Higgs Couplings to Fermions

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The good, the bad and the ugly

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the flavor hierarchy, the theory

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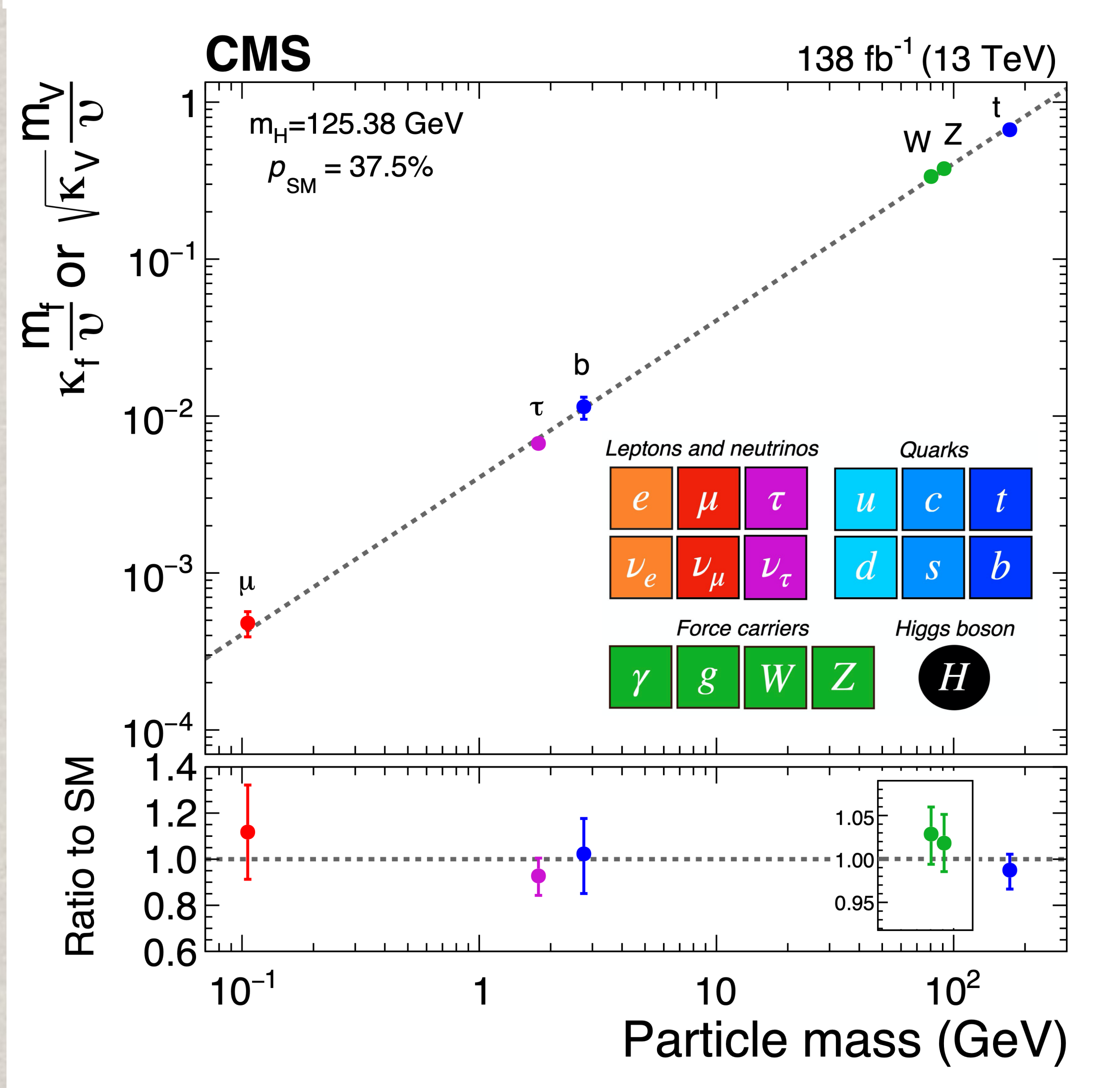
the practice: LHC, ILC & a **μ**C

y_t, y_c, y_μ and even y_e

(A). 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

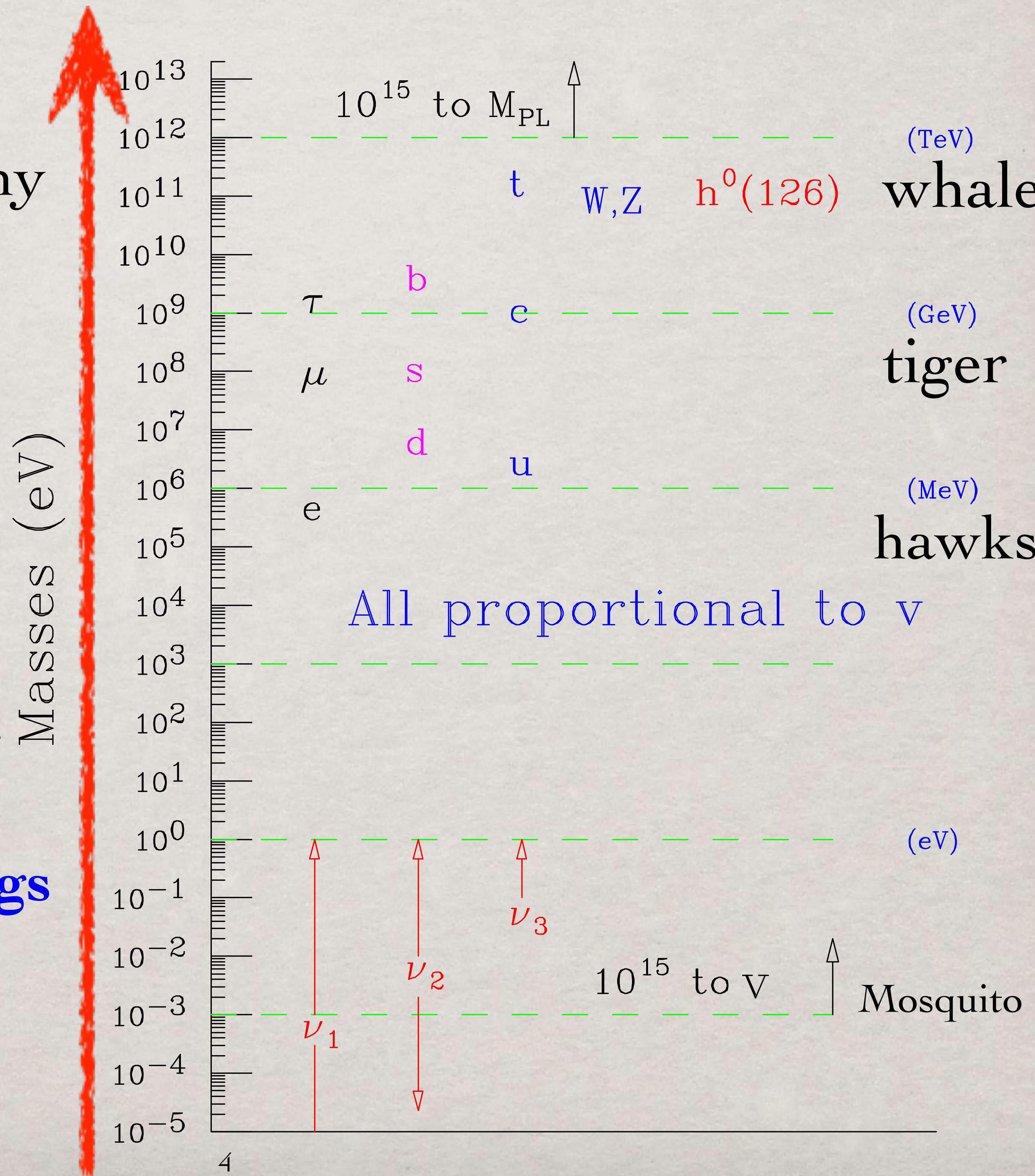
$$W = \int_{k<\Lambda} [\mathcal{D}g \ldots] \exp\left\{\frac{i}{\hbar}\int d^4x\sqrt{-g}\left[\frac{1}{16\pi G}R - \frac{1}{4}F^2 + \bar{\psi}i\not{D}\psi - \lambda\phi\bar{\psi}\psi + |D\phi|^2 - V(\phi)\right]\right\}$$

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

The Higgs Blemishes

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

Higgs Yukawa couplings as the pivot for all !



