Higgs Coupling Measurement @ CEPC

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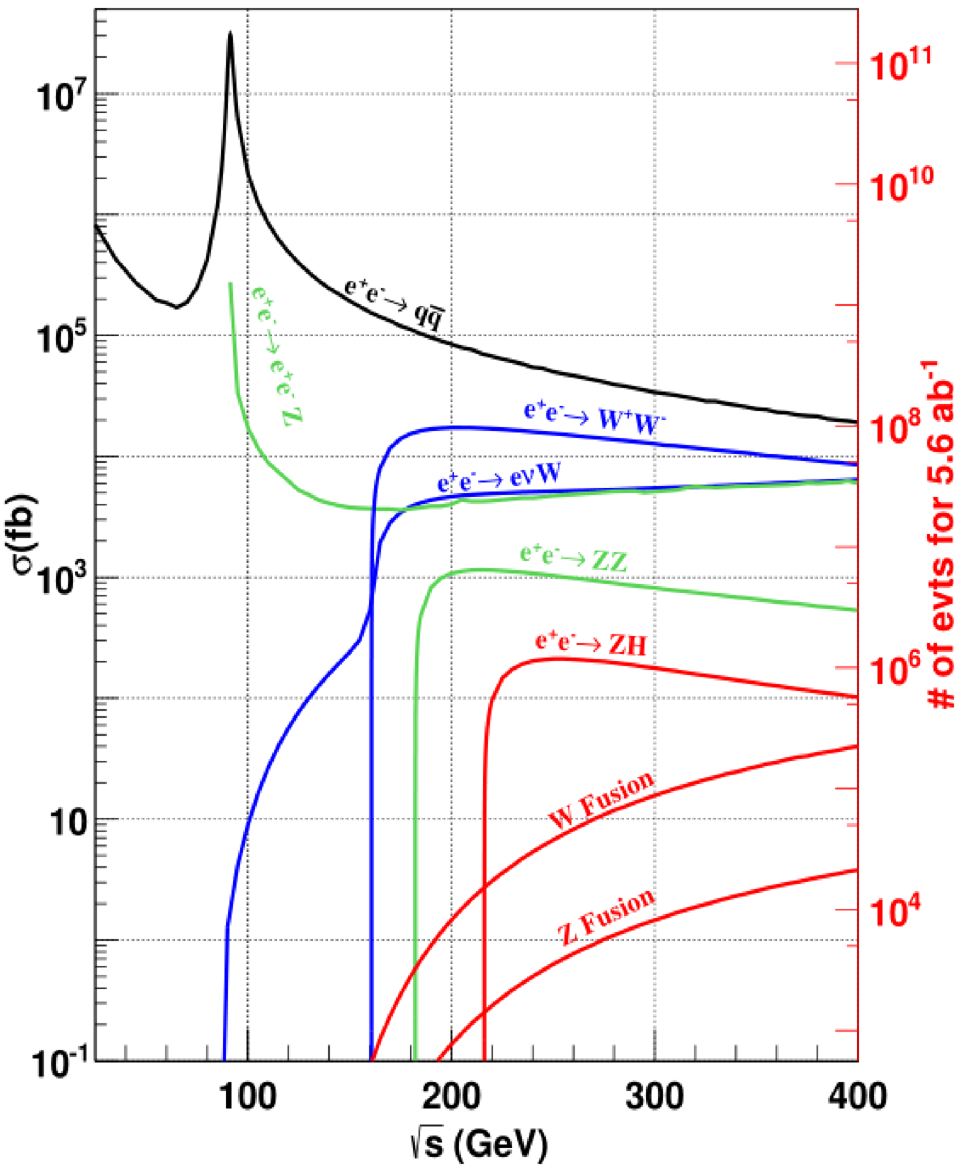
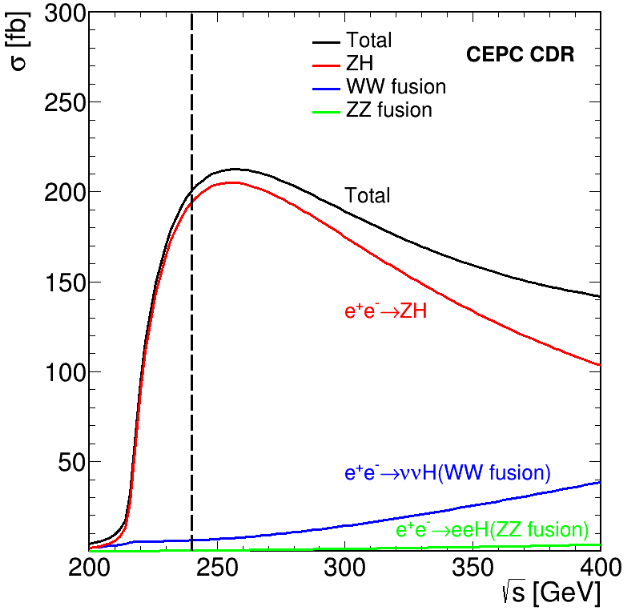
IAS Program on High Energy Physics 2020, HKUST
Physics Potential Study for Future e^+e^- Higgs Factories
18/01/2020

Circular Electron Positron Collider

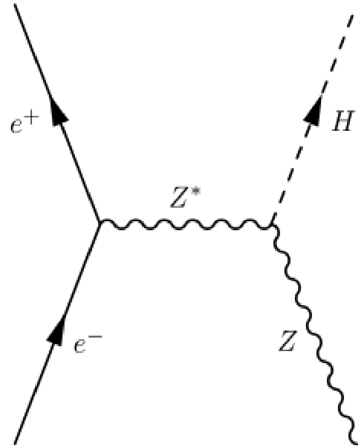




CEPC CDR: arxiv:1811.10545

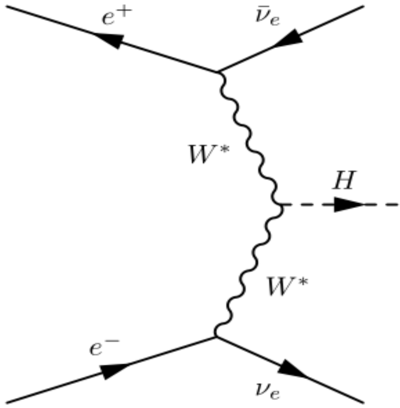
White Paper: arxiv:1810.09037

ZH:



1 Million Higgs in 240GeV, 5.6ab^{-1}

vvH:



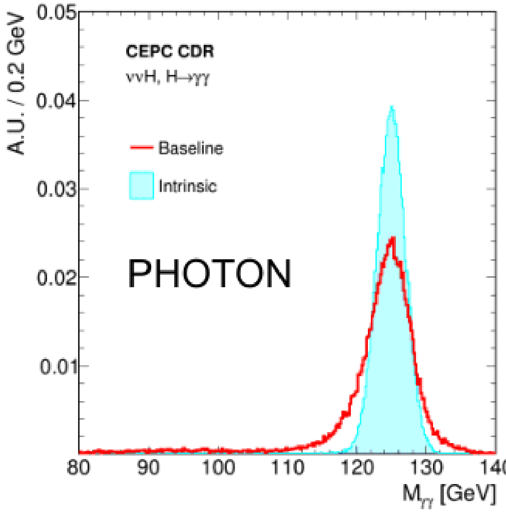
Process	Cross section	Events in 5.6 ab^{-1}
Higgs boson production, cross section in fb		
$e^+e^- \to ZH$	196.2	1.10×10^6
$e^+e^- \to \nu_e\bar{\nu}_e H$	6.19	3.47×10^4
$e^+e^- \to e^+e^- H$	0.28	1.57×10^3
Total	203.7	1.14×10^6

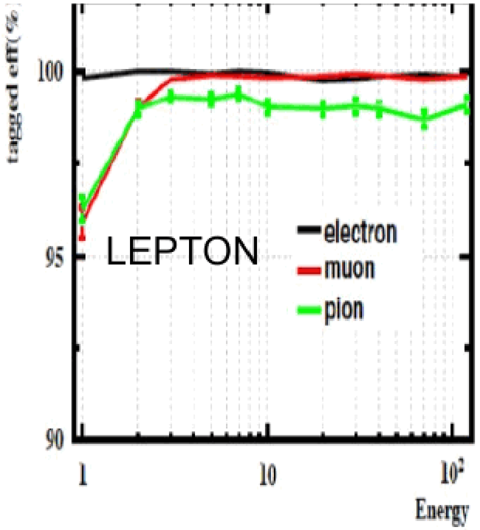
CEPC object performance

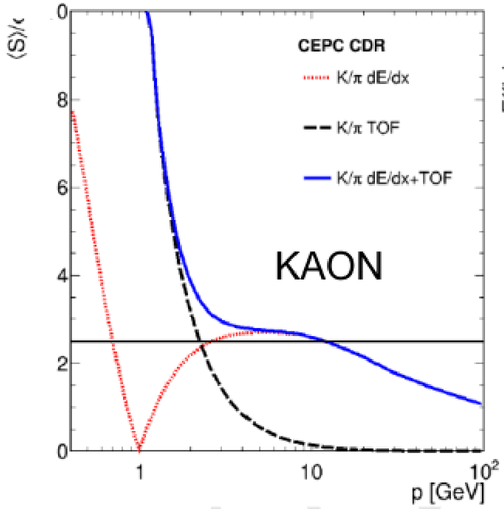
Always Evolving!

