THE 2018 INTERNATIONAL WORKSHOP ON HIGH ENERGY CIRCULAR ELECTRON POSITRON COLLIDER

Higgs Precision Fits

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A (evolving) technical review on the CEPC physics fit and results

Mainly based upon Higgs White paper and CDR
up-to-date results from previous studies.

Measurements to be interpreted

Observables at the colliders are the cross sections, a convolution of PDF (including CEPC, treating the beam energy spread), hard scattering, parton shower, detector response …

$$\kappa_i = \frac{g_i}{g_i^{SM}}, \kappa_\Gamma = \frac{\Gamma_{tot}}{\Gamma_{tot}^{SM}}$$

For the hard scattering*:

$$\sigma(i \to H \to j) \propto \frac{\Gamma_i \Gamma_j}{\Gamma_{tot}} \propto \frac{\kappa_i^2 \kappa_j^2}{\kappa_\Gamma}$$

All channels can be parametrized this way, simple extension possible for more channels/observables.

*zero-width approximation, Higgs width 10^{-5} of its mass, in general valid. Violations (% level correction) see ZL e t al, PRL 18'

κ-scheme

All SM Higgs couplings can be modified by factor κ(s).

e.g., SM Higgs mixes with a Singlet S

$$H \quad = \cos\theta\ h + sin\theta\ S$$

Basically all SM couplings reduced by a factor

$$\kappa = cos\theta$$

Theoretical motivation:

Hidden Valley, Higgs portal, singlet-assisted EWBG

See talks in BSM-2 session Wednesday morning

κ-scheme

All SM Higgs couplings can be modified by factor κ(s).

e.g., 2HDM with Z_2

$$H \quad = \cos\alpha\, h_1 + sin\alpha\, h_2$$

Basically all SM couplings reduced by several factors (Type-II)

$$\kappa_{z,w}, \kappa_u, \kappa_d, \kappa_l$$

Determined by model parameters

$$tan\beta, \alpha, (\lambda s)$$

For MSSM, radiative corrections modifies the Yukawas differently, inducing more κs.

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$$\sigma(i \to H \to j) \propto \frac{\Gamma_i \Gamma_j}{\Gamma_{tot}} \propto \frac{\kappa_i^2 \kappa_j^2}{\kappa_\Gamma}$$

If $\kappa_\Gamma = \kappa_i^2 \kappa_j^2$, the observed rates do not change.

This leads to a large flat direction of the Higgs coupling extraction, the future lepton colliders such as CEPC and handle this by the unique inclusive cross section measurement

$$\sigma(ee \to ZH, H \to anything) \propto \kappa_Z^2$$

Measurements to be interpreted

Observables at the colliders are the cross sections, a convolution of PDF (including CEPC, treating the beam energy spread), hard scattering, parton shower, detector response …

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If $\kappa_\Gamma = \kappa_i^2 \kappa_j^2$, the observed rates do not change.

- **All Kappas are positively correlated with the total width (from the point of cross sections);**
- **The naïve scaling of $\boldsymbol{\kappa_{tot} \propto \kappa_{i,f}^2}$, does not reflect this flat direction, one needs additional particle width to enter**

Constrained κ-scheme

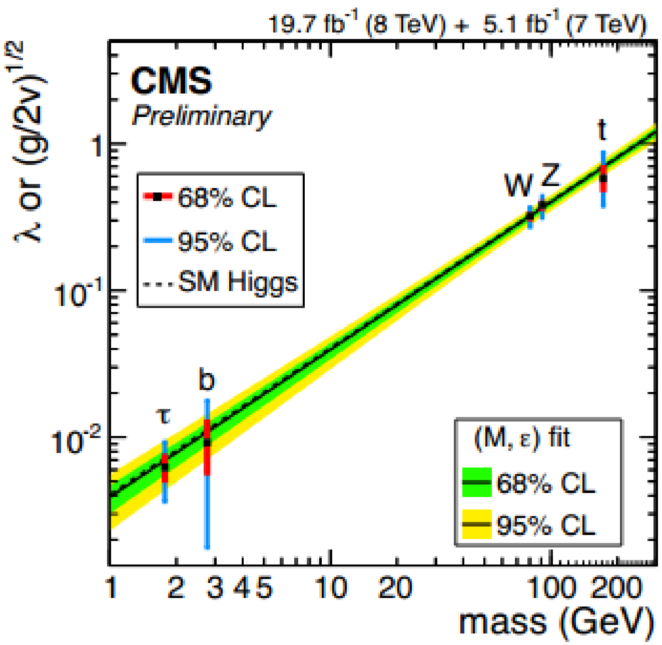
Add some assumptions

Assuming no Br_{exo}, so Γ_{tot} has to scale as f but not f^2 since

$$\Gamma_{tot} = \Sigma\Gamma_{observable}$$

Total width is no longer a free parameter, but rather a derived quantity from all observable partial widths.

Most of the LHC result seen are under this assumption.



