The impact of ATLAS and CMS single differential top-quark pair measurements at \(\sqrt{s} = 8\) TeV to CTEQ-TEA PDFs

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By applying the Error PDF Updating Method, we analyze the impact of the absolute and normalized single differential cross-sections of top-quark pair production data from the ATLAS and CMS detector at the Large Hadron Collider at a centre-of-mass energy of \(s = \sqrt{s}\) TeV on the CT14HERA2 and CT14HERA2mJ PDFs. We find that the top quark pair single differential distributions provide minor constraints on the CT14HERA2 gluon PDF when the inclusive jet production data included in the fit. But the weighted \(t\bar{t}\) data provide significant constraints on the CT14HERA2mJ gluon PDF, that are comparable to those obtained from inclusive jet production data. Furthermore, we study top quark mass sensitivity of the top-quark pair single differential distributions, we find that the invariant mass distribution of the \(t\bar{t}\) system is sensitive to top-quark mass.

Keywords: top-quark pair production; gluon PDF; ePump

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I Introduction

A precise measurement and prediction of the $t\bar{t}$ pair production is crucial for testing the quality of the standard model and for searching new physics beyond the standard model at hadron colliders [1]. And thus the understanding of uncertainties due to parton distribution functions (PDFs) is crucial for precise measurement and prediction of the $t\bar{t}$ pair production. By the virtue of the huge luminosity and high center of mass energy at the Large Hadron Collider (LHC), significant impact from the $t\bar{t}$ pair production measurement on the global analysis of PDFs become possible. The dominant contribution of $t\bar{t}$ pair production in LHC is through two gluons, and thus $t\bar{t}$ data can potentially constrain gluon PDF. For the first time, Czakon, Heymes and Mitov published [2, 3] fastNLO tables for the invariant mass of the top-quark pair, transverse momentum of the averaged top/antitop quark, rapidity of the average top/antitop quark and rapidity of the top-quark pair at NNLO in QCD with $m_t = 173.3$ GeV, the renormalization scale and factorization scale $\mu_R = \mu_f = H_T/4$, $H_T = \sqrt{m_t^2 + p_{T,t}^2} + \sqrt{m_{\bar{t}}^2 + p_{T,\bar{t}}^2}$ for $m_{t\bar{t}}$, $y_t$ and $y_{\bar{t}}$ distributions, and $\mu_R = \mu_f = m_T/4 = \frac{1}{4}\sqrt{m_t^2 + p_{T,t}^2}$ for $p_{T,t}$ distribution of the average top/antitop quark. And in their calculation they use the same binning (see Table I) as the ATLAS [4] and CMS [5] 8 TeV measurements of top-quark pair differential cross-sections.

**TABLE I: Summary of the fastNLO tables provided in the work [3].**

| Observable         | Binning                          | $\mu_F = \mu_R$ |
|--------------------|----------------------------------|-----------------|
| $d\sigma/dm_{t\bar{t}}$ [GeV] | $\{345, 400, 470, 550, 650, 800, 1100, 1600\}$ | $H_T/4$         |
| $d\sigma/dy_{avt}$              | $\{-2.5, -1.6, -1.2, -0.8, -0.4, 0.0, 0.4, 0.8, 1.2, 1.6, 2.5\}$ | $H_T/4$         |
| $d\sigma/dy_t$                 | $\{-2.5, -1.3, -0.9, -0.6, -0.3, 0.0, 0.3, 0.6, 0.9, 1.3, 2.5\}$ | $H_T/4$         |
| $d\sigma/dp_{T,avt}$ [GeV]     | $\{0, 60, 100, 150, 200, 260, 320, 400, 500\}$ | $m_T/2$         |

In this paper we study the impact of the ATLAS [4] and CMS [5] measurements of top-quark pair differential cross-sections data on the CT14HERA2 and CT14HERA2mJ PDFs, and thus in Table II we provide relevant basic information. For the measurements in Table II ATLAS collaboration provided statistical, fifty six correlated systematic errors including luminosity errors. CMS collaboration provided statistical, eleven correlated systematic errors including luminosity errors.

**TABLE II: Number of data points and $\chi^2/N_{pts}$ for inclusive jet and top-quark pair data, after ePump updating from the CT14HERA2 and CT14HERA2mJ PDFs.**

| Observable | Detector | $N_{pts}$ | $\chi^2/N_{pts}(\text{CT14HERA2})$ weight=1.0| $\chi^2/N_{pts}(\text{CT14HERA2mJ})$ weight=9.0 |
|------------|----------|-----------|-------------------------------------------|-------------------------------------------|
| inclusive jet | CDF [6] | 72 | 1.46 | 1.50 |
| inclusive jet | D0 [7]  | 110 | 1.03 | 1.03 |
| inclusive jet | ATLAS [8] | 90 | 0.57 | 0.57 |
| inclusive jet | CMS [9]  | 133 | 0.89 | 0.93 |
| $\frac{1}{\sigma \frac{d\sigma}{dp_{T,t}}}$, $\frac{1}{\sigma \frac{d\sigma}{dy_t}}$ | ATLAS, CMS [4, 5] | 3.88 | 0.39, 3.55 | 0.38, 2.20 | 0.38, 4.82 |
| $\frac{1}{\sigma \frac{d\sigma}{dp_{T,avt}}}$, $\frac{1}{\sigma \frac{d\sigma}{dy_{avt}}}$ | ATLAS, CMS [4, 5] | 5.10 | 2.40, 2.52 | 1.45, 2.50 | 5.34, 3.32 |
| $\frac{1}{\sigma \frac{d\sigma}{dp_{T,t}}}$, $\frac{1}{\sigma \frac{d\sigma}{dy_t}}$ | ATLAS, CMS [4, 5] | 7.77 | 0.25, 7.69 | 0.25, 3.96 | 0.35, 9.30 |
| $\frac{1}{\sigma \frac{d\sigma}{dp_{T,avt}}}$, $\frac{1}{\sigma \frac{d\sigma}{dy_{avt}}}$ | ATLAS, CMS [4, 5] | 5.10 | 2.21, 2.31 | 1.18, 1.07 | 5.21, 3.34 |
| $\frac{dc}{dp_{T,t}}$ | ATLAS [4] | 8 | 0.34 | 0.33 | 0.32 |
| $\frac{dc}{dy_t}$ | ATLAS [4] | 5 | 2.83 | 1.62 | 5.79 |
| $\frac{dc}{dp_{T,avt}}$ | ATLAS [4] | 7 | 0.45 | 0.42 | 0.40 |
| $\frac{dc}{dy_{avt}}$ | ATLAS [4] | 5 | 3.83 | 1.48 | 7.29 |
Ref. [10, 11] studied the impact of top-quark pair differential distributions measured by ATLAS [4] and CMS [5] at 8 TeV on the gluon PDF within NNPDF framework. And they found that the differential distributions from top-quark pair production provide a strong constraints on the large-x gluon. Within the MMHT framework Ref. [12] found that the impact of the ATLAS [4] data on the gluon PDF is small. With the CMS data [5], they found that both $y_t$ and $y_{Tt}$ distributions have an impact on gluon PDF at high x, the impact of the $y_{Tt}$ is larger than the $y_t$.

Ref. [13] have developed a software package, ePump [13], which can be used to obtain both the updated best-fit PDF and updated eigenvector PDFs from a PDF that is obtained by global analysis. In addition, Refs. [14], [15] and [16] as well [17] using ePump performed analysis to reduce the PDF induced errors in predicting the cross sections at the LHC.

In this paper, instead of implementing a real global analysis, using ePump (error PDF Updating Method Package) [13] we study the impact of the LHC 8 TeV single differential top-quark pair distribution data from ATLAS [4] and CMS [5] on gluon PDF in the framework of CT14HERA2 [18]. The CT14HERA2 PDFs is an update of the CT14 PDFs [19] with the HERA Run I data to be replaced by the combined HERA I+II data. Because the gluon PDF receive well constraint by the jet data that have already been included in the CT14HERA2 global analysis, additional eigenvector sets without the inclusion of jet data, which is named as CT14HERA2mJ, is also concerned throughout this paper. Absolute and normalized single differential $t\bar{t}$ measurements from ATLAS in $|y_{ti}|$, $dm_{ti}$, $p_T^t$ and $|y_t|$, and normalized single differential $t\bar{t}$ measurements from CMS in $y_{ti}$, $m_{ti}$, $p_T^{\bar{t}}$ and $y_t$ are listed in Table II. We also show the number of data points for jet data that are included in the CT14HERA2 fit. The values of $\chi^2/N_{DF}$ in the Table II are calculated by using ePump to update the CT14HERA2 and CT14HERA2mJ PDFs with the inclusion of each individual $t\bar{t}$ data sets.

