Snowmass2021 - Letter of Interest

Top quark physics at FCC-ee

Thematic Areas:

■ (EF03) EW Physics: Heavy flavor and top quark physics
■ (EF04) EW Physics: EW Precision Physics and constraining new physics

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Abstract:
Proposal for phenomenological and experimental physics studies of top quark properties at FCC-ee.

1 Introduction

Since its discovery by the CDF and D0 experiments[1,2], the top quark has been extensively studied at the Tevatron and the LHC. As it is the heaviest known particle, its mass is then the closest to the scale of electroweak symmetry breaking. It has thus a very particular place in the Standard Model (SM) precision measurements and Beyond Standard Models (BSM) searches. As the top quark mainly decays before it forms bound states, its properties can indeed be deeply probed through the analysis of its decay products.

At lepton colliders, such as the Future Circular Collider (FCC) in its e^+e^- configuration, ultimate precision can be achieved in many $t\bar{t}$ measurements.

2 Theoretical calculation and events generation

The evolution of the $e^+e^- \rightarrow W^+W^-b\bar{b}$ cross section around the $t\bar{t}$ mass threshold has been calculated at the NNNLO in QCD and NLO in electroweak, and including QED initial-state radiation[3,4]. The $t\bar{t}$ threshold scan shows a peak for which the position of the maximum depends on the top-quark mass. While the width of the peak is sensitive to the top-quark width, the height of the plateau above the $t\bar{t}$ threshold is sensitive to y_t and α_s. Accurate events generation is a key point of $t\bar{t}$ analyses at FCC-ee, as generators need to reproduce well enough the $t\bar{t}$ kinematics at the resonance peak. The underlying motivation is to verify that the signal events kinematic and acceptance is not significantly modified when including higher order corrections. Given the outstanding experimental precision expected at FCC-ee, it is very important to ensure that signal modelling reaches the same level of precision. We would then warmly invite MadGraph[5] and Whizard[6] developers to consider to release event generators allowing for a good description of the threshold scan. Having two generators is particularly important for performing comparisons and systematic

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studies. The Whizard program can already be used to effectively reproduce the expected threshold scan cross-sections with a good accuracy [7], even if a public version usable for events generation is not available yet.

While having accurate theoretical calculations is crucial, the initial state radiation (ISR) and beam effects also have to be accounted for. Among the beam effects, we can mention the Beam Energy Spread (BES), that enlarge the resonance peak, and beam backgrounds, which are effectively reducing the cross section and adding extra energy into the detector. Whizard contains the description of these important features, such as the description of ISR, an interfaced to GuineaPig++ [8] to account for beamstrahlung, and the possibility to introduce gaussian BES. The Madgraph community also expresses some plans to improve the generation at e^+e^- colliders, by including automated NLO QCD and eletroweak calculations, the matching to parton-shower, ISR and beamstrhalung [9,10].

3 Detector simulation

From the point of view of the detector design, the large diversity of objects in $t\bar{t}$ final states is the perfect playground for testing and optimizing detector and algorithm performances in a dense and complex environment.

Two independent detector designs have been studied so far in the context of the FCC-ee CDR [11] : the IDEA and the CLD detectors. The descriptions of these two detectors have been implemented into the Delphes fast simulation [12] and are available within the FCC software package. Once interfaced with FCCSW, the MA5 SFS Fastsimulation [13] could also be tested. The impact of detector resolutions and performances on benchmark analyses can be evaluated. In particular, the impact of the b- and c-charm tagging performances on the results can be studied to extract a target value. These studies based on Fast Simulation, however, can only constitute a first step toward more refine investigations, to be done based in full Geant4-based [14] simulations. The detector performance are actually strongly bounded to the performance of reconstruction algorithm. While performing detector optimization based on benchmark analyses, the interplay with algorithmic aspects has to be taken into account with caution.

