Testing Higgs CP properties at the CEPC with an additional ISR parameter

Egor Vasenin, Lebedev Physical Institute
Supervisor: Prof. Alexey Drutskoy, Lebedev Physical Institute

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Motivation

Within the Standard model the Higgs boson is predicted to be the CP-even scalar ($J^{CP} = 0^+$). Any admixture of the CP-odd component will indicate to BSM physics, with deep implications for the baryogenesis and electroweak scale dynamics.

The hypothesis of pure spin-1 or pure spin-2 Higgs has been excluded by ATLAS and CMS at 99% CL

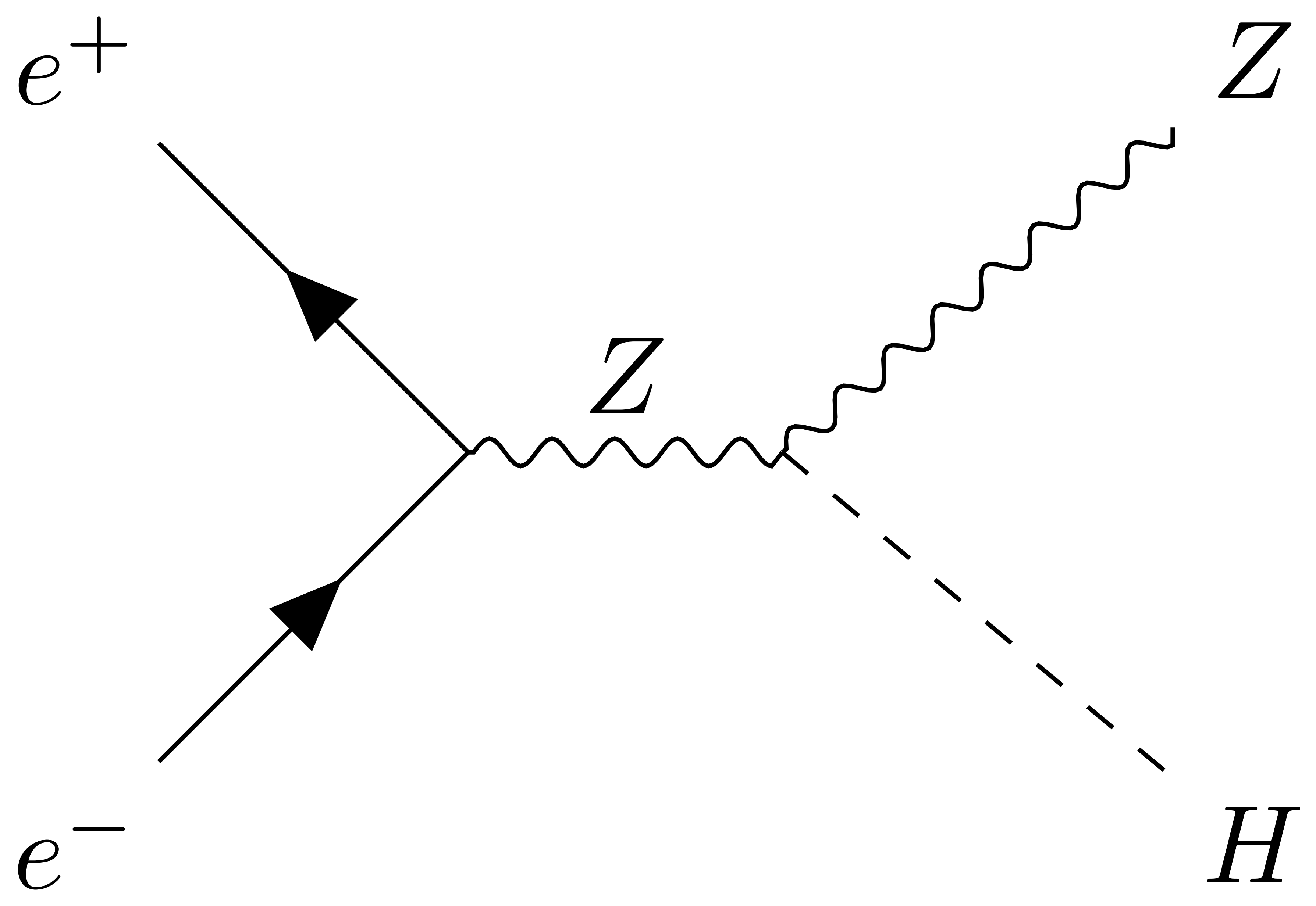
Their results show exclusion of the pure CP-odd scalar structure of the top quark Yukawa ($t\bar{t}H$) coupling at 3.9σ (3.2σ) and the fractional contribution of the CP-odd component is measured to be $f_{CP}^{H\bar{t}t} = 0.00 \pm 0.33$.

However, small anomalous contributions are not excluded!

Theoretical framework

In this study we focus on HZZ coupling in the $e^+e^- \to HZ$ process, as it is sensitive to Higgs boson CP-properties

There are several theoretical approaches to parametrize this vertex



$$\mathscr{L}^V = \cos\psi_{CP} \cdot \kappa_{SM} \frac{g_{HZZ}}{2} Z_\mu Z^\mu - \sin\psi_{CP} \cdot \frac{1}{4\Lambda} \kappa_{AZZ} Z_{\mu\nu} \tilde{Z}^{\mu\nu}$$

$$\mathscr{L}^V = c_{ZZ} H Z_\mu Z^\mu + c_{Z\tilde{Z}} H Z_{\mu\nu} \tilde{Z}^{\mu\nu}$$

$$\mathscr{L}_{CPV} = \frac{H}{v} \left(\tilde{c}_{ZZ} \frac{g_1^2 + g_2^2}{4} Z_{\mu\nu} \tilde{Z}^{\mu\nu} \right)$$

