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

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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 $e^+e^- \to HZ$ with the subsequent decay $H \to ZZ^\star$ to measure:

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

Constant, Error < 1% expected in calculations

Coupling HZZ Error < 0.5% expected from other ILC studies

Higgs boson width

Only one of Z bosons is reconstructed in lepton mode.

$Z \to jj \text{ or } ll, \quad Z^\star \to ll \text{ or } jj$

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
Examples: $WW\gamma$ *and* $ZZ\gamma$

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

No significant backgrounds are found for channels with on-shell $Z \to l_1l_2$, random lepton pairs have low mass

We tried to study events with 4 leptons, however number of such signal events is very small.

Event selection

Initial samples:

$$e^+e^- \to q\bar{q}H$$
$$e^+e^- \to \nu_e\bar{\nu}_eH$$
$$e^+e^- \to \nu_{\mu,\tau}\bar{\nu}_{\mu,\tau}H$$

Number of initial events for each sub-process = 500000

Sub-process	MC generator level extraction, N events	Isolated leptons tagging, N events	Weight factors	Number of weighted events
$Z_1 \to j_1j_2, Z \to j_1j_2, Z^\star \to l_1l_2$	605	416	0.803	334
$Z_1 \to j_1j_2, Z \to l_1l_2, Z^\star \to j_1j_2$	578	508	0.803	407
$Z_1 \to \nu_e\bar{\nu}_e, Z \to j_1j_2, Z^\star \to l_1l_2$	636	544	0.071	38
$Z_1 \to \nu_e\bar{\nu}_e, Z \to l_1l_2, Z^\star \to j_1j_2$	594	468	0.071	33
$Z_1 \to \nu_{\mu,\tau}\bar{\nu}_{\mu,\tau}, Z \to j_1j_2, Z^\star \to l_1l_2$	626	534	0.157	83
$Z_1 \to \nu_{\mu,\tau}\bar{\nu}_{\mu,\tau}, Z \to l_1l_2, Z^\star \to j_1j_2$	588	455	0.157	71

- Extraction of all 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.

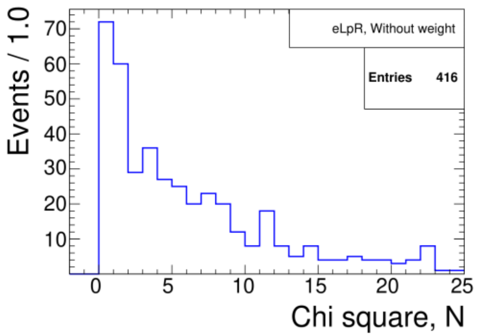
- *Jet reconstruction: **Jet Finder** processor with **Valencia algorithm** is used to force reconstruction of **2 or 4 jets**.*

Minimum χ^2_{min} calculation

All σ are estimated from data

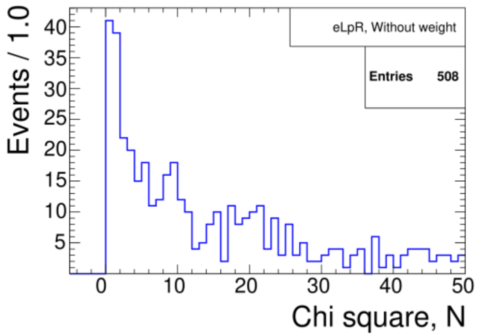
$$Z_1 \to jj, Z \to jj, Z^\star \to ll$$

$$\chi^2_{min} = \frac{(M_{Z_1} - M_{Z nom})^2}{\sigma^2_{M_{Z1}}} + \frac{(M_Z - M_{Z nom})^2}{\sigma^2_{M_Z}} + \frac{(P_{Z_1} - P_{Z nom})^2}{\sigma^2_{P_{Z_1}}} + \frac{(P_{Z+Z^*} - P_{Z nom})^2}{\sigma^2_{P_{Z+Z^*}}};$$



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

$$\chi^2_{min} = \frac{(M_{Z_1} - M_{Z nom})^2}{\sigma^2_{M_{Z1}}} + \frac{(P_{Z_1} - P_{Z nom})^2}{\sigma^2_{P_{Z_1}}} + \frac{(P_{Z+Z^*} - P_{Z nom})^2}{\sigma^2_{P_{Z+Z^*}}} + \frac{(E_{Z_1} - E_{Z nom})^2}{\sigma^2_{E_{Z_1}}};$$



In case of 4 jets in event we match jets to Z bosons selecting combination with minimal χ^2_{min} from 6 possible

