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

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Outline

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2. Theoretical framework
3. CEPC description
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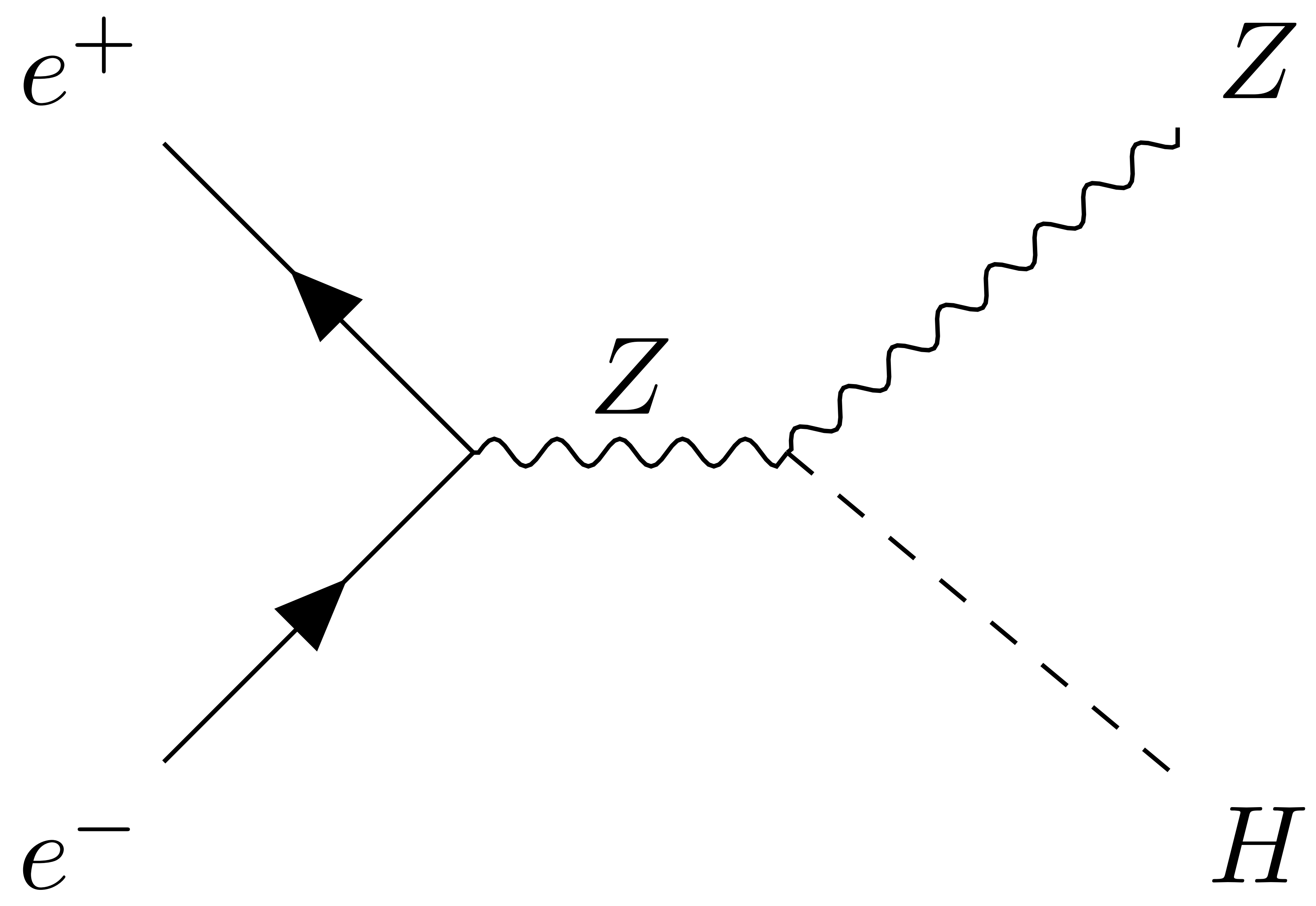
Motivation

- The Higgs boson is predicted to be a scalar particle ($J^{CP} = 0^{++}$) under the SM of particle physics. As a result, any observation of charge-parity violation (CPV) in Higgs would be a sign of physics BSM and could account for the explanation of the observed baryon asymmetry of the universe.
- 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 were not excluded!**

Theoretical framework

We study HZZ vertex in $e^+e^- \to HZ$ process. It is sensitive to CP-properties as Z bosons are vector particles



Higgs Characterization model:

$$H = \cos\psi_{CP} \cdot |0^+> + \sin\psi_{CP} \cdot |0^-> $$

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

Theoretical framework

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

If we fix the total cross section of the $e^+e^- \to HZ$ process at $\sqrt{s} = 240$ GeV, then $\frac{\kappa_{AZZ}}{\Lambda}$ is fixed and ψ_{CP} is the only degree of freedom

Another approaches, EFT:

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

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

$$\psi_{CP} \approx \tan\psi_{CP} = -0.31 \cdot \tilde{c}_{ZZ}$$

Previous works

- IHEP: arXiv:2203.11707 — 1σ upper limits on $\tilde{c}_{ZZ} = [-0.08, 0.07]$
- ECFA: arXiv:2506.15390 — constraint on f_{CP}^{HZZ}
  $f_{CP}^{HZZ} = \pm 4.3 \times 10^{-5} \rightarrow \tilde{c}_{ZZ} \approx 0.02$
- ATLAS: $f_4 = 0.15 \rightarrow \tilde{c}_{ZZ} \approx 1.24$

These constraints can be upgraded with our method

Experimental procedures

Software

- WHIZARD v3.1 with Higgs Characterization UFO 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

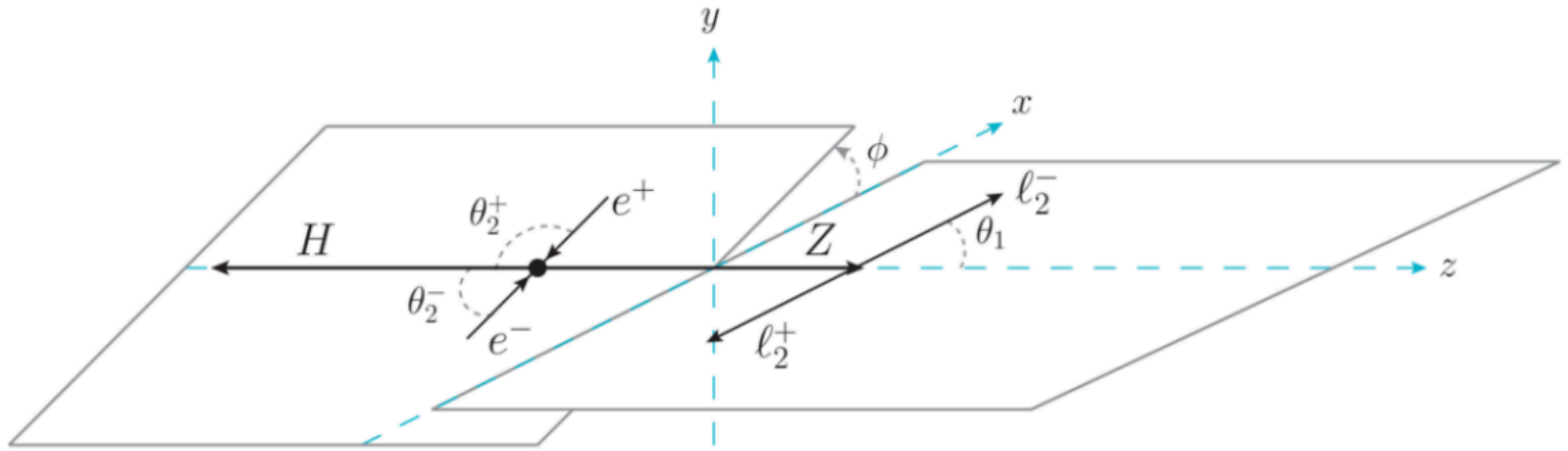
Samples with different $\tilde{c}_{ZZ}$ from 0 to 1 are generated with $\sqrt{s} = 240$ GeV and statistics of 5.6 ab^{-1}

