Top-quark pair production at NNLO QCD and NLO EW accuracy

mainly based on arXiv:1705.04105 and work in collaboration with M. Czakon, D. Heymes, A. Mitov, A. Papanastasiou, I. Tsinikos, M. Zaro

results and histograms available at http://www.precision.hep.phy.cam.ac.uk/results/ttbar-nnloqcd-nloew/

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TOP2017
Braga
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Motivation

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

8 TeV data have shown a tension with NLO QCD predictions for pt(top) distributions, which is partially explained by **NNLO QCD corrections**.
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**EW corrections** have a similar size ($\alpha_s^2 \sim \alpha$), with **Sudakov enhancements** in the boosted regime. However, only a part of them has been taken into account in experimental analyses, and no consistent combination with NNLO QCD (same input parameters, PDFs and scale) was available till recently.
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We provided predictions at complete NLO accuracy including also NNLO QCD corrections for differential distributions in top-quark pair production at 8 and 13 TeV.
Motivation (part 2)

If you do not believe that NNLO QCD + NLO EW corrections are essential: do you remember the forward-backward asymmetry at the Tevatron?

It is exactly the same process, at another hadron collider.

FIG. 1: The inclusive asymmetry in pure QCD (black) and QCD+EW[28] (red). Capital letters (NLO, NNLO) correspond to the unexpanded definition (2), while small letters (nlo, nnlo) to the definition (3).

A posteriori, it was realized that a large fraction of the discrepancy was due to the missing contributions from:

EW corrections  
(Hollik, DP ’11)

and

NNLO QCD corrections  
(Czakon, Fiedler, Mitov ’15)
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NEW PRELIMINARY RESULTS LATER IN THIS TALK!

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FIG. 1: The inclusive asymmetry in pure QCD (black) and QCD+EW[28] (red). Capital letters (NLO, NNLO) correspond to the unexpanded definition (2), while small letters (nlo, nnlo) to the definition (3).
The calculation of **NNLO QCD** corrections is based on Czakon, Fiedler, Mitov ’15

The calculation of the **complete NLO** corrections is performed with the EW branch of **MadGraph5_aMC@NLO** (Frixione, Hirschi, DP, Shao, Zaro ’14, ’15).

**Calculation framework**

All these orders are taken into account, without any approximation.
Choice of input parameters

\[ m_t = 173.3 \text{ GeV}, \quad m_H = 125.09 \text{ GeV}, \quad m_W = 80.385 \text{ GeV}, \quad m_Z = 91.1876 \text{ GeV}. \]

\[ G_\mu = 1.1663787 \cdot 10^{-5} \text{ GeV}^{-2} \quad \text{for the parametrization of the EW couplings} \]

Five-flavor-scheme for \( \alpha_s \)

Which Factorization and Renormalization scale?

Which PDF set?
NNLO QCD: scale definition

The dependence on the ren. and fac. scale is mainly due to QCD effects.
The scale that minimizes NLO and NNLO corrections can be chosen as optimal scale: “Principle of fastest convergence”.
The best-scale definition can also depend on the observable:

\[
\mu_0 = \begin{cases} 
  \frac{m_T}{2} & \text{for : } p_{T,t}, p_{T,\bar{t}} \text{ and } p_{T,t/\bar{t}}, \\
  \frac{H_T}{4} & \text{for : all other distributions}
\end{cases}
\]

\[
H_T = \sqrt{m_t^2 + p_{T,t}^2} + \sqrt{m_t^2 + p_{T,\bar{t}}^2}
\]
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 + (N)LO QED:

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

They both include a photon PDF!
EW corrections: PDFs choice

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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

![Feynman diagrams for photon induced t\bar{t} production at lowest order.](image)

**Figure 8:** Feynman diagrams for photon induced t\bar{t} production at lowest order.

In addition to the previously mentioned NLO QED contributions we also have to inspect the photon-induced production channels. These comprise at lowest order the gluon–photon fusion amplitudes illustrated in Fig. 8.

In general, photon-induced partonic processes vanish at the hadron level unless the NLO QED effects are taken into account. A direct consequence of including these effects into the evolution of parton distribution functions (PDFs) is the non-zero photon density in the proton, which leads to photon-induced contributions at the hadronic level by convoluting the photon-induced partonic cross sections with the PDFs at NLO QED. Since the photon distribution function is of order $\alpha$, they are formally not of the same overall order as the other NLO QED contributions. Numerically, however, they turn out to be sizeable, and we therefore include them in our discussion.

As the PDFs at NLO QED have become available only recently [42], the photon-induced hadronic processes have not yet been investigated. Here we present the first study of these effects on the top pair production.

For obtaining the hadronic cross section we have to convolute the various partonic cross sections with the corresponding parton densities and sum over all contributing channels, adding up contributions of the non-radiative and radiative processes. As already mentioned, only the sum of all virtual and real corrections is IR finite. Final step is the factorization of the remaining mass singularities.

### 3.1 Mass factorization

The mass-singular logarithmic terms proportional to $\ln m_q$ are not canceled in the sum of virtual and real corrections. They originate from collinear photon emission off the incoming light quarks. In analogy to the factorization of collinear gluon contributions, they have to be absorbed into the parton densities. This can be formally achieved by replacing the bare quark distributions $q_i(x)$ for each flavor by the appropriate scale dependent distribution $s_{q_i}(x, Q^2)$ in the following:
Results
Large scale unc. from
EW corrections

LUXQED +

NNPDF3.0QED

Photon PDF relevant

13 TeV
For theoretical consistency, a set of PDF including QED effects is recommended. While in the case of LUXQED, the photon PDF relevant at large rapidity is already included. LUXQED is shown in the plot as a red line the ratio of the central-scale predictions at QCD+EW and QCD accuracy, respectively. The three insets below the main panel display ratios of differential cross sections both at NNLO QCD accuracy, the black line labelled as "QCD", and including also the EW corrections, the red line labelled as "QCD+EW". This quantity can be directly compared to the relative scale uncertainties due to missing higher orders estimated via the 7-point variation of the observable. For this reason we decided to show always predictions with both the PDF sets.

