VLHC Predictions for $H \to \tau\tau$ in Weak Boson Fusion

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Higgs production in weak boson fusion with subsequent decay $H \to \tau\tau \to e\mu \not{p}_T$ provides a means to measure Higgs Yukawa couplings and Higgs interactions to weak bosons. The potential precision of cross section measurements at a VLHC is investigated.

Precision measurements of Higgs boson properties are an important goal of any post-LHC accelerator. The LHC is expected to yield a determination of the Higgs boson mass at the 10^{-3} level [1, 2]. A combination of observations of the Higgs boson, in various decay channels ($H \to \gamma\gamma,\ WW,\ ZZ,\ \tau\tau$), in inclusive searches and in the weak boson fusion (WBF) channel, is expected to yield measurements of various Higgs partial widths with accuracies of order 10–20% [3]. A linear collider (LC) can improve these measurements by up to one order of magnitude, achieving a clean separation of individual couplings [4].

In contrast, very little is known about the capabilities of a higher energy hadron collider for improving our knowledge of the Higgs sector. In this note we analyze a particular weak boson fusion process, $qq \to qqH$, $H \to \tau\tau$ with subsequent leptonic tau decays, within the SM, as a case study for possible VLHC reach in precision measurements of Higgs couplings. Unlike gluon fusion, WBF has small NLO QCD corrections, thus promising small systematic uncertainties. Second, the $H \to \tau\tau$ decay modes [5] are key processes in the coupling determination at the LHC. We closely follow this previous LHC analysis and determine signal rates and cross sections for the main physics backgrounds in pp collisions at $E_{\rm cm} = 50$, 100, and 200 TeV. These cross sections allow for a first estimate of the statistical accuracy of coupling measurements at a VLHC.

The signal process is $qq \to qqH$, which is mediated by t-channel W and Z exchange. We consider $H \to \tau\tau$ decays with subsequent leptonic decays of both taus, i.e. the final state is $jj\ell^+\ell'^- \not{p}_T$ where, for simplicity, we only consider the $e^\pm\mu^\mp$ combinations.In a previous LHC analysis [5] it was found that the physics backgrounds, Zjj production with $Z \to \tau^+\tau^-$, dominate overall backgrounds. Reducible backgrounds are mostly from leptonic decays of W pairs, e.g. from top-decays or $WWjj$ events. These can be distinguished from tau pairs by the angular correlation of charged lepton momenta and the missing momentum vector. Thus, we only consider QCD Zjj and electroweak Zjj production, i.e. $\tau^+\tau^-jj$ production at order $\alpha_s^2\alpha^2$ and α^4, respectively. These backgrounds and the signal are generated as in Ref. [5] and include off-shell Z's and photon-Z interference.

As compared to the LHC analysis we impose a higher p_T of the two forward "tagging jets" and a larger dijet invariant mass of these two candidate quark jets. Specifically the signal is required to have two jets and two charged leptons with

$$\begin{gathered} p_{T_j} \geq 30 \text{ GeV}, \quad |\eta_j| \leq 5.0, \quad \triangle R_{jj} \geq 0.6, \\ p_{T\ell_1} \geq 20 \text{ GeV}, \quad p_{T\ell_2} \geq 10 \text{ GeV}, \quad |\eta_\ell| \leq 3, \quad \triangle R_{j\ell} \geq 0.6, \end{gathered} \tag{1}$$

the two jets must be separated by at least 4.2 units of pseudorapidity, reside in opposite detector hemispheres and the two charged leptons must lie between the two jet definition cones of radius 0.6. The neutrinos must lead to missing transverse momentum of 50 GeV or more and we require

$$M_{jj} > 1000 \text{ GeV} \tag{2}$$

for the invariant mass of the two tagging jets. All other cuts are as in Ref. [5].

The surviving $e\mu\not{p}_T + 2$ jet events allow a reconstruction of the original tau-pair invariant mass by making use of the large boost of the individual taus and their decay products [6]: the charged leptons trace the original tau directions and the transverse momenta of e, μ and missing neutrinos allow to solve for the τ^+ and τ^- energies. The reconstruction relies on good missing transverse momentum resolution. We assume a performance of VLHC detectors equivalent to ATLAS, i.e.

