Higgs Couplings to Fermions

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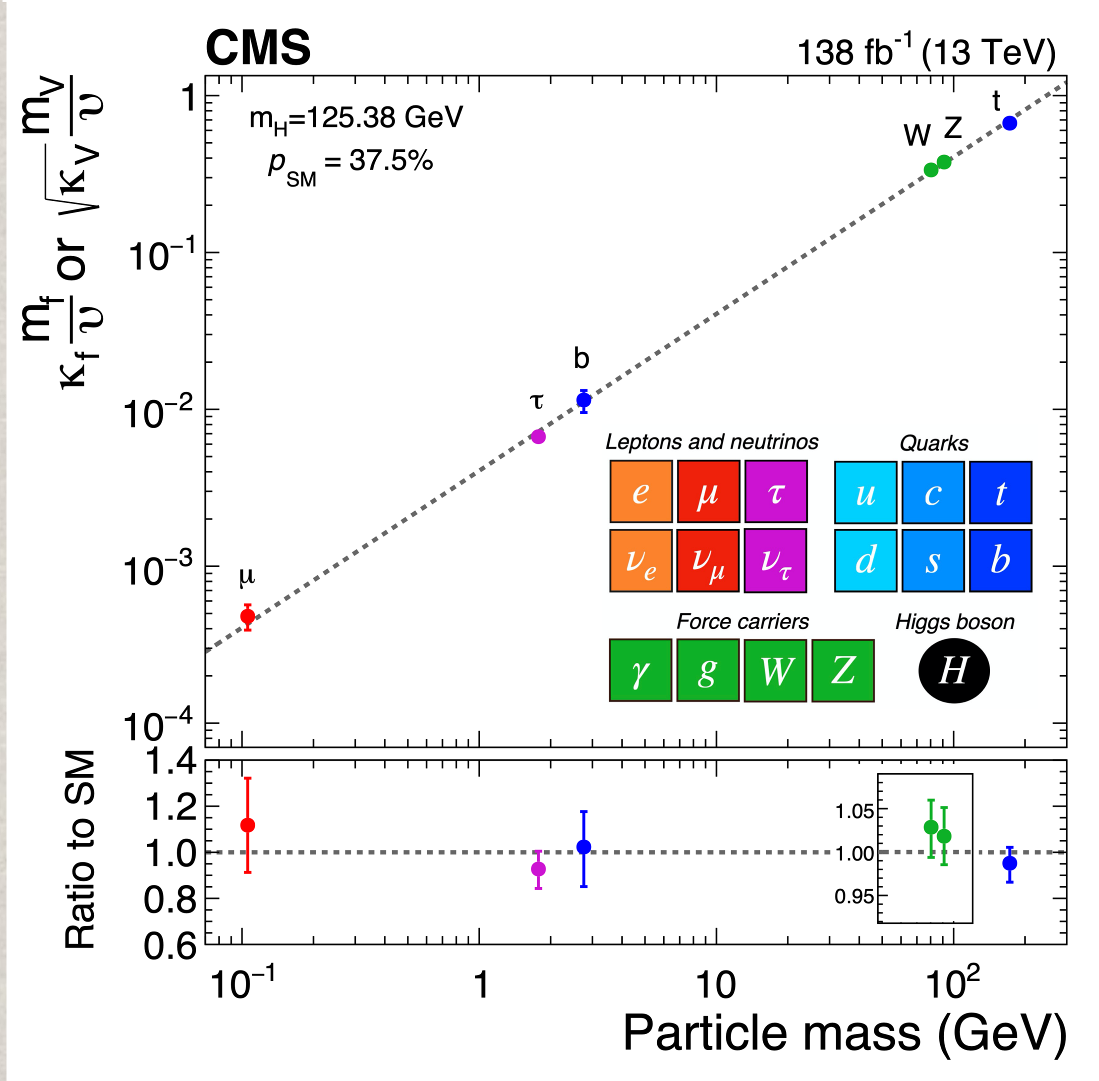
The Higgs Magic

$m_H = 125.38 \pm 0.14$ GeV *PLB 805 (2020) 135425*



The Standard Model – first time ever!

- Quantum mechanical
- Relativistic
- Renormalizable
- Perturbatively unitary

to exponentially high scales, perhaps to the Planck scale!

All known physics

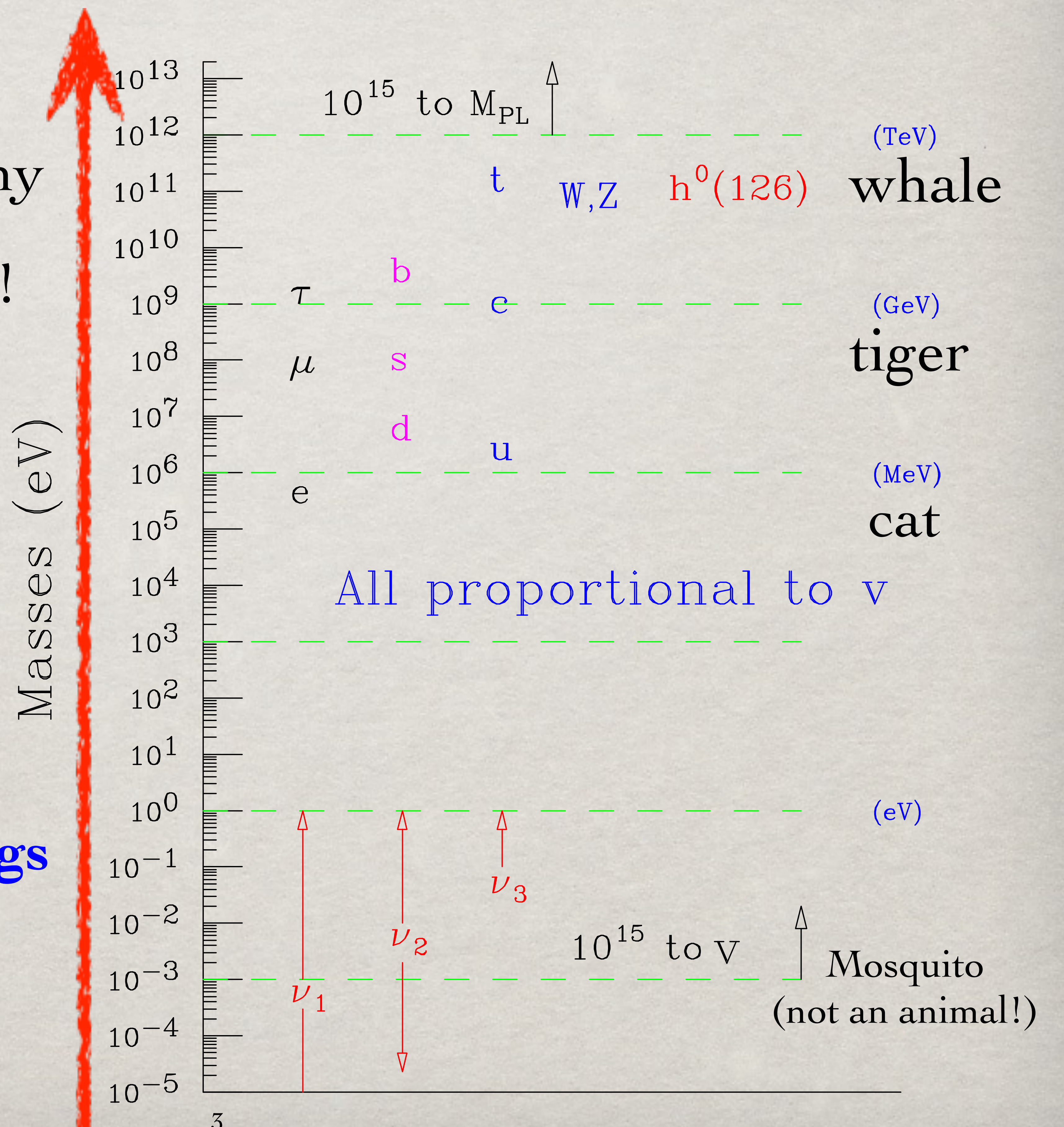
$$W = \int_{k<\Lambda} [\mathcal{D}g \ldots] \exp\left\{\frac{i}{\hbar}\int d^4x\sqrt{-g}\left[\frac{1}{16\pi G}R - \frac{1}{4}F^2 + \bar{\psi} i \not{D}\psi - \lambda\phi\bar{\psi}\psi + |D\phi|^2 - V(\phi)\right]\right\}$$

