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Hadronic single top-quark production: updated predictions and uncertainty estimates

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This talk reviews updated theoretical predictions for inclusive single top-quark production. Furthermore, a brief introduction to the Hathor programm—suitable for fast, state of the art, cross section calculations for top-quark production—is given. In addition uncertainty estimates are presented and discussed.

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[*] Speaker.

1. Introduction

Together with Higgs physics top-quark physics will play a major rôle in run II of the LHC. Top-quark physics is on the one hand part of the daily bread and butter physics, important to test and validate our theoretical and experimental tools. On the other hand, top-quark physics offers also an ideal laboratory for new physics searches. The large top-quark mass sets a high-energy scale allowing reliable calculations within perturbative QCD. Furthermore, non-perturbative effects are essentially cut-off by the top-quark width. While at the Tevatron and at the LHC run I the production of single top-quarks was difficult to assess due to experimental challenges and the restricted event sample, the large number of events available in run II will allow very detailed and precise measurements. Since single top-quark production is due to weak interaction, it is complementary to top-quark pair production which is dominated by QCD. Related to the production mechanism, singly produced top quarks are highly polarized in difference to top quarks produced in pairs where, within in the Standard Model, only a tiny polarization is imprinted by the production mechanism. The top-quark polarization offers interesting possibilities for detailed tests of the Standard Model and for new physics searches. Evidently, precise predictions within the Standard Model are a necessary prerequisite. Although fully differential predictions contain most information and offer the highest statistical power, this contribution focuses on the inclusive cross section. Sample diagrams contributing in leading order to single top-quark production are shown in Fig. 1. Depending on the virtuality of the W-boson one distinguishes a) t channel production, b) s channel production and c) tW production. For the dominant t channel process the QCD one-loop corrections have been calculated in Refs. [1, 2, 3]. At the LHC Wt production is the second important process for single top-quark production. The next-to-leading order (NLO) QCD corrections have been calculated in Refs. [4, 5]. Finally, s channel production, which contributes to the cross section at the LHC only at the level of a few percent, has been studied in QCD one-loop accuracy in Ref. [6]. In addition to the inclusive cross sections, differential distributions including also the decay of the top-quark and the parton-shower have been investigated in the literature. We refer to Ref. [7] for the corresponding references. The higher order corrections are also publicly available in form of various computer programs e.g. the *Monte Carlo for FeMtobarn processes* (MCFM) [8, 9, 10, 11], the program ZTOP [12] (only t and s channel), the Monte Carlo generators MC@NLO [13, 14] and POWHEG [15, 16] with the latter including also parton-shower corrections. While the aforementioned programs allow in principle also the calculation of inclusive cross sections, the main field of application is the evaluation of differential cross sections in NLO accuracy. As a consequence they are not optimized in terms of computing time for the evaluation of inclusive cross sections

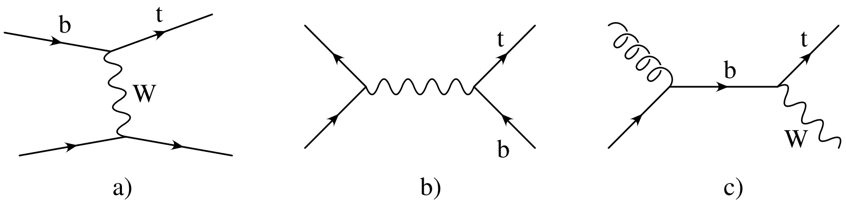

Figure 1: Sample diagrams contributing to single top-quark production.

leading to a non-negligible runtime when for example extensive PDF studies are performed. In Ref. [7] inclusive partonic cross sections for single top-quark production have been implemented in the Hathor framework [17] allowing a fast numerical evaluation of inclusive cross sections—well suited for extensive uncertainty studies and applications within Standard Model fits. Very recently, also partial next-to-next-to-leading (NNLO) QCD corrections have been calculated for the *t* channel production [18, 19].

