

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 $t\bar{t}$ production in the fully hadronic final state, WW production in the $e\mu$ final state, and $t\bar{t}t\bar{t}$ (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 $e^\pm e^\pm \mu^\mp \mu^\mp$ decay. This final state is chosen to suppress the large $t\bar{t}Z$ 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 $\sqrt{s} = 84$ TeV are listed in Table 1.

Table 1 Samples and corresponding cross-sections for the processes considered in this study.

Process	Name	Order	Cross Section
$pp \rightarrow jj$	mg_pp_jj_HT_200_2000_5f_84TeV	LO	2250 μ b
	mg_pp_jj_HT_2000_100000_5f_84TeV		2.27 nb
$pp \rightarrow t\bar{t}$	mg_pp_tt_HT_200_2000_5f_84TeV	LO	8.94 nb
	mg_pp_tt_HT_2000_100000_5f_84TeV		7.84 pb
$pp \rightarrow WW$	mg_pp_ww_HT_200_2000_5f_84TeV	LO	74.51 pb
	mg_pp_ww_HT_2000_100000_5f_84TeV		58 ab
$pp \rightarrow ZZ$	mg_pp_zz_HT_200_2000_5f_84TeV	LO	14.15 pb
	mg_pp_zz_HT_2000_100000_5f_84TeV		11.9 ab
$pp \rightarrow \tau\tau$	mg_pp_tautau_HT_200_2000_5f_84TeV	LO	5.88 pb
	mg_pp_tautau_HT_2000_100000_5f_84TeV		0.43 ab
$pp \rightarrow \ell\nu\ell\nu$ ($\ell = e, \mu, \tau$)	mg_pp_lv1v_HT_200_2000_5f_84TeV	LO	7.66 pb
	mg_pp_lv1v_HT_2000_100000_5f_84TeV		6.80 ab
$pp \rightarrow WWZ$	mg_pp_wwz_5f_84TeV	LO	1.20 pb
$pp \rightarrow WZZ$	mg_pp_wzz_5f_84TeV	LO	0.37 pb
$pp \rightarrow ZZZ$	mg_pp_zzz_5f_84TeV	LO	0.124 pb
$pp \rightarrow WWWZ$	mg_pp_wwwz_5f_84TeV	LO	14.2 ab
$pp \rightarrow WWWW$	mg_pp_www_5f_84TeV	LO	11.2 ab
$pp \rightarrow WWZZ$	mg_pp_wwzz_5f_84TeV	LO	9.80 ab
$pp \rightarrow WZZZ$	mg_pp_wzzz_5f_84TeV	LO	1.31 ab
$pp \rightarrow ZZZZ$	mg_pp_zzzz_5f_84TeV	LO	0.368 ab
$pp \rightarrow t\bar{t}W$	mg_pp_ttw_5f_84TeV	LO	5.22 pb
$pp \rightarrow t\bar{t}Z$	mg_pp_ttz_5f_84TeV	LO	28.15 pb
$pp \rightarrow t\bar{t}WZ$	mg_pp_ttwz_5f_84TeV	LO	58.61 ab
$pp \rightarrow t\bar{t}WW$	mg_pp_ttw_5f_84TeV	LO	0.56 pb
$pp \rightarrow t\bar{t}ZZ$	mg_pp_ttzz_5f_84TeV	LO	87.2ab
$pp \rightarrow t\bar{t}t\bar{t}$	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 $e^\pm\mu^\mp\nu\nu$. This final state is naturally free from the same flavor (ee , $\mu\mu$) Drell-Yan background. The dominant backgrounds are $Z^* \rightarrow \tau\tau$, 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 systematic 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 expected number of events in the large $m_{e\mu}$ regime is essentially background-free. Nevertheless, we attribute a flat 5% uncertainty in the $Z/\gamma^* \rightarrow \tau^+\tau^-$ background normalization for completeness. 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 systematic 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 6. 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