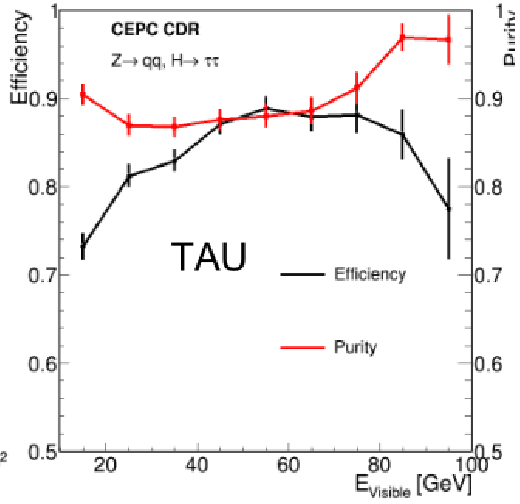
Eur. Phys. J. C (2017) 77: 591

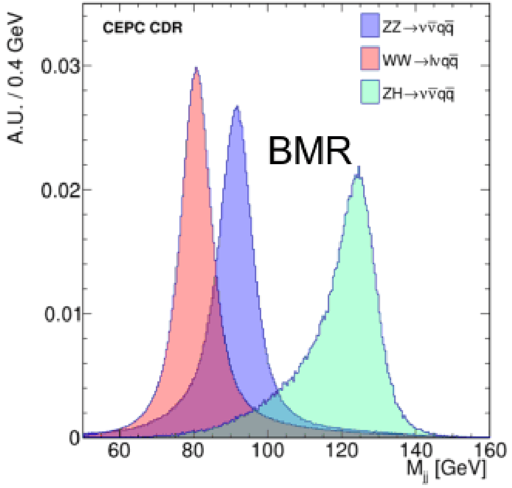
Eur. Phys. J. C (2018) 78:464

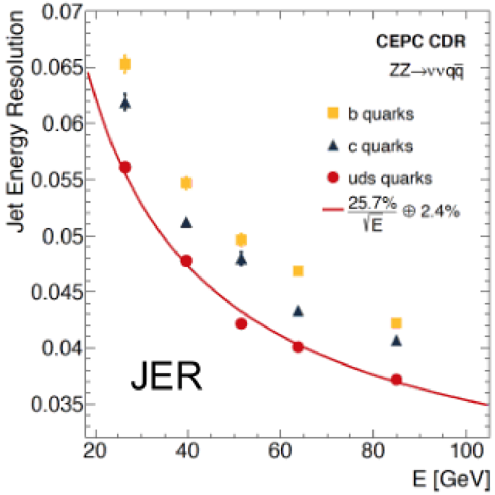


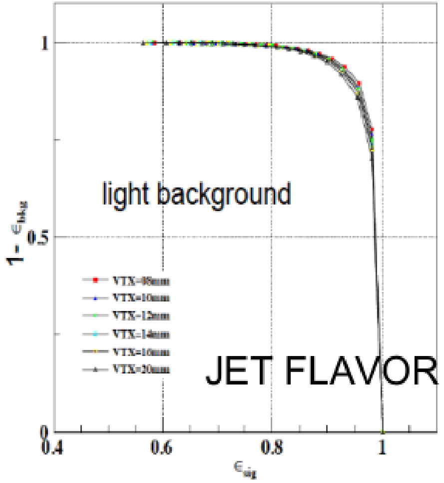


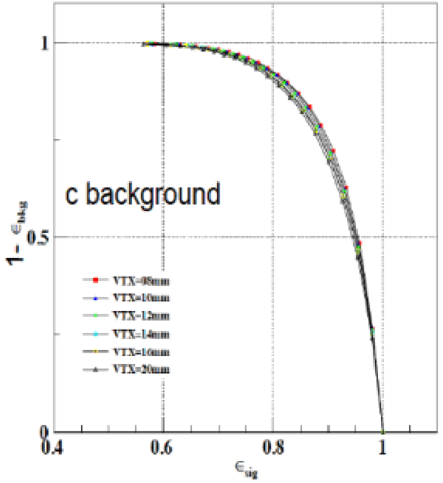






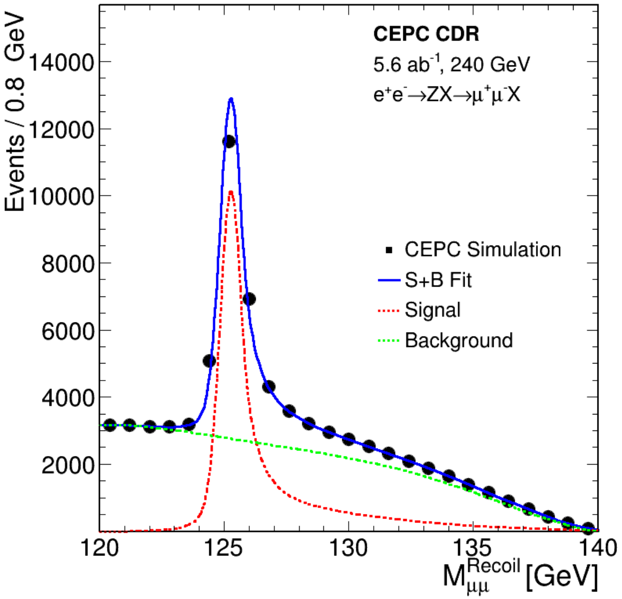


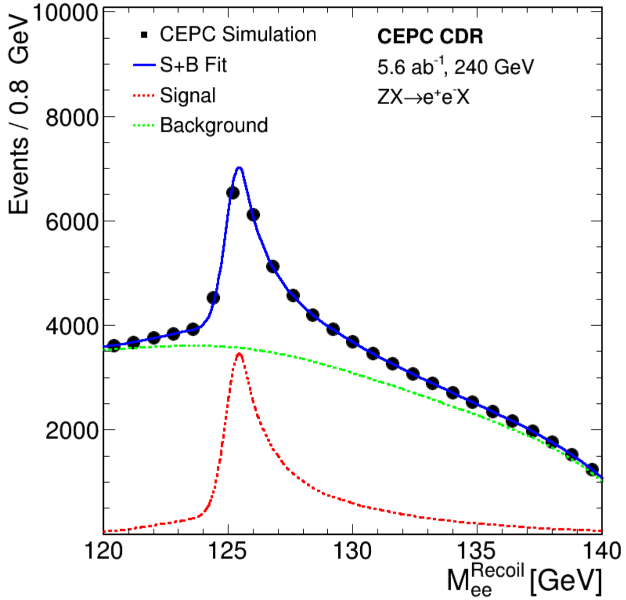


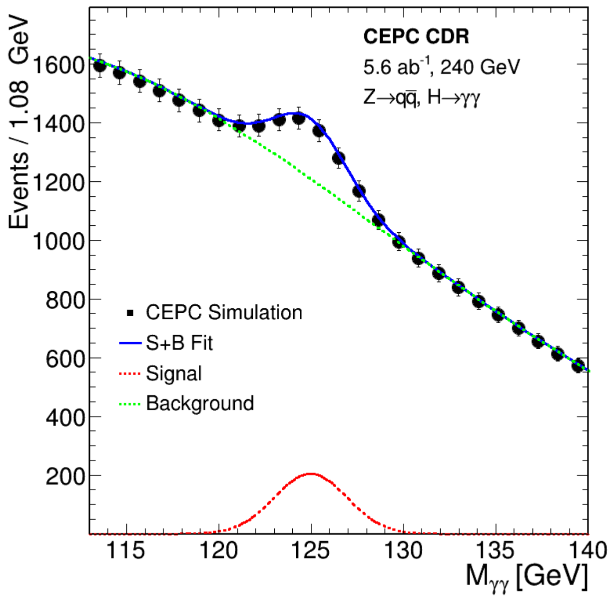


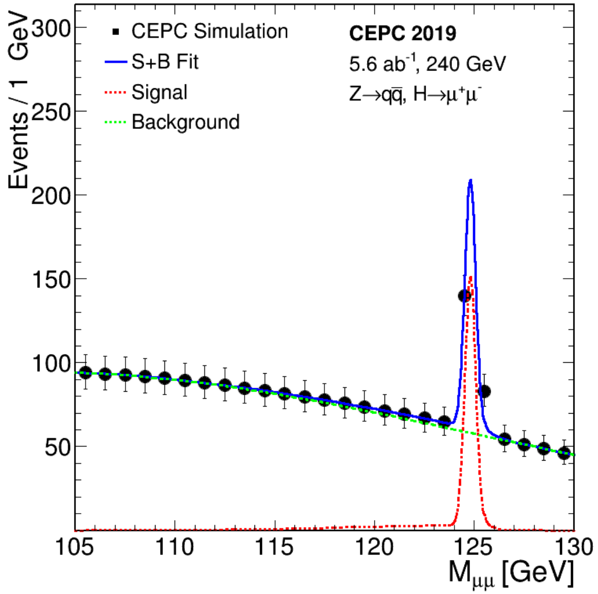
Eur. Phys. J. C (2018) 78: 426

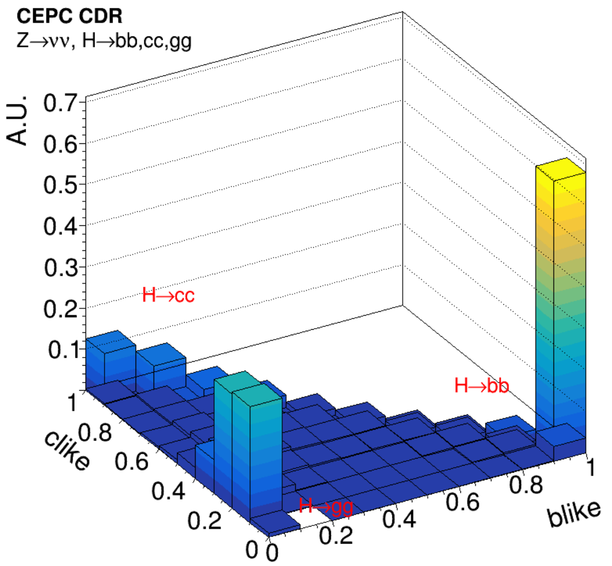
Typical individual channels

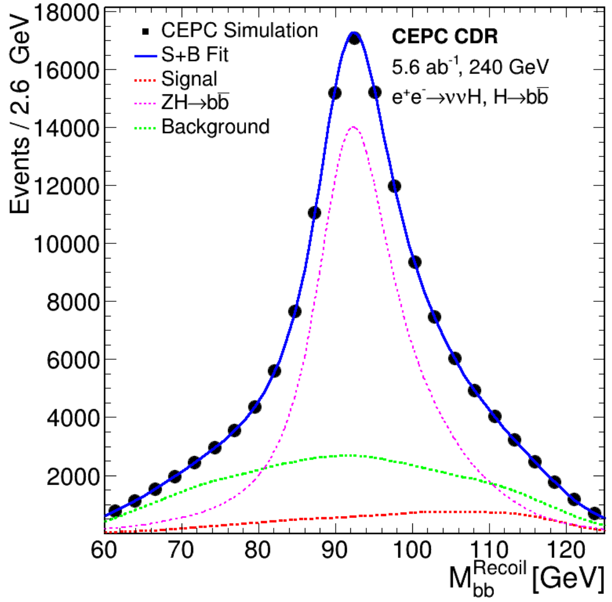


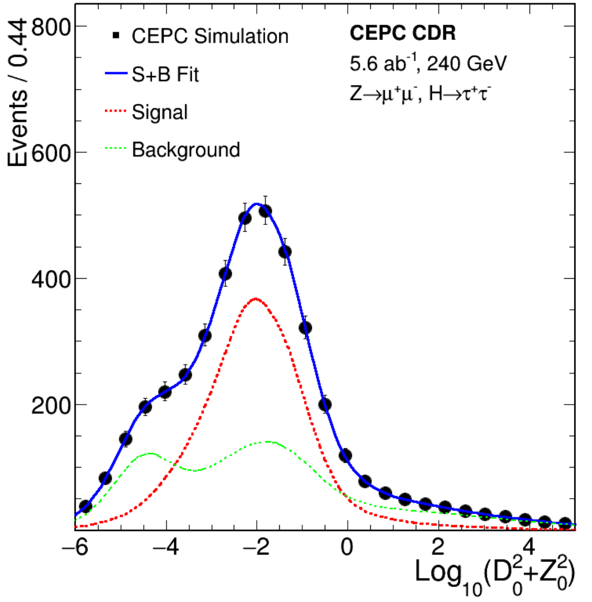












Related publications for each channel:

- $\sigma(ZH)$: 1601.05352;
- bb/cc/gg: 1905.12903;
- $\tau\tau$: 1903.12327……

Physics measurement

2020.01	240GeV, 5.6ab^{-1}	Reports Today
$\sigma(ZH)$	**0.50%**	
$\mathrm{H} \rightarrow \mathrm{bb}$	**0.27%**	
$\mathrm{H} \rightarrow \mathrm{cc}$	**3.3%**	
$\mathrm{H} \rightarrow \mathrm{gg}$	**1.3%**	
$\mathrm{H} \rightarrow \mathrm{WW}$	**1.0%**	
$\mathrm{H} \rightarrow \mathrm{ZZ}$	**5.1%**	**Ryuta Kiuchi**
$\mathrm{H} \rightarrow \tau\tau$	**0.8%**	**Dan Yu**
$\mathrm{H} \rightarrow \gamma\gamma$	**5.4%**	**Fangyi Guo**
$\mathrm{H} \rightarrow \mu\mu$	**12%**	
$\mathrm{H} \rightarrow Z\gamma$	**16%**	
$\mathrm{Br}_{\mathrm{upper}}(\mathrm{H} \rightarrow \mathrm{inv.})$	**0.24%**	**Yuhang Tan**
$\sigma(\mathrm{vv}H) * \mathrm{Br}(\mathrm{H} \rightarrow \mathrm{bb})$	**3.0%**	
Width	**3.0%**	

- Evolving analysis!
- To test the expected precision CEPC could ever reach, simultaneous combination fit is done.
- Only statistical uncertainty considered in the table.
  - theoretic and systematic uncertainties could be controlled decently on lepton collider, according to calculation.

Coupling: κ framework

- Defined as:

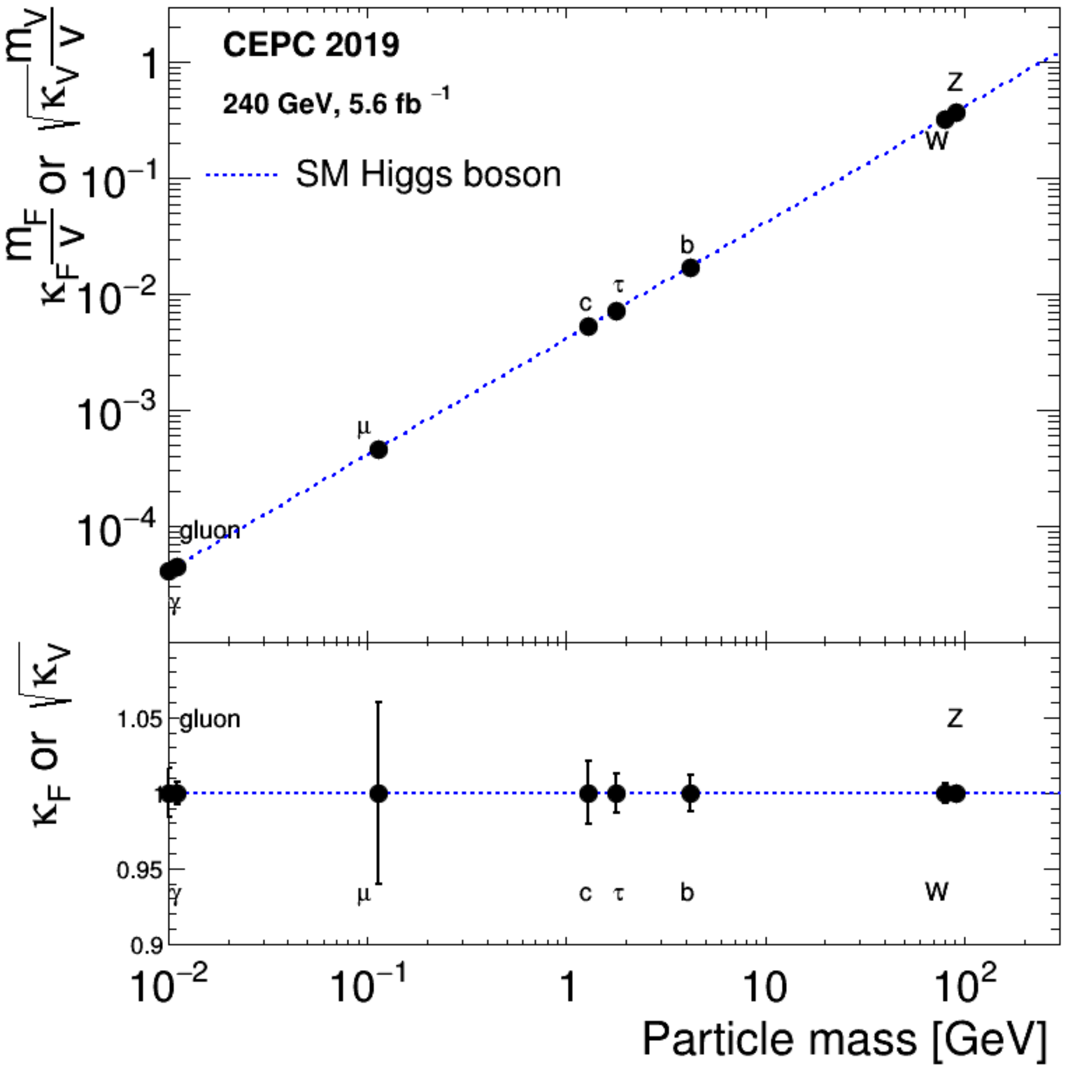
$$\kappa_Z^2 = \frac{g(HZZ)}{g_{SM}(HZZ)} = \frac{\sigma(ZH)}{\sigma_{SM}(ZH)} \qquad \text{->0.5\%;}$$

$$\sigma(\mathrm{vv}H) * \mathrm{Br}(\mathrm{H} \rightarrow \mathrm{bb}) \propto \kappa_{\mathrm{w}}^2 * \kappa_{\mathrm{b}}^2/\Gamma_H.$$

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

Extract width with branch ratio: Constrained 7-κ

Keep width independent: 10 κ

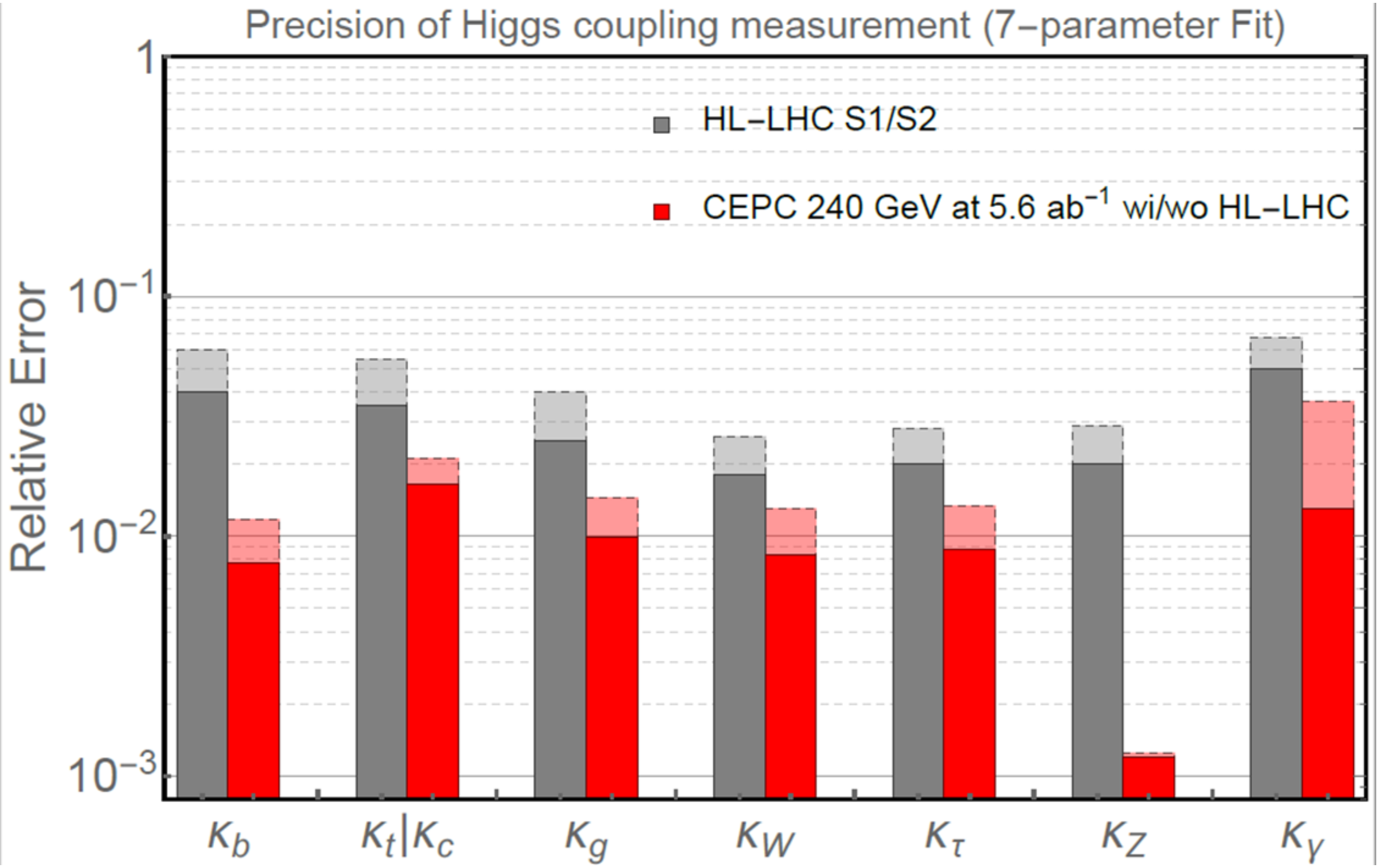


Constrained 7-κ framework

Results are updated with latest HL-LHC projections.

