Precision calculations for top-quark pair production at the LHC

Ioannis Tsinikos

Centre for Cosmology, Particle Physics and Phenomenology (CP3)

Université Catholique de Louvain (UCLouvain)

Technische Universität München (TUM)

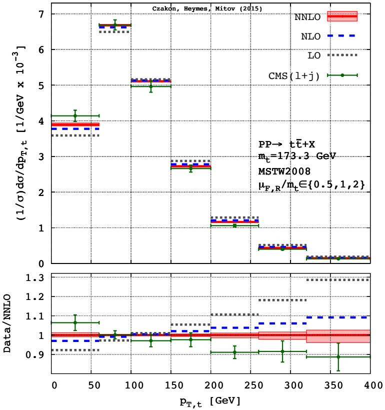
arXiv:1705.04105, *Michal Czakon, David Heymes, Alexander Mitov, Davide Pagani, IT, Marco Zaro*

Port Island, Kobe, Japan, 17 April 2018

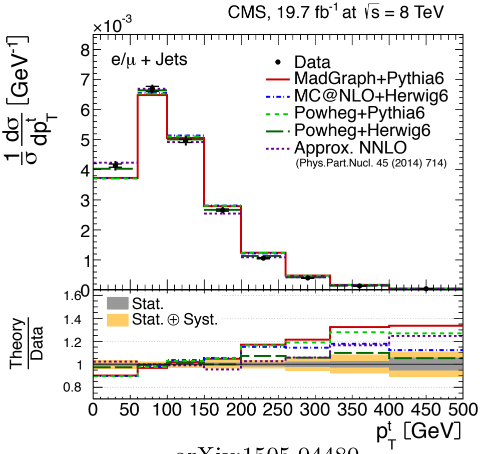
DIS 2018

Contents

- EW corrections
  - Tension between theory and data at high $p_T(t)$ region at 8 TeV
  - The p_T spectrum in data for top quarks is softer than expected



arXiv:1511.00549



arXiv:1505.04480

- EW corrections

  - Theory uncertainties decrease → Relevance of EW corrections increase

  - Experimental uncertainties will further decrease at LHC13

  - $t\bar{t}$ process enters many LHC analyses as signal or background → NNLO QCD and NLO EW predictions are necessary for $t\bar{t}$ production

  Weak: *Beenakker et al.*, Nu.Ph.B.411(1994), *Kuhn et al.*, hep-ph/0610335, arXiv:1305.5773, *Bernreuther et al.*, hep-ph/0508091, *Campbell et al.*, arXiv:1608.03356; **QED+$g\gamma$ LO**: *Hollik et al.*, arXiv:0708.1697; **FB asymmetry**: *Hollik et al.*, arXiv:1107.2606, *Kuhn et al.*, arXiv:1109.6830, *Manohar et al.*, arXiv:1201.3926, *Bernreuther et al.*, arXiv:1205.6580; **NLO+EW+decay (NWA)**: *Bernreuther et al.*, arXiv:1003.3926; **EW to $e^+\mu^-\nu\nu b\bar{b}$**: *Denner et al.*, arXiv:1607.05571; **NLO+EW to $t\bar{t}j$**: *Gütschow et al.*, arXiv:1803.00950

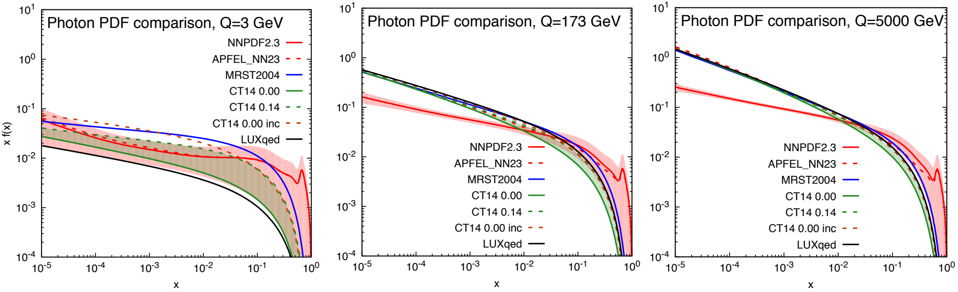
- Photon-induced contributions

  - The (negative) Sudakov suppression can be compensated by the (positive) photon-induced contributions

  PDF sets including $\gamma(x, Q)$: MRST2004QED: *Martin et al. '04*, NNPDF2.3QED: *Ball et al. '13*, CT14QED(inc): *Schmidt et al. '16*, NNPDF3.0QED: *Bertone, Carrazza '16*, LUXqed: *Manohar et al. '16*, NNPDF3.1luxQED, LUXQED17, additional Studies: *Harland-Lang, Khoze, Ryskin '16*

Different PDF sets

Different assumptions for the PDF sets



- At low $Q = 3$ GeV there is a similar behaviour
- At high Q values and low x, the NNPDF2.3QED is different due to different DGLAP QCD and QED running (not relevant for $t\bar{t}$)
- At high Q values and large $x \rightarrow \begin{cases} \text{NNPDF2.3QED, APFEL, large } \gamma(x,Q) \\ \text{CT14QED, LUXqed, small } \gamma(x,Q) \end{cases}$

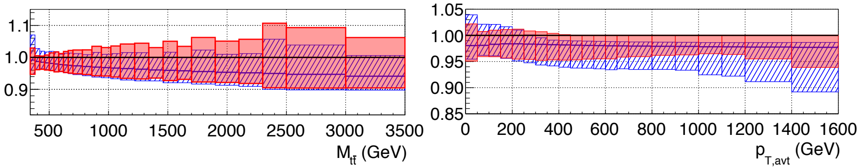
$t\bar{t}$ distributions at NNLO QCD+NLO EW accuracy

