Differential measurements at large Q^2 at the FCC-hh

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1 Introduction

The FCC-hh is designed to collide protons at a center-of-mass energy of 84 TeV over 25 years of operation, with two general-purpose experiments corresponding to a combined dataset of 30 ab^{-1}. Studying the potential for precision in differential measurements in the high Q^2 regime can offer a view of the physics reach of the FCC-hh that is complementary to direct searches of new physics. In this note, we document the projected precision for differential $\mathrm{t\bar{t}}$ production in the fully hadronic final state, WW production in the $\mathrm{e}\mu$ final state, and $\mathrm{t\bar{t}t\bar{t}}$ (four top) production in the fully leptonic final state. We also discuss the sensitivity for observing and measuring four top production at the FCC-hh. We show that this process can be measured with 4% precision at the FCC-hh using the very rare $\mathrm{e}^{\pm}\mathrm{e}^{\pm}\mu^{\mp}\mu^{\mp}$ decay. This final state is chosen in order to suppress the large $\mathrm{t\bar{t}Z}$ background. Further optimizations that will lead to percent-level precision and, hence, a fully differential measurement of this process are well within reach. The differential yields and corresponding statistical and systematic uncertainties are made public for a possible re-interpretation of the pseudo-data [1]. Unless indicated otherwise, the projections discussed in the following account exclusively for statistical and experimental systematic uncertainties, deliberately leaving out theoretical considerations, and the relative uncertainty on the integrated luminosity is assumed to be $\delta L/L = 1\%$.

2 Monte Carlo samples

The studies reported here have been performed using Monte Carlo simulated events using MadGraph_aMCatNLO [2, 3] and Pythia [4], and processed through the fast detector simulation package DELPHES [5]. The detector model is the baseline detector concept used for the FCC-hh physics studies, has been described in Ref. [6, 7] and its parameterization DELPHES is described in Ref. [8]. The processes used in this study, the corresponding samples, the accuracy, and the cross-sections at $\sqrt{s} = 84\,\text{TeV}$ are listed in Table 1.

Table 1 Cross sections at LO for various processes.

Process	Name	Order	Cross Section
$\text{pp} \to \text{jj}$	`mg_pp_jj_HT_200_2000_5f_84TeV`	LO	2250 μb
	`mg_pp_jj_HT_2000_100000_5f_84TeV`		2.27 nb
$\text{pp} \to \text{t}\bar{\text{t}}$	`mg_pp_tt_HT_200_2000_5f_84TeV`	LO	8.94 nb
	`mg_pp_tt_HT_2000_100000_5f_84TeV`		7.84 pb
$\text{pp} \to \text{WW}$	`mg_pp_ww_HT_200_2000_5f_84TeV`	LO	74.51 pb
	`mg_pp_ww_HT_2000_100000_5f_84TeV`		58 ab
$\text{pp} \to \text{ZZ}$	`mg_pp_zz_HT_200_2000_5f_84TeV`	LO	14.15 pb
	`mg_pp_zz_HT_2000_100000_5f_84TeV`		11.9 ab
$\text{pp} \to \tau\tau$	`mg_pp_tautau_HT_200_2000_5f_84TeV`	LO	5.88 pb
	`mg_pp_tautau_HT_2000_100000_5f_84TeV`		0.43 ab
$\text{pp} \to \ell\nu\ell\nu$ $(\ell = e, \mu, \tau)$	`mg_pp_lvlv_HT_200_2000_5f_84TeV`	LO	7.66 pb
	`mg_pp_lvlv_HT_2000_100000_5f_84TeV`		6.80 ab
$\text{pp} \to \text{WWZ}$	`mg_pp_wwz_5f_84TeV`	LO	1.20 pb
$\text{pp} \to \text{WZZ}$	`mg_pp_wzz_5f_84TeV`	LO	0.37 pb
$\text{pp} \to \text{ZZZ}$	`mg_pp_zzz_5f_84TeV`	LO	0.124 pb
$\text{pp} \to \text{WWWZ}$	`mg_pp_wwwz_5f_84TeV`	LO	14.2 ab
$\text{pp} \to \text{WWWW}$	`mg_pp_wwww_5f_84TeV`	LO	11.2 ab
$\text{pp} \to \text{WWZZ}$	`mg_pp_wwzz_5f_84TeV`	LO	9.80 ab
$\text{pp} \to \text{WZZZ}$	`mg_pp_wzzz_5f_84TeV`	LO	1.31 ab
$\text{pp} \to \text{ZZZZ}$	`mg_pp_zzzz_5f_84TeV`	LO	0.368 ab
$\text{pp} \to \text{t}\bar{\text{t}}\text{W}$	`mg_pp_ttw_5f_84TeV`	LO	5.22 pb
$\text{pp} \to \text{t}\bar{\text{t}}\text{Z}$	`mg_pp_ttz_5f_84TeV`	LO	28.15 pb
$\text{pp} \to \text{t}\bar{\text{t}}\text{WZ}$	`mg_pp_ttwz_5f_84TeV`	LO	58.61 ab
$\text{pp} \to \text{t}\bar{\text{t}}\text{WW}$	`mg_pp_ttww_5f_84TeV`	LO	0.56 pb
$\text{pp} \to \text{t}\bar{\text{t}}\text{ZZ}$	`mg_pp_ttzz_5f_84TeV`	LO	87.2ab
$\text{pp} \to \text{t}\bar{\text{t}}\text{t}\bar{\text{t}}$	`mg_pp_tttt_5f_84TeV`	LO	1.57 pb

