An analysis of $h \to \mu^+\mu^-$ mode at the center-of-mass energy of 500 GeV ILC — part 4

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Abstract

[1] This note summarizes the results of $h \to \mu^+\mu^-$ mode at the 500 GeV ILC. This is the fourth series of note [1–3].

[1]Release note

- 2017/1/18 release
- 2017/2/14 found bugs in analysis processor, all numbers and plots are changed

1 Introduction

In the previous analysis [3], I used TMVA to obtain better results. I obtained the best precision value but it was clearly overtrained. This gives low reliability of the analysis, so now I want to work on more reliable analysis methods. The another topic is the current muons in the signal process ($\nu\bar{\nu}h \to \nu\bar{\nu}\mu^+\mu^-$) are already isolated, but for the future expansion of the analysis, I want to implement IsolatedLeptonTagger in my analysis.

2 IsolatedLeptonTagger

2.1 Abstract

What is this processor is written in Ref. [4]. Originally this processor is developed under the Higgs self-coupling study, I will implement this processor to tag the leptons. Since this processor is for leptons, so that not only muons but also electrons are identified.

2.2 Event reconstruction

The IsolatedLeptonTagger uses simple cuts to select leptons first, then uses an already trained weight file to check isolation. The cuts also were used in the previous analysis, it is rather easy to understand. But this processor uses some different parameters. For the reference, the following parameters were used in previous analysis:

- $E_{\mathrm{ECAL}}/(E_{\mathrm{ECAL}} + E_{\mathrm{HCAL}})$
- $(E_{\mathrm{ECAL}} + E_{\mathrm{HCAL}})/|p|$
- E_{yoke}
- P_t

First two parameters are used to select muons, and remains are used to remove overlay backgrounds.

On the other hand, the following parameters are used in IsolatedLeptonTagger.

- $E_{\mathrm{ECAL}}/(E_{\mathrm{ECAL}} + E_{\mathrm{HCAL}})$ (only for electrons)
- $(E_{\mathrm{ECAL}} + E_{\mathrm{HCAL}})/|p|$
- E_{yoke}
- $|p|$
- $|d_0/\sigma(d_0)|$
- $|z_0/\sigma(z_0)|$
- MVA cut

The first three parameters are the same in previous analysis. However, the definition of ECAL and HCAL is different. In the previous analysis, the energy deposit on main ECAL and HCAL are considered, while IsolatedLeptonTagger uses all ECAL and HCAL in whole ILD system for counting energy deposit. The fourth parameter is the magnitude of momentum. Since this is a different parameter, I checked this parameter distribution. The fifth and sixth parameters are requiring primary vertex to reject muons from taus. The final MVA cut is for the isolation. The following figures are the distributions of each parameter.

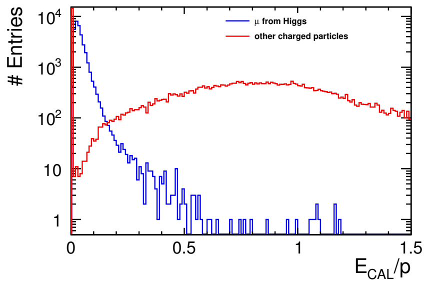

Figure 1: Distribution of $(E_{\rm ECAL} + E_{\rm HCAL})/|p|$.

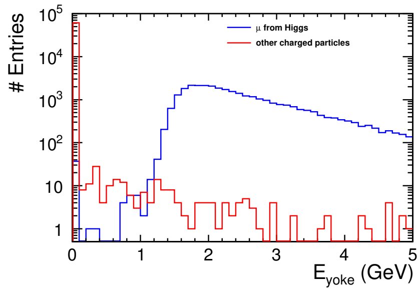

Figure 2: Distribution of $E_{\rm yoke}$.

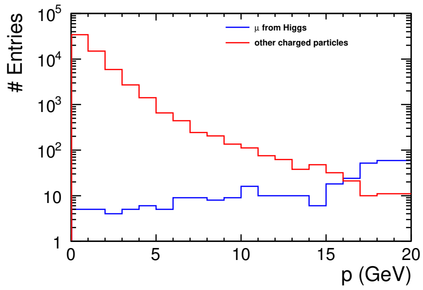

Figure 3: Distribution of $|p|$.

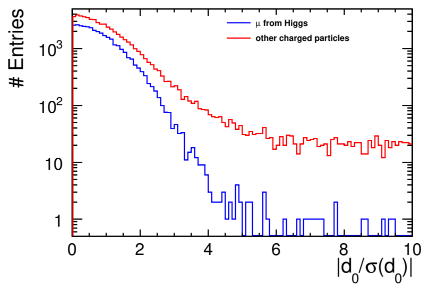

Figure 4: Distribution of $|d_0/\sigma(d_0)|$.

