Higgs precision physics @ CEPC

Kaili Zhang

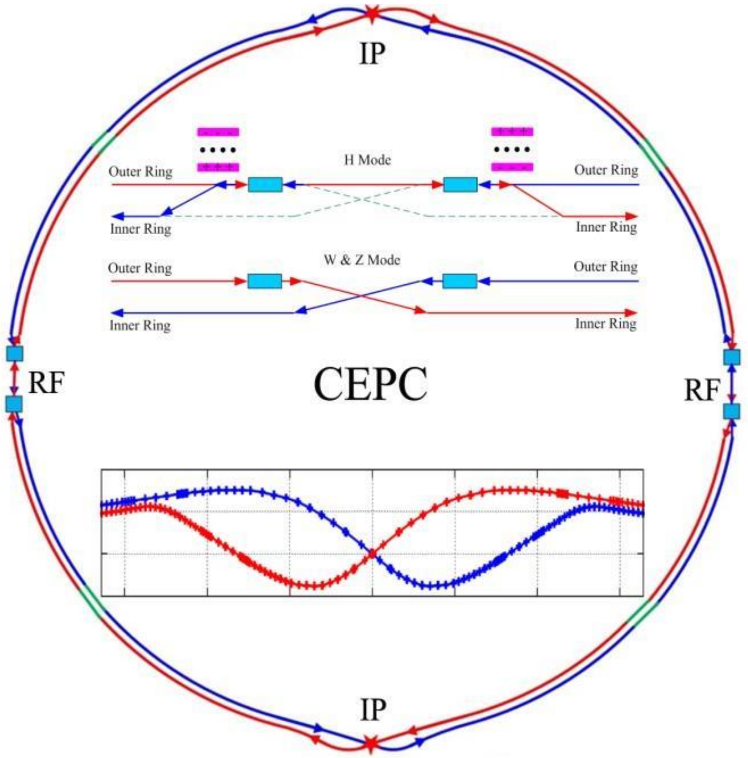
IHEP

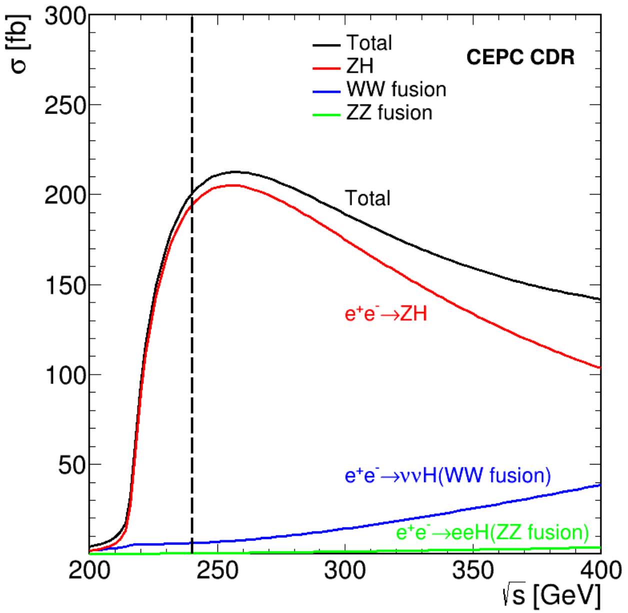
The 2023 international workshop on the high energy Circular Electron Positron Collider

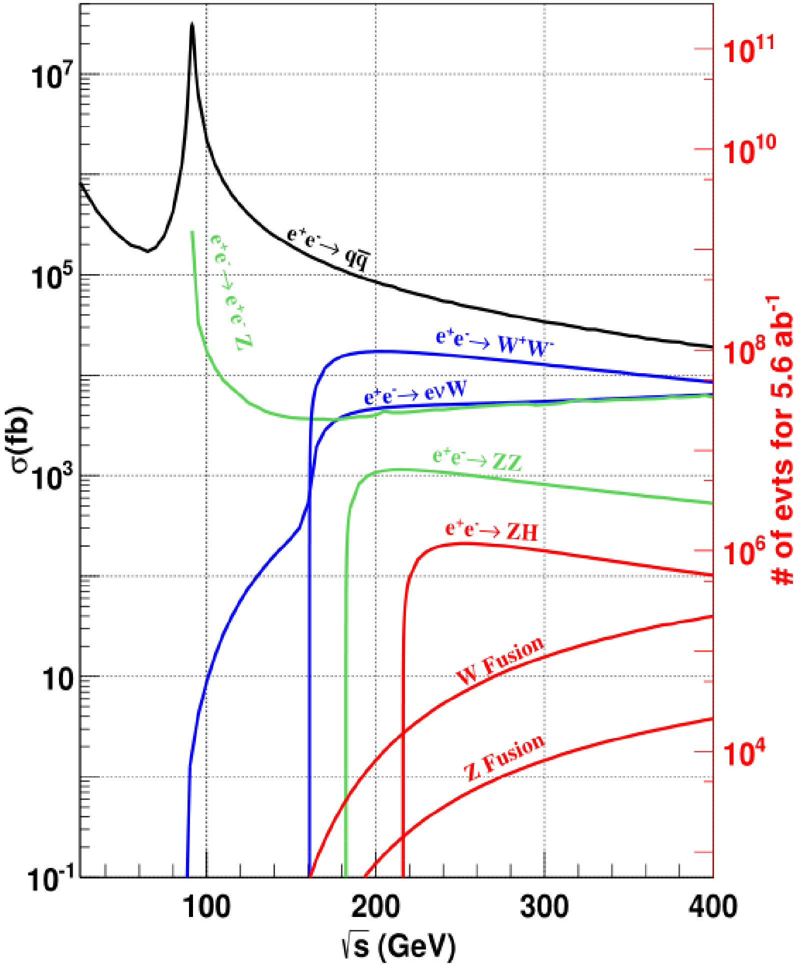
Oct. 23rd, 2023

Higgs@CEPC

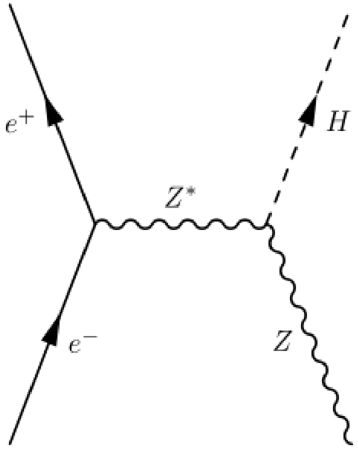
100km tunnel;
20iab data in 240GeV, 1iab in 360GeV.

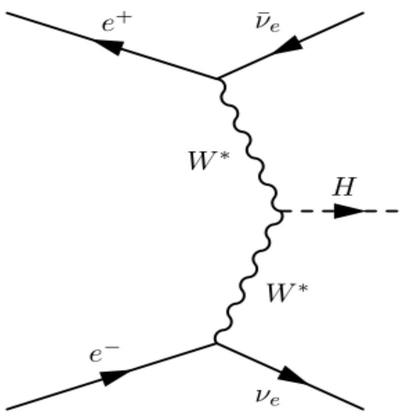






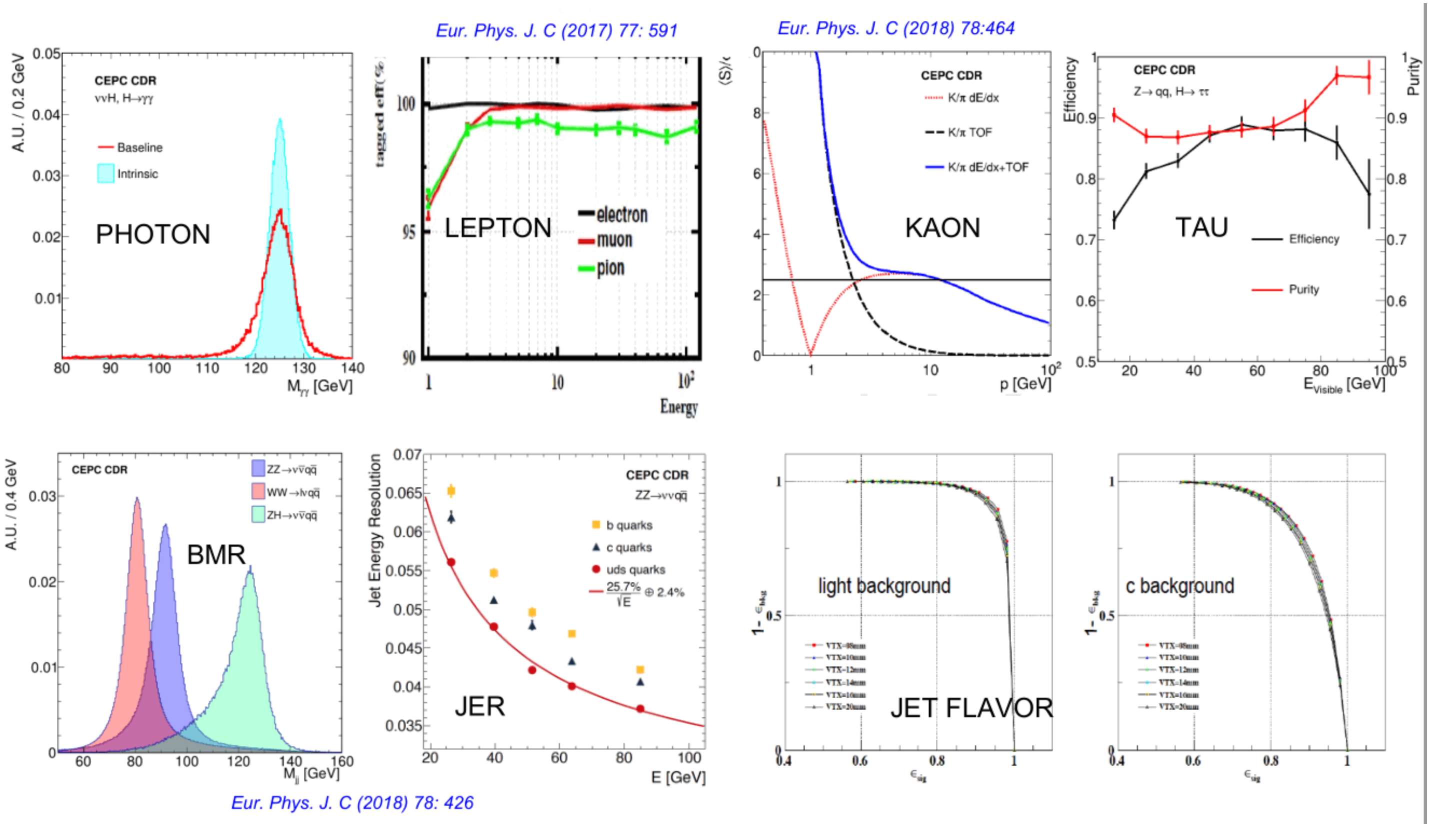
CEPC CDR: [arXiv:1811.10545]
White Paper: [arXiv:1810.09037]
CEPC Snowmass Report:
[arXiv:2205.08553]





