Higgs Physics at CEPC

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On behalf of CEPC White Paper Group

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Introduction

- The discovery of a Higgs boson in 2012 by ATLAS and CMS opened a new era in particle physics
- Subsequent measurements of the properties indicate Standard Model (SM) Higgs boson
- However, the SM does not predict the parameters in the Higgs potential.
  - Vast difference between the Planck scale and weak scale remains a major mystery
- Precision measurements of Higgs boson properties will be a critical component of any road map for high energy physics in the coming decades.

New Physics beyond the SM

- Deviations in the Higgs couplings from the SM expectations.

$$\delta = c\frac{v^2}{M_{\rm NP}^2}$$

v: vacuum expectation value of Higgs field

M_NP: Typical mass scale of new physics

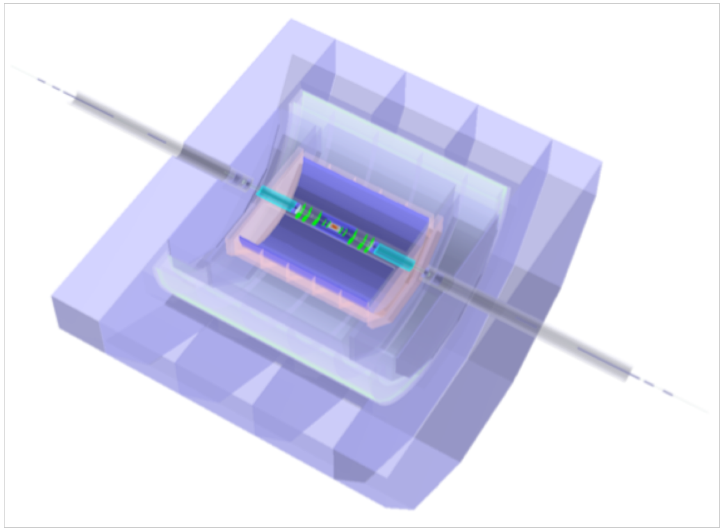
- The HL-LHC will measure the Higgs boson couplings ~5%.
- Probing new physics significantly beyond the LHC reach require ~% level of Higgs coupling measurement.
  ➔ Need for Higgs factory.

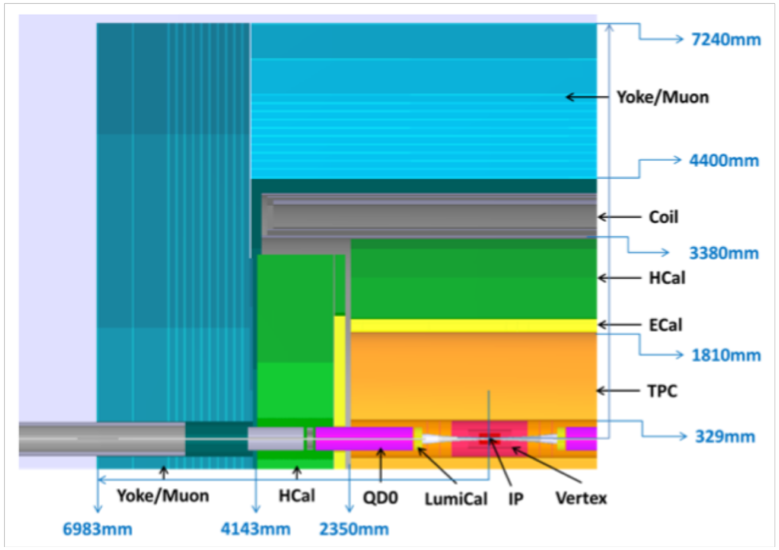
The Circular Electron-Positron Collider (CEPC)

- 100 km circumference
- Center-of-mass energy ~240 GeV
- Higgs production : e+e- → ZH , recoil mass method
- Expected int. lumi: 5.6/ab, 1M Higgs
- Higgs coupling to Z ~ 0.25%
- Invisible decay ~ 0.3%
- Model independent measurement of Higgs width

CEPC Detector Concept

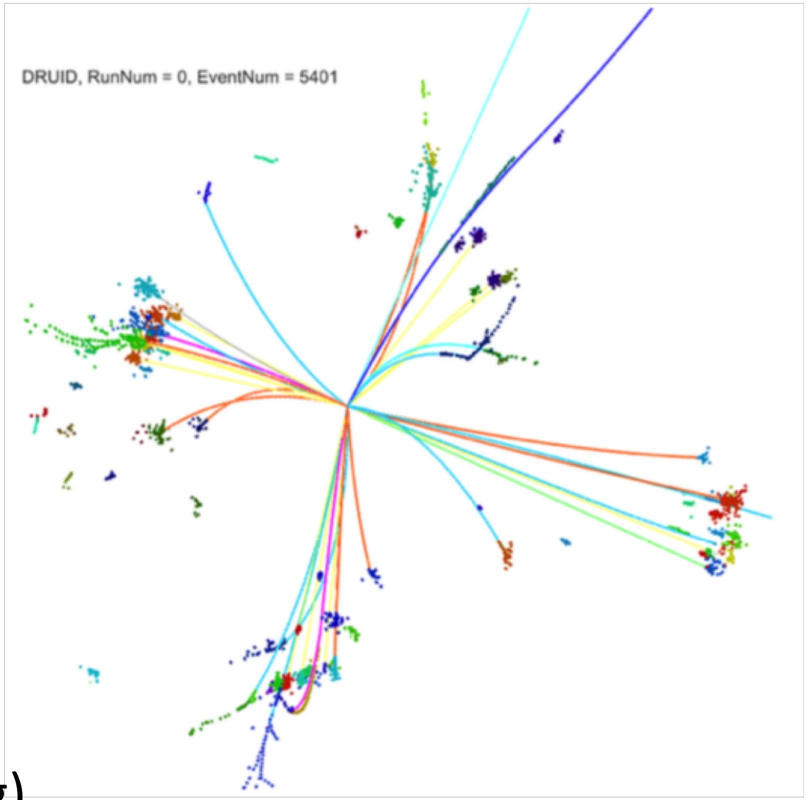
- Higgs factory √s = 240 GeV 7 yrs → 1M H, 1B Z, 100M W
- Z factory √s = 91.2 GeV → 10^{11} – 10^{12} Z bosons
- WW threshold scans ~ √s = 161 GeV → 10^{7}W





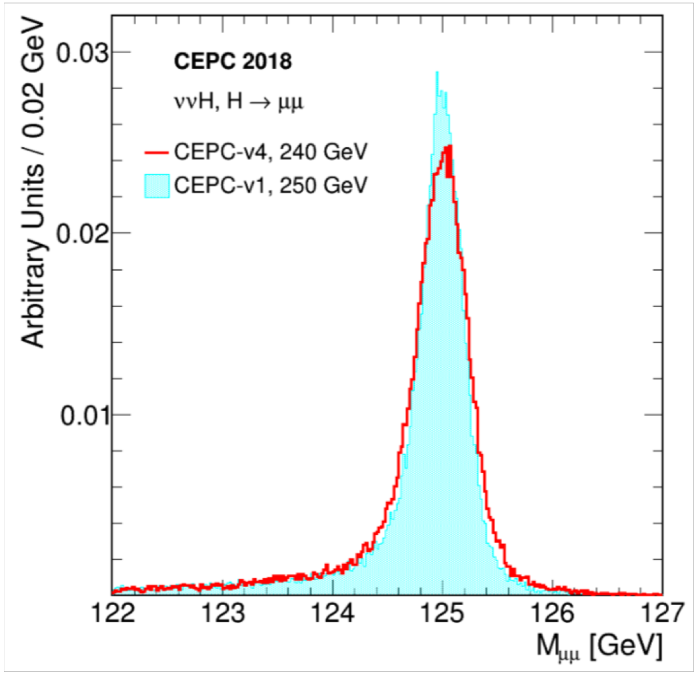
Object reconstruction and identification

- ARBOR particle flow
- Leptons
  - 7% H production with leptons
  - Lepton ID algo: LICH eff 99.9%
  - Dimu mass reso. 0.16%
- Photons
  - H2 gg and H2Zg
  - Tau leptons and jets
  - Mass reso. 2.5%
- Jets
  - 70% H decay into jets (bb, cc, gg)
  - 22% through WW,* ZZ* cascades
  - JES: 3-5%, W and Z: 4.4%.