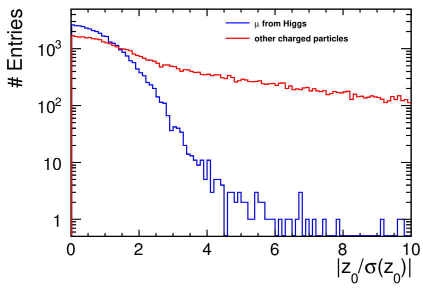

Figure 5: Distribution of $|z_0/\sigma(z_0)|$.

From these plots I decided cuts as below:

- $(E_{\rm ECAL} + E_{\rm HCAL})/|p| < 0.5$
- $E_{\rm yoke} > 0.5$ GeV
- $|p| > 5$ GeV
- $|d_0/\sigma(d_0)| < 5$
- $|z_0/\sigma(z_0)| < 5$
- MVA cut > 0.7

I used the default value for MVA cut. The reconstruction efficiency of the signal process was 94.9% and the purity was 100%.

By the way, we can set MVA cut value for electron and muon separately, I set more than 2 for electron to tag muons only and not to tag electrons in IsolatedLeptonTagger.

2.3 Analysis

I applied the following cuts as the precuts:

- exactly one μ^+ and one μ^-
- $\chi^2/\mathrm{Ndf}(\mu^\pm) < 1.5$
- innermost hit $(\mu^\pm) < 20$ mm
- $\sigma(M_{\mu\mu}) < 1$ GeV
- $N_{P_t > 5\mathrm{GeV}} \leq 1$
- $125 < E_{\mathrm{vis}} < 400$ GeV
- $100 < M_{\mu\mu} < 130$ GeV
- $\cos\theta_{\mu\mu} < 0.55$
- $|\cos\theta_{\mathrm{miss}}| < 0.999$
- $P_t > 5$ GeV

The second, third, and fourth cuts are for selecting well-measured muons. The fifth, sixth, and seventh cuts are for selecting signal-like events. The eighth, ninth, and tenth cuts are for mainly rejecting 2f background processes. The following figures are the distributions of each variable.

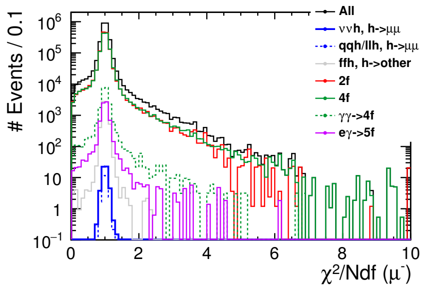

Figure 6: Distribution of $\chi^2/\mathrm{Ndf}(\mu^-)$.

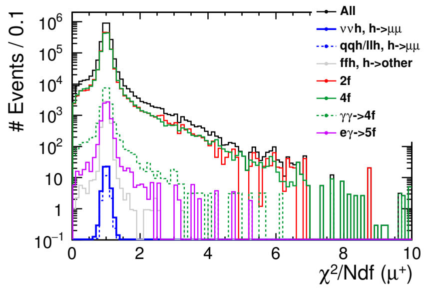

Figure 7: Distribution of $\chi^2/\mathrm{Ndf}(\mu^+)$.

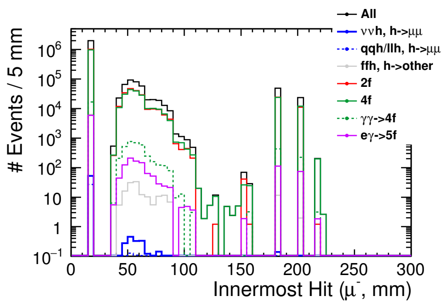

Figure 8: Distribution of μ^- innermost hit.

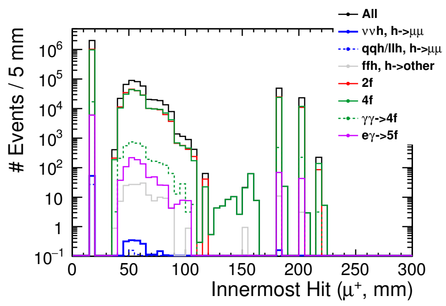

Figure 9: Distribution of μ^+ innermost hit.

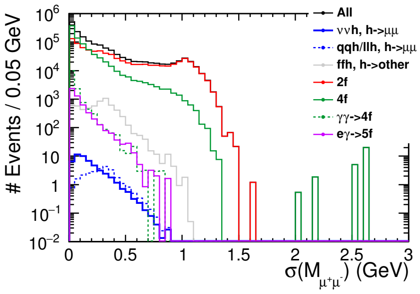

Figure 10: Distribution of $\sigma(M_{\mu^+\mu^-})$.

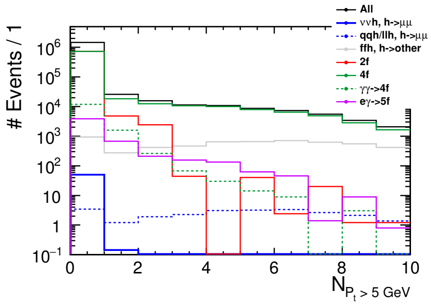

Figure 11: Distribution of $N_{P_t > 5\text{GeV}}$.

