Measurement of $t\bar{t}$ cross section in the lepton+jets channel at $\sqrt{s} = 13$ TeV with the ATLAS detector

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Abstract

Measurement of top quark pair production cross-section is an important physics result at the Large Hadron Collider. Precision measurement such as cross-section requires that the events are well reconstructed and that systematic uncertainties are small. In this context, we investigate two aspects of top quark cross-section measurements: kinematic fitting based event reconstruction and systematic uncertainty on luminosity measurement. Luminosity data collected in 2016 was analyzed for the Beams Condition Monitor, BCM, and the LUminosity Cherenkov Integrating Detector, LUCID. The discrepancy between luminosity values of the two detectors was determined to be both visible interaction rate, μ, and Bunch Crossing IDentification, BCID, dependent. Scale factors to make BCM in better agreement with LUCID were determined for this data. Data collected in 2015 at $\sqrt{s} = 13$ TeV with 3.2 fb^{-1} was used to compare the transfer functions derived at $\sqrt{s} = 8$ TeV and at $\sqrt{s} = 13$ TeV as implemented in the KLFitter tool.

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1 Introduction

The heaviest known elementary particle is the top quark. Because it has the largest mass of all fundamental particles, it has the strongest interaction with the Higgs boson [1]. The top quark also plays a special role in physics beyond the Standard Model [1]. Multiple decay channels of pair produced top quark events, or $t\bar{t}$ events, make up the dominant background for many new physics searches [1]. As shown is Figure 1, the decay products of $t\bar{t}$ are strikingly similar to those for hh and the supersymmetric top quark. Therefore, the need to thoroughly understand the top quark is growing as these searches for new physics become ever more imminent.

One quantity which provides vital information in the overall modeling of the top quark, is the cross-section measurement. Cross-section is the effective area for incoming particles to scatter from. Therefore, a small cross-section means a low probability of an interaction occurring. Understanding this quantity of the top quark and all the systematic uncertainties associated with it will determine how probable a $t\bar{t}$ event is and how well it is modeled. This probability will establish how much background from $t\bar{t}$ events should be expected when searching for the small signals of new physics. Therefore, it is important that we reconstruct $t\bar{t}$ events as accurately as possible.

In addition, reduction of systematic uncertainties of the top quark's cross-section will also help distinguish background from signal in these searches. Throughout Run2, BCM has produced luminosity values close to 20% off from LUCID. Analysis of the difference between BCM and LUCID will expose any possible dependence on μ or BCID. Scale factors reliant on μ and BCID will then be added to help reduce the 20% variation observed in BCM. Luminosity is an important piece of information when determining cross-section of the top quark as the rate at which $t\bar{t}$ events are seen is proportional to luminosity and cross-section: $\dot{N} = \mathcal{L}\sigma$. Reduction of the uncertainty on luminosity will help reduce total uncertainty of a cross-section measurement.

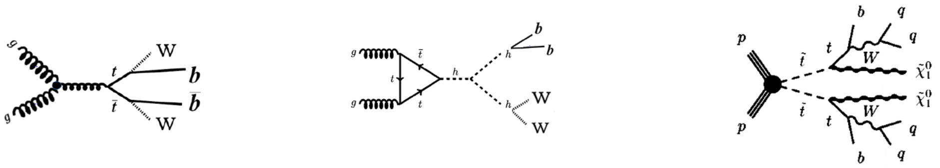

Figure 1: Feynams diagrams for $t\bar{t}$, hh, and stop quark. All have identical decay products as χ is a neutralino which is not detected by the detector directly.

2 ATLAS Detector

A Toroidal LHC ApparatuS, ATLAS, is a general purpose detector located 100 m underground at Point 1 of the Large Hadron Collider (LHC) in Geneva, Switzerland. The experiment's main goal is to study fundamental particles and conduct searches for new physics. It consists of an inner tracker region which is surrounded by two types of calorimeter. The electromagnetic calorimeter measures the energy deposited of all particles through their electromagnetic interactions, while the hadronic calorimeter measures the energy deposited by hadrons. The outer most layer of the ATLAS detector is the muon spectrometer, which measures the momentum of muons as they pass through.

