# Search for dark matter with top-quark pair production in final states with $t\bar{t}$ and $E_T^{miss}$

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**Abstract**

The analysis of searching for the direct pair prodution of top quarks targets spin-0 mediator models. The mediator decays into a pair of dark-matter particles and is produced in association with top quarks. The search uses data from proton-proton collisions delivered by Large Hadron Collider (LHC) in 2015 and 2016 at a centre-of-mass energy of $\sqrt{s} = 13$TeV and recorded by the ATLAS detector, corresponding to an integrated luminosity of 36 $fb^{-1}$. For the spin-0 mediator models, upper limits are set on the visible cross-section.

# Contents

# 1 Introduction

With the observation of a particle consistent with the Standard Model (SM) Higgs boson at the Large Hadron Collider (LHC), the hierarchy problem has gained additional attention. If the supersymmetric partners of the top quarks masses $\leq$ 1 TeV, looping diagrams involving top quarks, which are the dominant divergant contribution to the Higgs-boson mass, can largely cancel out. This report considers about the "simplified dark matter" model, which produces the final state consistent with $t\bar{t}$ and $E_T^{miss}$. The production in final states is one isolated charged lepton (electron or muon) from the decay of either a real or a virtual W boson. The search requires several jets and a significant amount of missing transverse momentum $\vec{p}_T^{miss}$, the magnitude of which is referred to as $E_T^{miss}$, from the two weakly interacting LSPs that escape detection. Results are interpreted in an alternative model where a spin-0 mediator is produced in association with top quarks and subsequently decays into a pair of DM particles.

# 2 Theory

Dark matter (DM) is a hypothetical form of matter. The hypothesis of DM has an elaborate and long history. Early in 1884, Lord Kelvin gave a talk that estimated the number of dark bodies in the Milky Way from the observed velocity dispersion of the stars orbiting around the center of the galaxy. According to the measurements, Kelvin estimated the mass of the galaxy and determined that it is different from the mass of the visible stars. Thus, he concluded that "many of our stars, perhaps a great majority of them, may be dark bodies". Actually, the first person who suggested the existence of DM is Dutch astrinmer Jocobus Kapteyn by using steller velocities in 1922. What we have known about DM is that it is thought to account for approximately 27% in the universe. It has negligible interactions with our "visible" world and negligible self-interaction. It shows no strong or electromagnetic interaction, and could have some weak or weak-like interaction. It feels gravity and its lifetime is larger than the age of the universe. It could be "cold" and moves at non-relativistic speeds. The majority of dark matter is thought to be non-baryonic in nature, possibly being composed of some as-yet undiscovered subatomic particles.

There are some different experiments to detect the dark matter particles. The first one is direct detection experiment, which search for the scattering of dark matter particles with a detector. And the second one, indirect experiments, is looking for the products of dark matter particles annihilations or decays. There is an alternative approach to detect in nature which produces dark matter particles in a laboratory, called collider searches. This report is based on this way. For a dark matter particle should have negligible interactions with normal visible matter, it may be detected indirectly as missing energy and momentum that escape the detectors, provided other (non-negligible) collision products are detected. In this model, we choose top quark to do the searches, because top quark is the heaviest, and we can get more mediators in the experiment.

In the search, the targeted sinal scenarios are simplified models, such as pure bino LSP model, wino NLSP model, higgsino LSP model, bino/higgsino mix model. The final state produced by these models is consistent with a $t\bar{t}$ and $E_T^{miss}$ final state. Exploiting the similarity, signal models with spin-0 mediator decaying into dark matter particles produced in association with $t\bar{t}$ are also studied assuming either a scalar mediator ($\phi$) or a pseudoscalar mediator (a). The example diagram for this process is shown in Figure 1.

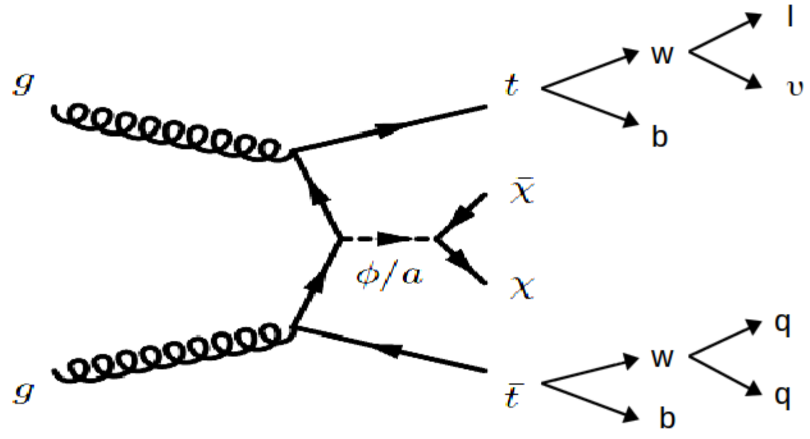



Figure 1: A representative Feynman diagram for spin-0 mediator production. The $\phi/a$ is the scalar/pseudoscalar mediator, which decays into a pair of dark matter ($\chi$) particles.

# 3 Measurement

## 3.1 Analysis strategy

The search presented is based on 16 dedicated analyses that target various scenarios. Each of these analyses corresponds to a set of event selection criteria, referred to as a signal region (SR), and is optimised to target one or more signal scenarios. By utilising different signal-to-background ratios in the various bins, the search sensitivity is enhanced in challenging scenarios where it is particularly difficult to seperate signal from background.

The main background processes after the signal selections include $t\bar{t}$, single-top $Wt$, $t\bar{t}$+$Z$ ($\rightarrow \nu\bar{\nu}$), and $W$+jets. Each of those standard model (SM) processes are estimated by building dedicated control regions enhanced in each of the processes, making the analysis more robust against potential mis-modelling effects in simulated events and reducing the uncertainties in the background estimates.

## 3.2 ATLAS detector and data collection

This analysis is based on a dataset collected in 2015 and 2016 at a collision energy of $\sqrt{s} = 13$TeV. The data contain an average number of simultaneous $pp$ interactions per bunch crossing, or "pile-up", of around 23.7 across the two years. After the application of beam, detector and data-quality requirements, the total integrated luminosity is 36.1 $fb^{-1}$ with an associated uncertainty of 3.2%. The events were primarily recorded with a trigger logic that accepts events with $E_T^{miss}$ above a given threshold. The trigger is fully efficient for events passing an offline-reconstructed $E_T^{miss} > 230$GeV requirement, which is the minimum requirement deployed in the signal regions and control regions relying on the $E_T^{miss}$ triggers. Evnets in which the offline reconstructed $E_T^{miss}$ is measured to be less than 230GeV are collected using single-lepton triggers, where the thresholds are set to obtain a constant efficiency as a function of the lepton $p_T$ of $\approx 90\%$ ($\approx 80\%$) for electrons (muons).

## 3.3 Simulated event samples

To describe the SM background processes and model the signals, samples of Monte Carlo (MC) simulated events are used. All samples were produced with varying numbers of minimum-bias interactions overlaid on the hard-scattering event to simulate the effect of multiple $pp$ interactions in the same or nearby bunch crossings. And the number of interactions per bunch crossing was reweighted to match the distribution in data. In my work, I just set: total_weight = weight*pu_weight*sf_jvt*sf_el*sf_mu*xs_weight*36000.

## 3.4 Discriminating variables

We consider top quark decaying into a b-hadron and W-boson, and W-boson decaying into a lepton ($e$ or $\mu$) and a neutrino ($\nu$), while $\bar{t}$ quark, decaying into a b-hardon and W-boson, and W-boson decaying into two quarks ($q$) in Figure 1. To reconstruct the hadronic top-quark decay, for every select event, four jets including two b-tagged jets and a lepton need considering. The background process contributing to the final state with one isolated lepton, jets and $E_T^{miss}$ are primarily semileptonic $t\bar{t}$ events with one of the $W$ bosons from two top quarks decaying leptonically, and $W$+jets events with a leptonic decay of W boson. A series of additional variables described below in table 1 are used to discriminate between the $t\bar{t}$ background and the signal processes.