2. Numerical evaluation of inclusive cross sections

For uncertainty studies of inclusive cross sections it is particularly useful to provide a numerical fast evaluation including as far as possible state of the art theory. In the Hathor program this is achieved for single and top-quark pair production by using inclusive partonic cross sections. Due to the complexity of the respective calculations these cross sections are typically not available in analytic form. To circumvent this problem Hathor uses fits or interpolations to the numerical results available in the literature. Since the phase space integration is done once and for all the evaluation of hadronic cross sections only involves the integration over the parton distribution functions (PDFs). As a consequence the required computing time for the evaluation of inclusive cross sections is significantly reduced allowing extensive uncertainty studies like PDF dependence and parametric uncertainties or the incorporation within Standard Model fits. As far as top-quark pair production is concerned Hathor includes LO, NLO, and NNLO QCD corrections as well as the dominant weak corrections. For single top-quark production LO and QCD one-loop results are included for the three production channels. Hathor allows an independent variation of the factorization (μ_f) and renormalization scale (μ_r). Inclusive single top-quark production depends in addition to the partonic center of mass energy squared $\hat{s}$ and the top-quark mass m_t also on the W-boson mass m_W. To allow also the cross section evaluation for a hypothetical heavy quark ($m_Q > m_t$), a two dimensional interpolation in $\hat{s}$ and m_t is used, while m_W is set to 80.385 GeV$/c^2$. This procedure has been validated in the mass range $m_t = 165 - 900\mathrm{GeV}/c^2$ at the sub per mill level [7]. Furthermore, Hathor keeps the full CKM matrix dependence. In particular, no assumptions concerning the mixing are made. Results using the MSTW2008lo/nlo PDF set are given in Tab. 1. The super- and subscripts show the scale and PDF uncertainty. The scale uncertainty is estimated by setting $\mu = \mu_f = \mu_r$ and varying μ by a factor two up and down using $\mu = m_t$ as central value.

	LHC 8 TeV				LHC 13 TeV			
	σ_t^{LO}	$\sigma_{\bar{t}}^{\mathrm{LO}}$	σ_t^{NLO}	$\sigma_{\bar{t}}^{\mathrm{NLO}}$	σ_t^{LO}	$\sigma_{\bar{t}}^{\mathrm{LO}}$	σ_t^{NLO}	$\sigma_{\bar{t}}^{\mathrm{NLO}}$
t	53.8	29.1	$55.2^{+2.9\%\ +0.6\%}_{-1.6\%\ -0.6\%}$	$30.1^{+3.0\%\ +1.0\%}_{-1.6\%\ -1.1\%}$	135	79.8	$137^{+3.0\%\ +0.7\%}_{-1.7\%\ -0.7\%}$	$82.1^{+3.1\%\ +0.7\%}_{-1.7\%\ -0.9\%}$
s	2.22	1.24	$3.30^{-1.9\%\ +2.1\%}_{+2.4\%\ -1.6\%}$	$1.90^{-1.8\%\ +2.2\%}_{+2.4\%\ -1.8\%}$	4.27	2.63	$6.25^{-1.0\%\ +2.0\%}_{+1.4\%\ -1.5\%}$	$3.97^{-0.9\%\ +2.0\%}_{+1.4\%\ -1.6\%}$
tW	8.86	8.85	$9.12^{+2.3\%\ +3.2\%}_{-4.2\%\ -3.9\%}$	$9.11^{+2.3\%\ +3.2\%}_{-4.2\%\ -3.9\%}$	29.1	29.1	$29.3^{+3.3\%\ +2.3\%}_{-4.5\%\ -2.8\%}$	$29.2^{+3.3\%\ +2.3\%}_{-4.5\%\ -2.8\%}$

Table 1: Cross section for single top-quark production in pb in LO and NLO QCD using $m_t = 173.3\,\mathrm{GeV}/c^2$ and the MSTW2008lo/nlo PDF set.

