Measurement of $\sigma(e^+e^- \to HZ)\times\mathrm{Br}(H \to ZZ^\star)$ at the 250 GeV ILC
Status report

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- Study of the sub-processes
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Introduction

The width of the Higgs boson *is difficult to measure at LHC in a model-independent approach* (the uncertainty *~20% after luminosity upgrade*)

We propose to use the process $\boldsymbol{e^+e^- \to HZ}$ with the subsequent decay $\boldsymbol{H \to ZZ^\star}$ to measure:

$$\sigma(e^+e^- \to HZ) \times Br(H \to ZZ^\star) = C \cdot g_Z^4/\Gamma_H$$

Constant, Error < 1% expected

Coupling HZZ Error < 0.5% expected

Higgs boson width

One of Z bosons is reconstructed in jets.

$\boldsymbol{Z \to jj\ or\ ll,} \qquad \boldsymbol{Z^\star \to ll\ or\ jj}$

Studied MC processes

Signal subprocesses with large ***significance***:

1) $e^+e^- \to Z_1(j_1j_2)H, \quad H \to Z(j_1j_2)Z^\star(l_1l_2)$
2) $e^+e^- \to Z_1(j_1j_2)H, \quad H \to Z(l_1l_2)Z^\star(j_1j_2)$
3) $e^+e^- \to Z_1(\nu\bar{\nu})H, \quad H \to Z(j_1j_2)Z^\star(l_1l_2)$
4) $e^+e^- \to Z_1(\nu\bar{\nu})H, \quad H \to Z(l_1l_2)Z^\star(j_1j_2)$

Significant *backgrounds*:

6-fermion $jjjj\,l^+l^-$ - background for channel 1 (← channel 1)
Examples: $WW\gamma$ and $ZZ\gamma$

$b\bar{b} \to jj\,l^+l^-\nu\bar{\nu}$ - background for channel 3 (← channel 3)

We tried to study events with 4 leptons. However number of such signal events is too small.

Samples parameters and analysis tools

- *Samples generated with Whizard 2.8.5*
- *ILD_l5_o1_v02 detector model*
- *100% initial beam polarization LR*
- *Initial state radiation (ISR) on*
- $\gamma\gamma$ *overlay on*

- *ILC-Soft v02-00-02*
- *IsolatedLeptonTagging processor*
- *FastJet processor (with Valencia jet reconstruction algorithm)*
- *Some additional processors*

Samples parameters

Process ID	Process Name	Polarization	Integrated luminosity, fb^{-1}	Cross section, fb^{-1}	Number of events
Signal samples					
402011	qqh	eLpR	$1.458 \cdot 10^3$	343.030	$5 \cdot 10^6$
402007	n1n1h		$8.285 \cdot 10^3$	60.351	$5 \cdot 10^6$
402009	n23n23h		$7.450 \cdot 10^3$	67.111	$5 \cdot 10^6$
Background samples					
401012	6f_ll_xyyx	eLpR	$5.816 \cdot 10^3$	3.439	20000
500010	2f_Z_hadronic		$5.510 \cdot 10^3$	7667.390	$38344 \cdot 10^3$

Table shows the basic information about all used samples
(taken from *generator meta data section of ELOG*)

Event selection

Sub-process	MC generator level extraction, N events	Isolated leptons tagging, N events	Weight factors	Number of weighted events
$Z_1 \to j_1 j_2, Z \to j_1 j_2, Z^\star \to l_1 l_2$	605	416	0.803	334
$Z_1 \to j_1 j_2, Z \to l_1 l_2, Z^\star \to j_1 j_2$	578	508	0.803	407
$Z_1 \to \nu_e \bar{\nu}_e, Z \to j_1 j_2, Z^\star \to l_1 l_2$	636	544	0.071	38
$Z_1 \to \nu_e \bar{\nu}_e, Z \to l_1 l_2, Z^\star \to j_1 j_2$	594	468	0.071	33
$Z_1 \to \nu_{\mu,\tau} \bar{\nu}_{\mu,\tau}, Z \to j_1 j_2, Z^\star \to l_1 l_2$	626	534	0.157	83
$Z_1 \to \nu_{\mu,\tau} \bar{\nu}_{\mu,\tau}, Z \to l_1 l_2, Z^\star \to j_1 j_2$	588	455	0.157	71

- Extraction of each sub-processes from initial samples
- ILT: *finding events with 2 leptons*
- Polarization weight factors to correct for *P = (0.8,0.3):*

$$w = \frac{\sigma_{LR\,eff} \cdot \mathcal{L}}{N_{events}}$$

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

$$LR:\ \sigma_{LR\,eff} = \sigma_{LR} \cdot \frac{(1+0{,}8)}{2} \cdot \frac{(1+0{,}3)}{2}$$

We tried to study RL polarization signal events. However number of such signal events is too small.

ISR and overlay removing

$\gamma\gamma$ overlay removed using *kT jet clustering*

From arXiv:2009.04340:

ISR photon candidate is selected if its energy E_{photon} is *greater than 10 GeV*

All charged particles in a cone with $cos\ \theta_{cone} = 0.95$ around the photon *are summed up.*

$E_{sum} < 5\%\ E_{photon}$ -> ISR photon

Jet reconstruction

Valencia algorithm is used to force the remaining particles into 2 or 4 jets.

It contains 3 parameters: R - generalized jet radius, $\boldsymbol{\gamma}$ *and* β - special capture parameters in beam distance

We use β = 1 and tune *R and* $\boldsymbol{\gamma}$ with this method ***from arXiv:1607.05039:***

$$\Delta M(Z) = M_{reco}(Z) - M_{gen}(Z)$$

$$Median = Q(0.5)$$

Choosing combination of minimum of IQR34, RMS90 and close to 0 median

$$IQR_{34} = \frac{Q(0.84) - Q(0.16)}{2}$$

$$M_{mean} = \frac{\sum \Delta M(Z)}{N_{entries}}$$

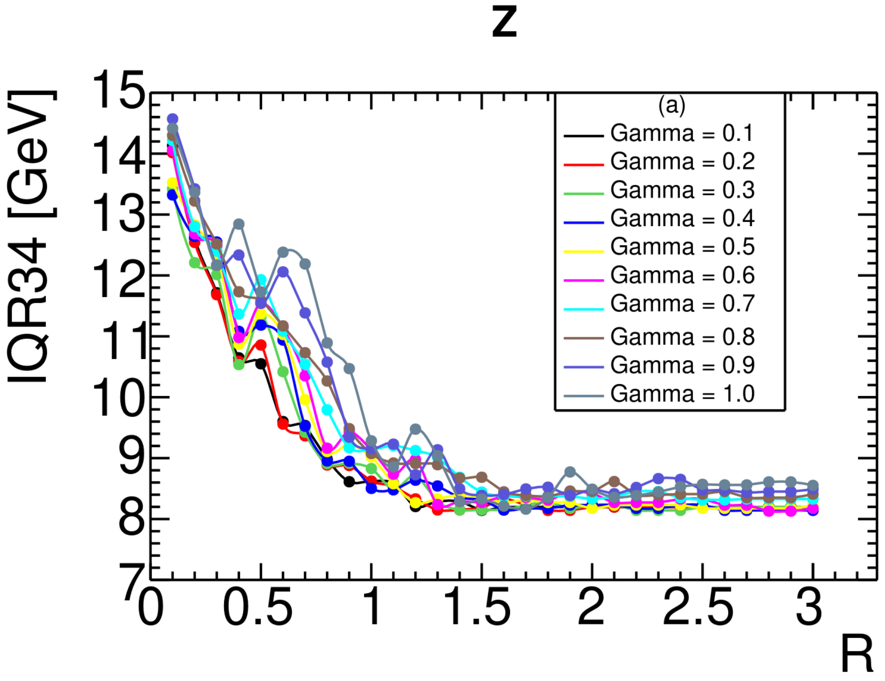
$$RMS_{90} = \sqrt{(|M_{mean}^2 - M_{mean}|)}$$

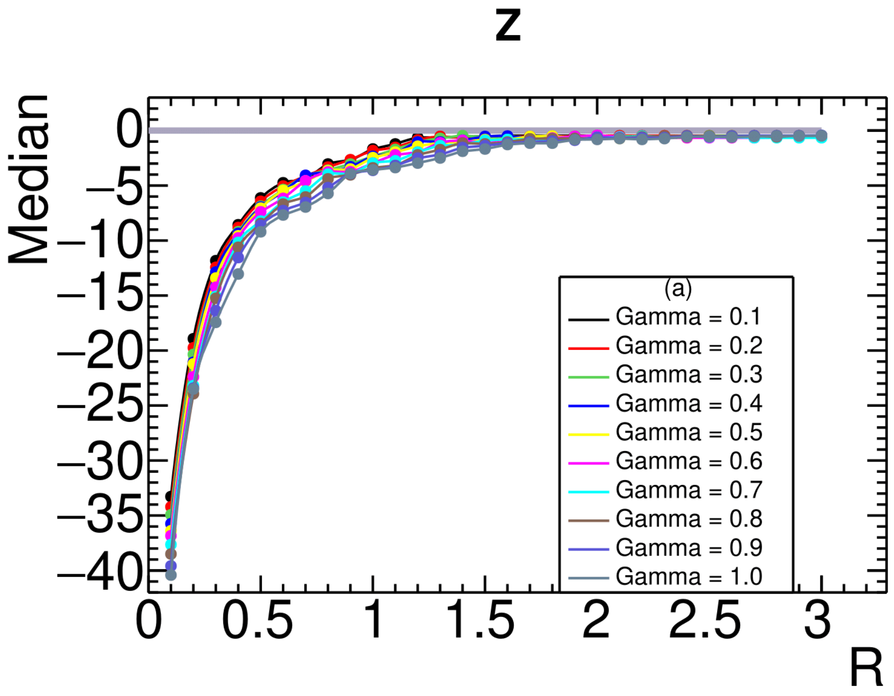
$$M_{mean}^2 = \frac{\sum (\Delta M(Z))^2}{N_{entries}}$$

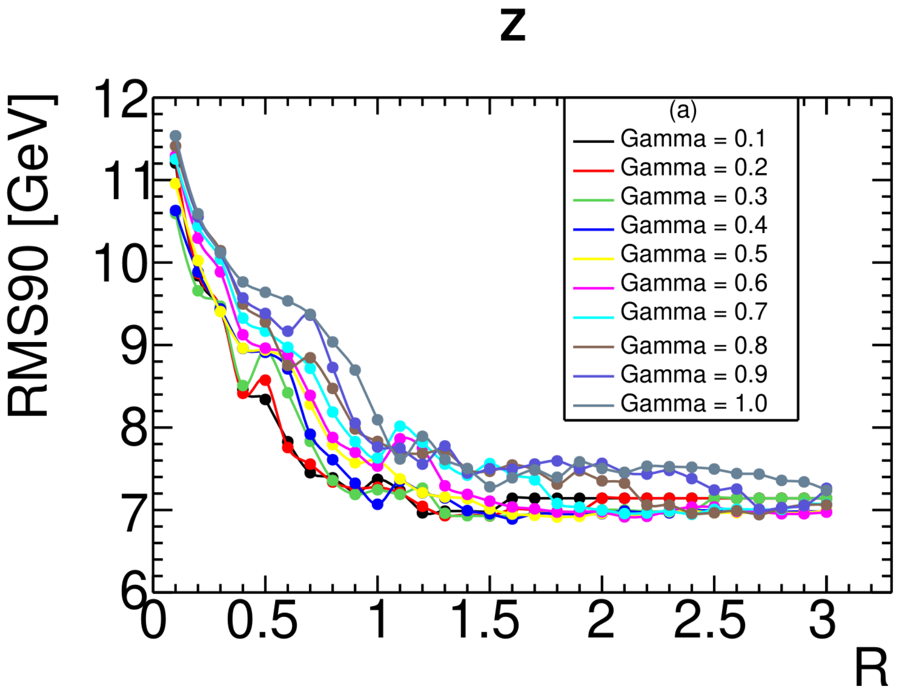
Jet reconstruction

Tune for *Z(jj)*

R[0.1, 3.0] and *γ[0.1, 1.0]* ranges



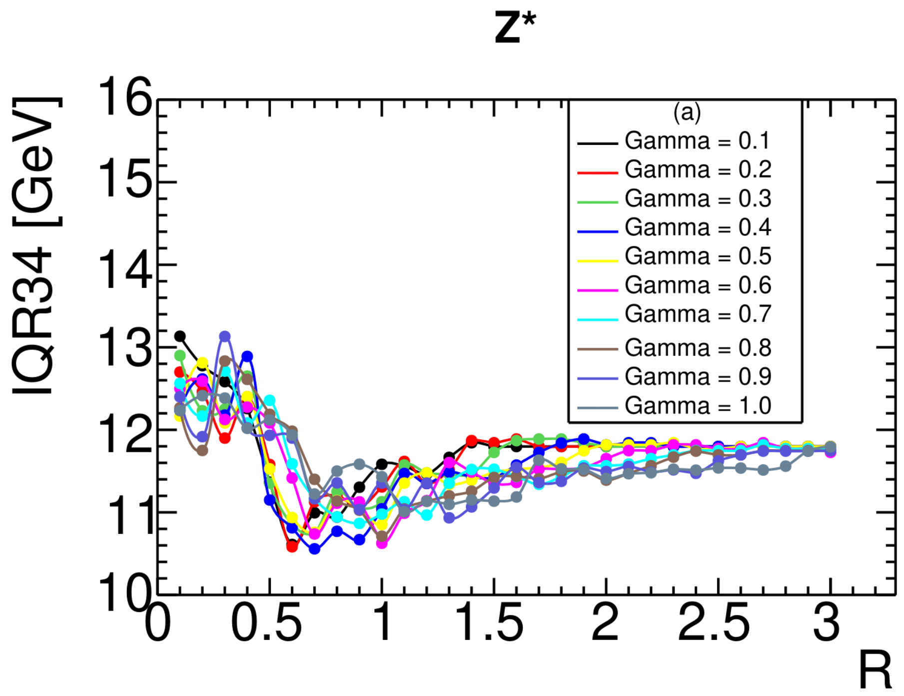


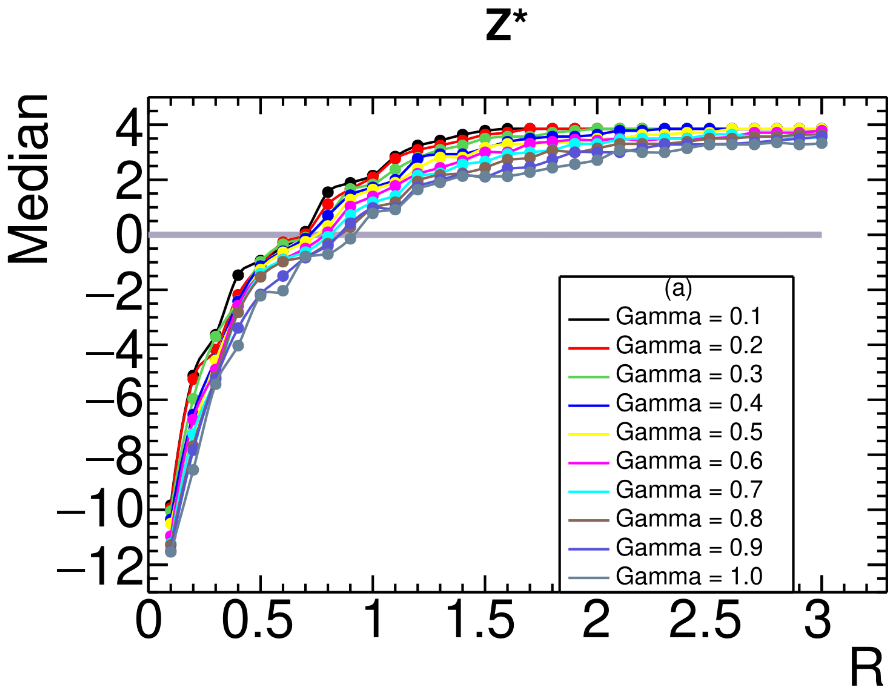


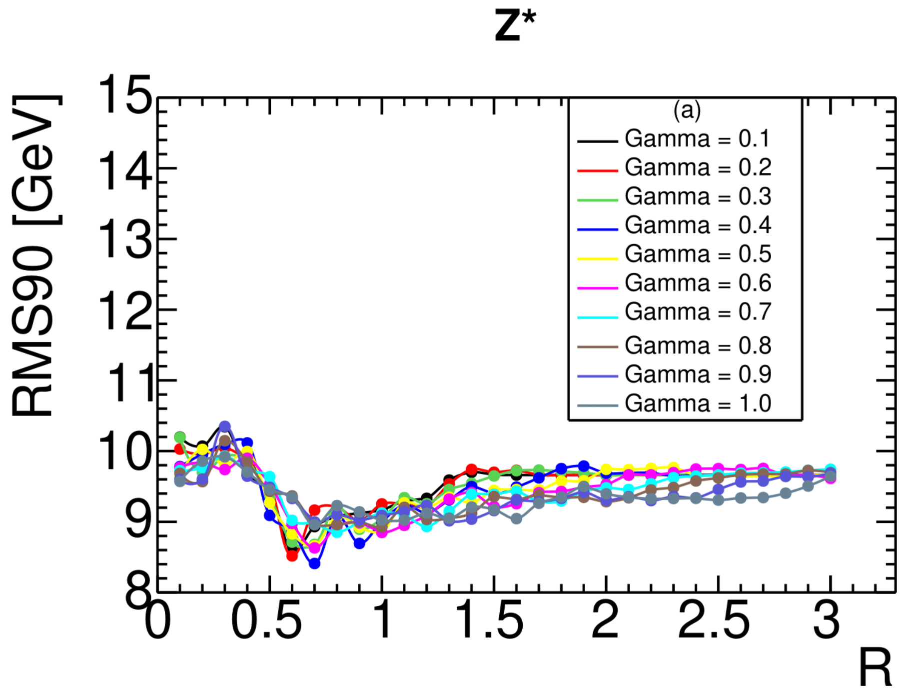
Jet reconstruction

Tune for *Z⋆(jj)*

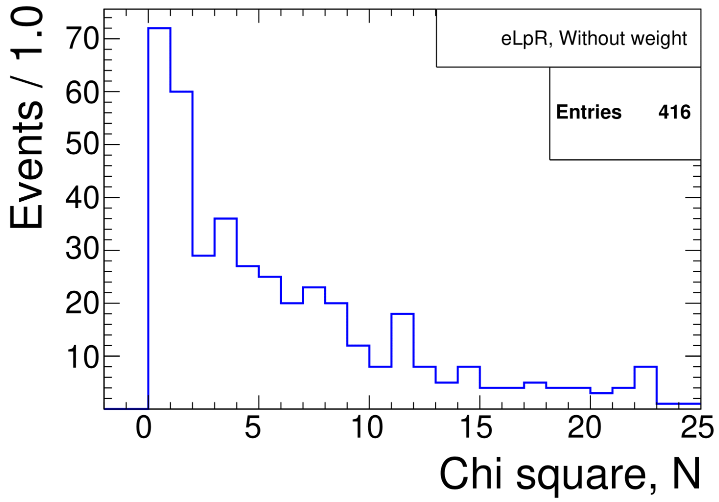
R[0.1, 3.0] and *γ[0.1, 1.0]* ranges







Minimum χ^2_{min} calculation



$$Z_1 \rightarrow jj, Z \rightarrow jj\,, Z^\star \rightarrow ll$$

$$\chi^2_{min} = \frac{(M_{Z_1} - M_{Z_{nom}})^2}{\sigma^2_{M_{Z_1}}} + \frac{(M_Z - M_{Z_{nom}})^2}{\sigma^2_{M_Z}} + \frac{(P_{Z_1} - P_{Z_{nom}})^2}{\sigma^2_{P_{Z_1}}} + \frac{(P_{Z+Z^*} - P_{Z_{nom}})^2}{\sigma^2_{P_{Z+Z^*}}};$$

6 combinations of jets:

1) J1+J2 , J3+J4
2) J1+J3 , J2+J4
3) J1+J4 , J2+J3
4) J2+J3 , J1+J4
5) J2+J4 , J1+J3
6) J3+J4 , J1+J2

$$M_{Z\,nom} = 91.2\ GeV$$

$$P_{Z\,nom} = 60.0\ GeV$$

All σ are estimated from data:

$$\sigma^2_{M_{Z_1}} = 11.41\ GeV$$

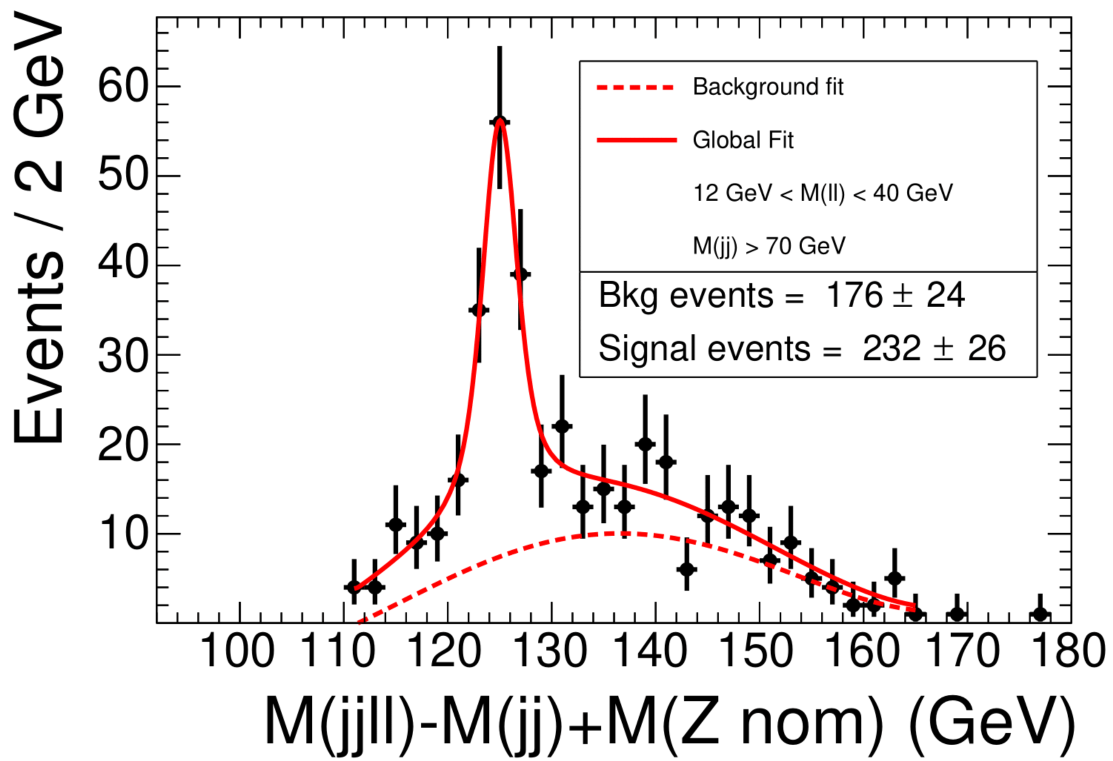
$$\sigma^2_{M_Z} = 13.97\ GeV$$

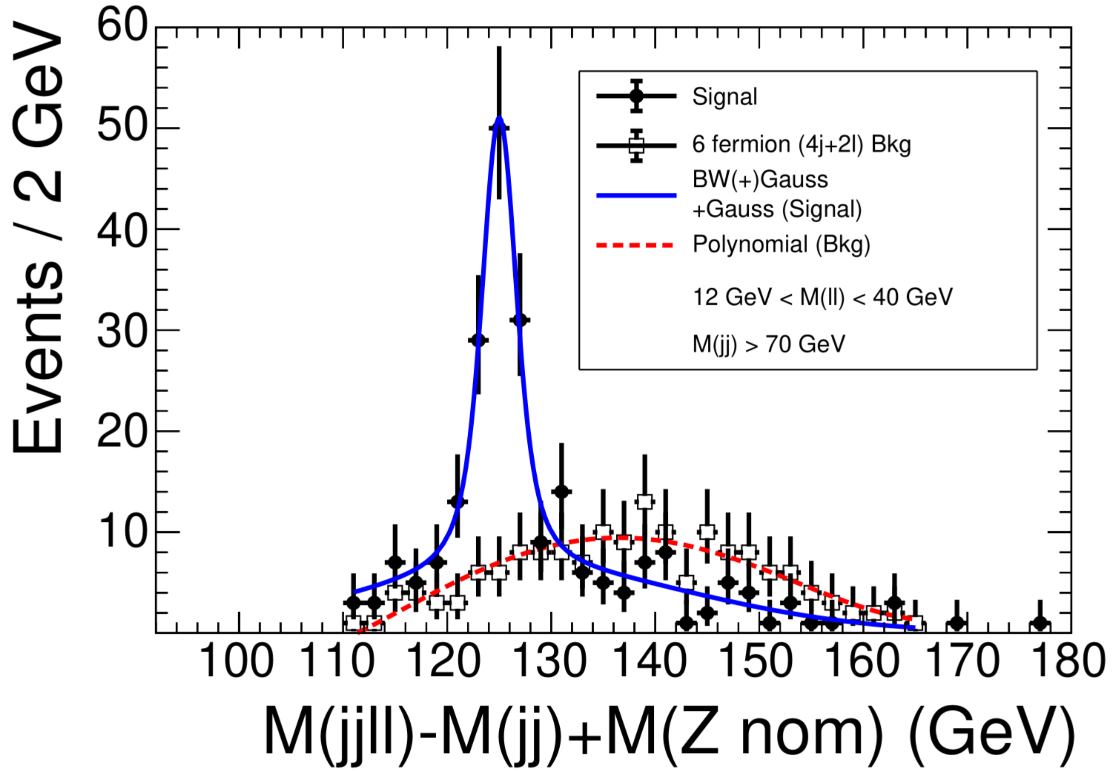
$$\sigma^2_{P_{Z_1}} = 9.62\ GeV$$

$$\sigma^2_{P_{Z+Z^*}} = 7.16\ GeV$$

$Z_1 \to jj, Z \to jj\,, Z^{\star} \to ll$

VLC:
γ = 0.4
R = 1.6

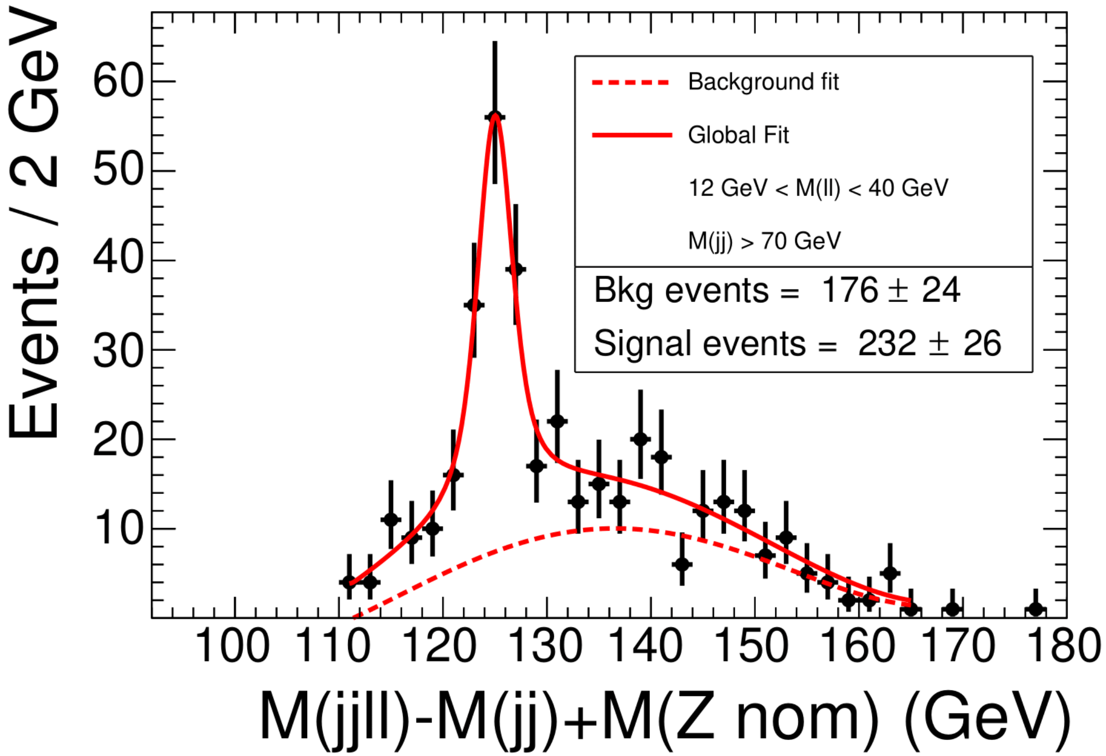


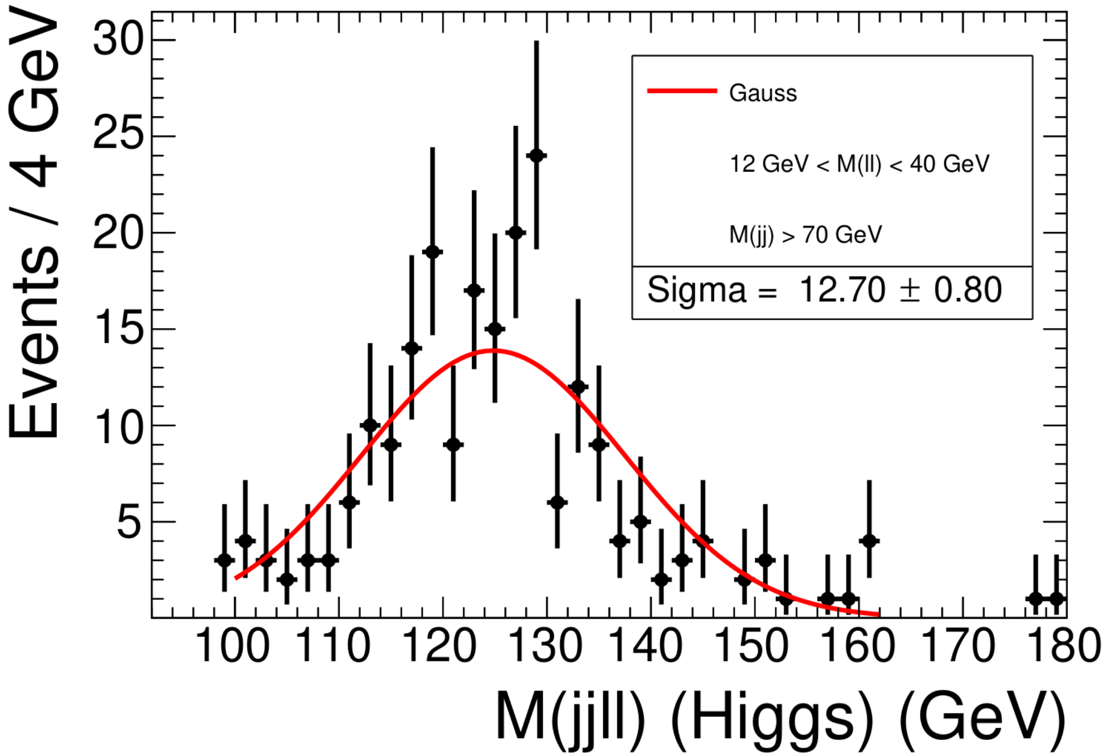


Significance of this channel = ***11.2%***

Signal is modelled by ***Voigtian + Gaussian*** *function*
Wide gaussian comes from $Z^{\star}Z^{\star}$ *tail*
Background is described by ***Chebychev3*** *function*

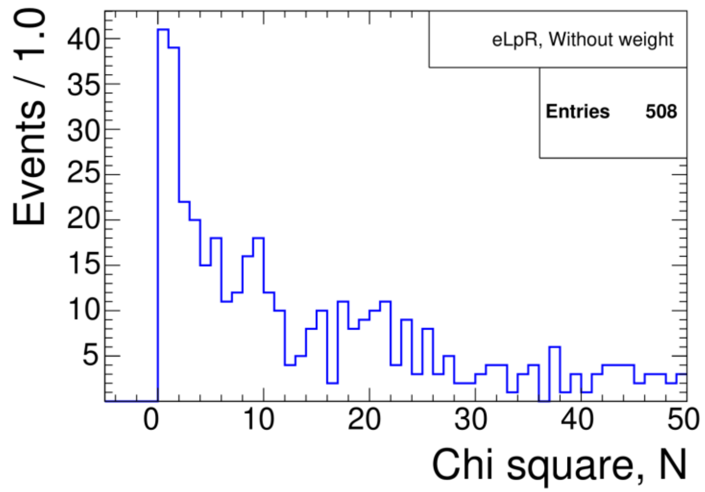
$Z_1 \rightarrow jj, Z \rightarrow jj\ , Z^{\star} \rightarrow ll$





The distribution peak of ***mass difference is more compact*** *then peak of direct* ***Higgs boson mass*** *reconstruction*

Minimum χ^2_{min} calculation



$$Z_1 \to jj,\, Z \to ll\,,\, Z^{\star} \to jj$$

$$\chi^2_{min} = \frac{(M_{Z_1} - M_{Z_{nom}})^2}{\sigma^2_{M_{Z_1}}} + \frac{(P_{Z_1} - P_{Z_{nom}})^2}{\sigma^2_{P_{Z_1}}} + \frac{(P_{Z+Z^*} - P_{Z_{nom}})^2}{\sigma^2_{P_{Z+Z^*}}} + \frac{(E_{Z_1} - E_{Z_{nom}})^2}{\sigma^2_{E_{Z_1}}};$$

6 combinations of jets:

1) J1+J2 , J3+J4
2) J1+J3 , J2+J4
3) J1+J4 , J2+J3
4) J2+J3 , J1+J4
5) J2+J4 , J1+J3
6) J3+J4 , J1+J2

$M_{Z\,nom} = 91.2\ GeV$

$P_{Z\,nom} = 60.0\ GeV$

$E_{Z\,nom} = 110.0\ GeV$

All σ are estimated from data:

$\sigma^2_{M_{Z_1}} = 21.84\ GeV$

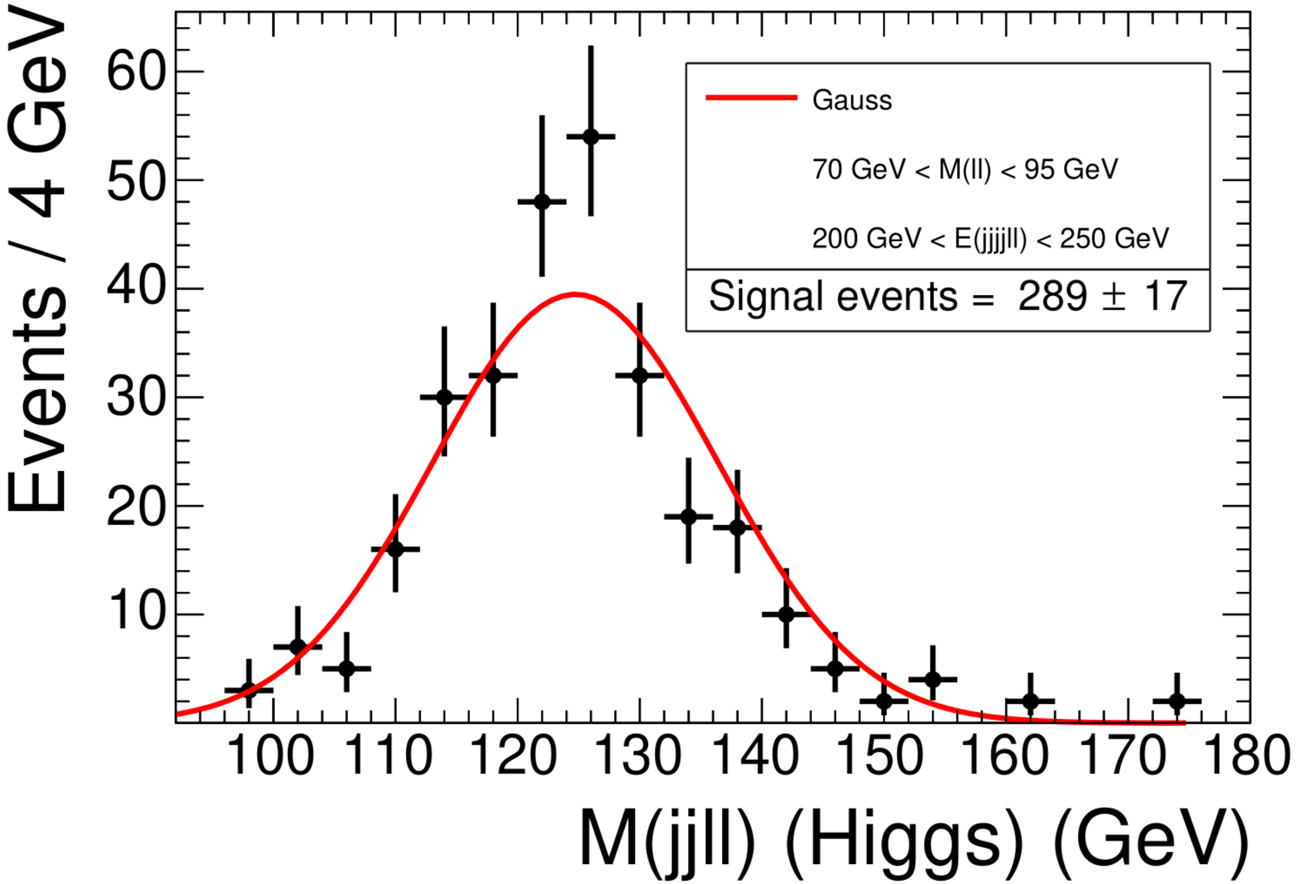
$\sigma^2_{P_{Z_1}} = 5.42\ GeV$

$\sigma^2_{P_{Z+Z^*}} = 10.37\ GeV$

$\sigma^2_{E_{Z_1}} = 4.86\ GeV$

$Z_1 \rightarrow jj, Z \rightarrow ll\,, Z^{\star} \rightarrow jj$

VLC:
γ = 0.4
R = 0.7



Signal is modelled by ***Gaussian*** *function*

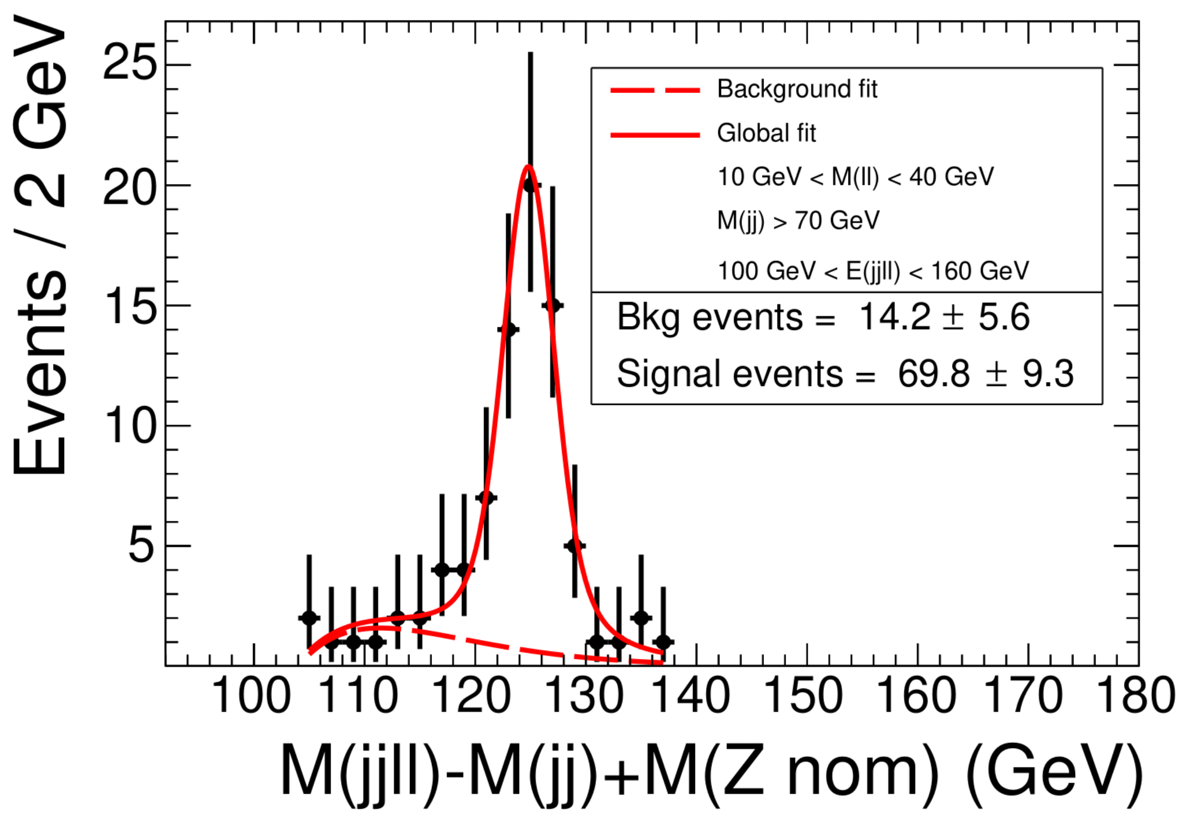
Suppression of uncorrelated ll backgrounds and $Z^{\star}Z^{\star}$ events using ***M(ll) and E(jjjjll) cuts***

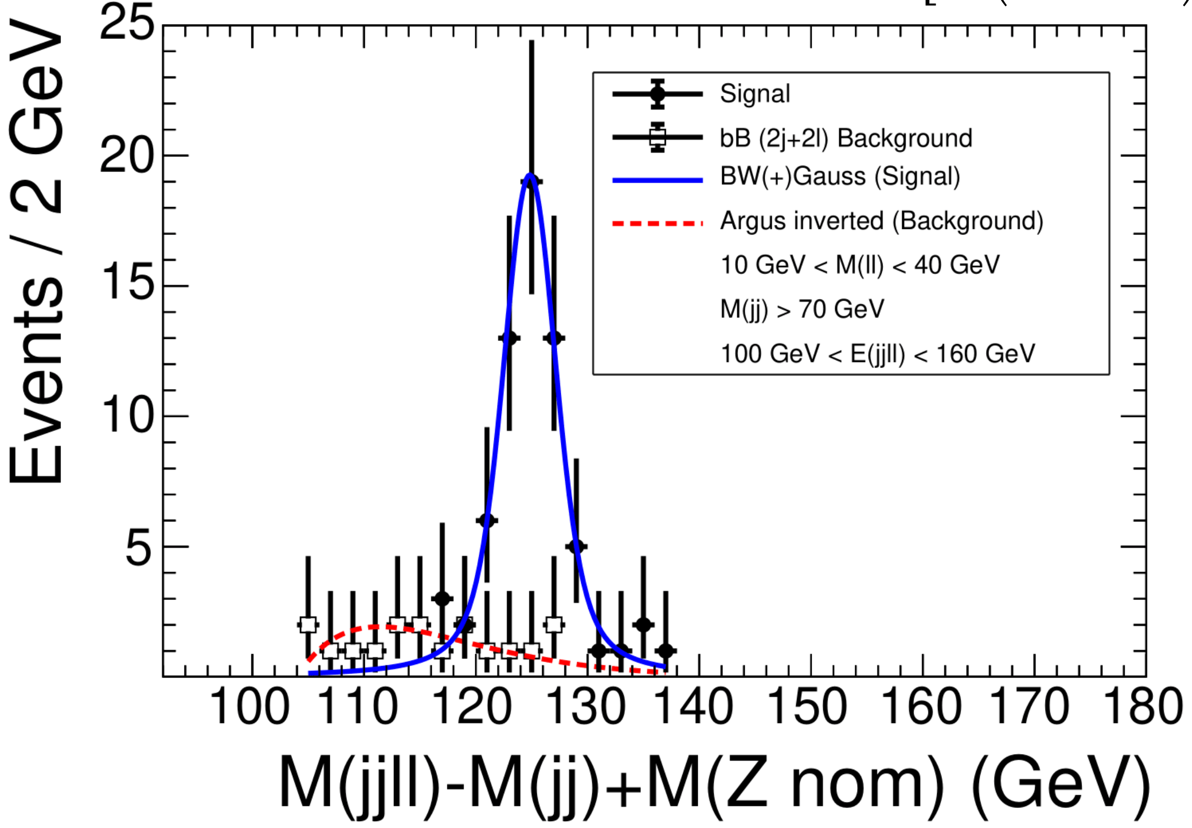
Significance of this channel = ***5.9%***