Experimental procedures

Reconstruction, angular distributions

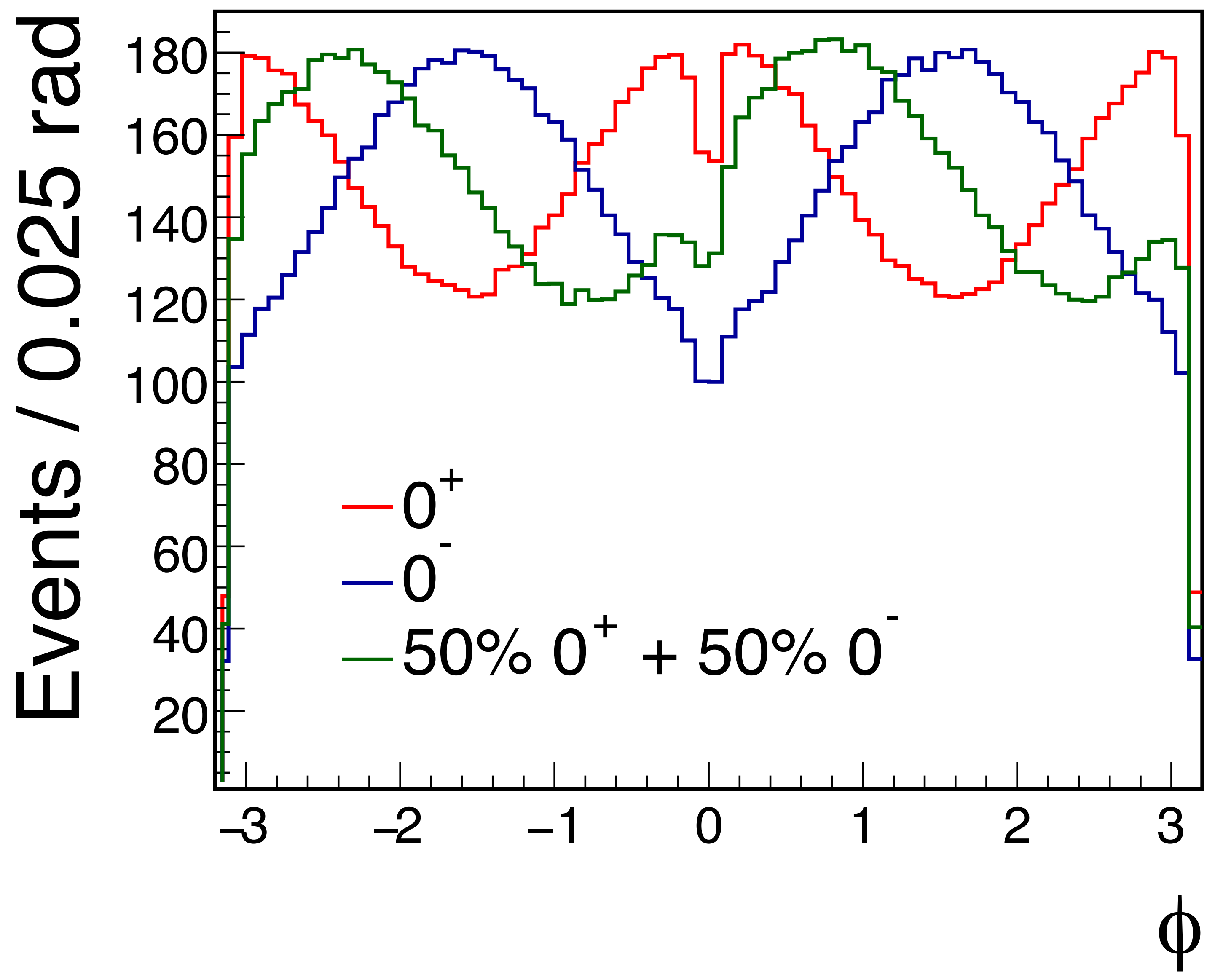
- We choose $Z \to \mu^+\mu^-$, $H \to$ incl channel for analysis. Z boson is reconstructed from 2 muons, Higgs boson is not reconstructed in this analysis.

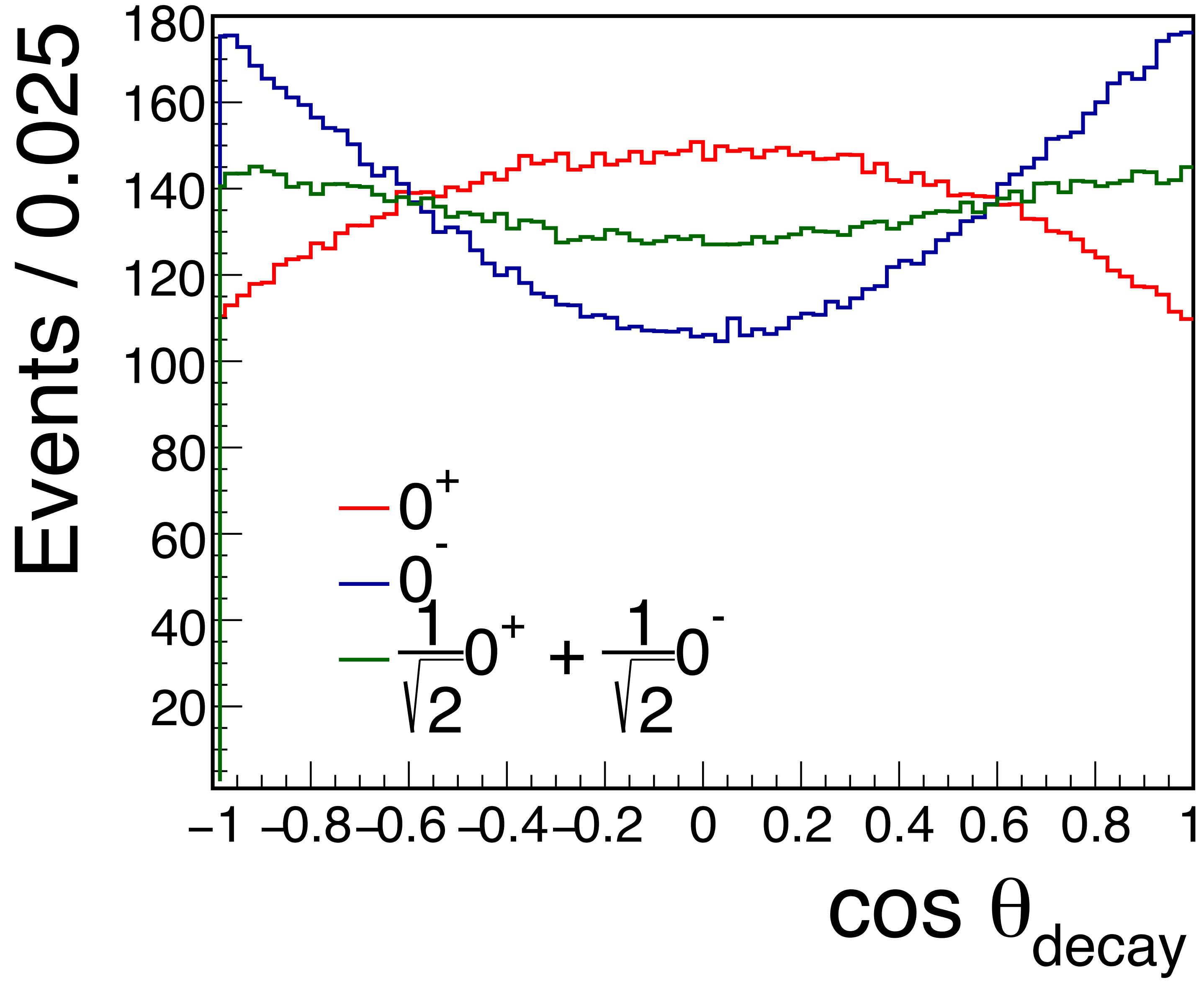
- Three angular distributions $\theta_1, \theta_2, \varphi$ are used for analysis

