

Central exclusive production of top quarks

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1 Introduction

This summer student project at CERN was dedicated to exclusive production of top quarks. For proton colliders exclusive production means that colliding protons after the collision do not get destroyed but through photons (25% of times) or gluons (75% of times) lose some of their momentum and create in our case top and anti top quark pair (see Feynman diagram, figure 1). Due to the momentum loss, these protons are more bent in the magnetic field of the accelerator and escape the beam.

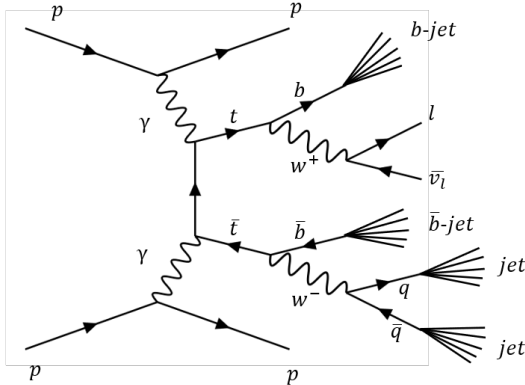


Figure 1: The Feynman diagram of the central exclusive production of the top quarks through photons. For this project we choose events where t quark decays into a b quark and a W. Then one of the W decays into two light jets, but another - into a lepton and a neutrino

There is no detector in the CMS to detect protons but as these protons are deflected from the beam only slightly, it is possible to detect them in special detec-

tors called Roman pots (RP) owned by the TOTEM experiment [1]. RP are aligned on both sides of the interaction point.

From the position in the RP where the proton was detected and knowing how protons interact with the magnetic field bending the proton beam, it is possible to calculate the fractional momentum loss ξ of a proton - how much momentum it lost after the collision. The proton interaction with the magnetic field can be described by the dispersion value D_x so that

$$x_{RP} = D_x(\xi)\xi$$

If the energy loss of both protons is known, it is also possible to reconstruct the invariant mass of the $t\bar{t}$ system by a formula:

$$m_{t\bar{t}} = \sqrt{s\xi_1\xi_2}, \quad (1)$$

where s is the centre of mass energy.

The exclusive production is a new research field at CERN because it uses data from detectors owned by two different experiments - CMS and TOTEM. Only in a recent years a joint experiment called CMS-TOTEM Precision Proton Spectrometer (CT-PPS) was created and so far only one paper on the exclusive production has been published. It provided an evidence for the semi exclusive $\mu\mu^-$ pair production - an event where only one of the protons was detected [2].

One of the problems for obtaining a good results for the exclusive top quark production is a large number of the background protons in the RP which could be solved by using the low pile up (low PU) data. The goal of this project was to make the first examination of data from the low PU run of 2018. At the time of doing this project the dispersion value D_x for the low pile up run of 2018 was not known but was to be

calculated soon. This work would ensure the usage of these data for the search of central exclusive top quark production as soon as all of the information about the dispersion of the protons for this run would be received.

The main tasks was to calculate the resolution of $t\bar{t}$ system for the 2018 data, improve the selection criteria, look for a shift of the P_T for the central system at low P_T scale and look if there are any problems with the data.

2 Obstacles for the search of the exclusive top quark production

The previous work done on the exclusive top quark production revealed some obstacles for calculating the invariant mass of the $t\bar{t}$ system from the proton momentum loss. The first one is that there are much more protons detected in the RP detectors then there are $t\bar{t}$ events. It was found that the number of protons detected in the RP grows with bigger vertex multiplicity, which leads to a conclusion that some of the excess protons come from the pile up events - collisions happening simultaneously. Another important characteristic was that sometimes there were more proton tracks than there were collisions in the interaction point. These tracks most probably come from other background effects.

So far there was no option to distinguish the protons coming from exclusive $t\bar{t}$ event from other protons. For this reason the calculations explained in section 1 did not give proper results. There were several attempts to extract these protons, but there was found no correlation between the mass of the $t\bar{t}$ system calculated from the momentum loss of protons (eq. 1) and mass of the $t\bar{t}$ calculated by the products detected in the CMS detectors.

There could also be the second reason for not seeing the correlation apart from the RP being swamped with protons. The resolution of $t\bar{t}$ is unknown. Maybe the resolution is so bad that the $t\bar{t}$ is often reconstructed incorrectly? This project will resolve this problem.

The problem of the large proton background in the RP could be solved by taking low PU data where

the β^* of the collision is increased, so more events with only one or two vertices are created. Some examination done on 2018 low PU data showed several promising events where t and $\bar{t}$ was created and also there was just one proton detected in the RP. Unfortunately, because the alignment information of the RP is not yet calculated it is not possible to look for a correlation between the mass of $t\bar{t}$ system calculated in both ways. But before running the calculations it is important to make sure the data have no flaws so the calculation would be possible to run as soon as the dispersion information is received.