This paper is organized as follows. In section II, first we show the correlation between CT14HERA2 gluon PDF and ATLAS 8TeV $t\bar{t}$ data, and then we compare the ePump updated gluon PDFs with the original CT14HERA2 gluon PDF. Furthermore we provide comparison between the NNLO theory predictions for differential distributions in the $t\bar{t}$ production and the corresponding ATLAS measurements. As a reflection of impact of the update gluon PDF, we also provide the corresponding update of the Higgs production in the gluon fusion channel $\sigma_{Hgg \rightarrow H}$ by the inclusion of the $t\bar{t}$ data in CT14HERA2. In section III, similar study on the CMS 8 TeV normalized single differential $t\bar{t}$ measurements . In section IV, We study the tension between ATLAS and CMS 8 TeV absolute and normalized single differential $t\bar{t}$ data with other data sets in the CT14HERA2 and CT14HERA2mJ PDFs. In section V, concerning the stronger constraint on gluon from the jet data, using same method we analyze the impact of the ATLAS 8 TeV absolute and normalized single differential $t\bar{t}$ measurements on the CT14HERA2mJ PDFs. In section VI A, we perform the same analysis on the normalized CMS 8TeV data in the framework of CT14HERA2mJ. In section VII, We illustrate the impact from CMS 7 TeV inclusive jet data and from the $t\bar{t}$ data in the framework of CT14HERA2mJ. In section VIII, preference of top quark mass from the single differential $t\bar{t}$ measurement is analysis in the view of PDF. Our conclusions are presented in section IX.

Before starting our study we summarise our notations in this work.

- The suffix “.54” in CT14HERA2.54 indicate that the error band is obtained with 54 eigen-vector PDF sets rather than with the whole 56 PDF sets, where the 55 and 56 sets are the two put-in-by-hand extreme gluon PDF sets of CT14HERA2 PDFs.
- CT14HERA2mJ PDF are obtained by the global analysis after excluding the four jet data in CT14HERA2 PDFs.
- The ePump updated CT14HERA2.54 (CT14HERA2mJ) via ATLAS 8 TeV absolute and normalized data in $|y_{ti}|$, $m_{ti}$, $|y_t|$ and $p_T^t$ distributions are denoted as CT14HERA2.54+ATLASXXX (CT14HERA2mJ+ATLASXXX), CT14HERA2.54+ATLASNXNX (CT14HERAmJ+ATLASNXNX); and the ePump updated CT14HERA2.54 (CT14HERA2mJ) using CMS 8 TeV normalized $t\bar{t}$ production in $y_{ti}$, $m_{ti}$, $y_t$ and $p_T^t$ distributions are denoted as CT14HERA2.54+CMSNXXX (CT14HERAmJ+CMSNXXX); where the "XXX" are the shorthand of individual distributions.
II The impact of ATLAS 8 TeV $t\bar{t}$ data on CT14HERA2 PDFs

In this section we provide comparisons of the CT14HERA2.54 [18] and ePump [13] updated CT14HERA2.54 PDFs, using the ATLAS absolute and normalized $t\bar{t}$ distributions [4] and fastNLO theory at NNLO in QCD [2, 3], CT14HERA2.54+ATLAS$|y_{t\bar{t}}|$, CT14HERA2.54+ATLAS$m_{t\bar{t}}$, CT14HERA2.54+ATLAS$|y_t|$, CT14HERA2.54+ATLAS$p_T^t$, and new PDFs CT14HERA2.54+ATLASN$|y_{t\bar{t}}|$, CT14HERA2.54+ATLASN$m_{t\bar{t}}$, CT14HERA2.54+ATLASN$|y_t|$, CT14HERA2.54+ATLASN$p_T^t$, that are obtained by adding full phase-space absolute and normalized differential $t\bar{t}$ production cross sections data as a function of the absolute value of the rapidity ($|y_{t\bar{t}}|$) of the $t\bar{t}$ system, the invariant mass ($m_{t\bar{t}}$) of the $t\bar{t}$ system, the absolute value of the rapidity ($|y_t|$) of the top quark, and the transverse momentum ($p_T^t$) of the top quark, respectively. The integrated luminosity of the ATLAS 8 TeV measurement is $20.3 \, fb^{-1}$.

A Correlation between CT14HERA2 gluon PDF and $t\bar{t}$ data

The correlation between a specific absolute and normalized $t\bar{t}$ data point and $g(x, Q)$ PDF at a given $x$ and $Q$ is presented by the correlation cosine $\cos \phi$ [20, 21]. The quantity $\cos \phi$ characterizes whether the data and PDF is correlated ($\cos \phi \sim 1$), anti-correlated ($\cos \phi \sim -1$) or uncorrelated ($\cos \phi \sim 0$). A large positive and negative values of $\cos \phi$ indicate direct sensitivity of the $t\bar{t}$ data to gluon PDF in a particular regions in $x$. In Fig. 1, correlation between CT14HERA2.54 $g(x, Q = 100 \, GeV)$ PDF and the absolute (left) and normalized (right) differential $t\bar{t}$ data is distinguished by different type of lines. Solid green lines, black dotted lines, red dashed lines, dark blue long-dashed-dotted lines correspond to ATLAS 8 TeV absolute (left) and normalized (right) differential $t\bar{t}$ cross-sections data as a function of the $|y_{t\bar{t}}|$, $m_{t\bar{t}}$, $|y_t|$, and $p_T^t$, respectively. We observe that, due to the kinematic range, the absolute $t\bar{t}$ distributions are highly positive correlated to the gluon PDF for $x \gtrsim 3 \times 10^{-2}$ and highly anti-correlated for $x \lesssim 10^{-2}$. We also observe that, due the total $t\bar{t}$ pair production in the denominator, the normalized $t\bar{t}$ distributions show different or even opposite patterns compared to the absolute distributions.
B Update CT14HERA2 PDFs with ATLAS 8 TeV \( t\bar{t} \) data

In this section, we use CT14HERA2.54 PDFs as a base, study the impact of the ATLAS 8 TeV data of absolute and normalized \( t\bar{t} \) full phase-space differential cross-sections as a function of the \(|y_{t\bar{t}}|\), \( m_{t\bar{t}} \), \( p_T^t \), and \(|y_t|\), on gluon PDF. Updated gluon PDF with the ATLAS \( t\bar{t} \) data included individually are presented comparing to the CT14HERA2 gluon PDF before update in Fig. 2 and 3. We observe that, there are no strong impact from both the absolute and normalized ATLAS 8 TeV \( t\bar{t} \) data on CT14HERA2.54 gluon PDF in the \( m_{t\bar{t}} \) and \( p_T^t \) distributions; however, by comparing to the gluon PDF uncertainty at the same x range, both absolute and normalized \( t\bar{t} \) data in \(|y_{t\bar{t}}|\) and \(|y_t|\) distributions have minor impact on gluon PDF at \( x > 0.2 \) region. Moreover, we also observe that, in all the absolute and normalized distributions, none of them produce a significant reduction on gluon PDF uncertainty. This imply that, either the ATLAS \( t\bar{t} \) single differential data receive strong tension with other data included in the CT14HERA2, or the gluon PDF is well constrained by some other data included in the CT14HERA2.

Note that in the framework of CT14HERA2, the gluon PDF are mainly constrained by DIS data and jet data.
FIG. 2: ePump updated CT14HERA2.54+ATLAS|\(y_{t\bar{t}}\)|, CT14HERA2.54+ATLAS|m_{t\bar{t}}|, CT14HERA2.54+ATLAS|\(y_{t\bar{t}}\)|, CT14HERA2.54+ATLAS|\(p_T\)| PDFs, which are obtained by including absolute ATLAS 8 TeV \(d\sigma/d|\(y_{t\bar{t}}\)|, \(d\sigma/dm_{t\bar{t}}|\), \(d\sigma/d|y_{t}\)| and \(d\sigma/dp_T\) data, are compared with the CT14HERA2.54 gluon PDF. The gluon PDF ratios for ePump-updated CT14HERA2.54+ATLAS|\(y_{t\bar{t}}\)|, CT14HERA2.54+ATLAS|m_{t\bar{t}}|, CT14HERA2.54+ATLAS|\(y_{t\bar{t}}\)|, and CT14HERA2.54+ATLAS|\(p_T\)| PDFs over the best-fit of the base CT14HERA2.54 gluon PDF.
FIG. 3: ePump updated CT14HERA2.54+ATLASN|y_{t\bar{t}}|, CT14HERA2.54+ATLASN_{m_{t\bar{t}}}, CT14HERA2.54+ATLASN_{p_{T}}, PDFs, which are obtained by including normalized ATLAS 8 TeV 1/σ dσ/d|y_{t\bar{t}}|, 1/σ dσ/dm_{t\bar{t}}, 1/σ dσ/d|y_{t}|, and 1/σ dσ/dp_{T} data, are compared with the CT14HERA2 gluon PDF. The gluon PDF ratios for ePump-updated CT14HERA2.54+ATLASN|y_{t\bar{t}}|, CT14HERA2.54+ATLASN_{m_{t\bar{t}}}, CT14HERA2.54+ATLASN_{y_{t}|}, and CT14HERA2.54+ATLASN_{p_{T}} over the best-fit of the base CT14HERA2.54 gluon PDFs.