Three Types of Masses in SM

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

The good, the bad, and the ugly

(1). $M_{W,Z}$: the good! In the SM: $\phi = \frac{1}{\sqrt{2}} e^{i \sum \xi^i L^i} \begin{pmatrix} 0 \\ \nu + H \end{pmatrix}$

$V(|\Phi|) = -\mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$ $\quad <|\Phi|> = v = (\sqrt{2} G_F)^{-1/2} \approx 246\ \mathrm{GeV}$

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

→ M_W, $M_Z = g\, v/2$ predicted, and:

$$\delta m_w^2 \sim m_w^2 \ln(\Lambda / m_w)$$

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

- Fundamental scalars (SUSY)
- Dynamical breaking (TC, composite …) $\quad \langle \bar{q}_L q_R + \bar{q}_R q_L \rangle \sim v^3$
- Non-linear realization (or even "Higgsless")

$$\Phi = \frac{1}{\sqrt{2}} (v + H) U \,, \qquad U = \exp[i \pi^a \tau^a / v]$$

- **All calculable and predictable → e.g. CDF M_W**

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

(2). m_H: the bad! $m_H = \sqrt{2}\,\mu = (2\lambda)^{1/2}\, v = 125$ GeV

In the SM, all fixed: → $\lambda \approx 0.13$; $\frac{1}{2} m_H^2\ H^2 + \frac{m_H^2}{2v}\ H^3 + \frac{m_H^2}{8v^2}\ H^4$

The value itself doesn't matter much ~ EW scale

→ Not too light (vacuum stable), not too heavy (unitarity).

But quantum corrections: $\delta\mu^2 = -\frac{3y_t^2}{8\pi^2}\Lambda^2$ $(M^2_{PL} \ldots)$

Quadratically sensitive to the new physics cutoff scale.

→ "Naturalness" or "Large hierarchy problem" ?

BSM: **easy to construct** a scalar model / potential, but model-parameters quadratically sensitive to a new physics scale: $\delta m_H^2 \propto -\frac{k^2}{4\pi^2}\Lambda^2$ $(M^2_{SUSY},\ M^2_{comp},\ \ldots)$

Not seeing other states nearby, we do not understand m_H

→ "Little hierarchy problem" !

⚠ Note: the quadratic mass corrections are NOT experimentally observable!

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

(3). mf: not governed by the gauge couplings

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

😇

- Couplings are fixed by the masses:

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

- Technically "natural" against quantum corrections:

$$\delta m_f \sim m_f \ln(\Lambda/m_w) \quad \text{(chiral symm)}$$

⚠ **Higgs is responsible for our existence!**

- Atoms/chemistry/biology governed by $Y_e \sim m_e$:

- Yt / m_t : not too large for vacuum stability!

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

(3). mf: the ugly!

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

BSM: **much harder** to accommodate!

- Generate multiple mass scales
- Avoid FCNC
- Avoid Excessive CP violation

- Why the flavor mixing aligned with the SM Yukawa form?
  → Minimal Flavor Violation (MFV)

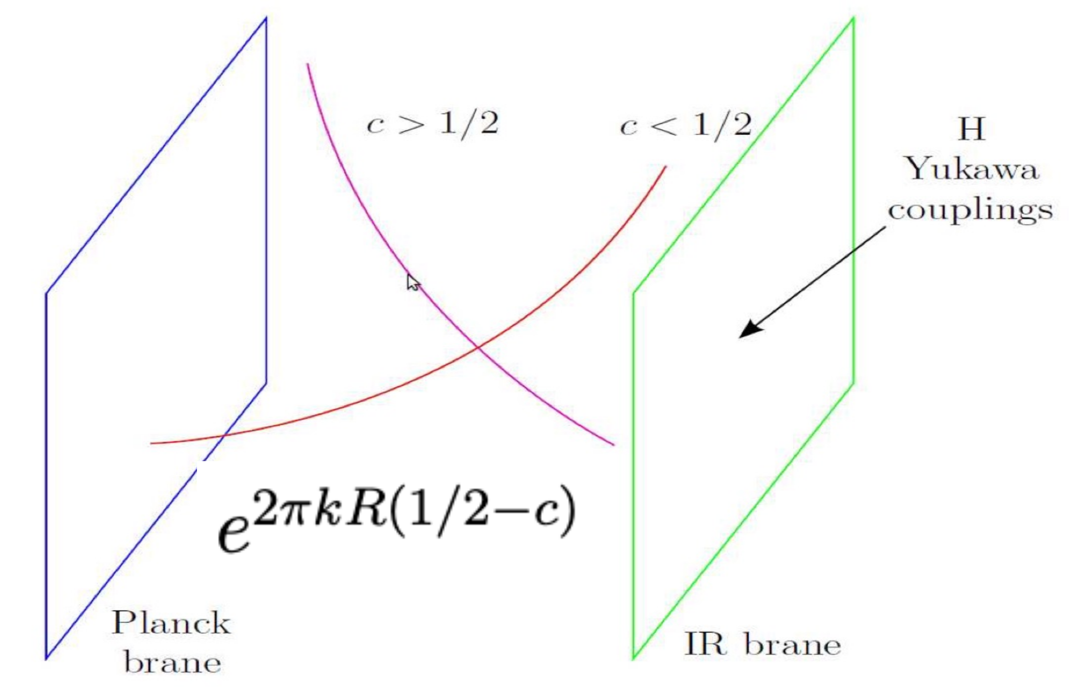
(B). Yukawa Couplings:
(1). Generate flavor hierarchies

- Horizontal flavor symmetry: Froggatt-Nielson mechanism
SM fermions charged [q_i, u_i, d_i] under $U(1)_{FN}$ symmetry
broken by <ϕ>/M ~ 0.2 Froggatt & Nielsen (1979)

$$(Y_u)_{ij} \sim \left(\frac{\langle\phi\rangle}{M}\right)^{[q_i]-[u_j]}, \qquad (Y_d)_{ij} \sim \left(\frac{\langle\phi\rangle}{M}\right)^{[q_i]-[d_j]}$$

- Warped extra-dimension:
Yukawa couplings determined by the overlapping with the Higgs brane.
→ dual to (partial) composite model.

Randall & Sundrun (1999); Huber & Shafi (2001); Agashe et al. (2005)



- Radiative generation of m_f:
The 3rd generation @ tree-level
Light generations by new particle loops ~ $1/16\pi^2$ ~ 10^{-2}.

S. Weinberg (1972)

(2). The Higgs sector extension

- **2HDM (MSSM):** well-motivated ($\tan\beta = v_2/v_1$; α the neutral Higgs mixing)

Talks in HPNP2023:
Pilaftsis; Haber; Takeuchi; Yagyu; Ferreira; De Curtis; Song; Dey; Kartayama; Heinemeyer; Muta; Ivanov; Sakurai … …

	Tree-level Normalized Higgs couplings			
	κ_h^u	κ_h^d	κ_h^e	κ_h^V
Type-I	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$\sin(\beta-\alpha)$
Type-II	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$\sin(\beta-\alpha)$
Type-L	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$\sin(\beta-\alpha)$
Type-F	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$\sin(\beta-\alpha)$

Decoupling/
Alignment limit:
κ's → 1

H. Haber & Y. Nir (1990)

- **Plus a singlet S (NMSSM):** more mixing & flavor physics, connect to dark sector

- **Add a triplet $\boldsymbol{\Phi}$ (Type-II seesaw):** $\boldsymbol{\phi}^{\pm\pm}$, $\boldsymbol{\phi}^{\pm}$, $\boldsymbol{\phi}^{0}$; connect to neutrino Majorana mass

For a review, see, i.e., G.C. Branco, M. Sher et al., arXiv:1106.0034 …

(3). SMEFT

SM Effective Field Theory: a linear representation

SM-like Higgs $\boldsymbol{\Phi} = \frac{1}{\sqrt{2}}\begin{pmatrix} \sqrt{2}\phi^+ \\ v + h + i\phi^0 \end{pmatrix}$

$$\mathcal{L}_Y \sim \sum_{n=0} \frac{Y_{ij}^n}{\Lambda^{2n}} (\Phi^\dagger \Phi)^n \bar{L}_{iL} \Phi e_{jR} \ \rightarrow \ m_f = \frac{v}{\sqrt{2}} \sum_{n=0} Y_n^f \frac{v^{2n}}{\Lambda^{2n}}$$

Yukawa coupling deviates from the mass relation!

At the dim-6 leading order:

$\rightarrow \delta\kappa_f \sim Y_1 \frac{v^2}{\Lambda^2} \sim O(\text{a few}\%)$ for $\Lambda \sim 2$ TeV!

This is the immediate target @ LHC!

(4). HEFT

Higgs Effective Field Theory: a non-linear representation

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

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

$$Y_f(H) = \frac{\sqrt{2} m_f}{v} + \sum_{n=1} y_{fn} (\frac{H}{v})^n$$

- The scale for new dynamics is at $\Lambda \sim 4\pi$ v → close by! The deviation can be sizable:

$$\rightarrow \delta\kappa_f \sim Y_1 \frac{H}{v} \sim O(1)$$

- Multiple Higgs couplings may be sizeable!

