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Higher Order Standard Model cross-sections at 7 TeV

Juan Alcaraz

CIEMAT, Madrid

Roberto Chierici

Institut de Physique Nucléaire de Lyon

Fabio Cossutti

Sezione di Trieste, INFN

Guillelmo Gómez-Ceballos

Massachusetts Institute of Technology

Sanjay Padhi

University of California, San Diego

Fabian Stoeckli

CERN

Silvano Tosi

Institut de Physique Nucléaire de Lyon

(On behalf of the CMS Collaboration)

Abstract

This study summarizes some of the higher order Standard Model (SM) cross sections using the latest available calculations for proton-proton collisions with 7 TeV centre-of-mass energy. The cross-section calculations are made choosing scales and parton distribution functions (PDFs) which are widely used in the CMS Collaboration for Monte Carlo simulations. The scale and PDF uncertainties are provided for these choices. Cross-sections using other higher order PDFs are also outlined along with their uncertainties.

1 Introduction

The LHC has recently started delivering proton-proton collisions at a centre-of-mass energy of 7 TeV. Physics analyses at the LHC often depend on various inputs from theory that are only known with limited accuracy. The predictions on process cross sections are a well known example; their accuracy depend on the order of perturbation theory of the calculation and the PDFs used.

Most often there is no unique prescription of what calculation and what input settings should be used in a given analysis when comparing to the data. This study makes use of certain conventions, suggested by the Monte Carlo simulations used in CMS, in performing the computations of higher order cross sections, along with the determination of the associated errors, and aims at establishing common reference values for most relevant SM cross sections which analyses can refer to.

This note is organised as follows: in Section 2, guidelines for the calculation of K-factors based on higher order cross sections, along with given scales and PDF uncertainties, are provided. In Section 3 the assumptions made for these calculations are given, followed by the results in Section 4. Finally, in Section 5, the results are summarized.

2 Normalization factors, scale and PDFs

As a general rule, the highest-order available calculation should be used when calculating cross-sections along with dependencies on kinematics. These predictions may be used to normalize or reweight the Monte Carlo distributions in the analyses. In doing so, generator level cuts which may have been used for a given Monte Carlo production should be taken into account also in the calculation of the K-factors. This requires that, for instance, the reference leading order (LO) parton shower based MC and the next-to-leading order (NLO) calculation should use as much as possible the same cuts, and similar PDFs. Applying an inclusive K-factor to a (LO) Monte Carlo generation implicitly assumes that the change in acceptance introduced by the analysis is not very sensitive to higher order QCD effects. This is an aspect that should be checked carefully by those analyses where such a sensitivity may be present. Alternatives to a constant K-factor are an event reweighting, function of some kinematic variables, or a determination of an *a posteriori* K-factor, if the same acceptance cuts of the analysis can be reproduced at parton level for the higher order calculation.

Other inputs that should be made uniform between leading and higher order calculations are the normalization μ_R and factorization μ_F scales, as well as the strong coupling constant and the PDFs. Additionally, the order of the PDFs used should match with the order of the matrix-element calculations in the ratio for the K-factors, with the exception for next-to-next-leading order (NNLO) calculations, for which one can only consider NLO PDFs.

2.1 Scale uncertainties

The calculation of cross-sections in a given order in perturbation theory implies a dependence on both renormalization (μ_R) and factorization (μ_F) scales. These are typically considered to be the same as the central value (μ_0) of the scale. For estimating the scale uncertainty, the scale choices are varied in the units of μ_0. Although μ_R and μ_F can be varied independently, in this study we vary by the same units at the same time. The uncertainty on the cross section given by the scale choices is then conventionally determined by a variation in the range $1/2\mu_0 < \mu_R, \mu_F < 2\mu_0$.

2.2 PDFs

In general the most recent PDF sets should be used for cross section and acceptance calculations. If an analysis acceptance is studied using PYTHIA [1] or HERWIG [2], the LO PDF (CTEQ6M [3] used in CMS simulations) should be used as a central value. However, the uncertainties on cross sections, and hence the uncertainties on acceptance, are computed with respect to the nominal choice at higher orders. We compute the PDF uncertainties using the prescription provided by the CTEQ Collaboration [3]. Additionally, the final systematics are computed using the envelopes provided by the central values and PDF errors from the MSTW08 [4], CTEQ6.6 [9] and NNPDF2.0 [5] PDFs, using each groups prescriptions for combining the two types of errors. This is also recommended by the PDF4LHC studies.

