PHENO 2022
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May 9 to 11
Latest topics in particle physics and related issues

Program Advisors

Higgs Precision at 125 GeV Muon Collider

Zhen Liu
University of Minnesota

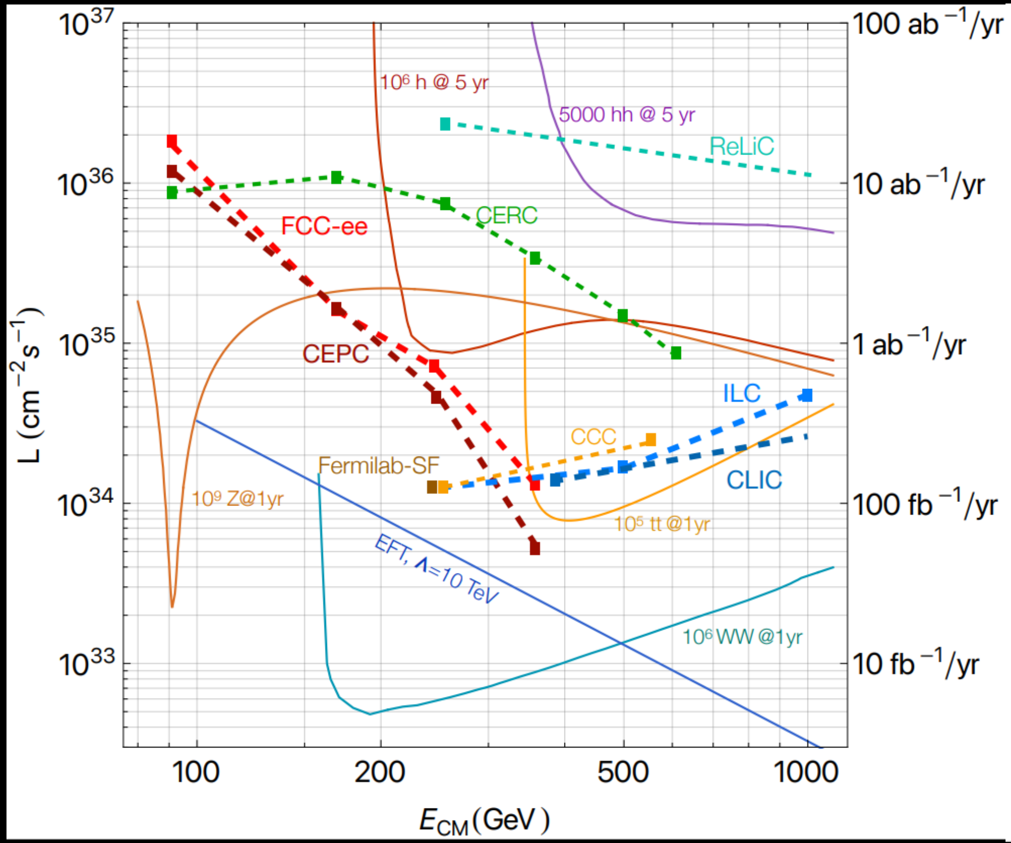
Mainly based upon
J. de Blas, Jiayin Gu, ZL,
2203.04324

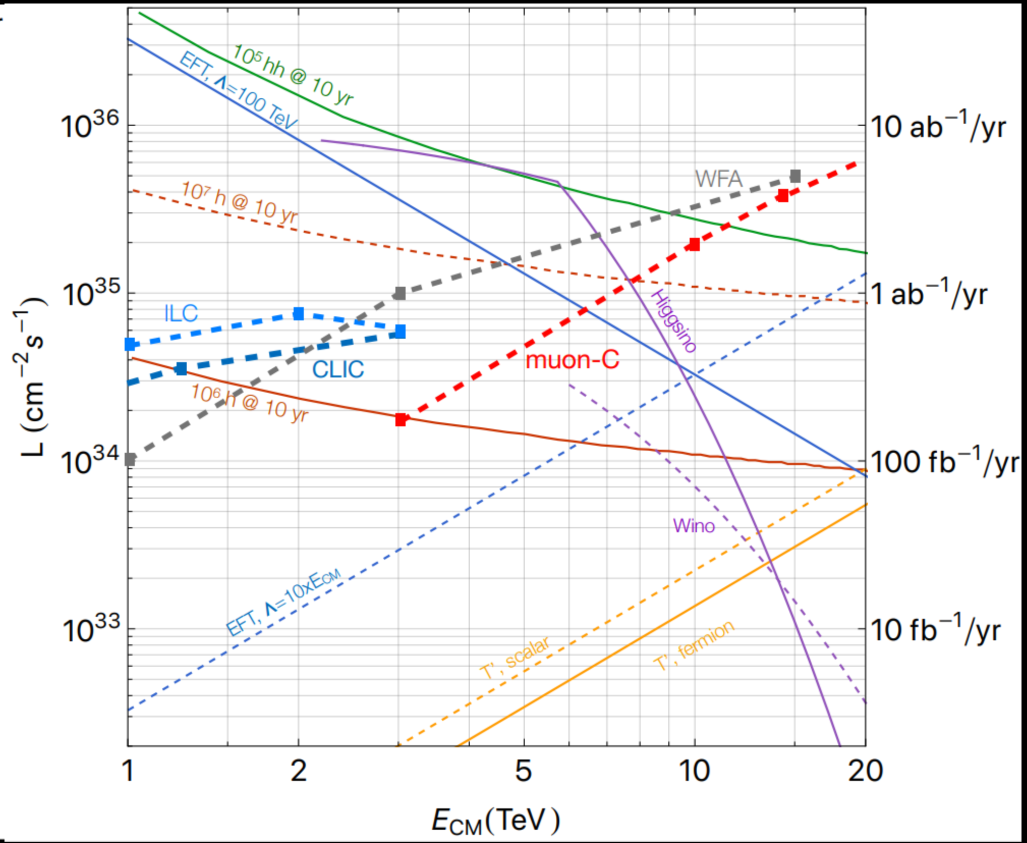
Two Distinctive Higgs Programs at Muon Colliders

- **125 GeV s-channel Resonant Higgs Factory**
- High Energy Higgs Factory (see talk by M. Forslund in this session.)

Many future collider options and excitement!

(also seen in the talk by Isobel Ojalvo.)

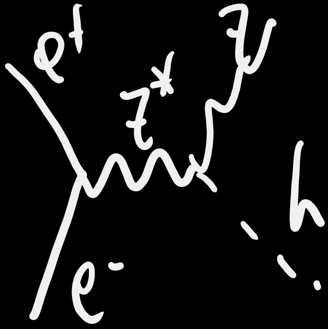


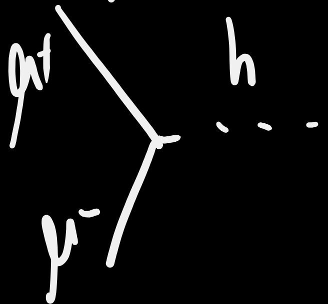


ZL, LT Wang, 2205.00031

Basics:

pp	e^+e^-	$\mu^+\mu^-$	$\mu^+\mu^-$





LHC 14 TeV	e^+e^- 240~250 GeV	$\mu^+\mu^-$ 125 GeV	$\mu^+\mu^-$ 10 TeV
50 pb	200 fb	22 pb × 65%	~ 1 pb
3 ab^{-1}	5 ab^{-1}	5~20 fb^{-1}	10 ab^{-1}
150 million Higgs	1 million Higgs	0.07 ~0.28 million Higgs	~10 million Higgs

