



Higgs Physics at CEPC

Gang Li (IHEP) on behalf of the CEPC study group

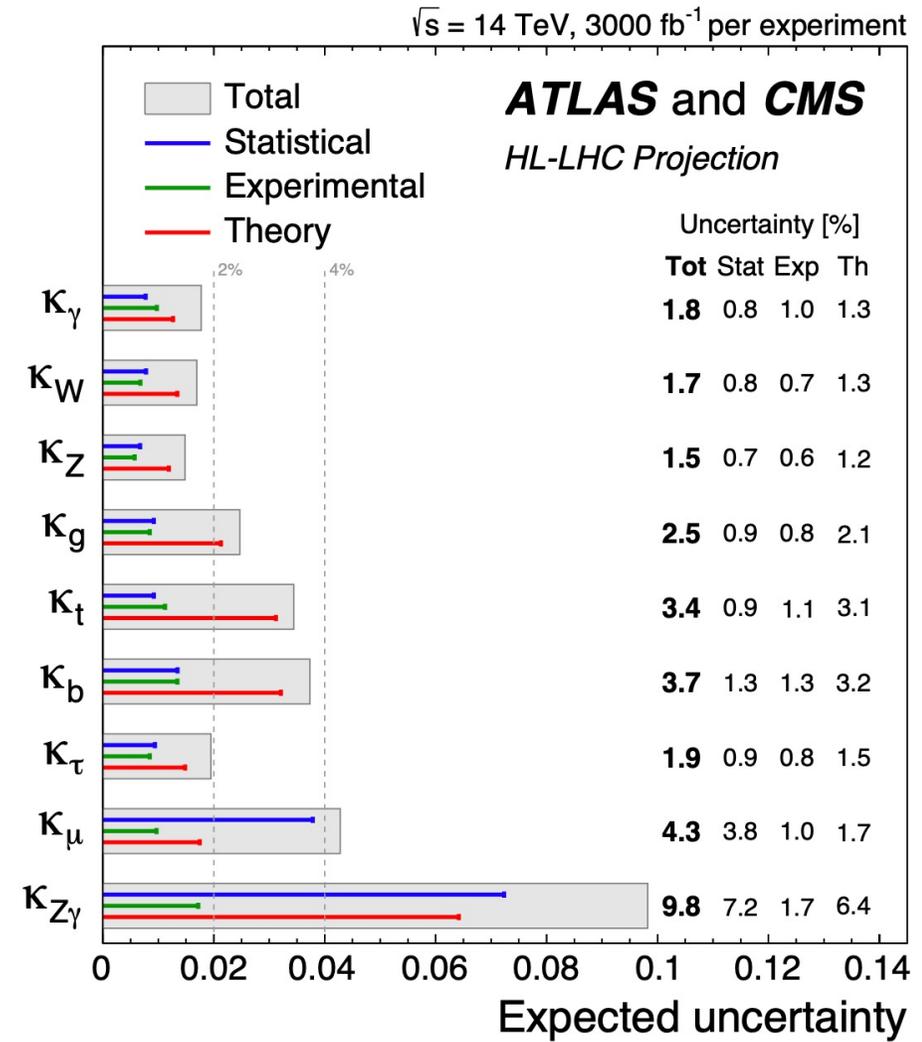
The 5th FCC Physics Workshop

Feb 7-11, 2022

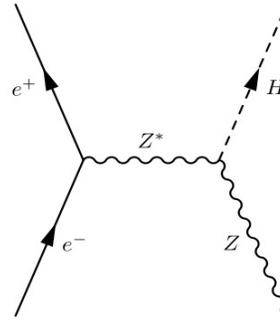
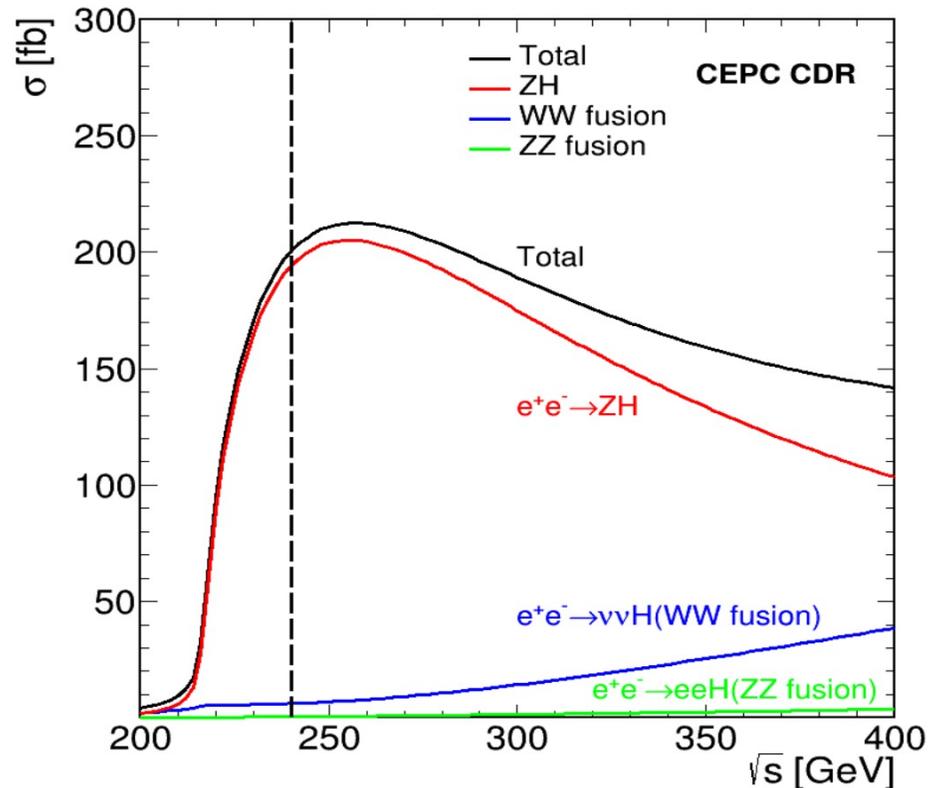
Landon and online

Why an e^+e^- collider

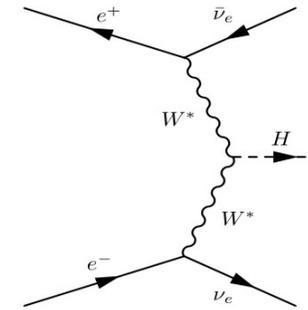
- (HL-)LHC is a discovery machine of TeV scale:
 - ▣ The precision of Higgs coupling with HL-LHC are at the level of a few percent.
 - ▣ Theoretical uncertainties to be dominant.
- An e^+e^- machine to precisely measure Higgs properties and to explore new physics is needed, if the NP is at the sub-percent level.



