A Study of Δg_{HHH} vs. Jet Energy Resolution

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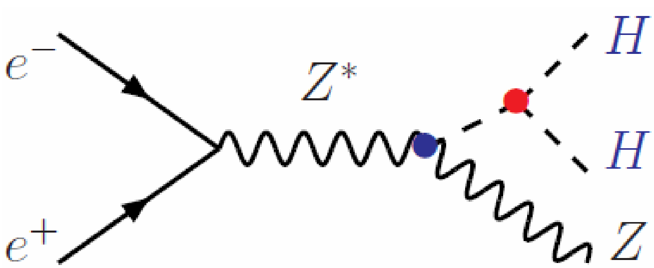
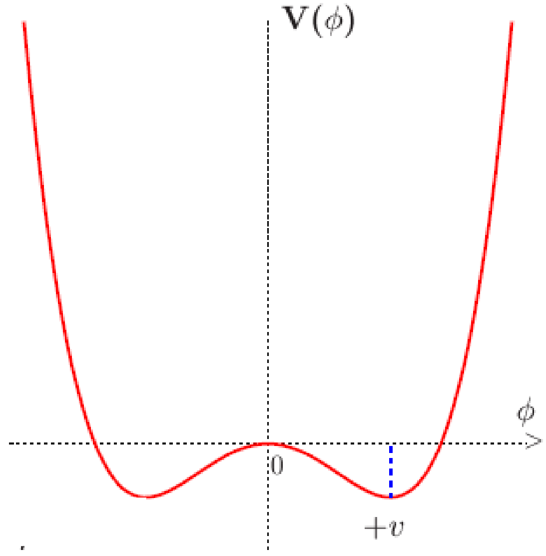
Mar 11, 2006



$g_{HHH} = -6\mu^2 / \mathrm{v}$



$$V(\phi) = \frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda\phi^4$$

Standard Model:

$$M_H^2 = 2\lambda \mathrm{v}^2 = -2\mu^2$$

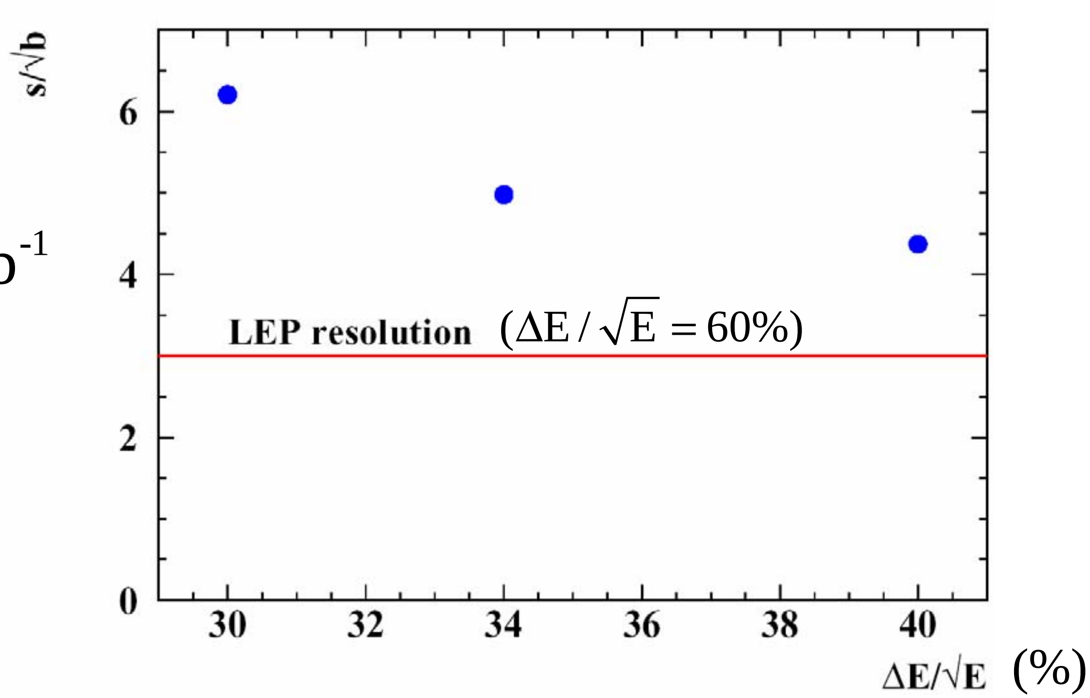
$e^+e^- \rightarrow ZHH \rightarrow q\bar{q}b\bar{b}b\bar{b}$

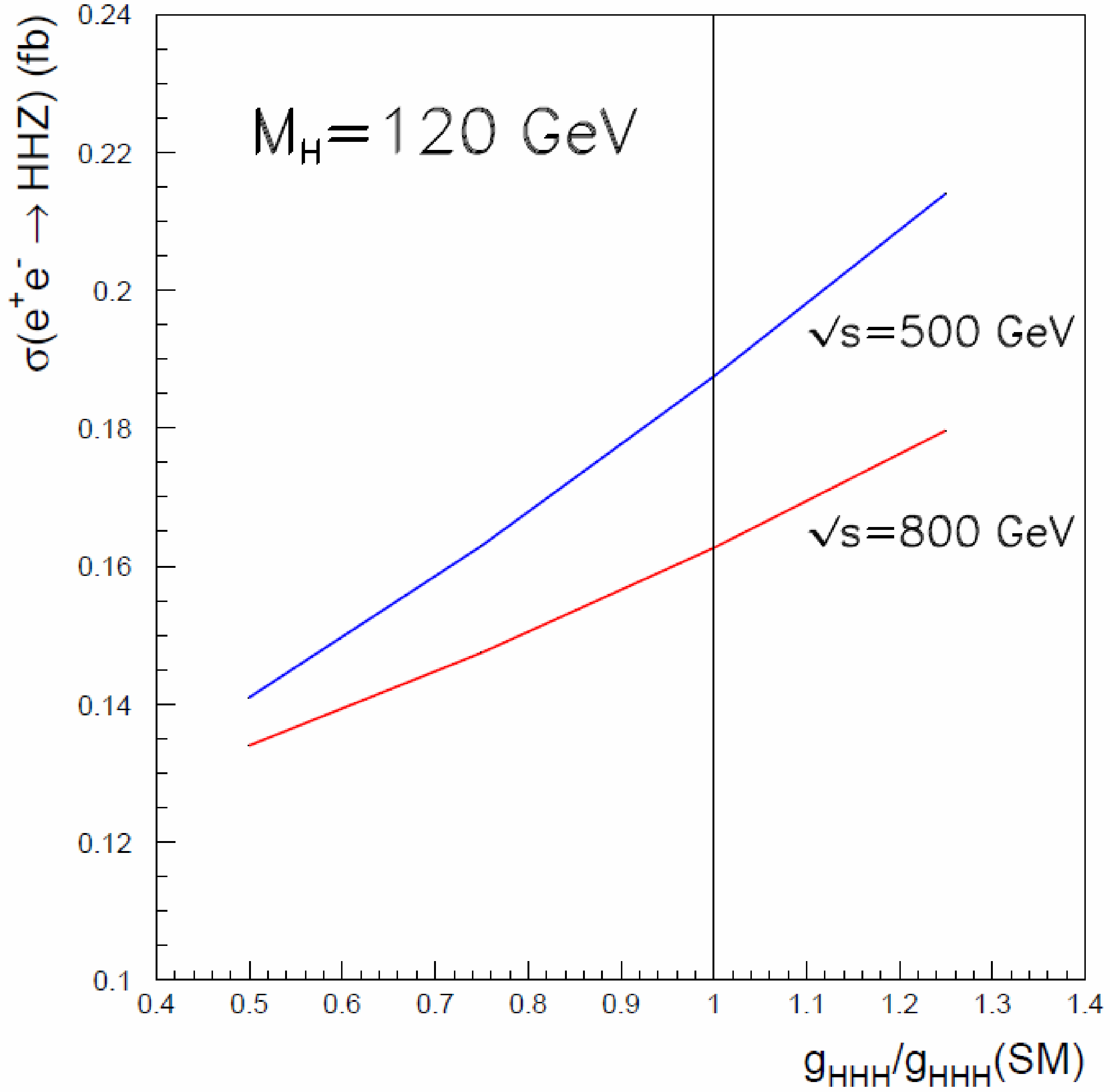
$\sqrt{s}$ = 500 GeV, L=1000 fb^{-1}

$\Delta E/\sqrt{E} = 60\% \rightarrow 30\%$

equiv to 4× Lumi

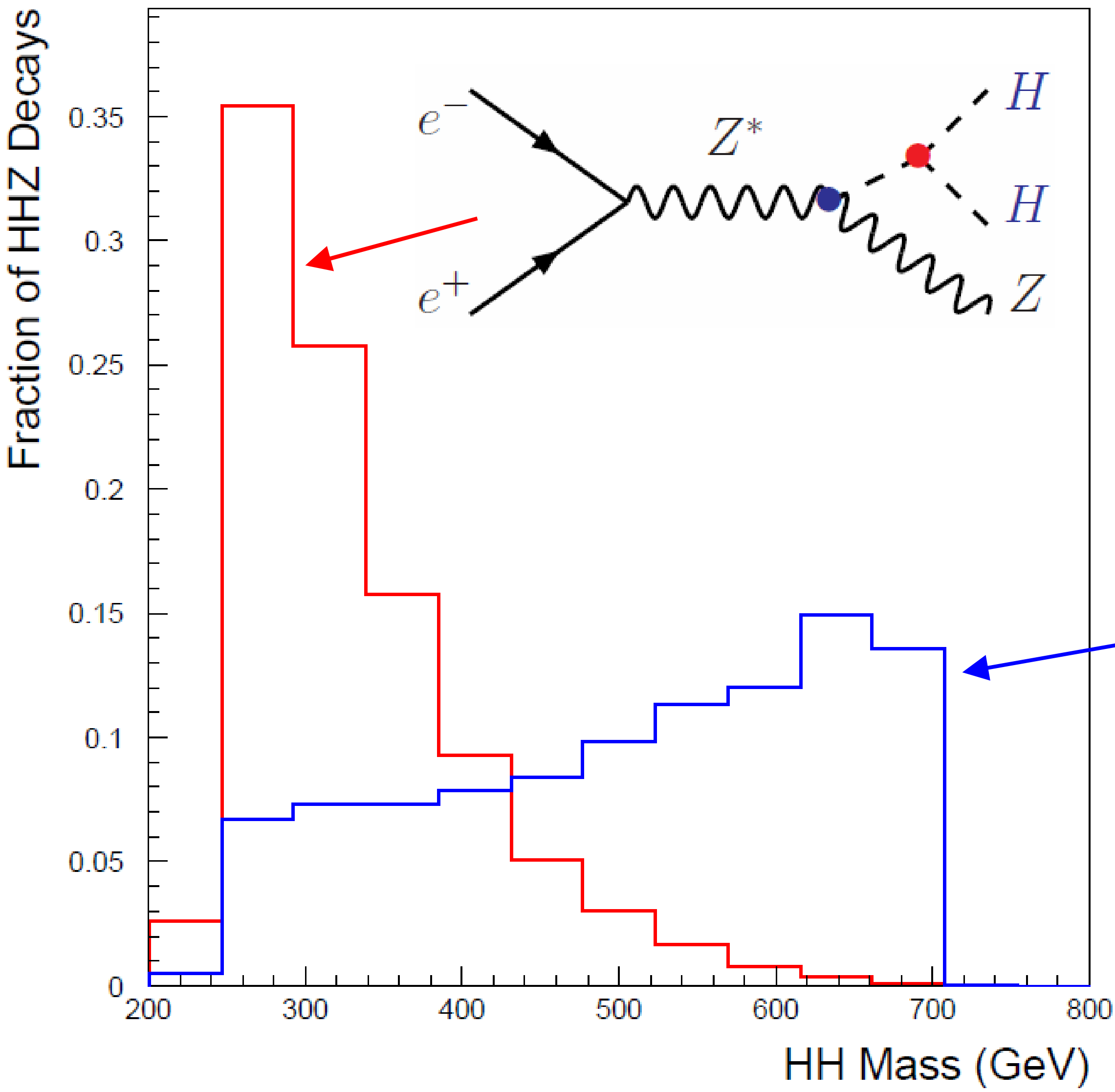
C. Castanier et al. hep-ex/0101028

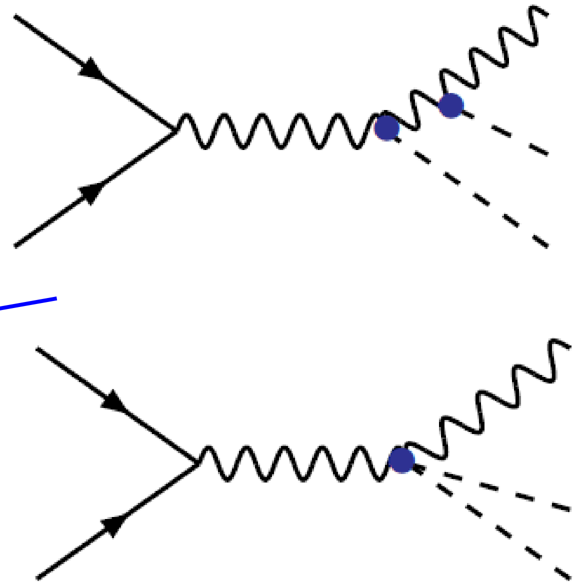




$M_H = 120$ GeV
$\sqrt{s} = 500$ GeV
$\sqrt{s} = 800$ GeV
$\sigma(e^+e^- \to HHZ)$ (fb)
$g_{HHH}/g_{HHH}(SM)$
0.24
0.22
0.2
0.18
0.16
0.14
0.12
0.1
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
1.4

Not All $e^+e^- \rightarrow ZHH$ Diagrams Contain the HHH Coupling





Goals of This Analysis

- Verify that triple Higgs coupling error depends strongly on jet energy resolution
- Understand and characterize the source of the strong dependency on jet energy resolution
- Perform analysis using a SM background sample that contains all 2,4,6,8-fermion processes.

