

Constraining Absolute Higgs Couplings using Vector Boson Fusion $H \rightarrow WW$ with FCC-hh

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Abstract

The absolute normalization scale of Higgs couplings is difficult to determine in hadron colliders. A experimentally and theoretically clean way to establish the coupling scale is measure the ratio of resonant Vector Boson Fusion $h \rightarrow WW^*$ production to non-resonant $qq \rightarrow qqWW$, because both the theoretical and detector response systematics all cancel to first order in the ratio. To set the scale of the scale of the sensitivity, a simple selection and fit is presented with gives a 1.8% statistical uncertainty on the ratio.

1 Introduction

Hadron colliders can produce large sample of Higgs bosons, their precision is limited by our knowledge of several factors: PDF and luminosity uncertainties, calculational challenges of QCD, detector simulation, and background estimation. For example reference [1] shows statistical power to measure Higgs couplings at FCC-hh of order 0.5% for several couplings, but systematic limitations limit the precision to the 1.5-2% range. This can be mitigated by using ratios where some of these uncertainties cancel. These ratios then limit ratios of Higgs-couplings, but leave the absolute scale of the couplings unconstrained. In some models, for example a singlet mixing with the Higgs, can lead to an overall suppression of Higgs couplings without modifying the ratios of couplings [2, 3].

There are ratios that can be taken between Higgs and other electroweak processes that provide absolute normalizations. Reference [4] presents ratios involved associated Higgs production WH to electroweak diboson production WZ . The ratio Vector Boson Fusion (VBF) production of Higgs to $WW \rightarrow e\nu\mu\nu$ over non-resonant VBF $qq \rightarrow WW \rightarrow e\nu\mu\nu$ provides an exceptionally clean example, because the protons are

coupling to vector boson with similar kinematics in both cases. The only differences are in mass scale and spin of the produced system. Furthermore the final state is identical except of the orientations and moderate differences in energy scale of the observed particles. The combination of these means that the PDF, luminosity, QCD, and detector simulation uncertainties should cancel to a high degree; leaving the statistical and background estimation uncertainties likely to be dominant. The different-flavor, $e\nu\mu\nu$, final state is selected to avoid large Drell-Yan background. This note presents a simple estimation of the background level and statistical power of such a measurement.

2 Samples

Madgraph [5] is used to simulate proton-proton collisions at 84 TeV and 100 TeV. Two signal processes are simulated VBF WW production via an s-channel Higgs boson and VBF WW production excluding diagrams with the Higgs boson, both with the W pair decaying fully leptonically. The two main backgrounds to the this process are $t\bar{t}$ where both W s in the top-quark decays decay leptonically, and $Z \rightarrow \tau\tau$ where the τ leptons decay to e or μ leptons. Pythia [6] is used to simulate the parton shower and DELPHES [7] with the FCC-hh scenario II card [8] is used to simulate the detector response. The processes shown in Figures 1a, 1b, and 1c are all generated in one sample requiring $pp \rightarrow jj\ell\nu\ell\nu$ with an s-channel Higgs Boson. The on-shell Higgs part is then separated based on the generated parton-level 4-lepton mass. The sample is normalized so that the produced rate in the 4-lepton mass peak is the 69 pb^{-1} on-shell VBF Higgs production cross-section calculated at NNLO-QCD and NLO-EWK[9]. The processes in Figures 1d and 1e are generated as $pp \rightarrow jj\ell\nu\ell\nu$ with QED=6 and with no Higgs or top in the diagrams. This means that the t -channel diagram and the interference of the two Higgs and Z process is not included which would have some effect, but not substantial compared to the level of precision presented. The $Z \rightarrow \tau\tau$ samples are generated with two jets above 80 GeV are normalize to the NNLO calculation of the cross-section using the NNPDF3.0 NNLO pdf [10].