\[
y(t\bar{t})
\]

\[
\frac{\sigma_{(QCD+EW)}/\sigma_{QCD}}{\sigma_{(QCD+EW)}}, \ LHC8, \ LUXqed
\]

\[
\frac{\sigma_{(QCD+EW)}/\sigma_{QCD}}{\sigma_{(QCD+EW)}}, \ 8 \text{ TeV}
\]

\[
\frac{\sigma_{(QCD+EW)}/\sigma_{QCD}}{\sigma_{(QCD+EW)}}, \ LHC8, \ NNPDF3.0QED
\]

\[
\frac{\sigma_{(QCD+EW)}/\sigma_{QCD}}{\sigma_{(QCD+EW)}}, \ 8 \text{ TeV}
\]
Can we do better?

Can we estimate NNLO mixed QCD-EW effects?
Can we reduce the scale-dependence from NLO EW effects?
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Combination of EW and QCD corrections in the multiplicative approach

When QCD and EW effects factorize (e.g. soft QCD and Sudakov Logarithms) multiplying NLO QCD with NLO EW is a good approximation for NNLO mixed QCD-EW effects. In general, it can be used as an estimate of uncertainties due to mixed QCD-EW higher order effects.
In order to help the reader and be as close as possible to the common notation, we further define the term "NLO EW corrections" for only the different way, which we rename for convenience $\alpha_s^2 \bar{t}$, $\alpha_s \bar{t}$, and $\alpha \bar{t}$, also the stabilisation of the scale dependence of the terms is also the stabilisation of the scale dependence of the general do not consider the e

$\Sigma_{QCD \times EW} \equiv \Sigma_{QCD} + K_{QCD}^{NLO} \Sigma_{NLO \ EW} + \Sigma_{LO \ EW} + \Sigma_{subleading}$
Multiplicative combination

\[ \Sigma_{QCD \times EW} \equiv \Sigma_{QCD} + K_{QCD}^{NLO} \Sigma_{NLO EW} + \Sigma_{LO EW} + \Sigma_{subleading} \]
The purpose of the multiplicative approach is to estimate the size of purely QCD quantities as an estimate of the leading missing mixed QCD-EW higher orders. The advantage of the inclusion of these contributions depends on the photon PDF. The dominant photon-induced initial state is the boson-radiation (HBR), as also done in ref. [3].

We will refer to the quantity $\sum_{\text{QCD}} \times \sum_{\text{EW}}$ as the multiplicative combination. The linear combination of NNLO QCD results and electroweak corrections can thus be defined as $\sum_{\text{QCD}} \times \sum_{\text{EW}} = \sum_{\text{QCD}} + K_{\text{QCD}}^{\text{NLO}} \sum_{\text{NLO EW}} + \sum_{\text{LO EW}} + \sum_{\text{subleading}}$. In this way, we will compare consistently with the notation in the plots of the previous section. With the term “EW corrections” we will refer to the quantity $\sum_{\text{EW}}$.
\[
\sum_{QCD \times EW} \equiv \sum_{QCD} + K_{QCD}^{NLO} \sum_{NLO \ EW} + \sum_{LO \ EW} + \sum_{\text{subleading}}
\]
In the following, consistently to what has been done in the previous section, with the term "EW correction" we define the quantity: 

\[ \Sigma_{QCD\times EW} \equiv \Sigma_{QCD} + K_{QCD}^{NLO} \Sigma_{NLO\ EW} + \Sigma_{LO\ EW} + \Sigma_{subleading} \]
\[ \Sigma_{QCD \times EW} \equiv \Sigma_{QCD} + K_{QCD}^{NLO} \Sigma_{NLO\ EW} + \Sigma_{LO\ EW} + \Sigma_{\text{subleading}} \]

\[ \Sigma_{QCD^2 \times EW} \equiv \Sigma_{QCD} + K_{QCD}^{NNLO} \Sigma_{NLO\ EW} + \Sigma_{LO\ EW} + \Sigma_{\text{subleading}} \]
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Results
The three insets below the main panel display ratios of distributions for $t\bar{t}$, LHC13, LUXQED and $t\bar{t}$, LHC13, NNPDF3.0. Both QCD and QCD+EW predictions are provided in the main panel for the central scale. Accuracy of the QCD+EW result is achieved by adding the EW corrections into the QCD prediction and thus we provide the scale-uncertainty band (red) for these predictions. Similarly to all the previous insets, when the gray band does not overlap the observable $f_{QCD+EW}/QCD$, we include them and are also NNLO QCD accurate are included.

For theoretical consistency, a set of PDF including QED corrections is used. Both QCD and QCD+EW predictions are provided in the main panel for the central scale. Accuracy of the QCD+EW result is achieved by adding the EW corrections into the QCD prediction and thus we provide the scale-uncertainty band (red) for these predictions. Similarly to all the previous insets, when the gray band does not overlap the observable $f_{QCD+EW}/QCD$, we include them and are also NNLO QCD accurate are included.

As can be noted by Figs. [DP: 1], the usage of different PDF sets leads to a very different impact of photon-induced contributions.