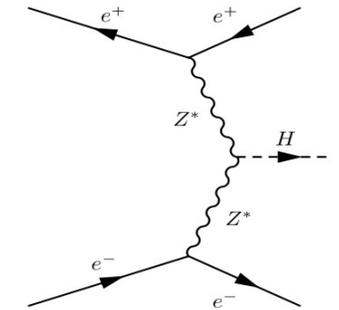
Higgs physics at e^+e^- collider



Higgs-Strahlung



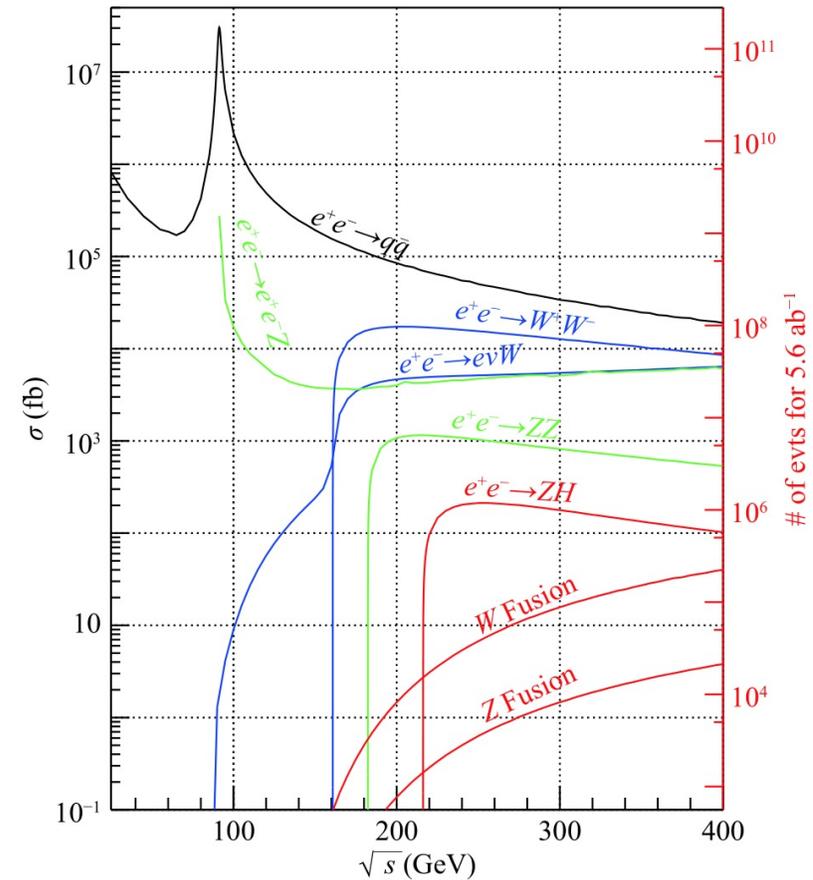
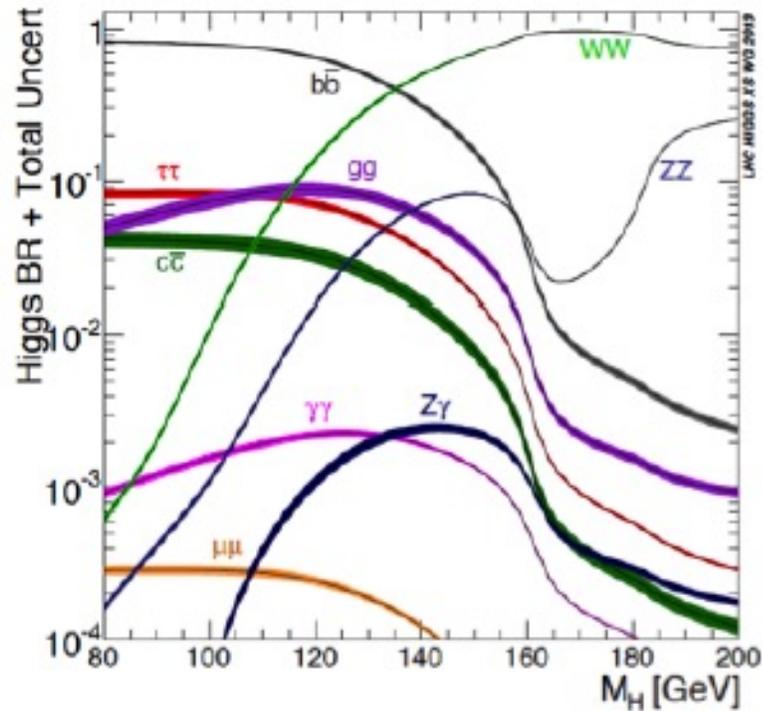
W Fusion



Z Fusion

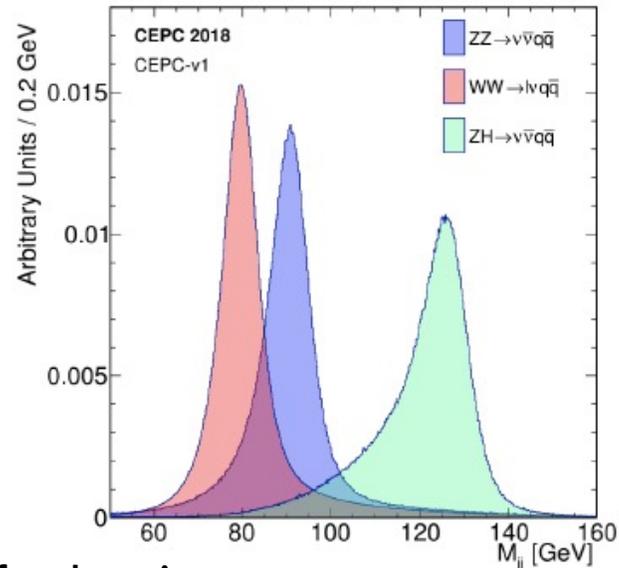
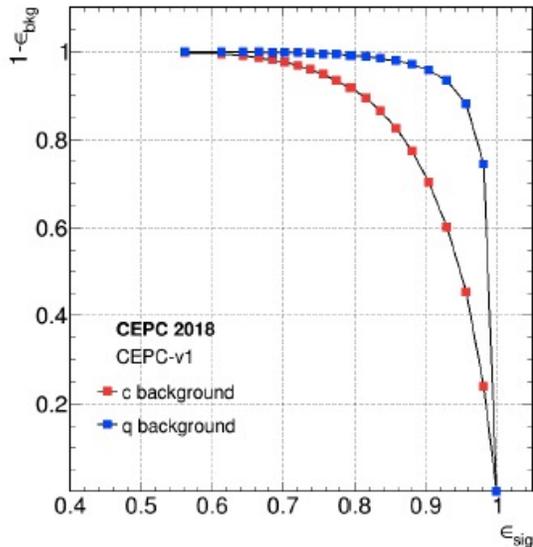
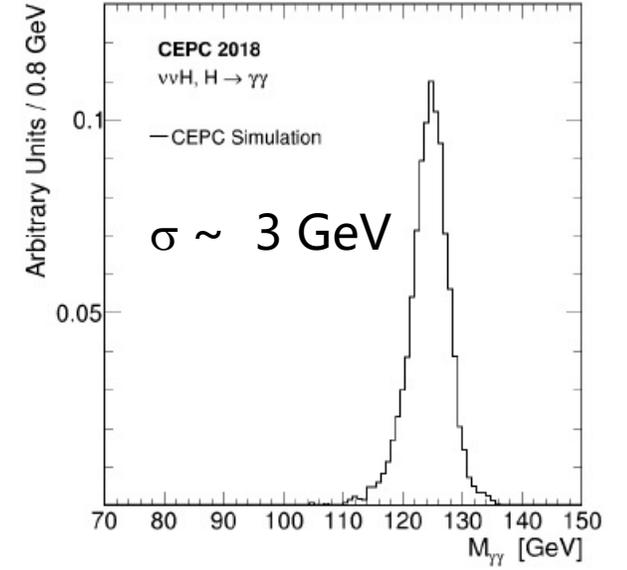
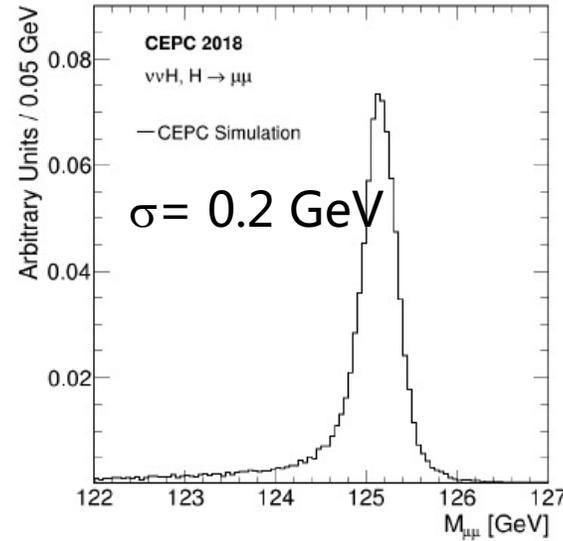
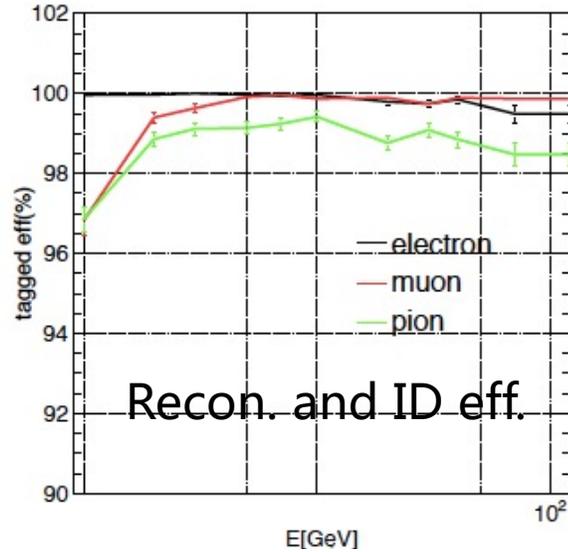
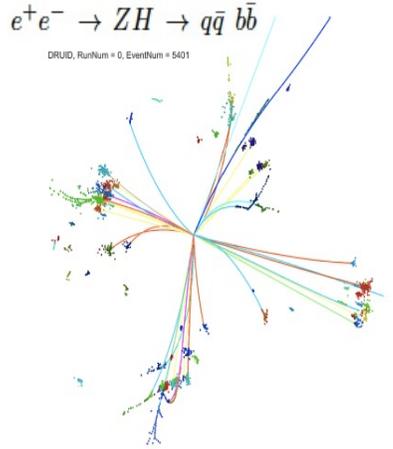
- With the energy increasing, different Higgs physics can be explored at e^+e^- colliders.
- Around 240 GeV, the Higgs-Strahlung, as well as the W/Z fusion could be studied intensively.
 - ❑ The dominant production is from HZ, the W/Z fusions contribute only a few percent of the total X-section.

