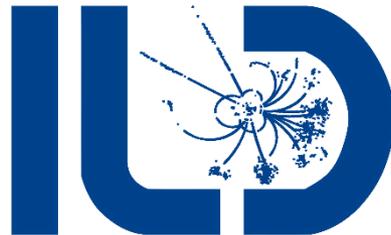


Measurement of $H \rightarrow Z\gamma$ decay at the 250 GeV ILC

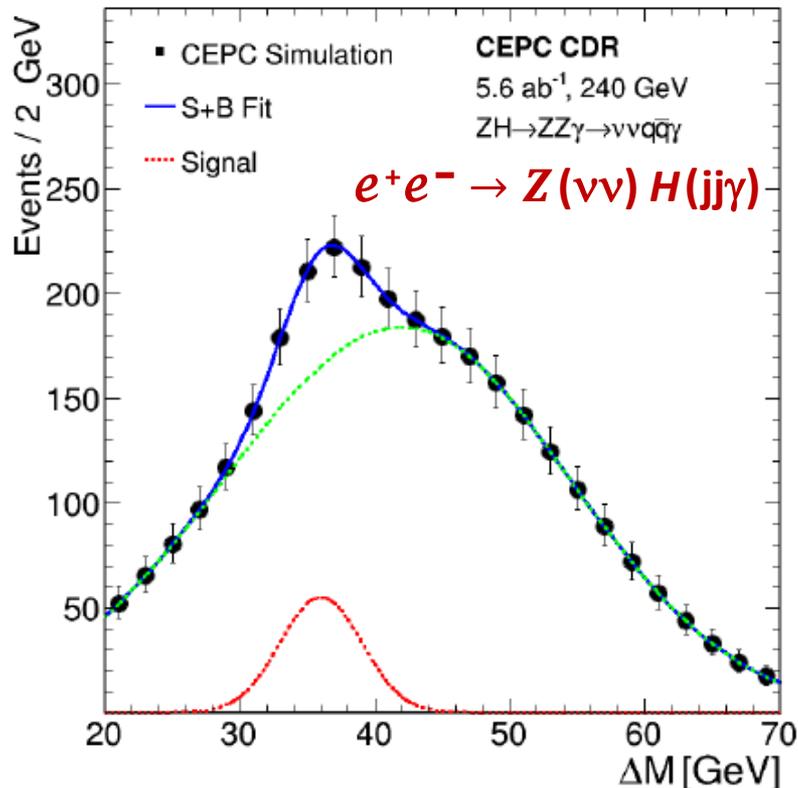
Evgeny Antonov, Alexey Drutskoy



ILD group meeting 06.12.2022

Introduction

CEPC accuracy of $H \rightarrow Z\gamma$ decay measurement using $Z \rightarrow \nu\nu$ and $Z \rightarrow jj$ modes



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

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

[Chinese Physics C, Volume 43, Number 4](#)

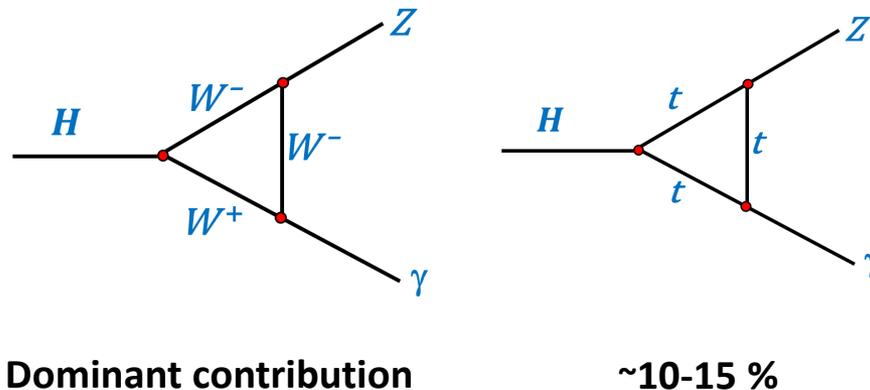
selected photon pairs for $Z \rightarrow \nu\bar{\nu}$. (b) $e^+e^- \rightarrow ZH$ production with $H \rightarrow Z\gamma$: the distribution of the mass difference between the reconstructed $Z\gamma$ and Z system including contributions from both $M(qq\gamma) - M(qq)$ and $M(\nu\bar{\nu}\gamma) - M(\nu\bar{\nu})$. 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 $H \rightarrow Z\gamma$ 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



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 $\beta = 1$, $R = 1.5$ and $\gamma = 0.5$.