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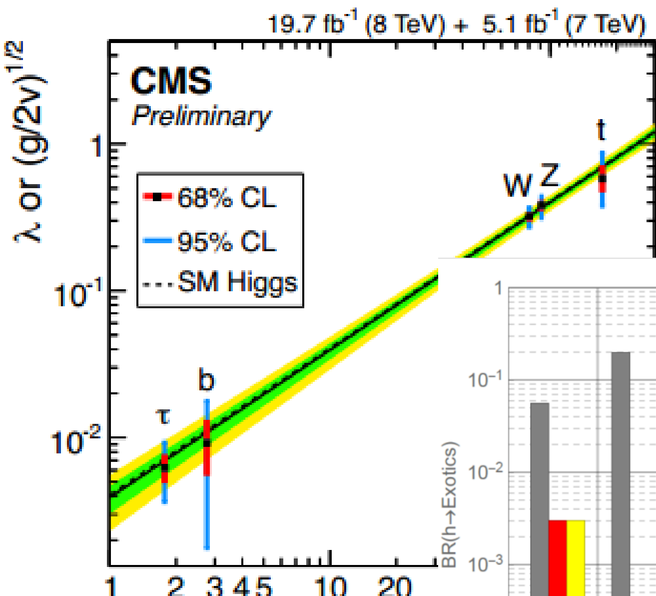
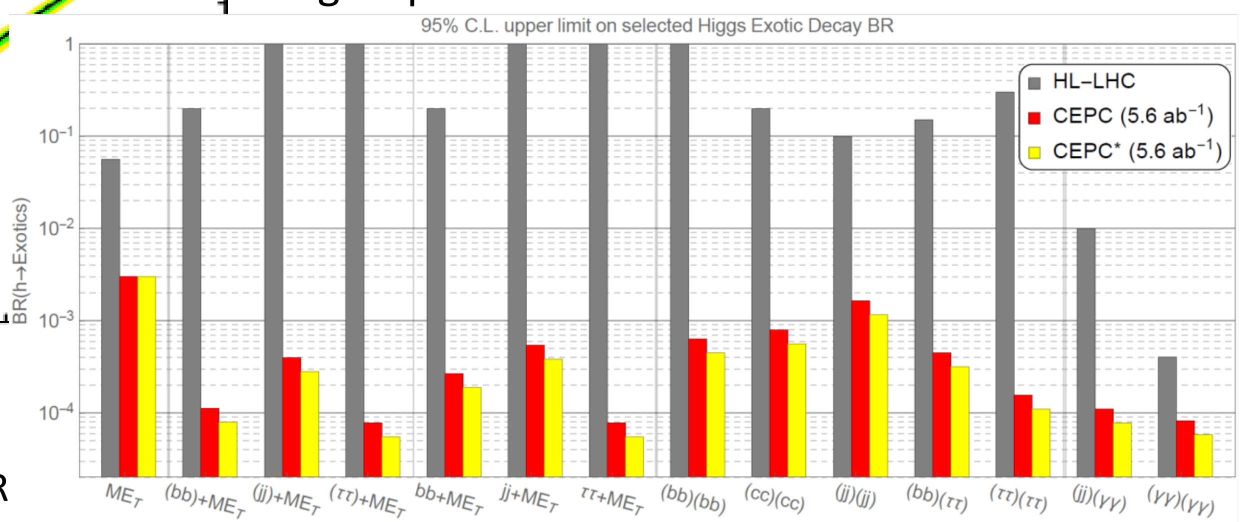


This assumption is justified that it's applicable to BSM models with no additional states lighter than the Higgs mass, provided that Higgs decays to light quarks not modified too much.



ZL, L.-T. Wang, H. Zhang, CPC16', Updated for CDR

Constrained κ-scheme

Add some assumptions

Assuming no Br_{exo}, so Γ_{tot} has to scale as f but not f^2 since

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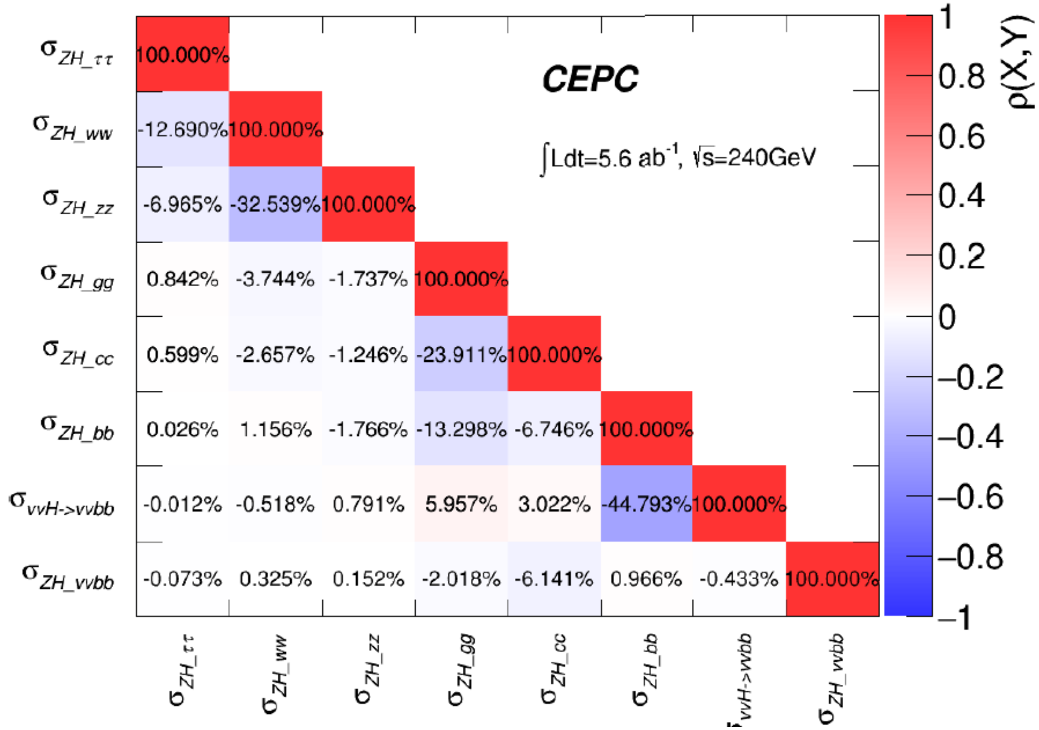
Total width is no longer a free parameter, but rather a derived quantity from all observable partial widths.

