Precision Higgs Physics at CEPC

Initial assessments of Higgs physics potential at the CEPC based on the white paper (to be submitted)

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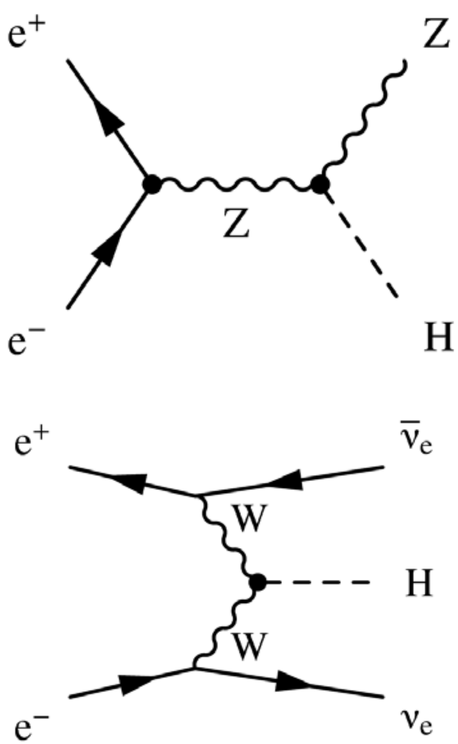
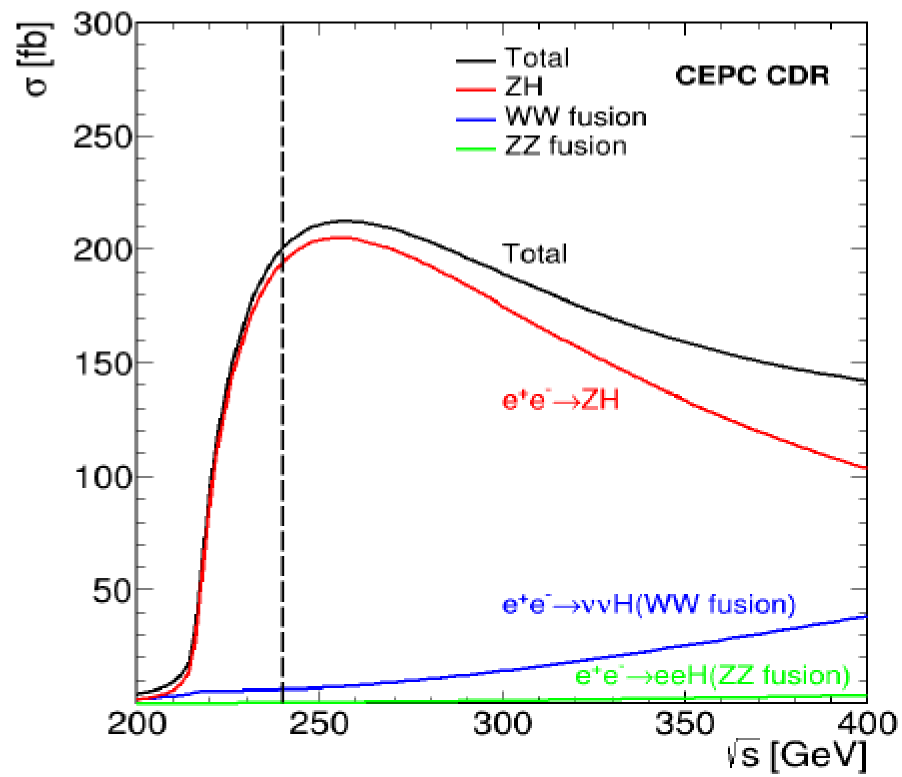
CEPC Higgs Factory Operation

Designed to produce 1 million Higgs bosons $\Rightarrow$ 7 years operation at $\sqrt{s} = 240$ GeV for an integrated luminosity of 5.6 ab^{-1} (2 IPs)

At $\sqrt{s} = 240$ GeV, $ee \rightarrow ZH$ production is near the maximum and dominates with a smaller contribution from $ee \rightarrow \nu\nu H$.



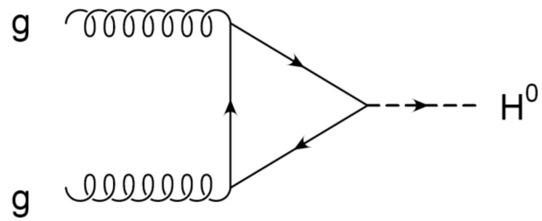


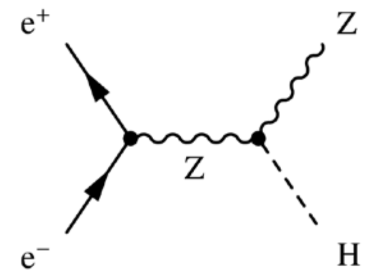
Event Rates in 5.6 ab^{-1}

Process	Cross section	Events in 5.6 ab^{-1}
Higgs boson production, cross section in fb		
$e^+e^- \to ZH$	196.2	1.10×10^6
$e^+e^- \to \nu_e\bar{\nu}_e H$	6.19	3.47×10^4
$e^+e^- \to e^+e^- H$	0.28	1.57×10^3
Total	203.7	1.14×10^6
Background processes, cross section in pb		
$e^+e^- \to e^+e^-$ (Bhabha)	~~24.7~~	~~1.4×10^8~~ To be updated
$e^+e^- \to q\bar{q}\,(\gamma)$	54.1	3.0×10^8
$e^+e^- \to \mu^+\mu^-\,(\gamma)$ [or $\tau^+\tau^-\,(\gamma)$]	5.3	3.0×10^7
$e^+e^- \to WW$	16.7	9.4×10^7
$e^+e^- \to ZZ$	1.1	6.2×10^6
$e^+e^- \to e^+e^-Z$	4.54	2.5×10^7
$e^+e^- \to e^+\nu W^-/e^-\bar{\nu}W^+$	5.09	2.6×10^7

Main differences with LHC

- **Production:**
  LHC: dominated by the QCD process $\Rightarrow$ large theoretical uncertainties
  CEPC: pure electroweak process $\Rightarrow$ precise theory calculations