(C). Higgs Couplings @ Colliders
theories in practice

- Seek for more Higgs bosons: $H^0,\ A^0,\ H^\pm$
- Continue to search for
  Z', *W*$^\pm$*'*, *T'* in light of FN, L-R, composite H, etc.
- Flavor Changing Neutral Currents:
  H → tc, tq; & **μτ** , e**μ**, e**τ** !

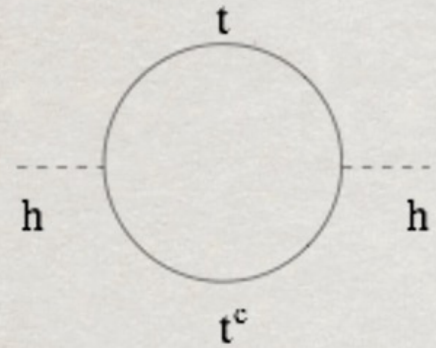
& possible new CPv phases in Yukawa …

Cheng & Sher, PRD (1987); G.W.S. Hou, PLB (1992);
TH, D. Marfatia, PRL 86, 1442 (2001); Harnik, Kopp, Zupan, arXiv:1209.1397.

In the absence of the new physics discovery:

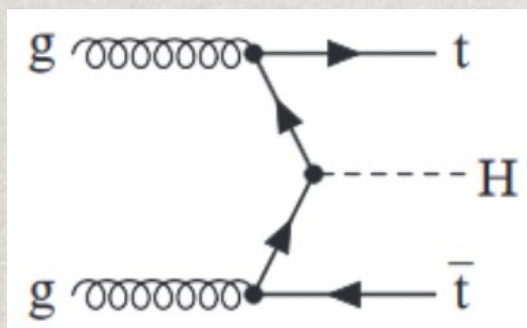
- Exploring flavor physics is complementary & rewarding.
- Measuring Higgs Yukawa couplings is indispensable:
  the smaller the coupling is, the more sensitive to deviations!

(1). The most-wanted: y_t



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

The current LHC sensitivity:



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

(ICHEP 2022)

Also, see Sanmay Ganguly & Xiaohu Sun

Future lepton collider sensitivity:

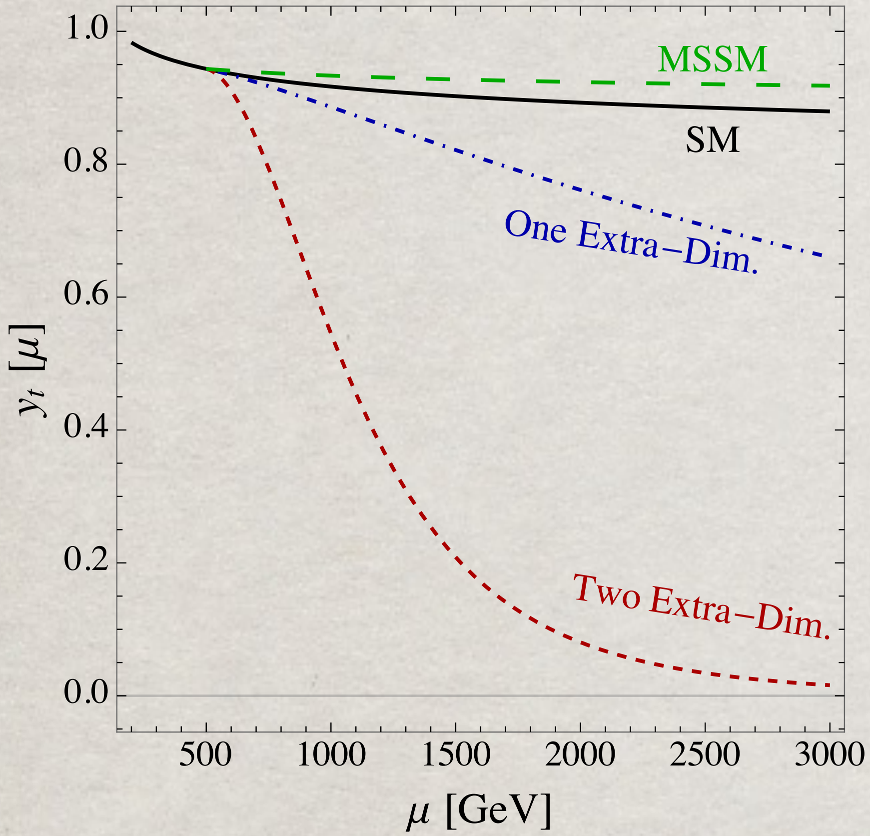
Values in % units		LHC	HL-LHC	ILC500	ILC550	ILC1000	CLIC
δy_t	Global fit	6.12	2.53	2.08	1.30	0.739	1.48
	Indiv. fit	5.08	1.85	1.80	1.17	0.705	1.26

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.

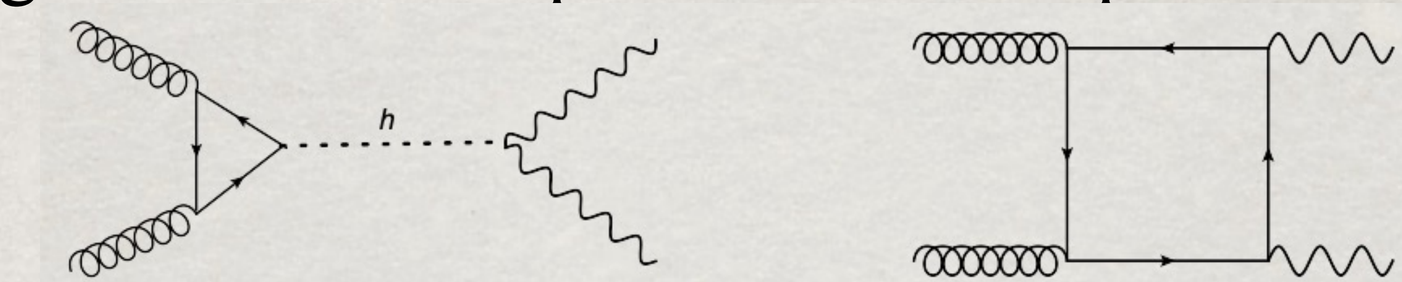
EF04 report: https://arxiv.org/pdf/2209.08078.pdf

ttH coupling @ high scales:

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



2. Off-shell probe of EFT operators:



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

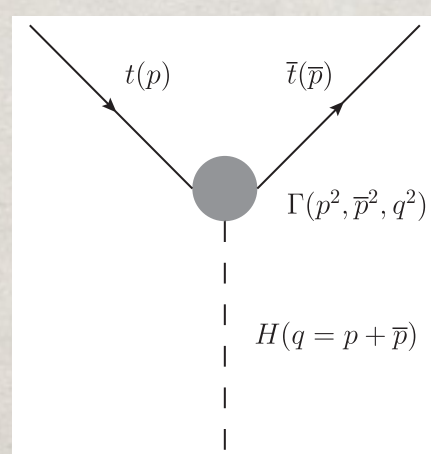
CMS/ATLAS: arXiv:2202.06923; 2304.01532

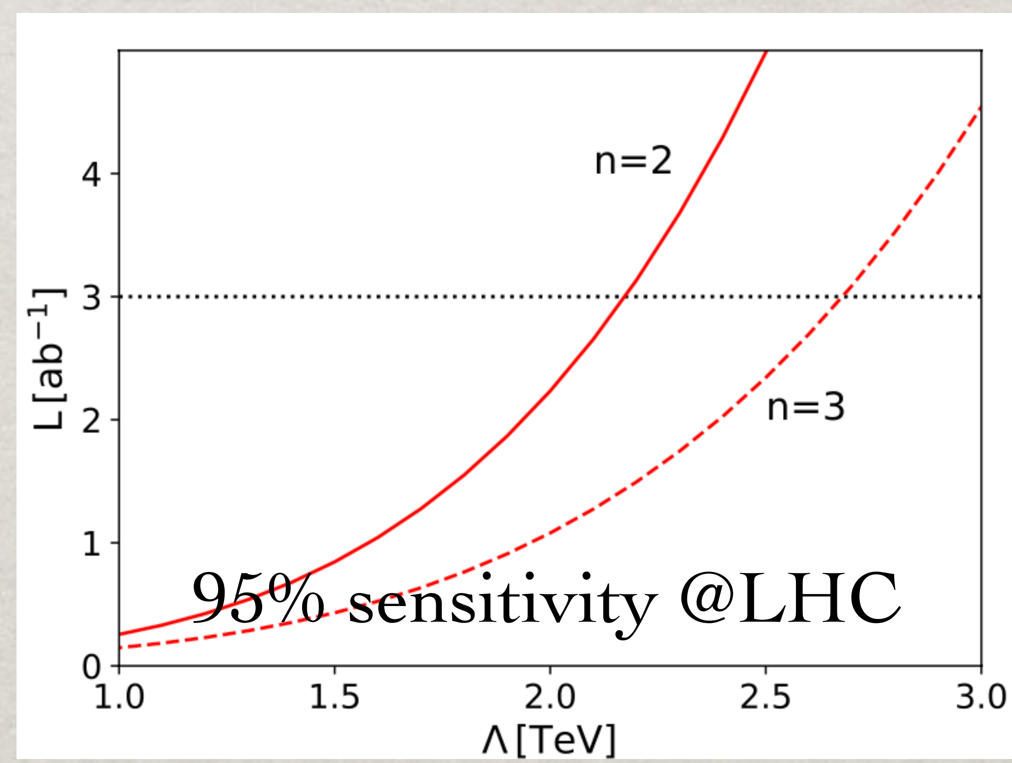
- $3.6\sigma/3.3\sigma$ observation for off-shell Higgs signal
- SM width bound: $3.2^{+2.4}_{-1.7}$ / $4.5^{+3.3}_{-2.5}$ MeV

(See Sanmay Ganguly & Xiaohu Sun)

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.

