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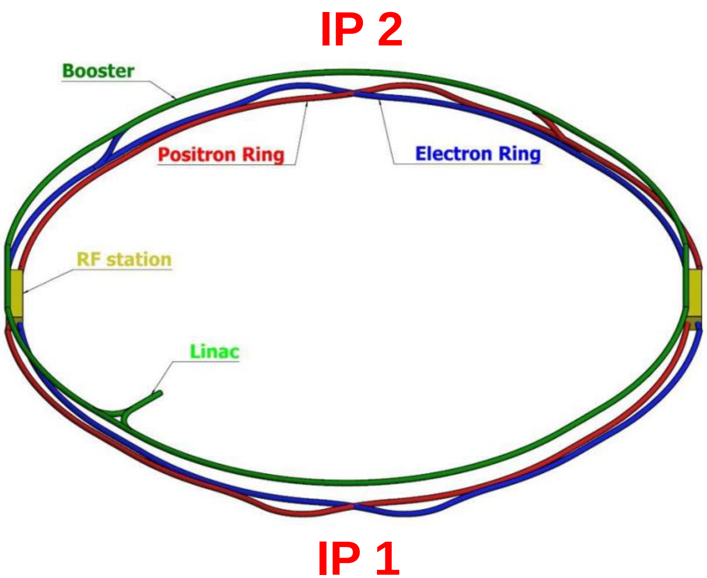
ФИАН

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

XXIII International seminar on HEP, QUARKS-2026

May 18-24, 2026, Petrozavodsk

Collider CEPC (Higgs factory)



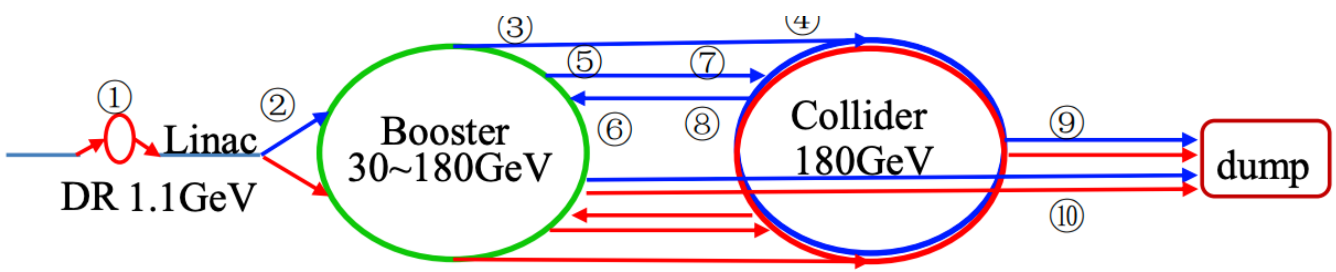
100 km ring, booster and collider in one tunnel. Two interaction points, two detectors.

Operation mode		ZH	Z	W^+W^-	$t\bar{t}$
$\sqrt{s}$ [GeV]		~240	~91	~160	~360
Run Time [years]		10	2	1	5
30 MW	L / IP [$\times 10^{34}$ cm^{-2}s^{-1}]	**5.0**	**115**	**16**	**0.5**
	$\int L\,dt$ [ab^{-1}, 2 IPs]	13	60	4.2	0.65
	Event yields [2 IPs]	2.6×10^6	2.5×10^{12}	1.3×10^8	4×10^5
50 MW	L / IP [$\times 10^{34}$ cm^{-2}s^{-1}]	**8.3**	**192**	**26.7**	**0.8**
	$\int L\,dt$ [ab^{-1}, 2 IPs]	21.6	100	6.9	1
	Event yields [2 IPs]	4.3×10^6	4.1×10^{12}	2.1×10^8	6×10^5

50 MW and $t\bar{t}$ mode – as upgrade

CEPC: to be ambitious

240 GeV: N(Higgs) = σ x $\mathcal{L}$ = 200 fb x 5.6 ab^{-1} ≈ 1.1 M



Motivation

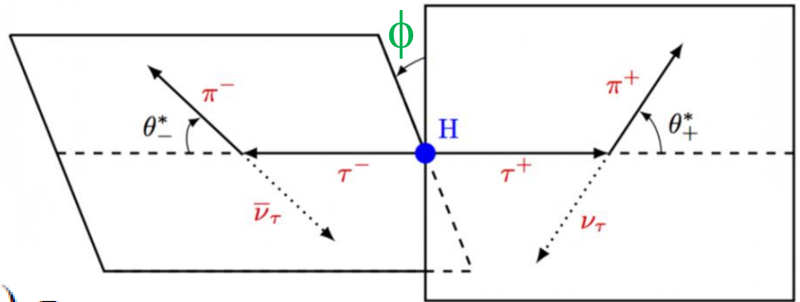
Optimist: Higgs boson will open a window into New Physics.
Pessimist: high precision Higgs studies will kill many BSM models.