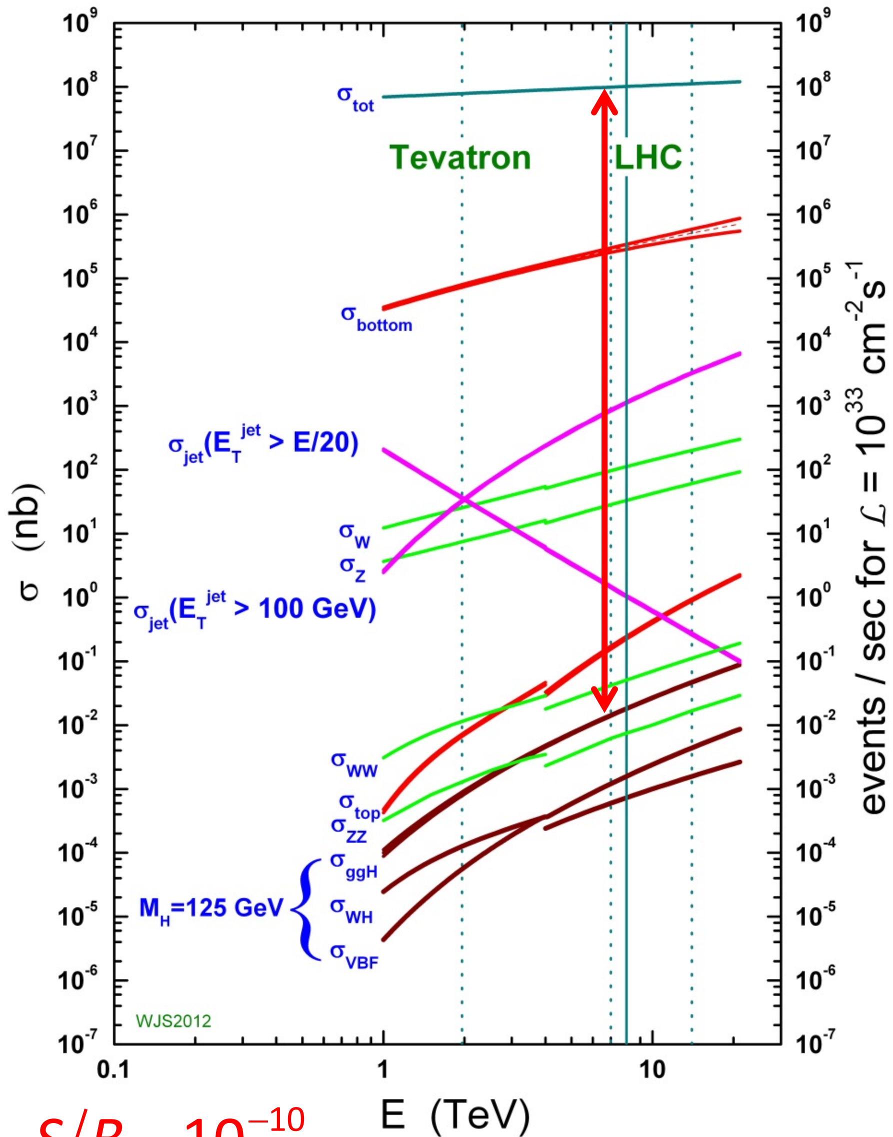
- **Trigger and identification:**
  LHC: based on specific Higgs boson decay signatures $\Rightarrow$ *measure $\sigma\times BR$*
  CEPC: Higgs boson decay blinded $\Rightarrow$ *measure σ and BR*

- **Environment:**
  LHC: suffer from underlying event and pileup effects
  CEPC: clean

- **Statistics**
  HL-LHC: ~ 300 million Higgs bosons, recording about ~2%
  CEPC: ~ 1 million Higgs bosons, every event is gold

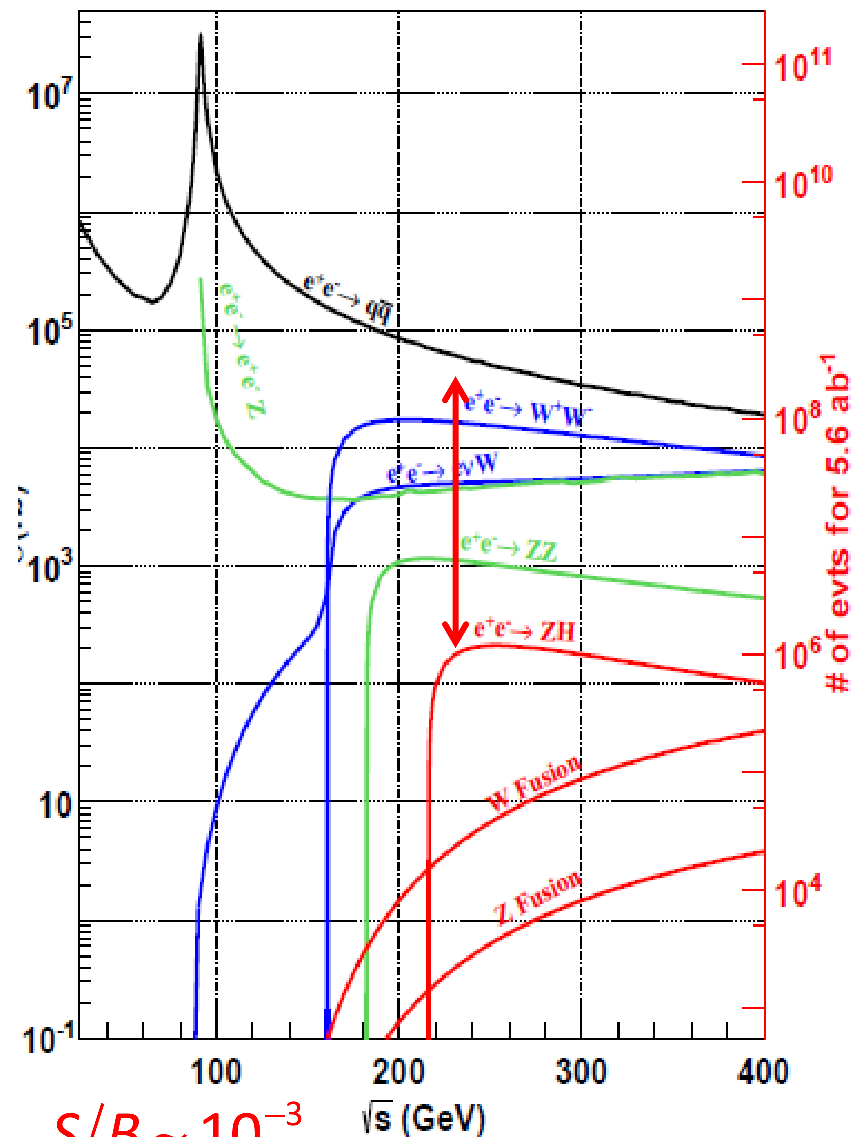
Cross Sections and Initial S/B's

proton - (anti)proton cross sections



$S/B \sim 10^{-10}$

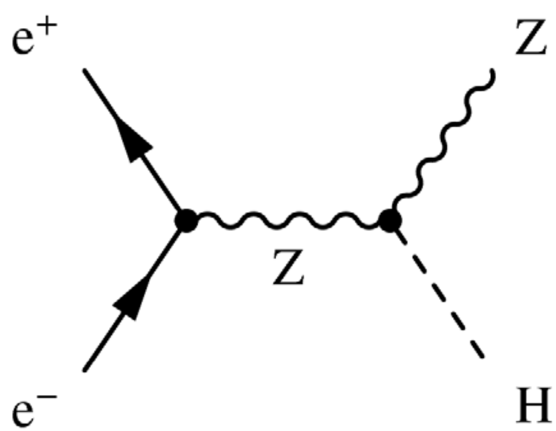
e^+e^- cross sections

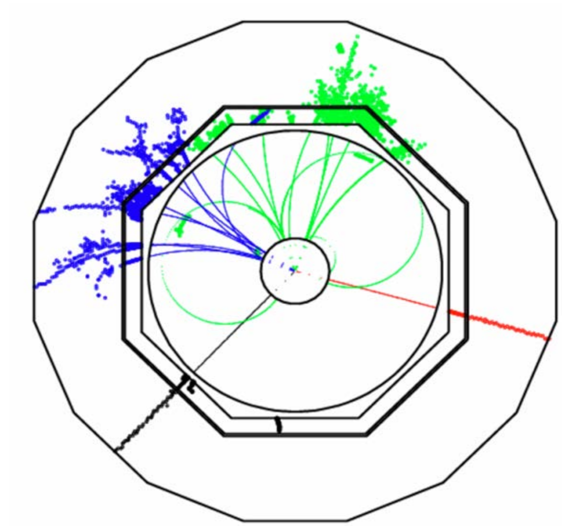


$S/B \sim 10^{-3}$

Decay-Blinded Tagging of Higgs Boson

Unique to lepton colliders, the energy and momentum of the Higgs boson in $ee \to ZH$ can be measured by looking at the Z kinematics only: $E_H = \sqrt{s} - E_Z, \quad \vec{p}_H = -\vec{p}_Z$





Recoil mass reconstruction:

$$m^2_{\text{recoil}} = \left(\sqrt{s} - E_Z\right)^2 - \left|\vec{p}_Z\right|^2$$

$\Rightarrow$ identify the Higgs boson without looking at the Higgs boson.

