QED Effects in PDFs:

DIS 2026, Bologna, Italy

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The University of Manchester

In collaboration with MSHT, CT, NNPDF colleagues and others -
T.C. L.A. Harland-Lang, R.S. Thorne; T.J. Hobbs, J. Huston, P. Nadolsky,
M. Ponce-Chavez, K. Xie; J. Cruz-Martinez; A. Cooper-Sarkar.

QED Effects in PDFs - Introduction

- All global PDF fitting groups include QED effects in PDFs.
- Requires inclusion of QED effects in DGLAP - combine up to aN3LO QCD evolution and QED at $\mathcal{O}(\alpha, \alpha\alpha_S, \alpha^2)$:

$$\begin{aligned}
\textbf{QED} \qquad & P_{ij} = \frac{\alpha}{2\pi} P_{ij}^{(0,1)} + \frac{\alpha\alpha_S}{(2\pi)^2} P_{ij}^{(1,1)} + \left(\frac{\alpha}{2\pi}\right)^2 P_{ij}^{(0,2)} \\
\textbf{NNLO QCD} \qquad & + \frac{\alpha_S}{2\pi} P_{ij}^{(1,0)} + \left(\frac{\alpha_S}{2\pi}\right)^2 P_{ij}^{(2,0)} + \left(\frac{\alpha_S}{2\pi}\right)^3 P_{ij}^{(3,0)} \\
\textbf{aN3LO QCD} \qquad & + \left(\frac{\alpha_S}{2\pi}\right)^4 P_{ij}^{(4,0)} \, .
\end{aligned}$$

Manohar et al 1607.04266

- Naturally leads to photon PDF via $q \to q\gamma$, constrain via LUXQED:

$$\begin{aligned}
x\gamma(x,Q_0^2) = \frac{1}{2\pi\alpha(Q_0^2)} \int_x^1 \frac{dz}{z} \Bigg\{ \int_{\frac{x^2 m_p^2}{1-z}}^{Q_0^2} \frac{dQ^2}{Q^2} \alpha^2(Q^2) \Bigg[\left(z P_{\gamma,q}(z) + \frac{2x^2 m_p^2}{Q^2} \right) F_2(x/z, Q^2) \\
- z^2 F_L(x/z, Q^2) \Bigg] - \alpha^2(Q_0^2) \left(z^2 + \ln(1-z) z P_{\gamma,q}(z) - \frac{2x^2 m_p^2 z}{Q_0^2} \right) F_2(x/z, Q_0^2) \Bigg\} \, ,
\end{aligned}$$

- Determines $\gamma(x, Q_0^2)$ from precise NC structure function data.
- Also incorporate EW corrections where relevant.

QED Effects in PDFs - Introduction

- Adding a γ PDF requires momentum:

$$\int_0^1 dx(\Sigma(x,Q^2)+g(x,Q^2))=1 \Rightarrow \int_0^1 dx(\Sigma(x,Q^2)+g(x,Q^2)+\gamma(x,Q^2))=1$$

$$\Rightarrow \text{Total momentum of QCD partons reduces.}$$

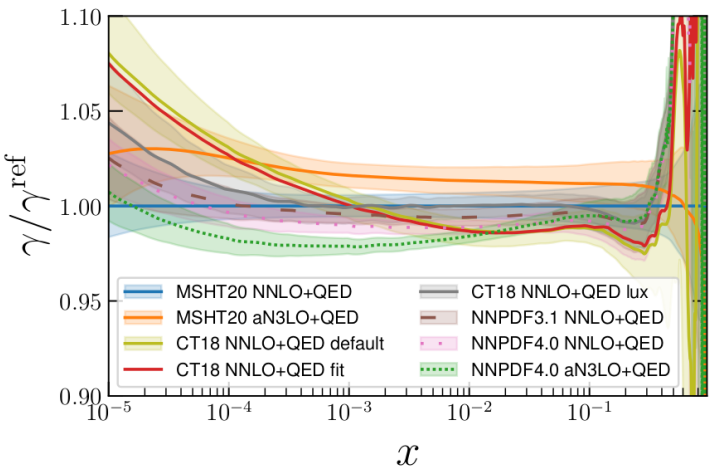
- Typical implementation of QED DGLAP effects in PDF fit:
  1. Extract $\gamma(x,Q_0^2)$ via LUXQED at some Q_0^2.
  2. Run to other Q^2 in full QCD $\otimes$ QED.
  3. Incorporate photon in momentum sum rule.

- Various subtleties in application:
  - How momentum conservation is imposed.
  - Baseline QCD PDFs.
  - Scale Q_0^2 at which LUXQED is applied.
  - EW corrections included.

QED Effects in PDFs - Status

See Cooper-Sarkar, T.C., CT + MSHT: 2508.06603

- How do global PDF groups' QED PDFs compare?



PDF Set	QCD order	$\langle x \rangle_\gamma$
CT18	NNLO	0
$\text{CT18}_{\text{QEDproton}}$	NNLO	0.00431
$\text{CT18}_{\text{QEDfit}}$	NNLO	0.00432
CT18_{LUX}	NNLO	0.00436
MSHT20	NNLO	0
$\text{MSHT20}_{\text{QED}}$	NNLO	0.00436
$\text{MSHT20}_{\text{QED\_QCD}}$	aN3LO	0
$\text{MSHT20}_{\text{QED}}$	aN3LO	0.00441
NNPDF3.1	NNLO	0
$\text{NNPDF3.1}_{\text{QED}}$	NNLO	0.00435
NNPDF4.0	NNLO	0
$\text{NNPDF4.0}_{\text{QED}}$	NNLO	0.00433
NNPDF4.0	aN3LO	0
$\text{NNPDF4.0}_{\text{QED}}$	aN3LO	0.00433

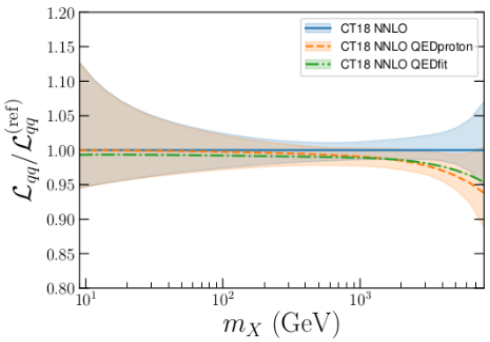
- γ PDF consistent at few % level.
- All agree on total γ momentum (0.4% at $Q = 125\text{GeV}$).

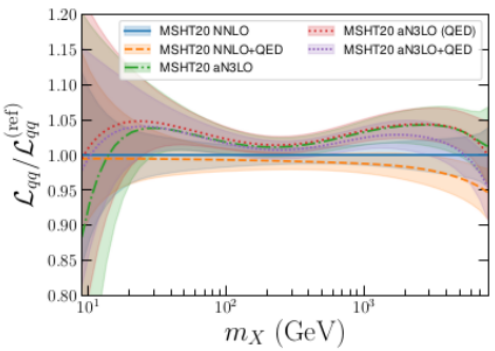
- What about other partons? Must be affected as net momentum of other partons must reduce to accomodate photon...

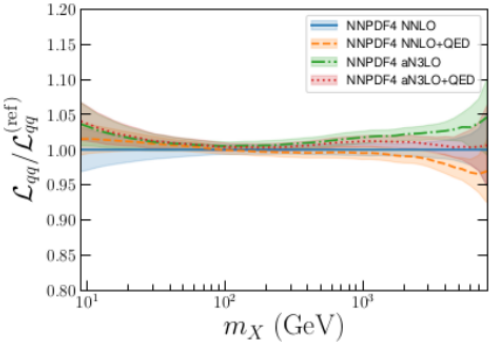
QED Effects in PDFs - Status

See Cooper-Sarkar, T.C., CT + MSHT: 2508.06603

- However some differences in where the momentum comes from, quarks:







PDF Set	QCD order	$\langle x \rangle_{\Sigma q\bar{q}}$	$\langle x \rangle_{\gamma}$
CT18	NNLO	0.528	0
$\mathrm{CT18}_{\mathrm{QEDproton}}$	NNLO	0.526	0.00431
$\mathrm{CT18}_{\mathrm{QEDfit}}$	NNLO	0.526	0.00432
$\mathrm{CT18}_{\mathrm{LUX}}$	NNLO	0.527	0.00436
MSHT20	NNLO	0.530	0
$\mathrm{MSHT20}_{\mathrm{QED}}$	NNLO	0.528	0.00436
$\mathbf{MSHT20}_{\mathbf{QED\_QCD}}$	aN3LO	0.538	0
$\mathrm{MSHT20}_{\mathrm{QED}}$	aN3LO	0.536	0.00441
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$\mathrm{NNPDF3.1}_{\mathrm{QED}}$	NNLO	0.527	0.00435
NNPDF4.0	NNLO	0.534	0
$\mathrm{NNPDF4.0}_{\mathrm{QED}}$	NNLO	0.533	0.00433
NNPDF4.0	aN3LO	0.537	0
$\mathrm{NNPDF4.0}_{\mathrm{QED}}$	aN3LO	0.536	0.00433

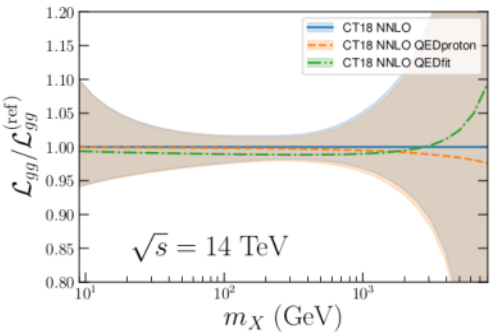
- Quarks depleted at high x (m_X in L_{qq}) due to $q \to q\gamma$.

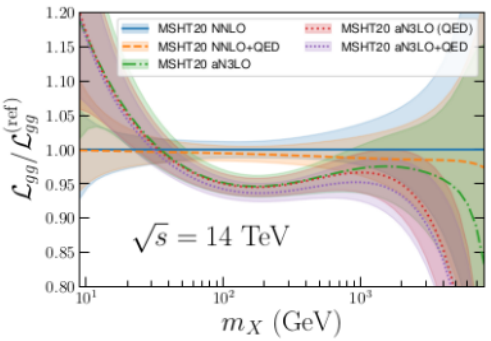
- Similar behaviour across groups for quarks. What about for the gluon?

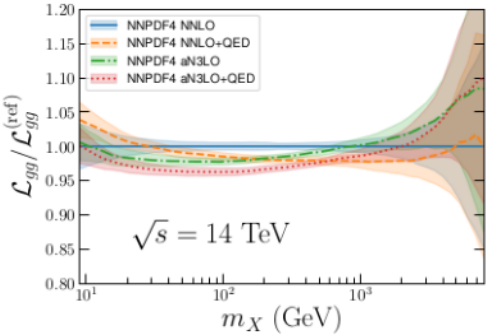
QED Effects in PDFs - Status

See Cooper-Sarkar, T.C., CT + MSHT: 2508.06603

- However some differences in where the momentum comes from, gluon:







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$\mathrm{CT18_{QEDfit}}$	NNLO	0.526	0.469	0.00432
$\mathrm{CT18_{LUX}}$	NNLO	0.527	0.470	0.00436
MSHT20	NNLO	0.530	0.470	0
$\mathrm{MSHT20_{QED}}$	NNLO	0.528	0.468	0.00436
$\mathbf{MSHT20_{QED,QCD}}$	aN3LO	0.538	0.460	0
$\mathrm{MSHT20_{QED}}$	aN3LO	0.536	0.457	0.00441
NNPDF3.1	NNLO	0.529	0.470	0
$\mathrm{NNPDF3.1_{QED}}$	NNLO	0.527	0.468	0.00435
NNPDF4.0	NNLO	0.534	0.466	0
$\mathrm{NNPDF4.0_{QED}}$	NNLO	0.533	0.463	0.00433
NNPDF4.0	aN3LO	0.537	0.463	0
$\mathrm{NNPDF4.0_{QED}}$	aN3LO	0.536	0.459	0.00433

- Gluon reduced to accommodate photon momentum.

- Differences in magnitude - CT18 QEDproton see least change, NNPDF4.0 see most change.

QED Effects in PDFs - Pheno Implications

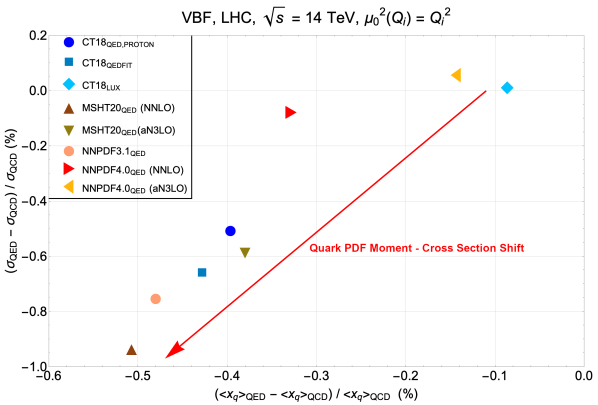
- Consider QED PDF effects on quark-initiated processes:

See Cooper-Sarkar, T.C., CT + MSHT: 2508.06603

- Quark momentum change drives VBF and W^+H xsec changes.

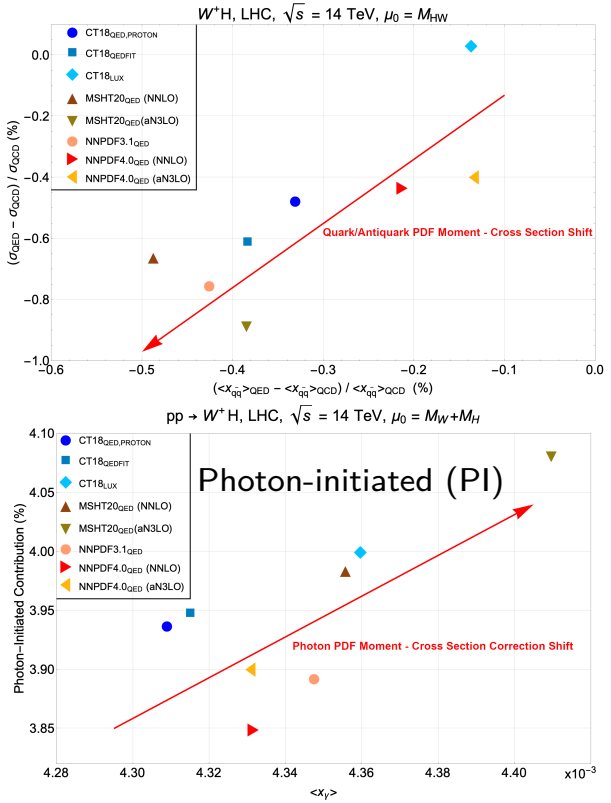
VBF

Xsec % change



Quark Momentum % change

W^+H



- CT18LUX shows no change.
- PI similar across groups for W^+H.
- NNPDF4.0 shows more difference than NNPDF3.1.

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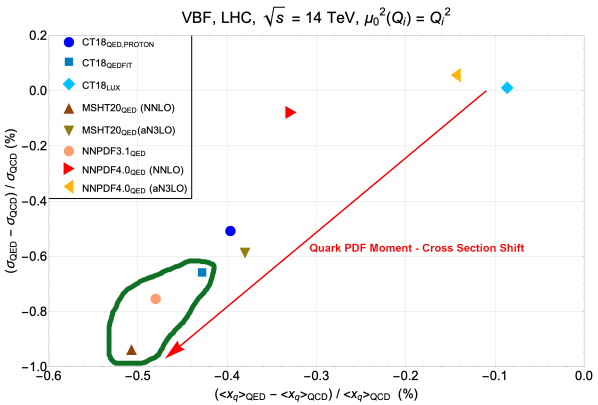

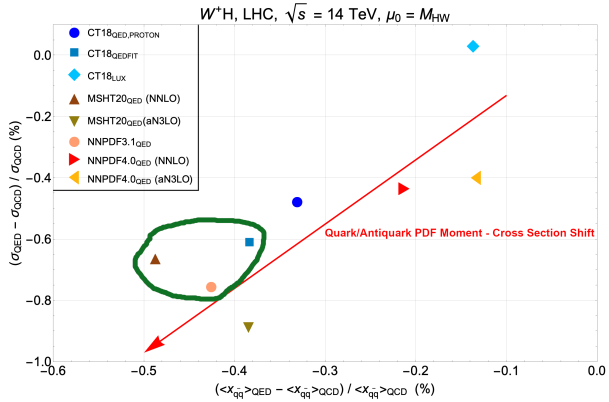

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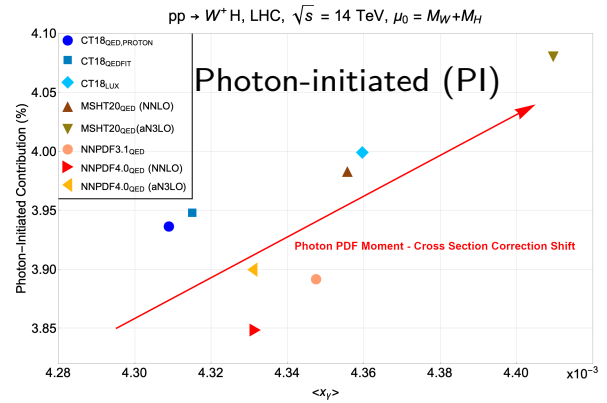


- PDF4LHC21 PDFs (CT18 (QEDfit), MSHT20, NNPDF3.1) show similar changes.