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

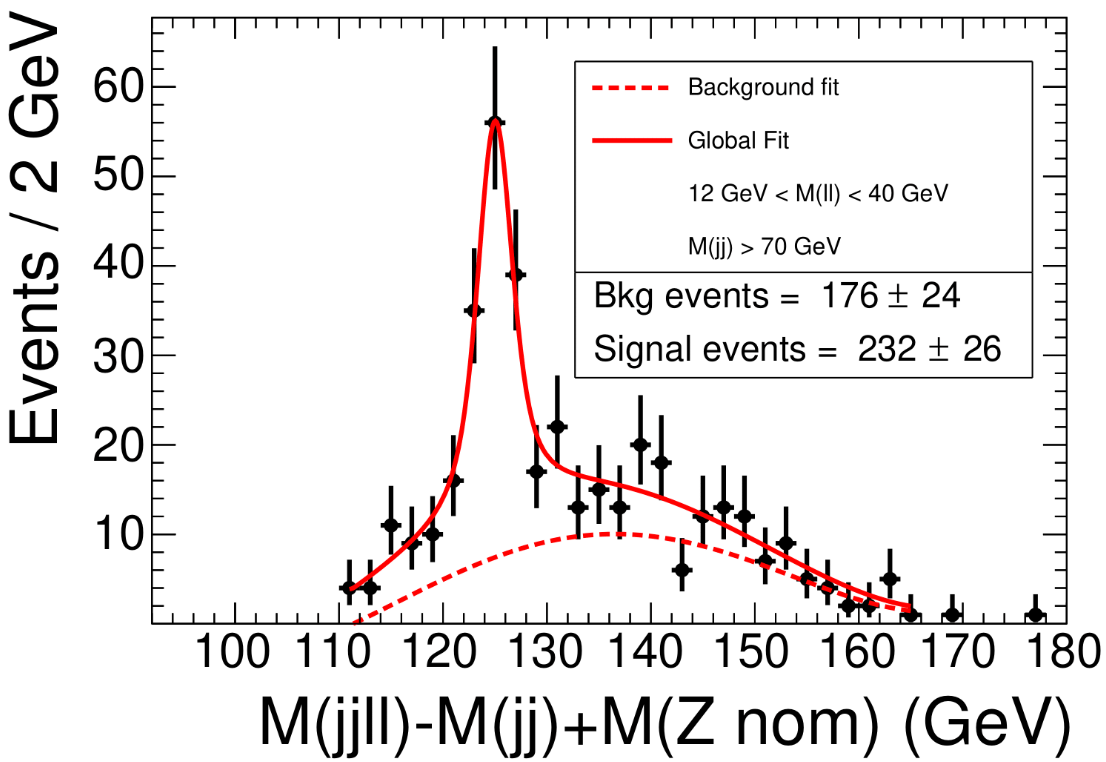
$$M_{Z\,nom} = 91.2\ GeV$$

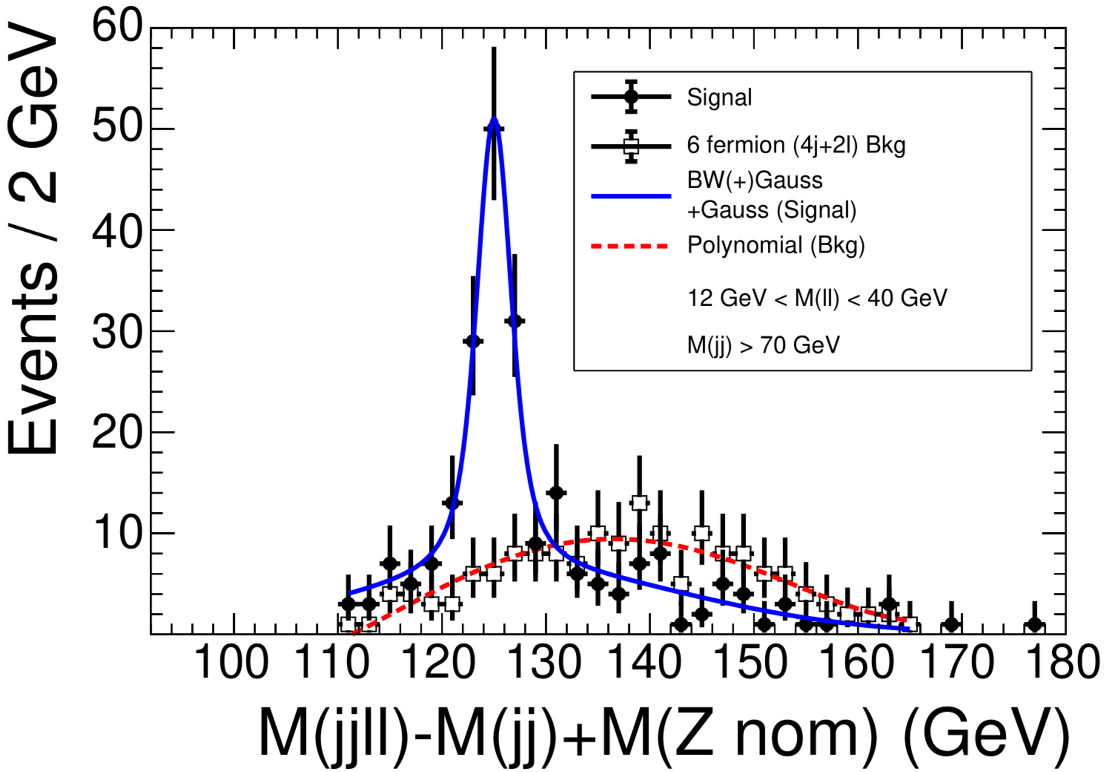
$$P_{Z\,nom} = 60.0\ GeV$$

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

$e^+e^- \rightarrow Z_1 H(Z Z^\star)$ $\qquad$ $Z_1 \rightarrow jj, Z \rightarrow jj, Z^\star \rightarrow ll$

Background $jjjj\, l^+l^-$ events come from $WW\gamma$ and $ZZ\gamma$ with off-shell γ (estimated for 2000 fb^{-1})





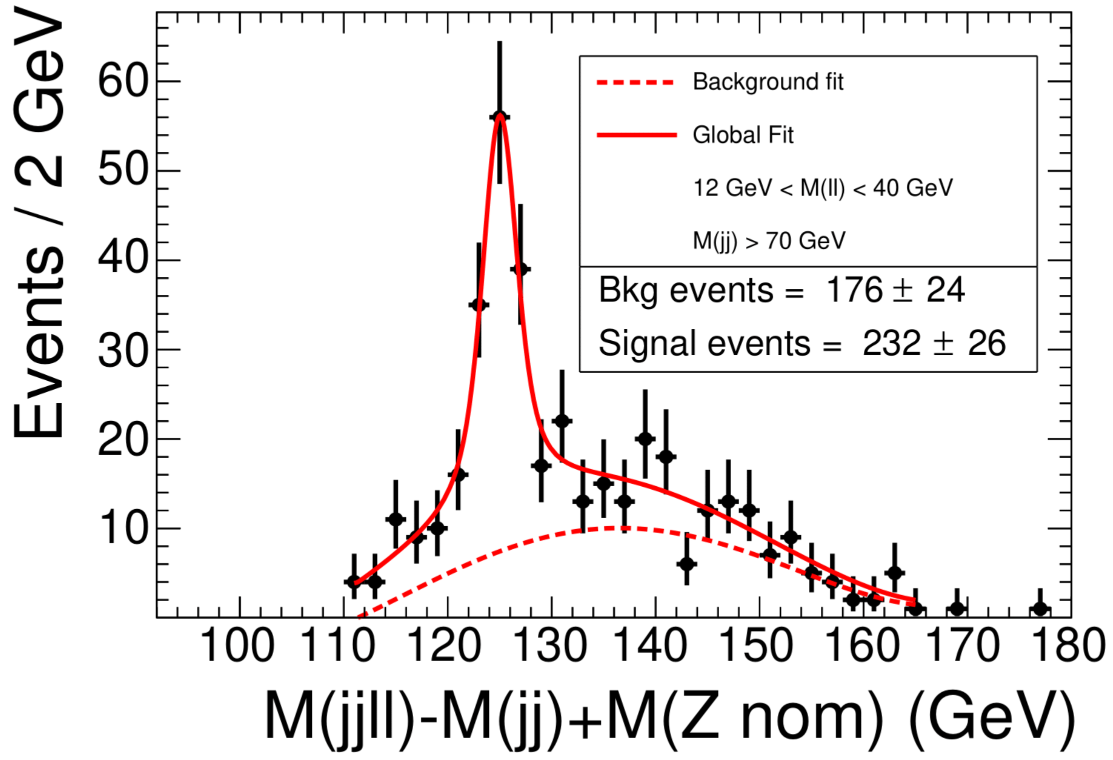
Fixed shapes, free normalizations in this fit

