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Higher-order QCD effects in the Higgs to ZZ search channel at the LHC

Rikkert Frederix[(a)] and **Massimiliano Grazzini**[(b)]

[(a)]Center for Particle Physics and Phenomenology (CP3),
Université catholique de Louvain, B-1348 Louvain-la-Neuve, Belgium

[(b)]INFN, Sezione di Firenze
I-50019 Sesto Fiorentino, Florence, Italy

Abstract

We present a consistent analysis of the signal as well as the irreducible background for the search of the SM Higgs boson in the ZZ decay channel at the LHC. Soft-gluons effects are resummed up to next-to-leading logarithmic accuracy, and the results are compared to those obtained with fixed order calculations and the MC@NLO event generator. The soft-gluon effects are typically modest but should be taken into account when precise predictions are demanded. Our results show that the signal over background ratio can be significantly enhanced with a cut on the transverse momentum p_T^{ZZ} of the ZZ pair. We also introduce a fully transverse angular variable that could give information about the CP nature of the Higgs boson.

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1 Introduction

The elucidation of the mechanism of electroweak symmetry breaking is one of the main goals of the LHC physics program. In the Standard Model (SM) and several popular extensions such as SUSY, mass generation is triggered by the Higgs mechanism, which predicts the existence of (at least) one scalar state, the Higgs boson. The search for the Higgs at collider experiments has now being on-going for two decades. The present direct lower limit of the Higgs mass in the SM is 114.4 GeV (at 95% CL) [1], while precision measurements point to a rather light Higgs, $m_h \lesssim 200$ GeV [2].

At the LHC, the main production mechanism will be $gg \to H$, and if $m_h > 180$ GeV, the Higgs decay into two Z bosons, $h \to ZZ$, will provide one of the cleanest signatures at hadron colliders, *i.e.*, four leptons. Such a final state will allow a very accurate mass reconstruction and the best of all possible discovery modes, a sharp peak over a rather flat background. At this stage, accurate predictions from theory will be helpful to design the best analysis but are not essential to claim a discovery as data alone will provide all the necessary information. However, to answer the key questions on the nature of the discovered particle, such as its spin, CP nature and couplings, accurate predictions for both signal and backgrounds will be required.

As far as the Higgs signal is concerned, QCD corrections at the next-to-leading order (NLO) have been known for some time [3, 4]: their effect increases the LO cross section by about 80–100%. In recent years, even next-to-next-to-leading order (NNLO) corrections have been computed, first for the total cross section [5], and more recently implemented in fully exclusive calculations [6, 7]. Note, however, that all the NNLO results use the large-m_{top} approximation, m_{top} being the mass of the top quark.

As far as ZZ production is concerned, NLO corrections have been known for some time [8, 9, 10]. More recent NLO calculations exist that, using the one-loop helicity amplitudes of Ref. [11], fully take into account spin correlations in the Z boson decay [12, 13].

The fixed-order calculations provide a reliable estimate of signal and background cross sections and distributions as long as the scales involved in the process are all of the same order. When the total transverse momentum of the ZZ pair is much smaller than its invariant mass the validity of the fixed-order expansion may be spoiled since the coefficients of the perturbative expansion can be enhanced by powers of the large logarithmic terms, $\ln^n M_{ZZ}/p_T^{ZZ}$. In the case of the Higgs signal, the resummation of such contributions has been performed up to next-to-next-to-leading-logarithmic (NNLL) accuracy [14, 15, 16].

The purpose of the present paper is twofold. We first consider transverse momentum resummation for ZZ production at the LHC. The resummation of such logarithmic contributions was first considered in Ref. [17]. Here we use the resummation formalism of Refs. [14, 15] together with the helicity amplitudes of Ref. [11] (including finite width effects from the Z bosons, but neglecting single-resonant contributions). Contrary to Ref. [17] we fully include the decay of the Z bosons, keeping track of their polarization in the leptonic decay. In the large p_T^{ZZ} region we use LO perturbation theory (ZZ+1 parton); in the region $p_T^{ZZ} \ll M_{ZZ}$ the large logarithmic contributions are resummed to NLL accuracy. The present study parallels the one performed in Ref. [19] in the case of WW production. By using these results, we perform a detailed comparison of signal and background cross sections and distributions.

