An analysis of $h \to \mu^+\mu^-$ mode at the center-of-mass energy of 500 GeV ILC — part 6

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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 sixth series of note [1–5].

[1]Release note

- 2017/5/22 release
- 2017/5/23 typo fixed

1 Introduction

In this note, I will write a bit modified analysis than Ref. [5]. Most of reconstruction is completely same as written in Ref. [5]. So I will skip writting if the contents are the same.

2 $e^+e^- \to q\bar{q}h$ (left-handed)

2.1 Analysis — precuts

I applied following cuts as precuts:

- exactly one μ^+ and one μ^-
- $0.5 < \chi^2/\mathrm{Ndf}(\mu^\pm) < 1.5$
- $\sigma(M_{\mu\mu}) < 1$ GeV
- $100 < M_{\mu\mu} < 130$ GeV
- $\cos\theta_{\mu\mu} < 0.55$
- number of jets is non-zero
- number of tracks should be grater or equal to 8
- $60 < M_{\mathrm{jets}} < 180$ GeV
- thrust < 0.95

The 1st - 5th cuts were for muons. The 2nd and 3rd cuts were for selecting only well-measured muons, while others for signal-like events. The 6th - 8th cuts were for jet-related variables, to select signal-like events. The final cut was for rejecting 2f/4f backgrounds.

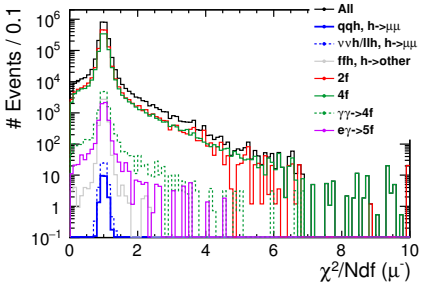

Figure 1: $\chi^2/\mathrm{Ndf}(\mu^-)$ distribution.

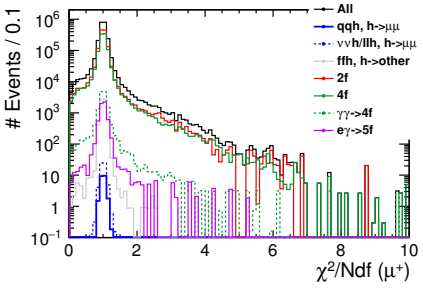

Figure 2: $\chi^2/\mathrm{Ndf}(\mu^+)$ distribution.

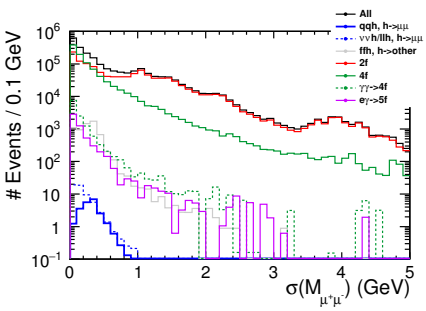

Figure 3: $\sigma(M_{\mu^+\mu^-})$ distribution.

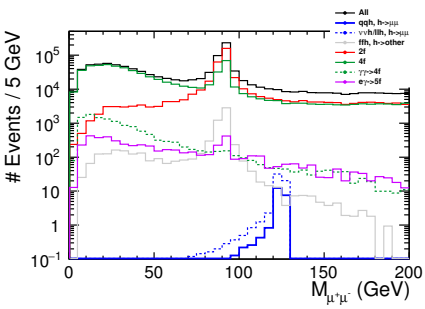

Figure 4: $M_{\mu^+\mu^-}$ distribution.

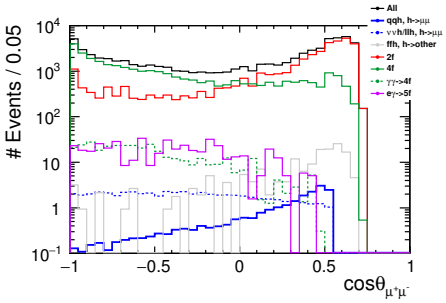

Figure 5: $\cos\theta_{\mu^+\mu^-}$ distribution.

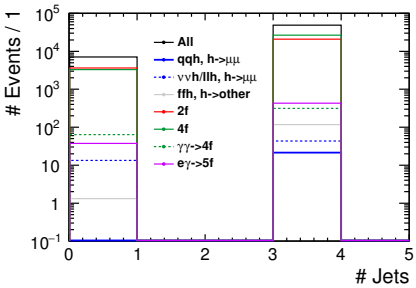

Figure 6: Number of jets distribution.