(2). The real challenge: y_c

Test the 2nd generation couplings:

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

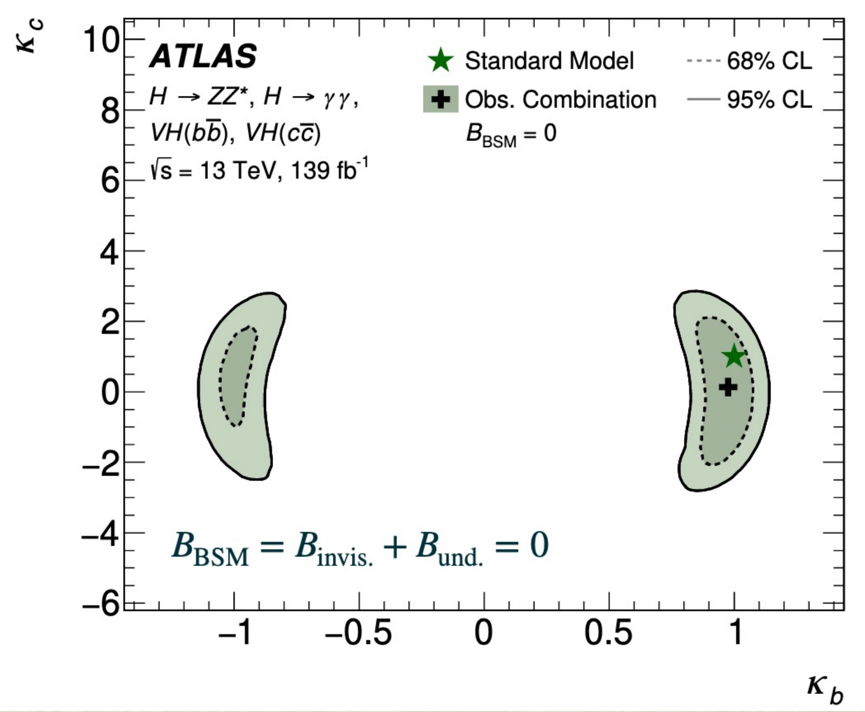
LHC Run 2: ATLAS $\kappa_c \leq 8.5$ [2201.11428], CMS $1.1 < |\kappa_c| < 5.5$ [2205.05550]

(See Sanmay Ganguly & Xiaohu Sun)

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
$B_{BSM} = 0$	[−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

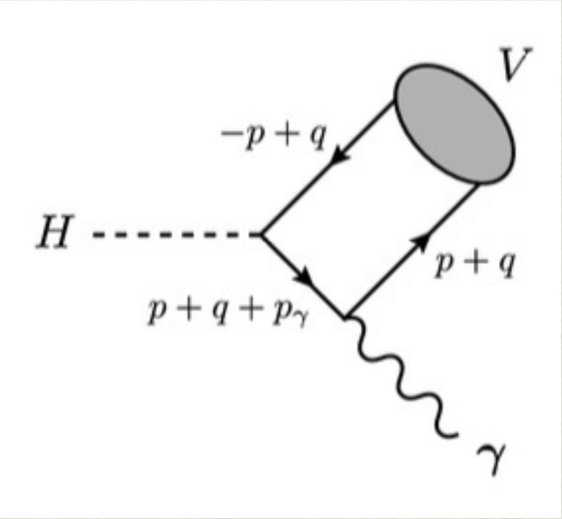
Future HL-LHC: $\kappa_c \leq 3.$ [2201.11428]

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

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

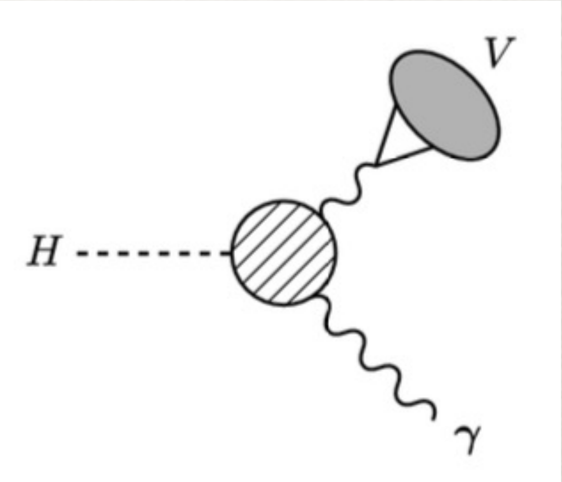
- H → J/ψ + γ
  → $\mu^+ \mu^-$ + γ

for Higgs coupling to charm



Note: BR(H → J/ψ+γ) = 2.8x10^{-6}

- Dominated by VMD γ^*→J/ψ, not H cc coupling.



→ This is no use to probe y_c !

Bodwin, Petriello et al. (2013, 2014, 2017); Konig, Neubert (2015)

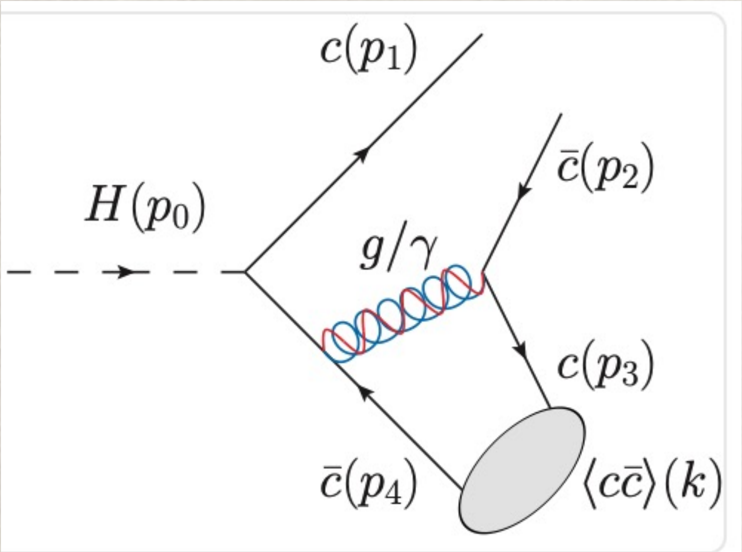
Higgs production rate is high: #H@LHC ~ 50 M /ab !
A new idea!

- H → J/ψ via charm-quark fragmentation:

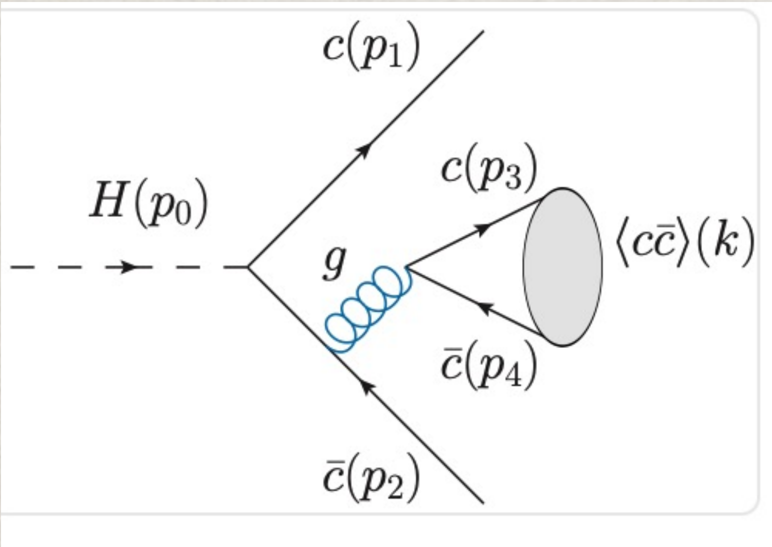
$$H \to c + \bar{c} + J/\psi \,(\text{or}\, \eta_c)$$

- ➢ Enhanced from the fragmentation
- ➢ Direct coupling to charm!

