CEPC Higgs Combination

Zhang Kaili[1], Wang Jin[1], Liu Zhen[2]

1.Institute of High Energy Physics
2.University of Maryland

The 2018 International Workshop on the High Energy Circular Electron-Positron Collider

2018, Nov. 13 Beijing

Outline

- Motivations
- Individual channel status
- Input correlations
- Fit results
- Summary

Why Combination?

- In current CEPC study, with S/B MC sample
  - Expected precision for each channel can be calculated
- Uniformed, simultaneous statistical framework
  - Get likelihood scan result   Robust & Reliable;
  - Correctly consider the correlations from individual inputs
    - Full Hadronic;   ZH bkg；   WW fusion; width……
  - Extensibility
    - Extrapolations, systematic uncertainties, theoretic assumptions
    - Currently uncertainties are statistical dominant.
  - Currently, with MC sample
    - Build Asimov data from signal and bkg spectrum
  - To get the estimated precisions of $\sigma * Br$, and κ.
    - Also other interesting values, significance, upper limits……

Individual Study
(No correlation)

↓

Combination
(With correlation)

↓

Implications like
κ, EFT … …
For physics models.

Fit techniques

- For each channel
  - Input observables from MC sample. Use unbinned, multi-dimensional input if possible;
  - Establish combined S+B Pdf: N_{bb}*Pdf+N_{cc}*Pdf_{cc}+……+N_{bkg}*Pdf_{bkg}

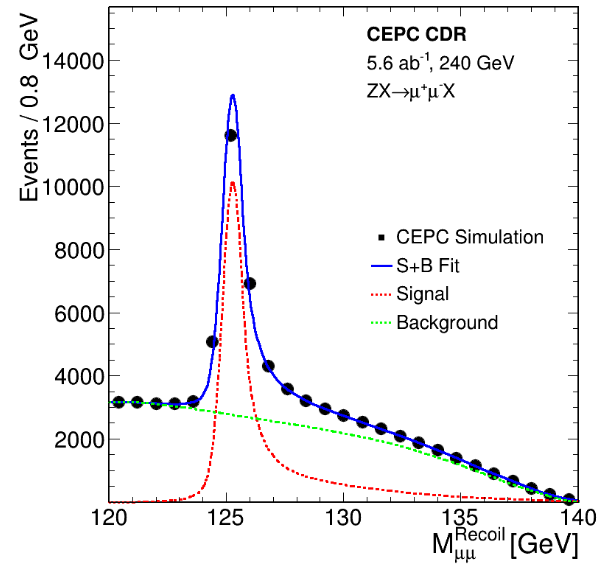
    Different components coupled this way;
  - Event yield N_{bb} can be described in the following scenario:
    - $N_{bb} = N_{bb\_SM} * \mu_{bb}$ $\sigma * Br$ N_{bb_SM} directly from SM prediction ($5.6ab^{-1}$)
    - $N_{bb} = N_{bb\_SM} * \frac{Br}{Br_{SM}} * \frac{\sigma(ZH)}{\sigma(ZH)_{SM}}$ Br $\Delta(\sigma(ZH)) = 0.50\%$
    - $N_{bb} = N_{bb\_SM} * \kappa_Z^2(\kappa_W^2) * \kappa_b^2/\Gamma_H$ κ
  - Channels share the same μ. e.g. $Z \to ee, \mu\mu, qq, \nu\nu$, share the same μ_{bb}
  - N_{bb} floated Pdf shapes fixed
- Use Combined pdf to make Asimov data
- Scan the likelihood and obtain the 1σ deviation

Extrapolation: CEPC-v1 to v4

- Most analyses are done in CEPC-v1 version
  - B=3.5T, $\sqrt{s} = 250GeV, L = 5ab^{-1}$
- Now: B=3T, $\sqrt{s} = 240GeV, L = 5.6ab^{-1}$
  - m_H resolution 15% worse in $H \to \mu\mu$ due to magnetic field
  - Scale the signal and background with the factor
    - 250 to 240GeV: Signal: ~-5%; 2f bkg: ~+8%; 4f bkg: ~+3%
    - 5 to 5.6ab^{-1}: All +12%;
  - In total there would be 1.13M Higgs; (Fcc-ee 1M)
  - Following result all scaled to the latest CEPC-v4.

$\sigma(ZH)$ measurement: H→inclusive

- Possible by tagging higgs with recoil mass
- Zhenxing: 1601.05352
  - Fit the Z → ee, Z→$\mu\mu$, model independently
  - Z->ee: 1.42%
  - Z→$\mu\mu$: 0.91%
  - Z→qq: 0.6%, extrapolated from 1404.3164
  - Combined: 0.5%



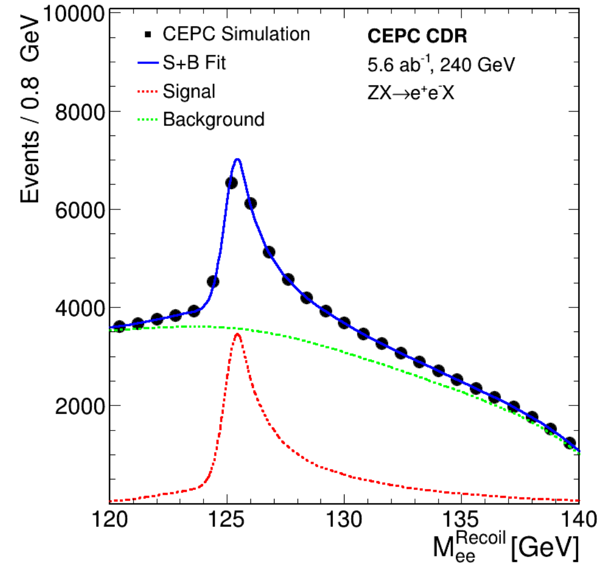


Table 3. Estimation of biases of σ_{ZH} caused by potential variances of the Higgs decay branching ratios.