3 Event Selection

The event selection uses a small set of standard VBF selection and top background suppression requirements to select for both Higgs to $WW \rightarrow e\nu\mu\nu$ and non-resonant VBF $qq \rightarrow WW \rightarrow e\nu\mu\nu$, specifically focusing on the final state with different lepton flavors to avoid Drell-Yan background with mismeasured missing transverse energy ($\cancel{E}_T$). The selection requires to two jets with $p_T > 100 \text{ GeV}$ and no additional jets with $p_T > 30 \text{ GeV}$, which acts as simple central-jet veto for the VBF signature. The two jets are required not to pass the loose b -tagging requirements to suppress $t\bar{t}$. To suppress non-VBF processes, the two jets are required to have $\Delta\eta_{jj} > 5.0$ and $m_{jj} > 2 \text{ TeV}$. Finally to further suppress $Z \rightarrow \tau\tau$, a estimate of for the Z mass is constructed by decomposing the 2-d MET vector along the directions of two leptons an plotting the resulting mass.

The resulting yields for 100 TeV and 84 TeV are shown in Figure 1. Figure 2 shows the m_{jj} and $\Delta\eta_{jj}$ distributions before the final requirements on those two variables. Figure 3 shows distributions of the final sample for Transverse mass of the $e\mu\nu\nu$ system

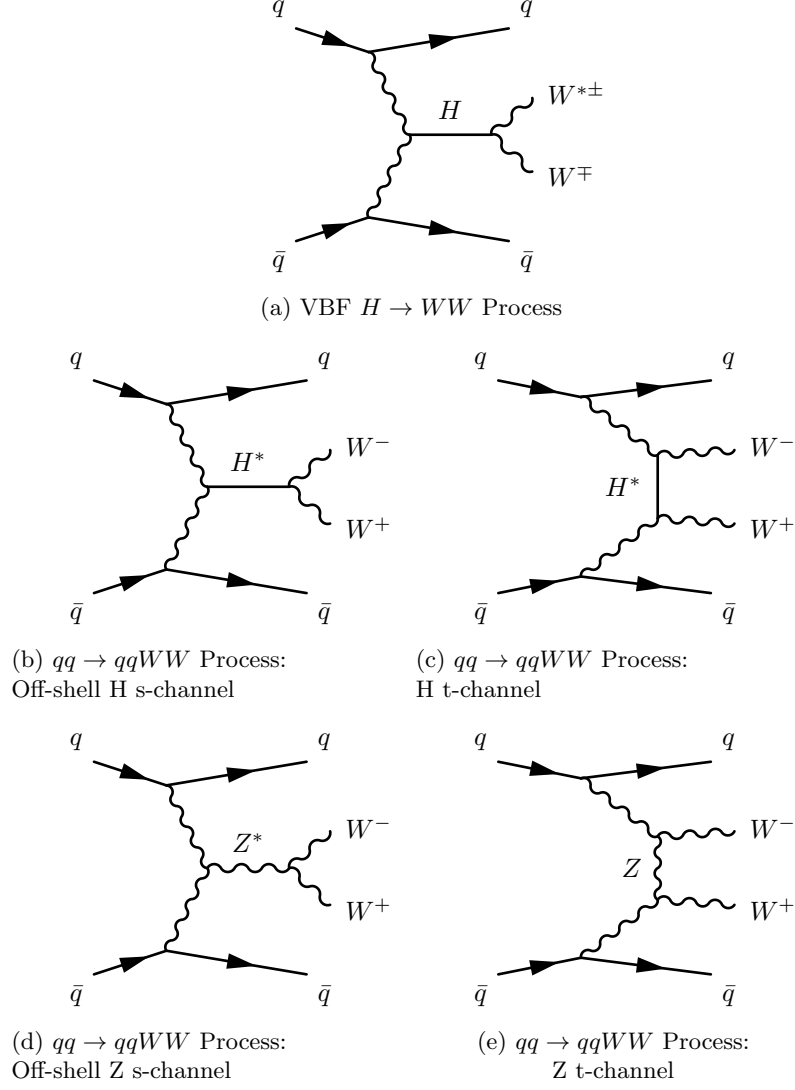


Fig. 1: Main diagrams contributing to Vector Boson Fusion production of $WW^{(*)}$

