CEPC Higgs Coupling in 240/360GeV

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IHEP

Joint Workshop of the CEPC Physics, Software and New Detector Concept in 2022

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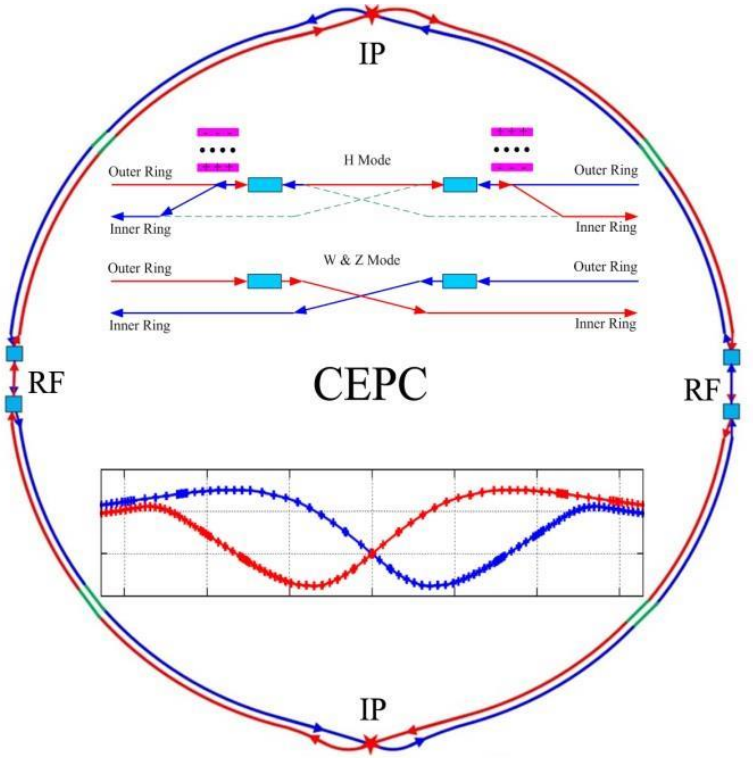
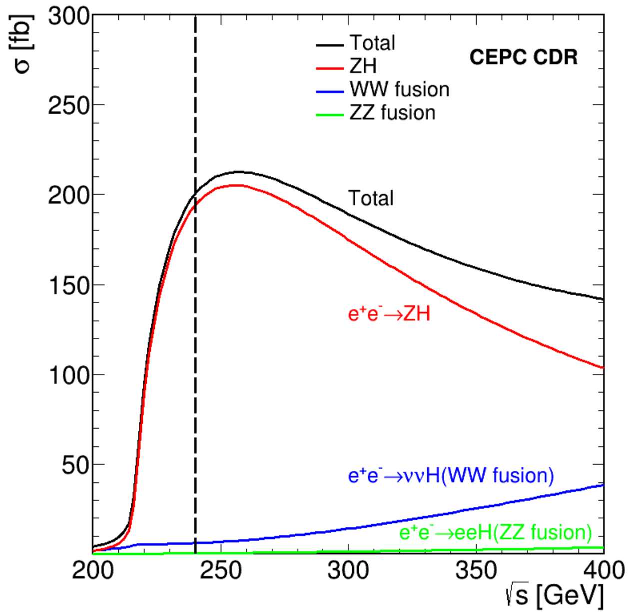
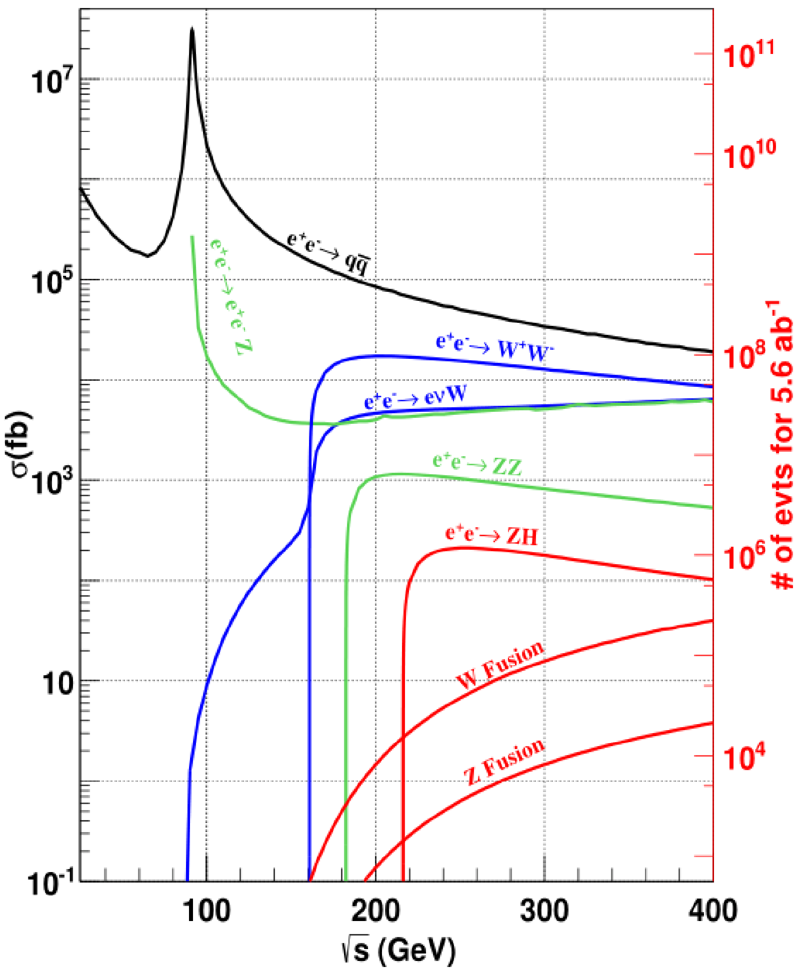
Higgs@CEPC

With 100km tunnel, CEPC will collect 4M Higgs for 20iab data in 240GeV.





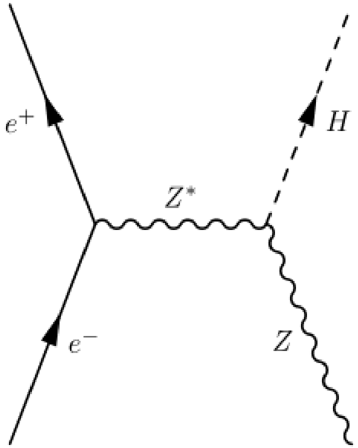


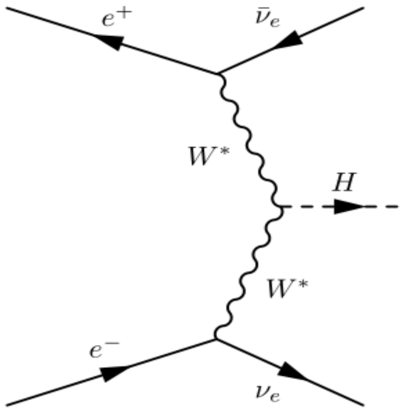
CEPC CDR: arxiv:1811.10545

White Paper: arxiv:1810.09037

CEPC Snowmass 2021(Latest):

