Higgs physics at Circular Electron-Positron Collider

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on behalf of the team of CEPC Higgs physics

Workshop on the Circular Electron-Positron Collider

25th Anniversary of the Rencontres du Vietnam

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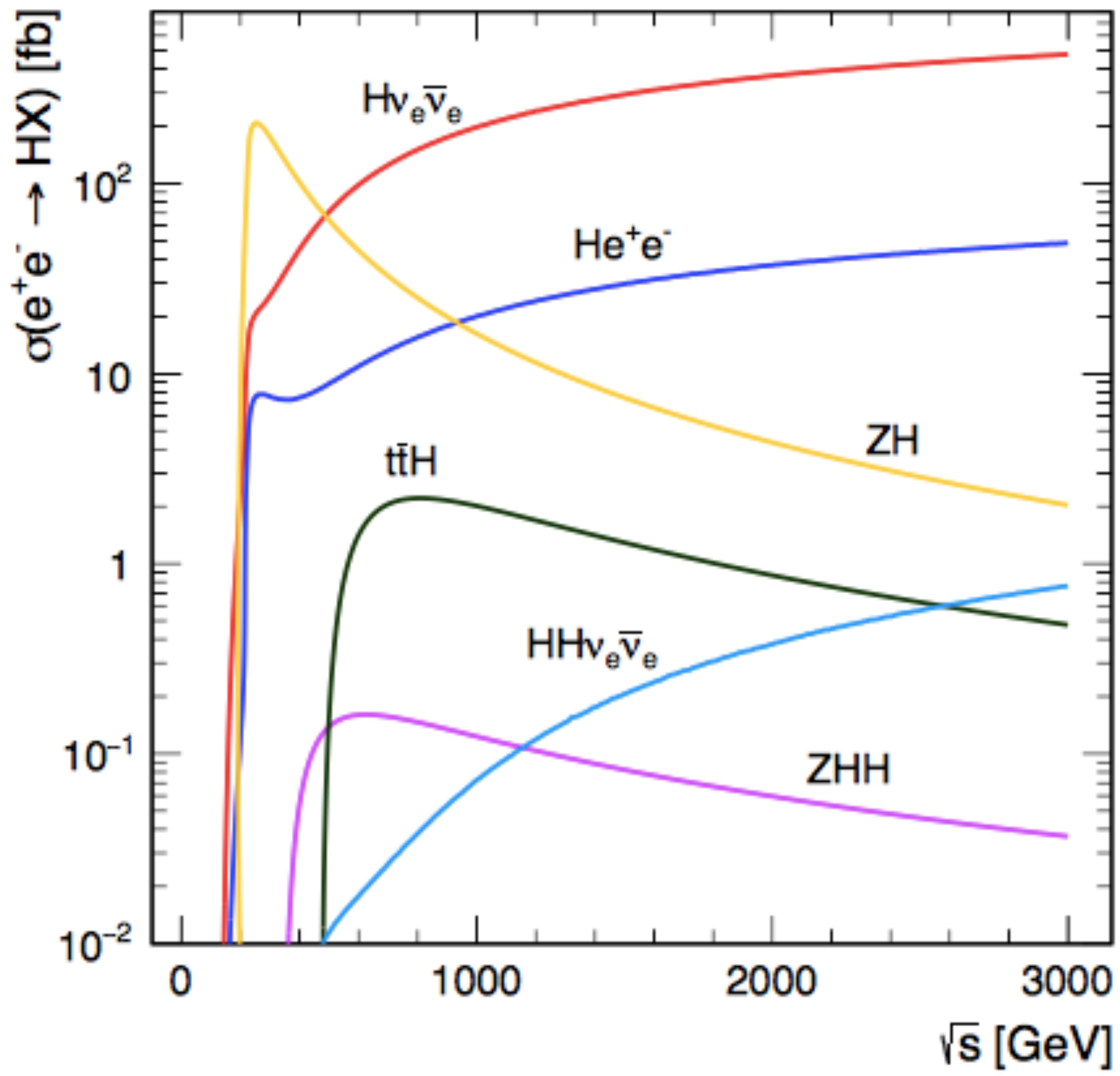
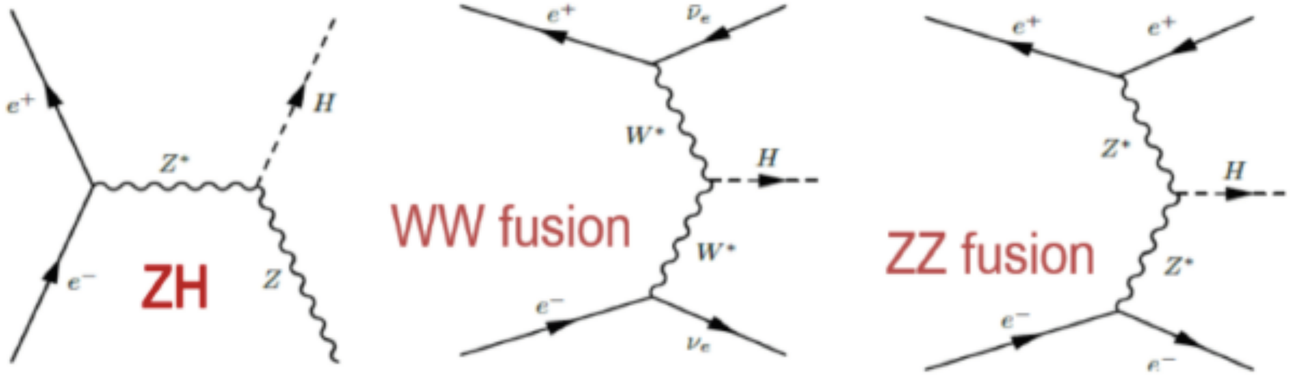
Higgs related physics at e^+e^- collider

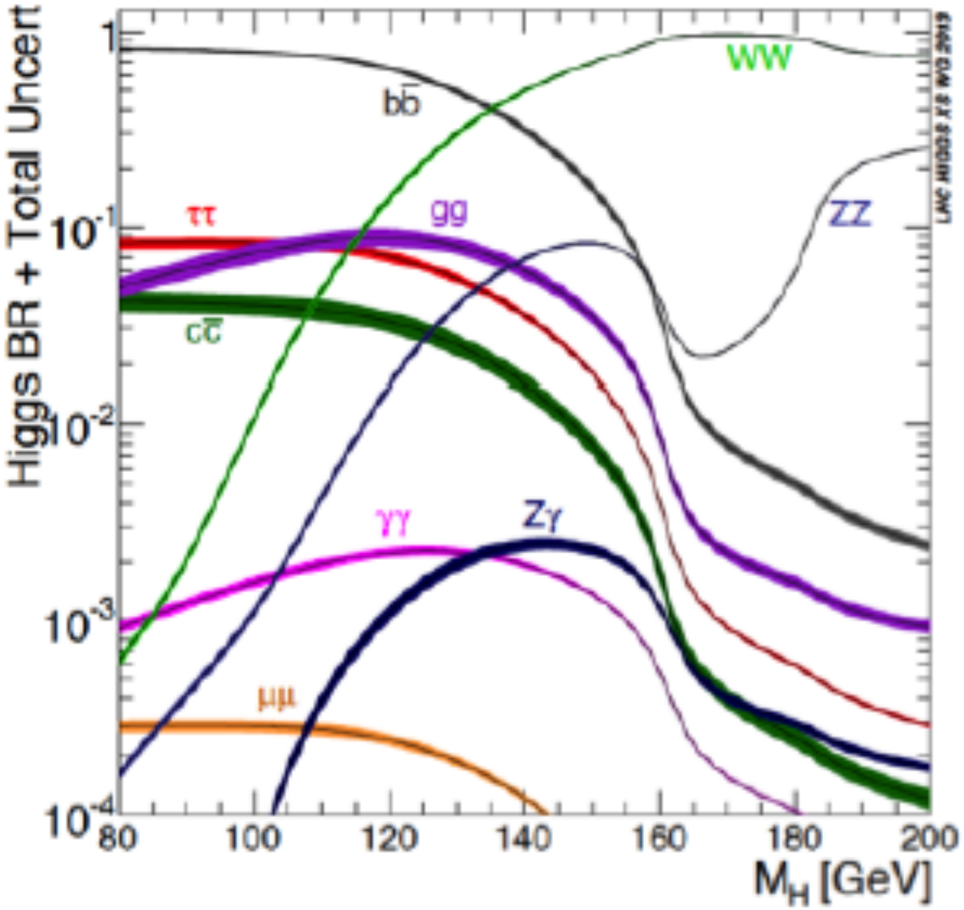


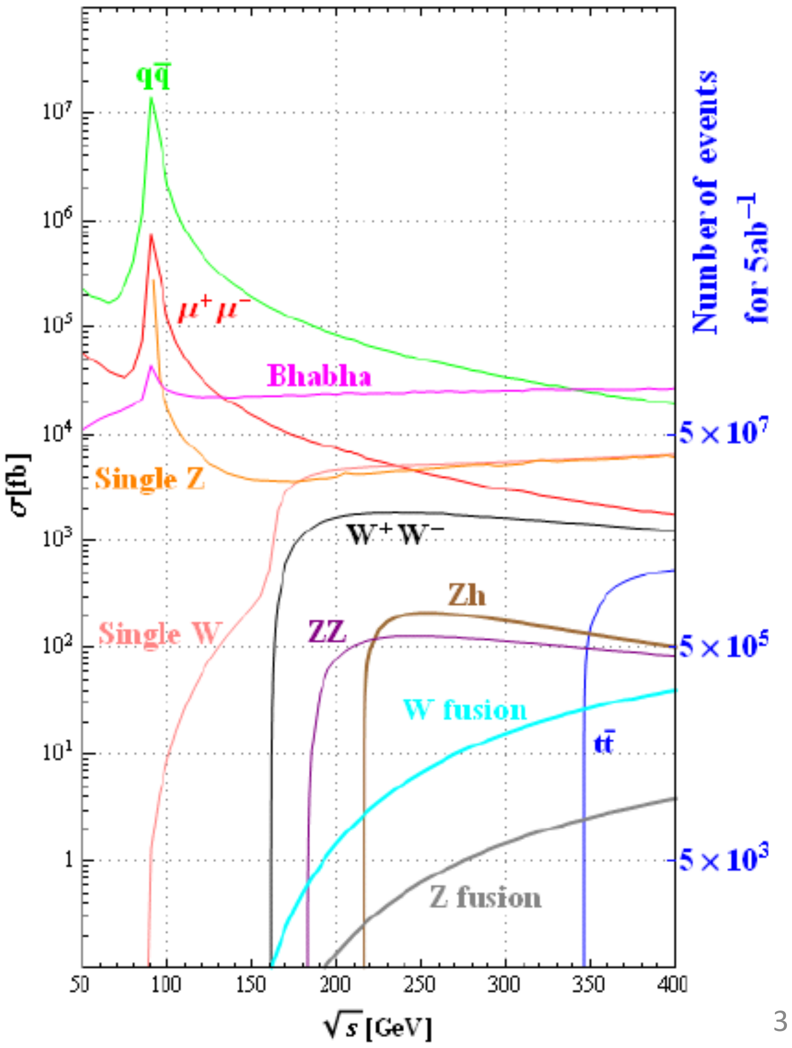


- With the increase of the energy, different Higgs related physics can be explored at e^+e^- collider.
- With the energy around 240 GeV, ZH as well as ww/zz fusion can be intensively studied.
  - the dominant production is from HZ, the WW/ZZ fusions contribute a few percent of the total cross-section.