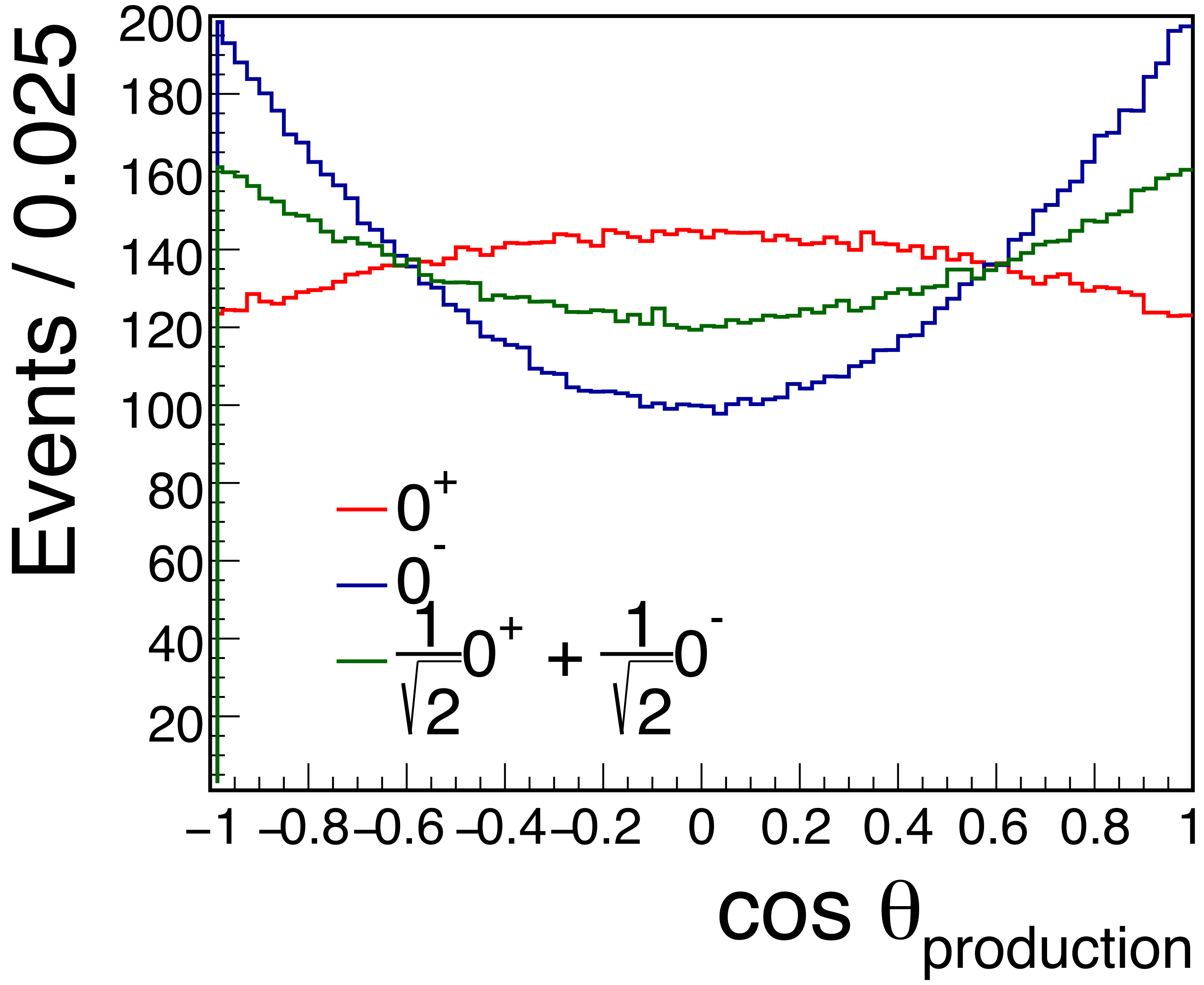


Experimental procedures

Method



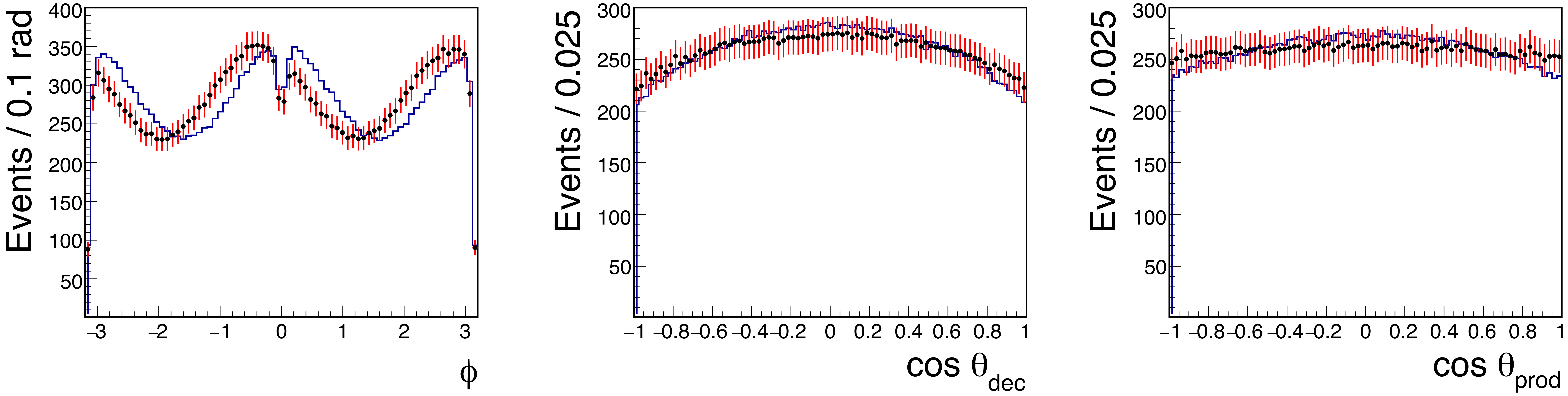




Angular distributions: red line — 0^+, blue line — 0^-, green line — 50/50