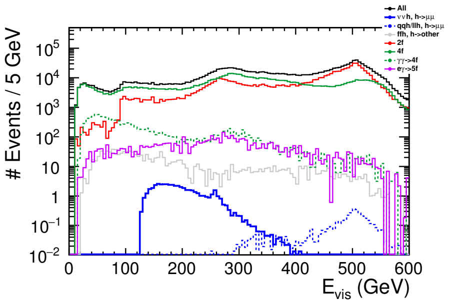

Figure 12: Distribution of E_{vis}.

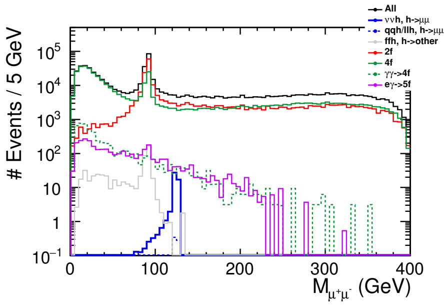

Figure 13: Distribution of $M_{\mu^+\mu^-}$.

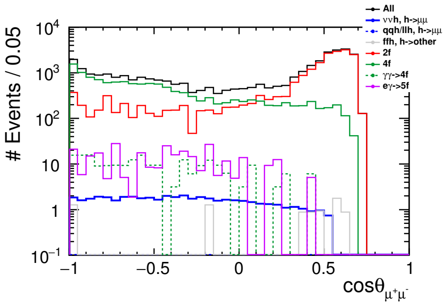

Figure 14: Distribution of $\cos\theta_{\mu^+\mu^-}$.

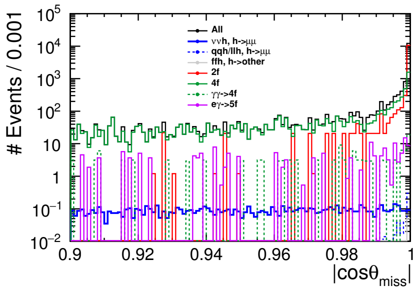

Figure 15: Distribution of $|\cos\theta_{\text{miss}}|$.

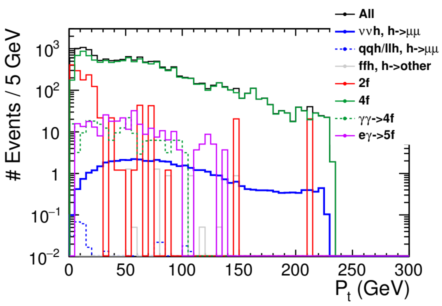

Figure 16: Distribution of P_t.

The next table is the cut table at the precuts.

Table 1: Cut table at the precuts.

	$\nu\nu h$ $h \to \mu\mu$	qqh+$\ell\ell h$ $h \to \mu\mu$	ffh $h \to$ other	2f	4f	$\gamma\gamma \to$ 4f	5f
No cut	57.53	31.13	4.116×10^5	4.224×10^7	4.592×10^7	3.356×10^5	2.209×10^5
# $\mu^\pm$	54.82	27.72	6553.83	1.314×10^6	1.262×10^6	2.216×10^4	7206.44
χ^2/Ndf	54.51	27.59	6525.51	1.261×10^6	1.208×10^6	2.107×10^4	6978.30
Innermost	50.26	26.18	6194.38	8.042×10^5	8.047×10^5	1.393×10^4	5185.97
$\sigma(M_{\mu\mu})$	50.25	26.18	6192.51	7.287×10^5	8.025×10^5	1.393×10^4	5185.97
$N_{P_t>5\mathrm{GeV}}$	50.22	4.64	1208.32	7.261×10^5	7.434×10^5	1.354×10^4	4567.99
E_{vis}	50.16	0.72	551.95	2.549×10^5	4.245×10^5	5379.29	3343.95
$M_{\mu\mu}$	48.65	0.72	8.06	2.076×10^4	1.364×10^4	217.37	304.69
$\cos\theta_{\mu\mu}$	48.64	0.72	5.40	1.197×10^4	1.328×10^4	217.37	304.69
$\cos\theta_{\mathrm{miss}}$	48.55	0.42	5.35	1417.20	1.171×10^4	198.64	295.95
P_t	48.45	0.39	5.35	1009.00	1.154×10^4	183.07	295.95

The contents of 2f processes are:

- $\mu\mu$: 874.58(86.7%)
- $\tau\tau$: 134.42(13.3%)

The contents of 4f processes are:

- $\nu = 0$
  - $2q + 2\mu$: 41.45(0.36%)
  - $2e + 2\mu$: 1572.19(13.6%)
  - $2\mu + 2\tau$: 40.13(0.35%)
- $\nu = 1$
  - $2q + 1\nu + 1\mu$: 40.25(0.35%)
  - $2q + 1\nu + 1\tau$: 20.13(0.17%)
- $\nu = 2$
  - $2\nu + 2\mu$: 8272.06(71.7%)
  - $2\nu + 2\tau$: 41.30(0.36%)
  - $2\nu + 1\mu + 1\tau$: 1510.71(13.1%)

The contents of $\gamma\gamma \to$ 4f processes are:

- $\nu = 0$
  - 4μ : 3.17(1.7%)
- $\nu = 2$
  - $2\nu + 2\mu$: 173.60(94.8%)
  - $2\nu + 1\mu + 1\tau$: 6.30(3.4%)

I also checked which backgrounds were remained at the precuts, and what is the actual event weight of the backgrounds. The following numbers are the process ID and its event weight.