$Z_1 \to \nu\nu, Z \to jj, Z^{\star} \to ll$

VLC:
γ **= 0.6**
R **= 1.4**

$$Argus\_inverted(m, m_0, c, p) = N \cdot m \cdot \left[\left(\frac{m}{m_0}\right)^2 - 1\right]^p \cdot \exp\left[c \cdot \left(\left(\frac{m}{m_0}\right)^2 - 1\right)\right]$$



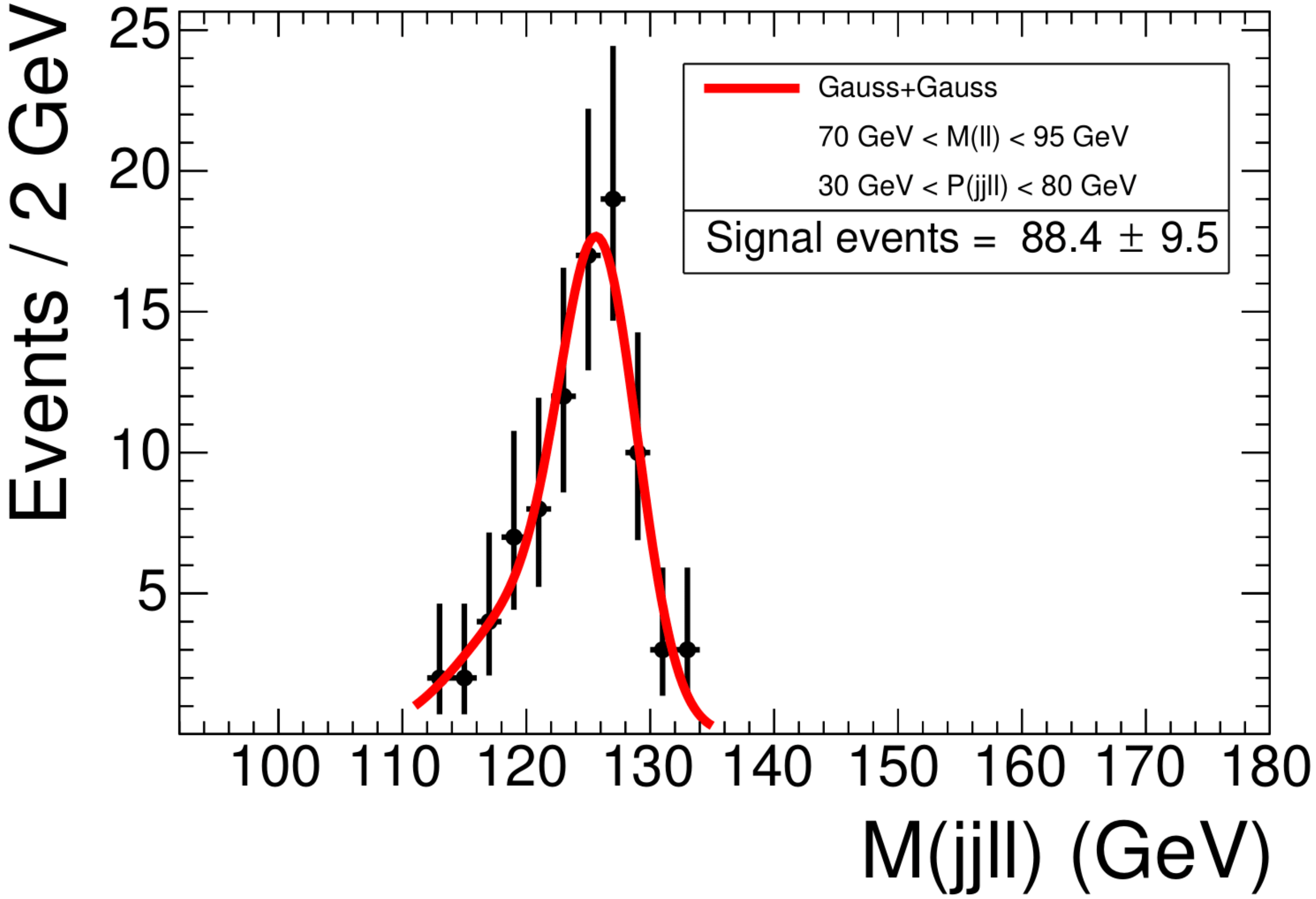


Significance of this channel = ***13.5%***

Signal is modelled by ***Voigtian*** *function*
Background is described by ***Argus_inverted custom*** *function*

$$Z_1 \to \nu\nu, Z \to ll\,, Z^\star \to jj$$

VLC:
γ **= 0.3**
R **= 1.4**



*Signal is modelled by **Gaussian+Gaussian** function*

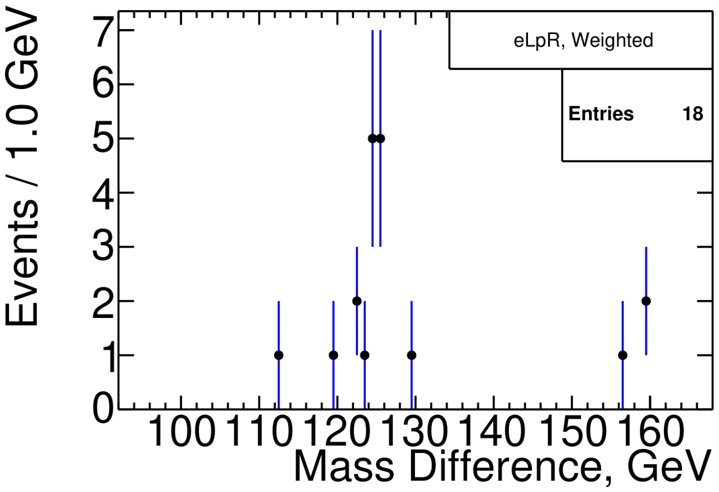
Small tail from $Z^\star Z^\star$ events

*Suppression of uncorrelated ll backgrounds and $Z^\star Z^\star$ events using **M(ll) and P(jjll) cuts.***

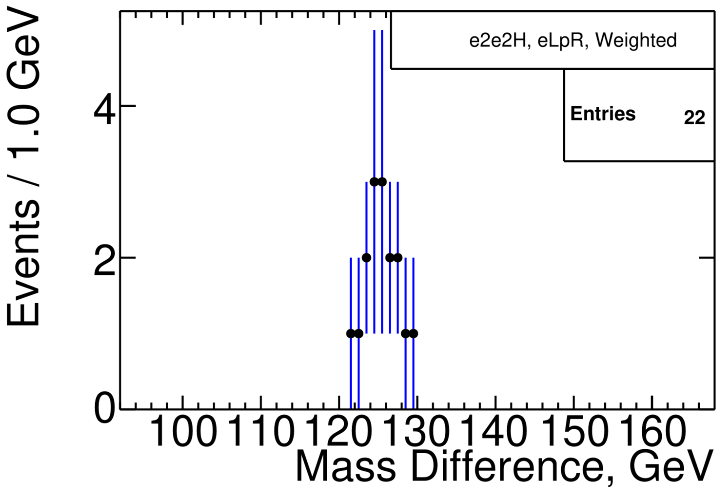
*Significance of this channel = **10.7%***

4 leptons channels

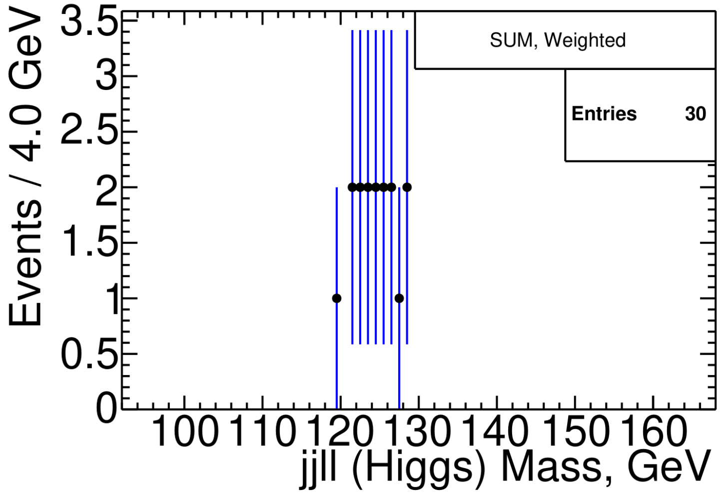
$Z_1 \to jj, Z \to ll , Z^{\star} \to ll$



$Z_1 \to ll, Z \to jj , Z^{\star} \to ll$



$Z_1 \to ll, Z \to ll , Z^{\star} \to jj$



Integrated significance of this method

We use this formula for full significance calculation:

$$\frac{1}{Sign} = \sqrt{\left(\frac{N_{ch\,1}}{Err_{ch\,1}}\right)^2 + \left(\frac{N_{ch\,2}}{Err_{ch\,2}}\right)^2 + \left(\frac{N_{ch\,3}}{Err_{ch\,3}}\right)^2 + \left(\frac{N_{ch\,4}}{Err_{ch\,4}}\right)^2}$$

$$\frac{1}{Sign} = \sqrt{\left(\frac{232}{26}\right)^2 + \left(\frac{289}{17}\right)^2 + \left(\frac{69.8}{9.3}\right)^2 + \left(\frac{88.4}{9{,}5}\right)^2}$$

Then full statistical significance of this method: $\boldsymbol{Sign = 4.4\%}$

Systematic uncertainty comes mostly from background shape description. Still this uncertainty is smaller then statistical one. It is difficult to estimate precisely without real data. Systematics due to reconstruction efficiency is small.

Conclusions

We studied $e^+e^- \rightarrow HZ$ process with $H \rightarrow ZZ^{\star}$decay.

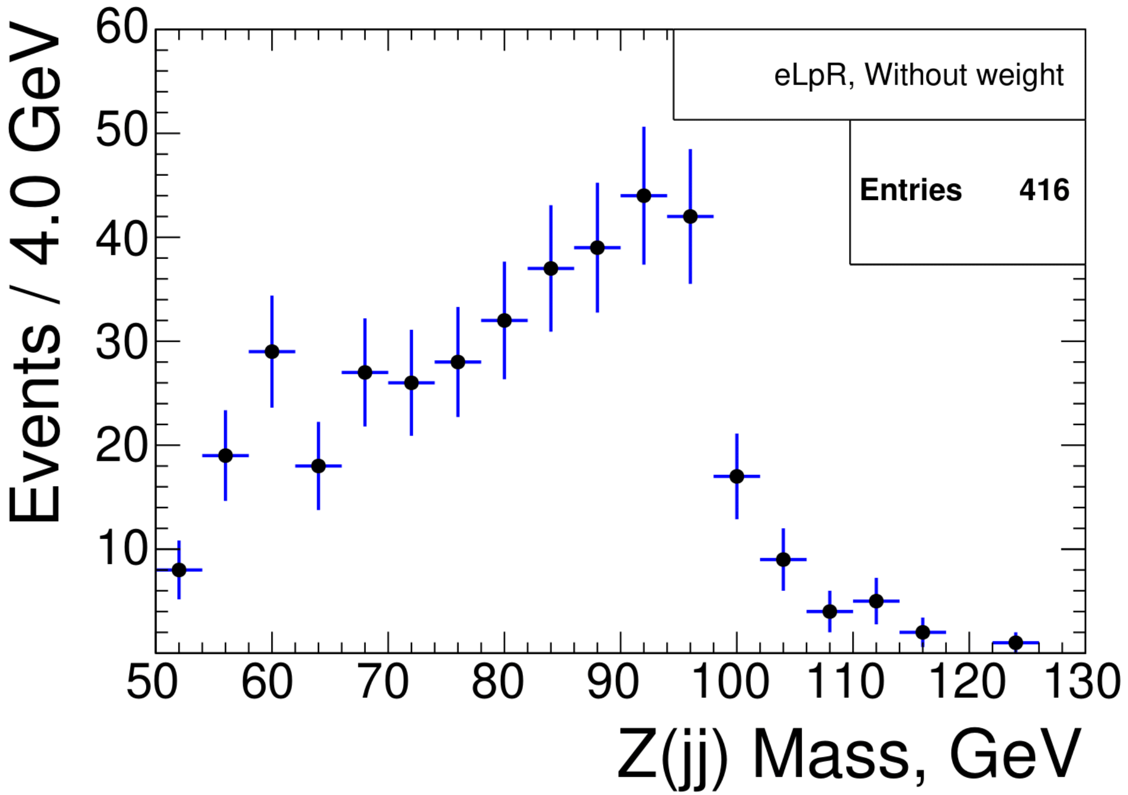
Four channels were studied, corresponding signals and backgrounds were estimated using MC simulation.

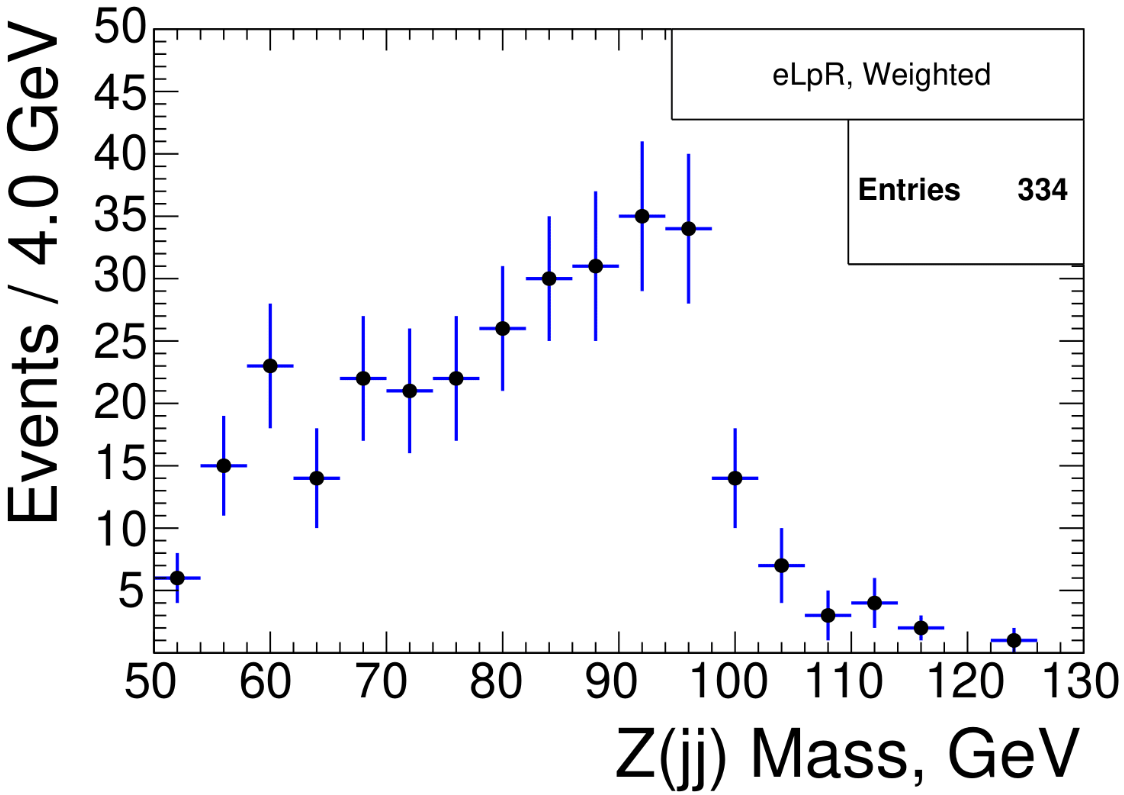
Full significance of this method = 4.4%.

Thank you for attention

Additional information

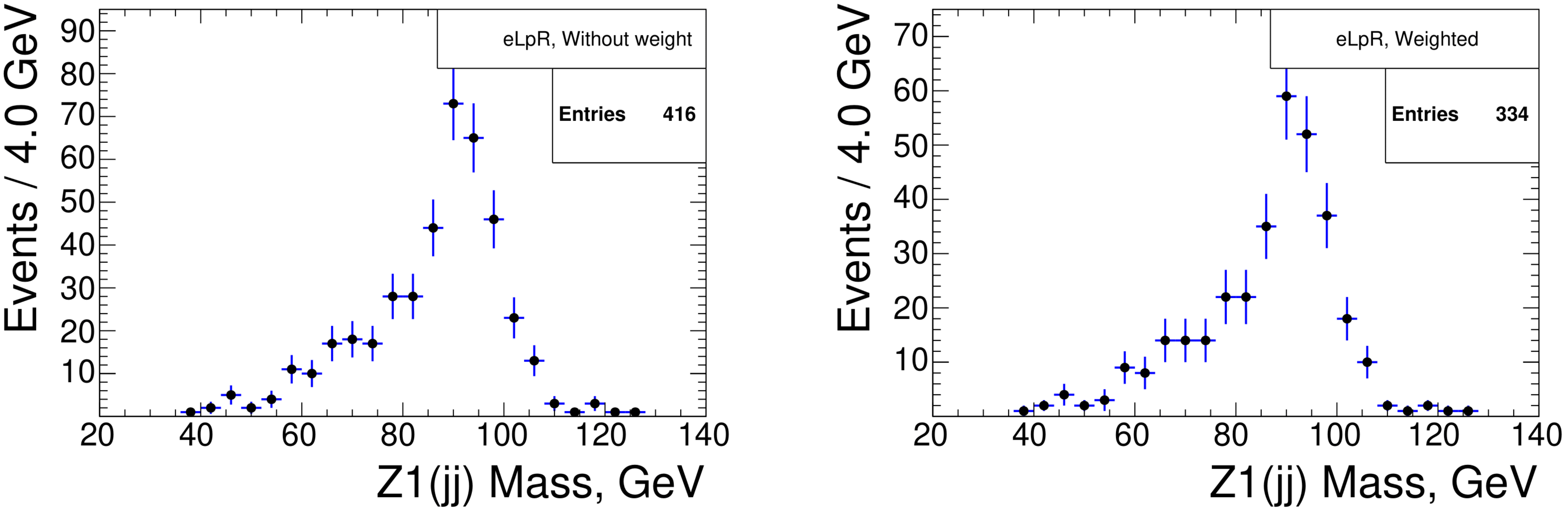
$$Z_1 \to jj, Z \to jj\ , Z^{\star} \to ll$$





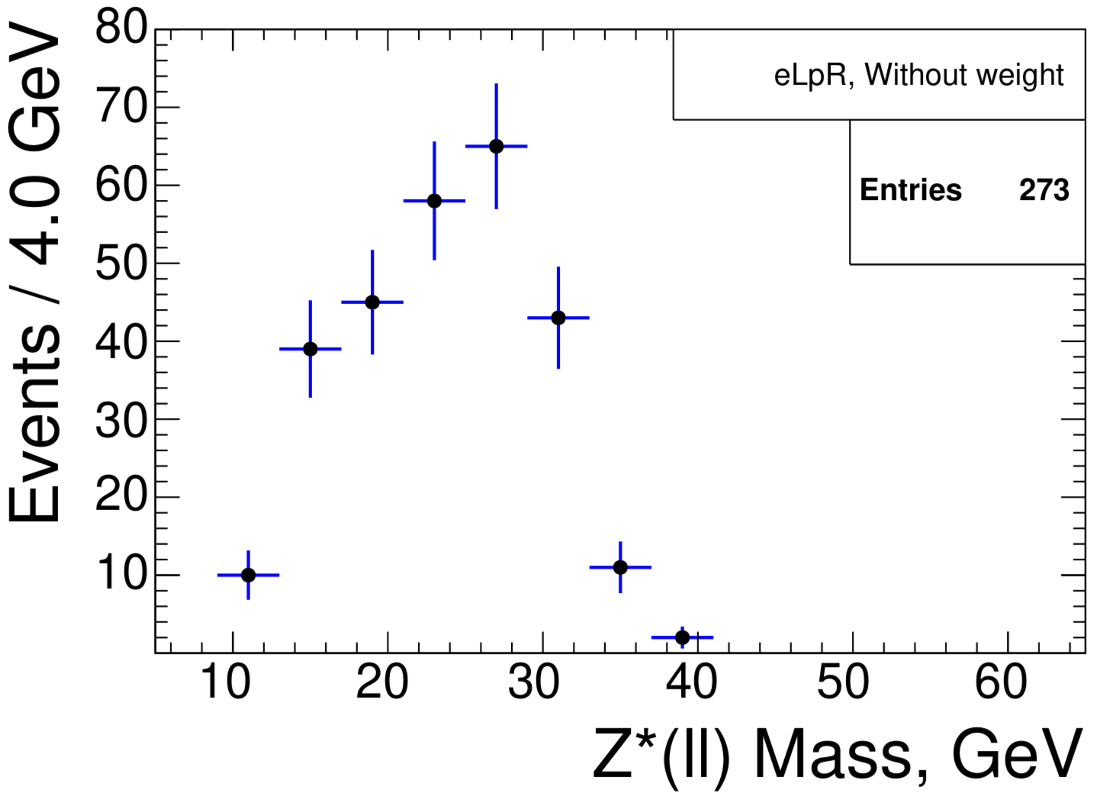
Additional information

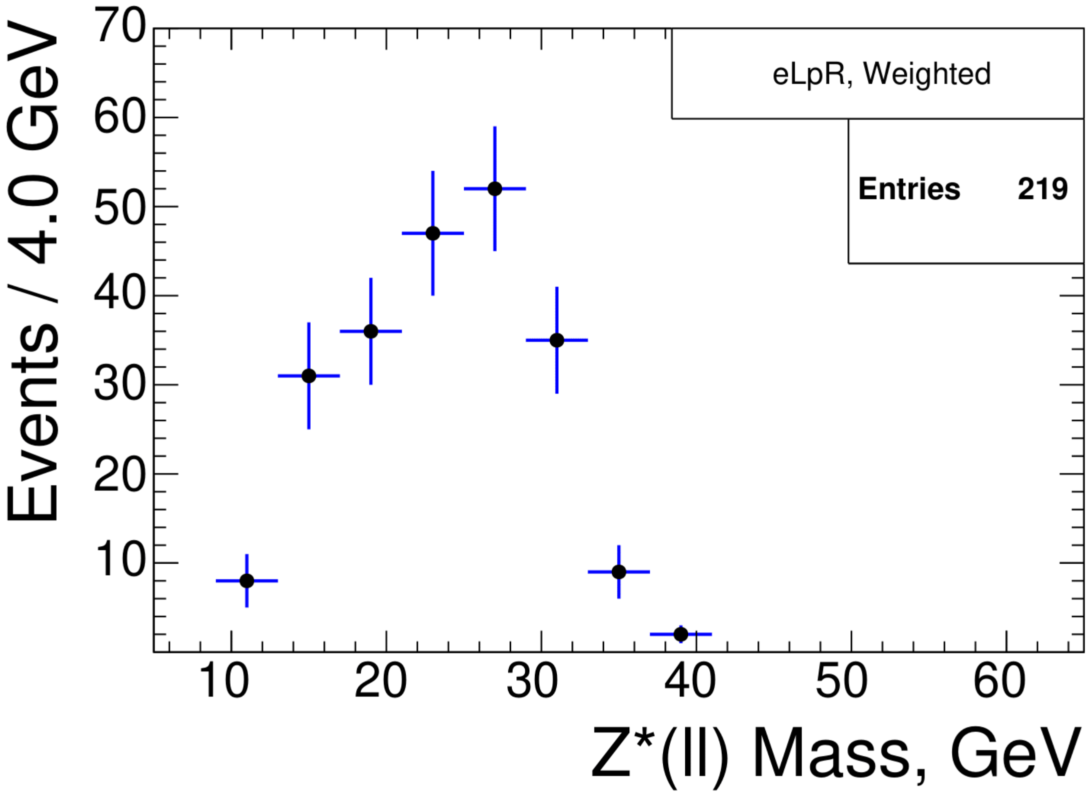
$Z_1 \rightarrow jj, Z \rightarrow jj\ , Z^{\star} \rightarrow ll$



