Electroweak corrections at the LHC: the contribution of photons

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Photon 2017

CERN

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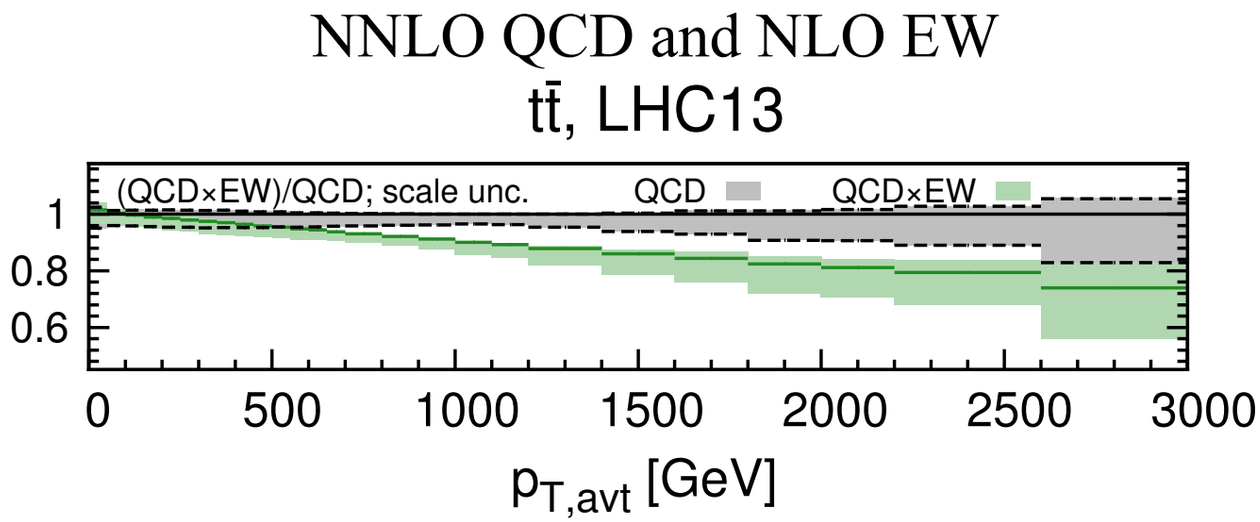
EW corrections at the LHC

The precision reached in the measurements of SM processes at the LHC has made both higher-order **QCD and EW corrections** unavoidable ingredients for a correct comparison of theory vs. experiment.

Whenever **NNLO QCD corrections** are relevant, **EW corrections cannot be neglected,** since they are expected to have a **similar size:** $\alpha_s^2 \sim \alpha$.

Moreover, in the **boosted regime** EW corrections include **negative Sudakov enhancements:** $-\frac{\alpha}{4\pi s_W^2}\log^2\frac{s}{M_W^2}$



Czakon, Heymes, Mitov, DP, Tzinikos, Zaro '17

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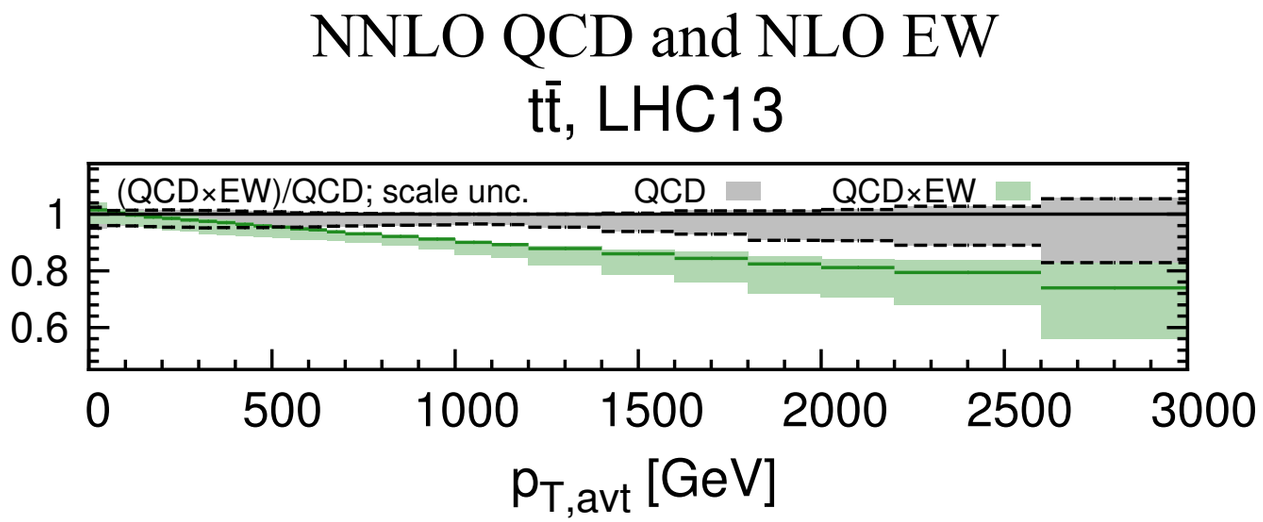


Czakon, Heymes, Mitov, DP, Tzinikos, Zaro '17

In this talk I will **not** focus on weak effects, such as the Sudakov logs, however, they are the **dominant contribution** in EW corrections at large transverse momenta.

Automation of NLO QCD and NLO EW

Modern calculations of leading photon effects are typically performed within the **complete** calculation of **NLO EW** (+ NLO QCD) corrections.

NLO EW (semi-)**automated calculations** have become available in the recent years, shifting the attention on their **phenomenological** impact.

MoCaNLO+Recola	$pp \to ll$ + 2 jets	[1411.0916]
	$pp \to e^+e^-\mu^+\mu^-$ / $\mu^+\mu^-\,\mu^+\mu^-$	[1601.07787] [1611.05338
	$pp \to e^+\nu_e\mu^-\nu_\mu$	[1605.03419]
	$pp \to (t\bar{t}) \to e^+\nu_e\mu^-\nu_\mu\, b\bar{b}$	[1607.05571]
	$pp \to e^+\nu_e\mu^-\nu_\mu$ + 2 jets (VBS)	[1611.02951]
	$pp \to (t\bar{t}H) \to e^+\nu_e\mu^-\nu_\mu\, b\bar{b}H$	[1612.07138]
Sherpa/Munich+OpenLoops	$pp \to W$+1,2,3 jets	[1412.5156]
	$pp \to ll/l\nu/\nu\nu$ + 0, 1, 2 jets	[1511.08692]
	$pp \to ll\nu\nu$	[1705.00598]
MadGraph_aMC@NLO +MadLoop	$pp \to tt$+H/Z/W	[1504.03446]
	$pp \to t\bar{t}$	[1606.01915] [1705.04105]
	$pp \to$ 2 jets	[1612.06548]
MadDipole+GoSam	$pp \to W$+2 jets	[1507.08579]

- many NLO QCD+EW calculations for multi-particle processes are becoming available
- NLO QCD+EW matching and merging with parton showers is under way (approximations available)

Slide taken from J. Lindert talk at LHCP2017, Shanghai

Leading photon effects in EW corrections

EW = Weak + QED *

QED → effects from photons

There are two different QED effects that can give large corrections:

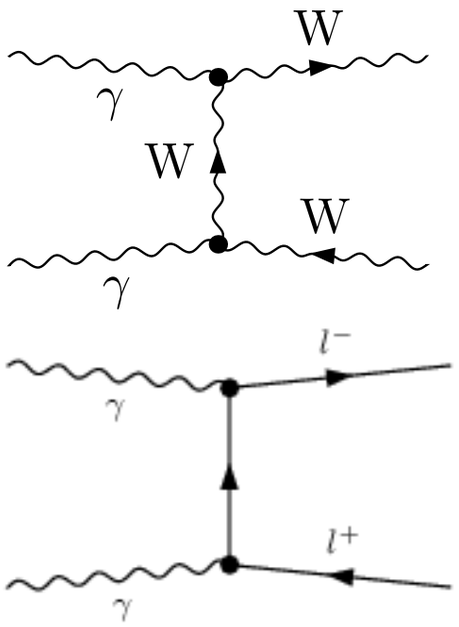
- ***Final State Radiation (FSR)***
  In sufficiently exclusive observable FSR induces corrections $\sim \alpha \log\left(\frac{m_f^2}{Q^2}\right)$.
  Photon-quark recombination reduces the size of this effect.

- ***Photon PDF***
  The photon PDF adds new partonic processes with initial-state photons.
  Different photon-PDF parametrizations lead to very different results.
  Effects due to the photon PDF are relevant not only at NLO EW

* for a generic process this separation is not gauge invariant

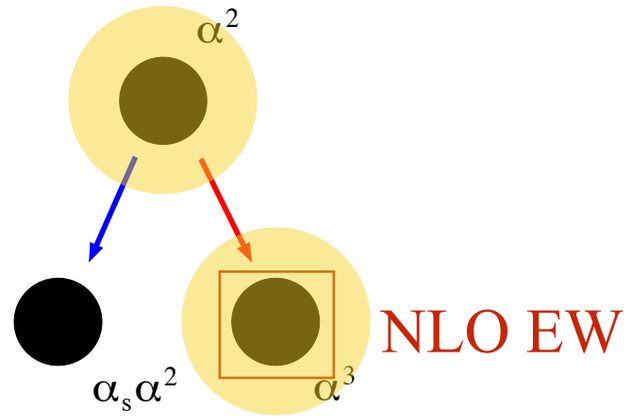
Photon PDF entering at different perturbative orders

WW, Drell-Yan

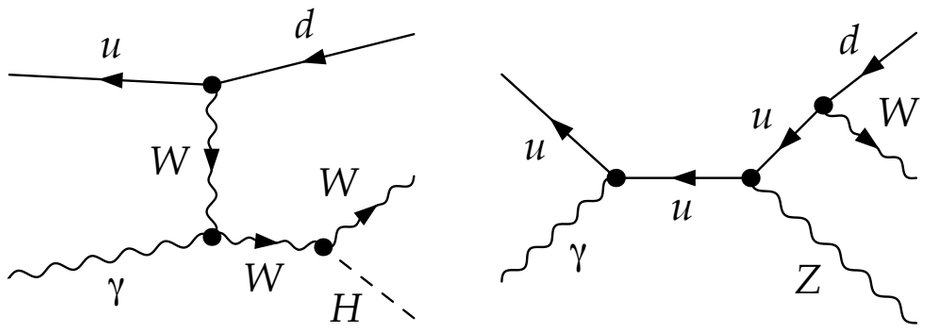


LO

NLO

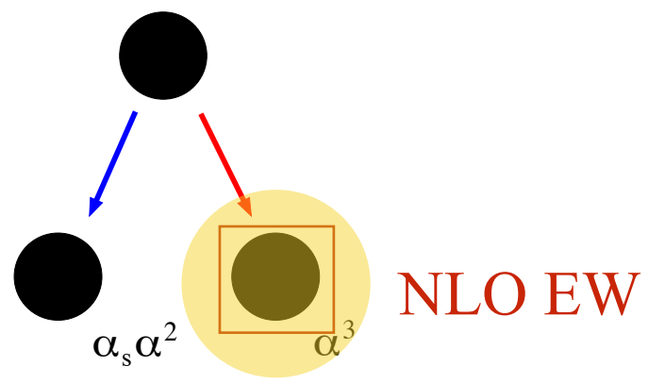


ZZ, ZW, HZ, HW

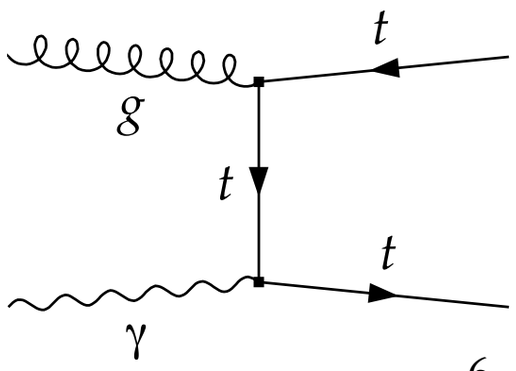


LO

NLO

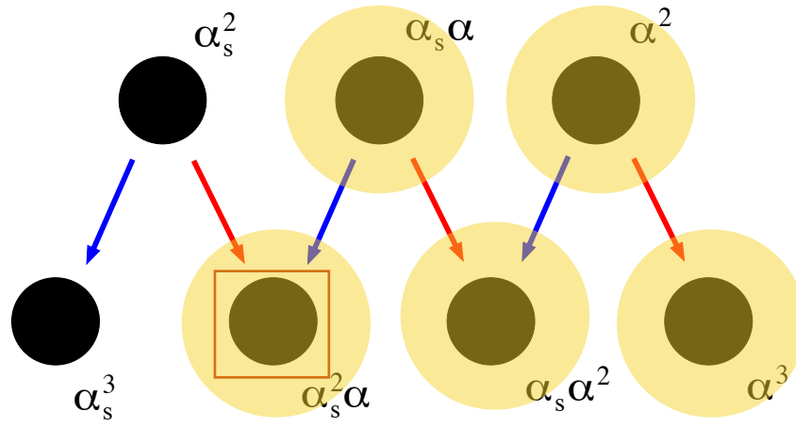


$t\bar{t}$



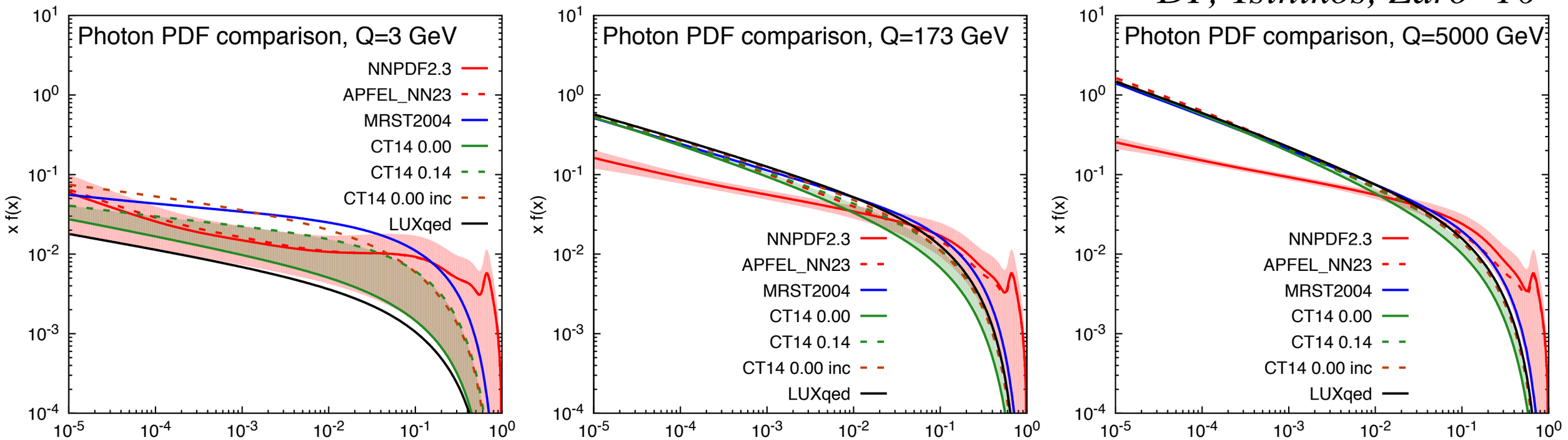
LO

NLO

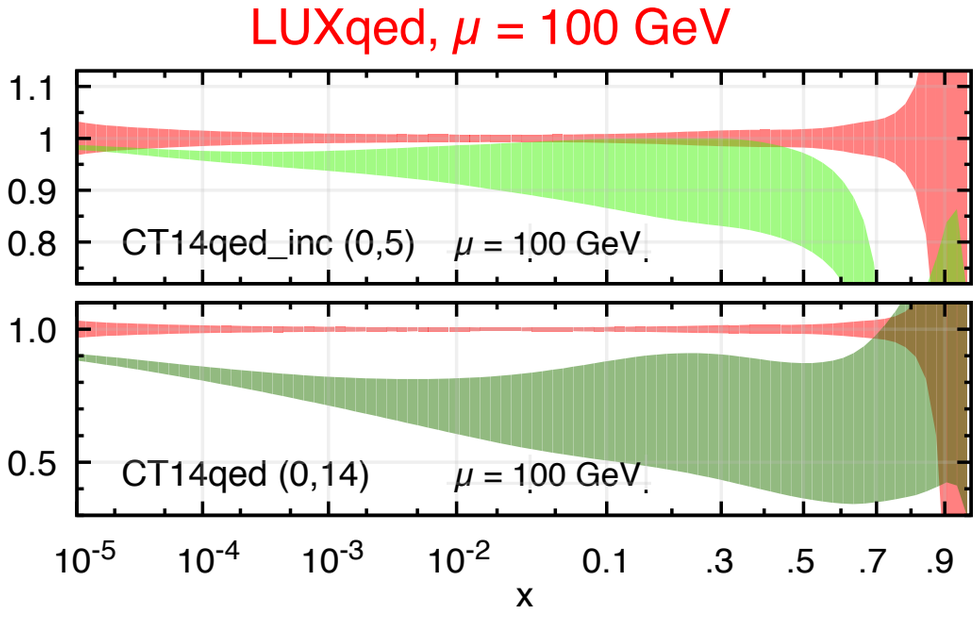


The different photon PDFs

DP, Tsinikos, Zaro '16



- In **LUXQED** the photon PDF has a **much smaller error** than in other PDF sets.
- Its central value at large x is much smaller than in the photon from NNPDF.



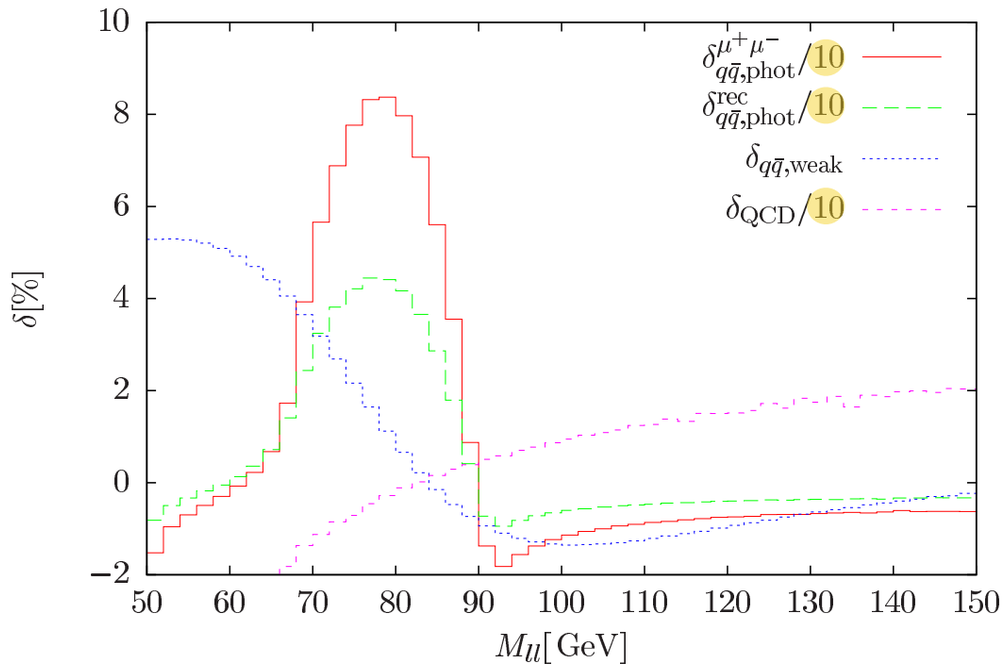
See also Talk of G. Zanderighi

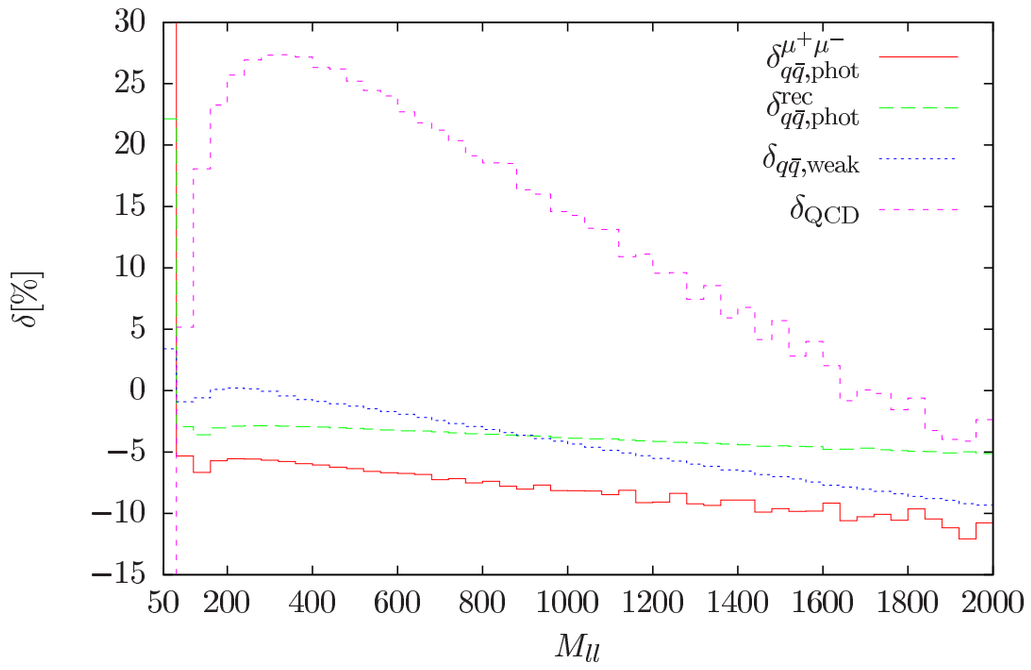
Manohar, Nason, Salam, Zanderighi '16

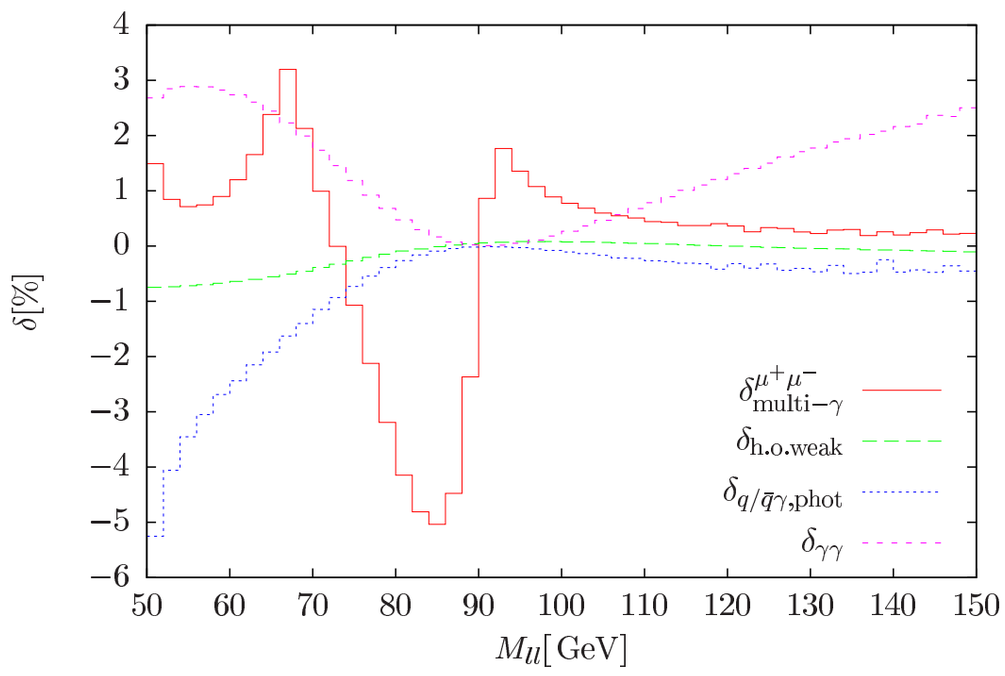
Drell-Yan

See also Talk of C. Schwinn

Drell-Yan (Z)







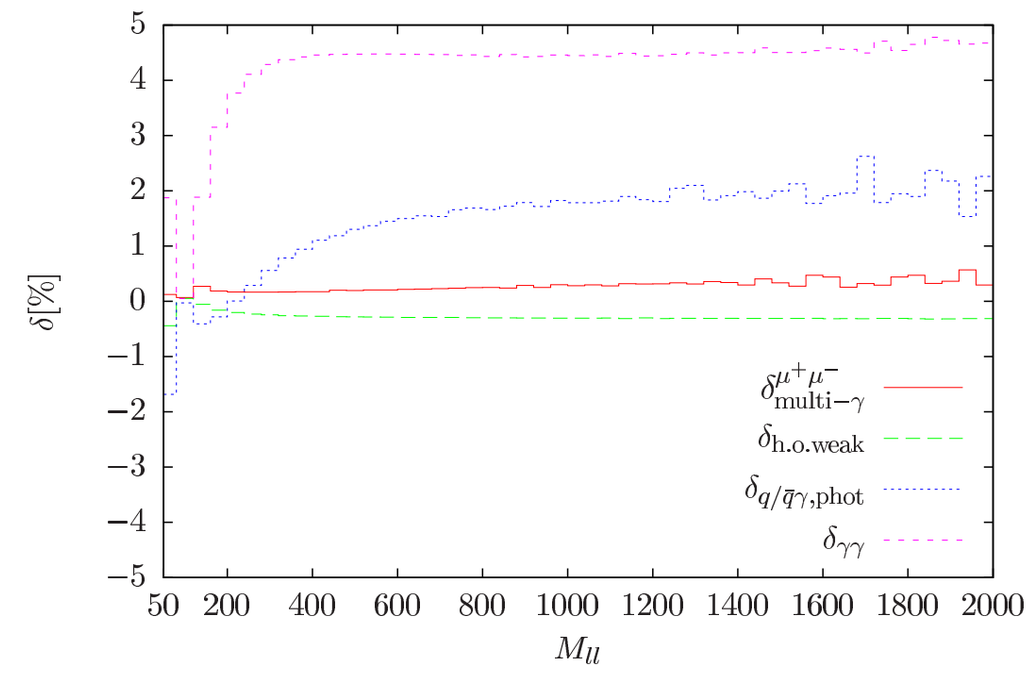
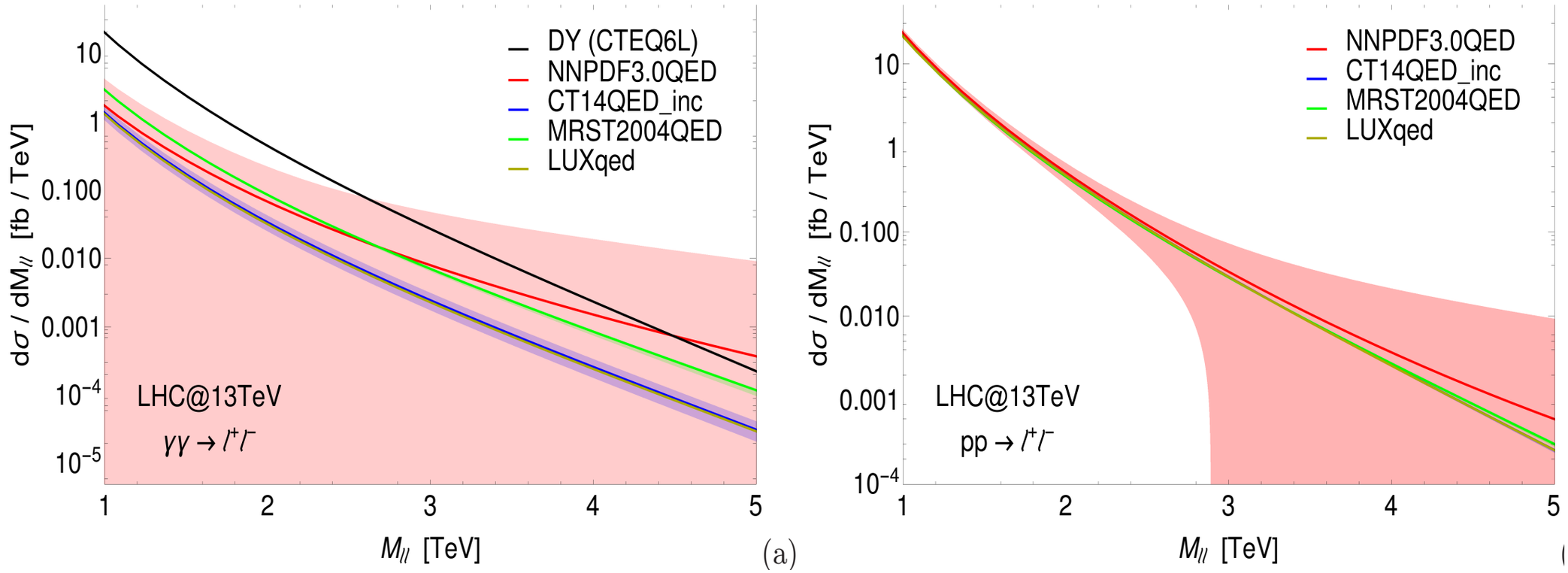


Figure 12: Dilepton invariant-mass distribution and correction factors at the LHC in the resonance region (left) and the high-invariant-mass region (right).