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

Z decay mode	Δm_H (MeV)	$\Delta\sigma(ZH)/\sigma(ZH)$
e^+e^-	14	1.4%
$\mu^+\mu^-$	6.5	0.9%
$q\bar{q}$	–	0.6%
Combination	5.9	0.5%

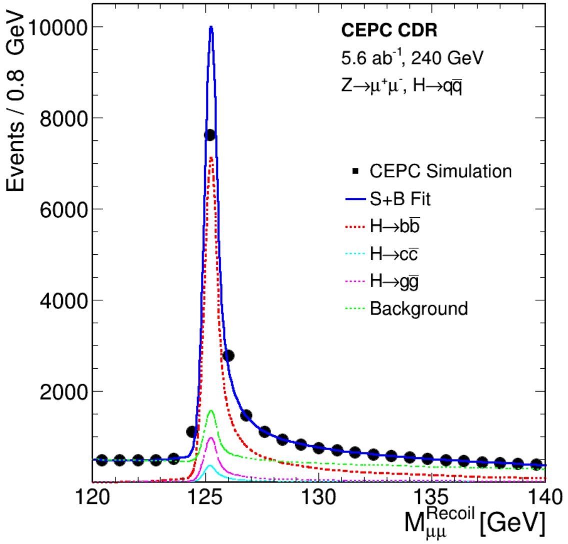
$H \rightarrow bb/cc/gg$

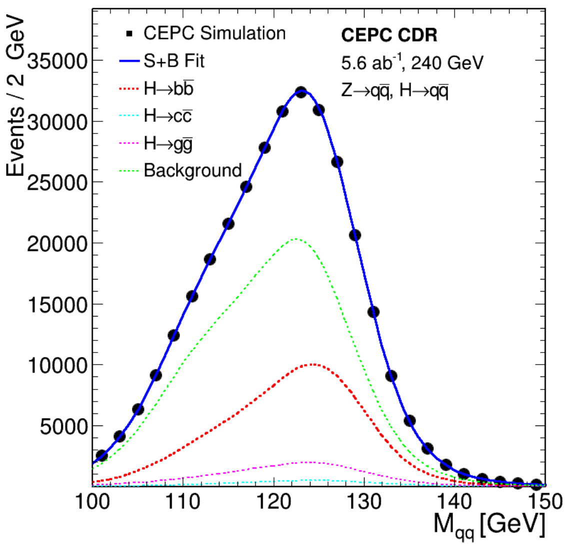
- b, c quark, gluon, and hadronic ww/zz can not be well separated.

- Mass distribution has no separation power
    - Flavor tagging algorithm
    - Each jet has the likeness bj1 and cj1;
    - Calculate dijet's B likeness and C likeness.

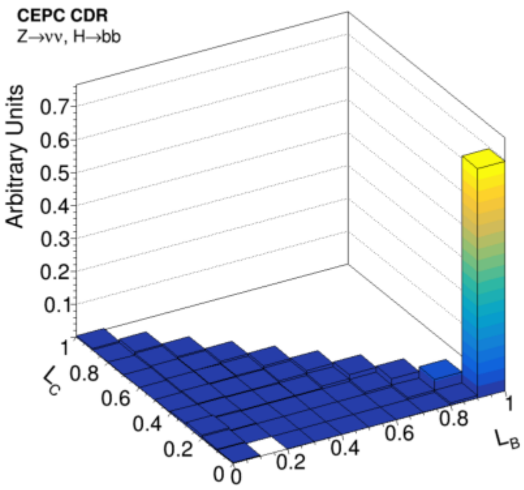
$$\boxed{B_{likeness} = \frac{b_{j1}b_{j2}}{b_{j1}b_{j2} + (1-b_{j1})(1-b_{j2})}}$$

- b/c quark likeness, from 0 to 1.
- 2d Template fit, 20*20 bin
- For llH, 3d fit, add recoil mass
- Each channel 7 parts: bb, cc, gg, ww, zz, tt, bkg_{sm}.