The SM Higgs decay branching ratios and background processes



- ✓ For 5.6 ab^{-1} samples, **>1M Higgs bosons** are produced.
- ✓ Most of the Higgs couplings can be determined with great precision

Performance



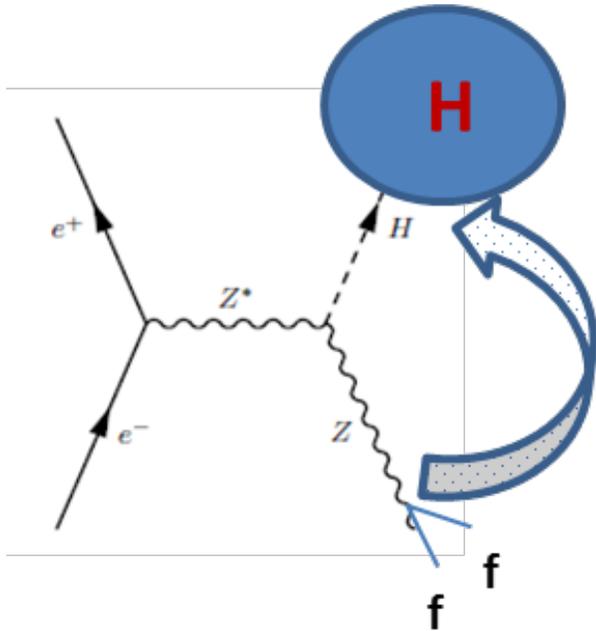
- Reliable Particle recon., ID and fake rejection
- Good mass resolution of Higgs masses.

B-tagging eff. vs rejection of other jets

Feb 7-11, 2022

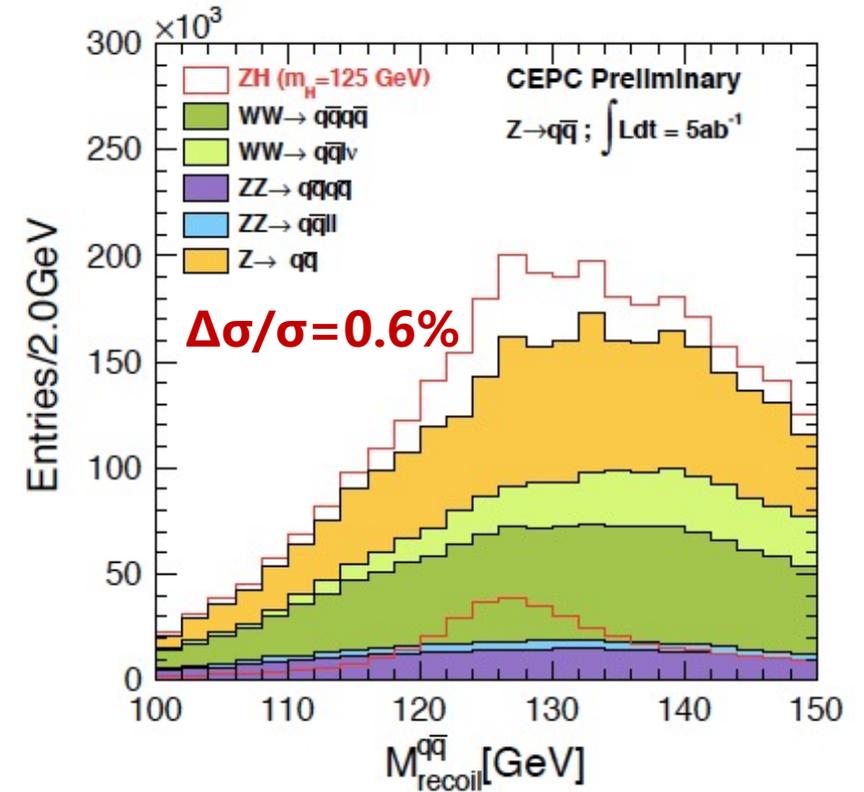
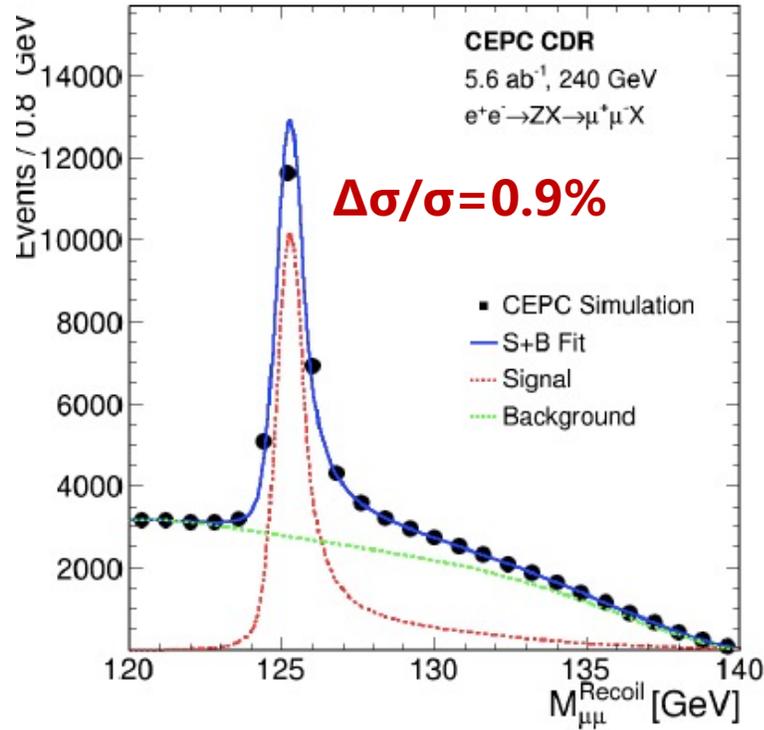
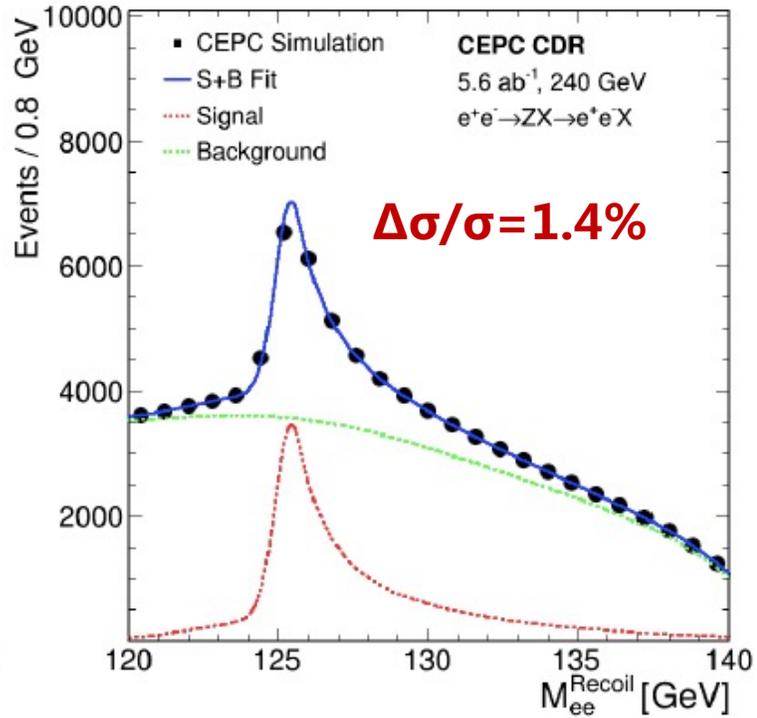
Measurements of Higgs cross-section and m_H

$$M_{\text{recoil}}^2 = (\sqrt{s} - E_{ff})^2 - p_{ff}^2 = s - 2E_{ff}\sqrt{s} + m_{ff}^2$$



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

Measurement of Higgs cross-section and m_H



- ✓ The combined precision with three channels is $\Delta\sigma/\sigma = 0.5\%$
- ✓ Similar sub-percent level for ILC/FCC-ee
- ✓ The mass of Higgs can be measured with a precision 6 MeV by combining $Z \rightarrow ee$ (14 MeV) and $Z \rightarrow \mu\mu$ (6.5 MeV)

Higgs width

- **Method 1:** Higgs width can be determined directly from the measurement of $\sigma(ZH)$ and Br. of $(H \rightarrow ZZ^*)$

$$\Gamma_H \propto \frac{\Gamma(H \rightarrow ZZ^*)}{\text{BR}(H \rightarrow ZZ^*)} \propto \frac{\sigma(ZH)}{\text{BR}(H \rightarrow ZZ^*)} \quad \leftarrow \text{Precision : 5.1\%}$$

- But the uncertainty of $\text{BR}(H \rightarrow ZZ^*)$ is relatively larger due to low statistics.

