# Study of Higgs Self-couplings at ILC

LCWS10 & ILC10

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# outline

- motivation
- methods to measure the higgs self-couplings
- analysis of fast simulation
- status of full simulation
- summary

# motivation

SM: $\tilde{\lambda} = \lambda = \lambda_{SM} = \frac{m_H^2}{2v^2}$

Higgs Potential: $$V(\eta_H) = \frac{1}{2} m_H^2 \eta_H^2 + \lambda v \eta_H^3 + \frac{1}{4} \tilde{\lambda} \eta_H^4$$

physical Higgs field

mass term

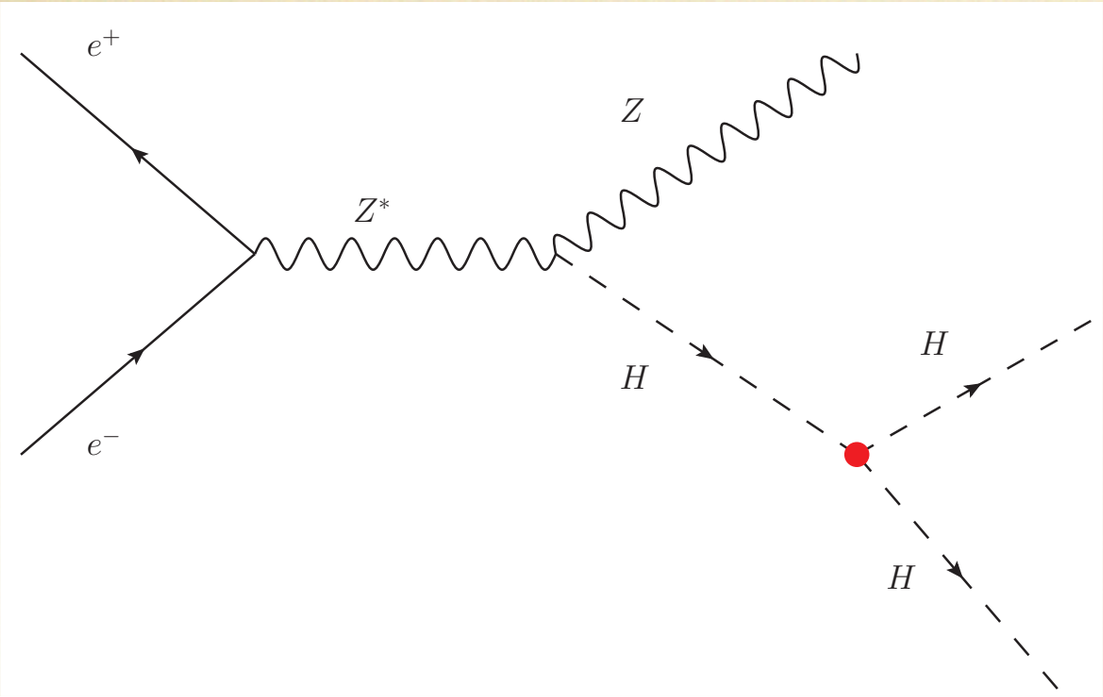
trilinear coupling

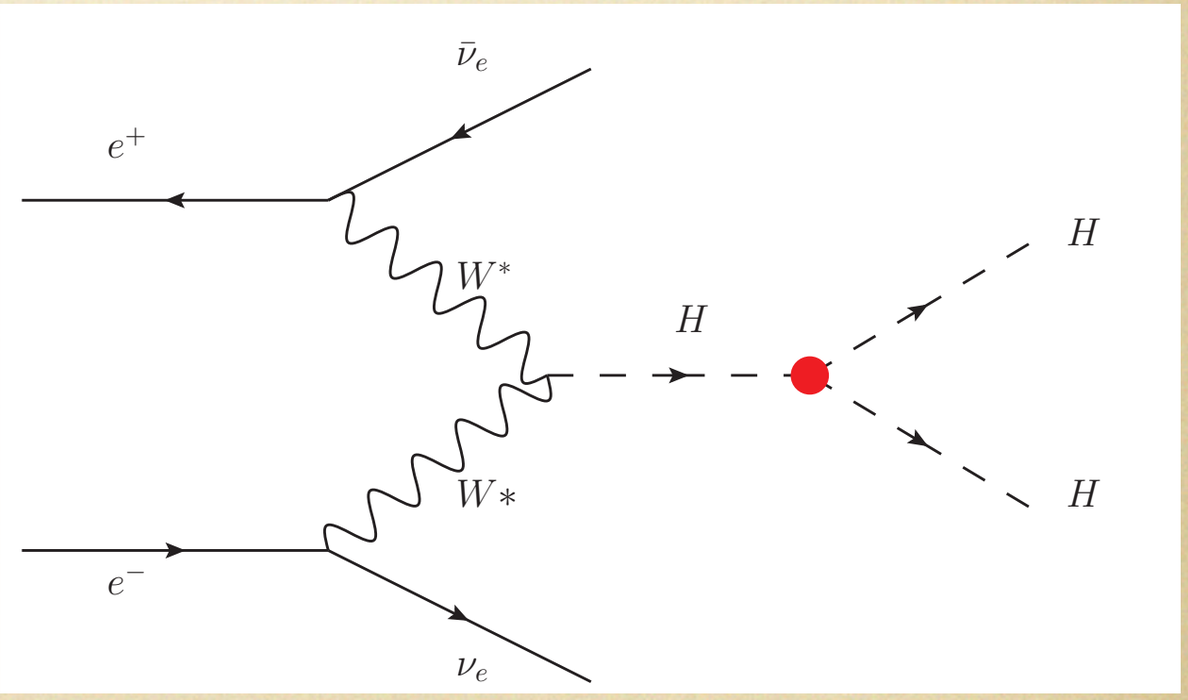
quartic Higgs coupling, which is difficult to measure at both LHC and ILC, even SLHC!

- a new interaction (non-gauge interaction).
- the non-trivial probe of the Higgs potential, offer a direct independent determination.
- accurate test of this coupling may reveal the extended nature of Higgs sector, like 2HDM and SUSY.
- difficult to measure at LHC for a light Higgs.

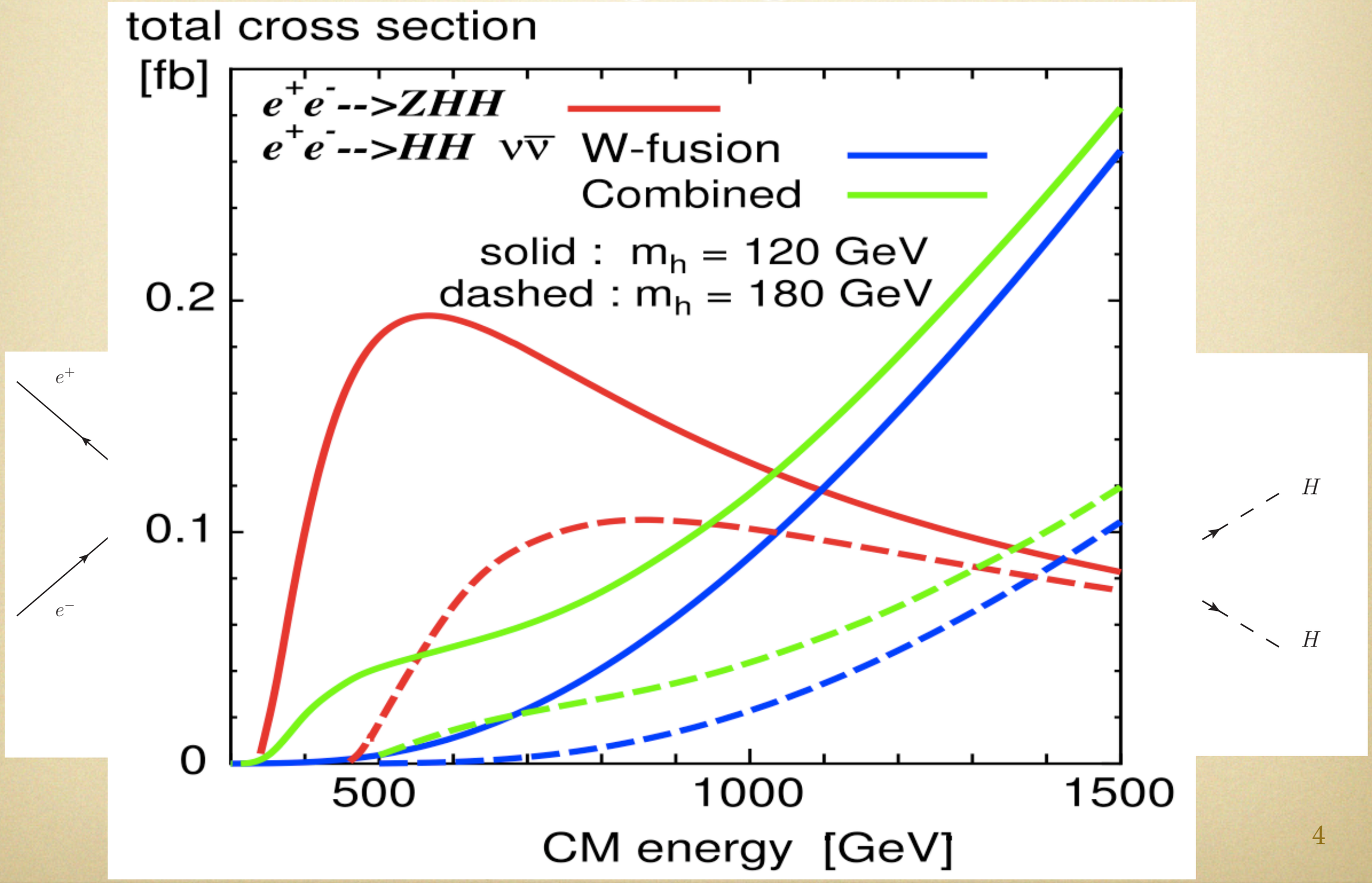
# Measurement of the trilinear Higgs self-coupling @ ILC

