Measurement of $\sigma(e^+e^- \to HZ)$×Br($H \to ZZ^\star$) 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:

$$\sigma(e^+e^- \to HZ) \times Br(H \to ZZ^\star) = C \cdot \mathrm{g}_{\mathrm{Z}}^{4} / \Gamma_H$$

Constant, Error < 1% expected

Coupling HZZ Error < 0.5% expected

Higgs boson width

One of Z bosons is reconstructed in jets.

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

Studied processes

The following processes are studied:

Channel 1: $e^+e^- \to Z_1(j_1 j_2)H, \quad H \to Z(j_3 j_4)Z^\star(l_1 l_2)$

Channel 2: $e^+e^- \to Z_1(j_1 j_2)H, \quad H \to Z(l_1 l_2)Z^\star(j_3 j_4)$

Channel 3: $e^+e^- \to Z_1(\nu\bar{\nu})H, \quad H \to Z(j_1 j_2)Z^\star(l_1 l_2)$

Channel 4: $e^+e^- \to Z_1(\nu\bar{\nu})H, \quad H \to Z(l_1 l_2)Z^\star(j_1 j_2)$

Event preselection

Preselection tools:

1. Only specific processes and decay chains are selected on *MCParticle* level.
2. Two isolated lepton candidates are identifying with *IsolatedLeptonTagging*
3. ISR identification and removing procedure
4. Jet reconstruction using *FastJet* clustering tools
5. Appling weight factors to each event to get expected number of signal or background events

$$W = \left[\frac{1 \pm 0.8}{2} \cdot \frac{1 \pm 0.3}{2}\right] \cdot \frac{2\ \mathrm{ab}^{-1}}{\mathcal{L}_{\mathrm{nom}}}$$

$\mathcal{L}_{\mathrm{nom}}$ - The sample nominal integrated luminosity

Channels	$\mathcal{P}_{e^-e^+}$	MC events	Lepton tagging, events	Weight factors	Weighted number of events
$Z_1(jj)$, $Z(jj)$, $Z^*(\ell\ell)$	eLpR eRpL	23989 23845	16088 16027	$2.1 \cdot 10^{-2}$ $1.3 \cdot 10^{-3}$	338 21
$Z_1(jj)$, $Z(\ell\ell)$, $Z^*(jj)$	eLpR eRpL	23261 23132	20879 20664	$2.1 \cdot 10^{-2}$ $1.3 \cdot 10^{-3}$	439 27
$Z_1(\nu_e\bar{\nu}_e)$, $Z(jj)$, $Z^*(\ell\ell)$	eLpR eRpL	24044 23910	17429 17259	$3.7 \cdot 10^{-3}$ $7.9 \cdot 10^{-5}$	65 1.4
$Z_1(\nu_e\bar{\nu}_e)$, $Z(\ell\ell)$, $Z^*(jj)$	eLpR eRpL	23059 23096	21108 21149	$3.7 \cdot 10^{-3}$ $7.9 \cdot 10^{-5}$	79 1.7
$Z_1(\nu_{\mu,\tau}\bar{\nu}_{\mu,\tau})$, $Z(jj)$, $Z^*(\ell\ell)$	eLpR eRpL	23840 23862	17103 17168	$4.1 \cdot 10^{-3}$ $1.6 \cdot 10^{-4}$	71 2.7
$Z_1(\nu_{\mu,\tau}\bar{\nu}_{\mu,\tau})$, $Z(\ell\ell)$, $Z^*(jj)$	eLpR eRpL	23189 23225	21168 21246	$4.1 \cdot 10^{-3}$ $1.6 \cdot 10^{-4}$	88 3.3

Isolated lepton identification

We use the *IsolatedLeptonTagging* processor with default set of parameters and weights to identify leptons.

The detectors instrumented in the magnet yoke surrounding the muon chamber are not used in the algorithm, it results in a small decrease in efficiency.

The $Z^{\star}$ and Z reconstruction efficiencies in the leptonic modes in the channel with four jets (two jets) are $\sim$67 % ($\sim$72 %) and $\sim$90 % ($\sim$91 %), respectively.

