Updates of $h \to \mu^+\mu^-$ at 500 GeV ILC

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Quick introduction

- This process is selected as one of the physics benchmark process of ILD optimization.

we have agreed on

- ☑ performance of new detector models will be evaluated eventually based on physics performance

process	physics	detector performance	Ecm
H—>cc	BR	c-tag, JER	any
H—>μμ	BR	high P tracking	500 GeV
H—>ττ	BR, CP	τ recon., PID, track separation	250 GeV
H—>bb	M_H, BR	JES, JER, b-tag	500 GeV
H—>invisible Z—>qq	Higgs Portal	JER	250 GeV
eνW—>eνqq	M_W, TGC	JES, JER	500 GeV
tt-bar—>6-jet	top coupling, A_{FB}	b-tag, jet charge	500 GeV
$\chi_1^+\chi_1^-, \chi_2^0\chi_1^0$ near degenerated	natural SUSY	low P tracking, PID	500 GeV
γXX	WIMPs	Photon ER & ES, Hermiticity	500 GeV

**this is just a minimum list

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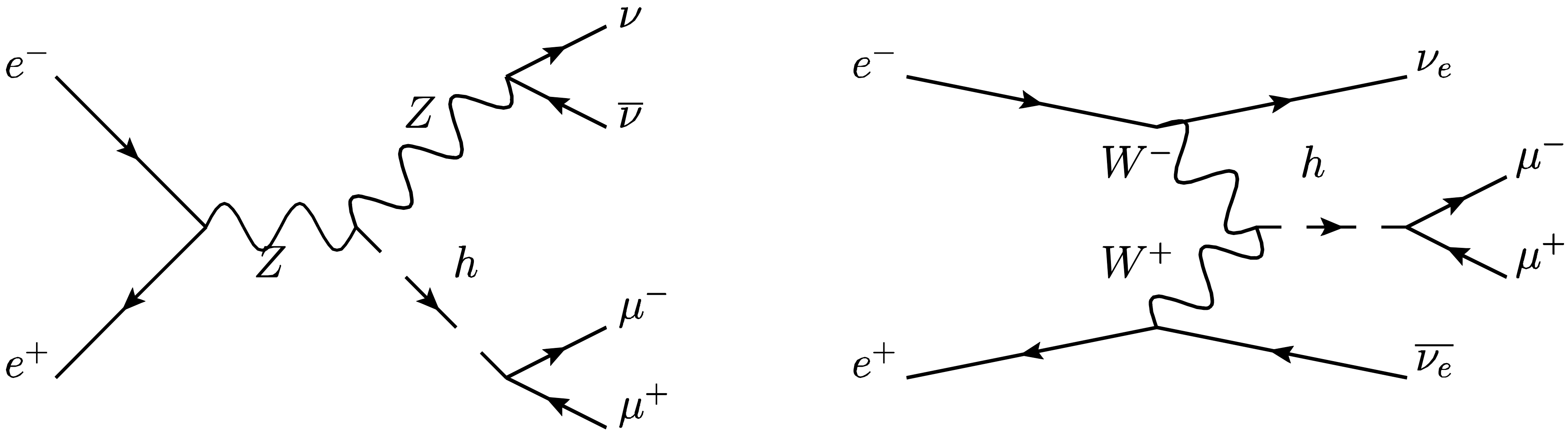
talk by J. Tian
ILD software and optimization workshop
(2016/Feb./22-26)

Signal diagram, Expected # events

signal: $e^+e^- \to \nu\bar{\nu}h, h \to \mu^+\mu^-$



BR($h \to \mu^+\mu^-$) ~ **2.2*10^-4^**

expected # events: **~60**

with 1600 fb^{-1}, $P(e^-, e^+)$ = (-0.8, +0.3) (“H20” scenario)

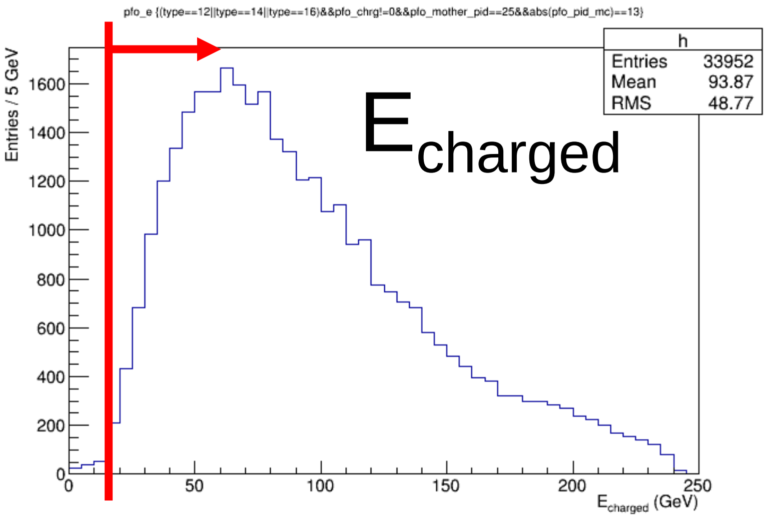
Updates from ECFALC2016

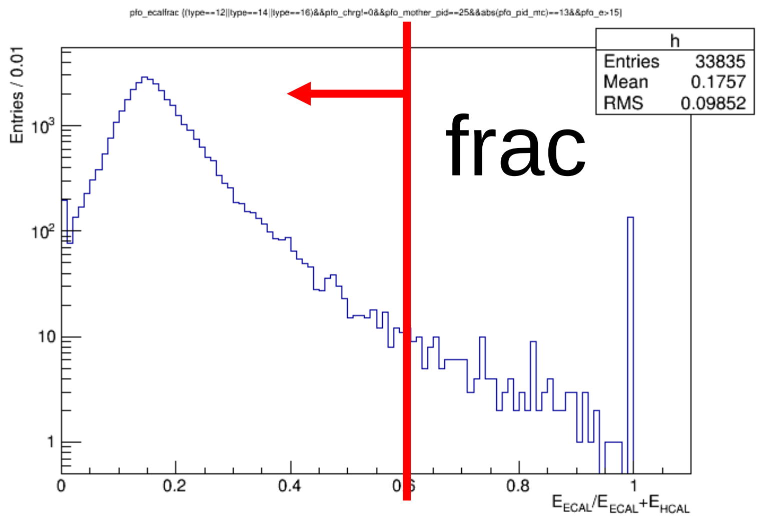
- SGV sample ---> fully-simulated sample
  - generated with DBD configuration using ILCDirac
  - analyzed with ILCSoft v01-17-09
  - many thanks to Akiya
- Apply FSR correction
- Re-weight using $\sigma(M_{\mu^+\mu^-})$ (error of muon pair mass): work in progress