The paper is organized as follows. In Sect. 2 we analyze the impact of transverse momentum resummation for ZZ production. In Sect. 3 we compare signal and background cross sections and distributions for the search of a Higgs boson of mass $m_h = 200$ GeV. In Sect. 4 we conclude with a summary of our results.

2 Transverse-momentum resummation for ZZ production

In this Section we discuss the effect of transverse-momentum resummation for ZZ production at the LHC, and present a comparison to fixed order NLO results obtained with MCFM [13] and to results obtained with MC@NLO [18].

We consider the process $pp \to ZZ + X \to e^+e^-\mu^+\mu^- + X$ and perform the all-order resummation of the logarithmically enhanced contributions at small p_T^{ZZ}. The implementation is completely analogous to the case of WW pair production discussed in Ref. [19] and is based on the formalism of Refs. [14, 15]. We refer the reader to the above papers for the technical details. The large logarithmic contributions at small transverse momenta of the ZZ pair are resummed up to NLL accuracy. The result is then matched to the fixed order LO calculation valid at large p_T^{ZZ}, to achieve NLL+LO accuracy.

We recall that the formalism of Refs. [14, 15] enforces a unitarity constraint such that resummation effects vanish when total cross sections are considered. As a consequence, at NLL+LO accuracy the integral of our resummed spectra coincides with the total NLO cross section if no cuts are applied.

To compute the ZZ cross section we use MRST2002 NLO parton densities [20] and α_S evaluated at two-loop order. Our resummed predictions depend on renormalization, factorization and resummation scales. The resummation scale parametrizes the arbitrariness in the resummation procedure, and is set equal to the invariant mass M_{ZZ} of the ZZ pair. Variations around this central value can give an idea of the size of yet uncalculated higher-order logarithmic contributions. Renormalization and factorization scales are set to $2M_Z$. The latter choice allows us to exploit our unitarity constraint and to exactly recover the total NLO cross section when no cuts are applied. At NLO we consistently use

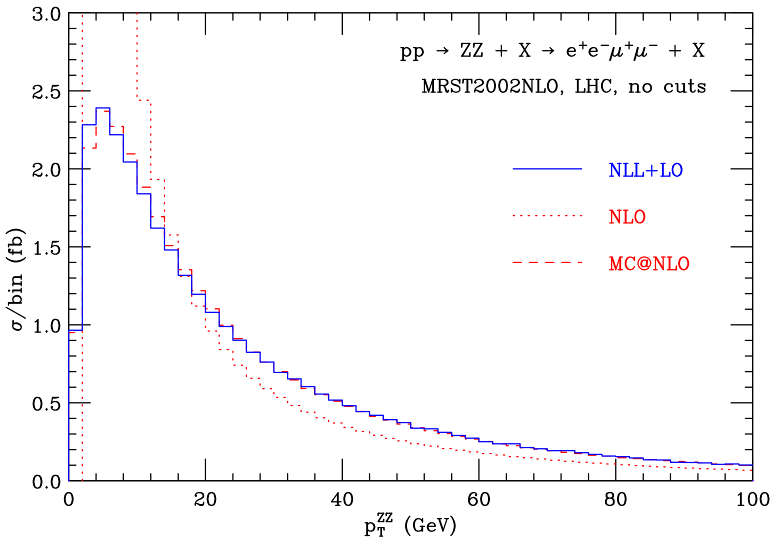

Figure 1: *Comparison of the transverse momentum spectra of the ZZ pair obtained at NLL+LO (solid) with MC@NLO (dashes) and NLO results (dots). No cuts are applied.*

$\mu_F = \mu_R = 2M_Z$ as default choice, whereas in MC@NLO μ_F and μ_R are set to the default choice, the average transverse mass of the Z bosons.

The predictions of resummation are implemented in a partonic Monte Carlo program which generates the full 5-body final state ($e^+e^-\mu^+\mu^-$ + 1 parton). Nonetheless, since the resummed cross section we use is inclusive over rapidity, we are not able to apply the usual rapidity cuts on the leptons. To the purpose of the present work, we do not expect this limitation to be essential.

We start by considering the inclusive cross sections. Our NLL+LO result is 33.76 fb, and agrees with the NLO one (33.99 fb) to about 1%. With MC@NLO we obtain 34.60 fb. As expected, the MC@NLO cross section is slightly larger because ZZ production is calculated in the narrow width approximation, while in the NLO and NLL+LO calculations, finite width effects are included.