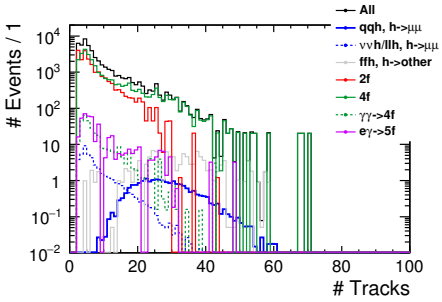

Figure 7: Number of tracks distribution.

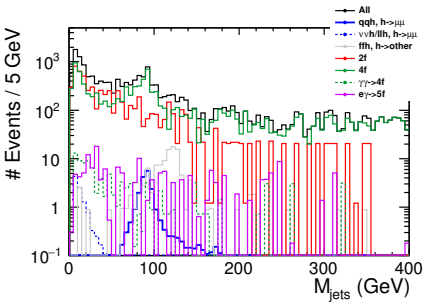

Figure 8: M_{jets} distribution.

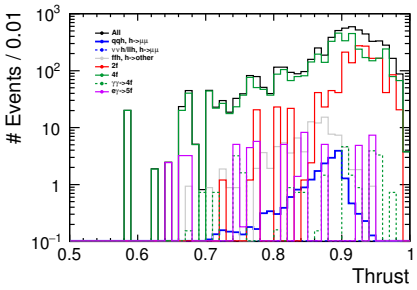

Figure 9: Thrust distribution.

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
χ^2/Ndf	22.59	59.07	6392.52	1.206×10^6	9.251×10^5	1.301×10^4	5526.02
$\sigma(M_{\mu\mu})$	22.19	58.50	6322.01	8.092×10^5	8.845×10^5	1.275×10^4	5415.43
$M_{\mu\mu}$	21.58	56.83	164.95	3.863×10^4	3.153×10^4	377.11	468.14
$\cos\theta_{\mu\mu}$	21.54	56.81	117.99	2.462×10^4	3.008×10^4	377.11	468.14
# jet	21.54	43.45	116.67	2.099×10^4	2.677×10^4	312.92	430.86
# tracks	21.54	13.05	112.87	5953.80	1.025×10^4	98.81	160.22
M_{jets}	19.99	0.83	101.17	1592.94	4049.17	25.42	56.36
thrust	19.90	0.83	101.17	1281.58	3492.73	21.39	56.36

2.2 Analysis — TMVA

I used TMVA (BDTG) as a tool. I used following 6 variables:

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

Next plot shows the distributions of each variable.

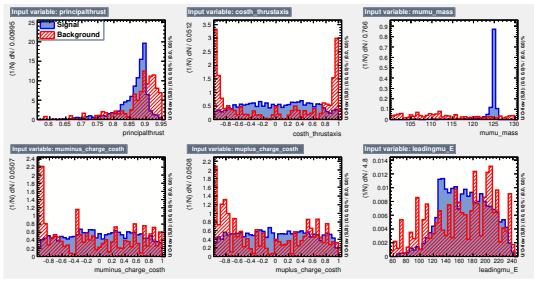

Figure 10: Distribution of each variable.

The next 2 figures show the result of TMVA analysis.

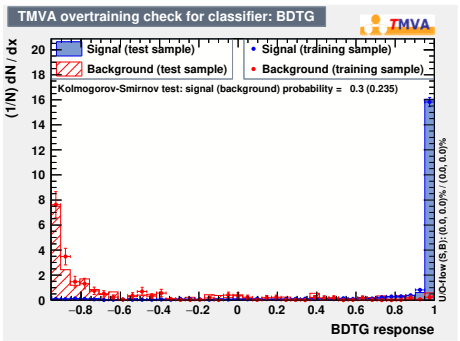

Figure 11: BDTG output distribution.

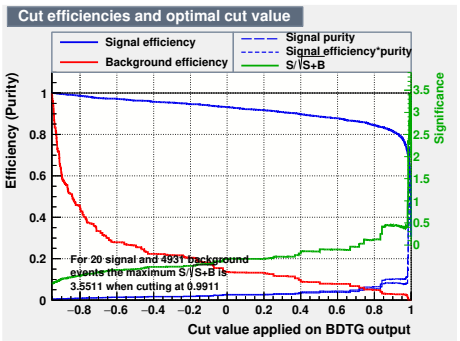

Figure 12: Significance distribution.

