A. Drutskoy,
LPI, Moscow

P.N. Lebedev Physical Institute of the Russian Academy of Sciences
Физический институт имени П.Н.Лебедева
ФИАН

LPI group activity for CEPC experiment

E-mail: drutskoy@lebedev.ru

April 17, 2025

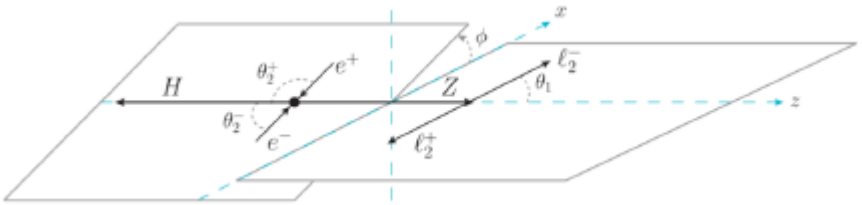
Outline

- Search for Higgs *CP*-odd admixture using ISR energy shift in process $e^+e^- \to Z\,h\,,\ Z \to \mu^+\mu^-$
- Search for invisible decays of Higgs boson at CEPC in process $e^+e^- \to Zh\,,\ Z \to jj\,,\ h \to invisible$
- Search for Higgs *CP*-odd admixture using angular distributions in process $e^+e^- \to Z\,h\,,\ h \to W^+W^{*-}\,,\ W \to jj,\ W^* \to jj$
- Angular and momenta distributions of ISR photons. Is it possible to register ISR photons using very forward detectors? (Study just started).

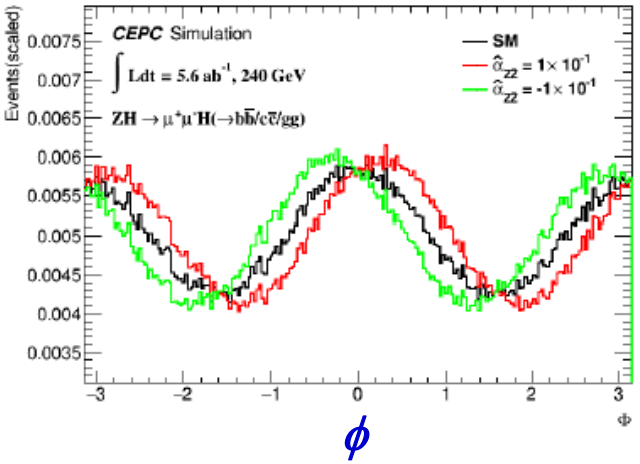
Search for Higgs *CP*-odd admixture using ISR energy shift

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

By the way, the CEPC paper refers [17] to my monography, A. Drutskoy, “International linear collider (ILC)“, Morgan & Claypool Publisher, 2018.



Angle ϕ between production plane and Z decay plane



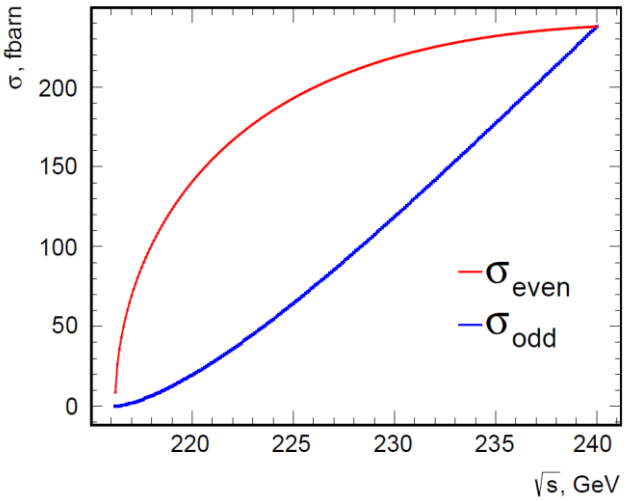
ϕ

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

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

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

General idea: cross section behaviors near threshold are different for *CP*-even and *CP*-odd Higgs boson.



