Search for SUSY Higgs $\rightarrow \tau\,\tau \rightarrow e\,\mu$

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Abstract

This work was meant to improve the sensitivity in the search in the eμ channel of neutral SUSY Higgs bosons, decaying into τ leptons, using a multivariate analysis method (MVA).

After a short introduction on the hMSSM scenario in the Minimal Supersymmetric extension to the Standard Model (MSSM) the results for the previous run in LHC will be shown. The signal we are looking for will be explained in further details and the major background contributions will be listed. A short introduction to the boosted decision tree will then be given, as well as the results for the training with Monte Carlo (MC) samples for the Drell-Yan process, used as signal due to its similar kinematic properties compared to the SUSY signals in this channel.

The results for the analysis after training on the SUSY signal will then be shown, as well as its agreement with data for 2016 run in the background region. This method will be used by the $H \rightarrow\ \tau\ \tau$ group at DESY in their future analysis.

Contents

1 Introduction

The Compact Muon Solenoid (CMS) is one of the major experiment at the Large Hadron Collider (LHC), along with ATLAS, LHCb and ALICE. It is designed to measure a broad range of signals and its goals range from high precision tests of QCD, electroweak interactions and flavour physics to the search of new physical phenomena, such as the decay of supersymmetric particles.
It started taking data in 2009, and in July 2012 along with the ATLAS collaborations it announced the discovery of a new particle with properties consistent with the Standard Model (SM) Higgs boson (H). The particle was identified through its decay in gauge bosons $H \to \gamma\gamma, ZZ, WW$. The combined data from the two experiments in RunI (2011-2014) were used to collect evidence at 5 standard deviation for the $H \to \tau\tau$ channel, which has a branching ratio of 6.3%.
The $H \to \tau\tau$ channel is the most sensitive channel to probe Yukawa couplings of the Higgs boson to leptons, and data is collected in the current run at 13 TeV to study this channel in its possible final states:

- e μ (BR∼6%),
- μ μ or e e (BR∼6%),
- lepton + hadron (BR∼46%),
- hadronic (BR∼43%).

In this report the eμ channel is used to search for signals of new physics, related to heavier supersymmetric partners of the Higgs boson.

1.1 Higgs sector in MSSM

In the minimal supersymmetric extension to the standard model two Higgs doublets are introduced:

$$\Phi_1 = \begin{pmatrix} \Phi_1^+ \\ \Phi_1^0 \end{pmatrix} \qquad \Phi_2 = \begin{pmatrix} \Phi_2^+ \\ \Phi_2^0 \end{pmatrix} \tag{1}$$

In this extension to the standard model the Φ_1 couples to down-like quarks, while Φ_2 couples to up-like quarks. The expectation values on the vacuum state are defined for the two doublets as:

$$\Phi_1 = \left\langle \begin{matrix} 0 \\ v_1 \end{matrix} \right\rangle \qquad \Phi_2 = \left\langle \begin{matrix} 0 \\ v_2 \end{matrix} \right\rangle \tag{2}$$

The parameter tan(β) is then defined as the ratio between the expectation values on the vacuum state for the two doublets:

$$\tan(\beta) = v_1/v_2 \tag{3}$$

Following the spontaneous breaking of symmetry $SU(2)_L \otimes U(1)_Y \to U(1)_{e.m.}$ five physical states are generated:

- h (scalar, neutral),
- H^0 (scalar, neutral),
- $H^{\pm}$ (scalars, charged),
- A (pseudo-scalar, neutral).

In the next chapters the symbol Φ will be used to identify any of the neutral SUSY Higgs fields h, H^0 or A, unless specified.

hMSSM scenario

One of the possible scenarios in the MSSM Higgs sector postulates that the h field is discovered scalar boson at mass 125 GeV identified in 2012 by the CMS and ATLAS collaborations. In this model two parameters are scanned to determine the consistency of the model with observed data:

- $\tan(\beta)$,
- m_A (or more generally m_Φ).

The other model parameters are extracted from the observed data.
Figure 1 shows the limits on $\tan(\beta)$ as a function of m_A obtained from analysis of 2015 dataset:

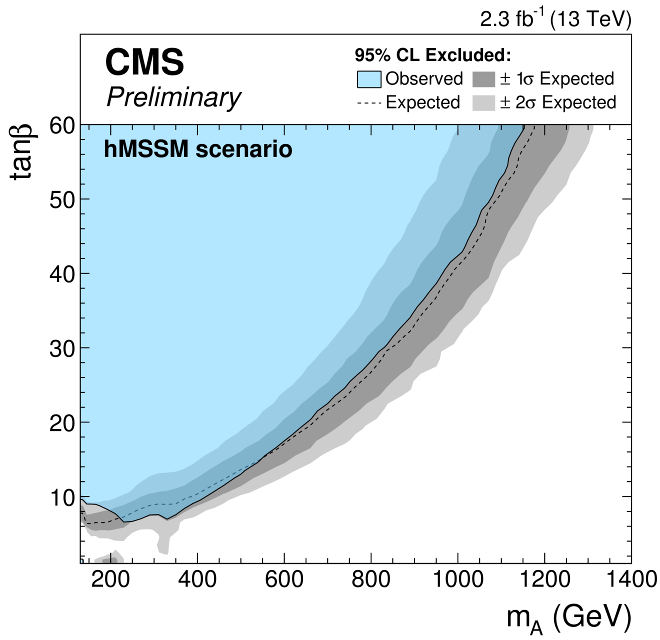

Figure 1: CMS preliminary limits on $\tan(\beta)$ versus m_A, obtained from the 2015 data, in the hMSSM scenario[1].