The only events with two identified isolated leptons are kept for the following analysis. These leptons are excluded from the following jet reconstruction procedure.

Jet reconstruction procedure

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.***

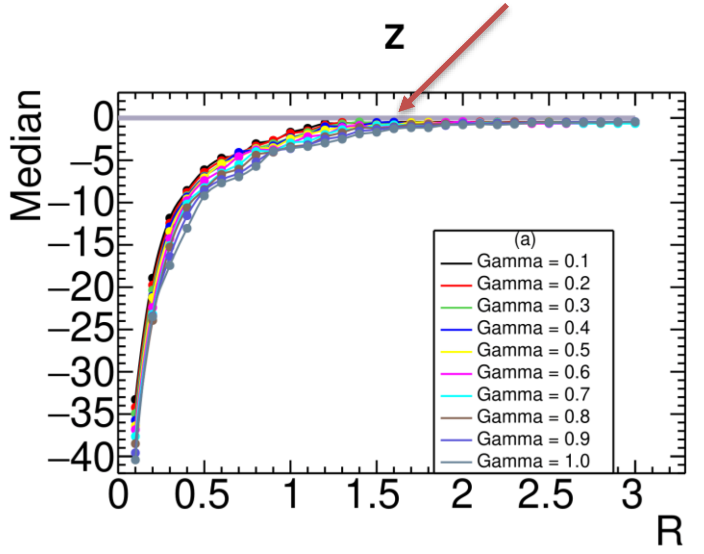
The best Valencia algorithm parameters chosen for the jet reconstruction in different channels:

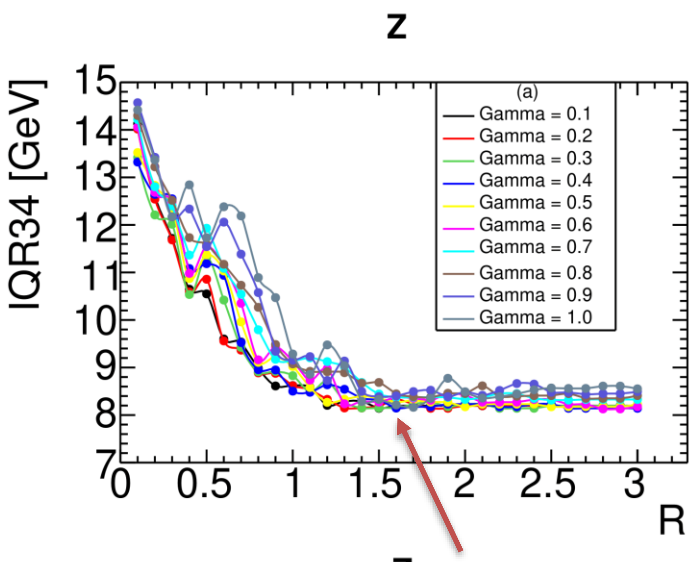
Valencia parameters	$Z_1(jj)$, $Z(jj)$, $Z^*(\ell\ell)$	$Z_1(jj)$, $Z(\ell\ell)$, $Z^*(jj)$	$Z_1(\nu\bar{\nu})$, $Z(jj)$, $Z^*(\ell\ell)$	$Z_1(\nu\bar{\nu})$, $Z(\ell\ell)$, $Z^\star(jj)$
β	1.0	1.0	1.0	1.0
γ	0.4	0.4	0.6	0.3
R	1.6	0.7	1.4	1.4

