# BSM search using Higgs to invisible decay at the ILC

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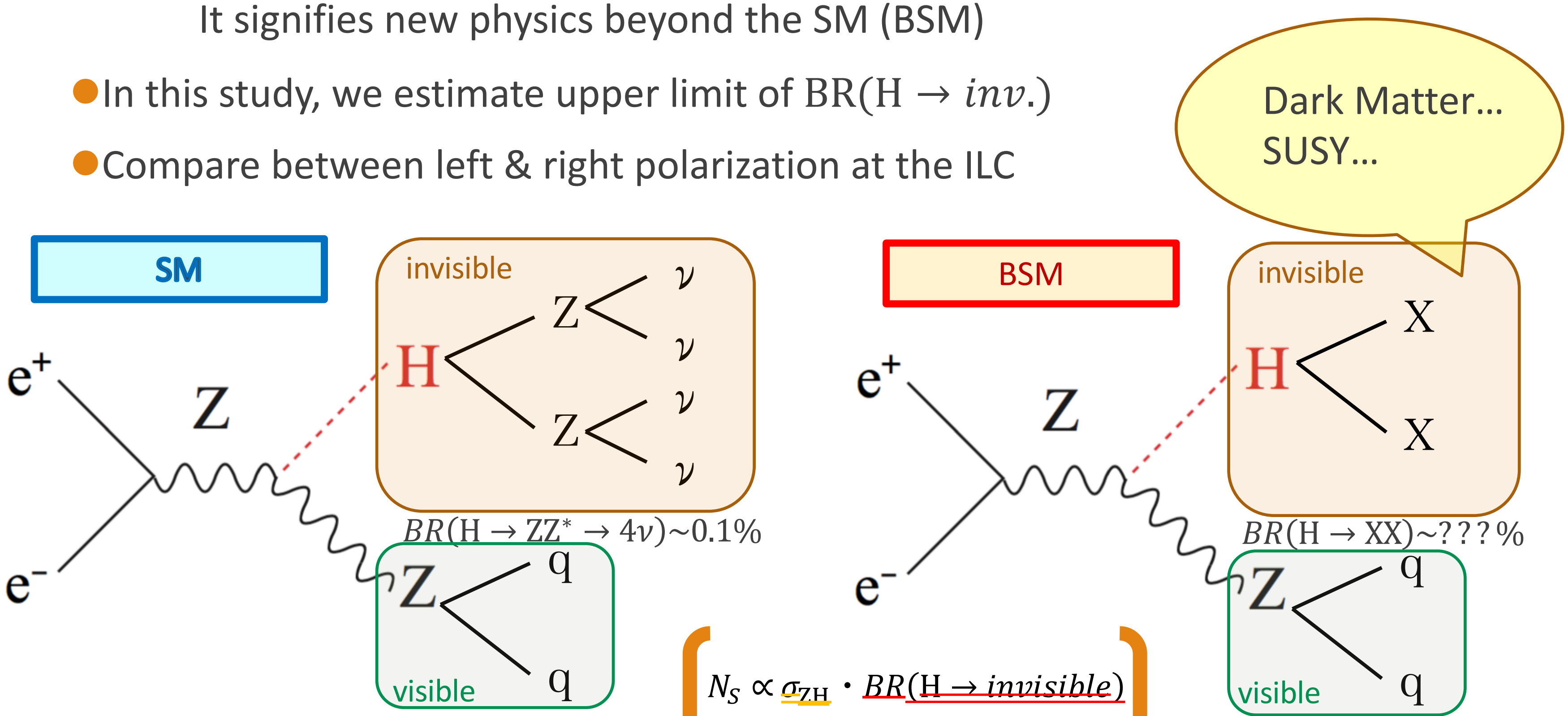
# Motivation

- In the SM, Higgs decays invisibly through
  $H \to ZZ^* \to 4\nu$ (BR($H \to inv.$)~0.1%)
- If BR($H \to inv.$) exceeds SM prediction ,
  It signifies new physics beyond the SM (BSM)
- In this study, we estimate upper limit of BR($H \to inv.$)
- Compare between left & right polarization at the ILC




$N_S \propto \sigma_{ZH} \cdot BR(H \to invisible)$

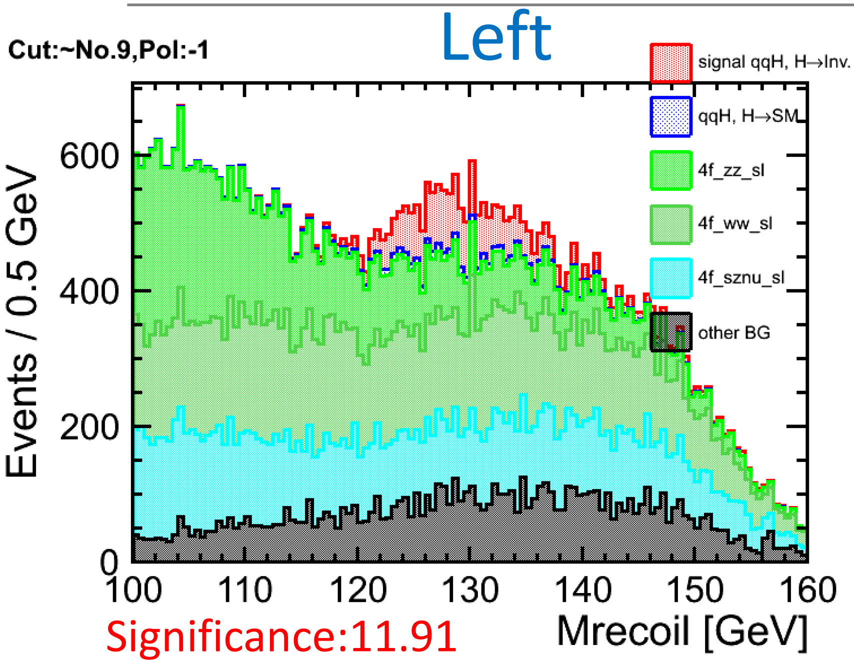
# Setting & Flow of analysis

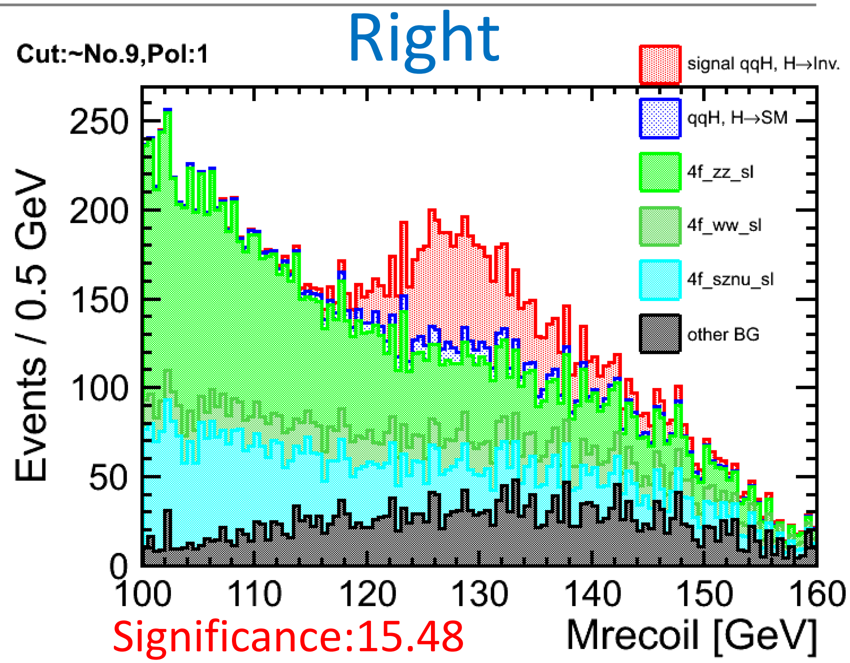
- Setting
  - Generator: WHIZARD 1.95
  - Samples: DBD sample + Dirac sample ($\mathrm{e^+e^- \to qqH, H \to ZZ^* \to 4\nu}$)
  - Detector: the ILD full simulation
  - $E_{cm}$ = 250 GeV, $\int Ldt$ = 250 $fb^{-1}$ , $(P_{e^-}, P_{e^+}) = (-0.8, +0.3), (+0.8, -0.3)$
- Flow of analysis
  - Isolated lepton tagging → veto
  - Jet clustering
    1. remove gamma-gamma overlay from particle flow objects (PandoraPFA) by using kt algorithm jet clustering
    2. forced 2-jet reconstruction using LCFIPlus
  - Event selection (mention next page)
    - assume BR(H→invisible)=10%
  - Fit & Toy Monte Carlo to set upper limit