New Physics (NP) ≡ physics Beyond the Standard Model (BSM).
Contributions from NP in processes with Higgs boson are predicted to be observable in some NP models. In particular, signatures of NP can appear in Higgs decay branching fractions and Higgs *CP* content. Here it will be discussed only potential Higgs *CP*-odd admixture. *CP*-odd admixture in h(125) appears in 2HDM (or SUSY) model due to mixing with heavy *CP*-odd Higgs boson (A). This contribution can be experimentally searched for at future e^+e^- Higgs factories, such as CEPC (China) or FCC-ee (CERN).

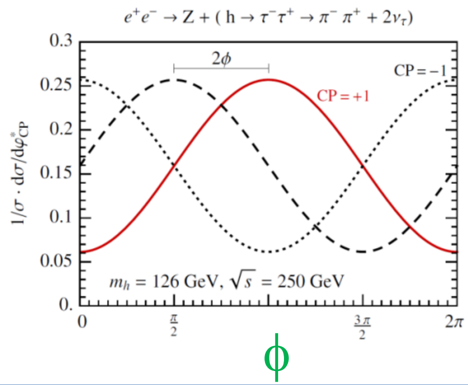
In this talk a search for *CP*-odd admixture in 125 GeV Higgs using additional ISR parameter in process $e^+e^- \to Zh, Z \to \mu^+\mu^-$ will be discussed. This process has been studied without accounting for ISR by CEPC (arXiv:2203.11707) and FCC-ee (ECFA, arXiv: 2506.15390).

Opportunities to search for *CPV* in Higgs sector

Best method to measure Higgs CPV is based on angular distributions in decay $H \to \tau^+\tau^-$, $\tau \to \pi/\rho\ \nu$.



$$\mathcal{L} = -\frac{m_\tau}{v}\, H\, \bar{\tau}\, (\cos\psi_{CP} + i\,\sin\psi_{CP}\,\gamma^5)\,\tau$$



Angle ϕ between decay planes is most sensitive.

ILD collaboration: arXiv:1804.01241, $\sigma(\psi_{CP}) \approx 4.3°$

ATLAS (ψ_{CP} = 9 ± 16°) and CMS (ψ_{CP} = -1 ± 19°) with 139 fb^{-1}

Studies of $h \to 4\ell$ angular distributions. Not enough statistics, low accuracy.

Electron EDM

JILA HfF+ experiment

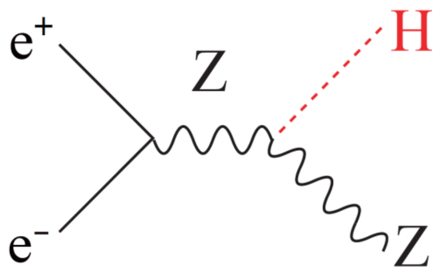
$|d_e| < 4.1 \times 10^{-30}$ e cm (90% *CL*)

$$\frac{d_e}{d_e^{\mathrm{ACME}}} = c_e\,(870.0\tilde{c}_t + 3.9\tilde{c}_b + 2.8\tilde{c}_c + 0.01\tilde{c}_s + 8\cdot10^{-5}\tilde{c}_u + 7\cdot10^{-5}\tilde{c}_d + 3.4\tilde{c}_\tau + 0.03\tilde{c}_\mu) + \tilde{c}_e\,(610.1c_t + 3.1c_b + 2.3c_c + 0.01c_s + 7\cdot10^{-5}c_u + 6\cdot10^{-5}c_d + 2.8c_\tau + 0.02c_\mu - 1082.6c_V)$$

Barr–Zee-type two-loop diagram with virtual Higgs

Observation of EDM will indicate to Higgs *CP*-odd admixture. However EDM upper limit cannot be translated to Higgs CP-odd limit. Many conditions, models (arXiv:2202.11753).

Theoretical framework (this study)



$$\mathcal{L}_{\rm eff} \supset c^{(1)}_{ZZ} H Z_\mu Z^\mu + c^{(2)}_{ZZ} H Z_{\mu\nu} Z^{\mu\nu} + c_{Z\tilde{Z}} H Z_{\mu\nu} \tilde{Z}^{\mu\nu}$$

CP-odd HZZ vertex is described by loop diagram

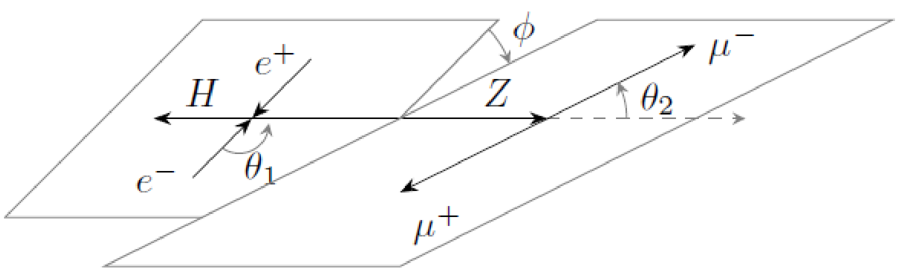
$$\mathcal{L}_{CPV} = \frac{H}{v}\left(\tilde{c}_{ZZ}\frac{g_1^2+g_2^2}{4} Z_{\mu\nu}\tilde{Z}^{\mu\nu}\right)$$