3 WW measurement at large invariant mass

To study WW production at large Q^2 we focus on the opposite flavor final state $\text{e}^{\pm}\mu^{\mp}\nu\nu$. This final state is naturally free from the same flavor (ee, $\mu\mu$) Drell-Yan background. The dominant backgrounds are $Z^* \to \tau\tau$, with both τ leptons decaying leptonically and $t\bar{t}$ (top pair) production. Other smaller backgrounds from single top production and W+jets, where jets are misidentified as an electron or a muon, are neglected.

Events with exactly one electron and one muon, with a transverse momentum $p_T > 100$ GeV, and a pseudo-rapidity $|\eta| < 4$ are selected. The two opposite flavor leptons must be reconstructed with an opposite charge. Finally, events with one or more jets identified as b-jets with $p_T > 30$ GeV and $|\eta| < 4$ are rejected (b-jet veto). The event selection efficiency and the event yields for the signal and background processes are shown in Fig. 1. We note that the effect of the b-jet veto on $t\bar{t}$ rejection is marginal. This can be explained because leptonic $t\bar{t}$ events with a large invariant mass ($m_{e\mu} > 1$ TeV) in $t\bar{t}$ events tend to produce non-isolated leptons and are therefore already rejected when requiring two isolated leptons. We also note that the apparent inefficiency in the two opposite sign, opposite flavor lepton selection is due to the presence of τ leptons in the generated signal samples. The differential distribution of the reconstructed invariant mass of the di-lepton $e\mu$ system $m_{e\mu}$ for signal and backgrounds is shown in Figure 2 (bottom). The differential distributions of the muon p_T and the transverse missing momentum p_T^{miss} are also shown in Figure 2 (top). All these observables are (correlated) proxies for the Q^2 of the WW process, and their expected precision can be employed to set bounds on new physics that would modify these spectra in the tails.

Our estimates of systematics uncertainties on the differential WW yield are based on simple error propagation but are rather conservative, as shown in what follows. As Figure 2 shows, the expectated number of events in the large $m_{e\mu}$ regime is essentially background-free. Nevertheless, for completeness, we attribute a flat 5% uncertainty in the $Z/\gamma^* \to \tau^+\tau^-$ background normalization. The $t\bar{t}$ background is measured instead in a dedicated control region (CR), with a similar event selection as the signal but with the orthogonal requirement on the presence of a b-jet. In the low invariant mass, low p_T regime, the dominant systematics is the $t\bar{t}$ background normalization, and in particular, the uncertainty on the b-tagging efficiency, which propagates when extrapolating the $t\bar{t}$ contribution in the signal region (SR). The electron and muon identification efficiencies are the dominant systematic uncertainties in the high mass regime. Our assumptions on the magnitude of the object identification efficiency systematics are shown in Figure 5. These uncertainties originate from the finite statistics of control high p_T Drell-Yan samples at the FCC-hh.

