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ACCURATE BACKGROUNDS TO HIGGS PRODUCTION AT THE LHC*

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Corrections of 10–30% for backgrounds to the $H \to WW \to \ell^+\ell^- \not{p}_T$ search in vector boson and gluon fusion at the LHC are reviewed to make the case for precise and accurate theoretical background predictions.

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1. Introduction

With full energy collisions in the Large Hadron Collider (LHC) scheduled for spring 2008, in the near future the TeV scale will become directly accessible in experiments. Theoretical arguments and precision measurements indicate that ground-breaking discoveries regarding the mechanism of electroweak symmetry breaking and the origin of mass can be expected [1]. The discovery and analysis of the Higgs boson predicted by the Standard Model (SM) with Higgs mechanism [2] or additional particles, for instance in supersymmetric extensions [3], are the primary goal of the LHC physics program [4].

For that purpose theoretical predictions are needed not only for signal processes, but also for background processes in search channels that do not allow for background determination from data (*e.g.* via sideband interpolation). While most background processes have previously been considered as signals, these calculations frequently employ approximations that are appropriate for signal selections, but may lead to inaccurate predictions for suppressed backgrounds. In many cases, higher order corrections have been calculated for inclusive cross sections, but not for fully differential cross sections due to the increased complexity. While inclusive corrections are in good approximation applicable to signal predictions, only fully differential

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corrections are guaranteed to provide accurate predictions for suppressed backgrounds. Although the discovery significance $S/\sqrt{B}$ is less affected by background corrections compared to signal corrections of similar size and sign, the applied selection cuts can strongly enhance suppressed background K-factors, but will not have a significant effect on the signal K-factor.

In the following we focus on the production of a SM Higgs boson in vector boson or gluon fusion that decays into W bosons, which in turn decay leptonically. These search channels contribute significantly to the LHC SM Higgs discovery potential for Higgs masses between 120 and 200 GeV [5–7]. Since the decay neutrinos escape detection, the Higgs momentum cannot be reconstructed. Signal and background can thus not be separated experimentally. Higgs observation becomes a counting experiment and reliable background predictions essential. For vector boson fusion (see Fig. 1) as well as gluon fusion, the dominant irreducible background is W-pair production and the leading reducible background is $t\bar{t}$ (+ jets) production.

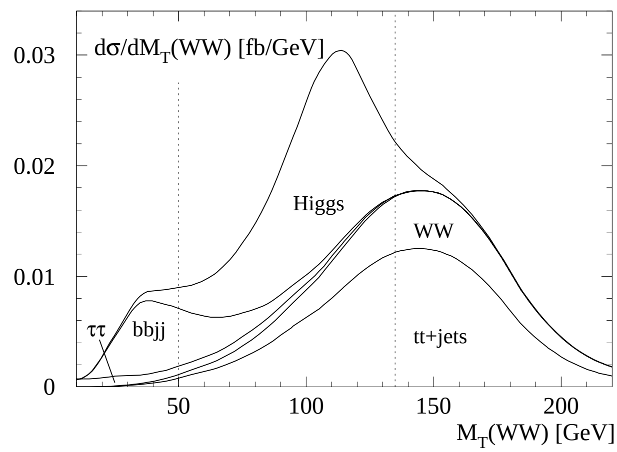

Fig. 1. Distribution of the WW “transverse mass” $d\sigma/dM_{\rm T}$ as Higgs invariant mass proxy ($M_H = 115\,\text{GeV}$) for $e^{\pm}\mu^{\mp}\ \not{p}_{\rm T}$ events in vector boson fusion at the LHC. The areas between curves represent the contributions from the signal and the various background classes, as indicated. For further details see Ref. [6] (Fig. 4).