The third inset is equivalent to the second one, but it concerns the PDF uncertainties. We combine, scale by scale in the 7-point variation approach, the QCD prediction and the EW corrections into the QCD+EW result and similarly to all the previous insets, when the gray band does not overlap the observable $f_{QCD+EW}/QCD$, we include them and are also NNLO QCD accurate are included.
m(\bar{t}t)

ADDITIVE MULTIPLICATIVE

**QCD+EW ~ QCDxEW**

LUXQED

NNPDF3.0QED

13 TeV
The three insets below the main panel display ratios of distributions for dileptons, dimuons, and dihadrons. The first inset is equivalent to the second one, but it concerns the PDF uncertainties. We combine, for theoretical consistency, a set of PDF including QED corrections to QCD accuracy, the black line labelled as "QCD", and including also the EW corrections, the red line labelled as "QCD+EW". In all cases, the central scale, the EW corrections in the numerator of this ratio. This quantity can be directly compared to the relative scale uncertainties due only to the theoretical uncertainties due to missing higher orders are estimated via the 7-point variation of µ/µ = f1/t1 m1/µavt1, normalised to the black line displayed in the main panel. In all the three insets we include them and are also NNLO QCD accurate are preferred whenever NLO EW corrections are computed. At the moment, the only two PDF sets that are covered by the red one, its borders are displayed as black dashed lines. Similarly to all the previous insets, when the gray band is the EW corrections into the QCD+EW result and thus we provide the scale-uncertainty band (red) for the PDF uncertainty band for the QCD predictions.

We may put them in a footnote? As can be noted by Figs. 1.1, the usage of di plays a role in the impact of photon-induced contributions is within the NNLO QCD effects in the DGLAP evolution, but they are not effects in the DGLAP evolution should always be preferred whenever NLO EW corrections are computed. At the moment, the only two PDF sets that are covered by the red one, its borders are displayed as black dashed lines. Similarly to all the previous insets, when the gray band is the EW corrections into the QCD+EW result and thus we provide the scale-uncertainty band (red) for the PDF uncertainty band for the QCD predictions. When the gray band is the EW corrections into the QCD+EW result and thus we provide the scale-uncertainty band (red) for the PDF uncertainty band for the QCD predictions.

The format of the plot is the same for each distribution and it is described in the following.

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Results

Best predictions

MULTIPLICATIVE
with LUXQED
MULTIPLICATIVE
with LUXQED

13 TeV

scale unc. ~ PDF unc
EW corrections ~ theory error

scale unc. < PDF unc
MULTIPLICATIVE
with LUXQED

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

scale unc. ~ PDF unc,
MULTIPLICATIVE
with LUXQED

\[ \frac{1}{\sigma} \frac{d\sigma}{dp_T, t} \text{ [1/GeV x 10^{-3}]} \]

\[ p_{T,\text{avt}} \]

Normalized distribution with smaller range
Leading-PT Top

\[ d\sigma/dp_T \text{ [pb/GeV]} \]

\[ \mu = m_T/2 \]

\[ \mu = H_T/4 \]

\[ \text{QCD} \times \text{EW} \]

\[ \text{scale unc.} \]

\[ \text{Stat} \]

\[ \text{Sys} \]

\[ \text{stat} \]

\[ \text{POWHEG P8} \]

\[ \text{NNLO QCD+NLO EW} \]

\[ \text{Herwig++} \]

\[ \text{Pythia8} \]

\[ \text{MG5 P8} \]

\[ \text{Stat} \]

\[ \text{Sys} \]

\[ \text{POWHEG H++} \]

\[ \text{MG5 P8 [FxFx]} \]

*taken from Hindrichs talk*

\[ \text{CMS e/\mu+jets} \]

\[ \text{Preliminary} \]

\[ \text{parton level} \]

\[ \text{CMS} \]

\[ \text{LHC13, LUXQED} \]

\[ \text{m}_T = 173.3 \text{ GeV} \]

\[ \text{QCD} \times \text{EW}, \mu = m_T/2 \]

\[ \text{QCD} \times \text{EW}, \mu = H_T/4 \]

\[ \text{LO+PS/LO} \]

\[ \text{LO} \]

\[ \text{NLO+PS/NLO} \]

\[ \text{NLO} \]

\[ \text{NLO} \]

\[ \text{NLO/LO} \]

\[ \text{LO} \]
In the limit of a very hard trailing top, the same effects observed in the limit of very soft leading top are expected: pathologies at fixed order. They are not present in the average-pt distribution.
Charge Asymmetry
What is already known:

- EW contribution is relevant.
- NLO≠NNLO, nlo~nnlo.
- |NNLO-nnlo| < |NLO-nlo|

Czakon, Fiedler, Mitov ’14

The bulk of EW corrections is not a Sudakov effect, it is of QED origin and it can easily be obtained from NLO QCD calculation.

Hollik, DP ’11

$$R_{QED}(Q_q) = \frac{\alpha \tilde{N}_1^{QED}}{\alpha_s N_1} = Q_q Q_t \frac{36}{5} \frac{\alpha}{\alpha_s}$$

PDF uncertainties are negligible; there are large cancellations in the ratio.
Preliminary results

Differential distributions

Additive approach (QCD + EW, all LO and NLO included)

Unexpanded definition for the asymmetry

\[ A_{FB} = \frac{\sigma_{QCD+EW}^+ - \sigma_{QCD+EW}^-}{\sigma_{QCD+EW}^+ + \sigma_{QCD+EW}^-} \]
Tevatron

EW corrections are larger than the NNLO QCD scale uncertainty

The theory uncertainty is much smaller than experimental errors.
The EW corrections are larger than the NNLO QCD scale uncertainty. The theory uncertainty is much smaller than experimental errors.
LHC 8 TeV
Central asymmetry

As at the Tevatron, EW corrections are larger than the NNLO QCD scale uncertainty and the theory uncertainty is much smaller than experimental errors.

\[ A_{C} = \frac{\sigma(\Delta|y| > 0) - \sigma(\Delta|y| < 0)}{\sigma(\Delta|y| > 0) + \sigma(\Delta|y| < 0)} \]

\[ \Delta|y| = |y_t| - |y_i| \]
LHC 8 TeV
Central asymmetry

\[ A_C^{t\bar{t}} = \frac{\sigma(\Delta|y| > 0) - \sigma(\Delta|y| < 0)}{\sigma(\Delta|y| > 0) + \sigma(\Delta|y| < 0)} \]

\[ \Delta|y| = |y_t| - |y_\bar{t}| \]
The top quark forward-backward asymmetry is defined as the ratio of the number of events with the top quark's rapidity greater than zero to the number of events with the top quark's rapidity less than zero, normalized by the total cross section.

\[
A_{FB}^{t\bar{t}} = \frac{\sigma(\Delta|y| > 0) - \sigma(\Delta|y| < 0)}{\sigma(\Delta|y| > 0) + \sigma(\Delta|y| < 0)}
\]

The variable \(\Delta|y|\) is defined as the absolute difference between the rapidities of the top quark and its antiparticle, \(|y_t| - |y_{\bar{t}}|\).