## 3.5 Signal selections

The signal region (SR) is designed to search for dark matter particles that are pair-producted via a spin-0 mediator (either scalar or pseudoscalar) produced in association

Table 1: Discriminating variables

| | | | | | |
|---|---|---|---|---|---|
| Jet $p_T$ | $b$-tagged jet $p_T$ | $E_T^{miss}$ | $H_{T,sig}^{miss}$ | $m_T$ | $am_{T2}$ |
| Number of tags | Number of $b$-tags | $\Delta$R($b_1$,$b_2$) | $\Delta\phi(l,\vec{p}_T^{miss})$ | $\|\Delta\phi(jet_0,\vec{p}_T^{miss})\|$ | $\|\Delta\phi(jet_1,\vec{p}_T^{miss})\|$ |

with $t\bar{t}$. The DM_low SR is optimised for mediator massed around $m_\phi = 300$GeV.
Table 2 details the event selections.

Table 2: overview of the event selections

| Signal region | DM | DM_low |
|---|---|---|
| Preselection | $E_T^{miss}$ | high-$E_T^{miss}$ |
| Number of (tags, $b$-tags) | $(\geq 4, \geq 1)$ | $(\geq 4, \geq 1)$ |
| $E_T^{miss}$ [GeV] | $> 230$ | $> 320$ |

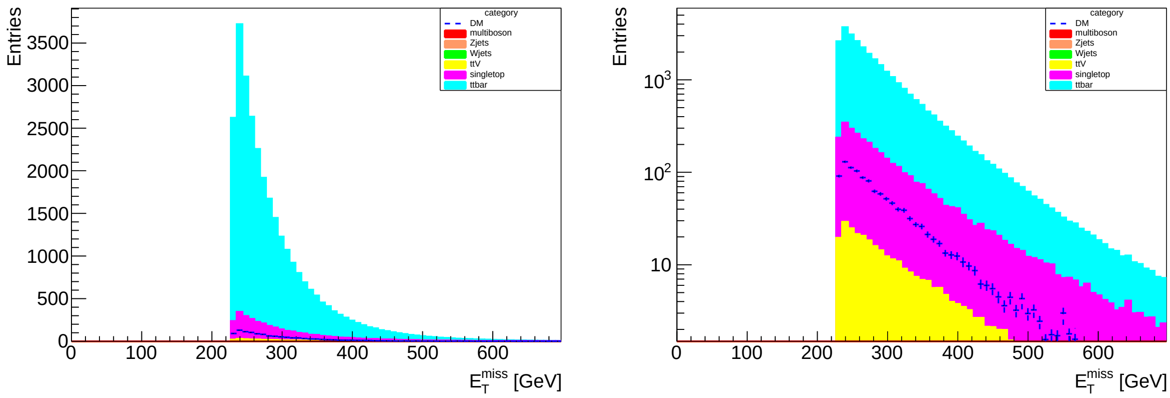
# 4 Results

## 4.1 Background and signal

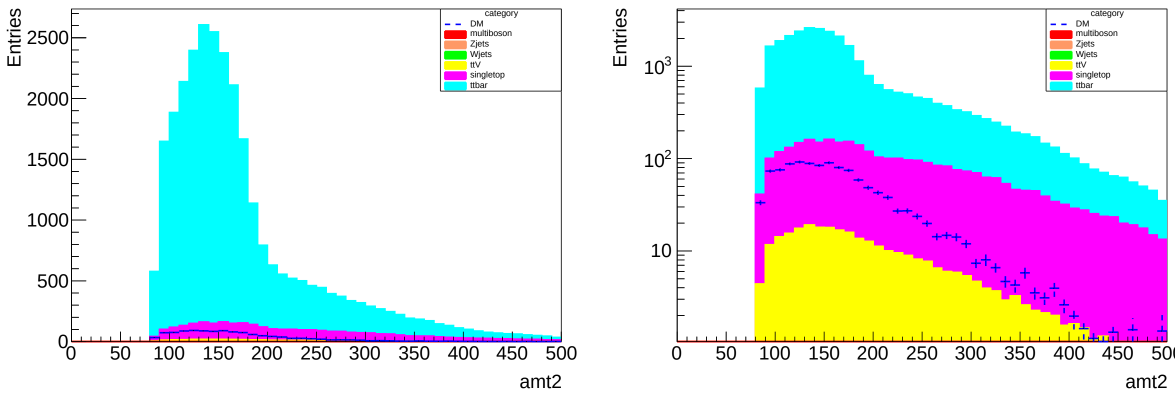
There are six kinds of background.

- multiboson
- single-top
- W+jets
- Z+jets
- ttV
- $t\bar{t}\,1L$

For every variable, there is a plot, so I just choose some of them to analyse.
In Figure 2 I just want to show the background and dark matter particle signal in different variables.




(a)




(b)

Figure 2: Distributions of discriminating variables: plot (a) for (left) $E_T^{miss}$ and (right) $E_T^{miss}$ in log coordinate, plot (b) for (left) $am_{T2}$ and (right) $am_{T2}$ in log coordinate.

In Figure 2 it is easily to find that the dotted line is for DM signals, the red histogram for multiboson background, orange one for Z+jets, green one for W+jets, yellow one for ttV, purple one for single-top, and blue one for $t\bar{t}$. We can find that in the left plot, it is difficult to see multiboson, Z+jets, and W+jets background, so I just change the plots in log coodinate showing in right plot to read clearly. In these plots, it is obvious that the DM signal has the same shape with the background, which is difficult for us to separate it from the background.

In Figure 3 I choose some variables to analyse in log coordinate.