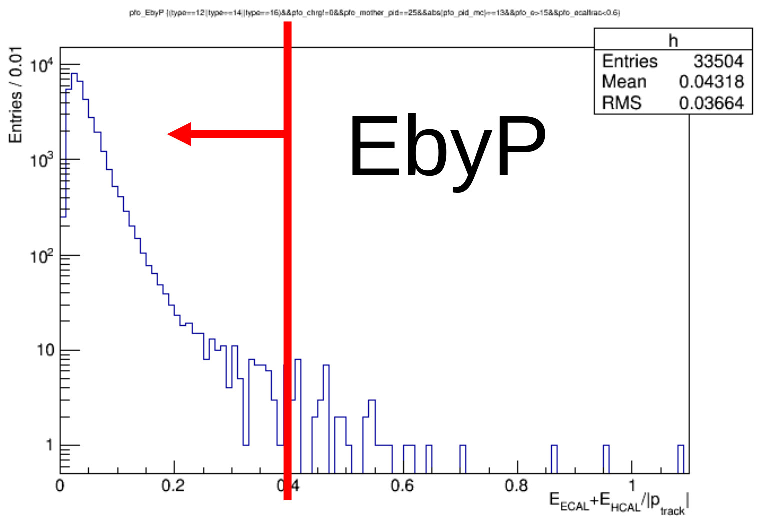
Muon reconstruction for signal

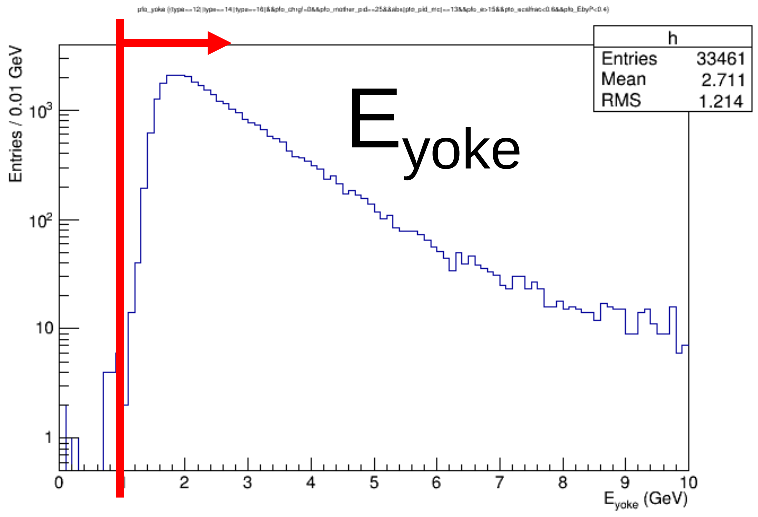
- $E_{charged}$ > 15 GeV
- $E_{ECAL}/(E_{ECAL}+E_{HCAL})$ < 0.6 (frac)
- $(E_{ECAL}+E_{HCAL})/|P_{track}|$ < 0.4 (EbyP)
- E_{yoke} > 1 GeV
- $|d_0/\text{sigma}(d_0)|$ < 5 ($d_0$sig)

