EW corrections on top-quark pair production: the impact of the photon PDF

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arXiv:1606.01915, *Davide Pagani, IT, Marco Zaro*

arXiv:17xx.xxxxx, *Michal Czakon, David Heymes, Alexander Mitov, Davide Pagani, IT, Marco Zaro*

Birmingham, 4 April 2017

DIS 2017

Contents

Motivation

- EW corrections

  - Tension between theory and data at high $p_T(t)$ region at 8 TeV

  - Theory uncertainties decrease $\rightarrow$ Relevance of EW corrections increase

  - Experimental uncertainties will further decrease at LHC13

  - $t\bar{t}$ process enters many LHC analyses as signal or background $\rightarrow$ 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

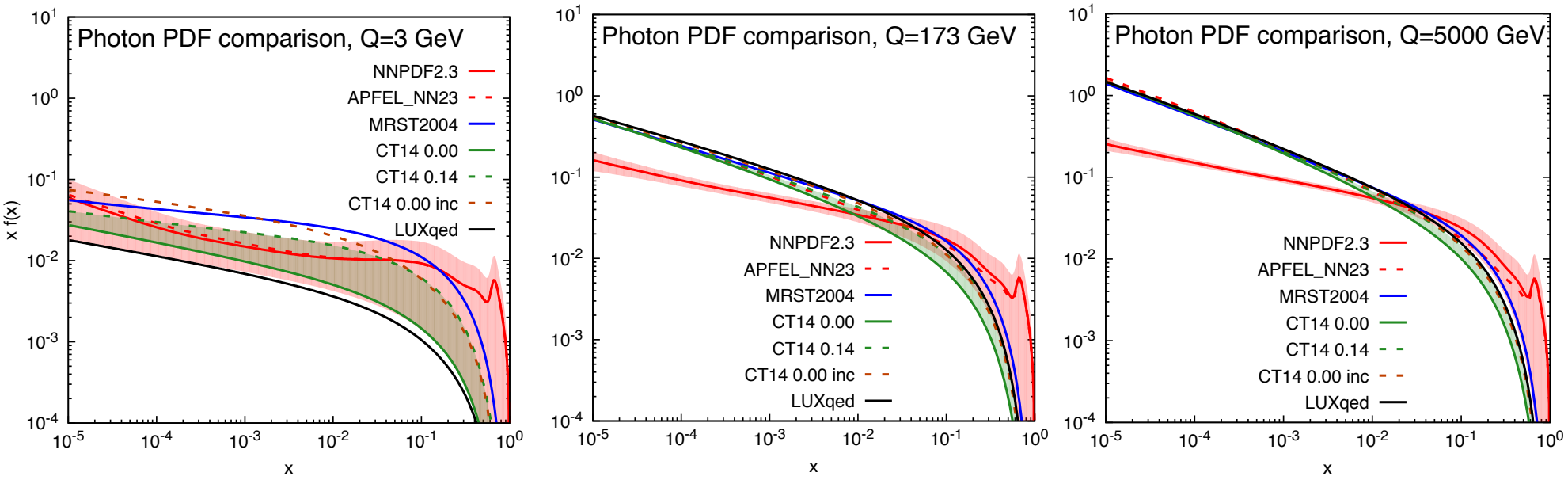
- Photon-induced contributions

  - The (negative) Sudakov suppression is 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*, MMHTQED (in progress), additional Studies: *Harland-Lang, Khoze, Ryskin '16*

Different PDF sets

Different assumptions for all 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 $x \rightarrow \begin{cases} \text{NNPDF2.3QED, large } \gamma(x,Q) \\ \text{CT14QED, LUXqed, small } \gamma(x,Q) \end{cases}$

Calculation framework

NLO QCD+EW corrections to $t\bar{t}$ production (MadGraph5_aMC@NLO)

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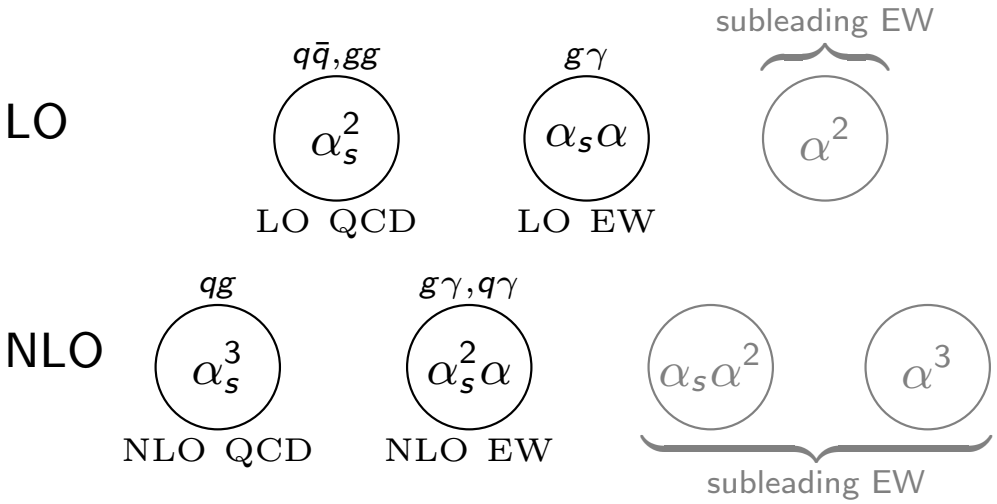
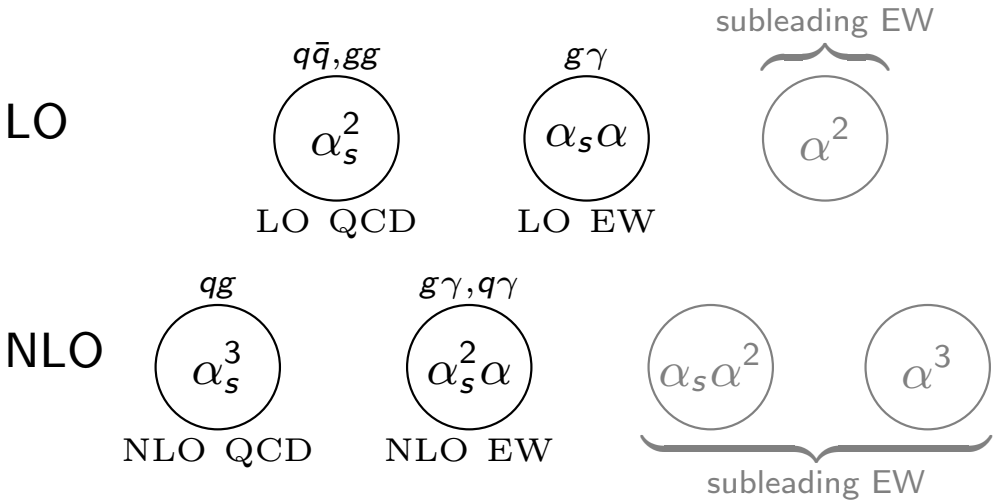
NLO QCD+EW corrections to $t\bar{t}$ production (MadGraph5_aMC@NLO)



$$\Sigma_{\text{QCD}} \equiv \Sigma_{\text{LO QCD}} + \Sigma_{\text{NLO QCD}}$$
$$\Sigma_{\text{EW}} \equiv \Sigma_{\text{LO EW}} + \Sigma_{\text{NLO EW}}$$
$$\Sigma_{\text{QCD+EW}} \equiv \Sigma_{\text{QCD}} + \Sigma_{\text{EW}}$$

Calculation framework

NLO QCD+EW corrections to $t\bar{t}$ production (MadGraph5_aMC@NLO)



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

- Input parameters

$$m_t = 173.3 \text{ GeV}, \quad m_H = 125.09 \text{ GeV},$$
$$m_W = 80.385 \text{ GeV}, \quad m_Z = 91.1876 \text{ GeV},$$
$$G_\mu = 1.1663787 \cdot 10^{-5} \text{ GeV}^{-2}$$

- Scale choice

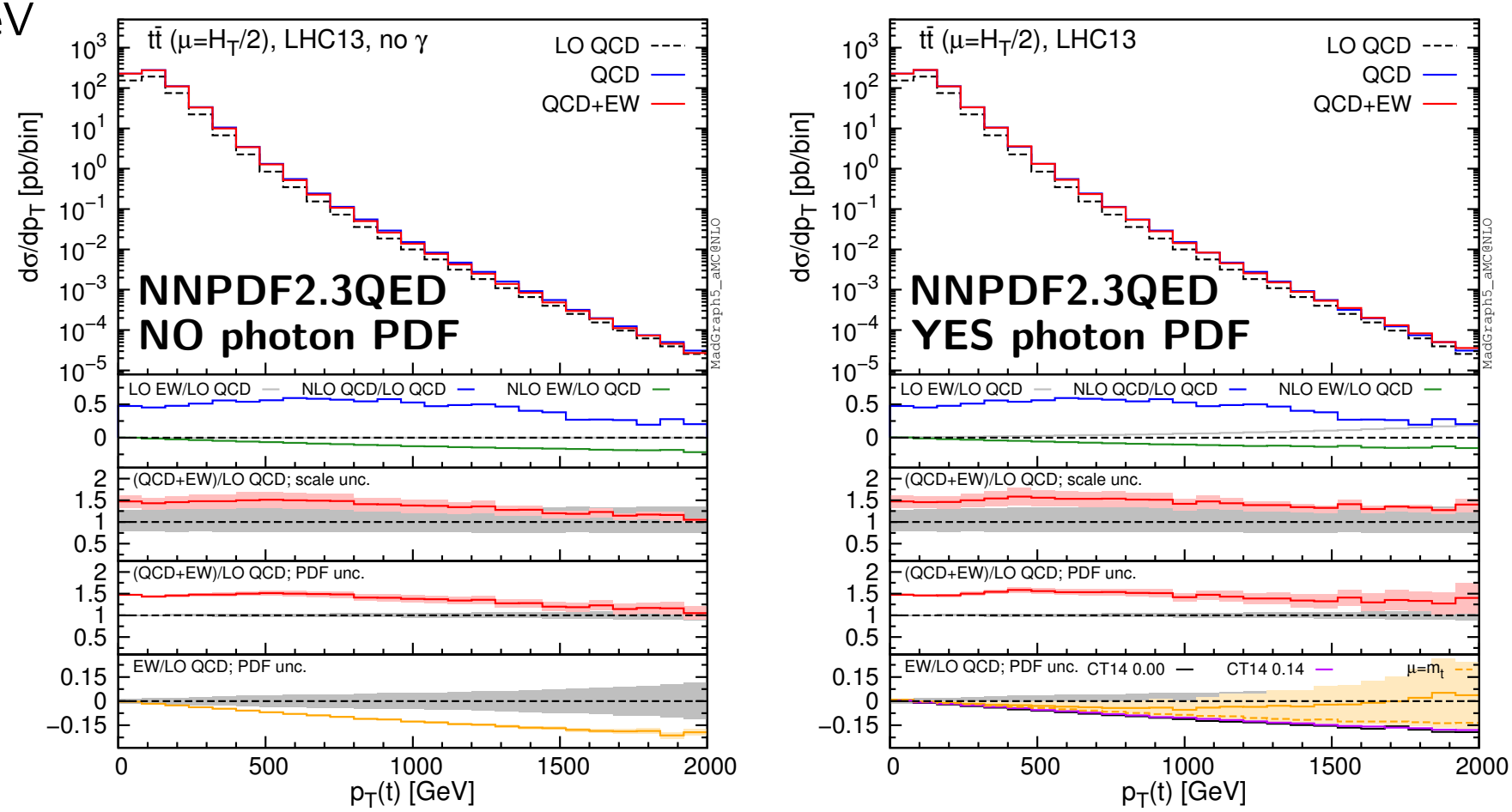
$$\mu = \frac{H_T}{2} = \frac{1}{2}\sum_i m_{T,i}$$