C Comparison between theory from CT14HERA2 and ePump updated CT14HERA2 and ATLAS 8 TeV t\bar{t} data

In this subsection we show the theory predictions after considering the t\bar{t} data are included and compare with the measurements. The comparisons between the theory predictions from before and after updated CT14HERA2 PDFs and the ATLAS 8 TeV absolute and normalized differential t\bar{t} data are presented in Figs. 4 and 5. In both figures, the magenta solid lines correspond to the theoretical predictions from CT14HERA2.54, the blue solid lines are the theoretical predictions from updated CT14HERA2.54 PDFs. The black and red error bars on each data and shifted data point include both statistical and uncorrelated systematic errors, added in quadrature. The blue bands in ratio plots indicate the total uncertainty, that are the quadratic sum of statistical and systematic uncorrelated uncertainties, on the data in each bin. The yellow bands in ratio plots indicate the statistical uncorrelated uncertainties on the data in each bin. The error bars on the theoretical predictions show the 68% C.L.. We see that there is an overall shift for all the raw data points. This means that the correlated systematic errors, weighted by their corresponding nuisance parameters, play an important role in the fitting. We find that there is little improvement in agreement with the measurements after calculating theoretical predictions evaluated with the new PDFs that obtained adding the t\bar{t} production cross sections data as a function of the |y_{t\bar{t}}|, m_{t\bar{t}}, p_{T} and |y_{t}|.
FIG. 4: Comparison of differential cross sections $\sigma/|y_{t\bar{t}}|$, $\sigma/dm_{t\bar{t}}$, $\sigma/d|y_{t}\bar{t}|$, $\sigma/dp_{T}$ from CT14HERA2.54 PDFs and from ePump updated CT14HERA2.54+ATLAS$|y_{t\bar{t}}|$, CT14HERA2.54+ATLAS$m_{t\bar{t}}$, CT14HERA2.54+ATLAS$|y_{t}\bar{t}|$, CT14HERA2.54+ATLAS$p_{T}$ PDFs and differential ATLAS 8 TeV $t\bar{t}$ production cross sections data as a function of the $|y_{t\bar{t}}|$, $m_{t\bar{t}}$, $|y_{t}|$ and $p_{T}$. 
FIG. 5: Comparison normalized differential cross sections $1/\sigma \frac{d\sigma}{d|y_{t\bar{t}}|}$, $1/\sigma \frac{d\sigma}{dm_{t\bar{t}}}$, $1/\sigma \frac{d\sigma}{dp_T}$, $1/\sigma \frac{d\sigma}{dy_{t\bar{t}}}$ from CT14HERA2.54 PDFs and from ePump updated CT14HERA2.54+ATLASN PDFs and normalized differential ATLAS 8 TeV $t\bar{t}$ production cross sections data as a function of the $|y_{t\bar{t}}|$, $m_{t\bar{t}}$, $|y_{t\bar{t}}|$ and $p_T$.

D Correlation between $\sigma_H(gg \rightarrow H)$ and CT14HERA2 PDFs

In order to see the impact from ATLAS 8 TeV $t\bar{t}$ single differential data on CT14HERA2 gluon PDF, we consider the 13 TeV Higgs production through gluon fusion channel $\sigma_H(gg \rightarrow H)$ at the LHC as a standard candle. In Fig. 6 we show the correlation between $\sigma_H(gg \rightarrow H)$ at 8 TeV and the CT14HERA2 PDFs of different flavors, as a function of the parton momentum fraction $x$. The correlation of two observables is measured by the cosine $\cos \phi$ of the angle between the gradient directions of the two observables in the PDF parameter space [20, 21]. From Fig. 6 we see a strong positive correlation between the $\sigma(gg \rightarrow H)$ and the CT14HERA2 gluon PDF at $x \sim 0.02$. As we also observe that the absolute $t\bar{t}$ single differential distribution data have strong negative correlation with CT14HERA2 gluon PDF.
at similar region as shown in Fig. 1, and thus the Higgs production $\sigma(gg \rightarrow H)$ should show anti-correlation to the absolute $t\bar{t}$ data. Moreover, according to the correlation between Higgs production $\sigma(gg \rightarrow H)$ and $t\bar{t}$ distribution at around $x \sim 0.02$ in Fig. 1, we expect to see the reduction of the uncertainty of Higgs production $\sigma(gg \rightarrow H)$ as well when the uncertainty of the gluon PDF is reduced after updating the CT14HERA2 PDFs using $t\bar{t}$ data. In the case of the normalized $t\bar{t}$ distribution, different bin show different correlation pattern with the gluon PDF at $x \sim 0.02$, and thus the correlation between Higgs production and normalized $t\bar{t}$ distribution depends on bin each too.

| $g$ | $u$ | $d$ | $c$ | $s$ | $\bar{u}$ | $\bar{d}$ |
|-----|-----|-----|-----|-----|--------|--------|
| 0.1 | 0.3 | 0.5 | 0.7 | 0.9 | 1.0    | 1.0    |

**FIG. 6: Correlation cosine between $\sigma(gg \rightarrow H)$ and CT14HERA2 PDFs at specific $x$ and at $Q = 125$ GeV.**

E Correlation between differential $t\bar{t}$ cross section and $\sigma_H(gg \rightarrow H)$

In order to illustrate the point we made according to the correlation cosine in the last subsection, we show correlation between the Higgs boson cross section (in pb) through gluon-gluon fusion ($gg \rightarrow H$) at the LHC with center of mass energy of 13 TeV and the absolute and normalized differential $t\bar{t}$ production cross sections as a function of $|y_{t\bar{t}}|$, $m_{t\bar{t}}$, $|y_t|$ and $p_T$ at 8 TeV. In Figs. 7 and 8, black and red ellipses and triangles correspond to theories from CT14HERA2.54 before and after the update by including the absolute and normalized ATLAS 8TeV $t\bar{t}$ single distribution data. Only the bin with largest correlation with Higgs production of each single differential $t\bar{t}$ distributions are shown in the figures. In Fig. 7, the Higgs production and absolute $t\bar{t}$ distributions show anti-correlation as we expect. We also notice that, the minor impact on gluon PDF for $x \sim 0.2$ by the inclusion of absolute $|y_{t\bar{t}}|$ and $|y_t|$ $t\bar{t}$ data as shown in Fig. 2 do cause a minor but visible anti-correlated shift to the central prediction of Higgs production. While the impact on the gluon PDF by the $t\bar{t}$ $m_{t\bar{t}}$ and $p_T$ distribution is too small to produce a tiny shift to central prediction of the Higgs production. In Fig. 8, we present the correlation between the Higgs production and the bins with smallest rapidity for the $|y_{t\bar{t}}|$ and $|y_t|$ distribution. As shown in Fig. 3, these bins are positive correlated to gluon PDF and thus positively correlated to the Higgs production.
FIG. 7: Predicted Higgs boson cross section through gluon-gluon fusion ($gg \rightarrow H$) at the LHC with center of mass energy of 13 TeV versus one of the theory points from differential cross sections $d\sigma/d|y_t\bar{t}|$, $d\sigma/dm_{t\bar{t}}$, $d\sigma/d|y_t|$, $d\sigma/dp^t_T$, from CT14HERA2 PDFs and ePump updated CT14HERA2.54+ATLAS $|y_t\bar{t}|$, CT14HERA2.54+ATLAS $m_{t\bar{t}}$, CT14HERA2.54+ATLAS $|y_t|$, CT14HERA2.54+ATLAS $p^t_T$. PDFs, PDF uncertainty is at the 90% C.L.
FIG. 8: Predicted Higgs boson cross section through gluon-gluon fusion ($gg \rightarrow H$) at the LHC with center of mass energy of 13 TeV versus one of the theory points normalized differential cross sections $1/\sigma \frac{d\sigma}{dy}$, $1/\sigma \frac{d\sigma}{dm}$, $1/\sigma \frac{d\sigma}{d|y_{t\bar{t}}|}$, $1/\sigma \frac{d\sigma}{d|y_t|}$, $1/\sigma \frac{d\sigma}{dp_T}$ from CT14HERA2 PDFs and ePump updated CT14HERA2.54+ATLASN PDFs, PDF uncertainty is at the 90% C.L..

