April 2004

Top Background Extrapolation for $H \to WW$ Searches at the LHC

N. Kauer

Institut für Theoretische Physik E, RWTH Aachen, 52056 Aachen, Germany

Abstract

A leading order (LO) analysis is presented that demonstrates that key top backgrounds to $H \to W^+W^- \to \ell^\pm\ell^\mp \not{p}_T$ decays in weak boson fusion (WBF) and gluon fusion (GF) at the CERN Large Hadron Collider can be extrapolated from experimental data with an accuracy of order 5% to 10%. If LO scale variation is accepted as proxy for the theoretical error, parton level results indicate that the $t\bar{t}j$ background to the $H \to WW$ search in WBF can be determined with a theoretical error of about 5%, while the $t\bar{t}$ background to the $H \to WW$ search in GF can be determined with a theoretical error of better than 1%. Uncertainties in the parton distribution functions contribute an estimated 3% to 10% to the total error.

I. INTRODUCTION

Recent studies indicate that the CERN Large Hadron Collider (LHC) will be able to discover a Standard Model (SM) Higgs boson with mass between 100 and 200 GeV with an integrated luminosity of only 10 to 30 fb^{-1} if weak boson fusion (WBF) followed by $H \to \tau\tau$ and $H \to WW$ channels are taken into account [1, 2, 3, 4]. This intermediate mass range is currently favored in light of a lower bound of 114.1 GeV from direct searches at LEP2 and an upper bound of 196 GeV from a SM analysis of electroweak precision data (at 95% CL) [5]. As discussed in detail in Ref. [3], Sec. A.1, the precise knowledge of the significance of any observed Higgs signal will require an accurate determination of the SM backgrounds. The $H \to WW \to \ell\ell \not{p}_T$ decay channel ($\ell = e, \mu$) in WBF as well as gluon fusion (GF) [3, 6, 7, 8] is particularly challenging, because missing momentum prevents the observation of a narrow mass peak that would allow an interpolation of the backgrounds from side bands. The purpose of this paper is to demonstrate how the extrapolation approach proposed in Ref. [3] can be applied to determine the top quark background to the $H \to WW$ di-lepton decay mode at the LHC with an accuracy that is in line with experimentalists' expectations. In the remainder of this section we briefly describe our conventions and the specifics of our calculations. We can then quantify the theoretical uncertainty of a conventional, leading order (LO) determination of the background rates under consideration. In Sections II and III, we show for WBF and GF, respectively, how experimental data allows to determine these backgrounds with significantly reduced theoretical uncertainty. In Section IV, we consider caveats and improvements and conclude with a summary in Section V.

To be specific, we consider the dominant $t\bar{t}$ + 1 jet background to the $H \to W^+W^- \to \ell_1^\pm \ell_2^\mp \not{p}_T$ search in WBF and apply the selection cuts of Ref. [2] (see Sec. II), which are very similar to the cuts adopted by the ATLAS and CMS collaborations. We further consider the large $t\bar{t}$ background to the inclusive $H \to WW$ search, i.e. the same Higgs decay mode in GF. In this case, we calculate results for ATLAS selection cuts as given in Ref. [8], Sec. 19.2.6, as well as CMS selection cuts [7] (see Sec. III).

To investigate the scale uncertainty of these backgrounds and how it can be reduced we apply the following definitions for the renormalization and factorization scales μ_R and μ_F. A factor ξ is then used to vary the scales around the central values. The suggestive scale choice for top production is the top mass $m_t = 175$ GeV:

$$\mu_R = \mu_F = \xi m_t \,. \tag{1}$$

Results for this scale choice are shown as solid curves in the figures. For WBF, due to forward tagging selection cuts, the dominant background arises from $t\bar{t}$ production with one additional hard jet. To avoid double counting in this case, we alternatively calculate with scales based on the minimal transverse mass:

$$\mu_F = \xi \min(m_{T,t}, m_{T,\bar{t}}, p_{T,j}) \quad \text{and} \quad \alpha_s^3 = \alpha_s(\xi m_{T,t})\alpha_s(\xi m_{T,\bar{t}})\alpha_s(\xi p_{T,j}) \,. \tag{2}$$

Results for this second definition are shown as dashed curves in the figures. In principle, the renormalization and factorization scales are independent. We find, however, that the strongest scale variation occurs if both scales are varied in the same direction and thus only introduce a single parameter ξ. Scale-dependent quantities are customarily condensed into the form $\hat{x} \pm \Delta\hat{x}$ based on a particular low and high scale choice. We use the convention

$$\hat{x} = (x(\xi = \frac{1}{2}) + x(\xi = 2))/2 \quad \text{and} \quad \Delta\hat{x} = |x(\xi = \frac{1}{2}) - x(\xi = 2)|/2 \,, \tag{3}$$

where x is a cross section or cross section ratio.

All cross sections are calculated using the parton-level Monte Carlo programs of Refs. [9] and [10], which include finite width effects and the complete LO matrix elements for $\ell_1^{\pm}\ell_2^{\mp}\nu\bar{\nu}b\bar{b}$ (+ jets) final states. We calculate with complete matrix elements unless otherwise noted and use the complex mass scheme (CMS) [11] to guarantee gauge invariance.[1] SM parameters and other calculational details are as described in Ref. [10], except that we use the updated parton distribution function (PDF) set CTEQ6L1.[2] The calculations take into account finite resolution and b decay effects and a suboptimal b tagging efficiency ε_{btag} based on expectations for the ATLAS and CMS detectors.