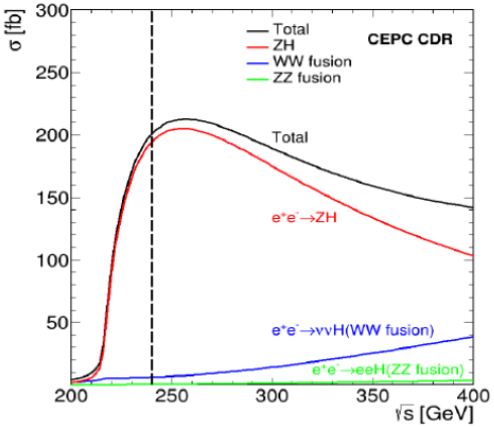
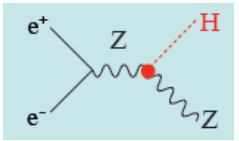


Figure 11.2: Production cross sections of $e^+e^- \to ZH$ and $e^+e^- \to (e^+e^-/\nu\bar{\nu})H$ as functions of $\sqrt{s}$ for a 125 GeV SM Higgs boson. The vertical dashed line indicates $\sqrt{s} = 240$ GeV, the nominal energy of the CEPC running as a Higgs factory.

Cross sections are obtained for ISR switched off.
CP-odd Xsection is normalized to *CP*-even Xsection at 240 GeV.

$Z \to H\,Z$



$1^- \to 0^+ 1^-$ s-wave ~p

$1^- \to 0^- 1^-$ p-wave ~p^3

$$\sigma\,(e^+e^- \to Z\,h\,,\ \sqrt{s},\ E_{ISR}) = \sigma\,(e^+e^- \to Z\,h\,,\ \sqrt{s} - E_{ISR}\,,\ 0)$$

Problem : we invented this method, it is not taken from literature, we are on thin ice.

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

Whizard 3 + Delphes (CEPC card)

Mostly only one beam (e- or e+) produces energetic ISR photon.

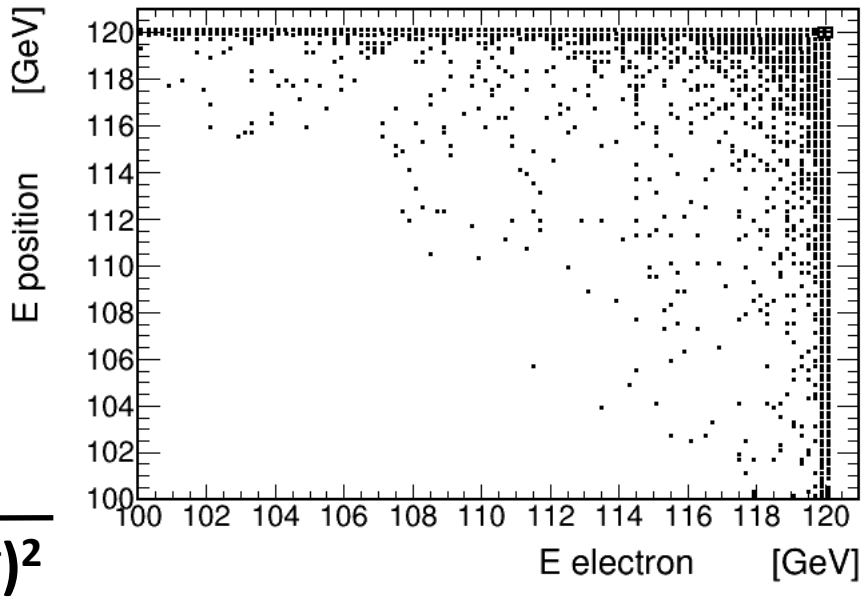
Corrected full energy after removing ISR can be approximately evaluated from formula ($e^+e^- \to Zh$) :

