An analysis of $h \to \mu^+\mu^-$ mode at the center-of-mass energy of 500 GeV ILC — part 5

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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 fifth series of note [1–4].

[1]Release note

- 2017/5/15 release

1 Introduction

In this note, I will write the first analysis results of $e^+e^- \to q\bar{q}h$ mode mainly. In this analysis, I increased total number of MC samples a bit, including all MC samples (except SGV, not included at all) generated before the end of the year 2016. I also did similar analysis for $e^+e^- \to \nu\bar{\nu}h$ mode with a bit increased MC samples, and discuss the results in this note.

2 $e^+e^- \to q\bar{q}h$

2.1 Overview

I can use not only the information of Higgs, but also of $Z \to q\bar{q}$. The number of signal events are smaller than $e^+e^- \to \nu\bar{\nu}h$ mode, but I expect I can obtain similar precision.

2.2 Event Reconstruction

2.2.1 Overview

The reconstruction procedure is as follows:

1. reconstruct isolated muon: IsolatedLeptonTagger
2. reconstruct jets and remove $\gamma\gamma \to$ hadrons overlay: k_T clustering (FastJet)

2.2.2 IsolatedLeptonTagger

Details of this processor can be found at Ref. [5]. The following parameters are used in this processor.

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

The following figures are the distributions of each parameter.

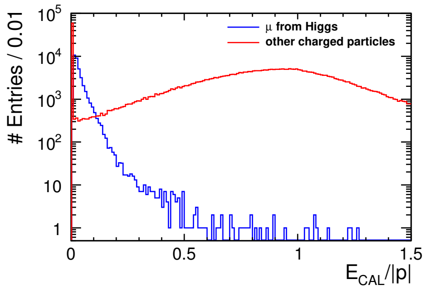

Figure 1: $(E_{\mathrm{ECAL}} + E_{\mathrm{HCAL}})/|p|$ distribution.

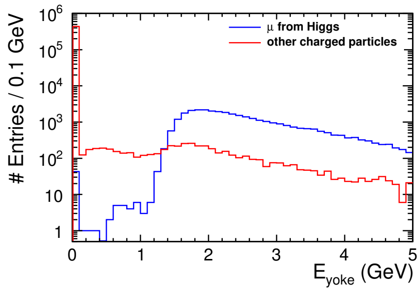

Figure 2: E_{yoke} distribution.

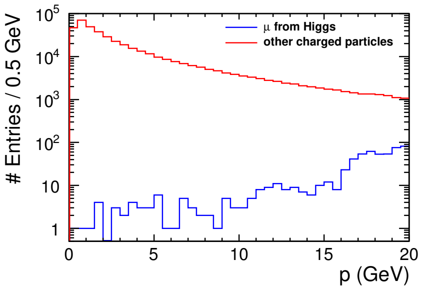

Figure 3: $|p|$ distribution.

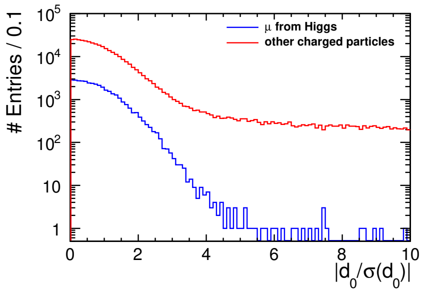

Figure 4: $|d_0/\sigma(d_0)|$ distribution.

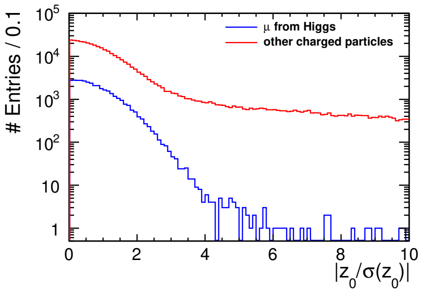

Figure 5: $|z_0/\sigma(z_0)|$ distribution.

From these plots, I decided to apply cuts as follows:

- $(E_{\rm ECAL} + E_{\rm HCAL})/|p| < 0.5$
- $E_{\rm yoke} > 0.5$ GeV
- $|p| > 10$ GeV
- $|d_0/\sigma(d_0)| < 5$
- $|z_0/\sigma(z_0)| < 5$
- MVA cut > 0.7

I used a default value for muon MVA cut. I set the MVA cut value of 2 for electrons, this processor will really behave as the isolated muon tagger. The reconstruction efficiency for signal process was 92.9%.

2.2.3 k_T clustering

Next, I used k_T clustering for PFO collection after removing isolated muons. In principle there are only 2 jets, but I required to reconstruct 3 jets to take into account of hard gluon jet. The R-value (jet radius) was optimized every 0.1, using mean value of Gaussian fit. I got $R = 1.0$ was optimum. The following plot shows the distribution of visible mass ($M_{\rm vis}$) of particles with overlay, and 3-jet invariant mass ($M_{\rm jets}$).

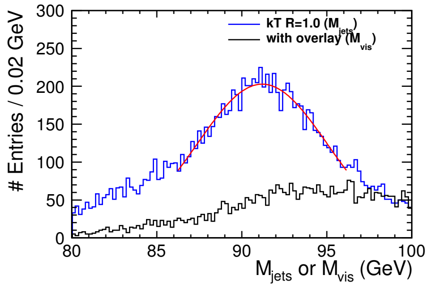

Figure 6: Mass distribution and Gaussian fit.

I performed Gaussian fit in the range of $[86.2, 96.2]$ GeV. The mean value was 91.201 ± 0.065 which is very near to Z boson mass.