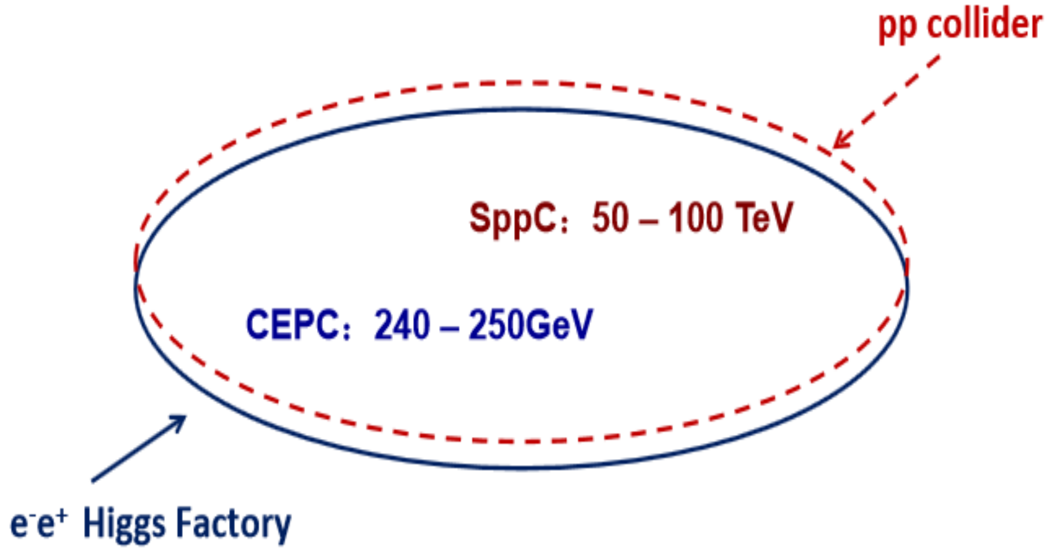
SM Higgs decay branching ratio, Bkg process

- ✓ e^+e^- collider provides a good opportunity to measure the jj, invisible decay of Higgs.
- ✓ For 5 ab^{-1} data with CEPC, 1M Higgs, 10M Z, 100M W are produced.





CEPC



- ✓ A CEPC (phase I)+ Super proton-proton Collider (SPPC) was proposed
- ✓ Ecm ~240-250 GeV, Lum 5 ab^{-1} for 10 years

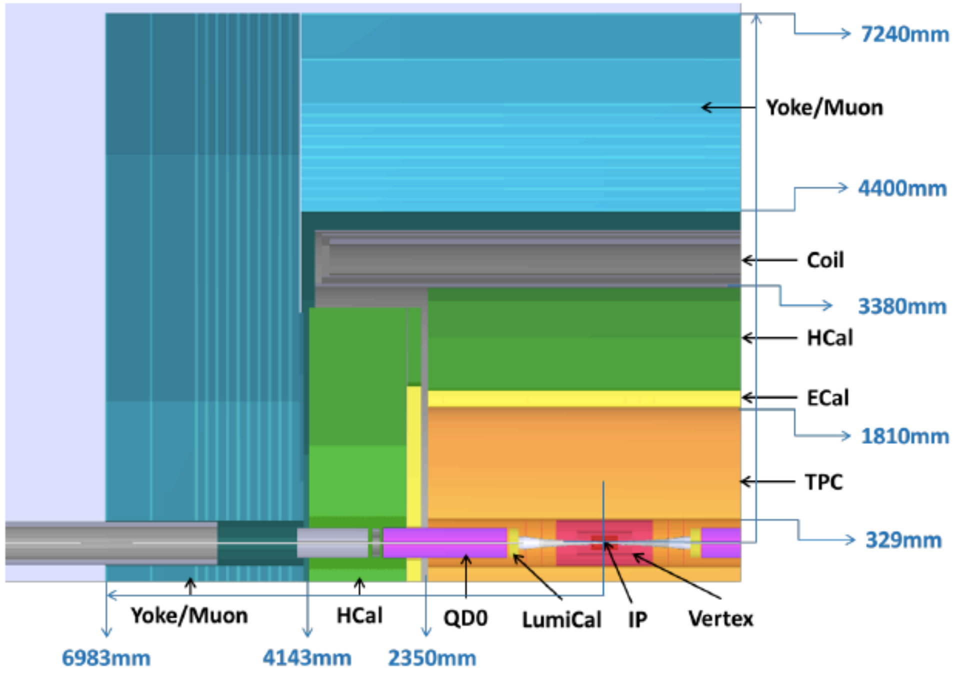
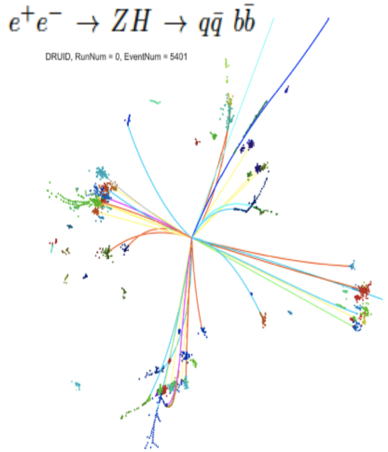
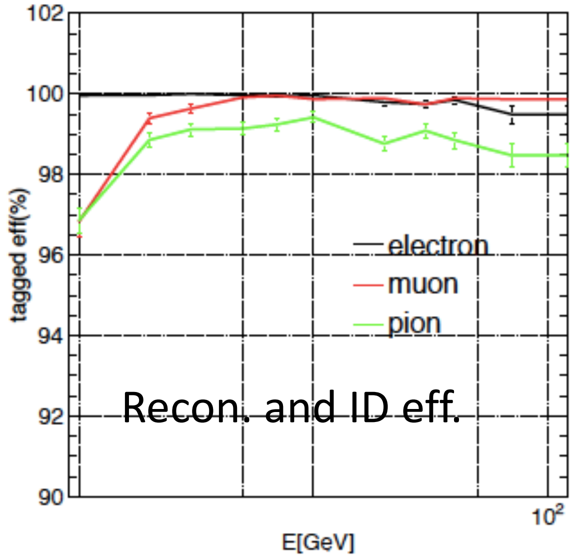


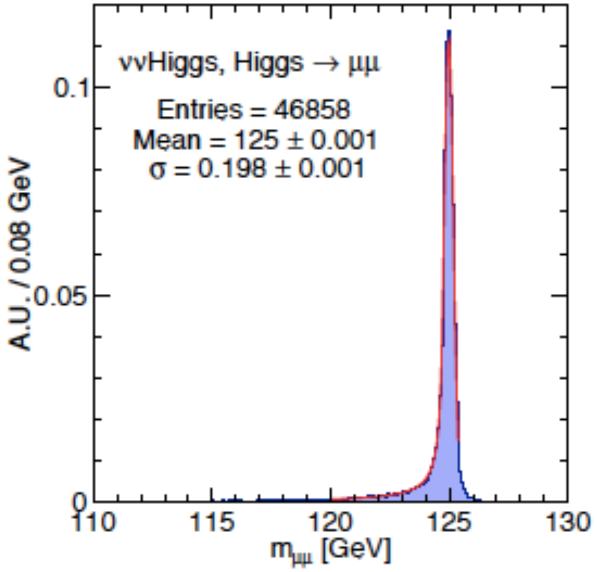
Table 2. Key characteristic/performance of a conceptual CEPC detector.

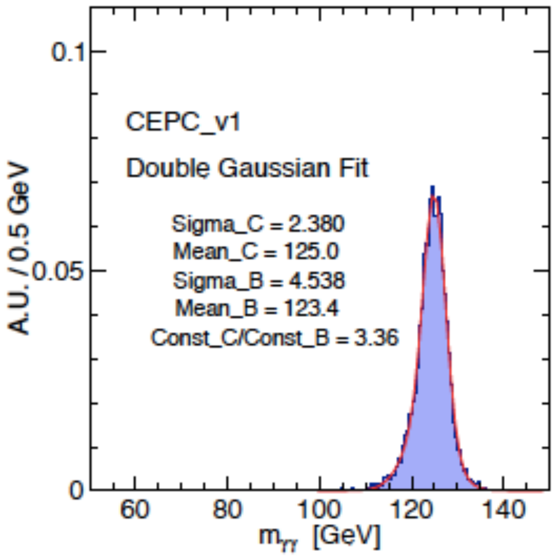
Geometry acceptance	TPC (97%), FTD (99.5%)
Tracking efficiency	$\sim$ 100% within geometry acceptance
Tracking performance	$\Delta(1/p_T) \sim 2 \times 10^{-5}$ (1/GeV)
ECAL intrinsic energy resolution	$16\%/\sqrt{E} \oplus 1\%$ (GeV)
HCAL intrinsic energy resolution	$60\%/\sqrt{E} \oplus 1\%$ (GeV)
Jet energy resolution	3-4%
Impact parameter resolution	5 μm