- double Higgs-strahlung (dominate at lower energy)
- WW fusion (dominate at higher energy)



# Measurement of the trilinear Higgs self-coupling @ ILC



# $e^+ + e^- \longrightarrow ZHH$

$\sigma = 152\text{ab}$ $\quad @E_{\text{cm}} = 500\text{GeV}, M_H = 120\text{GeV}$ $\quad \int Ldt = 2\text{ab}^{-1}$

- ll + 4 jets mode $(10\% \times 70\% \times 70\% \approx 4.9\%)$

  $Z \to l\bar{l} \quad H \to b\bar{b} \quad H \to b\bar{b}$

- 8 jets mode $(70\% \times 70\% \times 14\% \times 2 \times 45\% \approx 6.3\%)$

  $Z \to q\bar{q} \quad H \to b\bar{b} \quad H \to WW^* \to 4jets$

- lv + 6 jets mode $(70\% \times 70\% \times 14\% \times 2 \times 45\% \approx 6.3\%)$

  $Z \to q\bar{q} \quad H \to b\bar{b} \quad H \to WW^* \to l\nu + 2jets$

- 4 jets mode $(20\% \times 70\% \times 70\% \approx 9.8\%)$

  $Z \to \nu\bar{\nu} \quad H \to b\bar{b} \quad H \to b\bar{b}$

- 6 jets mode $(70\% \times 70\% \times 70\% \approx 34\%)$

  $Z \to q\bar{q} \quad H \to b\bar{b} \quad H \to b\bar{b}$

today's topic

work is ongoing

(arXiv:0907.2524v1)

# Part I: Fast Simulation

set up: JSF framework

- Generator: Physsim

  i. helicity amplitudes are calculated by HELAS

  ii. phase space integration and four momentum generation are performed by BASES/SPRING

  iii. parton showering and hadronization are carried out by PYTHIA

- Simulator: JSFQuickSimulator

  - GLD geometry and detector performance related parameters are implemented (GLD V4')

initial state radiation, beam width, beamstrahlung, w/o beam polarization

$$e^+ + e^- \to ZHH \to (l\bar{l})(b\bar{b})(b\bar{b}) \to 2 \text{ leptons} + 4 \text{ bjets}$$

## pre-selection:

- number of tracks >= 25
- total visible energy between (300,600) GeV
- two isolated charged leptons
- force the other tracks to four jets
- combine the four jets by minimizing

$$\chi^2 = \frac{(M(b,\bar{b}) - M_H)^2}{\sigma^2_{H_1}} + \frac{(M(b,\bar{b}) - M_H)^2}{\sigma^2_{H_2}} + \frac{(M(l,\bar{l}) - M_Z)^2}{\sigma^2_Z}$$

# signal and main backgrounds

$\int Ldt = 2\mathrm{ab}^{-1}$

| | cross section (fb) | expected number | survived (pre-selection) |
|---|---|---|---|
| ZHH | 0.152 | 304 | 15.4 |
| ZH | 70.0 | 140000 | 1618 |
| ZZ | 515 | 1030000 | 3560 |
| t t-bar | 531 | 1062000 | 9023 |
| WWZ | 36 | 72300 | 1943 |
| ZZZ | 0.8 | 1600 | 125 |

for the further selections, efficiency is very important!

# algorithm of b tagging used in fast simulation

for a track:

$$Norm = \sqrt{(\frac{r}{\delta r})^2 + (\frac{z}{\delta z})^2}$$

helix parameters

r, z : the coordinates of the track origin

δr, δz : the errors of the coordinates

for a jet:

define a cut fNsigCut = 2.5, and count the number of tracks which satisfy Norm>fNsigCut

2 leptons 4 b-jets mode

# preliminary result

$\int Ldt = 2\mathrm{ab}^{-1}$

| | ZHH | ZH | ZZ | t t-bar | WWZ | ZZZ |
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| mva_wwz>1.0<br>mva_zz>0.97<br>mva_zh>0.97<br>mva_tt>0.98<br>mva_zzz>0 | 11.7 | 5.6 | 16.5 | 312 | 12.7 | 12.9 |
| 70GeV<M(Z)<110GeV | 9.7 | 0.56 | 16.5 | 106 | 7.5 | 11.7 |
| Ycut>0.015 | 9.1 | 0 | 6.6 | 91.3 | 6.9 | 10.6 |
| 2b(H1) (Noffv > 0) | 6.3 | 0 | 0 | 28 | 1.8 | 5.5 |
| 2b(H2) (Noffv > 1) | 3.5 | 0 | 0 | 0.71 | 0 | 2.3 |
| mva_zzz>0.5224 | 2.7 | 0 | 0 | 0 | 0 | 0.48 |

2 leptons 4 b-jets mode

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significance: 2.5σ

2 leptons 4 b-jets mode

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| mva_zzz>0.5224 | 2.7 | 0 | 0 | 0 | 0 | 0.48 |

significance: 2.5σ

$$e^+ + e^- \rightarrow ZHH \rightarrow (q\bar{q})(b\bar{b})(WW^*) \rightarrow 8jets$$

## pre-selection:

- number of tracks >= 25
- total visible energy between (300,600)
- force to 7 jets (from cheating information, it is more possible to reconstruct W* as one jet).
- combine the 7 jets by minimizing

$$\chi^2 = \frac{(M(b,\bar{b}) - M_H)^2}{\sigma^2_{M_H}} + \frac{(M(W,W^*) - M_H)^2}{\sigma^2_{M_H}} + \frac{(M(q,\bar{q}) - M_Z)^2}{\sigma^2_{M_Z}} + \frac{(M(q,\bar{q}') - M_W)^2}{\sigma^2_{M_W}}$$

# 8 jets mode preliminary result $\int Ldt = 2\mathrm{ab}^{-1}$

$ZHH \to (q\bar{q})(b\bar{b})(WW^*) \to 8jets$ only!!

| | signal | t t-bar |
|---|---|---|
| expected | 18.3 | 1062000 |
| pre-selection | 12.6 | 483949 |
| chi2<20 | 5.2 | 65144 |
| 90<M(H1)<130 | 5.1 | 63157 |
| 110<M(H2)<150 | 3.6 | 36670 |
| 70<M(Z)<110 | 3.5 | 34359 |
| ycut>0.005 | 2.3 | 8454 |
| ycut>0.0076 | 1.1 | 2644 |

cut based

neural-net

| | signal | t t-bar |
|---|---|---|
| expected | 304 | 1062000 |
| pre-selection | 190.6 | 483949 |
| mva_tt>0.32816 | 113.0 | 105563 |
| mva_tt>0.62930 | 50.7 | 30173 |
| mva_tt>0.77987 | 9.1 | 3000 |
| mva_tt>0.80740 | 2.0 | 634 |
| mva_tt>0.81256 | 1.0 | 338 |

challenging!

$$e^+ + e^- \rightarrow ZHH \rightarrow (q\bar{q})(b\bar{b})(WW^*) \rightarrow lv + 6jets$$

## pre-selection:

- number of tracks >= 25
- total visible energy between (300,600)
- one isolated charged lepton
- force the others tracks to 6 jets
- combine the 6 jets by minimizing

$$\chi^2 = \frac{(M(b,\bar{b}) - M_H)^2}{\sigma^2_{H_1}} + \frac{(M(q,\bar{q}) - M_Z)^2}{\sigma^2_Z} + \frac{(M(q,\bar{q'}) - M_W)^2}{\sigma^2_W}$$

# lv+6 jets mode

## preliminary result

$\int Ldt = 2\mathrm{ab}^{-1}$

| 1.87σ | expected | pre-selection | mva_mlp >0.8367 |
|---|---|---|---|
| ZHH | 304 | 31.2 | 9.87 |
| WWZ | 72300 | 5224 | 15.5 |
| ZZZ | 1600 | 43.9 | 2.49 |

| 0.17σ | expected | pre-selection | mva_mlp >0.8358 |
|---|---|---|---|
| ZHH | 304 | 31.2 | 11.8 |
| t t-bar | 1062000 | 229515 | 4800 |

challenging!

the pre-selection efficiency is even higher than signal

# summary (part i)

$$e^+ + e^- \to ZHH \to$$

- ll + 4 b-jets mode is possible to observe the higgs trilinear coupling with 2.5σ significance based on current fast simulation. Actually, b-tagging still can be improved to suppress the c c-bar contamination in ZZZ background. It is necessary to do the full simulation.

- 8 jets mode and lv + 6 jets mode are very challenging to suppress the t t-bar background effectively.

# Part II: Full Simulation

set up: Marlin framework

- Generator: Whizard
- Simulator: Mokka
  - ILD geometry and detector performance related parameters are implemented
- Reconstruction and Analysis: Marlin

initial state radiation, beam width, beamstrahlung, w/ beam polarization

$$e^+ + e^- \to ZHH \to (l\bar{l})(b\bar{b})(b\bar{b}) \to 2 \text{ leptons} + 4 \text{ bjets}$$

## selection criteria:

read out from PandoraPFOs Collection

- number of tracks >= 25
- total visible energy between (300,600)
- at least two isolated charged leptons (the pair nearest to Z mass is selected)
- force the other tracks to four jets
- combine the four jets by minimizing

$$\chi^2 = \frac{(M(b,\bar{b}) - M_H)^2}{\sigma^2_{H_1}} + \frac{(M(b,\bar{b}) - M_H)^2}{\sigma^2_{H_2}} + \frac{(M(l,\bar{l}) - M_Z)^2}{\sigma^2_Z}$$

do not effect minimization

# lepton selection (preliminary)

ECal and HCal informations can be used for lepton identification.