(m_T) , ϕ between the two leptons, ϕ between the two jets, and the subleading jet p_T . The m_T is calculated as

$$m_T = \sqrt{2m_{e\mu}^2 + 2 \left(\sqrt{m_{e\mu}^2 + p_{T,e\mu}^2} \sqrt{m_{e\mu}^2 + E_T^2} - \vec{p}_{T,e\mu} \cdot \vec{E}_T \right)} \quad (1)$$

Table 1: Yields for the simulated 100 TeV sample and scaled to 84 TeV cross-sections assuming the same 30 ab^{-1} integrated luminosity.

Process	Yield for 30 ab^{-1}	
	100 TeV	scaled to 84 TeV
Resonant VBF $h \rightarrow WW^*$	23000 ± 600	
Non-resonant VBF $qq \rightarrow qqWW$	170000 ± 13000	
Gluon Fusion $h \rightarrow WW^*$	4000 ± 1000	
$t\bar{t}$	75000 ± 19000	
$Z \rightarrow \tau\tau$	13000 ± 8000	

which corresponds to ignoring the unmeasured components parallel to the beam and assuming the mass of the neutrino system is the same as the mass of the lepton system, which is valid in the limit that the W and W^* are at rest in the Higgs frame. Figure 3a shows a clear resonant peak just below the 125 GeV Higgs mass with a long tail to high m_T due to the non-resonant Higgs processes (Figure 1b). Figure 3c shows the classic preference for small $\Delta\phi_{e\mu}$ values due to the spin correlations of the W and W^* in the $H \rightarrow WW$ process. There also an enhancement at large $\Delta\phi_{e\mu}$ which is correlated with the large m_T (non-resonant Higgs) region).

4 Fitting Results

The m_T distribution of the selected sample is then fit for the fractions of Higgs to $WW \rightarrow e\nu\mu\nu$ and non-resonant VBF $qq \rightarrow WW \rightarrow e\nu\mu\nu$. To exploit that the resonant Higgs signal is primarily at low $\Delta\phi_{e\mu}$ and m_{em} , and high $p_{T,e\mu}$ due to the scalar nature of the Higgs boson, the sample is divide into a Higgs-like and non-Higgs-likes signal regions for fitting. The Higgs-like signal region (SR1) requires $\Delta\phi_{e\mu} < 0.8$ and $m_{e\mu} < 50 \text{ GeV}$, and high $p_{T,e\mu} > 60 \text{ GeV}$. The non-Higgs-like SR is the remainder of the selected events.

A mock data sample is constructed by summing all the modeled contributions and Gaussian fluctuating them. A fit is then performed for the fraction of each contribution, holding Gluon Fusion $h \rightarrow WW^*$ and $t\bar{t}$ constant assuming that their normalizations would be constrained from control regions. If $t\bar{t}$ is allowed to float in the fit to reflect that only the shape is determined for control regions the uncertainty on the ratio increases by 5% of itself. However, it is critical that the Gluon Fusion $h \rightarrow WW^*$ is constrained as m_T and $\Delta\phi_{e\mu}$ do not distinguish it from the VBF signal. The fit setup is shown in Figure 4. The resulting expected statistical uncertainty on the ratio of resonant VBF $h \rightarrow WW^*$ to non-resonant VBF $qq \rightarrow qqWW$ is 1.8%.

