$H \rightarrow \tau\tau$ branching ratio study in the ILC with the ILD detector

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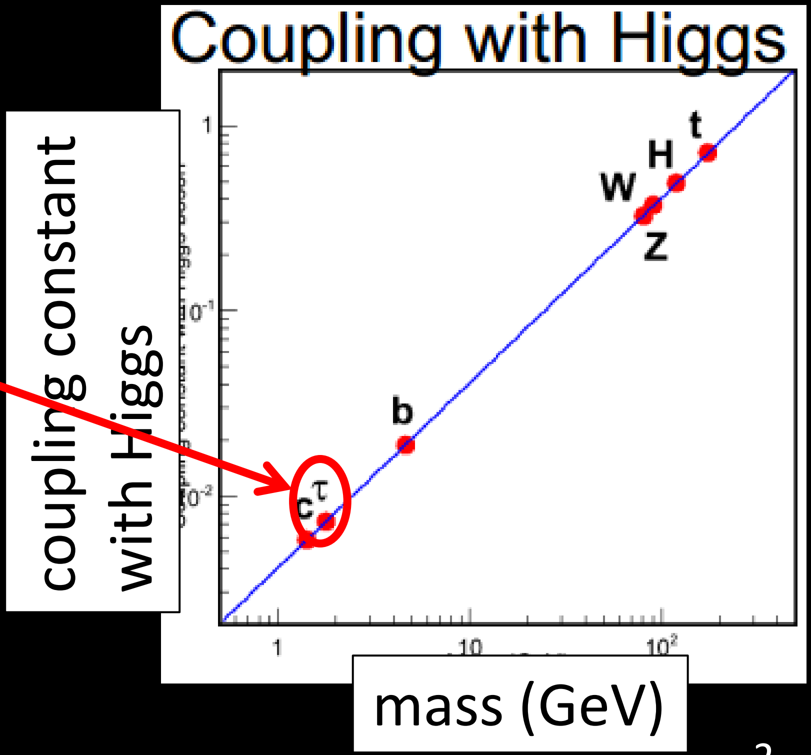
Introduction

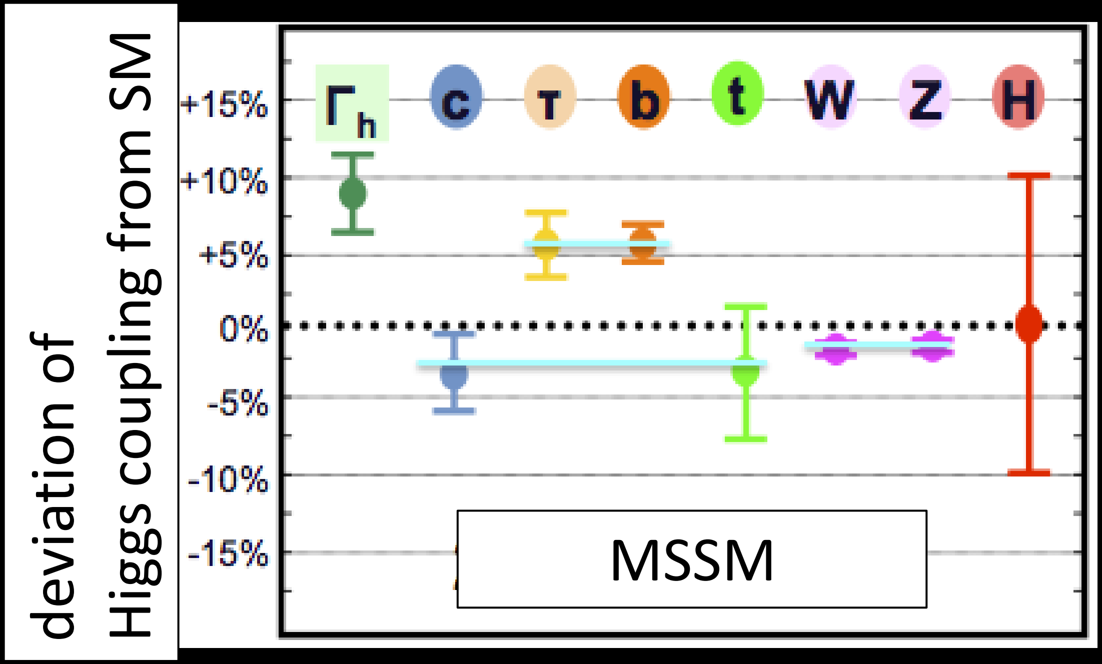
Since the discovery of Higgs boson, the investigation of its properties has become one of the most important themes in particle physics, especially the verification of the mass generation mechanism.

Full simulation of $H \rightarrow \tau\tau$ mode



Motivation for Precise Measurement

Any deviation in Higgs coupling and mass relation is an indication of new physics.



The small theoretical uncertainty in tau mass makes $H \to \tau\tau$ branching ratio an ideal probe for new physics.

Target of This Study

Estimation of the precision of
the branching ratio of $H \to \tau\tau$ mode

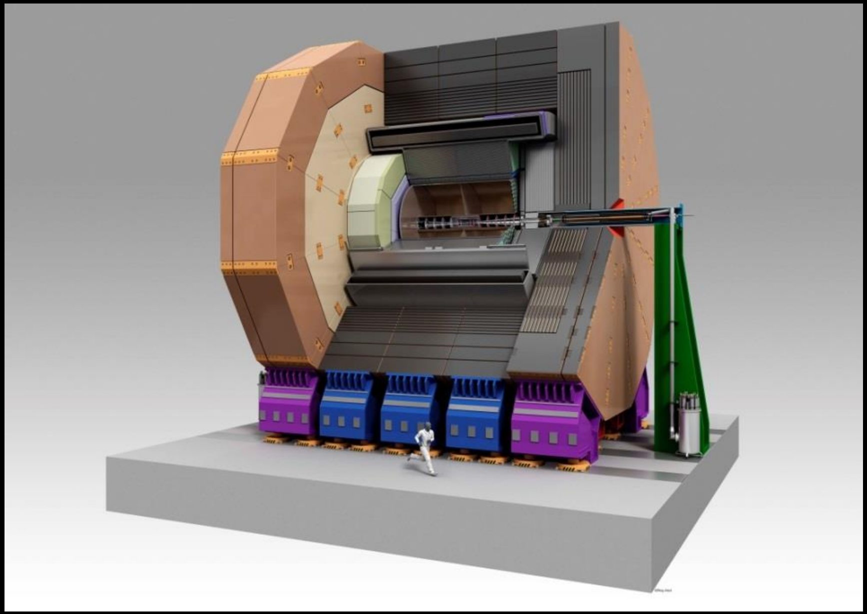
Previous **fast simulation** study (written in RDR)

$$\frac{\Delta(\sigma\cdot\mathrm{Br})}{(\sigma\cdot\mathrm{Br})} = 4.6 \sim 7.1\ \%\ (M_H = 120\ \mathrm{GeV}, \int L\,dt = 500\ \mathrm{fb}^{-1})$$

We estimated the precision with
full detector simulation (ILD) at $\sqrt{s} = 250\ \mathrm{GeV}$.

Simulation Settings

Higgs properties : $M_H = 120\ \mathrm{GeV}, \mathrm{Br}(H \to \tau\tau) = 8.0\ \%$
Machine parameters : $\sqrt{s} = 250\ \mathrm{GeV}, \int L\, dt = 250\ \mathrm{fb}^{-1}$,
beam pol. $P(e^-, e^+) = (-0.8, +0.3)$
Using samples which generated in the context of LoI (2009)
scaled results to 125 GeV will be shown at the end of this talk

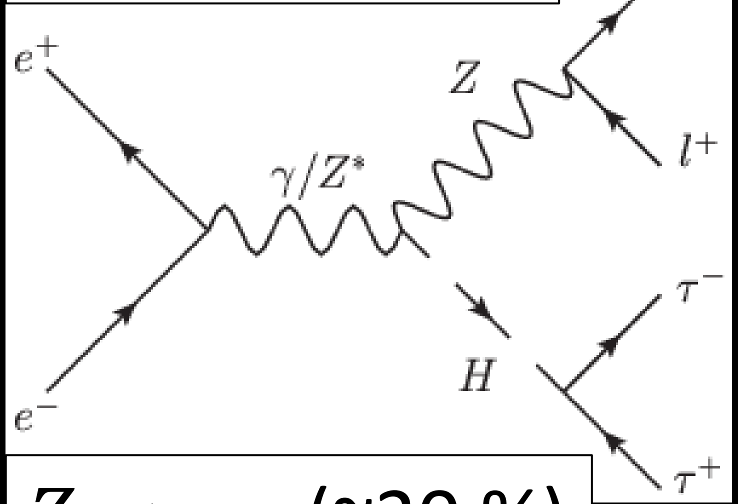


full simulation with
ILD detector model

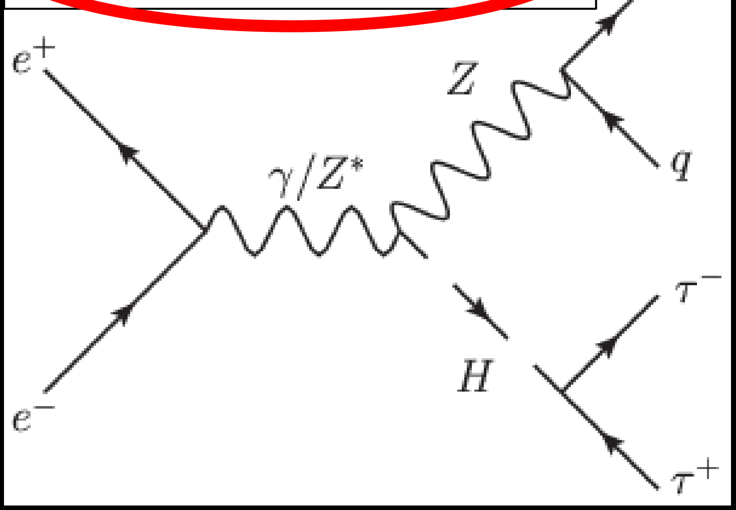
Signal

$e^+e^- \to ZH$
with $H \to \tau\tau$

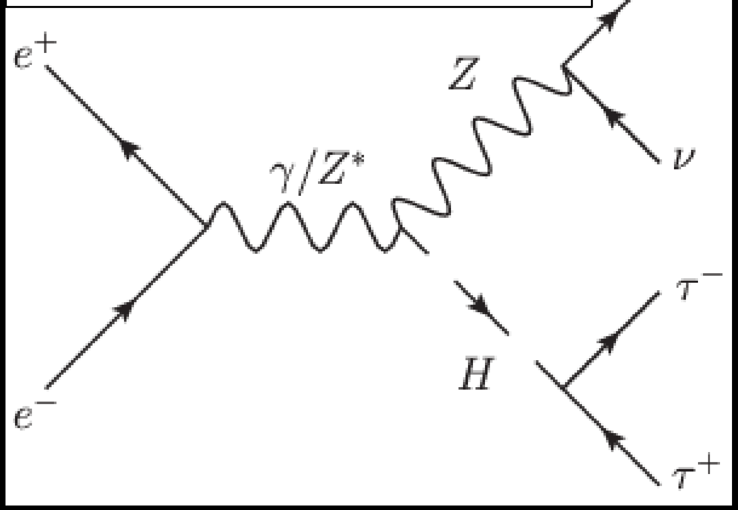
$Z \to ll$ (~10 %)