Previous works, 68% upper limits

- Eur. Phys. J. C 82, 981 (2022): $\tilde{c}_{ZZ} = [-0.08, 0.07]$ (CEPC) ($Z \to \mu^+\mu^-, 5.6$ ab^{-1})
- ATL-PHYS-PUB-2013-013: $f_{g4} = 0.15 \to \tilde{c}_{ZZ} \approx 1.35$ (HL-LHC) ($H \to ZZ^* \to 4l, 300$ fb^{-1})
- CERN-2025-005: $f_{CP}^{HZZ} = 3.7 \times 10^{-5} \to \tilde{c}_{ZZ} = 0.02$(?) (FCC-ee) ($Z \to \mu^+\mu^-, 10.8$ ab^{-1})

These constraints can be updated with our method

Experimental procedures

Software

- WHIZARD v3.1.6 with Higgs Characterization model is used for event generation. ISR effects are taken into account in WHIZARD
- PYTHIA6 performs hadronization
- DELPHES with CEPC card is used for detector fast simulation

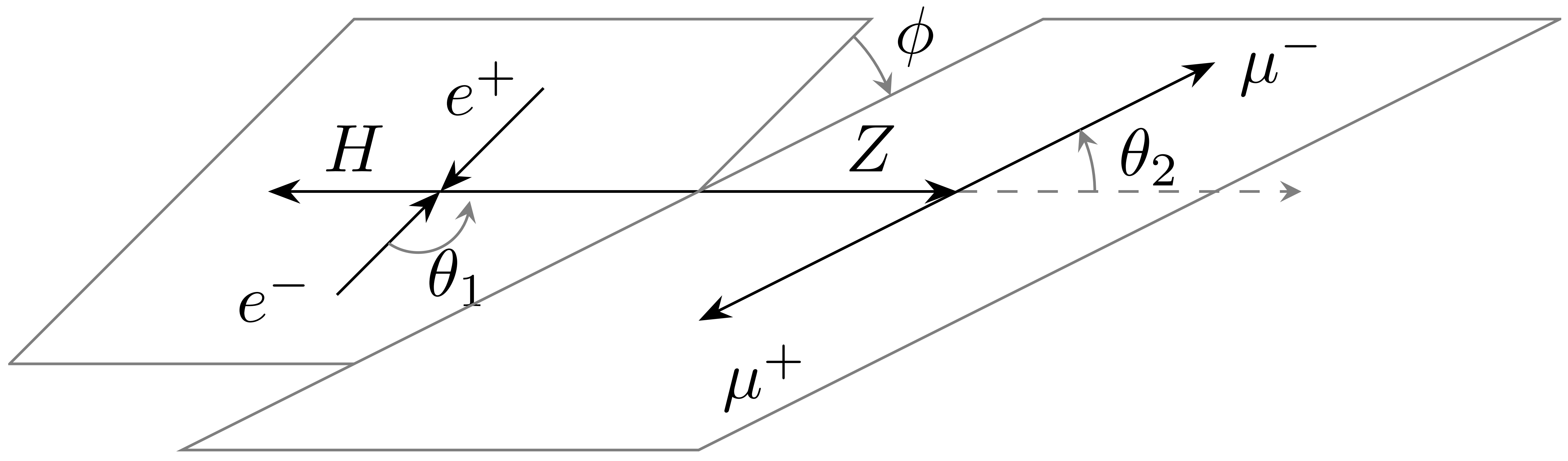
Samples with different values of ψ_{CP} corresponding to $\tilde{c}_{ZZ}$ in range [-1.2,1.2] are generated at $\sqrt{s} = 240$ GeV and statistics of 5.6 ab^{-1}

Experimental procedures

Reconstruction, angular distributions

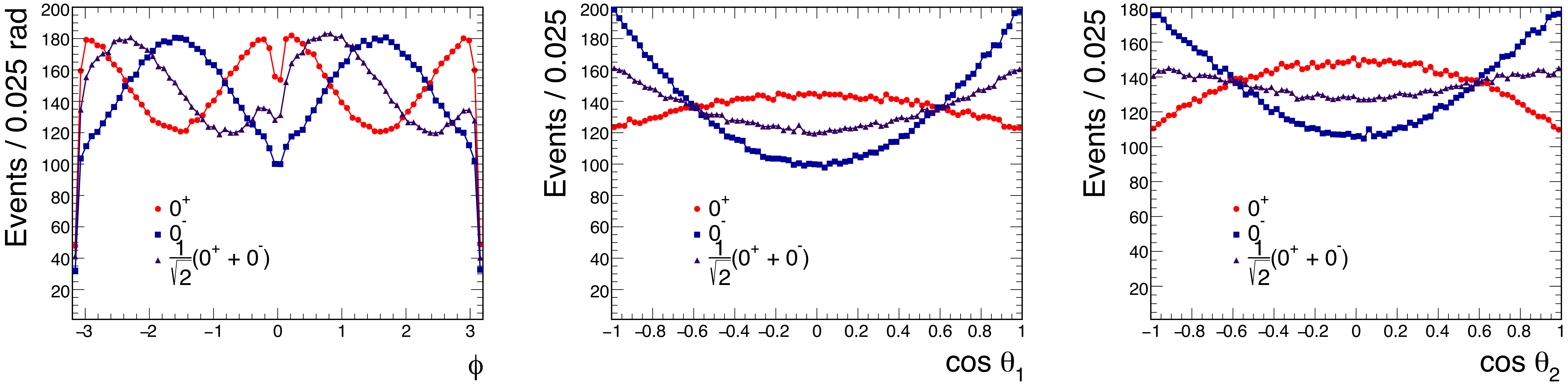
The $Z \to \mu^+\mu^-$, $H \to$ incl process is chosen for the analysis. Z boson is reconstructed from 2 muons, Higgs boson is not reconstructed in this analysis.