2. Top background corrections

Perturbative predictions for the production and decay of heavy particles have frequently relied on the narrow-width approximation (NWA), which significantly reduces the number of Feynman diagrams that have to be taken into account. The parametric error estimate of $\mathcal{O}(\Gamma/m) \sim 1\%$ is reliable if applied selection cuts do not affect the resonant region and additional sub- and non-resonant diagrams with the same final state can be neglected. While this is usually the case for SM signal cross sections, the same is not true for suppressed background cross sections. For backgrounds, it is thus important to verify that the NWA is appropriate by comparing with calculations that take into account the complete fixed-order amplitude. For the Higgs search channels considered here, this comparison has been performed for the dominant reducible background due to top pair production in Ref. [8]. Off-shell predictions with the complete leading-order (LO) amplitude for $t\bar{t}$, $t\bar{t}$ + 1 jet and $t\bar{t}$ + 2 jets (with 87, 600 and 5820 Feynman diagrams contributing for the at the LHC dominant gg subprocess, respectively) were obtained using the `PP2TTNJ` program [9][1]. The complete LO predictions are typically 10–20% larger than the corresponding NWA predictions. The standard NWA uncertainty estimate is thus not applicable. Note that this even holds for the total cross section at the LHC, which is enhanced by about 5% if single- and non-resonant diagrams are taken into account[2].

In gluon fusion the applied central jet veto increases the single-resonant contribution[3] to approximately match the double-resonant contribution. Since the LO background uncertainty is large and the techniques for a complete $WWb\bar{b}$ calculation at next-to-leading order (NLO) are still under development (see Sec. 5), inspired by the natural separation of the double- and single-resonant graphs into gauge-invariant subsets ($t\bar{t}$ and Wt) at LO when the NWA is applied, the authors of Ref. [11] studied approaches to combine the corresponding $t\bar{t}$ and Wt cross sections known at NLO and discuss heuristic prescriptions to handle the overlap between real corrections to Wt and $t\bar{t}$ at LO.

3. *WW* background corrections

The dominant irreducible background to $pp \to H \to WW \to \ell^+\ell^-\ \not{p}_{\mathrm{T}}$ is W-pair production, which occurs in quark–antiquark annihilation. The gluon-induced subprocess formally enters at next-to-next-to-leading order (NNLO), but its importance is enhanced by the large gluon flux at the LHC and by experimental Higgs search cuts[4]. Recently, a fully differential calculation of $gg \to W^*W^* \to \ell\bar{\nu}\bar{\ell}'\nu'$ including the top–bottom massive quark loop contribution and the intermediate Higgs contribution with

[1] For $t\bar{t}$ production without additional jets, the subset of all graphs that contain an intermediate W^+ and W^- boson is available in the user process package `AcerMC` [10], which features interfaces to the general-purpose event generators PYTHIA and HERWIG.

[2] The NWA uncertainty of the Tevatron total cross section, on the other hand, is estimated correctly.

[3] With respect to top.

[4] Standard cuts are $p_{\mathrm{T},\ell} > 20\mathrm{GeV}, |\eta_\ell| < 2.5, \not{p}_{\mathrm{T}} > 25\mathrm{GeV}$. Additional Higgs search cuts are $\Delta\phi_{\mathrm{T},\ell\ell} < 45^\circ$, $m_{\ell\ell} < 35$ GeV, jet veto : $p_{\mathrm{T}j} > 20$ GeV and $|\eta_j| < 3$, 35 GeV $< p_{\mathrm{T}\ell,\max} < 50$ GeV, 25 GeV $< p_{\mathrm{T}\ell,\min}$.

full spin and decay angle correlations and allowing for arbitrary invariant masses of the W bosons has been completed [12]. The gluon-induced contribution enhances the NLO WW background prediction by approximately 30%. Though NNLO, it is the dominant higher-order correction (see Fig. 2). Signal-background interference effects range from -4 to $+11\%$ for intermediate Higgs masses when Higgs search cuts are applied (see Table I). The calculation is available as event generator `GG2WW` [9]. Work on a program `GG2ZZ` [9] for the process $gg \to Z^*Z^* \to 4$ charged leptons is in progress.