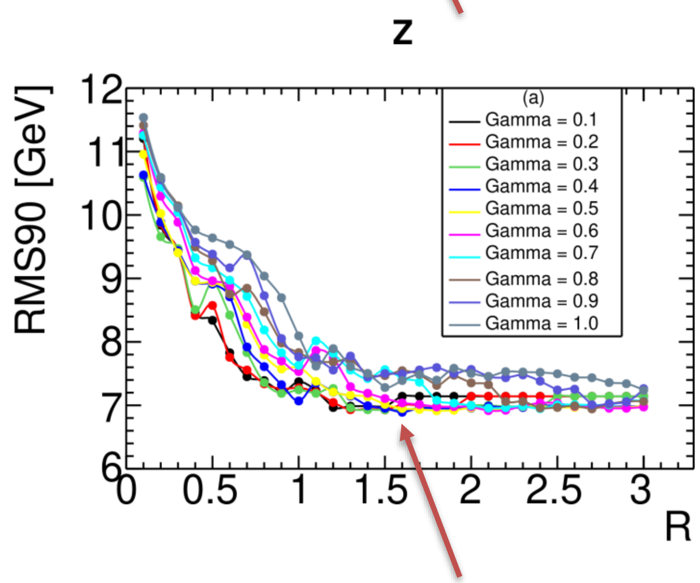
Jet reconstruction procedure

Example of jet parameters choosing procedure for $Z(jj)$

R[0.1, 3.0] and *γ[0.1, 1.0]* ranges







The best *R* and γ parameters are chosen.

Channel 1: $Z_1 \to jj, Z \to jj\ , Z^\star \to ll$

The final state of the first studied channel includes *two leptons and four jets*. To form the Z_1 and Z bosons from these four jets we calculate χ^2 for six possible two-jet combinations:

$$\chi^2 = \frac{(M(Z_1) - M(Z_{nom}))^2}{\sigma^2{}_{M_{Z_1}}} + \frac{(M(Z) - M(Z_{nom}))^2}{\sigma^2{}_{M_Z}} + \frac{(P(Z_1) - \overline{P}(Z_1))^2}{\sigma^2{}_{P_{Z_1}}} + \frac{(P(Z + Z^\star) - \overline{P}(Z_1))^2}{\sigma^2{}_{P_{Z+Z^\star}}}$$

$\overline{P}(Z_1) = 60.0\ \mathrm{GeV}/c$ is the mean Z_1 momentum

$M(Z_{\mathrm{nom}}) = 91.2\ \mathrm{GeV}$

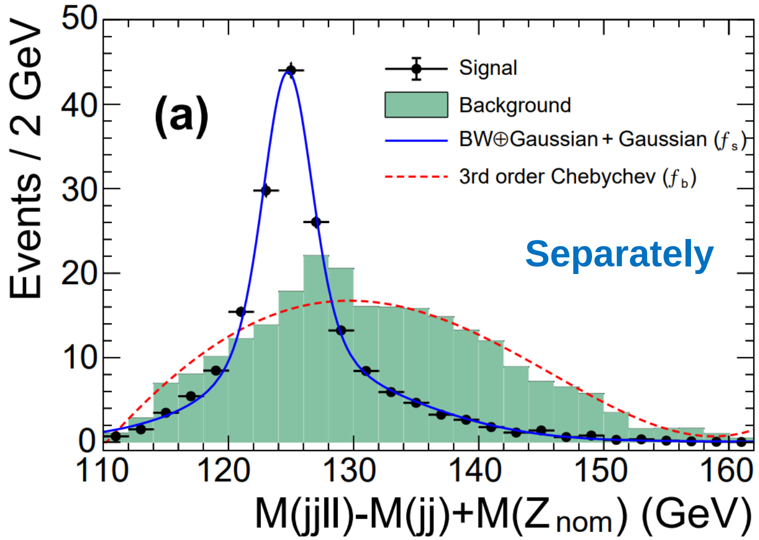
All **σ** parameters are the mean widths of corresponding mass or momentum distributions on the reconstruction level.