Monte Carlo Production

- WHIZARD Monte Carlo is used to generate all 0,2,4,6-fermion and t quark dominated 8-fermion processes.
- 1 ab^{-1} @ 0.5 TeV using ILC params has been generated. Beamstrahlung and linac beam energy spread effects included.
- 100% electron and positron polarization is assumed in all event generation. Arbitrary electron, positron polarization is simulated by properly combining data sets.
- Fully fragmented MC data sets are produced. PYTHIA is used for final state QED & QCD parton showering, fragmentation, particle decay.

SM Final States

0-fermion

$e^+e^- \to$	$\gamma\gamma$	
	$\gamma\gamma\gamma$	
	$\gamma\gamma\gamma\gamma$	
	$\gamma\gamma\gamma\gamma\gamma$	

2-fermion

$e^+e^- \to$	ff	$f \neq \nu$
	$\nu\nu\gamma$	
	$\nu\nu\gamma\gamma$	
	$\nu\nu\gamma\gamma\gamma$	
$e^-\gamma \to$	$e^-\gamma$	
$\gamma e^+ \to$	$e^+\gamma$	

4-fermion

$e^+e^- \to$	$\nu\nu\nu\nu\gamma$	6 total
	$u_j\overline{d}_j d_k\overline{u}_k$	25 total
		$\nu_e e^+ e^- \overline{\nu}_e$
		$\nu_e e^+ \mu^- \overline{\nu}_\mu$
		$\nu_e e^+ \tau^- \overline{\nu}_\tau$
		$\nu_e e^+ d\overline{u}$
		.
		.
		$c\overline{s}s\overline{c}$
	$u_j\overline{u}_j u_k\overline{u}_k$	9 total
	$u_j\overline{u}_j d_k\overline{d}_k$	25 total
	$d_j\overline{d}_j d_k\overline{d}_k$	21 total
$\gamma\gamma \to$	$f\overline{f}$	8 total
$e_L^-\gamma \to$	$\nu_e d_k\overline{u}_k$	5 total
$e^-\gamma \to$	$e^- f\overline{f}$	10 total
$\gamma e_R^+ \to$	$\overline{\nu}_e u_k\overline{d}_k$	5 total
$\gamma e^+ \to$	$e^+ f\overline{f}$	10 total

6-fermion

$e^+e^- \to$	$u_i\overline{u}_i u_j\overline{d}_j d_k\overline{u}_k$	125 total
	$d_i\overline{d}_i u_j\overline{d}_j d_k\overline{u}_k$	150 total
	$u_i\overline{u}_i u_j\overline{u}_j u_k\overline{u}_k$	25 total
	$u_i\overline{u}_i u_j\overline{u}_j d_k\overline{d}_k$	65 total
	$u_i\overline{u}_i d_j\overline{d}_j d_k\overline{d}_k$	75 total
	$d_i\overline{d}_i d_j\overline{d}_j d_k\overline{d}_k$	56 total
$\gamma\gamma \to$	$u_j\overline{d}_j d_k\overline{u}_k$	25 total
	$u_j\overline{u}_j u_k\overline{u}_k$	9 total
	$u_j\overline{u}_j d_k\overline{d}_k$	25 total
	$d_j\overline{d}_j d_k\overline{d}_k$	21 total
$e_L^-\gamma \to$	$\nu_e u_j\overline{u}_j d_k\overline{u}_k$	25 total
	$\nu_e d_j\overline{d}_j d_k\overline{u}_k$	30 total
$e^-\gamma \to$	$e^- u_j\overline{d}_j d_k\overline{u}_k$	20 total
	$e^- u_j\overline{u}_j u_k\overline{u}_k$	10 total
	$e^- u_j\overline{u}_j d_k\overline{d}_k$	20 total
	$e^- d_j\overline{d}_j d_k\overline{d}_k$	21 total
$\gamma e_R^+ \to$	$\overline{\nu}_e u_j\overline{d}_j u_k\overline{u}_k$	25 total
	$\overline{\nu}_e u_j\overline{d}_j d_k\overline{d}_k$	30 total
$\gamma e^+ \to$	$e^+ u_j\overline{d}_j d_k\overline{u}_k$	20 total
	$e^+ u_j\overline{u}_j u_k\overline{u}_k$	10 total
	$e^+ u_j\overline{u}_j d_k\overline{d}_k$	20 total
	$e^+ d_j\overline{d}_j d_k\overline{d}_k$	21 total

8-fermion

$e^+e^- \to$	$f\overline{f}t\overline{t}$
$\gamma\gamma \to$	$t\overline{t}$
$e^-\gamma \to$	$e^- t\overline{t}$
	$\nu_e b\overline{t}$
$\gamma e^+ \to$	$e^+ t\overline{t}$
	$\overline{\nu}_e t\overline{b}$

Note: Cabbibo suppressed combinations of qq′ are not included right now. Could be important for WW and tt background to ZHH.

Plan for Analyis

- Perform analysis on qqbbbb channel only at E_{cm}=500 GeV assuming -90% electron polarization (increases signal statistics by factor of 1.2 over unpolarized beams).
- Use org.lcsim Fast MC simulation of baseline SiD. This MC includes a reasonable algorithm for smearing charged track angles, curvature and impact parameters. Calorimeter simulation consists of simple single neutral particle smearing with EM resolution for photons and HAD res for n,$K0_{L.}$
- Scale single particle calorimeter resolutions to get a particular ΔE_{jet} .
- Use org.lcsim ZVTOP for b-tagging

Perfect PFA : What theory predicts

- Jet energy resolution
  $\sigma^2(E_{jet}) = \sigma^2(ch.) + \sigma^2(\gamma) + \sigma^2(h^0) + \sigma^2(conf.)$
- Excellent tracker :
  $\sigma^2(ch.) << \sigma^2(\gamma) + \sigma^2(h^0) + \sigma^2(conf.)$
- Perfect PFA : $\sigma^2(conf.) = 0$
- $\sigma^2(E_{jet}) = A_\gamma^2 E_\gamma + A_h^2 E_{h0} = w_\gamma A_\gamma^2 E_{jet} + w_{h0} A_h^2 E_{jet}$
  $\sigma(E_{\gamma,h})/E_{\gamma,h} = A_{\gamma,h}/\sqrt{E_{\gamma,h}}$

Typically $w_\gamma = 25\%$; $w_{h0} = 13\%$

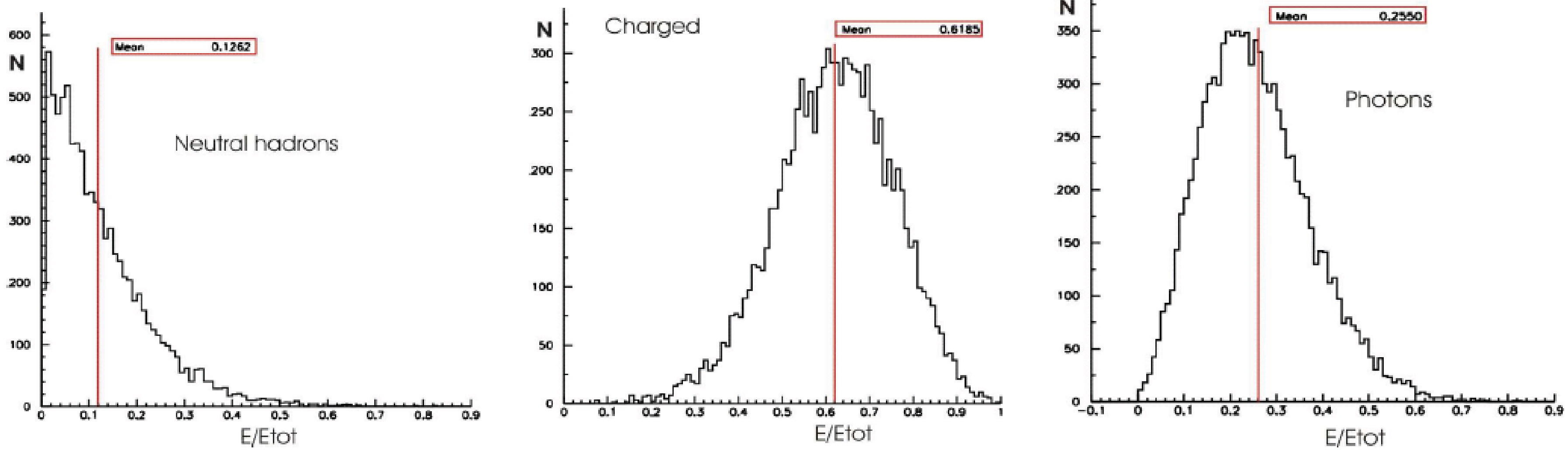
I find w_γ=28%; w_{h0}=10%

$A_\gamma = 11\%$; $A_{h0} = 34\%$

=> $\sigma(E_{jet})/E_{jet} = 12\%/\sqrt{E_{jet}}$

$A_\gamma = 11\%$; $A_{h0} = 50\%$

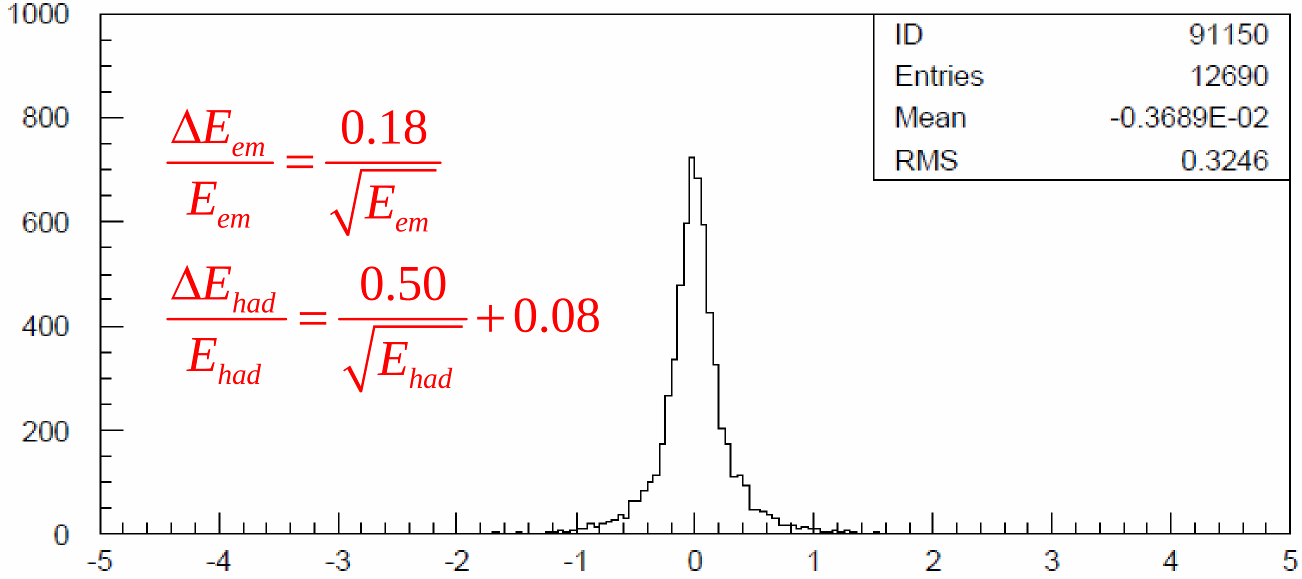
=> $\sigma(E_{jet})/E_{jet} = 17\%/\sqrt{E_{jet}}$