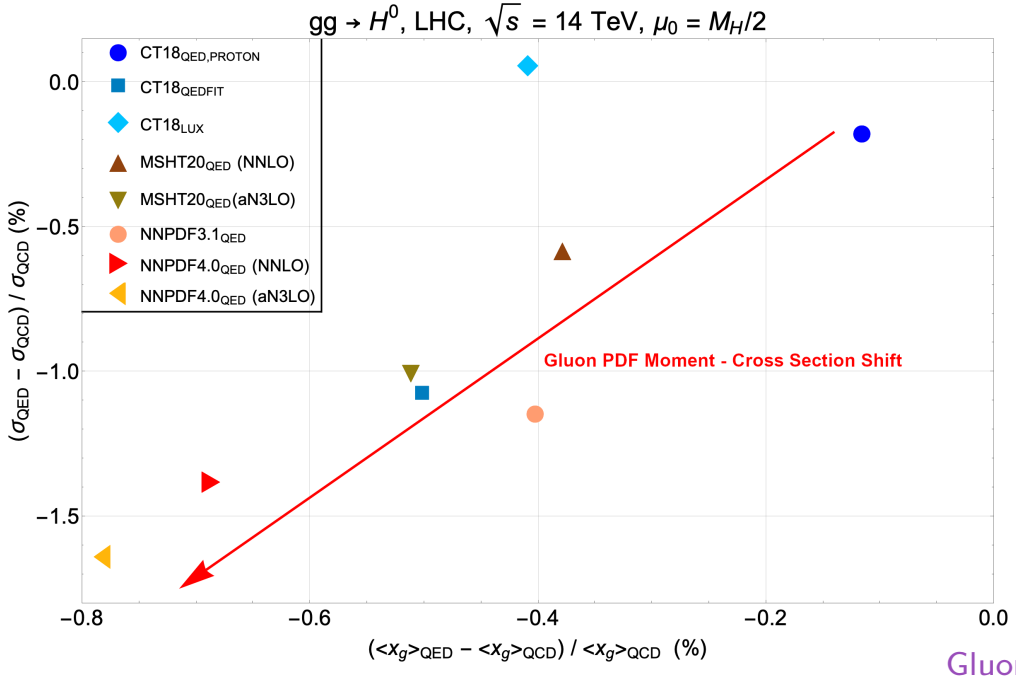
QED Effects in PDFs - Pheno Implications

See Cooper-Sarkar, T.C., CT + MSHT: 2508.06603

- Consider QED PDF effects on gluon-initiated processes:
- Gluon momentum change drive ggH xsec changes.

ggH

Xsec % change



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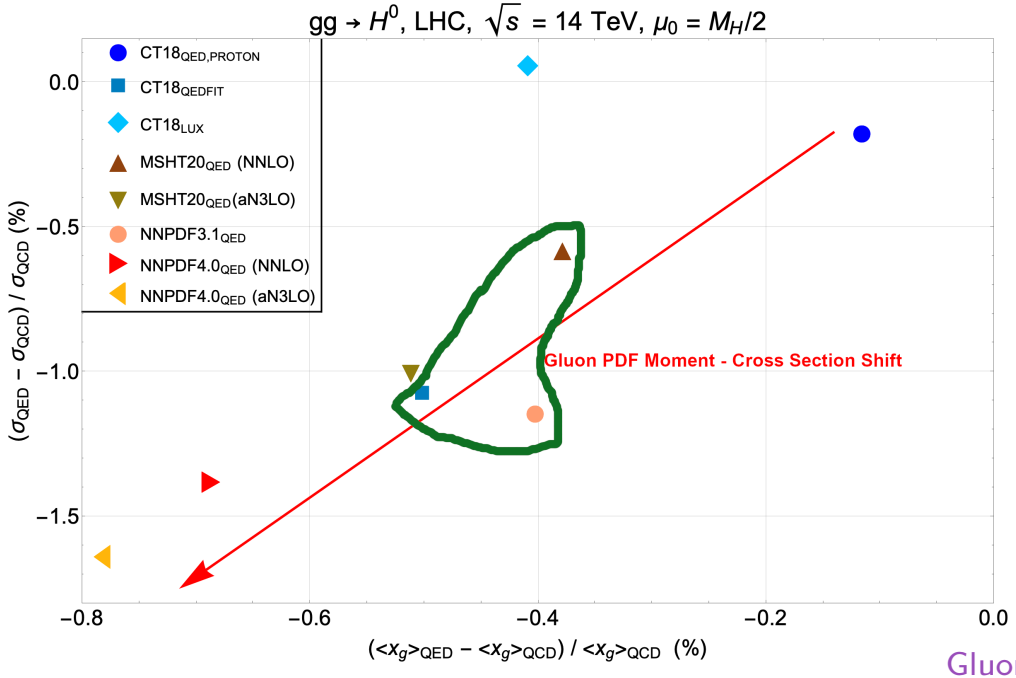

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QED Effects in PDFs - Why differences?

- Various subtleties in application of QED effects in PDFs:
  - How momentum conservation is imposed.
  - Baseline QCD PDFs.
  - Scale Q_0^2 at which LUXQED is applied.
  - EW corrections included.

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- CT18LUX adds γ PDF without refitting momenta, CT18 QED proton subtracts photon momentum from sea quarks.
- MSHT and NNPDF allow PDF fit to redistribute momentum (similar to CT18 QEDfit) $\Rightarrow$ some momentum taken from gluon.