- PDF sets considered
  - Main results → NNPDF3.0QED, LUXQED
- Scale choice based on arXiv:1606.03350 (*Czakon, Heymes, Mitov*)
- Fastest convergence → Choose the scale that minimizes the NLO and NNLO corrections in an observable by observable basis

$$\mu = \begin{cases} m_T/2 \text{ for } p_{T,avt} \\ H_T/4 \text{ for } m(t\bar{t}), y_{avt}, y(t\bar{t}) \end{cases}$$

- Supported by the NNLO+NNLL' agreement with the NNLO (arXiv:1803.07623)

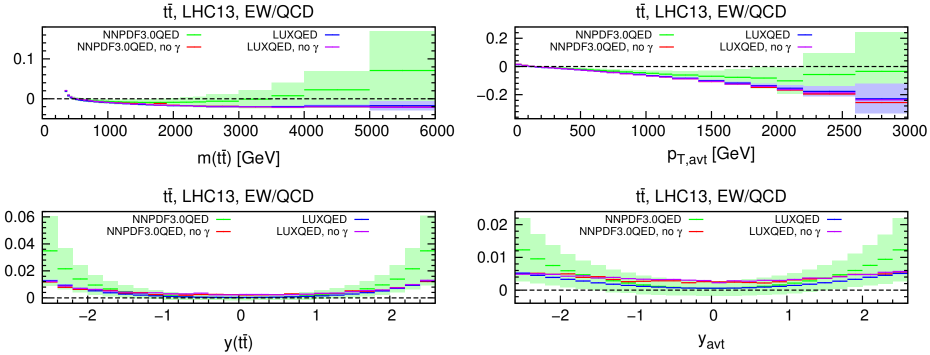
[ratio (NNLO+NNLL')/NNLO]



- Different approaches to combine the perturbative orders
  - Additive vs. multiplicative

PDF comparison

NNPDF3.0QED vs LUXQED



- photon PDF impact $\longrightarrow$ large in NNPDF3.0QED, negligible in LUXQED
- LUXQED $\longleftrightarrow$ NNPDF3.0QED (no $\gamma(x, Q)$)
- LUXQED and NNPDF3.0QED in agreement within uncertainties

Additive approach

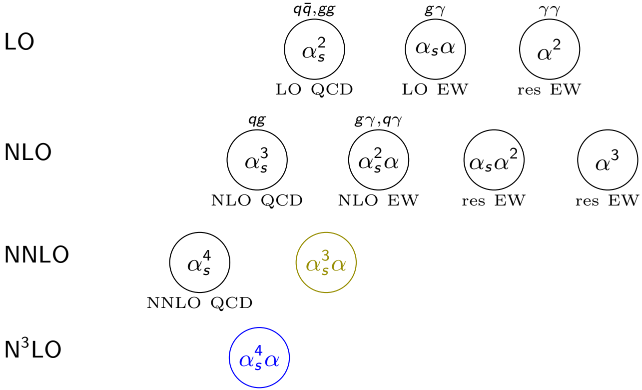
LO	$q\bar{q},gg$: α_s^2 (LO QCD)	$g\gamma$: $\alpha_s\alpha$ (LO EW)	$\gamma\gamma$: α^2 (res EW)	
NLO	qg: α_s^3 (NLO QCD)	$g\gamma,q\gamma$: $\alpha_s^2\alpha$ (NLO EW)	$\alpha_s\alpha^2$ (res EW)	α^3 (res EW)
NNLO	α_s^4 (NNLO QCD)			

$$\Sigma_{\rm QCD} \equiv \Sigma_{\rm LO\ QCD} + \Sigma_{\rm NLO\ QCD} + \boxed{\Sigma_{\rm NNLO\ QCD}}$$

$$\Sigma_{\rm EW} \equiv \Sigma_{\rm LO\ EW} + \Sigma_{\rm NLO\ EW} + \boxed{\Sigma_{\rm res\ EW}(\alpha^2 + \alpha_s\alpha^2 + \alpha^3)}$$

$$\Sigma_{\rm QCD+EW} \equiv \Sigma_{\rm QCD} + \Sigma_{\rm EW}$$

Additive vs multiplicative combination



$$\Sigma_{\mathrm{QCD+EW}} \equiv \Sigma_{\mathrm{QCD}} + \overbrace{\Sigma_{\mathrm{LO\ EW}} + \Sigma_{\mathrm{NLO\ EW}} + \Sigma_{\mathrm{res\ EW}}}^{\Sigma_{\mathrm{EW}}}$$

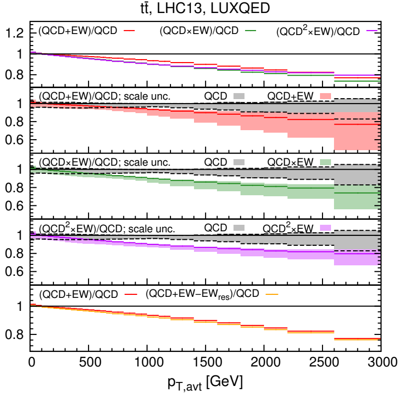
$$\Sigma_{\mathrm{QCD\times EW}} \equiv \Sigma_{\mathrm{QCD}} + K_{\mathrm{QCD}}^{\mathrm{NLO}}\Sigma_{\mathrm{NLO\ EW}} + \Sigma_{\mathrm{LO\ EW}} + \Sigma_{\mathrm{res\ EW}}$$

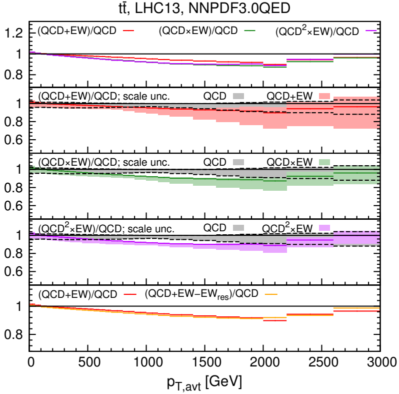
$$\Sigma_{\mathrm{QCD^2\times EW}} \equiv \Sigma_{\mathrm{QCD}} + K_{\mathrm{QCD}}^{\mathrm{NNLO}}\Sigma_{\mathrm{NLO\ EW}} + \Sigma_{\mathrm{LO\ EW}} + \Sigma_{\mathrm{res\ EW}}$$