Dittmaier, Huber '10

Drell-Yan (Z)

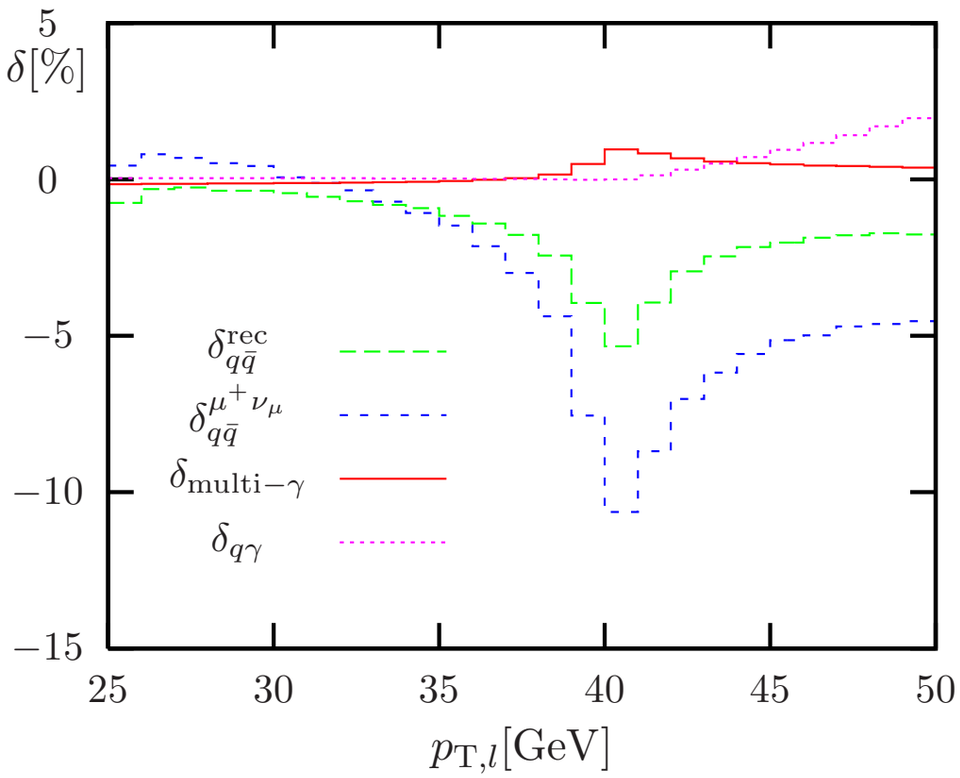


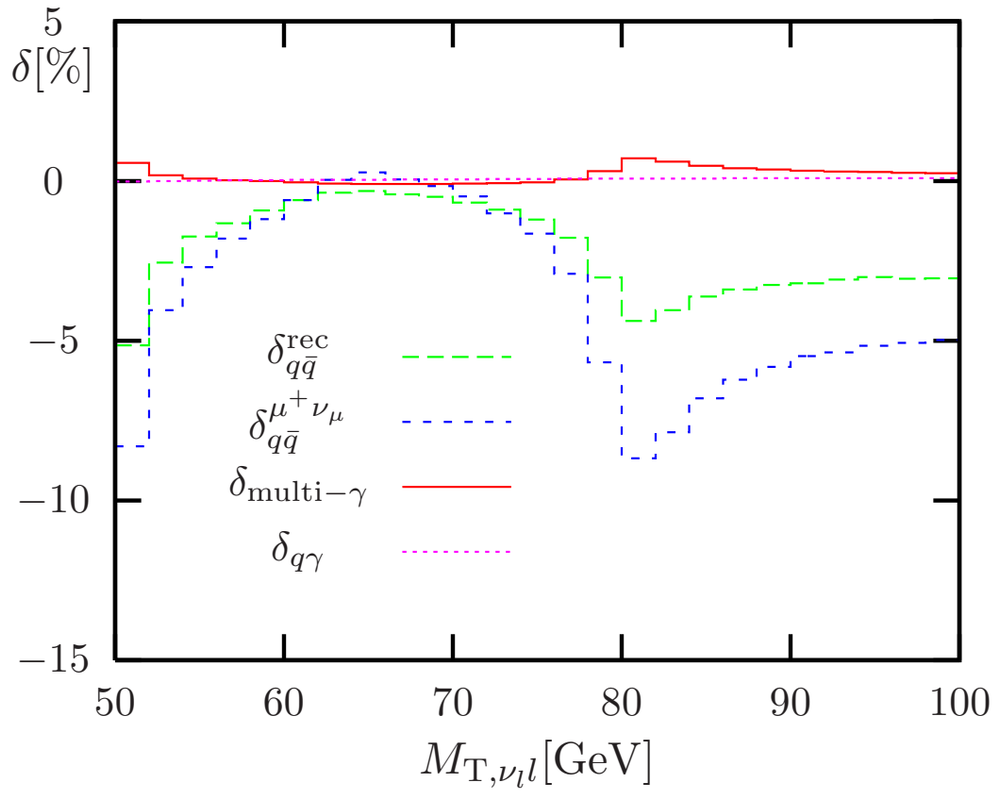
Accomando, Fiaschi, Hautmann, Moretti, Shepherd-Themistocleus '17

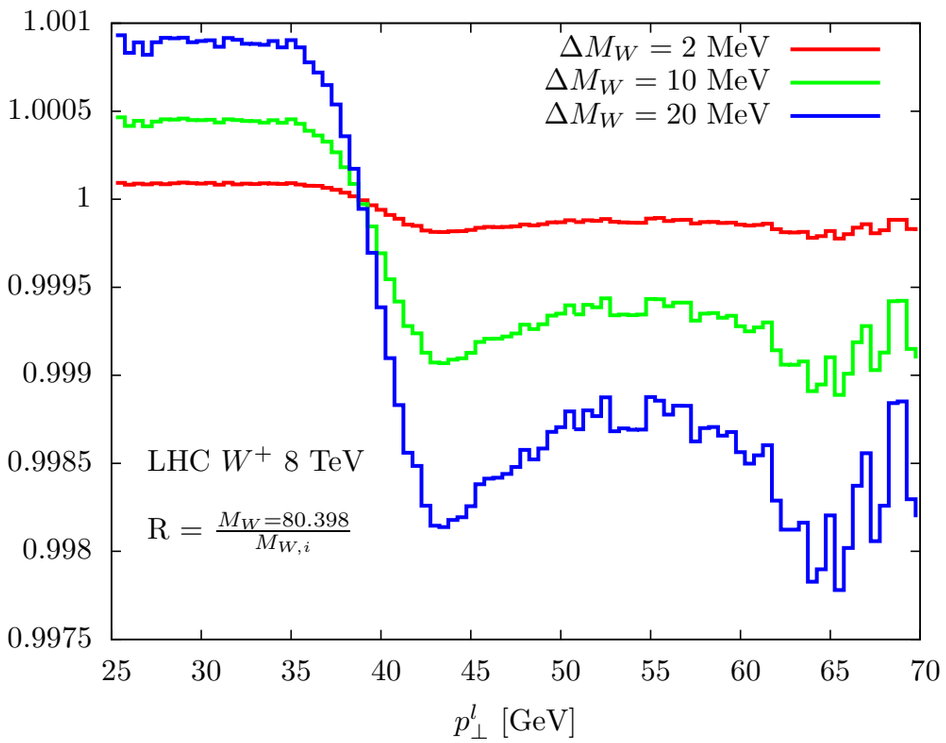
Invariant mass distribution strongly depends on the photon PDF parametrization.

Drell-Yan (W)

Brensing, Dittmaier, Krämer, Mück, '08







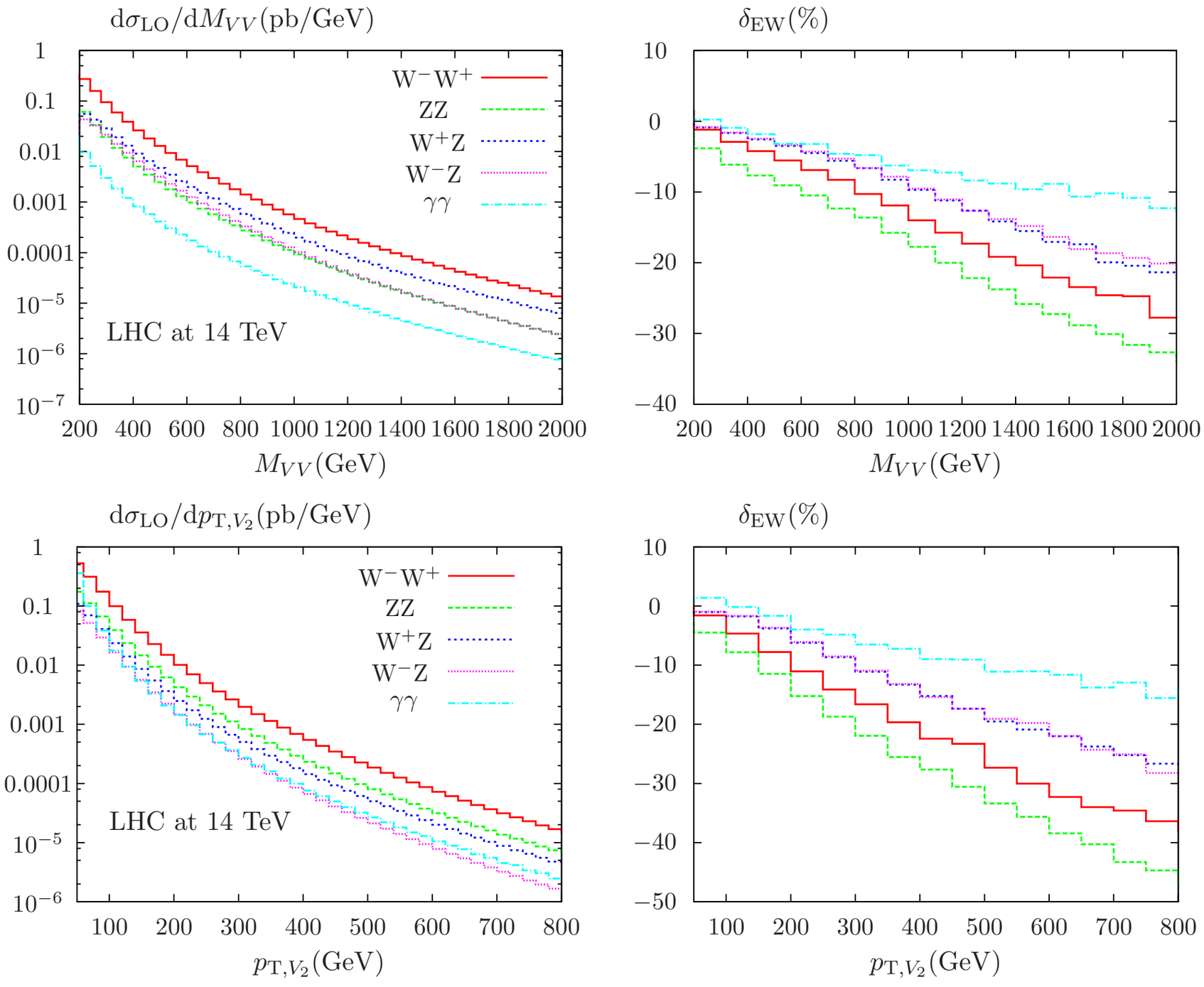
We need accuracy at permill level for the determination of W mass with an uncertainty ~ 10-20 MeV

Bozzi, Citelli, Vicini '15

VV, V=W, Z

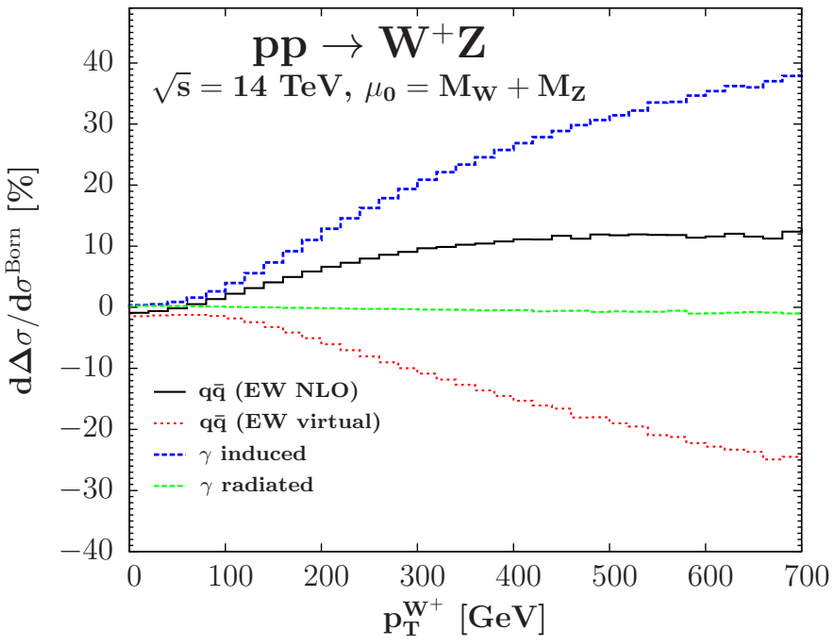
ZZ, WZ, WW (neglecting photon PDF)

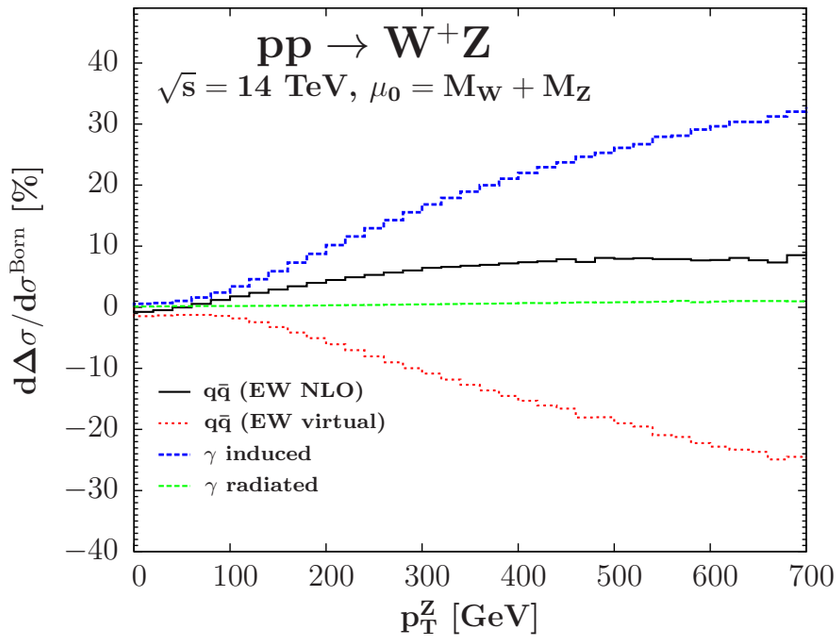
$$p_{\mathrm{T},V_i} > 15\ \mathrm{GeV}\,, \quad |y_{V_i}| < 2.5\,, \quad i = 1,2\,,$$

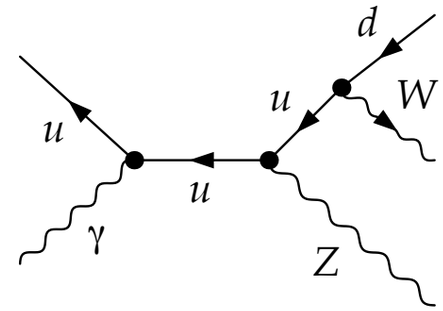


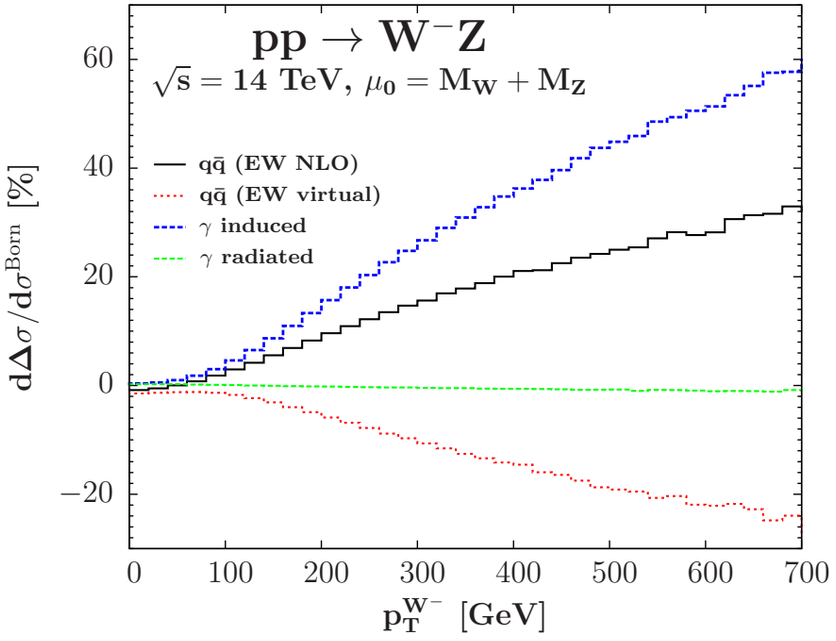
Bierweiler, Kasprzik, Kühn '13

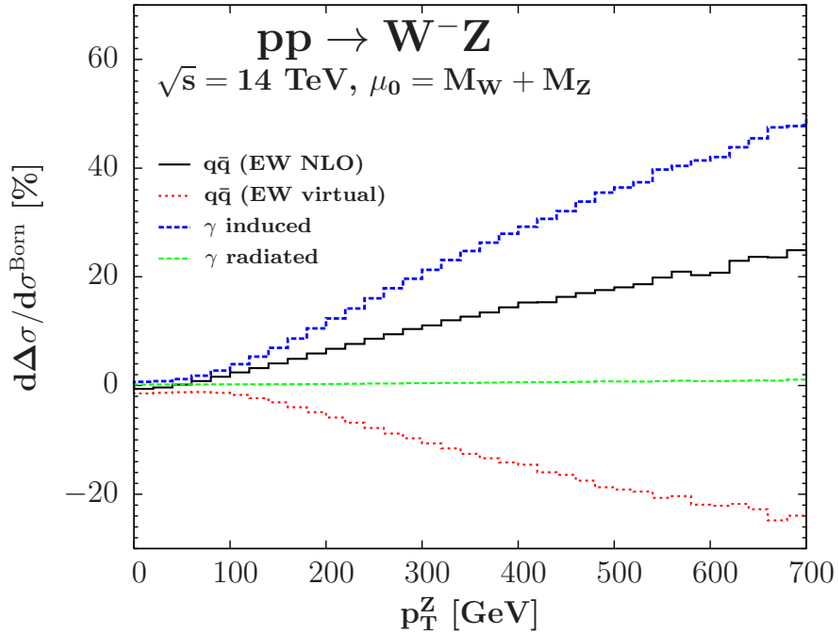
WZ









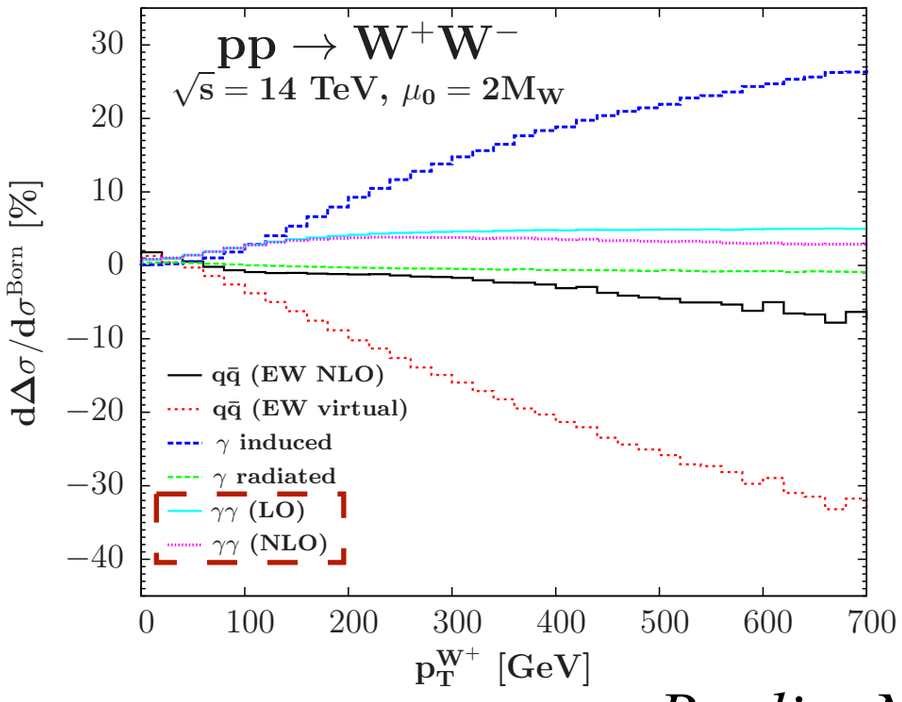


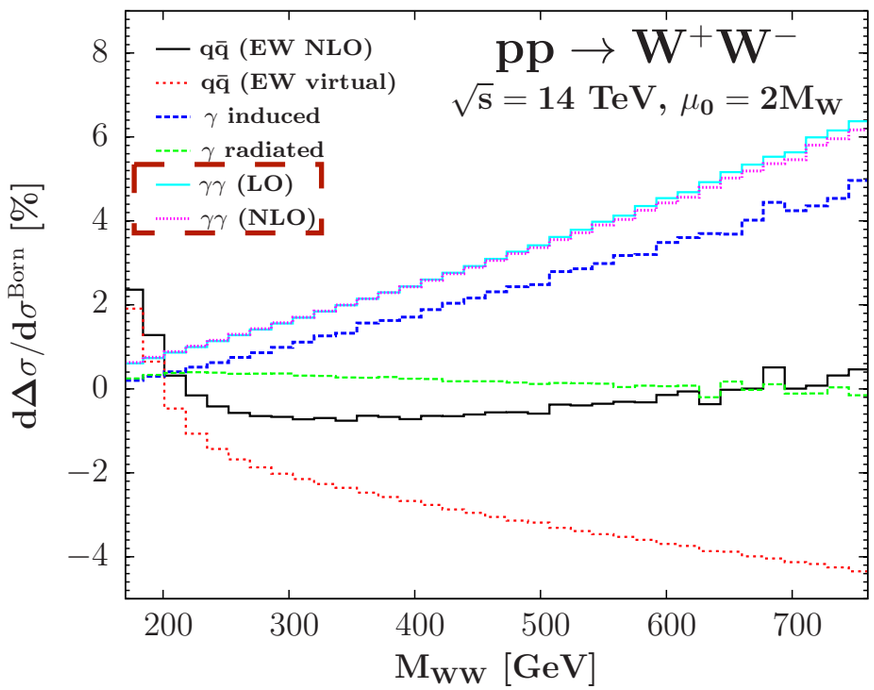
Baglio, Ninh, Weber '13

NLO EW:

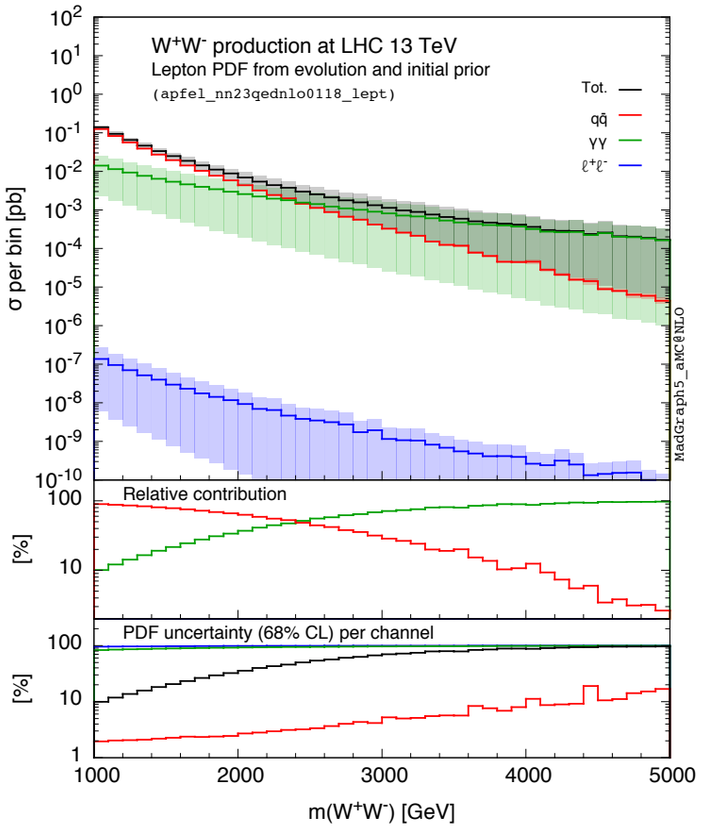
Sudakov logs are compensated by the γq initial-state contribution.