Measure $\sigma\left(ee \to ZH\right)$ independent of its decay !

$\big($LHC always measures $\sigma \times$BR$\big)$

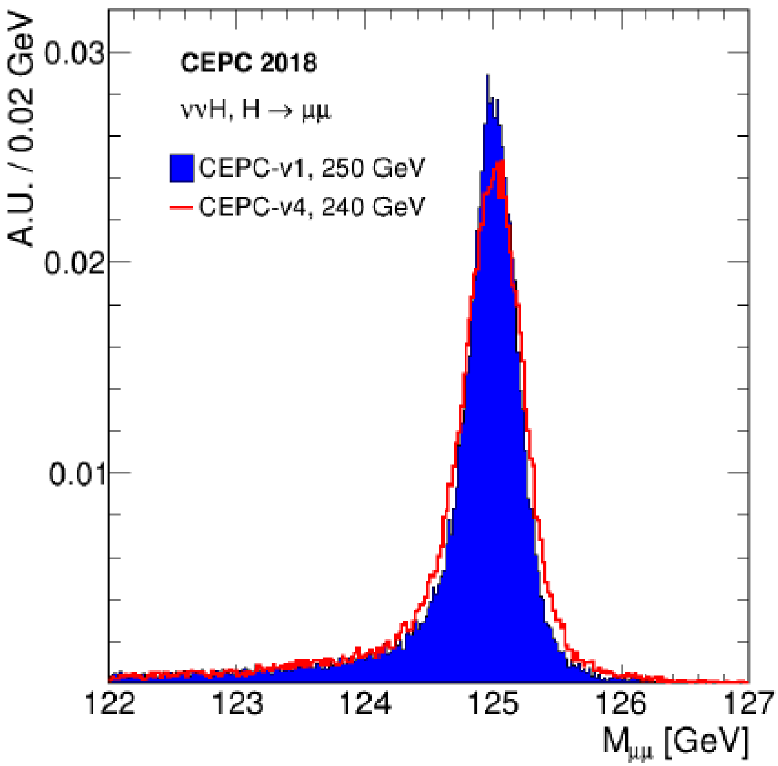
Simulation Studies

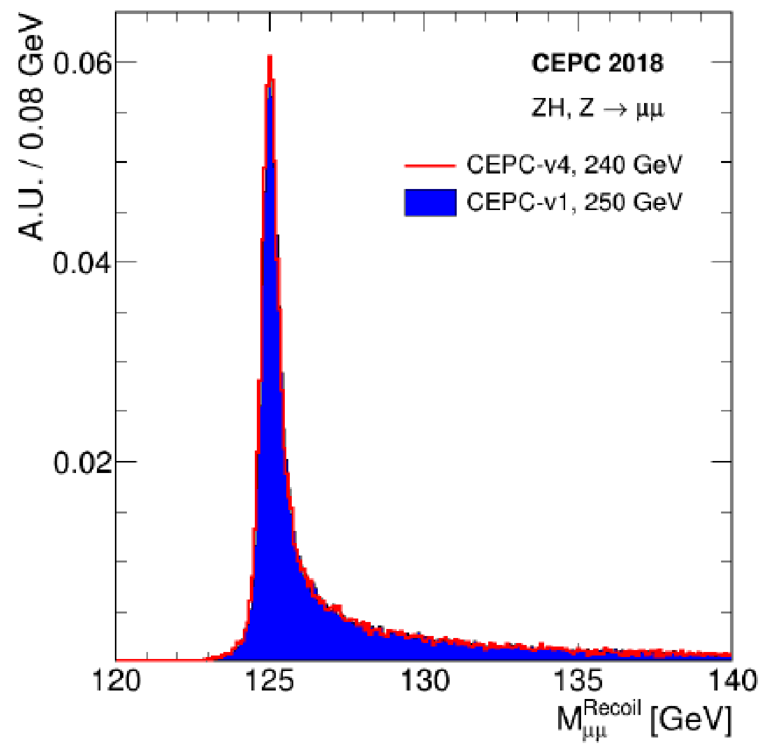
Most of the simulation studies were performed for CEPC-v1. The results were extrapolated to CEPC-v4, the setup for CDR.

CEPC-v1: B = 3.5 T, 250 GeV, 5×5 mm^2 ECAL

CEPC-v4: B = 3 T, 240 GeV, 10×10 mm^2 ECAL

The largest impact on the performance is the degraded track momentum resolution, Other changes are small. The extrapolation takes into account cross section changes as well.





Accessible Decay Modes

SM decay		Accessible?	
mode	branching ratio	(HL-)LHC	Higgs factories
$H \to bb$	57.7%	✓, × *	✓
$H \to gg$	8.57%	×	✓
$H \to cc$	2.91%	×	✓
$H \to ss$	2.46×10^{-4}	×	?
$H \to \tau\tau$	6.32%	✓	✓
$H \to \mu\mu$	2.19×10^{-4}	✓	✓
$H \to WW$	21.5%	✓	✓
$H \to ZZ$	2.64%	✓	✓
$H \to \gamma\gamma$	0.23%	✓	✓
$H \to Z\gamma$	0.15%	✓	✓

* Not all production mode.

Limitations: statistics at Higgs factories,
trigger and systematics at (HL-)LHC

Final States Studied

$H \to bb / cc / gg$

Z decay mode	$H \to b\bar{b}$	$H \to c\bar{c}$	$H \to gg$
$Z \to e^+e^-$	1.3%	12.8%	6.8%
$Z \to \mu^+\mu^-$	1.0%	9.4%	4.9%
$Z \to q\bar{q}$	0.5%	10.6%	3.5%
$Z \to \nu\bar{\nu}$	0.4%	3.7%	1.4%
Combined	0.3%	3.1%	1.2%

$H \to WW^*$

ZH final state		Precision
$Z \to e^+e^-$	$H \to WW^* \to \ell\nu\ell'\nu,\ \ell\nu q\bar{q}$	2.6%
$Z \to \mu^+\mu^-$	$H \to WW^* \to \ell\nu\ell'\nu,\ \ell\nu q\bar{q}$	2.4%
$Z \to \nu\bar{\nu}$	$H \to WW^* \to \ell\nu q\bar{q}, q\bar{q}q\bar{q}$	1.5%
$Z \to q\bar{q}$	$H \to WW^* \to q\bar{q}q\bar{q}$	1.7%
Combined		0.9%