See Cooper-Sarkar, T.C., CT + MSHT: 2508.06603

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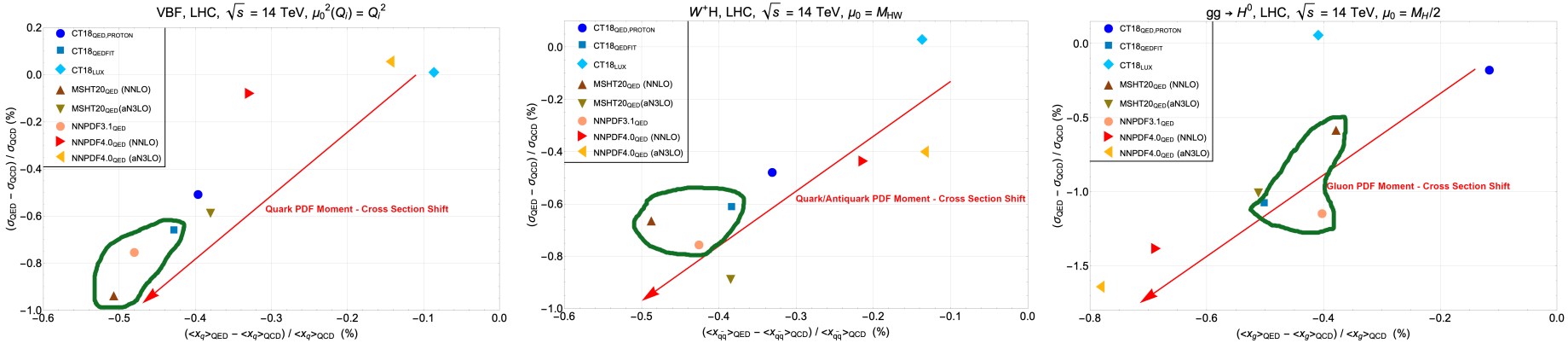
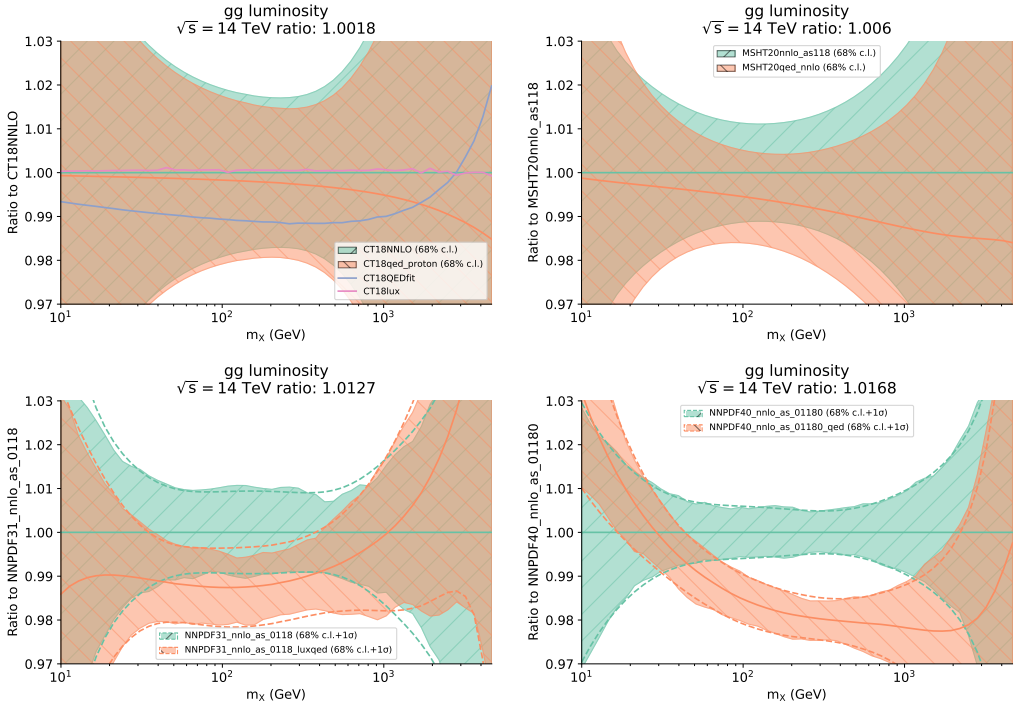


- Explains differences in CT18. CT18 QEDfit in PDF4LHC21 comparisons.

QED Effects in PDFs - Why differences?

- NNPDF4.0 shows different, larger QED effects than NNPDF3.1 - why?



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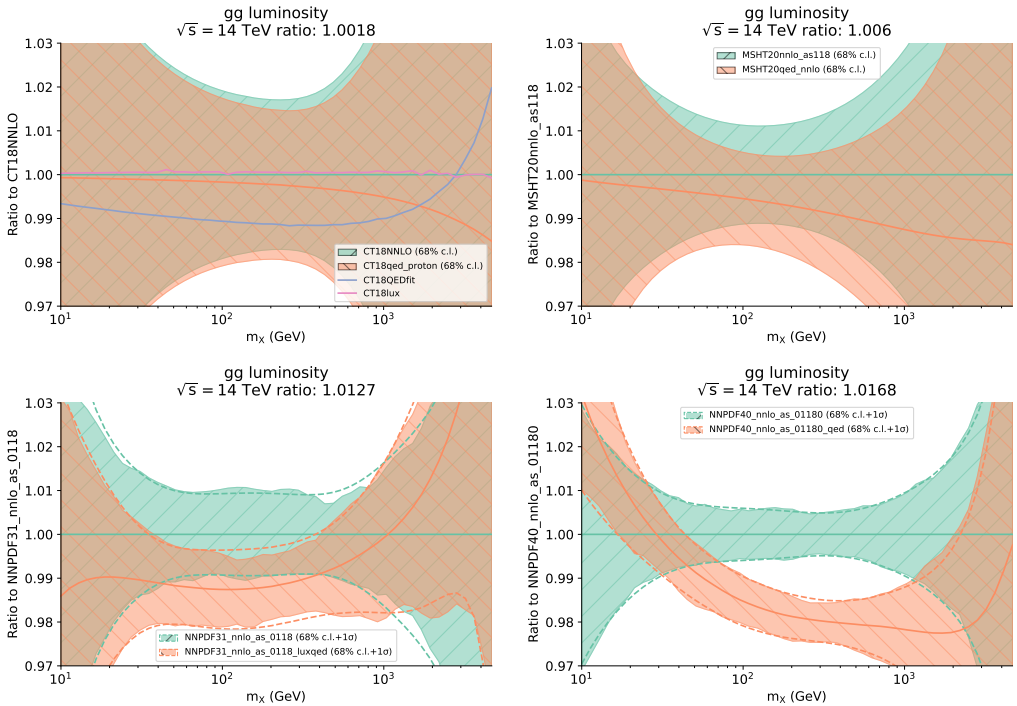

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- Various subtleties in application of QED effects in PDFs:
  - How momentum conservation is imposed.
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  - Scale Q_0^2 at which LUXQED is applied.
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- CT and MSHT apply LUXQED at low scales $Q_0^2 \gtrsim 1\ \mathrm{GeV}$, NNPDF apply at large scales $Q^2 \approx 100\ \mathrm{GeV}$.

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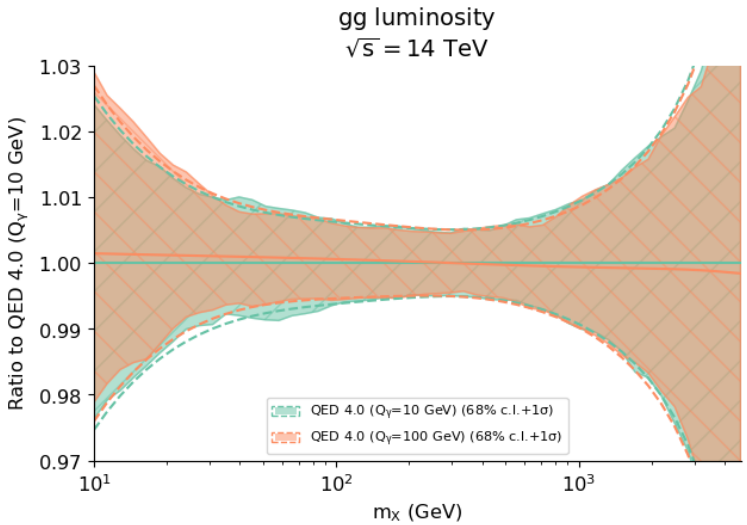
- Various subtleties in application of QED effects in PDFs:
  - How momentum conservation is imposed.
  - Baseline QCD PDFs.
  - Scale Q_0^2 at which LUXQED is applied. ✗
  - EW corrections included.
- CT and MSHT apply LUXQED at low scales $Q_0^2 \gtrsim 1\ \mathrm{GeV}$, NNPDF apply at large scales $Q^2 \approx 100\ \mathrm{GeV}$. $\Rightarrow$ Makes negligible difference.



Apply at $Q = 100\ \mathrm{GeV}$

Apply at $Q = 10\ \mathrm{GeV}$

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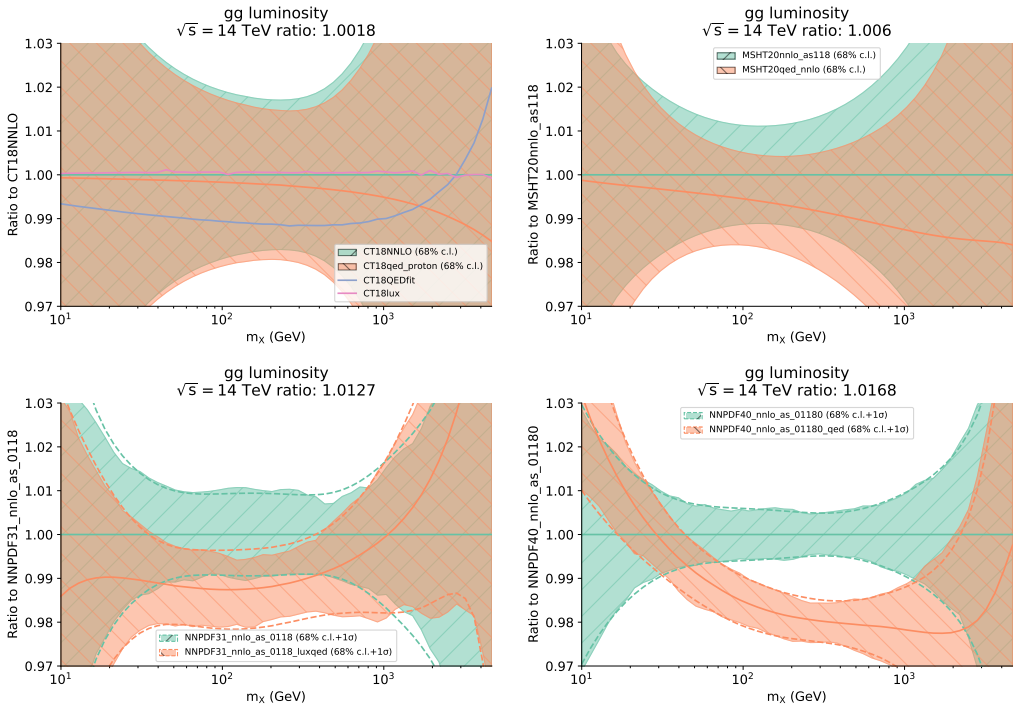