In Fig. 1 we show the corresponding p_T^{ZZ} distribution, computed at NLL+LO (solid), with MC@NLO (dashed) and at NLO (dots). As is well known, the NLO result diverges to $+\infty$ as $p_T^{ZZ} \to 0$, and this divergence is cancelled by the (negative) weight of the first bin, due to the virtual contribution. On the contrary, the NLL+LO and MC@NLO results are well behaved as $p_T^{ZZ} \to 0$ and are very close to each other, showing a peak around $p_T^{ZZ} \sim 5$ GeV.

In order to study the perturbative uncertainties affecting our resummed calculation, we have varied the renormalization and factorization scale by a factor 2 around the central value. We find that the effect of μ_R and μ_F variations is rather small, of the order of $\pm 1\%$, and comparable with the estimated accuracy of our numerical code. Similar effects are

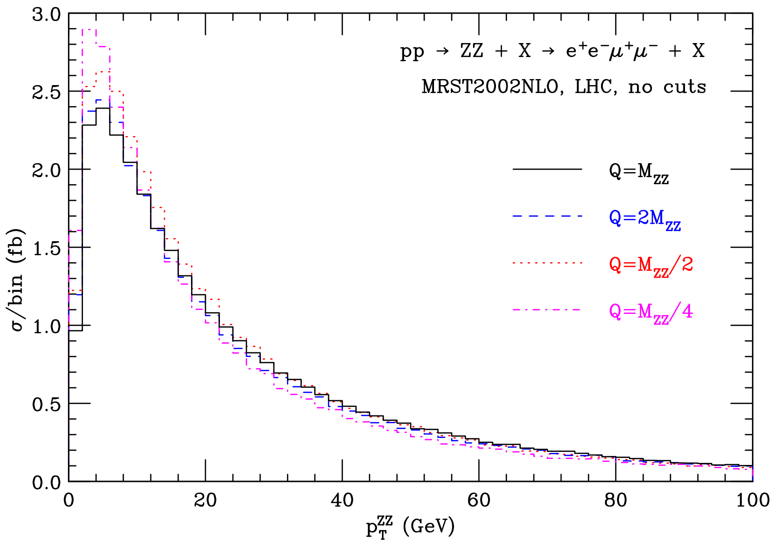

Figure 2: *Comparison of the transverse momentum spectra of the ZZ pair obtained at NLL+LO for different values of the resummation scale Q. No cuts are applied.*

found at NLO.

The dependence of our NLL+LO results on the resummation scale Q is instead stronger. In Fig. 2 we show the NLL+LO prediction for different choices of the resummation scale Q. We see that varying the resummation scale the effect on the p_T^{ZZ} spectrum is visible and amounts to about $\pm 10\%$ at the peak. For lower (higher) values of Q the effect of resummation is confined to smaller (larger) values of p_T^{ZZ}. Thanks to our unitarity constraint, the total rate is instead insensitive to resummation scale variations, within the numerical accuracy of our code.

As in the case of Higgs [15] and WW [19] production, we find that the choice $Q = 2M_{ZZ}$ gives (slightly) negative cross sections at very large p_T^{ZZ}. In order to define a range of variations of Q, we prefer to avoid values that give a bad behaviour at large p_T^{ZZ}. For this reason, in the following, we will consider resummation scale variations in the range $M_{ZZ}/4 \leq Q \leq M_{ZZ}$.

We now consider the selection cuts designed for the search of a Higgs boson of mass $m_h = 200$ GeV in the $e^+e^-\mu^+\mu^-$ channel [22]. The final-state leptons, ordered according to decreasing p_T, should fulfil the following thresholds:

$$p_{T1} > 22 \text{ GeV} \quad p_{T2} > 20 \text{ GeV} \quad p_{T3} > 15 \text{ GeV} \quad p_{T4} > 7 \text{ GeV}, \tag{1}$$