$Z \to qq$ (~70 %)

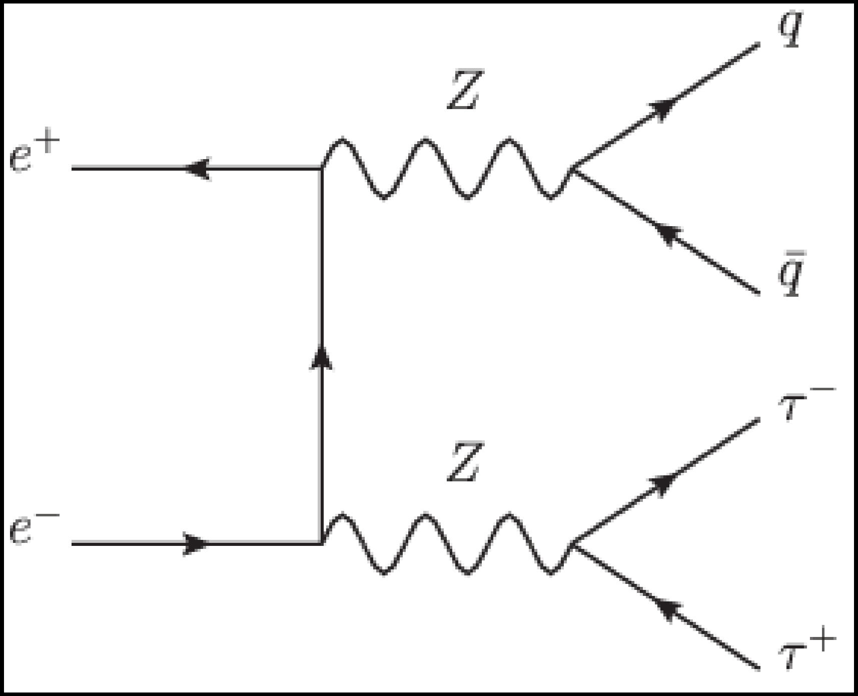


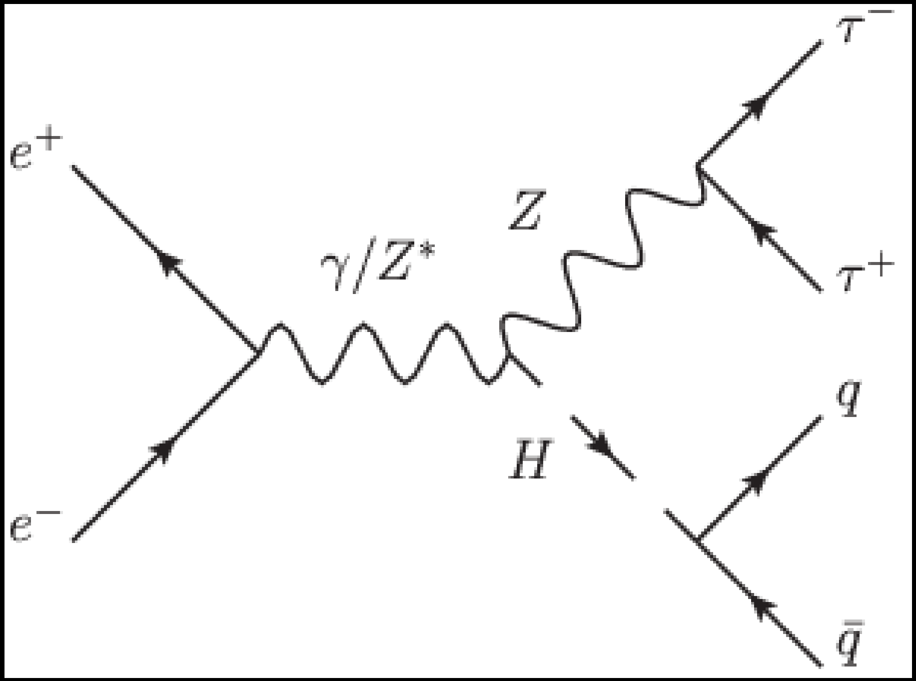
$Z \to \nu\nu$ (~20 %)



Analysis of $Z \to qq$ Mode

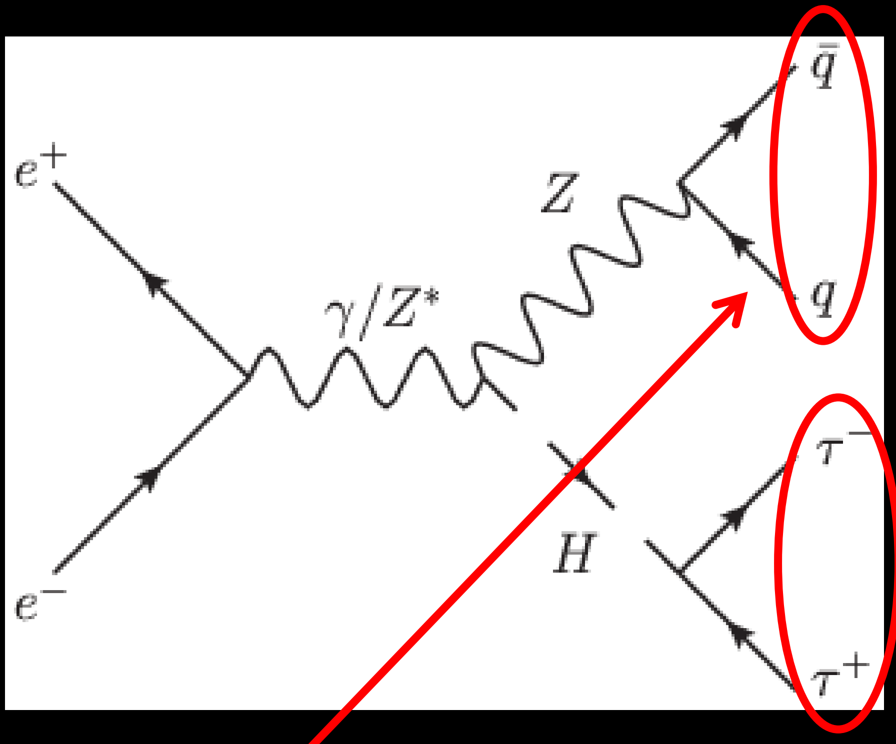
Main Background





$e^+e^- \to qqqq, qqll, qql\nu$ $qq\tau\tau$: irreducible	$e^+e^- \to ZH \to (ll)(qq)$ $ZH \to \tau\tau qq$: mimic signal

Event Reconstruction



1 : $\tau\&H$ reconstruction

- **tau jet finder**

clustering based on tau mass

- **collinear approximation**

tau pair mass reconstruction

2 : Z reconstruction

Durham 2-jet clustering

by T. Suehara

TaJet finder (1)

High-purity tau tagging
in presence of jet background

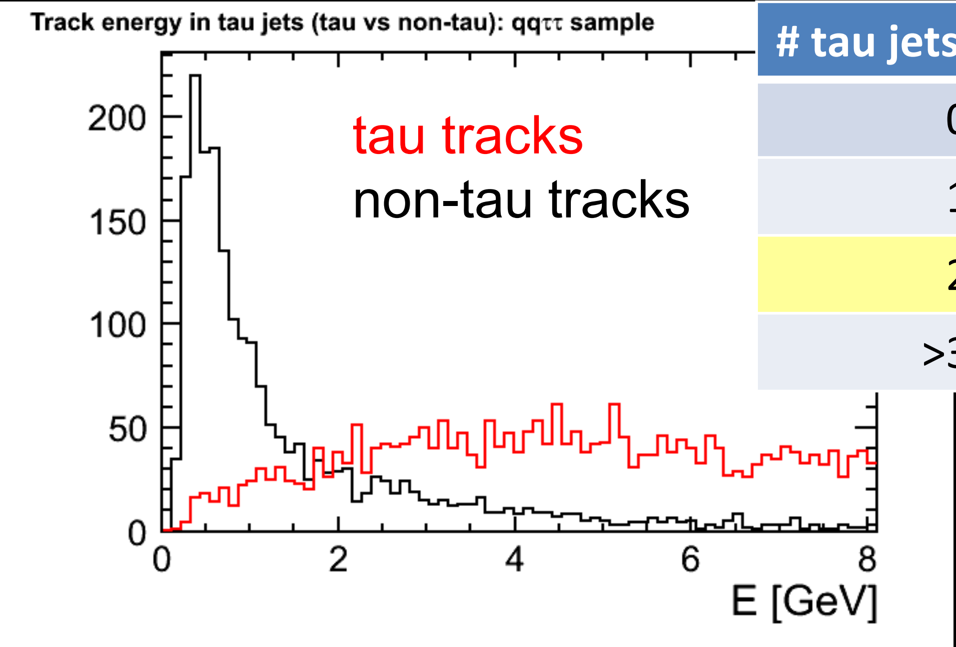
1. Order charged tracks by largest energy
2. Select the first track
3. Combine neighboring particles -> “Tau Jet”
   - Combined mass < 2 GeV && $\cos\theta$ w.r.t. jet axis > 0.98
4. Tau selection (tuned for rejecting qq background)
   1. Tau Jet energy > 3 GeV
   2. Veto >=3 prong + neutrals (> 1 GeV)
   3. Cone energy ($E_{cone} < 0.1E_{taujet}$) with $\cos\theta_{cone} = 0.9$

ZZ -> qq$\tau\tau$ 250 GeV, 13600 taus	1-prong		3-prong wo/ neutral		3-prong w/ neutral	
	tau	non-tau	tau	non-tau	tau	non-tau
No cut	10326	43286	716	1616	777	4280
$E_{taujet} > 3$	8679	7145	708	1304	742	4244
$E_{cone} < 0.5E_{taujet}$	7170	1009	621	181	681	1813
$E_{cone} < 0.2E_{taujet}$	6455	446	567	64	616	1020
$E_{cone} < 0.1E_{taujet}$	6001	254	527	30	570	620

by T. Suehara

TaJet finder (2)

5. Jet charge recovery (for better efficiency)
   - Tracks with energy < 2 GeV are detached one by one until tau jet has 1 or 3 tracks and sum charge is +1 or -1
   - Jet is rejected if above condition cannot be satisfied after detaching all < 2 GeV tracks
6. Return to 2. (previous page) with the remaining tracks
   - Stop after all E > 2 GeV tracks have been processed



# tau jets	$qq\tau\tau$	$qql\nu$
0	27.1%	47.6%
1	36.3%	46.6%
2	34.0%	5.4%
>3	2.4%	0.3%

efficiency:
58.1% (1-prong)
73.6% (3-prong)

purity of tau in $qq\tau\tau$:
94.2% (overall)
96.5% (# tau jets == 2)

Collinear Approximation

Method of reconstructing tau pair mass ($M_{\tau\tau} = M_H$)

Assumptions :