$E_{total}=E_{ECAL}+E_{HCAL}$

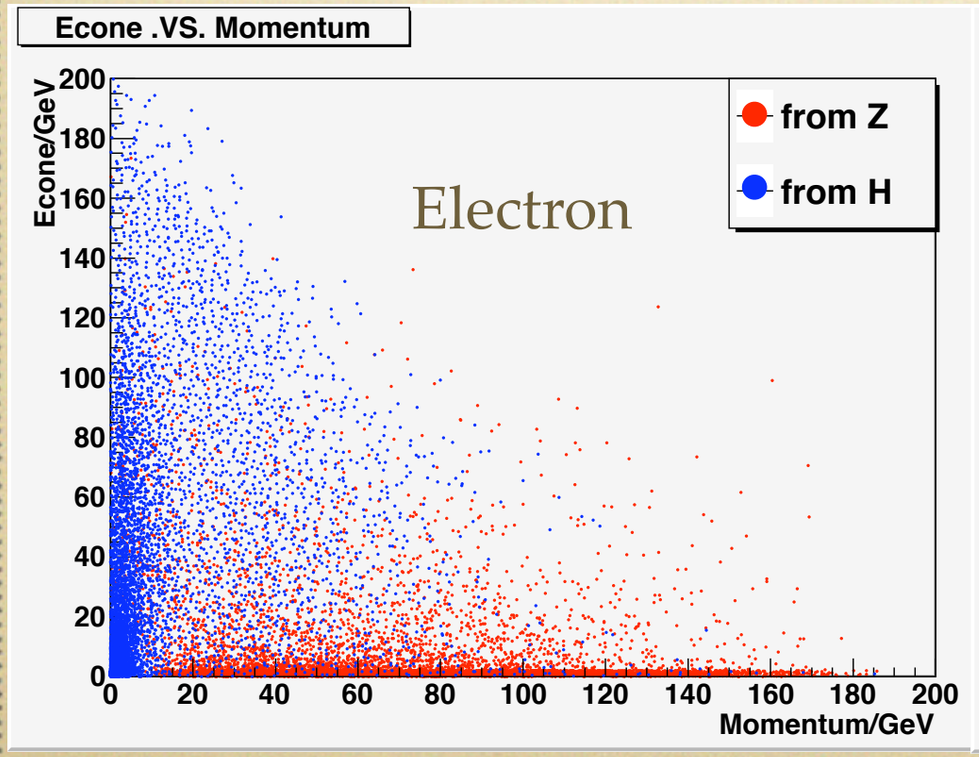
| P>15 GeV | e-identification | μ-identificantion |
|---|---|---|
| $E_{ECAL}/E_{total}$ | >0.6 | <0.5 |
| $E_{total}/P_{track}$ | >0.9 | <0.3 |

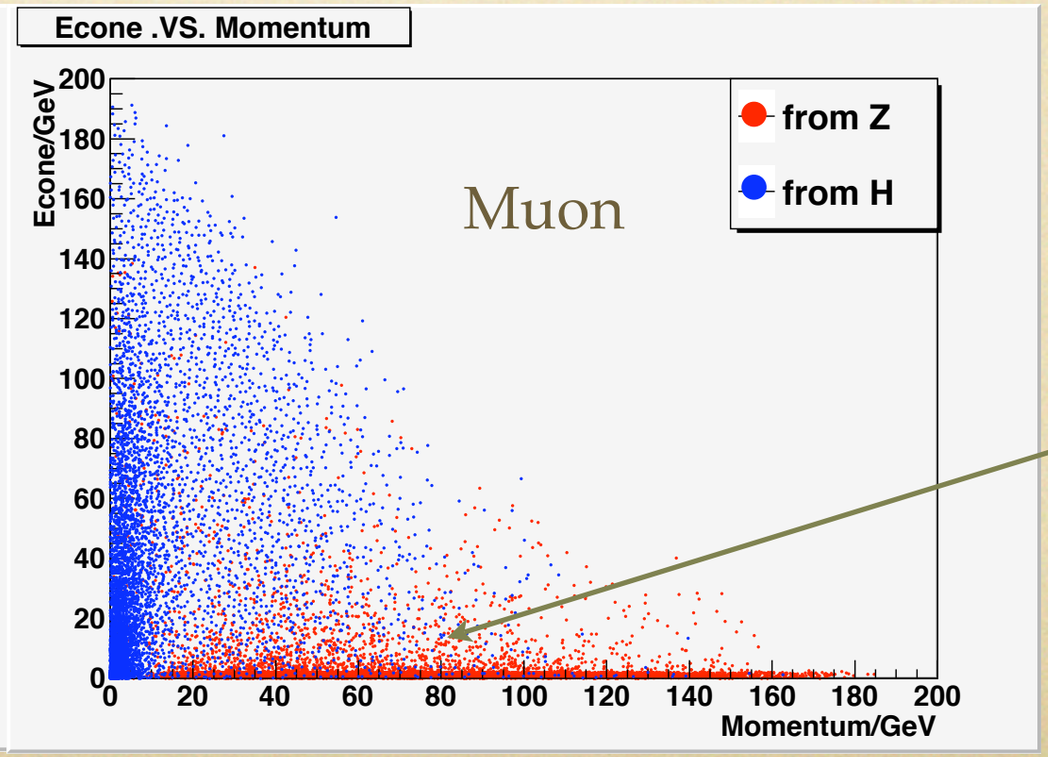
HZ recoil mass by ILD

| P>20 GeV | e-identification | μ-identificantion |
|---|---|---|
| $E_{ECAL}/E_{total}$ | >0.8 | <0.5 |
| $E_{total}/P_{track}$ | [0.8,1.2] | <0.5 |