4 Top pair at large invariant mass

As discussed in Section 3, the leptons from top decays are not isolated when produced with a large invariant mass (or a large Lorentz boost). Both leptonic and hadronic tops produce collimated top jets at sufficiently large boosts and, therefore, have to be identified with a dedicated top jet tagging algorithm. The QCD di-jet background is 3-4 orders of magnitude larger than the $t\bar{t}$ production across all the invariant mass spectrum m_{jj}. To measure $t\bar{t}$ production at large p_T, or equivalently, $m_{t\bar{t}}$, the top tagging algorithms must be highly efficient at the FCC-hh to reject the large QCD background.

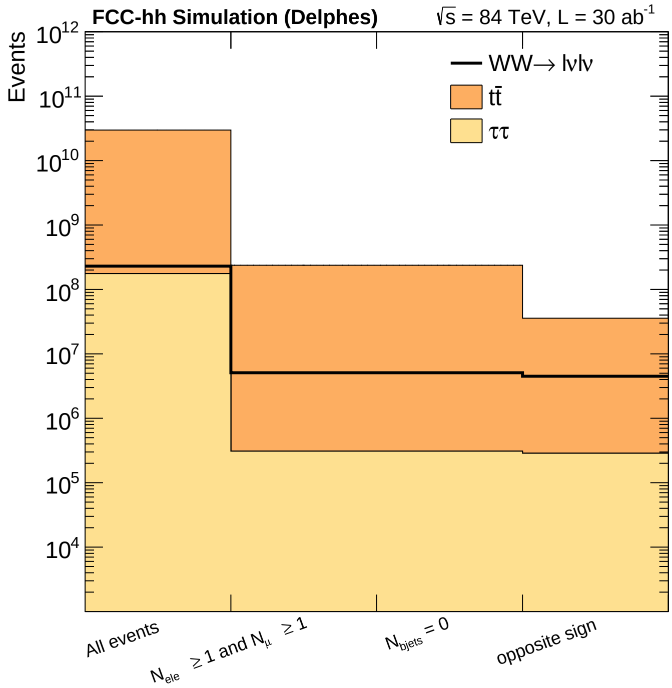

Fig. 1 Signal ($W^+W^- \to e\mu\nu\nu$) and background ($t\bar{t}$ and $Z^* \to \tau\tau$) contributions as a function of the selection criteria. The event yields are normalized to an integrated luminosity of 30 ab^{-1}.

Boosted object identification capabilities have dramatically improved over the past few years, thanks to recent developments in Machine Learning (ML) techniques. In CMS, it is possible to identify a top quark with $p_T = 1$ TeV with a 40% efficiency and a 0.1% mis-tagging probability from a QCD jet. However, identifying top jets with p_T = 5-20 TeV is significantly more challenging since the angular separation of the top decay product scales as $1/p_T$. Eventually, at $p_T > 10$ TeV, all the top decay products are contained within a single calorimeter cell. Despite the higher granularity foreseen in FCC-hh multipurpose detectors, the calorimetric angular resolution will not be sufficient to disentangle the top decay products and resolve their substructure. A possibility is to use tracking information to resolve the sub-structure of the jet. Ref [9] showed that using only tracking information (hence sacrificing the neutral particle information) and combinations of n-points energy correlation functions, one can identify a top quark jet with 40% efficiency and 3% mis-tag rate. We assume here, rather conservatively, that a factor 3 improvement in background rejection with ML techniques and the exploitation of additional features of hyper-boosted tops (e.g. the deadcone effect [10] and the large b hadron flight distance) is easily conceivable. Therefore, we assume a constant 40% top tagging efficiency with a fake rate varying from 0.1% at 1 TeV to 1% at 10 TeV.