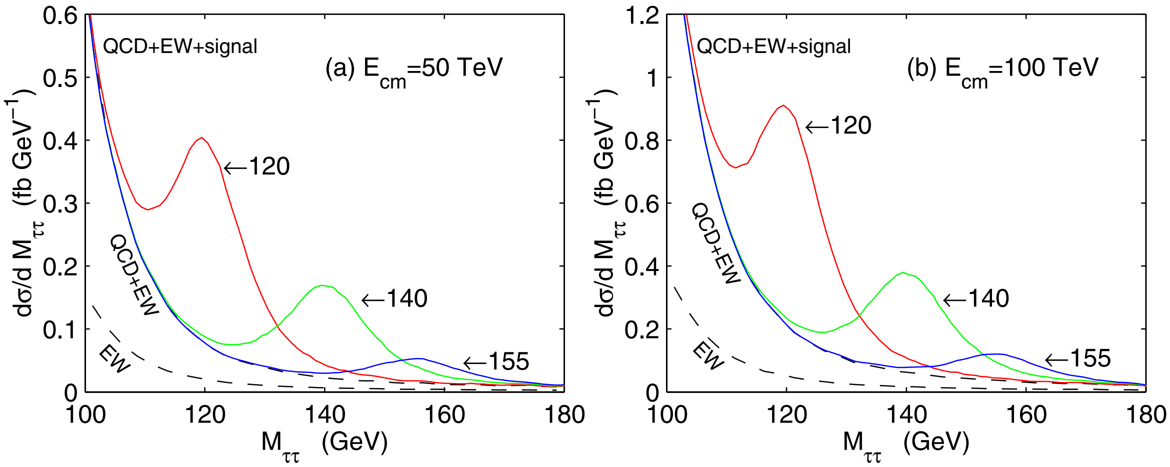

Figure 1: Reconstructed tau-pair invariant mass distribution at a VLHC of (a) 50 TeV and (b) 100 TeV center of mass energy. Signal peaks for $m_H = 120$, 140, and 155 GeV are added to the combined physics backgrounds from electroweak and QCD $\tau\tau jj$ production. See text for cuts.

energy smearing and $\not{p}_T$ resolution is handled as in Ref. [5] and reproduces ATLAS simulations for $H/A \to \tau\tau$ events [7].

The resulting reconstructed $M_{\tau\tau}$-spectra are shown in Figure 1 for VLHC energies of 50 and 100 TeV. The Higgs peak is clearly visible above the physics backgrounds, even for Higgs masses as large as 155 GeV. The statistical significance of the signal can be estimated by considering the signal and background rates in a reasonable mass window, which we take as $m_H - 15$ GeV $< M_{\tau\tau} < m_H + 15$ GeV.

Resulting cross sections are given in Table I. It is quite remarkable that we may expect signal to background ratios well above 1 over the entire intermediate mass range. This is combined with large signal rates, of order hundreds to a thousand, for an integrated luminosity of 100 fb^{-1}. Given the expected number of signal events, S, and background events, B, we can estimate the statistical error with which the signal cross section can be estimated as $\Delta\sigma_H/\sigma_H = \sqrt{S+B}/S$. The corresponding statistical errors are listed in the last column of Table I and reside in the 5–10% range for a 50 TeV machine and Higgs masses between 120 and 150 GeV, and improve to the 3–6% range for a 200 TeV machine.

The numbers presented in the left half of Table I do not include efficiency factors for jets or for lepton identification and isolation. In previous studies these factors amounted to overall efficiency factors of 0.67 for signal and backgrounds [5]. (Note that geometric acceptance is included in our simulation.) Other reduction factors for the signal will arise from parton shower corrections: including QCD radiation, the selection of the 2 quark jets is not unique. Misidentified tagging jets then tend to fall below the M_{jj} threshold of Eq. (2). Since QCD radiation is relatively suppressed for the t-channel color singlet exchange of the signal, this effect is modest [8] and we may assume an overall efficiency of $\epsilon_{\rm WBF} = 0.5$ for WBF processes compared to $\epsilon = 0.67$ for the QCD Zjj background.

The cross sections of Table I do not yet make use of another characteristic of WBF events: they are mediated by the t-channel exchange of a colorless object. Destructive interference between initial and final state radiation in such processes leads to suppressed gluon radiation in the central region, between the two quark jets [9]. QCD background processes, which are dominated by t-channel gluon exchange, predominantly radiate in the central region. This difference can be exploited by a veto on central jets, in the region

$$\eta^{\rm tag}_{j,min} + 0.6 < \eta^{\rm veto}_j < \eta^{\rm tag}_{j,max} - 0.6\,. \qquad (3)$$

A detailed study on feasible p_T thresholds at a VLHC is still needed. For the LHC, an parton level analysis indicates that a veto of central jets of $p_T > 20$ GeV will suppress the signal by a factor $P_{\rm surv} = 0.9$, while analogous factors for the EW and the QCD Zjj backgrounds are 0.75 and 0.3, respectively [10]. Due to the increased M_{jj} values and the larger rapidity distance between the quark jets of the signal, these numbers may improve at a VLHC. However, higher p_T thresholds of

Table I Signal and background cross sections (in fb) for $qq \to qqH$, $H \to \tau\tau \to e\mu \not{p}_T$ events at a VLHC of center of mass energy 50, 100, and 200 TeV, for SM Higgs masses between 120 and 160 GeV. The S/B and $\sqrt{S+B}/S$ columns give signal to background ratios and statistical errors for a determination of the signal cross section with 100 fb^{-1} of data. The first two columns give these estimates without taking into account reconstruction efficiencies or a central jet veto. The second set uses LHC inspired assumptions for ε and $P_{\rm surv}$. See text for details.