my requirement

isolation requirement: Econe<20 GeV



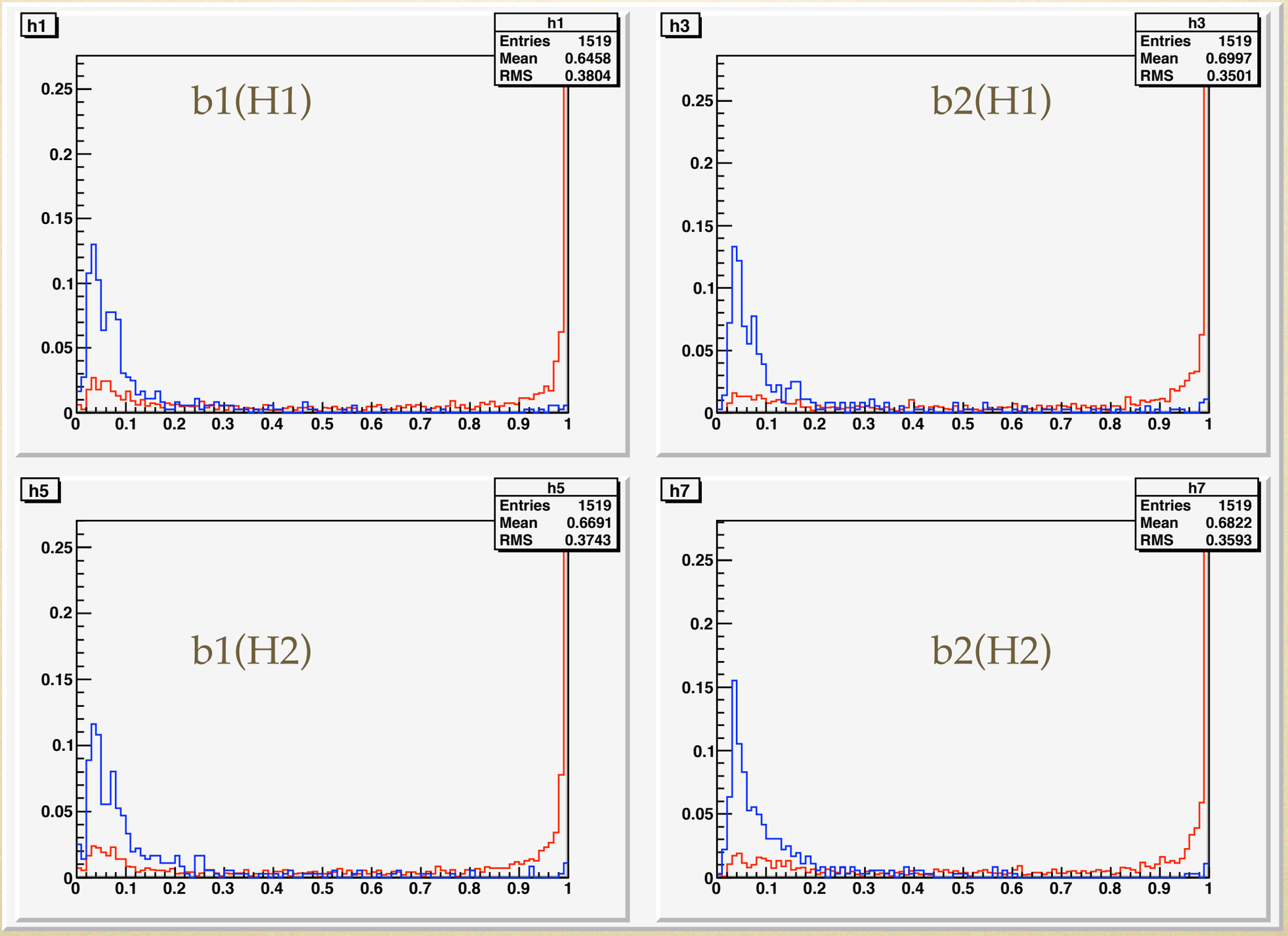

$\cos_{cone} = 0.99$

very small angle, still high cone energy

# Btag (LCFIVertex)

red: both H to bb

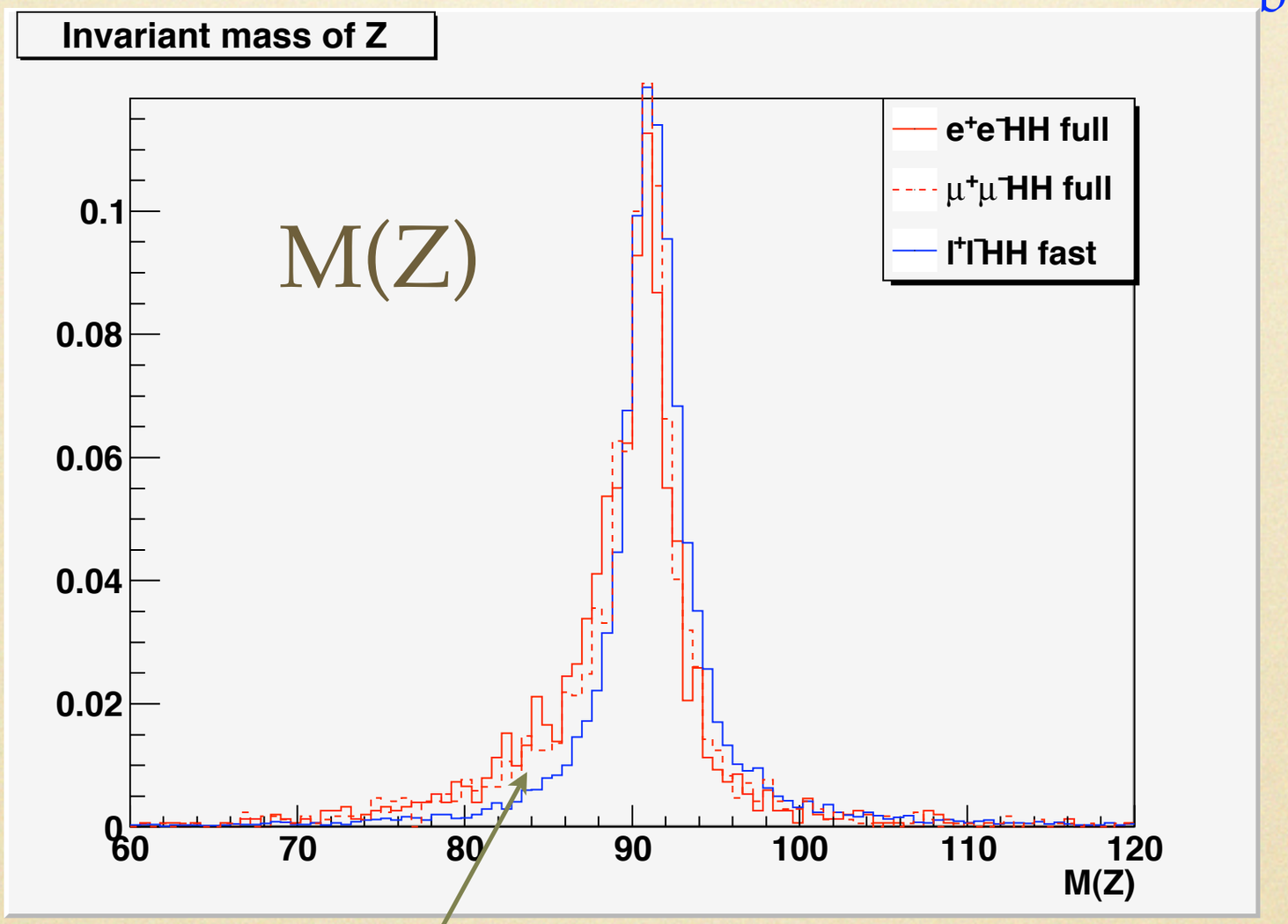
blue: both H to non-bb




b-likeness

# preliminary results
# and compare with fast simulation

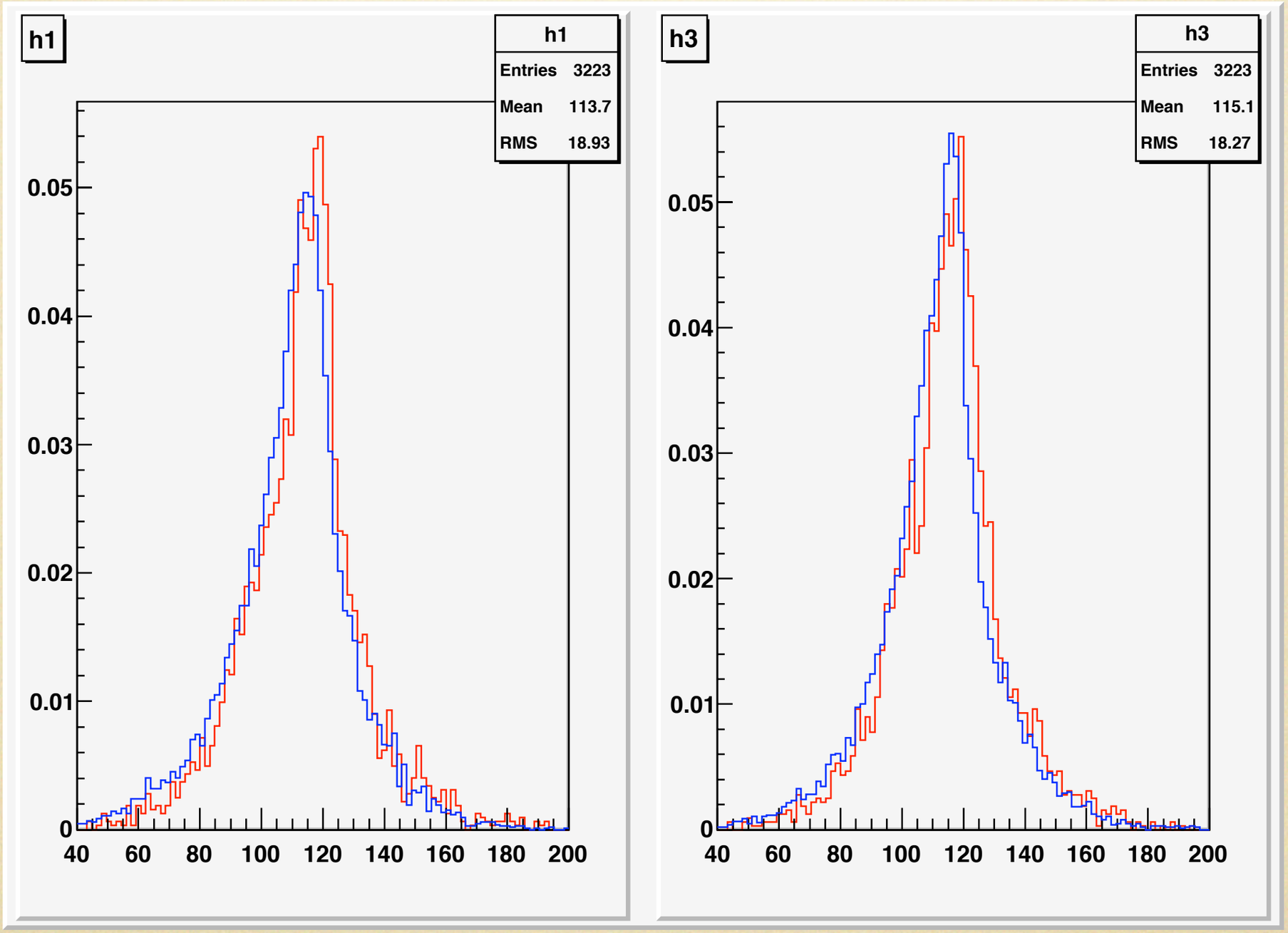
red: full simulation
blue: fast simulation




