Measurement of $H \to Z\gamma$ decay at the 250 GeV ILC

Update

Evgeny Antonov, Alexey Drutskoy

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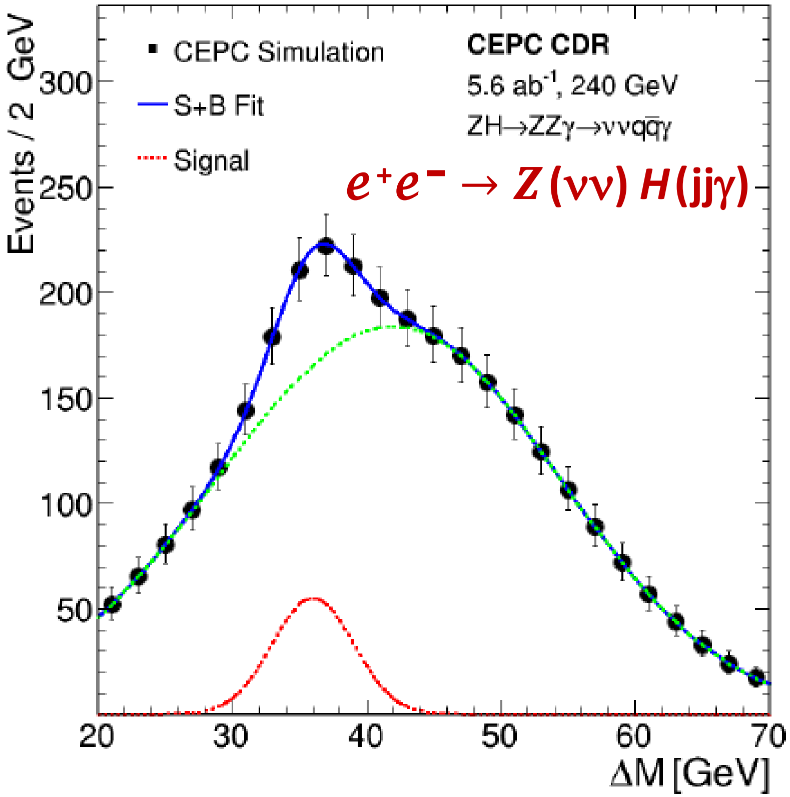
Introduction

CEPC accuracy of H→Zγ decay measurement using Z→νν and Z→*jj* modes



Decay mode	$\sigma(ZH) \times \mathrm{BR}$	BR
$H \to b\bar{b}$	0.27%	0.56%
$H \to c\bar{c}$	3.3%	3.3%
$H \to gg$	1.3%	1.4%
$H \to WW^*$	1.0%	1.1%
$H \to ZZ^*$	5.1%	5.1%
$H \to \gamma\gamma$	6.8%	6.9%
$H \to Z\gamma$	15%	15%

Combining 2 channels accuracy of 13% is obtained for 5.6 ab^{-1}.

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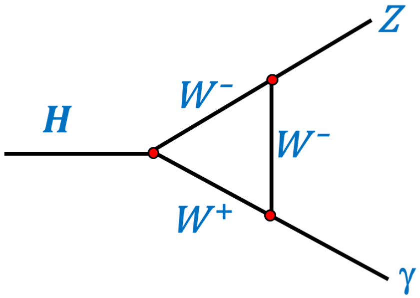
selected photon pairs for $Z \to \nu\bar{\nu}$. (b) $e^+e^- \to ZH$ production with $H \to Z\gamma$: the distribution of the mass difference between the reconstructed $Z\gamma$ and Z system including contributions from both $M(qq\gamma) - M(qq)$ and $M(\nu\bar{\nu}\gamma) - M(\nu\bar{\nu})$. The markers and their uncertainties represent expectations from a CEPC dataset of 5.6 ab^{-1}, whereas the solid blue curves are the signal-plus-background fit results. The dashed curves are the signal and background components.

Introduction

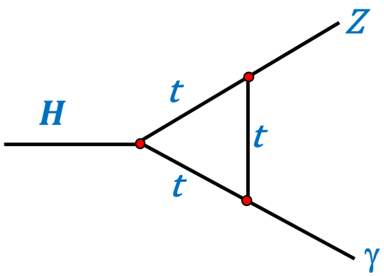
Decay H→Zγ go through loop diagram with charged particles inside loop.
It is sensitive to heavy charged BSM particles contributions.

The expected significance of this signal for the Standard model (SM) Higgs boson was evaluated by the ATLAS and CMS collaborations for the full Run 2 dataset and the value 1.2σ was obtained by both experiments.

High sensitivity to loop contributions of heavy charged BSM particles.
The relative probability depends weakly on the W boson mass, this effect is well inside uncertainties obtained in this analysis



Dominant contribution



~10-15 %

The basic information for the MC samples for the signal and the backgrounds with significant contributions. The given cross sections are corrected for the decay branching fractions indicated in the first column.