Experimental procedures

Angular distributions

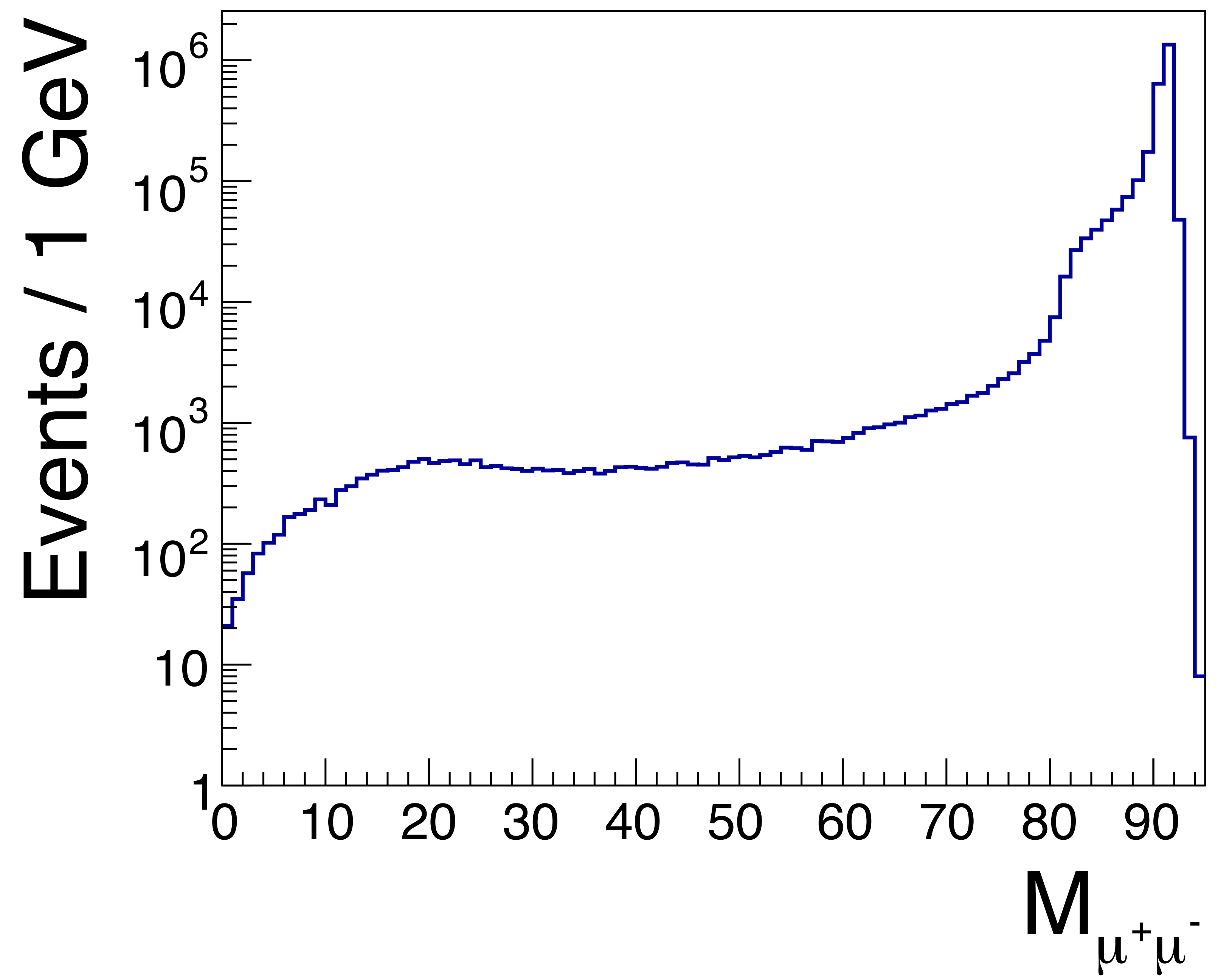


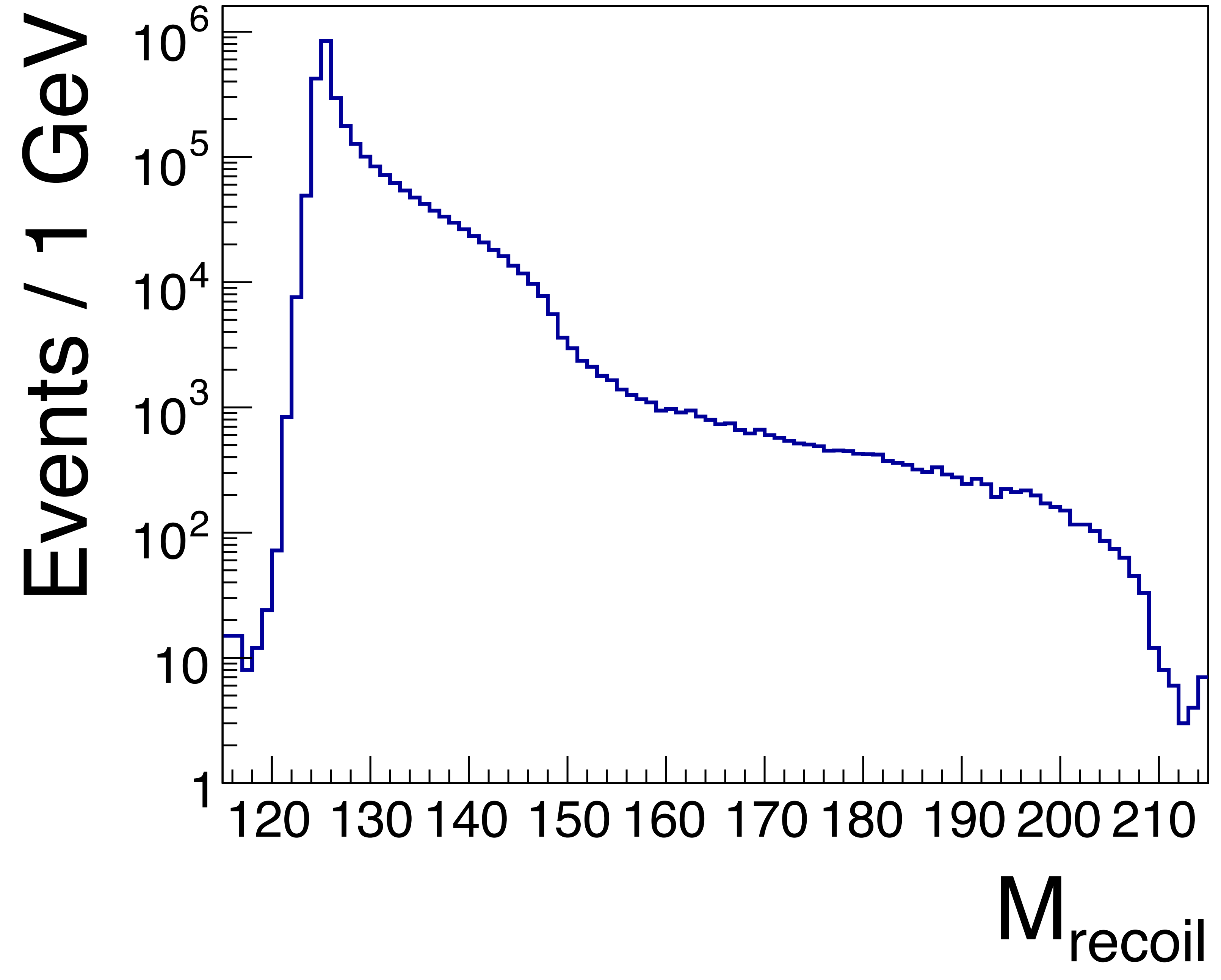
Blue line corresponds to pure 0^+ state, points correspond to $\tilde{c}_{ZZ} = 1.2$

