Analysis of the peak in the 1 lepton 1 tau same-sign events at $\sqrt{s} = 13$ TeV

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Abstract

This paper presents the results of the analysis of the 1 lepton 1 tau events from the ATLAS open data. The analysis targets final states including two same sign particles, $\ell^{\pm}\tau^{\pm}$ (where $\ell = e$ or μ) and at least two hadronic jets. In the invariant mass spectrum was an unexpected peak of events at 200-210 GeV. There was a significance of $\sigma = 2.8$, which is a hint of a new particle. The properties of this peak showed that the events are mostly two positive particles and the same amount of events with electrons and muons. The pseudorapidity of the τ particles showed a peak around $|2|$ rad. The azimuthal angle $\Delta\phi_{\tau M_{ET}}$ also shows weird signs where most events are around 1 rad. No definite evidence was found for or against the existence of a new particle. More data and research would be needed to get to a conclusion of this analysis.

Furthermore, a measurement was done on unlike sign e^+e^- and $\mu^+\mu^-$ events. This measurement could be used to determine lepton universality for a possible leptoquark decay using the vector boson scattering.

Contents

1 Introduction

The initial goal of this research was to look for signs of a heavy majorana neutrino in same-sign $W^{\pm}W^{\pm}$ events at $\sqrt{s} = 13$ TeV. Neutrino oscillation experiments showed that there are non-zero neutrino masses, which can not be explained by the current particles in the Standard Model of particle physics. One of the more supported hypothesis is the existence of majorana neutrinos.

Beyond the SM models include heavy neutrinos. The mass of these particles is unknown, since they have not been detected yet. If the mass of these particles is too high, they cannot be created in the Large Hadron Collider (LHC). At lower energies (< 1000 GeV), Particles can be created and detected in the LHC. This analysis aims to probe two sets of data to search for evidence for heavy majorana neutrinos at low energies created by the LHC in same sign events. These two data sets are the exactly two leptons and 1-lepton-1-tau events from the open data. The exactly two lepton data set was also used in an unlike sign analysis for the lepton universality of leptoquark decays.

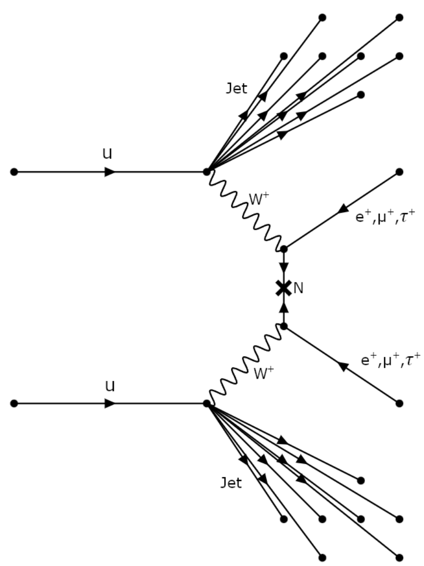

Figure 1: The Feynman diagram of the annihilation of a heavy majorana neutrino that this analysis seeks to find. The 2 majorana neutrinos annihilate at N.

The second goal is to test lepton universality with possible leptoquark decays. The following is a Feynman diagram how a decay with a leptoquark would look like for the decay of a B meson to a kaon.

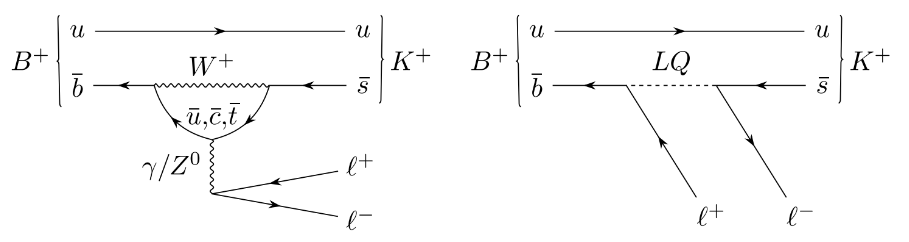

Figure 2: Feynman diagrams of the decay of a B^+ into a $K^+\ell^+\ell^-$. (left) The bosons W^+,Z^0 and γ, with an $\bar{u}, \bar{c}$ or $\bar{t}$ contribute. (right) A theoretical leptoquark (LQ) contributes. [1]

In the left Feynman diagram, electrons, muons and tau particles have the same interaction strength with the Z^0 particle. This mean that there is an equal chance for the leptons to be electrons, muons and tau particles. Such decays are said to respect lepton universality. There is an exception for interactions with the Higgs particle, since the mass of the leptons is not the same. If there are leptoquarks and the right decay would be possible, then there could be different interaction strengths between the leptoquark and the leptons. These interaction strengths can be calculated with the R_K ratio.

$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to J/\psi(\to \mu^+\mu^-)K^+)} \Bigg/ \frac{\mathcal{B}(B^+ \to K^+e^+e^-)}{\mathcal{B}(B^+ \to J/\psi(\to e^+e^-)K^+)} \tag{1}$$

The four term in this formula are the relevant branching fractions of the decays they represent. The decays with J/γ represent the left Feynman diagram in figure 2. This decay respects lepton universality, and the branching fractions are measured to be within 0.4% of each other. With this equation, only the efficiency of the $B^+ \to K^+e^+e^-$ decay with respect to the $B^+ \to J/\psi(\to e^+e^-)K^+$ decay, instead of the efficiency between $B^+ \to K^+e^+e^-$ and $B^+ \to K^+\mu^+\mu^-$. This is more efficient since the detector signals are similar for the two reactions that result in the same leptons. Therefore, uncertainties in the measurement would dominate the $B^+ \to K^+\mu^+\mu^-/B^+ \to K^+e^+e^-$ ratio. There is a lot of interest in lepton universality, since [1] presents evidence of a decay that does not obey lepton universality.

This analysis does not look for B meson decays, but for vector boson scattering (VBS). In this case, two W bosons collide and with a propagator create two leptons (see the following Feynman diagram).

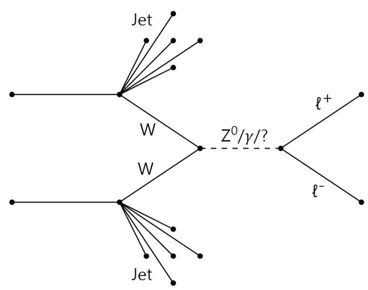

Figure 3: The Feynman diagram of VBS.

Where the decay $VBSZ \to \ell^+\ell^-$ obeys lepton universality. The $VBS \to \ell^+\ell^-$ is to be determined in this analysis.

2 ATLAS

In this analysis, the open data from the ATLAS detector was used [1]. It is one of the detectors in the LHC of CERN. It measures the particles that are created by a collision in the LHC at a certain centre-of-mass energy. Electrons & muons can be observed directly. Quarks and gluons form jets that can be detected. Tau particles decay before they are detected (see table 3). The taus that decay into electrons and muons are classified as electrons and muons respectively. The other decays can be measured, but when measured it is not certain that the particles came from a tau. Only a chance that those particles came from a tau can be calculated. Lastly, a W or Z boson decays into a pair of fermions.

This data is in four periods in the ATLAS detector and Monte Carlo (MC) simulations of events at the ATLAS detector (A, B, C & D). The data from all four periods is used in this analysis. The MC simulations are split up into different possible events that are possible in the LHC. The simulations provide the same data that a measured event would collect. The MC simulations do have some extra data with them like the weight of the event because not every event is as likely as another. To be more realistic, simulated events that are less likely to happen have a smaller weight. It makes it so the event will not be counted as heavy as an event that is more likely to happen.

Events in the LHC can only be detected by what particles come out of a collision. Some particles like neutrinos can not be measured. To get some information of the particles that are not detected the missing energy is used. At the LHC the missing energy in the transverse direction of the collider is used, this is

[1] https://atlas-opendata.web.cern.ch/atlas-opendata/samples/2020/exactly2lep/

zero initially. If the total energy of an event is known, it is possible to determine how much energy should be in particles that are not detected. Using conservation of energy, the energy of the detected particles can be calculated. From the detected particle, everything is measured. The energy, charge, direction in which it travels. After the collision, the transverse momentum of all measured particles is not necessarily zero. Therefore, one can determine the transverse energy of the neutrinos. One other important property that can be calculated this way is the invariant mass, the total mass of the lepton pair:

$$M_{ll} = \sqrt{(E_1 + E_2)^2 - \|\vec{(p_1)} + \vec{p_2}\|^2} \tag{2}$$

$$= \sqrt{(E_1 + E_2)^2 - (p_1^x + p_2^x)^2 - (p_1^y + p_2^y)^2 - (p_1^z + p_2^z)^2} \tag{3}$$

Where 1 and 2 are particles and E are their energies and p their momentum. This formula can also be used for the jets to calculate their invariant mass.
These properties can be used to only select the events at which certain particles could be created. In this analysis, the events were selected such that only events where $W^{\pm}W^{\pm}$ are possible. In these events, the theorized majorana neutrino could be found if it exists and has a certain mass. A lot of research has already been done to find this particle.