Figs. 1(a), 2(a), 3(a) and 4(a) show the large scale variation that is expected for the LO background cross sections in both search channels. For the WBF search channel, the scale scheme (1) yields a background cross section of 0.37 ± 0.15 fb, whereas the scheme (2) yields

[1] In Ref. [10], we showed that the finite width scheme uncertainty, i.e. deviations due to different prescriptions to include finite width effects, is smaller than 1% for the backgrounds considered here. We hence neglect it in this study.

[2] Note that CTEQ4L was employed in Ref. [2].

0.57 ± 0.25 fb. The theoretical uncertainty is 40–45%. Since the second cross section is not consistent with the first within 1σ, it seems more appropriate to apply the prescription (3) to the envelope of both curves. All subsequent WBF results will be given using this procedure. Then, one obtains 0.52 ± 0.30 fb, with an even larger uncertainty of 60%. These results assume a b tagging efficiency of 40%. With a more optimistic assumption of 60% one obtains a 27% smaller background with similar uncertainty: 0.38 ± 0.22 fb. For the top background in the inclusive $H \to WW$ search a somewhat smaller theoretical uncertainty is obtained, i.e. 3.4 fb (4.4 fb) with an uncertainty of 25% (25%) for ATLAS (CMS) selection cuts (with $\varepsilon_{btag} = 50\%$). For both channels it is obvious that the accuracy of theoretical background calculations at LO is insufficient to determine the total background with an accuracy of order 10%, as required by experimental physicists [4].

II. TOP BACKGROUND TO $H \to WW$ DECAY IN WEAK BOSON FUSION

The extrapolation approach allows a more accurate determination of a background cross section σ_{bkg} if a reference selection with a corresponding well-defined, measurable event rate $\sigma_{ref} \cdot \mathcal{L}$ can be found, so that the theoretical uncertainty of the ratio $\sigma_{bkg}/\sigma_{ref}$ is small and a sufficient number of events are observed during the run that σ_{ref} can be measured with low experimental uncertainty.[3] The background cross section can then be approximated through

$$\sigma_{bkg} \approx \underbrace{\left(\frac{\sigma_{bkg,\,\mathrm{LO}}}{\sigma_{ref,\,\mathrm{LO}}}\right)}_{\substack{\text{low theoret.}\\ \text{uncertainty}}} \cdot \underbrace{\sigma_{ref}}_{\substack{\text{low experim.}\\ \text{uncertainty}}} . \tag{4}$$

Qualitatively, the smaller the difference between the cuts for background and reference selection, the lower the uncertainty of $\sigma_{bkg}/\sigma_{ref}$. On the other hand, the selection cuts have to be modified sufficiently, so that σ_{ref} can be measured with good accuracy. Thus, to derive suitable reference selections from the corresponding background selections in the case at hand, we propose the following strategy: The WBF and inclusive $H \to WW$ search channel top backgrounds are effectively suppressed through a central jet veto. Discarding this veto leads to a sizable increase of the cross sections. Secondly, to identify the top backgrounds in both cases, we require that only events be considered that contain at least

[3] We neglect $\Delta\mathcal{L}$ and other systematic experimental uncertainties.

one identified b jet. In our calculations we assume that each b (or $\bar{b}$) quark can be identified independently with probability ε_{btag} if it is in the phase space region with b tagging detector capability, which we assume to be

$$p_{T,btag} > 15 \text{ GeV}, \ \eta_{btag} < 2.5 \ . \tag{5}$$

The probability P_{btag} for a parton-level event to fulfill the b tagging criterion is then given by

$$P_{btag} = \begin{cases} 1-(1-\varepsilon_b)^2 & \text{if } b \text{ and } \bar{b} \text{ quark fulfill (5),} \\ \varepsilon_b & \text{if either } b \text{ or } \bar{b} \text{ quark fulfill (5),} \\ 0 & \text{if neither } b \text{ nor } \bar{b} \text{ quark fulfill (5),} \end{cases} \tag{6}$$

and the reference cross section is calculated by integrating $P_{btag}\, d\sigma_{ref}$. Since events that are identified as top production via b tagging can be eliminated from the signal sample, we calculate all background cross sections by integrating $(1-P_{btag})\, d\sigma_{bkg}$. If, after demanding a tagged b jet and discarding the central jet veto, the resulting reference rate is still too small, we also discard the lepton pair cuts.

In the search for a light Higgs boson in WBF the selection is given by the forward tagging cuts

$$\begin{gathered} p_{Tj} > 20 \text{ GeV}, \ |\eta_j| < 4.5, \ \Delta R_{jj} > 0.6, \\ p_{T\ell_1} > 20 \text{ GeV}, \ p_{T\ell_2} > 10 \text{ GeV}, \ |\eta_\ell| < 2.5, \ \Delta R_{j\ell} > 1.7, \\ \eta_{j,min} + 0.6 < \eta_{\ell_{1,2}} < \eta_{j,max} - 0.6, \\ \eta_{j_1} \cdot \eta_{j_2} < 0, \\ m_{jj} > 600 \text{ GeV}, \ |\eta_{j_1} - \eta_{j_2}| > 4.2, \\ \not{p}_T > 20 \text{ GeV} \qquad \text{provided } p_{TH} < 50 \text{ GeV} \end{gathered} \tag{7}$$

and the lepton pair cuts

$$\begin{gathered} m_{\ell\ell} < 60 \text{ GeV}, \ \Delta\phi_{\ell\ell} < 140^\circ, \\ x_{\tau_1} > 0, \ x_{\tau_2} > 0, \ m_{\tau\tau} > m_Z - 25 \text{ GeV}, \\ 50 \text{ GeV} < m_{T,1}(WW) < m_H + 20 \text{ GeV}, \\ \Delta\phi(\ell\ell, \not{p}_T) + 1.5\, p_{TH} > 180, \quad 12\, \Delta\phi(\ell\ell, \not{p}_T) + p_{TH} > 360 \end{gathered} \tag{8}$$