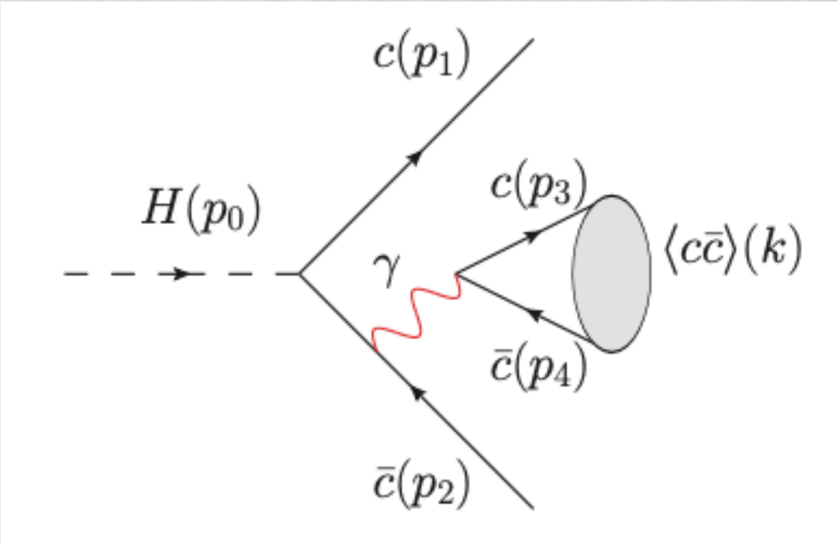
Color-singlet (CS)
(leading)



Color-octet (CO)
(sub-leading, ½ of CS)



QED
(sub-leading, ¼ of CS)



TH, A. Leibovich, Y. Ma, X.Z. Tan: aXive:2202.08273

- $H \rightarrow J/\psi$ via charm-quark fragmentation:

$$H \to c + \bar{c} + J/\psi \,(\text{or}\, \eta_c)$$

TH, A. Leibovich, Y. Ma, X.Z. Tan: aXive:2202.08273

$$\Gamma = \sum_{\mathbb{N}} \hat{\Gamma}_{\mathbb{N}}(H \to (Q\bar{Q})[\mathbb{N}] + X) \times \langle \mathcal{O}^h[\mathbb{N}] \rangle,$$

$$d\hat{\Gamma}_{\mathbb{N}} = \frac{1}{2m_H} \frac{|\mathcal{M}|^2}{\langle \mathcal{O}^{Q\bar{Q}} \rangle} d\Phi_3$$

Calculating the short-distance decay rates,
fit the long-distance hadronic matrix elements,
we obtain:

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

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

- Sensitivity $S \simeq N_{\text{signal}}/\sqrt{N_{\text{Background}}}$
  $\Rightarrow$ It is possible to reach 2σ for $\kappa_c \approx 2.4$.

→ At the end, should be better than $J/\psi + \gamma$: $\kappa_c \sim 50$

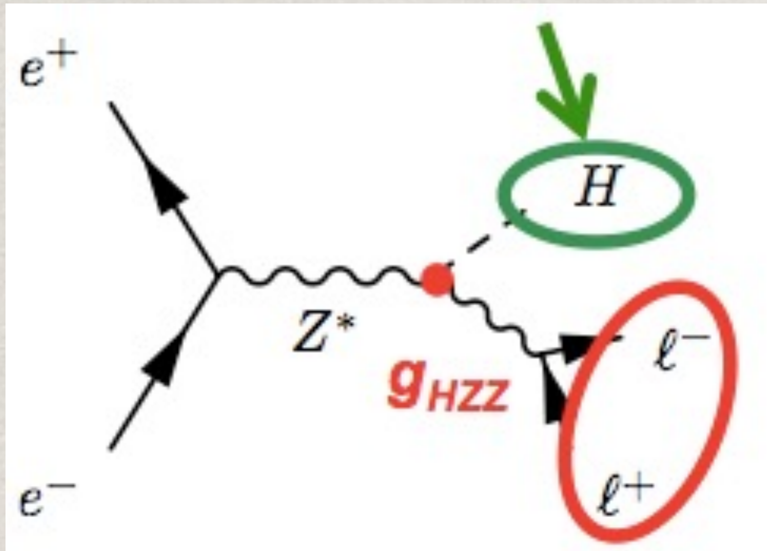
→ May not beat W/Z+H → W/Z+cc : $\kappa_c \sim 3$

Active study/simulation on-going!