- ffh, others
  - $\mu\mu h$, 106519($\sim$0.8), 106520(<0.1)
  - $\tau\tau h$, 106522(<0.1)

- $\nu\nu h$, 106523(∼1.2)

- 2f
  - leptonic, 250106(∼20.5), 250108(∼1.2)
- 4f
  - ZZ semileptonic, 250014(∼20.1), 250016(∼1.1)
  - WW semileptonic, 250018(∼20.1)
  - ZZ leptonic, 250022(∼20), 250024(∼1.1)
  - WW leptonic, 250026(∼20.1), 250028(∼1.1)
  - ZZ and WW mix leptonic, 250030(∼1.8), 250032(∼0.1)
  - single Z e leptonic, 250033(∼2.6), 250034(∼5), 250035(∼0.5), 250036(∼0.2)
  - single Z ν leptonic, 250054(∼1.8), 250056(∼0.1)
- $\gamma\gamma \to$ 4f
  - $2\ell + 2\nu$, 37401(∼3.1), 37402(∼2.9), 37403(∼3)
  - 4ℓ, 37453(∼3.1)
- 5f
  - $e + 2\ell + 2\nu$, 37189(∼5), 37190(∼4.2), 37191(∼0.5), 37192(∼0.2), 37305(∼1.8), 37306(∼0.8), 37307(∼3.6), 37308(∼3.1)
  - $3\ell + 2\nu$, 37193(∼1.5), 37194(∼0.4)
  - $e + \nu + \ell + x + y$, 37225(∼5.7)
  - $2\ell + \nu + x + y$, 37315(∼3.2)
  - $e + 2\ell + 2x$, 37242(∼4.8)
  - $e + 4\ell$, 37258(∼4.8), 37259(∼0.5)

It is clear that many processes have less statistics, unfortunately.

2.4 Separation

The signal is a mixture of Higgs-strahlung (Zh) process and WW-fusion process (WWF). To improve the precision, I will separate these processes and optimize for each process. I used recoil mass this time. This recoil mass should be correspond to Z mass in signal process. The next plot is the distribution of recoil mass.

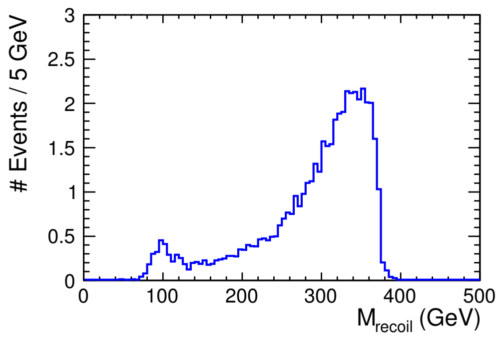

Figure 17: Distribution of recoil mass.

The peak around 100 GeV indicates the Zh process. Since there are no FSR corrections in current analysis, the peak is shifted to higher mass region. From this figure, I decided the cut point at 120 GeV. With this cut, 2.65 events are categorized as Zh events, and remaining 45.80 events are categorized as WWF.

2.5 Cut-based Analysis

I performed cut-based analysis first. In this analysis I did not consider separation. The optimum cuts were:

- $124 < M_{\mu^+\mu^-} < 126$ GeV
- $E_{\text{vis}} < 265$ GeV
- $P_t > 60$ GeV
- thrust < 0.88
- charge $* \cos\theta_{\mu^\pm} > -0.8$

The next figures are the distributions of each variable.

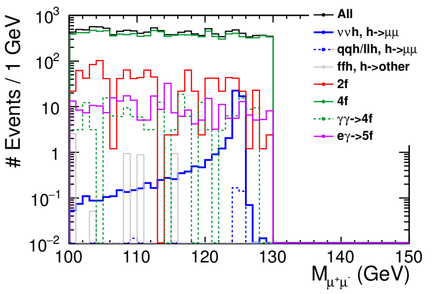

Figure 18: Distribution of $M_{\mu^+\mu^-}$.

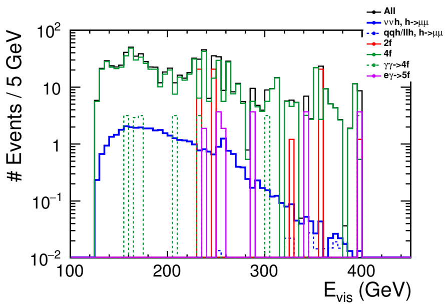

Figure 19: Distribution of E_{vis}.