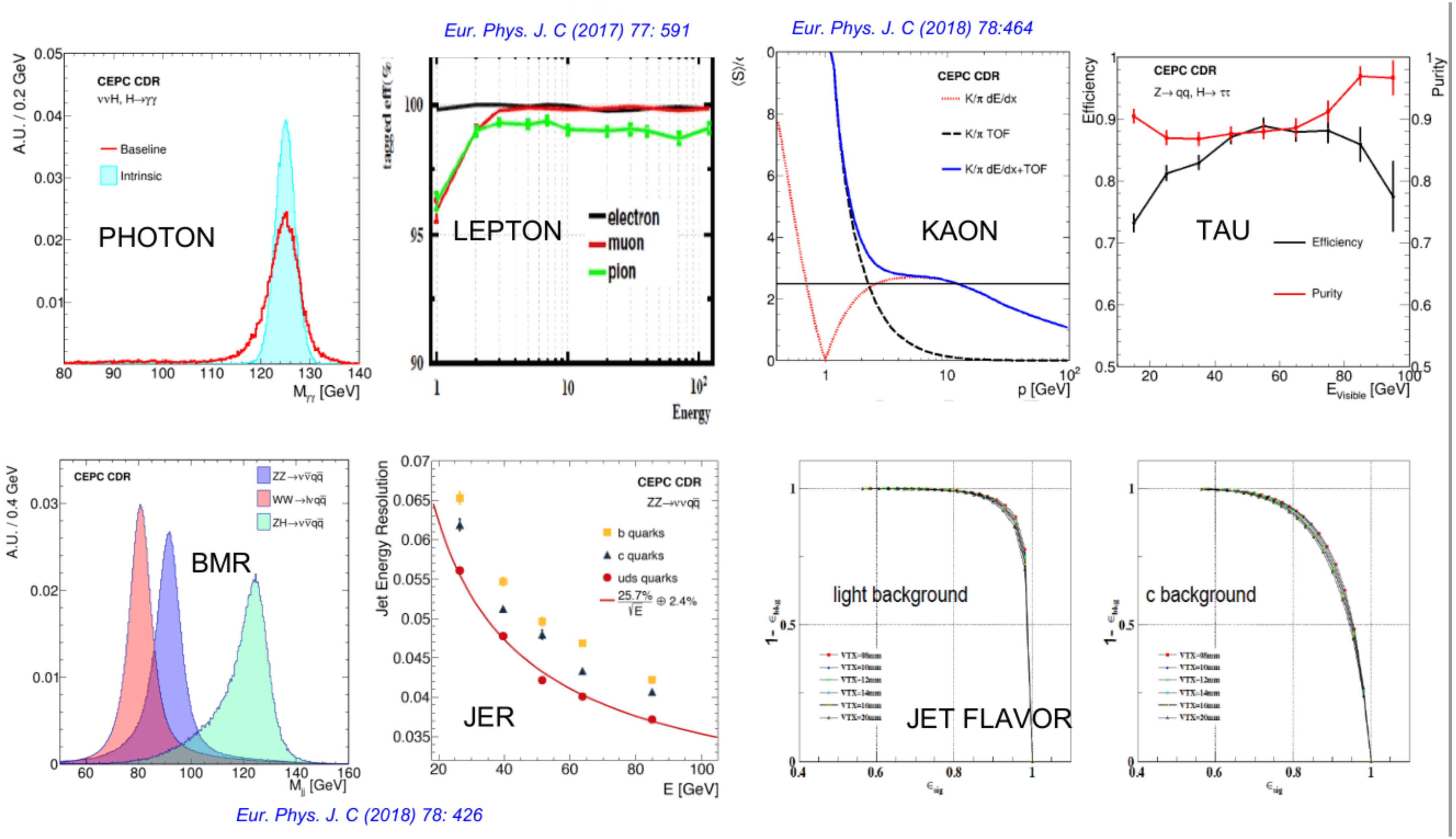
Arxiv:2205.08553



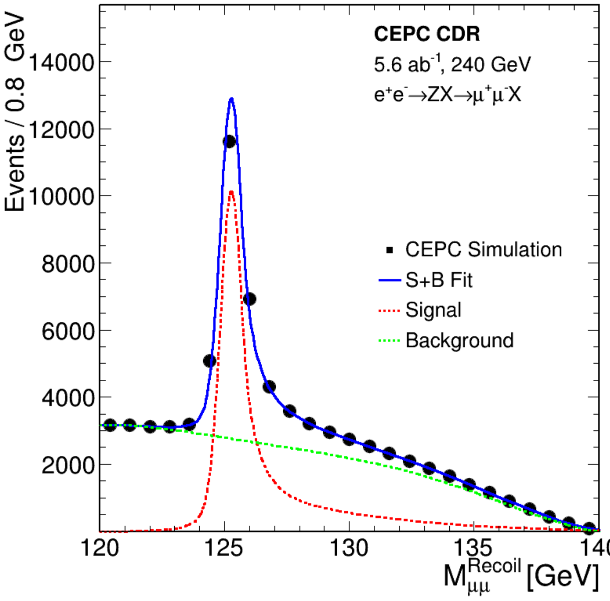


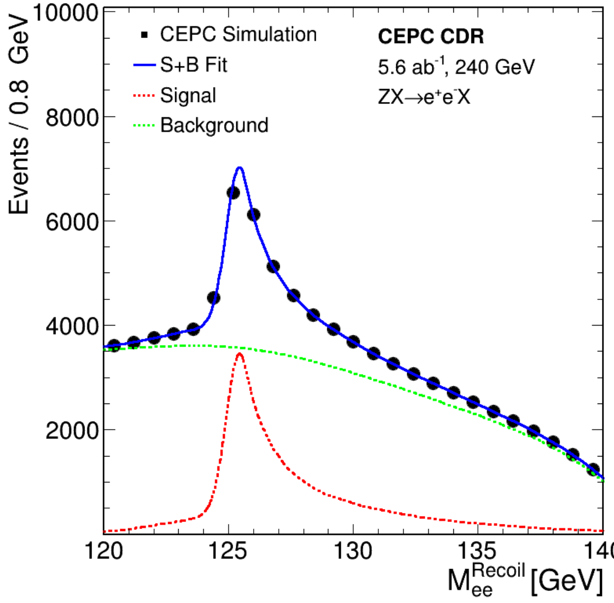
CEPC (evolving) object performance

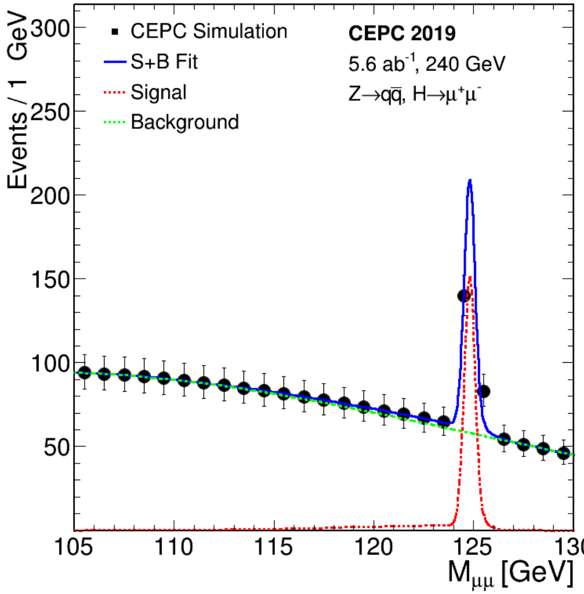
With certain detector parameter and certain reconstruction algorithm, CEPC Higgs measurements are predictable.

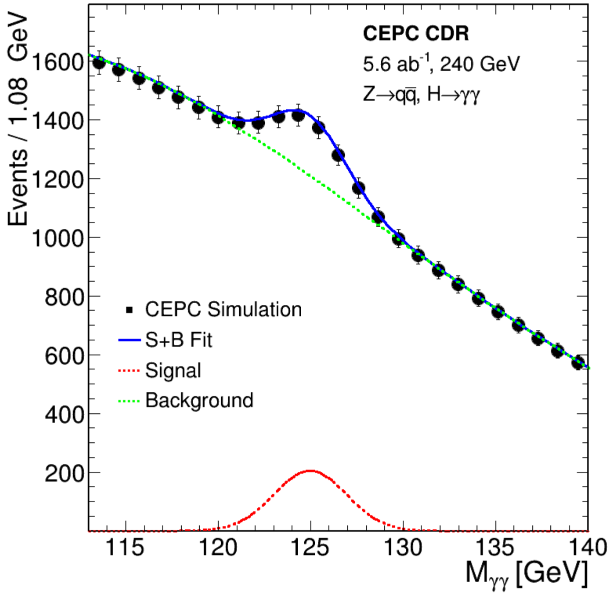


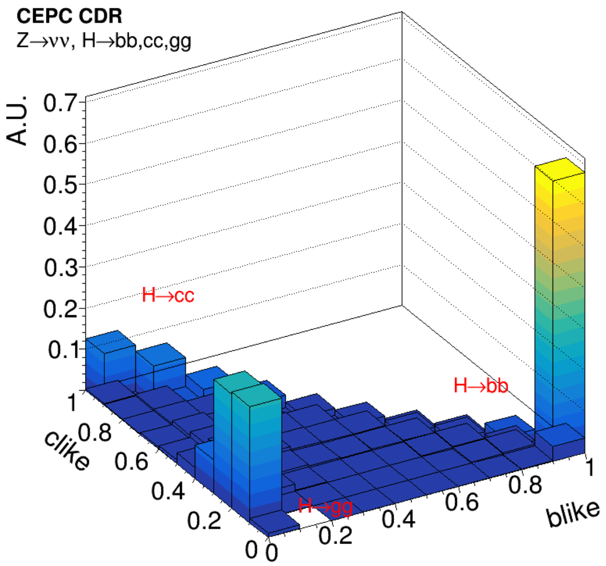
Individual sub channels

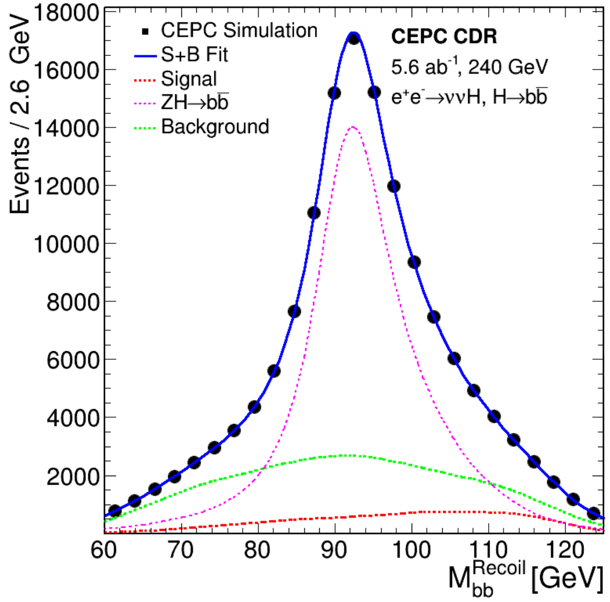


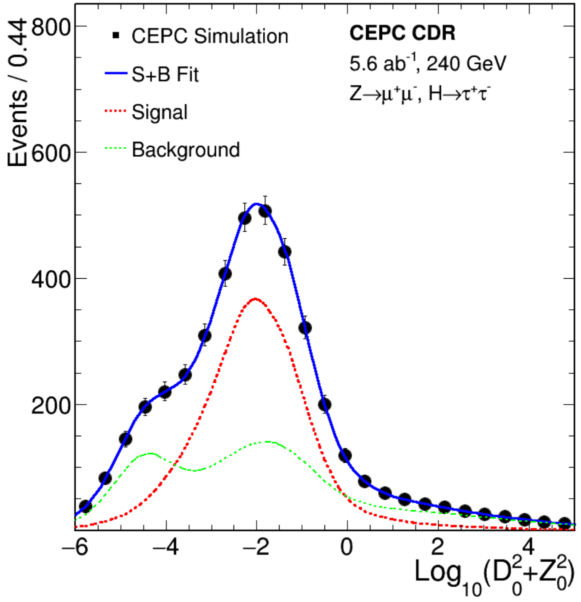












These results are based in 2018 CEPC-v4 layout.

(Ecal: $1.4\%\oplus\frac{16.7\%}{\sqrt{E}}$)

Existing results:240GeV, 5.6iab

(240GeV,5.6ab^{-1})	CDR	2022.05
$\sigma(ZH)$	**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%**	**3.8%**
$\sigma(ZH) * \mathrm{Br}(\mathrm{H} \rightarrow \mathrm{gg})$	**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%**	**5.7%**
$\sigma(ZH) * \mathrm{Br}(\mathrm{H} \rightarrow \mu\mu)$	**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 Yongfeng's for latest bb/cc/gg.

Related publication:
$\sigma(ZH)$: 1601.05352;
bb/cc/gg: 1905.12903/ 2203.01469;
$\tau\tau$: 1903.12327;
Invisible: 2001.05912;
ZZ: 2103.09633;

Several channels improved since CDR published.
Mostly from better analysis strategy.

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

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

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;
  - Fcc-ee/ILC/CLIC all have similar plan
- benchmark: 1ab^{-1} @ 360GeV
  - 360GeV saves 10% energy with respect to 365 GeV
  - With current lumi, ~5 years to collect 1iab data.
  - Also plan for threshold scan for top mass;

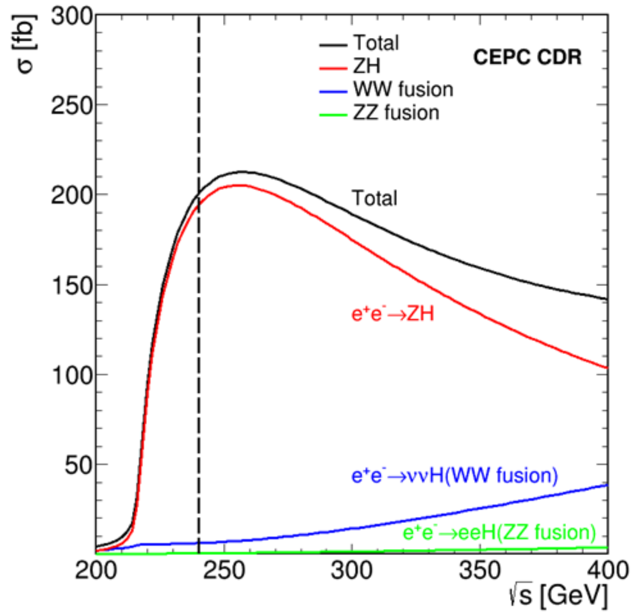
Fcc-ee has the plan for
0.2ab^{-1} 350GeV Scan + 1.5ab^{-1} 365GeV

Signal Cross Sections

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)