# Event Selection

1. Isolated lepton veto
2. Loose restriction of transverse di-jet momentum, di-jet invariant mass, and recoil mass from di-jet
3. Number of particle flow objects(PFO) and charged tracks: $N_{pfo}$, $N_{track}$
4. Transverse di-jet (Z) momentum: $Pt_Z$
5. Invariant mass of di-jet (Z mass): $M_Z$
6. Polar angle of di-jet (Z) direction: $\theta_Z$
7. Acoplanarity angle: $\varphi = \pi - (\phi_1 - \phi_2)$
   ($\phi_i$: transverse direction angle of jet)
8. Recoil mass: $M_{recoil}$
9. Boosted Decision Tree(BDT) method selection (multi-variate analysis)

# Recoil Mass Plots [Ecm = 250 GeV, 250 $fb^{-1}$,BR(H->inv.)=10%]




| MVA input variables | |
|---|---|
| mz | cosj1 |
| cosz | cosj2 |

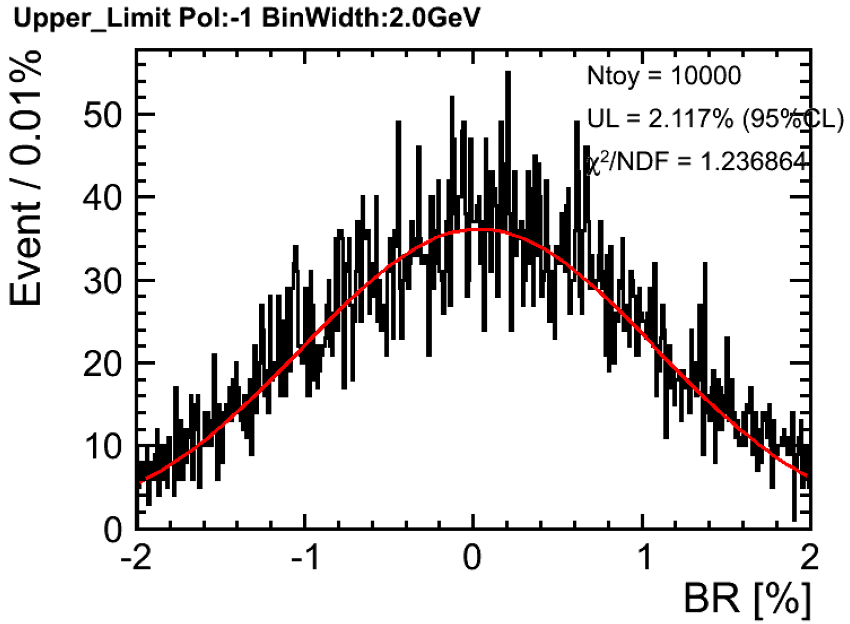
TMVA v-4.2.0

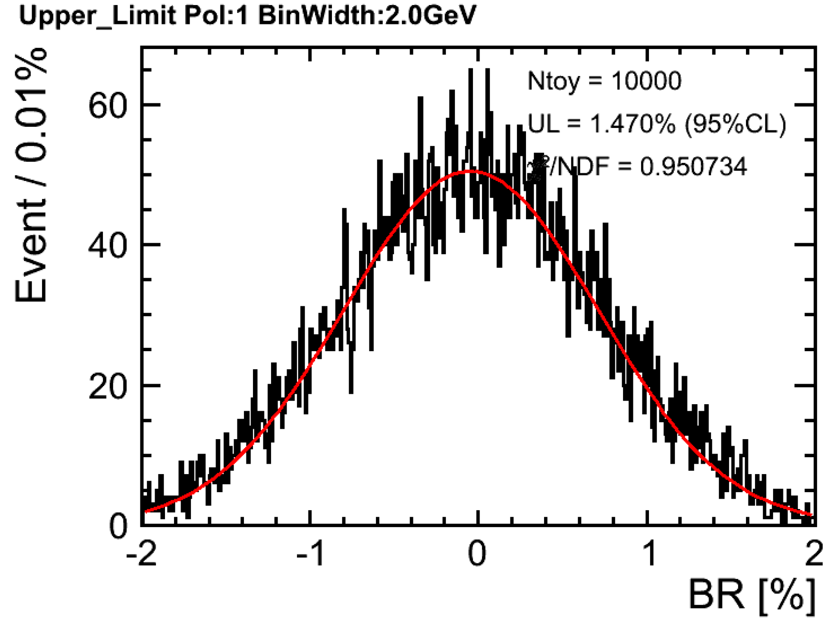
| No. | Cut | No. | Cut |
|---|---|---|---|
| 1 | Isolated lepton veto | 6 | \|cosθZ\|<0.9 |
| 2 | Loose Cut (Ptz,Mz,Mrecoil) | 7 | Acoplanarity < 3.0 |
| 3 | Npfo>15 & Ntrack>6 & Ntrackji>1 | 8 | 100 < Mrecoil < 160 |
| 4 | 20 < Ptz < 80 | 9 | BDT cut |
| 5 | 80 < Mz < 100 | | |

# Toy Monte Carlo to set upper limit

bin width:2.0 GeV
bkg : all fixed

| Left | Right |
|---|---|




UL=2.12% (95%CL)

UL=1.47% (95%CL)

# Summary & Plans

Use the measurement of $\mathrm{BR}(\mathrm{H} \rightarrow inv.)$ as a means for indirect BSM search

- Motivation
  - set upper limit (UL) on $\mathrm{BR}(\mathrm{H} \rightarrow inv.)$
  - develop analysis method to achieve high sensitivity
  - compare between alternative polarization
  - study is based on full ILD detector simulation, at $\mathrm{E_{cm}}$ = 250 GeV, assuming 250 $\mathrm{fb}^{-1}$
- Status
  - optimized data selection methods
  - set UL using toy MC for both left and right scenario

| | Left polarization | Right polarization |
|---|---|---|
| UL of BR [%] (95%CL) | 2.12 | 1.47 |

- Plan
  - improve sensitivity through further optimization of analysis methods and jet energy resolution
  - analysis at $\mathrm{E_{cm}}$ = 350, 500 GeV, compare between different scenarios
    --> contribute to optimization of ILC run scenario
  - study systematic errors

# Back Up

# Recoil Mass Method

- We can measure Higgs without directly looking at it
  → model independent

$$M_{rec}^2 = (\sqrt{s} - E_Z)^2 - |\vec{p}_Z|^2$$

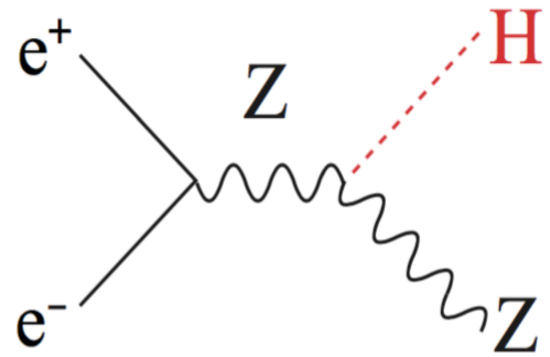
- Higgs-strahlung cross section can be obtained using the leptonic decay of Z

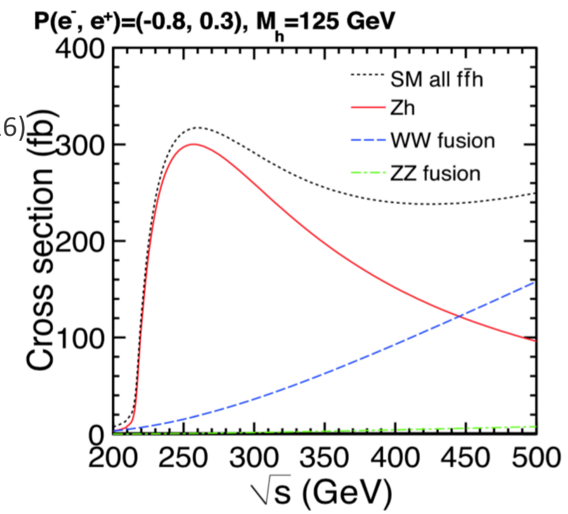
$$\sigma_{\mathrm{ZH}} = \frac{N_S}{BR(\mathrm{Z} \to l^+ l^-)\varepsilon_S L}$$