the invariant mass of the e^+e^- and the $\mu^+\mu^-$ pairs should be between

$$60 \text{ GeV} < M_{e^+e^-,\mu^+\mu^-} < 105 \text{ GeV} \tag{2}$$

and the invariant mass of the ZZ pair should fulfil

$$190 \text{ GeV} < M_{ZZ} < 210 \text{ GeV}. \tag{3}$$

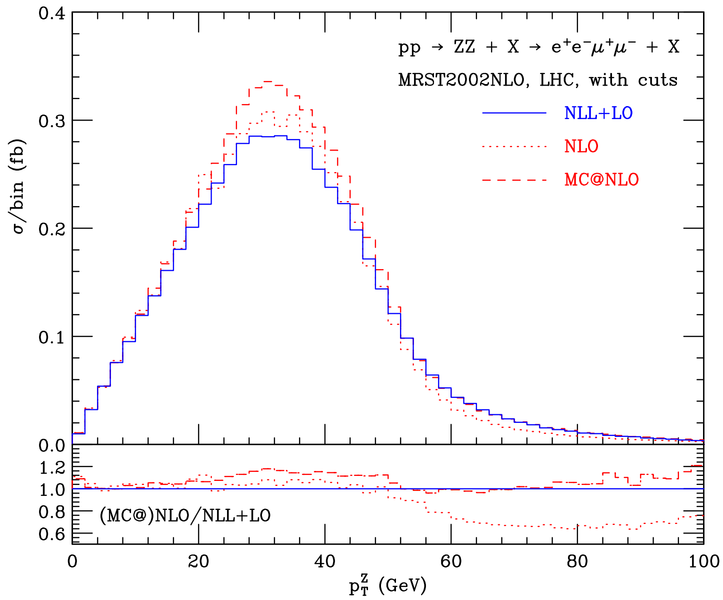

Figure 3: *Comparison of the transverse momentum spectra of one of the Z at NLL+LO (solid) with NLO (dots) and MC@NLO (dashed) results. The lower part of the plot shows the NLO and MC@NLO results normalized to NLL+LO.*

With these cuts the NLL+LO result is 5.42 fb, which is about 2% smaller than the NLO one (5.51 fb). The cross section from MC@NLO is about 11% larger (6.01 fb). This is mainly due to the fact that MC@NLO calculates the cross section in the narrow width approximation, and therefore the cuts on the invariant masses of the e^+e^- and $\mu^+\mu^-$ pairs are always fulfilled. As in the inclusive case, the effect of scale variations on the rate is very small, of the order of $\pm 1\%$.

We point out that single-resonant contributions are neglected in our calculation. We have used MadGraph/MadEvent [21] to check that these contributions are indeed small and found that at LO the effects are smaller than the permille level. Effects from off-shell photons $pp \to Z\gamma^* \to e^+e^-\mu^+\mu^-$ are larger. At NLO they decrease the cross section by about 1% with the cuts described above, due to negative interference between the Z boson and the photon. The shapes of the distributions are, however, not significantly changed. Hence, it is safe to neglect these two contributions in the NLL+LO approximation with the cuts described above. For selection cuts used in Higgs searches where its mass is smaller than the ZZ threshold, the effects from off-shell photons cannot be neglected and have to be included.

In Fig. 3 we show the p_T distribution of one of the Z bosons, computed at NLL+LO, NLO and with MC@NLO. Contrary to the p_T^{ZZ} spectrum, this distribution is well behaved at NLO but the effect of resummation is still visible on its shape. This is evident from the lower part of the plot, showing the NLO and MC@NLO result normalized to NLL+LO.