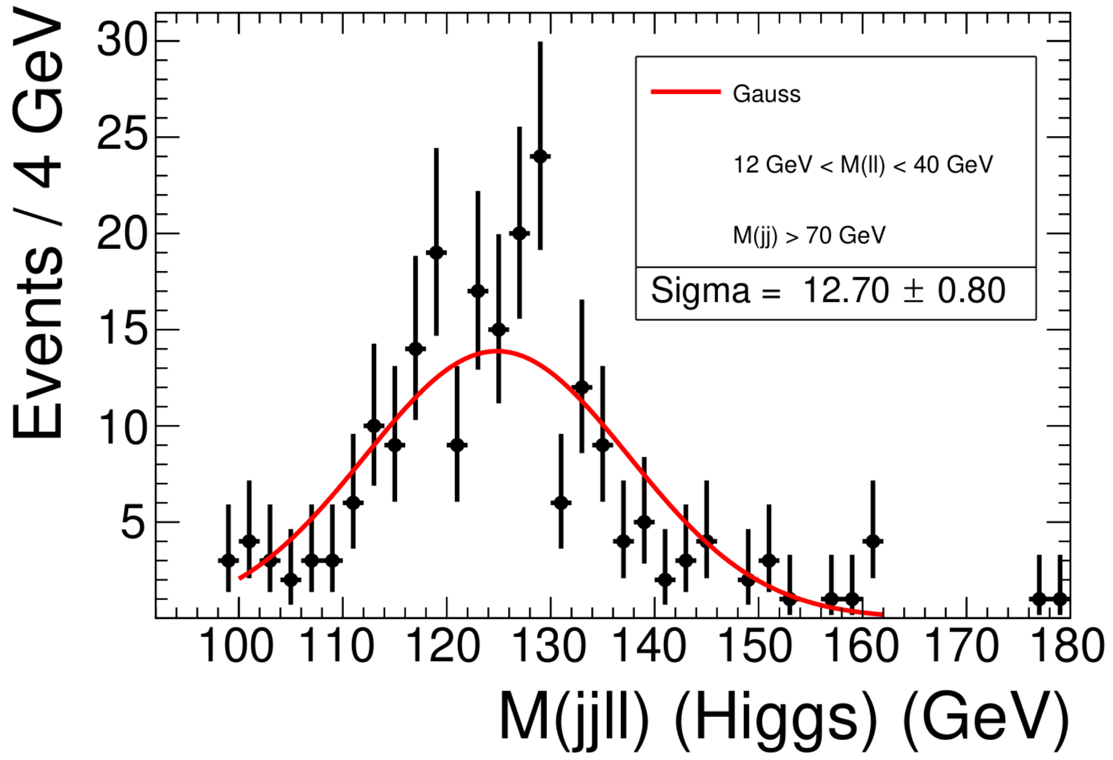
$\sqrt{s}$ = 250 GeV $\qquad \mathcal{L} = 2000\ fb^{-1}$

Statistical uncertainty = ***11.2 %***

Signal is modelled by ***Gaussian⊕BW + Gaussian*** *function (wide gaussian comes from $Z^\star Z^\star$ tail). Background is described by* ***Chebychev3*** *function*