$\varepsilon_S$: signal efficiency, $\mathrm{N_S}$: # of signal, $L$ : integrated luminosity

J.Yan(KEK) *et al.* "Measurement of the Higgs boson mass and $e^+e^- \to$ ZH cross section using $Z \to \mu^+\mu^-$ and $Z \to e^+e^-$ at the ILC" (2016)

- For BSM search, this study uses hadronic channel $Z \to qq$ and $E_{cm} = 250$ GeV



# Hadronic Channel Analysis

## Cut table [Ecm=250GeV,250fb$^{-1}$,Left]

Polarization: (e-,e+) = (-0.8,+0.3)

Reduction Table

| Process | 2f_l | 2f_h | 4f_l | 4f_sl | 4f_h | llH | BG | qqH | Signal | Signf |
|---|---|---|---|---|---|---|---|---|---|---|
| Cross Section | 38176.9 | 78046.1 | 5655.8 | 18398.3 | 16799.3 | 109.233 | 157186 | 210.184 | 21.0184 | |
| Generated | 5.76948e+06 | 3.17329e+06 | 3.14632e+06 | 4.9795e+06 | 2.74204e+06 | 280686 | | 568687 | 39601 | |
| Expected | 9.54422e+06 | 1.95115e+07 | 1.41395e+06 | 4.59957e+06 | 4.19983e+06 | 27308.2 | 3.92964e+07 | 52546 | 5254.6 | 0.837615 |
| Cut0 | 9.16132e+06 | 1.94897e+07 | 1.35278e+06 | 4.59883e+06 | 4.19983e+06 | 27124.7 | 3.88296e+07 | 52546 | 5254.06 | 0.84254 |
| Cut1 | 1.71542e+06 | 1.93796e+07 | 162691 | 1.64702e+06 | 4.19268e+06 | 19411.4 | 2.71168e+07 | 47847.5 | 5248.7 | 1.00695 |
| Cut2 | 151655 | 385894 | 38813 | 351506 | 112295 | 9742.59 | 1.04991e+06 | 3541.23 | 4900.03 | 4.76305 |
| Cut3 | 858.166 | 301045 | 329.353 | 261376 | 104008 | 9056.2 | 676673 | 3288.26 | 4757.17 | 5.749 |
| Cut4 | 447.409 | 56407.6 | 261.745 | 224864 | 94406.5 | 8332.75 | 384720 | 3043.3 | 4522.98 | 7.22142 |
| Cut5 | 150.217 | 11283.9 | 108.044 | 96769.5 | 17966.9 | 2578.67 | 128857 | 976.355 | 3560.58 | 9.74882 |
| Cut6 | 145.312 | 5988.7 | 99.5936 | 85404.1 | 15545.7 | 2516.72 | 109700 | 910.916 | 3439.33 | 10.1842 |
| Cut7 | 10.7462 | 5252.55 | 88.5166 | 81391.3 | 15258.4 | 2381.82 | 104383 | 889.332 | 3305.78 | 10.0323 |
| Cut8 | 10.6587 | 5208 | 85.6002 | 81088.7 | 15240.2 | 2367.81 | 104001 | 888.704 | 3301.29 | 10.0366 |
| Cut9 | 6.1032 | 1360.8 | 53.2566 | 41402.1 | 4634.01 | 1451.31 | 48907.6 | 484.159 | 2717.91 | 11.9063 |

# Hadronic Channel Analysis

## Cut table [Ecm=250GeV,250fb$^{-1}$,Right]

Polarization: (e-,e+) = (+0.8,-0.3)

Reduction Table

| Process | 2f_l | 2f_h | 4f_l | 4f_sl | 4f_h | llH | BG | qqH | Signal | Signf |
|---|---|---|---|---|---|---|---|---|---|---|
| Cross Section | 34983.6 | 46214.9 | 1467.78 | 2063.18 | 1568.29 | 63.9953 | 86361.8 | 141.951 | 14.1951 | |
| Generated | 5.76948e+06 | 3.17329e+06 | 3.14632e+06 | 4.9795e+06 | 2.74204e+06 | 280686 | | 568687 | 39601 | |
| Expected | 8.74591e+06 | 1.15537e+07 | 366946 | 515794 | 392073 | 15998.8 | 2.15904e+07 | 35487.8 | 3548.78 | 0.763055 |
| Cut0 | 8.3892e+06 | 1.15318e+07 | 355972 | 515506 | 392073 | 15895.6 | 2.12004e+07 | 35487.8 | 3548.26 | 0.769916 |
| Cut1 | 1.47311e+06 | 1.14602e+07 | 54961.3 | 220242 | 391346 | 10916.8 | 1.36107e+07 | 32298.4 | 3544.2 | 0.959414 |
| Cut2 | 107981 | 241389 | 4395.3 | 52923.6 | 11049.2 | 5664.63 | 423403 | 2376.08 | 3303.43 | 5.04307 |
| Cut3 | 530.851 | 185648 | 34.1624 | 44254.5 | 10254.8 | 5275.35 | 245998 | 2209.22 | 3204.19 | 6.39037 |
| Cut4 | 255.591 | 29948.8 | 26.4309 | 38270.7 | 9234.84 | 4917.57 | 82654 | 2047.21 | 3037.24 | 10.2538 |
| Cut5 | 78.9459 | 5488.86 | 8.79024 | 22133 | 2002.74 | 1484.08 | 31196.5 | 657.579 | 2381.7 | 12.872 |
| Cut6 | 69.9076 | 2688.71 | 7.5148 | 19426.4 | 1720.71 | 1449.48 | 25362.7 | 619.917 | 2305.86 | 13.7097 |
| Cut7 | 9.38775 | 2448.04 | 6.85208 | 18506.1 | 1692.47 | 1376.41 | 24039.3 | 607.134 | 2208.31 | 13.4757 |
| Cut8 | 7.92505 | 2423.53 | 6.67759 | 18462.6 | 1690.81 | 1368.73 | 23960.2 | 606.369 | 2205.93 | 13.4818 |
| Cut9 | 4.73756 | 846.263 | 5.5476 | 11387.7 | 789.307 | 1065.89 | 14099.5 | 424.513 | 1989.68 | 15.4832 |

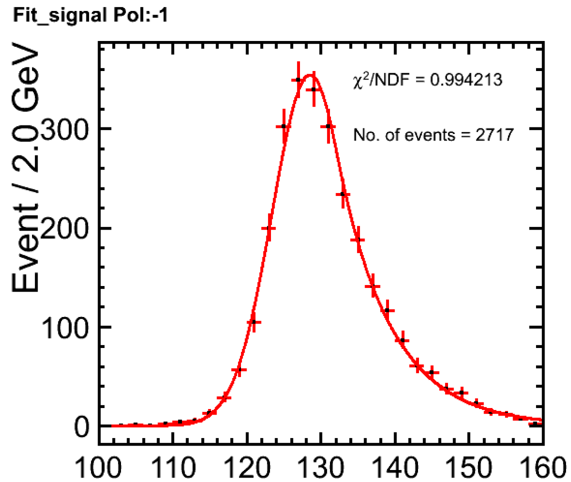
# Fit signal & bkg

signal: GPET (Gaussian + Exponential)