2 Data

Table 1: List of samples used for the analysis.

data/process	**directory (/nfs/dust/cms/group/higgs-kit/80x_v1(3)/..)**
data-runB	MuonEG__Run2016B-PromptReco-v2/
data-runC	MuonEG__Run2016C-PromptReco-v2/
data-runD	MuonEG__Run2016D-PromptReco-v2/
SUSY gg→ Φ($Mass)	SUSYGluGluToHToTauTau_M- $(Mass) _TuneCUETP8M1_13TeV-pythia8
SUSY gg→bbΦ($Mass)	SUSYGluGluToBBHToTauTau_M- $(Mass) _TuneCUETP8M1_13TeV-pythia8
Drell-Yan	DYJetsToLL_M-50_TuneCUETP8M1_13TeV-madgraphMLM-pythia8
$t\ \bar{t}$	TT_TuneCUETP8M1_13TeV-powheg-pythia8_ext4-v1
WW→l+ν+2q	WWTo1L1Nu2Q_13TeV_amcatnloFXFX_madspin_pythia8
VV→2l+2ν	VVTo2L2Nu_13TeV_amcatnloFXFX_madspin_pythia8
WZ→l+ν+2q	WZTo1L1Nu2Q_13TeV_amcatnloFXFX_madspin_pythia8
WZ→l+3ν	WZTo1L3Nu_13TeV_amcatnloFXFX_madspin_pythia8
WZ→2l+2q	WZTo2L2Q_13TeV_amcatnloFXFX_madspin_pythia8
ZZ→2l+2q	ZZTo2L2Q_13TeV_amcatnloFXFX_madspin_pythia8
ST_t-channel_top_4f_leptonDecays	ST_t-channel_top_4f_leptonDecays_13TeV-powheg-pythia8_TuneCUETP8M1
ST_t-channel_antitop_4f_leptonDecays	ST_t-channel_antitop_4f_leptonDecays_13TeV-powheg-pythia8_TuneCUETP8M1
ST_tW_top_5f_inclusiveDecays	ST_tW_top_5f_inclusiveDecays_13TeV-powheg-pythia8_TuneCUETP8M1
ST_tW_antitop_5f_inclusiveDecays	ST_tW_antitop_5f_inclusiveDecays_13TeV-powheg-pythia8_TuneCUETP8M1
WJets→l+ν	WJetsToLNu_TuneCUETP8M1_13TeV-madgraphMLM-pythia8

The data used in this analysis are the 2016 data collected up to 15 July 2016, for a total luminosity of 12.9 fb^{-1}. As reported in Table 1 the data set is MuonEG, which requires at least one muon or one electron (or γ) in the final state.
The trigger used was the logic OR between:

- Mu23_Ele12,
- Mu8_Ele23.

This trigger requires a transverse momentum greater than 23 GeV for the leading lepton, while for the other lepton's momentum a minimum value of 8 GeV for the muon and 12 GeV for the electron is required.
The MC samples used for the SUSY signals and all possible backgrounds are also listed in Table 1. The SUSY signal was generated both in the gluon fusion (gg) and in the b-associated production (bbΦ) modes, for masses ranging from 130 to 2000 GeV.

2.1 Data and MC selection

The searched signal is the Φ decay into two τ leptons, with one decaying in an electron and one in a muon. Because of the kinematics of the process the leptons are expected to be highly isolated and with rather high transverse momenta.
To select a final state with this characteristics the following selection was applied to both data and MC samples:

- $P_{T,leading}$ >24 GeV,
- $P_{T,2^{nd}lepton}$ >8 GeV for muon, and $P_{T,2^{nd}lepton}$ >13 GeV for electron,
- $|\eta_\mu|$ <2.5,
- $|\eta_e|$ <2.4,
- the two leptons should satisfy quality requirements and be isolated, i.e. no energy deposition in a cone ΔR <0.4,
- the two leptons should have opposite charge,
- ΔR >0.3
  - ΔR is the distance in η, ϕ between the two leptons direction of flight:

$$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} \tag{4}$$

- veto for second electron with P_T >10 GeV,
- veto for second muon with P_T >10 GeV.

These condition are used to select a final state where the leptons have high enough energy and are isolated.

2.2 Control plots

In this section the control plots for some variables are shown for data and MC samples. The samples used are listed in Table 1 and were added according to the cross section of the associated physical process. The QCD sample is estimated from data using same sign eμ pairs, scaled to opposite sign pairs with a normalisation factor obtained in a control region dominated by QCD dijet events. As shown in Figures 2 to 7 there is good agreement between the MC and data within systematic uncertainties, shown as a band in the plots.

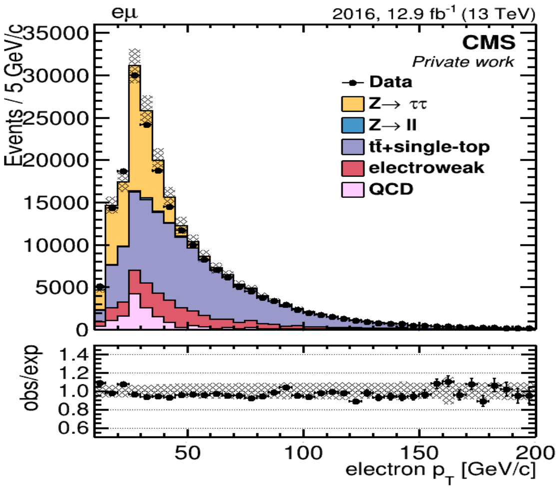

Figure 2: Electron P_T distribution.

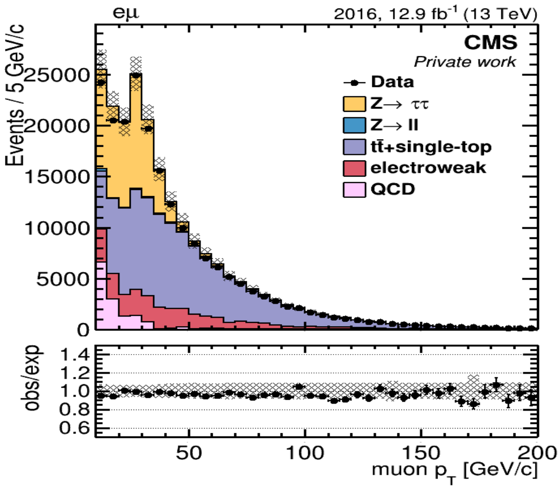

Figure 3: Muon P_T distribution.

