Energy Frontier Workshop
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Higgs Precision at Muon Collider

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Two Distinctive Higgs Programs at Muon Colliders

- 125 GeV s-channel Resonant Higgs Factory
- High Energy Higgs Factory

Basics:

pp

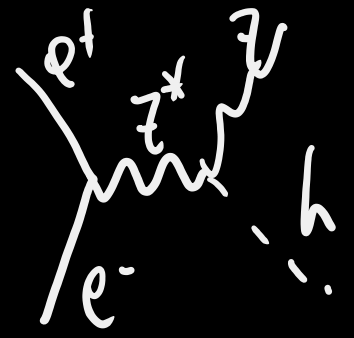
LHC 14 TeV

50 pb

3 ab^{-1}

0.15 billion Higgs

e^+e^-



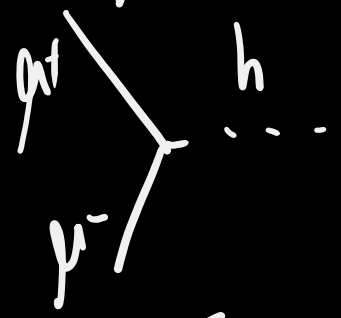
e^+e^- 240~250 GeV

200 fb

5 ab^{-1}

1 million Higgs

$\mu^+\mu^-$



$\mu^+\mu^-$ 125 GeV

22 pb × 65%

5~20 fb^{-1}

0.07 million Higgs

~0.28

$\mu^+\mu^-$

$\mu^+\mu^-$ 10 TeV

~ 1 pb

10 ab^{-1}

~10 million Higgs

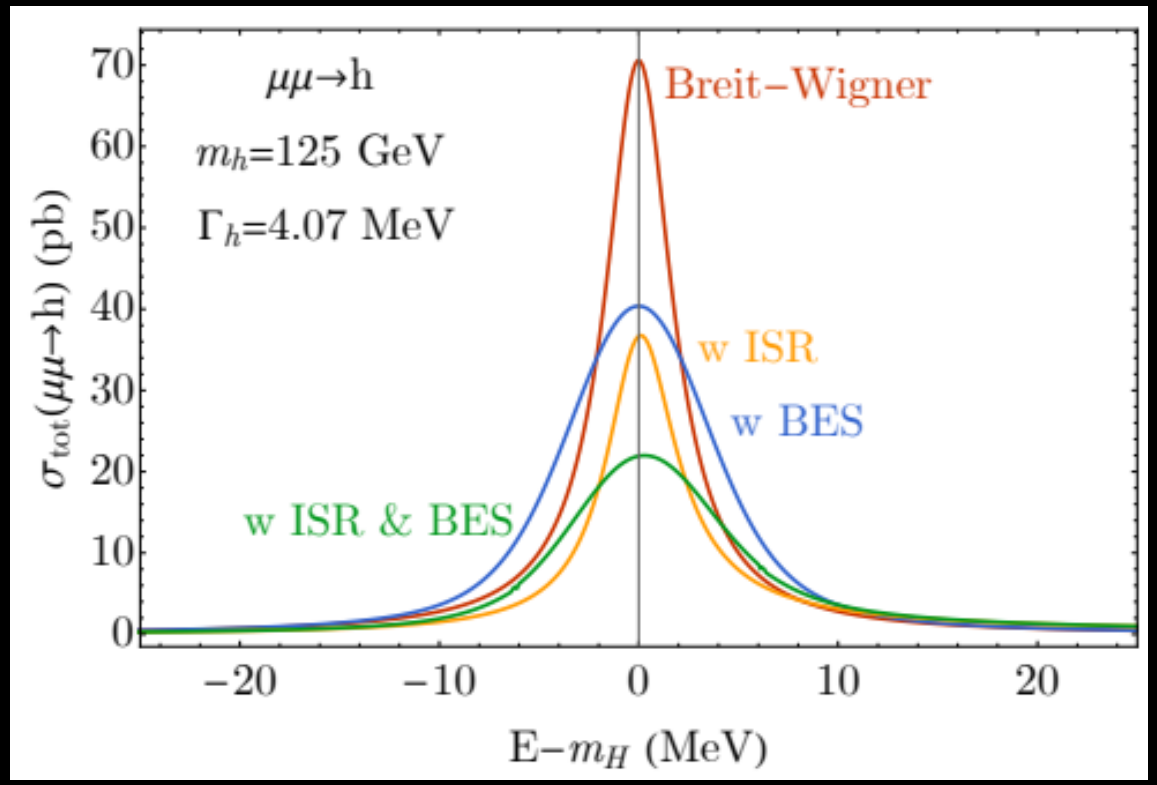
Lots of open questions

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

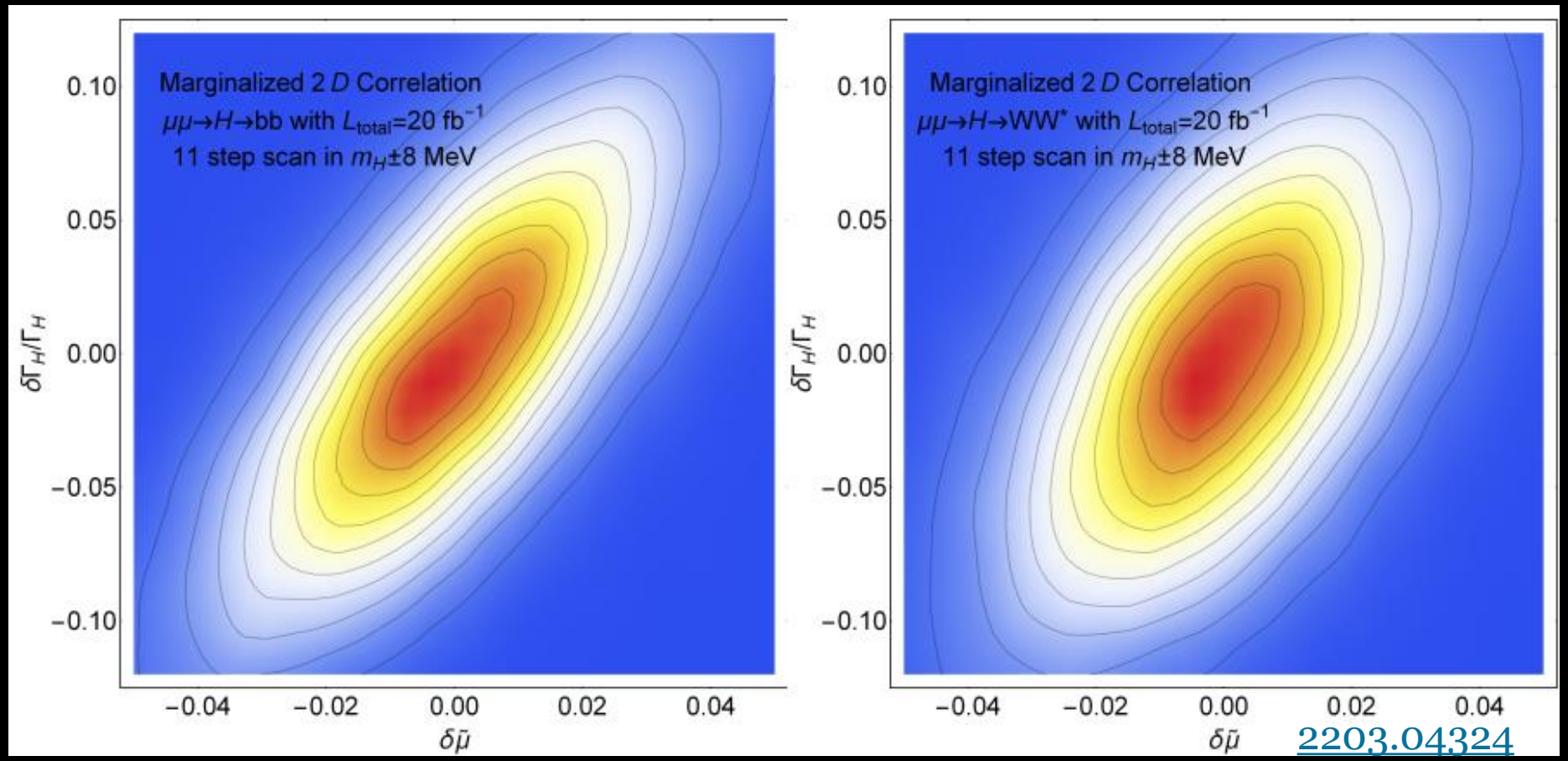
The convolution of various effects are highly non-trivial. So new studies will help understand better:

- 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

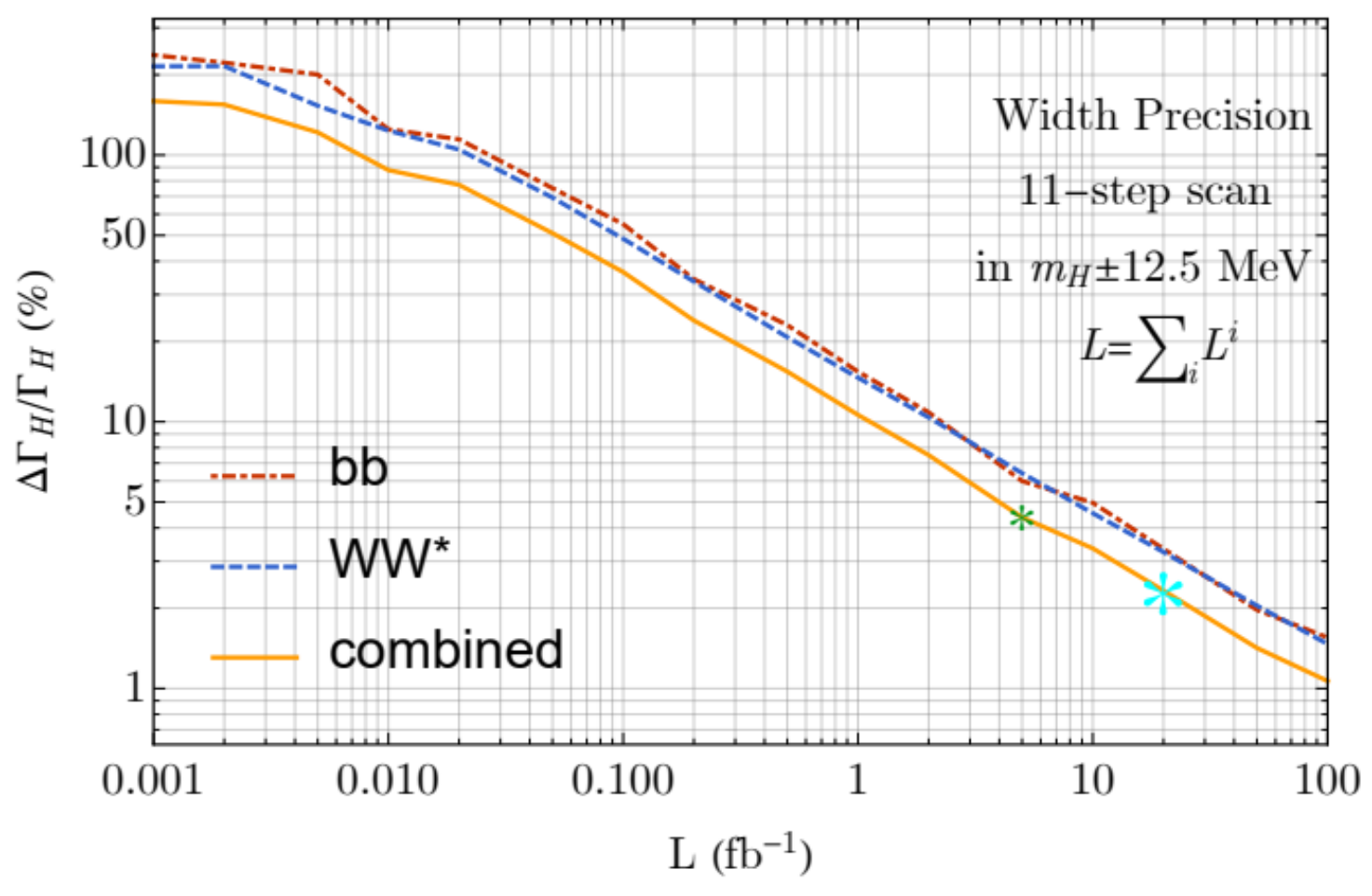
Correlations!