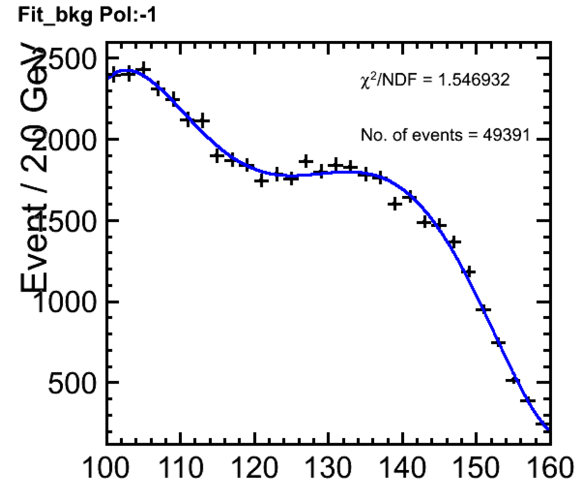
bkg : $5^{th}$ order polynomial

bin width:2.0 GeV

## Left

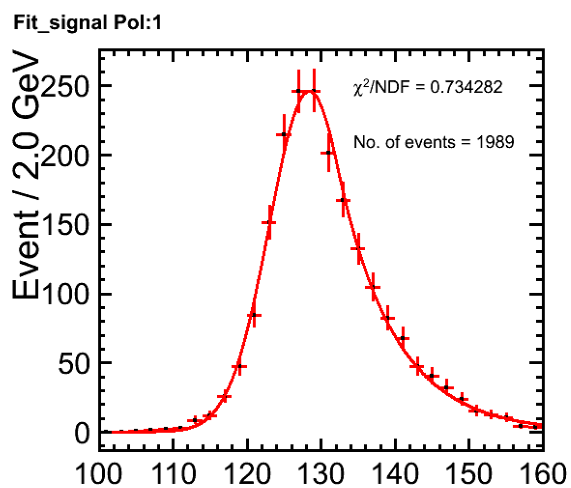



$\chi^2/\mathrm{NDF} = 0.994$

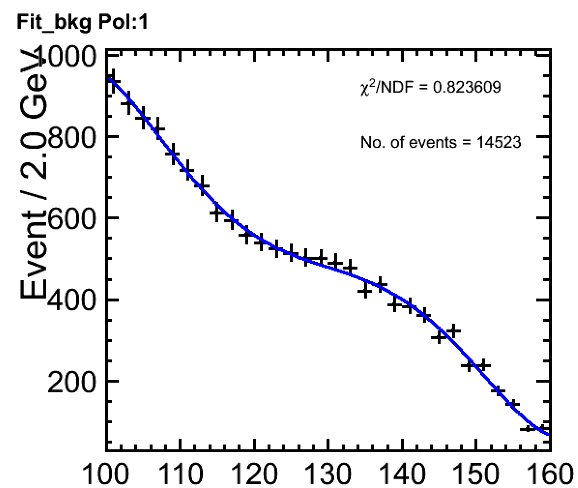



$\chi^2/\mathrm{NDF} = 1.55$

## Right




$\chi^2/\mathrm{NDF} = 0.734$

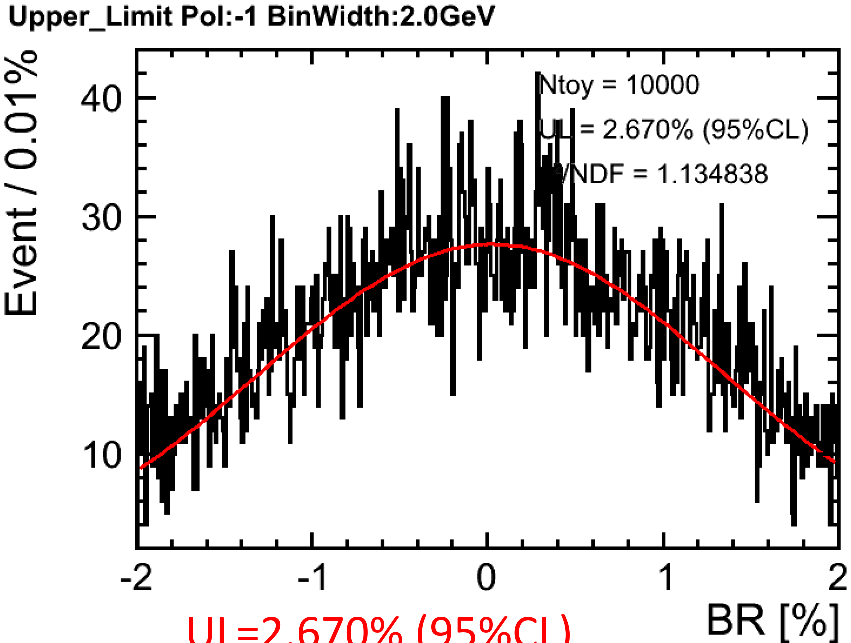



$\chi^2/\mathrm{NDF} = 0.824$

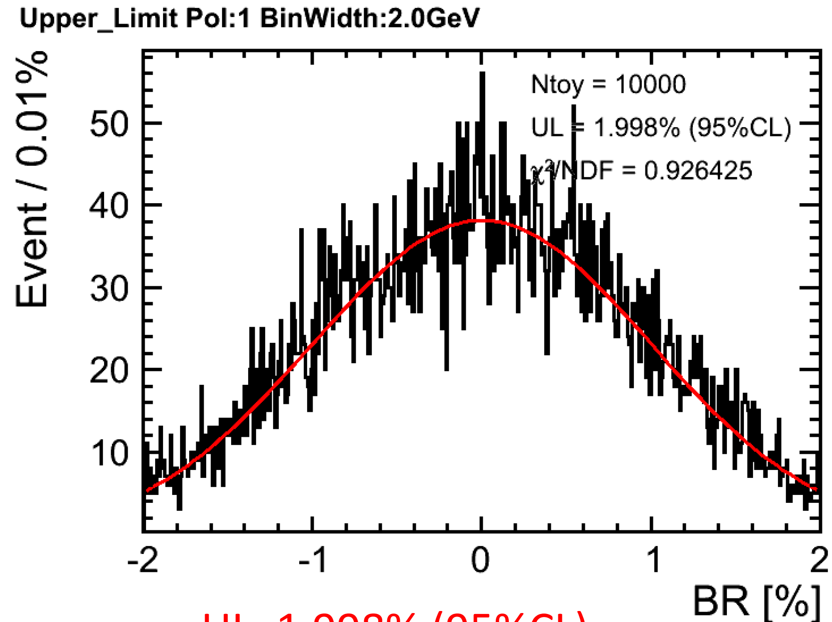
# Toy Monte Carlo to set upper limit

bin width:2.0 GeV
bkg : only yields are floated

| Left | Right |
| --- | --- |




UL=2.670% (95%CL)




UL=1.998% (95%CL)

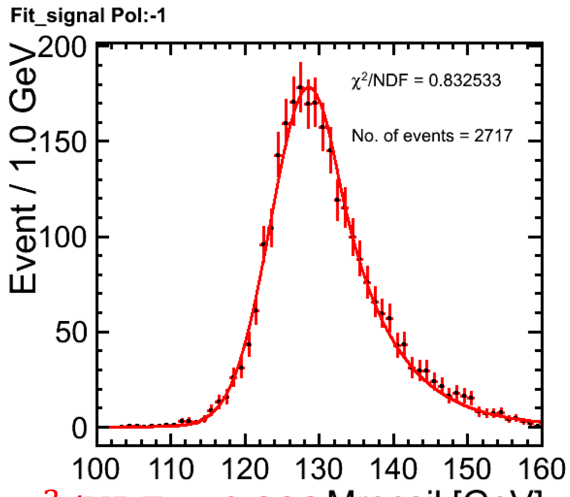
# Fit signal & bkg

signal: GPET (Gaussian + Exponential)