3. Uncertainty estimates

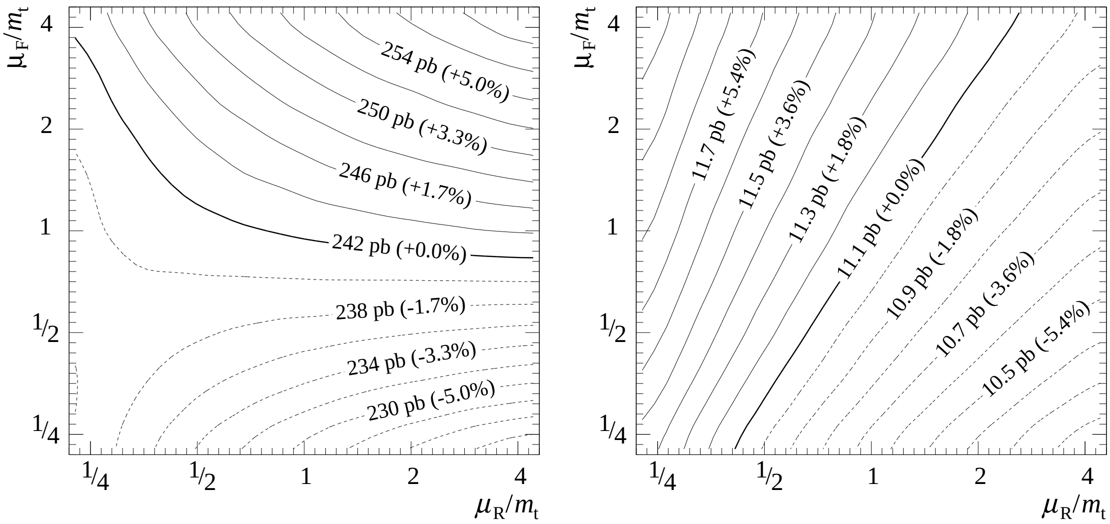

Figure 2: Scale variation of t and s channel cross section ($t+\bar{t}$, NLO QCD) for 14 TeV using CT10nlo PDF set [7].

Two different kinds of uncertainties of the theoretical predictions can be identified: 1. Uncertainties related to uncalculated higher order corrections. 2. Uncertainties related to the parametric uncertainties of the input parameters like the coupling constant of the strong interaction α_s, the top-quark mass m_t, and the PDF sets.

3.1 Higher order corrections

The standard procedure to estimate higher order corrections is to vary the renormalization and factorization scale. This is illustrated in Fig. 2. Restricting the variation to the square $m_t/2 \le \mu_r, \mu_f \le 2m_t$ the change in the t channel covers the range -1.7 % to $+3$ %. For the s channel one observes that a variation with $\mu_f = \mu_r$ underestimates the uncertainties. Allowing an independent variation of μ_r and μ_f in the square $m_t/2 \le \mu_r, \mu_f \le 2m_t$ leads to a scale variation of the order $\pm 3.6\%$. One may argue that in the upper left and lower right corner additional "large" logarithms are produced because the ratio of μ_r and μ_f takes its extreme value. Restricting the considered variation to the region where the ratio between the two scales never exceeds 2 leads to a scale dependence of the order ± 1.8 %. We note that in the above estimates a constant scale has been chosen. For distributions covering a large range in energy this might not be a good choice and a dynamical scale may provide more reasonable estimates. Compared to other inclusive cross sections where the scale variation is often above 10% the above results show rather small effects even in the case that μ_r and μ_f are varied independently. In that context one should keep in mind that despite of being a one-loop calculation the QCD corrections to s and t channel production provide only the leading order QCD contribution. The scale variation may thus not provide a reliable estimate of higher order corrections. For the t channel production one can compare the estimates based on the scale variation with recent NNLO results [18, 19] as shown in Tab. 2. As can be seen from Tab. 2 the size of the leading color two-loop corrections are very well consistent

	σ_{LO}, pb	σ_{NLO}, pb	δ_{NLO}	σ_{NNLO}, pb	δ_{NNLO}
t	$53.8^{+3.0}_{-4.3}$	$55.1^{+1.6}_{-0.9}$	$+2.4\%$	$54.2^{+0.5}_{-0.2}$	-1.6%
$\bar{t}$	$29.1^{+1.7}_{-2.4}$	$30.1^{+0.9}_{-0.5}$	$+3.4\%$	$29.7^{+0.3}_{-0.1}$	-1.3%

Table 2: Two-loop leading color QCD corrections to t channel single top-quark production [18].

with the uncertainty estimate based on the scale variation of the QCD one-loop corrections. Very recently approximate QCD NNLO corrections have been derived for the s channel production based on soft gluon resummation [20, 21]. The higher order effects observed within this approximation are slightly larger than the estimates based on the scale variation.

3.2 Parametric uncertainties of input

Single top-quark production depends on various input parameters, e.g. m_t, α_s, $\sin(\theta_W)$, α, m_W. As major sources for the parametric uncertainties α_s and m_t can be identified since the other parameters are very well measured. In addition, the PDF sets are another major source of uncertainty.