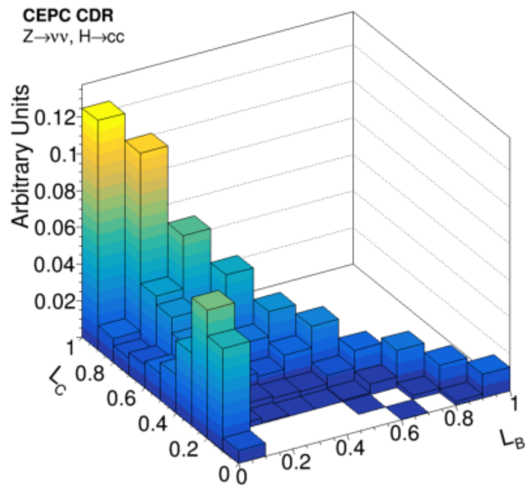




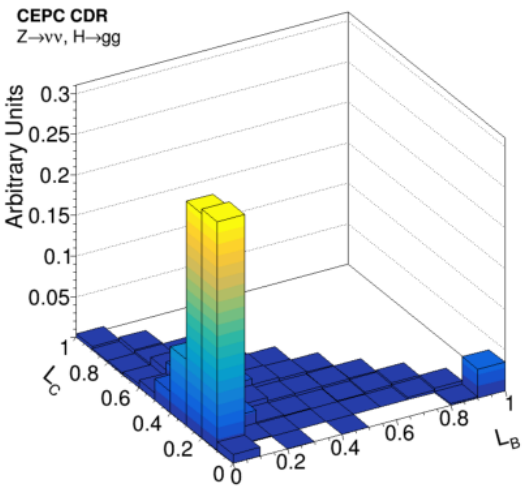
H → bb/cc/gg



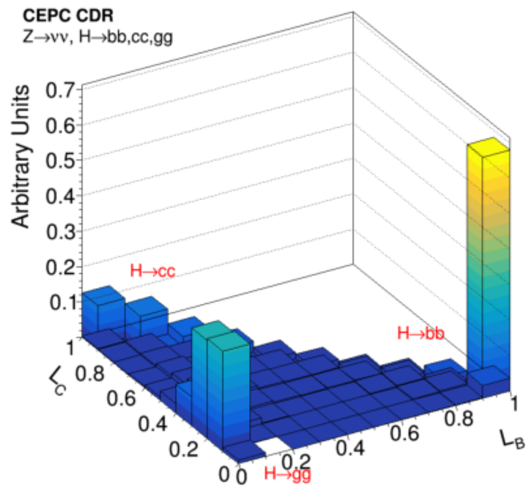
(a)



(b)



(c)



(d)

In mass plot bb/cc/gg share the same behavior,
But in L_B, L_C good separation.

Still tricky for gg/WW/ZZ components.

Next step: plan to establish different categories to study bb/cc/gg/ww/zz.

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%

WW, ZZ

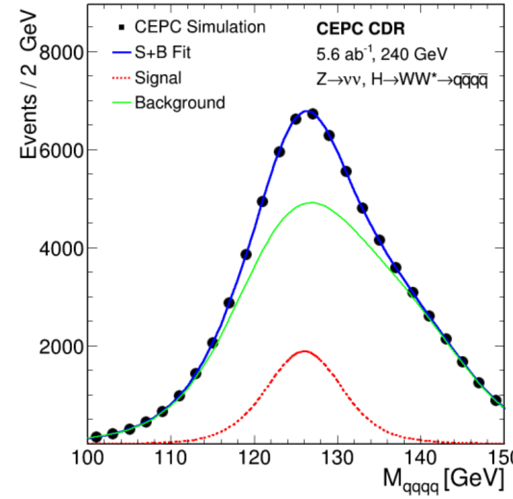
	preCDR	Now
WW	1.5%	**1.0%**
ZZ	4.3%	**5.1%**

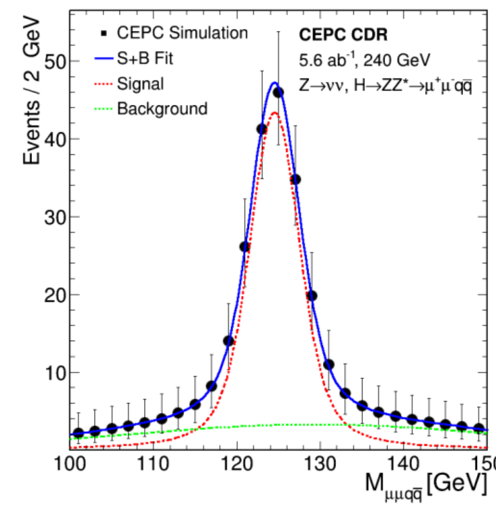
- ZZ
  - Pre_CDR ZZ result extrapolated from Fcc-ee. Overestimated;
  - Current ZZ study suffered from huge background
  - Also gained contribution from H → bb/cc/gg/WW decay.
  - Undergoing study Kong LingTeng
- WW
  - Much more channels studied since Pre_CDR.
  - Poster: Li Tong

