CEPC Physics Workshop
@PKU CHEP

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

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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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

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

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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

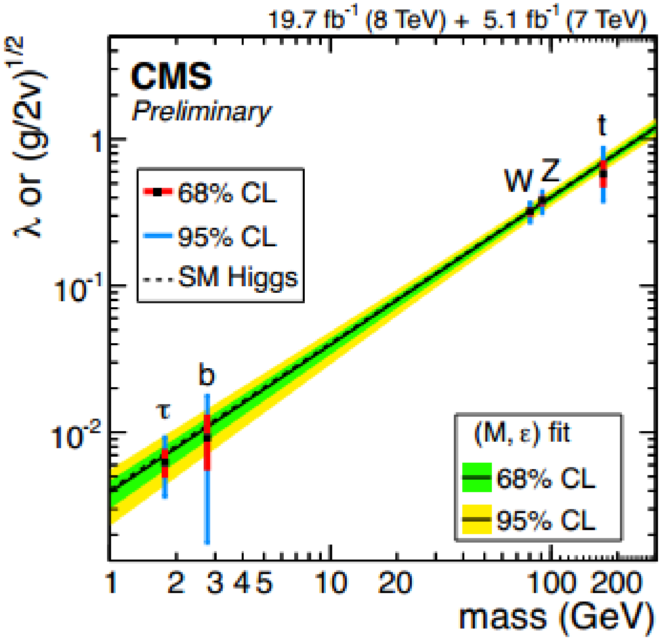
Add some assumptions

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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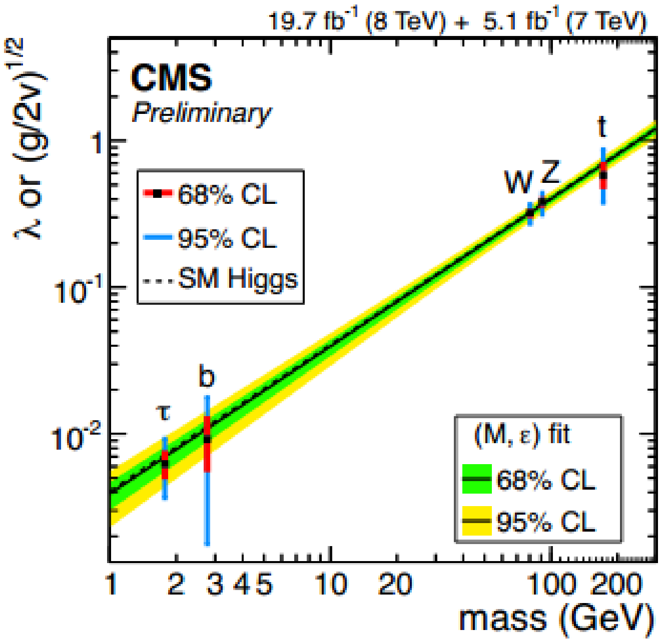
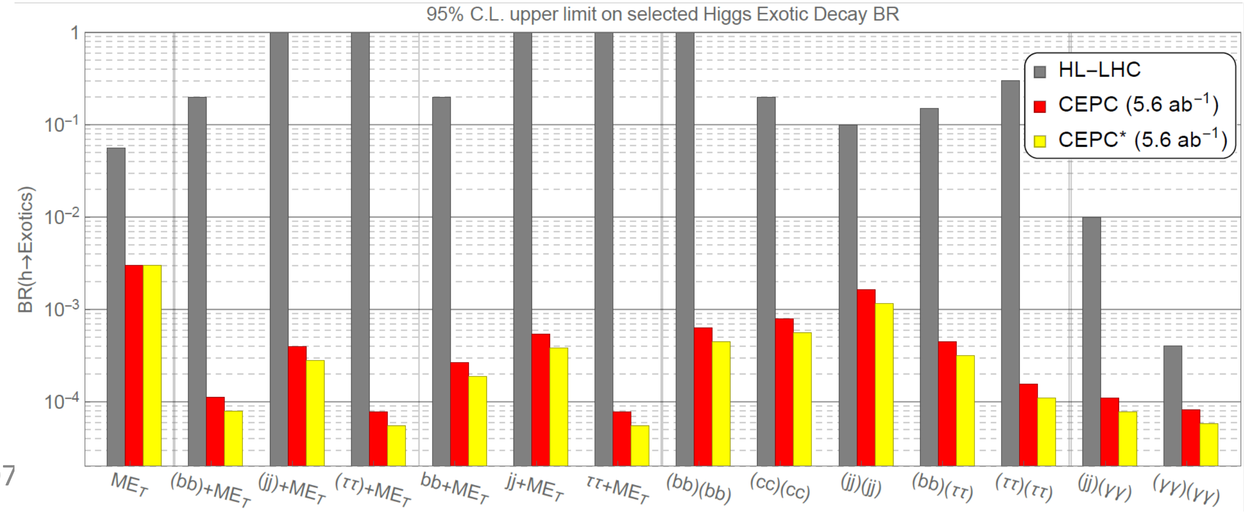


This assumption is applicable to BSM models with no additional states lighter than the Higgs mass, provided that Higgs decays to light quarks not modified too much.



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

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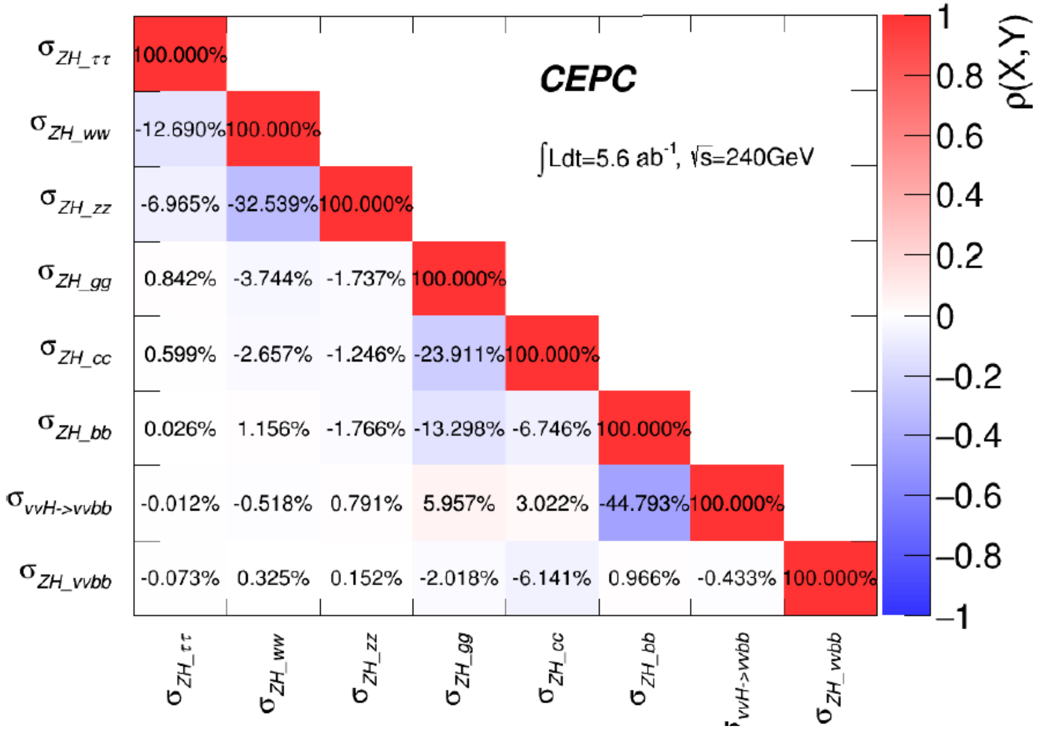
Total width is no longer a free parameter, but rather a derived quantity from all observable partial widths.

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).
- Constrained κ-scheme are closest to the EFT (when EFT colleagues attempted to make it as κ-scheme like as possible)

Advancements since preCDR

- Improvement in the simulation and analysis, detector design & performance, larger luminosity
- 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!)



	$\sigma_{ZH\_\tau\tau}$	σ_{ZH_ww}	σ_{ZH_zz}	σ_{ZH_gg}	σ_{ZH_cc}	σ_{ZH_bb}	$\sigma_{\nu\nu H\text{->}\nu\nu bb}$	$\sigma_{ZH\_\nu\nu bb}$
$\sigma_{ZH\_\tau\tau}$	100.000%							
σ_{ZH_ww}	-12.690%	100.000%						
σ_{ZH_zz}	-6.965%	-32.539%	100.000%					
σ_{ZH_gg}	0.842%	-3.744%	-1.737%	100.000%				
σ_{ZH_cc}	0.599%	-2.657%	-1.246%	-23.911%	100.000%			
σ_{ZH_bb}	0.026%	1.156%	-1.766%	-13.298%	-6.746%	100.000%		
$\sigma_{\nu\nu H\text{->}\nu\nu bb}$	-0.012%	-0.518%	0.791%	5.957%	3.022%	-44.793%	100.000%	
$\sigma_{ZH\_\nu\nu bb}$	-0.073%	0.325%	0.152%	-2.018%	-6.141%	0.966%	-0.433%	100.000%

Most measurements are anti-correlated !!!

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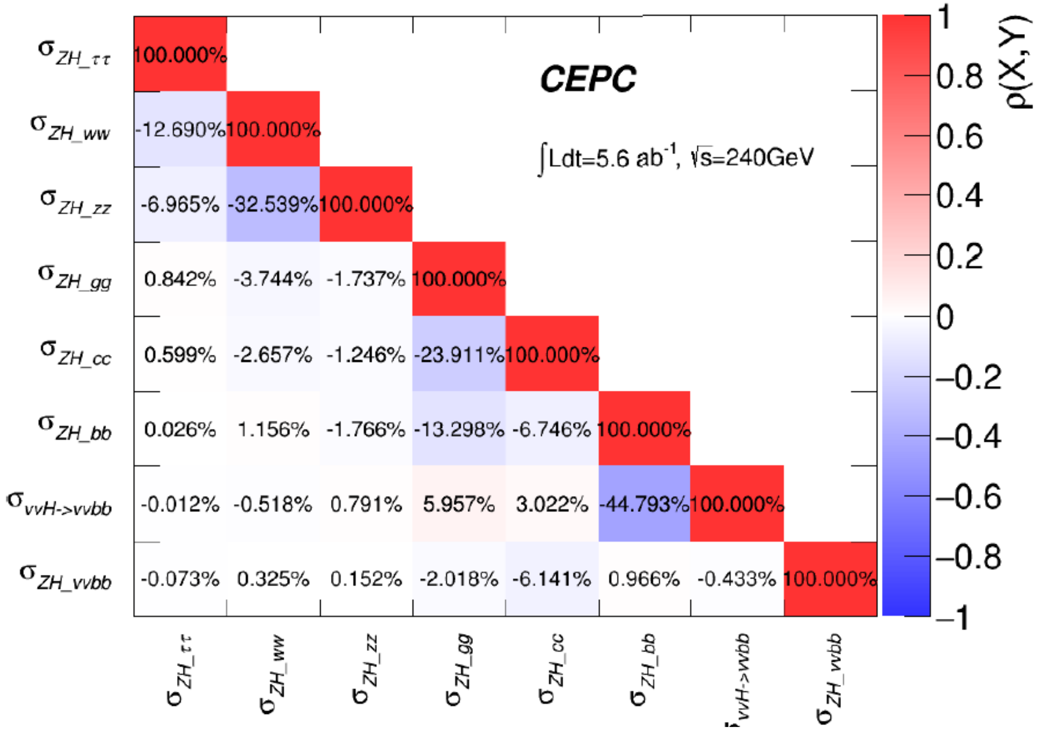