Process	Integrated luminosity, ab^{-1}		Cross section, fb		Number of events	
	eLpR	eRpL	eLpR	eRpL	eLpR	eRpL
			Signal samples			
	eLpR	eRpL	eLpR	eRpL	eLpR	eRpL
$q\bar{q}H(Z\gamma)$	191	298	0.52	0.34	$1{\cdot}10^5$	$1{\cdot}10^5$
			Background samples			
	eLpR	eRpL	eLpR	eRpL	eLpR	eRpL
$q\bar{q}$	5.00	5.00	$128{\cdot}10^3$	$70.4{\cdot}10^3$	$6.40{\cdot}10^8$	$3.52{\cdot}10^8$
$W(q\bar{q})W(q\bar{q})$	5.00	5.12	$14.8{\cdot}10^3$	225	$7{\cdot}10^7$	$7{\cdot}10^5$
$Z(q\bar{q})Z(q\bar{q})$	5.05	5.11	$1.41{\cdot}10^3$	607	$7{\cdot}10^6$	$3{\cdot}10^6$
$Z/W(q\bar{q})Z/W(q\bar{q})$	5.00	5.32	$12.4{\cdot}10^3$	226	$6{\cdot}10^7$	10^6
$Z(q\bar{q})Z(\mu^+\mu^-/\tau^+\tau^-)$	5.01	5.14	838	467	$4{\cdot}10^6$	$2{\cdot}10^6$
$q\bar{q}H(b\bar{b})$	0.50	0.78	199	128	10^5	10^5
$q\bar{q}H(\tau^+\tau^-)$	23.2	36.3	21.5	13.8	$5{\cdot}10^5$	$5{\cdot}10^5$
$q\bar{q}H(W^+W^-)$	6.81	10.6	73.4	47.0	$5{\cdot}10^5$	$5{\cdot}10^5$
$q\bar{q}H(ZZ)$	55.6	86.9	8.99	5.75	$5{\cdot}10^5$	$5{\cdot}10^5$
$\tau^+\tau^-H(\text{all})$	7.45	11.6	67.1	42.9	$5{\cdot}10^5$	$5{\cdot}10^5$

List of studied background samples

2f_hadronic (eLpR, eRpL)
2f_leptonic (eLpR, eRpL)
2f_eehiq (eLpR, eRpL, eLpL, eRpR)
4f_singleW_leptonic (eLpR, eRpL, eLpL, eRpR)
4f_singleW_semileptonic (eLpR, eRpL, eLpL, eRpR)
4f_singleZee_leptonic (eLpR, eRpL, eLpL, eRpR)
4f_singleZee_semileptonic (eLpR, eRpL, eLpL, eRpR)
4f_singleZnunu_leptonic (eLpR, eRpL)
4f_singleZnunu_semileptonic (eLpR, eRpL)
4f_singleZsingleWMix_leptonic (eLpR, eRpL, eLpL, eRpR)
4f_WW_hadronic (eLpR, eRpL)
4f_WW_leptonic (eLpR, eRpL)
4f_WW_semileptonic (eLpR, eRpL)
4f_ZZ_hadronic (eLpR, eRpL)
4f_ZZ_leptonic (eLpR, eRpL)
4f_ZZ_semileptonic (eLpR, eRpL)
4f_Znunu_leptonic (eLpR, eRpL)
4f_Znunu_semileptonic (eLpR, eRpL)
4f_ZZWWMix_hadronic (eLpR, eRpL)
4f_ZZWWMix_leptonic (eLpR, eRpL)
6f_eexxxx (eLpR, eRpL, eLpL, eRpR)
6f_eexyyx (eLpR, eRpL, eLpL, eRpR)
6f_eeyyyy (eLpR, eRpL, eLpL, eRpR)
6f_llxxxx (eLpR, eRpL)
6f_llxyyx (eLpR, eRpL)
6f_llyyyy (eLpR, eRpL)
6f_vvxxxx (eLpR, eRpL)
6f_vvxyyx (eLpR, eRpL)
6f_vvyyyy (eLpR, eRpL)

e1e1H (eLpR, eRpL, eLpL, eRpR)
e2e2H (eLpR, eRpL)
e3e3H (eLpR, eRpL)
n1n1H (eLpR, eRpL)
n23n23H (eLpR, eRpL)
qqh_aa (eLpR, eRpL)
qqh_bb (eLpR, eRpL)
qqh_cc (eLpR, eRpL)
qqh_e2e2 (eLpR, eRpL)
qqh_e3e3 (eLpR, eRpL)
qqh_gg (eLpR, eRpL)
qqh_ww (eLpR, eRpL)
qqh_zz (eLpR, eRpL)

Jet reconstruction procedure

We identify isolated leptons and photons using ***IsolatedLeptonTagging and IsolatedPhotonTagging*** processors with standard parameters and separate it from all PFO's before jet reconstruction.

For jet reconstruction and b-tagging we use ***FastJet*** processor with the ***Valencia algorithm***.

The Algorithm contains 3 parameters: R - generalized jet radius, γ and β - special capture parameters in beam distance.
We use **β = 1, R = 1.5 and γ = 0.5**.

Process $e^+e^- \to W^+W^-\gamma$ gives a strong background contribution. To suppress this background we select only events with one of **Z bosons decaying to b-jets**.

The selection criteria for event tagging with b-jets: at least one jet with **more than 90%** probability is identified as b-jet. The efficiency of the b-tagging is **87%** for the signal process. Number of misstagging events less then **1%**.