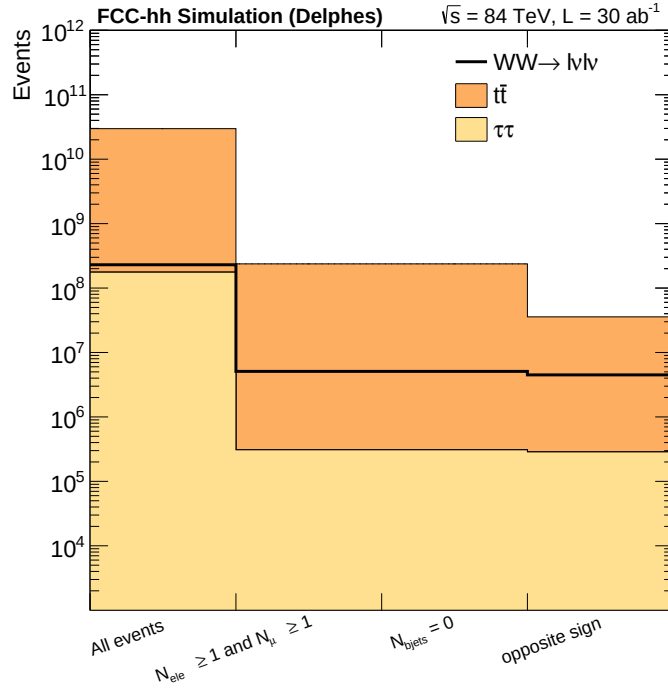


Fig. 1 Signal ($W^+W^- \rightarrow e\mu\nu\nu$) and background ($t\bar{t}$ and $Z^* \rightarrow \tau\tau$) contributions as a function of the selection criteria. The event yields are normalized to an integrated luminosity of 30 ab^{-1} .

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. 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 $p_T = 1 \text{ TeV}$ with a 40% efficiency and a 0.1% mis-tagging probability from a QCD jet. However, identifying top jets with $p_T = 5\text{-}20 \text{ TeV}$ is significantly more challenging since the angular separation of the top decay product scales as $1/p_T$. Eventually, at $p_T > 10 \text{ TeV}$, 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.