amplitude | current understanding | quantum mechanics | spacetime | gravity | strong & electroweak | matter | Higgs

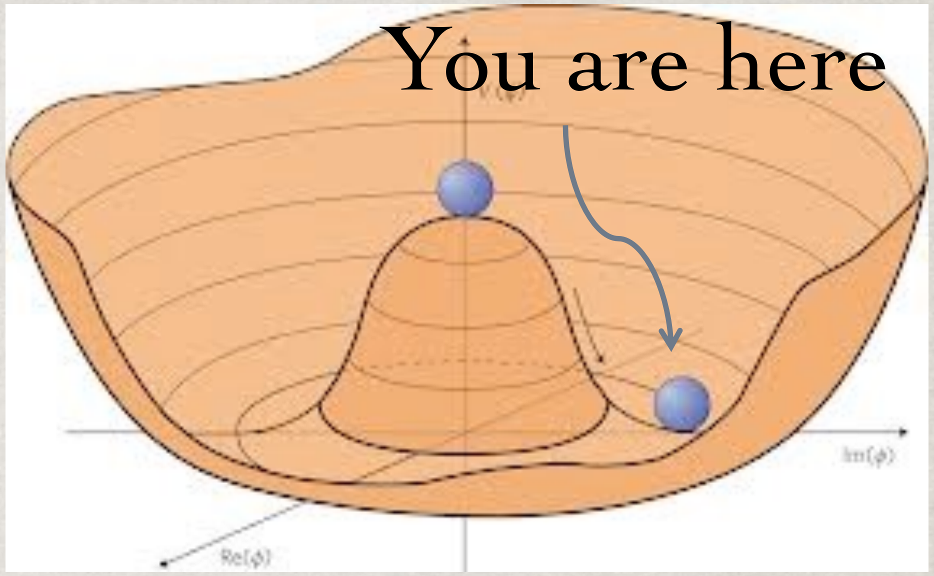
The Higgs Blemishes

- Particle mass hierarchy
- Tiny neutrino masses!
- Patterns of quark, neutrino mixings
- New CP-violation sources?

Higgs Yukawa couplings as the pivot for all !



The Higgs Inquiries



In the SM:

$$V(|\Phi|) \quad = \quad -\mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$$

$$<|\Phi|> = v = (\sqrt{2}G_F)^{-1/2} \approx 246 \text{ GeV}$$

$$m_H \approx 126 \text{ GeV}$$

$M_{W,Z}$ versus m_H versus m_f:

(1). $M_{W,Z}$: $M_W^2\ W^{\mu+}W_\mu^-\ (1+\frac{H}{v})^2 + \frac{1}{2}M_Z^2\ Z^\mu Z_\mu\ (1+\frac{H}{v})^2$

BSM: easy to break $SU(2)_L$ gauge sector:

- Fundamental scalars (SUSY)
- Dynamical breaking (TC, composite …)
- Non-linear realization ($m_H \rightarrow \infty$, or "Higgsless")

(2). m_H: $\frac{1}{2}m_H^2\ H^2 + \frac{m_H^2}{2v}\ H^3 + \frac{m_H^2}{8v^2}\ H^4$

BSM: easy to construct a scalar model, but model-parameters quadratically sensitive to a new physics scale:

$$\delta m_H^2 \propto -\frac{k^2}{4\pi^2}\Lambda^2 \quad (M^2_{SUSY},\ M^2_{comp},\ M^2_{PL}\ \ldots)$$

The Higgs Inquiries

(3). m_f :

In the SM:

$$\mathcal{L}_Y \sim -\sum_{i,j}(Y^d_{ij}\bar{Q}_{iL}\Phi d_{jR} + Y^u_{ij}\bar{Q}_{iL}\tilde{\Phi} u_{jR} + Y^e_{ij}\bar{L}_{iL}\Phi e_{jR} + Y^\nu_{ij}\bar{L}_{iL}\tilde{\Phi}\nu_{jR})$$

$$\mathcal{L}_Y \sim \sum_f m_f \bar{f} f (1 + H/v) \qquad Y_f = \frac{\sqrt{2}\, m_f}{v}$$

- Vastly different hierarchical masses
- Neutrino masses: Dirac vs. Majorana?
- Weak interactions with ad hoc flavor mixings and the CPv phase(s)

Higgs is responsible for our existence!

But is Y_e fixed by m_e? i.e., new physics modification?

Giulia Zanderighi's talk

The Higgs Inquiries

(3). m_f :

In the SM:

$$\mathcal{L}_Y \sim -\sum_{i,j} (Y^d_{ij}\bar{Q}_{iL}\Phi d_{jR} + Y^u_{ij}\bar{Q}_{iL}\tilde{\Phi}u_{jR} + Y^e_{ij}\bar{L}_{iL}\Phi e_{jR} + Y^\nu_{ij}\bar{L}_{iL}\tilde{\Phi}\nu_{jR})$$

$$\mathcal{L}_Y \sim \sum_f m_f \bar{f} f (1 + H/v) \qquad Y_f = \frac{\sqrt{2}\, m_f}{v}$$

BSM: much harder to accommodate

- Generate multiple mass scales
- Avoid FCNC
- Avoid Excessive CPv

Q's:

- Minimal Flavor Violation?
  Why the flavor mixing aligned with the SM Yukawa form?

Exploring flavor physics is complementary & rewarding,
Measuring Higgs Yukawa couplings is indispensable:
The smaller the coupling is, the more sensitive to deviations!

The Higgs Pursuits

Seeking for deviations from the SM: $\kappa_f = \frac{Y_f}{Y_f^{\rm SM}}$

- 2HDM: $\kappa_{u,d} = \frac{\cos\alpha}{\sin\beta}, \quad \frac{\sin\alpha}{\cos\beta}$ (Type I, II, L, ...)