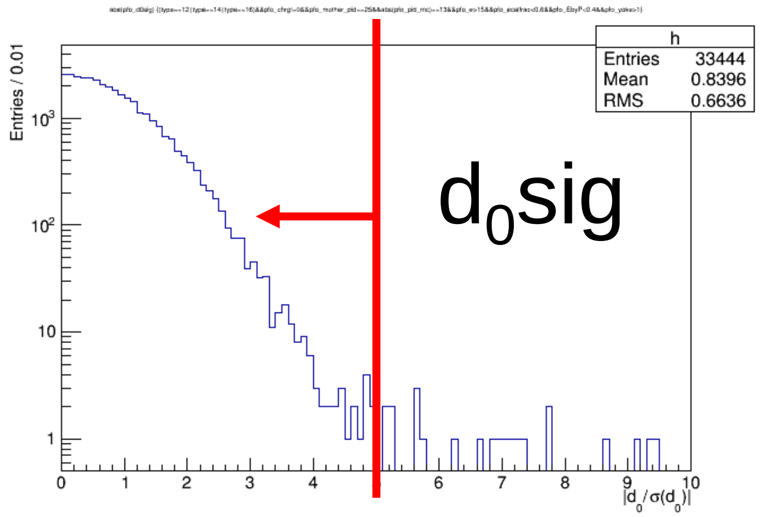
Muon reconstruction for signal





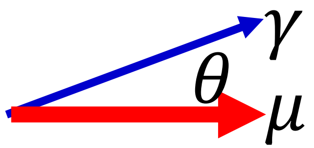






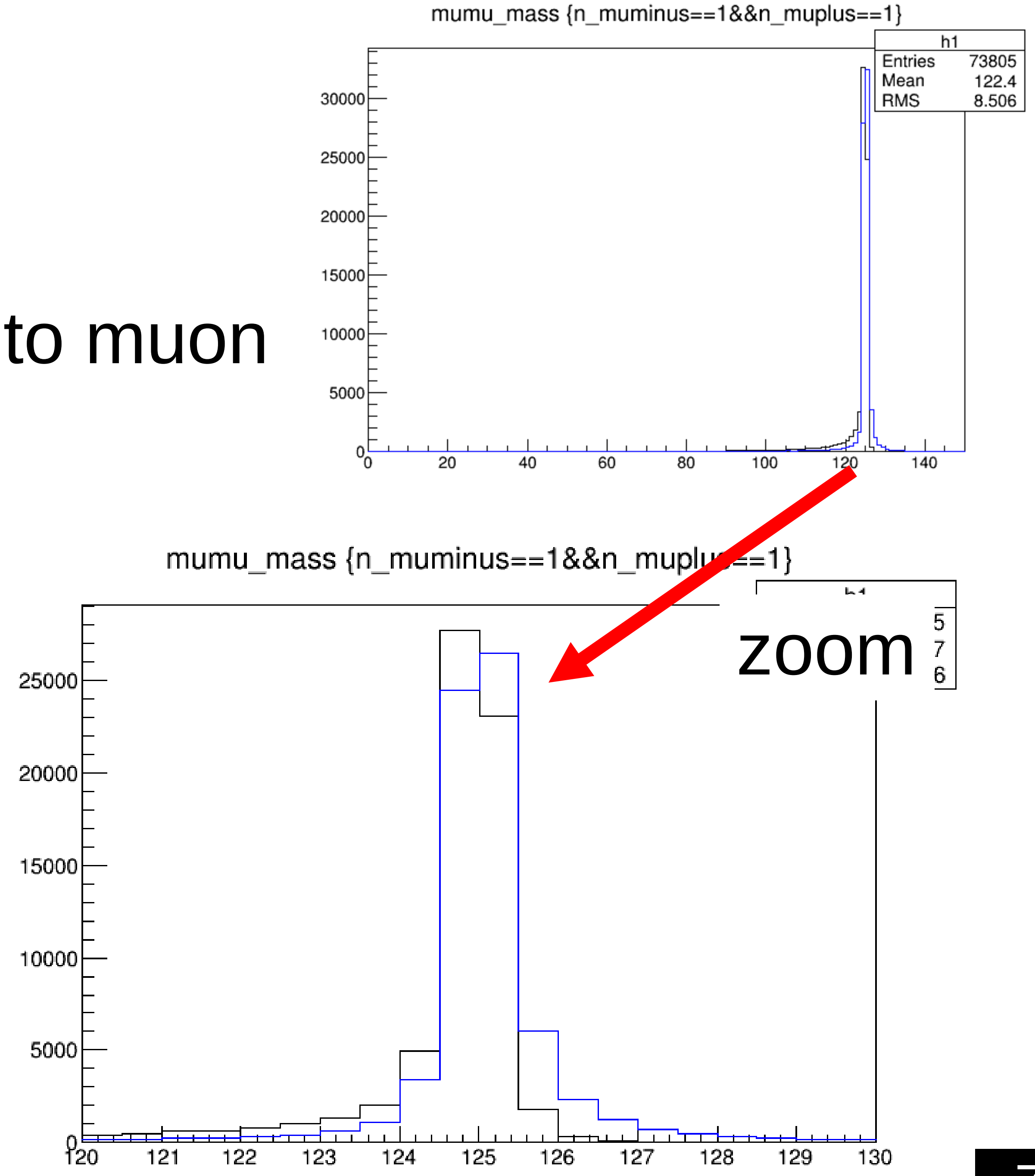
one μ^+ & one μ^-
= 94.6%

FSR recovery



recover range: $\cos\theta > 0.99$

add 4-mom. of neutral particle(s) to muon



MC in $124 < M_{\mu^+\mu^-} < 126$ GeV

(events only one μ^+ & one μ^-)

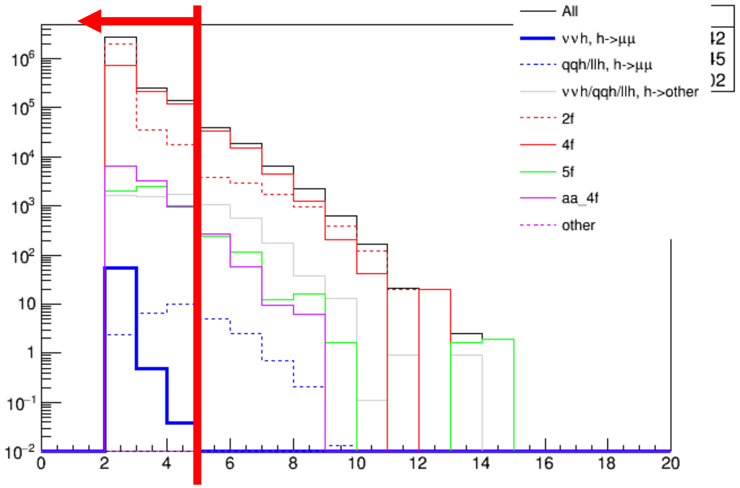
without recovery: 12676

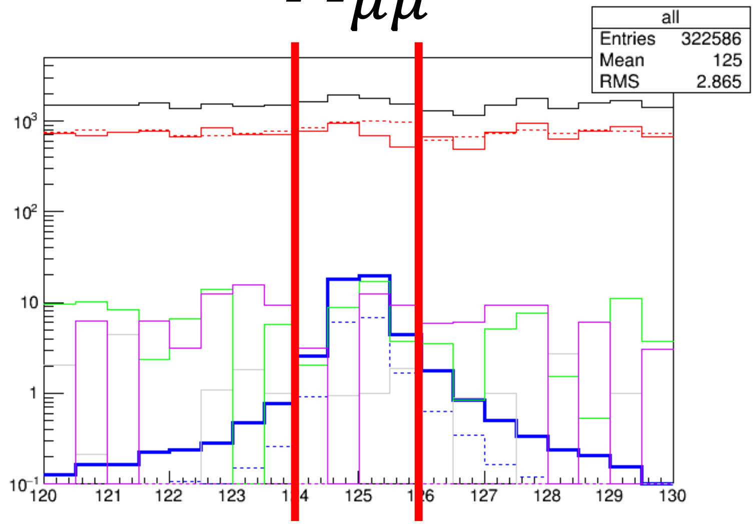
with recovery: 13410

~5.8% improved

Precuts

one μ^+ & one μ^- &
$N^{track}_{E>15\ GeV}$ <= 4 &
$124 < M_{\mu\mu} < 126$ GeV

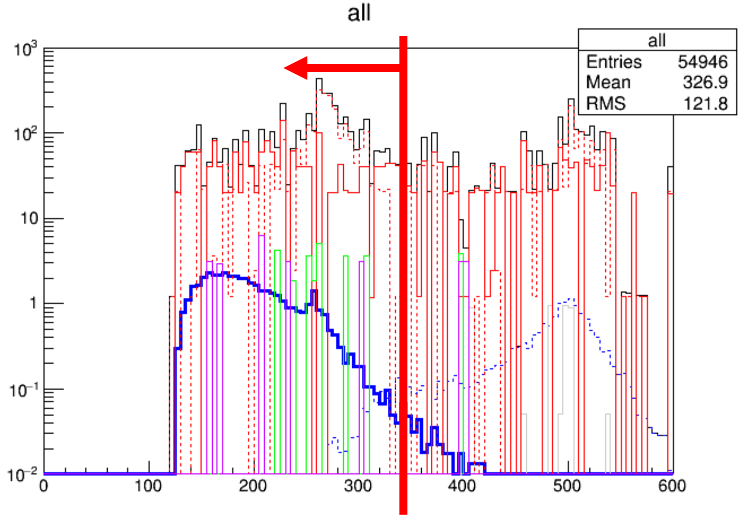




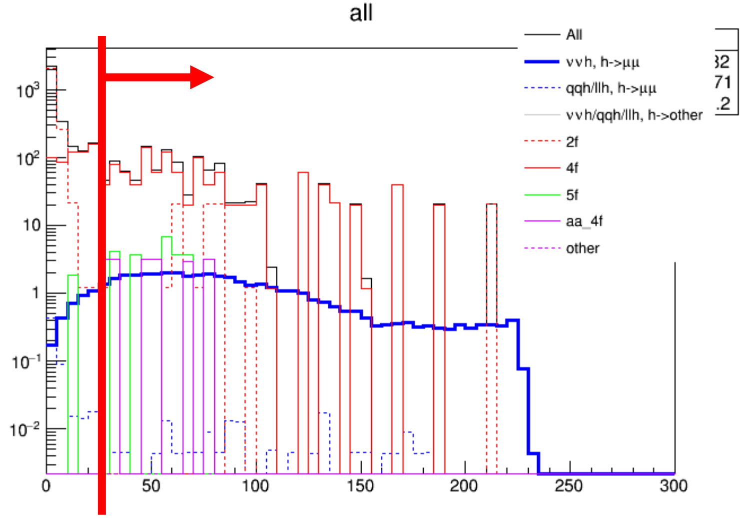
$N^{track}_{E>15\ GeV}$: avoid overlay effects