Only $Z \to \mu^+\mu^-$ is reconstructed, Higgs - inclusive

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

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

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



Parameter $\tilde{c}_{ZZ}$ can be measured using ϕ, $\cos\theta_1$ and $\cos\theta_2$ angular distributions

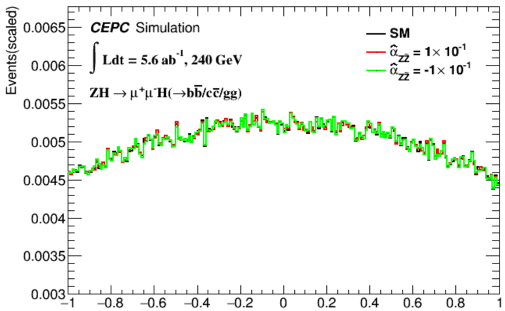
Estimates of $\tilde{c}_{ZZ}$ (1σ) : [-0.33, 0.33] HL-LHC, 3 ab^{-1}, $H \to Z^*Z \to 4\ell$

[-0.06, 0.06] CEPC, 5.6 ab^{-1}, μμ/ee ; [-0.08. 0.07] only μμ channel

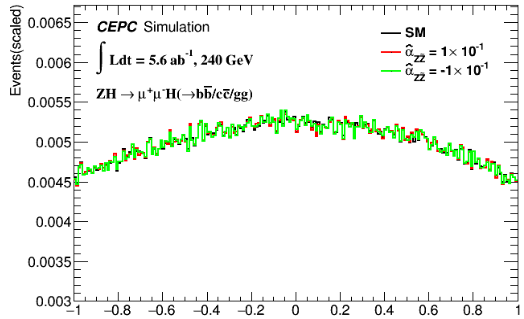
[-0.06, 0.06] FCC-ee, 10.8 ab^{-1}, μμ/ee

Comparison previous CEPC and FCC-ee studies

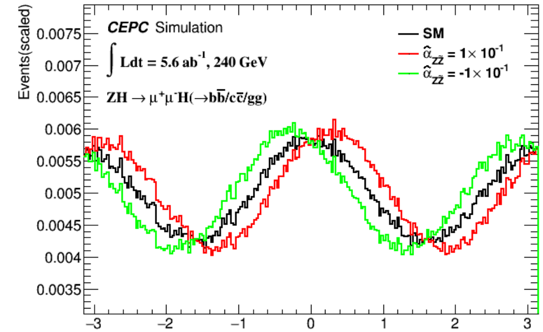
CEPC angular distributions (arXiv: 2203.11707)



$\cos\theta_1$

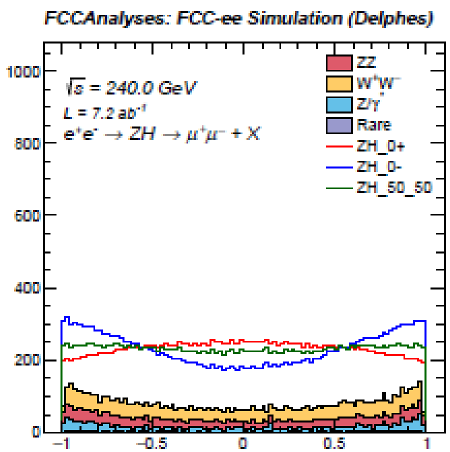


$\cos\theta_2$

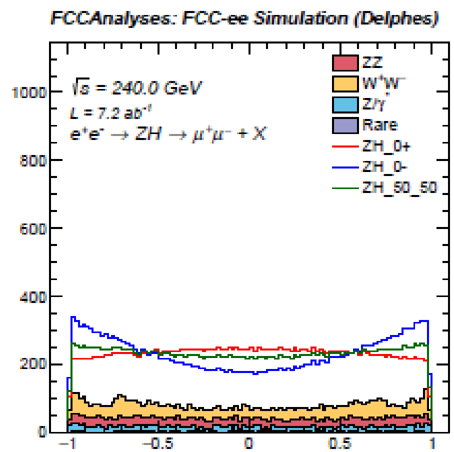


ϕ

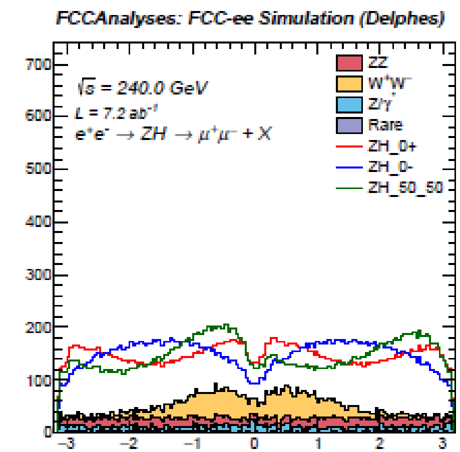
FCC-ee angular distributions (ECFA, arXiv: 2506.15390)



$\cos\theta_1$



$\cos\theta_2$



ϕ

Very similar methods and distributions at CEPC and FCC-ee.