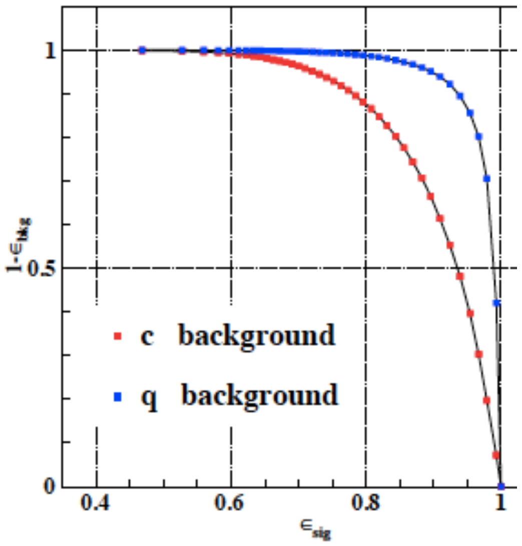
Performance

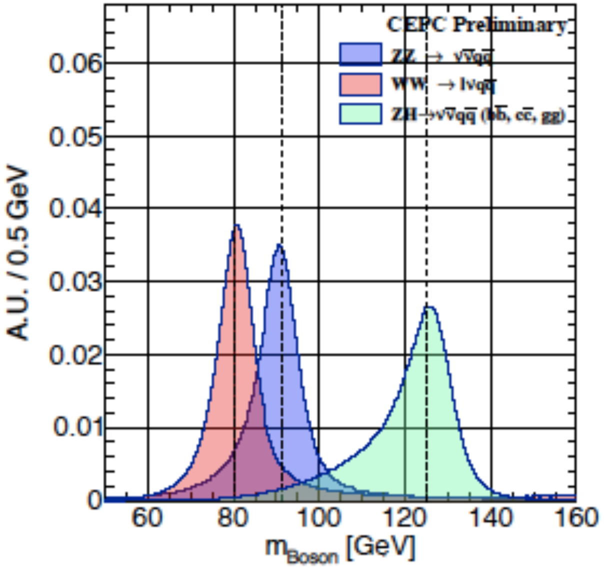


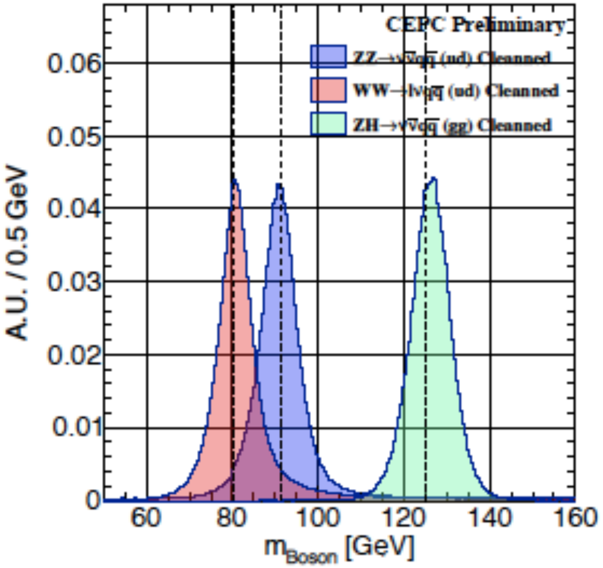








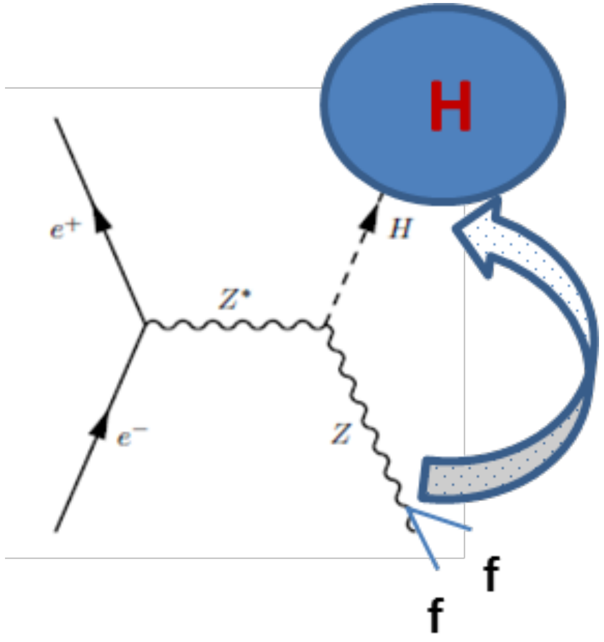




- Reliable Particle recon., ID and fake rejection
- Good mass resolution of Higgs (more can be found in Performance talks)

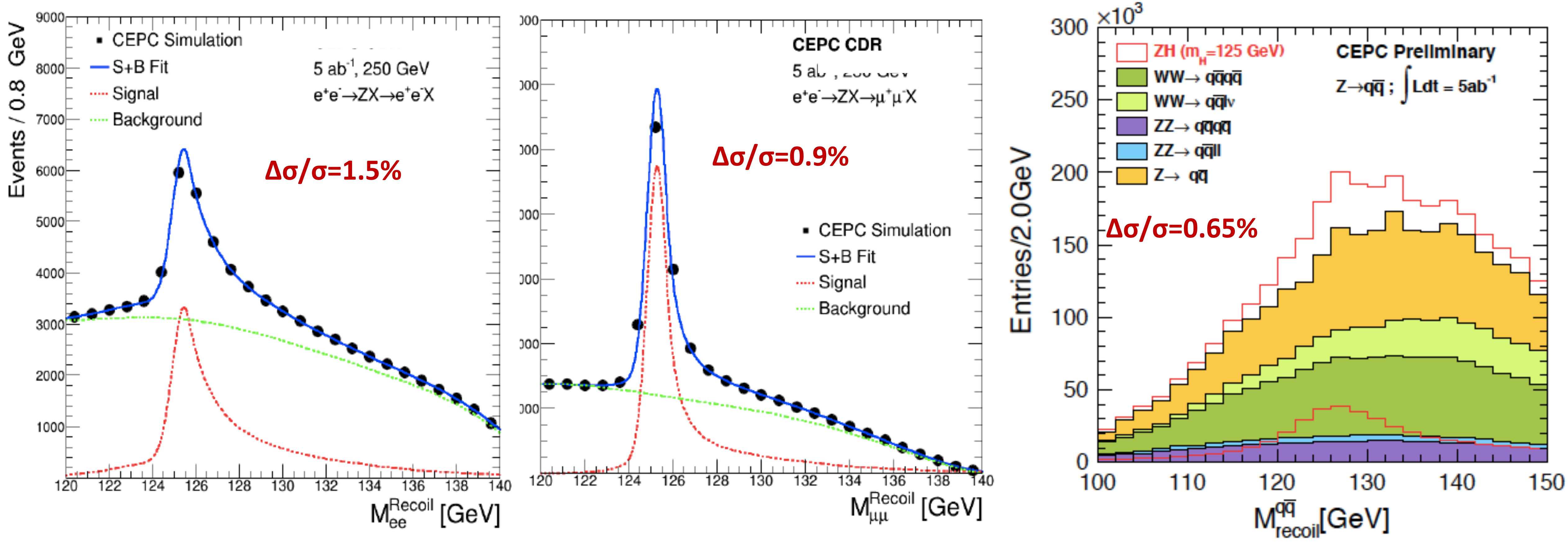
Direct measurement of Higgs cross-section

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



- ✓ **For this model independent analysis, we reconstruct the recoil mass of Z without touching the other particles in a event.**
- ✓ **The M_{recoil} should exhibit a resonance peak at m_H for signal; Bkg is expected to smooth.**
- ✓ **The best resolution can be achieved from $Z(\rightarrow e^+e^-, \mu^+\mu^-)$.**

Direct measurement of Higgs cross-section



- ✓ **The combined precision with three channels is** **$\Delta\sigma/\sigma=0.5\%$**
- ✓ **Similar sub-percent level for ILC/FCC-ee**

Measurements of (σ▪Br)/(σ▪Br) and ΔBr/Br

1. **A likelihood L(Θ) is built :**

$$f(n_{cb}, a_p \mid \phi_p, \alpha_p, \gamma_b) = \prod_{c \in \text{channels}} \prod_{b \in \text{bins}} \text{Pois}(n_{cb}|\nu_{cb}) \cdot G(L_0|\lambda, \Delta_L) \cdot \prod_{p \in \mathbb{S}+\Gamma} f_p(a_p|\alpha_p)$$

Shape info. for the discriminating Variables considered.

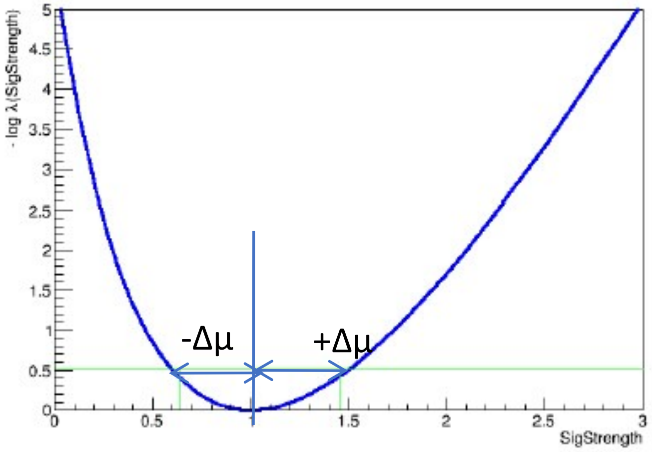
Likelihood as usual

$$L(\boldsymbol{\theta}) = \prod_{i=1}^{n} f(y_i; \boldsymbol{\theta})$$

2. **A profile likelihood ratio λ(μ) (μ signal strength in our case: σ▪Br) is constructed to estimate the parameters of interest:**

$$\lambda(\mu) = \frac{L(\mu, \hat{\hat{\boldsymbol{\theta}}})}{L(\hat{\mu}, \hat{\boldsymbol{\theta}})} \qquad 0 \leq \lambda \leq 1$$

3.