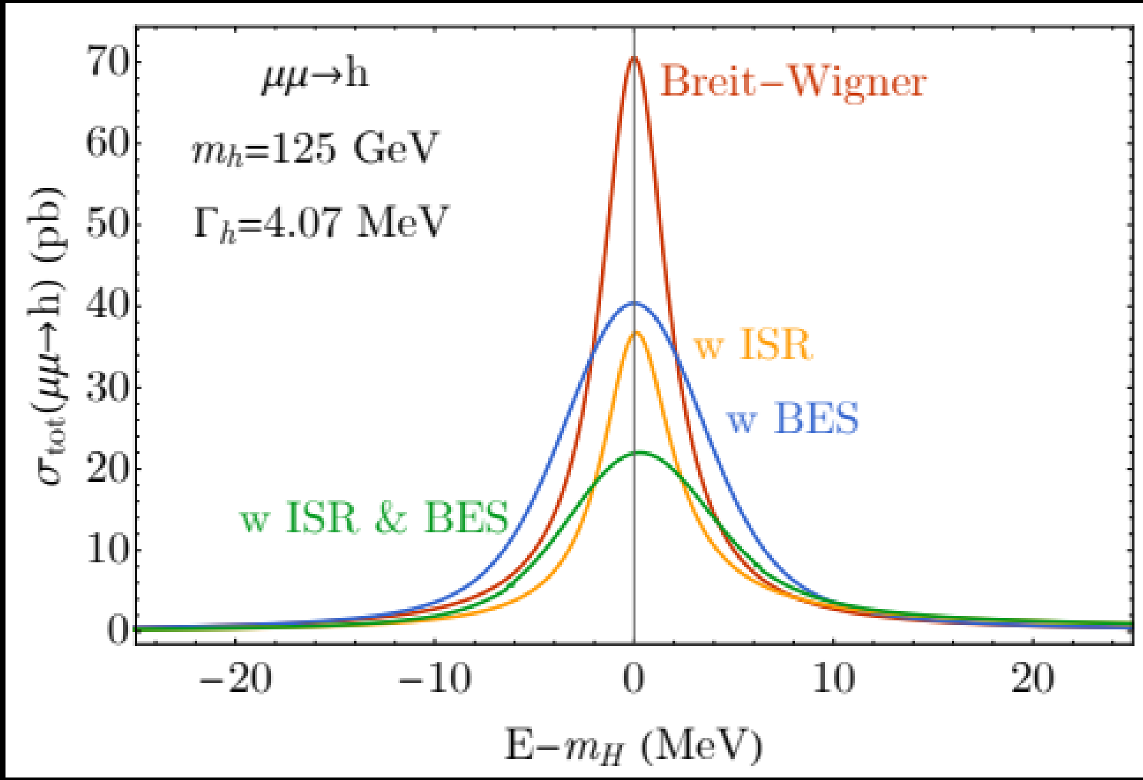
Lots of open questions

How would the width, mass, signal strength fit scale in various scenarios?

- Change of Luminosity (expecting some non-linearities from the beam energy spread);
- Lineshape scanning steps
- Lineshape scanning range
- Inclusion of more channels

The convolution of various effects are highly non-trivial. So new studies will help understand better:

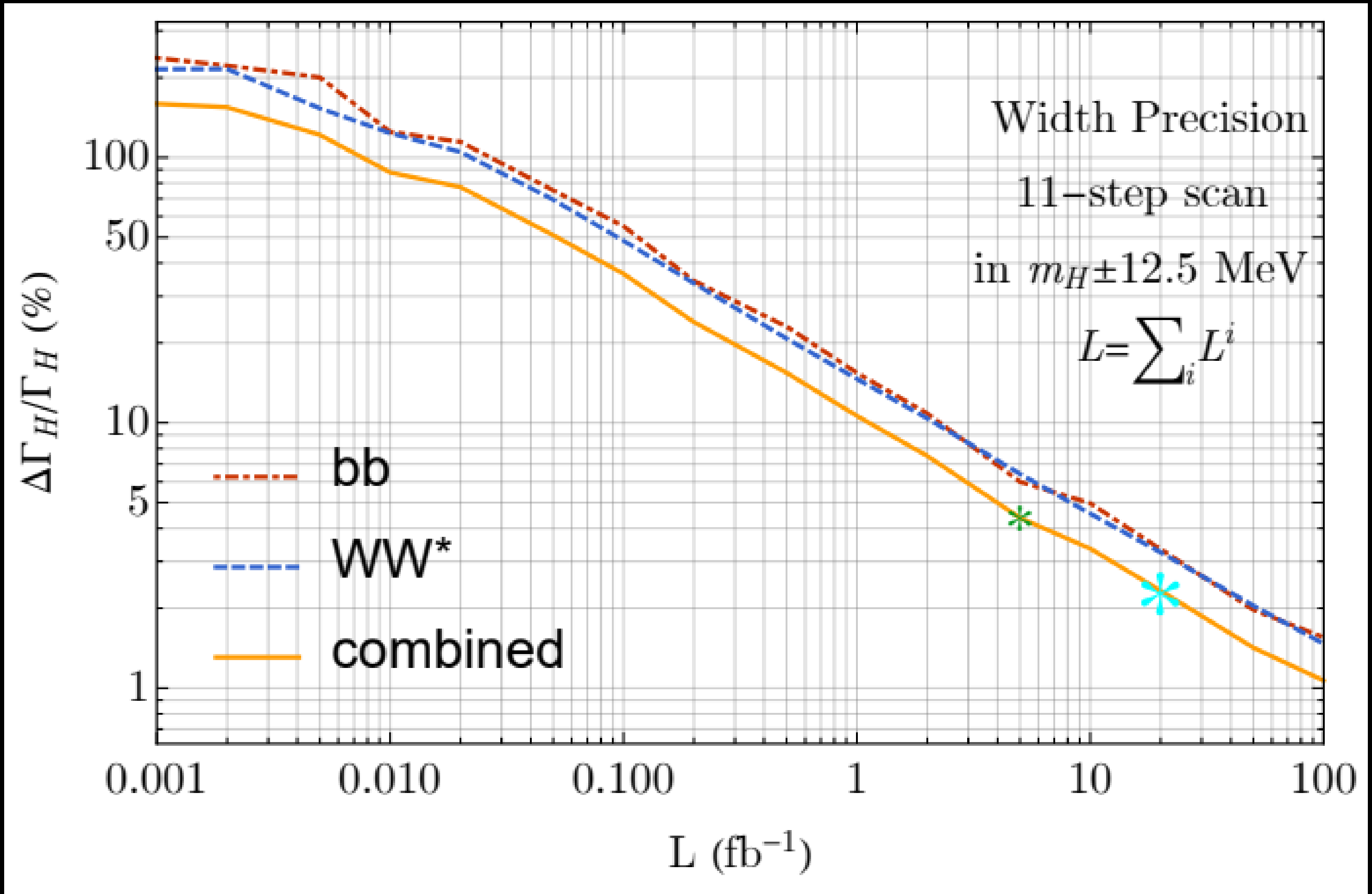
- 125 MuC Higgs physics
- Robustness of the width fit
- Allowing future studies on systematics

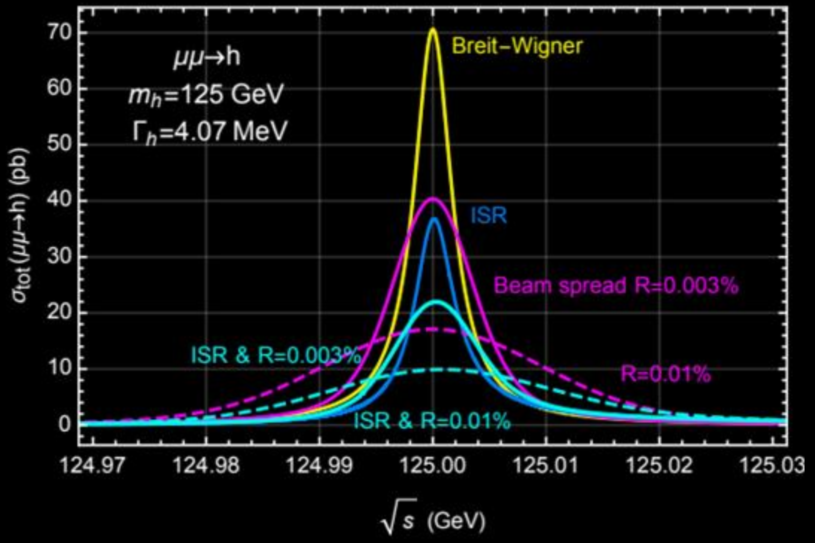


We made attempt to address these in our recent study,
J. de Blas, Jiayin Gu, ZL, 2203.04324

