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

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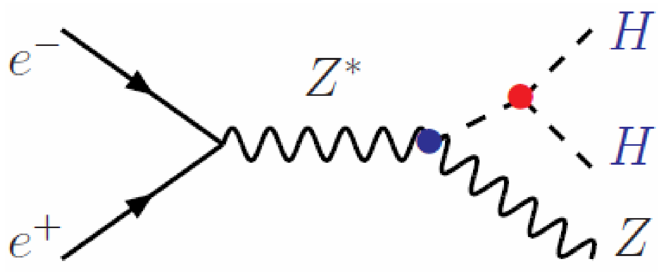
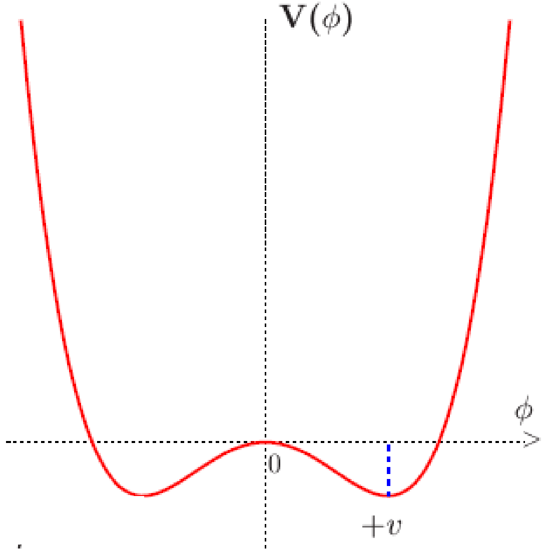


$$g_{HHH} = -6\mu^2 / \mathrm{v}$$



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

Standard Model:

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

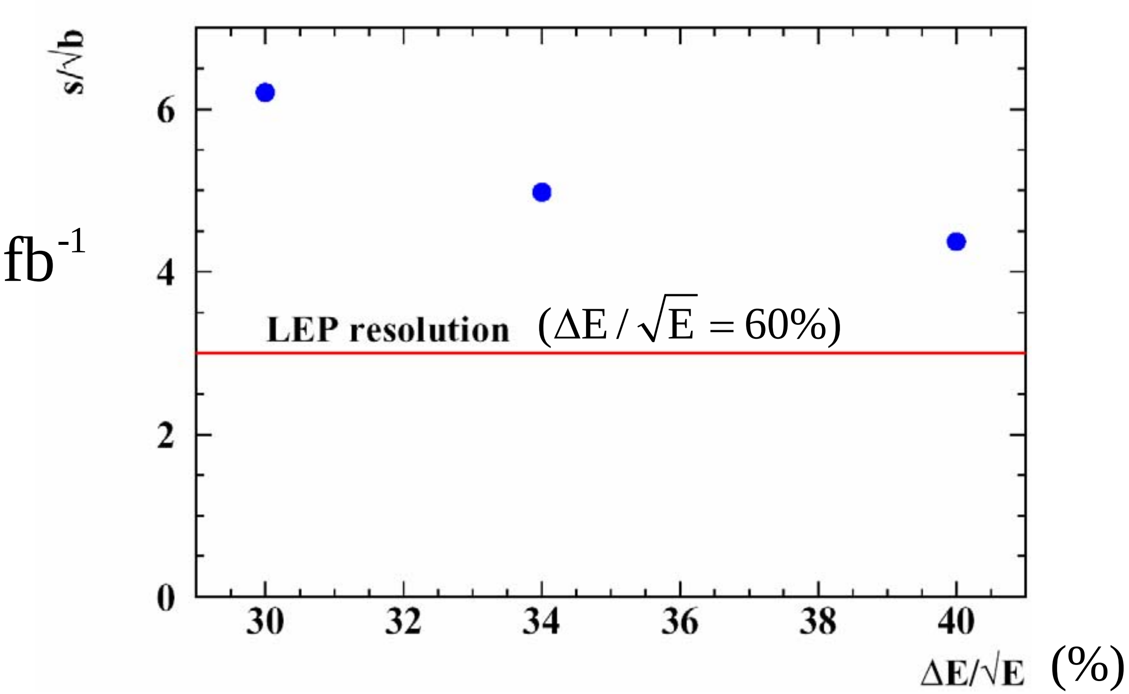
$$e^+e^- \to ZHH \to q\bar{q}b\bar{b}b\bar{b}$$

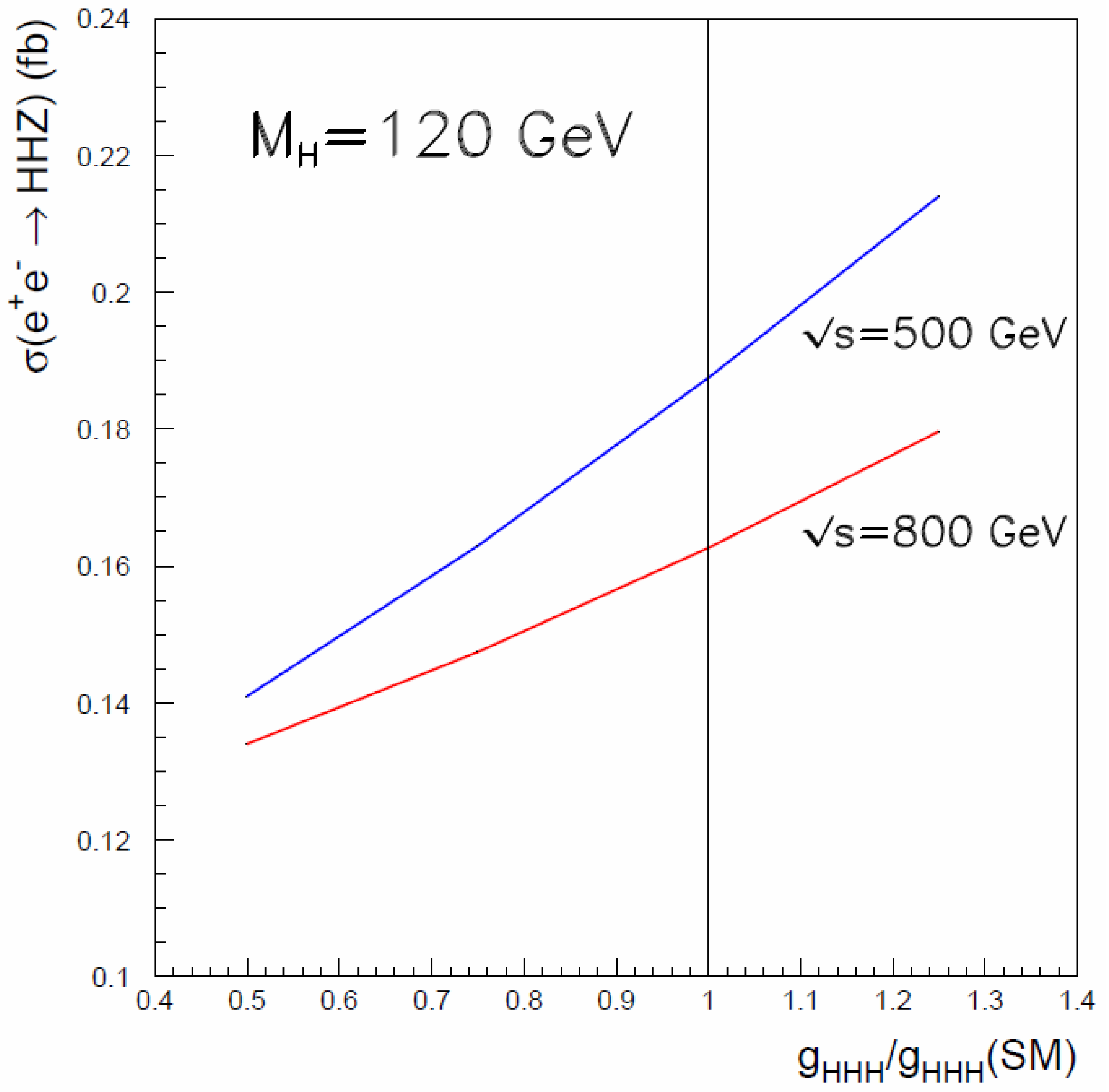
$\sqrt{s}$ = 500 GeV, L=1000 fb^{-1}

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

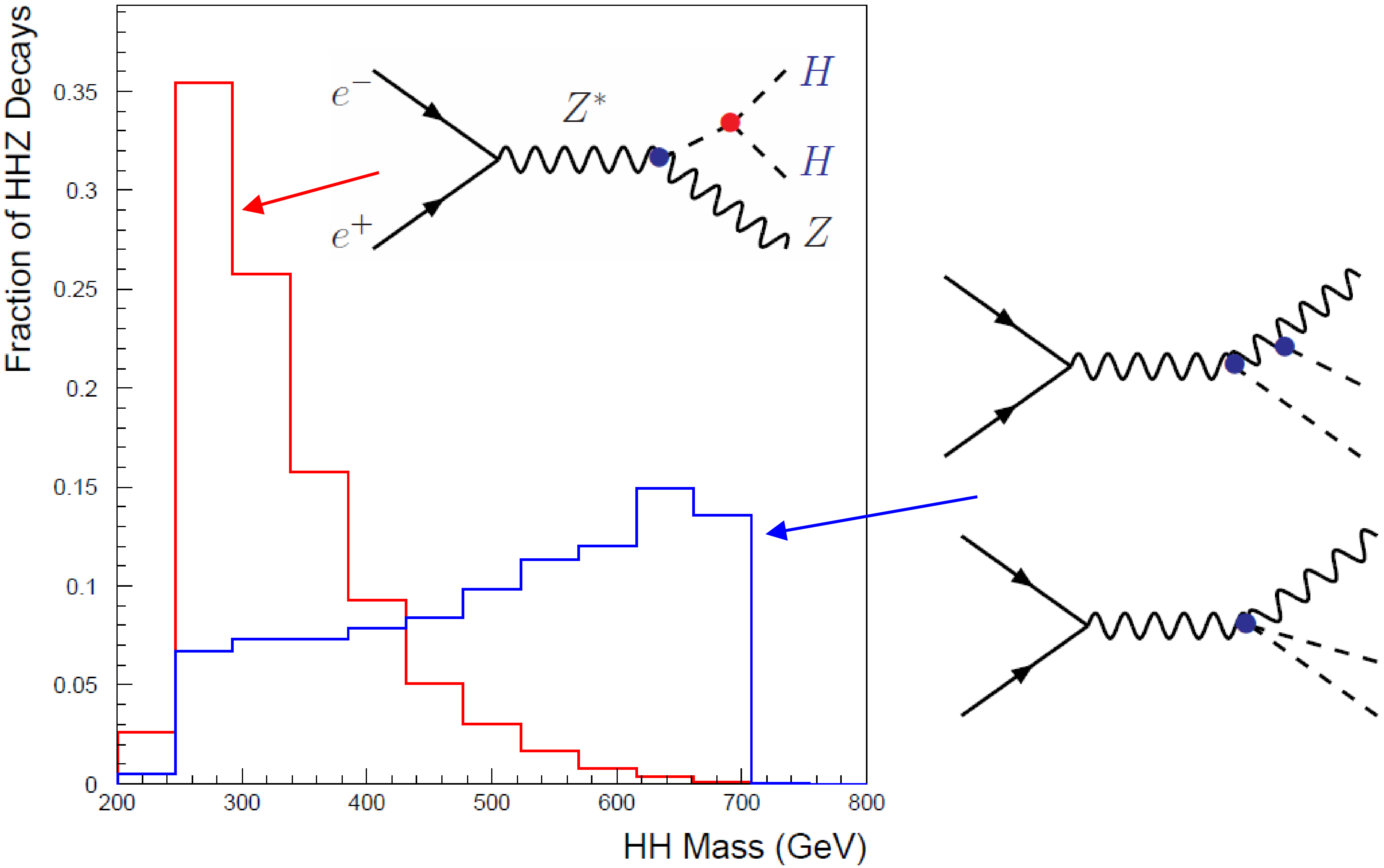
equiv to 4× Lumi

C. Castanier et al. hep-ex/0101028




$\sigma(e^+e^- \to HHZ)$ (fb)
M_H=120 GeV
$\sqrt{s}$=500 GeV
$\sqrt{s}$=800 GeV
$g_{HHH}/g_{HHH}(SM)$
0.1
0.12
0.14
0.16
0.18
0.2
0.22
0.24
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

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

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

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

Plan for Analyis

- Perform analysis on qqbbbb channel only at E_{cm}=500 GeV assuming 0% electron polarization. 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