- ✓ **If the likelihood ratio follows a χ^2 distribution, the significance can be approximately computed as sqrt[-2*log(λ)] with μ=1;**
- ✓ **Similarly, one can scan μ (Minuit) and the error of μ is the distance of x-axis between μ=1 and the point on the curve corresponding to –log(λ)= 0.5.**
- ✓ **For the measurement of Br, the uncertainty from total xsection obtained from previous page is incorporated into the fit.**
- ✓ **A simultaneous fit to different channels is implemented to take into account the correlations.**

Measurement of Higgs width

- **Method 1: Higgs width can be determined directly from the measurement of σ(ZH) and Br. of (H->ZZ*)**

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

Precision : 5.4%

  - **But the uncertainty of Br(H->ZZ*) is relatively high due to low statistics.**

- **Method 2: It can also be measured through:**

$$\Gamma_H \propto \frac{\Gamma(H \to bb)}{BR(H \to bb)}$$

$$\sigma(\nu\bar{\nu}H \to \nu\bar{\nu}b\bar{b}) \propto \Gamma(H \to WW^*) \cdot \mathrm{BR}(H \to bb) = \Gamma(H \to bb) \cdot \mathrm{BR}(H \to WW^*)$$

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

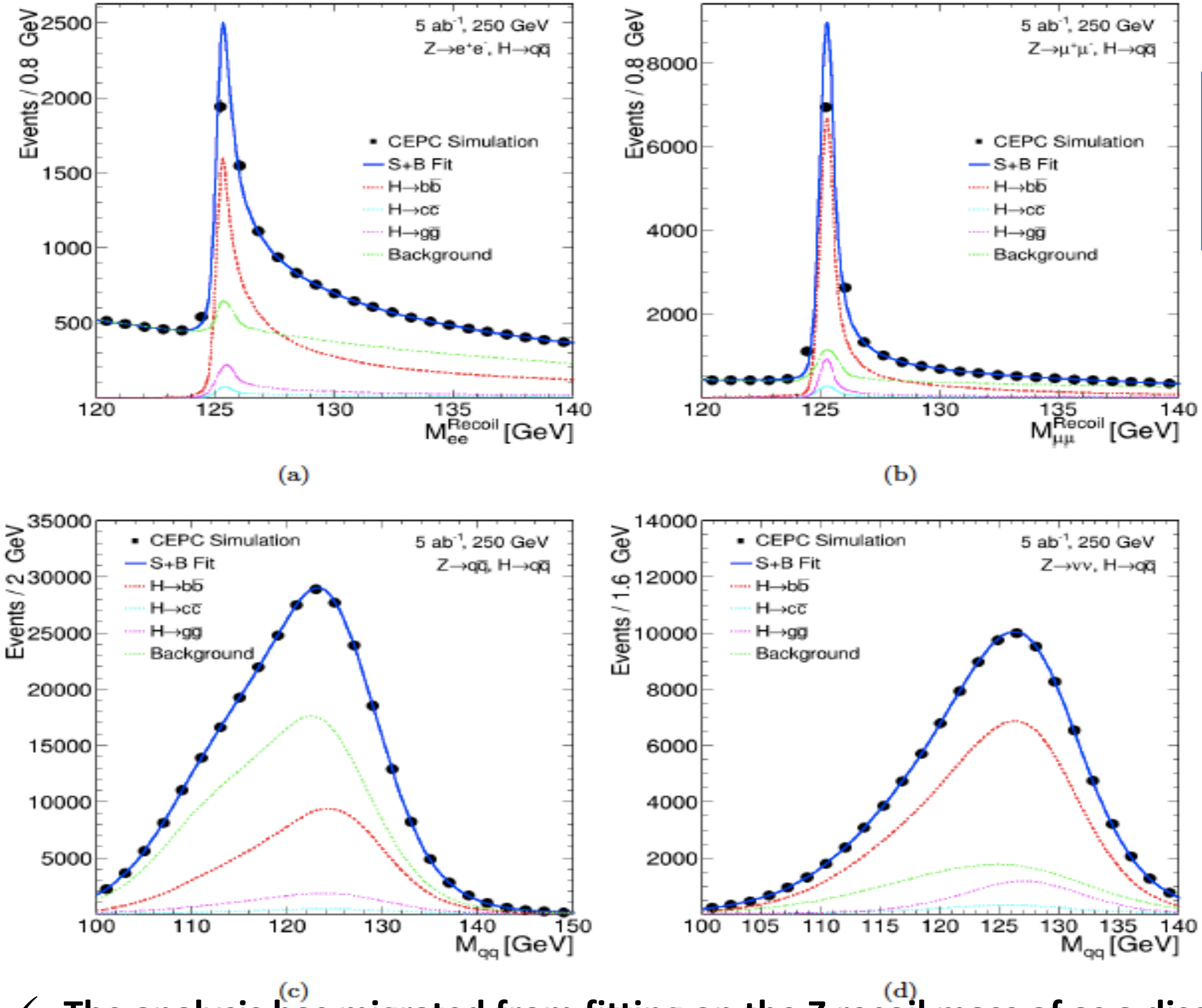
3.0%

Precision : 3.7%

- **These two orthogonal methods can be combined to reach the best precision.**

Precision : 3.3%

Measurement of Δ(σ▪Br)/(σ▪Br) of ZH(jj)

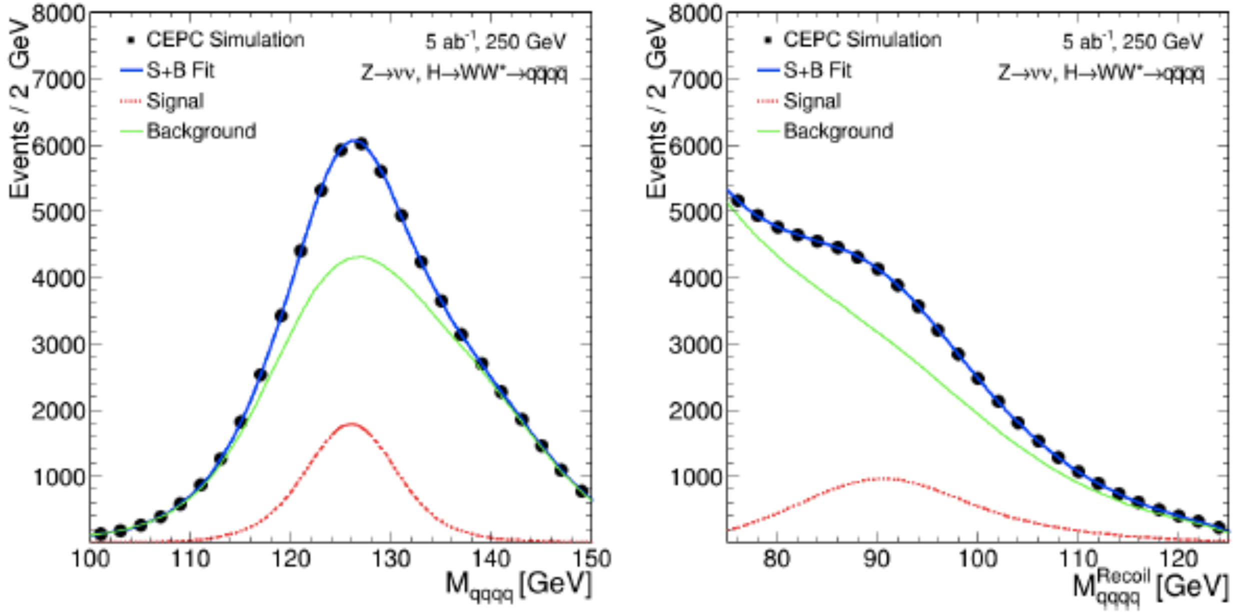


$$B_{likeness} = \frac{b_{j1}b_{j2}}{b_{j1}b_{j2} + (1 - b_{j1})(1 - b_{j2})}$$

Z decay mode	$H \to b\bar{b}$	$H \to c\bar{c}$	$H \to gg$
$Z \to e^+e^-$	1.3%	11.8%	6.2%
$Z \to \mu^+\mu^-$	1.0%	9.4%	4.9%
$Z \to q\bar{q}$	0.5%	11.2%	3.7%
$Z \to \nu\bar{\nu}$	0.4%	3.8%	1.5%
Combined	0.3%	3.3%	1.3%

- ✓ **The analysis has migrated from fitting on the Z recoil mass of as a discriminating variable to on the flavor-tagging (2-D fit with B-likeliness & C-likeliness); The method of 3-D fit will be more effective.**
- ✓ **The combined precisions of for the measurement of H->bb,cc,gg for CEPC are 0.3%, 3.3%, 1.3% respectively.**

Measurement of Δ(σ▪Br)/(σ▪Br) of ZH(WW*)

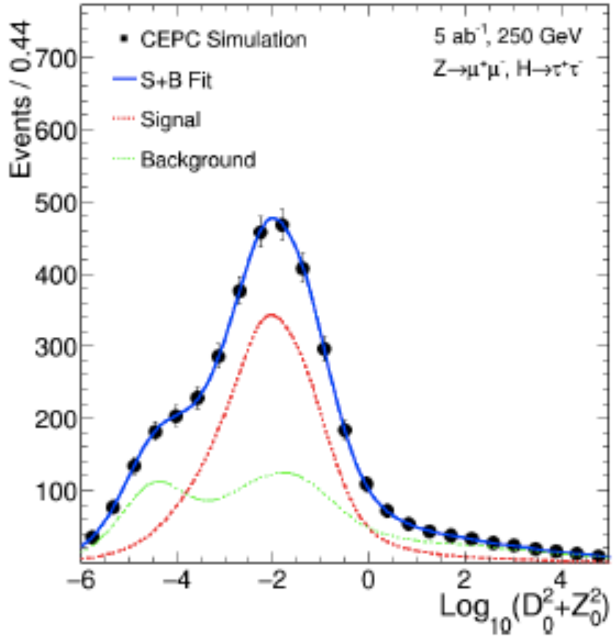


ZH final state		Precision
$Z \to e^+e^-$	$H \to WW^* \to \ell\nu\ell'\nu,\ \ell\nu q\bar{q}$	2.8%
$Z \to \mu^+\mu^-$	$H \to WW^* \to \ell\nu\ell'\nu,\ \ell\nu q\bar{q}$	2.6%
$Z \to \nu\bar{\nu}$	$H \to WW^* \to \ell\nu q\bar{q}, q\bar{q}q\bar{q}$	1.7%
$Z \to q\bar{q}$	$H \to WW^* \to q\bar{q}q\bar{q}$	1.8%
Combined		1.0%