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

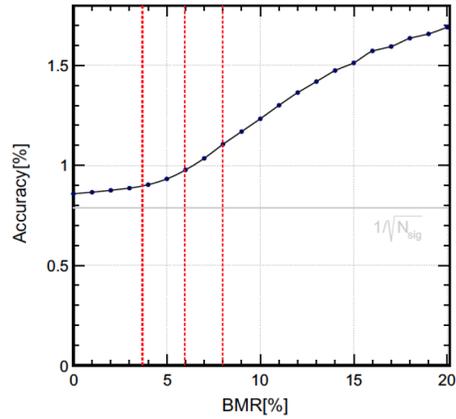
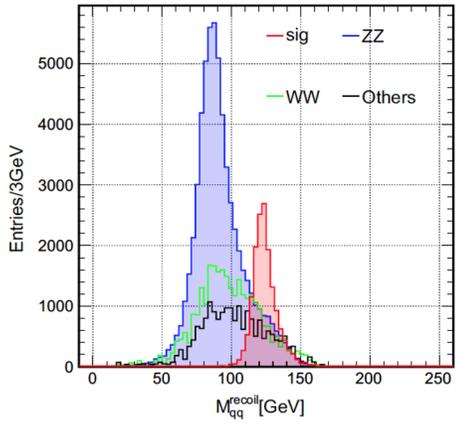
$$\Gamma_H \propto \frac{\Gamma(H \rightarrow bb)}{\text{BR}(H \rightarrow bb)} \quad \sigma(\nu\bar{\nu}H \rightarrow \nu\bar{\nu}b\bar{b}) \propto \Gamma(H \rightarrow WW^*) \cdot \text{BR}(H \rightarrow bb) = \Gamma(H \rightarrow bb) \cdot \text{BR}(H \rightarrow WW^*)$$

$$\Gamma_H \propto \frac{\Gamma(H \rightarrow bb)}{\text{BR}(H \rightarrow bb)} \propto \frac{\sigma(\nu\bar{\nu}H \rightarrow \nu\bar{\nu}b\bar{b})}{\text{BR}(H \rightarrow b\bar{b}) \cdot \text{BR}(H \rightarrow WW^*)} \quad \leftarrow \text{3.0\%} \quad \text{Precision : 3.5\%}$$

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

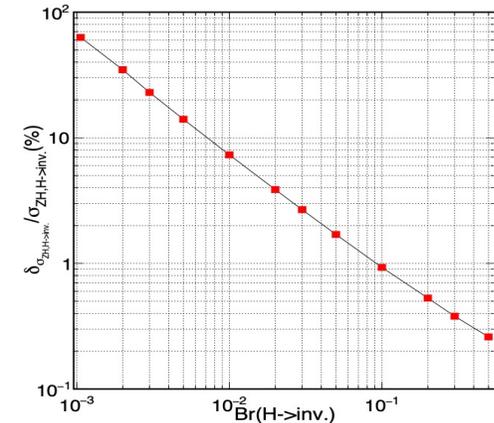
Combined: 2.9%

Other improvements on the Higgs



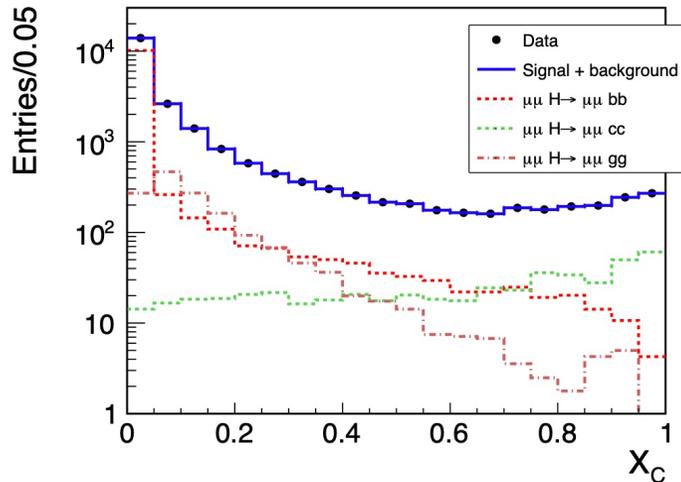
Higgs $\rightarrow \tau\tau$

Euro. Phys. J. C(2020) 80:7



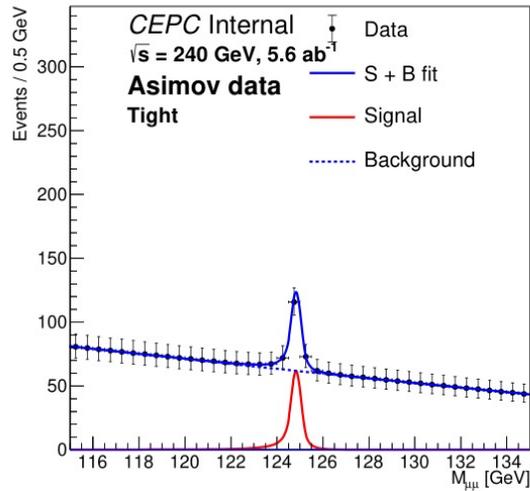
Higgs \rightarrow invisible

CPC Vol. 44, No. 12 (2020) 123001



H $\rightarrow bb, cc, gg$

CPC Vol. 44, No.1 (2020)013001



Higgs $\rightarrow \mu\mu$

Submitted to CPC

Category	$\frac{\Delta(\sigma \cdot BR)}{(\sigma \cdot BR)} [\%]$	
	cut-based	BDT
$\mu\mu H \nu\nu qq^{\text{cut/mva}}$	15.5	13.6
$\mu\mu H qq \nu\nu^{\text{cut/mva}}$	48.0	42.1
$\nu\nu H \mu\mu qq^{\text{cut/mva}}$	11.9	12.5
$\nu\nu H qq \mu\mu^{\text{cut/mva}}$	23.5	20.5
$qq H \nu\nu \mu\mu^{\text{cut/mva}}$	45.3	37.0
$qq H \mu\mu \nu\nu^{\text{cut/mva}}$	52.4	44.4
Combined	8.34	7.89

H $\rightarrow ZZ$

Eur.Phys.J.C 81 (2021) 10, 879

Precision for the Measurement of Higgs

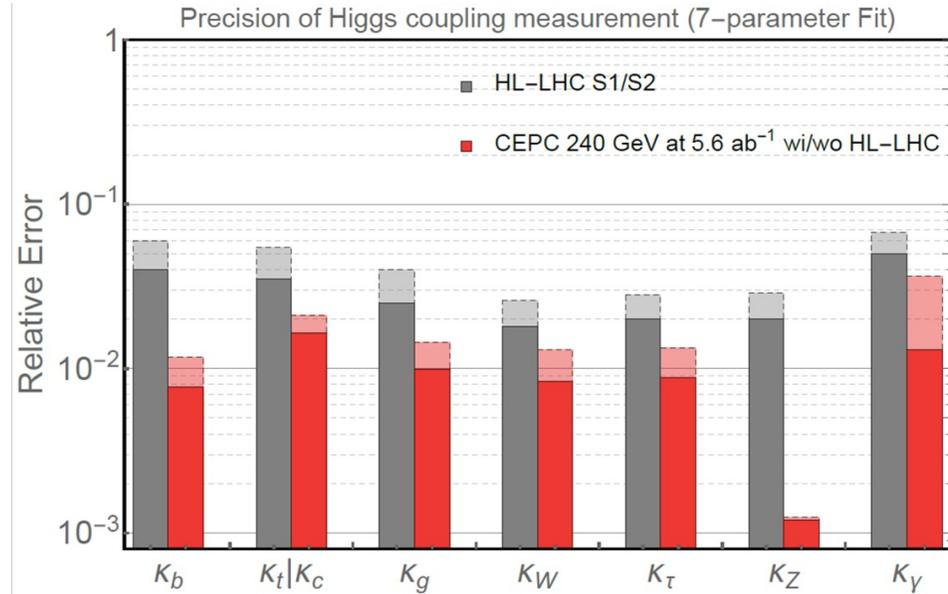
Property	Estimated Precision	
	CEPC-v1	CEPC-v4
m_H	5.9 MeV	5.9 MeV
Γ_H	2.7%	2.8%
$\sigma(ZH)$	0.5%	0.5%
$\sigma(\nu\bar{\nu}H)$	3.0%	3.2%