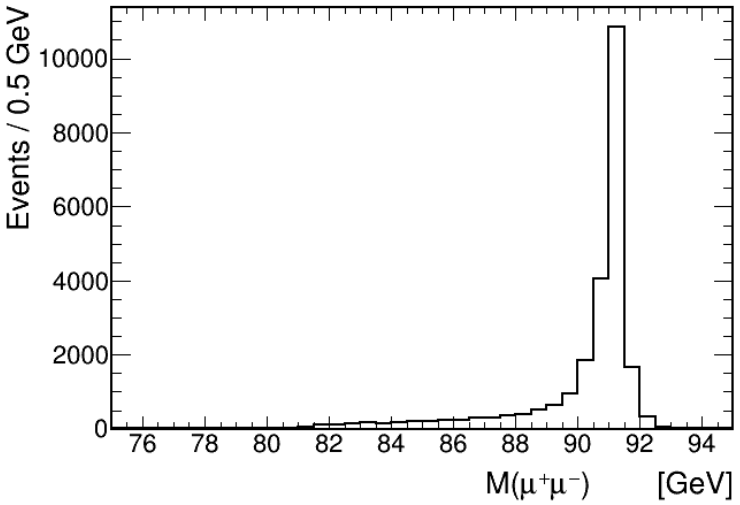
$$E_{corr} = E(\mu^+\mu^-) + \sqrt{M(h)^2 + P(\mu^+\mu^-)^2}$$

$E_{ISR} = 240 - E_{corr}$ - full lost energy

$M(\mu^+\mu^-)$ has long tail from Z mass to smaller values. This tail is not due to ISR. It will corrupt proposed formula.

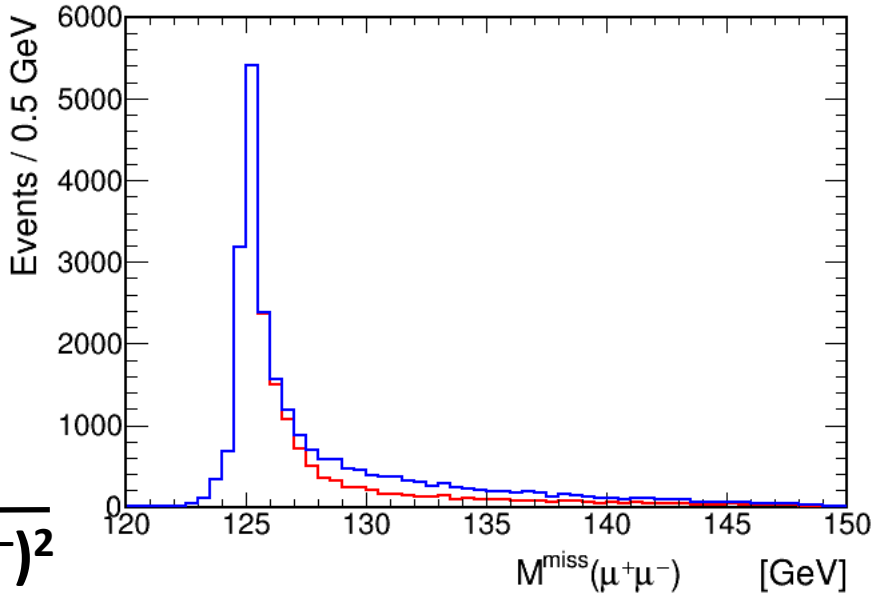
Cut applied: $M(\mu^+\mu^-) > 90$ GeV.