Process $e^+e^- \rightarrow W^+W^-\gamma$ 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 misstaggering events less than **1%**.

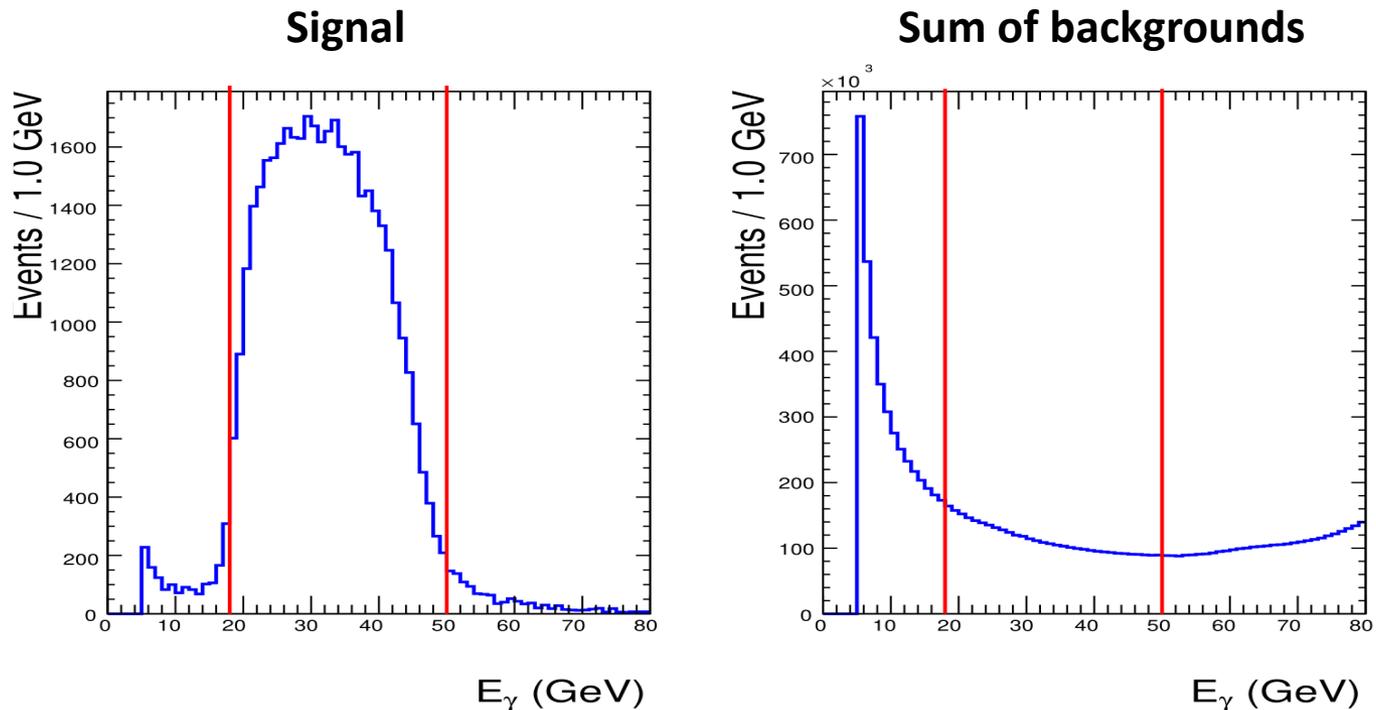
Studied backgrounds

We study many background sources: 2-, 4-, 6-fermion processes, $H(jj)$ where $H \rightarrow all$ 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