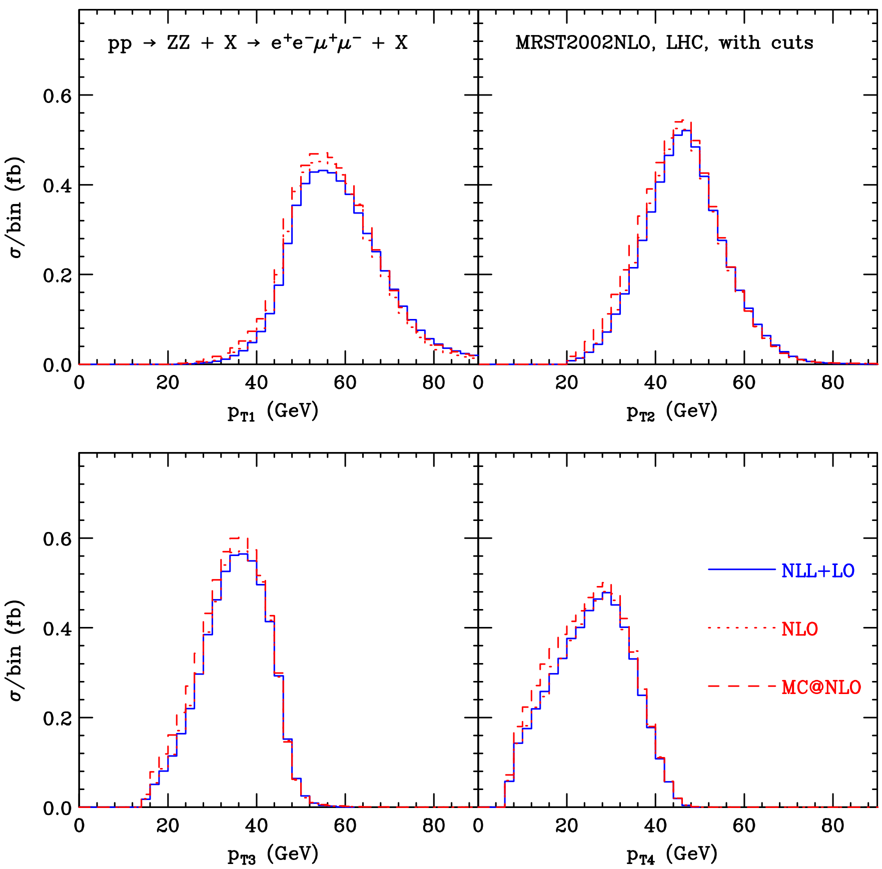

Figure 4: *Transverse momentum spectra of the leptons: NLL+LO (solid), MC@NLO (dashes) and NLO (dots).*

In Fig. 4 we show the p_T distributions of the charged leptons, ordered according to decreasing p_T. Here the NLO prediction is in good agreement with the NLL+LO one. MC@NLO, however, predicts slightly softer leptons.

The effect of scale variations is still very small for the above distributions. Only in the high-p_T tail of the p_T^Z distribution resummation scale variations give a visible effect, being of about $\pm 10\%$ at $p_T^Z \sim M_Z$.

In Fig. 5 we consider the distribution in the variable $\Delta\phi_T$ defined as follows. We consider the separation between the e^- and the μ^- where their momenta are taken in the rest frame of their parent Z boson, by neglecting all the longitudinal components. In this way the $\Delta\phi_T$ is manifestly longitudinally invariant. As will be illustrated later, see Sect. 3, this angle is sensitive to the CP nature of a Higgs boson resonance. Due to the fully transverse nature of this angle, it can potentially be reconstructed also if only three leptons are detected together with missing E_T.

We see that the shapes of the NLO and NLL+LO distributions are qualitatively similar.

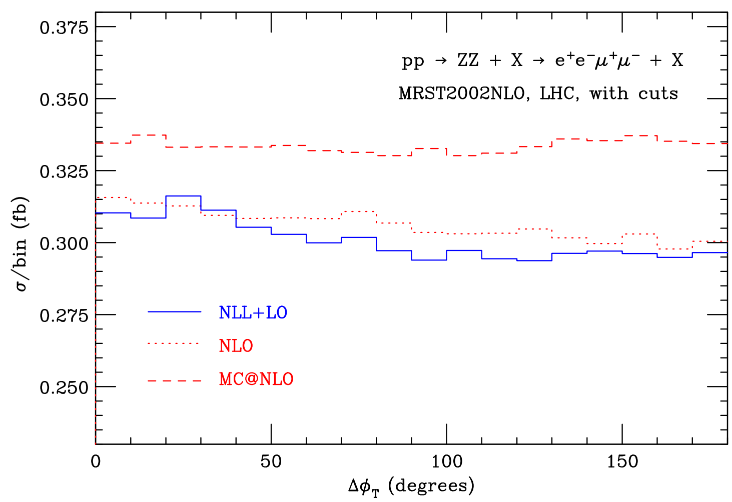

Figure 5: *Same as in Fig. 4 but for the $\Delta\phi_T$ distribution.*

Both decrease with increasing separation angle, the NLL+LO prediction slightly more at small angles before it flattens out, while the NLO prediction has a more constant slope. The differences are, however, small. The effect of scale variations on the NLO and NLL+LO results is again of the order or smaller than 1%.