with $m_{T,1}(WW) := [(E_{T,\ell\ell} + \not{E}_T)^2 - (\vec{p}_{T,\ell\ell} + \vec{\not{p}}_T)^2]^{1/2}$ with transverse energies $E_{T,\ell\ell} = (p_{T,\ell\ell}^2 + m_{\ell\ell}^2)^{1/2}$ and $\not{E}_T = (\not{p}_T^2 + m_{\ell\ell}^2)^{1/2}$. We fix $m_H = 120$ GeV, which defines the transverse mass window cut. The jet veto is applied by discarding all events where an additional jet is located between the tagging jets,

$$p_{Tv} > 20 \text{ GeV}, \;\; \eta_{j,min} < \eta_v < \eta_{j,max} \,. \tag{9}$$

The reference selection obtained by eliminating the veto (9) and requiring at least one tagged b jet yields a cross section of 13 fb, which, with 30 fb^{-1}, would result in a statistical uncertainty for the measured rate of about 5% (using Poisson statistics). We therefore also discard the lepton pair cuts (8). The resulting reference cross section of 118 ± 66 fb gives rise to a statistical error of slightly less than 2% with 30 fb^{-1} of data for $\varepsilon_{btag} = 60\%$ (and also with 87 ± 48 fb for $\varepsilon_{btag} = 40\%$). Note that the scale uncertainty of these reference cross sections is very similar to that of the background cross sections. However, the scale variation of the corresponding ratios $\sigma_{bkg}/\sigma_{ref}$ is significantly reduced as shown in Figs. 1(b) and 2(b). One obtains 0.0059 ± 0.0003 for $\varepsilon_{btag} = 40\%$ and 0.0031 ± 0.0002 for $\varepsilon_{btag} = 60\%$, or a relative error of 5%. Note that the applicable ratio depends strongly on the achieved b tagging efficiency.[4]

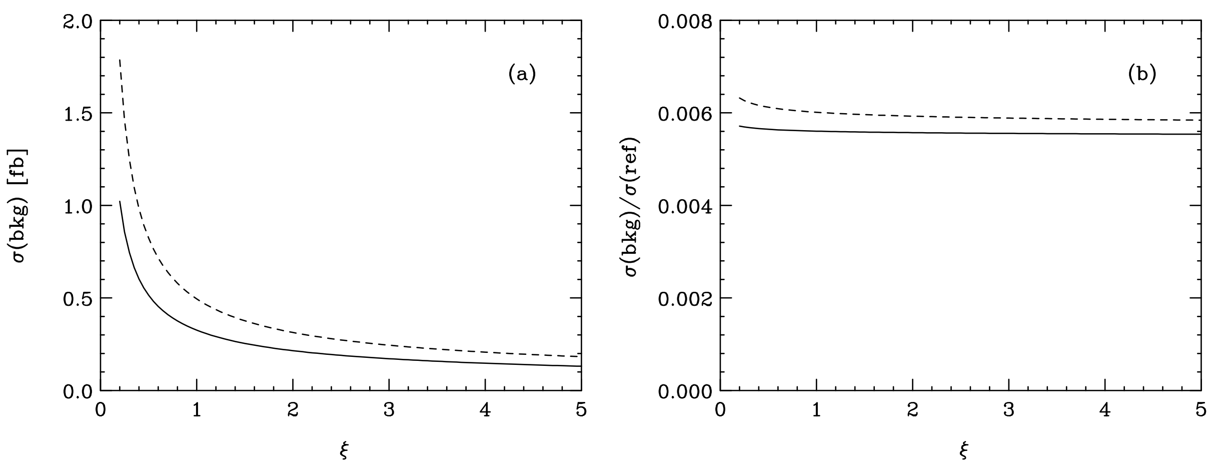

FIG. 1: Renormalization and factorization scale variation of $t\bar{t}j$ background cross section (a) and ratio with reference cross section (b) to $H \to W^+W^- \to \ell_1^\pm \ell_2^\mp \not{p}_T$ search in weak boson fusion at the LHC for different scale definitions (see main text) and $\varepsilon_{btag} = 40\%$.

[4] The details of b-tagged event rejection for σ_{bkg} also strongly affect the ratio. If, for example, only events with b-tagged forward tagging jets are discarded, background and ratio increase by 30%. The sensitivity to variations in the gluon PDF is smaller: Calculating with CTEQ4L instead of CTEQ6L1 reduces the ratio by 7%.

TABLE I: Expected number of events E and statistical experimental error for WBF reference selection for different integrated luminosities.

	$\varepsilon_{btag} = 40\%$		$\varepsilon_{btag} = 60\%$	
$\int \mathcal{L}\, dt$	E	$\Delta E/E$	E	$\Delta E/E$
10 fb^{-1}	870	$\pm$ 3.4%	1180	$\pm$ 2.9%
30 fb^{-1}	2610	$\pm$ 2.0%	3540	$\pm$ 1.7%
100 fb^{-1}	8700	$\pm$ 1.1%	11800	$\pm$ 0.9%

