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# Search for CP violation in top quark pair at $\sqrt{s} = 13$ TeV in CMS

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## **Abstract**

This is a template abstract for my L<sup>A</sup>T<sub>E</sub>X notes.

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# **I Introduction**

Particle physics has been started from

## **I.1 Ingredients of the materials**

The standard language of



## **II Experimental Apparatus**

## III Physical Objects Reconstruction and Selection

### III.1 Lepton

The selected lepton in the analysis is required to obey the criteria of one passed *selected lepton* and zero *veto lepton* passed. The veto criteria means that there would be no lepton passing the veto criteria except the selected one. In other words, the veto criteria can filter the physical objects which are lepton-like but not really like after reconstructed from particle level to detector level. The selected criteria corresponds to tight lepton's criteria, and veto criteria follows loose lepton's criteria:

#### III.1.1 Muon

#### III.1.2 Electron

### III.2 Jet

#### III.2.1 B-tagged jet

### III.3 Vertex

### III.4 Trigger

## IV Data and Simulation samples

### IV.1 Data sample

### IV.2 Simulation sample

### IV.3 Correction on simulation sample

#### IV.3.1 Pile-up Reweighing

#### IV.3.2 Jet Energy correction, smearing and resolution

#### IV.3.3 Efficiency Scale Factor

#### IV.3.4 Weigh to Luminosity

Process sample	Cross Section (pb)	k-factor	Events Number	Generator
$t\bar{t} \rightarrow b\bar{b}jjl\nu$	XXX	1	CCCCC	AAAAAA
cell7	cell8	XXXXXX	cell7	cell8

## V Events Selection and Reconstruction

To calculate the asymmetry from top quark in  $t\bar{t}$ , there must be some selections to extract the  $t\bar{t}$  sample from other background samples. Also, there would be several analysis strategies to recognize physical objects and pick them out. The chapter will do these discussion and make some comparison and organization.

In this analysis, doing reasearch by the channel of lepton + jets, which means 2 tops have different decay modes. One decays leptonically, and another decays hadronically(they will be called *hadronic top* and *leptonic top* in following context). It is expected that the hadronic top can be constructed with 1 b-tagged jet and 2 non b-tagged jets and the other top can be constructed incompletely with 1 b-tagged jet, 1 lepton with missing neutrino 4-momentum by detector issue.

### V.1 Trigger

In addition to L1 online trigger mentioned in [III.4](#), there are also offline trigger here to filter specific events. It's called **High Level Trigger(HLT)**. It's a software trigger usually filter events with kinematics like energy( $E$ ), invariant mass( $M$ ), transverse momentum( $p_T$ ), etc. With final states including one selected isolated lepton in this analysis, if they are unprescaled during the entire data collecting, single lepton triggers are chose. For both 2016 data and MC, there are the HLT we use on SingleMuon and SingleElectron sample individually:

- **Single Muon:** *HLT IsoMu24 or HLT IsoTkMu24*, which pick out events whose muon with reconstructed  $p_T > 24$  GeV, or track reconstructed muons with reconstructed  $p_T > 24$  GeV.
- **Single Electron:** *HLT Ele27 WPTight*, which pick out events whose electron with reconstructed  $p_T > 27$  GeV.

### V.2 Events Selection : Signal Region

For the **Signal Region(SR)**, the region with selection cut to extract signal in an analysis, there are the selection cuts below:

- 1 selected lepton which are a tight muon or a tight electron
- 0 lepton pass veto criteria which are loose muon and loose electron criterion
- $\geq 4$  selected jets with passing medium jet criteria
- exact 2 btagged jets(deepCSV Medium criteria) in these selected jets
- each selected jets are isolated from the selected lepton with  $\Delta R > 0.4$

The  $\Delta R$  criteria here means the angle distribution between selected jets and selected lepton in  $\phi - \eta$  phase space with  $\Delta R > 0.4$ . This would avoid the confusing cases that the lepton is really coming from jets or that the jets have some correlation with lepton in reconstruction process... etc.

$$\Delta R = \sqrt{(\eta_{jet} - \eta_{lep})^2 - (\phi_{jet} - \phi_{lep})^2} > 0.4 \quad (1)$$

Under SR selection to extract the semi-leptonic  $t\bar{t}$ (signal), and also following the high level trigger, they are shown in muon and electron channels to classify the selected sample in the following analysis.

### V.3 Events Reconstruction

To reconstruct the semi-leptonic  $t\bar{t}$  system, it is suggested that to reconstruct the hadronic top quark. It's an advantage that we can avoid dealing with missing 4-momentum from neutrino decays from leptonic top. And under the SR selection, if we can reconstruct the top which decays hadronically, the decay objects of leptonic decay top would be picked up simultaneously. This is a direct and common way to correctly identify selected candidates.

#### V.3.1 $\chi^2_{min}$ Method

There are multiple combinations of 1 b-tagged jet and 2 non b-tagged jet in an event. And how do we reconstruct hadronic top? In known and published analysis, based on the reco-level invariant mass of top quark itself and the intermediate particle in decay - W boson, they are used as constraints to invariant mass which is reconstructed from each combination. With the defined  $\chi^2_{min}$  value, which shows below:

$$\chi^2 = \left(\frac{m_{jjb} - m_t}{\sigma_t}\right)^2 + \left(\frac{m_{jj} - m_W}{\sigma_W}\right)^2 \quad (2)$$

where  $m_t$ ,  $m_W$ ,  $\sigma_t$  and  $\sigma_W$  are the mean and width of top quark and W boson, coming from artificial fitting with jets corresponding to real decay quark with generator information in simulation sample(in appendix\*\*\*\*), which are 168.15GeV, 81.25GeV, 20.6GeV and 12.1GeV seperately. Back to the part of  $\chi^2$ , for each combination,  $m_{jjb}$  is the invariant mass of 1 b-tagged jet and 2 non-btagged jets;  $m_{jj}$  is the invariant mass of 2 non b-tagged jets which are same 2 jets in  $m_{jjb}$ . the combination who have the minimum  $\chi^2$  value in all of them is chosen as physical objects coming from hadronically decay top.

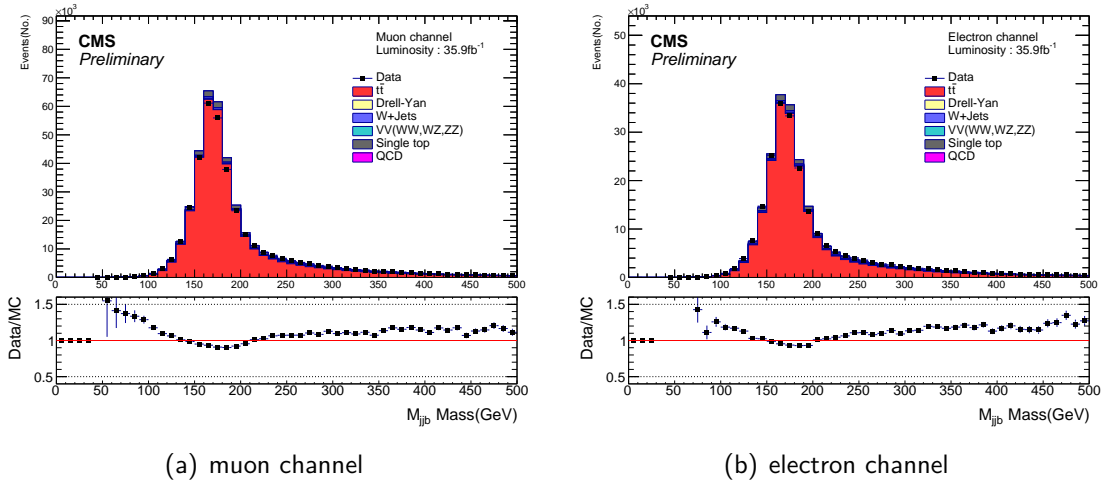


Figure 1: Reconstructed  $M_{jjb}$  with  $\chi^2_{min}$  algorithm (w/o cut)

### V.3.2 MVA Method

However, to improve the reconstruction performance in my analysis, there is another method - **Multi-Variate Analysis (MVA)** can be adopted to do well in this reconstruction part. It has been not a common way to used in this step yet compared to signal and background samples' classification. In order to check the improvement between usual and new method, in the following rest analysis, the comparison of analysis results of  $\chi^2_{min}$  method and MVA method will be shown simultaneously.

The concept of MVA is to use basic machine learning method to classify signal and background, we'll take advantage of MVA discriminating ability to improve the correctness rate of selection compared with  $\chi^2_{min}$  method.

As the usage of classification, one should define the "signal" and "background" in MVA configuration. In most particle physics analysis with MVA, "signal" means the physics sample which is expected to be analyzed and as a target sample and the "background" means samples from the other known physics. Different as usual, in this analysis,

- **Sample** : signal simulation sample( $t\bar{t}$  MC) with full event selection(V.2)
- Randomly half for training sample, another half for testing sample
- In each event,
  1. **Signal** is recognized as the correct combination of objects hadronically decaying from  $t(\bar{t})$ -quark in an event
  2. **Background** are all the other incorrect combinations in an event

To identify whether one combination is the 2 jets and the correct detector-level's objects from generator-level's particles, the  $\Delta R$  method is used to match them. The matching method is to compare the angle distribution between detector-level objects and generator-level particles with  $\Delta R < 0.4$ .

$$\Delta R = \sqrt{(\eta_{det} - \eta_{gen})^2 - (\phi_{det} - \phi_{gen})^2} < 0.4 \quad (3)$$

With concept of machine learning, we need to train with informations of classes( "signal" and "background" in this case ) and get out an algorithm to make distinguishment. Following the original  $\chi^2_{min}$  method's variables, we started MVA with inputting 2 variables :  $m_{jj}$ ,  $m_{jjb}$ , as informations to be used for distinguishment. There are three machine learning methods I used for testing: **MLP**(ANN, Artificial Neuro-Network), **BDT**(Boasted Decision Tree), **BDTG**(Boasted Decision Tree Gradient).

With respect to the input variables for distinguishment training, we can check the seperation shows on input variables originally in advance:

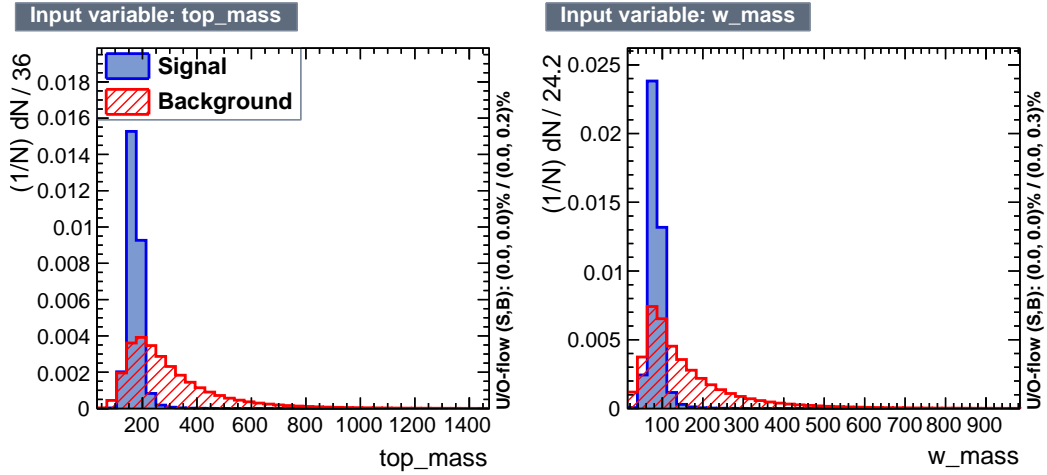


Figure 2: Input training variables separation between "signal" and "background".(2 variables)

And the training result shows below:

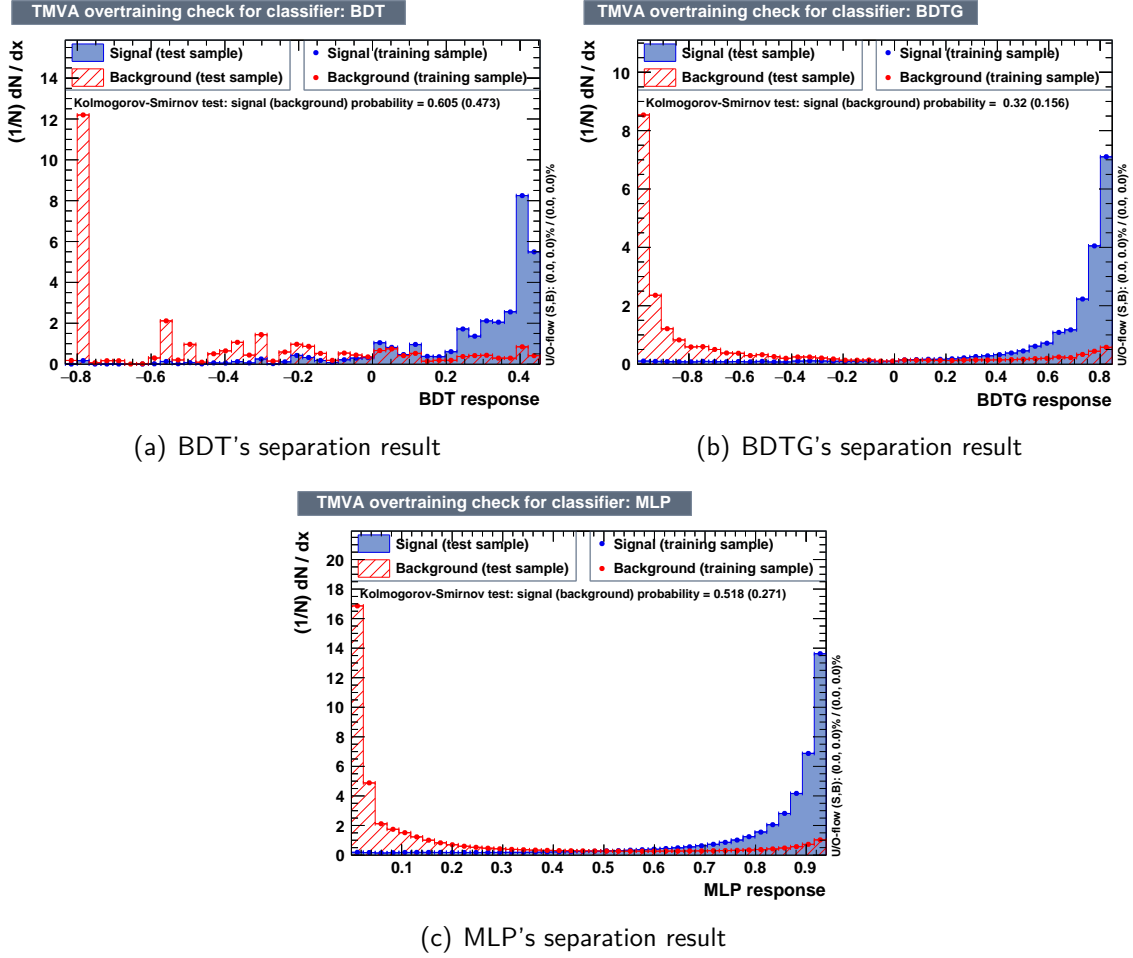


Figure 3: The separating distribution on signal and background

The separation plots Fig.3 shows the machine learning methods' separating ability through the input training variables. The distributions in these plots are the final separation performance between "signal" and "background" (right and wrong objects combination) with the training values which is propagated from separations of all input variables (Fig.2). It is also the separation performance under training sample and testing sample with given machine learning method. As we can see that if we want to pick out "signal" (right combination), just choose the jjb combination who has the *highist* MVA score as the right one.



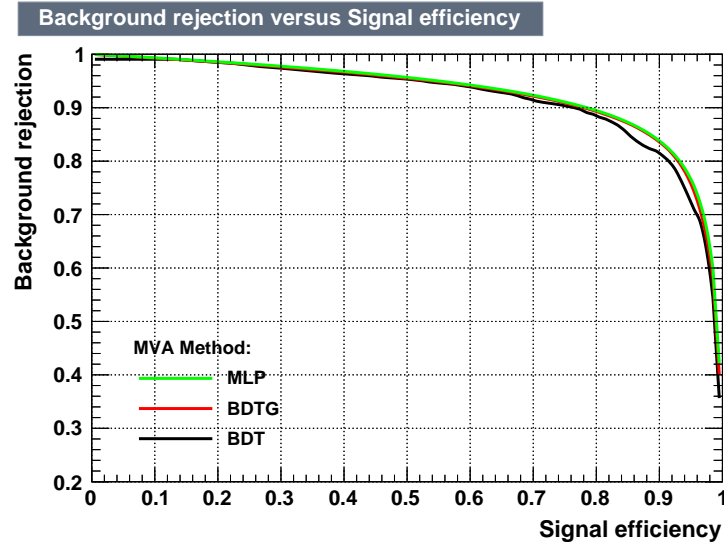


Figure 4: Receiver Operating Characteristic(ROC) curve of various machine learning method

The **Receiver Operating Characteristic(ROC)** curve plot Fig.4 can tell if it's given a cut on the output MVA score in separation distribution Fig.3 to extract the "signal", how the background rejection ratio vary when signal efficiency change. It can be inferred that, the good performance is that when one rejects more ratio of background and at the same time reserves more ratio of signal(high signal efficiency). In other words, the bigger area under the ROC curve, the better the method is. However, the previous ROC criterion are just available and meaningful for the common case - one use MVA to separate the 2 different physics sample which are independent to each other, for example, use MVA to separate sigle  $t$  and  $t\bar{t}$  sample. In this analysis case, the signal and background are not separate like that kind in common. Being not independent 2 samples, signal and background are at the same time in one event instead. There are couple of complicated correlation between them. Therefore, the separation and ROC plots are not really fair anymore. As they going to not to be relative directly, there must be a standard to tell how MVA perform(That is the  $b\bar{b}$  separation in V.4).