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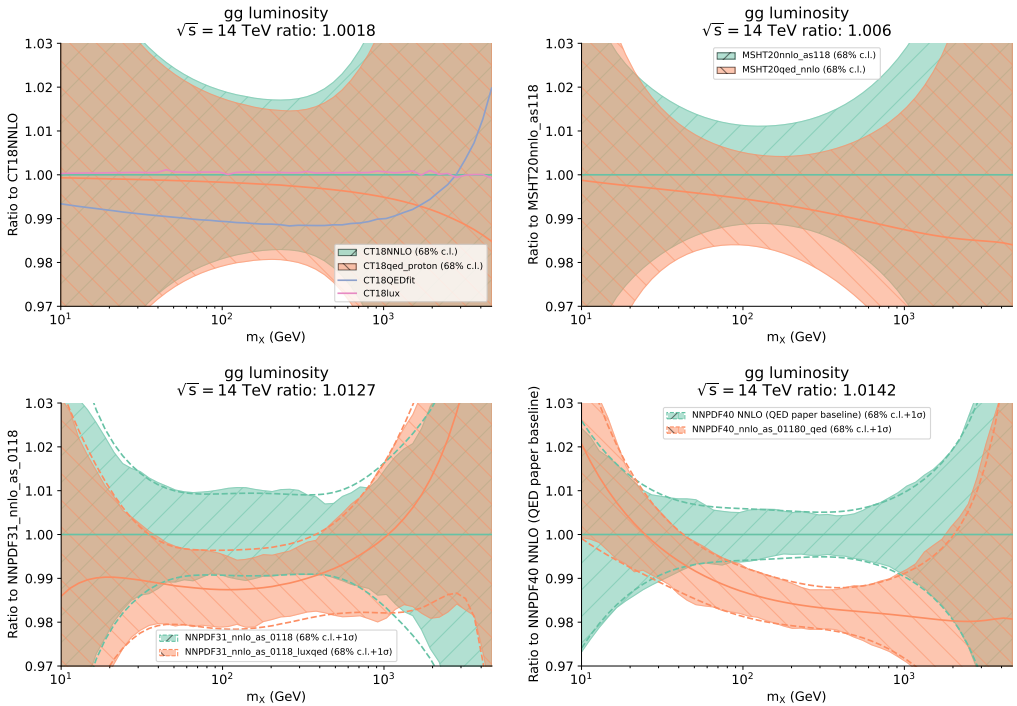

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- Small changes in QCD baseline between NNPDF4.0 QCD and QED PDFs. $\Rightarrow$ Size of reduction now $\approx$ NNPDF3.1 but different shape.

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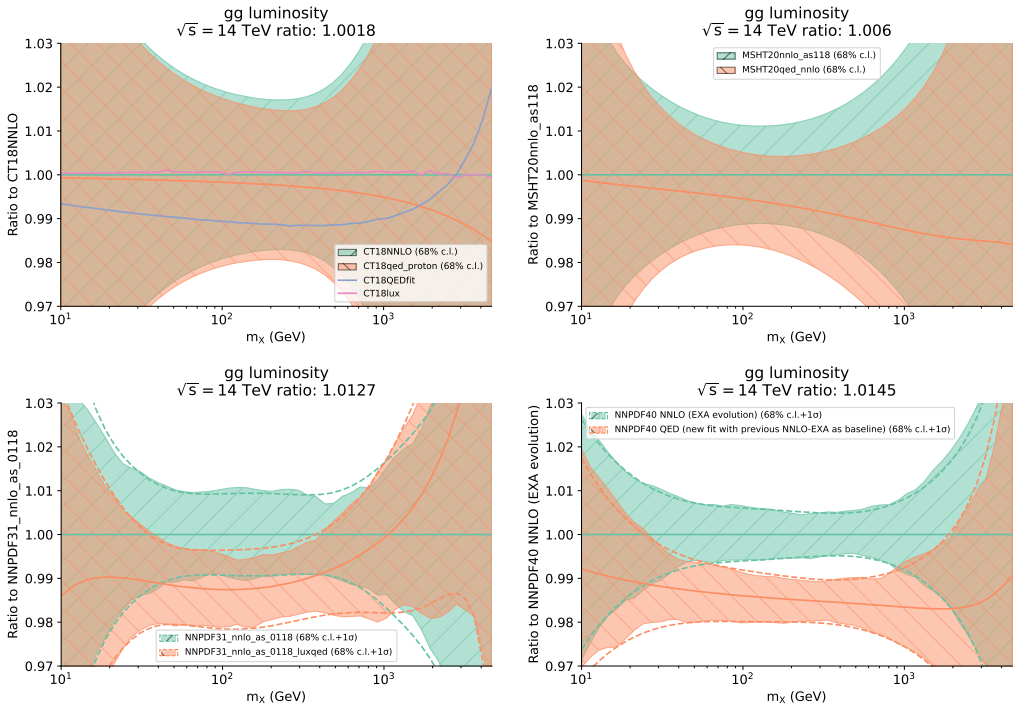

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See NNPDF 2401.08749 for more info.

- Furthermore, 4.0 QED used exact evolution c.f. truncated evolution in 4.0 QCD (used in 3.1 QCD and QED) $\Rightarrow$ affects low m_X shape.

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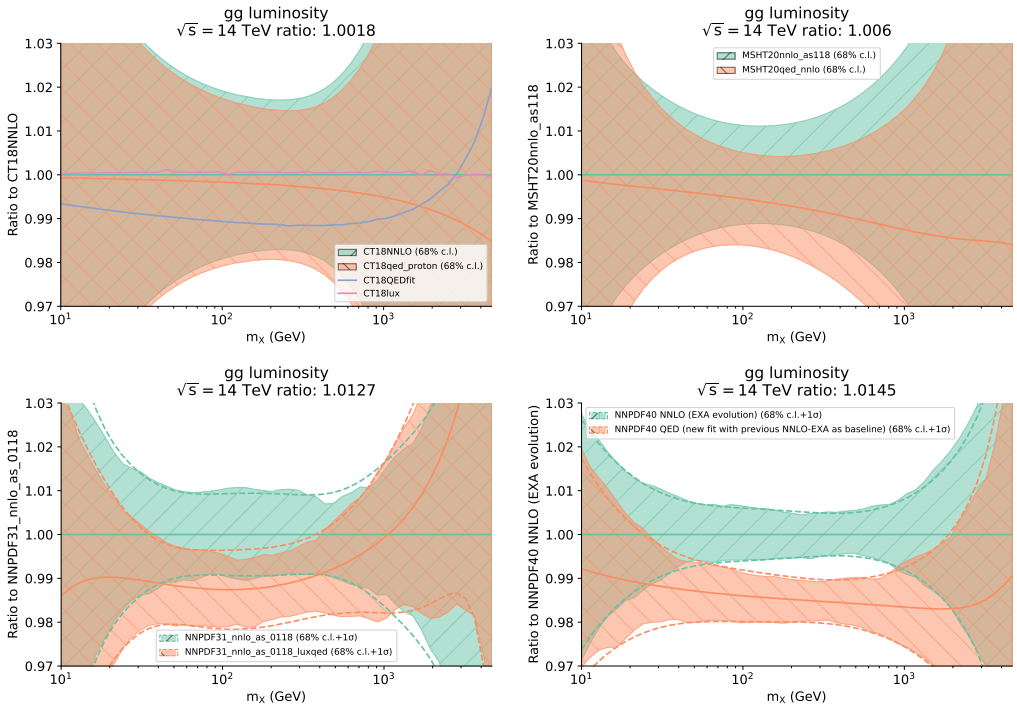