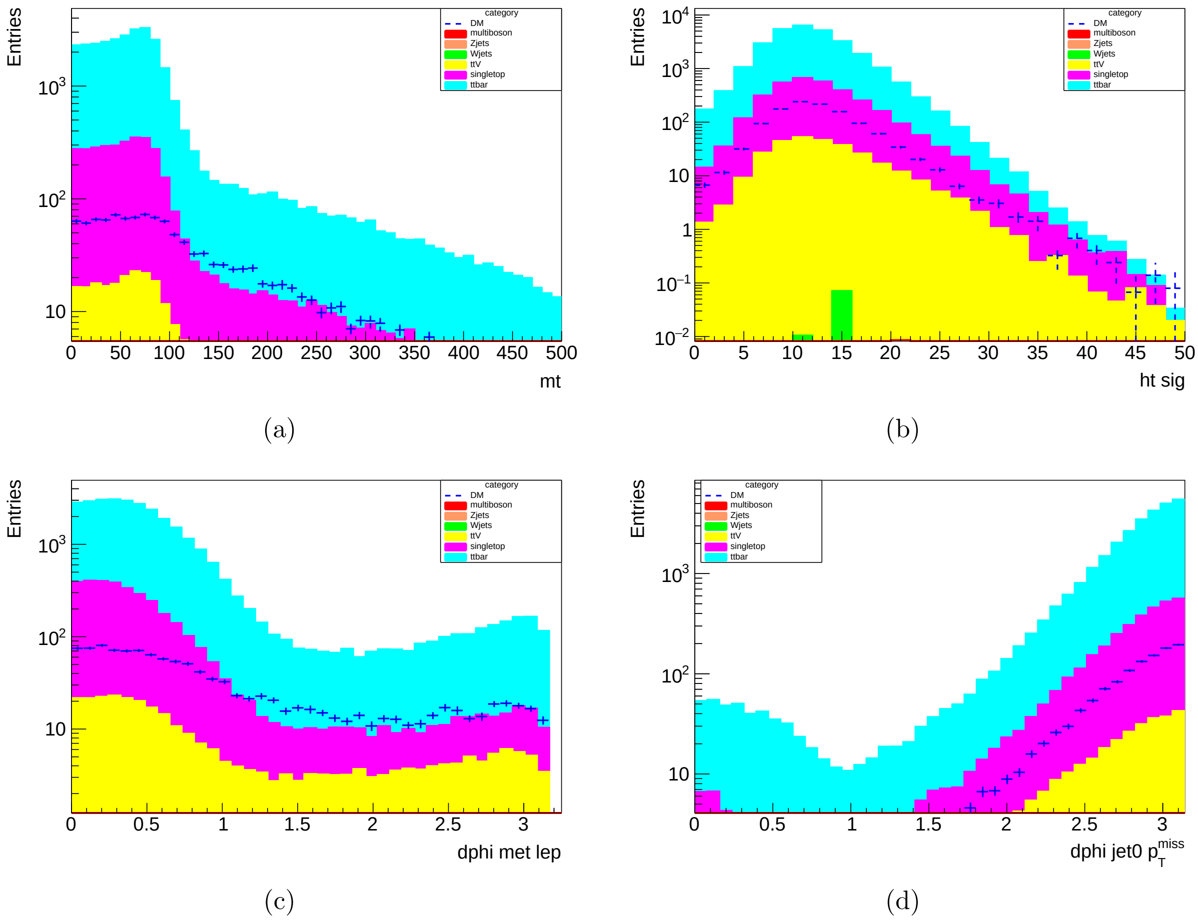



Figure 3: Distributions of discriminating variables: (a) $m_T$, (b) $H_{T,sig}^{miss}$, (c) $\Delta\phi(l,\vec{p}_T^{miss})$, and (d) $|\Delta\phi(jet_0,\vec{p}_T^{miss})|$ in log coordinate. The category is the same as Figure 2: the dotted line is for DM signals, the red histogram for multiboson background, orange one for Z+jets, green one for W+jets, yellow one for ttV, purple one for single-top, and blue one for $t\bar{t}$.

In Figure 3 we can find that if we set a line in the plot (a) at around 370GeV, then we would not find any siginal in the right of the line. And if we do this at around 120GeV, we can get rid of nearly all of the background except $t\bar{t}$ one. Actually it provides a guide for us to select the DM signal. As for plot (b), we would better do this at around 37 GeV. However, in this plot, it is not very obvious. In plot (c), we set the $\Delta\phi(l,\vec{p}_T^{miss})$ greater than 1.2GeV, the DM signal can be purer. Of course, $t\bar{t}$ background is the largest one, and I cannot get rid of it. In the last plot (d), there only have $t\bar{t}$ background before 1.5GeV, but without DM signals.

As for changing the signal region to DM_low, which is optimised for mediator masses around $m_\phi = 20$GeV in Figure 4, we can find some differences with Figure 3.

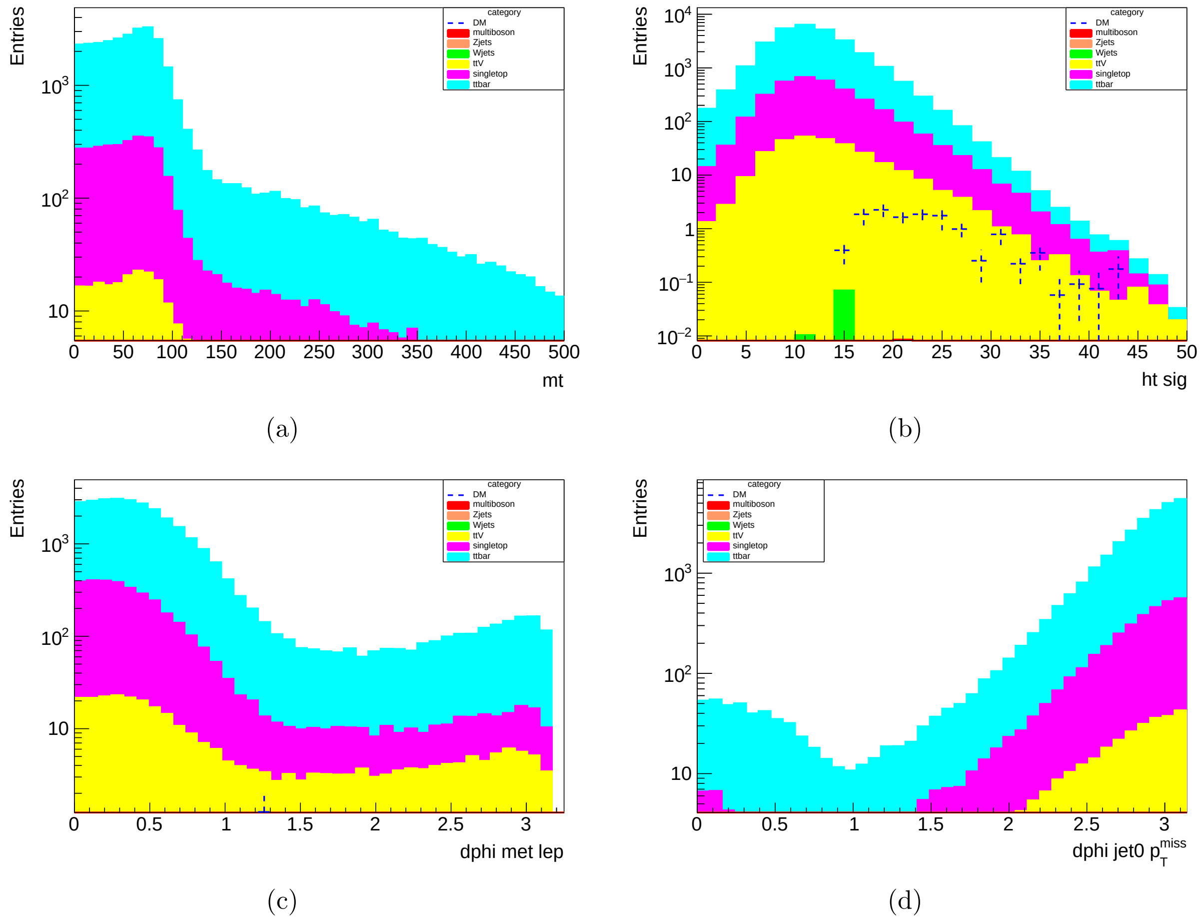



Figure 4: Overview of the event selections for the DM_low SR. Distributions of discriminating variables: (a) $m_T$, (b) $H_{T,sig}^{miss}$, (c) $\Delta\phi(l,\vec{p}_T^{miss})$, and (d) $|\Delta\phi(jet_0,\vec{p}_T^{miss})|$ in log coordinate. The category is the same as Figure 3.

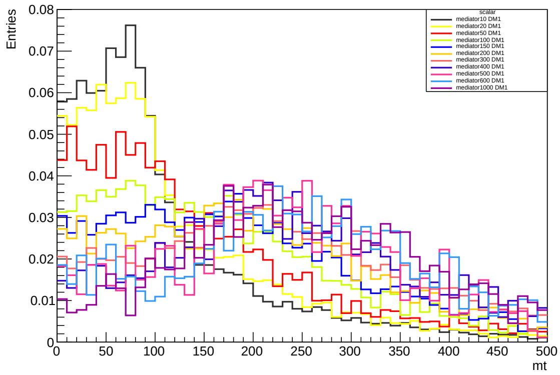
In the plot (a), (c), and (d) of Figure 4, we cannot find any DM signal. In plot (b), it is not as clear as plot (b) in Figure 3 to get a better DM signal separating from the background. Comparing with the Figure 3, the shape of the background are all the same, while only less DM signal. It may because of the lower mediator mass, next I am trying to find the influence of the different mediator mass and different dark matter particle mass.