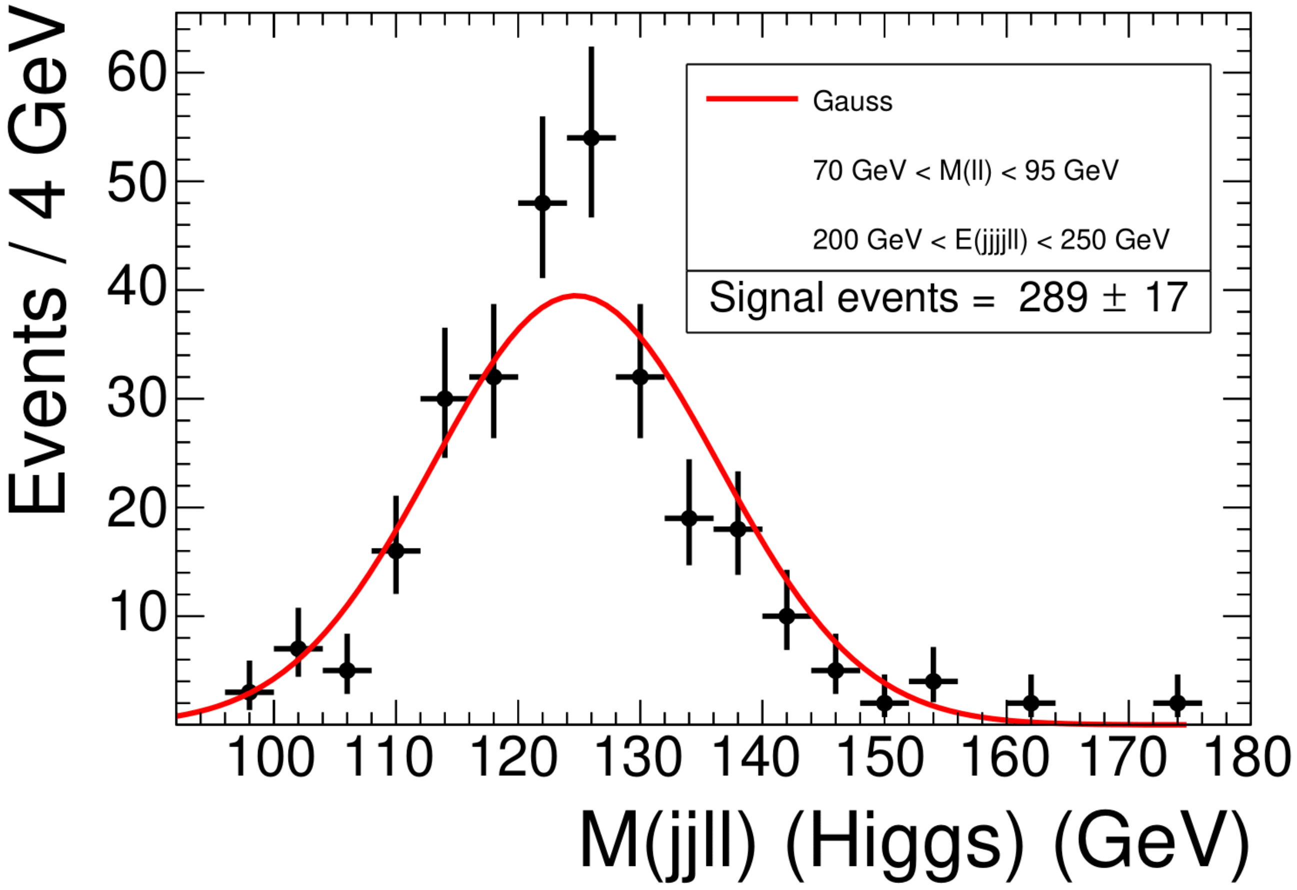
$e^+e^- \rightarrow Z_1 H(Z Z^{\star})$ $\quad$ $Z_1 \rightarrow jj, Z \rightarrow jj, Z^{\star} \rightarrow ll$





***Mass difference method** allows to obtain more narrow peak comparing to **direct mass** reconstruction*

$$e^+e^- \rightarrow Z_1 H(Z Z^\star) \qquad Z_1 \rightarrow jj, Z \rightarrow ll , Z^\star \rightarrow jj$$



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

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

Gaussian σ = *11.2 GeV*

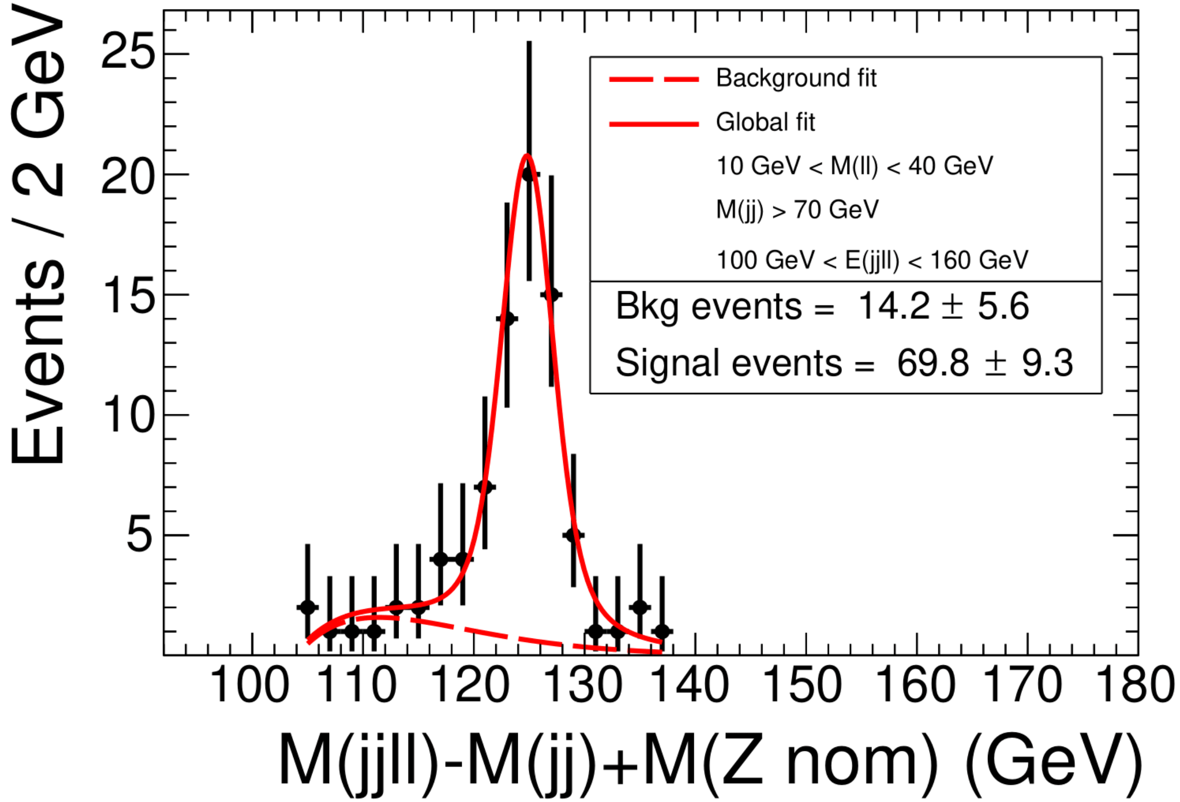
$\sqrt{s}$ = 250 GeV $\qquad \mathcal{L} = 2000 \ fb^{-1}$

Statistical uncertainty = ***5.9 %***

$$e^+e^- \to Z_1 H(Z Z^\star) \qquad Z_1 \to \nu\nu,\ Z \to jj,\ Z^\star \to ll$$