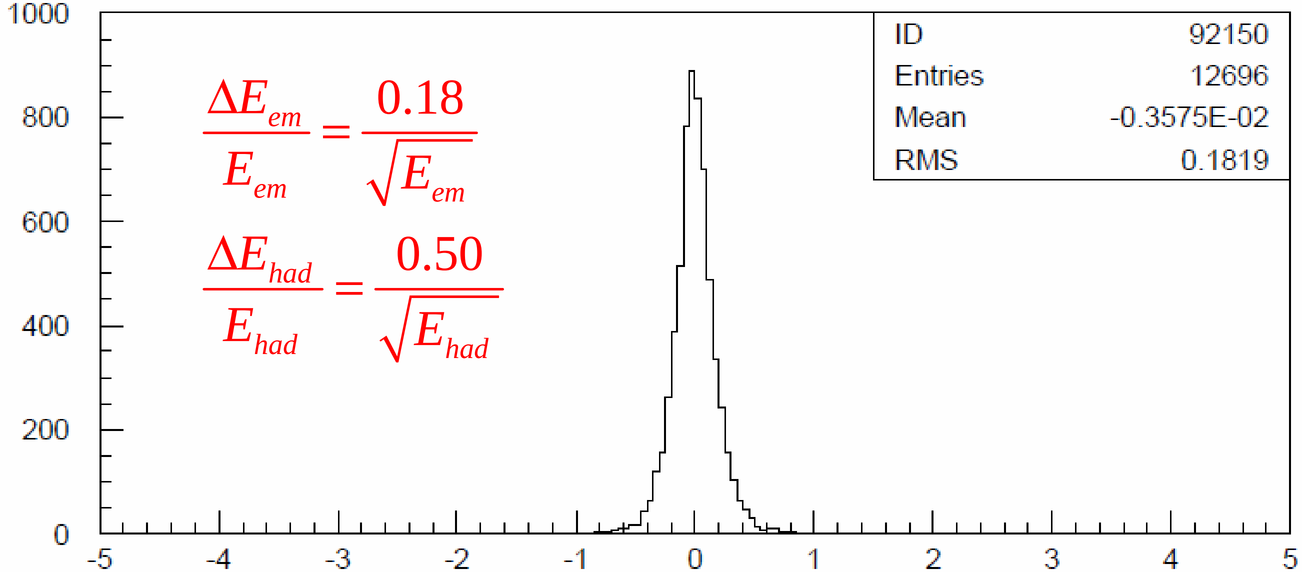


$\sqrt{s} = 500$ GeV

$e^+e^- \to u\bar{u}$

E_{true} is adjusted for neutrinos and particles outside detector acceptance





$$\Delta E_{jet} = (E_{rec} - E_{true}) / \sqrt{E_{true}}$$

Drop constant term in single particle resolution for now. Assume negligible contribution from charged particles to jet energy resolution and write

$$\sigma^2 = (1+\lambda(1-r))A_\gamma^2 w_\gamma E_{jet} + (1+\lambda r)A_h^2 w_h E_{jet} = c^2 E_{jet}$$

where $c = 0.3, 0.4, 0.5, 0.6$

$r =$ hadronic resolution degradation fraction

($r = 1$ to only degrade hadronic resolution

$r = 0$ to only degrade em resolution)

$A_\gamma = 0.18 \quad A_h = 0.50 \quad w_\gamma = 0.28 \quad w_h = 0.10$

Given a desired jet energy resolution c the parameter λ is given by

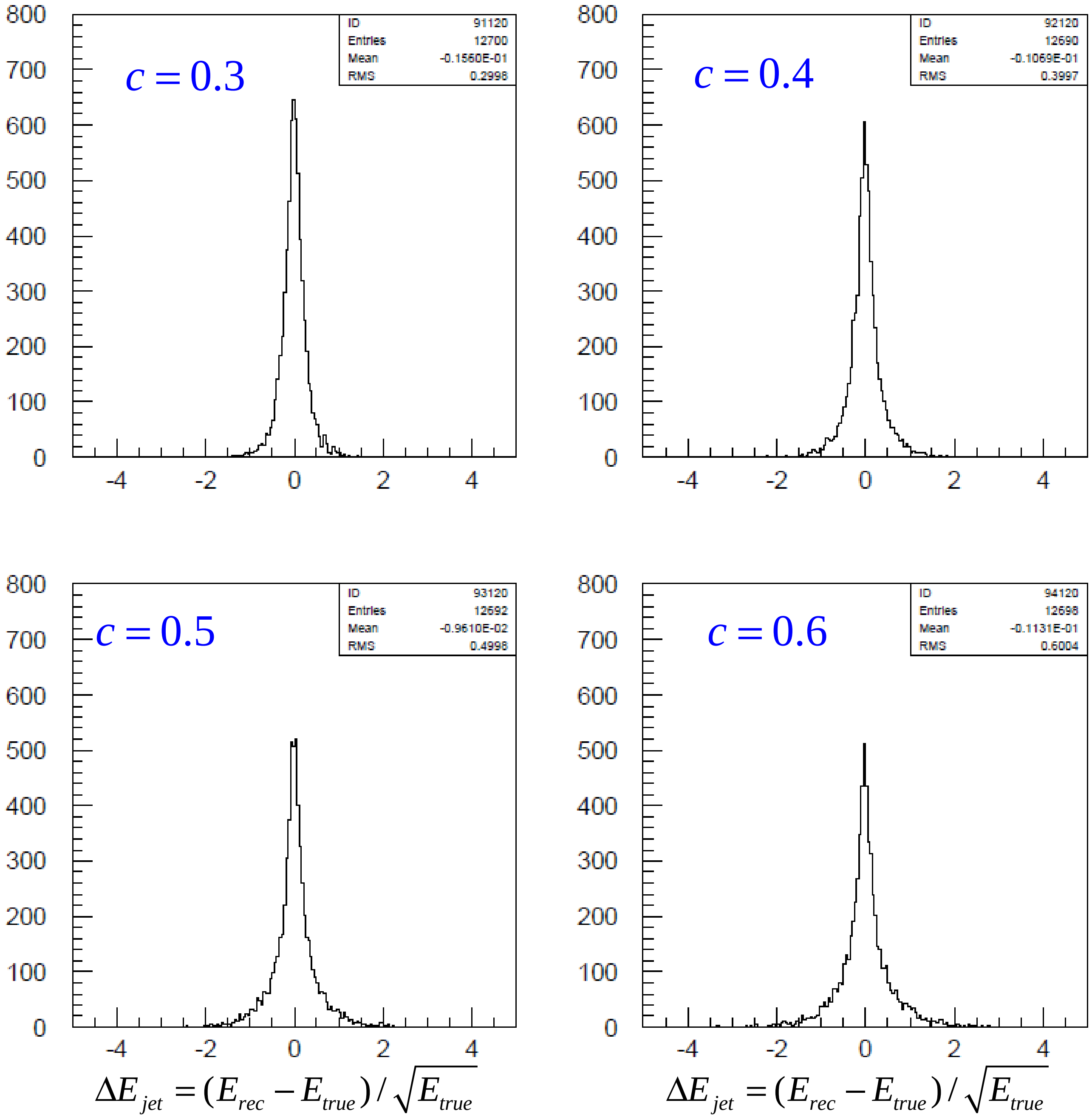
$$\lambda = \frac{c^2 - A_\gamma^2 w_\gamma - A_h^2 w_h}{(1-r)A_\gamma^2 w_\gamma + rA_h^2 w_h}$$

$$e^+e^- \to u\bar{u}$$

$\sqrt{s} =$ 500 GeV

$r = 1.0$

(only degrade had resolution)

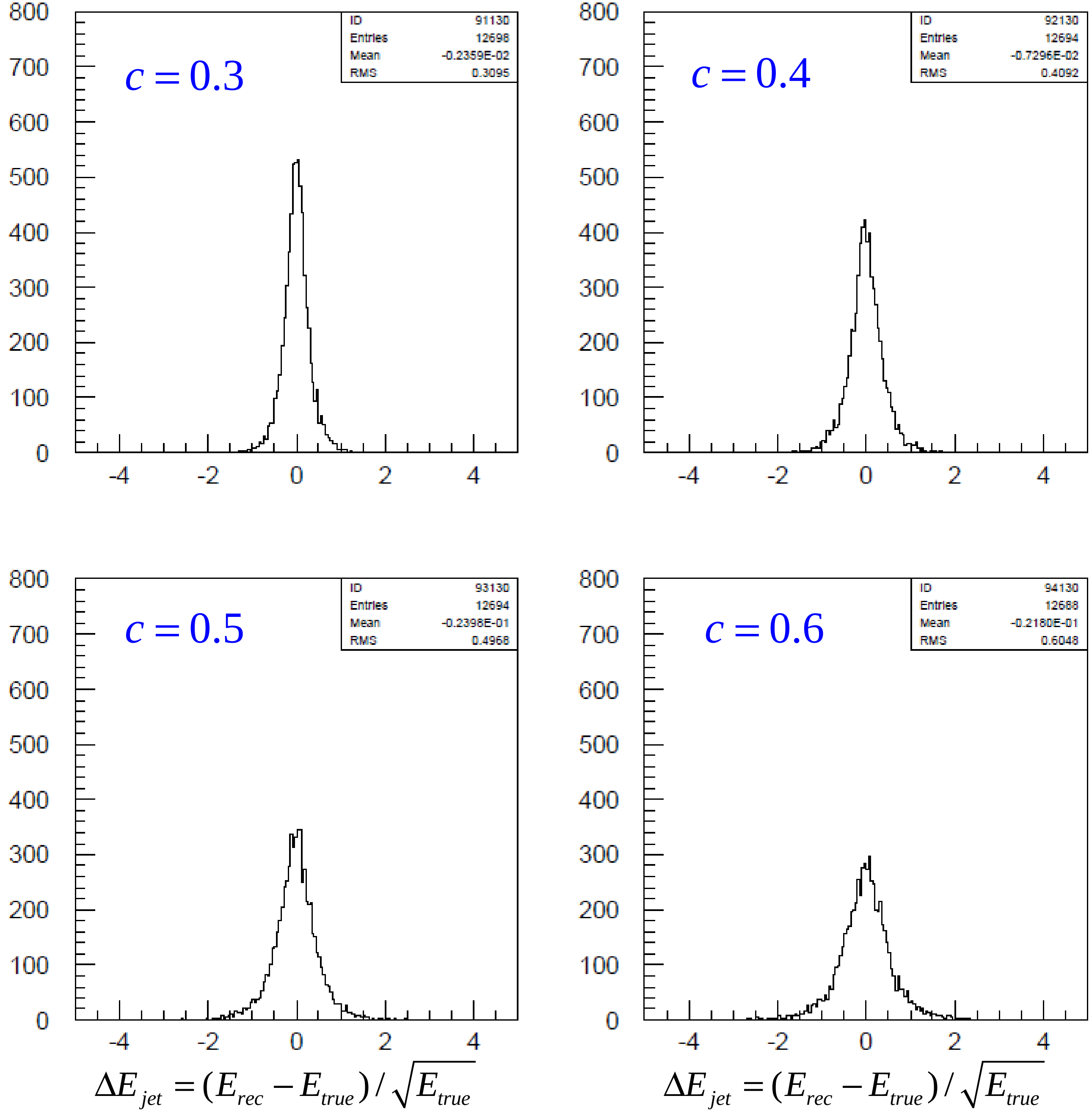


$e^+e^- \to u\bar{u}$

$\sqrt{s} = 500$ GeV

$r = 0.5$

(degrade em & had resolutions with equal wgt)



NN_{btag}

- Use udscb jets in ZHH events to train NN_{btag}
- Perform jet analysis on charged and neutral objects allowing number of jets to vary; for each jet perform ZVTOP analysis as implemented in org.lcsim
- Use the following variables in the btag neural net:

E_{jet}

E_{vtx}

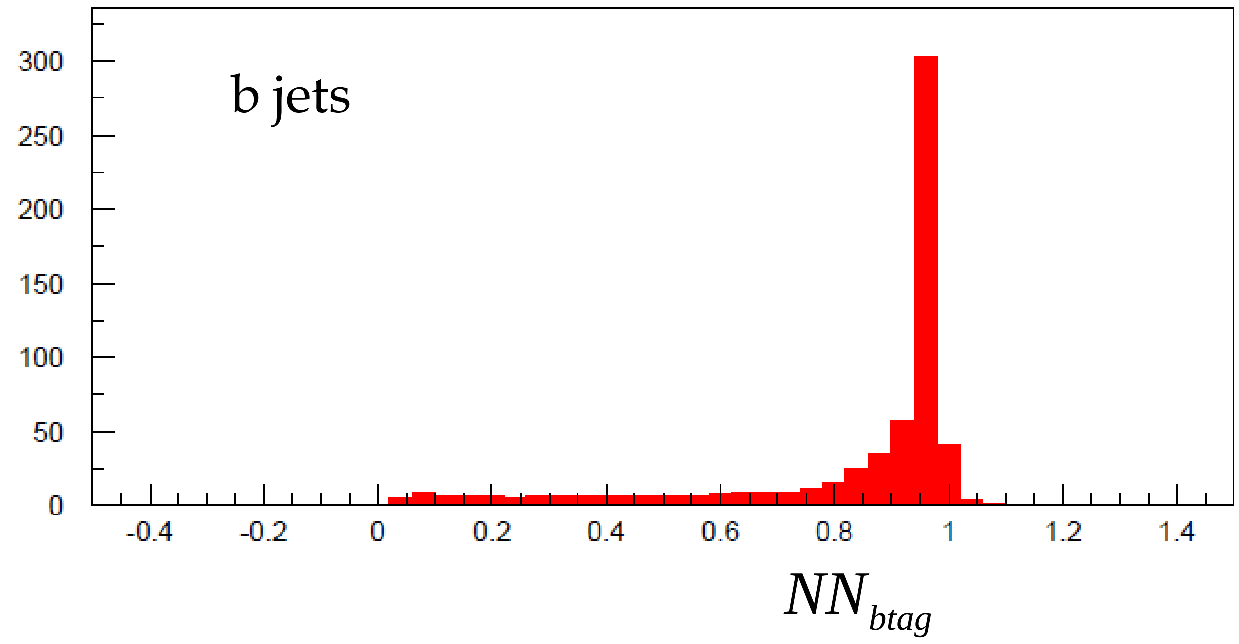
M_{vtx}

Pt-Corrected M_{vtx}

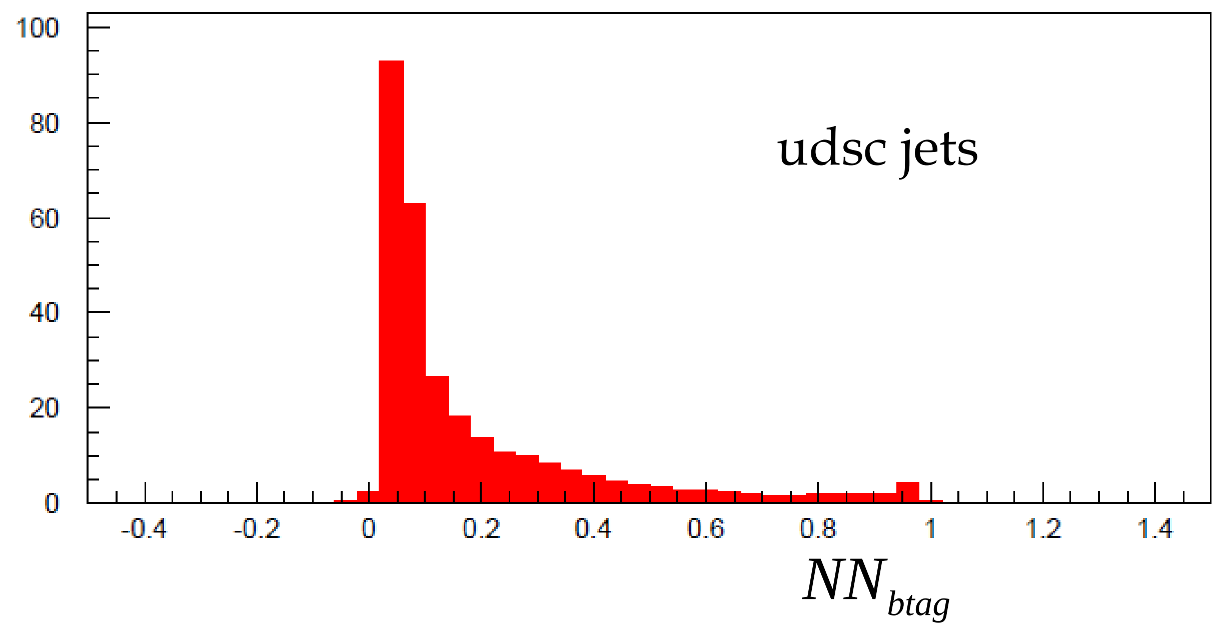
Secondary Vertices

Unassociated Large Impact Parameter Tracks

ZHH events



b jets
300
250
200
150
100
50
0
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
1.2
1.4
NN_{btag}



udsc jets
100
80
60
40
20
0
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
1.2
1.4
NN_{btag}

χ^2_{ZHH}

- Force charged and neutral objects into 6 jets
- Loop over 45 jet-pair combinations & minimize χ^2_{ZHH}

$$\chi^2_{ZHH} = \chi^2_{ZHH\_ZHHmass} + \sum_{j=3}^{6} \frac{(NNbtag_j - 1)^2}{\sigma^2_{NNbtag}}$$

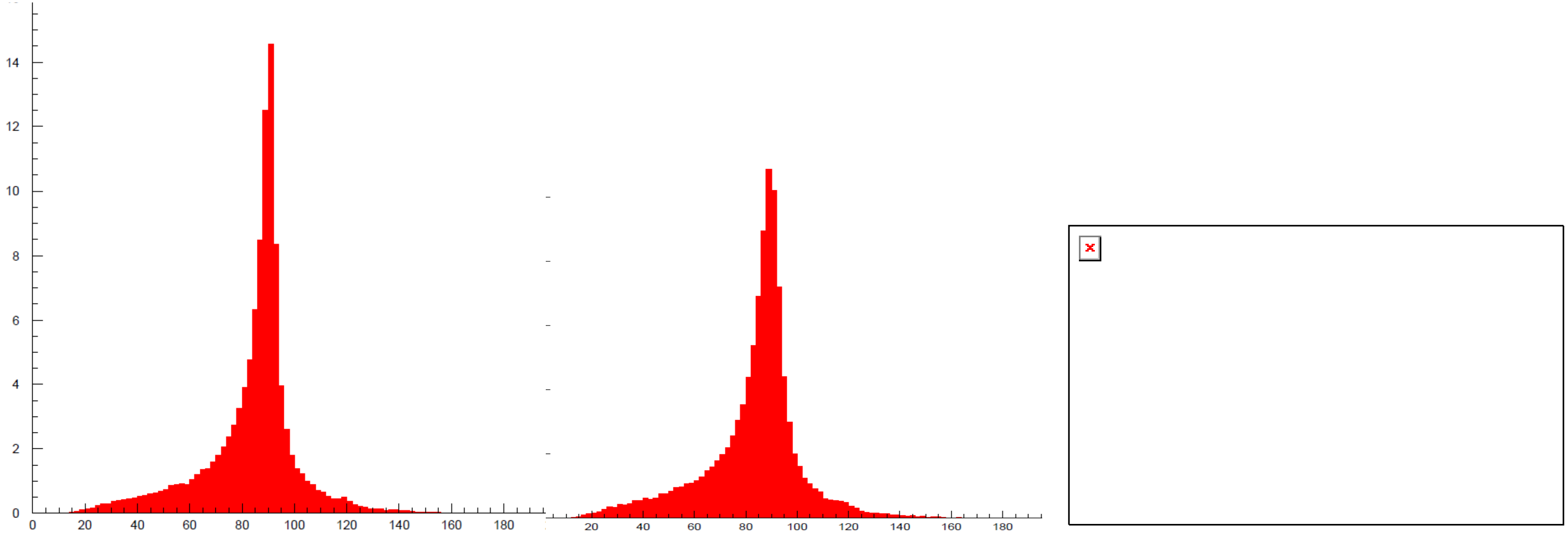
$$\chi^2_{ZHH\_ZHHmass} = \chi^2_{ZHH\_HHmass} + \frac{(M_{12} - M_Z)^2}{\sigma^2_{M_Z}}$$

$$\chi^2_{ZHH\_HHmass} = \frac{(M_{34} - M_H)^2}{\sigma^2_{M_H}} + \frac{(M_{56} - M_H)^2}{\sigma^2_{M_H}}$$

M_{ij} = Mass for jet-pair combination *ij*

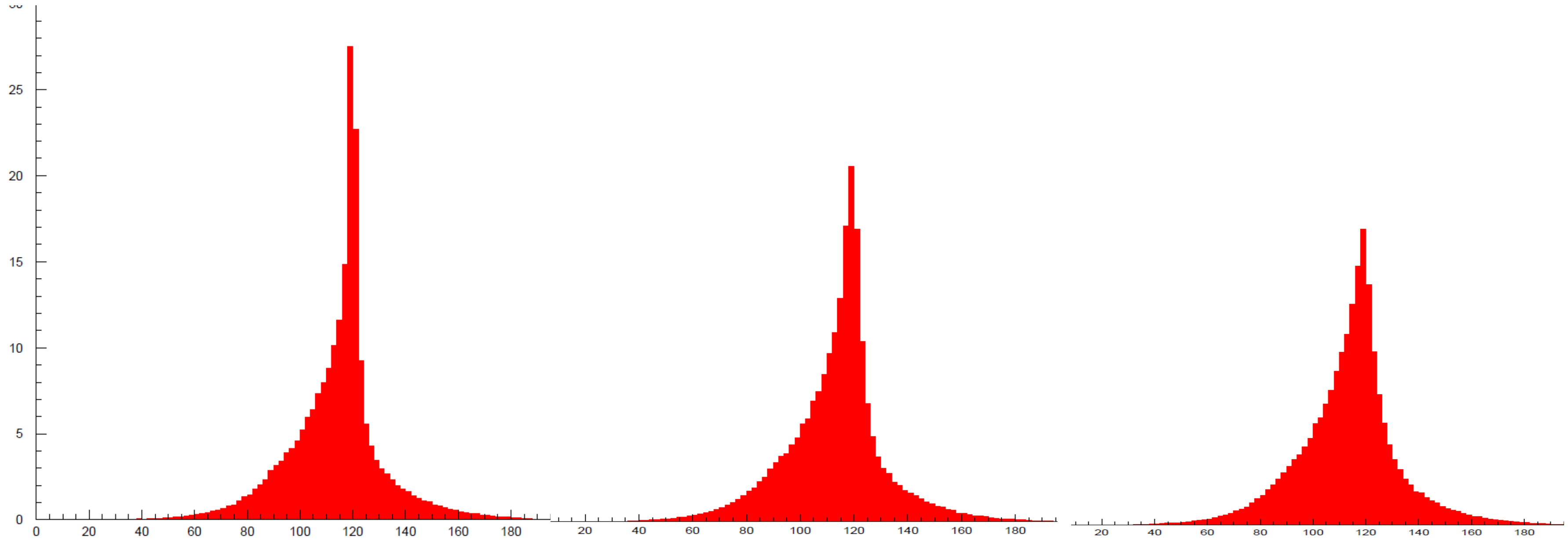
$NNbtag_j$ = btag neural net variable for jet j