$H \to ZZ^*$

ZH final state		Precision
$Z \to \mu^+\mu^-$	$H \to ZZ^* \to \nu\bar{\nu}q\bar{q}$	7.2%
$Z \to \nu\bar{\nu}$	$H \to ZZ^* \to \ell^+\ell^-q\bar{q}$	7.9%
Combined		4.9%

$H \to \tau\tau$

ZH final state		Precision
$Z \to \mu^+\mu^-$	$H \to \tau^+\tau^-$	2.6%
$Z \to e^+e^-$	$H \to \tau^+\tau^-$	2.6%
$Z \to \nu\bar{\nu}$	$H \to \tau^+\tau^-$	2.5%
$Z \to q\bar{q}$	$H \to \tau^+\tau^-$	0.9%
Combined		0.79%

$H \to$ Invisible

ZH final state studied		Relative precision on $\sigma \times$ BR	Upper limit on BR($H \to$ inv)
$Z \to e^+e^-$	$H \to$ inv	339%	0.82%
$Z \to \mu^+\mu^-$	$H \to$ inv	232%	0.60%
$Z \to q\bar{q}$	$H \to$ inv	217%	0.57%
Combined		143%	0.41%

Other final states:

$H \to \gamma\gamma$: $Z \to \mu\mu, \tau\tau, \nu\nu, qq$

$H \to Z\gamma$: $ZZ \to \nu\nu qq$

$H \to \mu\mu$: $Z \to \ell\ell,\ \nu\nu,\ qq$

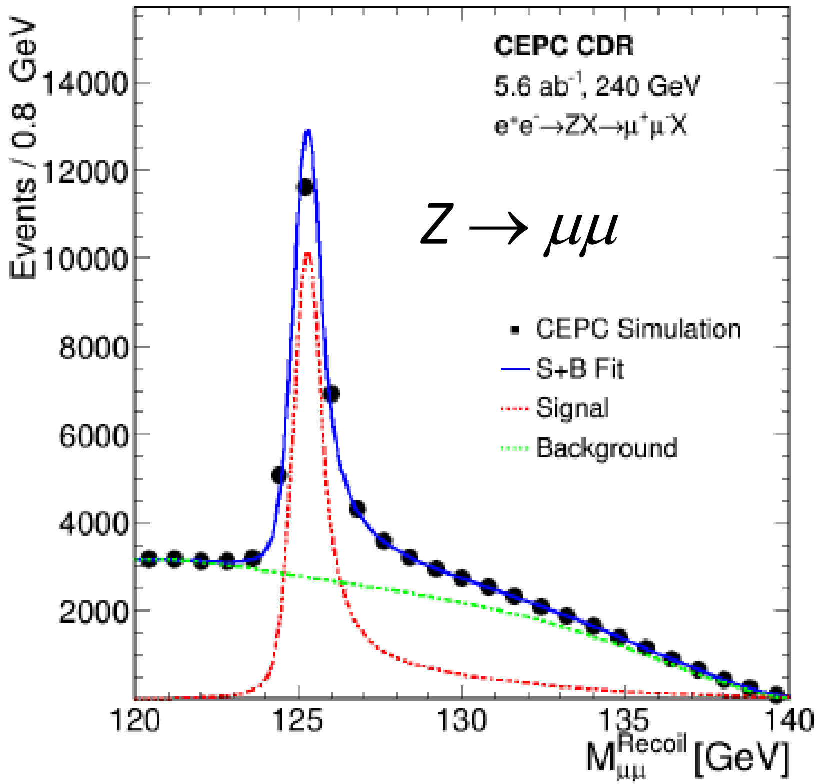
$ee \to \nu\nu H \to \nu\nu bb$

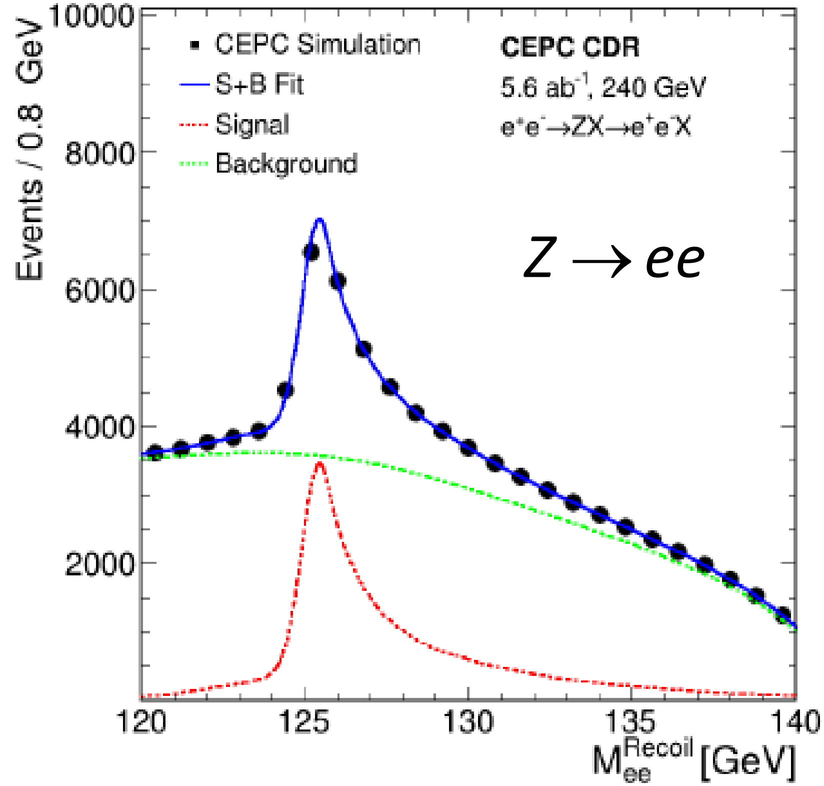
A lot final states have been studied, many more remain unexplored…

Recoil mass analyses

$$\text{Peak position} \Rightarrow m_H; \quad \text{peak height} \Rightarrow \sigma(ZH)$$

(Inclusive Higgs boson decays)