bremsstrahlung + multi scattering

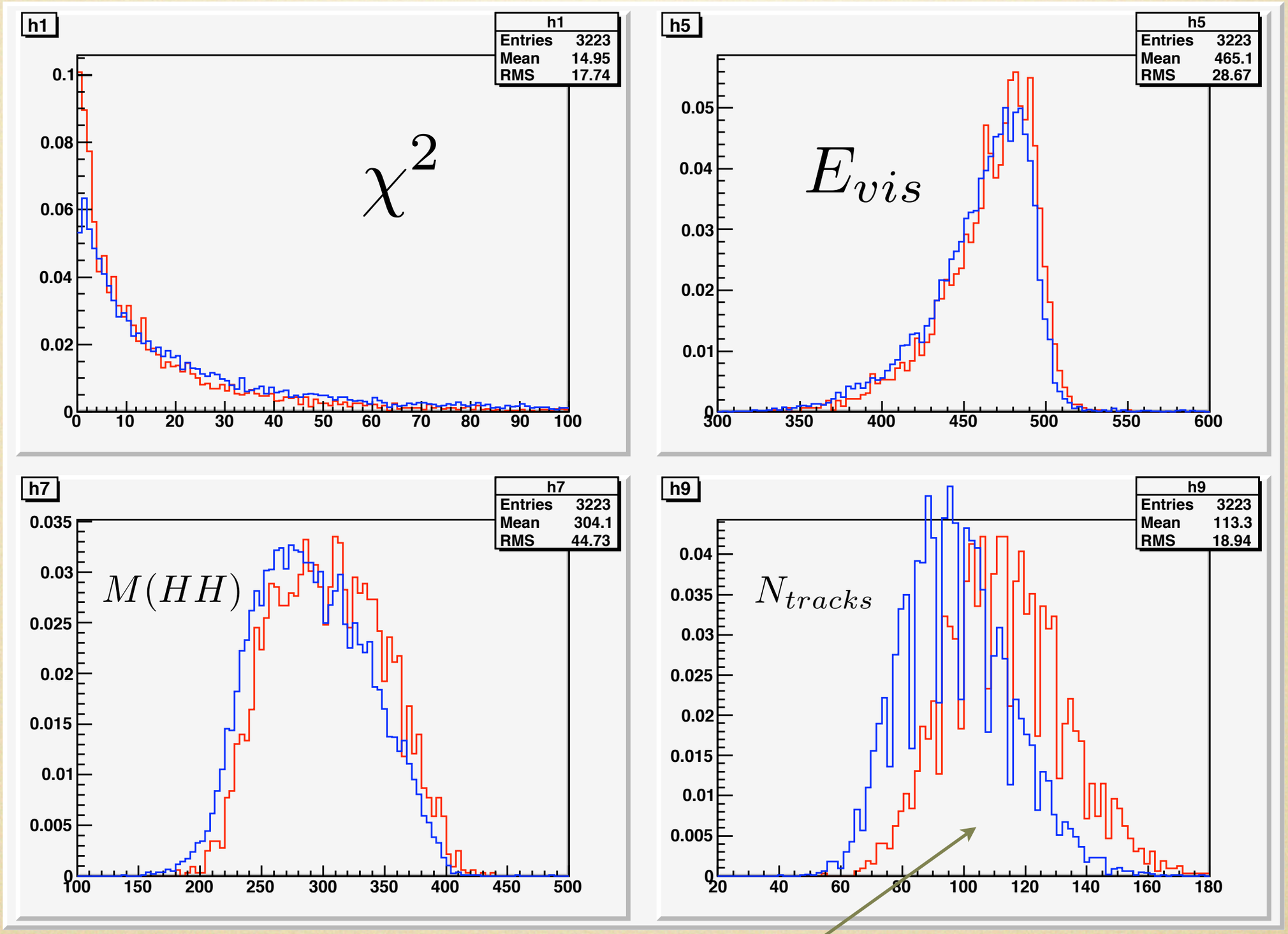
# Higgs masses

red: full simulation
blue: fast simulation



# others...

red: full simulation
blue: fast simulation




more complicated interactions between particle and detector

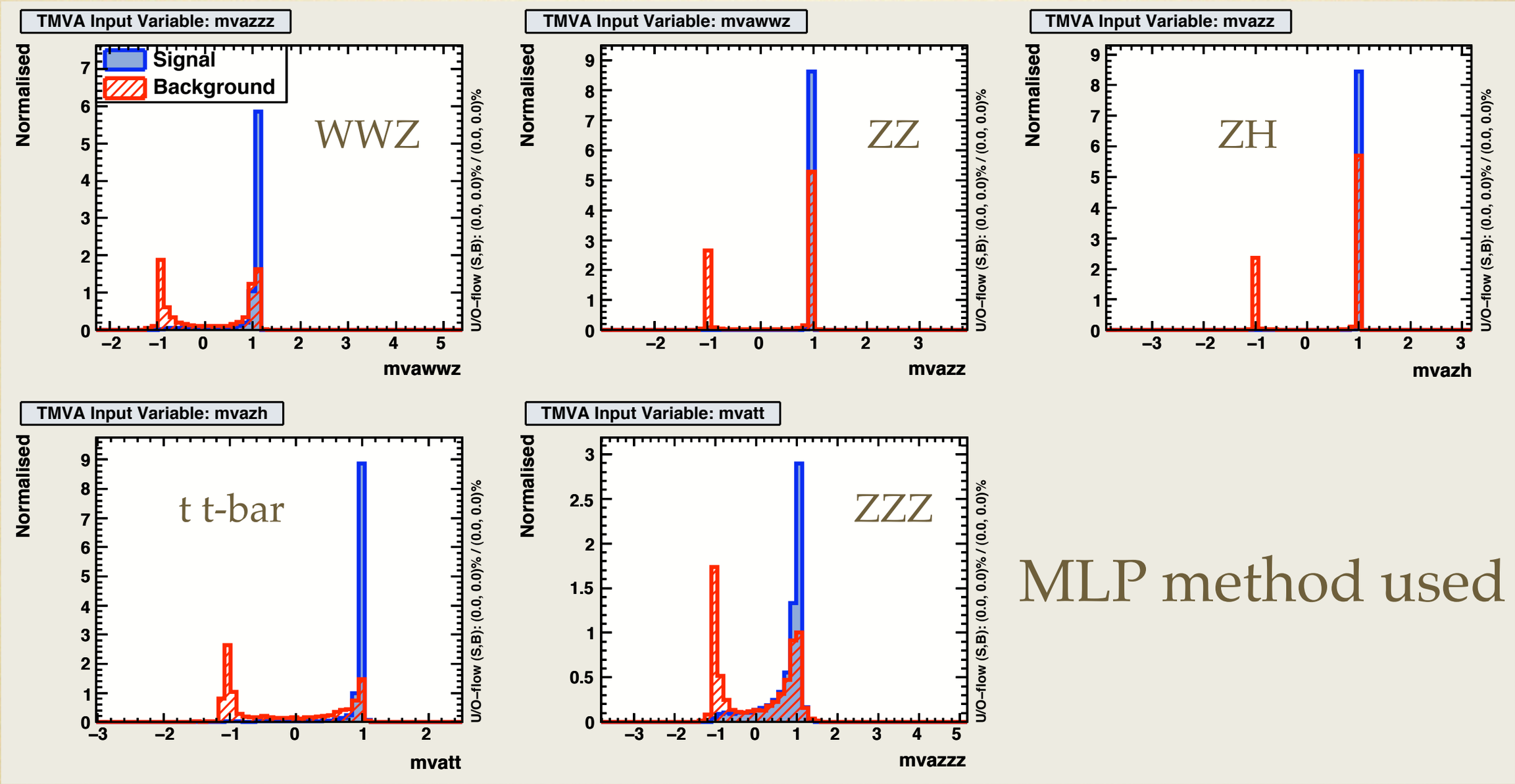
# Summary (Part ii)

- analysis framework has been completed and basic check done.
- the preliminary result of full simulation shows consistency with fast simulation.
- more full simulation samples are generating and need to be analyzed.
- work is ongoing...

Thank you very much!

# back up

# some feelings of the output classifiers for signal and backgrounds




MLP method used

each event has five classifiers

# significance

$$p(n \geq m) = \sum_{n=m}^{\infty} \frac{\nu^n e^{-\nu}}{n!} = 1 - \sum_{n=0}^{m-1} \frac{\nu^n e^{-\nu}}{n!}$$

| event number | p-value | p_signal | significance |
|---|---|---|---|
| m=3 | 5.0% | 95.0% | 2σ |
| m=4 | 1.0% | 99.0% | 3σ |
| m=5 | 0.2% | 99.8% | |

# neural-net analysis for the last step

input:

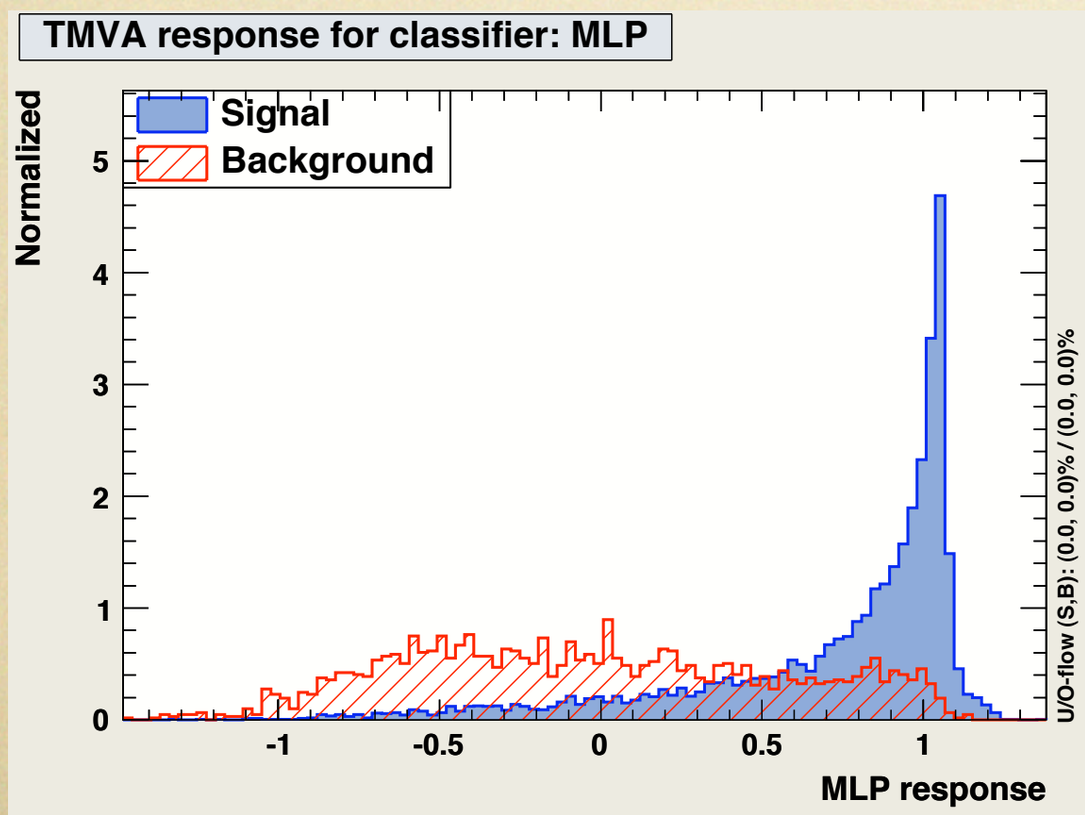
$Y_{cut}$ $E_{vis}$ $mva\_zzz$

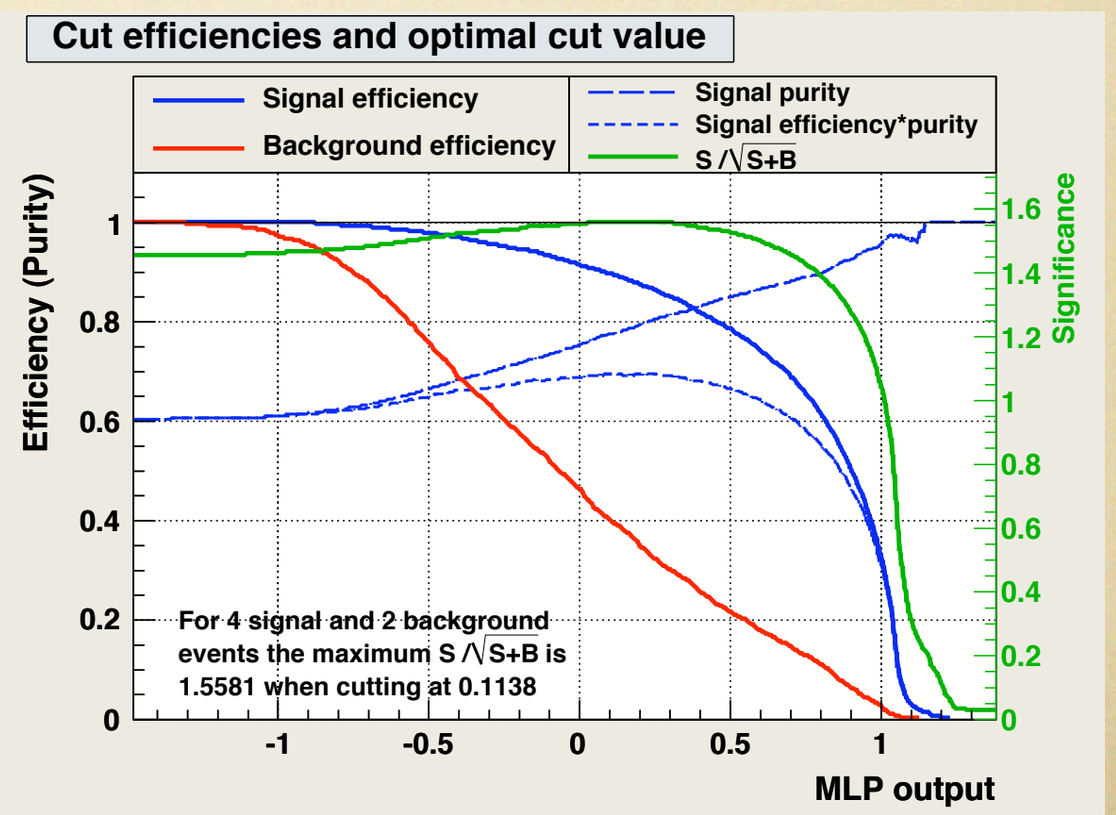
$M(H_1)$ $M(H_2)$

$\cos\theta_2$ $\cos\theta_3$

$|\cos\theta_{j11}|$ $|\cos\theta_{j21}|$

```
-------------------------------------------------
Ranking result (top variable is best ranked)
-------------------------------------------------
Rank : Variable    : Importance
-------------------------------------------------
   1 : ycut        : 4.945e+02
   2 : evis        : 3.046e+01
   3 : mh2         : 3.701e+00
   4 : csz2        : 3.106e+00
   5 : mh1         : 2.231e+00
   6 : csz3        : 3.159e-01
   7 : mvatt       : 3.024e-01
   8 : abs_csj11h_ : 3.395e-02
   9 : abs_csj21h_ : 2.313e-04
-------------------------------------------------
```