$\frac{\Delta E_{jet}}{\sqrt{E_{jet}}} =$ 0.0 0.3 0.6



Z candidate jet-jet mass (GeV) for minimum χ^2_{ZHH}

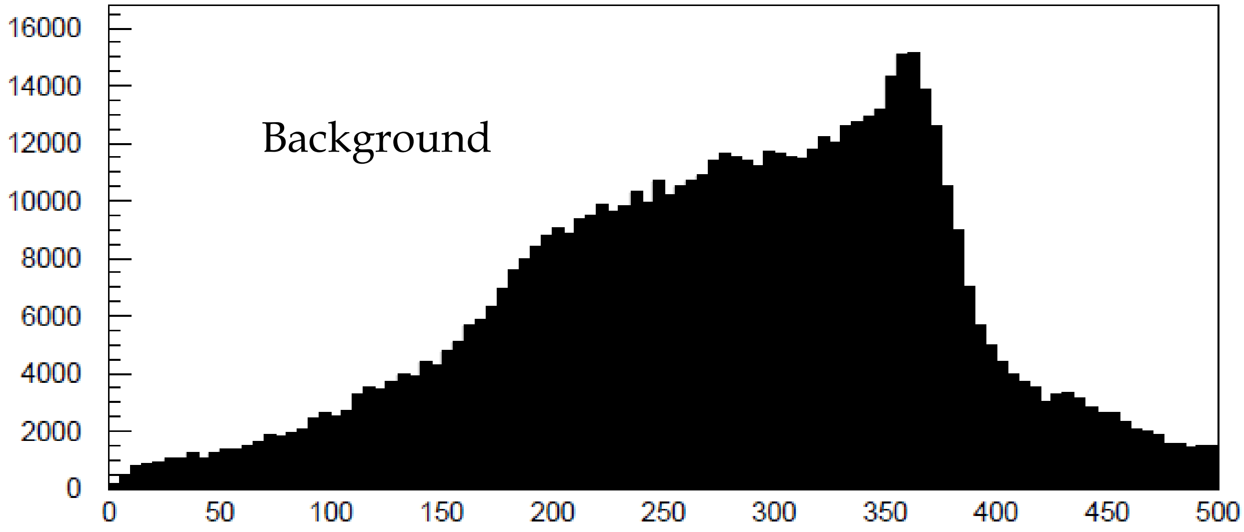
$$\frac{\Delta E_{jet}}{\sqrt{E_{jet}}} = \quad 0.0 \qquad 0.3 \qquad 0.6$$

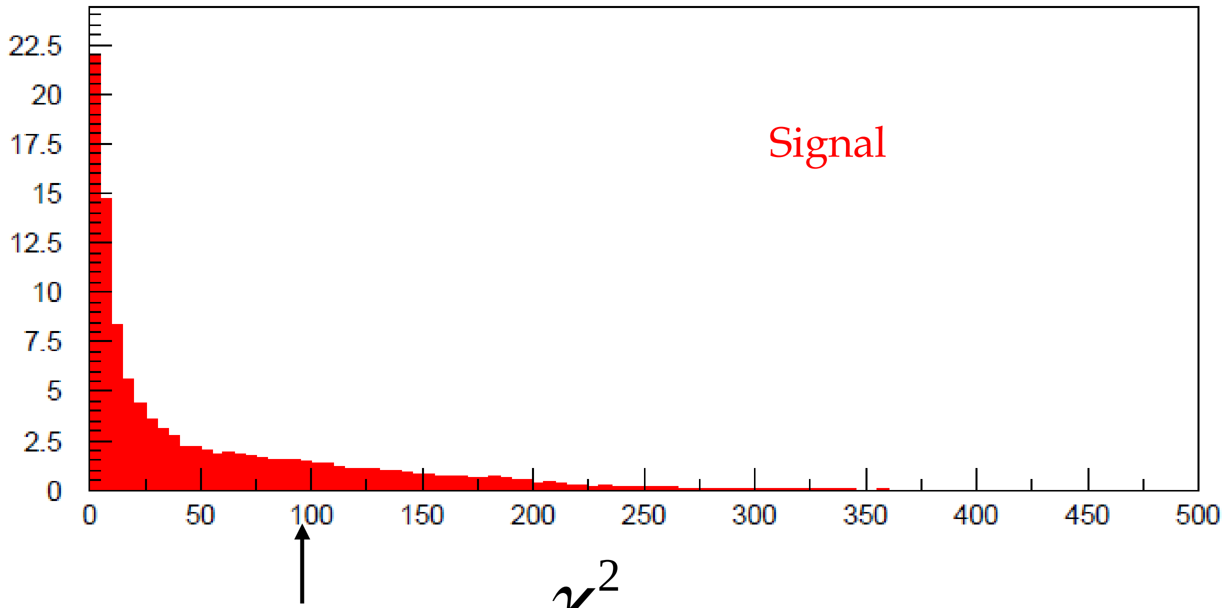


H candidate jet-jet masses (GeV) for minimum χ^2_{ZHH}

$$\frac{\Delta E_{jet}}{\sqrt{E_{jet}}} = 0.0$$

$$\chi^2_{ZHH} < 90$$

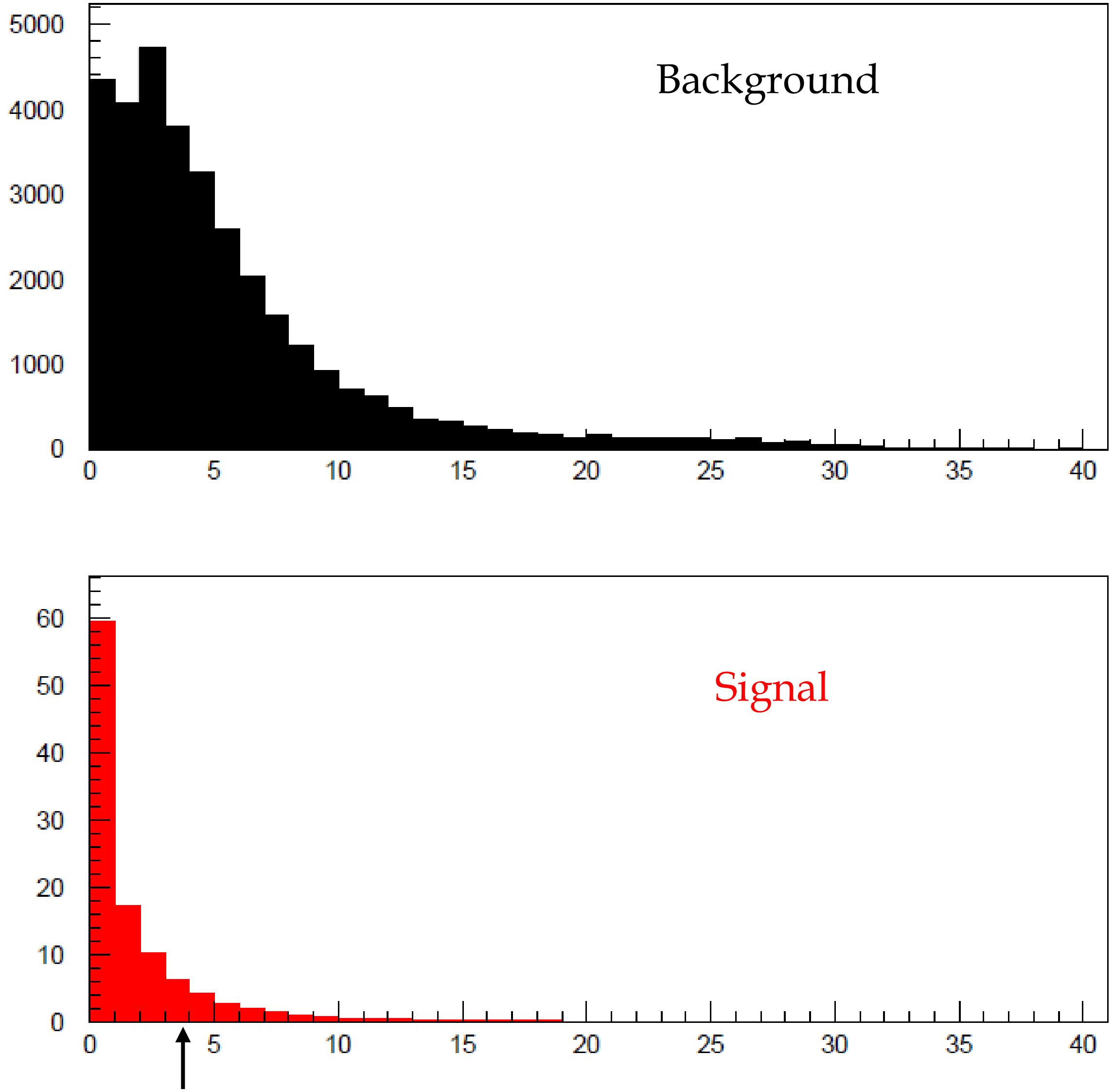




$$\chi^2_{ZHH}$$

$$\frac{\Delta E_{jet}}{\sqrt{E_{jet}}} = 0.0$$

$\chi^2_{ZHH\_HHmass} < 4$



$\chi^2_{ZHH\_HHmass}$

χ^2_{ZH}

- Force charged and neutral objects into 4 jets
- Loop over 6 jet-pair combinations & minimize χ^2_{ZH}

$$\chi^2_{ZH} = \chi^2_{ZH\_ZHmass} + \sum_{j=3}^{4} \frac{(NNbtag_j - 1)^2}{\sigma^2_{NNbtag}}$$

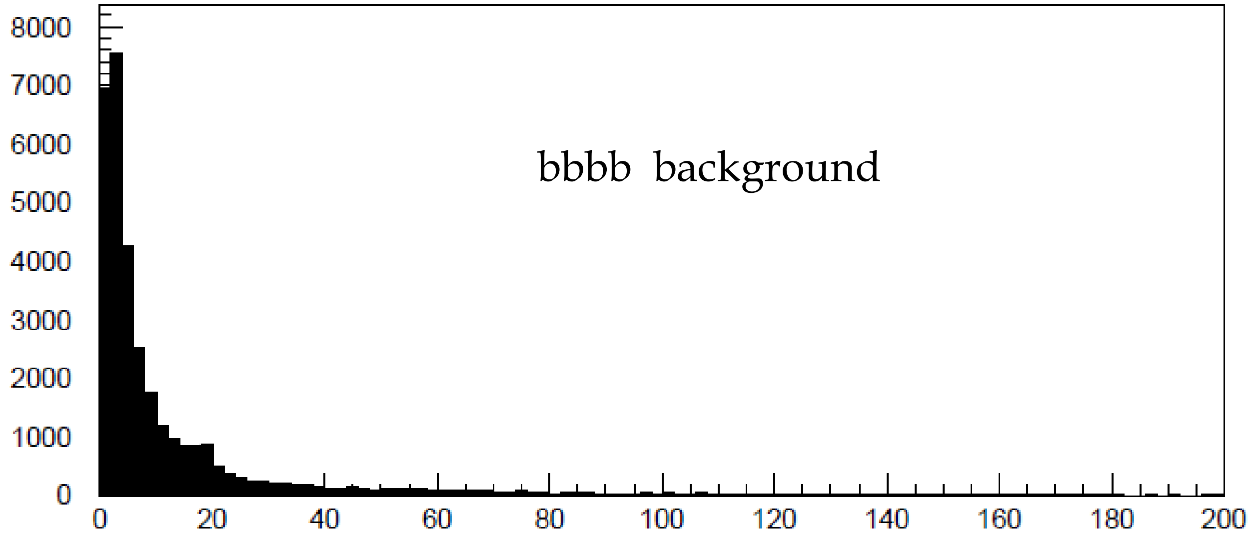
$$\chi^2_{ZH\_ZHmass} = \frac{(M_{12} - M_Z)^2}{\sigma^2_{M_Z}} + \frac{(M_{34} - M_H)^2}{\sigma^2_{M_H}}$$

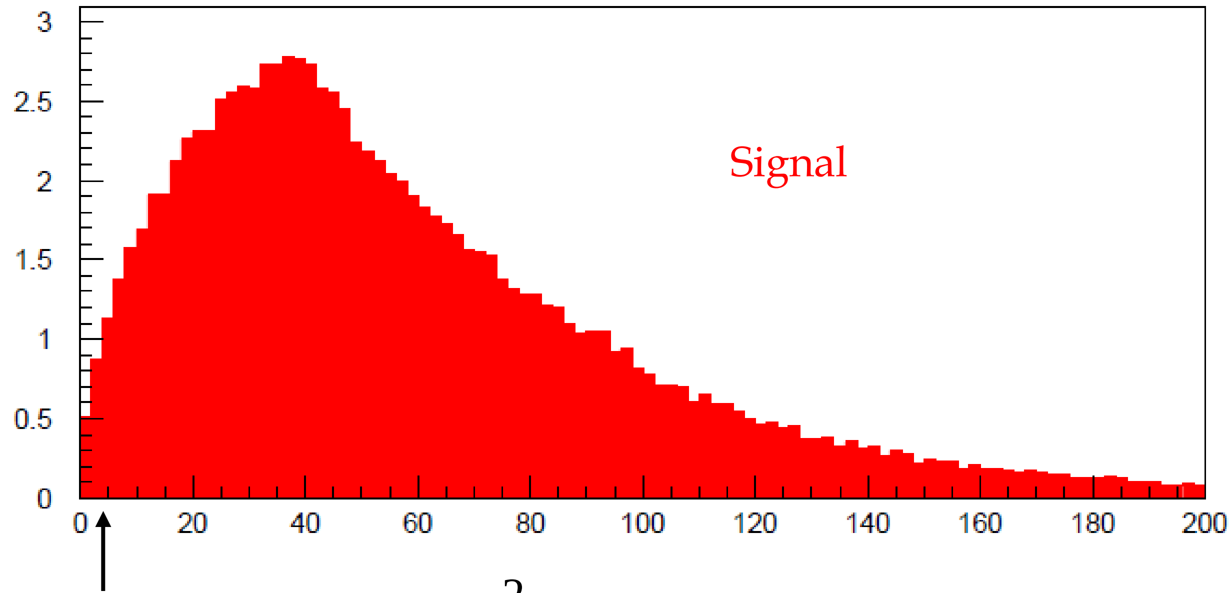
$M_{ij} =$ Mass for jet-pair combination ij