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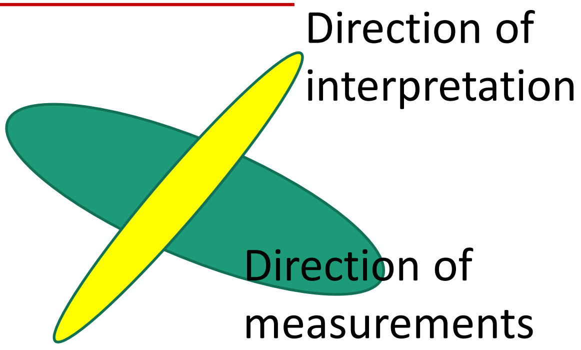
We can now fully exploit Higgs information in the data

<u>Most measurements are anti-correlated !!!</u>



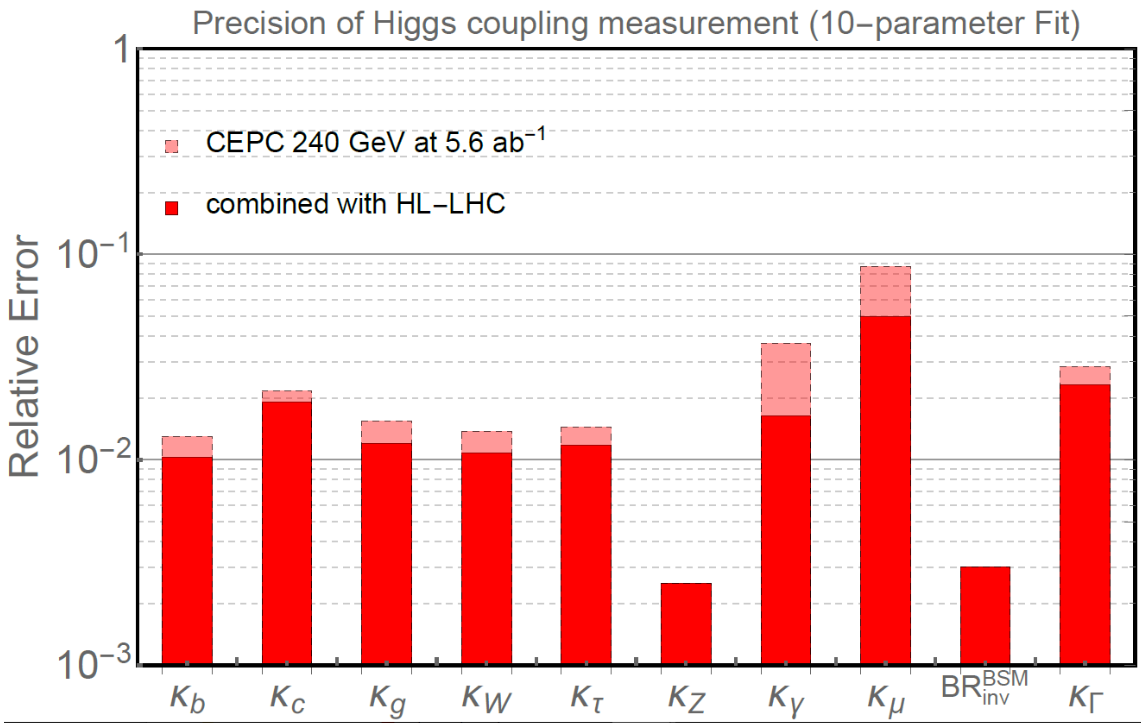
Advancements since preCDR

- 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!)
- 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%~20% for LHC measurements interpreted in this framework, assuming additional input from off-shell ZZ measurements to bound the Higgs total width)



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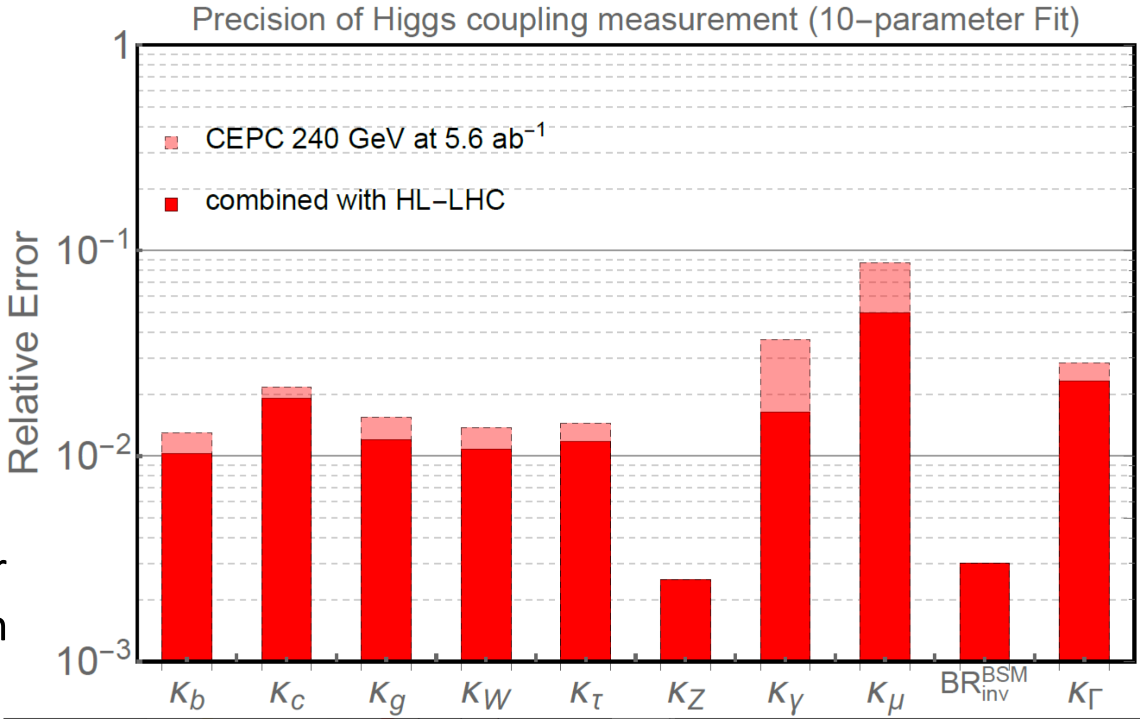
- Unique fit possible at CEPC and other lepton colliders
- Impossible to do at the HL-LHC*
- CEPC & HL-LHC synergy
- Signature numbers
  - κ_Γ 2.8%
  - κ_z 0.25%
  - κ_b 1.3%



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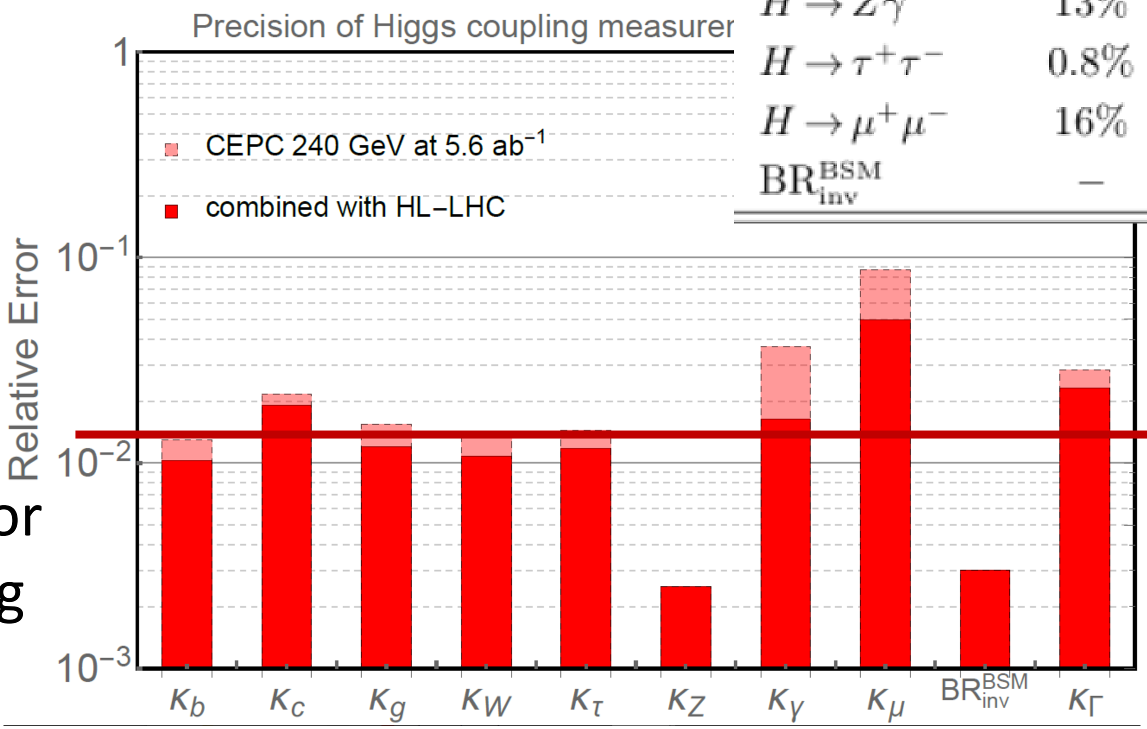
Decay mode	$\sigma\times$BR
$H\to b\bar{b}$	0.26%
$H\to c\bar{c}$	3.1%
$H\to gg$	1.2%
$H\to WW^*$	0.9%
$H\to ZZ^*$	4.9%
$H\to\gamma\gamma$	6.2%
$H\to Z\gamma$	13%
$H\to\tau^+\tau^-$	0.8%
$H\to\mu^+\mu^-$	16%
$\mathrm{BR}_{\mathrm{inv}}^{\mathrm{BSM}}$	–



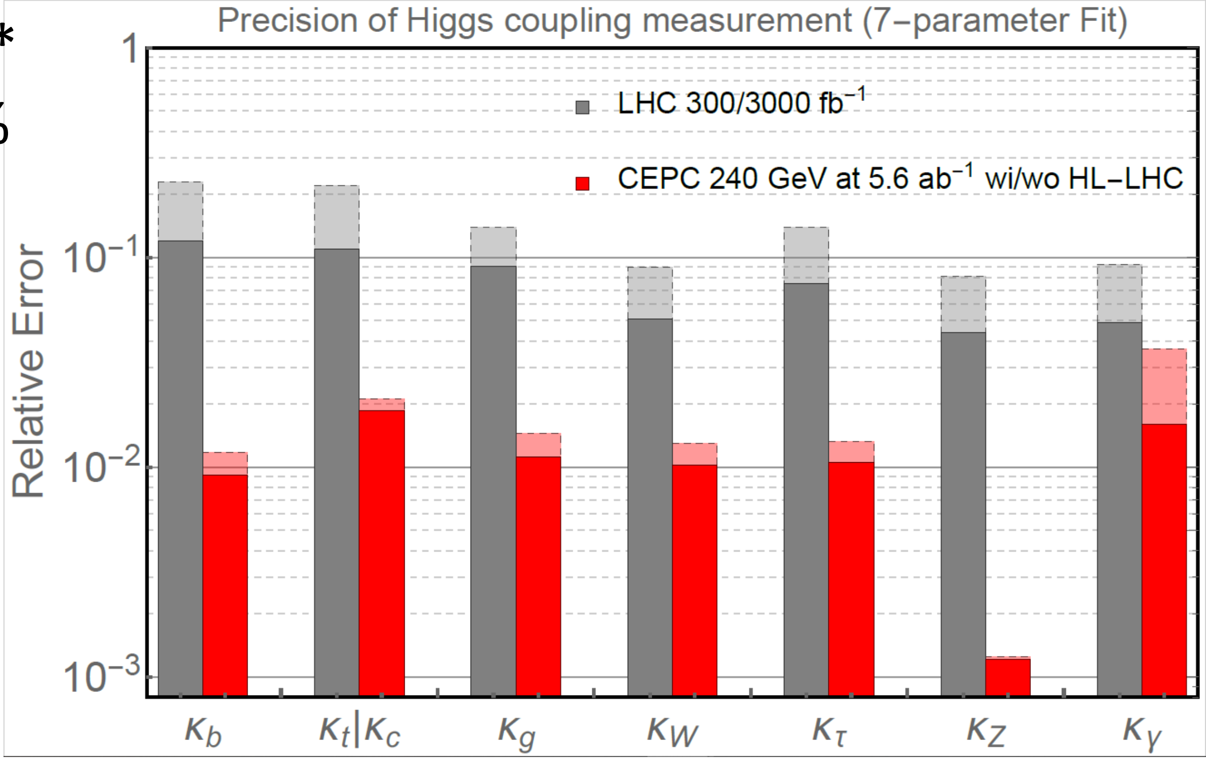
The total width sets a floor for the individual coupling extraction as:

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

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

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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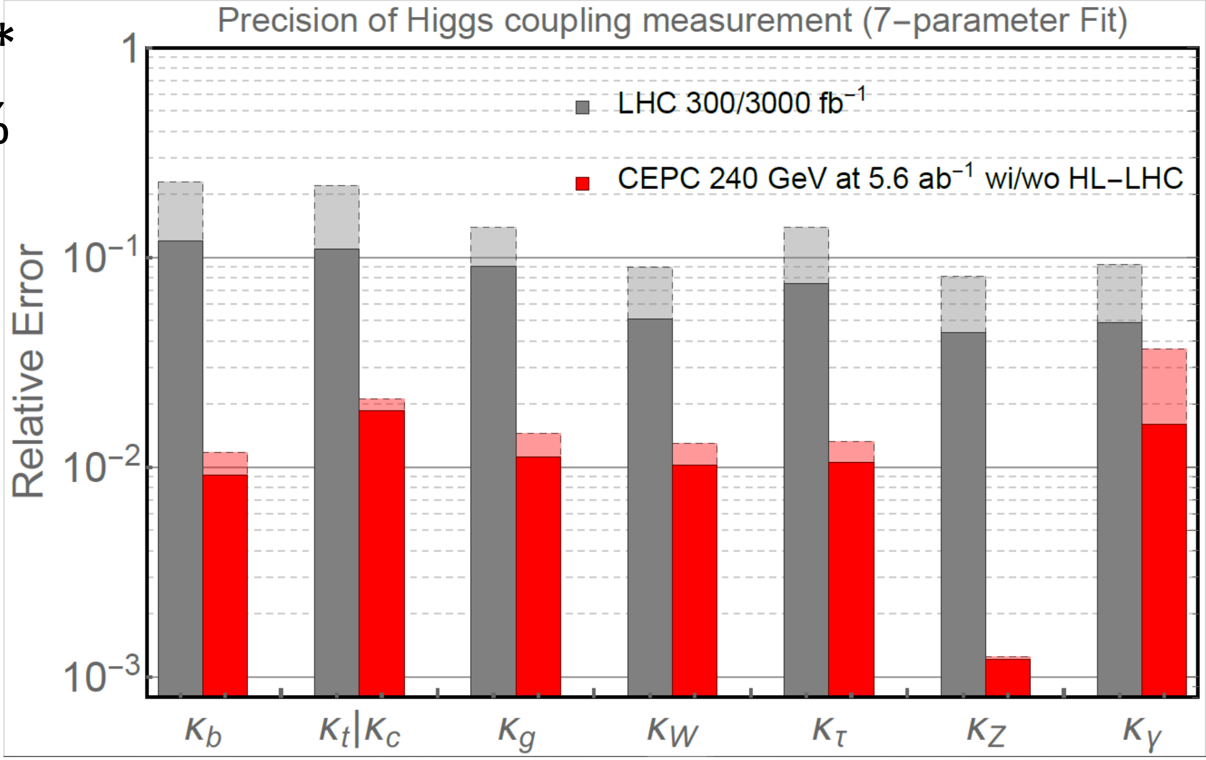
Significant improvement for the κ_Z from the additional constraints



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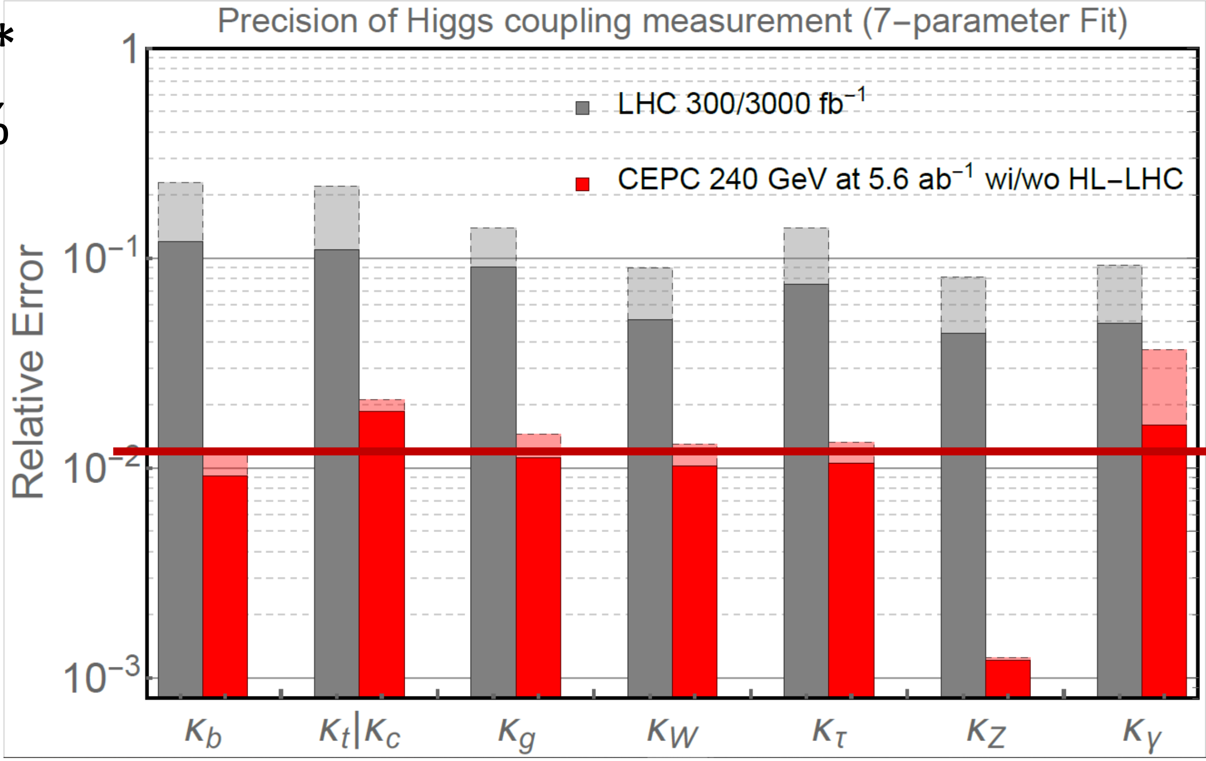
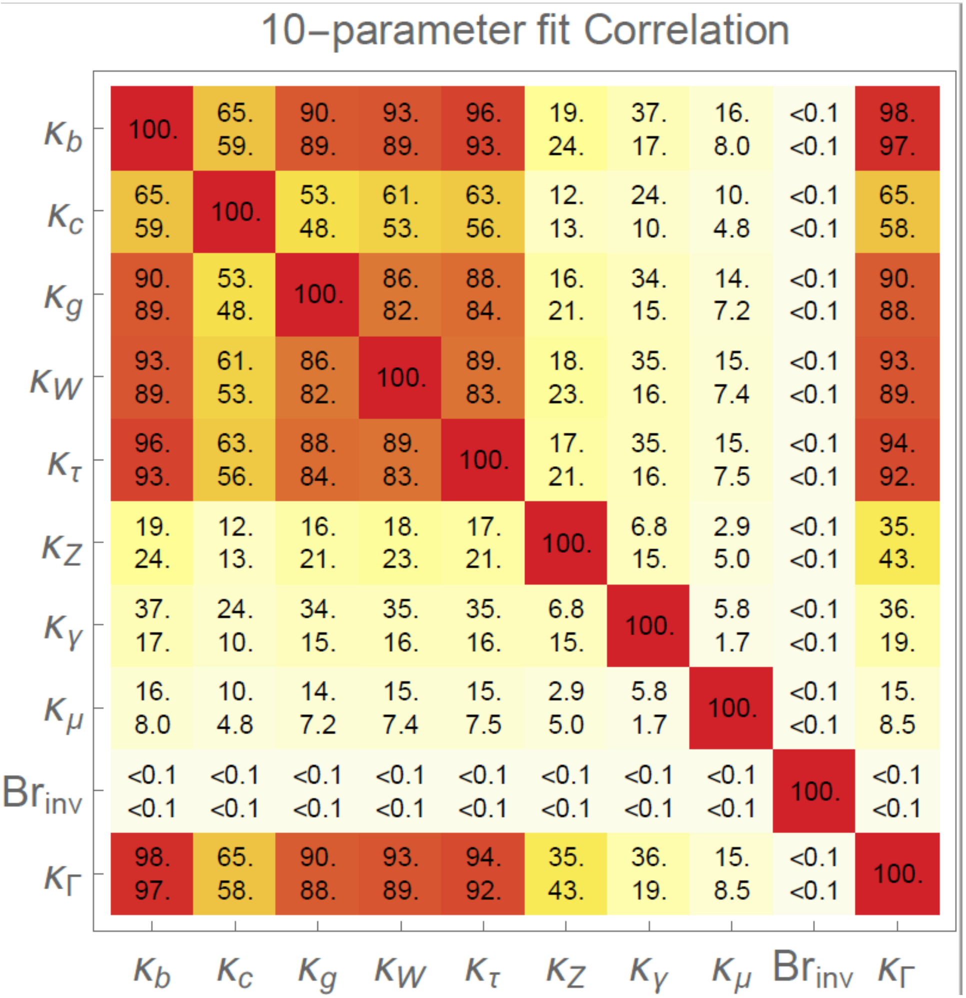


The total width (still!) sets a floor for the individual coupling extraction.