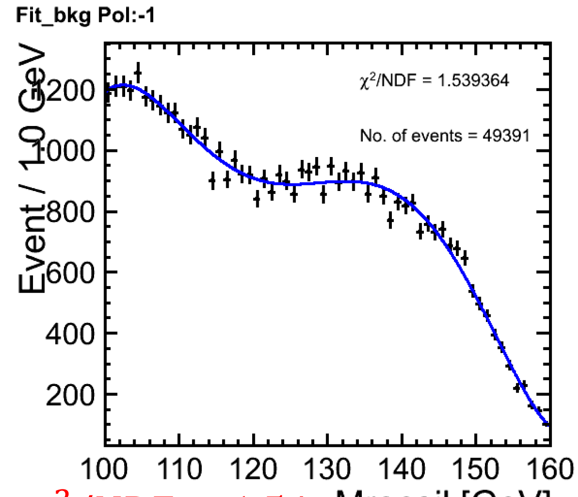
bkg : $5^{rd}$ order polynomial

bin width:1.0 GeV

## Left

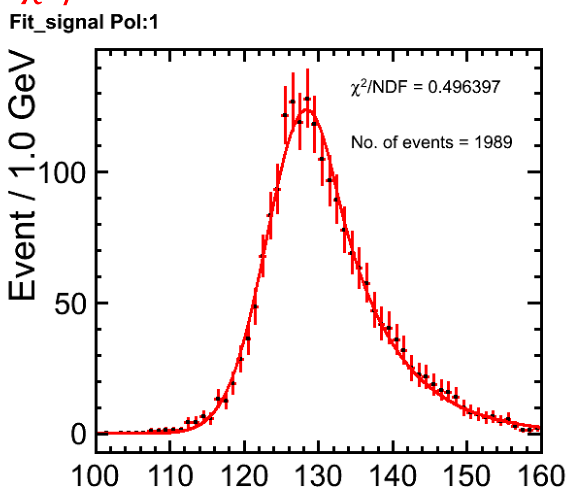



$\chi^2/\mathrm{NDF} = 0.833$

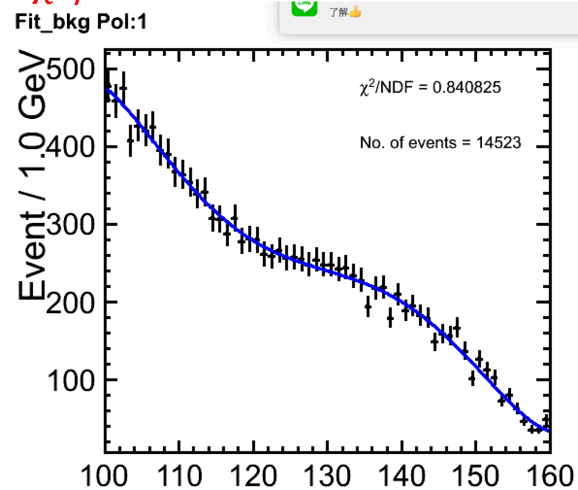



$\chi^2/\mathrm{NDF} = 1.54$

## Right




$\chi^2/\mathrm{NDF} = 0.496$




$\chi^2/\mathrm{NDF} = 0.841$

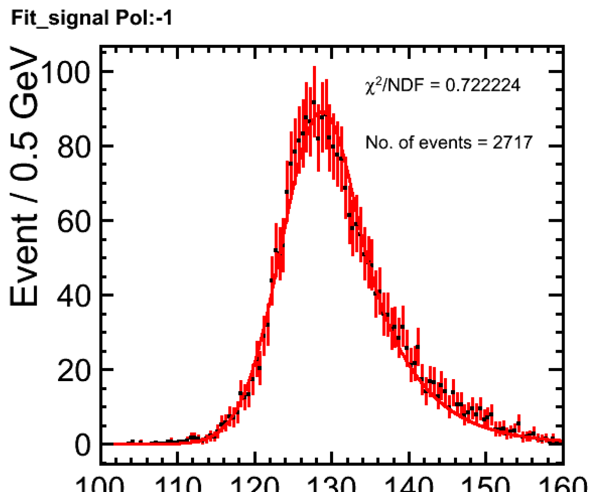
# Fit signal & bkg

signal: GPET (Gaussian + Exponential)