- visible tau decay products and neutrinos are collinear
- contribution of missing momentum comes only from neutrinos of tau decay

$$\tau_{1\mathrm{vis}} \equiv (E_{\mathrm{vis1}}, \boldsymbol{p}_{\mathrm{vis1}}), \tau_{2\mathrm{vis}} \equiv (E_{\mathrm{vis2}}, \boldsymbol{p}_{\mathrm{vis2}})$$

visible products from tau

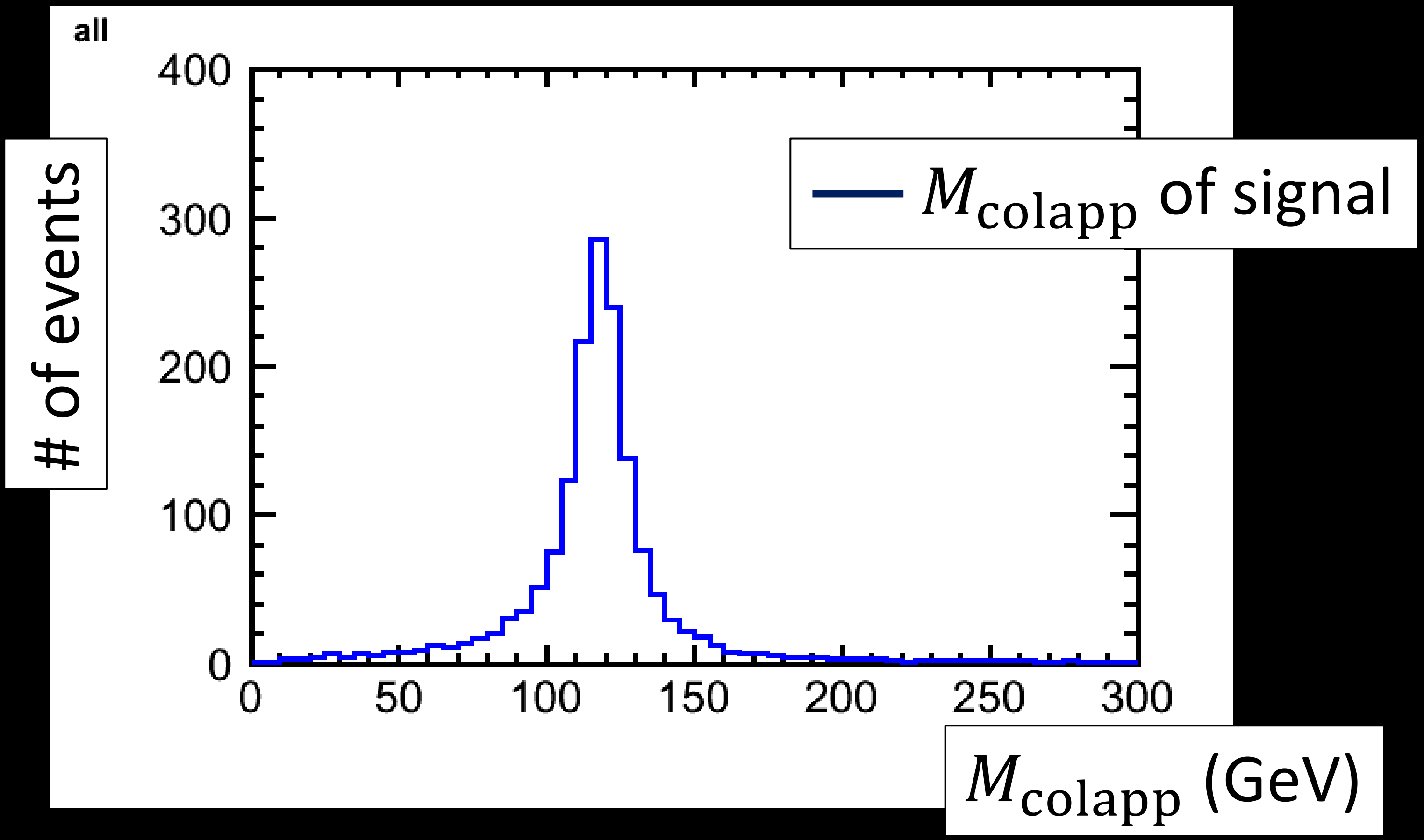
$$\tau_{1\mathrm{inv}} = a(|\boldsymbol{p}_{\mathrm{vis1}}|, \boldsymbol{p}_{\mathrm{vis1}}), \tau_{2\mathrm{inv}} = b(|\boldsymbol{p}_{\mathrm{vis2}}|, \boldsymbol{p}_{\mathrm{vis2}})$$

neutrinos from tau

$$\begin{cases} a = \dfrac{p_{\mathrm{mis}_y} p_{\tau 2\mathrm{vis}_x} - p_{\mathrm{mis}_x} p_{\tau 2\mathrm{vis}_y}}{p_{\tau 1_y} p_{\tau 2_x} - p_{\tau 1_x} p_{\tau 2_y}} \\ b = \dfrac{p_{\mathrm{mis}_y} p_{\tau 1\mathrm{vis}_x} - p_{\mathrm{mis}_x} p_{\tau 1\mathrm{vis}_y}}{p_{\tau 1_x} p_{\tau 2_y} - p_{\tau 2_x} p_{\tau 1_y}} \end{cases}$$

Plot of M_{colapp}

M_{colapp} : mass of tau pair with collinear approximation



Event Selection

Cut 0 (pre-selection):

of q jet = 2, # of τ^+ = 1, # of τ^- = 1, # of tracks in τ <= 3

Cut 1: 9 <= # of tracks < 50

Cut 2: $110 < E_{\mathrm{vis}} < 235$

Cut 3: $|\cos\theta_{\mathrm{miss}}| < 0.98$

Cut 4: $77 < M_Z(M_{qq}) < 135$

Cut 5: $80 < E_Z(E_{qq}) < 135$

Cut 6: $\cos\theta_{\tau^+\tau^-} < -0.5$

Cut 7: $\log_{10}(|d_0\mathrm{sig}(\tau^+)|) + \log_{10}(|d_0\mathrm{sig}(\tau^-)|) > -0.7$

Cut 8: $\log_{10}(|z_0\mathrm{sig}(\tau^+)|) + \log_{10}(|z_0\mathrm{sig}(\tau^-)|) > -0.1$