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

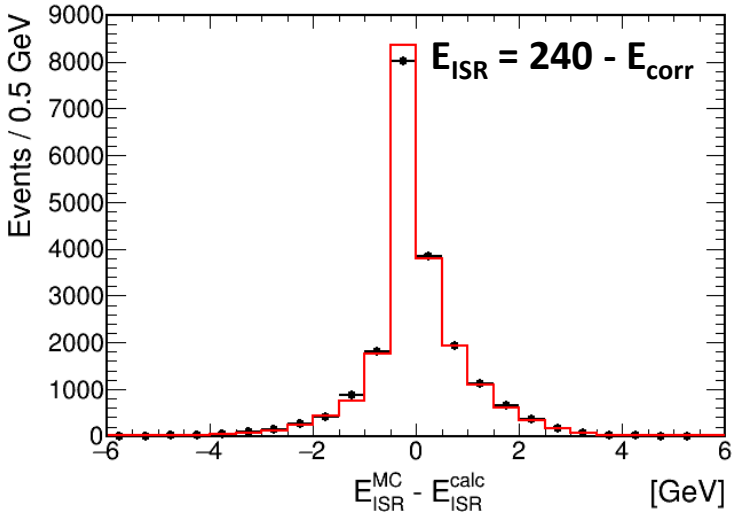
After **$M(\mu^+\mu^-) > 90$ GeV** cut tail in recoil (missing) mass (red line) becomes smaller comparing with distribution before cut (blue line).
Tail (red line) is reflection of ISR.



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

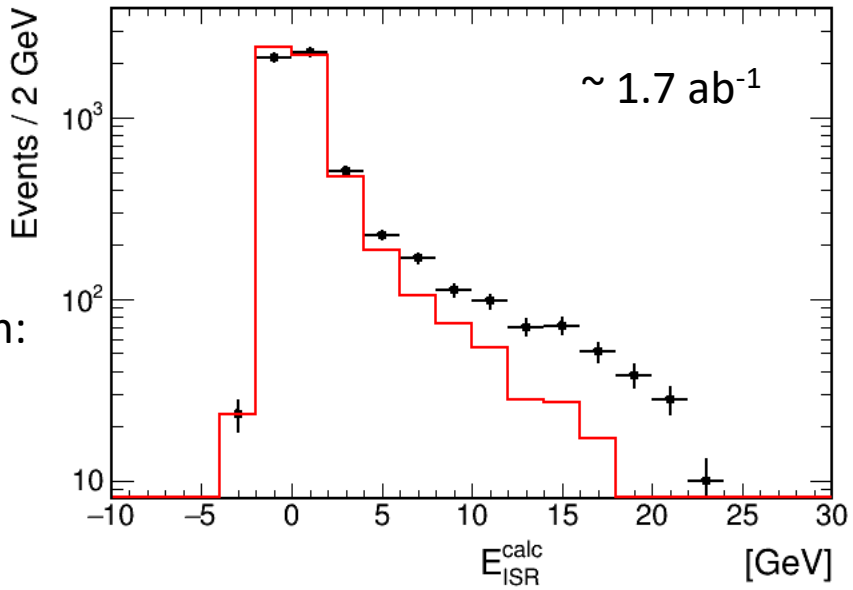
Difference between full energy after ISR on MC level and obtained from formula is not large, about 1 GeV.

Now we can check E_{ISR} distribution for *CP*-even Higgs and with *CP*-odd admixture.



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

First of all, we compare $\mathbf{E_{ISR}}$ distribution for pure CP-even (points) and pure CP-odd (red histogram) cases.



There is clear difference.

Whizard model is based on PDG Lagrangian:

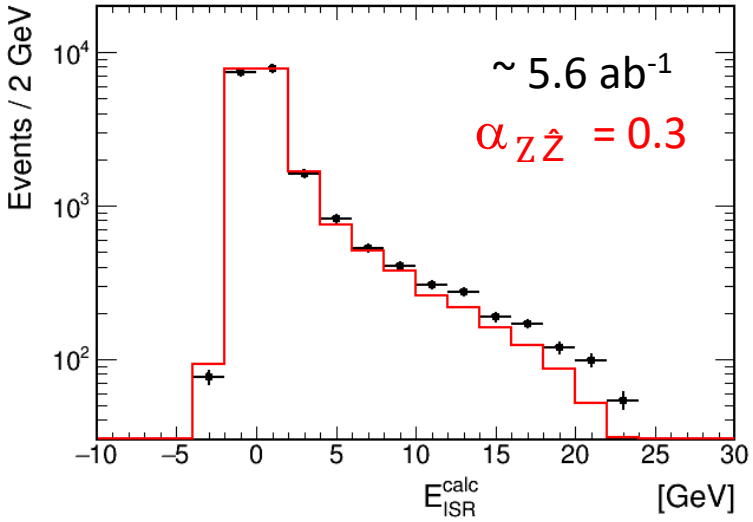
$$\mathcal{L}_0^{\prime,Z} \supset \left\{ \cos(\alpha)\kappa_{\rm SM} \left[\frac{1}{2} g_{HZZ} Z_\mu Z^\mu + \right. \right.$$

$$\left. \left. - \frac{1}{4\Lambda} \left[\cos(\alpha)\kappa_{HZZ} Z_{\mu\nu} Z^{\mu\nu} + \sin(\alpha)\kappa_{AZZ} Z_{\mu\nu} \tilde{Z}^{\mu\nu} \right] \right. \right.$$

arXiv: 2203.11707 [hep-ex]

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

$$c_{Z\tilde{Z}} = \left(\sqrt{2} G_F \right)^{1/2} \hat{\alpha}_{Z\tilde{Z}}$$

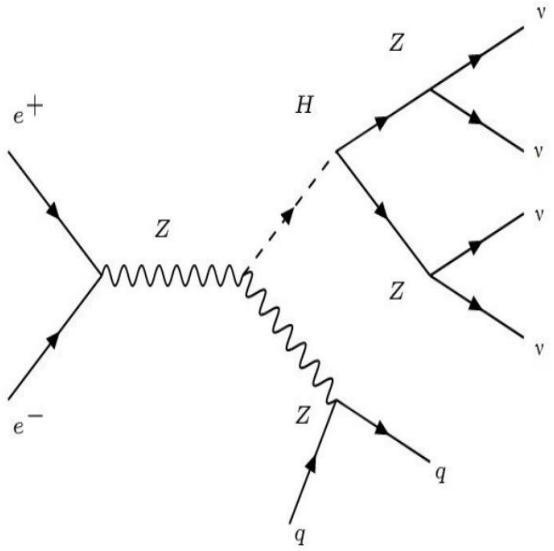


Rough projection ⇨ 1σ corresponds to $\alpha_{Z\hat{Z}}$ = 0.03-0.07 (~ 0.01 in CEPC paper).

Not sure, that we have correct normalization.

Search for invisible decays of Higgs boson at CEPC

- **Motivation**
- **Use Z→ jj channel with recoil Higgs mass and no any other activity**
- SM process H→ZZ* →4ν not observed yet due to very low branching fraction (0.12%);
- current upper limit from LHC approx. 11% [Phys.Lett.B 842 (2023) 137963]
- expected upper limit by simulation of SiD at ILC: 0.16% [arXiv: 2203.08330]



Analysis strategy

- Promising production channel – higgsstrahlung: e^+e^-→Zh
- @240 GeV (Z→inclusive, h→ZZ* →4ν); recoil mass technique
- the most clean di-muon channel with BR(Z→μμ) ≈ 3% preliminary studied by CEPC colleagues; add di-electron
- **We are going to use dijet channel with BR(Z→qq) ≈ 70% tradeoff problem: statistical vs systematic uncertainty**
- potentially possible to combine channels

Tasks for dijet analysis

- check and tune PF reconstruction algorithms; apply software compensation to improve jet energy resolution [EPJC 77 (2017) 10, 698; Phys.Atom.Nucl. 86 (2023) 4, 551]
- tune jet finders in various modes
- apply ML for background rejection