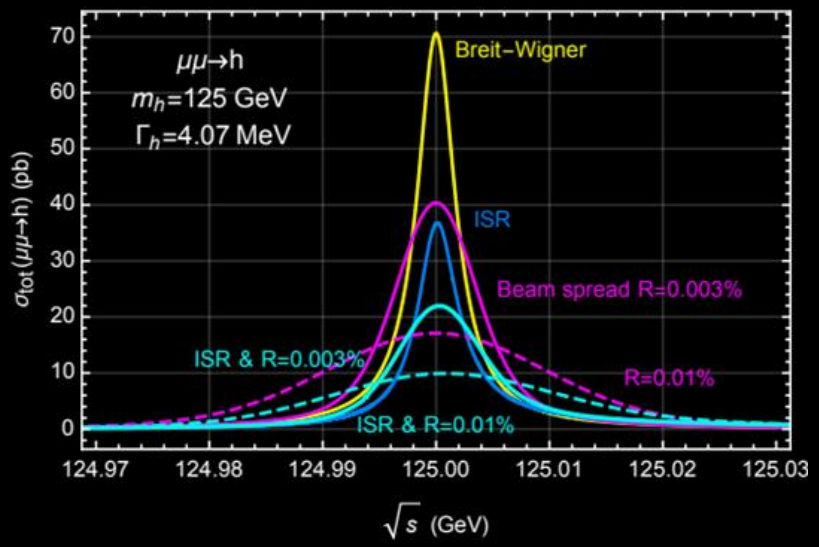


2203.04324

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

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 $20\ fb^{-1}$.

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

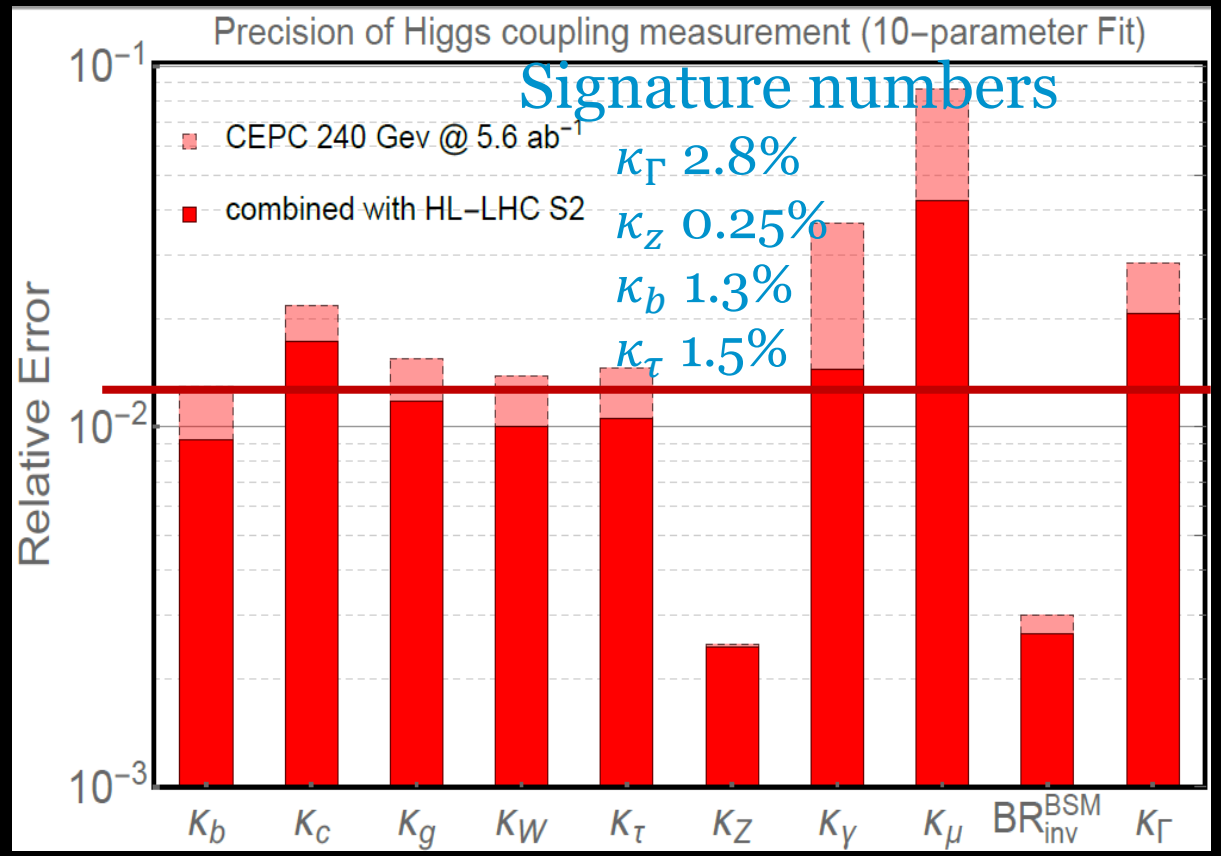
Decay mode	$\sigma(ZH) \times$ BR
$H \to bb$	0.28%
$H \to cc$	2.2%
$H \to gg$	1.6%
$H \to \tau\tau$	1.2%
$H \to WW$	1.5%
$H \to ZZ$	4.3%
$H \to \gamma\gamma$	9.0%
$H \to \mu\mu$	17%
$H \to$ inv	0.28%

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	Precision [%] 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

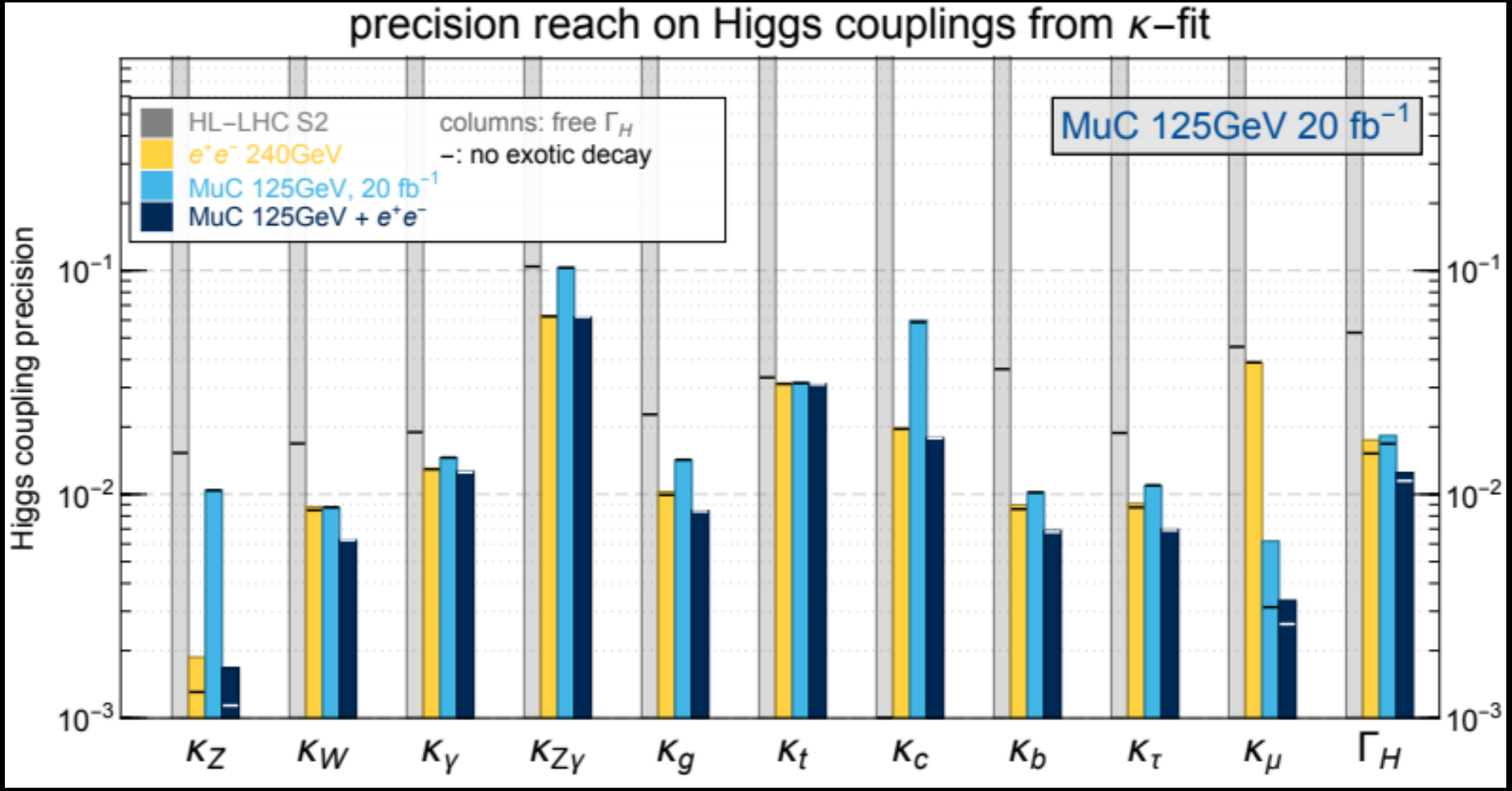
Individual Channel Precision.

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	
$\ell\nu\tau_{\text{had}}\nu$ ($\ell = e, \mu$)	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	
$\tau_{\text{had}}\nu jj$	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	
$2\tau_{\text{had}}2\nu^\dagger$	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
- We have a global picture of the 125 GeV MuC Higgs physics potential, which helps us with planning.



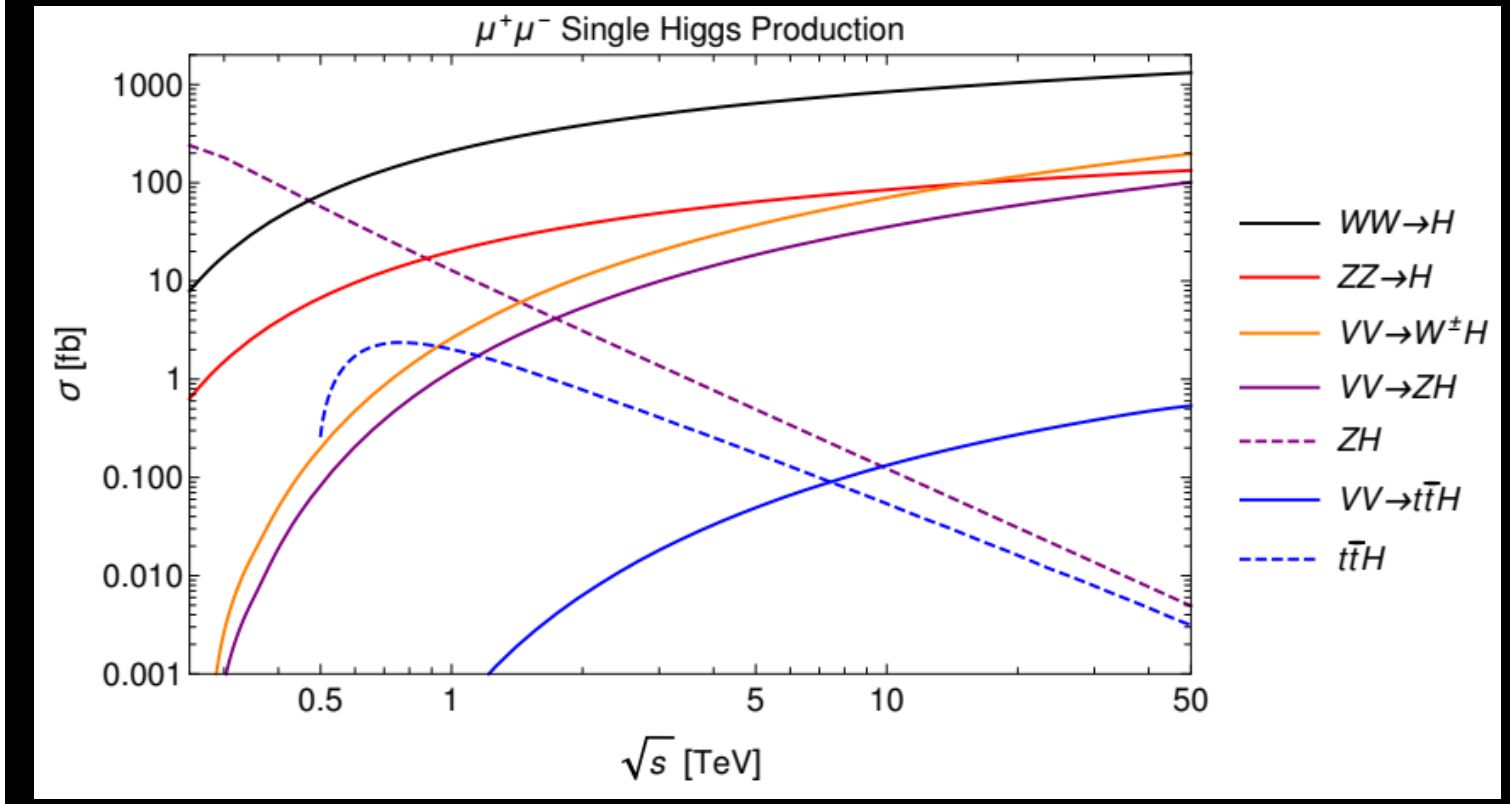
Higgs at High-Energy MuC

High Energy Muon Collider provides a vibrant and growing Higgs physics program:

- Baseline Precision couplings
- Higgs Self-coupling
- Top Yukawa through interference
- Muon Yukawa at different energies
- + many more (see talks by A. Wulzer, F. Maltoni, and Snowmass Muon Collider forum discussion later today)

Baseline Higgs Measurements

Production	Decay	$\Delta\sigma/\sigma$ (%)	
		3 TeV	10 TeV
WW-fusion	bb	0.84	0.24
	cc	14	4.4
	gg	4.2	1.2
	$\tau^+\tau^-$	4.5	1.3
	$WW^*(jj\ell\nu)$	1.8	0.50
	$WW^*(4j)$	5.7	1.4
	$ZZ^*(4\ell)$	48	13
	$ZZ^*(jj\ell\ell)$	12	3.5
	$ZZ^*(4j)$	67	16
	$\gamma\gamma$	7.7	2.1
	$Z(jj)\gamma$	73	20
	$\mu^+\mu^-$	43	11
ZZ-fusion	bb	7.9	2.2
	bb, $(N_\mu \geq 2)$	2.6	0.77
	$WW^*(4j)$	49	12
	$WW^*(4j)$, $(N_\mu \geq 2)$	17	4.3
tth	bb	61	53



M. Forslund, P. Meade, 2203.09425

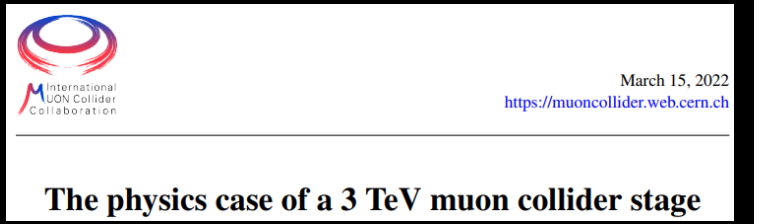
See also discussion in
Muon Smasher's Guide, 2103.14043
T. Han, Y. Ma, K.-P. Xie, 2007.14300;
Costanini, De Lillo, Maltoni, Mantani, Mattelaer, 2005.10289

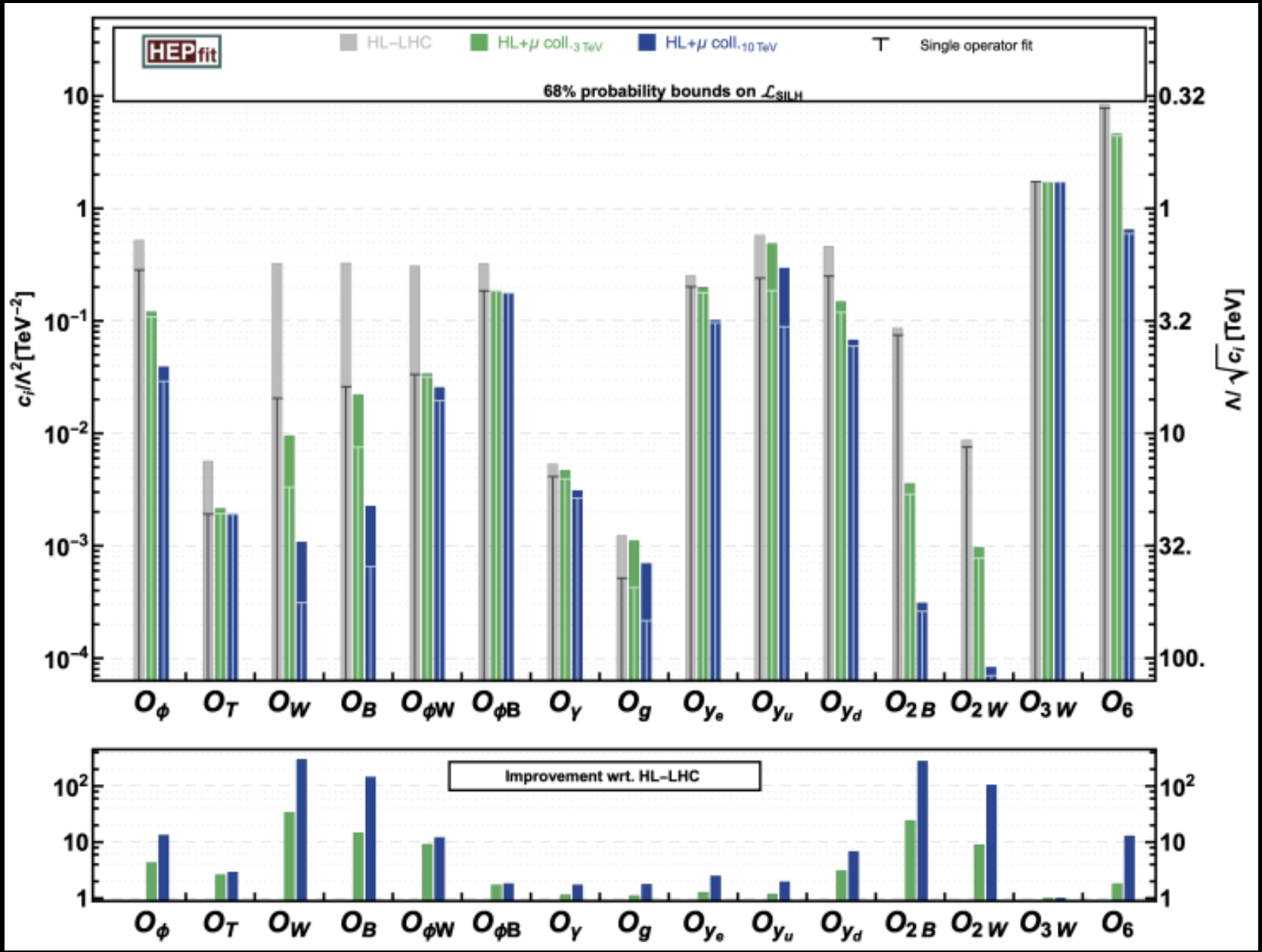
Higgs Precision

Fit Result [%]

	$\mu^+\mu^-$		+ HL-LHC		+ HL-LHC + 250 GeV e^+e^-	
	3 TeV	10 TeV	3 TeV	10 TeV	3 TeV	10 TeV
κ_W	0.45	0.13	0.39	0.12	0.34	0.11
κ_Z	3.4	0.94	1.3	0.77	0.12	0.11
κ_g	2.4	0.67	1.5	0.63	0.76	0.50
κ_γ	3.9	1.1	1.3	0.84	1.2	0.81
$\kappa_{Z\gamma}$	37	10	37	10	4.1	3.8
κ_c	7.5	2.3	7.4	2.3	1.8	1.4
κ_t	35	53	3.2	3.2	3.2	3.2
κ_b	0.98	0.27	0.88	0.27	0.45	0.23
κ_μ	22	5.4	4.7	3.6	4.1	3.3
κ_τ	2.5	0.71	1.3	0.64	0.63	0.43

Higgs Precision

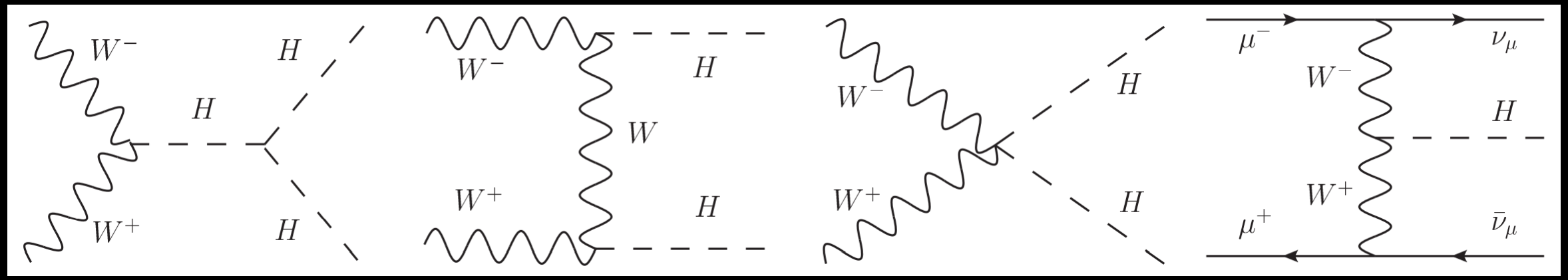




Multi-Higgs & Higgs Self-couplings

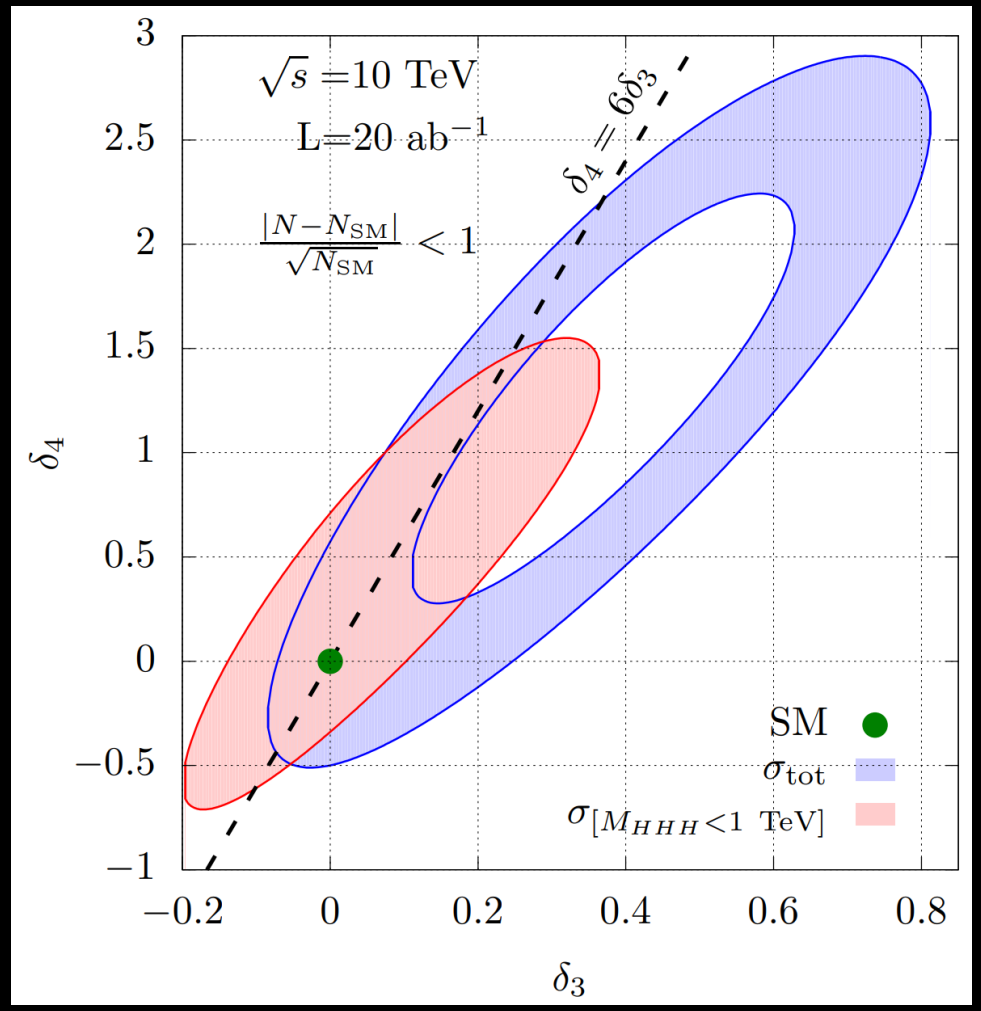
$\sqrt{s}$ (lumi.)	3 TeV (1 ab^{-1})	6 (4)	10 (10)	14 (20)	30 (90)	Comparison
WWH ($\Delta\kappa_W$)	0.26%	0.12%	0.073%	0.050%	0.023%	0.1% [41]
$\Lambda/\sqrt{c_i}$ (TeV)	4.7	7.0	9.0	11	16	(68% C.L.)
ZZH ($\Delta\kappa_Z$)	1.4%	0.89%	0.61%	0.46%	0.21%	0.13% [17]
$\Lambda/\sqrt{c_i}$ (TeV)	2.1	2.6	3.2	3.6	5.3	(95% C.L.)
$WWHH$ ($\Delta\kappa_{W_2}$)	5.3%	1.3%	0.62%	0.41%	0.20%	5% [36]
$\Lambda/\sqrt{c_i}$ (TeV)	1.1	2.1	3.1	3.8	5.5	(68% C.L.)
HHH ($\Delta\kappa_3$)	25%	10%	5.6%	3.9%	2.0%	5% [22, 23]
$\Lambda/\sqrt{c_i}$ (TeV)	0.49	0.77	1.0	1.2	1.7	(68% C.L.)