There are also the reconstructed  $M_{jjb}$  with MVA algorithm. ( $m_{jjb}$ ,  $m_{jj}$ ) There is just MLP (instead of BDT/BDTG) results shown here.

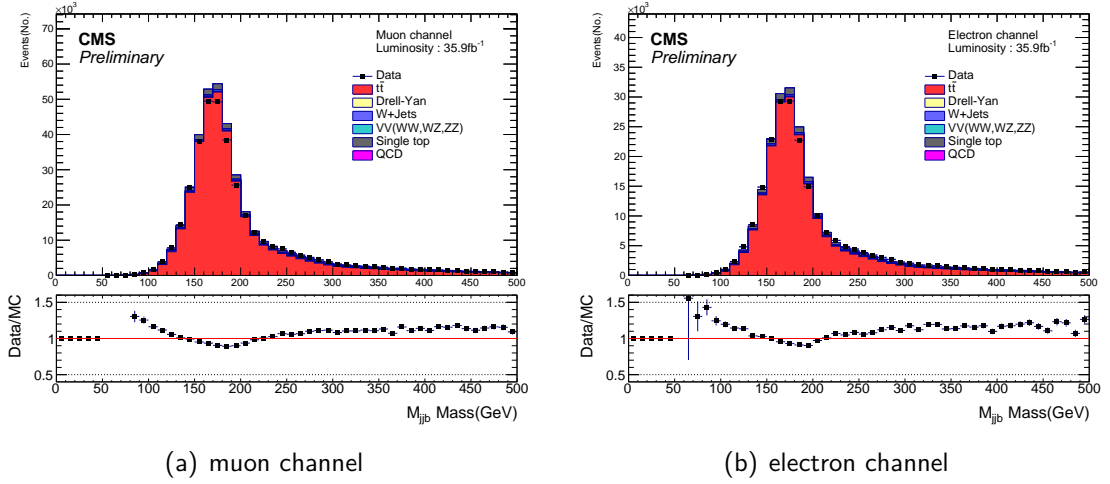


Figure 5: Reconstructed  $M_{jjb}$  with 2 variables MLP algorithm (w/o cut)

And also, it is better to use MVA with more variables than just  $m_{jj}$  and  $m_{jjb}$ . There are 3 variables sets after a bunch of trials here to input and train. It's a remindful item that they are the variables of each combination in any event.

1. The first set: (2 variables)

- $m_{jjb}, m_{jj}$

2. The second set: (8 variables)

- $m_{jjb}, m_{jj}$
- 2 jets'(jj) *sum of*  $P_T, \Delta\phi, \Delta\eta$
- selected lepton and leptonic b-jet's *sum of*  $P_T, \Delta\phi, \Delta\eta$

3. The third set: (20 variables)

- $m_{jjb}, m_{jj}$
- 2 jets'(jj) *sum of*  $P_T, |\Delta P_T|, \Delta R$
- hadronic W(j+j) and hadronic b-jet's *sum of*  $P_T, |\Delta P_T|, \Delta R$
- selected lepton and hadronic b-jet's *sum of*  $P_T, |\Delta P_T|, \Delta R$
- selected lepton and hadronic W(j+j)'s *sum of*  $P_T, |\Delta P_T|, \Delta R$
- hadronic W(j+j) and MET's *sum of*  $P_T, |\Delta P_T|, \Delta\phi$
- hadronic b-jet and MET's *sum of*  $P_T, |\Delta P_T|, \Delta\phi$

Besides the training result of the 2 variables' set have been shown(Fig.2, Fig.3, Fig.4), there are also the training results of 8 variables and 20 variables' cases:

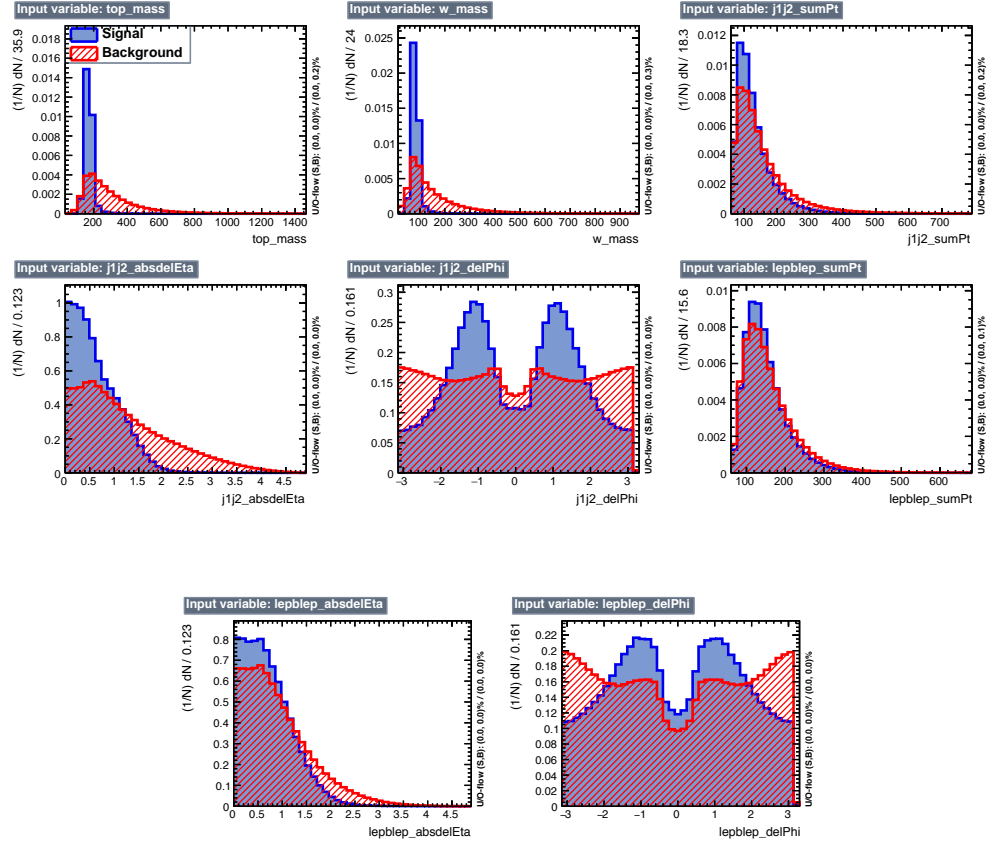
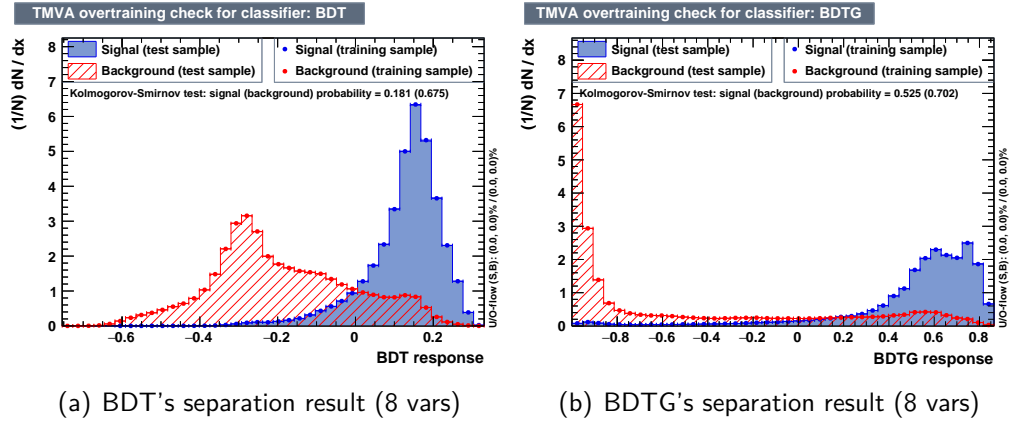
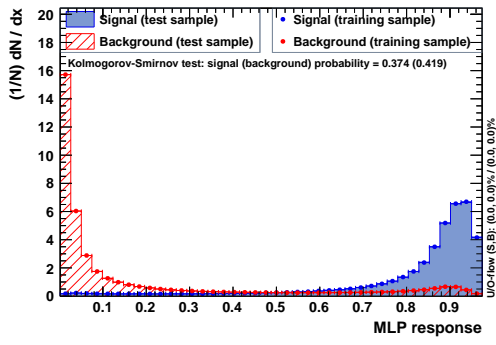


Figure 6: Input training variables separation between "signal" and "background".(8 variables)

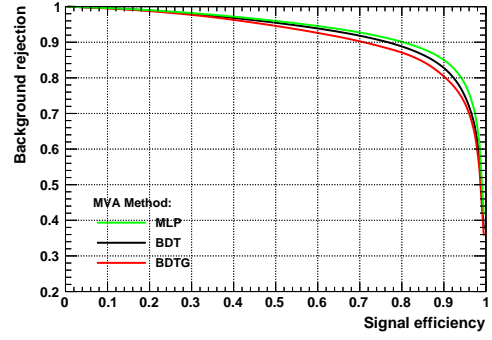


TMVA overtraining check for classifier: MLP



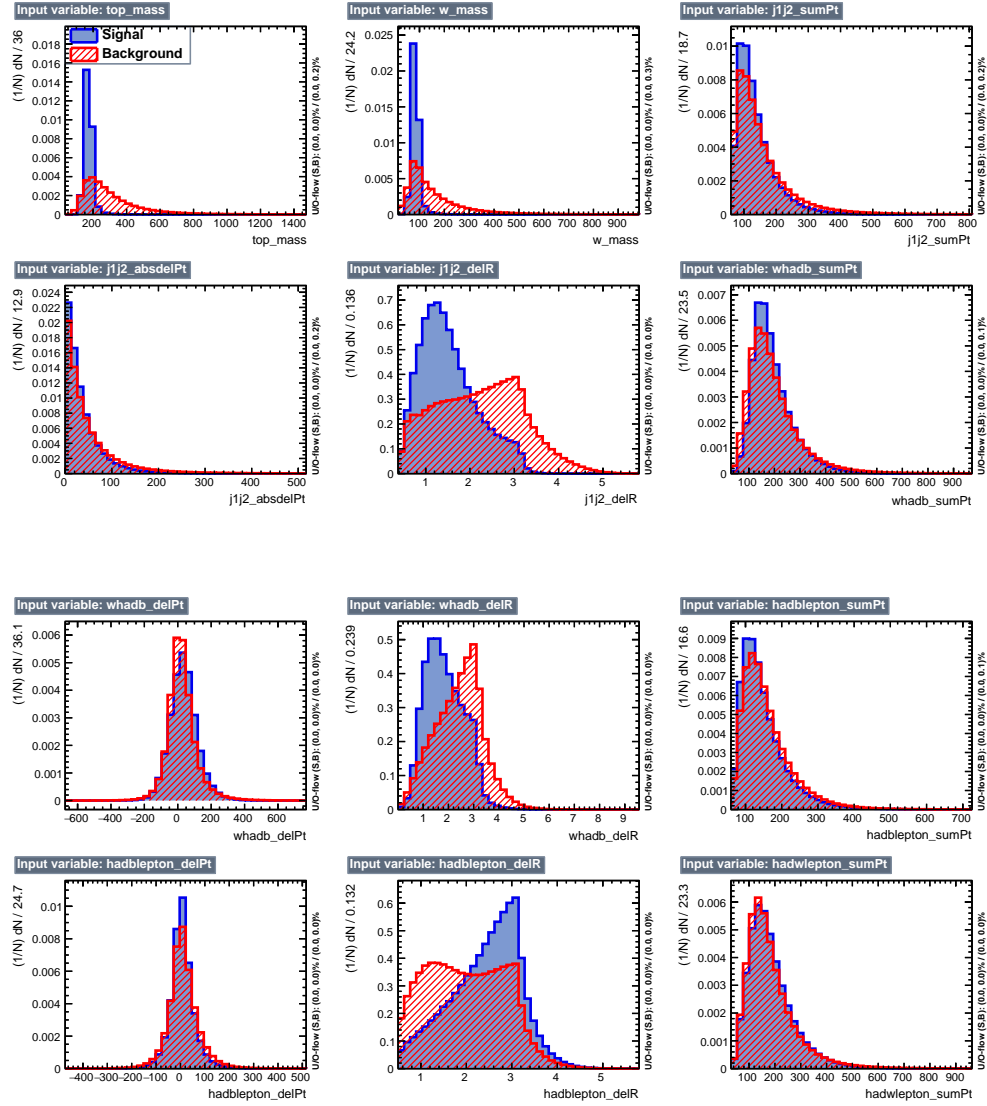
(c) MLP's separation result (8 vars)

Background rejection versus Signal efficiency



(d) ROC curve (8 vars)

Figure 7: The training result of 8 variables set



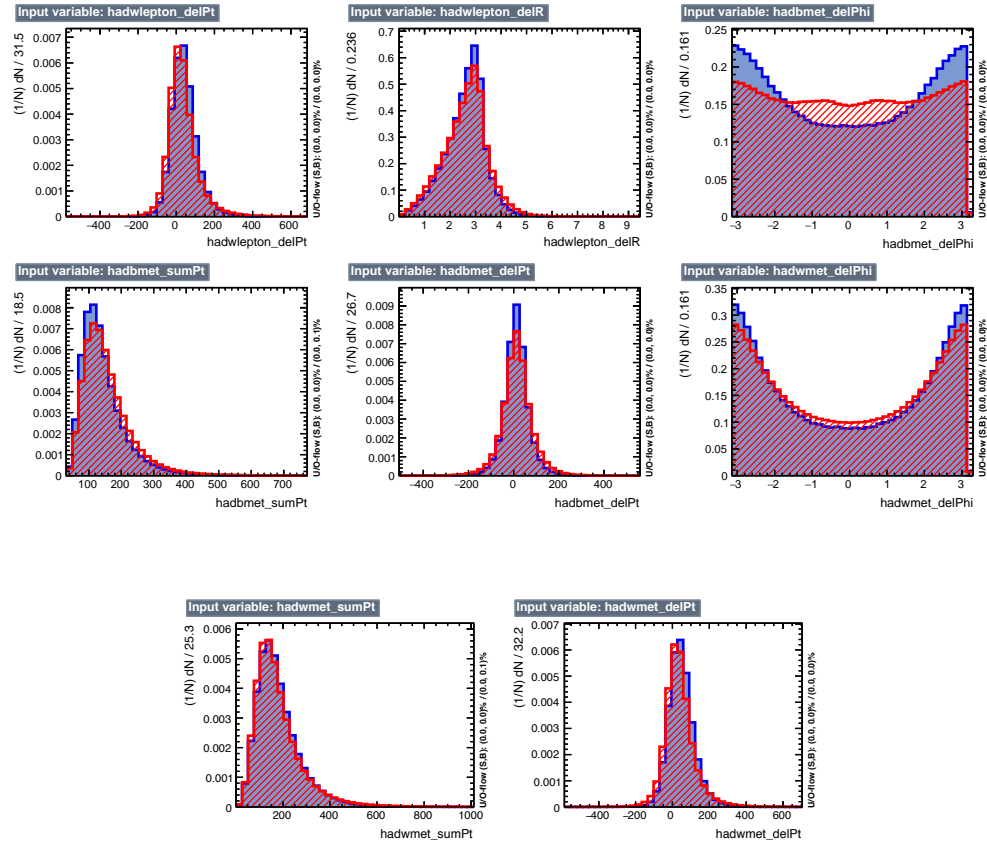
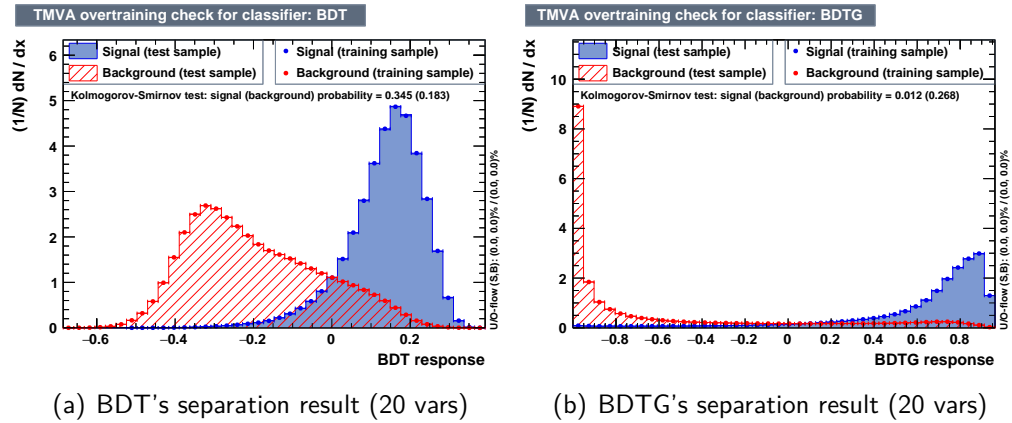


Figure 8: Input training variables separation between "signal" and "background" .(20 variables)



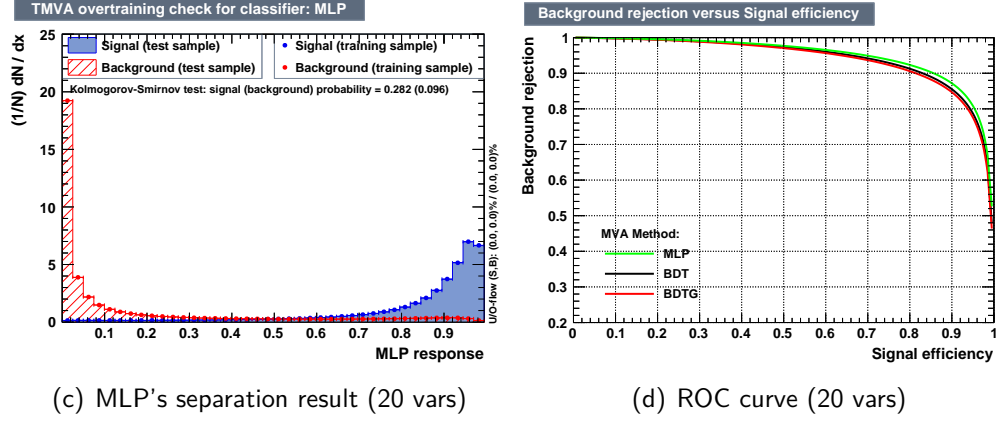


Figure 9: The training result of 20 variables set

This is shown that the MLP(ANN) training algorithm has the best performance under ROC criteria from training results. But as previous mentioning, the ROC performance cannot totally represent the training performance completely in these analysis case.