2.1 BCM Sub-Detector

ATLAS contains several sub-detectors with various roles. The BCM consists of eight 10×10 mm^2 CVD diamond sensor modules. Four of these modules are placed on each side of the inner tracker region, arranged in a cross pattern 1.7 m from the interatction point at 5 cm from the beam [2]. The hardness of diamond gives it the ability to withstand radiation with little deterioration of its abilities [?]. Specially, the BCM has the overall goal of protecting the more sensitive silicon tracker and delivering luminosity measurement values. The BCM determines which interactions come from interaction point collisions of the two beams and how many are due to beam background. This is done by keeping track of the time of flight of particles as they hit BCM modules on either side of the interaction point. Moreover, using the number of hits, it is possible to obtain a value of luminosity.

2.2 Luminosity

Luminosity is a vital piece of information when determining cross-sections as the rate of the number of specific events occurring is expressed in the following equation: $\dot{N} = \mathcal{L}\sigma$, where N is the number of events, $\mathcal{L}$ is the luminosity, and σ is the cross-section. The ATLAS sub-detectors record values of μ, the visible interaction rate, per bunch crossing [2]. μ values are obtained by recording how many interactions the sub-detector's algorithm sees, N_{OR}, as well as the total number of interactions which occur in a bunch crossing, N_{BC}. With these two values and the Poissonian statistics of event counting, μ can be calculated with the following equation: $\mu = ln(1 - \frac{N_{OR}}{N_{BC}})$. For details of the various counting algorithms used by BCM and LUCID see [2]. μ and cross-section are related by $\mathcal{L} = (\mu n_b f)/(\sigma)$, where n_b and f are the number and frequency of bunches respectively. The LHC is divided into bunches which contain 3564 BCID each of length 25 ns. These bunches can be either filled with protons or empty.

Obtaining $\mathcal{L}$ in order to relate μ to σ is done through the van der Meer calibration scan. During this scan the two beam lines start separated and are slowly brought together to overlap slightly. The overlap region of the beam lines continues to grow. Eventually the beams become separated again, with their final positions flipped with respect to their initial positions. For this process, the luminosity is found by $\mathcal{L} = (n_b f n_1 n_2)/(2\pi\Sigma_x\Sigma_y)$, where n_n is the number of protons in beam n, and Σ_x and Σ_y are the horizontal and vertical convolved beam widths respectively, which are known well during a van der Meer scan. Once $\mathcal{L}$ and μ are determined for the sub-detectors, a cross-section measurement can be obtained using $\mathcal{L} = (\mu n_b f)/(\sigma)$.

The luminosity uncertainties provide one of the major systematic uncertainties for cross-section measurements. A breakdown of the different uncertainties due to luminosity can be found with more detail in [2]. The largest of such uncertainties comes from error when interpolating from the low μ seen during calibration, to the high μ obtained in data collection which is 1.6% of a total uncertainty of 2.2%.

2.2.1 Adjustment of BCM Luminosity Values

In order to understand the discrepancy between BCM and LUCID, luminosity data collected in 2016 from both detectors was studied with algorithms BCMHOR and LCDOR_PMT, which select on average only one out of every ten hits. In particular, subsequent filled bunches, called a bunch train, were analyzed to more clearly determine what the divergence depended on. The ratio between BCM and LUCID μ values was evaluated for the first full bunch train. As shown in Figure 2, the overall shape of the data indicates a dependence on BCID within a bunch train, while the vertical shifting shows a dependence on the visible interaction rate.

Once the dependencies of the variation were determined, scale factors were added to better align the two sub-detectors' output. First, scale factors were applied to $\mu = 15$ depending on BCID to remove the shape of the data. Once the BCID dependent scale factors were chosen, they were applied to all μ values. This resulted in straight lines at varying distances from one. Second, an overall scale factor was determined for each μ value to combat the vertical shifting. The results of theses scale factors can be seen in the right plot of Figure 2.