For a given central choice of scale and PDF, we estimate the uncertainties based on N PDF sets of eigenvectors for an observable X. We use 2 PDF sets for each of the N eigenvectors, along the $\pm$ directions respectively. The uncertainty due to the PDFs is then defined as:

$$\Delta X^{\pm} = \sqrt{\Sigma_i [max(X_i^{\pm} - X_0, X_i^{\mp} - X_0, 0)]^2} \quad (1)$$

where X_i^+ and X_i^- are the values of X computed from the two PDF sets along $\pm$ direction of the $i-$th eigenvector, and X_0 the central value. The additional statistical uncertainties due to limited MC statistics can be evaluated by reweighting the MC events as a function of the parton flavours q_1 and q_2, parton momenta x_1, x_2 as well as μ_F. Finally, it should be noted that if the perturbative order of the MC simulations is different from the one of the cross-section calculation, also the choice of the α_s may be different. Since this residual dependence is very difficult to factorise, it can be estimated by reweighting the sample.

3 Central values and choices for generator parameters

We perform the computation of the cross sections by using the most appropriate and recent calculations that are made available by the theory community. FEWZ [6] is used for the computation of NNLO cross-sections involving W and Z bosons, while we use MCFM 5.8 [7] for the rest of the SM processes at LO and NLO in perturbation theory. The study is performed for proton-proton collisions at a centre-of-mass energy of 7 TeV. The input parameters are the same used for the nominal MC simulation in CMS.

Some of the parameter settings in accordence with the PDG [8] recommendation for performing the calculations are given in Table 1.

Input parameters	Values for Central Choice
PDF Set	CTEQ6M
W boson mass	80.398 GeV
W boson Width	2.141 GeV
Z boson mass	91.1876 GeV
Z boson Width	2.4952 GeV
t quark mass	172.5 GeV
b quark mass	4.8 GeV
c quark mass	1.27 GeV
fine-structure constant	0.007297352

Table 1: Input parameters used for obtaining the central value for various SM processes.

The cross sections for heavy quarks (b or c) associated with bosons are calculated using inclusive in the number of jets. We use k_T-algorithm with the following parameters.

Input parameters
P_T Jet $>$ 10 GeV
$\|\eta\|$ Jet $<$ 5.0
$P_T^{b,c}$ Jet $>$ 10 GeV
$\|\eta^{b,c}\| < 2.5$
pseudo-cone size, R = 0.7

Table 2: Input parameters used for processes involving heavy quarks.

4 Higher order cross sections

The NNLO cross sections computed with FEWZ for W and Z boson production are summarized in Table 3- 4. The total PDF uncertainties are based on the respective general-purpose PDF sets from CTEQ, MSTW08 and NNPDF2.0. The combined uncertainties are then computed using:

$$\Delta X_{total} = \frac{1}{2}[Max(X_1 + \Delta X_1, X_2 + \Delta X_2, X_3 + \Delta X_3) - Min(X_1 - \Delta X_1, X_2 - \Delta X_2, X_3 - \Delta X_3)] \quad (2)$$

where X_1, X_2, X_3 are central values from CTEQ6.6, MSTW08 and NNPDF2.0. The ΔX_i's are the associated uncertainties with variation in their eigenvectors along $\pm$ directions.

Processes	Generator	Phase Space cuts	Order	Final state	Cross-section (pb) PDF = CTEQ6M	Error (pb) Scale, PDF
W^+	FEWZ	-	NNLO	$W \to l\nu_l, l = e, \mu, \tau$	16670	$\pm$114, $\pm$ 843
W^-	FEWZ	-	NNLO	$W \to l\nu_l, l = e, \mu, \tau$	11379	$\pm$146, $\pm$ 759
Total W	FEWZ	-	NNLO	$W \to l\nu_l, l = e, \mu, \tau$	28049	$\pm$186, $\pm$ 1134
Z/γ^*	FEWZ	$m_{ll} >$ 20 GeV	NNLO	$Z \to l^+l^-, l = e, \mu, \tau$	4486	$\pm$111, $\pm$220
Z/γ^*	FEWZ	$m_{ll} >$ 50 GeV	NNLO	$Z \to l^+l^-, l = e, \mu, \tau$	2906	$\pm$55, $\pm$111

Table 3: NNLO cross sections for W and Z bosons using CTEQ6M. The cross sections are computed for exclusive decays to leptons. The final inclusive values for W are obtained using appropriate branching fractions from the PDG [8].

Processes	Generator	Phase Space cuts	Order	Final state	Cross-section (pb) PDF = CTEQ6.6	Error (pb) Scale, PDF
W^+	FEWZ	-	NNLO	$W \to l\nu_l, l = e, \mu, \tau$	17137	$\pm$115, $\pm$ 942
W^-	FEWZ	-	NNLO	$W \to l\nu_l, l = e, \mu, \tau$	11534	$\pm$149, $\pm$ 754
Total W	FEWZ	-	NNLO	$W \to l\nu_l, l = e, \mu, \tau$	28671	$\pm$188, $\pm$ 1307
Z/γ^*	FEWZ	$m_{ll} >$ 20 GeV	NNLO	$Z \to l^+l^-, l = e, \mu, \tau$	4644	$\pm$164, $\pm$352
Z/γ^*	FEWZ	$m_{ll} >$ 50 GeV	NNLO	$Z \to l^+l^-, l = e, \mu, \tau$	3087	$\pm$99, $\pm$230

Table 4: NNLO cross sections for W and Z bosons using CTEQ6.6. The cross sections are computed for exclusive decays to leptons. The final inclusive values for W are obtained using appropriate branching fractions from the PDG [8].