There are results of reconstructed  $M_{jjb}$  by 8 variables' and 20 variables' MLP algorithm.

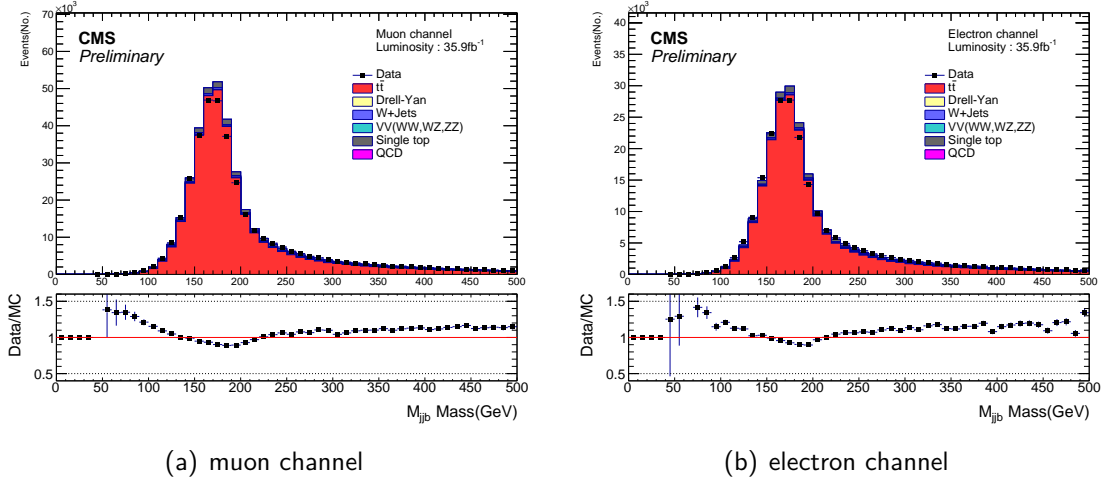


Figure 10: Reconstructed  $M_{jjb}$  with 8 variables MLP algorithm (w/o cut)

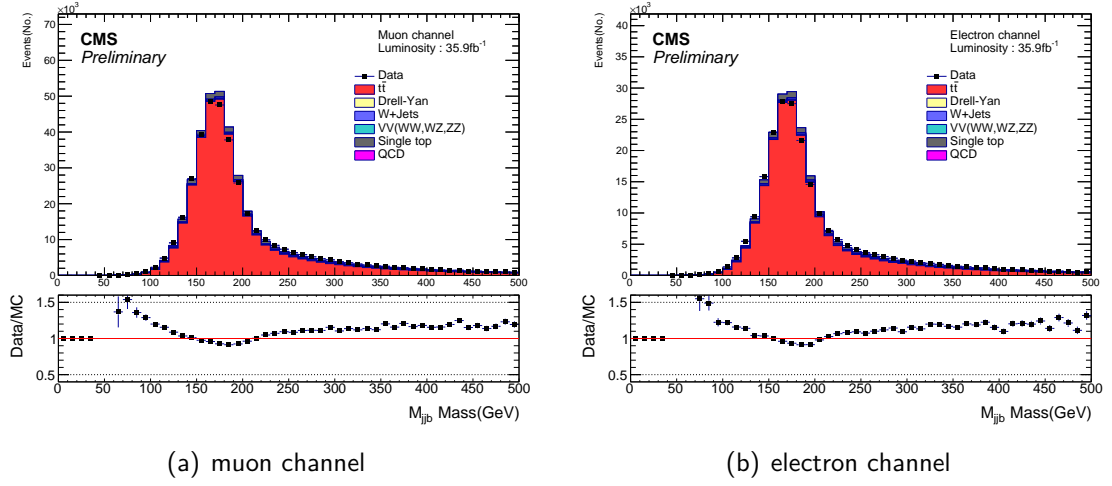


Figure 11: Reconstructed  $M_{jjb}$  with 20 variables MLP algorithm (w/o cut)

There are the max MVA score's distribution with 2/8/20 variables and BDT/BDTG/MLP results.

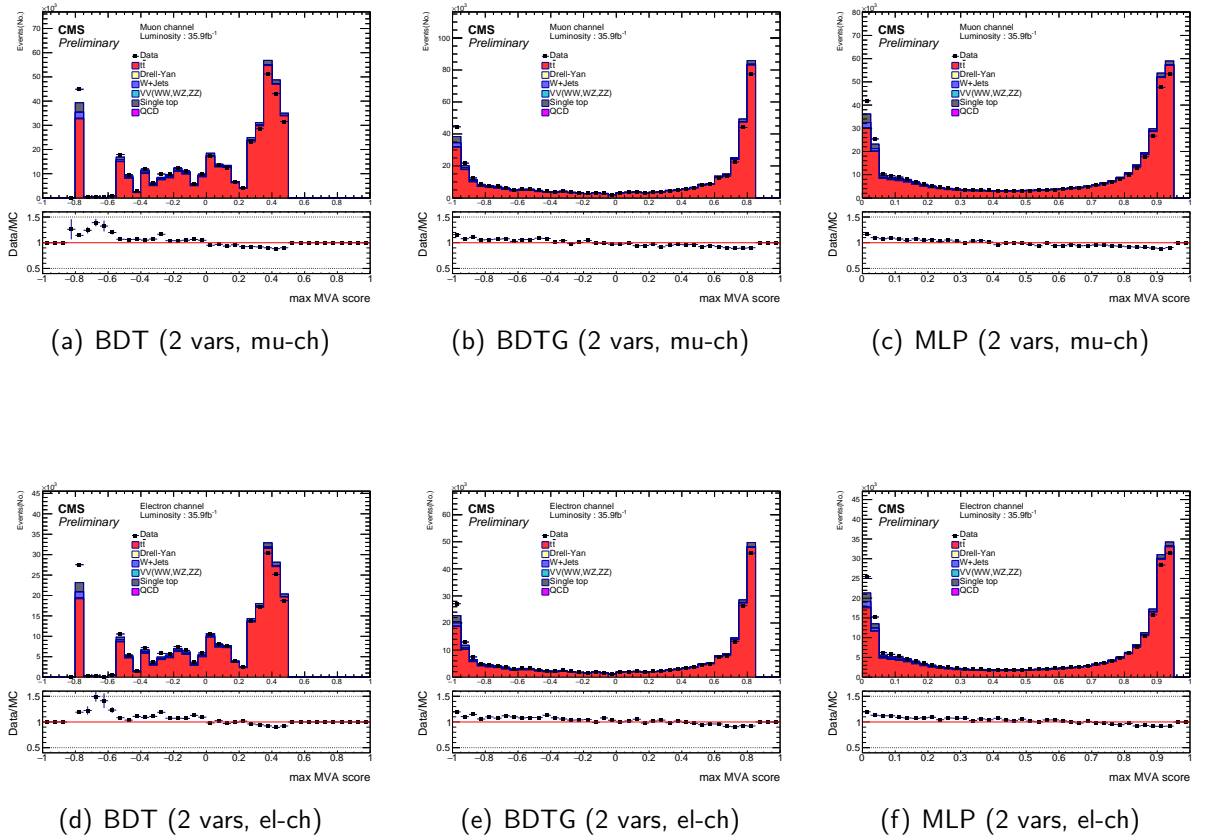
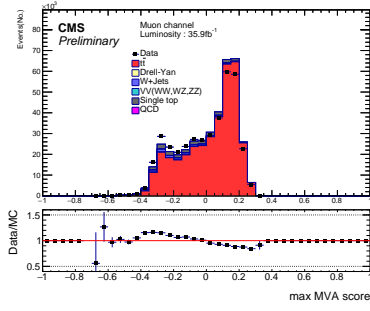
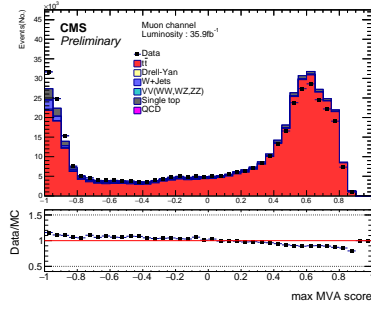


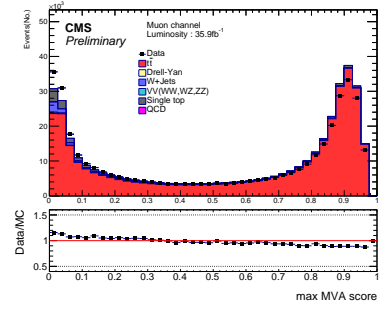
Figure 12: max MVA score in each event, comparing Data and MC.(2 variables training)



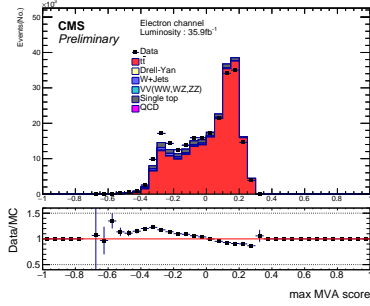
(a) BDT (8 vars, mu-ch)



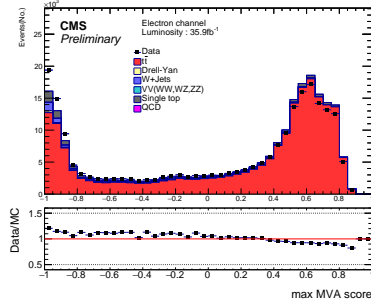
(b) BDTG (8 vars, mu-ch)



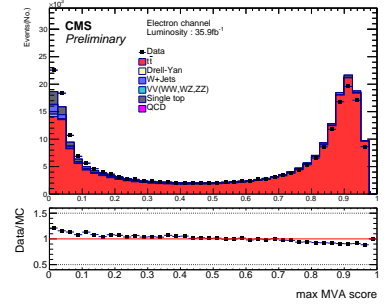
(c) MLP (8 vars, mu-ch)



(d) BDT (8 vars, el-ch)

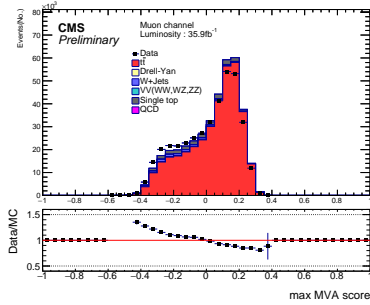


(e) BDTG (8 vars, el-ch)

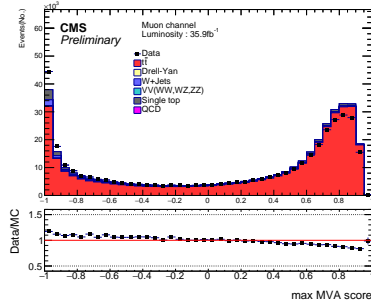


(f) MLP (8 vars, el-ch)

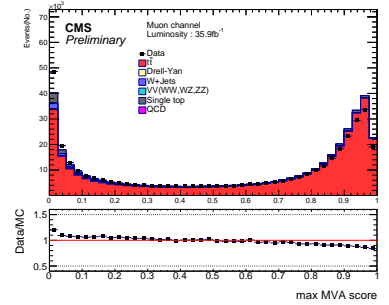
Figure 13: max MVA score in each event, comparing Data and MC.(8 variables training)



(a) BDT (20 vars, mu-ch)



(b) BDTG (20 vars, mu-ch)



(c) MLP (20 vars, mu-ch)



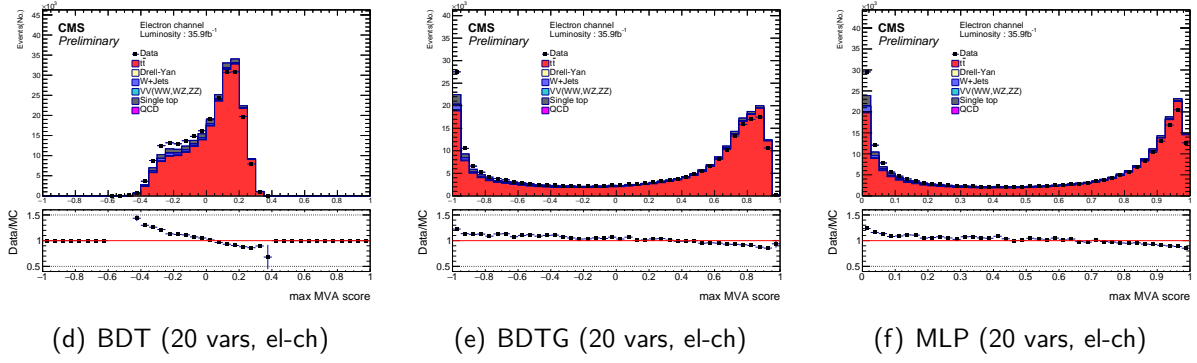


Figure 14: max MVA score in each event, comparing Data and MC.(20 variables training)

The training variables may have correlation with each other. If there are too much characteristic to be trained alike between variables, the most of input informations would duplicate. To check the variables' correlation score is necessary: (20 variables' case is shown)