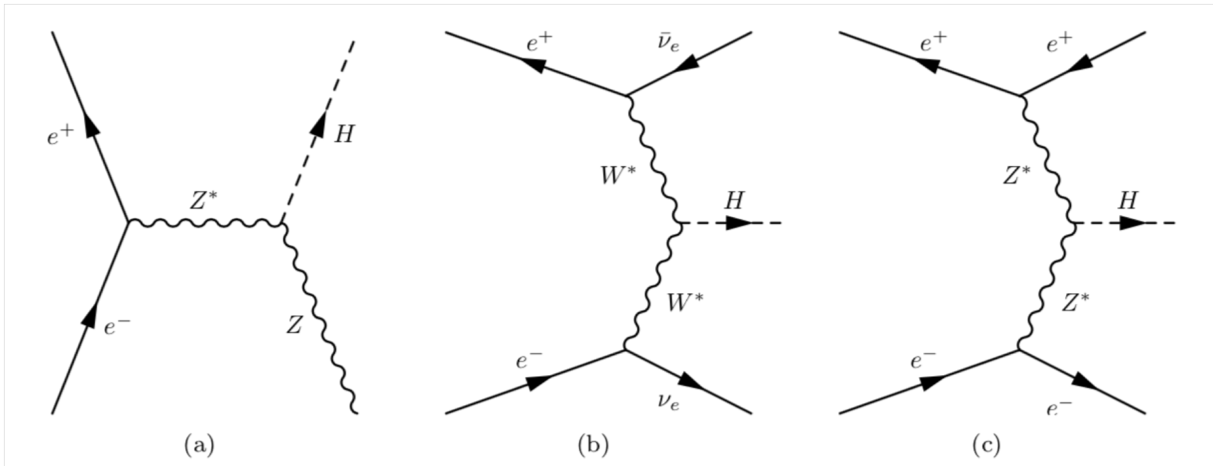


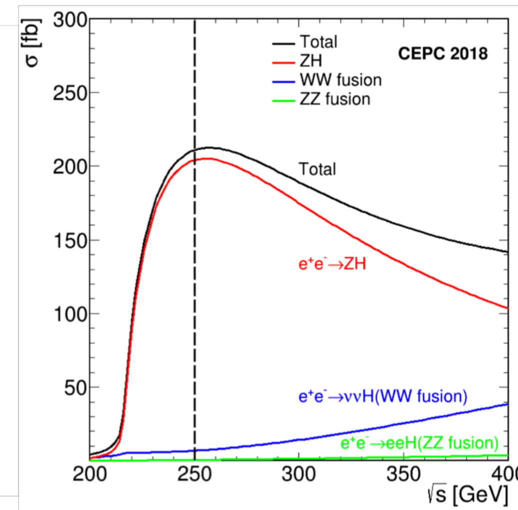
CEPCv4 and optimization

- Smaller solenoidal field 3T
  (14% degrades of momentum reso.)
- Reduced calorimeter dimensions
- ECAL readout sensor size changed from 5x5 to 10x10 mm^2
- Add Time-of-Flight for flavor physics potential



Higgs production and decay





ZH associate production

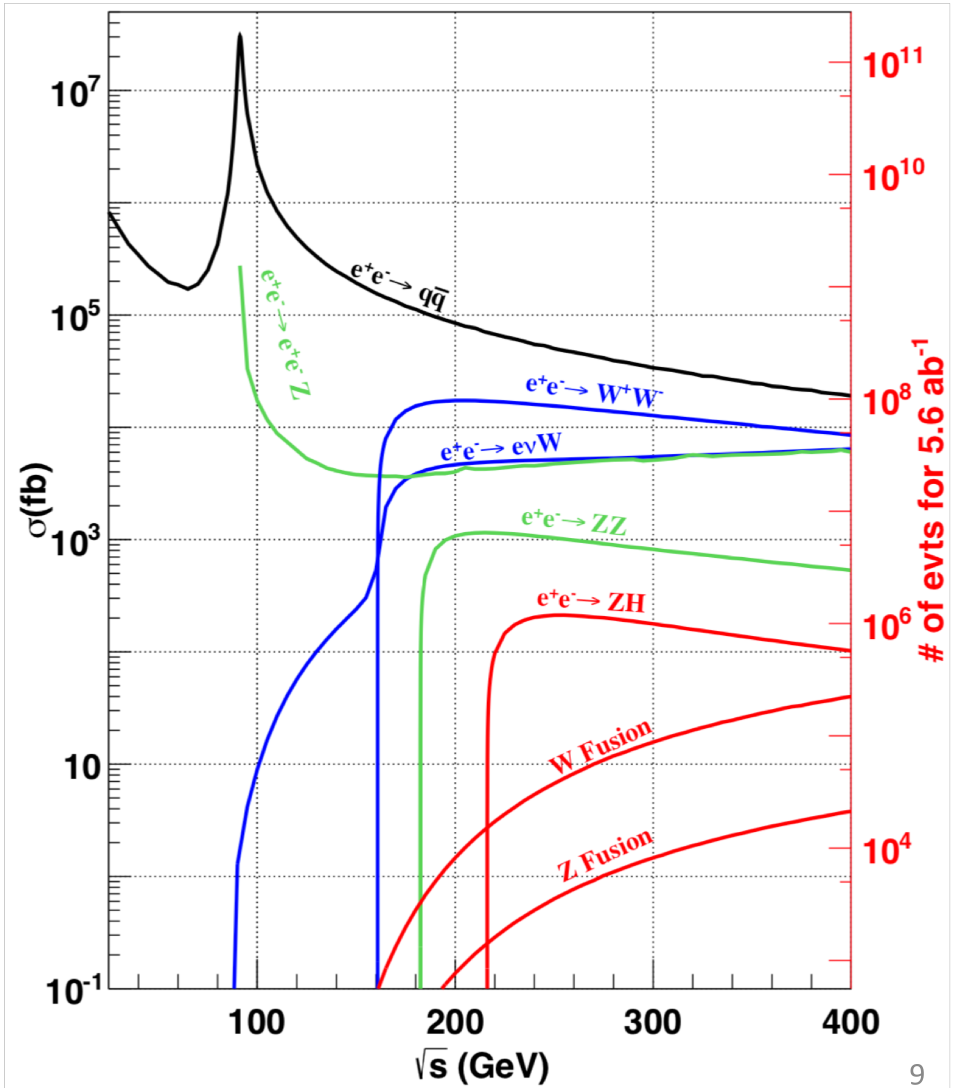
W fusion

Z fusion

Vector-boson fusion (VBF)

Background processes

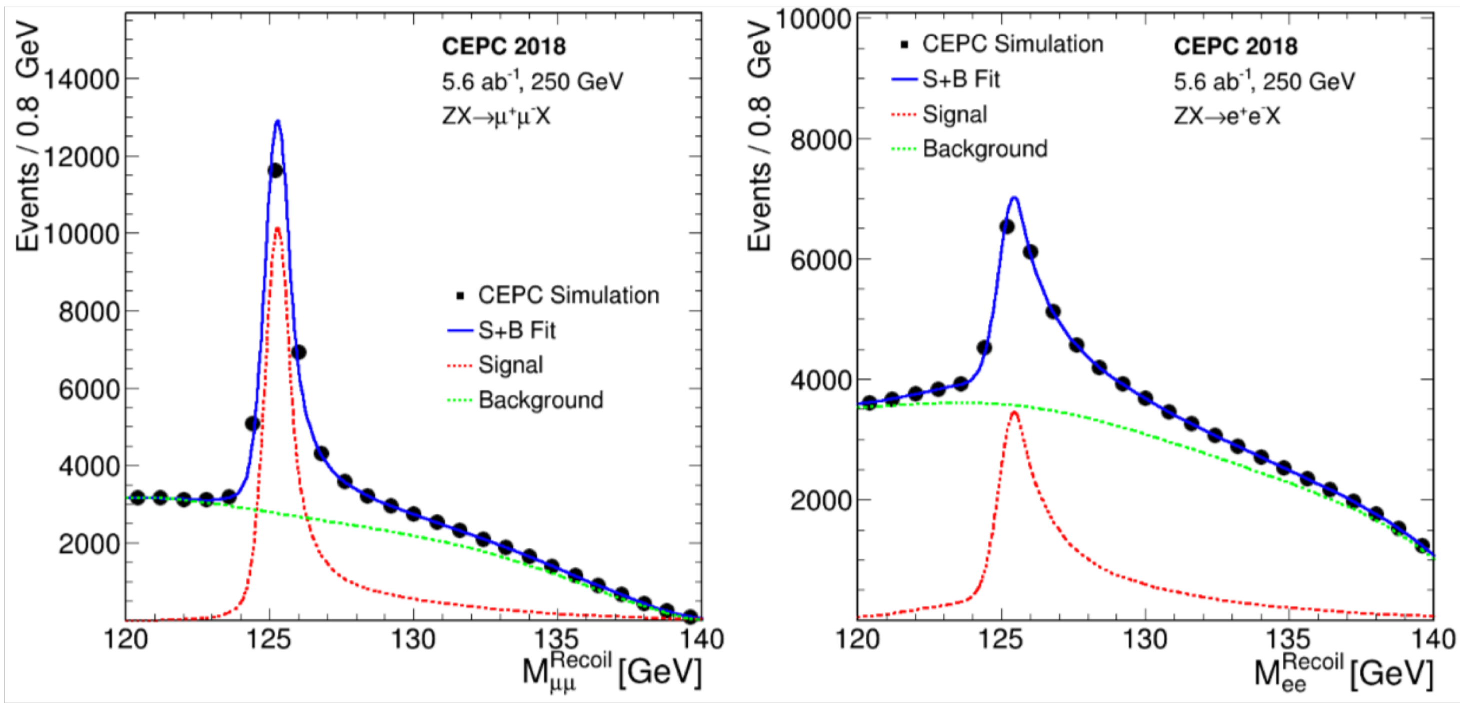
- Bhabha scattering (ee)
- ISR return (Z gamma)
- Diboson (WW/ZZ)
- Single boson production (eeZ, evW)