New method: additional ISR energy parameter

MC: Whizard 3 + Delphes (CEPC card)

E_{CMS} = 240 GeV $\mathcal{L}_{int}$ = 5.6 ab^{-1}

$e^+e^- \rightarrow Zh\,(+\gamma_{ISR}),\, Z \rightarrow \mu^+\mu^-$

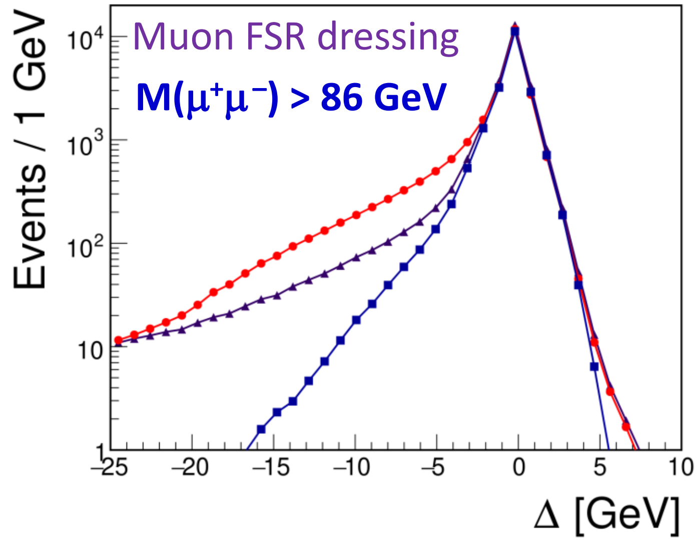
NEW: to calculate true energy of e^+e^- collision in case of energetic ISR photon, approximate formula can be used:

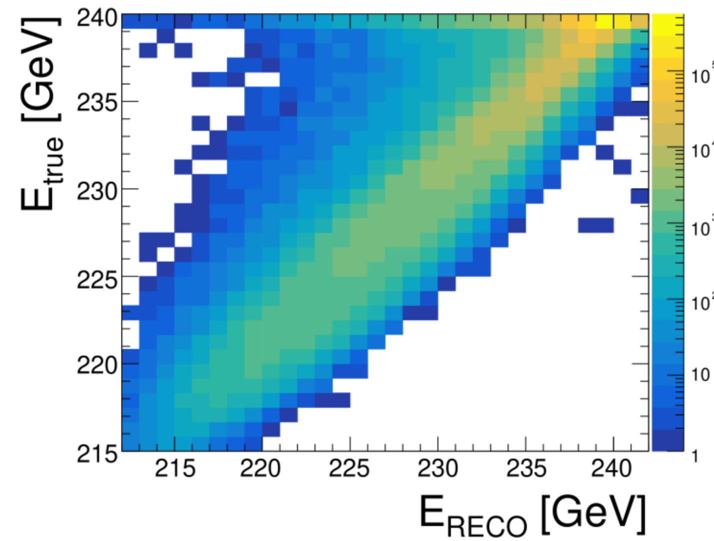
$$E_{RECO} = E(\mu^+\mu^-) + \sqrt{M(h)^2 + P(\mu^+\mu^-)^2}$$

Here we use **P(H) ≈ P(Z)**

$$\Delta E = E_{TRUE} - E_{RECO}$$

Effective Gaussian width for Δ is 0.48 GeV.





Cross sections for different Higgs *CP*

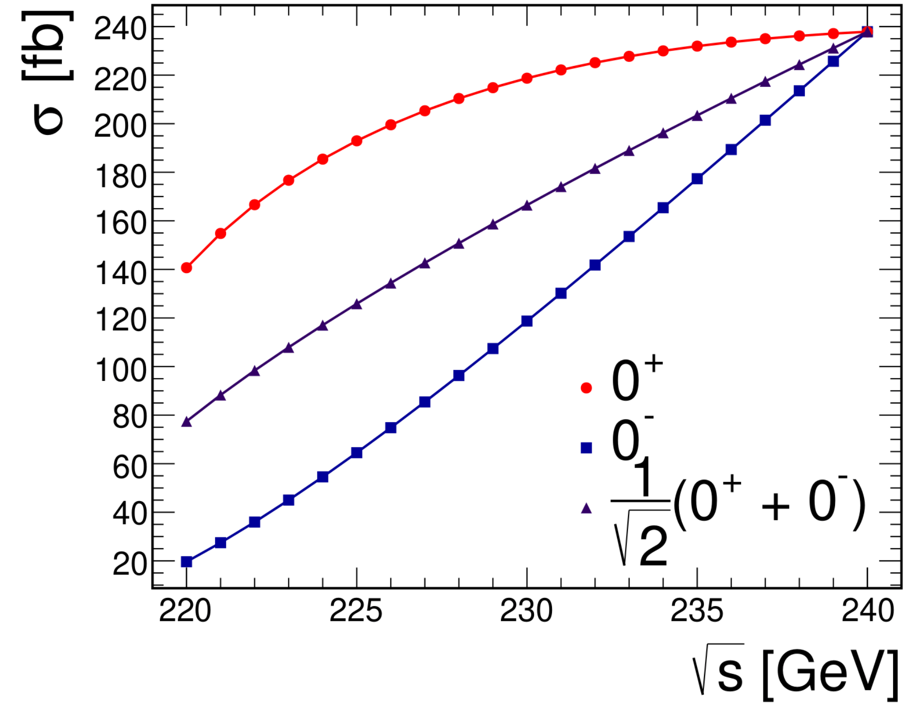
MC calculations, where cross sections are forced to be equal at 240 GeV.