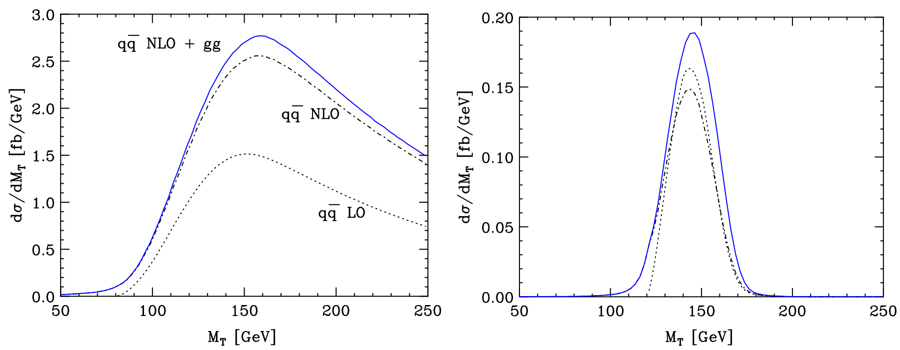

Fig. 2. Distribution of M_{T} (see Fig. 1) with standard cuts[4] (left) and Higgs search cuts[4] (right). Displayed are the total background from quark scattering at NLO and gluon-fusion (solid), and from quark scattering alone at LO (dotted) and NLO (dot-dashed).

TABLE I

Interference effects between the signal and gluon-induced background processes $gg(\to H) \to W^*W^* \to \ell\bar{\nu}\bar{\ell}'\nu'$ with Higgs search selection cuts (see footnote 4) and cross sections in fb.

M_H[GeV]	140	170	200
σ[signal]	1.8852(5)	12.974(2)	1.6663(7)
σ[bkg(gg)]	—	1.4153(3)	—
σ[signal + bkg(gg)]	3.174(2)	15.287(6)	3.413(2)
$\frac{\sigma[\text{signal+bkg(gg)}]}{\sigma[\text{signal}]+\sigma[\text{bkg(gg)}]}$	0.962	1.062	1.108

4. BSM corrections

In extensions of the SM additional heavy particles lead to more complicated decay chains. To simplify calculations in these models, the NWA has been applied extensively, even though the number of non-resonant diagrams that are neglected increases. Consider, for instance, $g\bar{b} \to (H^+ \to h\,W^+)\,\bar{t}$, which has been studied in NWA in Ref. [13]. For SPS1a with no selection cuts applied one obtains at the LHC $\sigma_{\rm complete}/\sigma_{\rm NWA} = 110$ (see Fig. 3). The 8 non-resonant diagrams neglected in NWA dominate the cross section[5]. This dramatic effect serves as a warning to expect surprises[6]. Other examples and a more detailed discussion can be found in Ref. [14].

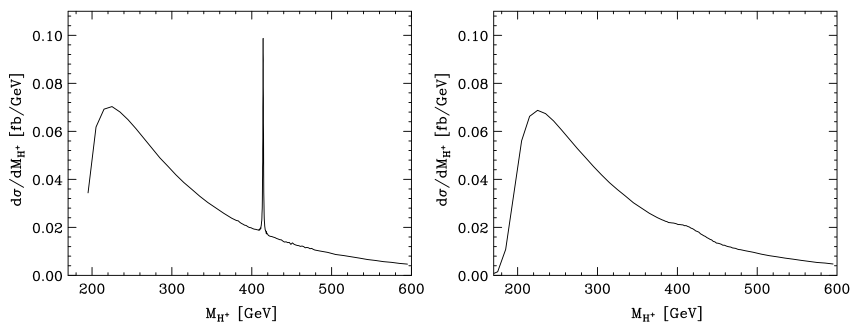

Fig. 3. H^+ invariant mass distribution for the process $g\bar{b} \to (H^+ \to h\,W^+)\,\bar{t}$ at the LHC calculated with complete LO amplitude with perfect detector resolution (left) and with realistic detector resolution (right) at SPS1a. No selection cuts are applied.

5. Reducing the theoretical uncertainty

LO QCD cross sections are affected by large scale uncertainties (see Fig. 4(a)). The following complementary approaches allow to obtain theoretical predictions with an uncertainty of $\lesssim 10\%$

- calculation of higher order corrections;
- extrapolation of measured cross sections.