- PDF sets considered

  - Main results → NNPDF2.3QED, NNPDF2.3QED (no $\gamma(x, Q)$)
  - Comparison with CT14QED

Results at 13 TeV

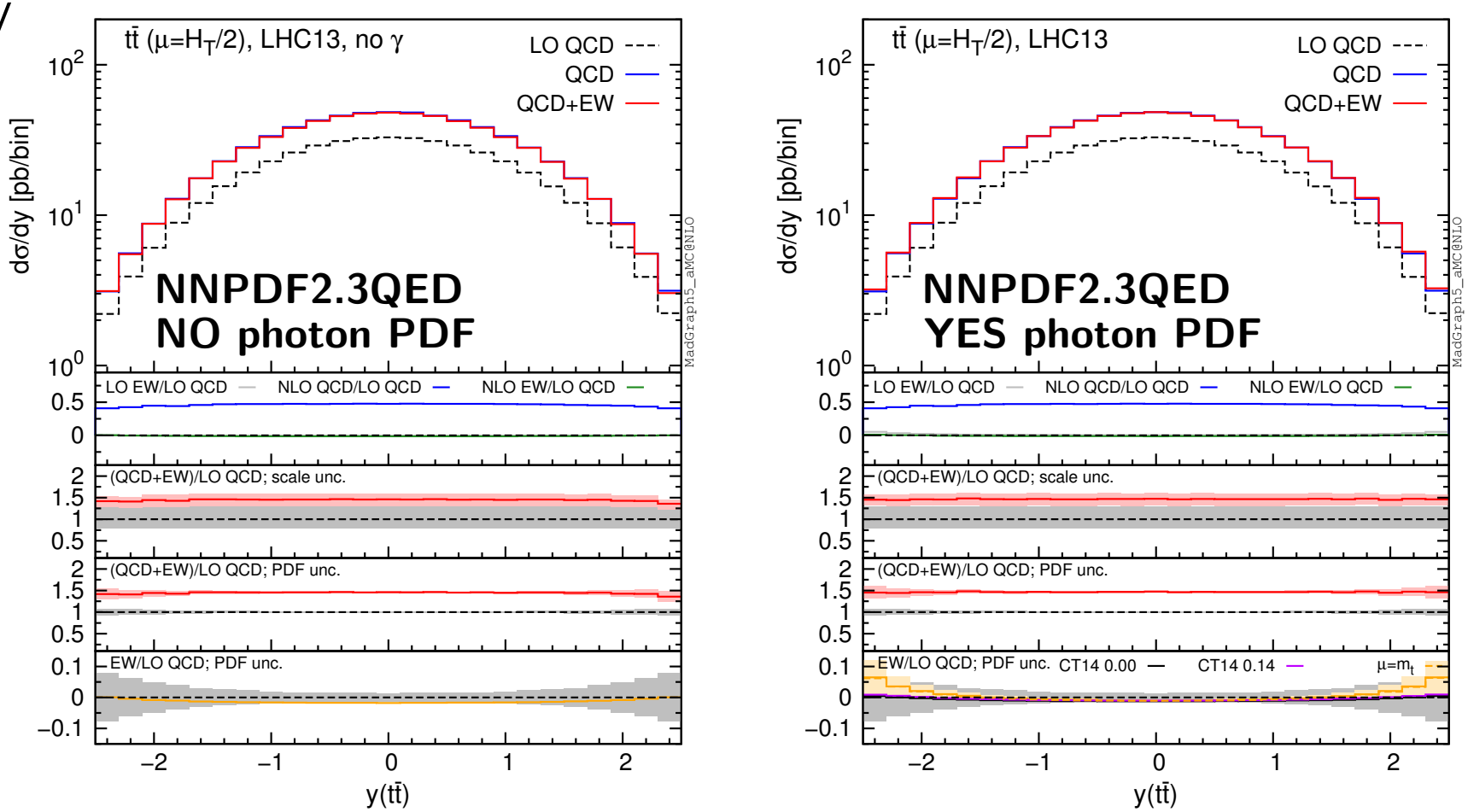
13 TeV



- NNPDF2.3QED: Photon PDF effect is mostly due to LO EW contribution
- NNPDF2.3QED: Large cancellations between Sudakov logs and photon-induced contributions
- photon PDF impact $\longrightarrow$ large in NNPDF2.3QED, negligible in CT14QED

Results at 13 TeV

13 TeV



- NNPDF2.3QED: $\sim 5\%$ effect of photon PDF at large rapidity regions, which are reachable experimentally
- CT14QED $\longleftrightarrow$ NNPDF2.3QED (no $\gamma(x, Q)$)
- CT14QED and NNPDF2.3QED in agreement within uncertainties

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

in collaboration with
Michal Czakon, David Heymes, Alex Mitov, Davide Pagani, Marco Zaro

- 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

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

- PDF sets considered

  - Main results → NNPDF3.0QED, LUXqed

Calculation framework

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

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

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

Calculation framework

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

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

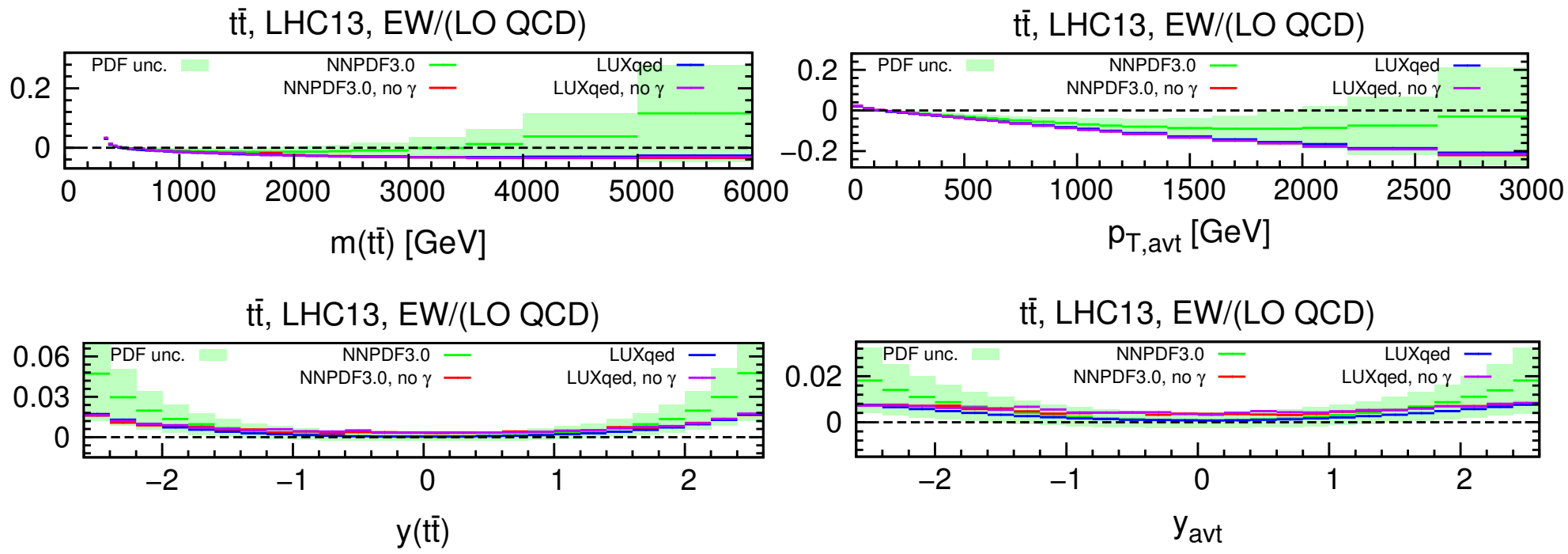
$$\Sigma_{\text{QCD}} \equiv \Sigma_{\text{LO QCD}} + \Sigma_{\text{NLO QCD}} + \boxed{\Sigma_{\text{NNLO QCD}}}$$