G.C. Branco et al., arXiv:1106.0034.

Other extensions, See talks by Ian Lewis, Heidi Rzehak, Tania Robins …

- SMEFT: a linear representation:

$$\mathcal{L}_Y \sim \sum_{n=0} \frac{Y^n_{ij}}{\Lambda^{2n}} (\Phi^\dagger \Phi)^n \bar{L}_{iL} \Phi e_{jR} \quad \to \delta\kappa_f \sim Y_1 \frac{v^2}{\Lambda^2} \sim O(\text{a few\%})$$ the target!

and perhaps flavor changing $H \to \mu\tau$!
new CPv phases in Yukawa …

TH, D. Marfatia, PRL 86, 1442 (2001);
Harnik, Kopp, Zupan, arXiv:1209.1397.

- HEFT: a non-linear representation:

$$U = e^{i\phi^a \tau_a / v} \quad \text{with} \quad \phi^a \tau_a = \sqrt{2} \begin{pmatrix} \frac{\phi^0}{\sqrt{2}} & \phi^+ \\ \phi^- & -\frac{\phi^0}{\sqrt{2}} \end{pmatrix}$$

$$L_{\rm Y} \sim -\frac{v}{2\sqrt{2}} \left[\sum_{n \geq 0} y_n \left(\frac{H}{v}\right)^n (\bar{\nu}_L, \bar{\mu}_L) U (1 - \tau_3) \begin{pmatrix} \nu_R \\ \mu_R \end{pmatrix} + \text{h.c.} \right]$$

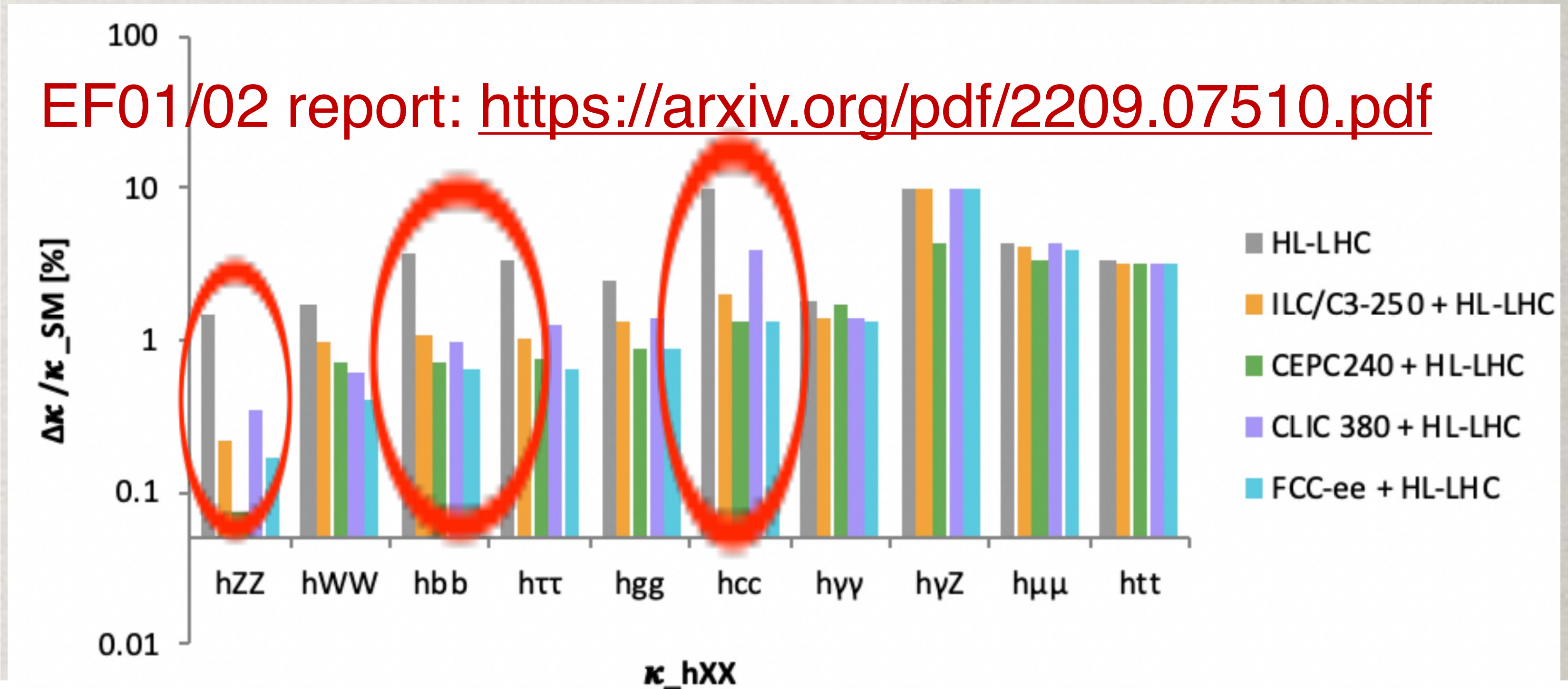
The scale is at $\Lambda \sim 4\pi\, v$ ← close by
the deviation can be sizable: $\to \delta\kappa_f \sim Y_1 \frac{H}{v} \sim O(1)$