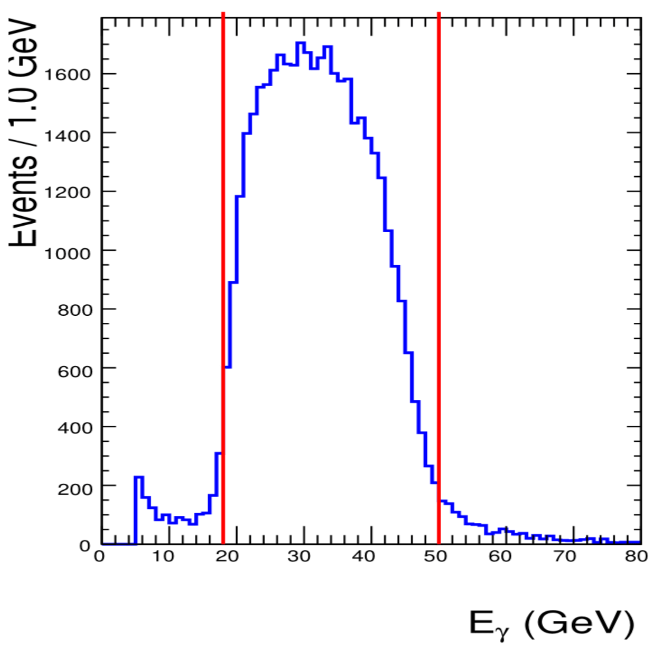
Studied backgrounds

We study many background sources: 2-, 4-, 6-fermion processes, $H(jj)$ where $H \to all$ and other Higgs boson processes.
Dangerous backgrounds come from 2f_hadronic, 4f_ZZ and e3e3H samples.
Small background comes from 4f_WW and qqH_e3e3 samples.

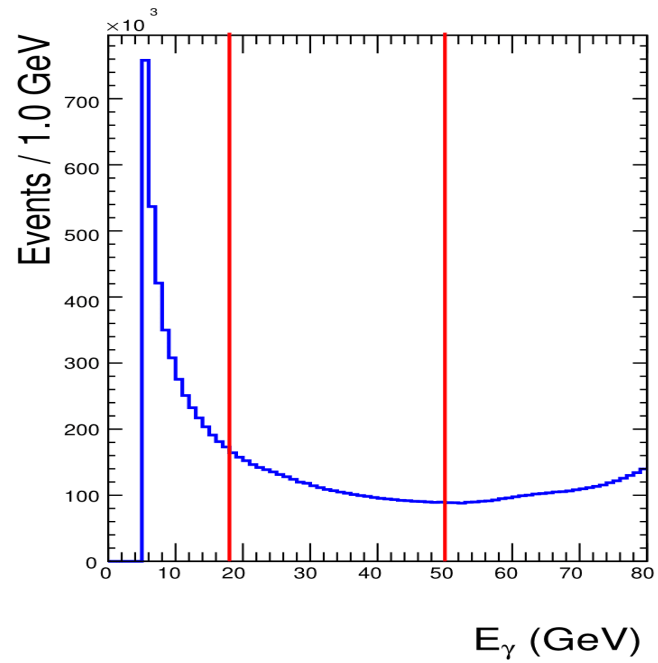
To suppress backgrounds we applied several cuts:

1) E_{γ} in $[18, 50]$ GeV

Signal



Sum of backgrounds



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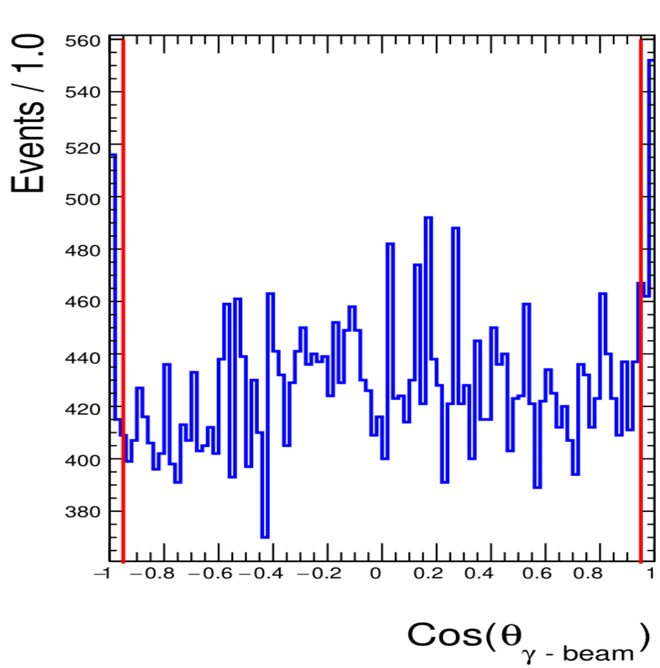
Small background comes from 4f_WW and qqH_e3e3 samples.

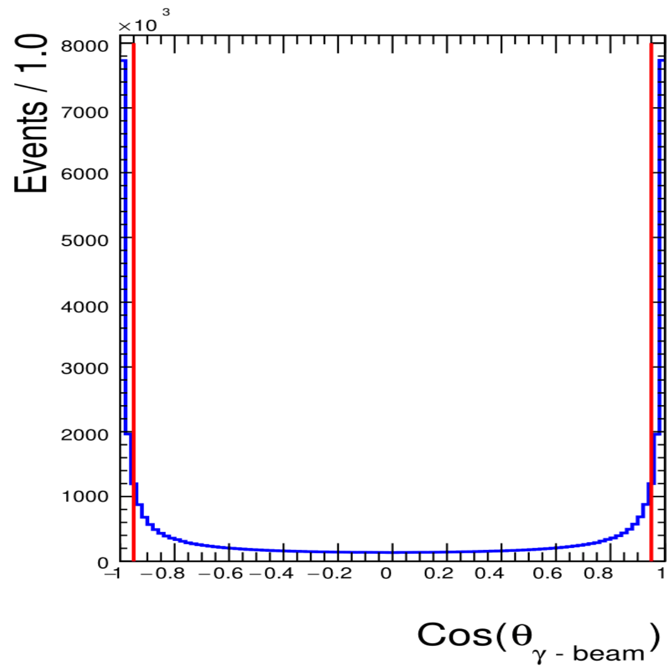
To suppress backgrounds we applied several cuts:

2) $cos(\theta_{\gamma-beam}) < |0.95|$

Signal



Sum of backgrounds



Studied backgrounds

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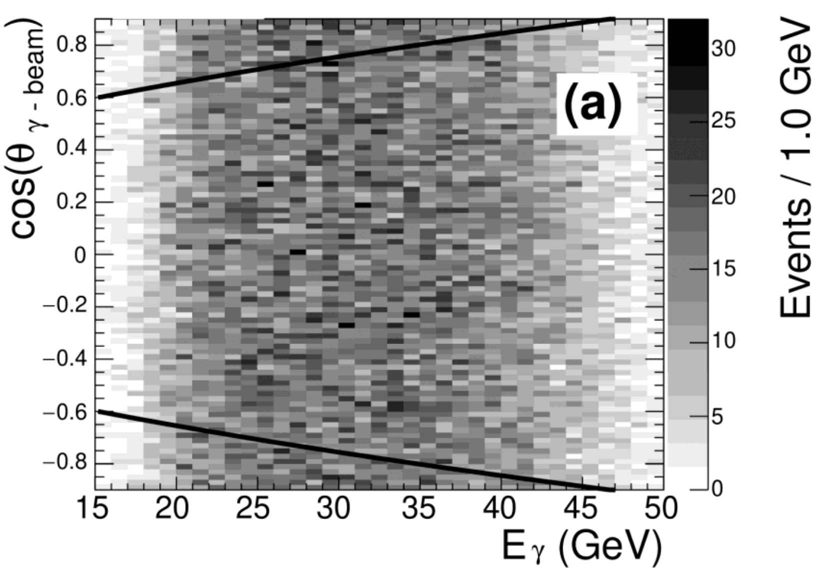
Dangerous backgrounds come from 2f_hadronic, 4f_ZZ and e3e3H samples.

Small background comes from 4f_WW and qqH_e3e3 samples.

To suppress backgrounds we applied several cuts:

3)|$E_{\gamma} - 70 \cdot cos^2(\theta_{\gamma-beam})$ > -10 GeV/c| :

Signal



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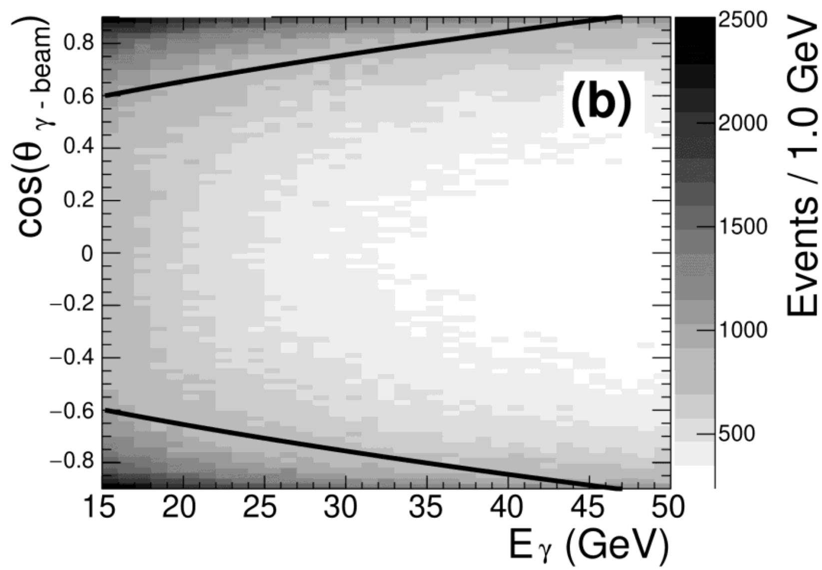

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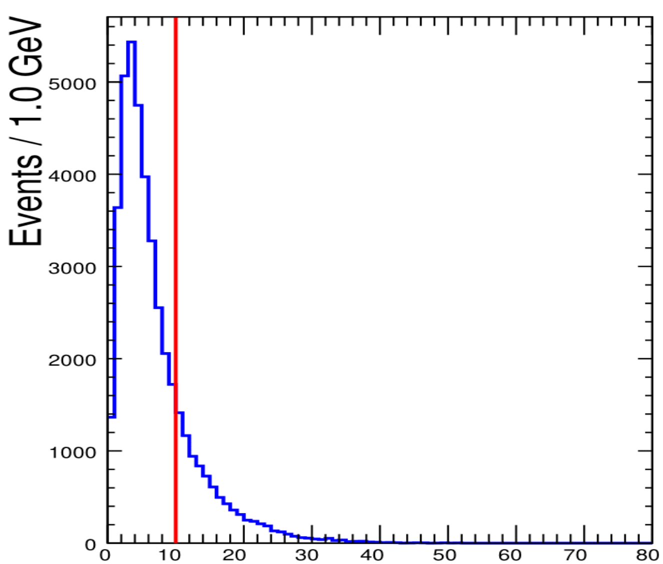
Dangerous backgrounds come from 2f_hadronic, 4f_ZZ and e3e3H samples.
Small background comes from 4f_WW and qqH_e3e3 samples.