Additional information

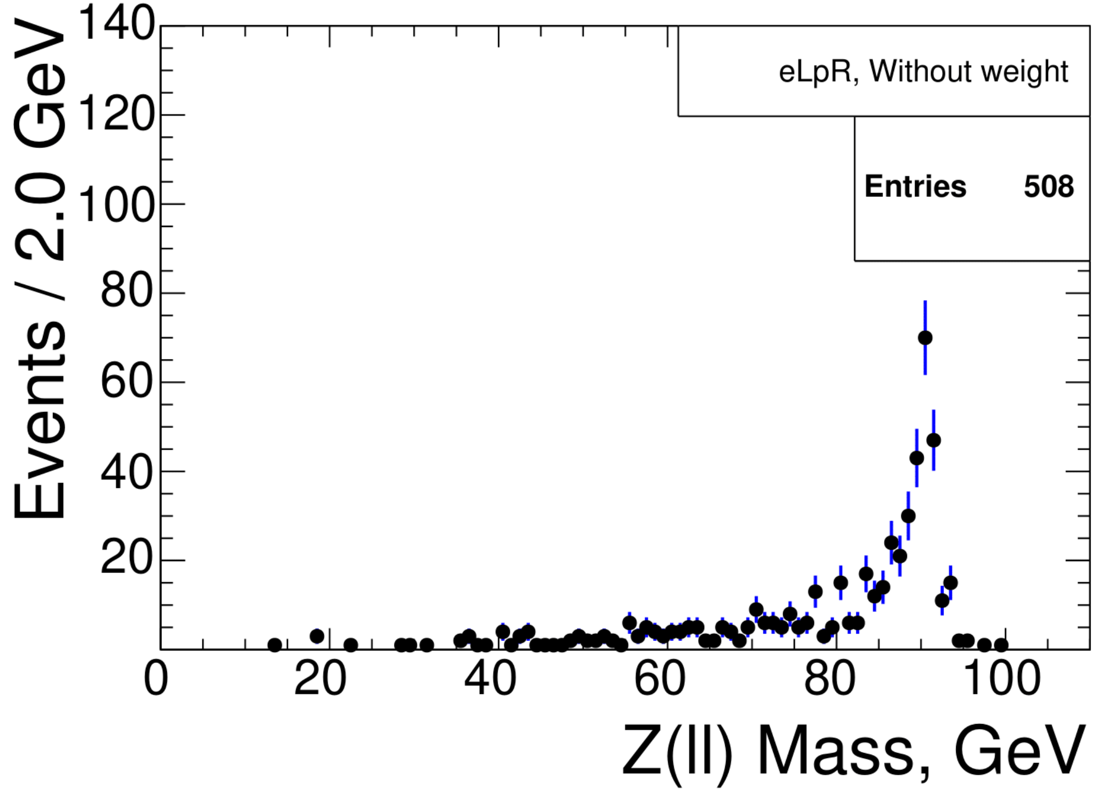
$$Z_1 \rightarrow jj, Z \rightarrow jj\ , Z^{\star} \rightarrow ll$$

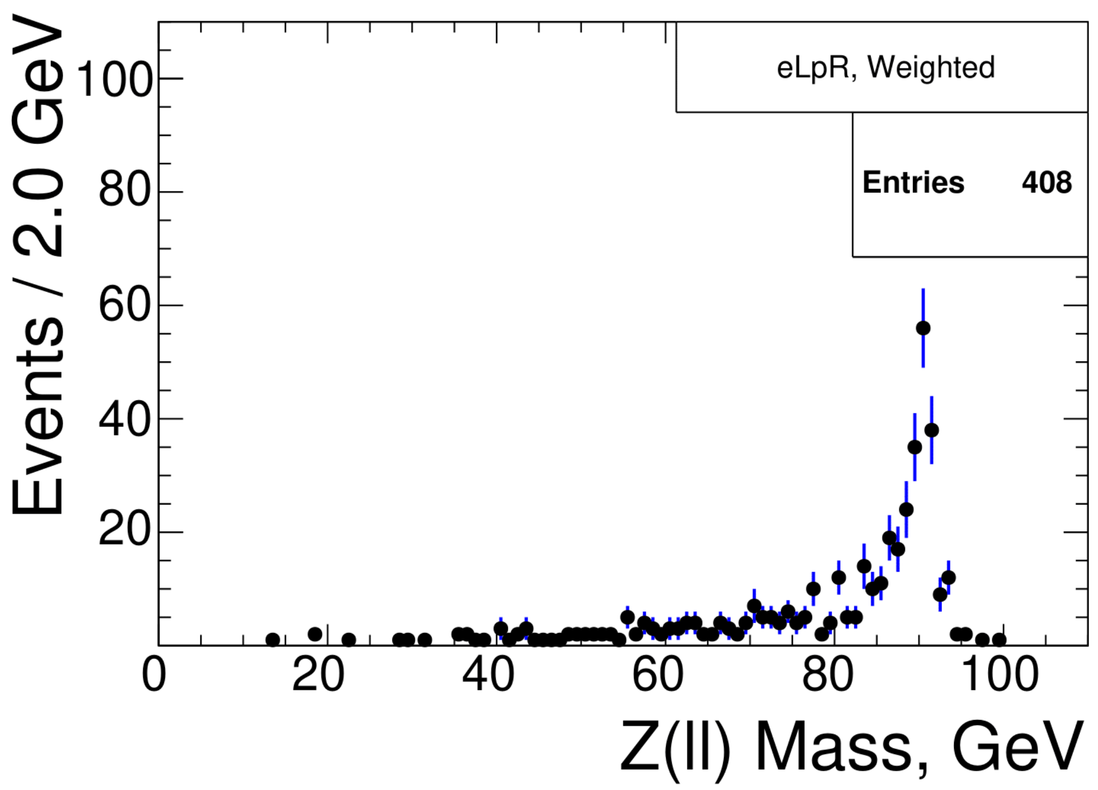




Additional information

$Z_1 \to jj, Z \to ll\ , Z^{\star} \to jj$





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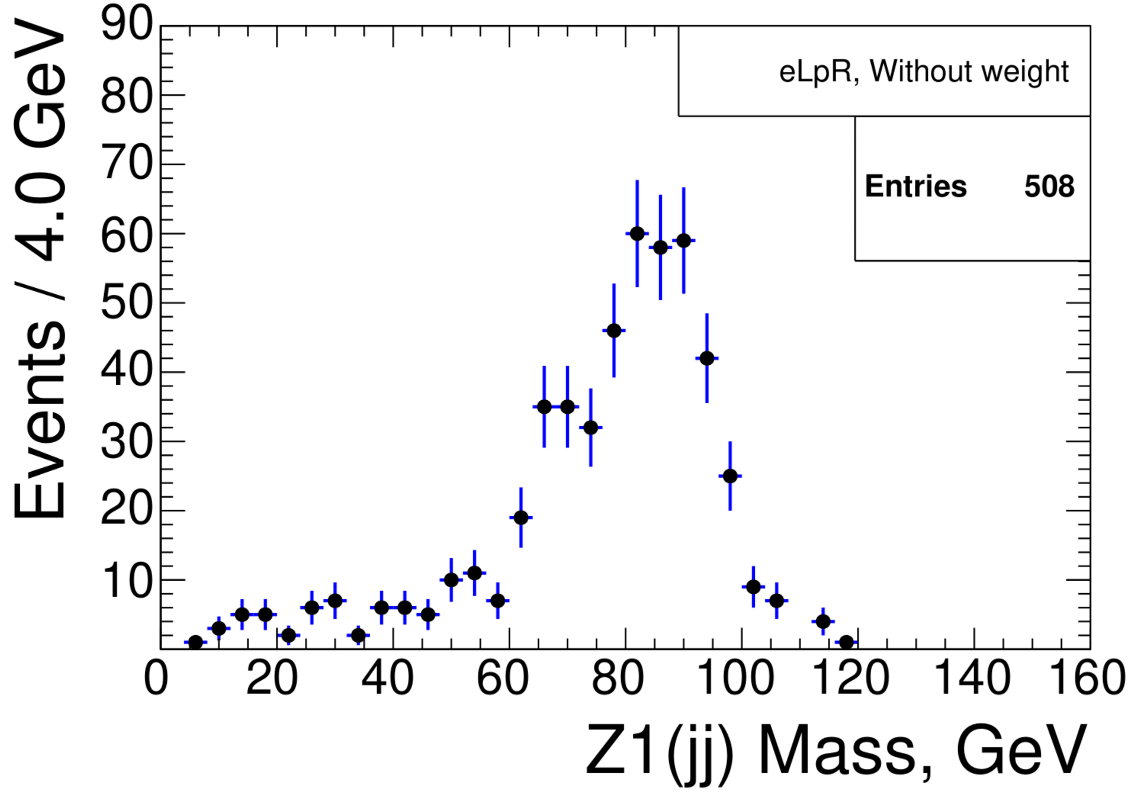

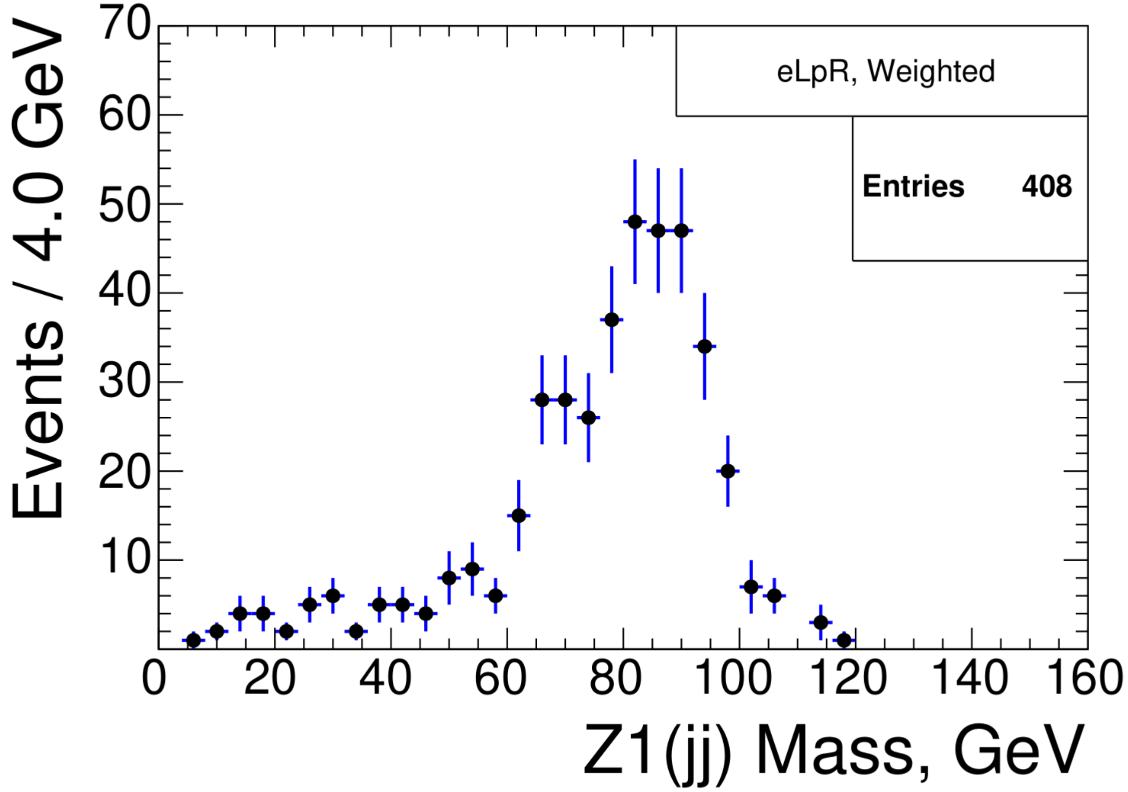

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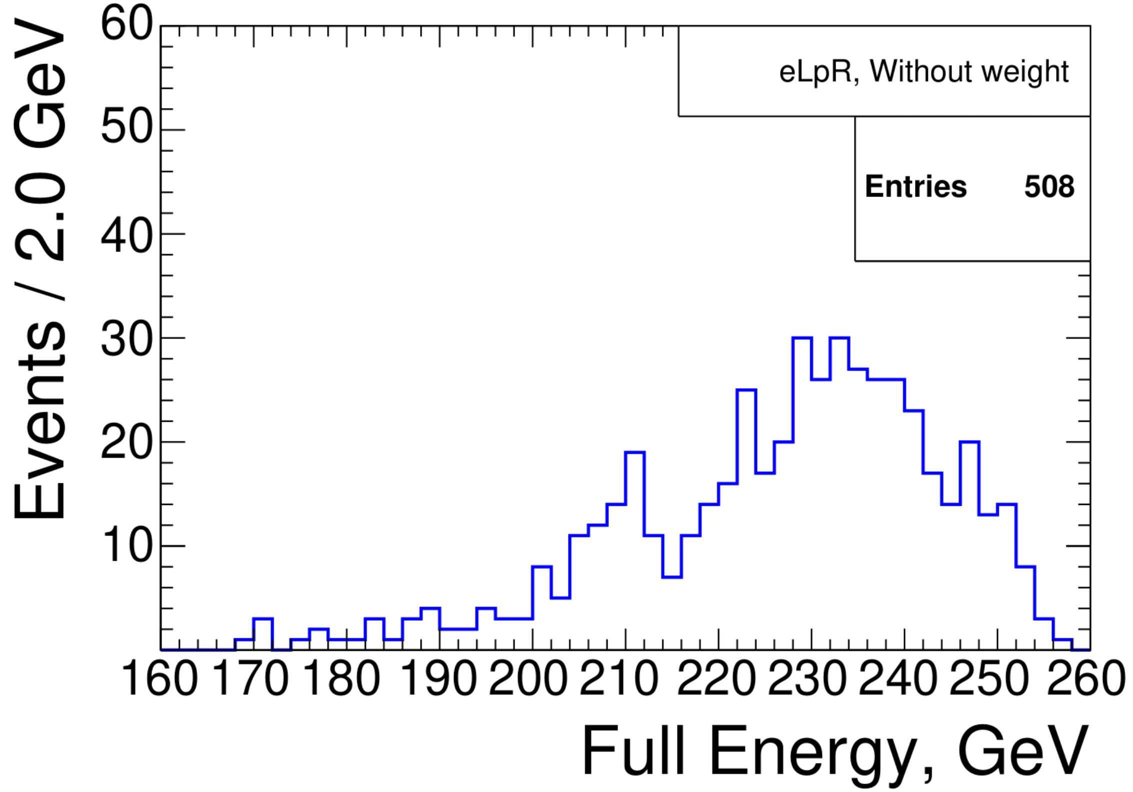