In the analysis, in the new analyses this quantity has not been measured and in the previous measurements their deviations from theoretical predictions can be easily explained using this particular definition and the partonic and hadronic rest frames. Conversely, at the LHC, the top quark forward-backward asymmetry is used at the Tevatron with the semi-leptonic signature.

The measurements of this asymmetry have been found in [106]. The values measured at the Tevatron have not been measured at the LHC.

The top quark forward-backward asymmetry is calculated using the number of events from the partonic and hadronic contributions.

\[
A_{FB}^{t\bar{t}} = \frac{\sigma(\Delta|y| > 0) - \sigma(\Delta|y| < 0)}{\sigma(\Delta|y| > 0) + \sigma(\Delta|y| < 0)}
\]

The variables \(\Delta|y|\) are respectively the three-momenta of the top quark and its antiparticle, \(y_t\) and \(y_{\bar{t}}\), respectively used at the Tevatron and the LHC with the dilepton channel. Practically, in the experiments, the number of events from the phase space regions is not simple counted. However, asymmetries are dimensionless values measured at the Tevatron and the LHC with the dilepton channel.
NNLO accuracy is present only in the first bin.

EW corrections are large w.r.t. the “NNLO” results. They are within the “NNLO” scale uncertainty only from the second bin on.
NNLO accuracy is present in all bins. EW corrections are large. They are outside the NNLO scale uncertainty band.

$$A_{FB}(p_{T,t\bar{t}} < p_{T,t\bar{t}}^{\text{cut}})$$

back to Tevatron

NNLO accuracy is present in all bins.

EW corrections are large. They are **outside** the NNLO scale uncertainty band.
Conclusion

We provided predictions at **NNLO QCD** accuracy and including **EW** corrections (complete-NLO) for ttbar production at the LHC (8, 13 TeV). Both **differential distributions** and **asymmetries** have been considered.

In pt distributions at 13 TeV EW corrections are outside the NNLO QCD scale-uncertainty band (for LUXQED). Additively combining EW corrections, the total scale uncertainty is larger than with QCD only.

Results are strongly affected by the photon PDF parametrization (LUXqed vs. NNPDF3.0) and LUXqed should be preferred.

The combination in the multiplicative approach leads to a reduction of scale uncertainties. Still, in pt distribution, EW corrections are comparable to the total theory uncertainty (scale+PDF), and QCD and QCDxEW bands do not overlap.

more results and histograms available at

[http://www.precision.hep.phy.cam.ac.uk/results/ttbar-nnlogcd-nloew/]
EXTRA SLIDES
Checks EW and QCD factorisation

\[
\frac{d\sigma}{dP_T} \quad [\text{pb/bin}]
\]

\begin{align*}
\text{ttj} \ (m_T(t)/2), \text{LHC13} \\
\text{no cut} \\
p_T(t) > 0.5 \text{ TeV} \\
p_T(t) > 1 \text{ TeV}
\end{align*}

\begin{align*}
\text{P}_T(j) \ [\text{GeV}] \\
\text{P}_T(t) \ [\text{GeV}]
\end{align*}
Checks EW and QCD factorisation

\textbf{tt, LHC13, LUXQED}

\begin{itemize}
  \item $(QCD+EW)/QCD$
  \item $(QCD\times EW)/QCD$
  \item $(QCD^2\times EW)/QCD$
\end{itemize}

\begin{itemize}
  \item $(QCD+EW)/QCD$; scale unc.
  \item $(QCD\times EW)/QCD$; scale unc.
  \item $(QCD^2\times EW)/QCD$; scale unc.
\end{itemize}

\begin{itemize}
  \item $(QCD+EW- EW_{res})/QCD$
\end{itemize}

\begin{itemize}
  \item $p_{T,av}$ [GeV]
  \item $m(tt)$ [GeV]
\end{itemize}
Individual subleading contributions

$t\bar{t}$, LHC13, LUXQED

$P_{T,avt}$ [GeV]

$m(t\bar{t})$ [GeV]
Tevatron Numerator $p_T(tt)$ asymmetry

$\tilde{p}\tilde{p} \rightarrow tt$

$m_t = 173.3 \text{ GeV}$

MSTW2008(68cl)

Czakon, Heymes, Mitov, Pagani, Tsinikos, Zaro (2017)

NNLO+EW/NNLO

$0 \leq \Delta \leq 9$
Tevatron

Denominator $p_T(tt)$ asymmetry
At LO partonic processes are not asymmetric. QCD produces the asymmetry only at NLO! NLO in the cross-section, LO in $A_{FB}$

\[
A_{FB} = \frac{N}{D} = \frac{\alpha^2 \tilde{N}_0 + \alpha_s^3 N_1 + \alpha_s^2 \alpha \tilde{N}_1 + \alpha_s^4 N_2 + \cdots}{\alpha^2 \tilde{D}_0 + \alpha_s^2 D_0 + \alpha_s^3 D_1 + \alpha_s^2 \alpha \tilde{D}_1 + \cdots} = \alpha_s \frac{N_1}{D_0} + \alpha \frac{\tilde{N}_1}{D_0} + \frac{\alpha^2 \tilde{N}_0}{\alpha_s^2 D_0}
\]
At LO partonic processes are not asymmetric. QCD produces the asymmetry only at NLO! NLO in the cross-section, LO in $A_{FB}$

\[
A_{FB} = \frac{N}{D} = \frac{\alpha_s^2 \tilde{N}_0 + \alpha_s^3 N_1 + \alpha_s^2 \alpha \tilde{N}_1 + \alpha_s^4 N_2 + \cdots}{\alpha_s^2 \tilde{D}_0 + \alpha_s^3 D_0 + \alpha_s^2 \alpha \tilde{D}_1 + \cdots} = \frac{\alpha_s N_1}{D_0} + \frac{\alpha \tilde{N}_1}{D_0} + \frac{\alpha_s^2 \tilde{N}_0}{D_0}
\]

gg initial state doesn’t contribute to Tevatron and LHC asymmetry numerator! q-qbar QCD contribution only from interaction between initial and final state!

\[
\alpha_s \frac{N_1}{D_0}
\]

VIRTUAL (Only Boxes)

NO UV, NO Coll. Div.