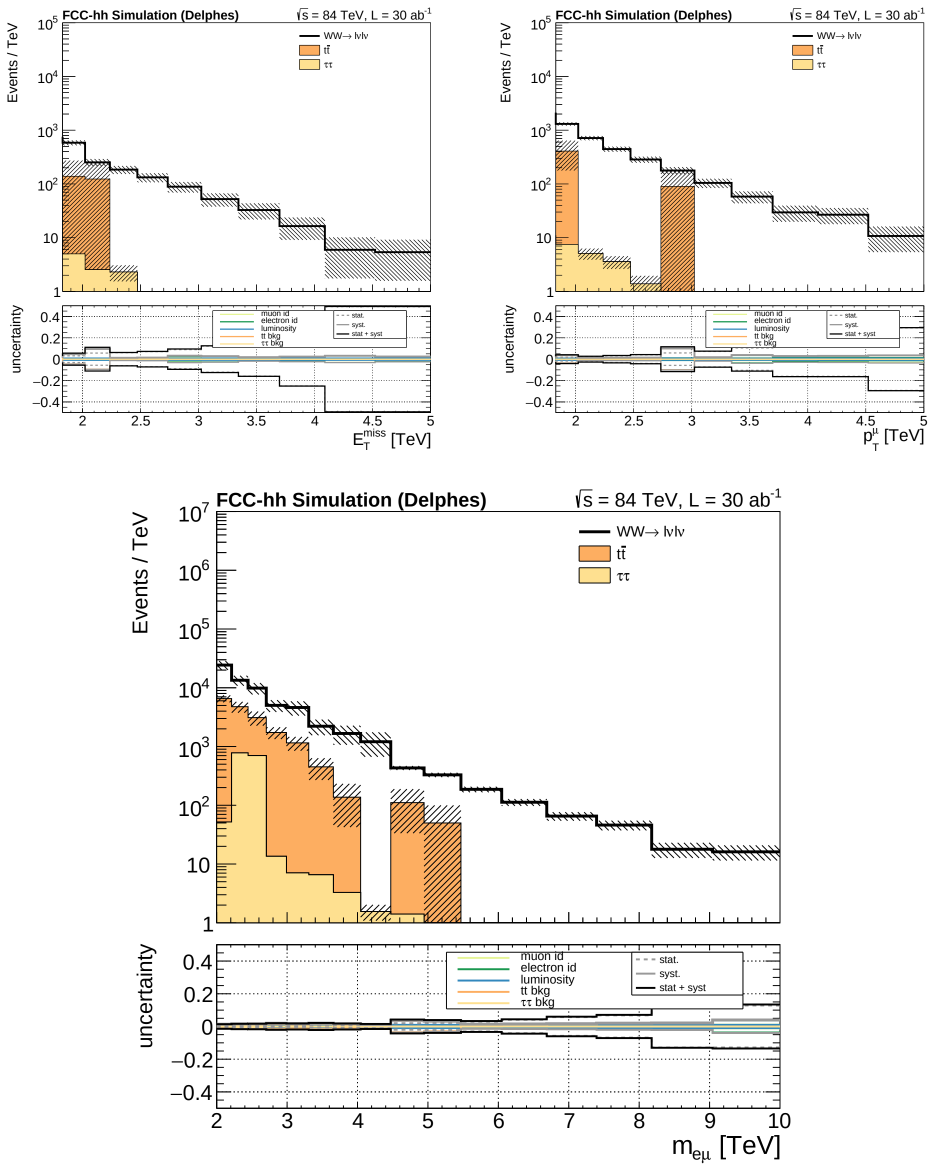

Fig. 2 Distribution of the reconstructed missing transverse momentum, the muon p_T, and the invariant mass of the di-lepton $e\mu$ system $m(e\mu)$ for signal ($W^+W^- \to e\mu\nu\nu$) and backgrounds ($t\bar{t}$ and $Z^* \to \tau\tau$) after the full event selection. The event yields are normalized to an integrated luminosity of 30 ab^{-1}. The bottom panel displays the relative contribution of the statistical and each systematic uncertainty component.