Most of the LHC result seen are under this assumption.

- Should be careful when comparing results, often have different assumptions.
- Fortunately, many groups start to show results in a same fashion (kappa-framework, constrained or unconstrained, as well as EFT).

Advancements since preCDR

- Improvement in the simulation and analysis, detector design & performance, larger luminosity (see many talks at this workshop, also from Joao Costa and Manqi Ruan Monday)
- Inclusion of input correlations 🡐 Higgs boson decays themselves are often largest background for different channels (great improvement in the Higgs physics study; thanks Kaili Zhang et al for the work!)



Most measurements are anti-correlated !!!

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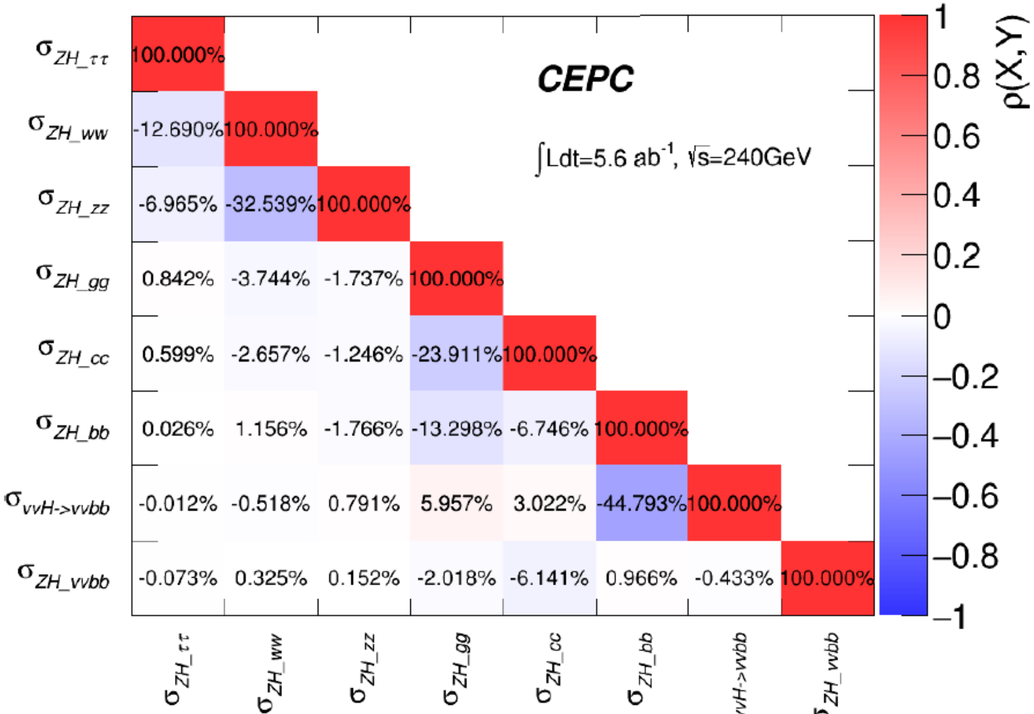
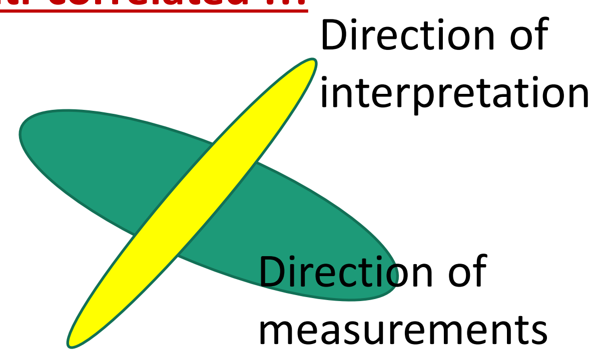


We can now fully exploit Higgs information in the data

Most measurements are anti-correlated !!!