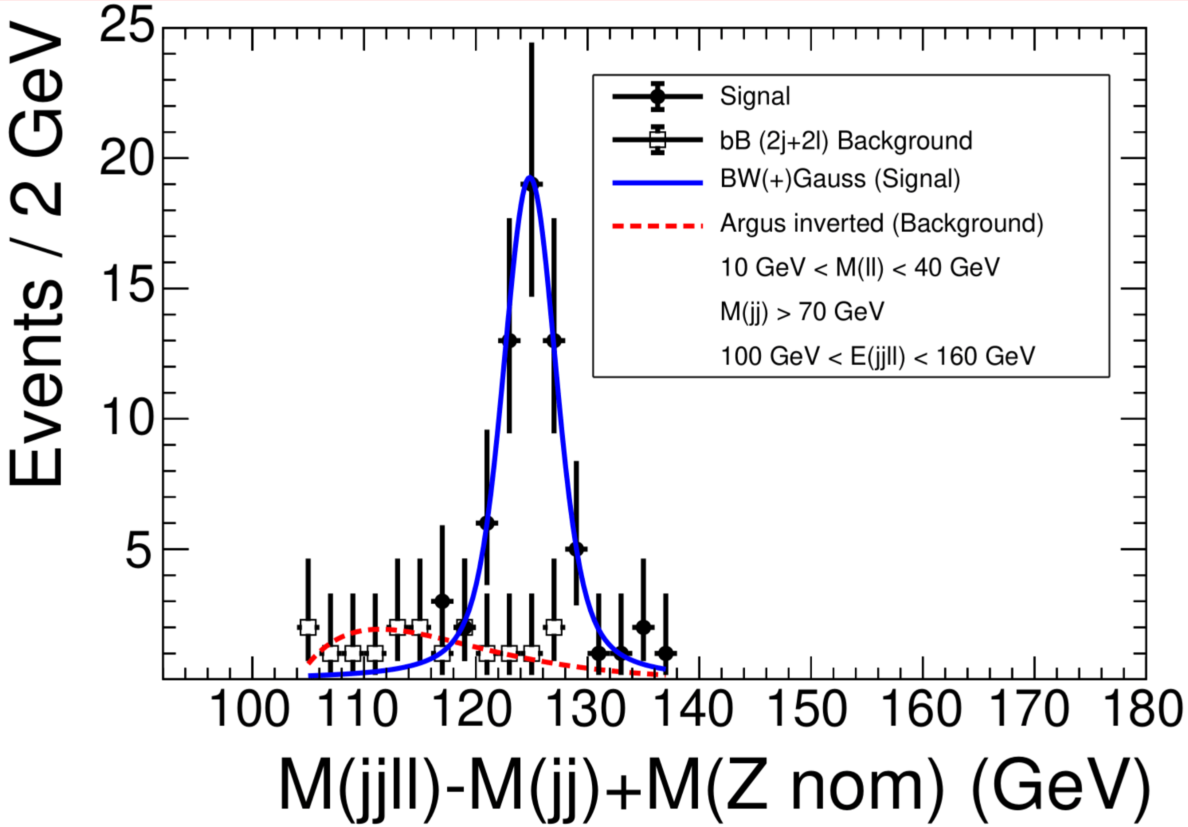
$\sqrt{s}$ = 250 GeV $\quad \mathcal{L} = 2000\ fb^{-1}$

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



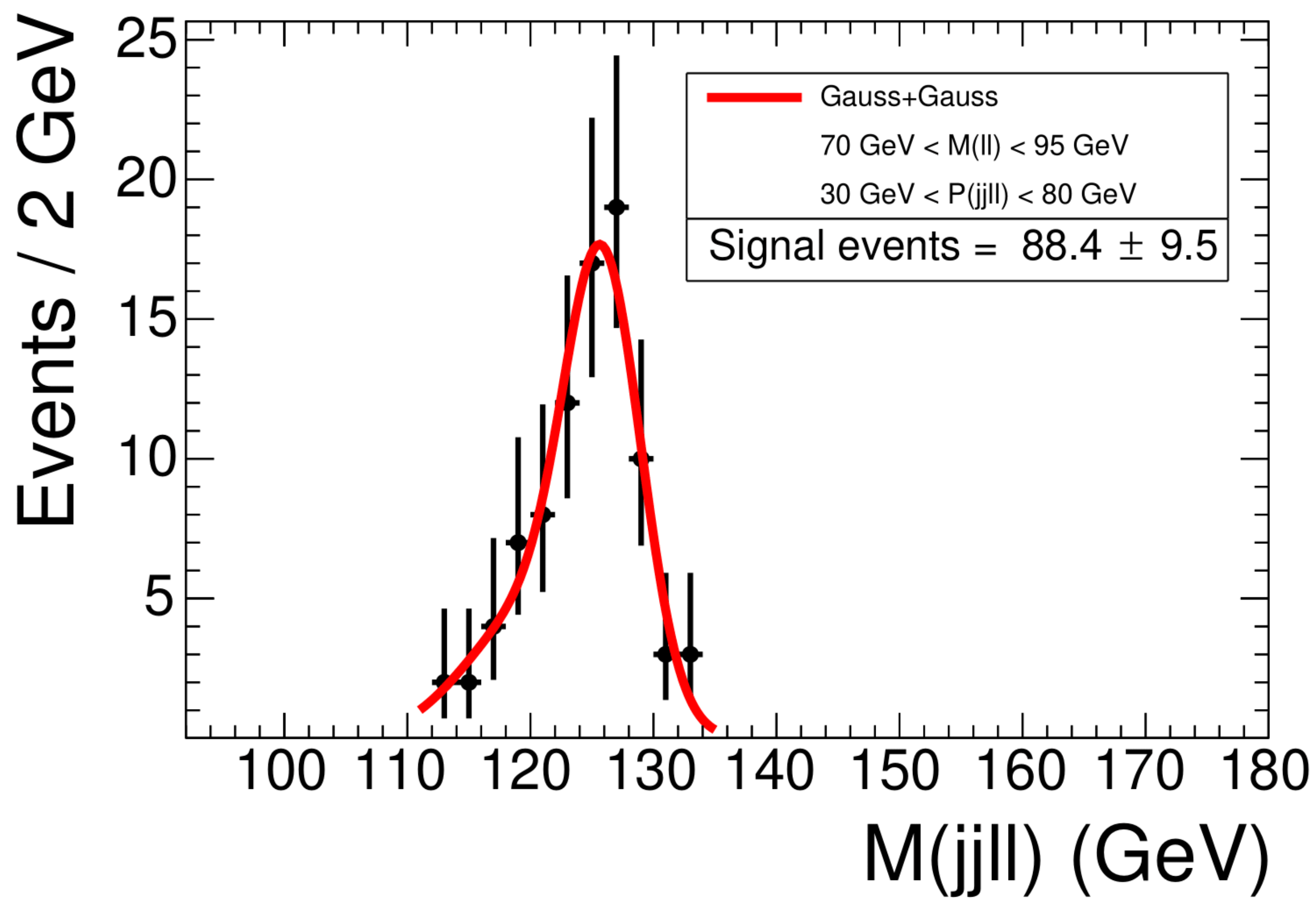
Fixed shapes, free normalizations in this fit