We also plotted the prediction for this angle by MC@NLO, although we remind the reader that MC@NLO does not include spin correlations in the Z decay. Despite this fact, the shape of this distribution is not too different from those obtained at NLO and NLL+LO.

3 Signal and background

In this Section we perform a consistent comparison of signal and background cross sections for the Higgs search in the $gg \to h \to ZZ \to e^+e^-\mu^+\mu^-$ channel at the LHC. We consider a Higgs boson with mass $m_h = 200$ GeV and use the numerical program of Refs. [14, 15] to compute its transverse momentum spectrum. To be consistent with the background[†], we work at NLL+LO accuracy and we generate a set of events containing a Higgs boson which is then let decay using the MadGraph package [21]. We use the same cuts as in Sect. 2.

The signal cross section is 7.74 fb. Comparing with the background we get $S/B = 1.43$. In Fig. 6 we plot the p_T spectra of the leptons for signal and background. We see that the spectrum of the leading lepton tends to be slightly harder for the signal, compared to the

[†]In our simplified analysis, we consider only the ZZ irreducible background. We neglect other sources of reducible background like $t\bar{t}$ and $Zb\bar{b}$ which are known to give a much smaller contribution [22].

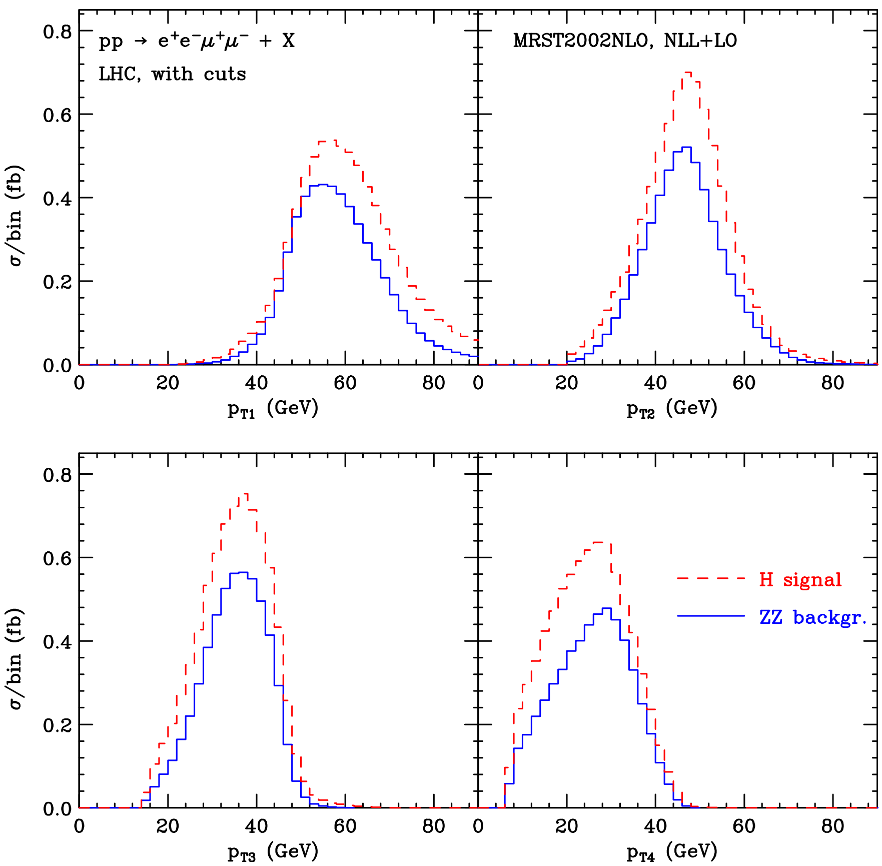

Figure 6: *Leptons p_T spectra for Higgs signal (dashes) and ZZ background (solid).*

background, whereas the opposite happens for the lepton with the minimum p_T.

In Fig. 7 we plot the $\Delta\phi_T$ distribution defined in Sect. 2 for signal and background. Since this distribution is expected to be sensitive to the CP nature of the Higgs, we also consider the case of a pseudo-scalar Higgs boson. As in the case of the scalar, the events are generated starting from the transverse momentum spectrum at NLL+LO and then letting the Higgs boson decay using the MadGraph package [21]. The computation of the spectrum for the pseudoscalar has been done by using a modified version of the numerical program of Refs. [14, 15], using the results of Ref. [23][‡].