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				

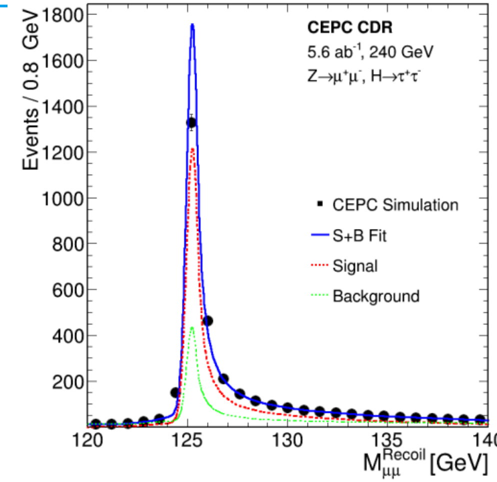




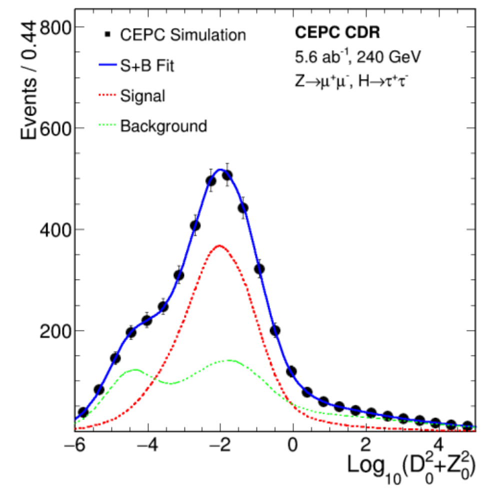
$\tau\tau$, $\mu\mu$

	Pre_CDR	Now
$\tau\tau$	1.2%	**0.81%**
$\mu\mu$	17%	**17%**

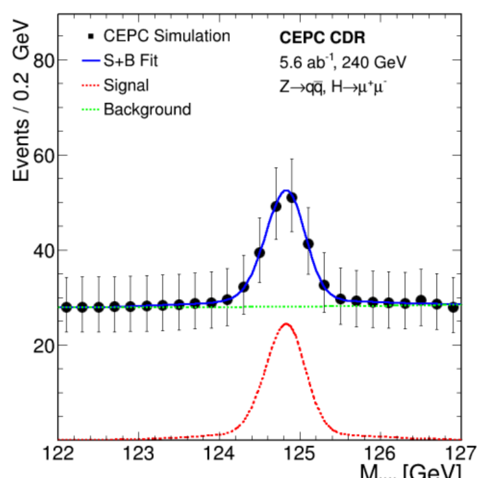
- $\tau\tau$:
  - Develop LICH to identify lepton. Eff>99%
  - Signal and ZH events(Main WW) share the same shape
  - use $\log_{10}(D_0^2 + Z_0^2)$ + mass 2d fit to separate signal
    - Impact parameter, Distance from beam spot,
  - Poster: Yu Dan



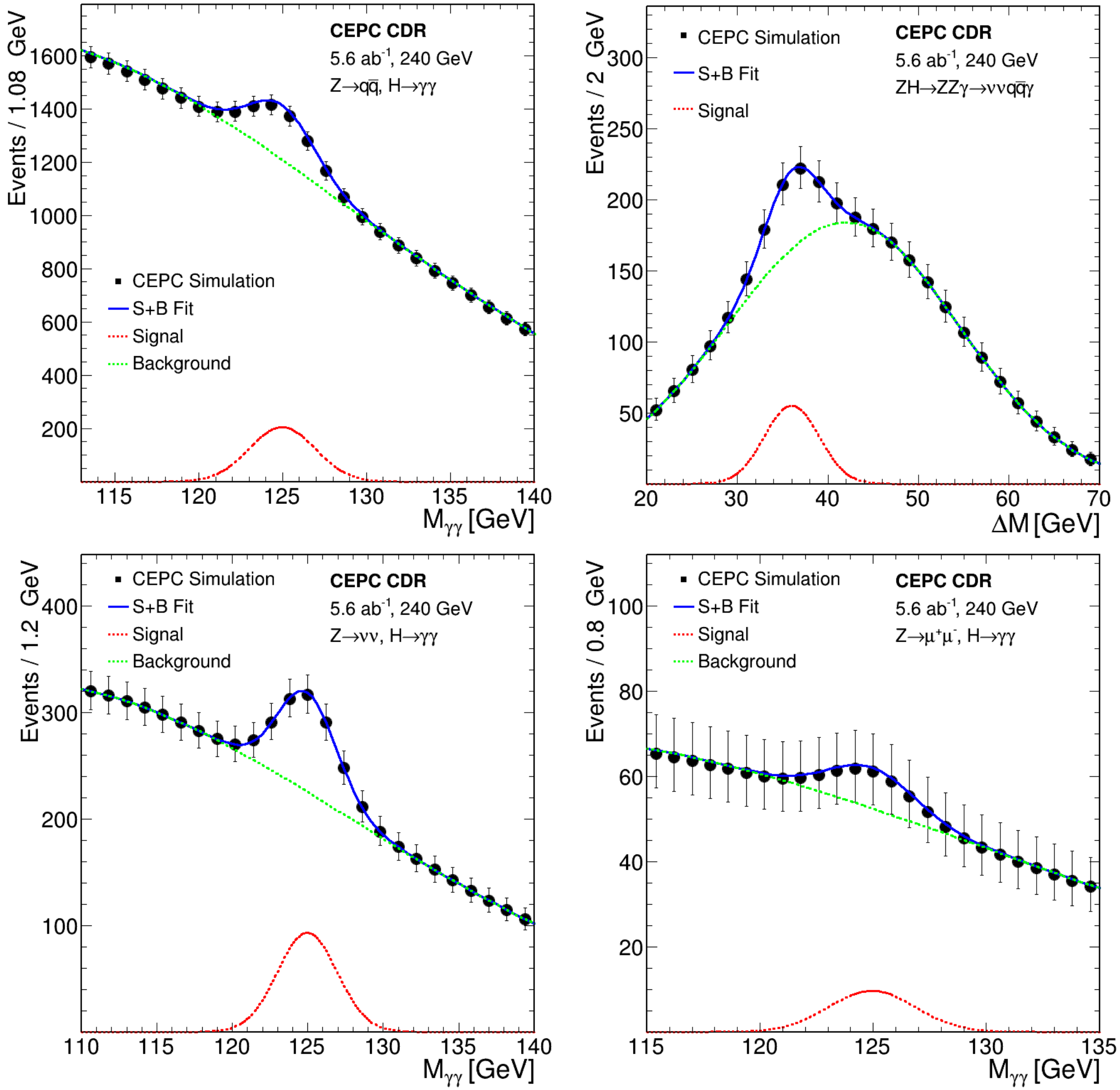
ZH final state		Precision
$Z\to\mu^+\mu^-$	$H\to\tau^+\tau^-$	2.6%
$Z\to e^+e^-$	$H\to\tau^+\tau^-$	2.7%
$Z\to\nu\bar{\nu}$	$H\to\tau^+\tau^-$	2.5%
$Z\to q\bar{q}$	$H\to\tau^+\tau^-$	0.9%
Combination		0.8%