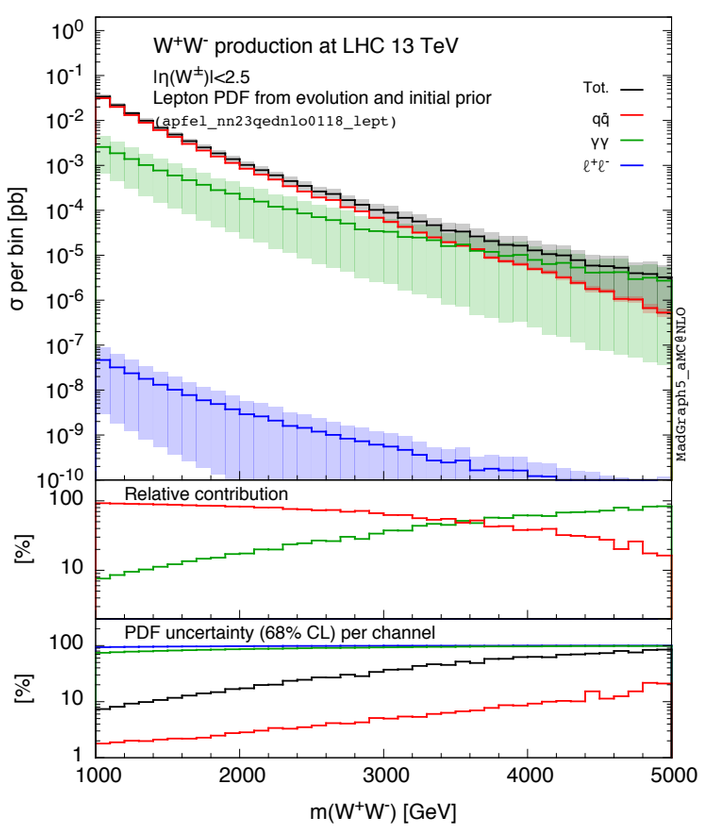
WW



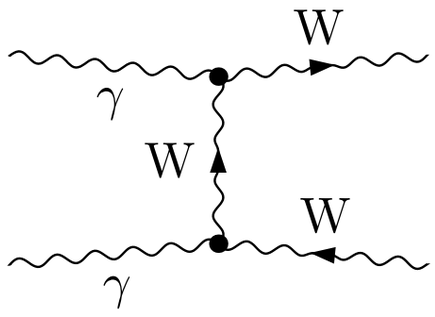


Baglio, Ninh, Weber '13





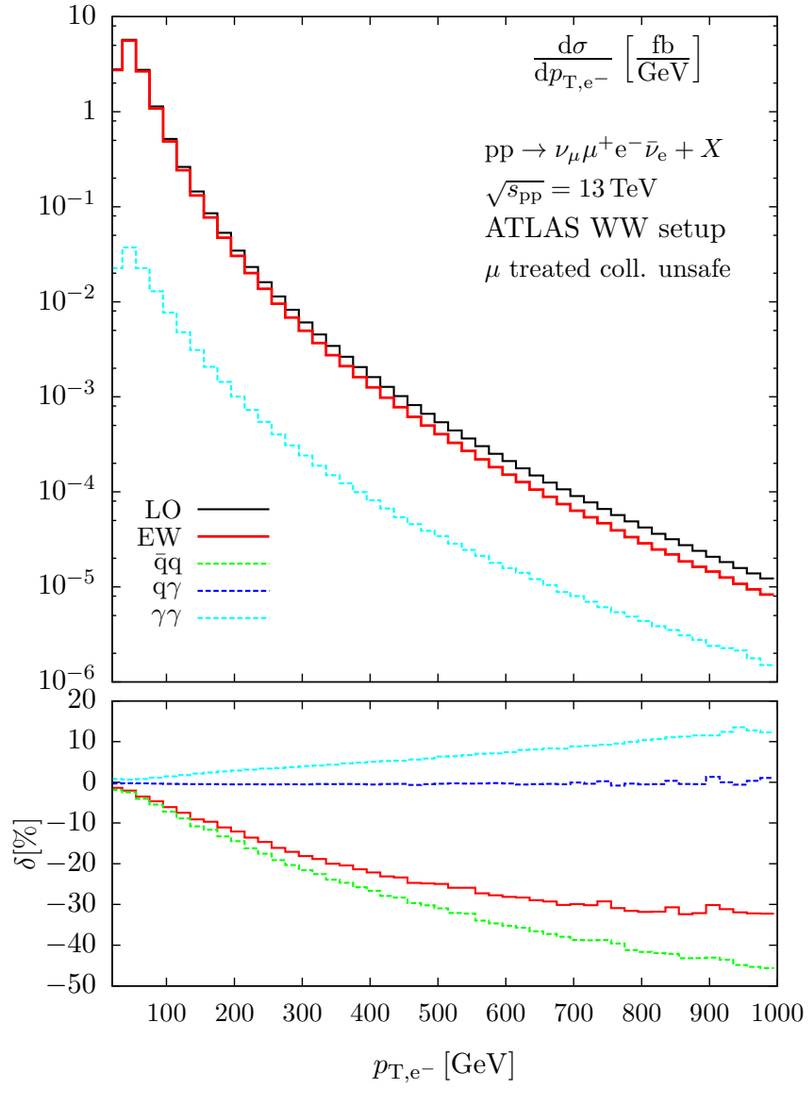
Photons at LO and NLO EW

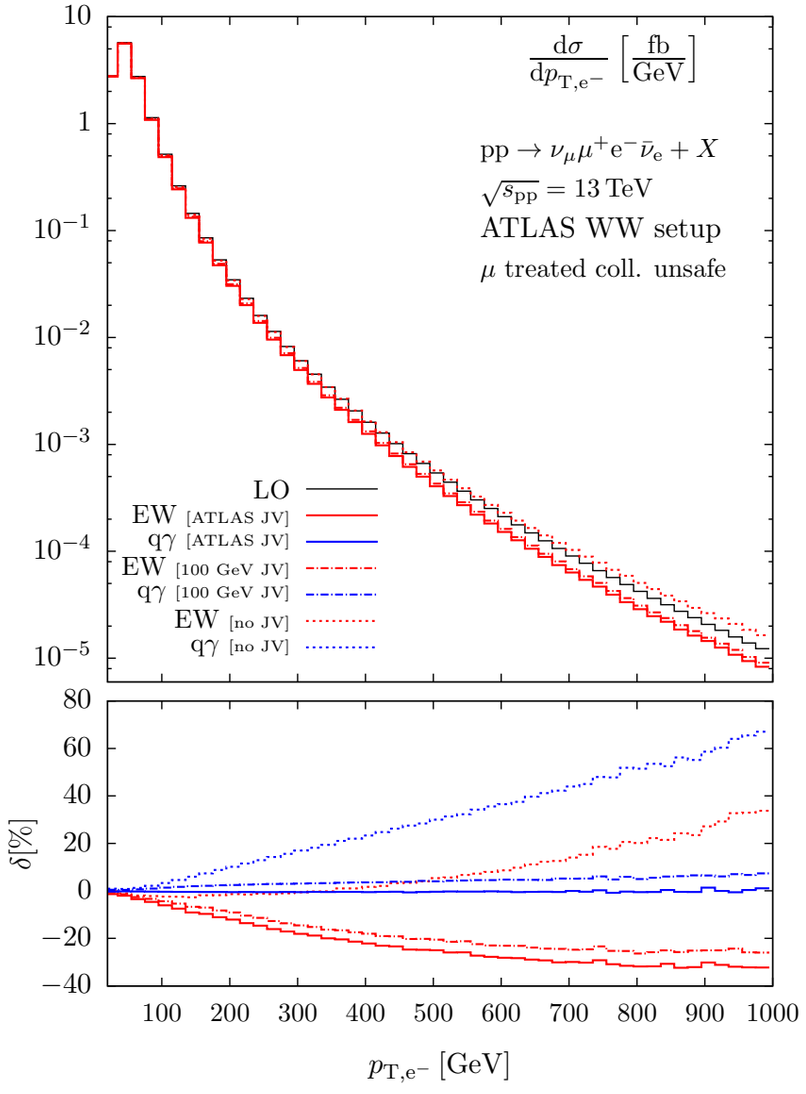


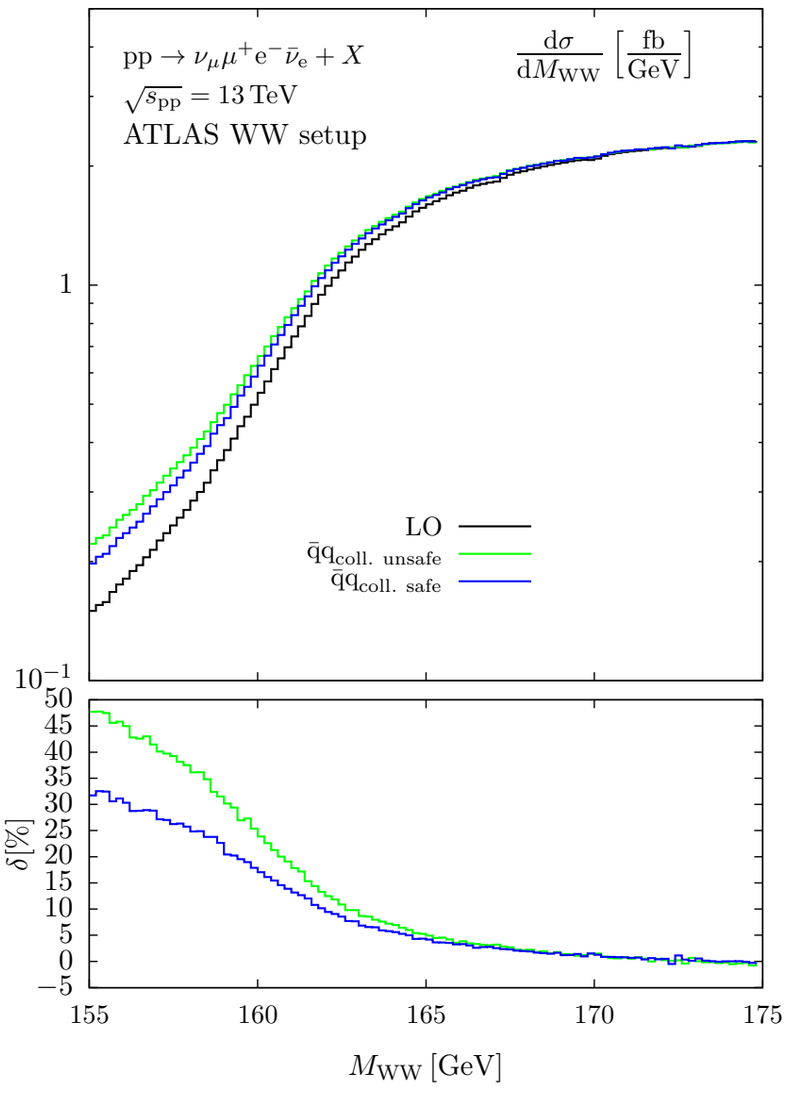
Bertone, Carrazza, DP, Zaro 15'

$pp \to W^+W^- \to 4\,\text{leptons}$ at the LHC

Jet veto suppresses photon-quark contribution.







FSR is relevant for lepton distributions and off-shell effects.

$p_{T,\ell}^{\text{leading}} > 25\,\text{GeV}, \qquad R_{e^-\mu^+} > 0.1, \qquad M_{e^-\mu^+} > 10\,\text{GeV}.$

$E_T^{\text{miss}} = |\vec{p}_T^{\,\text{miss}}| > 25\,\text{GeV},$

veto all events with $p_{T,\text{jet}} > 25\,\text{GeV}$

$R_{\gamma\ell}^{\text{recomb}} = 0.1$

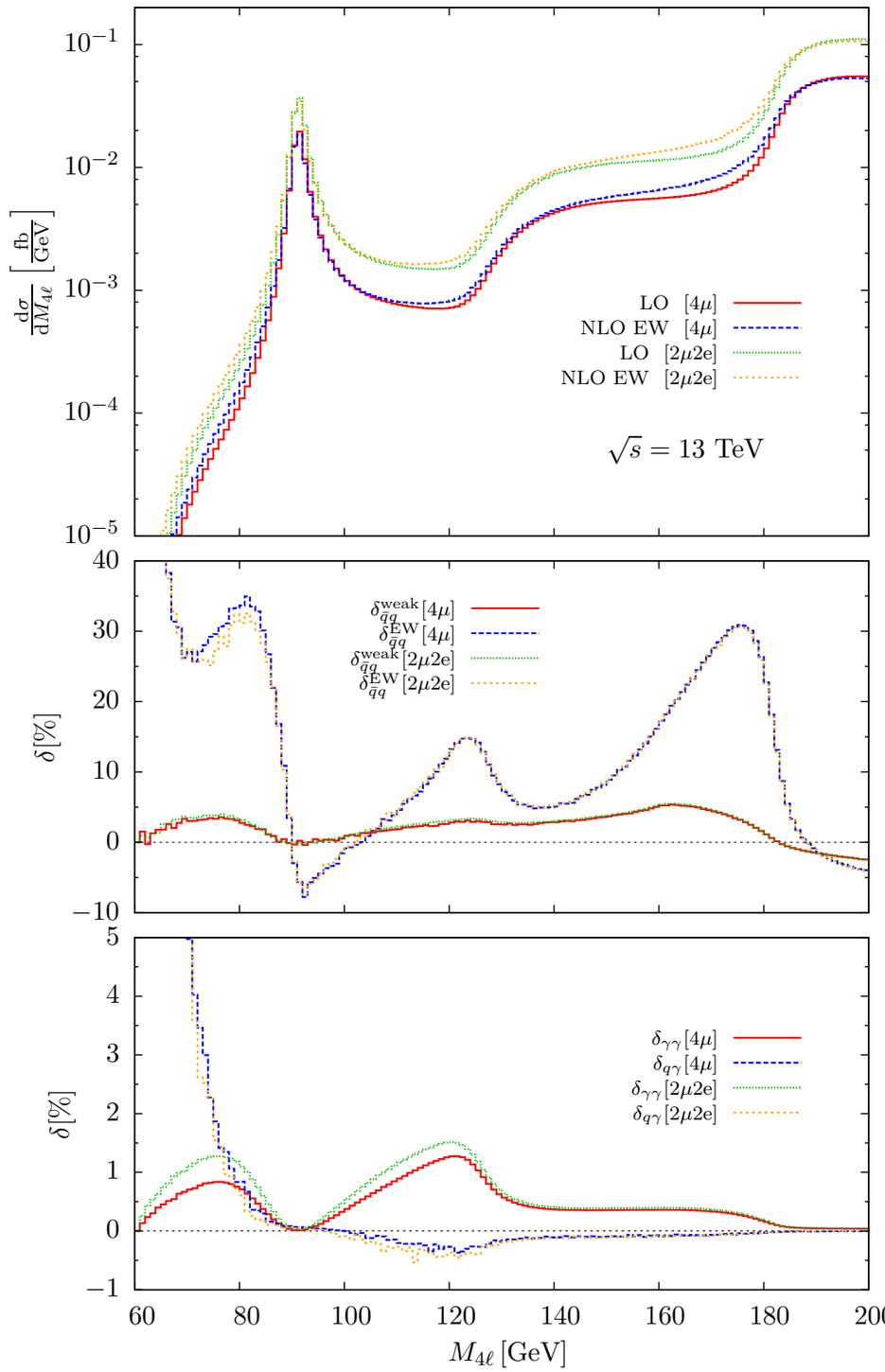
$p_{T,\ell} > 20\,\text{GeV}$

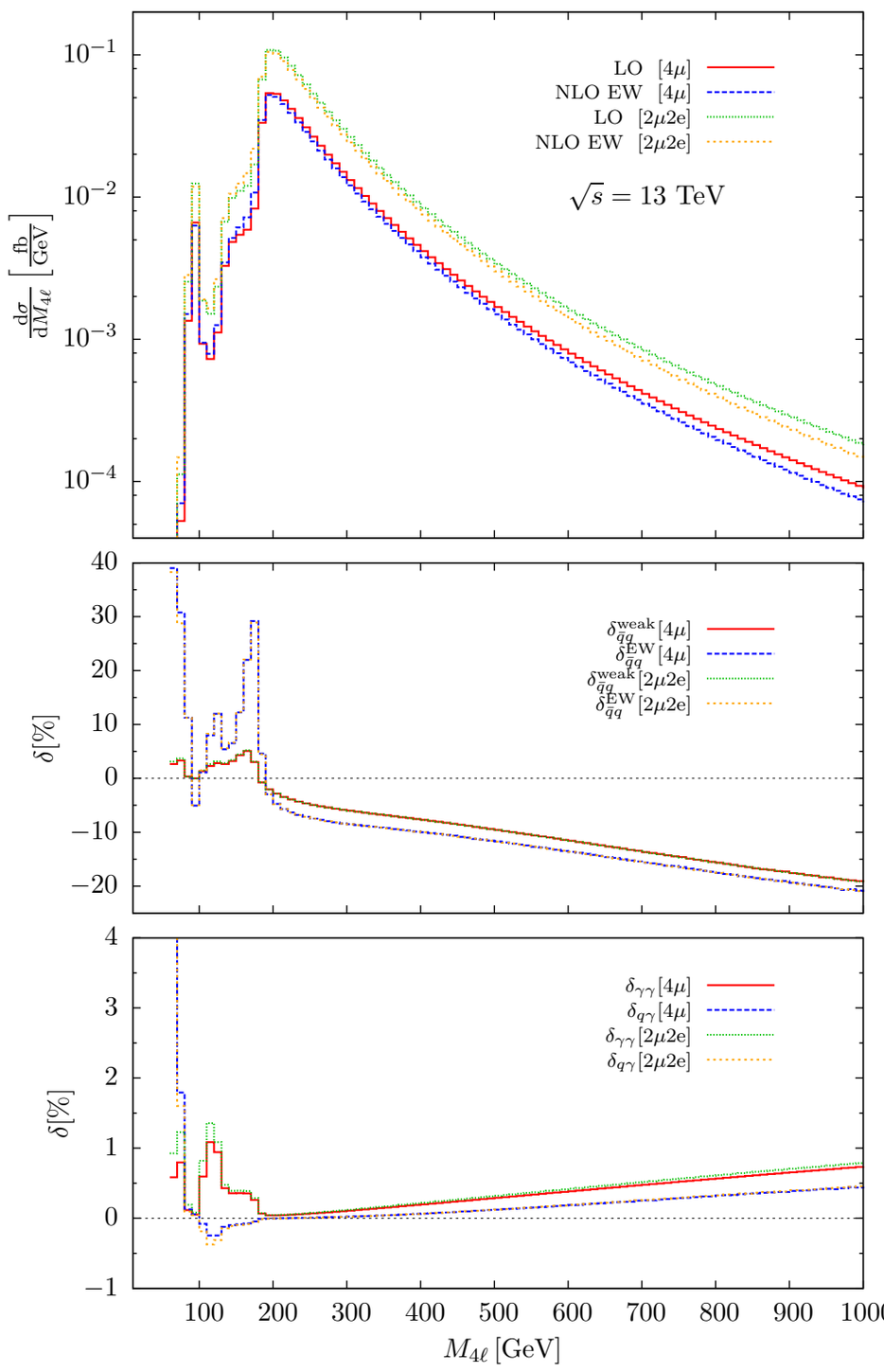
$|y_\ell| < 2.5.$

rejecting any event with $R_{\text{jet},\ell} < 0.4.$

Biedermann, Billoni, Denner, Dittmaier, Hofer, Jäger, Salfelder '16

four charged leptons at the LHC (ZZ)





$$p_{\mathrm{T},\ell_i} > p_{\mathrm{T},\mathrm{min}} = 15\,\mathrm{GeV},$$

$$|y_{\ell_i}| < 2.5.$$

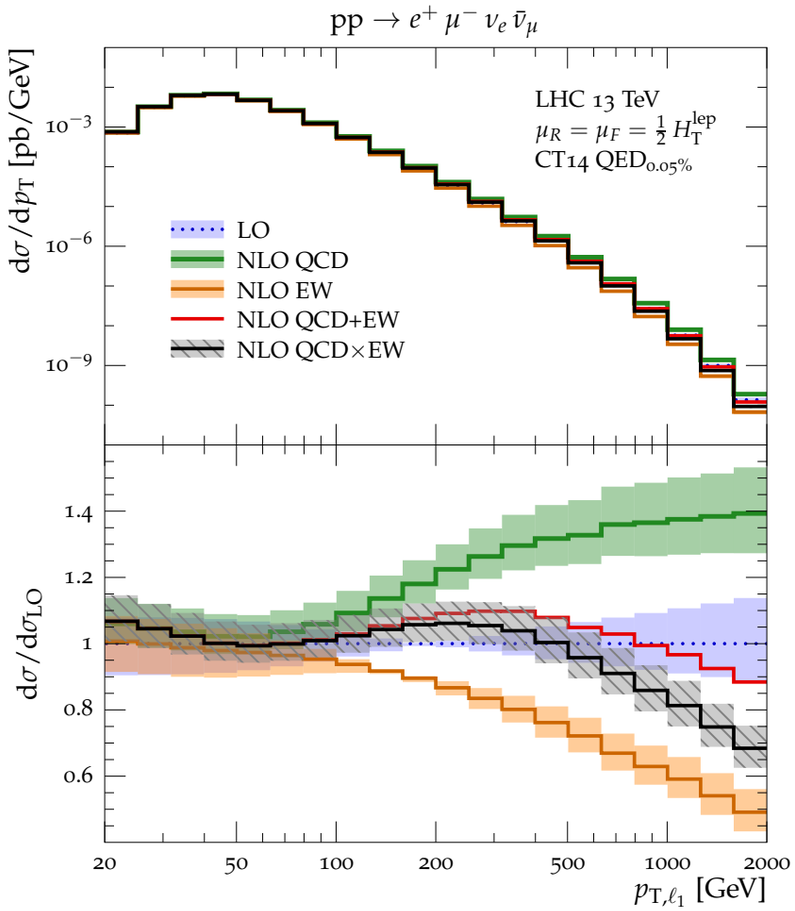
$$\Delta R_{\ell_i,\ell_j} > 0.2.$$

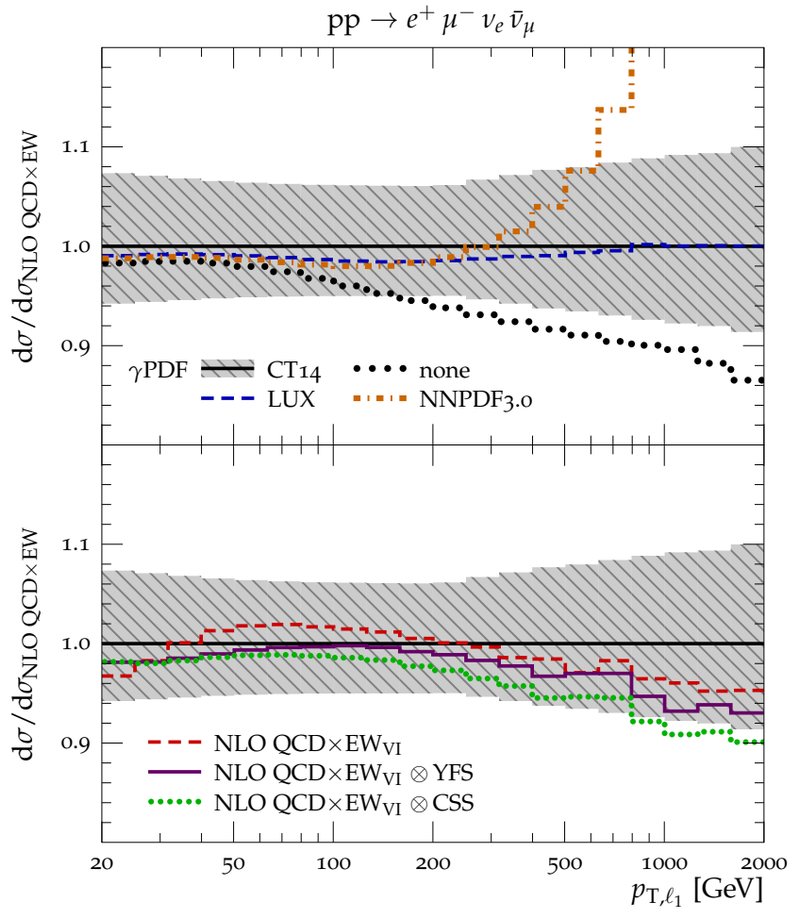
Leptons recombined with photons

$$\Delta R_{\ell_i,\gamma} = \sqrt{(y_{\ell_i} - y_\gamma)^2 + (\Delta\phi_{\ell_i\gamma})^2} < 0.2.$$

Biedermann, Denner, Dittmaier, Hofer, Jäger, '16

$pp \to e^+\mu^-\nu_e\bar{\nu}_\mu$ and $pp \to e^+e^-\nu\bar{\nu}$ $\left(W^+W^-,\ ZZ,\ \gamma Z\right)$





Inclusive cuts	
$\not{E}_{\rm T}$	$> 20\,\text{GeV}$
$p_{{\rm T},\ell^\pm}$	$> 20\,\text{GeV}$
$\lvert\eta_{\ell^\pm}\rvert$	< 2.5
$\Delta R_{\ell^+\ell^-}$	> 0.2
$H_{\rm T}^{\rm jet}$	$< 0.2\,H_{\rm T}^{\rm lep}$

$$\Delta R_{\ell\gamma} = \sqrt{\Delta\phi_{\ell\gamma}^2 + \Delta\eta_{\ell\gamma}^2} < R_{\rm rec} = 0.1$$

Leptons recombined with photons

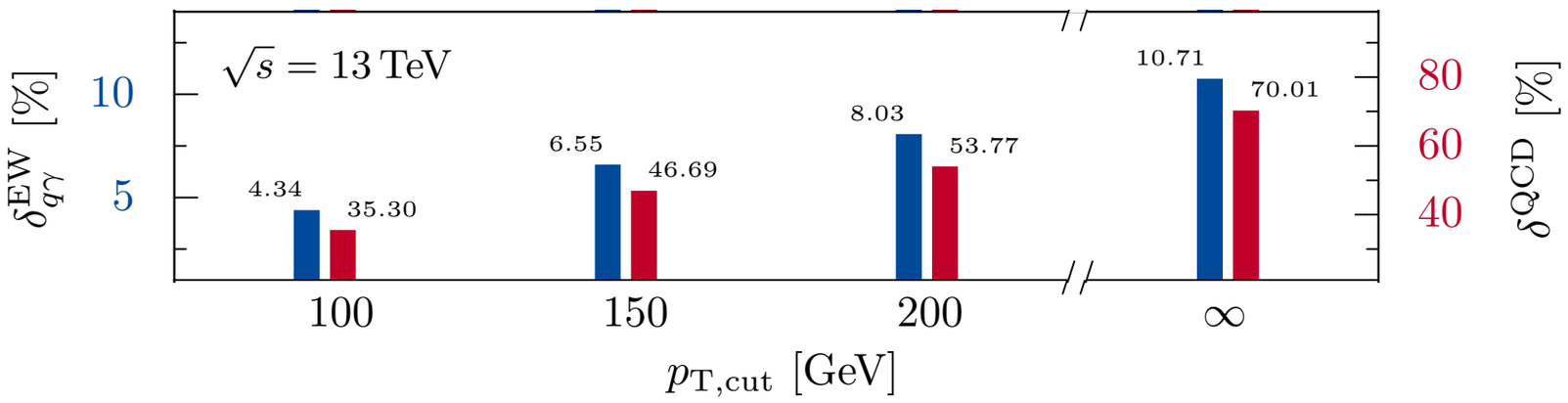
Also with LUXqed the photon PDF contribution cannot be neglected

YFS soft-photon resummation and CSS photon-shower correctly describe at % level accuracy the pt of the hardest lepton for pt < 1 TeV.

CSS is not resonance-aware and can lead to distortions of the m(lν) distribution. However this distribution is not experimentally measurable.