2.3 Analysis — precuts

I applied following cuts as precuts:

- exactly one μ^+ and one μ^-
- number of jets is non-zero
- $\chi^2/\mathrm{Ndf}(\mu^\pm) < 1.5$
- $\sigma(M_{\mu\mu}) < 1$ GeV
- number of tracks should be grater or equal to 8
- $100 < M_{\mu\mu} < 130$ GeV
- $\cos\theta_{\mu\mu} < 0.55$
- $60 < M_{\mathrm{jets}} < 180$ GeV
- thrust < 0.95

The 3rd and 4th cuts were for selecting well-measured muons only, 5th, 6th, 7th, and 8th cuts were for selecting signal-like events. The 9th cut was for rejecting some of 2f/4f backgrounds. The following figures show each distribution of variable.

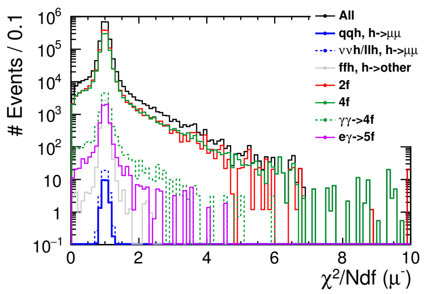

Figure 7: $\chi^2/\mathrm{Ndf}(\mu^-)$ distribution.

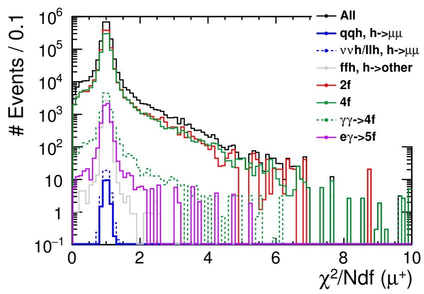

Figure 8: $\chi^2/\mathrm{Ndf}(\mu^+)$ distribution.

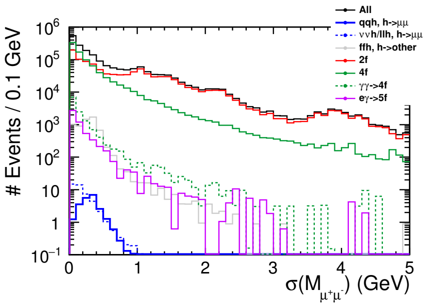

Figure 9: $\sigma(M_{\mu^+\mu^-})$ distribution.

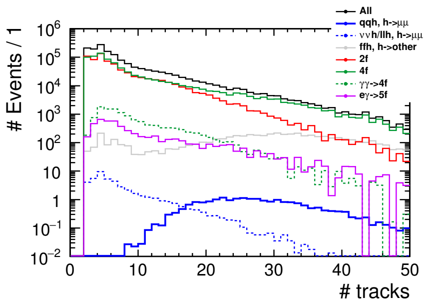

Figure 10: Number of tracks distribution.

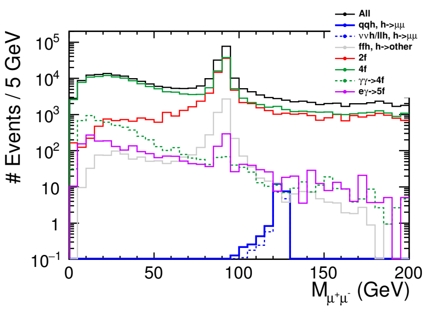

Figure 11: $M_{\mu^+\mu^-}$ distribution.

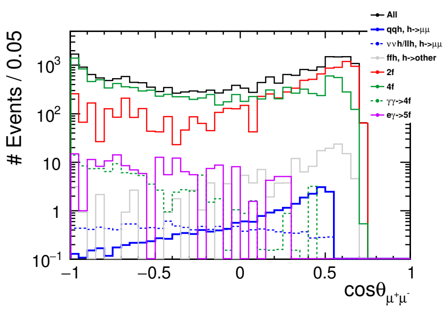

Figure 12: $\cos\theta_{\mu^+\mu^-}$ distribution.

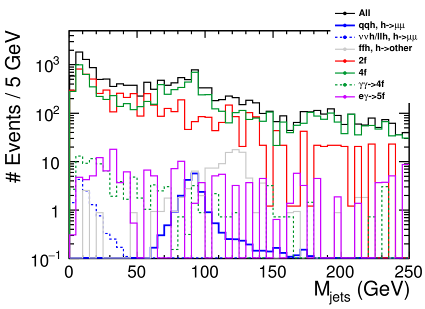

Figure 13: M_{jets} distribution.

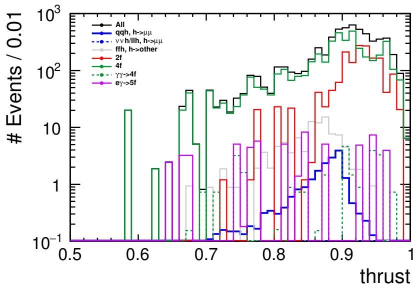

Figure 14: Thrust distribution.

Next table shows the cut table at the precuts.