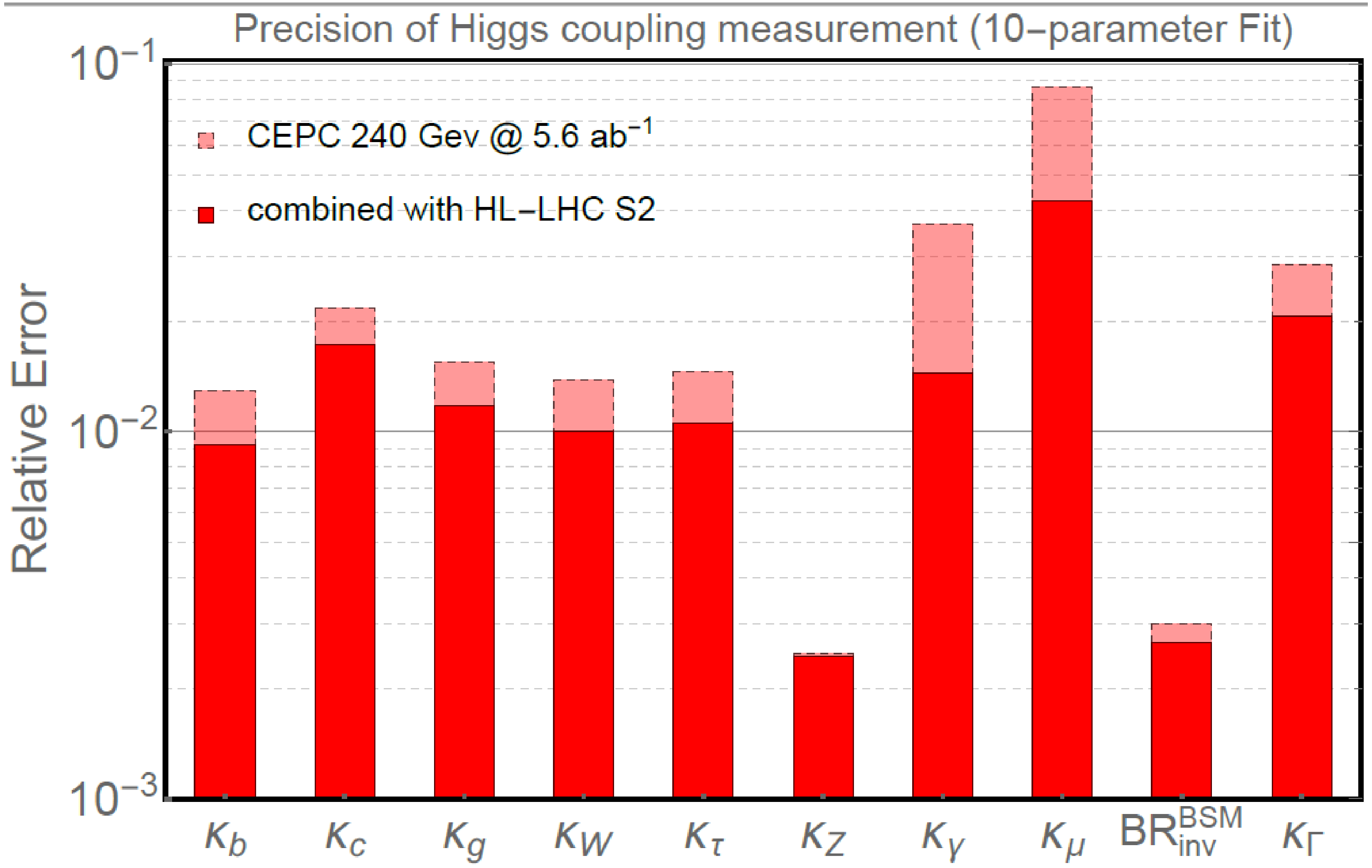
CEPC would have ~1 order of magnitude improvement compared to pp collider.

While HL-HLC has good $\gamma/lepton$ search. Add constrain like κ_γ/κ_Z would significantly improve the coupling.



Independent κ fit

Let Higgs width free. Highlights of lepton collider.



Higgs width brings a floor effect around 1.3%.

Correlation Matrix

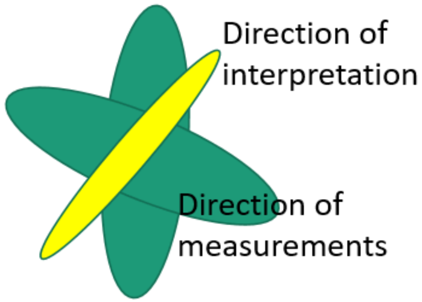
Input

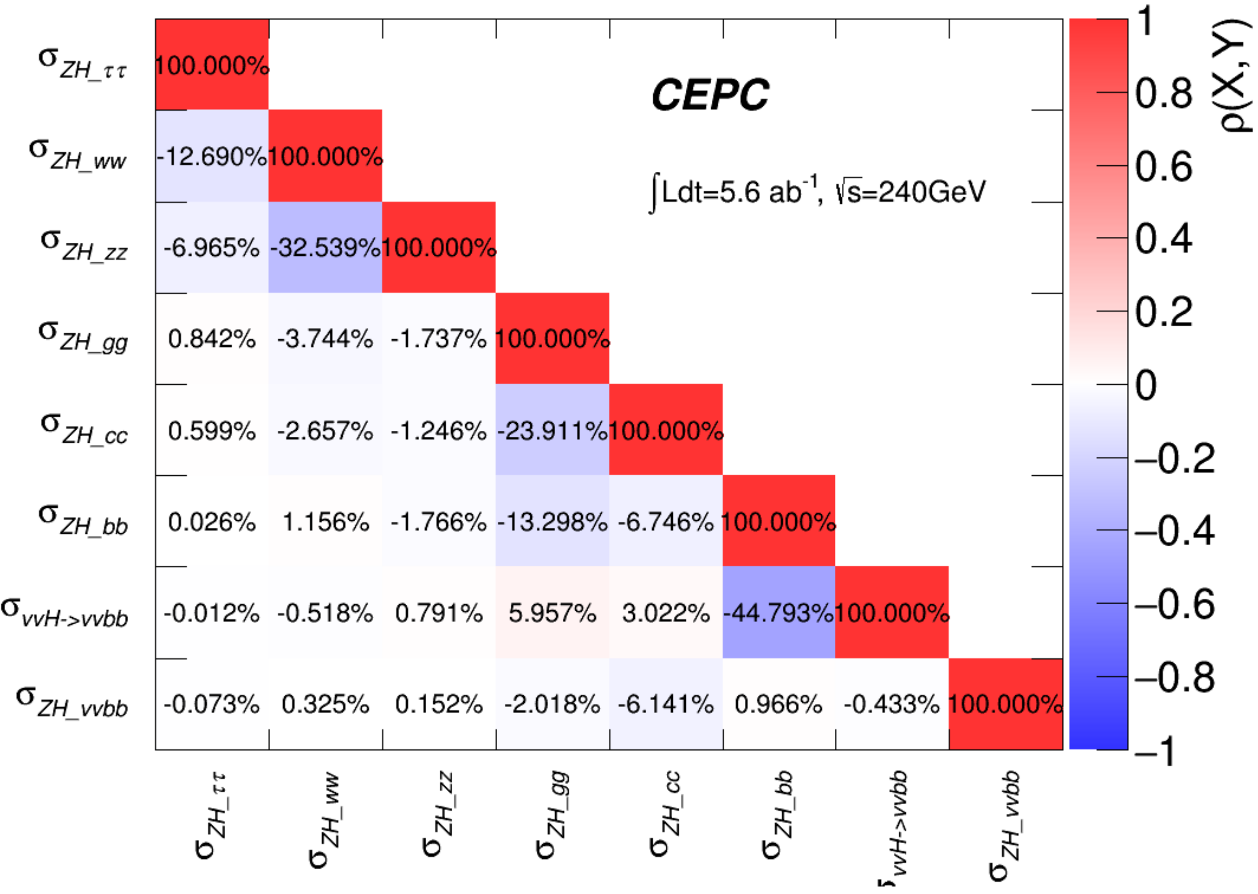
Measurement

+ Interpretation

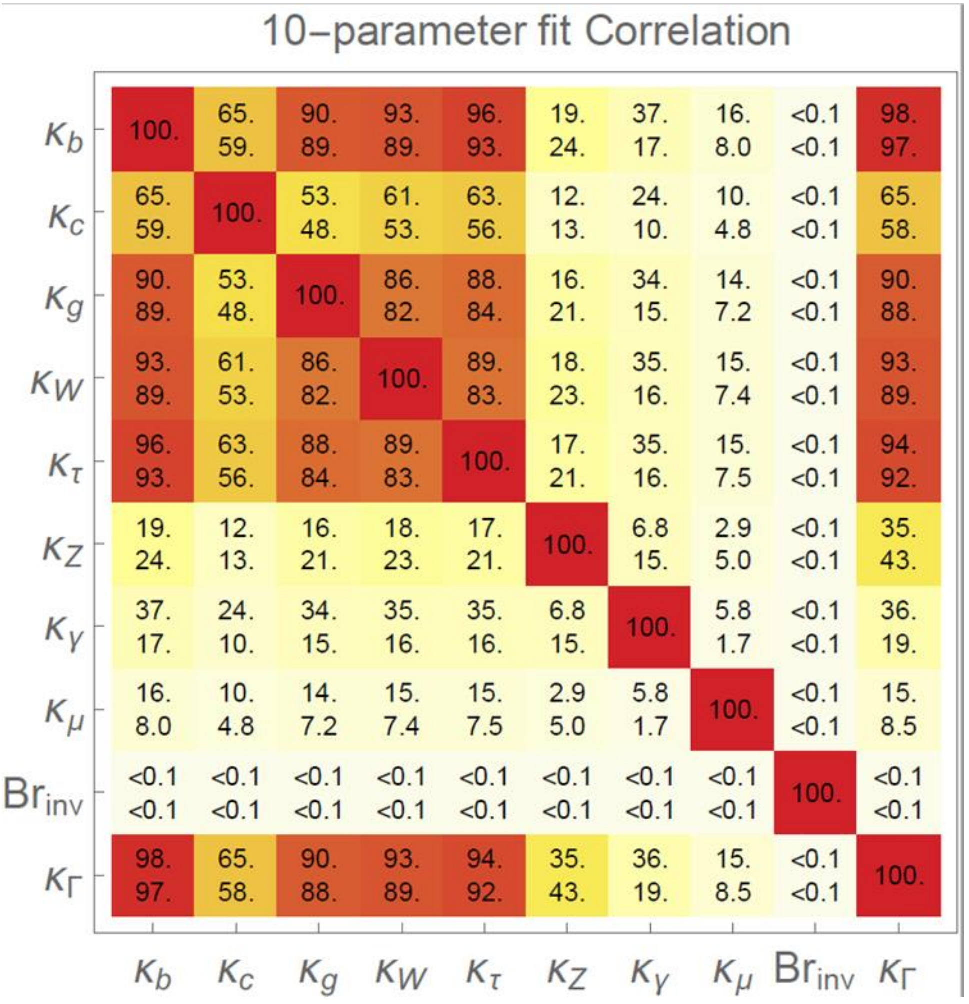
Output

Coupling





Input correlation considered in measurement.