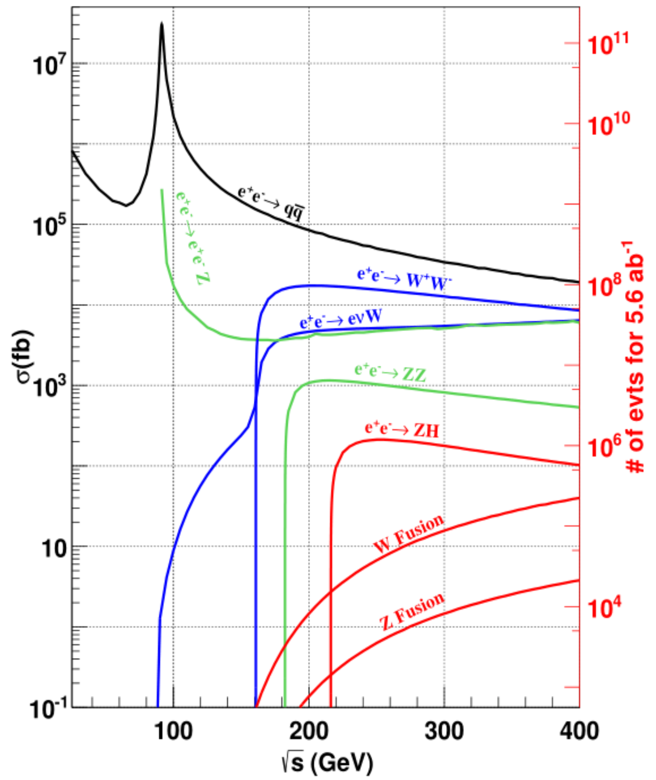
fb	240	350	360	365	360/240
ZH	196.9	133.3	126.6	123.0	-36%
WW fusion	6.2	26.7	29.61	31.1	+377%
ZZ fusion	0.5	2.55	2.80	2.91	+460%
Total	203.6		159.0		
Total Events	4M		0.16M		



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

Major background cross sections

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%



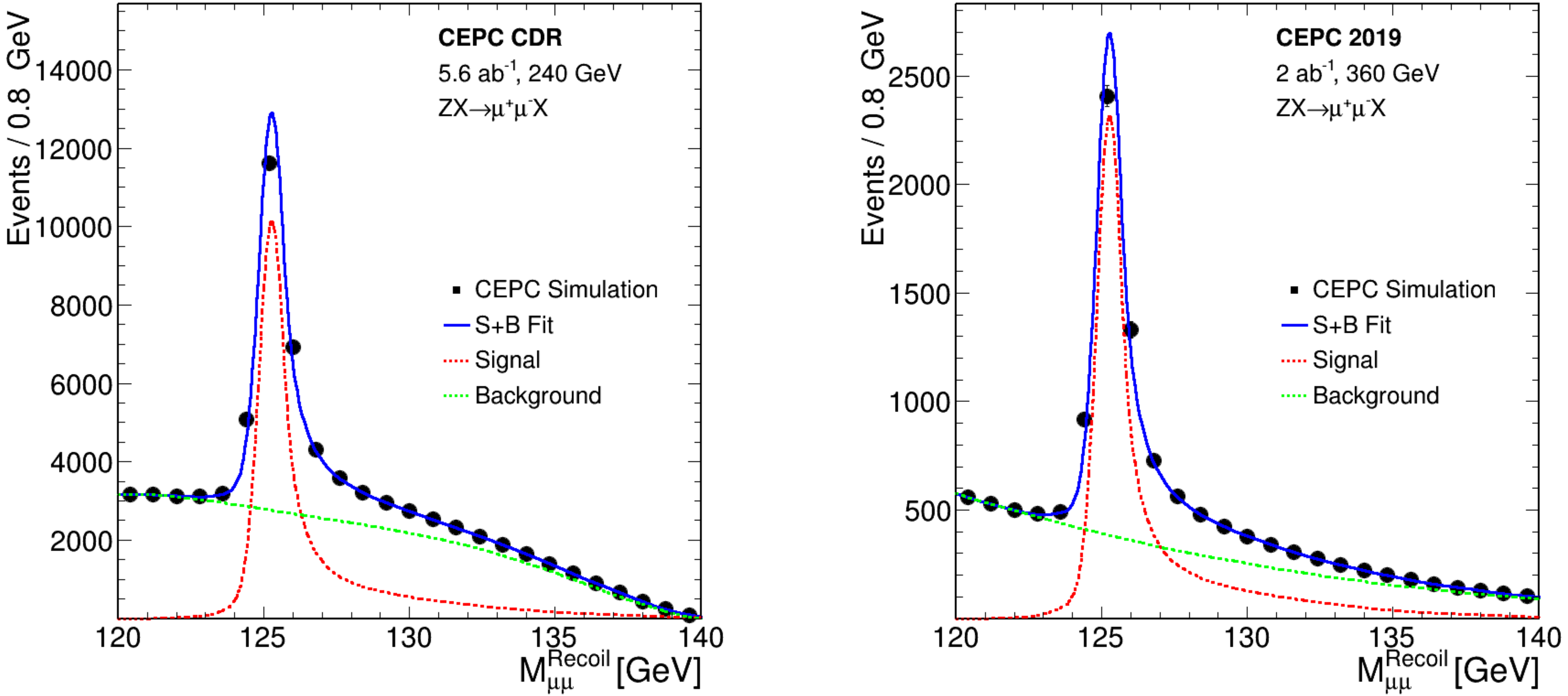
While 2fermion bkg and WW, ZZ bkg reduced, W/Z fusion and $t\bar{t}$ raise.

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.

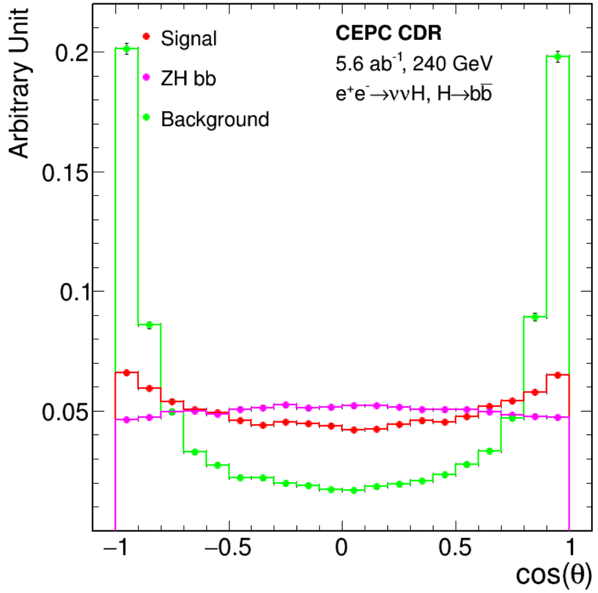
Extrapolations

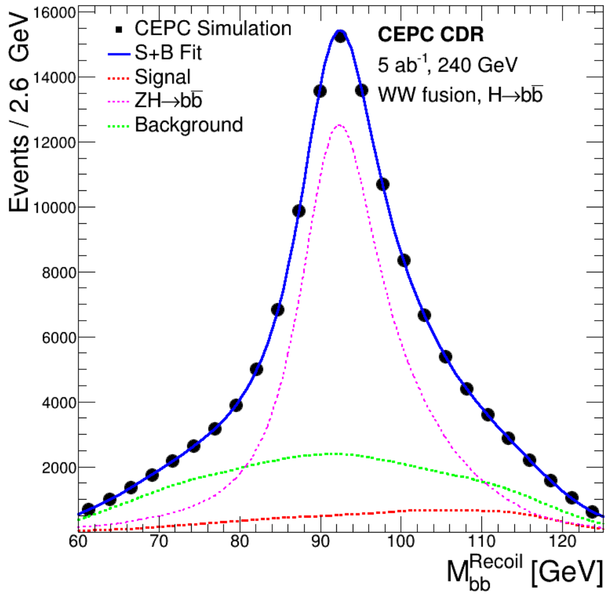
Ideal model independent inclusive $Z \to \mu\mu$: $0.92\% \to 1.72\%$



$\nu\nu H \to bb$: 240GeV

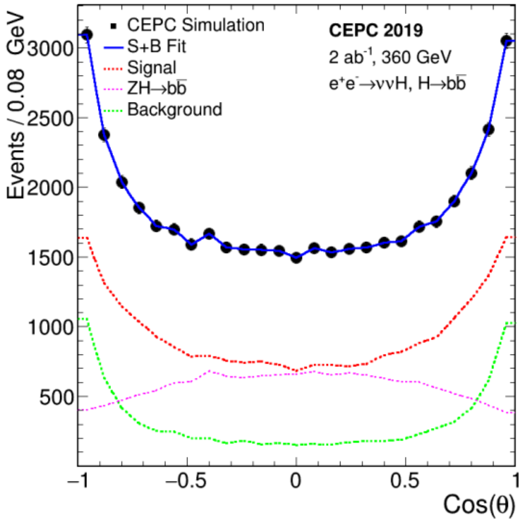
- 2d fit M_{jj}^{reco} & $\cos\theta_{jj}$
- $\nu\nu H \to bb$ and $ZH \to bb$
  - Interference ~10% of vvH. (generally, 60: 1 : 10)
    - Add the interference term to vvH side currently;
  - $\nu\nu H \to bb$ and $ZH \to bb$ share the anti-correlation -45%. (-34% in ILC(1708.08912))
- $\sigma(\nu\nu H) * Br(H \to bb)$: 3.0% ;



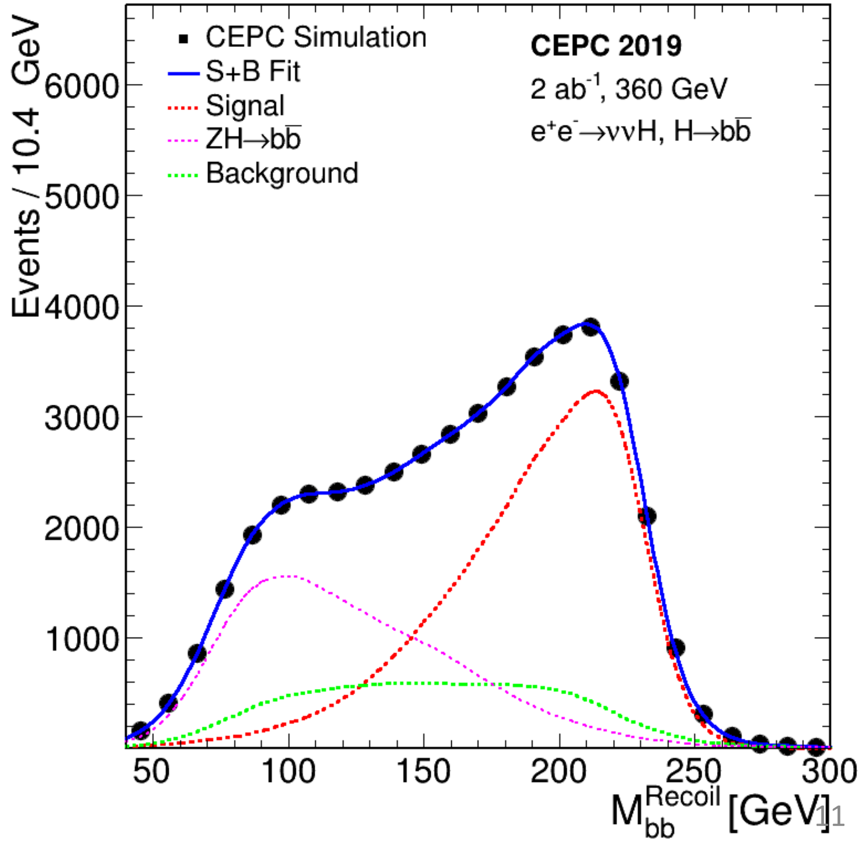


- if fix ZH process, Initial $\nu\nu H \to bb$ uncertainty is 2.8%.
- if float ZH process, $\nu\nu H \to bb$ would be 3.4%.
- Need use other ZH processes to constrain ZH.