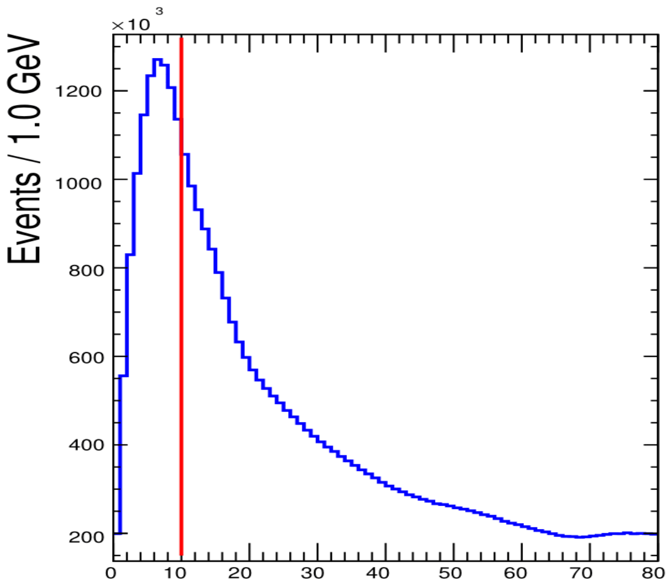
To suppress backgrounds we applied several cuts:

4) P_t of $jjjj\gamma$ system $< 10\ GeV/c$

Signal



Sum of backgrounds



Studied backgrounds

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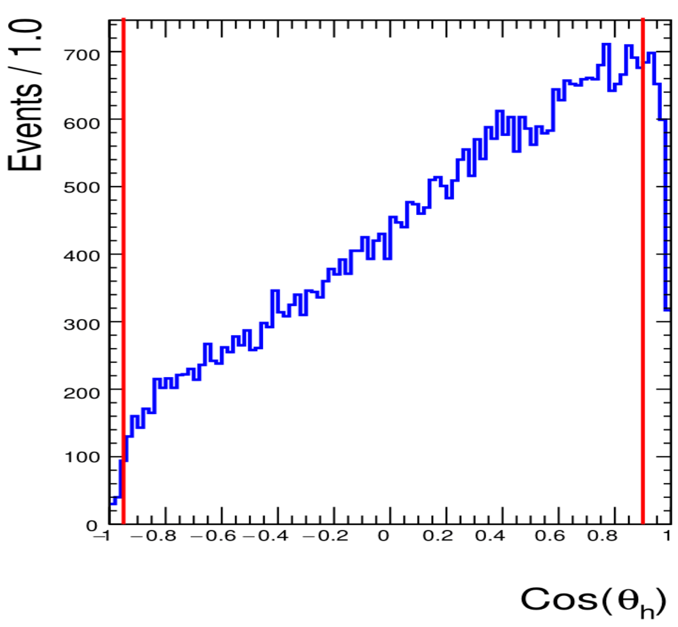
Small background comes from 4f_WW and qqH_e3e3 samples.

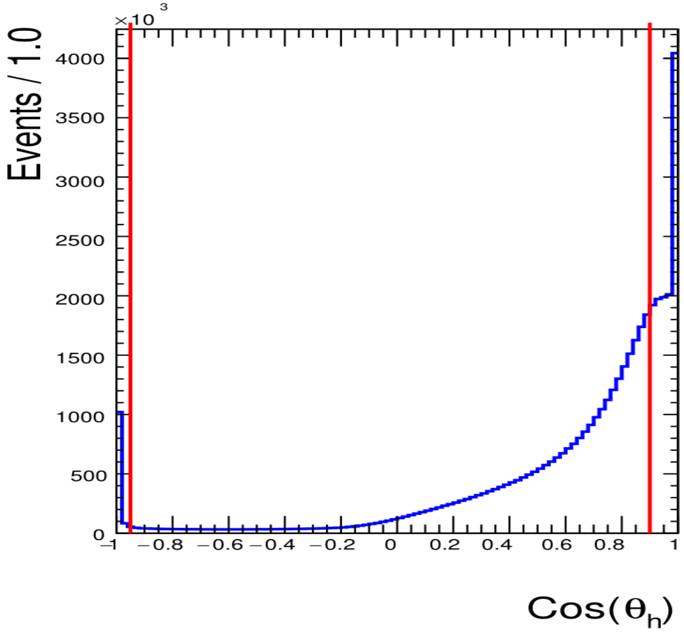
To suppress backgrounds we applied several cuts:

5) Helicity angle between Higgs and jet from Z boson $cos(\theta_h)$ in $[-0.95, 0.9]$:

Signal



Sum of backgrounds



Studied backgrounds

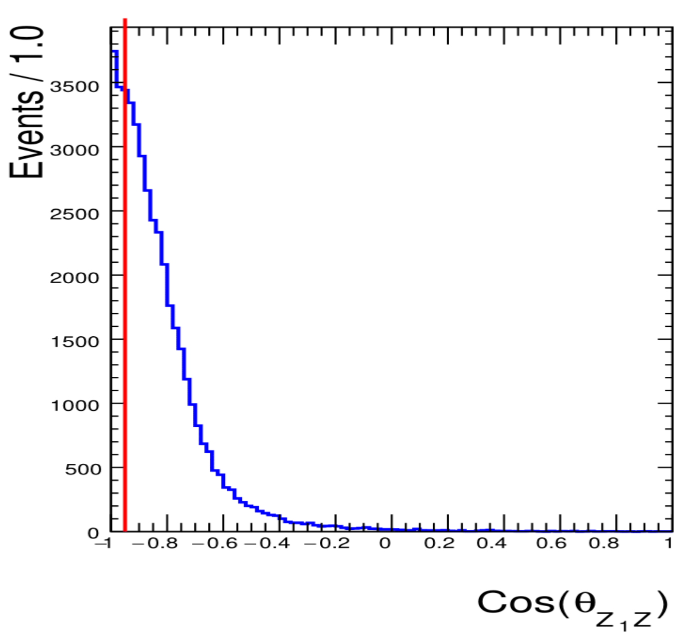
We study many background sources: **2-, 4-, 6-fermion processes**, $\boldsymbol{H(jj)}$ **where** $\boldsymbol{H \to all}$ and other Higgs boson processes.
Dangerous backgrounds come from 2f_hadronic, 4f_ZZ and e3e3H samples.
Small background comes from 4f_WW and qqH_e3e3 samples.

To suppress backgrounds we applied several cuts:

6) $\boldsymbol{cos(\theta_{Z_1 Z}) > -0.95}$ **:**

7) $\boldsymbol{N_{PFO's} > 60}$ **– to suppress leptonic backgrounds.**

Signal



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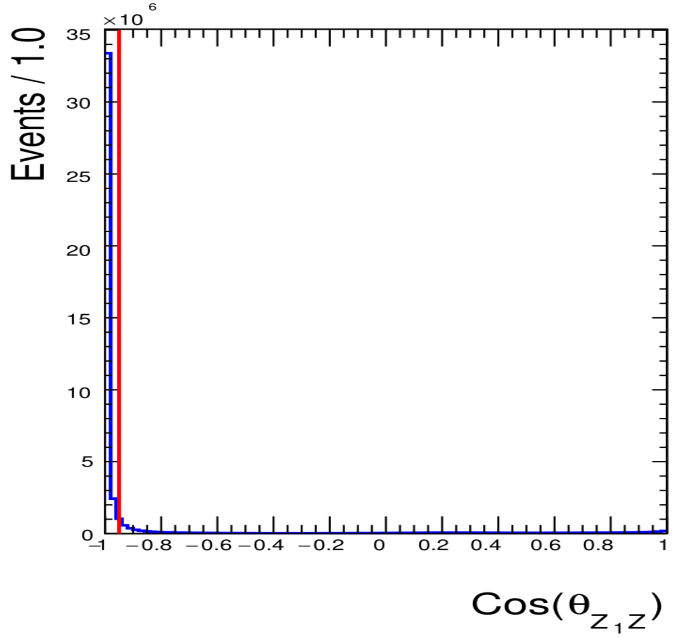


Technical issues

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

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

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

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

All **σ** parameters are the mean widths of corresponding mass or momentum distributions on the reconstruction level: $\sigma_{M_{Z_1}} = 14.2$ GeV, $\sigma_{M_Z} = 14.3$ GeV, $\sigma_{P_{Z_1}} = 7.1$ GeV, $\sigma_{P_{Z+\gamma}} = 7.7$ GeV

We take only events with $\chi^2 < 15$

To get expected number of signal or background events we apply weight factors to each event:

$$W_{LR/RL} = \left[\frac{(1 \pm 0.8)}{2} \cdot \frac{(1 \pm 0.3)}{2}\right] \cdot \frac{2 \text{ ab}^{-1}}{\mathcal{L}}$$

Mass difference is used to get a better mass resolution:

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

The numbers of signal events before and after cuts. The integrated luminosity 2 ab^{-1} and polarization $P_{e^-e^+} = (-0.8, +0.3)$ is assumed. The percentage of the number of events from the previous step is indicated in brackets.

$e^+e^- \to Z_1(jj)Z(jj)\gamma$	eLpR	eRpL
MC events	70100	69786
Weight factors	$6.1 \cdot 10^{-3}$	$2.4 \cdot 10^{-4}$
Weighted MC events	430.5	16.4
Photon tagging, weighted events	388.9 (90.3%)	14.8 (90.4%)
b-tagging, weighted events	131.5 (33.8%)	5.0 (34.0%)
Weighted events after all cuts	58.0 (44.1%)	2.0 (39.0%)

Results with 2 ab^{-1}

After weighting and applying all cuts the $\boldsymbol{M}_{\Delta}$ distributions is obtained for $\mathcal{P}_{e^-e^+} = (-0.8, +0.3)$ with $2\ ab^{-1}$ integrated luminosity.