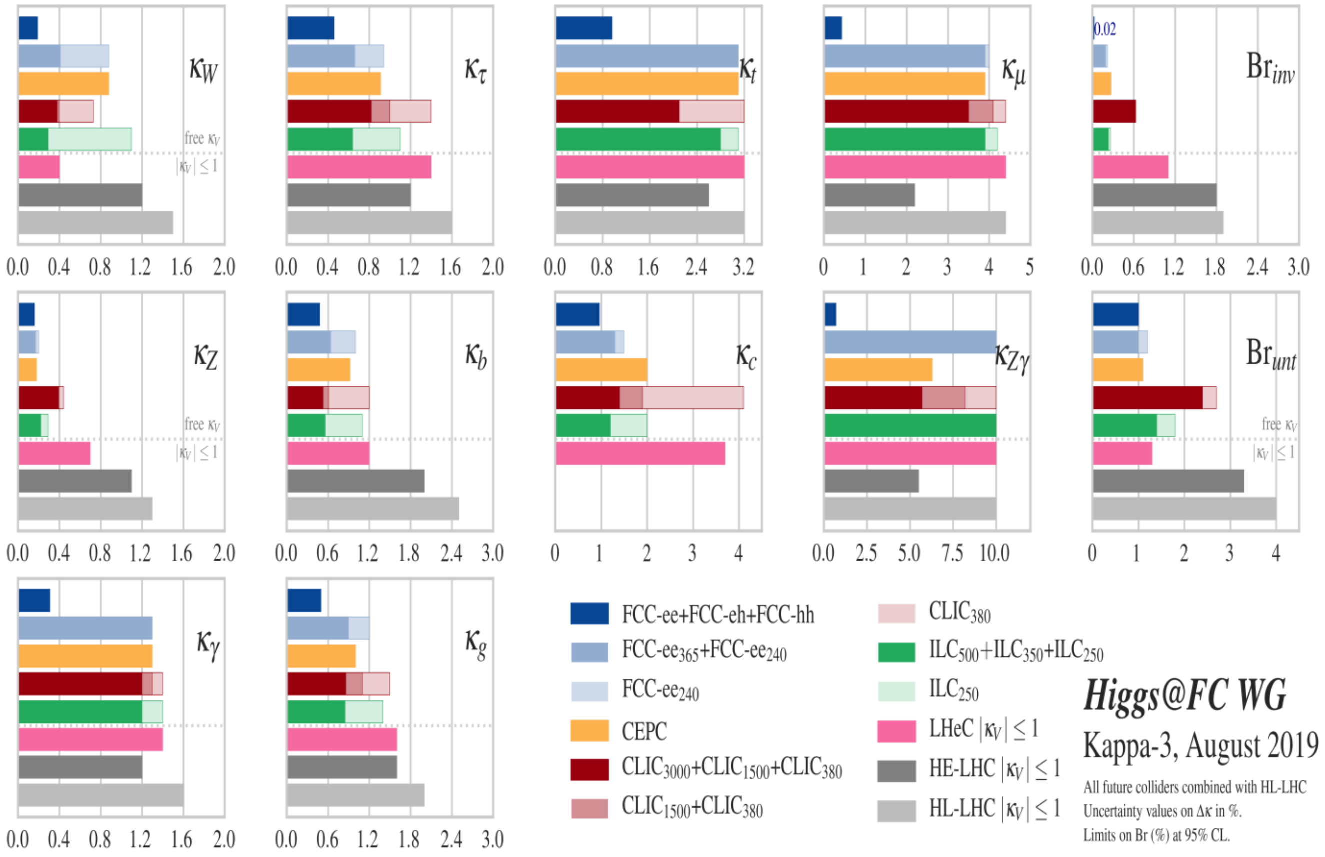


Upper entries: CEPC alone;

Lower entries: combining with HL-LHC (Corrleation reduced);

Synergies with other experiments

See: Higgs@FutureColliders WG report. arXiv:1905.03764
Inputs from CEPC evolves a bit but did not influence the comparison.



kappa-0	HL-LHC	LHeC	HE-LHC S2	HE-LHC S2′	ILC 250	ILC 500	ILC 1000	CLIC 380	CLIC 15000	CLIC 3000	CEPC	FCC-ee 240	FCC-ee 365	FCC-ee/eh/hh
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.

Future CEPC: Higher energy?

- $t\bar{t}$ run helps Higgs couplings a lot
  - Other than benefits in Top physics
  - Larger vvH cross section. Better width constrain.
  - Statistics oriented, not sensitive to specific mass point (340-365GeV)

- Fcc-ee use 0.2iab Threshold scan + 1.5iab 365GeV
- Current temporary benchmark for CEPC extrapolation: 2 iab @ 365GeV
  - Up to now, CEPC has NO OFFICIAL PLAN for higher energy run.

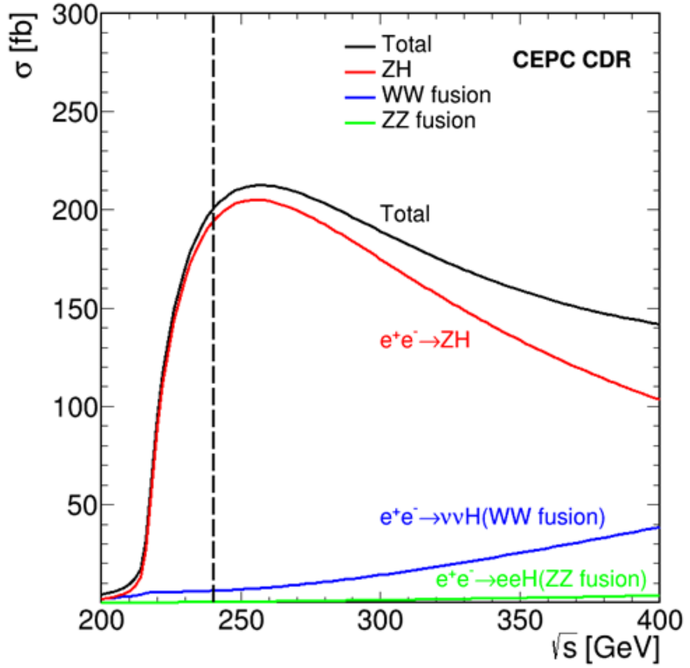
Major Processes

Cross section numbers in table calculated by Whizard.

Temporary

fb	240	350	360	365	365/240
ZH	196.9	133.3	126.6	123.0	-38%
WW fusion	6.2	26.7	29.61	31.1	+401%
ZZ fusion	0.5	2.55	2.80	2.91	+482%
Total	203.6		159.0	157.0	
Total Events	1.14M		0.32M	0.31M	

pb	240	350	360	365	365/240
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%
$t\bar{t}$	\	0.49	0.60	0.65	+
sZ	4.54	5.72	5.78	5.83	+27%
sW	5.09	5.89	6.00	6.04	+18%

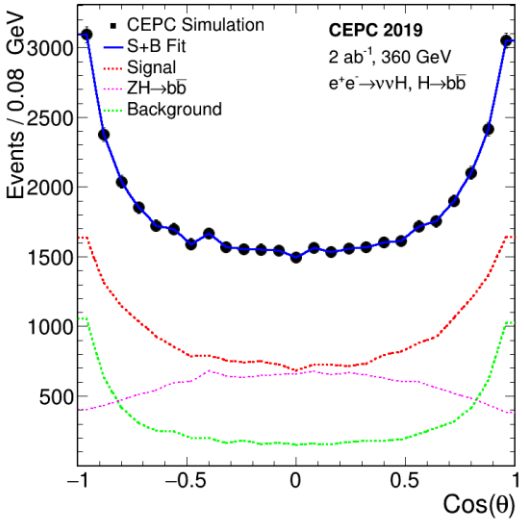


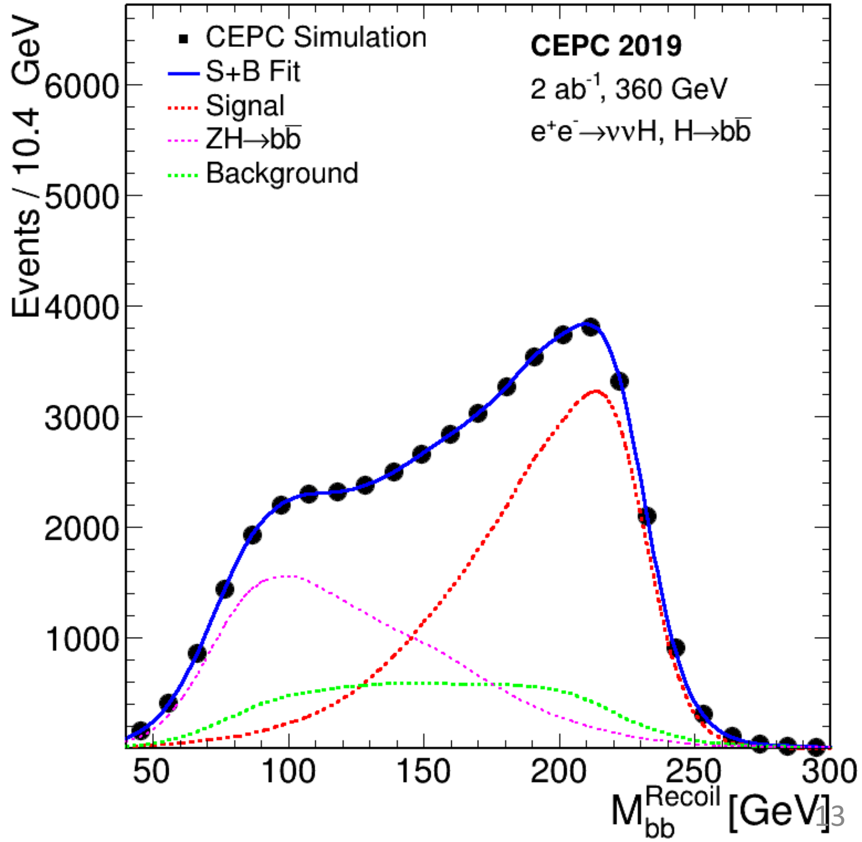
In total ~1.45M Higgs would be collected in CEPC 240+365GeV.
Interference between ZH and vvH considered.
More higgs events expected in 360GeV than 365GeV.
So we scale the processes according to the yields, to extrapolate to 360GeV from the existing 240GeV.

vvH->bb, 360GeV full simulation

Done by Hao Liang;

- 2d Recoil qq + Cos θ_{qq} Fit
- Clear separation between ZH and vvH.
- Constrain from other ZH->bb($ee, \mu\mu, qq$) considered
  - $\sigma(\mathrm{vv}H) * \mathrm{Br}(\mathrm{H} \rightarrow \mathrm{bb})$:0.76%
  - $\sigma(\mathrm{Z}H) * \mathrm{Br}(\mathrm{H} \rightarrow \mathrm{bb})$: 0.63%
  - share the anti-correlation -15.8%.
  - Much better than 240GeV 3%.