5 Conclusion

A 1.8% level sensitivity to the absolute normalization of the Higgs-coupling scale is demonstrated. A more sophisticated machine-learning-based approach plus a fit that differentiates more regions that have different signal to background ratios as is often implemented for current LHC analyses would like improve upon this. Furthermore, is likely that more sophisticate reconstruction, specifically using tracking, could suppress

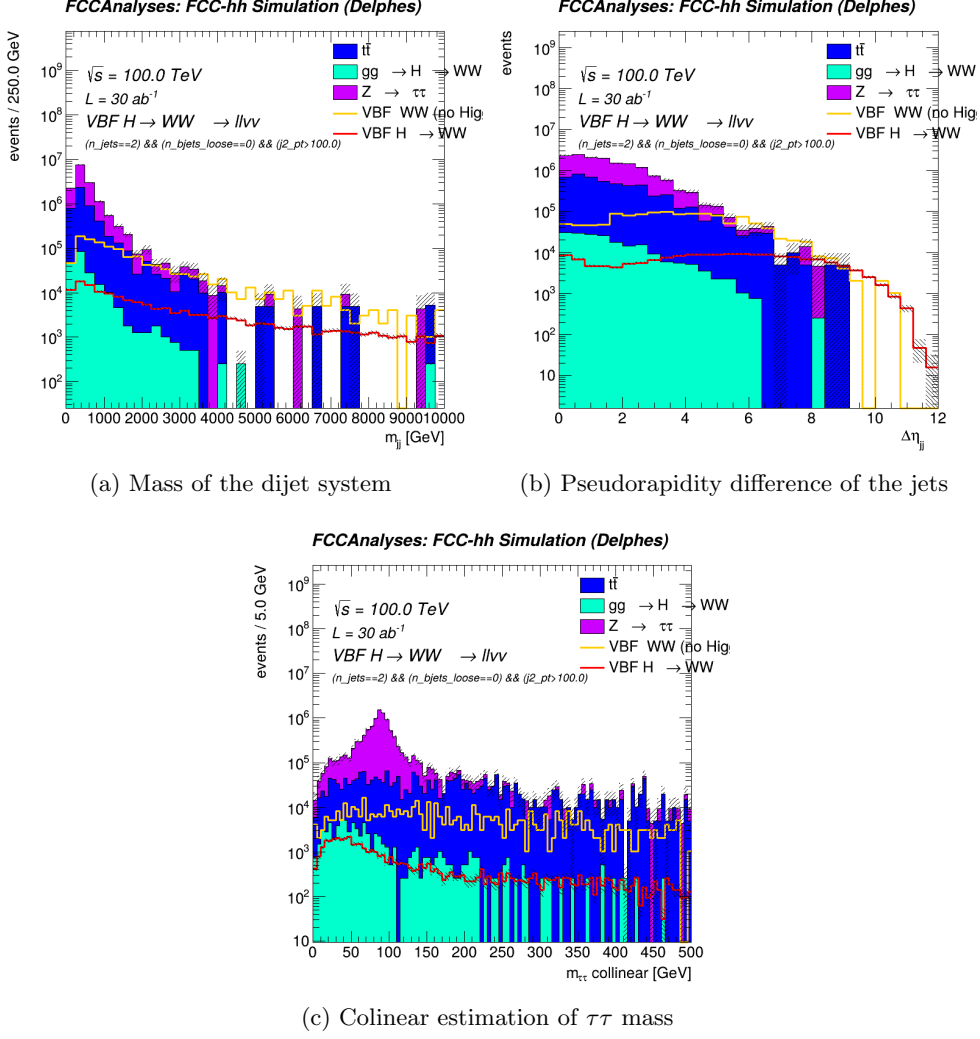


Fig. 2: Distributions after the jet p_T , jet veto, and b -jet veto

the $t\bar{t}$ background. Such improvements would probably lead the full sensitivity to be in the 1-2% range.