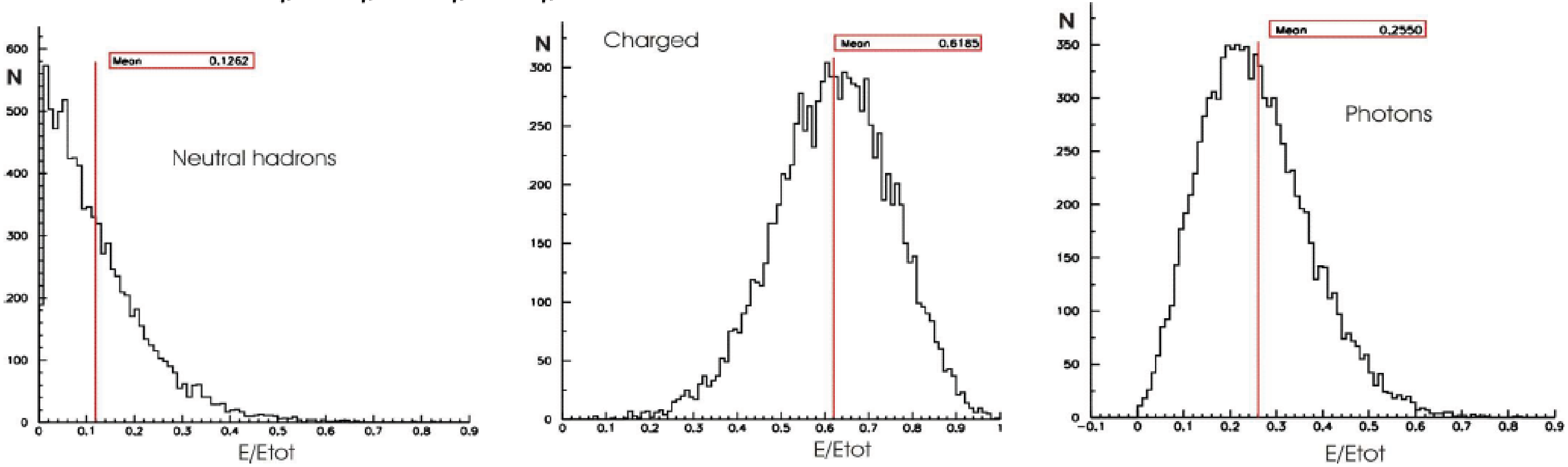
- Jet energy resolution
  $\sigma^2(E_{jet}) = \sigma^2(ch.) + \sigma^2(\gamma) + \sigma^2(h^0) + \sigma^2(conf.)$
- Excellent tracker :
  $\sigma^2(ch.) << \sigma^2(\gamma) + \sigma^2(h^0) + \sigma^2(conf.)$
- Perfect PFA : $\sigma^2(conf.) = 0$
- $\sigma^2(E_{jet}) = A_\gamma^2 E_\gamma + A_h^2 E_{h0}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

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

I find w_γ=28%; w_{h0}=10%

$A_\gamma = 11\%$; $A_{h0} = 34\%$
=> $\sigma(E_{jet})/E_{jet} = 12\%/\sqrt{E_{jet}}$

$A_\gamma = 11\%$; $A_{h0} = 50\%$
=> $\sigma(E_{jet})/E_{jet} = 17\%/\sqrt{E_{jet}}$

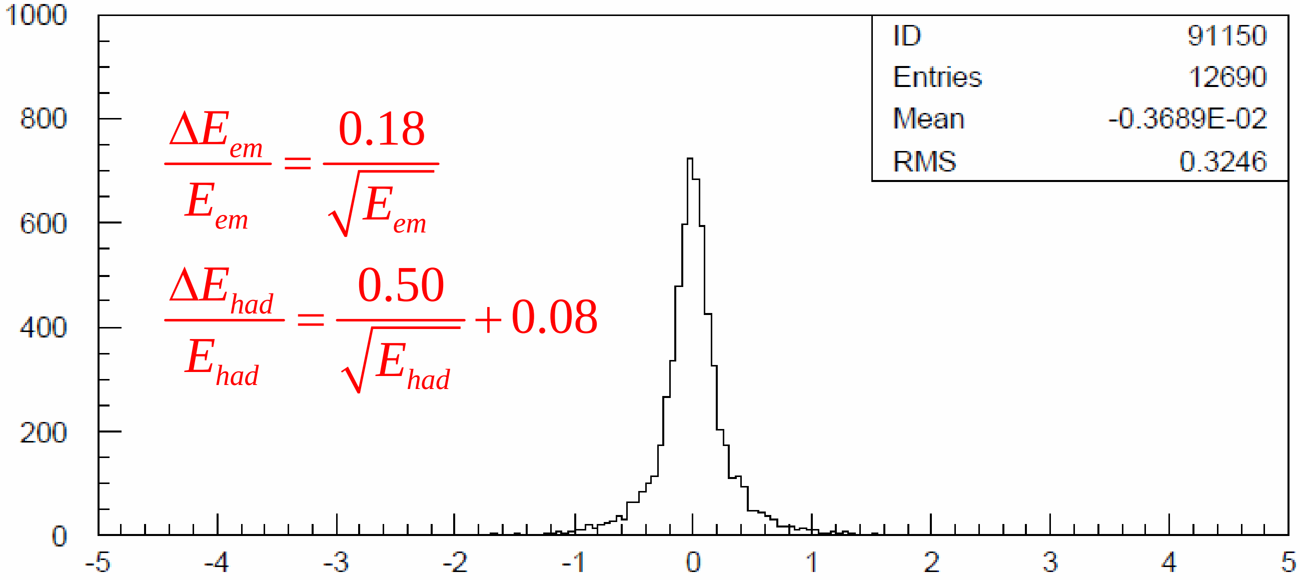


Alexei Raspereza, DESY, ILC Workshop, Snowmass, August 26, 2005

$\sqrt{s} = 500$ GeV

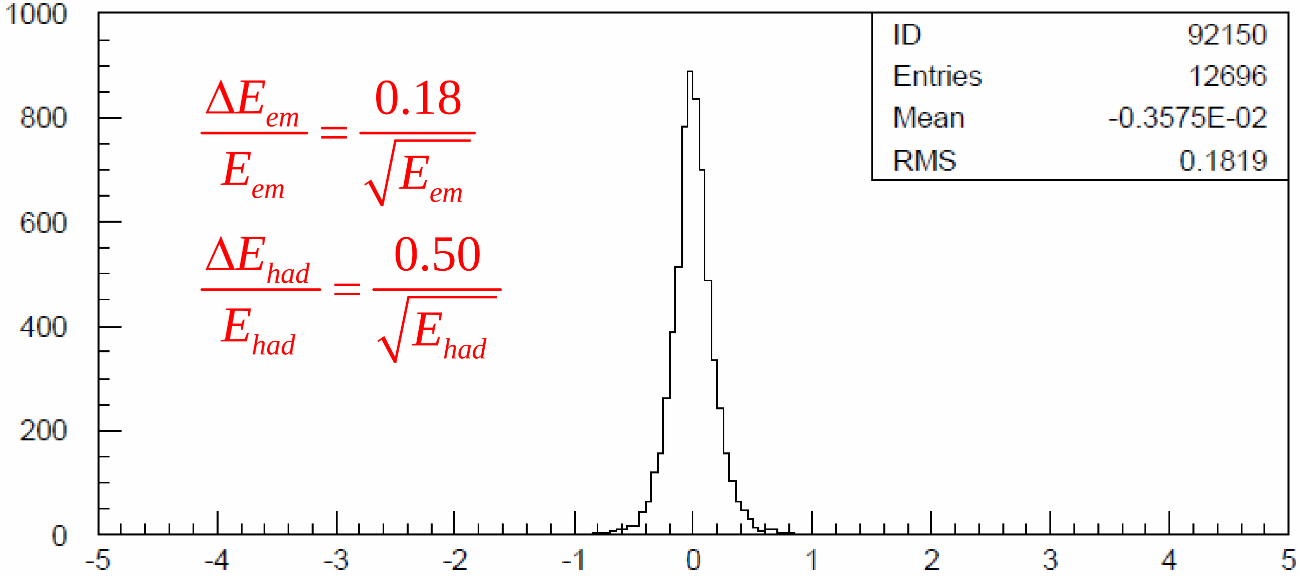
$e^+e^- \rightarrow u\bar{u}$

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



$$\frac{\Delta E_{em}}{E_{em}} = \frac{0.18}{\sqrt{E_{em}}}$$

$$\frac{\Delta E_{had}}{E_{had}} = \frac{0.50}{\sqrt{E_{had}}} + 0.08$$



$$\frac{\Delta E_{em}}{E_{em}} = \frac{0.18}{\sqrt{E_{em}}}$$

$$\frac{\Delta E_{had}}{E_{had}} = \frac{0.50}{\sqrt{E_{had}}}$$

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

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

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

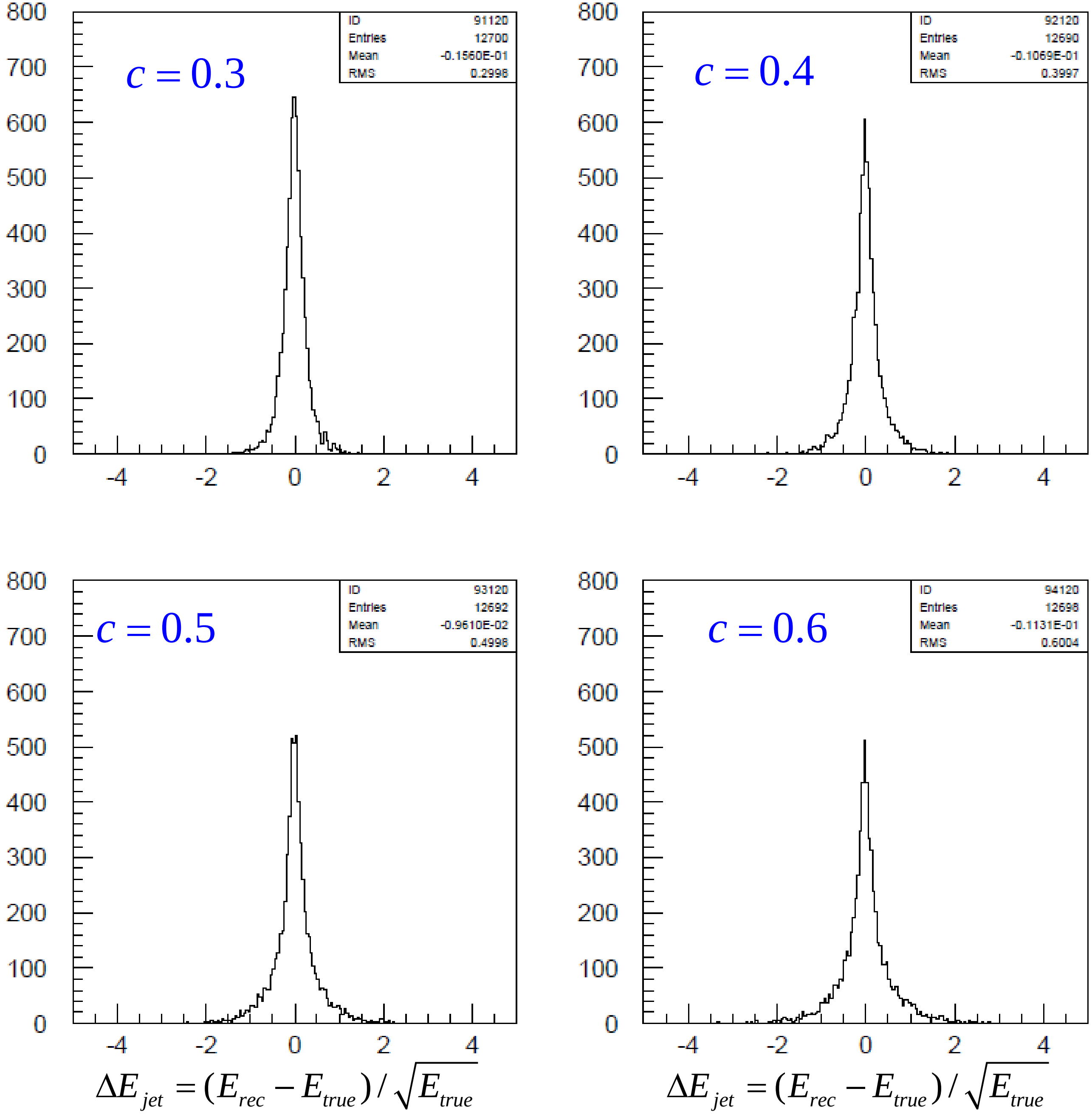
$e^+e^- \to u\bar{u}$

$\sqrt{s} = 500$ GeV

$r = 1.0$

(only degrade had resolution)

call this the "non-Gaussian parameterization"



