Associated $t\bar{t}\mathcal{H}$ Production at a VLHC: measuring the top-quark Yukawa coupling

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Future hadron colliders will have the potential to measure some of the most relevant Higgs boson couplings with high precision. In this paper we investigate the potential of a Very Large Hadron Collider (VLHC) to measure the top-quark Yukawa coupling.

1. Introduction

As part of the Snowmass effort to investigate the physics potential of future hadron colliders, we have addressed the problem of how some of the most relevant precision measurements of Higgs boson physics could benefit from the very high energy and statistics of these future facilities.

We imagine a scenario in which one or more Higgs bosons have been discovered at either the Fermilab Tevatron or the CERN Large Hadron Collider (LHC), and a rich program of Higgs boson physics has already been developed. We then work under the assumption that precise determinations of the Higgs boson mass(es) and width(s), as well as determinations of various Higgs boson production cross sections, branching ratios, and ratios of Higgs boson couplings within a 10–20% uncertainty are available. The next generation of colliders will then play a crucial role in getting to a more precise determination of the Higgs boson couplings, therefore constraining its nature. It has been shown that an e^+e^- Linear Collider, operating with high luminosity, can reach precisions of a few percents on all Higgs boson couplings except the Higgs boson self-couplings [1, 15]. The question is therefore what is the corresponding potential of a next generation hadron collider like a Very Large Hadron Collider (VLHC).

Among the most important Higgs boson couplings, the Higgs-boson coupling to the top quark plays a special role. Because of the intriguingly large size of the top-quark mass, this coupling is largely enhanced with respect to all other Yukawa couplings and could shed some light on the obscure pattern of fermion mass generation and electroweak symmetry breaking.

In this context, it is interesting to assess the precision with which the top-quark Yukawa coupling could be measured at a pp VLHC, running at center of mass energies of $\sqrt{s} = 40, 100, 200$ TeV respectively. The golden mode for this measurement is the associated production of a Higgs boson with a pair of top-antitop quarks, $pp \to t\bar{t}\mathcal{H}$, [9]. The Higgs boson is radiated either from the top or from the antitop quarks and the cross section is directly proportional to the top-quark Yukawa coupling [7, 10]. We mainly focus on a Standard Model (SM) like Higgs boson ($\mathcal{H} = h_{SM}$), giving only some qualitative indication of how the analysis could be generalized to the Minimal Supersymmetric Standard Model (MSSM) Higgs sector ($\mathcal{H} = h^0, H^0, A^0$). In our analysis we consider the Higgs boson decaying into $b\bar{b}$, $\gamma\gamma$, and $\tau^+\tau^-$ and we determine the significance of the signal over the background in these three cases. As a result, all three channels turn out to be viable, even for fairly low integrated luminosities, providing a determination of the top-quark Yukawa coupling at the few percent level over a large range of Higgs boson masses.

The layout of our presentation is as follows. The characteristics of the the associated production of a SM like Higgs boson in $pp \to t\bar{t}\mathcal{H}$ are described in Sec. 2. In Sec. 3 we compare signal and background, in the SM, for the three Higgs boson decay channels discussed above, and estimate

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the relative error with which the SM top-quark Yukawa coupling could be measured at a VLHC. We also give some qualitative indications of how the results could change if the MSSM Higgs sector is considered. Sec. 4 contains our conclusions.

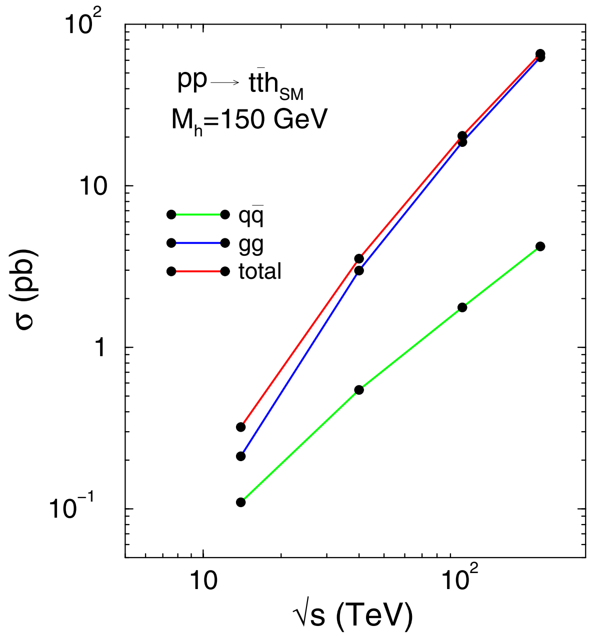

Figure 1: Relative contributions of the $q\bar{q}$ and gg parton level channels to the total cross section for $pp \to t\bar{t}h_{SM}$ as functions of the center of mass energy $\sqrt{s}$.