We initially worked on Higgs width alone T. Han, ZL, 1210.7803

Luminosity Scaling

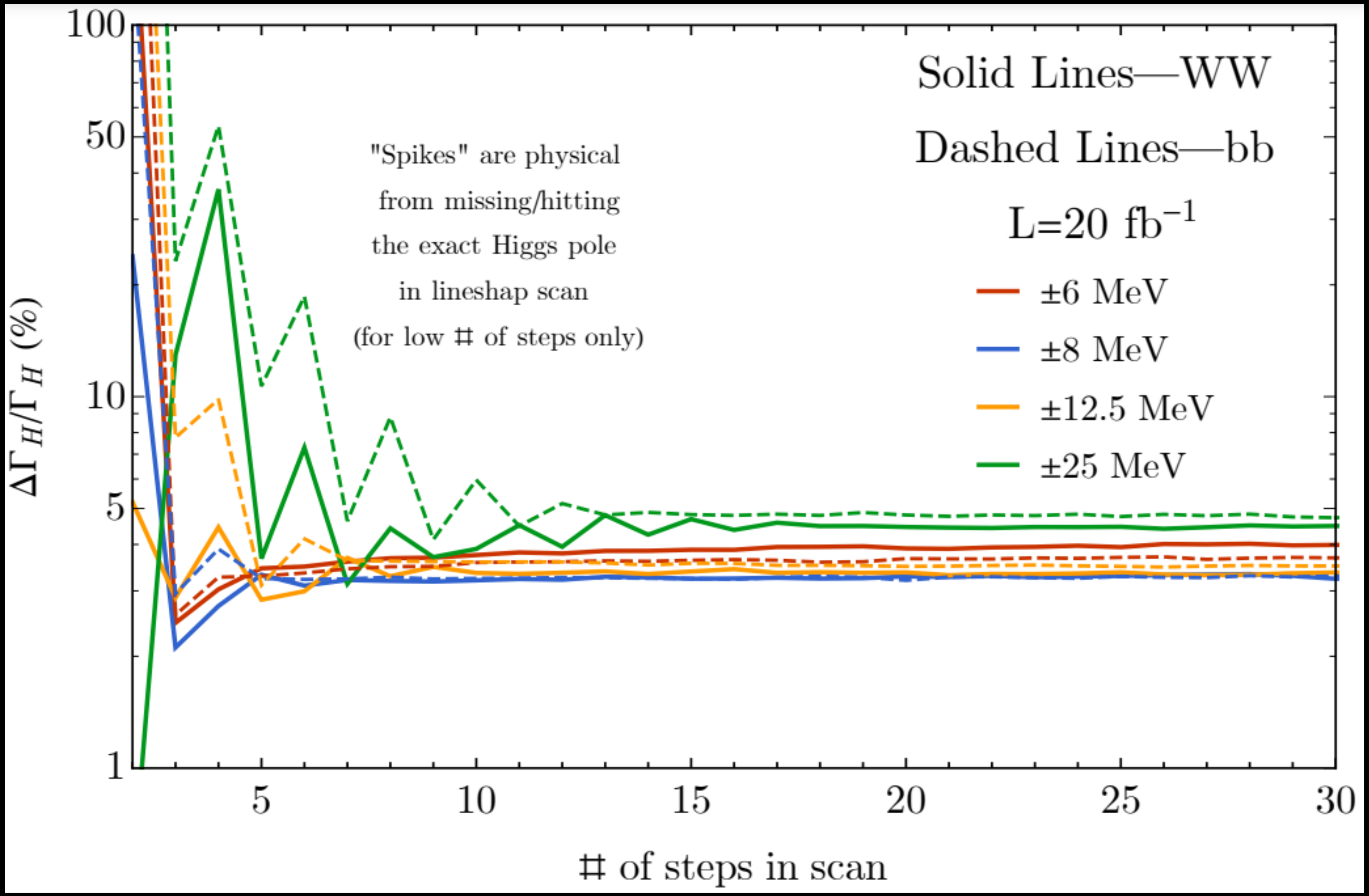


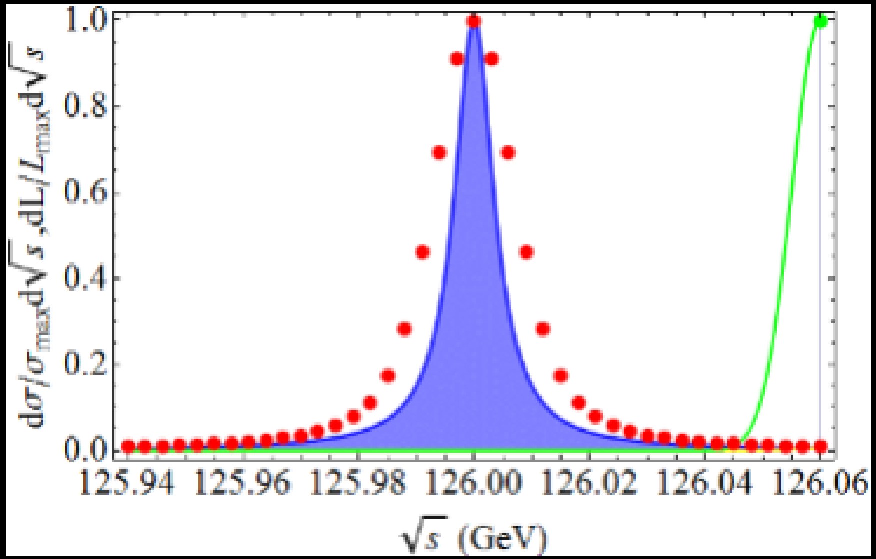


Using our new Monte Carlo fit, we show that:
Width precision basically scales as 1/Sqrt[L], so we can gain a lot with higher lumi.

The Snowmass Muon Collider Forum benchmark Luminosity 20 fb^{-1}.