Additive vs multiplicative combination

- Additive ($\Sigma_{\mathrm{QCD+EW}}$)
  → Exact up to the order of truncation
- Multiplicative ($\Sigma_{\mathrm{QCD\times EW}}$)
  → Approximates leading higher order EW corrections i.e. $O(\alpha_s^3\alpha)$
  → Rescale NLO EW corrections with NLO QCD K-factors
  → Motivated by the soft QCD and EW Sudakov log factorisation
  → Stabilisation of scale dependence
- Stability check ($\Sigma_{\mathrm{QCD^2\times EW}}$)
  → Use NNLO QCD K-factors to estimate $O(\alpha_s^4\alpha)$

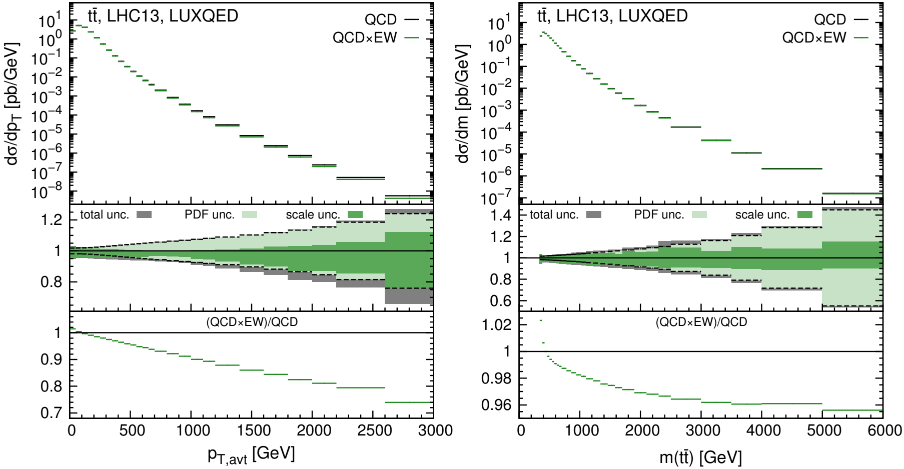
Additive vs multiplicative combination





- Central value $\rightarrow \mathrm{QCD} + \mathrm{EW} \sim \mathrm{QCD} \times \mathrm{EW}$
- NNLO QCD corrections reduce the scale dependence significantly
- Reduction of scale unc. in the multiplicative approach
- In the LUXQED PDF set the total result deviates from the pure QCD one, especially after the 1 TeV region

Differential distributions

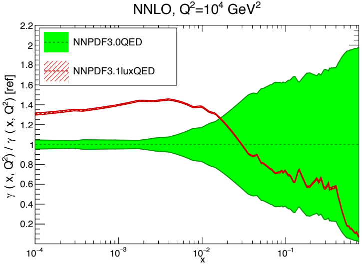


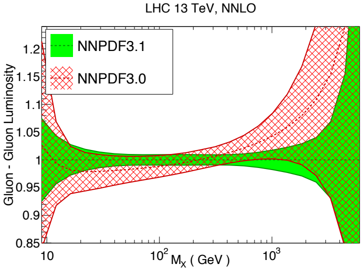
- EW corrections are of the order of the theory unc. at high $P_{T,avt}$
- At high regions the PDF unc. is larger than the scale unc. in $m(t\bar{t})$

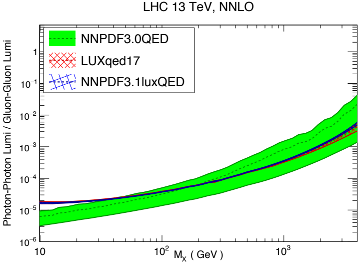
New PDF sets

LUXQED→LUXQED17,NNPDF30QED→NNPDF31luxQED

arXiv:1706.00428, arXiv:1712:07053



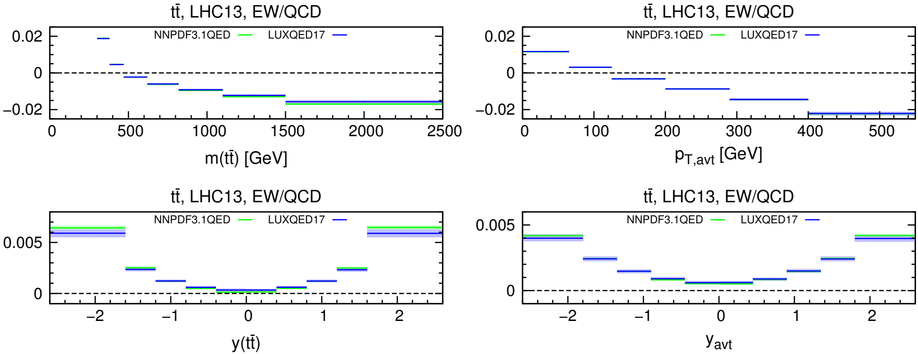




- NNPDF3.1 adopts the LUXQED approach
- $\gamma\gamma$ Luminosity in agreement between the two PDF sets
- In NNPDF3.1 the PDF uncertainties from the QCD part reduce