Decay mode	$\sigma \times BR$	BR	$\sigma \times BR$	BR
$H \rightarrow b\bar{b}$	0.26%	0.56%	0.27%	0.56%
$H \rightarrow c\bar{c}$	3.1%	3.1%	3.3%	3.3%
$H \rightarrow g\bar{g}$	1.2%	1.3%	1.3%	1.4%
$H \rightarrow WW^*$	0.9%	1.1%	1.0%	1.1%
$H \rightarrow ZZ^*$	4.9%	5.0%	5.1%	5.1%
$H \rightarrow \gamma\gamma$	6.2%	6.2%	6.8%	6.9%
$H \rightarrow Z\gamma$	13%	13%	16%	16%
$H \rightarrow \tau^+\tau^-$	0.8%	0.9%	0.8%	1.0%
$H \rightarrow \mu^+\mu^-$	16%	16%	17%	17%
BR_{inv}^{BSM}	—	< 0.28%	—	< 0.30%

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Precision Higgs Physics at the CEPC*

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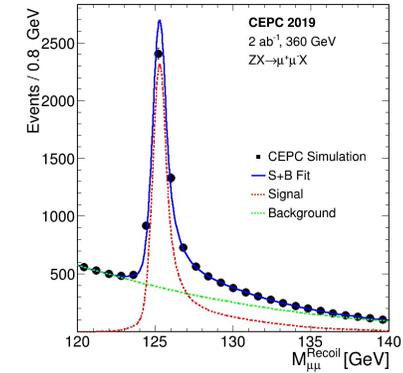
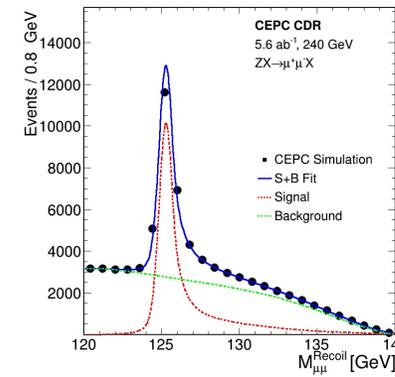


- ✓ Combining $\sigma(\nu\bar{\nu}H(\rightarrow b\bar{b})) / Br(H\rightarrow ZZ) / Br(H\rightarrow WW)$, achieved the Γ_H with the precision of ~3%.
- ✓ Most precisions are a few percent or lower (bb, invisible), allowing us to be sensitive to BSM deviation
- ✓ Higgs white paper are published at CPC (arxiv: [1810.09037](https://arxiv.org/abs/1810.09037)) and the results also included in the [CDR](#).
- Other publications: $\sigma(ZH)$:[1601.05352](#); $bb/cc/gg$:[1905.12903](#); $\tau\tau$:[1903.1232](#) Invisible: [2001.05912](#)
- ✓ CEPC is complementary to LHC at the Higgs precision measurement.

arXiv:1810.09037v2 [hep-ex] 4 Mar 2019

Extrapolation to 360 GeV

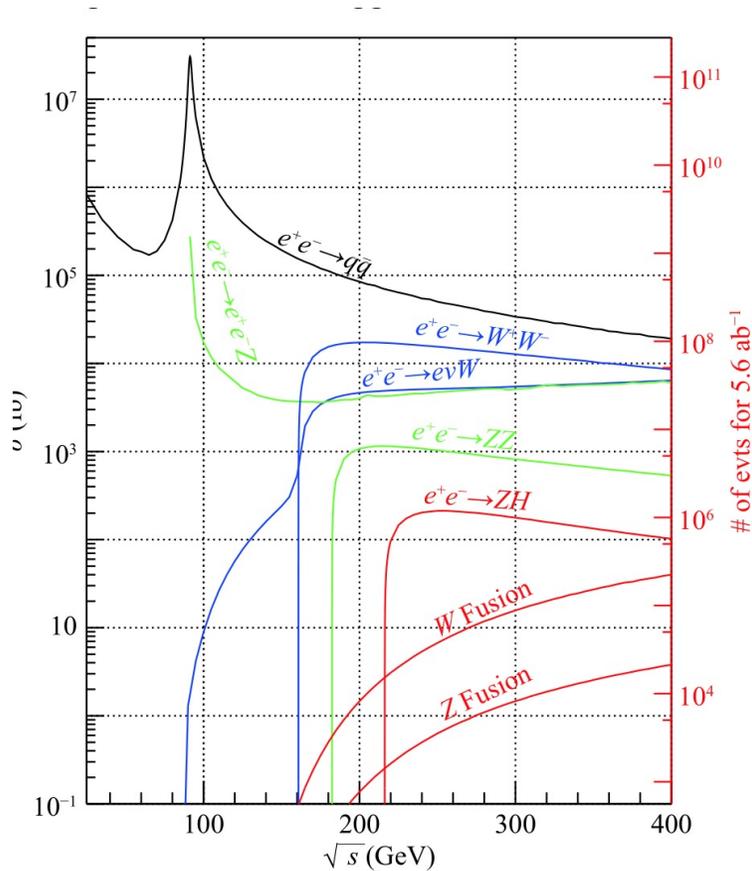
- Mainly scale yields from 240 GeV.
- $\sigma(ZH)$: preliminarily, around 1%
 - Need patient work on qqH channel



Ideal inclusive $Z \rightarrow \mu\mu$: 0.92% → 1.72%

- Resolution change: 2 benchmarks
 - Di-muon: would worse; from ~0.3 GeV to 1 GeV; (23% -> 29%)
 - Di-photon: would better; from ~2.8 GeV to 2.3 GeV; (9% -> 8%)

Additional sensitivity on Higgs measurement



	240GeV, 5.6ab ⁻¹	360GeV, 2ab ⁻¹	
	ZH	ZH	ννH
any	0.50%	1%	\
H → bb	0.27%	0.63%	0.76%
H → cc	3.3%	6.2%	11%
H → gg	1.3%	2.4%	3.2%
H → WW	1.0%	2.0%	3.1%
H → ZZ	5.1%	12%	13%
H → ττ	0.8%	1.5%	3%
H → γγ	5.7%	8%	11%
H → μμ	12%	29%	40%
Br _{upper} (H → inv.)	0.2%	\	\
σ(ZH) * Br(H → Zγ)	16%	25%	\
Width	2.9%		
Combined Width	1.4%		

FCC-ee 240 GeV/365 GeV:
[CERN-ACC-2018-0057](#)

√s (GeV)	240	365		
Luminosity (ab ⁻¹)	5	1.5		
δ(σBR)/σBR (%)	HZ	ννH	HZ	ννH
H → any	±0.5		±0.9	
H → bb̄	±0.3	±3.1	±0.5	±0.9
H → c̄c̄	±2.2		±6.5	±10
H → gg	±1.9		±3.5	±4.5
H → W ⁺ W ⁻	±1.2		±2.6	±3.0
H → ZZ	±4.4		±12	±10
H → ττ	±0.9		±1.8	±8
H → γγ	±9.0		±18	±22
H → μ ⁺ μ ⁻	±19		±40	
H → invisible	< 0.3		< 0.6	

Combined width: 1.3%

➤ 360 GeV run can significantly improve the Higgs width measurement.

Higgs CP study at CEPC

$$ee \rightarrow ZH \rightarrow \mu\mu H(\text{di} - \text{jet})$$

Differential cross section could be represent as:

$$\frac{d\sigma}{d\cos\theta_1 d\cos\theta_2 d\phi} = N \times (J_{CP\text{-even}}(\theta_1, \theta_2, \phi) + p \times J_{CP\text{-odd}}(\theta_1, \theta_2, \phi)).$$

An **Optimal Variable** ω which combines the information from $\{\theta_1, \theta_2, \phi\}$ defined as:

$$\omega = \frac{J_{CP\text{-odd}}(\theta_1, \theta_2, \phi)}{J_{CP\text{-even}}(\theta_1, \theta_2, \phi)} \text{ to measure CP-odd strength}$$

Used ML-fit in ω distribution to constrain p .