The uncertainties due to scale variations contribute to $\approx 1, 2$% for W and Z/γ^* decays. The PDF variations are $\approx X_1, X_2$%, respectively. Table 5 shows the LO and NLO cross sections for various SM processes. Processes with c and b quarks are treated using the massive-quark scheme.

The cross sections for $t\bar{t}$ are in very good agreement with $\sigma_{t\bar{t}}^{NNLL} = 165 \pm 10$ pb using NNLL resummations [11], with a top mass of 173 GeV. Similarly, the single top production in s-channel agrees well with the NNLL approximations studies [12] within uncertainties $\sigma_{Singletop}^{NNLL} = 4.6 \pm 0.06 \pm 0.13$ pb. The results presented here can serve to compute K-factors, which can be defined as the ratio N^{k}LO/LO for the analysis, keeping into accounts the comments in section 2.1.

5 Summary and conclusions

This note provides some calculations of higher-order cross-sections for several SM processes in pp collisions at 7 TeV. The cross-sections are computed using the FEWZ and MCFM calculators for a given choice of input parameters. The dominant systematic uncertainties on the cross-sections are due to the uncertainties in the PDFs, which are typically of the order of ($y1 - y2$)% on the total cross sections. The scale uncertainties within the variation of $1/2\mu_0 < \mu_R, \mu_F < 2\mu_0$ are found to be at ($x1 - x2$)% level.