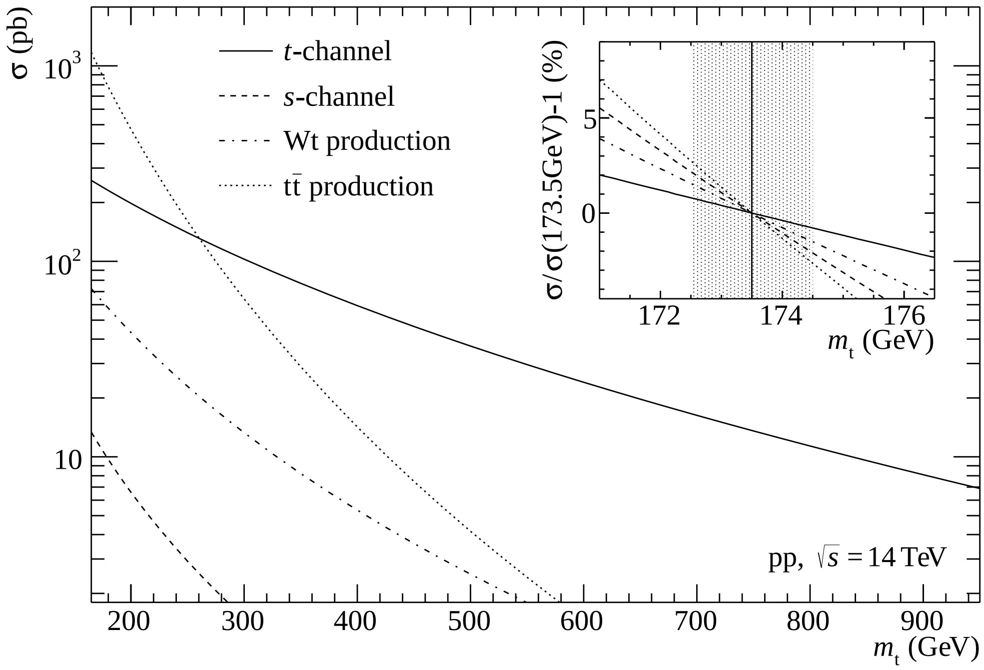

Figure 3: Mass dependence of top-quark cross sections [7].

Top-quark mass:
Fig. 3 illustrates the mass dependence of different top-quark cross sections. Among single top-quark production the s channel shows the largest sensitivity. At a center of mass energy of 8 TeV

one finds [7]:

$$\frac{\Delta\sigma_t}{\sigma_t} \approx -1.6 \times \frac{\Delta m_t}{m_t}, \quad \frac{\Delta\sigma_s}{\sigma_s} \approx -3.9 \times \frac{\Delta m_t}{m_t}, \quad \frac{\Delta\sigma_{Wt}}{\sigma_{Wt}} \approx -3.1 \times \frac{\Delta m_t}{m_t}. \tag{3.1}$$

At 13 TeV the dependence is slightly reduced. Assuming a top-quark mass uncertainty of 500 MeV (0.3%) the s channel cross sections suffers from a parametric uncertainty of about one per cent. The parametric uncertainty of the dominant t channel cross section is significantly smaller and of the order of 0.5% assuming again $\Delta m_t = 500$ MeV. As can be seen from Eq. 3.1 single top-quark production is, compared to top-quark pair production, less sensitive to the top-quark mass. Nevertheless, the top-quark mass can be extracted using the experimental results on the cross section measurements. This has been done for example in Ref. [7]. A recent update using more recent measurements and theoretical predictions employing the running top-quark mass and taking some NNLO QCD corrections into account can be found in Ref. [21].

QCD coupling constant:
To estimate the dependence of the cross sections on the strong coupling constants one needs to take into account that the PDFs also depend on α_s. Fig. 4 shows a consistent evaluation of the t channel cross section including the effects of the PDFs. The points show the estimates using the best fit value for α_s with its uncertainty as provided by the individual PDF set. The dependence of the cross section on α_s is almost linear as one would have expected from a naive error propagation ignoring the α_s dependence of the PDFs. A one percent uncertainty on α_s translates into a one percent uncertainty of the predictions. Although in total a small effect it is significantly larger compared to the naive expectation ignoring the PDF effects. This is because also the leading-order predictions are affected through the PDF dependence. Results for the s and Wt channel are given in Ref. [7].