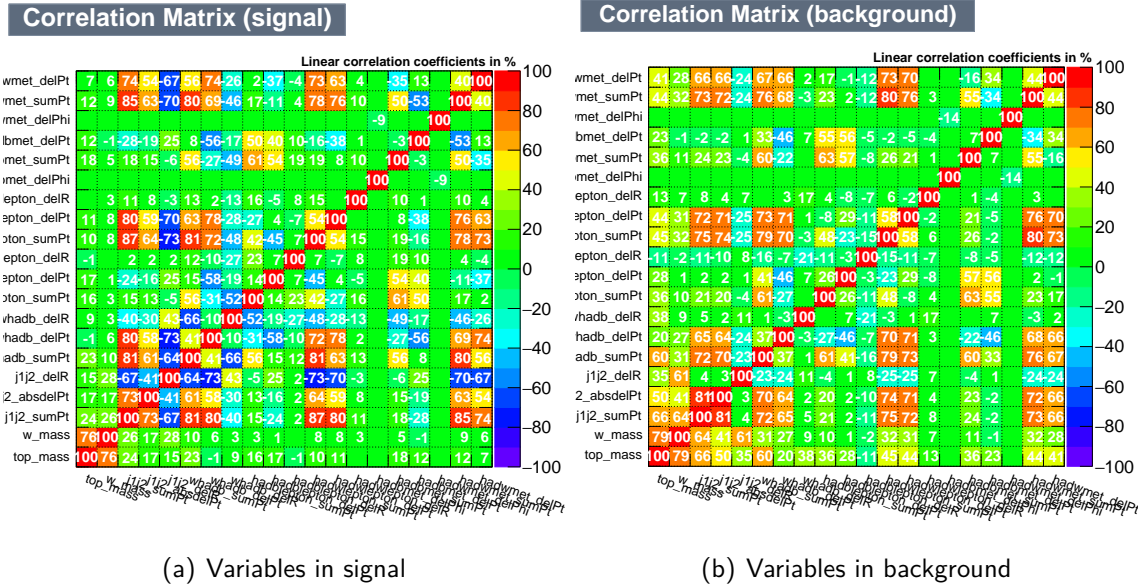
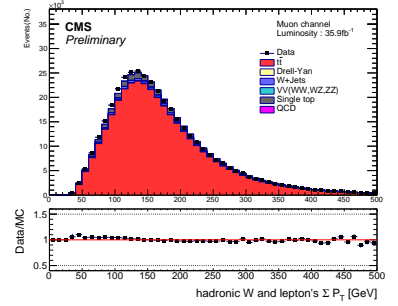
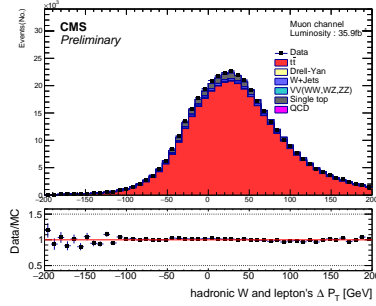
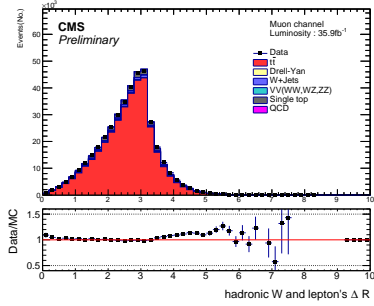
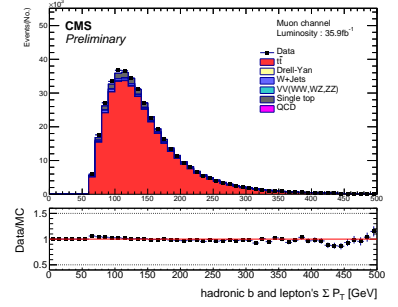
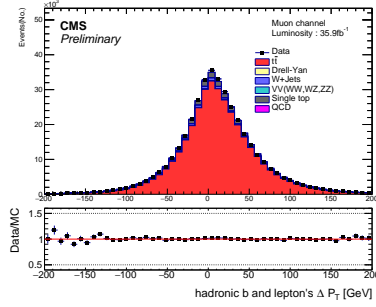
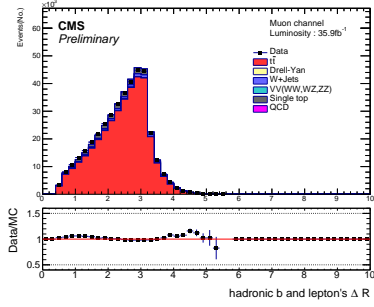
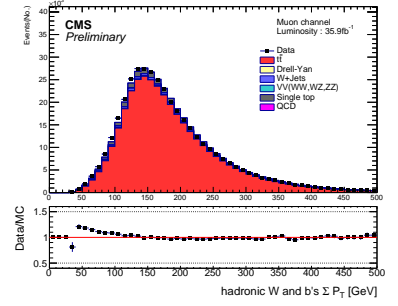
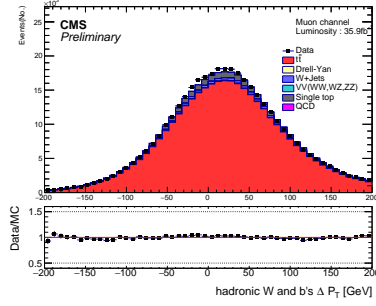
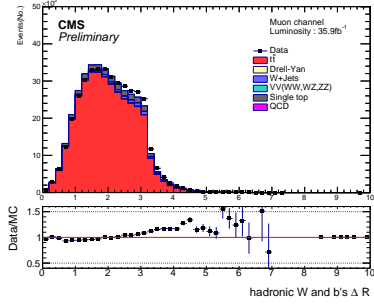
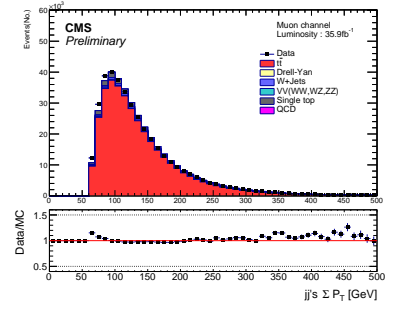
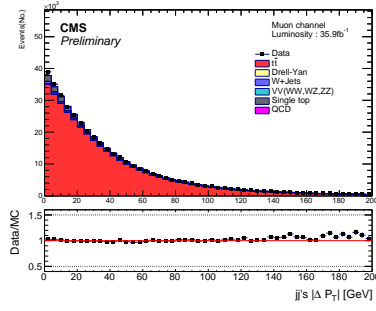
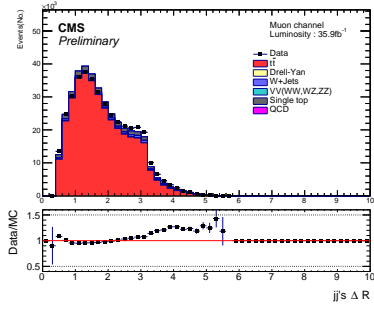


Figure 15: Variables correlation with each other

No excess of correlation appear in training variables. The training variables would be also validated match between Data and MC:(20 variables MLP, muon channel is shown)



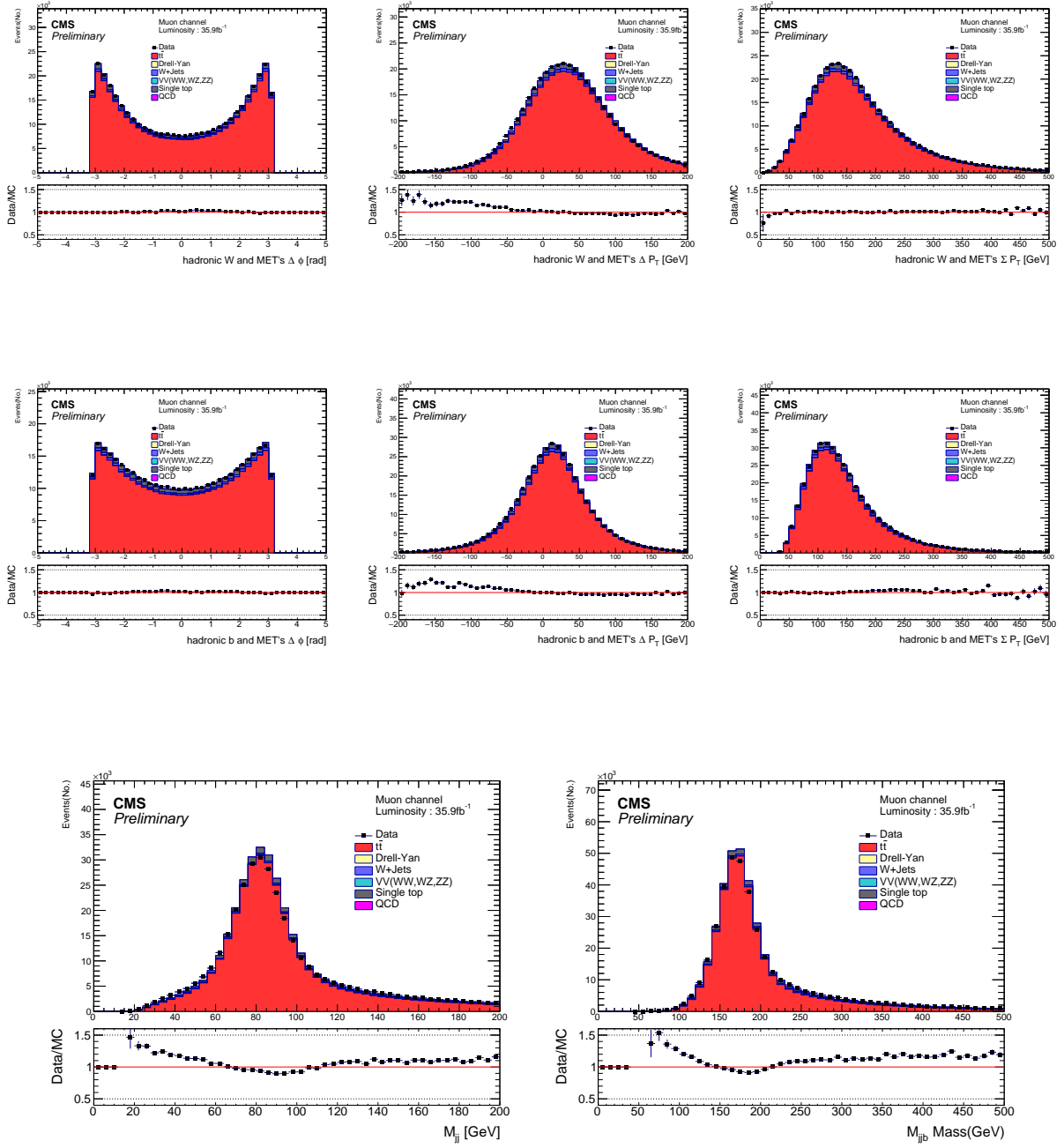


Figure 16: 20 variables' Data/MC comparison(MLP, mu-ch)

## V.4 $b\bar{b}$ separation and distinguishment

The good correctness of chosen physical objects is necessary in this analysis. By the basis for discovering new physics, the observables require precise identification of particles. And the important is, in our selected observables, to distinguish  $b$ - between  $\bar{b}$ -quark which are both b-tagged jets detected from smashing and hadronization of b-flavor quarks. For example, the

identification is highly correlated with observable  $O_6$  which is  $q_l(\vec{p}_b - \vec{p}_{\bar{b}}) \cdot (\vec{p}_l \times \vec{p}_{j_1})$ , the mis-ordered  $b/(\bar{b})$  will cause the wrong sign on this observable. On the other hand, it is not requirement for us to correctly pick up the 2 jets from hadronic top quark in this analysis. Also, the long tail in reconstructed hadronic top invariant mass ( $M_{jjb}$ , Fig.5, Fig.10, Fig.11) deviated too much from known top mass 172.5GeV. And the source of this tail is inferred coming from  $b/\bar{b}$  wrong identified cases. In this way, the identification between  $b$  and  $\bar{b}$  is the most critical implication. And that is also what we need to test the performance of reconstruction algorithm ( $\chi^2_{min}$ , MVA).

All the following study in V.4 is worked only under the signal simulation sample ( $t\bar{t}$  Monte Carlo). All the selected physical objects include jets and leptons will be matched to particle with the generator-level information in MC sample with  $\Delta R < 0.4$  method. (Eq.3)

To standardize the  $b/\bar{b}$  distinguishment, there are 3 classifications listed:

- **Correct:**  $b$ -quark is identified as  $b$ -jets and  $\bar{b}$ -quark is identified as  $\bar{b}$ -jets
- **$b/\bar{b}$  mis-identified:**  $b$ -quark is identified as  $\bar{b}$ -jets and  $\bar{b}$ -quark is identified as  $b$ -jets
- **Mistag:** non  $b(\bar{b})$ -quark is identified as  $b(\bar{b})$ -jet

With applying the various algorithm on signal simulation sample ( $t\bar{t}$  MC), there are the  $b/\bar{b}$ -distinguishment results after reconstructed the hadronic top and make a identification of physical objects via  $\chi^2_{min}$  and MVA methods:

Table 1:  $b/\bar{b}$  disdistinguishment under different algorithm (w/o cut)

[%]		Correct	$b\bar{b}$ mis-identified	Mistag
$\chi^2_{min}$		61.18	25.21	13.38
2 variables	MLP	63.18	23.22	13.60
	BDT	60.89	25.49	13.60
	BDTG	63.02	23.37	13.61
8 variables	MLP	72.36	14.02	13.62
	BDT	72.02	14.37	13.60
	BDTG	71.00	15.39	13.61
20 variables	MLP	71.27	15.13	13.61
	BDT	71.07	15.32	13.61
	BDTG	69.59	16.79	13.61

This is shown that the MLP algorithm have the best performance under these 3 training variables sets. As our expected, the 2 variables training result is close to  $\chi^2_{min}$  method's because

of their same variables input to be deduced. And the 8 variables set and 20 variables set are both good at discriminate  $b/\bar{b}$ , which can lead us to choose these to be optimized one. It is also known that *Mistag*'s ratio in Table.1 are almost the same since it is primarily pre-decided by the b-tagged selection.

In addition to applying algorithm to reconstruct  $M_{jjb}$  and identify the physical objects, there are also some optimization cut done on this step. In the concept of  $\chi^2_{min}$  method, the smaller the  $\chi^2$  value(Eq.2), the less possibility that this combination is the one we want. So we can apply cut on  $\chi^2$  value. If in an event the chosen combination whose  $\chi^2_{min}$  is still bigger than the cut, the event will be threw away. These thrown away events are identified as the events which come from the mis-tag objects from detector or some events come from other physics decay(background) not  $t\bar{t}$ . The most important is that, it can cut out the events which are not  $b/\bar{b}$ -correct distinguished. So the cut is set to be at  $\chi^2_{min} < 20$ , and to standardize the optimization, there are also use the  $b/\bar{b}$  distinguishment results to see the performance.

There is the cross-check plot(Fig.17) which shows that the high  $\chi^2$  value correspond to the  $m_{jjb}$  distant from the expected  $m_{jjb}$  in Eq.2.

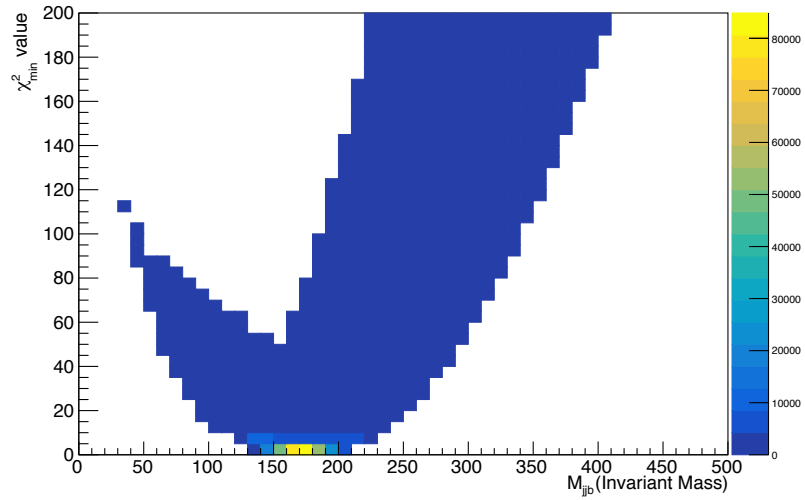


Figure 17:  $\chi^2_{min}$ -reco  $m_{jjb}$

To check that the cut on the  $\chi^2_{min}$  really rule out incorrect  $b/\bar{b}$ -identified more effeciently than correct case. This plot(Fig.18) shows that the incorrect cases(exchange-identified and mistag) do have more ratio at the higher  $\chi^2_{min}$  score than the correct case. It make the  $\chi^2_{min}$  cut more persuasive.

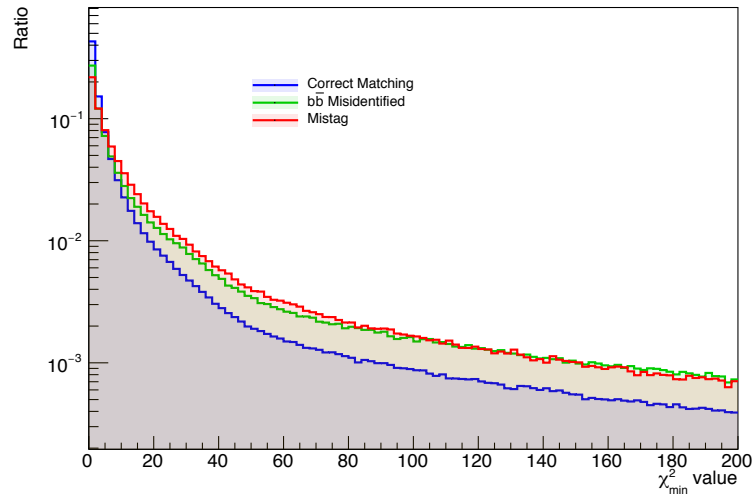


Figure 18:  $b/\bar{b}$  identified result related to  $\chi^2_{min}$  (pdf)

There is the result that if we cut on the  $\chi^2_{min}$  value and how the 3  $b/\bar{b}$ -identified classifications' ratios vary. It is also shown that the events efficiency which is the ratio of events survived under this optimized cut.

