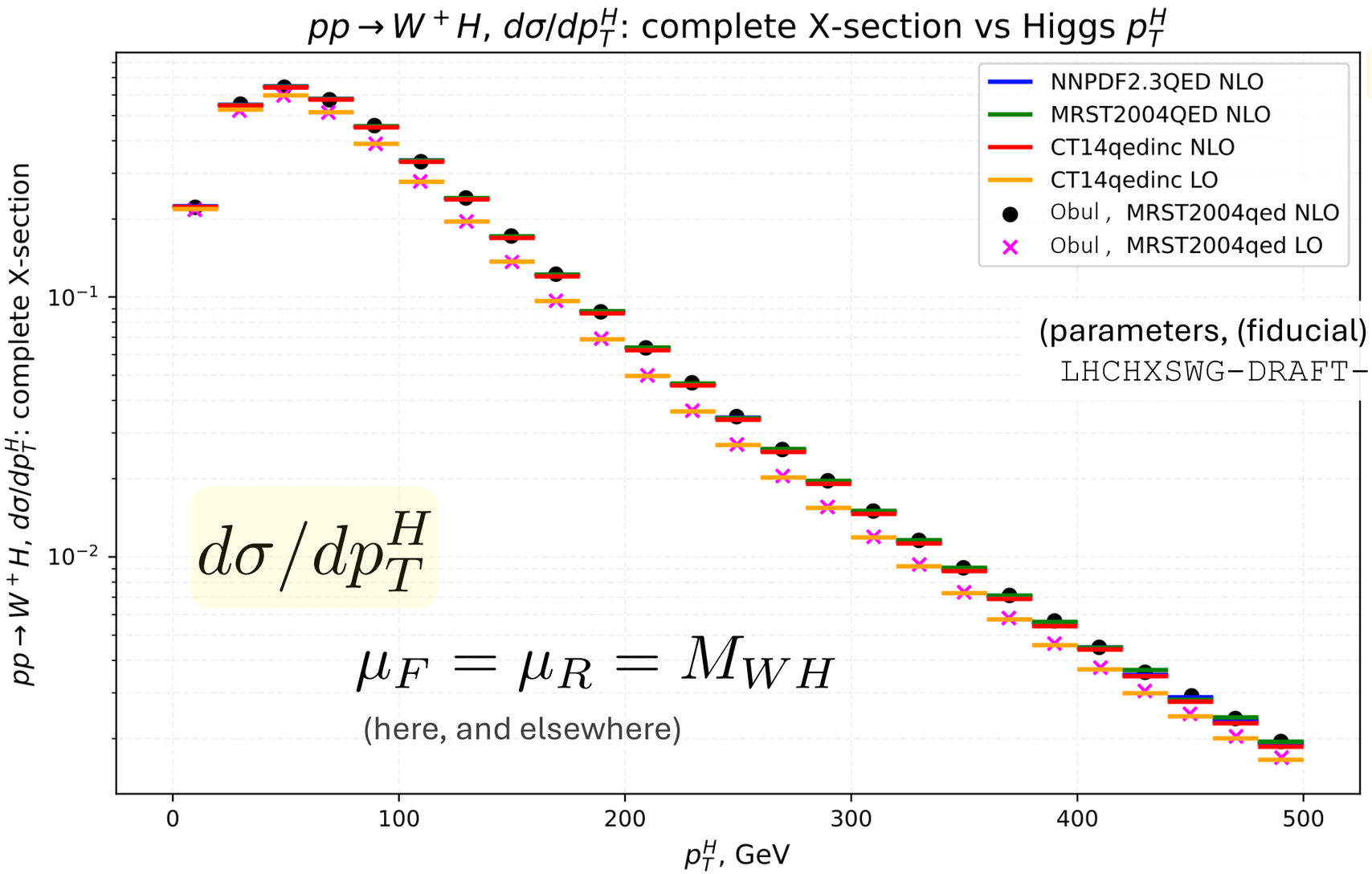
indications of subtle correlations in QED-shifted PDF moments and LHC cross sections

→ in the end, examining more **differential distributions** may inform QED-corrected PDF effects

revisiting electroweak *differential distributions*: Higgs-strahlung

$pp \to W^+H$

W^+H is a representative example → other processes qualitatively similar (W^-H, ZH, VBF, …)



Obul et al., 2018 Chinese Phys. C 42 093105

(parameters, (fiducial) cuts: `LHCHXSWG-DRAFT-INT-2016-008`)