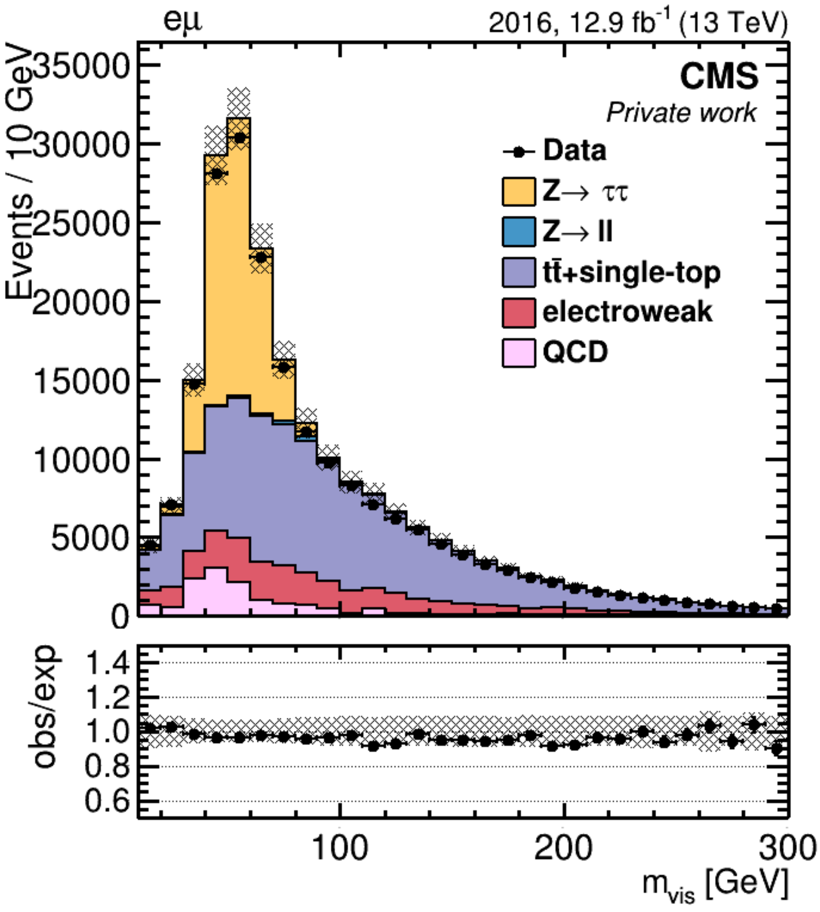

Figure 4: Distribution for the reconstructed transverse mass of the leptonic system.

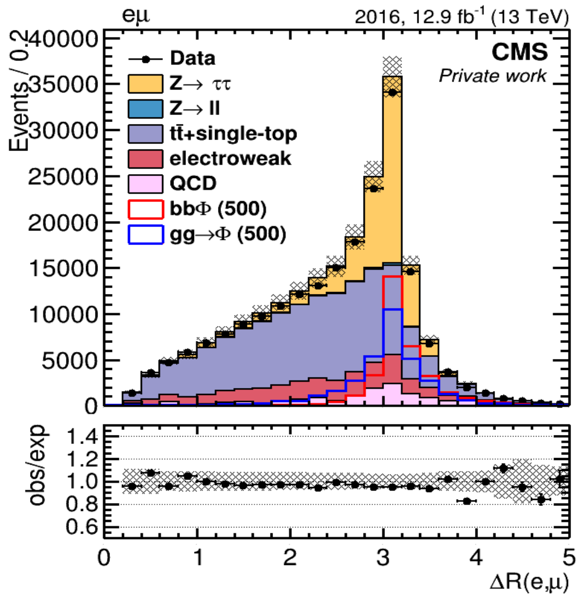

Figure 5: ΔR distribution.

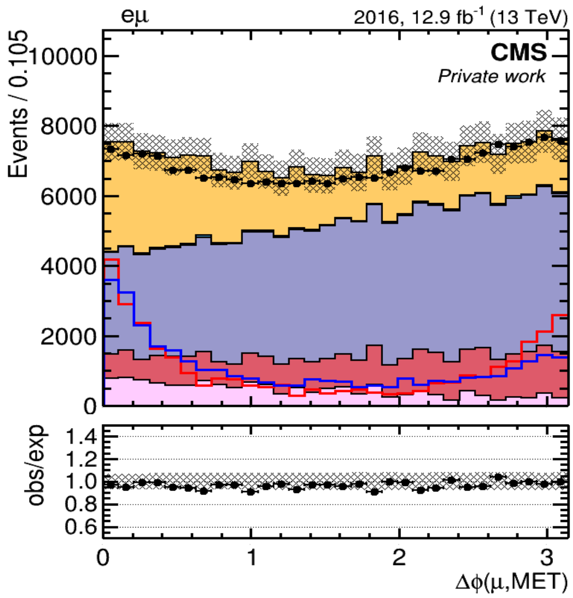

Figure 6: Angular distance between the muon and the MET directions.

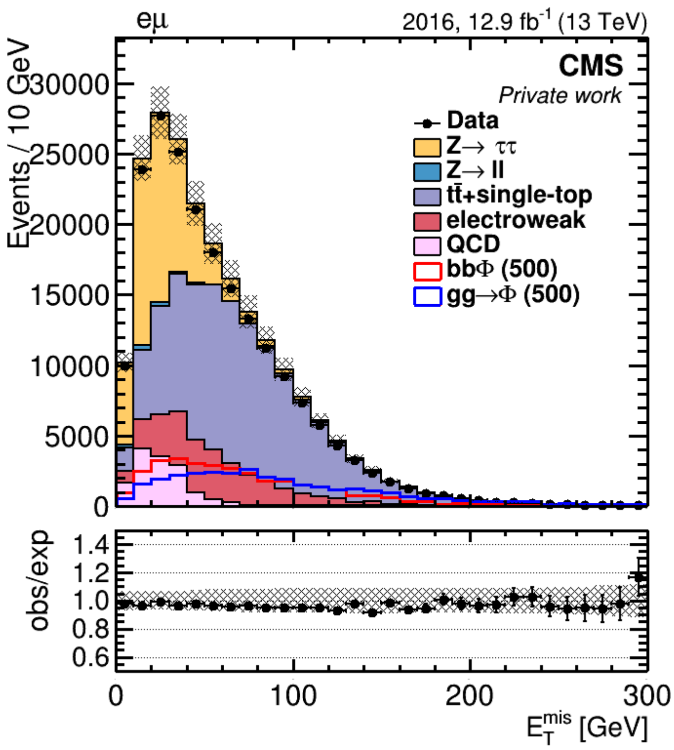

Figure 7: Missing transverse energy distribution.