Cut 9: $M_{\tau^+\tau^-} < 115$

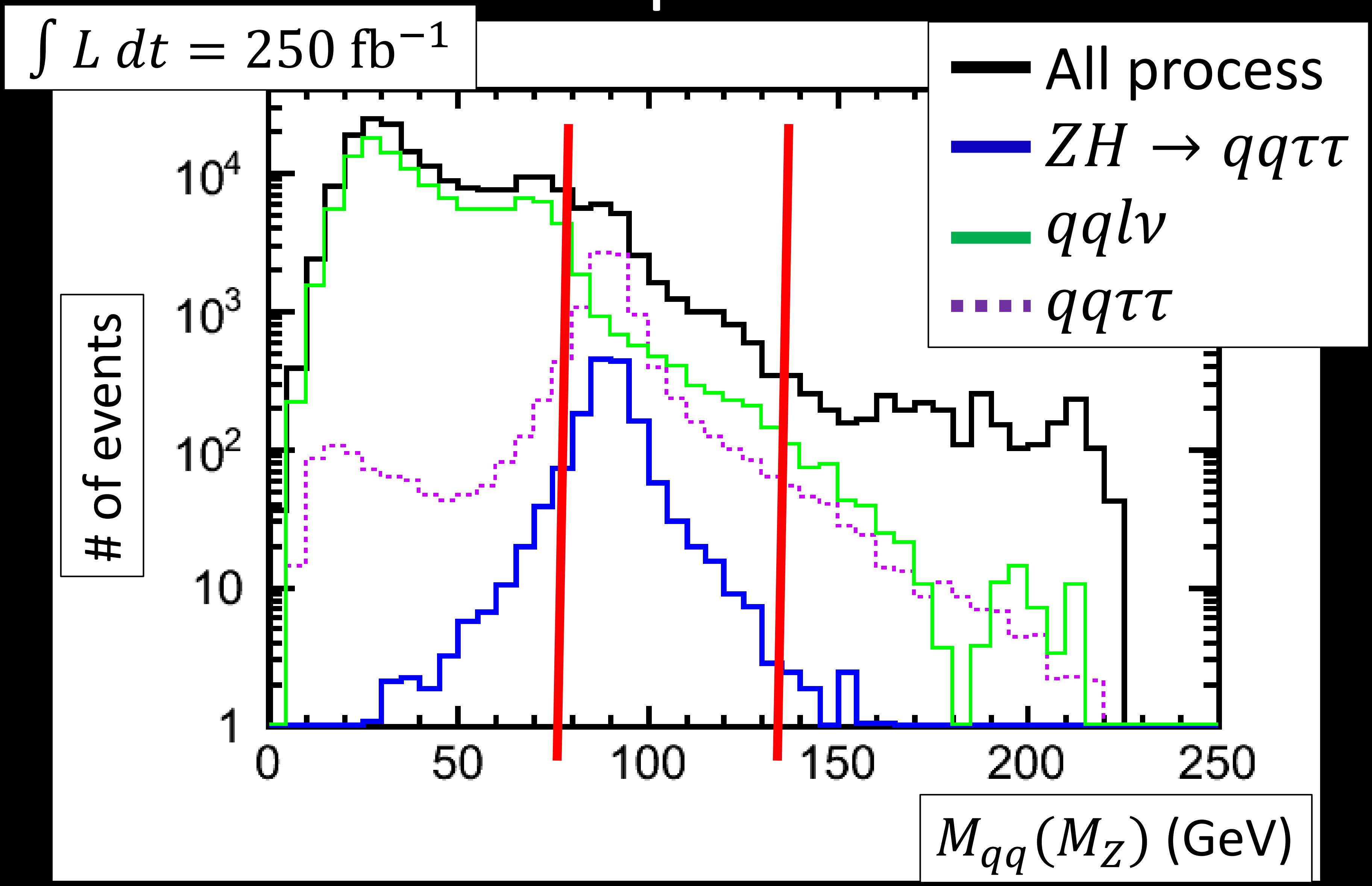
Cut 10: $E_{\tau^+\tau^-} < 125$

Cut 11: $100 < M_{\mathrm{colapp}}(M_H) < 170$

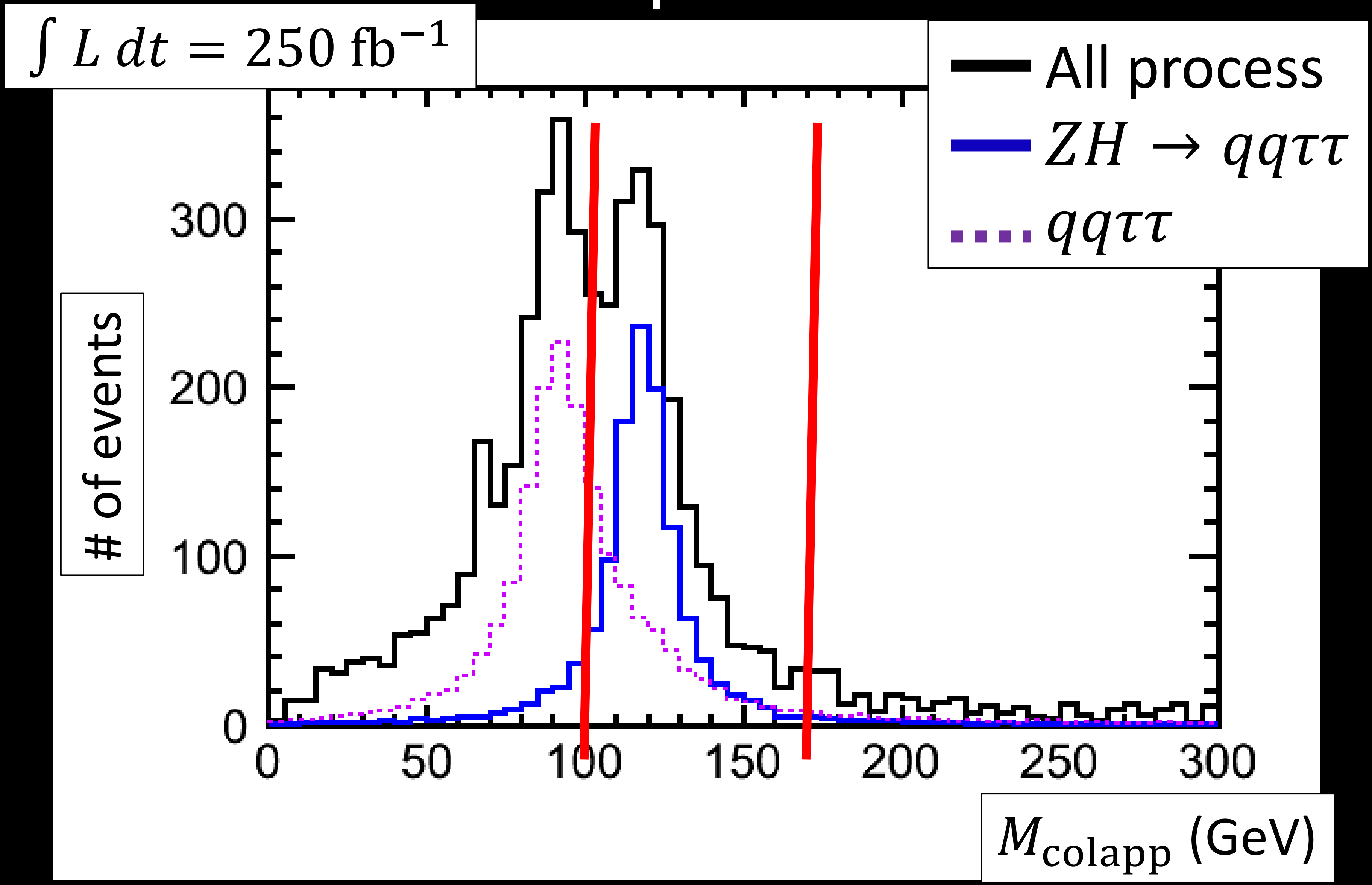
Cut 12: $100 < E_{\mathrm{colapp}}(E_H) < 280$

Cut 13: $112 < M_{\mathrm{recoil}} < 160$

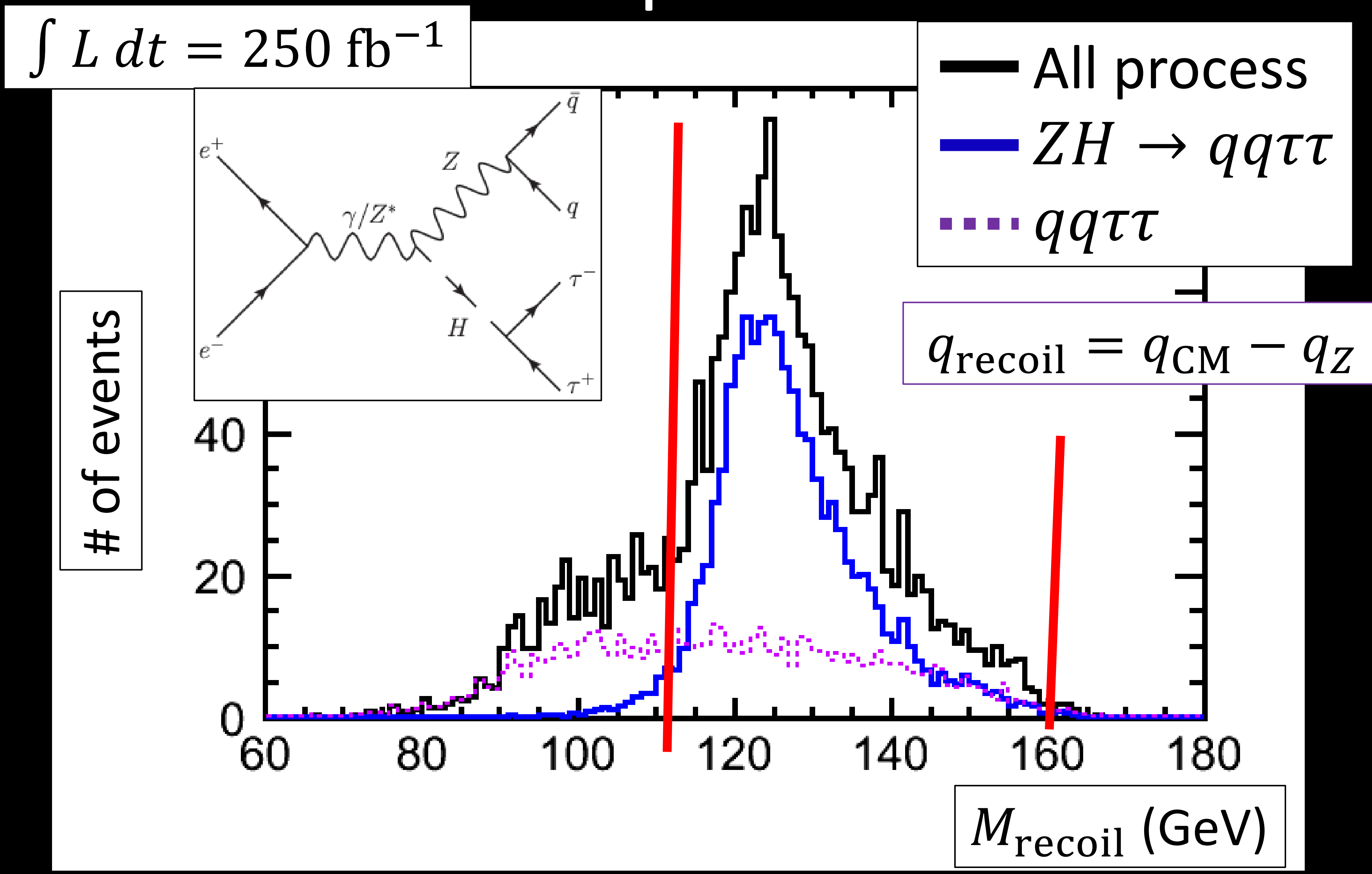
Example Plot



Example Plot



Example Plot



Results of $Z \to qq$ Mode ($M_H = 120$ GeV)

	$e^+e^- \to ZH \to qq\tau\tau$ (signal)	$e^+e^- \to ZH \to qqH, H \nrightarrow \tau\tau$	$e^+e^- \to qq\tau\tau$	$e^+e^- \to ZH, Z \to ll$	other SM bkg.
No cut	4233	4.827e+04	4.168e+05	7974	1.495e+10
After cut	**1032**	2.1	369.5	35.9	157.3

precision with $Z \to qq$: $\frac{\Delta(\sigma \cdot \mathrm{Br})}{(\sigma \cdot \mathrm{Br})} = \mathbf{3.9\ \%}$

Results of each mode

$Z \to ee$	$Z \to \mu\mu$	$Z \to qq$	$Z \to \nu\nu$
8.0σ	8.8σ	25.8σ	3.0σ

Combined : 28.6σ

$$\frac{\Delta(\sigma \cdot \mathrm{Br})}{(\sigma \cdot \mathrm{Br})} = \mathbf{3.5\ \%}$$

Summary & Next Plan

We evaluated the precision of the branching ratio of $H \to \tau\tau$ mode with the ILD full detector simulation.

scaled results to 125 GeV

$\sqrt{s} = 250\ \mathrm{GeV},\ M_H = 125\ \mathrm{GeV},\ \mathrm{Br}(H \to \tau\tau) = 6.32\ \%,$
$\int L\,dt = 250\ \mathrm{fb}^{-1},\ P(e^-, e^+) = (-0.8, +0.3)$

precision : $\frac{\Delta(\sigma \cdot \mathrm{Br})}{(\sigma \cdot \mathrm{Br})} = \mathbf{4.1\ \%}$

Next : Analysis with samples with
latest simulation tools & $M_H = 125\ \mathrm{GeV}$
$(\sqrt{s} = 250\ \mathrm{GeV}, 350\ \mathrm{GeV}, 500\ \mathrm{GeV}, 1\ \mathrm{TeV})$

BACKUP SLIDES

	$M_H = 120$ GeV	$M_H = 125$ GeV
Xsec $e^+e^- \to ZH$	303.1 fb	303.0 fb
$\mathrm{Br}(H \to \tau\tau)$	8.0 % (PYTHIA)	6.32 % (LHC-HiggsXsec-WG)
$Z \to ee$	8.0σ	6.8σ
$Z \to \mu\mu$	8.8σ	7.4σ
$Z \to qq$	25.8σ	21.9σ
$Z \to \nu\nu$	3.0σ	2.4σ
Combined	28.6σ	24.2σ
$\frac{\Delta(\sigma \cdot \mathrm{Br})}{\sigma \cdot \mathrm{Br}}$	3.5 %	4.1 %

Previous & Current Results

My talk @ LCWS12

mode	$Z \to ee$	$Z \to \mu\mu$	$Z \to qq$	$Z \to \nu\nu$
significance	7.4σ	8.5σ	none	none

⇨ precision : $\frac{\Delta(\sigma \cdot \mathrm{Br})}{(\sigma \cdot \mathrm{Br})} = 9\ \%$

Current results

mode	$Z \to ee$	$Z \to \mu\mu$	$Z \to qq$	$Z \to \nu\nu$
significance	8.0σ	8.8σ	$\mathbf{25.8\sigma}$	3.0σ