New PDF sets

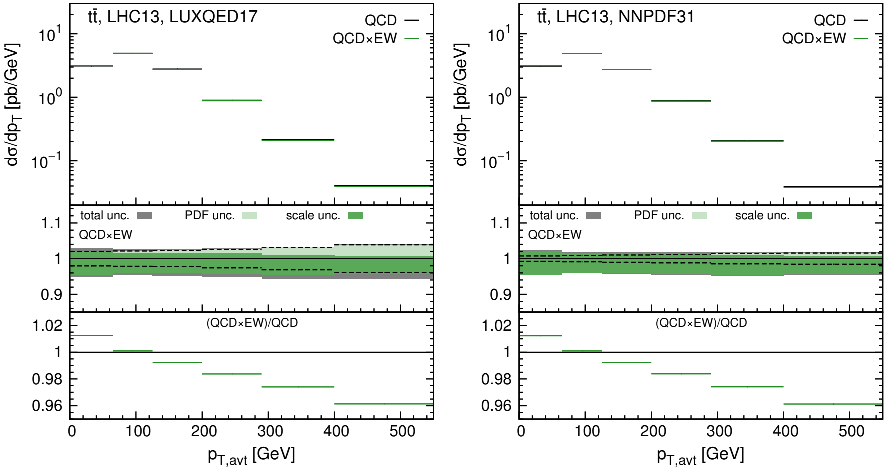
NNPDF3.1luxQED vs LUXQED17



- photon PDF impact ⟶ negligible
- LUXQED ⟷ NNPDF3.1luxQED
- LUXQED17 and NNPDF3.1luxQED in agreement within uncertainties

New PDF sets

Recent results



- EW corrections not sensitive to the PDF choice
- Reduction of PDF unc. in NNPDF3.1luxQED

Conclusions

- 13 TeV results

  - NNLO QCD are necessary in order to reduce the scale dependence

  - At 13 TeV, in p_T distributions EW corrections induce deviations w.r.t. the pure QCD ones (LUXQED(17), NNPDF3.1luxQED)

- PDF sets

  - NNPDF2.3(3.0)QED $\rightarrow$ Large impact of photon-induced contributions accompanied with large uncertainties

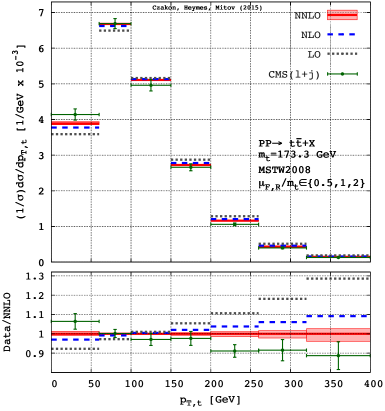
  - CT14QED, LUXQED(17), NNPDF3.1luxQED $\rightarrow$ Negligible impact of photon-induced contributions in $t\bar{t}$ distributions

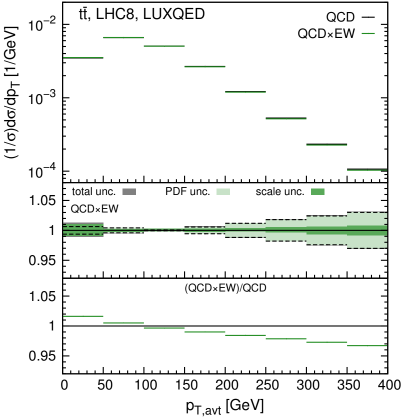
  - NNPDF3.1luxQED $\rightarrow$ Reduces the QCD uncertainty w.r.t. NNPDF3.0QED

- Recent results available to be compared with CMS data

  `http://www.precision.hep.phy.cam.ac.uk/results/ttbar-nnloqcd-nloew`

$P_T(t)$ spectrum





- Fixed scale $\mu = m_t$
- Only scale unc.

- Dynamical scale scale $\mu = m_T/2$
- Scale+PDF unc.

EW Corrections

EW α renormalisation schemes

- $\alpha(0)$-scheme
  - $\rightarrow$ Pure QED $\rightarrow$ Tomson scattering, m_e
  - $\rightarrow$ Preferable for external photons
- $\alpha(m_Z)$-scheme
  - $\rightarrow$ Drell-Yan, m_Z
  - $\rightarrow$ Avoid $log\frac{m_Z^2}{m_e^2}, log\frac{m_Z^2}{m_q^2}$ terms
  - $\rightarrow$ Still pure QED
- G_μ-scheme
  - $\rightarrow \alpha_{G_\mu}(G_\mu, m_W, m_Z) = \frac{\sqrt{2}G_\mu m_W^2}{\pi}(1 - \frac{m_W^2}{m_Z^2})$
  - $\rightarrow \alpha(m_Z)$ and G_μ from muon decay (Weak)
  - $\rightarrow$ Include EW effects
  - $\rightarrow$ Preferable for external W's

- Running of α effects

  $\log\frac{m_Z^2}{m_e^2} \Leftrightarrow \log\frac{Q^2}{m_Z^2}$

  $Q \sim 1.6 \times 10^4$ TeV

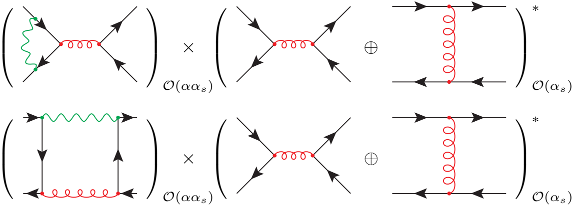
  $\rightarrow$ Not significant for LHC energies
- Scheme dependence

  $\rightarrow\sim 3\%$ for $O(\alpha^3)$ perturbative order

EW Corrections

Sudakov logarithms

- The QED part of the EW corrections $\Longleftrightarrow$ QCD corrections
- Weak virtual corrections are finite even without real contributions (massive vector bosons)
- The Sudakov logs are the IR limit of virtual 1-loop EW corrections



- $DL(s) = -\dfrac{\alpha}{4\pi s_w^2} \log^2 \dfrac{Q^2}{m_W^2}$
- $SL(s) = +\dfrac{\alpha}{4\pi s_w^2} \log \dfrac{Q^2}{m_W^2}$