Dζ variable[2]

One variable that was used for signal identification in the analysis for $H \to \tau\tau \to e\mu$ is $D\zeta$, which is defined as the projection of the missing transverse momentum on the bisector between the two leptons flight directions (Fig. 8):

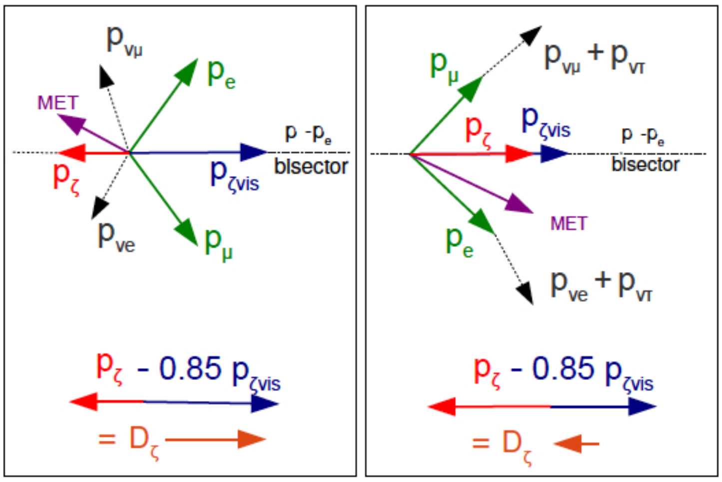

Figure 8: Sketch of the $D\zeta$ as discriminating variable.

$$D\zeta = \overrightarrow{\not{E}_T} \cdot \hat{\zeta} - \alpha \left(\overrightarrow{P_{T,e}} + \overrightarrow{P_{T,\mu}} \right) \cdot \hat{\zeta}, \tag{5}$$

where:

- $\overrightarrow{P_{T,e}}$ and $\overrightarrow{P_{T,\mu}}$ are the transverse momenta of electron and muon,
- $\hat{\zeta} = \frac{\overrightarrow{P_{T,e}} + \overrightarrow{P_{T,\mu}}}{\left|\overrightarrow{P_{T,e}} + \overrightarrow{P_{T,\mu}}\right|}$, is the bisector between the two leptons flight directions,
- $\overrightarrow{\not{E}_T}$ is the missing transverse momentum,
- α is a parameter chosen to obtain the best discrimination from the $t\bar{t}$ background, in this analysis $\alpha = 0.85$.

As can be observed in Fig. 9 the $D\zeta$ variable is good for reducing the $t\bar{t}$ background, and to select the Drell-Yan process, which is similar to the SUSY signals we are looking for.

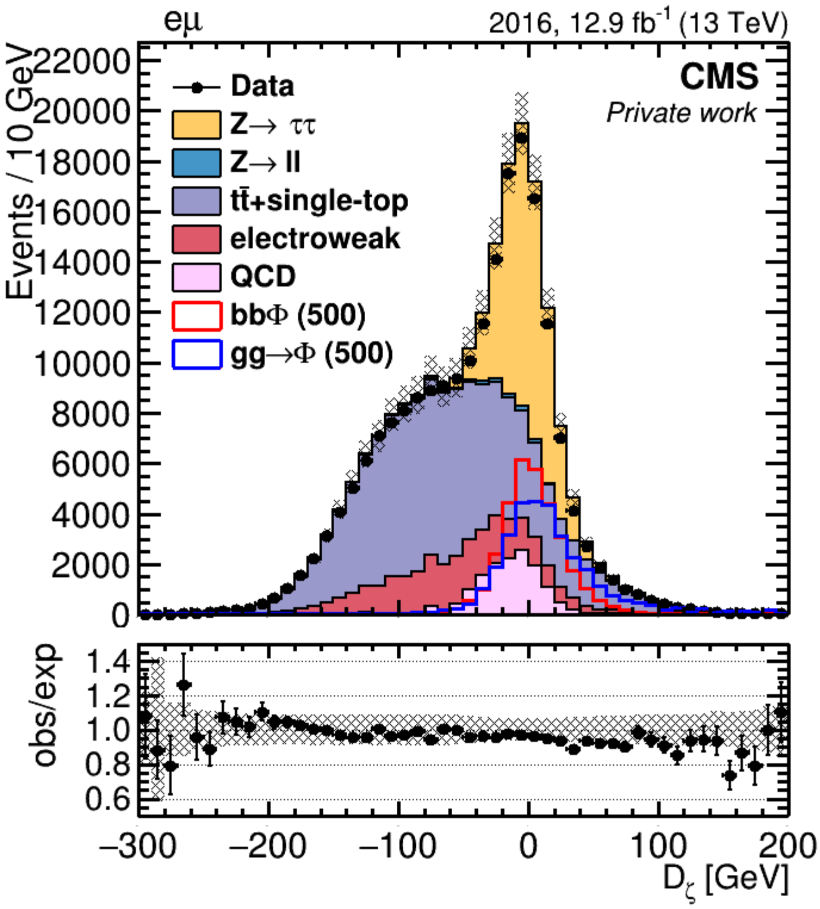

Figure 9: $D\zeta$ distribution.

2.3 Results with $D\zeta$ cut

In previous analyses, a cut $D\zeta > -20$ GeV was applied to suppress the $t\bar{t}$ background. The reconstructed $m_{T,tot}$ after applying the cut in $D\zeta$ is shown in Fig. 10.
The variable $m_{T,tot}$ is defined as follows:

$$m_{T,tot} = \sqrt{m_T^2(e, p_T^{mis}) + m_T^2(\mu, p_T^{mis}) + m_T^2(e, \mu)}, \tag{6}$$

where:

$$m_T(L_1, L_2) = \sqrt{2P_T^1 P_T^2(1 - cos\theta_{1,2})}, \tag{7}$$

with $\theta_{1,2}$ angle between the two spatial momenta, and it is the variable which will be used to extract the signal.
There is a good agreement between data and MC samples in the background region, while the data in the signal region are blinded to avoid any bias in further analysis.