Table 1: Cut table at the precuts.

	qqh $h \to \mu\mu$	$\nu\nu h$+$\ell\ell h$ $h \to \mu\mu$	ffh $h \to$ other	2f	4f	$\gamma\gamma \to$ 4f	5f
No cut	24.56	64.10	4.116×10^5	4.224×10^7	4.592×10^7	3.356×10^5	2.231×10^5
# $\mu^\pm$	22.76	59.72	6450.41	1.309×10^6	1.015×10^6	1.472×10^4	5922.55
# jet	22.76	45.98	6269.61	1.087×10^6	8.925×10^5	1.394×10^4	5664.37
χ^2/Ndf	22.65	45.72	6242.67	1.044×10^6	8.507×10^5	1.309×10^4	5461.88
$\sigma(M_{\mu\mu})$	22.21	45.13	6153.01	6.914×10^5	8.006×10^5	1.268×10^4	5328.00
# tracks	22.21	13.50	5519.68	1.972×10^5	2.578×10^5	5716.82	2531.53
$M_{\mu\mu}$	21.60	13.07	156.19	9093.54	1.154×10^4	102.26	164.16
$\cos\theta_{\mu\mu}$	21.57	13.07	112.87	5978.01	1.058×10^4	102.26	164.16
M_{jets}	20.00	0.83	101.17	1614.74	4242.11	25.42	60.30
thrust	19.91	0.83	101.17	1302.17	3552.63	21.39	56.36

2.4 Analysis — TMVA

I used TMVA (BDTG) as a tool. I used following 5 variables:

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

Next plots show the distributions of each variable.

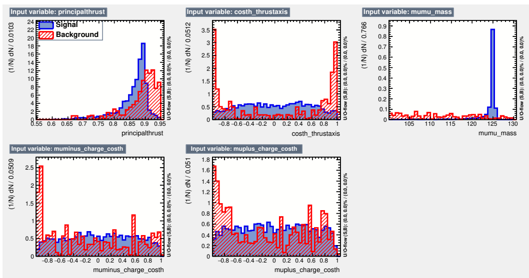

Figure 15: Distribution of each variable.

The next 2 figures show the result of TMVA analysis.

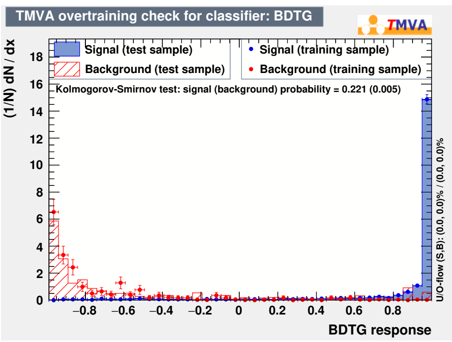

Figure 16: BDTG output distribution.

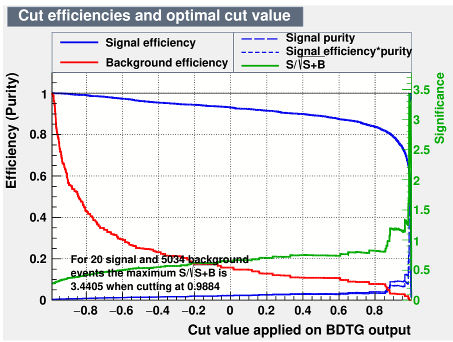

Figure 17: Significance distribution.

From this analysis, I obtained $N_{\text{sig}} = 12.25$ and $N_{\text{bkg}} = 0.42$, gives the signal significance of 3.4, also corresponds to the precision $\dfrac{\Delta(\sigma \times \text{BR})}{(\sigma \times \text{BR})} = 29\%$. The ideal (100% signal efficiency and no backgrounds) precision is 20%, this result is factor 1.5 from ideal. Of course we should not forget about the problem of limited MC statistics.

3 $e^+e^- \to q\bar{q}h$ (right-handed)

In the previous section, it was the analysis of left-handed beam polarization. Of course I can do similar analysis with right-handed case.

3.1 Event Reconstruction

The event reconstruction is completely same as written in section 2.2.

3.2 Analysis — precuts

The precuts are the same as written in section 2.3, except one point as following:

- $60 < M_{\text{jets}} < 180$ GeV $\to$ $60 < M_{\text{jets}} < 150$ GeV

The following figures are the distributions of each variable.

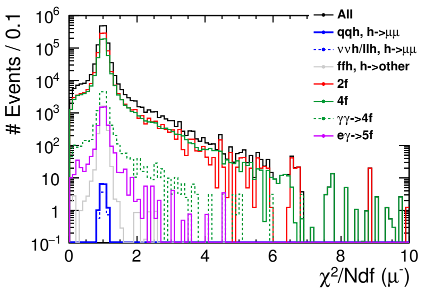

Figure 18: $\chi^2/\text{Ndf}(\mu^-)$ distribution.

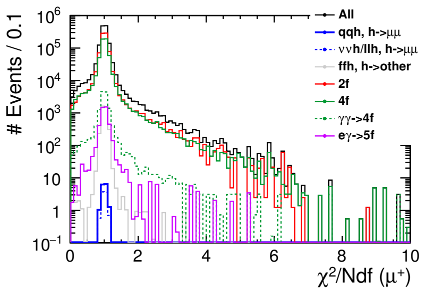

Figure 19: $\chi^2/\text{Ndf}(\mu^+)$ distribution.

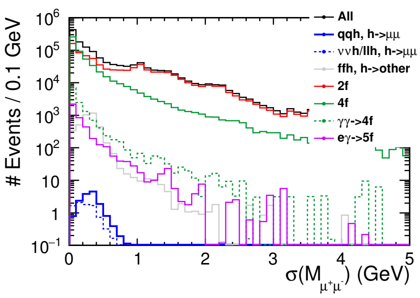

Figure 20: $\sigma(M_{\mu^+\mu^-})$ distribution.

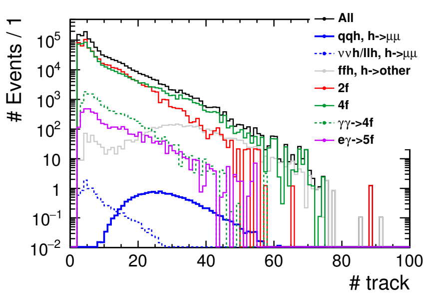

Figure 21: Number of tracks distribution.