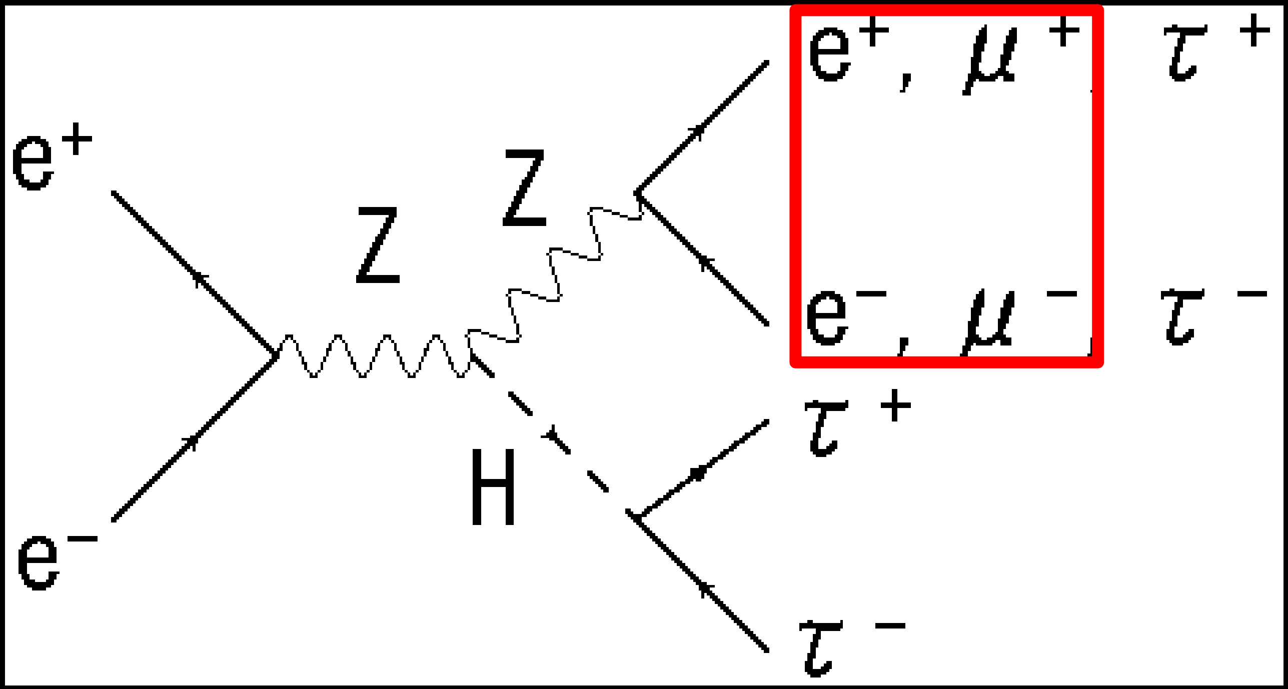
⇨ precision : $\frac{\Delta(\sigma \cdot \mathrm{Br})}{(\sigma \cdot \mathrm{Br})} = \mathbf{3.5\ \%}$

scaling to 125 GeV : $\frac{\Delta(\sigma \cdot \mathrm{Br})}{(\sigma \cdot \mathrm{Br})} = \mathbf{4.1\ \%}$

Analysis of $Z \rightarrow ll$ Mode

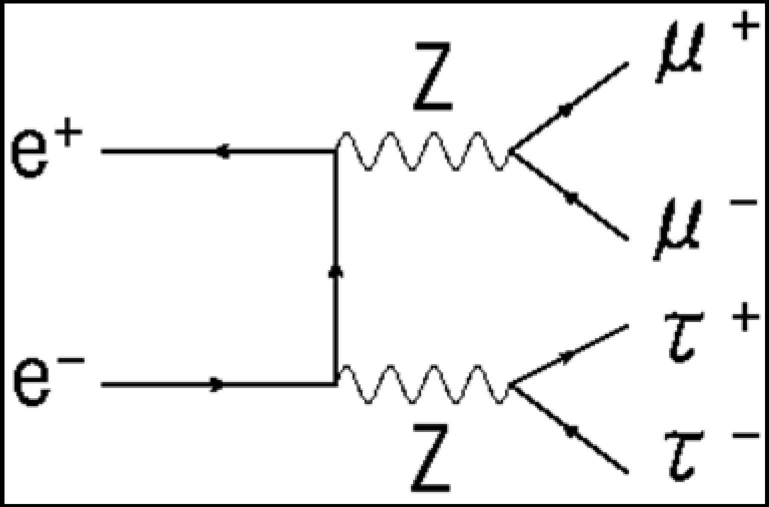
Signal Process

We concentrated on $Z \to ee$ and $Z \to \mu\mu$.

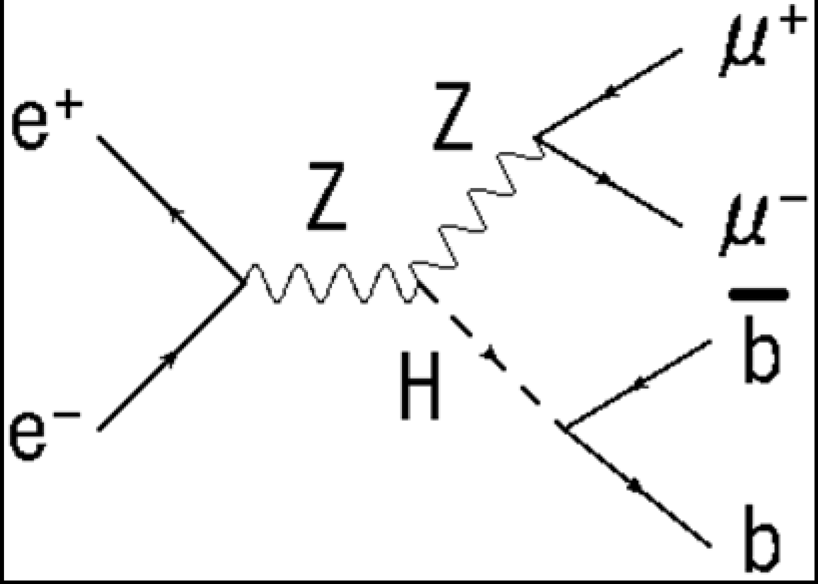


Main Background

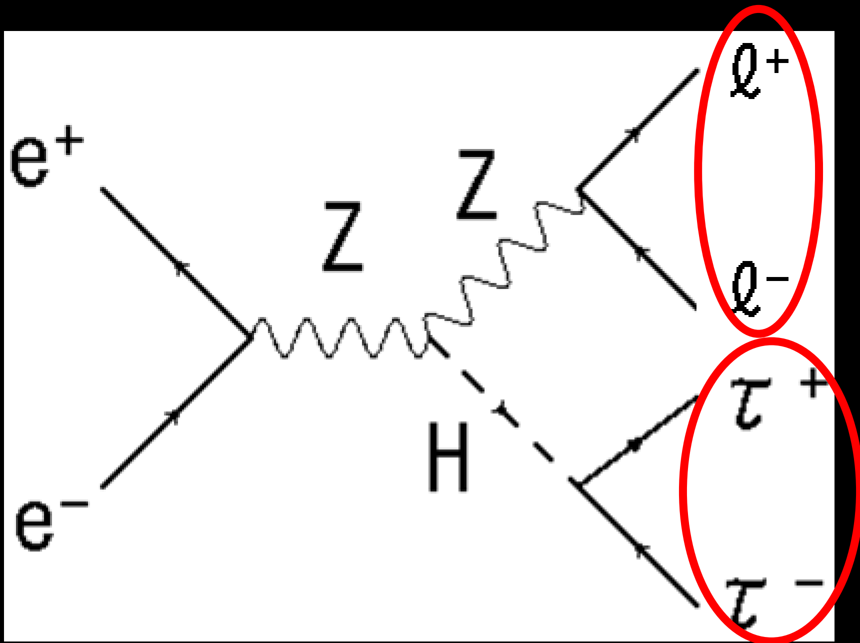
4 leptons background
$eeee, ee\mu\mu, ee\tau\tau,$
$\mu\mu\mu\mu, \mu\mu\tau\tau, \tau\tau\tau\tau$



ZH with other Higgs decays



Event Reconstruction



1: Z reconstruction

- lepton ID

identify e/μ by using

$$\frac{E_{\mathrm{ECAL}}}{E_{\mathrm{ECAL}}+E_{\mathrm{HCAL}}} \text{ and } \frac{E_{\mathrm{ECAL}}+E_{\mathrm{HCAL}}}{P_{\mathrm{track}}}$$