Scanning Range & Steps

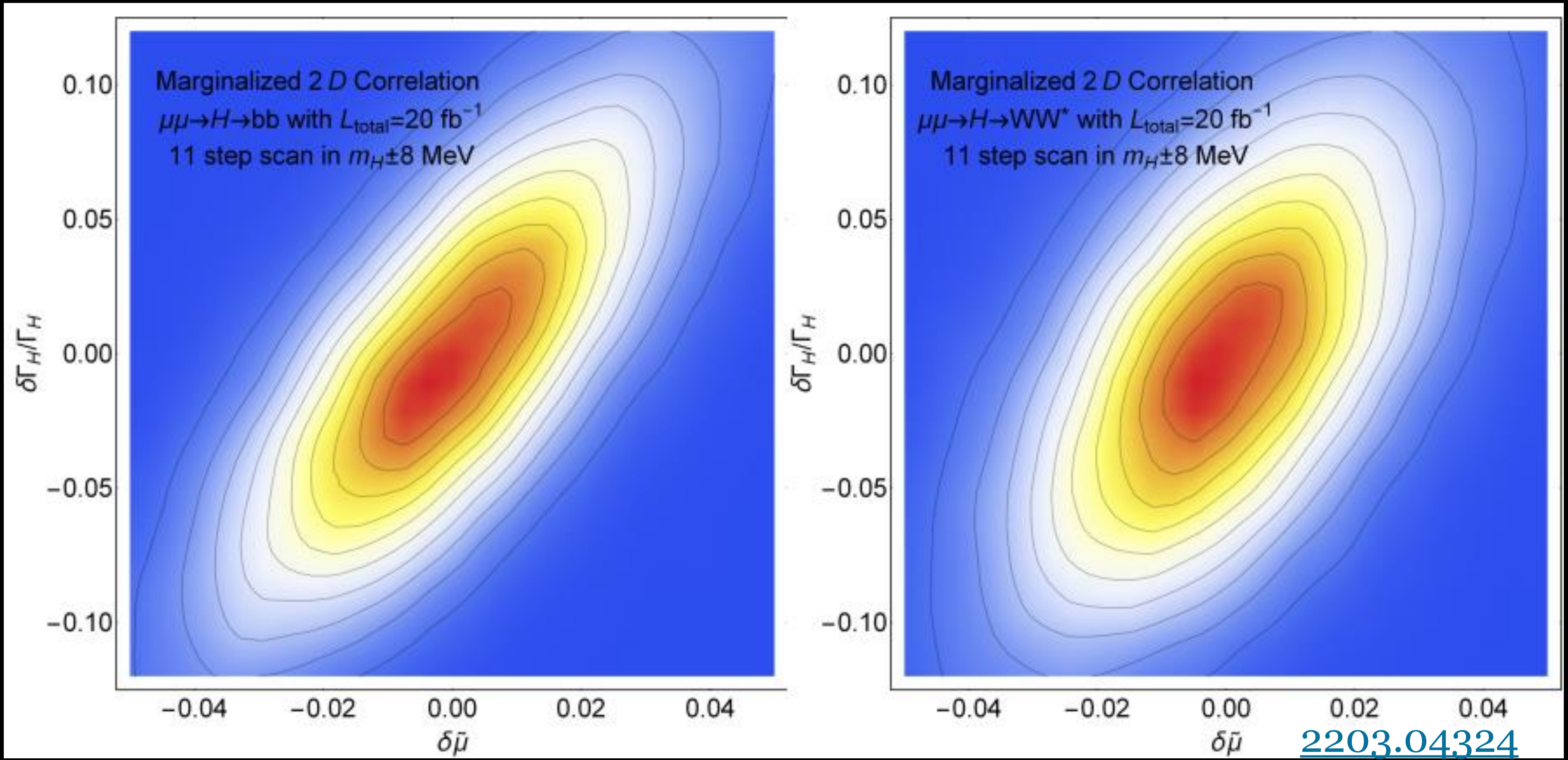




New insights:

- Optimal scanning range around +-10 MeV
- Need at least 6 points to stabilize, 10 points scan should be sufficient

Correlations!



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Larger width corresponds to larger coupling^2.
Note: this is a different power compared to the normal “flat direction”, which is coupling^4.

General κ fit
(so called “model independent fit”)

ΔM_H	Γ_H	$\sigma(ZH)$
5.5 MeV	2.8%	0.51%

CEPC per channel precision

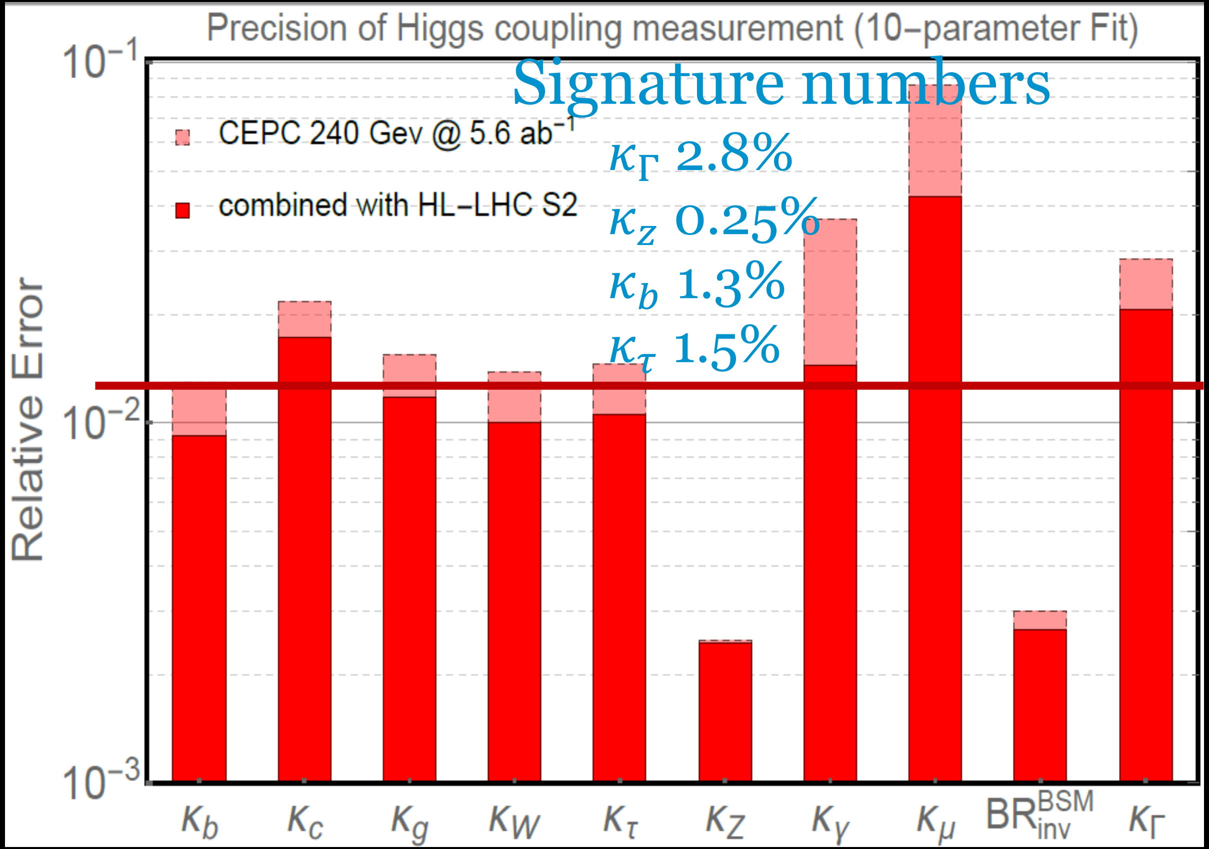
Decay mode	$\sigma(ZH) \times \mathrm{BR}$
$H \to bb$	0.28%
$H \to cc$	2.2%
$H \to gg$	1.6%
$H \to \tau\tau$	1.2%
$H \to WW$	1.5%
$H \to ZZ$	4.3%
$H \to \gamma\gamma$	9.0%
$H \to \mu\mu$	17%
$H \to \mathrm{inv}$	0.28%

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

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

$$\Delta\kappa_j = 1/2(\Delta\kappa_j^2)$$

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



Individual Channel Precision

Let's check precision with ~1/4 on-shell statistics (with different bkg)

Channel $\mu^+\mu^- \to h \to X$	Rate [pb]	Signal Events	Background Events	Precision [%] Cut & Count		Binned
			Results for 5/20 fb^{-1}			
$b\bar{b}$	13	19000/77000	45000/180000	1.0/0.51		0.97/0.49
$c\bar{c}$	0.63	2300/9200	43000/170000	24/12		23/12
gg	1.8	5400/22000	260000/10^6	11/5.5		11/5.3
$\tau^+_{\text{had}}\tau^-_{\text{had}}$	0.58	1400/5600	19000/76000	10/5.1	6.8/3.4	4.8/2.4
$\tau^+_{\text{had}}\tau^-_{\text{lept}}$	0.63	1500/6100	18000/71000	9.1/4.5		
$\gamma\gamma$	0.05	150/605	180000/730000	280/140		190/94