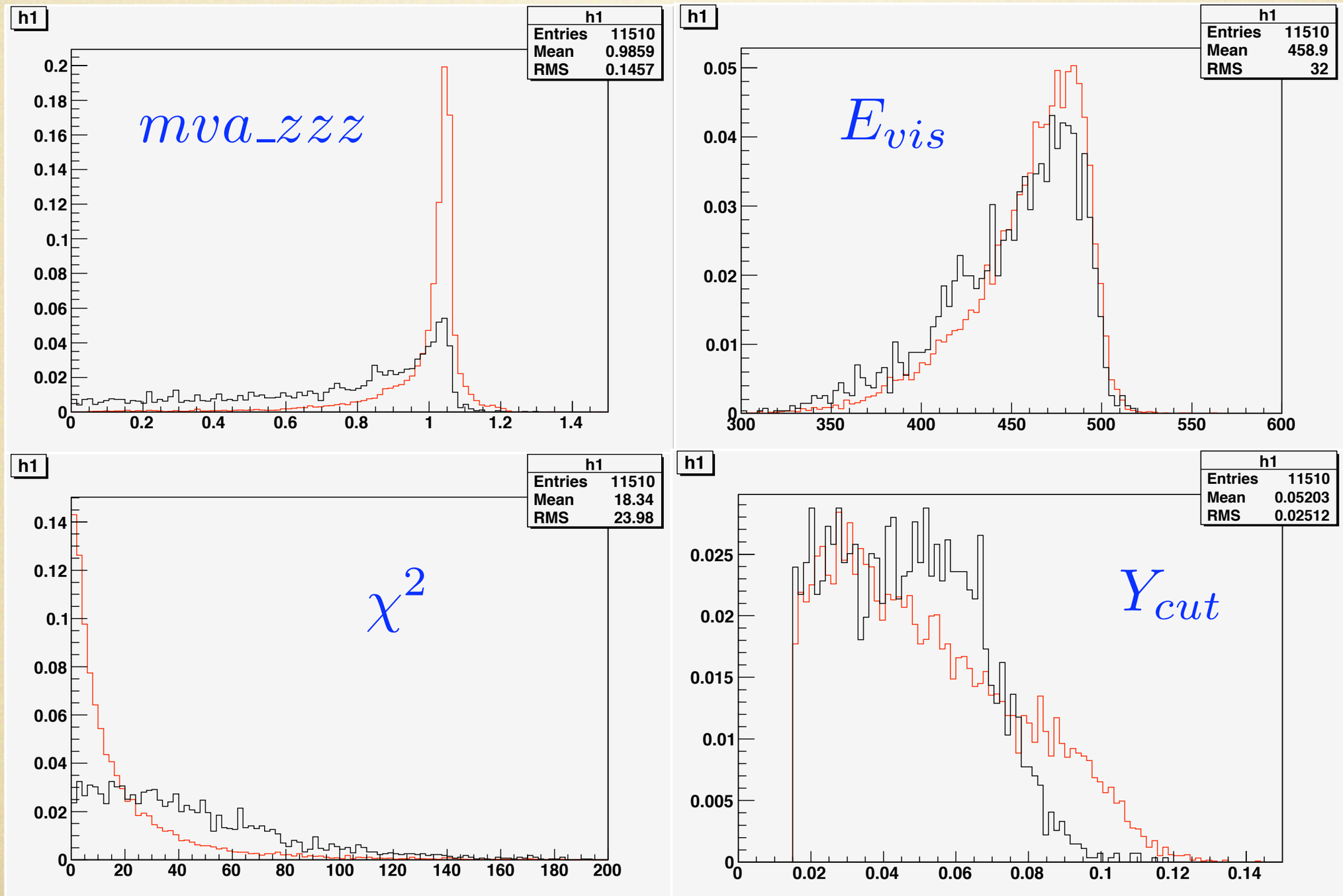


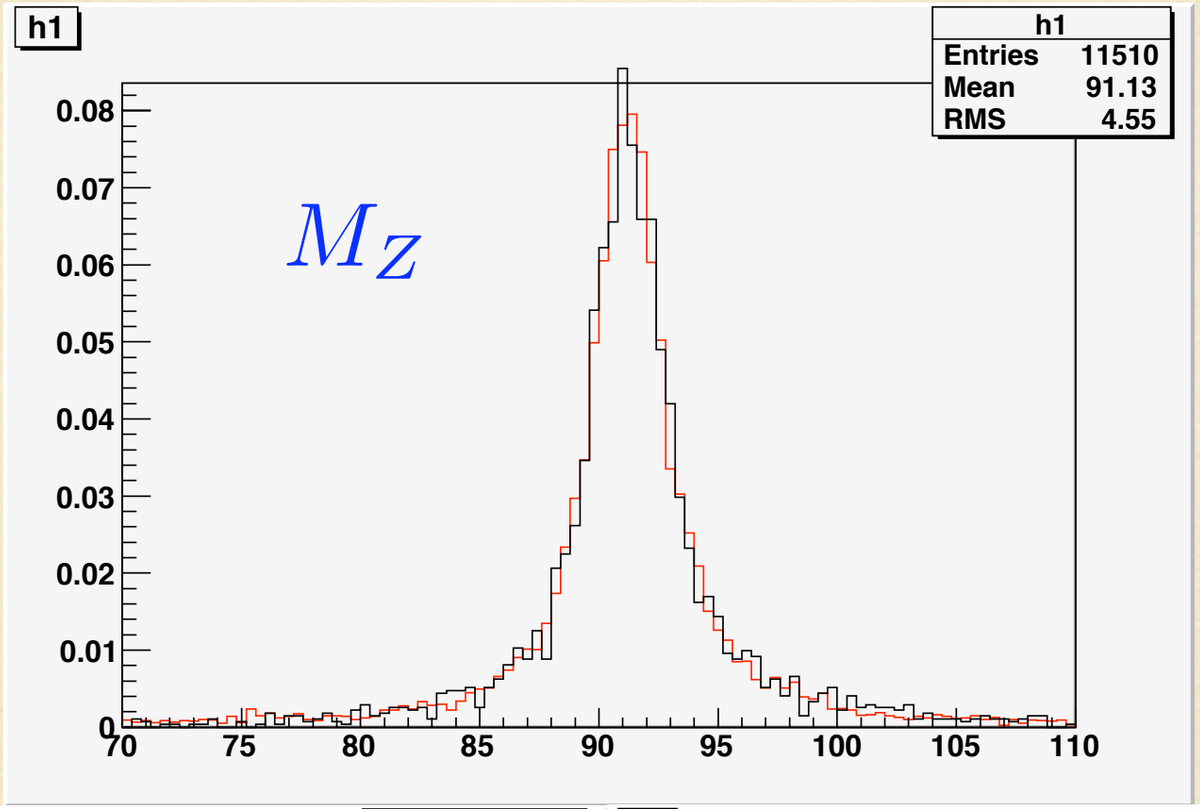
# signal .VS. background

after cuts

red: signal
black: ZZZ

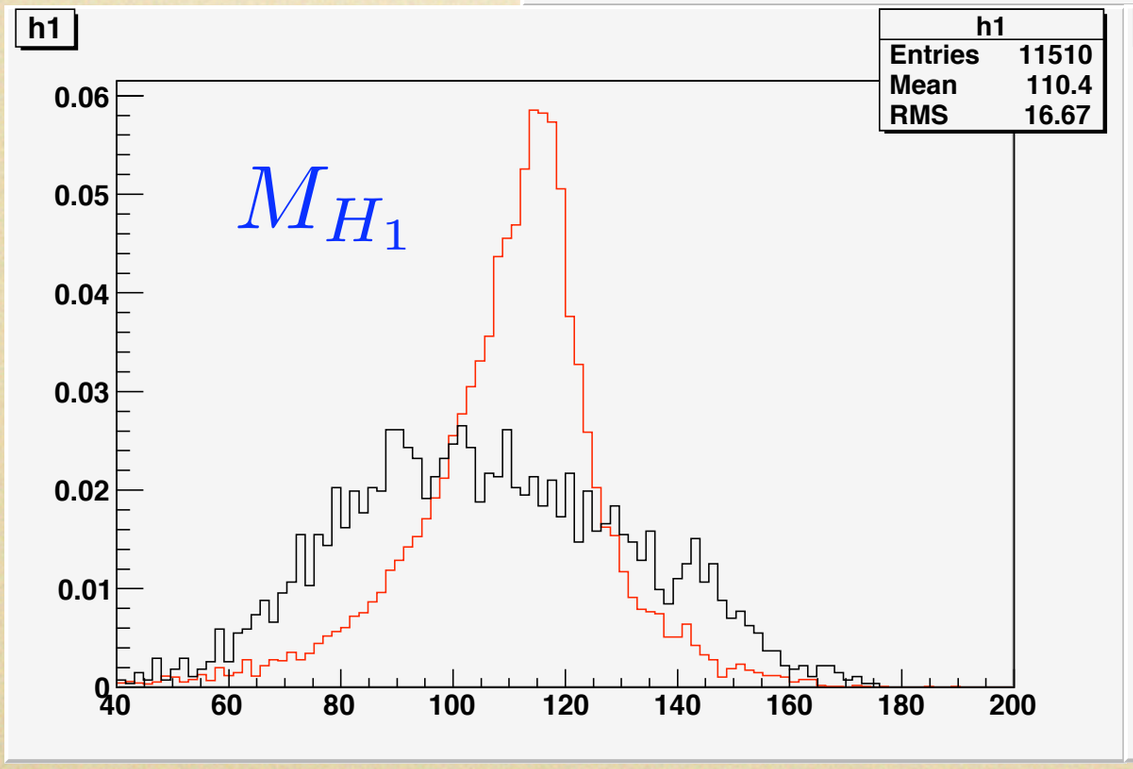


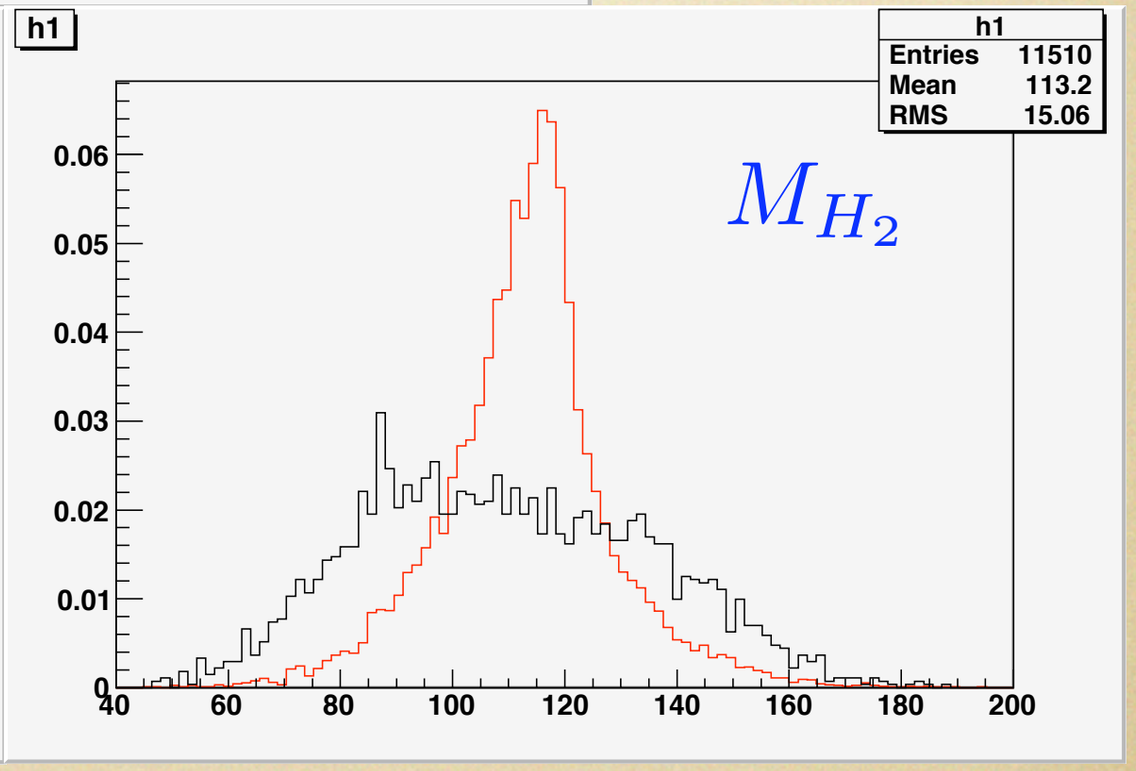
# invariant masses




red: signal

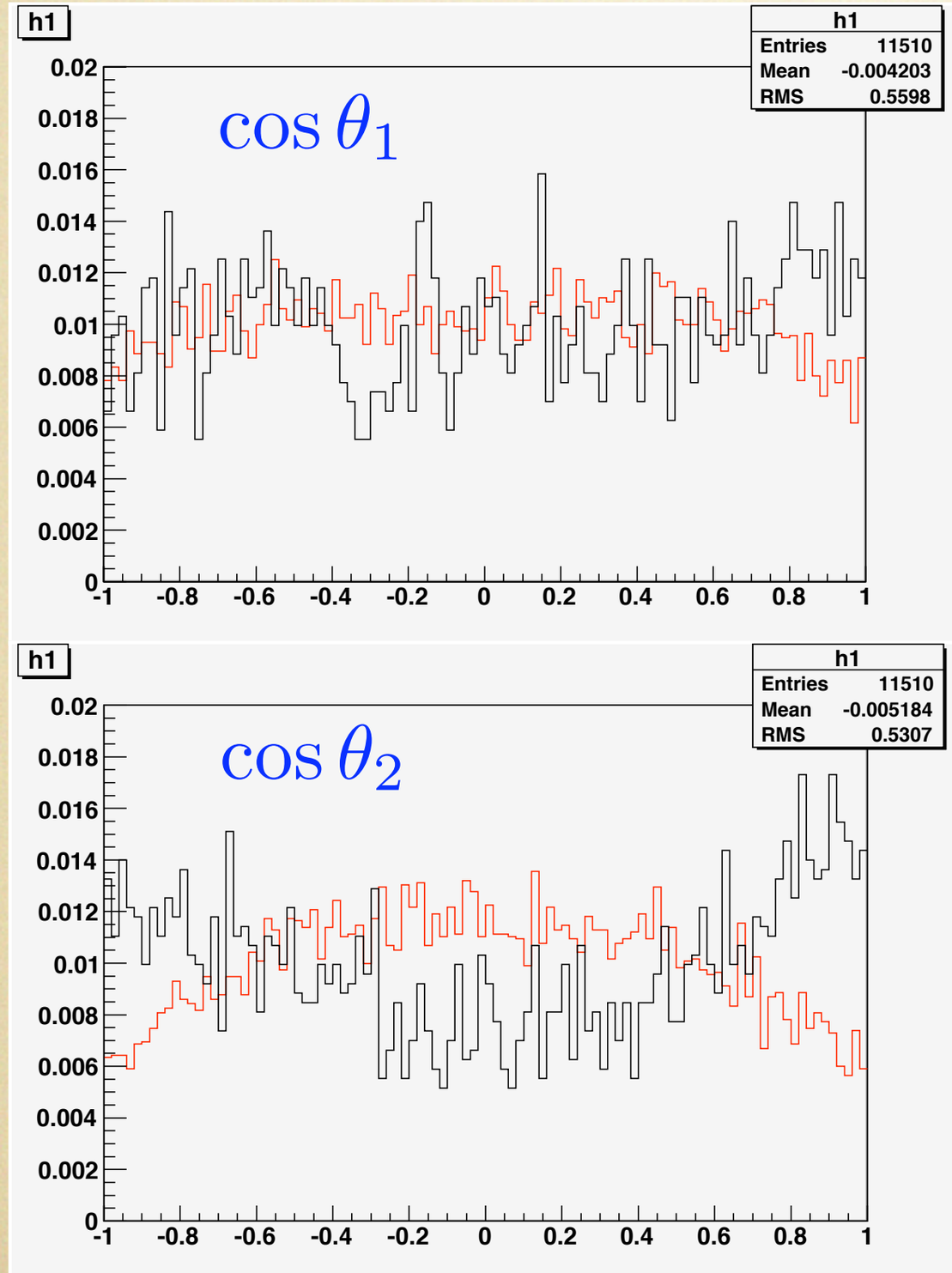
black: ZZZ



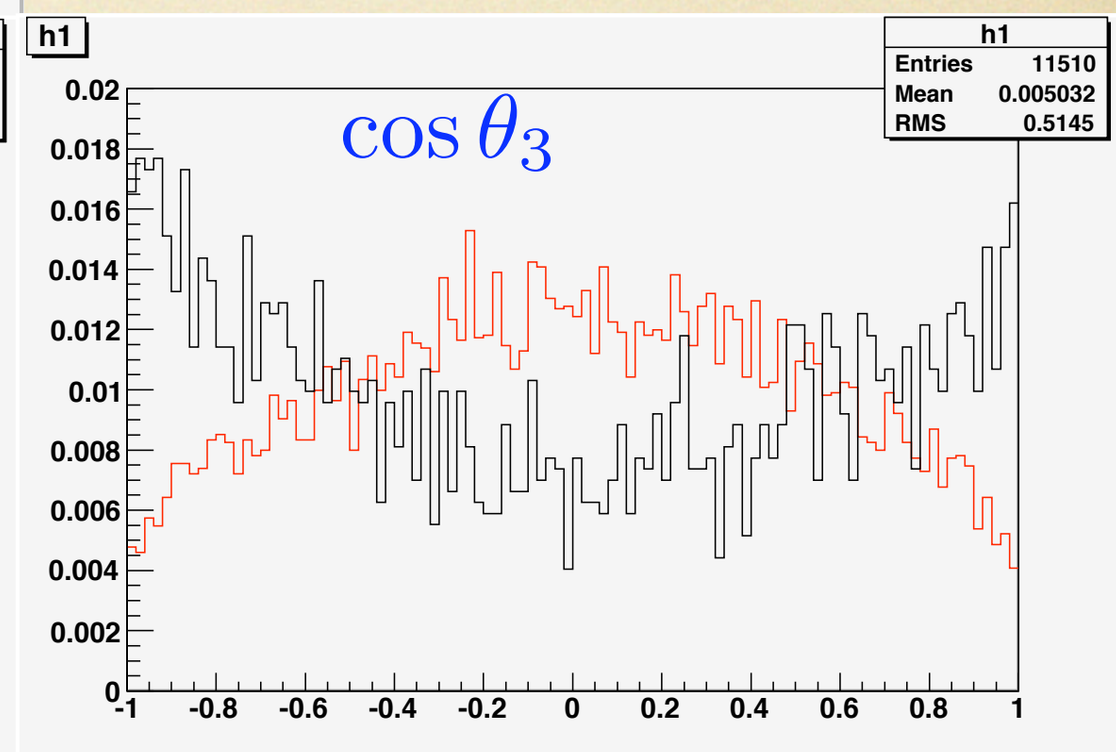
# polar angles (Z, H1, H2)

red: signal
black: ZZZ




the angles were arrayed as:

$$p_1 \leq p_2 \leq p_3$$



# look into the ZZZ background event by event

$$e^+ + e^- \to ZZZ \to \begin{cases} (b\bar{b})(b\bar{b})(l\bar{l}) & 0.47\% & 7.52 \\ (b\bar{b})(c\bar{c})(l\bar{l}) & 0.73\% & 