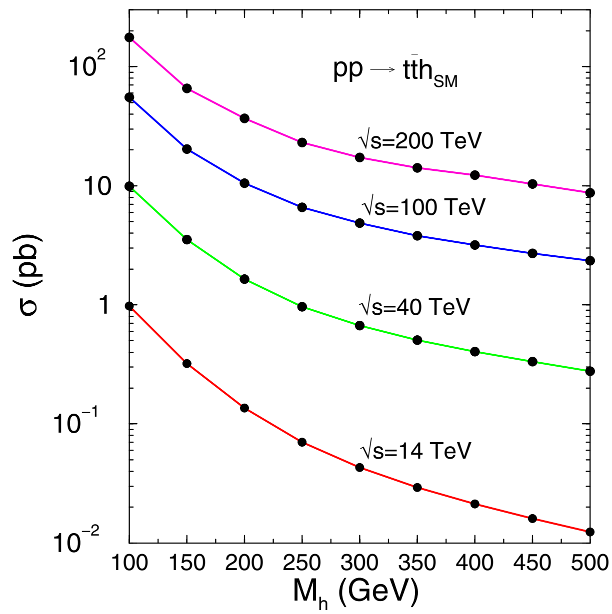

Figure 2: Total cross section for $pp \to t\bar{t}h_{SM}$ as a function of $M_{h_{SM}}$, for various center of mass energies.

2. Signal

The total hadronic cross section for $pp \to t\bar{t}\mathcal{H}$ ($\mathcal{H} = h_{SM}, h^0, H^0, A^0$) consists of two parton level sub-processes: $q\bar{q} \to t\bar{t}\mathcal{H}$ and $gg \to t\bar{t}\mathcal{H}$. Taking $\mathcal{H} = h_{SM}$ for illustrative purposes, we plot in Figure 1 the relative contribution of the two subprocesses, for $M_{\mathcal{H}} = 150$ GeV. As expected, the gg contribution dominates as the center of mass energy is increased.

In Figure 2 we also show the dependence of the total cross section from $M_{\mathcal{H}}$, again when $\mathcal{H} = h_{SM}$, for $\sqrt{s} = 14$ TeV (LHC) and $\sqrt{s} = 40, 100, 200$ TeV (VLHC). For the highest center of mass energy considered in this paper, $\sqrt{s} = 200$ TeV, the total cross section is enhanced by two to three orders of magnitude with respect to the corresponding cross section at the LHC, depending on the Higgs boson mass.

All the results presented in this paper are obtained using tree-level cross sections, both for the signal and for the backgrounds, calculated using CTEQ4L [8] parton distribution functions and the strong coupling constant $\alpha_s(\mu)$ at one-loop. As usual, tree-level cross sections have a very large renormalization/factorization scale dependence and, as a result, a large uncertainty. At present, only the next-to-leading QCD corrections to the signal are known [3, 11, 12]. Since we do not aim at a precise determination of the cross section, but at a study of signal vs. background, we prefer to consistently use only quantities calculated at leading order, without including any K-factors. The renormalization and factorization scales have been set to a common value $\mu = m_t + M_{\mathcal{H}}/2$, with $m_t = 174$ GeV.