Output correlations

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



10–parameter fit Correlation

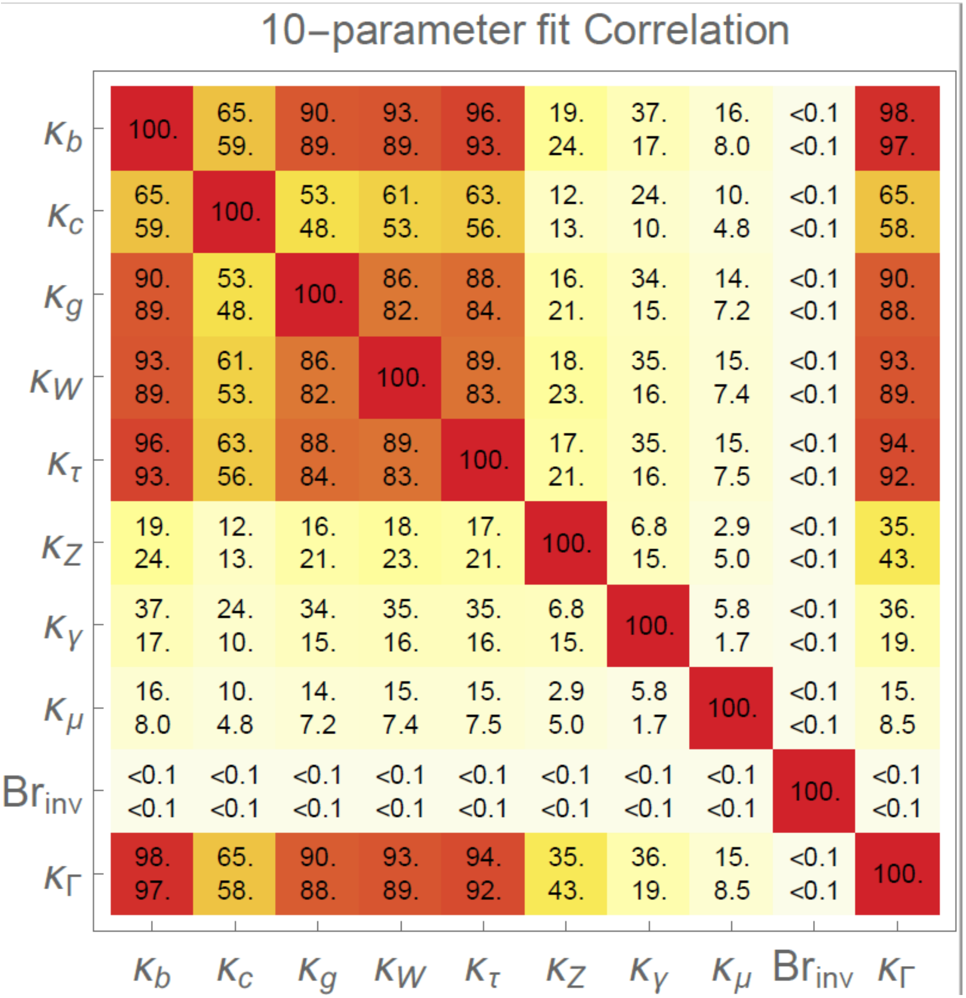
	κ_b	κ_c	κ_g	κ_W	κ_τ	κ_Z	κ_γ	κ_μ	$\mathrm{Br}_{\mathrm{inv}}$	κ_Γ
κ_b	100.	65. 59.	90. 89.	93. 89.	96. 93.	19. 24.	37. 17.	16. 8.0	<0.1 <0.1	98. 97.
κ_c	65. 59.	100.	53. 48.	61. 53.	63. 56.	12. 13.	24. 10.	10. 4.8	<0.1 <0.1	65. 58.
κ_g	90. 89.	53. 48.	100.	86. 82.	88. 84.	16. 21.	34. 15.	14. 7.2	<0.1 <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);



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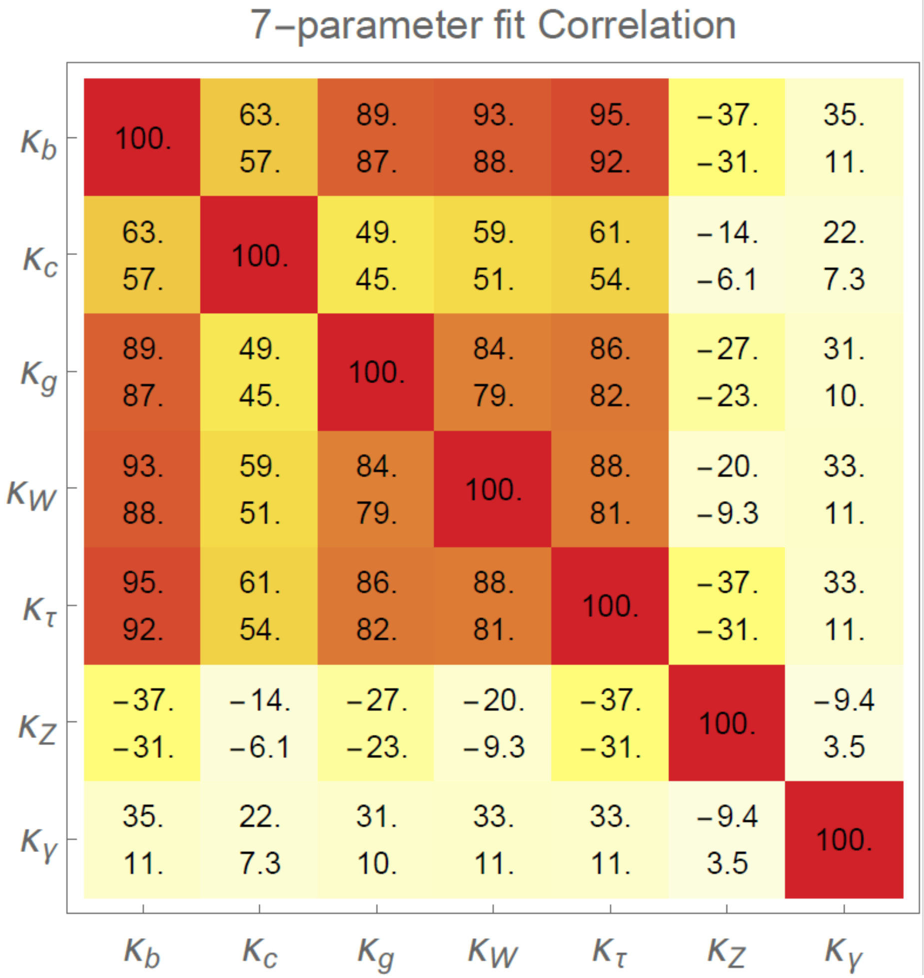

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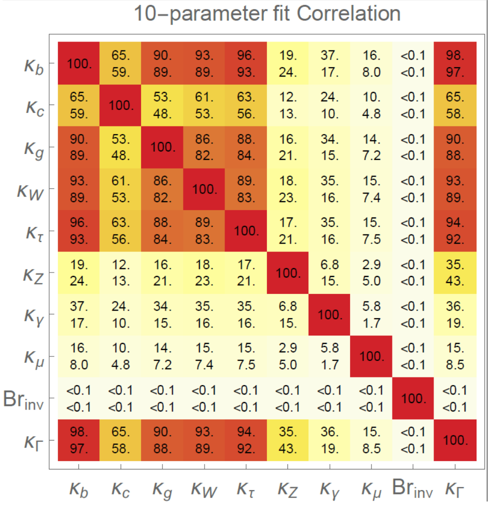

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Same pattern on correlations for the constraint fit (7-parameter fit), with the following highlights:

- 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;

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

CDR kappa 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, especially flexible for new light degree of freedoms;
- 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
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Towards TDR?

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- κ-framework is relatively simple but extendable, captures the main physics of the Higgs precision program, especially flexible for new light degree of freedoms;
- Developing our own fitting tools; my codes are theorists level, eventually, it should be taken over by experimental-grade coding;
- We can also consider to pick the most flexible and promising Higgs fitting program to make our study more “open”, which also have the benefits of getting other people’s evolving study results easily;
- 240 GeV only ➔+ 350-365 GeV (will be useful for kappa and EFT)
- Cut and count ➔full shape analysis, consider to use “matrix element method” this will provide a true ultimate limit of CEPC; One can also consider to just do a brute-force analysis on the full data sample and label them and pass it to neuro-networks, just to get some idea of the ultimate reach

While the Higgs precision fits (Kappa and EFT) moves along:

Opportunity: Higgs Exotic Decays

- Higgs boson can easily and well-motivated to be the portal to other BSM sectors. While most searches focus on heavy BSM particles, there is a whole zoo of light BSM particle not well explored at colliders.

  (checking all the possibility; theoretical interests.)

  ((H^+H) lowest mass dimensional spinless gauge singlet structure, easily a portal to BSM)

- The precision does not pin-point a scale, the exotic decays are to fully probe the scale below Higgs mass. **

  (complementarity)

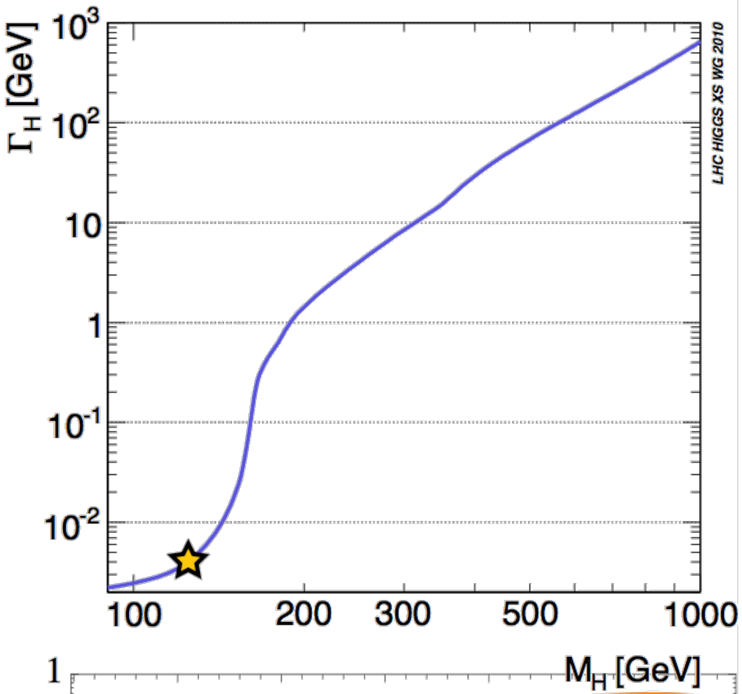
Why Exotic Decays? (continued)

- Higgs has tiny width ~4 MeV

$$\frac{\Gamma}{M} = O(10^{-5})$$

all its decay modes are suppressed by various factors, couplings, loop-factors, phase-space, etc.

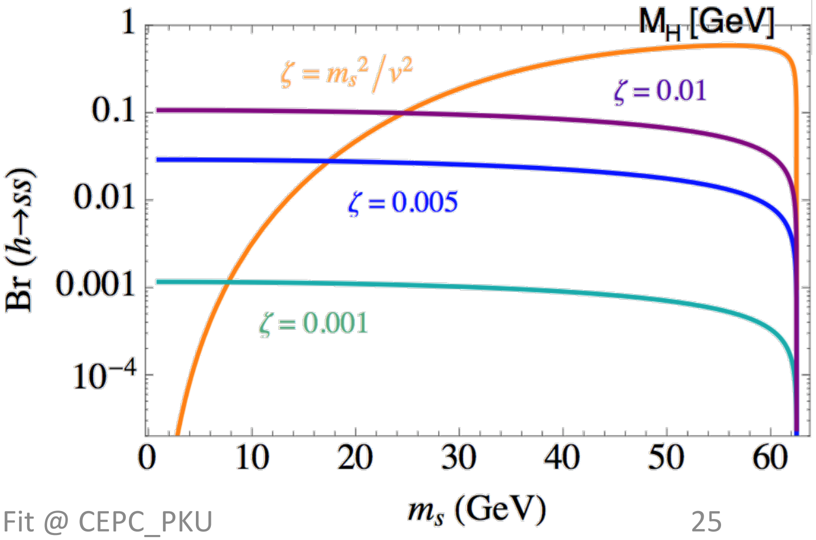
Dominant decays into bottom quark pairs are suppressed by the tiny coupling $y_b = 0.017$