11.7 \\ (c\bar{c})(c\bar{c})(l\bar{l}) & 0.29\% & 4.6 \\ (b\bar{b})(q\bar{q})(l\bar{l}) & 2.62\% & 41.9 \end{cases}$$

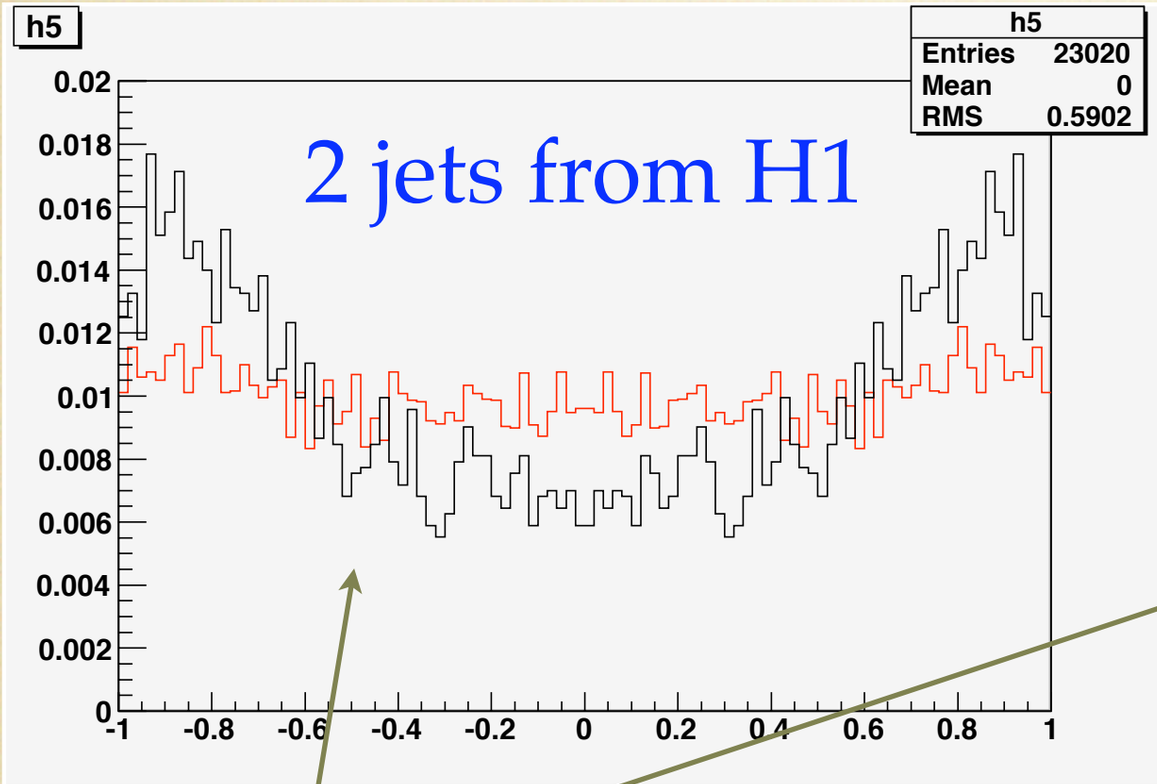
after all the cuts except the last one

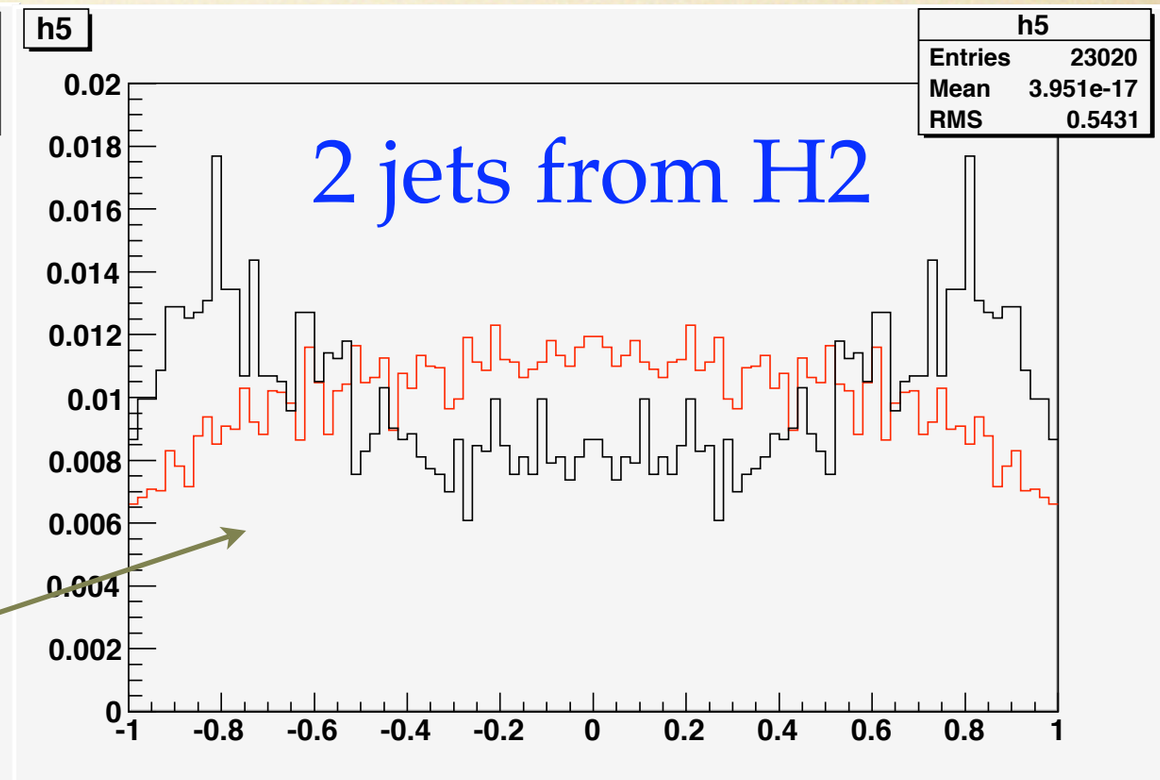
| survived events | event number | % | efficiency(%) |
|---|---|---|---|
| $(b\bar{b})(b\bar{b})(l\bar{l})$ | 86 | 57.7 | 18.3 |
| $(b\bar{b})(c\bar{c})(l\bar{l})$ | 47 | 31.5 | 6.4 |
| $(c\bar{c})(c\bar{c})(l\bar{l})$ | 5 | 3.4 | 1.7 |
| $(b\bar{b})(q\bar{q})(l\bar{l})$ | 8 | 5.4 | 0.3 |
| other | 3 | 2.0 | 0.003 |

2 run investigated (100K)

# decay angles

red: signal
black: ZZZ




a little different, why?