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

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

Results at 13 TeV

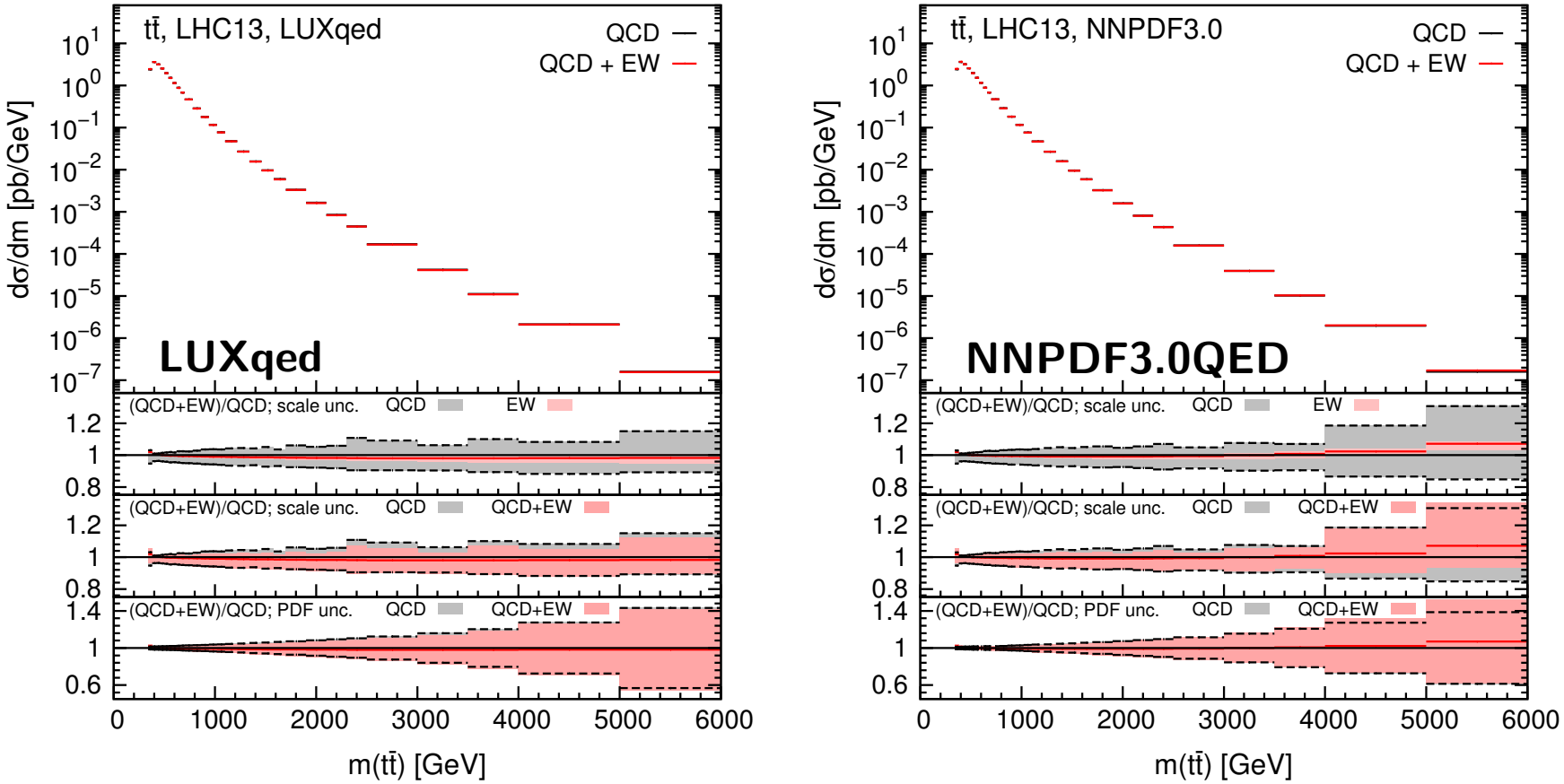
NNPDF3.0QED vs LUXqed



- 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

Results at 13 TeV

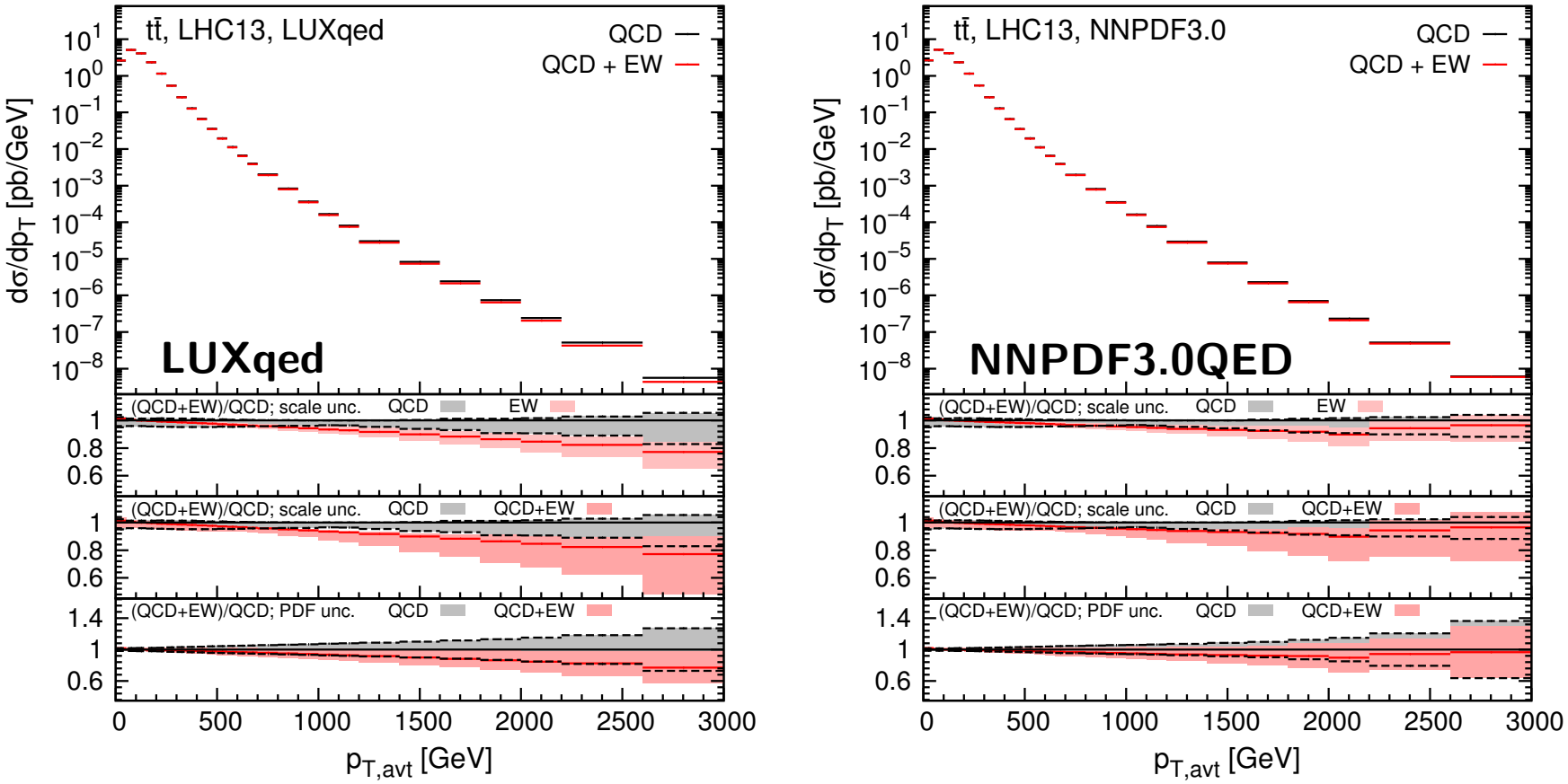
13 TeV



- Both in the the LUXqed and NNPDF3.0QED PDF sets the EW correction is small
- PDF uncertainties become dominant at high $m(t\bar{t})$ region