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

$\sqrt{s} =$ 500 GeV

$r = 1.0$

but use calor E

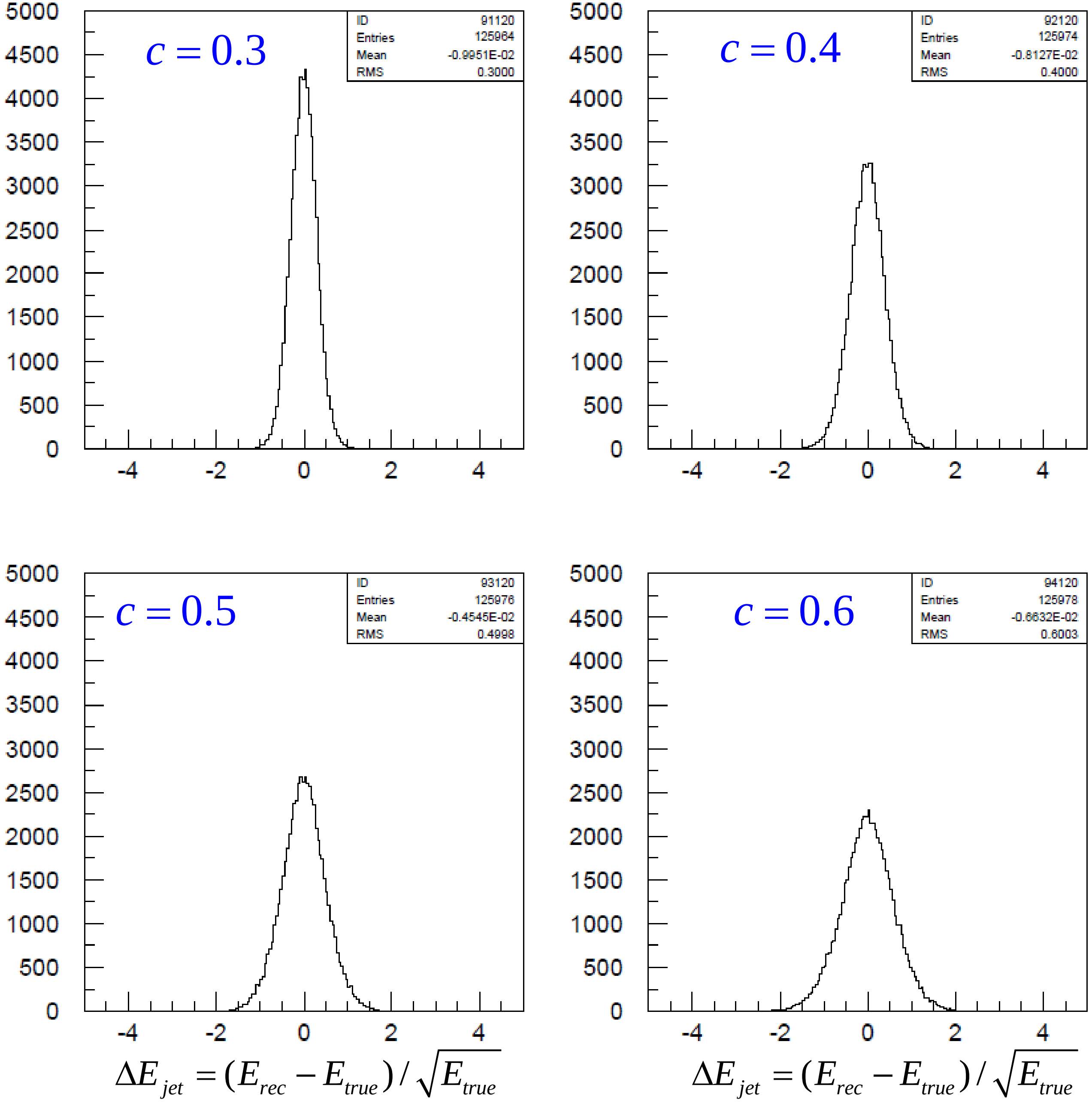
for all chg had

$\Rightarrow w_h = 0.71$

call this the

"Gaussian

parameterization"



ZHH Preselection

Require:

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

$$thrust < 0.85$$

$$P_{tot}(z) < 50 \text{ GeV}$$

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

$$N_{isolated\ leptons} = 0$$

$$6 \leq N_{jets} \leq 8$$

$$N_{chrg\ tracks} \geq 35$$

$$E_{jet}(photons) / E_{jet}(total) < 0.8 \text{ for all 6 jets}$$

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}

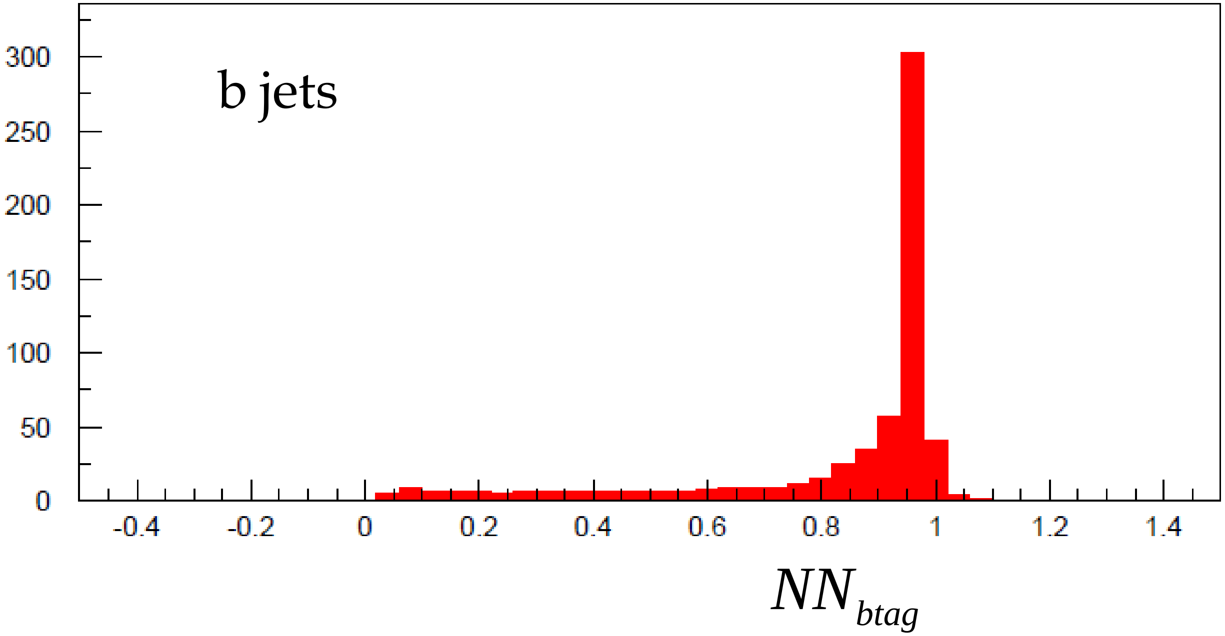
M_{vtx}

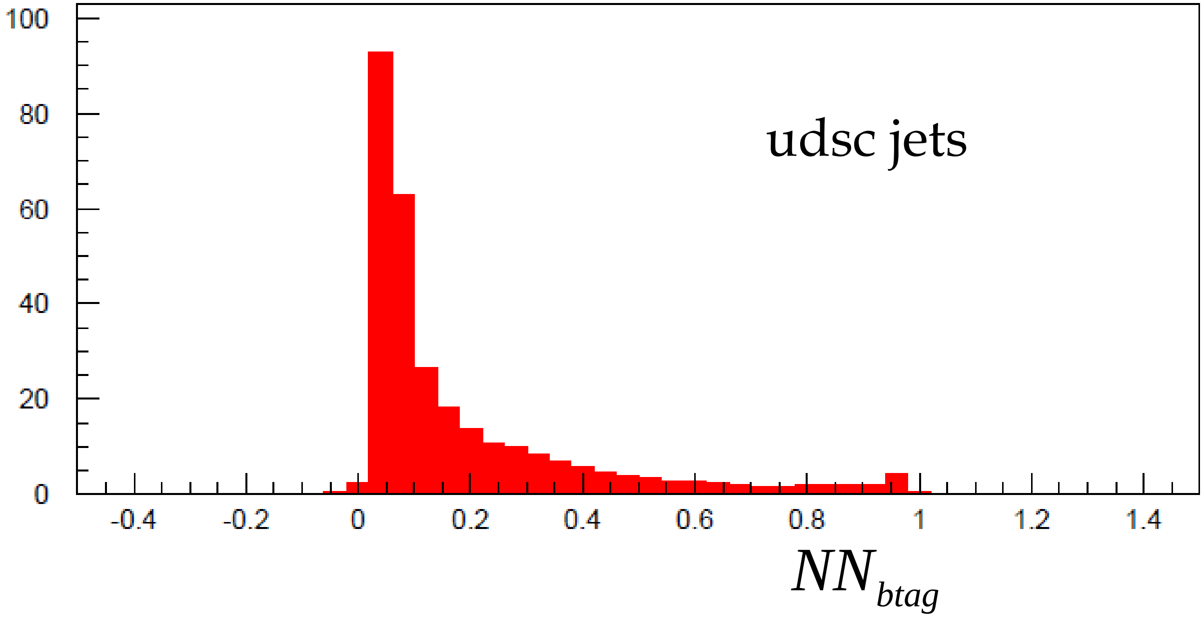
Pt-Corrected M_{vtx}

Secondary Vertices

Unassociated Large Impact Parameter Tracks

ZHH events

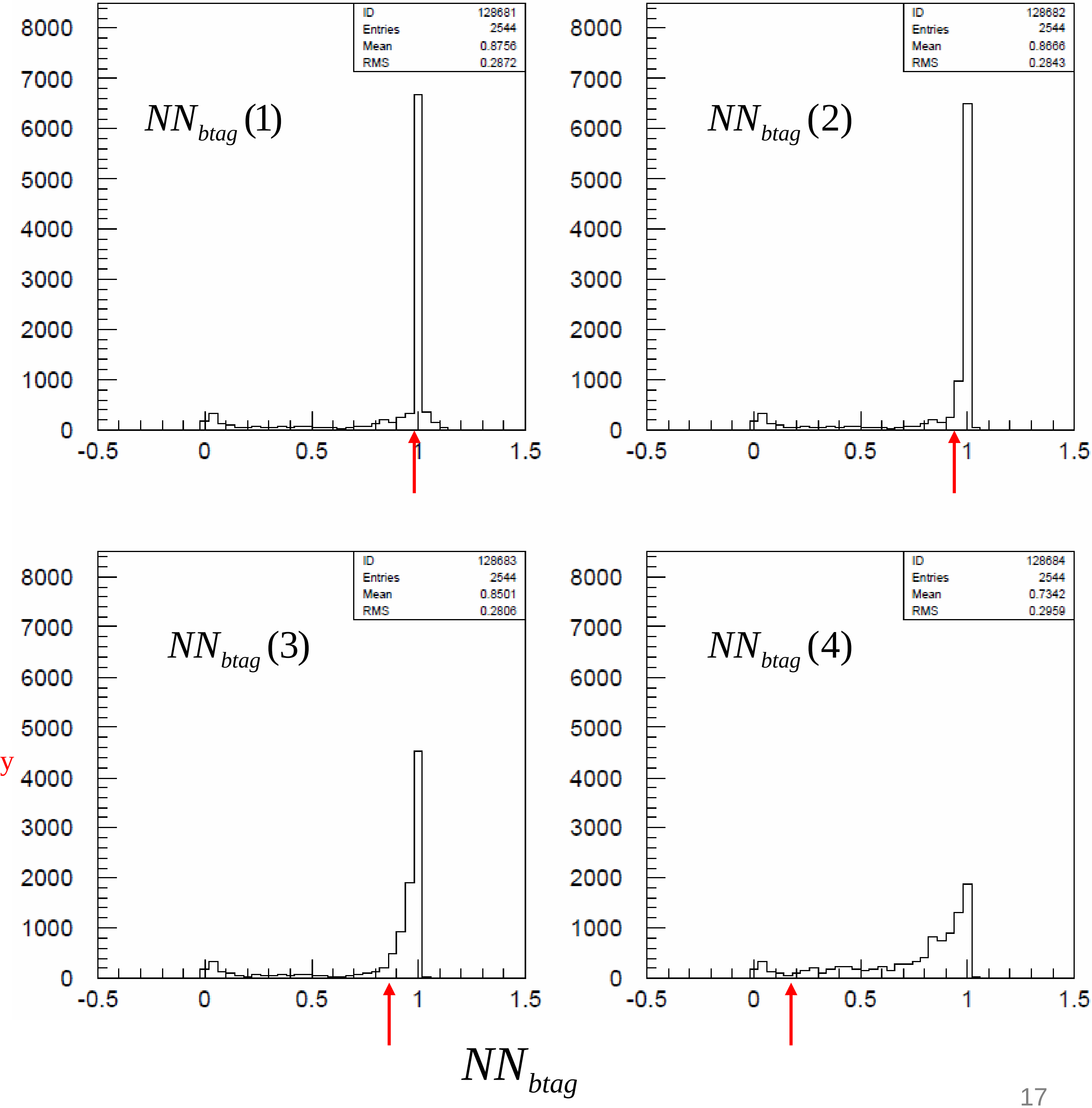

b jets
300
250
200
150
100
50
0
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
1.2
1.4
NN_{btag}


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}

ZHH→qqbbbb

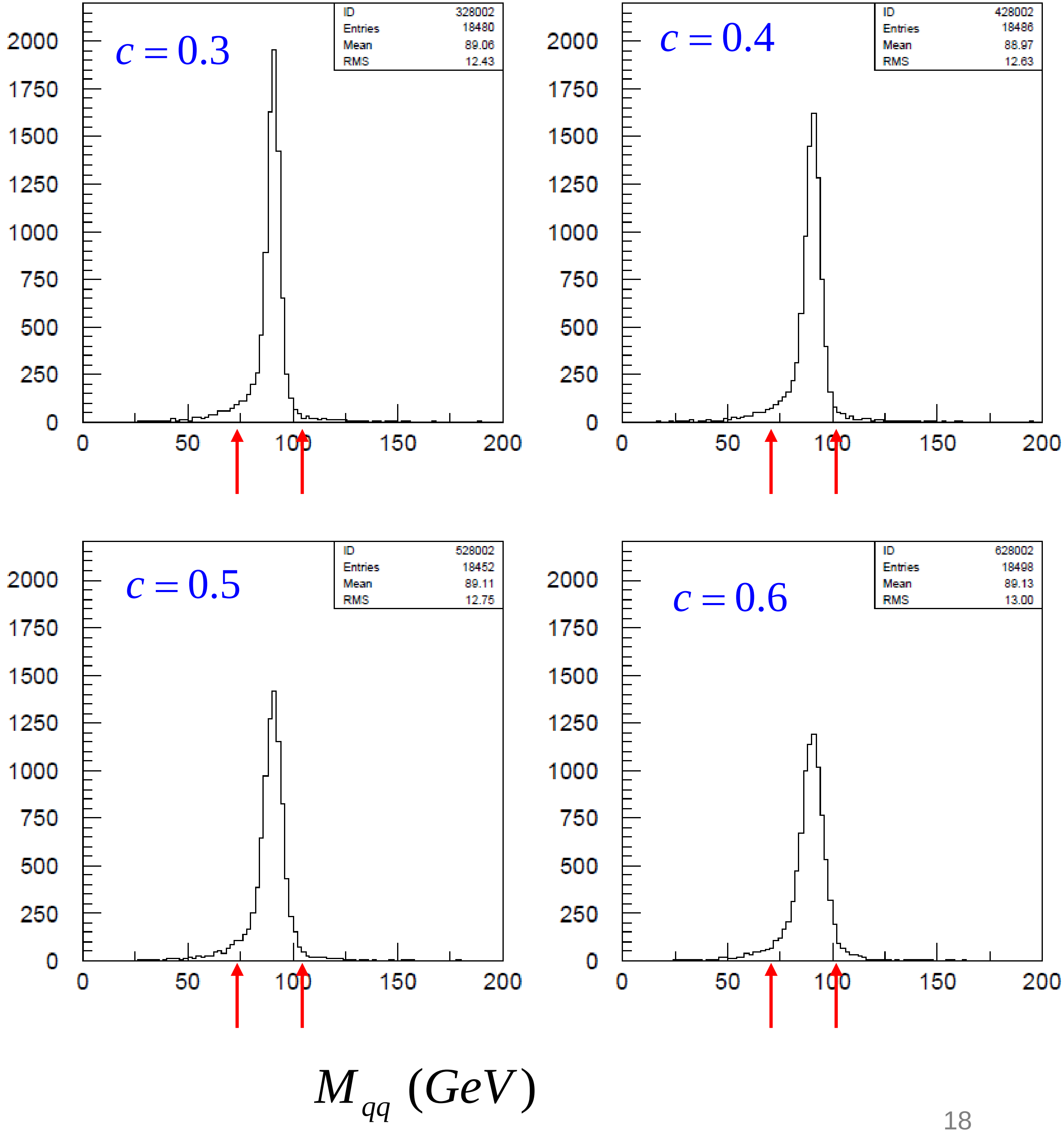
Order NN_{btag} for candidate 4jets from HH . Reject 4jet comb if any jet fails min NN_{btag} cut (red arrows)