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

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

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

$$\sigma(\sqrt{s}, E_{ISR}) = \sigma(\sqrt{s} - E_{ISR}, 0)$$

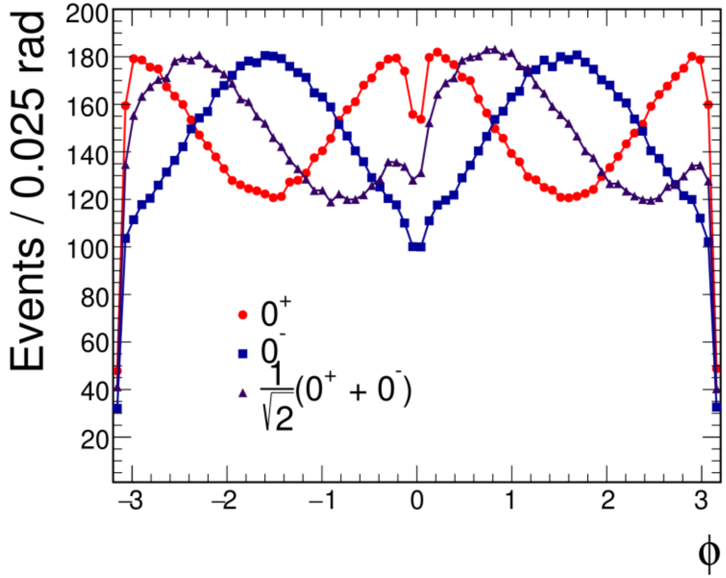


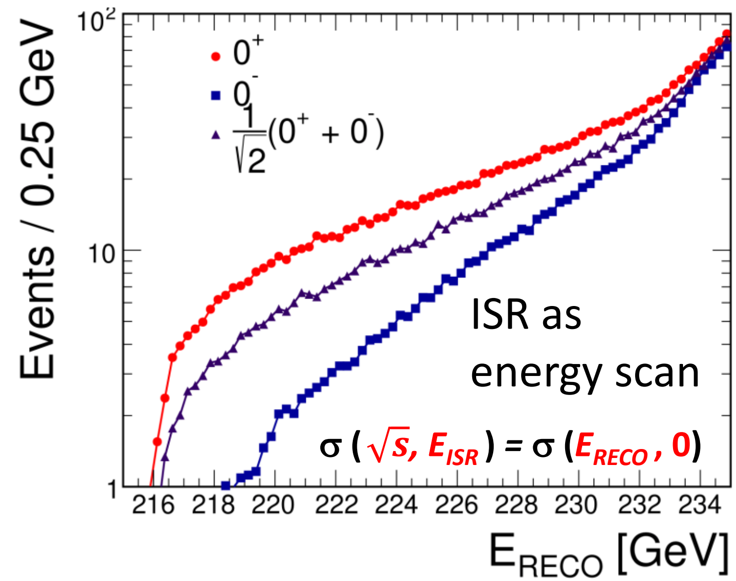
Cross section dependences vs E_{CMS} for different Higgs *CP* content

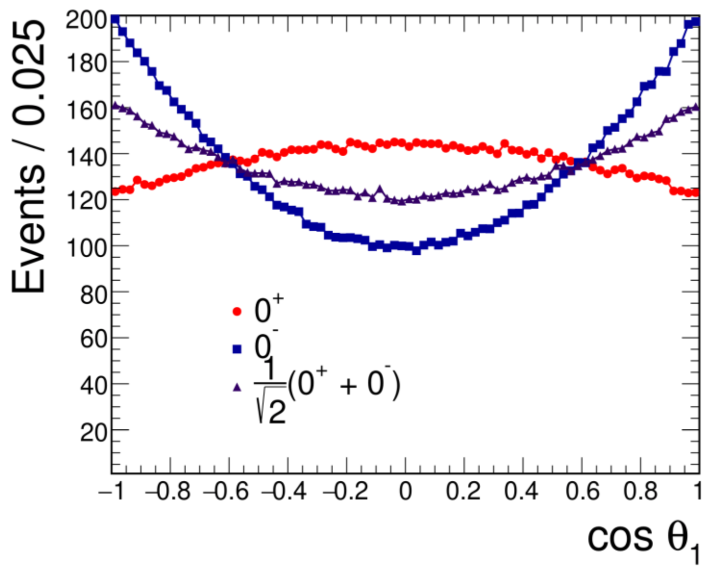
Moreover, ϕ, cos θ_1 and cos θ_2 angular distributions are changing with E_{CMS}