Results at 13 TeV

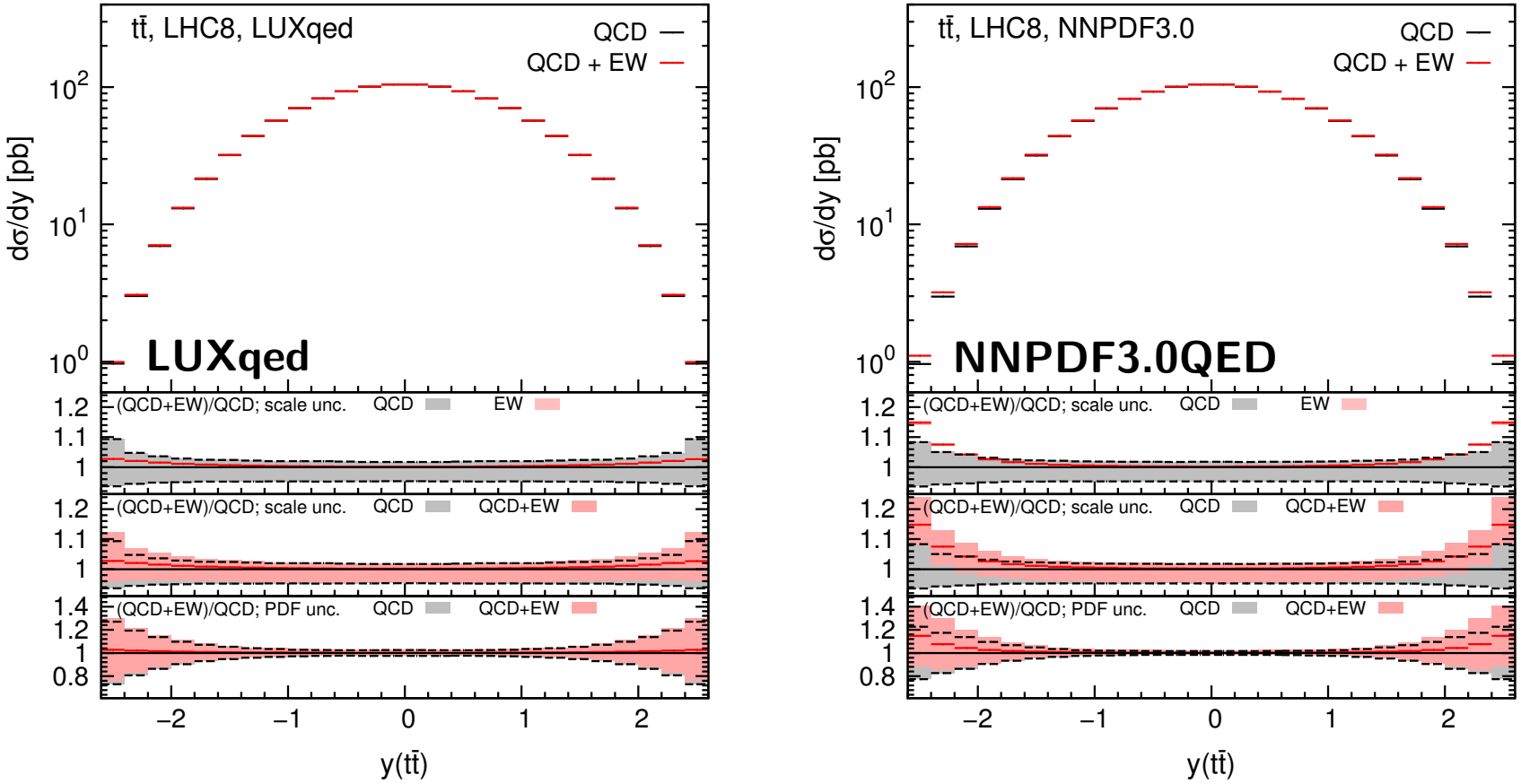
13 TeV



- NNLO QCD corrections reduce the scale dependence significantly
- In the LUXqed PDF set the total result deviates from the pure QCD one already at the 1 TeV region

Results at 8 TeV

8 TeV



- $\sqrt{s} \downarrow \Longrightarrow$ Bjorken x's $\uparrow \Longrightarrow$ More sentitive to photon-induced contribitions
- NNPDF3.0QED: $\sim 15\%$ effect of photon PDF at large rapidity regions

Conclusions

- PDF sets

  - NNPDFQED → Large impact of photon-induced contributions accompanied with large uncertainties

  - CT14QED, LUXqed → Negligible impact of photon-induced contributions in $t\bar{t}$ distributions

- 8, 13 TeV

  - 8 TeV data $(y(t), y(t\bar{t}))$ can be sensitive to the impact of the photon-induced contributions at experimentally reachable regions (NNPDFQED)

  - At 13 TeV, in p_T distributions EW corrections induce significant deviations w.r.t. the pure QCD ones (LUXqed)

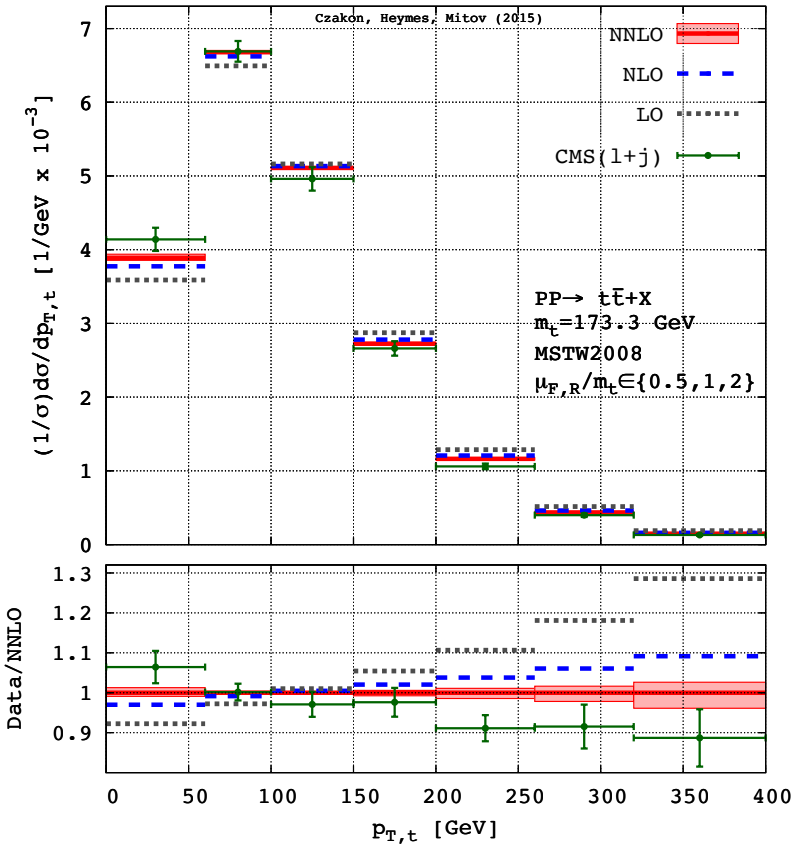
  - NNLO QCD are necessary in order to reduce the scale dependence

- Further research

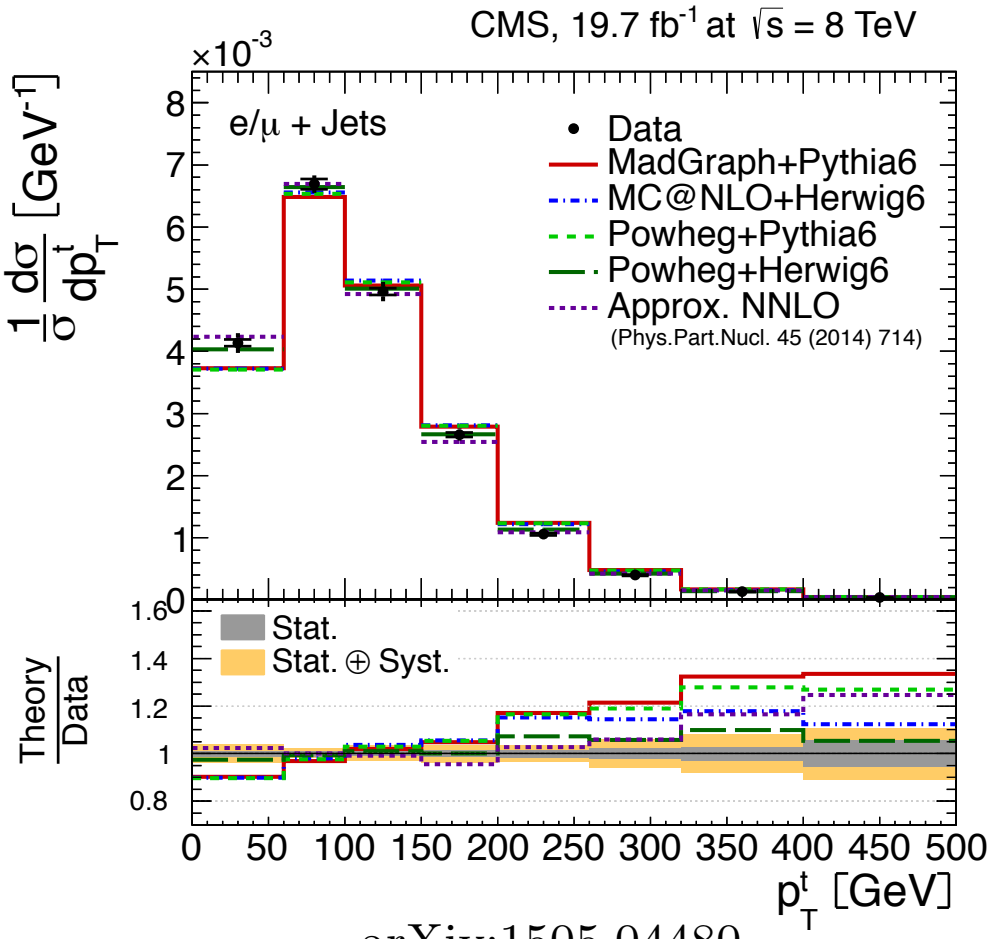
  - Additive vs multiplicative approach

  - $t\bar{t}$ asymmetry at NNLO QCD+NLO EW at 8 TeV

Theory vs data tension



arXiv:1511.00549



arXiv:1505.04480

- The p_T spectrum in data for top quarks is softer than expected

The photon PDF

- NNPDF2.3QED

  - No assumption for the $\gamma(x, Q^0)$ functional form

  - Different scales for QCD/QED evolutions

- 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)