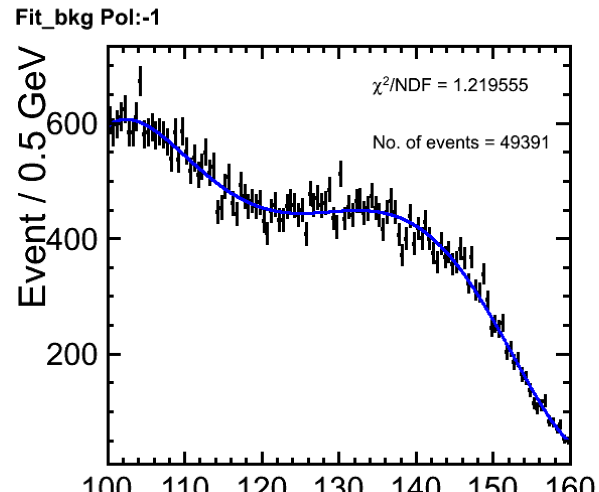
bkg : $5^{rd}$ order polynomial

bin width:0.5 GeV

## Left

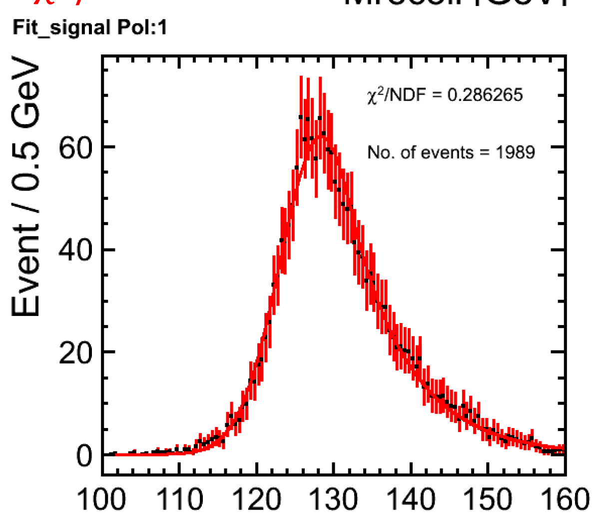



$\chi^2/\mathrm{NDF} = 0.722$

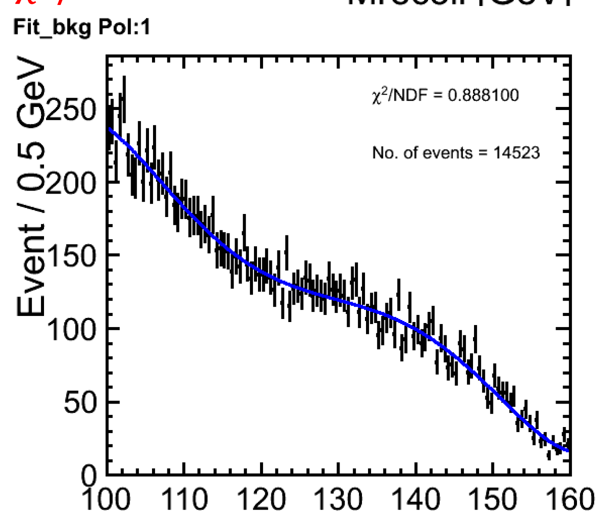



$\chi^2/\mathrm{NDF} = 1.22$

## Right

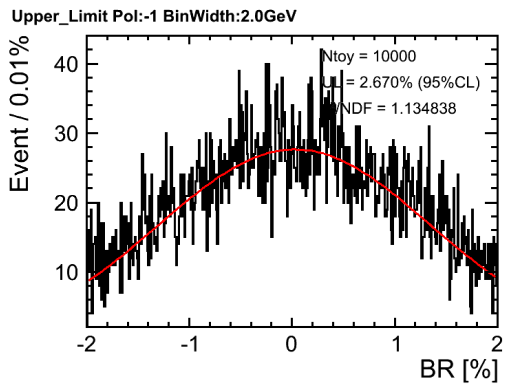
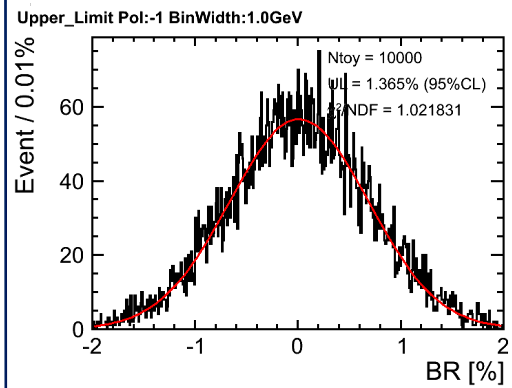
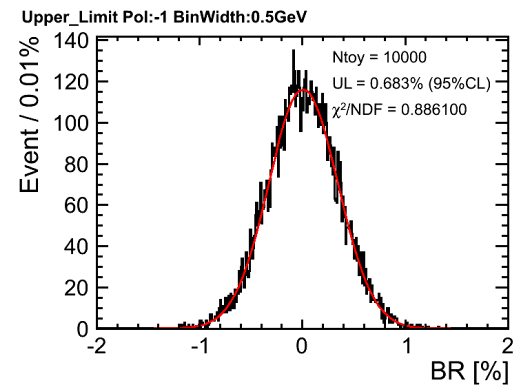
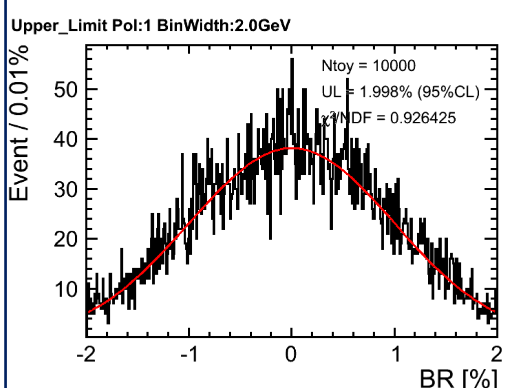
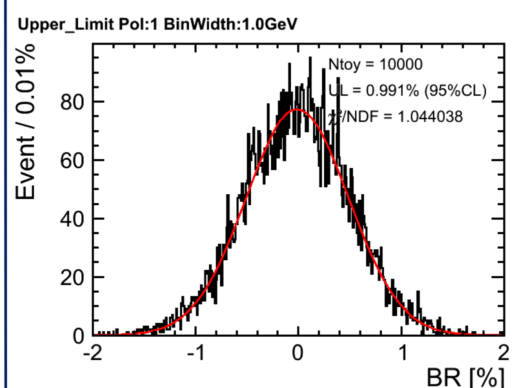
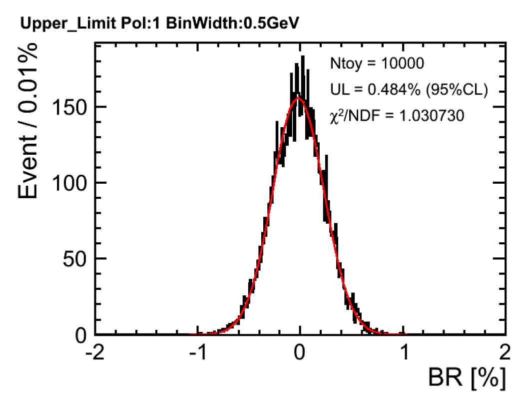



$\chi^2/\mathrm{NDF} = 0.286$



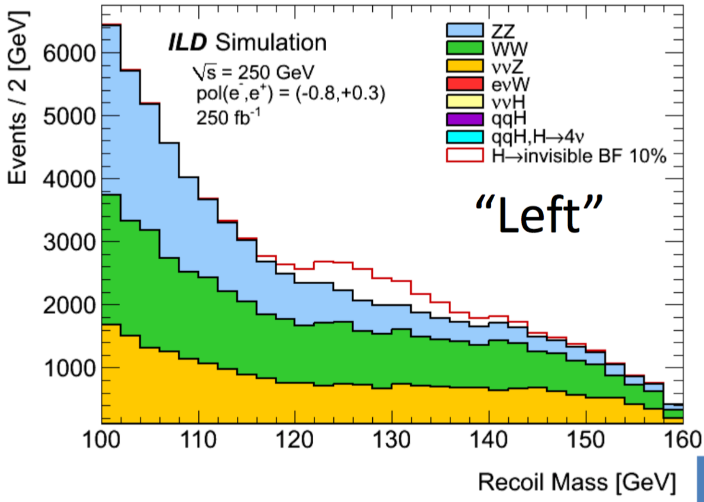

$\chi^2/\mathrm{NDF} = 0.888$

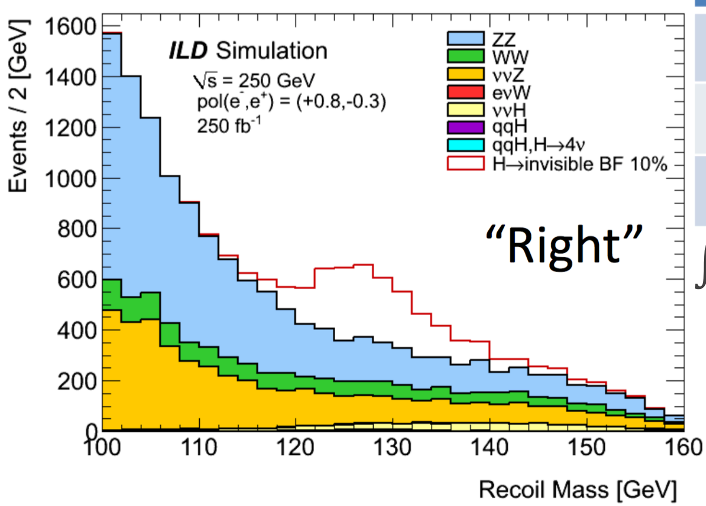
# Toy Monte Carlo to set upper limit

| | bin width:2.0 GeV | 1.0 GeV | 0.5 GeV |
|---|---|---|---|
| Left |  UL=2.670% (95%CL) |  UL=1.365% (95%CL) |  UL=0.683% (95%CL) |
| Right |  UL=1.998% (95%CL) |  UL=0.991% (95%CL) |  UL=0.484% (95%CL) |

# Previous study

Akimasa Ishikawa (Tohoku Unv.),
"Search for Invisible Higgs Decays at the ILC" LCWS2014@Belgrade




- In the previous study the following results were obtained.
- We aim to improve this result.

| UL on BF [%] | "Left" | "Right" |
|---|---|---|
| 250GeV | 0.95 | 0.69 |
| 350GeV | 1.49 | 1.37 |
| 500GeV | 3.16 | 2.30 |

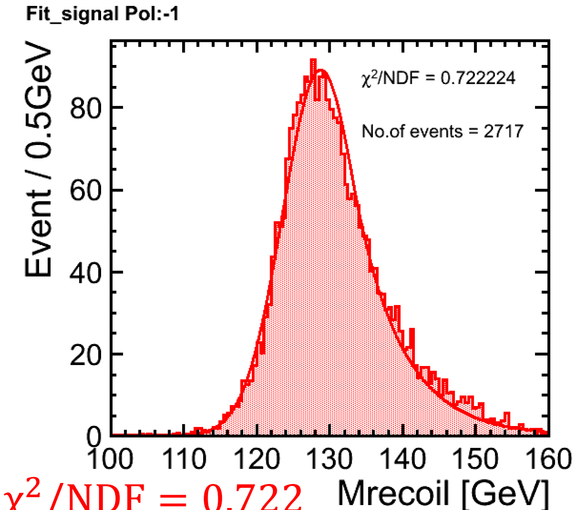
$\int Ldt$ =250,350,500fb$^{-1}$ for $E_{cm}$ =250,350,500GeV

# Fit signal & bkg

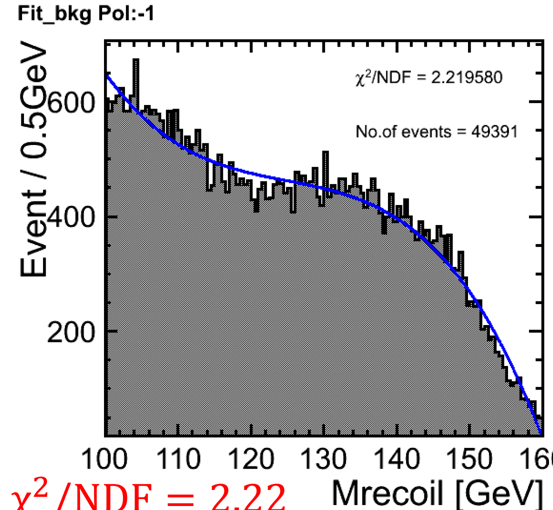
signal: GPET (Gaussian + Exponential)