Results shows:

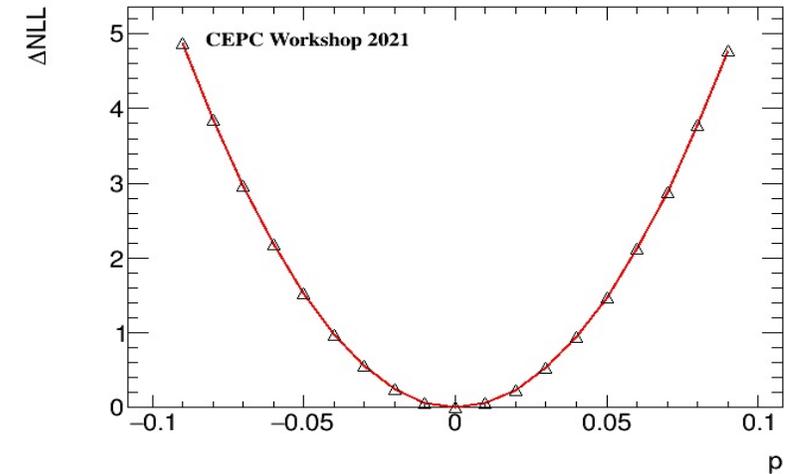
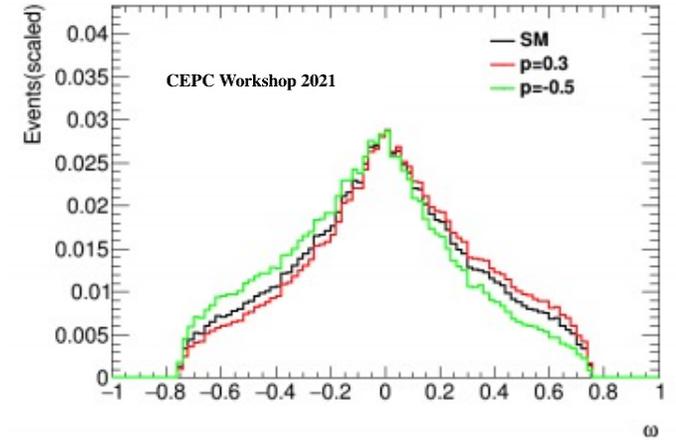
For p :

$$68\% \text{ CL: } [-2.9 \times 10^{-2}, 2.9 \times 10^{-2}]$$

$$95\% \text{ CL: } [-5.7 \times 10^{-2}, 5.7 \times 10^{-2}]$$

Sensitivities of CP-odd couplings

$$\hat{\alpha}_{A\tilde{Z}}, \hat{\alpha}_{Z\tilde{Z}} < 10^{-5}$$



Global analysis for Higgs branching fractions

A classifier modulates production
into observation

$$N \rightarrow n$$

$$\mathbf{n} = \mathbf{E}N .$$

N observes multinomial
distribution, so its
covariance

$$\Sigma^N = N_t^e \begin{pmatrix} B_1(1 - B_1) & -B_1B_2 & \dots & -B_1B_m \\ -B_2B_1 & B_2(1 - B_2) & \dots & -B_2B_m \\ \vdots & \vdots & \ddots & \vdots \\ -B_mB_1 & -B_mB_2 & \dots & B_m(1 - B_m) \end{pmatrix} ,$$

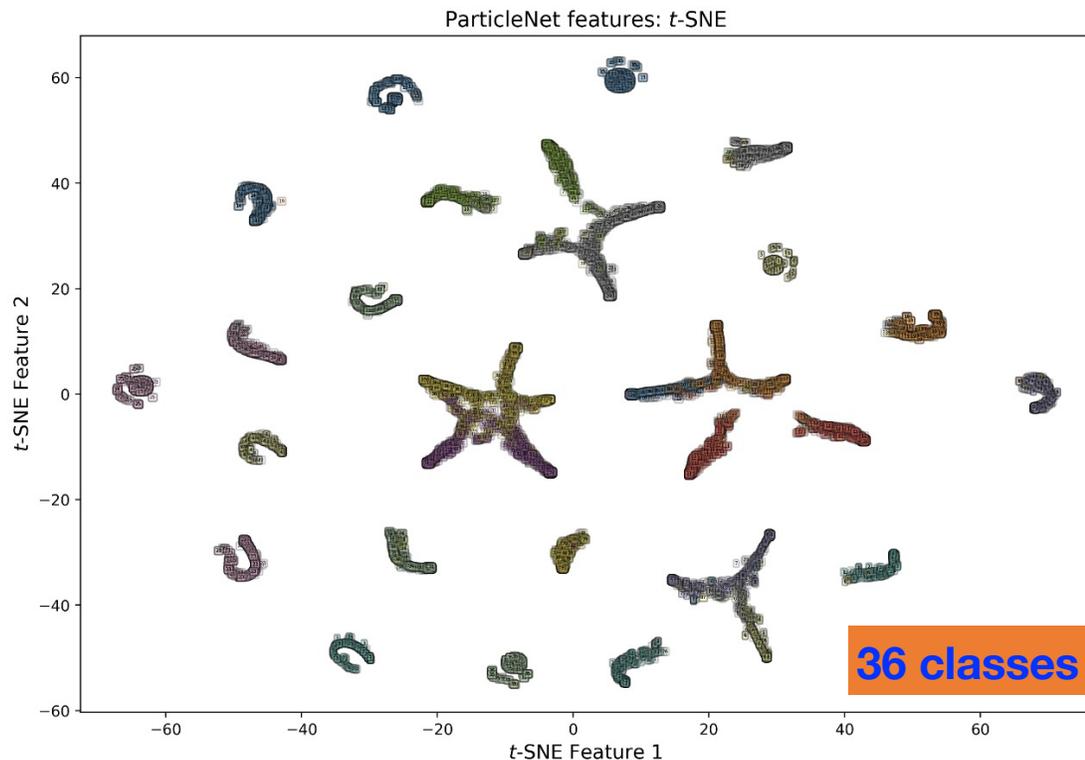
And the covariance of n

$$\Sigma^n \equiv (c_{ij}^n) = \mathbf{E}\Sigma^N\mathbf{E}^T ,$$

Solve all N_i by minimizing

$$\chi_{ee}^2 = \sum_i \frac{(\sum_k \epsilon_{ik} N_k - n_i)^2}{c_{ii}} + \frac{(\sum_k N_k - N_t^e)^2}{\sigma_{N_t}^2} ,$$

Global analysis : Enhance Higgs coupling precision

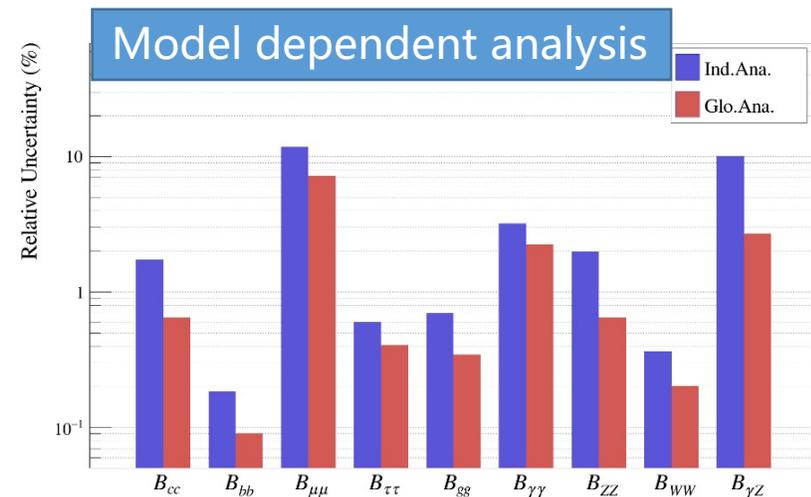


Calculate the efficiency matrix with [the ParticleNet](#)

Using particle level information, no jet-clustering, lepton/photon isolation, ...

A proof-of-principle study shows precision could be improved by factors of ~2

Full simulation study ongoing ...