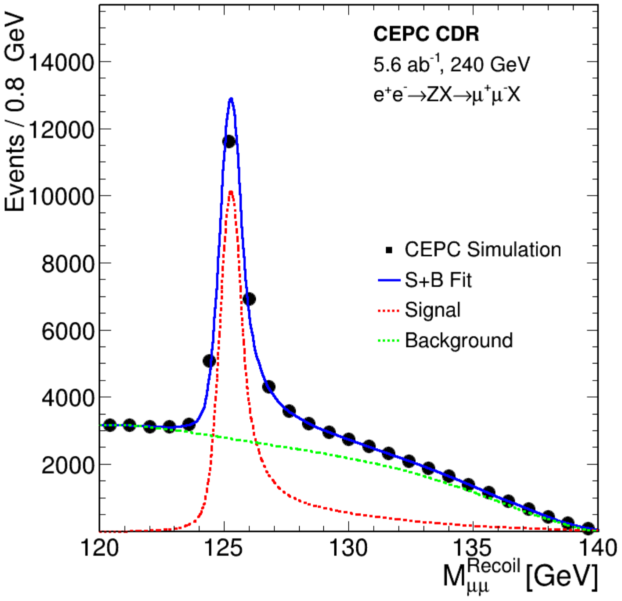
CEPC (evolving) object performance

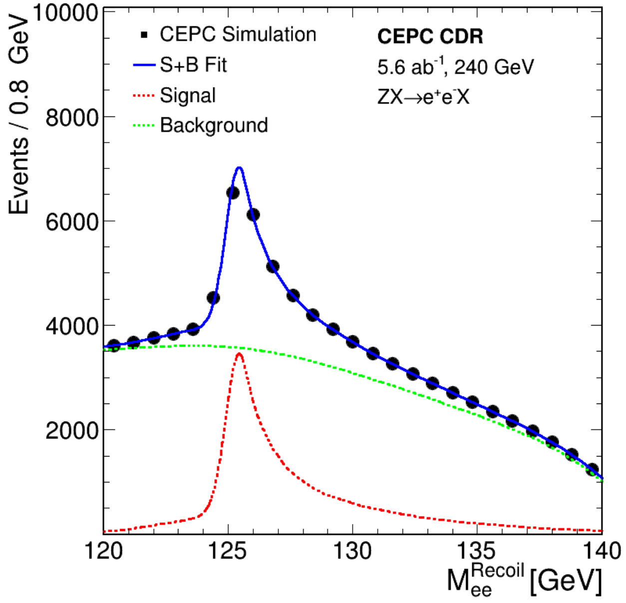
With certain detector parameter and certain reconstruction algorithm, CEPC Higgs measurements are predictable.
Reconstruction overview: arXiv:1806.04879

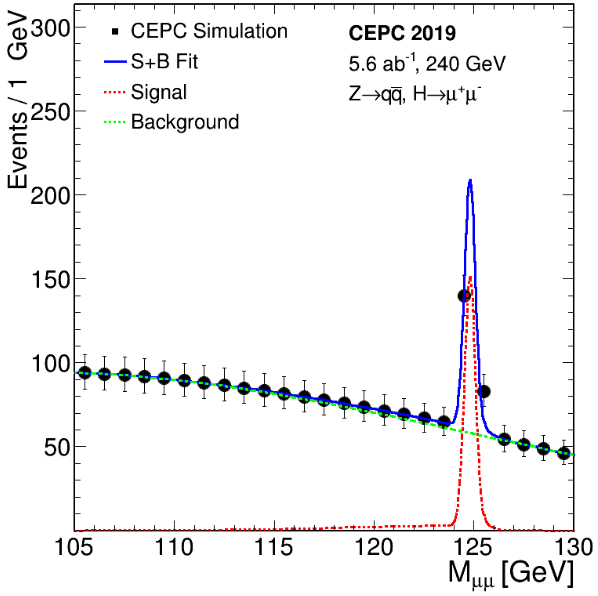


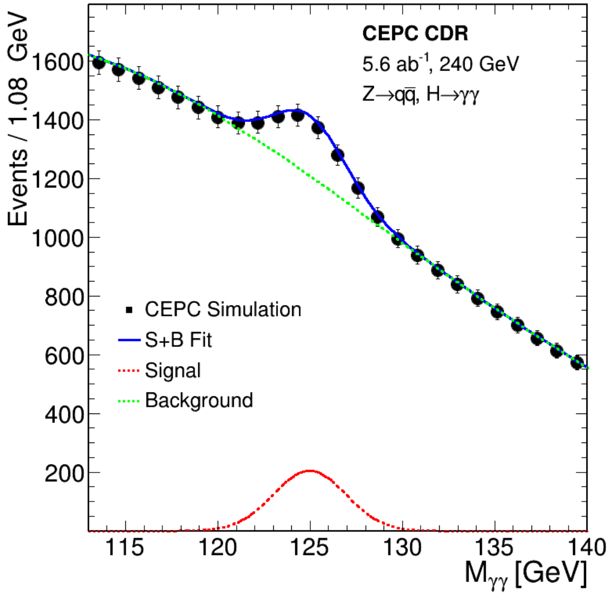
New results:
Jet: arXiv:2104.05029
Track: arXiv:2209.00397
dE/dx: arXiv:2209.14486
Cluster time: arXiv:2209.02932

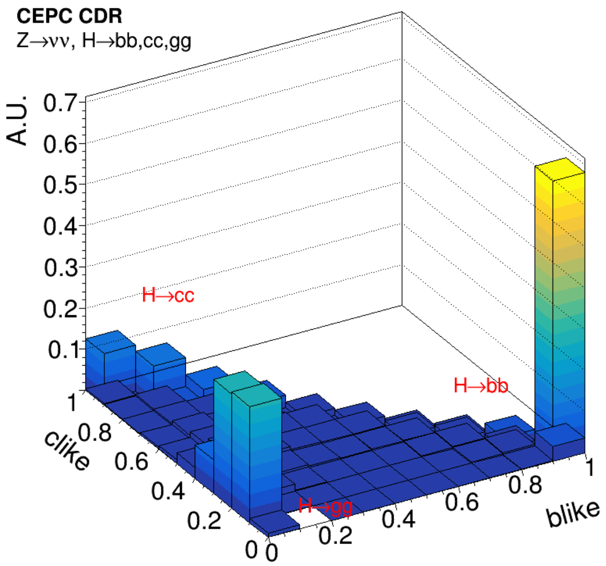
Individual sub channels

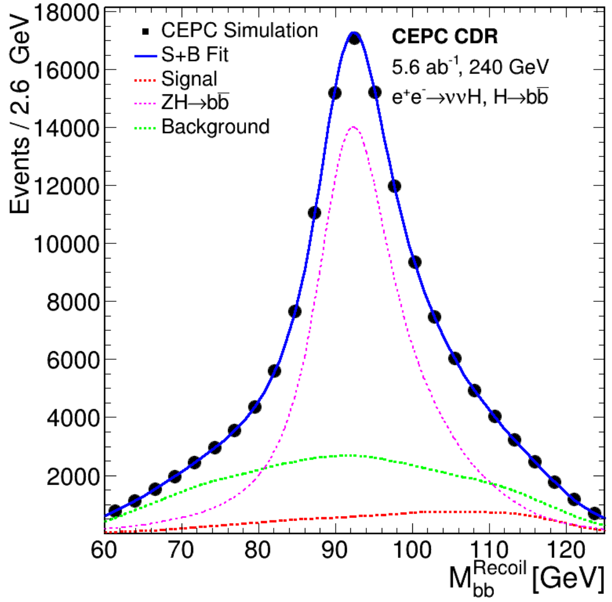


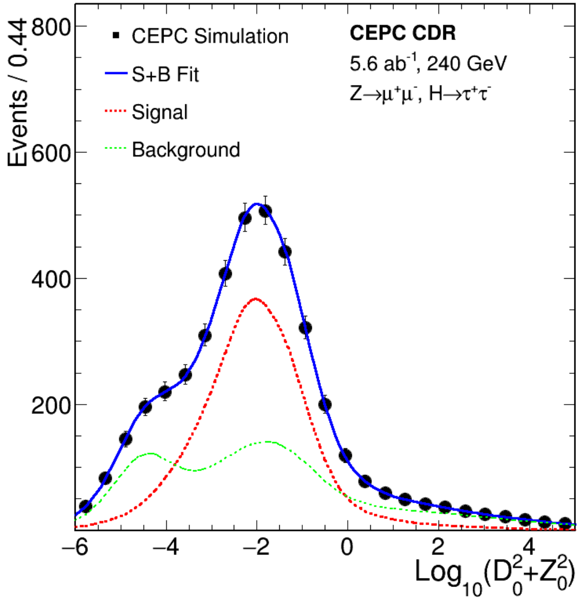








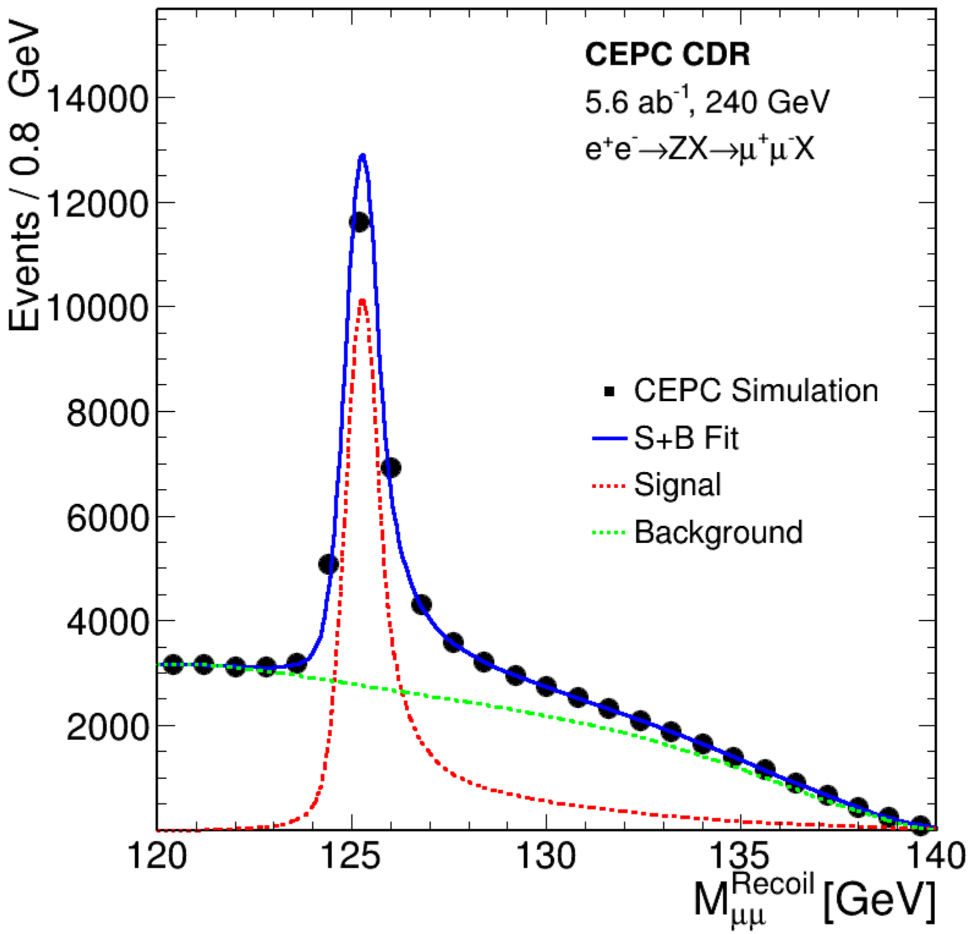


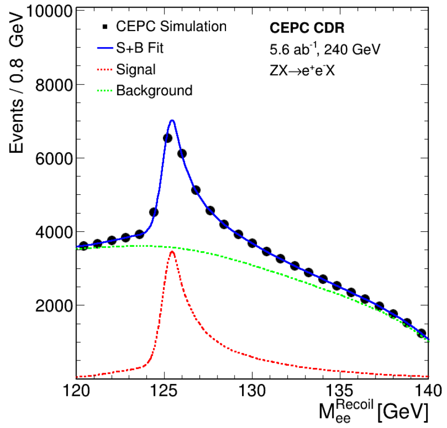


All these results are based in 2018 CEPC-v4 layout, ECM=240GeV and total statistics 5.6iab.