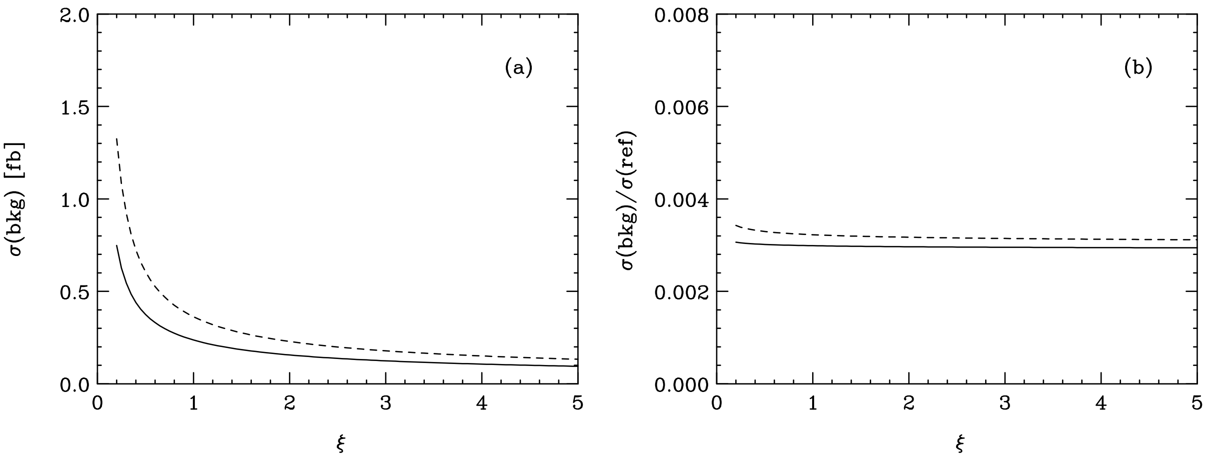

FIG. 2: As Fig. 1, but for $\varepsilon_{btag} = 60\%$.

As seen in Table I, an integrated luminosity of 30 fb^{-1} would allow a measurement of the WBF reference cross section with a statistical error of 2% or less. Combining the uncertainty of both extrapolation factors in quadrature yields a WBF background estimate with an accuracy of about 5%.

Since top backgrounds are often calculated with top quark in narrow width approximation (NWA), we show in Table II the change of background cross section and ratio for the WBF selection if sub- and non-resonant amplitude contributions are omitted. The complete off-shell matrix element increase of 15% for the background is reduced to 5% for the ratio—a level also found for inclusive top pair production at the LHC (see Ref. [10]).

Besides scale variation, a second, smaller source of uncertainty in the background determination arises due to uncertainties in the PDFs. Since top pair production at the LHC is dominated by gluon scattering, the large gluon density uncertainty for $x \gtrsim 0.2$ leads to

TABLE II: Change of background cross section and ratio for WBF selection using scale scheme (2) (with $\xi = 1$) if calculated with complete tree-level matrix elements [9, 10] relative to calculating with top quark in narrow width approximation (NWA).

	$x_{\rm CMS}/x_{\rm NWA}$ factor	
x	$\varepsilon_{btag} = 40\%$	$\varepsilon_{btag} = 60\%$
σ_{bkg}	1.15	1.16
$\sigma_{bkg}/\sigma_{ref}$	1.05	1.05

large uncertainties for theoretical cross section calculations. In Ref. [10], we observed that PDF improvements lead to relative changes of inclusive cross sections by 10-20%, while cross section ratios of the type shown in Table II are almost constant. To properly quantify the PDF uncertainty of an observable, an eigenvector basis approach to the Hessian method can be used (see e.g. Ref. [12]). Unfortunately, this method is currently only available for NLO PDF sets, whereas a LO fit is most appropriate for the calculations performed here. Nevertheless, to provide an estimate for the PDF uncertainty of σ_{bkg} and $\sigma_{bkg}/\sigma_{ref}$, we show results in Table III that use the "best fit" PDF sets CTEQ6L1 (LO) and CTEQ6.1M (NLO), and in addition use the corresponding eigenvector basis CTEQ61.01-40 to calculate PDF uncertainties according to (3) in Ref. [12]. When comparing the results for σ_{bkg} and $\sigma_{bkg}/\sigma_{ref}$, one finds that the relative error decreases from 12% to about 5%, while the relative deviation of LO and NLO PDF results increases to about 10%. We therefore estimate the PDF uncertainty of the WBF ratio $\sigma_{bkg}/\sigma_{ref}$ at 5-10%.

III. TOP BACKGROUND TO $H \to WW$ DECAY IN GLUON FUSION

The analysis of the extrapolation of the top background to the $H \to WW$ di-lepton decay mode in gluon fusion proceeds along the same lines as Sec. II. For this Higgs search channel, which is important for Higgs masses between 140 and 180 GeV, we consider the selection

TABLE III: WBF top background cross section $\sigma := \sigma_{bkg}$ and cross section ratio $K := \sigma_{bkg}/\sigma_{ref}$ calculated with PDF sets CTEQ6L1 and CTEQ6.1M (= CTEQ61.00) using scale scheme (2) (with $\xi = 1$). The NLO sets CTEQ61.01-40 allow to calculate a PDF uncertainty for observables (see main text).

$\varepsilon_{btag} = 40\%$	σ	$\frac{\Delta\sigma}{\sigma}$	K	$\frac{\Delta K}{K}$
CTEQ6L1 (LO)	0.50 fb	–	0.0060	–
CTEQ6.1M (NLO)	0.49 fb	± 12%	0.0066	± 4.7%