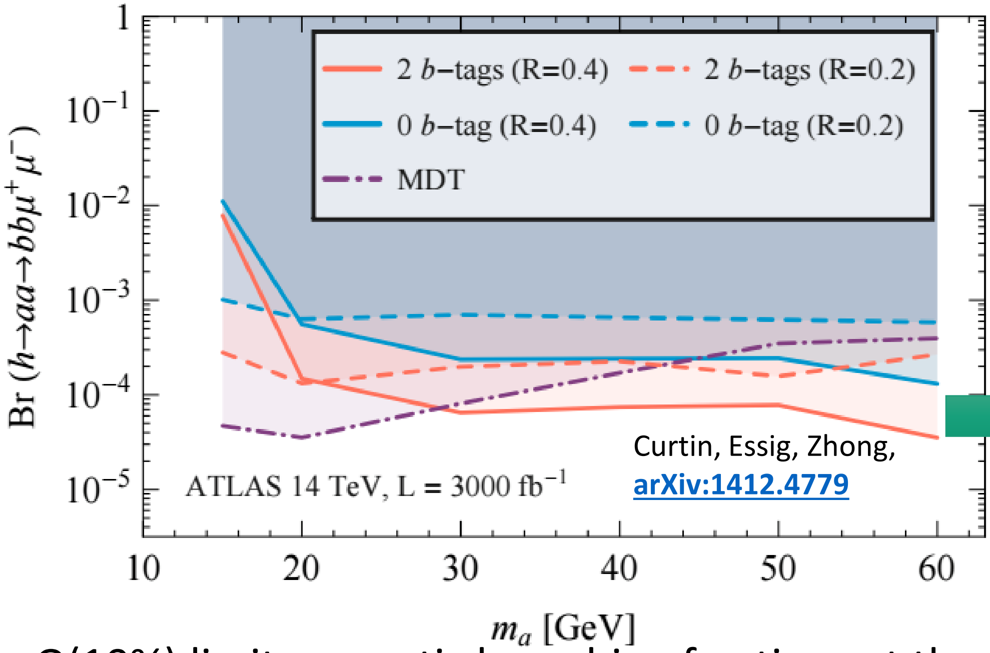
- small couplings to BSM could have sizable branching, e.g.,

$$\text{L} = \frac{\zeta}{2} s^2 |H|^2$$

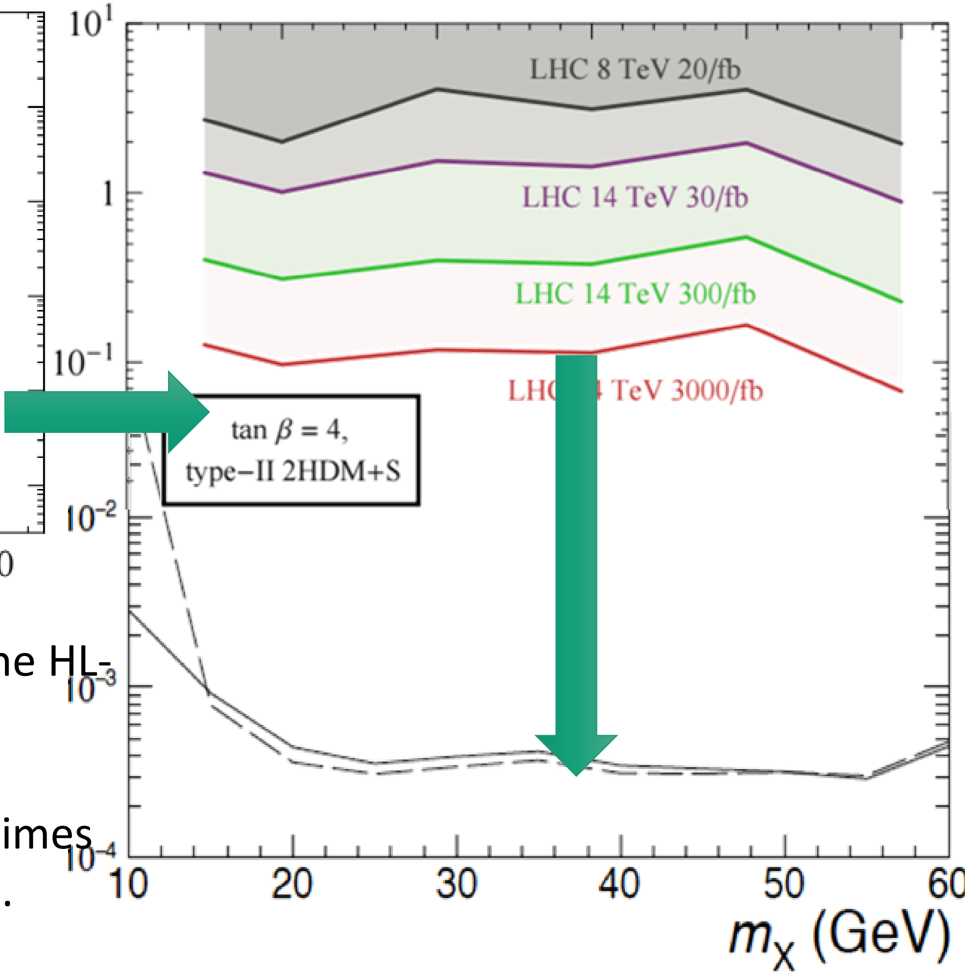
(common building block in extended Higgs sectors) can give BR(h➞ss)~O(10%) for ζ *as small as* 0.01 !



Exotic Decays $H \to aa$ interpretation



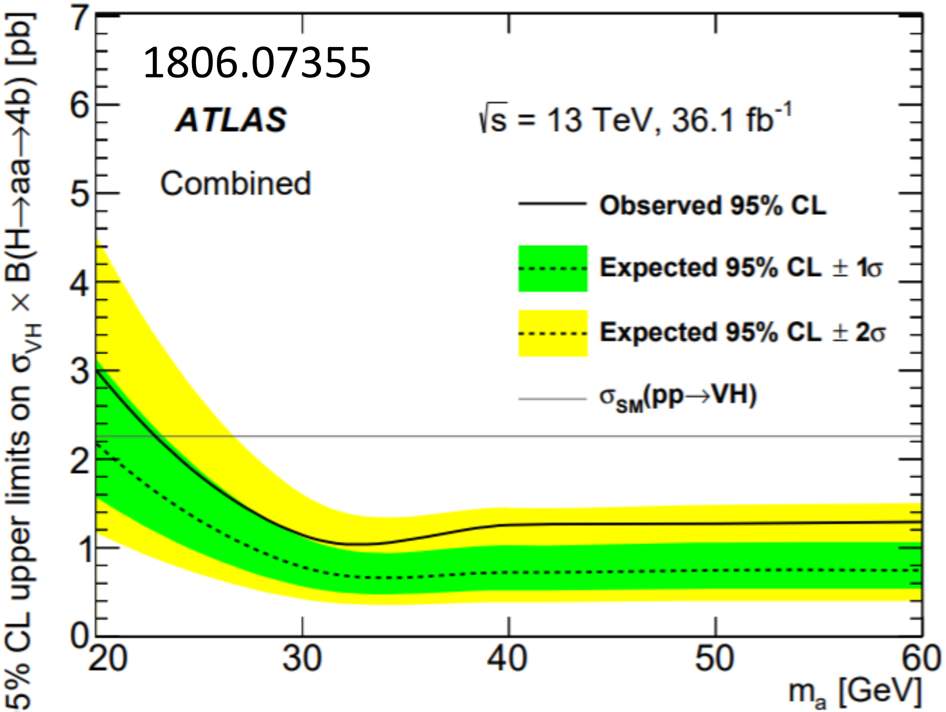
Curtin, Essig, Zhong, arXiv:1412.4779

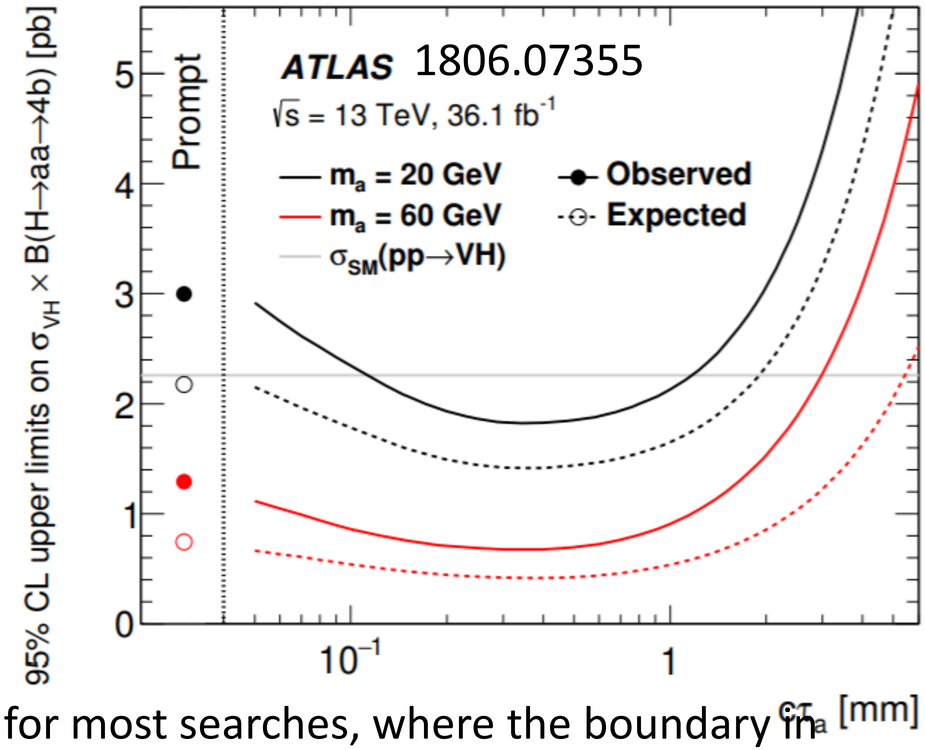


O(10%) limit on exotic branching fractions at the HL-LHC.

lepton colliders will improve the limits by two orders of magnitude, hitting more relevant regimes for various models' preferred parameter space.

Prompt→ LLP





Experimental searches use standard particle ID for most searches, where the boundary in displacement the prompt search can be applied to is really hard to guess/estimate.

Higgs exotic decays H->(bb)(bb) made a first step, in a same publication, reinterpreted their own prompt searches for long-lived intermediate particles:

- Prompt limits dies-off above a few mm;
- Long-lived limits is better than prompt limit in a prompt search; (maybe next time when an excess/discovery hard to fit your favorite model in rate, consider LLPs ☺)