$\sigma(ZH)$: $H \rightarrow$ inclusive

- Possible by tagging Higgs with recoil mass
- Zhenxing: arXiv:1601.05352
  - Z → ee, 1.4%; Z→$\mu\mu$, 0.9%;
    - model independently
  - Z→ qq: 0.65%, by Janice
    - extrapolated from 1404.3164
  - Combined: 0.5%

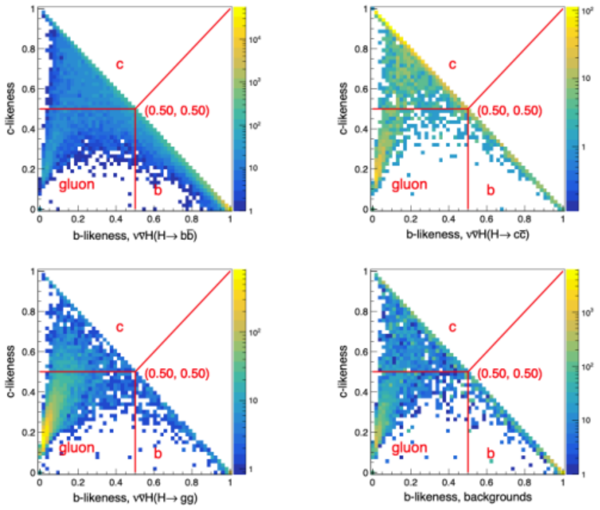


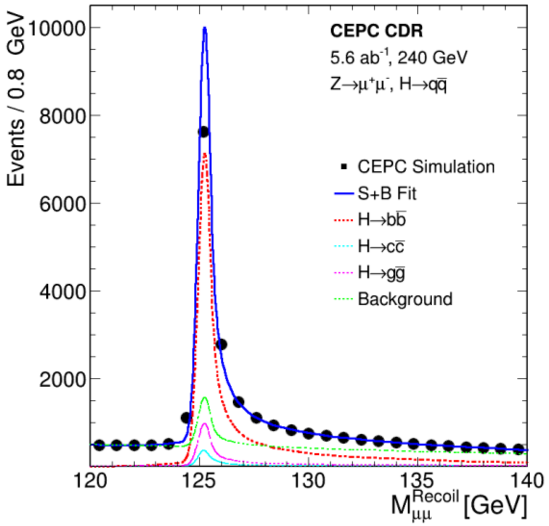


bb, cc, gg

vvH, qqH by Yongfeng Zhu, arXiv:2203.01469
eeH, mmH by Yu Bai, arXiv:1905.12903

- vvH, qqH used jet b-c likeness 2-d template fit
  - No direct truth information used in the analysis.
- eeH, mmH + recoil mass, 3-d fit
- Brief systematics, dependence on detector performance studied;





- New studies:

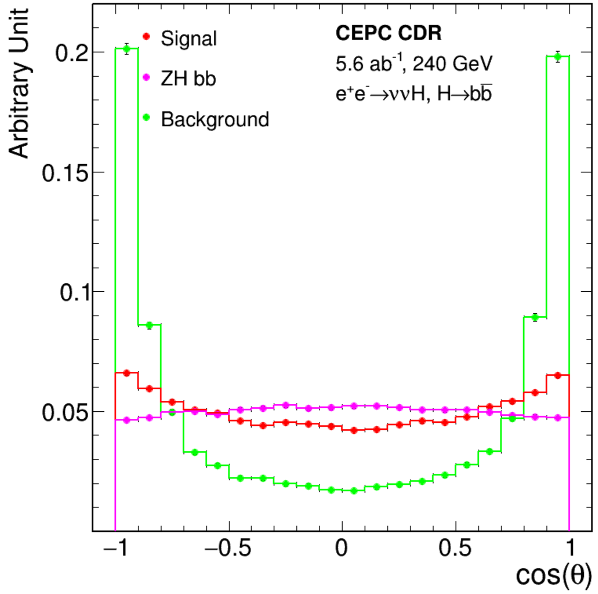
ParticleNet on Flavor tagging 2309.13231

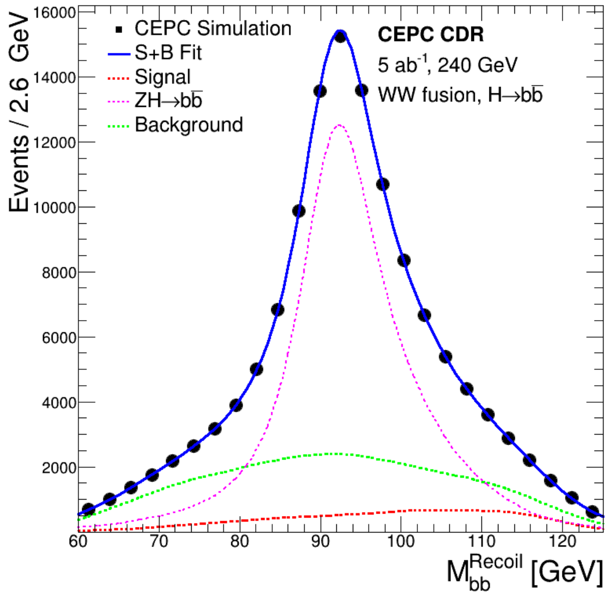
Rare decay like ss, dd, uu 2310.03440

Z decay mode	$H\to b\bar{b}$	$H\to c\bar{c}$	$H\to gg$
$Z\to e^+e^-$	1.57%	14.43%	10.31%
$Z\to \mu^+\mu^-$	1.06%	10.16%	5.23%
$Z\to q\bar{q}$	0.35%	7.74%	3.96%
$Z\to \nu\bar{\nu}$	0.49%	5.35%	1.77%
combination	0.27%	4.03%	1.56%

$\nu\nu H \rightarrow bb$

- Crucial channel for Higgs width
- 2d fit M_{jj}^{reco} & Cos θ_{jj}
- $\nu\nu H \rightarrow bb$ and $ZH \rightarrow bb$
  - Interference ~10% of vvH. (generally, 60: 1 : 10)
    - CEPC add the interference term to vvH side currently;
  - $\nu\nu H \rightarrow bb$ and $ZH \rightarrow bb$ share the anti-correlation -45%. (-34% in ILC(1708.08912))
- $\sigma(\nu\nu H) * Br(H \rightarrow bb)$: 3.0% ;





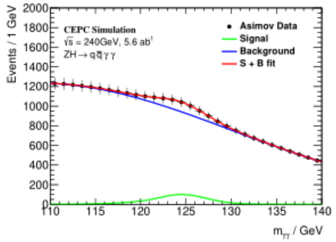
- if fix ZH process, Initial $\nu\nu H \rightarrow bb$ uncertainty is 2.8%.
- if float ZH process, $\nu\nu H \rightarrow bb$ would be 3.4%.
- Need use other ZH processes to constrain ZH.

$H \to \gamma\gamma$

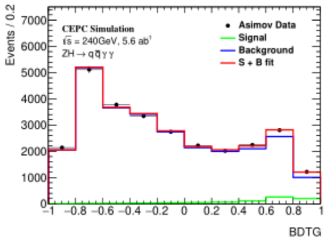
arXiv:2205.13269 by Fangyi Guo;
Previous studied by Feng Wang, Yitian Sun;

Diphoton heavily rely on Ecal performance;

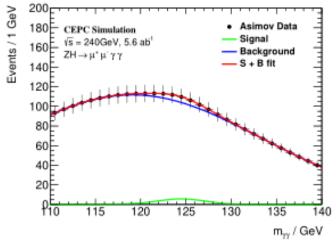
- BDT+mass 2d fit;



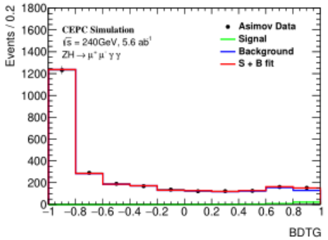
(a) $q\bar{q}\gamma\gamma$ $m_{\gamma\gamma}$ model



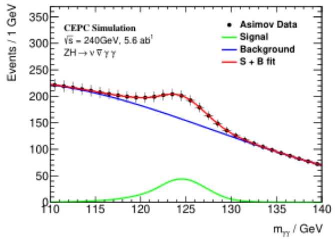
(b) $q\bar{q}\gamma\gamma$ BDT model



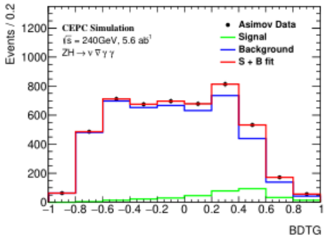
(c) $\mu^+\mu^-\gamma\gamma$ $m_{\gamma\gamma}$ model



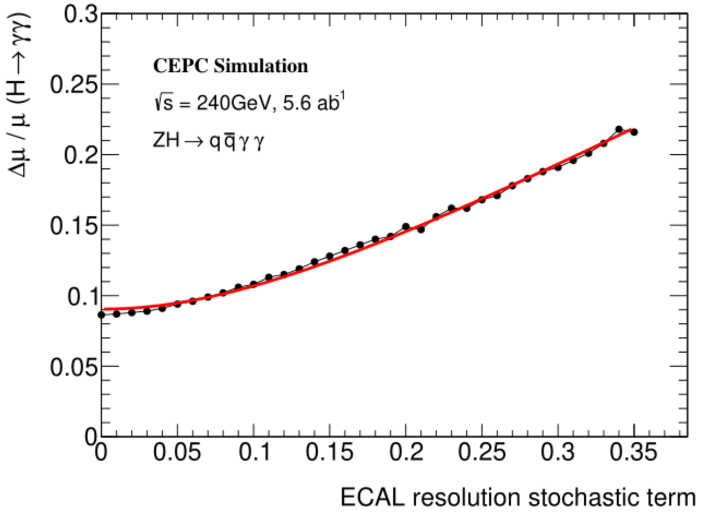
(d) $\mu^+\mu^-\gamma\gamma$ BDT model



(e) $\nu\bar{\nu}\gamma\gamma$ $m_{\gamma\gamma}$ model



(f) $\nu\bar{\nu}\gamma\gamma$ BDT model

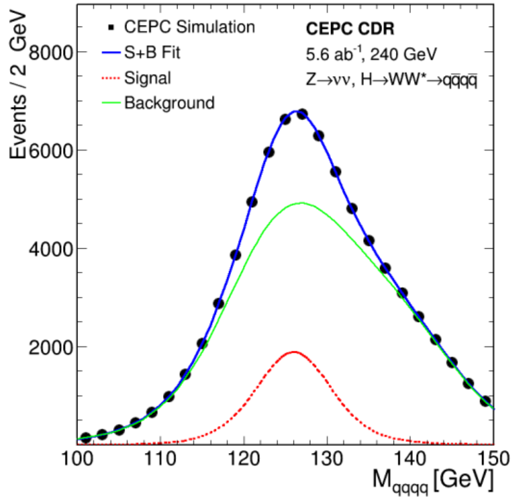


Channel	μ @ 5.6 ab^{-1}	μ @ 20 ab^{-1}
$q\bar{q}\gamma\gamma$	1.00 ± 0.0879	1.00 ± 0.0465
$\mu^+\mu^-\gamma\gamma$	1.00 ± 0.3571	1.00 ± 0.1920
$\nu\bar{\nu}\gamma\gamma$	1.00 ± 0.1142	1.00 ± 0.0605
Combined	1.00 ± 0.0688	1.00 ± 0.0364

H → WW, ZZ

CEPC use LCFIplus for Jet clustering;
See jet separation in 10.1140/epjc/s10052-019-6719-2 and arXiv:1812.09478

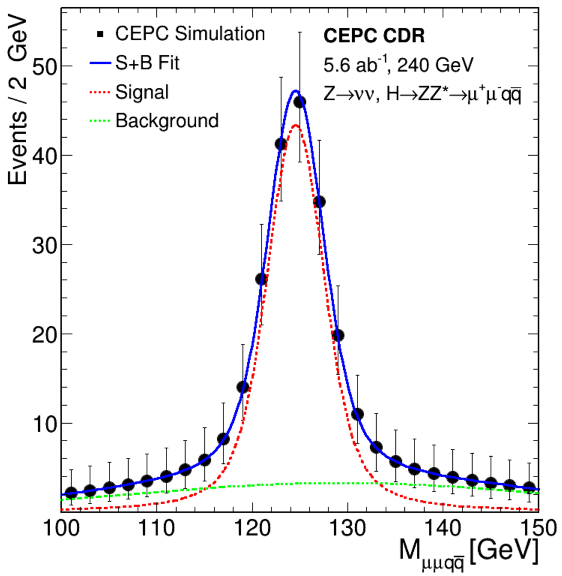
- Leptonic, semi-leptonic WW by Libo Liao;
- Hadronic WW by Mila Pandurovic;
- ZZ by Ryuta Kiuchi, Yanxi Gu and Min Zhong. arXiv:2103.09633



	Z	ee	μμ	νν	qq
WW	eν+eν				
	μν+μν				
	eν+μν				
	eν+qq				
	μν+qq				
	qq+qq				

Signal		Precision
Z	H	
H->WW		
ee	lvlv	9.2%
	evqq	4.6%
	μvqq	3.9%
μμ	lvlv	7.3%
	evqq	4.0%
	μvqq	4.0%
vv	qqqq	2.0%
	evqq	4.7%
	μvqq	4.2%
	lvlv	11.3%
qq	lvqq	2.2%(ILC)
ZH bkg contribution		3.0%