From this analysis, I obtained $N_{\text{sig}} = 12.99$ and $N_{\text{bkg}} = 0.39$, gives the signal significance of 3.6, also corresponds to the precision $\dfrac{\Delta(\sigma \times \text{BR})}{(\sigma \times \text{BR})} = 28\%$. The ideal (100% signal efficiency and no backgrounds) precision is 20%, this result is factor 1.4 from ideal.

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

3.1 Analysis — precuts

The precuts are the same as written in section 2.1. The following figures are the distributions of each variable.

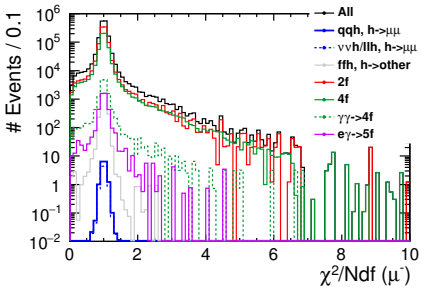

Figure 13: $\chi^2/\text{Ndf}(\mu^-)$ distribution.

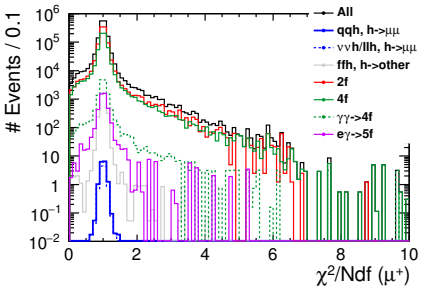

Figure 14: $\chi^2/\text{Ndf}(\mu^+)$ distribution.

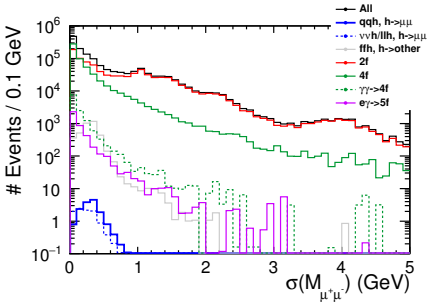

Figure 15: $\sigma(M_{\mu^+\mu^-})$ distribution.

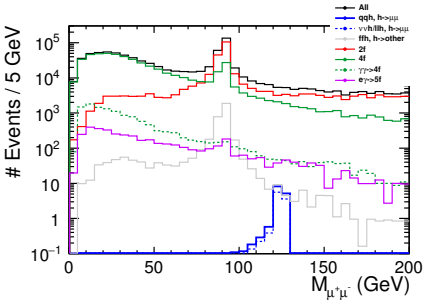

Figure 16: $M_{\mu^+\mu^-}$ distribution.

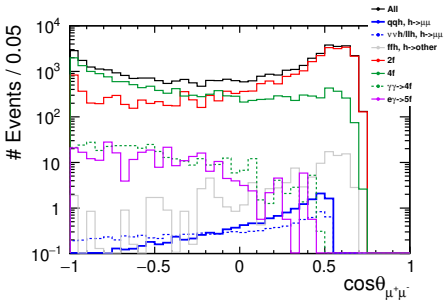

Figure 17: $\cos\theta_{\mu^+\mu^-}$ distribution.

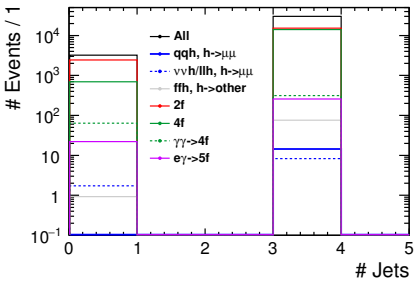

Figure 18: Number of jets distribution.

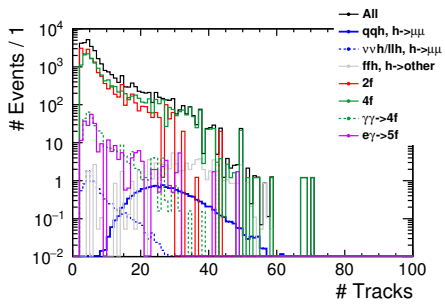

Figure 19: Number of tracks distribution.

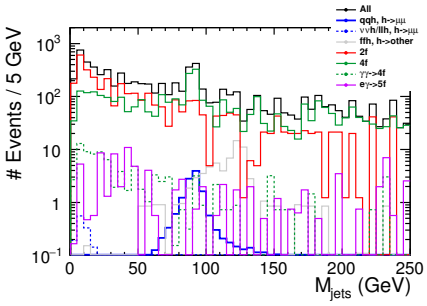

Figure 20: M_{jets} distribution.