The signal distribution was described by the convolution of Breit-Wigner and Gaussian functions + additional wide Gaussians to describe both tails:

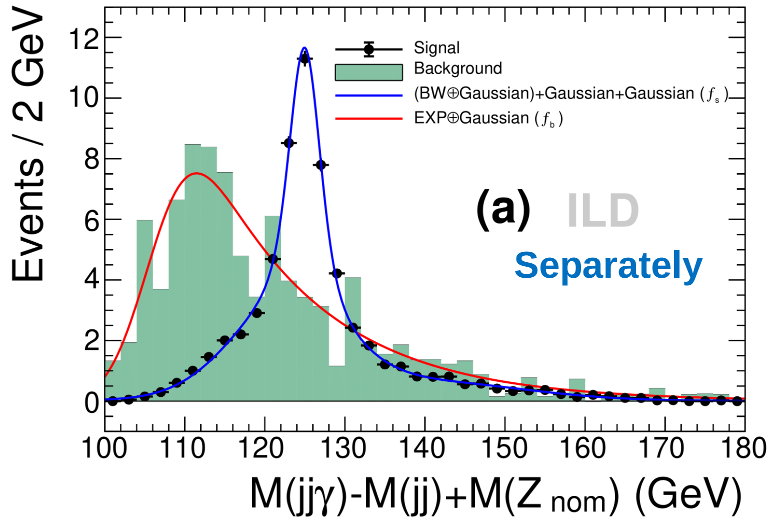
$$F_S(m) = f_1\,\mathrm{BW}\otimes G_1 + (1-f_1)\times[f_2\,G_2 + (1-f_2)\,G_3]$$

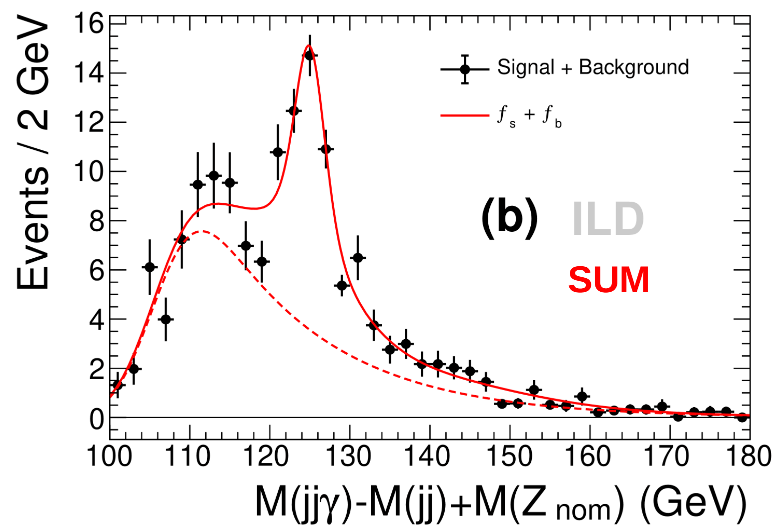
The background distribution is described by:

$$F_B(m) = exp(-m/\tau) \otimes G_4$$

The fit yields 60 ± 13 signal events for $2\ ab^{-1}$ with single polarization.

This corresponds to uncertainty of 22%.