500 GeV 1600 fb^{-1} left-handed	$\nu\nu h$ $h \to \mu\mu$	qqh & $\ell\ell h$ $h \to \mu\mu$	ffh $h \nrightarrow \mu\mu$	2f	4f	5f	aa_4f
No cut	57.53	31.13	$4.116*10^5$	$4.225*10^7$	$3.808*10^7$	$2.209*10^5$	$3.356*10^5$
# $\mu^\pm$	54.41	27.46	6818.81	$2.025*10^6$	$1.124*10^6$	5979.80	$1.109*10^4$
# N^{track}	54.41	18.92	4920.84	$2.015*10^6$	$1.069*10^6$	5592.42	$1.074*10^4$
$M_{\mu\mu}$	44.70	15.46	3.80	3782.87	2894.26	31.63	24.96

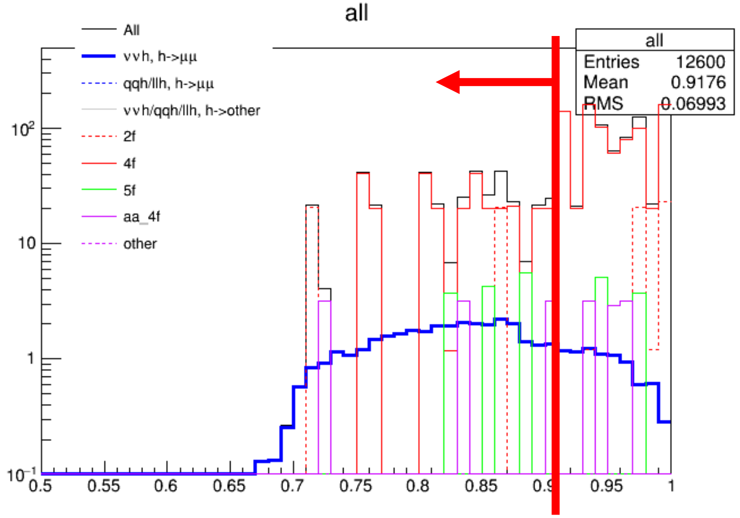
E_{vis}

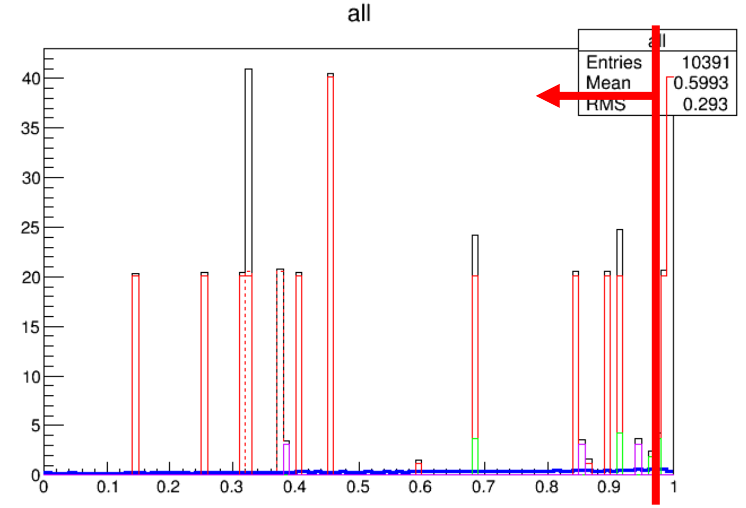


P_t

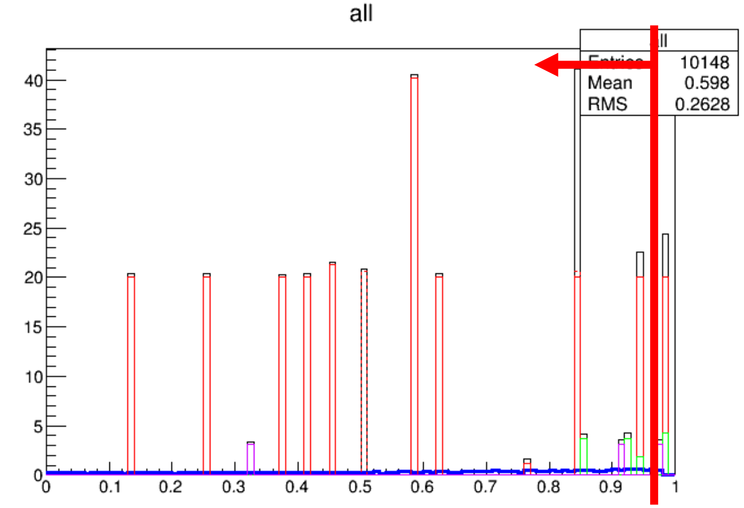


thrust





$\cos\theta_{\mathrm{thrust}}$



$\cos\theta_{\mathrm{miss}}$

$E_{vis} < 335$ GeV
$P_t > 25$ GeV
thrust < 0.91
$|\cos\theta_{\mathrm{thrust}}| < 0.98$
$|\cos\theta_{\mathrm{miss}}| < 0.98$

Cut-based analysis: results

500 GeV 1600 fb^{-1} left-handed	$\nu\nu h$ $h \to \mu\mu$	qqh & $\ell\ell h$ $h \to \mu\mu$	ffh $h \nrightarrow \mu\mu$	2f	4f	5f	aa_4f
precuts	44.70	15.46	3.80	3782.87	2894.26	31.63	24.96
E_{vis}	44.26	0.71	0	2454.88	1721.20	24.10	18.66
P_t	40.95	0.15	0	87.20	1129.30	22.22	18.66
thrust	32.88	0.15	0	41.19	283.65	13.46	9.45
θ_{thrust}	31.86	0.144	0	41.19	223.35	13.46	9.45
θ_{miss}	31.77	0.144	0	41.19	203.26	9.24	9.45

$$\frac{S}{\sqrt{S+B}} = 1.85$$

$$\frac{\Delta(\sigma \times \mathrm{BR})}{(\sigma \times \mathrm{BR})} = 54\%$$

※some weight (= 1600/generated lumi.) for background is high! (~20)