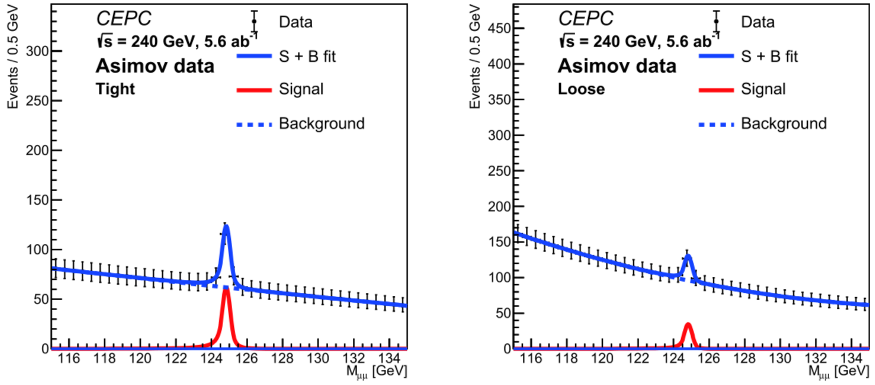
Category	$\frac{\Delta(\sigma\cdot BR)}{(\sigma\cdot BR)}$ [%] cut-based	BDT
$\mu\mu H\nu\nu qq^{cut/mva}$	15	14
$\mu\mu Hqq\nu\nu^{cut/mva}$	48	42
$\nu\nu H\mu\mu qq^{cut/mva}$	12	12
$\nu\nu Hqq\mu\mu^{cut/mva}$	23	20
$qqH\nu\nu\mu\mu^{cut/mva}$	45	37
$qqH\mu\mu\nu\nu^{cut/mva}$	52	44
Combined	8.3	7.9



Both WW ZZ can obtain improvements from full hadronic bb/cc/gg ZH backgrounds.

H → $\mu\mu$ and $\tau\tau$

- $\mu\mu$ by Qi Liu, Kunlin Ran *CPC* **46** 093001
- Previous studied by Zhenwei Cui;
- BDT+mass fit, based in 3T magnet;



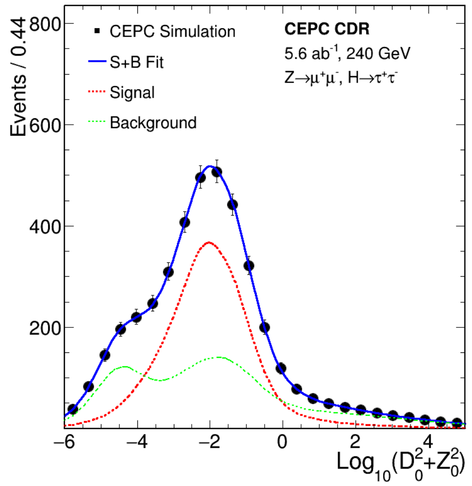
(a) Tight (b) Loose

Table 3. Expected signal strength μ, significance, and reduction in significance with the resolution of the muon momentum smeared by 25%, 50%, and 100%.

Smearing	25%	50%	100%
μ	$1.00^{+0.21}_{-0.20}$	$1.00^{+0.22}_{-0.21}$	$1.00^{+0.25}_{-0.24}$
Significance	5.5σ	5.1σ	4.4σ
Reduction in significance	10%	16%	28%

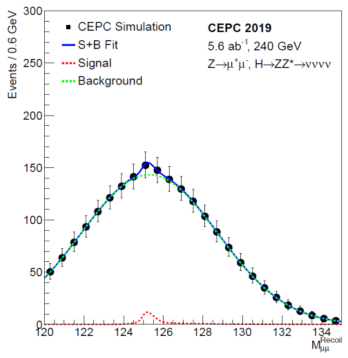
- $\tau\tau$, by Dan Yu arXiv:1903.12327
- Develop LICH to identify lepton, Eff>99%
- Use $\log_{10}(D_0^2 + Z_0^2)$ + mass 2d fit to separate signal from WW
  - Impact parameter, Distance from beam spot

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%

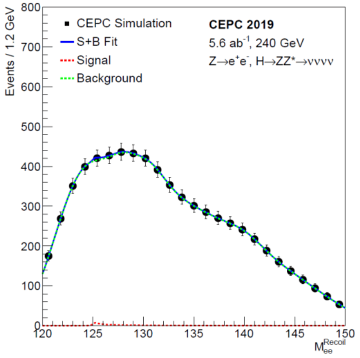


H →invisible and $Z\gamma$

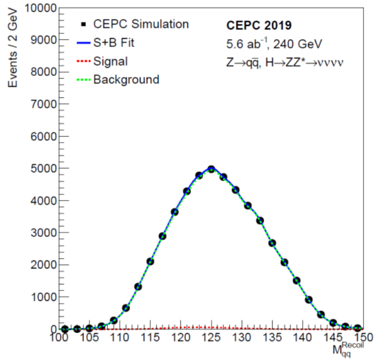
Invisible, arXiv:2001.05912 by Yuhang Tan;
Previous studied by Xin Mo;



ZH(Z->$\mu^+\mu^-$,H->invisible)



ZH(Z->e^+e^-,H->invisible)

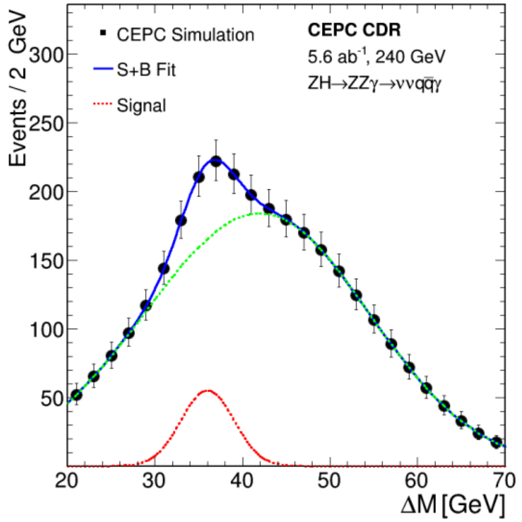


ZH(Z->qq,H->invisible)

ZH final state studied	Relative precision on $\sigma(ZH)\times$BR	Upper limit on BR (H→inv.)
Z→ e^+e^-, H→inv.	403%	0.96%
Z→ $\mu^+\mu^-$, H→inv.	98%	0.31%
Z→ $q\bar{q}$, H→inv.	85%	0.29%
Combination	63%	0.24%

In SM, H →invisible refers
$H \to ZZ \to \nu\nu\nu\nu$, 0.106%.
For BSM contribution, limit set to 0.13%.

- H → $Z\gamma$, by Wei-Ming Yao;
- Br 0.154%;



- $\Delta M(M_{qq\gamma} - M_{qq}, or\ M_{\nu\nu\gamma} - M_{\nu\nu})$ shown.
- Sensitivity 16%.

Existing results:240GeV, 5.6iab

(240GeV,5.6ab^{-1})	CDR	2023.10
$\sigma(ZH)$	**0.50%**	
$\sigma(ZH) * \mathrm{Br}(\mathrm{H} \rightarrow \mathrm{bb})$	**0.27%**	**0.27%**
$\sigma(ZH) * \mathrm{Br}(\mathrm{H} \rightarrow \mathrm{cc})$	**3.3%**	**4.0%**
$\sigma(ZH) * \mathrm{Br}(\mathrm{H} \rightarrow \mathrm{gg})$	**1.3%**	**1.5%**
$\sigma(ZH) * \mathrm{Br}(\mathrm{H} \rightarrow \mathrm{WW})$	**1.0%**	
$\sigma(ZH) * \mathrm{Br}(\mathrm{H} \rightarrow \mathrm{ZZ})$	**5.1%**	**7.9%**
$\sigma(ZH) * \mathrm{Br}(\mathrm{H} \rightarrow \tau\tau)$	**0.8%**	
$\sigma(ZH) * \mathrm{Br}(\mathrm{H} \rightarrow \gamma\gamma)$	**6.8%**	
$\sigma(ZH) * \mathrm{Br}(\mathrm{H} \rightarrow \mu\mu)$	**17%**	**18%**
$\sigma(\mathrm{vv}H) * \mathrm{Br}(\mathrm{H} \rightarrow \mathrm{bb})$	**3.0%**	
$\mathrm{Br}_{\mathrm{upper}}(\mathrm{H} \rightarrow \mathrm{inv.})$	**0.41%**	**0.24%**
$\sigma(ZH) * \mathrm{Br}(\mathrm{H} \rightarrow Z\gamma)$	**16%**	
Width	**2.8%**	

See previous slides for related publications.
Changes mostly from better analysis strategy.

All existing results are based in (240 GeV,5.6ab^{-1}).

Now with the scenario upgrade published in Snowmass 2022, the new run will based in (240 GeV 20ab^{-1} + 360 GeV 1ab^{-1}).

7 years 240 GeV
->
10 years 240 GeV + 5 years 360 GeV.