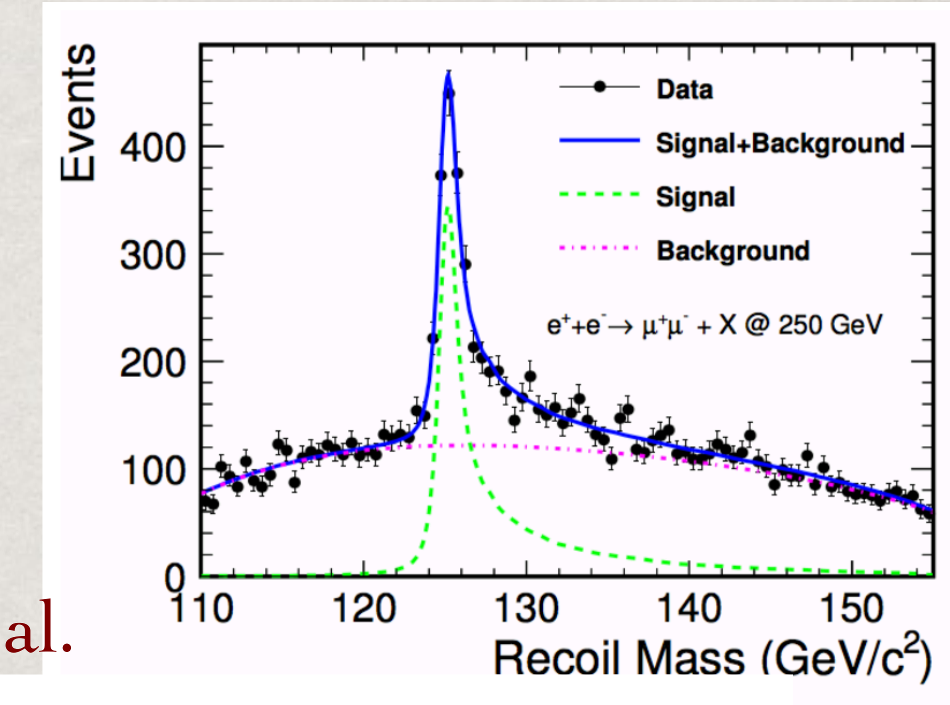
ILC as the Higgs factory

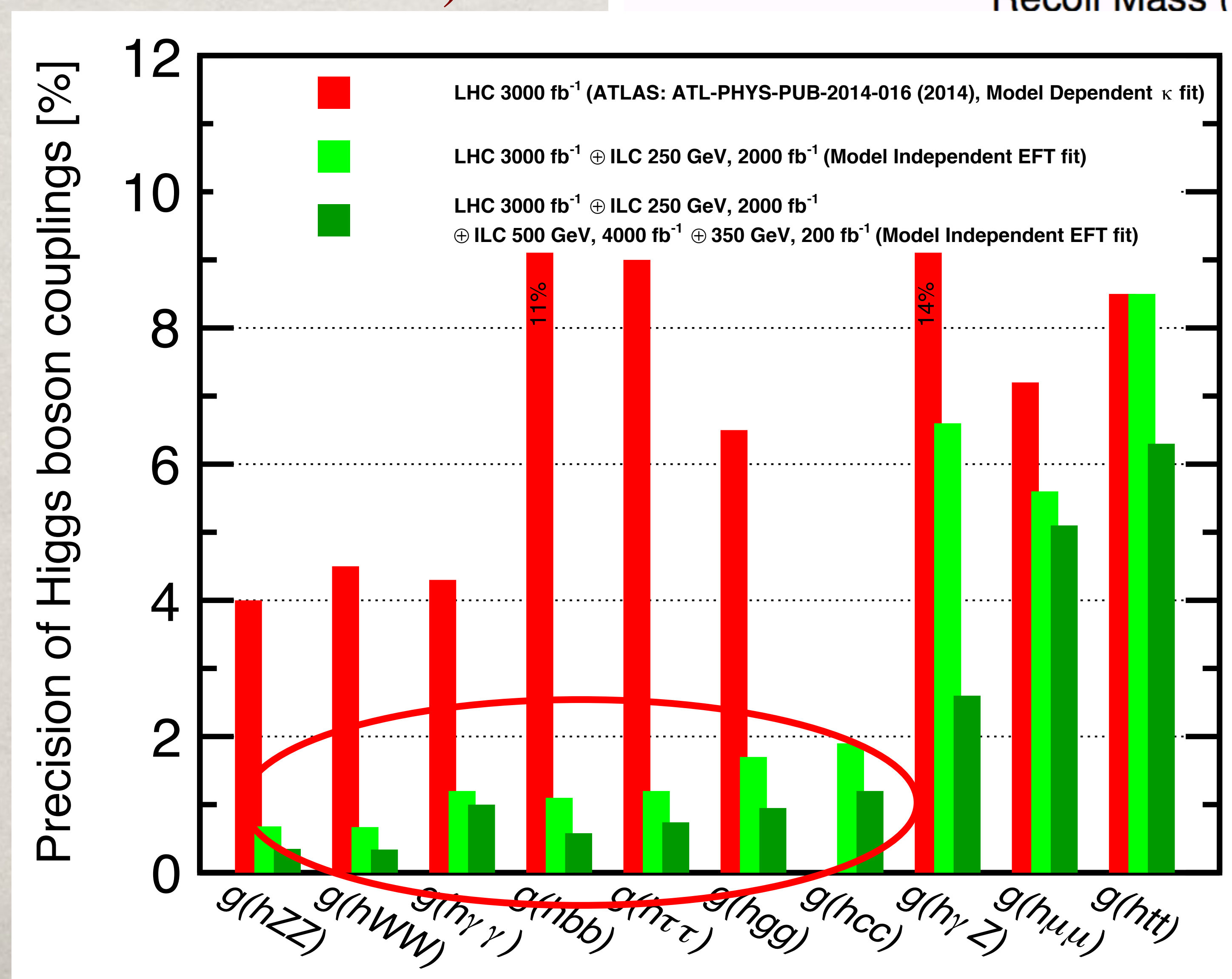
$$m_h^2 = (p_{e+}^2 + p_{e-}^2 - p_{\ell+}^2 - p_{\ell-}^2)^2$$

See Junping Tian's talk



arXiv:1710.07621, LCC, Fujii et al.





(3). A promising channel: y_μ

The 2nd generation Y_μ: The next hope!

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

Current search result:
ATLAS: 2.0σ;   CMS 3.0σ

HL-LHC sensitivity projection: BR($H \to \mu\mu$) < 10%

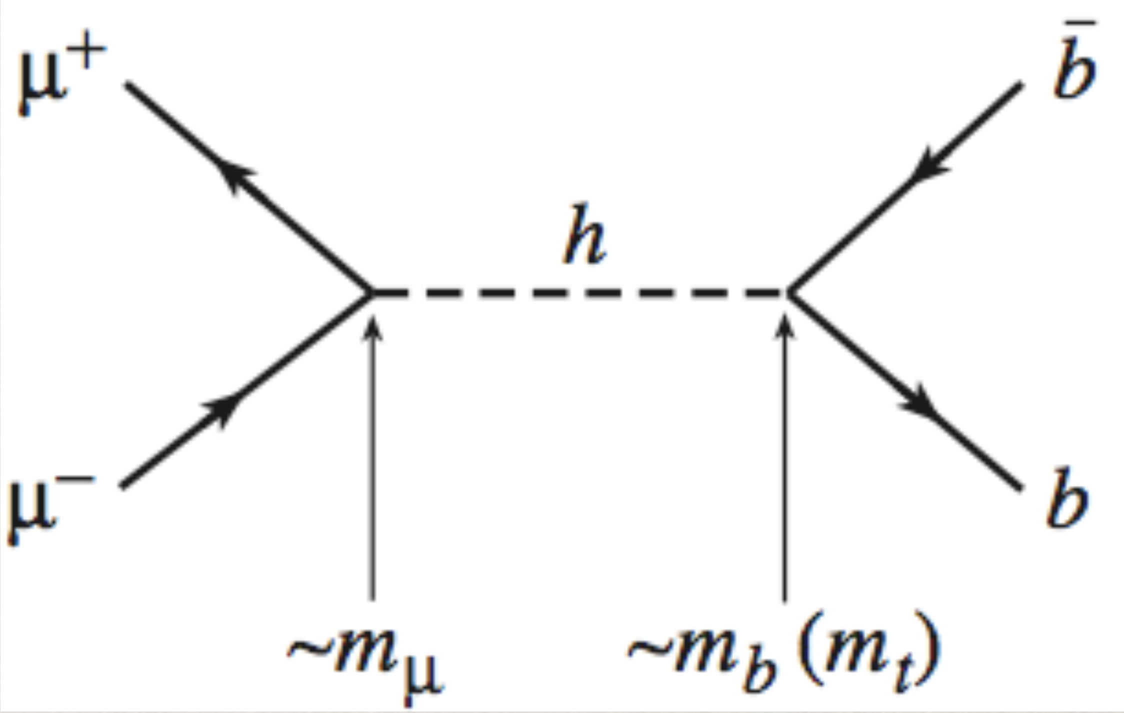
- Assuming the SM width,
  but won't know it better than a factor of 2-ish
- ILC may not improve this much (low rate)

Plehn & Rainwater, arXiv:hep-ph/0107180;
TH & McElrath, arXiv:hep-ph/0201023

(4). Model-independent measurement on y_μ

A muon collider Higgs factory:

Resonant Production:



$$\sigma(\mu^+\mu^- \to h \to X) = \frac{4\pi\Gamma_h^2 \mathrm{Br}(h \to \mu^+\mu^-)\mathrm{Br}(h \to X)}{(\hat{s} - m_h^2)^2 + \Gamma_h^2 m_h^2}.$$

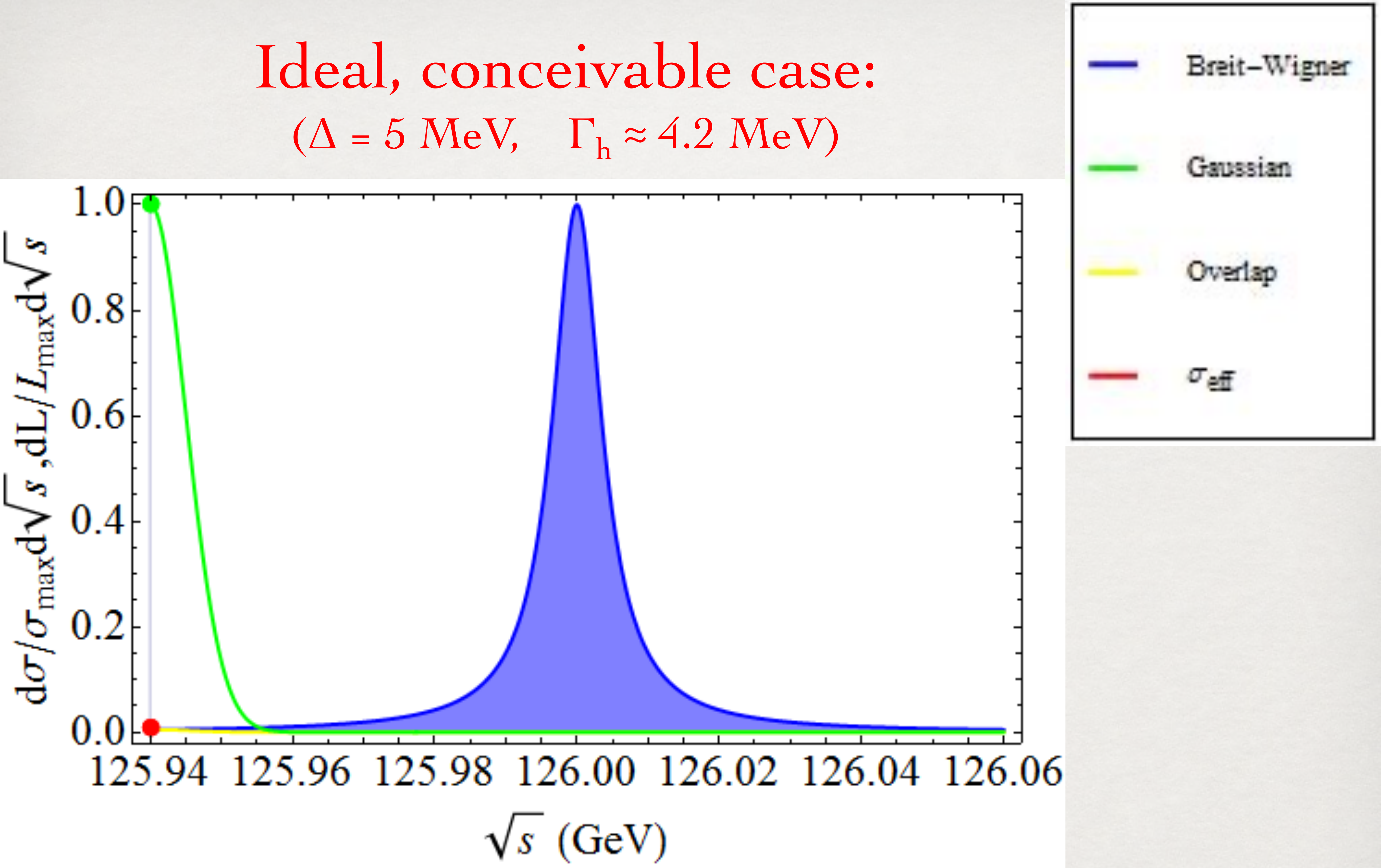
$$\begin{aligned} \sigma_{peak}(\mu^+\mu^- \to h) &= \frac{4\pi}{m_h^2} BR(h \to \mu^+\mu^-) \\ &\approx 71 \text{ pb at } m_h = 125 \text{ GeV}. \end{aligned}$$