$\varepsilon_{btag} = 60\%$	σ	$\frac{\Delta\sigma}{\sigma}$	K	$\frac{\Delta K}{K}$
CTEQ6L1 (LO)	0.36 fb	–	0.0032	–
CTEQ6.1M (NLO)	0.37 fb	± 13%	0.0036	± 6.4%

cuts adopted by the ATLAS collaboration:

$$\begin{gathered} p_{T\ell_1} > 20 \text{ GeV},\ p_{T\ell_2} > 10 \text{ GeV},\ |\eta_\ell| < 2.5,\ \not{p}_T > 40 \text{ GeV}, \\ m_{\ell\ell} < 80 \text{ GeV},\ \Delta\phi_{\ell\ell} < 1.0 \text{ rad},\ |\theta_{\ell\ell}| < 0.9 \text{ rad},\ |\eta_{\ell_1} - \eta_{\ell_2}| < 1.5, \\ m_H - 30 \text{ GeV} < m_{T,2}(WW) < m_H \end{gathered} \tag{10}$$

with $m_{T,2}(WW) := [2p_T^{\ell\ell}\not{p}_T(1 - \cos\Delta\phi(\ell\ell, \not{p}_T))]^{1/2}$ and the transverse mass window cut fixed by choosing $m_H = 170$ GeV in our ATLAS calculations. The ATLAS selection cuts also include a central jet veto, that discards all events with jets that fulfill

$$p_{Tv} > 15 \text{ GeV},\ |\eta_v| < 3.2\ . \tag{11}$$

We also present results for the selection cuts adopted by the CMS collaboration:

$$\begin{gathered} p_{T\ell_1} > 25 \text{ GeV},\ p_{T\ell_2} > 10 \text{ GeV},\ |\eta_\ell| < 2.4, \\ \theta_{\ell\ell} > 30^\circ,\ |\eta_{\ell_1} - \eta_{\ell_2}| < 1.25,\ \Delta\phi_{\ell\ell} < 45^\circ\ . \end{gathered} \tag{12}$$

Here, all events are discarded that have jets that fulfill

$$p_{Tv} > 20 \text{ GeV},\ |\eta_v| < 3\ . \tag{13}$$

The reference cuts for the ATLAS and CMS selections are obtained by requiring at least one tagged b jet in detector region (5) and eliminating the central jet veto (11) and (13), respectively. b tagging capability is utilized as described in Sec. II. Since the jet vetos cover most of the b tagging detector region (5), little additional background suppression is possible. We therefore use $\varepsilon_{btag} = 50\%$ for all GF results. A reference cross section of 390 ± 97 fb (950 ± 240 fb) is obtained for ATLAS (CMS) selection cuts. With 30 fb^{-1} of data, a statistical accuracy of better than 1% can therefore be expected, and no need to eliminate the lepton pair cuts arises for the GF selections. Again, the scale uncertainty of the reference cross sections is very similar to that of the background cross sections. The scale variation of the ratio $\sigma_{bkg}/\sigma_{ref}$ is shown in Figs. 3(b) and 4(b). It is remarkably reduced. For the ratio, one obtains 0.0088 (0.0046) for ATLAS (CMS) selection cuts with negligible scale variation.

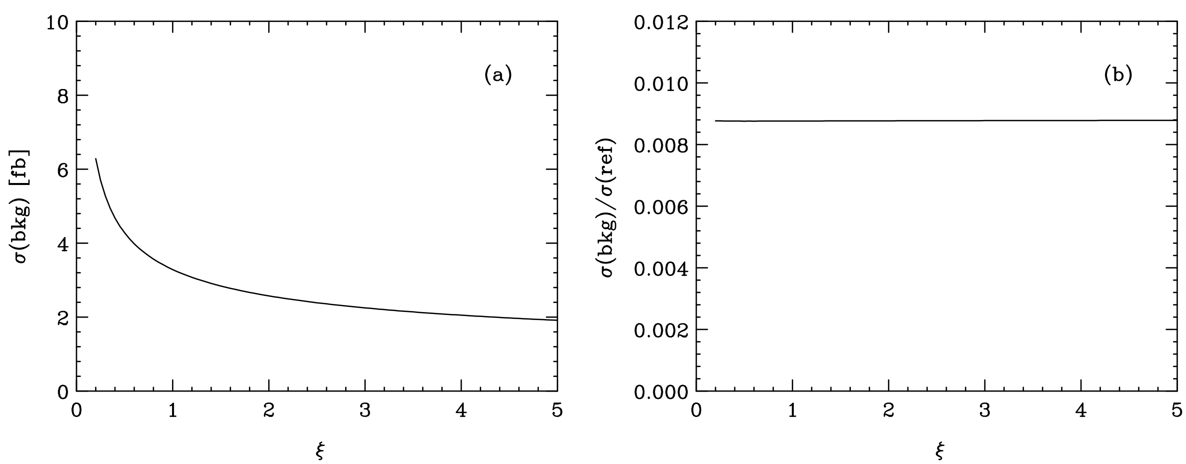

FIG. 3: Renormalization and factorization scale variation of $t\bar{t}$ background cross section (a) and ratio with reference cross section (b) to $H \to W^+W^- \to \ell_1^\pm \ell_2^\mp \not{p}_T$ search in gluon fusion at the LHC for ATLAS GF cuts (10, 11) and $\varepsilon_{btag} = 50\%$.

As seen in Table IV, an integrated luminosity of 30 fb^{-1} would allow a measurement of the GF reference cross section with a statistical error of better than 1%. Combining the uncertainty of both extrapolation factors yields a GF background estimate with an accuracy of better than 1%.