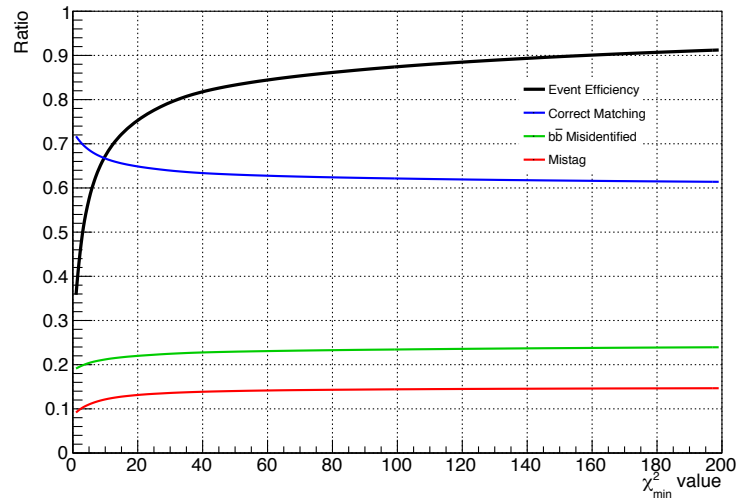


Figure 19: cut on  $\chi^2_{min}$  and ratio of 3 classification

Table 2:  $b/\bar{b}$  disdistinguishment under  $\chi^2_{min}$  method (w/  $\chi^2_{min} < 20$  cut)

[%]	Channel	Correct	$b\bar{b}$ mis-identified	Mistag
-----	---------	---------	---------------------------	--------

$\chi^2_{min}$	Electron Channel	65.47	22.29	12.24
	Muon Channel	65.65	22.29	12.06

And as same concept as the optimized cut on  $\chi^2_{min}$  value in  $\chi^2_{min}$  method, there would be also optimization cut applied on MVA method. In comparison with that low  $\chi^2$  value is better choice, combination with high MVA score is the better one in MVA method. It also can have a cut on MVA score to subtract incorrect  $b/\bar{b}$ -identified selection. Same scenario as  $\chi^2_{min}$  method, if in an event the maximum MVA score(which belongs to the chosen combination) is still lower than the cut, the event will be threw away. To check the relation between MVA score and  $M_{jjb}$ , and also check the ratio of 3  $b/\bar{b}$ -classifications that the incorrect cases has more ratio at lower MVA score. There are the plots of 2 variables/8 variables/20 variables sets with MLP/BDT/BDTG training method:

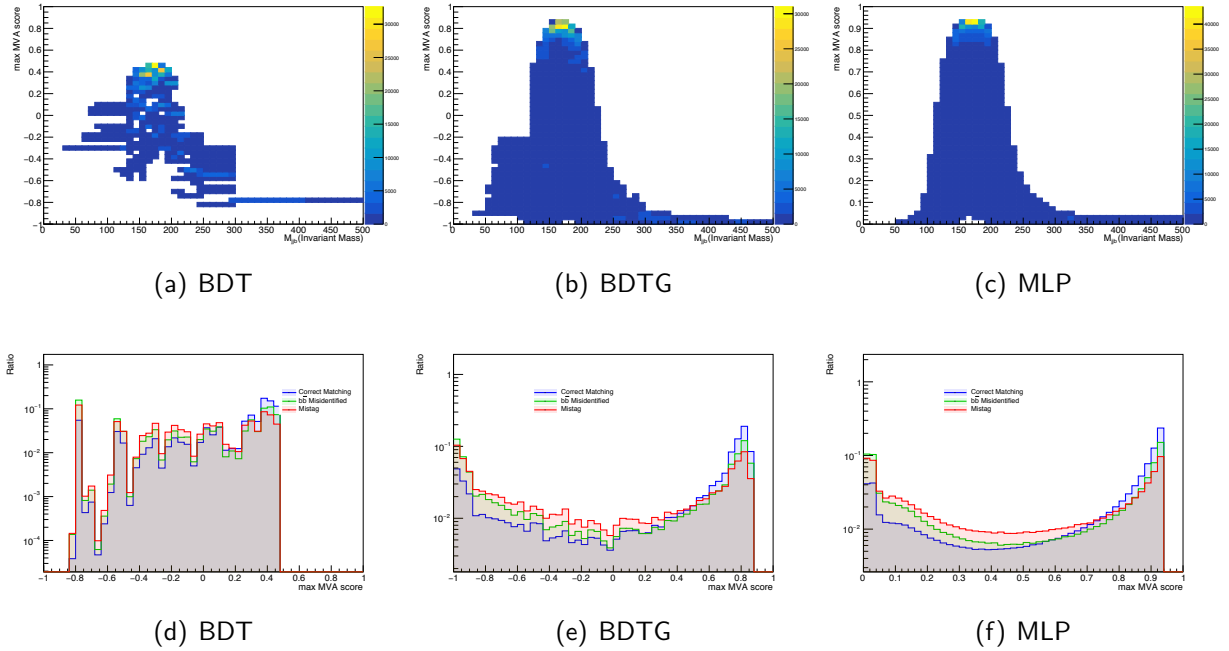


Figure 20: MVA score-reco  $m_{jjb}$  plots and  $b/\bar{b}$  identified result related to MVA value (2 variables training)

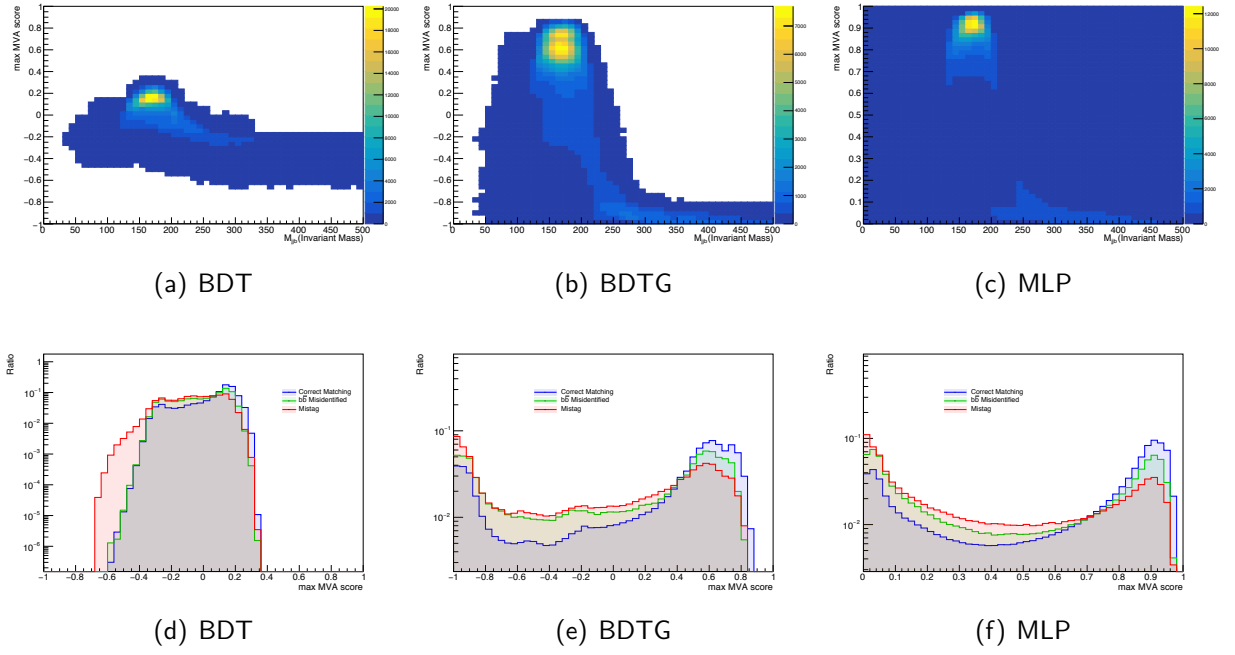


Figure 21: MVA score-reco  $m_{jjb}$  plots and  $b/\bar{b}$  identified result related to MVA value (8 variables training)

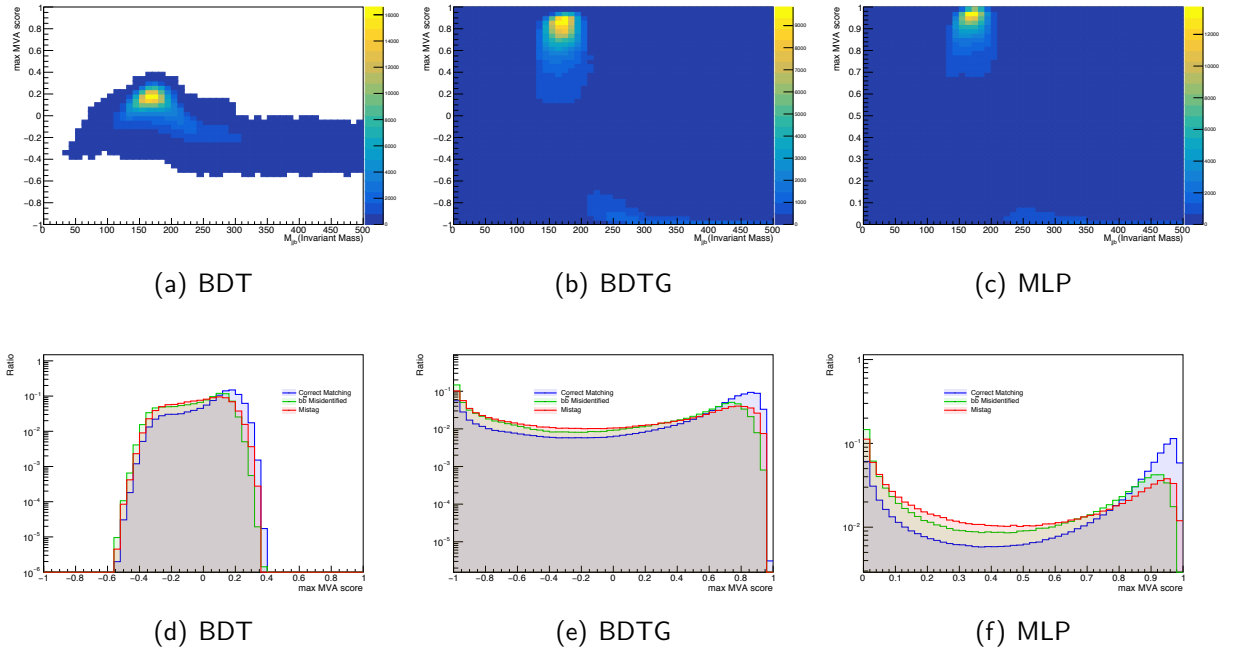


Figure 22: MVA score-reco  $m_{jjb}$  plots and  $b/\bar{b}$  identified result related to MVA value (20 variables training)



There are also the efficiency plots shows that if it's given a cut on MVA score, how these 3  $b/\bar{b}$ -identified cases' ratio vary.

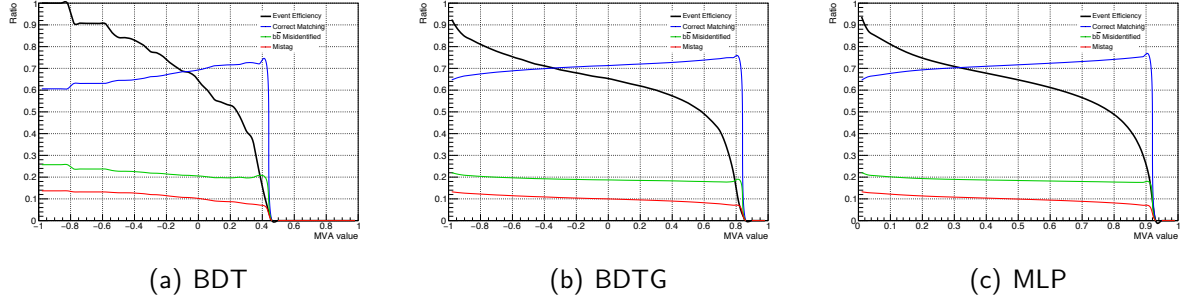


Figure 23: cut on MVA score and ratio of 3 classification (2 variables training)

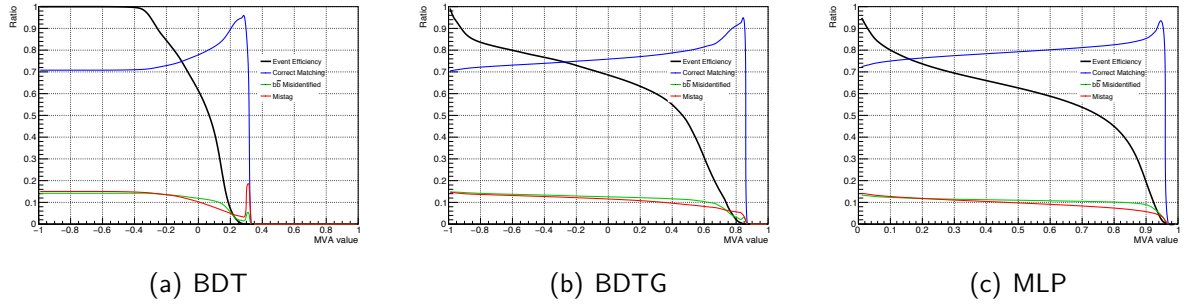


Figure 24: cut on MVA score and ratio of 3 classification (8 variables training)

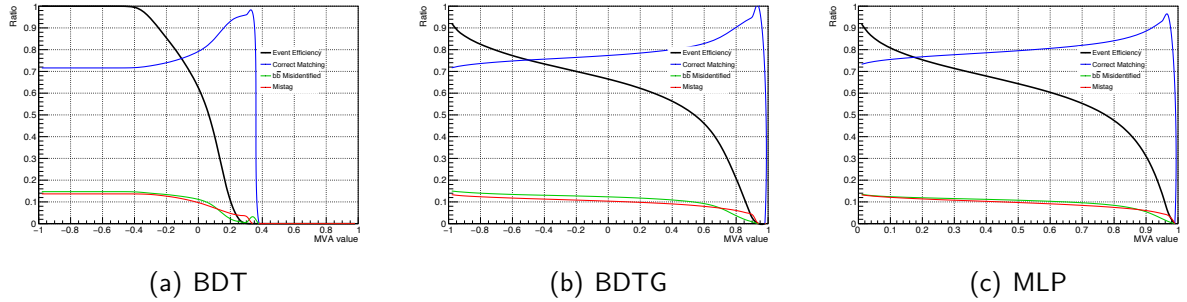


Figure 25: cut on MVA score and ratio of 3 classification (20 variables training)

The correct ratio increase when the MVA score-cut is applied on higher value. Based on the target to optimized from  $\chi^2_{min}$  method, we have cut on the same events efficiency as  $\chi^2_{min}$  method when cutting on  $\chi^2_{min} < 20$ , which is  $\sim 75\%$ , to get the better ratio of correct- $b/\bar{b}$  case. There are the MVA-score cut at events efficiency  $\sim 75\%$ :

Table 3: MVA-score cut at events efficiency  $\sim 75\%$

MVA score cut	BDT	BDTG	MLP(ANN)
2 variables	-0.21	-0.57	0.2
8 variables	-0.1	-0.28	0.16
20 variables	-0.1	-0.5	0.22

There are the  $b/\bar{b}$ -identified classifications' ratio after cut on events efficiency at  $\sim 75\%$ (cut value in Table.3), test by signal simulation sample( $t\bar{t}$  MC):

Table 4:  $b/\bar{b}$  disdistinguishment under different algorithm (w/ MVA cut)

[%]		Correct	$b\bar{b}$ mis-identified	Mistag
$\chi^2_{min}$		65.58	22.33	12.09
2 variables	MLP	69.22	19.43	11.35
	BDT	68.26	20.95	10.79
	BDTG	68.95	19.69	11.36
8 variables	MLP	76.88	12.35	10.77
	BDT	75.98	13.08	10.94
	BDTG	75.37	13.68	10.95
20 variables	MLP	76.41	12.34	11.25
	BDT	75.13	13.20	11.67
	BDTG	74.72	13.76	11.52

Comparing Table.1 to Table.4, it really make progress on the  $b/\bar{b}$  separation with cut on algorithm value.

Besides the hadronic top's mass spectrum, there would be checked that the leptonic top's invariant mass( $M_{lb}$ ) shows. Even though the missing neutrino's 4-momentum cause the leptonic top reconstructed incompletely, it's also valuable of  $M_{lb}$  to be an independent information for other analysis strategy. Exactly, the  $M_{lb}$  is the primary variable to be analyzed for the relation between signal/background and between data/simulation in this analysis! For instatnce, the following background estimation(Chapter.VI).

And for the  $b/\bar{b}$  part,  $b/\bar{b}$ -identified types can also be shown under  $M_{lb}$ , they are also separated obviously with  $\chi^2_{min}$  method:

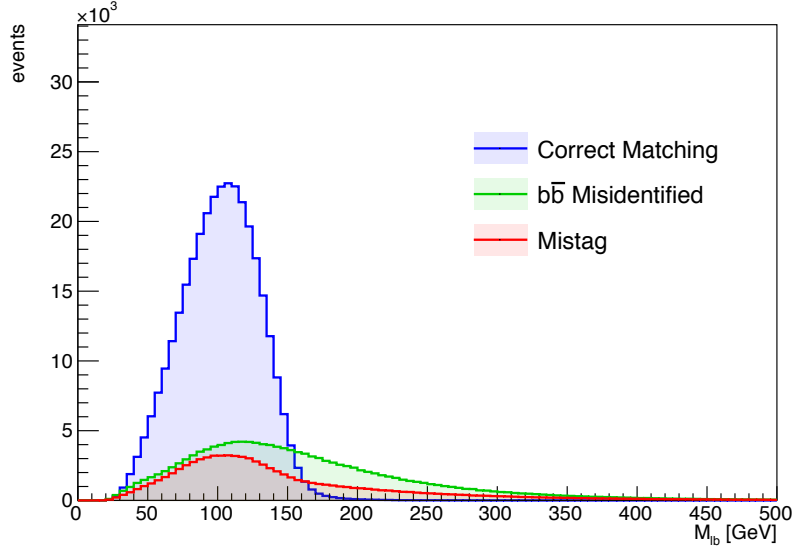


Figure 26: The  $M_{lb}$  and corresponding  $b/\bar{b}$ -separation under  $\chi^2_{min}$  method.