$NNbtag_j =$ btag neural net variable for jet j

$$\frac{\Delta E_{jet}}{\sqrt{E_{jet}}} = 0.0$$

$$\chi^2_{ZH\_ZHmass} > 2$$





$$\chi^2_{ZH\_ZHmass}$$

χ^2_{ZZ}

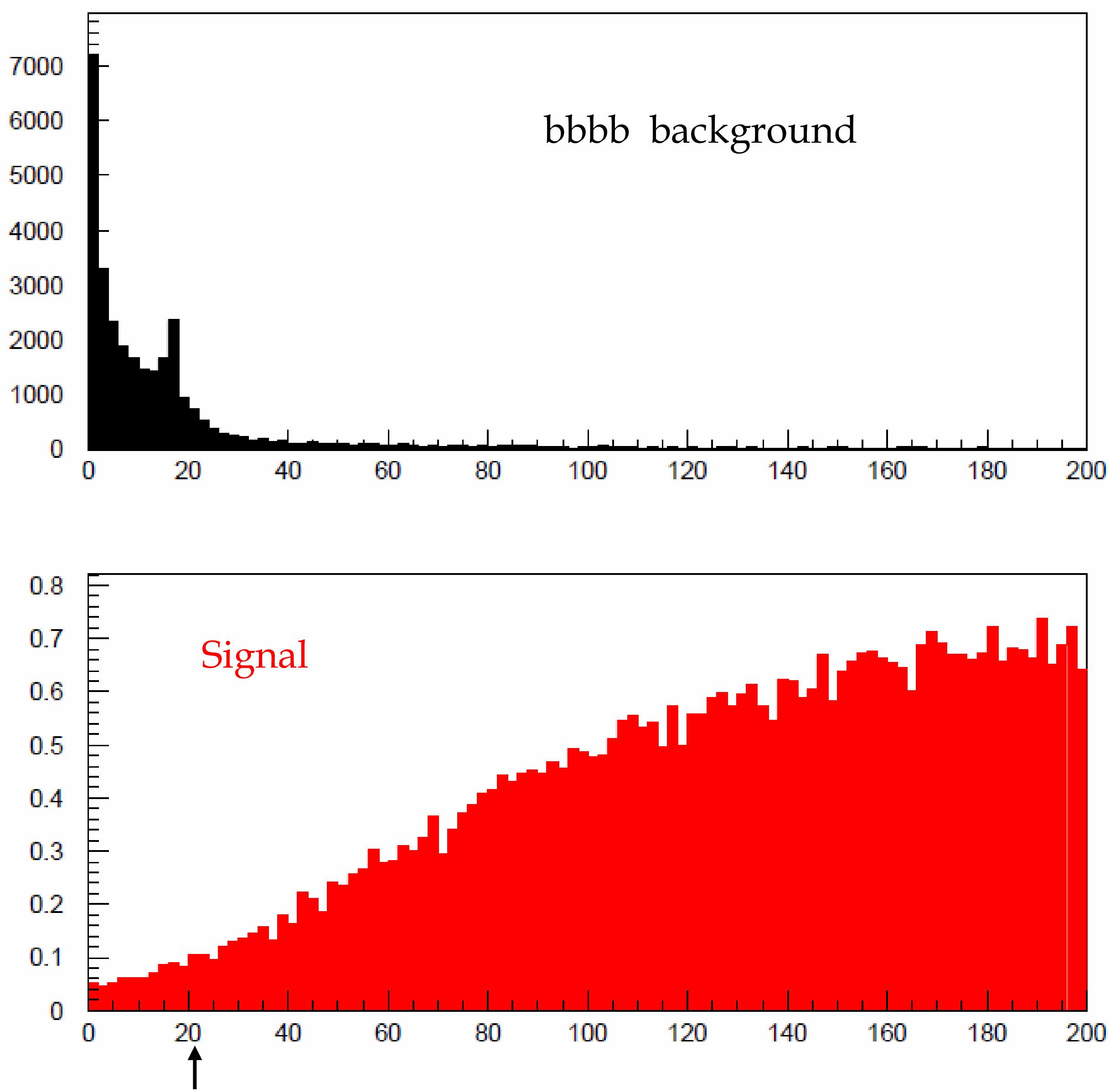
- Force charged and neutral objects into 4 jets
- Loop over 3 jet-pair combinations & minimize χ^2_{ZZ}

$$\chi^2_{ZZ} = \frac{(M_{12} - M_Z)^2}{\sigma^2_{M_Z}} + \frac{(M_{34} - M_Z)^2}{\sigma^2_{M_Z}}$$

$M_{ij} =$ Mass for jet-pair combination *ij*

$$\frac{\Delta E_{jet}}{\sqrt{E_{jet}}} = 0.0$$

$$\chi^2_{ZZ} > 20$$



$$\chi^2_{ZZ}$$

ZHH Preselection

Require:

$|\cos\theta_{thrust}| < 0.95$

$thrust < 0.85$

$M_{thrust\_hemisphere} > 110$ GeV for at least 1 thrust hemisphere

$N_{isolated\ leptons} = 0$

$6 \leq N_{jets} \leq 7$

$\chi^2_{ZHH\_HHmass} / N_{DF} < 2$

$\chi^2_{ZHH\_ZHHmass} / N_{DF} < 7$

$\chi^2_{ZHH} / N_{DF} < 13$

$\chi^2_{ZH\_ZHmass} / N_{DF} > 1$

$\chi^2_{ZZ} / N_{DF} > 10$

χ^2_{ZZZ}

- Force charged and neutral objects into 4 jets
- Loop over 3 jet-pair combinations & minimize χ^2_{ZZZ}

$$\chi^2_{ZZZ} = \frac{(M_{12} - M_Z)^2}{\sigma^2_{M_Z}} + \frac{(M_{34} - M_Z)^2}{\sigma^2_{M_Z}} + \frac{(M_{56} - M_Z)^2}{\sigma^2_{M_Z}}$$

M_{ij} = Mass for jet-pair combination *ij*

χ^2_{ZZH}

- Force charged and neutral objects into 6 jets
- Loop over 45 jet-pair combinations & minimize χ^2_{ZZH}

$$\chi^2_{ZZH} = \chi^2_{ZZH\_ZZHmass} + \sum_{j=5}^{6} \frac{(NNbtag_j - 1)^2}{\sigma^2_{NNbtag}}$$

$$\chi^2_{ZZH\_ZHHmass} = \frac{(M_{12} - M_Z)^2}{\sigma^2_{M_Z}} + \frac{(M_{34} - M_Z)^2}{\sigma^2_{M_Z}} + \frac{(M_{56} - M_H)^2}{\sigma^2_{M_H}}$$

$M_{ij} =$ Mass for jet-pair combination ij

$NNbtag_j =$ btag neural net variable for jet j

χ^2_{TT}

- Force charged and neutral objects into 6 jets
- Loop over 45 jet-pair combinations & minimize χ^2_{TT}

$$\chi^2_{TT} = \chi^2_{TT\_TTmass} + \sum_{j=1}^{2} \frac{(NNbtag_j - 1)^2}{\sigma^2_{NNbtag}}$$

$$\chi^2_{TT\_TTmass} = \chi^2_{TT\_WWmass} + \frac{(M_{134} - M_t)^2}{\sigma^2_{M_t}} + \frac{(M_{256} - M_t)^2}{\sigma^2_{M_t}}$$

$$\chi^2_{TT\_WWmass} = \frac{(M_{34} - M_W)^2}{\sigma^2_{M_W}} + \frac{(M_{56} - M_W)^2}{\sigma^2_{M_W}}$$

M_{ij} = Mass for jet-pair combination *ij*

$NNbtag_j$ = btag neural net variable for jet j

NN_{ZHH}

- Use signal and background events that pass preselection to train NN_{ZHH}
- Use the following variables in the ZHH neural net:

χ^2_{ZHH} $\chi^2_{ZHH\_HHmass}$ $\chi^2_{ZHH\_ZHHmass}$

χ^2_{TT} $\chi^2_{TT\_WWmass}$ $\chi^2_{TT\_TTmass}$

χ^2_{ZZZ} $\chi^2_{ZZH\_ZZHmass}$

χ^2_{ZZ} $\chi^2_{ZH\_ZHmass}$

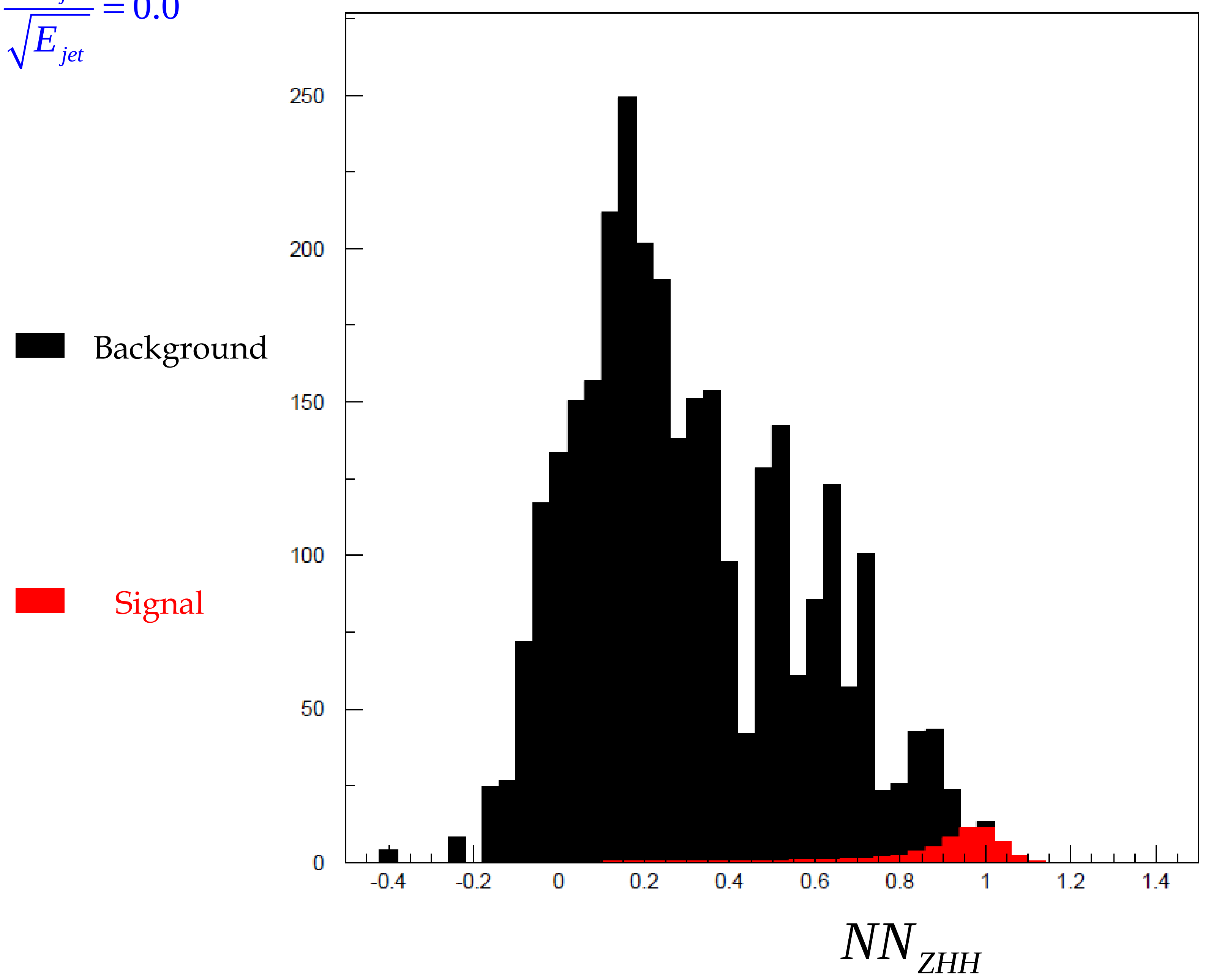
$NNbtag_j \ , \ j = 1, 2, 3, 4, 5, 6$

$\min(M_{jet}(k) \ , k = 1, 2, 3, 4, 5, 6)$

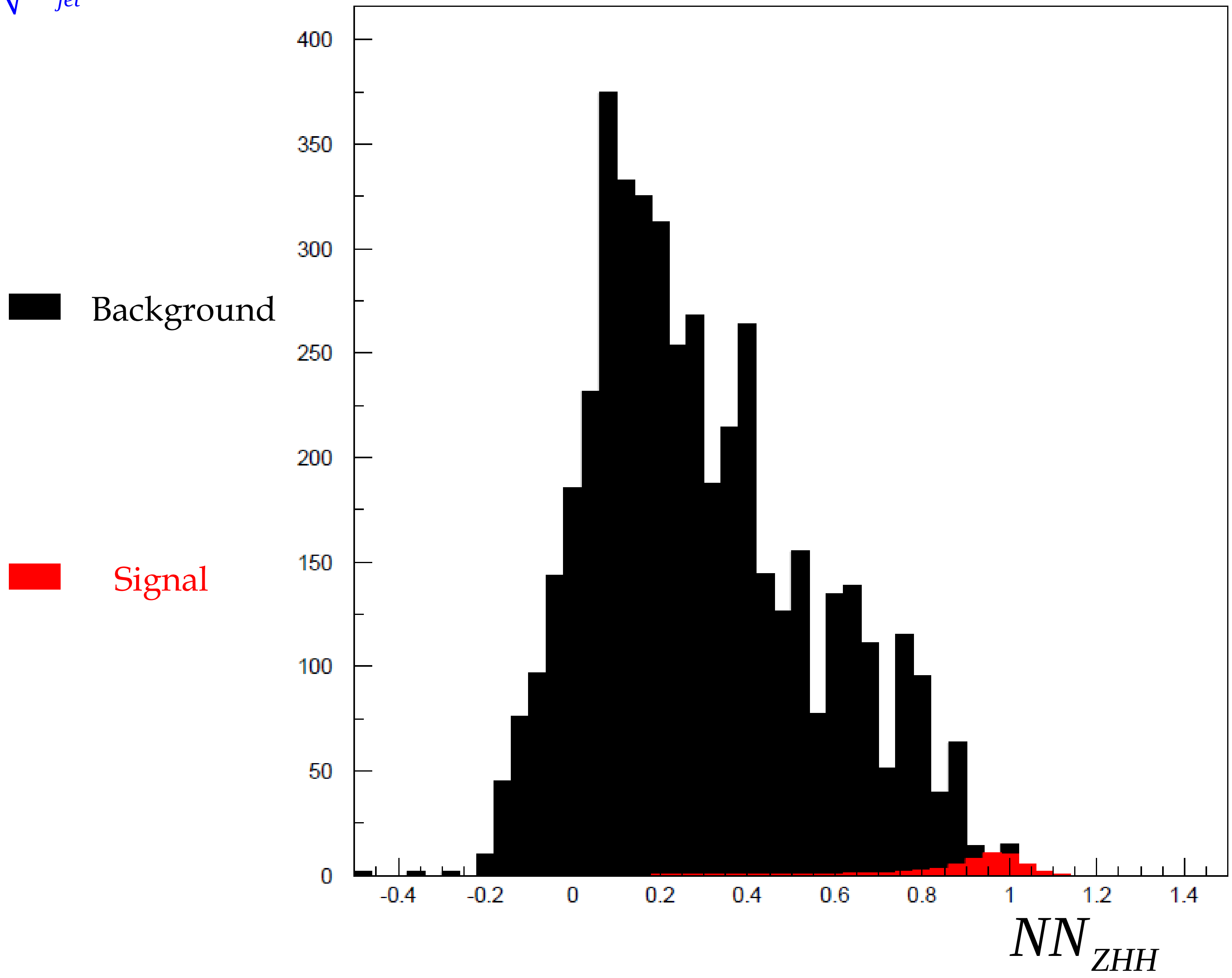
$|\cos\theta_{thrust}|$

$\#$ jets

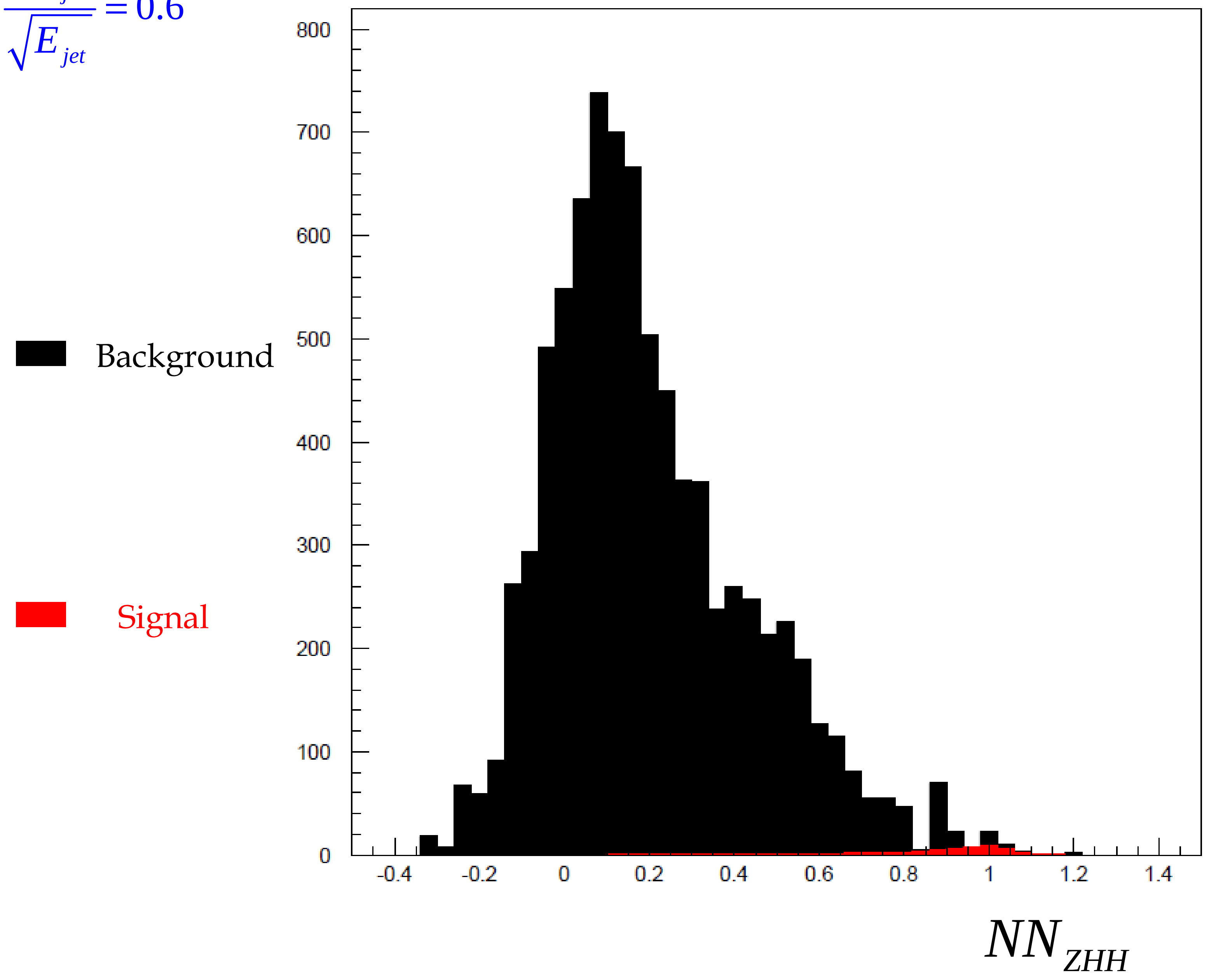
$$\frac{\Delta E_{jet}}{\sqrt{E_{jet}}} = 0.0$$



$$\frac{\Delta E_{jet}}{\sqrt{E_{jet}}} = 0.3$$



$$\frac{\Delta E_{jet}}{\sqrt{E_{jet}}} = 0.6$$



Results for $\frac{\Delta E_{jet}}{\sqrt{E_{jet}}} = 0.0$ L=2000 fb^{-1}

process	resonances	before cuts	preselection	$NN_{ZHH} > 0.9$
$q\bar{q}b\bar{b}b\bar{b}$	ZHH	254	58	41
------	----	----	----	----
$b\bar{b}b\bar{b}$	ZZ/ZH	46600	148	24
$q\bar{q}b\bar{b}$	ZZ/ZH	301600	39	0
$u\bar{d}s\bar{c}$	WW	6.5×10^6	0	0
$u\bar{d}d\bar{u}, c\bar{s}s\bar{c}$	ZZ/WW	6.5×10^6	0	0
$b\bar{b}u\bar{d}s\bar{c}$	$t\bar{t}$	322800	1760	0
$b\bar{b}u\bar{d}d\bar{u}, b\bar{b}c\bar{s}s\bar{c}$	$t\bar{t}$	322200	2670	16
$b\bar{b}u\bar{d}l^-\bar{\nu}_l, b\bar{b}c\bar{s}l^-\bar{\nu}_l$	$t\bar{t}$	670200	357	0
$b\bar{b}q\bar{q}q\bar{q}$	ZZZ/ZZH	720	4	0.2
$q\bar{q}b\bar{b}b\bar{b}$	ZZZ/ZZH	430	48	10.8
$l^+l^-b\bar{b}b\bar{b}$	ZZZ/ZZH	130	2	0.2
------	------	------	------	------
$TOTAL\ BGND$			5026	51.6

Example bbbb event which passes all cuts:

parton	p_x	p_y	p_z	E	M
$\sum ISR\ \gamma$	0.000	0.001	–19.238	19.341	1.989
b	–7.093	4.233	–0.851	8.796	2.900
$\bar{b}$	2.342	10.600	162.793	163.180	2.900
b	27.561	–24.145	–201.575	204.899	2.900
$\bar{b}$	–15.115	–0.335	–2.649	15.620	2.900
$\sum gluons$	–7.694	9.645	62.459	88.746	61.826
$\sum all\ partons$	0.000	0.000	0.940	500.582	500.581