Higgs to LLPs

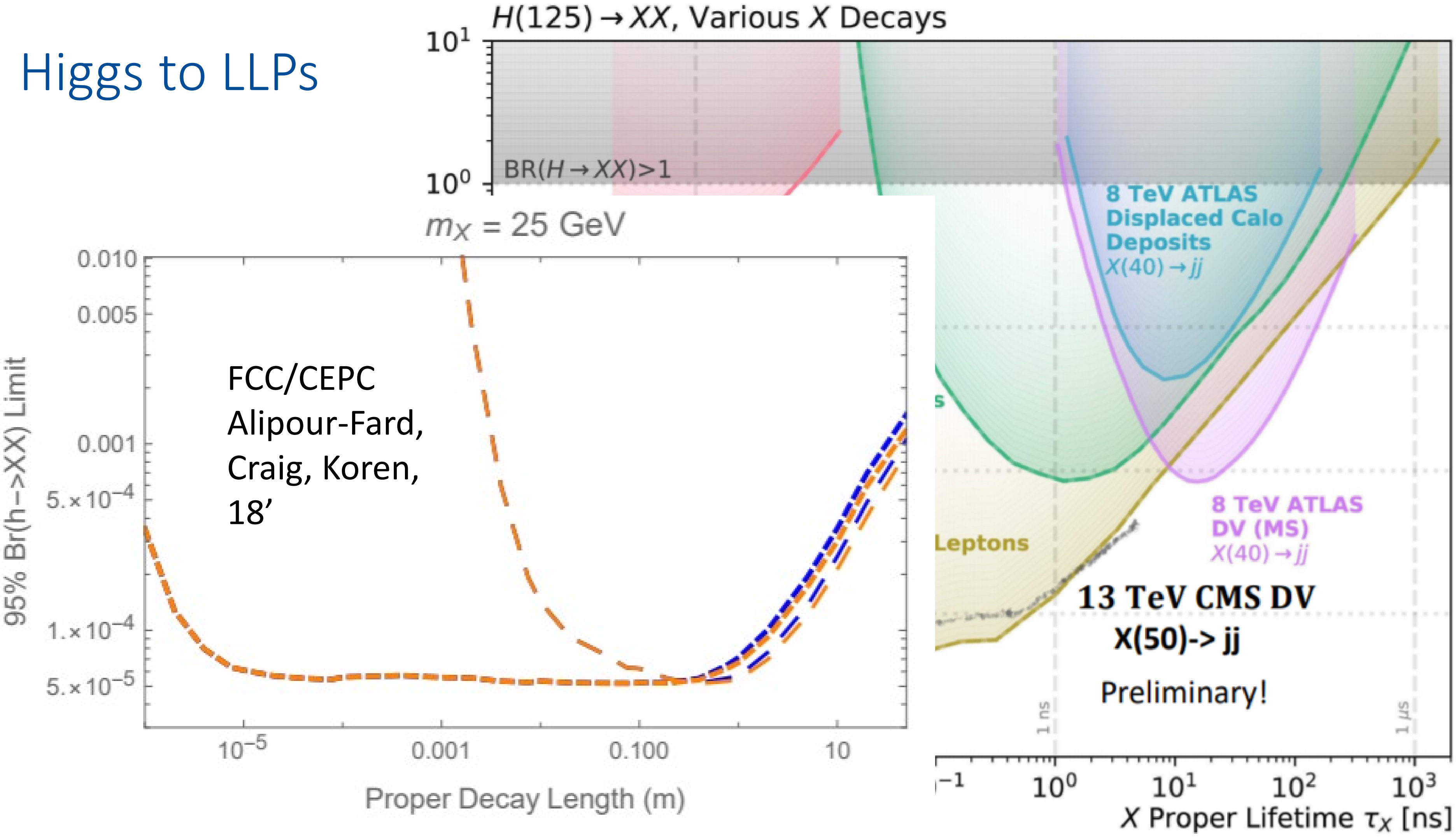


Figure from Lee, Ohm, Soffer, Yu (1810.12602)

New ideas of using timing information at the LHC, J. Liu, ZL, L.T. Wang, 18’

See also, M. Carena, ZL, Y.K. Wang, appearing soon.

Beyond the Z_2 limit

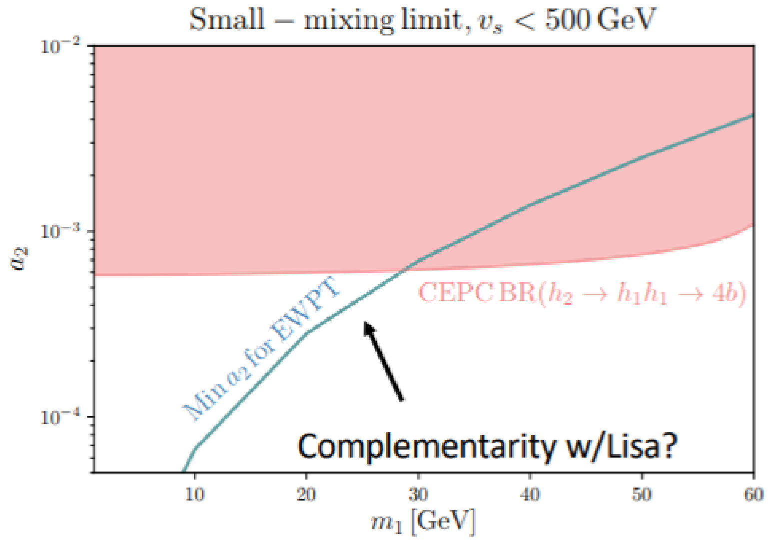
General case more complicated. Simplifies in the small-mixing limit

$$V_0(H,S) = -\mu^2 |H|^2 + \lambda |H|^4 + \frac{1}{2} a_1 \cancel{|H|^2 S} + \frac{1}{2} a_2 |H|^2 S^2$$
$$+ \cancel{b_1 S} + \frac{1}{2} b_2 S^2 + \frac{1}{3} b_3 S^3 + \frac{1}{4} b_4 S^4$$

Now b_3 can potentially compensate for small a_2. However, imposing requirements from vacuum stability, completion of the PT, etc still place a lower bound on *BR($h_2 \rightarrow h_1 h_1$)*:

Larger mixing angles require numerical scans; expect similar conclusions

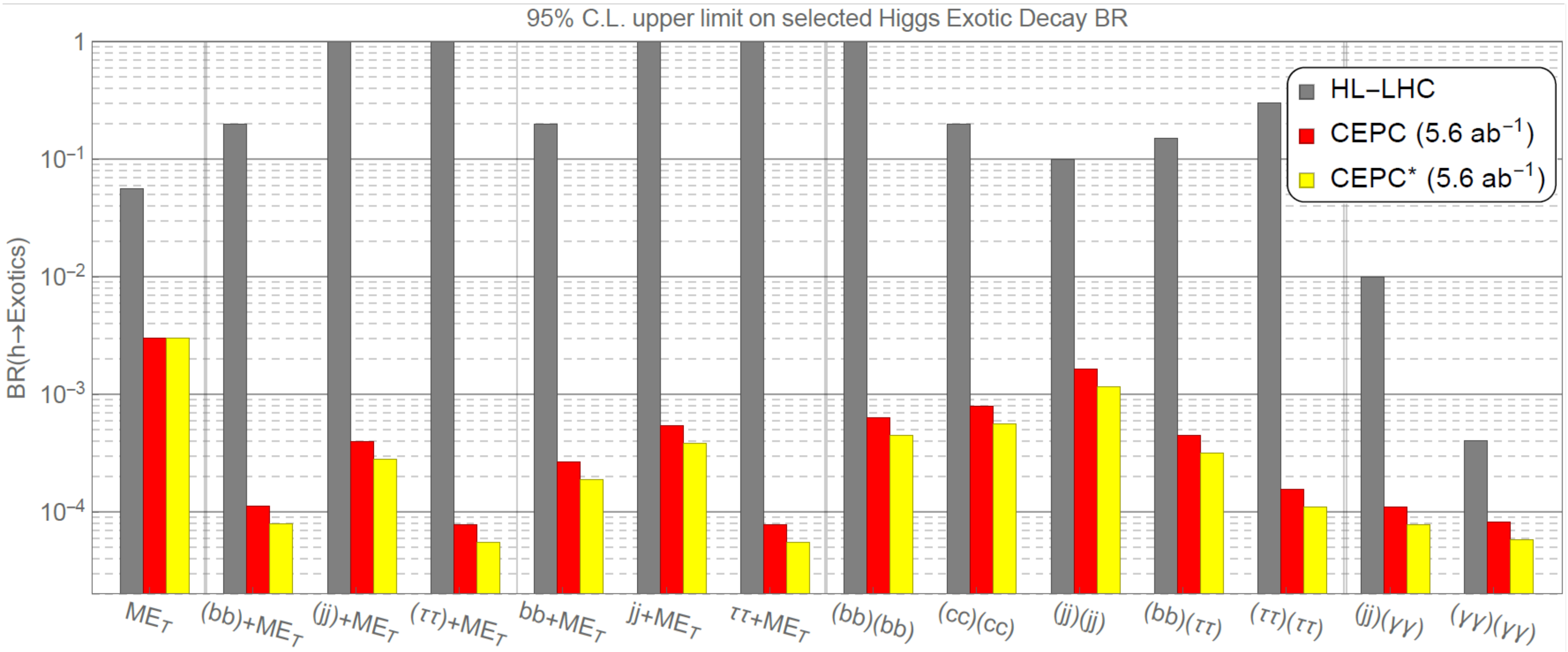
Projected CEPC sensitivity taken from Liu, Wang, Zhang 2016



Complementarity w/Lisa?

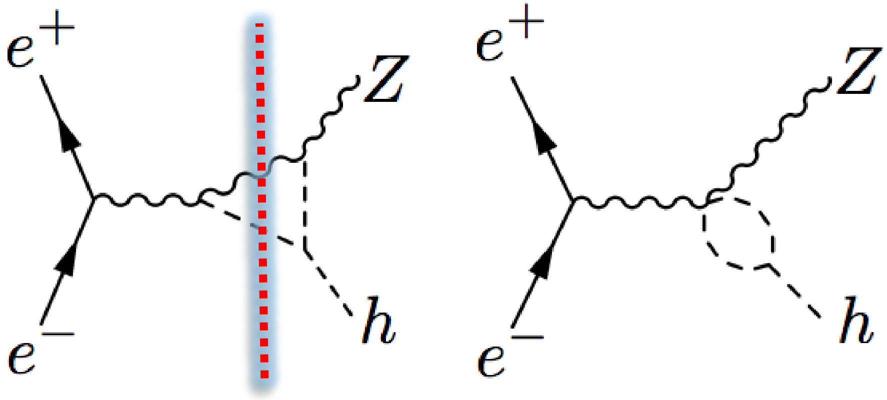
CEPC should be able to probe light visibly-decaying scalars consistent with a strong EWPT and other pheno requirements down to ~30 GeV.

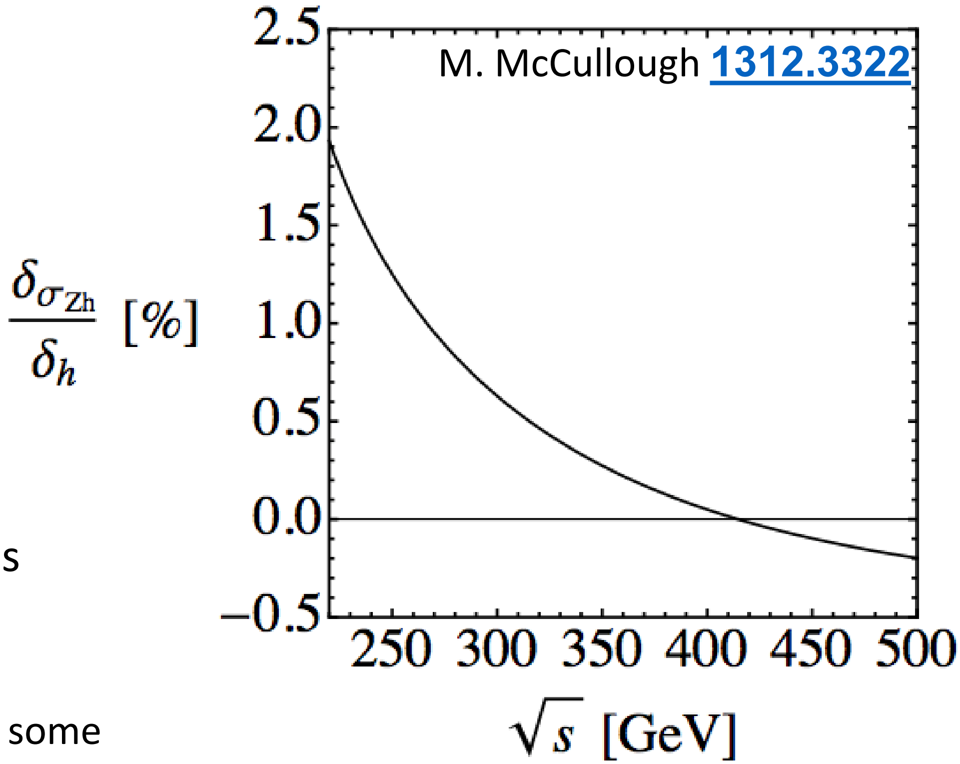
Work in progress with M. J. Ramsey-Musolf and J. Shelton



- Higgs Exotic decays is a very important component of Higgs program at future colliders
- Lepton colliders show great advantage for decays that are very challenging at the LHC, such as Higgs decays into jets and Higgs decays with missing energy
- Hadron colliders and lepton colliders are complementary in probing Higgs exotic decays and could together provide a much more coherent picture for discovery
- Many more works for Higgs exotic decays at both the LHC and future colliders are interesting and are needed.