ArXiv:2105.14997

Decay Mode	Ind. Ana.	Glo. Ana.	IP	CEPC CDR
$H \rightarrow c\bar{c}$	1.8%	0.65%	2.7	3.3%
$H \rightarrow b\bar{b}$	0.19%	0.09%	2.1	0.56%
$H \rightarrow \mu^+\mu^-$	12%	7.2%	1.7	17%
$H \rightarrow \tau^+\tau^-$	0.61%	0.41%	1.4	1.0%
$H \rightarrow gg$	0.7%	0.35%	2.0	1.4%
$H \rightarrow \gamma\gamma$	3.3%	2.3%	1.4	6.9%
$H \rightarrow ZZ$	2.0%	0.65%	3.0	5.1%
$H \rightarrow W^+W^-$	0.37%	0.21%	1.7	1.1%
$H \rightarrow \gamma Z$	11%	2.8%	3.9	15%

Improved a lot for the ones with more contaminations or larger Brs

Summary

- After the CDR and the Higgs white paper done in 2018, several publications are available and more analyses ongoing at the CEPC
 - New methods to improve the precisions
 - Differential analysis
- A generic study on Higgs physics at 360 GeV (2 ab^{-1})
 - Can bring some improvements in Higgs precision.
 - Significant improvement on Higgs width measurement.

backup slides

Precision for the measurement of Higgs

CEPC CDR: arxiv: 1811.10545

Property	Estimated Precision	
m_H	5.9 MeV	
Γ_H	3.1%	
$\sigma(ZH)$	0.5%	
$\sigma(\nu\bar{\nu}H)$	3.2%	

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

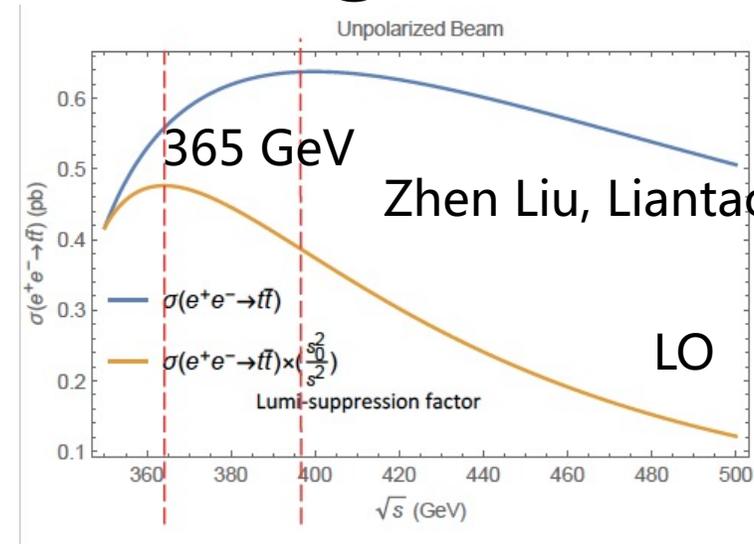
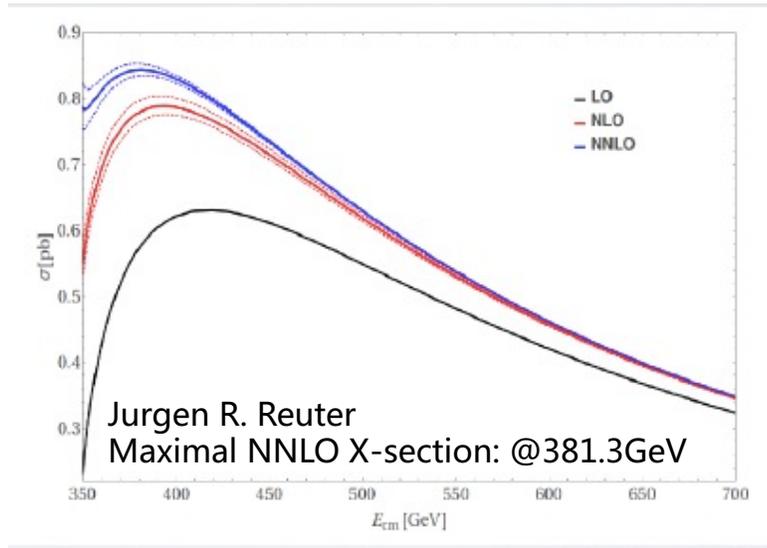
Fcc-ee 240 GeV/365 GeV:

[CERN-ACC-2018-0057](#)

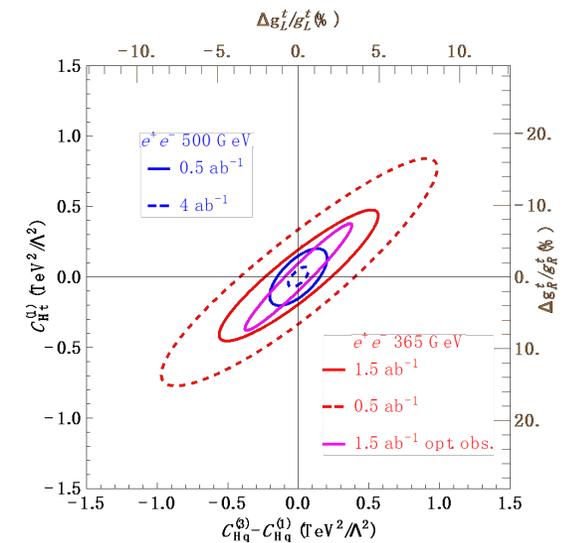
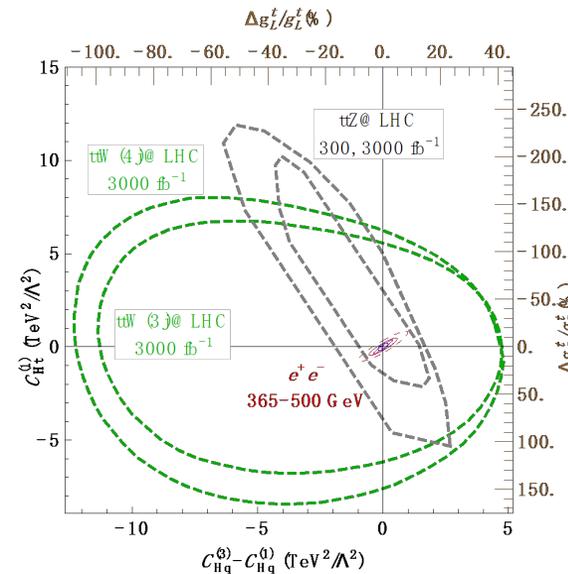
\sqrt{s} (GeV)	240		365	
Luminosity (ab^{-1})	5		1.5	
$\delta(\sigma\text{BR})/\sigma\text{BR}$ (%)	HZ	$\nu\bar{\nu}H$	HZ	$\nu\bar{\nu}H$
$H \rightarrow \text{any}$	± 0.5		± 0.9	
$H \rightarrow b\bar{b}$	± 0.3	± 3.1	± 0.5	± 0.9
$H \rightarrow c\bar{c}$	± 2.2		± 6.5	± 10
$H \rightarrow gg$	± 1.9		± 3.5	± 4.5
$H \rightarrow W^+W^-$	± 1.2		± 2.6	± 3.0
$H \rightarrow ZZ$	± 4.4		± 12	± 10
$H \rightarrow \tau\tau$	± 0.9		± 1.8	± 8
$H \rightarrow \gamma\gamma$	± 9.0		± 18	± 22
$H \rightarrow \mu^+\mu^-$	± 19		± 40	
$H \rightarrow \text{invisible}$	< 0.3		< 0.6	

- FCC-ee has similar results as CEPC but including a 365 GeV run improving the measurement of Higgs width.

Higgs related physics at 360 GeV (generic study)



- ❖ With the NNLO calculation, the highest X-section is at the energy of 381.3 GeV
- ❖ Considering the Lumi-suppression factor when going to higher energy, the effective highest X-section is around 365 GeV.
- ❖ The effective X-section from 360 GeV is not much different from that of 365 GeV.
- ❖ If we choose higher order correction, the peak could be even lower than 360 GeV.
- ❖ For 2 ab^{-1} data, it will take 4-5 years with optimized setup of the accelerator.