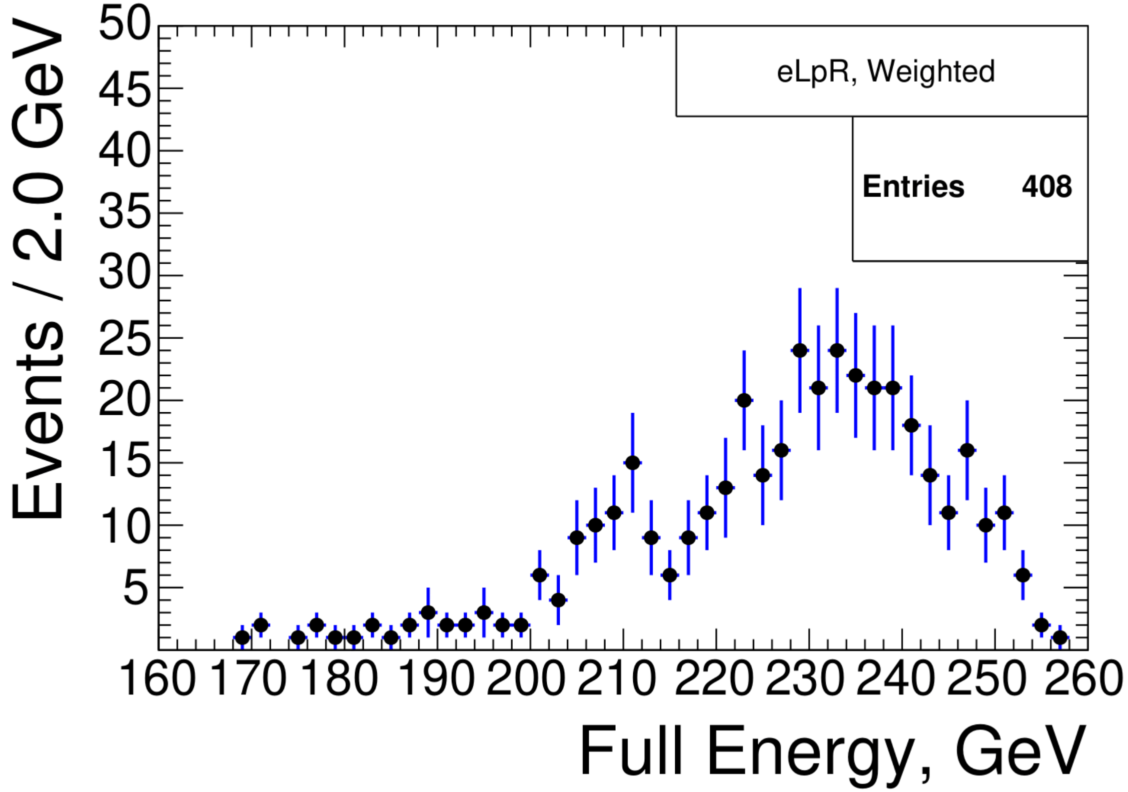

Additional information

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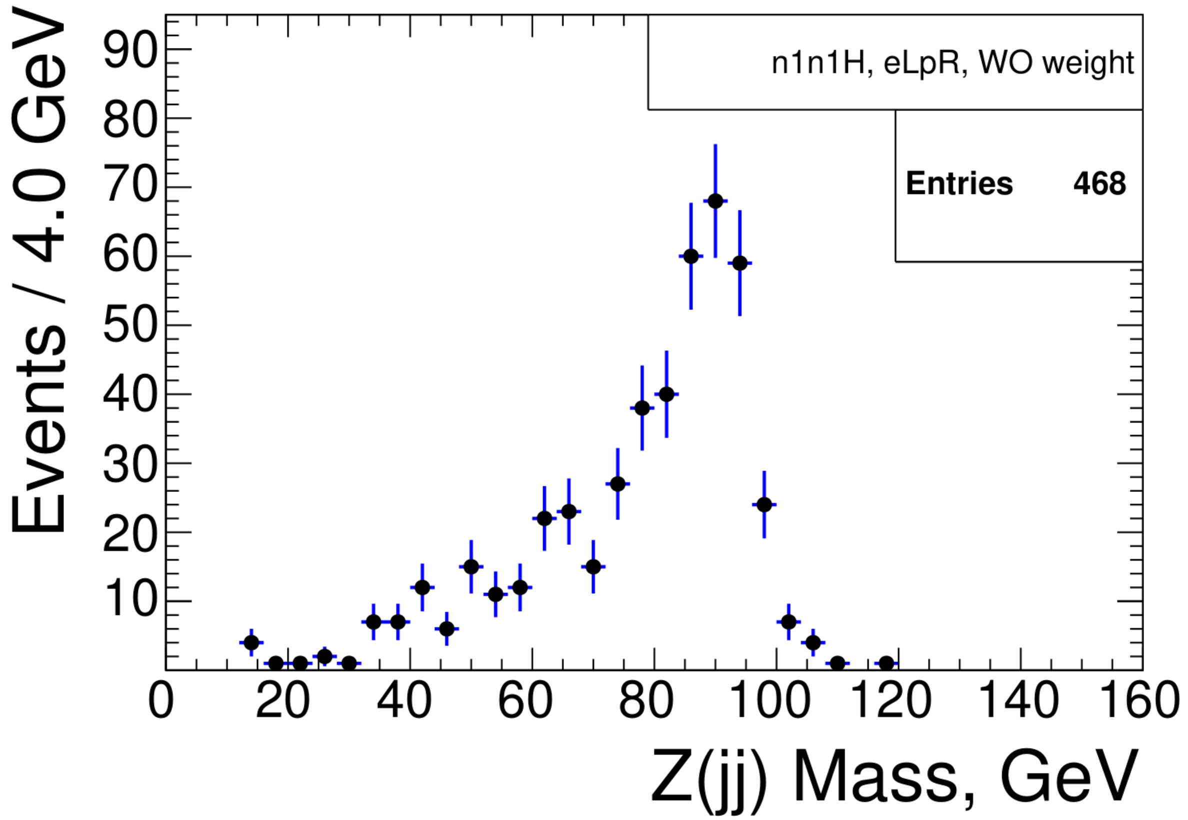
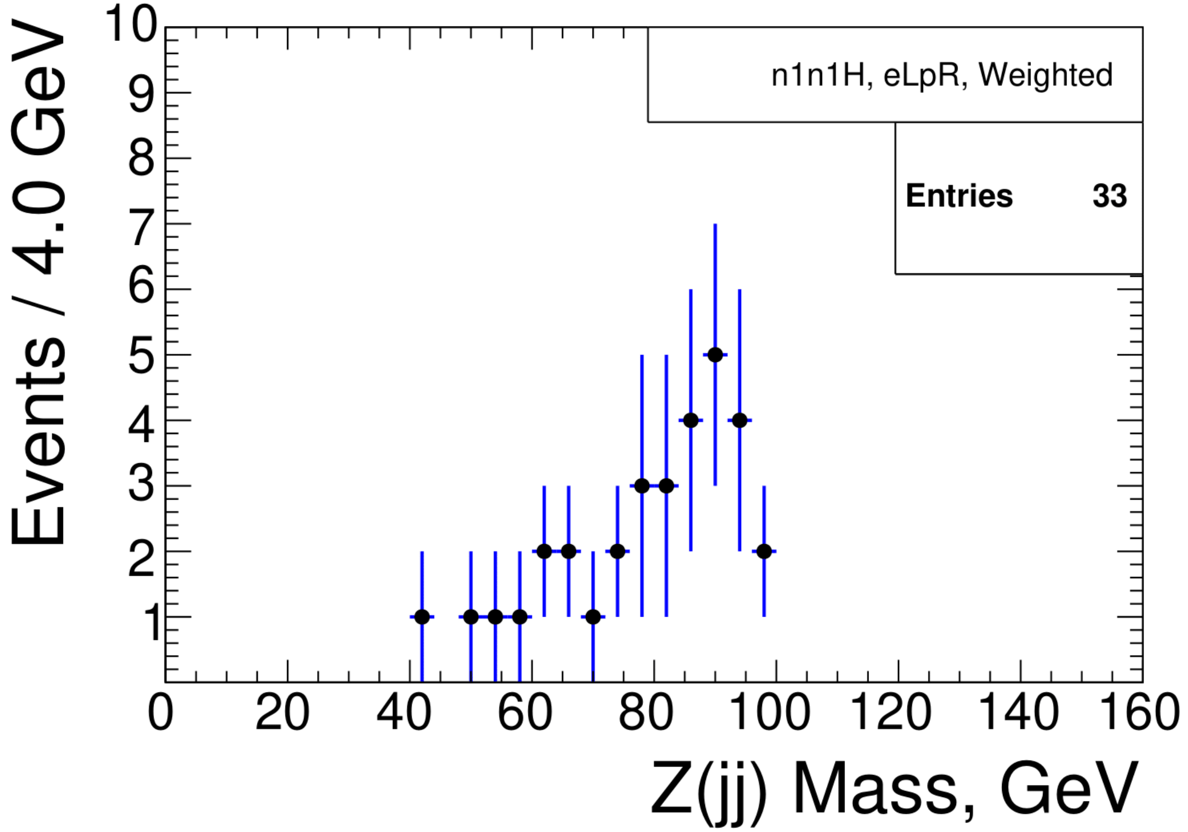
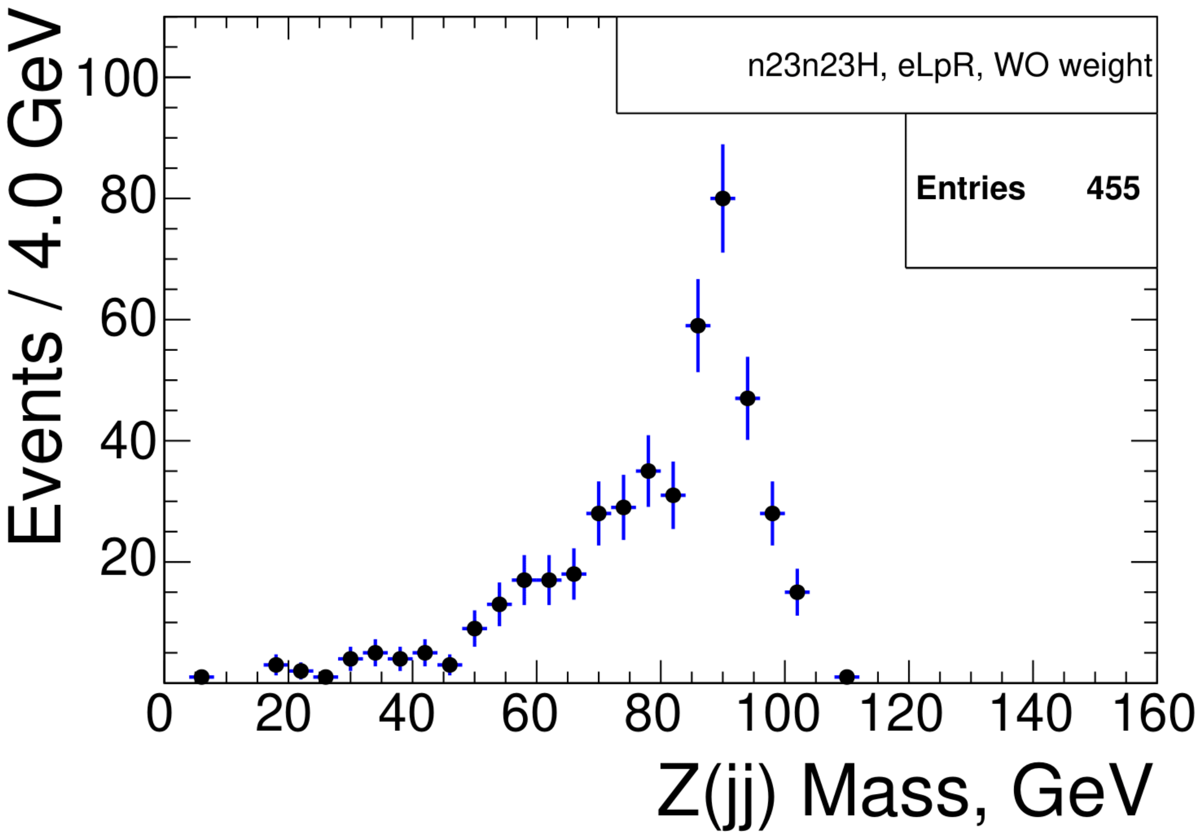
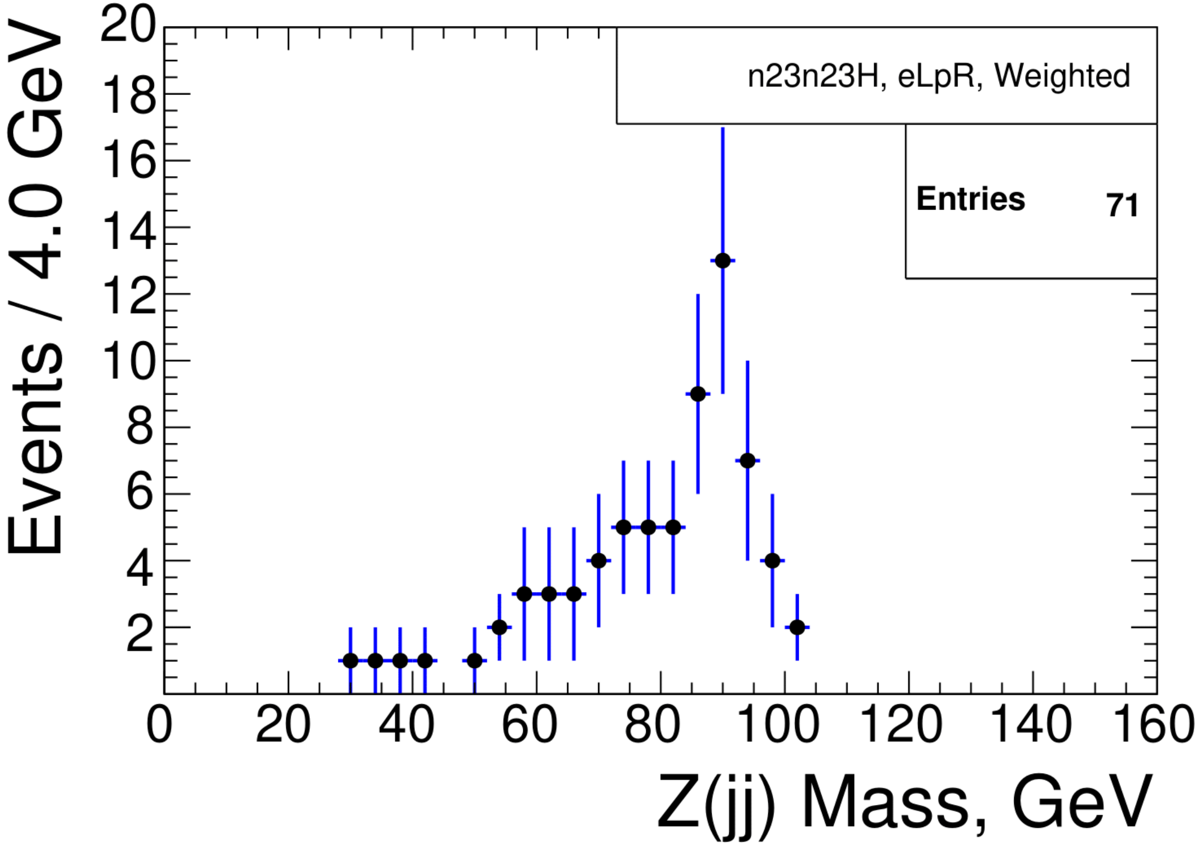




Additional information

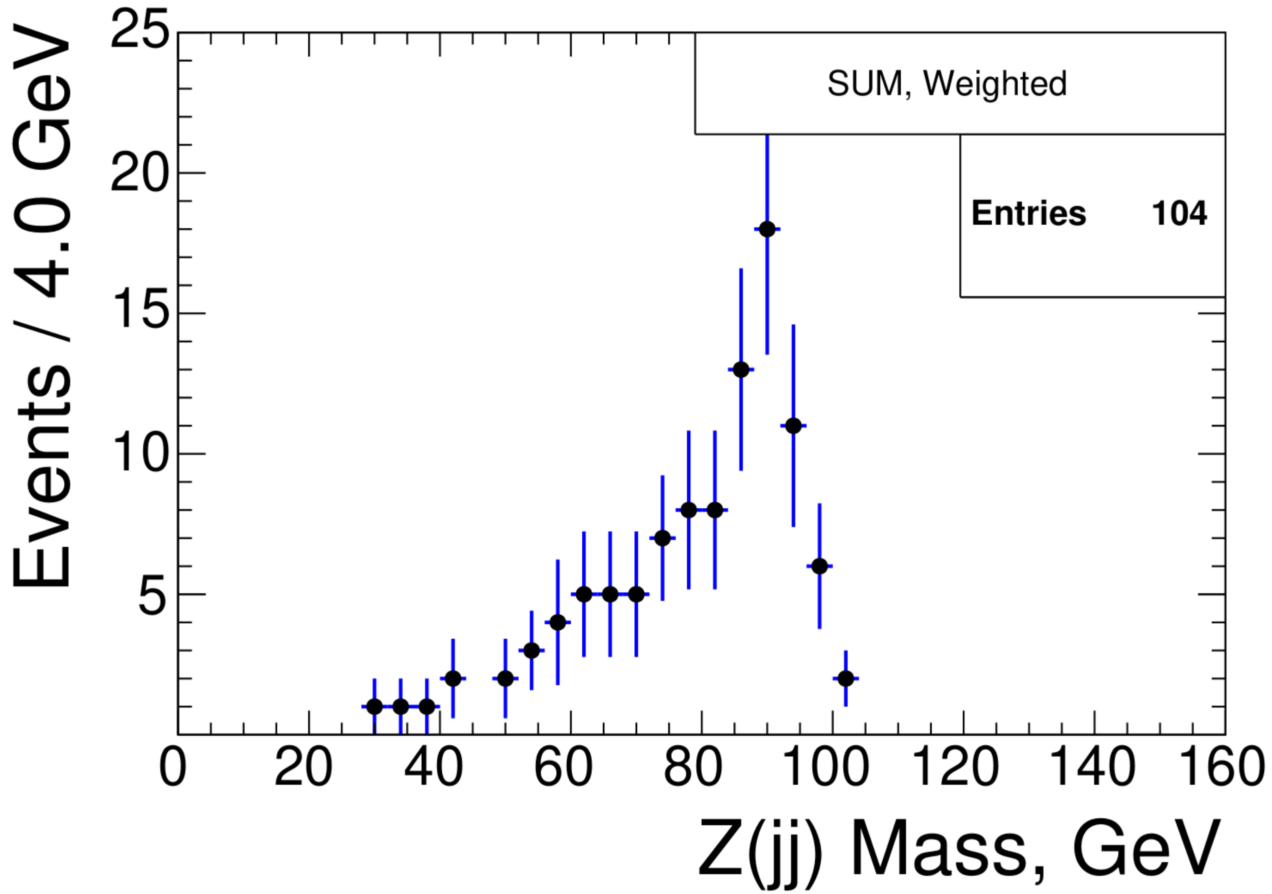
$$Z_1 \rightarrow \nu_{\mu,\tau}\nu_{\mu,\tau}\ ,\ Z \rightarrow jj\ ,\ Z^{\star} \rightarrow ll$$





Additional information

$$Z_1 \to \nu\nu, Z \to jj\ , Z^{\star} \to ll$$



Additional information

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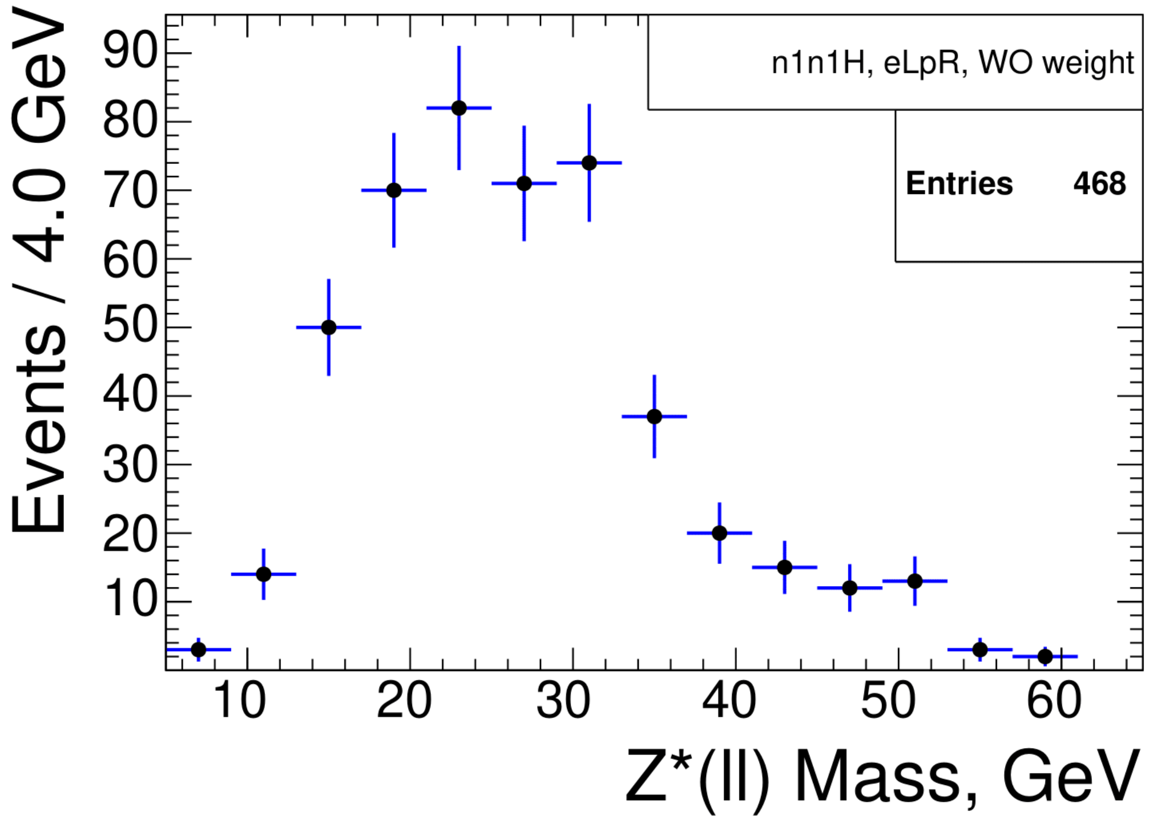