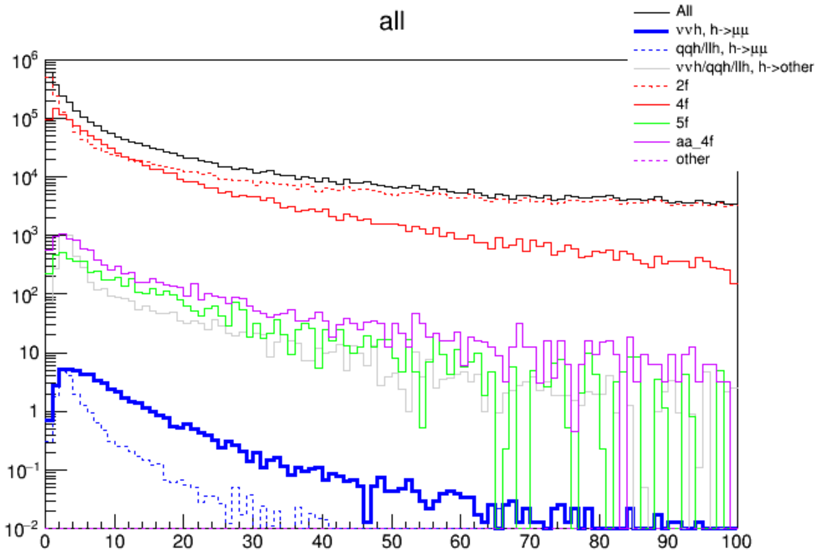
Comparison with SGV

- performed similar analysis using SGV signal samples, and optimized (see backup for detail)
  - FSR correction included (not included in my talk at ECFALC2016)

- obtained precision = **34%**
  - $N^{track}_{E > 15\ GeV}$ cut is changed to N_{track}
  - N_{track} is powerful separation tool in SGV case but not in full case, because of $\gamma\gamma \rightarrow$ hadrons overlay.

Summary & Next Step

- Analyzed SGV case and full case both
  - precision = 54% in full case
  - relatively ~40% worse than SGV case, N_{track} is no longer powerful
- Event-by-event re-weight using $\sigma(M_{\mu^+\mu^-})$
  - sig.: well measured, small σ in M_h region
  - bkg.: badly measured, larger σ than signal
  - re-weighting by $1/\sigma$ would be useful



$1/\sigma$ plot

one μ^+ & one μ^- & $N^{track}_{E > 15\ GeV}$ <= 4

BACKUP SLIDES

Numbers of $h \to \mu^+\mu^-$

We only have extrapolated numbers for 500 GeV ILC.

ref.: ILC operating scenario (arXiv:1506.07830 [hep-ex])

$\int \mathscr{L} dt$ at $\sqrt{s}$	$250\,\mathrm{fb}^{-1}$ at 250 GeV		$330\,\mathrm{fb}^{-1}$ at 350 GeV		$500\,\mathrm{fb}^{-1}$ at 500 GeV		
$P(e^-, e^+)$	(-80%,+30%)						
production	Zh	$\nu\bar{\nu}h$	Zh	$\nu\bar{\nu}h$	Zh	$\nu\bar{\nu}h$	$t\bar{t}h$
decay	$\Delta(\sigma \cdot BR)/(\sigma \cdot BR)$						
$h \to \mu^+\mu^-$ [45]	72%	-	76%	140%	88%	72%	-

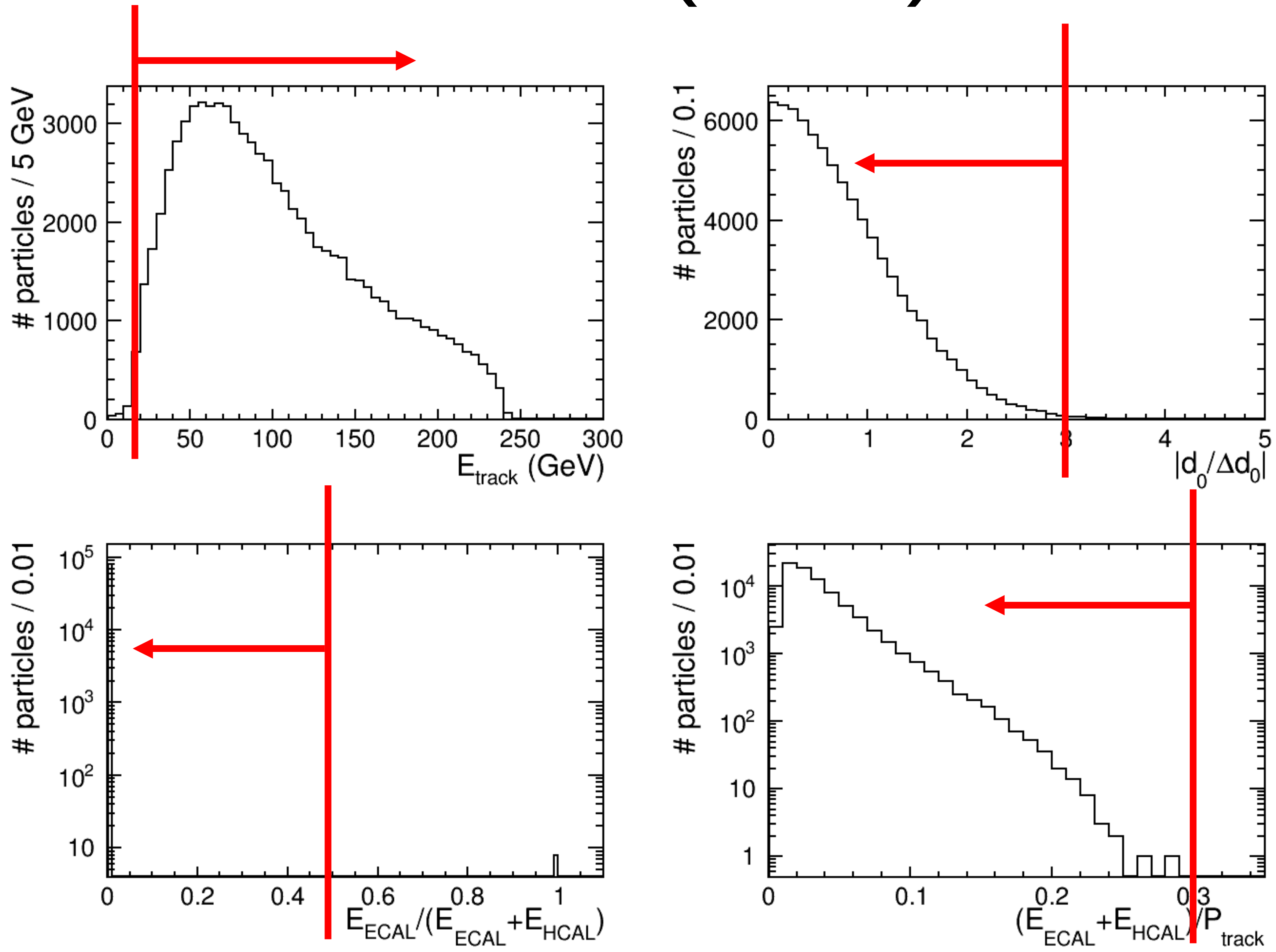
[45] C. Calancha, private communication.

