Higgs branching ratio studies I : τ pair

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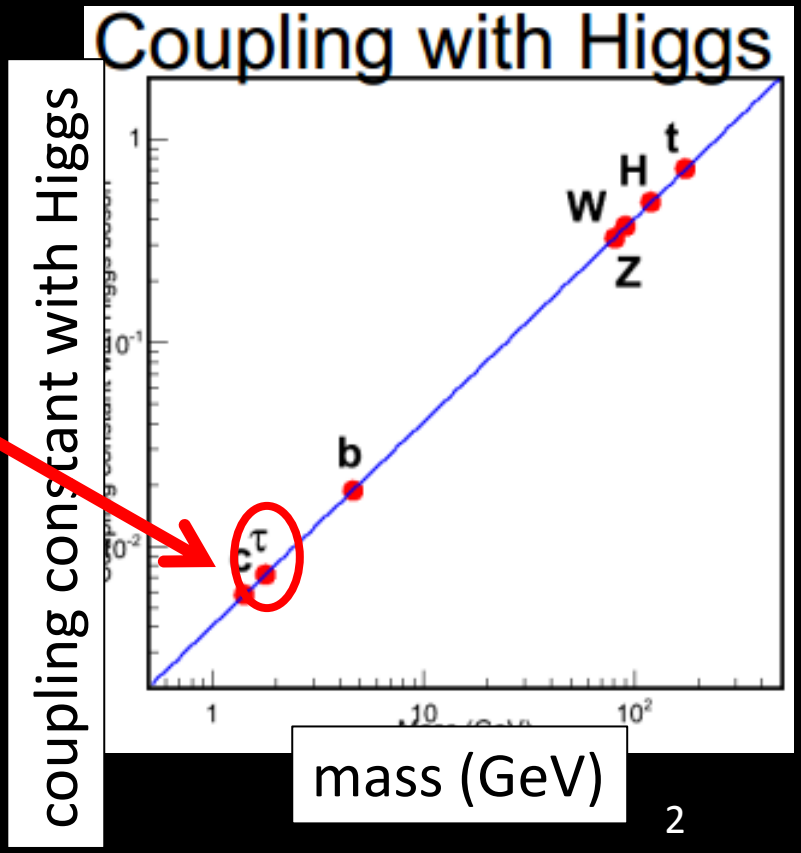
Introduction

- Higgs-like particle was found at the LHC!
- Investigation of the detail of that particle is important, especially the verification of mass generation mechanism.

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

Previous study with fast simulation
-> 4.6 - 7.1 % ($M_H = 120$ GeV, RDR)



Analysis condition

- Higgs properties
  - $M_H = 120\ \mathrm{GeV}$
  - $\mathrm{Br}(H \to \tau\tau) = 8.0\ \%$ (PYTHIA)
- Machine parameters
  - $E_{\mathrm{CM}} = 250\ \mathrm{GeV}$
  - Integrated luminosity $L = 250\ \mathrm{fb}^{-1}$
  - Polarization $P(e^+, e^-) = (+0.3, -0.8)$
- Simulation conditions
  - Full simulation with ILD_00 detector model
  - Using LOI samples for now

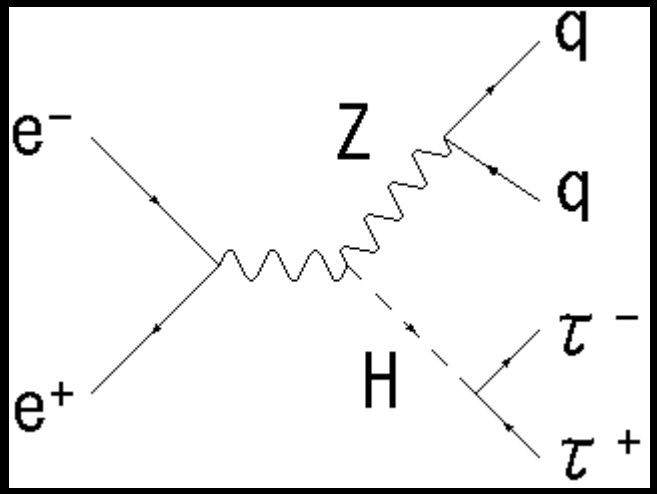
Signal process

$e^+e^- \rightarrow ZH$

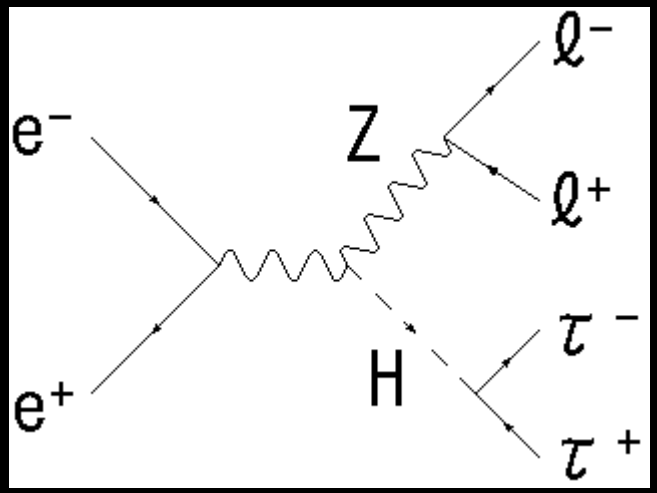
$\tau^+\tau^-$

- $\nu\bar{\nu}$ (~20 %)
- $q\bar{q}$ (~70 %)
- l^+l^- (~10 %)

$Z \rightarrow qq$



$Z \rightarrow ll$

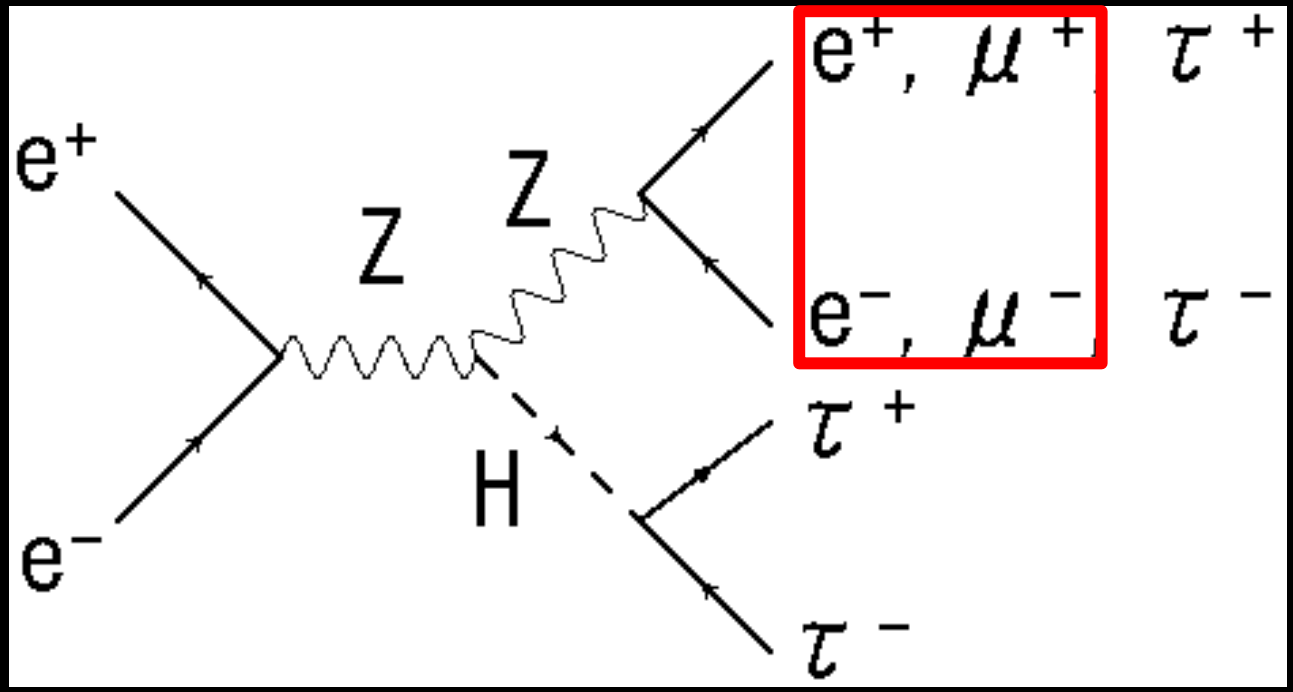


Analysis of $Z \to ll$ mode

(See also my talk @ LCWS12)