vvH->bb : 360 GeV, full sim

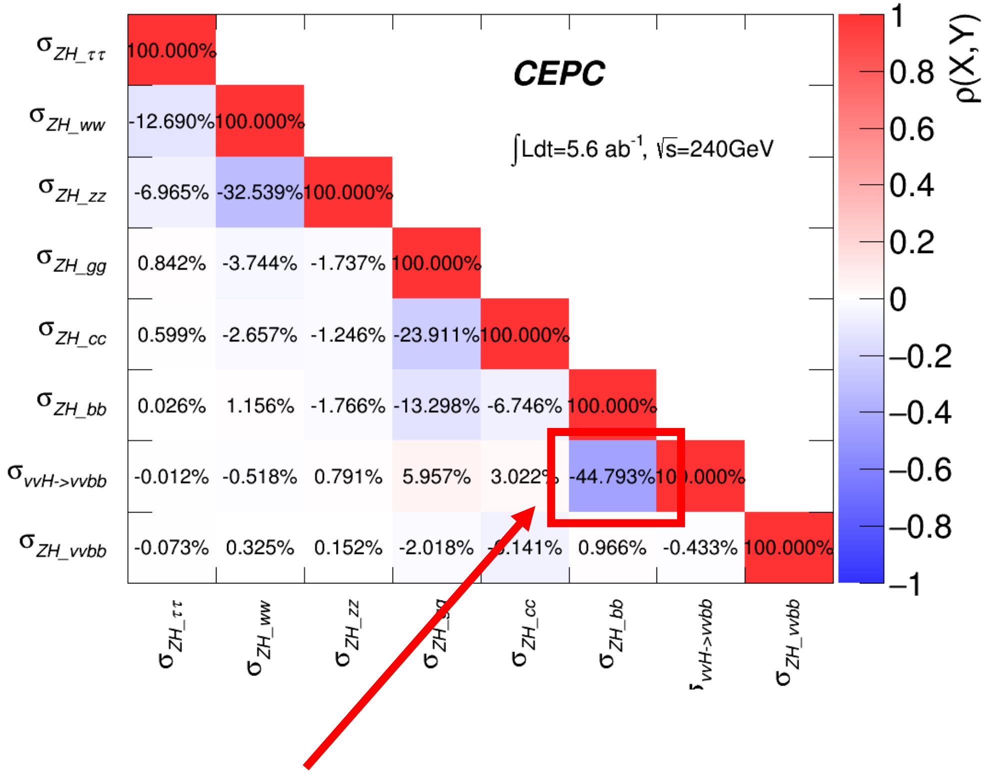


- Clear separation between ZH and vvH.
- Constrain from other ZH->bb($ee, \mu\mu, qq$) considered.
- In current 1iab,
  - $\sigma(\mathrm{vv}H) * \mathrm{Br}(\mathrm{H} \rightarrow \mathrm{bb})$: 1.10%
  - $\sigma(\mathrm{Z}H) * \mathrm{Br}(\mathrm{H} \rightarrow \mathrm{bb})$: 0.90%
  - share the anti-correlation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

κ framework

- Higgs coupling defined as:

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

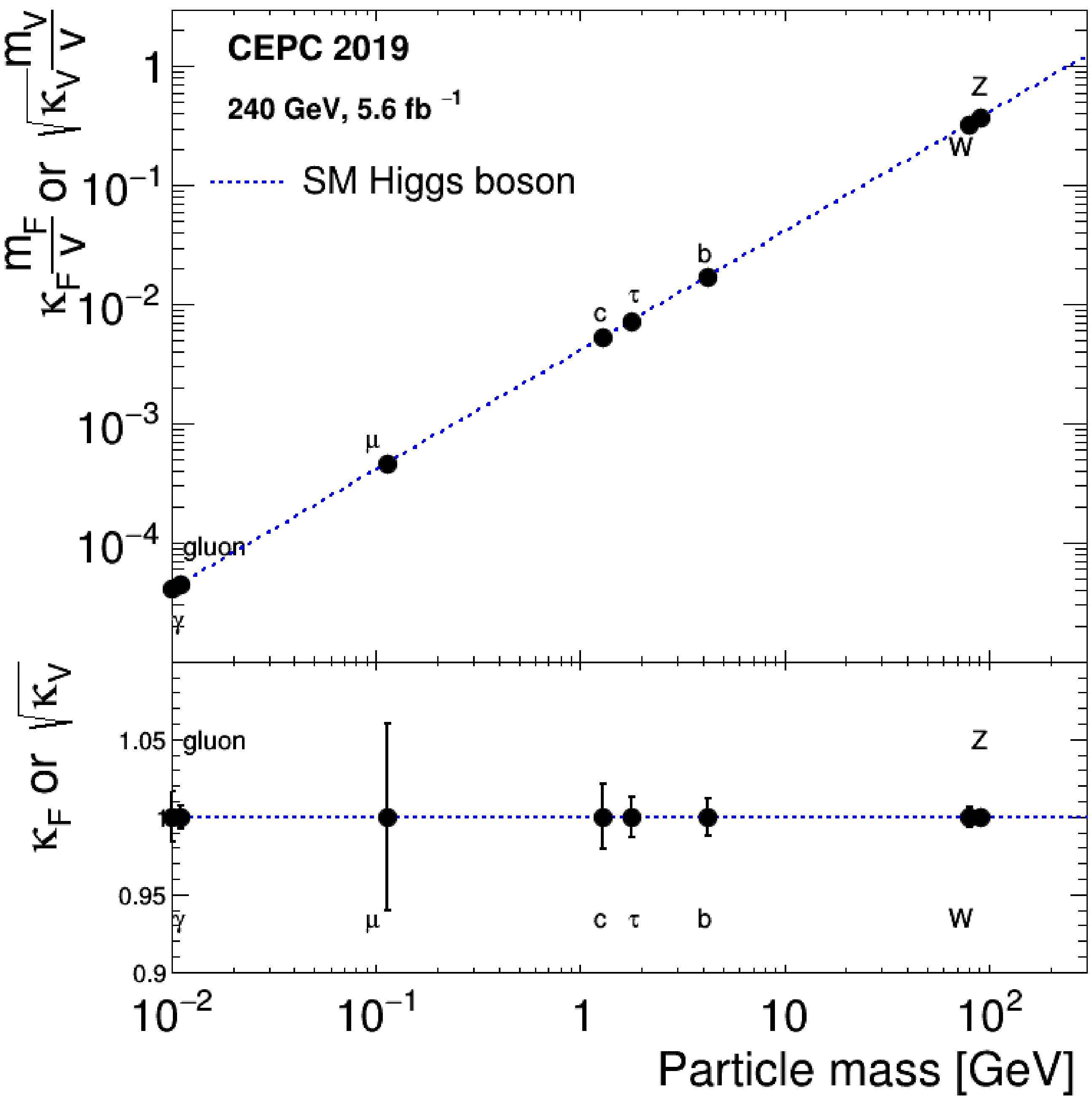
$$\sigma(\mathrm{vv}H) * \mathrm{Br}(\mathrm{H} \to \mathrm{bb}) \propto \frac{\kappa_\mathrm{W}^2 * \kappa_\mathrm{b}^2}{\Gamma_H}.$$

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

- 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:

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.