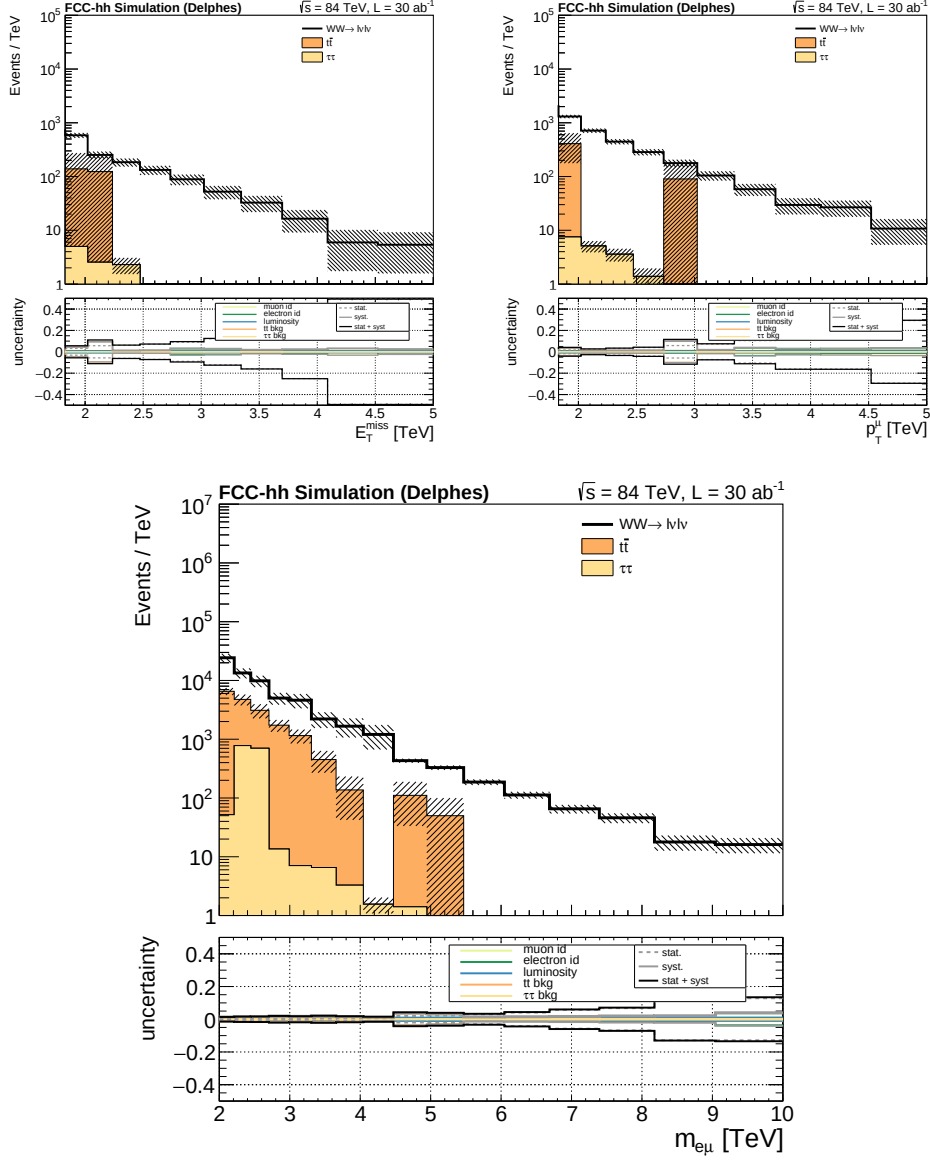


Fig. 2 Distribution of the reconstructed missing transverse momentum, the muon p_T , and the invariant mass of the di-lepton $e\mu$ system $m(e\mu)$ for signal ($W^+W^- \rightarrow e\mu\nu\nu$) and backgrounds ($t\bar{t}$ and $Z^* \rightarrow \tau\tau$) after the full event selection. The event yields 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.

98 Therefore, we assume a constant 40% top tagging efficiency with a fake rate varying
 99 from 0.1% at 1 TeV to 1% at 10 TeV.