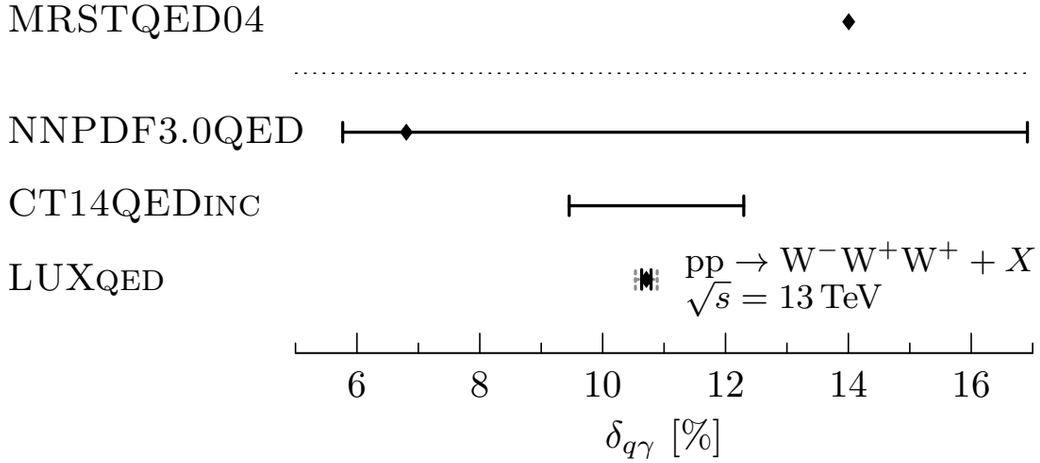
Kallweit, Lindert, Pozzorini, Schönherr '17

WWW



PDF set	$\delta^{\text{EW}}_{q\gamma}$ [%]
MRSTQED04	14.00
NNPDF3.0QED	$6.81^{+10.11}_{-1.04}$
CT14QEDINC	$10.88^{+1.42}_{-1.42}$
LUXQED	$10.71^{+0.08}_{-0.08}$

$p_{\text{T,cut}} = \infty$

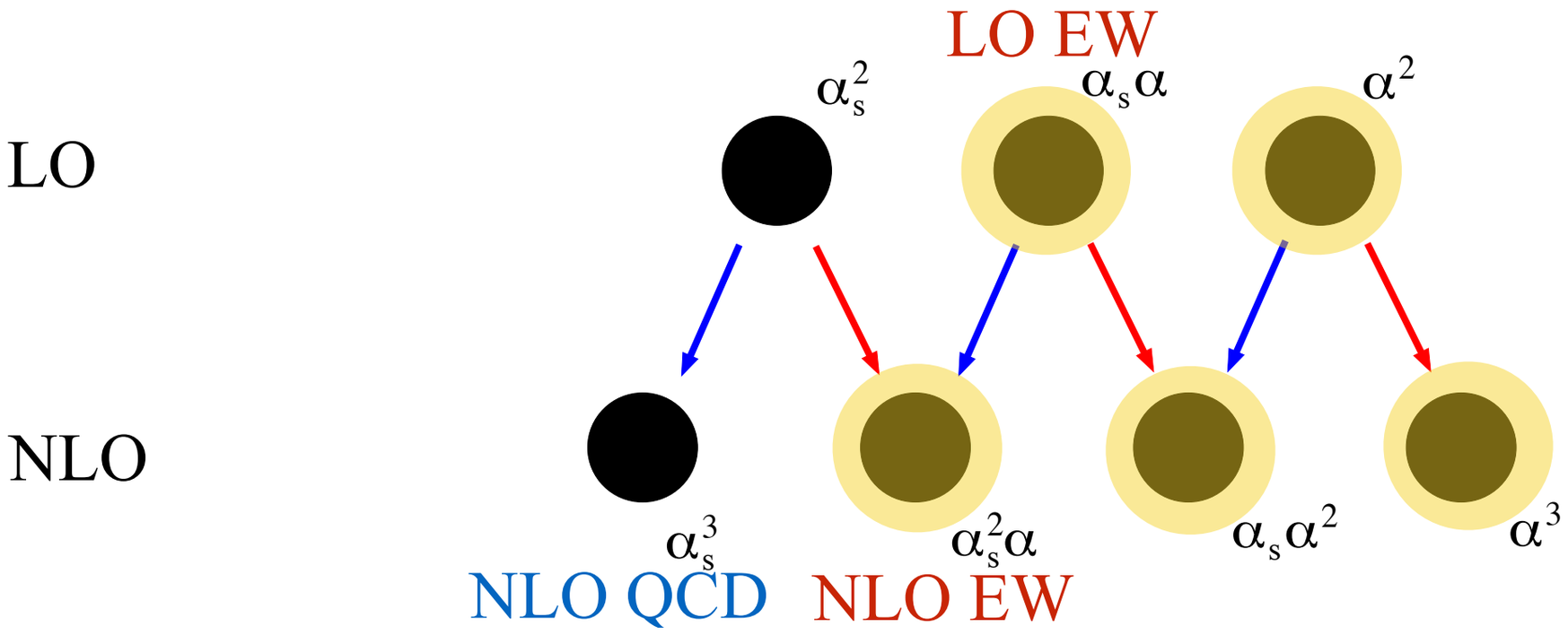


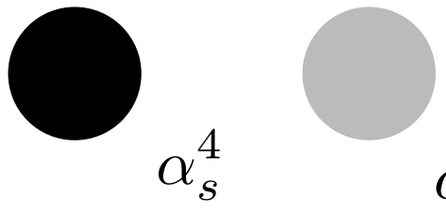
Photon-quark contribution is relevant, PDF dependent and jet-veto dependent

Dittmaier, Huss, Knippen '17

Top-quark pair production

NNLO QCD and NLO EW corrections in $t\bar{t}$





Czakon, Heymes, Mitov, DP, Tzinikos, Zaro '17

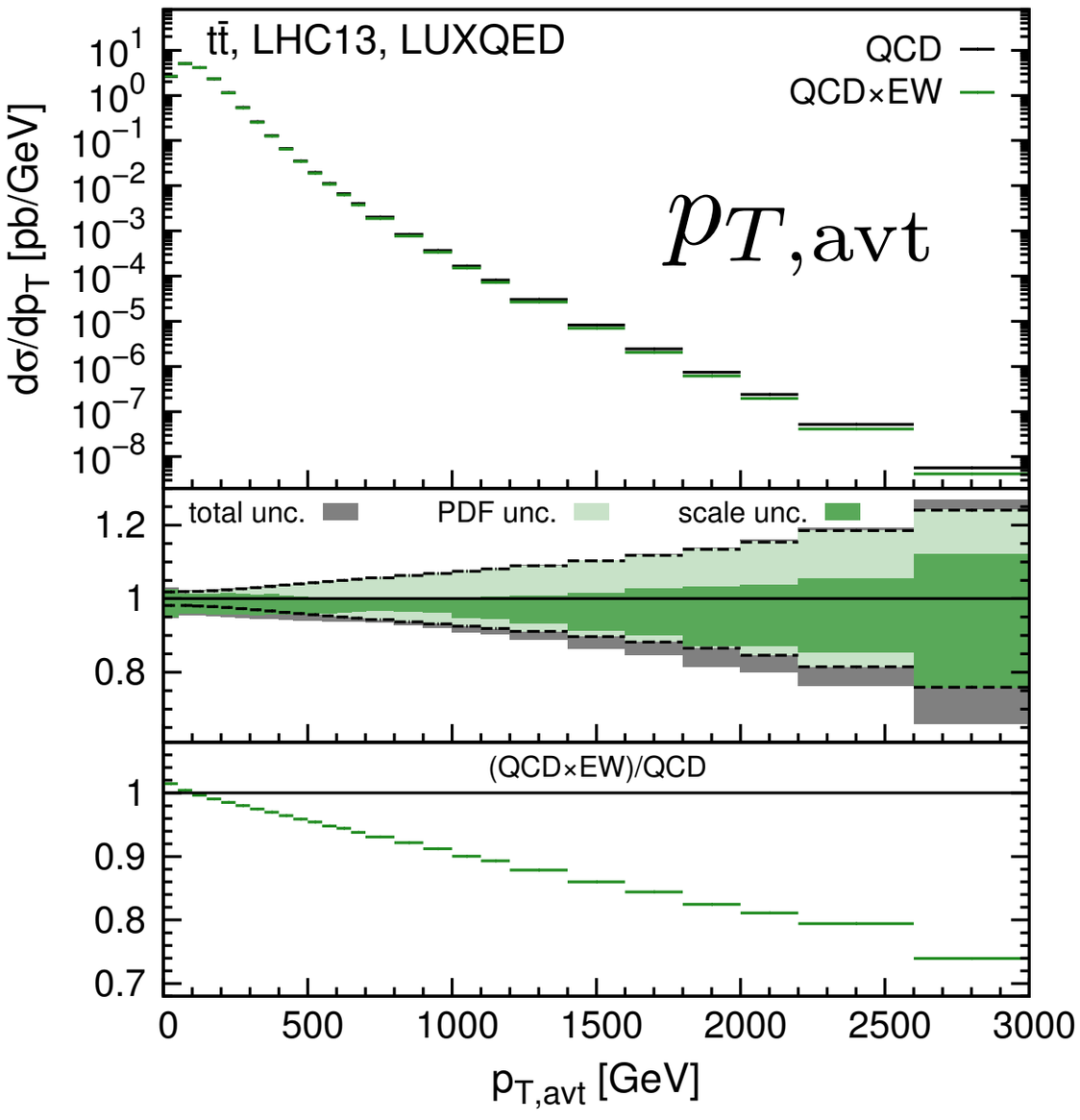
MULTIPLICATIVE

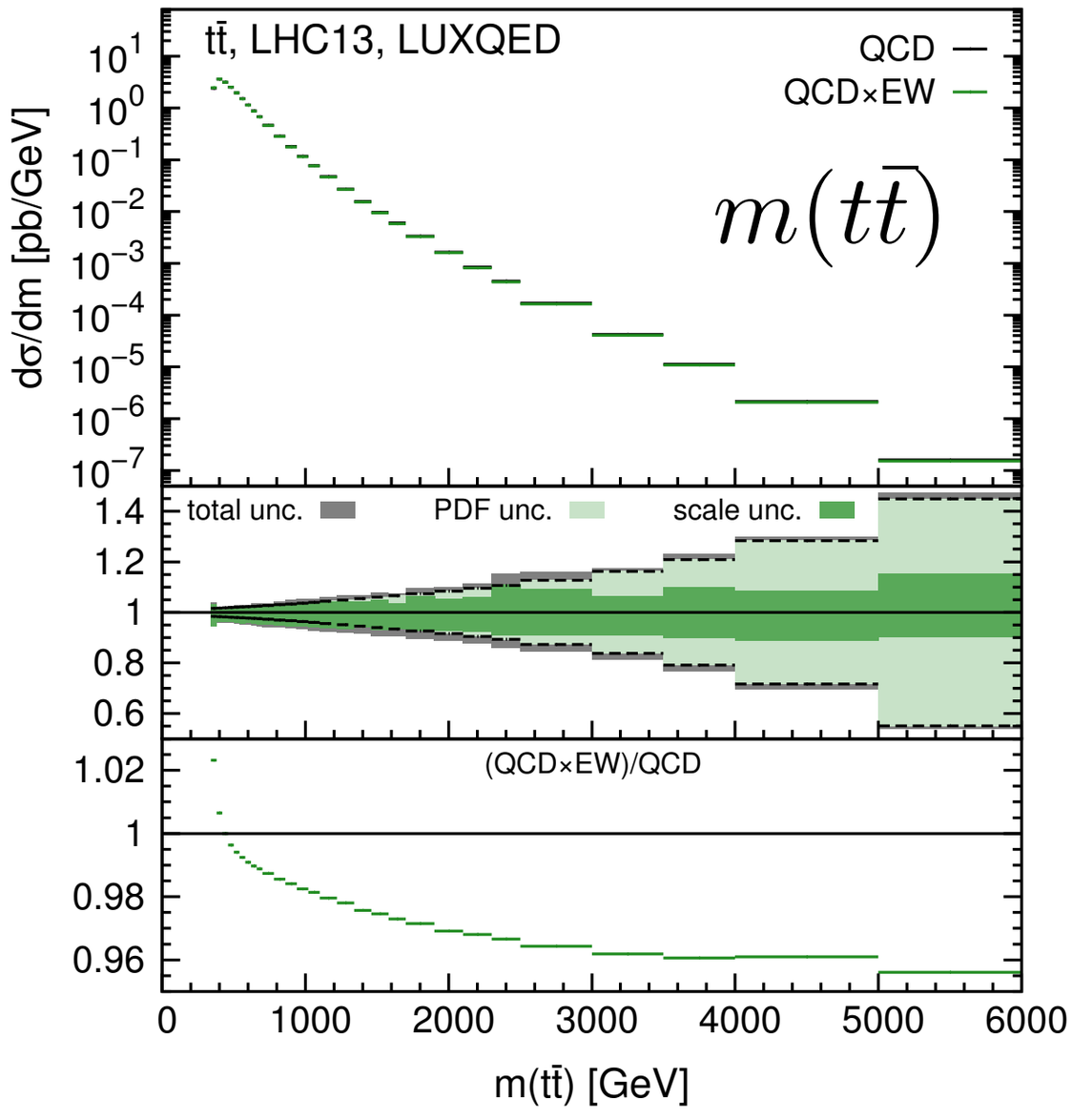
$$\Sigma_{\mathrm{QCD}\times\mathrm{EW}} \equiv \Sigma_{\mathrm{QCD}} + K_{\mathrm{QCD}}^{\mathrm{NLO}}\,\Sigma_{\mathrm{NLO\ EW}} + \Sigma_{\mathrm{LO\ EW}} + \Sigma_{\mathrm{subleading}}$$