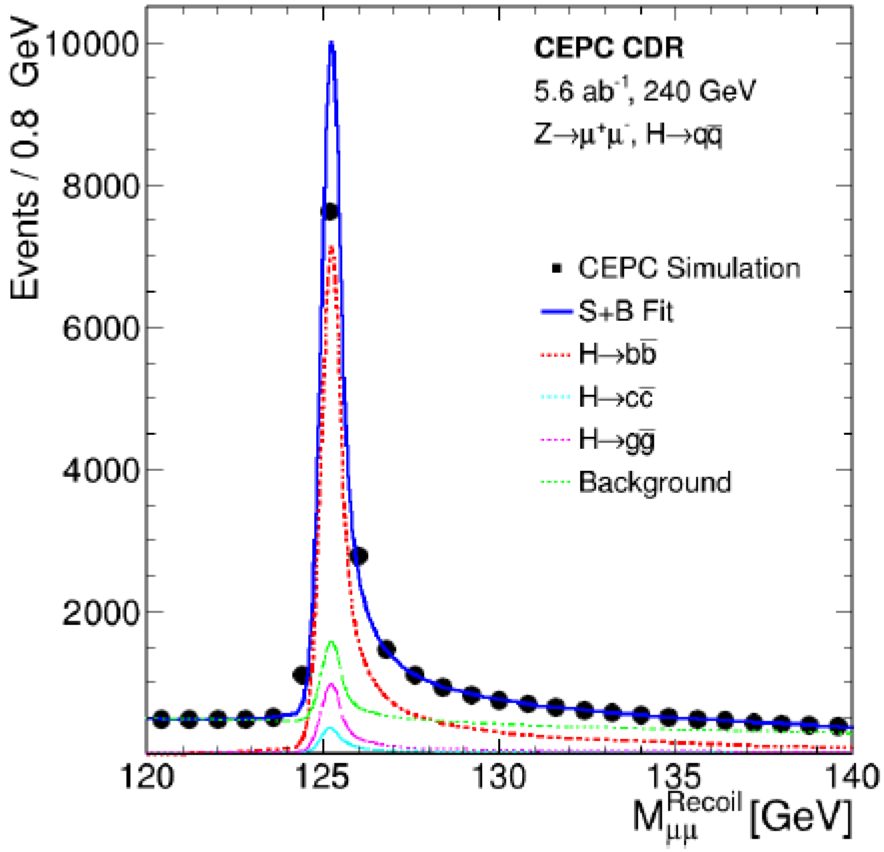




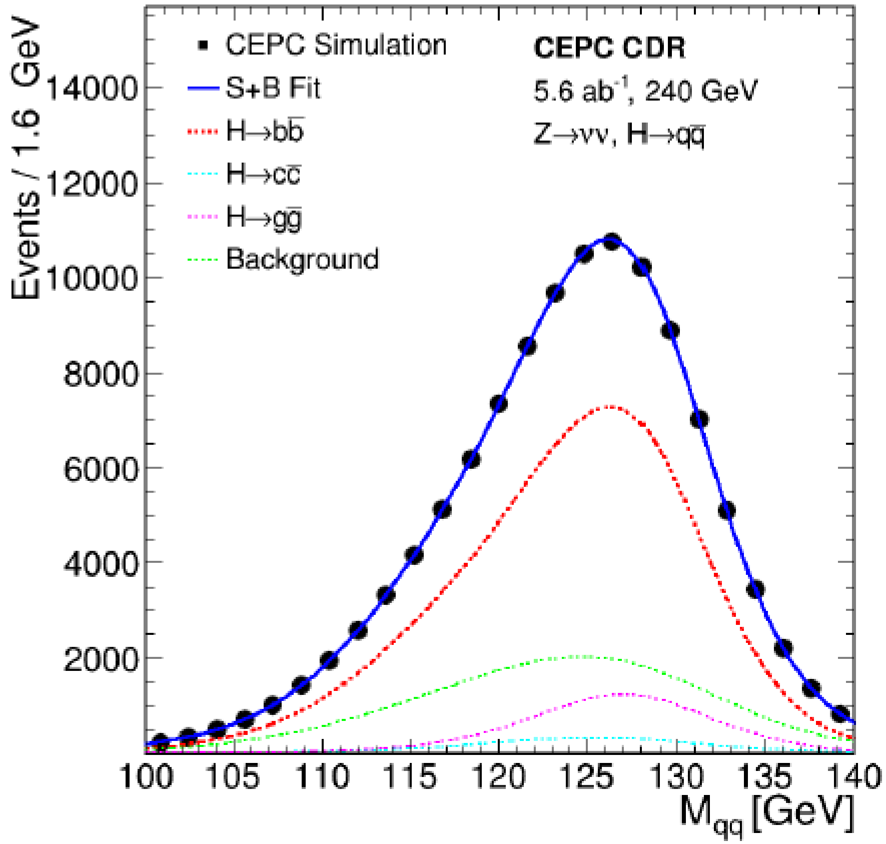
No Bremstrahlung radiation recovery yet, *ee* channel suffers from the large two-photon background.

Higgs Boson Decay Analyses

$Z \to \mu\mu,\ H \to b\bar{b} / c\bar{c}\ \ / gg$



$Z \to \nu\nu,\ H \to b\bar{b} / c\bar{c}\ \ / gg$



(Other Higgs boson decays are included in the background for individual analyses, but are treated as signal in the combination.)

Expected Precision from Combination

Property	Estimated Precision
m_H	5.9 MeV
Γ_H	3.1%
$\sigma(ZH)$	0.5%
$\sigma(\nu\bar{\nu}H)$	3.0%

Decay mode	$\sigma(ZH) \times$ BR	BR
$H \to b\bar{b}$	0.27%	0.56%
$H \to c\bar{c}$	3.3%	3.3%
$H \to gg$	1.3%	1.4%
$H \to WW^*$	1.0%	1.1%
$H \to ZZ^*$	5.1%	5.1%
$H \to \gamma\gamma$	6.8%	6.9%
$H \to Z\gamma$	15%	15%
$H \to \tau^+\tau^-$	0.8%	1.0%
$H \to \mu^+\mu^-$	17%	17%
$H \to$ inv	–	$< 0.30\%$

Statistical uncertainties only, but *taking into account correlations* among analyses.

Systematic uncertainties are expected to be small, but need studies

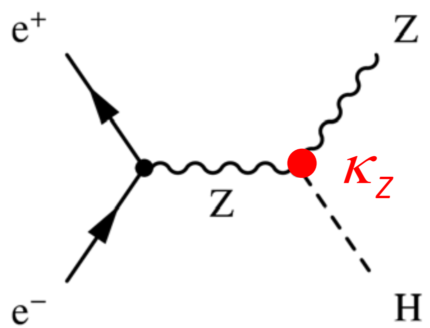
Width measurements:

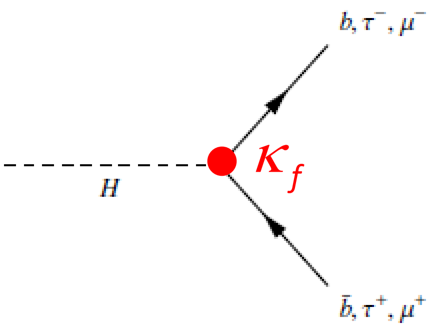
$$\Gamma_H = \frac{\Gamma(H \to ZZ^*)}{\mathrm{BR}(H \to ZZ^*)} \propto \frac{\sigma(ZH)}{\mathrm{BR}(H \to ZZ^*)}$$

$$\Gamma_H = \frac{\Gamma(H \to WW^*)}{\mathrm{BR}(H \to WW^*)} \propto \frac{\sigma(\nu\bar{\nu}H)}{\mathrm{BR}(H \to WW^*)}$$

$\Leftarrow$ 95% CL upper limit on BSM contribution

Relative Precision on Coupling Modifiers





Relative percentage precision

	10-parameter fit		7-parameter fit	
	CEPC	+HL-LHC	CEPC	+HL-LHC
Γ_H	3.1	2.5	–	–
κ_b	1.6	1.2	1.5	1.1
κ_c	2.2	1.9	2.2	1.9
κ_g	1.6	1.3	1.6	1.2
κ_W	1.4	1.1	1.4	1.0
κ_τ	1.5	1.2	1.5	1.1
κ_Z	0.25	0.25	0.15	0.15
κ_γ	3.7	1.6	3.7	1.6
κ_μ	8.7	5.0	–	–
$\mathrm{BR}_{\mathrm{inv}}^{\mathrm{BSM}}$	0.30	0.30	–	–