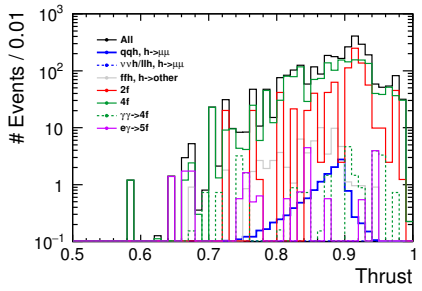

Figure 21: Thrust distribution.

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
χ^2/Ndf	15.19	10.46	3815.54	9.043×10^5	5.552×10^5	1.301×10^4	4226.24
$\sigma(M_{\mu\mu})$	14.94	10.33	3765.55	6.226×10^5	5.294×10^5	1.275×10^4	4141.14
$M_{\mu\mu}$	14.51	10.01	109.04	2.655×10^4	1.556×10^4	377.11	279.94
$\cos\theta_{\mu\mu}$	14.49	10.01	76.56	1.773×10^4	1.486×10^4	377.11	279.94
# jet	14.49	8.29	75.64	1.529×10^4	1.417×10^4	312.92	257.74
# tracks	14.49	2.58	71.17	3464.06	4941.36	98.81	86.77
M_{jets}	13.38	0.49	67.08	898.60	1803.33	25.42	19.00
thrust	13.31	0.49	67.08	838.60	1646.66	21.39	19.00

3.2 Analysis — TMVA

After precuts, I performed TMVA (BDTG) analysis. I used same variables as written in section 2.2, but I re-optimized training parameters. The following figures show the distributions of each variable.

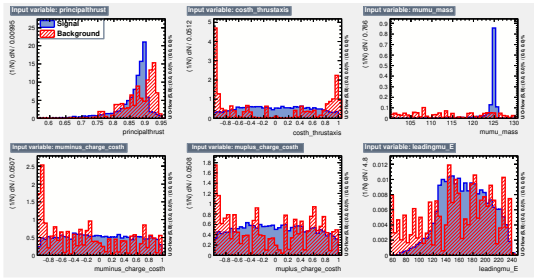

Figure 22: Parameter distribution.

The following figures show the results of TMVA analysis.

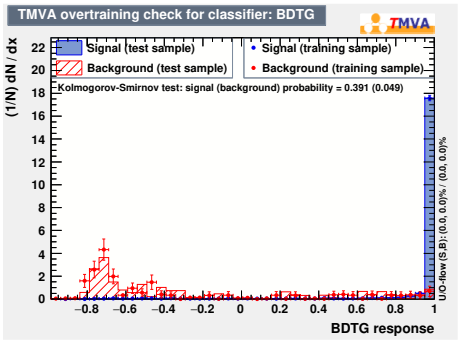

Figure 23: BDTG output distribution.

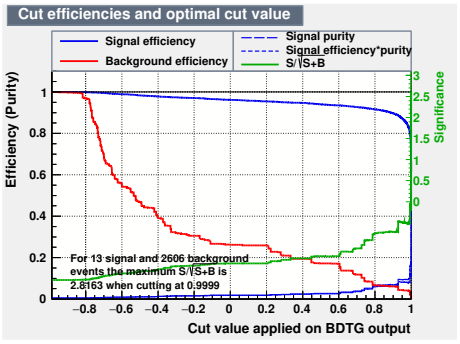

Figure 24: Significance distribution.

From this analysis, I obtained $N_{\rm sig} = 8.18$ and $N_{\rm bkg} = 0.25$, gives the signal significance of 2.8, also corresponds to the precision $\dfrac{\Delta(\sigma \times \mathrm{BR})}{(\sigma \times \mathrm{BR})} = 35\%$. The ideal (100% signal efficiency and no backgrounds) precision is 25%, this result is factor 1.4 from ideal.

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

4.1 Analysis — precuts

I applied following cuts as the precuts:

- exactly one μ^+ and one μ^-
- $0.5 < \chi^2/\mathrm{Ndf}(\mu^\pm) < 1.5$
- $\sigma(M_{\mu\mu}) < 1$ GeV
- $100 < M_{\mu\mu} < 130$ GeV
- $\cos\theta_{\mu\mu} < 0.55$
- $N_{P_t>5\mathrm{GeV}} \leq 1$
- $125 < E_{\rm vis} < 320$ GeV
- $P_t > 5$ GeV
- $|\cos\theta_{\rm miss}| < 0.99$

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 following figures show the distributions of each variable.