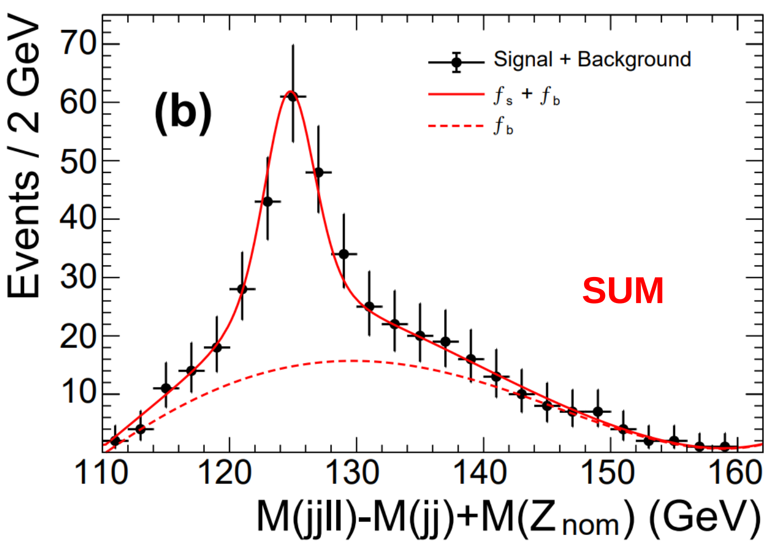
Mass difference is used to get a better mass resolution:

$$M_\Delta = M(jj\ell\ell) - M(jj) + M(Z_{nom})$$

Channel 1: $Z_1 \to jj, Z \to jj\ , Z^\star \to ll$

$$M_\Delta = M(jj\ell\ell) - M(jj) + M(Z_{nom})$$





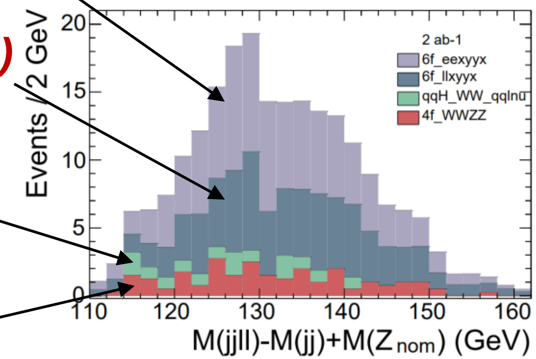
Background contributions:

$e^+e^- \to W^+W^-/ZZ\gamma^\star(e^+e^-)$

$e^+e^- \to W^+W^-/ZZ\gamma^\star(\mu^+\mu^-)$

$e^+e^- \to Z(jj)H, H \to W^+(jj)W^-(l\nu)$

$e^+e^- \to W^+(jj)W^-(jj)$ **and** $e^+e^- \to Z(jj)Z(jj)$



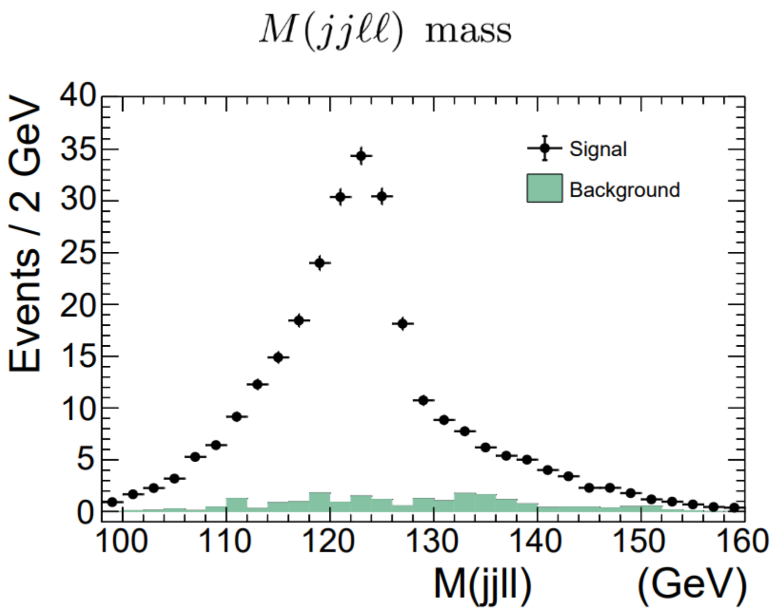
Additional wide Gaussian in fit function described residual $Z^\star Z^\star$ events and a few events due to a wrong jet matching in the χ^2 selection.