`HAWK-2.0` code
Denner et al., CPC195 (2015) 161

13 TeV

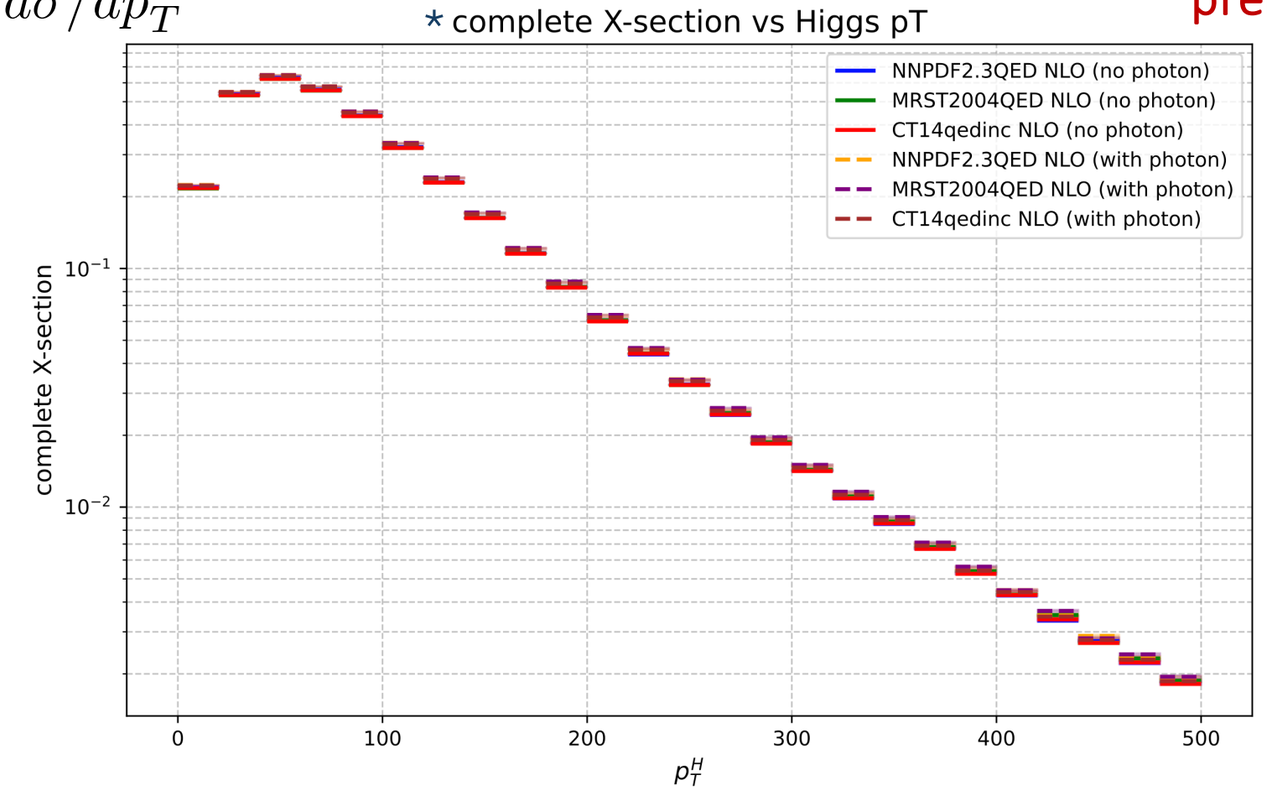
ratios of photon-induced to no-photon Higgs-strahlung