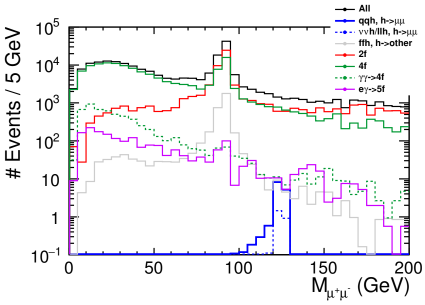

Figure 22: $M_{\mu^+\mu^-}$ distribution.

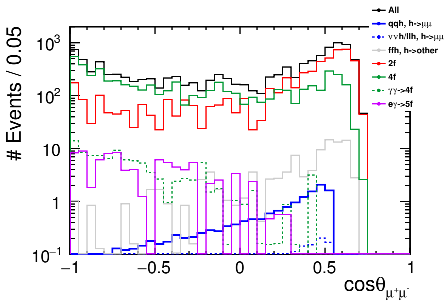

Figure 23: $\cos\theta_{\mu^+\mu^-}$ distribution.

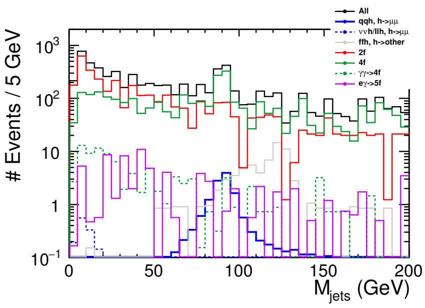

Figure 24: M_{jets} distribution.

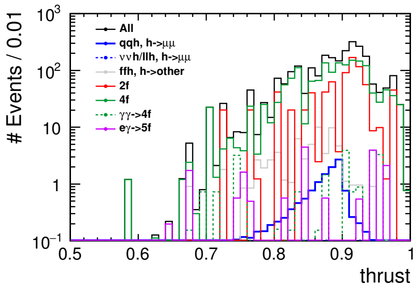

Figure 25: Thrust distribution.

The next table shows the cut table at the precuts.

Table 2: Cut table at the precuts.

	qqh $h \to \mu\mu$	$\nu\nu h$+$\ell\ell h$ $h \to \mu\mu$	ffh $h \to$ other	2f	4f	$\gamma\gamma \to$ 4f	5f
No cut	16.45	12.19	1.274×10^5	2.820×10^7	1.744×10^7	3.356×10^5	1.472×10^5
# $\mu^\pm$	15.29	10.56	3843.84	9.802×10^5	6.168×10^5	1.472×10^4	4532.72
# jet	15.29	8.79	3810.90	8.143×10^5	5.702×10^5	1.394×10^4	4328.89
χ^2/Ndf	15.24	8.75	3797.25	7.830×10^5	5.407×10^5	1.309×10^4	4173.92
$\sigma(M_{\mu\mu})$	14.96	8.61	3736.79	5.322×10^5	5.076×10^5	1.268×10^4	4062.08
# tracks	14.95	2.67	3509.83	1.555×10^5	1.482×10^5	5716.82	1900.04
$M_{\mu\mu}$	14.52	2.58	101.74	5516.61	5475.96	102.26	88.89
$\cos\theta_{\mu\mu}$	14.51	2.58	71.17	3525.66	5039.28	102.26	88.89
M_{jets}	12.88	0.45	63.57	771.66	1603.05	21.79	16.83
thrust	12.82	0.45	63.57	715.40	1468.32	18.49	14.71

3.3 Analysis — TMVA

After precuts, I performed TMVA (BDTG) analysis. I used following 7 variables.

- E_{vis}、thrust、$\cos\theta_{\text{thrust}}$
- $M_{\mu\mu}$
- charge * $\cos\theta_{\mu^+}$、charge * $\cos\theta_{\mu^-}$、$E_{\text{subleading}}$

The following figures show the distributions of each variable.

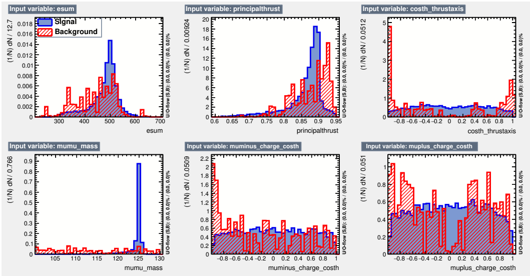

Figure 26: Parameter distribution 1.

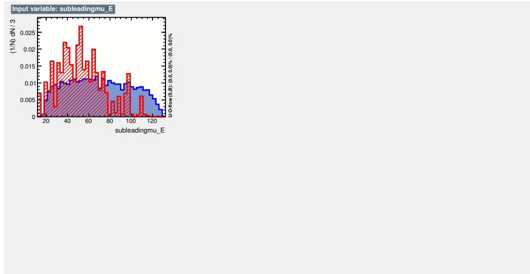

Figure 27: Parameter distribution 2.

The following figures show the results of TMVA analysis.

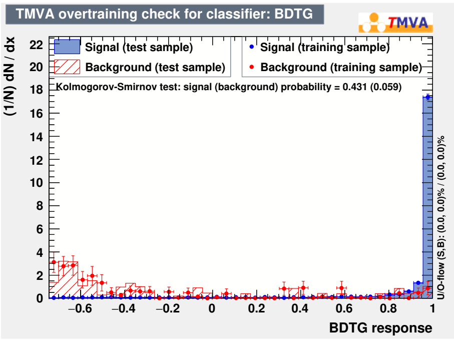

Figure 28: BDTG output distribution.