The fit yields 193.4 ± 24.5 signal events
The toy MC yields 192.4 ± 24.9 signal events

Statistical uncertainty is 12.9%

*We used **toy MC** to obtain final results*

Channel 2: $Z_1 \to jj,\ Z \to ll,\ Z^\star \to jj$



χ^2 for six possible two-jet combinations:

$$\chi^2 = \frac{(M(Z_1) - M(Z_{nom}))^2}{\sigma^2{}_{M_{Z_1}}} + \frac{(E(Z_1) - \overline{E}(Z_1))^2}{\sigma^2{}_{E_{Z_1}}} + \frac{(P(Z_1) - \overline{P}(Z_1))^2}{\sigma^2{}_{P_{Z_1}}} + \frac{(P(Z+Z^\star) - \overline{P}(Z_1))^2}{\sigma^2{}_{P_{Z+Z^\star}}}$$

$\overline{E}(Z_1) = 110.0$ GeV is the mean Z_1 energy

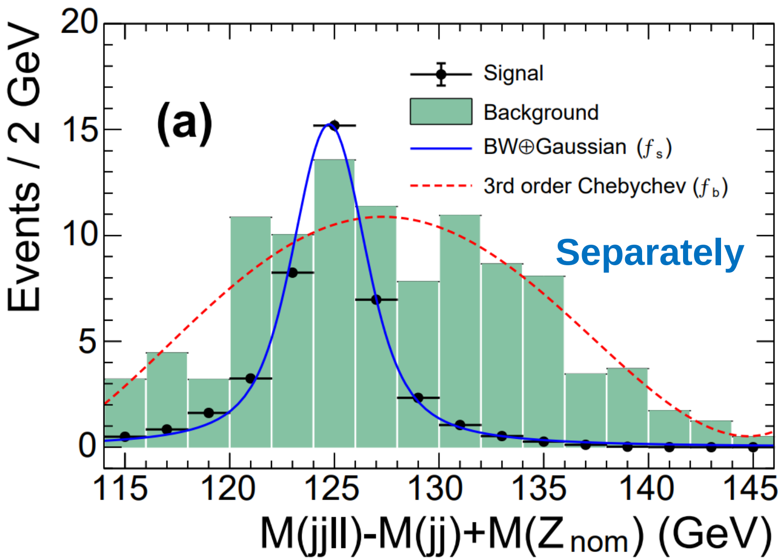
The background is very small, the integral over all bins is 18.3 events

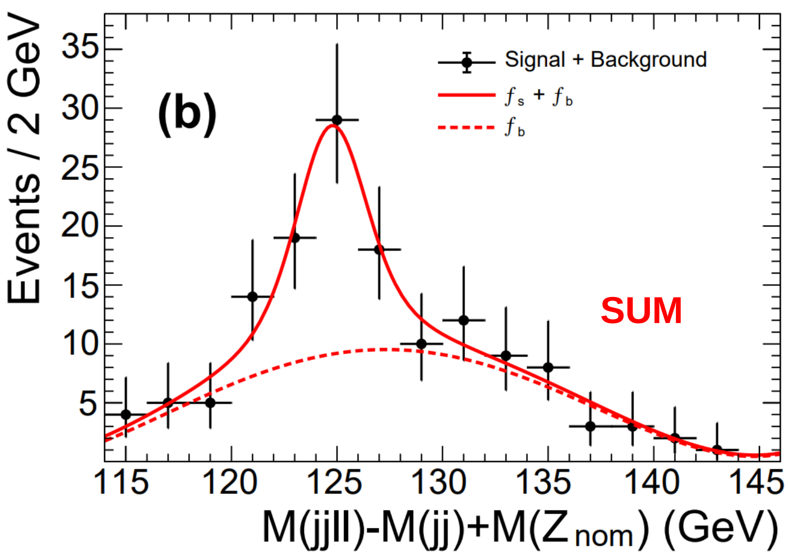
The signal mean value and uncertainty is 275.3 ± 17.2