$E_{\rm cm}$	m_H	Signal	QCD $\tau\tau jj$	EW $\tau\tau jj$	QCD + EW $\tau\tau jj$	S/B ($L = 100$ fb^{-1}, $\varepsilon \equiv 1$)	$\sqrt{S+B}/S$ ($L = 100$ fb^{-1}, $\varepsilon \equiv 1$)	S/B ($L = 100$ fb^{-1}, $\varepsilon = \varepsilon_{\rm LHC}$)	$\sqrt{S+B}/S$ ($L = 100$ fb^{-1}, $\varepsilon = \varepsilon_{\rm LHC}$)
50 TeV	120	4.98	2.48	0.83	3.31	1.50	5.8%	2.76	7.8%
	130	3.86	1.04	0.38	1.42	2.72	6.0%	4.95	8.3%
	140	2.48	0.56	0.22	0.78	3.17	7.3%	5.70	10.3%
	150	1.23	0.36	0.16	0.52	2.38	10.7%	4.22	14.9%
	155	0.70	0.31	0.14	0.44	1.59	15.3%	2.81	20.7%
	160	0.23	0.27	0.12	0.39	0.59	34%	1.04	44%
100 TeV	120	10.67	6.84	2.07	8.91	1.20	4.1%	2.23	5.5%
	130	8.32	2.94	0.95	3.89	2.14	4.2%	3.96	5.8%
	140	5.37	1.57	0.55	2.12	2.53	5.1%	4.63	7.1%
	150	2.66	1.00	0.38	1.38	1.93	7.6%	3.49	10.4%
	155	1.51	0.84	0.33	1.17	1.29	10.8%	2.33	14.5%
	160	0.49	0.71	0.29	1.00	0.49	25%	0.87	31%
200 TeV	120	20.6	16.9	4.43	21.3	0.96	3.1%	1.83	4.1%
	130	16.1	7.35	2.04	9.38	1.71	3.1%	3.23	4.3%
	140	10.4	3.98	1.19	5.17	2.01	3.8%	3.75	5.2%
	150	5.16	2.55	0.81	3.36	1.54	5.7%	2.84	7.6%
	155	2.92	2.14	0.70	2.84	1.03	8.2%	1.90	10.8%
	160	0.95	1.83	0.62	2.45	0.39	19.4%	0.71	23.7%

vetoed jets will counteract such improvements. We take the LHC values as an educated guess for a VLHC as well. Including these efficiency factors and survival probabilities, signal and background rates are given in the right half of Table I. Signal to background rates improve further, due to the background suppression of the central jet veto. However, the statistical accuracy of the cross section determination suffers somewhat, due to the more realistic assumptions on reconstruction efficiencies. Nevertheless, statistical errors of 5% or better are possible at a VLHC with a mere 100 fb^{-1} of data. This can be improved significantly by including other tau decay channels like hadronic decays of one tau and leptonic decays into $e^+e^-\not{p}_T$, $\mu^+\mu^-\not{p}_T$ [3, 5].

A point of concern are Higgs backgrounds. $H \to WW \to e\mu\not{p}_T$ events become the dominant reducible WW background for Higgs masses above 125 GeV at the LHC, and contribute about a third of the overall background at $m_H = 150$ GeV [5]. The same should be expected at a VLHC. In addition, gluon fusion becomes a more pronounced source of Hjj events at the higher VLHC energies [11], and thus the clean separation of gluon fusion and WBF cross sections will require additional efforts. However, we do not expect these complications to significantly alter the previous optimistic findings.

We conclude that a VLHC can study $H \to \tau\tau$ decays with high precision in WBF events. Integrated luminosities of a few hundred fb^{-1} provide high statistics and clean samples which allow to measure $H\tau\tau$ Yukawa couplings with statistical errors at the 10^{-2} level. At the same time the small QCD NLO corrections to WBF promise small systematic errors. Detailed studies of WBF channels at a VLHC are required to assess experimental systematic errors.

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