Since exact cross sections are scale independent, higher fixed-order results tend to have a strongly reduced scale uncertainty. In special kinematic regimes large logarithms occur and need to be resummed in order to obtain an acceptable convergence of the perturbative series. Without NWA

[5] Interference effects are negligible.

[6] Note that the branching ratio is small in the MSSM. For SPS1a, $\mathrm{BR}_{H^+\to hW^+} = 2\times 10^{-3}$. It could, however, be much larger in the NMSSM or general 2HDMs.

decomposition, calculations of backgrounds usually involve many-particle final states, and the calculational complexity increases considerably order by order. Adequate methods that allow to efficiently evaluate and integrate the 1-loop multi-leg amplitudes of $2 \to 3$ and $2 \to 4$ processes at NLO are therefore currently under development (see *e.g.* [15]).

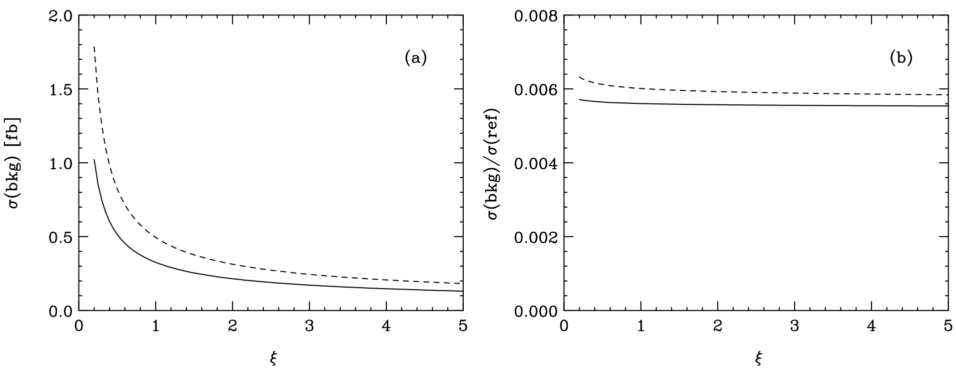

Fig. 4. Renormalization and factorization scale variation of LO $t\bar{t}j$ background cross section (a) and ratio with reference cross section (b) to the $H \to WW \to \ell^+\ell^- \not{p}_{\mathrm{T}}$ search in vector boson fusion at the LHC for different scale definitions. For details see Ref. [17] (Fig. 1).

In ratios the scale dependence of fixed-order cross sections can partly compensate resulting in a significantly reduced theoretical uncertainty (see Fig. 4(b)). A reference cross section that can be measured with low uncertainty can thus be extrapolated to the background region without introducing large theoretical uncertainties [16, 17]:

$$\sigma_{\mathrm{bkg}} \approx \underbrace{\left(\frac{\sigma_{\mathrm{bkg,\ fixed-order\ prediction}}}{\sigma_{\mathrm{ref,\ fixed-order\ prediction}}}\right)}_{\text{low theoretical uncertainty}} \times \underbrace{\sigma_{\mathrm{ref,\ measured}}}_{\text{low experimental uncertainty}} .$$

6. Summary

Theoretical arguments and precision measurements indicate that groundbreaking discoveries regarding the mechanism of electroweak symmetry breaking and the origin of mass can be expected at the LHC. For that purpose theoretical predictions are needed not only for signal processes, but also for important background processes in search channels that do not allow for background determination from data. We reviewed NWA and higher order corrections of 10–30% for the dominant $t\bar{t}$ (+ jets) and WW backgrounds to the Higgs boson search channel $H \to WW \to \ell^+\ell^- \not{p}_{\mathrm{T}}$ in vector boson and gluon fusion. In extensions of the SM, where additional heavy particles lead to more complicated decay chains and enhanced non-resonant contributions, NWA corrections can be significant not only for suppressed backgrounds, but also for signal cross sections. Two complementary approaches can be applied to reduce the theoretical uncertainty of fixed-order background predictions. We conclude that enhanced background predictions are necessary and feasible and that improved parton-level programs and event generators are available [9].

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