3 Results

I began my research on the new low PU data by trying to reconstruct the mass of the $t\bar{t}$ system. First important feature is that the luminosity of these data is 5 pb^{-1} which compared with the luminosity of 2017 data (41.4 fb^{-1}) is more than 8 000 less. To get sufficiently large signal we had to lighten the selection criteria. The lower border of the P_T of the detected leptons was reduced from 30 to 25 GeV. As it is possible to see in the event diagram (fig. 1), top quark can decay into a lepton, neutrino and a b jet or into 2 light jets coming from W and a b jet. Such events were selected where one of the t quarks would decay through one way and the other - through the other way. So the new selection criteria are following:

1. Exactly one good lepton
2. Number of the light jets ≥ 2
3. Number of the b jets ≥ 2

We allow more jets than needed because the Feynman diagram (Figure 1) diagram can be extended and new jets can be produced from different places.

The result is shown in the figure 2 where we see two important properties. First is that even with the reduced selection criteria we see a good data purity corresponding to a data/background ratio of 8.5.

3.1 An improved event selection on 2018 Low PU data

Some additional selection was added to see a sharper peak $M_{t\bar{t}}$. First, if more than 2 light jets were detected, then those jets were selected, for which the

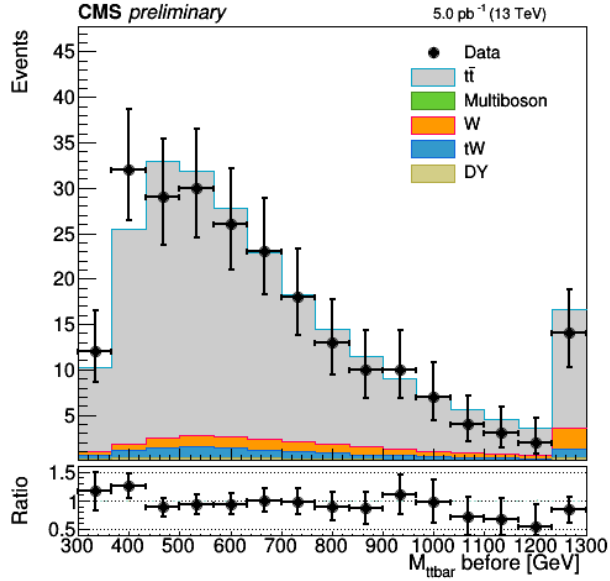


Figure 2: Invariant mass of the $t\bar{t}$ system done for 2018 low PU data and compared to the Monte Carlo simulations of 2017

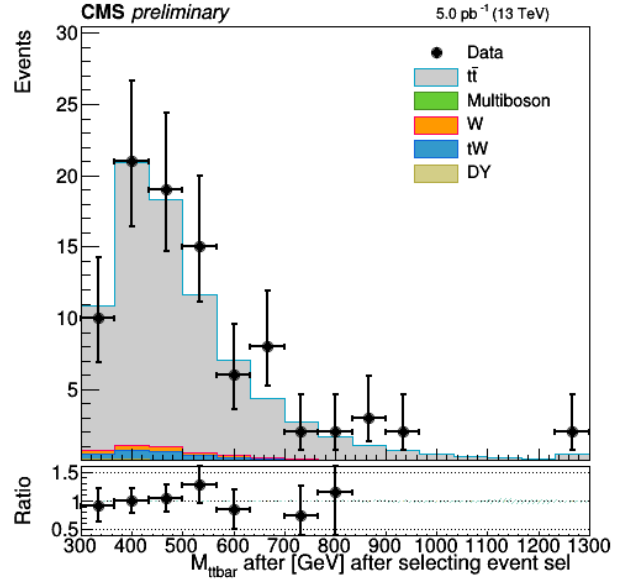


Figure 3: Invariant mass of the $t\bar{t}$ system done for 2018 low PU data and compared to the Monte Carlo simulations of 2017 after the selection of W mass and t mass

invariant mass would be closest to W mass ($m_W = 80$ GeV). So that these jets would have most probably come from the W. Before this jet selection was random. Also after this only those events were selected for which the invariant mass of W would fall into interval 80 ± 15 GeV.

Similarly was done for the t mass selection. Different combinations of the products were selected, so that they would most probably have come from t quarks.

The histogram of the invariant $M_{t\bar{t}}$ for the improved selection is shown in the figure 3. We indeed see a sharper peak with fewer background events. Although the number of data was reduced 2.8 times, the the purity of these calculations was improved from a signal-to-background ration of 8.5 to 20.

The comparison is better visible in the figure 4 where we clearly see a sharper peak for the data after selection, also it is more symmetrical.