Higgs tagging with recoil mass

- Higgsstrahlung(ee->ZH), Z decays to a pair of visible fermions(ff), the recoil mass against the Z:

$$M^2_{\text{recoil}} = (\sqrt{s} - E_{ff})^2 - p^2_{ff} = s - 2E_{ff}\sqrt{s} + m^2_{ff}$$



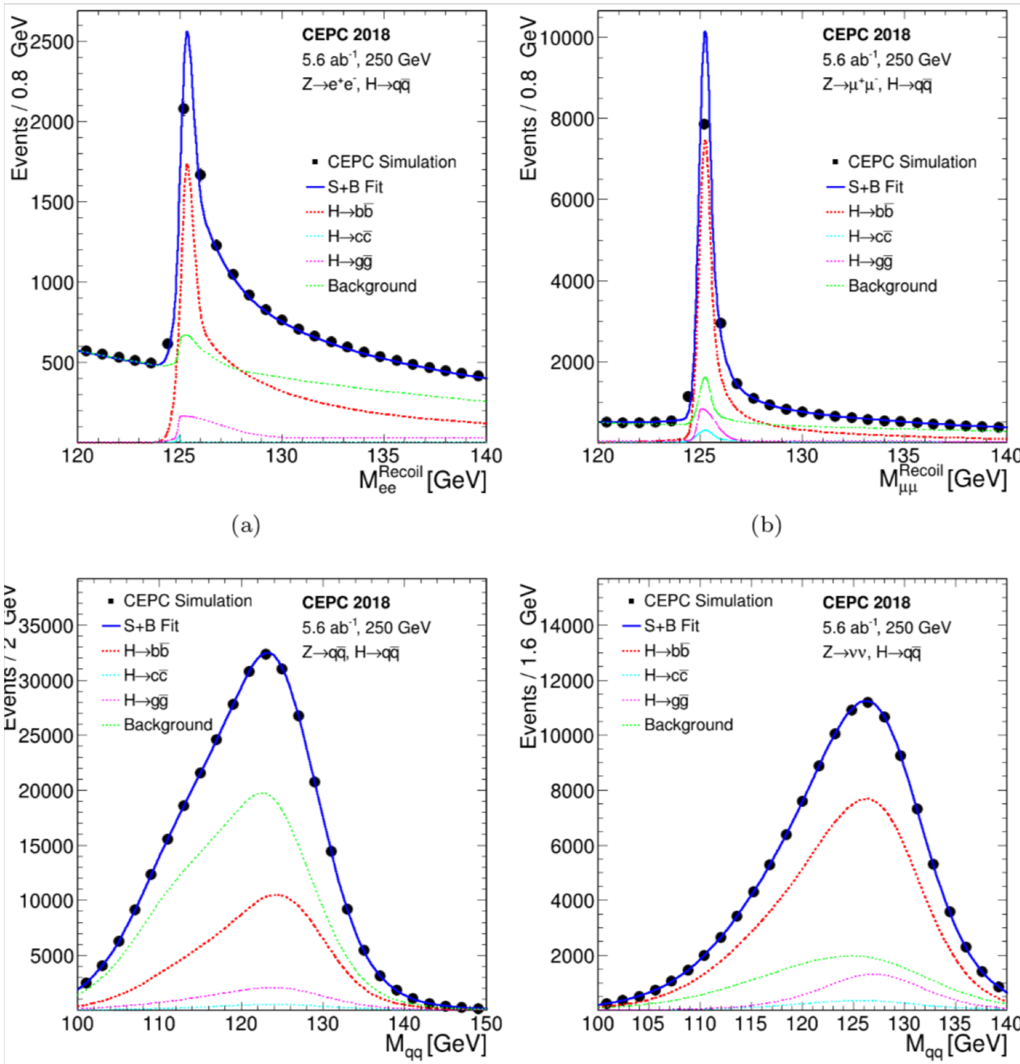
Measurements of σ(ZH) and m_H

- $e^+e^- \rightarrow Z + X \rightarrow l^+ l^-$ /qqbar + X to extract ZH production cross section and Higgs boson mass m_H

Z decay mode	Δm_H (MeV)	$\Delta\sigma(ZH)/\sigma(ZH)$
e^+e^-	14	1.43%
$\mu^+\mu^-$	6.5	0.86%
$q\bar{q}$	–	0.61%
Combined	5.9	0.5%

Individual Decay Modes

H -> bb/cc/gg



- 70% of Higgs decay to a pair of jets: b (58%) c (3%) g(9%)

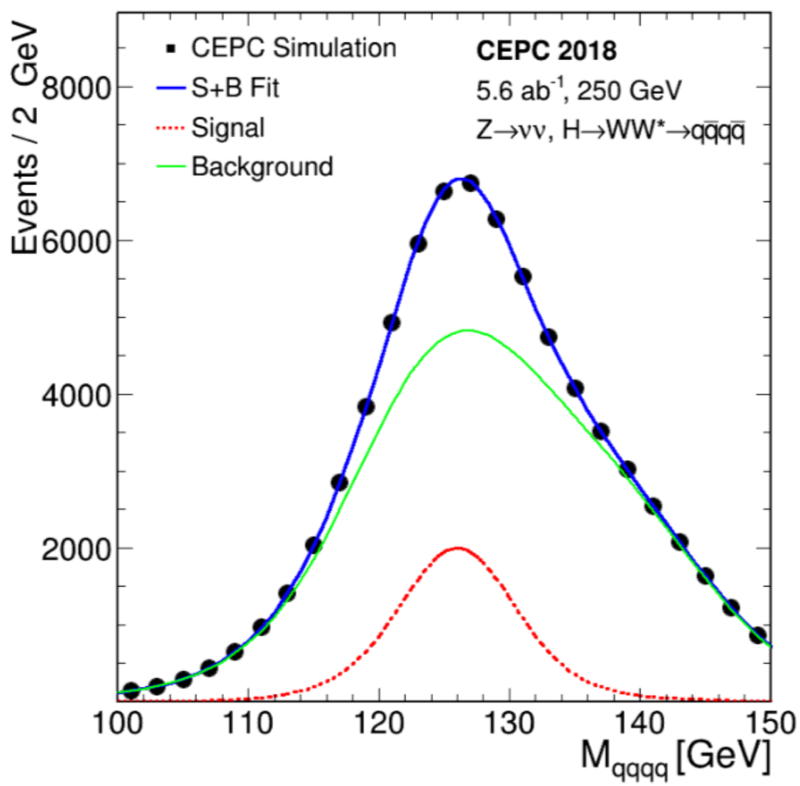
Expected relative precision on σ(ZH)× BR