Allow %-level trilinear Higgs measurements, and a consistent measurement between gauge boson-Higgs coupling measurements.



T. Han, D. Liu, I. Low, X. Wang, 2008.12204

Multi-Higgs & Higgs Self-couplings

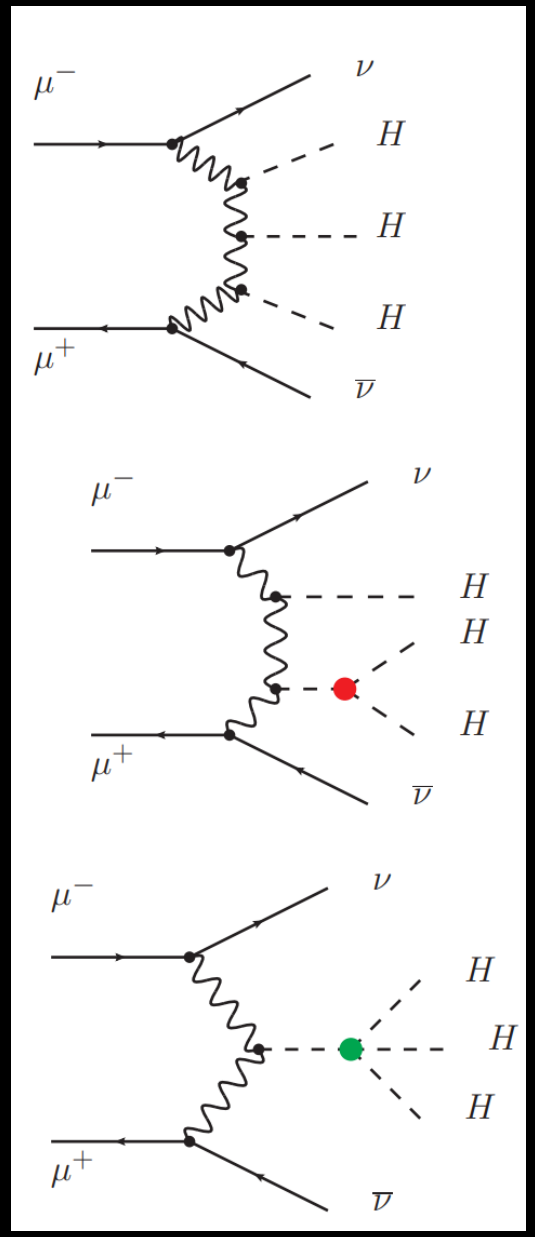


O(1) quartic determination possible.

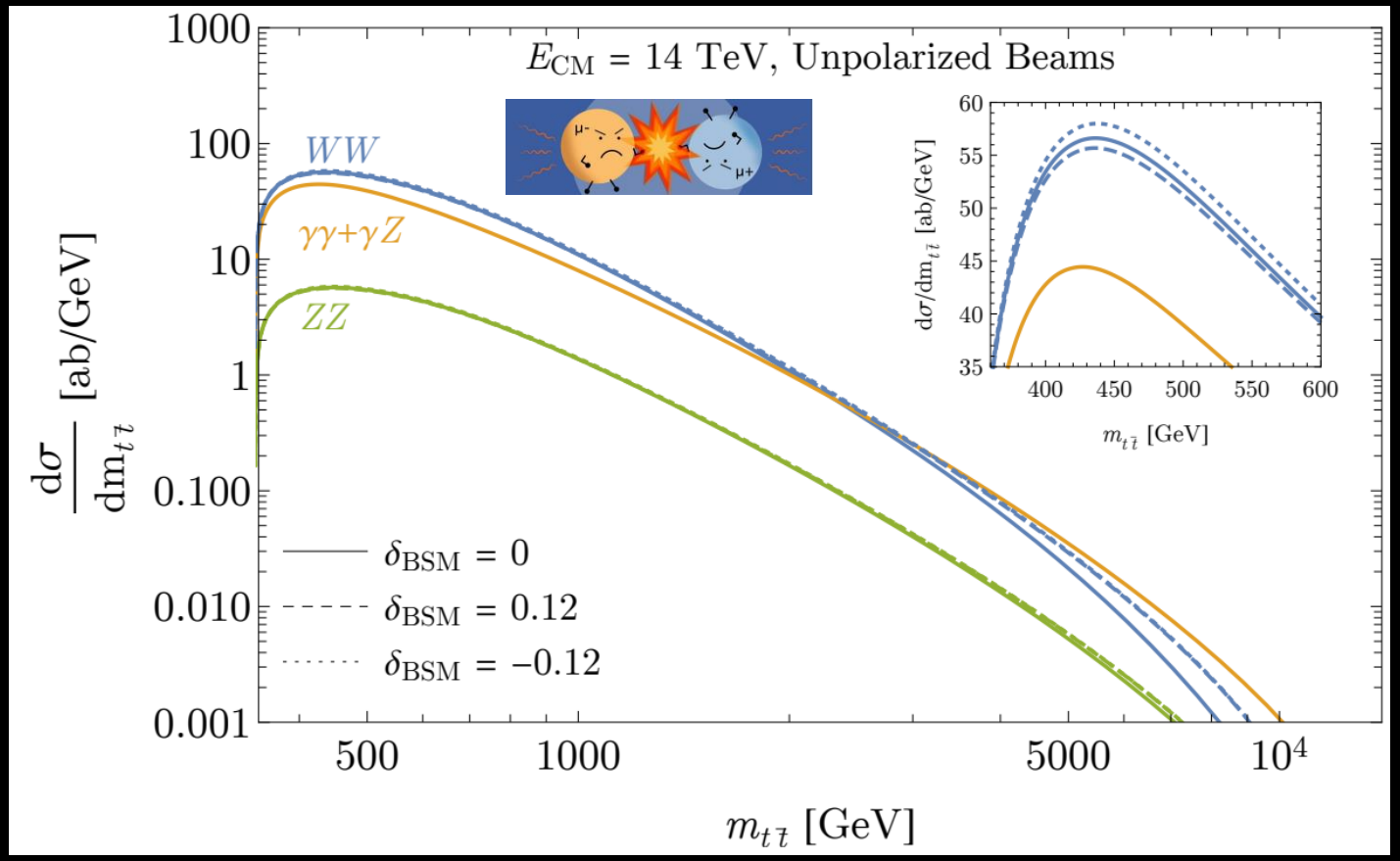
Chiesa, Maltoni, Mantani, Mele, Piccinini, 2003.13628

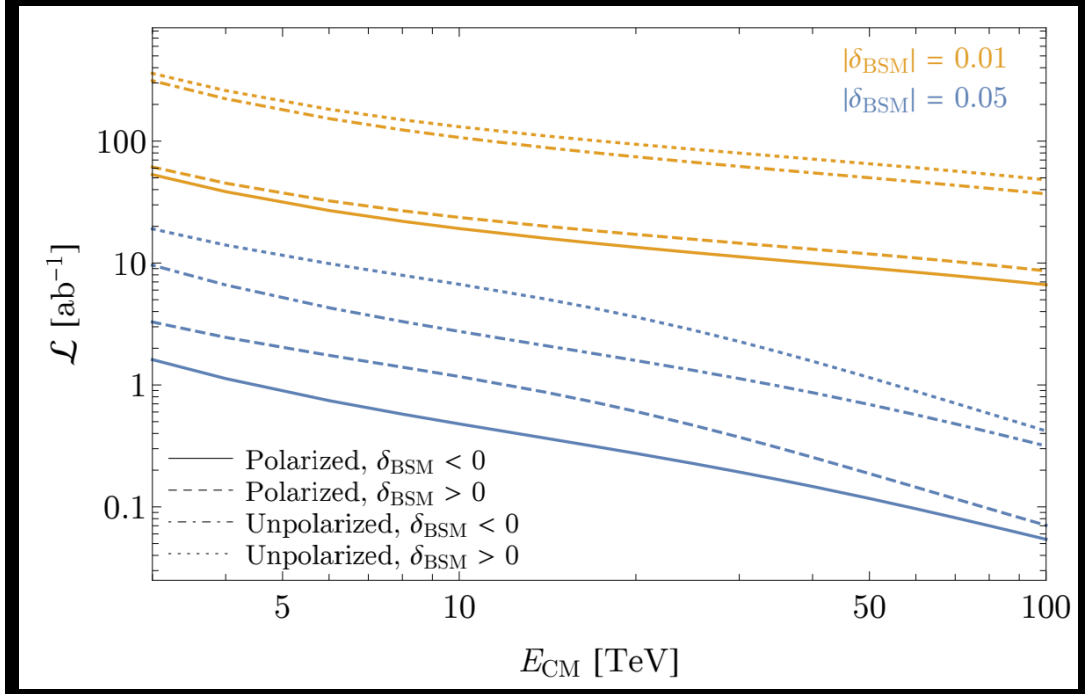
Correlated measurements of trilinear and quartic couplings reveals deep information about EFT and EWPT.

e.g, Huang, Joglekar, Wagner, 1512.00068 , Falkowski, Gonzalez-Alonso, Grejio, Marzocca, M. Son, 1609.06312, Chang, Luty, 1902.05556,+Abu-Ajamieh, M. Chen, 2009.11293; DiHiggs review 1910.00012



Top Yukawa from interference





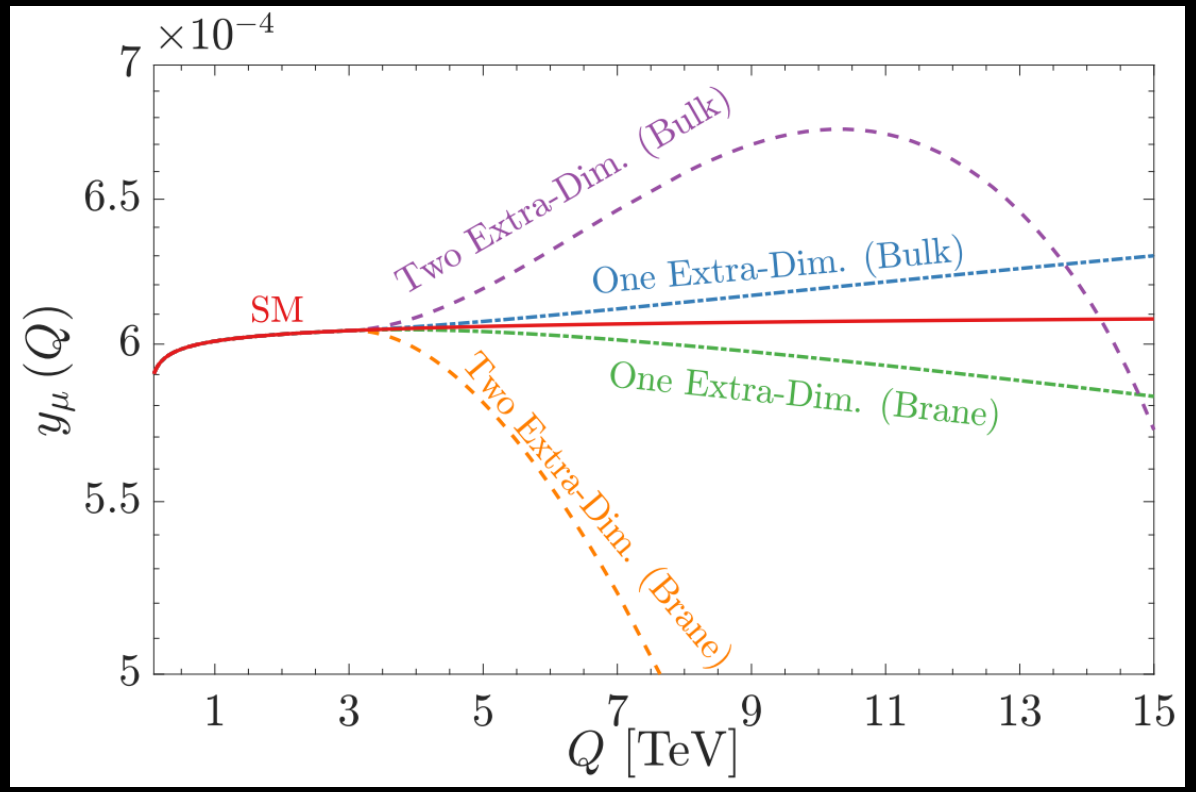
$$\mathcal{M}(W_L^+ W_L^- \to t\bar{t}) \simeq -\frac{m_t}{v^2}\delta_{BSM}\sqrt{\hat{s}}$$