To select large invariant mass $t\bar{t}$ events, we select events with at least two central ($|\eta| < 4$) high p_T jets ($p_T > 500\,\text{GeV}$). The two leading jets are required to be top-tagged according to the algorithm described above. The only background we consider

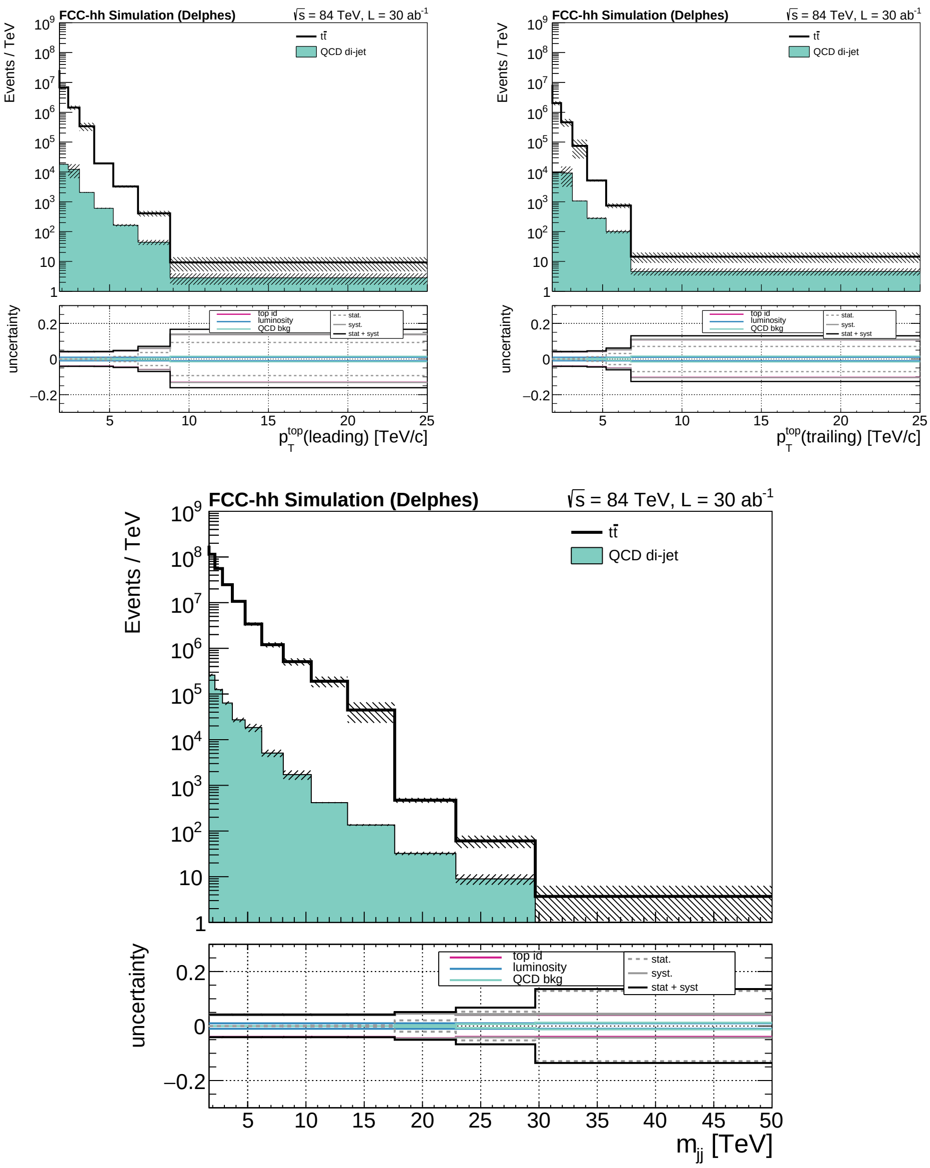

Fig. 3 Distribution of the reconstructed leading top transverse momentum, the sub-leading top $\mathrm{p_T}$, and the invariant mass of the di-jet system ($m_{t\bar{t}}$) for signal ($t\bar{t}$) and backgrounds (QCD di-jet) after the full event selection. The event yields are normalized to an integrated luminosity of 30 ab^{-1}. The bottom panel displays the relative contribution of the statistical and each systematic uncertainty component.

