Summer Student Report

Top Electroweak Coupling at FCC-ee

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1. Introduction

As a summer student at Cern, I was part of the CMS department working on the Future Circular Collider project.

The FCC-ee experiment marks the first phase of the two-part FCC project, prioritizing precision measurements. In the subsequent FCC-hh phase, the focus shifts to pushing energy boundaries. FCC-ee, a proposed circular collider, is designed for e^+e^- collisions at threshold energies ranging from 90 GeV to 350 GeV, followed by a second stage with proton-proton collisions at 90 GeV to 240 GeV. Notably, researchers at FCC-ee concentrate on studying the top quark, the heaviest known particle, seeking insights into fundamental forces shaping the universe and potentially unraveling new mysteries in particle physics.

2. FCC-SW

We've performed analyses using Future Circular Collider Software (FCCSW), a sophisticated computational framework meticulously designed to simulate, analyze, and interpret the intricate interactions occurring within these high-energy experiments. The significant elements in this context include DELPHES, Pythia8, and EDM4HEP, all falling within the scope of the Key4HEP framework. As a part of FCCAnalyses Software, there is a library of C++ analysers. All code lives in the FCCAnalyses namespace which is by default loaded when running fccanalysis command. Libraries also include the Jet Clustering Interface and the Jet Tagging Utilities. The Jet Clustering Interface facilitates adaptive jet clustering using FastJet, primarily designed for the hadron collider environment. The interface offers a subset of FastJet's jet algorithms and recombination schemes.

The FCCAnalyses framework is based on the RDataFrame interface which allows fast and efficient analysis of ROOT's TTrees and on samples following the EDM4HEP event data model. The content of an EDM4HEP file can be seen by opening it in ROOT, and by inspecting the content of the events tree with a TBrowser.

3. Sample

We were using the p8_ee_tt_ecm365 sample. This simulation, generated by Pythia8, involves electron-positron collisions at a center-of-mass energy of 365 GeV, specifically focusing on the production of top quark pairs.

The top-quark predominantly decays by t $\rightarrow$ bW+ hence the top-quark pair production mostly results in

$$\mathbf{e^+e^-\rightarrow t\bar{t}\rightarrow bW^+\bar{b}W^-} \tag{1}$$

Each W-boson can decay either hadronically ($W \rightarrow q\bar{q}'$) or leptonically ($W \rightarrow \ell\nu$) where the hadronic decay mode has a branching fraction of 67.5%. Consequently, in the decay of $t\bar{t}$ pairs, there's a semileptonic scenario occurring in 44% of cases, where one W-boson decays hadronically and the other decays leptonically, a fully hadronic where both W-bosons decay hadronically and the last scenario in which W-bosons decay leptonically.

$$\mathbf{t\bar{t}\rightarrow bW^+\bar{b}W^-\rightarrow b\bar{b}q\bar{q}^{'}}\ell\nu \tag{2}$$

$$\mathbf{t\bar{t}\rightarrow bW^+\bar{b}W^-\rightarrow b\bar{b}q\bar{q}^{'}q\bar{q}^{'}} \tag{3}$$

$$\mathbf{t\bar{t}\rightarrow bW^+\bar{b}W^-\rightarrow b\bar{b}}\ell\nu\ell\nu \tag{4}$$

4. Development of tree and event selections

The aim of the project was to develop a tree and add new variables to the n-tuples. Our starting point was an example tree for sample p8_ee_ZH_Zmumu_ecm240 in which a final state with two leptons and two b-jets was selected. Considering that the dilepton $t\bar{t}$ decay channel has a similar final state, just with more missing energy, it was a helpful beginning.

Selections and cuts we've performed to reconstruct a dilepton final state are:

- Leptons with momentum greater than 20 GeV
- Implementation of a lepton isolation cut set at 0.1
- Events with two leptons and with at least one isolated one were selected
- Selection of events with 2 opposite-sign leptons
- We've created a new collection removing leptons and performed the jet clustering algorithm in exclusive N=2 mode
- Using the jet flavor algorithm we've selected two jets to be B-like

We defined functions for calculating the invariant mass of two leptons and invariant mass of all combinations of leptons and two b-jets. All added variables in n-tuples are:

- Invariant mass of two leptons - ll_m
- Invariant mass of all lepton-b jet combinations – lb_m_comb
- TlorentzVector of jets - jets_p4
- Momentum of two jets - jet1_p, jets2_p
- Number of jets – n_jets
- Missing momentum – missing_p
- Jet tagging score - scoresum_B
- Number of leptons – leptons_no