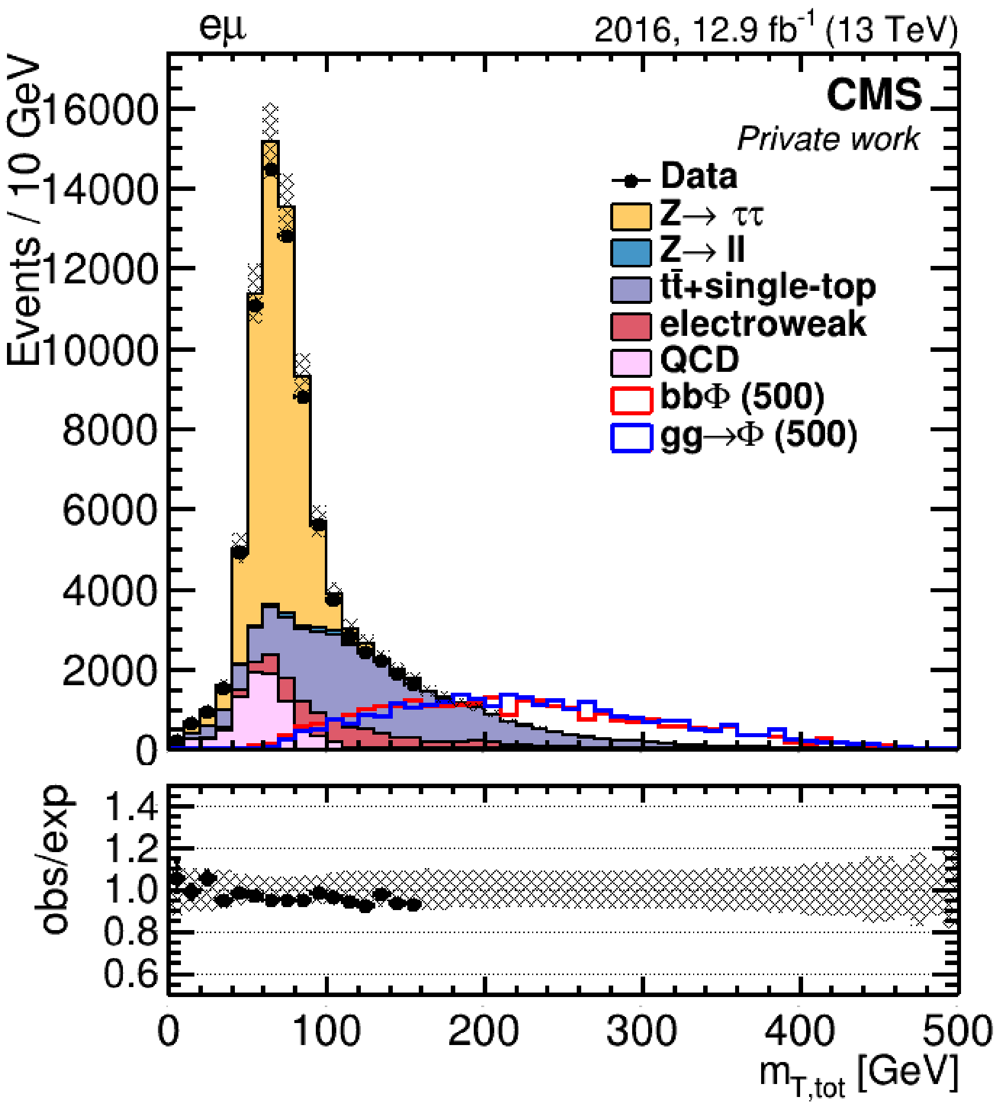

Figure 10: $m_{T,tot}$ distribution.

3 Multivariate analysis: BDT

To increase the sensitivity in the search for new physics this work has the aim to improve the $D\zeta$ cut selection, by using a multivariate analysis method (MVA), with the TMVA extension of the ROOT analysis framework.
The first signal used to train the method was the Drell-Yan process (Table 1), while the other samples were combined as background according to their cross section.
The first test was to choose the TMVA method with best performances, considering both the resulting background rejection and signal efficiency (ROC curve), and the time taken for computing. The methods tested were:

- CutBased (sharp cuts on different variables),
- Fisher Discriminant,
- Likelihood,
- Boosted Decision Tree (BDT),
- Multilayer Perceptrons (MLP).

The best performing method resulted to be the Boosted Decision Tree, which combines selection on a set of variables to apply weights to the events, to identify signal from background. The Multilayer Perceptrons method gave slightly better results than BDT, taking, however, 5 times longer computing time.

3.1 Variables

The next step in the analysis was to choose the set of variables for the BDT training. The following is a list of all the variables used for the first run:

- P_T, η, dxy and dZ (secondary vertex displacement) for both leptons;
- Missing E_T, ϕ of the Missing E_T;
- $P_{T,tot}$, ΔR, $\Delta\phi_{e,\mu}$, $\Delta\phi_{\mu,met}$, $D\zeta$;
- number of b-jets, P_T of the b-jets, η and ϕ of the b-jets.

After removing highly correlated variables (like $\Delta\phi_{e,\mu}$, since it is correlated with ΔR and $D\zeta$) or variables that still require some study (like dxy and dZ), this is the list of variables chosen for the analysis:

- P_T for both leptons,
- MET,
- ΔR,
- $\Delta\phi_{\mu,met}$,
- $D\zeta$.

The variables related to b-tagging were removed because even though they are useful for Drell-Yan signals they might not be usefull for search of SUSY Higgs produced via bbΦ process.

3.2 Training with Drell-Yan

In this section the results for the training of the BDT method are shown using Drell-Yan as a signal.
In Fig. 11 the BDT response for training and test sample is shown. The two samples were made taking random events from the whole sample to keep a ratio of 5 between the number of events used for training the method and the ones used for testing. As shown by the consistency of the two distribution for test and training samples, there was no overtraining of the method, and a good value for discriminating between signal and background is BDT∼0.

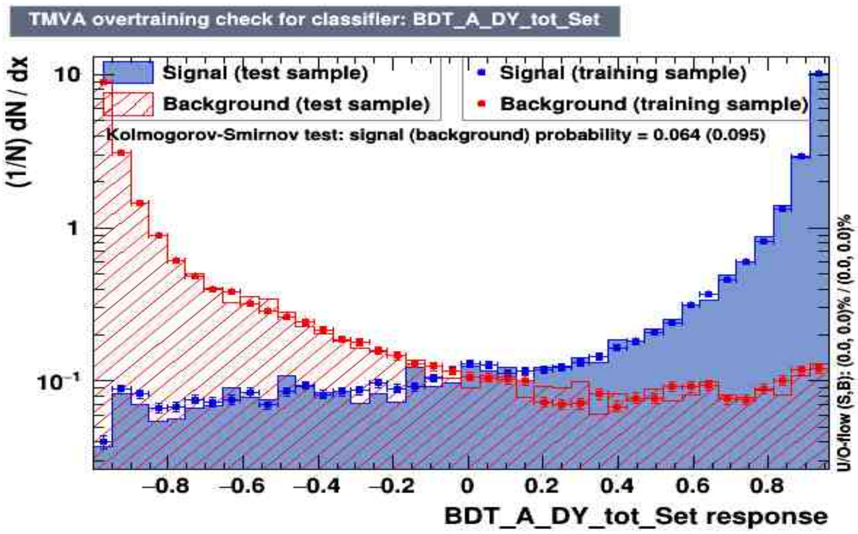

Figure 11: BDT response distribution.