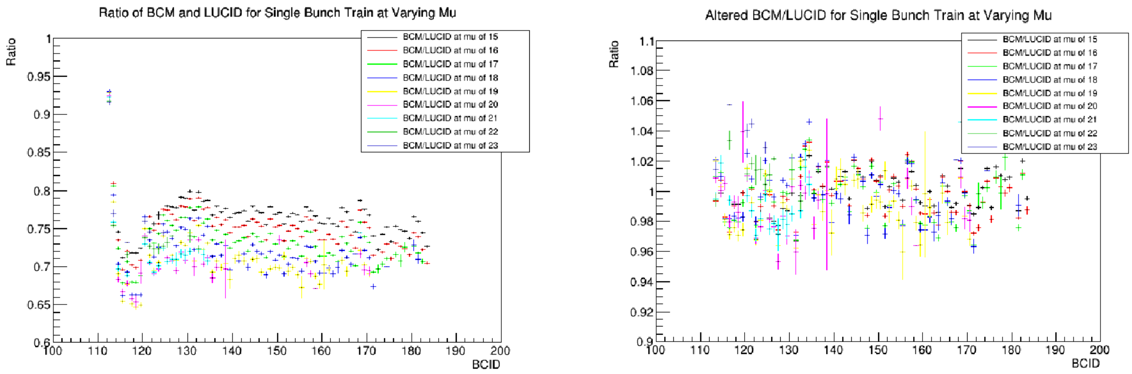

Figure 2: Ratio between BCM and LUCID at various visible interaction rates (μ) for a single bunch train without (left) and with (right) the scale correction factors.

With the correction factors the BCM is approximately 5% different from LUCID, a large improvement from the initial 20%. However, refinement of these scale factors is needed for better agreement. The figures above show only the first full bunch train in the data. To determine if the overall dependence of both μ and BCID was reliant on bunch train, the second full bunch train was analyzed. The scale factors obtained for the first were applied to the second and the ratios became centered around one, much like for the first bunch train. Though there were several outliers, overall there appears no dependence on bunch train.

3 Kinematic Likelihood Fit

This analysis is performed in the single-lepton channel in which one W boson decays into a lepton and a neutrino, and the other into two light quarks. The quarks undergo a process of hadronization, resulting in jets whose energies are measured by the calorimeter. Multi-jet topology of $t\bar{t}$ events make it difficult to discern which quark each jet originates from. The kinematic likelihood fit helps assign jets to the respective quarks from which they come. Kinematic fitting also helps improve the reconstruction of event kinematics by constraining kinematic variables within their resolutions and for given hypothesis.

This approach works to obtain the best value of the measured quantity within the detector resolution by maximizing the log likelihood of a given hypothesis, $t\bar{t}$ in this case. The likelihood value is computed for all permutations of the jets. At the end, the “best fit” value corresponds to the highest log likelihood for the event being a $t\bar{t}$ event. This assign the best permutation of jets and also gives the best fitted values for the kinematic variables. While the former helps with jet-quark assignment, the latter improves mass resolution by exploiting the detector resolution and kinematic constraints.

The detector resolutions are also called transfer functions. The parameterizations of the transfer functions were determined by analyzing Monte Carlo simulations of $t\bar{t}$ events [3]. This was done for Monte Carlo sample in $\sqrt{s} = 8$ TeV and also at $\sqrt{s} = 13$ TeV. More information about the derivation of the 13 TeV transfer functions can be found at [3].

4 Analysis

After reconstructing the event under $t\bar{t}$ hypothesis, selection of more pure $t\bar{t}$ events is important. In order to select more $t\bar{t}$-like events, which set of transfer functions to use for the kinematic likelihood fit must be decided. To do this a full comparison of the data after it was processed with each of the two sets of transfer functions was needed. The data analyzed to compare the 8 TeV transfer functions and the 13 TeV transfer functions was data collected in 2015. The center of mass energy at this time was 13 TeV and the total luminosity of the collected data was 3.2 fb^{-1}.