Table V shows significant decreases of about 40–50% for σ_{bkg} and $\sigma_{bkg}/\sigma_{ref}$ if matrix elements with top quark in NWA are used instead of complete tree-level matrix elements. This sizable decrease is caused by large sub-resonant contributions to the jet-veto-suppressed

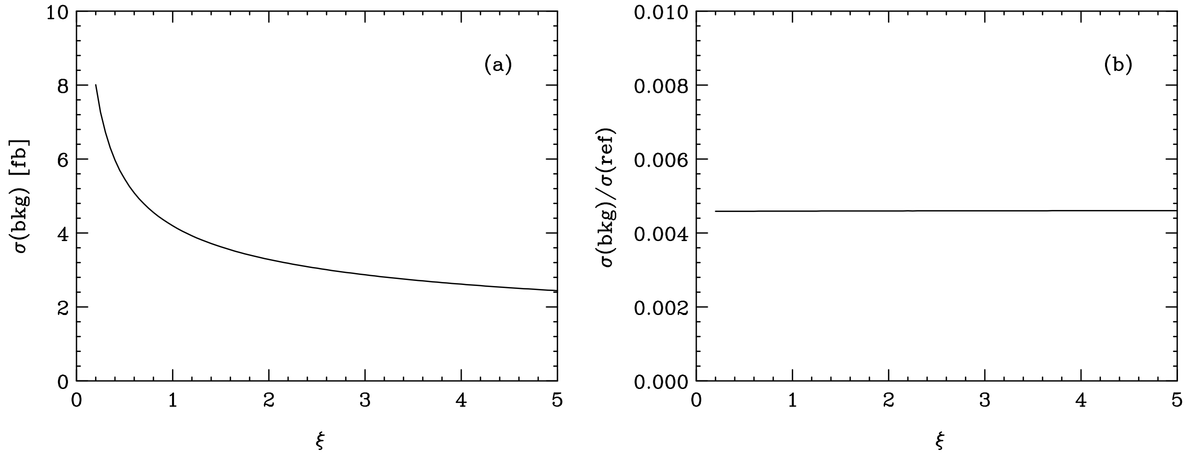

FIG. 4: As Fig. 3, but for CMS GF cuts (12,13).

TABLE IV: Expected number of events E and statistical experimental error for ATLAS and CMS GF reference selection for different integrated luminosities.

	ATLAS		CMS	
$\int \mathcal{L}\, dt$	E	$\Delta E/E$	E	$\Delta E/E$
10 fb^{-1}	3900	$\pm$ 1.6%	9500	$\pm$ 1.0%
30 fb^{-1}	11700	$\pm$ 0.9%	28500	$\pm$ 0.6%
100 fb^{-1}	39000	$\pm$ 0.5%	95000	$\pm$ 0.3%

GF backgrounds that are neglegted in NWA. The reference cross sections with no jet veto, on the other hand, decrease only by ca. 5%.

In Table VI we provide an estimate for the PDF uncertainty of backgrounds and ratios for the GF selections. Here, the relative error is similar for backgrounds and ratios. One obtains about 9% (3%) for ATLAS (CMS) selection cuts. The relative deviation of LO and NLO PDF results for the ratio is about 7% (4%) for ATLAS (CMS) cuts. We therefore estimate the PDF uncertainty of the GF ratio $\sigma_{bkg}/\sigma_{ref}$ at 9% (4%) for ATLAS (CMS) cuts.

IV. DISCUSSION

The approximation (4) would become an identity if the ratio $\sigma_{bkg}/\sigma_{ref}$ could be evaluated to all orders in perturbation theory. At fixed order in perturbation theory, a scale dependence

TABLE V: Change of background cross section and ratio for ATLAS and CMS GF selections if calculated with complete tree-level matrix elements [9, 10] relative to calculating with top quark in narrow width approximation (NWA).

	$x_{\mathrm{CMS}}/x_{\mathrm{NWA}}$ factor	
x	ATLAS cuts	CMS cuts
σ_{bkg}	2.1	1.7
$\sigma_{bkg}/\sigma_{ref}$	2.0	1.7

TABLE VI: GF top background cross section $\sigma := \sigma_{bkg}$ and cross section ratio $K := \sigma_{bkg}/\sigma_{ref}$ calculated for ATLAS and CMS selection cuts with PDF sets CTEQ6L1 and CTEQ6.1M (= CTEQ61.00). The NLO sets CTEQ61.01-40 allow to calculate a PDF uncertainty for observables (see main text, Sec. II).

ATLAS	σ	$\frac{\Delta\sigma}{\sigma}$	K	$\frac{\Delta K}{K}$
CTEQ6L1 (LO)	3.3 fb	–	0.0088	–
CTEQ6.1M (NLO)	3.2 fb	$\pm$ 8.2%	0.0094	$\pm$ 9.3%

CMS	σ	$\frac{\Delta\sigma}{\sigma}$	K	$\frac{\Delta K}{K}$
CTEQ6L1 (LO)	4.2 fb	–	0.0046	–
CTEQ6.1M (NLO)	3.9 fb	$\pm$ 3.0%	0.0048	$\pm$ 3.1%

remains and, depending on the specific scale choice, the result will deviate to a greater or lesser extent from the exact result.[5] We refer to this error as residual theoretical error. In practice, it is commonly estimated from the scale variation using a prescription like (3). Since differential distributions can change significantly if new subprocesses or kinematic degrees of freedom are activated in higher fixed order calculations, it is generally desirable to calculate $\sigma_{bkg}/\sigma_{ref}$ and its scale variation at NLO. A NLO analysis would also allow to obtain better estimates for the PDF uncertainties. Unfortunately, a full NLO calculation of

[5] Note that this deviation is in addition to any computational error made in the fixed order calculation.

processes with 6 or 7 final state particles is well beyond present capabilities. At the time of writing a hadron collider program to calculate $t\bar{t}$ + 1 jet production at NLO QCD with top quark in double pole approximation is not yet available. However, for the WBF $H \to WW$ search channel already at LO the dominant $t\bar{t}j$ background features 3-body kinematics and quark-gluon scattering subprocesses contribute. One can therefore expect NLO ratios and residual theoretical error estimates to be compatible with the ones we computed. On the other hand, for $t\bar{t}$ production without an additional hard jet, i.e. the leading top background for the GF $H \to WW$ search channel, this is not the case. However, for this background NLO QCD programs (in double pole approximation) exist with full spin correlations [13] and parton shower interface [14], which could be used in combination with the results in Table V to improve the GF extrapolation analysis. The extremely low scale variation of GF ratios at LO suggests that the proposed reference selections will allow the determination of the GF background with the desired accuracy of 10% or better.