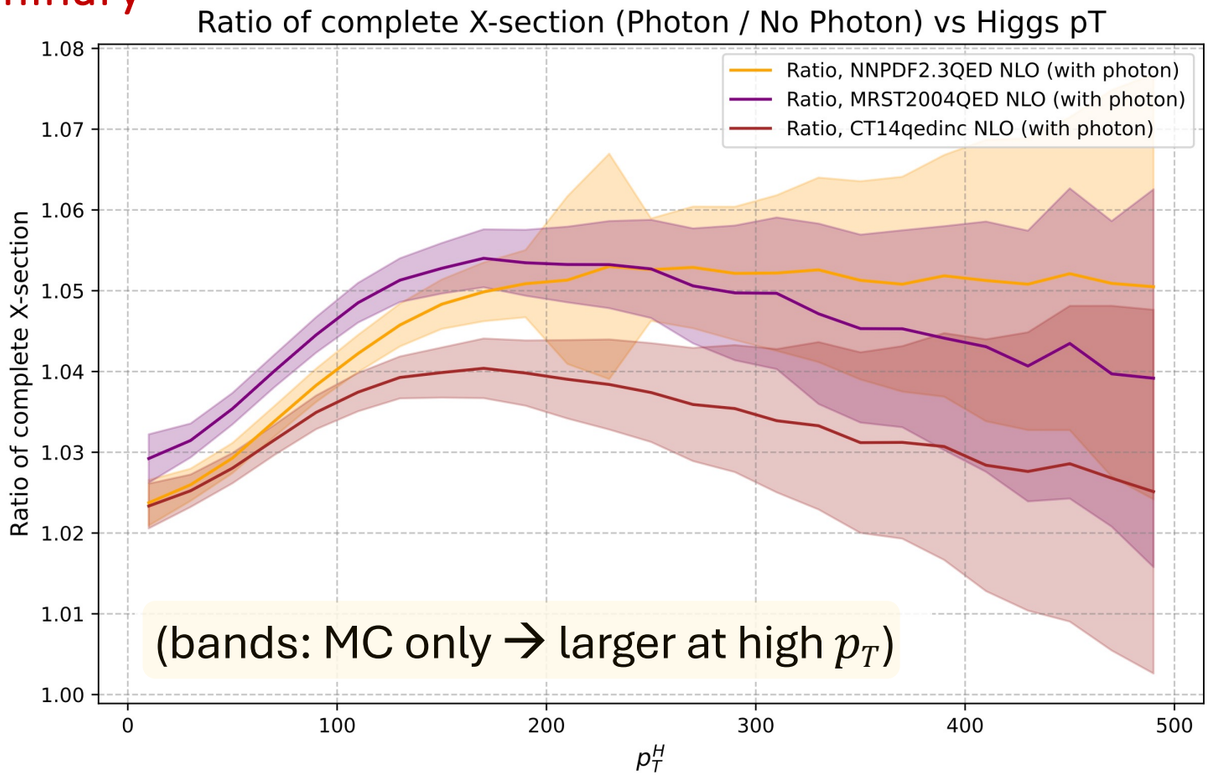
$pp \to W^+H$

- examine NLO EW corrections; photon-induced contributions sensitive to photon-PDF treatment

$d\sigma/dp_T^H$

preliminary





*NB: complete cross section represents LO + NLO QCD + NLO QED

13 TeV

- pre-LUX photon calculations evidence modest PDF dependence in (Photon / No Photon) ratio