*Statistical uncertainty = **13.5 %***



*Signal is modelled by **Gaussian⊕BW** function*
*Background is described by **Argus** function*

$$e^+e^- \rightarrow Z_1 H(Z Z^\star) \qquad Z_1 \rightarrow \nu\nu, Z \rightarrow ll\,, Z^\star \rightarrow jj$$



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

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

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

Signal is narrow because there are only 2 jets in event: no wrong Z-jet matching, wrong particle-jet matching does not change results

$\sqrt{s}$ = 250 GeV $\quad \mathcal{L} = 2000 \ fb^{-1}$

*Statistical uncertainty = **10.7 %***

Integrated significance of this method

We use this formula calculate integrated statistical significance:

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

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

Integrated statistical significance and uncertainty obtained:

$$\boldsymbol{Sign = 22.6\,\sigma}$$

$$\boldsymbol{Stat.Uncertainty = 4.4\%}$$

Dominant systematic uncertainty is expected to come from description of background shapes. It is difficult to estimate this uncertainty precisely without real data. This uncertainty is expected to be smaller then statistical uncertainty. Systematics due to event selection efficiency and reconstruction efficiency should be small.

Conclusions

We studied $e^+e^- \to HZ$ process with subsequent $H \to ZZ^\star$ decay. The analysis was performed assuming integrated luminosity 2000 fb^{-1} collected at e^+e^- collisions with center-of-mass energy 250 GeV.

4 channels were studied; corresponding signals and backgrounds are estimated using MC simulation.

Summing up results obtained in 4 studied channels we obtain statistical significance of this method = $22.6\ \sigma$ and statistical uncertainty = 4.4%.

Thank you for attention

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, γ *and* **β** - special capture parameters in beam distance

We use **β = 1** and tune ***R*** *and* γ 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

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

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

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

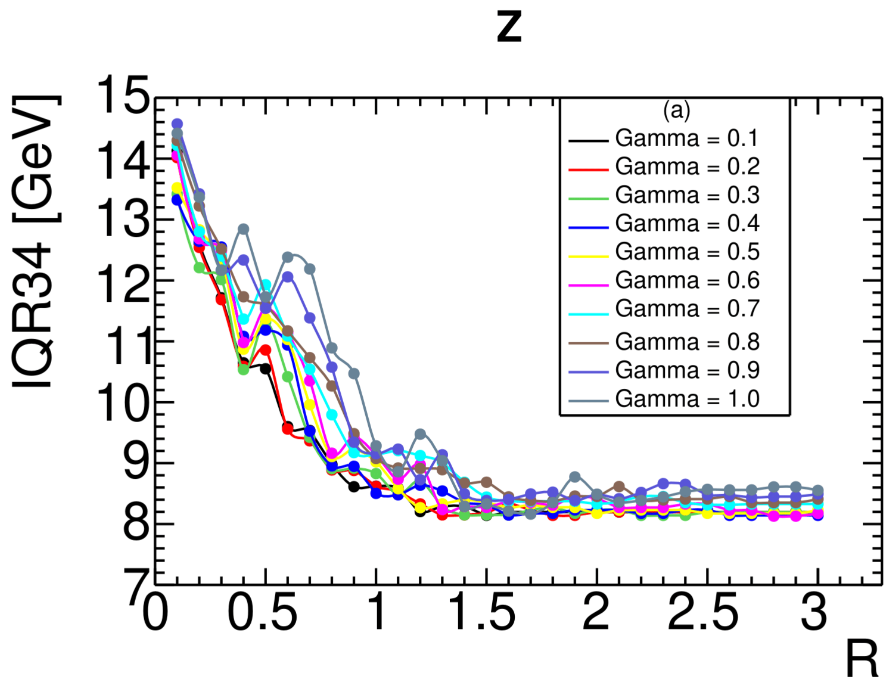
$$M^2_{mean} = \frac{\sum (\Delta M(Z))^2}{N_{entries}}$$