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Processes	Phase Space cuts	Final state	CTEQ6M $\sigma\pm$ PDF $\pm$ Scale	CTEQ6.6 $\sigma\pm$ PDF $\pm$ Scale	MSTW08NLO 68% C.L $\sigma\pm$ PDF $\pm$ Scale	NNPDF2.0 $\sigma\pm$ PDF $\pm$ Scale
$t\bar{t}$	-	Inclusive	$154.5 \pm xx^{+18.5}_{-20.1}$	$150.5 \pm xx^{+17.9}_{-19.5}$	$162 \pm xx^{+19.9}_{-21.7}$	$163 \pm xx^{+20.2}_{-20.7}$
$\bar{t}$ (s-channel)	-	Inclusive	$1.4 \pm xx^{+0.03}_{-0.03}$	$1.4 \pm xx^{+0.03}_{-0.03}$	$1.5 \pm xx^{+0.04}_{-0.03}$	$1.4 \pm xx^{+0.03}_{-0.02}$
t (s-channel)	-	Inclusive	$2.6 \pm xx^{+0.06}_{-0.05}$	$2.6 \pm xx^{+0.08}_{-0.05}$	$2.7 \pm xx^{+0.07}_{-0.05}$	$2.7 \pm xx^{+0.07}_{-0.05}$
Total t (s-channel)	-	Inclusive	$4.0 \pm xx^{+0.09}_{-0.08}$	$4.0 \pm xx^{+0.11}_{-0.08}$	$4.2 \pm xx^{+0.11}_{-0.08}$	$4.1 \pm xx^{+0.10}_{-0.07}$
$\bar{t}$ (t-channel)	-	Inclusive	$21.6 \pm xx^{+0.51}_{-0.45}$	$21.3 \pm xx^{+0.58}_{-0.42}$	$22.1 \pm xx^{+0.67}_{-0.41}$	$23.0 \pm xx^{+0.79}_{-0.30}$
t (t-channel)	-	Inclusive	$41.5 \pm xx^{+1.23}_{-0.70}$	$40.8 \pm xx^{+1.29}_{-0.52}$	$41.4 \pm xx^{+1.30}_{-0.51}$	$43.4 \pm xx^{+1.56}_{-0.50}$
Total t (t-channel)	-	Inclusive	$63.1 \pm xx^{+1.74}_{-1.15}$	$62.1 \pm xx^{+1.87}_{-0.94}$	$63.5 \pm xx^{+1.97}_{-0.92}$	$66.4 \pm xx^{+2.35}_{-0.80}$
$W^+\bar{t}$	-	$\bar{t}$ as Incl., $W \to l\nu_l$	$5.3 \pm xx^{+0.34}_{-0.56}$	$5.1 \pm xx^{+0.33}_{-0.54}$	$5.5 \pm xx^{+0.35}_{-0.59}$	$5.9 \pm xx^{+0.37}_{-0.60}$
W^-t	-	t as Incl., $W \to l\nu_l$	$5.3 \pm xx^{+0.34}_{-0.56}$	$5.1 \pm xx^{+0.33}_{-0.55}$	$5.5 \pm xx^{+0.36}_{-0.59}$	$5.9 \pm xx^{+0.38}_{-0.58}$
Total tW	-	t as Incl., $W \to l\nu_l$	$10.6 \pm xx^{+0.68}_{-1.12}$	$10.2 \pm xx^{+0.66}_{-1.09}$	$11.0 \pm xx^{+0.71}_{-1.18}$	$11.8 \pm xx^{+0.75}_{-1.18}$
$W^+\bar{c}$	-	Inclusive	$1736 \pm xx^{+62.0}_{-65.3}$	$1969 \pm xx^{+79.1}_{-86.1}$	$1823 \pm xx^{+87.8}_{-77.8}$	$1661 \pm xx^{+59.8}_{-44.1}$
W^-c	-	Inclusive	$1889 \pm xx^{+108.6}_{-58.9}$	$2132 \pm xx^{+126.1}_{-103.9}$	$2066 \pm xx^{+113.3}_{-96.2}$	$1914 \pm xx^{+88.1}_{-73.4}$
Total Wc	-	Inclusive	$3625 \pm xx^{+170.6}_{-124.2}$	$4101 \pm xx^{+205.2}_{-190.0}$	$3889 \pm xx^{+201.1}_{-174.0}$	$3575 \pm xx^{+148.0}_{-117.5}$
$W^+b\bar{b}$	-	Inclusive, LO	$21.8 \pm xx^{+4.2}_{-3.6}$	$22.2 \pm xx^{+4.6}_{-3.4}$	$23.2 \pm xx^{+4.9}_{-3.8}$	$22.4 \pm xx^{+4.5}_{-3.3}$
$W^-b\bar{b}$	-	Inclusive, LO	$13.0 \pm xx^{+2.6}_{-1.9}$	$13.3 \pm xx^{+2.6}_{-2.1}$	$14.4 \pm xx^{+2.9}_{-2.3}$	$13.5 \pm xx^{+2.6}_{-2.0}$
Total $Wb\bar{b}$	-	Inclusive, LO	$34.8 \pm xx^{+6.8}_{-5.5}$	$35.5 \pm xx^{+7.2}_{-5.5}$	$37.6 \pm xx^{+7.8}_{-6.1}$	$35.9 \pm xx^{+7.1}_{-5.3}$
$Z/\gamma^* b\bar{b}$	$m_{ll} > 20$ GeV	Inclusive, LO	$68.0 \pm xx^{+18.2}_{-13.9}$	$66.7 \pm xx^{+18.4}_{-13.7}$	$71.6 \pm xx^{+20.0}_{-14.9}$	$71.1 \pm xx^{+20.3}_{-14.9}$
W^+W^-	-	Inclusive	$43.0 \pm xx^{+1.5}_{-1.2}$	$43.5 \pm xx^{+1.6}_{-1.0}$	$45.1 \pm xx^{+1.5}_{-1.2}$	$43.8 \pm xx^{+1.5}_{-1.1}$
W^+Z/γ^*	$m_{ll} > 40$ GeV	Inclusive	$11.8 \pm xx^{+0.6}_{-0.5}$	$11.9 \pm xx^{+0.6}_{-0.5}$	$12.1 \pm xx^{+0.6}_{-0.5}$	$12.0 \pm xx^{+0.7}_{-0.4}$
W^-Z/γ^*	$m_{ll} > 40$ GeV	Inclusive	$6.4 \pm xx^{+0.3}_{-0.3}$	$6.4 \pm xx^{+0.3}_{-0.3}$	$6.9 \pm xx^{+0.3}_{-0.3}$	$6.6 \pm xx^{+0.4}_{-0.3}$
Total WZ/γ^*	$m_{ll} > 40$ GeV	Inclusive	$18.2 \pm xx^{+0.9}_{-0.8}$	$18.3 \pm xx^{+0.9}_{-0.8}$	$19.0 \pm xx^{+0.9}_{-0.8}$	$18.6 \pm xx^{+1.1}_{-0.7}$
$Z/\gamma^* Z/\gamma^*$	$m_{ll} > 40$ GeV	Inclusive	$5.9 \pm xx^{+0.2}_{-0.1}$	$6.0 \pm xx^{+0.2}_{-0.1}$	$6.2 \pm xx^{+0.2}_{-0.1}$	$6.0 \pm xx^{+0.1}_{-0.1}$

Table 5: LO and NLO cross sections for various SM processes using MCFM. The cross sections are generally computed for inclusive decays. For the single top Wt contribution, the subtraction scheme used in [10] is used.

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