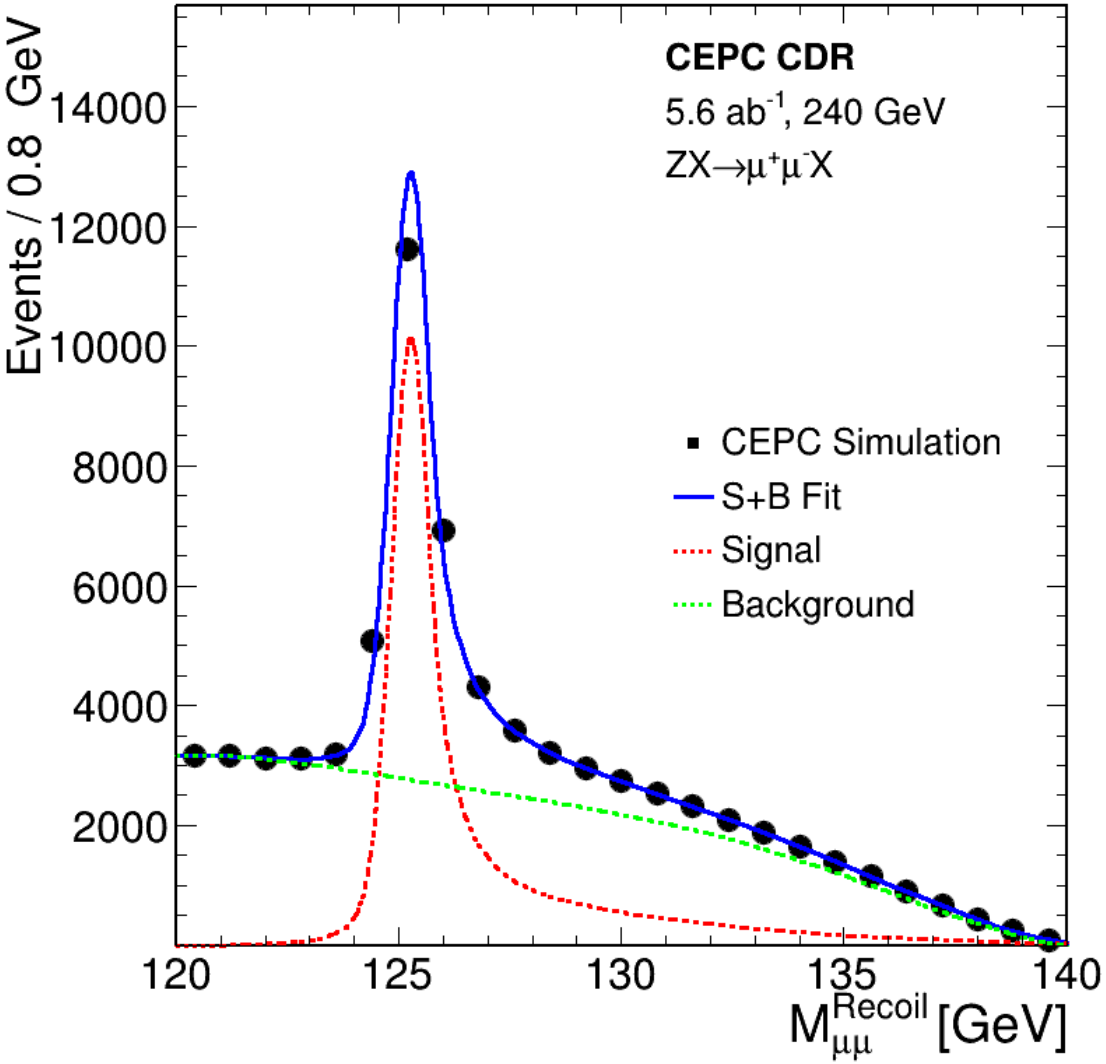
360GeV: Higher Energy Run

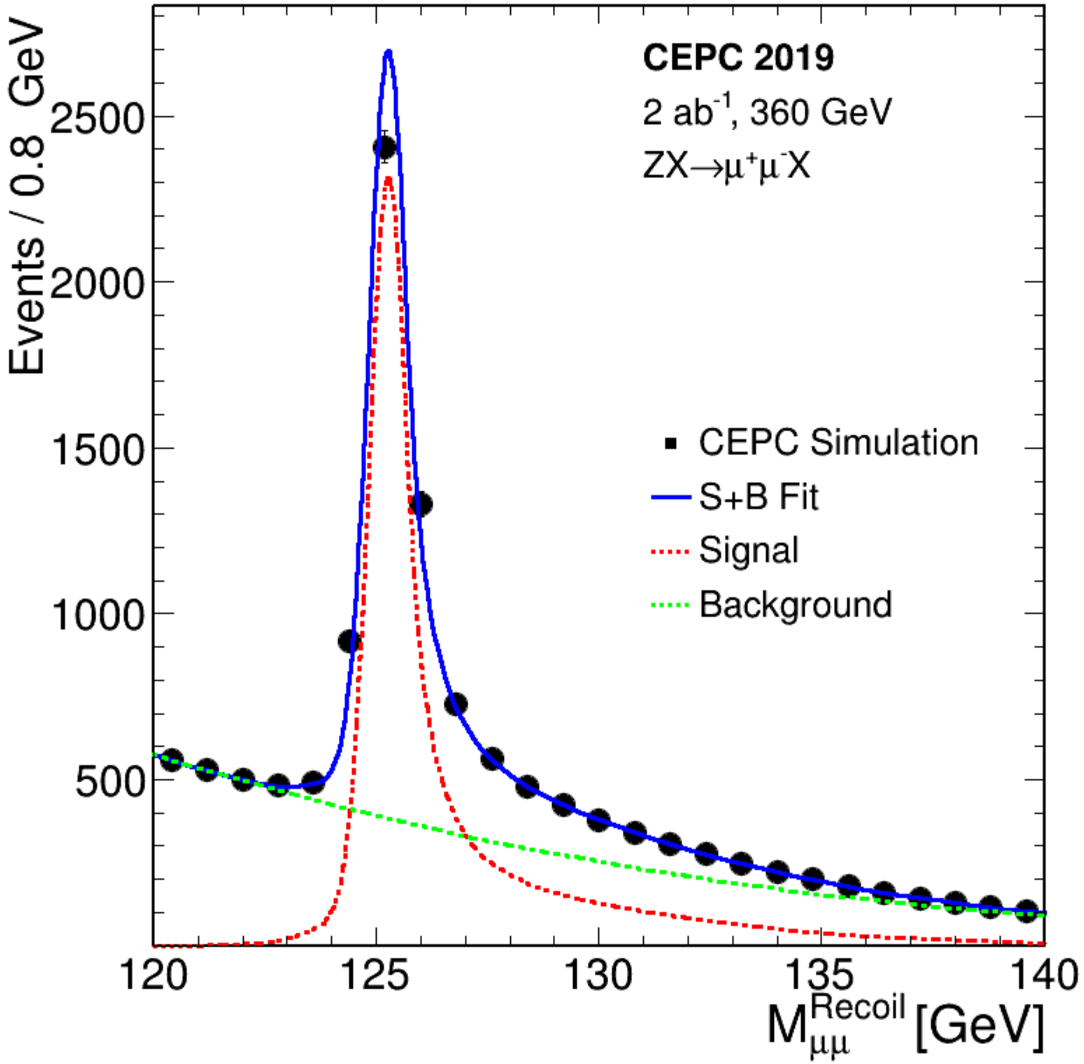
- 350~365GeV $t\bar{t}$ Run:
  - For Higgs: Larger vvH cross section; Benefit width measurement
  - More advantages for EW/Theoretical part;
- Current benchmark: 1ab^{-1} @ 360GeV
  - 360GeV saves 10% energy with respect to 365 GeV
  - Plan to use 5 years to collect 1iab data.
- $t\bar{t}$ threshold scan plan
  - See Zhan's report for top mass scan measurement.

Plan from Fcc-ee:
0.2ab^{-1} 350GeV Scan + 1.5ab^{-1} 365GeV

Extrapolations

Ideal model independent inclusive $Z \to \mu\mu$: $0.92\% \to 1.72\%$

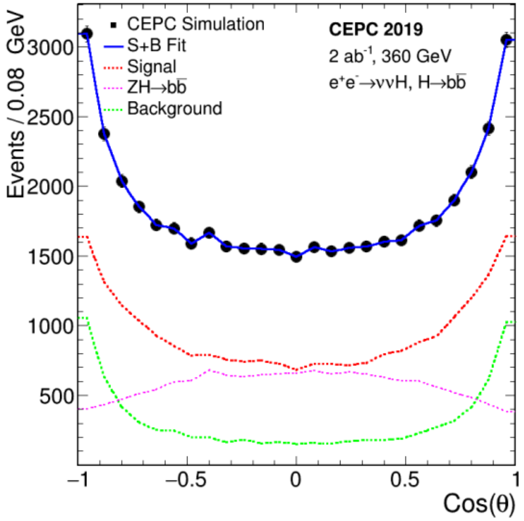


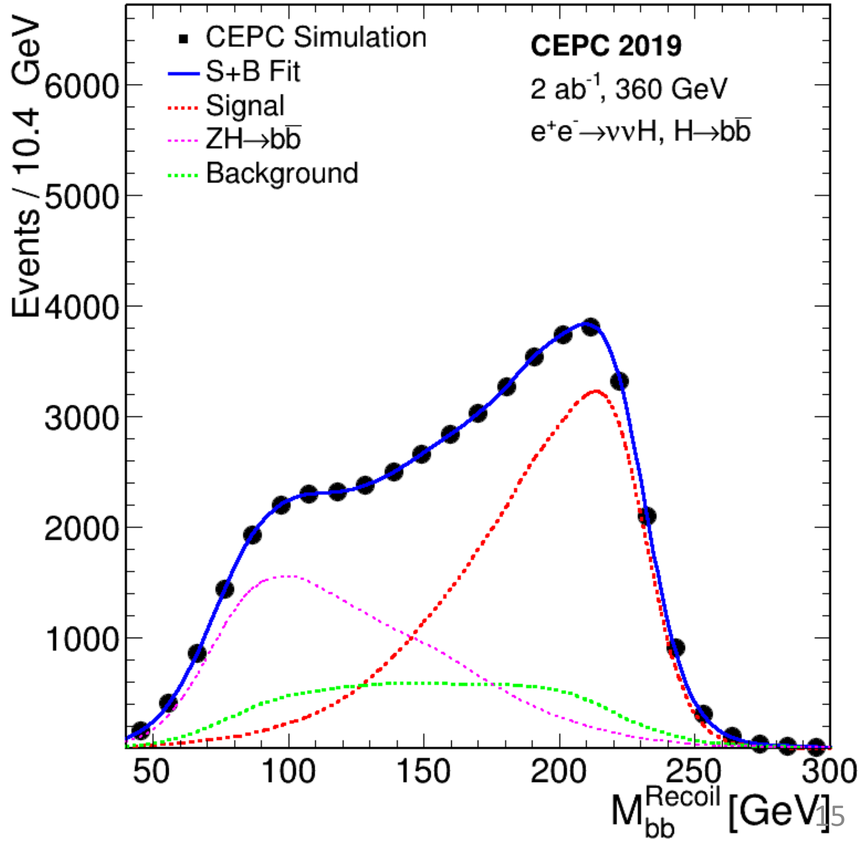


vvH->bb : 360 GeV, full sim

- Clear separation between ZH and vvH.
- Constrain from other ZH->bb($ee, \mu\mu, qq$) considered.
- In current 1iab,
  - $\sigma(\mathrm{vv}H) * \mathrm{Br}(\mathrm{H} \rightarrow \mathrm{bb})$: 1.10%
  - $\sigma(\mathrm{Z}H) * \mathrm{Br}(\mathrm{H} \rightarrow \mathrm{bb})$: 0.90%
  - share the anti-correlation -15.8%.

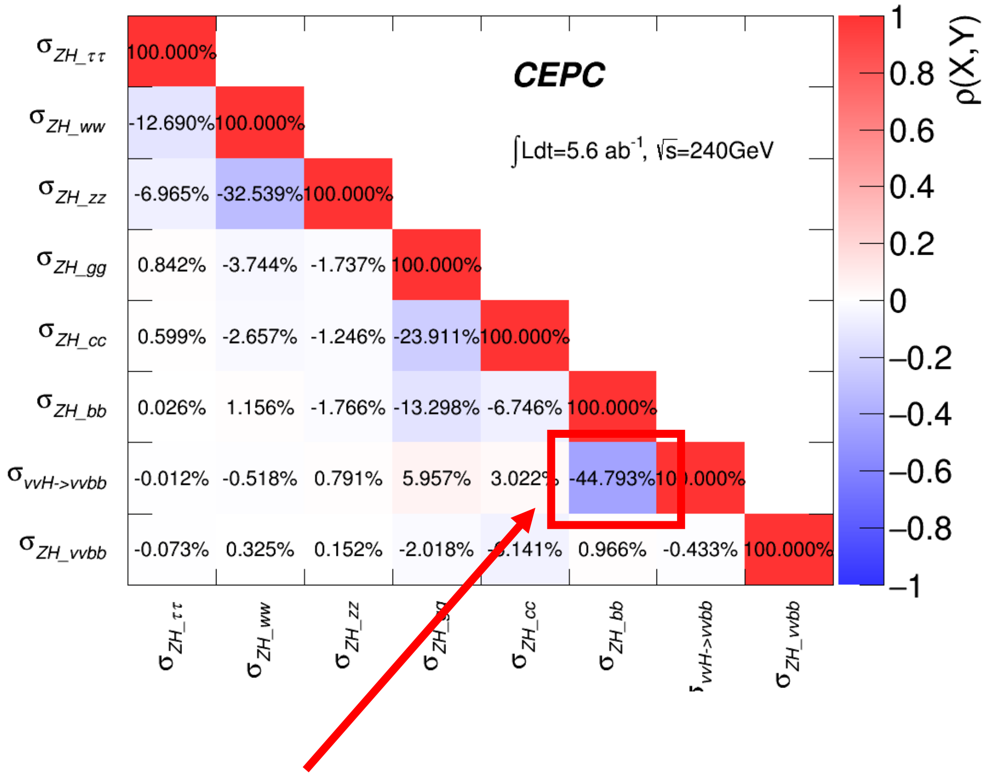
This measurement gives very excellent constrain for Higgs width.





Combination Framework

- Easy for extrapolation
- Multiple observables for workspace
  - Mass spectrum, BDT output, Flavor tagging likeness
  - Apply multi dimensional fit if possible
- Input correlation considered
  - σ∗Br + Correlation Matrix = Complete Input.
  - Anti-correlation from measurement;
  - Major form: Higgs yields overlap
  - Cannot be ignored for some crucial channel, like vvH & ZH, H->bb



Results in Snowmass: 2205.08553

	240 GeV, 20 ab^{-1}		360 GeV, 1 ab^{-1}		
	ZH	**vvH**	ZH	**vvH**	**eeH**
any	**0.26%**		**1.40%**	\	\
H→bb	**0.14%**	**1.59%**	**0.90%**	**1.10%**	**4.30%**
H→cc	**2.02%**		**8.80%**	**16%**	**20%**
H→gg	**0.81%**		**3.40%**	**4.50%**	**12%**
H→WW	**0.53%**		**2.80%**	**4.40%**	**6.50%**
H→ZZ	**4.17%**		**20%**	**21%**	
$H \to \tau\tau$	**0.42%**		**2.10%**	**4.20%**	**7.50%**
$H \to \gamma\gamma$	**3.02%**		**11%**	**16%**	
$H \to \mu\mu$	**6.36%**		**41%**	**57%**	
$Br_{upper}(H \to inv.)$	**0.07%**		\	\	
$H \to Z\gamma$	**8.50%**		**35%**	\	
Width	**1.65%**		**1.10%**		

Fcc:

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

Generally, CEPC and Fcc-ee results are comparable in Higgs precision measurement.
For Higgs coupling, also similar performance could be expected.