The Higgs Pursuits

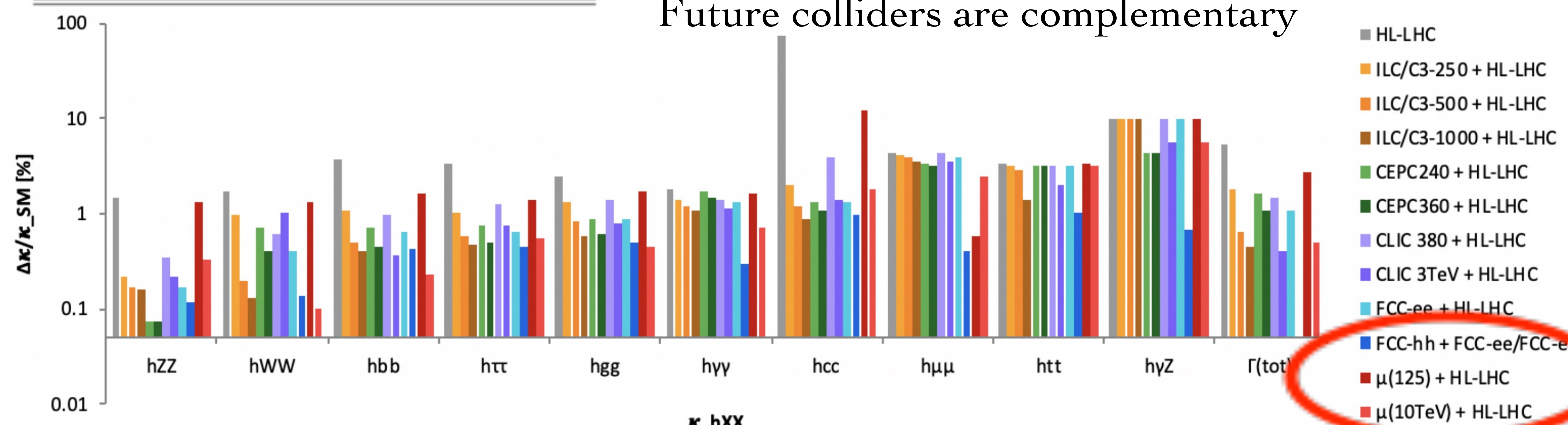
Snowmass Energy Frontier summaries

Collider	Type	$\sqrt{s}$	$\mathcal{P}[\%]$ e^-/e^+	$\mathcal{L}_{\text{int}}$ ab^{-1}/IP
HL-LHC	pp	14 TeV		3
ILC and C^3 c.o.m almost similar	ee	250 GeV	$\pm80/\pm30$	2
		350 GeV	$\pm80/\pm30$	0.2
		500* GeV	$\pm80/\pm30$	4
		1 TeV	$\pm80/\pm20$	8
CLIC	ee	380 GeV	$\pm80/0$	1
CEPC	ee	M_Z		60
		$2M_W$		3.6
		240 GeV		20
		360 GeV		1
FCC-ee	ee	M_Z		150
		$2M_W$		10
		240 GeV		5
		2 M_{top}		1.5
muon-collider (higgs)	$\mu\mu$	125 GeV		0.02

EF01/02 report: https://arxiv.org/pdf/2209.07510.pdf



Future colliders are complementary



EF04 report: https://arxiv.org/pdf/2209.08078.pdf

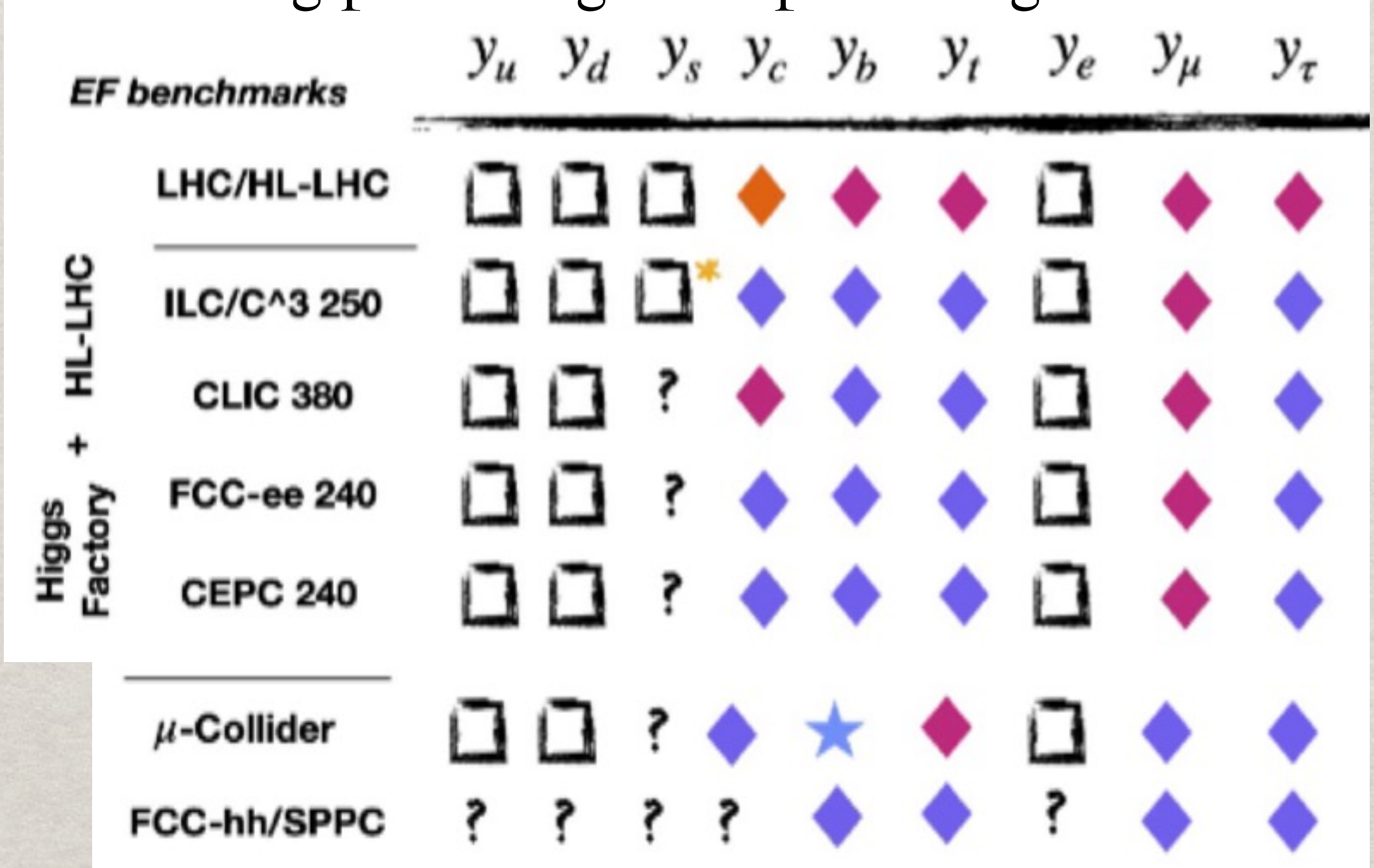
Higgs couplings@LHC: talk by Stefano Rosati

Sensitivities to Yukawa couplings at Higgs factories

EF01/02 report: https://arxiv.org/pdf/2209.07510.pdf

Symbols of sensitivities:

Achieving percentage/sub-percentage level!



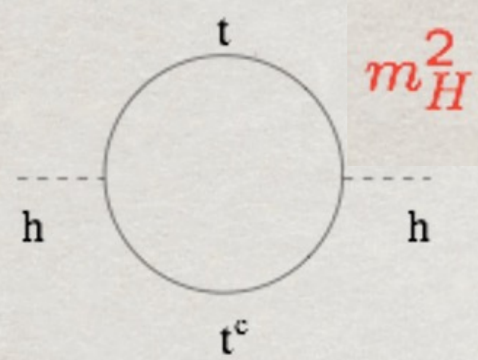
Higgs couplings@LHC: Stefano Rosati et al.

The Higgs Pursuits

$H\bar{f}f$ couplings :

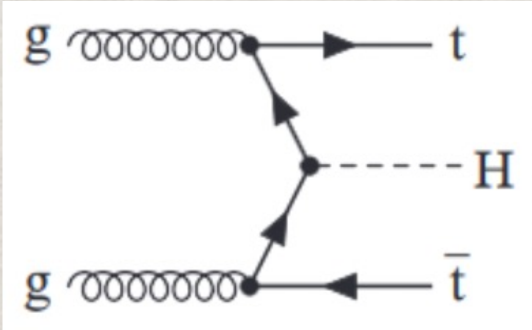
Much work has been done, many great talks,
I will discuss some ideas.