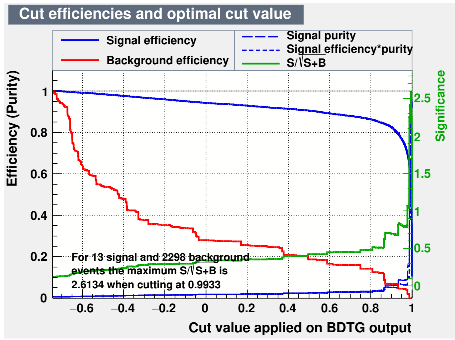

Figure 29: Significance distribution.

From this analysis, I obtained $N_{\text{sig}} = 7.20$ and $N_{\text{bkg}} = 0.39$, gives the signal significance of 2.6, also corresponds to the precision $\dfrac{\Delta(\sigma \times \text{BR})}{(\sigma \times \text{BR})} = 38\%$. The ideal (100% signal efficiency and no backgrounds) precision is 25%, this result is factor 1.5 from ideal. Of course we should not forget about the problem of limited MC statistics.

4 $e^+e^- \to \nu\bar{\nu}h$

4.1 Event Reconstruction

The procedure of event reconstruction and its parameters are the same as written in Ref. [4]. However, I found a mistake in Ref. [4]. I put the MVA cut value of 0.5 for electrons at that time. In this note it is set as 2.

4.2 Analysis — precuts

I applied following cuts as the precuts:

- exactly one μ^+ and one μ^-
- $\chi^2/\text{Ndf}(\mu^\pm) < 1.5$
- $\sigma(M_{\mu\mu}) < 1$ GeV
- $100 < M_{\mu\mu} < 130$ GeV
- $\cos\theta_{\mu\mu} < 0.55$
- $N_{P_t > 5\text{GeV}} \leq 1$

- $125 < E_{\mathrm{vis}} < 320$ GeV
- $P_t > 5$ GeV
- $|\cos\theta_{\mathrm{miss}}| < 0.99$

The 2nd and 3rd cuts were for selecting only well-measured muons, 4th to 7th cuts were for selecting signal-like events, and 8th and 9th cuts were for rejecting some 2f/4f backgrounds. The difference from Ref. [4] is two: removed innermost hit and made the cuts for E_{vis} and θ_{miss} tighter. The following figures show the distributions of each variable.

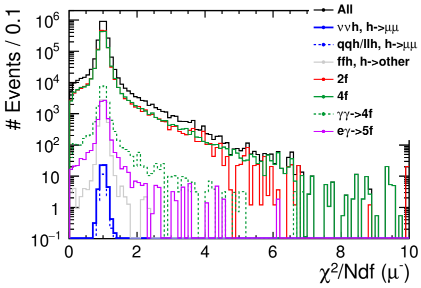

Figure 30: $\chi^2/\mathrm{Ndf}(\mu^-)$ distribution.

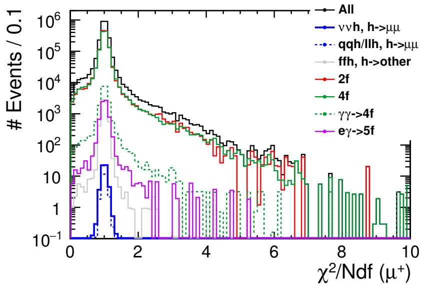

Figure 31: $\chi^2/\mathrm{Ndf}(\mu^+)$ distribution.

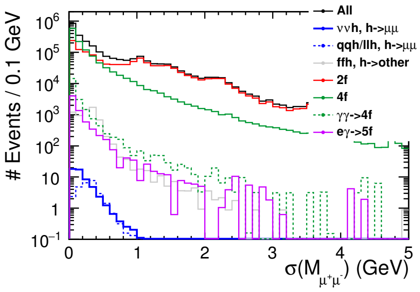

Figure 32: $\sigma(M_{\mu^+\mu^-})$ distribution.

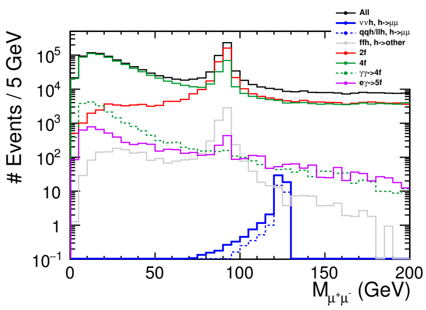

Figure 33: $M_{\mu^+\mu^-}$ distribution.

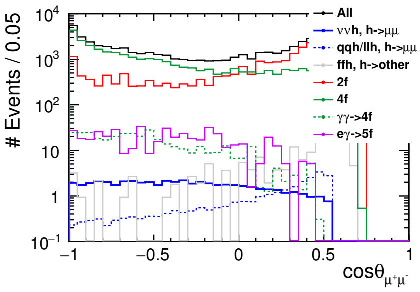

Figure 34: $\cos\theta_{\mu^+\mu^-}$ distribution.

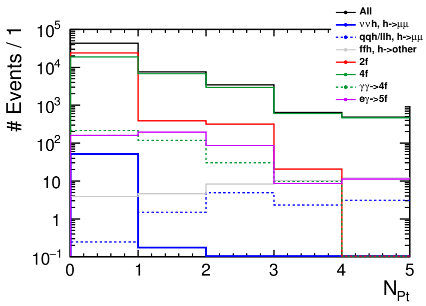

Figure 35: $N_{P_t>5\mathrm{GeV}}$ distribution.