- $\mu\mu$:
  - Dominant by Z->qq H-> $\mu\mu$;



$\gamma\gamma, Z\gamma$



	Pre_CDR	Now
$\gamma\gamma$	9.0%	6.8%
$Z\gamma$	\	16%

- Use $m_{\gamma\gamma}, m_{\gamma\gamma}^{recoil}$ 2d fit to improve $\gamma\gamma$ precision.
- Photon convention not counted in current study.

Constrained by Ecal resolution

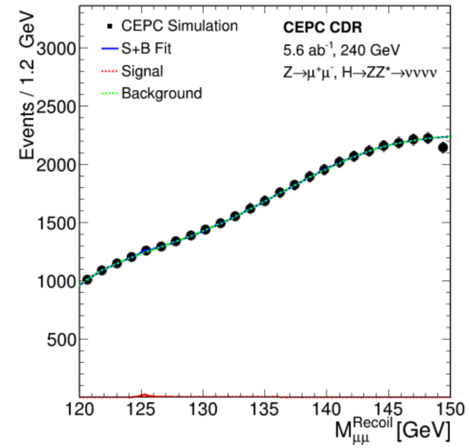
- Current design: $15.1\%/\sqrt{E}$

Poster: Guo Fangyi

Invisible decay

	preCDR	Now
invisible	0.28%	0.41%

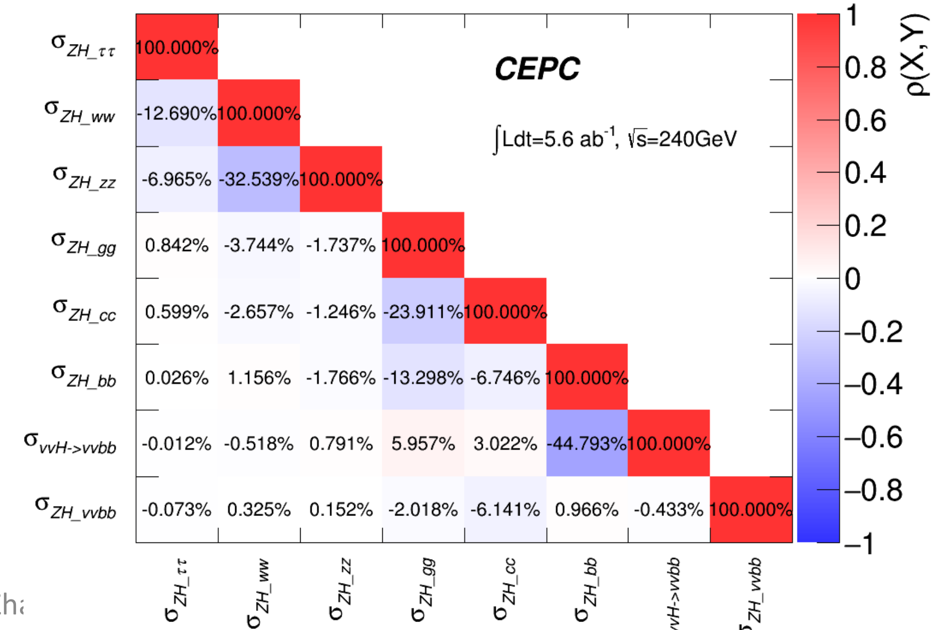
- Pre_CDR's 0.28% is one exotic study. Different story.
- H → ZZ → vvvv
  - Large irreducible bkg, use BDT and seek upper limit.
  - Huge fluctuation, use Asimov Data to get correct fit result.
  - precision 153%, upper limit for Br: 0.41%
  - Upper limit for BSM H → invisible: 0.30%
  - See more in Ryuta's report !