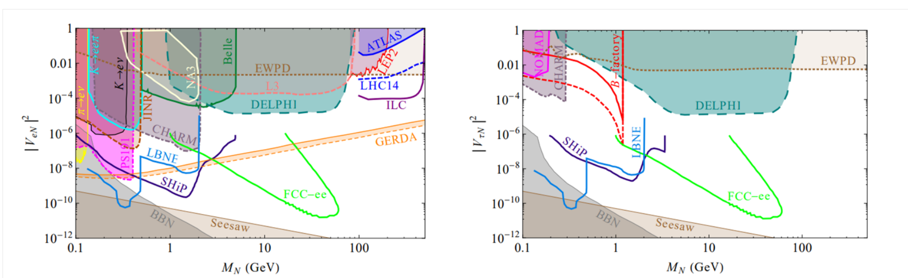

Figure 4: Limits on the current and expected coupling between the (left) electron & (right) tau neutrino and a single heavy neutrino in the mass range 100 MeV - 500 GeV.[2]

In these graphs, the neutrino mixing parameter,$|V_{(e/\tau)N}|^2$, is plotted against the heavy neutrino mass. The mixing parameter V_{eN} gives the coupling between an electron and heavy neutrino, and $V_{\tau N}$ is the coupling between a tau and the heavy neutrino. The fields that are colored in are the regions where has been searched without any signs of a heavy majorana neutrino. The lines that don't have a field with their color are experiments that are experiments that have been planned to search the neutrino, only the LHC14 experiment has begun taking measurements. ATLAS detects particles that have a high mass. In the top right side of the graph. For the two lepton events research has already been done in this area but not in the region for one lepton one tau events.

3 Exactly 2 lepton analysis

Initially, the analysis was done on the exactly 2 lepton open data from the ATLAS detector. This was done as an exercise to get to know the data and the program that was used for the analysis. For the base of the program, a program from ATLAS data tools was used. Specifically, the ttZ_2l_analysis from the ATLAS Outreach repository on GitHub with all files that go with it [2]. The event selection needed to be altered to fit this analysis. The selection criteria from the following note were implemented [3].
With these criteria, there remained too few events to analyze. So the selection criteria were relaxed. With the new selection criteria, there also remained too few events in same-sign events, as the following graph shows.

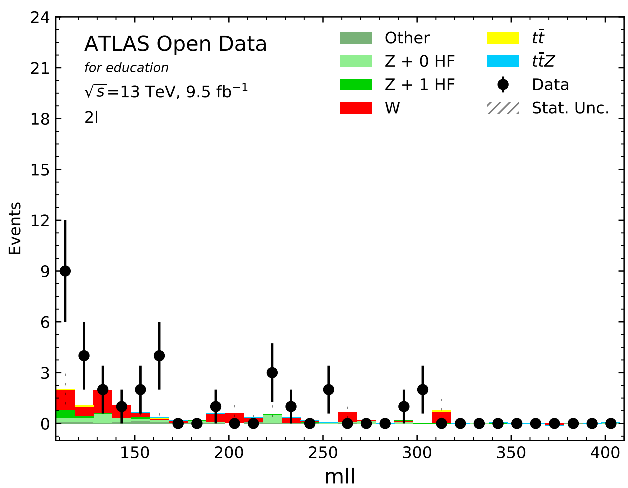

Figure 5: Invariant mass spectrum of 2 leptons in same sign events.

Therefore, on this data set, opposite sign events were used to see if the simulated data was consistent with the measured data in the signal region and in the $t\bar{t}$, W and Z control regions. This data was also later used to calculate the R_K ratio.

[2] https://github.com/atlas-outreach-data-tools/atlas-outreach-Python-uproot-framework-13tev

3.1 Lepton Selection

The only requirement on the leptons was on the transverse energy, which is approximated by the transverse momentum. Also, a cut was set on the leptons to have the same charge, since this analysis is done on same sign events.

Table 1: Caption

Feature	Criterion
lepton pt	> 10 GeV
lepton charge	$\neq 0$
M_{jj}	> 300 GeV
$\Delta\eta_{jj}$	> 3
Jet_{pt}	> 20 GeV
Algorithm	MV2c10
b-veto	on
Operating point	$Eff = 85\%$
E_T^{miss}	$< 40 GeV$

The requirements were set on the angles and the invariant mass of the jets. Only events that had at least two jets were considered. In case there were more than two jets, only the two jets with the highest transverse energy taken into consideration.
The invariant mass of the jet, M_{jj}, is calculated the same way as the invariant mass for particles. The only difference is that the energy and momentum of the jets is used. The requirement of $M_{jj} > 300$GeV is so to select VBS events.
The b-tag determines the probability that b hadron decay occurred. A b hadron has a lifetime that is just long enough to travel a few millimeters before decaying. After that decay, a jet of other hadrons is created. Tracking the jet shows where it originated, if that was away from the collision it could be because of a b hadron. An algorithm calculates the chance that a jet is because of b hadron decay, in this case the MV2c10 algorithm. A requirement can then be set on the chance that it as beta decay. With this algorithm, a value between -1 and 1 is given. For an efficiency of 85% a value above 0.1758 is needed [3]. We put a veto on b-tag on the events because a W boson couples to a top and a bottom quark most of the time. With a b-veto, those events can be cut from the analysis. In the $t\bar{t}$ control region, the b-veto is turned off because the decay into top quarks should be in that control region.

[3] https://cds.cern.ch/record/2160731/files/ATL-PHYS-PUB-2016-012.pdf, table 2, page 15

4 1 lepton 1 tau Analysis

The creation of a heavy majorana neutrino was also possible in 1 lepton 1 tau events. Almost the same requirements from the 2 lepton events could be used with slight adjustments for the tau particle.

4.1 Lepton Selection

These are the same requirements set on the 2 lepton analysis, except that the tau particle has another requirement for the transverse energy. (see table 1)

Table 2: Requirements on the lepton and tau

Feature	Criterion
lepton pt	> 10 GeV
tau pt	> 20 GeV
lepton charge	$= 0$
M_{jj}	> 300 GeV
$\Delta\eta_{jj}$	> 3
Algorithm	MV2c10
Operating point	$Eff = 85\%$
E_T^{miss}	< 40 GeV

Requirements were set on the angles and the invariant mass of the jets. Only events that had at least two jets were considered. In cases where there were more than two jets, only the two jets with the highest transverse energy were taken into consideration.

4.2 Control Regions

Control regions are used to check if the MC simulations correctly simulate the events. In the control regions one would not expect to find any peaks in the data since the reaction that is looked for would not happen in the control regions. If there is a peak in one of the control regions in the same place as the peak in the signal region, it would probably not be the particle that was looked for.

5 Results

5.1 Signal Region

The following graph shows the invariant mass spectrum of the same sign 1 lepton 1 tau analysis.

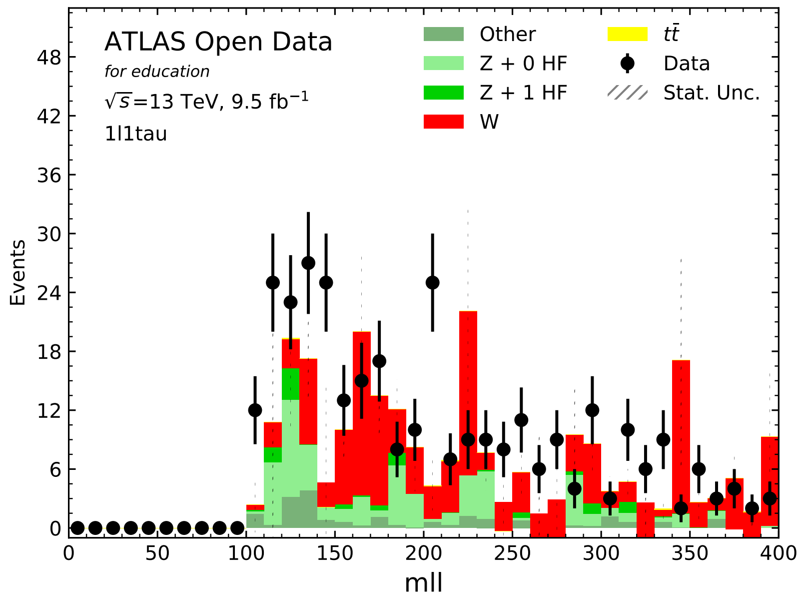

Figure 6: Invariant mass spectrum of 1 lepton 1 tau events.