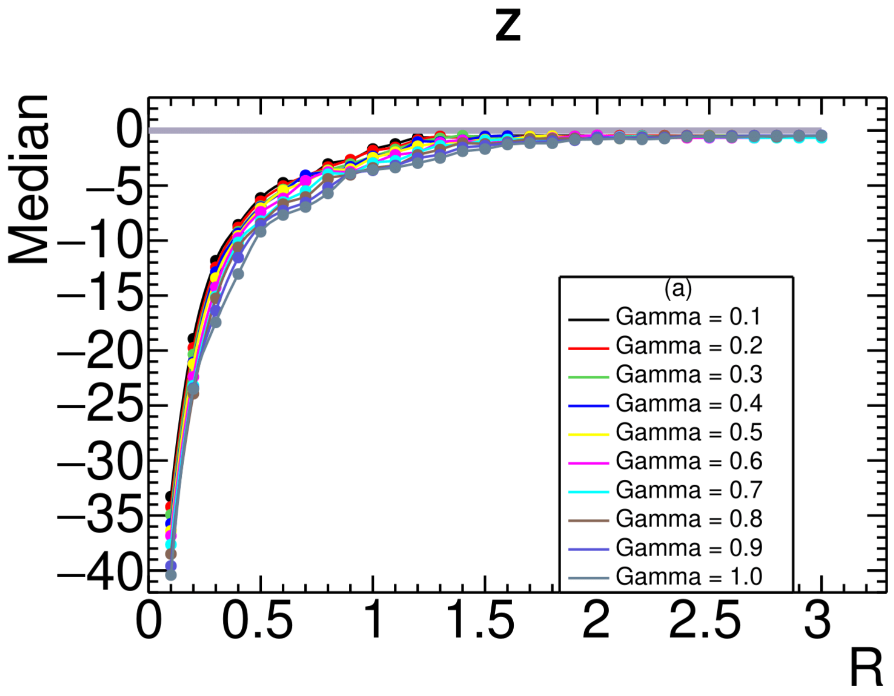
Jet reconstruction

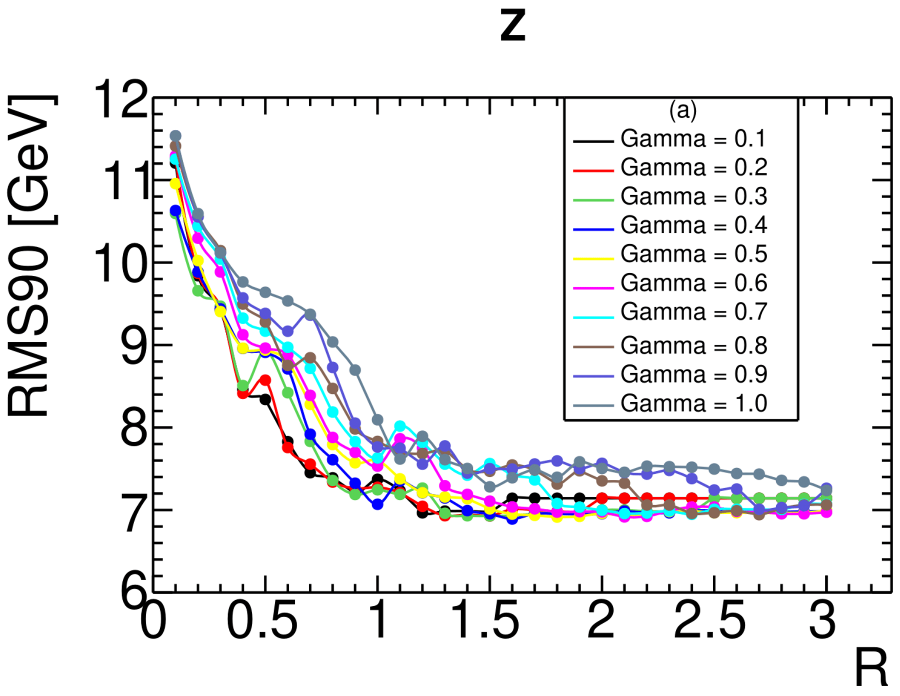
Example of tune for *Z(jj)*

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

R[0.1, 3.0] and γ*[0.1, 1.0]* ranges





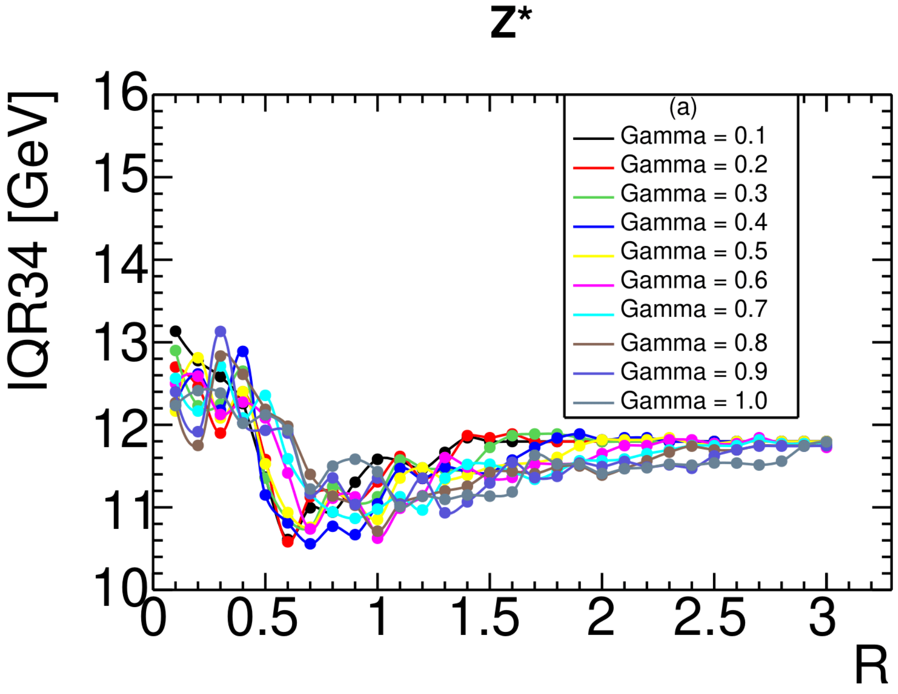


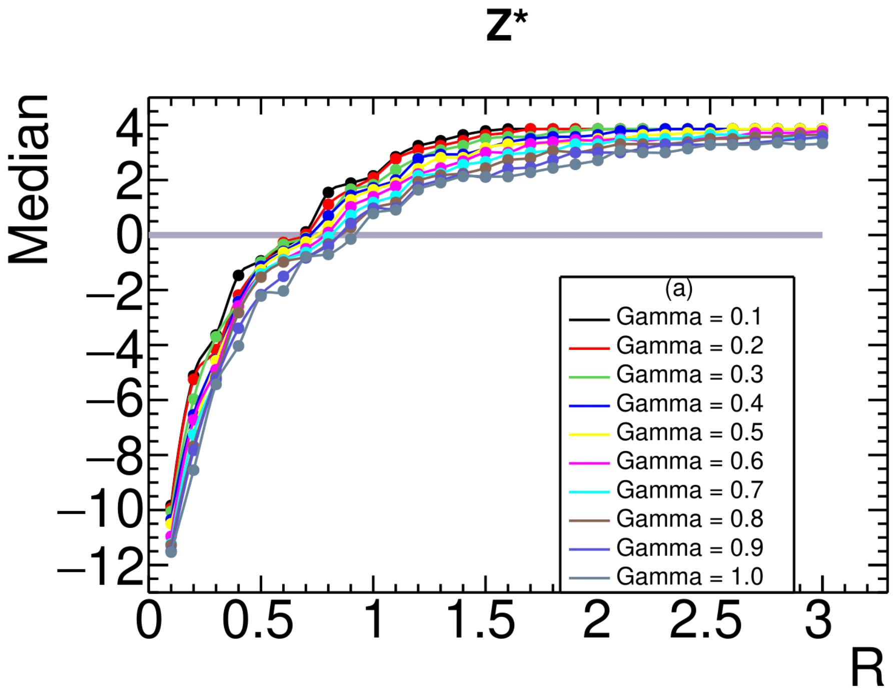
Jet reconstruction

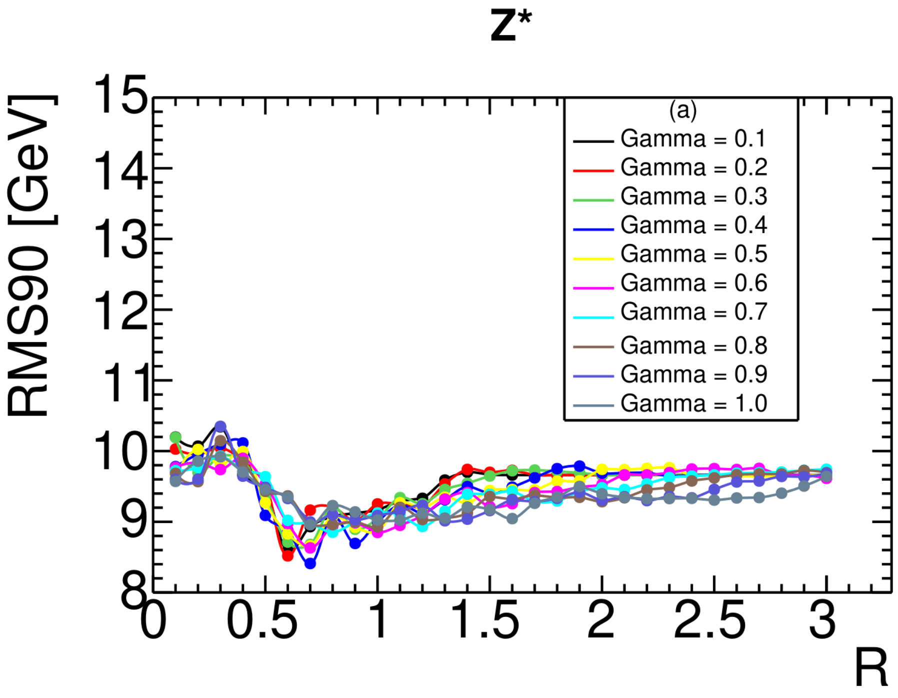
Example of tune for *Z⋆(jj)*

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

R[0.1, 3.0] and $\boldsymbol{\gamma}$*[0.1, 1.0]* ranges







Jet reconstruction