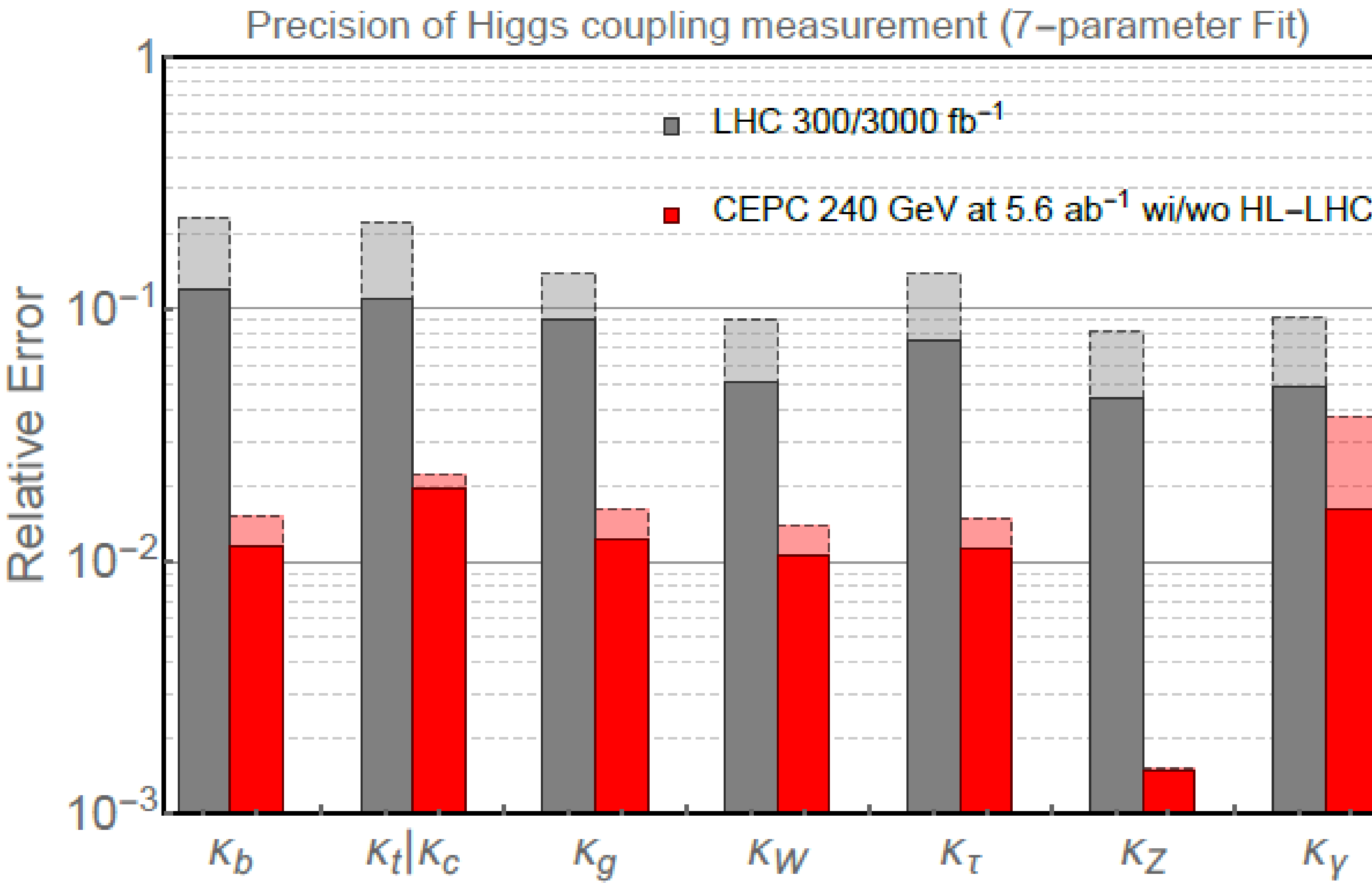
$\mathrm{BR}_{\mathrm{inv}}^{\mathrm{BSM}}$ shown are 95% CL upper limits

$$\sigma(ZH) = \boxed{\kappa_Z^2} \cdot \sigma_{SM}(ZH)$$

$$\mathrm{BR}(H \to ff) = \boxed{\frac{\kappa_f^2}{\kappa_H^2}} \cdot \mathrm{BR}_{SM}(H \to ff)$$

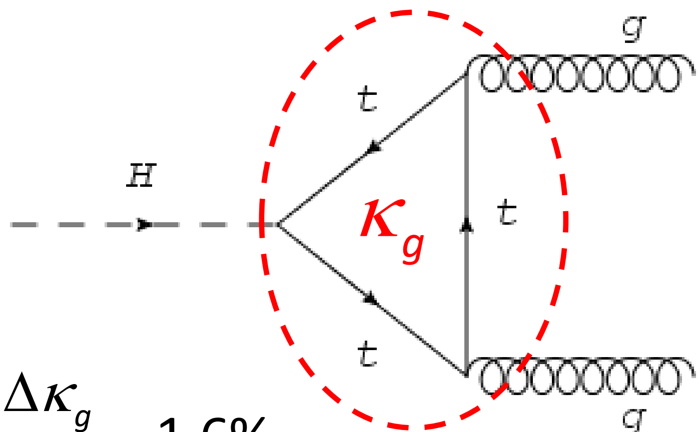
7-parameter fit assumes lepton universality and no BSM Higgs boson decays