(1). y_t: The most wanted!



$$m_H^2 = m_{H0}^2 - \frac{3}{8\pi^2} y_t^2 \Lambda^2$$

The current LHC sensitivity:



$$\delta\kappa_t = 0.35^{+0.36}_{-0.34} \quad \text{(ATLAS)}$$

(G. Di Gregorio, ICHEP 2022)

talks by Giulia Zanderighi; Judith Katzy

Future lepton collider sensitivity:

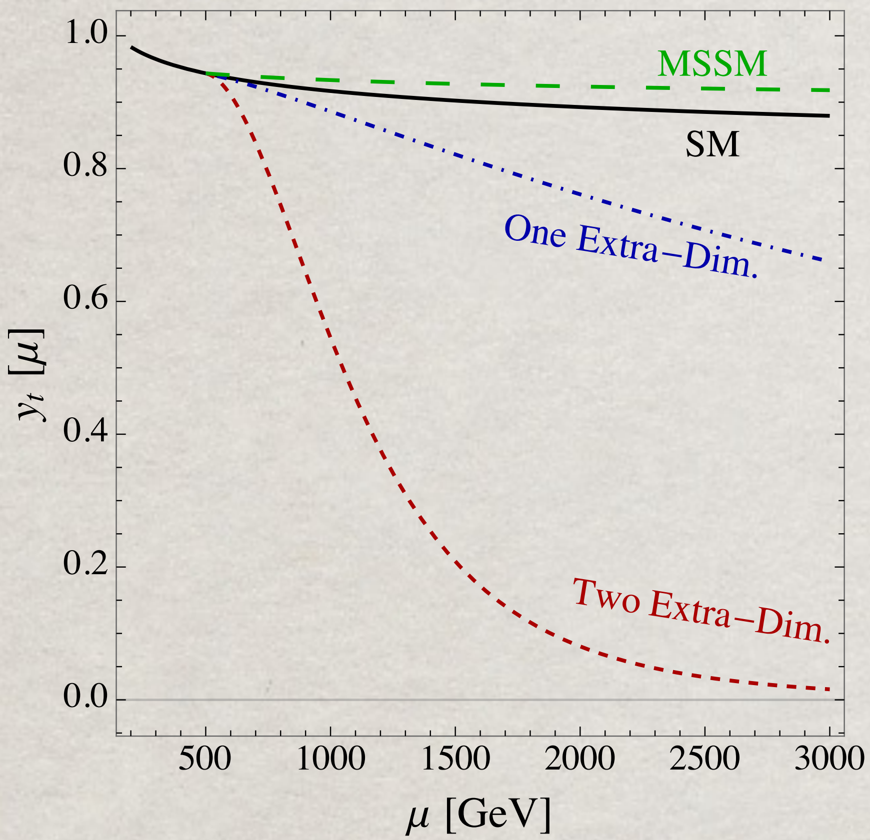
Values in % units		LHC	HL-LHC	ILC500	ILC550	ILC1000	CLIC
δy_t	Global fit	6.12	2.53	2.08	1.30	0.739	1.48
	Indiv. fit	5.08	1.85	1.80	1.17	0.705	1.26

Table 8: Uncertainties for the top-quark Yukawa coupling at 68% probability for different scenarios, in percentage. The ILC500, ILC550 and CLIC scenarios also include the HL-LHC. The ILC1000 scenario includes also ILC500 and HL-LHC.

EF04 report: https://arxiv.org/pdf/2209.08078.pdf

ttH coupling @ high scales:

1. Yukawa $y_t(Q)$ RGE running:



2. Off-shell probe of EFT operators:

$$\sigma_{\rm on} \propto \frac{g_i^2(m_h^2)g_f^2(m_h^2)}{m_h\Gamma_h} \text{ and } \sigma_{\rm off} \propto \frac{g_i^2(Q^2)g_f^2(Q^2)}{Q^2}$$

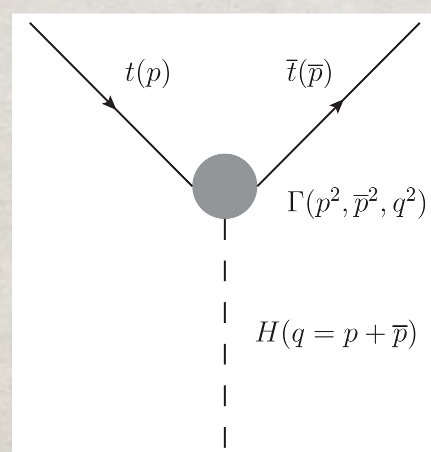
HL-LHC@3 ab^{-1} on new physics scale:

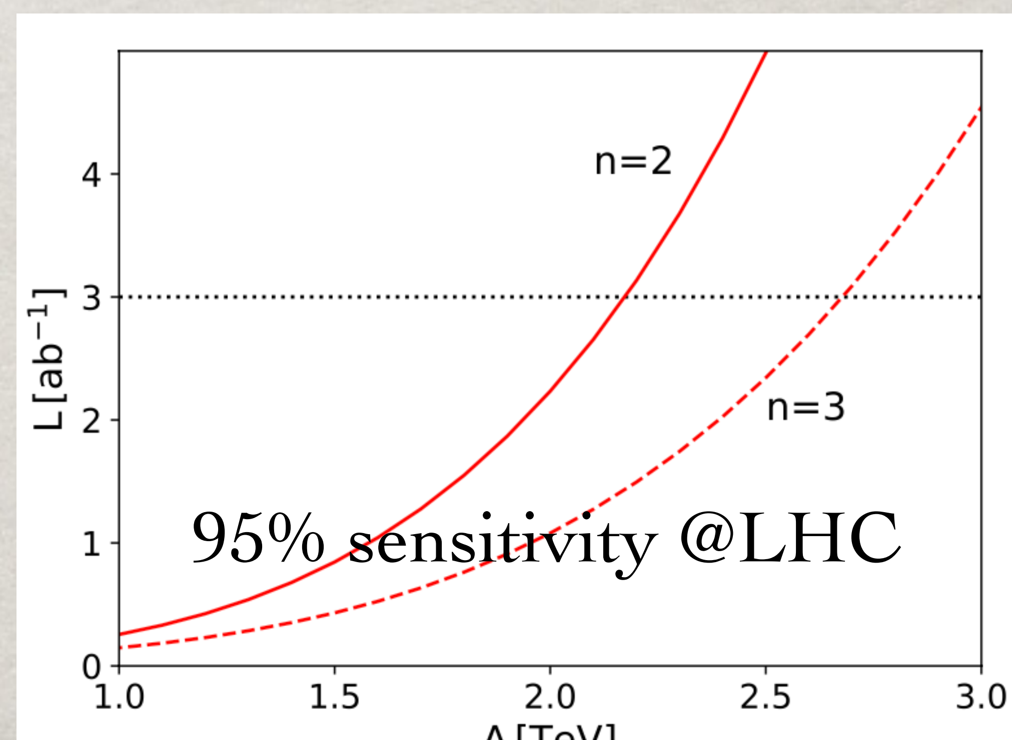
	Γ_H/Γ_H^{SM}	Λ_{EFT}
$H^* \to ZZ \to \ell\ell\nu\nu$	1.31	0.8 TeV
$H^* \to ZZ \to 4\ell$	1.3 (68% CL) [33]	0.55 TeV [34]

Higgs off-shell: talks by Pascal Vanlaer, Michiel Jan Veen

3. Composite form factors:

$$\Gamma(q^2/\Lambda^2) = \frac{1}{(1+q^2/\Lambda^2)^n}$$





D. Goncalves, TH, S. Mukhopadhyay, arXiv:1710.02149 (PRL, 2017); arXiv:1803.09751;
D. Goncalves, TH. I. Leung, H. Qin, arXiv:2012.05272;
R. Abraham, D. Goncalves, TH, S.C.I. Leung, H. Qin, arXiv:2012.05272.