## 4.2 Dark matter signal

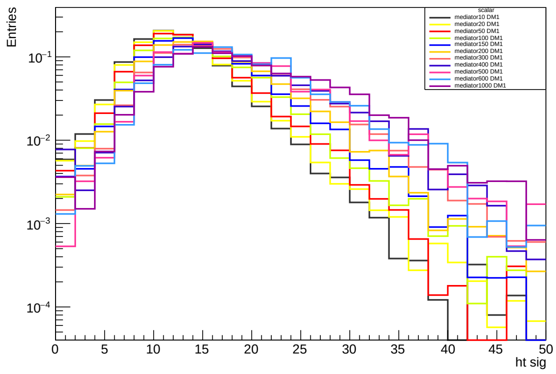
To search for the influence of the different mass of scalar or pseudoscalar mediators and DM particles, I draw some plots shown below.
I set four different condition to find out the results

- scalar mediator mass = 10, 20, 50, 100, 150, 200, 300, 400, 500, 600, 1000GeV
  dark matter mass = 1GeV
- scalar mediator mass = 10GeV
  dark matter mass = 10, 20, 50, 75, 100, 125, 150, 175, 200, 250, 300, 500GeV
- pseudoscalar mediator mass = 10, 20, 50, 100, 150, 200, 250, 300, 400, 500, 600, 1000GeV
  dark matter mass = 1GeV
- pseudoscalar mediator mass = 10GeV
  dark matter mass = 10, 20, 50, 75, 100, 125, 150, 175, 200, 250, 300, 500GeV

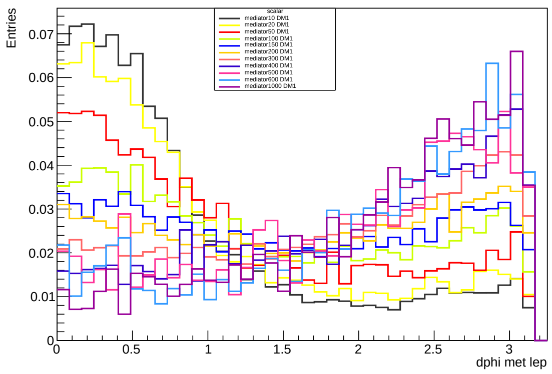
The Figure 5 display for the first condition.



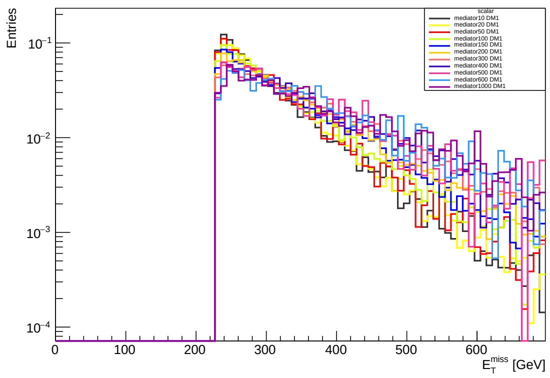

(a)




(b)




(c)

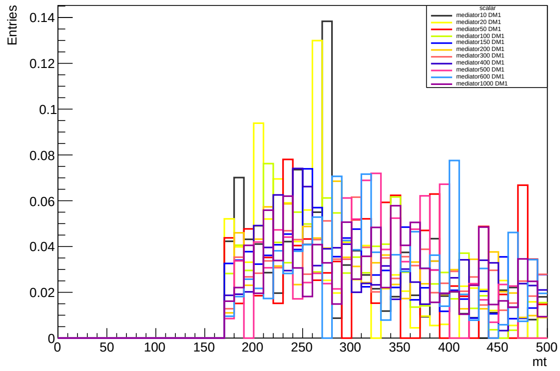



(d)

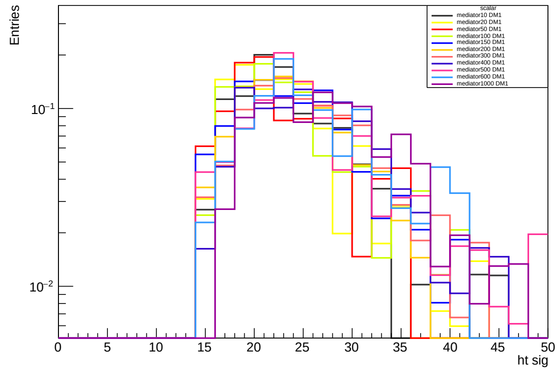
Figure 5: Distributions of discriminating variables: (a) $m_T$, (b) $H_{T,sig}^{miss}$, (c) $\Delta\phi(l,\vec{p}_T^{miss})$, and (d) $E_T^{miss}$ in normalization. The category shows different color representing different mass of the scalar mediator. Plot (b), (d) are in log coordinate.

For so many lines to compare, we can just pay attention to twice of them to find out the results. The black line represents that scalar mediator mass is 10GeV, and dark matter mass is 1GeV. And the purple one shows 1000GeV mediator and 1GeV DM. It is clearly that with the increasing energy of $m_T$, the black line decreases. At lower energy, the scalar mediator with the lower energy has better DM signal. As for the purple line, it is the lowest in lower $m_T$, but with the increasement of variable, higher mass mediator will work better. In the Figure 3, we can find that all of the background is higher when $m_T$ is in lower energy. And if we want to get rid of the most of the background, we had better using the higher mass scalar mediator to get more better DM signal. This can also explain why there is no signal showing in plot (a) in Figure 4. We can do the same explanation to the other variables. It is easily to get that the scalar mediator with higher mass always shows better in plots.

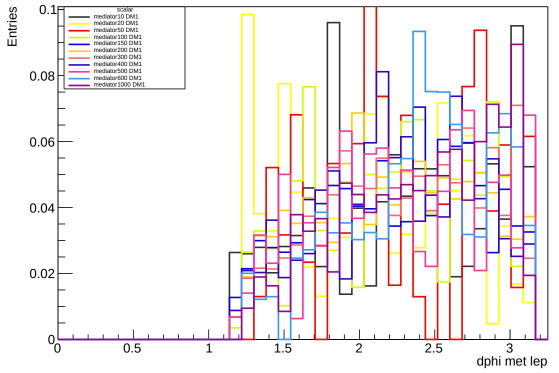
The DM_low SR is shown in Figure 6



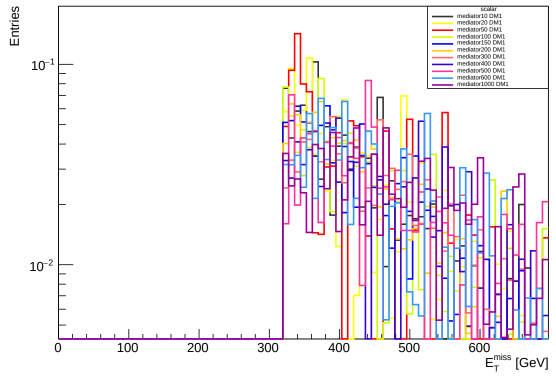

(a)




(b)




(c)

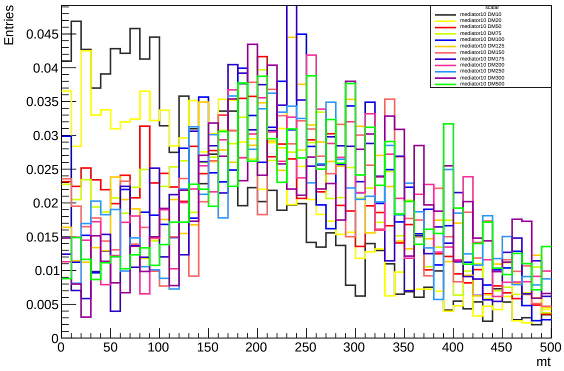



(d)

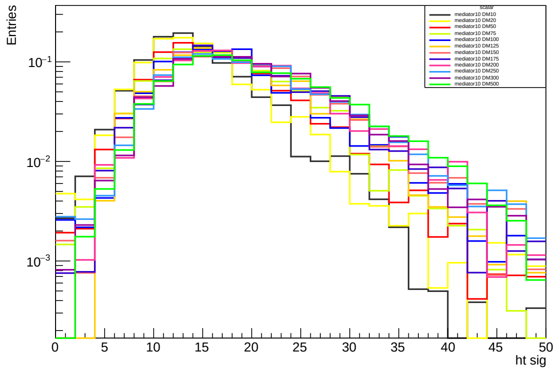
Figure 6: Overview of the event selections for the DM_low SR. Distributions of discriminating variables: (a) $m_T$, (b) $H_{T,sig}^{miss}$, (c) $\Delta\phi(l,\vec{p}_T^{miss})$, and (d) $E_T^{miss}$ in normalization. The category shows different color representing different mass of the scalar mediator. Plot (b), (d) are in log coordinate.