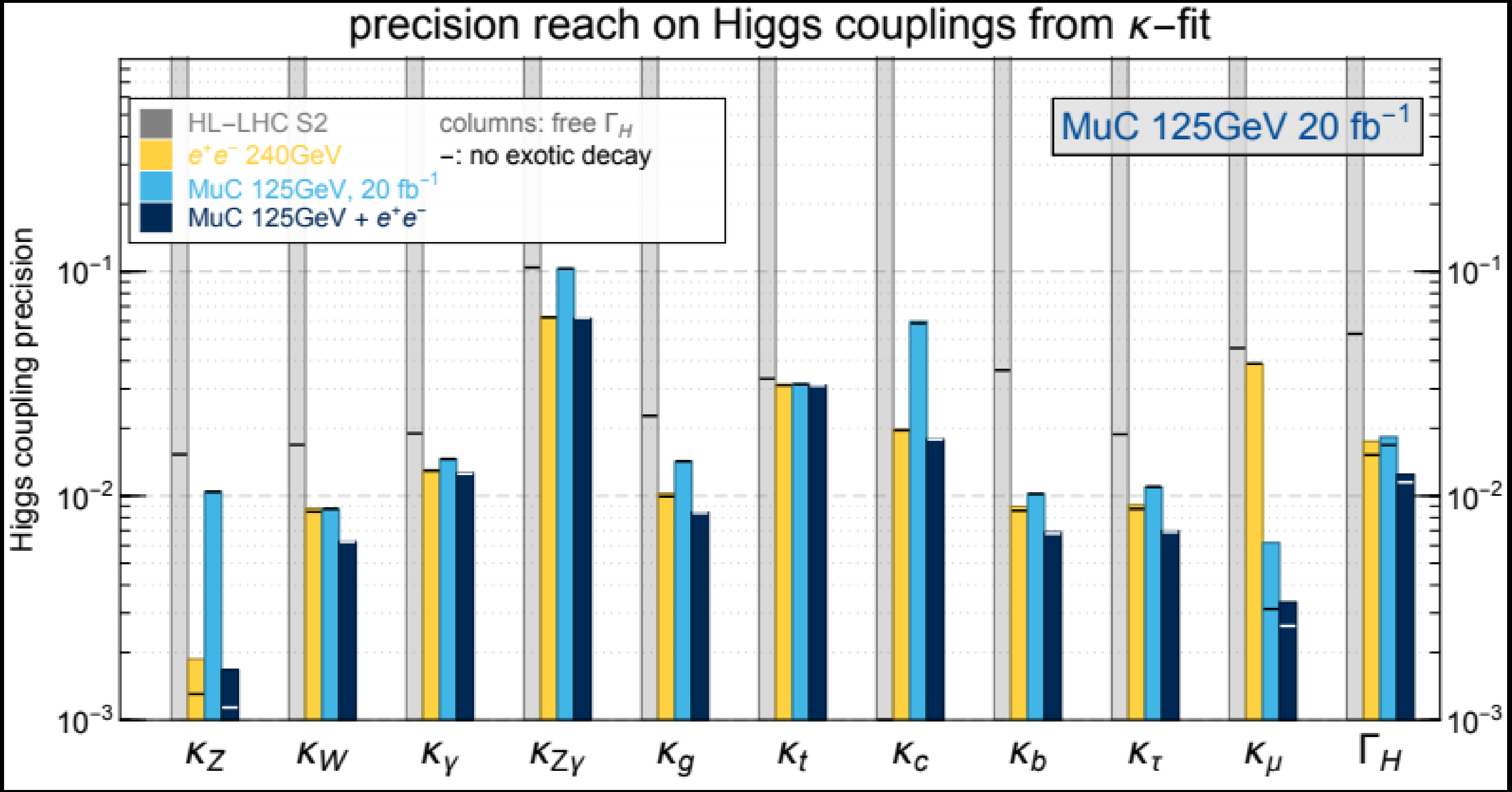
Individual Channel Precision.

Let's check precision with ~1/4 on-shell statistics (with different bkg)

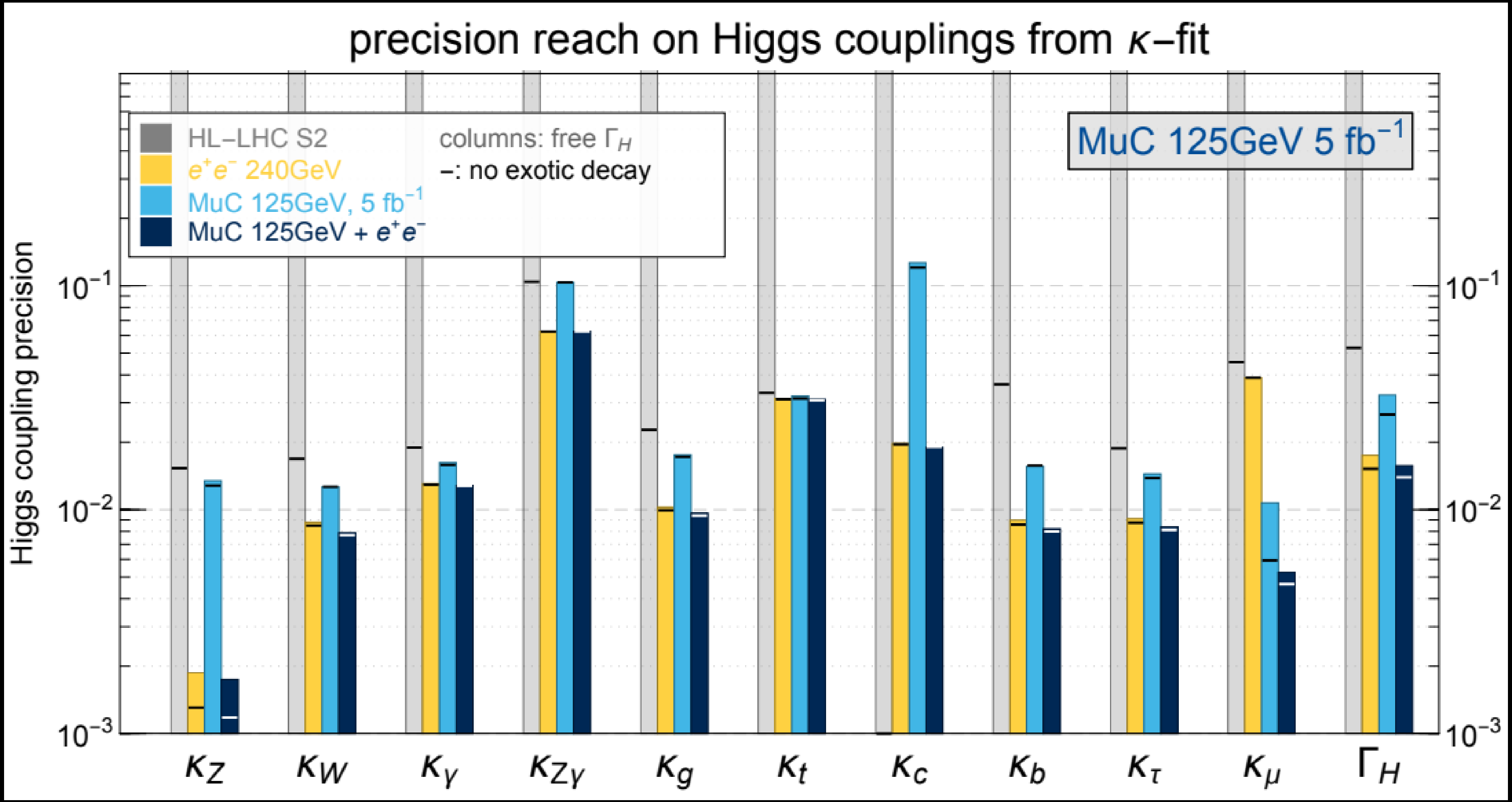
Channel $\mu^+\mu^- \to h \to X$	Rate [pb]	Signal Events	Background Events	Precision [%] Cut & Count	Precision [%] Binned
			Results for 5/20 fb^{-1}		
$2\ell 2q$ ($\ell = e, \mu$)	0.05	130/530	1200/4800	28/14	
$2\nu 2j$	0.16	450/1800	320/1300	6.1/3.1	5.8/2.9
$2e2\nu^{\ddagger}$	0.005	8/33	0/1	35/18	
$2\mu 2\nu^{\ddagger}$	0.005	9/35	0/1	34/17	
$e\nu\mu\nu$	0.11	320/1300	9/35	5.7/2.8	
$\ell\nu\tau_{had}\nu$ ($\ell = e, \mu$)	0.14	330/1300	8/32	5.6/2.8	
$\ell\nu jj$ ($\ell = e, \mu$)	1.4	3800/15000	88/350	1.6/0.82	
$\tau_{had}\nu jj$	0.45	1000/4000	20/79	3.2/1.6	1.3/0.67
$2e2\nu^{\dagger}$	0.06	160/660	86/340	9.6/4.8	
$2\mu 2\nu^{\dagger}$	0.06	160/650	76/310	9.5/4.7	
$2\tau_{had}2\nu^{\dagger}$	0.023	46/180	24/97	18/9.1	
$4j (j \neq b)$	2.3	3400/14000	51000/210000	6.8/3.4	