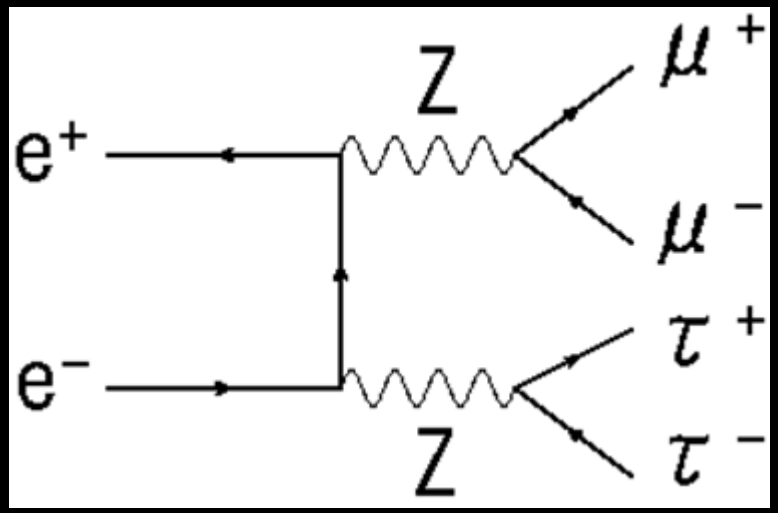
Signal process

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

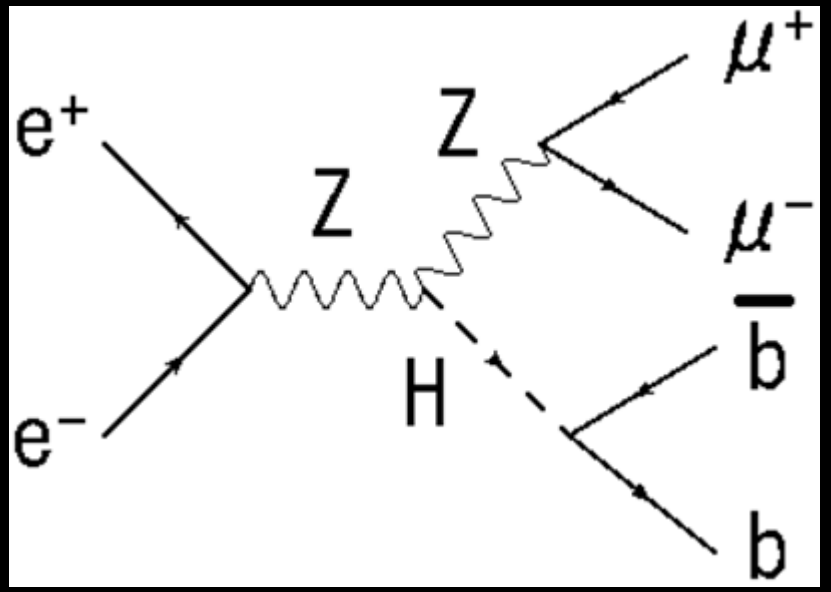


Main background

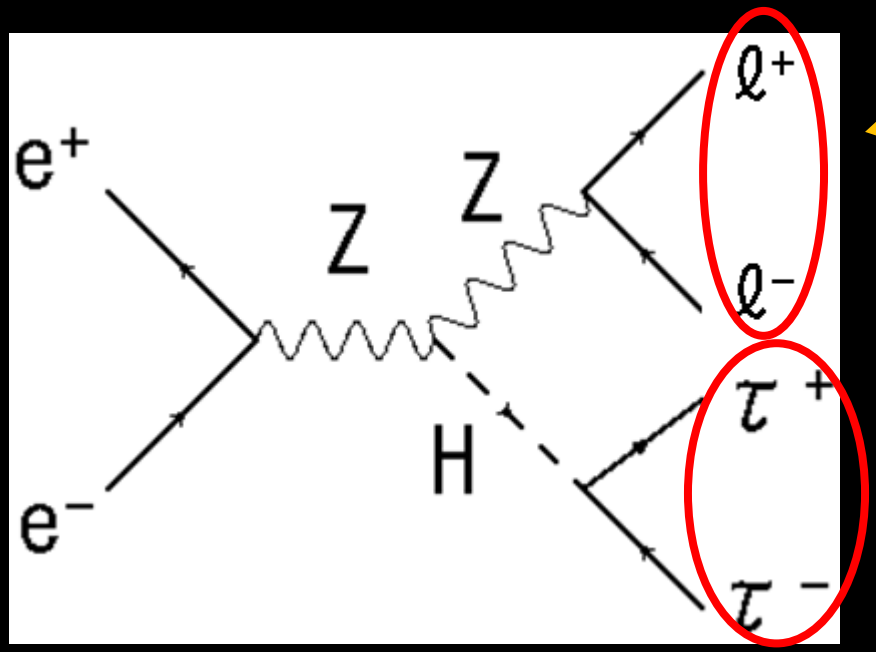
4 leptons background
$eeee, ee\mu\mu, ee\tau\tau,$
$\mu\mu\mu\mu, \mu\mu\tau\tau, \tau\tau\tau\tau$



ZH with other Higgs decays



Event reconstruction



1: Z reconstruction

- lepton ID

identify e/μ by using $\frac{E_{\mathrm{ECAL}}}{E_{\mathrm{ECAL}}+E_{\mathrm{HCAL}}}$ and $\frac{E_{\mathrm{ECAL}}+E_{\mathrm{HCAL}}}{P_{\mathrm{track}}}$