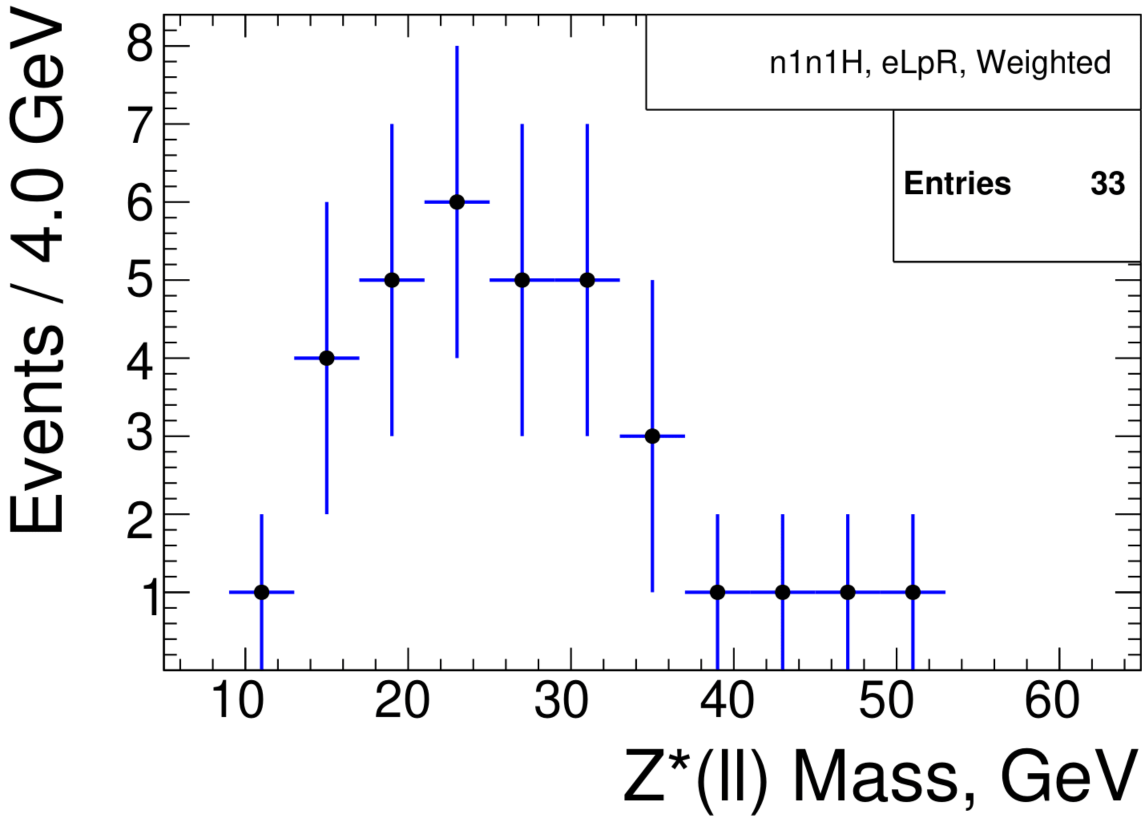

Additional information

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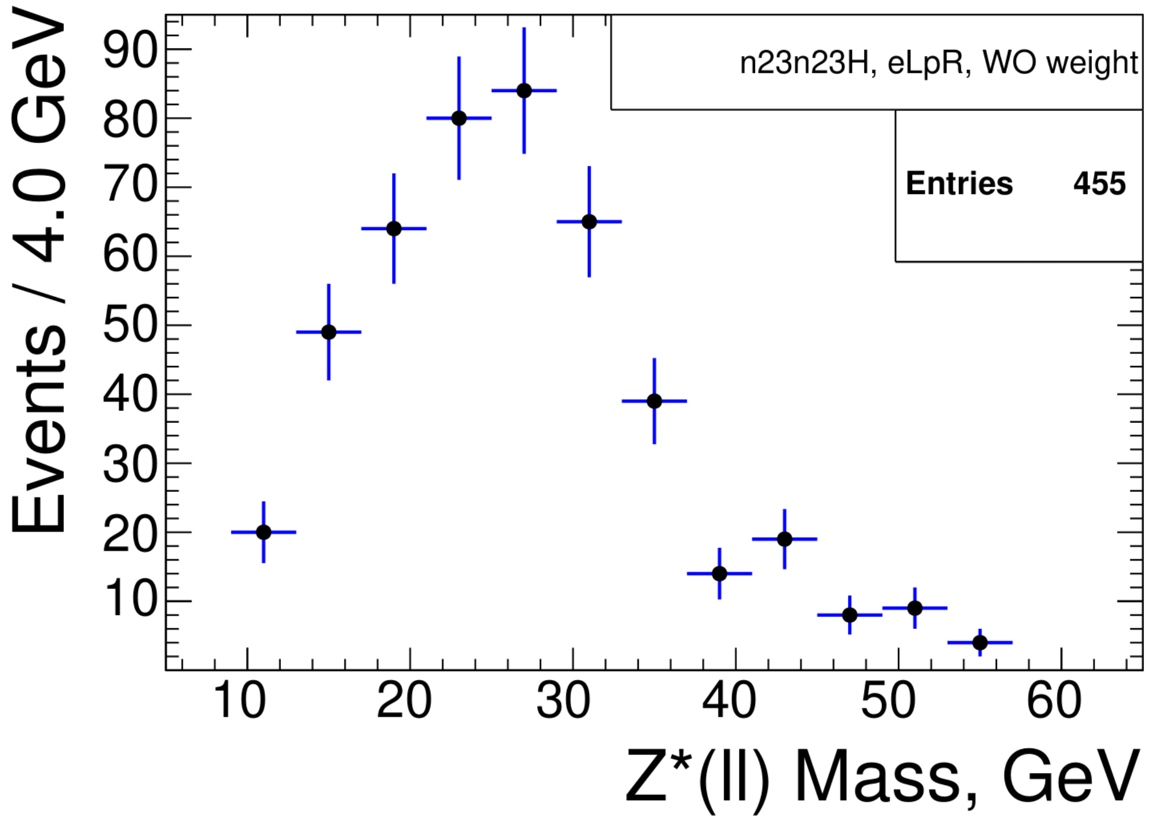
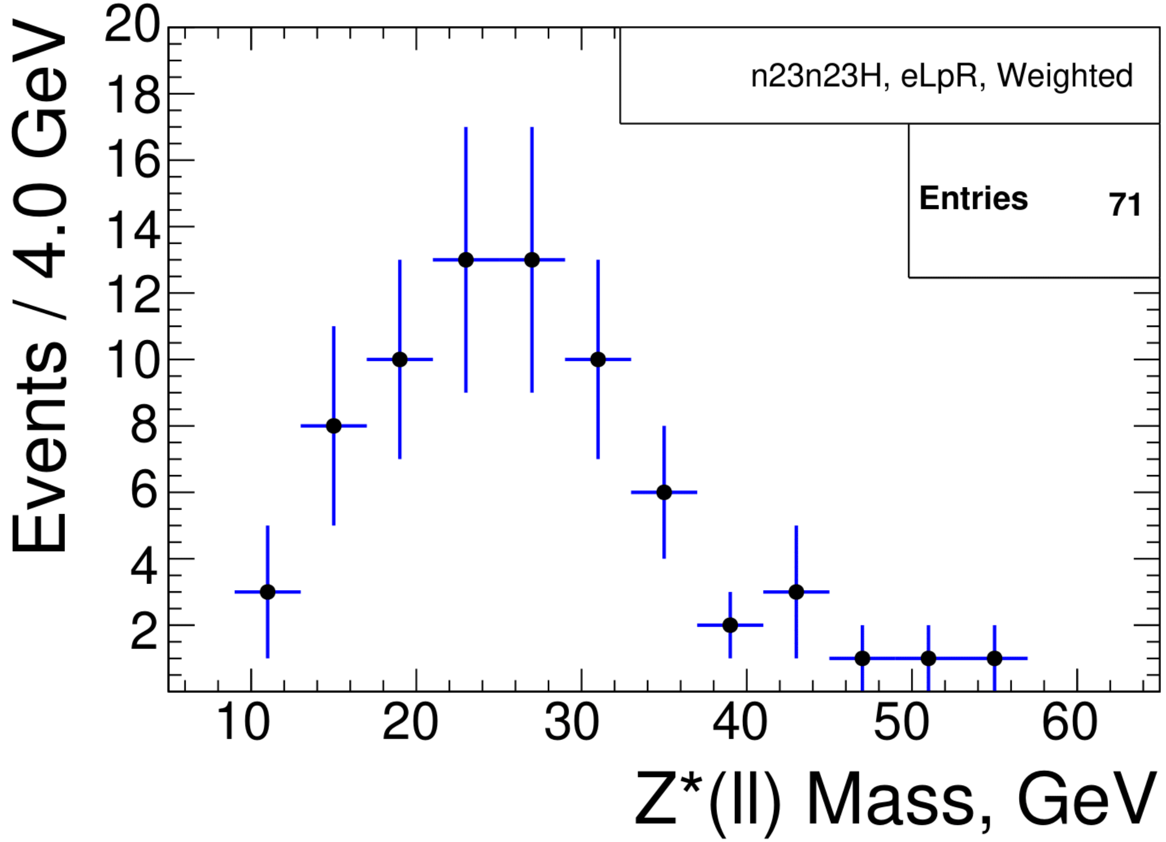
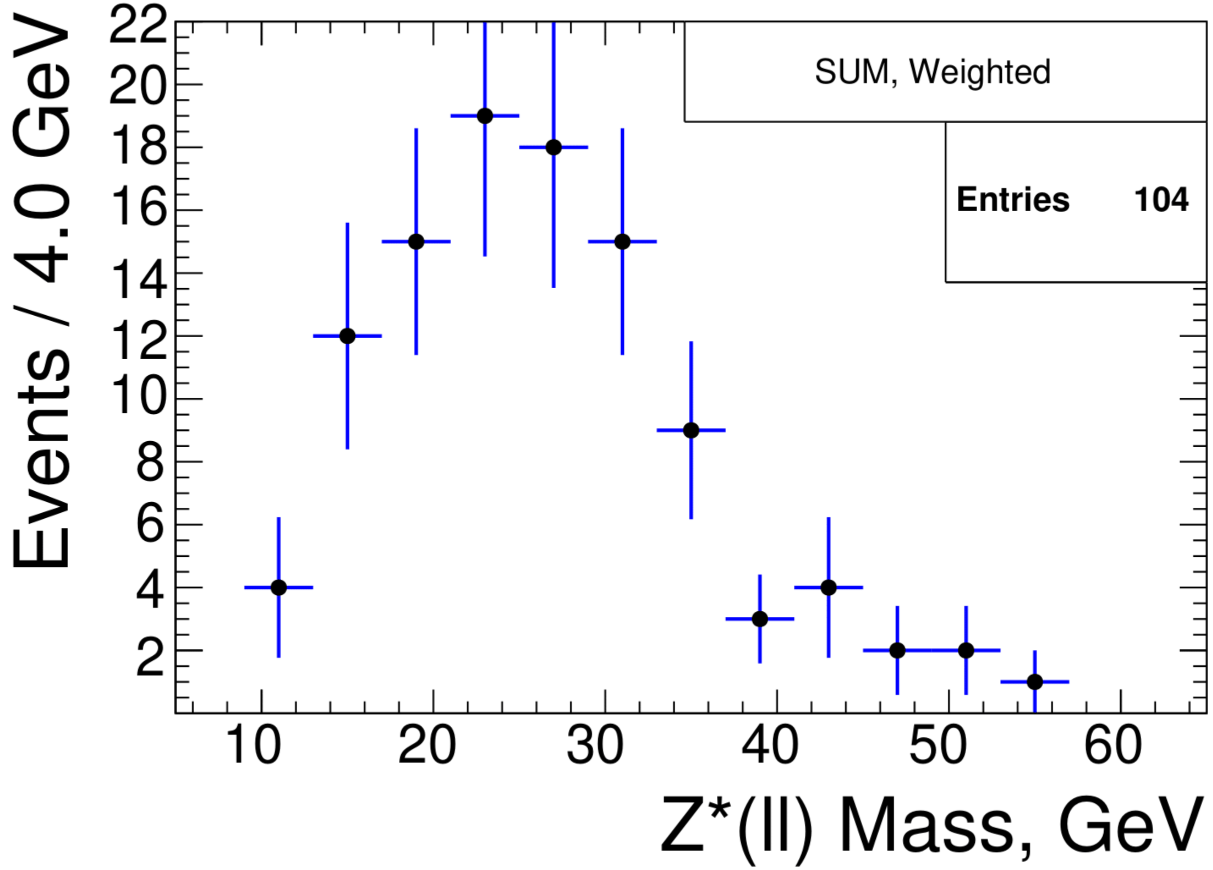




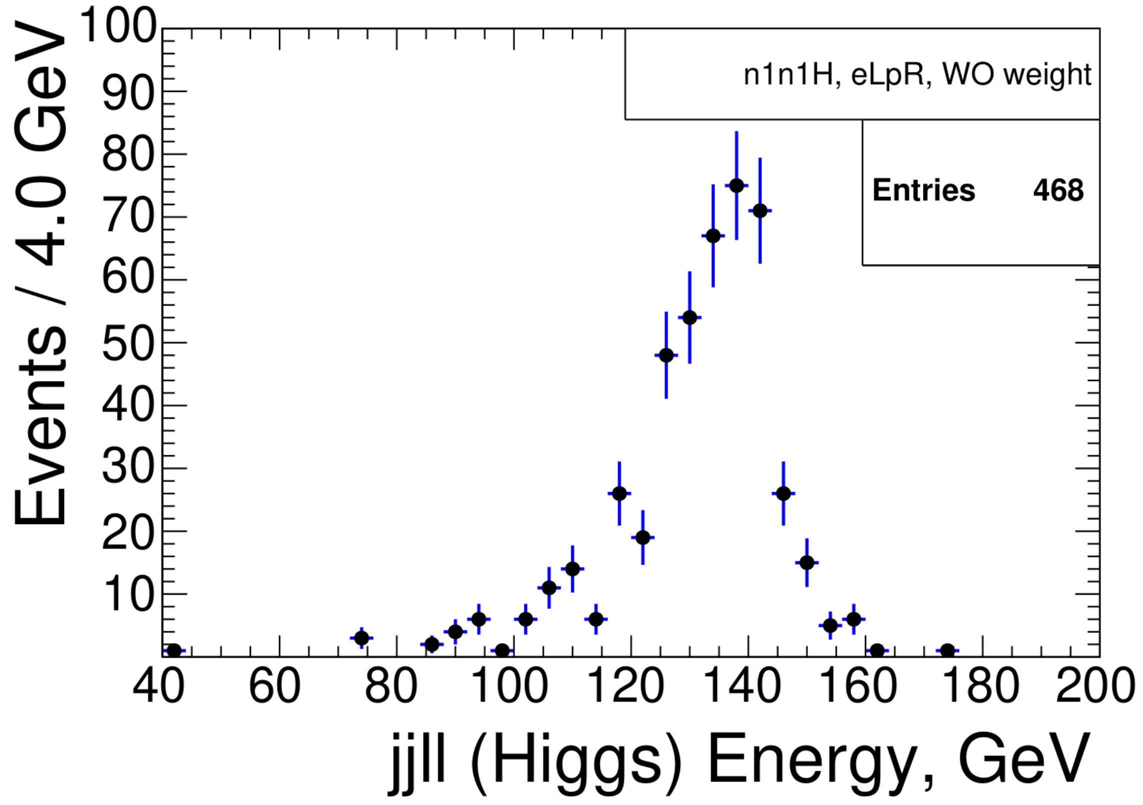
Additional information

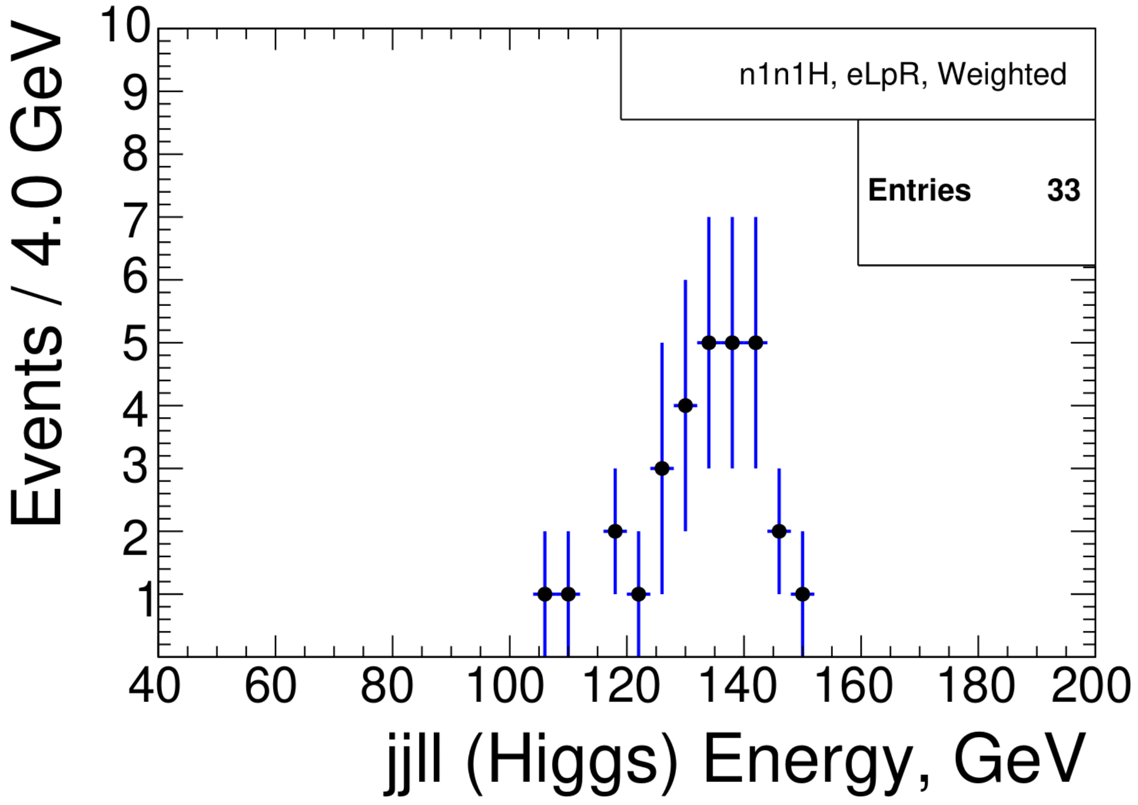
$$Z_1 \to \nu\nu, Z \to jj\ , Z^\star \to ll$$



Additional information

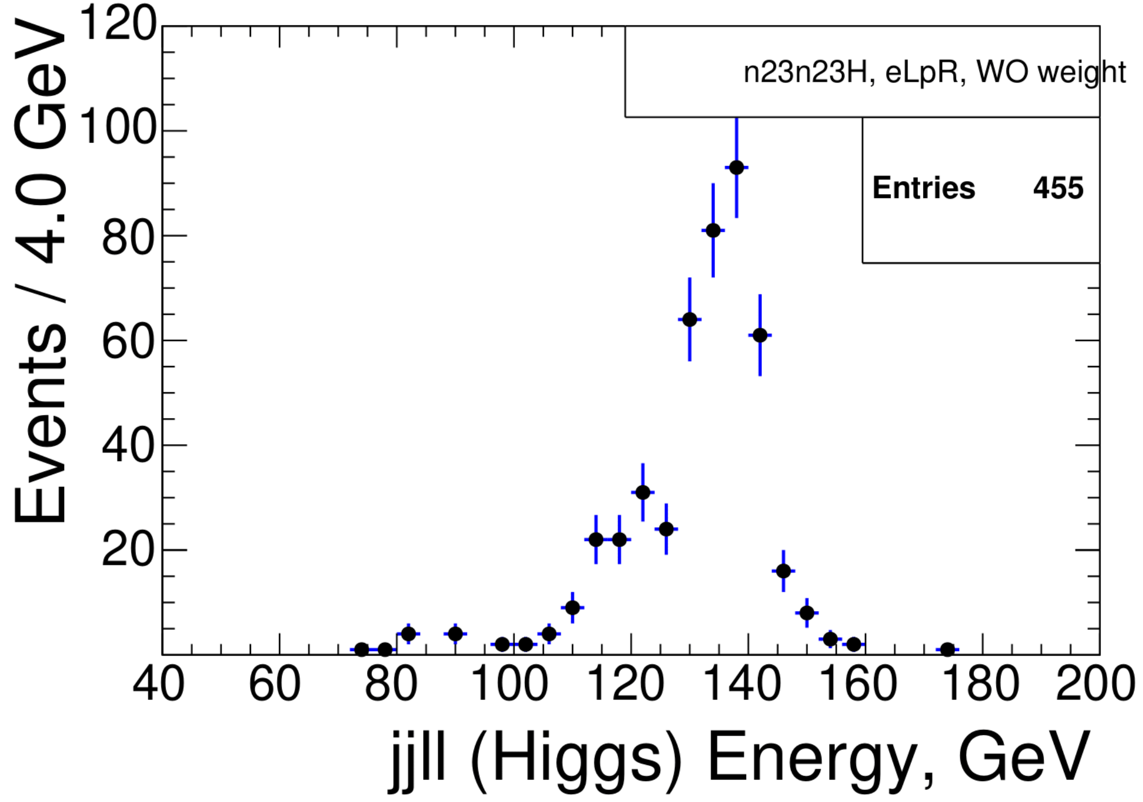
$$Z_1 \to \nu_e \nu_e \,,\, Z \to jj \,,\, Z^{\star} \to ll$$

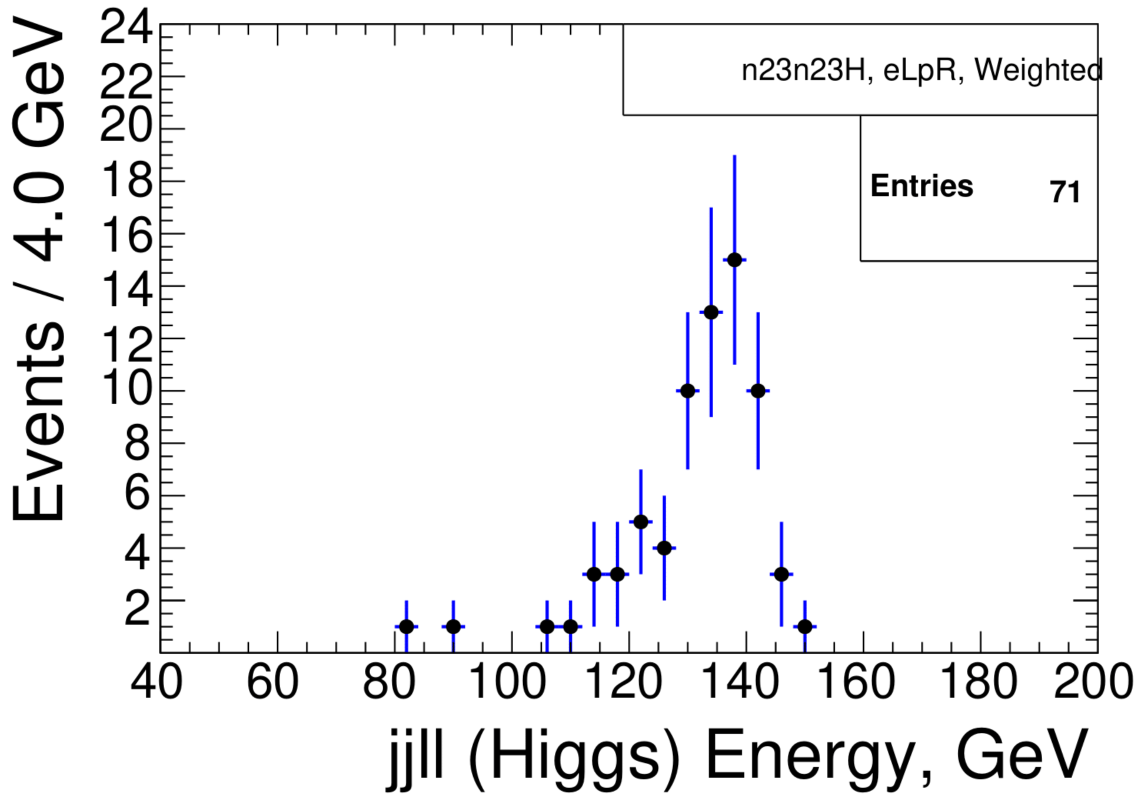




Additional information

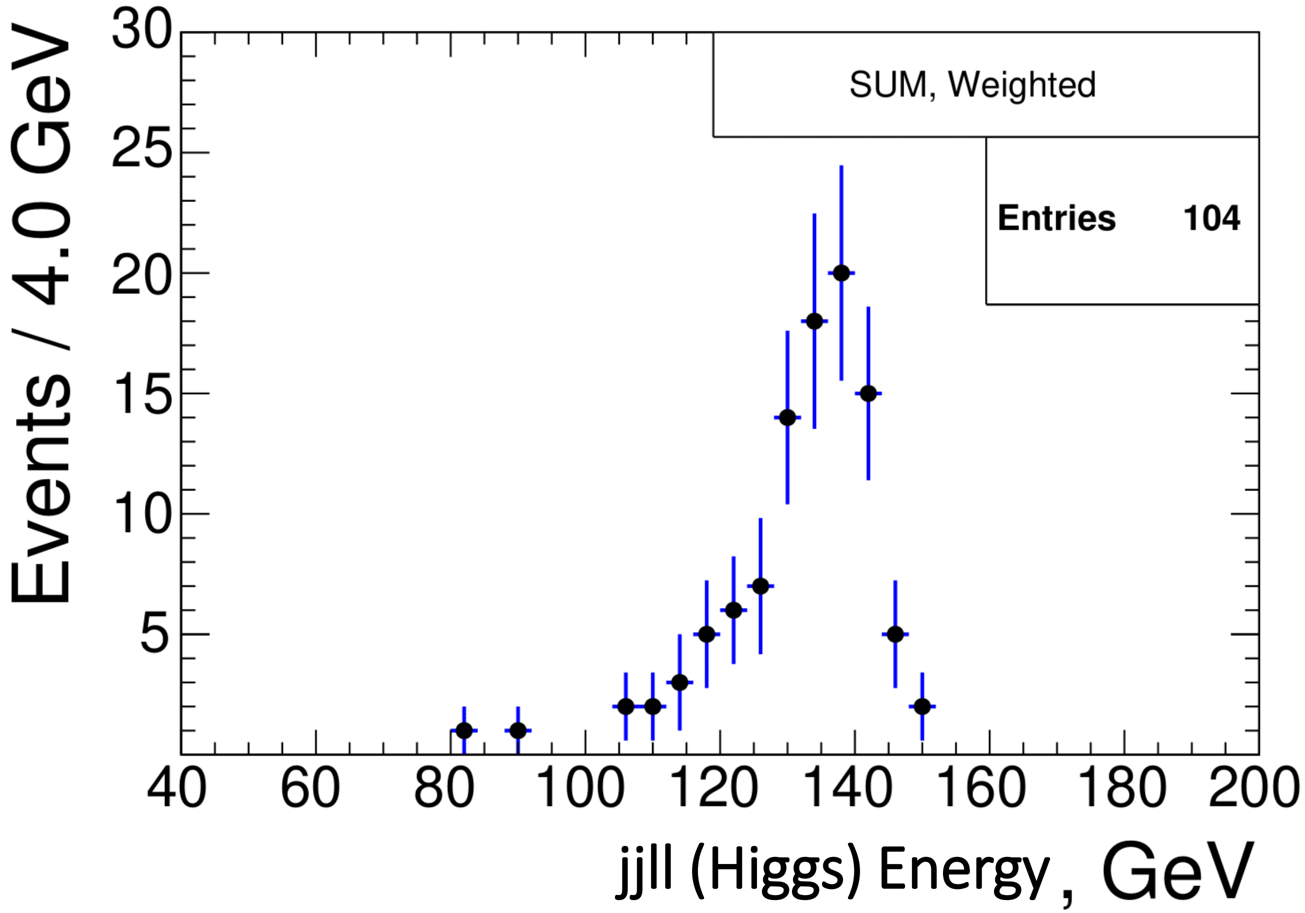
$$Z_1 \to \nu_{\mu,\tau}\nu_{\mu,\tau}, Z \to jj\ , Z^{\star} \to ll$$