scale to 1600 fb^{-1}:
~40% expected

MC Samples & Analysis Setting (SGV)

- Signal
  - STDHEP files were already generated
  - limited fully-simulated samples, we used SGV-simulated samples instead
  - SGV can be used many different types of detector configurations
    ---> good tool for detector optimization study
- Background
  - DBD samples
    - 2f, 4f (except WW/ZZ-hadronic), 5f, aa_4f, higgs_ffh
- ILCSOFT: v01-17-09

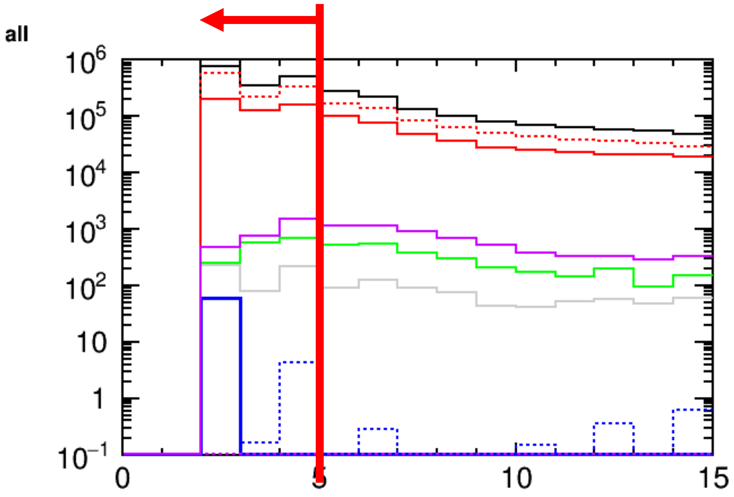
Muon Reconstruction (SGV)



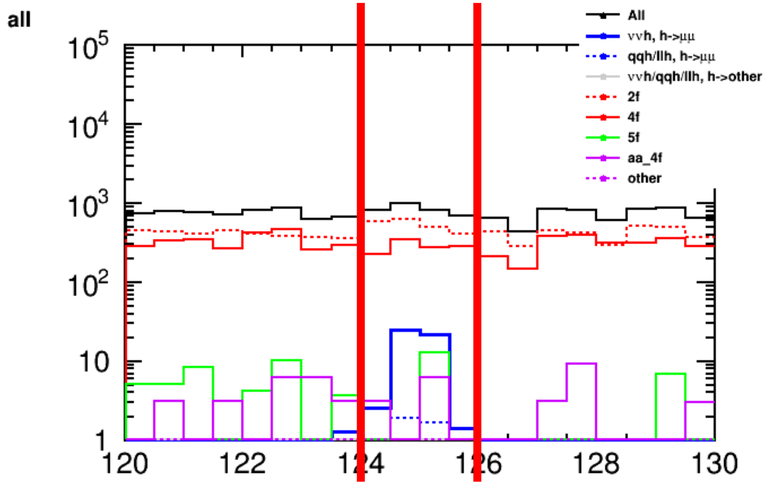
Precuts (SGV)

one μ^+ & one μ^- &
N^{track} <= 4 &
124 < $M_{\mu\mu}$ < 126 GeV

N^{track}



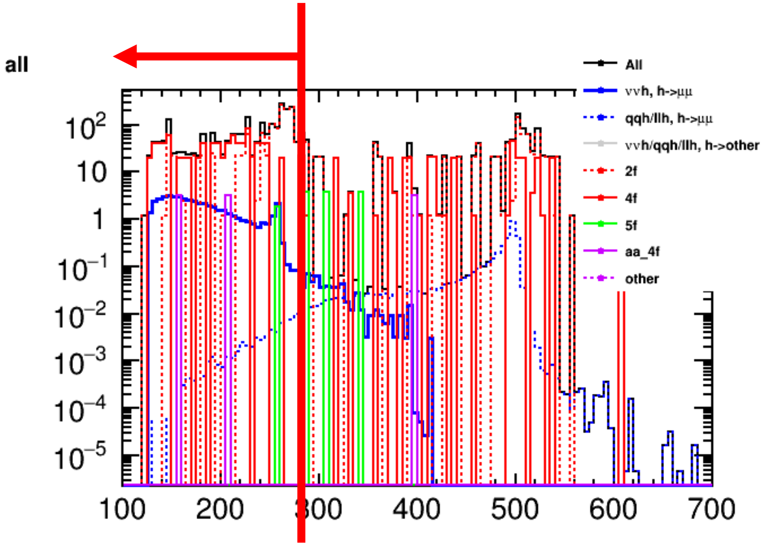
$M_{\mu\mu}$



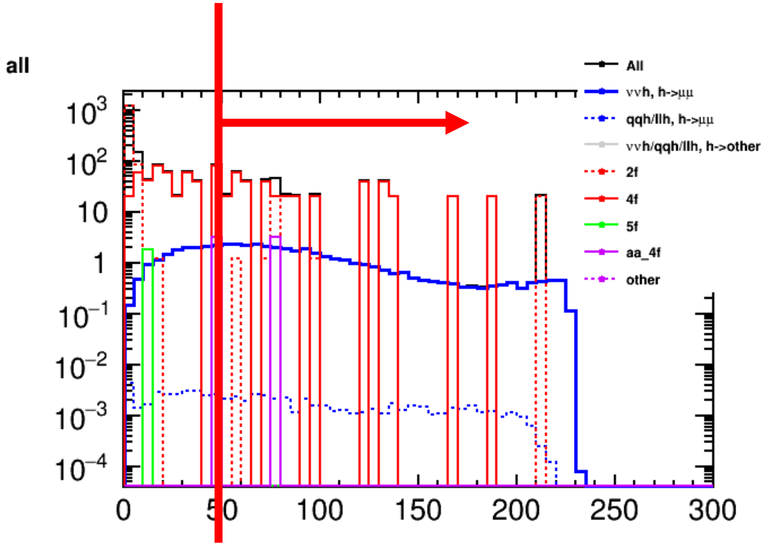
500 GeV 1600 fb-1 left-handed	$\nu\nu h$ $h\to\mu\mu$	qqh & $\ell\ell h$ $h\to\mu\mu$	ffh $h\nrightarrow\mu\mu$	2f	4f	5f	aa_4f
No cut	60.04	20.20	4.119*10^5	4.273*10^7	3.802*10^7	2.208*10^5	3.356*10^5
# $\mu^\pm$	58.93	18.25	6669.55	1.998*10^6	1.125*10^6	5891.06	1.095*10^4
# N^{track}	58.93	4.47	528.13	1.135*10^6	4.901*10^5	1523.30	2725.73
$M_{\mu\mu}$	50.71	3.86	0	2135.56	1133.50	12.92	9.45