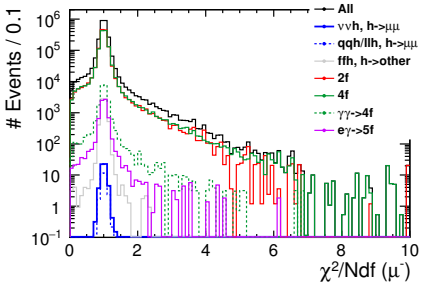

Figure 25: $\chi^2/\mathrm{Ndf}(\mu^-)$ distribution.

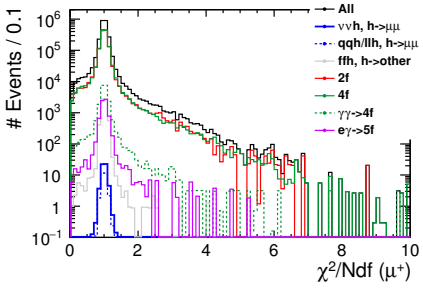

Figure 26: $\chi^2/\mathrm{Ndf}(\mu^+)$ distribution.

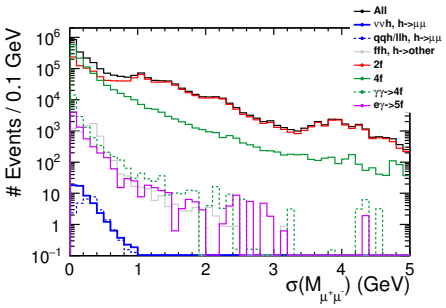

Figure 27: $\sigma(M_{\mu^+\mu^-})$ distribution.

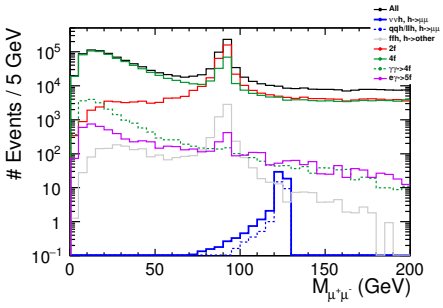

Figure 28: $M_{\mu^+\mu^-}$ distribution.

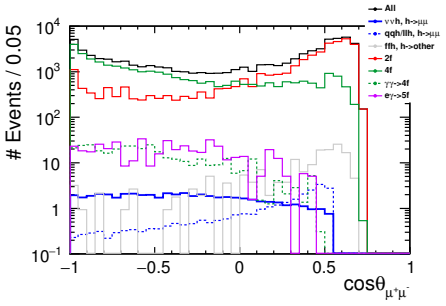

Figure 29: $\cos\theta_{\mu^+\mu^-}$ distribution.

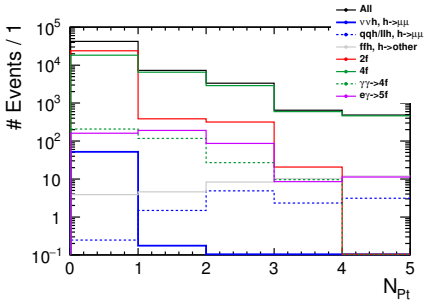

Figure 30: $N_{Pt>5\mathrm{GeV}}$ distribution.

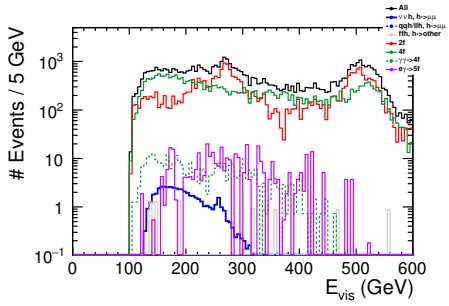

Figure 31: $E_{\rm vis}$ distribution.

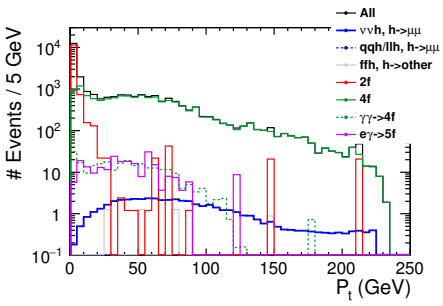

Figure 32: P_t distribution.