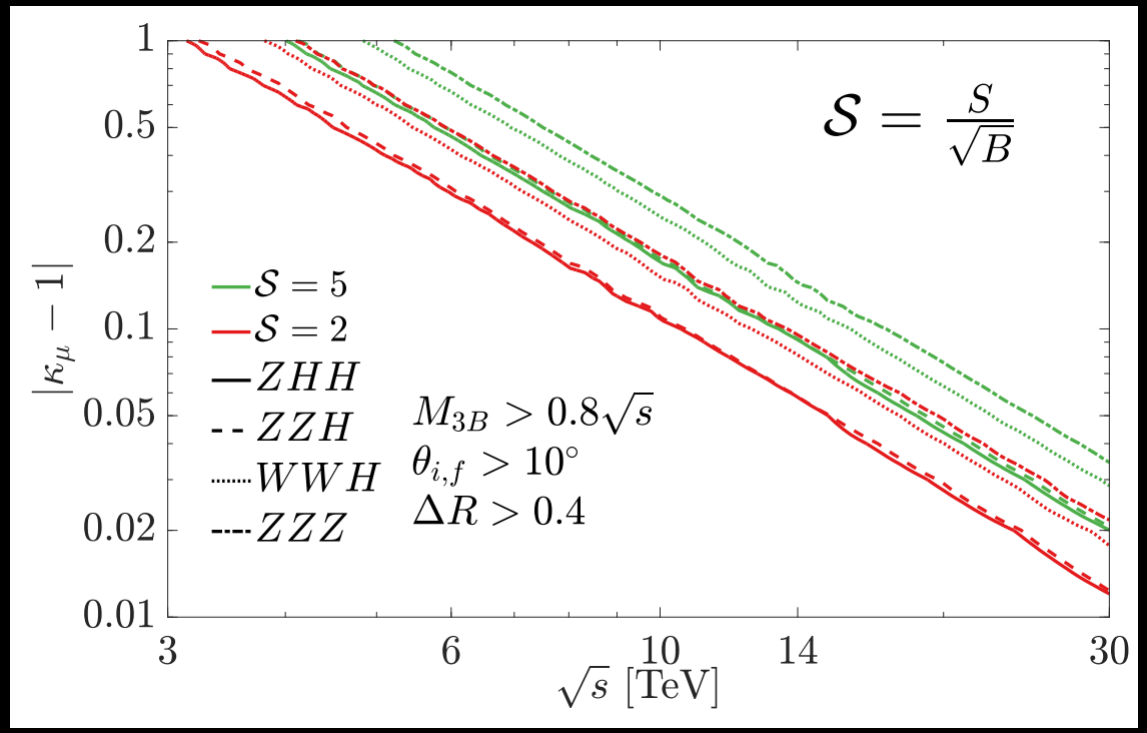
$t\bar{t}$ dominated by WW-fusion. The $W_L W_L$ contribution is large and sensitive to Higgs Yukawa deviations.
Higgs unitarize the $W_L W_L \to t\bar{t}$ to be $\log \hat{s}$.

Higgs Muon Couplings

Running Yukawa

T. Han, W. Kilian, N. Kreher, Y. Ma, J. Reuter, 2108.05362





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.

High Energy Muon Collider provides a vibrant and growing Higgs physics program:

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- Higgs Self-coupling
- Top Yukawa through interference
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- + many more (see talks by A. Wulzer, F. Maltoni, and Snowmass Muon Collider forum discussion later today)

$$\beta_{y_t} = \frac{\mathrm{d}y_t}{\mathrm{d}t} = \frac{y_t}{16\pi^2}\left(\frac{9}{2}y_t^2 - 8g_3^2 - \frac{9}{4}g_2^2 - \frac{17}{20}g_1^2\right), \tag{2.1}$$

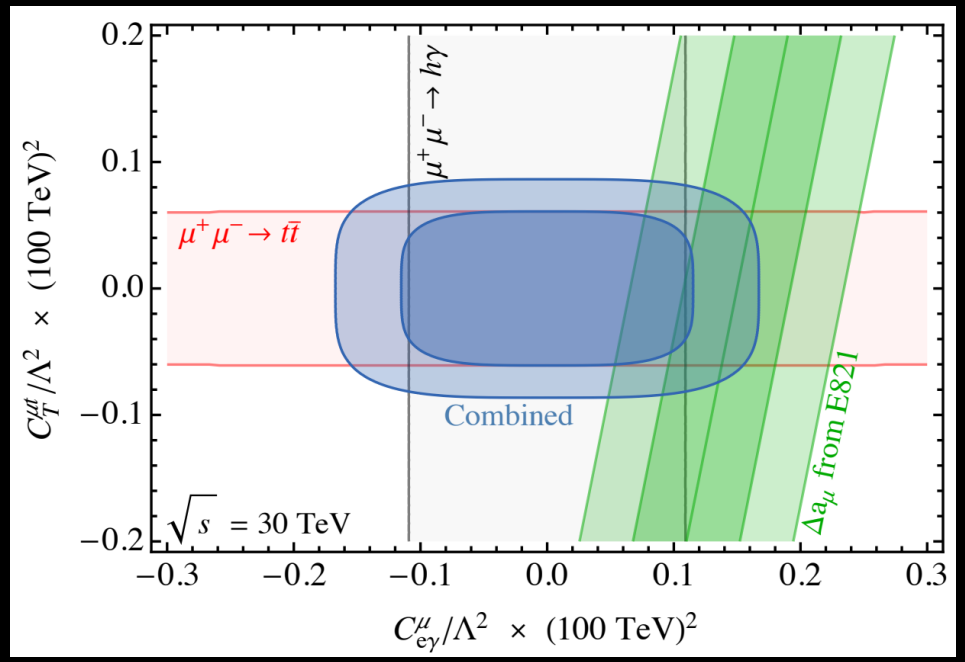
$$\beta_{y_\mu} = \frac{\mathrm{d}y_\mu}{\mathrm{d}t} = \frac{y_\mu}{16\pi^2}\left(3y_t^2 - \frac{9}{4}(g_2^2 + g_1^2)\right), \tag{2.2}$$

$$\beta_v = \frac{\mathrm{d}v}{\mathrm{d}t} = \frac{v}{16\pi^2}\left(\frac{9}{4}g_2^2 + \frac{9}{20}g_1^2 - 3y_t^2\right), \tag{2.3}$$

$$\beta_{g_i} = \frac{\mathrm{d}g_i}{\mathrm{d}t} = \frac{b_i g_i^3}{16\pi^2}, \tag{2.4}$$

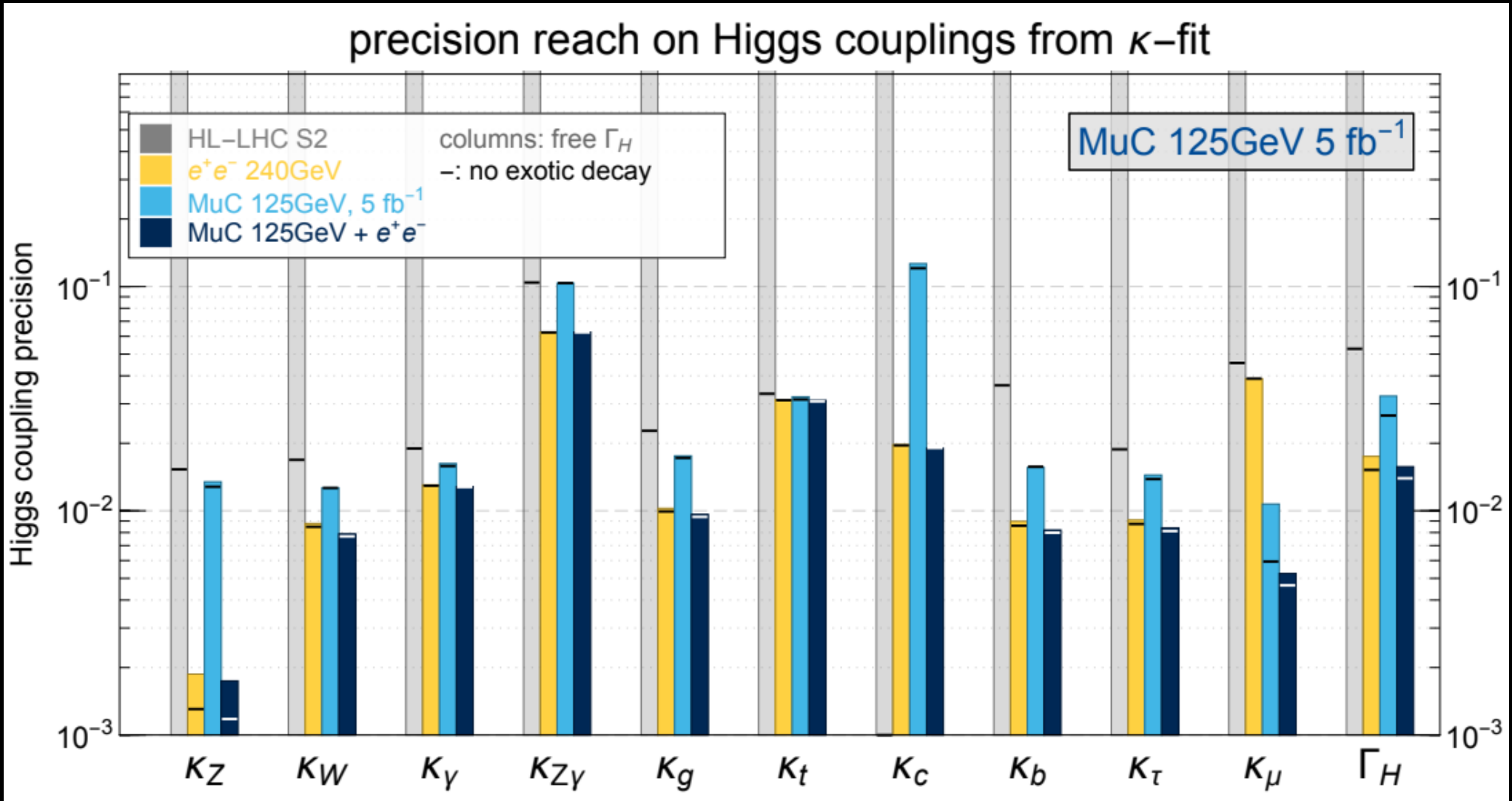
with $t = \ln(Q/M_Z)$ and the coefficients b_i for the gauge couplings (g_1, g_2, g_3) given as