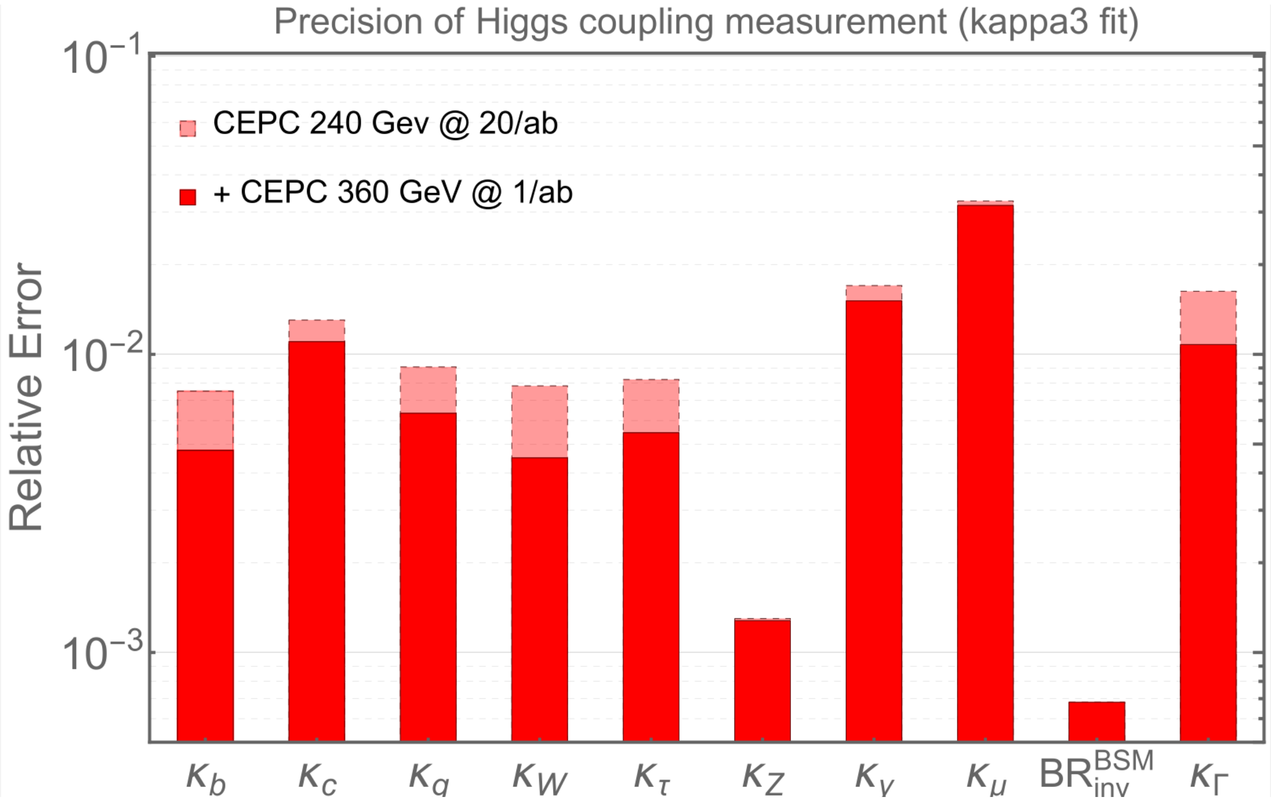
$$\Delta(\Gamma_H) \approx 1.10\%$$

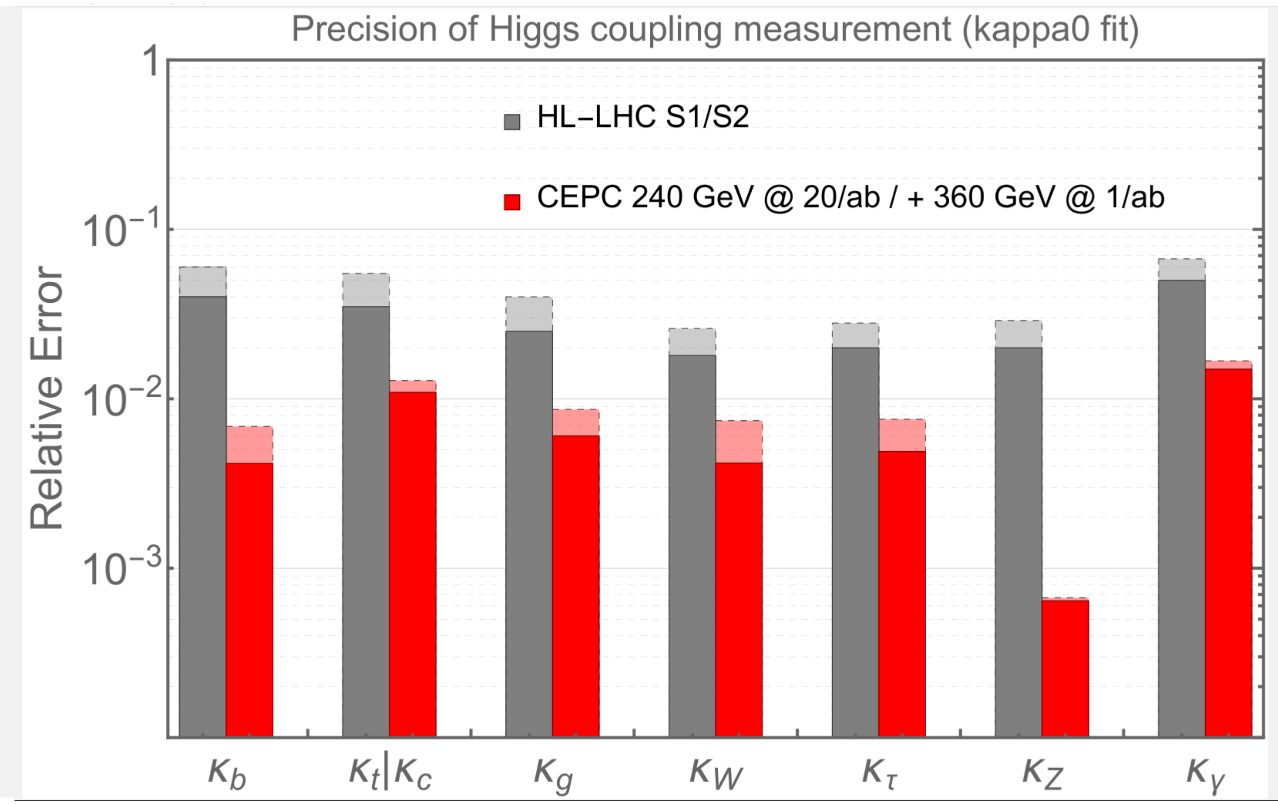
As width in everywhere, width helps all kappas even better.

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

κ : CEPC latest

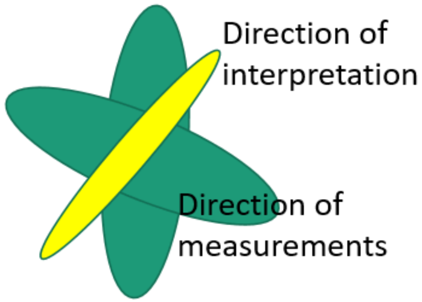
- Compared to HL-LHC, lepton colliders 1-2 order better in Higgs coupling.
- Adding 360GeV will signifantly improve κ results.





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

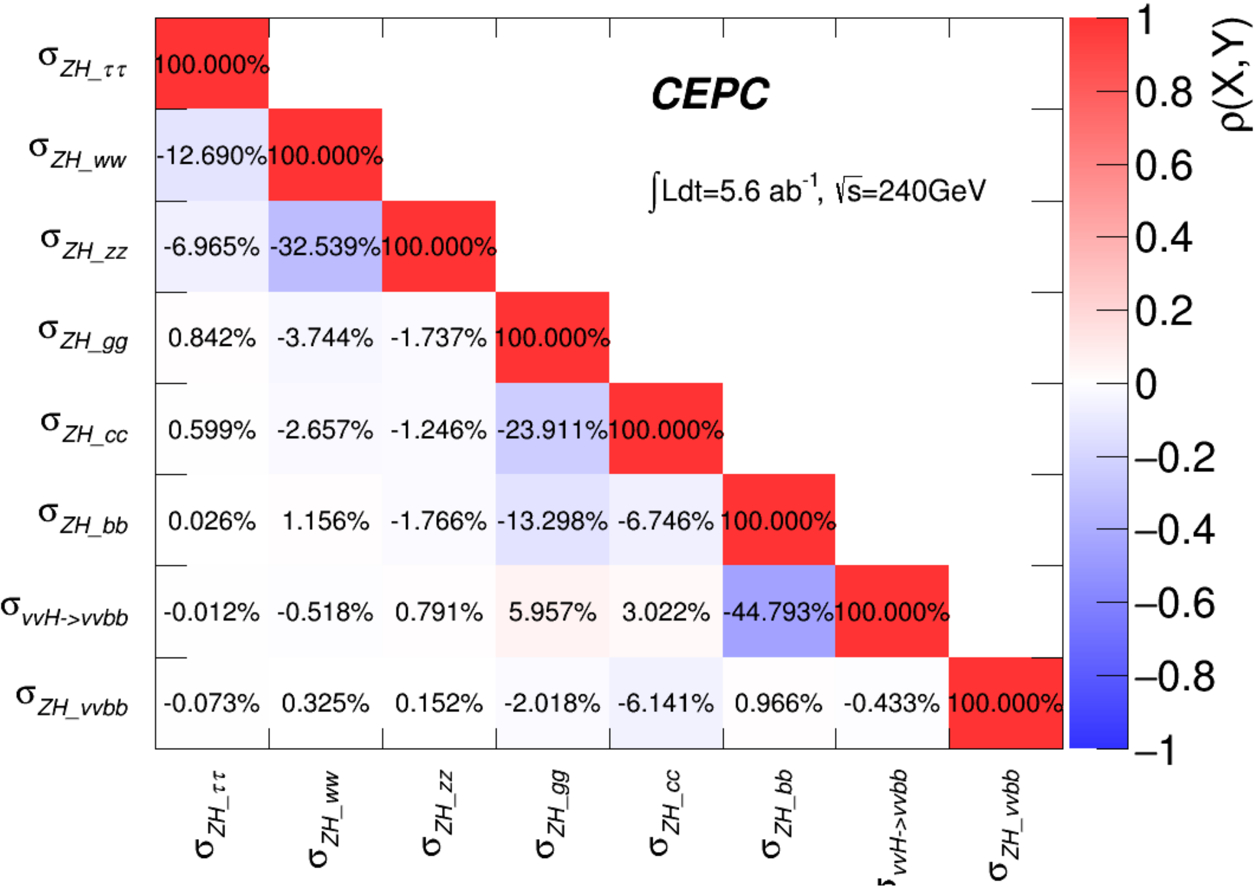
Correlation Matrix

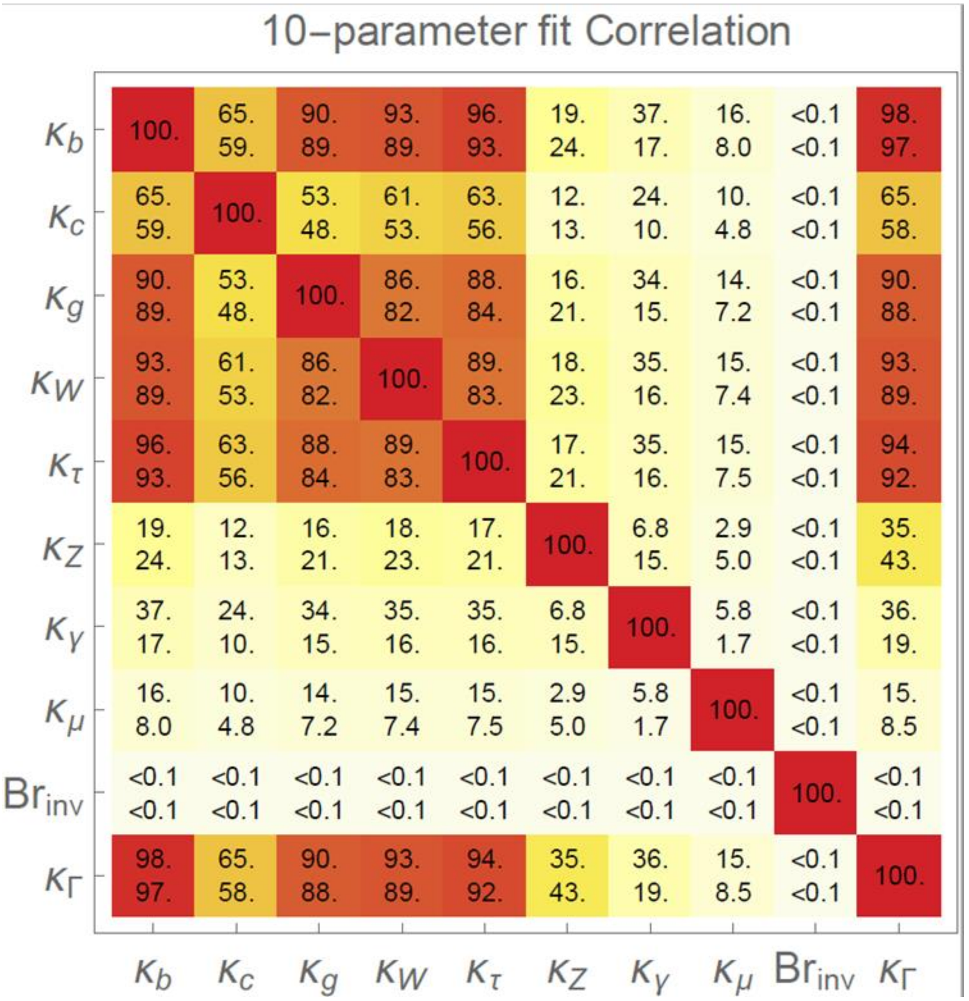


Input | + Interpretation | Output

Measurement → Coupling

2nd correlation differential matters, in the future.





Since the correlation is in the different direction, results get improved slightly.