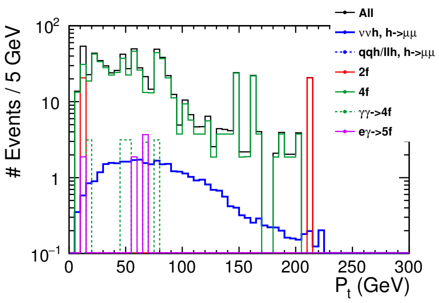

Figure 20: Distribution of P_t.

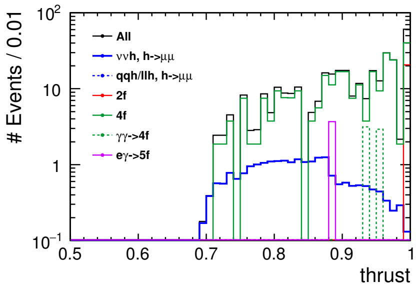

Figure 21: Distribution of thrust.

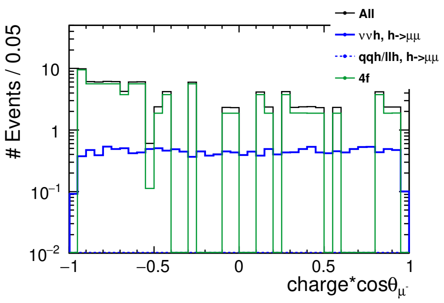

Figure 22: Distribution of charge $* \cos\theta_{\mu^-}$.

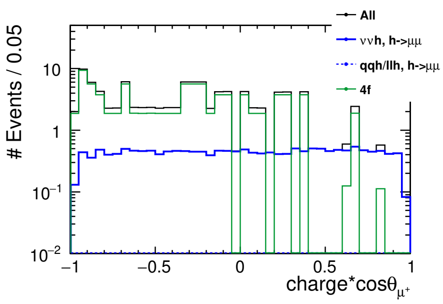

Figure 23: Distribution of charge $* \cos\theta_{\mu^+}$.

Next table is cut table.

Table 2: Cut table.

	$\nu\nu h$ $h \to \mu\mu$	qqh+$\ell\ell h$ $h \to \mu\mu$	ffh $h \to$ other	2f	4f	$\gamma\gamma \to$ 4f	5f
precuts	48.45	0.39	5.35	1009.00	1.154×10^4	183.07	295.95
$M_{\mu\mu}$	39.44	0.31	0	64.20	747.29	21.81	18.48
E_{vis}	36.14	0.05	0	41.19	597.99	15.52	7.44
P_t	22.72	0.03	0	20.60	277.38	6.07	3.68
thrust	17.38	0.02	0	0	88.33	0	0
charge * $\cos\theta_{\mu^\pm}$	14.67	0.02	0	0	48.85	0	0

From the analysis, I obtained $N_{\text{sig}} = 14.67$ and $N_{\text{bkg}} = 48.87$ which gives the significance of 1.8 and corresponding precision $\dfrac{\Delta(\sigma \times \text{BR})}{(\sigma \times \text{BR})} = 54\%$.

2.6 TMVA Analysis

From now I will use TMVA. I tested 3 patterns (Zh only, WWF only, and mixed) this time. The most powerful parameter is of course $M_{\mu\mu}$, therefore usually everything is determined by this parameter. Thus, I tested both case: without $M_{\mu\mu}$ and with $M_{\mu\mu}$. In the without case, I will optimize BDTG analysis using without $M_{\mu\mu}$, then apply a cut to $M_{\mu\mu}$ for final optimization.

2.6.1 Analysis 1 — Zh without $M_{\mu\mu}$

I used following 6 parameters.

- E_{vis}, P_t, thrust, $\cos\theta_{\text{thrust}}$
- charge * $\cos\theta_{\mu^+}$, charge * $\cos\theta_{\mu^-}$

The next figures are the distributions of each parameter.

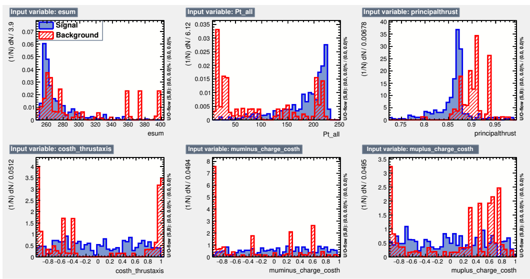

Figure 24: Distributions of each parameter.

The following 2 figures show the results of the analysis.

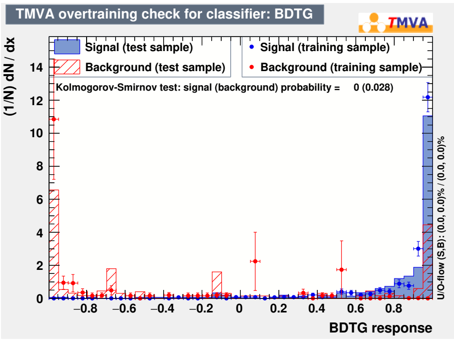

Figure 25: Distribution of BDTG output.