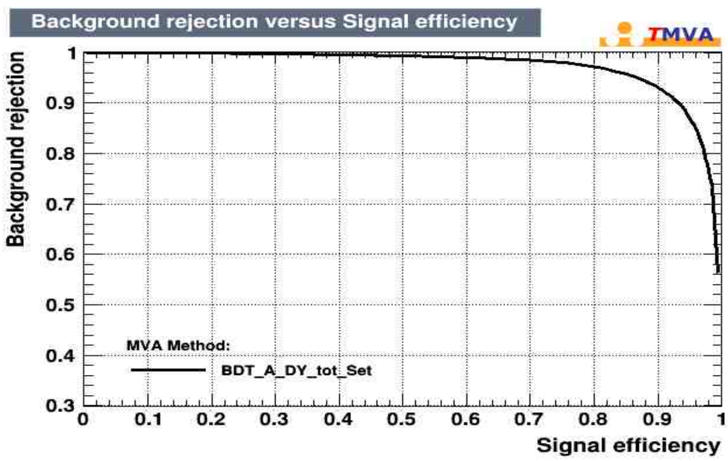

Figure 12: ROC curve.

The ROC curve shown in Fig. 12 represents the background rejection as a function of the signal efficiency. As can be observed a highly pure sample with a background contamination of few % can be obtained with an efficiency around 70%.

4 Results

4.1 Training with SUSY

The promising result from the Drell-Yan analysis were carried into the analysis of the SUSY Higgs samples. Two different processes where tested, as shown in Table 1:

- $g\ g \longrightarrow \Phi(Mass[GeV])$;
- $g\ g \longrightarrow b\ b\ \Phi(Mass[GeV])$.

The searched Φ particle is probed at different masses ranging from 130 to 2000 GeV. The detailed list of the probed masses is presented in Table 2 (where the values are expressed in GeV).

Table 2: List of samples used for the analysis.

130	140	160	180	200	250	300
350	400	450	500	700	800	900
1000	1200	1400	1500	1600	1800	2000

Figure 13 shows the variables distribution for the $g\ g \rightarrow \Phi$ signal, compared to the background, which is the same one used when applying the method to the Drell-Yan signal. In doing so the contribution of Drell-Yan process is not taken into account, i.e. it was not added to the background sample in the training. This choice was made for the following reasons:

- Drell-Yan signal has properties similar to those of the SUSY signals we are looking for, and its presence in the background greatly affects the results of the BDT analysis;
- the contribution of Drell-Yan signal to the background is negligible at high mass, in the region where we are searching for new physics.

A good separation between SUSY and the background is shown for the 6 variables, the same is observed in the bbΦ process.
Figures 14 and 15 show the correlation matrix of the variables for signal and backgrounds. The presence of some highly correlated variables for the signal (ΔR, $D\zeta$ and MET) was ignored in this analysis because it greatly differs from the correlation observed for background, this validates the choice of variables made with the Drell-Yan sample.

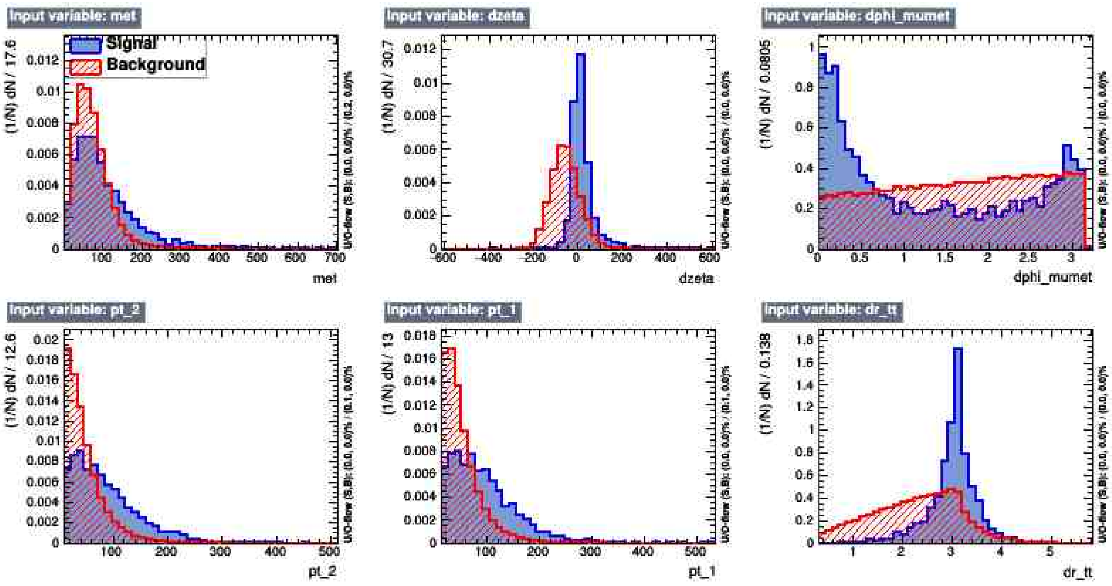

Figure 13: Variables distribution for $g\ g \to \Phi$ signal and background samples.

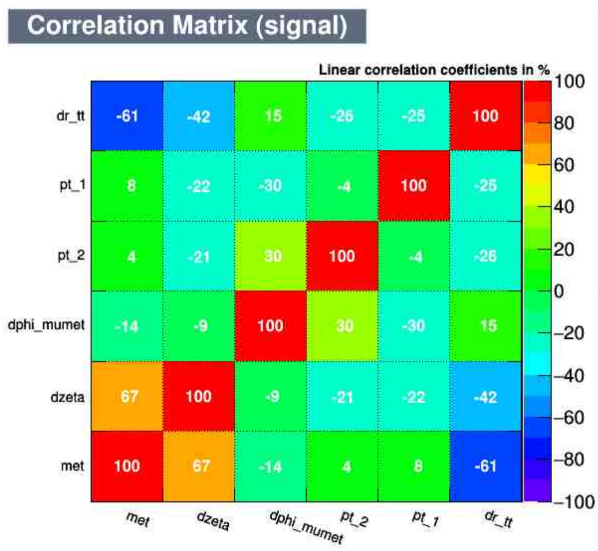

Figure 14: gg: variable correlation matrix for signal.