Results from other channels can be found in backup

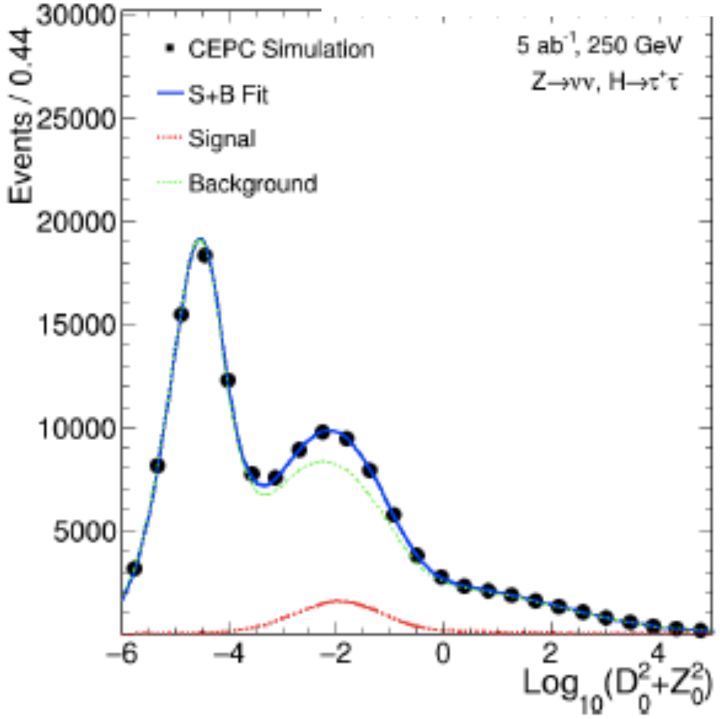
- ✓ **This channel is necessary for the Higgs width measurement.**
- ✓ **Hadronic, Leptonic and semi-leptonic decays of W bosons can be used in the analyses.**
- ✓ **Considering its complicate final states, MVA technique can be implemented to further suppress bkg.**
- ✓ **The most dominant one is Z(->vv)H(->4j) and the combined expected precision is 1.0%.**

Measurement of Δ(σ▪Br)/(σ▪Br) of ZH(ττ)



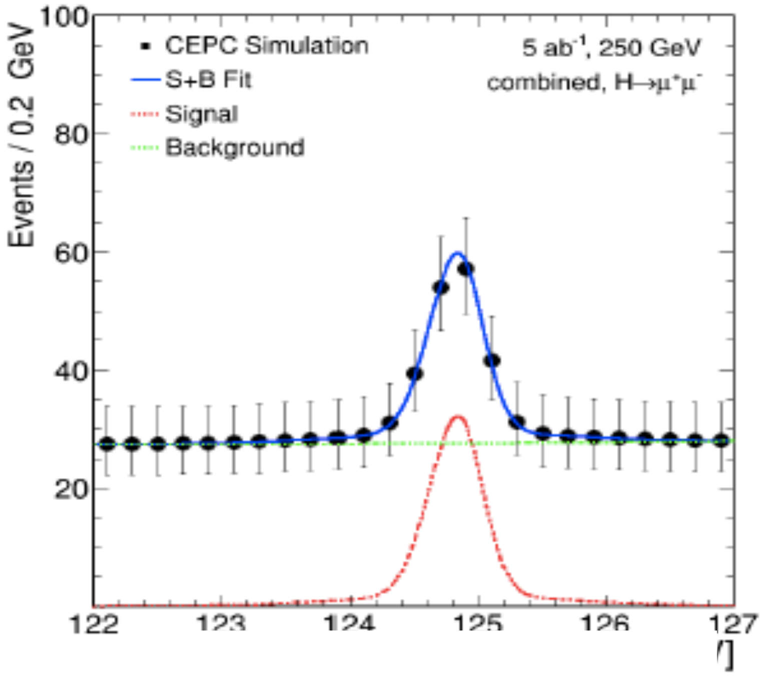
- Develop LICH to identify tau.
- Signal and ZH events(Main WW) share the same shape
    - use $\log_{10}(D_0^2 + Z_0^2)$ fit to separate signal from bkgs.
        - Impact parameter, Distance from beam spot

ZH final state		Precision
$Z \to \mu^+\mu^-$	$H \to \tau^+\tau^-$	2.3%
$Z \to e^+e^-$	$H \to \tau^+\tau^-$	2.7%
$Z \to \nu\bar{\nu}$	$H \to \tau^+\tau^-$	3.1%
$Z \to q\bar{q}$	$H \to \tau^+\tau^-$	0.9%
Combined		0.79%

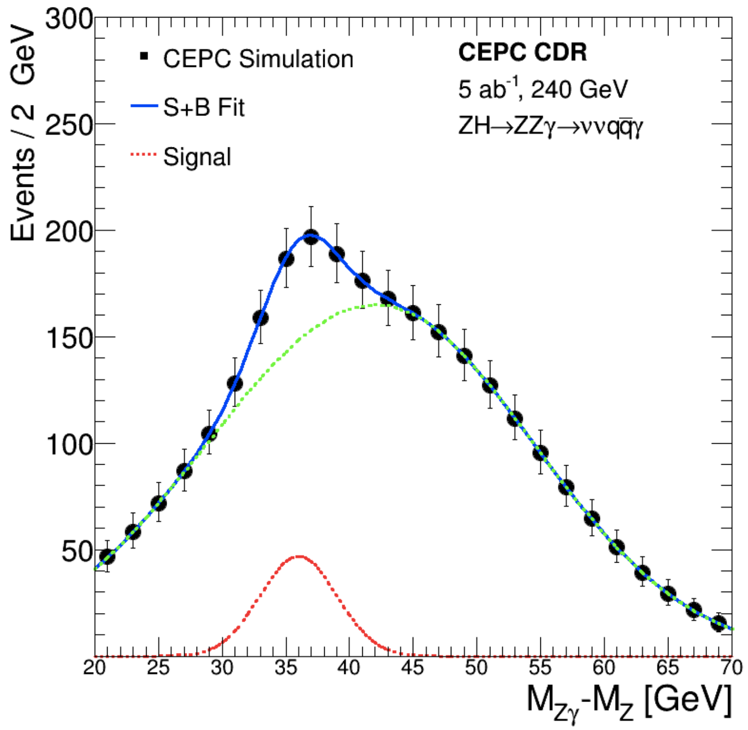


Higgs rare decays and ww-fusion

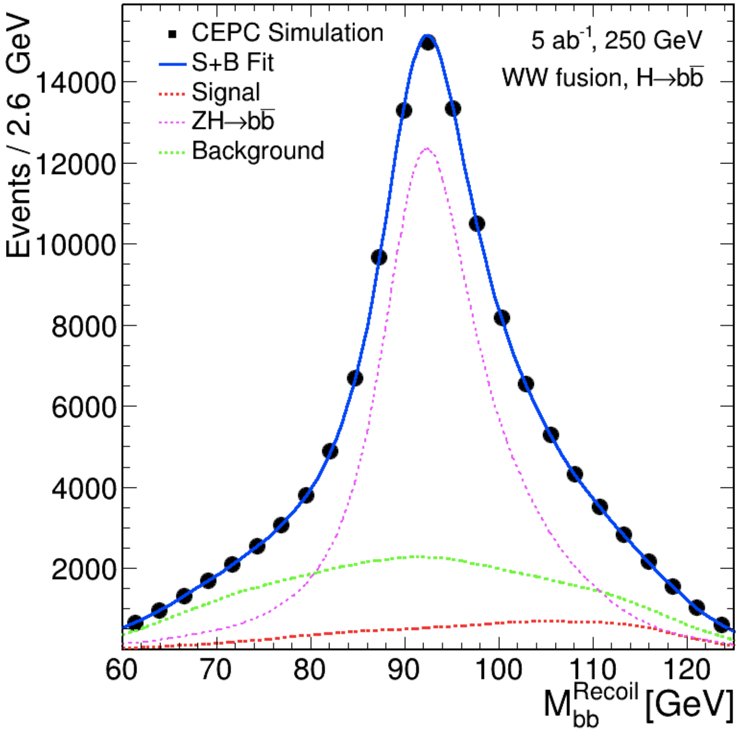
H->μμ



H->Zγ



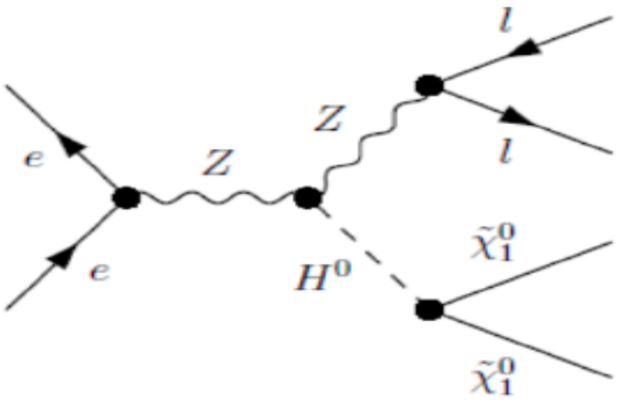
ww fusion (ννH->bb)



- ✓ **The expected precision is 15.9% for H->μμ.**
- ✓ **The process of Z(->νν)H(->Zγ->qqγ) is studied and dMass=$M_{qq\gamma}$-M_{qq} is used.**
  - **The expected precision is 21%, 4σ with 5 ab^{-1} for CEPC**
- ✓ **For WW fusion:**
  - **the Z(->vv)H->bb is the irreducible bkg.**
  - **2D fit on polar angle and recoil mass is used.**
  - **Expected precision is 3.0%**

Measurement of the invisible decay of Higgs

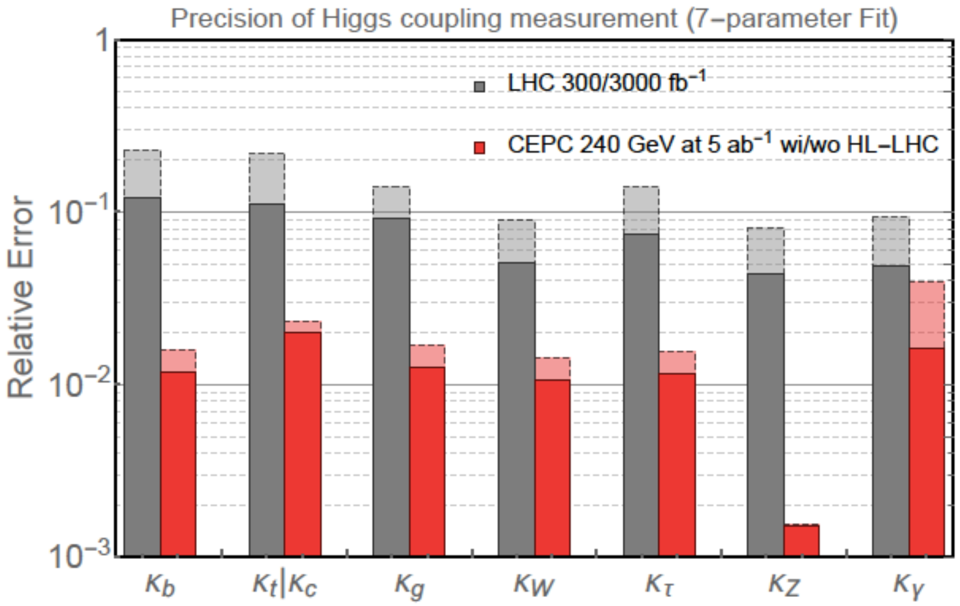
- Invisible can be produced e.g. by the invisible decay of Higgs,NMSSM,2HDM+singlet…
- The recoil mass method provides a chance to have the direct measurement.