4.1 Selection Criteria

The pre-selection requirements of events used in this analysis are as follow: a single lepton trigger; a primary vertex with at least 2 tracks coming from it; at least four jets in the event, with at least two of those jets b-tagged; each jet must have a transverse momentum greater than 20 GeV and an absolute value of eta less than 2.5; and one trigger-matched lepton. These selection criteria are slightly different than those used to derive the transfer functions in 13 TeV. Details about the derivation of the 13 TeV transfer functions and the pre-selection requirements used in their calculation can be found at [3]. Even though the analysis framework used to process the data was obtained from the Higgs group of the ATLAS collaboration, object and event selections are essentially identical to those used by the Top group.

4.2 Comparing Transfer Functions

The analysis was done by comparing the results of the kinematic likelihood fit when the 8 TeV transfer functions and the 13 TeV transfer functions were used. A difference between using one set of transfer functions versus the other can be seen when looking at the log likelihood of a $t\bar{t}$ event shown in Figure 3. Figure 3 shows how likely an event is $t\bar{t}$, with the x-axis offset so values closer to -40 mean a higher probability. Log likelihood value of -48 was used as a cut to obtain more $t\bar{t}$ like events in the comparisons as determined in Re. [4]. It can be seen in Figure 3 that as more pure $t\bar{t}$ events are selected, the difference between 8 TeV versus 13 TeV transfer functions is not negligible. In all kinematic variable distributions there appeared to be discrepancies when using one set of transfer functions over the other. Representative kinematic variable plots can be found in Appendix A.

4.3 Resolution Improvement

The kinematic variable distribution of the hadronically decaying W boson was analyzed and fitted separately for each transfer function set. A double Gaussian was used in the fit. This kinematic variable was fitted to obtain the resolution of the mass of the hadronic W boson. By fitting the data and obtaining a standard deviation value for both transfer function sets, the transfer functions which produce the best resolution could be determined. One such variable can been seen in Figure 4, with the determination that the 13 TeV transfer functions result in a better resolution.