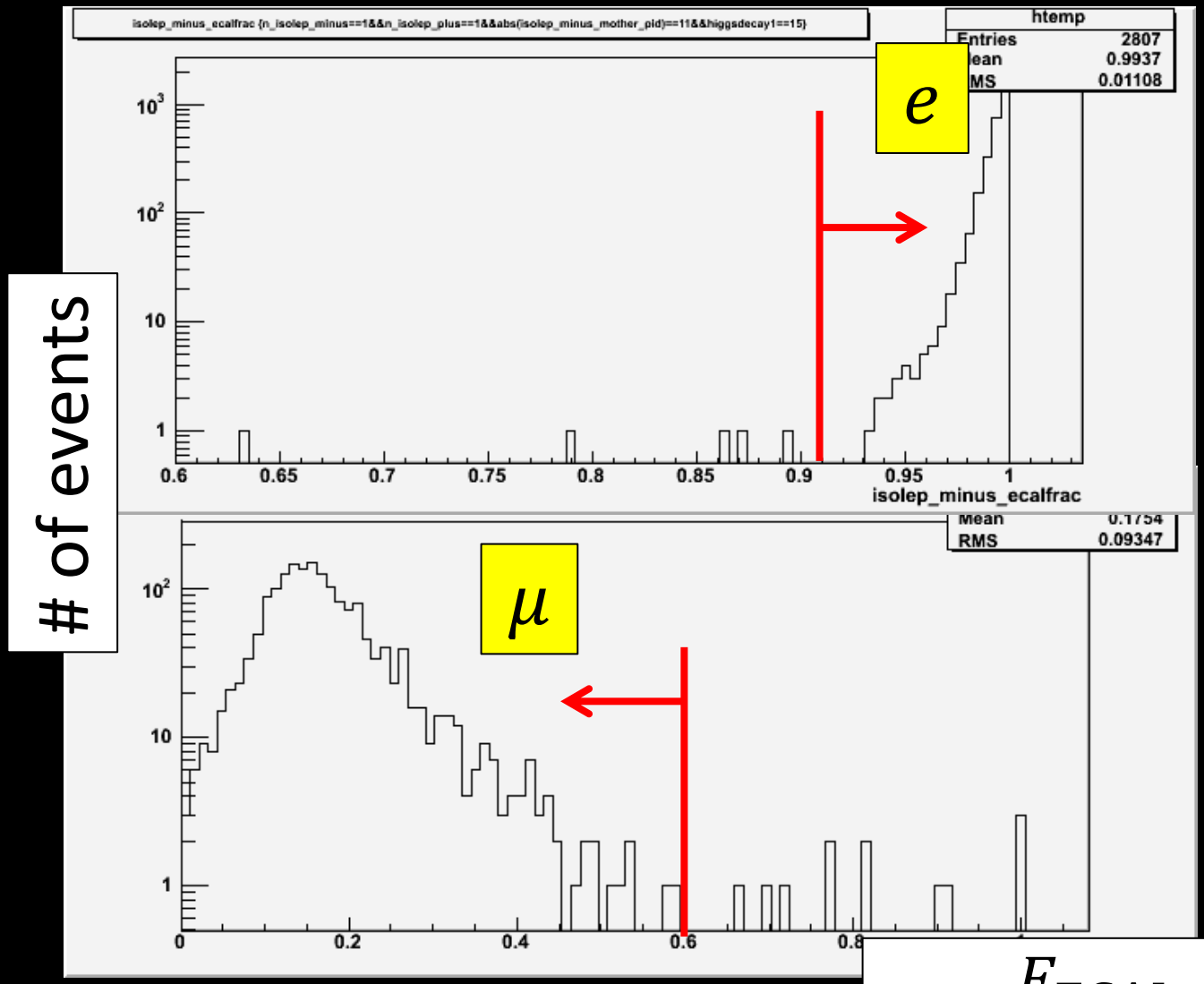
- τ rejection

do not use tracks displaced from IP

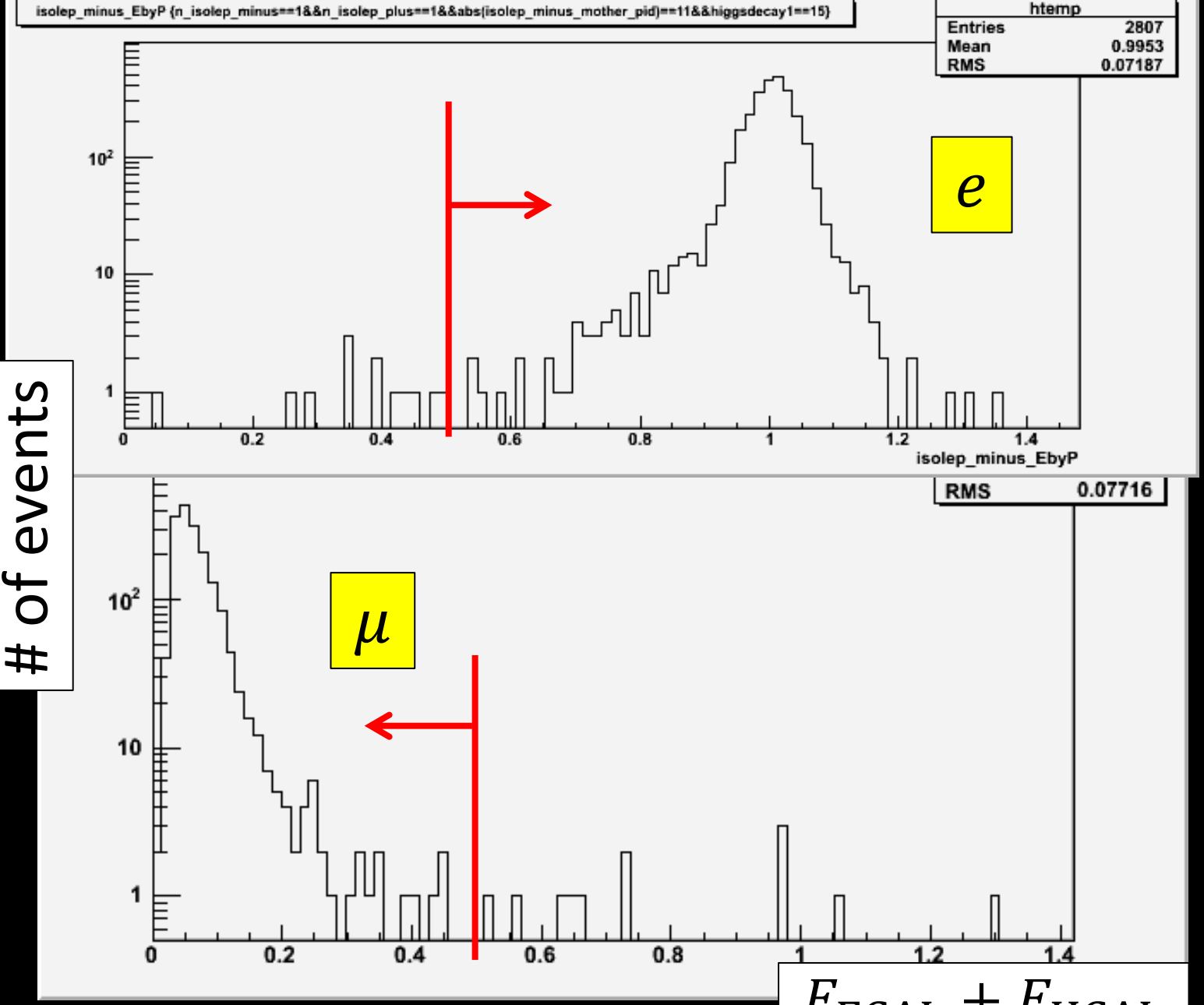
2: τ reconstruction

clustering based on τ mass

Z reconstruction (1) : Lepton ID

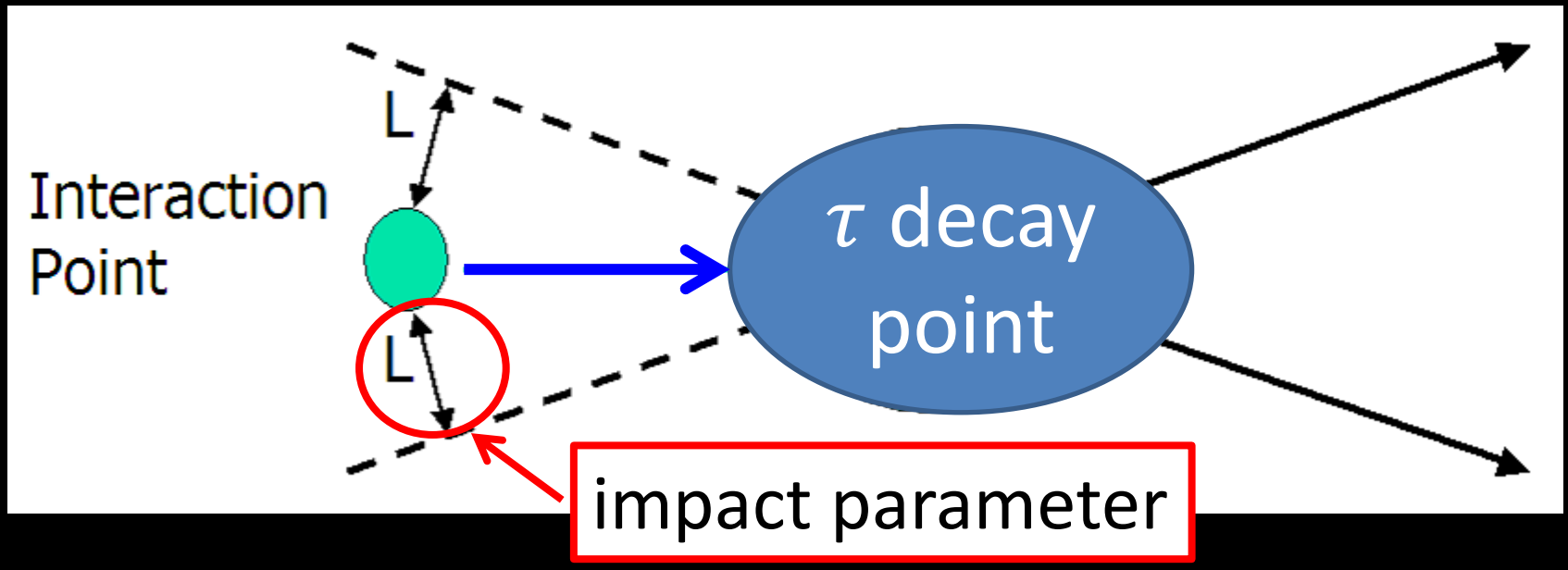


$$\frac{E_{\mathrm{ECAL}}}{E_{\mathrm{ECAL}} + E_{\mathrm{HCAL}}}$$



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