Cut (SGV)

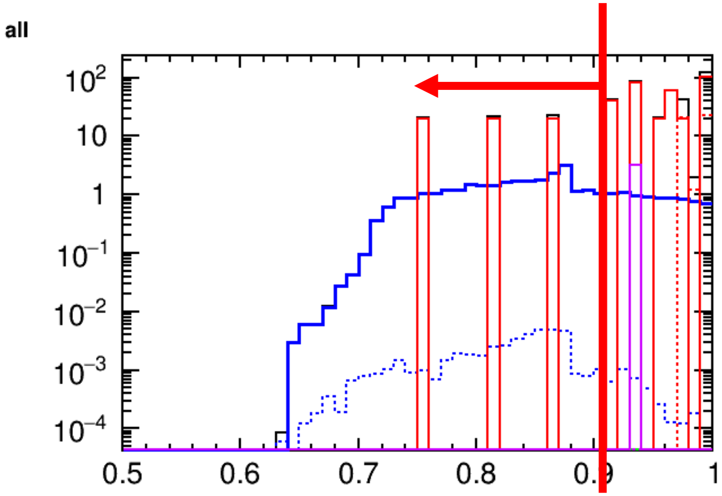
E_{vis}



P_t



thrust



E_{vis} < 285 GeV
P_t > 50 GeV
thrust < 0.91

Cut-based analysis (SGV)

500 GeV 1600 fb^{-1} left-handed	$\nu\nu h$ $h \to \mu\mu$	qqh & $\ell\ell h$ $h \to \mu\mu$	ffh $h \nrightarrow \mu\mu$	2f	4f	5f	aa_4f
precuts	50.71	3.86	0	2135.56	1133.50	12.92	9.45
E_{vis}	50.19	0.08	0	1354.20	845.73	1.88	6.30
P_t	35.73	0.05	0	44.81	381.91	0	3.15
thrust	27.61	0.05	0	0	60.26	0	0

$$\frac{S}{\sqrt{S+B}} = 2.94$$

$$\frac{\Delta(\sigma \times \mathrm{BR})}{(\sigma \times \mathrm{BR})} = 34\%$$

※some weight (= 1600/generated lumi.) for background is high! (~20)

$\sigma(M_{\mu^+\mu^-})$ Covariance Matrix in Momenta Space

- ref.: C. Calancha's talk
  - http://agenda.linearcollider.org/event/6315/contribution/1/material/slides/0.pdf
  - http://agenda.linearcollider.org/event/6343/contribution/2/material/slides/0.pdf
  - http://agenda.linearcollider.org/event/6361/contribution/10/material/slides/0.pdf
  - http://agenda.linearcollider.org/event/6372/contribution/4/material/slides/0.pdf

For Further Improvement: $\sigma\left(M_{\mu^+\mu^-}\right)$

error of measured $M_{\mu^+\mu^-}$:

$$\sigma^2\left(M_{\mu^+\mu^-}\right) = \frac{1}{M_{\mu^+\mu^-}^2}\left[P_1^T\Sigma_2 P_1 + P_2^T\Sigma_1 P_2\right]$$

P: a matrix filled with 4-momentum of muon

$$P_i: \begin{pmatrix} E_i \\ p_{xi} \\ p_{yi} \\ p_{zi} \end{pmatrix}$$

$$P_i^T: \begin{pmatrix} E_i & -p_{xi} & -p_{yi} & -p_{zi} \end{pmatrix}$$

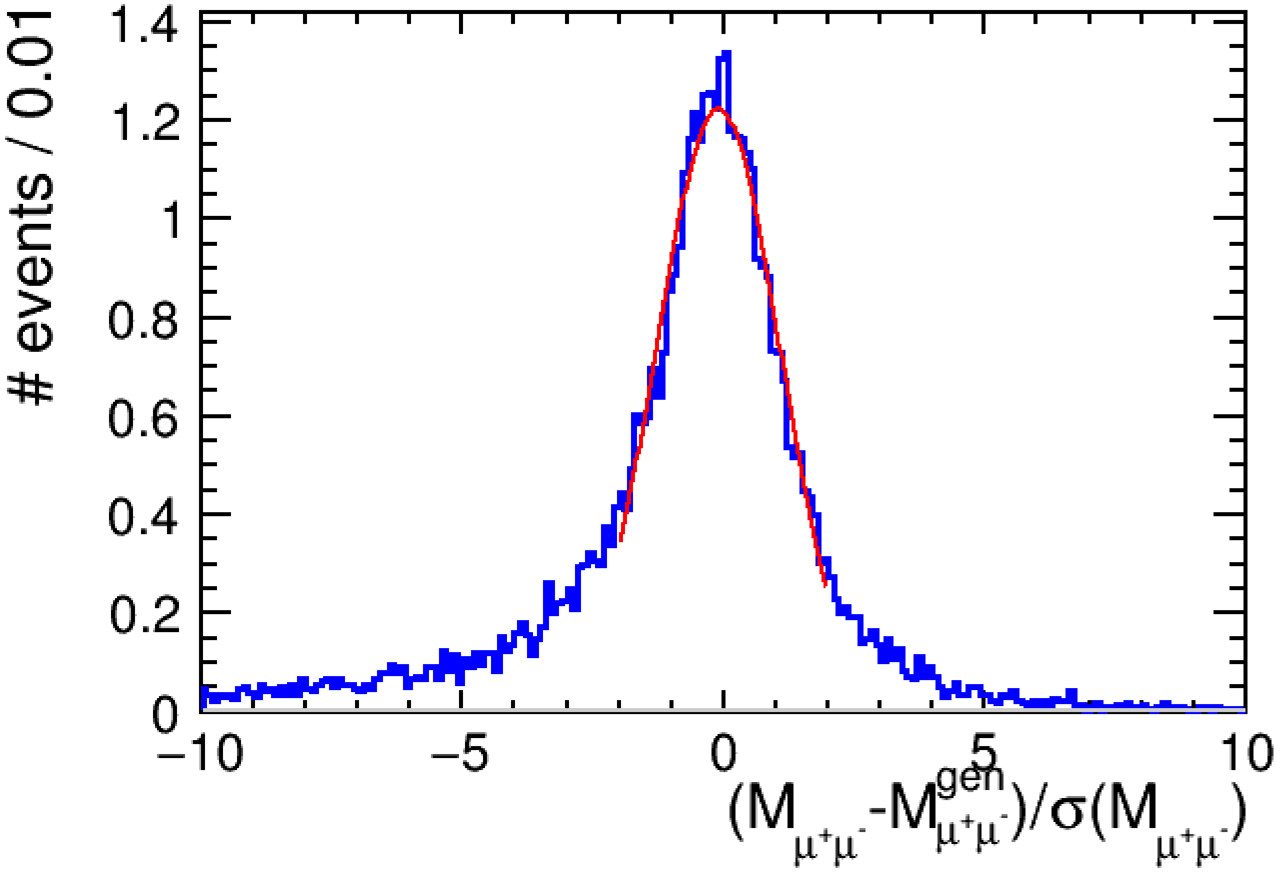
Σ_i: covariance matrix in momenta space of muon i