Now the Model-Independent MuC Width matters!

- This MuC width is a parametrically new measurement; the correlations with other parameters are distinctive.
- Complementary to other lepton collider Higgs factories
- Sub-percent muon Yukawa
- Good lumi scaling with couplings
- Excellent improvement when combined with e+e- Higgs factories

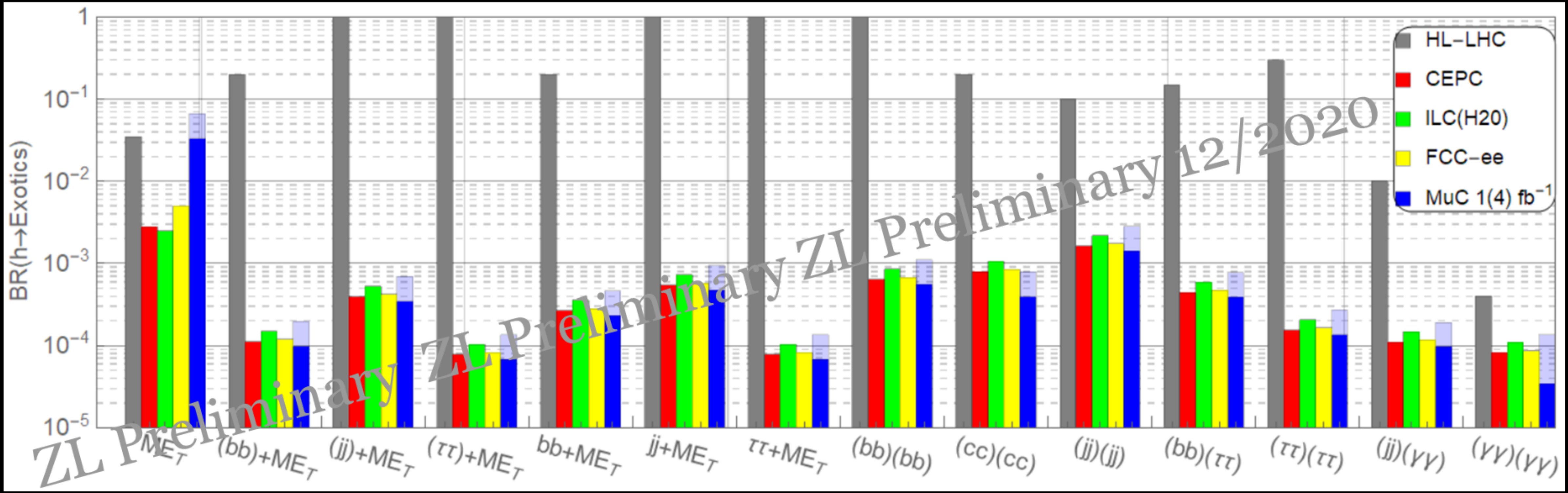


125 Kappa with 5 fb^{-1}



Exotic Decay Overall Picture

Our study on CEPC/ILC/FCC-ee only used Z(->ll)H, there is 10x statistics to be used



125 GeV MuC: no tagging spectator Z issues and less combinatoric background.

with missing Energy (SUSY motivated, DM motivated channels)

3-4 orders of magnitude improvement for the constraints on such exotic branching fractions

$h \to 4f$ generic Higgs sector extensions, also Higgs portals

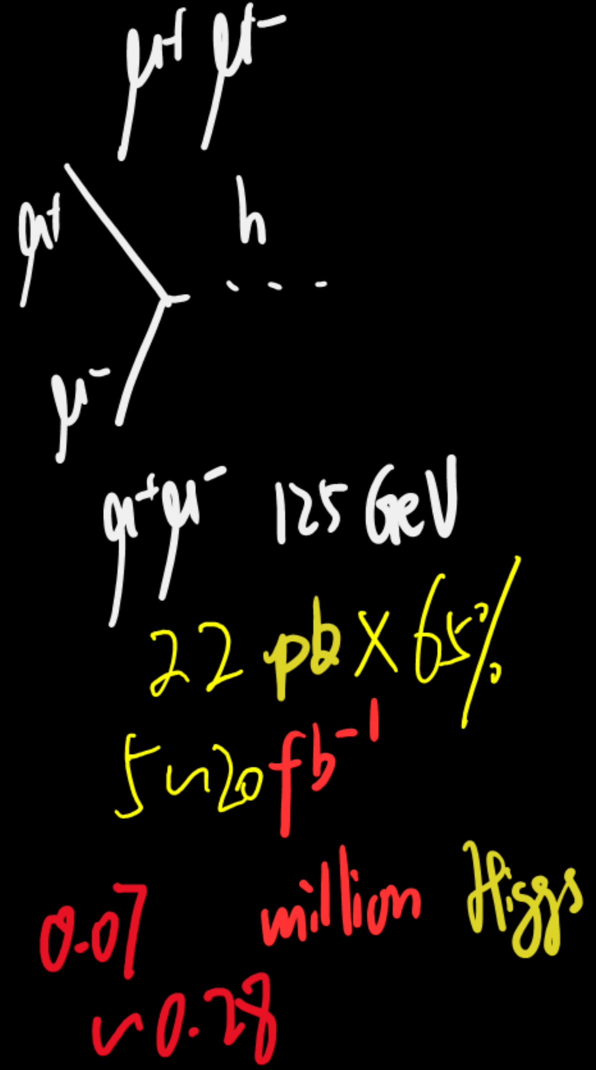
2-3 orders of magnitude improvement for the constraints on such exotic branching fractions

Original plot without MuC, ZL, Wang, Zhang, 1612.09284 , updated by ZL following future collider program updates; MuC very preliminary results compiled by ZL.

Summary

125 GeV s-channel resonant Higgs Factory

- This MuC width is a distinctive measurement;
- Complementary to other lepton collider Higgs programs
- Sub-percent muon Yukawa
- Global picture of the 125 GeV MuC Higgs physics potential, which helps us with planning.