Only IR

REAL

Only interference of initial and final gluon emission is asymmetric.

*Kuhn, Rodrigo ’99*
It’s useful to divide electroweak contribution into QED (photon) and weak (Z) part.

QED can be easily obtained from QCD calculation and the substitution of one gluon into one photon in the squared amplitudes.
It’s useful to divide electroweak contribution into QED (photon) and weak (Z) part.

QED can be easily obtained from QCD calculation and the substitution of one gluon into one photon in the squared amplitudes.

\[ |\mathcal{M}^{tt}\rangle^{2}_{\mathcal{O}(\alpha_s^3)} \]

\[
\frac{\#(\text{QED diagrams})}{\#(\text{QCD diagrams})} = 3
\]

\[ |\mathcal{M}^{ttg}\rangle^{2}_{\mathcal{O}(\alpha^2)} \]

\[ |\mathcal{M}^{ttg}\rangle^{2}_{\mathcal{O}(\alpha^2)} \]

\[ |\mathcal{M}^{ttg}\rangle^{2}_{\mathcal{O}(\alpha^2)} \]

\[ |\mathcal{M}^{tt\gamma}\rangle^{2}_{\mathcal{O}(\alpha^2)} \]

DIFFERENCES:
Only couplings and color factor!
processes for the next calculations.

partonic processes are the denominator in

to distinguish which subprocesses can give rise to contribution to

Now we can start to look at the partonic subprocesses that gener

At LHC applies also to

it contributes with the same partonic weight also to

so, assuming CP conserving interactions, (5a) is true thanks to th

The terms up to 1 loop have been already calculated (5a)

We can also rewrite

that the initial state doesn’t depend on the perturbative order, so thanks to (6) we ca

Before starting the analysis of the non-vanishing partonic contrib

2 Theoretical prevision

$\frac{N}{D} = \frac{\alpha^2 N_0 + \alpha_s^3 N_1 + \alpha_s^2 \alpha N_1 + \alpha_s^4 N_2 + \cdots}{\alpha^2 \tilde{D}_0 + \alpha_s^2 D_0 + \alpha_s^3 D_1 + \alpha_s^2 \alpha \tilde{D}_1 + \cdots} = \alpha_s \frac{N_1}{D_0} + \alpha \frac{N_1}{D_0} + \frac{\alpha^2}{\alpha_s} \frac{N_0}{D_0}$

$R_{QED}(Q_q) = \frac{\alpha \tilde{N}_1^{QED}}{\alpha_s N_1} = Q_q Q_t \frac{36}{5} \frac{\alpha}{\alpha_s}$

QED correction can be obtained from QCD × $R_{QED}$

Hollik, D.P. ’11
\[
A_{FB} = \frac{N}{D} = \frac{\alpha^2 N_0 + \alpha_s^3 N_1 + \alpha_s^2 \alpha N_1 + \alpha_s^4 N_2 + \cdots}{\alpha^2 \hat{D}_0 + \alpha_s^2 D_0 + \alpha_s^3 D_1 + \alpha_s^2 \alpha \hat{D}_1 + \cdots} = \alpha_s \frac{N_1}{D_0} + \alpha \frac{N_1}{D_0} + \frac{\alpha^2 N_0}{\alpha_s^2 D_0}
\]

\[
R_{QED}(Q_q) = \frac{\alpha \tilde{N}_1^{QED}}{\alpha_s N_1} = Q_q Q_t \frac{36}{5} \frac{\alpha}{\alpha_s}
\]

QED correction can be obtained from QCD \(\times R_{QED}\)

**Weak**

The same diagrams as QED part, but \(\gamma \rightarrow Z\).

\(Z\) is not massless \(\rightarrow\) If we write Weak=QCD \(\times R_{\text{Weak}}\).

\(R_{\text{Weak}}\) does not depend only on couplings and color factor.
Before starting the analysis of the non-vanishing partonic contributions, the hadronic collision is constituted by partonic subprocesses. The exclusion of terms in the numerator.

QED correction can be obtained from QCD × R_{QED}

The same diagrams as QED part, but γ → Z.

Z is not massless → If we write \text{Weak}=\text{QCD} \times R_{\text{Weak}}.

R_{\text{Weak}} does not depend only on couplings and color factor.

\[
A_{FB} = \frac{N}{D} = \frac{\alpha^2 \tilde{N}_0 + \alpha_s^3 N_1 + \alpha_s^2 \alpha \tilde{N}_1 + \alpha_s^4 N_2 + \cdots}{\alpha^2 \tilde{D}_0 + \alpha_s^2 D_0 + \alpha_s^3 D_1 + \alpha_s^2 \alpha \tilde{D}_1 + \cdots} = \frac{\alpha_s N_1}{D_0} + \frac{\alpha \tilde{N}_1}{D_0} + \frac{\alpha_s^2 N_0}{\alpha_s^2 D_0}
\]

\[
R_{QED}(Q_q) = \frac{\alpha \tilde{N}_1^{QED}}{\alpha_s N_1} = Q_q Q_t \frac{36}{5} \frac{\alpha}{\alpha_s}
\]

\[
\frac{\alpha^2 \tilde{N}_0}{\alpha_s^2 D_0}
\]

Different couplings for different chiralities produce asymmetric terms in the cross-section.