	Precision	Br Upper limit
Z->ee	370%	
Z->mm	245%	
Z->qq	232%	
Combined	153%	0.41%

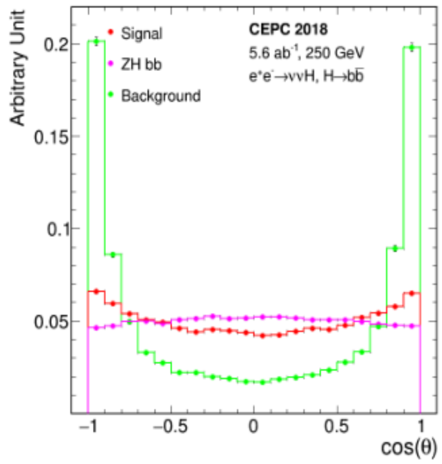
Input correlations among channels

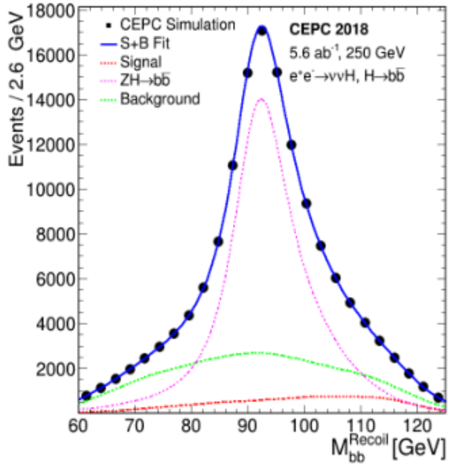
- In individual analysis, other Higgs processes usually tagged as bkg;
  - Should be taken into account in combination.
  - e.g. $Z(\rightarrow \mu\mu)H(\rightarrow \tau\tau)$, main bkg is $H \rightarrow WW$.
    - Those WW events should be considered when computing μ_{WW}.
  - Full hadronic decay
    - bb/cc/gg/WW/ZZ mixed together.
- Anti-correlation matrix
- Overlap
  - Fix some components to simplify
  - Undergoing



Correlation: $\nu\nu H \rightarrow bb$

- 2d fit M_{jj}^{reco} & Cos θ_{jj}





- Correlated with ZH → bb
  - Fix ZH process, Initial uncertainty is 2.8%.
- Use the likelihood from $Z(\rightarrow ee/\mu\mu\ /qq)H(\rightarrow bb)$ to constrain
  - No assumption made
  - $\nu\nu H \rightarrow bb$ 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%.
- See more in Hao's report!

	Error
Fix ZH	2.8%
Float ZH	3.0%

Correlation: Higgs width

- In Pre_CDR, width determined by

$$\Gamma_H = \frac{\Gamma_{H\to ZZ}}{Br(H\to ZZ)} \propto \frac{\sigma(ZH)}{Br(H\to ZZ)} \text{ and } \Gamma_H = \frac{\Gamma_{H\to bb}}{Br(H\to bb)} \propto \frac{\sigma(\nu\nu H\to \nu\nu bb)}{Br(H\to bb)Br(H\to WW)}$$

- If two independent: 2.7% （ZZ: 5.1% WW fusion: 3.3%）

- But width correlated with all channels
  - Like correlation like $\nu\nu H \to \nu\nu bb$ and $ZH \to bb$ -45% not included -> would worse the result

- Combined fit in 10κ framework:

$$\Delta(\Gamma_H) = 2.8\%$$

Channels Table (2018.11)

All scaled to 240 GeV， 5.6ab^{-1}

Signal Z	Signal H	Precision	Signal Z	Signal H	Precision	Signal Z	Signal H	Precision
H->qq			H->WW			H→γγ, Zγ		
ee	bb	1.32%	ee	lνlν	9.52%	μμ+ττ	γγ	23.7%
	cc	13.5%		eνqq	4.56%	νν		10.5%
	gg	7.22%		μνqq	3.93%	qq		9.84%
μμ	bb	0.99%	μμ	lνlν	7.29%	νν	Zγ(qqγ)	15.7%
	cc	9.54%		eνqq	3.90%	ννH(WW fusion)		
	gg	5.01%		μνqq	3.90%	νν	bb	3.00%
qq	bb	0.46%	νν	qqqq	1.90%	H→μμ		
	cc	11.1%		eνqq	4.65%	qq	μμ	17.1%
	gg	3.64%		μνqq	4.14%	ee		
νν	bb	0.39%		lνlν	11.5%	μμ		
	cc	3.83%	qq	qqqq	1.75%	νν		
	gg	1.47%	H->ZZ			H→ττ		
H->Invisible			νν	μμqq	8.26%	ee	ττ	2.75%
qq	ZZ(νννν)	232%	νν	eeqq	40%	μμ		2.61%
ee		370%	μμ	ννqq	7.32%	qq		0.95%
μμ		245%	ZH bkg contribution		19.4%	νν		2.66%