Statistical uncertainty is 6.3%

Channel 3: $Z_1 \to \nu\bar{\nu}\,,\, Z \to jj\,,\, Z^\star \to ll$

$$M_\Delta = M(jj\ell\ell) - M(jj) + M(Z_{nom})$$





There are many background sources with large cross sections, which can contribute to this channel

Significant backgrounds:

$e^+e^- \to Z(jj)Z(\tau^+\tau^-)$ *with following leptonic decays*

$e^+e^- \to W^+(jj)W^-(l\nu)$

$e^+e^- \to b\bar{b}, e^+e^- \to ZH(b\bar{b})$

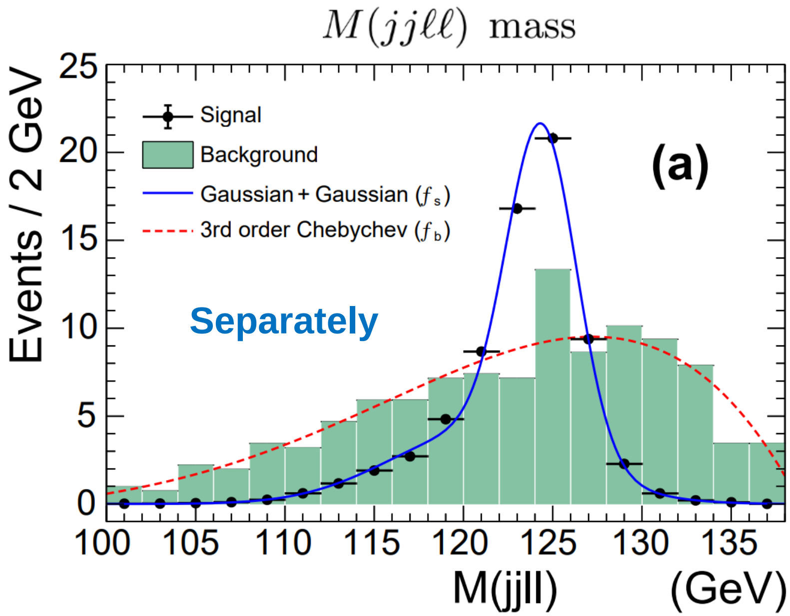
$H \to Z^\star Z^\star$

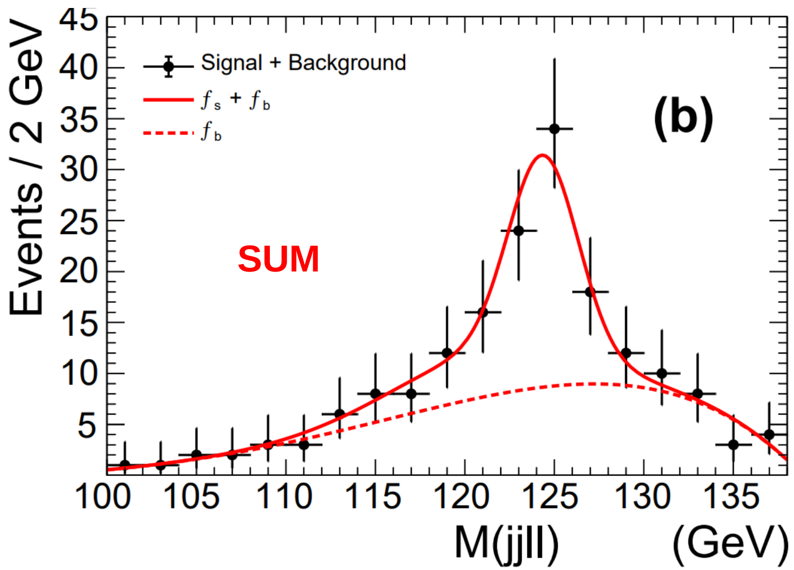
The fit yields 52.0 ± 12.7 signal events