\[
d\sigma_{\text{asym}} = 2\pi \alpha^2 \cos \theta \left(1 - \frac{4m_t^2}{s}\right) \left[\kappa Q_q Q_t A_q A_t \frac{\tilde{Q}_q \tilde{Q}_t A_q A_t}{(s - M_Z^2)} + 2\kappa^2 A_q A_t V_q V_t \frac{s}{(s - M_Z^2)^2}\right]
\]
Forward-backward asymmetry

\[ A_{FB}^{t\bar{t}} \]

<table>
<thead>
<tr>
<th>( A_{FB}^{t\bar{t}} )</th>
<th>( \mu = m_t/2 )</th>
<th>( \mu = m_t )</th>
<th>( \mu = 2m_t )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mathcal{O}(\alpha^3) ) ( u\bar{u} )</td>
<td>7.01%</td>
<td>6.29%</td>
<td>5.71%</td>
</tr>
<tr>
<td>( \mathcal{O}(\alpha^3) ) ( d\bar{d} )</td>
<td>1.16%</td>
<td>1.03%</td>
<td>0.92%</td>
</tr>
<tr>
<td>( \mathcal{O}(\alpha^2)_{QED} ) ( u\bar{u} )</td>
<td>1.35%</td>
<td>1.35%</td>
<td>1.35%</td>
</tr>
<tr>
<td>( \mathcal{O}(\alpha^2)_{QED} ) ( d\bar{d} )</td>
<td>-0.11%</td>
<td>-0.11%</td>
<td>-0.11%</td>
</tr>
<tr>
<td>( \mathcal{O}(\alpha^2)_{weak} ) ( u\bar{u} )</td>
<td>0.16%</td>
<td>0.16%</td>
<td>0.16%</td>
</tr>
<tr>
<td>( \mathcal{O}(\alpha^2)_{weak} ) ( d\bar{d} )</td>
<td>-0.04%</td>
<td>-0.04%</td>
<td>-0.04%</td>
</tr>
<tr>
<td>( \mathcal{O}(\alpha^2) ) ( u\bar{u} )</td>
<td>0.18%</td>
<td>0.23%</td>
<td>0.28%</td>
</tr>
<tr>
<td>( \mathcal{O}(\alpha^2) ) ( d\bar{d} )</td>
<td>0.02%</td>
<td>0.03%</td>
<td>0.03%</td>
</tr>
<tr>
<td>tot ( p\bar{p} )</td>
<td>9.72%</td>
<td>8.93%</td>
<td>8.31%</td>
</tr>
</tbody>
</table>

- \( R_{QED}^{u\bar{u}} = (0.192, 0.214, 0.237) \)
- \( R_{QED}^{d\bar{d}} = (-0.096, -0.107, -0.119) \)

\( \mathcal{O}(\alpha^2)_{QED} \) is the dominant contribution of the electroweak corrections. It is stable under factorization and renormalization scale variation.

**Hollik, DP '11**

\( \mathcal{O}(\alpha^2)_{weak} \) \( u \) and \( d \) have different charges: contributions of opposite sign for \( \mathcal{O}(\alpha^2_{weak}) \).
Charge asymmetry

At the LHC same partonic processes, but different partonic luminosities.

The gluon-gluon luminosity is larger, so the asymmetry is smaller. Gluon-quark initial states start to be “interesting” (per mill).

The ratio of integrated luminosities $u\bar{u}/d\bar{d}$ at the Tevatron (LHC) is $4(2)$. The cancellation between QED contributions is bigger. The EW contribution at the LHC is in general smaller ($\sim 15\%, 20\%$ of QCD contribution).

$$R_{QED}(Q_q) = \frac{\alpha \tilde{N}_{1}^{QED}}{\alpha_s N_{1}} = Q_q Q_t \frac{36 \alpha}{5 \alpha_s}$$

<table>
<thead>
<tr>
<th>$\sqrt{s}$</th>
<th>QCD: $A_G^{[\beta]} (%)$</th>
<th>QCD + EW: $A_G^{[\beta]} (%)$</th>
<th>$M_c = 2m_t$</th>
<th>0.5 TeV</th>
<th>0.7 TeV</th>
<th>1 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 TeV</td>
<td>1.07 (4)</td>
<td>1.23 (5)</td>
<td>1.07 (4)</td>
<td>1.27 (4)</td>
<td>1.68 (4)</td>
<td>2.06 (5)</td>
</tr>
<tr>
<td></td>
<td>1.11 (4)</td>
<td>1.48 (4)</td>
<td>1.11 (4)</td>
<td>1.48 (4)</td>
<td>1.95 (4)</td>
<td>2.40 (6)</td>
</tr>
<tr>
<td>8 TeV</td>
<td>0.96 (4)</td>
<td>1.33 (5)</td>
<td>0.96 (4)</td>
<td>1.14 (4)</td>
<td>1.48 (4)</td>
<td>1.85 (4)</td>
</tr>
<tr>
<td></td>
<td>1.11 (4)</td>
<td>1.73 (5)</td>
<td>1.11 (4)</td>
<td>1.33 (5)</td>
<td>1.73 (5)</td>
<td>2.20 (5)</td>
</tr>
<tr>
<td>14 TeV</td>
<td>0.58 (3)</td>
<td>0.86 (5)</td>
<td>0.58 (3)</td>
<td>0.74 (3)</td>
<td>1.11 (5)</td>
<td>1.72 (10)</td>
</tr>
<tr>
<td></td>
<td>0.67 (4)</td>
<td>1.32 (8)</td>
<td>0.67 (4)</td>
<td>0.86 (5)</td>
<td>1.32 (8)</td>
<td>2.12 (10)</td>
</tr>
</tbody>
</table>