Note that we are effectively requiring that 3 of the 4 jets recoiling against the Z be tagged as b-jets



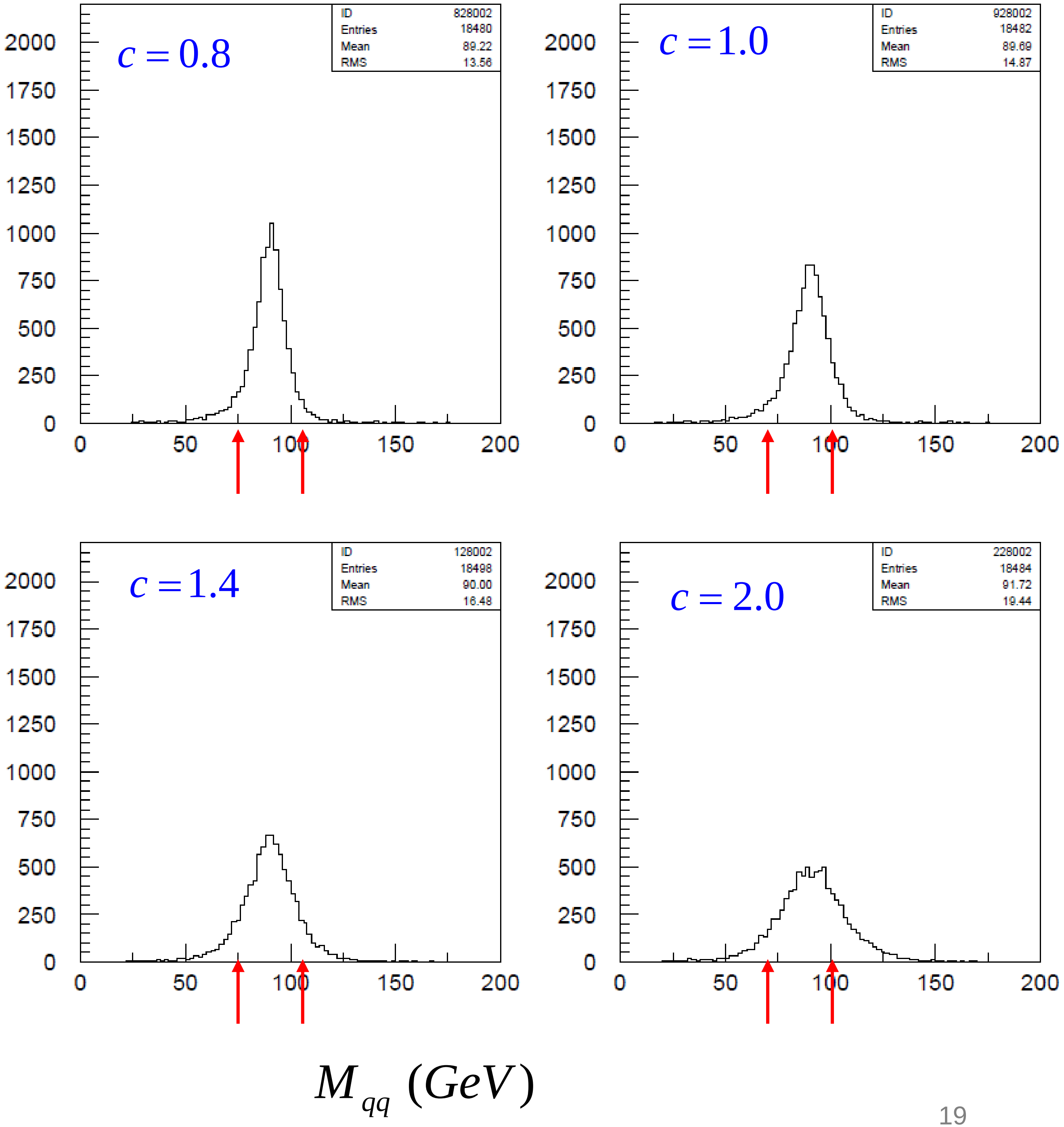
ZHH→qqbbbb
Z mass

Reject Z → 2jet comb if mass outside range $74 < M_{qq} < 104\,\text{GeV}$ (red arrows)



ZHH→qqbbbb

Z mass



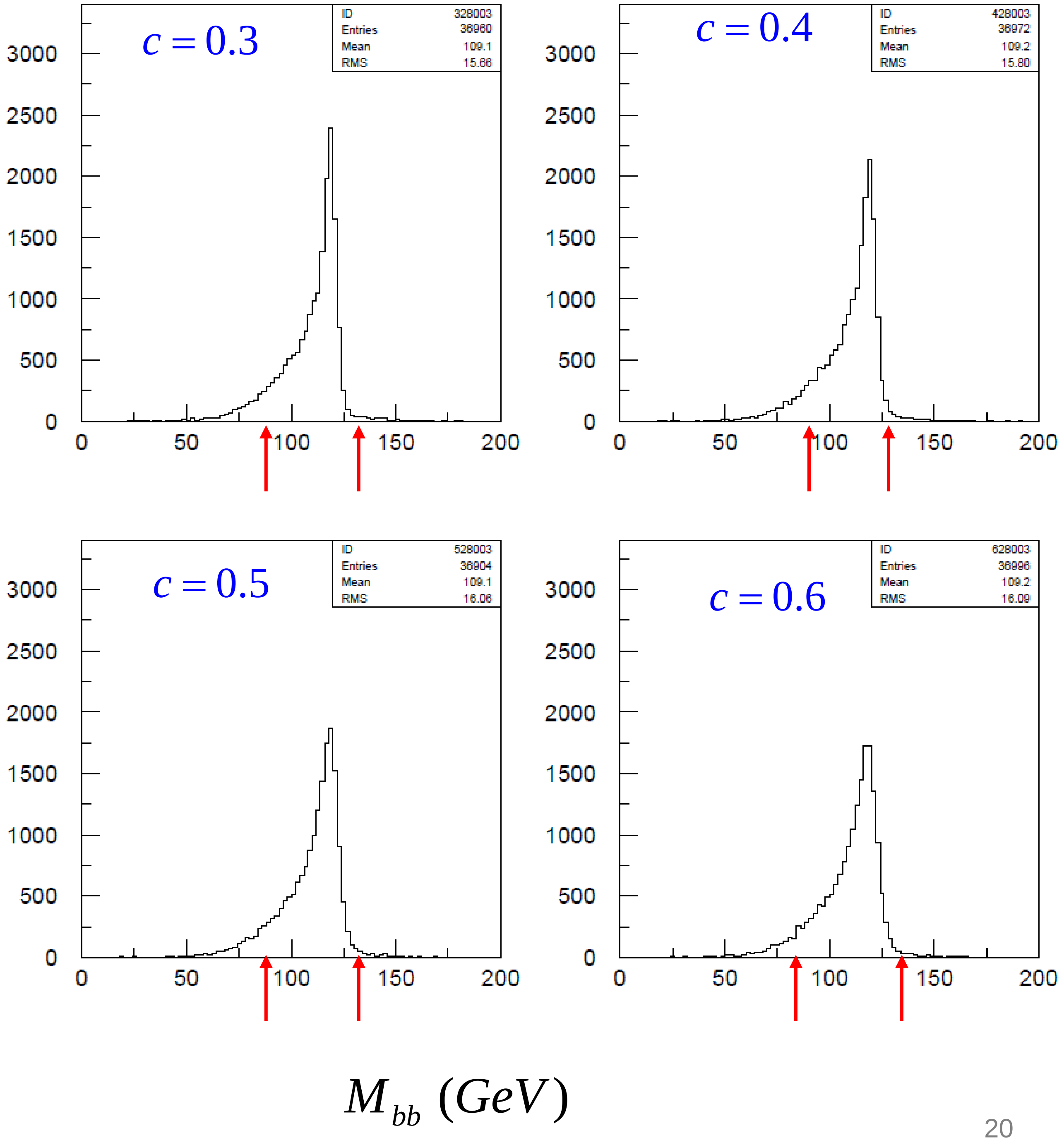
Reject Z → 2jet comb if mass outside range

$74 < M_{qq} < 104\,\text{GeV}$

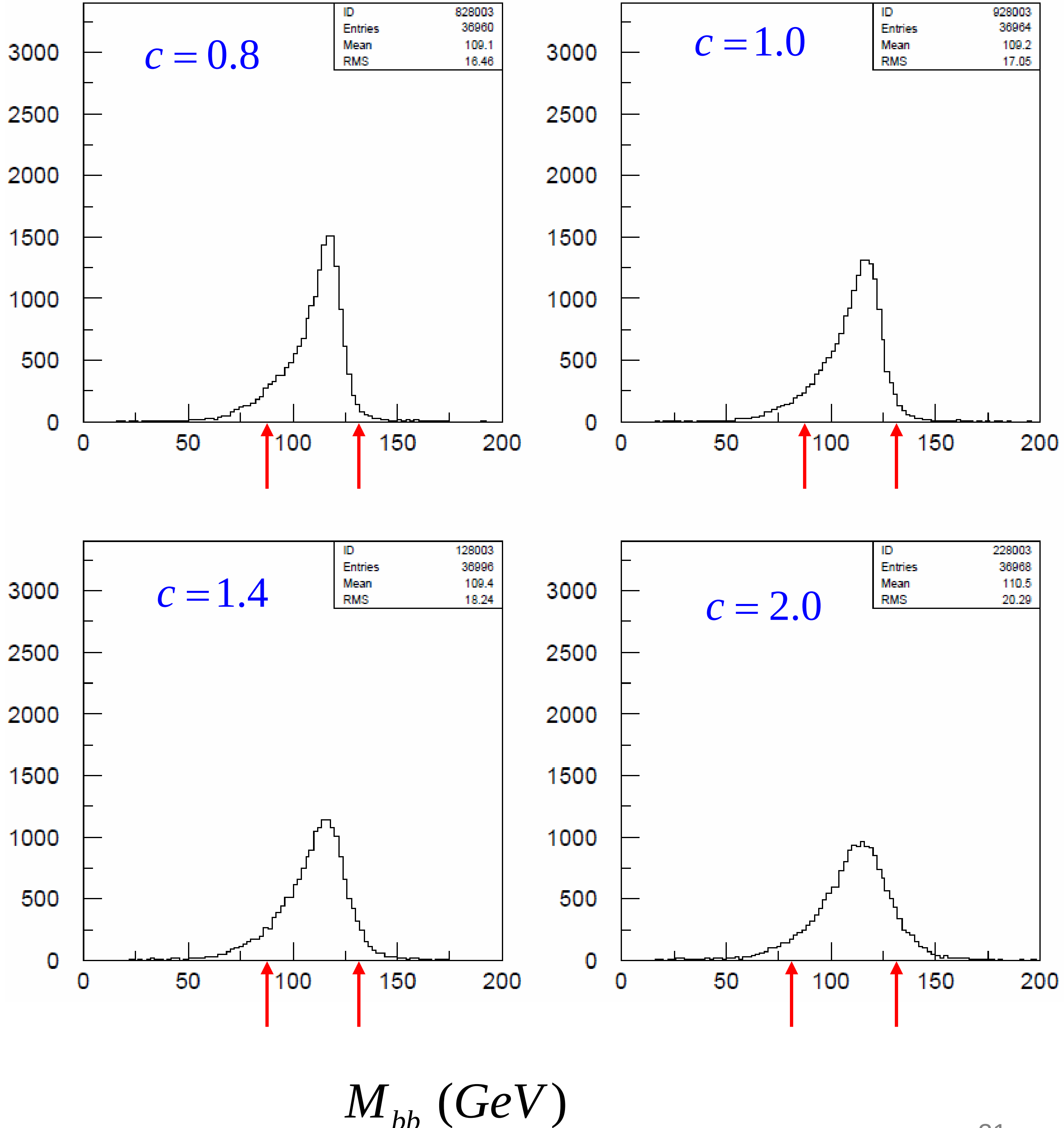
(red arrows)