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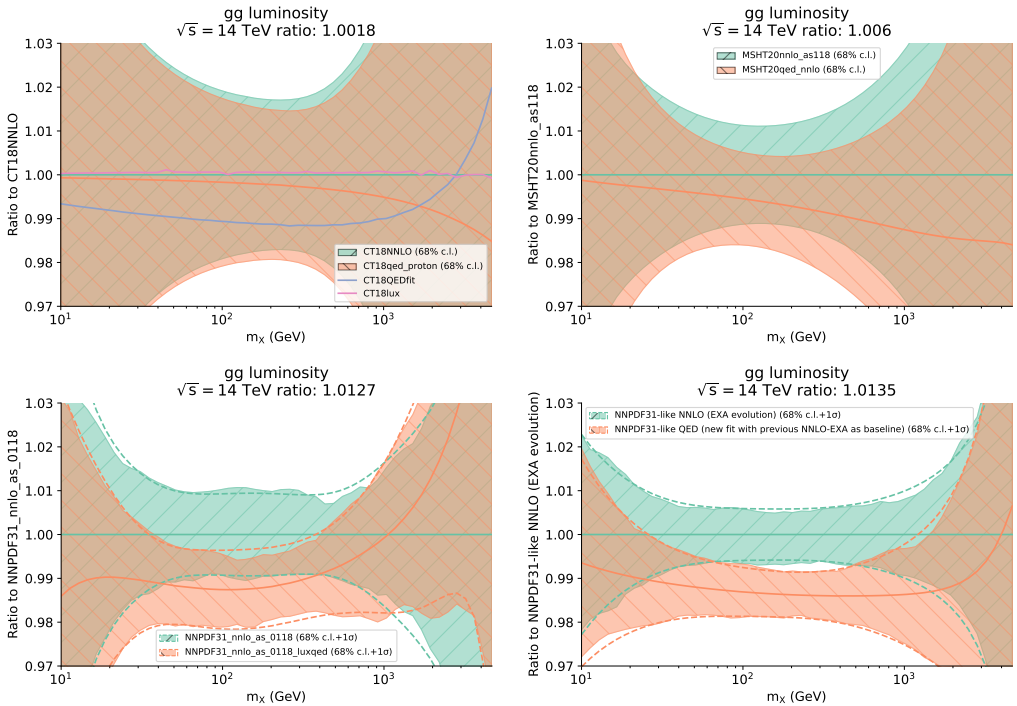


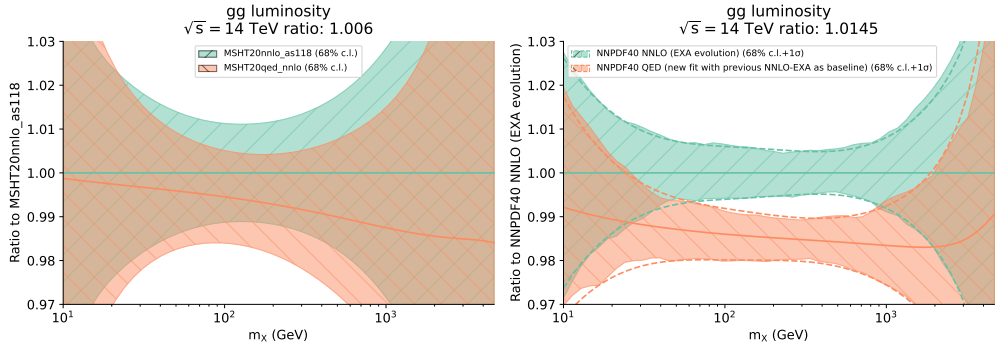
See T.C., J. Cruz-Martinez, J. Huston: 2602.06908

- NNPDF4.0 has a larger dataset than 3.1, does that make a difference?
  $\Rightarrow$ Slightly increases reduction from QED effects on ggH at m_H.

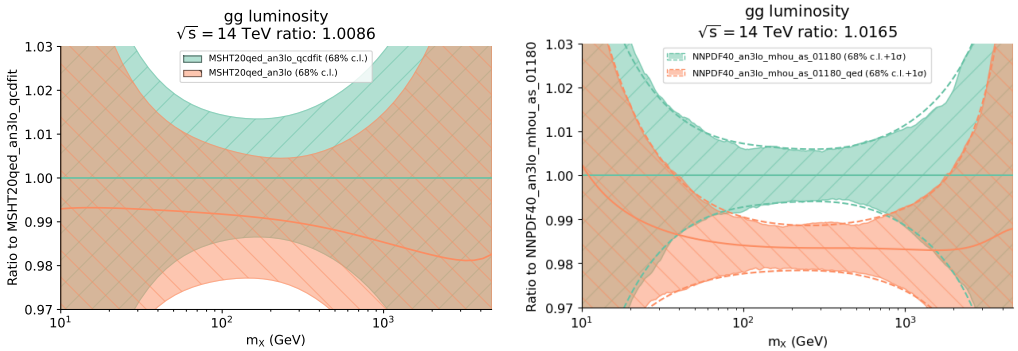
QED Effects in PDFs - What about aN3LO?

- How do the differences at NNLO and aN3LO compare?:

NNLO



aN3LO



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- Very similar though slightly larger effects seen in both MSHT and NNPDF at aN3LO vs NNLO, effect of QED almost independent of order.
- NNPDF again see slightly larger QED effects - brings aN3LO QCD+QED results together. (See MSHTxNNPDF aN3LO combination paper: 2411.05373).

QED Effects in PDFs - Overall

- Observe important reductions across ggH, VBF, VH cross-sections from QED effects for all groups:

See Cooper-Sarkar, T.C., CT + MSHT: 2508.06603

PDF Set	QCD order	$\sigma_{gg\to H}$	σ_{VBFH}	σ_{ZH}	σ_{W^+H}	σ_{W^-H}
CT18	NNLO	51.7	4.45	0.880	0.985 (0.904)	0.626 (0.576)
$\mathrm{CT18}_{\mathrm{QEDfit}}$	NNLO	51.2	4.42	0.874	0.979 (0.898)	0.622 (0.572)
δ_{QEDfit}		-1.08%	-0.660%	-0.609%	-0.611%	-0.602%
MSHT20	NNLO	51.8	4.53	0.885	0.984 (0.903)	0.624 (0.574)
$\mathrm{MSHT20}_{\mathrm{QED}}$	NNLO	51.5	4.49	0.878	0.977 (0.896)	0.619 (0.570)
δ_{QED}		-0.575%	-0.933%	-0.757%	-0.660%	-0.715%
$\mathbf{MSHT20}_{\mathrm{QED\_QCD}}$	aN3LO	50.8	4.67	0.882	0.980 (0.903)	0.622 (0.574)
$\mathrm{MSHT20}_{\mathrm{QED}}$	aN3LO	50.3	4.64	0.877	0.975 (0.894)	0.619 (0.570)
δ_{QED}		-0.850%	-0.582%	-0.545%	-0.503%	-0.450%
NNPDF3.1	NNLO	52.8	4.49	0.900	1.010 (0.926)	0.634 (0.583)
$\mathrm{NNPDF3.1}_{\mathrm{QED}}$	NNLO	52.2	4.46	0.893	0.998 (0.915)	0.630 (0.580)
δ_{QED}		-1.14%	-0.751%	-0.745%	-0.753%	-0.690%
$\mathbf{NNPDF4.0}_{\mathrm{QCD}}$	NNLO	52.0	4.61	0.912	1.020 (0.936)	0.642 (0.591)
$\mathrm{NNPDF4.0}_{\mathrm{QED}}$	NNLO	51.3	4.60	0.909	1.010 (0.926)	0.638 (0.587)
δ_{QED}		-1.39%	-0.081%	-0.333%	-0.437%	-0.497%
NNPDF4.0	aN3LO	52.8	4.64	0.900	1.000 (0.917)	0.632 (0.582)
$\mathrm{NNPDF4.0}_{\mathrm{QED}}$	aN3LO	51.9	4.65	0.898	1.000 (0.917)	0.630 (0.580)
δ_{QED}		-1.65%	0.053%	-0.291%	-0.403%	-0.456%

- Comparative magnitude of effects now largely understood, many differences down to baseline QCD PDFs.