About O(70k) events produced per fb^{-1}

Requirement: $E_{cm} = m_H$, $\Delta E_{cm} \sim 5$ MeV, $L \sim 1\ \mathrm{fb}^{-1}/\mathrm{yr}$.

Ideal, conceivable case:

(Δ = 5 MeV, $\Gamma_h \approx$ 4.2 MeV)



An optimal fitting could reach $\delta\Gamma_h$ ~ 0.15 MeV, or 3.5%

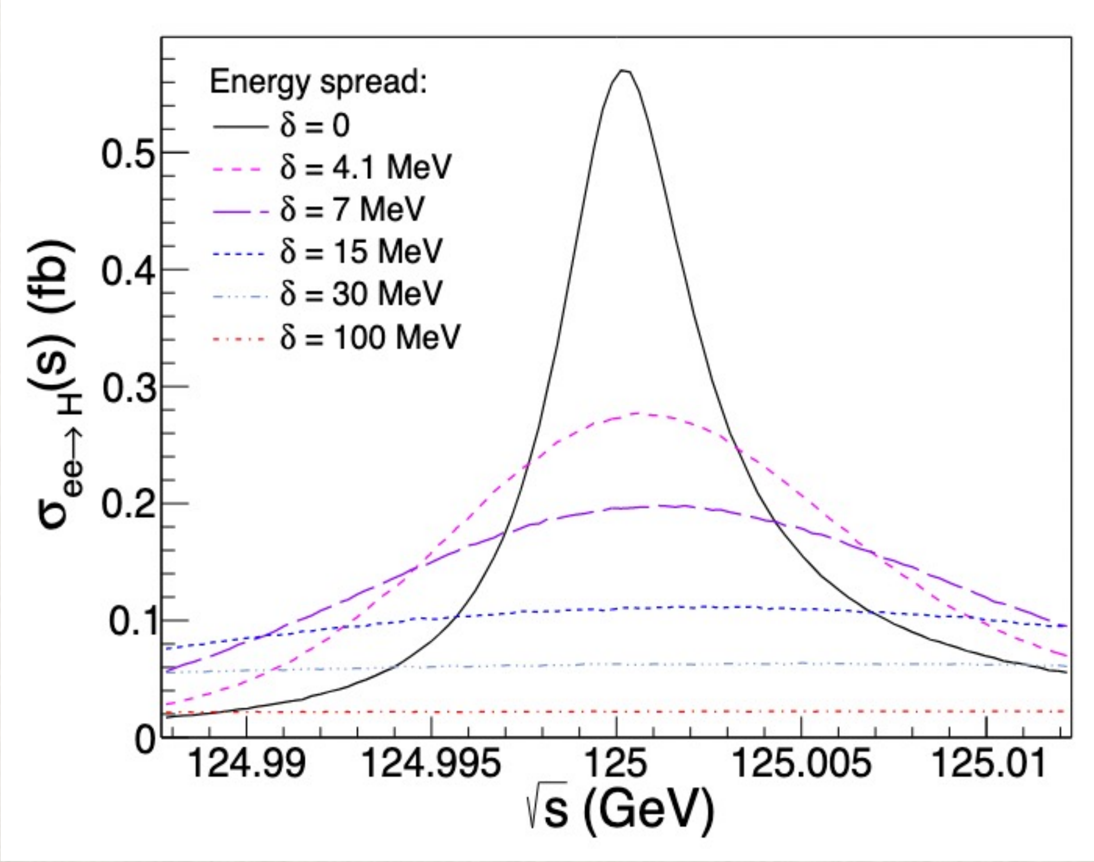
TH, Liu: 1210.7803; Greco, TH, Liu: 1607.03210

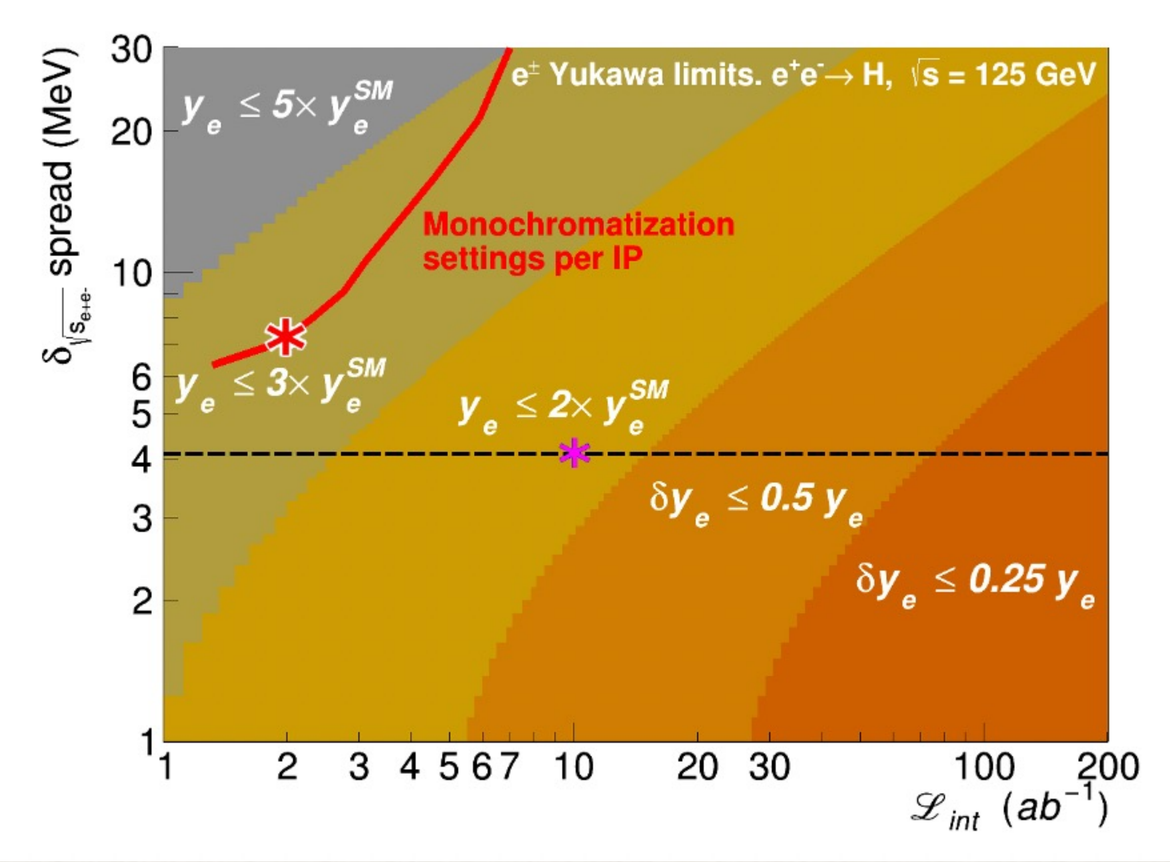
(5). The ultimate test : y_e

The 1st generation y_e: There is a chance!