ZH final state studied		Relative precision on $\sigma \times$ BR	Upper limit on BR($H \to$ inv)
$Z \to e^+e^-$	$H \to$ inv	325%	0.84%
$Z \to \mu^+\mu^-$	$H \to$ inv	229%	0.62%
$Z \to q\bar{q}$	$H \to$ inv	220%	0.59%
Combined		150%	0.42%

Summary of the precision for the measurement of Higgs

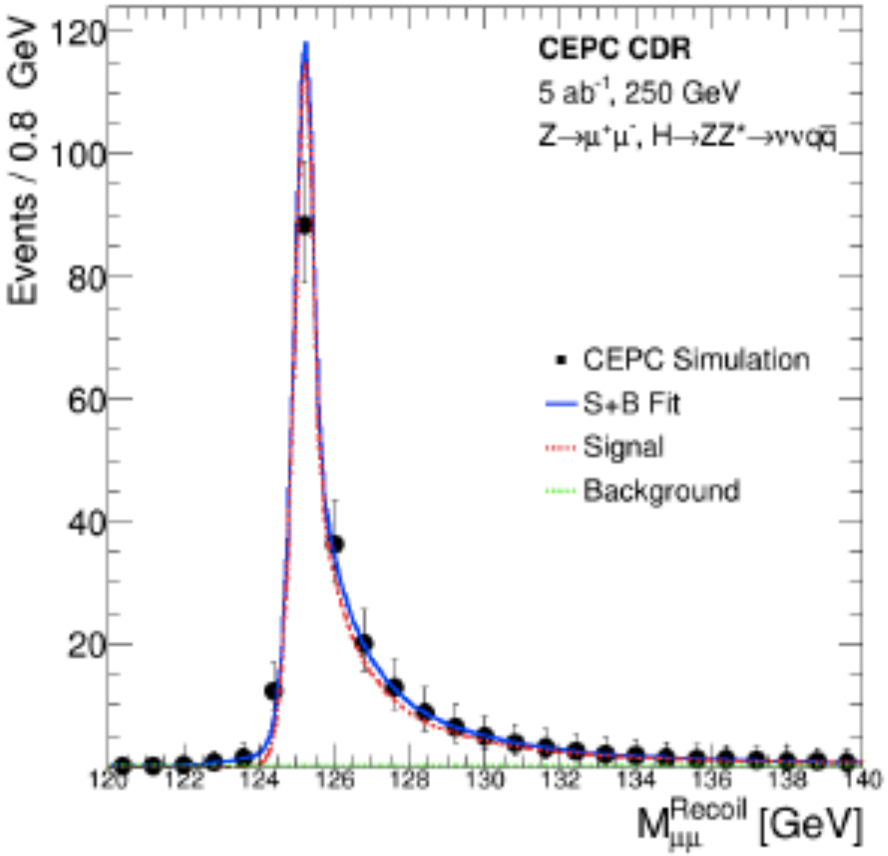
Property	Estimated Precision	
	CEPC-v1	CEPC-v4
m_H	5.9 MeV	
Γ_H	3.2%	3.3%
$\sigma(ZH)$	0.50%	0.50%
$\sigma(\nu\bar{\nu}H)$	3.05%	3.20%
Decay mode	$\sigma(ZH) \times \mathrm{BR}$	
$H \to b\bar{b}$	0.28%	0.29%
$H \to c\bar{c}$	3.27%	3.42%
$H \to gg$	1.28%	1.34%
$H \to \tau^+\tau^-$	0.83%	0.87%
$H \to WW^*$	1.00%	1.04%
$H \to ZZ^*$	5.12%	5.21%
$H \to \gamma\gamma$	6.62%	7.25%
$H \to \mu^+\mu^-$	16%	17%
$H \to Z\gamma$	20%	22%
$\mathrm{BR_{BSM}}(H \to \mathrm{inv})$	$< 0.31\%$	$< 0.33\%$

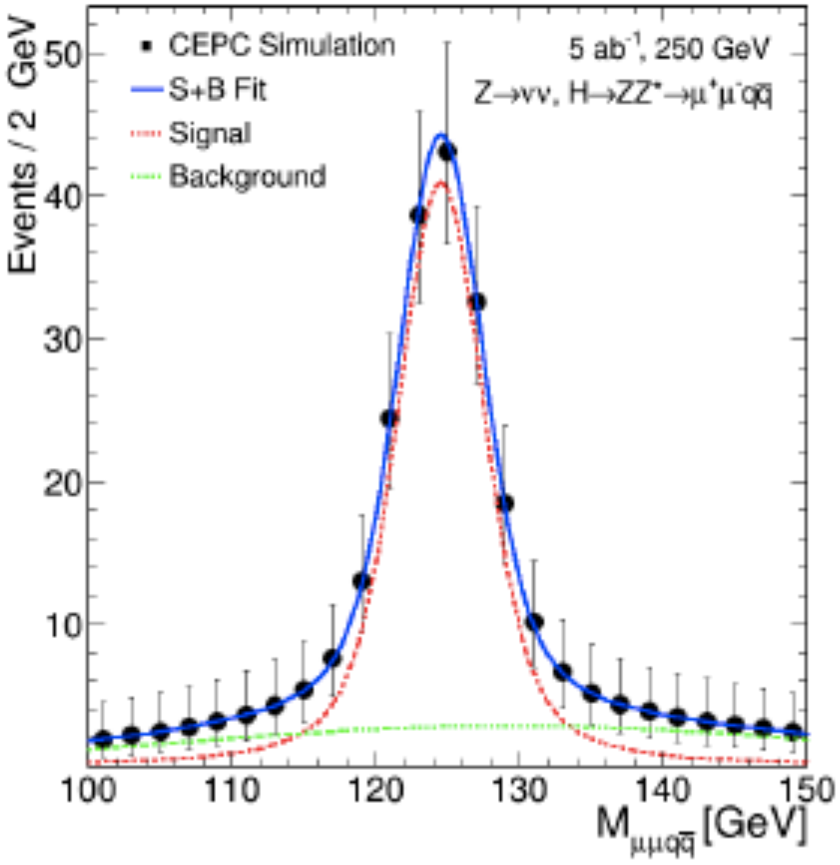


- ✓ **With combination of σ▪Br of vvH(→bb) /Br(H->bb)/Br(H->ww) and the direct measurement, one can obtain the decay width of Higgs with the precision at ~3%.**
- ✓ **The measurement of Br is done by introducing the uncertainty of xsection of ZH from the direct measurement around sub-precent level.**
- ✓ **Most precisions are a few percent or lower (bb, invisible), allowing us to be sensitive to BSM deviation**
- ✓ **In comparison with HL-LHC, e^+e^- machine is expected to have much better performance in the measurements of the coupling constants .**
- ✓ **From CEPC-v1 to CEPC-v4, the differences on the precision measurements are not significant.**

Backup slides

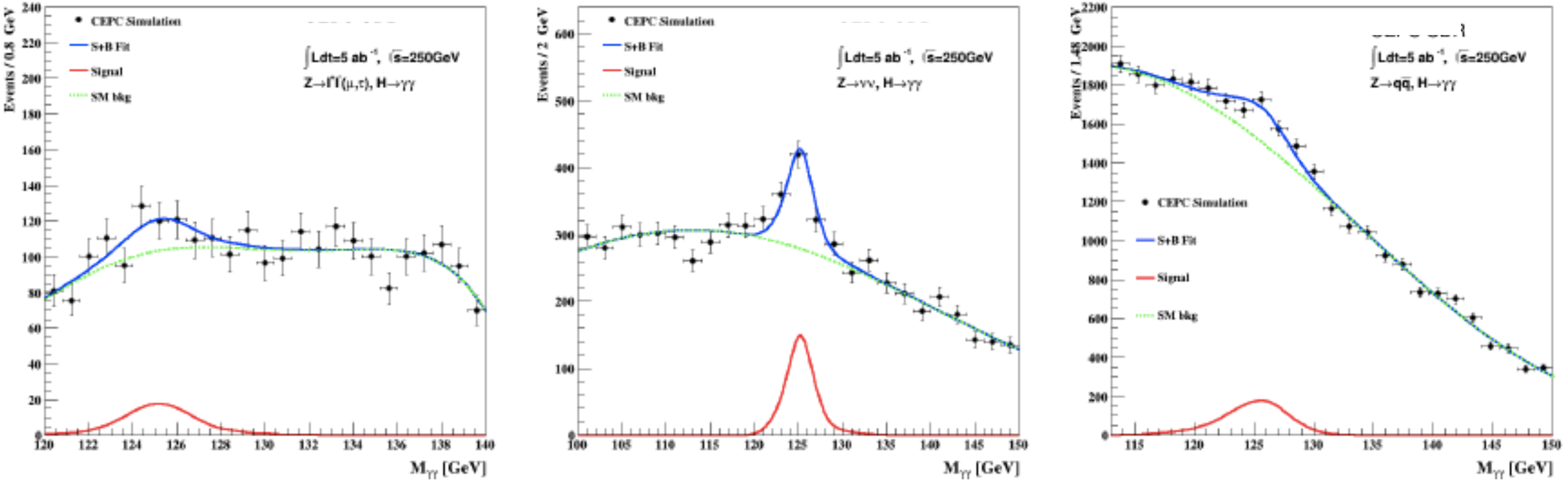
Measurement of Δ(σ▪Br)/(σ▪Br) of ZH(ZZ*)