3. Signal versus Background for Various Decay Channels

In this section we present some studies of the irreducible backgrounds and discuss the expected precision with which a measurement of the SM top-quark Yukawa coupling can be performed at a VLHC. For illustration purposes, we consider the case of a VLHC operating at $\sqrt{s} = 100$ TeV. In Figure 3 we compare the cross sections for the signal, $pp \to t\bar{t}h_{SM}$, and for the irreducible backgrounds consisting of $t\bar{t}XX$ production with $X = b, \gamma, \tau$ [1]. The cross sections for the signal include the branching ratios $h_{SM} \to XX$, calculated using HDECAY [5]. In order to take into account finite mass resolution effects, the background events are plotted in bins of 40, 5, and 20 GeV for b, γ, and τ respectively. To simulate the detector acceptance, the decay products of the Higgs boson are required to have a transverse momentum $p_T > 25$ GeV and a pseudorapidity $|\eta| < 3$. The set of parton distribution functions is CTEQ4L and the renormalization and factorization scales are set equal to $m_t + M_{XX}/2$, where M_{XX} is the invariant mass of the XX pair. Qualitatively, the signal to background ratios are similar to those expected at the LHC [4]. For the

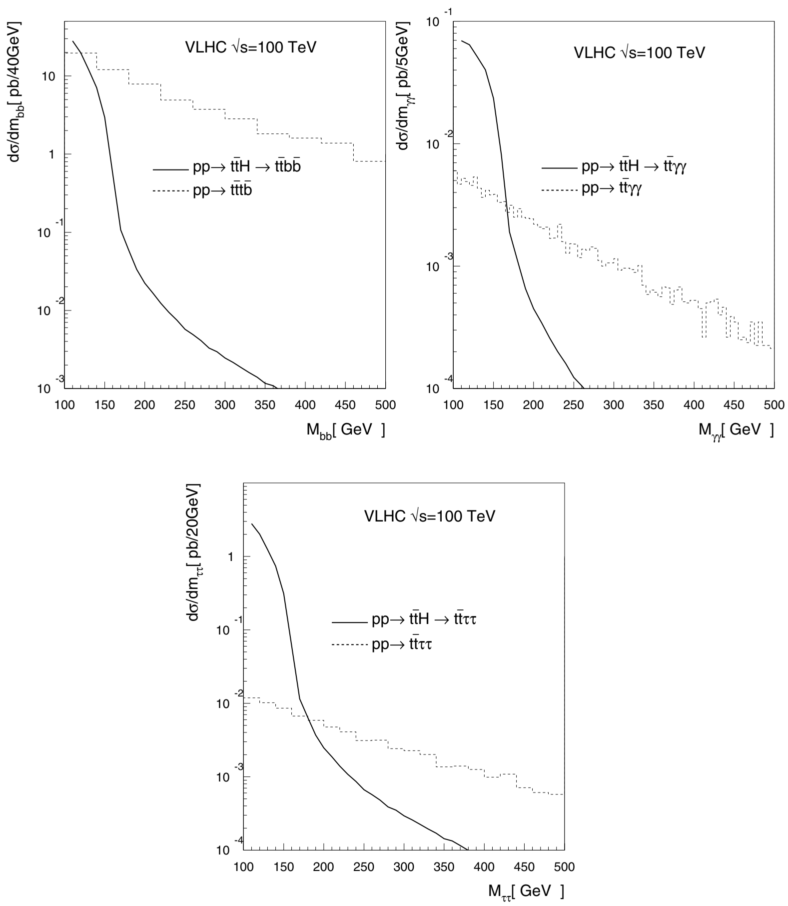

Figure 3: Cross sections for both signal (solid line) and irreducible background (dashed histogram) for the three signatures $t\bar{t}XX$ for $X = b, \gamma, \tau$, as functions of the invariant mass M_{XX} of the XX pair, at a VLHC with $\sqrt{s} = 100$ TeV. The background cross sections are plotted in M_{XX} bins of 40, 5, and 20 GeV, respectively. To simulate the detector acceptance we require $p_T > 25$ GeV and $|\eta| < 3$.

leading decay channel $h_{SM} \to b\bar{b}$ the QCD background is comparable to the signal, while for the $h_{SM} \to \gamma\gamma$ and $h_{SM} \to \tau^+\tau^-$ decay channels the background is small, if not negligible. However, for these last two channels, the advantage of a VLHC over the LHC is manifest. Already with 100 fb^{-1} of integrated luminosity, at a VLHC with $\sqrt{s} = 100$ TeV, the number of signal events is increased by about a factor of 50–100 (for $M_{h_{SM}} = 100$–200 GeV) with respect to the LHC, therefore allowing studies that are statistically limited at the LHC. Even for the $h_{SM} \to b\bar{b}$ decay channel, assuming that efficiencies similar to those at the LHC could be attained, the significance of the signal (directly related to the accuracy with which the top Yukawa coupling can be measured)