Experimental procedures

ISR energy shift

- ISR energy shift is defined as $\Delta = 240 - \sqrt{s}$, where $\sqrt{s}$ is event total energy
- As Higgs boson is not reconstructed, event energy is calculated in approximation of $\sum \vec{p} = 0$, then $E(H) = \sqrt{p(H)^2 + M_H^2} = \sqrt{p(Z)^2 + M_H^2}$ and $\sqrt{s} = E(H) + E(Z)$
- $M(\mu^+\mu^-) > 88$ cut is required to suppress FSR effects





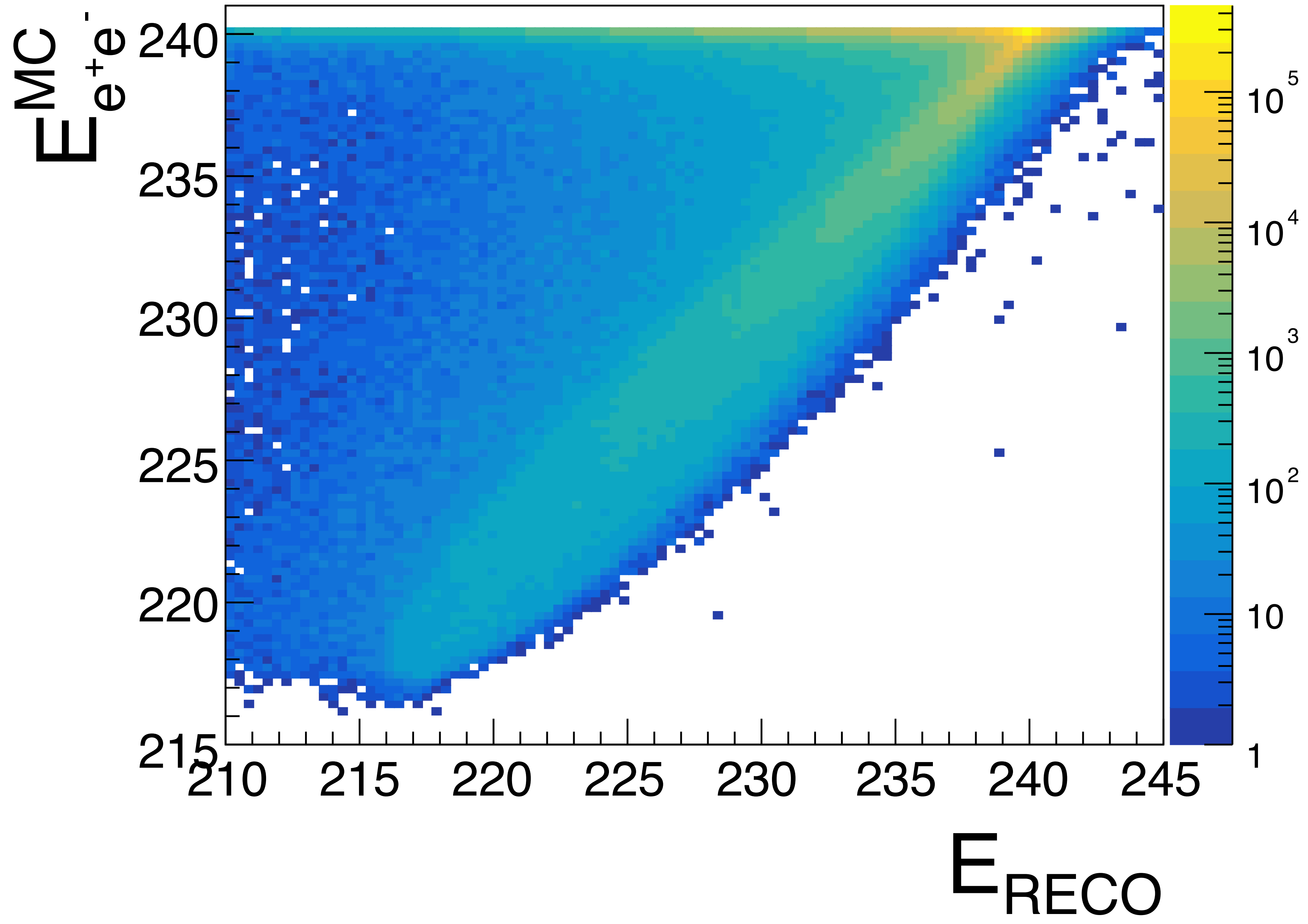
Experimental procedures

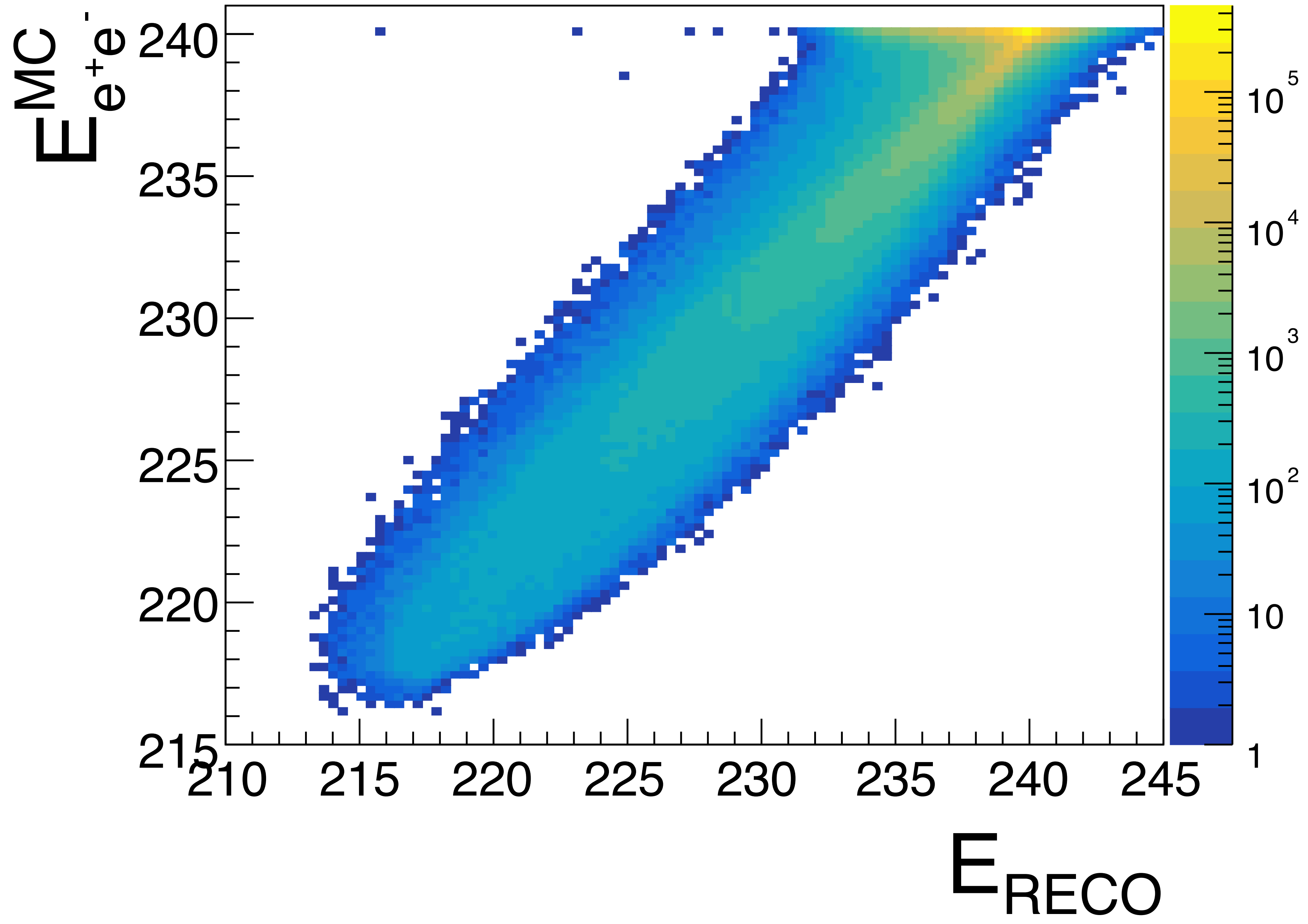