The Higgs Pursuits

(2). 2nd generation y_c: The real challenge!

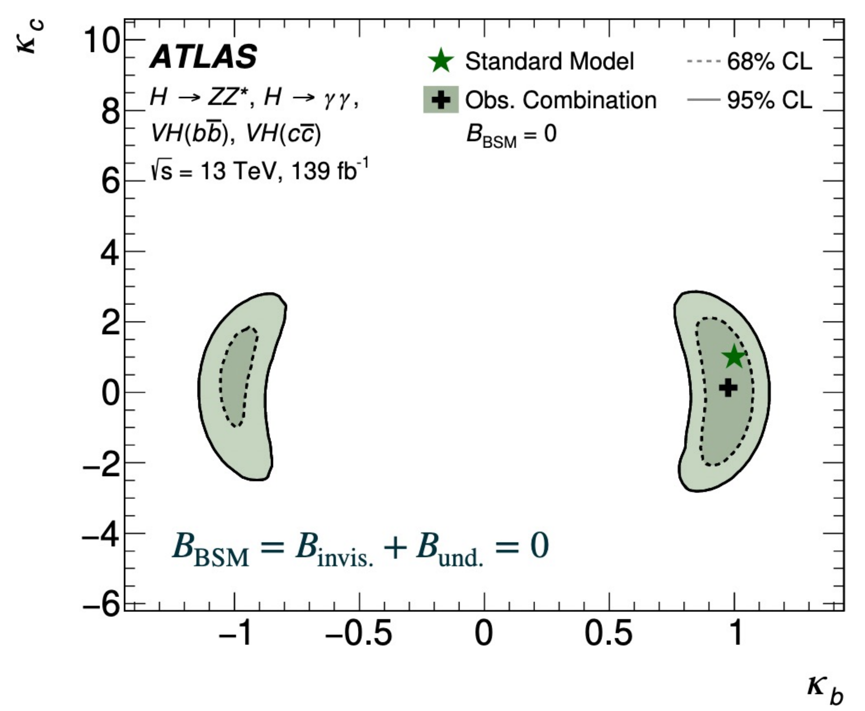
The current LHC sensitivity: $BR^{SM}_{H\to c\bar{c}} = (2.88^{+0.16}_{-0.06})\%$

LHC Run 2: ATLAS $\kappa_c \leq 8.5$ [2201.11428], CMS $1.1 < |\kappa_c| < 5.5$ [2205.05550]

Adding the VH(cc) and VH(bb) datasets
Miha Muškinja Submitted to JHEP [2207.08615]

Upper limit on κ_c of 4.8×SM at 95% CL

Scenario	Observed 68% confidence interval	Observed 95% confidence interval
$B_{\rm BSM} = 0$	[−1.61, 1.70]	[−2.47, 2.53]
No assumption	[−2.63, 3.01]	[−4.46, 4.81]



HL-LHC sensitivity projection: a factor of few from SM

Future HL-LHC: $\kappa_c \leq 3.$ [2201.11428]

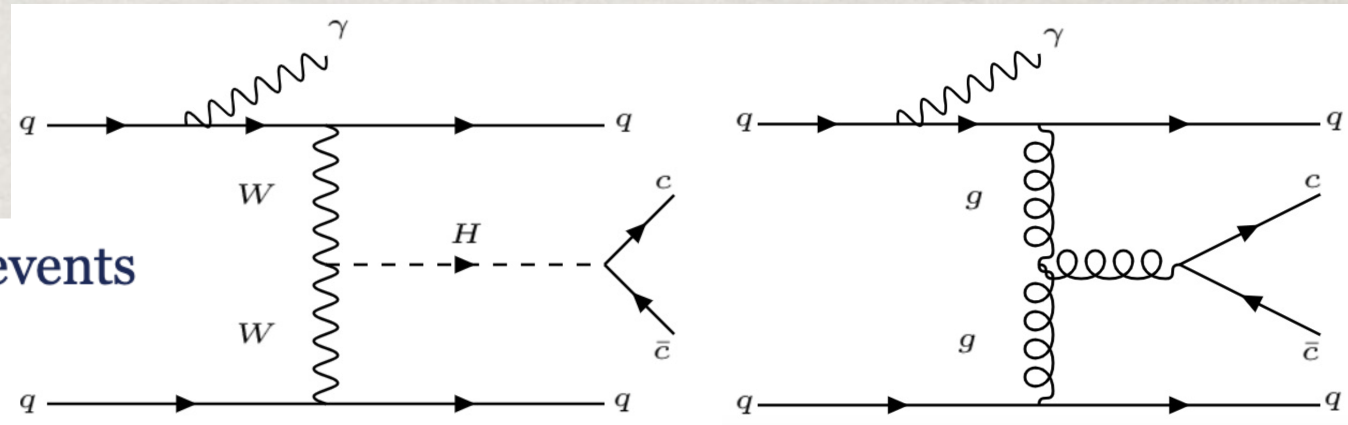
EF01/02 report: https://arxiv.org/pdf/2209.07510.pdf

Hbb, Hcc: talks by Susan Dittmer, Alessandro Calandri; Marco Stamenkovic, Miha Muskinja

The Higgs Pursuits

Higgs production rate is high: #H@LHC ~ 50 M /ab !
Need new ideas!

- VBF → H+**γ** :



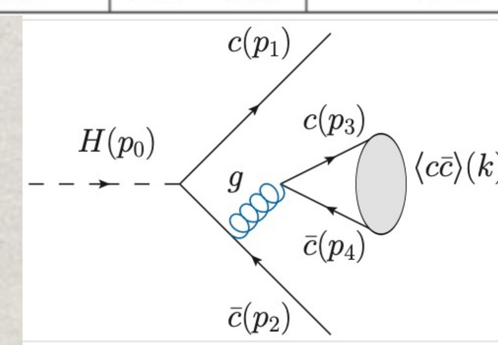
- Striking signatures and sizable signal events
- Extra handle to trigger on
- Suppression of gluon-rich background

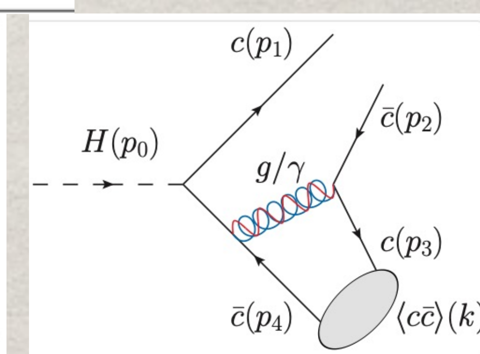
B. Carlson, TH, I. Leung, aXive:2105.08738