An important aspect of the full NLO correction to the studied top backgrounds is the impact of the NLO correction to the SM top quark width, which reduces it by about 10% [15]. The top pair production cross section has an amplified sensitivity to changes in the top quark width, as can be seen from its LO dependence in NWA: $\sigma_{\rm NWA}(t\bar{t}) \propto 1/\Gamma_t^2$. Table VII shows the sensitivity of the LO top background cross section and ratio for representative WBF and GF selections. In both cases, the ratio is less sensitive than the background cross section. For the WBF channel the sensitivity is reduced considerably. The impact of a reduced top quark width on the off-shell matrix element increase (Tables II and V) is shown in Table VIII. The complete off-shell matrix element increase for the top backgrounds is almost entirely due to additional subresonant matrix element contributions rather than a kinematic perturbation of the top quark Breit-Wigner resonance distributions through selection cuts that effectively eliminate the central part of the distributions (instead of more or less uniformly suppressing them). The background dependence on the top width is hence qualitatively similar to the inclusive dependence, where the ratio of a single resonant to a double resonant matrix element contribution scales approximately linear with the width. The complete off-shell matrix element increases should therefore change by less than 10% if one switches from LO to NLO top width. This is confirmed by the results in Table VIII.

The WBF and GF selection cuts we applied allow collinear $g \to b\bar{b}$ configurations for initial state gluons, which give rise to large log-enhanced higher-order contributions. If these

TABLE VII: Top background cross section σ_{bkg} and ratio $\sigma_{bkg}/\sigma_{ref}$ calculated with LO and NLO SM values for the top width Γ_t (using $\Gamma_t(\text{NLO}) = 0.9\ \Gamma_t(\text{LO})$). The WBF results use scale scheme (2) (with $\xi = 1$) and $\varepsilon_{btag} = 60\%$. The GF results use ATLAS cuts (10, 11).

	WBF		GF	
	σ_{bkg}	$\frac{\sigma_{bkg}}{\sigma_{ref}}$	σ_{bkg}	$\frac{\sigma_{bkg}}{\sigma_{ref}}$
$\Gamma_t = \Gamma_t(\text{LO})$	0.36 fb	0.0032	3.3 fb	0.0088
$\Gamma_t = \Gamma_t(\text{NLO})$	0.45 fb	0.0033	3.7 fb	0.0080

TABLE VIII: As Tables II and V, but cross sections calculated with NLO SM top width $\Gamma_t = 0.9\ \Gamma_t(\text{LO})$. Calculational details for WBF and GF selections are as in Table VII.

	$x_{\text{CMS}}/x_{\text{NWA}}$ factor	
x	WBF	GF
σ_{bkg}	1.15	1.94
$\sigma_{bkg}/\sigma_{ref}$	1.06	1.86

contributions dominate, the expansion parameter of the perturbation series is $\alpha_s \log(\mu^2/m_b^2)$ rather than α_s, and a resummation becomes necessary if the scale μ is of the order of m_t. To detect if log-enhanced contributions dominate the cross sections and ratios under study, we calculate how much they increase if the b quark mass is reduced by a factor 100. The results are shown in Table IX and indicate that log-enhanced contributions are small for the WBF selection cuts, but significant for the GF selection cuts. A resummation might thus be necessary to obtain reliable results in the latter case. We note that this resummation can not be accomplished by convoluting the b PDF with $gb \to bW^+W^-$, $g\bar{b} \to \bar{b}W^+W^-$ and $b\bar{b} \to W^+W^-$ matrix elements [16] if the top background is suppressed by central jet vetos like (9), (11) or (13), or by eliminating events with tagged b jets (as described in Sec. II), since then the "spectator" b or $\bar{b}$ quark is potentially resolved and thus cannot be integrated out to derive a suitable b quark density.

In addition to the discussed theoretical improvements, systematic experimental uncertainties should also be taken into account in future studies.

TABLE IX: As Table VIII, but showing the increase of the top background and ratio for WBF and GF if the b quark mass is reduced by a factor 100 (using LO SM top width and complete matrix elements).

	$\frac{x(m_b = 0.01\, m_b(\mathrm{SM}))}{x(m_b = m_b(\mathrm{SM}))}$	
x	WBF	GF
σ_{bkg}	1.2	2.4
$\sigma_{bkg}/\sigma_{ref}$	1.2	2.3

V. CONCLUSIONS

A LO analysis was presented that demonstrates that key top backgrounds to $H \to W^+W^- \to \ell^\pm\ell^\mp \not{p}_T$ decays in weak boson fusion and gluon fusion at the CERN Large Hadron Collider can be extrapolated from experimental data with an accuracy of order 5% to 10%. A prescription to derive the required reference selections was given. If LO scale variation is accepted as proxy for the theoretical error, parton level results indicate that the $t\bar{t}j$ background to the $H \to WW$ search in WBF can be determined with a theoretical error of about 5%, while the $t\bar{t}$ background to the $H \to WW$ search in GF can be determined with a theoretical error of better than 1%. Uncertainties in the parton distribution functions contribute an estimated 3% to 10% to the total error. In order to accurately extrapolate the GF background, contributions beyond LO should be taken into account in future studies.