ZHH→qqbbbb
H mass

Reject $H \to 2\text{jet}$ comb if mass outside range $86 < M_{bb} < 133\,\text{GeV}$ (red arrows)

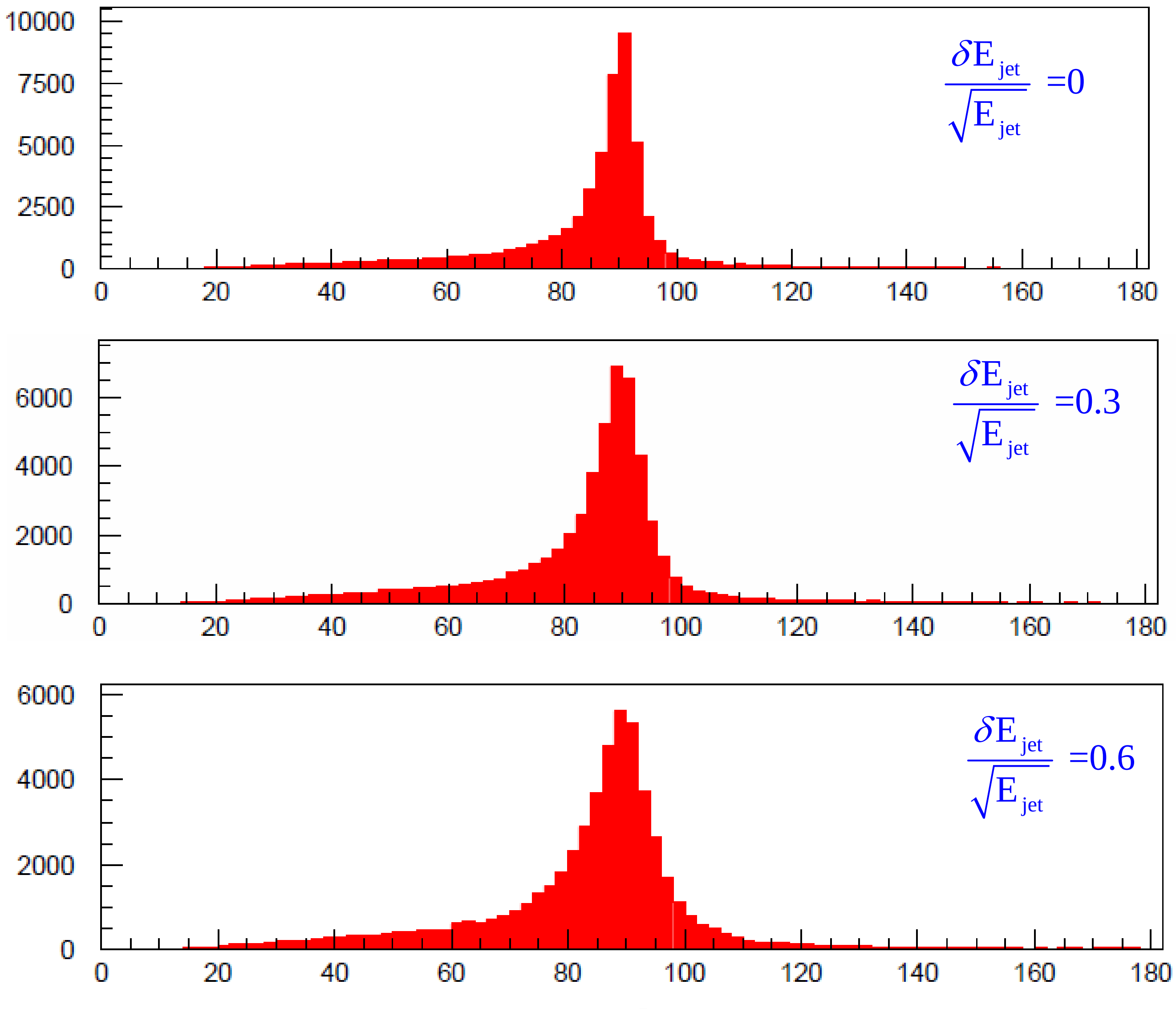


ZHH→qqbbbb
H mass



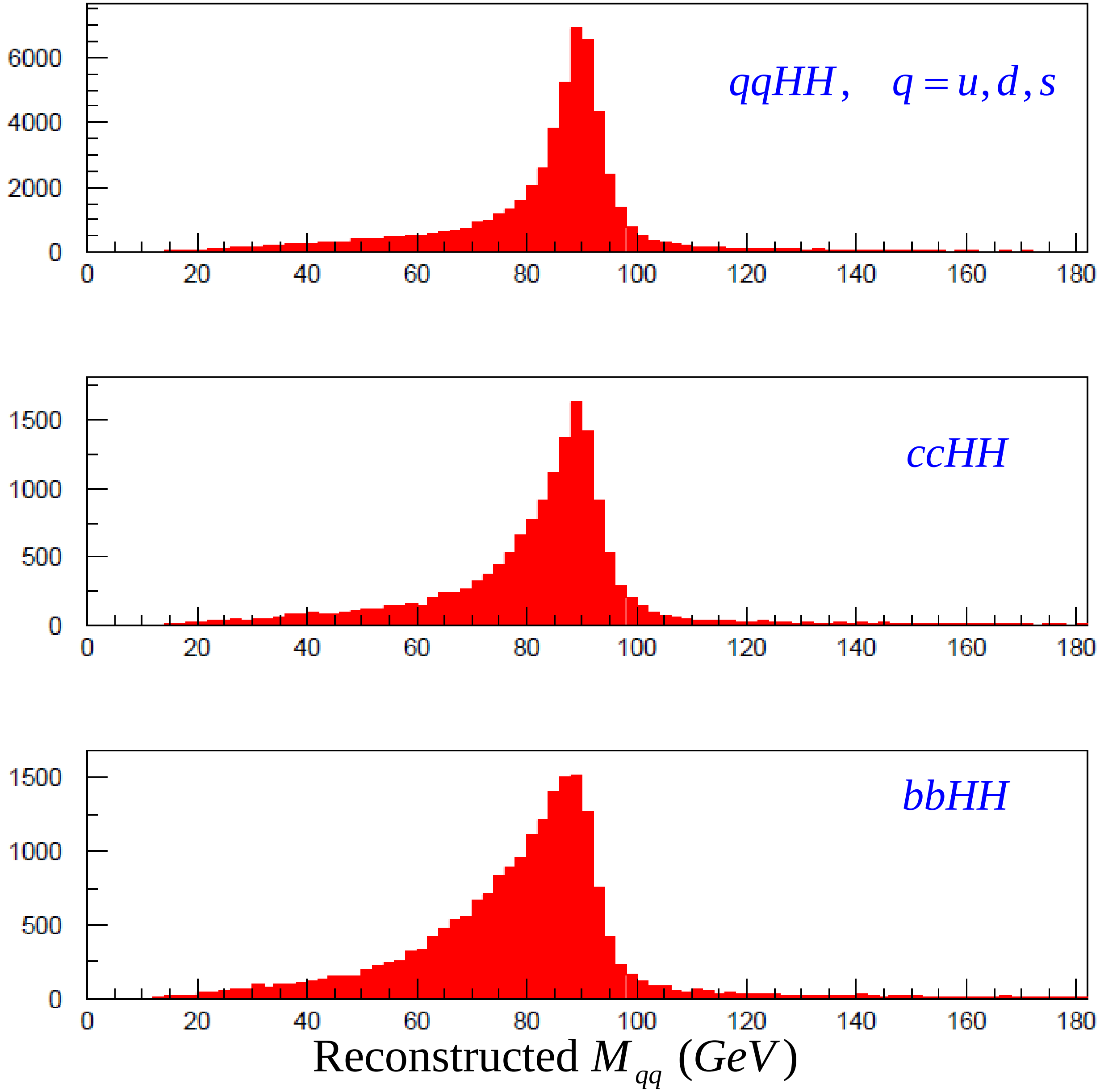
Reject H $\rightarrow$ 2jet comb if mass outside range $86 < M_{bb} < 133\,\text{GeV}$ (red arrows)

$e^+e^- \rightarrow qqHH, \quad q = u, d, s$ non-Gaussian Parameterization



Reconstructed M_{qq} (GeV)

$e^+e^- \to qqHH, \quad \frac{\delta \mathrm{E}_{\mathrm{jet}}}{\sqrt{\mathrm{E}_{\mathrm{jet}}}} = 0.3,$ non-Gaussian Parameterization



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

χ^2_{ZHH}

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

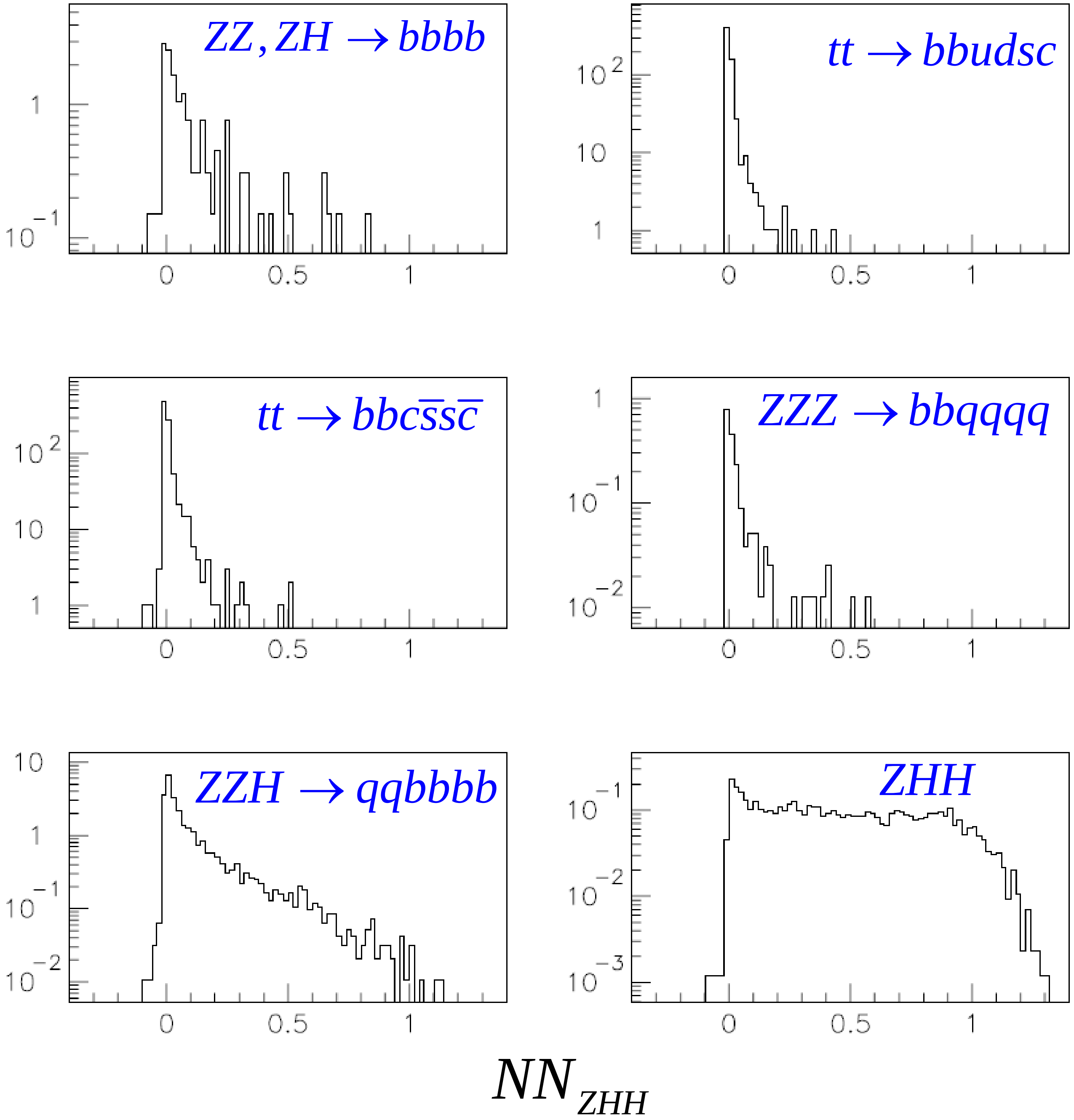
$$\chi^2_{ZHH} = \chi^2_{ZHH\_ZHHmass} + \sum_{j=3}^{6} \frac{(NNbtag_j - 1)^2}{\sigma^2_{NNbtag}}$$