Three angular distributions $\theta_1, \theta_2, \varphi$ are used for analysis, shown in the figure:



Experimental procedures

Angular distributions



Angular distributions for different Higgs CP-properties: red circles — 0^+, blue squares — 0^-, purple triangles— 50/50

Experimental procedures

ISR energy shift

ISR photons are predominantly emitted close to the beam axis, carrying away part of the event energy

The reconstructed total event energy, corrected for the ISR effects, is defined as $E_{\mathrm{RECO}} = E_H + E_Z$

Since the Higgs boson is not directly reconstructed, E_H is obtained under the assumption of zero total event momentum:

$$E_H = \sqrt{p_H^2 + m_H^2} \approx \sqrt{p_Z^2 + m_H^2}$$

Experimental procedures

Cross section dependence

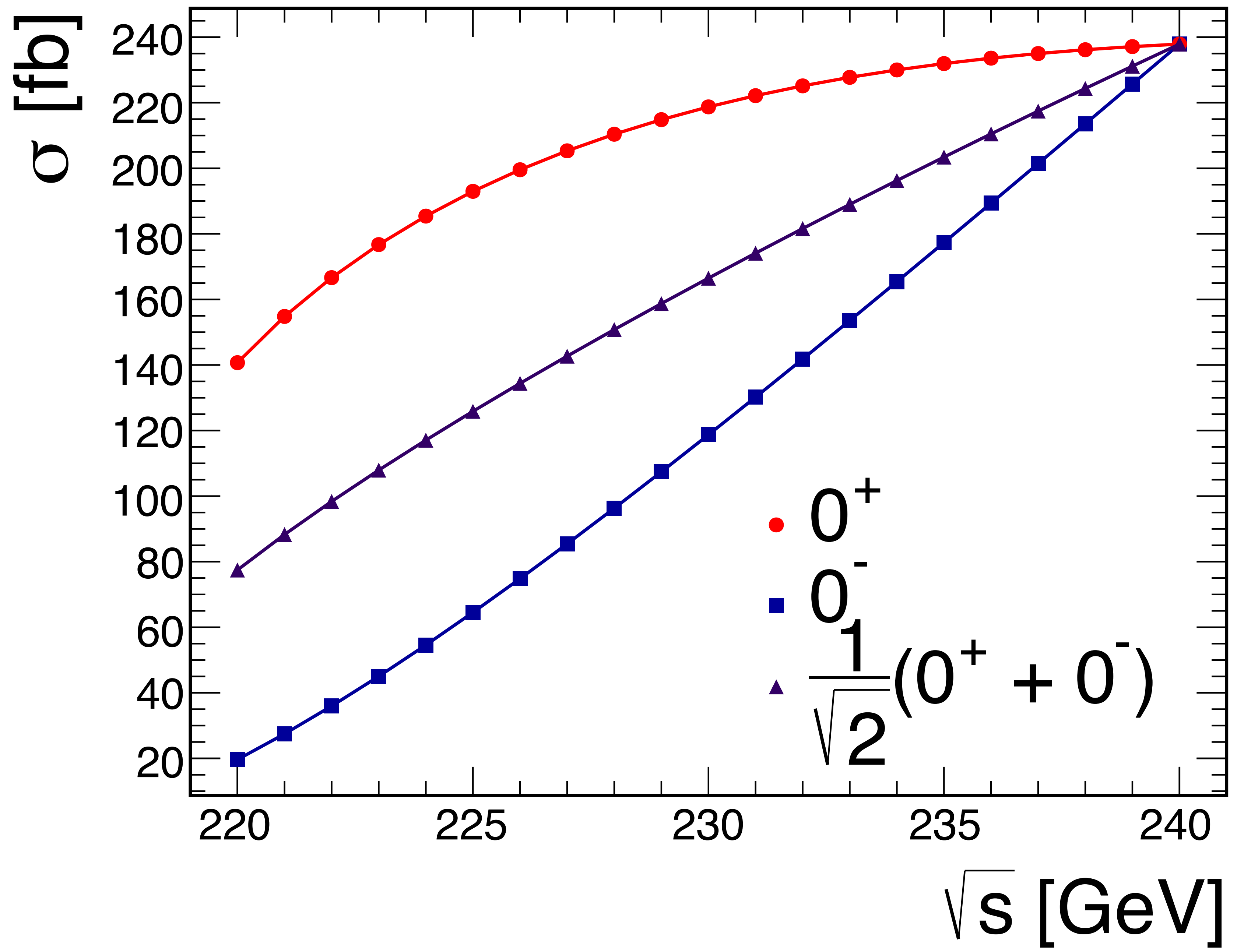
Total cross section vs $\sqrt{s}$ shape depends on Higgs CP-properties