$$b_i^{\mathrm{SM}} = (41/10, -19/6, -7). \tag{2.5}$$

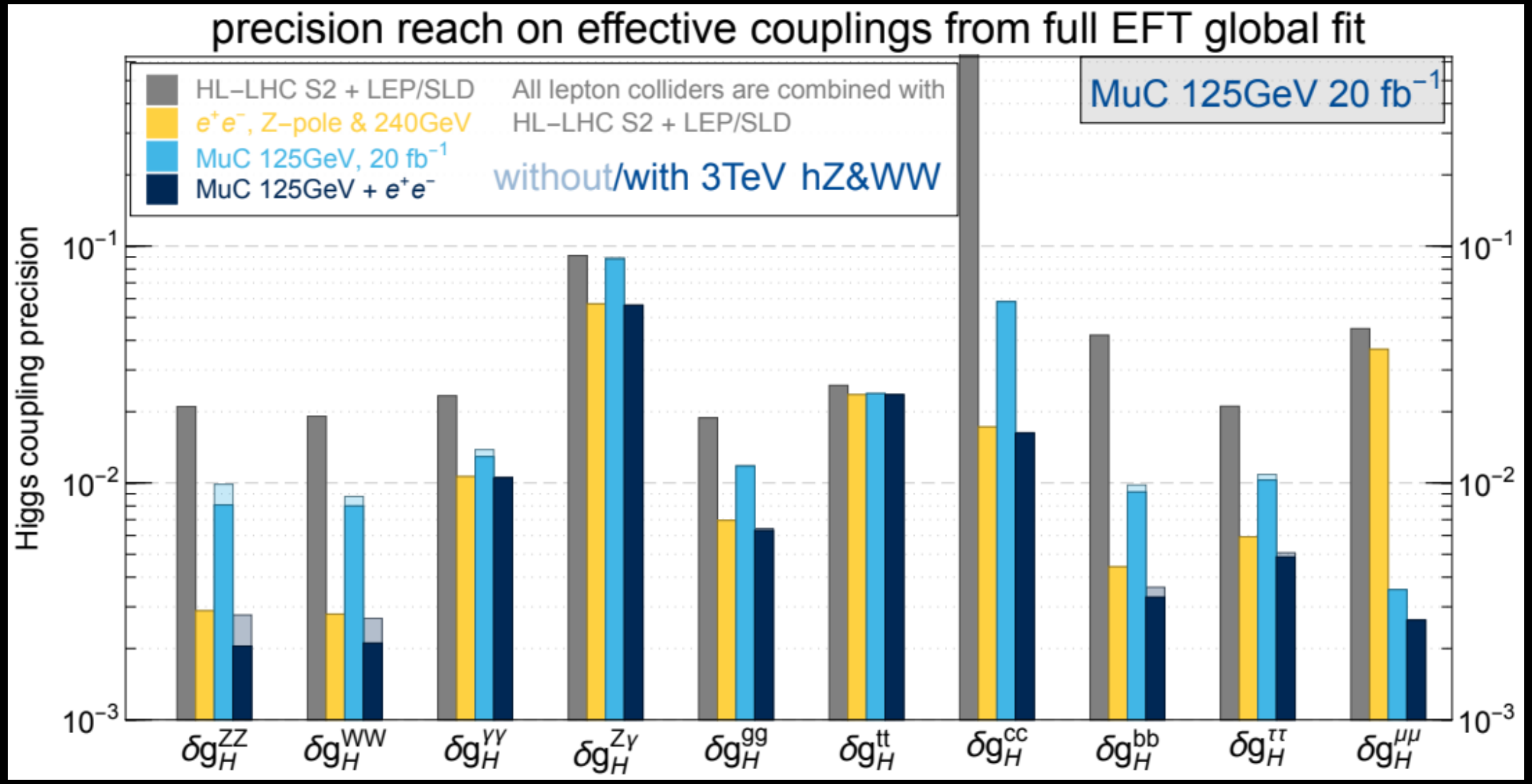


$\sqrt{s}$ (TeV)	Lumi (ab^{-1})	Constraints on δ_4 (with $\delta_3 = 0$) x-sec only, acceptance cuts		
		1 σ	2 σ	3 σ
6	12	$[-0.50, 0.70]$	$[-0.74, 0.95]$	$[-0.93, 1.15]$
10	20	$[-0.37, 0.54]$	$[-0.55, 0.72]$	$[-0.69, 0.85]$
14	33	$[-0.28, 0.43]$	$[-0.42, 0.58]$	$[-0.52, 0.68]$
30	100	$[-0.15, 0.30]$	$[-0.24, 0.38]$	$[-0.30, 0.45]$
3	100	$[-0.34, 0.64]$	$[-0.53, 0.82]$	$[-0.67, 0.97]$

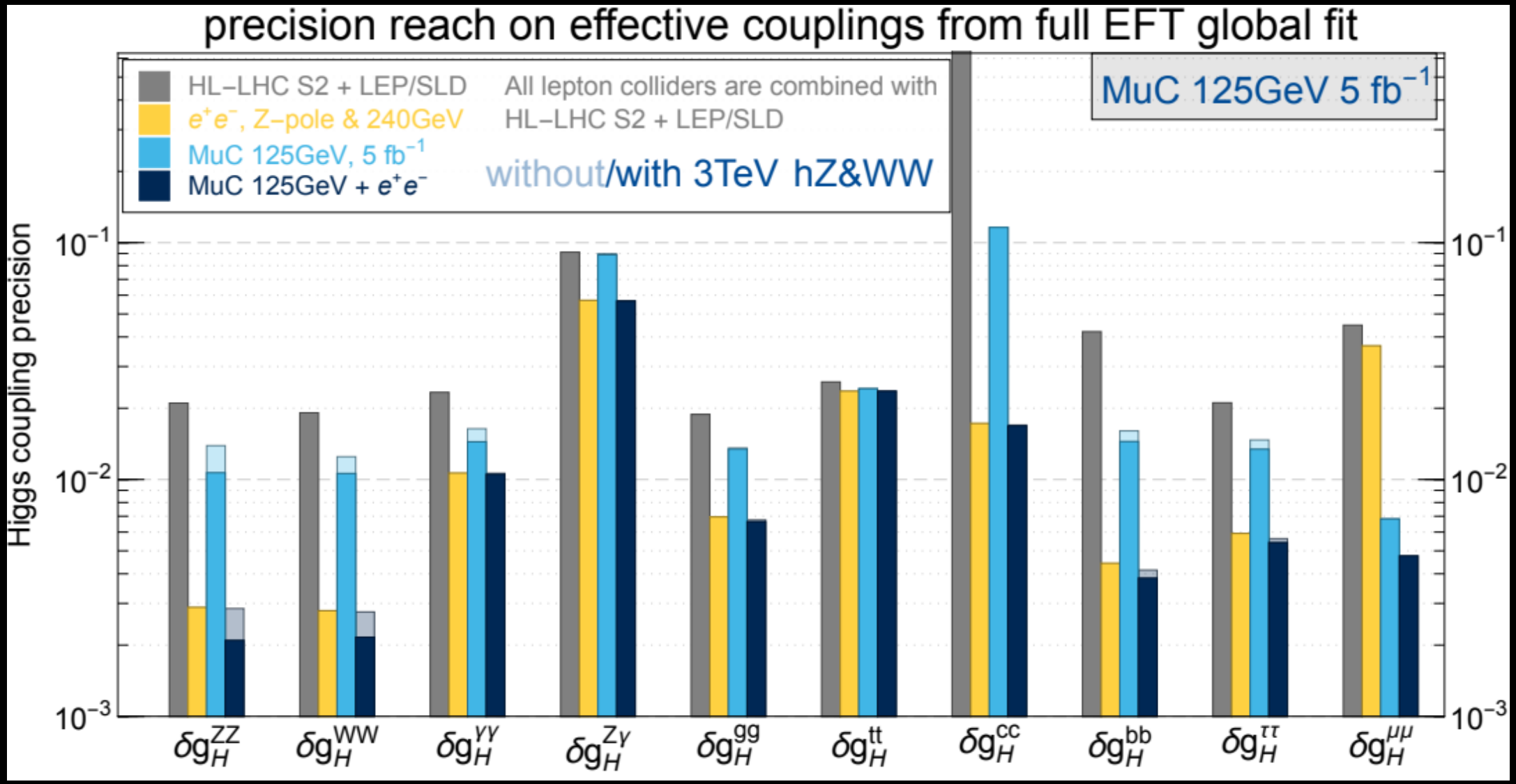
125 Kappa with 5 fb^-1



125 EFT with 20 fb^-1

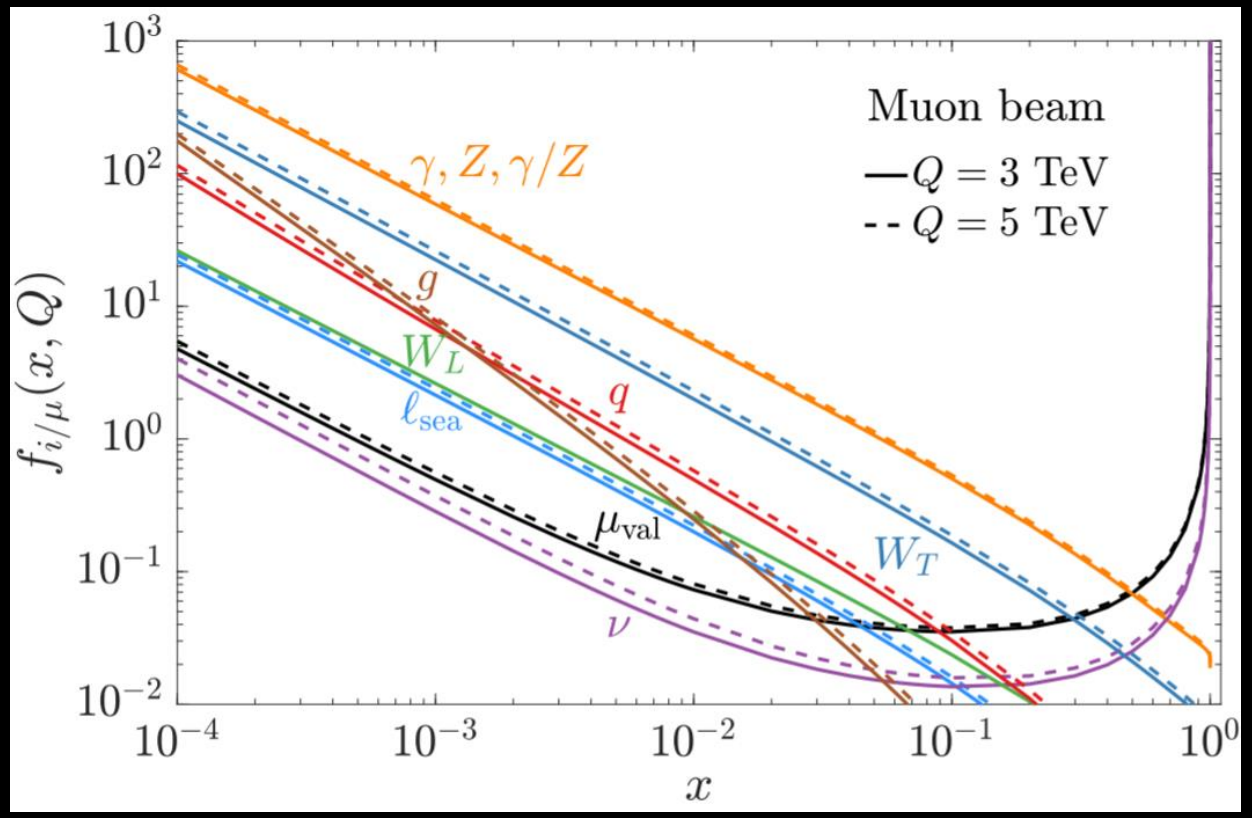


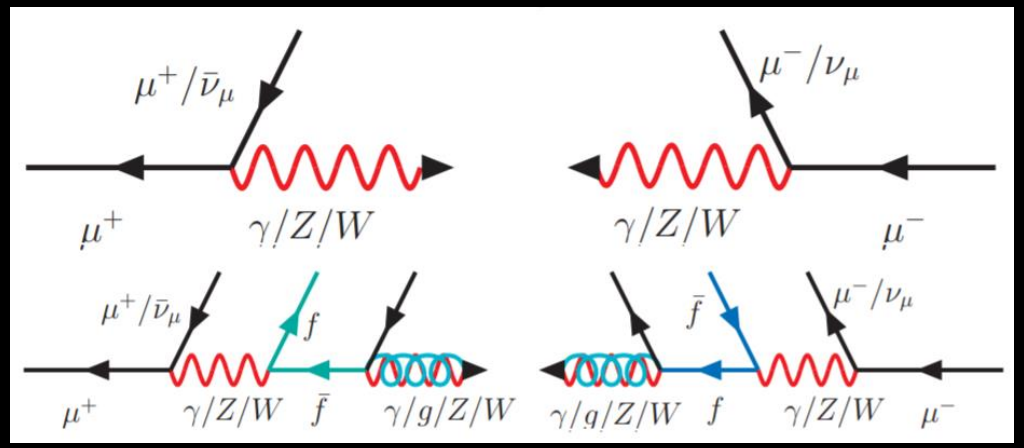
125 EFT with 5 fb^-1



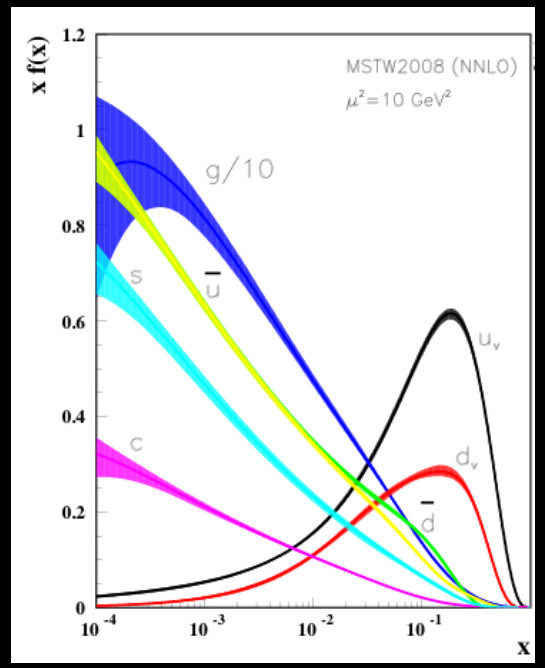
Muon "structure"

When colliding high energy leptons, we are colliding a bunch of electroweak states.