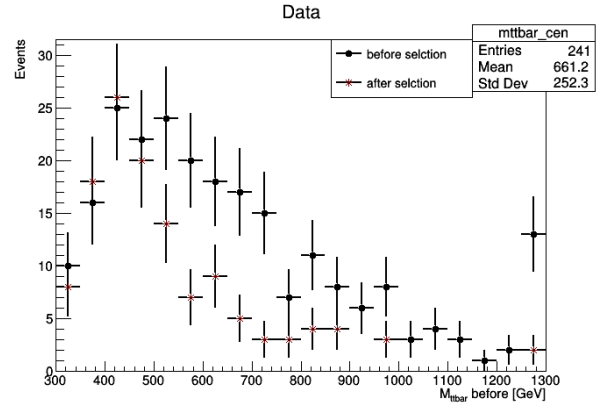


Figure 4: Comparison of the invariant mass of $t\bar{t}$ system using two selections - the usual selection, and the selection with added W mass and t mass selection.

3.2 Resolution of the $t\bar{t}$

In this project an answer to question about the resolution of the $t\bar{t}$ was provided. In the Monte Carlo (MC) simulation data information is available about

the properties of the generated top quarks, such as their momentum. Afterwards the MC simulates also the decay of these quarks and the interactions of the products with the detectors. We can compare how well it is possible from the products detected in the detectors to reconstruct the mass of the generated t quarks.

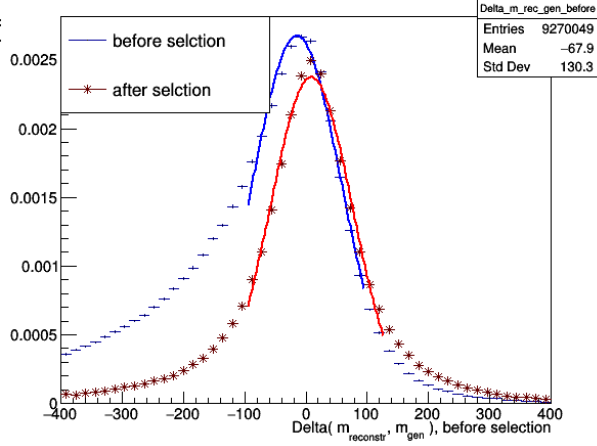


Figure 5: Histogram of the difference between m_{gen} - the mass of the $t\bar{t}$ system calculated from the generated top quarks and $m_{reconstr}$ - the mass of the $t\bar{t}$ system calculated from the simulated products detected in the detectors for the 2017 MC data

The difference between two masses calculated by both ways (m_{gen} - the mass of the $t\bar{t}$ system calculated from the generated top quarks and $m_{reconstr}$ - the mass of the $t\bar{t}$ system calculated from the simulated products detected in the detectors) is shown in figure 5 and we see a good correlation between both. We see that the difference tends to be around zero and the distribution is similar to a normal distribution. We can also notice that the improved selection gives a better resolution. The distribution is more symmetrical, the standard deviation of the fit with the Gaussian decreased from $\sigma = 72.1 \pm 0.2 GeV$ to $\sigma = 66.6 \pm 0.2 GeV$. Also the mean of the distribution shifted from $\bar{x} = -14.9 \pm 0.2 GeV$ to $\bar{x} = 8.7 \pm 0.1 GeV$ so it is closer to zero. So we can conclude that the resolution of the $t\bar{t}$ is good enough to reconstruct it well and the main problem with no correlation discussed in the section 2 is due to the proton

background.

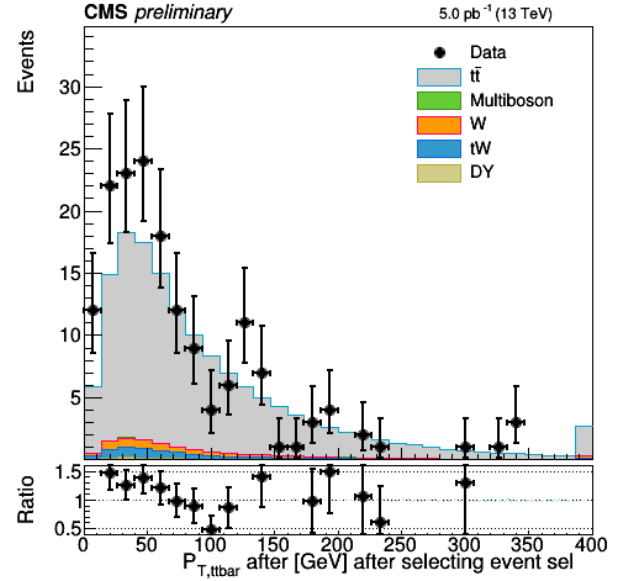


Figure 6: P_T of the central system for the 2018 low PU data compared with 2017 high PU MC data.