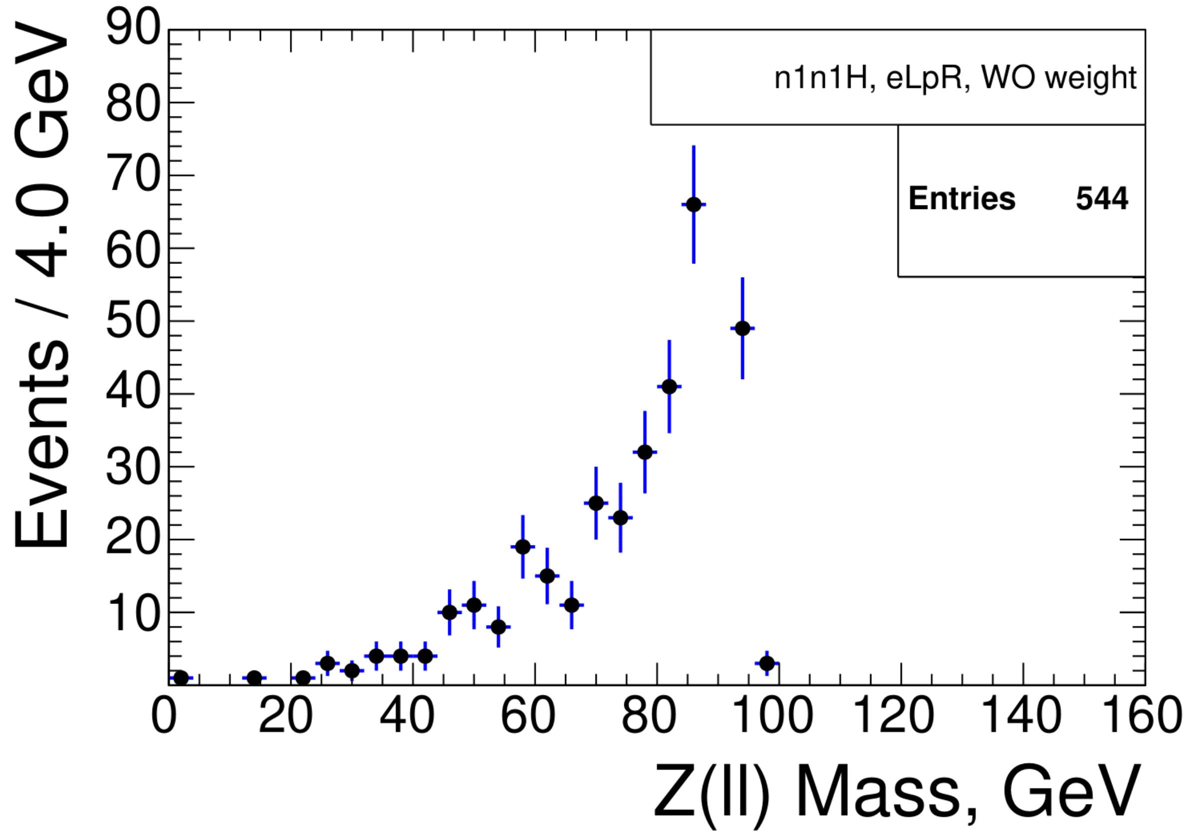
Additional information

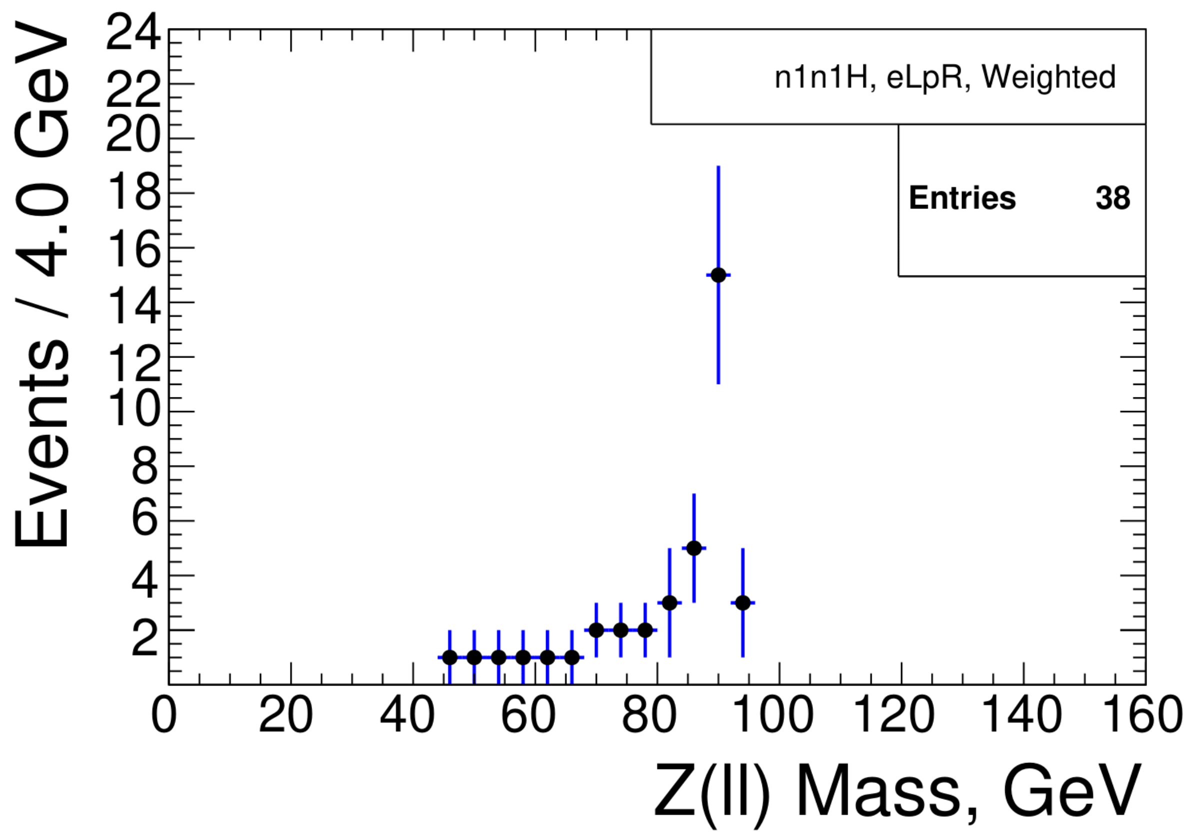
$Z_1 \to \nu\nu, Z \to jj \ , Z^{\star} \to ll$



Additional information

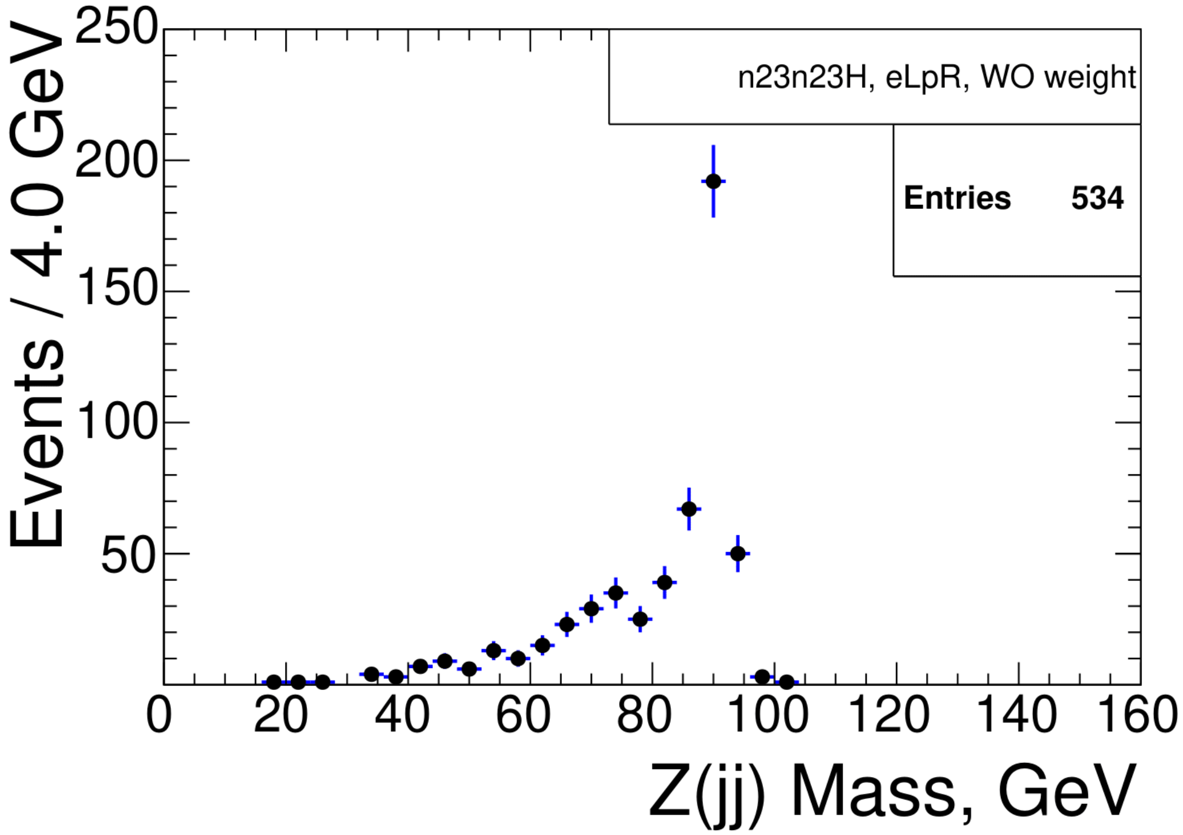
$Z_1 \to \nu_e \nu_e \, , Z \to ll \, , Z^{\star} \to jj$

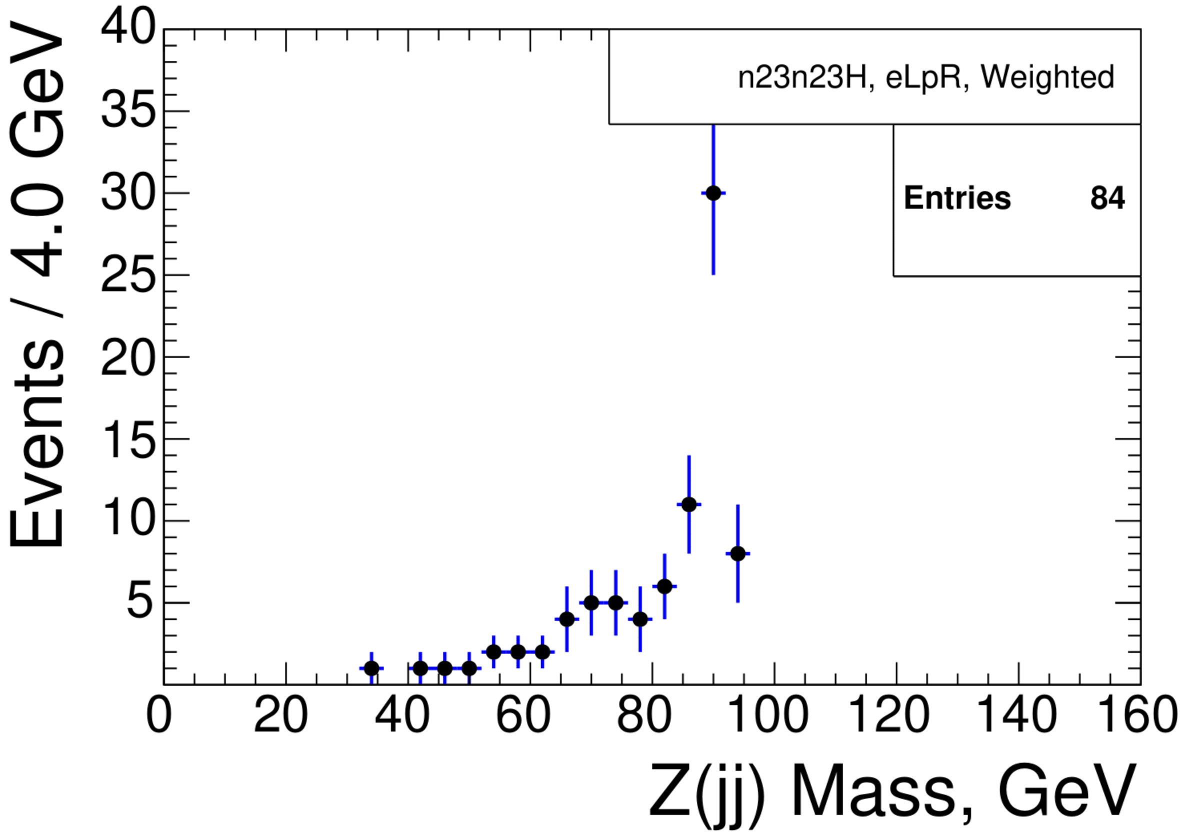




Additional information

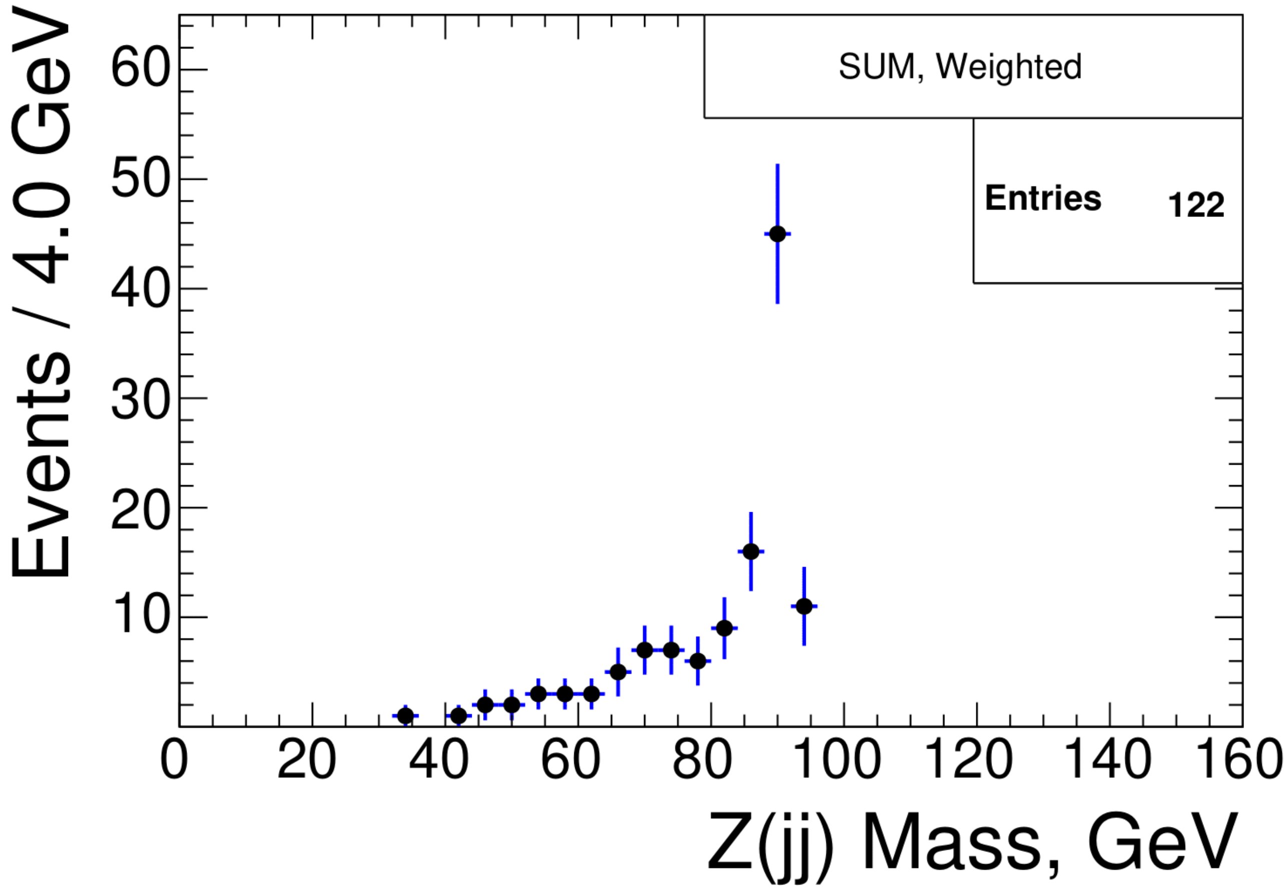
$$Z_1 \to \nu_{\mu,\tau}\nu_{\mu,\tau}, Z \to ll\ , Z^{\star} \to jj$$





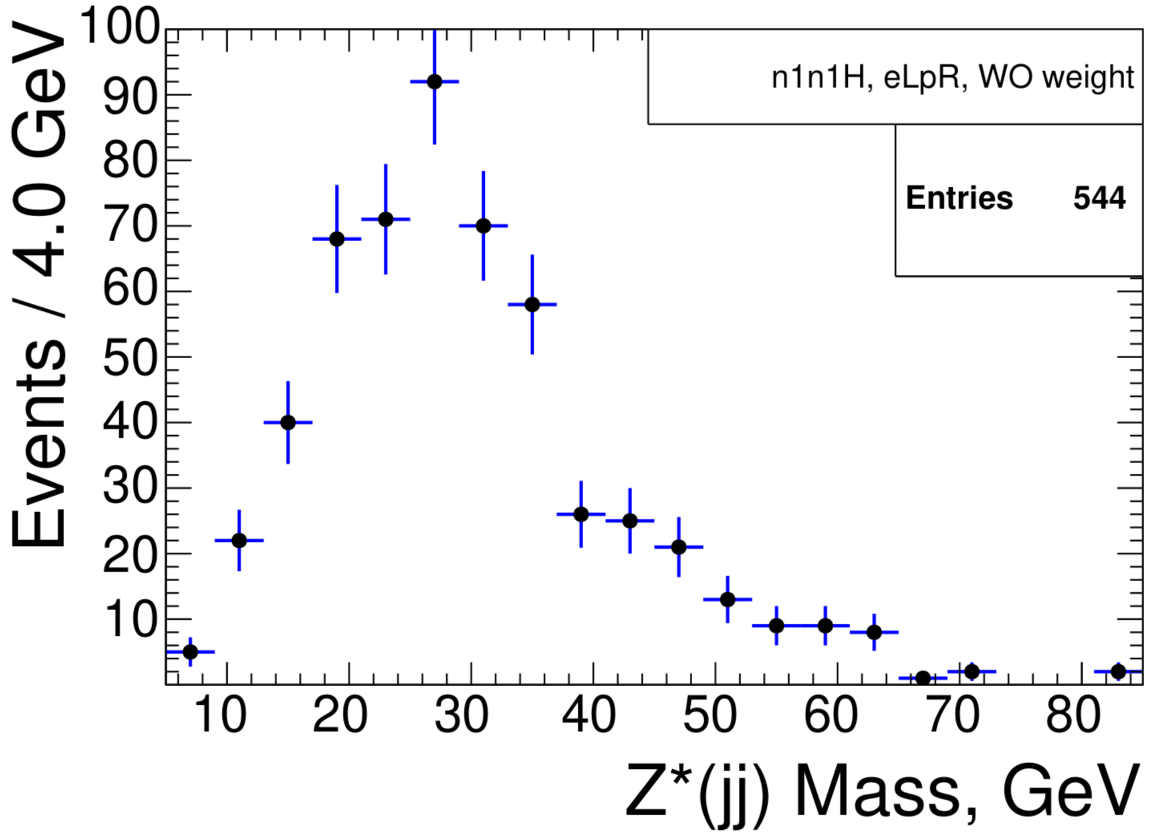
Additional information

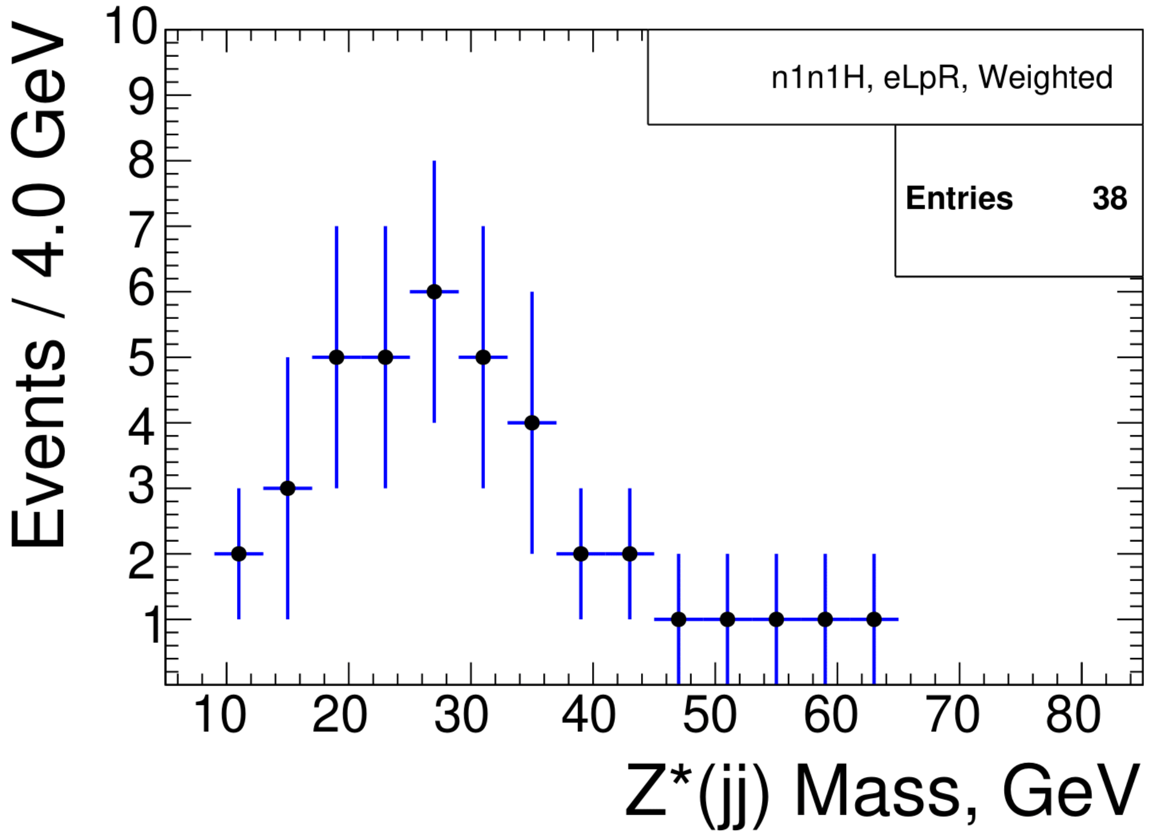
$$Z_1 \to \nu\nu, Z \to ll\,, Z^{\star} \to jj$$