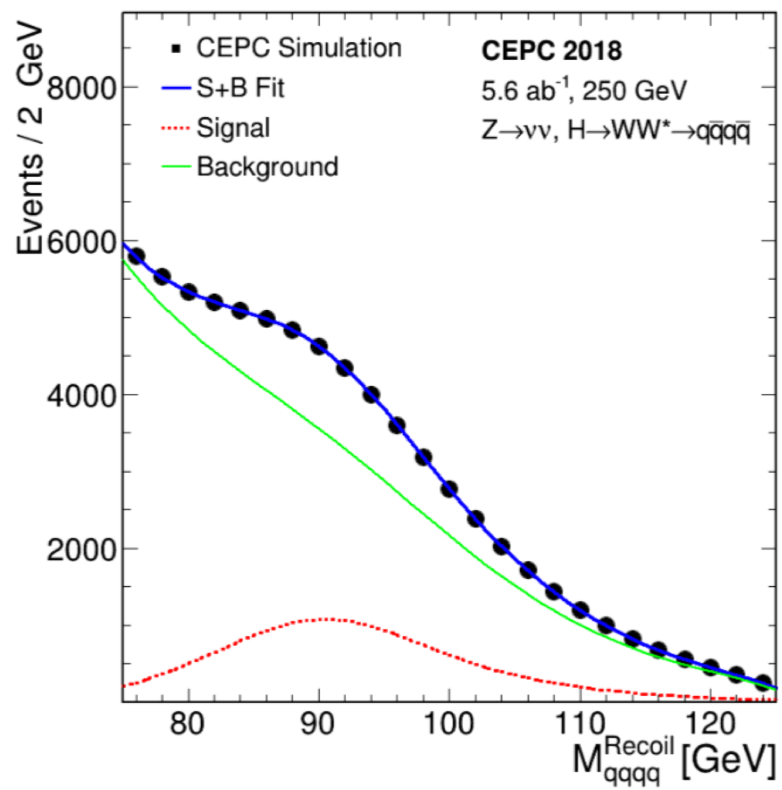
Z decay mode	$H\to b\bar{b}$	$H\to c\bar{c}$	$H\to gg$
$Z\to e^+e^-$	1.3%	12.8%	6.8%
$Z\to \mu^+\mu^-$	1.0%	9.4%	4.9%
$Z\to q\bar{q}$	0.5%	10.6%	3.5%
$Z\to \nu\bar{\nu}$	0.4%	3.7%	1.4%
Combination	0.3%	3.1%	1.2%