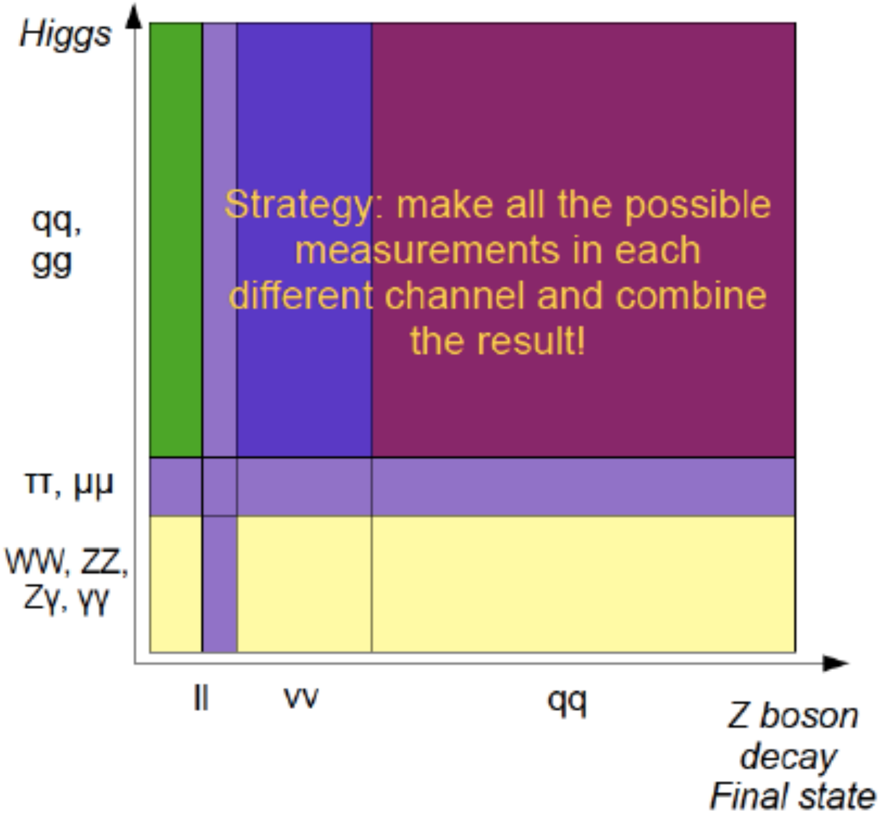
ZH final state		Precision
$Z \to \mu^+\mu^-$	$H \to ZZ^* \to \nu\bar{\nu}q\bar{q}$	7.3%
$Z \to \nu\bar{\nu}$	$H \to ZZ^* \to \ell^+\ell^-q\bar{q}$	8.0%
Combined		5.1%

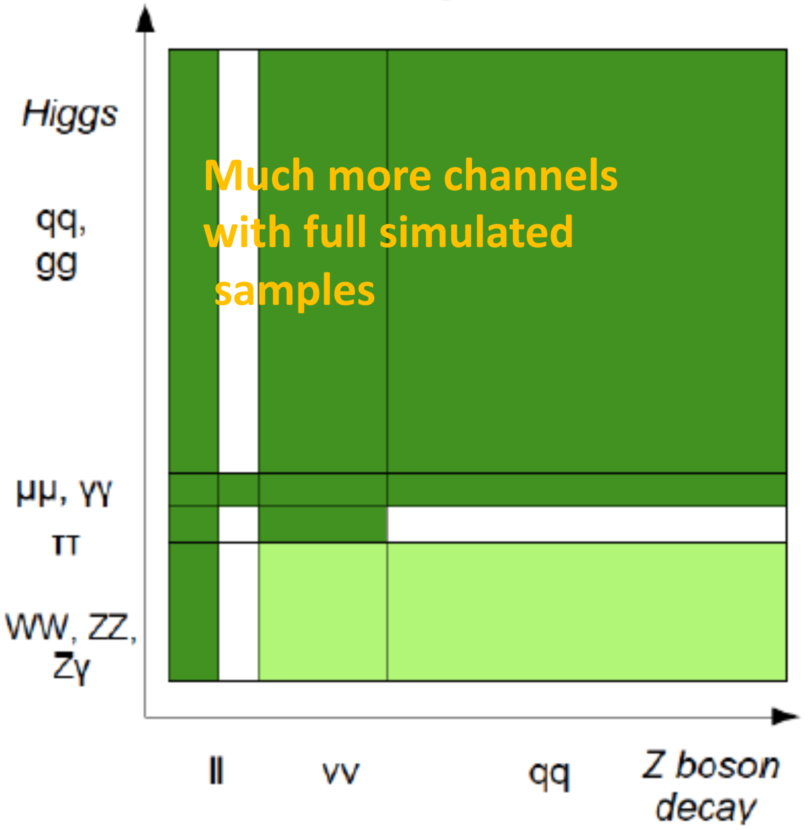
Measurement of Δ(σ▪Br)/(σ▪Br) of ZH(γγ)

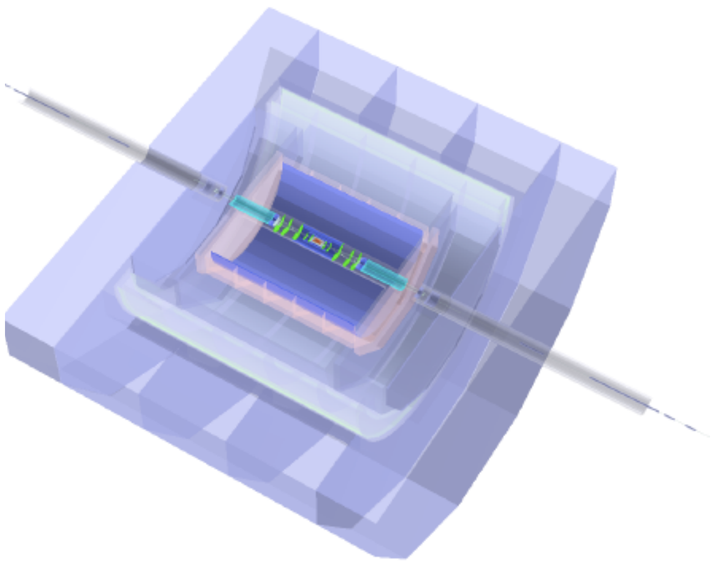


- ✓ **Z(->ee)H(->γγ) is not considered due to large bkg from Bhabha process.**
- ✓ **A mixed fast ((Z->ll)H(->γγ)-full (Z(->qq)H->γγ) simulated signal samples used in the analyses.**
- ✓ **The combined expected precision is 6.6%.**

Higgs analyses toward CEPC CDR

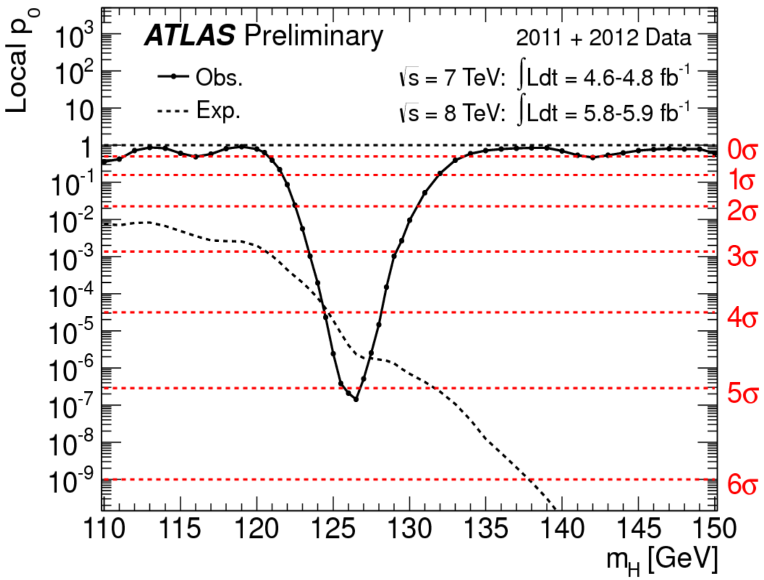


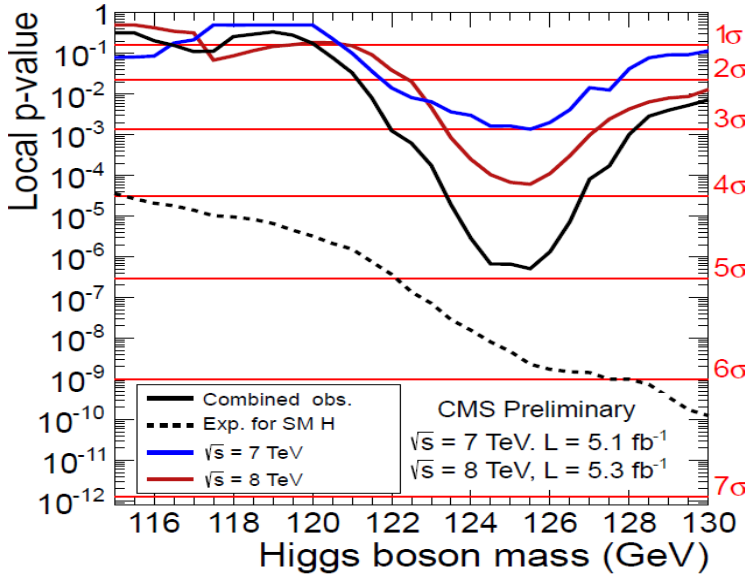


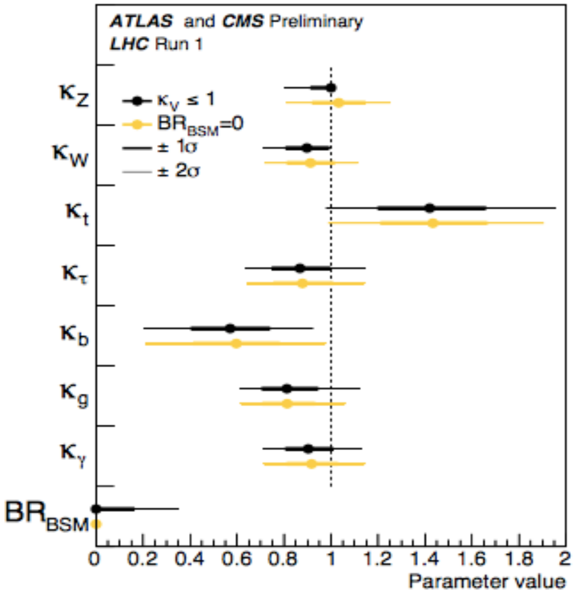


CEPC-v1: 250 GeV/3.5T,…
CEPC-v4: 240 GeV/3T,….