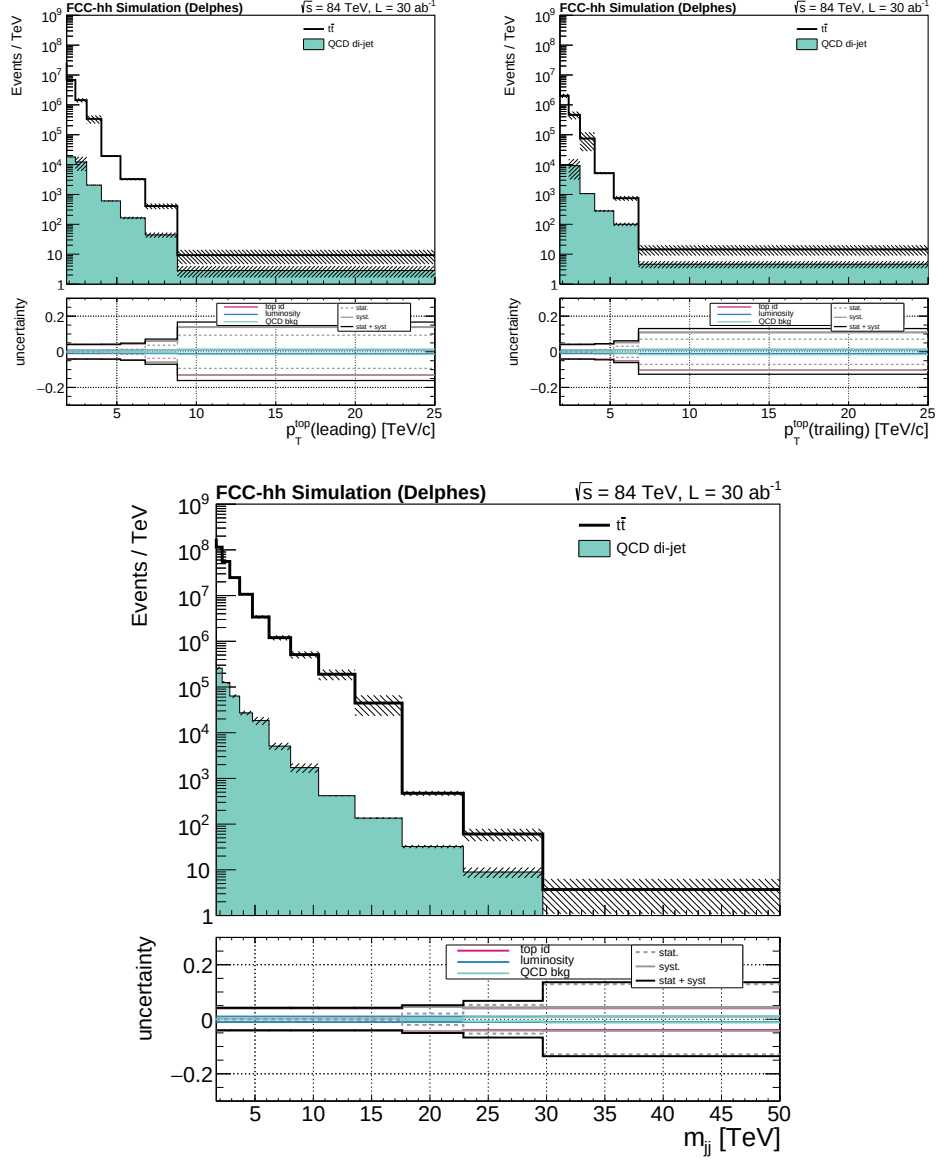


Fig. 3 Distribution of the reconstructed leading top transverse momentum, the sub-leading top p_T , and the invariant mass of the di-jet system ($m_{t\bar{t}}$) for signal ($t\bar{t}$) and backgrounds (QCD di-jet) after the full event selection. The event yields are normalized to an integrated luminosity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

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

is QCD dijet, which will be the dominant one. The leading top p_T , the sub-leading top 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 6. 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 6.

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 $\sqrt{s} = 84$ TeV is $\sigma_{t\bar{t}t\bar{t}} = 1.57$ 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, $t\bar{t}V$, $t\bar{t}VV$, and multi-boson production (VVV , $VVVV$, ...) and $t\bar{t}H$. The samples used in this analysis and their cross-section are given in Table 1.

We select events with exactly four isolated leptons $\ell = e, \mu$ 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 $t\bar{t}Z$ (with $Z \rightarrow \ell\ell$) and $t\bar{t}H$ (with $H \rightarrow$ 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:

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

To further suppress $t\bar{t}Z$, 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 $Z \rightarrow \tau^+ \tau^-$ 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 $t\bar{t}H$) to ≈ 500 events and the $t\bar{t}t\bar{t}$ signal to ≈ 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.

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.

process	$0.2 < Q < 1 \text{ TeV}$	$1 < Q < 3 \text{ TeV}$	$3 < Q < 10 \text{ TeV}$	$10 < Q < 30 \text{ TeV}$	$30 < Q < 84 \text{ TeV}$
$pp \rightarrow \ell\ell$	$6.03e+01$	$3.58e-01$	$7.21e-03$	$3.46e-05$	$1.17e-08$
$pp \rightarrow \ell\nu$	$1.67e+02$	$9.00e-01$	$1.82e-02$	$9.26e-05$	$2.89e-08$
$pp \rightarrow jj \text{ (all)}$	$5.22e+08$	$4.07e+07$	$4.64e+06$	$9.73e+04$	$8.21e+01$
$pp \rightarrow t\bar{t}$	$1.73e+04$	$1.21e+03$	$1.87e+01$	$4.72e-02$	$6.33e-06$
$pp \rightarrow b\bar{b}$	$1.06e+06$	$1.19e+04$	$6.23e+02$	$4.07e+00$	$4.73e-04$
$pp \rightarrow c\bar{c}$	$1.24e+06$	$2.68e+04$	$2.04e+03$	$1.48e+01$	$2.58e-03$
$pp \rightarrow jj \text{ (u, d, s, g)}$	$1.13e+09$	$8.71e+07$	$8.71e+06$	$8.95e+04$	$7.65e+01$

Table 2 Cross sections for various processes at $\sqrt{s} = 84 \text{ TeV}$ in different Q -bins.