There is a peak between 200 and 210 GeV invariant mass. This shows that a new particle could be created. If that is the case, that would explain why there would be a peak in the graph. Another reason that there is a peak is that something went wrong in the event selection that would artificially create this peak. It is also possible or that something went wrong in the detection of these events. We could check these possibilities by looking at certain properties of the events.

5.2 $t\bar{t}$ Control Region

In the $t\bar{t}$ Control Region, events are required to have at least one jet with a b-tag.

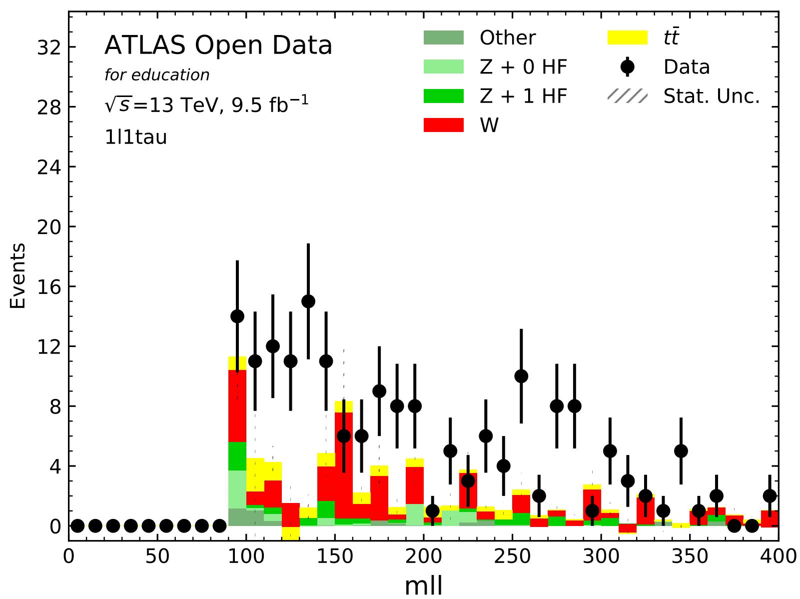

Figure 7: Invariant mass spectrum in the $t\bar{t}$ control region

There are almost no data points in the region between 200 and 210 GeV, while that is the region where the peak is in the signal region. This could be because of the low sample size. Fluctuations like this are more likely with smaller samples. The data is also consistently higher than the MC simulations. This could signify that there are samples missing from the simulations, or that the weight of the generated samples is off. Looking at the average events in each bin, no oddities are in this control region.

5.3 W control Region

In the W control region, events with a higher missing energy are selected. Only events with $M_{ET} > 40$GeV are selected. Whereas in the signal region, events with $M_{ET} < 40$GeV were selected.

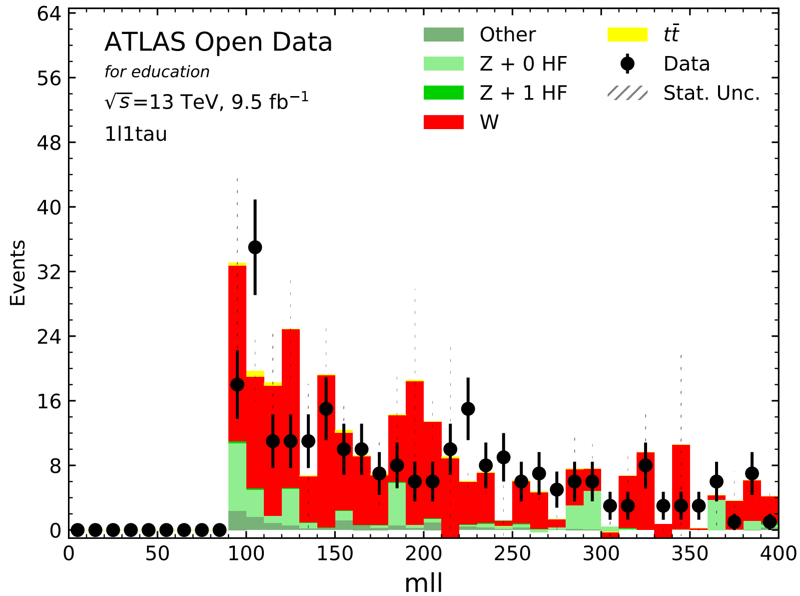

Figure 8: Invariant mass spectrum in the W control region

There are no real oddities in the W control region. There are some higher points between 200 and 250 GeV. This peak is not significant enough to analyze, This peak is also too broad to represent another particle.

5.4 Peak Analysis

To estimate the significance of the peak, the 20 GeV left and right from the peak was used to approximate the expected background signal. Using

$$\sigma = \frac{N_{data} - \frac{1}{4}N_{Background}}{\sqrt{N_{data} + \frac{1}{4}N_{Background}}} \tag{4}$$

With N_{data} being the number of data points in the peak and $N_{Background}$ being the amount of events in the 2 bins left and right of the peak. Since $N_{Background}$ uses data from four bins, $\frac{1}{4}N_{Background}$ is the average value in one of those bins. In this case, $N_{data} = 25$ and $N_{Background} = 35$. This gives σ = 2.79

5.5 Properties

lepton charge & type

Looking at the properties of the events in the peak can give information about what particle could be created in these events.

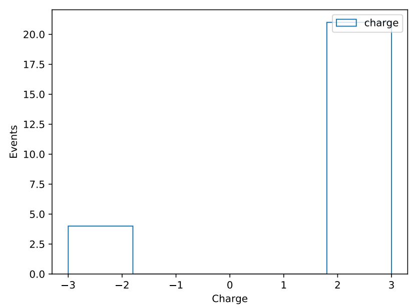

Figure 9: Charge distribution of events in the 200-210 GeV region

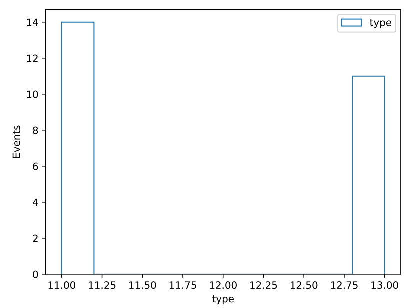

Figure 10: Lepton type distribution of events in the 200-210 GeV region

In the peak, there are mostly events between 2 positive particles. And the distribution of electrons and muons is approximately equal (see figure 9).

Rapidity

Looking at the rapidity of the tau also gives some interesting properties. (figure 11, 12 & 13). Almost all eta angles in the peak are around 2 rad. In the data set, the distribution also has a lot of data between -1 and 1. These points are mostly absent after the event selection.

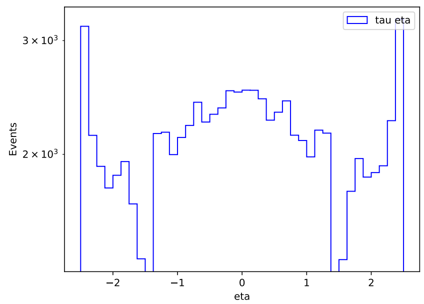

Figure 11: The η_{tau} distribution of all data in the 1lepton 1 tau data set

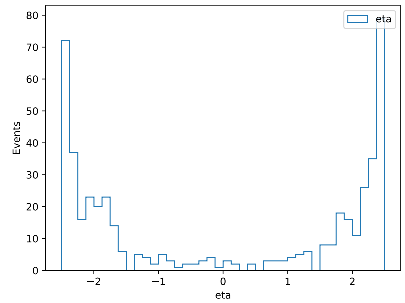

Figure 12: The η_{tau} distribution between of all data points after the event selection

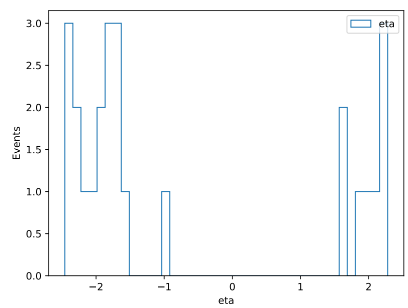

Figure 13: The η_{tau} distribution between 200 and 210 Gev invariant mass

The event selection filters out the central rapidity. From there to the peak, it is unclear if the last of the central rapidity events is filtered out or if they there are no points there because of the small sample size in the peak.