See T.C., J. Cruz-Martinez, J. Huston: 2602.06908

- Differences between groups smaller, sub-percent and less when directly compared.

QED Effects in PDFs - PDF4LHC recommendation

- QED effects significant and must be accounted for in precision pheno.
- PDF4LHC21 PDFs most alike in QED effects - CT18 (QED fit), MSHT20, NNPDF3.1.

$$f_a(x, Q_0)_{\mathrm{PDF4LHC21}} = \frac{1}{3}\left(f_a(x, Q_0)_{\mathrm{CT18}} + f_a(x, Q_0)_{\mathrm{MSHT20}} + f_a(x, Q_0)_{\mathrm{NNPDF3.1}}\right).$$

$$\hookrightarrow \delta^{\mathrm{QED}}_{\mathrm{PDF4LHC21}} = \frac{1}{3}\left(\langle\delta^{\mathrm{QED}}\rangle_{\mathrm{CT18}} + \delta^{\mathrm{QED}}_{\mathrm{MSHT20}} + \delta^{\mathrm{QED}}_{\mathrm{NNPDF3.1}}\right),$$

- Can estimate correction to PDF4LHC21 by averaging QED effects of three groups, correct both central value and error PDFs.

PDF Set	$\sigma_{gg\to H}$	σ_{VBF}	σ_{ZH}	σ_{W^+H}	σ_{W^-H}
PDF4LHC21$_{40}$ NNLO	52.0	4.51	0.887	0.988	0.627
$\langle\delta^{\mathrm{QED}}\rangle_{\mathrm{CT18}}$	-0.398%	-0.385%	-0.333%	-0.353%	-0.301%
$\delta^{\mathrm{QED}}_{\mathrm{MSHT20}}$	-0.575%	-0.933%	-0.757%	-0.660%	-0.715%
$\delta^{\mathrm{QED}}_{\mathrm{NNPDF3.1}}$	-1.14%	-0.751%	-0.745%	-0.753%	-0.690%
$\delta^{\mathrm{QED}}_{\mathrm{PDF4LHC21}}$	-0.7%	-0.7%	-0.6%	-0.6%	-0.55%
PDF4LHC$_{\mathrm{QED}}$ NNLO	51.6	4.48	0.882	0.982	0.624

Conclusions

- PDF groups see consistent effects of inclusion of QED, reduce momentum in quark and gluon PDFs.
- Knock-on impacts on cross-sections must be included at level of precision targetting.
- Effects typically -0.5 to -1% depending on Higgs production cross-section.
- Small differences between groups observed, largely now understood and due to differences in settings of QED or baseline QCD PDFs.
- QED PDF impacts should be included in PDF4LHC21 predictions for Higgs, can estimate by averaging QED impacts of three PDF groups.

More information in: Cooper-Sarkar, T.C., CT + MSHT: 2508.06603
T.C., J. Cruz-Martinez, J. Huston: 2602.06908.

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Thankyou!

Any Questions?

More information in: Cooper-Sarkar, T.C., CT + MSHT: 2508.06603
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Backup Slides

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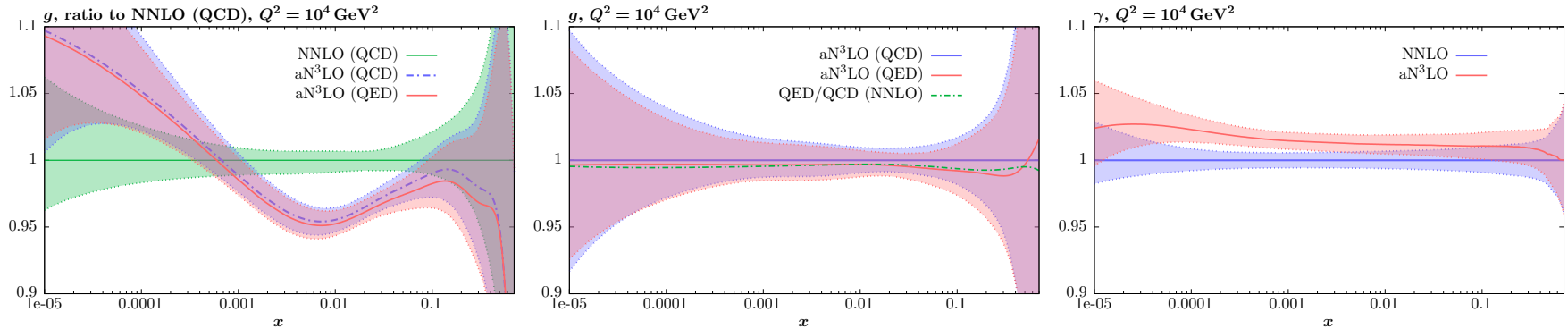
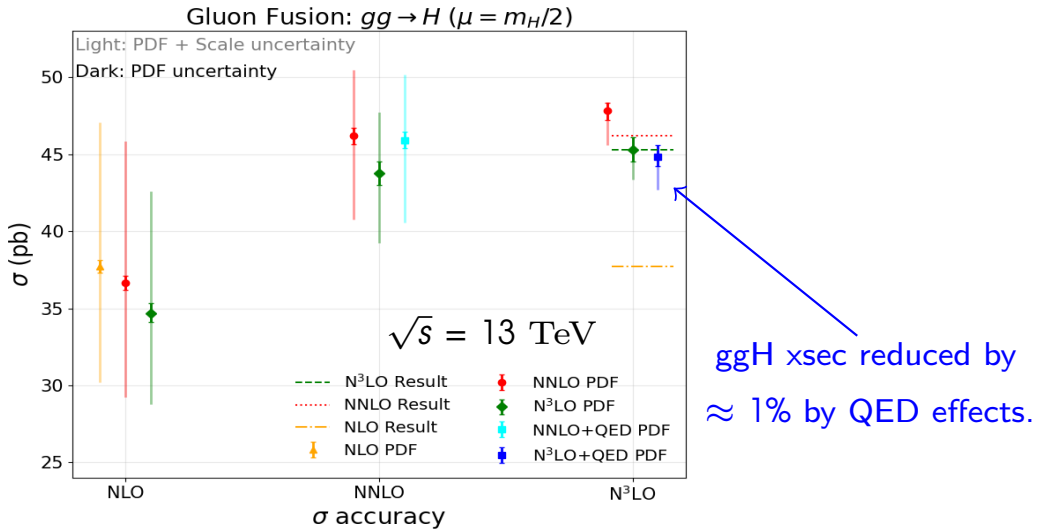
aN3LO QCD + QED:

T.C., L.A. Harland Lang, R.S. Thorne 2312.07665.

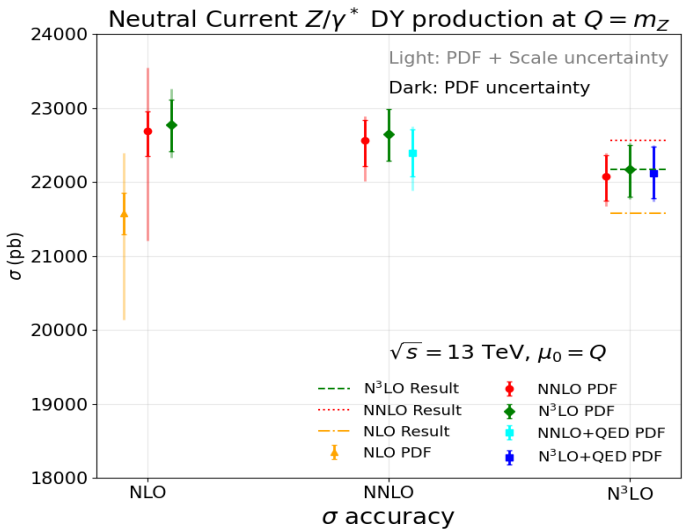
- Impact small relative to aN3LO QCD corrections in most regions.
- Effect of adding QED similar when applied to NNLO and aN3LO.



- Knock-on impact on cross-sections, ggF Higgs (left), Z (right):



ggH xsec reduced by ≈ 1% by QED effects.