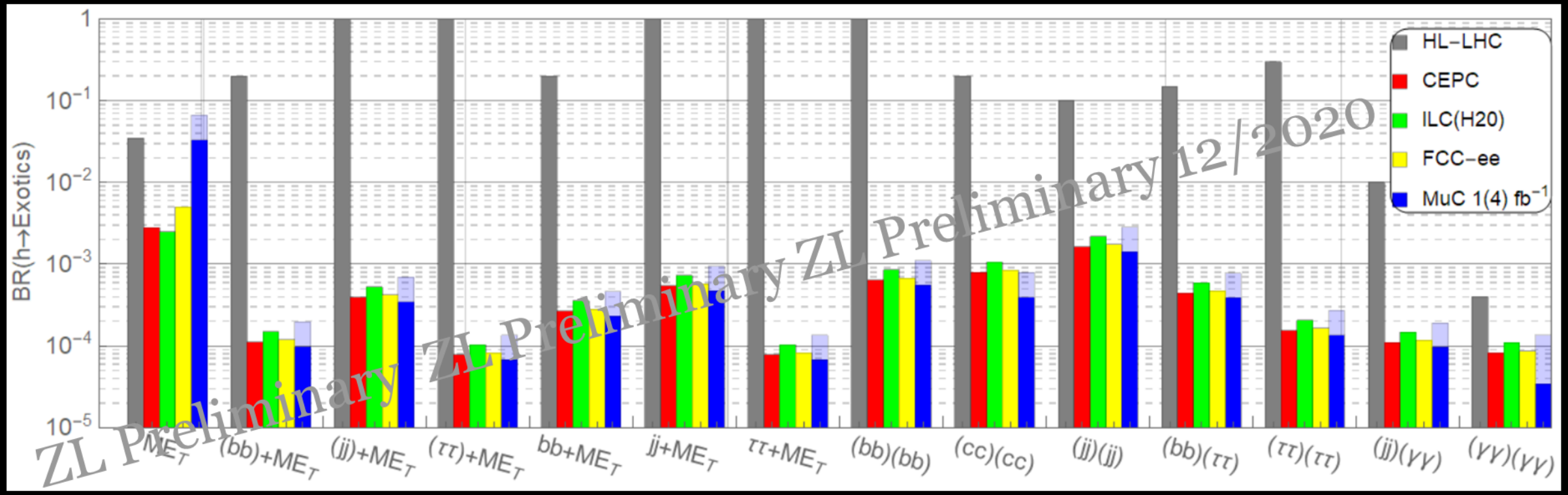
Quite different from proton



See in-depth discussion by T. Han, Y. Ma, K.-P. Xie, 2007.14300, 2103.09844; Ali et al, Muon Smasher's guide 2103.14043

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)

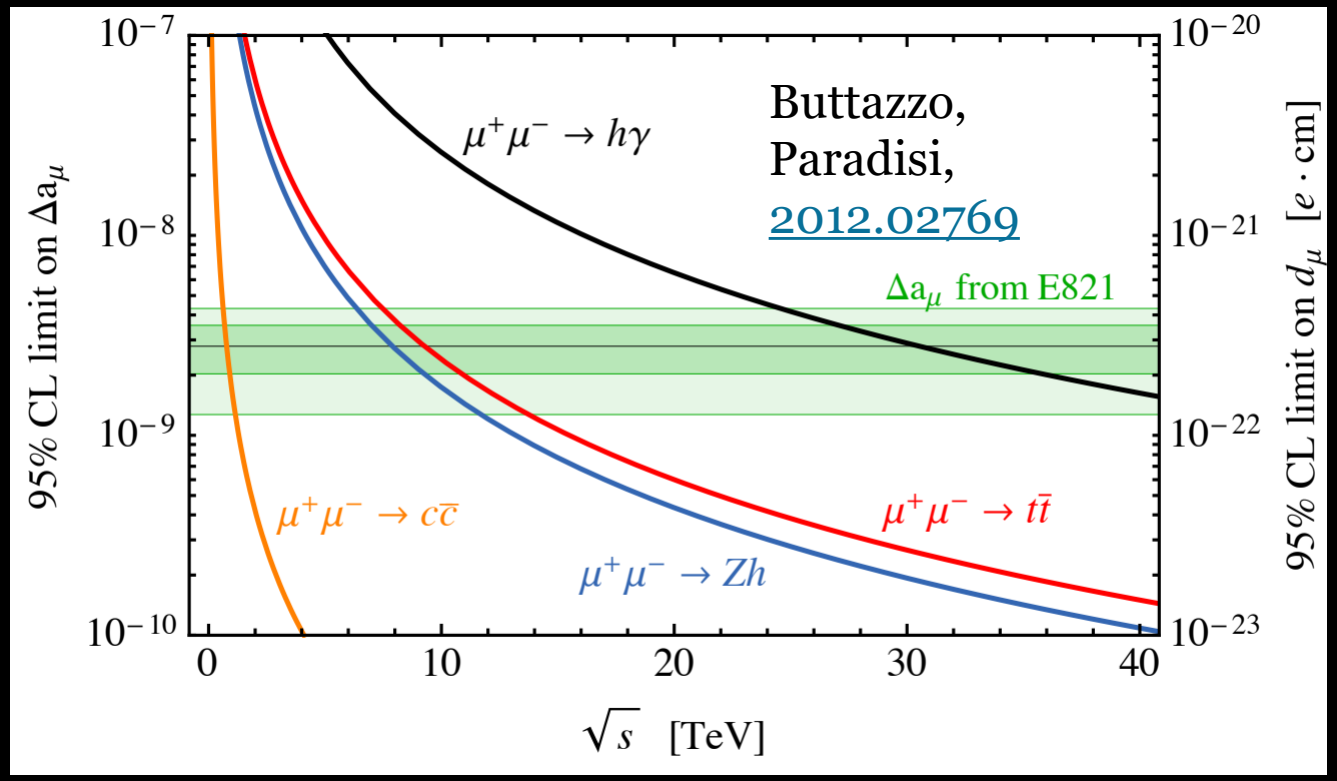
3-4 orders of magnitude improvement for the constraints on such exotic branching fractions

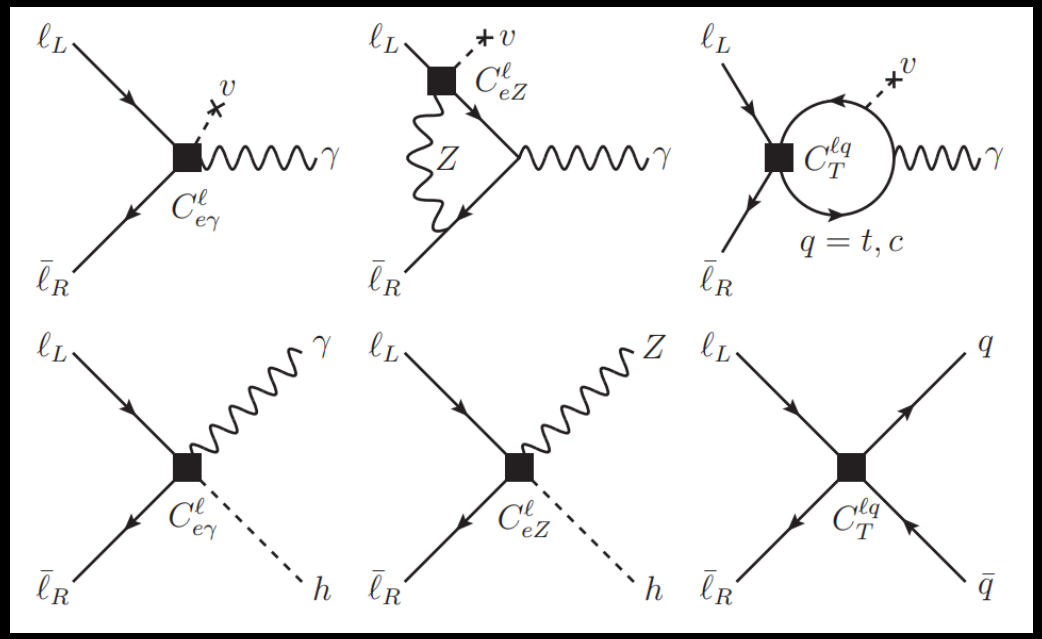
$h \to 4f$ generic Higgs sector extensions, also Higgs portals

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.

Complementarity: Muon g-2

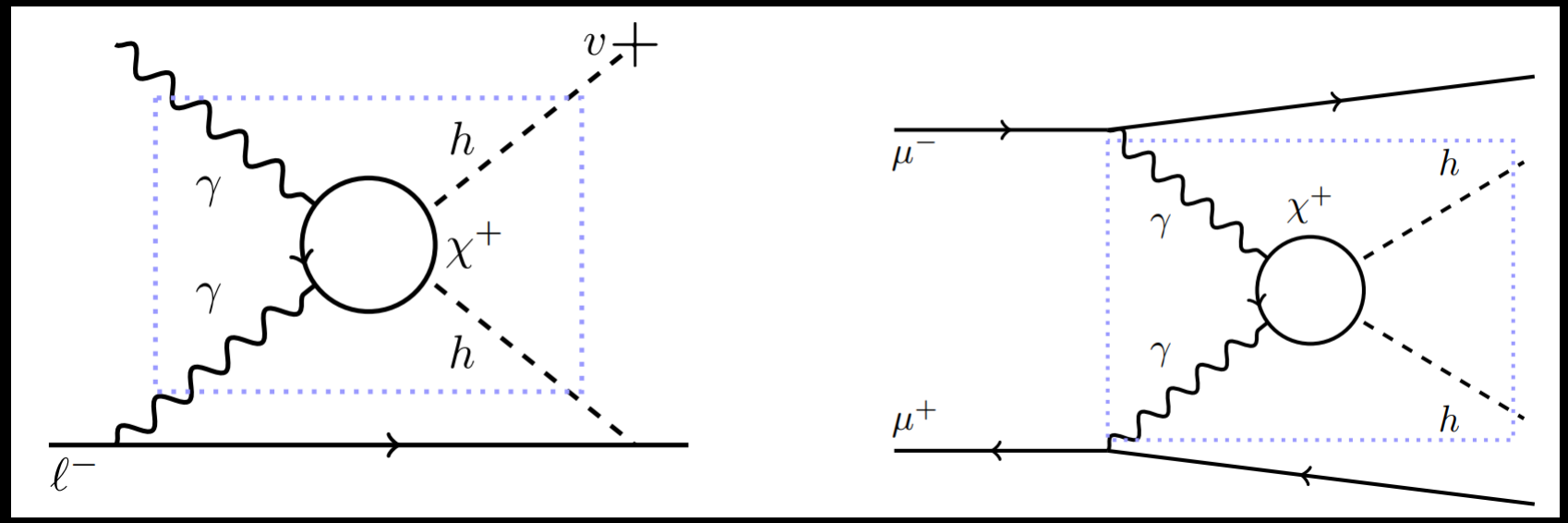




$$\mathcal{L} = \frac{C^{\ell}_{eB}}{\Lambda^2}(\bar{\ell}_L\sigma^{\mu\nu}e_R)HB_{\mu\nu} + \frac{C^{\ell}_{eW}}{\Lambda^2}(\bar{\ell}_L\sigma^{\mu\nu}e_R)\tau^I HW^I_{\mu\nu}$$
$$+ \frac{C^{\ell}_{T}}{\Lambda^2}(\bar{\ell}^a_L\sigma_{\mu\nu}e_R)\varepsilon_{ab}(\overline{Q}^b_L\sigma^{\mu\nu}u_R) + h.c. \quad (2$$

Also see various model-specific (complementary / comprehensive) discussions in Capdevilla, Curtin, Kahn, Krnjaic, 2006.16277, 2101.10334; W. Yin, Yamaguchi, 2012.03928; N. Chen, B. Wang, C.-Y., Yao, 2102.05619; Dermisek, Hermanek, McGinnis, 2108.10950