F Update Higgs cross section using new CT14HERA2 with ATLAS 8 TeV $t\bar{t}$ data

Accurate predictions for the inclusive production cross section of Higgs boson are crucial for precision tests of the Higgs mechanism in Standard Model. And thus, using ePump we also calculated the inclusive production cross section of Higgs-boson through gluon-gluon fusion, at the LHC with center of mass energies of 13 TeV based on CT14HERA2.54 before and after the update with the ATLAS 8 TeV absolute and normalized $t\bar{t}$ data. We observe the central prediction of the Higgs prediction increase by 0.1% for the absolute and normalized $|y_{t\bar{t}}|$ and $|y_t|$ distributions. As shown in the Fig. 2, the gluon PDF reduce by the inclusion of the $t\bar{t}$ data for the $|y_{t\bar{t}}|$ and $|y_t|$ distributions, and the gluon PDF is anti-correlated to the Higgs production as shown in Fig. 6, the Higgs production increase by the inclusion of $t\bar{t}$ data for $|y_{t\bar{t}}|$ and $|y_t|$ distributions.
TABLE III: Higgs boson inclusive cross section $\sigma(gg \rightarrow H)$ based on the CT14HERA2.54 and new PDFs. Here the PDF uncertainty is given at 68% C.L..

| $\sigma(gg \rightarrow H)$ LHC | 13 TeV (68% C.L.) |
|-------------------------------|--------------------|
| CT14HERA2.54                  | 42.50$^{+1.76\%}_{-2.10\%}$ |
| CT14HERA2.54+ATLAS$|y_{\ell\bar{\ell}}|$ | 42.58$^{+1.74\%}_{-2.07\%}$ |
| CT14HERA2.54+ATLAS$m_{tt}$    | 42.49$^{+1.75\%}_{-2.10\%}$ |
| CT14HERA2.54+ATLAS$|y_{t}$ | 42.57$^{+1.74\%}_{-2.07\%}$ |
| CT14HERA2.54+ATLAS$p_{T}$    | 42.50$^{+1.75\%}_{-2.10\%}$ |

CT14HERA2.54+ATLASN$|y_{\ell\bar{\ell}}|$ | 42.54$^{+1.75\%}_{-2.08\%}$ |
| CT14HERA2.54+ATLASN$m_{tt}$  | 42.50$^{+1.75\%}_{-2.10\%}$ |
| CT14HERA2.54+ATLASN$|y_{t}$ | 42.56$^{+1.74\%}_{-2.07\%}$ |
| CT14HERA2.54+ATLASN$p_{T}$  | 42.50$^{+1.75\%}_{-2.10\%}$ |

III The impact of CMS 8 TeV $t\bar{t}$ data on CT14HERA2 PDFs

In this section we provide comparisons of the CT14HERA2.54 and ePump updated CT14HERA2.54 PDFs that are obtained by adding CMS 8 TeV normalized $t\bar{t}$ differential production in $y_{\ell\bar{\ell}}$, $m_{tt}$, $y_{t}$, and $p_{T}$ that correspond to integrated luminosities of 19.7 fb$^{-1}$.

A Update CT14HERA2 PDFs with CMS 8 TeV $t\bar{t}$ data

In Fig. 9, we show the CT14HERA2.54 PDFs before and after ePump updated by including CMS 8 TeV normalized $t\bar{t}$ data. Different from the ATLAS data, we observe that the CMS normalized data provide relatively larger impact on both the central predictions and uncertainty bands of the CT14HERA2.54 gluon PDF at high $x$ region for the $y_{\ell\bar{\ell}}$, $m_{tt}$ and $p_{T}$ distribution, while the $y_{t}$ distribution do not provide significant impact. In the region $x > 0.1$, one can also see that the $y_{\ell\bar{\ell}}$, $m_{tt}$ and $p_{T}$ data deceases the gluon PDF, but the updated gluon PDF are well within the PDF error band. We also observe that, similar to the ATLAS data, the CMS $t\bar{t}$ data provide limited constraint to the uncertainty of the gluon PDF.
FIG. 9: The gluon PDF ratios for ePump-updated CT14HERA2.54+CMSNyt\(_t\), CT14HERA2.54+CMSNm\(_t\), CT14HERA2.54+CMSNy\(_t\) and CT14HERA2.54+CMSNp\(_T\) over the best-fit of the base CT14HERA2.54 gluon PDFs.

### B Comparison between theory from CT14HERA2 and ePump updated CT14HERA2 and CMS 8 TeV \(t\bar{t}\) data

In this section we provide comparisons of the normalized differential \(t\bar{t}\) production cross section as a function of \(y_{t\bar{t}}\), \(m_{t\bar{t}}\), \(y_{t}\), and \(p_T^t\) with the CMS 8 TeV measurements with integrated luminosities 19.7 fb\(^{-1}\). The distributions from theory and experiments in the rapidity \(y_{t\bar{t}}\) (first row left) of the top pair, the invariant mass \(m_{t\bar{t}}\) (first row right) of the top pair, the rapidity \(y_{t}\) (second row left) of the top, and the transverse momentum of the top \(p_T^t\) (second row right) are shown in Fig. 10. The upper part of each Fig. 10 shows comparison of the predictions from ePump fastNNLO with the measurements. The upper part of each figure shows comparison of the measurements with the theory predictions before and after ePump update. The lower part of each figure shows the ratio of the predictions to data. The error bars on the data points and shifted data points denote the total uncertainty, which is obtained by adding the statistical and systematic uncertainties in quadrature. In those figures the magenta solid lines correspond to the theoretical predictions from CT14HERA2.54, the blue solid lines are the theoretical predictions from new CT14HERA2.54 PDFs. The black and red error bars on each data and shifted data point that include both statistical and uncorrelated systematic errors, added in quadrature. The blue bands in ratio plots indicate the total uncertainty, that are the quadratic sum of statistical and systematic uncorrelated uncertainties, on the data in each bin. The yellow bands in ratio plots indicate the statistical uncorrelated uncertainties on the data in each bin. The error bars on the theoretical predictions are shown in 68% C.L.. We observe the large \(\chi^2\) values for the CMS normalized data as shown in Table II. By the direct comparison between data and theory, we observe that, in the case of the \(m_{t\bar{t}}\) distribution, the large \(\chi^2\) comes from the large \(m_{t\bar{t}}\) bins; while for the \(p^t_T\) distribution, it comes from the different
shape between the data and theory prediction.

FIG. 10: Comparison normalized differential cross sections $1/\sigma \frac{d\sigma}{dyt}$, $1/\sigma \frac{d\sigma}{dm_{t\bar{t}}}$, $1/\sigma \frac{d\sigma}{dp_{T}}$, $1/\sigma \frac{d\sigma}{d|yt|}$ from CT14HERA2.54 PDFs and from ePump updated CT14HERA2.54+CMSN PDFs and CMS 8 TeV normalized differential $t\bar{t}$ production cross sections data as a function of the $yt$, $m_{t\bar{t}}$, $yt$, and $p_{T}$.

C Correlation between normalized differential $t\bar{t}$ cross section and $\sigma_{H}(gg \rightarrow H)$

In view of the relative stronger impact from the CMS normalized $t\bar{t}$ data on gluon PDF, we show correlation between the Higgs boson cross section (in pb) through gluon-gluon fusion ($gg \rightarrow H$) at the LHC with center of mass energy of 13 TeV and the normalized differential $t\bar{t}$ production cross section as a function of $yt$, $m_{t\bar{t}}$, $yt$, and $p_{T}$ at 8 TeV. In Figure 11, black and red ellipses and triangles correspond to before and after ePump update results with CMS.
8 TeV top quark-pair production data. We select the bins which has strongest correlation with the Higgs production for each distributions. It shows that, stronger impact from the $t\bar{t}$ data on gluon PDF also change the correlation between Higgs production and the top quark-pair production. For example, for $y_{tt}$ distribution, the correlation for the bin $-0.3 < y_{tt} < 0$ update from $\cos\phi = 0.48$ to $\cos\phi = 0.43$; for $m_{tt}$ distribution, the correlation for the bin $400 < m_{tt} < 470$ update from $\cos\phi = 0.64$ to $\cos\phi = 0.63$; for $y_{t}$ distribution, the correlation for the bin $1.2 < y_{t} < 1.6$ update from $\cos\phi = -0.56$ to $\cos\phi = -0.53$; and for $p_{T}^{t}$ distribution, the correlation for the bin $260 < p_{T}^{t} < 320$ update from $\cos\phi = -0.73$ to $\cos\phi = -0.72$. It shows that, the CMS $p_{T}^{t}$ distribution gives the strongest anti-correlation with the Higgs production, which can be seen in the Fig. 1 for $x \sim 0.02$; while the CMS $y_{tt}$ distribution provide the strongest impact not just on gluon PDF but also on both the central prediction and uncertainty of the 13 TeV Higgs production. Different from the normalized $m_{tt}$ and $p_{T}^{t}$ distributions from ATLAS, which provide very good $\chi^{2}$ and minor impact, the CMS normalized $m_{tt}$ and $p_{T}^{t}$ distributions show large $\chi^{2}$ and relative stronger impact to both gluon PDF and the Higgs production.

**FIG. 11: Predicted Higgs boson cross section through gluon-gluon fusion ($gg \rightarrow H$) at the LHC with center of mass energy of 13 TeV versus the CMS top quark pair $t\bar{t}$ production cross sections at 8 TeV, PDF uncertainty is at the 90% C.L.**

**D Update Higgs cross section using new CT14HERA PDFs with CMS 8 TeV $t\bar{t}$ data**

Similar to that in ATLAS, we also calculate the Higgs-boson production through gluon-gluon fusion at 13 TeV based on CT14HERA2.54 after the ePump update by the CMS 8TeV normalized $t\bar{t}$ single distributions in $y_{tt}$, $m_{tt}$, $y_{t}$ and $p_{T}^{t}$ as shown in Table III D, where the PDF uncertainty is at the 68% C.L.. We observe the central prediction of
the Higgs prediction increase by 0.3% for $y_{t\bar{t}}$, $m_{t\bar{t}}$ and $p_T^j$ and the uncertainty reduced by 0.3% by the $y_{t\bar{t}}$ distribution.