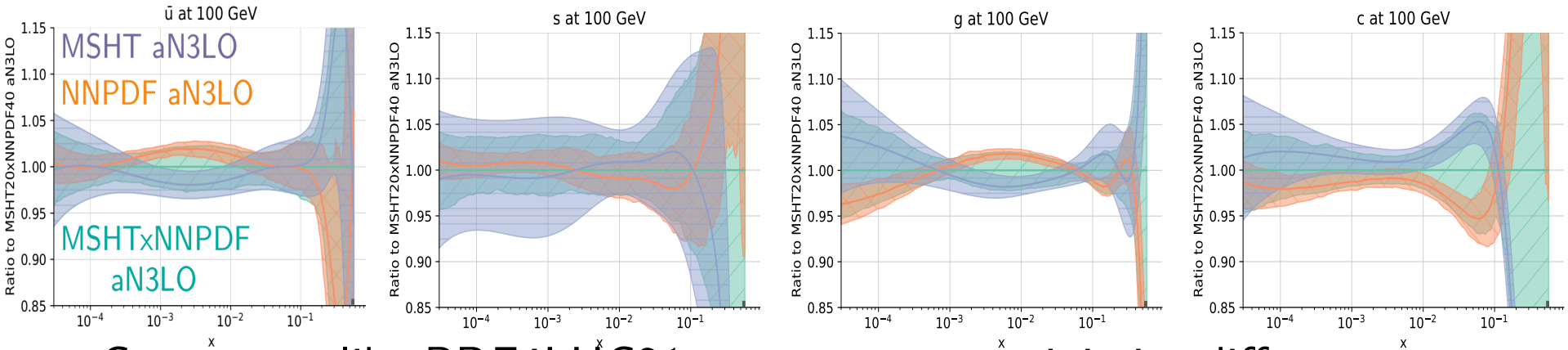
Combination of the aN3LO PDFs:

- Given the different aN3LO PDFs, a conservative approach to estimate the total aN3LO PDF uncertainty is to combine them.

> Central value: unweighted average of two sets
> Uncertainty: accounts for both individual PDF sets' uncertainties and any differences in their central values.

- À la PDF4LHC21, constructed by combining 100 replicas of MSHT and NNPDF aN3LO sets.

(See TC et al - MSHT and NNPDF - 2411.05373)



- Caveat - unlike PDF4LHC21 no attempt to minimise differences, e.g. different heavy quark masses $\Rightarrow$ use only at sufficiently large Q^2.

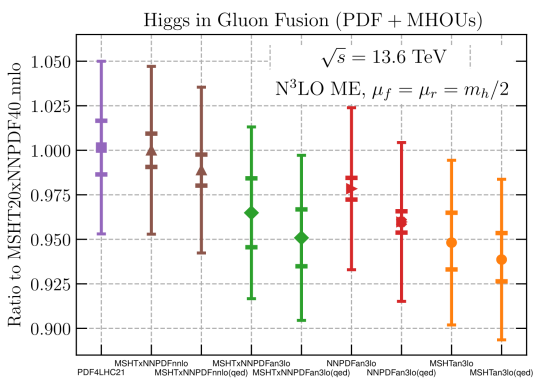
aN3LO PDF effects on Cross-sections: Higgs

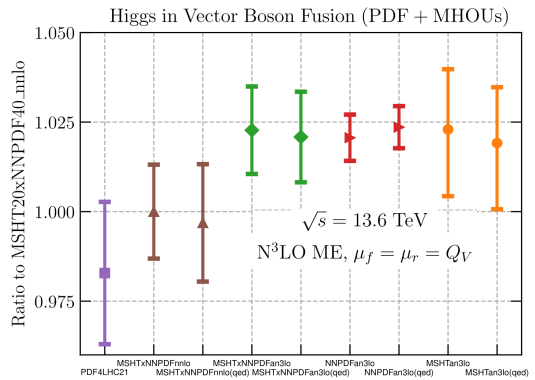
- Largest aN^{3}LO effect is on Higgs production in gluon-gluon fusion.

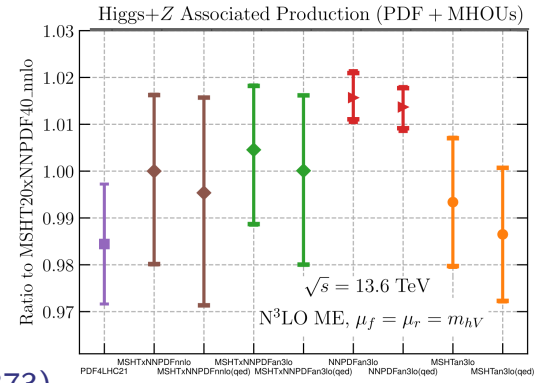
PDF		MSHT	NNPDF	MSHTxNNPDF
ggF xsec shift relative to NNLO	aN3LO	-5%	-2%	-4%
	aN3LO+QED	-6%	-4%	-5%

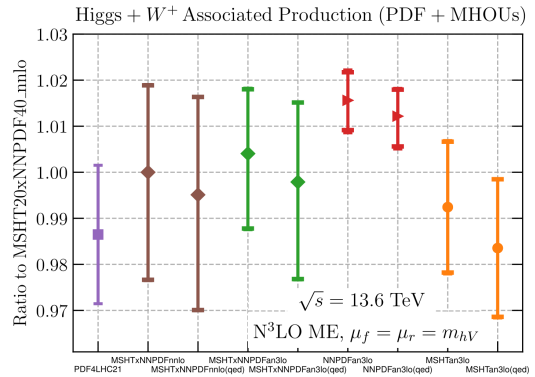
- Smaller aN^{3}LO effects for quarks and hence for VBF, ZH, $W^{\pm}H$.

- VBF: aN^{3}LO+QED result in +2.5%.
- ZH and $W^{\pm}H$: all observe $\approx$ +0.5% from aN^{3}LO+QED.
- Consistent trends in all cases between MSHT and NNPDF aN^{3}LO PDFs.









(See TC et al - MSHT and NNPDF - 2411.05373)

aN3LO PDF effects on Xsecs:

- aN3LO PDFs can be used:
  1. With N3LO matrix elements to compute cross-sections more precisely.
  2. To evaluate the PDF uncertainty from using NNLO PDFs with N3LO cross-sections (previous "highest order" available).

- Before aN3LO PDFs, often N3LO cross-section with NNLO PDFs taken as "highest order" result + $\Delta^{\text{approx}}_{\text{NNLO}}$ for PDF MHOU uncertainty.

$$\Delta^{\text{approx}}_{\text{NNLO}} = \frac{1}{2}\left|\frac{\sigma^{\text{NNLO-xsec}}_{\text{NNLO-PDF}} - \sigma^{\text{NNLO-xsec}}_{\text{NLO-PDF}}}{\sigma^{\text{NNLO-xsec}}_{\text{NNLO-PDF}}}\right|$$

2. Compare with $\Delta^{\text{exact}}_{\text{NNLO}}$:

$$\Delta^{\text{exact}}_{\text{NNLO}} = \left|\frac{\sigma^{\text{N3LO-xsec}}_{\text{N3LO-PDF}} - \sigma^{\text{N3LO-xsec}}_{\text{NNLO-PDF}}}{\sigma^{\text{N3LO-xsec}}_{\text{N3LO-PDF}}}\right|$$

PDF set	Δ	$\sigma(\text{gg} \to \text{H})$	$\sigma(\text{H VBF})$
MSHT20	$\Delta^{\text{exact}}_{\text{NNLO}}$	5.3%	2.3%
	$\Delta^{\text{approx}}_{\text{NNLO}}$	1.4%	1.3%
NNPDF4.0	$\Delta^{\text{exact}}_{\text{NNLO}}$	2.2%	1.3%
	$\Delta^{\text{approx}}_{\text{NNLO}}$	0.2%	0.2%
MSHT20xNNPDF4.0	$\Delta^{\text{exact}}_{\text{NNLO}}$	3.3%	2.3%
	$\Delta^{\text{approx}}_{\text{NNLO}}$	1.6%	0.5%

- $\Delta^{\text{approx}}_{\text{NNLO}}$ is very unreliable, underestimating $\Delta^{\text{exact}}_{\text{NNLO}}$ for ggF and VBF.

(See TC et al - MSHT and NNPDF - 2411.05373)