Z reconstruction (2) : τ rejection

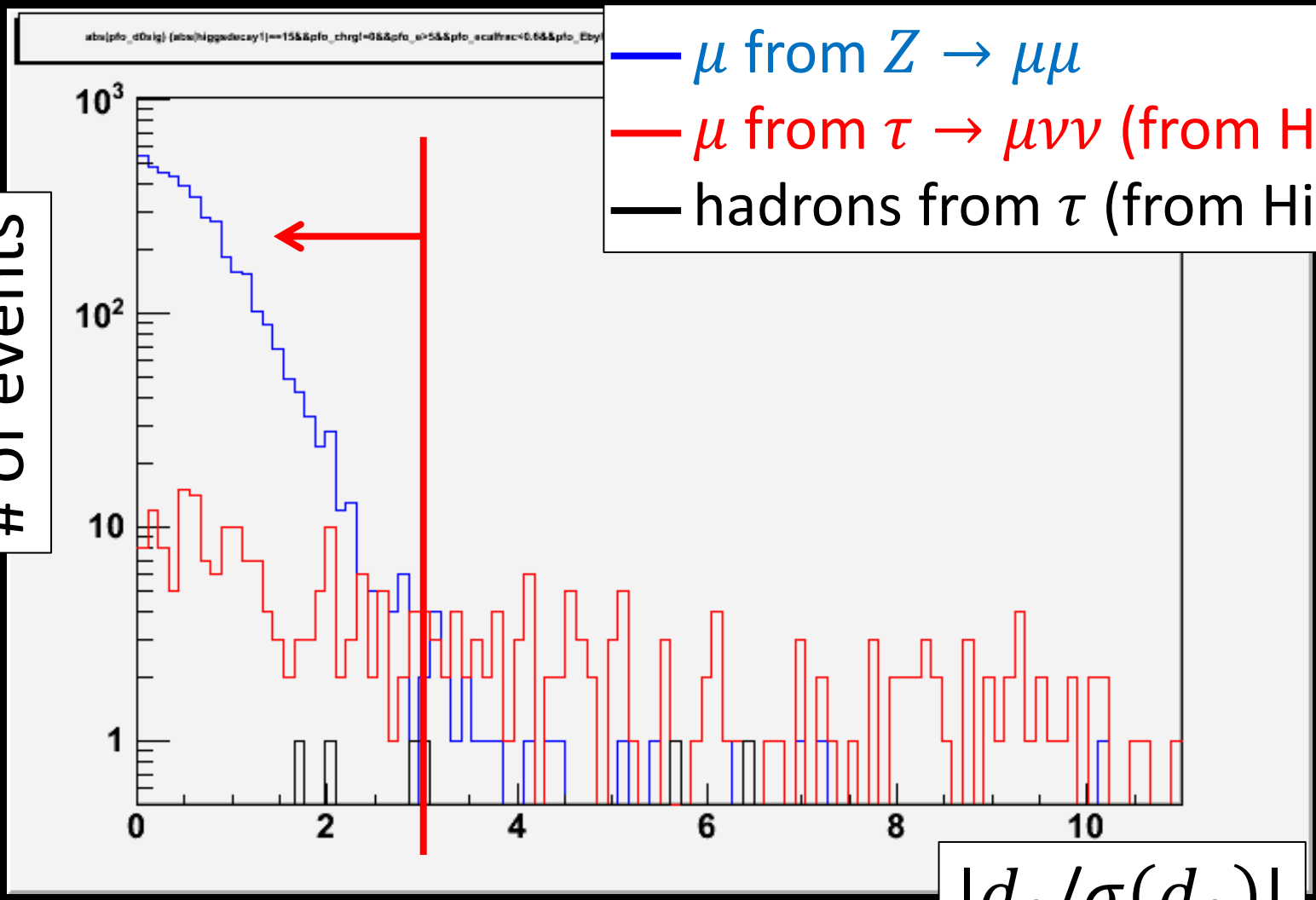


use impact parameter for τ rejection

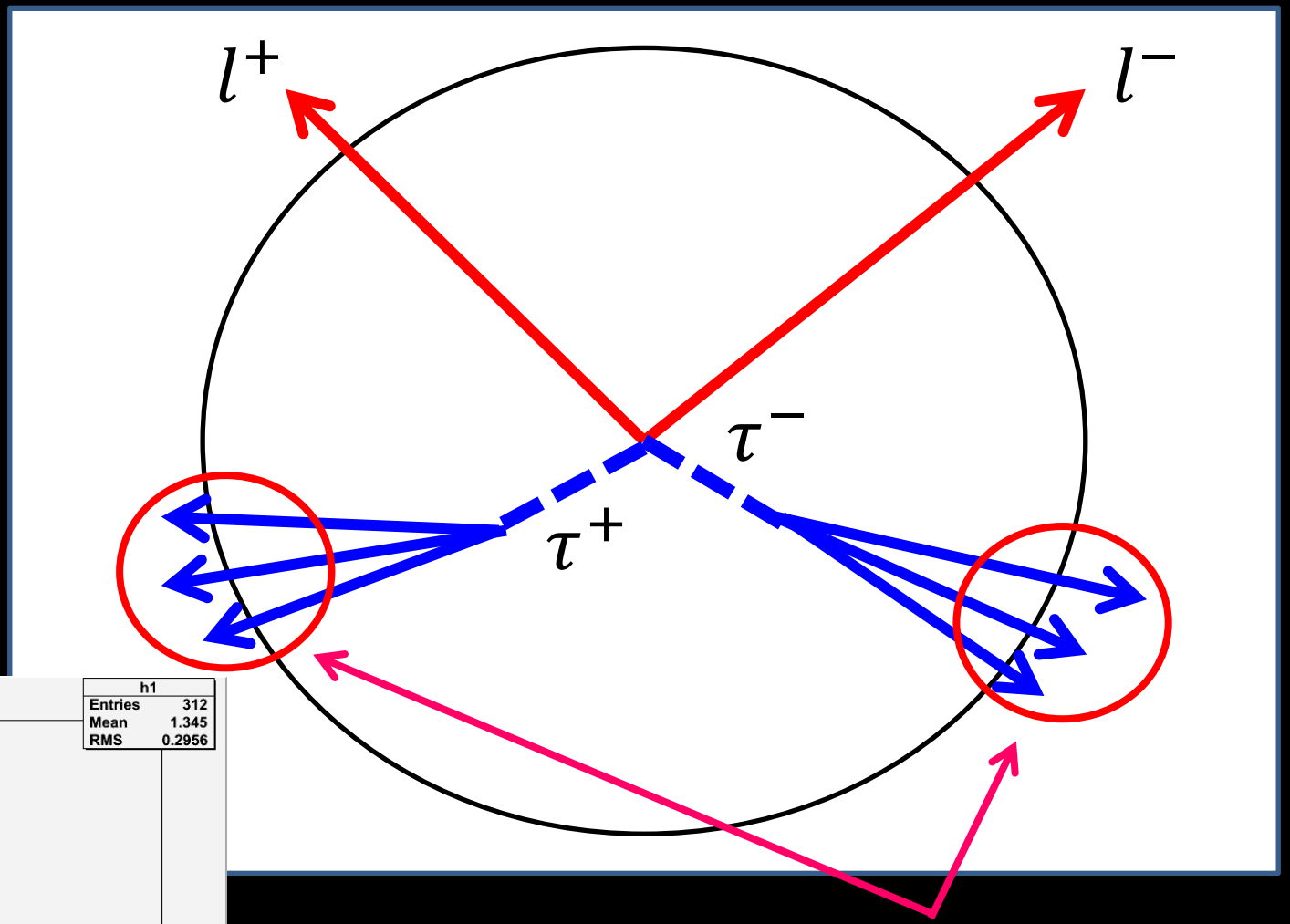
d_0: perpendicular to beam axis (x-y plane)

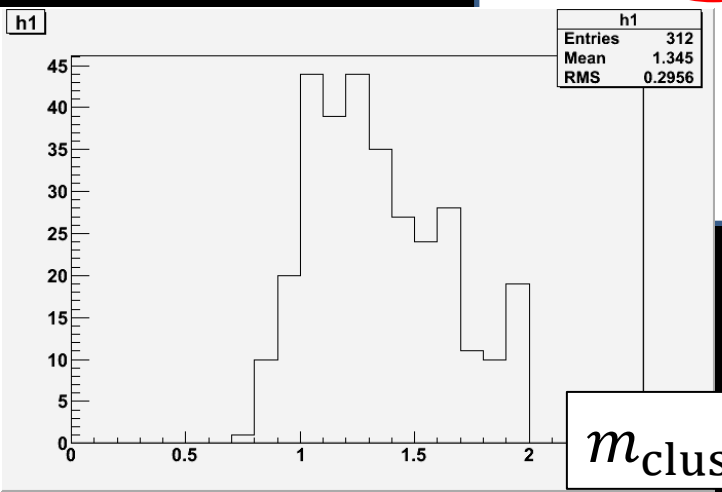
z_0: along to beam axis

τ rejection : example plot



τ reconstruction





m_{cluster} (GeV)