Acknowledgments

We thank D. Zeppenfeld for drawing our attention to the extrapolation approach and N. Akchurin, B. Mellado and A. Nikitenko as well as J. Huston, M. Krämer, W. K. Tung and M. Whalley for useful comments and suggestions. We also thank the organizers for invitations to and hospitality at the Les Houches workshop 2003 and the Higgs meeting during the September CMS week at CERN. This research was supported by the DFG Sonderforschungsbereich/Transregio 9 “Computer-gestützte Theoretische Teilchenphysik”.

---

[1] D. Rainwater and D. Zeppenfeld, Phys. Rev. **D60**, 113004 (1999) [Erratum-ibid. **D61**, 099901 (2000)]; C. M. Buttar, R. S. Harper, and K. Jakobs, ATL-PHYS-2002-033 (2002); K. Cranmer, *et al.*, ATL-PHYS-2003-002 and ATL-PHYS-2003-007 (2003); D. Rainwater, D. Zeppenfeld, and K. Hagiwara, Phys. Rev. **D59**, 014037 (1999); T. Plehn, D. Rainwater, and D. Zeppenfeld, Phys. Rev. **D61**, 093005 (2000); D. Rainwater and D. Zeppenfeld, JHEP **9712**, 005 (1997) [arXiv:hep-ph/9712271]; K. Cranmer, *et al.*, ATL-PHYS-2003-036 and ATL-PHYS-2003-006 (2003) [arXiv:hep-ph/0401088]; T. Han, G. Valencia, and S. Willenbrock, Phys. Rev. Lett. **69**, 3274 (1992); T. Figy, C. Oleari, and D. Zeppenfeld, Phys. Rev. **D68**, 073005 (2003); E. L. Berger and J. Campbell, ANL-HEP-PR-04-4 (2004) [arXiv:hep-ph/0403194].

[2] N. Kauer, T. Plehn, D. Rainwater, and D. Zeppenfeld, Phys. Lett. **B503**, 113 (2001).

[3] D. Cavalli, *et al.*, proceedings of the Workshop on Physics at TeV Colliders, Les Houches, France, 2001 [arXiv:hep-ph/0203056].

[4] S. Asai, *et al.*, Eur. Phys. J. **C** direct, DOI: 10.1140/epjcd/s2003–01–010–8 (2003) [arXiv:hep-ph/0402254].

[5] R. Barate, *et al.* [ALEPH Collaboration], Phys. Lett. **B565**, 61 (2003). M. W. Grunewald, UCD-EXPH-030401 (2003) [arXiv:hep-ex/0304023].

[6] M. Dittmar and H. K. Dreiner, Phys. Rev. **D55**, 167 (1997) and [arXiv:hep-ph/9703401]; K. Jakobs and T. Trefzger, ATL-PHYS-2000-015 (2000); S. Catani, D. de Florian, and M. Grazzini, JHEP **0105**, 025 (2001) [arXiv:hep-ph/0102227]; R. V. Harlander and W. B. Kilgore, Phys. Rev. **D64**, 013015 (2001) and Phys. Rev. Lett. **88**, 201801 (2002); C. Anastasiou and K. Melnikov, Nucl. Phys. **B646**, 220 (2002); V. Ravindran, J. Smith, and W. L. van Neerven, Nucl. Phys. **B665**, 325 (2003); G. Davatz, *et al.*, CERN-PH-TH-2004-035 (2004) [arXiv:hep-ph/0402218].

[7] M. Dittmar and H. Dreiner, CMS-NOTE-1997-083 (1997).

[8] ATLAS Collaboration, Technical Design Report, Vol. 2, CERN-LHCC-99-15 (1999).

[9] N. Kauer and D. Zeppenfeld, Phys. Rev. **D65**, 014021 (2002).

[10] N. Kauer, Phys. Rev. **D67**, 054013 (2003).

[11] G. Lopez Castro, J. L. Lucio, and J. Pestieau, Mod. Phys. Lett. **A6**, 3679 (1991); A. Denner,

S. Dittmaier, M. Roth, and D. Wackeroth, Nucl. Phys. **B560**, 33 (1999).

[12] J. Pumplin, *et al.*, JHEP **0207**, 012 (2002) [arXiv:hep-ph/0201195].

[13] W. Beenakker, F. A. Berends, and A. P. Chapovsky, Phys. Lett. **B454**, 129 (1999); W. Bernreuther, A. Brandenburg, and Z. G. Si, Phys. Lett. **B483**, 99 (2000); W. Bernreuther, A. Brandenburg, Z. G. Si, and P. Uwer, Phys. Lett. **B509**, 53 (2001); W. Bernreuther, A. Brandenburg, Z. G. Si, and P. Uwer, Phys. Rev. Lett. **87**, 242002 (2001); W. Bernreuther, A. Brandenburg, Z. G. Si, and P. Uwer, CERN-PH-TH/2004-046 (2004) [arXiv:hep-ph/0403035].

[14] S. Frixione and B. R. Webber, JHEP **0206**, 029 (2002) [arXiv:hep-ph/0204244]; S. Frixione, P. Nason, and B. R. Webber, JHEP **0308**, 007 (2003) [arXiv:hep-ph/0305252].

[15] M. Jezabek and J. H. Kühn, Nucl. Phys. **B314**, 1 (1989); A. Czarnecki, Phys. Lett. **B252**, 467 (1990); C. S. Li, R. J. Oakes, and T. C. Yuan, Phys. Rev. **D43**, 3759 (1991); A. Czarnecki and K. Melnikov, Nucl. Phys. **B544**, 520 (1999).

[16] S. Moretti, Phys. Rev. **D56**, 7427 (1997); A. S. Belyaev, E. E. Boos, and L. V. Dudko, Phys. Rev. **D59**, 075001 (1999); T. M. P. Tait, Phys. Rev. **D61**, 034001 (2000); A. Belyaev and E. Boos, Phys. Rev. **D63**, 034012 (2001).