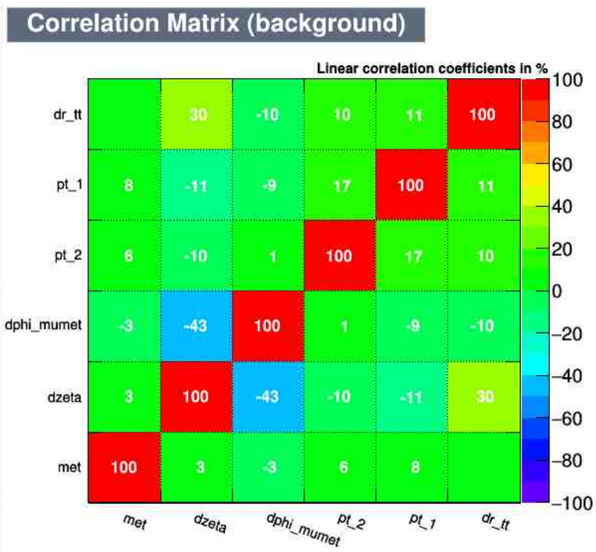

Figure 15: gg: variable correlation matrix for background.

Figures 16-19 are used to show the results of the BDT analysis on both processes at a value of 500 GeV for the Φ particle mass.
Figures 20 and 21 show the significance for the two processes as a function of the BDT response. For the bbΦ process there is a wide range of values where the significance is almost flat.

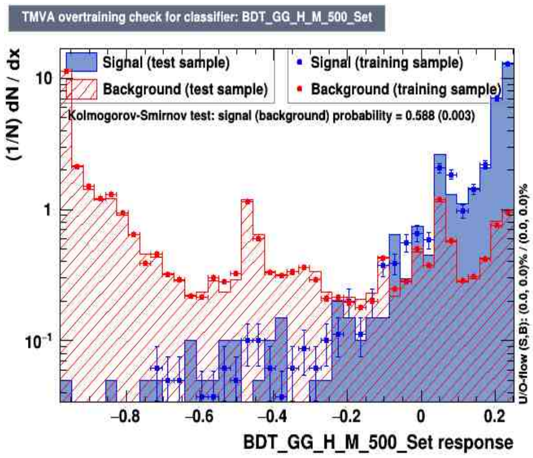

Figure 16: gg process BDT response.

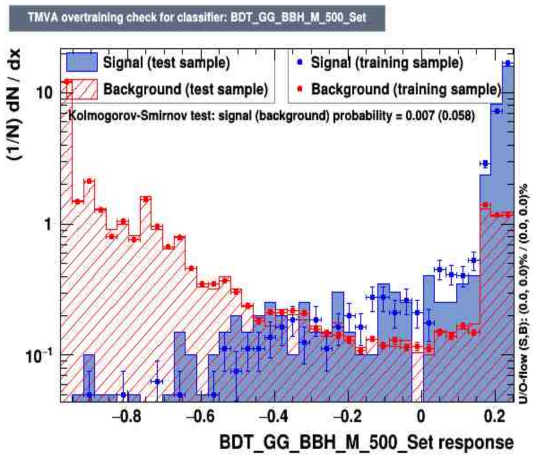

Figure 17: bbΦ BDT response.

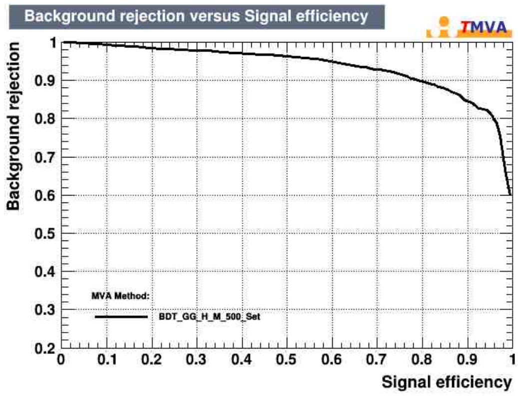

Figure 18: gg: ROC curve.

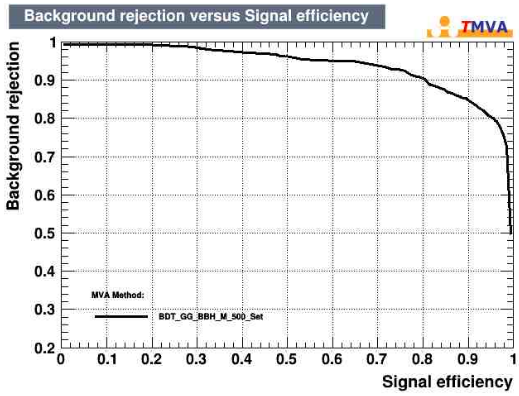

Figure 19: bbΦ: ROC curve.

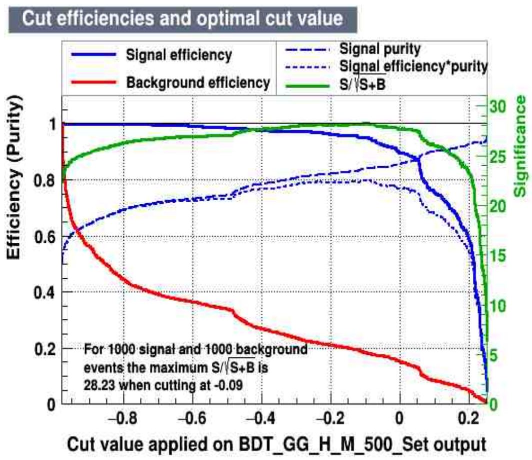

Figure 20: gg: significance, purity and efficiency curves.

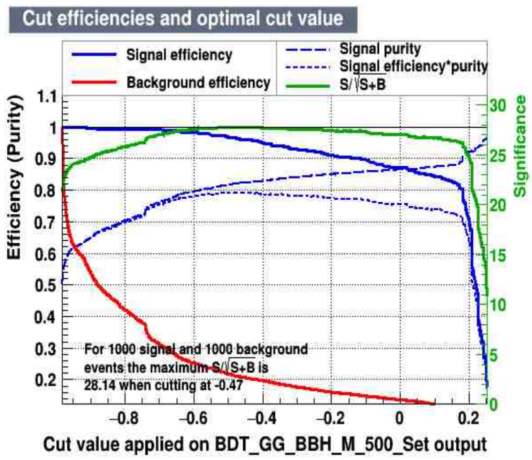

Figure 21: bbΦ: significance, purity and efficiency curves.

4.2 BDT evaluation and expected limits

The BDT value was then calculated in the data.