We can get the same results from DM_low plots, though it is not as clear as Figure 5. At lower energy, the scalar mediator with the lower energy has better DM signal. As for the purple line, it is the lowest in lower $m_T$, but with the increasement of variable, higher mass mediator will work better. In the Figure 3, we can find that all of the background is higher when $m_T$ is in lower energy. And if we want to get rid of the most of the background, we had better using the higher mass scalar mediator to get more better DM signal. It is the same with plots showing in Figure 4 that DM signal is less. We can also do the same explanation to the other variables.

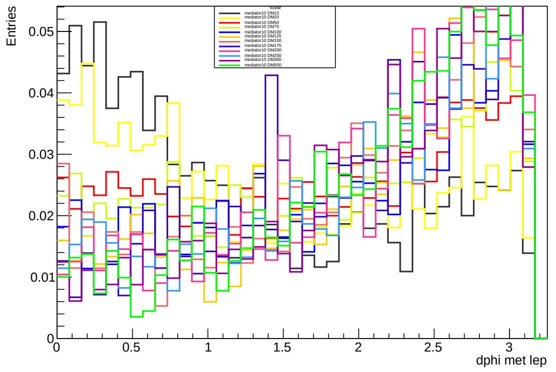
The Figure 7 display for the second condition.



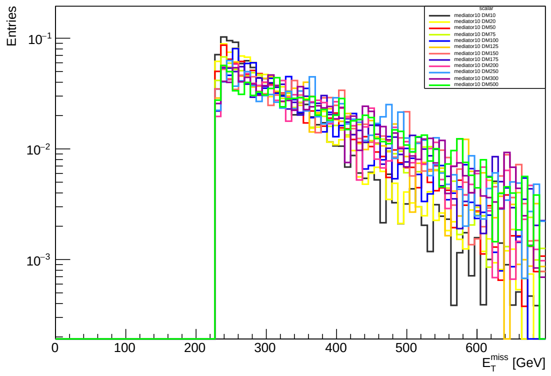

(a)




(b)




(c)

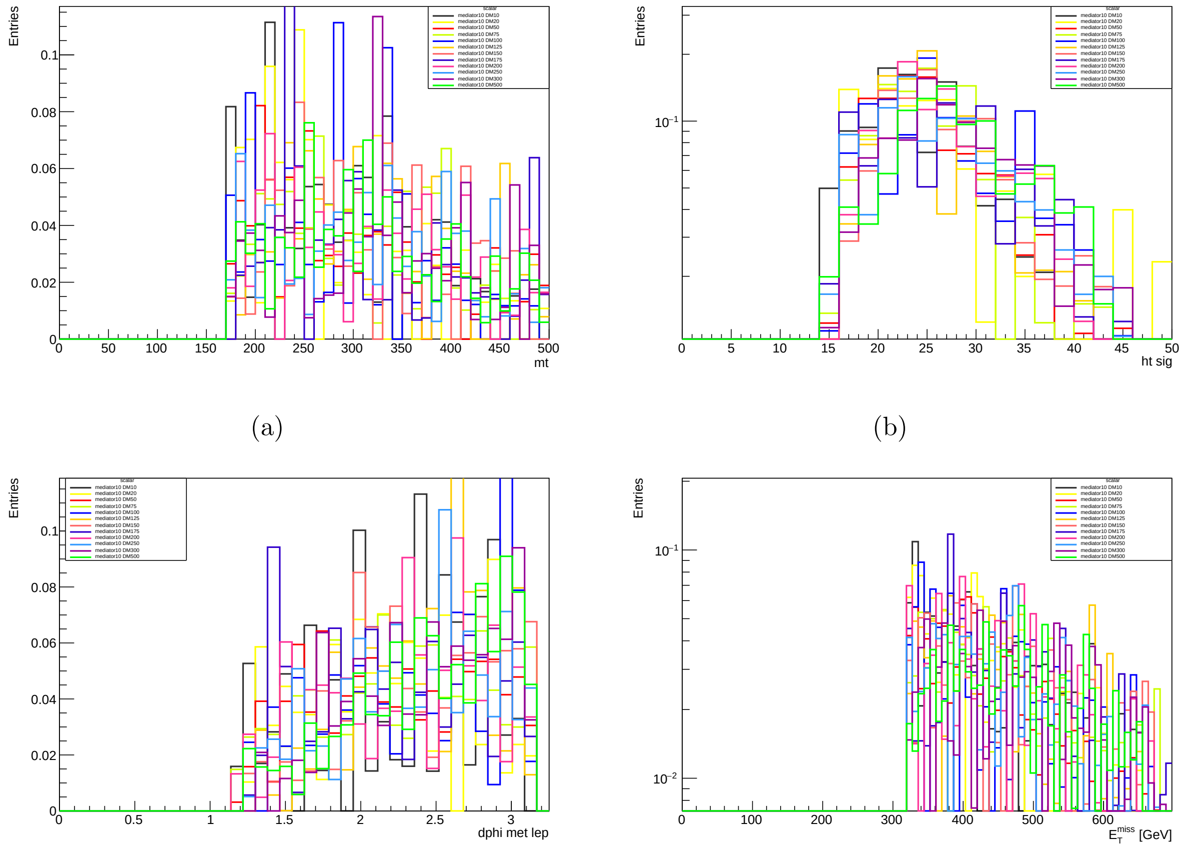



(d)

Figure 7: Distributions of discriminating variables: (a) $m_T$, (b) $H^{miss}_{T,sig}$, (c) $\Delta\phi(l,\vec{p}^{miss}_T)$, and (d) $E^{miss}_T$ in normalization. The category shows different color representing different mass of the dark matter particle. Plot (b), (d) are in log coordinate.

In the Figure 7 we keep the mass of scalar mediator, and change the mass of DM particle. Focusing on the black line and the green one, we can find it has the same tendency with what the plots in Figure 5. And the results is that with the increasement of variable, DM particle with higher matter works better. If we want to get rid of more background, we had better choose higher mass DM particle.

The corresponding DM_low SR is shown in Figure 8

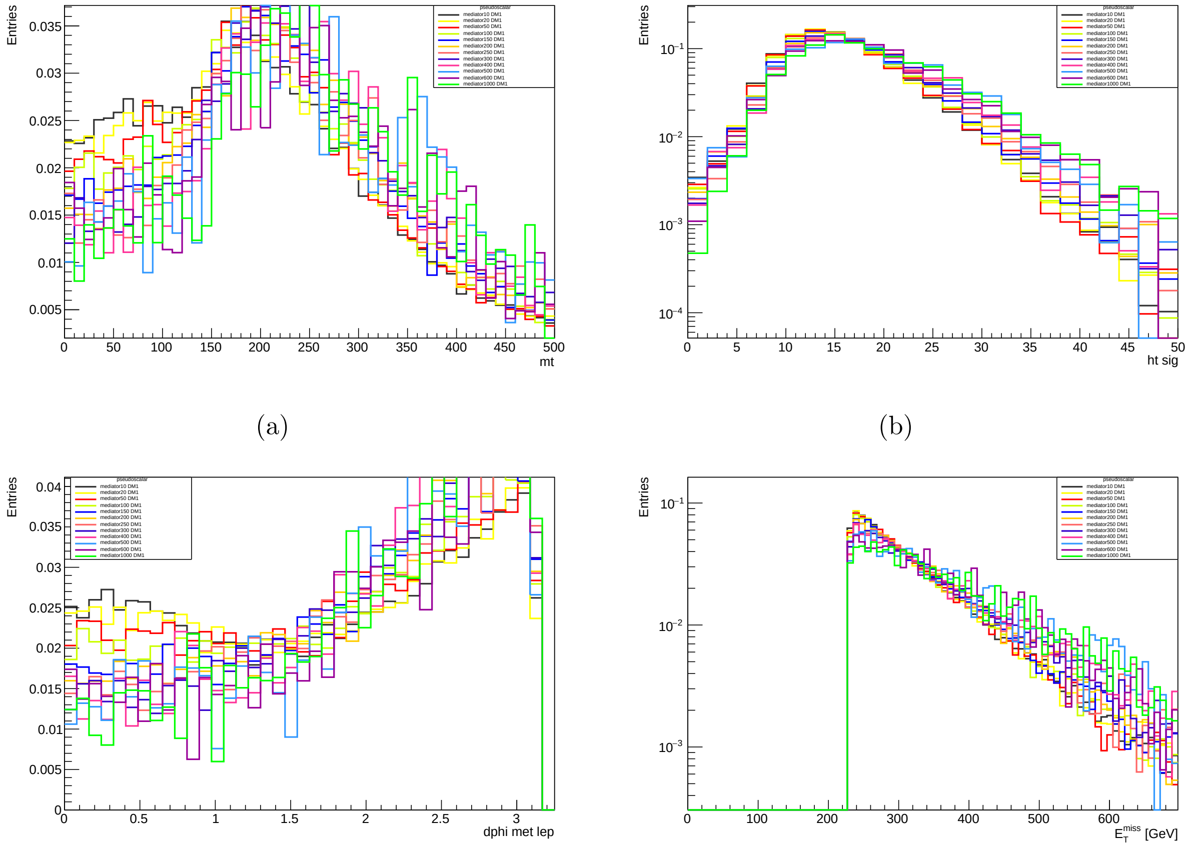



(a) (b) (c) (d)