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

Event selection ($Z \to ee$)

Cut 0 (pre-selection):
require e^+e^- candidate,
of τ^- candidate == 1,
of τ^+ candidate == 1,

select e and τ

Cut 1: # of tracks <= 8

Cut 2: $110 < E_{\mathrm{vis}} < 240$

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

Cut 4: $70 < M_Z < 110$

Z mass cut

Cut 5: $90 < E_Z < 120$

Cut 6: $\cos\theta_{e^-} < 0.92, \cos\theta_{e^+} > -0.92$

Cut 7: $20 < E_{e^-} < 90, 20 < E_{e^+} < 90$

Cut 8: $\cos\theta_{e^+e^-} < -0.2$

Cut 9: $\cos\theta_{\tau^+\tau^-} < -0.4$

Cut 10: $\cos\theta_{\tau^-} < 0.92, \cos\theta_{\tau^+} > -0.92$

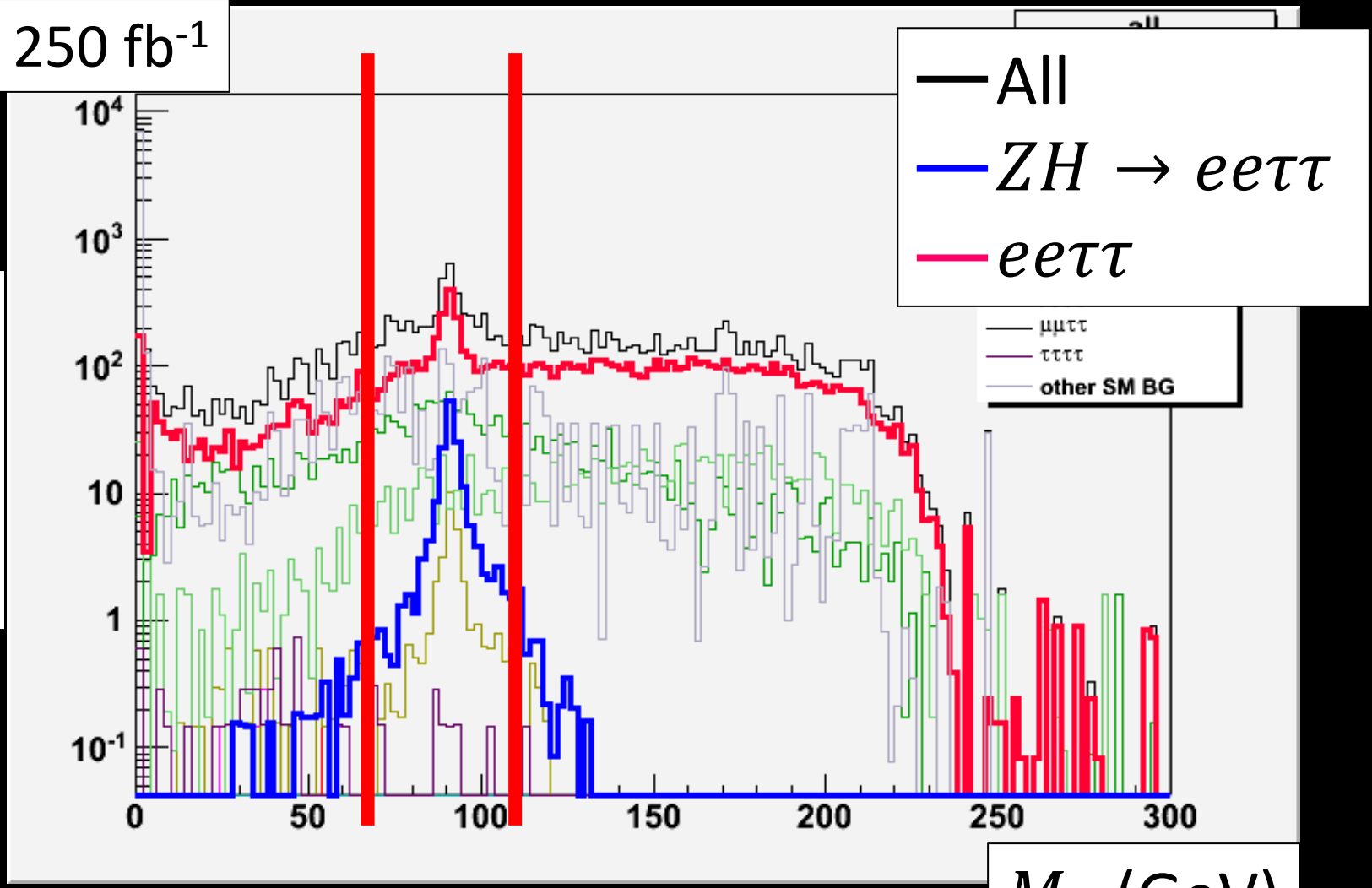
suppress
t-channel diagram

Cut 11: $116 < M_{\mathrm{recoil}} < 134$

suppress
irreducible bkg

Event selection ($Z \to ee$)

$L = 250$ fb^{-1}



Event selection ($Z \to \mu\mu$)

Cut 0 (pre-selection):
require $\mu^+\mu^-$ candidate,
of τ^+ candidate == 1,
of τ^- candidate == 1

select μ and τ

Cut 1: # of tracks <= 8

Cut 2: $110 < E_{\mathrm{vis}} < 240$

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

Cut 4: $70 < M_Z < 110$

Z mass cut

Cut 5: $90 < E_Z < 120$

Cut 6: $E_{e^+} < 90, E_{e^-} < 90$

Cut 7: $\cos\theta_{e^+e^-} < -0.2$

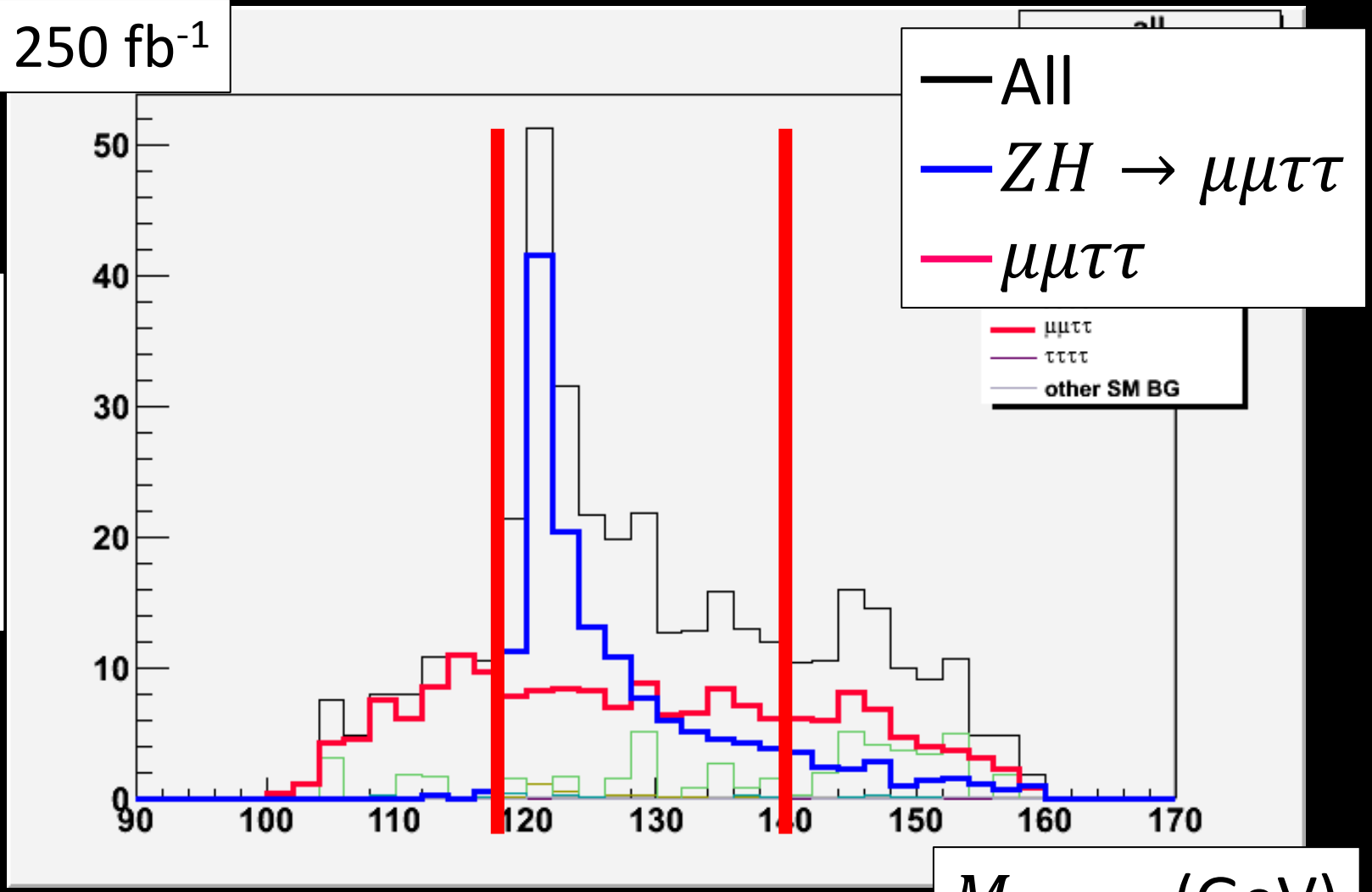
Cut 8: $\cos\theta_{\tau^+\tau^-} < -0.45$