- Upper bound on κ_c at 95% C.L in absence of systematics:

	LHC	Cut-based	BDT	ZH [16, 17]	Fit [33]	Hc [31]	$H \to c\bar{c}\gamma$ [41]
κ_c	36.1 fb^{-1}	20	16	10	-	-	-
	3 ab^{-1}	6.5	5.4	2.5	1.2	2.6 - 3.9	8.6

- H → J/ψ via fragmentation:
  - ➢ Enhanced from the fragmentation
  - ➢ Direct coupling to charm





TH, A. Leibovich, Y. Ma, X.Z. Tan: aXive:2202.08273 (and talk by Ma)

$$\mathrm{BR}(H \to c\bar{c} + J/\psi) = (2.0 \pm 0.5) \times 10^{-5}$$
$$\mathrm{BR}(H \to c\bar{c} + \eta_c) = (6.0 \pm 1.0) \times 10^{-5}$$

Note: BR(H → J/ψ+**γ**) = 2.8x10^{-6}
- ➢ Dominated by VMD

Hcc: talks by Alessandro Calandri; Marco Stamenkovic

The Higgs Pursuits

(3). 2nd generation y_μ: The next hope!

The current LHC sensitivity: $BR^{SM}_{H\to\mu^+\mu^-} = (2.17 \pm 0.04) \times 10^{-4}$

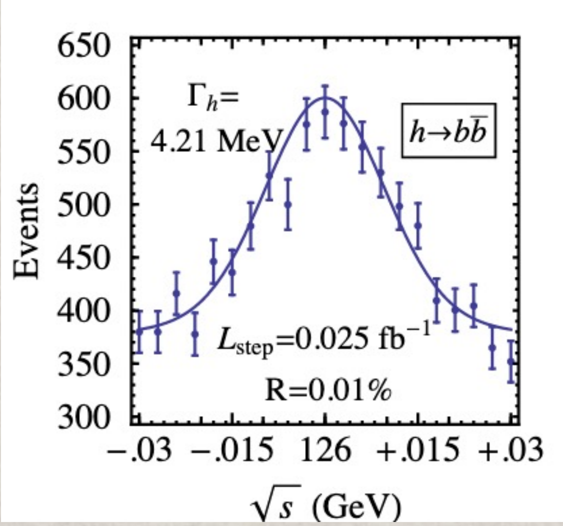
Observation: ATLAS: 2.0σ; CMS 3.0σ

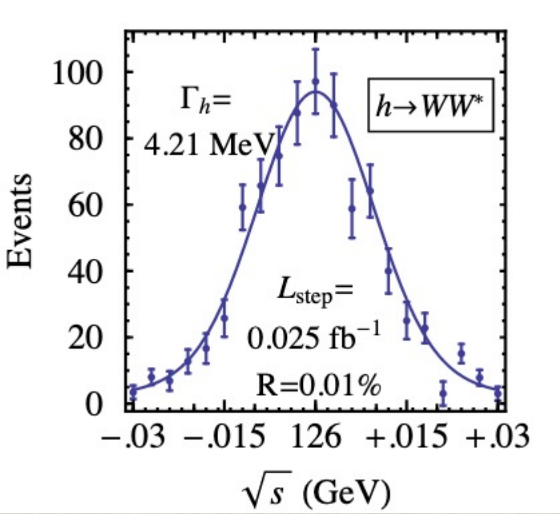
Talk by Stefano Rosati, P. Lenzi

HL-LHC sensitivity projection: BR(H→μμ) < 10%

(assuming the SM width)

Model-independent measurement at a muon Higgs factory:





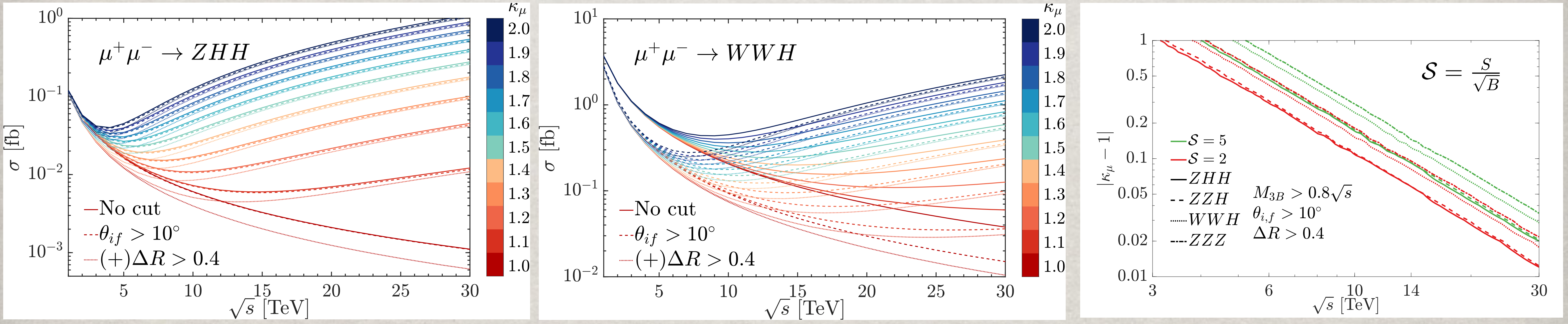
$\Gamma_h = 4.21$ MeV	L_{step} (fb^{-1})	$\delta\Gamma_h$ (MeV)	δB	δm_h (MeV)
$R = 0.01\%$	0.005	0.73	6.5%	0.25
	0.025	**0.35**	**3.0%**	**0.12**
	0.2	0.17	1.1%	0.06
$R = 0.003\%$	0.01	0.30	4.4%	0.12
	0.05	**0.15**	**2.0%**	**0.06**
	0.2	0.08	1.0%	0.03

Barger, Berger, Gunion, Han: https://arxiv.org/abs/hep-ph/9504330;
TH, Z. Liu: https://arxiv.org/abs/1210.7803;
M. Greco, TH, Z. Liu: https://arxiv.org/abs/1607.03210

The Higgs Pursuits

Model-independent measurement off the resonance: High energy option

- To enhance the Yukawa coupling effects, multiple Higgs/Goldstone boson production more beneficial.
- Due to the energy-dependence, higher energy collider preferred.



At 30 TeV: $\delta\kappa_\mu$~ 1% - 4%, corresponding to Λ ~ 30 TeV – 100 TeV.