From Fig. 7 we see that the shape of the distribution shows remarkable differences in the three cases. As shown in Fig. 5, for the background the distribution is rather flat. On the contrary, for the pseudoscalar, the distribution is peaked at central values of $\Delta\phi_T$, whereas for the scalar the distribution has a minimum in this region. We conclude that this angular variable has a good discriminating potential to assess the CP nature of the

[‡]The spectrum for the pseudoscalar at NLL+LO accuracy can be easily obtained by using the fact that the real corrections (in the large-m_{top} approximation) are the same as for the scalar. As such, the only difference from the case of the scalar is in the finite part of the virtual corrections [23].

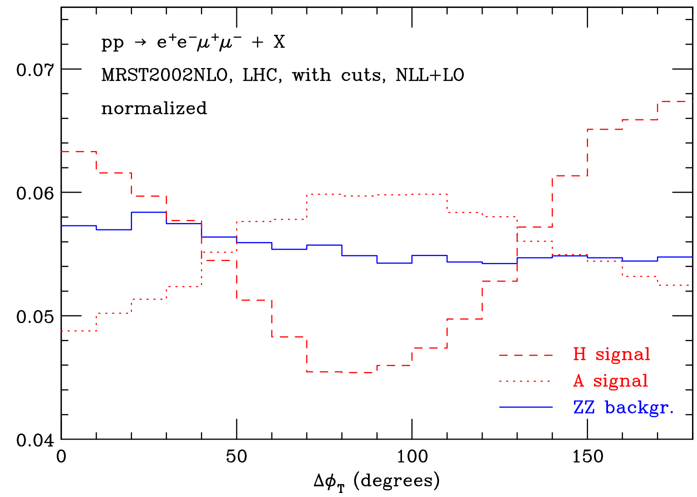

Figure 7: *The $\Delta\phi_T$ distribution for scalar (dashes), pseudo-scalar (dots) and ZZ background (solid) at NLL+LO.*

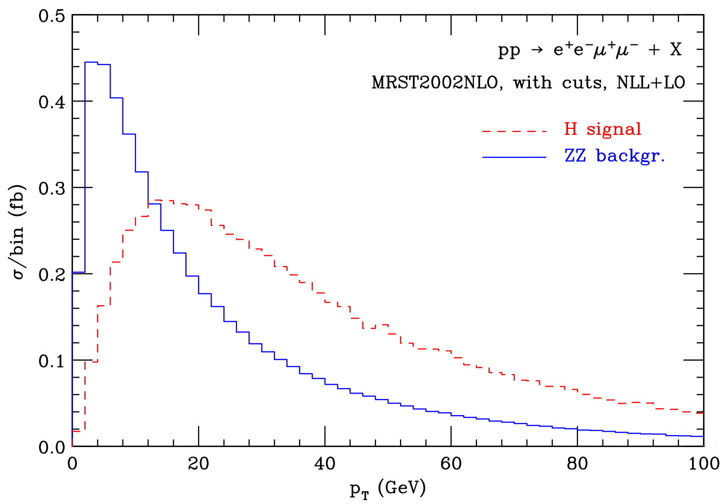

Figure 8: *Comparison of p_T spectra of signal and background at NLL+LO, when standard cuts are applied.*

Higgs boson.

We finally consider the possibility to apply an additional cut on the total transverse momentum of the four leptons. This idea is inspired by a comparison of the transverse momentum spectra of the Higgs boson and of the ZZ pair in Fig. 8.