H-> WW*

- BR 21.5%

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%
Combination		0.9%

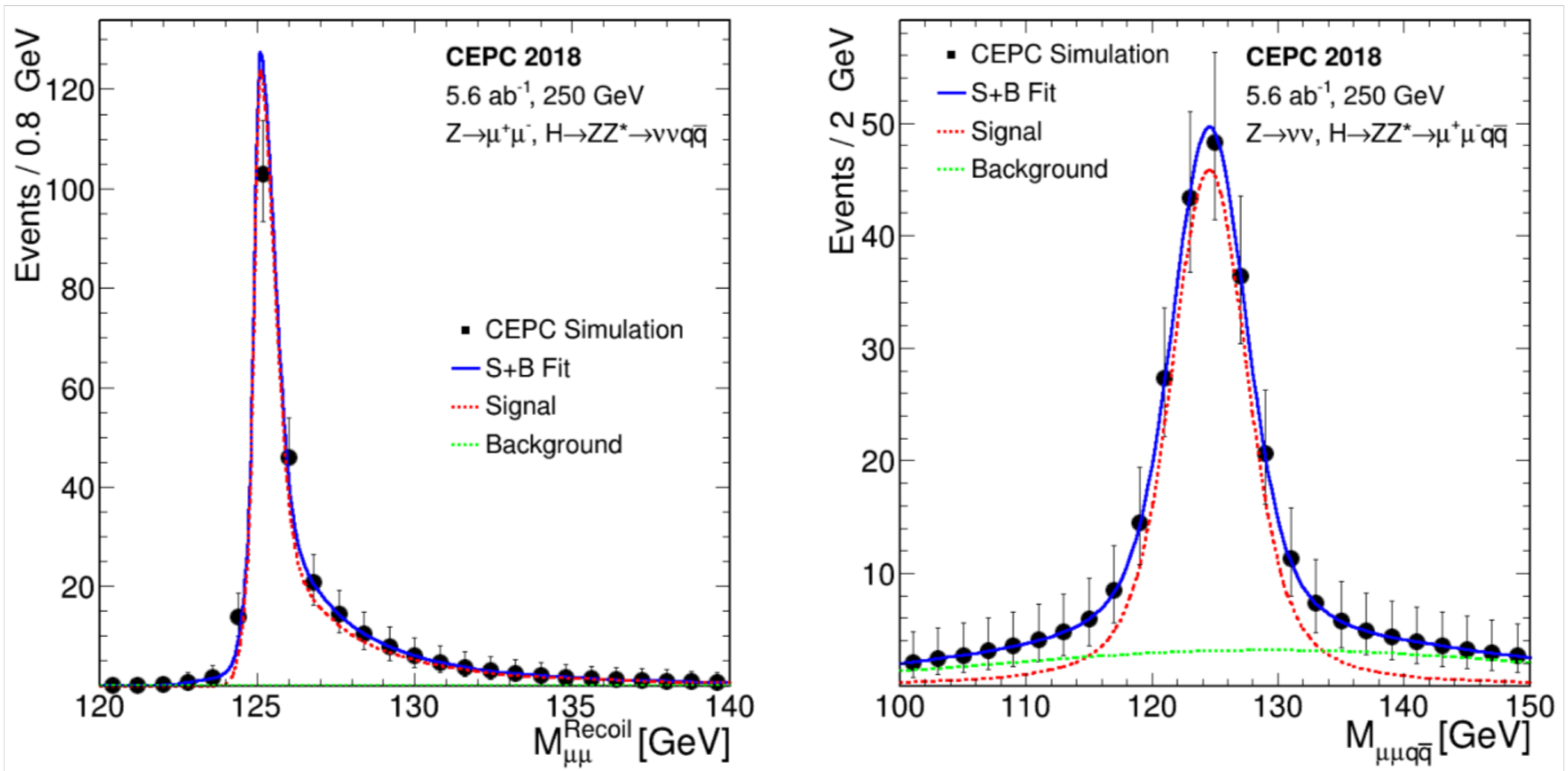




H->ZZ*

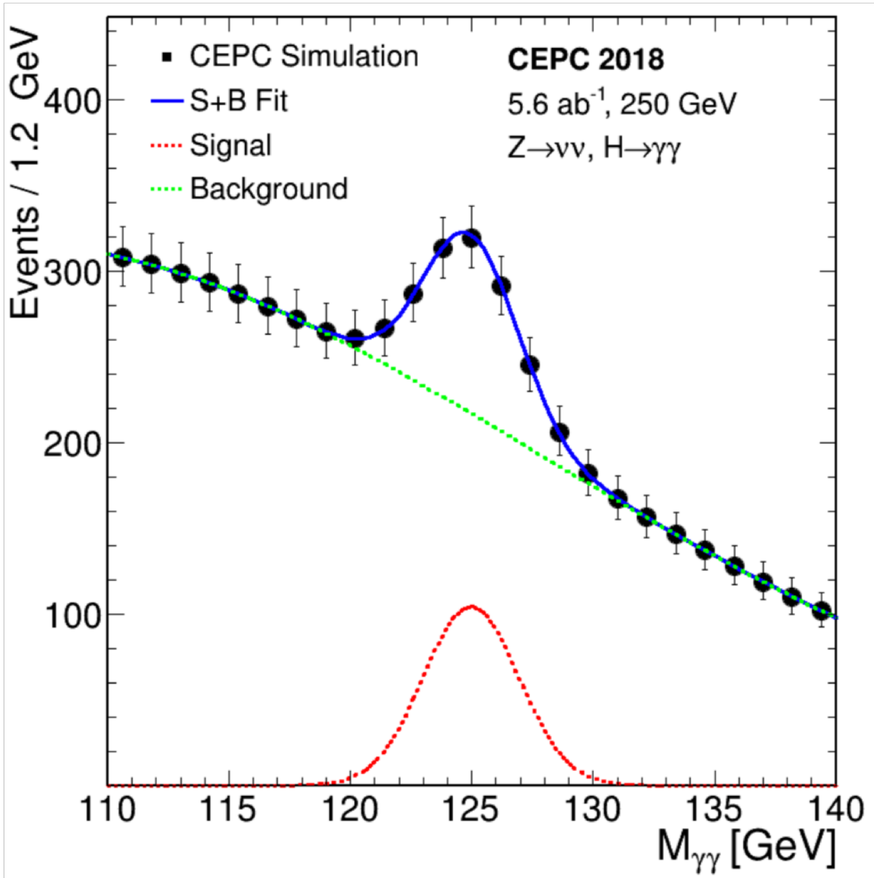
- BR 2.6%

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%
Combination		4.9%

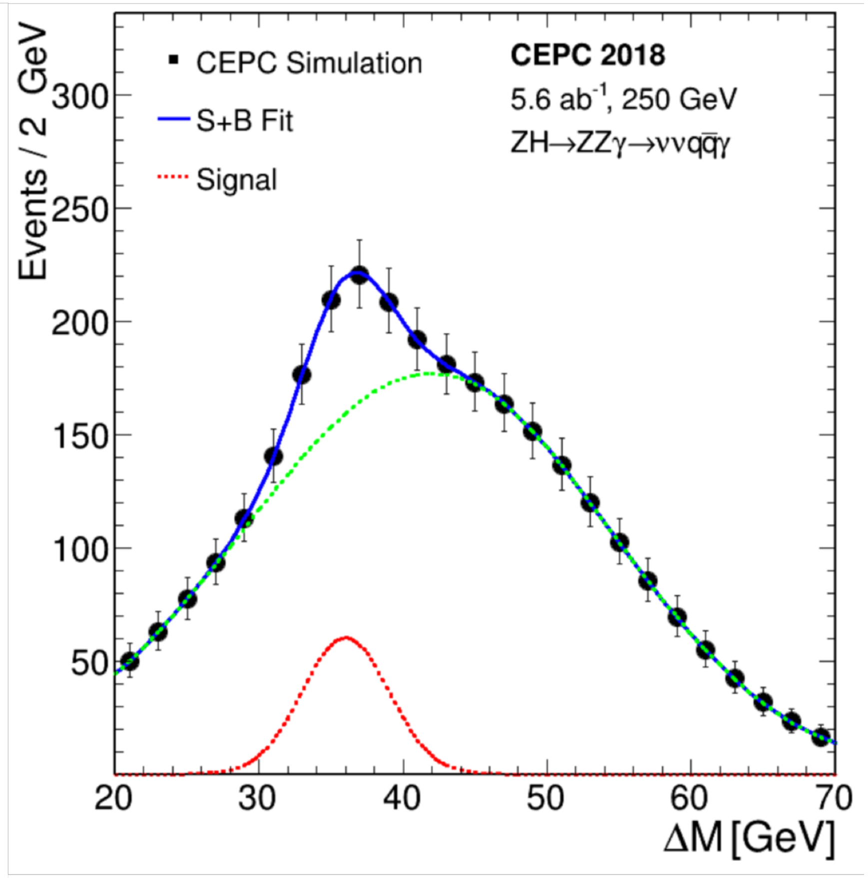


H -> $\gamma\gamma$, H-> Z γ

- BR 0.23%
- BR 0.15%



6.2% on σ(ZH) × BR(H → γγ)

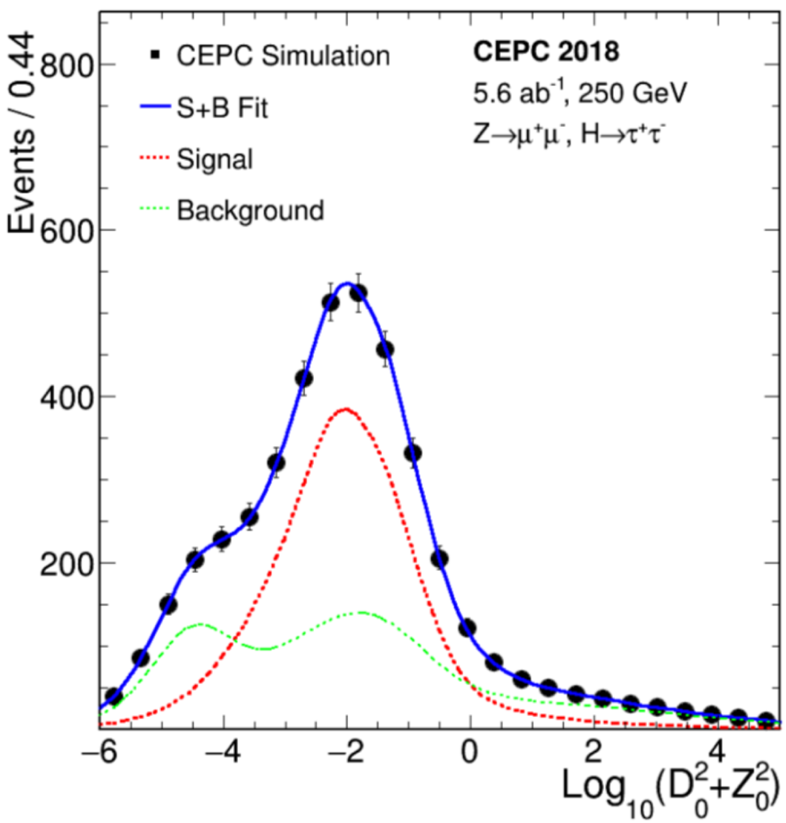


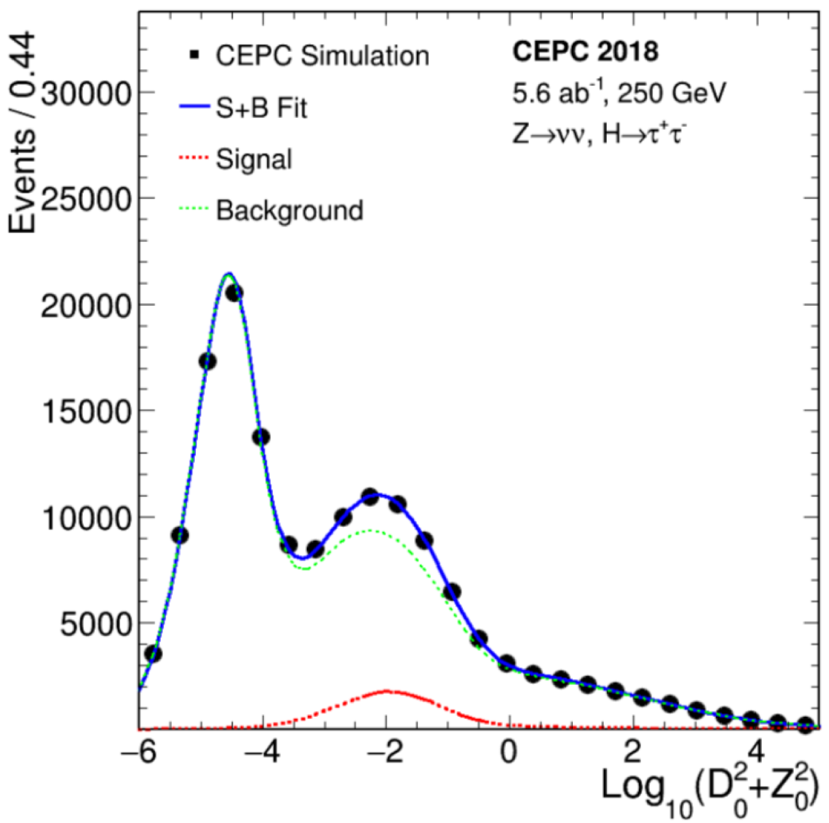
13% on σ(ZH)×BR(H →Zγ).

H -> $\tau\ \tau$

- BR 6.3%

ZH final state		Precision
$Z \to \mu^+\mu^-$	$H \to \tau^+\tau^-$	2.6%
$Z \to e^+e^-$	$H \to \tau^+\tau^-$	2.7%
$Z \to \nu\bar{\nu}$	$H \to \tau^+\tau^-$	2.5%
$Z \to q\bar{q}$	$H \to \tau^+\tau^-$	0.9%
Combination		0.8%