Studied backgrounds

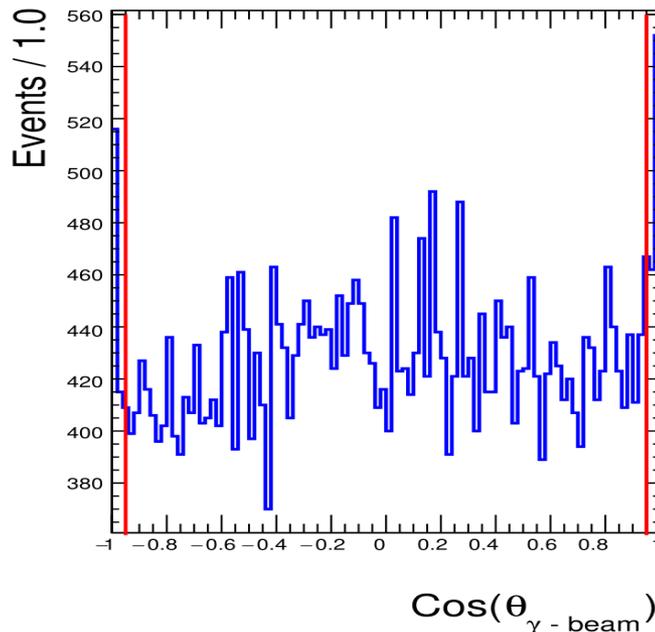
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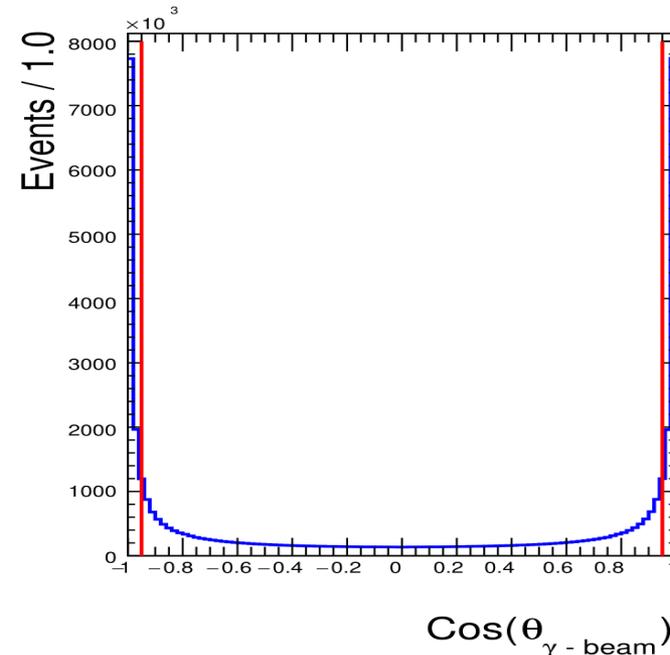
To suppress backgrounds we applied several cuts:

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

Signal



Sum of backgrounds



Studied backgrounds

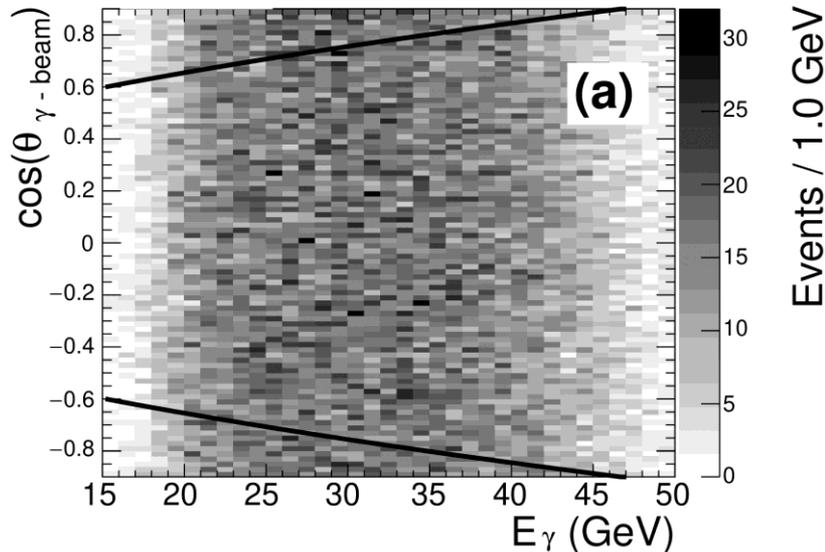
We study many background sources: 2-, 4-, 6-fermion processes, $H(jj)$ where $H \rightarrow all$ and other Higgs boson processes.