6 Associated $t\bar{t}Z$ production

The associated production of a top quark pair and Z boson ($t\bar{t}Z$) is an important process of the SM to measure the coupling between the top and the electroweak sector. The direct sensitivity to the top-Z vertex makes it an important probe of the SM, as it can be affected by new physics scenarios such as effective field theories operator. With the LHC data, a precision of 6.5% on the $t\bar{t}Z$ production cross section is obtained by the ATLAS collaboration [13]. The large dataset of the FCC-hh will allow to increase this precision significantly. More importantly, much higher energy scales can be reached to probe the process, enabling measurements in kinematic regions with high sensitivity to new physics. The LO cross section at $\sqrt{s} = 84 \text{ TeV}$ is $\sigma_{t\bar{t}Z} = 28.15 \text{ pb}$. Which is 32 times greater than the cross-section obtained by ATLAS (0.86 pb) during the LHC Run 2 [13]. In this study, we focus exclusively on the leptonic final states due to their higher achievable purity. We divide the analysis into two channels: the three lepton (3ℓ), where one of the top quarks decays leptonically, and four lepton (4ℓ), where both top quarks decay leptonically. In both cases, the Z boson decays to two leptons: e^+e^- or $\mu^+\mu^-$. A more restrictive selection can be applied on the 4ℓ channel, leading to higher purity, but better statistical precision is obtained in the 3ℓ channel. The two channels are combined to improve the precision of the result. The backgrounds consist of top quark pair, $t\bar{t}$, as well as four top, $t\bar{t}t\bar{t}$, $t\bar{t}H$, as well as all combination of $t\bar{t}$ with two vector bosons $t\bar{t}VV$, and multi-boson processes.

For the 4ℓ channel, we select events with exactly four isolated leptons $\ell = e, \mu$ and one or two b-jets, all with $p_T > 30 \text{ GeV}$ and $|\eta| < 4$. In the 3ℓ channel we select exactly 3