[1] Even though we do not include in this study other decay modes, such as, for instance, $h_{SM} \to WW, ZZ$, they are potentially interesting and more detailed analysis are in progress.

would be increased by a factor $\simeq \sqrt{50}$. The statistics for both signal and background roughly doubles at $\sqrt{s} = 200$ TeV. A first estimate of the precision with which the SM top-quark Yukawa

Table I Number of signal events for $t\bar{t}h_{SM}$, $M_{h_{SM}} = 130$ GeV, and irreducible $t\bar{t}XX$ background events with $X = b, \gamma, \tau$, at a VLHC with $\sqrt{s} = 100$ TeV and integrated luminosity of 100 fb^{-1}. Same conventions as in Figure 3. In the total number of events the branching ratios for $h_{SM} \to XX$ with $X = b, \gamma, \tau$ are included. In the second line the top-quark and τ branching ratio into final states are included. Detector and reconstruction efficiencies are estimated from LHC studies (e.g., [4]) and inserted in the third line. In the last line the expected precision on the extraction of the Yukawa coupling of the SM Higgs boson to the top quark is given.

	$b\bar{b}$		$\gamma\gamma$		$\tau^+\tau^-$	
	S	B	S	B	S	B
# events	$1.2 \cdot 10^6$	$2.4 \cdot 10^6$	$3.8 \cdot 10^3$	$5.7 \cdot 10^2$	$9.0 \cdot 10^4$	$1.2 \cdot 10^3$
w/BR's	$1.8 \cdot 10^5$	$3.6 \cdot 10^5$	$5.7 \cdot 10^2$	86	$5.5 \cdot 10^3$	74
w/efficiencies	$3.4 \cdot 10^3$	$6.7 \cdot 10^3$	60	9	$2.1 \cdot 10^2$	3
S/B	0.5		6		70	
$\delta y_t/y_t$ (%)	1.5		7		3.5	

coupling could be measured at a VLHC is given in Table I, for $\sqrt{s} = 100$ TeV and $M_{h_{SM}} = 130$ GeV. In our analysis we assume 100 fb^{-1} of total integrated luminosity, corresponding to roughly one year of running of a VLHC with luminosity $\mathcal{L} = 10^{34}$ cm^{-2}s^{-1}. In analogy with similar studies performed for the LHC [4, 13, 14], we consider a sample where one top quark decays leptonically, in order to have an unambiguous lepton tag, and the other top decays hadronically. We apply a $t\bar{t}$ pair reconstruction efficiency $\epsilon_{t\bar{t}} = 0.15$. We also use a b tagging efficiency $\epsilon_b = 0.6$, a τ tagging efficiency $\epsilon_\tau = 0.6$, and a photon identification efficiency $\epsilon_\gamma = 0.9$. Moreover, in order to account for the efficiency of the invariant mass finite cut imposed by the binning procedure, we multiply the results for the $t\bar{t}b\bar{b}$ and $t\bar{t}\tau^+\tau^-$ signatures by $\epsilon_{mc}^{b,\tau} = 0.7$, and the results for the $t\bar{t}\gamma\gamma$ signature by $\epsilon_{mc}^{\gamma} = 0.9$. The $t\bar{t}b\bar{b}$ signature is further reduced by a factor $\epsilon_{\mathrm{comb}} = 0.5$, to take into account the combinatorics due to the four b quarks in the final state. Finally, we only consider the $t\bar{t}\tau^+\tau^-$ signature where the τ's decay hadronically and we therefore multiply by $\mathrm{Br}(\tau \to \mathrm{hadrons}) = 0.63$ for each τ lepton in the final state [2].