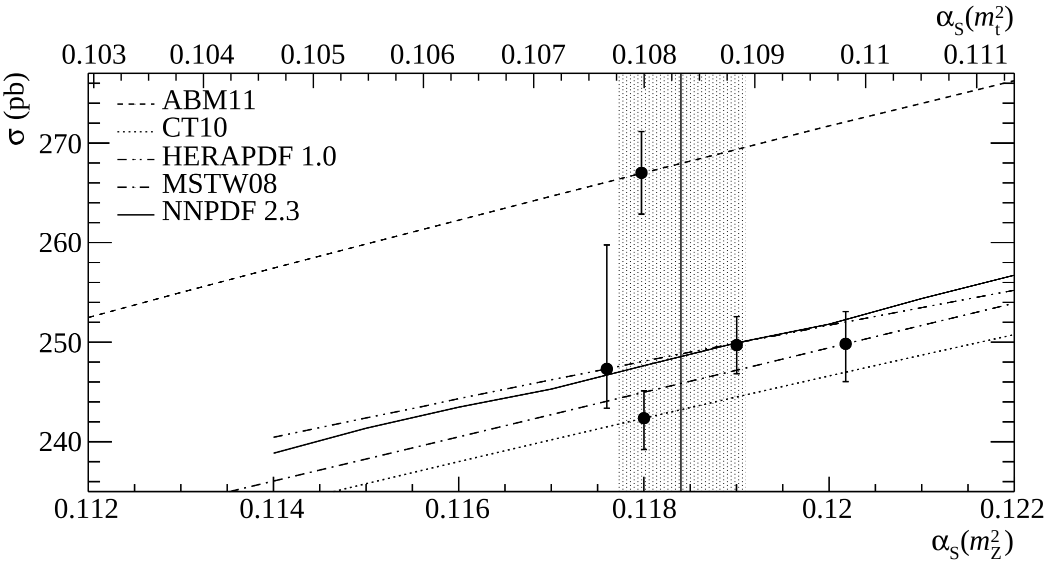

Figure 4: Dependence of t channel single top-quark production on α_s (LHC 14 TeV) [7].

Parton distribution functions:
Fig. 5 shows the PDF dependence of the t and Wt channel for different centre of mass energies including also the α_s uncertainty. With increasing collider energy the PDF uncertainties decrease. While at very low energies the PDF uncertainty is about five per cent for the t channel and of the order of ten per cent for the Wt channel it is reduced at high energies to $\pm(1-2)\%$ for the t channel and to about $\pm5\%$ for the Wt channel. For the Wt channel different PDF sets lead to consistent predictions at high energies. However, this is not the case for the t channel. For the t channel the NNPDF2.3 set [22] and the MSTW2008 set [23] are in good agreement. The CT10 [24] set leads to 3% smaller predictions, while the ABM11 set [25] in contrast predicts significantly larger cross sections at high energies. The almost 7% difference with respect to the MSTW/NNPDF23 sets and the 10% difference with respect to CT10 is outside the uncertainty bands of the individual PDF sets. With the increasing precision of the cross section measurements LHC will allow to discriminate between the different PDF sets.