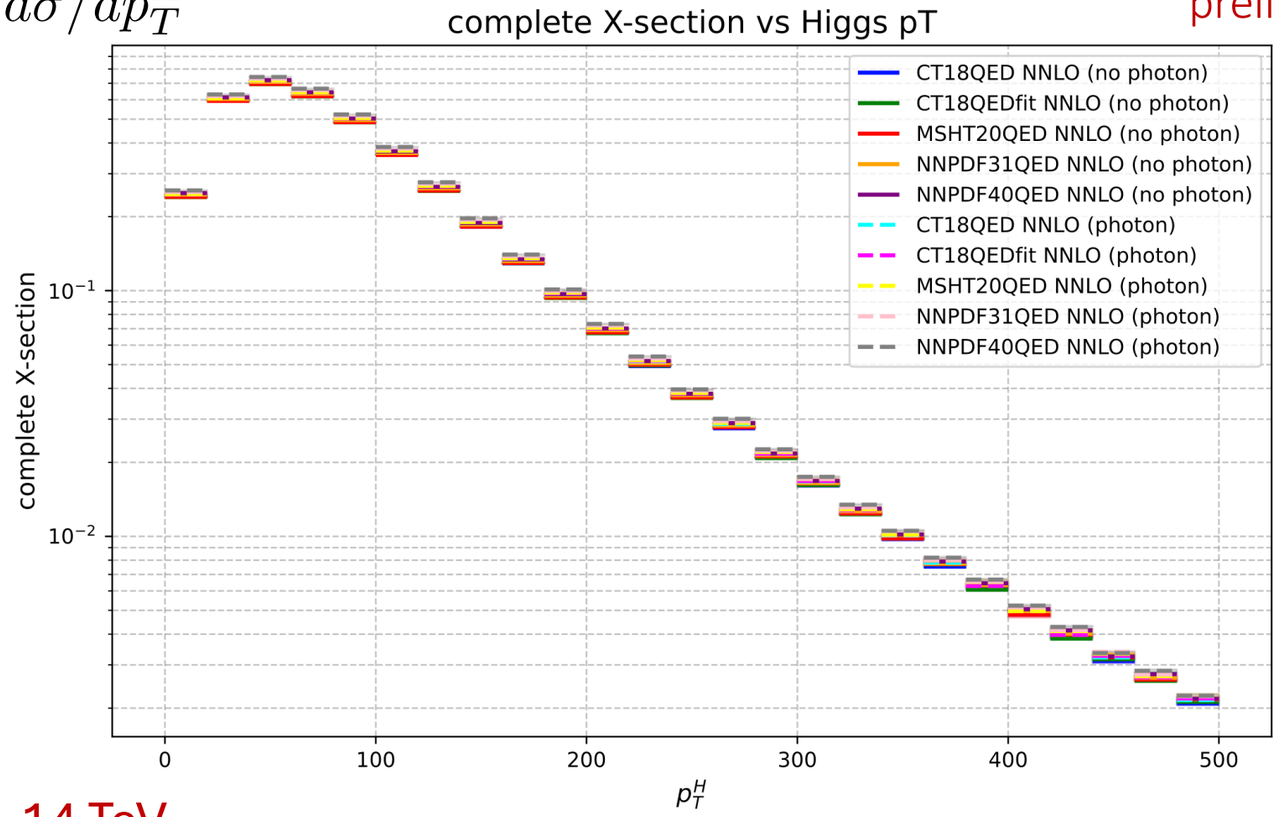
updated PDF dependence post-LUX

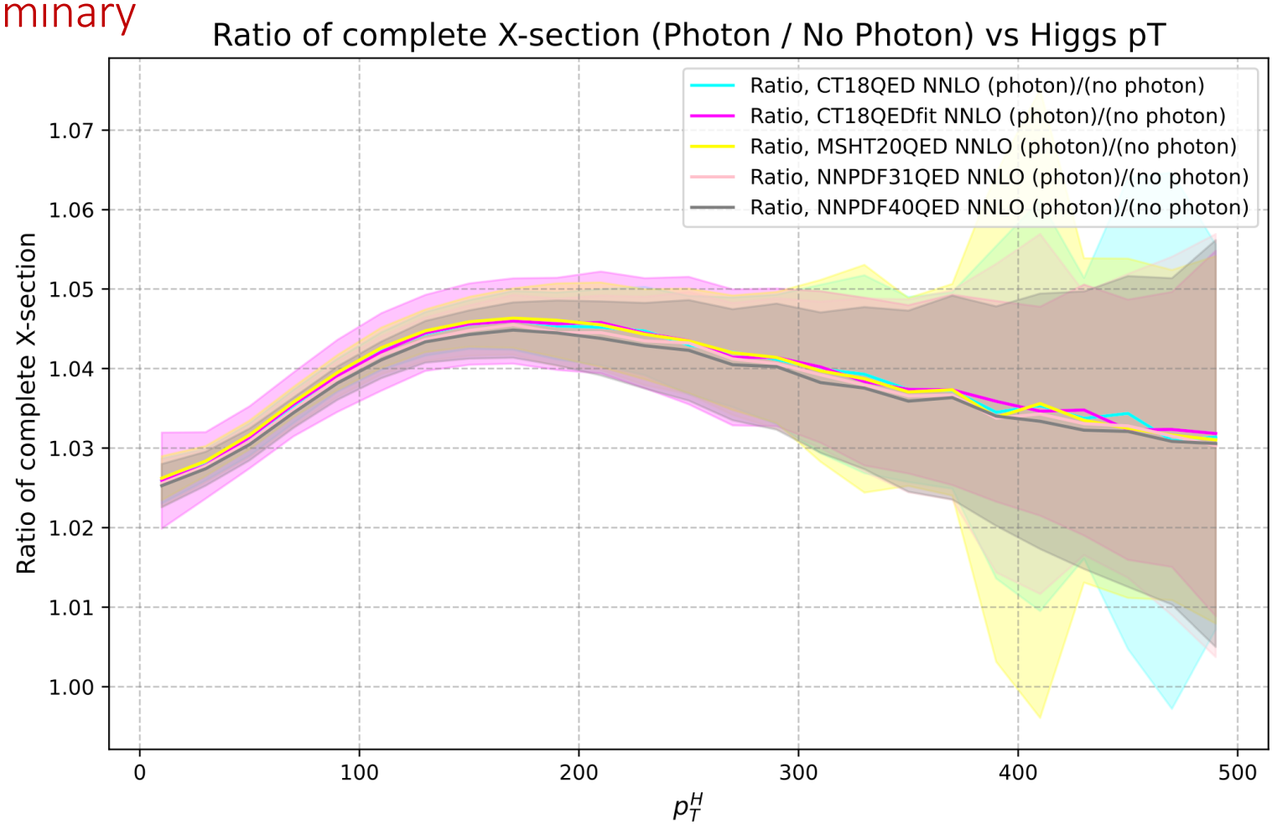
$pp \to W^+H$

- analogue of (previous) legacy PDF plots; now with modern LUX-based NNLO QED analyses

$d\sigma/dp_T^H$

preliminary





14 TeV

- kinematic cuts, coarser binning can slightly enhance statistics

→ PDF dependence significantly reduced in the photon/no-photon correction ratio (right)