- NNPDF3.0QED

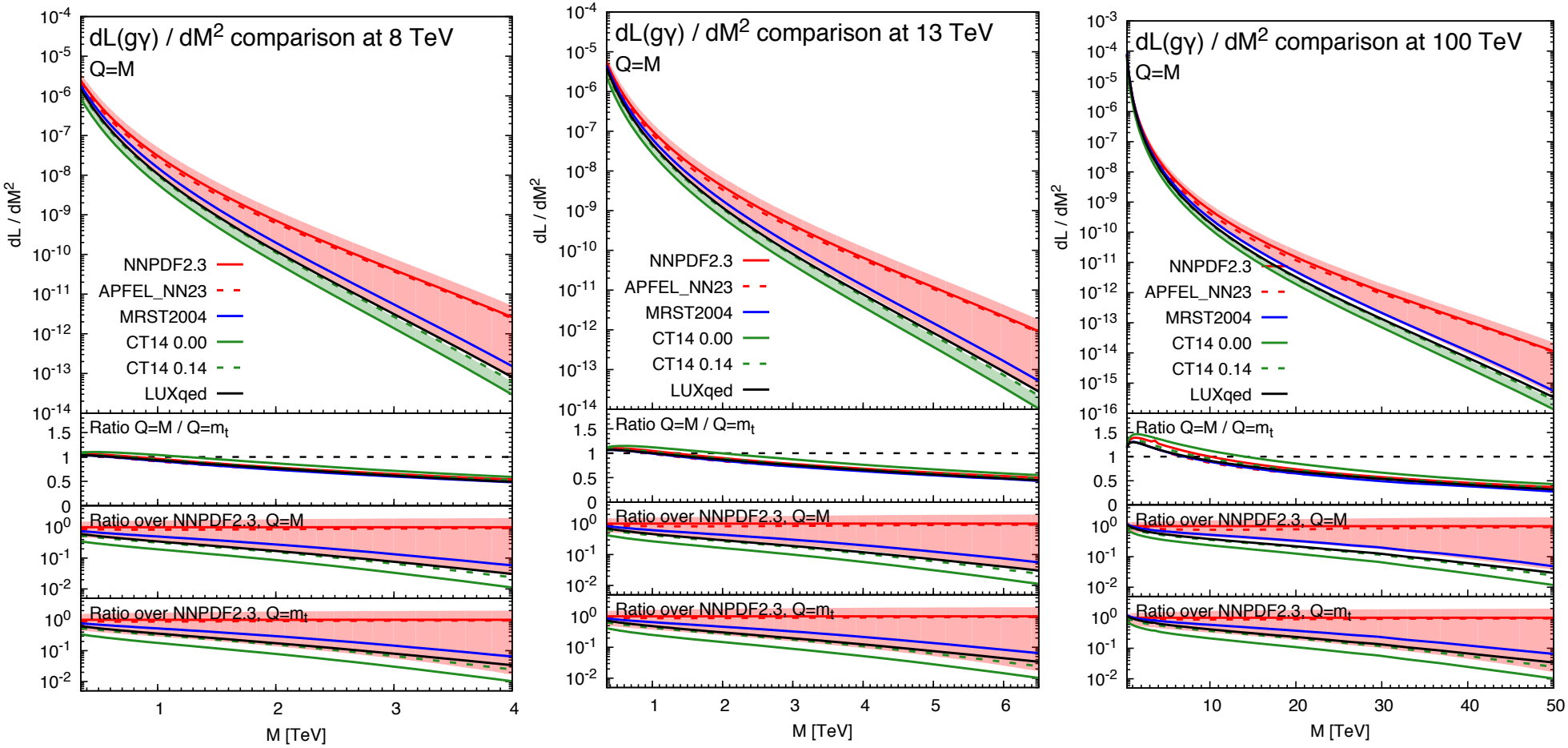
  - Simultaneous evolution of QCD/QED is implemented (also in APFEL_NN23), which changes the low x behaviour, but with no effect in $t\bar{t}$ phenomenology

- LUXqed

  - Match the Master formula with the Parton model formula $\sigma \rightarrow$ extract $\gamma(x, Q^0)$

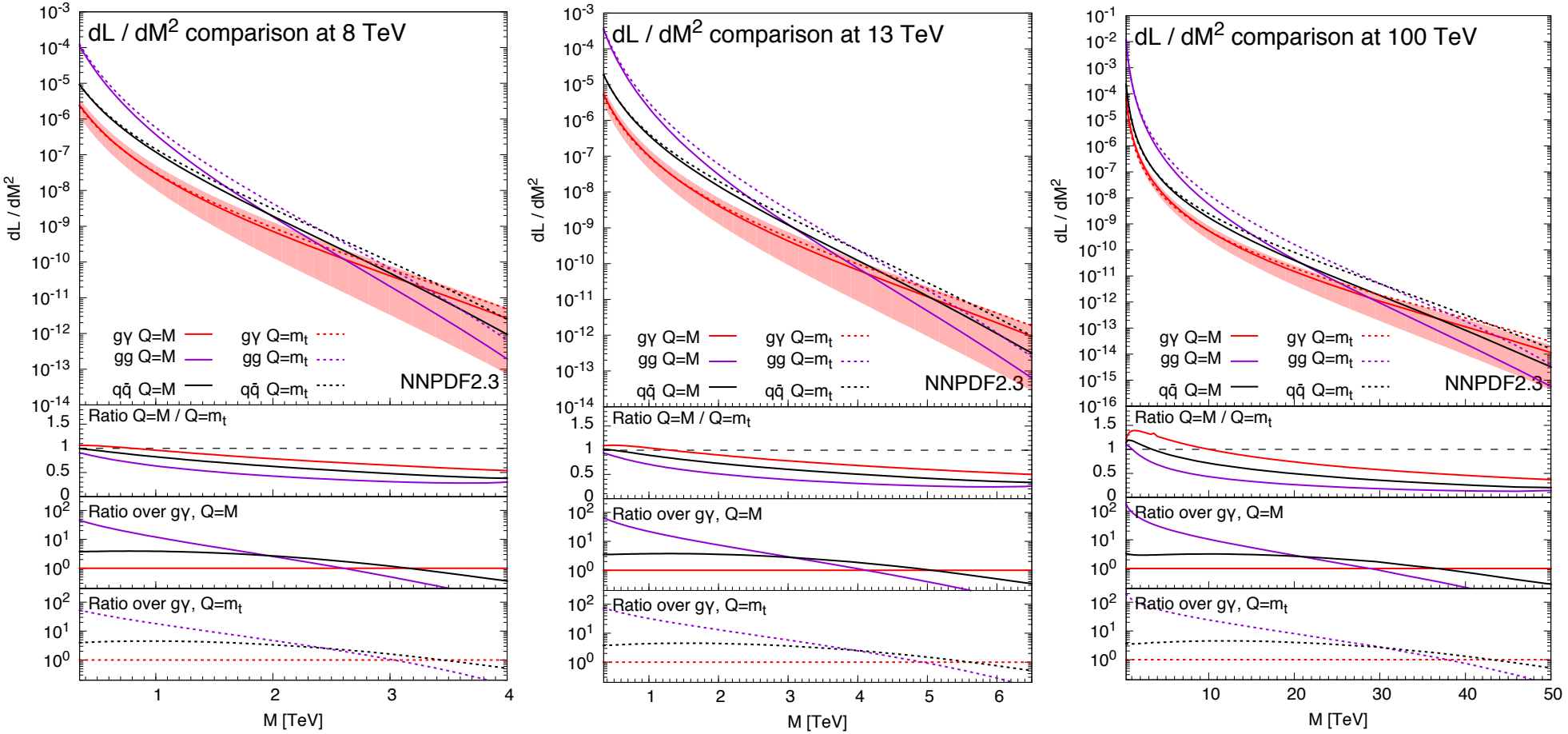
  - Splitting functions at $O(\alpha + \alpha_s \alpha)$

The $g\gamma$ Luminosity



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

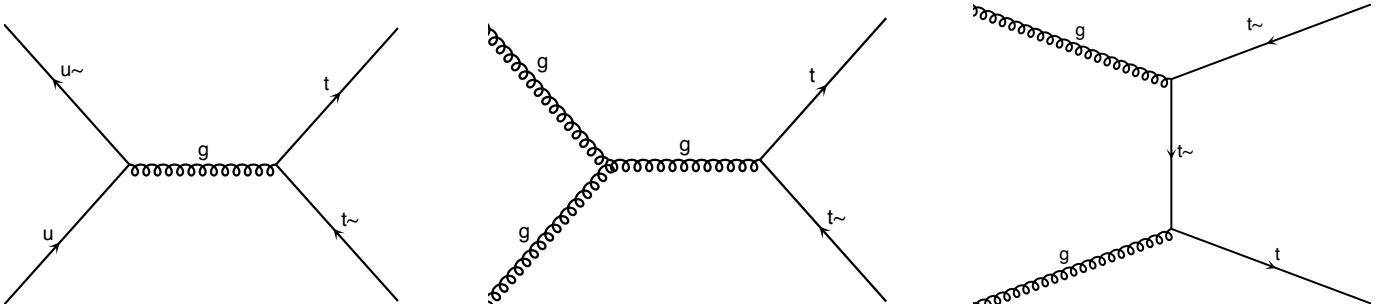
Parton Luminosities and scale choice



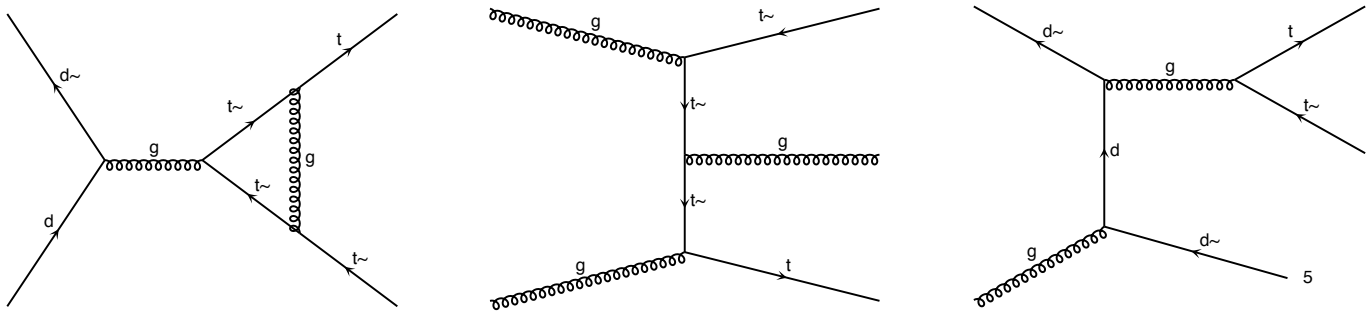
- In both dynamical and fixed scales the $g\gamma$ luminosity is suppressed with respect to the gg one at the low M region

Representative Feynman diagrams (QCD)

- LO QCD (α_s^2)

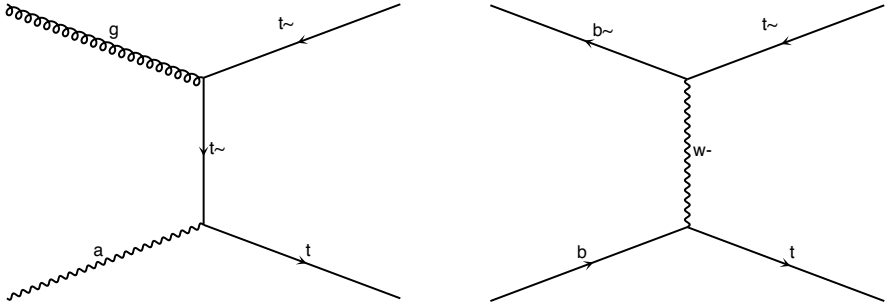


- NLO QCD (α_s^3)