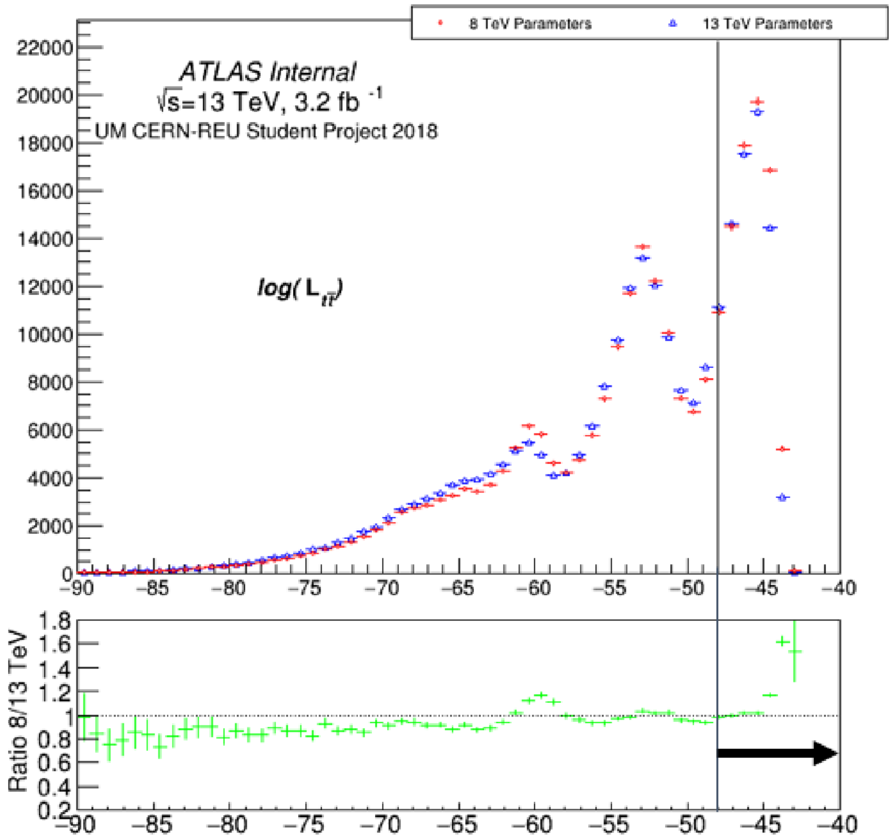

Figure 3: Log likelihood of the event selected being $t\bar{t}$. Red markers are 8 TeV and blue 13 TeV transfer functions. The bottom panel shows the ratio between the two sets of transfer functions.

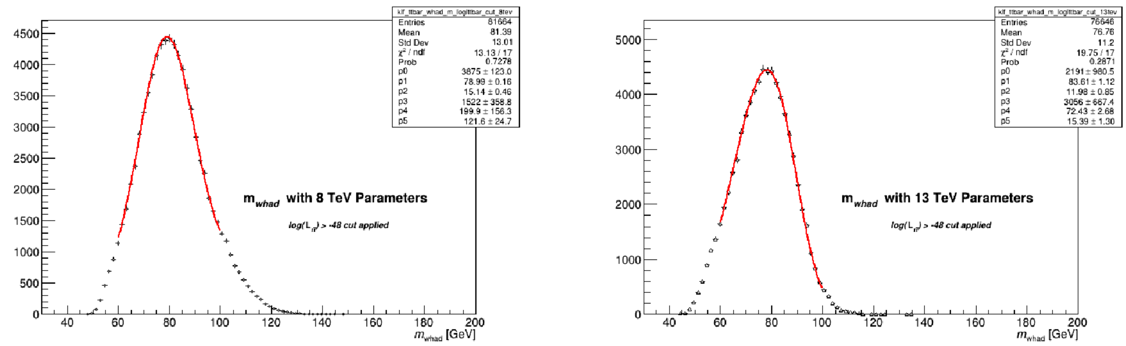

Figure 4: Hadronic W boson reconstructed with 8 TeV transfer functions (left) and 13 TeV transfer functions (right). The black markers are the data while the red line is the fit. The mass resolution improves about 2-3 GeV when using the 13 TeV transfer functions compared to the 8 TeV transfer functions.

5 Conclusion

Understanding the top quark plays an important part in searches for new physics. Once the top quark events is understood, it will become easier to differentiate between top quark as background and the rare signals of new physics. The luminosity measurements of the BCM sub-detector has a dependence on μ and BCID which causes it to be in disagreement with other sub-detectors. Lack of knowledge about this discrepancy is one factor which causes BCM luminosity measurements not fully usable. After correction factors were applied, alignment of luminosity measurements of the sub-detectors increased. The best set of transfer functions to use in a kinematic likelihood fit which will help reconstruct events under the hypothesis of $t\bar{t}$ was also determined. We found approximately 10% discrepancy when comparing event yields between using the 8 TeV transfer functions and the 13 TeV transfer functions in data of $\sqrt{s} = 13$ TeV. We also found that the 13 TeV transfer functions improve the mass resolution of the hadronically decaying W boson.

References

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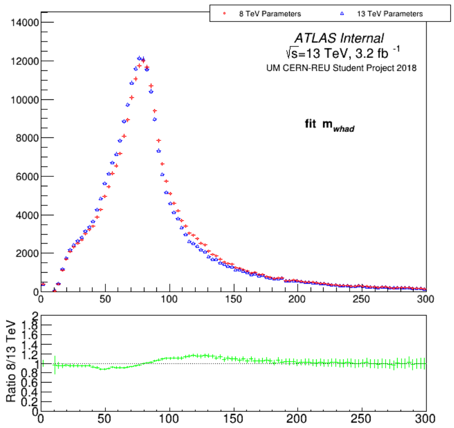
[2] ATLAS Collaboration, *Luminosity determinationin pp collisions at $\sqrt{s} = 8TeV$ using the ATLAS detector at the LHC*, Eur. Phys. J. C (2016) 76: 653 DOI: 10.1140/epjc/s10052-016-4466-1.