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

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

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

$NNbtag_j$ = btag neural net variable for jet j

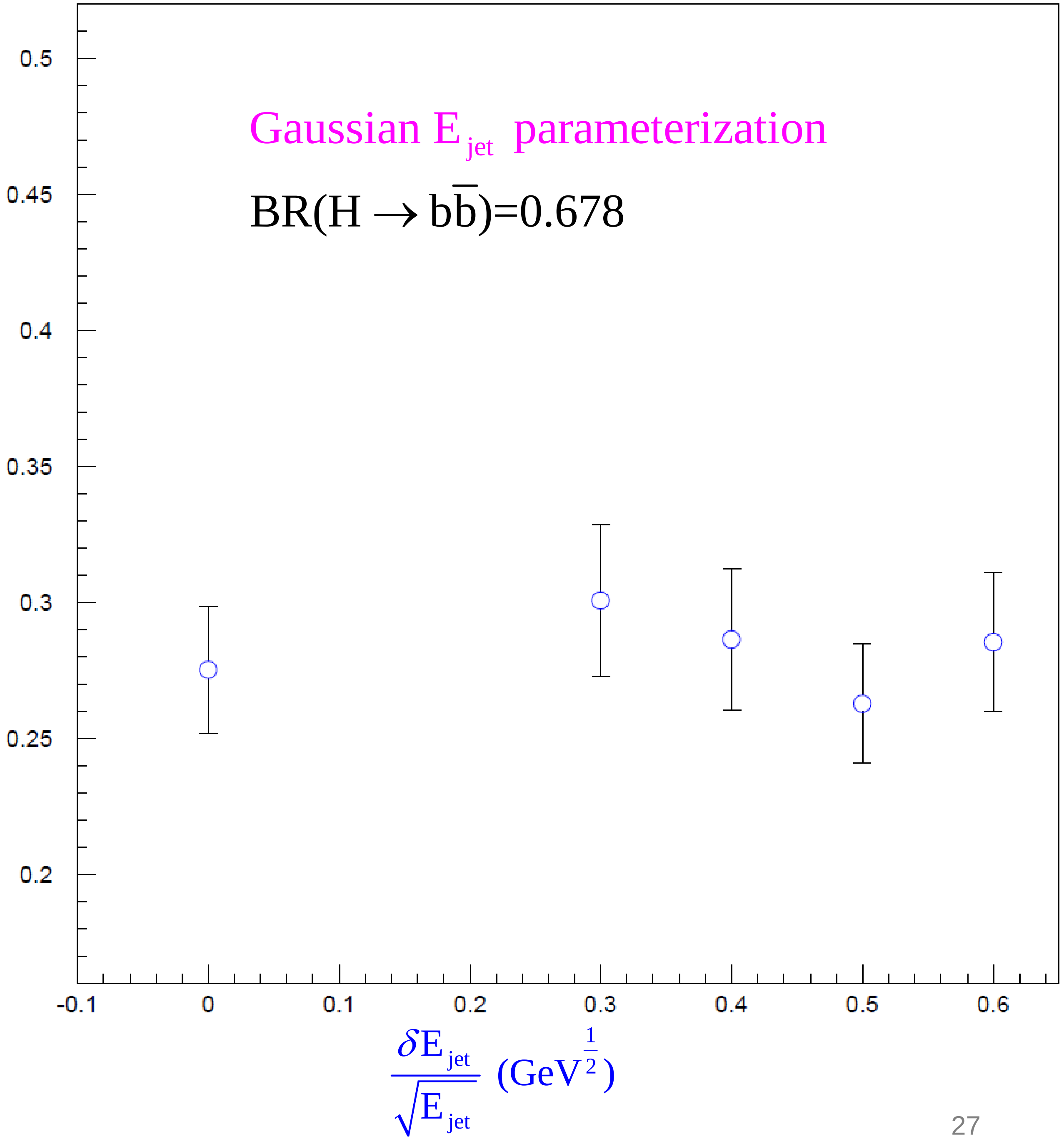

$ZZ, ZH \to bbbb$
$tt \to bbudsc$
$tt \to bbc\bar{s}s\bar{c}$
$ZZZ \to bbqqqq$
$ZZH \to qqbbbb$
ZHH
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
0
0.5
1
NN_{ZHH}

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

$$\to qqb\bar{b}b\bar{b}$$

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

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

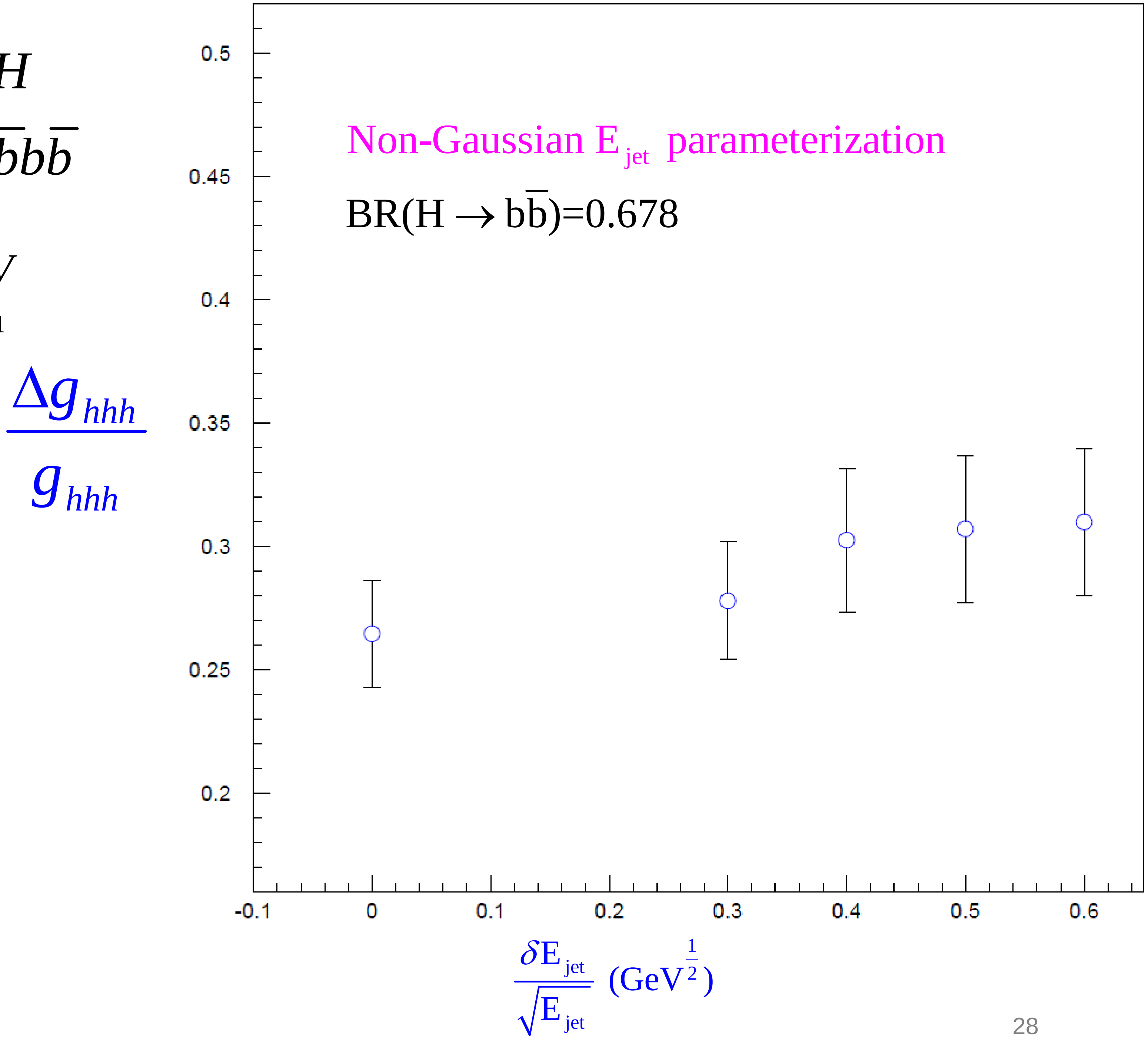


$$e^+e^- \rightarrow ZHH$$

$$\rightarrow qqb\bar{b}b\bar{b}$$

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

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

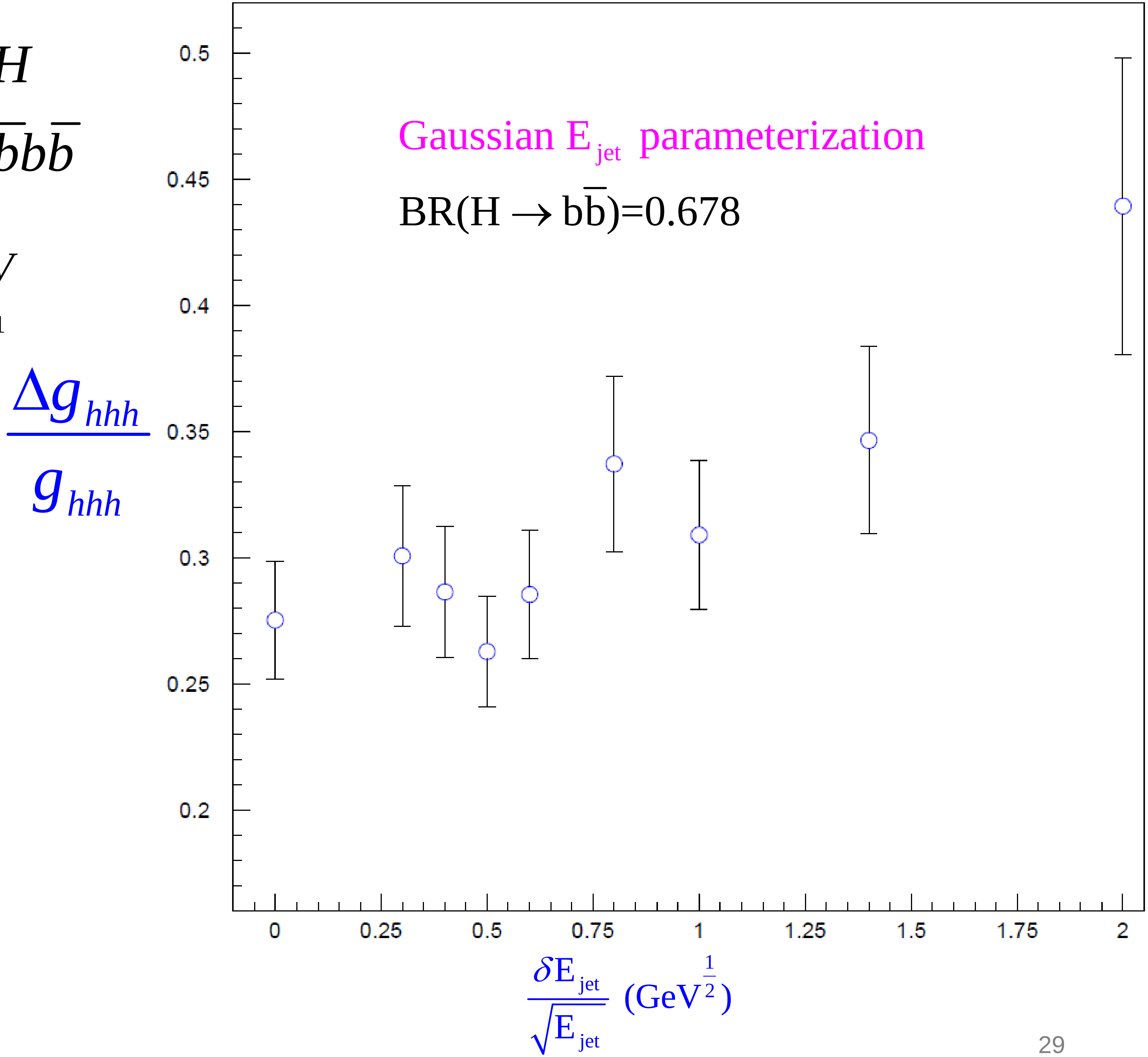


$$e^+e^- \to ZHH$$

$$\to qqb\bar{b}b\bar{b}$$

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

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



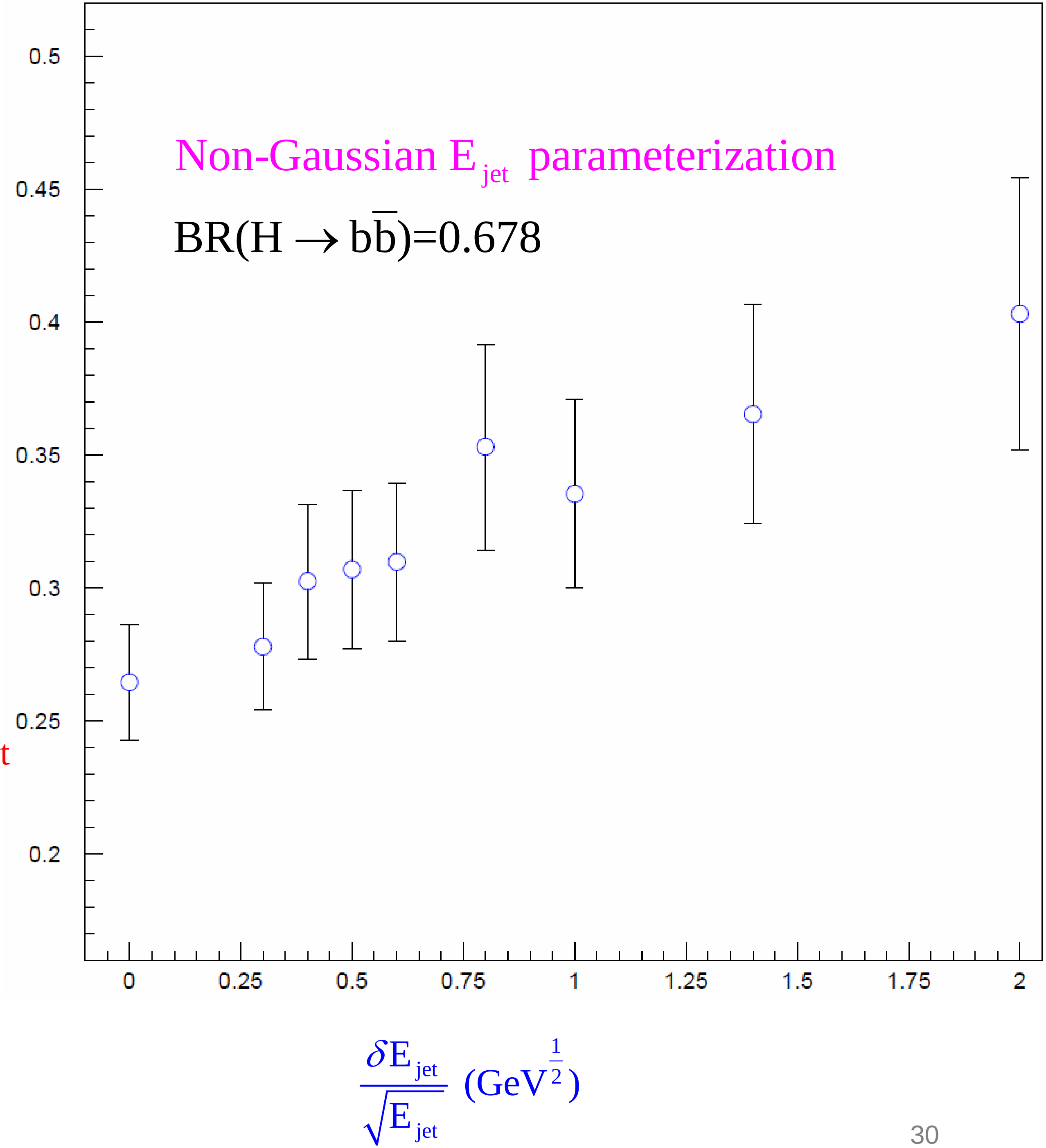
$$e^+e^- \rightarrow ZHH$$

$$\rightarrow qqb\bar{b}b\bar{b}$$

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

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

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



Similarity with Gaussian E_{jet} result on previous slide seems to imply total r.m.s. of E_{jet} distribution more important than core width