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

Evolving Combination

- Good enough results, still a lot of to do
  - Many progress from Accelerator, Detector, and object performance since CDR didn't enter the combination yet.
  - Still need to understand the correlation
    - More powerful tools: HEPFit? Matrix method?
  - Far from the CEPC fully/ultimate potential. 4M Higgs!
    - Global optimization for combination needed in the beginning of study.
- Your effort would be appreciate!

Detector performance + Reco algorithm

↓

Individual Analysis (No correlation)

↓

Combination (With correlation) Output: $\sigma * Br$

↓

Coupling & Interpretation

And new physics?

Summary

- Latest CEPC Higgs combination, $\sigma * \mathrm{Br}$ and coupling results are shown.
- Extrapolation to 360GeV applied
  - 1.10% precision for width expected.

	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%
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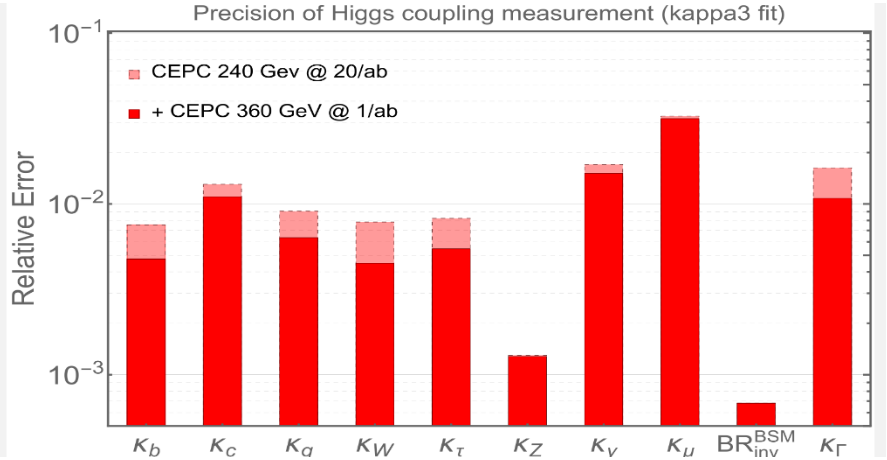
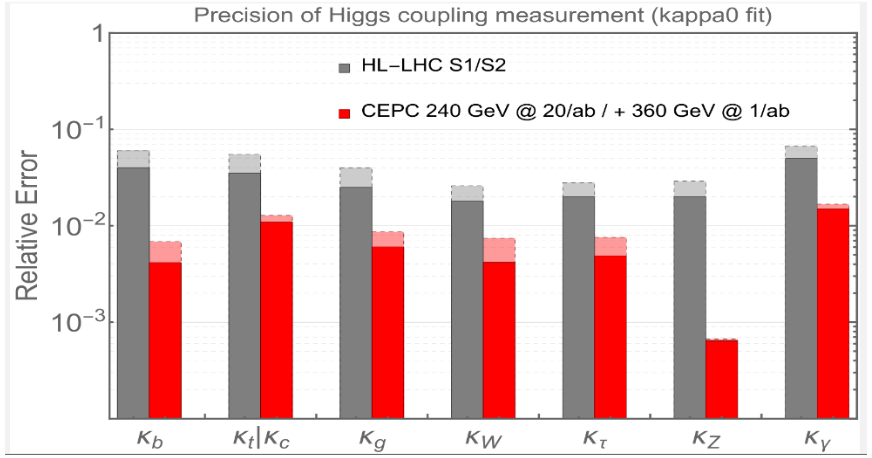
$Br_{upper}(H \to inv.)$	0.07%		\	\	
$H \to Z\gamma$	8.50%		35%	\	
Width	1.65%		1.10%		





backups

$\sigma(ZH)$: H→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%
- $\sigma(ZH)$ correlations

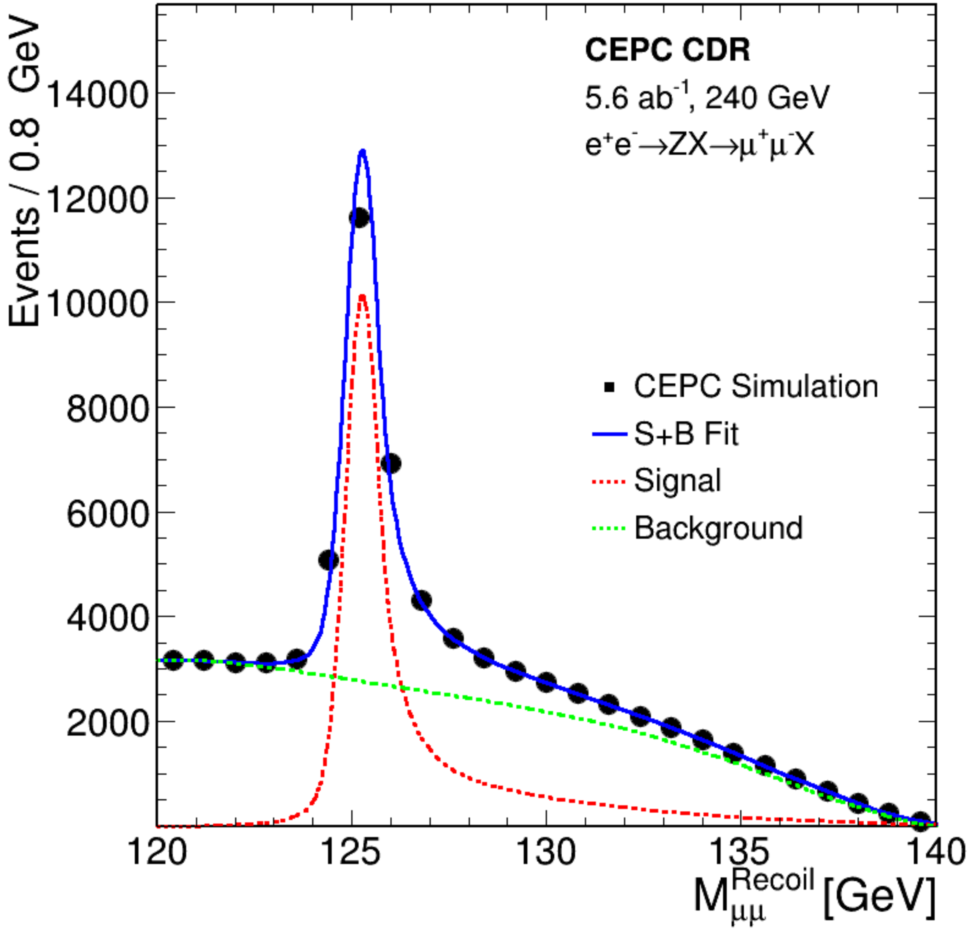


Table 3. Estimation of biases of σ_{ZH} caused by potential variances of the Higgs decay branching ratios.

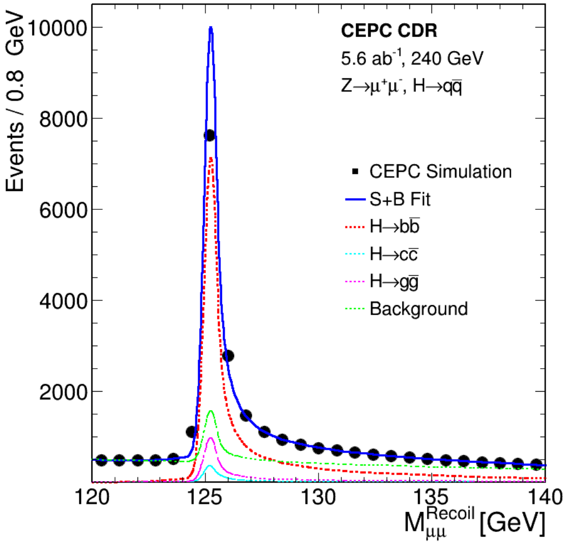
Decay mode	Bias($\times 10^{-4}$)
$H \to b\bar{b}$	-0.10
$H \to WW$	+0.20
$H \to gg$	-0.18
$H \to \tau\tau$	+1.11
$H \to c\bar{c}$	+0.05
$H \to ZZ$	-1.85
$H \to \gamma\gamma$	+2.56
$H \to \gamma Z$	-2.08
$H \to$ inv.	+5.75

Full hadronic jets: bb/cc/gg/WW/ZZ

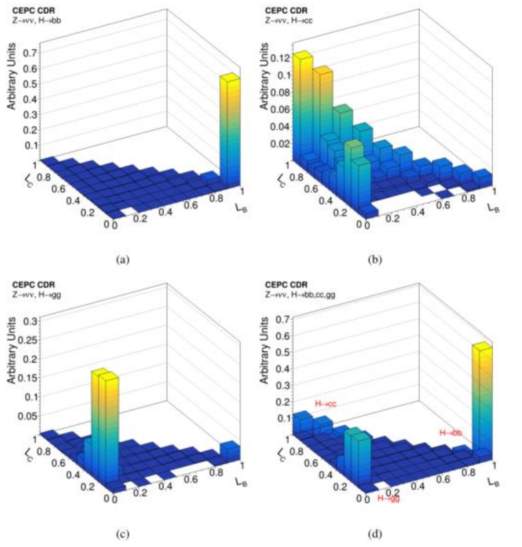
See: 1905.12903;

- Heavily relies on jet clustering algorithm; Hard to separate.
- 3d template fit
    - Mass
    - Dijet’s B likeness and C likeness
- (Z → vv H → bb excluded the vvH part)
- Still, WW/ZZ suffered from the huge ZH events

Scan	μ_{bb}	μ_{cc}	μ_{gg}
eeH	1.3%	13.5%	7.2%
mmH	1.0%	9.5%	5.0%
qqH	0.5%	11.1%	3.6%
vvH	0.4%	3.8%	1.5%
Combined	0.28%	3.3%	1.3%