Cut 9: $118 < M_{\mathrm{recoil}} < 140$

suppress irreducible bkg

Event selection ($Z \to \mu\mu$)

$L = 250$ fb^{-1}



$Z \to ll$ mode results

	$ZH \to ee\tau\tau$	ZH no τ	$ee\tau\tau$	other 4 lep.	other SM Bkg
No cut	228.3	7320	2.382e+05	5.423e+05	1.494e+10
After cut	**97.2**	2.5	63.6	7.7	0.025

$$\text{significance}(Z \to e^+e^-) = \frac{97.2}{\sqrt{97.2 + 73.8}} = \mathbf{7.4\sigma}$$

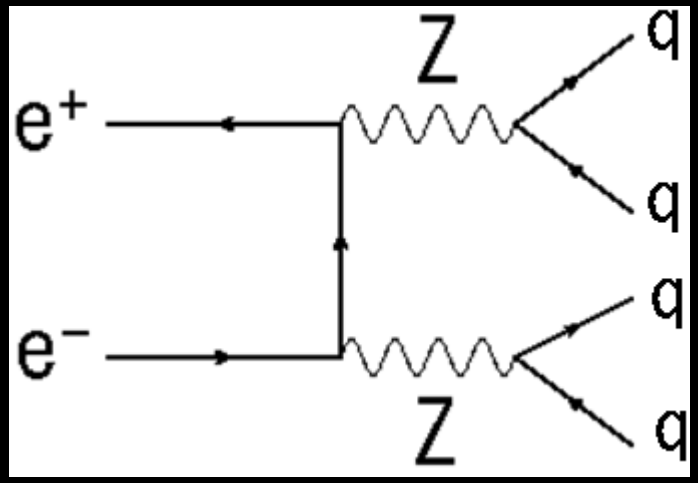
	$ZH \to \mu\mu\tau\tau$	ZH no τ	$\mu\mu\tau\tau$	other 4 lep.	other SM Bkg
No cut	211.1	7320	3513	7.589e+05	1.494e+10
After cut	**129.5**	3.2	84.0	17.8	0.16

$$\text{significance}(Z \to \mu^+\mu^-) = \frac{129.5}{\sqrt{129.5 + 105.2}} = \mathbf{8.5\sigma}$$

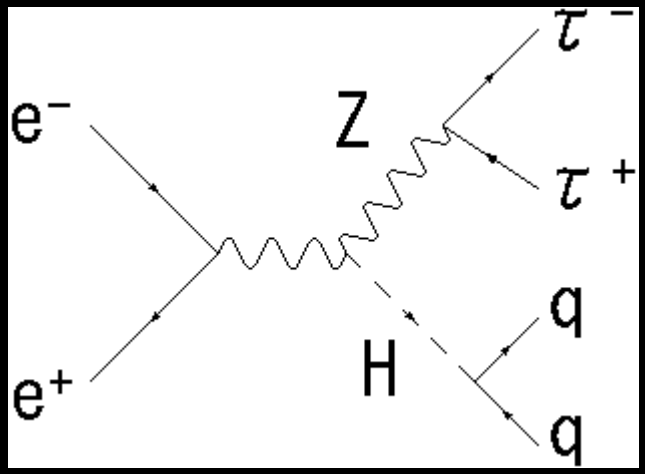
Analysis of $Z \rightarrow qq$ mode

Main background

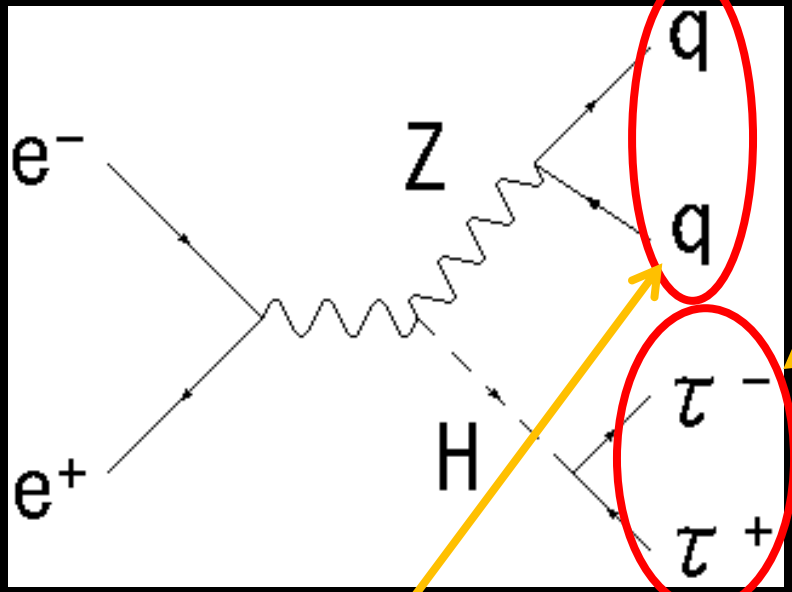
$qqqq$
$qqll$ ($qq\tau\tau$: irreducible)
$qq\nu\nu$



$ZH \rightarrow llqq$
($Z \rightarrow \tau\tau$: mimic signal)



Event reconstruction



1: τ reconstruction

clustering based on τ mass

τ-jet finder

2: Z reconstruction

Durham 2-jet clustering

by T. Suehara

TaJet finder (1)

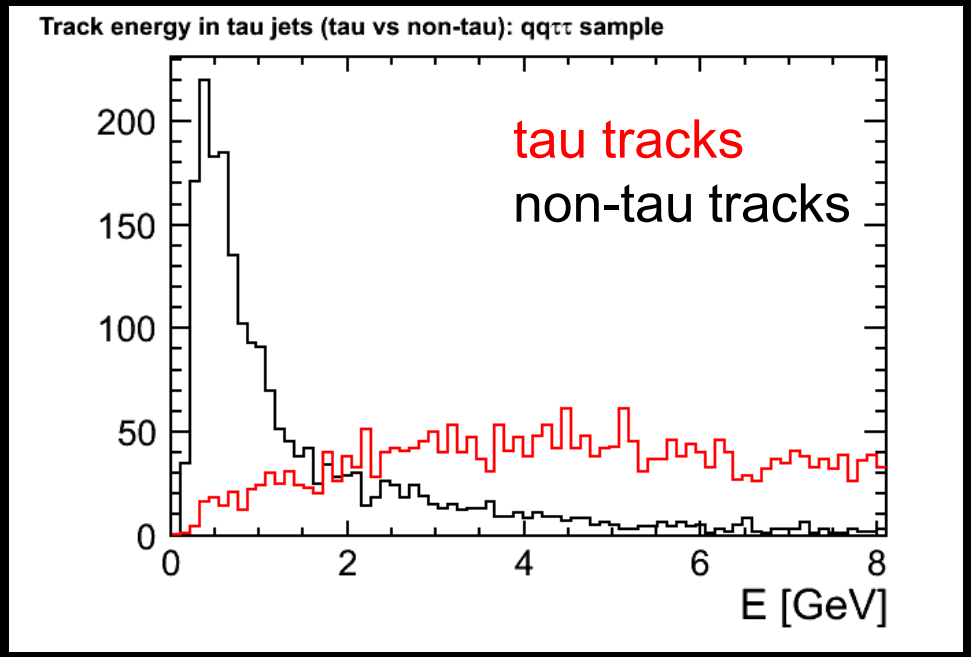
High-purity tau tagging
in presence of jet background