Couplings: κ framework

- Higgs coupling defined as:

$$\kappa_Z^2 = \frac{g(HZZ)}{g_{SM}(HZZ)} = \frac{\sigma(ZH)}{\sigma_{SM}(ZH)} \qquad \text{->0.5\%;}$$

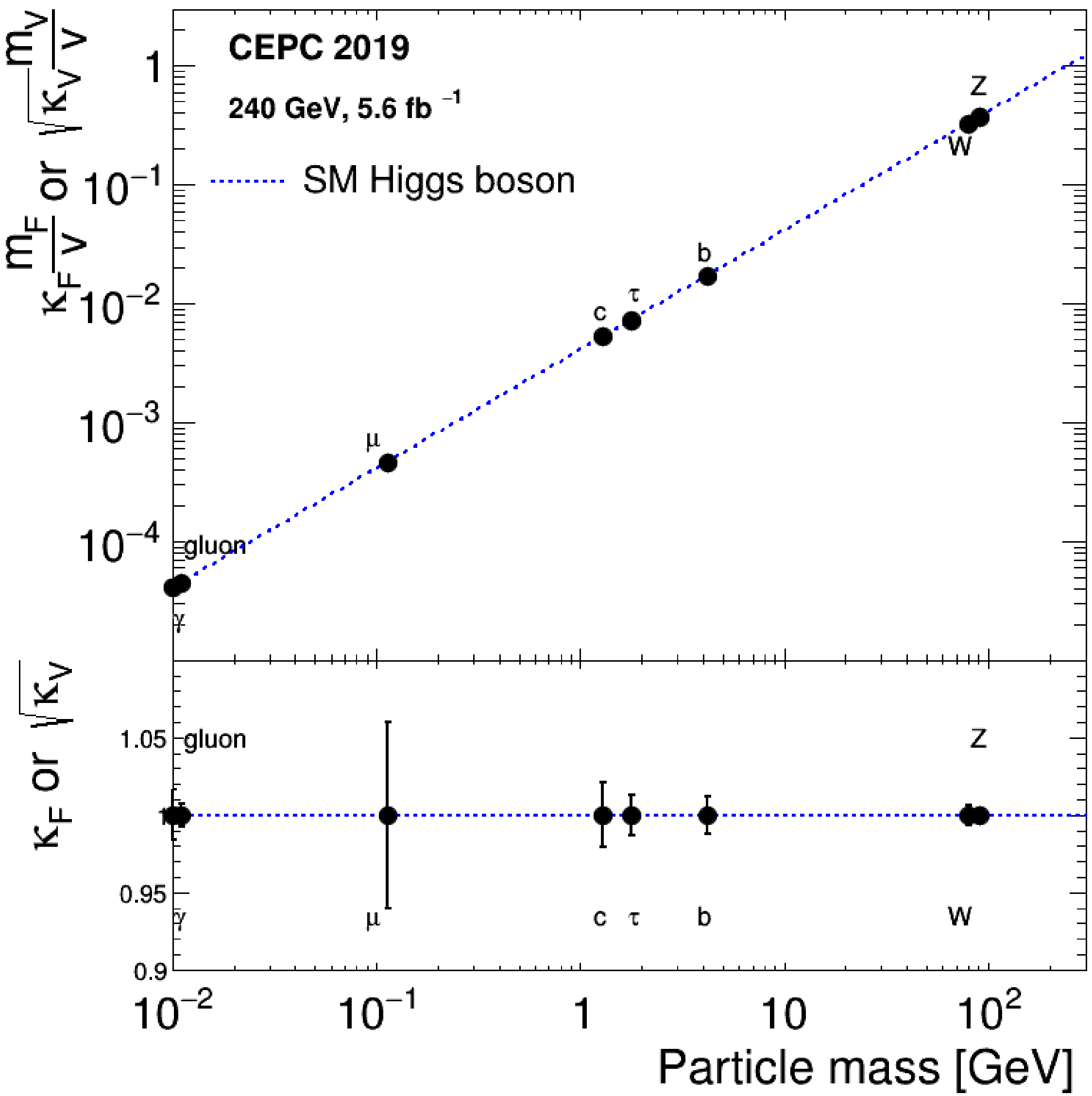
$$\sigma(\nu\nu H) * \mathrm{Br}(\mathrm{H} \to \mathrm{bb}) \propto \frac{\kappa_\mathrm{W}^2 * \kappa_\mathrm{b}^2}{\Gamma_H}.$$

We expect excellent κ_Z measurement from $\sigma(ZH)$,

and all other channel suffered from Higgs width.

Extract width with branch ratio: Constrained 7-κ

Keep width independent: 10 κ



Higgs width

Results not sensitive to the statistics for 360GeV run
For Higgs, we do not need too much 360GeV events;
But we do need it for the independent constrain.

- CEPC Higgs width is fitted in the 10κ framework.
- Adding one mass point would significantly improve the constrain.
  - Standalone 240GeV 20ab^{-1} gives 1.65%, while 360GeV 1ab^{-1} alone gives 3.65%.
  - These 2 points are independent.
  - Combined χ^2 fit gives:

For the constrained-Γ_H fit, the outcome of this analysis is similar to that presented in Ref. [25], with the exception of the CEPC results where one observes the expected improvement in the sensitivity to Higgs couplings derived from the increase in the luminosity at 240 GeV, together with the addition of the new set of measurements that would be possible at 360 GeV. The sensitivity to the aTGC via the optimal

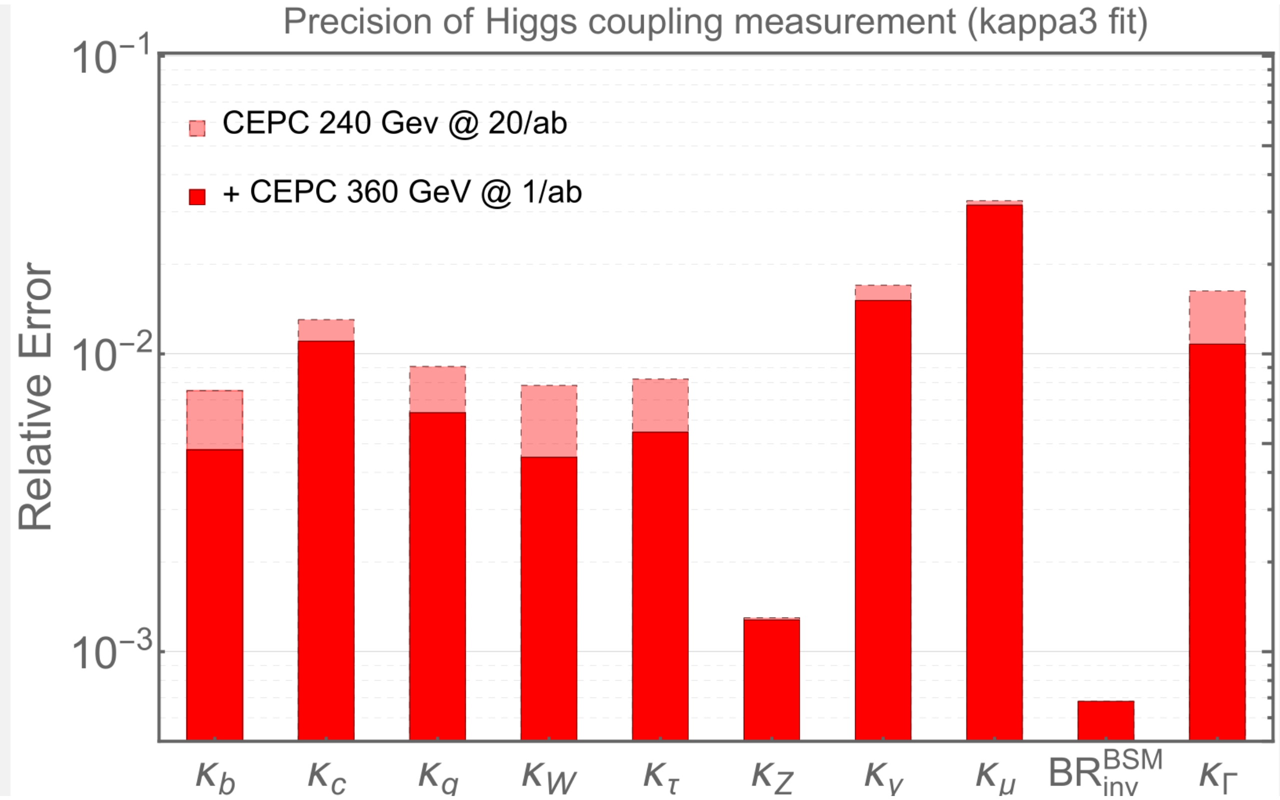
$$\Delta(\Gamma_H) \approx 1.10\%$$

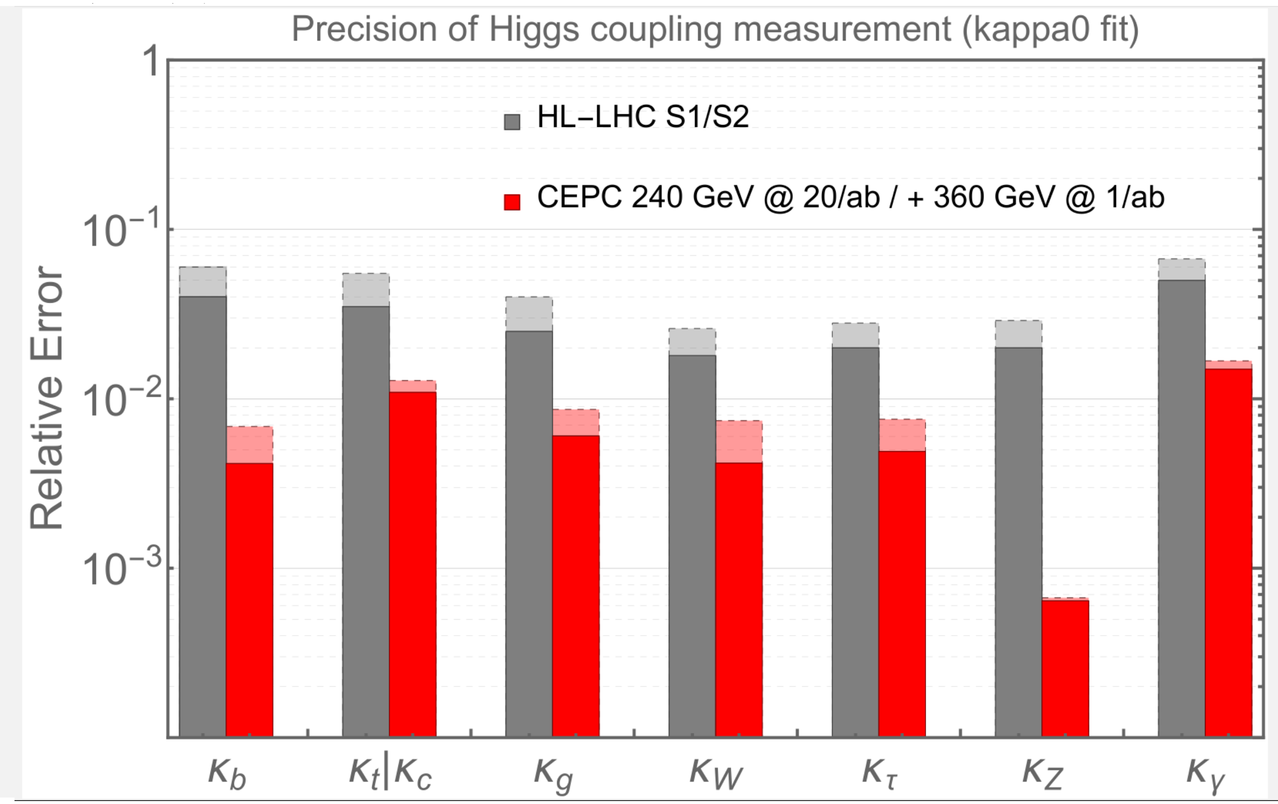
As width in everywhere, width helps all kappas even better.