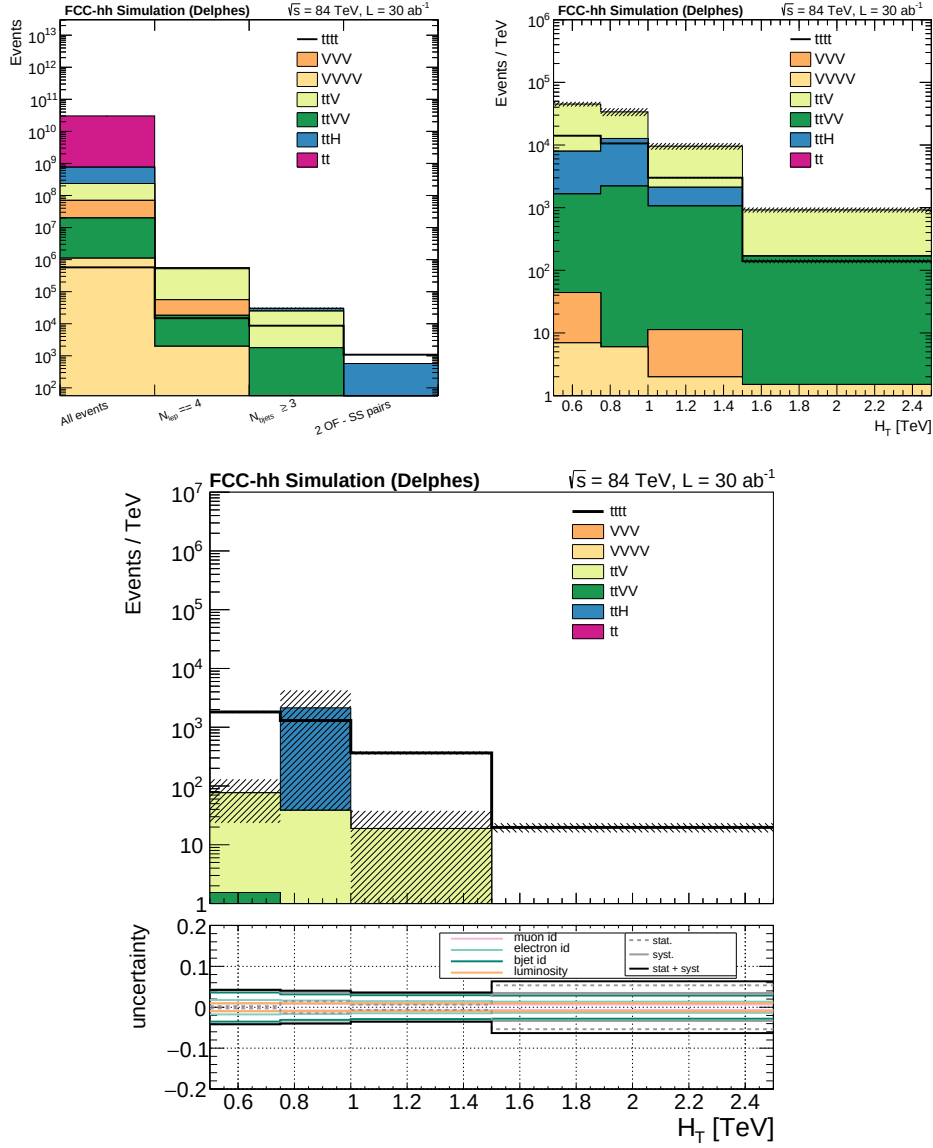


Fig. 4 Top Left: Signal ($t\bar{t}t\bar{t}$) and backgrounds (VVV , $VVVV$, $t\bar{t}V$, $t\bar{t}V\bar{V}$, $t\bar{t}H$, $t\bar{t}$) contributions as a function of the selection criteria. The event yields are normalized to an integrated luminosity of 30 ab⁻¹. Top Right and Bottom: Distribution of the reconstructed H_T , the scalar sum of the p_T of reconstructed leptons and b-jets, before (Top right) and after (bottom) the selection of two opposite flavor same sign di-lepton pairs. The bottom panel in the figure displays the relative contribution of the statistical and systematic uncertainty components.

leptons, while the rest of the requirement on b-jets is unchanged.
To further suppress the four top background in both channels, we request one of the

177 leptonic pairs to be comprised of same-flavour opposite-sign leptons (SFOS) and this
 178 same pair must have an invariant mass within the $80 - 100$ GeV window, i.e., it must
 179 be compatible with a resonant Z boson decay. For the 3ℓ channel, this selection is
 180 sufficient to suppress most backgrounds in the 3ℓ channel as shown in Figure 5 (Top
 181 Left).

182 . The remaining dominant backgrounds are $ZZjj$ and $t\bar{t}H$. At higher values of p_T ,
 183 VVV and $t\bar{t}VV$ backgrounds become more important, as can be seen on Figure 5 (Top
 184 Right and Bottom Right). The 4ℓ channel allows for one more level of filtering by
 185 requiring that the second lepton pair is made of opposite-flavor (OF) leptons e, μ .
 186 This selection is aimed at suppressing the $ZZjj$ and $t\bar{t}H$ backgrounds. The kinematic
 187 variable reconstructing the Q^2 is the transverse momentum p_T of the lepton pair
 188 originating from the Z. We define it as the vectorial sum of the two leptons:

$$p_T(Z_u) = p_T(\ell_1) + p_T(\ell_2) \quad (2)$$

189 With $\ell_1 = \mu^\pm$ or $e^\pm$ and $\ell_2 = \mu^\mp$ or $e^\mp$.

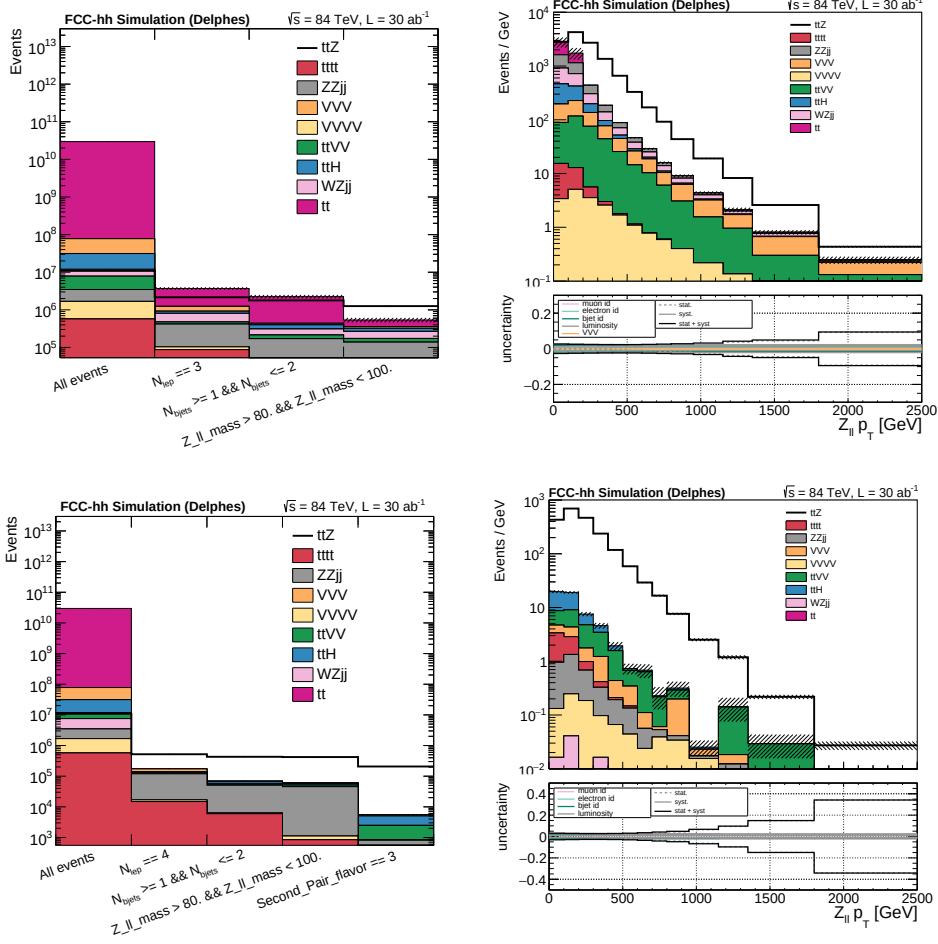


Fig. 5 Top Left and Right: Signal (ttZ) and background ($VVV, VVVV, t\bar{t}H, ZZjj, t\bar{t}t$) contributions as a function of the selection criteria for the 3ℓ (left) and 4ℓ (right) channels. The event yields are normalized to an integrated luminosity of 30ab^{-1} . Bottom Left and Right: Distribution of the reconstructed p_T for the lepton pair resonant on Z , along with the relative contribution of the statistical and systematic uncertainty components.

We show the $p_T(Z_{\ell\ell})$ distribution for both channels in Figure 5. The selection described previously is particularly stringent in the 4ℓ channel, achieving a signal efficiency of 1.9%. Nonetheless, the high event rates foreseen at FCC-hh energies ensure that a sufficient number of expected signal events pass through the selection ($\approx 2 \cdot 10^5$). A small background contamination of $t\bar{t}H$ remains, with $\approx 3 \cdot 10^3$ events. An advantage of this highly exclusive selection is its purity, allowing us to reduce the correlation between background processes.