The toy MC yields 51.9 ± 13.0 signal events

Statistical uncertainty is 25.1%

Channel 4: $Z_1 \to \upsilon\bar{\upsilon}, Z \to ll\ , Z^{\star} \to jj$





The dangerous background sources are similar to the previous channel, except the $b\bar{b}$ background

Significant backgrounds:

$e^+e^- \to Z(jj)Z(\tau^+\tau^-)$ *with following leptonic decays*
$e^+e^- \to W^+(jj)W^-(l\upsilon)\ H \to Z^{\star}Z^{\star}$

The fit yields 74.1 ± 13.9 signal events
The toy MC yields 73.3 ± 14.2 signal events

Statistical uncertainty is 19.3%

Table of cuts for all channels

Selection	Channel 1: $Z_1(jj)$, $Z(jj)$, $Z^*(\ell\ell)$	Channel 2: $Z_1(jj)$, $Z(\ell\ell)$, $Z^*(jj)$	Channel 3: $Z_1(\nu\bar{\nu})$, $Z(jj)$, $Z^*(\ell\ell)$	Channel 4: $Z_1(\nu\bar{\nu})$, $Z(\ell\ell)$, $Z^\star(jj)$
$M(\ell\ell)$ (GeV/c^2)	[13, 36]	[70, 95]	[13, 34]	[80, 95]
$M(Z \to jj)$ (GeV/c^2)	> 70	< 50	[80, 113]	[13, 38]
$M(Z_1 \to jj)$ (GeV/c^2)	> 70	> 70		
$E(jjjj\ell\ell)$ (GeV)	[200, 260]	[200, 260]		
$E(jj\ell\ell)$ (GeV)			< 145	< 145
$P_{\max}(\ell)$ (GeV/c)	< 32		< 40	
$P_{\min}(\ell)$ (GeV/c)	> 9		> 8	
$P_{\max}(j_1)$ (GeV/c)				< 22
$P_{\max}(j_2)$ (GeV/c)				< 42
$P(jj\ell\ell)$ (GeV/c)			[30, 70]	[40, 70]
$\lvert cos\,\theta_{vis}\rvert$			< 0.8	< 0.9
$\Delta\phi_{ZZ^\star}$ (degree)			< 120	< 140

Combined signal significance estimate

We calculate the combined statistical uncertainty for the four studied channels:

$$S_{\text{comb}} = 1/\sqrt{\sum_{i=1}^{4} S_i^{-2}}$$

Alternatively, we assumed two data samples with the polarizations and 0.9 ab^{-1} luminosity each.
The same analysis is repeated for this data taking scheme

$$\mathcal{P}_{e^-e^+} = (-0.8, +0.3)$$
$$\mathcal{P}_{e^-e^+} = (+0.8, -0.3)$$

Number of signal events and uncertainties obtained from ***toy MC*** for each channel:

	$Z_1(jj)$, $Z(jj)$, $Z^*(\ell\ell)$	$Z_1(jj)$, $Z(\ell\ell)$, $Z^*(jj)$	$Z_1(\nu\bar{\nu})$, $Z(jj)$, $Z^*(\ell\ell)$	$Z_1(\nu\bar{\nu})$, $Z(\ell\ell)$, $Z^\star(jj)$	Sum
	2 ab^{-1} eLpR				
Number of events	192.4 $\pm$ 24.9	275.3 $\pm$ 17.2	51.9 $\pm$ 13.0	73.3 $\pm$ 14.2	- -
Statistical uncertainty	12.9%	6.3%	25.1%	19.3%	5.29%
	0.9 ab^{-1} eLpR + 0.9 ab^{-1} eRpL				
Number of events	135.2 $\pm$ 20.4	202.2 $\pm$ 14.7	30.9 $\pm$ 10.7	67.3 $\pm$ 14.3	- -
Statistical uncertainty	15.1%	7.3%	34.6%	21.2%	6.15%

Conclusions

We studied the $e^+e^- \to HZ$ process with the subsequent $H \to ZZ^\star$ decay.