Potential task force: 2 senior researches, 1 master student, 1 bachelor student

Current status: familiarising ourselves with CEPSSW; simulation started of generated samples containing signal events using CEPC TDR detector model

Backgrounds:

- e^+e^- → WW (W → qq, W → lν)
- e^+e^- → e ν W
- e^+e^- → e^+e^-Z , (Z → qq)
- e^+e^- → ZZ , (Z → qq; Z → νν)
- e^+e^- → ννZ , (Z → qq)
- e^+e^- → ννh, (h → qq, τ τ)
- e^+e^- → Zh, (h → qq, τ τ ; Z → νν)

Higgs *CP*-properties in the $H \to WW^* \to 4j$ decay

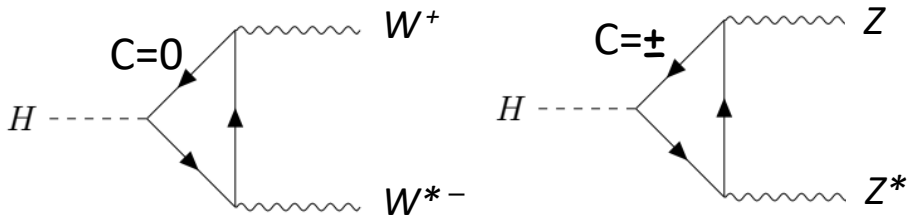
The invariant amplitude that describes the interaction between Higgs boson of arbitrary parity and two spin-one gauge bosons:

$$A(X \to VV) = v^{-1}\varepsilon_1^{*\mu}\varepsilon_2^{*\nu}\left(a_1 g_{\mu\nu} m_X^2 + a_2 q_\mu q_\nu + a_3 \varepsilon_{\mu\nu\alpha\beta} q_1^\alpha q_2^\beta\right)$$

a_1 corresponds to tree level amplitude ($a_1 = \frac{M_V^2}{M_X^2}$ in SM). a_2 and a_3 correspond to loop interactions of *CP*-even and *CP*-odd mixtures respectively, therefore can be sensitive to BSM physics.

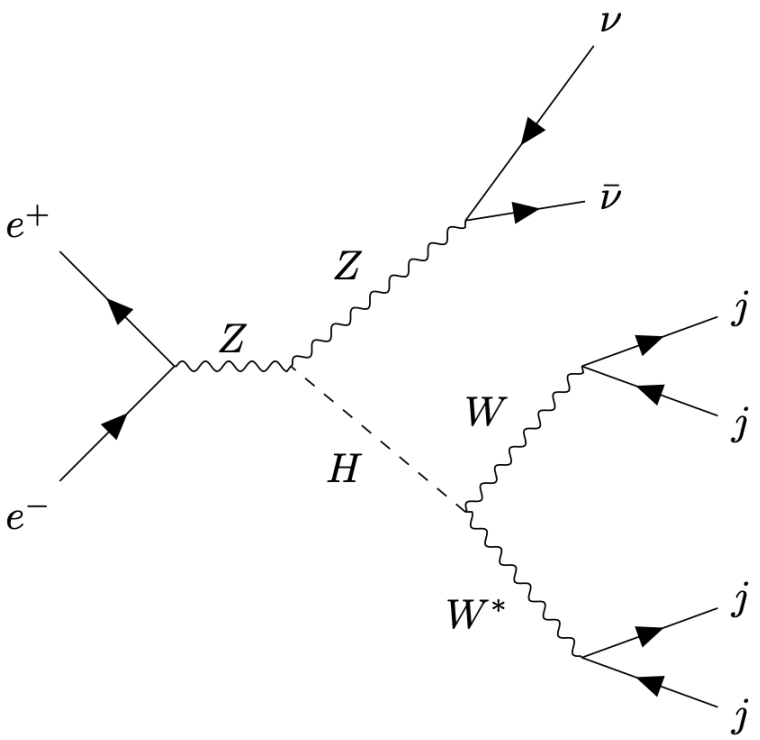
The final state observables sensitive to the parity of a spin-0 boson decaying $WW^* \to 4j$ are the masses of the intermediate W bosons M_W and M_{W^*} and three decay angles: φ, θ_1 and θ_2. Production angle of the WW^* system have a flat distribution for any parity of a decaying spin-0 particle.