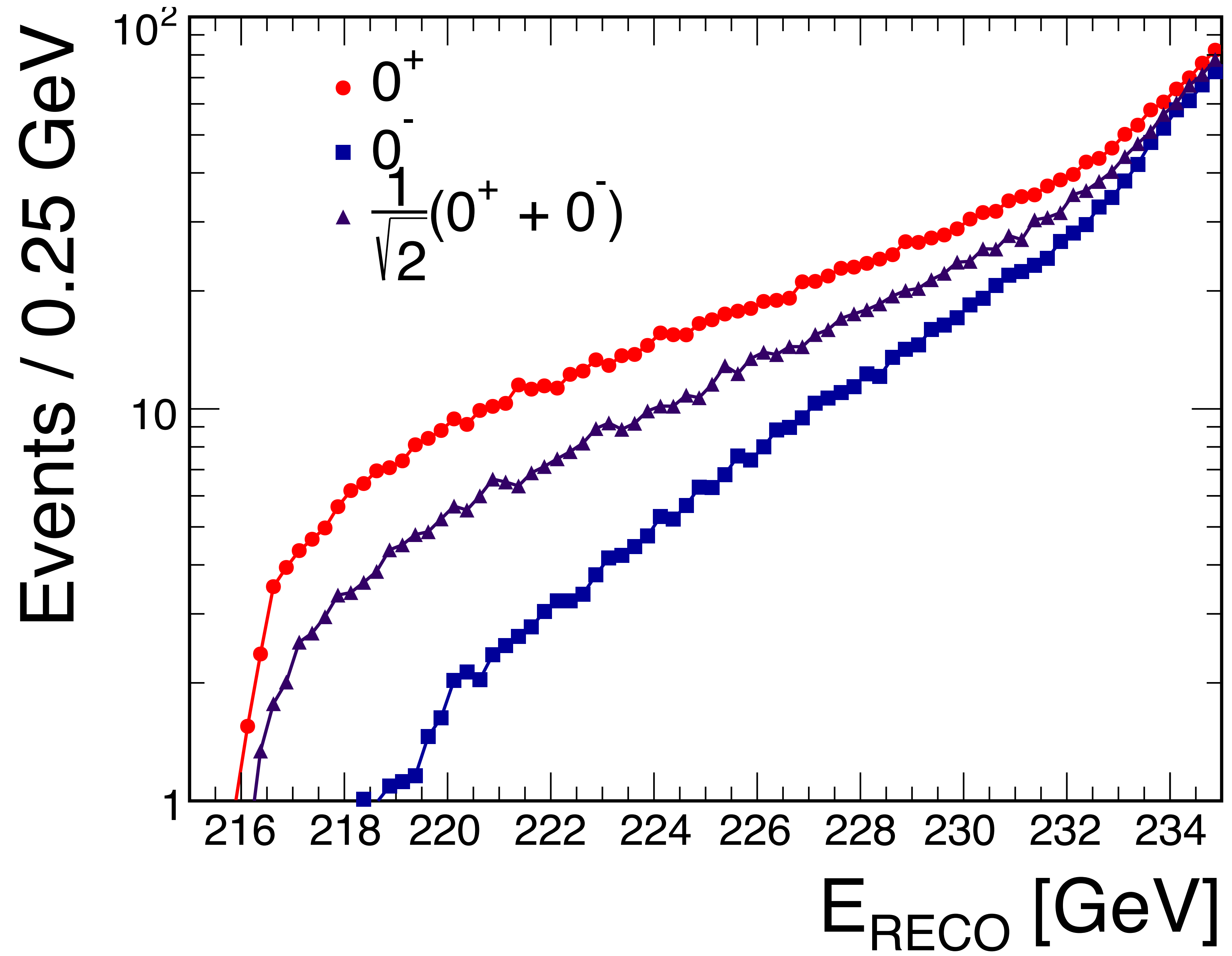
$e^+e^- \to Z* \to HZ$

$1^- \to 0^+1^-$(s-wave) for CP-even

$1^- \to 0^-1^-$ (p-wave) for CP-odd

E_{RECO} distributions are proportional to cross section, therefore are sensitive to CP state of Higgs boson





Experimental procedures

Backgrounds and selections

The main backgrounds for the signal process are:

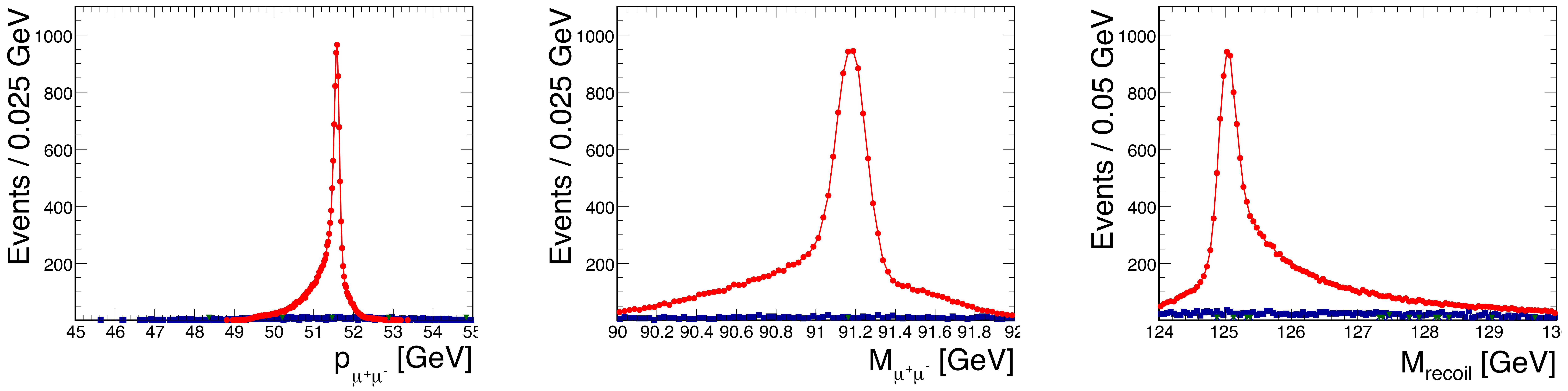
- $e^+e^- \to ZZ$
- $e^+e^- \to W^+W^-$
- $e^+e^- \to \mu^+\mu^-$
- $e^+e^- \to \tau^+\tau^-$

The reconstruction algorithm requires exactly 2 muons and any additional detector activity. This preselection effectively suppresses last three processes, although a small number of events pass the preselection due to FSR and hadronization effects.