Bernreuther, Si ’12
<table>
<thead>
<tr>
<th>( m_{t\bar{t}} ) [GeV]</th>
<th>( A_{FB}(m_{t\bar{t}}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NLO</td>
</tr>
<tr>
<td>[ 350 ; 450 ]</td>
<td>( 4.10^{+1.66+0.07\pm1.66} \times 10^{-2} )</td>
</tr>
<tr>
<td>[ 450 ; 550 ]</td>
<td>( 7.71^{+3.69+0.09\pm3.69} \times 10^{-2} )</td>
</tr>
<tr>
<td>[ 550 ; 650 ]</td>
<td>( 1.08^{+0.61+0.09\pm0.62} \times 10^{-1} )</td>
</tr>
<tr>
<td>[ 650 ; 750 ]</td>
<td>( 1.56^{+1.19+0.03\pm1.19} \times 10^{-1} )</td>
</tr>
</tbody>
</table>

**Table 11.** \( m_{t\bar{t}} \) dependent \( A_{FB} \) in NLO and NNLO QCD. The format is \( central \pm scales \pm pdf \pm total \). The lowest and highest bins contain spillover events.
MULTIPLICATIVE
with LUXQED

8 TeV

\[ \rho_{T, \text{avt}} \]

\[ m(\bar{t}t) \]

- In each plot, the main panel displays the considered differential cross section both at NNLO QCD and QCD×EW.
- Distributions for different PDF sets are shown, where each one of the PDF members, the QCD prediction, and the EW corrections are included.
- The PDF uncertainty band for the QCD predictions is clearly centered around one and shown as a gray band.
- The impact of photon-induced contributions is estimated via the 7-point variation of theoretical uncertainties due to missing higher orders.
- For the moment, LUXQED is NNPDF3.0 with photon equal to zero. We describe everything including them and are also NNLO QCD accurate.

- The PDF sets include LUXQED, which is already there.
- The observable \( m(T,t) \) is used as the scale.
- In all cases, it is expected to be negligible.
MULTIPLICATIVE
with LUXQED

\[ y(t\bar{t}) \]

\[ Y_{avt} \]

8 TeV
scale uncertainty. A notable exception is the case of the NNPDF and method in LUXQED? We may put them in a footnote?

Similarly to all the previous insets, when the gray band thus we provide the PDF uncertainty band (red) for QCD+EW quantity. The gray band corresponds to the scale-uncertainty band of each one of the PDF members, the QCD prediction and the EW corrections into the QCD+EW result and the first inset.

The three insets below the main panel display ratios of di

accuracy, the black line labelled as "QCD", and including also the EW corrections, the red line labelled as LUXQED is already there in Fig.

The plots on the left are produced using the PDF sets include them and are also NNLO QCD accurate are

For theoretical consistency, a set of PDF including QED e

The third inset is equivalent to the second one, but it concerns the PDF uncertainties. We combine, for

In each plot, the main panel displays the considered di

For the moment LUXQED is NNPDF3.0 with photon equal to zero!!!! We describe everything

The PDF sets

The observable

(µ)

scales defined as

The PDF sets

The impact of photon-induced contributions is

theoretical uncertainties due to missing higher orders are estimated via the 7-point variation of

...
Abstract

Preliminary results

1. Introduction

2. Main results: NNLO QCD + EW corrections

In the following we present predictions at NNLO QCD accuracy including also EW corrections for $t\bar{t}$ distributions at 13 TeV. In particular, we focus on distributions for the top-pair invariant mass $m(t\bar{t})$, the average transverse momentum ($p_T, \text{avt}$) and rapidity ($y, \text{avt}$) of the top and antitop quark, and the rapidity of the $t\bar{t}$ system, $y(t\bar{t})$. In the cases of both $p_T, \text{avt}$ and $y, \text{avt}$ we do not calculate these observables on a event-by-event base; we average the results of the histograms for the transverse momentum (rapidity) of the top and the antitop.

In this section we linearly combine predictions at NNLO accuracy, i.e. including complete $O(\alpha_s^n)$ term up to $n=4$, with all the possible remaining LO and NLO terms arising from QCD and electroweak interactions in the SM. In other words, at LO we include not only the purely QCD $O(\alpha_s^2)$ contribution, but also all the $O(\alpha_s^3)$ and $O(\alpha_s^4)$ terms. Similarly, at NLO we take into account not only the $O(\alpha_s^3)$ contribution, the NLO QCD, but also the $O(\alpha_s^2\alpha)$ one, the so-called NLO EW, and the subleading contributions of $O(\alpha_s\alpha_s^n)$ with $n>0$. The description of the single contributions and a discussion of their individual phenomenological impact are postponed to Sec.

Our calculation is performed using the following input parameters

\begin{align}
    m_t &= 173.3 \text{ GeV} \\
    m_H &= 125.09 \text{ GeV} \\
    m_W &= 80.385 \text{ GeV} \\
    m_Z &= 91.1876 \text{ GeV}
\end{align}

and setting all the other fermion masses to zero. All masses are renormalised on-shell and all decay widths are set to zero. The renormalization of $\alpha_s$ is performed in the 5 Flavour scheme (5FS), while EW parameters are chosen in the $G_\mu$-scheme, with $G_\mu = 1.1663787 \times 10^5$ GeV$^2$.

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ALL masses are renormalised on-shell and all decay widths contributions will be introduced.

In other words, at LO we include not only the purely QCD O\(\tau\)QCD, but also the O\(\tau\)EW contributions. Similarly, at NLO we take into account not only the O\(\tau\)EW term, but also all the LO and NLO terms arising from QCD and electroweak interactions.

In the cases of both O\(\tau\)EW and the subleading contributions of O\(\tau\)\(2\)EW, one, the so-called NLO EW, we do not calculate these observables on an event-by-event base; we average the results of the histograms for the transverse momentum (rapidity) of the top and the antitop.