Motivation





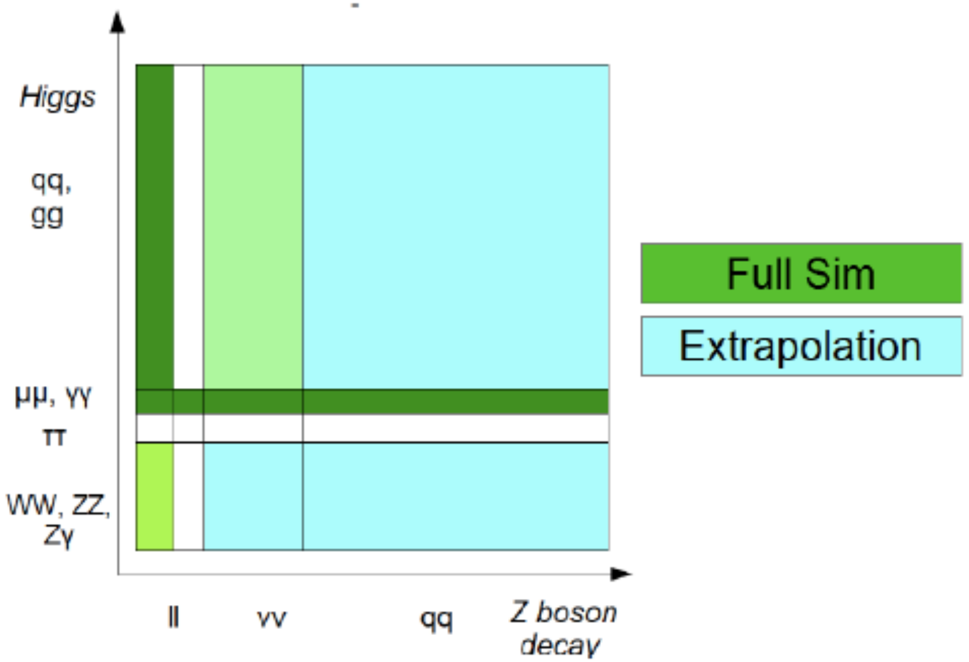


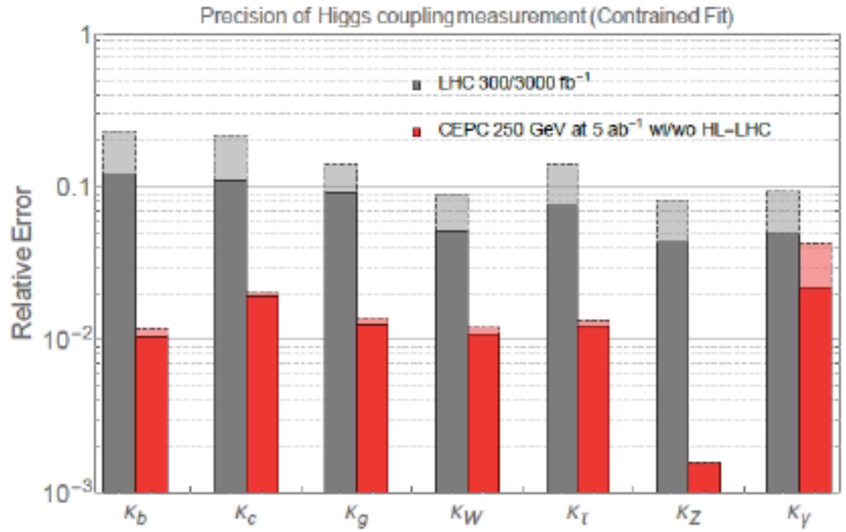
- **The discovery of Higgs in 2012 is a milestone of particle physics.**
- **The further measurements of the properties of the particle confirm it is SM Higgs.**
- **The precision of Higgs measurement is important since the new physics (NP) could introduce a deviation (Δ~$cv^2/M_{NP}^{\ 2}$) which is proportional to $1/M_{NP}^2$.**
- **With LHC, some systematics shows the bottleneck, e.g. theoretical sys. , for the precise measurements of the Higgs coupling etc…**
- **A lepton collider Higgs factory can provide a direct measurement of the Higgs xsection.**

Higgs analyses at Pre-CDR

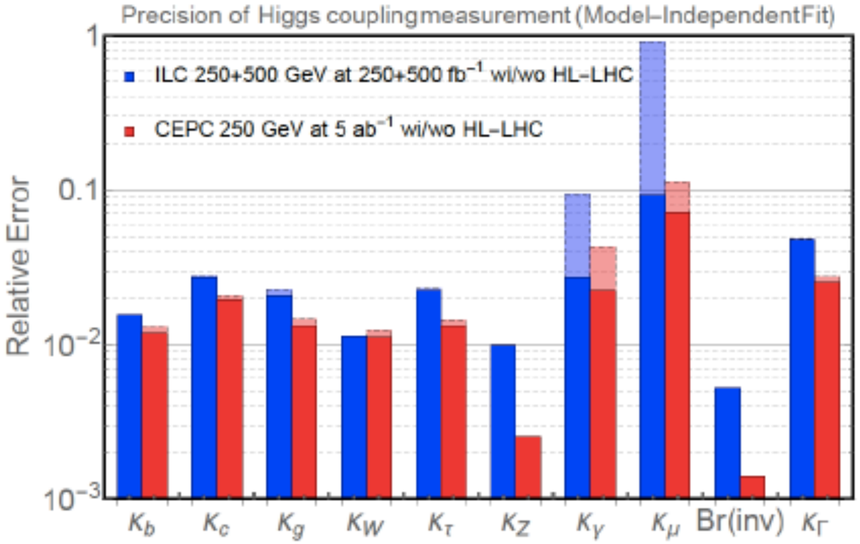
$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{M^2}\mathcal{O}_{6,i} \qquad \delta \sim c_i \frac{v^2}{M^2}$$

% precision ➔ M ~ 1 TeV
to new physics ➔ ~ × 10 over LHC





Kappa-framework
model-dependent measurements



$\Delta(Br * \sigma)$ fit Result

- Most consistent, for difference:
  - Pre_CDR use different simulation sample, and some assumption/extrapolation.
  - Manqi's from data input, Front & fit from mass distribution. End.
  - Data entry
    - Some data not prepared. ($\nu\bar{\nu}H$, e^+e^-H, WW fusion, and some WW, ZZ channel……)
    - Some data outdated. ($\gamma\gamma$)
  - Fit strategy
    - For bb/cc/gg/$\tau\tau$, not only mass distribution used.
    - Next step, will repeat their fit in the likelihood model to raise precision.

κ framework

- Define as the ratio of the coupling to SM expects. $\kappa_f = \frac{g(hff)}{g(hff;\mathrm{SM})}, \ \kappa_V = \frac{g(hVV)}{g(hVV;\mathrm{SM})}$
- In CEPC, κ occurs on three places:
  - For Production, as now only ZH sample, κ_Z^2;
  - For Partial decay, no top quark κ_t like: $\kappa_Z^2, \kappa_W^2, \kappa_b^2, \kappa_c^2, \kappa_g^2, \kappa_\tau^2, \kappa_\gamma^2, \kappa_\mu^2, \kappa_{Inv}^2$ ... ...
  - For Total width Γ_H. $\Gamma_H = \Gamma_{SM} + \Gamma_{BSM}$ for exotic decays.
- κ framework varies for different assumptions.
- Here our fit, as sample limited, we set:
  - $\Gamma_{BSM} = 0$

  $$\kappa_H^2 = 0.57\kappa_b^2 + 0.22\kappa_W^2 + 0.09\kappa_g^2 + 0.06\kappa_\tau^2 + 0.03\kappa_Z^2 + 0.03\kappa_c^2 + 0.0023\kappa_\gamma^2 + 0.0016\kappa_{Z\gamma}^2 + 0.0001\kappa_s^2 + 0.00022\kappa_\mu^2$$

  - Assume Γ_H constant currently. and here no $Z\gamma$ or s quark sample;
  - So set 9 κ: $\kappa_Z^2, \kappa_W^2, \kappa_b^2, \kappa_c^2, \kappa_g^2, \kappa_\tau^2, \kappa_\gamma^2, \kappa_\mu^2, \kappa_{Inv}^2$

Feasibility & Optimized Parameters

Feasibility analysis: TPC and Passive Cooling Calorimeter is valid for CEPC

	CEPC_v1 (~ ILD)	Optimized (Preliminary)	Comments
Track Radius	1.8 m	>= 1.8 m	Requested by Br(H->di muon) measurement
B Field	**3.5 T**	**3 T**	**Requested by MDI**
ToF	**-**	**50 ps**	**Requested by pi-Kaon separation at Z pole**
ECAL Thickness	84 mm	84(90) mm	84 mm is optimized on Br(H->di photon) at 250 GeV; 90mm for bhabha event at 350 GeV
ECAL Cell Size	5 mm	10 – 20 mm	Passive cooling request ~ 20 mm. 10 mm should be highly appreciated for EW measurements – need further evaluation
ECAL NLayer	30	20 – 30	Depends on the Silicon Sensor thickness
HCAL Thickness	**1.3 m**	**1 m**	-
HCAL NLayer	**48**	**40**	Optimized on Higgs event at 250 GeV; Margin might be reserved for 350 GeV.