*: Here we do not have the assumption about the exotic decay. This treatment is different with Fcc-ee, which believes exotic Br can not be less than 0. If we take this assumption, the model-dependent width precision would be even better.

κ : CEPC latest

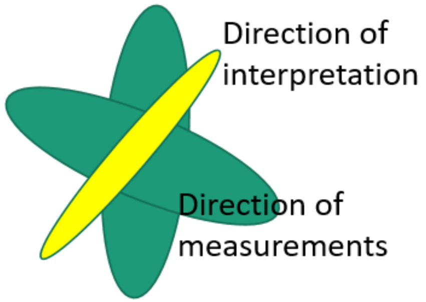
- Compared to HL-LHC, lepton colliders 1-2 order better in Higgs coupling.
- Adding 360GeV will signifantly improve κ results.





For kappa0 and kappa3 fit and the comparison among future colliders, see [de Blas, J. *et al.* arXiv:1905.03764]

Correlation Matrix



Input

+ Interpretation

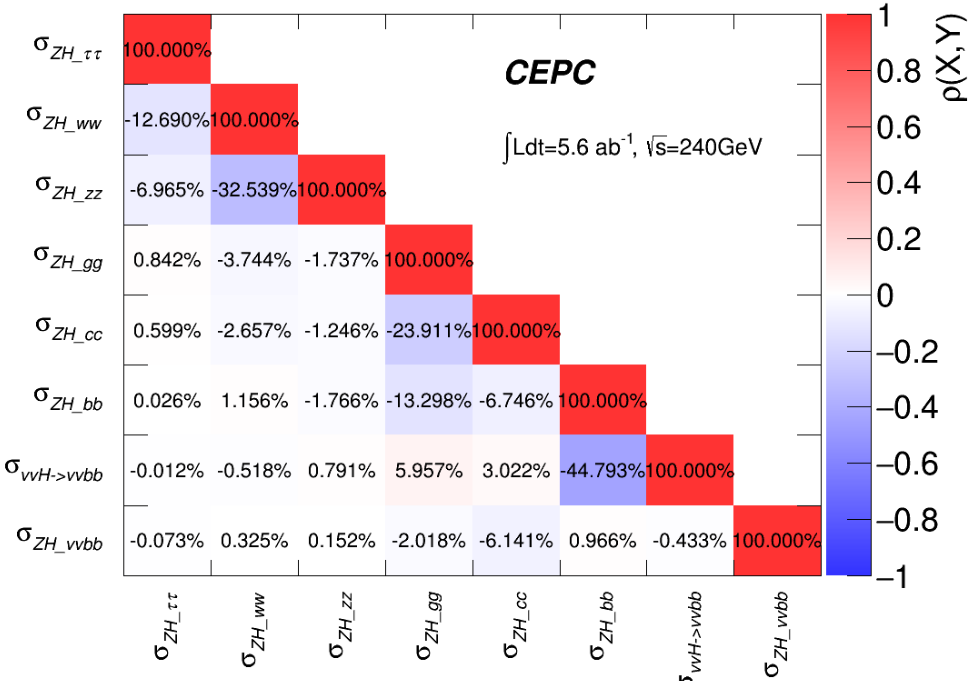
Measurements → Couplings

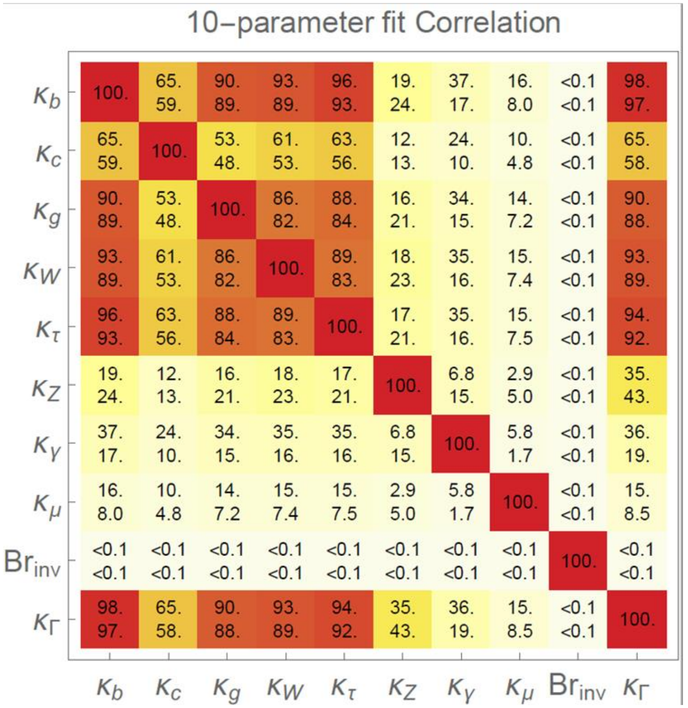
Anti-correlated

Output

Coupled by width

2nd correlation differentials

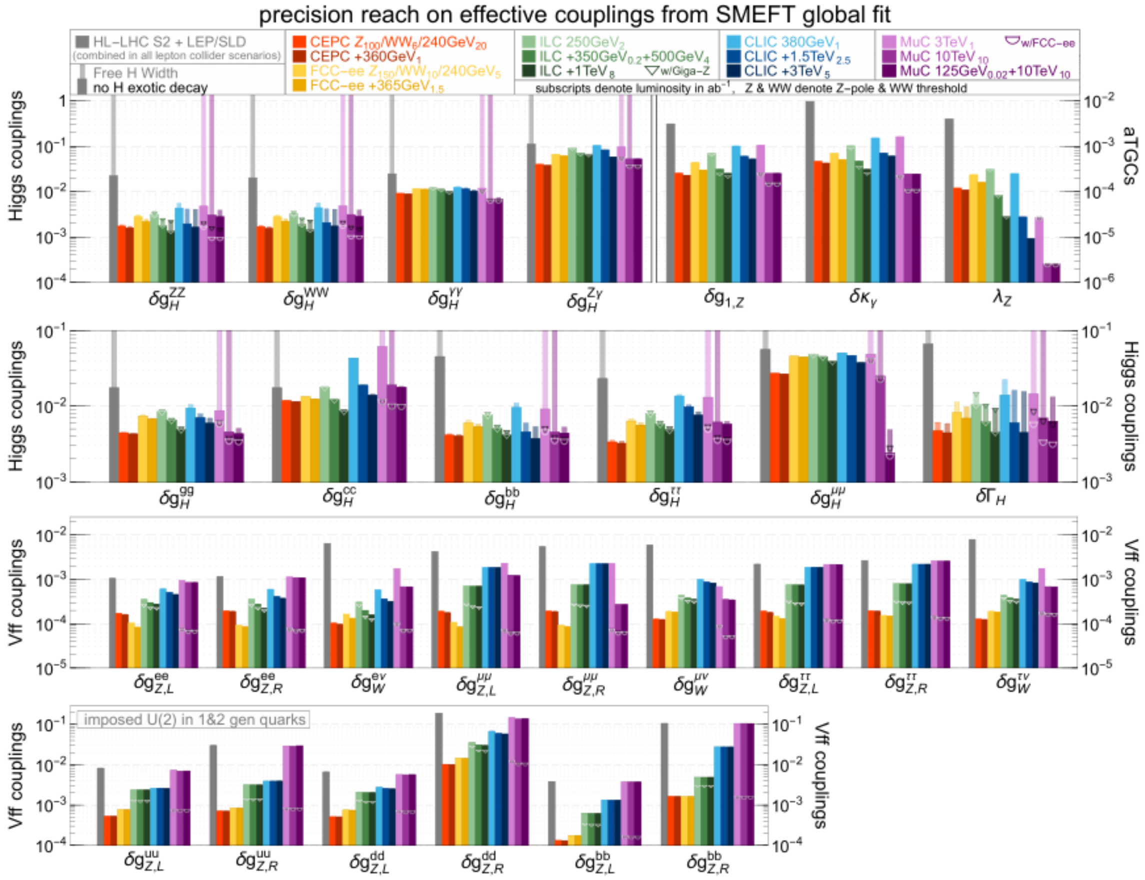




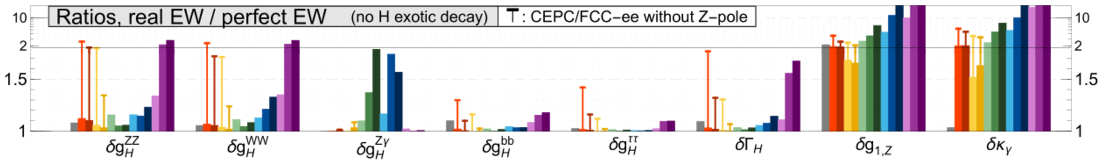
Upper entries: CEPC alone;
Lower entries: combining with HL-LHC (get reduced);

Global fit synergy with other experiments

- [de Blas, J. *et al.* arXiv:2206.08326]
  - Also kappa and EFT results are shown between CEPC240, CEPC360, HL-LHC, Fcc, ILC……



More theory interpretations can be found reports from Jiayin and QingHong.

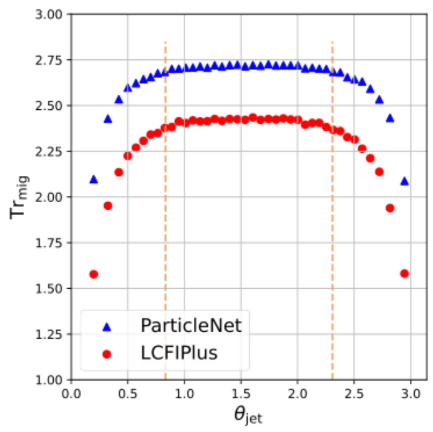


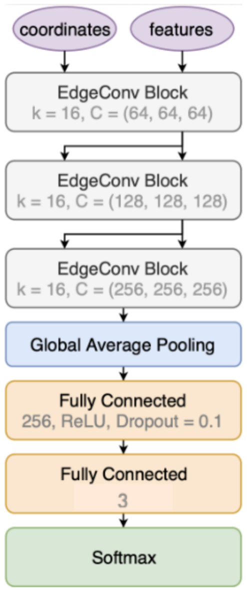
Scenario	BR_{inv}	BR_{unt}	include HL-LHC
kappa-0	fixed at 0	fixed at 0	no
kappa-1	measured	fixed at 0	no
kappa-2	measured	measured	no
kappa-3	measured	measured	yes

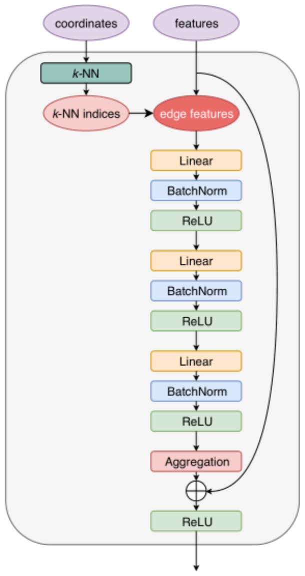
$$\Gamma_H = \frac{\Gamma_H^{SM} \cdot \kappa_H^2}{1 - (BR_{inv} + BR_{unt})}$$

Evolving Combination

- Significant progress from Accelerator, Detector, and Object performance in the past and now
- Global optimization to handle the correlations
- Careful systematic estimation required by precise result ($H \rightarrow bb$ 0.14%)
- Far from the CEPC ultimate potential. 4M Higgs!