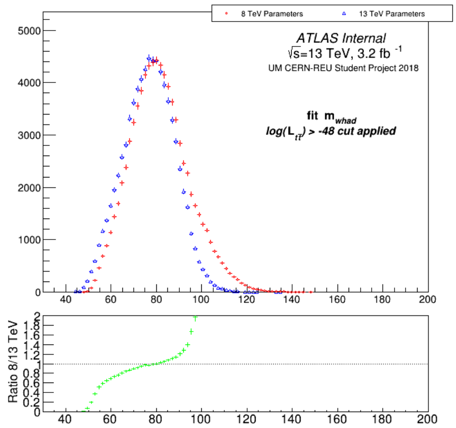
[3] Anthony Ciavarella, *Analysis of Top Quarks Using a Kinematic Likelihood Method*, The Ohio State University. Department of Physics Undergraduate Research Theses; 2017 `https://kb.osu.edu/handle/1811/80663`

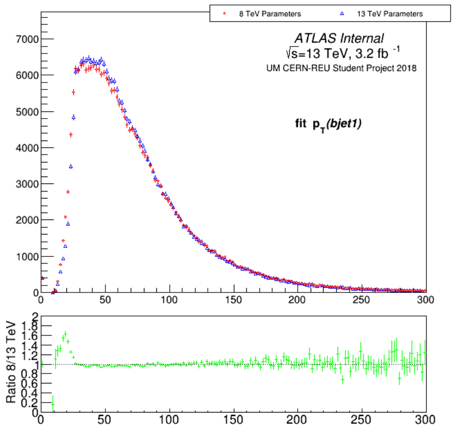
[4] ATLAS Collaboration, *Measurement of the W boson polarisation in t t events from pp collisions at $\sqrt{s} = 8TeV$ in the lepton + jets channel with ATLAS*, Eur. Phys. J. C (2017) 77:264 DOI 10.1140/epjc/s10052-017-4819-4.

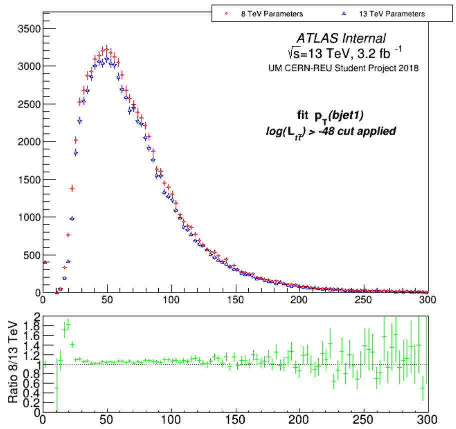
Appendix A

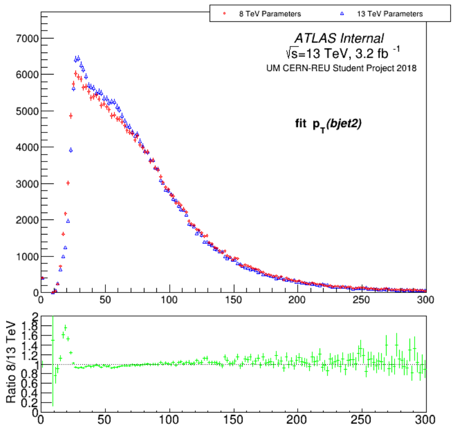
In this section, we present a few representative kinematic variables. In all the plots, red markers are for data when using 8 TeV transfer functions, while blue markers are data when using 13 TeV transfer functions. The bottom panel shows the ratio between the two sets of transfer functions.