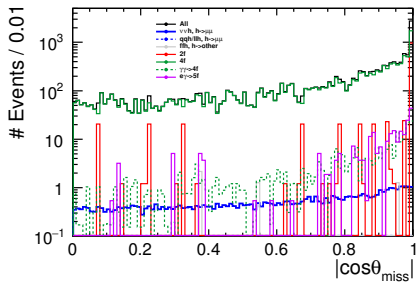

Figure 33: $\cos\theta_{\rm miss}$ distribution.

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	54.21	27.51	6494.56	1.210×10^6	1.157×10^6	2.023×10^4	6775.69
$\sigma(M_{\mu\mu})$	53.68	27.06	6424.05	8.132×10^5	1.116×10^6	1.999×10^4	6665.11
$M_{\mu\mu}$	52.08	26.32	164.85	3.863×10^4	3.152×10^4	364.55	468.14
$\cos\theta_{\mu\mu}$	52.07	26.29	117.99	2.462×10^4	3.007×10^4	364.55	468.14
N_{P_t}	52.03	1.73	8.44	2.428×10^4	2.480×10^4	324.86	351.40
$E_{\rm vis}$	51.29	0.19	4.85	1.267×10^4	1.391×10^4	265.82	240.07
P_t	51.11	0.11	4.85	1172.44	1.298×10^4	234.55	234.35
$\cos\theta_{\rm miss}$	50.07	0.08	4.85	208.25	1.126×10^4	210.81	190.87

4.2 Analysis — TMVA

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

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

The following figures show the distributions of each variable.

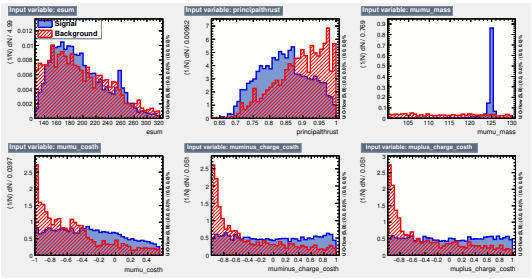

Figure 34: Parameter distribution 1.

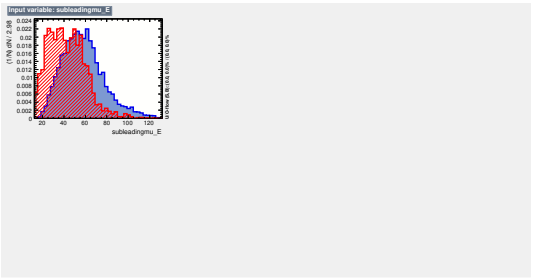

Figure 35: Parameter distribution 2.

The following 2 figures show the result of TMVA analysis.

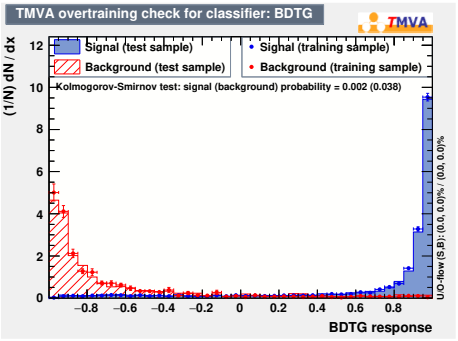

Figure 36: BDTG output distribution.

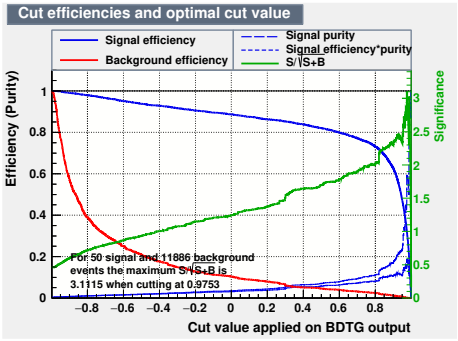

Figure 37: Significance distribution.

From this analysis, I obtained $N_{\text{sig}} = 16.25$ and $N_{\text{bkg}} = 11.63$, gives the signal significance of 3.1, also corresponds to the precision $\dfrac{\Delta(\sigma \times \text{BR})}{(\sigma \times \text{BR})} = 32\%$. The ideal (100% signal efficiency and no backgrounds) precision is 13%, this result is factor 2.5 from ideal.

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

5.1 Analysis — precuts

I applied same precuts as written in section 4.1. The following figures show the distributions of each variable.