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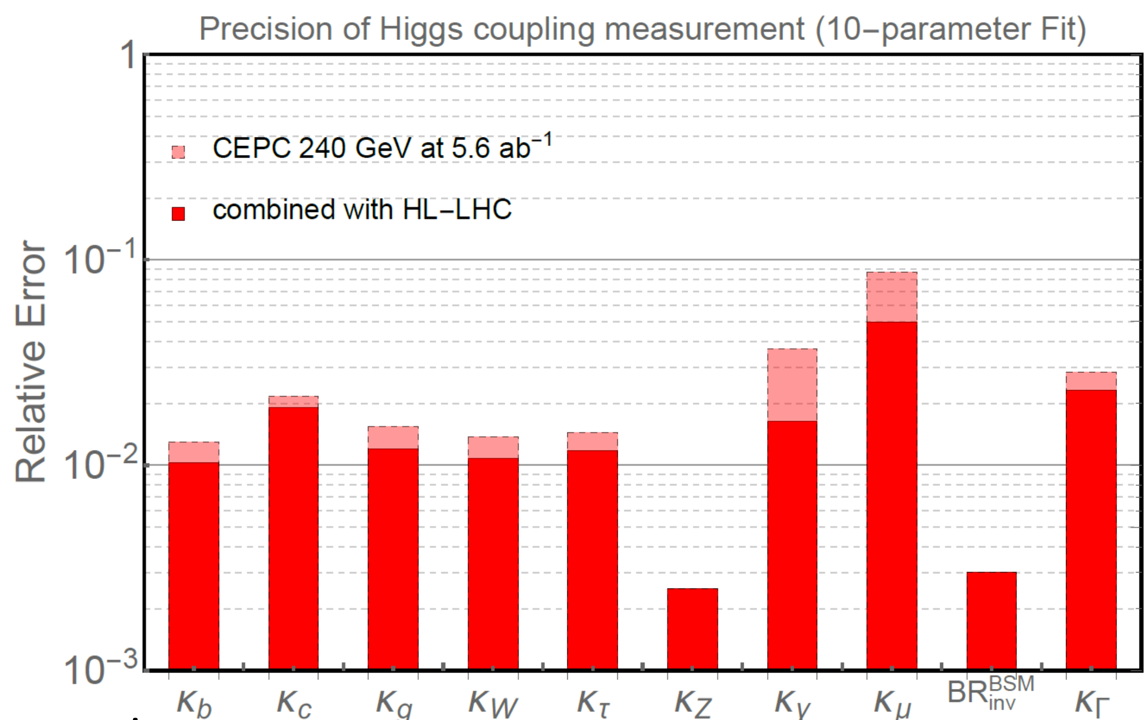
- Inclusion of input correlations ← Higgs boson decays themselves are often largest background for different channels (great improvement in the Higgs physics study; thanks Kaili Zhang et al for the work!)
- Having the output correlations for fit results for better understanding, prioritization, and information transfer without loss
- Advance into EFT interpretation for consistent information extraction from different energy scales and higher order effects
- New observables proposed and included in the EFT fits, including angular asymmetry observables, EWPO (TGC), and Higgs trilinear corrections (see the next talk by Jiayin Gu.)

General κ fit (so called "model independent fit")

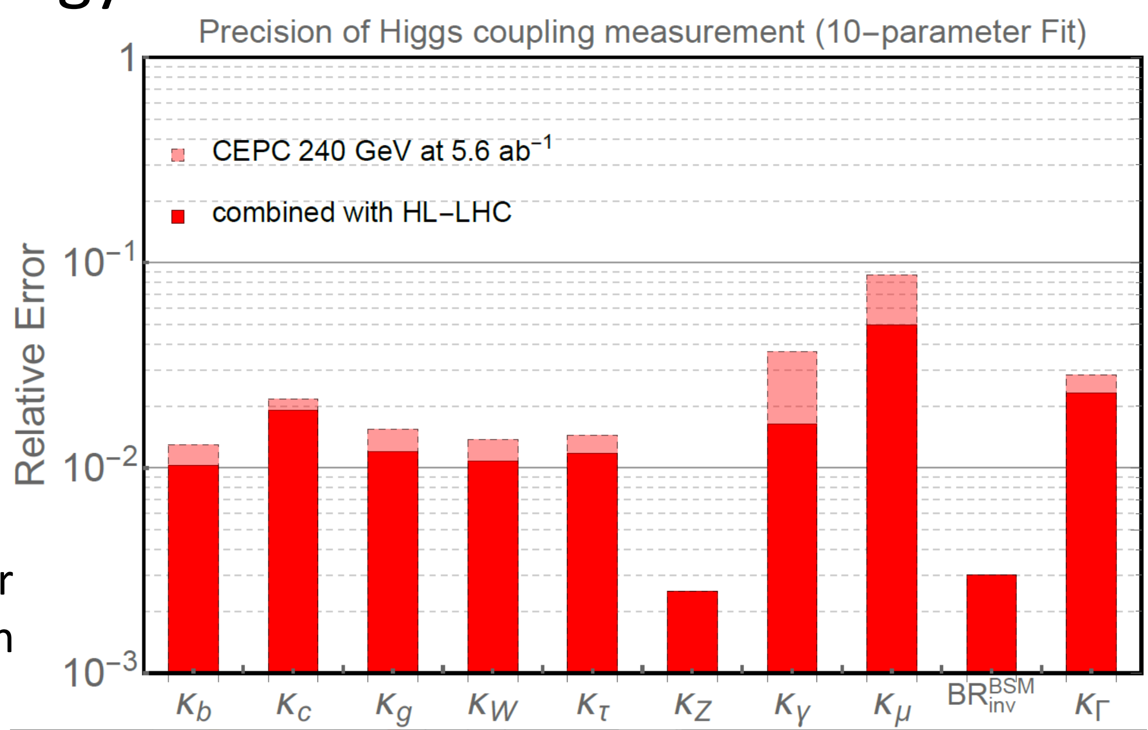
- Unique fit possible at CEPC and other lepton colliders
- Impossible to do at the HL-LHC*



*since LHC width measurement is poor, putting a universal floor of around 10% for LHC measurements interpreted in this framework, assuming additional input from off-shell ZZ measurements to bound the Higgs total width)

General κ fit (so called "model independent fit")

- Unique fit possible at CEPC and other lepton colliders
- Impossible to do at the HL-LHC*
- CEPC & HL-LHC synergy
- Signature numbers
  - κ_Γ 2.8%
  - κ_z 0.25%
  - κ_b 1.3%



Combination with the HL-LHC, fuller representation of our knowledge on Higgs boson at CEPC;
CEPC and HL-LHC synergy in various channels. (note we have log y-axis, the improvement is factor of a few!)