5.6 Azimuthal angle $\Delta\phi_{\tau M_{ET}}$

The angle between the missing E_T and the tau particle shows some weird properties.

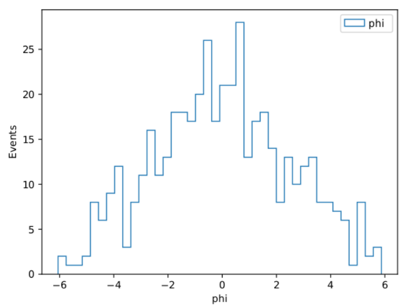

Figure 14: $\Delta\phi$ between the tau and the missing E_t in the signal region

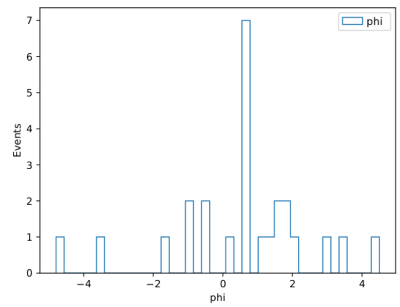

Figure 15: $\Delta\phi$ between the tau and the missing E_t in the signal region in the 200-210 GeV peak

In the peak, the events have an obviously peak. It is unclear why this peak is there. Looking at all data from the signal region shows that this peak is in the same place where there are the most events. It does not explain however why it is way more prominent if only the events in the peak are taken into account. It could be an error of the detector, but this could not be checked because the event numbers were not correct (see 5.6.1).

Transverse mass

Another weird property is the transverse mass. It is calculated as follows:

$$M_T = (E_{T,tau} + E_{T,lep})^2 - (\vec{p}_{T,tau} + \vec{p}_{T,lep})^2 \tag{5}$$

The transverse mass is the mass of the particles along the z-axis of the collider, the axis along which the particles travel. The graph of the Transverse mass from all events In the 200 GeV invariant mass peak looks as follows.

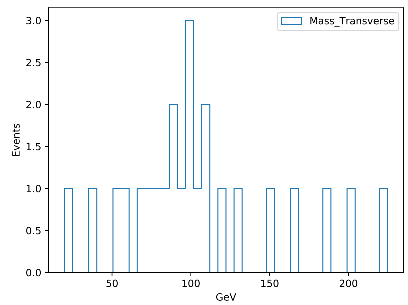

Figure 16: Transverse mass of events in the peak

It is notable that here there is obviously a peak at 100 GeV while all these events have an invariant mass between 200 and 210 GeV. So the transverse mass is significantly lower than the invariant mass. It is also notable that the transverse mass peak, 100 GeV, is close to the Z boson mass, 91 GeV. It would be strange if there was any connection because these are same sign events which should not result in Z bosons.

Collinear mass

Another mass property to look at is the collinear mass. This mass term tries to correct for missing neutrinos that are created in tau decays. It is calculated similar to the invariant mass, but in this calculation there are two constants before the momentum of the particles such that:

$$k_1 * p_1^x + k_2 * p_2^x = M_{E_t}^x \tag{6}$$
$$k_1 * p_1^y + k_2 * p_2^y = M_{E_t}^y \tag{7}$$

Solving these equations gives:

$$k_2 = \frac{-(\frac{M_{E_x} * p_{y1}}{p_{x1} + M_{E_y}})}{p_{y2} - \frac{p_{x2} * p_{y1}}{p_{x1}}} \tag{8}$$
$$k_1 = M_{E_x} - \left(\frac{k_2 * p_{x2}}{p_{x1}}\right) \tag{9}$$

Using these constants the collinear mass can be calculated. This is done the same as the invariant mass (3) except that the momentum of the particles are scaled with k_1 and k_2:

$$\vec{p_{p1}^*} = k_1 * \vec{p_{p1}} \tag{10}$$
$$\vec{p_{p2}^*} = k_2 * \vec{p_{p2}} \tag{11}$$

The calculation of the collinear mass can only be done if the azimuthal angle of the two particles are far enough away from each other. In this analysis, we only calculated the collinear mass from the events with the following restriction.

$$||\phi_1 - \phi_2| - \pi| > 0.2 \tag{12}$$

Otherwise, the constants k_1 and k_2 make the value in the square root of the invariant mass calculation negative. This results in imaginary values for the collinear mass. Calculating the collinear mass for the relevant events results in the following graph:

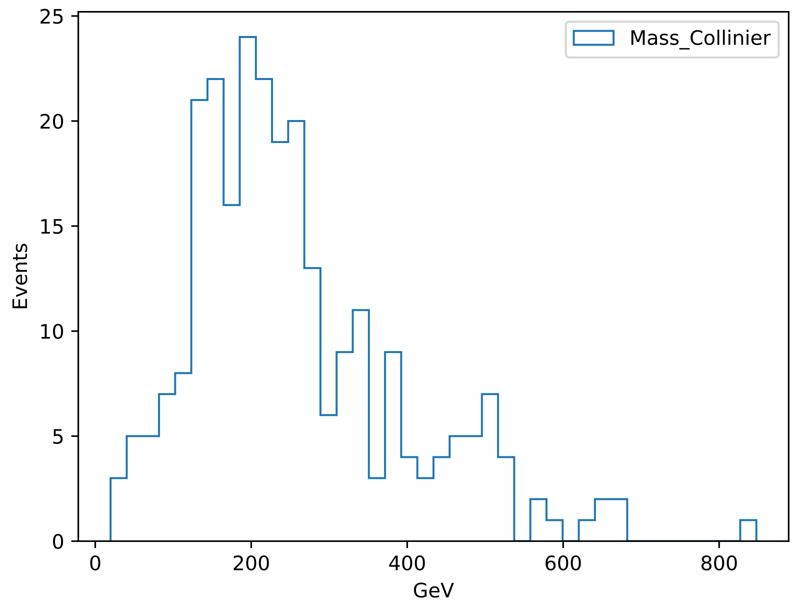

Figure 17: Collinear mass of all relevant events that passed the event selection.

In this figure is no peak visible that would indicate any oddities.

Tau n_tracks

A reason that this peak would not indicate a new particle is that all particles in the peak are miss identified tau particle, particles that are identified as taus but originally were other leptons. In an event, particles are recognized by properties. With these properties the probability that a particle was a certain particle can be determined, this is called object reconstruction. An indication that this peak is not due to miss identified tau particles is by looking at the measured tracks of the particle.

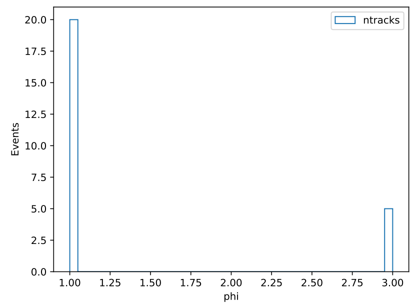

Figure 18: The number of tracks from the tau from events in the peak

The n_tracks property shows that 80% of the events have one track and 20% have three tracks. These tracks are from the particle that a tau decays into. The number of tracks is how many measurable particles it has decayed into. The decay of a particle is random, but has a certain chance of happening. The table below shows the most likely decays with their branching ratio:

mode	Best Fit Branching Ratio (%)
$e^-\nu_e\nu_\tau$	17.83 ± 0.04
$\mu^-\nu_\mu\nu_\tau$	17.41 ± 0.04
$\pi^-\nu_\tau$	10.83 ± 0.06
$\pi^-\pi^0\nu_\tau$	25.52 ± 0.09
$\pi^-2\pi^0\nu_\tau$	9.30 ± 0.11
$\pi^-3\pi^0\nu_\tau$	1.05 ± 0.07
$\pi^-\pi^+\pi^-\nu_\tau$	8.99 ± 0.06
$\pi^-\pi^+\pi^-\pi^0\nu_\tau$	2.70 ± 0.08

Table 3: Beset fit values for the chance of a tau decay into each configuration of child particles for the most common decays [4].