Figure 8: Overview of the event selections for the DM_low SR. Distributions of discriminating variables: (a) $m_T$, (b) $H_{T,sig}^{miss}$, (c) $\Delta\phi(l,\vec{p}_T^{miss})$, and (d) $E_T^{miss}$ in normalization. The category shows different color representing different mass of the DM particle. Plot (b), (d) are in log coordinate.

We can get the same results from DM_low plots, though it is not as clear as Figure 7. And the results is that with the increasement of the variable, DM particle in DM_low signal region with higher matter works better. If we want to get rid of more background, we had better choose higher mass DM particle.

The Figure 9 display for the third condition.

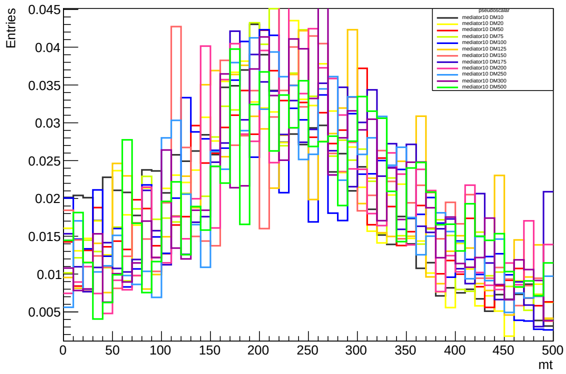



(a) (b) (c) (d)

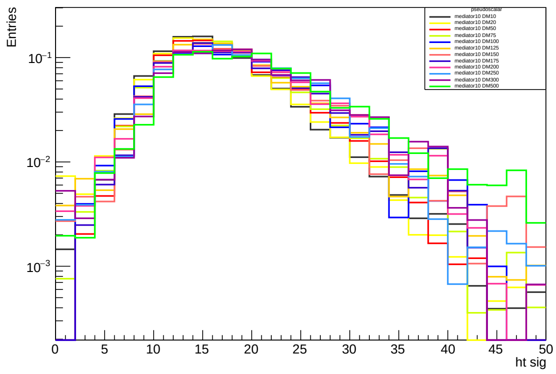
Figure 9: Distributions of discriminating variables: (a) $m_T$, (b) $H_{T,sig}^{miss}$, (c) $\Delta\phi(l,\vec{p}_T^{miss})$, and (d) $E_T^{miss}$ in normalization. The category shows different color representing different mass of the pseudoscalar mediator. Plot (b), (d) are in log coordinate.

In the Figure 9 we keep the mass of dark matter particle, and change the mass of pseudoscalar mediator. Focusing on the black line representing 10GeV of mediator mass and 1GeV of DM mass, and the green one with 1000GeV of mediator mass and 1GeV of DM mass, we can find some plots shows different tendency with the plots in Figure 5. In plot (c), with the increasement of $\Delta\phi(l,\vec{p}_T^{miss})$, the black line of pseudoscalar mediator decreases, while it increases in scalar meditor. What is the same is the higher mass of mediator, the DM signal looks better in the high energy. If we want to get rid of more background, we had better choose higher mass of mediator. It has the same tendency with DM_low signal region, and I donot show plots here.

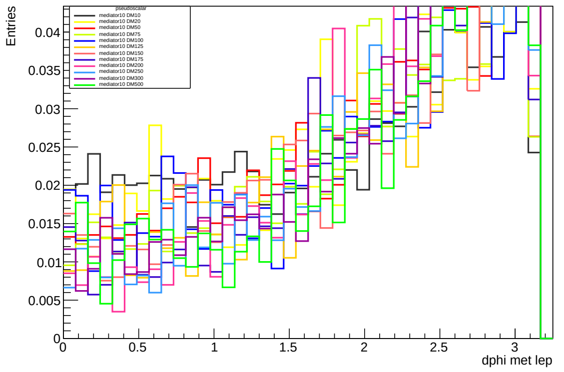
The Figure 10 display for the fourth condition.



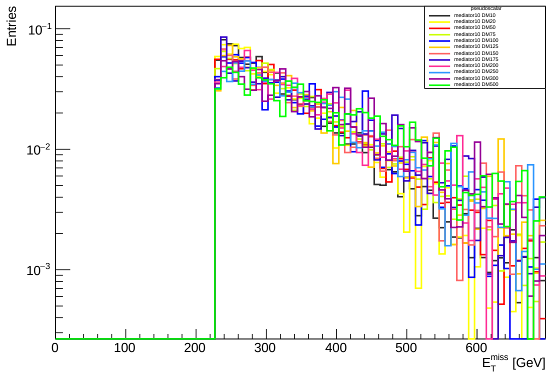

(a)




(b)




(c)




(d)

Figure 10: Distributions of discriminating variables: (a) $m_T$, (b) $H_{T,sig}^{miss}$, (c) $\Delta\phi(l,\vec{p}_T^{miss})$, and (d) $E_T^{miss}$ in normalization. The category shows different color representing different mass of the DM particle. Plot (b), (d) are in log coordinate.

In the Figure 10 we keep the mass of pseudoscalar mediator, and change the mass of DM particle just like Figure 7. The plots in Figure 10 looks the same with those in Figure 9, and some different with Figure 7.In plot (a), with the increasement of $m_T$, the black line of pseudoscalar mediator increases first and then decreases, while it decreases in scalar meditor in Figure 7. We can also get the results that the higher mass of DM particle, the DM signal looks better in the high energy. If we want to get rid of more background, we had better choose higher mass of DM particle. It has the same tendency with DM_low signal region, and I donot show plots.

Here are some plots showing the other variables with the same condition of Figure 10.