Constraints from $e^+e^- \to ZH$

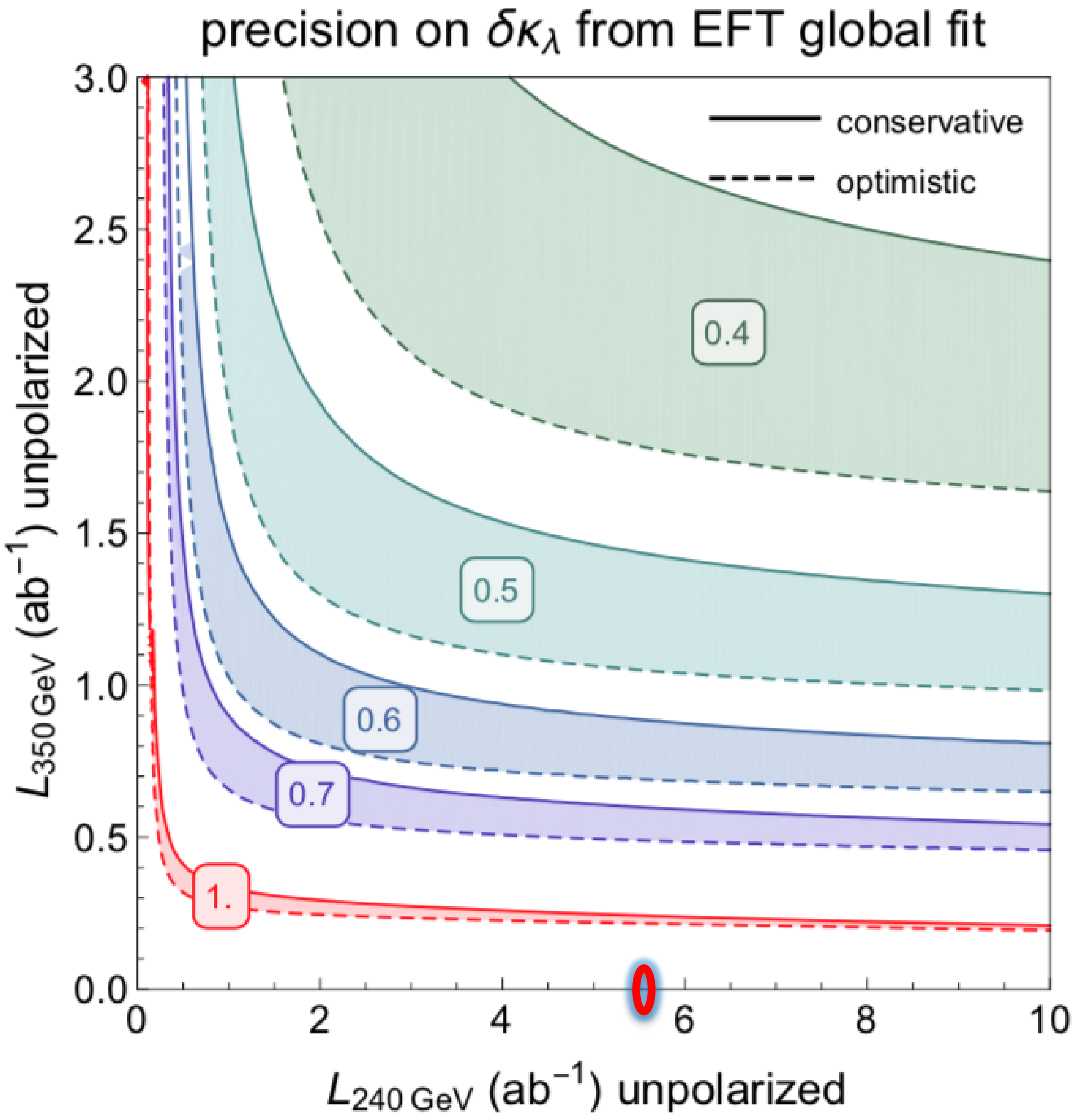


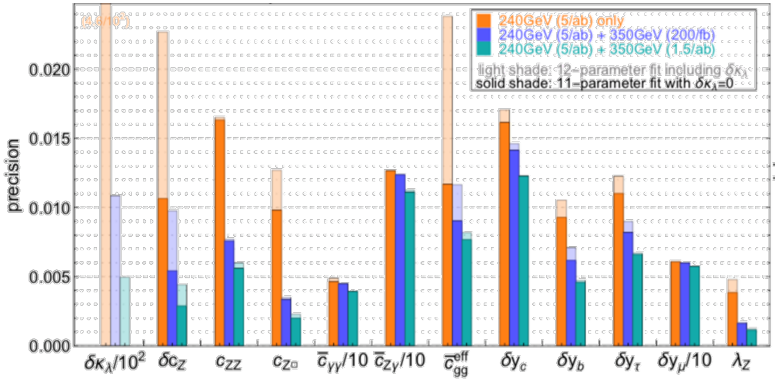

M. McCullough 1312.3322

A natural/free threshold enhancement helps enhancing the sensitivity;

O(30%) precision achievable at FCC-ee, with some assumptions that we will break down in the next few slides;

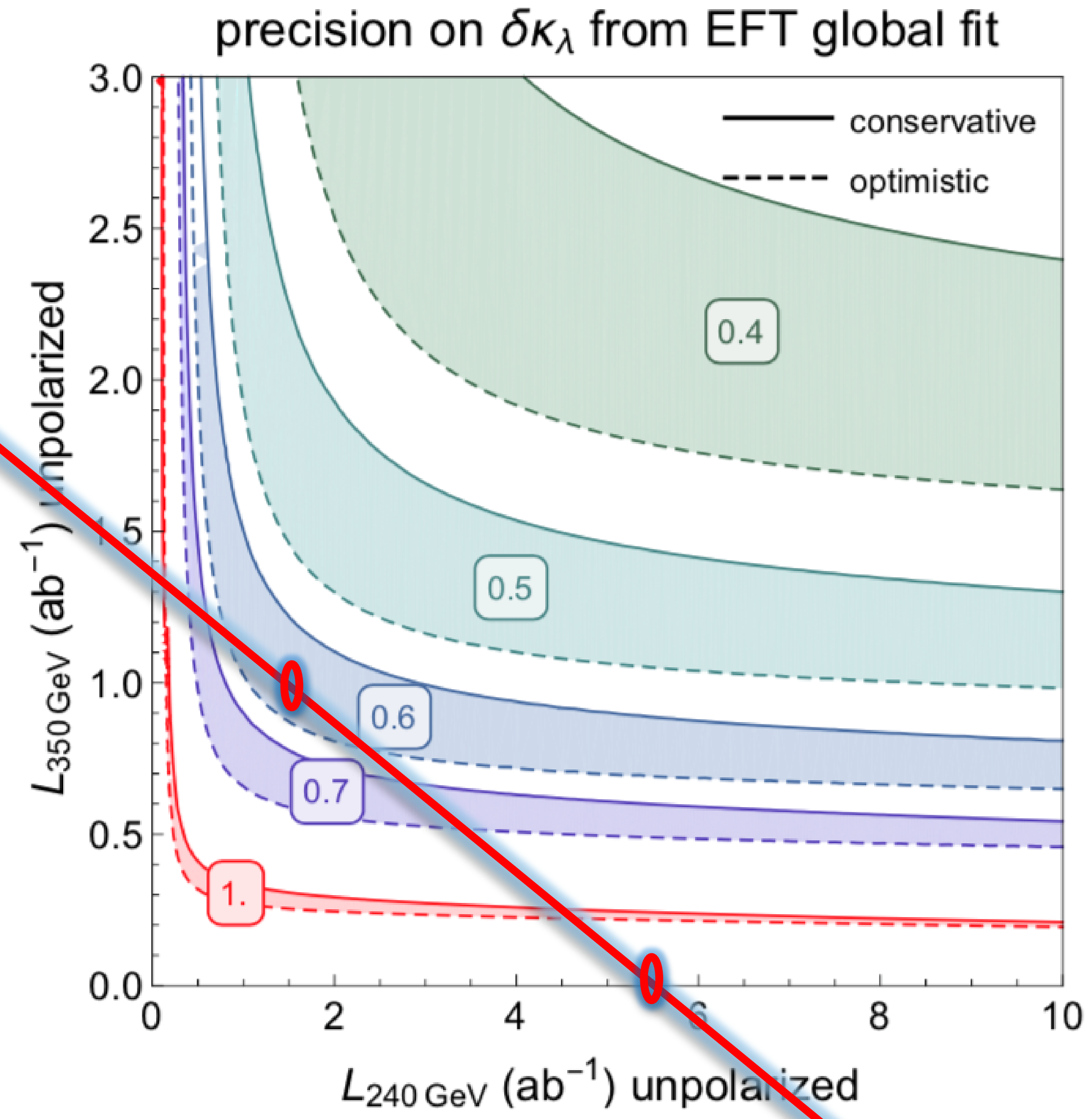
Results: 240 GeV and 350 GeV interplay





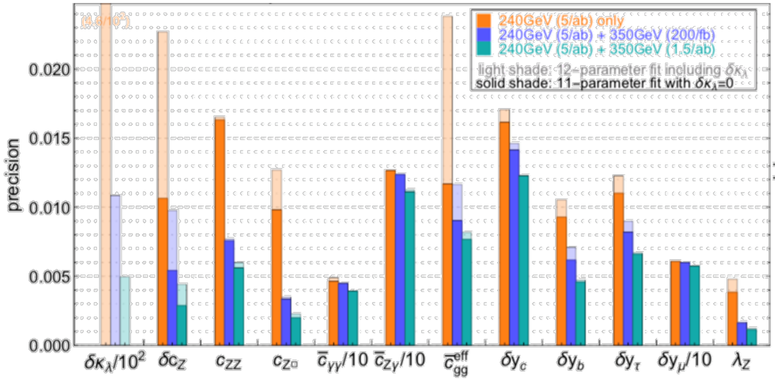
*bands corresponds to 0.1% to 1% systematic uncertainties assumed for aTGCs