There are a few more possible decays, but those have a smaller chance of happening. Neutrinos can not be measured, so they do not contributed to the number of measured tracks. Electrons and muons are not measured as tau particles, so their branching rations also do not contribute to the tracks in the graph. π^0 decays into γ and thus will not contribute to the tracks.
What is left are four decays into a single charged pion and two decays into three charged pions. These are the possible tracks that can be seen in the graph.Adding up the possibilities from the table gives a 46.7% for 1 track and a 11.7% chance for 3 tracks. Renormalizing those values gives a 79.97% chance for 1 track and a 20.03% chance for 3 tracks. This is also the ratio that can be seen in the graph. This indicates that the measured tau particles were indeed tau particles.

5.6.1 Tau Tightness

Another way to see if the measured particles are truly taus is with the tau_istight property. As stated before, tau particles decay before they can be measured. Thus, measuring a tau can only be done with the resulting particles from its decay. In the same manner as with a b hardon decay, the chance that a tau was measured can be calculated. This is the tau_istight property. A requirement can be set to only included events that have a high chance to be taus. Doing this resulted in the following graph:

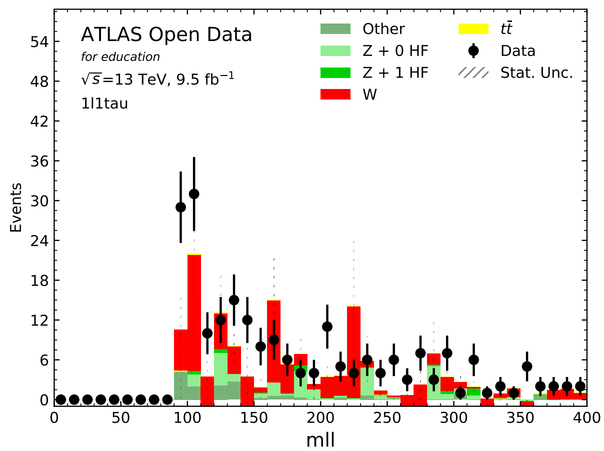

Figure 19: The number of tracks from the tau from events in the peak

The peak at 200 GeV is still visible. This also signifies that the measurement of taus was done correctly.

100 GeV missing transverse energy

In the following graph, the allowed missing energy was set to < 100 GeV instead of 40:

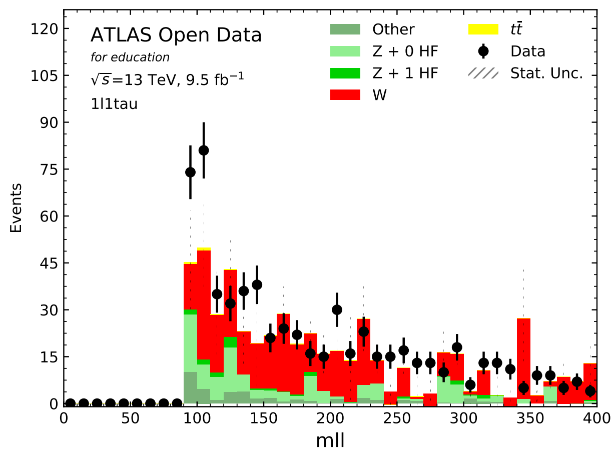

Figure 20: The number of tracks from the tau from events in the peak

The peak is still visible, but not as significant when the allowed E_T^{miss} was set to 40 GeV.

Event numbers

One more oddity was that the event numbers could be negative. This is probably due to bit compression or the change from signed integers to unsigned integers. Signed integers can express a value from $-(n-1)^2$ to $(n-1)^2-1$ where unsigned integers can express values from 0 to n^2-1 where n is the number of bits that the integer of the integer. switching between these two integers can convert a high unsigned integer into a negative integer, since the Most Significant Bit dictates the sign of a signed integer. Checking the root files showed that there the event numbers are also negative there. This should not be the case, but is not something that could impact the results of this analysis. The only effect of this is that the events could not be found and analyzed in an event reconstruction.

5.7 Results

As a separate check, the data from the exactly two lepton dataset was used. Separating the e^+e^- events from the $\mu^+\mu^-$ events to get the following graph:

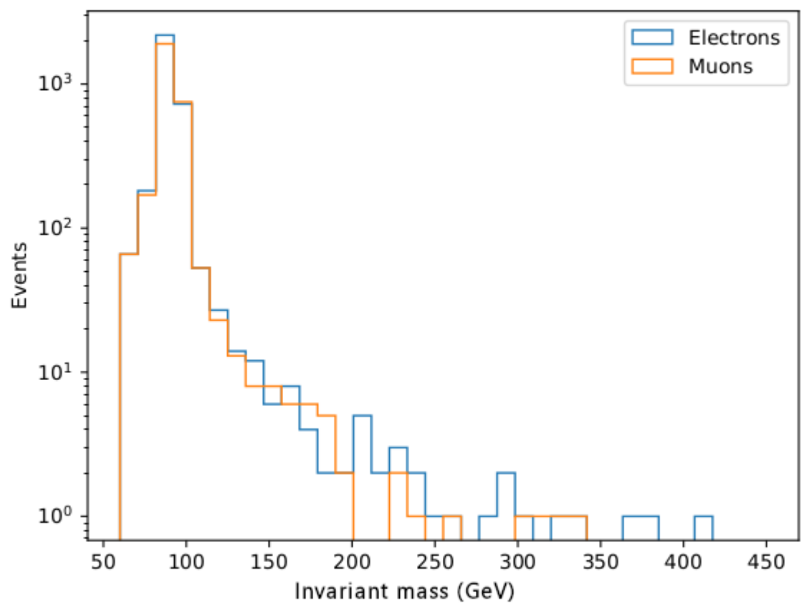

Figure 21: Number of opposite sign e^-e^+ and $\mu^-\mu^+$ events against the invariant mass of the events.

Here the Z boson peak is clearly visible. In that peak, there are approximately the same amount of electron-electron events as muon-muon events. That is because the Z boson acts the same for electrons and muons. Because of this, there should be approximately the same amount of events with electrons and muons around the Z boson mass. The events outside that range will be used to test lepton universality for other possible decays.

5.8 leptoquark

This data is used in the second part of this analysis, the VBS. In this analysis, the decays close to the mass of the Z boson (91 $\pm$ 25 GeV) were counted as $VBS \quad Z \rightarrow \ell^+\ell^-$ decays with lepton universality. Decays with a higher energy were labeled as $VBS \rightarrow \ell^+\ell^-$ decays. This gave the following results:

Decay	Number of decays
$VBS\ Z \to e^+e^-$	3191 ± 56
$VBS\ Z \to \mu^+\mu^-$	2919 ± 54
$VBS \to e^+e^-$	95 ± 10
$VBS \to \mu^+\mu^-$	77 ± 9

Table 4: Number of decays with a Z boson and with a leptoquark

To determine if lepton universality applies, we can use formula 1 with the relevant decays.

$$\frac{VBS \to e^+e^-}{VBS\ Z \to e^+e^-} / \frac{VBS \to \mu^+\mu^-}{VBS\ Z \to \mu^+\mu^-} \tag{13}$$

This gives a value of 0.88 ± 0.14. This error is dominated by the measurements of $VBS \to \ell^+\ell^-$ because of the low amount of data. With this large error, lepton universality could still be conserved. More research and data is needed.

6 Discussion

More data is needed to determine if the actual significance of the peak. It could just be an artifact because of the lack of data. This analysis was only done on the open data. If there was more data available, it could provide better results for this analysis.
One possible explanation of the peak could be the existence of the aforementioned leptoquark. A leptoquark has a charge of $\pm\frac{5}{3}$ but could decay into $e^+\pi^+$ which would result in a measurement of a charge of $+2$. This however would not be likely. The decay into $e^+\pi^+$ would not be the most likely decay. Other experiments that are searching for leptoquarks with more probable decays, like HERA, ZEUS & H1, were not able to find them.
There were no oddities found that would indicate that this would definitely not be a new particle. Some properties are questionable, like η_{tau} and $\Delta\phi_{\tau M_{ET}}$. But the checks indicate that these are correct measurements.
The VBS decay has a rather large error. But with more data, it should become smaller. Also here, more research is needed before drawing a conclusion

References

[1] LHCb collaboration,(957 additional authors not shown), “Test of lepton universality in beauty-quark decays,” *Nature Physics*, vol. 18, no. 3, pp. 277–282, mar 2022. [Online]. Available: https://arxiv.org/abs/2103.11769

[2] F. F. Deppisch, P. S. B. Dev, and A. Pilaftsis, “Neutrinos and collider physics,” *New Journal of Physics*, vol. 17, no. 7, p. 075019, aug 2015. [Online]. Available: https://arxiv.org/abs/1502.06541

[3] Cyril Becot, James Boyd, Samuel Dysch, Benjamin Fuks, Nico Giangiacomi, Chan Gwake, Nikolina Ilic, Jonas Neundorf, Krisztian Peters, Jacopo Pinzino, Karolos Patamianos, Darren Price, Michaela Queitsch-Maitland, Richard Ruiz, Matthias Saimpert, Pierre Savard, Benjamin James Wilson, “Search for majorana neutrinos in same-sign $w^{\pm}w^{\pm}$ scattering events at $\sqrt{s}$ = 13 tev,” *ATLAS*, apr 2021.