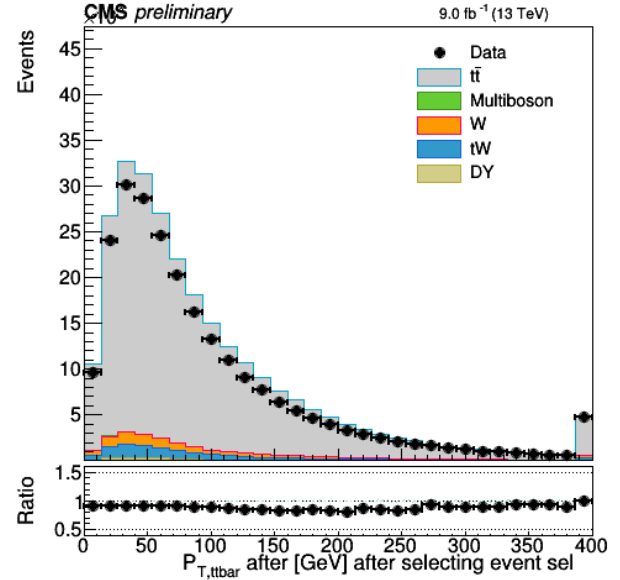


Figure 7: P_T of the central system for the general 2018 data compared with 2017 high PU MC data.

3.3 Excess of the P_T at low GeV

From the theory, both t quarks created from two photons should travel with an angle of π between them, i.e. they should go back to back. This means that momentum of this system should be around 0. I checked if it is possible to see an excess. In the figure 6 we indeed see the excess close to zero, but first of all it is not exactly zero. Secondly if we look at the general data of 2018 7, then it turns out that there is no such excess anymore. So we conclude that this excess should be caused by some factor other than exclusive $t\bar{t}$ production. Probably the reason is that for the data with low PU, detectors have better resolution at low P_T , i.e. if there is not that many background particles in the detector it can better detect small changes. This causes the results for a low PU data to be slightly shifted.

3.4 Angular distribution of the missing energy.

From the theory there should be no preferred direction in the transverse plane for any of the product. For most of these products it really is true. Only for the missing energy from which we calculate the energy of the neutrino this distribution works not as expected. As we can see in the figure 8 there is some preferred direction also for the MC data. This can be explained by some detector peculiarities but this effect should have disappeared when a proper selection for the data is done. Also we see that for data of 2018 this direction has changed for which there is no reason yet. This effect should be examined more through application of some other selection and check of some more details.

4 Conclusion

The main conclusions of this work are:

- Despite the low number of data for the low PU data of 2018 it is still possible to reconstruct the $t\bar{t}$
- The resolution of $t\bar{t}$ for the improved selection is better.

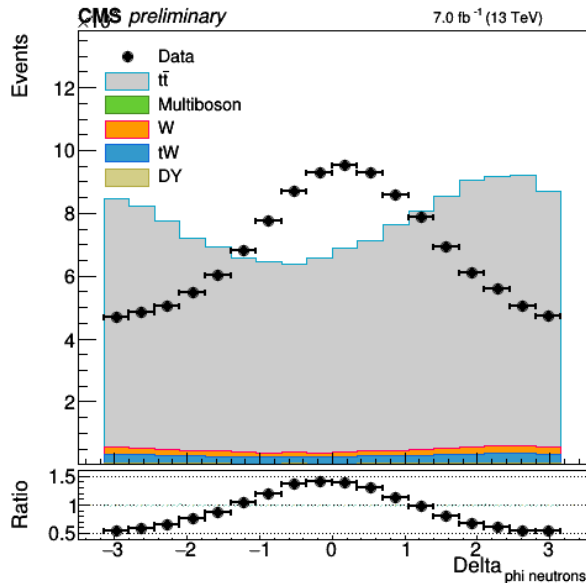


Figure 8: Angular of the distribution of the missing energy for 2017 low PU data compared with 2018 high PU MC data.

- The excess P_T of the central system with low values was investigated and explained to be because of the better resolution of the detectors for low PU data
- It is still not clear why the distribution of the missing energy of the collision is not uniform and this distribution differs for 2017 data and 2018 data.

References

- [1] TOTEM Collaboration, “The TOTEM Experiment at the CERN Large Hadron Collider,” *Journal of Instrumentation*, vol. 3, no. 08, p. S08007, 2008.
- [2] CMS Collaboration and TOTEM Collaboration, “Evidence for proton-tagged, central semi-exclusive production of high-mass muon pairs at 13 TeV with the CMS-TOTEM Precision Proton Spectrometer,” 2017.