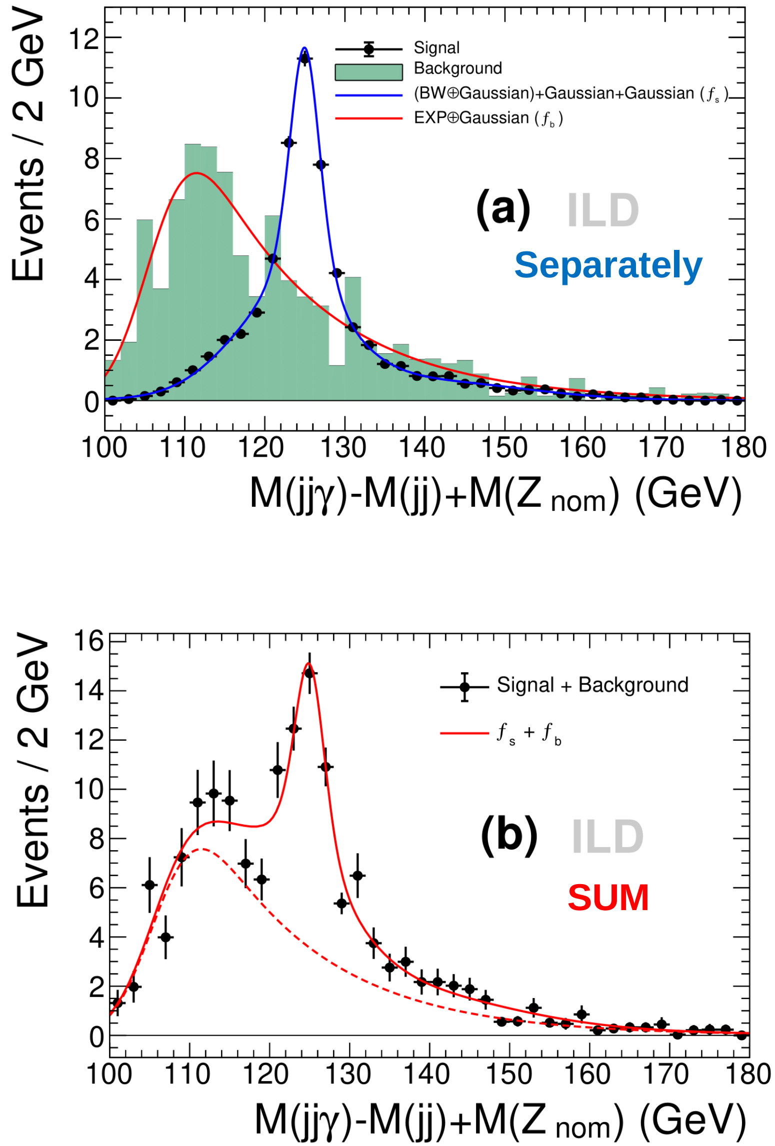




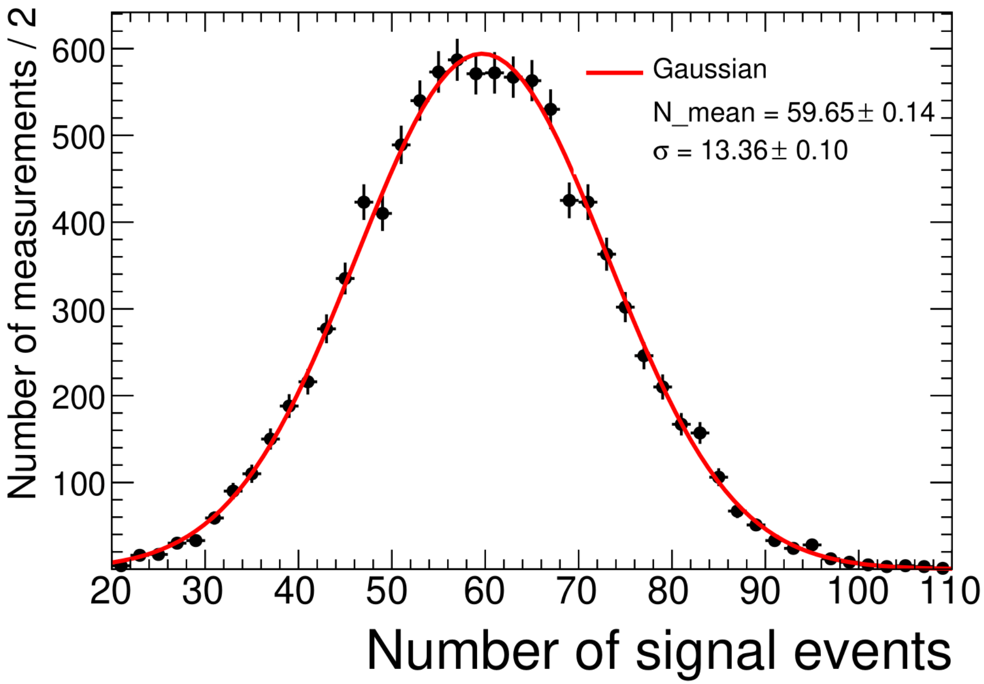
Results with 2 ab^{-1}

The parameters obtained from the separate signal and background fits

Signal	
Breit-Wigner mean, μ	124.99 ± 0.06 GeV
Gaussian 1 width	1.38 ± 0.09 GeV
Gaussian 2 mean	140.63 ± 1.76 GeV
Gaussian 2 width	12.05 ± 0.75 GeV
Gaussian 3 mean	122.54 ± 0.31 GeV
Gaussian 3 width	7.11 ± 0.18 GeV
Fraction f_1 (Gauss sum and BW)	0.55 ± 0.02
Fraction f_2 (Gauss sum)	0.73 ± 0.04
Background	
Exponential τ	14.59 ± 0.97
Gaussian 4 mean	106.08 ± 0.59 GeV
Gaussian 4 width	4.18 ± 0.66 GeV



Toy MC results with $2\ ab^{-1}$



The **10000** $\boldsymbol{M_{\Delta}}$ mass distributions are generated using the shapes and normalizations for the sum of the signal and background distributions obtained separately.

Toy MC also yields 22% of uncertainty.

The ILC strawman running scenario:

0.9 ab^{-1} with $P_{e^-e^+} =$ **(−0.8, +0.3)** and $P_{e^-e^+} =$ **(+0.8, -0.3)** each,
plus **0.1** ab^{-1} with $P_{e^-e^+} =$ **(−0.8, -0.3)** and $P_{e^-e^+} =$ **(+0.8, +0.3)** each.

We therefore also reweighted the events passing our analysis to the combination of **0.9** ab^{-1} with $P_{e^-e^+} =$ **(−0.8, +0.3)** and **0.9** ab^{-1} with $P_{e^-e^+} =$ **(+0.8, −0.3)** , obtaining a statistical uncertainty of **24%**.

This result takes into account the increase in effective luminosity compared to an unpolarized dataset of **1.8** ab^{-1} , but not the full advantage of polarized beams. For optimal results, the selection should be tuned separately for each of the datasets, in order to exploit their different intrinsic signal-to-background ratios. We leave this part for future work.

Conclusions

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

The analysis is performed assuming the integrated luminosity $2\ \mathrm{ab}^{-1}$ 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 repeat the analysis assuming two data samples with integrated luminosities $0.9\ \mathrm{ab}^{-1}$ each and two beam polarizations $\mathcal{P}_{e^-e^+} = (\mp 0.8, \pm 0.3)$.

The corresponding signal and background contributions are estimated using full MC simulated samples.

We obtain the statistical uncertainty of 22% with $2\ \mathrm{ab}^{-1}$ at 250 GeV.
We repeat this analysis for two samples of $0.9\ \mathrm{ab}^{-1}$ and obtained the statistical uncertainty of 24%.

The accuracy of this method is about the same as one obtained at CEPC and can be combined to further improve the accuracy.