bkg : 3rd order polynomial

## Left

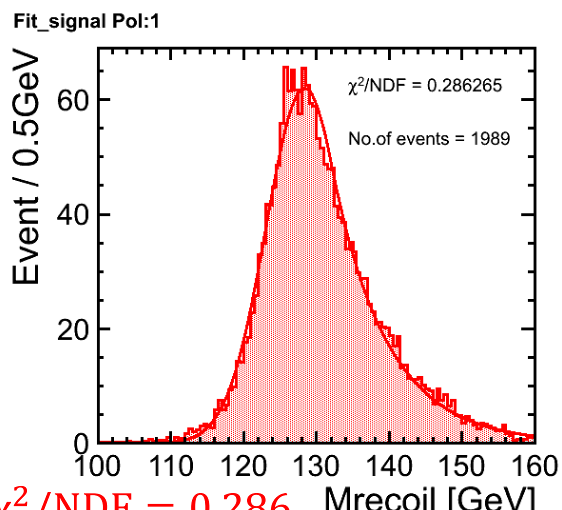



$\chi^2/\mathrm{NDF} = 0.722$

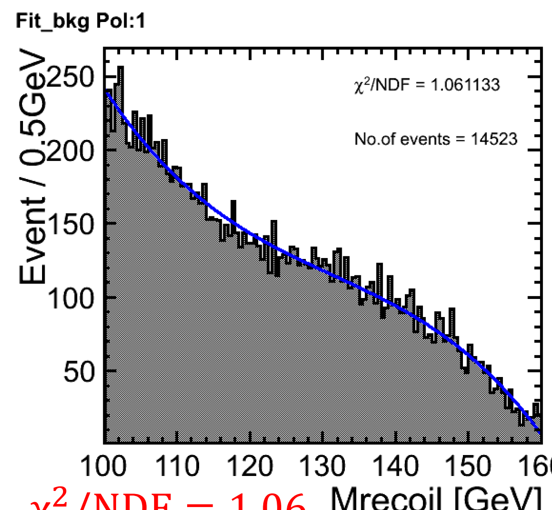



$\chi^2/\mathrm{NDF} = 2.22$

## Right




$\chi^2/\mathrm{NDF} = 0.286$

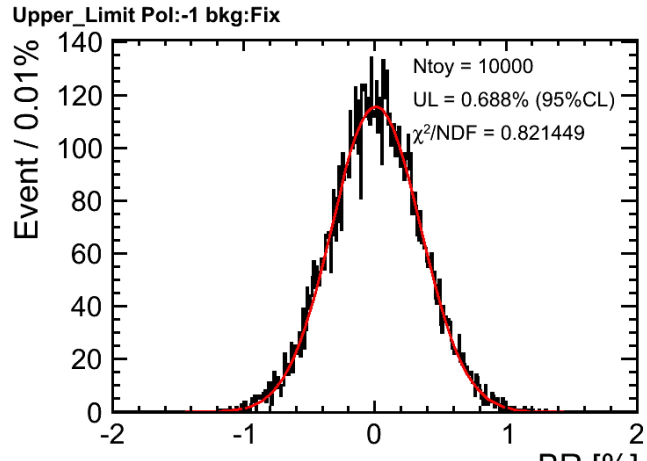



$\chi^2/\mathrm{NDF} = 1.06$

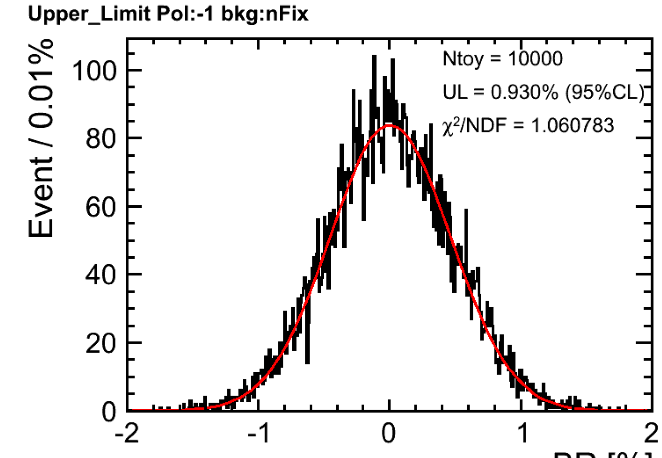
# Toy Monte Carlo to set upper limit

only yields are floated | bkg shape also floated

## Left

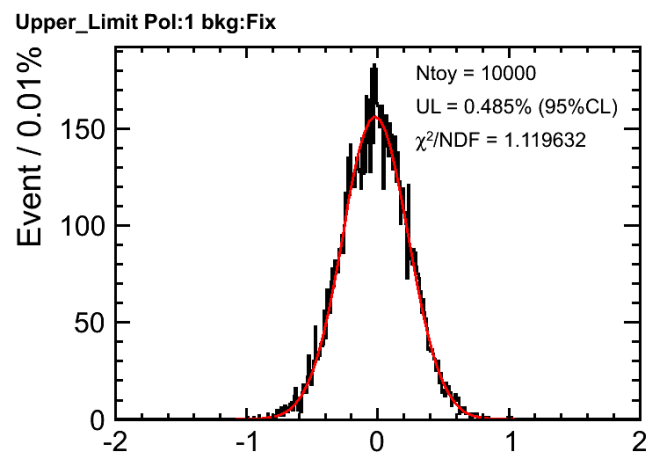



UL=0.688% (95%CL)

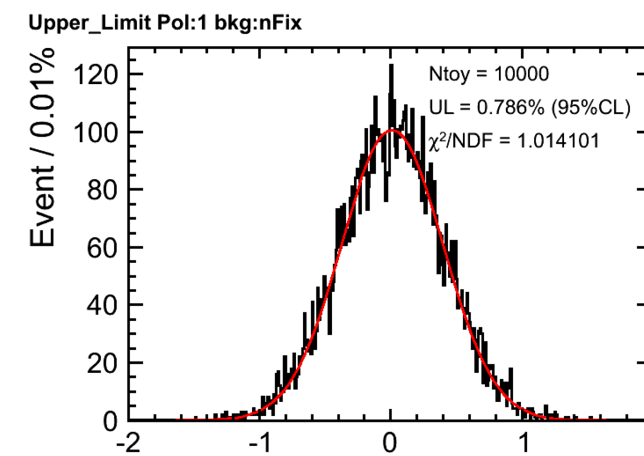



UL=0.930% (95%CL)

## Right

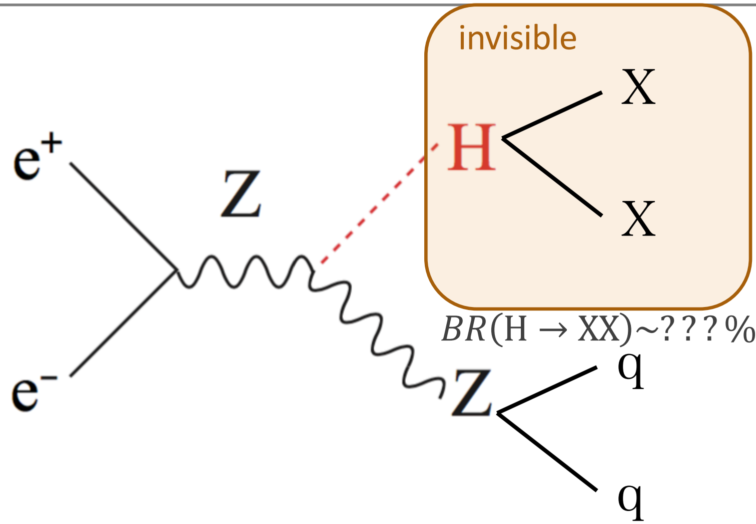



UL=0.485% (95%CL)




UL=0.786% (95%CL)

# Signal feature [hadronic channel]



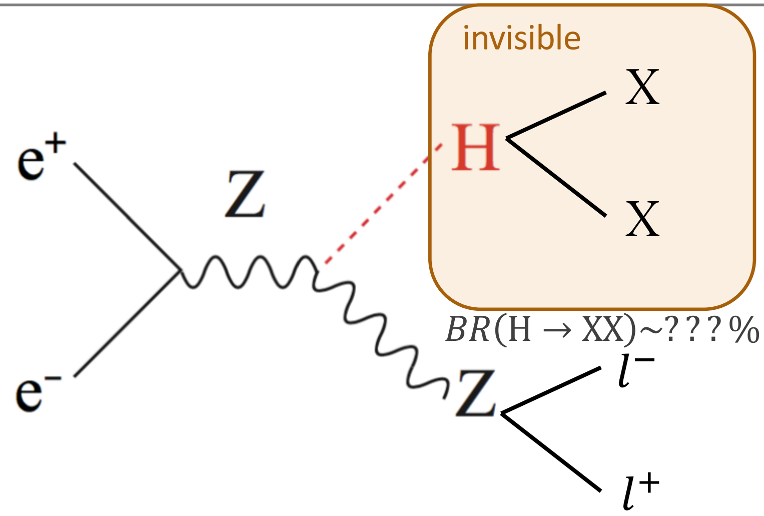

- Two-Jet
- Invisible particle exist
- $M_{qq} \approx M_Z \ (BR(\mathrm{Z} \rightarrow qq) \sim 70\%)$
- $M_{recoil} \approx M_{Higgs}$

# Major Backgrounds [hadronic channel]

The major backgrounds have the final states qqll,qqlv,qqvv.