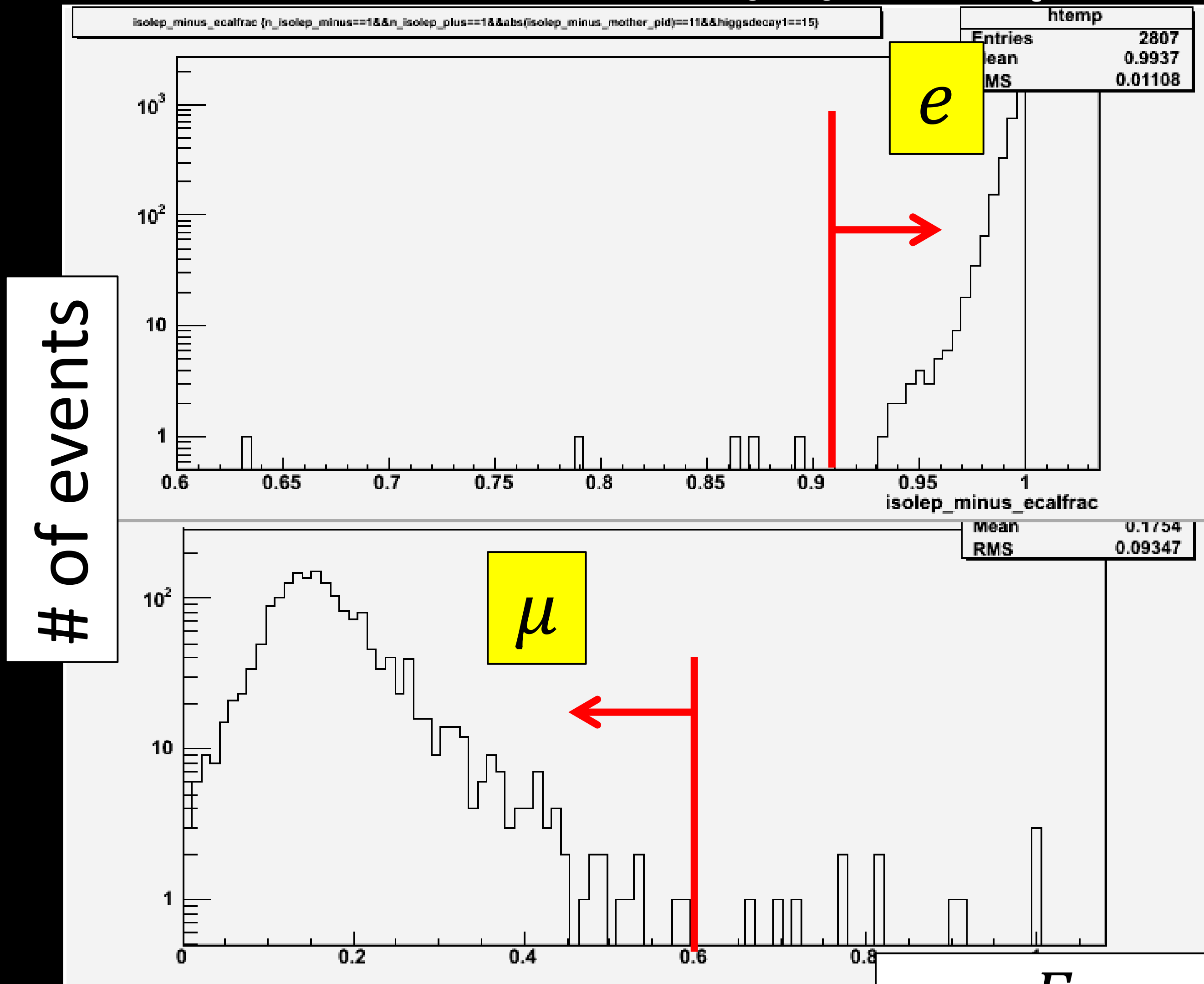
- τ rejection

do not use tracks displaced from IP

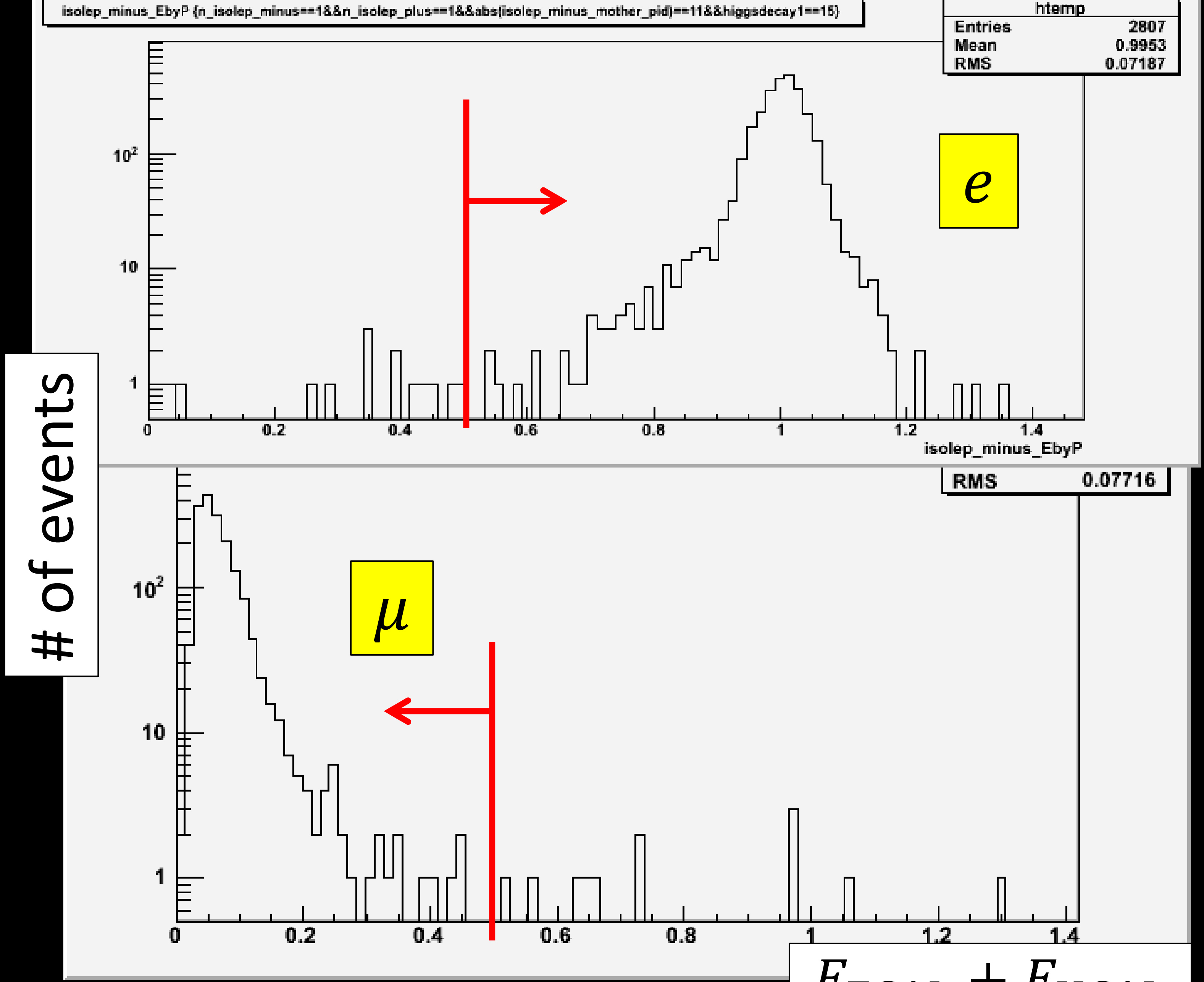
2: τ reconstruction

clustering based on τ mass

Z Reconstruction (1) : Lepton ID

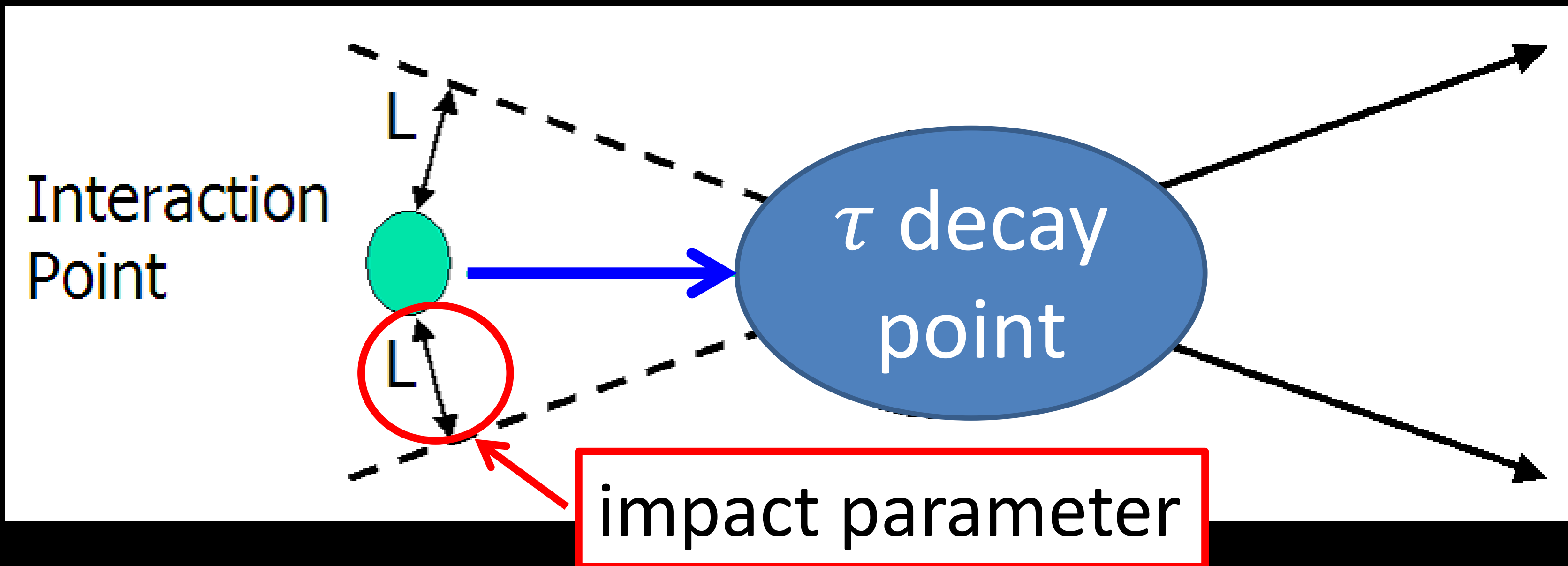


$$\frac{E_{\mathrm{ECAL}}}{E_{\mathrm{ECAL}} + E_{\mathrm{HCAL}}}$$



$$\frac{E_{\text{ECAL}} + E_{\text{HCAL}}}{P_{\text{track}}}$$

Z Reconstruction (2) : τ Rejection

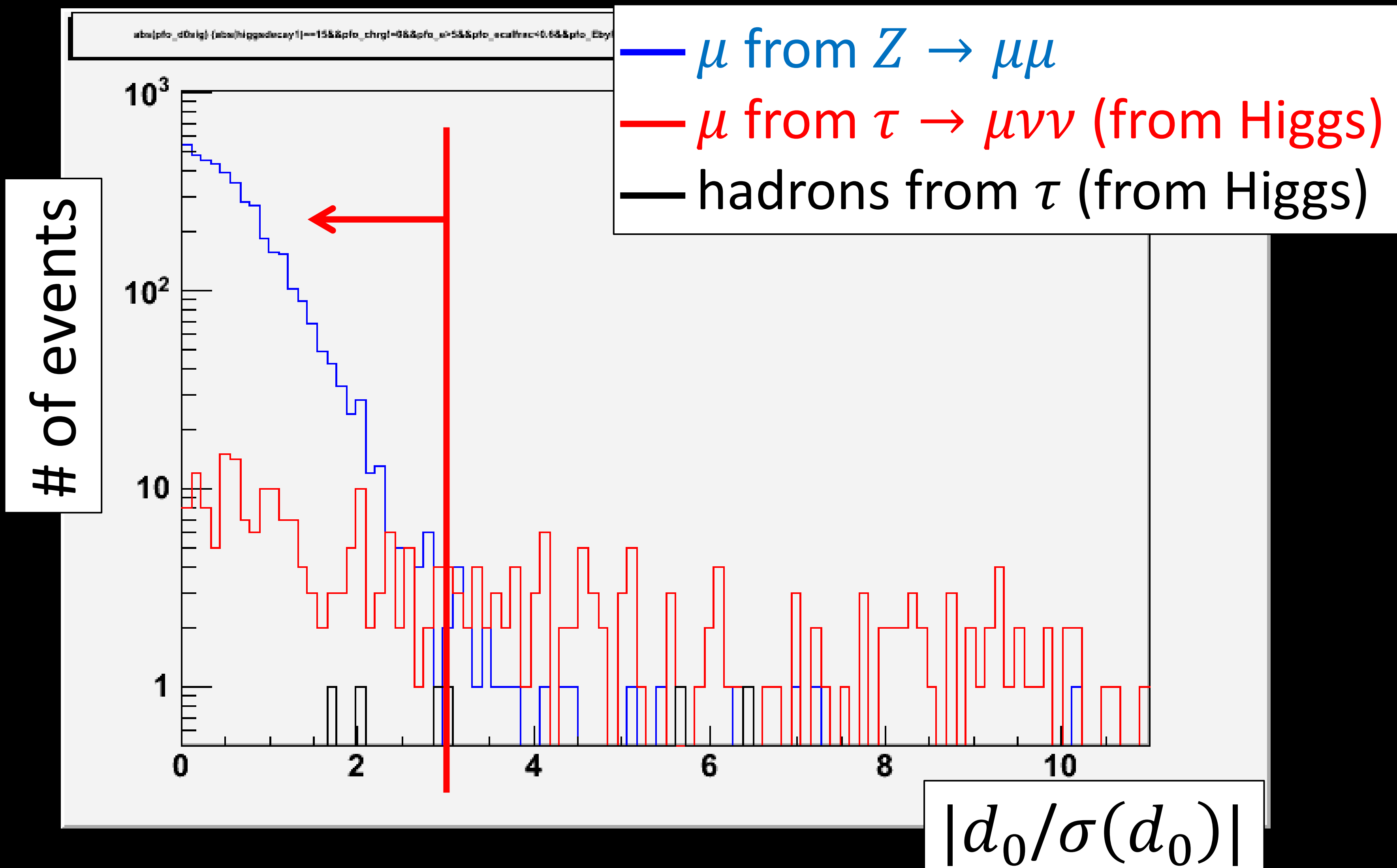


use impact parameter for τ rejection

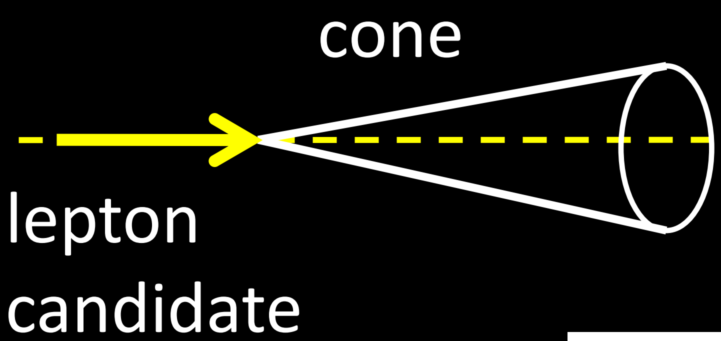
d_0: perpendicular to beam axis (x-y plane)