Comparisons with HL-LHC



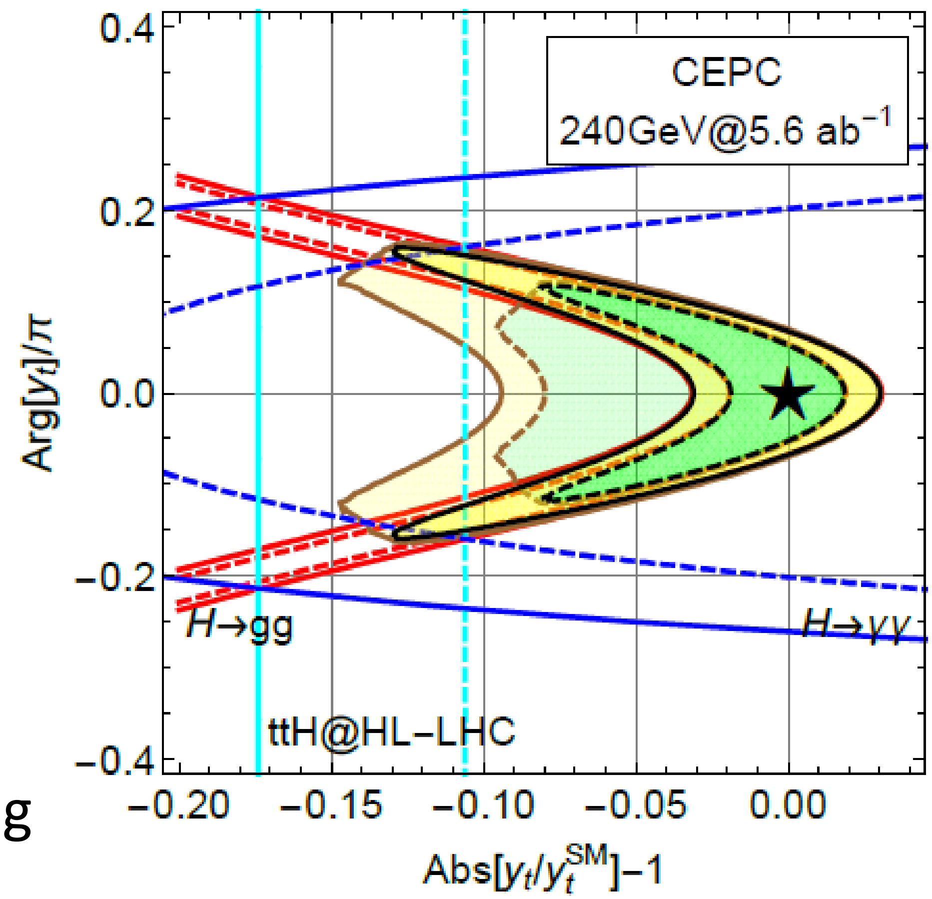
Higgs and Top Coupling

CEPC will be sensitive to the Higgs-Top coupling through the loop $H \to gg$ decay.



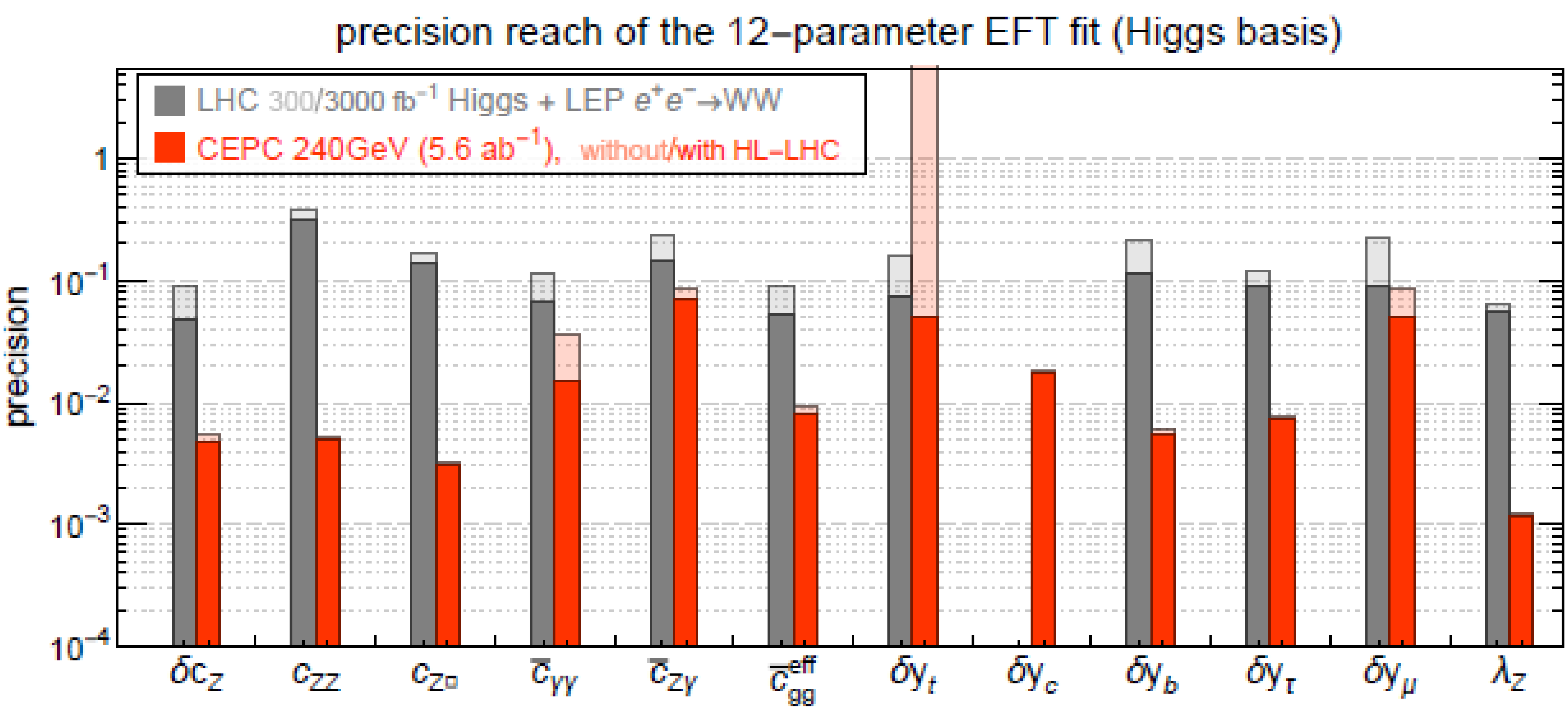
$$\frac{\Delta\kappa_g}{\kappa_g} \sim 1.6\%$$

The expected high precision in the coupling measurement can be used to constrain the coupling as well as CP-violating phase

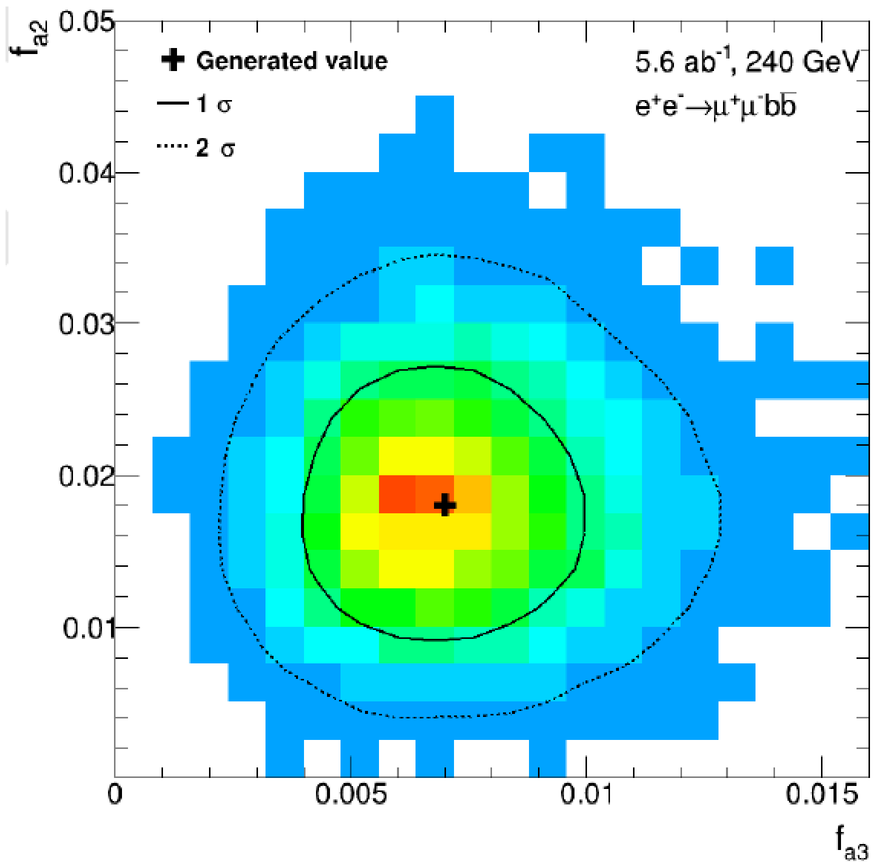


Precision of EFT Fits

A complete set of CP-even dimension-6 operators that contribute to the Higgs boson and diboson measurements, but not to the Z-pole observables, the W mass and fermion dipole interaction



Higgs Boson CP Studies



f_{a2} : fraction of high-order CP-even contribution due to SM or BSM physics

f_{a3} : fraction of CP-odd contribution due to BSM physics

3σ discovery potential from $ZH \to \mu\mu bb$

$f_{a2} > 0.018$ or $f_{a3} > 0.007$

Summary

A preliminary assessment of CEPC's Higgs physics potential has been performed based on the simulation studies of the CEPC conceptual detector.