The description of the single contributions and a discussion of their individual phenomenological impact are postponed to Sec. 2.
$\sigma / dy \ [pb]$ 

$QCD$ 

$QCD + EW$ 

$t\bar{t}$, LHC13, LUXqed 

$t\bar{t}$, LHC13, NNPDF3.0 

$LUXQED$ 

$13$ $TeV$ 

$y_{avt}$ 

$y_{avt}$ 

$LUXQED$ 

$NNPDF3.0QED$ 

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In the following we present predictions at NNLO QCD accuracy including also EW corrections for $t\bar{t}$ distributions at $13$ TeV. In particular, we focus on distributions for the top-pair invariant mass $m(t\bar{t})$, the average transverse momentum ($p_T, avt$) and rapidity ($y, avt$) of the top and antitop quark, and the rapidity of the $t\bar{t}$ system, $y(t\bar{t})$. In the cases of both $p_T, avt$ and $y, avt$ we do not calculate these observables on a event-by-event base; we average the results of the histograms for the transverse momentum (rapidity) of the top and the antitop.

In this section we linearly combine predictions at NNLO accuracy, i.e. including complete $O(\alpha^4)$ term up to $n=4$, with all the possible remaining LO and NLO terms arising from QCD and electroweak interactions in the SM. In other words, at LO we include not only the purely QCD $O(\alpha^2)$ contribution, but also all the $O(\alpha^2)$ and $O(\alpha^3)$ terms. Similarly, at NLO we take into account not only the $O(\alpha^3)$ contribution, the NLO QCD, but also the $O(\alpha^2)$ one, the so-called NLO EW, and the subleading contributions of $O(\alpha^4)$ and $O(\alpha^3)$. For brevity, we will denote as "EW corrections" the sum of all the LO and NLO terms of $O(\alpha^m)$ with $n>0$. The description of the single contributions and a discussion of their individual phenomenological impact are postponed to Sec. 3, where also a more elaborate notation for the classification of the different contributions will be introduced.

Our calculation is performed using the following input parameters $m_t = 173.3$ GeV, $m_H = 125.09$ GeV, $m_W = 80.385$ GeV, $m_Z = 91.1876$ GeV, and setting all the other fermion masses to zero. All masses are renormalised on-shell and all decay widths are set to zero. The renormalization of $\alpha_s$ is performed in the 5 Flavour scheme (5FS), while EW parameters are chosen in the $G_\mu$-scheme, with $G_\mu=1.1663787 \cdot 10^{-5}$ GeV$^2$. 

Preprint submitted to Elsevier November 17, 2016

13 TeV 

$LUXQED$ 

$NNPDF3.0QED$ 

67
We may put them in a footnote.

Similarly to all the previous insets, when the gray band corresponds to the scale-uncertainty band (red) for the QCD+EW result and thus we provide the scale-uncertainty band (red) for the PDF uncertainty band (red) for QCD+EW quantity. The gray band corresponds to the uncertainty for the QCD prediction, which is clearly centered around one and shown as a gray band.

We use a dynamical reference scale for the central values of the renormalization ($\mu$) scales defined as:

$$\mu = \frac{m_{t\bar{t}}}{2}$$

where $m_{t\bar{t}}$ is the average transverse mass of the top quark and antitop quark.

As can be noted by Figs. (13) and (14), the impact of EW corrections are in general within the NNLO QCD effects in the DGLAP evolution, but they are not included in the PDF sets, while those on the right using $\mu_{r}$, LHC13, LHC13, LUXQED effects in the DGLAP evolution should always be larger and with very large uncertainties, in the case of NNPDF3.0QED.

For this reason we decided to show always predictions with both the PDF sets.

The three insets below the main panel display ratios of different quantities always over the QCD prediction, which can be directly compared to the relative scale uncertainty for the QCD+EW result and thus we provide the scale-uncertainty band (red) for the PDF uncertainty band (red) for QCD+EW quantity.

In the first inset we also show as a red band around the red line the scale uncertainty due only to the different PDF sets leads to a very different impact of photon-induced contributions is expected to be negligible. In all cases, the PDF sets are the same PDF set.

For theoretical consistency, a set of PDF including QED effects in the numerator of this ratio. This quantity can be directly compared to the relative scale uncertainty for the QCD prediction, which is clearly centered around one and shown as a gray band.

The format of the plot is the same for each distribution and it is described in the following.

As can be noted by Figs. (13) and (14), the impact of EW corrections are in general within the NNLO QCD effects in the DGLAP evolution, but they are not included in the PDF sets, while those on the right using $\mu_{r}$, LHC13, LHC13, LUXQED effects in the DGLAP evolution should always be larger and with very large uncertainties, in the case of NNPDF3.0QED.
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 …

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

Image taken from Manohar, Nason, Salam, Zanderighi ’16 and adapted for this slide.
... and the different photon-gluon luminosities

- **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

**Fig. 10.** Differential distributions for the $p_T(t)$ at 100 TeV. The format of the plots is described in detail in the text.

**Fig. 11.** Differential distributions for the $m(t\bar{t})$ at 100 TeV. The format of the plots is described in detail in the text.

By comparing plots in figs. 10-13 with their corresponding ones at 13 TeV, it can be noticed that the impact of the photon PDF is strongly reduced at 100 TeV. In each figure, the plot on the right (with photons in the initial state) does not exhibit any qualitatively different behaviour w.r.t. the plot on the left. The smaller impact of the photon-induced contributions at 100 TeV w.r.t. the 13 TeV case is due to the different range of $x$ spanned in the PDFs; keeping the hardness of the process fixed, a larger energy of the hadronic collisions corresponds to probing smaller values of $x$, where parton luminosities involving photons are suppressed with respect to those involving QCD partons, as shown in fig. 3. For the same reason, the impact of the photon PDF at the LHC at 8 TeV is even larger than at 13 TeV, as it will be discussed in the next session. Moreover, at 100 TeV, for a given value of $p_T(t)$ or $m(t\bar{t})$, EW corrections are slightly smaller than at 13 TeV.
Fig. 14. Integrated distributions for the $p_T(t \bar{t})$ at 100 TeV. The format of the plots is described in detail in the text.

Fig. 15. Integrated distributions for the $m(t \bar{t})$ at 100 TeV. The format of the plots is described in detail in the text.