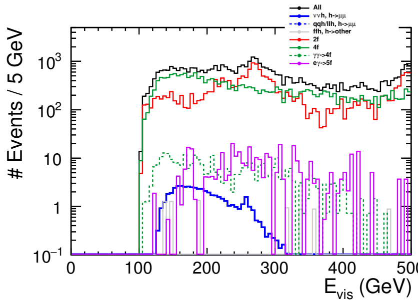

Figure 36: E_{vis} distribution.

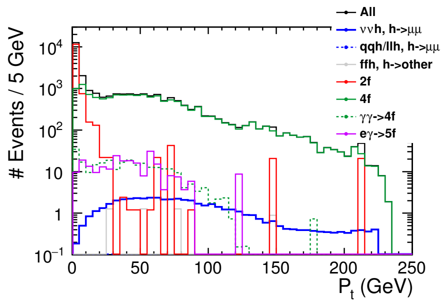

Figure 37: P_t distribution.

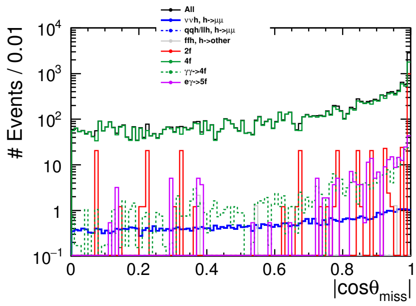

Figure 38: $\cos\theta_{\mathrm{miss}}$ distribution.

The next table shows the cut table at the precuts.

Table 3: 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	2.231×10^5
# $\mu^{\pm}$	54.82	27.72	6553.83	1.314×10^6	1.262×10^6	2.227×10^4	7206.44
χ^2/Ndf	54.51	27.59	6525.51	1.261×10^6	1.208×10^6	2.118×10^4	6978.30
$\sigma(M_{\mu\mu})$	53.84	27.10	6434.58	8.171×10^5	1.154×10^6	2.078×10^4	6844.43
$M_{\mu\mu}$	52.23	26.37	164.85	3.879×10^4	3.238×10^4	373.65	472.07
$\cos\theta_{\mu\mu}$	52.22	26.33	117.99	2.477×10^4	3.093×10^4	373.65	472.07
N_{P_t}	52.19	1.74	8.44	2.444×10^4	2.559×10^4	330.82	355.34
E_{vis}	51.44	0.19	4.85	1.278×10^4	1.435×10^4	270.32	244.01
P_t	51.25	0.11	4.85	1193.04	1.336×10^4	235.91	234.35
$\cos\theta_{\mathrm{miss}}$	50.22	0.08	4.85	208.25	1.156×10^4	212.17	190.87

Even I applied tighter cuts to E_{vis} and $\cos\theta_{\mathrm{miss}}$ from Ref [4], the number of signal events are increased, and most of background events are reduced. Therefore, the innermost hit cut was “bad” cut. 4f and $\gamma\gamma \to$ 4f processes are increased, but I think this is the effect of additional MC samples.

4.3 Analysis — TMVA

After precuts, I performed TMVA(BDTG) analysis. I used following 8 variables

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

The following figures show the distributions of each variable.

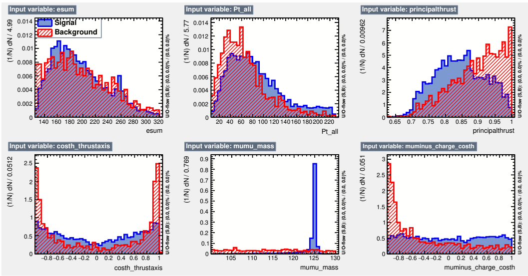

Figure 39: Parameter distribution 1.

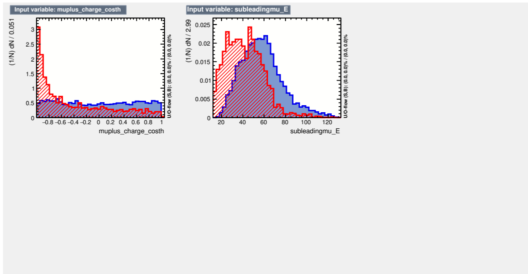

Figure 40: Parameter distribution 2.

The following 2 figures show the result of TMVA analysis.

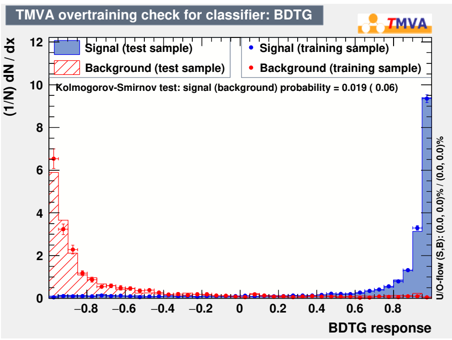

Figure 41: BDTG output distribution.

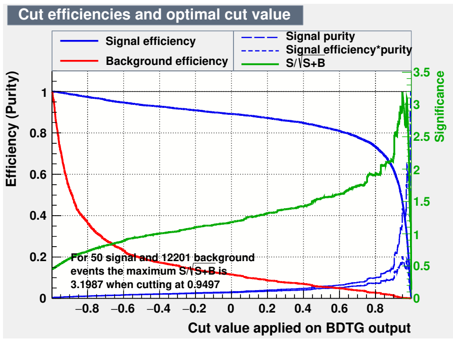

Figure 42: Significance distribution.