Percent-level precision or better can be achieved for many of the Higgs boson couplings, improving HL-LHC measurements by an order of magnitude in many cases.

More studies are needed to fully understand the potential of the CEPC as a Higgs factory. For some final states, significant further Improvements are expected.

CEPC will open a new frontier in precision physics and can "undress" the Higgs boson as what LEP has done to the Z boson. It has the potential to shed lights on new physics.

Comparison with FCC-ee

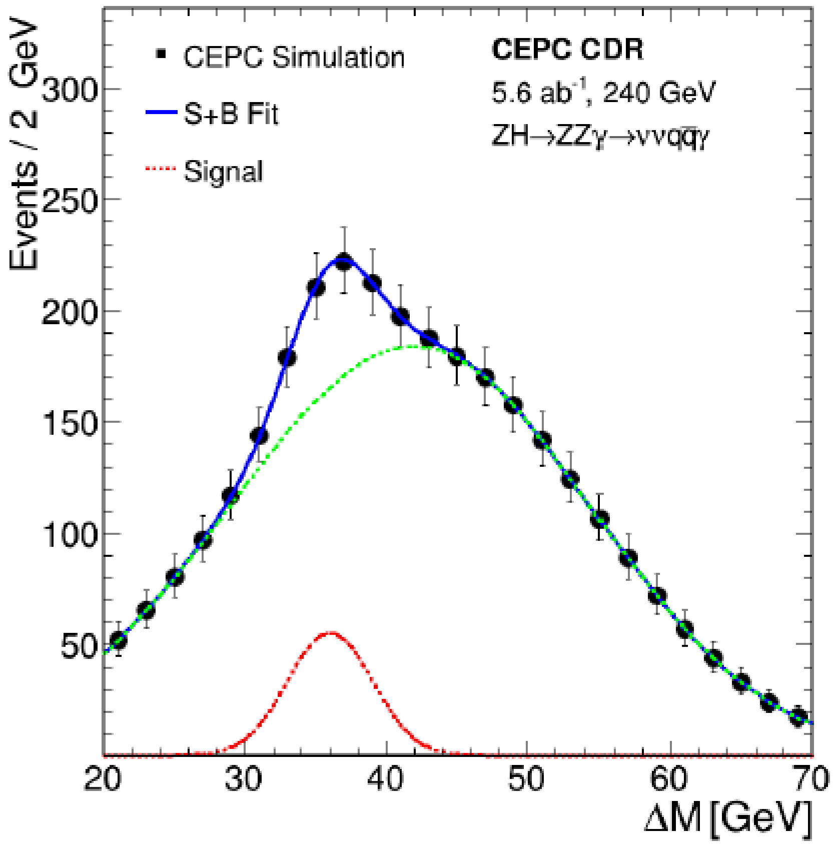
Relative precision of Higgs couplings

	CEPC		FCC-ee*
	5.6 ab^{-1}, 240 GeV		5 ab^{-1}, 240 GeV
Correlations	included	ignored	ignored
Γ_H	3.1%	2.9%	2.8%
κ_b	1.6%	1.4%	1.4%
κ_c	2.2%	2.1%	1.8%
κ_g	1.6%	1.5%	1.7%
κ_W	1.4%	1.3%	1.3%
κ_Z	0.25%	0.25%	0.25%
κ_γ	3.7%	3.7%	4.7%
κ_τ	1.5%	1.4%	1.4%
κ_μ	8.7%	8.7%	9.6%
BR_{inv}^{BSM}	$< 0.3\%$	$< 0.3\%$	–

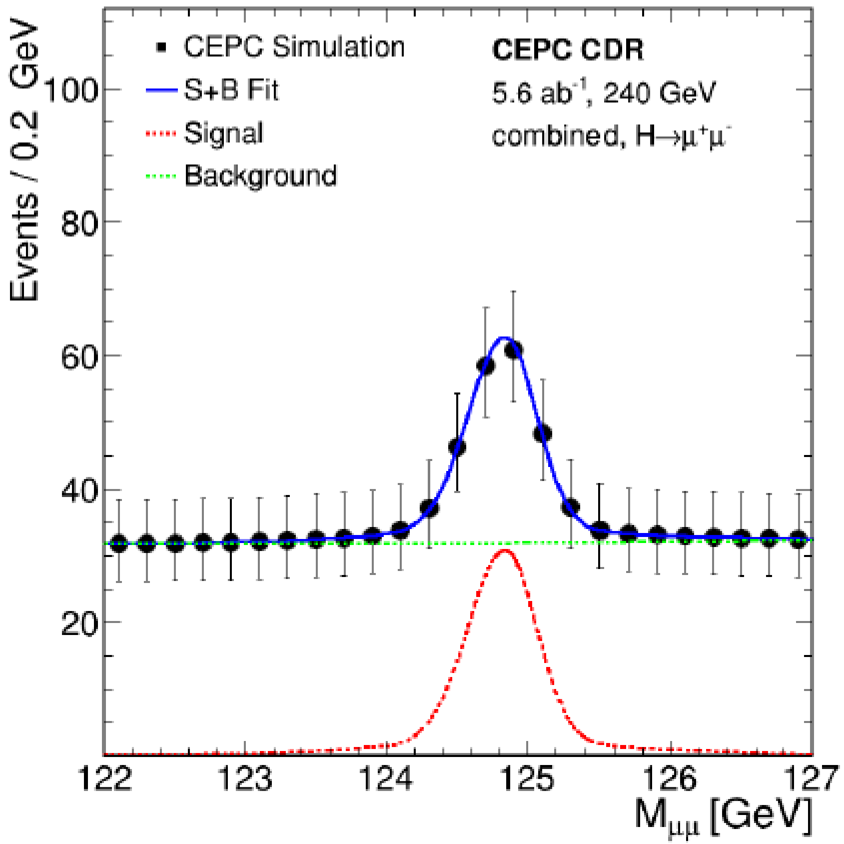
* presented at ICHEP 2018

Higgs Boson Decay Analyses

$$ZH \to ZZ\gamma \to \nu\bar{\nu}q\bar{q}\gamma$$



$$Z \to (\ell\ell, \nu\nu, qq),\ H \to \mu\mu$$



$$\Delta M = M(q\bar{q}\gamma) - M(q\bar{q}) \text{ or } M(\nu\bar{\nu}\gamma) - M(\nu\bar{\nu})$$