Czakon, Heymes, Mitov, DP, Tzinikos, Zaro '17

13 TeV

QCD x EW with LUXQED





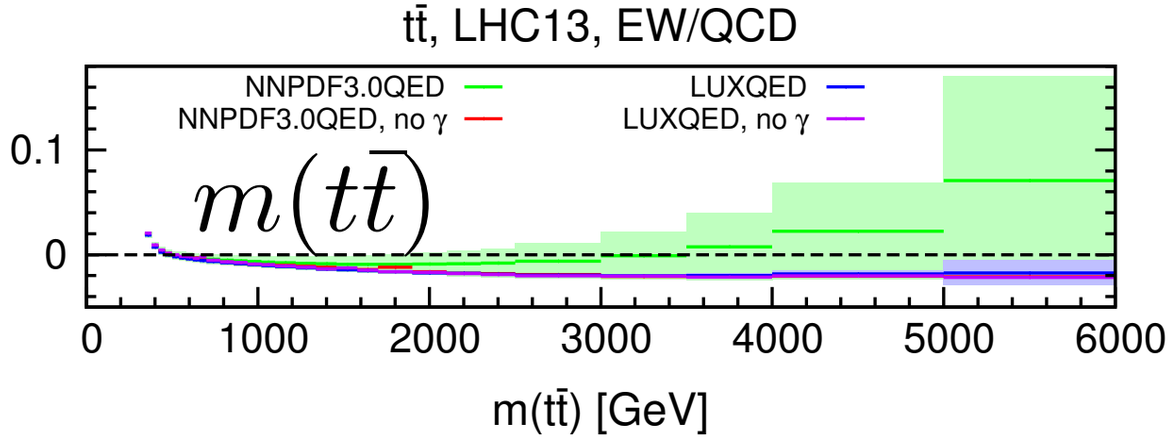
scale unc. ~ PDF unc

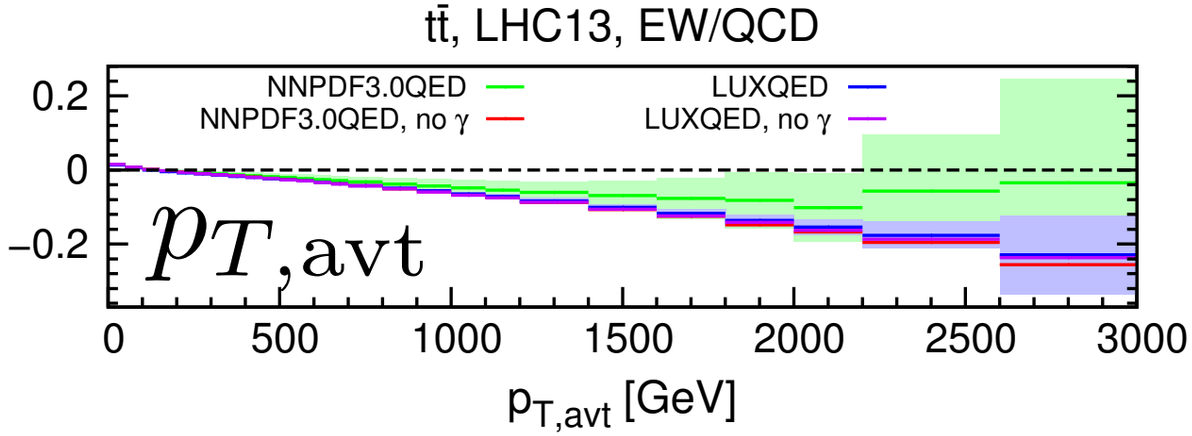
EW corrections ~ theory error

scale unc. < PDF unc

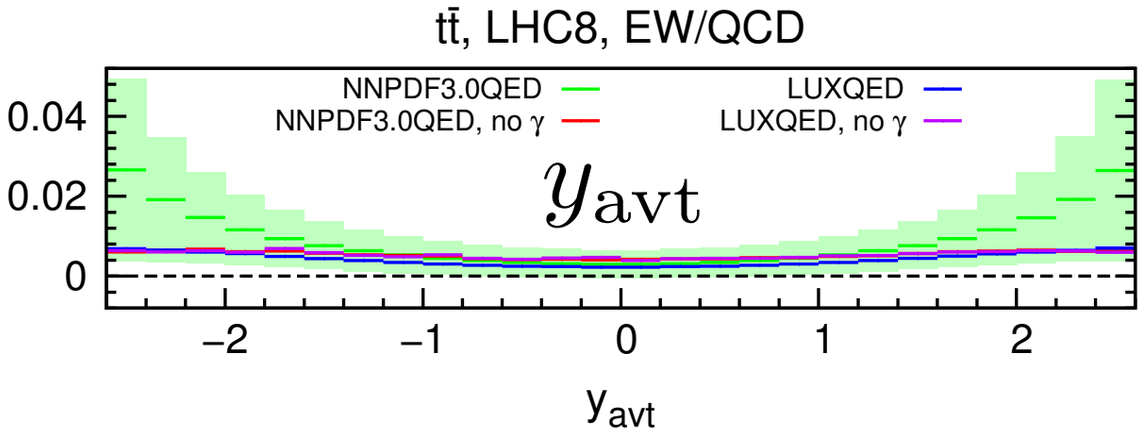
Photon PDF: LUXqed vs. NNPDF3.0

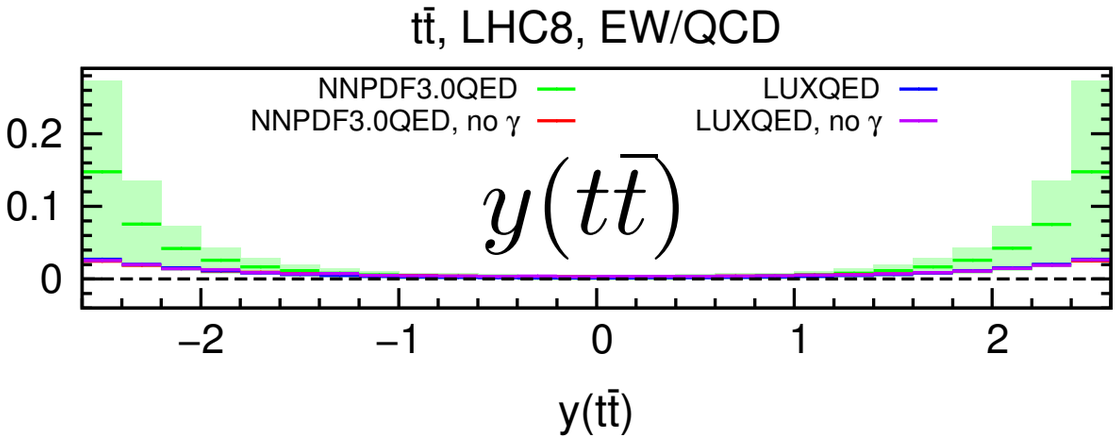
13 TeV





8 TeV

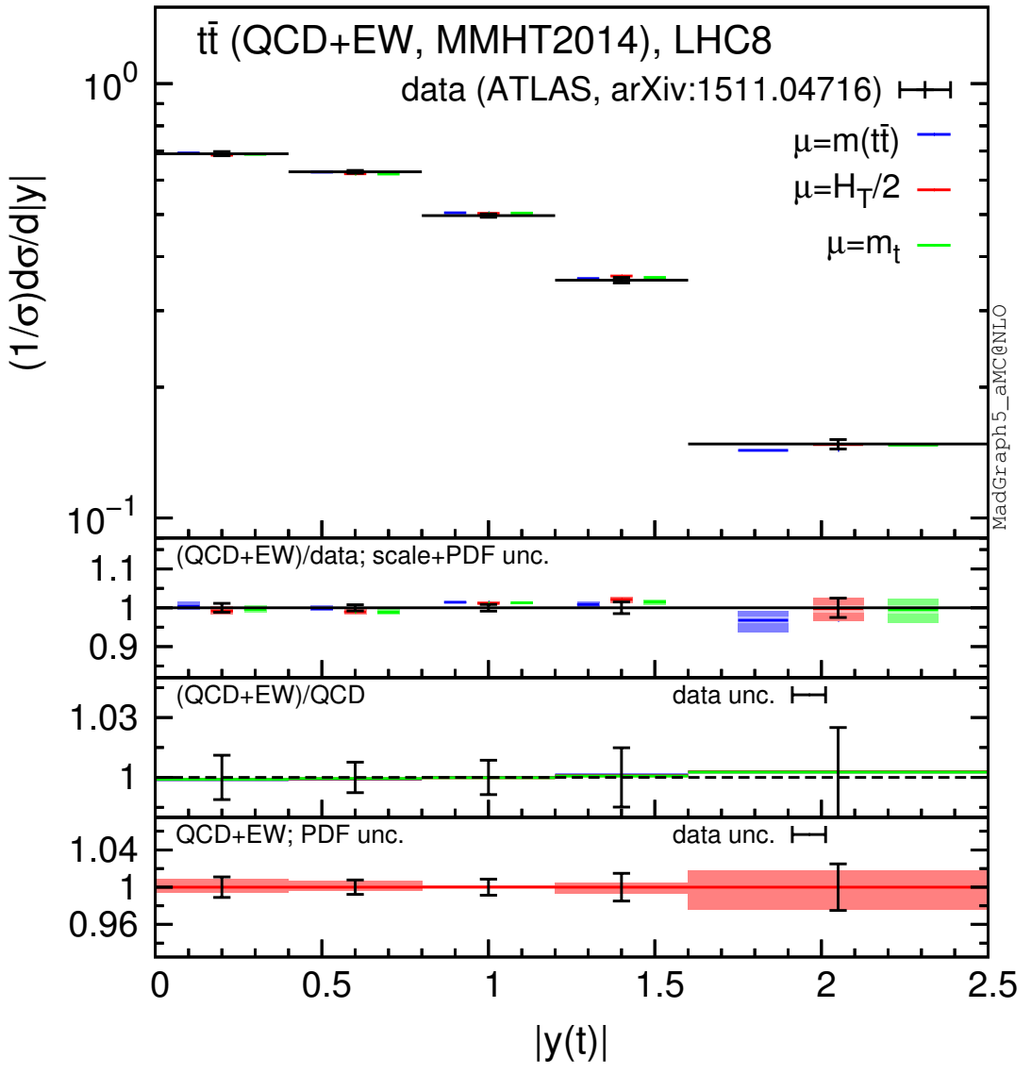


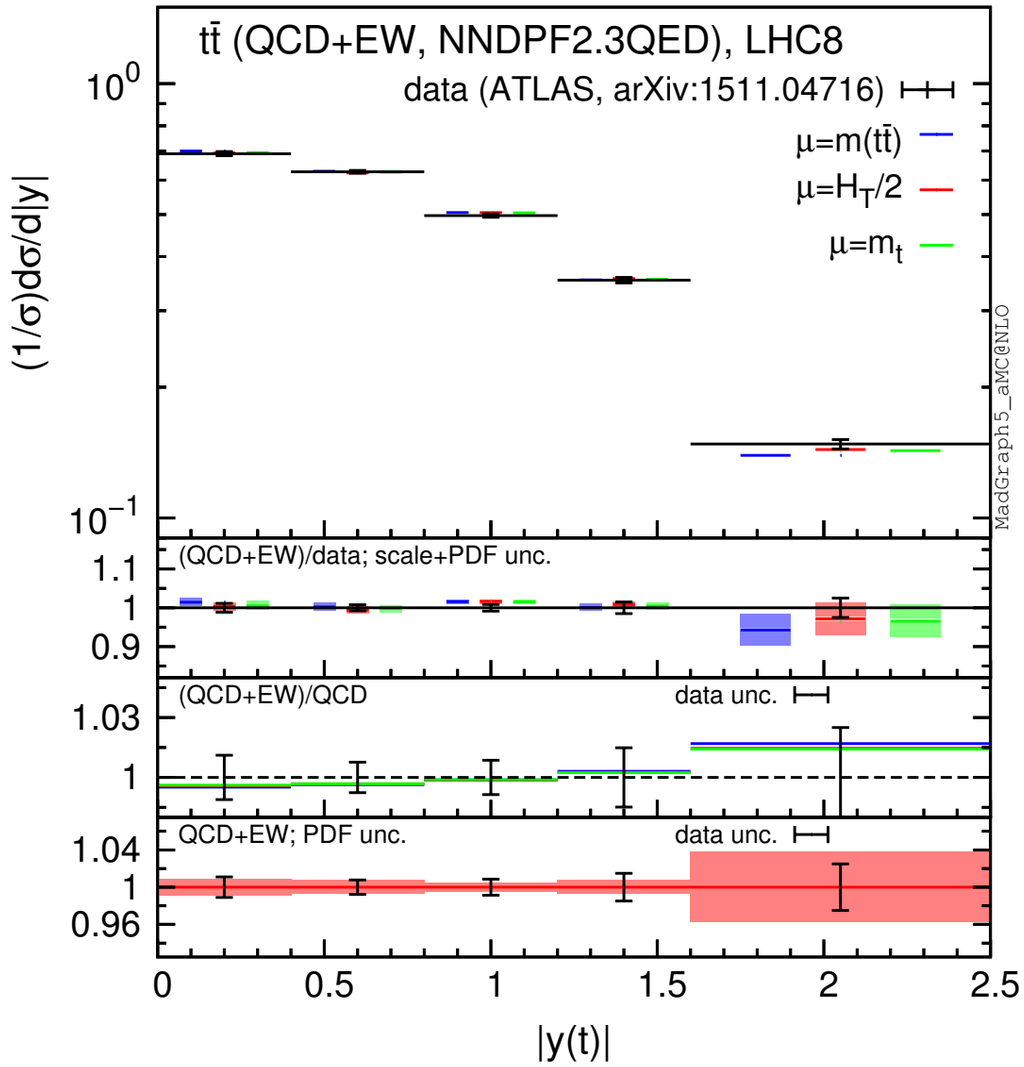


Czakon, Heymes, Mitov, DP, Tzinikos, Zaro '17

Sensitivity of data to the photon PDF

pre-LUXqed study

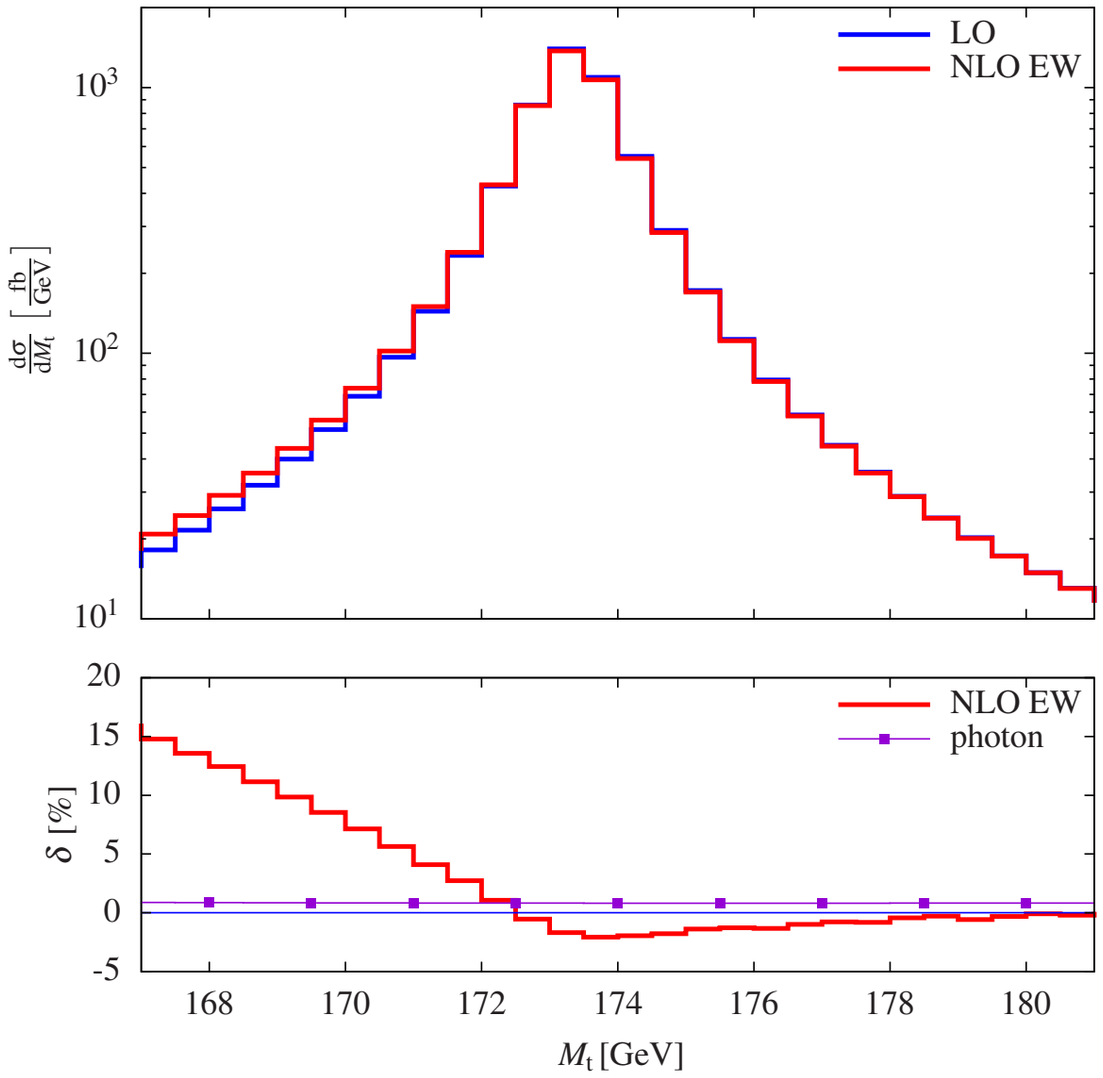


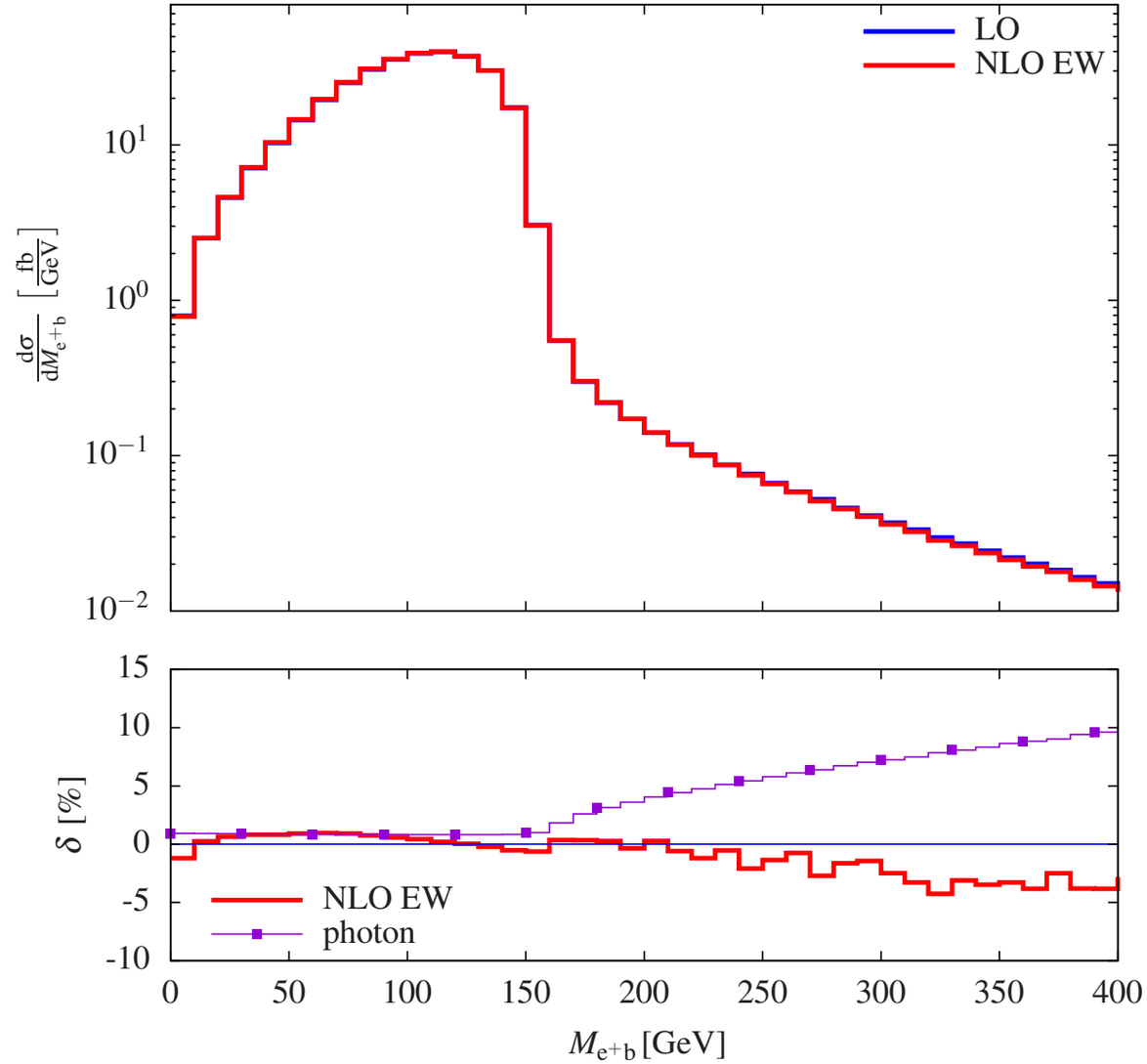


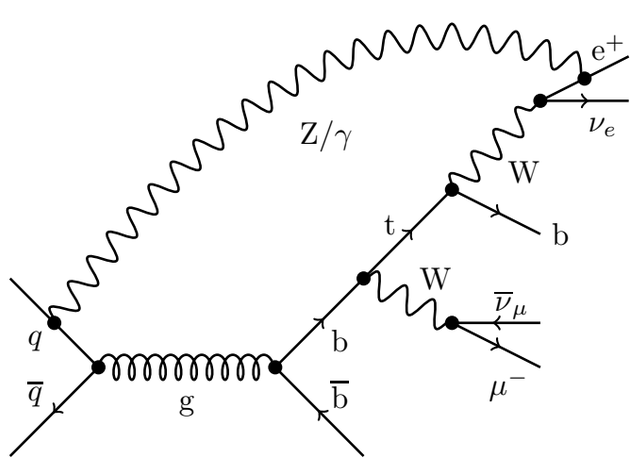
DP, Tzinikos, Zaro '16

photon PDF **NO** photon PDF **YES**

$pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}$ (dilepton top-quark pair signature)







$M^2_{e^+b} < M^2_t - M^2_W \simeq (154\,\text{GeV})^2$ for on-shell top

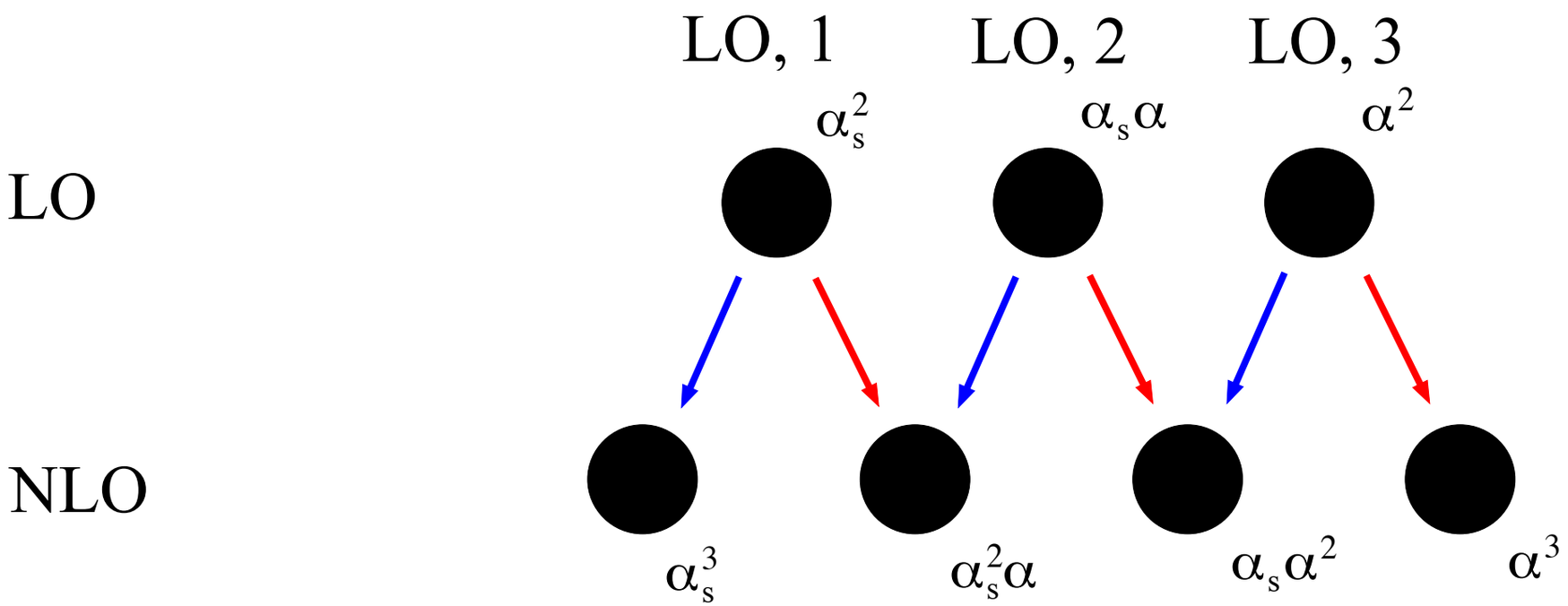
FSR and photon PDF (NNPDF) are relevant in off-shell distributions

Denner, Pellen '16

Dijet

dijet: all orders at LO and NLO

Democratic jets: also photons and leptons are clustered into jets



NLO, 1 NLO, 2 NLO, 3 NLO, 4

Frederix, Frixione, Hirschi, DP, Shao, Zaro '16

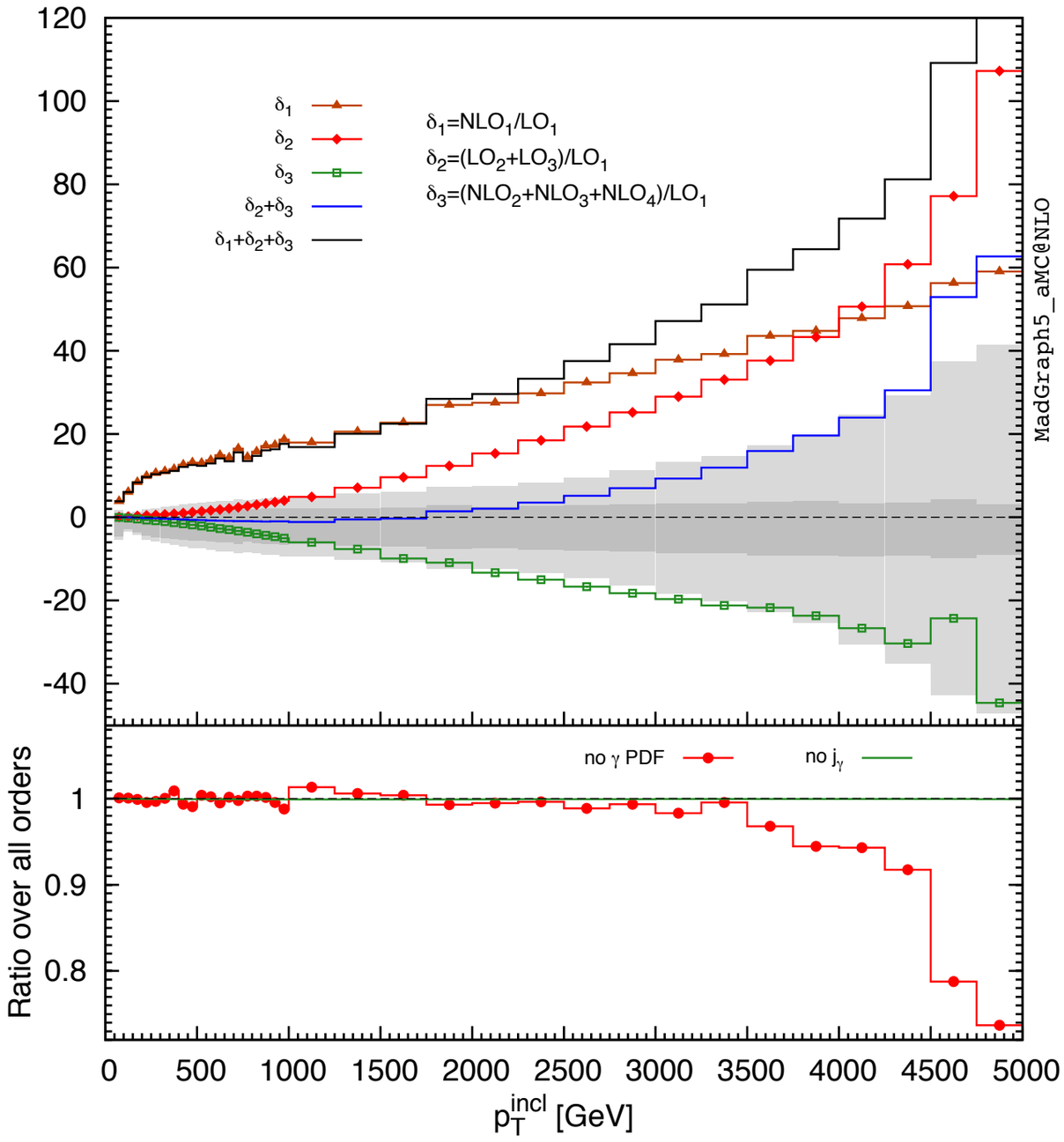
Photons can be in the initial and final state.

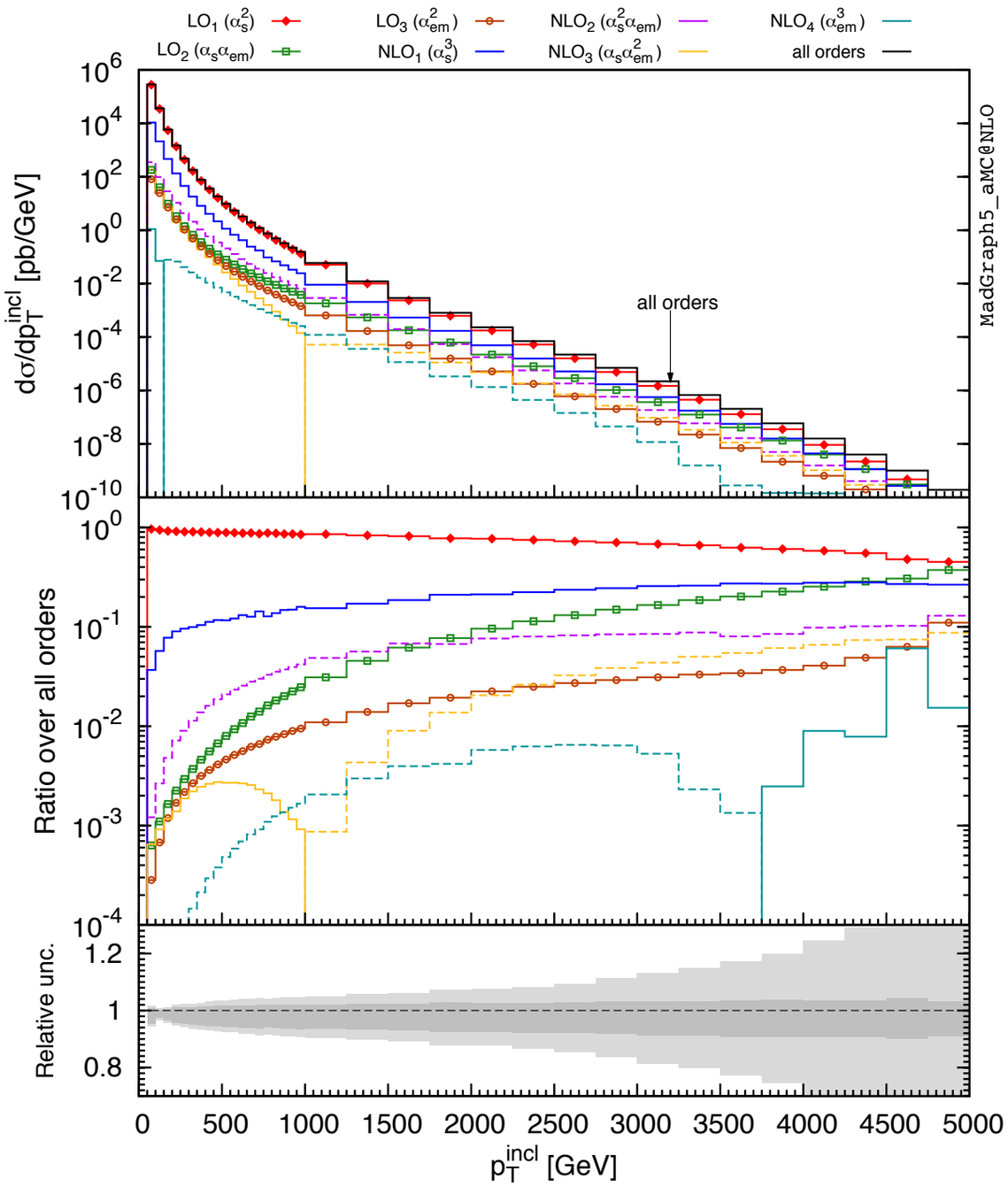
Only in the following perturbative orders final state photons can be isolated from purely hadronic jets using standard isolation procedures.

$$1\gamma: \quad \mathcal{O}(\alpha_S\alpha + \alpha_S^2\alpha) \equiv \Sigma_{\mathrm{LO}_2} + \Sigma_{\mathrm{NLO}_2}$$

$$2\gamma: \quad \mathcal{O}(\alpha^2 + \alpha_S\alpha^2) \equiv \Sigma_{\mathrm{LO}_3} + \Sigma_{\mathrm{NLO}_3}$$

dijet: photon in the initial and final state





Contribution of isolated-photons in final state is negligible.

Frederix, Frixione, Hirschi, DP, Shao, Zaro '16

Conclusion

Precise predictions require the calculation of NNLO QCD and NLO EW corrections in order to match the experimental accuracy achieved at the LHC.

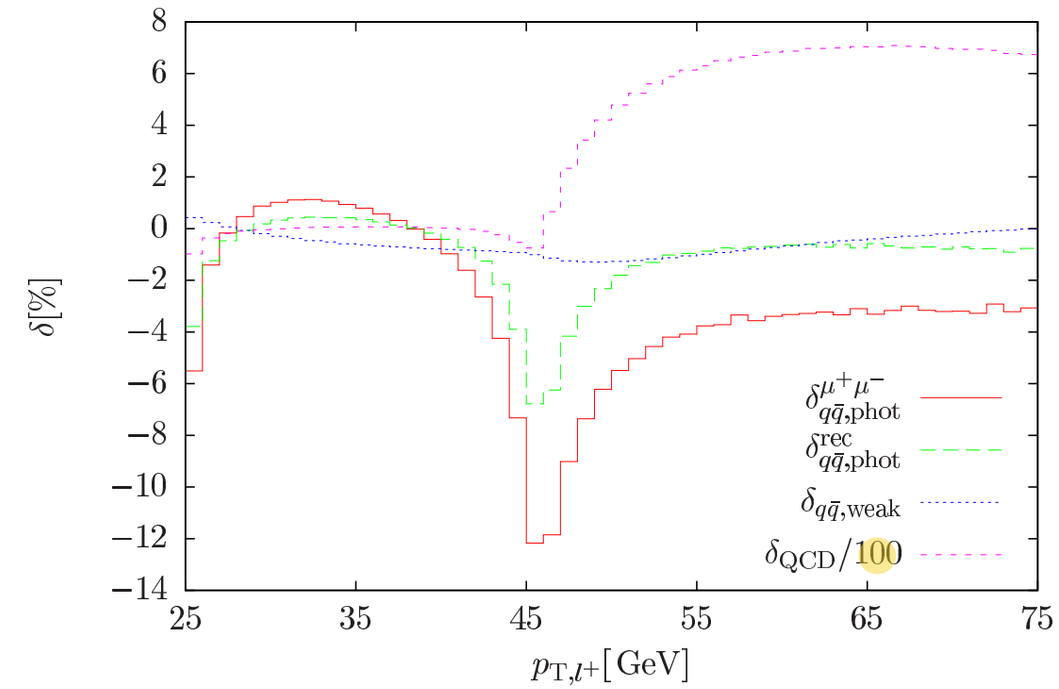
Leading photon effects originate from Final-State-Radiation (FSR) and from the opening of new photon-induced partonic channels (Photon PDF).

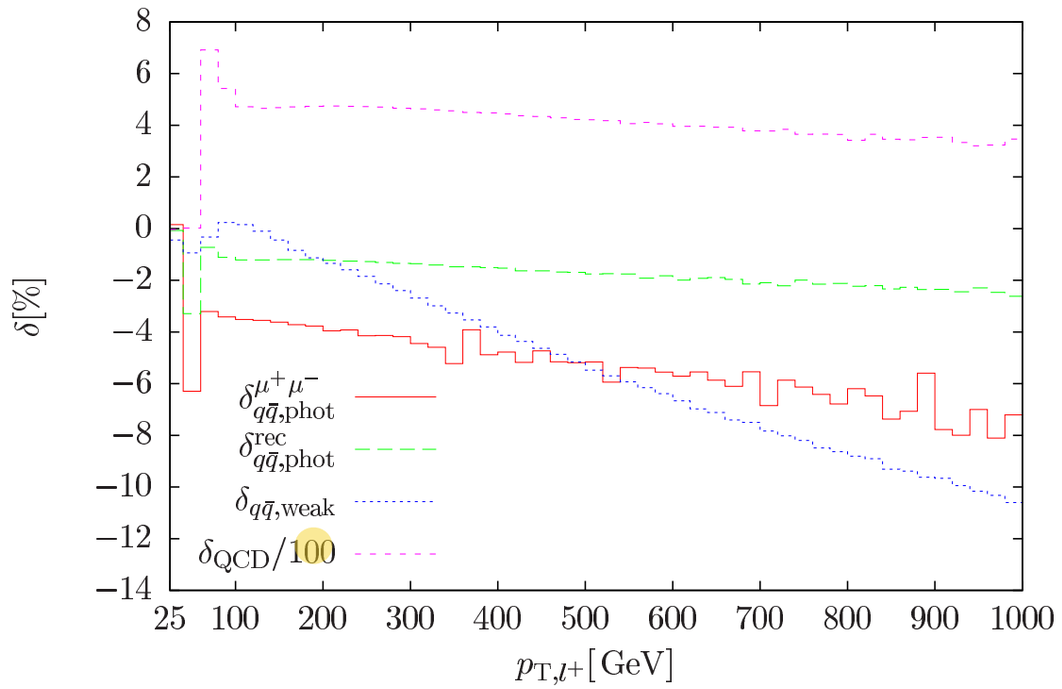
FSR effects are particular relevant around the resonance (W, Z, top).

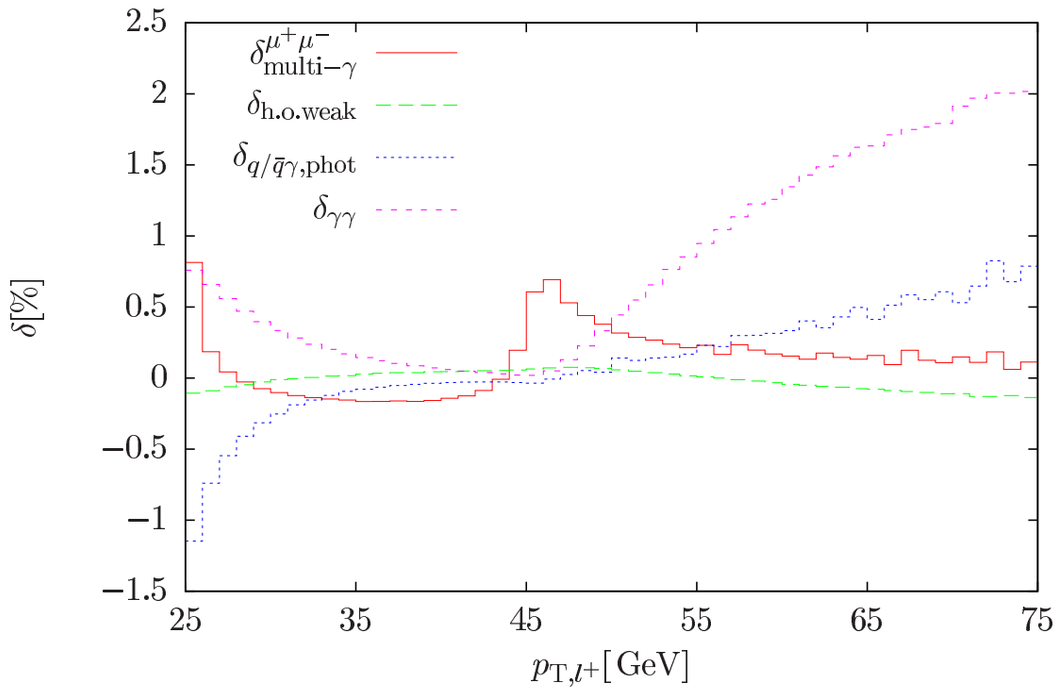
Although LUXqed photon density at large x is smaller and with much smaller uncertainty than in other PDF sets, photon-initiated processes cannot be in general ignored.
Depending on the process and the experimental cuts (jet vetos), they can lead to non-negligible contributions, compensating weak Sudakov logarithms.

EXTRA SLIDES

Drell-Yan (Z)







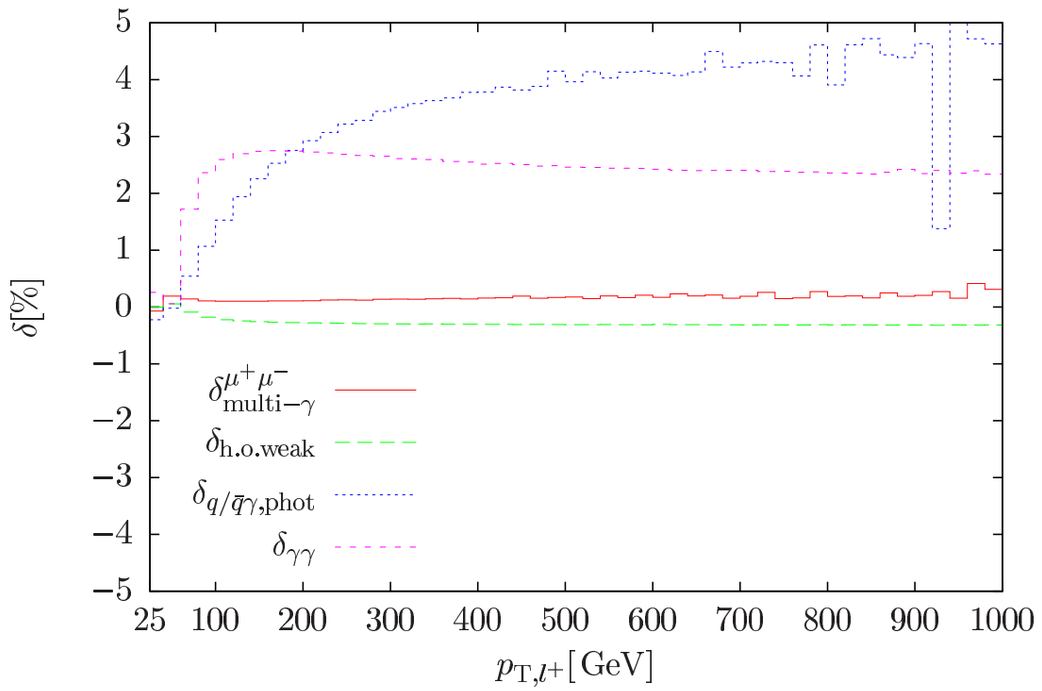


Figure 13: Lepton p_{T,l^-}-distribution and correction factors at the LHC in the resonance region (left) and the high-p_{T} region (right).

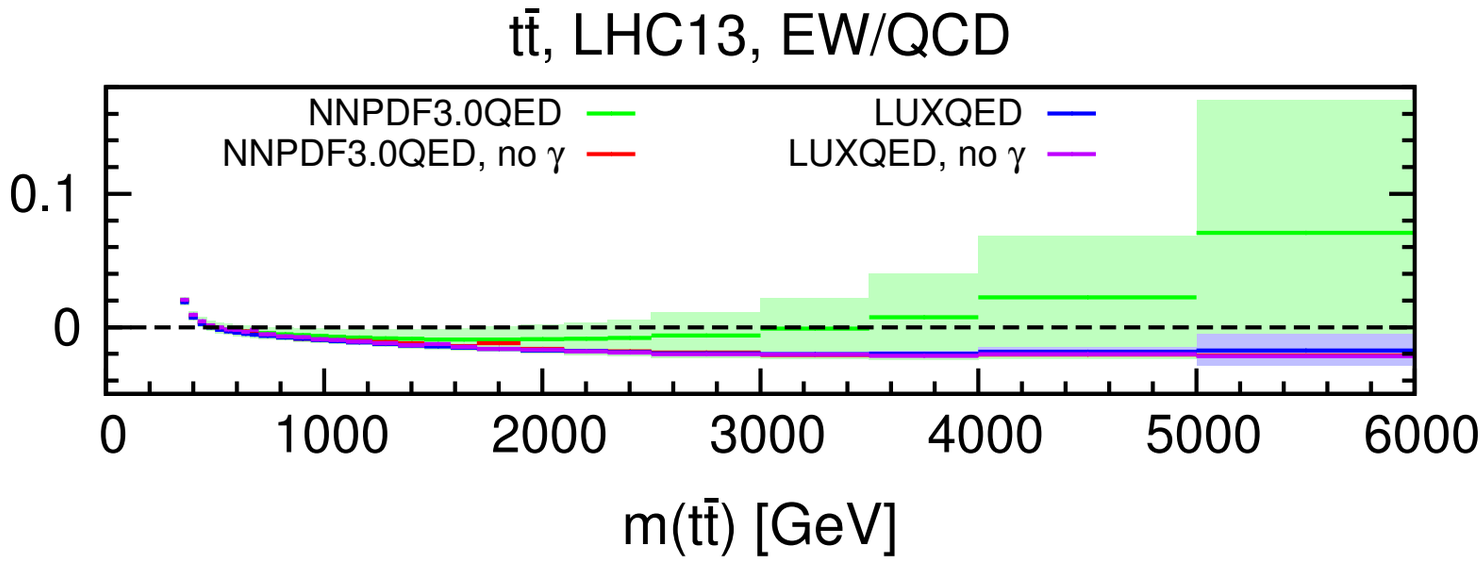
EW corrections: PDFs choice

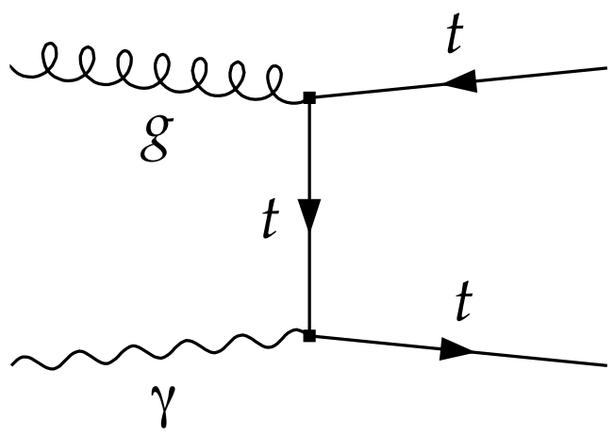
PDFs must have the same accuracy of the calculation of the matrix elements; not only NNLO QCD but also NLO QED accuracy is necessary.
The best on the market is NNLO QCD + LO QED:

NNPDF3.0QED *Bertone, Carrazza '16*
LUXQED *Manohar et al. '16*

They both include a photon PDF!