Event energy resolution

- Pictures show 2D histogram of reconstructed event energy vs true energy taken from MC generator collection

- Top picture shows resolution without $M(\mu^+\mu^-) > 88$ cut

- Bottom picture shows resolution with cut (suppressed FSR effects)





Experimental procedures

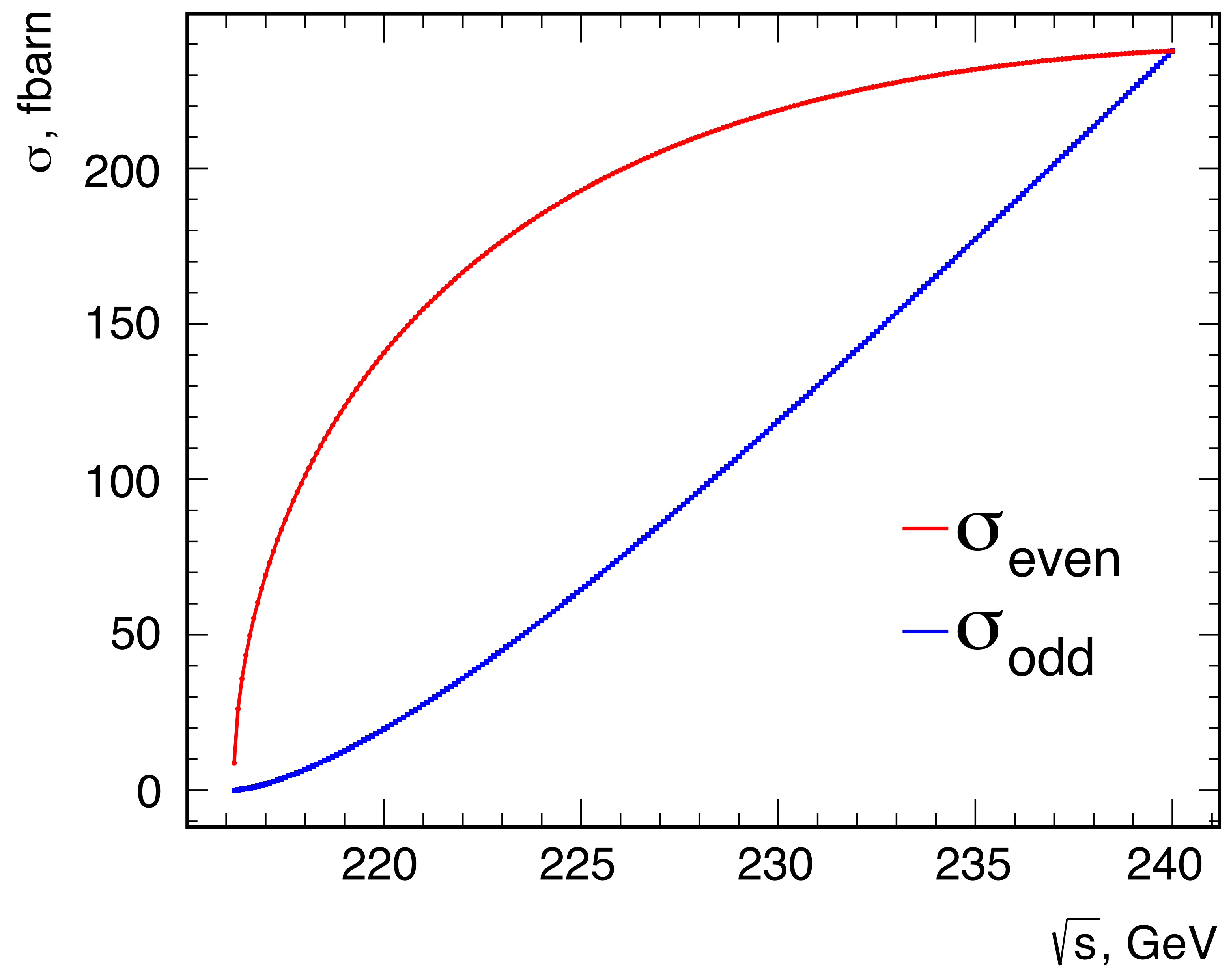
Cross section dependence

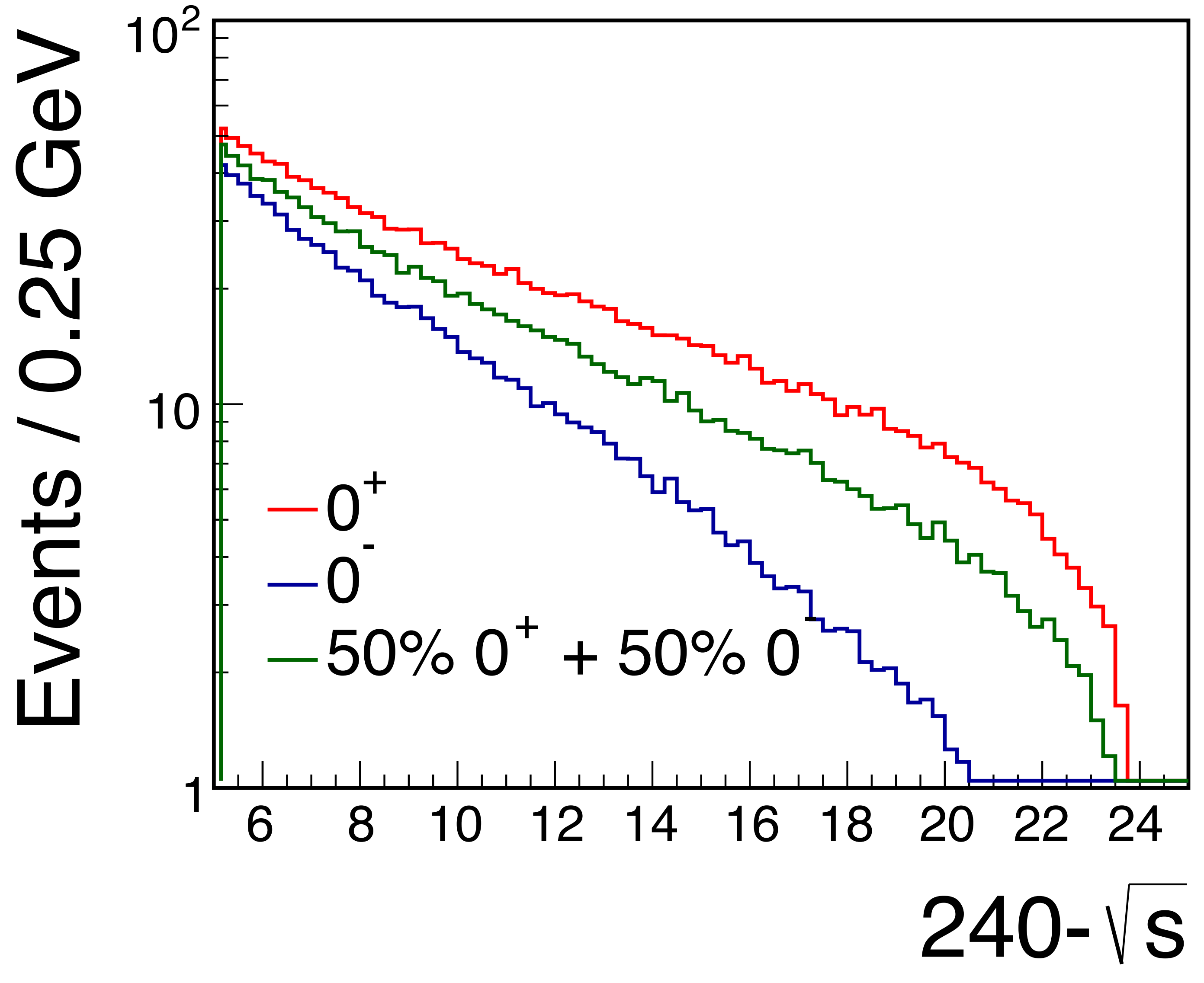
Total cross section from $\sqrt{s}$ form depends on Higgs CP-properties