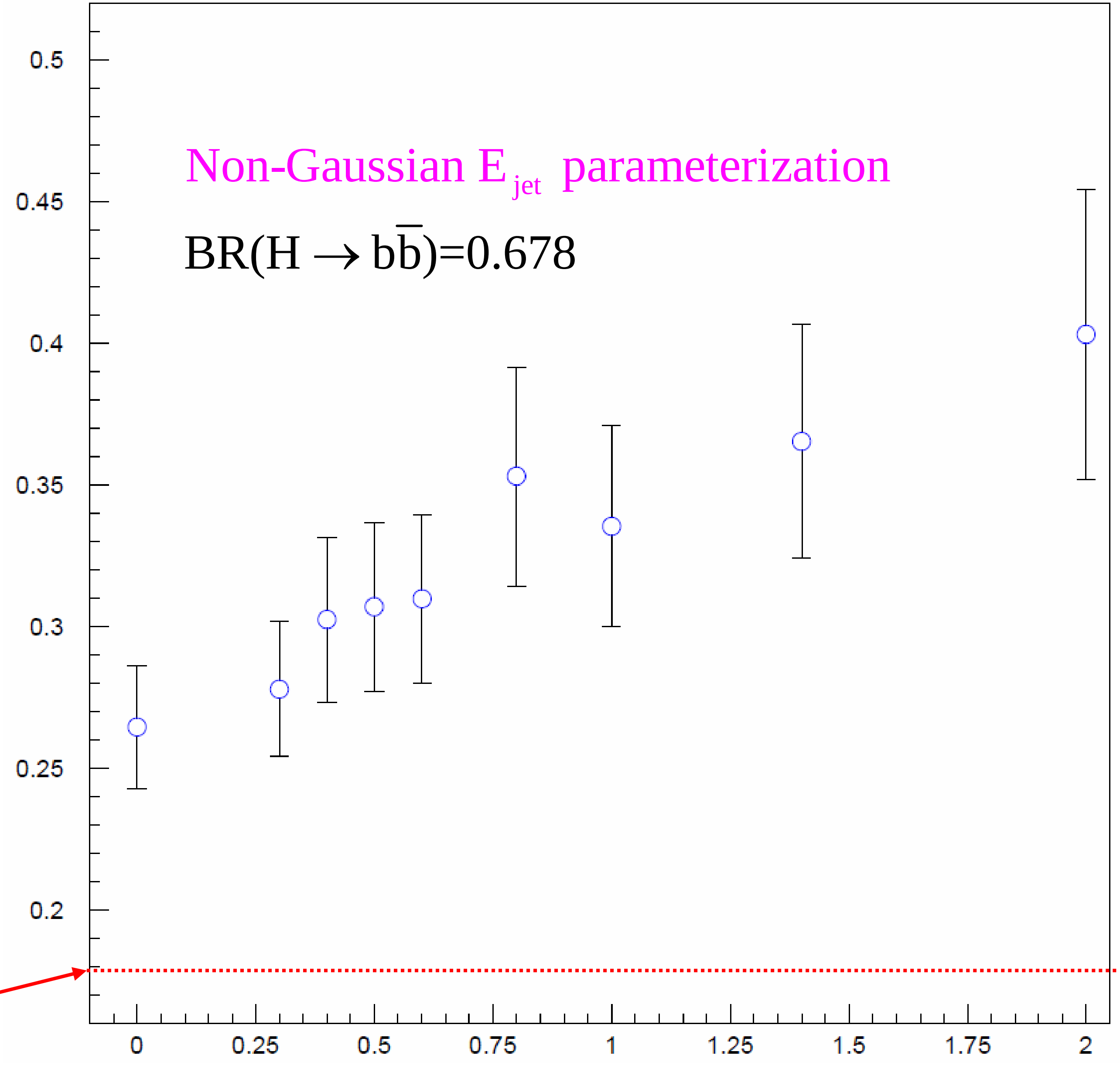
$$e^+e^- \to ZHH$$

$$\to qqb\bar{b}b\bar{b}$$

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

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

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



Non-Gaussian E_{jet} parameterization

$BR(H \to b\bar{b}) = 0.678$

TESLA TDR result

for $\frac{\delta E_{jet}}{\sqrt{E_{jet}}} = 0.3$

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

TESLA TDR Analysis Utilizes qqbbcc, qqbbgg, qqbbWW*, qqZZ* Final States, in Addition to qqbbbb

$\sigma(e^+e^- \to ZHH) = 0.186\ \text{fb at } \sqrt{s} = 500\ \text{GeV}$

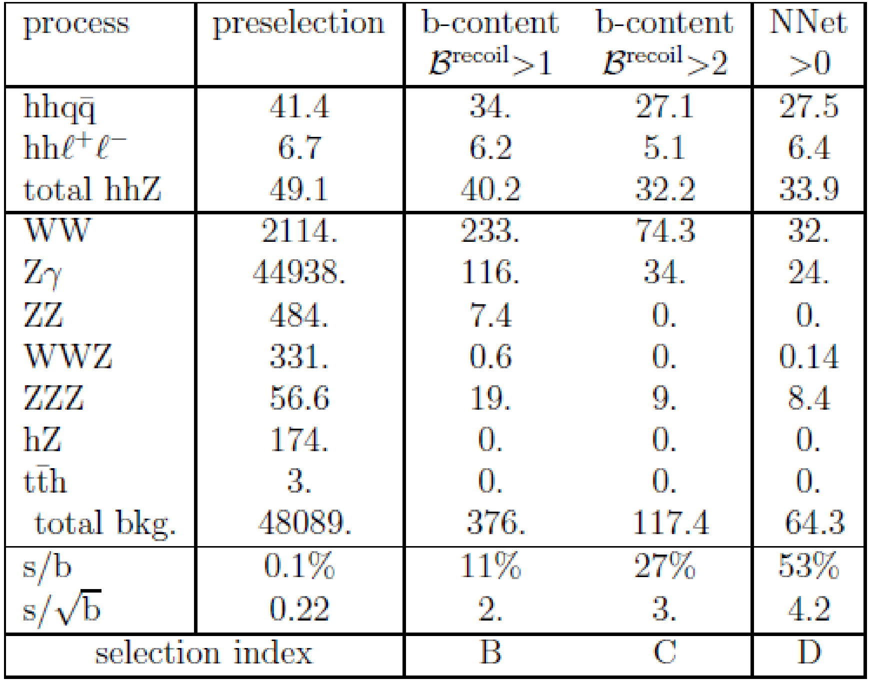
$\text{BR}(\text{H} \to \text{b}\bar{\text{b}})=0.678 \text{ for } M_H = 120\ \text{GeV} \quad \text{BR}(\text{Z} \to \text{qq})=0.699 \quad \text{BR}(\text{Z} \to l^+l^-) = 0.1$

$\text{Before cuts } N_{qqHH} = 65 \quad N_{llHH} = 9 \quad \text{and} \quad N_{qqbbbb} = 30 \quad N_{llbbbb} = 4 \quad \text{for 500 fb}^{-1}$

$B^{recoil} > 1$ means one or more b-jets in system recoiling against Z

$B^{recoil} > 2$ means two or more b-jets in system recoiling against Z

W$^+$W$^-$ and Zγ are mostly $W^+\bar{t}b$ and $t\bar{t}\gamma$ -- i.e. $t\bar{t}$



process	preselection	b-content $\mathcal{B}^{\text{recoil}}>1$	b-content $\mathcal{B}^{\text{recoil}}>2$	NNet >0
$hhq\bar{q}$	41.4	34.	27.1	27.5
$hh\ell^+\ell^-$	6.7	6.2	5.1	6.4
total hhZ	49.1	40.2	32.2	33.9
WW	2114.	233.	74.3	32.
Zγ	44938.	116.	34.	24.
ZZ	484.	7.4	0.	0.
WWZ	331.	0.6	0.	0.14
ZZZ	56.6	19.	9.	8.4
hZ	174.	0.	0.	0.
$t\bar{t}h$	3.	0.	0.	0.
total bkg.	48089.	376.	117.4	64.3
s/b	0.1%	11%	27%	53%
$s/\sqrt{b}$	0.22	2.	3.	4.2
selection index		B	C	D

Table 2: *Numbers of events with* $\mathcal{L}$= *500fb*$^{-1}$ *expected both for signal and background processes at preselection level, standard selections (two set of cut on* $\mathcal{B}^{\text{recoil}}$*) and multivariable analysis; s/b and* $s/\sqrt{b}$ *are also indicated.*

One major difference between this analysis and TESLA TDR is that we find that you must require that at least 3 of the jets recoiling against the Z be tagged as b-jets in order to begin to control $t\bar{t}$ background, given these preselection cuts.

C. Castanier et al. hep-ex/0101028

Do we have a jet energy resolution calibration problem when we compare different physics studies?

Is core jet energy resolution the relevant quantity for physics measurement error or is total r.m.s a more important parameter?