1. Order charged tracks by largest energy
2. Select the first track
3. Combine neighboring particles -> “Tau Jet”
   - Combined mass < 2 GeV && cosθ 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 -> qqττ 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

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	qqττ	qqln
0	27.1%	47.6%
1	36.3%	46.6%
2	34.0%	5.4%
>3	2.4%	0.3%

purity of tau in qqττ:
94.2% overall
96.5% for # tau jets == 2

Event selection ($Z \to qq$)

Cut 0 (pre-selection)
of q jets == 2, # of τ jets == 2, # of τ^+ jet == 1, # of τ^- jet == 1,
of tracks in $\tau[0]$ jet <= 3, # of tracks in $\tau[1]$ jet <= 3,
!(# of tracks in $\tau[0]$ jet == 3 && # of tracks in $\tau[1]$ jet == 3)

select τ

Cut 1: 9 <= # of tracks < 50

Cut 2: $120 < E_{\mathrm{vis}} < 235$

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

Cut 4: $80 < M_Z(M_{qq}) < 100$ → Z mass cut

Cut 5: $80 < E_Z(E_{qq}) < 130$

Cut 6: $\cos\theta_{qq2j} < -0.2$

Cut 7: $15 < M_{\tau^+\tau^-} < 115$

Cut 8: $E_{\tau^+\tau^-} < 120$

Cut 9: $\cos\theta_{\tau^+\tau^-} < -0.45$

Cut 10: $\log_{10}(|d_0\mathrm{sig}(\tau^+)|) + \log_{10}(|d_0\mathrm{sig}(\tau^-)|) > 0$

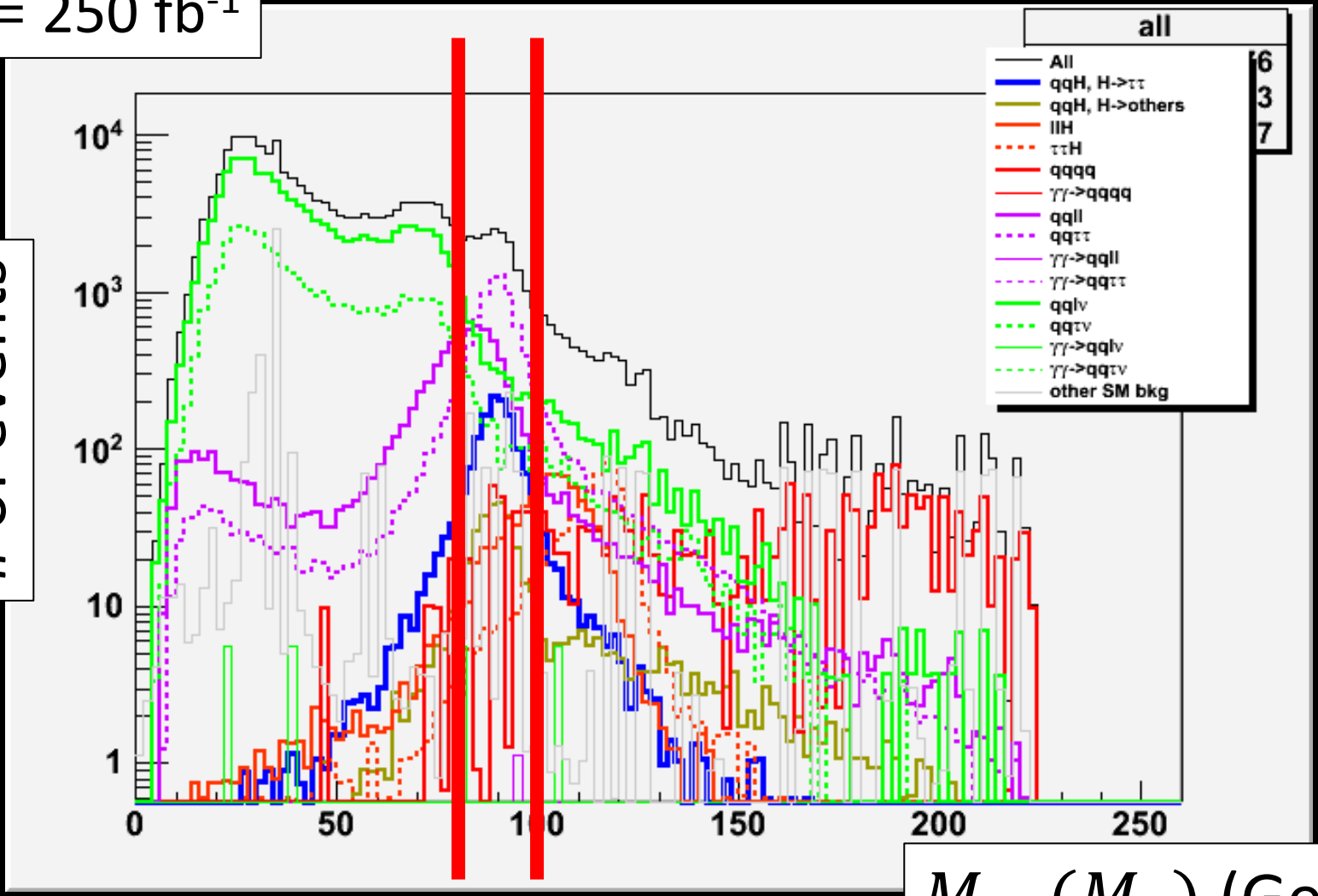
Cut 11: $\log_{10}(|z_0\mathrm{sig}(\tau^+)|) + \log_{10}(|z_0\mathrm{sig}(\tau^-)|) > -0.1$

Cut 12: $113 < M_{\mathrm{recoil}} < 154$

suppress irreducible bkg

Event selection ($Z \to qq$)

$L = 250$ fb^{-1}



$Z \to qq$ mode result

	$ZH \to qq\tau\tau$	ZH no τ	$qq\tau\tau$	ZH with $Z \to \tau\tau$	other SM Bkg
No cut	4233	4.803e+04	4.168e+05	2596	1.475e+10
After cut	**927.9**	8.6	681.8	31.5	325.4

$$\text{significance}(Z \to qq) = \frac{927.9}{\sqrt{927.9 + 1047}} = \mathbf{20.9\sigma}$$

Summary

- We estimated the precision of the branching ratio of $H \to \tau\tau$ mode with full detector simulation (ILD model) at E_{CM} = 250 GeV.