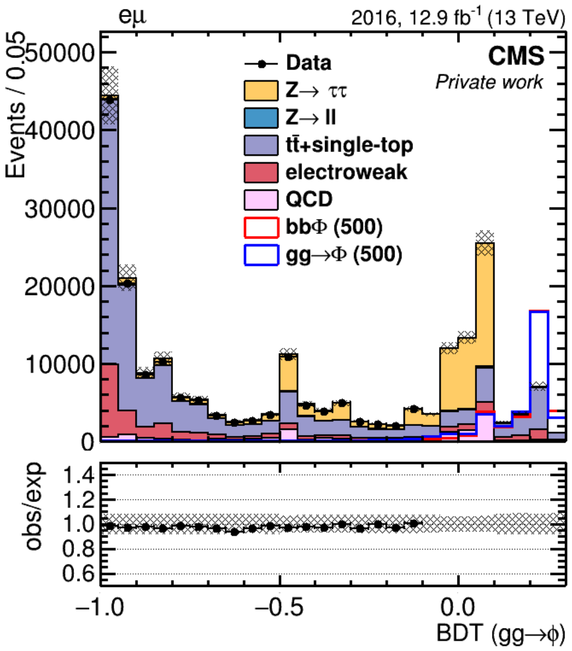

Figure 22: BDT evaluation using the gg weights.

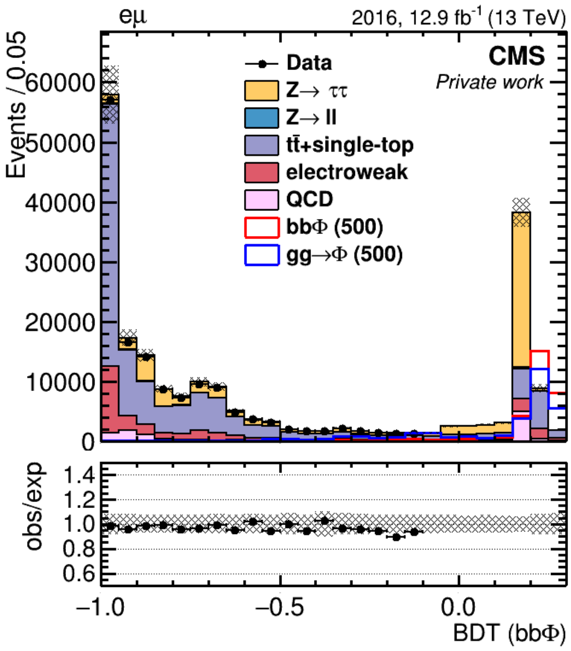

Figure 23: BDT evaluation using the bbΦ weights.

Figures 22 and 23 show the two BDT values for the 2016 data versus the sum of all background contributions. The SUSY Φ signal is shown separately on top as continous lines for a mass of 500 GeV. Both plots are shown with the signal region still blinded, and show good agreement between data and MC in the background region. We also observe that the agreement accounts for the contribution of Drell-Yan process to the background even though it was not used as background sample for the BDT training. This validates, at least for high mass values, the assumption that in the signal region the Drell-Yan contribution is low enough, such that it does not create discrepancies between the physical scenario described by the analysis (which neglects Drell-Yan process) and the real one.
The new expected limits for the cross section of the two processes are shown in Figure 24 and 25, where the limits were calculated using a BDT > 0.1 cut for both processes. A good improvement can be found for the bbΦ process, compared to the one associated to the $D\zeta$ cut. A slight improvement is also shown for the $g\ g \to \Phi$ process.

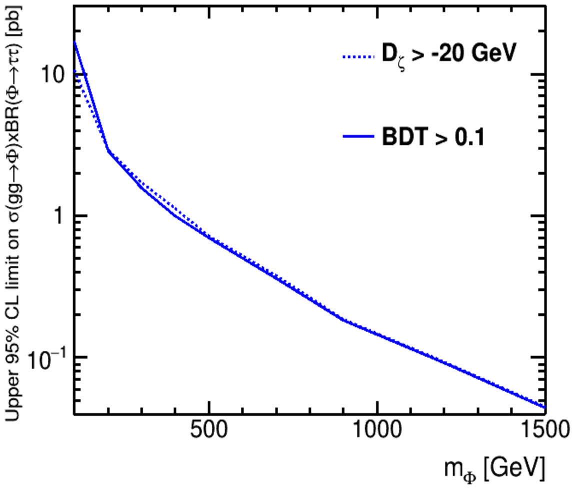

Figure 24: Expected limits for gg signal.

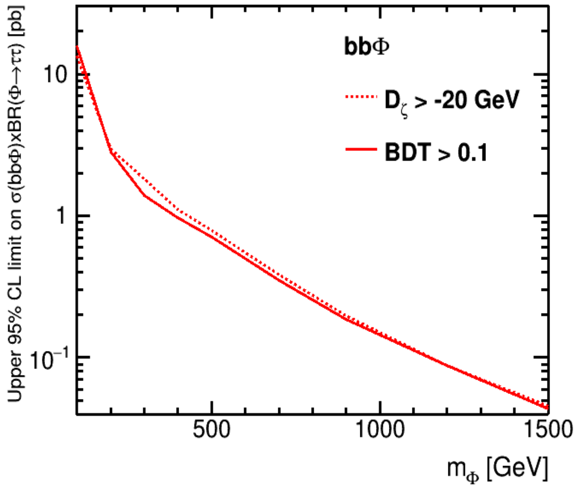

Figure 25: Expected limits for bbΦ signal.

5 Summary and conclusion

As shown in this work the BDT training of this analysis achieved for masses greater than 200 GeV a better sensitivity in the search of signals of SUSY $\Phi \to \tau\tau \to e\mu$, compared with the traditional $D\zeta$ cut, especially in the bbΦ channel. The slight improvement seen for the $g\ g \to \Phi$ process may hint at the need to change the variables for this signal and operate a different analysis, compared to the one for the $g\ g \to b\ b\ \Phi$ process. A possible improvement in this direction could be explored adding variables related to the b-tagging, as we expect no b-jets for this signal.
The technique developed for this analysis will be used by the CMS $H \to \tau\tau$ group at DESY and applied to the official CMS SUSY $H \to \tau\tau \to e\mu$ analysis.

References

[1] CMS collaboration. *Search for a neutral MSSM Higgs boson decaying into ττ at 13 TeV*, CMS PAS HIG-16-006.

[2] Luigi Calligaris. *Search for a Heavy Neutral Higgs Boson decaying into Tau Pairs with the CMS Experiment at the LHC.* PhD thesis, Hamburg 2015.