It's decide to cut on  $M_{lb} = 150$  GeV and leave the events below the value. It can effectively eliminate the high ratio of events whose decay objects are wrong-identified. And follow the same reason as  $\chi^2_{min}$  method, the MVA methods are also check with  $M_{lb}$  spectrum:

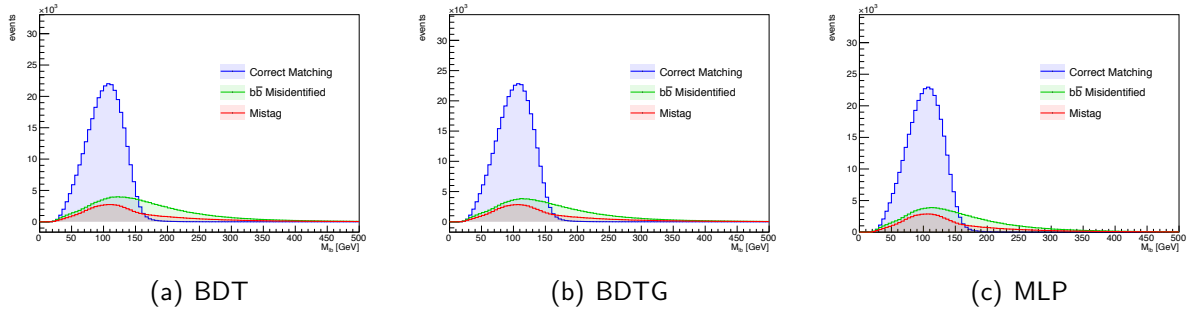


Figure 27: Relation between  $M_{lb}$  and  $b/\bar{b}$  with MVA reconstruction result.(2 variables)

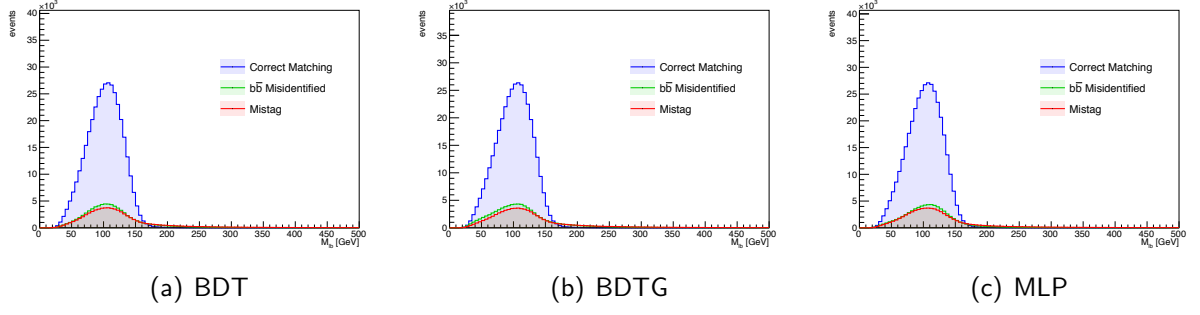


Figure 28: Relation between  $M_{lb}$  and  $b/\bar{b}$  with MVA reconstruction result.(8 variables)

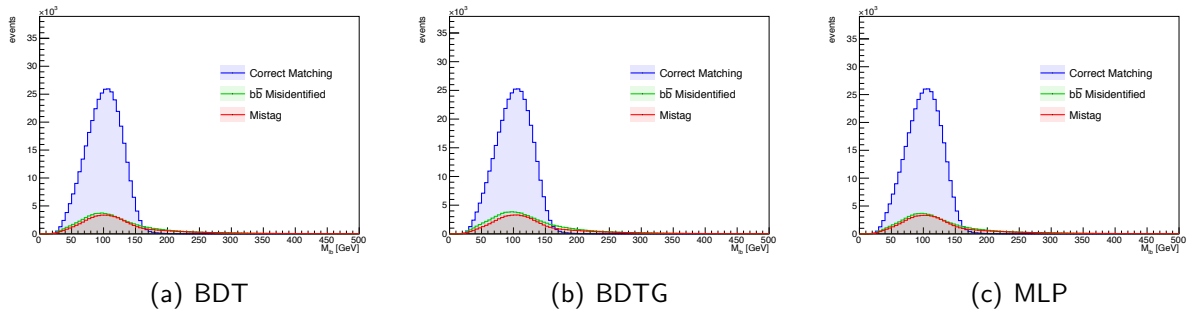


Figure 29: Relation between  $M_{lb}$  and  $b/\bar{b}$  with MVA reconstruction result.(20 variables)

In 8 variables and 20 variables cases, the  $M_{lb}$  looks not to be separated by  $b/\bar{b}$ -identification obviously, that is, it may not improve when applying  $M_{lb}$  cut at 150 GeV. However, there are the  $b/\bar{b}$ -identified ratio after MVA(or  $\chi^2$ ) cut and  $M_{lb}$  cut.

Table 5:  $b/\bar{b}$  disdistinguishment under different algorithm (w/ MVA cut and  $M_{lb}$  cut)

[%]		Correct	$b\bar{b}$ mis-identified	Mistag	Events efficiency
$\chi^2_{min}$		75.56	14.70	9.74	65.39
2 variables	MLP	78.03	12.92	9.00	64.84
	BDT	77.66	13.69	8.65	64.92
	BDTG	77.91	13.01	9.08	64.57
8 variables	MLP	78.77	11.50	9.73	71.55
	BDT	78.12	12.05	9.83	71.44
	BDTG	77.05	12.94	10.01	71.29
20 variables	MLP	80.51	10.24	9.25	69.26
	BDT	79.34	11.01	9.65	69.09
	BDTG	78.67	11.76	9.57	69.99

- Final  $\chi_{min}^2$  strategy is decided to be with  $\chi_{min}^2$  value cut at 20 and  $M_{lb}$  cut at 150GeV. It is called  $\chi_{min}^2$  **strategy** in the following content.

The improvement is still shown with  $M_{lb}$  cut in all MVA method by comparing Table.4 and Table.5. The MLP is the most suitable algorithm after these test. The 8 variables case will be eliminated for the reason explained at Fig.40 in V.5, so the finally decided method which is the most optimized is 20 variables training with MLP algorithm. There are 2 choice of analysis strategy with this 20 variables MLP training result:

1. **The first** is with MVA(MLP) cut at 0.22 (events efficiency  $\sim 75\%$ ) and also cut on  $M_{lb}$  at 150GeV.  
The correct  $b/\bar{b}$  ratio is  $\sim 5\%$ (80.51%/75.56%) better and the events efficiency is  $\sim 4\%$ (69.26%/65.39%) more than  $\chi_{min}^2$  strategy.  
This MVA result would be called **MVA-A strategy** in the following content;
2. **The second** is only with MVA(MLP) cut at 0.22 but  $M_{lb}$  cut.  
Though the correct  $b/\bar{b}$  ratio is just  $\sim 1\%$ (76.88%/75.56%) better, the events efficiency would be reserve  $\sim 9.5\%$ (74.97%/65.39%) more than  $\chi_{min}^2$  strategy. The advantage of this is that the more statistics we retain, the precise the calculation of asymmetry eventually because the statistical and systematic uncertainty would be smaller.(Explained at Chapter\*\*\*\*)  
This MVA result would be called **MVA-B strategy** in the following content.

There are the data events number passed full-selection(V.2) also with  $\chi_{min}^2$  **strategy** and the expected signal( $t\bar{t}$ ) and background events number of simulation sample in Table.6. The Table.7 present the expected process ratio after full-selection cut and analysis strategy; The Data and MC comparison plots of hadronic top's invariant mass( $M_{jjb}$ ) and leptonic top's invariant mass( $M_{lb}$ ) are also shown(†) with this criteria.

Table 6: Data and MC events number passing the full selection(w/  $\chi_{min}^2$ ,  $M_{lb}$  cut)

	Muon Channel	Electron Channel
Data	243790	136151
Expected $t\bar{t}$	244680	135600
Expected background	9877.63	5537.45

Table 7: Expected process ratio passing the full selection(w/  
 $\chi^2_{min}$ ,  $M_{lb}$  cut)

Process	Muon Channel (%)	Electron Channel (%)
$t\bar{t} + jets$	96.12	96.08
$Z/\gamma^* + jets$	0.17	0.31
$W + jets$	0.77	0.70
$ZZ/WW/WZ$	0.04	0.05
<i>Single top</i>	2.91	2.86

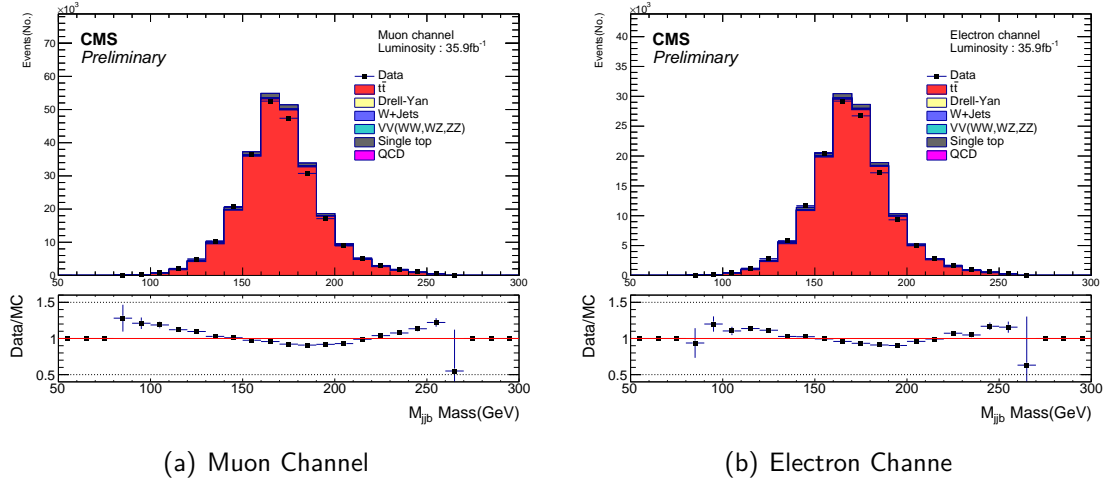


Figure 30: Data and MC comparison plots of hadronic top's invariant mass( $M_{jjb}$  w/  $\chi^2_{min}$ ,  $M_{lb}$  cut)

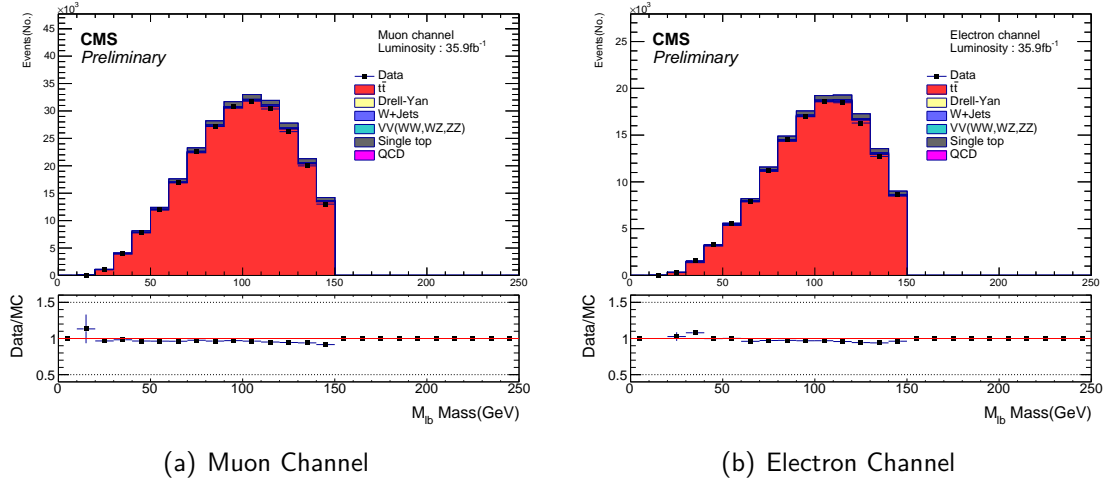


Figure 31: Data and MC comparison plots of leptonic top's invariant mass( $M_{lb}$  w/  $\chi^2_{min}$ ,  $M_{lb}$  cut)

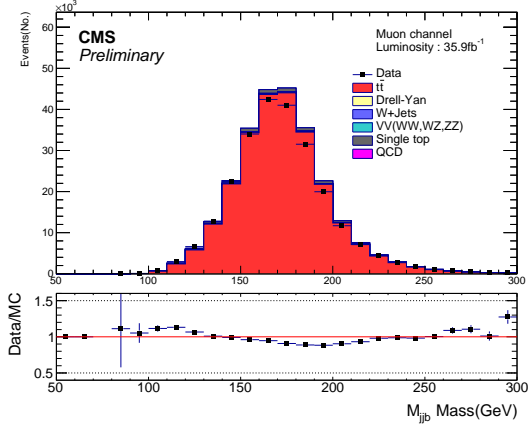
There are also the full selection results with **MVA-A strategy**(Table.8, Table.9, Fig.32, Fig.33) and **MVA-B strategy**(Table.10, Table.11, Fig.34, Fig.35):

Table 8: Data and MC events number passing the full selection in SR(w/ MVA,  $M_{lb}$  cut)

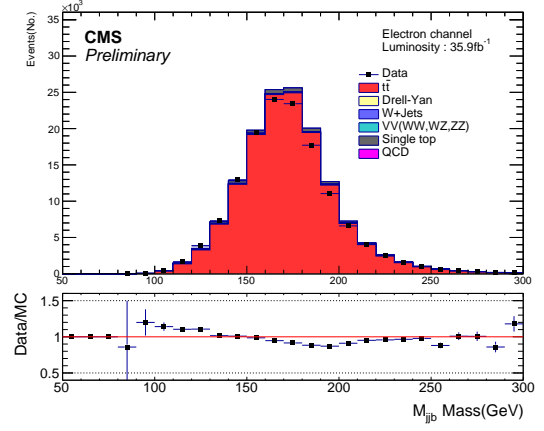
	Muon Channel	Electron Channel
Data	245436	139432
Expected $t\bar{t}$	251862	142211
Expected background	9164.09	5238.32

Table 9: Expected process ratio passing the full selection in SR(w/ MVA,  $M_{lb}$  cut)

Process	Muon Channel (%)	Electron Channel (%)
$t\bar{t} + jets$	96.49	96.45
$Z/\gamma^* + jets$	0.14	0.26
$W + jets$	0.67	0.62
$ZZ/WW/WZ$	0.03	0.05
<i>Single top</i>	2.67	2.64

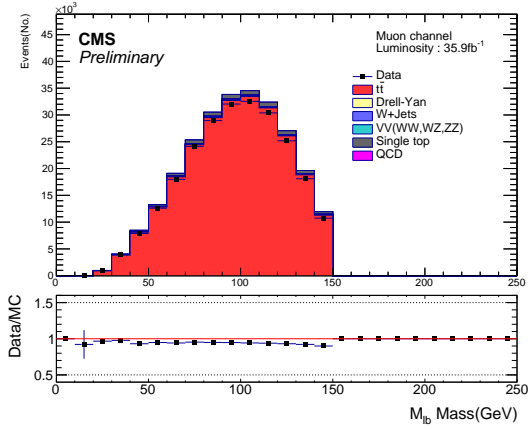


(a) Muon Channel

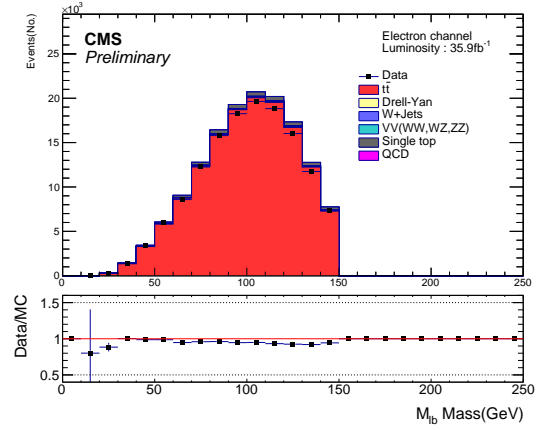


(b) Electron Channel

Figure 32: Data and MC comparison plots of hadronic top's invariant mass( $M_{jjb}$  w/ MVA,  $M_{lb}$  cut)



(a) Muon Channel



(b) Electron Channel

Figure 33: Data and MC comparison plots of leptonic top's invariant mass( $M_{lb}$  w/ MVA,  $M_{lb}$  cut)

Table 10: Data and MC events number passing the full selection in SR(w/ MVA cut)

	Muon Channel	Electron Channel
Data	272583	157510



Expected $t\bar{t}$	273154	155766
Expected background	14715.9	8957.06

Table 11: Expected process ratio passing the full selection in SR(w/ MVA cut)

Process	Muon Channel (%)	Electron Channel (%)
$t\bar{t} + jets$	94.89	94.56
$Z/\gamma^* + jets$	0.21	0.39
$W + jets$	1.22	1.17
$ZZ/WW/WZ$	0.05	0.06
<i>Single top</i>	3.63	3.82