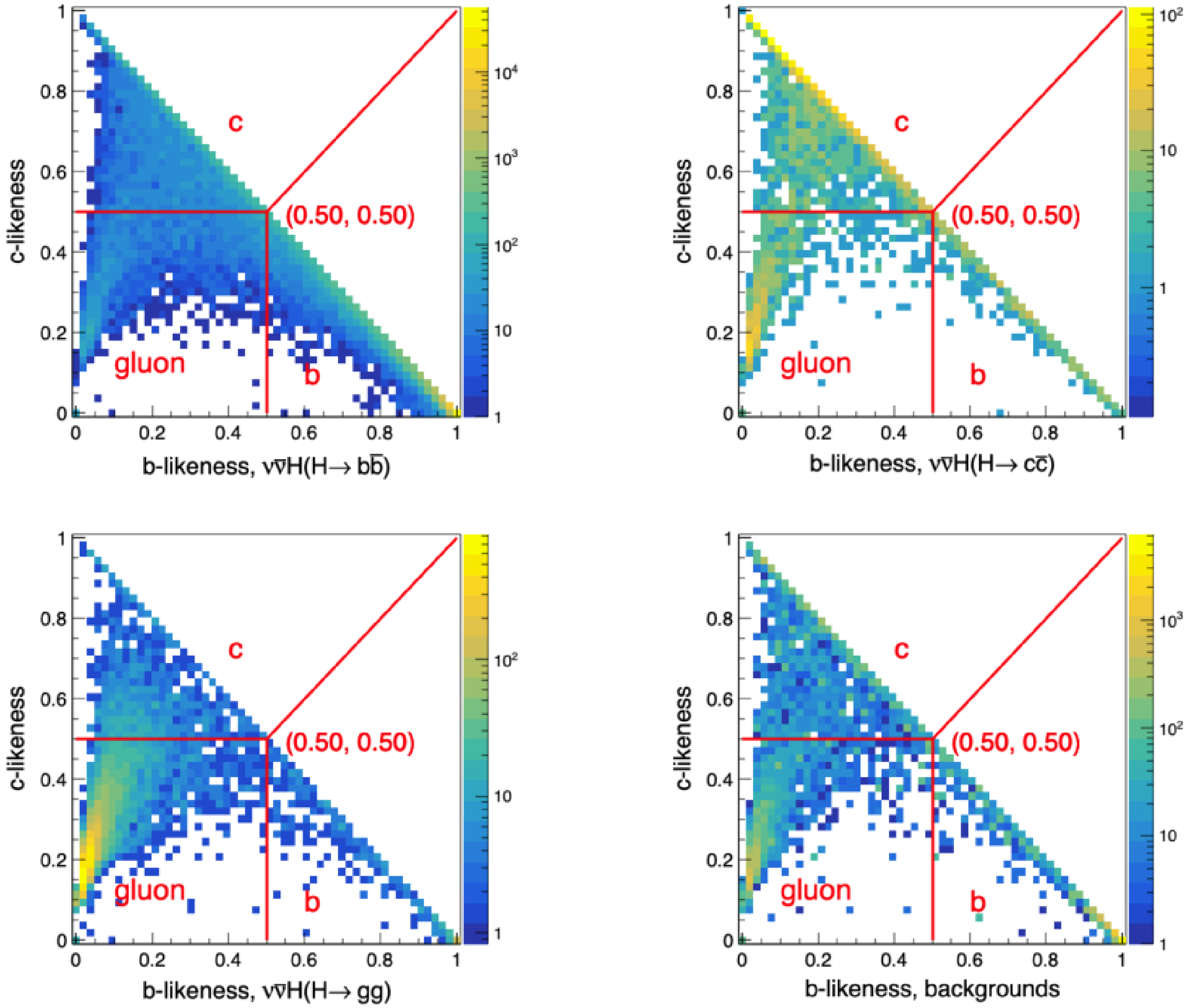
- Plan to apply categories like “STXS” to avoid the overlap.



Current combination didn’t use the full hadronic W/Z
and b/c/g correlation value. More study are needed to understand.

New bb/cc/gg by Yong Feng

2203.01469;



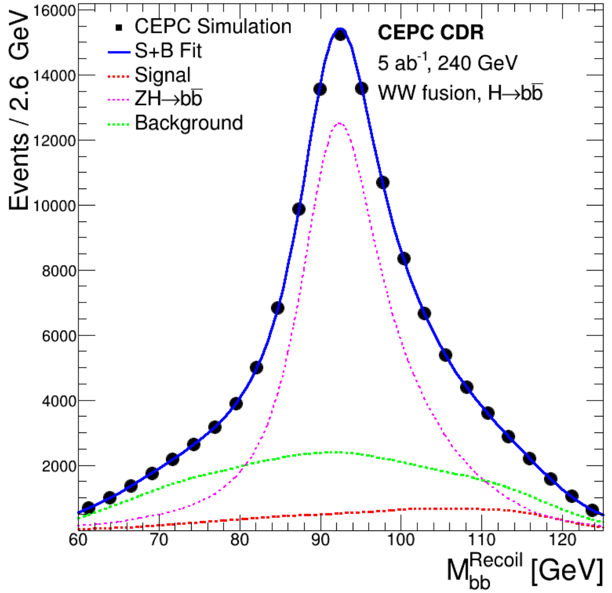
- Color singlet identification(CSI)
- Template fit with real yield with Hessian matrix;

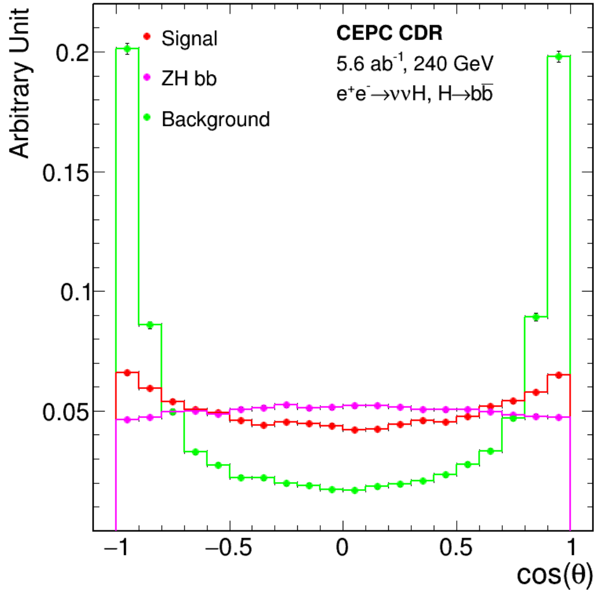
Correlations:

- ZH bb & cc: -15.40%
- ZH bb & gg: -17.04%
- ZH cc & gg: -25.68%

$\nu\nu H \rightarrow bb$

- 2d fit M_{jj}^{reco} & $\cos\theta_{jj}$
- $\nu\nu H \rightarrow bb$ and $ZH \rightarrow bb$
  - Interference ~10% of vvH. (generally, 60: 1 : 10)
    - Add the interference term to vvH side currently;
  - If fix ZH process, Initial uncertainty is 2.8%.
  - ZH->bb constrained by other bb channels. If not, would be 3.4%.
  - $\nu\nu H \rightarrow bb$ and $ZH \rightarrow bb$ share the anti-correlation -45%. (-34% in ILC(1708.08912))
- $\sigma(\nu\nu H) * Br$： 3.0% ;
  - $\sigma(\nu\nu H)$: 3.2%.

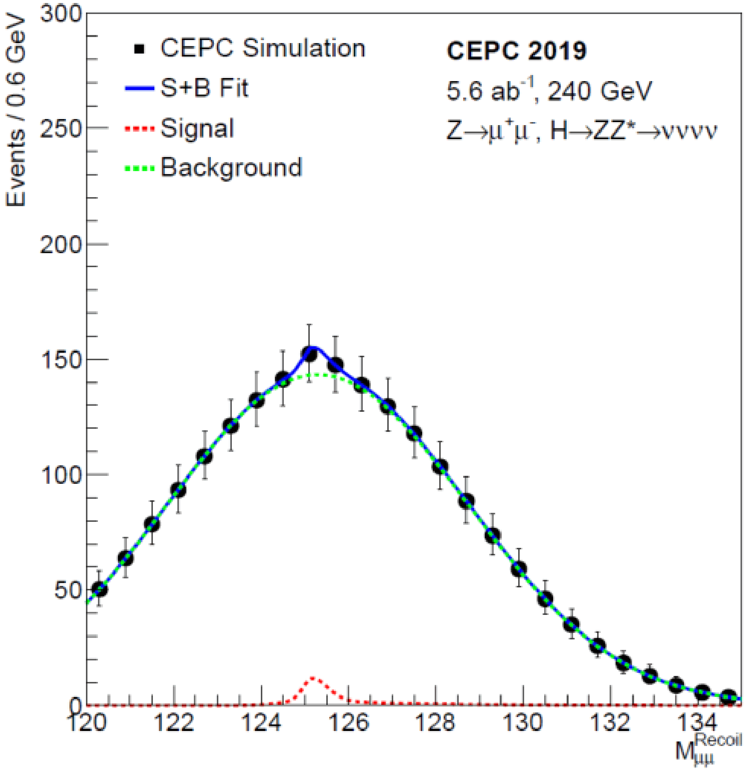




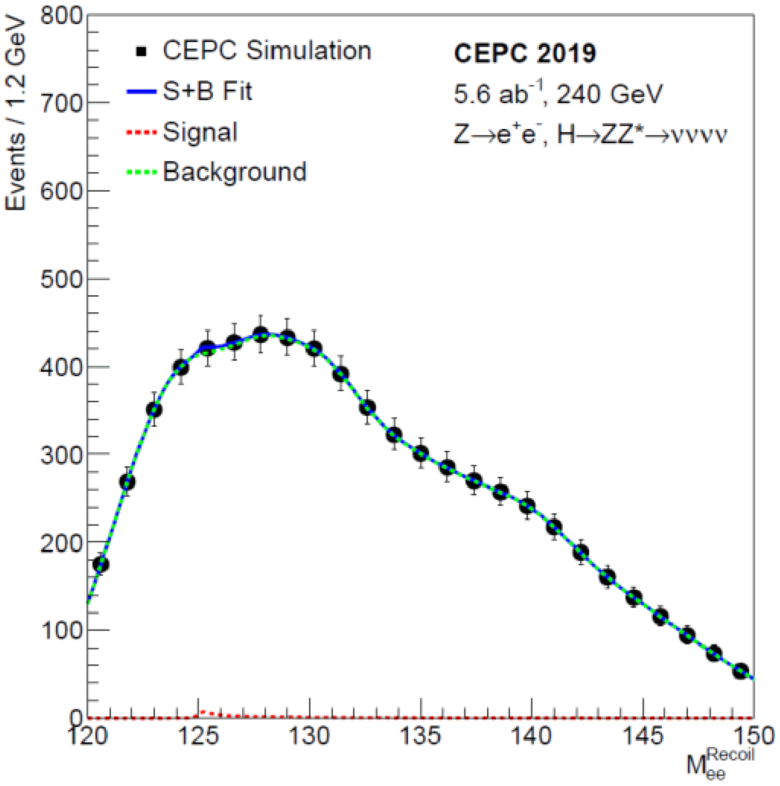
Invisible

See 2001.05912;