Fit result of $\sigma(ZH) * \mathrm{Br}$

(5.6ab^{-1})	Current 2018.11	ILC 250	Fcc-ee
$\sigma(ZH)$	**0.50%**	1.2%	0.40%
$\sigma(ZH) * \mathrm{Br(H \rightarrow bb)}$	**0.27%**	0.6%	0.2%
$\sigma(ZH) * \mathrm{Br(H \rightarrow cc)}$	**3.3%**	3.9%	1.2%
$\sigma(ZH) * \mathrm{Br(H \rightarrow gg)}$	**1.3%**	3.3%	1.4%
$\sigma(ZH) * \mathrm{Br(H \rightarrow WW)}$	**1.0%**	3.0%	0.9%
$\sigma(ZH) * \mathrm{Br(H \rightarrow ZZ)}$	**5.1%**	8.4%	3.1%
$\sigma(ZH) * \mathrm{Br}(\mathrm{H} \rightarrow \tau\tau)$	**0.8%**	2.0%	0.7%
$\sigma(ZH) * \mathrm{Br}(\mathrm{H} \rightarrow \gamma\gamma)$	**6.8%**	16%	3.0%
$\sigma(ZH) * \mathrm{Br}(\mathrm{H} \rightarrow \mu\mu)$	**17%**	46.6%	13%
$\sigma(\mathrm{vv}H) * \mathrm{Br(H \rightarrow bb)}$	**3.0%**	11%	2.4%
$\mathrm{Br_{upper}(H \rightarrow inv.)}$	**0.41%**	0.4%	0.50%
$\sigma(ZH) * \mathrm{Br}(\mathrm{H} \rightarrow Z\gamma)$	**16%**		

ILC: 1310.0763
FCC-ee: 1308.6176
Maybe obsoleted!
ILC's result could be better adding ILC 500.

Compared to Fcc-ee:

bb/cc/gg: Can't separate them in reality;

ZZ: Constrained by channels studied;

γγ: Constrained by Ecal resolution;

vvH, H→bb: Correlation with ZH;

Our study considered input correlations and more reality factors.

κ Framework result

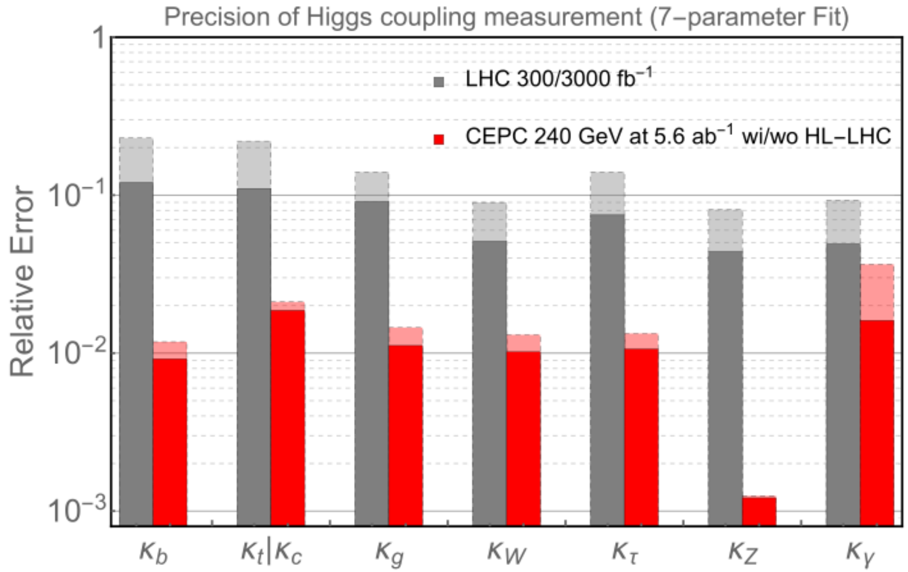
See more in Zhen's report!

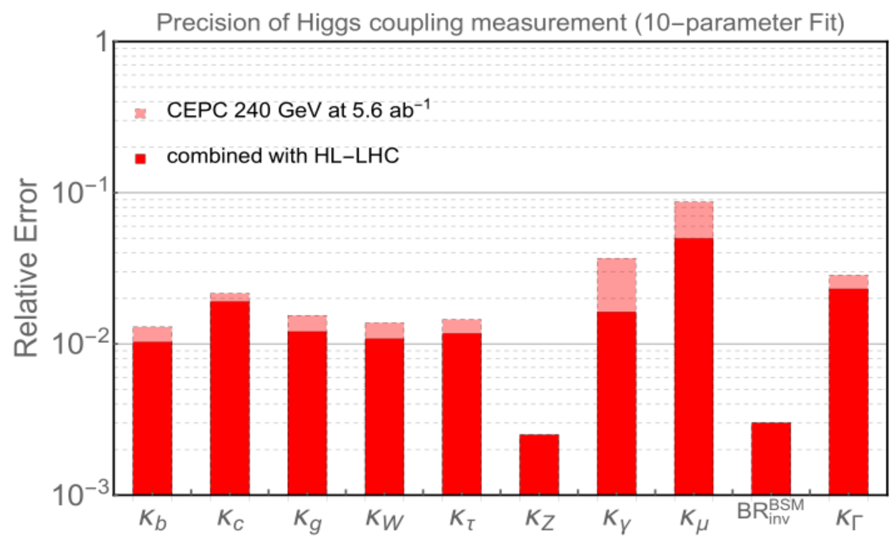
HL-LHC: ATL-PHYS-PUB-2014-016

The improvement of κ_γ from ${}^{Br_{ZZ}}/_{Br_{\gamma\gamma}} = 4\%$

Relative coupling measurement precision and the 95% CL upper limit on $\mathrm{BR}^{\mathrm{BSM}}_{\mathrm{inv}}$

	10-parameter fit		7-parameter fit	
Quantity	CEPC	CEPC+HL-LHC	CEPC	CEPC+HL-LHC
κ_b	1.3%	1.0%	1.2%	0.9%
κ_c	2.2%	1.9%	2.1%	1.9%
κ_g	1.5%	1.2%	1.5%	1.1%
κ_W	1.4%	1.1%	1.3%	1.0%
κ_τ	1.5%	1.2%	1.3%	1.1%
κ_Z	0.25%	0.25%	0.13%	0.12%
κ_γ	3.7%	1.6%	3.7%	1.6%
κ_μ	8.7%	5.0%	–	–
$\mathrm{BR}^{\mathrm{BSM}}_{\mathrm{inv}}$	$<0.30\%$	$<0.30\%$	–	–
Γ_H	2.8%	2.3%	–	–





Correlation of κ

For each entry,
upper one is CEPC result
lower one is CEPC+HL-LHC result.