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- Signature numbers
  - κ_Γ 2.8%
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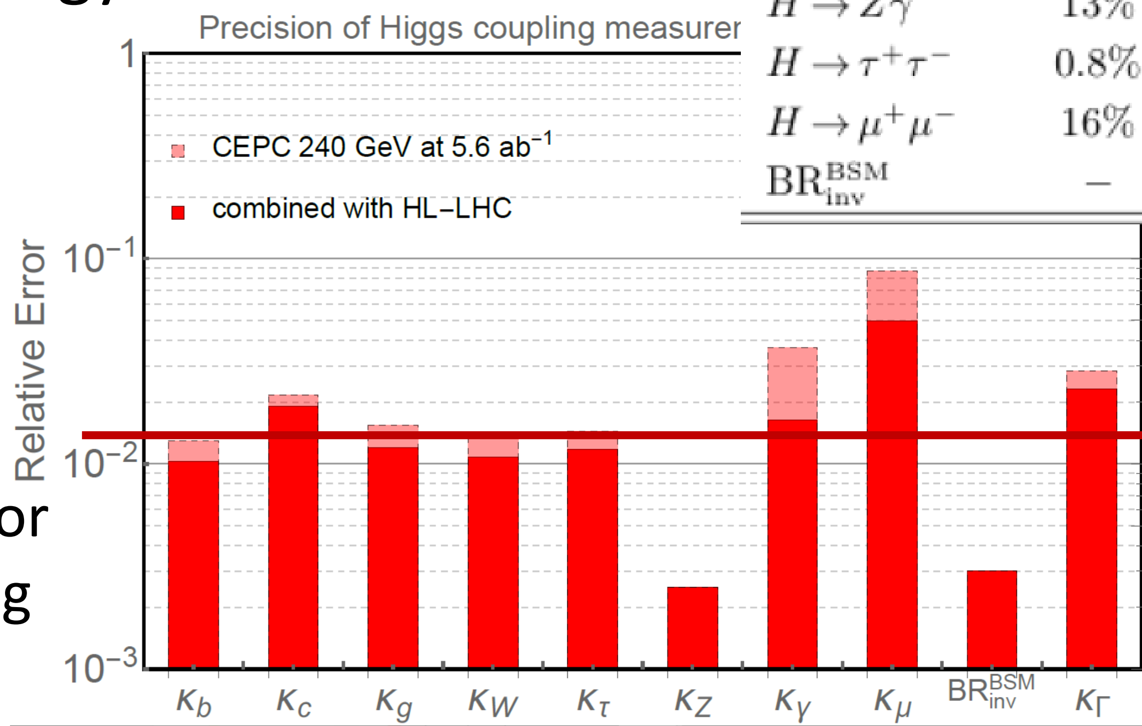
  - κ_b 1.3%

Decay mode	$\sigma \times \mathrm{BR}$
$H \to b\bar{b}$	0.26%
$H \to c\bar{c}$	3.1%
$H \to gg$	1.2%
$H \to WW^*$	0.9%
$H \to ZZ^*$	4.9%
$H \to \gamma\gamma$	6.2%
$H \to Z\gamma$	13%
$H \to \tau^+\tau^-$	0.8%
$H \to \mu^+\mu^-$	16%
$\mathrm{BR}_{\mathrm{inv}}^{\mathrm{BSM}}$	–



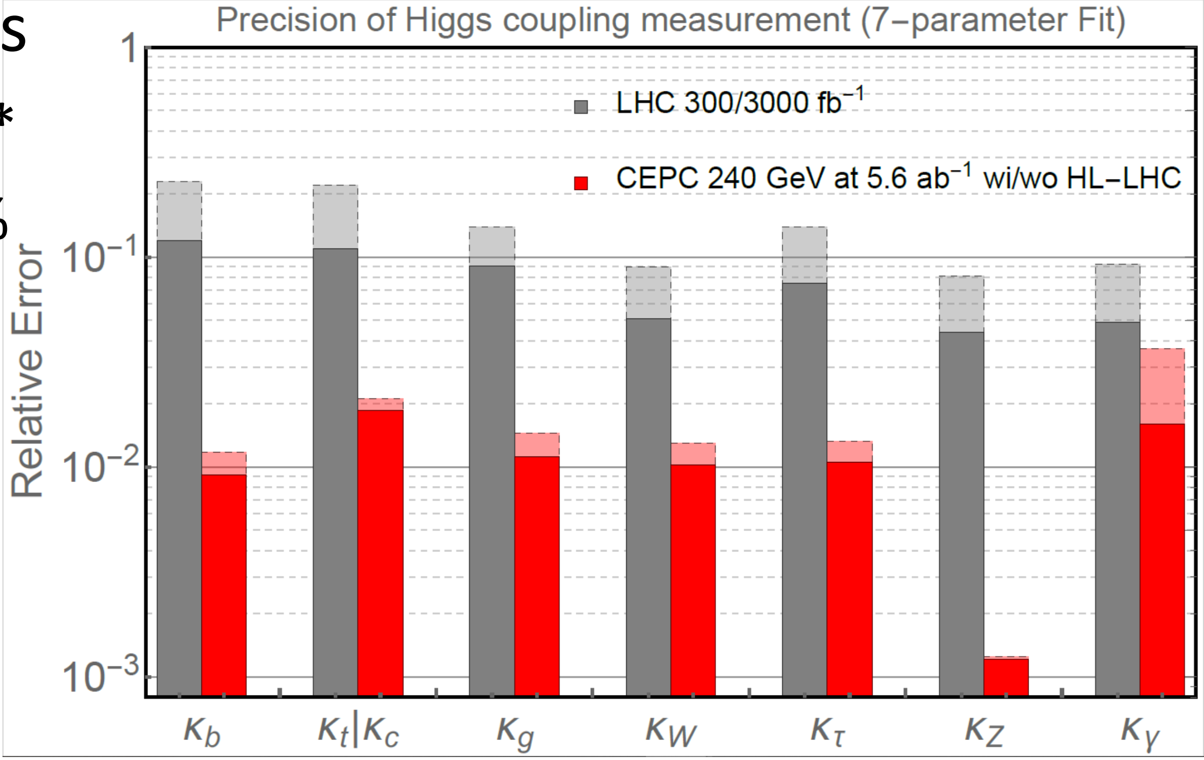
The total width sets a floor for the individual coupling extraction as:

$$\sigma(i \to H \to j) \propto \frac{\Gamma_i \Gamma_j}{\Gamma_{tot}} \propto \frac{\kappa_i^2 \kappa_j^2}{\kappa_\Gamma} \Rightarrow$$

$$\Delta\kappa_j = 1/2(\Delta\kappa_j^2) = 1/2(\Delta\kappa_\Gamma \oplus \Delta\sigma(i \to H \to j) \oplus \Delta\kappa_i^2)$$

Constrained κ fit (7-parameter fit)

- Can be compared with the HL-LHC
- Large improvement (~one order of magnitude)
- Result improved from additional constraints
- Signature numbers
  - κ_Γ 2.8%→(2.4%)*
  - κ_z 0.25%→0.13%
  - κ_b 1.3%→1.2%



*not a free parameter; but useful intermediate quantity

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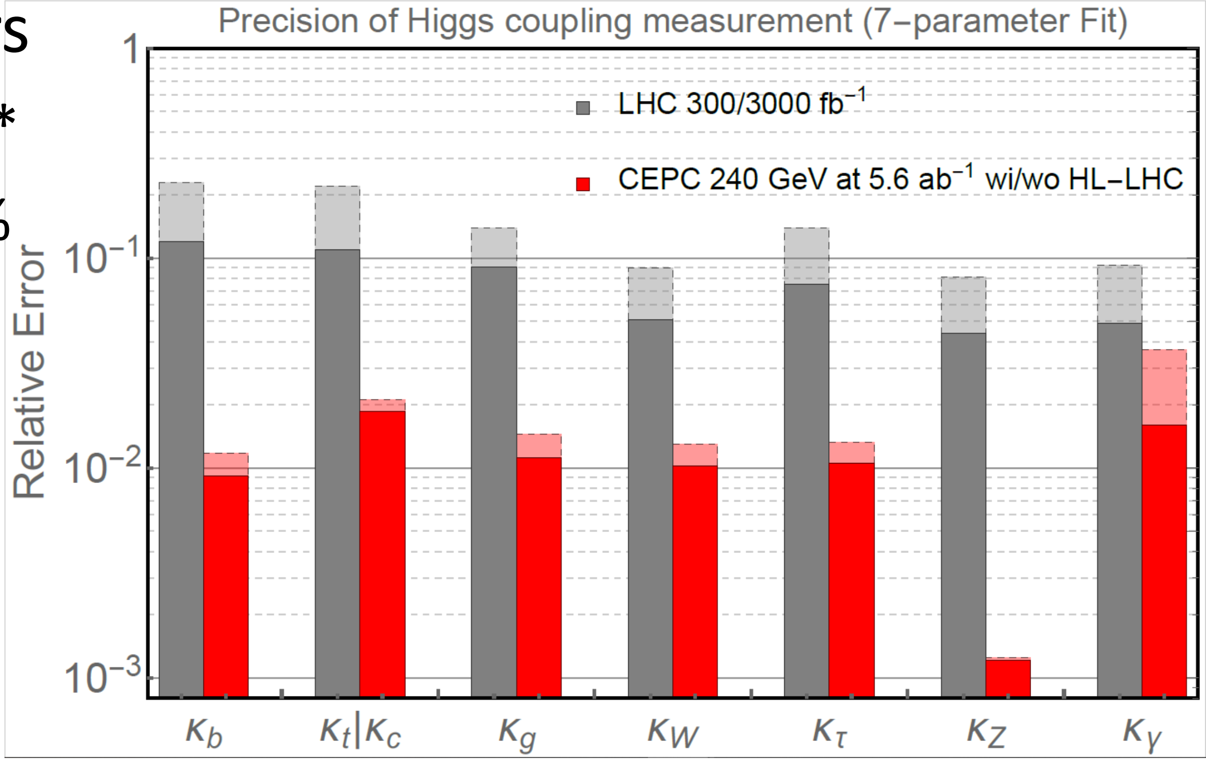
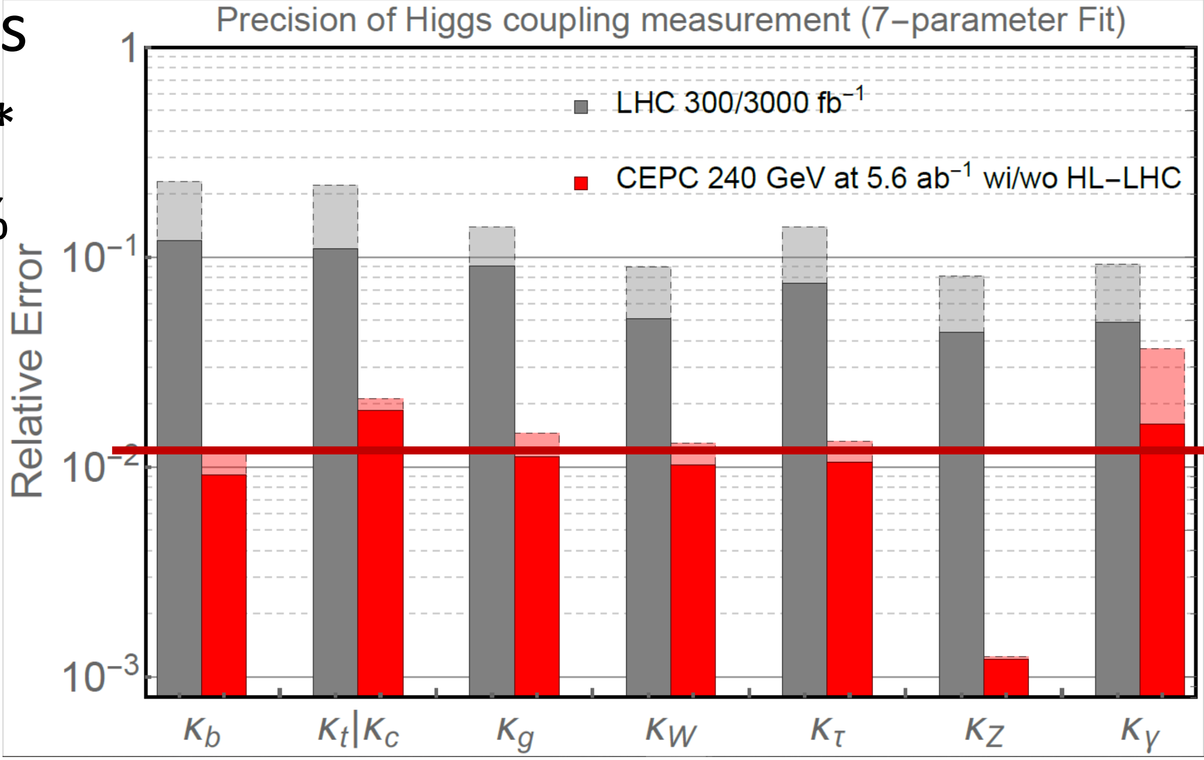