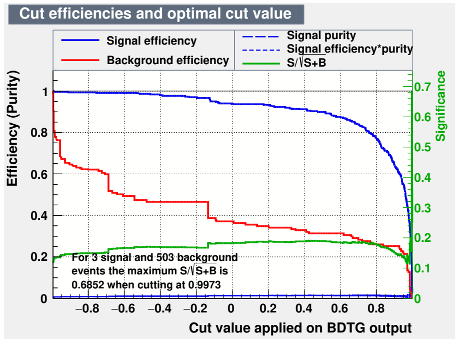

Figure 26: Distribution of significance.

From the analysis, I obtained $N_{\text{sig}} = 0.47$ and $N_{\text{bkg}} = 0$ which gives the significance of 0.7 and corresponding precision $\dfrac{\Delta(\sigma \times \text{BR})}{(\sigma \times \text{BR})} = 146\%$. Since remained backgrounds are 0, there are no meaning to apply more cuts.

2.6.2 Analysis 2 — Zh with $M_{\mu\mu}$

I used following 6 parameters.

- P_t, $\cos\theta_{\text{thrust}}$, $\cos\theta_{\text{thrustaxis}}$
- $M_{\mu\mu}$
- charge * $\cos\theta_{\mu^+}$, charge * $\cos\theta_{\mu^-}$

The next figures are the distributions of each parameter.

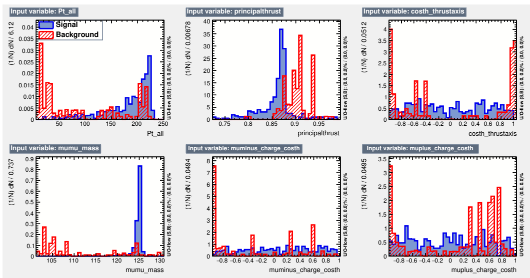

Figure 27: Distribution of each parameter.

The following 2 figures show the results of the analysis.

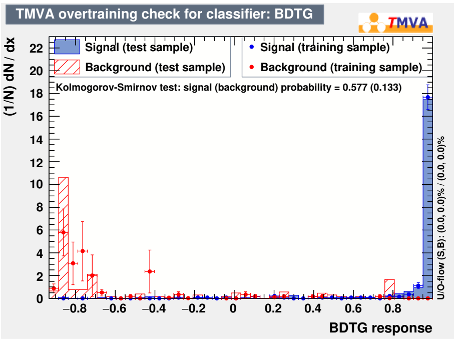

Figure 28: Distribution of BDTG output.

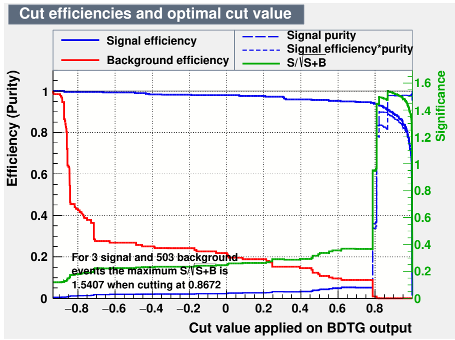

Figure 29: Distribution of significance.

From the analysis, I obtained $N_{\text{sig}} = 2.43$ and $N_{\text{bkg}} = 0.05$ which gives the significance of 1.5 and corresponding precision $\dfrac{\Delta(\sigma \times \text{BR})}{(\sigma \times \text{BR})} = 65\%$.

2.6.3 Analysis 3 — WWF without $M_{\mu\mu}$

I used following 5 parameters.

- E_{vis}, P_t, thrust
- charge * $\cos\theta_{\mu^+}$, charge * $\cos\theta_{\mu^-}$

The next figures are the distributions of each parameter.

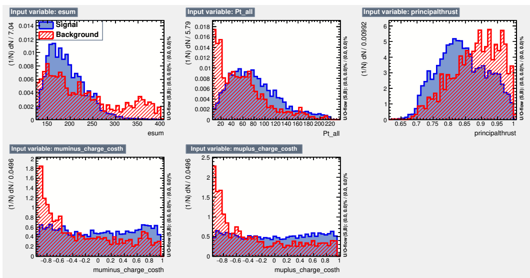

Figure 30: Distribution of each parameter.

The following 2 figures show the results of the analysis.

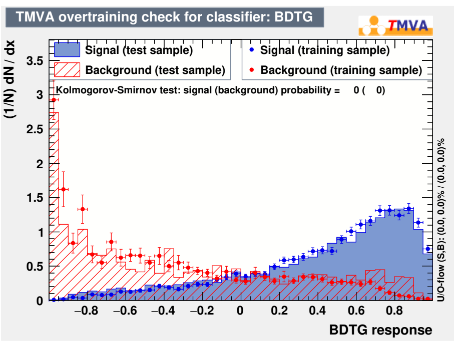

Figure 31: Distribution of BDTG output.