is QCD dijet, which will be the dominant one. The leading top $\mathrm{p_T}$, the sub-leading top $\mathrm{p_T}$, and the invariant mass of the di-jet system ($m_{t\bar{t}}$) for signal ($t\bar{t}$) and backgrounds (QCD di-jet) after the full event selection are shown in Figure 3. The uncertainty on the QCD background normalization is assumed to be 5%. The dominant uncertainty is related to the knowledge of the top tagging efficiency. To address it, we assign a p_T dependent systematic uncertainty for each top tag (hence correlated for the two top jets), whose value is extracted from Figure 5. Provided that the tagger will be pure and efficient, with real data-taking, the tagging efficiency will be measured in situ by comparing the fraction of single and double-tagged events. Its uncertainty will be commensurate to the finite statistics of the $t\bar{t}$ sample from which it will be calibrated. A quantitative assessment of this systematic uncertainty would require the implementation of a top tagging algorithm for the FCC-hh, which is a work in progress. In Ref. [1], we provide alternative systematic variations around the nominal assumptions described here. The aggressive (I) (conservative (III)) scenarios assume a top tagging systematic of 0.5 (2) times compared to the nominal (II) one from Figure 5.

5 Four top production

The four top quark production ($t\bar{t}t\bar{t}$) is a rare Standard Model (SM) process sensitive to top Yukawa coupling modifications and possible new physics that couples to the third generation quarks, particularly top-philic new physics. Measuring its rate, possibly differentially, is an important test of the SM. The LHC experiments have recently observed $t\bar{t}t\bar{t}$ production [11, 12], but only the FCC-hh can precisely measure this process. The leading-order (LO) cross-section at $\sqrt{s} = 84\,\text{TeV}$ is $\sigma_{t\bar{t}t\bar{t}} = 1.57\,\text{pb}$. In this study, we focus on the fully leptonic mode, i.e. all four top quarks decay to either an electron or a muon. The branching fraction for this mode is only 0.1%, and one expects approximately 100,000 such events at the FCC-hh with 30 ab^{-1}. The backgrounds consist of all possible combinations of $t\bar{t}$ in association with one or two vector bosons (V=W,Z), for example, ttV, ttVV, and multi-boson production (VVV, VVVV, ..) and ttH. The samples used in this analysis and their cross-section are given in Table 1.

We select events with exactly four isolated leptons $\ell = \text{e}, \mu$ and 3 b-jets, all with $p_T > 30$ GeV and $|\eta| < 4$. This selection suppresses most of the reducible backgrounds. The remaining large backgrounds are ttZ (with $Z \to \ell\ell$) and ttH (with $H \to$ leptons), as can be seen in Figure 4 (top-left). As a proxy for the Q^2 of the process, we define the H_T variable, defined as:

$$H_T = \sum_{\ell=e,\mu} p_T(\ell) + \sum_{b} p_T(b). \tag{1}$$

To further suppress ttZ, we request that the four leptons form two opposite flavor same-sign (OFSS) pairs, i.e. $e^{\pm}e^{\pm}\mu^{\mp}\mu^{\mp}$. This selection is highly effective, as only a small contamination from $Z \to \tau^+\tau^-$ events with leptonically decaying τ leptons survives the selection. However, this requirement selects only a small fraction (1/8) of the $t\bar{t}t\bar{t}$ signal as shown in Figure 4. We show the H_T distribution before and after the OFSS selection in the top-right and bottom. The final selection reduces the background (mainly ttH) to $\approx$ 500 events and the $t\bar{t}t\bar{t}$ signal to $\approx$ 1000 events. Accounting for the p_T dependent signal selection efficiency systematic uncertainties (electron, muons, and b-tagging efficiency) and a 10% background normalization uncertainty yields an expected precision of 3.8% on $t\bar{t}t\bar{t}$ production at the FCC-hh.