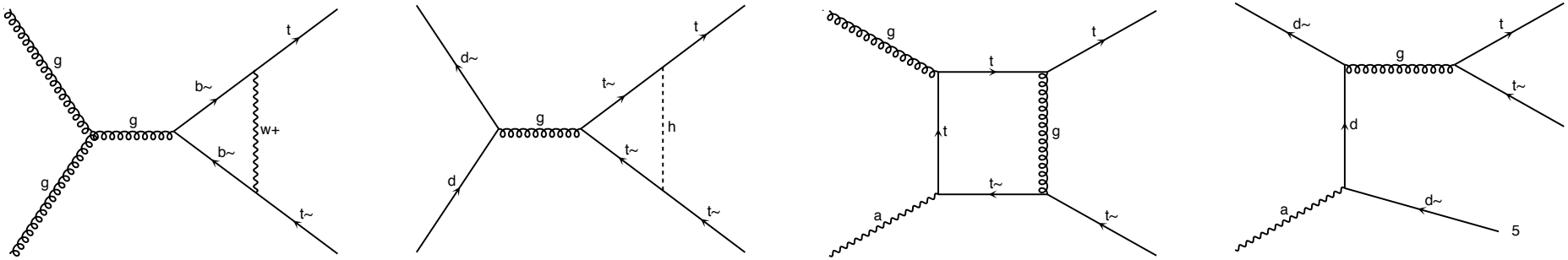


Representative Feynman diagrams (EW)

- LO EW ($\alpha_s \alpha$)

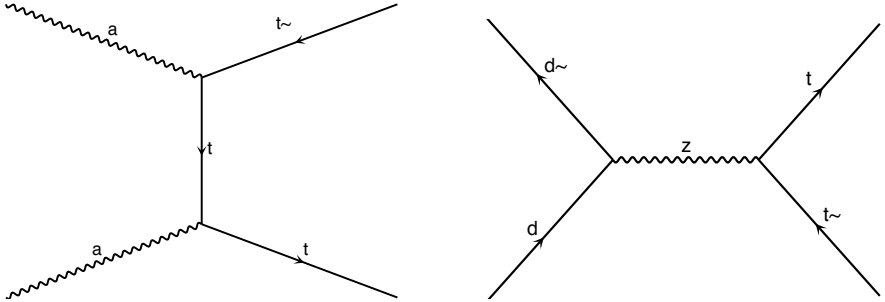


- NLO EW ($\alpha_s^2 \alpha$)

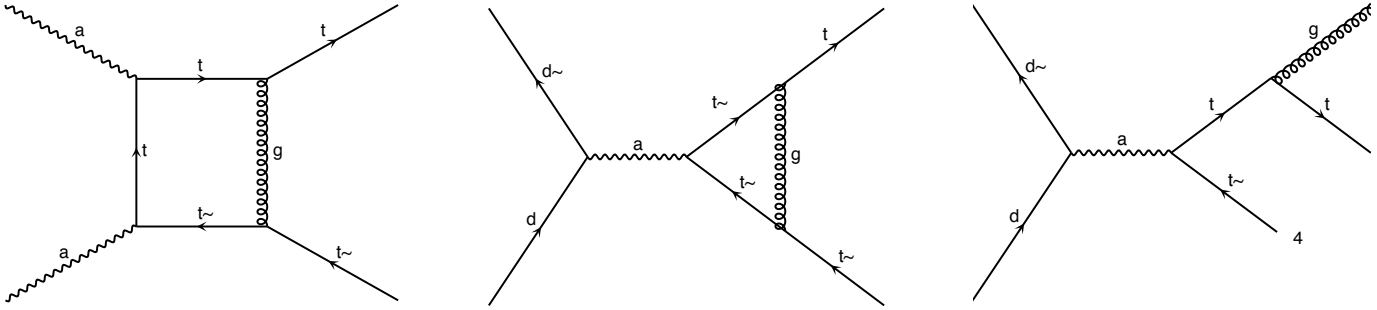


Representative Feynman diagrams (sub EW)

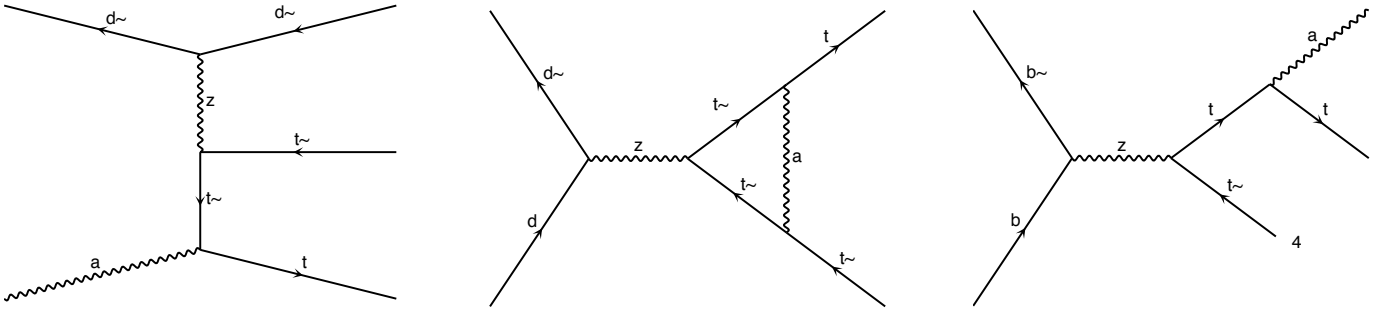
- LO3 (α^2)



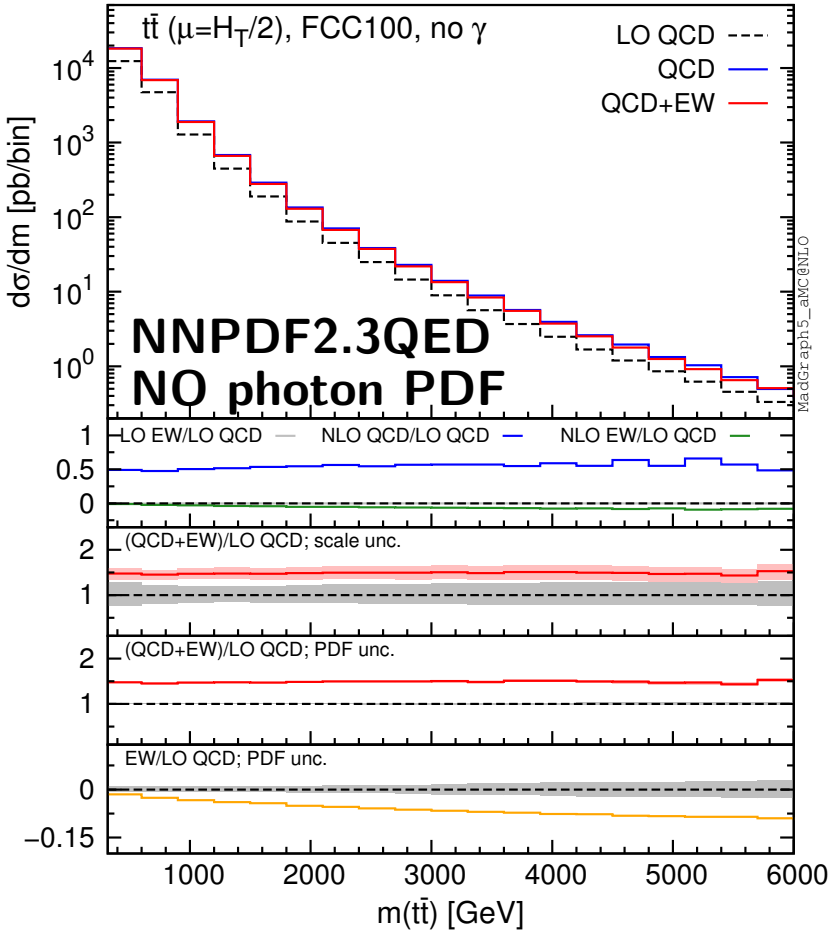
- NLO3 ($\alpha_s\alpha^2$)

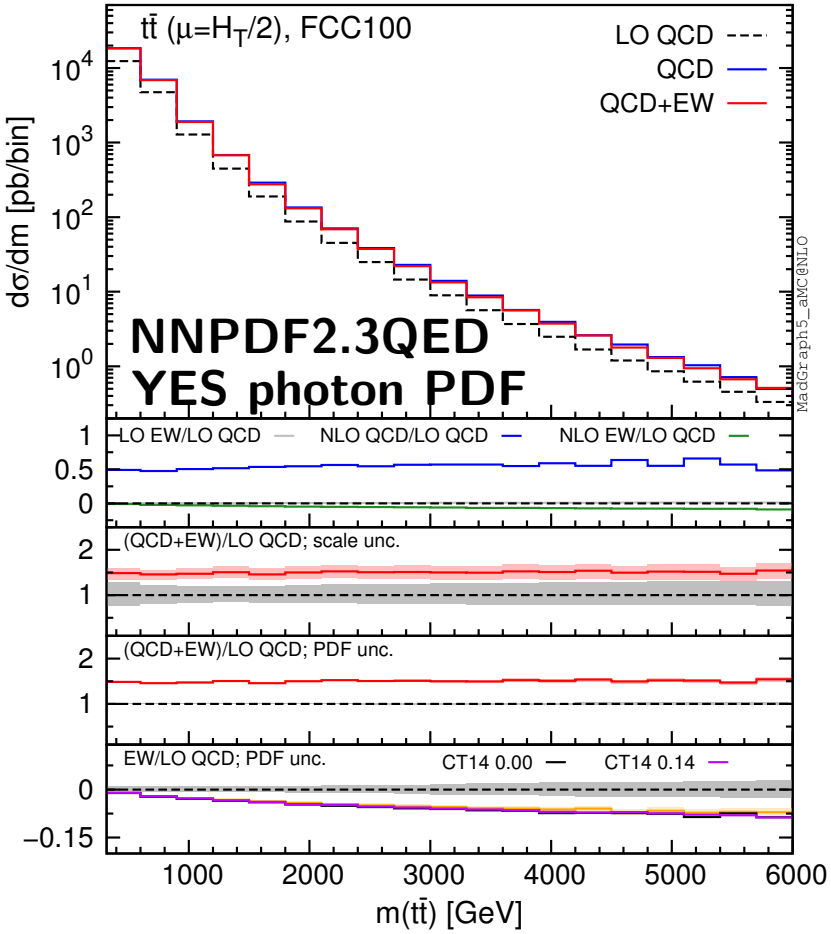


- NLO4 (α^3)