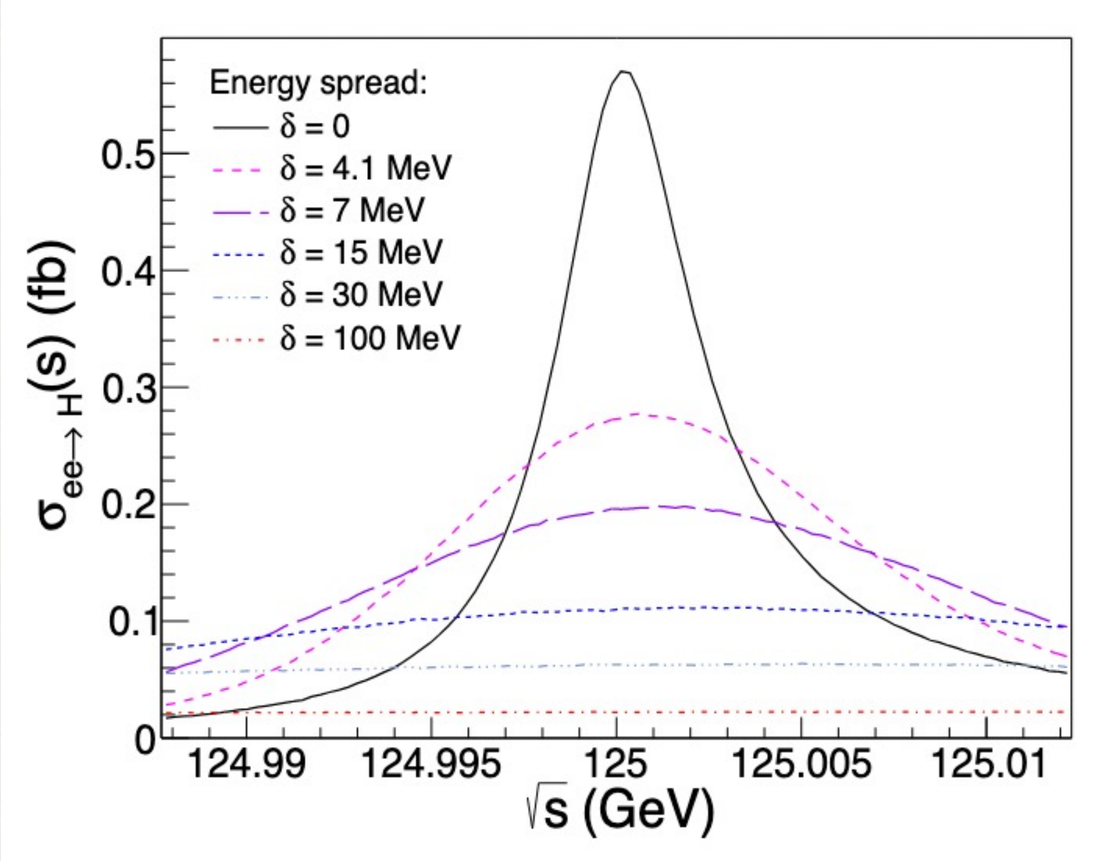
TH, W. Kilian, N. Kreher, Y. Ma, J. Reuter, T. Striegl, K. Xie: https://arxiv.org/abs/2108.05362;
E. Celada, TH, W. Kilian, N. Kreher, Y. Ma, F. Maltoni, D. Pagani, J. Reuter, T. Striegl, K. Xie; to appear.

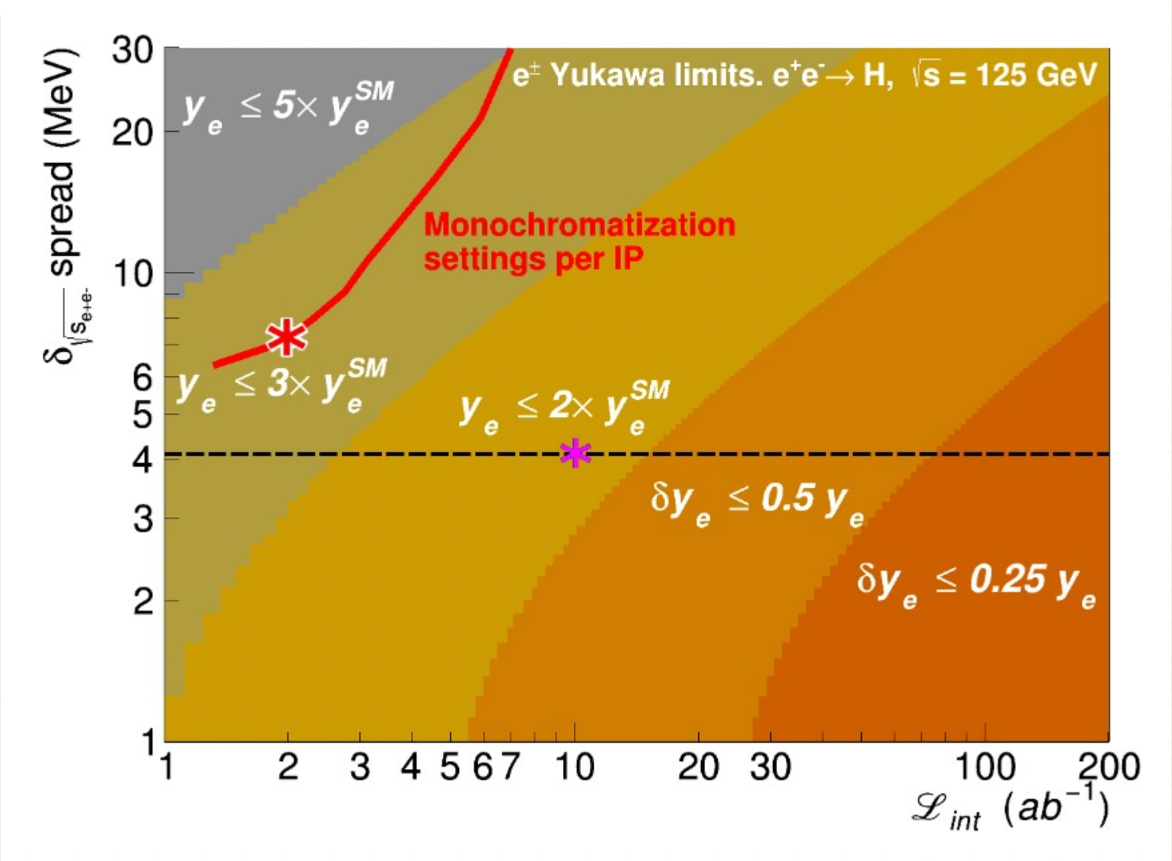
The Higgs Pursuits

(4). 1st generation y_e: There is a chance!

$$y_e = \sqrt{2} m_e / v = 2.9 \times 10^{-6}$$

$$e^+e^- \to H$$





M. Greco, TH, Z. Liu: https://arxiv.org/abs/1607.03210

Accel. Frontier report: https://arxiv.org/pdf/2203.06520.pdf

Conclusions:

- The fern sector involves multiple scales;
  numerous mixing parameters, CP phase(s)
  → rich physics, but least predictive!

- Exploring flavor physics is complementary & rewarding, measuring Higgs Yukawa couplings is indispensable

- SMEFT sets a target: $\delta\kappa_f \sim Y_1 \frac{v^2}{\Lambda^2} \sim O(\text{a few\%})$

- HEFT could be nearly: $\delta\kappa_f \sim Y_1 \frac{H}{v} \sim O(1)$

- Many well-motivated models lead to characteristic signatures to look for:
  flavor violating decays, invisible decays,
  more Higgses, neutrino connection …

More work to do & lots of fun!