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

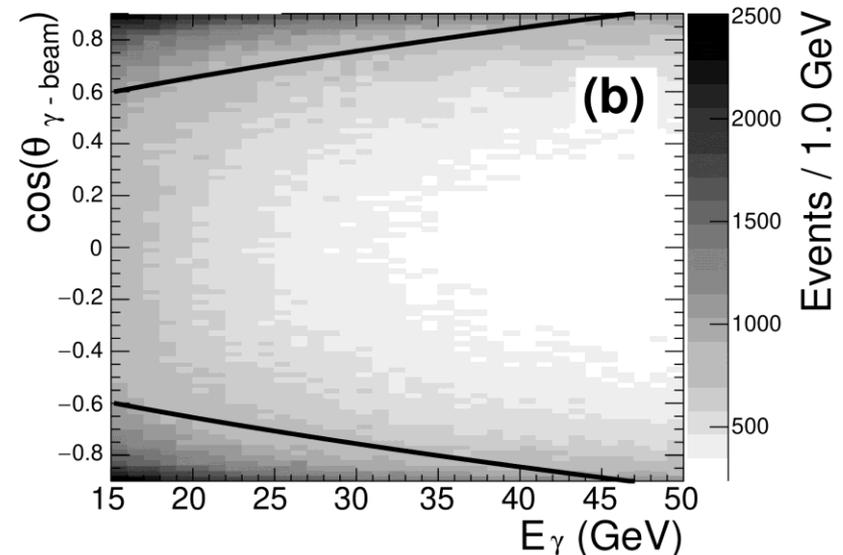
To suppress backgrounds we applied several cuts:

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

Signal



Sum of backgrounds



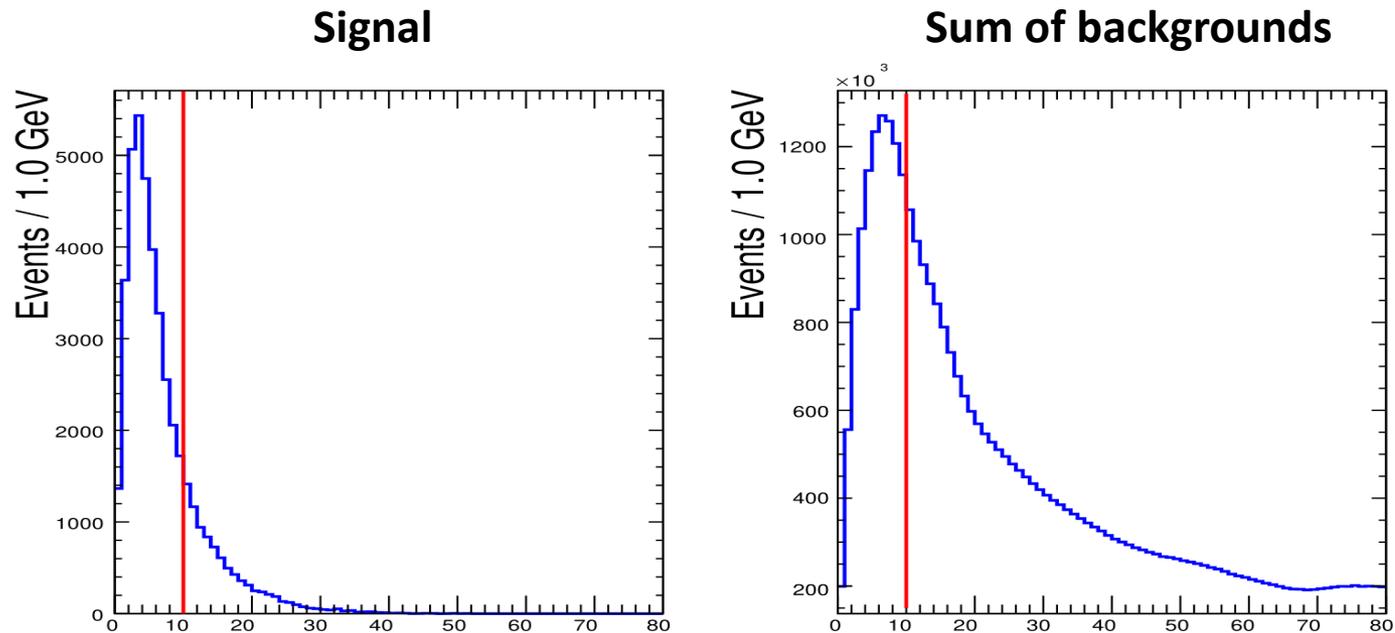
Studied backgrounds

We study many background sources: 2-, 4-, 6-fermion processes, $H(jj)$ where $H \rightarrow all$ 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:

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



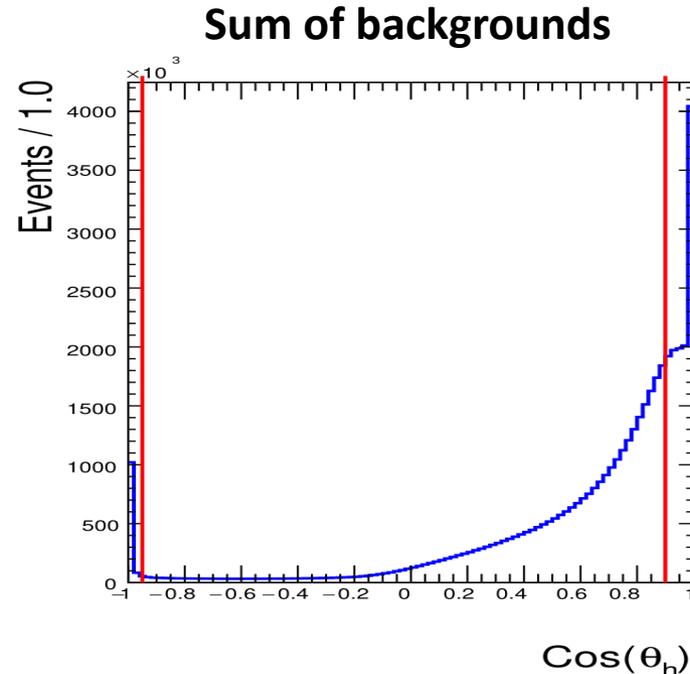
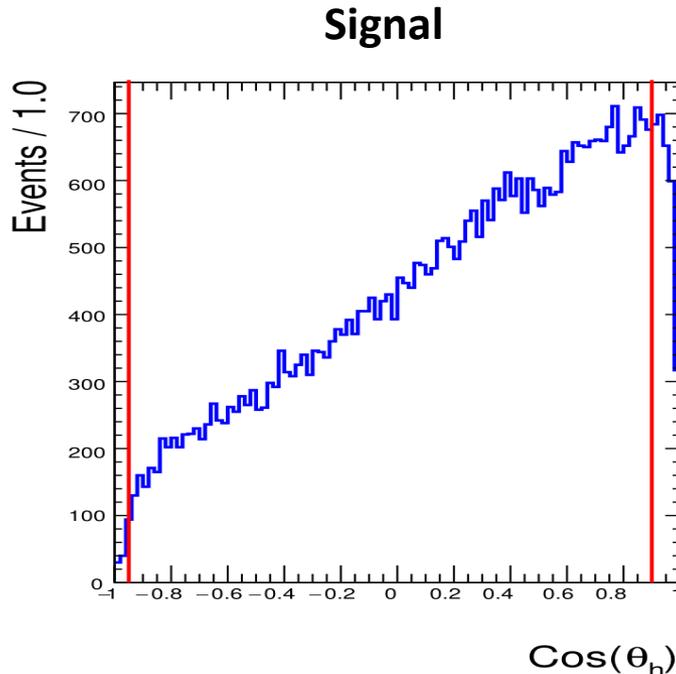
Studied backgrounds

We study many background sources: 2-, 4-, 6-fermion processes, $H(jj)$ where $H \rightarrow all$ 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:

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



Studied backgrounds

We study many background sources: **2-, 4-, 6-fermion processes**, $H(jj)$ where $H \rightarrow all$ and other Higgs boson processes.