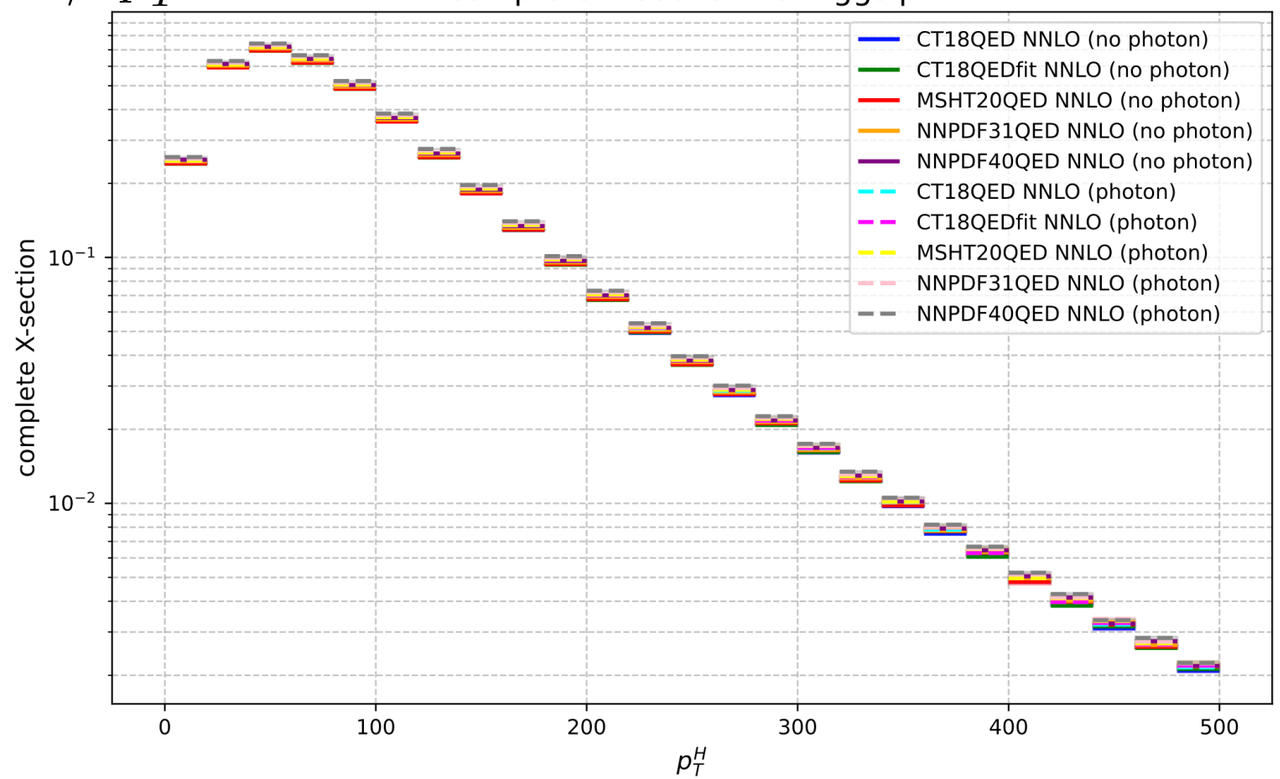
PDF dependence of full (NLO EW) cross sections

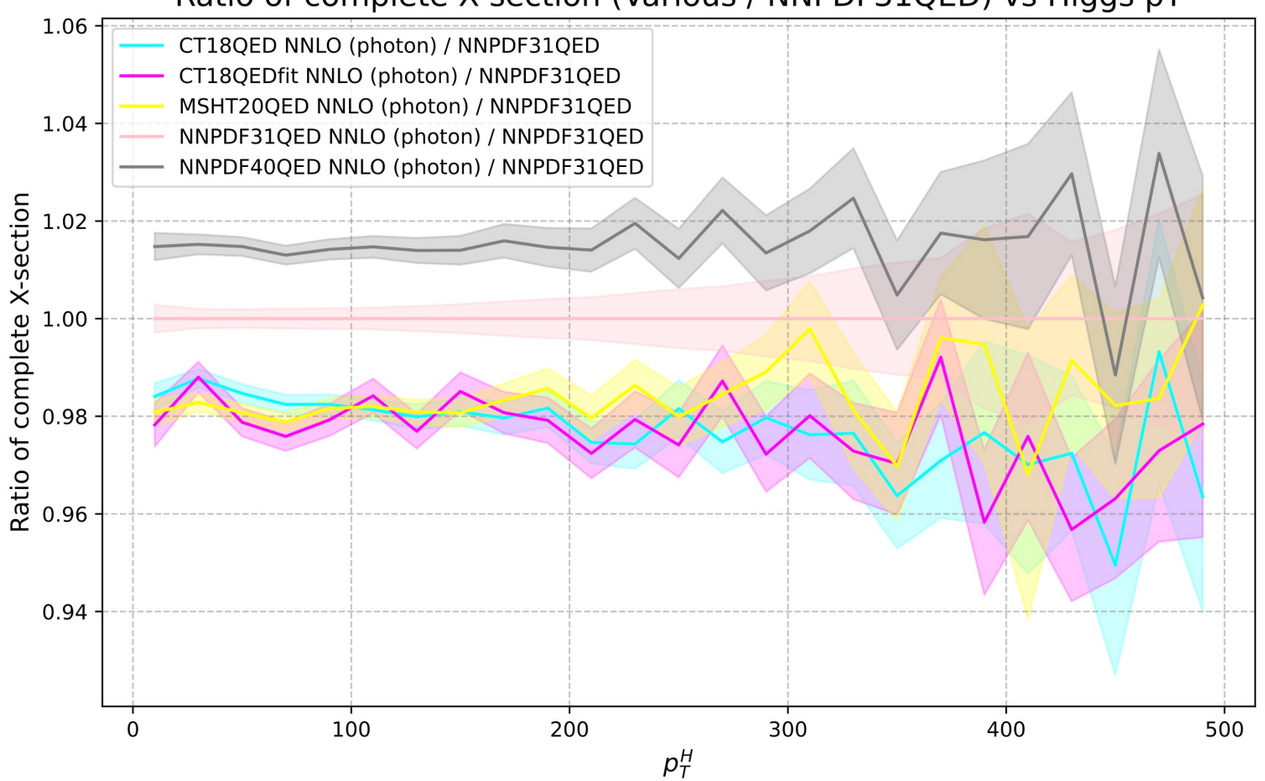
$pp \to W^+H$

- modest PDF-driven variations (~2%) in NLO-corrected (EW) p_T^H spectra

$d\sigma/dp_T^H$

preliminary





14 TeV

- next steps: minimize MC jitter, further quantify PDF uncertainty

- cf. anomalous Higgs trilinear couplings shift WH spectrum at both low ($\lesssim 100$ GeV) and high[er] p_T