The selections are chosen differently in different E_{RECO} ranges. Such a procedure suppresses background processes and accounts for the evolution of angular observables with E_{RECO}

Experimental procedures

Backgrounds and selections



The distributions of observables used in selections

HZ (red circles), ZZ (blue squares), W^+W^- (purple up-triangles), $\mu^+\mu^-$(green down-triangles), $\tau^+\tau^-$ (black stars)

Experimental procedures

Likelihood approach

The analysis is based on a three-dimensional, binned likelihood constructed from the angular observables:

$$\mathscr{L} = \prod_{i,j,k} \text{Poiss}(\mu_{i,j,k} | N_{i,j,k}),$$

i, j, k — bin indices in ϕ, $\cos\theta_1$,and $\cos\theta_2$

$N_{i,j,k}$ — observed number of events in bin

$\mu_{i,j,k}$ — expected number of events according to the SM

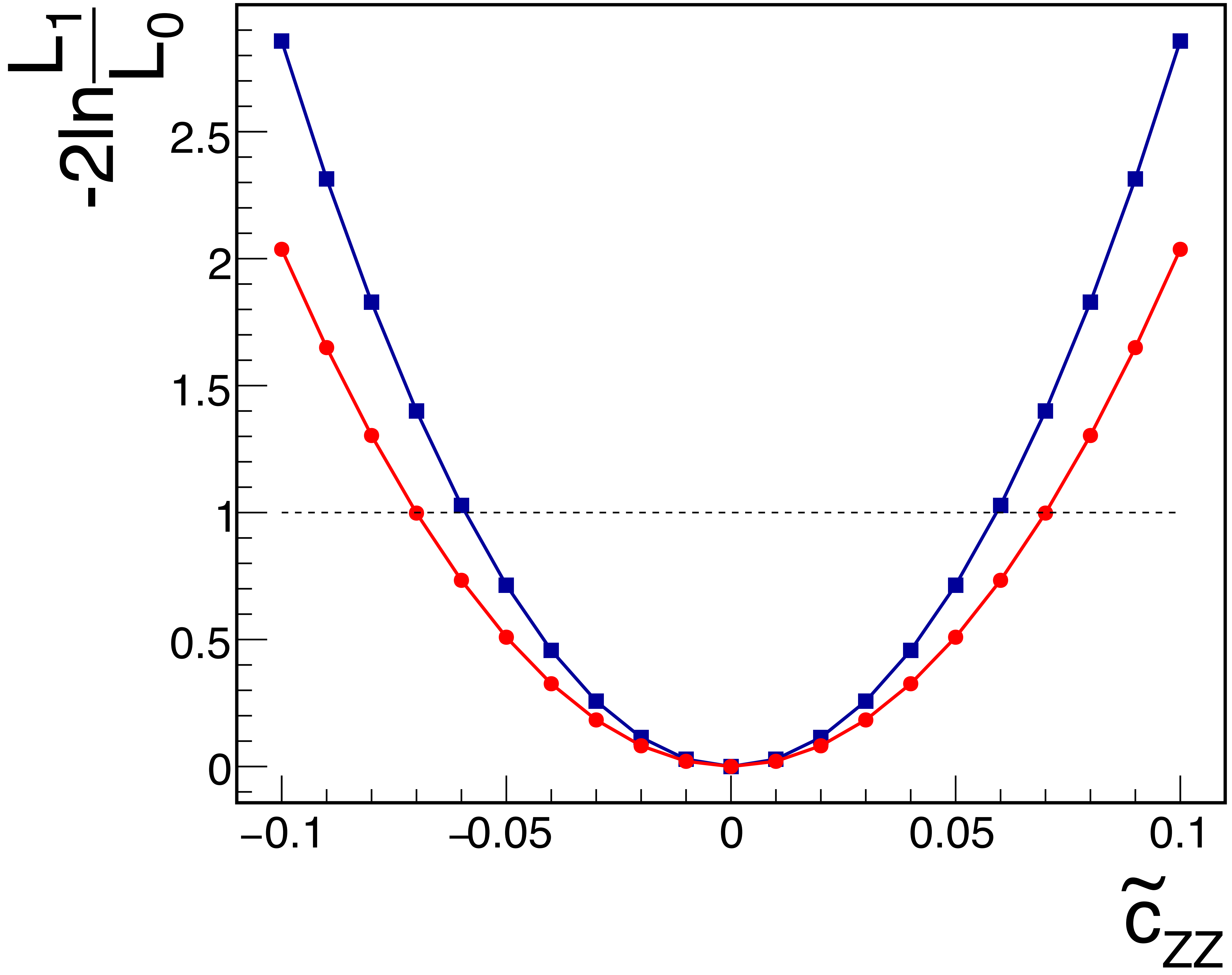
This likelihood is calculated in four different E_{RECO} ranges with respective selection criteria

1. [238,242] GeV
2. [235,238] GeV
3. [230,235] GeV
4. [215,230] GeV

Results

For 68%CL(1σ) the upper limits are:

- $\tilde{c}_{ZZ} = 0.071$ for angular analysis, which is consistent with previous CEPC result for $\mu^+\mu^-$ channel
- $\tilde{c}_{ZZ} = 0.058$ for analysis with ISR, which is improvement of $\approx 20\,\%$



Red circles represents angular observables only analysis, blue squares — analysis with ISR correction

Conclusions

- We obtained upper limit on $\tilde{c}_{ZZ} = \pm\, 0.071$ from standard angular analysis, which agrees well with the CEPC result for $\mu^+\mu^-$ channel Eur. Phys. J. C 82, 981 (2022): $\tilde{c}_{ZZ} = [-0.08, 0.07]$

- Additional ISR related variable improves the result by $\approx 20\,\%$ to the upper limit $\tilde{c}_{ZZ} = \pm\, 0.058$