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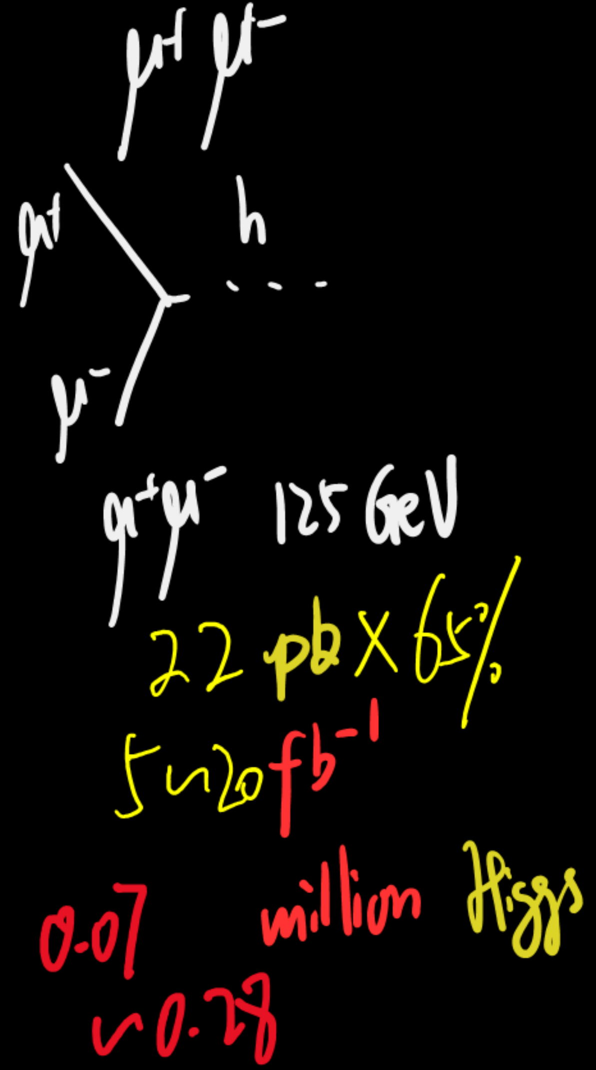
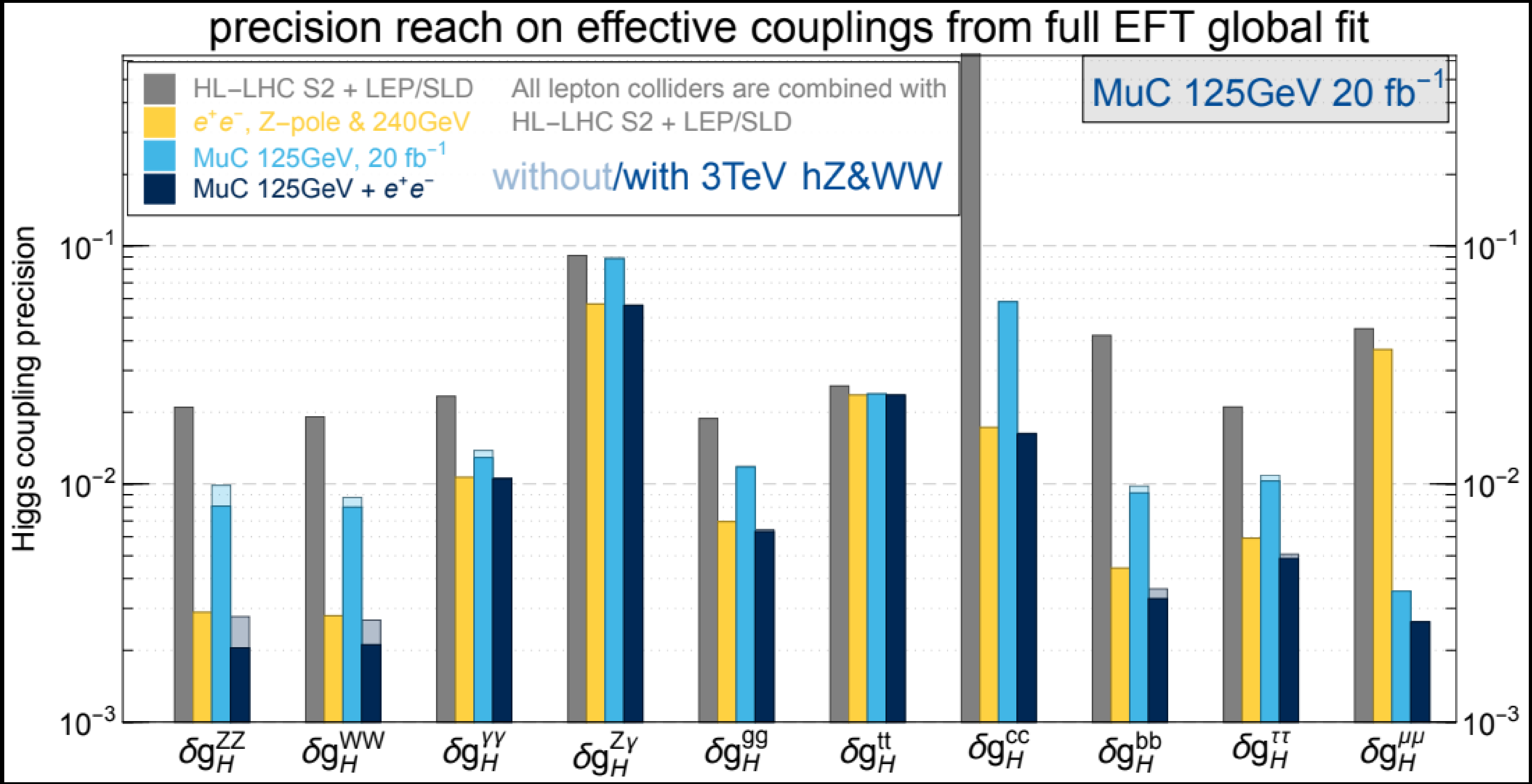
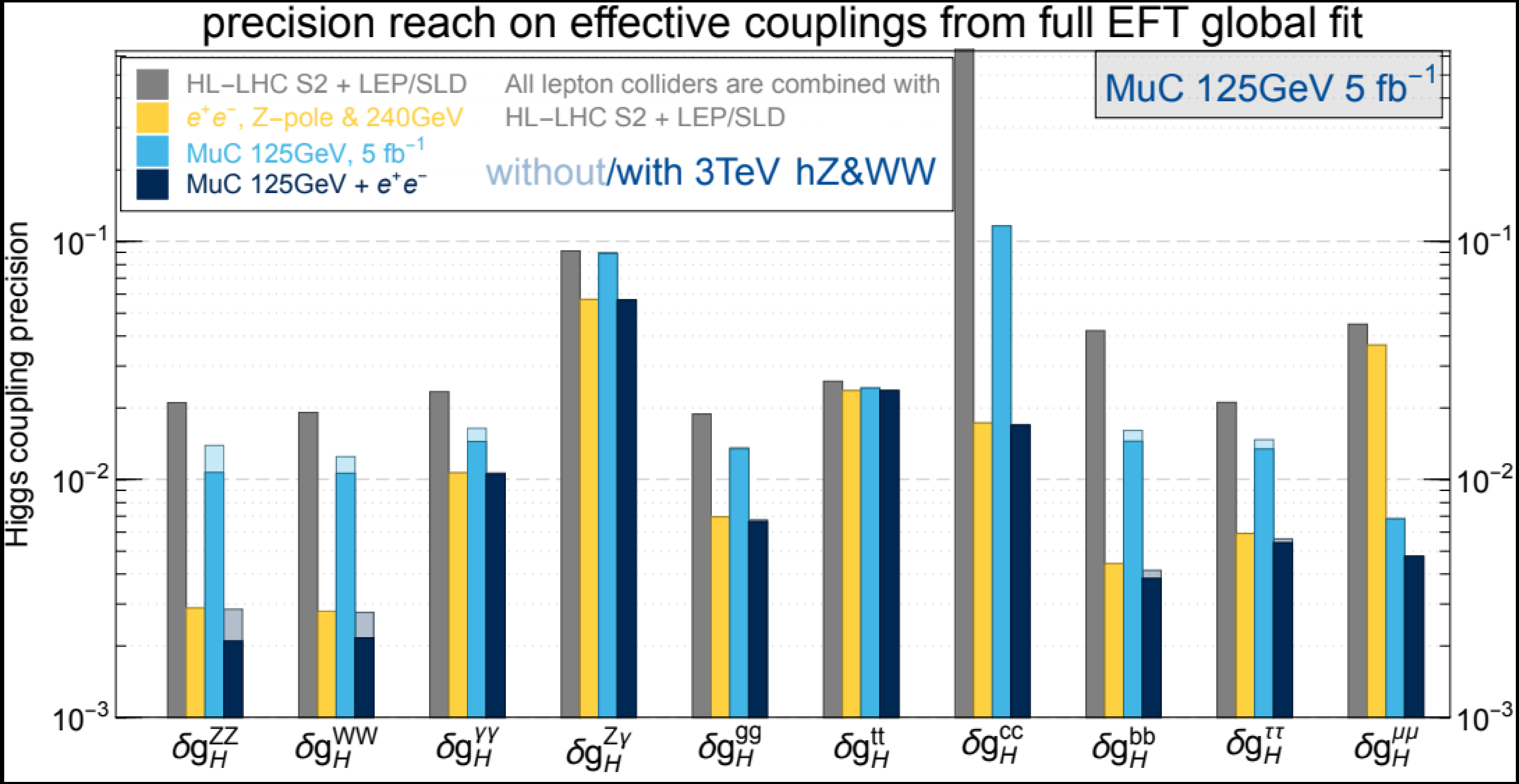
Thank you!