TABLE IV: Higgs boson inclusive cross section $\sigma(gg \to H)$ based on the CT14HERA2.54 and new PDFs. Here the PDF uncertainty is given at 68 % C.L..

| $\sigma(gg \to H)$ LHC | 13 TeV (68% C.L.) |
|-------------------------|-------------------|
| CT14HERA2.54            | 42.50 $^{+1.76\%}_{-2.10\%}$ |
| CT14HERA2.54+CMSN$y_{t\bar{t}}$ | 42.65 $^{+1.72\%}_{-2.00\%}$ |
| CT14HERA2.54+CMSNm_{t\bar{t}} | 42.65 $^{+1.73\%}_{-2.07\%}$ |
| CT14HERA2.54+CMSNy_{t} | 42.49 $^{+1.73\%}_{-2.04\%}$ |
| CT14HERA2.54+CMSNp_{T}^{j} | 42.61 $^{+1.73\%}_{-2.07\%}$ |

IV Consistency between $t\bar{t}$ data and data in CT14HERA2

As we present in the last two sections, we observe the CT14HERA2 gluon PDF receive minor impact after including the 8 TeV ATLAS absolute and normalized and CMS normalized $t\bar{t}$ data. This can be a result of strong tension from the data included in the CT14HERA2 PDF. In order to study for possible tensions between the single differential $t\bar{t}$ data from ATLAS and CMS and the data sets included in the CT14HERA2 PDFs, we increase the weight of the $t\bar{t}$ data when we updating the CT14HERA2 PDFs using the $\epsilon$Pump. We consider weight from zero to nine for the single differential $t\bar{t}$ data individually for testing the tension among the $t\bar{t}$ and data included in the CT14HERA2 PDF. Weight zero case is just the CT14HERA2 fit without any change. Weight one case corresponds to CT14HERA2 fit with $t\bar{t}$ data included individually. Weight larger than one is equivalent to having more $t\bar{t}$ data points with the same experimental uncertainties [15]. Instead of $\chi^2$, we present the change of goodness-of-fit of each data by the variable $S_n$ [22], which can be treated as a rescale of $\chi^2$ base on the number of data points of the data. Values of $S_n$ between $-1$ and 1 correspond to a good fit(at the 68% C.L.); large positive values of $S_n$ ($\geq 2$) correspond to a poor fit; while large negative values ($\lesssim -2$) means that it fit unusually well. If we increase the weight of the ATLAS and CMS $t\bar{t}$ data in the fit, the $S_n$ of the $t\bar{t}$ data decreases with its reduced $\chi^2$, as it should be; when the weight of the $t\bar{t}$ data is becoming large, the $S_n$ of some particular data in CT14HERA2 may increase by noticeable amount. If some of the data in CT14HERA2 have tension with the $t\bar{t}$ data, the $S_n$ of those data will become larger when the weight of the $t\bar{t}$ data increases. We find that most of the data in CT14HERA2 do not show significant tension with the 8TeV single differential ATLAS and CMS $t\bar{t}$ data. However, we observe that some data in CT14HERA2 do show some tension with the $t\bar{t}$ data. In Figs. 12-13, we show the change of $S_n$ for some data in CT14HERA2 as the weight of the $t\bar{t}$ data increases from 0 to 9. We observe that some of the data in CT14HERA2 has minor change in $S_n$ as the weight of the $t\bar{t}$ data increases. For example, we see that the $S_n$ of the CDF jet data [6] and/or the D0 jet data [7] increases the most; while the $S_n$ of the CMS 7 TeV jet data [9] reduce mildly when the weight of the ATLAS normalized $|y_{t\bar{t}}|$ data or CMS normalized $p_T^j$ increase. As a result, we did not observe strong tension on the ATLAS and CMS single differential $t\bar{t}$ data from the data included in the CT14HERA2 PDF. But we do observe that, the jet data is relatively more sensitive to the inclusion of the $t\bar{t}$ data. It is quite reasonable, because the jet data provide constraint on gluon PDF as the $t\bar{t}$ data do. The inclusion of the $t\bar{t}$ data would forming a "competitive" relationship with the jet data on constraining gluon PDF.
FIG. 12: The equivalent Gaussian variable Sparsity $S_n$ of some data in cPump updated CT14HERA2 versus weight of the ATLAS absolute and normalized data for the absolute value of the rapidity $|y_t|$ of the top quark distribution and top-quark pair rapidity $|y_{t\bar{t}}|$ distribution at 8 TeV.
V The impact of ATLAS 8 TeV $t\bar{t}$ data on CT14HERA2mJ PDFs

As we learn from the last section that, before the $t\bar{t}$ data, the gluon PDF of the CT14HERA2 receive well constraint from the jet data, namely CDF [6], D0 [7], ATLAS [8] and CMS [9]. In order to see the impact of the $t\bar{t}$ data on gluon PDF, we need to suppress the contribution from jet data. For this purpose, first, we generated the Hessian eigenvector sets "CT14HERA2mJ" ("mJ" here means "minus jet") by global analysis after removing the four inclusive jet production data from Tevatron and LHC Run I in the CT14HERA2.54 fit. And the we update CT14HERA2mJ PDFs using $\text{ePump}$ by including $t\bar{t}$ data one by one. In this section, we provide comparisons of the CT14HERA2mJ before and after the $\text{ePump}$ updated by adding the ATLAS 8 TeV absolute and normalized differential $t\bar{t}$ production cross section as a function of $|y_{t\bar{t}}|$, $m_{t\bar{t}}$, $|y_t|$ and $p_T$. 

A Correlation between CT14HERA2mJ gluon PDF and $t\bar{t}$ data

We first check the correlation between the absolute(left) and normalized(right) differential $t\bar{t}$ data and the CT14HER2mJ $g(x, Q = 100 \text{ GeV})$ PDF is shown in Fig. 14. Without the inclusion of the jet data in the CT14HER2mJ, the gluon PDF receive constraints mostly from the deep inelastic scattering(DIS) data, and have different behavior as the gluon in the CT14HERA2 PDF. As showing in Fig. 14, the correlation between $t\bar{t}$ data and the gluon CT14HER2mJ PDF keep the main features as that for the gluon PDF in CT14HERA2 PDF shown in Fig. 1.
FIG. 14: Correlation cosine $\cos \phi$ between CT14HERA2mJ $g(x, Q = 100 GeV)$ PDF and FastNNLO predictions for each bins of the absolute (left) and normalized (right) $|y_{t\bar{t}}|$ (solid green), $m_{t\bar{t}}$ (dark magenta), $|y_{t}|$ (red) and $p_{T}$ (blue) top-quark differential distributions.

B Update CT14HERA2mJ PDFs with ATLAS 8 TeV $t\bar{t}$ data

In Figs. 15 and 16, we show ePump updated PDFs, starting from CT14HERA2mJ PDFs by including absolute and normalized ATLAS 8 TeV $t\bar{t}$ data. The impact on gluon PDF from those $t\bar{t}$ data can be seen by comparing the difference between the gluon PDF before and after ePump updating. It is obvious that, without the jet data in the fit, the absolute $d\sigma/d|y_{t\bar{t}}|$, $d\sigma/d|y_{t}|$ and normalized $1/\sigma d\sigma/d|y_{t\bar{t}}|$, $1/\sigma d\sigma/d|y_{t}|$ data have rather obvious impact on both the central predictions and uncertainty band of the CT14HERA2mJ gluon PDF. More specifically, we observe obvious raising of CT14HERA2mJ gluon PDF for $x \sim 0.05$ and lowering for $x \gtrsim 0.01$. We also observe obvious reduction of the gluon PDF for $x \sim 0.05$. However, we still do not see obvious impact on CT14HERA2mJ gluon PDF after including the absolute $d\sigma/dm_{t\bar{t}}$, $d\sigma/dp_{T}$, and normalized $1/\sigma d\sigma/dm_{t\bar{t}}$, $1/\sigma d\sigma/dp_{T}$ data. The result shown in the Figs. 15 and 16 directly confirm our understanding from the last section that, the reason why we see only minor impact on CT14HERA2 gluon PDF is because the CT14HERA2 gluon PDF is well contrained by the four jet data included in the CT14HERA2 PDF.
FIG. 15: The gluon PDF ratios for ePump-updated CT14HERA2mJ+ATLAS$|y_{t\bar{t}}|$, CT14HERA2mJ+ATLAS$m_{t\bar{t}}$, CT14HERA2mJ+ATLAS$|y_t|$, CT14HERA2mJ+ATLAS$p_T$ PDFs, which are obtained by including ATLAS 8 TeV absolute $d\sigma/d|y_{t\bar{t}}|$, $d\sigma/dm_{t\bar{t}}$, $d\sigma/d|y_t|$, and $d\sigma/dp_T$ data, over the best-fit of the base CT14HERA2.54 gluon PDFs.
FIG. 16: The gluon PDF ratios for $eP_{\text{pump}}$-updated CT14HERA2mJ+ATLAS$|y_t|$, CT14HERA2mJ+ATLAS$mt$, CT14HERA2mJ+ATLAS$|y_t|$, CT14HERA2mJ+ATLAS$p_T^T$ PDFs, which are obtained by including ATLAS 8 TeV normalized $1/\sigma \, d\sigma /dy_t$, $1/\sigma \, d\sigma /dm_t$, $1/\sigma \, d\sigma /dy_t$, $1/\sigma \, d\sigma /dp_T^T$ data, over the best-fit of the base CT14HERA2.54 gluon PDFs.
C Comparison between theory from CT14HERA2mJ and ePump updated CT14HERA2mJ and ATLAS 8 TeV \( t\bar{t} \) data