z_0: along to beam axis

τ Rejection : Example Plot



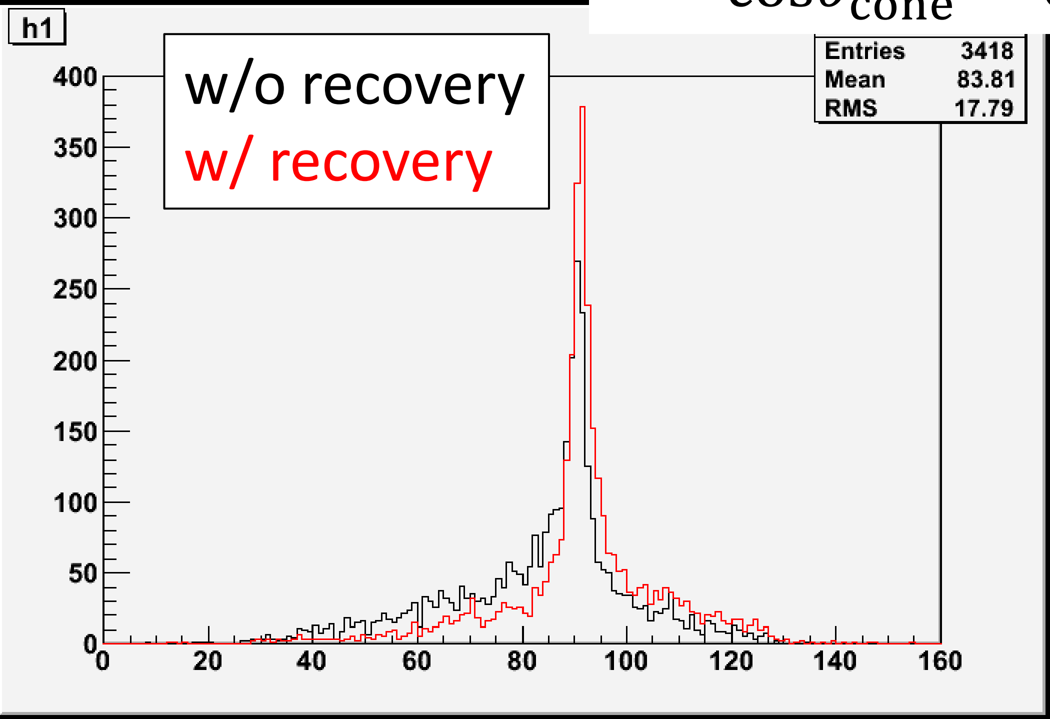
FSR / Bremsstrahlung Recovery



Neutral particles in the cone are combined with the lepton candidate.

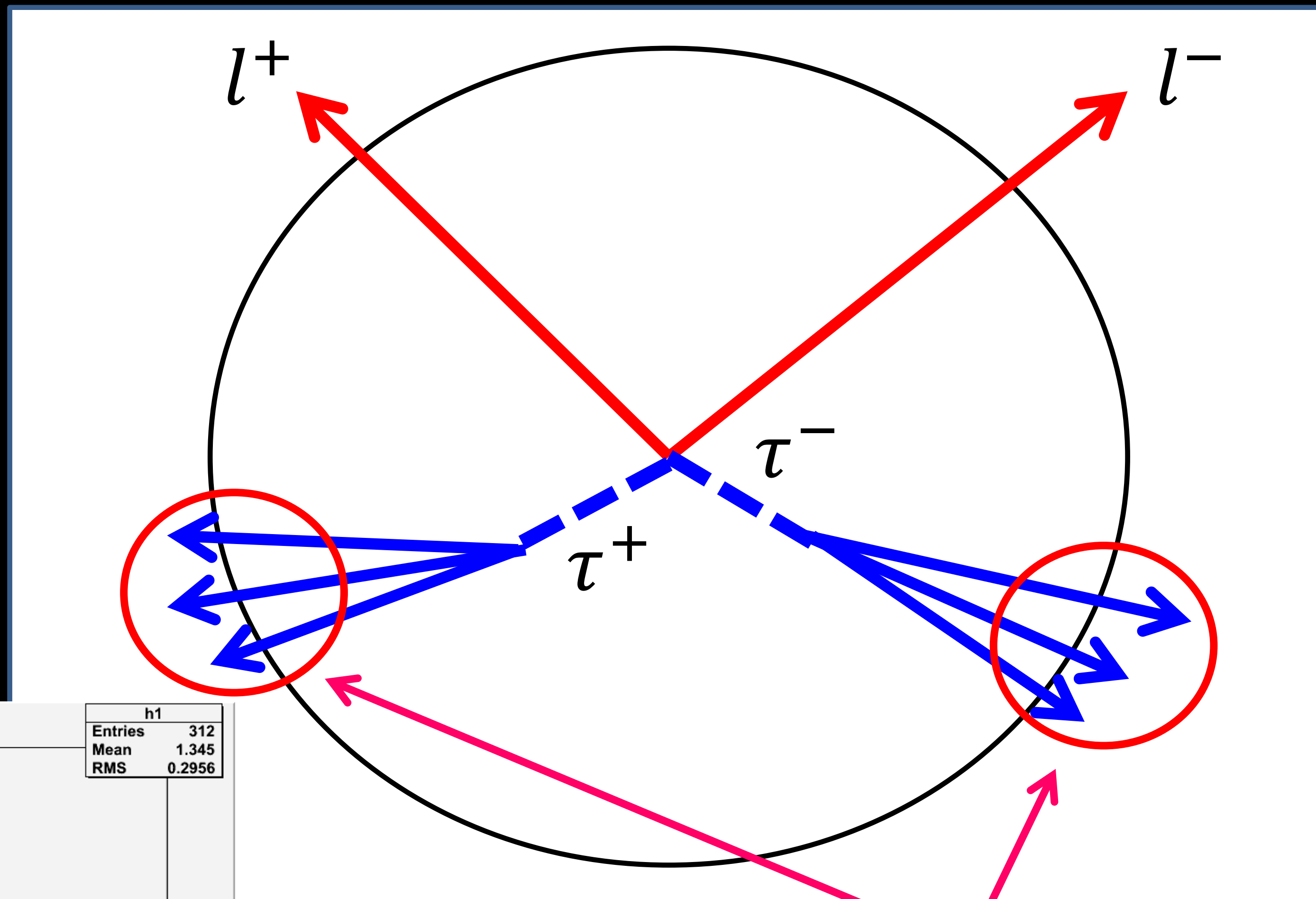
Z mass plot of $ZH \to ee\tau\tau$

$\cos\theta_{\text{cone}} = 0.999$

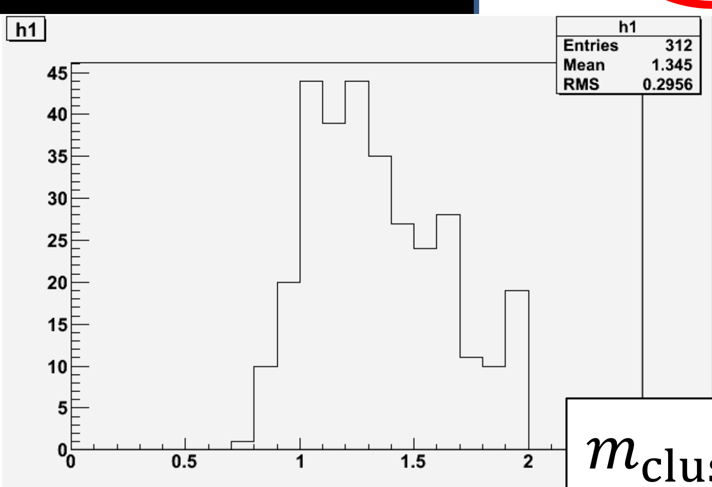


In case of more than 2 lepton tracks, the pair most consistent with Z mass is chosen.

τ Reconstruction



$m_{\mathrm{cluster}} < 2$ GeV



m_{cluster} (GeV)

Event Selection ($Z \to ee$)

Cut 0 (pre-selection):
require e^+e^- candidate, # of τ^- == 1, # of τ^+ == 1,
Cut 1: # of tracks <= 8
Cut 2: $115 < E_{\mathrm{vis}} < 230$
Cut 3: $|\cos\theta_{\mathrm{missmom}}| < 0.99$
Cut 4: $81 < M_Z < 113$
Cut 5: $\cos\theta_{e^-} < 0.92, \cos\theta_{e^+} > -0.92$
Cut 6: $E_{e^-} < 90, E_{e^+} < 90$
Cut 7: $\cos\theta_{\tau^+\tau^-} < -0.45$
Cut 8: $\cos\theta_{\tau^-} < 0.92, \cos\theta_{\tau^+} > -0.92$
Cut 9: $116 < M_{\mathrm{recoil}} < 142$

Event Selection ($Z \rightarrow \mu\mu$)

Cut 0 (pre-selection):
require $\mu^+\mu^-$ candidate, # of τ^+ == 1, # of τ^- == 1
Cut 1: # of tracks <= 8
Cut 2: $115 < E_{\mathrm{vis}} < 235$
Cut 3: $|\cos\theta_{\mathrm{missmom}}| < 0.98$
Cut 4: $72 < M_Z < 107$
Cut 5: $E_{e^+} < 90, E_{e^-} < 90$
Cut 6: $\cos\theta_{\tau^+\tau^-} < -0.5$
Cut 7: $118 < M_{\mathrm{recoil}} < 143$

$Z \to ll$ Mode Results

	$ZH \to ee\tau\tau$	$ZH, H \nrightarrow \tau\tau$	$ee\tau\tau$	other 4 leptons.	other SM bkg.
No cut	228.3	7320	2.382e+05	5.423e+05	1.494e+10
After cut	**108.9**	2.5	72.4	1.1	0.034