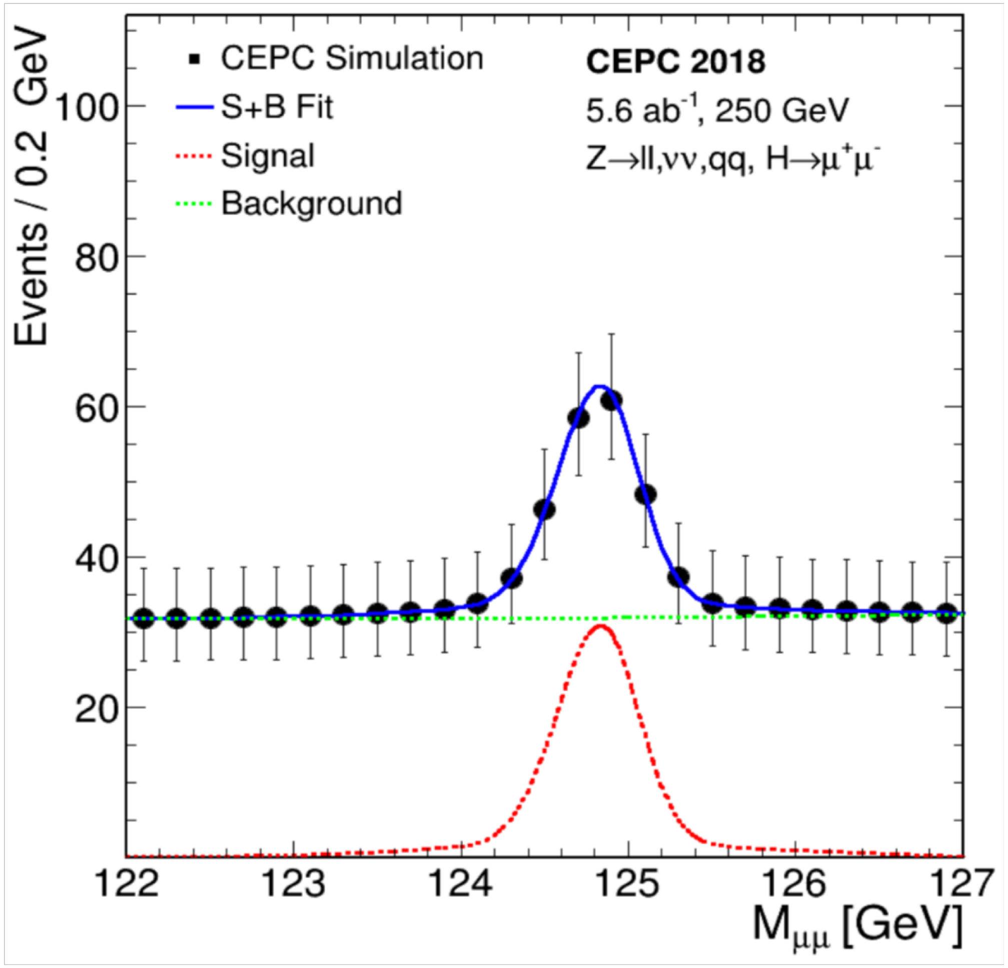




H -> μ μ

- BR: 2×10^{-4}

Precision: σ(ZH)xBR(H->μμ) ~ 16%



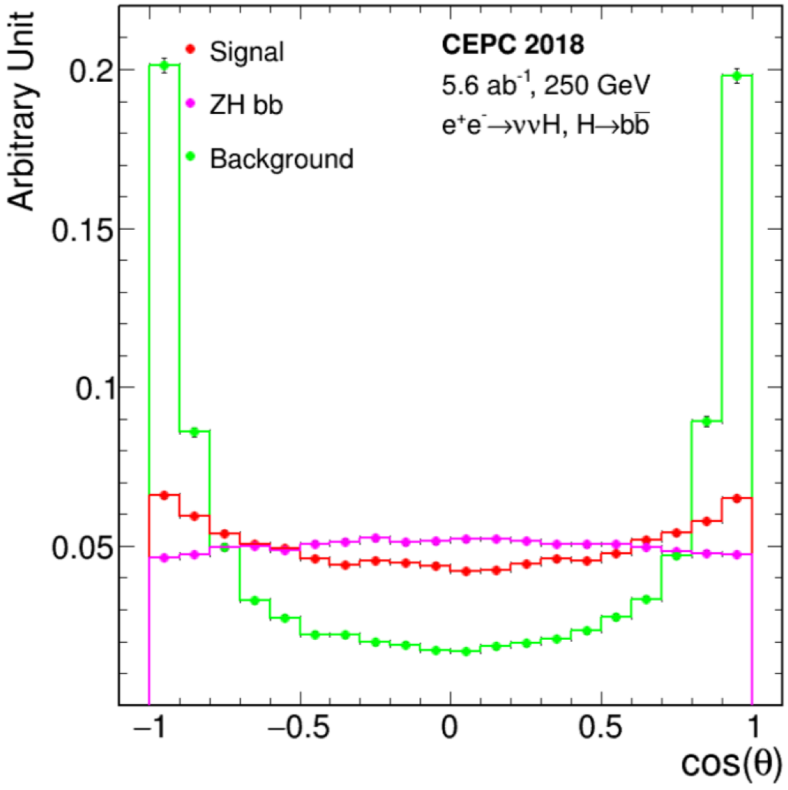
Higgs -> Invisible

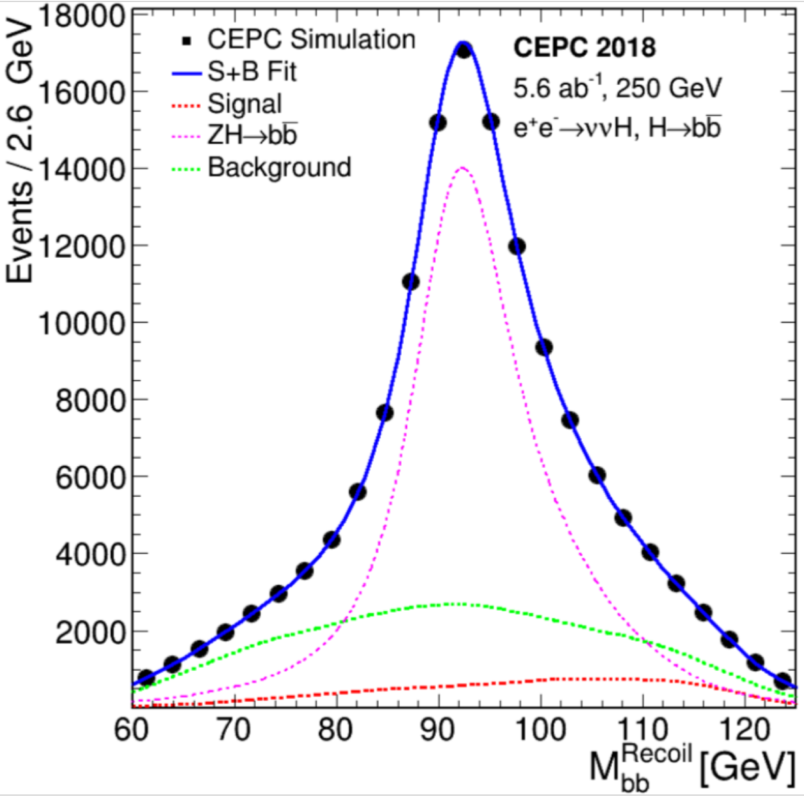
- BR (H->ZZ*-> νννν) 1×10^{-3}

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

Measure σ(ee->ννH)xBR(H->bb)

- W-fusion, 3.3% of ZH process, precision 2.6%





Combinations of Individual Measurements

Combine σ x BR

Property	Estimated Precision CEPC-v1		Estimated Precision CEPC-v4	
m_H	5.9 MeV		5.9 MeV	
Γ_H	2.7%		2.8%	
$\sigma(ZH)$	0.5%		0.5%	
$\sigma(\nu\bar{\nu}H)$	3.0%		3.2%	
Decay mode	**$\sigma \times$ BR**	**BR**	**$\sigma \times$ BR**	**BR**
$H \to b\bar{b}$	0.26%	0.56%	0.27%	0.56%
$H \to c\bar{c}$	3.1%	3.1%	3.3%	3.3%
$H \to gg$	1.2%	1.3%	1.3%	1.4%
$H \to WW^*$	0.9%	1.1%	1.0%	1.1%
$H \to ZZ^*$	4.9%	5.0%	5.1%	5.1%
$H \to \gamma\gamma$	6.2%	6.2%	6.8%	6.9%
$H \to Z\gamma$	13%	13%	16%	16%
$H \to \tau^+\tau^-$	0.8%	0.9%	0.8%	1.0%
$H \to \mu^+\mu^-$	16%	16%	17%	17%
$\mathrm{BR}_{\mathrm{inv}}^{\mathrm{BSM}}$	–	$< 0.28\%$	–	$< 0.30\%$