The comparisons between the theory predictions from CT14HERA2mJ and ePump updated CT14HERA2 PDFs and the ATLAS 8 TeV absolute and normalized differential \( t\bar{t} \) data are presented in Figs. 17 and 18. In both figures, the blue solid lines correspond to the theoretical predictions from CT14HERA2mJ, the magenta solid lines are the theoretical predictions from ePump updated CT14HERA2mJ PDFs. The black and red error bars on each data and shifted data point include both statistical and uncorrelated systematic errors, added in quadrature. The blue bands in ratio plots indicate the total uncertainty, that are the quadratic sum of statistical and systematic uncorrelated uncertainties, on the data in each bin. The yellow bands in ratio plots indicate the statistical uncorrelated uncertainties on the data in each bin. The error bars on the theoretical predictions show the 68% C.L.. As we see that the ePump predictions provides somewhat better description of the data.
FIG. 17: Comparisons of differential cross sections $d\sigma/d|y_{t\bar{t}}|$, $d\sigma/dm_{t\bar{t}}$, $d\sigma/dp_T$, $d\sigma/d|y_{t}|$ from CT14HERA2mJ PDFs and ePump updated CT14HERA2mJ+ATLAS$|y_{t\bar{t}}|$, CT14HERA2mJ+ATLAS$m_{t\bar{t}}$, CT14HERA2mJ+ATLAS$|y_{t}|$, CT14HERA2mJ+ATLAS$p_T$ PDFs and differential ATLAS 8 TeV $t\bar{t}$ production cross sections data. The black and red error bars on each data point of the unshifted and shifted data include both statistical and uncorrelated systematic errors, added in quadrature.
FIG. 18: Comparisons of normalized differential cross sections $1/\sigma \frac{d\sigma}{dy_{t\bar{t}}}$, $1/\sigma \frac{d\sigma}{dm_{t\bar{t}}}$, $1/\sigma \frac{d\sigma}{dp_{T}}$, $1/\sigma \frac{d\sigma}{dy_{t}}$ from CT14HERA2mJ PDFs and ePump updated CT14HERA2mJ+ATLASN $|y_{t\bar{t}}|$, CT14HERA2mJ+ATLASN $m_{t\bar{t}}$, CT14HERA2mJ+ATLASN $|y_{t}|$, CT14HERA2mJ+ATLASN $p_{T}$ PDFs and differential ATLAS 8 TeV $t\bar{t}$ production cross sections data. The black and red error bars on each data point of the unshifted and shifted data include both statistical and uncorrelated systematic errors, added in quadrature.

D Correlation between differential $t\bar{t}$ cross section and $\sigma_{H}(gg \rightarrow H)$

Now we show correlation between the Higgs boson cross section (in pb) through gluon-gluon fusion ($gg \rightarrow H$) at the LHC with center of mass energy of 13 TeV and the absolute and normalized differential $t\bar{t}$ production cross sections as a function of $|y_{t\bar{t}}|$, $m_{t\bar{t}}$, $|y_{t}|$, and $p_{T}$ at 8 TeV. Here we show one of the point for each $t\bar{t}$ theory prediction from CT14HERA2mJ and new CT14HERA2mJ PDFs. In Figs. 19 and 20, black and red ellipses and triangles correspond to theories from CT14HERA2mJ, and CT14HERA2mJ+ATLASN $|y_{t\bar{t}}|$, CT14HERA2mJ+ATLASN $m_{t\bar{t}}$, CT14HERA2mJ+ATLASN $|y_{t}|$, CT14HERA2mJ+ATLASN $p_{T}$ PDFs, as well as new CT14HERA2mJ+ATLASN $|y_{t\bar{t}}|$,.
We see from Figs. 19 and 20 that the Higgs boson cross section does not have large anti-correlation and correlation with the $t\bar{t}$ cross section, because the two processes are dominated by the gluon PDF in somewhat different $x$ regions.

FIG. 19: Predicted Higgs boson cross section through gluon-gluon fusion ($gg \rightarrow H$) at the LHC with center of mass energy of 13 TeV versus the ATLAS top quark pair $t\bar{t}$ production absolute cross sections at 8 TeV, PDF uncertainty is at the 90% C.L.
FIG. 20: Predicted Higgs boson cross section through gluon-gluon fusion ($gg \rightarrow H$) at the LHC with center of mass energy of 13 TeV versus the ATLAS top quark pair $t\bar{t}$ production normalized cross sections at 8 TeV, PDF uncertainty is at the 90% C.L.

E Update Higgs cross section using new CT14HERA2mJ with ATLAS 8 TeV $t\bar{t}$ data

Here, using ePump we provide the inclusive production cross section of Higgs-boson through gluon-gluon fusion, at the LHC with center of mass energies of 8 TeV based on CT14HERA2mJ and CT14HERA2mJ+ATLAS$|y_{t\bar{t}}|$, CT14HERA2mJ+ATLAS$|m_{t\bar{t}}|$, CT14HERA2mJ+ATLAS$|y_{t\bar{t}}|$, CT14HERA2mJ+ATLAS$|p_{T}^{t\bar{t}}|$, PDFs, as well as ePump-updated PDFs, namely CT14HERA2mJ+ATLASN$|y_{t\bar{t}}|$, CT14HERA2mJ+ATLASN$|m_{t\bar{t}}|$, CT14HERA2mJ+ATLASN$|y_{t\bar{t}}|$, CT14HERA2mJ+ATLASN$|p_{T}^{t\bar{t}}|$, PDFs in Table V. As we see that PDF uncertainties are slightly reduced.
TABLE V: Higgs boson inclusive cross section $\sigma(gg \rightarrow H)$ based on the CT14HERA2mJ and ePump updated CT14HERA2mJ with ATLAS 8 TeV $t\bar{t}$ data. Here the PDF uncertainty is given at 68 % C.L.

| $\sigma(gg \rightarrow H)$ LHC | $13 \text{ TeV (68 \% C.L.)}$ |
|--------------------------------|-------------------------------|
| CT14HERA2mJ                   | $42.13^{+2.78%}_{-3.30%}$    |
| CT14HERA2mJ+ATLAS$|y_{t\bar{t}}|$ | $42.70^{+2.62%}_{-2.88%}$    |
| CT14HERA2mJ+ATLAS$m_{t\bar{t}}$ | $42.13^{+2.75%}_{-3.24%}$    |
| CT14HERA2mJ+ATLAS$|y_{t}|$ | $42.56^{+2.66%}_{-2.96%}$    |
| CT14HERA2mJ+ATLAS$p_{T}^{t}$ | $42.15^{+2.75%}_{-3.23%}$    |
| CT14HERA2mJ+ATLASN$|y_{t\bar{t}}|$ | $42.52^{+2.66%}_{-3.01%}$    |
| CT14HERA2mJ+ATLASN$m_{t\bar{t}}$ | $42.16^{+2.74%}_{-3.22%}$    |
| CT14HERA2mJ+ATLASN$|y_{t}|$ | $42.56^{+2.66%}_{-2.93%}$    |
| CT14HERA2mJ+ATLASN$p_{T}^{t}$ | $42.15^{+2.75%}_{-3.23%}$    |

VI The impact of CMS 8 TeV $t\bar{t}$ data on CT14HERA2mJ PDFs

In this section we provide comparisons of the CT14HERA2mJ and ePump updated CT14HERA2 PDFs that are obtained by adding normalized differential $t\bar{t}$ production cross section as a function of $y_{t\bar{t}}$, $m_{t\bar{t}}$, $y_{t}$, and $p_{T}^{t}$ with the CMS 8 TeV measurements, that are correspond to integrated luminosities of 19.7 fb$^{-1}$.