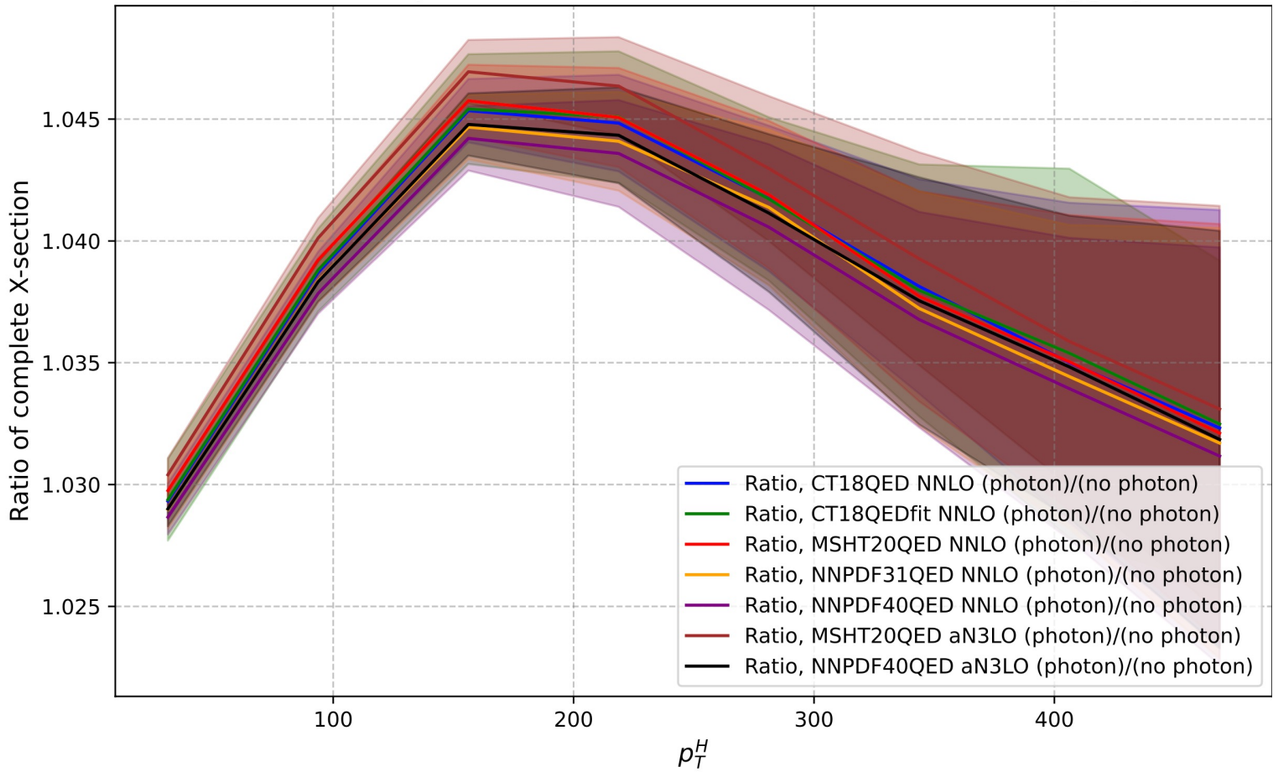
→ *e.g.*, Maltoni et al. EPJC77 (2017) 887

effects of recent aN3LO PDFs

$pp \to W^+H$

- including **coarser** binning scheme along corresponding **aN3LO PDFs**: results qualitatively similar