The selection on 3ℓ is less strict, resulting in higher signal efficiency: 11.6% of signal events pass the selection ($\approx 1.3 \cdot 10^6$ events). The poor lepton reconstruction drives the large efficiency discrepancy between the 3ℓ and 4ℓ channels: requiring three leptons to

be identified among the final state objects increases the number of signal events by a factor of 10 compared to the 4ℓ channel. In return, the background contamination is higher, mainly caused by $t\bar{t}H$ with $\approx 1.2 \cdot 10^5$ events, and $ZZjj$ with $\approx 1.3 \cdot 10^5$ events.

Accounting for the same systematic uncertainties as in the four top analysis (section 5), we find an expected precision of 2.6% on the inclusive $t\bar{t}Z$ production cross section at the FCC-hh, with both 3ℓ and 4ℓ channels combined.

This study demonstrates that, in addition to enhancing the precision of the $t\bar{t}Z$ inclusive production cross section, the FCC-hh enables the probing of this process in new kinematic regimes, such as high $p_T(Z_{\ell\ell})$, where sensitivity is achieved up to 2.5 TeV. In comparison, ATLAS reached sensitivity up to $p_T(Z_{\ell\ell}) \approx 400$ GeV in the 3ℓ and 4ℓ channels combined [13]. This opens increased sensitivity to potential deviation from the SM, such as EFT scenarios.

The main limitation of this analysis is the low lepton reconstruction efficiency, $\approx 50\%$ for a single lepton, which leads to $\approx 12\%$ of the 3ℓ signal events and $\approx 4.6\%$ of the 4ℓ passing through the first layer of selection. The most significant way to enhance the final statistics is to improve the lepton selection efficiency.

7 Associated $t\bar{t}\gamma$ production

8 Lepton reconstruction improvement

As explained in section 6, the lepton reconstruction efficiency is the primary factor contributing to the decrease in signal statistics. This section describes the work done to improve this efficiency, and presents the final results for $t\bar{t}Z$ after improvement.

The detector acceptance of $p_T > 30$ GeV and $|\eta| < 4$ contributes to an efficiency of $\approx 79\%$ on a single lepton. However, the leptons lost due to the detector constraints are mostly non-prompt. The prompt lepton efficiency can be increased by optimizing the isolation criteria.

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272 **A Assumptions of object identification systematic**
 273 **uncertainties**

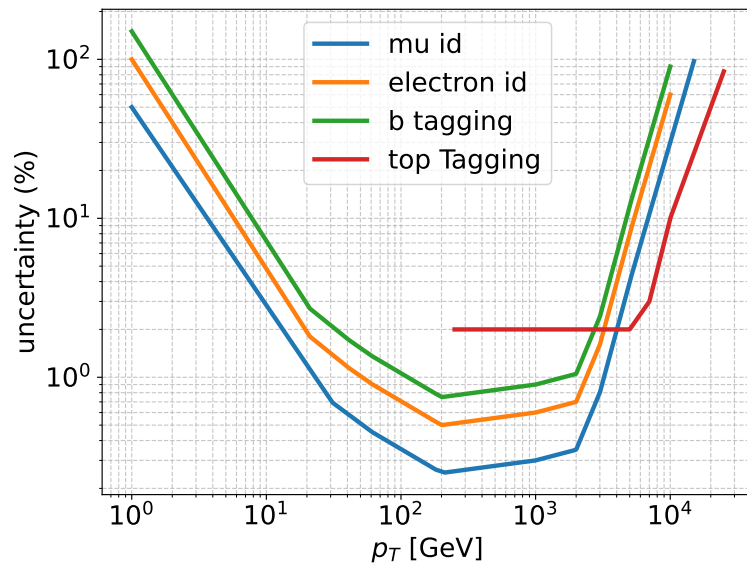


Fig. 6 Uncertainty on the electron and muon identification efficiencies and the b-jet and top tagging efficiencies as a function of p_T .