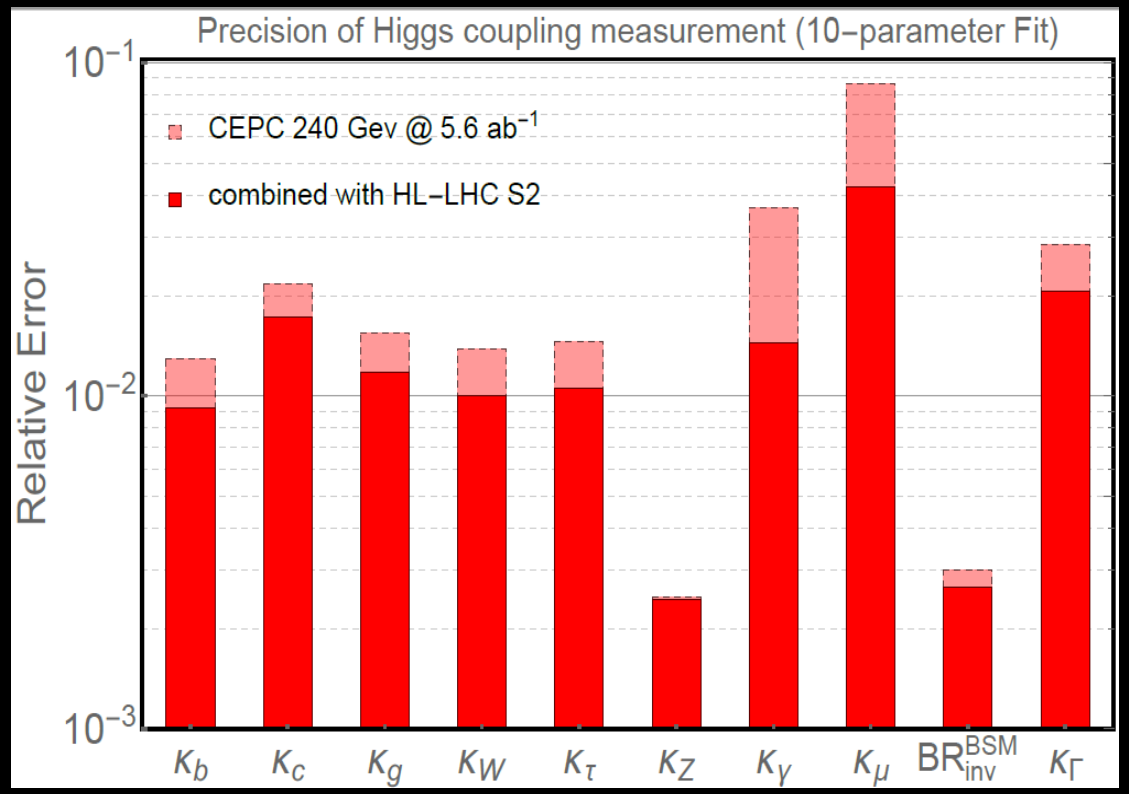
Complementarity: EDM

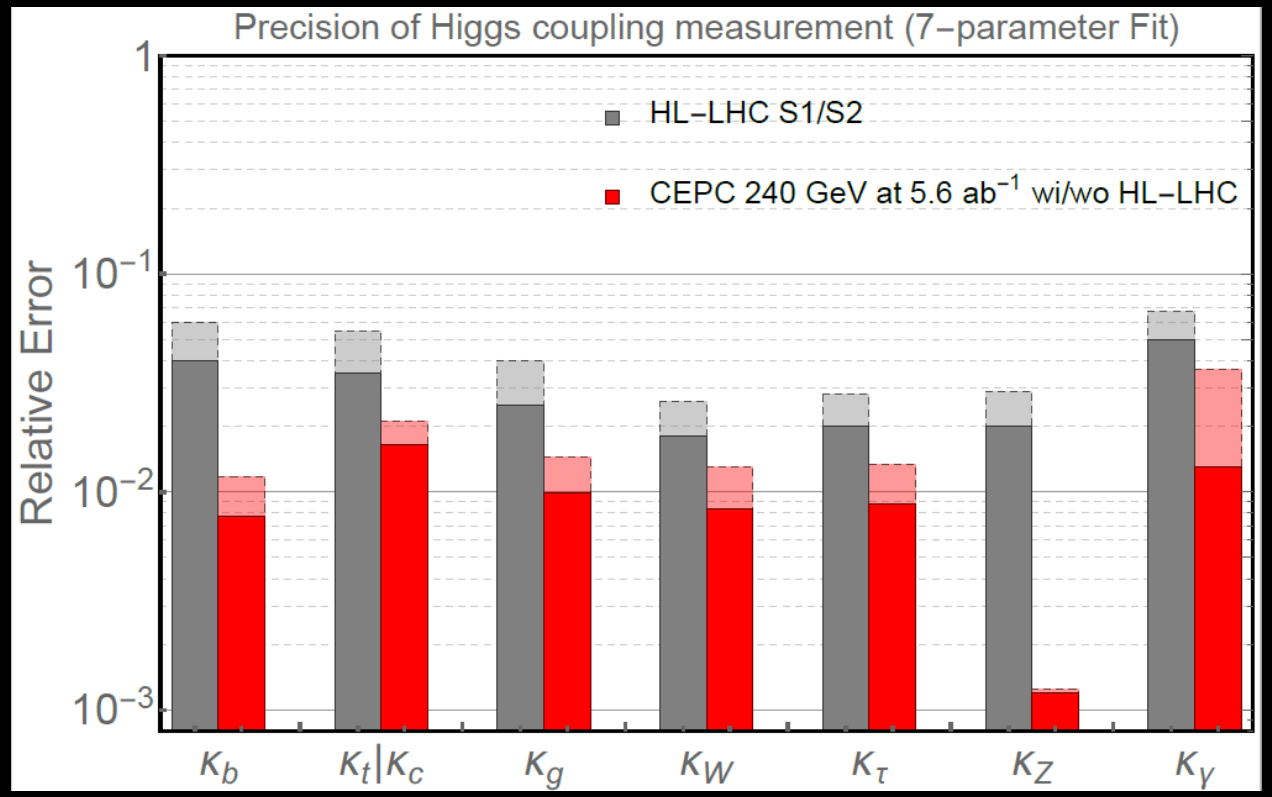


$$d_e \sim \sin(\delta_{\rm CP}) \frac{e\, m_e}{M^2} \left(\frac{\alpha}{4\pi}\right)^k \simeq 10^{-32}\, e\,\mathrm{cm} \sin(\delta_{\rm CP}) \times \begin{cases} (1\ \mathrm{PeV}/M)^2 & \text{for } k=1 \\ (20\ \mathrm{TeV}/M)^2 & \text{for } k=2 \end{cases}$$

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)*

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.

*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)

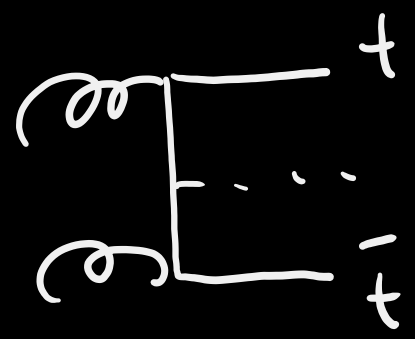
Every future collider is a Higgs factory!

pp

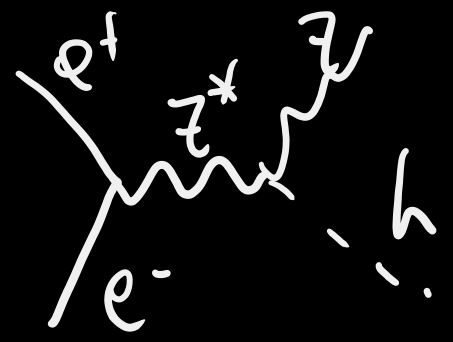
+

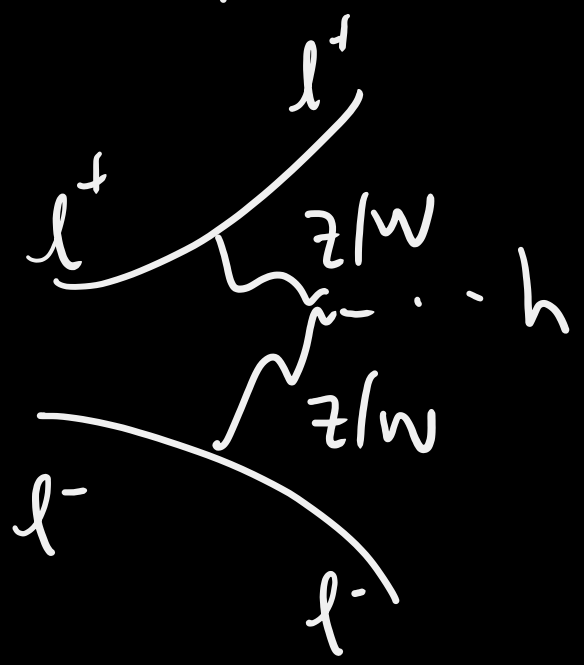
VBF, Wh, Zh, $t\bar{t}h$

+



e^+e^-





$\mu^+\mu^-$

LEAST understood

Now the Model-Independent MuC Width matters!

Let's check precision with 1/5 on-shell statistics (with different bkg)

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

e+e- collider per channel precision

Decay mode	$\sigma(ZH) \times$ 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%
$H \to$ inv	0.28%

Channel $\mu^+\mu^- \to h \to X$	Rate [pb]	Signal Events	Background Events	Precision [%] Cut & Count	Precision [%] 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
$\tau^+_{\rm had}\tau^-_{\rm had}$	0.58	1400/5600	19000/76000	10/5.1	6.8/3.4	4.8/2.4
$\tau^+_{\rm had}\tau^-_{\rm lept}$	0.63	1500/6100	18000/71000	9.1/4.5		
$\gamma\gamma$	0.05	150/605	180000/730000	280/140		190/94
$2\ell 2q$ ($\ell = e, \mu$)	0.05	130/530	1200/4800	28/14	5.8/2.9	
$2\nu 2j$	0.16	450/1800	320/1300	6.1/3.1		
$2e2\nu^\ddagger$	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		
$\ell\nu\tau_{\rm had}\nu$ ($\ell = e, \mu$)	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		
$\tau_{\rm had}\nu jj$	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		
$2\tau_{\rm had}2\nu^\dagger$	0.023	46/180	24/97	18/9.1		
$4j (j \neq b)$	2.3	3400/14000	51000/210000	6.8/3.4		

Baseline Higgs Measurements

10 TeV @ 10 ab^{-1}

Production	Decay	Rate [fb]	$A \cdot \epsilon$ [%]	$\Delta\sigma/\sigma$ [%]
W-fusion	bb	490	7.4	0.17
	cc	24	1.4	1.7
	jj	72	37	0.19
	$\tau^+\tau^-$	53	6.5	0.54
	$WW^*(jj\ell\nu)$	53	21	0.30
	$WW^*(4j)$	86	4.9	0.49
	$ZZ^*(4\ell)$	0.1	6.6	12
	$ZZ^*(jj\ell^+\ell^-)$	2.1	8.9	2.3
	$ZZ^*(4j)$	11	4.6	1.4
	$\gamma\gamma$	1.9	33	1.3
	$Z(jj)\gamma$	0.9	27	2.0
	$\mu^+\mu^-$	0.2	37	0.37
Z-fusion	bb	51	8.1	0.49
	$WW^*(4j)$	8.9	6.2	1.3
W-fusion tth	bb	0.06	12	12

The Muon Smasher's Guide

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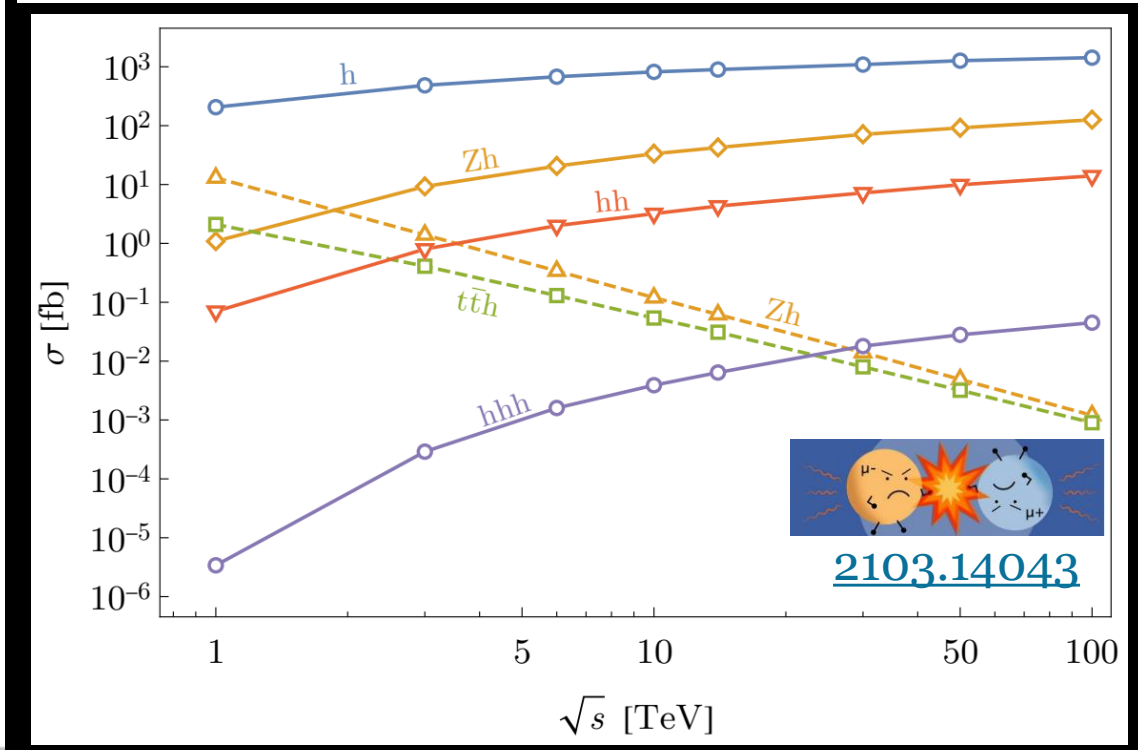

See also discussion in T. Han, Y. Ma, K.-P. Xie, 2007.14300; Stevini, De Lillo, Maltoni, Mantani, Mattelaer, 2005.12289