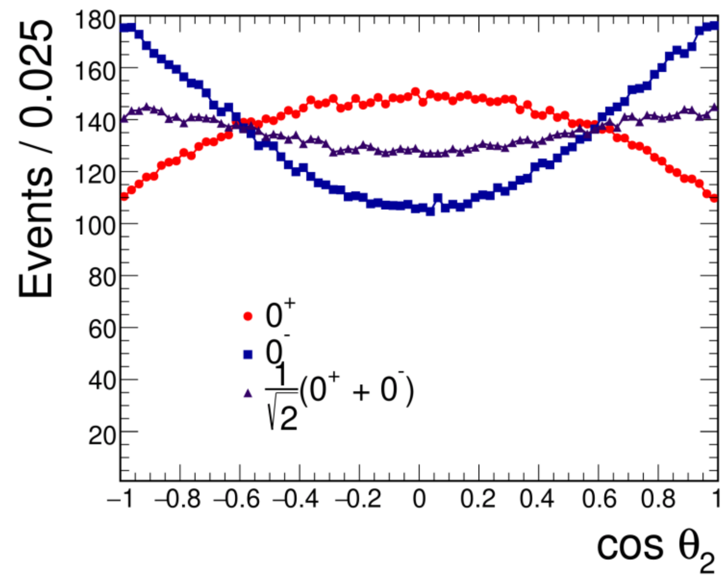
Both effects can be taken into account in calculations to improve accuracy of $\tilde{c}_{ZZ}$

Angular and ISR distributions for $e^+e^- \to Z\,h$









Experimental technique

Preselections: 2 oppositely charged muons, additionally: at least one jet or electron

Applied selection:

86 GeV < $M(\mu^+\mu^-)$ < 96 GeV

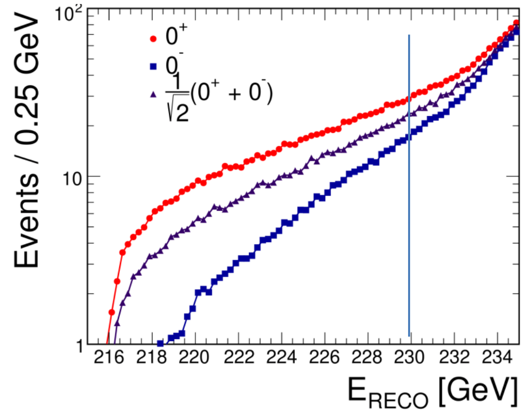
$|\cos\theta_1| < 0.98$

We divide full data sample in four regions:

1. $238 < E_{\mathrm{RECO}} < 242$ GeV, $45 < p_{\mu^+\mu^-} < 57$ GeV;
2. $235 < E_{\mathrm{RECO}} < 238$ GeV, $42 < p_{\mu^+\mu^-} < 54$ GeV;
3. $230 < E_{\mathrm{RECO}} < 235$ GeV, $39 < p_{\mu^+\mu^-} < 49$ GeV;
4. $215 < E_{\mathrm{RECO}} < 230$ GeV, $26 < p_{\mu^+\mu^-} < 42$ GeV.

To take into account ISR

Process $e^+e^- \to$	Events before preselection	Events after preselection	ε (%)
$HZ, \quad Z \to \mu^+\mu^-$	36400	25273	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}