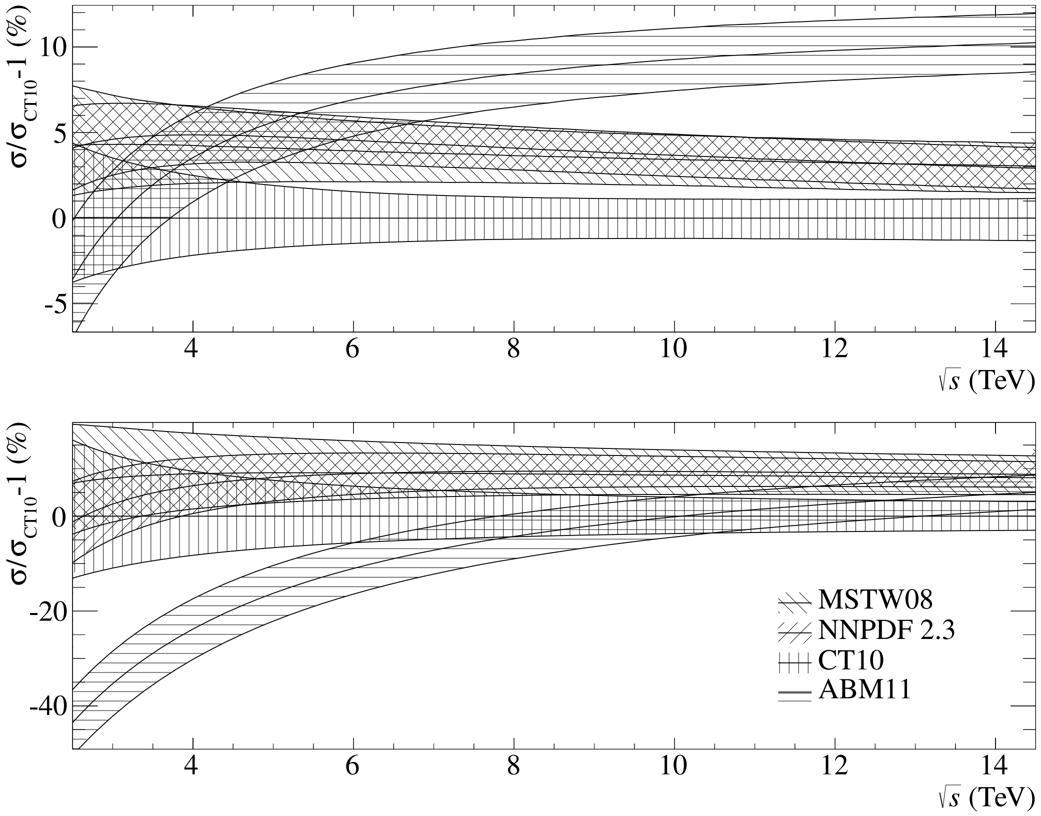

Figure 5: Combined PDF and α_s uncertainties for t channel (upper plot) and Wt channel (lower plot) single top-quark production (LHC 14 TeV) [7].

4. Conclusion

Tab. 3 summarizes for the t channel the dominant uncertainties of the NLO cross section. Not shown is the impact of the uncertainty of the top-quark mass which is roughly of the order

PDF Set	Cross section	PDF uncert.	α_s uncert.	PDF+α_s uncert.	Scale uncert.
ABM11	267.0 pb	$\pm 1.3\,\%$	$\pm 0.8\,\%$	$\pm 1.6\,\%$	$^{+2.8\,\%}_{-1.6\,\%}$
CT10	242.4 pb	$^{+0.9\,\%}_{-1.1\,\%}$	$^{+0.7\,\%}_{-0.8\,\%}$	$^{+1.1\,\%}_{-1.3\,\%}$	$^{+3.0\,\%}_{-1.7\,\%}$
HERAPDF 1.0	247.3 pb	$^{+5.0\,\%}_{-1.3\,\%}$	$\pm 0.9\,\%$	$^{+5.0\,\%}_{-1.6\,\%}$	$^{+3.3\,\%}_{-1.7\,\%}$
MSTW 2008	249.8 pb	$\pm 0.6\,\%$	$^{+1.2\,\%}_{-1.4\,\%}$	$^{+1.3\,\%}_{-1.5\,\%}$	$^{+3.0\,\%}_{-1.6\,\%}$
NNPDF 2.3	249.6 pb	$\pm 0.5\,\%$	$\pm 1.1\,\%$	$\pm 1.2\,\%$	$^{+3.2\,\%}_{-1.8\,\%}$

Table 3: Theoretical uncertainties for t channel single top-quark production at NLO in pp collisions with $\sqrt{s} = 14\,\text{TeV}$ for various NLO PDF sets ($t + \bar{t}$) [7].

of 0.5% for the t channel. The individual uncertainties are at the per cent level with the largest contribution coming from the scale variation leading to effects between -2% and $+3\%$. Taking the scale uncertainty as a measure for the uncalculated higher orders the estimate is in perfect agreement with recent results for the QCD two-loop leading color contribution [18, 19]. As can also be seen from Tab. 3 the differences between different PDF sets give a substantial contribution to the theoretical uncertainties. In particular, the spread in the predictions is not covered by the uncertainty estimates provided by the individual PDF sets. More precise LHC measurements will help to discriminate between the different PDF sets. Once this is solved the dominant uncertainty will be due to higher order effects.

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