Results: 240 GeV and 350 GeV interplay

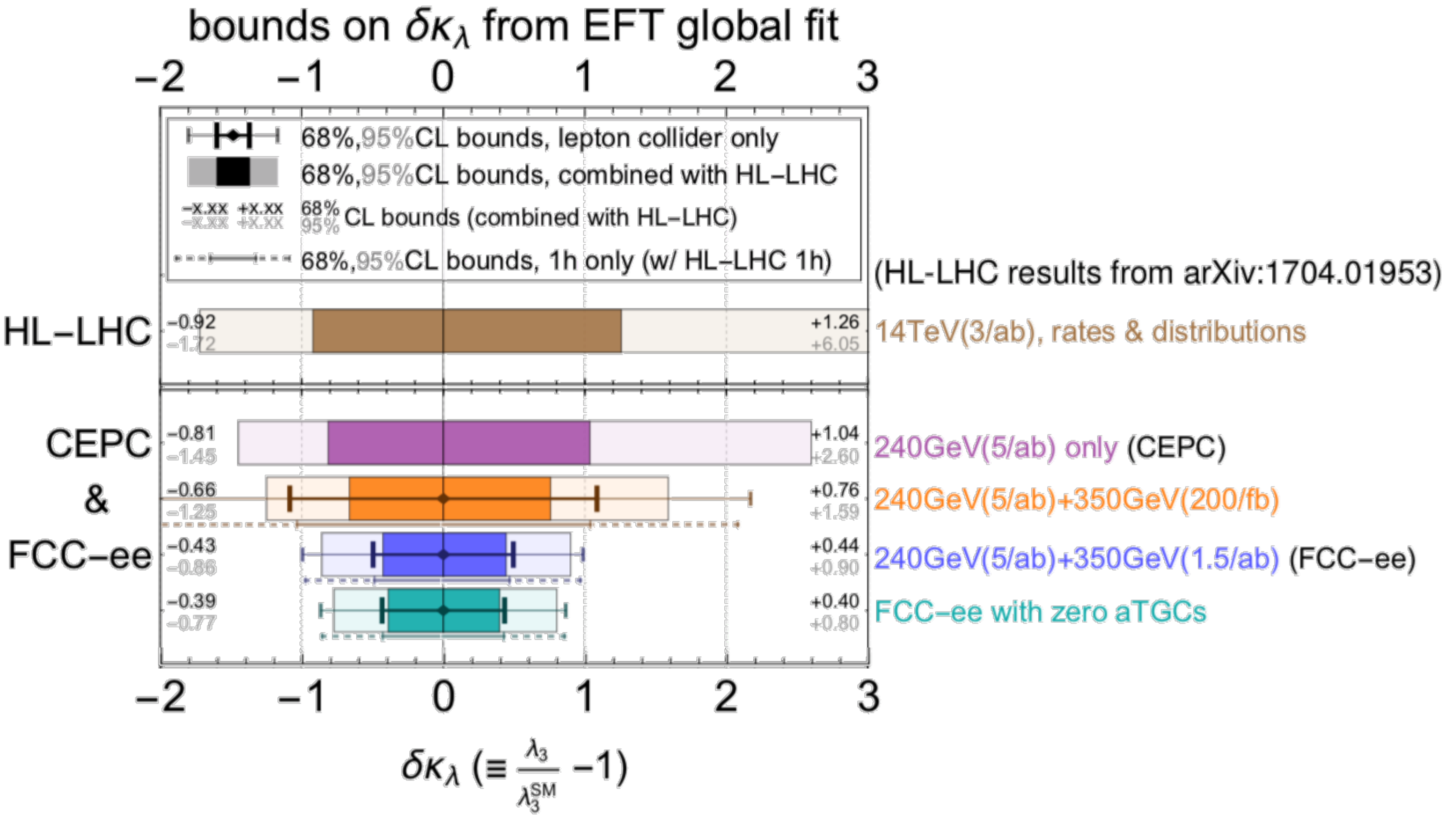


- Assuming that the instantaneous luminosity of 350 GeV is ¼ of 240 GeV run, one can find the optimal running point for the Higgs trilinear;

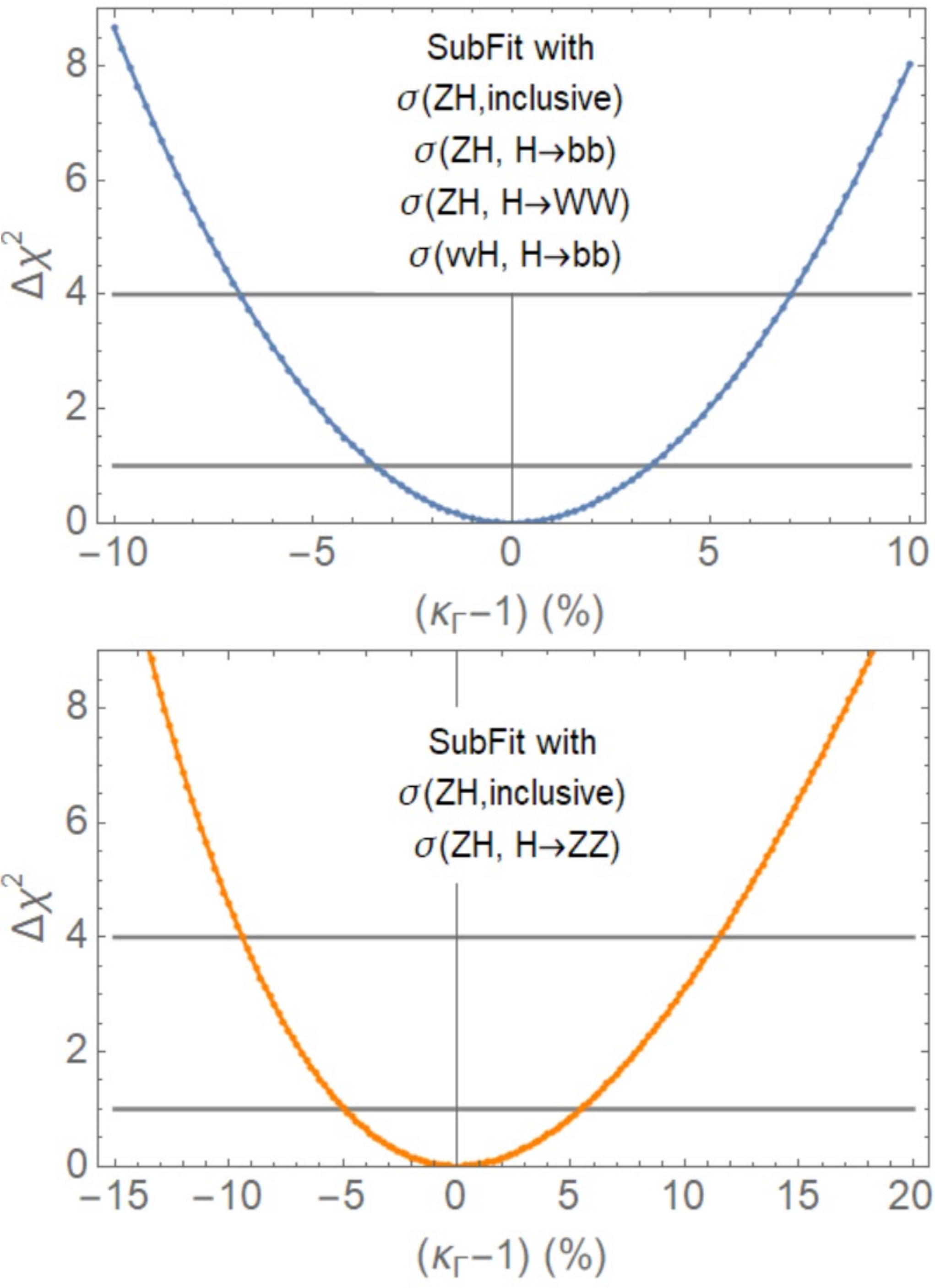
- Similar practice can be done for many others, physics goals need to be chosen carefully.

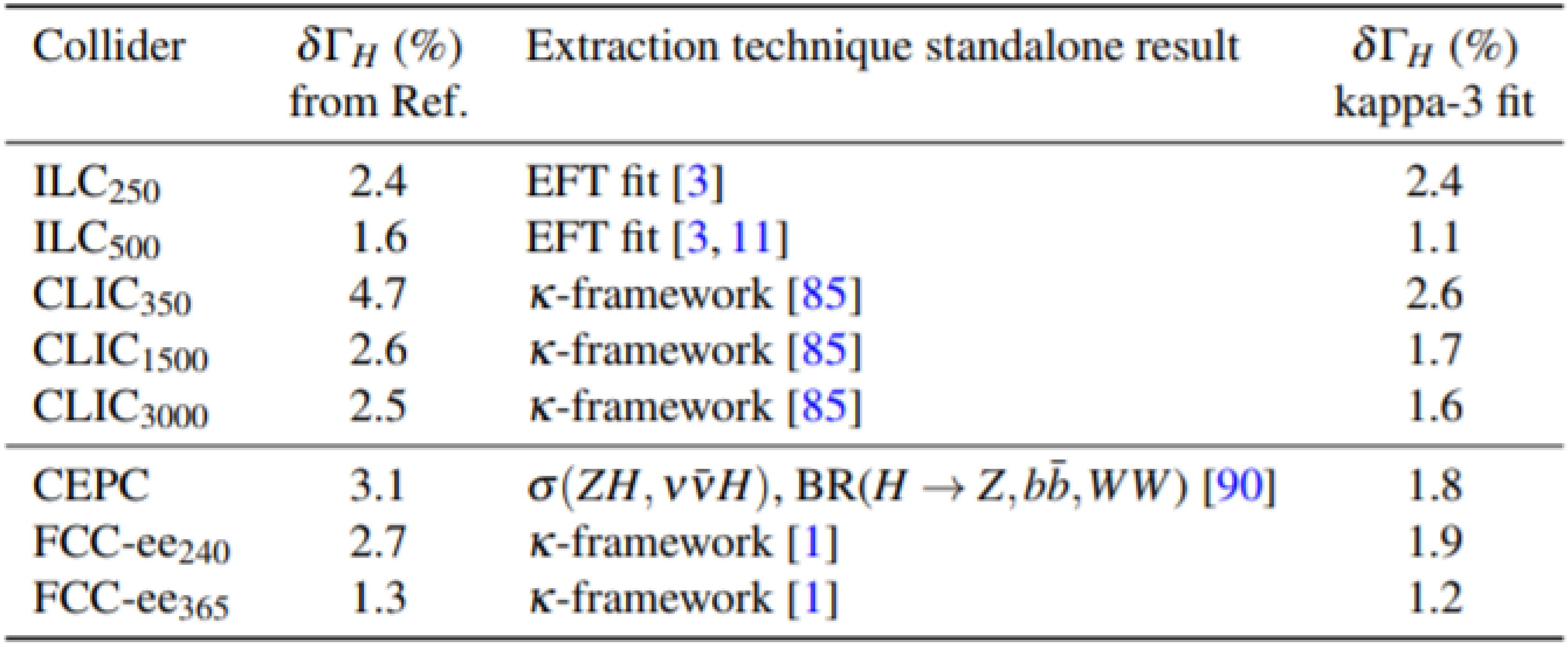


*bands corresponds to 0.1% to 1% systematic uncertainties assumed for aTGCs



- Higgs self-couplings are the keys to reveal nature of EWPT and EWBG;
- FCC-ee could use precision Higgs measures to constrain Higgs trilinear couplings in a robust way in the general EFT framework; we setup the framework and include more observables;
- Interplay between Higgs precision and EWPO, 240 GeV and 350 GeV, FCC-ee and other future collider programs, can be studied in this framework and provide useful information; This direction needs support from simulation groups for various channels and programs;
- Independent probes are always useful, even if we can achieve 5% precision at 100 TeV;


SubFit with
σ(ZH,inclusive)
σ(ZH, H→bb)
σ(ZH, H→WW)
σ(ννH, H→bb)
Δχ²
0
2
4
6
8
−10
−5
0
5
10
(κ_Γ−1) (%)
SubFit with
σ(ZH,inclusive)
σ(ZH, H→ZZ)
Δχ²
0
2
4
6
8
−15
−10
−5
0
5
10
15
20
(κ_Γ−1) (%)



Collider	$\delta\Gamma_H$ (%) from Ref.	Extraction technique standalone result	$\delta\Gamma_H$ (%) kappa-3 fit
ILC_{250}	2.4	EFT fit [3]	2.4
ILC_{500}	1.6	EFT fit [3, 11]	1.1
CLIC_{350}	4.7	κ-framework [85]	2.6
CLIC_{1500}	2.6	κ-framework [85]	1.7
CLIC_{3000}	2.5	κ-framework [85]	1.6
CEPC	3.1	$\sigma(ZH, \nu\bar{\nu}H)$, $\text{BR}(H \to Z, b\bar{b}, WW)$ [90]	1.8
FCC-ee_{240}	2.7	κ-framework [1]	1.9
FCC-ee_{365}	1.3	κ-framework [1]	1.2