$\sqrt{s} = 500$ GeV

L=2000 fb^{-1}

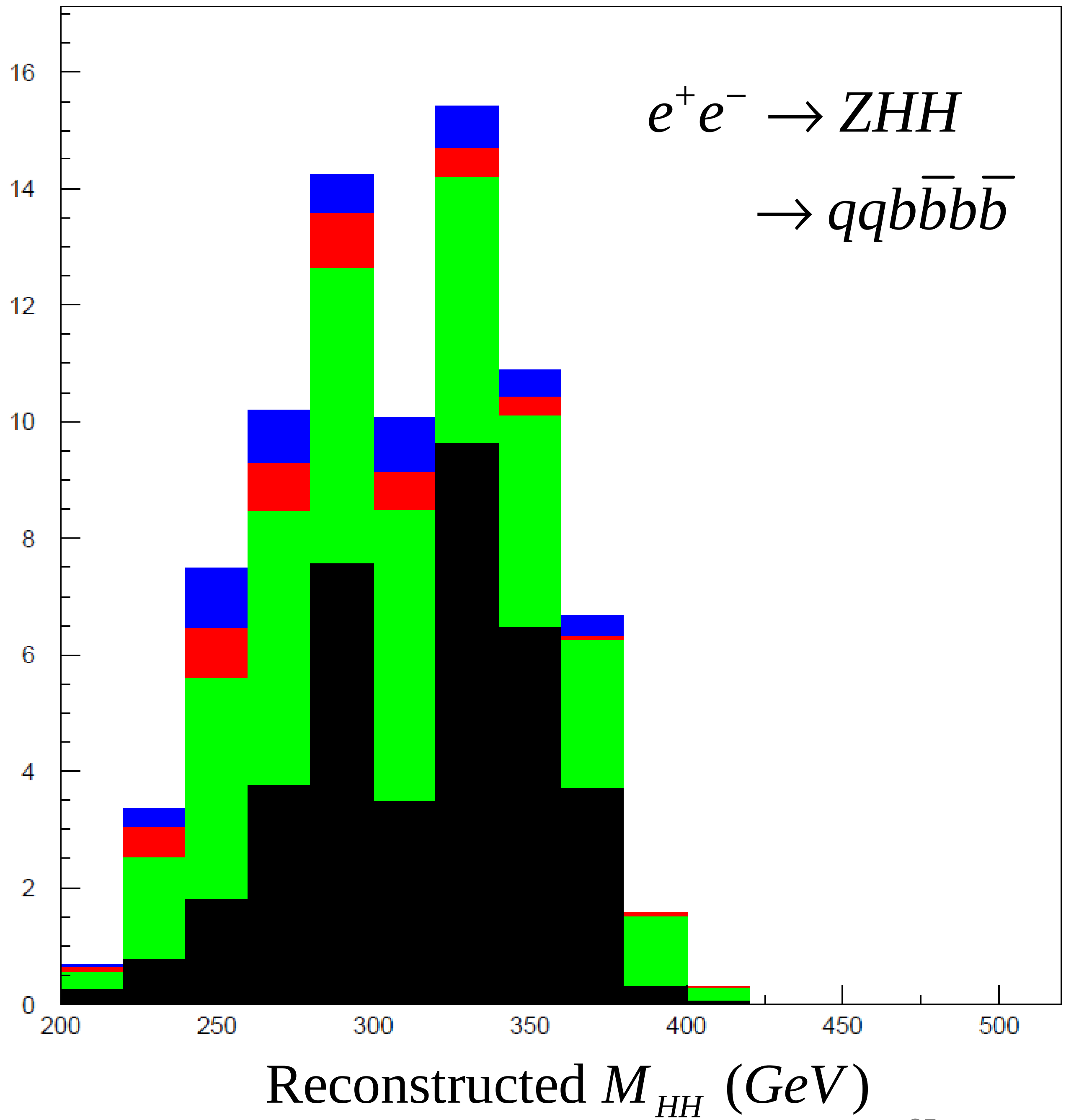
signal $\frac{g_{HHH}}{g_{HHH}^{SM}} = 1.25$

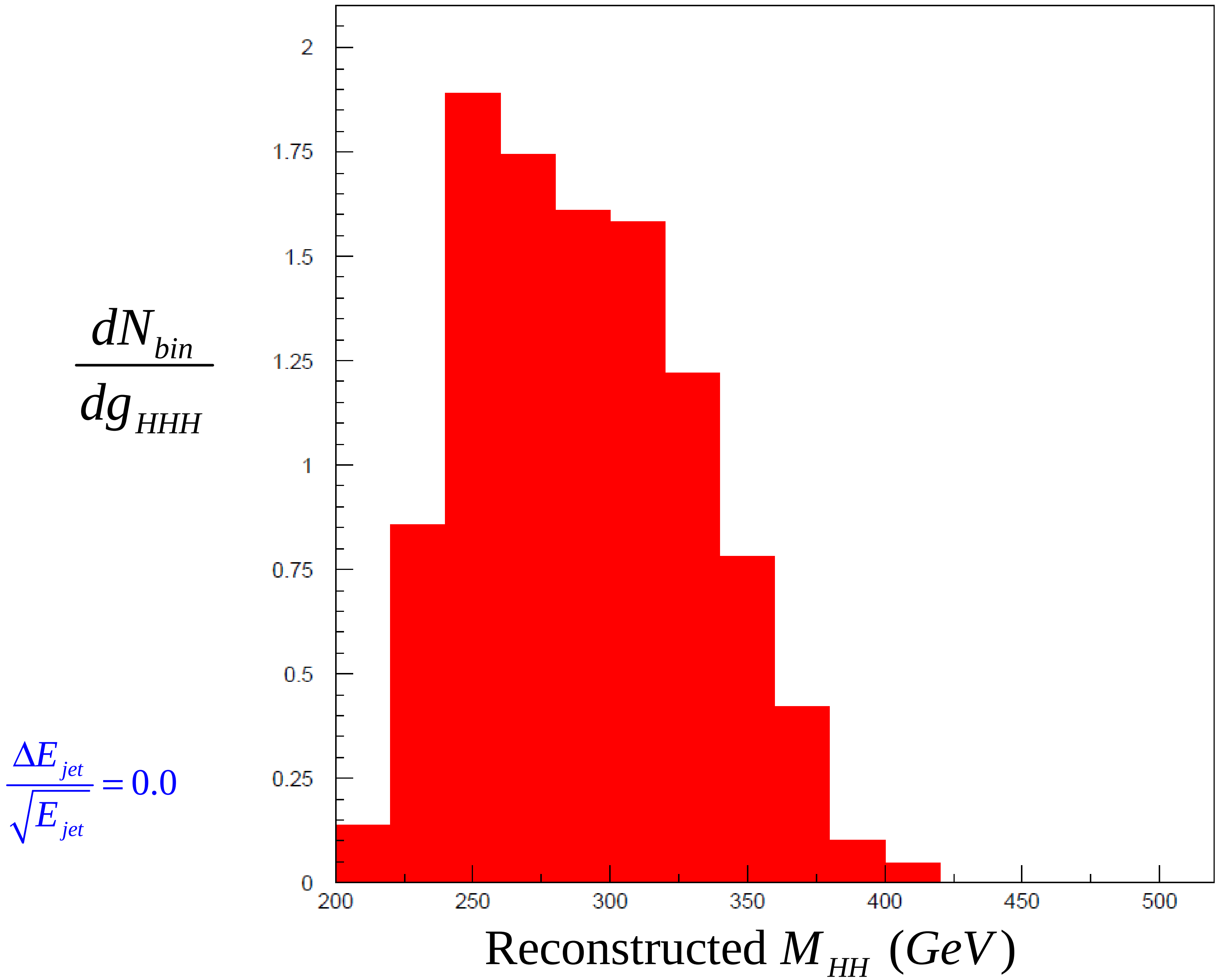
signal $\frac{g_{HHH}}{g_{HHH}^{SM}} = 1.00$

signal $\frac{g_{HHH}}{g_{HHH}^{SM}} = 0.75$

background

$\frac{\Delta E_{jet}}{\sqrt{E_{jet}}} = 0.0$





$\frac{dN_{bin}}{dg_{HHH}}$
$\frac{\Delta E_{jet}}{\sqrt{E_{jet}}} = 0.0$
2
1.75
1.5
1.25
1
0.75
0.5
0.25
0
200
250
300
350
400
450
500
Reconstructed M_{HH} (GeV)

Results for qqbbbb only, $\sqrt{s}$=500 GeV , L=2000 fb^{-1}

Note: NN_{ZHH} is retrained for each $\dfrac{\Delta E_{jet}}{E_{jet}}$

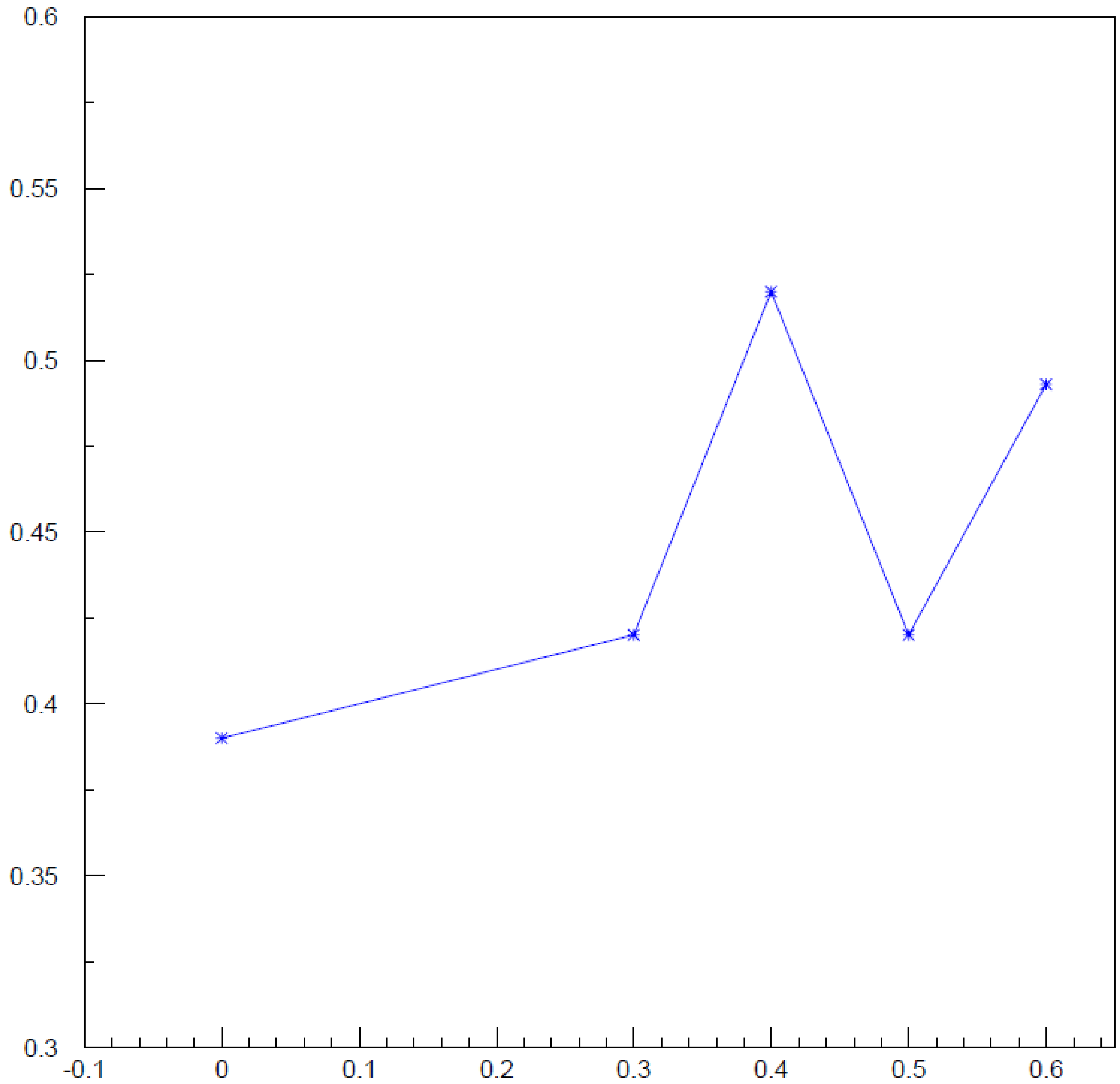
$\dfrac{\Delta E_{jet}}{\sqrt{E_{jet}}}$	N_{bgnd}	N_{signal}	$\dfrac{\Delta g_{HHH}}{g_{HHH}}$
0.	51	41	0.39
0.3	38	38	0.42
0.4	75	36	0.52
0.5	33	34	0.42
0.6	70	35	0.49

$$e^+e^- \to ZHH$$
$$\to qqb\bar{b}b\bar{b}$$

$\sqrt{s} = 500\,GeV$

$L = 2000\ fb^{-1}$

$$\frac{\Delta g_{hhh}}{g_{hhh}}$$



$$\frac{\delta E_{jet}}{\sqrt{E_{jet}}}\ (\text{GeV}^{\frac{1}{2}})$$

Conclusions

- The coupling g_{HHH} is measured with an accuracy of 40 – 50% at Ecm=500 GeV and L=2000 fb^{-1}, which is twice the error quoted in the TESLA TDR analysis. We have not yet included Cabbibo suppressed W decays in WW and tt events, so our results might get even worse.
- The biggest difference between the analyses is the level of background following cuts. The increased background could be due to many things:
  - This analysis may be missing an important ingredient.
    - NNbtag training not optimized ?
    - Preselection cuts based largely on χ^2 variables and their components may not be optimal
    - Association of reconstructed jets with true jets not optimized?
    - Algorithm to force event into 6 jets can be improved?
    - Was it a mistake to use -90% e- polarization?

Conclusions (cont.)

- There may be more gluon radiation in our background sample.
- The difference between n-fermion production, where resonances are included in matrix elements, and Z/W/t resonance production followed by decay may be bigger than one might have expected.
- We might be being misled to some degree by low statistics in the tails of ZZ/ZH and tt event samples. Larger statistics in tails will give us a more reliable picture of background level and improve NN training.

• Until the nature of ZZ/ZH and tt backgrounds are understood, no conclusions can be drawn from this analysis regarding the dependency of the triple Higgs coupling error on jet energy resolution.