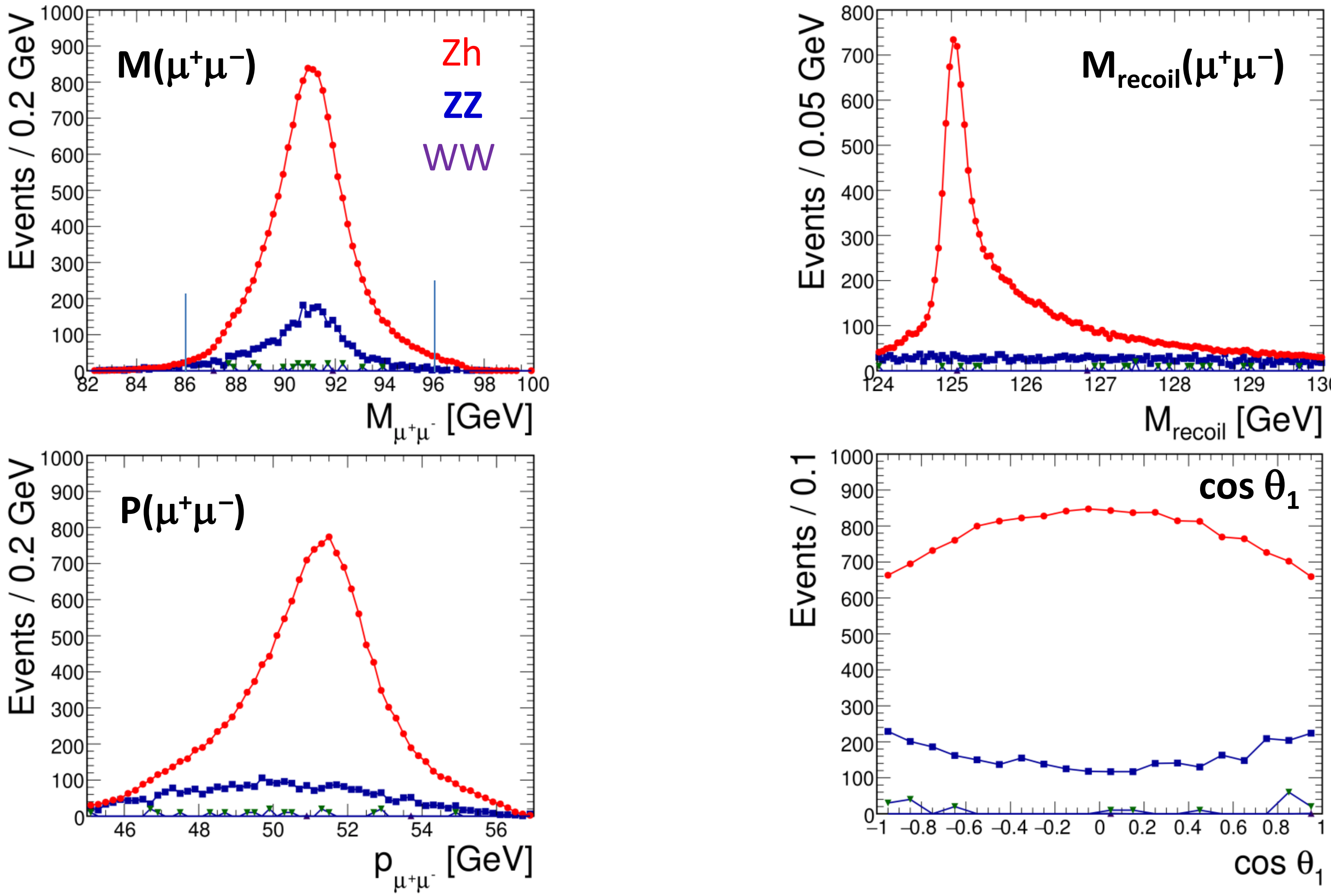
Studied backgrounds:

1. $e^+e^- \to ZZ$,
2. $e^+e^- \to W^+W^-$,
3. $e^+e^- \to \mu^+\mu^-$,
4. $e^+e^- \to \tau^+\tau^-$.

Others are negligible

Process/Range [GeV]	[238, 242]	[235, 238]	[230, 235]	[215, 230]
HZ	14901	2309	3152	400
ZZ	2688	832	3371	289
W^+W^-	2	1	0	3
$\mu^+\mu^-$	12	18	18	10
$\tau^+\tau^-$	0	0	0	1

Distributions for process $e^+e^- \to Zh$ (in RECO region 1)



The figures are obtained with all cuts applied except the cut on the variable shown.

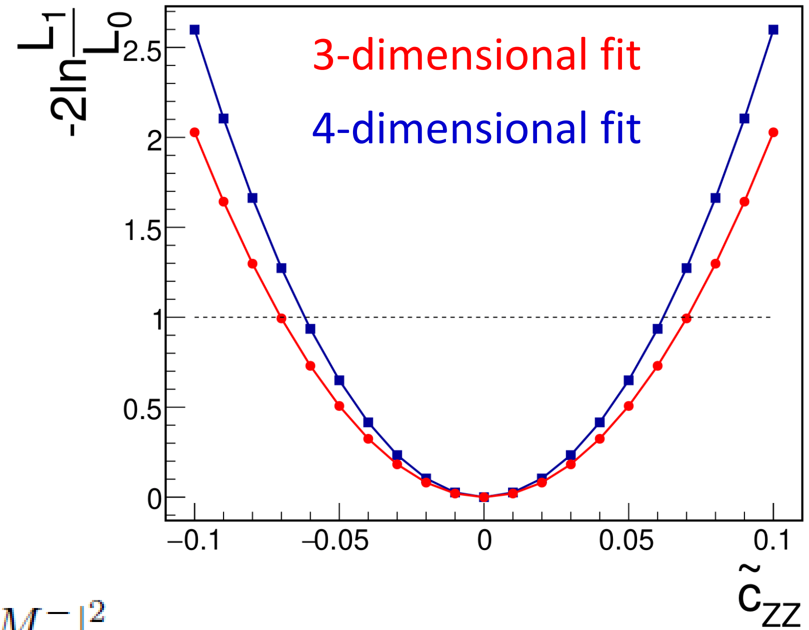
Comparison of methods

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

Four-dimensional, binned likelihood with ϕ, $\cos\theta_1$, $\cos\theta_2$ and E_{RECO}.
$\mu_{I,j,k}$ values are obtained from SM MC for each E_{RECO} region.

$$S = -2\ln\frac{\mathcal{L}_1}{\mathcal{L}_0},$$

$$|M|^2 = |M^+|^2 + 2\tilde{c}_{ZZ}\text{Re}(M^+(M^-)^\dagger) + \tilde{c}_{ZZ}^2|M^-|^2$$



$ax^2 + bx^4$

Accuracy of $\tilde{c}_{ZZ}$ measurement in muon channel can be improved by 15% from 0.071 in 3-dimensional fit to 0.062 in 4-dimensional fit at 1σ limit.