[4] R. L. Workman and Others, “Review of Particle Physics,” *PTEP*, vol. 2022, p. 083C01, 2022.

Appendices

A All results from the 1 lepton 1 tau analysis

Here will be all generated results from the analysis. The peak in the signal region is between 200 and 210 GeV.

Mass spectrum plots

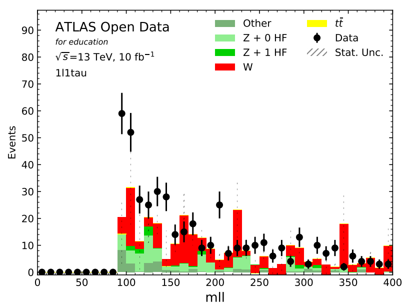

Figure 22: Mass spectrum in the signal region

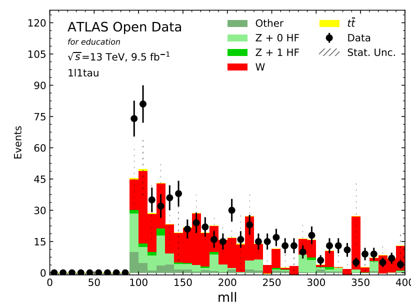

Figure 23: Mass spectrum with the missing transverse enery at 100 GeV

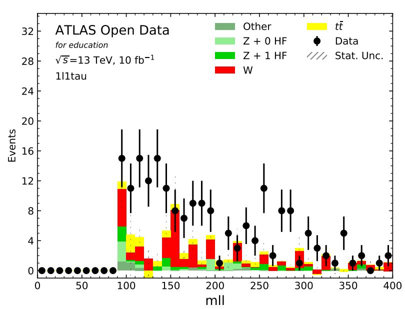

Figure 24: Mass spectrum in the $t\bar{t}$ control region

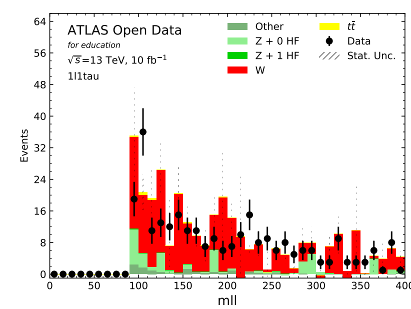

Figure 25: Mass spectrum in the W control region

Lepton type plots

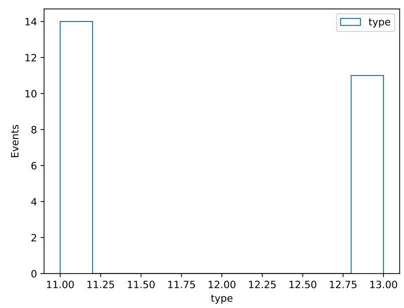

Figure 26: Lepton types in the signal region

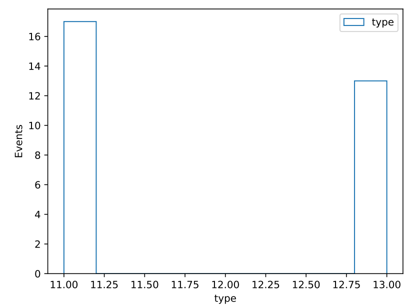

Figure 27: Lepton type in the area with the missing transverse energy at 100 GeV

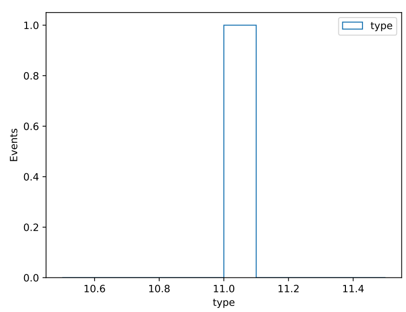

Figure 28: Lepton types in the $t\bar{t}$ control region

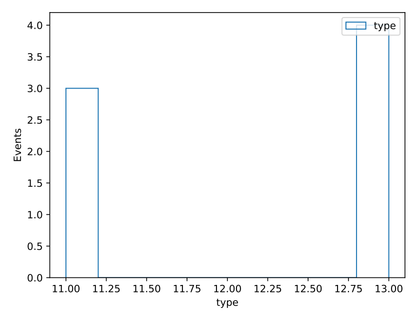

Figure 29: Lepton types in the W control region

Charge plots

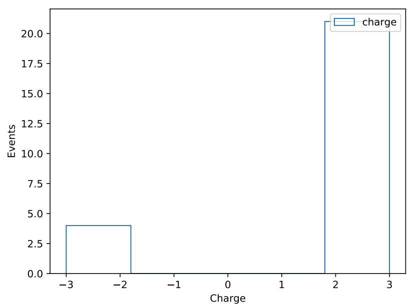

Figure 30: Charge in the signal region

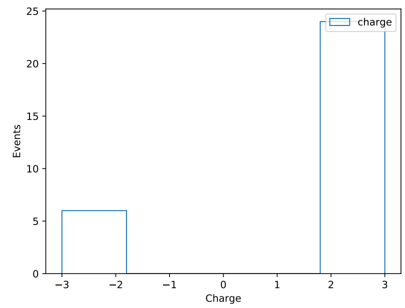

Figure 31: Charge in the area with the missing transverse energy at 100 GeV

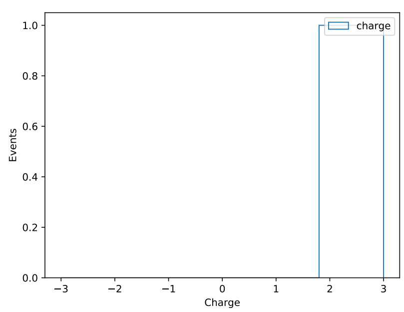

Figure 32: Charge in the $t\bar{t}$ control region

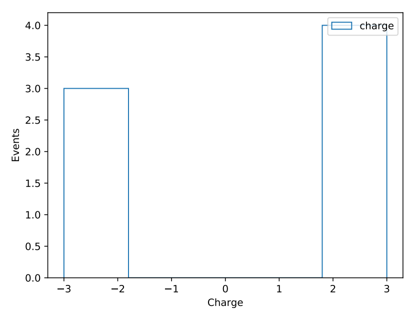

Figure 33: Charge in the W control region

Δϕ lepton-tau

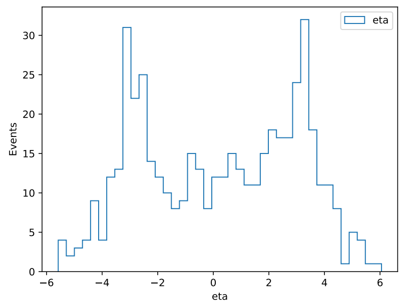

Figure 34: Δϕ between the lepton and the tau in the signal region

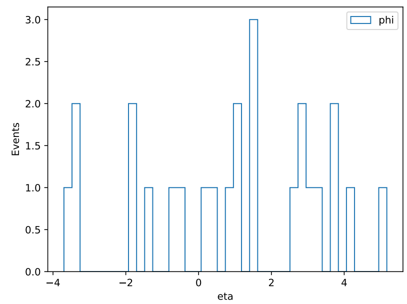

Figure 35: Δϕ between the lepton and the tau in the signal region in the peak

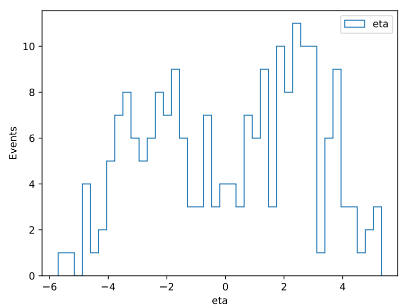