- $Q^2 \sim \hat{s}, \hat{t}, \hat{u}$. When $Q^2 \gg m_V^2, m_H^2$, EW corrections are dominated by Sudakov-like corrections

The photon PDF

- NNPDF2.3QED
  - No assumption for the $\gamma(x, Q^0)$ functional form
  - Different scales for QCD/QED evolutions - Splitting functions at $O(\alpha)$
- CT14QED
  - Uses an ansatz like MRST2004 with one free parameter
  - The momentum fraction carried by the photon is constrained to be $\leq 0.14\%$ at 90% CL
  - A set including the elastic photon contribution is also provided (CT14QEDinc)
- LUXQED
  - The QCD part is from PDF4LHC (CT14, MMHT14, NNPDF3.0)
  - Match the Master formula with the Parton model formula $\sigma \rightarrow$ extract $\gamma(x, Q^0)$
  - Splitting functions at $O(\alpha + \alpha_s \alpha)$

The photon PDF

- NNPDF3.0QED

  - Simultaneous evolution of QCD/QED is implemented (also in APFEL_NN23), which changes the low x behaviour, but with no effect in $t\bar{t}$ phenomenology

  - Splitting functions at $O(\alpha)$

- LUXQED17

  - Splitting functions at $O(\alpha + \alpha_s\alpha + \alpha^2)$

- NNPDF3.1luxQED (arXiv:1706.00428)

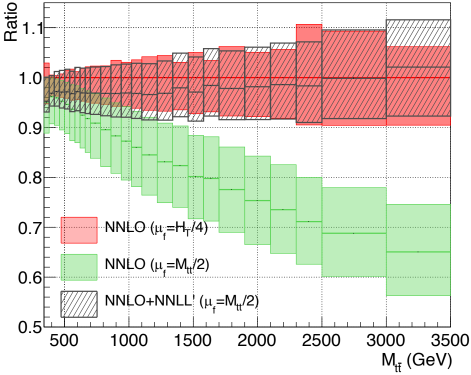
  - Adopts the LUXQED approach for the photon PDF

  - PDF unc. reduced from 5% (NNPDF3.0) to 1-2% for the range of $|y| \leq 2$ and 100 GeV $\leq M_x \leq$ 1 TeV

  - Significant reduction of gluon uncertainty: combination of many mutually consistent constraints on the gluon from DIS (especially at HERA), Z transverse momentum distributions, jet production, and top pair production, which taken together cover a very wide kinematic range

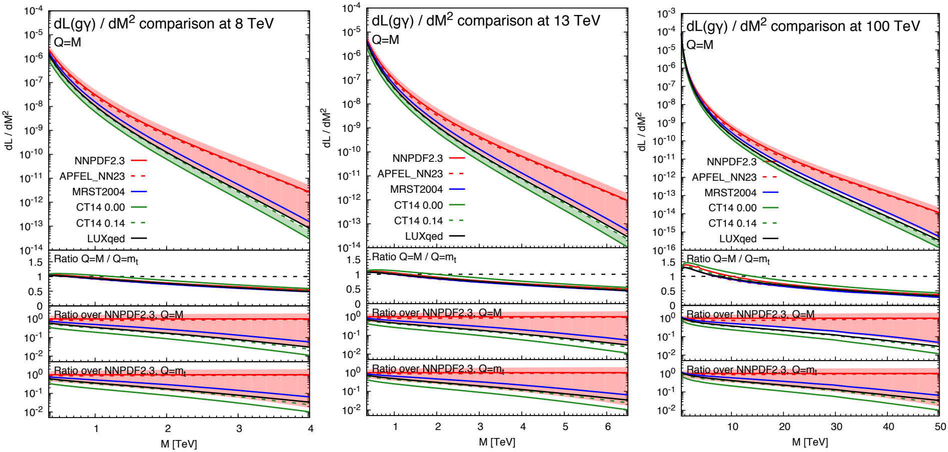
Scale choice

- NNLO+NNLL' insensitive to the scale choice



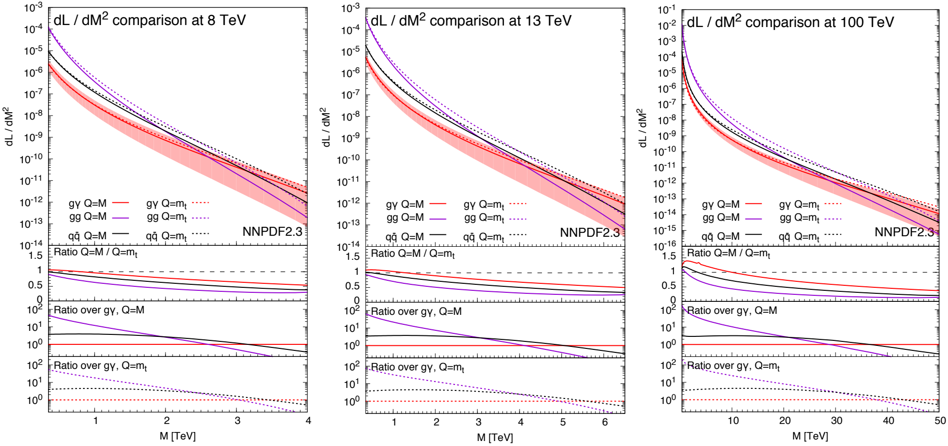
arXiv:1803.07623

The $g\gamma$ Luminosity



- LUXqed lies very close to CT14QED
- Effects due to the different evolution in NNPDF2.3QED are not visible