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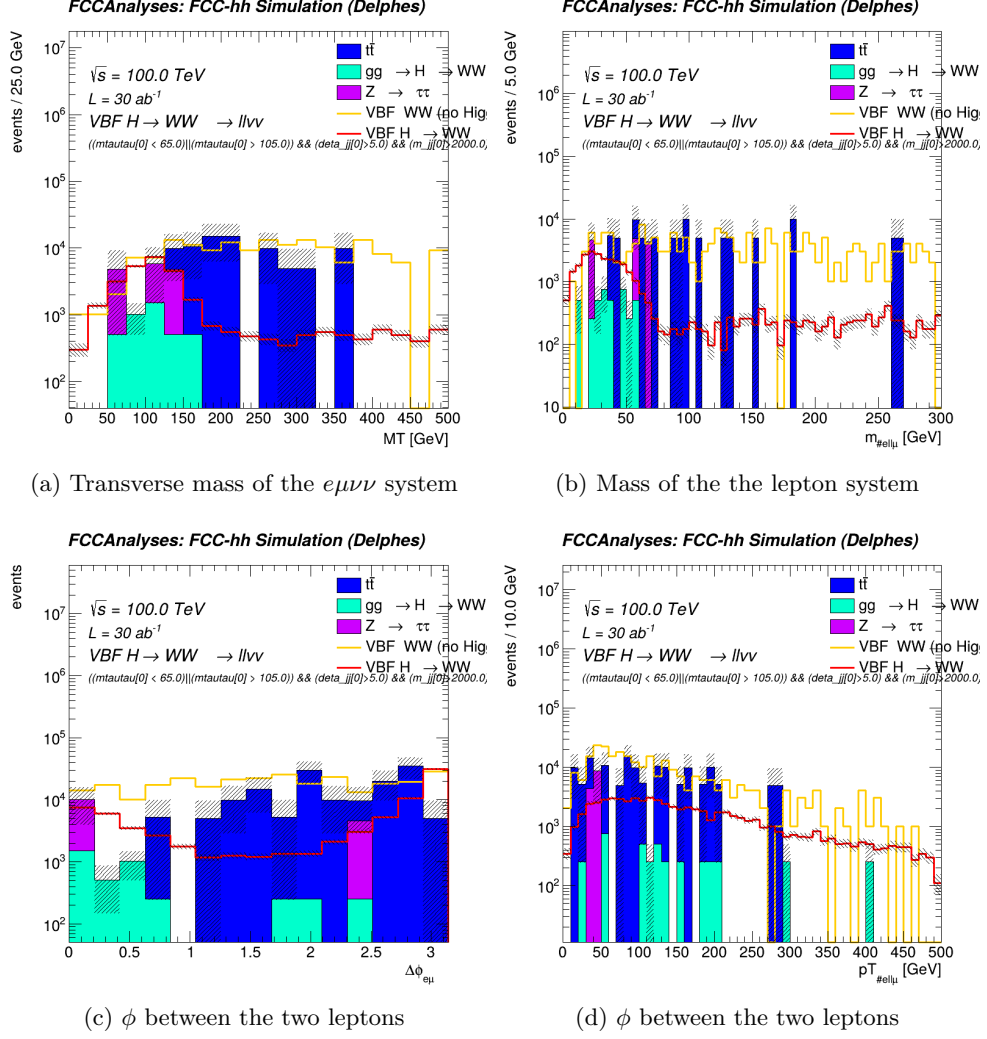


Fig. 3: Distributions after the jet p_T , jet veto, and b -jet veto

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References

- [1] A. Abada, et al., FCC Physics Opportunities: Future Circular Collider Conceptual Design Report Volume 1. Eur. Phys. J. C **79**(6), 474 (2019). <https://doi.org/10.1140/epjc/s10052-019-6904-3>