$d\sigma/dp_T^H$



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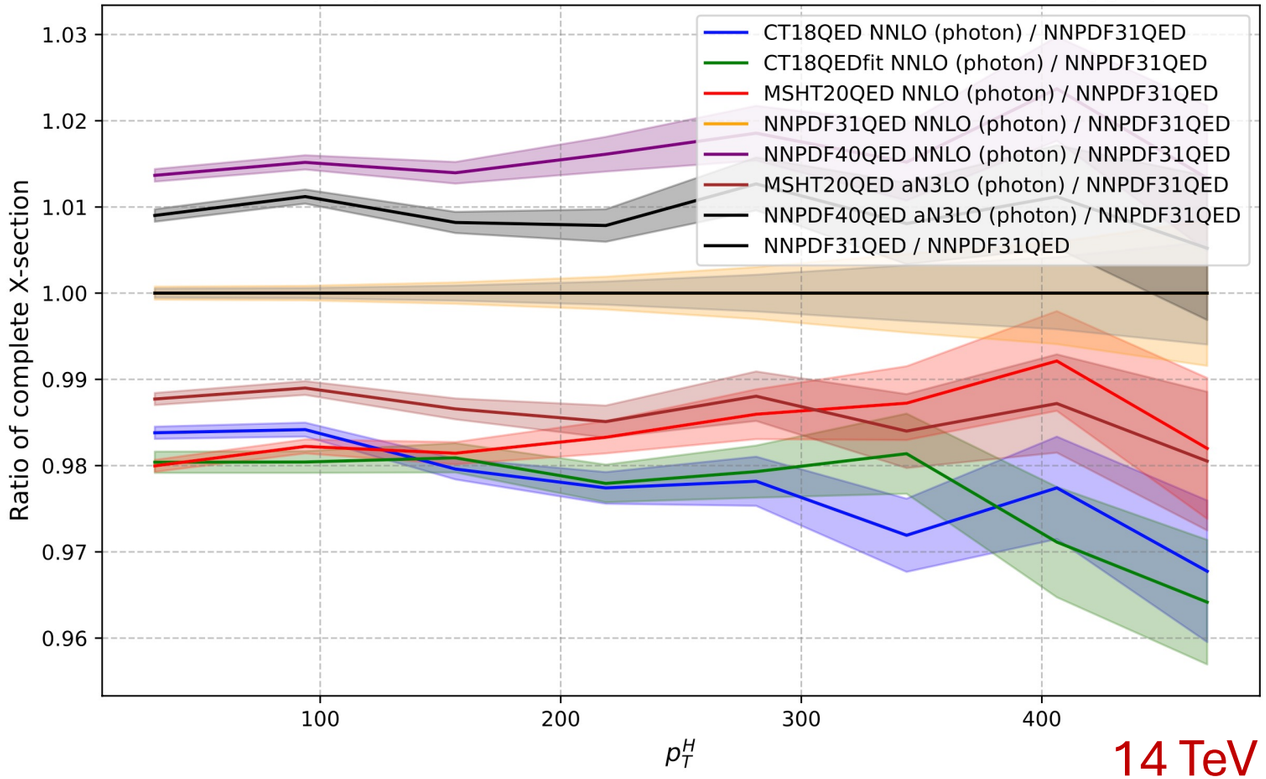


14 TeV

→ approximate PDF independence of photon-induced correction; ~2% spread in full cross sections

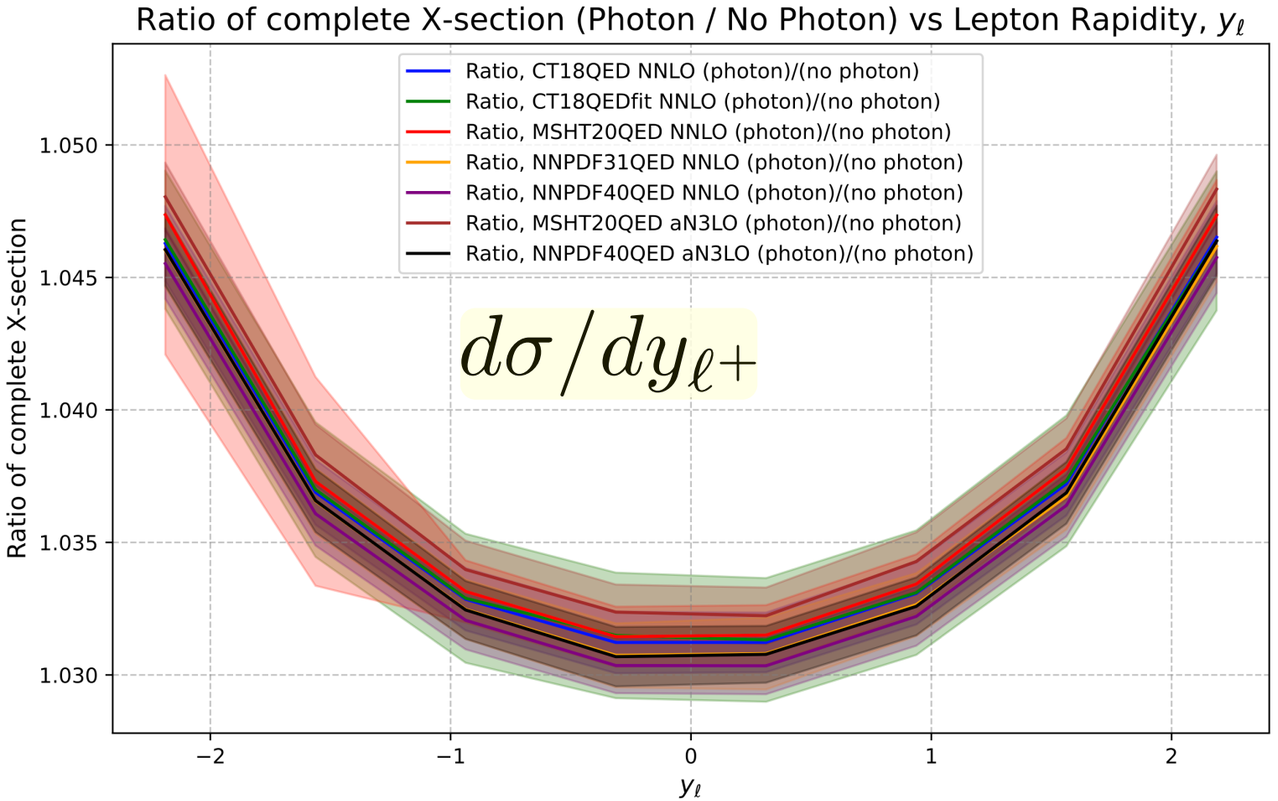
→ calculations with aN3LO PDFs adjacent to the corresponding NNLO results