5. Results

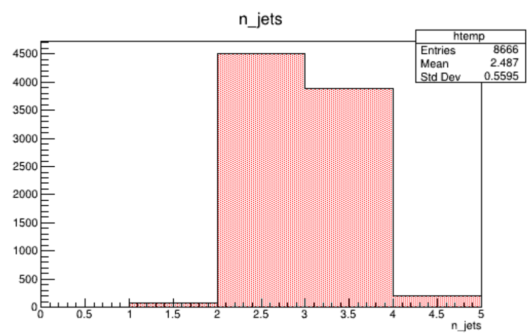

Figure 1: N(jet) distribution for dilepton final state

Considering the N(jet) distribution histogram for dilepton final state shown in figure 1, clustering, and selections were well-performed because most events are with two jets in the final state which was expected. The observed events with different jet multiplicities are a reflection of the underlying complexity of particle collisions and the inherent limitations of clustering algorithms.

The next step was to reconstruct one lepton final state. We've now selected events with one lepton. After performing cuts on lepton momentum and isolation we removed the lepton and ran the N=4 jet clustering algorithm.

By examining the histogram in figure 2, we notice that it isn't very accurate, as most events feature 3 jets instead of the expected 4 jets

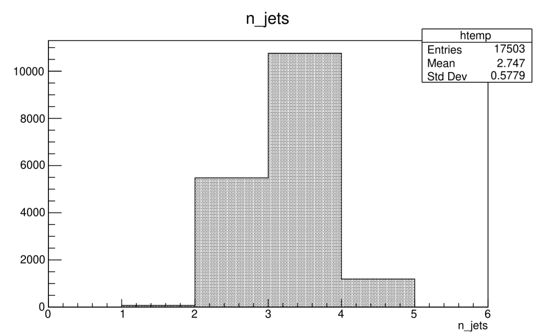

Figure 2: N(jet) distribution for one lepton final state

and contribution of 4 jets is too small. This discrepancy suggests that the current jet algorithm might not be suitable for this process or we haven't done properly the selection part.

In the last step, we carried out an inclusive jet clustering algorithm involving all reconstructed particles, planned to be followed by selections. After defining pseudo jets and running the clustering algorithm, we created a function to count the number of pseudo jets within each event.From the figure 3 it seems like jet clustering haven't been done properly because the peak should be at 5 or 6 in general. The reason may be a double counting of the leptons inside the jets.

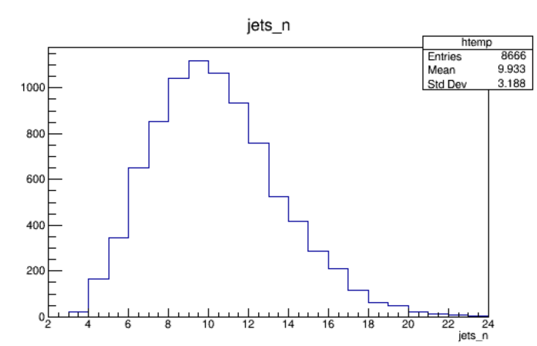

Figure 3: Inclusive clustering N(jet) distribution

The next step for this would be performing selection of events with zero,one and two leptons.

One of the interesting histograms we've obtained is N(lepton) distribution defined counting the tight lepton.

In the N(Lepton) distribution of our $t\bar{t}$ decay analysis at 365 GeV shown in figure 4 , we observe a majority of events with zero leptons,

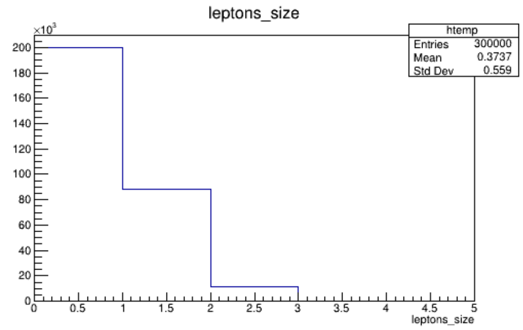

Figure 4: N(lepton) distribution

followed by events with one and two leptons. This distribution reflects the prevalence of the all-hadronic decay channel, contributing to the absence of leptons.

6. Learning outcomes

My time as a summer student at CERN provided a transformative experience that challenged me to learn programming languages like Python and C++, along with the ROOT framework. This intense learning journey pushed my limits, resulting in a rapid acquisition of valuable skills that will undoubtedly shape my future endeavors. Additionally, attending lectures on various physics and engineering topics broadened my knowledge and enriched my understanding of diverse fields.

References

Julie Munch Torndal(2021). "A Study of Top Anomalous Couplings at a Future e+e Collider"(Master's thesis).University of Copenhagen.

"2. Generators, Fast Simulation and Analysis — FCC Tutorials documentation." https://hep-fcc.github.io/fcc-tutorials/master/fast-sim-and-analysis/READM E.html.