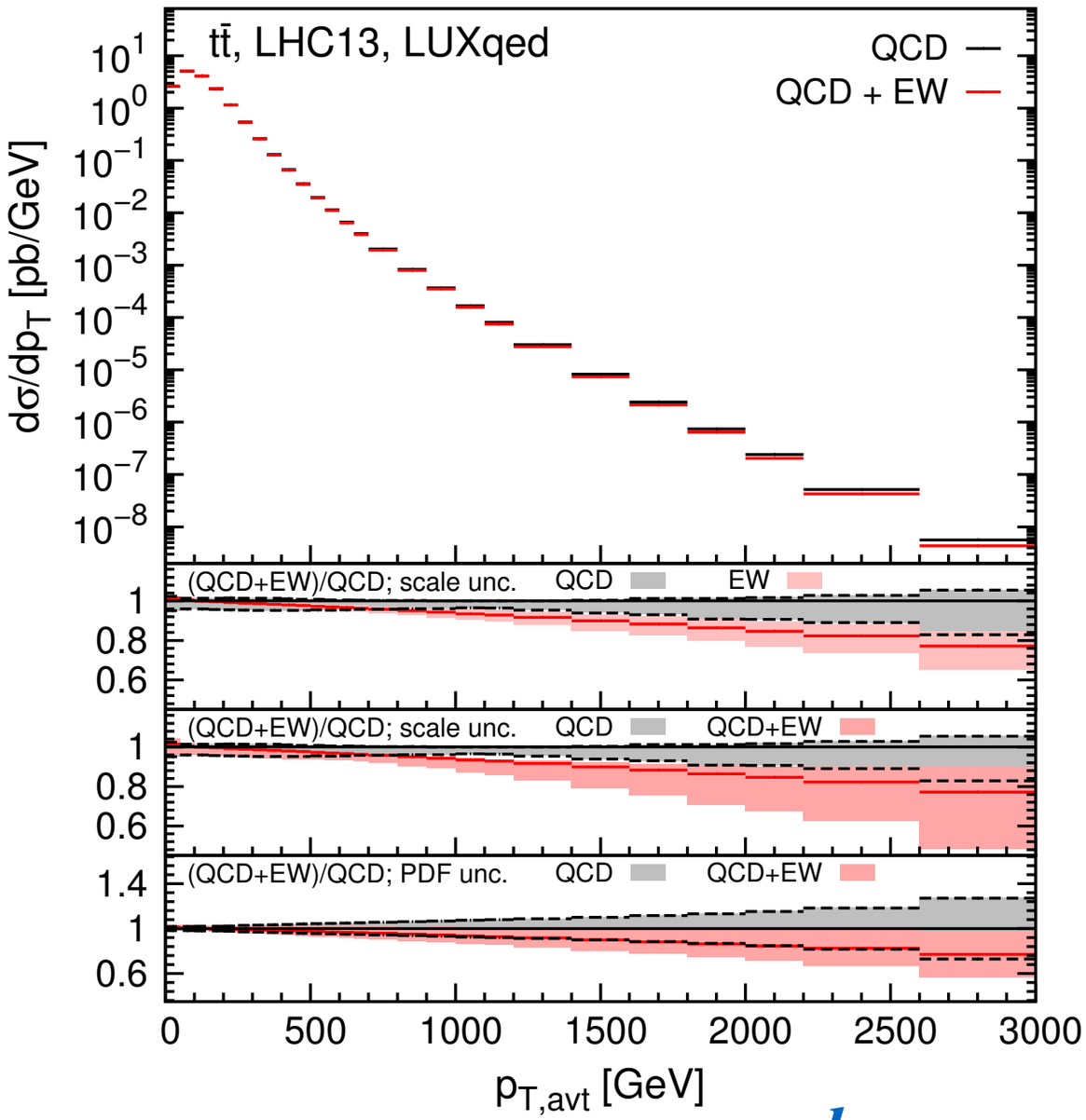
While the impact of the NNPDF photon PDF is huge in ttbar differential distributions (and with large uncertainties), in the case of LUXQED is small.
Cancellation between Sudakov Logarithms and photon-induced results depends on the scale definition. *DP, Tsinikos, Zaro '16*

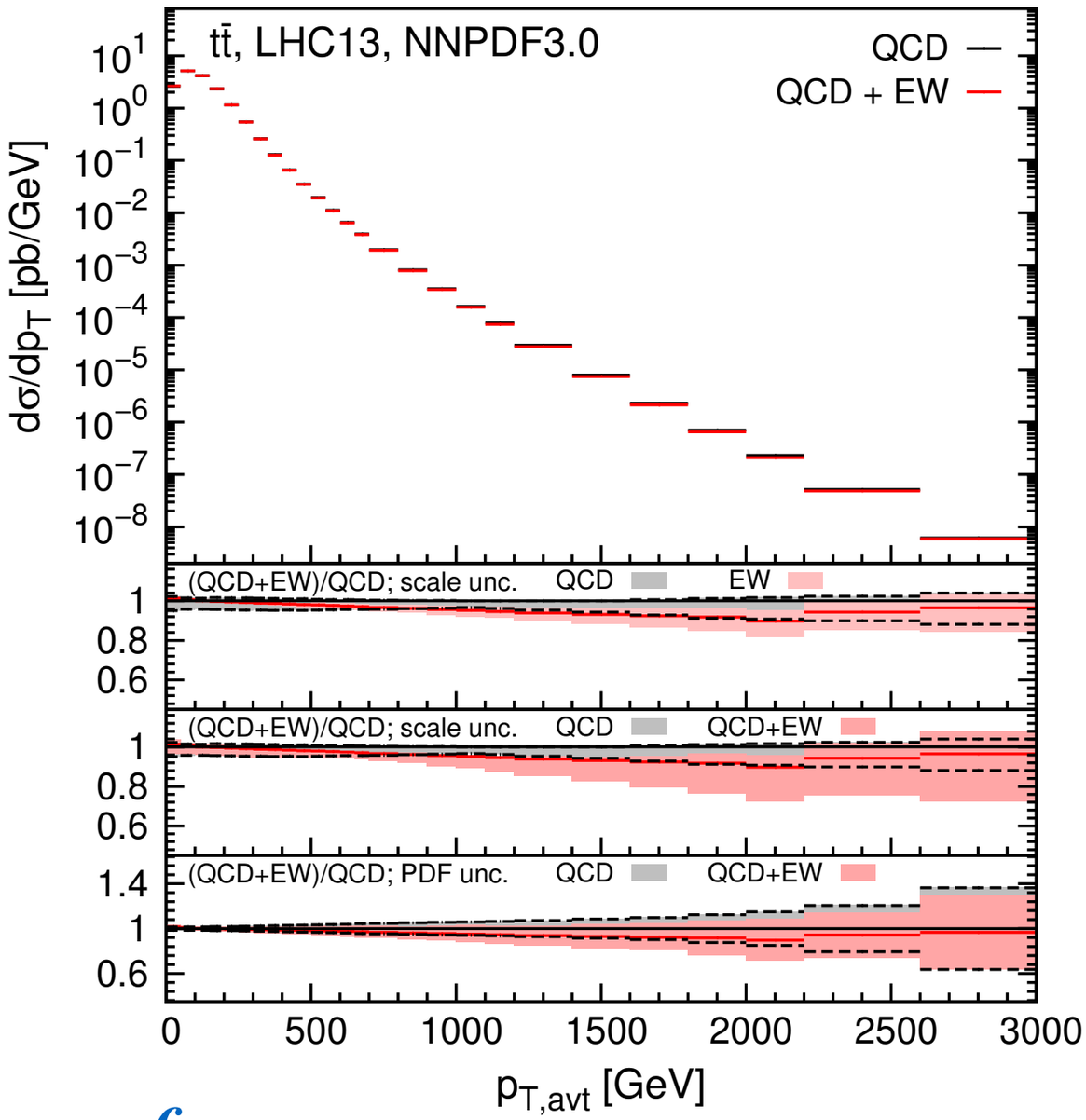




13 TeV

$p_{T,\mathrm{avt}}$





large scale unc. from EW corrections

\+

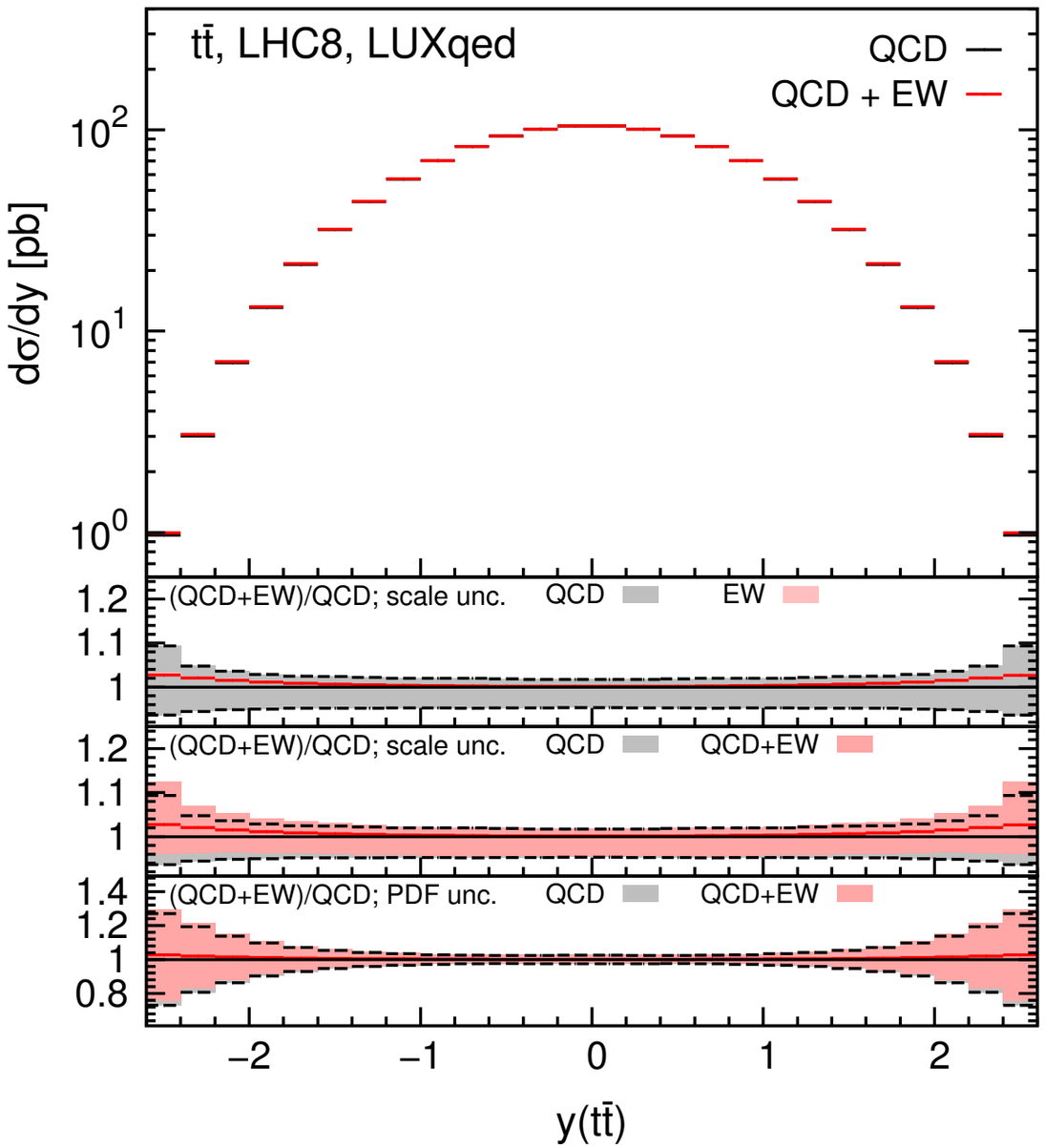
photon PDF relevant

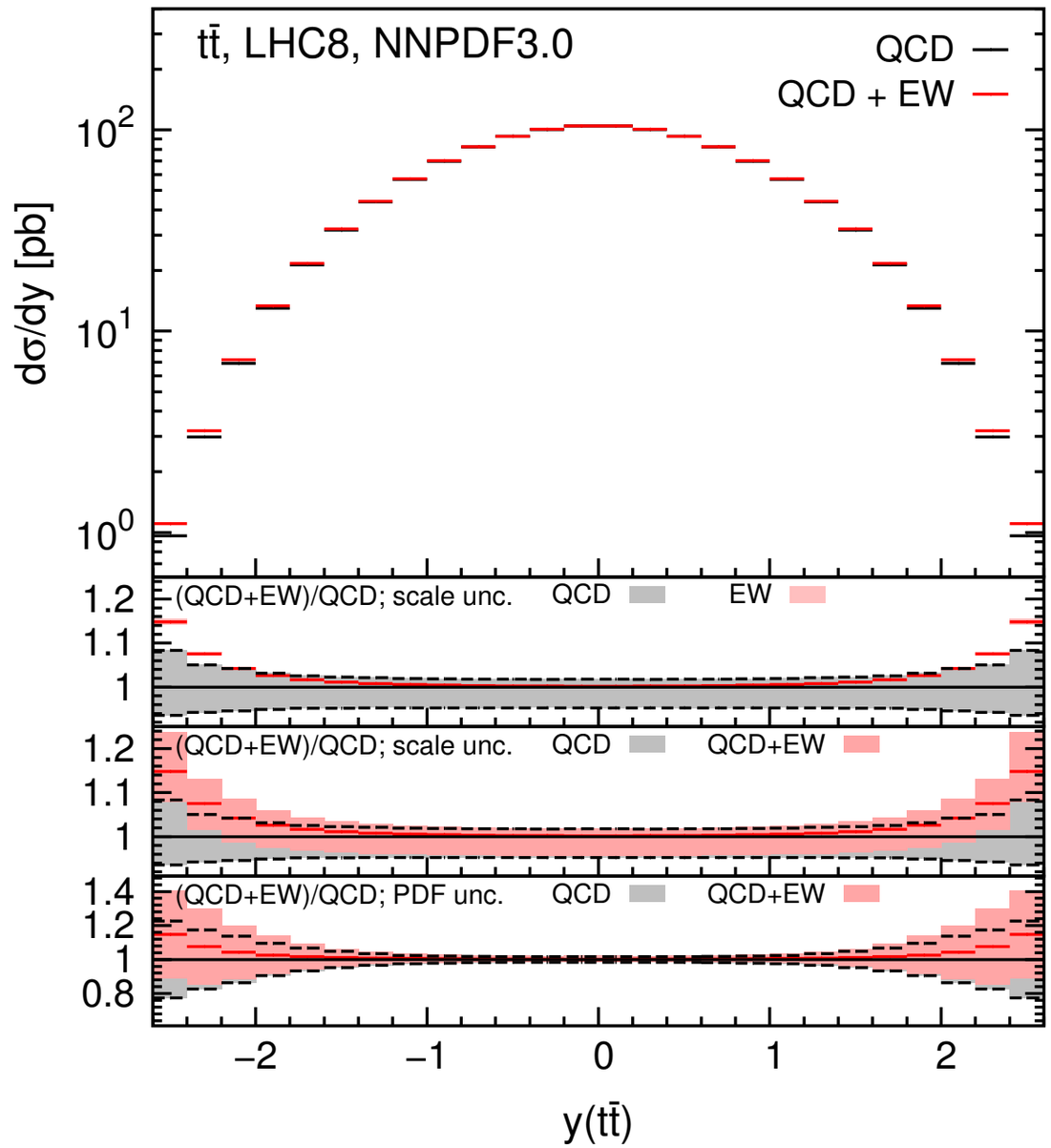
LUXQED

NNPDF3.0QED

$y(t\bar{t})$

8 TeV





LUXQED

photon PDF relevant at large rapidity

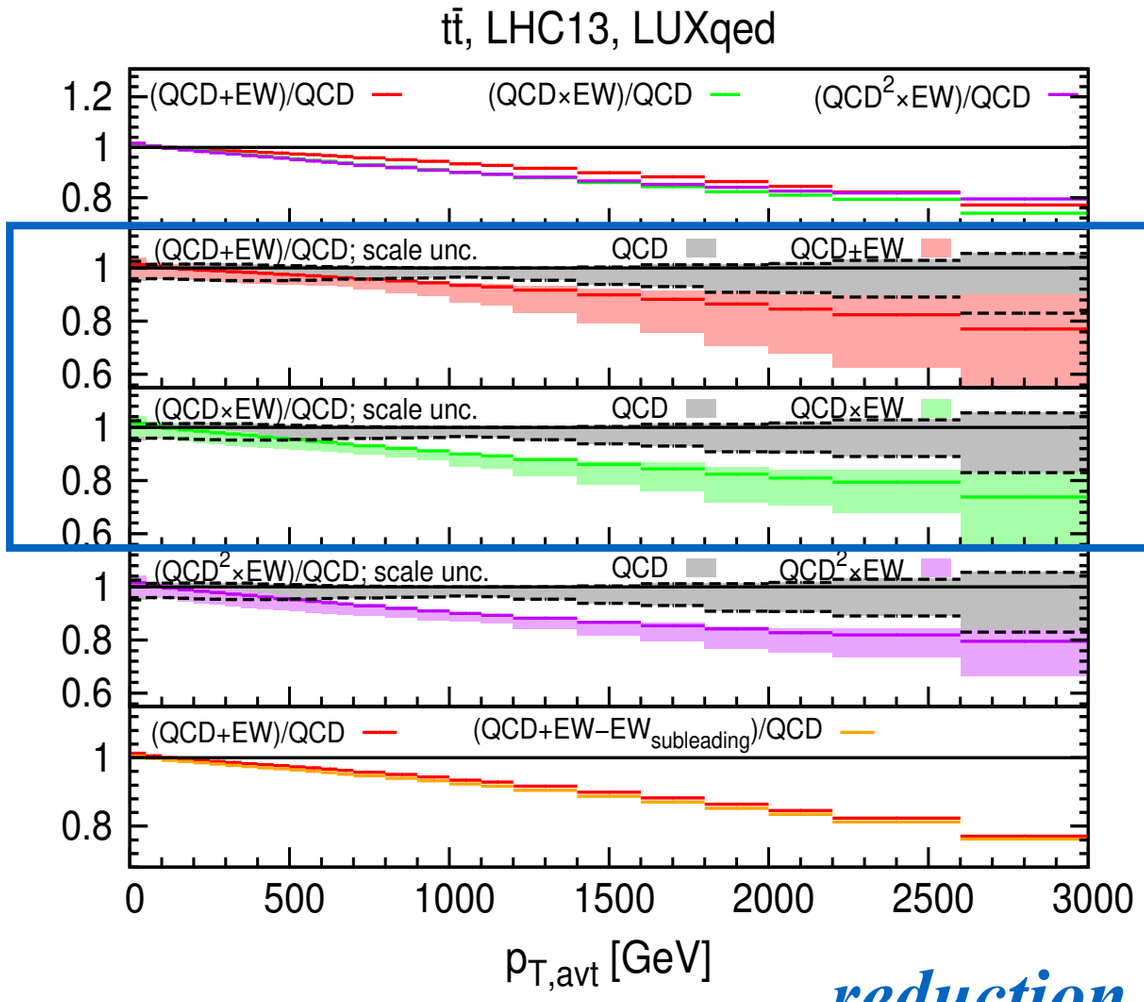
NNPDF3.0QED

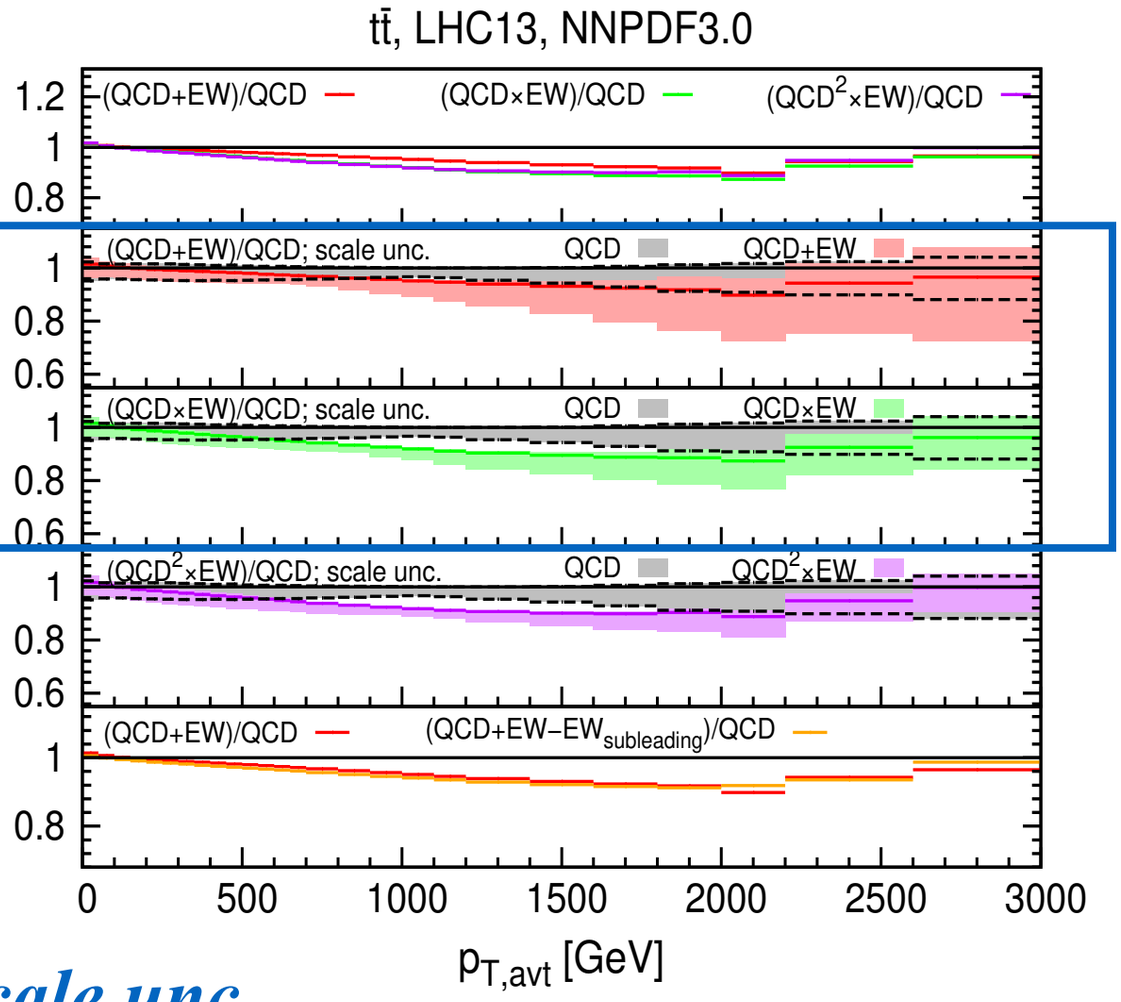
$p_{T,\mathrm{avt}}$

13 TeV

ADDITIVE

MULTIPLICATIVE





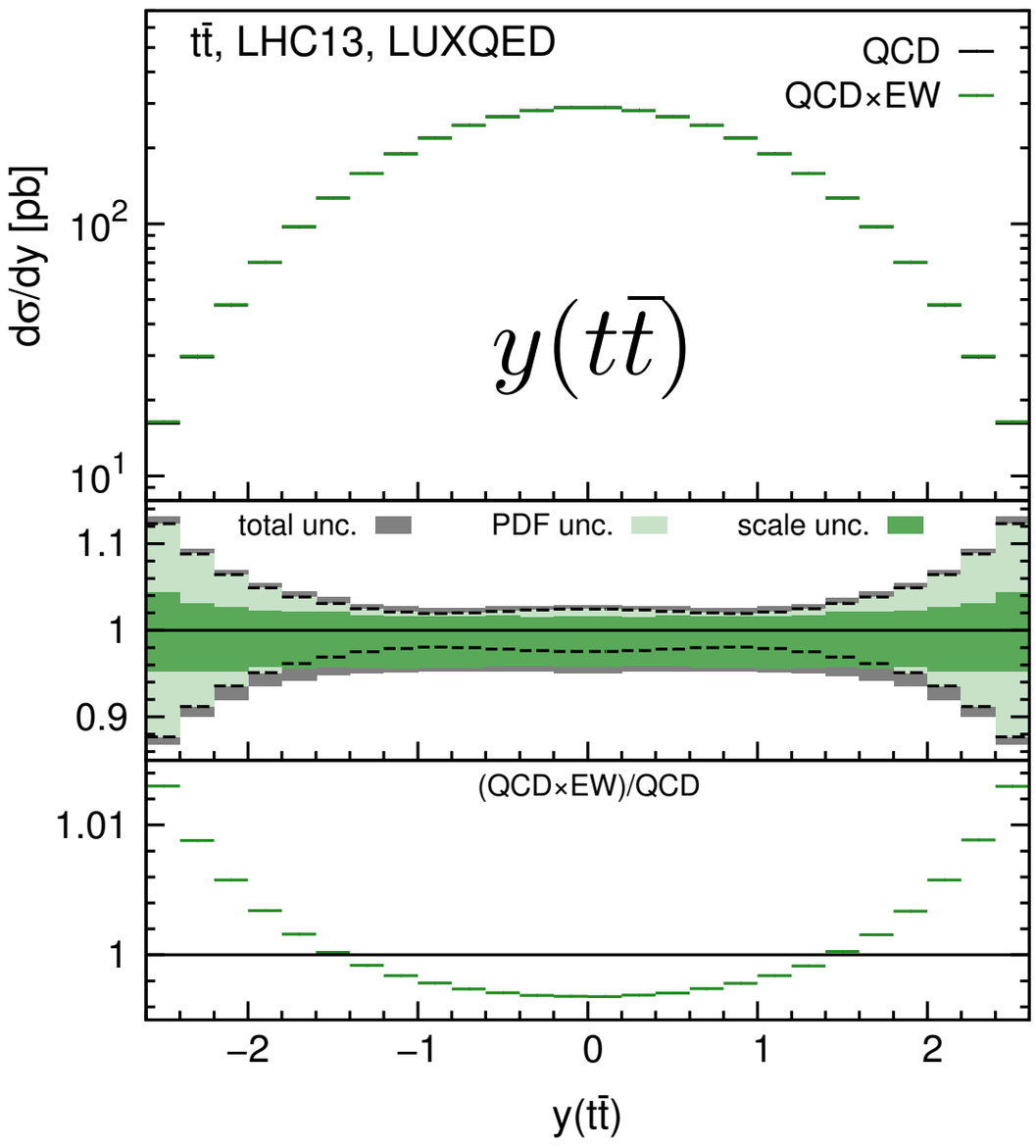
LUXQED

NNPDF3.0QED

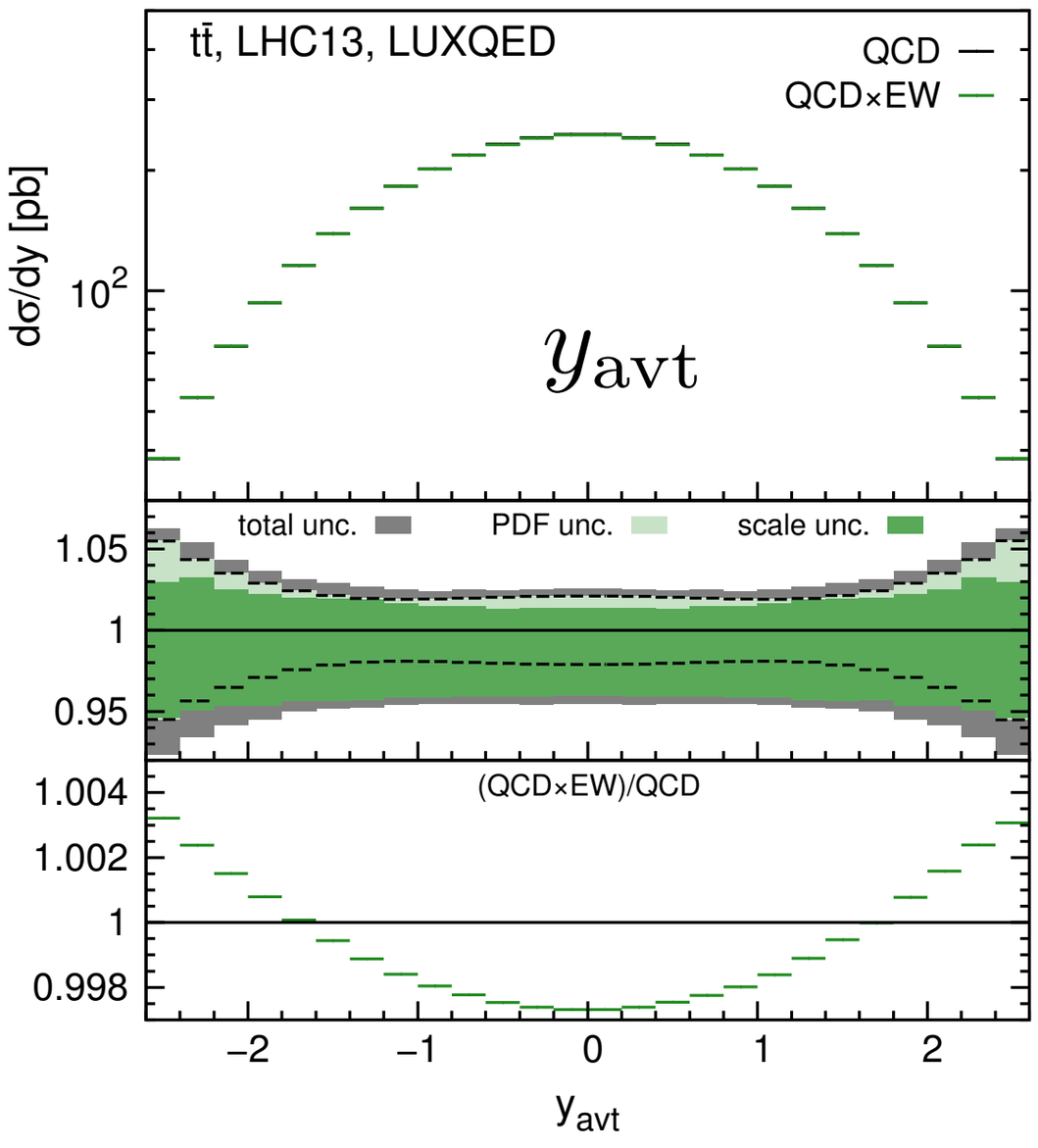
reduction of scale unc. due to EW corrections, QCD and QCDxEW do not overlap (with LUXQED)