Higgs width

- Now CEPC Higgs width is fitted in the 10- κ framework.
- Adding one mass point would significantly improve the constrain.
  - Much more vvH event and better separation. Significantly improve the constrain.
    - No more floor effect. Now coupling could be better than ½ $\Delta(\Gamma_H)$.
  - Standalone 240GeV gives 3.0%, while 360GeV alone gives 2.8%.
  - Combined fit

$$\Delta(\Gamma_H) \approx 1.4\%$$

*: Fcc-ee assumes that exotic Br can not smaller than 0. This assumption lower the negative side, Like (-1.2%, 1.4%). Then Fcc use median 1.3%, We didn't take this assumption.

Higgs measurement extrapolations

Temporary

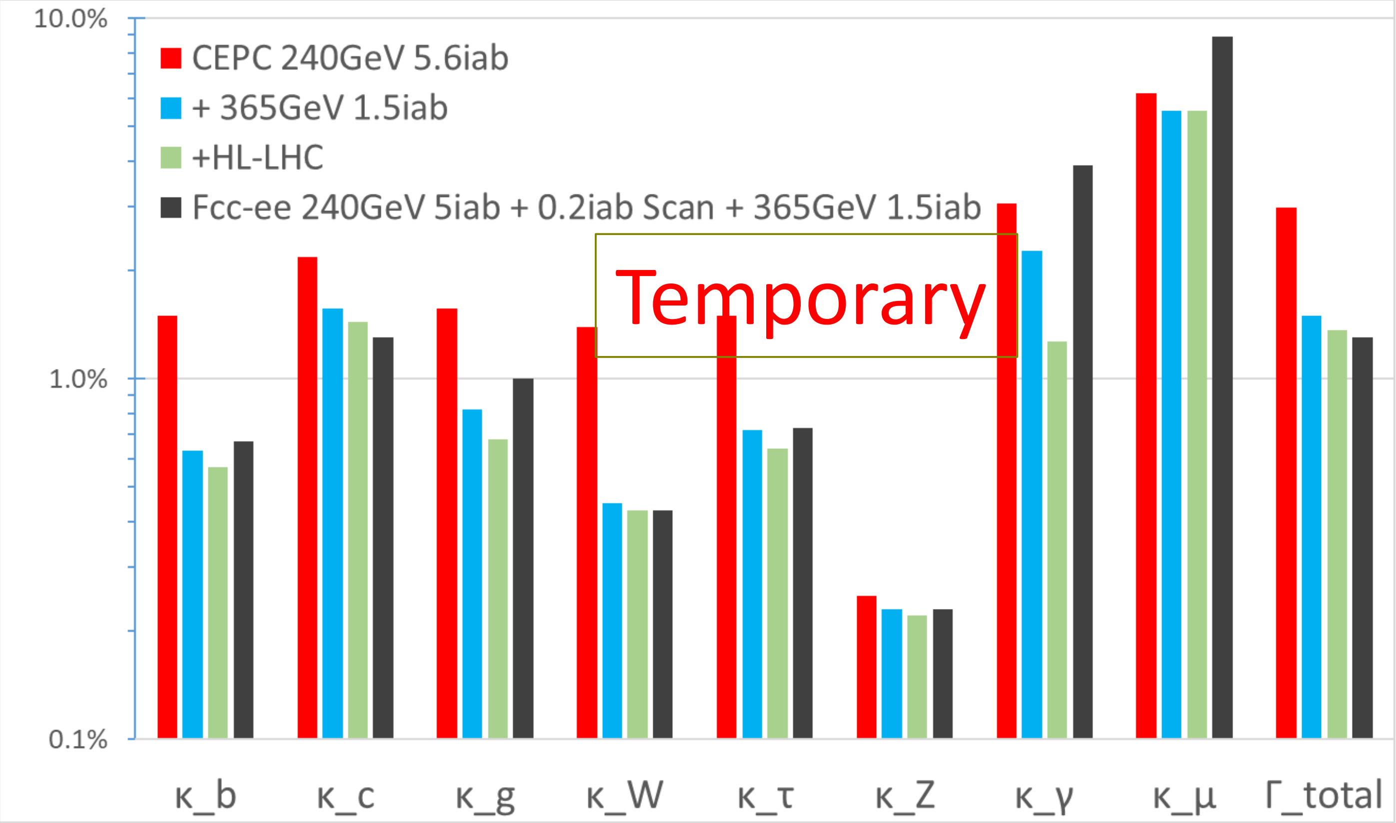
2020.01	240GeV, 5.6ab^{-1}	360GeV, 2ab^{-1}	
	ZH	ZH	ννH
any	**0.50%**	**1%**	****
$H \to bb$	**0.27%**	**0.63%**	**0.76%**
$H \to cc$	**3.3%**	**6.2%**	**11%**
$H \to gg$	**1.3%**	**2.4%**	**3.2%**
$H \to WW$	**1.0%**	**2.0%**	**3.1%**
$H \to ZZ$	**5.1%**	**12%**	**13%**
$H \to \tau\tau$	**0.8%**	**1.5%**	**3%**
$H \to \gamma\gamma$	**5.4%**	**8%**	**11%**
$H \to \mu\mu$	**12%**	**29%**	**40%**
$Br_{upper}(H \to inv.)$	**0.24%**	****	****
$\sigma(ZH) * Br(H \to Z\gamma)$	**16%**	**25%**	****
Width	**3.0%**	**1.4%**	

Generally, since the extrapolation is not so accurate, expected CEPC measurement would be comparable with Fcc-ee.
So for Higgs coupling, also similar performance could be expected.
Higgs Performance would not have huge deviation for 360 and 365GeV.

Compared to Fcc-ee

Note that Fcc-ee κ_Z number in CDR 0.17% result is Γ constrained fit. Γ free fit would give same result as CEPC.

	CEPC 240 5.6iab	
	+ 365 1.5iab	+HL-LHC
κ_b	0.63%	0.57%
κ_c	1.57%	1.44%
κ_g	0.82%	0.68%
κ_W	0.45%	0.43%
κ_τ	0.72%	0.64%
κ_Z	0.23%	0.22%
κ_γ	2.26%	1.27%
κ_μ	5.53%	5.52%
Γ_{total}	1.49%	1.36%

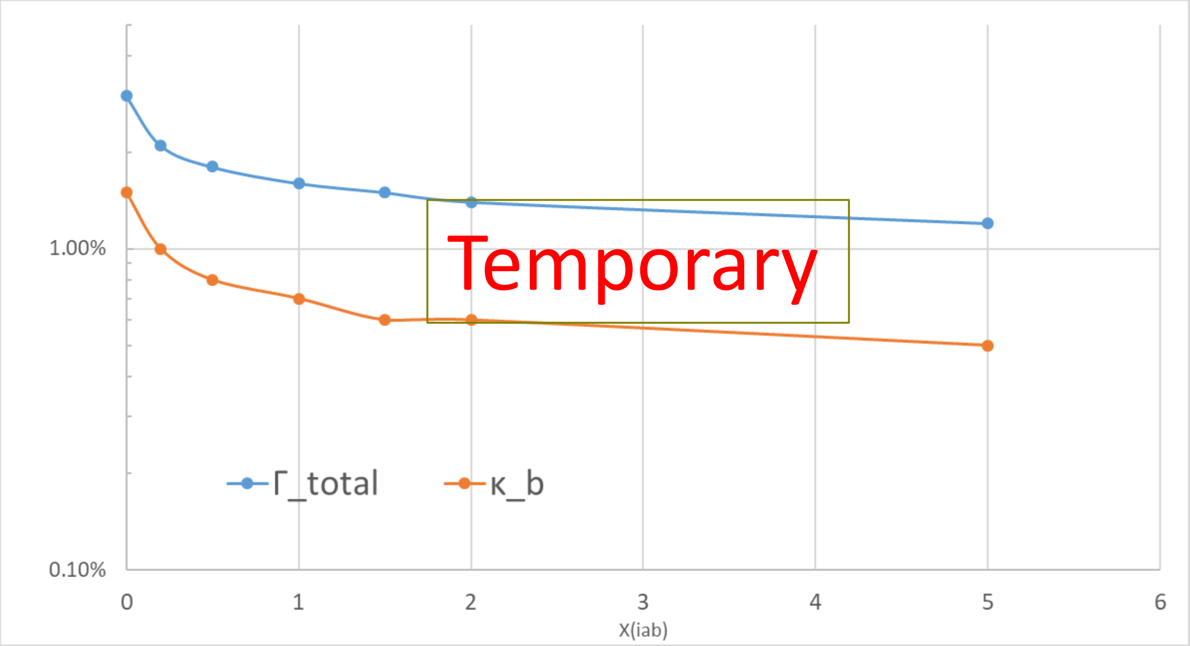


$\kappa_b, \kappa_W, \kappa_Z$ could be expected to have excellent precision in ttbar threshold run, since $\sigma(\mathrm{vv}H) * \mathrm{Br}(\mathrm{H} \rightarrow \mathrm{bb}) \propto \kappa_{\mathrm{w}}^2 * \kappa_{\mathrm{b}}^2/\Gamma_H$.

So CEPC shares similar performance as Fcc-ee. Other calculation in arXiv:1905.03764 could be extrapolated, accordingly.