We see from Fig. 8 that the Higgs signal is definitely harder than the ZZ background, being peaked at $p_T \sim 17$ GeV. The ZZ background is instead peaked at $p_T \sim 5$ GeV. As such, a cut on the total transverse momentum of the leptons may increase the statistical significance. Starting with the standard set of cuts used in the rest of the paper, we

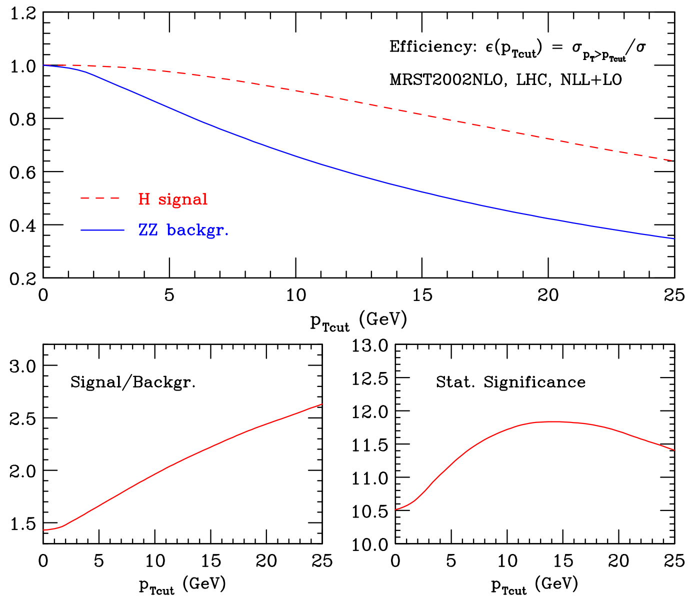

Figure 9: *The upper plot shows the NLL+LO efficiency as a function of $p_{T\mathrm{cut}}$ for the Higgs signal (dashed) and the ZZ background (solid). The lower left plot shows the signal over background ratio and the lower right the statistical significance for an integrated luminosity of 10 fb^{-1}.*

compute the efficiency of the additional cut by defining

$$\epsilon(p_{T\mathrm{cut}}) = \sigma_{p_T>p_{T\mathrm{cut}}}/\sigma\,. \tag{4}$$

In Fig. 9 we plot the efficiency as a function of $p_{T\mathrm{cut}}$ for the signal and the background. We see that the efficiency of this additional cut decreases more rapidly for the background than for the signal. As should be expected, the resummation effect is crucial in this case. The fixed order NLO efficiencies, not shown in Fig. 9, become unphysically larger than unity for small values of $p_{T\mathrm{cut}}$. Due to the fact that the efficiency of the background decreases more rapidly compared to the signal, the signal over background ratio increases with increasing $p_{T\mathrm{cut}}$, as can also be seen from the lower left plot of Fig. 9. The lower right plot shows the statistical significance for an integrated luminosity of 10 fb^{-1}, We observe that the statistical significance is maximum when $p_{T\mathrm{cut}} \sim 15$ GeV.

The latter point, however, requires a word of caution. The predictions presented in the present paper are based on resummed calculations obtained in a purely perturbative framework. Intrinsic-p_T effects are known (see e.g. Ref. [24] and references therein) to affect transverse-momentum distributions, particularly at small transverse momenta. These effects are not taken into account in our calculation.

As noted in Ref. [15], these non-perturbative effects have the same qualitative impact as the inclusion of higher-order logarithmic contributions, *i.e.*, they tend to make the resummed p_T distribution harder. The quantitative results shown in Fig. 9 will certainly depend on these effects, although the qualitative picture should not change dramatically.

4 Summary

Higgs boson production by gluon-gluon fusion, followed by the decay mode $h \to ZZ \to 4$ leptons, provides the best discovery channel at the LHC for Higgs masses above 180 GeV. For a precise determination of the properties of the Higgs resonance, such as its mass and CP nature, detailed theoretical predictions for the signal and backgrounds are necessary.

In this work we considered a Higgs boson with mass $m_h = 200$ GeV and performed the resummation of multiple soft-gluon emission for the ZZ background. We then compared the results with those for the signal in the case of a (pseudo-)scalar Higgs boson. The effects from the resummation of soft gluons are modest for observables like the transverse momentum of the final state leptons. However, the transverse momentum spectra of the Z bosons and of the ZZ pair are sensitive to these effects.

An angle $\Delta\phi_T$ that is sensitive to the CP nature of the Higgs signal is also introduced. This angle is defined in a fully transverse way, such that it is longitudinally boost invariant. This angle can potentially be reconstructed also if only three leptons are detected together with missing E_T.

We also argued that an additional cut on the transverse momentum of the ZZ pair may significantly increase the signal over background ratio and the statistical significance. The impact of resummation is of course crucial in this case. The above cut could be helpful to claim an early discovery or to obtain an easier determination of the nature of the discovered particle.

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