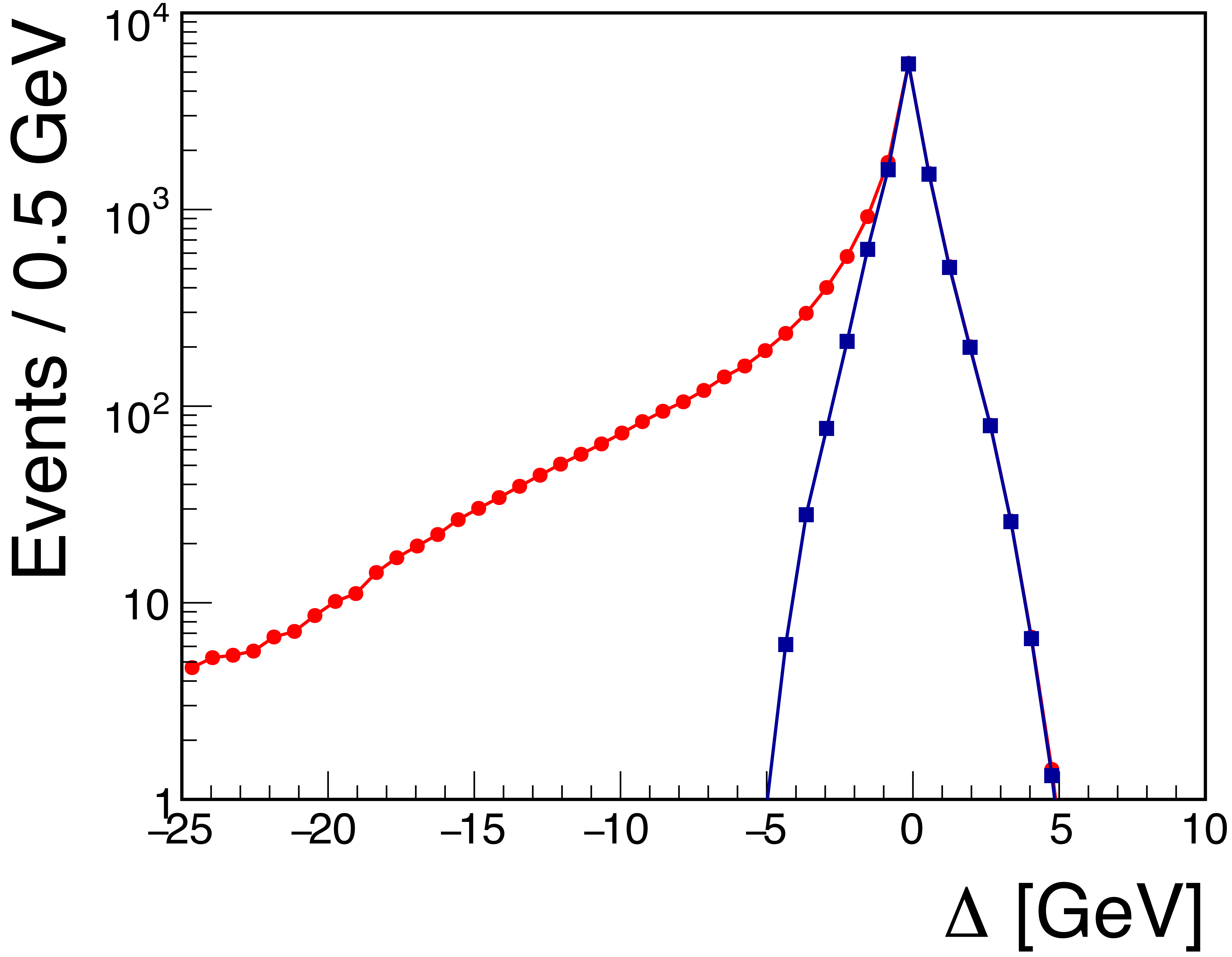
- The $Z \to e^+e^-$ channel can be additionally investigated to further improve upper limits

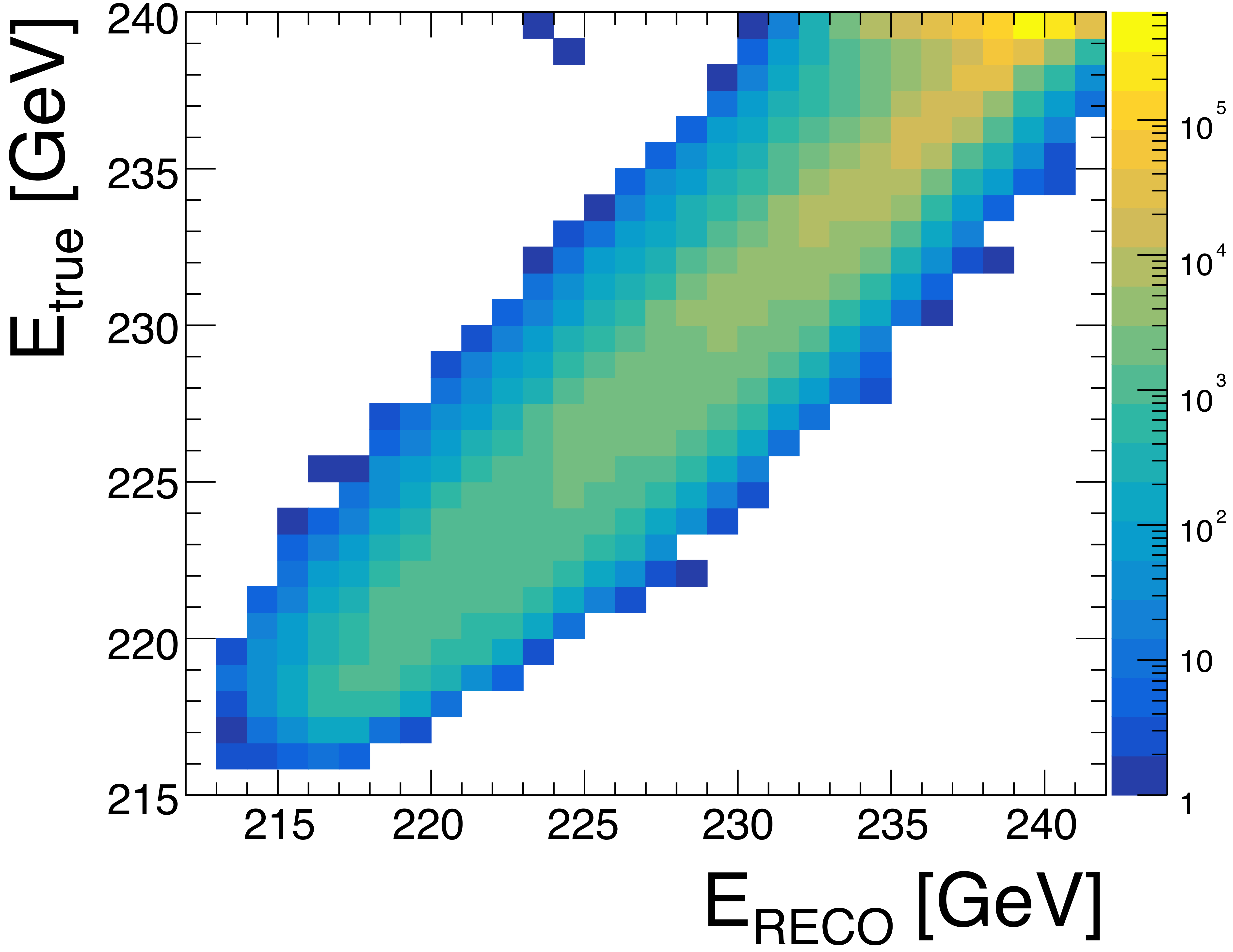
- We also plan to investigate the phase of the coupling Arg $\tilde{c}_{ZZ}$ to obtain two-dimensional upper limits