Figure 36: Δϕ between the lepton and the tau in the $t\bar{t}$ control region

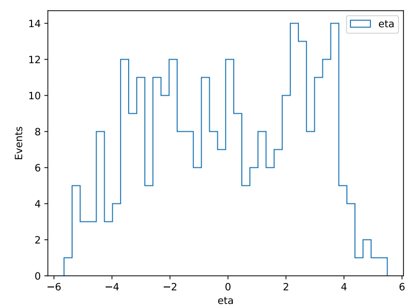

Figure 37: Δϕ between the lepton and the tau in the W control region

$\Delta\phi$ lepton-missing E_t

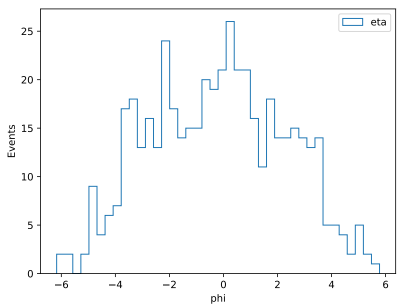

Figure 38: $\Delta\phi$ between the lepton and the missing E_t in the signal region

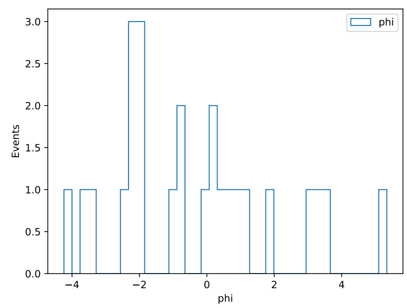

Figure 39: $\Delta\phi$ between the lepton and the missing E_t in the signal region in the peak

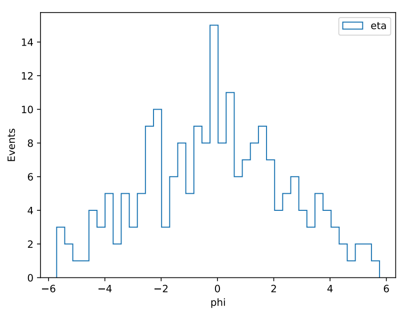

Figure 40: $\Delta\phi$ between the lepton and the missing E_t in the $t\bar{t}$ control region

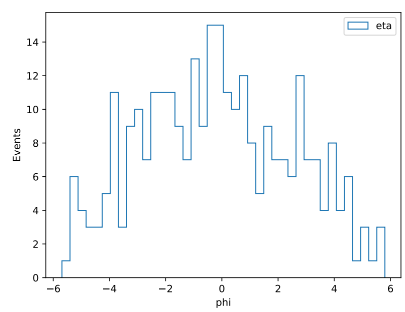

Figure 41: $\Delta\phi$ between the lepton and the missing E_t in the W control region

Δϕ tau-missing E_t

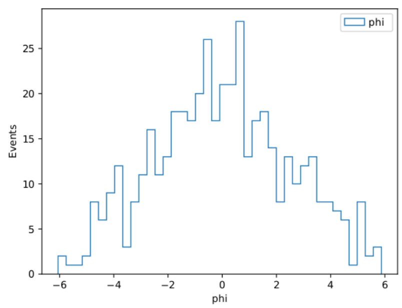

Figure 42: Δϕ between the tau and the missing E_t in the signal region

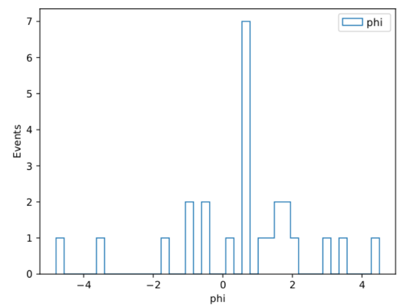

Figure 43: Δϕ between the tau and the missing E_t in the signal region in the peak

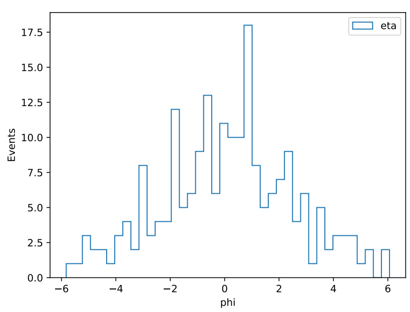

Figure 44: Δϕ between the tau and the missing E_t in the $t\bar{t}$ control region

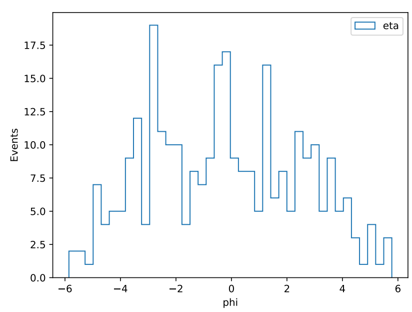

Figure 45: Δϕ between the tau and the missing E_t in the W control region

ΔR lepton-tau

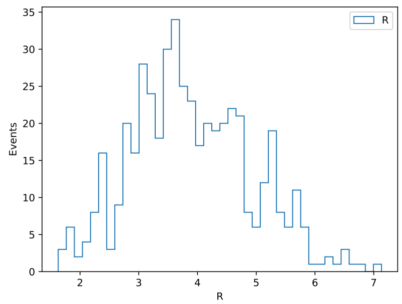

Figure 46: ΔR between the lepton and the tau in the signal region

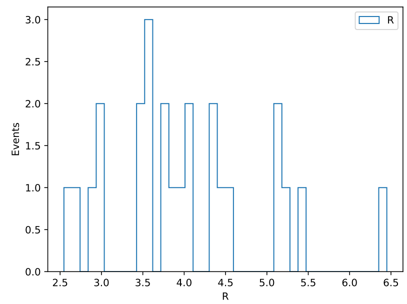

Figure 47: ΔR between the lepton and the tau in the signal region in the peak

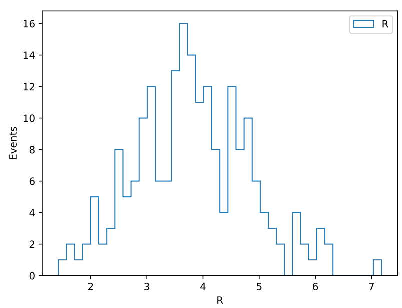

Figure 48: ΔR between the lepton and the tau in the $t\bar{t}$ control region

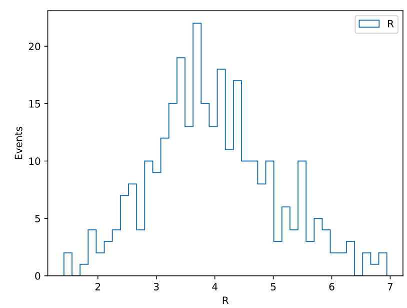

Figure 49: ΔR between the lepton and the tau in the W control region

Lepton η

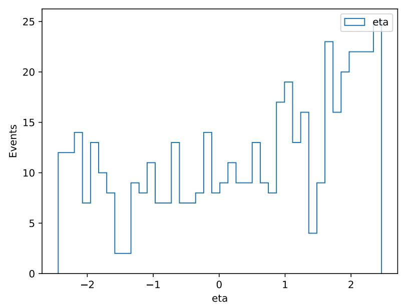

Figure 50: Lepton η in the signal region.