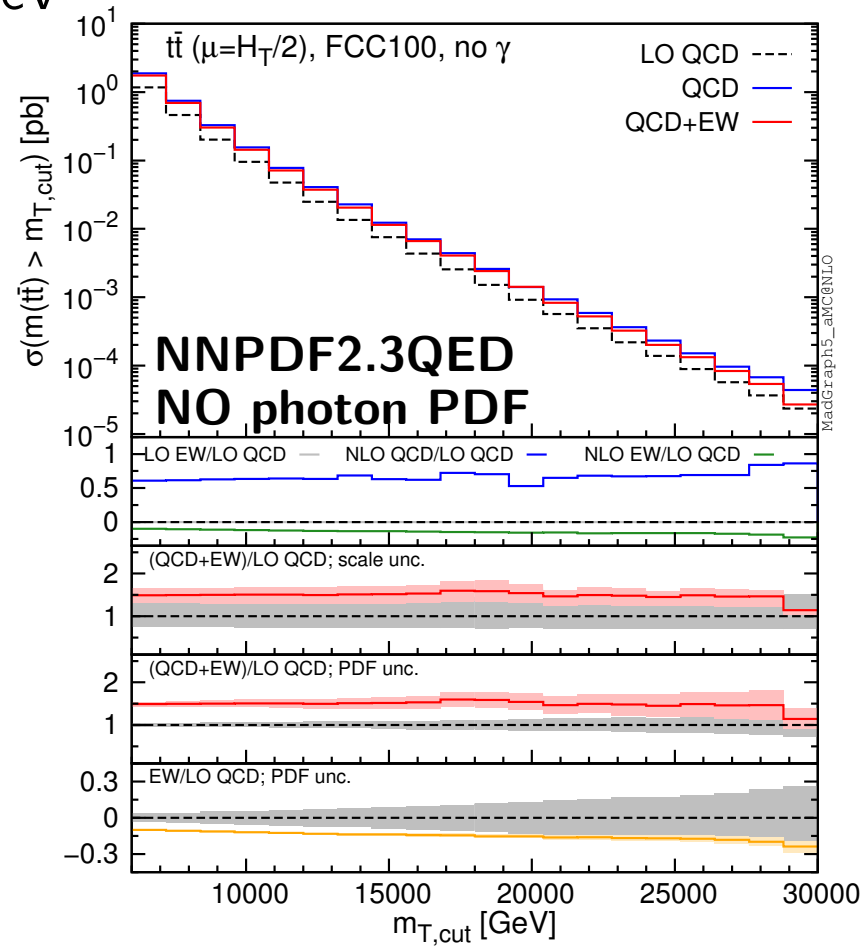
100 TeV

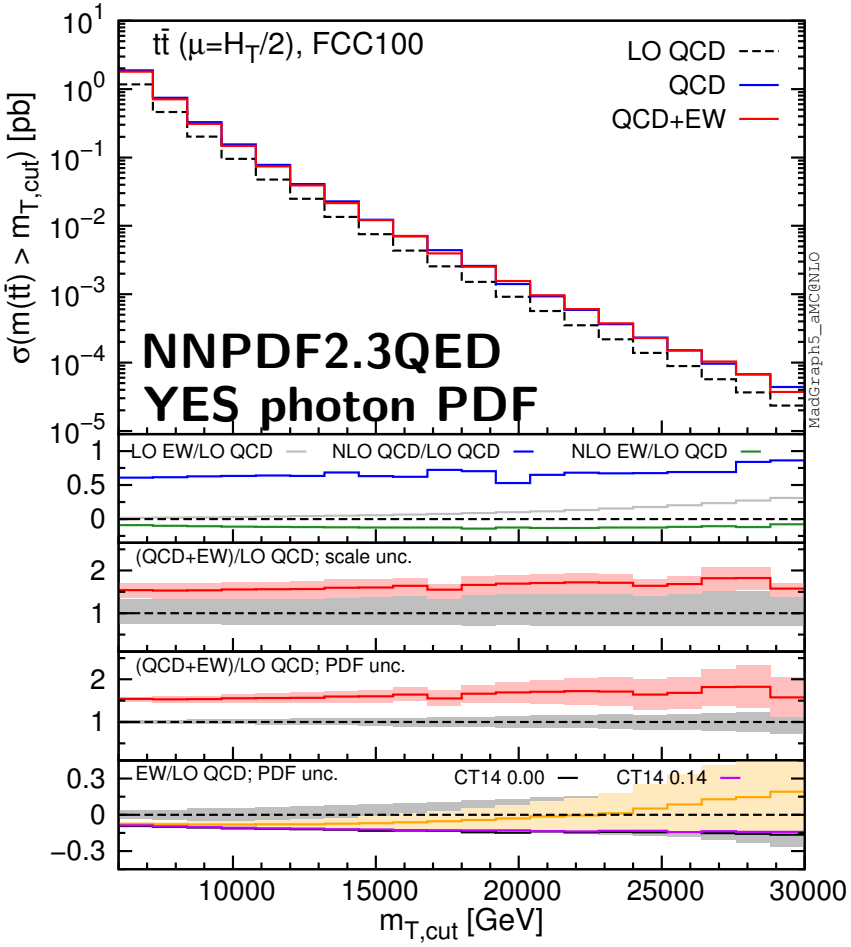




- At 100 TeV $t\bar{t}$ differential distributions are not sensitive to photon-induced contributions
- $\sqrt{s} \uparrow \Longrightarrow$ Bjorken x's $\downarrow$

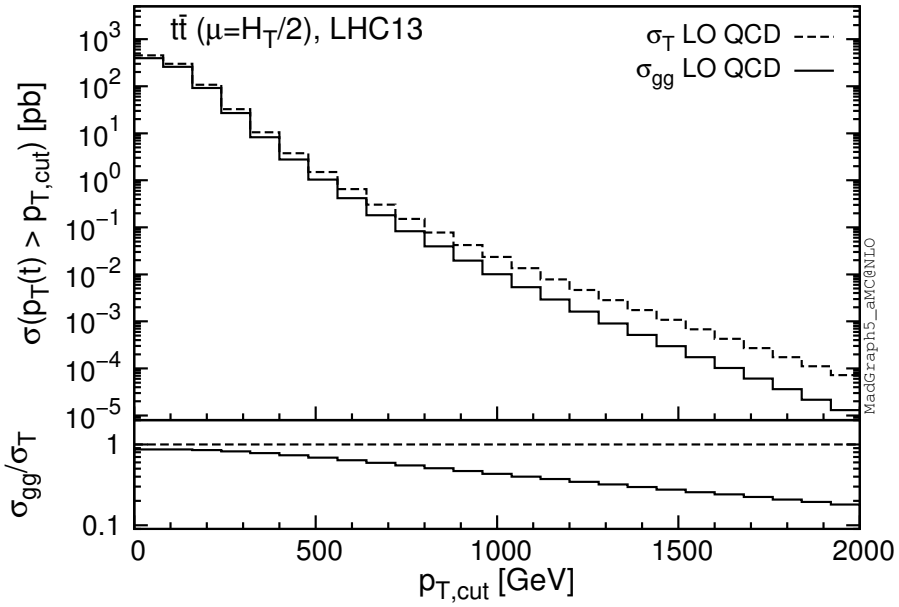
100 TeV

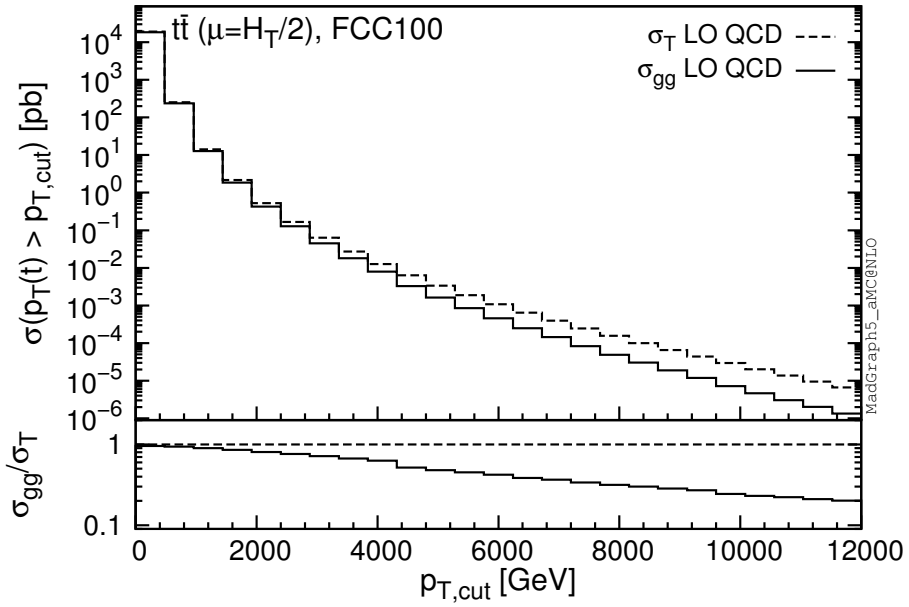




- The effect of the photon-induced contributions becomes visible only at very high $m(t\bar{t})$ (and $p_T(t)$) regions
- Larger effects are expected at 8 TeV, where already we have data