A Update CT14HERA2mJ PDFs with CMS 8 TeV $t\bar{t}$ data

In this section by including the normalized CMS 8 TeV $1/\sigma \, d\sigma/dy_{t\bar{t}}$, $1/\sigma \, d\sigma/dm_{t\bar{t}}$, $1/\sigma \, d\sigma/dy_{t}$, and $1/\sigma \, d\sigma/dp_{T}^{t}$ data one by one, update CT14HERA2mJ PDFs. The impact on gluon PDF from $t\bar{t}$ data can be seen by comparing the difference between the gluon PDF before and after the ePump updating. From Fig. 21 we see that, without the jet data in the fit, the normalized differential CMS 8 TeV $t\bar{t}$ data $y_{t\bar{t}}$, $m_{t\bar{t}}$, $y_{t}$ and $p_{T}^{t}$ have rather obvious impact on both the central predictions and uncertainty bands of the CT14HERA2mJ gluon PDF at the region $10^{-4} < x < 0.6$, namely, each $t\bar{t}$ data increases the gluon PDF in the $10^{-4} < x < 10^{-1}$ while each $t\bar{t}$ data deceases it in the $10^{-1} < x < 0.6$, but the updated gluon PDF in four cases are well within the uncertainty bands of PDFs.
FIG. 21: The gluon PDF ratios for ePump-updated CT14HERA2mJ+CMSNyt, CT14HERA2mJ+CMSNm, CT14HERA2mJ+CMSNpt PDFs over the best-fit of the base CT14HERA2mJ gluon PDFs.
B Comparison between theory from CT14HERA2mJ and ePump updated CT14HERA2mJ and CMS 8 TeV $t \bar{t}$ data

In this section we provide comparisons of the normalized differential $t \bar{t}$ production cross section as a function of $y_{t \bar{t}}$, $m_{t \bar{t}}$, $y_t$, and $p_T^t$ with the CMS 8 TeV measurements with integrated luminosities 19.7 fb$^{-1}$. The distributions from theory and experiments in the transverse momentum of the top $p_T^t$ (first raw left) and its rapidity $y_t$ (first raw right), together with the invariant mass $m_{t \bar{t}}$ (second raw left) and rapidity $y_{t \bar{t}}$ (second raw right) of the top pair are shown in Fig. 22. The upper part of each Fig. 22 shows comparison of the predictions from ePump and fastNNLO with the measurements. The lower part of each figure shows the ratio of the predictions to data. The error bars on the data points and shifted data points denote the total uncertainty (is obtained by adding the statistical and systematic uncertainties in quadrature). The error bars on the theoretical predictions show the 68% C.L.. Predictions from ePump and fastNNLO both for the transverse momentum of the top $p_T^t$ and invariant mass $m_{t \bar{t}}$ of the top pair are higher at the region $200 < p_T^t < 400$ GeV, and $m_{t \bar{t}} > 600$ GeV. The $y_t$ predictions are in agreement within experimental uncertainties. The $y_{t \bar{t}}$ distribution in theory is in agreement with data at the region $0 < y_{t \bar{t}} < 1.6$, and it is higher than the data for $y_{t \bar{t}} > 1.6$ and $y_{t \bar{t}} < -1.0$. 
FIG. 22: Comparison of normalized differential $t\bar{t}$ production cross section at 8 TeV, as a function of the $y_{t\bar{t}}$, $m_{t\bar{t}}$, $y_t$, and $p_T^t$. PDFs uncertainties are given at 68%.

C Correlation between normalized differential $t\bar{t}$ cross section and $\sigma_H (gg \rightarrow H)$

Now we show correlation between the Higgs boson cross section (in pb) through gluon-gluon fusion ($(gg \rightarrow H)$) at the LHC with center of mass energy of 13 TeV and the normalized differential $t\bar{t}$ production cross sections as a function of $y_{t\bar{t}}$, $m_{t\bar{t}}$, $y_t$, and $p_T^t$ at 8 TeV. Here show one of the point for each $t\bar{t}$ theory prediction from CT14HERA2mJ and new CT14HERA2mJ PDFs. In Fig. 23, black and red ellipses and triangles correspond to theories from CT14HERA2mJ+CMSNy_t, CT14HERA2mJ+CMSNm_t, CT14HERA2mJ+CMSNy_t, CT14HERA2mJ+CMSNp_T PDFs, with top quark mass and Higgs boson mass are set to $m_t = 173.3$ GeV and $m_H = 125$ GeV. We see that the normalized differential $t\bar{t}$ production cross section and Higgs boson cross section through gluon-gluon fusion at LHC with center of mass energy of 13 TeV from CT14HERA2mJ and new CT14HERA2mJ+CMSNy_t,
CT14HERA2mJ+CMSNm_{tt}, CT14HERA2mJ+CMSN_{tt}, CT14HERA2mJ+CMSN_{lT}, PDFs, PDFs are anticorrelated and correlated. We see from Figs. 19 and 20 that the Higgs boson cross section does not have large anti-correlation and correlation with the $t\bar{t}$ cross section, because the two processes are dominated by the gluon PDF in somewhat different $x$ regions.

Now we show the correlation between $\sigma_{H}(gg \rightarrow H)$ at $8\, \text{TeV}$ and the CT14HERA2mJ PDFs of different flavors, as a function of the parton momentum fraction $x$. The correlation of two observables is measured by the cosine of the angle between the gradient directions of the two observables in the PDF parameter space [20, 21]. From Fig. 6 we can see a strong correlation between the $gg \rightarrow H$ cross section and the gluon PDF at $x \sim 0.01$, as expected. The charm and bottom PDFs track the gluon PDF in these plots, since they arise through gluon splitting.

D Correlation between CT14HERA2mJ gluon PDF and $\sigma_{H}(gg \rightarrow H)$

Now we show the correlation between $\sigma_{H}(gg \rightarrow H)$ at $8\, \text{TeV}$ and the CT14HERA2mJ PDFs of different flavors, as a function of the parton momentum fraction $x$. The correlation of two observables is measured by the cosine of the angle between the gradient directions of the two observables in the PDF parameter space [20, 21]. From Fig. 6 we can see a strong correlation between the $gg \rightarrow H$ cross section and the gluon PDF at $x \sim 0.01$, as expected. The charm and bottom PDFs track the gluon PDF in these plots, since they arise through gluon splitting.

24.
E Update Higgs cross section using new CT14HERA2mJ with CMS 8TeV $t\bar{t}$ data

Here, using ePump we provide the inclusive production cross section of Higgs-boson through gluon-gluon fusion, at the LHC with center of mass energies of 8 TeV based on CT14HERA2mJ and new CT14HERA2mJ+CMSN_{yt}, CT14HERA2mJ+CMSN_{mt}, CT14HERA2mJ+CMSN_{yt}, CT14HERA2mJ+CMSN_{pt}, PDFs in Table VI. As we see that the PDF uncertainty of $\sigma(gg \rightarrow H)$ is reduced after including the $t\bar{t}$ data in the fit.

TABLE VI: Higgs boson inclusive cross section $\sigma(gg \rightarrow H)$ based on the CT14HERA2mJ and ePump updated CT14HERA2mJ with CMS 8 TeV $t\bar{t}$ data. Here the PDF uncertainty is given at 68% C.L..

| $\sigma(gg \rightarrow H)$ LHC | 13 TeV (68% C.L.) |
|-------------------------------|-------------------|
| CT14HERA2mJ                  | 42.13^{+2.78%}_{-3.30%} |
| CT14HERA2mJ+CMSN_{pt}        | 42.98^{+2.54%}_{-2.49%} |
| CT14HERA2mJ+CMSN_{yt}        | 42.27^{+2.63%}_{-3.02%} |
| CT14HERA2mJ+CMSN_{mt}        | 42.49^{+2.57%}_{-2.65%} |
| CT14HERA2mJ+CMSN_{yt\bar{t}}| 42.56^{+2.63%}_{-3.03%} |

VII The impact of CMS 7 TeV inclusive jet data on CT14HERA2mJ

In Fig. 25, we compare gluon PDFs from CT14HERA2mJ, CT14HERA2mJpJ, and CT14HERA2mJ+CMS7J. Here CT14HERA2mJpJ and CT14HERA2mJ+CMS7J are obtained by ePump by adding four jet data [6–9] into CT14HERA2mJ fit, and including the CMS 7 TeV inclusive jet data [9] into CT14HERA2mJ fit. We first observe that the CT14HERA2mJpJ gluon PDF has smaller uncertainty band than the CT14HERA2mJ+CMS7J gluon PDF, which tells that the four jet data have a strong impact on the gluon PDF. It is therefore understandable why we don’t see significant impact on the CT14HERA2 PDF from the $t\bar{t}$ data. Despite difference on uncertainty between CT14HERA2mJpJ gluon PDF and CT14HERA2mJ + $t\bar{t}$ (from ATLAS and CMS) gluon PDF, it is worth to note that, both the $t\bar{t}$ (from ATLAS and CMS) and jet data give similar impact on the gluon central PDF, which shows
the agreement between the impact on gluon PDF from $t\bar{t}$ and jet data.

It is obvious to see that, the CMS 7 TeV inclusive jet data dominate the contribution of constraining the gluon PDF among the four jet data. Therefore, in the following study, we consider only the CMS 7 TeV inclusive jet data.