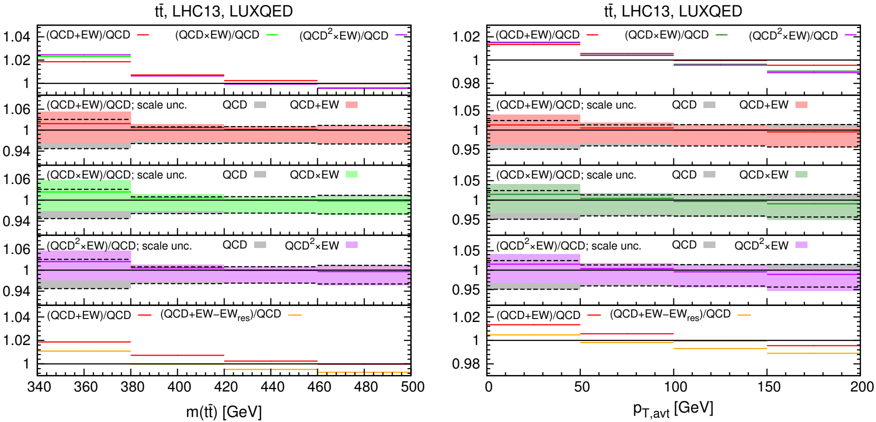
Parton Luminosities and scale choice



- In both dynamical and fixed scales the $g\gamma$ luminosity is suppressed with respect to the gg one at the low M region

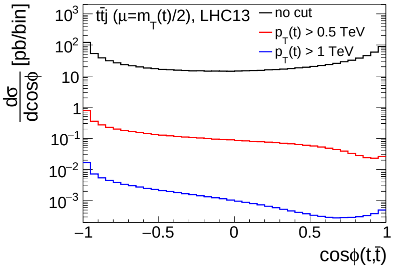
Multiplicative approach

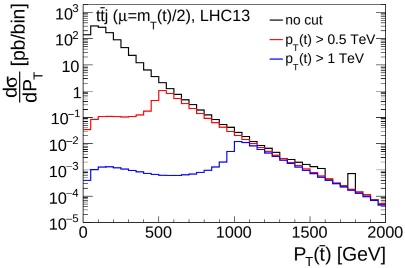
- Small QCD K-factors. Check the threshold regions, they are not driven by Sudakov logs, there should be no effect

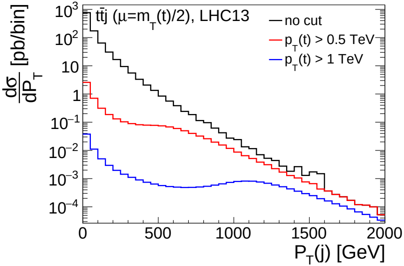


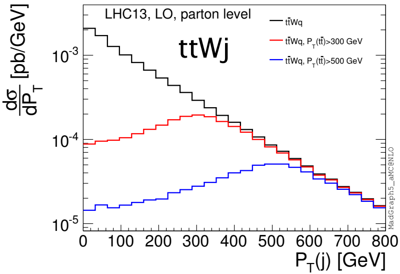
- Check if the QCD corrections are driven by the soft part in the high p_T region. Look in $t\bar{t}j$. Show also $t\bar{t}Wj$ as a counter example

Multiplicative approach

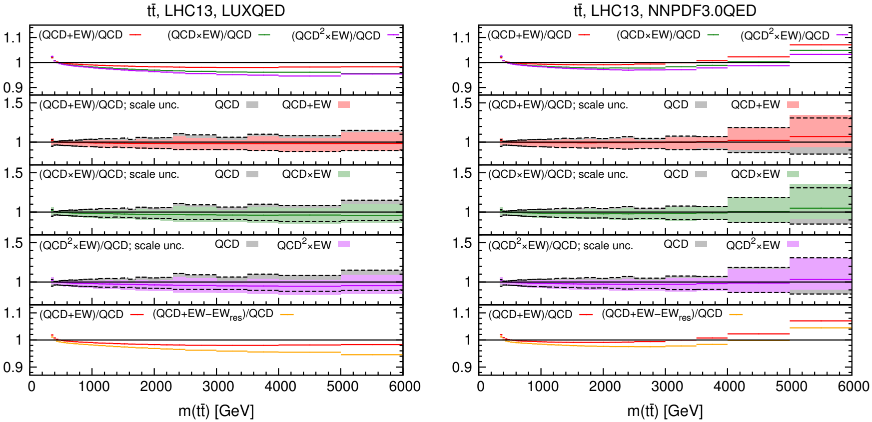








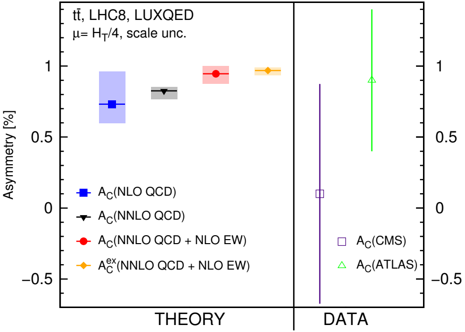
Additive vs multiplicative combination

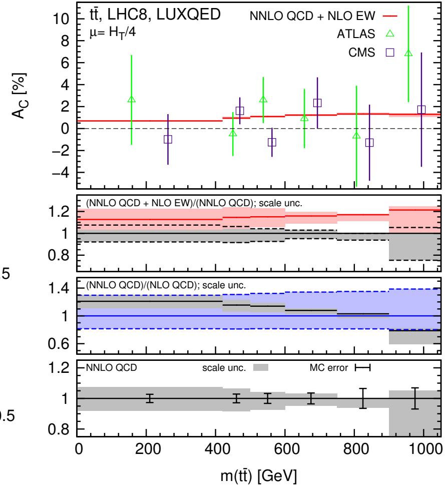


- $\mathrm{QCD} + \mathrm{EW} \sim \mathrm{QCD} \times \mathrm{EW}$

$t\bar{t}$ asymmetry at 8 TeV

	QCD	QCD+EW
$A_{\rm C}[\%]$	$0.79^{+0.05}_{-0.06}$	$0.90^{+0.07}_{-0.07}$
$A_{\rm C}^{\rm ex}[\%]$	$0.86^{+0.02}_{-0.04}$	$0.95^{+0.02}_{-0.04}$