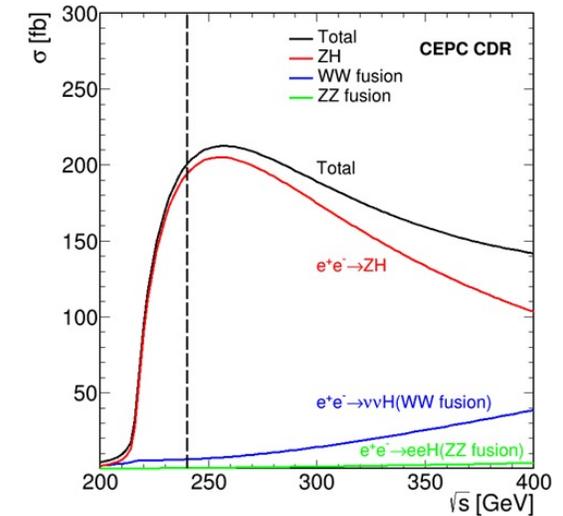
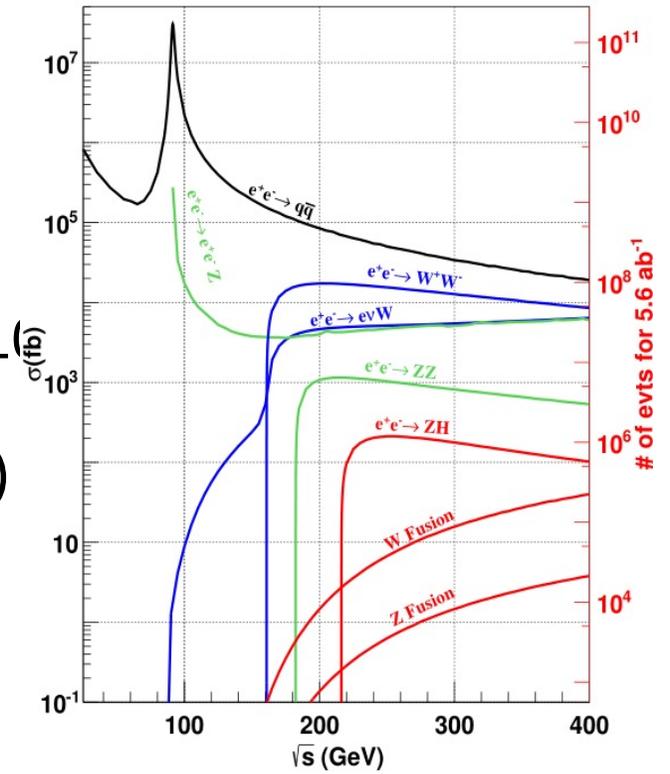
Signal/bkg Cross Sections

Kaili Zhang

- 240GeV:
 - ZH: 196.9; vvH: 6.2; interference: ~10% of vvH; about 318:1
- 360GeV: (vvH ~ 117% Z->vv), (eeH ~ 67% Z->ee)

fb	240	350	360	365	360/240
ZH	196.9	133.3	126.6	123.0	-36%
WW fusion	6.2	26.7	29.61	31.1	+377%
ZZ fusion	0.5	2.55	2.80	2.91	+460%
Total	203.6		159.0		
Total Events	1.14M		0.32M		

In total ~1.5M Higgs would be collected in CEPC 240+360.
More fusion events, also eeH can not be ignored in 360GeV.



Results and systematics for $H \rightarrow bb, cc, gg$

Combination of the 4 channels:

Statistic precision of $\sigma(ZH) \times \text{Br}(H \rightarrow bb/cc/gg)$ is 0.3% 3.3% and 1.3%

**Consistent with the goal expected
in pre-CDR with full simulation samples**

Decay mode	$\sigma(ZH) \times \text{BR}$	BR
$H \rightarrow b\bar{b}$	0.28%	0.57%
$H \rightarrow c\bar{c}$	2.2%	2.3%
$H \rightarrow gg$	1.6%	1.7%

IIH with 3D fit and systematic uncertainties considered:

Table 2. Uncertainties of $H \rightarrow b\bar{b}$, $H \rightarrow c\bar{c}$ and $H \rightarrow gg$

	$\mu^+ \mu^- H$			$e^+ e^- H$		
	$H \rightarrow b\bar{b}$	$H \rightarrow c\bar{c}$	$H \rightarrow gg$	$H \rightarrow b\bar{b}$	$H \rightarrow c\bar{c}$	$H \rightarrow gg$
Statistic Uncertainty	1.1%	10.5%	5.4%	1.6%	14.7%	10.5%
Fixed Background	-0.2%	+4.1%	7.6%	-0.2%	+4.1%	7.6%
	+0.1%	-4.2%		+0.1%	-4.2%	
Event Selection	+0.7%	+0.4%	+0.7%	+0.7%	+0.4%	+0.7%
	-0.2%	-1.1%	-1.7%	-0.2%	-1.1%	-1.7%
Flavor Tagging	-0.4%	+3.7%	+0.2%	-0.4%	+3.7%	+0.2%
	+0.2%	-5.0%	-0.7%	+0.2%	-5.0%	-0.7%
Non uniformity	< 0.1%			< 0.1%		
Combined Systematic Uncertainty	+0.7%	+5.5%	+7.6%	+0.7%	+5.5%	+7.6%
	-0.5%	-6.6%	-7.8%	-0.5%	-6.6%	-7.8%

**Analysis with more reliable
approaches. Systematic
uncertainties considered.**

Theory model

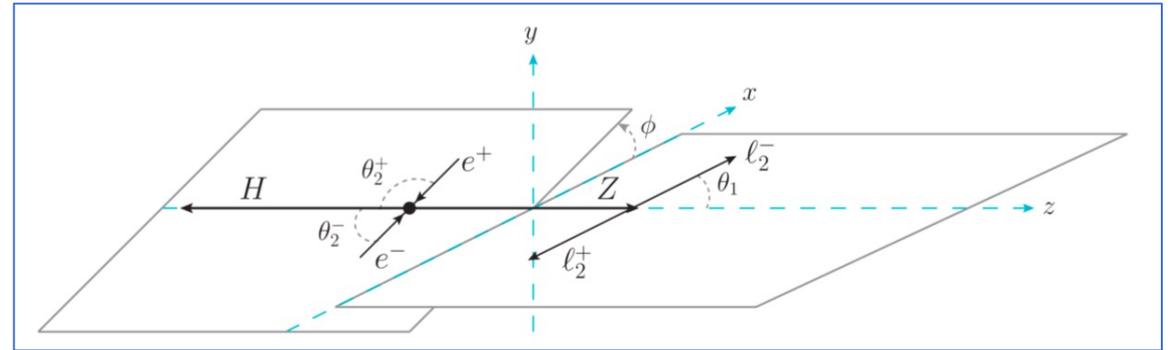
[JHEP 03\(2016\) 050](#)

[JHEP 11\(2014\) 028](#)

- Differential cross section for $ee \rightarrow ZH \rightarrow llH$:

$$\frac{d\sigma}{d\cos\theta_1 d\cos\theta_2 d\phi} = \frac{\mathcal{N}_\sigma(q^2)}{m_H^2} \mathcal{J}(q^2, \theta_1, \theta_2, \phi),$$

$$\mathcal{N}_\sigma(q^2) = \frac{1}{2^{10}(2\pi)^3} \cdot \frac{1}{\sqrt{r}\gamma_Z} \cdot \frac{\sqrt{\lambda(1,s,r)}}{s^2}$$



$$\begin{aligned} \mathcal{J}(q^2, \theta_1, \theta_2, \phi) = & J_1(1 + \cos^2 \theta_1 \cos^2 \theta_2 + \cos^2 \theta_1 + \cos^2 \theta_2) \\ & + J_2 \sin^2 \theta_1 \sin^2 \theta_2 + J_3 \cos \theta_1 \cos \theta_2 \\ & + (J_4 \sin \theta_1 \sin \theta_2 + J_5 \sin 2\theta_1 \sin 2\theta_2) \sin \phi \\ & + (J_6 \sin \theta_1 \sin \theta_2 + J_7 \sin 2\theta_1 \sin 2\theta_2) \cos \phi \\ & + J_8 \sin^2 \theta_1 \sin^2 \theta_2 \sin 2\phi + J_9 \sin^2 \theta_1 \sin^2 \theta_2 \cos 2\phi. \end{aligned}$$

Variables for studying distribution: θ_1, θ_2, ϕ

Efficiency matrix determined by DL multi-classification

$$\begin{pmatrix} n_1 \\ n_2 \\ \vdots \\ n_9 \end{pmatrix} = \begin{pmatrix} \epsilon_{11} & \epsilon_{12} & \cdots & \epsilon_{19} \\ \epsilon_{21} & \epsilon_{22} & \cdots & \epsilon_{29} \\ \vdots & \vdots & \ddots & \vdots \\ \epsilon_{91} & \epsilon_{92} & \cdots & \epsilon_{99} \end{pmatrix} \begin{pmatrix} N_1 \\ N_2 \\ \vdots \\ N_9 \end{pmatrix}$$

“on-shop” measurement
more efficient, better precision