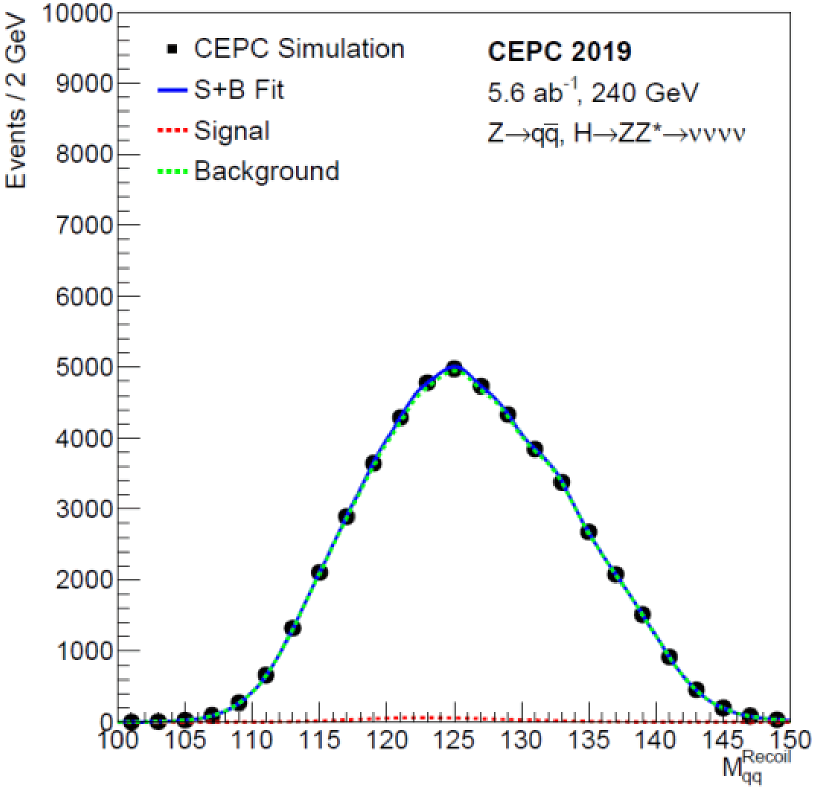
ZH final state studied	Relative precision on $\sigma(ZH)\times$BR	Upper limit on BR (H$\to$inv.)
Z$\to e^+e^-$, H$\to$inv.	403%	0.96%
Z$\to \mu^+\mu^-$, H$\to$inv.	98%	0.31%
Z$\to q\bar{q}$, H$\to$inv.	85%	0.29%
Combination	63%	0.24%



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



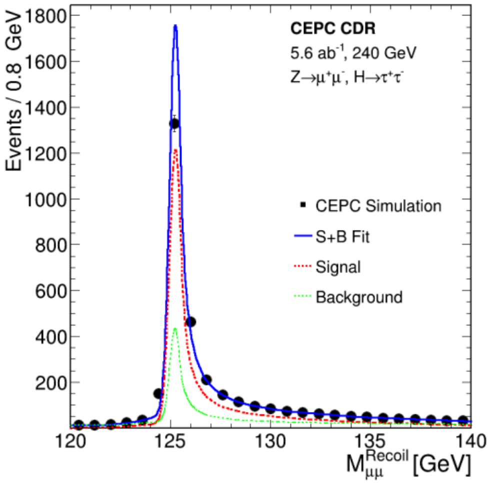
ZH(Z->e^+e^-,H->invisible)



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

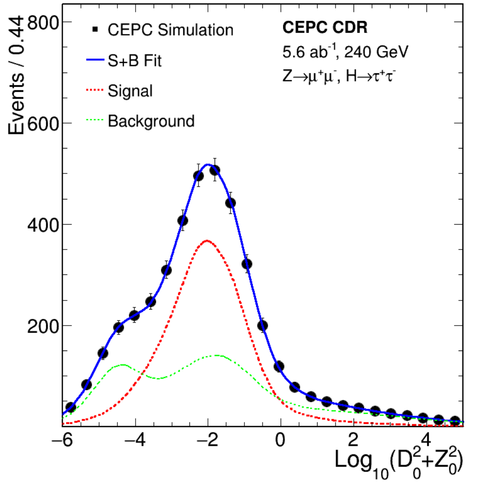
$\tau\tau, \mu\mu$

- $\tau\tau$: 1903.12327;
  - Develop LICH to identify lepton. Eff>99%
  - Signal and ZH events(Main WW) share the same shape
  - use $\log_{10}(D_0^2 + Z_0^2)$ + mass 2d fit to separate signal
    - Impact parameter, Distance from beam spot

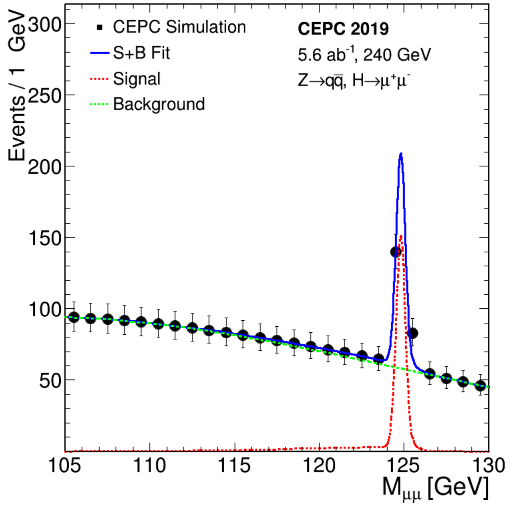


- $\mu\mu$
  - See Ran Kunlin's report in 2021 Yangzhou.

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%



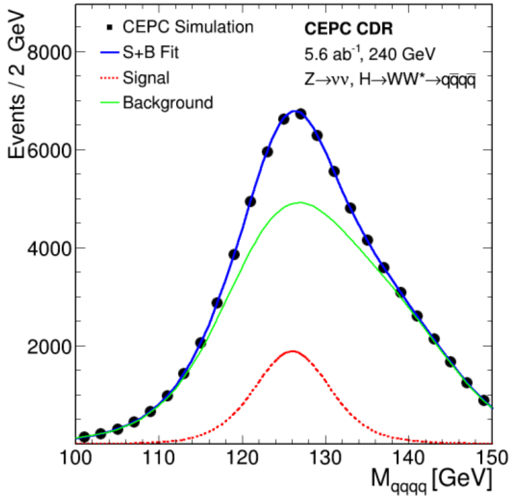
	qqh_e2e2		
[%]	Stat	Eff	Rel
Initial	148.85	100	100
N_mum > 0, N_mup > 0	148	99.43	99.43
105 < M_mumu < 130 GeV	123.75	83.14	83.62
25 < N_particle < 115	123.02	82.64	99.41
55 < M_qq < 125 GeV	122.02	81.97	99.19
P_ppmumu < 32 GeV, 195 < E_ppmumu < 265 GeV	121.32	81.51	99.43
35 < E_mum < 100 GeV, 35 < E_mup < 100 GeV	120.89	81.22	99.65
16 < p_mumu < 72 GeV	120.31	80.82	99.51
N_em < 6, N_ep < 6, N_e < 10	119.33	80.17	99.19
E_em < 10 GeV, E_ep < 10 GeV, E_ee < 19 GeV	116	77.93	97.21
124 < m_mumu < 125 GeV	73.27	49.22	63.17

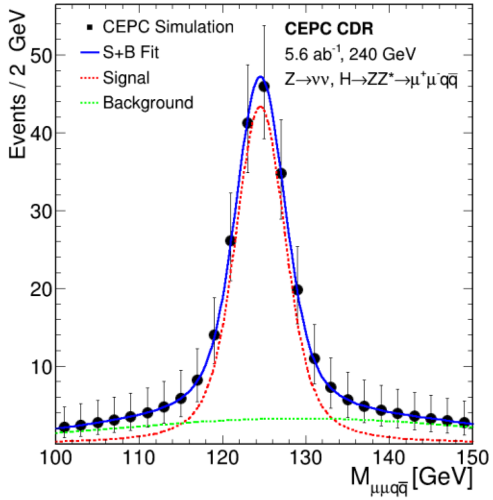


WW, ZZ

- ZZ: 2103.09633;
  - CDR ZZ results a bit overestimated;
  - Current ZZ 7.9% didn't include all the possible ZZ channels yet,
  - Still have room to improve.

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





- WW
  - Much more channels studied since Pre_CDR.

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

Synergy with other experiments

- The comparison is mainly referring [de Blas, J. *et al.* arXiv:1905.03764]
  - Also kappa and EFT results are shown between CEPC240, HL-LHC, Fcc, ILC……
  - In the paper, only CEPC 240GeV 5.6iab results included.

kappa-0	HL-LHC	LHeC	HE-LHC		ILC			CLIC			CEPC	FCC-ee		FCC-ee/eh/hh
			S2	S2′	250	500	1000	380	15000	3000		240	365	
κ_W [%]	1.7	0.75	1.4	0.98	1.8	0.29	0.24	0.86	0.16	0.11	1.3	1.3	0.43	0.14
κ_Z [%]	1.5	1.2	1.3	0.9	0.29	0.23	0.22	0.5	0.26	0.23	0.14	0.20	0.17	0.12
κ_g [%]	2.3	3.6	1.9	1.2	2.3	0.97	0.66	2.5	1.3	0.9	1.5	1.7	1.0	0.49
κ_γ [%]	1.9	7.6	1.6	1.2	6.7	3.4	1.9	98⋆	5.0	2.2	3.7	4.7	3.9	0.29
$\kappa_{Z\gamma}$ [%]	10.	–	5.7	3.8	99⋆	86⋆	85⋆	120⋆	15	6.9	8.2	81⋆	75⋆	0.69
κ_c [%]	–	4.1	–	–	2.5	1.3	0.9	4.3	1.8	1.4	2.2	1.8	1.3	0.95
κ_t [%]	3.3	–	2.8	1.7	–	6.9	1.6	–	–	2.7	–	–	–	1.0
κ_b [%]	3.6	2.1	3.2	2.3	1.8	0.58	0.48	1.9	0.46	0.37	1.2	1.3	0.67	0.43
κ_μ [%]	4.6	–	2.5	1.7	15	9.4	6.2	320⋆	13	5.8	8.9	10	8.9	0.41
κ_τ [%]	1.9	3.3	1.5	1.1	1.9	0.70	0.57	3.0	1.3	0.88	1.3	1.4	0.73	0.44

kappa-3 scenario	HL-LHC+									
	ILC_{250}	ILC_{500}	ILC_{1000}	$CLIC_{380}$	$CLIC_{1500}$	$CLIC_{3000}$	CEPC	FCC-ee_{240}	FCC-ee_{365}	FCC-ee/eh/hh
κ_W [%]	1.0	0.29	0.24	0.73	0.40	0.38	0.88	0.88	0.41	0.19
κ_Z[%]	0.29	0.22	0.23	0.44	0.40	0.39	0.18	0.20	0.17	0.16
κ_g[%]	1.4	0.85	0.63	1.5	1.1	0.86	1.	1.2	0.9	0.5
κ_γ [%]	1.4	1.2	1.1	1.4∗	1.3	1.2	1.3	1.3	1.3	0.31
$\kappa_{Z\gamma}$ [%]	10.∗	10.∗	10.∗	10.∗	8.2	5.7	6.3	10.∗	10.∗	0.7
κ_c [%]	2.	1.2	0.9	4.1	1.9	1.4	2.	1.5	1.3	0.96
κ_t [%]	3.1	2.8	1.4	3.2	2.1	2.1	3.1	3.1	3.1	0.96
κ_b [%]	1.1	0.56	0.47	1.2	0.61	0.53	0.92	1.	0.64	0.48
κ_μ [%]	4.2	3.9	3.6	4.4∗	4.1	3.5	3.9	4.	3.9	0.43
κ_τ [%]	1.1	0.64	0.54	1.4	1.0	0.82	0.91	0.94	0.66	0.46
BR_{inv} (<%, 95% CL)	0.26	0.23	0.22	0.63	0.62	0.62	0.27	0.22	0.19	0.024
BR_{unt} (<%, 95% CL)	1.8	1.4	1.4	2.7	2.4	2.4	1.1	1.2	1.	1.

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

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

Though CEPC@360GeV not included in the synergy, we expect similar performance compared to Fcc-ee.