- Agreement with data at inclusive and differential level
- Theory unc. much smaller than the experimental one

Asymmetry definition

- NNLO QCD

$$A_C^{\rm NNLO} = \frac{\alpha_s N_3 + \alpha_s^2 N_4}{D_2 + \alpha_s D_3 + \alpha_s^2 D_4} = \frac{\alpha_s N_3}{D_2}\left(1 + \frac{\alpha_s N_4}{N_3}\right)\left(1 + \frac{\alpha_s D_3}{D_2} + \frac{\alpha_s^2 D_4}{D_2}\right)^{-1}$$

$$A_C^{\rm ex,NNLO} = A_C^{\rm NNLO} K^{\rm NNLO} - A_C^{\rm NLO}(K^{\rm NLO} - 1)K^{\rm NLO} + O(\alpha_s^3)$$

- NNLO QCD + NLO EW

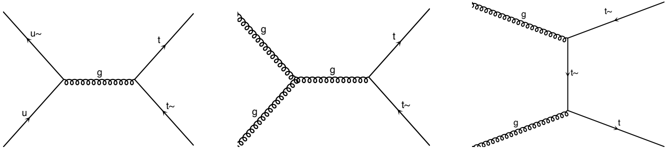
$$A_C^{\rm NNLOQCD+EW} = \frac{\alpha_s N_3 + \alpha_s^2 N_4 + \alpha_s^{-2} N_{\rm EW}}{D_2 + \alpha_s D_3 + \alpha_s^2 D_4} =$$

$$= \left(\frac{\alpha_s N_3 + \alpha_s^2 N_4 + \alpha_s^{-2} N_{\rm EW}}{D_2}\right)\left(1 + \frac{\alpha_s D_3}{D_2} + \frac{\alpha_s^2 D_4}{D_2}\right)^{-1}$$

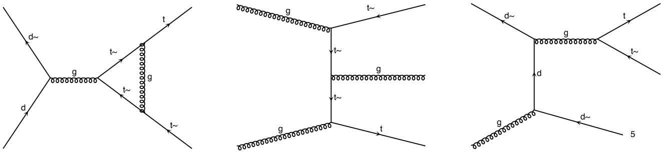
$$A_C^{\rm ex,NNLOQCD+EW} = A_C^{\rm NNLOQCD+EW} K^{\rm NNLO} - A_C^{\rm NLO}(K^{\rm NLO} - 1)K^{\rm NLO} + O(\alpha_s^3)$$

Representative Feynman diagrams (QCD)

- LO QCD (α_s^2)

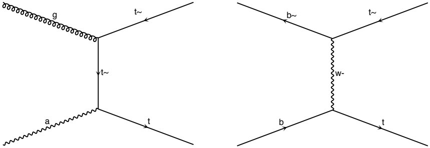


- NLO QCD (α_s^3)

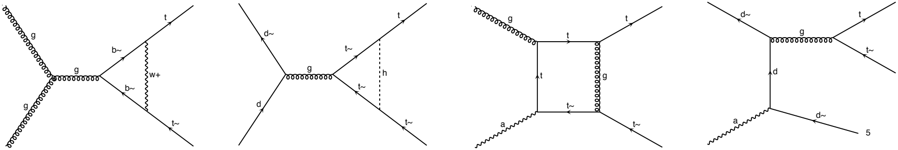


Representative Feynman diagrams (EW)

- LO EW ($\alpha_s \alpha$)

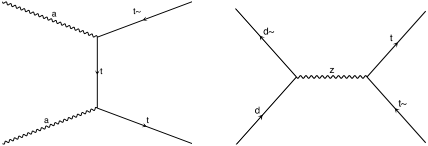


- NLO EW ($\alpha_s^2 \alpha$)

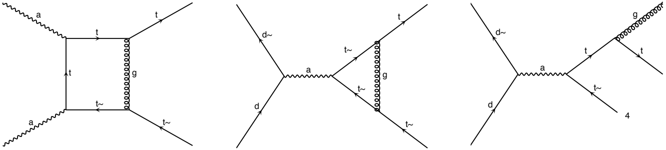


Representative Feynman diagrams (sub EW)

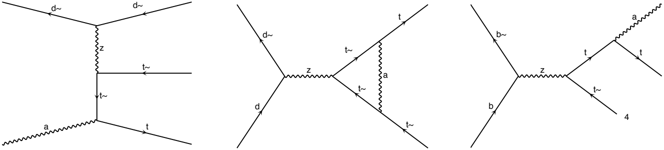
- LO3 (α^2)



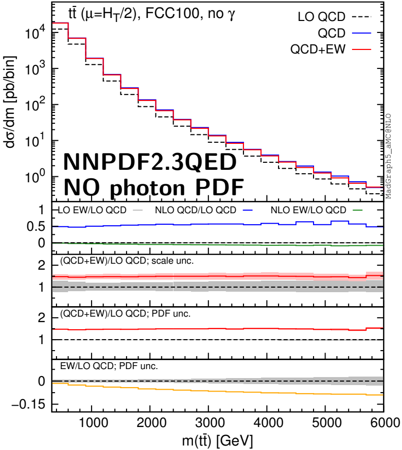
- NLO3 ($\alpha_s \alpha^2$)

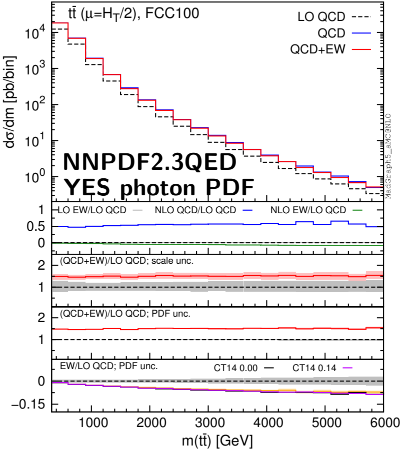


- NLO4 (α^3)