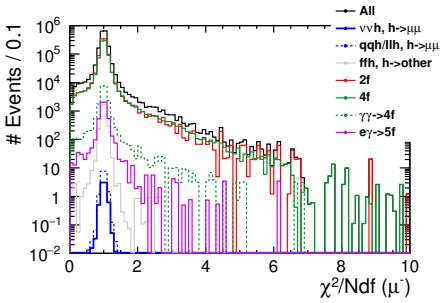

Figure 38: $\chi^2/\text{Ndf}(\mu^-)$ distribution.

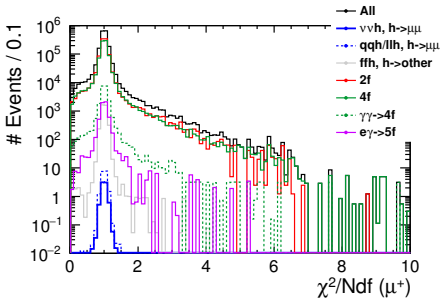

Figure 39: $\chi^2/\text{Ndf}(\mu^+)$ distribution.

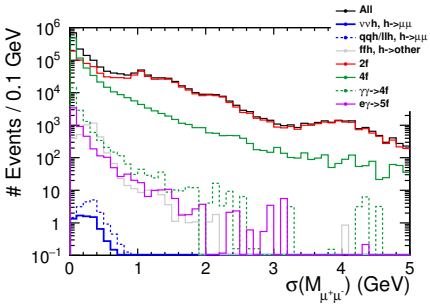

Figure 40: $\sigma(M_{\mu^+\mu^-})$ distribution.

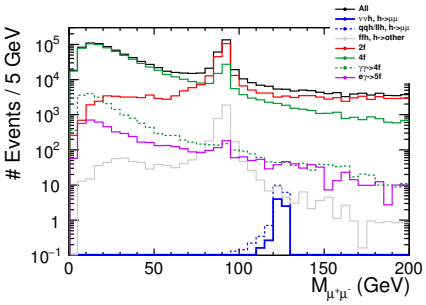

Figure 41: $M_{\mu^+\mu^-}$ distribution.

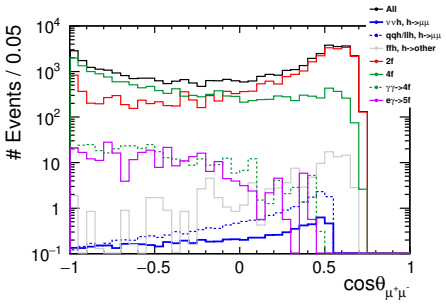

Figure 42: $\cos\theta_{\mu^+\mu^-}$ distribution.

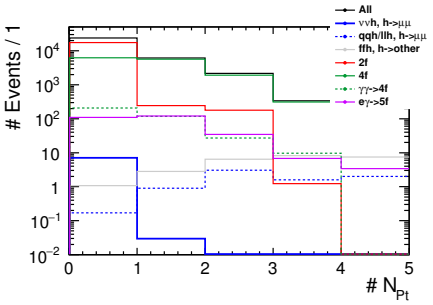

Figure 43: $N_{P_t>5\mathrm{GeV}}$ distribution.

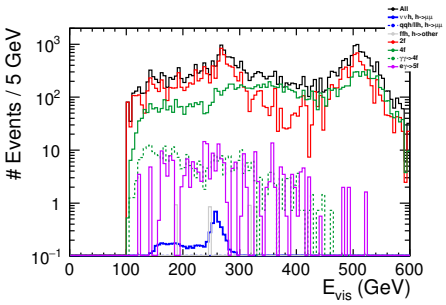

Figure 44: E_{vis} distribution.

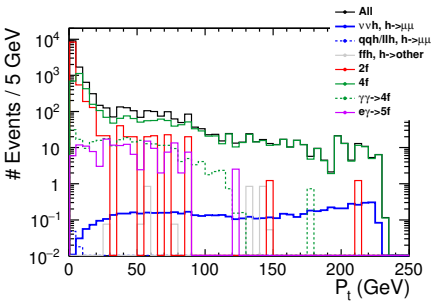

Figure 45: P_t distribution.

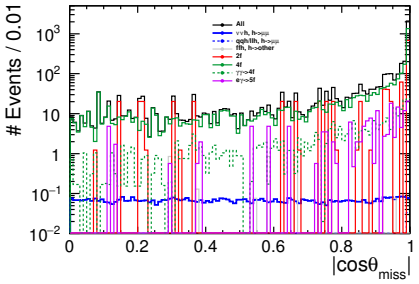

Figure 46: $\cos\theta_{\mathrm{miss}}$ distribution.