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

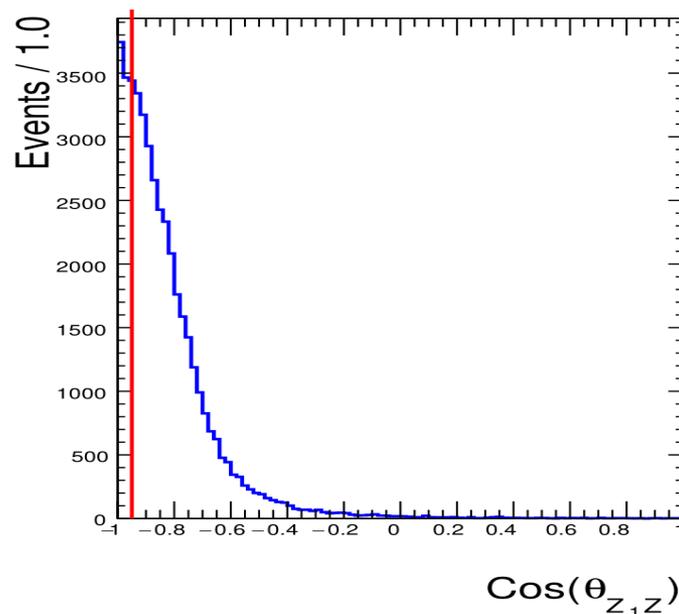
Small background comes from **4f_WW** and **qqH_e3e3** samples.

To suppress backgrounds we applied several cuts:

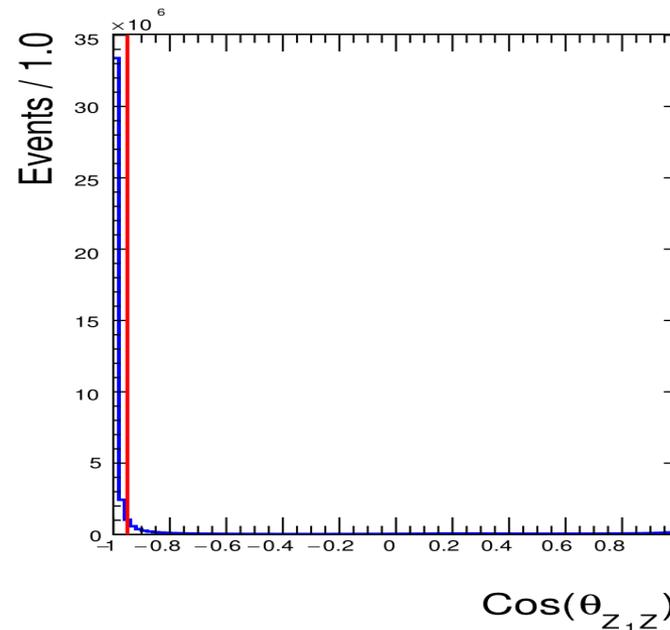
6) $\cos(\theta_{Z_1 Z}) > -0.95$:

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

Signal



Sum of backgrounds



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:

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

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

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

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

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:

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

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.

$e^+e^- \rightarrow Z_1(jj)Z(jj)\gamma$	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 M_{Δ} 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:

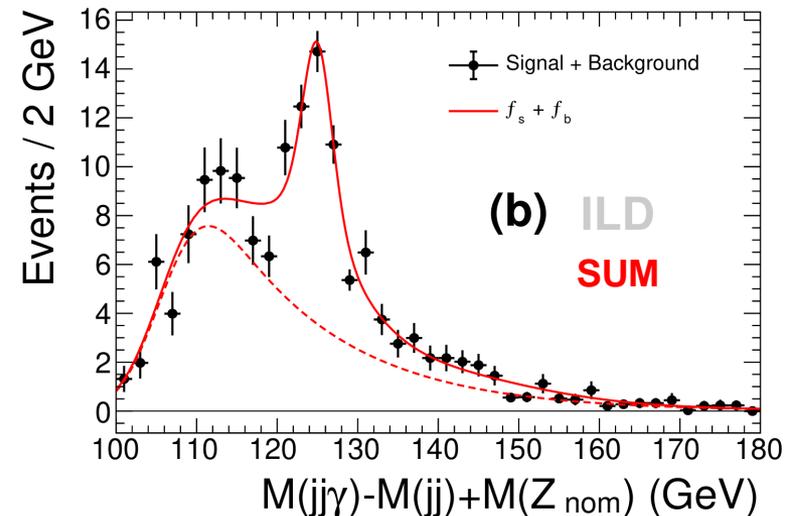
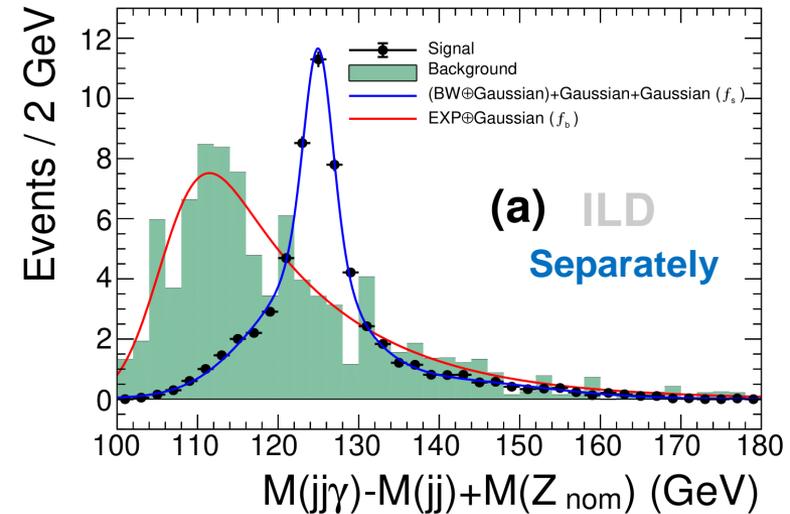
$$F_S(m) = f_1 \text{BW} \otimes G_1 + (1 - f_1) \times [f_2 G_2 + (1 - f_2) G_3]$$

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.

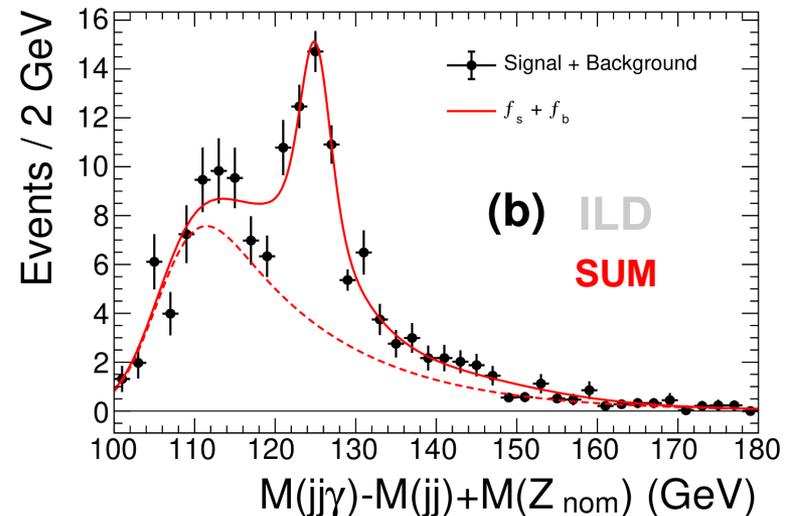
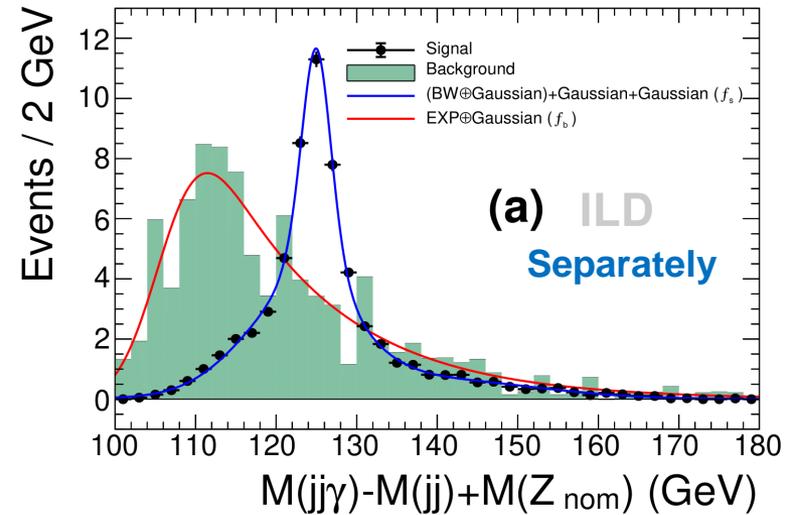
This corresponds to uncertainty of **22%**.