Measurement of Higgs boson width

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

~5.1%

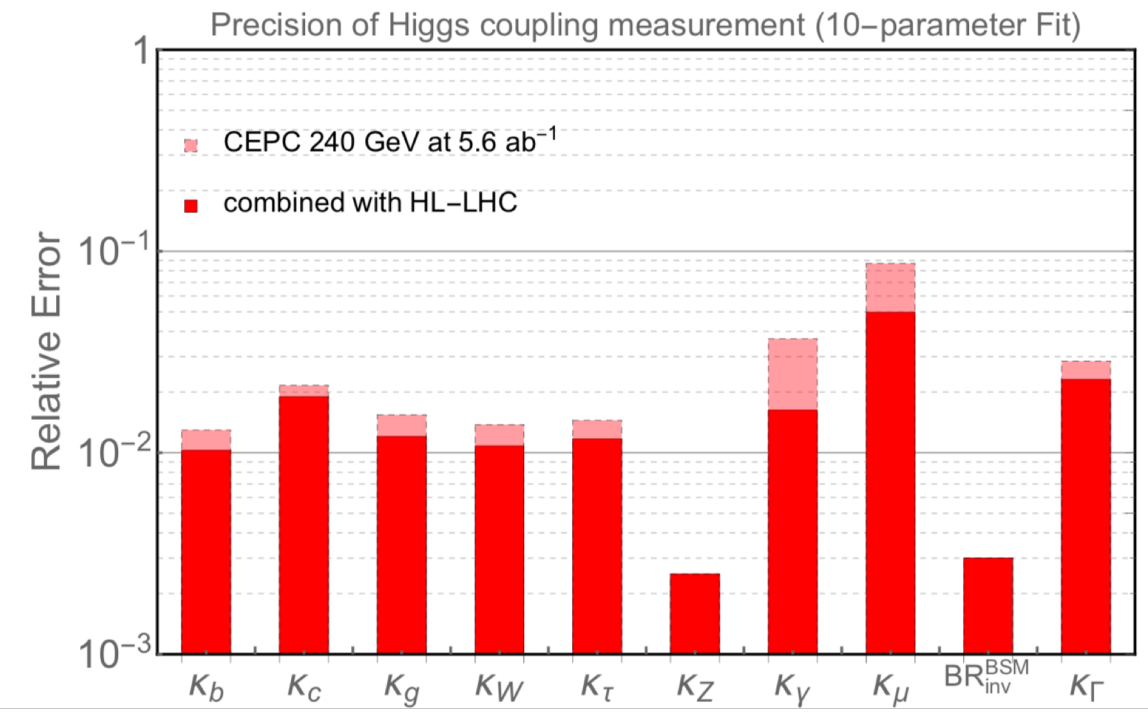
$$\Gamma_H = \frac{\Gamma(H \to b\bar{b})}{\mathrm{BR}(H \to b\bar{b})} \propto \frac{\sigma(e^+e^- \to \nu_e\bar{\nu}_e H)}{\mathrm{BR}(H \to WW^*)}$$

~3.5%

Higgs coupling measurements

- Coupling fits in the κ-framework

$$\kappa_f = \frac{g(Hff)}{g_{\rm SM}(Hff)}, \quad \kappa_V = \frac{g(HVV)}{g_{\rm SM}(HVV)}$$

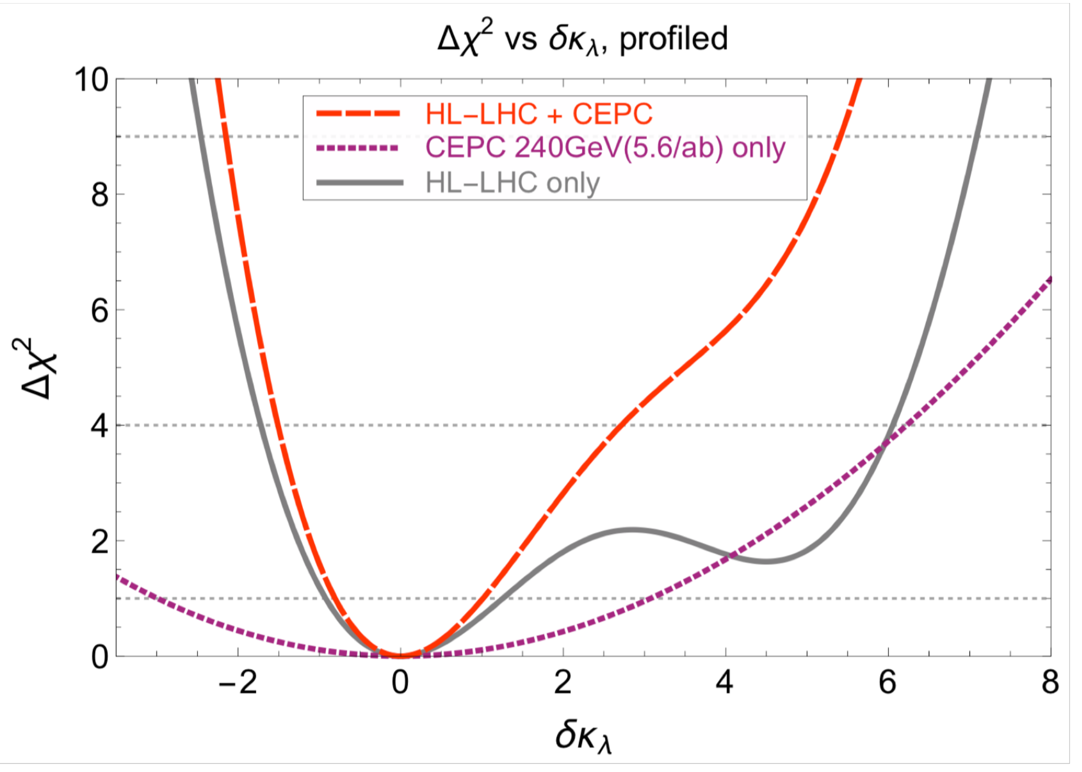


Higgs boson self-coupling

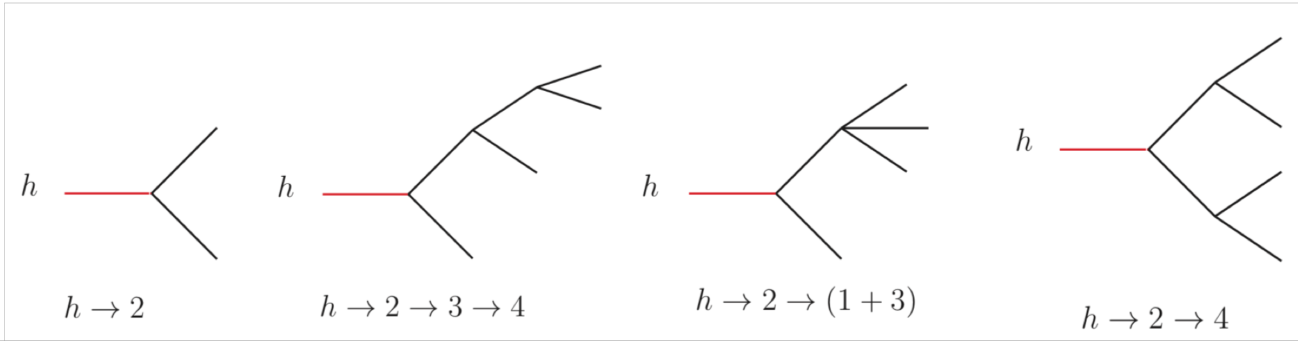
$$\kappa_\lambda \equiv \frac{\lambda_3}{\lambda_3^{\rm sm}}\,, \qquad \lambda_3^{\rm sm} = \frac{m_H^2}{2v^2}\,.$$