Different time scale on $t\bar{t}$ run

+365GeV Xiab	0	0.2	0.5	1	1.5	2	5
κ_b	1.5%	1.0%	0.8%	0.7%	0.6%	0.6%	0.5%
κ_c	2.2%	1.9%	1.8%	1.6%	1.6%	1.5%	1.3%
κ_g	1.6%	1.2%	1.0%	0.9%	0.8%	0.8%	0.6%
κ_W	1.4%	0.9%	0.7%	0.5%	0.5%	0.4%	0.3%
κ_τ	1.5%	1.1%	0.9%	0.8%	0.7%	0.7%	0.6%
κ_Z	0.3%	0.3%	0.2%	0.2%	0.2%	0.2%	0.2%
κ_γ	3.1%	2.8%	2.6%	2.4%	2.3%	2.1%	1.7%
κ_μ	6.2%	6.0%	5.9%	5.7%	5.5%	5.4%	4.7%
Γ_{total}	3.0%	2.1%	1.8%	1.6%	1.5%	1.4%	1.2%



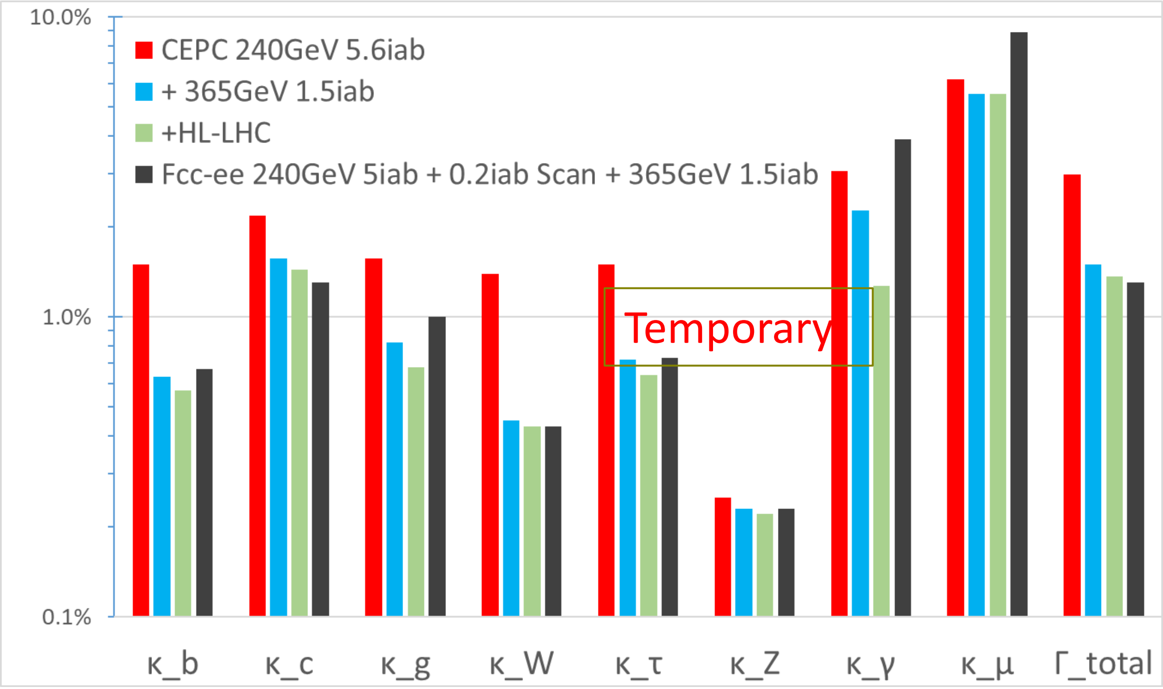
2iab data may need long time to take, so shorter statistics is also acceptable for Higgs physics.

Even only threshold scan (200fb) would help Higgs coupling. (3% -> 2.1%)

Considering cost, we do not need too much events on $t\bar{t}$ run.

Summary

- CEPC Expected Higgs measurement precision and coupling results shown.
- Synergies with other experiments shown -> Comparable.
- Extrapolations to higher energy
  - One $t\bar{t}$ run could improve Higgs coupling a lot.
  - Do not care too much for mass point;
  - Do not need too much statistics;
- Significant improvement could be made.

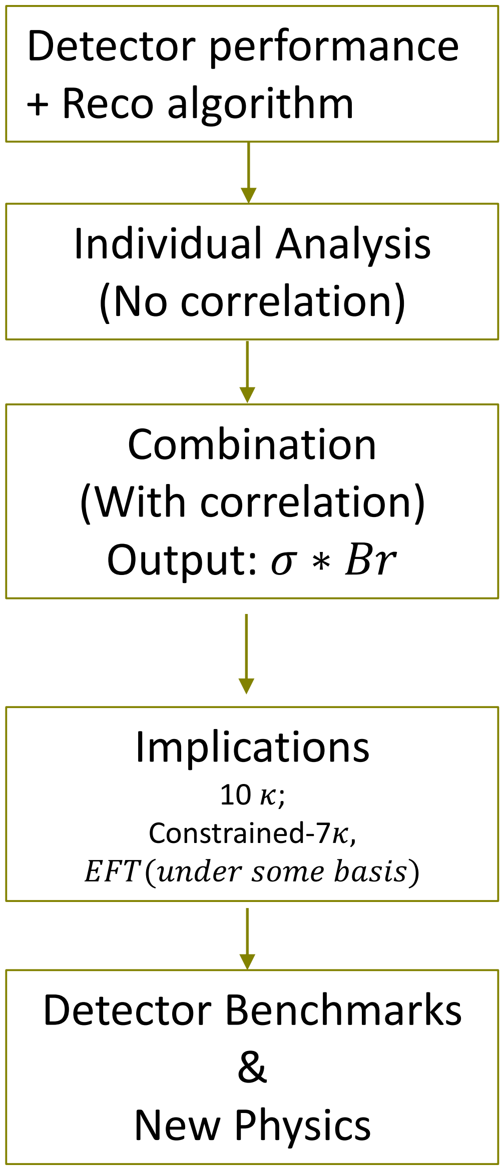


backups

- Good enough results, still a lot of to do
  - Analysis update slowly. Esp. for some crucial channels.
  - Results in performance part didn’t enter the combination yet. like jet separation, tau finding……

  -> Limited manpower, Your effort would be appreciated!

  - Still need to understand the correlation
  - Far from the CEPC fully/ultimate potential. 1M higgs!
    - Matrix element method?



$\sigma(ZH)$: 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

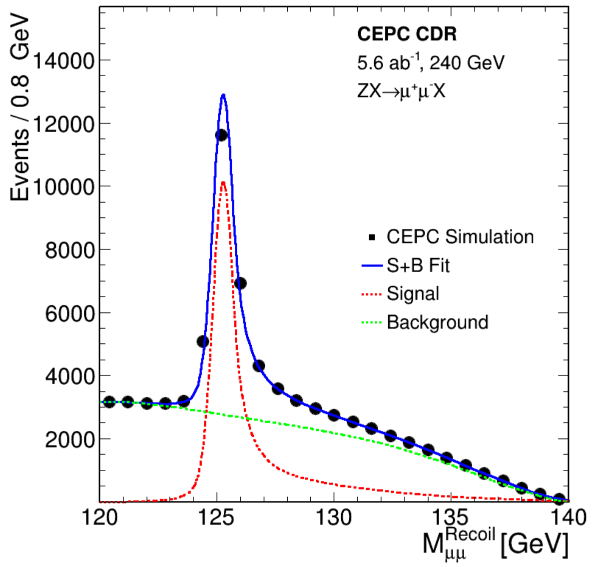


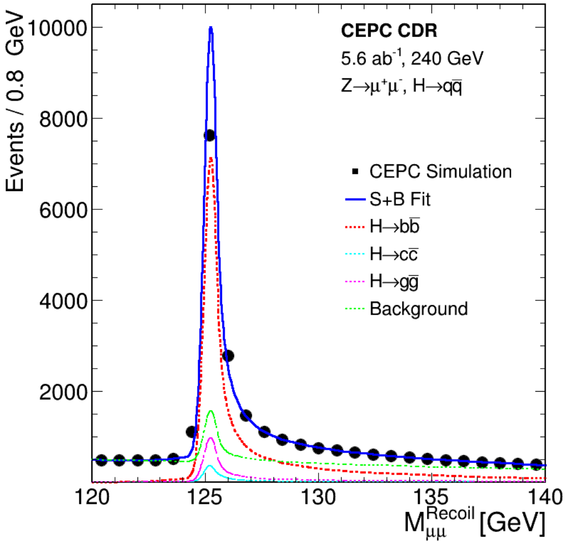
Table 3. Estimation of biases of σ_{ZH} caused by potential variances of the Higgs decay branching ratios.

Decay mode	Bias($\times10^{-4}$)
$H\to b\bar{b}$	-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

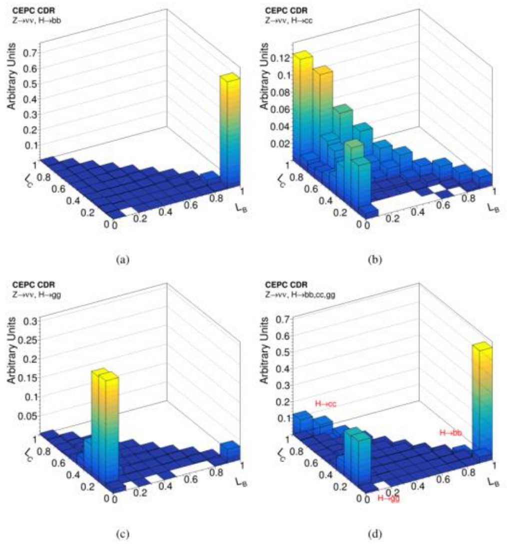
Full hadronic jets: bb/cc/gg/WW/ZZ

- 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%



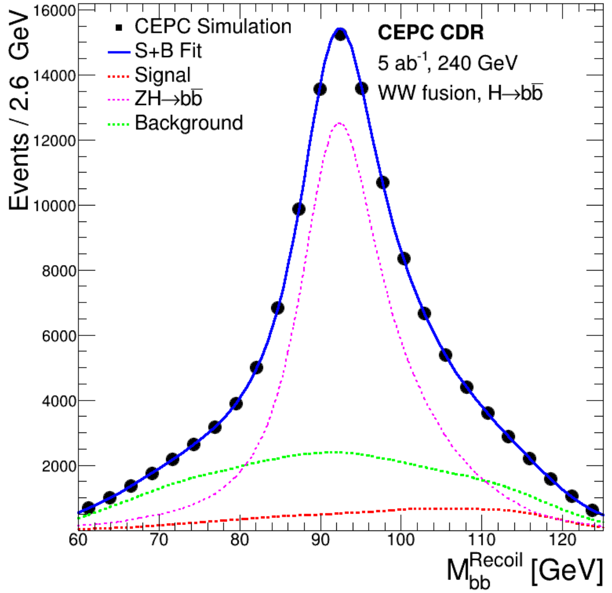
- Plan to apply categories like STXS for hardonic jets.