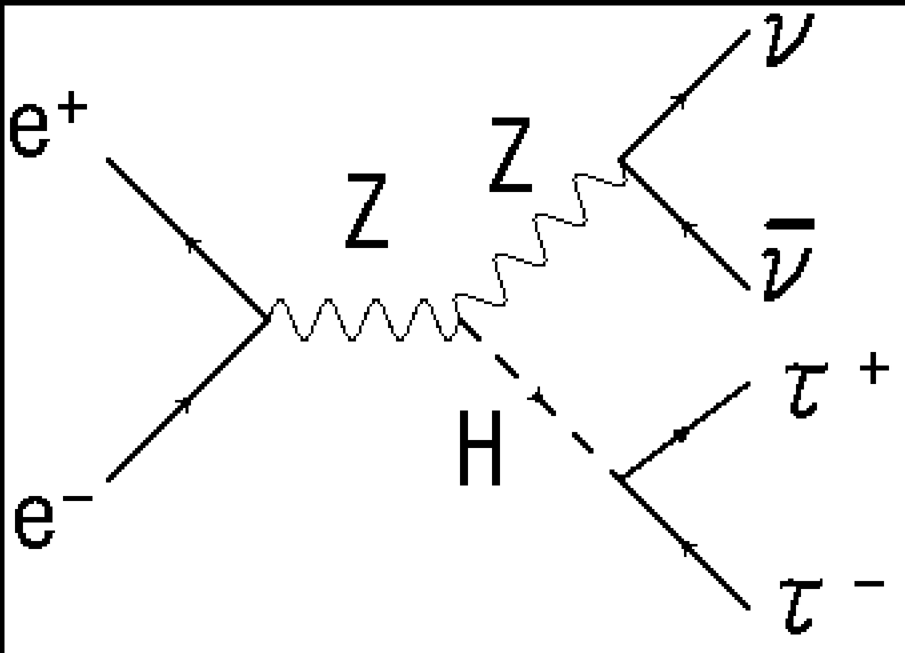
$$\text{significance}(Z \to e^+e^-) = \frac{108.9}{\sqrt{108.9 + 76.0}} = \mathbf{8.0\sigma}$$

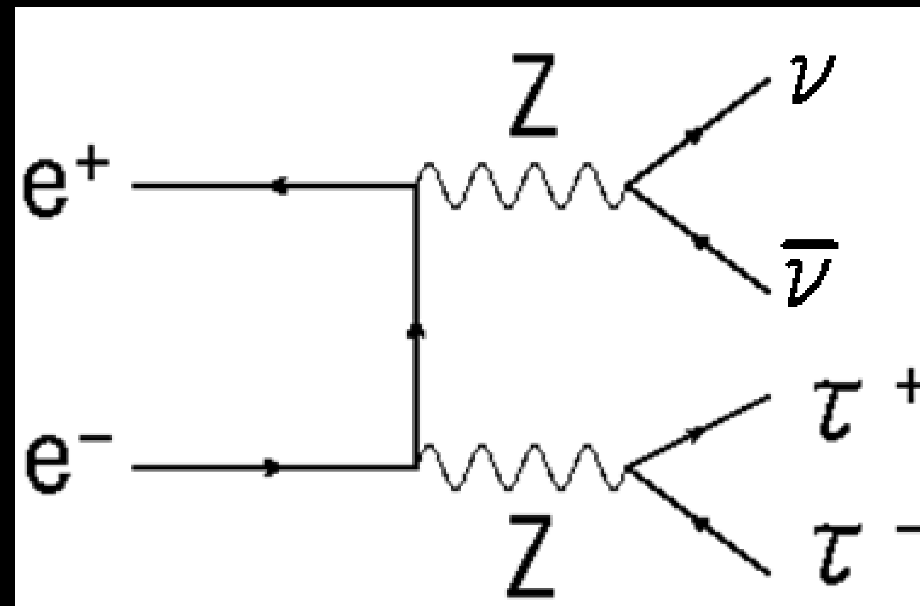
	$ZH \to \mu\mu\tau\tau$	$ZH, H \nrightarrow \tau\tau$	$\mu\mu\tau\tau$	other 4 leptons	other SM bkg.
No cut	211.1	7320	3513	7.589e+05	1.494e+10
After cut	**131.2**	2.9	82.8	5.3	0.30

$$\text{significance}(Z \to \mu^+\mu^-) = \frac{131.2}{\sqrt{131.2 + 91.2}} = \mathbf{8.8\sigma}$$

Analysis of $Z \rightarrow \nu\nu$ Mode

Signal & Background



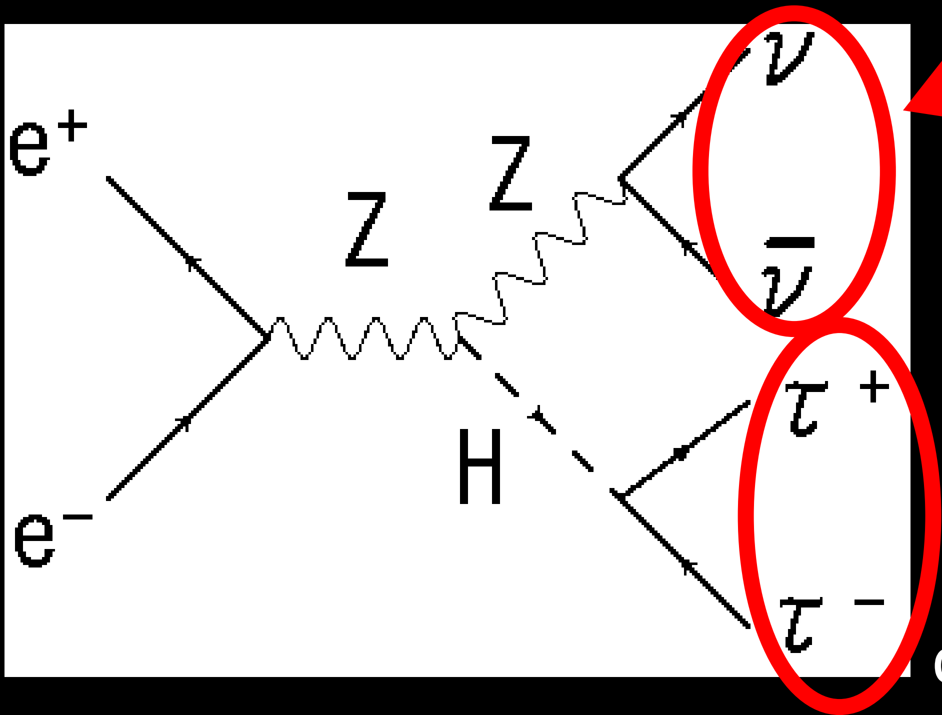


Signal

Background

Mainly comes from WW and ZZ

Event Reconstruction



can't reconstruct...

τ reconstruction

clustering based on τ mass
(This is the same method
which applied at $Z \rightarrow ll$ mode.)

Event Selection

pre-selection
(# of τ^+ == 1, # of τ^- == 1)

# of tracks == 2

# of tracks == 4

# of tracks == 6

applying cuts to each categories

Event Selection : # of tracks = 2

Cut 0 (pre-selection):
of τ^- jet == 1, # of τ^+ jet == 1, # of tracks == 2
Cut 1: # of pfos < 15
Cut 2: $30 < E_{\mathrm{vis}} < 105$
Cut 3: $5 < M_{\mathrm{vis}} < 90$
Cut 4: $M_{\mathrm{inv}} > 135$
Cut 5: $|\cos\theta_{\mathrm{missmom}}| < 0.95$
Cut 6: $0.75 < \mathrm{thrust} < 0.99$
Cut 7: $E_{\tau^+\tau^-} > 25$
Cut 8: $-0.92 < \cos\theta_{\tau^+\tau^-} < -0.5$
Cut 9: $\cos\theta_{\mathrm{acop}} < 0.98$
Cut 10: $\log_{10}|\min(d_0\mathrm{sig})\,| > -0.5$
Cut 11: $\log_{10}|\min(z_0\mathrm{sig})\,| > 0.3$
Cut 12: $\log_{10}|z_0\mathrm{sig}(\tau^-)\,| + \log_{10}|z_0\mathrm{sig}(\tau^+)\,| > 0.9$

Event Selection : # of tracks = 4

Cut 0 (pre-selection):
of τ^- jet == 1, # of τ^+ jet == 1, # of tracks == 4
Cut 1: # of pfos < 25
Cut 2: $30 < E_{\mathrm{vis}} < 115$
Cut 3: $M_{\mathrm{vis}} < 100$
Cut 4: $M_{\mathrm{inv}} > 110$
Cut 5: $\max P_{\mathrm{t}} > 5$
Cut 6: $|\cos\theta_{\mathrm{missmom}}| < 0.95$
Cut 7: $0.84 < \mathrm{thrust} < 0.99$
Cut 8: $M_{\tau^+\tau^-} < 115$
Cut 9: $-0.85 < \cos\theta_{\tau^+\tau^-} < -0.45$
Cut 10: $\cos\theta_{\mathrm{acop}} < 0.98$
Cut 11: $\log_{10}|\min(z_0\mathrm{sig})| > 0.1$
Cut 12: $\log_{10}|z_0\mathrm{sig}(\tau^-)| + \log_{10}|z_0\mathrm{sig}(\tau^+)| > 0.3$

Event Selection : # of tracks = 6

Cut 0 (pre-selection):
of τ^- jet == 1, # of τ^+ jet == 1, # of tracks == 6
Cut 1: 6 <= npfos < 20
Cut 2: $55 < E_{\mathrm{vis}} < 135$
Cut 3: $M_{\mathrm{vis}} < 120$
Cut 4: $M_{\mathrm{inv}} > 85$
Cut 5: $5 < \max P_{\mathrm{t}} < 45$
Cut 6: $|\cos\theta_{\mathrm{missmom}}| < 0.95$
Cut 7: $0.85 < \mathrm{thrust} < 0.95$
Cut 8: $M_{\tau^+\tau^-} > 45$
Cut 9: $-0.85 < \cos\theta_{\tau^+\tau^-} < -0.45$
Cut 10: $\cos\theta_{\mathrm{acop}} < 0.99$
Cut 11: $\log_{10}|\min(d_0\mathrm{sig})\,| > -1.5$
Cut 12: $\log_{10}|\min(z_0\mathrm{sig})\,| > -0.5$

$Z \rightarrow \nu\nu$ Mode Results

# of tracks == 2	$ZH \rightarrow \nu\nu\tau\tau$	$\tau\tau$	$\gamma\gamma \rightarrow \tau\tau$	$\nu\nu\tau\tau$	other SM bkg.	significance
Before cut	923.6	1.323e+06	2.905e+09	7.408e+04	3.088e+08	0.0163
After cut	290.5	1505	0	1.129e+04	3957	2.23

# of tracks == 4	$ZH \rightarrow \nu\nu\tau\tau$	$\tau\tau$	$\gamma\gamma \rightarrow \tau\tau$	$\nu\nu\tau\tau$	other SM bkg.	significance
Before cut	371.2	5.321e+05	6.216e+08	2.616e+04	5.839e+07	0.0142
After cut	140.9	290.9	0	4013	1771	1.79

# of tracks == 6	$ZH \rightarrow \nu\nu\tau\tau$	$\tau\tau$	$\gamma\gamma \rightarrow \tau\tau$	$\nu\nu\tau\tau$	other SM bkg.	significance
Before cut	50.30	7.709e+04	4.864e+07	3092	2.104e+07	0.00602
After cut	22.53	0	0	380.9	140.4	0.966

Combined significance : 3.0σ