1. ZZ semileptonic
2. WW semileptonic
3. $\mathrm{Z}\nu_e\nu_e, \mathrm{Z} \rightarrow \mathrm{qq}$
4. $\mathrm{W}\nu_e\nu_e, \mathrm{W} \rightarrow \mathrm{qq}$
5. $\nu\nu\mathrm{H}, \mathrm{H} \rightarrow \mathrm{ZZ}, \mathrm{Z} \rightarrow qq$
6. $\mathrm{qqH}, \mathrm{H} \rightarrow \mathrm{SM\ decay}$

# Signal feature [leptonic channel]




- Two-leptons
- Invisible particles without neutrino
- $M_{ll} \approx M_Z$ $(BR(Z \rightarrow ll)\text{~}3.4\%)$
- $M_{recoil} \approx M_{Higgs}$

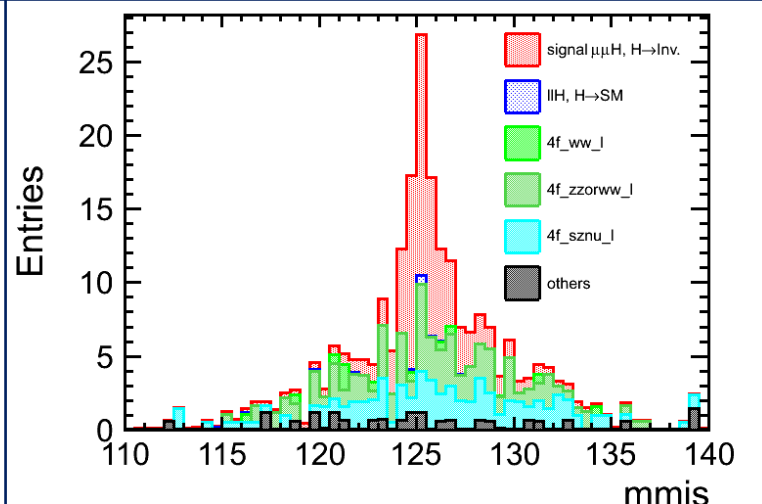
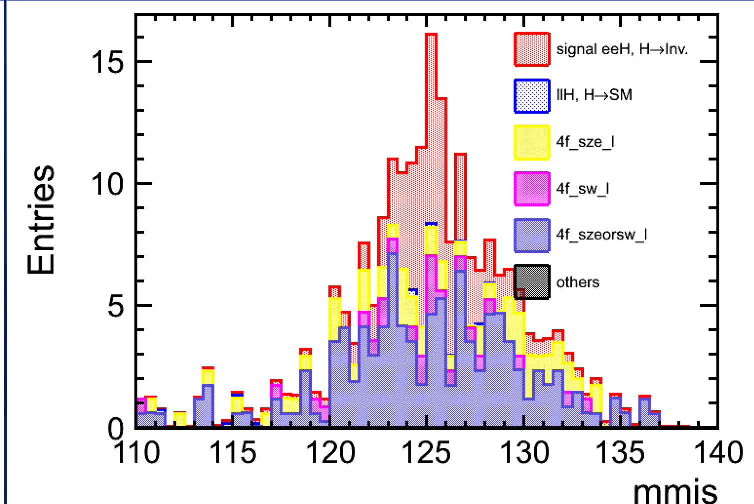
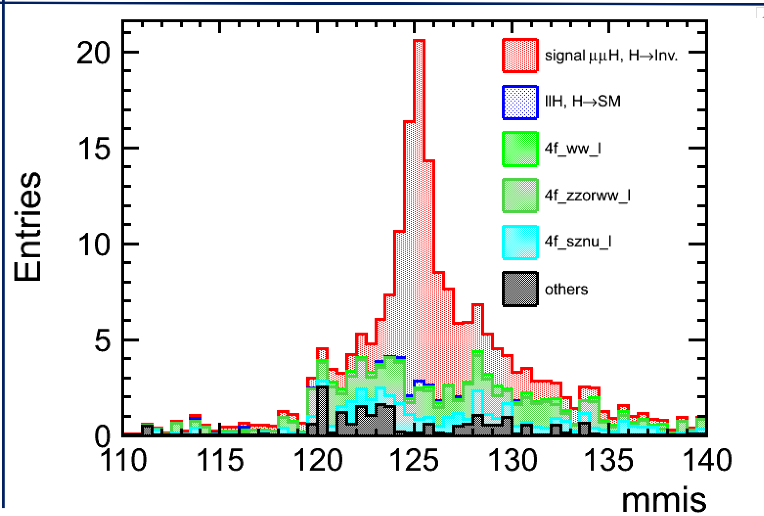
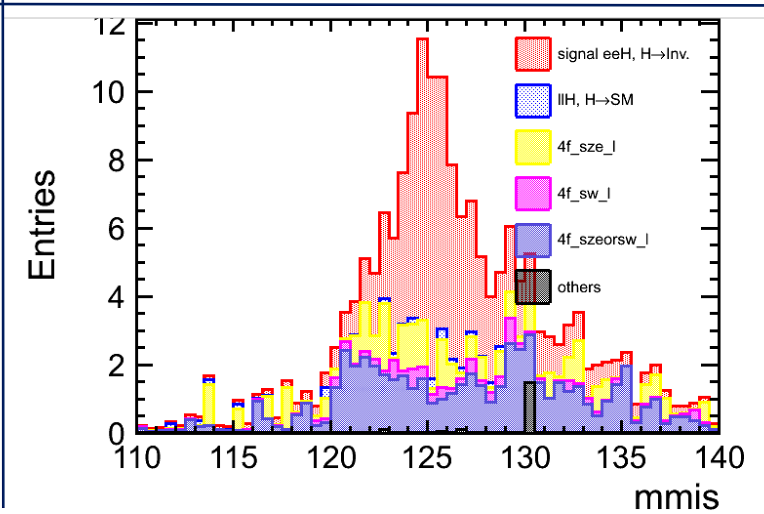
# Major Backgrounds [leptonic channel]

The major backgrounds have the final states with di-lepton & missing energy .

1. ZZ leptonic
2. WW leptonic
3. single $\mathrm{Z}$ & $\nu_e \nu_e, \mathrm{Z} \rightarrow ll$
4. single $\mathrm{W}$ & $\mathrm{e}\ \nu_e, \mathrm{W} \rightarrow \mathrm{e}\ \nu_\mathrm{e}$
5. $\nu\nu\mathrm{H}, \mathrm{H} \rightarrow \mathrm{ZZ}, \mathrm{Z} \rightarrow ll$
6. $ll\mathrm{H}, \mathrm{H} \rightarrow \mathrm{SM\ decay}$

# Leptonic Channel Analysis

## Missing Mass Plots [Ecm=250 GeV, 250 $fb^{-1}$]

| | $\mu\mu H, H \rightarrow inv(BR = 0.1)$ | $eeH, H \rightarrow inv(BR = 0.1)$ |
|---|---|---|
| Left |  |  |
| Right |  |  |

# Improvements

- modified cut variables and trained MVA again
  - In the previous MVA, I used SM sample as signal.←corrected
- Significance improved, while efficiency decreased.
  - ➢Which has higher priority ?

| 250GeV,250fb$^{-1}$,H→inv(BR=0.1) | | significance | efficiency |
|---|---|---|---|
| $\mu\mu$H | Left | 4.86 → 5.69 | 47.4% → 33.5% |
| | Right | 6.48 → 7.39 | 67.9% → 58.9% |
| eeH | Left | 4.07 → 4.51 | 43.9% → 24.9% |
| | Right | 5.61 → 6.39 | 52.7% → 48.2% |