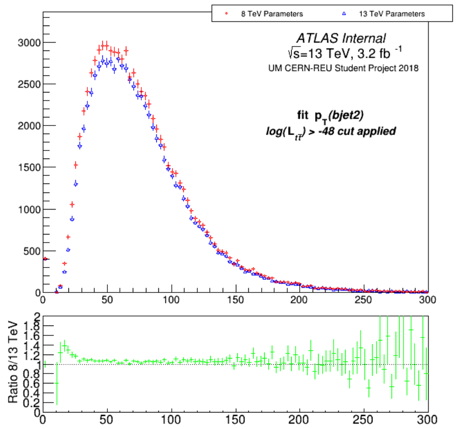


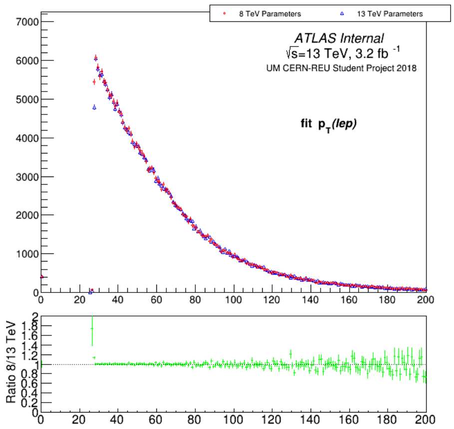








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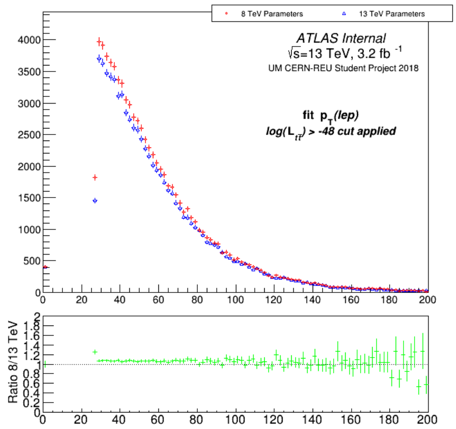
fit p_T(lep)
Ratio 8/13 TeV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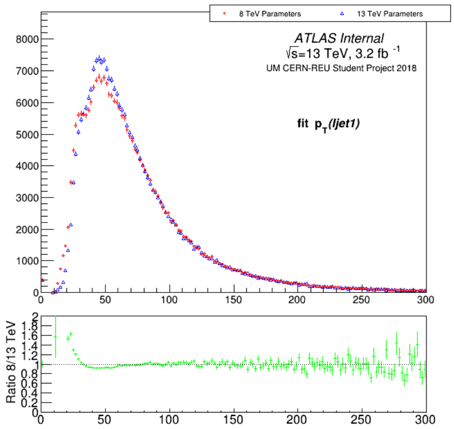
Ratio 8/13 TeV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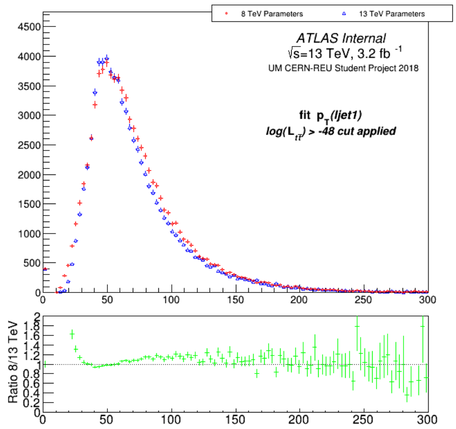
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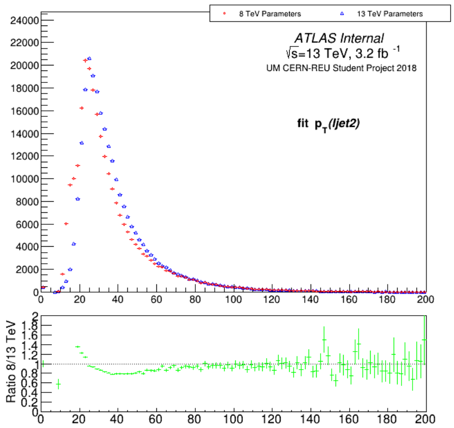