Previous CEPC study (arXiv:2203.11707) : $\tilde{c}_{ZZ}$ [-0.08, 0.07].

This work supported by the Russian Science Foundation,
project 25-22-00716

Российский
научный
фонд

The paper (arXiv:2511.06353) was submitted to Phys. Rev. D

LPI group is actively working for a few physics and detector topics for CEPC

The international workshop on CEPC will take place in Shanghai Oct 22-26, 2026.
https://indico.ihep.ac.cn/event/28911
(I am a member of Scientific Program Committee of this workshop).

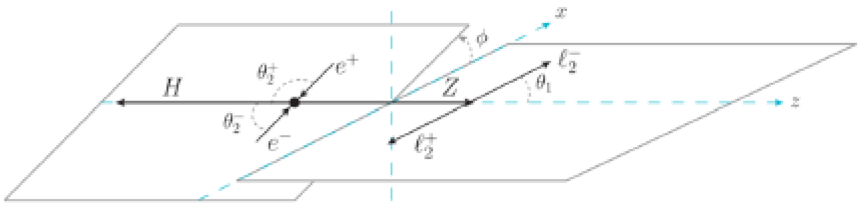
Conclusions

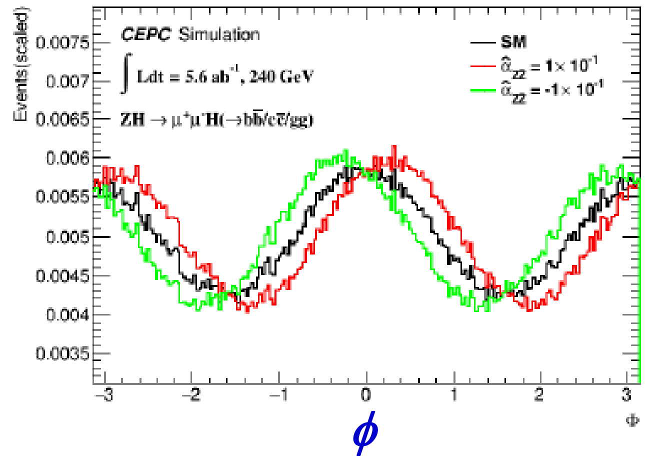
Accuracy of Higgs *CP*-odd admixture upper limit in process $e^+e^- \to Zh\,,\, Z \to \mu^+\mu^-$ can be improved by 15% using ISR energy shift parameter. Additional ISR parameter is used for studies of Higgs *CP* properties for the first time.

This method can be used in studies of some other processes.

Search for Higgs *CP*-odd admixture using ISR energy shift

Paper "Probing Higgs CP properties at the CEPC". **arXiv: 2203.11707 [hep-ex]**





Angle ϕ between production plane and Z decay plane

$$\mathcal{L}_{\rm eff} \supset c^{(1)}_{ZZ} H Z_\mu Z^\mu + c^{(2)}_{ZZ} H Z_{\mu\nu} Z^{\mu\nu} + c_{Z\tilde{Z}} H Z_{\mu\nu} \widetilde{Z}^{\mu\nu} + c_{AZ} H Z_{\mu\nu} A^{\mu\nu} + c_{A\tilde{Z}} H Z_{\mu\nu} \widetilde{A}^{\mu\nu}$$
$$+ H Z_\mu \bar{\ell}\gamma^\mu (c_V + c_A\gamma_5)\ell + Z_\mu \bar{\ell}\gamma^\mu (g_V - g_A\gamma_5)\ell - g_{\rm em} Q_\ell A_\mu \bar{\ell}\gamma^\mu \ell,$$

CP-odd component results from loop diagram, however it can be large in some BSM

2. Complementarity with others indirect Higgs CP measurements
   - For example, electron EDM measurements enforce a strong constraint on the Higgs CP properties. It would be very helpful to clarify how useful the projections presented in this paper are given the constraints from other indirect Higgs CP measurements.

2) We added text about EDM measurements and their constraints on the Higgs CP properties. However, EDM limits cannot be converted into the $\tilde{c}_{ZZ}$ parameter because EDM frameworks involve additional parameters that are subject to different constraints in different regions of parameter space.

In addition to the text in the paper: As an example, in the type-II 2HDM, constraints from current EDM data on the Higgs CP-odd admixture are typically at the same level as or stronger than the precision obtained in our study. However, this holds only under the conditions that the additional Higgs states are not too heavy ($\leq$ a few TeV), the Hee coupling has the SM value, and no cancellations occur among the CP-violating parameters. In contrast, a significantly weaker upper limit on the CP-odd admixture is expected in the type-I 2HDM.