$$\Sigma_i \equiv \begin{pmatrix} \mathrm{cov}[E,E] & \mathrm{cov}[E,p_x] & \mathrm{cov}[E,p_y] & \mathrm{cov}[E,p_z] \\ \mathrm{cov}[E,p_x] & \mathrm{cov}[p_x,p_x] & \mathrm{cov}[p_x,p_y] & \mathrm{cov}[p_x,p_z] \\ \mathrm{cov}[E,p_y] & \mathrm{cov}[p_x,p_y] & \mathrm{cov}[p_y,p_y] & \mathrm{cov}[p_y,p_z] \\ \mathrm{cov}[E,p_z] & \mathrm{cov}[p_x,p_z] & \mathrm{cov}[p_y,p_z] & \mathrm{cov}[p_z,p_z] \end{pmatrix}$$

$h \to \mu^+\mu^-$: small σ when $M_{\mu^+\mu^-} \sim M_h$

background: no peak in small σ when $M_{\mu^+\mu^-} \sim M_h$

Pull distribution ($\nu\nu h, h \to \mu^+\mu^-$)



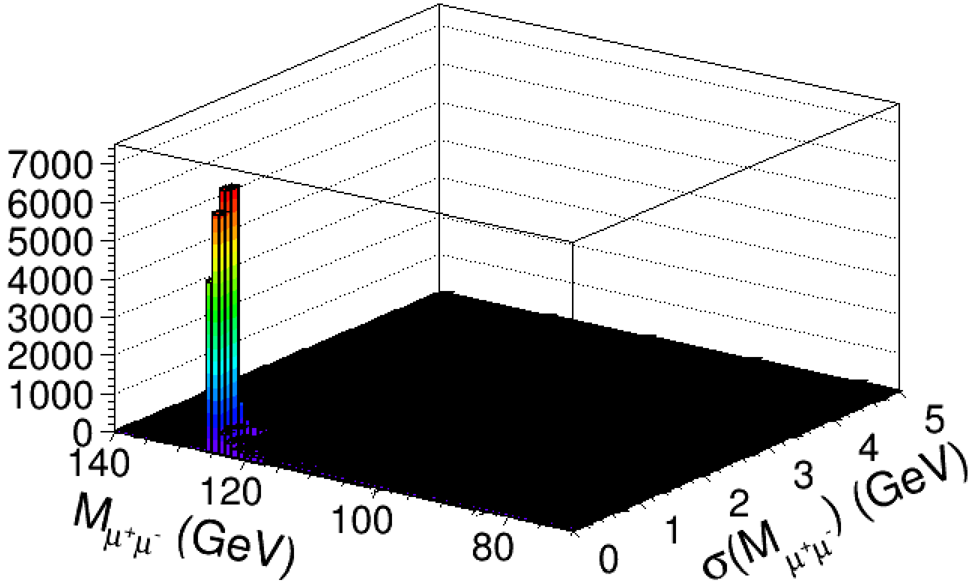
after precuts
Gaussian fit: [-2,2]
sigma = 1.18 +- 0.03

- first analysis-level application of FourMomentumCovMat
- width of pull distribution looks fine
- tails due to FSR

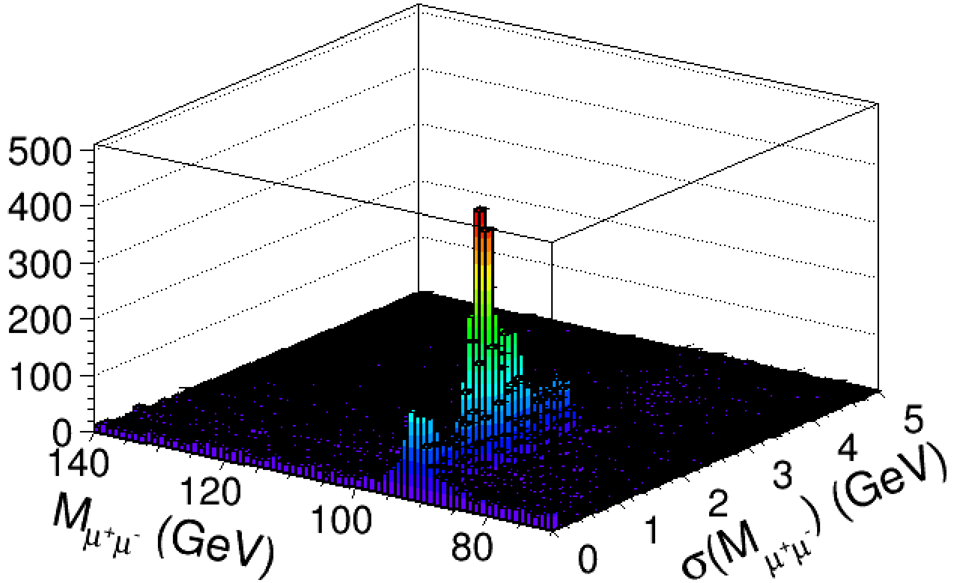
$M_{\mu^+\mu^-}$ v.s. $\sigma(M_{\mu^+\mu^-})$

※# of MC events after precuts, not luminosity weighted

$h \to \mu^+\mu^-$ samples



background



- hot spot in small $\sigma(M_{\mu^+\mu^-})$ around $M_{\mu^+\mu^-} \simeq M_h$ in $h \to \mu^+\mu^-$ samples, as expected
- peak around M_z with larger $\sigma(M_{\mu^+\mu^-})$ in background (probably going forward) and no peak in signal region

Zoom: $M_{\mu^+\mu^-}$ v.s. $\sigma\left(M_{\mu^+\mu^-}\right)$

※# of MC events after precuts,
not luminosity weighted
zoom in M_h region