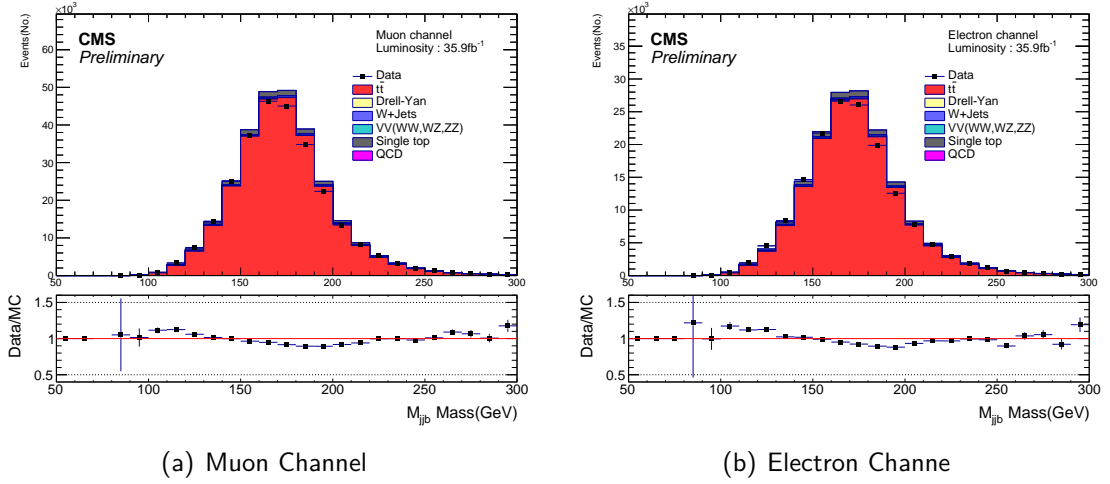


Figure 34: Data and MC comparison plots of hadronic top's invariant mass( $M_{jjb}$  w/ MVA cut)

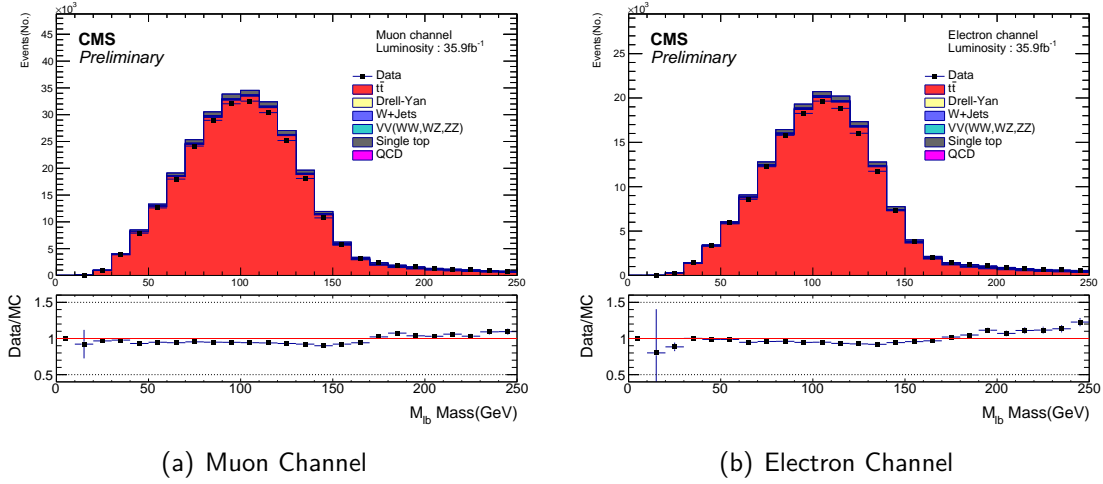


Figure 35: Data and MC comparison plots of leptonic top's invariant mass( $M_{lb}$  w/ MVA cut)

As previously mentioned, the  $M_{lb}$  instead of  $M_{jjb}$  is the variable used to do background estimation and calculate the target asymmetry. This is because the  $\chi^2_{min}$  method and MVA method are directly use the  $M_{jjb}$  variables to distinguish physical object, it is decided by us and being artificial. The  $M_{jjb}$  is just used to validate the reconstruction and objects identification, relatively, the information-isolated variable  $M_{lb}$  is appropriate to used in the following analysis.

## V.5 Control Region

In the calculation of asymmetry of  $t\bar{t}$ , there are some effect from non- $t\bar{t}$  background diving in and causing spurious result. To study the background asymmetry effects from detector and reconstruction, and to subtract these effects from data's asymmetry calculation, there are 2 **Control Region(CR)** samples introduced. Control region usually means a region which is orthogonal to signal region and also usually used to study the background in an analysis. The background estimation and study part is set in Chapter.VI. In the analysis, the first CR is a **W+jets-dominant CR** samples:

- 1 selected lepton which are a tight muon or a tight electron
- 0 lepton pass veto criteria which are loose lepton criterion **with NO isolation restriction\***
- $\geq 4$  selected jets with passing medium jet criteria
- **NO** btagged jets(deepCSV Loose) in these selected jets\*
- each selected jets are isolated from the selected lepton with  $\Delta R > 0.4$

The selection of b-tagged jets and veto lepton criteria is set to have difference between SR(V.2) and W+jets-dominant CR(V.5). Zero jet passes deepCSV-Loose btagged criteria may enhance the fraction of background and diminish  $t\bar{t}$  contribution, which is based on difference of efficiency of  $t\bar{t}$  and background passing btagged algorithm(deepCSV); The modification of veto lepton criteria to release veto isolation restriction means tighten the leptons selection. It may eliminate the possibility of some lepton-like objects are the secondary lepton comes from b-quark jet's propagating, in other words, lessen the possibility of existence of b-jets.

Besides, the reconstruction method of  $M_{jjb}$  is same with SR by  $\chi^2_{min}$  method or MVA method(20 variables, MLP). However the  $M_{lb}$  is the critical variable for this analysis to do background estimation, the reconstruction of  $M_{lb}$  is necessary. In the W+jets-dominant CR sample, there are not 2 selected b jets in the beginning of reconstruction, it is 2 different criteria for  $\chi^2_{min}$  method and MVA method to reconstruct  $M_{jjb}$  and  $M_{lb}$  in CR. For the  $\chi^2_{min}$  method, we put in all the jets in  $\chi^2$  equation Eq.2 to pick out the combination with minimum  $\chi^2$  value as the ingredients of  $M_{jjb(j)}$ (one jet is seen as "b"). And for the  $M_{lb(j)}$  part, there are  $\geq 2$  jets rest. The jet which is the most close to selected lepton by  $\Delta R$  is the jet seen as the b in  $M_{lb}$ ; For the MVA method, there is already leptonic b's information input to be trained for the algorithm which reconstruct  $M_{jjb}$ , which means the product algorithm from training would distinguish leptonic b automatically not just hadronic jjb, so we just input all the selected jets in the training algorithm to see when the highest MVA score occur, which one is the role of hadronic b, which one is the role of leptonic b...,etc. It is used to study background with  $M_{lb}$  variable with CR sample, so there is not  $M_{lb}$  cut for CR selection strategy. There are the  $M_{lb}$  with  $\chi^2_{min}$  reconstruction of W+jets-dominant CR:

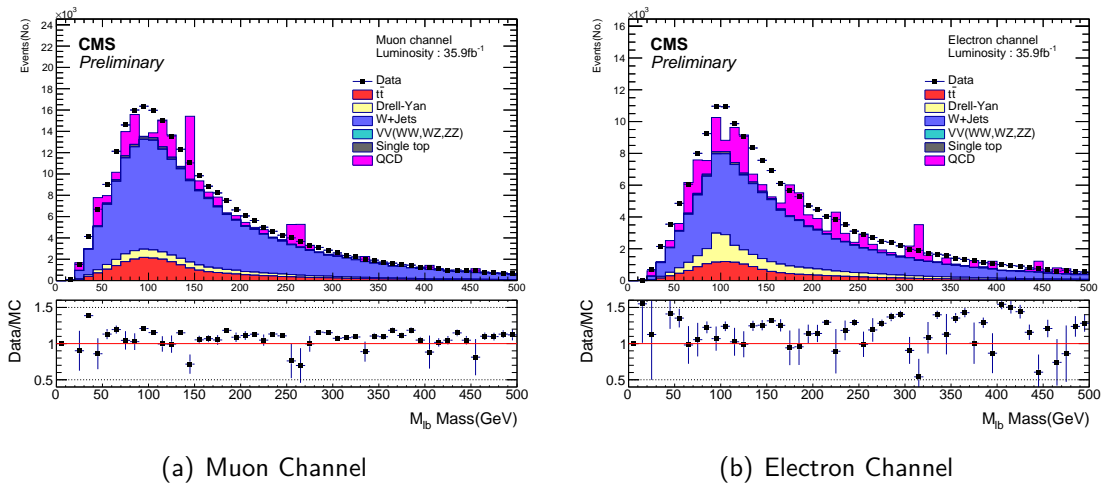


Figure 36: Data and MC comparison plots of leptonic top's invariant mass(w/  $\chi^2_{min}$ -reco) in W+jets-dominant CR

There are more spike-shape happening in QCD MC samples shown in Fig.???. They come from the reason that QCD has much larger cross section than other simulation samples. In this

case, if one QCD simulation event pass or fail the selection, it would be reweighed by a large value. The necessity to reweigh to luminosity leads to that one QCD simulation event's effect would cause an enormous variation showing on plots after selection. To make up this demonstration type, there is the second CR which is enriched with QCD samples:

- 1 selected lepton with tight lepton with **inverse ISolation criteria\***
- 0 lepton pass veto criteria which are loose lepton criterion **with NO isolation restriction**
- $\geq 4$  selected jets with passing medium jet criteria
- **NO** btagged jets(deepCSV Loose) in these selected jets
- each selected jets are isolated from the selected lepton with  $\Delta R > 0.4$

We can see that between W+jets-dominant CR and QCD-dominant CR, there is just a deviation that the selected lepton is chosed as the non-isolated one because of the property of QCD sample. And below is the Data/MC comparison of  $M_{lb}$  with  $\chi^2_{min}$  reconstruction in QCD-dominant CR:

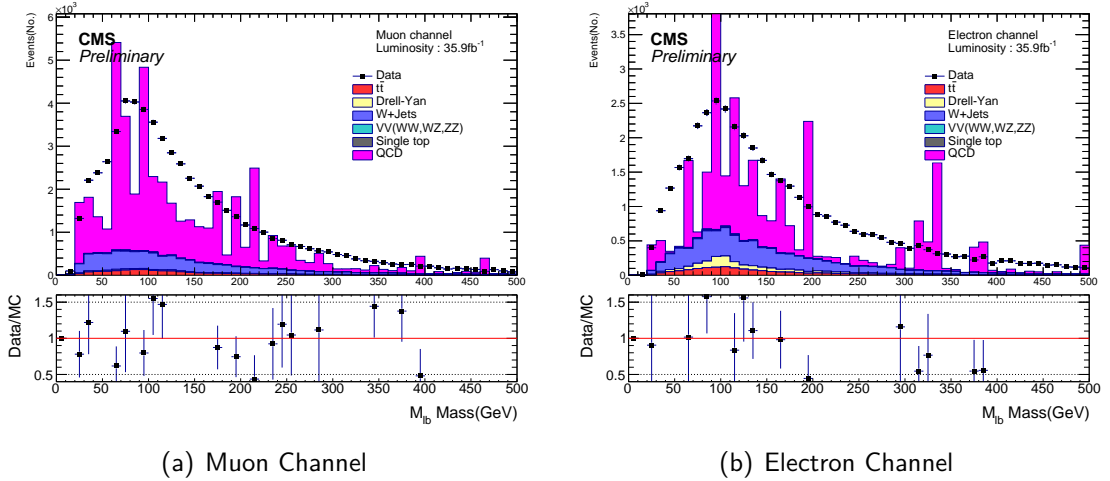


Figure 37: Data and MC comparison plots of leptonic top's invariant mass(w/  $\chi^2_{min}$ -reco) in QCD-dominant CR

This QCD-dominant CR which is exactly orthogonal to W+jets-dominant CR could be studied as one of the "background" of W+jets-dominant CR. Therefore the shape of data in QCD-dominant CR may represent the shape of QCD in W+jets-dominant CR and also the number of events follows the events number of QCD MC. This method is called **Data-Driven** method for using data's characteristic to supplant simulation's. There are the Data/MC comparison of  $M_{lb}$  with  $\chi^2_{min}$  reconstruction in W+jets-dominant CR after applying QCD's data-driven.

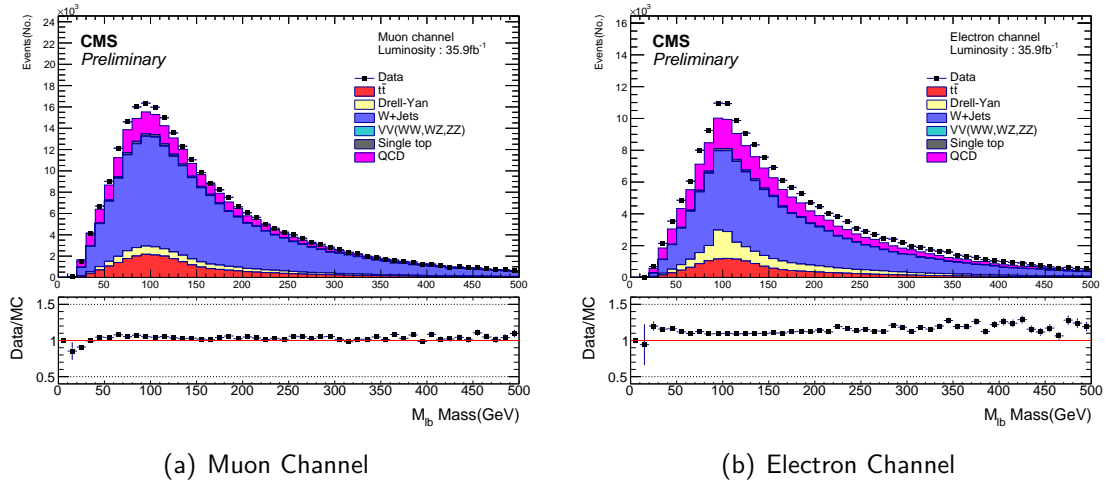


Figure 38: Data and MC comparison plots of leptonic top's invariant mass(w/  $\chi^2_{min}$ -reco) in W+jets-dominant CR(w/ data-driven QCD)

And the CR comparison's plots of MVA method(20 variables, MLP) are also shown here(after data-driven of QCD):

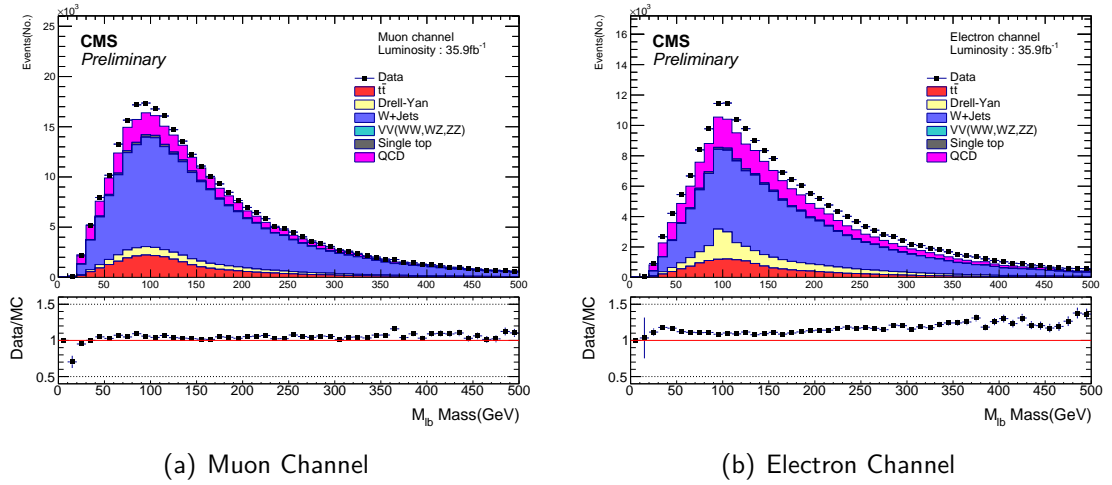


Figure 39: Data and MC comparison plots of leptonic top's invariant mass(w/ MVA-reco) in W+jets-dominant CR(w/ data-driven QCD)

Furthermore, the process ratio and composition of W+jets-dominant CR are calculated:

Table 12: Expected process ratio passing the full selection and  $\chi^2_{min}$ -reconstruction in W+jets-dominant CR(w/  $\chi^2_{min}$  cut)

Process	Muon Channel (%)	Electron Channel (%)
$t\bar{t} + jets$	10.70	9.60
$Z/\gamma^* + jets$	5.27	10.86
$W + jets$	70.16	58.32
<i>Single top</i>	1.33	1.22
<i>QCD</i>	12.54	20.0

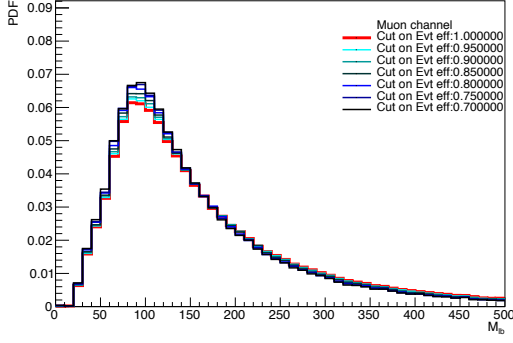
Table 13: Expected process ratio passing the full selection and MVA-reconstruction in W+jets-dominant CR(w/ MVA cut)

Process	Muon Channel (%)	Electron Channel (%)
$t\bar{t} + jets$	11.17	10.03
$Z/\gamma^* + jets$	5.26	10.82
$W + jets$	69.74	58.03
<i>Single top</i>	1.35	1.24
<i>QCD</i>	12.48	19.87

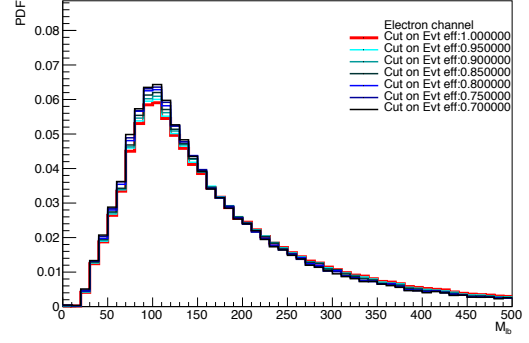
Though the non- $t\bar{t}$  background in SR is minority relative to  $t\bar{t}$ , there must be eliminated for the precision measurement. Because of little ratio of non- $t\bar{t}$  background, there may be much fluctuation and bias to study low statistics samples. For improvement, there is also a data-driven method to make W+jets-dominant CR's data as the role of background simulation sample in SR. It can smooth the issue of low MC statistics. And for the analysis, the W+jets-dominant CR's data is used to do template fit to estimate signal and background yields by its  $M_{lb}$  shape. At the same time, the effect of asymmetry from background is also studied with W+jets-dominant CR's data.