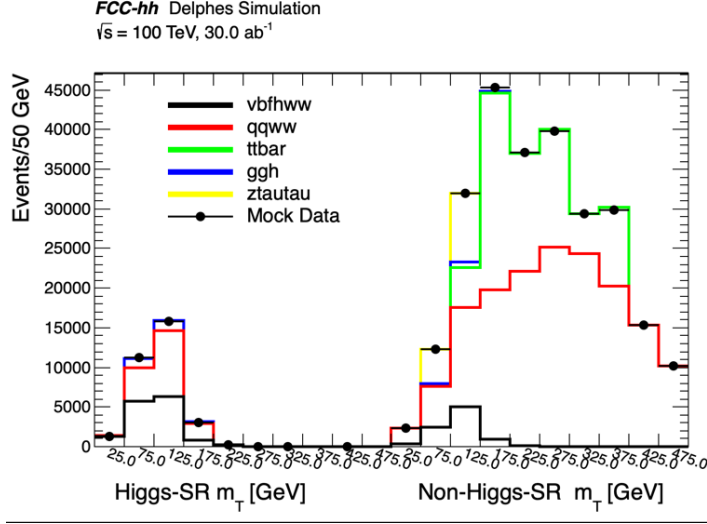


Fig. 4: Fit results to mock data with the m_T distribution split into high and low $\Delta\phi_{e\mu}$ regions.

- [2] T. Barklow, K. Fujii, S. Jung, R. Karl, J. List, T. Ogawa, M.E. Peskin, J. Tian, Improved Formalism for Precision Higgs Coupling Fits. *Phys. Rev. D* **97**(5), 053003 (2018). <https://doi.org/10.1103/PhysRevD.97.053003>. [arXiv:1708.08912](https://arxiv.org/abs/1708.08912) [hep-ph]
- [3] S. Di Vita, C. Grojean, G. Panico, M. Riembau, T. Vantalon, A global view on the Higgs self-coupling. *JHEP* **09**, 069 (2017). [https://doi.org/10.1007/JHEP09\(2017\)069](https://doi.org/10.1007/JHEP09(2017)069). [arXiv:1704.01953](https://arxiv.org/abs/1704.01953) [hep-ph]
- [4] M. Mangano, Higgs Physics Potential of FCC-hh Standalone. Tech. rep., CERN, Geneva (2019). URL <https://cds.cern.ch/record/2681378>
- [5] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H.S. Shao, T. Stelzer, P. Torrielli, M. Zaro, The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations. *JHEP* **07**, 079 (2014). [https://doi.org/10.1007/JHEP07\(2014\)079](https://doi.org/10.1007/JHEP07(2014)079). [arXiv:1405.0301](https://arxiv.org/abs/1405.0301) [hep-ph]
- [6] T. Sjöstrand, S. Ask, J.R. Christiansen, R. Corke, N. Desai, P. Ilten, S. Mrenna, S. Prestel, C.O. Rasmussen, P.Z. Skands, An introduction to PYTHIA 8.2. *Comput. Phys. Commun.* **191**, 159 (2015). <https://doi.org/10.1016/j.cpc.2015.01.024>. [arXiv:1410.3012](https://arxiv.org/abs/1410.3012) [hep-ph]
- [7] de Favereau, J. and Delaere, C. and Demin, P. and Giammanco, A. and Lemaître, V. and Mertens, A. and Selvaggi, M., DELPHES 3, A modular framework for fast simulation of a generic collider experiment. *JHEP* **02**, 057 (2014). <https://arxiv.org/abs/1302.2771>

[//doi.org/10.1007/JHEP02\(2014\)057](https://doi.org/10.1007/JHEP02(2014)057). [arXiv:1307.6346](#) [hep-ex]

- [8] M. Selvaggi, A Delphes parameterisation of the FCC-hh detector. Tech. rep., CERN, Geneva (2020). URL <https://cds.cern.ch/record/2717698>
- [9] R. Contino, et al., Physics at a 100 TeV pp collider: Higgs and EW symmetry breaking studies (2016). <https://doi.org/10.23731/CYRM-2017-003.255>. [arXiv:1606.09408](#) [hep-ph]
- [10] M.L. Mangano, et al., Physics at a 100 TeV pp Collider: Standard Model Processes (2016). <https://doi.org/10.23731/CYRM-2017-003.1>. [arXiv:1607.01831](#) [hep-ph]