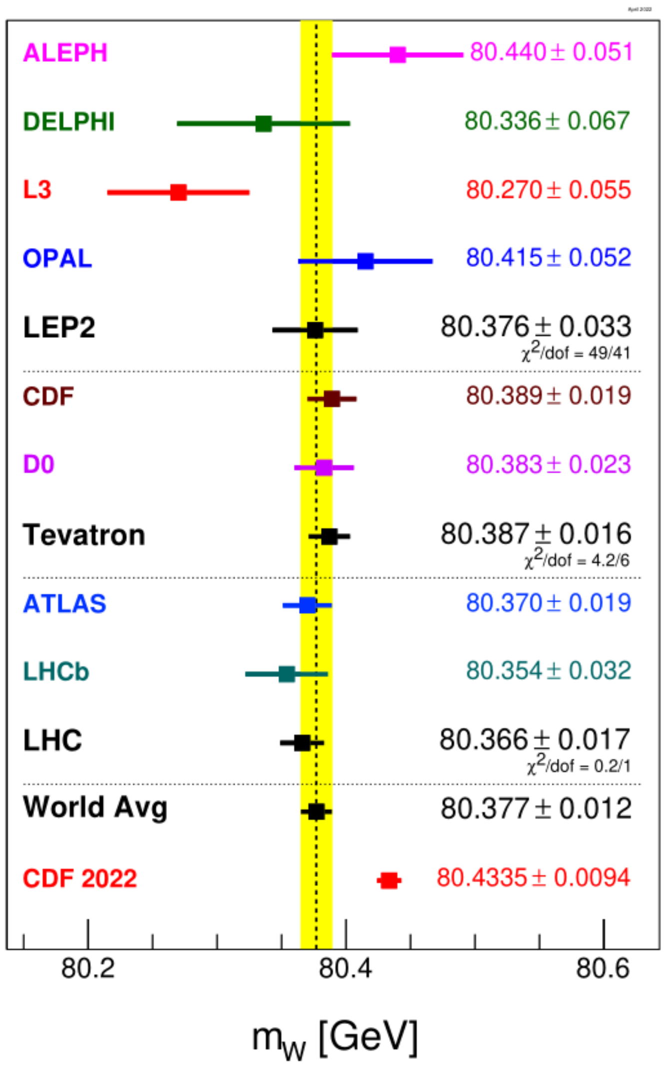
Significant improvement from new tool like ParticleNet.

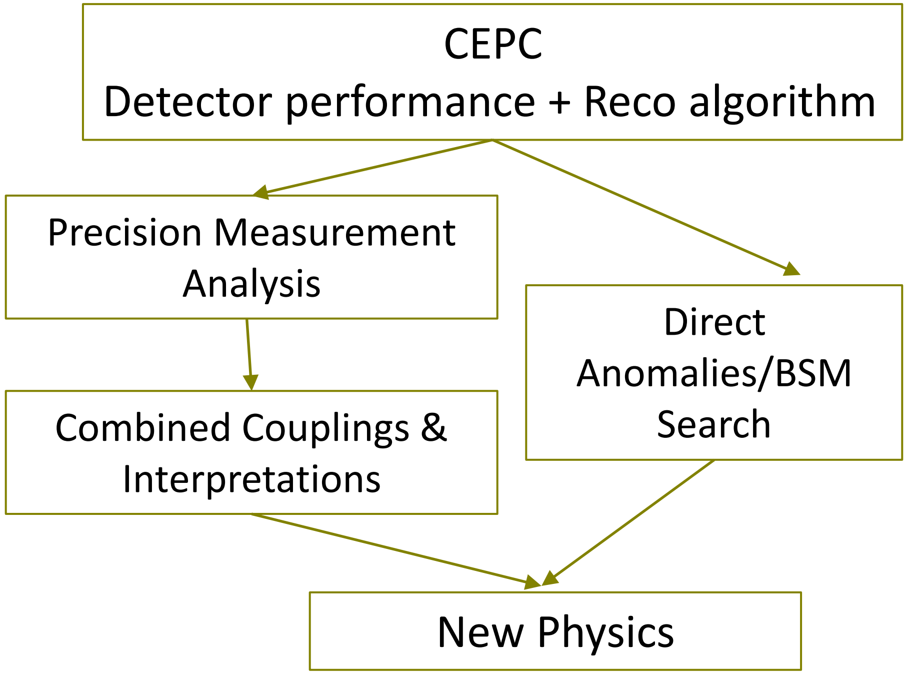
Precision measurement: it matters

With evolving performance, existing results show discrepancies, which uncertainties can't cover.

New Physics?

CEPC has great benchmarks to solve these tensions in precision measurement.

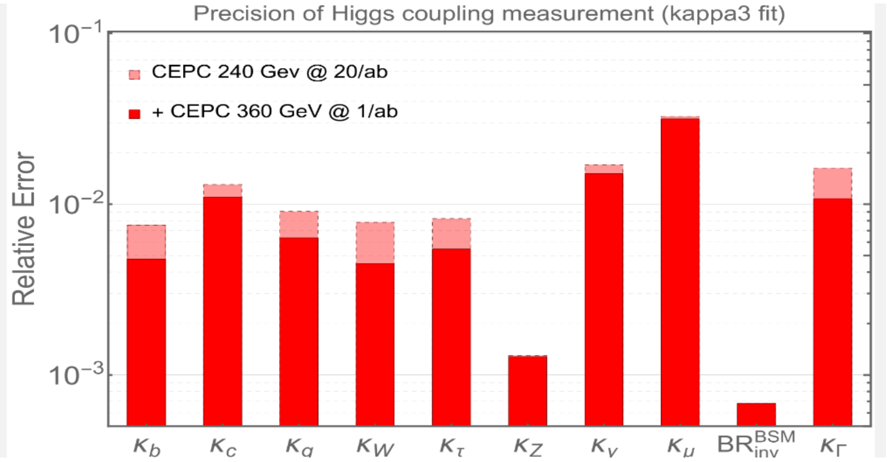


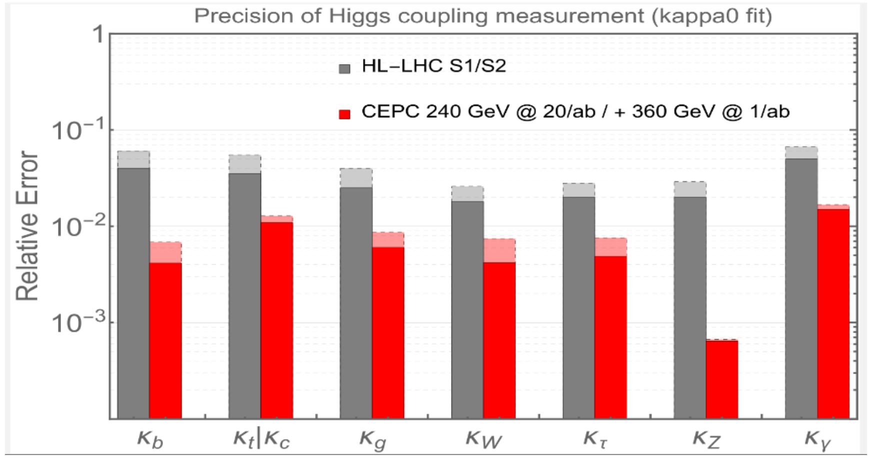


Summary

- Latest CEPC Higgs combination, $\sigma * \mathrm{Br}$ and coupling results are shown.
- Extrapolation to 360GeV applied
  - 1.10% precision for width expected.
- CEPC is the ideal fantastic machine for both precision measurement and BSM search.

	240 GeV, 20 ab^{-1}		360 GeV, 1 ab^{-1}		
	ZH	vvH	ZH	vvH	eeH
any	0.26%		1.40%	\	\
H→bb	0.14%	1.59%	0.90%	1.10%	4.30%
H→cc	2.02%		8.80%	16%	20%
H→gg	0.81%		3.40%	4.50%	12%
H→WW	0.53%		2.80%	4.40%	6.50%
H→ZZ	4.17%		20%	21%	
$H \to \tau\tau$	0.42%		2.10%	4.20%	7.50%
$H \to \gamma\gamma$	3.02%		11%	16%	
$H \to \mu\mu$	6.36%		41%	57%	
$Br_{upper}(H \to inv.)$	0.07%		\	\	
$H \to Z\gamma$	8.50%		35%	\	
Width	1.65%		1.10%		



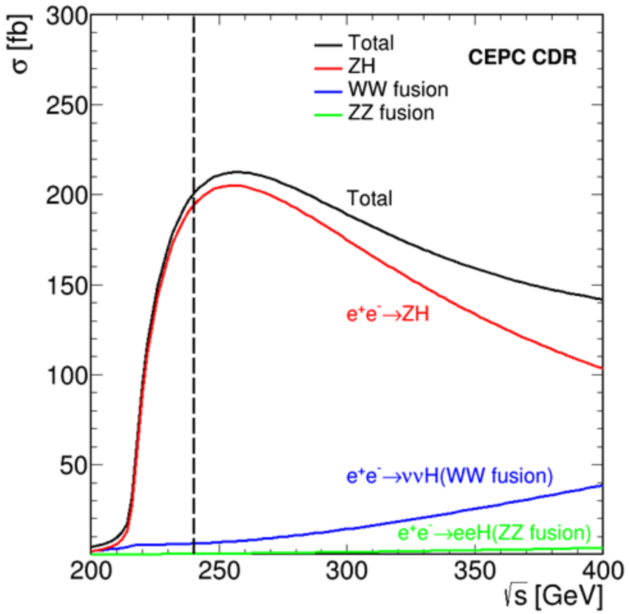


Extrapolations: signals

ZH/vvH interference already considered.

- 240GeV:
  - ZH: 196.9; vvH: 6.2; interference: ~10% of vvH; about 318:10:1; (Z->vv : vvH = 6.4:1)
- 360GeV: (vvH ~ 117% Z->vv), (eeH ~ 67% Z->ee)

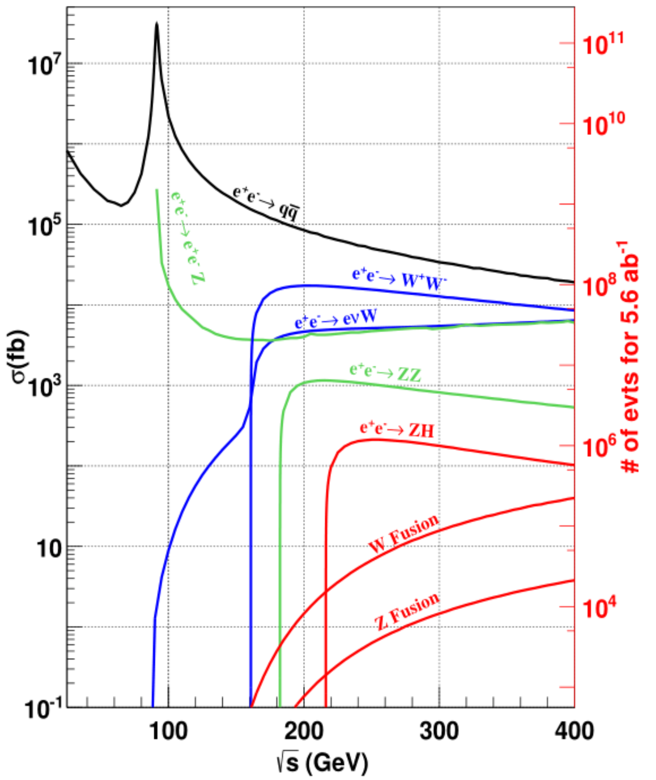
fb	240	350	360	365	360/240
ZH	196.9	133.3	126.6	123.0	-36%
WW fusion	6.2	26.7	29.61	31.1	+377%
ZZ fusion	0.5	2.55	2.80	2.91	+460%
Total	203.6		159.0		
Total Events	4M		0.16M		



In total ~4M Higgs would be collected in CEPC 240+360.
More fusion events, also eeH can not be ignored in 360GeV.

Extrapolations: backgrounds

pb	240	350	360	365	360/240
ee(γ)	930	336	325	319	-65%
$\mu\mu(\gamma)$	5.3	2.2	2.1	2.1	-60%
qq(γ)	54.1	24.7	23.2	22.8	-57%
WW	16.7	10.4	10.0	9.81	-40%
ZZ	1.1	0.66	0.63	0.62	-43%
$t\bar{t}$	\	0.155	0.317	0.369	
sZ	4.54	5.72	5.78	5.83	+27%
sW	5.09	5.89	6.00	6.04	+18%



While 2fermion bkg and WW, ZZ bkg reduced, W/Z fusion and $t\bar{t}$ raise.

Generally, with larger phase space and smaller bkg cross sections, continuum background would reduce.

Processes are extrapolated to 360GeV in this ratio.
Kinematic distributions are also scaled with phase space.