$L = 250\ \mathrm{fb}^{-1}, M_H = 120\ \mathrm{GeV}, Br(H \to \tau\tau) = 8.0\ \%$

	$Z \to ee$	$Z \to \mu\mu$	$Z \to qq$
significance	7.4σ	8.5σ	20.9σ

⇨ Combined significance = $\mathbf{23.7\sigma}$

⇨ $\dfrac{\Delta(\sigma \cdot \mathrm{Br})}{\sigma \cdot \mathrm{Br}} = \mathbf{4.2\ \%}$

Extrapolated to 125 GeV

	$M_H = 120$ GeV	$M_H = 125$ GeV
$\mathrm{Br}(H \to \tau\tau)$	8.0 % (PYTHIA)	6.32 % (LHC-tuned)
$Z \to ee$	7.4σ	5.8σ
$Z \to \mu\mu$	8.5σ	6.5σ
$Z \to qq$	20.9σ	15.9σ
Combined	23.7σ	18.1σ
$\frac{\Delta(\sigma \cdot \mathrm{Br})}{\sigma \cdot \mathrm{Br}}$	4.2 %	5.5 %

Future plans

- Higgs mass ($\tau\tau$ mass) reconstruction
- Analysis of $Z \rightarrow \nu\nu$ mode
- Analysis with Neural Network

Backup slides

Cut Summary
$Z \rightarrow ee$ mode

Cuts	eeH	not $H \to \tau\tau$	$ee\tau\tau$	other 4 leptons	ee	$e\gamma$	$\gamma\gamma$	other SM Bkg	sig.
none	228.3	7320	2.382e+05	5.243e+05	4.325e+09	3.022e+09	7.532e+09	6.350e+07	0.00187
pre-sel	171.3	47.05	1.338e+04	2.091e+05	4.692e+06	1.365e+06	4.146e+06	4.702e+04	0.0534
# of tracks <= 8	169.4	41.56	1.316e+04	2.083e+05	4.560e+06	1.352e+06	4.131e+06	4.218e+04	0.0532
$110 < E_{\mathrm{vis}} < 240$	167.4	39.41	1.216e+04	1.562e+04	2.422e+06	8.830e+05	3.406e+06	2.563e+04	0.0642
$\lvert\cos\theta_{\mathrm{missmom}}\rvert < 0.98$	164.4	38.33	8987	3164	6.936e+05	4.364e+04	31.26	1.044e+04	0.189
$70 < M_Z < 110$	154.7	30.60	2653	1039	6177	2.091e+04	23.83	1130	0.863
$90 < E_Z < 120$	150.6	28.99	1085	394.5	0	1.840e+04	23.83	638.3	1.05
$\cos\theta_{e^-} < 0.92$ $\cos\theta_{e^+} > -0.92$	136.2	25.43	473.8	111.5	0	225.0	0	311.9	3.80
$20 < E_{e^-} < 90$ $20 < E_{e^+} < 90$	135.5	25.40	407.1	100.9	0	225.0	0	259.3	3.99
$\cos\theta_{e^-e^+} < -0.2$	134.0	25.05	354.7	89.55	0	225.0	0	257.5	4.07
$\cos\theta_{\tau^-\tau^+} < -0.4$	132.2	4.159	214.6	64.91	0	0	0	151.2	5.55
$\cos\theta_{\tau^-} < 0.92$ $\cos\theta_{\tau^+} > -0.92$	124.7	3.697	186.8	19.69	0	0	0	3.545	6.78
$116 < M_{\mathrm{recoil}} < 134$	97.19	2.491	63.61	7.657	0	0	0	0.025	7.43

Cut Summary
$Z \to \mu\mu$ mode

Cuts	$\mu\mu H$	not $H \to \tau\tau$	$\mu\mu\tau\tau$	other 4 leptons	ee	$e\gamma$	$\gamma\gamma$	other SM Bkg	sig.
none	211.1	7320	3513	7.589e+05	4.325e+09	3.023e+09	7.532e+09	6.350e+07	0.00187
pre-sel	168.5	43.01	1698	7547	0	6062	71.56	1598	1.28
# of tracks <= 8	167.4	39.65	1684	7538	0	6062	71.56	1266	1.29
$110 < E_{\mathrm{vis}} < 240$	164.8	37.85	1629	2973	0	3081	33.17	638.7	1.78
$\lvert\cos\theta_{\mathrm{missmom}}\rvert < 0.98$	160.6	36.97	1423	434.1	0	0	0	61.42	3.49
$70 < M_Z < 110$	156.2	33.01	1078	129.0	0	0	0	47.94	4.11
$90 < E_Z < 120$	154.6	32.55	394.5	81.93	0	0	0	38.15	5.86
$E_{e^-} < 90$ $E_{e^+} < 90$	154.6	32.55	366.4	73.89	0	0	0	34.01	6.01
$\cos\theta_{e^+e^-} < -0.2$	152.8	32.23	321.4	68.64	0	0	0	33.85	6.19
$\cos\theta_{\tau^+\tau^-} < -0.45$	149.0	3.948	184.2	52.78	0	0	0	0.603	7.54
$118 < M_{\mathrm{recoil}} < 140$	129.5	3.185	84.02	17.76	0	0	0	0.155	8.46

Cut Summary
$Z \to qq$ mode

$l = e$ or μ	qqH $H \to \tau\tau$	qqH $H \to$ others	$qqqq$	$\gamma\gamma$ $\to qqqq$	$qqll$	$\gamma\gamma$ $\to qqll$	$qqlv$	$\gamma\gamma$ $\to qqlv$	sig.
No cut	4233	4.803e+04	4.084e+06	733.6	3.555e+05	1627	2.788e+06	394.3	0.03
pre-sel 1	1659	605.3	1.450e+04	0.108	6.426e+04	375.0	1.314e+05	28.18	0.32
pre-sel 2	1647	578.8	1.284e+04	0.108	6.378e+04	375.0	1.249e+05	22.55	0.32
pre-sel 3	1629	568.8	1.193e+04	0.108	6.370e+04	375.0	1.247e+05	22.55	0.32
# of tracks	1625	543.7	1.150e+04	0.108	6.054e+04	278.9	1.213e+05	22.55	2.02
E_{vis}	1581	485.2	4132	0	2.098e+04	86.31	1.186e+05	22.55	2.52
$\cos\theta_{\mathrm{missmom}}$	1547	467.9	2014	0	8304	1.122	1.165e+05	22.55	3.57
$M_Z(M_{qq})$	1230	274.1	258.2	0	3780	1.122	3962	5.630	8.88
$E_Z(E_{qq})$	1230	274.1	238.0	0	3541	1.122	3868	5.630	9.19
$\cos\theta_{qq2j}$	1153	257.9	139.3	0	2278	1.122	2366	5.630	10.7
$M_{\tau\tau}$	1148	229.1	100.3	0	2117	1.122	2211	5.630	11.0
$E_{\tau\tau}$	1131	229.1	90.15	0	1671	1.122	2165	5.630	11.1
$\cos\theta_{\tau\tau}$	1125	31.94	29.97	0	704.9	1.122	867.7	0	15.7
$d_0\mathrm{sig}$	1006	11.69	19.64	0	139.5	0	269.4	0	17.7
$z_0\mathrm{sig}$	973.6	8.771	19.64	0	65.83	0	198.4	0	17.9
M_{recoil}	927.9	8.625	19.64	0	47.78	0	116.2	0	20.9

$l = e$ or μ	qqH $H \to \tau\tau$	llH	$\tau\tau H$	$qq\tau\tau$	$\gamma\gamma \to qq\tau\tau$	$qq\tau\nu$	$\gamma\gamma \to qq\tau\nu$	other SM bkg	sig.
No cut	4233	5377	2596	4.168e+04	1762	1.326e+06	225.6	1.474e+10	0.03
pre-sel 1	1659	2765	811.2	1.172e+04	64.58	5.213e+04	0	2.621e+07	0.32
pre-sel 2	1647	2761	801.6	1.161e+04	35.30	4.948e+04	0	2.570e+07	0.32
pre-sel 3	1629	2761	792.2	1.149e+04	34.81	4.839e+04	0	2.545e+07	0.32
# of tracks	1625	2680	756.6	1.133e+04	32.38	4.697e+04	0	3.892e+05	2.02
E_{vis}	1581	1015	731.9	1.088e+04	30.55	4.423e+04	0	1.907e+05	2.52
$\cos\theta_{\mathrm{missmom}}$	1547	860.3	713.1	1.004e+04	1.832	4.162e+04	0	5419	3.57
$M_Z(M_{qq})$	1230	275.4	81.36	7138	0	1553	0	641.6	8.88
$E_Z(E_{qq})$	1230	275.0	81.07	6309	0	1506	0	567.8	9.19
$\cos\theta_{qq2j}$	1153	269.5	78.54	3541	0	921.5	0	562.2	10.7
$M_{\tau\tau}$	1148	266.6	76.59	3424	0	781.6	0	483.2	11.0
$E_{\tau\tau}$	1131	263.3	76.58	3420	0	781.6	0	481.4	11.1
$\cos\theta_{\tau\tau}$	1125	152.9	41.97	1362	0	354.2	0	464.4	15.7
$d_0\mathrm{sig}$	1006	27.94	36.93	1211	0	270.5	0	238.0	17.7
$z_0\mathrm{sig}$	973.6	12.21	36.03	1161	0	237.2	0	237.6	17.9
M_{recoil}	927.9	10.25	31.48	681.8	0	130.3	0	1.263	20.9