Thank you!

Backup

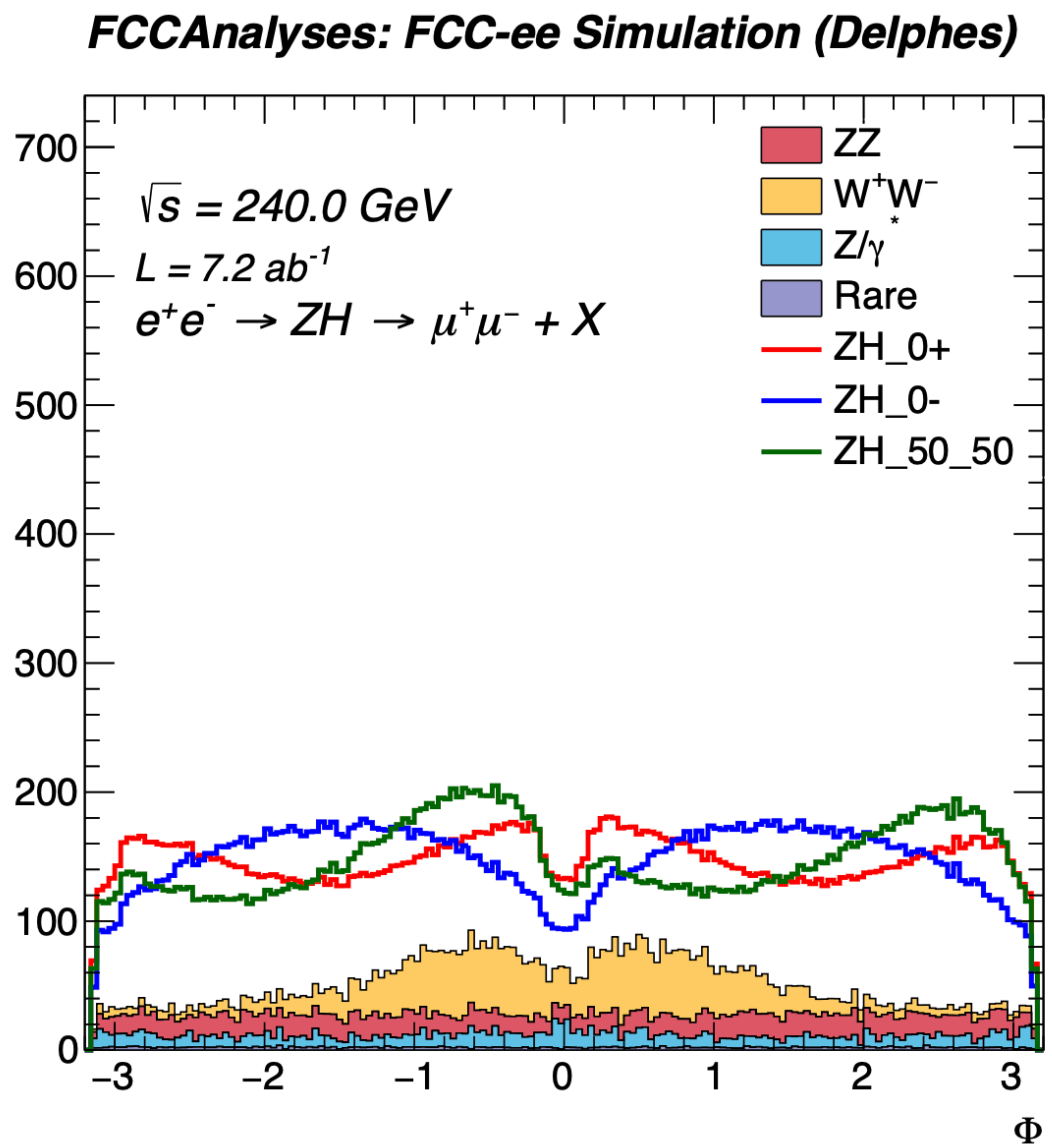
Energy reconstruction resolution





$\Delta = E_{\text{true}} - E_{\text{RECO}}$, red circles before preselections, blue squares after $M_{\mu^+\mu^-} > 88$ GeV