The analysis is performed assuming the integrated luminosity $2\,ab^{-1}$ collected at the e^+e^- collisions with center-of-mass energy 250 GeV and the beam polarizations $\mathcal{P}_{e^-e^+} = (-0.8, +0.3)$. We also repeated the analysis assuming two data samples with integrated luminosities $0.9\ ab^{-1}$ each and two beam polarizations $\mathcal{P}_{e^-e^+} = (\mp 0.8, \pm 0.3)$.

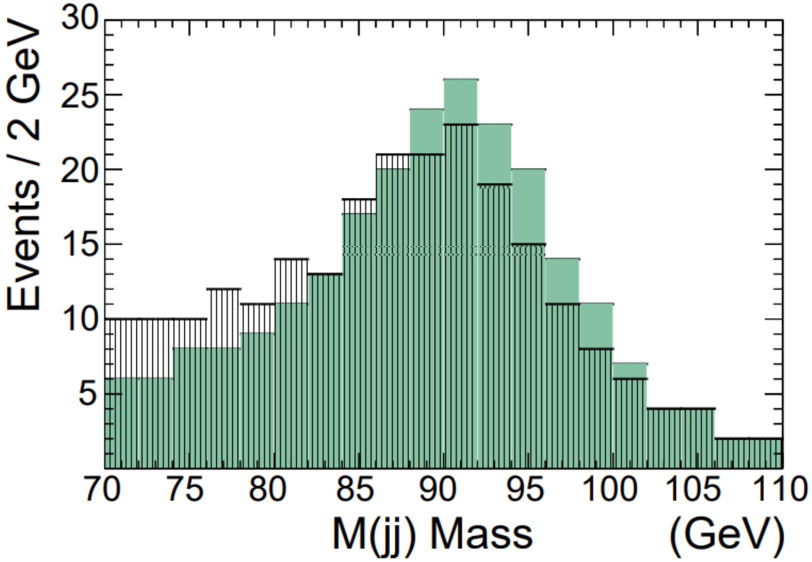
Four channels are studied and the corresponding signal and background contributions are estimated using MC simulation.

Summing results obtained in the four studied channels we obtain the combined statistical uncertainty 5.29% with $2\ ab^{-1}$ at 250 GeV.

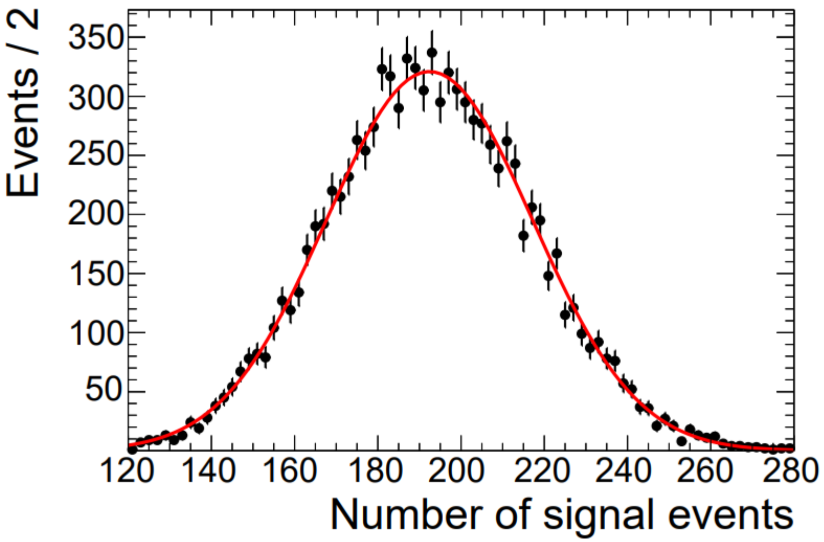
This indicates, that the Higgs width can be measured using this method with an accuracy of about (5-6)% within the model-independent approach.

Thank you for attention

Additional: **Toy MC and jj masses**



The $M(j_1 j_2)$ (hatched histogram) and $M(j_3 j_4)$ (shaded histogram) mass distributions are shown for ***Channel 1****.*



The distribution of the number of the signal events obtained from the ***toy MC fits*** *(dots with errors).*