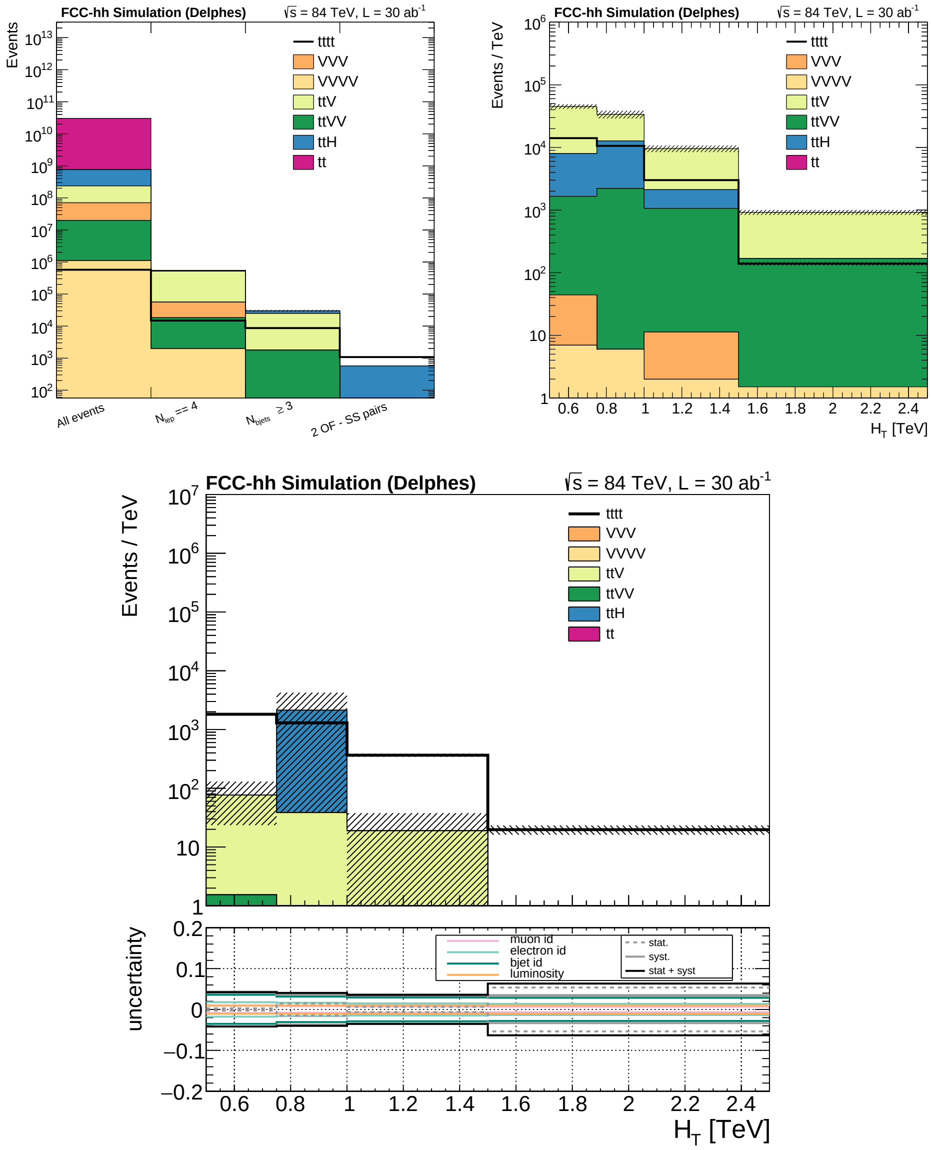

Fig. 4 Distribution of the reconstructed missing transverse momentum, the muon p_T, and the invariant mass of the di-lepton $e\mu$ system $m(e\mu)$ for signal ($W^+W^- \to e\mu\nu\nu$) and backgrounds ($t\bar{t}$ and $Z^* \to \tau\tau$) after the full event selection. The event yields are normalized to an integrated luminosity of 30 ab^{-1}. The bottom panel displays the relative contribution of the statistical and each systematic uncertainty component.

This study shows that a percent-level precision of $t\bar{t}t\bar{t}$ production is possible at the FCC-hh by applying a pure selection. For a more precise measurement, it might be worth exploring more advanced event selection techniques, i.e., by forming lepton pair combinations and vetoing those compatible with Z decays or applying MVA techniques to leverage the large final state multiplicity. A 1% precision in the inclusive $t\bar{t}t\bar{t}$ rate seems feasible at the FCC-hh, which would pave the way for precise differential measurements.