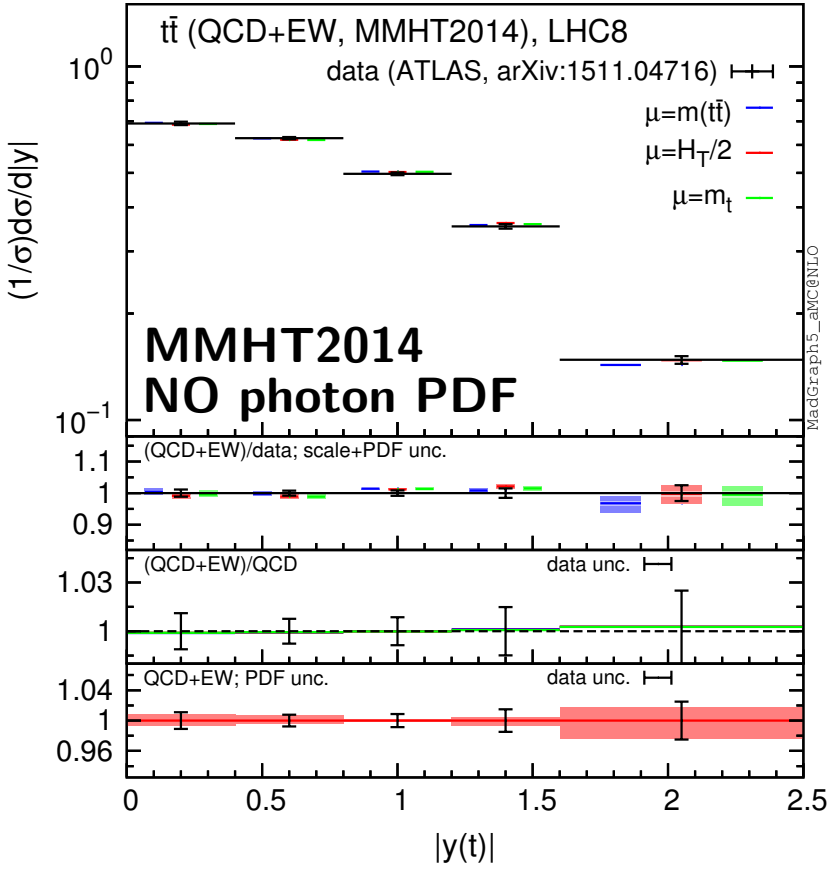
LHC13, FCC100, σ_{gg}/σ_T vs p_T

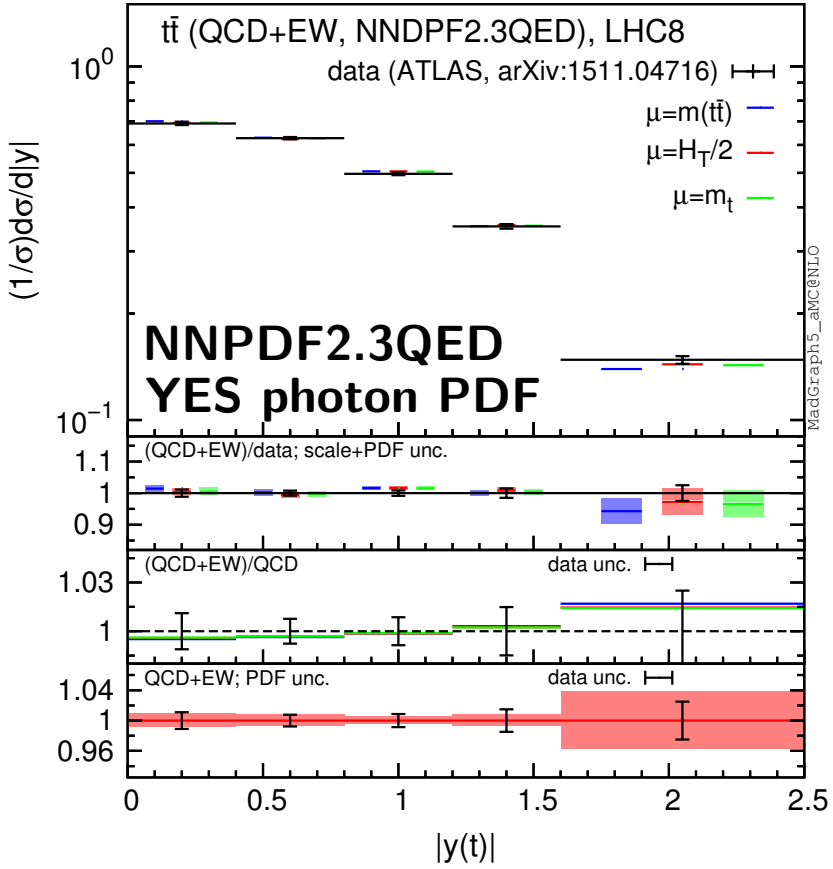




- $p_T \uparrow \Longrightarrow$ tops are central $\Longrightarrow s-$channel favoured $\Longrightarrow \dfrac{\sigma_{q\bar{q}}}{\sigma_{gg}} \uparrow \Longrightarrow K-$factor$\downarrow$

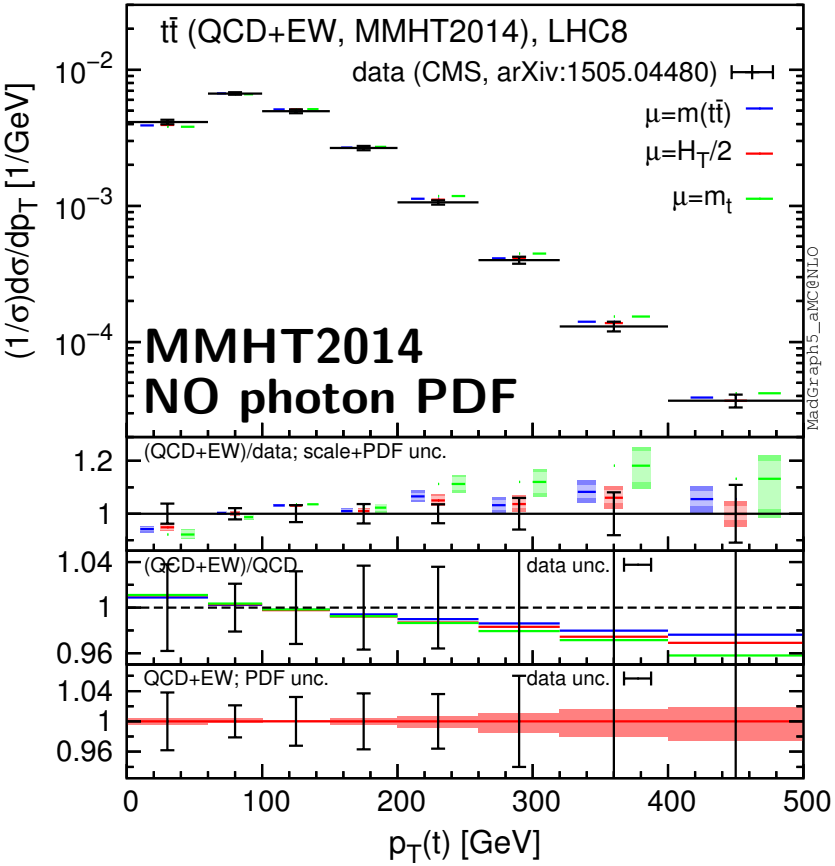
8 TeV

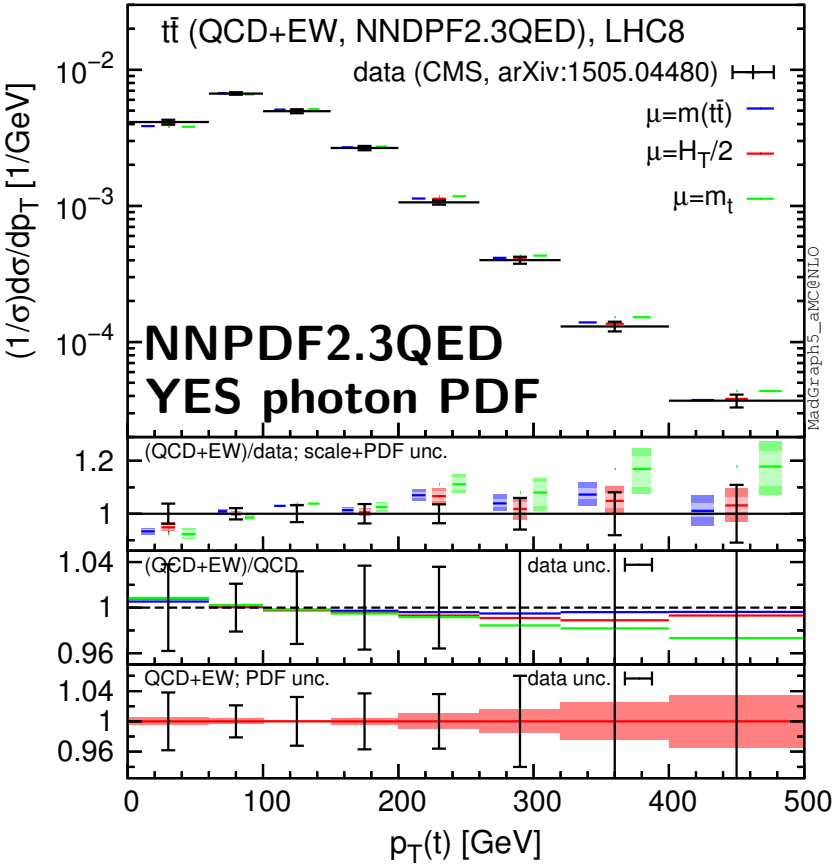




- Normalised $(1/\sigma)$ rapidity distributions $\rightarrow$ Exp. errors reduce at few % level.
- Large PDF uncertainties and visible impact of photon PDF (NNPDF2.3QED)
- Can be used for constraining the photon PDF (NNPDF2.3QED)

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

Multiplicative approaches

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

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

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

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