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

$\sqrt{s}$ = 500 GeV

use calor E

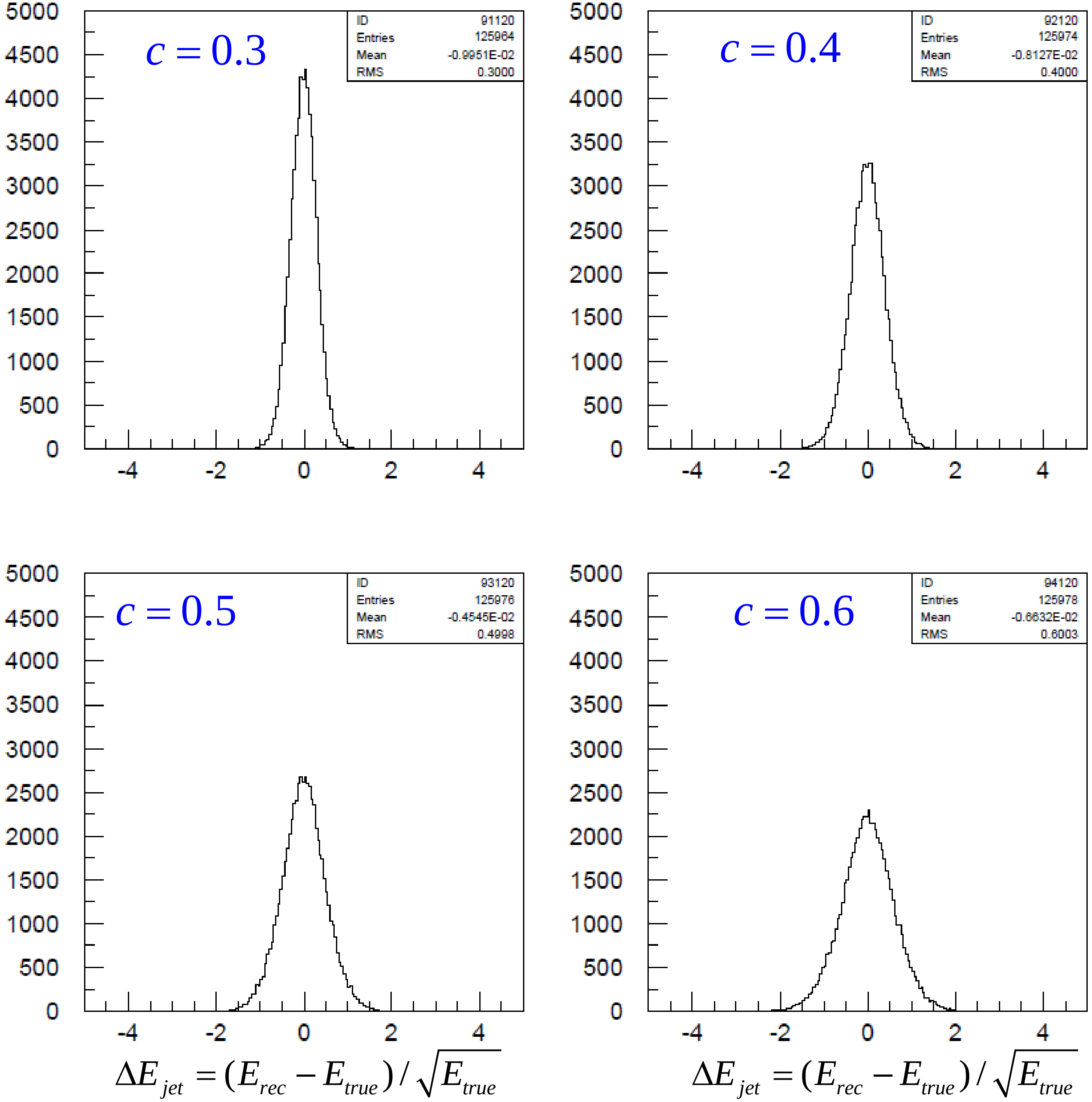
for all chg had

=> $w_h = 0.71$

Gaussian core with

no tail

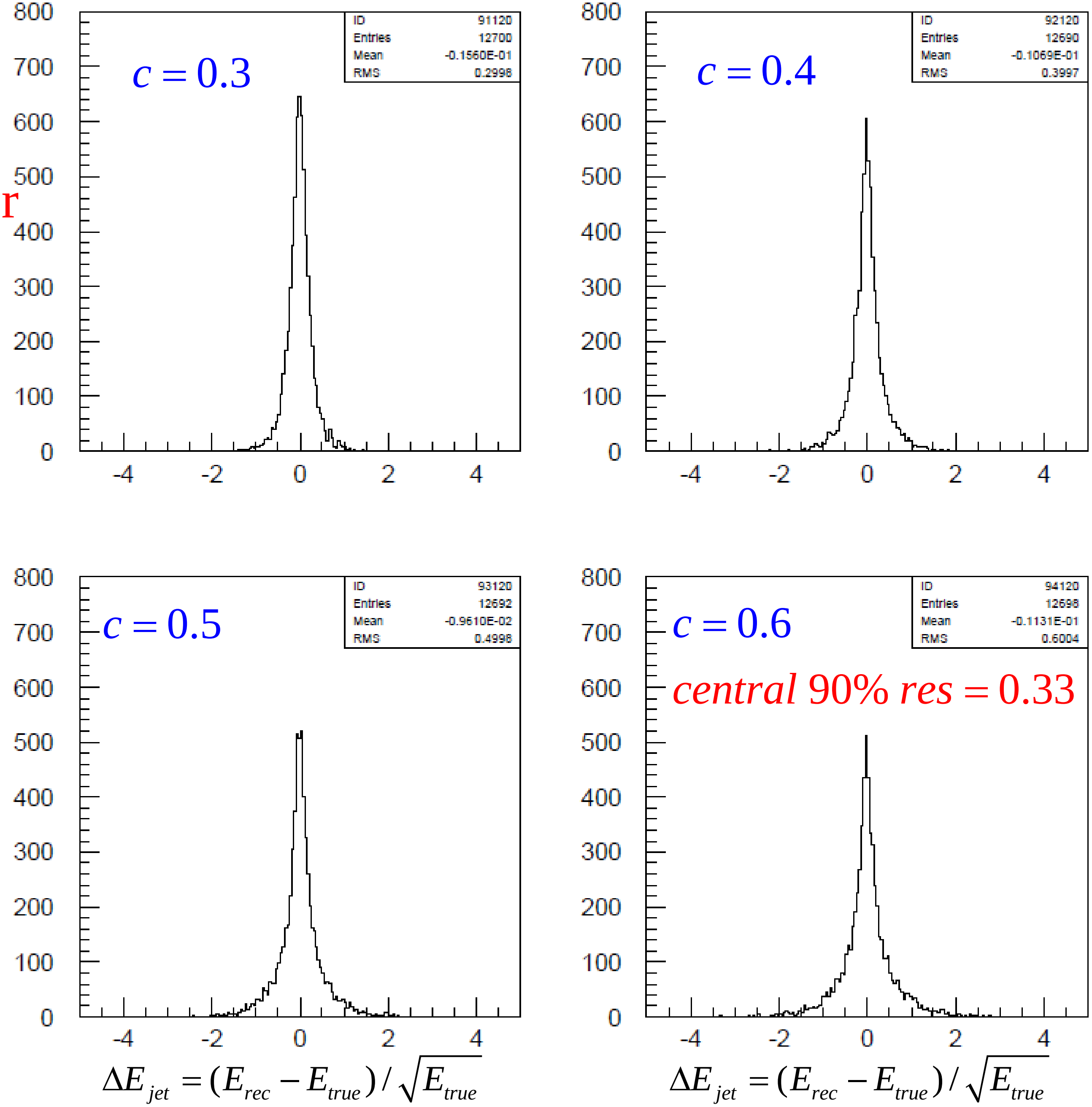
org.lcsim Fast MC



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

$\sqrt{s} =$ 500 GeV

Always use tracker momentum for chrg had.



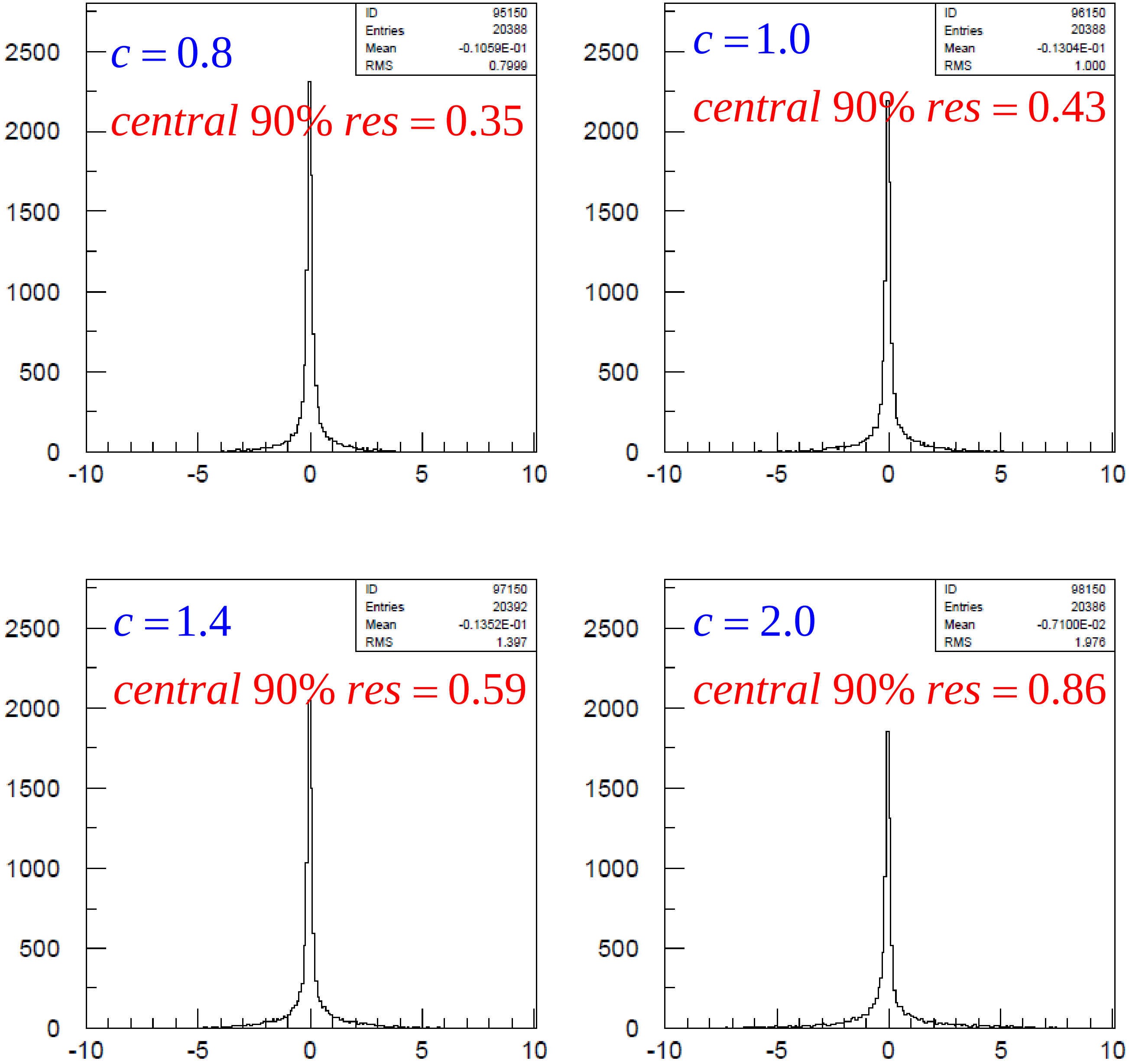
central 90% *res* = 0.33

org.lcsim Fast MC

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

$\sqrt{s} =$ 500 GeV

Always use tracker momentum for chrg had.



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

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

org.lcsim Fast MC

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

$$\to qqb\bar{b}b\bar{b}$$

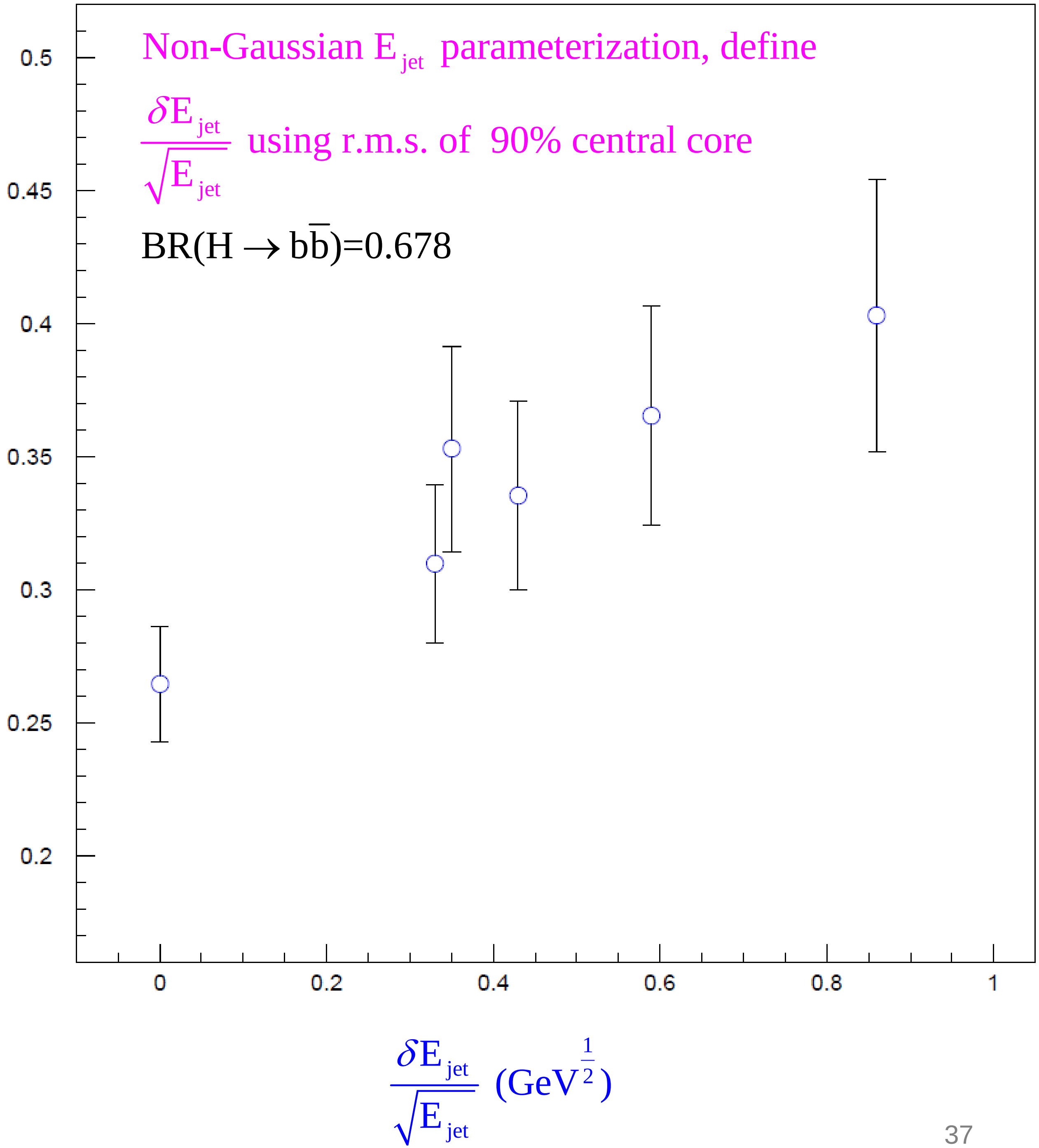
$$\sqrt{s} = 500\ GeV$$

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

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

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

equiv to 1.4× Lumi



Non-Gaussian E_{jet} parameterization, define

$\frac{\delta E_{jet}}{\sqrt{E_{jet}}}$ using r.m.s. of 90% central core

$BR(H \to b\bar{b})=0.678$

Conclusions

- The coupling g_{HHH} will be measured with an accuracy of 30% at Ecm=500 GeV and L=2000 fb^{-1} in the qqbbbb channel assuming a jet energy resolution of 30%/sqrt(E). This is substantially larger than the 18% error on g_{HHH} quoted in the TESLA TDR analysis under the same conditions of energy, luminosity, and jet energy resolution. The reason for this discrepancy is being pursued.
- The g_{HHH} coupling error shows little dependence on the jet energy resolution in the range 30 to 60%/sqrt(E) assuming the jet energy resolution is defined by total rms. If the jet energy resolution is defined by the rms of the central 90% core then the improvement in the g_{HHH} precision for 60% →30%/sqrt(E) is equivalent to a 40% gain in luminosity. Either way this result does not agree with the dependence shown in the TESLA TDR. The reason for this discrepancy is also being pursued.