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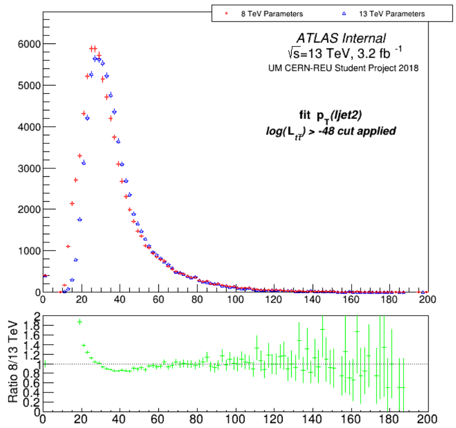
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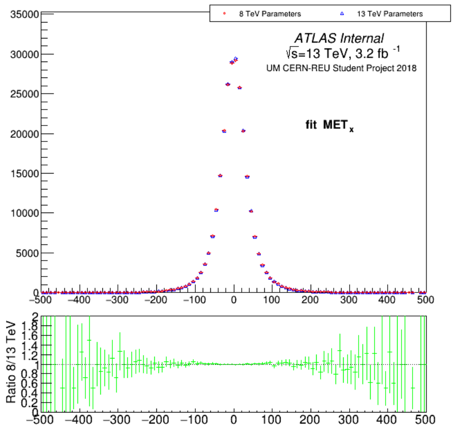
Ratio 8/13 TeV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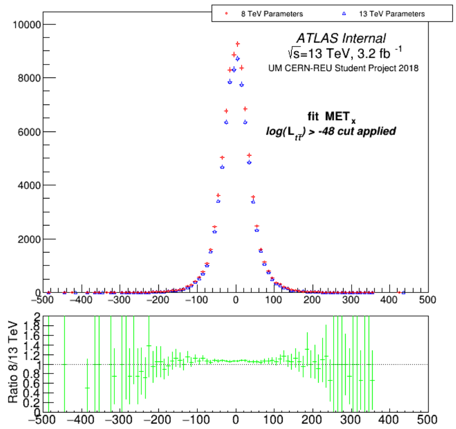
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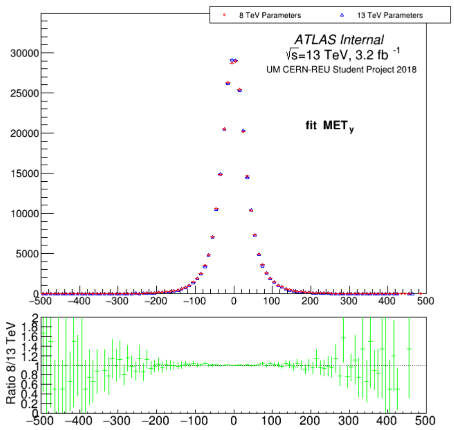
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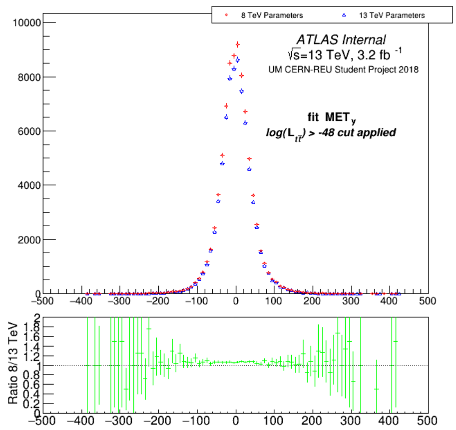
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Ratio 8/13 TeV