Additional information

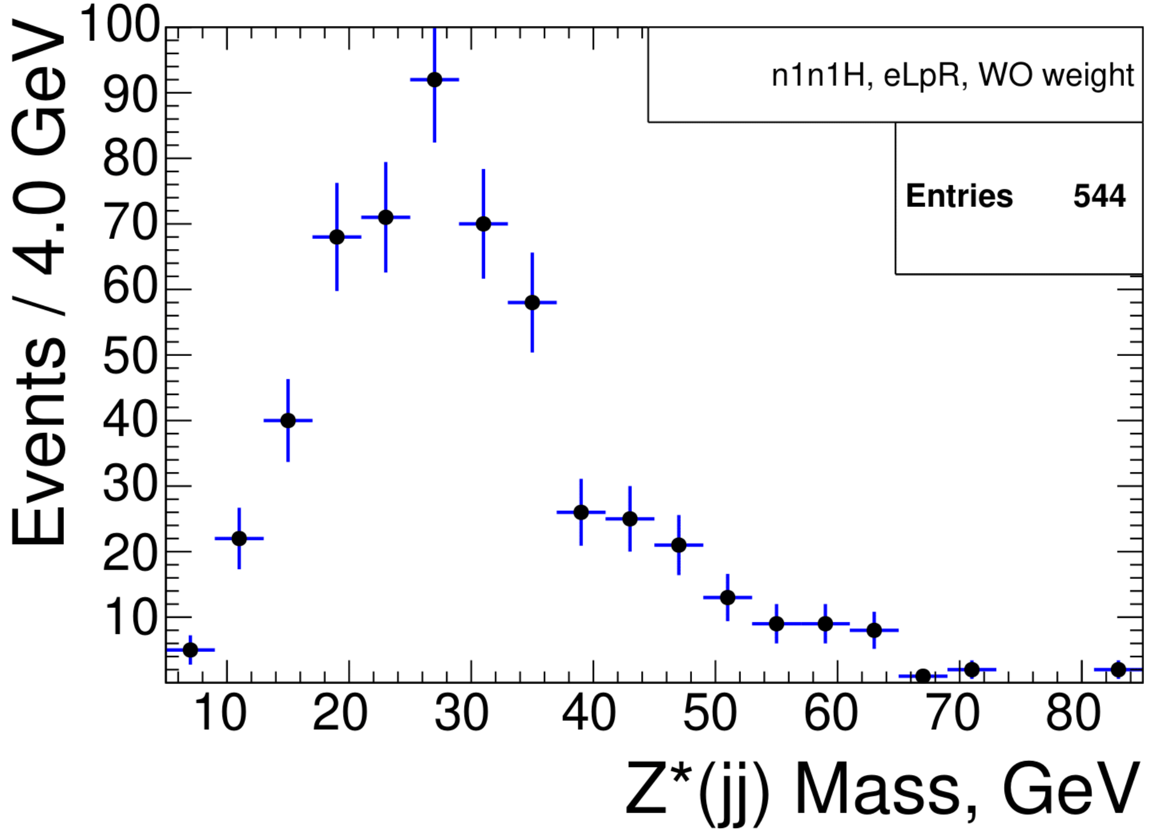
$$Z_1 \rightarrow \nu_e \nu_e\,, Z \rightarrow ll\,, Z^{\star} \rightarrow jj$$

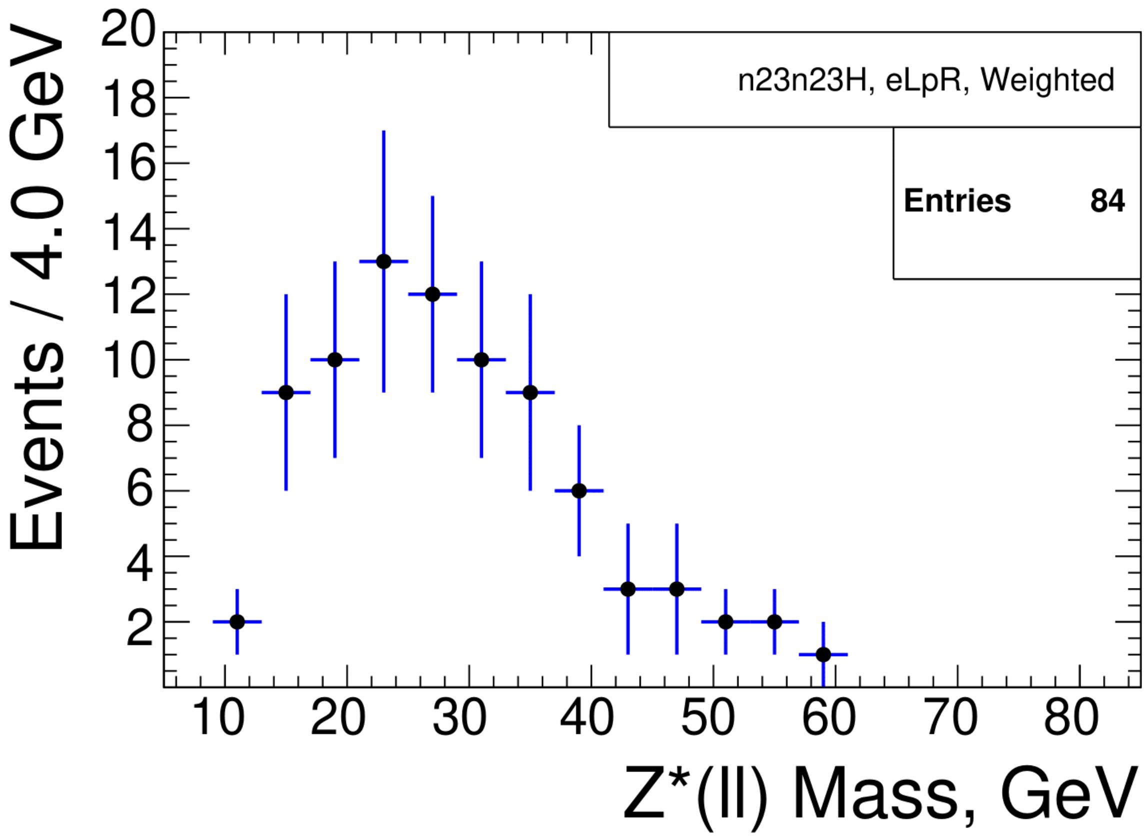




Additional information

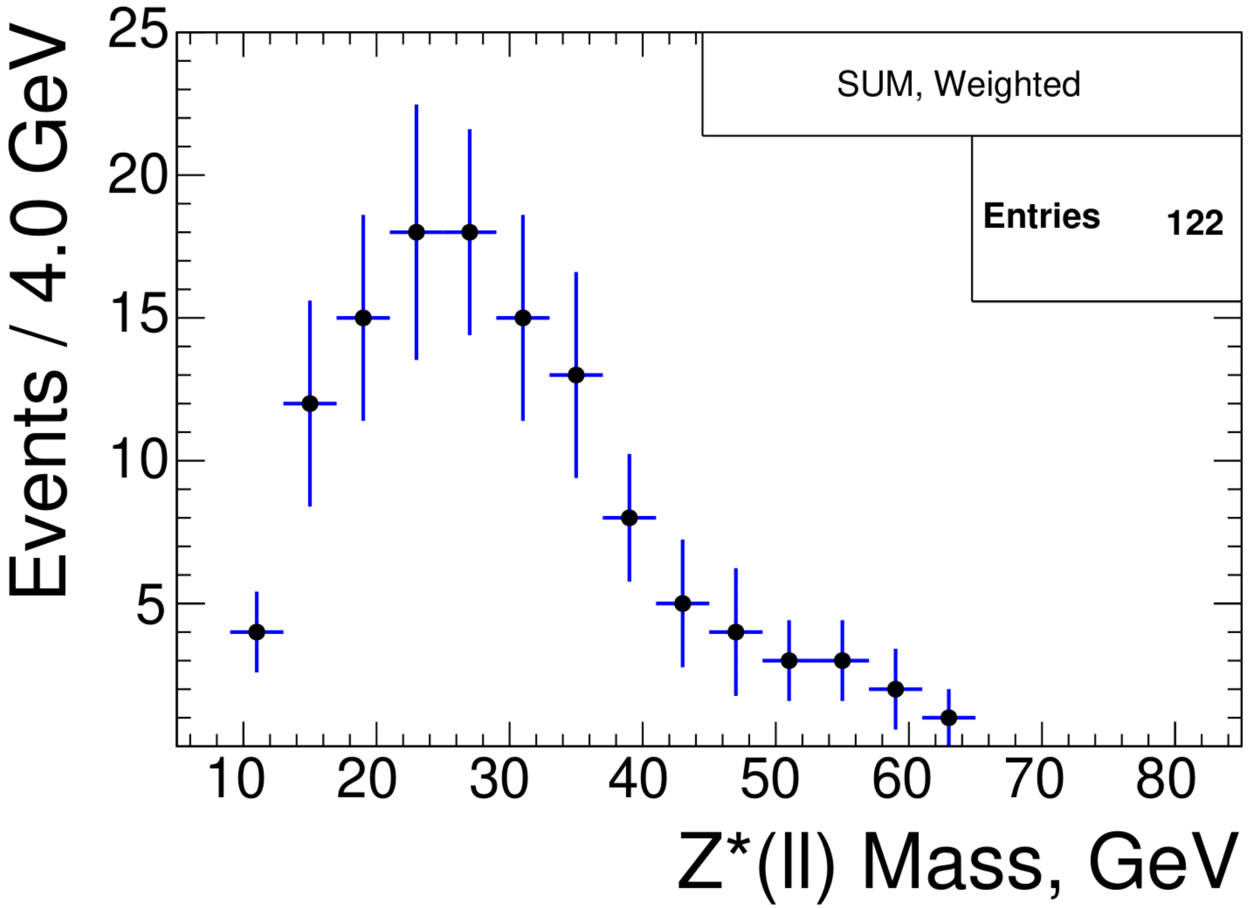
$$Z_1 \rightarrow \nu_{\mu,\tau}\nu_{\mu,\tau}, Z \rightarrow ll\ , Z^{\star} \rightarrow jj$$





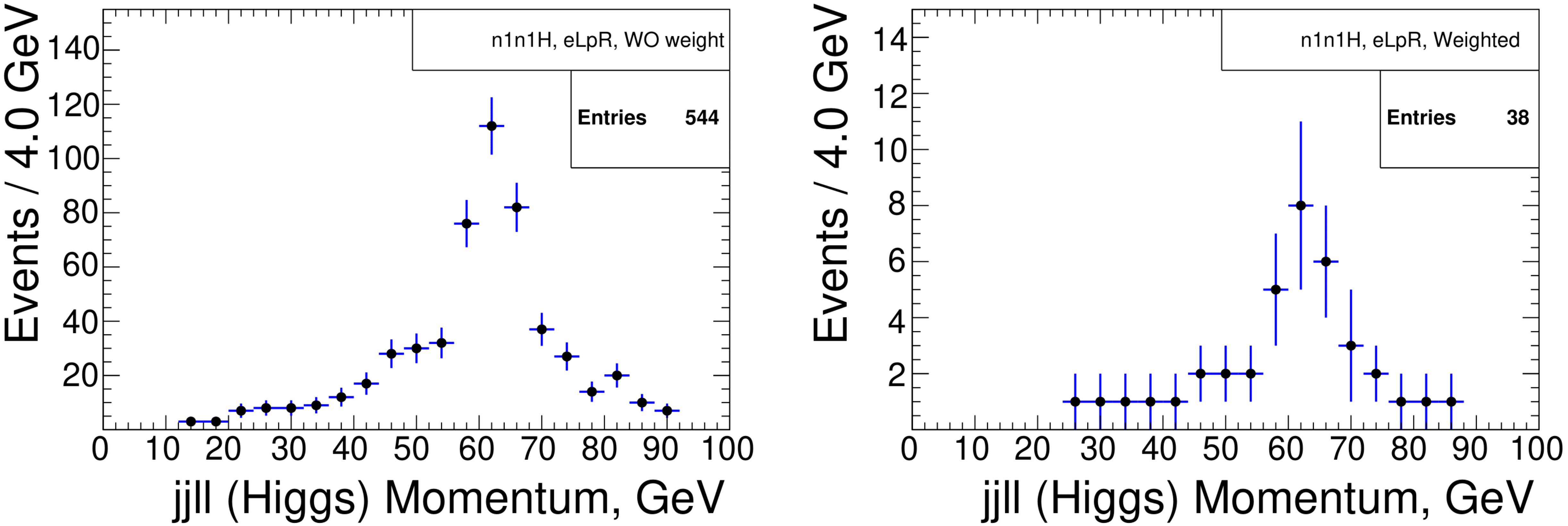
Additional information

$$Z_1 \rightarrow \nu\nu, Z \rightarrow ll\ , Z^{\star} \rightarrow jj$$



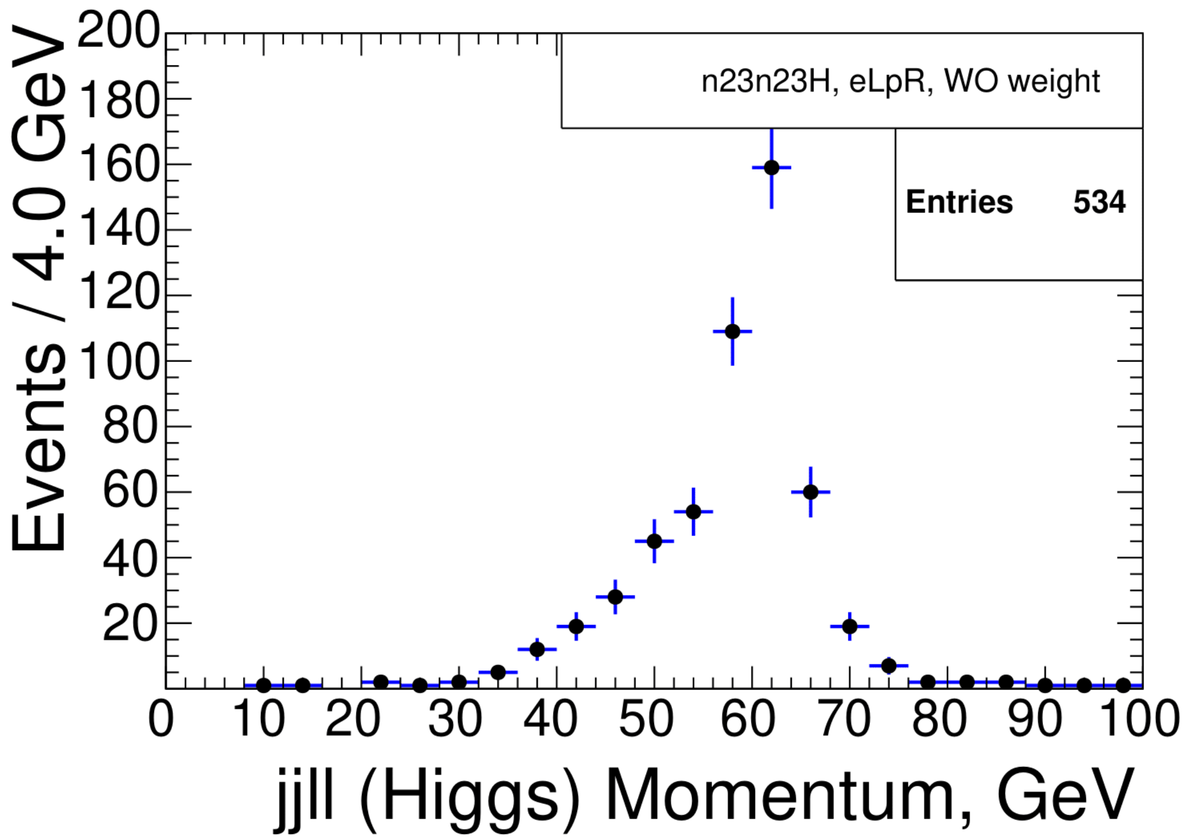
Additional information

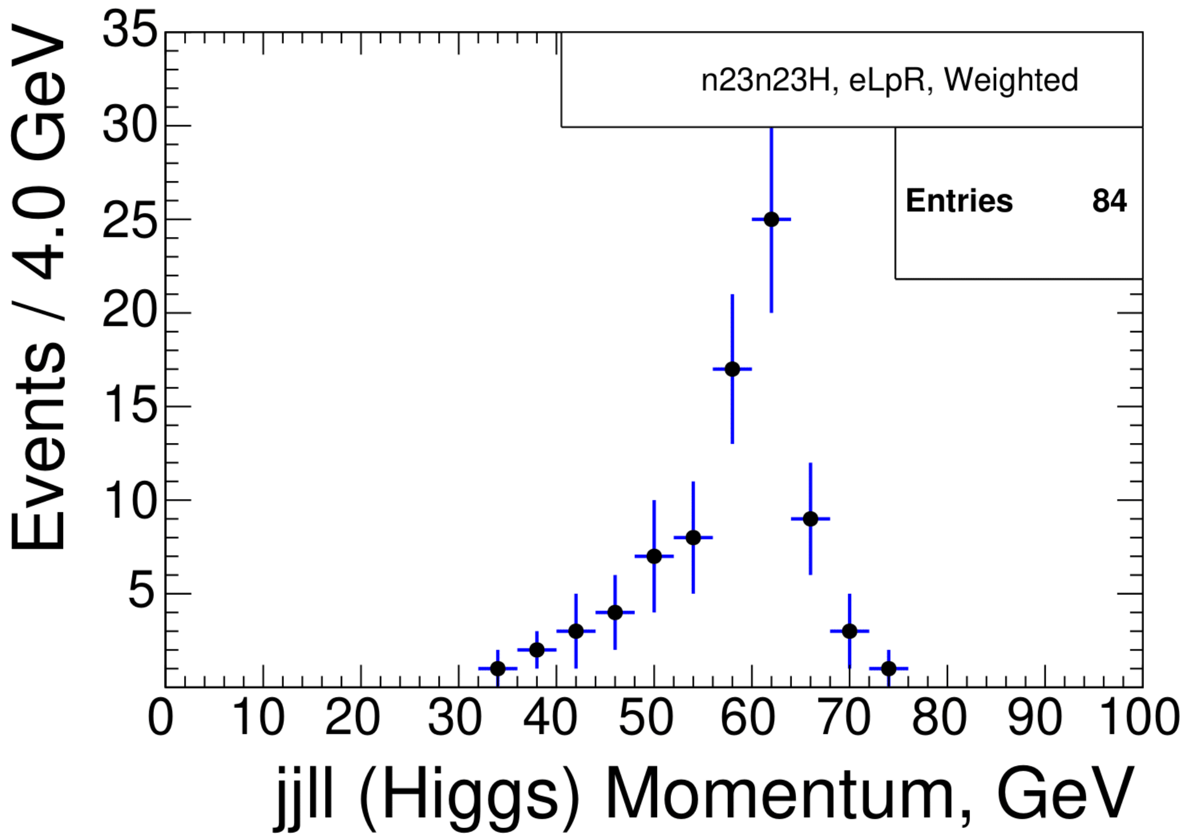
$$Z_1 \to \nu_e \nu_e \,, Z \to ll \,, Z^{\star} \to jj$$



Additional information

$$Z_1 \rightarrow \nu_{\mu,\tau}\nu_{\mu,\tau}, Z \rightarrow ll\ , Z^{\star} \rightarrow jj$$





Additional information

$$Z_1 \to \nu\nu, Z \to ll\,, Z^{\star} \to jj$$