7−parameter fit Correlation

	κ_b	κ_c	κ_g	κ_W	κ_τ	κ_Z	κ_γ
κ_b	100.	63. / 57.	89. / 87.	93. / 88.	95. / 92.	−37. / −31.	35. / 11.
κ_c	63. / 57.	100.	49. / 45.	59. / 51.	61. / 54.	−14. / −6.1	22. / 7.3
κ_g	89. / 87.	49. / 45.	100.	84. / 79.	86. / 82.	−27. / −23.	31. / 10.
κ_W	93. / 88.	59. / 51.	84. / 79.	100.	88. / 81.	−20. / −9.3	33. / 11.
κ_τ	95. / 92.	61. / 54.	86. / 82.	88. / 81.	100.	−37. / −31.	33. / 11.
κ_Z	−37. / −31.	−14. / −6.1	−27. / −23.	−20. / −9.3	−37. / −31.	100.	−9.4 / 3.5
κ_γ	35. / 11.	22. / 7.3	31. / 10.	33. / 11.	33. / 11.	−9.4 / 3.5	100.

10−parameter fit Correlation

	κ_b	κ_c	κ_g	κ_W	κ_τ	κ_Z	κ_γ	κ_μ	Br_{inv}	κ_Γ
κ_b	100.	65. / 59.	90. / 89.	93. / 89.	96. / 93.	19. / 24.	37. / 17.	16. / 8.0	<0.1 / <0.1	98. / 97.
κ_c	65. / 59.	100.	53. / 48.	61. / 53.	63. / 56.	12. / 13.	24. / 10.	10. / 4.8	<0.1 / <0.1	65. / 58.
κ_g	90. / 89.	53. / 48.	100.	86. / 82.	88. / 84.	16. / 21.	34. / 15.	14. / 7.2	<0.1 / <0.1	90. / 88.
κ_W	93. / 89.	61. / 53.	86. / 82.	100.	89. / 83.	18. / 23.	35. / 16.	15. / 7.4	<0.1 / <0.1	93. / 89.
κ_τ	96. / 93.	63. / 56.	88. / 84.	89. / 83.	100.	17. / 21.	35. / 16.	15. / 7.5	<0.1 / <0.1	94. / 92.
κ_Z	19. / 24.	12. / 13.	16. / 21.	18. / 23.	17. / 21.	100.	6.8 / 15.	2.9 / 5.0	<0.1 / <0.1	35. / 43.
κ_γ	37. / 17.	24. / 10.	34. / 15.	35. / 16.	35. / 16.	6.8 / 15.	100.	5.8 / 1.7	<0.1 / <0.1	36. / 19.
κ_μ	16. / 8.0	10. / 4.8	14. / 7.2	15. / 7.4	15. / 7.5	2.9 / 5.0	5.8 / 1.7	100.	<0.1 / <0.1	15. / 8.5
Br_{inv}	<0.1 / <0.1	<0.1 / <0.1	<0.1 / <0.1	<0.1 / <0.1	<0.1 / <0.1	<0.1 / <0.1	<0.1 / <0.1	<0.1 / <0.1	100.	<0.1 / <0.1
κ_Γ	98. / 97.	65. / 58.	90. / 88.	93. / 89.	94. / 92.	35. / 43.	36. / 19.	15. / 8.5	<0.1 / <0.1	100.

Summary

- Latest CEPC Higgs combination results are shown.
- Input correlations are taken in consideration.
- CDR and CEPC Higgs white paper
- To dos:
  - bb/cc/gg/ww/zz
  - $\sigma(ZH)$ correlations
  - ……

Property	Estimated Precision CEPC-v1		Estimated Precision 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
$H\to b\bar{b}$	0.26%	0.56%	0.27%	0.56%
$H\to c\bar{c}$	3.1%	3.1%	3.3%	3.3%
$H\to gg$	1.2%	1.3%	1.3%	1.4%
$H\to WW^*$	0.9%	1.1%	1.0%	1.1%
$H\to ZZ^*$	4.9%	5.0%	5.1%	5.1%
$H\to\gamma\gamma$	6.2%	6.2%	6.8%	6.9%
$H\to Z\gamma$	13%	13%	16%	16%
$H\to\tau^+\tau^-$	0.8%	0.9%	0.8%	1.0%
$H\to\mu^+\mu^-$	16%	16%	17%	17%
$\mathrm{BR}_{\mathrm{inv}}^{\mathrm{BSM}}$	–	$<0.28\%$	–	$<0.30\%$