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

$1^- \to 0^+1^-$ or $1^- \to 0^-1^-$ (p-wave)

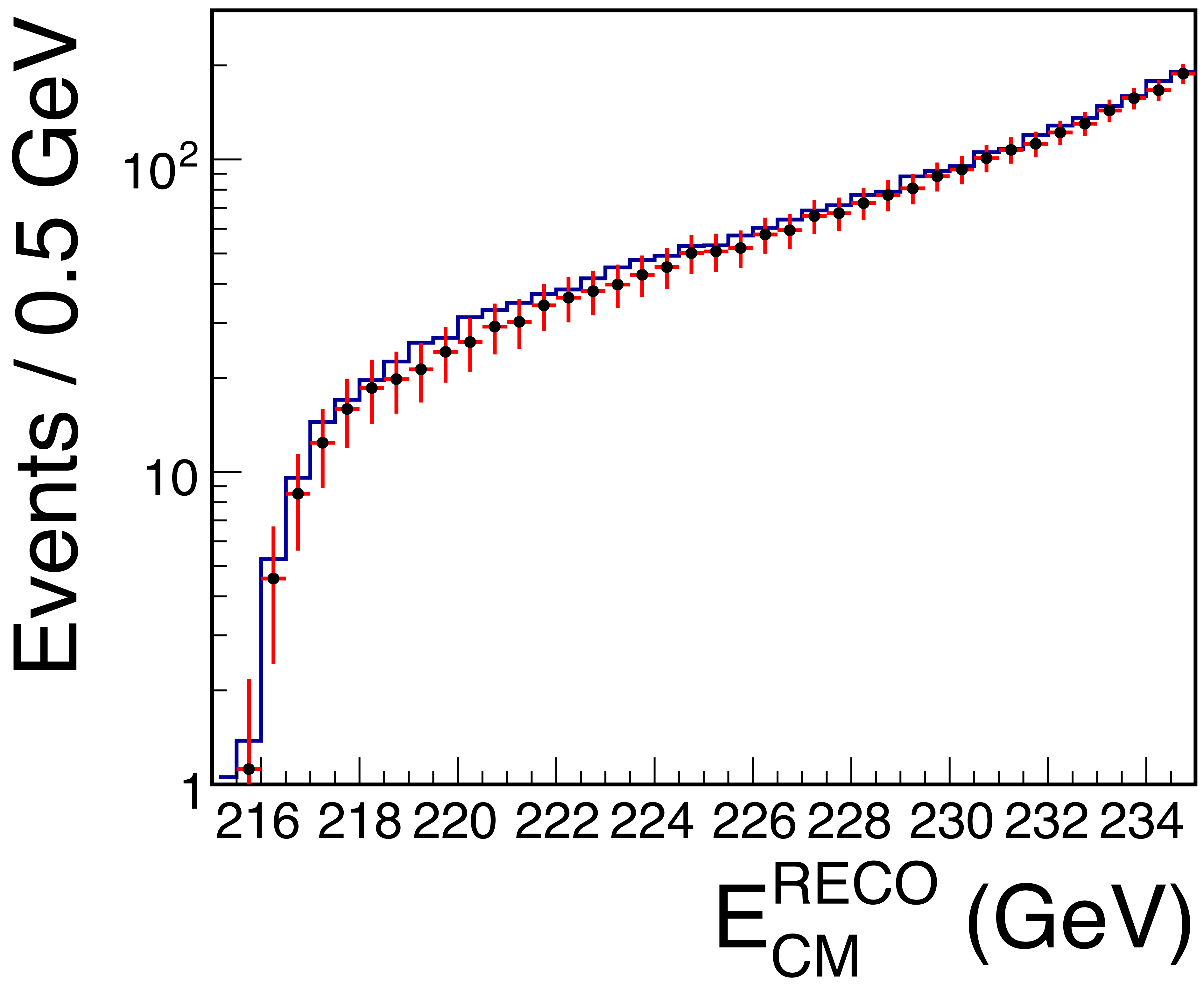
ISR energy shift distributions are proportional to cross section, therefore are sensitive to CP state of Higgs boson