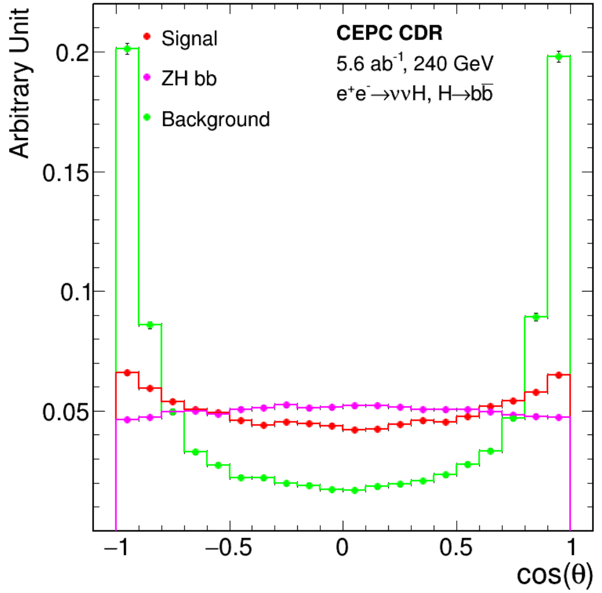


Current combination didn't use the full hadronic W/Z
and b/c/g correlation value. More study are needed to understand.

$vvH \to bb$

- 2d fit M_{jj}^{reco} & $\text{Cos}\ \theta_{jj}$
- $vvH \to bb$ and $ZH \to bb$
  - 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%.
  - $vvH \to bb$ and $ZH \to bb$ share the anti-correlation -45%. (-34% in ILC(1708.08912))
- $\sigma(vvH) * Br$： 3.0% ;
  - $\sigma(vvH)$: 3.2%.

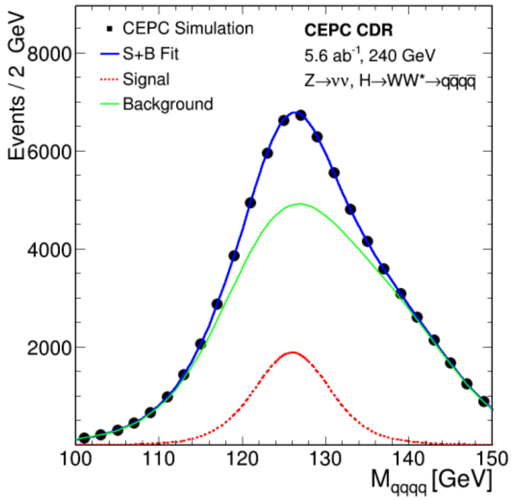


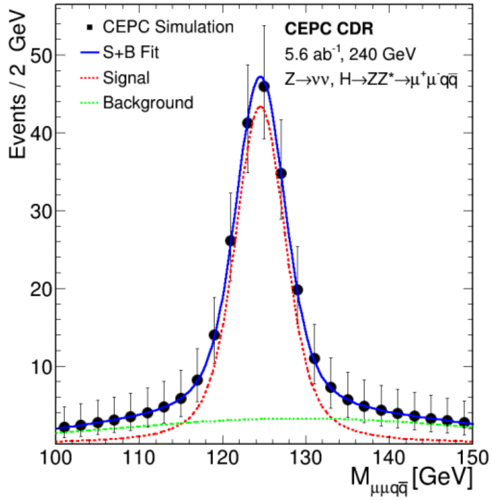


WW, ZZ

- ZZ
  - Pre_CDR ZZ result extrapolated from Fcc-ee. Overestimated;
  - Current ZZ study suffered from huge background
  - Also gained contribution from H → bb/cc/gg/WW decay.

- WW
  - Much more channels studied since Pre_CDR.





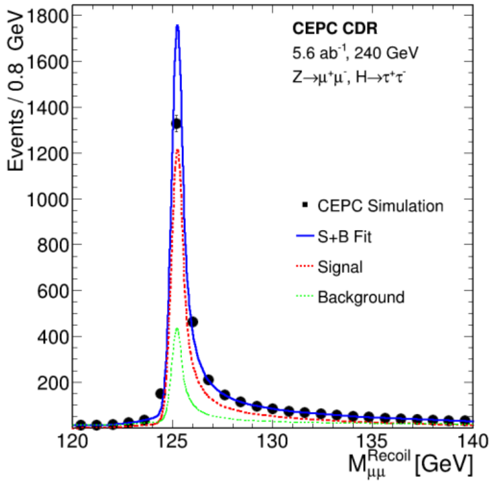
Green: studied
Yellow: Problematic

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

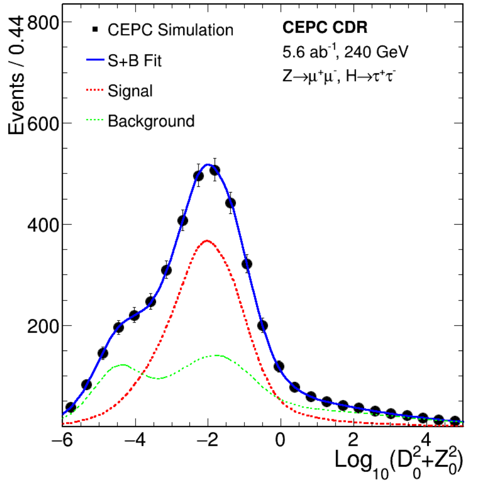
	Z	ee	μμ	νν	qq
ZZ	ee+qq				
	μμ+qq				
	νν+qq				
	ll+ll				
(Invi)	νν+νν				
	qq+qq				
	ll+νν				

$\tau\tau, \mu\mu$

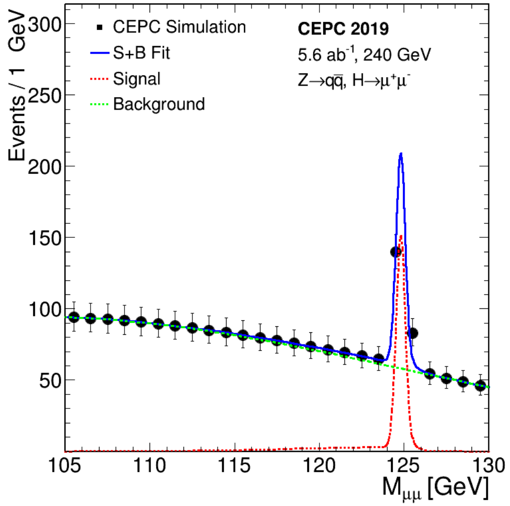
- $\tau\tau$:
  - Develop LICH to identify lepton. Eff>99%
  - Signal and ZH events(Main WW) share the same shape
  - use $\log_{10}(D_0^2 + Z_0^2)$ + mass 2d fit to separate signal
    - Impact parameter, Distance from beam spot
- $\mu\mu$
  - By Kunlin



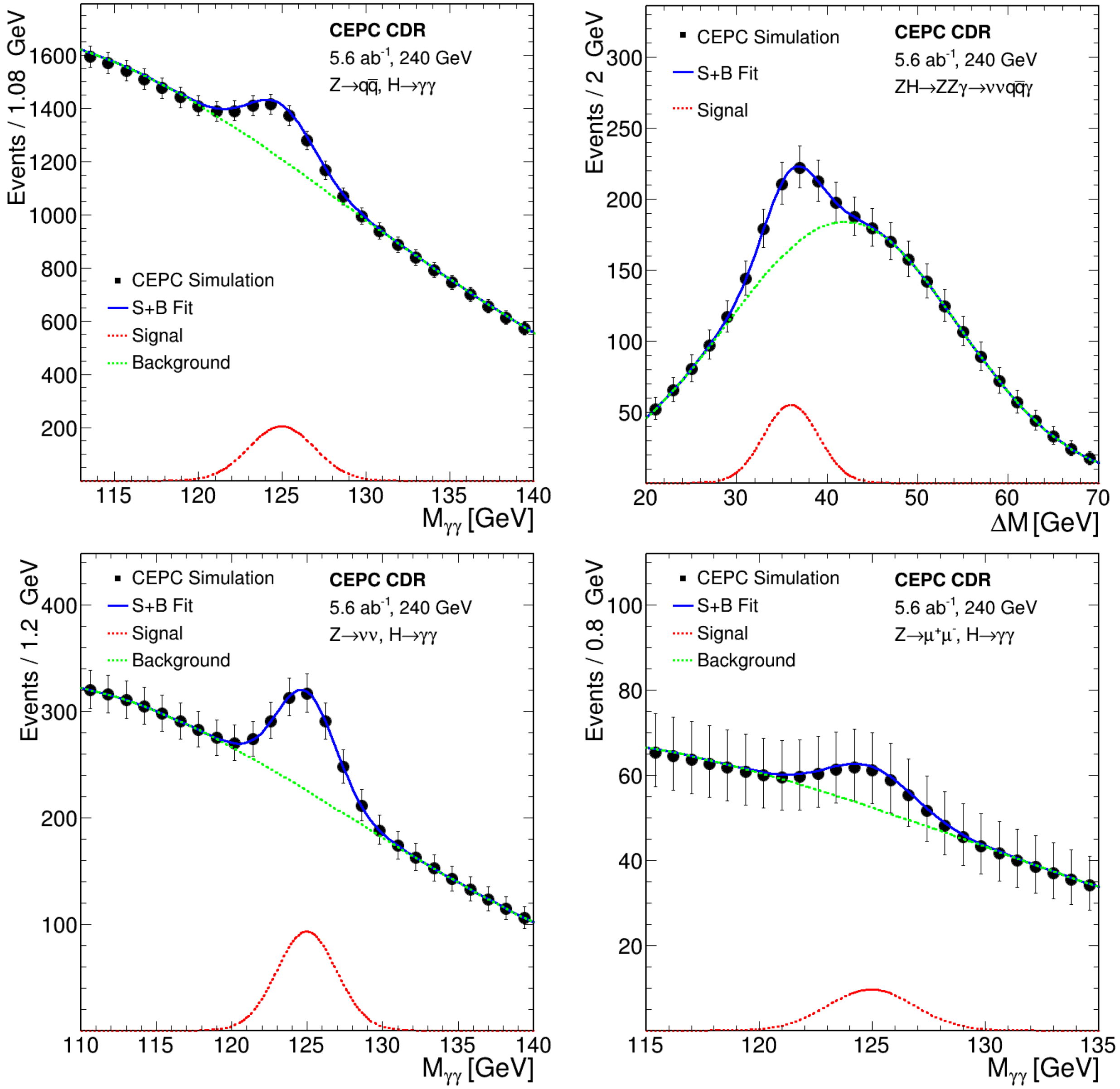
ZH final state		Precision
$Z\to\mu^+\mu^-$	$H\to\tau^+\tau^-$	2.6%
$Z\to e^+e^-$	$H\to\tau^+\tau^-$	2.7%
$Z\to\nu\bar{\nu}$	$H\to\tau^+\tau^-$	2.5%
$Z\to q\bar{q}$	$H\to\tau^+\tau^-$	0.9%
Combination		0.8%



	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



$\gamma\gamma, Z\gamma$



- Use $\mathrm{m}_{\gamma\gamma}, \mathrm{m}_{\gamma\gamma}^{recoil}$ 2d fit to improve $\gamma\gamma$ precision.
- MVA improved more
- Photon convention not counted in current study.