125 EFT with 20 fb^-1

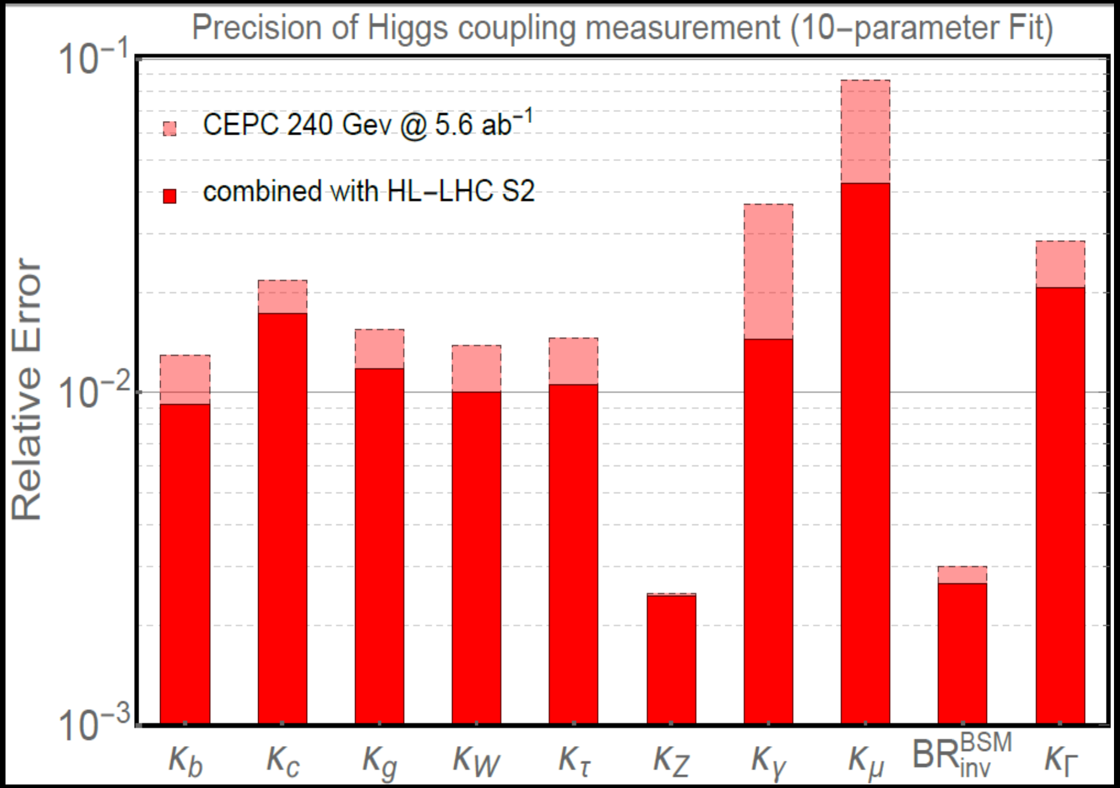


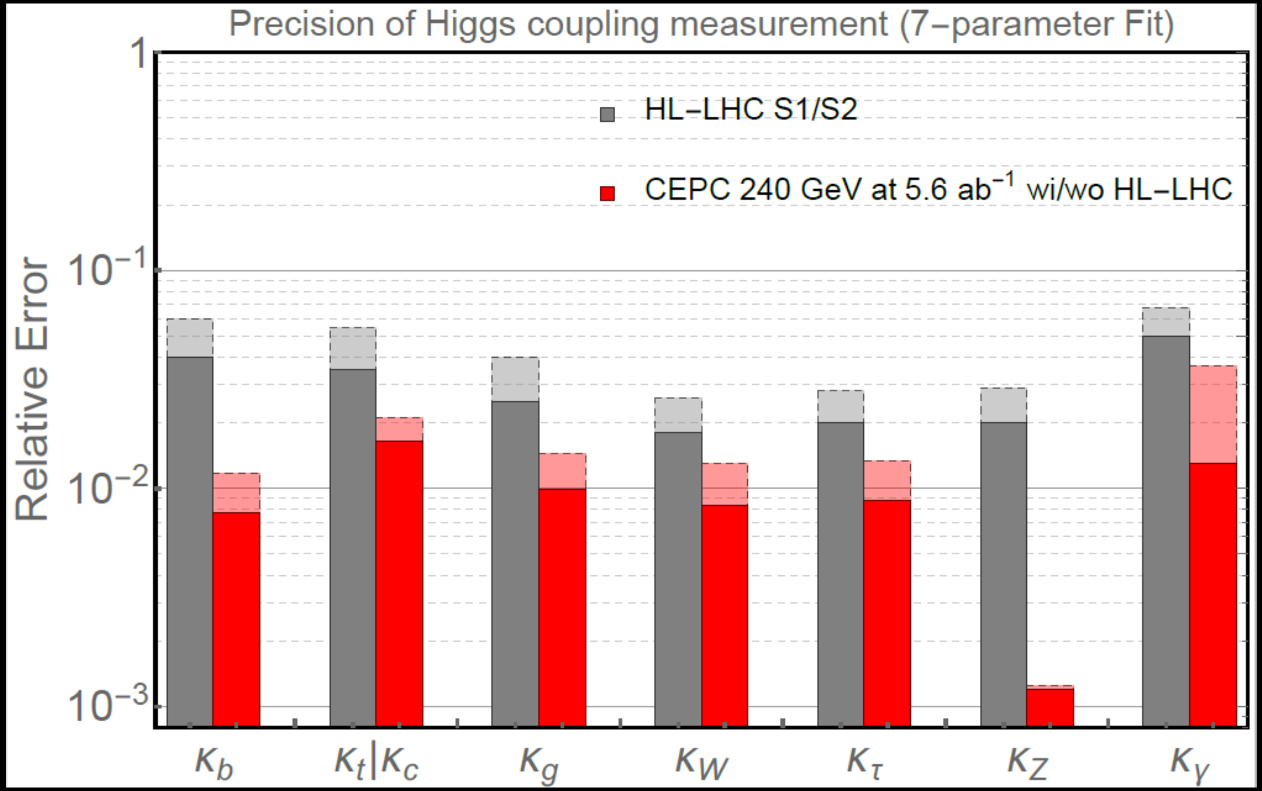
125 EFT with 5 fb^-1



Official CEPC results, updated with HL-LHC projection for ESU

A representative view (CEPC/FCC-ee/ILC)





Without external constraints on the coupling strength (width), HL-LHC fit has huge flat direction (the fit does not close)*

*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)

Higgs factories improves in b, c, g, W, and especially Z coupling.
HL-LHC provide crucial inputs for muon Yukawa, Higgs to $\gamma\gamma$, etc.