From this analysis, I obtained $N_{\rm sig} = 23.54$ and $N_{\rm bkg} = 30.62$, gives the signal significance of 3.2, also corresponds to the precision $\dfrac{\Delta(\sigma \times {\rm BR})}{(\sigma \times {\rm BR})} = 31\%$. The ideal (100% signal efficiency and no backgrounds) precision is 13%, this result is factor 2.4 from ideal. Of course we should not forget about the problem of limited MC statistics. The result was relatively worse than the result written in Ref. [4], but not changed drastically.

5 $e^+e^- \to \nu\bar{\nu}h$ (right-handed)

I can also do analysis with right-handed beam polarization case. However, the precision will be expected as worse because the number of signal is very small.

5.1 Event Reconstruction

The procedure and parameters for event reconstruction is completely same as written in section 4.1.

5.2 Analysis — precuts

I applied same precuts as written in section 4.2., except following one:

- $125 < E_{\rm vis} < 320$ GeV $\to$ $125 < E_{\rm vis} < 380$ GeV

The following figures show the distributions of each variable.

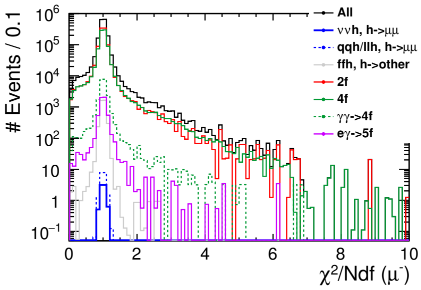

Figure 43: $\chi^2/\mathrm{Ndf}(\mu^-)$ distribution.

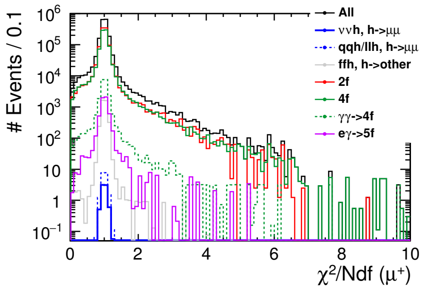

Figure 44: $\chi^2/\mathrm{Ndf}(\mu^+)$ distribution.

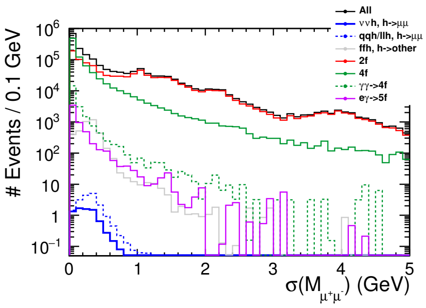

Figure 45: $\sigma(M_{\mu^+\mu^-})$ distribution.

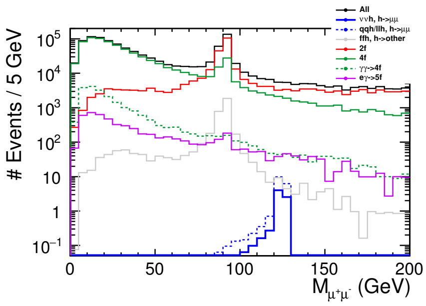

Figure 46: $M_{\mu^+\mu^-}$ distribution.

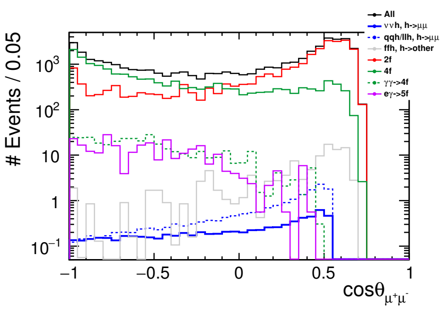

Figure 47: $\cos\theta_{\mu^+\mu^-}$ distribution.

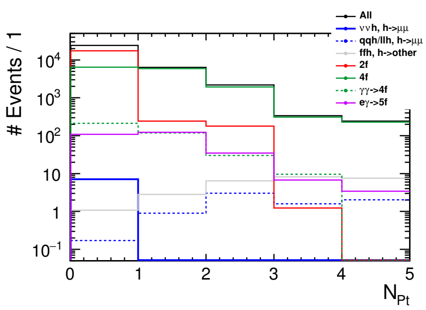

Figure 48: $N_{P_t>5\mathrm{GeV}}$ distribution.

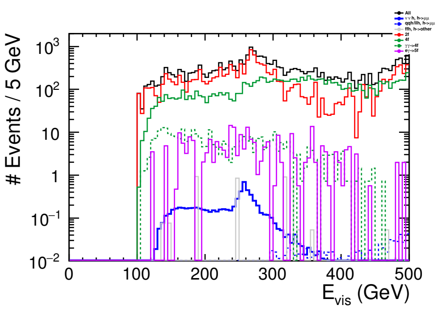

Figure 49: E_{vis} distribution.

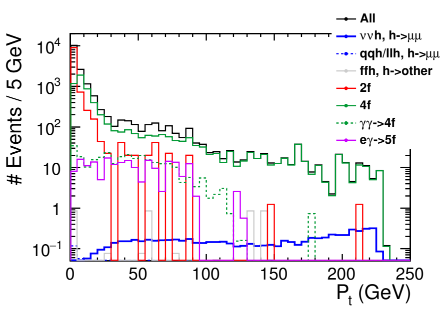

Figure 50: P_t distribution.

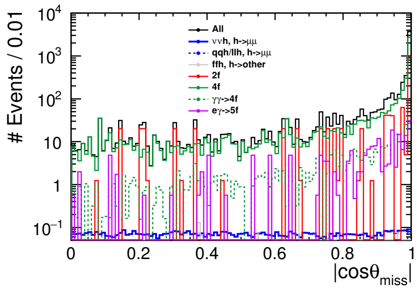

Figure 51: $\cos\theta_{\text{miss}}$ distribution.