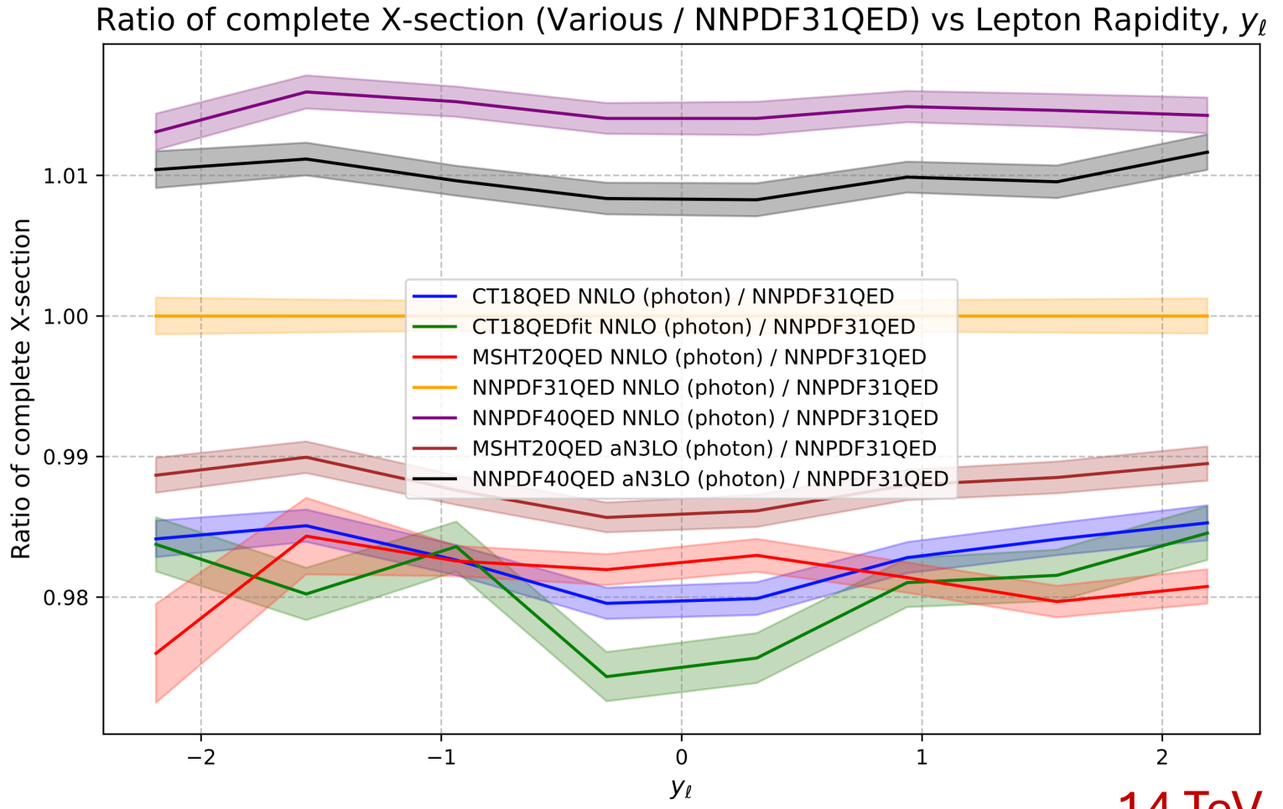
other singly-differential observables: lepton rapidities

$pp \to W^+H$

- as with p_T spectra, PDF-related shifts only weakly dependent on kinematics

preliminary





14 TeV

- similarly: CT, MSHT modestly smaller than NNPDF; by ~1-2% (NNPDF3.1); ~3% (NNPDF4.0)

→ spread possibly (slightly) reduced for aN3LO PDFs

conclusions and outlook

- advancing (QCD) theory accuracy: parallel development of EW/QED justified (precision effects)
  - → NLO-corrected (EW) theory calculations: ~1-2% theory and PDF variations
  - → PDF fitting groups have generally adopted LUX formalism into analysis paradigms
  - → further benchmarking for key EW channels is of value

- coming developments in PDF4LHC (QED) calculations and benchmarking
  - → PDF dependence in NLO (EW)-corrected calculations appears quite mild post-LUX
  - → PDF uncertainties; (estimation of) NNLO+ QCD, further investigation of interplay with aN3LO QCD
  - → results qualitatively consistent across Higgs channels (beyond W^+H); more study needed
  - → again, results here are preliminary: stay tuned for more PDF4LHC updates