As a result, the statistical error on the top Yukawa coupling measurement for a SM Higgs boson with mass 130 GeV is at the percentage level for both the $t\bar{t}b\bar{b}$ and $t\bar{t}\tau^+\tau^-$ signatures, while for the $t\bar{t}\gamma\gamma$ signature it is a bit lower than 10%. In general, for Higgs boson masses up to 150 GeV all three signatures allow a measurement of the top Yukawa coupling with precisions better than 10%. As we said early on, these estimates are obtained assuming that all other Higgs boson couplings entering our analysis have been determined with good precision. We note that the level of precision obtained is comparable with the precision that could be attained at a high energy Linear Collider, running at the optimal center of mass energy of $\sqrt{s} = 800$ GeV, when 10^3 fb^{-1} of integrated luminosity are used [2, 6]. On the other hand, our results are obtained using a quite low integrated luminosity, 10^2 fb^{-1}, and could therefore be further improved by more available statistics.

Finally, it is worth having a quick look at $t\bar{t}\mathcal{H}$ production in the MSSM (for $\mathcal{H} = h^0, H^0, A^0$). For the MSSM scenario we assume some "typical" set of parameters: $\tan\beta = 40$, $m_{\tilde{q}} = 500$ GeV, $\mu = 300$ GeV, $A_t = A_b = A$ with $A = \mu/\tan\beta + \sqrt{6}m_{\tilde{q}}$, according to the "maximal mixing" scenario where loop corrections maximize the light Higgs boson mass. The total cross sections for the signal $t\bar{t}\mathcal{H}$ as well as the total cross sections multiplied by the branching ratios for

[2] In a more complete analysis other data samples should be added to this channel. For instance, the case where one τ decays leptonically, providing the lepton tag, and both the top quarks decay hadronically has a comparable rate.