The next table shows the cut table at the precuts.

Table 4: 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	7.93	20.71	1.274×10^5	2.820×10^7	1.744×10^7	3.356×10^5	1.472×10^5
$\#\ \mu^\pm$	7.48	18.38	3870.91	9.847×10^5	8.587×10^5	2.227×10^4	5773.28
χ^2/Ndf	7.44	18.32	3855.31	9.458×10^5	8.193×10^5	2.118×10^4	5590.78
$\sigma(M_{\mu\mu})$	7.33	18.00	3794.77	8.291×10^5	7.845×10^5	2.078×10^4	5478.94
$M_{\mu\mu}$	7.11	17.44	107.34	2.670×10^4	1.603×10^4	373.65	202.06
$\cos\theta_{\mu\mu}$	7.11	17.43	76.56	1.788×10^4	1.533×10^4	373.65	202.06
N_{P_t}	7.10	1.07	3.89	1.770×10^4	1.233×10^4	330.82	231.76
E_{vis}	7.05	0.32	3.79	1.043×10^4	5843.63	299.35	203.90
P_t	7.03	0.20	2.94	1392.60	4661.13	264.94	195.81
$\cos\theta_{\text{miss}}$	6.95	0.11	2.94	442.29	1959.48	237.98	164.98

5.3 Analysis — TMVA

After precuts, I used TMVA(BDTG) as a tool. I used 8 variables as following:

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

The following figures show the distributions of each variable.

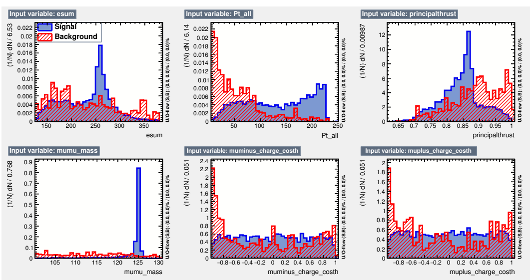

Figure 52: Parameter distribution 1.

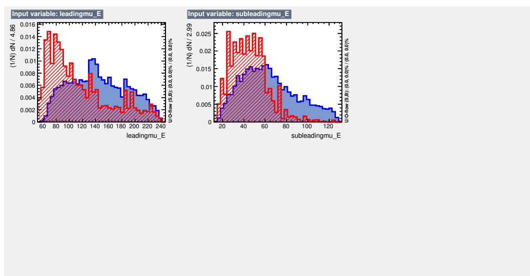

Figure 53: Parameter distribution 2.

The following 2 figures show the result of TMVA analysis.

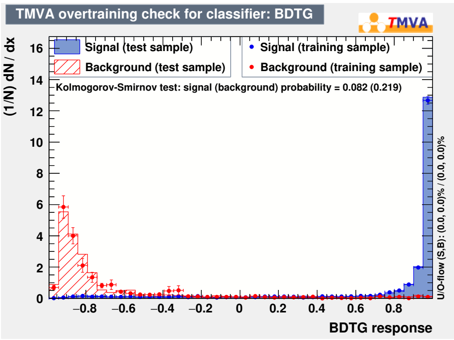

Figure 54: BDTG output distribution.

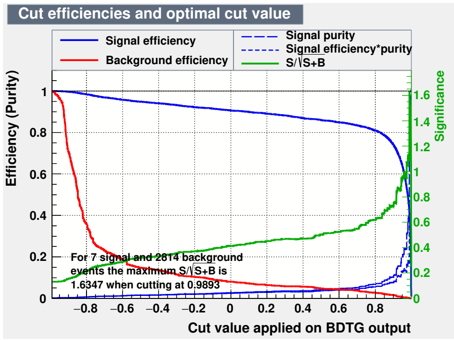

Figure 55: Significance distribution.

From this analysis, I obtained $N_{\text{sig}} = 2.90$ and $N_{\text{bkg}} = 0.24$, gives the signal significance of 1.6, also corresponds to the precision $\dfrac{\Delta(\sigma \times \text{BR})}{(\sigma \times \text{BR})} = 61\%$. The ideal (100% signal efficiency and no backgrounds) precision is 36%, this result is factor 1.7 from ideal. Of course we should not forget about the problem of limited MC statistics.

6 Summary and Prospects

I provided the preliminary results of $e^+e^- \to q\bar{q}h$ mode at 500 GeV for the first time. The precision with left(right)-handed beam polarization was estimated to be $\dfrac{\Delta(\sigma \times \text{BR})}{(\sigma \times \text{BR})} = 29\%(38\%)$. I also fixed bug in my analysis of $e^+e^- \to \nu\bar{\nu}h$ mode. The precision of this process with left(right)-handed beam polarization was estimated to be $\dfrac{\Delta(\sigma \times \text{BR})}{(\sigma \times \text{BR})} = 31\%(61\%)$.

The remaining problems are:

- FSR study.
- IsolatedLeptonTagger checks E_{yoke}. If we require the number of muons as the cut, all SGV samples ($\gamma\gamma \to$ 2f and $e\gamma \to$ 3f) are removed. How to handle this?
- How to understand and apply re-weighting?
- Analysis at 250 GeV case.

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

[5] Junping Tian, Claude Dürig "isolated lepton finder"

`https://agenda.linearcollider.org/event/6787/contributions/33415/`

`attachments/27509/41775/IsoLep_HLRec2016.pdf`