Different BSM particles in loops in CP-odd Higgs decays: neural in WW and charged in ZZ



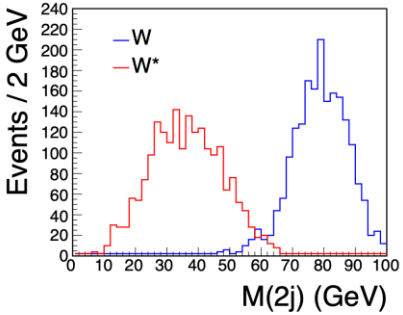
The CP-odd admixture can be tested in this decay!

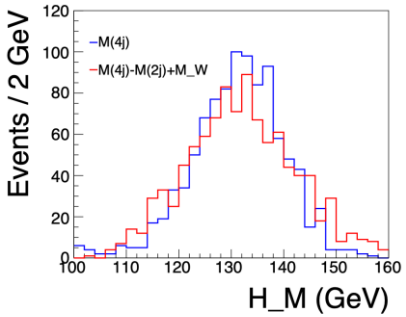
Higgs *CP*-properties in the $H \to WW^* \to 4j$ decay



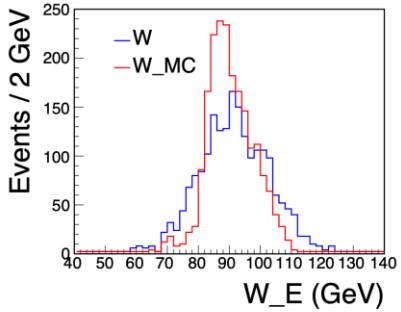
- $\sqrt{s} = 240\,GeV$
- ~20k events
- Good signature to suppress background processes

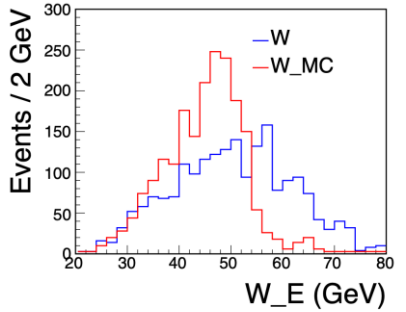
Whizard + CEPCSW simulation





M_W and M_{W^*} distributions look reasonable.
But Higgs mass is **7 GeV larger**





Basic CEPCSW simulation does not give good energy calibration.

Do we use obsolete CEPC software version?

Is it possible to detect ISR photons by special forward detector?

We are interested to participate in detector development efforts, probably simulations.

There are many ISR photons, which result in resolution worsening of many measurements. Such photons escape detection because of small outcome angles relative to beams.

It is difficult to install respective detectors in linear collider, however it is probably possible in circular collider.

We are going to study angular and momenta distributions of ISR photons and also to check geometry of CEPC collider.

Please tell us, if this work is useful or not.

Conclusion

- Higgs *CP*-odd admixture is studied using ISR energy shift in process $e^+e^- \to Z\,h\,,\, Z \to \mu^+\mu^-$. If somebody can join to our efforts and help with parameter calculations it will be very useful. We are not sure that we understand normalizations. Potentially this new variable can be included in common fit.

- There are a few topics, which we are studying. In particular, it is search for invisible decays of Higgs boson, *CP*-composition in $h \to W^+W^{*-}$ decay, angular and momenta distribution of ISR photons. It would be very useful to have contacts with CEPC people, who are working in these areas.

- Our LPI group members have expertise in physics at lepton colliders and software for calorimeters. There is also a possibility (limited) to produce hardware work, some tests (instrumentation).