Experimental procedures

ISR energy shift distributions



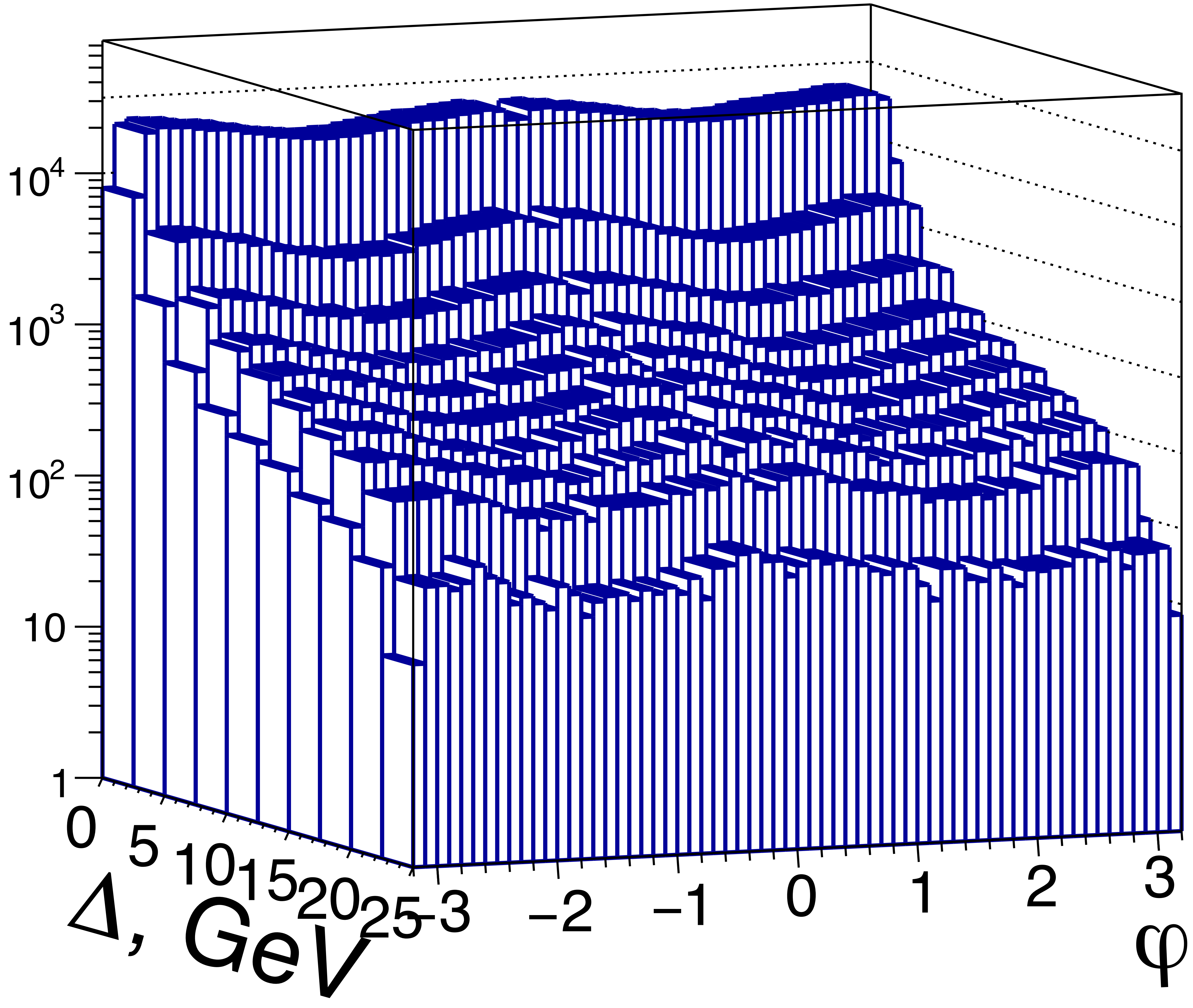
Blue line corresponds to pure 0^+ state, dots correspond to $\tilde{c}_{ZZ} = 1.2$,

Experimental procedures

Likelihood approach

- Previous analyses used angular likelihood approach to calculate significance

- However, in events with large ISR energy shift $\Delta > 15$ angular distribution flattens



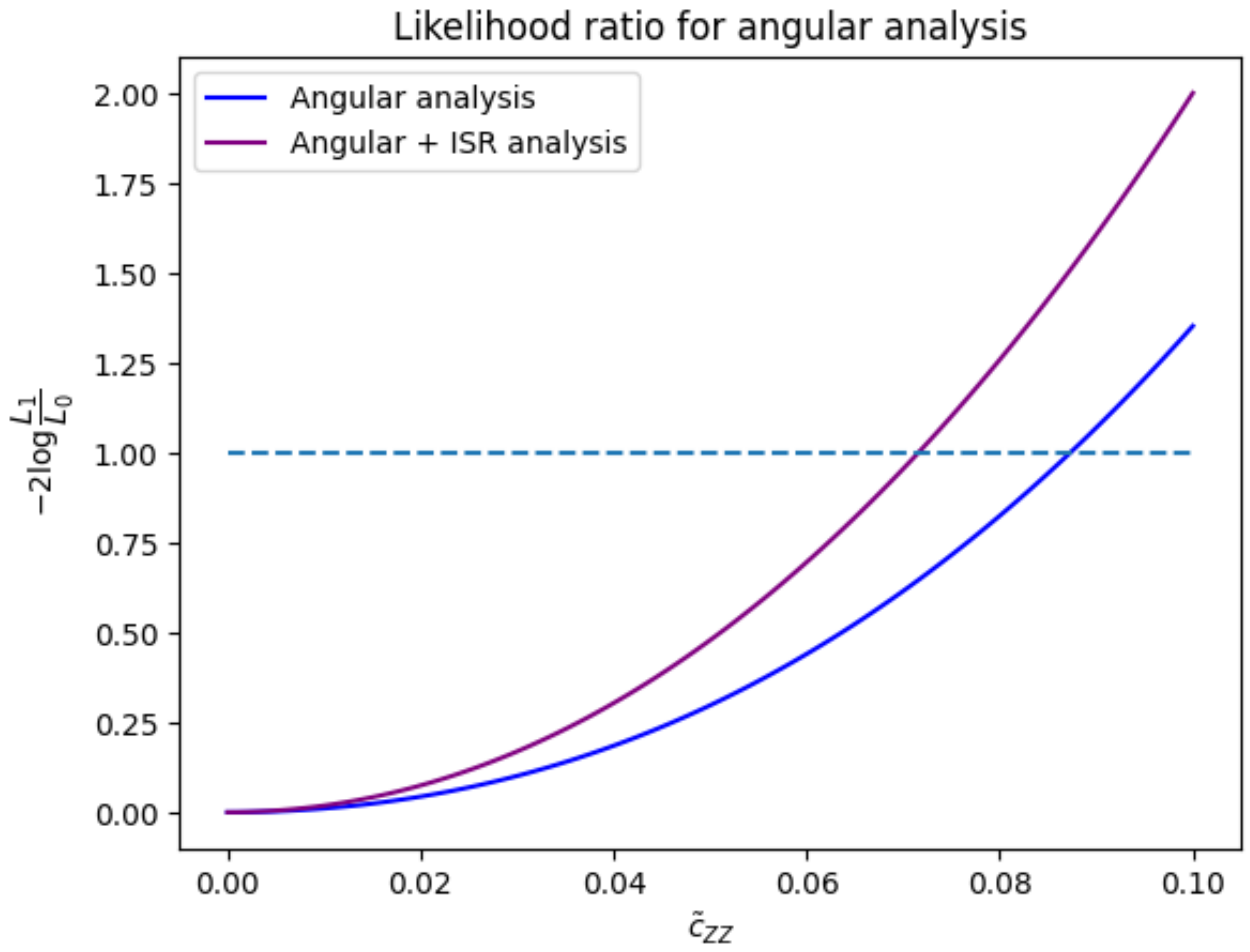
Experimental procedures

Likelihood approach

- We construct likelihood function from two L_{angular} and L_{ISR} so the total likelihood $L = L_{\text{angular}} \times L_{\text{ISR}}$
- $L_{\text{angular}} = \prod_{i,j,k} \text{Poiss}(\mu_{ijk} | N_{ijk})$, where i, j, k are bins in 3D histogram for $\varphi, \cos\theta_1, \cos\theta_2$ for $\Delta > 15$ GeV
- $L_{\text{ISR}} = \text{Poiss}(\mu | N)$, where μ and N are just number of events for $\Delta > 15$
- μ is obtained by generating x100 events and scaling

Results

- This plot shows signal significance as a function of CP-odd Higgs admixture value
- From pure angular analysis we obtain 1σ upper limit on $\tilde{c}_{ZZ} = 0.087$
- ISR method improves upper limit to $\tilde{c}_{ZZ} = 0.72$ which is 20% better



Plans

- Generate background processes samples
- Optimize cuts to suppress background processes
- Calculate upper limits on $\tilde{c}_{ZZ}$ for CEPC