Significant improvement for the κ_Z from the additional constraints

Constrained κ fit (7-parameter fit)

- Can be compared with the HL-LHC
- Large improvement (~one order of magnitude)
- Result improved from additional constraints
- Signature numbers
  - κ_Γ 2.8%→(2.4%)*
  - κ_z 0.25%→0.13%
  - κ_b 1.3%→1.2%

The total width (still!) sets a floor for the individual coupling extraction.



Output correlations

Upper entries: correlation coefficients at CEPC alone;

Lower entries: correlation coefficients after combining with HL-LHC (get reduced);

10−parameter fit Correlation

	κ_b	κ_c	κ_g	κ_W	κ_τ	κ_Z	κ_γ	κ_μ	$\mathrm{Br}_{\mathrm{inv}}$	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
$\mathrm{Br}_{\mathrm{inv}}$	<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.

Output correlations

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

- "strong correlations" between total width and all results;
- This correlation induces seemingly strong correlations between the couplings whose results are limited by the total width;
- All parameters are correlated through the total width (as total width is far worse than the inclusive ZH cross section);

10−parameter fit Correlation

	κ_b	κ_c	κ_g	κ_W	κ_τ	κ_Z	κ_γ	κ_μ	$\mathrm{Br}_{\mathrm{inv}}$	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.
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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
$\mathrm{Br}_{\mathrm{inv}}$	<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.

Output correlations

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
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10−parameter fit Correlation

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$\mathrm{Br}_{\mathrm{inv}}$	<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.

Same pattern on correlations for the constraint fit (7-parameter fit), with the following highlights:

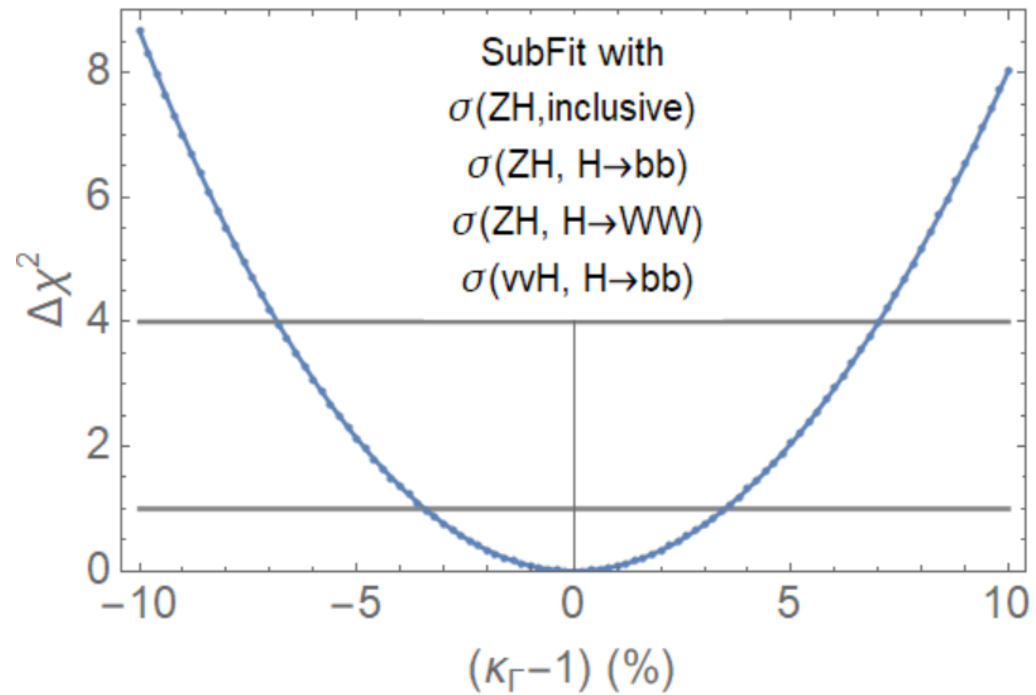
- The total width as a sum of all individual channels add anticorrelations between couplings, reducing the correlation with respect to the 10-parameter fit;
- Kappa_Z anticorrelates with the rest now;

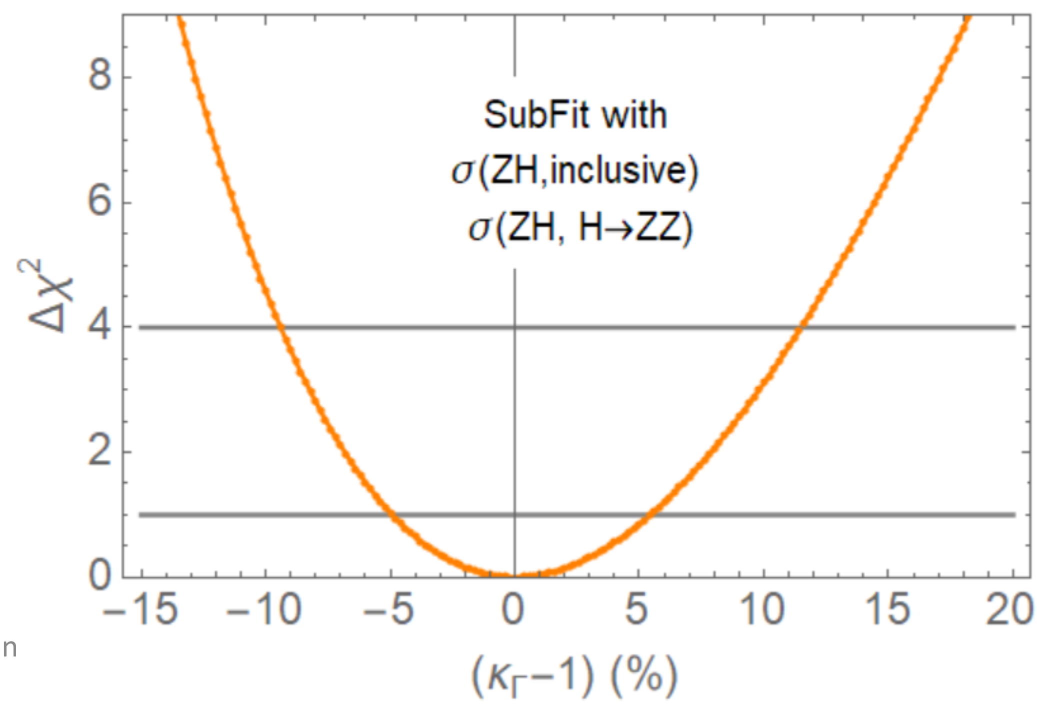
$$\sigma(i \to H \to j) \propto \frac{\kappa_i^2 \kappa_j^2}{\kappa_\Gamma}$$

Summary

- CEPC Higgs factory will improve our knowledge on the Higgs boson to unprecedented territories;
- κ-framework is relatively simple but extendable, captures the main physics of the Higgs precision program;
- Congratulations on the CDR works, A lot of advances since preCDR:
  - Improvement in the simulation and analysis, detector design & performance, larger luminosity
  - Inclusion of input correlations
  - Having the output correlations for fit results for better understanding, prioritization, and information transfer without loss
  - Advance into EFT interpretation for consistent information extraction from different energy scales and higher order effects
  - New observables proposed and included in the EFT fits, including angular asymmetry observables, EWPO (TGC), and Higgs trilinear corrections

Relative coupling measurement precision and the 95% CL upper limit on $\mathrm{BR}_{\mathrm{inv}}^{\mathrm{BSM}}$				
	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%	–	–
$\mathrm{BR}_{\mathrm{inv}}^{\mathrm{BSM}}$	$< 0.30\%$	$< 0.30\%$	–	–
Γ_H	2.8%	2.3%	–	–


SubFit with
σ(ZH,inclusive)
σ(ZH, H→bb)
σ(ZH, H→WW)
σ(ννH, H→bb)
Δχ²
(κΓ−1) (%)


SubFit with
σ(ZH,inclusive)
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