Valencia algorithm parameters tuned for each sub-process:

$Z_1 \to jj, Z \to jj, Z^\star \to ll$: β = 1, γ = 0.4, R = 1.6

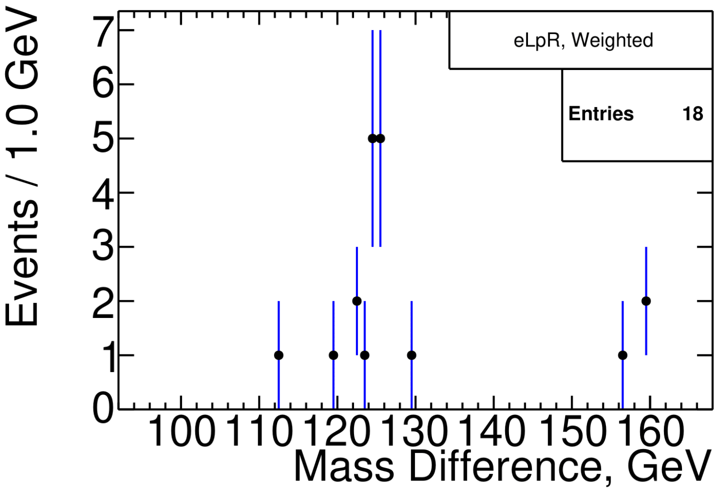
$Z_1 \to jj, Z \to ll, Z^\star \to jj$: β = 1, γ = 0.4, R = 0.7

$Z_1 \to \nu\nu, Z \to jj, Z^\star \to ll$: β = 1, γ = 0.6, R = 1.4

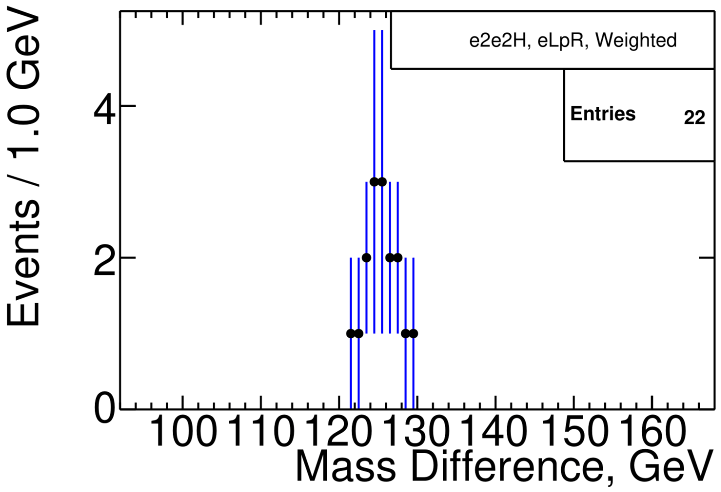
$Z_1 \to \nu\nu, Z \to ll, Z^\star \to jj$: β = 1, γ = 0.3, R = 1.4

4 leptons channels

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



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



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