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	7.41	18.26	3840.66	9.083×10^5	7.822×10^5	2.023×10^4	5411.67
$\sigma(M_{\mu\mu})$	7.31	17.97	3790.67	6.265×10^5	7.561×10^5	1.999×10^4	5326.57
$M_{\mu\mu}$	7.10	17.42	107.34	2.655×10^4	1.556×10^4	364.55	279.94
$\cos\theta_{\mu\mu}$	7.09	17.40	76.56	1.773×10^4	1.486×10^4	364.55	279.94
N_{P_t}	7.08	1.07	3.89	1.755×10^4	1.189×10^4	324.86	229.64
$E_{\rm vis}$	6.77	0.14	2.83	9359.68	3625.09	265.82	160.85
P_t	6.76	0.09	2.83	1072.68	2937.32	234.55	154.87
$\cos\theta_{\rm miss}$	6.68	0.05	2.83	393.42	1587.83	210.81	134.19

5.2 Analysis — TMVA

After precuts, I used TMVA(BDTG) as a tool. I used same variables as written in section 4.1, but training parameters are optimized. The following figures show the distributions of each variable.

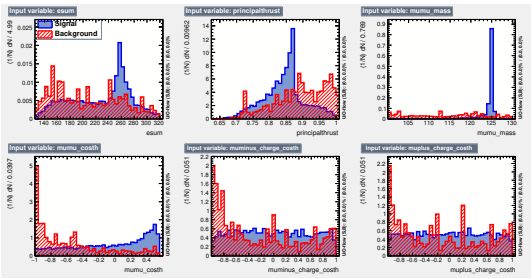

Figure 47: Parameter distribution 1.

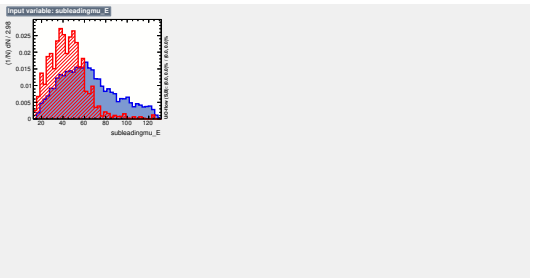

Figure 48: Parameter distribution 2.

The following 2 figures show the result of TMVA analysis.

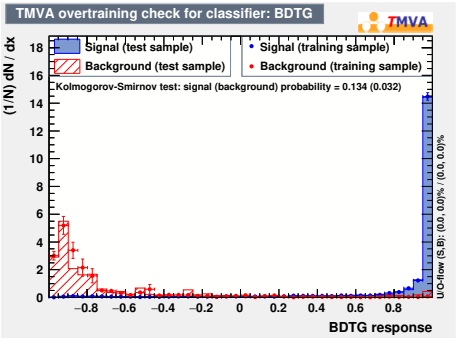

Figure 49: BDTG output distribution.

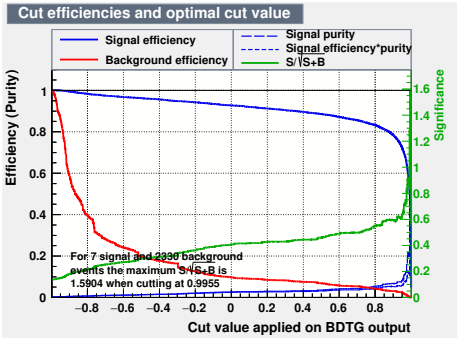

Figure 50: Significance distribution.

From this analysis, I obtained $N_{\rm sig} = 2.75$ and $N_{\rm bkg} = 0.24$, gives the signal significance of 1.6, also corresponds to the precision $\dfrac{\Delta(\sigma \times \mathrm{BR})}{(\sigma \times \mathrm{BR})} = 63\%$. The ideal (100% signal efficiency and no backgrounds) precision is 36%, this result is factor 1.8 from ideal.

6 Summary and Prospects

The results are summrized in next table.

Table 5: The obtained precision $\frac{\Delta(\sigma \times \mathrm{BR})}{(\sigma \times \mathrm{BR})}$ from the analysis.

	$q\bar{q}h$	$\nu\bar{\nu}h$
left-handed	28%	32%
right-handed	35%	63%

The MC statistics is not enough, but I obtained numbers based on real analysis. The combined precision will be 17%. In the HL-LHC with 3000 fb^{-1}, the precision is estimated to be 14%. This is reaching similar value.

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

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

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

`attachments/27509/41775/IsoLep_HLRec2016.pdf`