For the following template fit(VI.1), it is necessary to retain the isolation of information about  $M_{lb}$  when reconstructing the hadronic top mass  $M_{jjb}$ . There is a check to see if a cut on mva score is given, whether the  $M_{lb}$ 's pdf(probability density function) shape change. If the cut on mva score which is designed and trained for reconstructing  $M_{jjb}$  would vary the  $M_{lb}$  shape, there are some obvious interference from reconstructing  $M_{jjb}$  to information of  $M_{lb}$ . That is what we

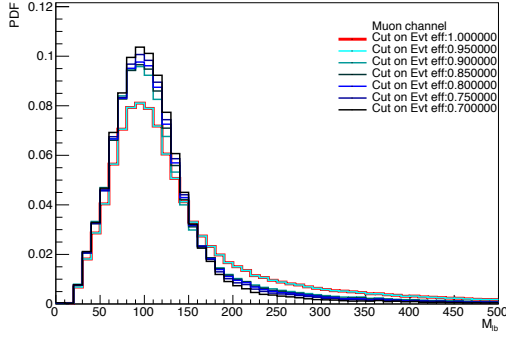
need to circumvent for following analysis strategy. There are the  $W$ +jets-dominant CR's data's  $M_{lb}$  shape with MVA score cuts below(Fig.40). The 8 variables training case obviously vary when mva-cut applied. It is because for the 8 training variables(3), there are leptonic b and lepton's information(selected lepton and leptonic b-jet's  $sum\ of\ P_T, \Delta\phi, \Delta\eta$ ) input for training. These informations can directly use the  $M_{lb}$ 's information to distinguish objects, making the product algorithm is  $M_{lb}$ -related. So this is the reason why the 8 variables training case was abandoned.



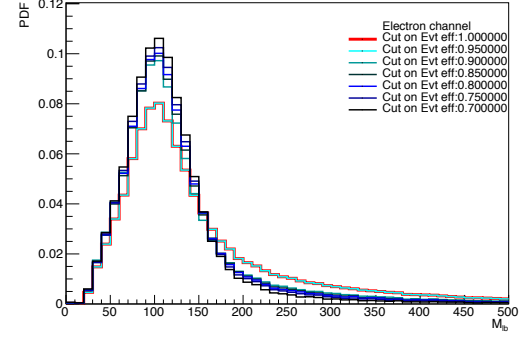
(a) 2 variables, MLP, mu-ch



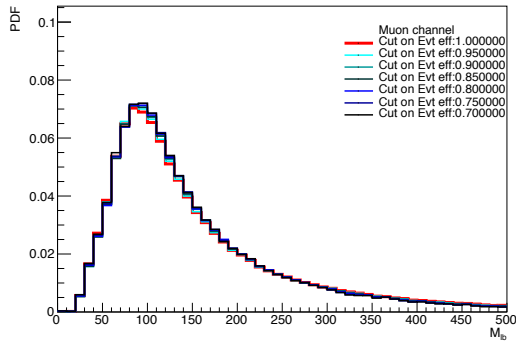
(b) 2 variables, MLP, el-ch



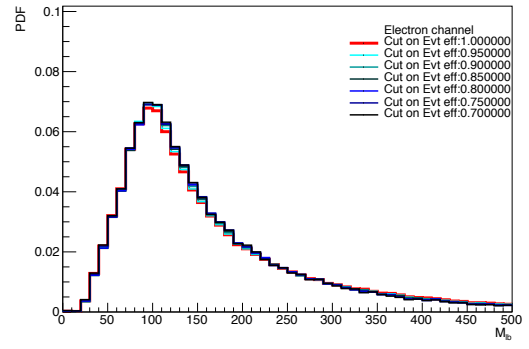
(c) 8 variables, MLP, mu-ch



(d) 8 variables, MLP, el-ch



(e) 20 variables, MLP, mu-ch



(f) 20 variables, MLP, el-ch

Figure 40: Relation between  $M_{lb}$  shape(W+jets-dominant CR's data) when cut on MVA score which leave different events efficiency

Here is an arrangement of signal region and 2 control region as a table:

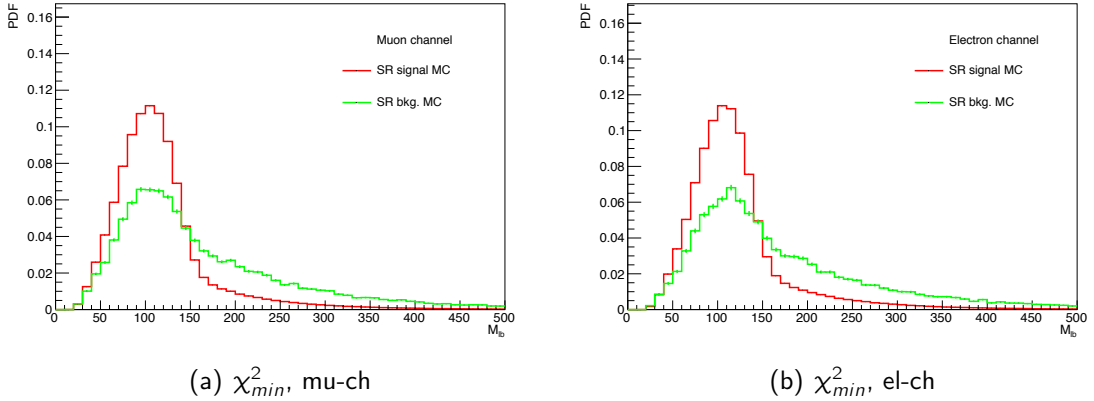


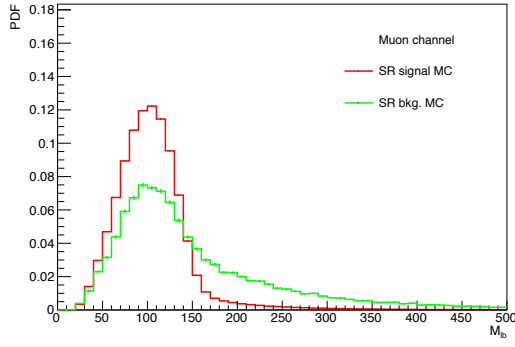
## VI Background Estimation

According to the simulation, the events of interests occupy dominant ratio under signal region selection (includes  $\chi^2_{min}$ , MVA-A, MVA-B strategy), but also about 4~6 % of events which came from non- $t\bar{t}$  background are collected. Even though the selected events are under high signal purity, the randomly combined background events would contaminate the final measurement of asymmetry. In fact, the minority of background may still dilute the calculating results of  $A'_{cp}$  critically in this precision measurement analysis. Thus, the background study should be attached importance to. The  $A'_{cp}$  value of  $t\bar{t}$  would be extracted, at the same time, backgrounds' contribution would be cast aside.

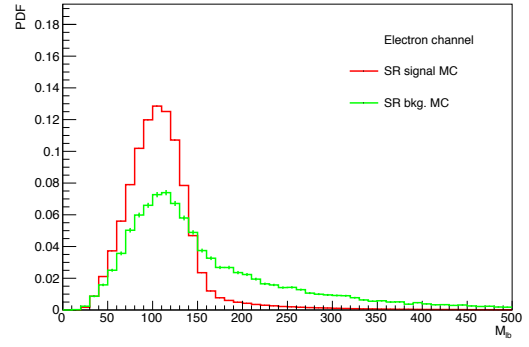
It is a common and usual way to estimate background in data by using simulation samples. It depends more on the theoretical modeling and detector simulation with simulation sample. The background in simulation cannot be quite close to real data perfectly. This situation would disorder the asymmetry measurement eventually. It is suggested that in many high energy experiments' analysis to directly acquire background from real data. Therefore, the data-driven way is applied.

In this analysis, it is found that the  $M_{lb}$  variable shows really difference between signal and background in shape (Fig.41). Thus, with the diverse shape, there is an advantage to discern signal and background and then separate them with template fit.





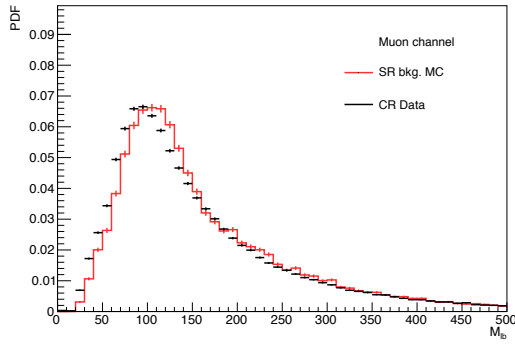
(c) MVA(20 variables, MLP), mu-ch



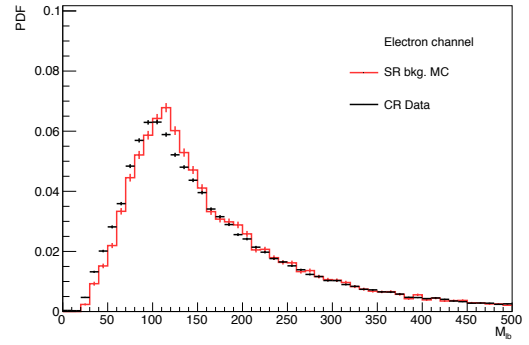
(d) MVA(20 variables, MLP), el-ch

Figure 41: Comparison of  $M_{lb}$  shape between SR's signal and background

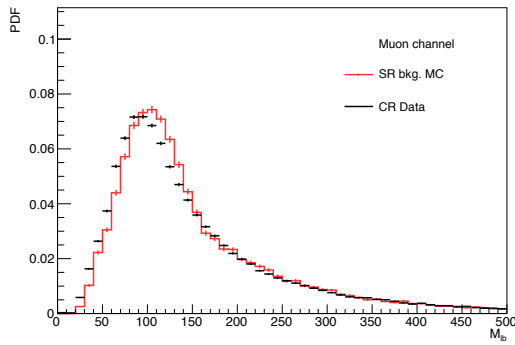
As mentioned that the W+jets-dominant CR's data is used to data-driven background in SR, it must be checked that how the similarity of  $M_{lb}$ 's pdf shape they have:



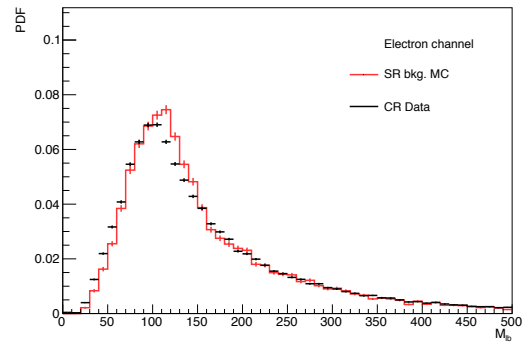
(a)  $\chi^2_{min}$ , mu-ch



(b)  $\chi^2_{min}$ , el-ch



(c) MVA(20 variables, MLP), mu-ch



(d) MVA(20 variables, MLP), el-ch

Figure 42: Comparison of  $M_{lb}$  shape between SR's background and CR's data

## VI.1 Template Fit

The method **Template Fit** is used to estimate background yields and subtract them in this analysis. The template in this method means a pdf(probability density function) with unvaried shape under specific variable's spectrum. Also following pdf's characteristic, the template have to be normalized(integrated area of this shape is unity). This template fit is one of general fitting with **Maximum-Likelihood Method**.

With respect to Maximum-Likelihood Method, it uses the likelihood function  $L$  and minimizes the  $-2 \ln L$  by computing resource to get the more appropriate parameters in function we want to predict. The signal and background yields in this analysis are both the target parameters in fitting. The likelihood function comes from joint pdf of  $N$  independent observation with  $\mathbf{X}$  which is the set of observables, the joint pdf is Eq.4.

$$P(\mathbf{X}|\theta) = \prod_{i=1}^N f(X^i|\theta) \quad (4)$$

Eq.4 shows the product of all  $i$ -th observation's function and the  $\theta$  is the set of parameters in the pdf. When we substitute the observed data  $\mathbf{X}^0$  for variables  $\mathbf{X}$ , the PDF becomes the **Likelihood function  $L(\theta)$** :

$$L(\theta) = P(\mathbf{X}^0|\theta) = p(N|\theta) \prod_{i=1}^N f(X^i|\theta) \quad (5)$$

There are  $N$  times measurements in likelihood function. Also, the  $p(N|\theta)$  is usually a poisson distribution in most common case because of the common counting condition. In order to get the most appropriate parameters to match the observed data, the larger value of likelihood function  $L(\theta)$ , the more matched the parameters demonstrate. Therefore, the maximum  $L(\theta)$  case should be the target for final decision of parameters. However, the modern technics are usually used to minimize some values, so it is turned to negative sign and being have to be minimized. On the other hand, it is convenient to calculate with addition instead of product, so doing the natural logarithm on likelihood function make it easier(Eq.6). In conclusion, Maximum-Likelihood method minimizes the  $-2 \ln L(\theta)$  and get the fitting parameters.

$$L(\theta) \implies \ln L(\theta) \quad , \quad \prod_{i=1}^N f(X^i|\theta) \implies \sum_{i=1}^N \ln L(\theta) \quad (6)$$

In the cases that the number of observation is also the parameters and as random variables, the **extended-likelihood function** is often adopted. The extended-likelihood function includes the poisson distribution  $p(N|\theta)$  of Eq.5 in. So the extended-likelihood function shows as the

pattern in Eq.7.

$$L(\theta)_{ext} = p(N|\theta) \prod_{i=1}^N f(X^i|\theta) = \frac{e^{-\mu(\theta)} \mu(\theta)^N}{N!} \prod_{i=1}^N f(X^i|\theta) \quad (7)$$

In this analysis, there are signal and background templates being pdf shapes, and the only parameters of  $\theta$  set are the event numbers of signal and background ( $n_S, n_B$ ). Thus the extended-likelihood function of this analysis is demonstrated as Eq.8. The  $f_S, f_B$  are the fraction of signal and background. That is to say,  $f_S = n_S/(n_S + n_B)$ ,  $f_B = n_B/(n_S + n_B)$ , and the  $P_S$  and  $P_B$  are the templates of signal and background. Also, we just fit under the  $M_{lb}$  variable(observable), so the  $X^i$  in Eq.7 is  $M_{lb}$ .

$$\begin{aligned} L(n_S, n_B)_{ext} &= \frac{e^{-(n_S+n_B)} (n_S + n_B)^N}{N!} \prod_{i=1}^N f(M_{lb}^i | n_S, n_B) \\ &= \frac{e^{-(n_S+n_B)} (n_S + n_B)^N}{N!} \prod_{i=1}^N [f_S P_S(M_{lb}^i) + f_B P_B(M_{lb}^i)] \\ &= \frac{e^{-(n_S+n_B)}}{N!} \prod_{i=1}^N [n_S P_S(M_{lb}^i) + n_B P_B(M_{lb}^i)] \end{aligned} \quad (8)$$

Eventually, in our analysis we use binned-likelihood function as the observed mode. In other words, the  $i = 1, 2, \dots, N$  means that input observations are the results of  $N$  bins under the observable –  $M_{lb}$  spectrum. By contrast, the unbinned-likelihood method uses event-by-event as the observation, costing too much resource and time, so it has not been used.

### VI.1.1 Fitting Result

Table 14: Data and MC estimated events number after template fit(w/  $\chi^2_{min}, M_{lb}$  cut)

	Muon Channel	Electron Channel
Data	243790	136151
Expected $t\bar{t}$	230766	135600
Expected background	12146.9	5537.45

Table 15: Data and MC estimated events number after template fit(w/ MVA-A strategy)

	Muon Channel	Electron Channel
Data	245436	139432
Expected $t\bar{t}$	236226	133894
Expected background	8520.95	5102.1

Table 16: Data and MC estimated events number after template fit(w/ MVA-B strategy)

	Muon Channel	Electron Channel
Data	272583	157510
Expected $t\bar{t}$	256196	146656
Expected background	15479	10217.6

### VI.1.2 Goodness of Fit

## **VII Asymmetry Bias**

## **VIII    Systematic Uncertainty**

### **VIII.1   Simulation Uncertainty**

### **VIII.2   Fit Uncertainty**

## **IX CP Asymmetry in Top quarks pair and corresponding observables/models**

### **IX.1 Models**

#### **IX.1.1 CEDM model**

#### **IX.1.2 2HDM model**

### **IX.2 Observables**

#### **IX.2.1 Classification**

#### **IX.2.2 Observable property**



## **X Results and Conclusion**

## References