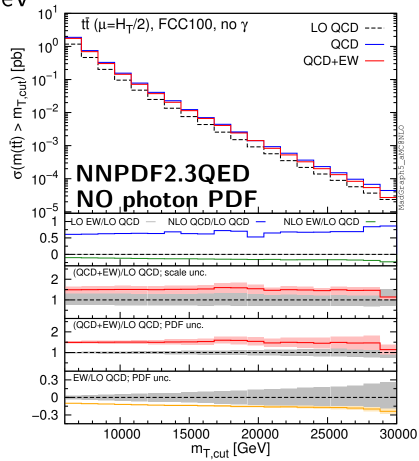
100 TeV

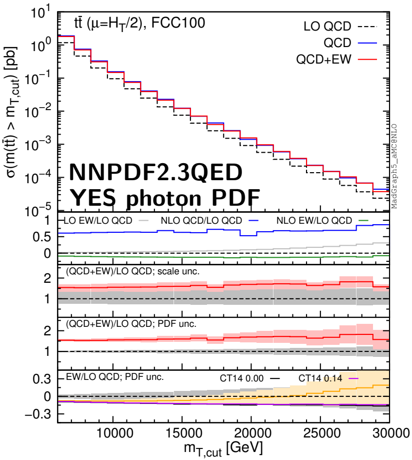




- At 100 TeV $t\bar{t}$ differential distributions are not sensitive to photon-induced contributions
- $\sqrt{s} \uparrow \Longrightarrow$ Bjorken x's $\downarrow$

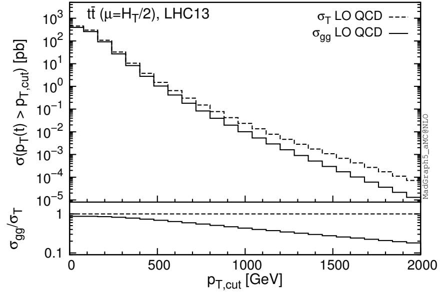
100 TeV

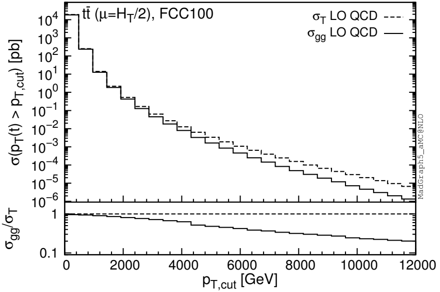




- The effect of the photon-induced contributions becomes visible only at very high $m(t\bar{t})$ (and $p_T(t)$) regions
- Larger effects are expected at 8 TeV, where already we have data

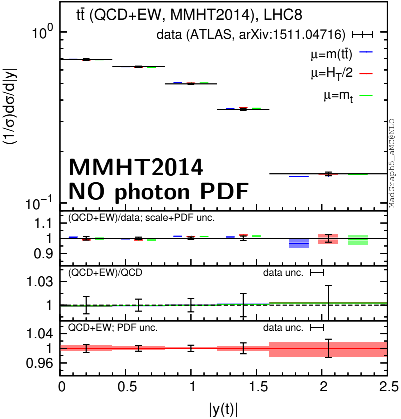
LHC13, FCC100, σ_{gg}/σ_T vs p_T

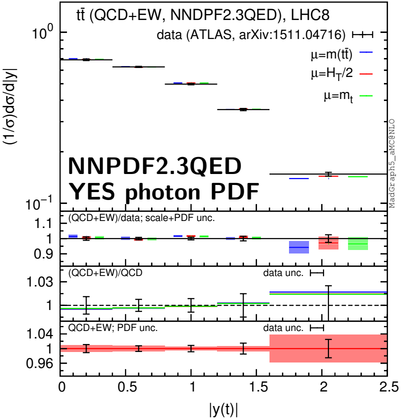




- $p_T \uparrow \Longrightarrow$ tops are central $\Longrightarrow$ $s-$channel favoured $\Longrightarrow \dfrac{\sigma_{q\bar{q}}}{\sigma_{gg}} \uparrow \Longrightarrow K-$factor$\downarrow$

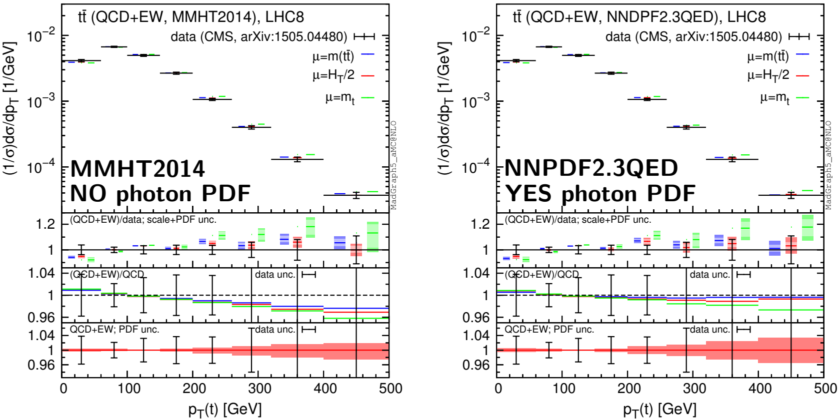
8 TeV





- Normalised $(1/\sigma)$ rapidity distributions → Exp. errors reduce at few % level.
- Large PDF uncertainties and visible impact of photon PDF (NNPDF2.3QED)
- Can be used for constraining the photon PDF (NNPDF2.3QED)

8 TeV



- In p_T distributions the impact of the photon PDF is larger at the tail
- Sudakov logs vs $\gamma(x, Q)$ compensation depends on the scale definition
- For 13 TeV comparisons between theory and experiment EW corrections and photon-induced contributions need to be taken into account
- Scale uncertainty still large at NLO QCD $\rightarrow$ NNLO QCD needed