ϕ gap



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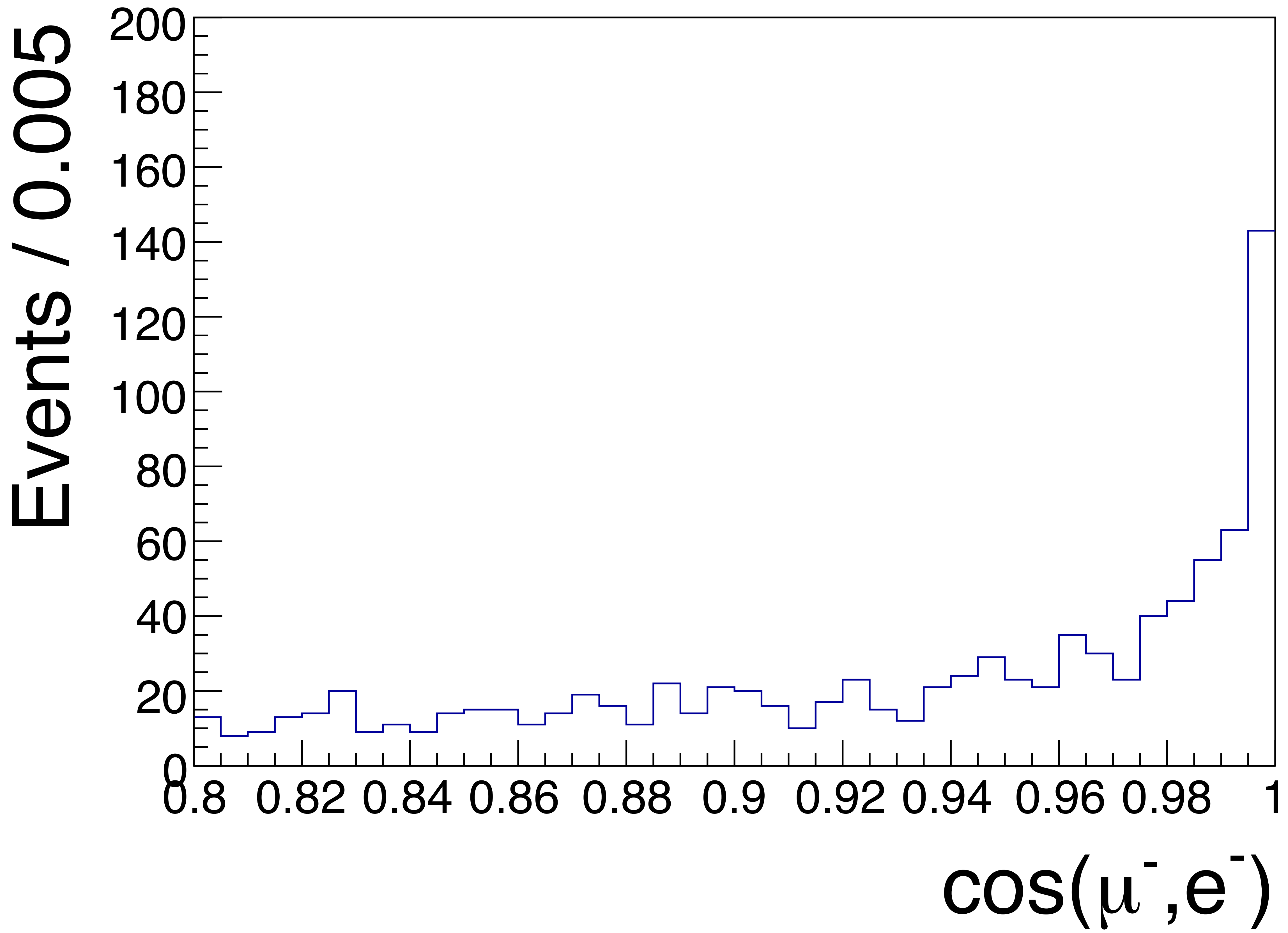

Distribution of the $\cos\theta$ for μ^{-} in the ϕ gap region, taken from the generator. Muons are going to the beam pipe

Preselection efficiency

Process $e^+e^- \to$	Events before preselection	Events after preselection	ε (%)
$HZ, \quad Z \to \mu^+\mu^-$	38400	26884	70.0
ZZ	$6.2 \cdot 10^6$	211470	3.4
W^+W^-	$9.3 \cdot 10^7$	199	2×10^{-4}
$\mu^+\mu^-$	$3.1 \cdot 10^7$	30670	0.1
$\tau^+\tau^-$	$2.7 \cdot 10^7$	830	3×10^{-4}

Selections and efficiency

1. $238 < E_{\mathrm{RECO}} < 242$:

   $49 < p_{\mu^+\mu^-} < 53$,
2. $235 < E_{\mathrm{RECO}} < 238$:

   $48 < p_{\mu^+\mu^-} < 51$,
3. $230 < E_{\mathrm{RECO}} < 235$:

   $39 < p_{\mu^+\mu^-} < 49$,
4. $215 < E_{\mathrm{RECO}} < 230$:

   $26 < p_{\mu^+\mu^-} < 40$.

and

$$88 < M_{\mu^+\mu^-} < 92$$

Process/Range [GeV]	[238, 242]	[235, 238]	[230, 235]	[215, 230]
HZ	15212	2331	3111	290
ZZ	1473	532	3188	129
W^+W^-	1	0	0	0
$\mu^+\mu^-$	4	6	38	4
$\tau^+\tau^-$	0	0	3	0