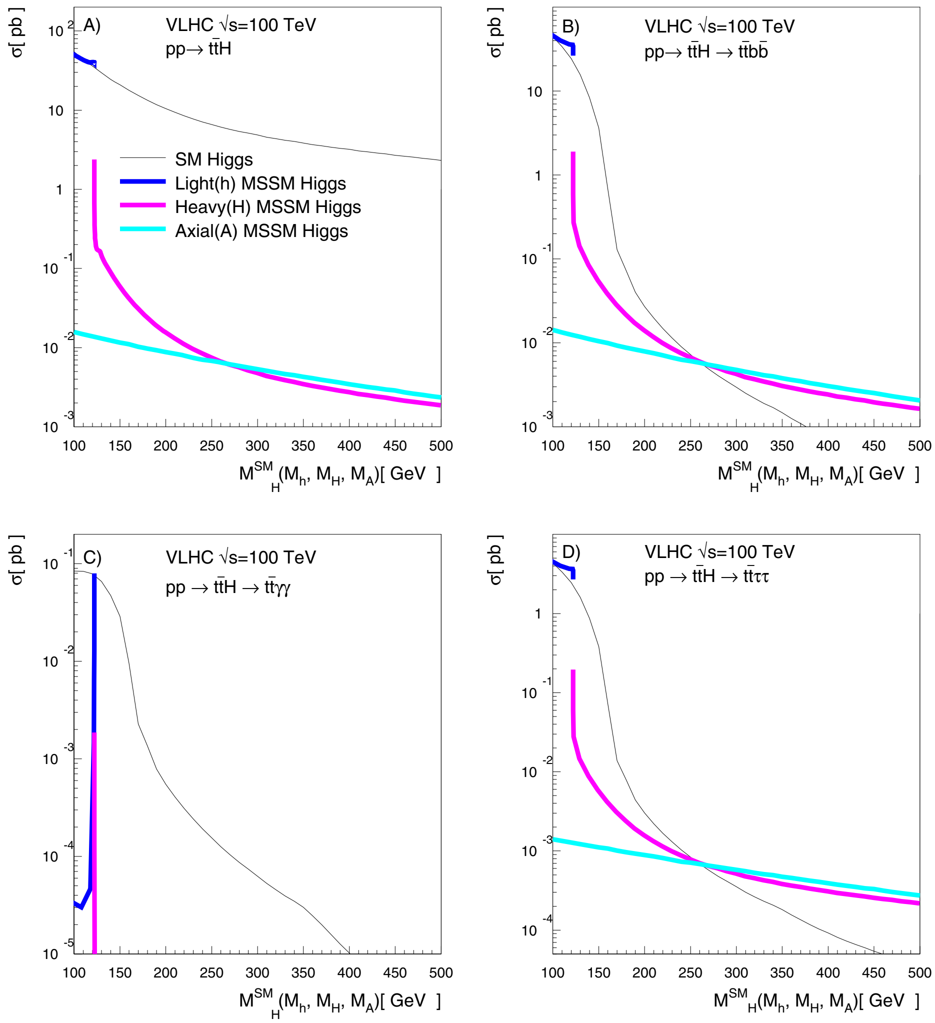

Figure 4: Cross sections for $t\bar{t}h_{SM}$ (thin solid line) and $t\bar{t}\mathcal{H}$ ($\mathcal{H} = h^0, H^0$ and A^0) production (thick black, dark-grey and light-grey lines), at a VLHC with $\sqrt{s} = 100$ TeV: A) total cross sections; B)-D) cross sections times branching ratios for $\mathcal{H} \to b\bar{b}, \gamma\gamma, \tau^+\tau^-$ respectively.

$\mathcal{H} \to b\bar{b}, \gamma\gamma, \tau^+\tau^-$ are presented in Figure 4.

The cross sections for $t\bar{t}h^0$ and $t\bar{t}h_{SM}$ are close to each other in the narrow, but crucial, region up to $M_{\mathcal{H}} = 120$ GeV or slightly above that. However, we note that, when the branching ratios are included, both the $t\bar{t}b\bar{b}$ and $t\bar{t}\tau^+\tau^-$ MSSM signatures for h^0 are 30–40% higher than the corresponding SM signatures. Above 120 GeV only the $t\bar{t}H^0$ and $t\bar{t}A^0$ associated production can take place. The $t\bar{t}H^0$ signal is suppressed by a factor of $\cos\beta^2$ compared to the corresponding SM signal. It is similar to the light Higgs boson (h^0) signal only in the small region around 120 GeV, where all three MSSM Higgs bosons are degenerate in mass. For $M_{\mathcal{H}} > 120$ GeV the $t\bar{t}H^0$ cross section drops rapidly and becomes comparable to the $t\bar{t}A^0$ cross section for Higgs boson masses above 200 GeV. The cross sections for both $t\bar{t}H^0$ and $t\bar{t}A^0$ above 120 GeV are 2–3 orders of magnitude below the SM cross section. However, when we take into account the corresponding Higgs boson decay branching ratios, the situation can be very different. For instance, when $\mathcal{H} \to \tau^+\tau^-$, the MSSM cross sections start dominate the SM one over the entire mass region $M_{\mathcal{H}} > 200$ GeV. This happens because the MSSM $\mathcal{H} \to \tau^+\tau^-$ branching ratio is significant over the entire Higgs boson mass region for high $\tan\beta$. With this respect, the $t\bar{t}\tau^+\tau^-$ supersymmetric signature (summed over the $t\bar{t}A^0$ and $t\bar{t}H^0$ channels) could be interesting in the high MSSM Higgs boson mass range ($M_{\mathcal{H}} \geq 200$ GeV). Since however, even at a VLHC, this channel appears to be statistically limited, it will require a large integrated luminosity. We note that the MSSM $t\bar{t}b\bar{b}$

signature also dominates over the SM one for large Higgs masses, but in this case, contrary to $t\bar{t}\tau^+\tau^-$, the background is overwhelming.

4. Conclusions

In this note we have studied the precision with which the top-quark Yukawa coupling could be determined at a pp VLHC through the measurement of the cross section for the process $pp \to t\bar{t}\mathcal{H}$, with the Higgs boson subsequently decaying into $b\bar{b}$, $\gamma\gamma$, and $\tau^+\tau^-$. We have mainly focused on a SM like Higgs boson, but have also looked at some interesting MSSM signatures, for both light and heavy Higgs bosons. The results show that all the three Higgs boson decay channels could provide a determination of the top-quark Yukawa coupling at the few percent level, over a large range of Higgs boson masses. In particular, the $\gamma\gamma$ and $\tau^+\tau^-$ channels, which will be statistically limited at the LHC, are at the VLHC particularly clean and already significant with just 100 fb^{-1} of integrated luminosity.

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