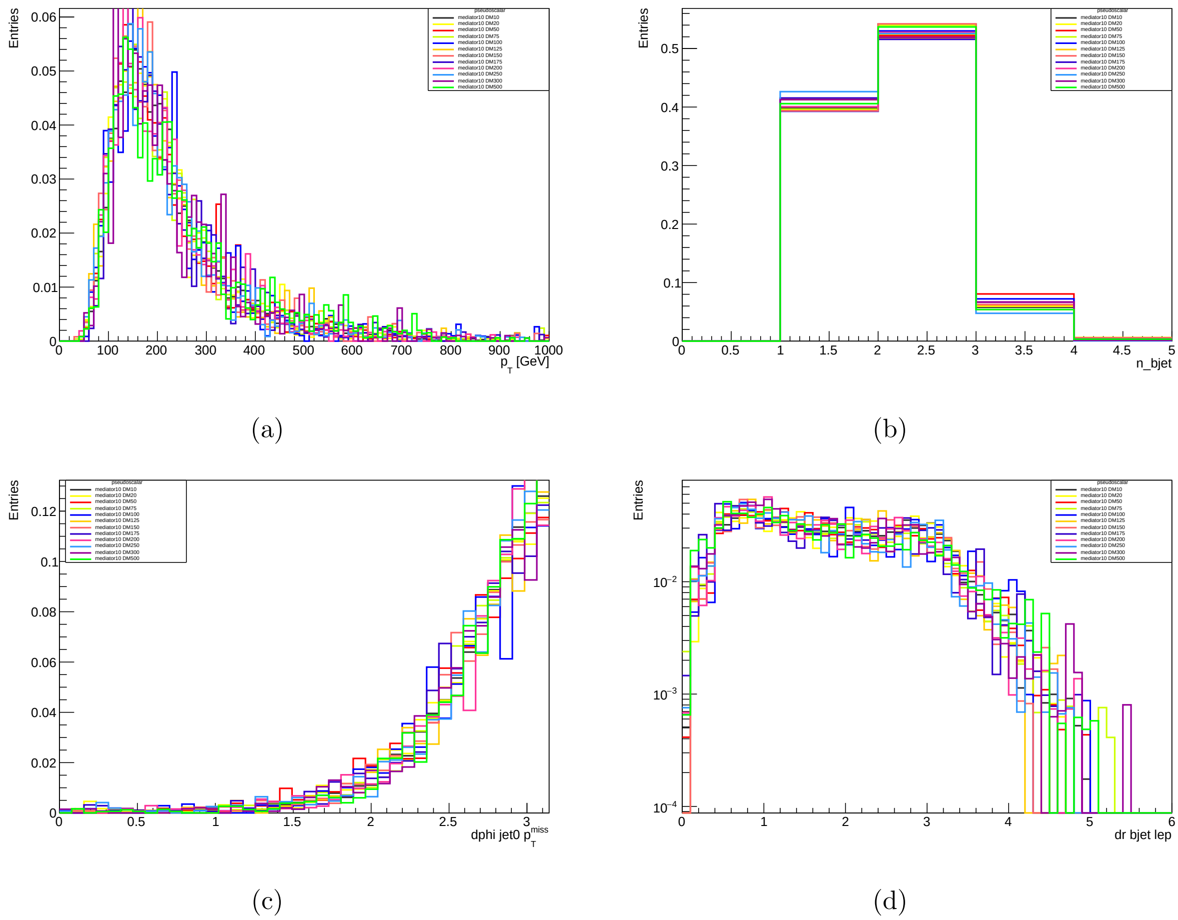



Figure 11: Distributions of discriminating variables: (a) the first jet $p_T$, (b) Number of $b$-tags (c) $|\Delta\phi(jet_0,\vec{p}_T^{miss})|$, and (d) $\Delta$R($b_1$,$b_2$) in normalization. The category shows different color representing different mass of the DM particle. Plot (d) is in log coordinate.

It is easily to find that these variables have the same tendency with the changing of the DM mass. We cannot judge from the plots if the higher mass one is better or the lower one.

Next I will compare the difference with the scalar and pseudoscalar mediator. First, we set the mediator mass equals to 20GeV, and dark matter particle mass equals to 1GeV. The plots shows in the Figure 12.

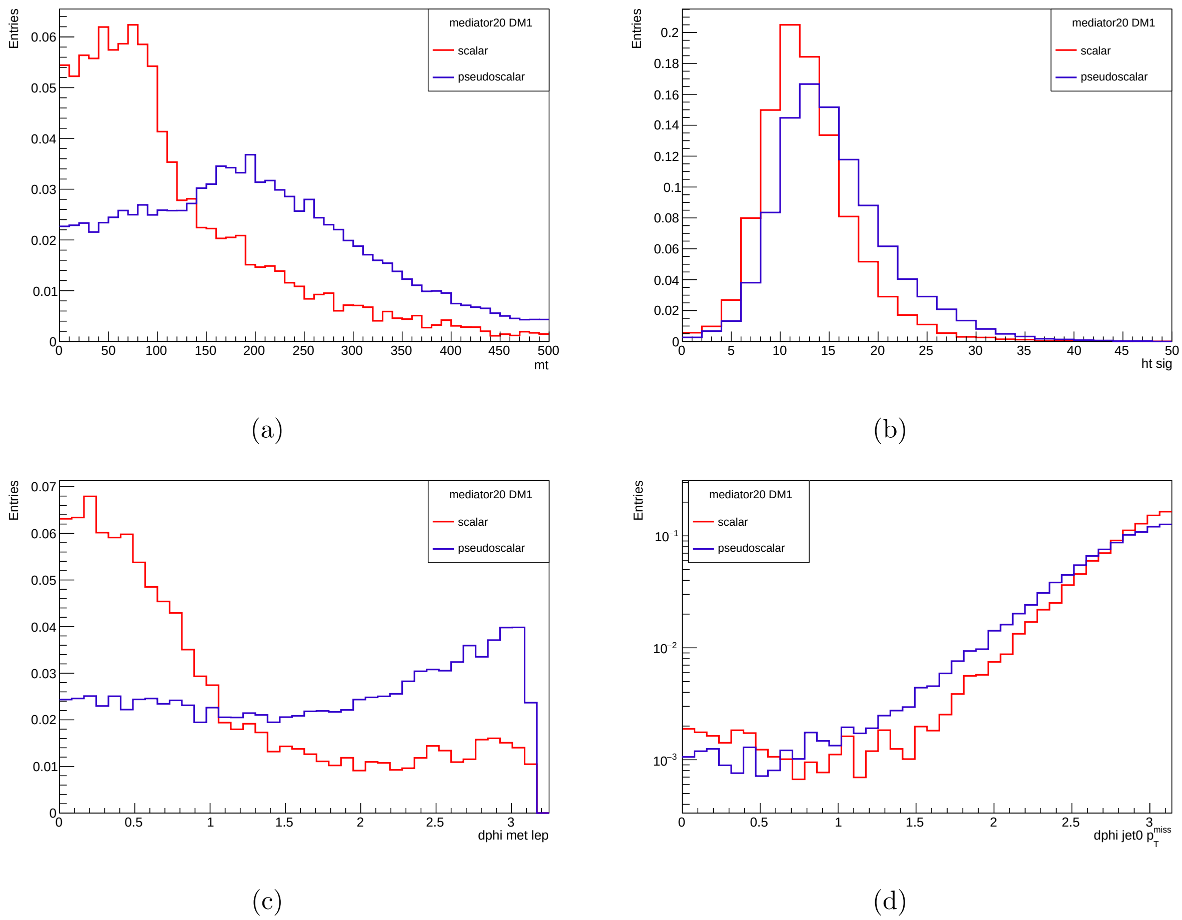
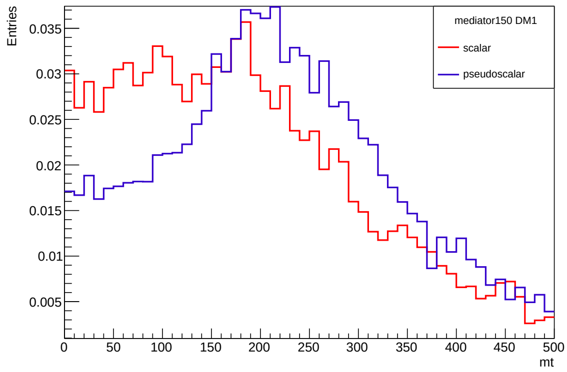


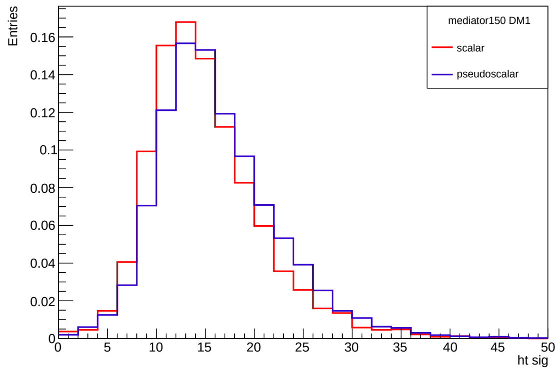

Figure 12: Distributions of discriminating variables: (a) $m_T$, (b) $H_{T,sig}^{miss}$, (c) $\Delta\phi(l,\vec{p}_T^{miss})$, and (d) $|\Delta\phi(jet_0,\vec{p}_T^{miss})|$ in normalization. The category shows red representing scalar mass and blue one representing pseudoscalar different mass of the DM particle. Plot (d) is in log coordinate.