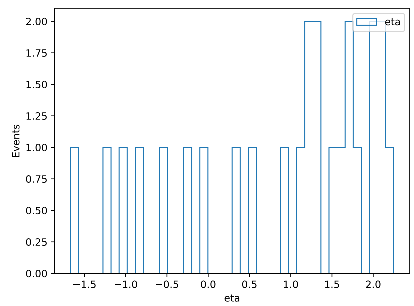

Figure 51: Lepton η in the signal region in the peak

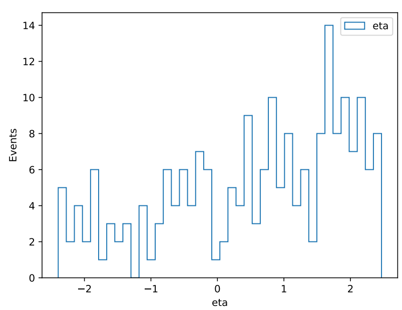

Figure 52: Lepton η in the $t\bar{t}$ control region

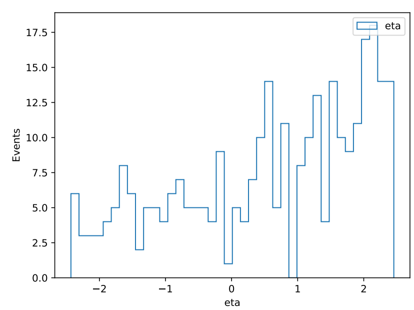

Figure 53: Lepton η in the W control region

Lepton p_t

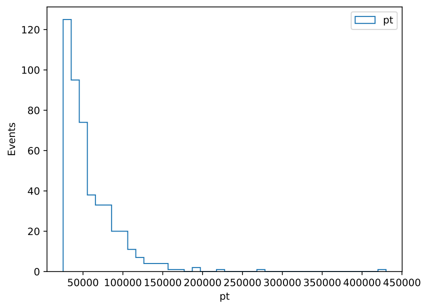

Figure 54: Lepton p_t in the signal region.

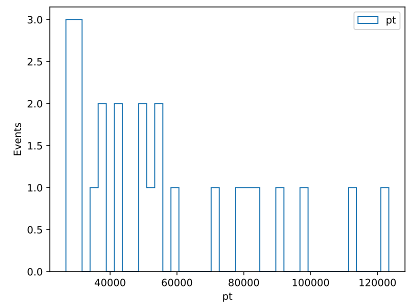

Figure 55: Lepton p_t in the signal region in the peak

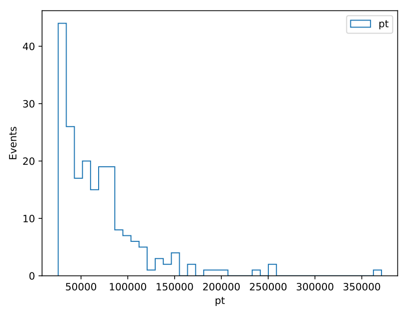

Figure 56: Lepton p_t in the $t\bar{t}$ control region

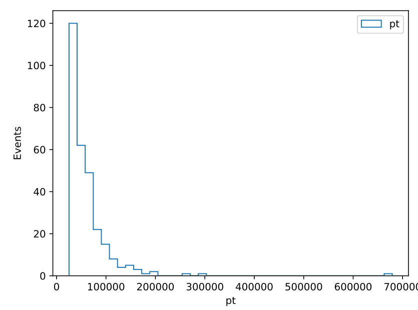

Figure 57: Lepton p_t in the W control region

Tau η

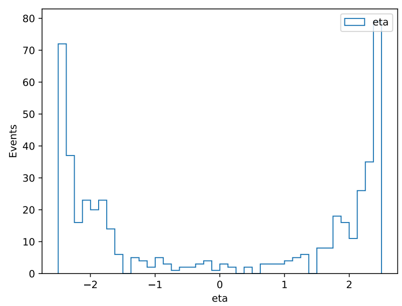

Figure 58: Tau η in the signal region

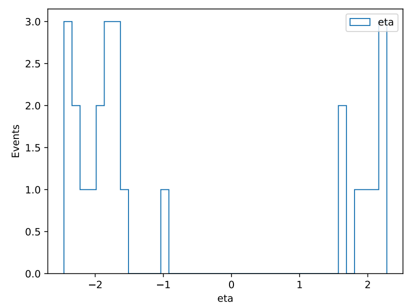

Figure 59: Tau η in the signal region in the peak

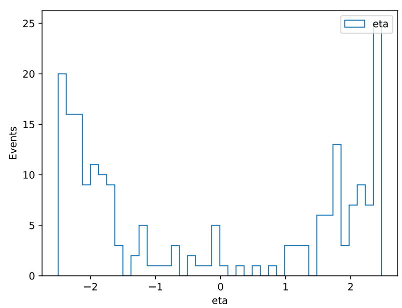

Figure 60: Tau η in the $t\bar{t}$ control region

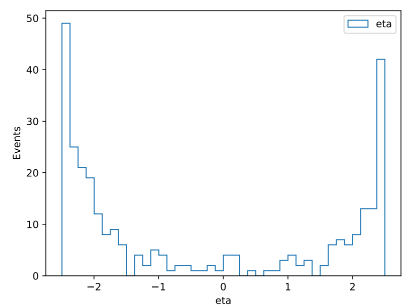

Figure 61: Tau η in the W control region

Tau p_t

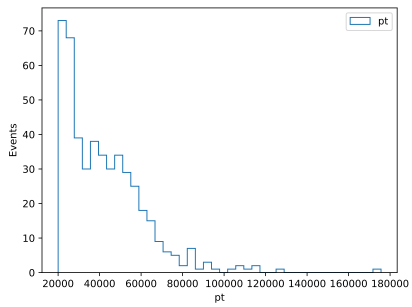

Figure 62: Tau p_t in the signal region

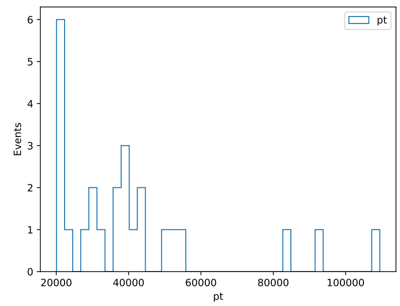

Figure 63: Tau p_t in the signal region in the peak

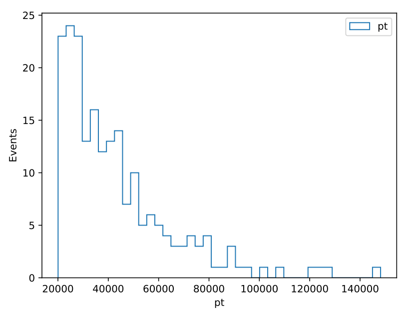

Figure 64: Tau p_t in the $t\bar{t}$ control region

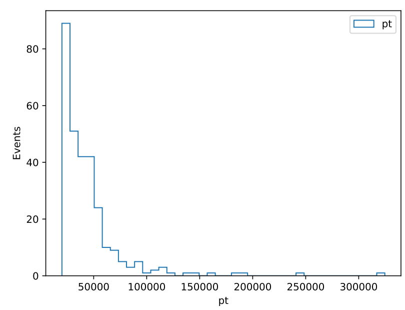

Figure 65: Tau p_t in the W control region

peak signal region

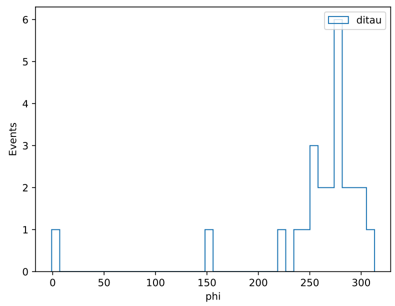

Figure 66: Ditau property in the peak of the signal region

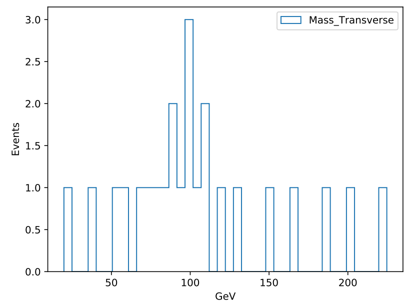

Figure 67: Transverse mass in the peak of the signal region

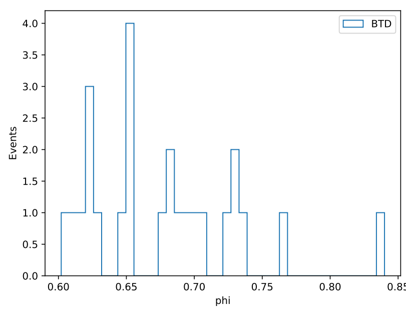

Figure 68: Tau BTD id in the peak of the signal region

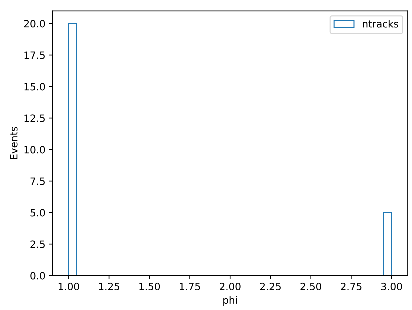

Figure 69: Tau ntracks in the peak of the signal region