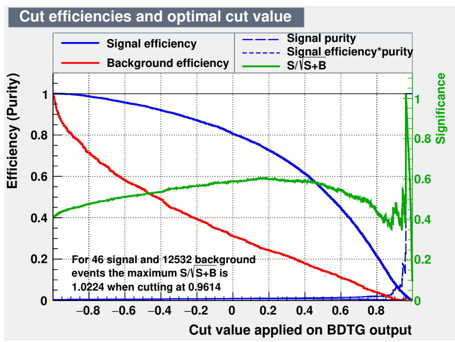

Figure 32: Distribution of significance.

From the analysis, I obtained $N_{\text{sig}} = 1.05$ and $N_{\text{bkg}} = 0$ which gives the significance of 1.0 and corresponding precision $\dfrac{\Delta(\sigma \times \text{BR})}{(\sigma \times \text{BR})} = 98\%$. Since remained backgrounds are 0, there are no meaning to apply more cuts.

2.6.4 Analysis 4 — WWF with $M_{\mu\mu}$

I used following 5 parameters.

- P_t, thrust
- $M_{\mu\mu}$
- charge * $\cos\theta_{\mu^+}$, charge * $\cos\theta_{\mu^-}$

The next figures are the distributions of each parameter.

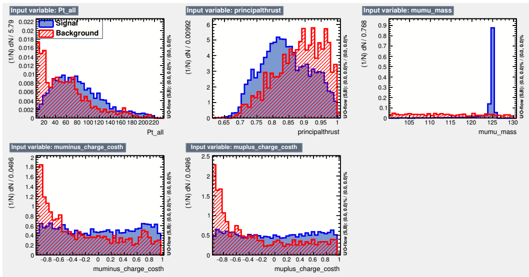

Figure 33: Distribution of each parameter.

The following 2 figures show the results of the analysis.

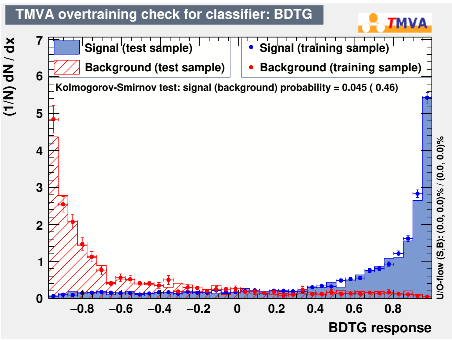

Figure 34: Distribution of BDTG output.

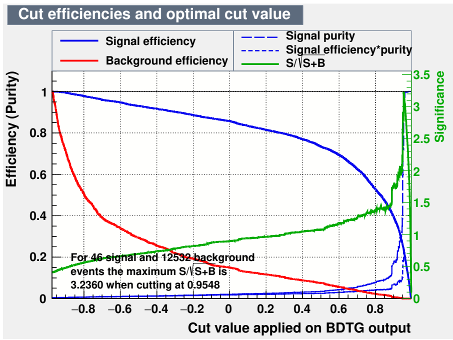

Figure 35: Distribution of significance.

From the analysis, I obtained $N_{\text{sig}} = 10.96$ and $N_{\text{bkg}} = 0.51$ which gives the significance of 3.2 and corresponding precision $\dfrac{\Delta(\sigma \times \text{BR})}{(\sigma \times \text{BR})} = 31\%$.

2.6.5 Analysis 5 — Mixed without $M_{\mu\mu}$

I used following 6 parameters.

- E_{vis}, P_t, thrust, $\cos\theta_{\text{thrust}}$
- charge * $\cos\theta_{\mu^+}$, charge * $\cos\theta_{\mu^-}$

The next figures are the distributions of each parameter.

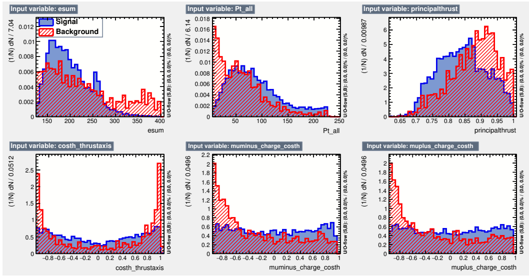

Figure 36: Distribution of each parameter.

The following 2 figures show the results of the analysis.

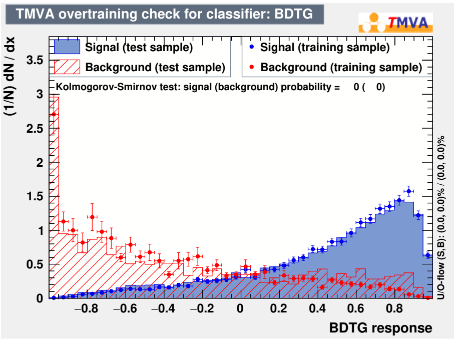

Figure 37: Distribution of BDTG output.