It is worth to note that, the $t\bar{t}$ production data have rather smaller number of data points than the jet data by about a factor of 10. After testing the impact on CT14HERA2 and CT14HERA2mJ PDFs, it is interesting to compare the sensitivity per data point for the jet and $t\bar{t}$ data. In order to see this, a hypothetical weight is implemented to the single differential $t\bar{t}$ production data with the weight to be equal to the ratio between number of data points of the CMS 7 TeV jet data and the $t\bar{t}$ data. Taking the CMS 8TeV normalized $p_T$ distribution as an example, the hypothetical weight that apply to the data is equal to $w = 133/8 = 16.6$. In practice, a larger weight can arise from increasing the event statistics or reducing the experimental errors.

In this naive estimation, we assume the central values of the measurement do not change such that the central prediction after updating with the hypothetical weight is rather less meaningful. For this reason, in the following we show the comparison of the PDFs uncertainty.

In Figs. 26-28, we compare the impact of the CMS 7 TeV inclusive jet data and CMS 8 TeV normalized $t\bar{t}$ production data with the hypothetical weight on gluon PDF uncertainty. We find that, the weighted $t\bar{t}$ production data provide stronger constraint on gluon PDFs for $10^{-3} \lesssim x \lesssim 5 \times 10^{-2}$. It is also true for the absolute ATLAS 8 TeV $t\bar{t}$ production data. With the hypothetical weight equal to the ratio of number of jet and $t\bar{t}$ data points, the absolute $t\bar{t}$ production data provide about the same constraint on gluon PDF as the jet data, which is shown in Fig. 27.
FIG. 26: Comparison of the gluon PDF error band from CT14HERA2mJ+CMS7J (red shaded band), CT14HERA2mJ+CMSNyt\bar{t}W13.3 (top left, green shaded band), CT14HERA2mJ+CMSNm\bar{t}W19.0 (top right, green shaded band), CT14HERA2mJ+CMSNm\bar{t}W16.6 (bottom left, green shaded band), CT14HERA2mJ+CMSNyt\bar{t}W13.3 (bottom right, green shaded band) PDFs, that are obtained by adding CMS 7 TeV inclusive jet data, CMS 8 TeV normalized $1/\sigma \, d\sigma/dy_{\bar{t}}$ data with weight 13.3, $1/\sigma \, d\sigma/dm_{\bar{t}}$ data with weight 19.0, $1/\sigma \, d\sigma/dy_{\bar{t}}$ data with weight 13.3, $1/\sigma \, d\sigma/dp_T$ data with weight 16.6 at $Q = 100$ GeV and at 90% C.L., with the base CT14HERA2mJ gluon PDF (blue band).
FIG. 27: Comparison of the gluon PDF error band from CT14HERA2mJ+CMS7J (red shaded band), CT14HERA2mJ+ATLAS|y_t|W26.6 (top left, green shaded band), CT14HERA2mJ+ATLAS|m_t|W19.0 (top right, green shaded band), CT14HERA2mJ+ATLAS|^p_T|W16.6 (bottom left, green shaded band), CT14HERA2mJ+ATLAS|y_t|W26.6 (bottom right, green shaded band) PDFs, which are obtained by adding CMS 7 TeV inclusive jet data, ATLAS 8 TeV absolute \(d\sigma/d|y_t|\) data with weight 26.6, \(d\sigma/dm_{tt}\) data with weight 19.0, \(d\sigma/d|y_t|\) data with weight 26.6, and \(d\sigma/d|p_T|\) data with weight 16.6 at \(Q = 100\) GeV and at 90% C.L., are compared with the base CT14HERA2mJ gluon PDF (blue band).
Next, we examine the impact of the CT14HERA2.54, CT14HERA2mJ, and updated PDFs, obtained by including CMS 8 TeV normalized $1/\sigma \, d\sigma/dy_{tt}$ data, and CMS 7 TeV inclusive jet via ePump updating, to observable. The Higgs production rate through gluon-gluon fusion at the LHC is sensitive to gluon PDF in the middle-$x$ region, which is constrained by both CMS 7 TeV inclusive jet and $1/\sigma \, d\sigma/dy_{tt}$ data. In Fig. 29, we show the correlation ellipses between CMS 8 TeV normalized $d\sigma/dy_{tt}$ data for various rapidity bins and Higgs production through gluon-gluon fusion at 13 TeV for CT14HERA2 (black), CT14HERA2mJ+CMSN$_{yt\bar{t}}$ (blue), CT14HERA2mJ+CMSN$_{yt\bar{t}}$W13.3 (cyan), CT14HERA2mJ+CMS7J (green) and CT14HERA2mJ (red). The central prediction of the CT14HERA2mJ+CMSN$_{yt\bar{t}}$W13.3 is obtained by assuming the central measurement is the same as that in CT14HERA2mJ+CMSN$_{yt\bar{t}}$. 

FIG. 28: ePump updated CT14HERA2mJ+CMS7J (red shaded band), CT14HERA2mJ+ATLASN$_{|yt\bar{t}}|W26.6$ (top left, green shaded band), CT14HERA2mJ+ATLASm$_{tt}W19.0$ (top right, green shaded band), CT14HERA2mJ+ATLASN$_{p}W16.6$ (bottom left, green shaded band), CT14HERA2mJ+ATLASN$_{|yt\bar{t}}|W26.6$ (bottom right, green shaded band) PDFs, which are obtained by adding CMS 7 TeV inclusive jet data, ATLAS 8 TeV normalized $1/\sigma \, d\sigma/dy_{tt}$ data with weight 26.6, $1/\sigma \, d\sigma/dm_{tt}$ data with weight 19.0, $1/\sigma \, d\sigma/dy_{tt}$ data with weight 26.6, and $1/\sigma \, d\sigma/dp_{T}^{T}$ data with weight 16.6 at $Q = 100$ GeV and at 90% C.L., are compared with the CT14HERA2mjet gluon PDF (blue band).
FIG. 29: Correlation ellipse between of the Higgs production rate via gluon-gluon fusion and the CMS 13 TeV normalized $1/\sigma d\sigma/dy_{t\bar{t}}$ differential cross section, for ePump updated CT14HERA2mJ+CMSN_yt, CT14HERA2mJ+CMSN_ytW13.3, CT14HERA2mJ+CMS7J and CT14HERA2mJ PDFs.

VIII Top quark mass dependence

In this section we study top-quark mass dependence of the differential top pair production distributions as function of $m_{t\bar{t}}$, $p_T$, $|y_{t\bar{t}}|$ and $|y_t|$ at 8 TeV. In Fig. 30 we show the chi-square function, $\chi^2$ versus the top-quark mass, for the absolute and normalized 8 TeV single differential cross sections as a function of the invariant mass $m_{t\bar{t}}$ of the top-quark pair. The $d\sigma/dm_{t\bar{t}}$ is shown in red; the $1/\sigma d\sigma/dm_{t\bar{t}}$ is shown in green. The parabolic curves are fitted from
calculation with many values of top mass from 171.0 GeV to 175.0 GeV. As we see that the two curves have slightly different minimum, $m_t = 173.0$ GeV for absolute distributions and $m_t = 173.5$ GeV for normalized distributions. It may be because the anti correlation of the the inverse of the total cross section. We also perform same the study for the $p_T^t$, $|y_t|$ and $|y_{tt}|$ distributions, and we find that differential cross sections as a function of $p_T^t$, $|y_t|$ and $|y_{tt}|$ do not depend on top-quark mass. The Ref. [10] have also studied and found that the invariant mass of the top pair $m_{tt}$, the top transverse momentum $p_T^t$ have stronger dependence on top mass than the top rapidity $y_t$ and the rapidity of the top pair $y_{tt}$.

![Graph](image.png)

**FIG. 30:** The chi-square function $\chi^2$ versus the top mass for the absolute and normalized 8 TeV single differential cross sections as a function of the invariant mass of the top pair $m_{tt}$.

IX Conclusions

In this paper, we examined the impact of the $t\bar{t}$ data on the CT14HERA2 and CT14HERA2mJ PDFs using ePump package. We found that all the top-quark pair production data—top quark pair invariant mass $m_{tt}$, top quark pair rapidity $y_{tt}$, the individual top quark/antiquark transverse momentum $p_T^t$, and absolute value of the top quark rapidity $|y_t|$ show minor impact on CT14HERA2 gluon PDF when jet data have been included in the global analysis. It is because the number of data points for the $t\bar{t}$ data is much less than the jet data. By giving a hypothetical weight on the $t\bar{t}$ data as the ratio of number of data points between jet data and $t\bar{t}$ data, the $t\bar{t}$ data show good agreement with the impact from jet data with similar strength. Hence, the sensitivity per data point of $t\bar{t}$ data is similar to that of jet data, while the total sensitivity of the data set depends on the total number of data points. We also investigated top mass dependence of the differential top pair production distributions at 8 TeV. We found that only $d\sigma/dm_{tt}$ distribution is sensitive to the top-quark mass with the minimum at around 173.3 GeV.

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