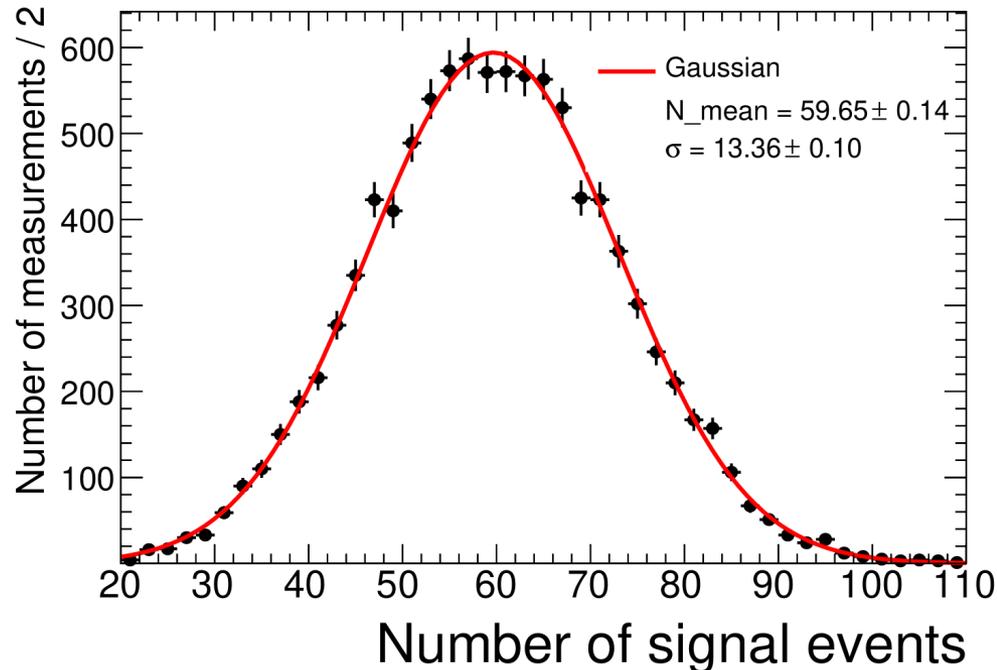
Results with 2 ab^{-1}

The parameters obtained from the separate signal and background fits

Signal	
Breit-Wigner mean, μ	$124.99 \pm 0.06 \text{ GeV}$
Gaussian 1 width	$1.38 \pm 0.09 \text{ GeV}$
Gaussian 2 mean	$140.63 \pm 1.76 \text{ GeV}$
Gaussian 2 width	$12.05 \pm 0.75 \text{ GeV}$
Gaussian 3 mean	$122.54 \pm 0.31 \text{ GeV}$
Gaussian 3 width	$7.11 \pm 0.18 \text{ GeV}$
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	$106.08 \pm 0.59 \text{ GeV}$
Gaussian 4 width	$4.18 \pm 0.66 \text{ GeV}$



Toy MC results with 2 ab^{-1}



The **10000** M_{Δ} 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 $e^+e^- \rightarrow HZ$ process with the subsequent $H \rightarrow Z\gamma$ 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 repeat the analysis assuming two data samples with integrated luminosities 0.9 ab^{-1} each and two beam polarizations $\mathcal{P}_{e^-e^+} = (\mp 0.8, \pm 0.3)$.

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

We obtain the statistical uncertainty of 22% with 2 ab^{-1} at 250 GeV .

We repeat this analysis for two samples of 0.9 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.