In plot (a), before around 140GeV, the scalar mediator is better than pseudoscalar one to describe the $m_T$ variable. While greater than 140GeV, the pseudoscalar mediator works better. According to the background we show in the Figure 3, we can get rid of the most background and have a good DM signal in the higher energy of $m_T$, so we can choose pseudoscalar to do. The same analysis can be done for the rest of the plots. And we can find out that pseudoscalar mediator is better to get rid of the background.

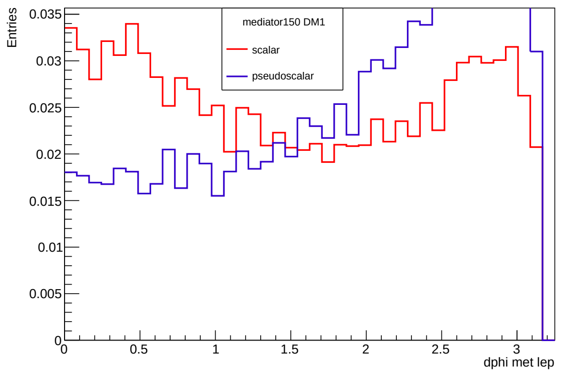
Second, we set the mediator mass equals to 150GeV, and dark matter particle mass equals to 1GeV the same as the first condition. The plots shows in the Figure 13.



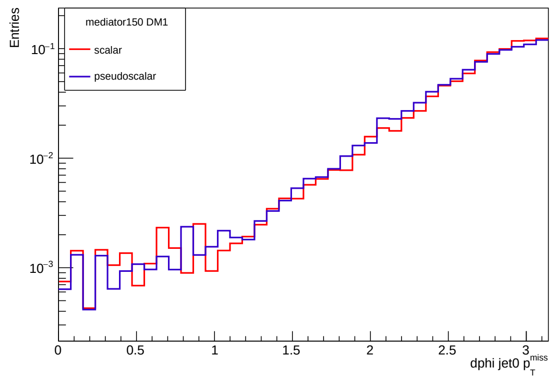

(a)




(b)




(c)




(d)

Figure 13: Distributions of discriminating variables: (a) $m_T$, (b) $H_{T,sig}^{miss}$, (c) $\Delta\phi(l,\vec{p}_T^{miss})$, and (d) $|\Delta\phi(jet_0,\vec{p}_T^{miss})|$ in normalization. The category shows red representing scalar mass and blue one representing pseudoscalar different mass of the DM particle. Plot (d) is in log coordinate.

In Figure 13 plot (a), the difference with the Figure 12, before around 160GeV, the scalar mediator is better than pseudoscalar one to describe the $m_T$ variable. While greater than 160GeV, the pseudoscalar mediator works better. According to the background we show in the Figure 3, we can get rid of the most background and have a good DM signal in the higher energy of $m_T$, so we can choose pseudoscalar to do. It can be explained that the higher mass mediator has, the better DM signal will be shown just as the conclusion we get before. The same analysis can be done for the rest of the plots. And we can find out that pseudoscalar mediator is better to get rid of the background.
Finally, we set the mediator mass equals to 300GeV, and dark matter particle mass equals to 1GeV the same as the condition we set before. The plots shows in the Figure 14 and at this time, the DM_low SR plots are also be displayed.

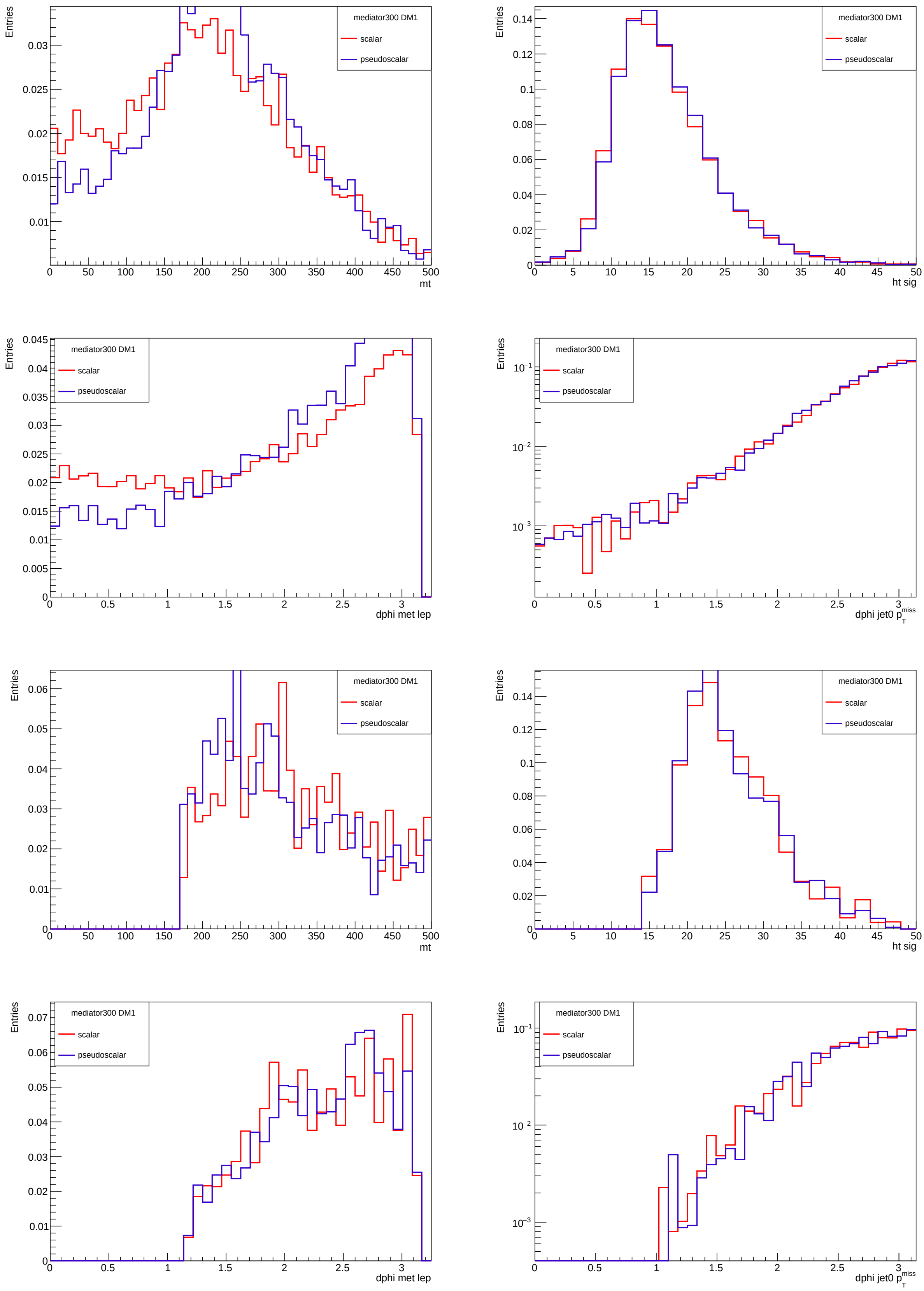



Figure 14: Distributions of discriminating variables:$m_T$,$H^{miss}_{T,sig}$,$\Delta\phi(l,\vec{p}_T^{miss})$,and$|\Delta\phi(jet_0,\vec{p}_T^{miss})|$.

# 5 Summary and conclusions

This report presents searches for a spin-0 mediator decaying into pair-produced dark matter particles produced in association with $t\bar{t}$ using the final state with one isolated lepton, jets, and $E_T^{miss}$.
The search uses $36fb^{-1}$ of $pp$ collision data collected by the ATLAS experiment at the LHC at a centre-of-mass energy of $\sqrt{s}$ = 13TeV. Exclusion limits at 95% confidence level are derived for the considered models.
From the plots I have got, I can find out that if we have higher mass of mediator, especially pseudoscalar, and dark matter particle, we can get rid of more background, and get a better DM signal.
In the future, I will try to change the entries to get the expected number of events.

# References

[1] Study of Search for top-squark pair production in final states with one lepton, jets, and missing transverse momentum using $36fb^{-1}$ of $\sqrt{s} = 13$TeV $pp$ collision data with the ATLAS detector. *The ATLAS collaboration*