13 TeV

MULTIPLICATIVE with LUXQED



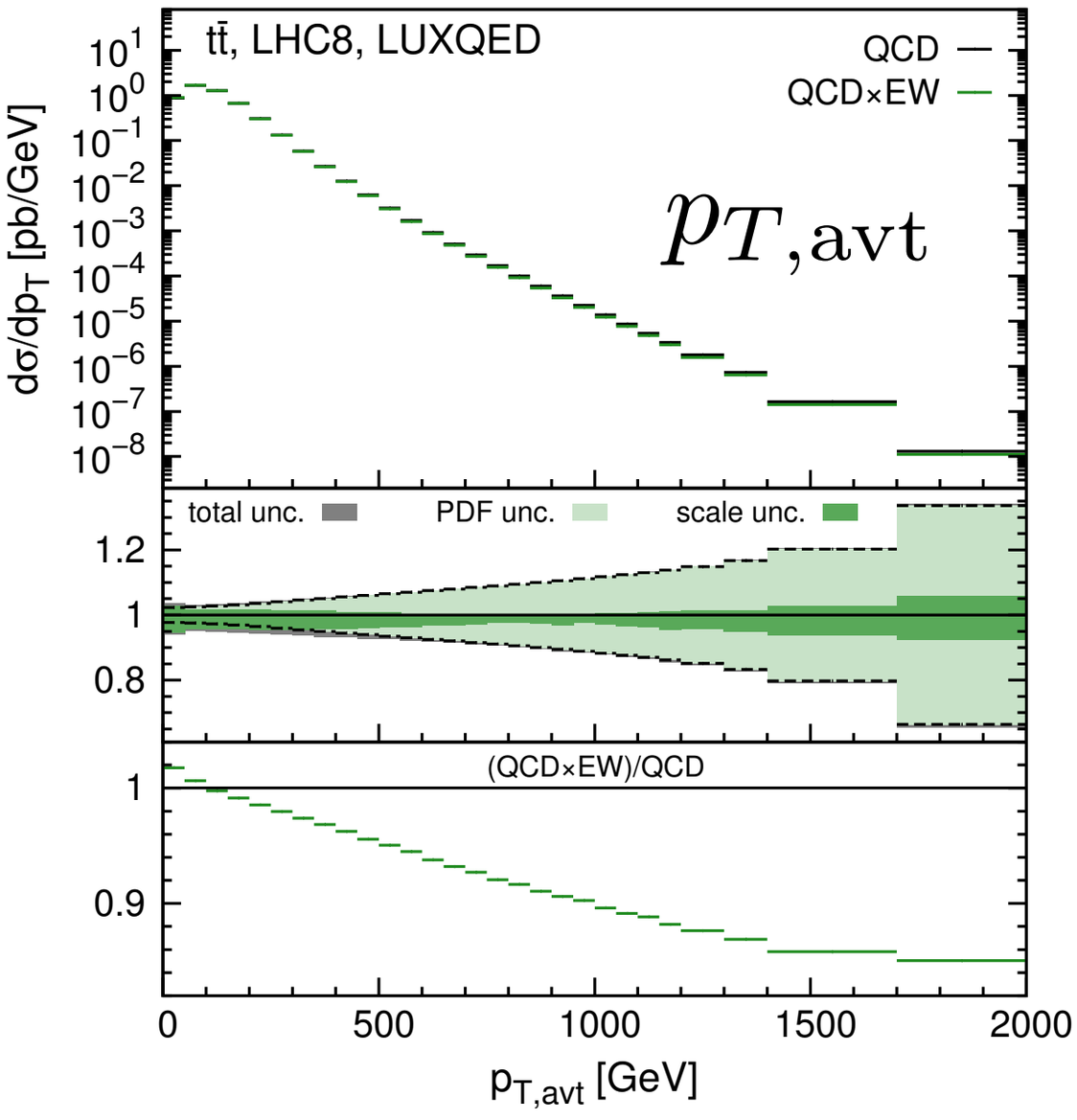
scale unc. ~ PDF unc, larger PDF unc. at large y

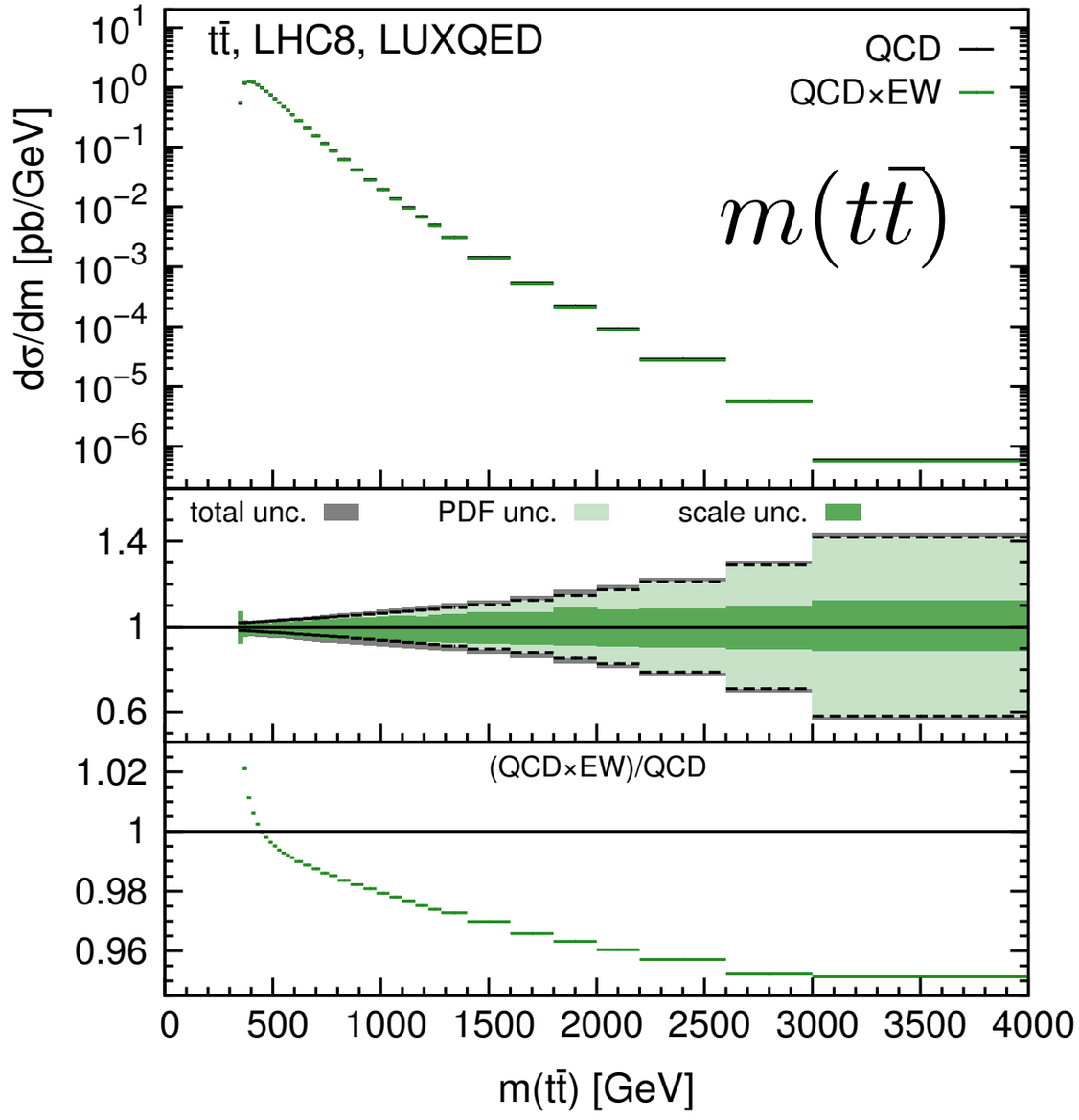


scale unc. ~ PDF unc,

8 TeV

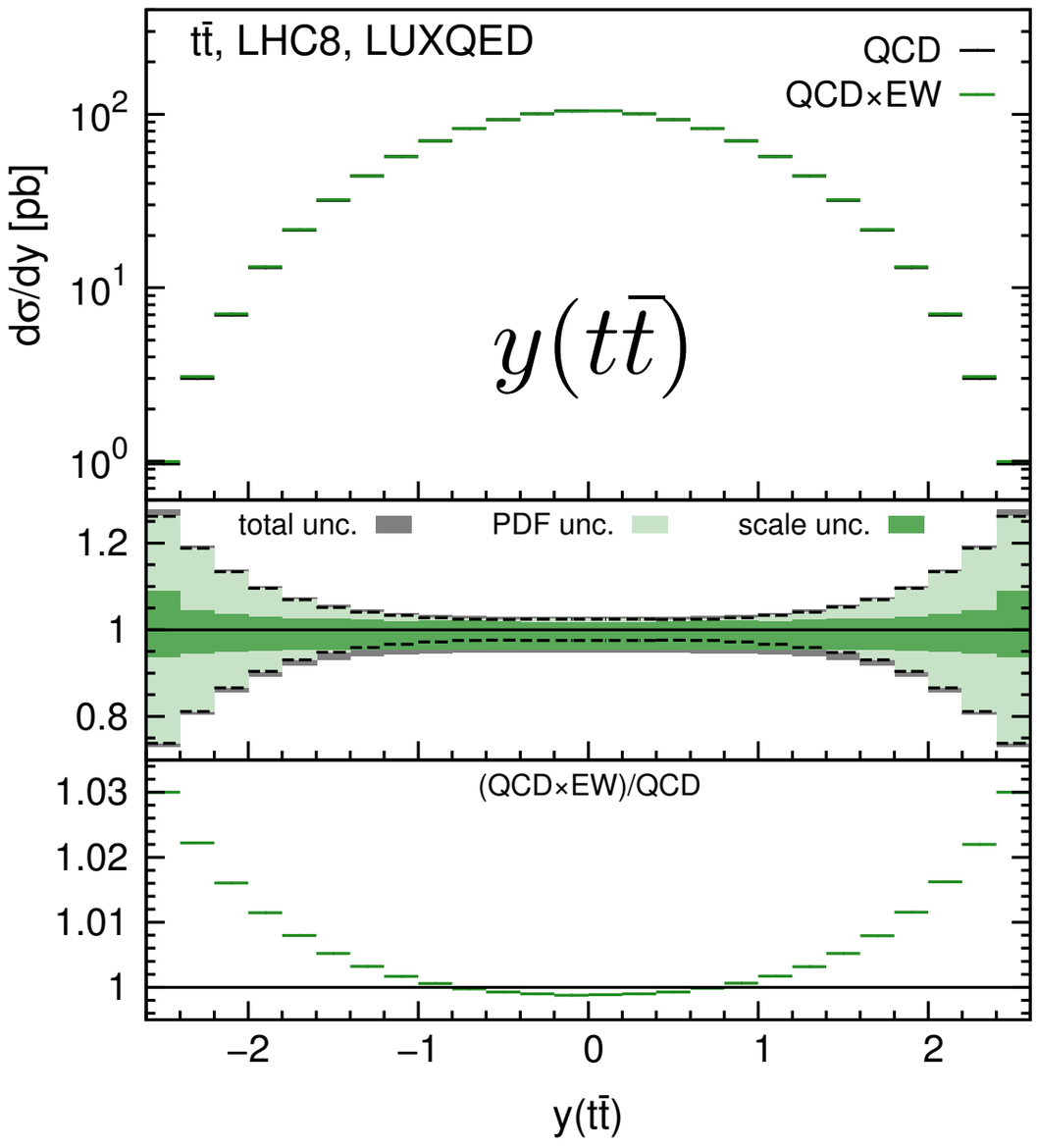
MULTIPLICATIVE with LUXQED

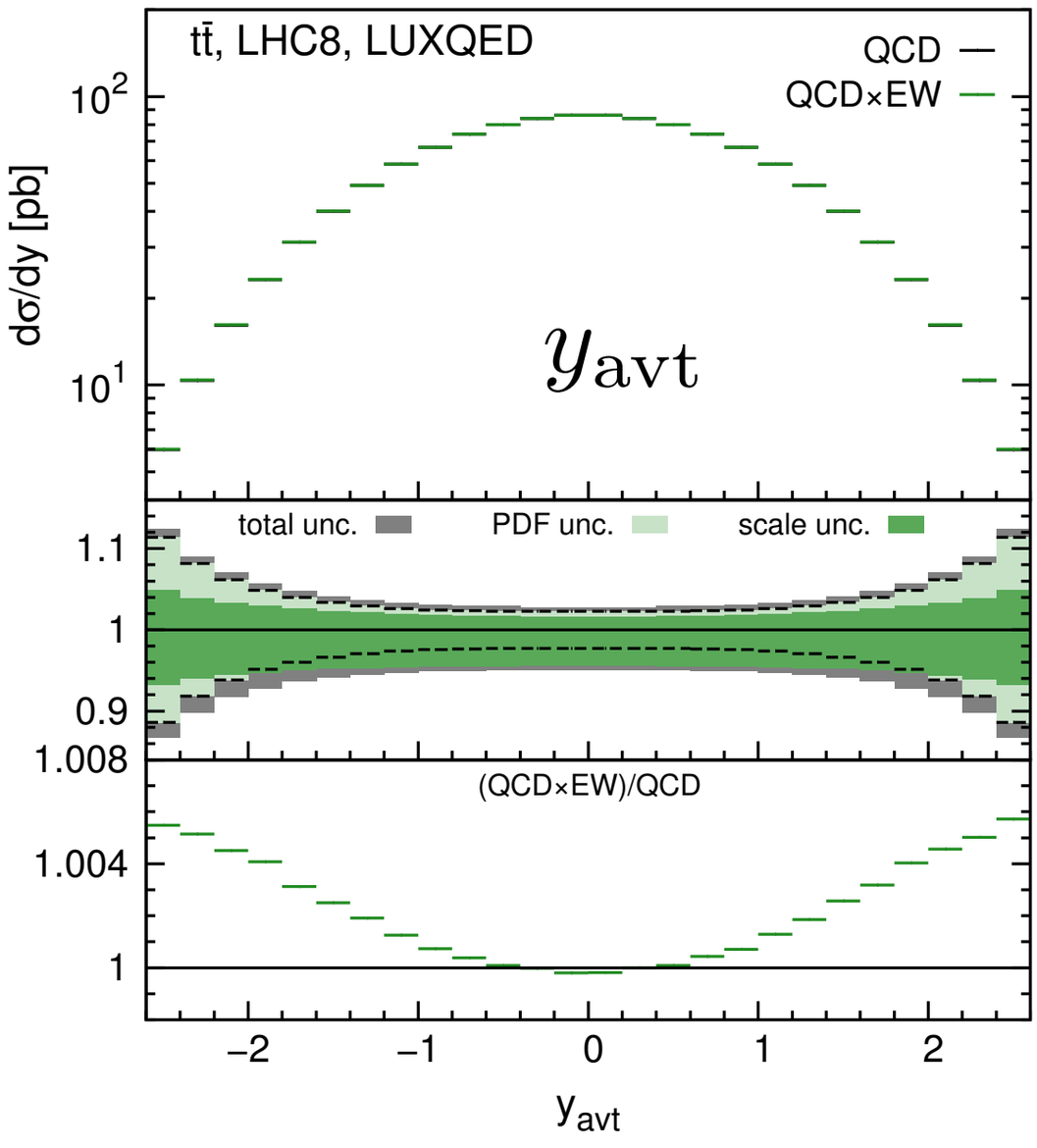




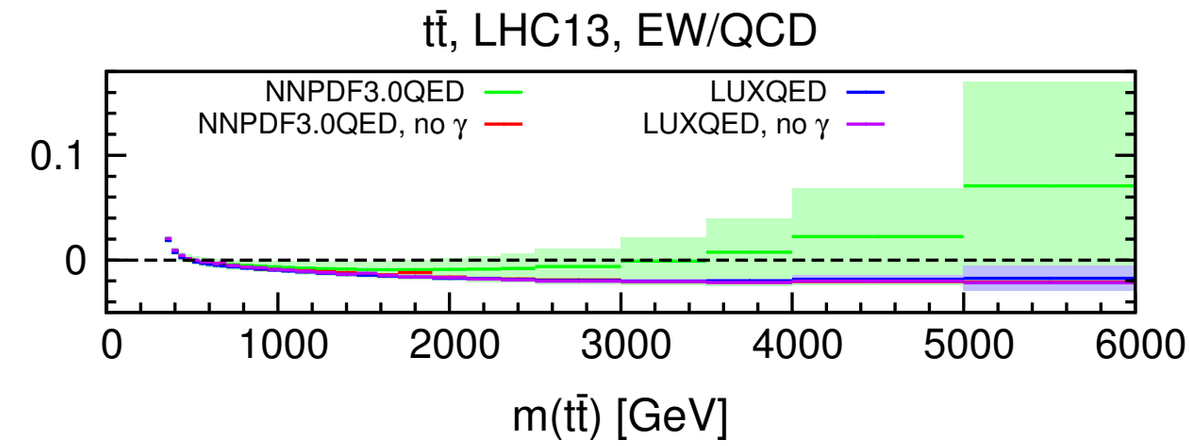
13 TeV

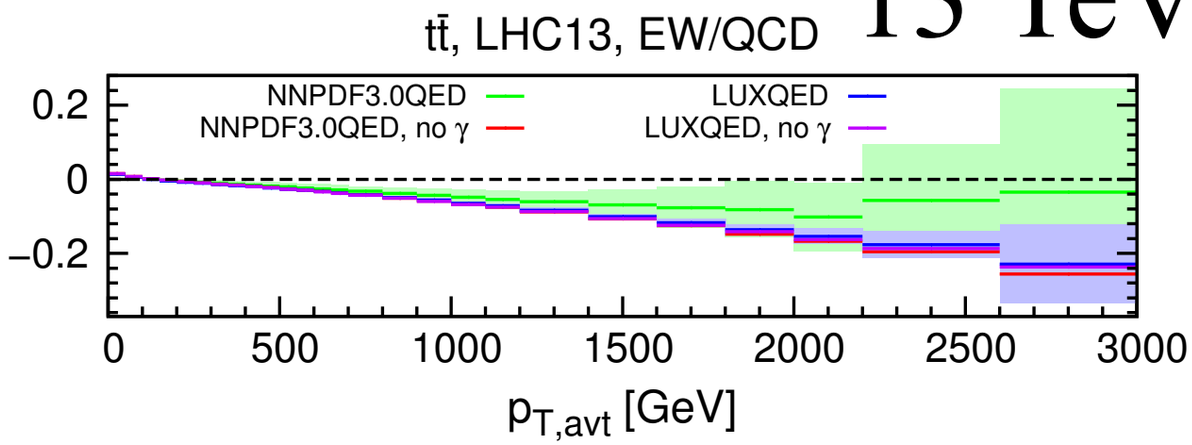
MULTIPLICATIVE with LUXQED

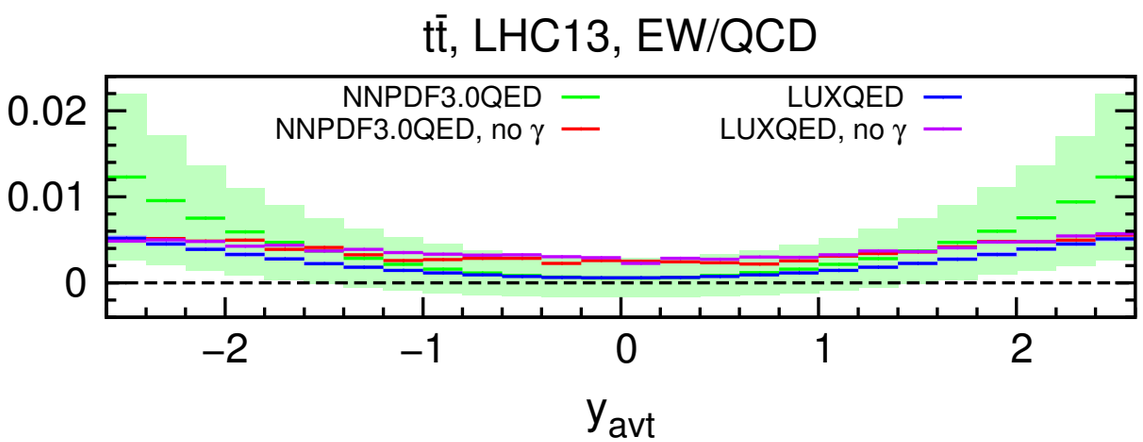




13 TeV


tt̄, LHC13, EW/QCD
NNPDF3.0QED
NNPDF3.0QED, no γ
LUXQED
LUXQED, no γ
0.1
0
0
1000
2000
3000
4000
5000
6000
m(tt̄) [GeV]


tt̄, LHC13, EW/QCD
NNPDF3.0QED
NNPDF3.0QED, no γ
LUXQED
LUXQED, no γ
0.2
0
−0.2
0
500
1000
1500
2000
2500
3000
p_T,avt [GeV]


tt̄, LHC13, EW/QCD
NNPDF3.0QED
NNPDF3.0QED, no γ
LUXQED
LUXQED, no γ
0.02
0.01
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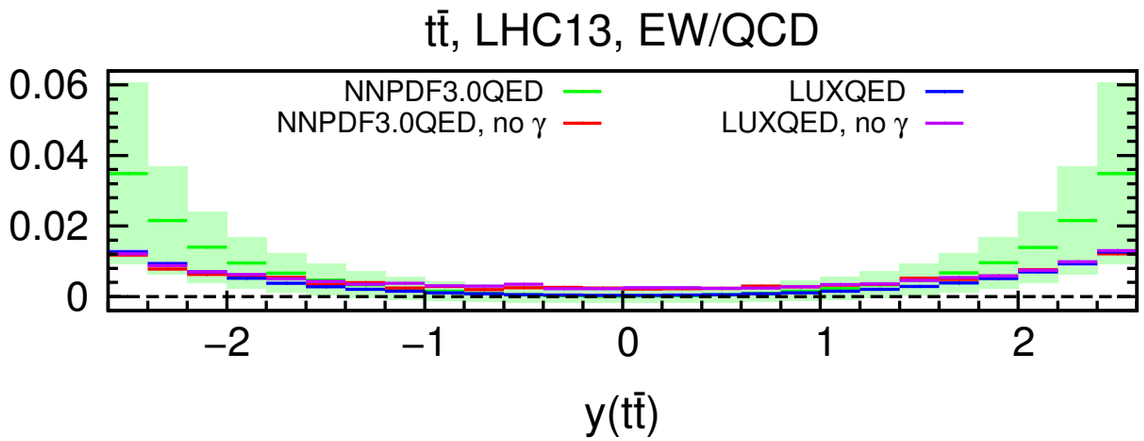
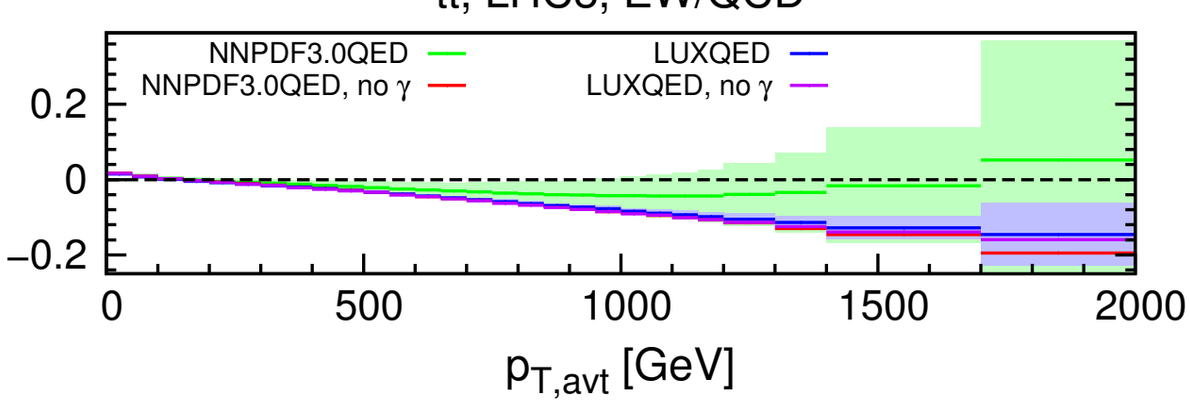
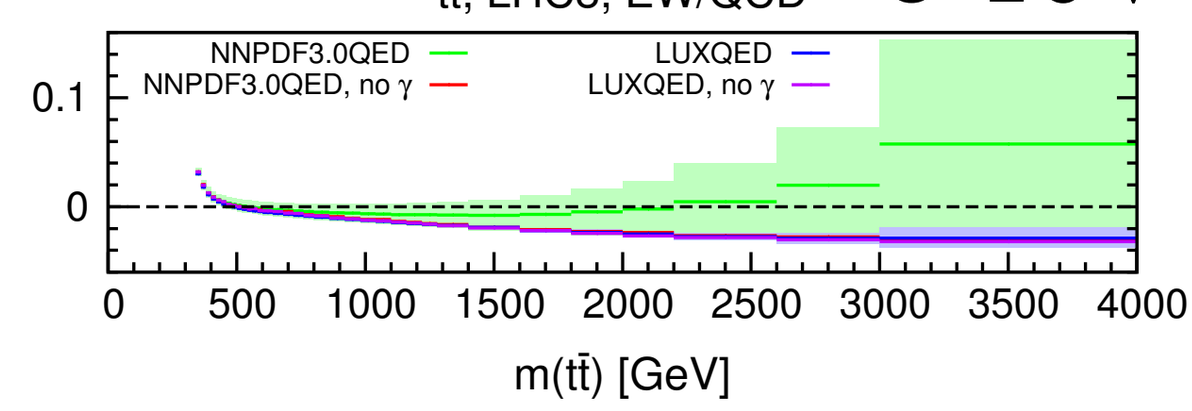
−1
0
1
2
y_avt


tt̄, LHC13, EW/QCD
NNPDF3.0QED
NNPDF3.0QED, no γ
LUXQED
LUXQED, no γ
0.06
0.04
0.02
0
−2
−1
0
1
2
y(tt̄)