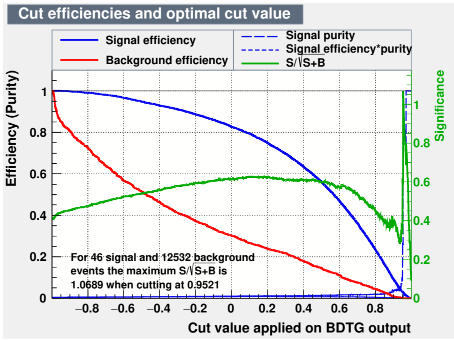

Figure 38: Distribution of significance.

From the analysis, I obtained $N_{\text{sig}} = 1.33$ and $N_{\text{bkg}} = 0.22$ which gives the significance of 1.1 and corresponding precision $\dfrac{\Delta(\sigma \times \text{BR})}{(\sigma \times \text{BR})} = 94\%$.

2.6.6 Analysis 6 — Mixed with $M_{\mu\mu}$

I used following 5 parameters.

- P_t, thrust
- $M_{\mu\mu}$
- charge * $\cos\theta_{\mu^+}$, charge * $\cos\theta_{\mu^-}$

The next figures are the distributions of each parameter.

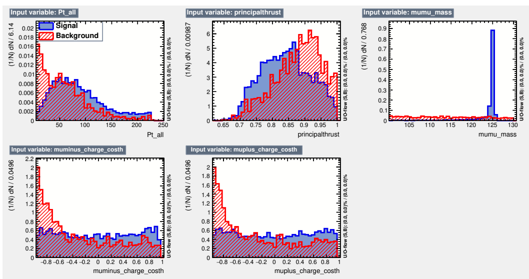

Figure 39: Distribution of each parameter.

The following 2 figures show the results of the analysis.

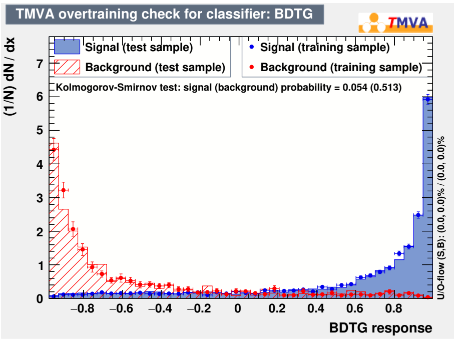

Figure 40: Distribution of BDTG output.

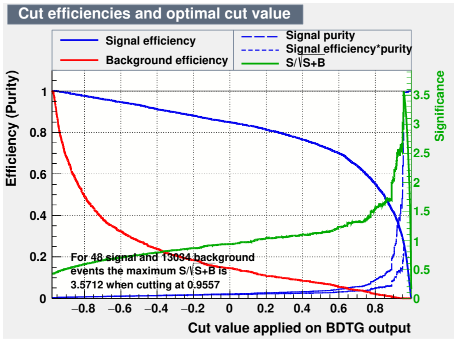

Figure 41: Distribution of significance.

From the analysis, I obtained $N_{\mathrm{sig}} = 13.04$ and $N_{\mathrm{bkg}} = 0.30$ which gives the significance of 3.6 and corresponding precision $\dfrac{\Delta(\sigma \times \mathrm{BR})}{(\sigma \times \mathrm{BR})} = 28\%$.

3 Summary of results

In next table I summarized all obtained results from the analysis.

Table 3: Summary of analysis results.

	Zh	WWF	Mixed
without $M_{\mu\mu}$	146%	98%	94%
with $M_{\mu\mu}$	65%	31%	28%

I can obtain 28% precision if I combine the results of Zh and WWF with $M_{\mu\mu}$. The result is the same as Mixed with $M_{\mu\mu}$. If we consider ideal case (100% signal efficiency and no backgrounds) which gives 13% precision, these results are factor 2 worse. Of course we should not forget about the low MC statistics.

4 Conclusion and outlook

I developed more efficient precuts and proceed TMVA analysis. I obtained 28% in the best case. These results are factor 2 worse than ideal case. I also confirmed the number of MC statistics quantitatively.

The remaining problems are:

- IsolatedLeptonTagger checks E_{yoke}. If we require the number of muons as the cut, all SGV samples ($\gamma\gamma \to$ 2f and 3f) are removed. How to handle this?
- How to understand and apply re-weighting?

References

[1] Shin-ichi Kawada “An analysis of $h \to \mu^+\mu^-$ mode at the center-of-mass energy of 500 GeV ILC”

[2] Shin-ichi Kawada “An analysis of $h \to \mu^+\mu^-$ mode at the center-of-mass energy of 500 GeV ILC — part 2”

[3] Shin-ichi Kawada “An analysis of $h \to \mu^+\mu^-$ mode at the center-of-mass energy of 500 GeV ILC — part 3”

[4] Junping Tian, Claude Dürig “isolated lepton finder”

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