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References

[1] Selvaggi, Michele. FCC-hh Differential distributions and associated uncertainties public data. Public link (2025). URL https://mselvaggi.web.cern.ch/public/diff_fcchh/

[2] 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. arXiv:1405.0301 [hep-ph]

[3] S. Frixione, O. Mattelaer, M. Zaro, X. Zhao, Lepton collisions in MadGraph5_aMC@NLO (2021). arXiv:2108.10261 [hep-ph]

[4] 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 [hep-ph]

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

[6] A. Abada, et al., FCC-hh: The Hadron Collider: Future Circular Collider Conceptual Design Report Volume 3. Eur. Phys. J. ST **228**, 755 (2019). https://doi.org/10.1140/epjst/e2019-900087-0

[7] M. Aleksa, et al., Conceptual design of an experiment at the FCC-hh, a future 100 TeV hadron collider **2/2022** (2022). https://doi.org/10.23731/CYRM-2022-002

[8] M. Selvaggi, A Delphes parameterisation of the FCC-hh detector. Tech. rep., CERN, Geneva (2020). URL https://cds.cern.ch/record/2717698

[9] A.J. Larkoski, F. Maltoni, M. Selvaggi, Tracking down hyper-boosted top quarks. JHEP **06**, 032 (2015). https://doi.org/10.1007/JHEP06(2015)032. arXiv:1503.03347 [hep-ph]

[10] F. Maltoni, M. Selvaggi, J. Thaler, Exposing the dead cone effect with jet substructure techniques. Phys. Rev. D **94**(5), 054015 (2016). https://doi.org/10.1103/PhysRevD.94.054015. arXiv:1606.03449 [hep-ph]

[11] A. Hayrapetyan, et al., Observation of four top quark production in proton-proton collisions at s=13TeV. Phys. Lett. B **847**, 138290 (2023). https://doi.org/10.1016/j.physletb.2023.138290. arXiv:2305.13439 [hep-ex]

[12] G. Aad, et al., Observation of four-top-quark production in the multilepton final state with the ATLAS detector. Eur. Phys. J. C **83**(6), 496 (2023). https://doi.org/10.1140/epjc/s10052-023-11573-0. [Erratum: Eur.Phys.J.C 84, 156 (2024)]. arXiv:2303.15061 [hep-ex]

A Assumptions of object identification systematic uncertainties

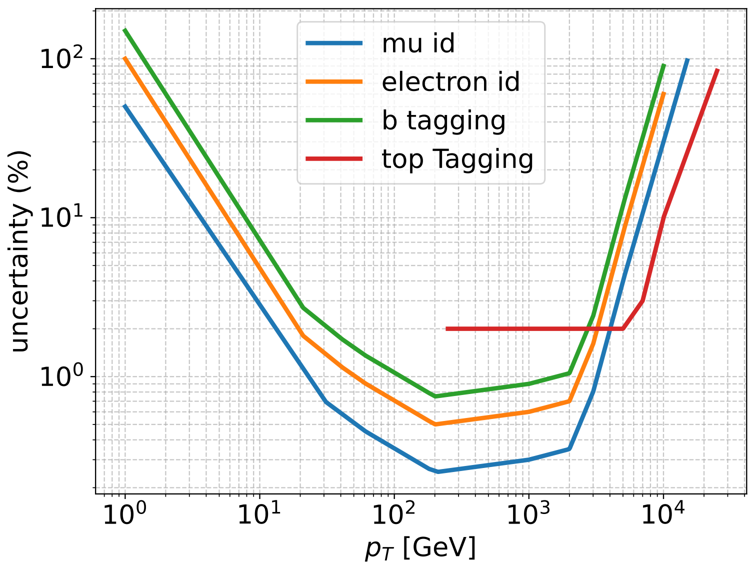

Fig. 5 Uncertainty on the electron and muon identification efficiencies and the b-jet and top tagging efficiencies as a function of p_T.