4 Analyses at $t\bar{t}$ threshold and above

At the FCC-ee the perfect knowledge of the initial state allows to measure the $t\bar{t}$ cross section as a function of the centre of mass energy $\sqrt{s}$, in particular around the $t\bar{t}$ mass threshold. From such measurements, referred to as "threshold scan", one can access the top-quark pole-mass with an unprecedented precision (profiting also from the lower beam energy spread [15]), but also the top-quark width and the top-quark Yukawa-coupling y_t.

In its most simple form, the analysis strategy for the threshold scan can be reduced to a simple counting analysis. After the event selection and the extraction of the background contamination, the observed number of signal events for each $\sqrt{s}$ point can be simply fitted with a function determined by theory. The first source of systematics would arise then from the determination of the backgrounds contamination. Particular attention must be spent on the events selection optimisation, in order to reach a good purity while keeping the statistical error low. The uncertainties from backgrounds can be further reduced by fitting simultaneously the signal sample with background enriched regions. Another category of systematic sources is related to the modeling of the signal acceptance and selection efficiencies. Such systematics can either arise from experimental uncertainties (reconstruction and selection efficiencies) or from theoretical origins (uncertainties on the kinematics of the $t\bar{t}$ events). In the former case, the reconstruction and selection efficiencies have to be most precisely estimated from data. All relevant systematic effects have to be accounted for in future prospective works. We plan to refine this analysis by considering differential distributions, rather than just events counting. This would help in constraining systematic uncertainties, while potentially gaining sensitivity to the top-quark mass. Such approach should be explored to examine with a different angle the performance needed in the reconstruction (resolutions and efficiencies). It would be useful to develop strategies to extract more information from the available data and at the same help constrain systematics.

Above the $t\bar{t}$ mass threshold, where both top quarks are produced on shell, the full $t\bar{t}$ kinematics can be precisely reconstructed from the top-quark decay products. This allows to perform a wide range of analyses, such as the direct measurements of the (MC) top-quark mass[16] and top-quark couplings to electroweak bosons[17]. Several distributions, such as forward-backward asymmetry, top quark polarisation or angular distributions, have proven their sensitivity to top-quark EFT couplings [18]. It still has to be investigated how the sensitivity to EFT with un-polarized beam at the FCC energy of 365 GeV can benefit best from the large statistic available.

5 Analysis opportunities at $\sqrt{s} = 240$ GeV, FCNC

FCNC transitions of the top quark are forbidden at tree level and highly suppressed in the Standard Model, with BR at the level of $10^{-12} - 10^{-15}$. These transitions could be strongly enhanced in BSM models, increasing BR to $10^{-6} - 10^{-8}$. These processes can be studied at the FCC-ee both in the top decay ($t \to q\gamma/Z$) in top pair production at $\sqrt{s} = 365$ GeV or in the anomalous production of $e^+e^- \to tq$ (q=u,c) at $\sqrt{s} = 240$ GeV. Preliminary analyses[19] have shown a sensitivity that could reach $10^{-5} - 10^{-6}$. These analyses are extremely dependent on the performance of b- and c-tagging, both in terms of signal efficiency and background rejection. The plan would be to study the optimization of the flavor tagging algorithms to reach the ultimate sensitivity. The results at the two different energies can be combined and also interpreted in a EFT framework as well[20,21].

6 Conclusion

The FCC-ee is one of the most valuable options for the next e^+e^- high energy collider. The recent release of the European Strategy opened the way to the study of technical and financial feasibility of the FCC colliders. These studies should go together with deep and complete studies of physics benchmark processes, in order to determine best possible detector designs and algorithmic performances. $t\bar{t}$ signatures constitute here one of the best physics benchmark to achieve this goal. While the studies at the $t\bar{t}$ threshold are particularly interesting, several other analyses opportunities still have to be explored. The $t\bar{t}$ physics program at FCC-ee should reach its full maturity by working on events generation, detector simulation and reconstruction, and analysis techniques. This for the many interesting physics measurements at hand.

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