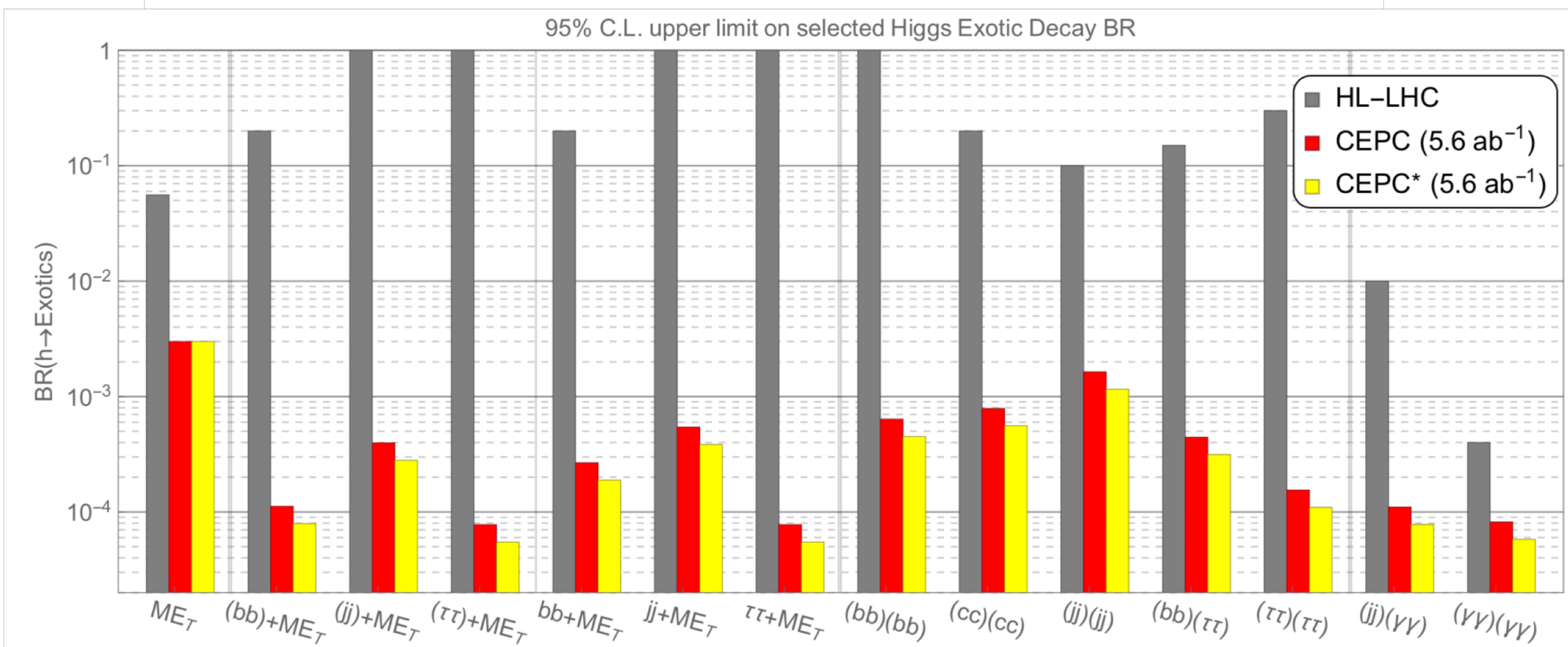
New Physics

$$\delta\kappa_\lambda \equiv \kappa_\lambda - 1$$



Higgs boson exotic decays





* yellow bars include extrapolation with the inclusion of the Z hadronic decay

Summary

- The discovery of Higgs at LHC is a major breakthrough on both experiment and theory.
- The CEPC complements the LHC to study the Higgs in great detail with unprecedented precision.
  - Measure Higgs total width and decay BRs in a model-independent way
- The clean environment of the CEPC will allow the identification of potential unknown decay modes that are impractical to test at LHC.

Backup slides

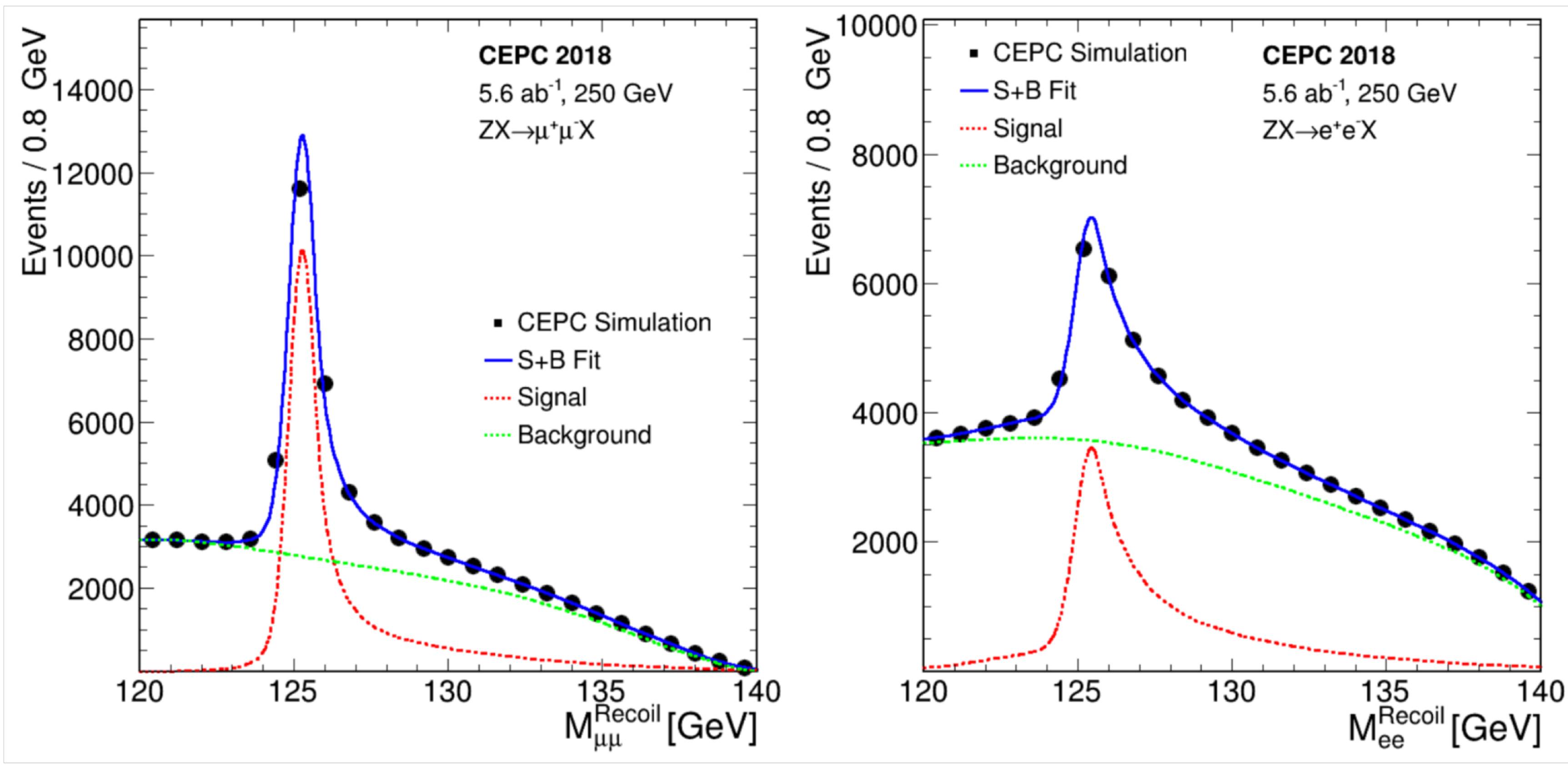
CEPC operating scenarios

Operation mode	Z pole	WW threshold	Higgs factory
$\sqrt{s}$ (GeV)	91.2	161	240
Instantaneous luminosity ($10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$)	16–32	10	3
Run time (year)	2	1	7
Integrated luminosity (ab^{-1})	8–16	2.6	5.6
Higgs boson yield	–	–	10^6
W boson yield	–	10^7	10^8
Z boson yield	10^{11}–10^{12}	10^9	10^9

Higgs production and other SM processes @ 250 GeV

Process	Cross section	Events in 5.6 ab^{-1}
Higgs boson production, cross section in fb		
$e^+e^- \to ZH$	204.7	1.15×10^6
$e^+e^- \to \nu_e\bar{\nu}_e H$	6.85	3.84×10^4
$e^+e^- \to e^+e^- H$	0.63	3.53×10^3
Total	212.1	1.19×10^6
Background processes, cross section in pb		
$e^+e^- \to e^+e^-(\gamma)$ (Bhabha)	850	4.5×10^9
$e^+e^- \to q\bar{q}(\gamma)$	50.2	2.8×10^8
$e^+e^- \to \mu^+\mu^-(\gamma)$ [or $\tau^+\tau^-(\gamma)$]	4.40	2.5×10^7
$e^+e^- \to WW$	15.4	8.6×10^7
$e^+e^- \to ZZ$	1.03	5.8×10^6
$e^+e^- \to e^+e^- Z$	4.73	2.7×10^7
$e^+e^- \to e^+\nu W^- / e^-\bar{\nu} W^+$	5.14	2.9×10^7

Z -> $l^+ l^-$



Selection entirely based on the info of two leptons, independent of Higgs BR.

SM predictions of Higgs Decay

Decay mode	Branching ratio	Relative uncertainty
$H \to b\bar{b}$	57.7%	+3.2%, −3.3%
$H \to c\bar{c}$	2.91%	+12%, −12%
$H \to \tau^+\tau^-$	6.32%	+5.7%, −5.7%
$H \to \mu^+\mu^-$	2.19×10^{-4}	+6.0%, −5.9%
$H \to WW^*$	21.5%	+4.3%, −4.2%
$H \to ZZ^*$	2.64%	+4.3%, −4.2%
$H \to \gamma\gamma$	2.28×10^{-3}	+5.0%, −4.9%
$H \to Z\gamma$	1.53×10^{-3}	+9.0%, −8.8%
$H \to gg$	8.57%	+10%, −10%
Γ_H	4.07 MeV	+4.0%, −4.0%