8 TeV


tt̄, LHC8, EW/QCD
NNPDF3.0QED
NNPDF3.0QED, no γ
LUXQED
LUXQED, no γ
0.2
0
−0.2
0
500
1000
1500
2000
p_T,avt [GeV]


tt̄, LHC8, EW/QCD
NNPDF3.0QED
NNPDF3.0QED, no γ
LUXQED
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0.1
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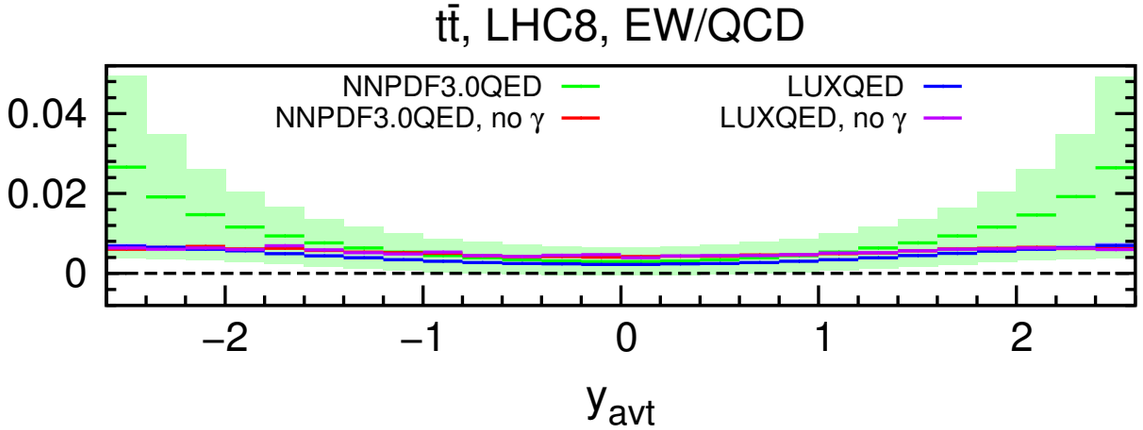
3500
4000
m(tt̄) [GeV]


tt̄, LHC8, EW/QCD
NNPDF3.0QED
NNPDF3.0QED, no γ
LUXQED
LUXQED, no γ
0.04
0.02
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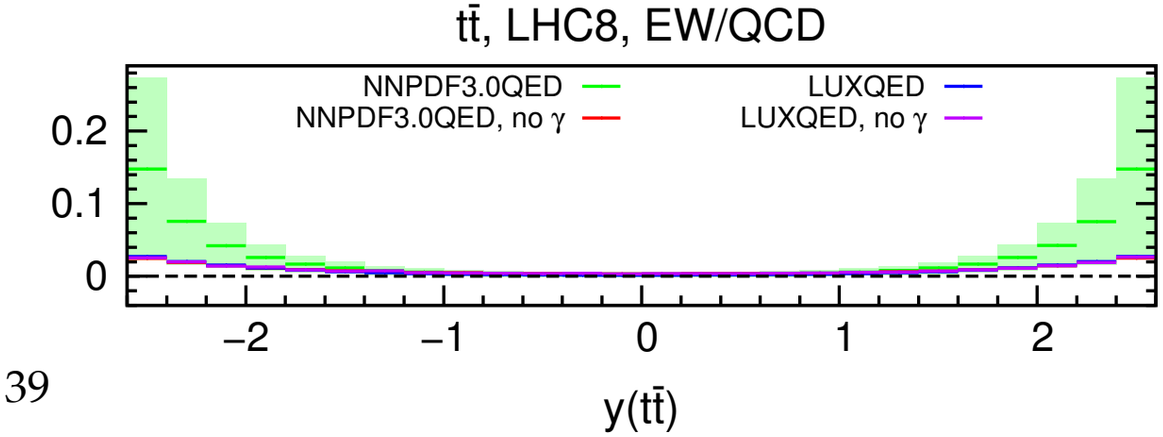
0
1
2
y_avt


tt̄, LHC8, EW/QCD
NNPDF3.0QED
NNPDF3.0QED, no γ
LUXQED
LUXQED, no γ
0.2
0.1
0
−2
−1
0
1
2
y(tt̄)

PDF sets with a photon density

MRST2004QED: *Martin et al. '04*
NNPDF2.3QED: *Ball et al. '13*
CTEQ14QED(inc): *Schmidt et al. '16*
NNPDF3.0QED: *Bertone, Carrazza '16*
LUXQED: *Manohar et al. '16*
MMHTQED? '16 ?
Additional Studies: *Harland-Lang, Khoze, Ryskin '16*

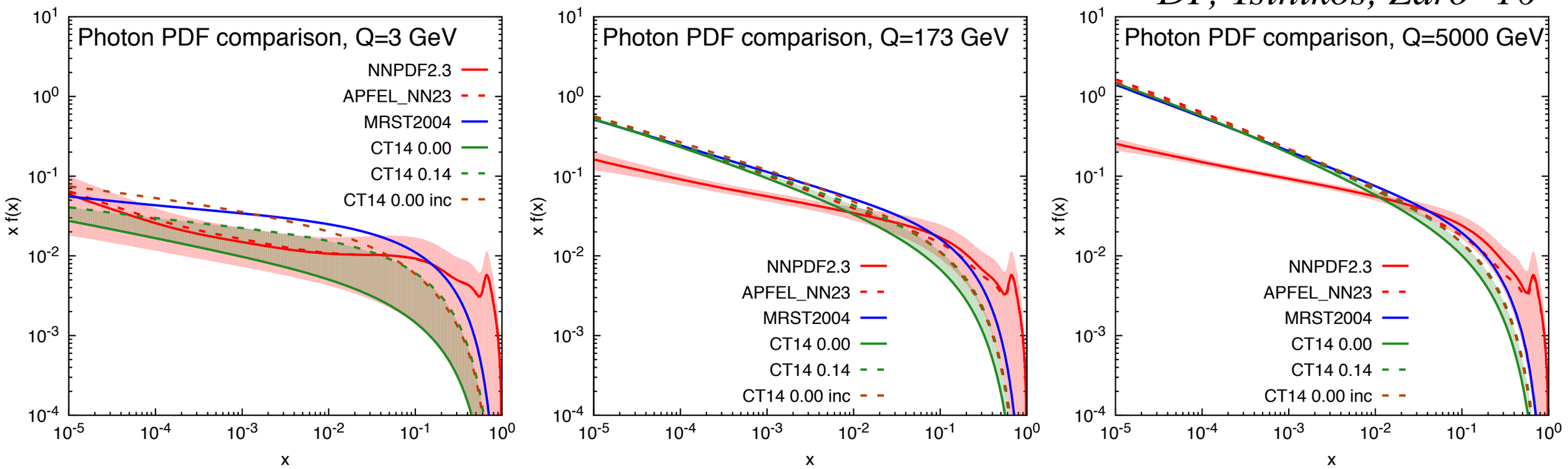
These PDF sets have at least NLO QCD + LO QED terms in the DGLAP evolution.

- The photon PDF determination is very different in the various sets.

- The different treatment of the QED and QCD DGLAP evolution has a huge impact at small x and large Q (**NNPDF2.3QED**), but does **not** lead to visible effects in ttbar phenomenology.

The different photon PDFs …

DP, Tsinikos, Zaro '16



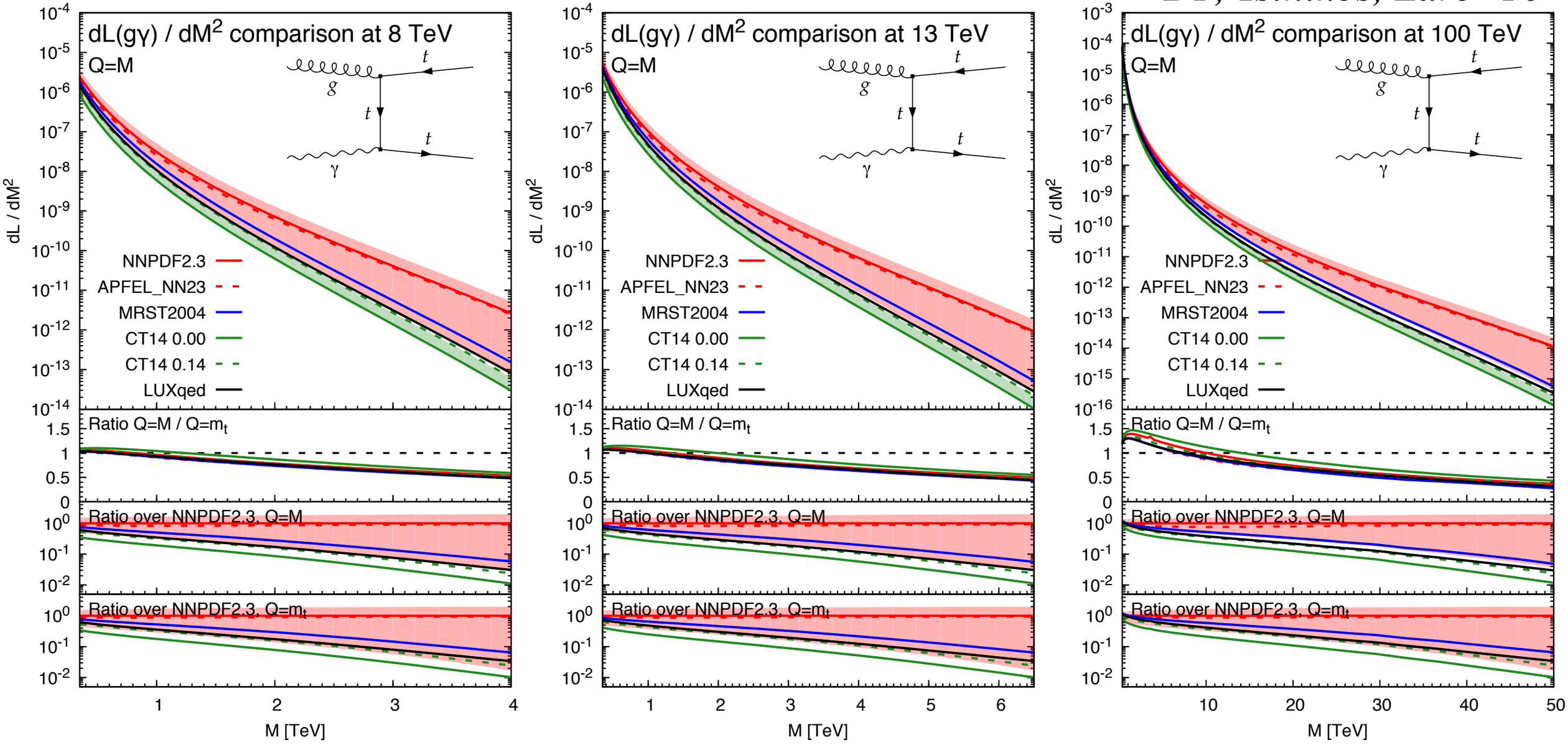
- APFEL_NN23 (*Bertone, Carrazza, DP, Zaro '15*) is at the initial scale equivalent to **NNPDF2.3QED** for all the PDFs. But, the DGLAP QCD and QED running is consistent (similar to **NNPDF3.0QED**, where also quark and gluons have been updated to **NNPDF3.0**).

- At small Q: **APFEL_NN23** is like **NNPDF2.3QED.** At large Q: it is like **CTEQ14QED** at small x, while it is like **NNPDF2.3QED** at large x.

- CTEQ14QED is close to the upper edge of the **CTEQ14QEDinc** band.

… and the different photon-gluon luminosities

DP, Tsinikos, Zaro '16

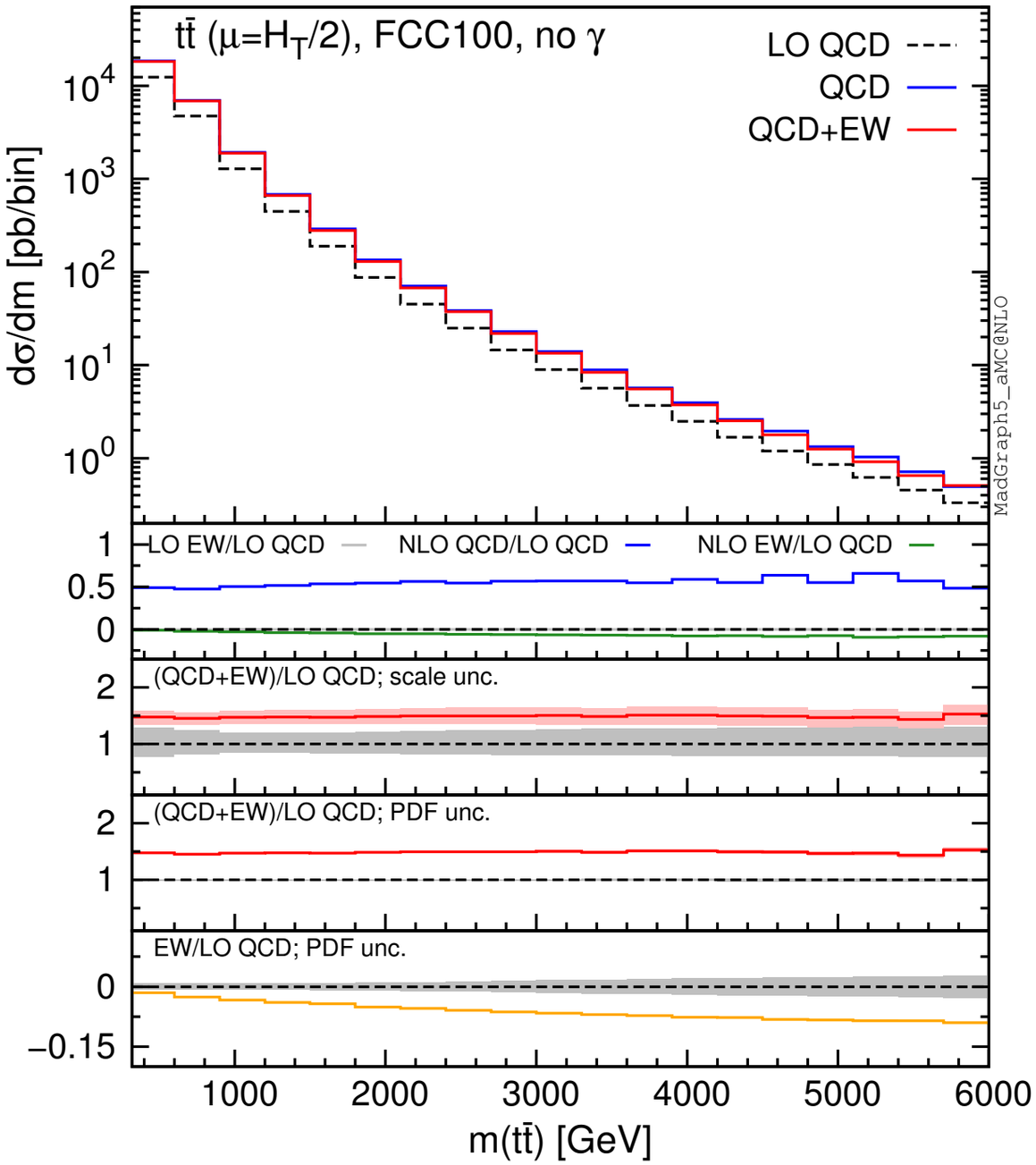


- **LUXQED** luminosity is very close to **CTEQ14QED**
- **NNPDF2.3QED** and **APFEL_NN23** are equivalent! (diff. running is not relevant)

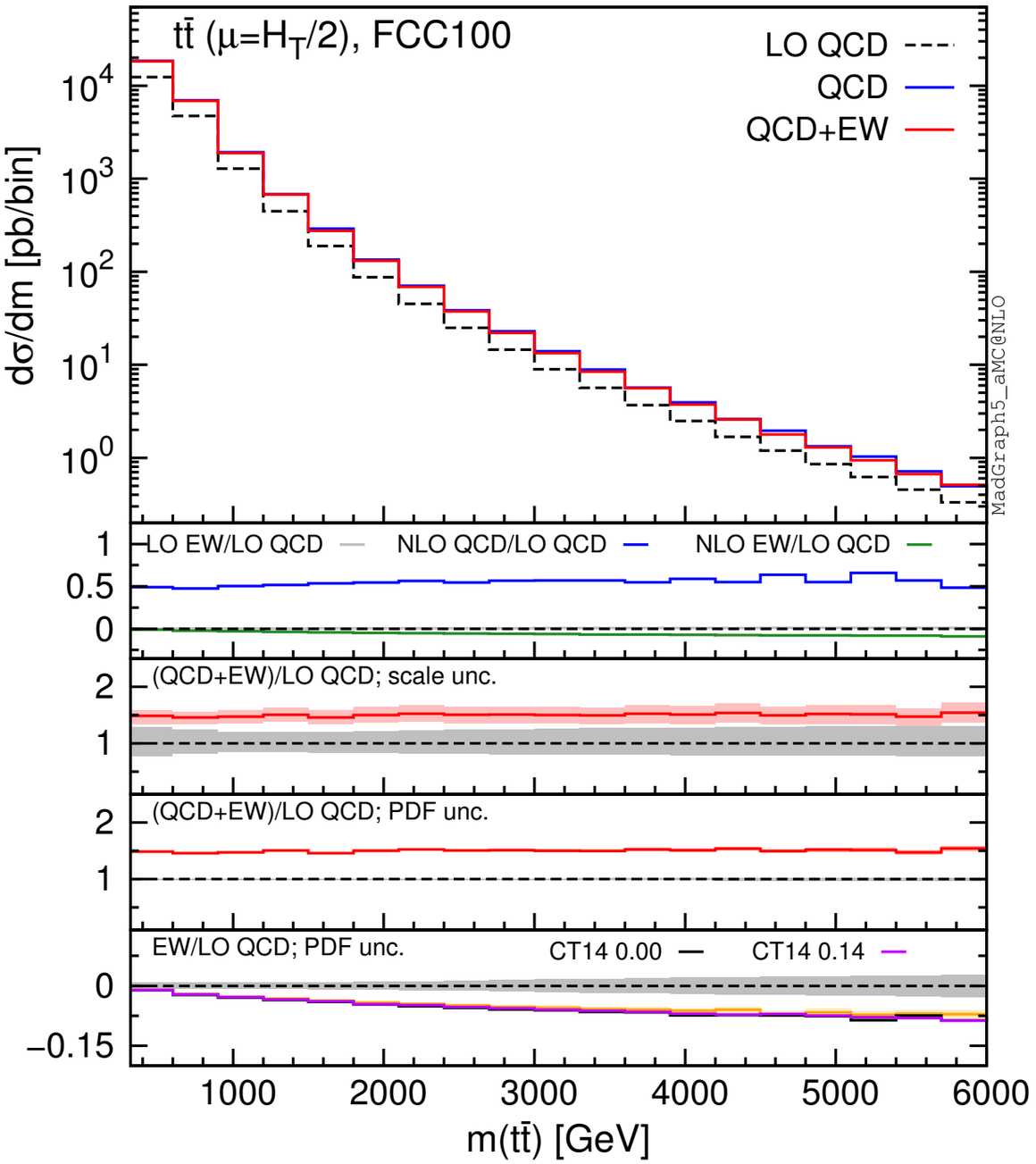
NNPDF2.3QED representative for **(NNPDF3.0QED, APFEL_NN23)**
CTEQ14QED representative for **(CTEQ14QEDinc, LUXQED)**

100 TeV

DP, Tsinikos, Zaro '16



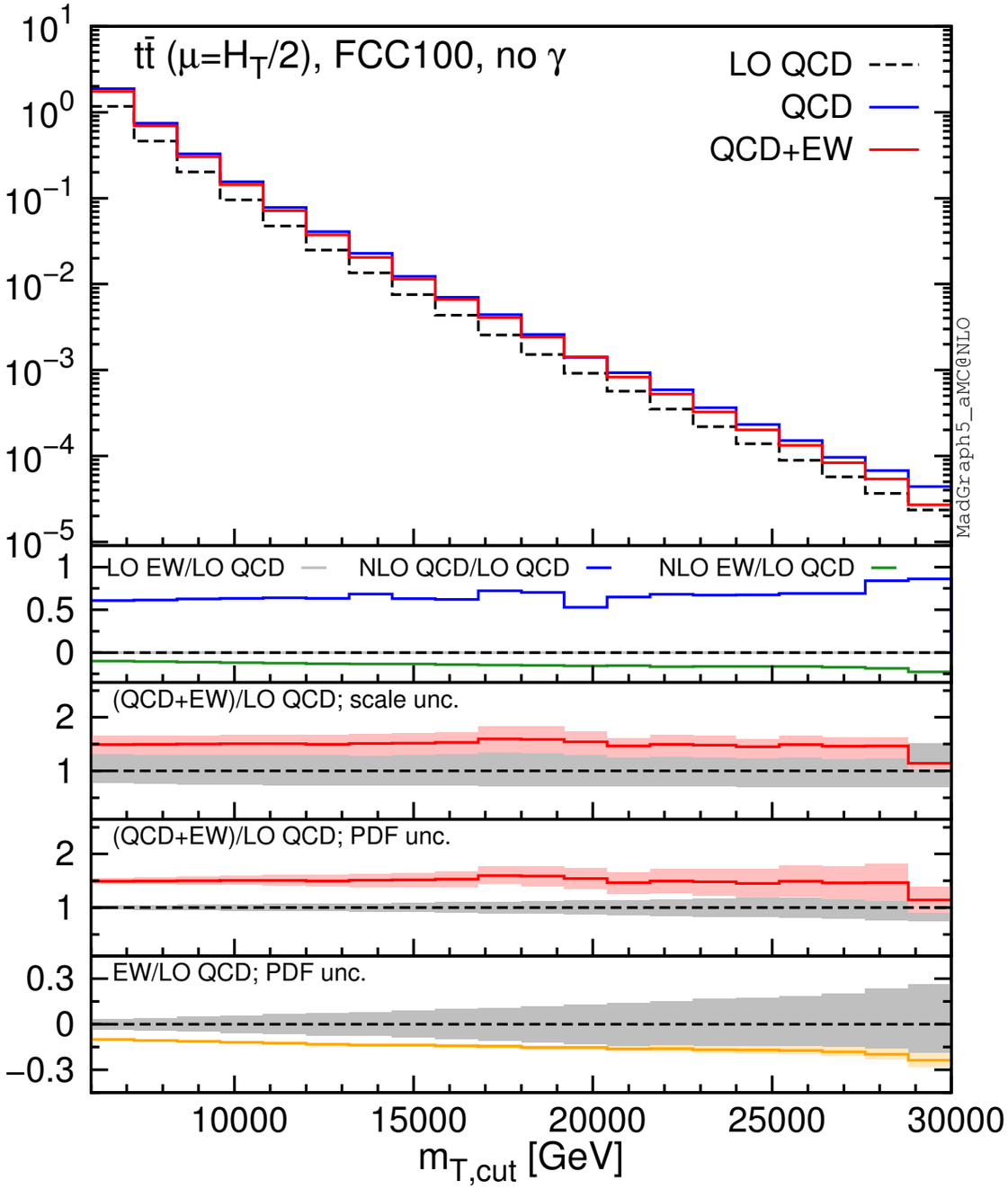
photon PDF **NO**



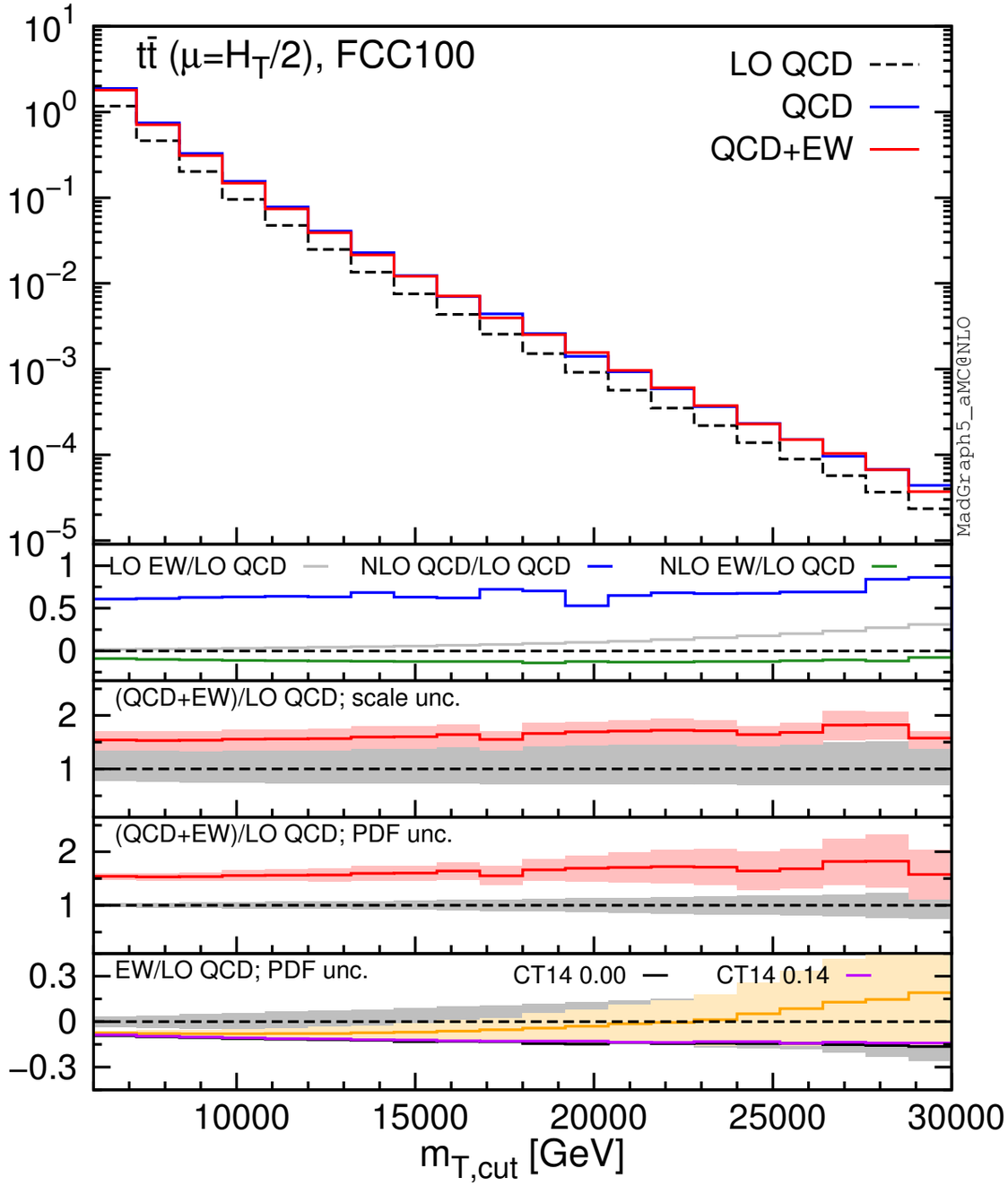
photon PDF **YES**

100 TeV

DP, Tsinikos, Zaro '16



photon PDF **NO**



photon PDF **YES**