$y_e = \sqrt{2} m_e / v = 2.9 \times 10^{-6}$ SM $BR(H \to ee) \sim 5 \cdot 10^{-9}$

$e^+e^- \to H$



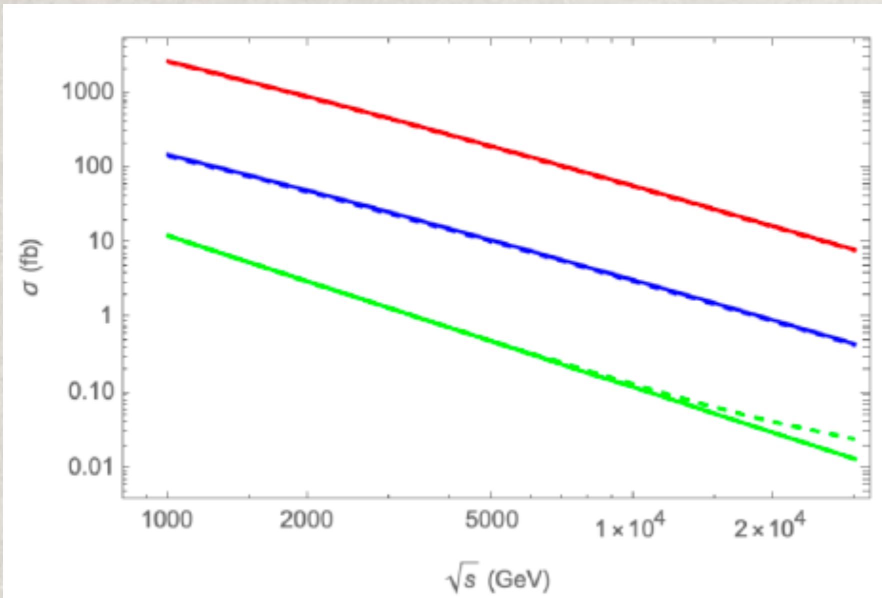


M. Greco, TH, Z. Liu: https://arxiv.org/abs/1607.03210

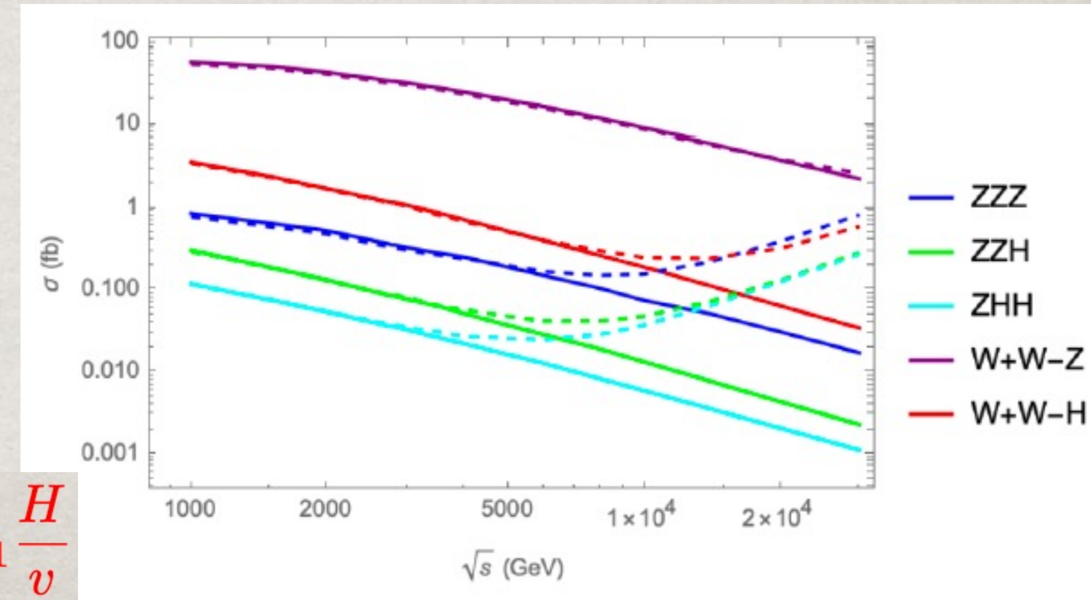
Accel. Frontier report: https://arxiv.org/pdf/2203.06520.pdf

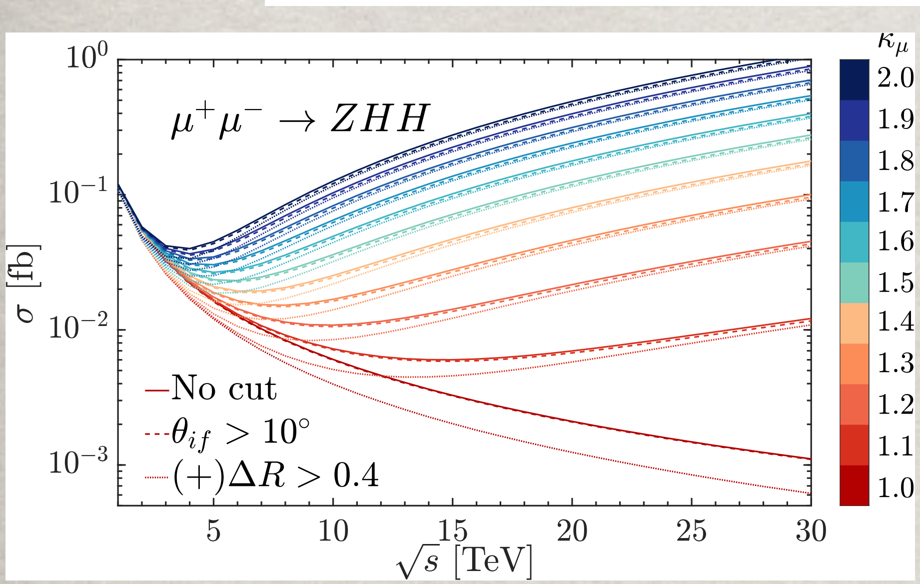
(6). High-energy option on y_μ

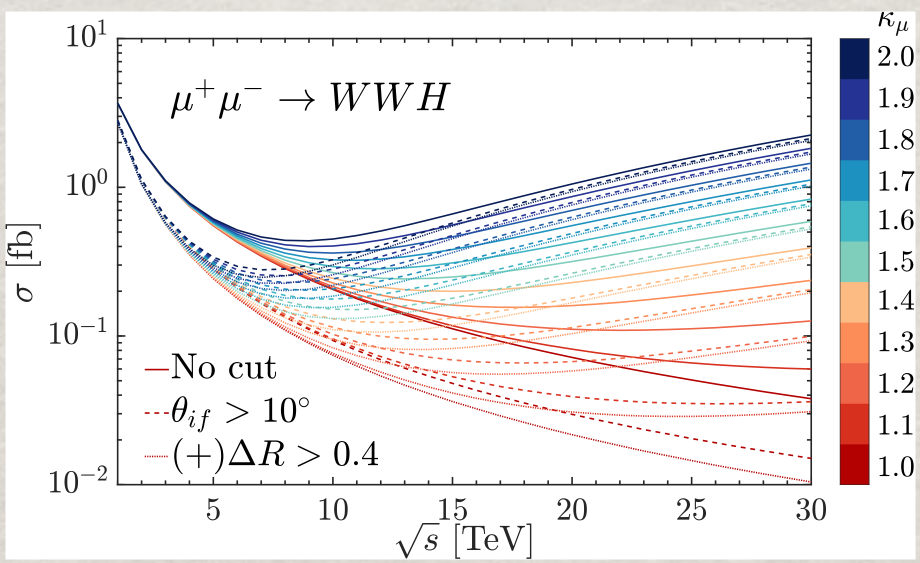
To enhance the Yukawa coupling effects,
multiple Higgs/Goldstone boson production more beneficial.

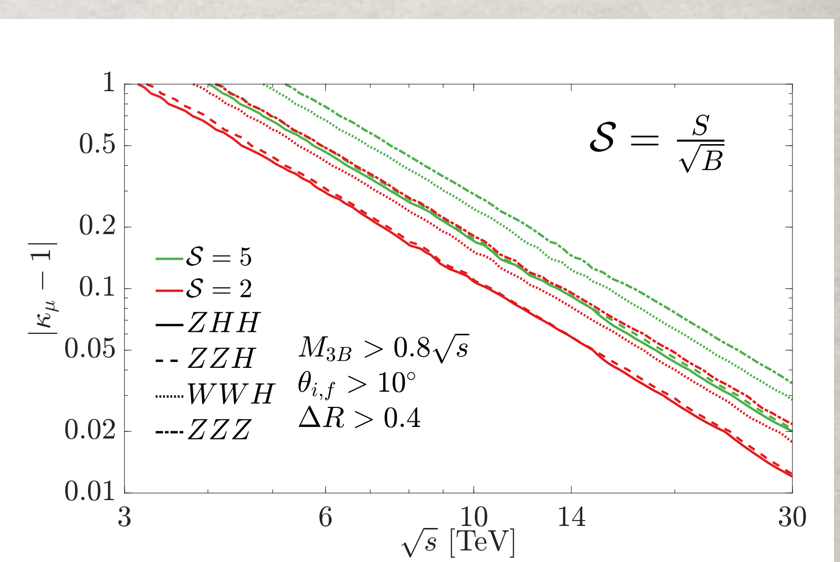


$$\delta\kappa_f \sim Y_1 \frac{H}{v}$$









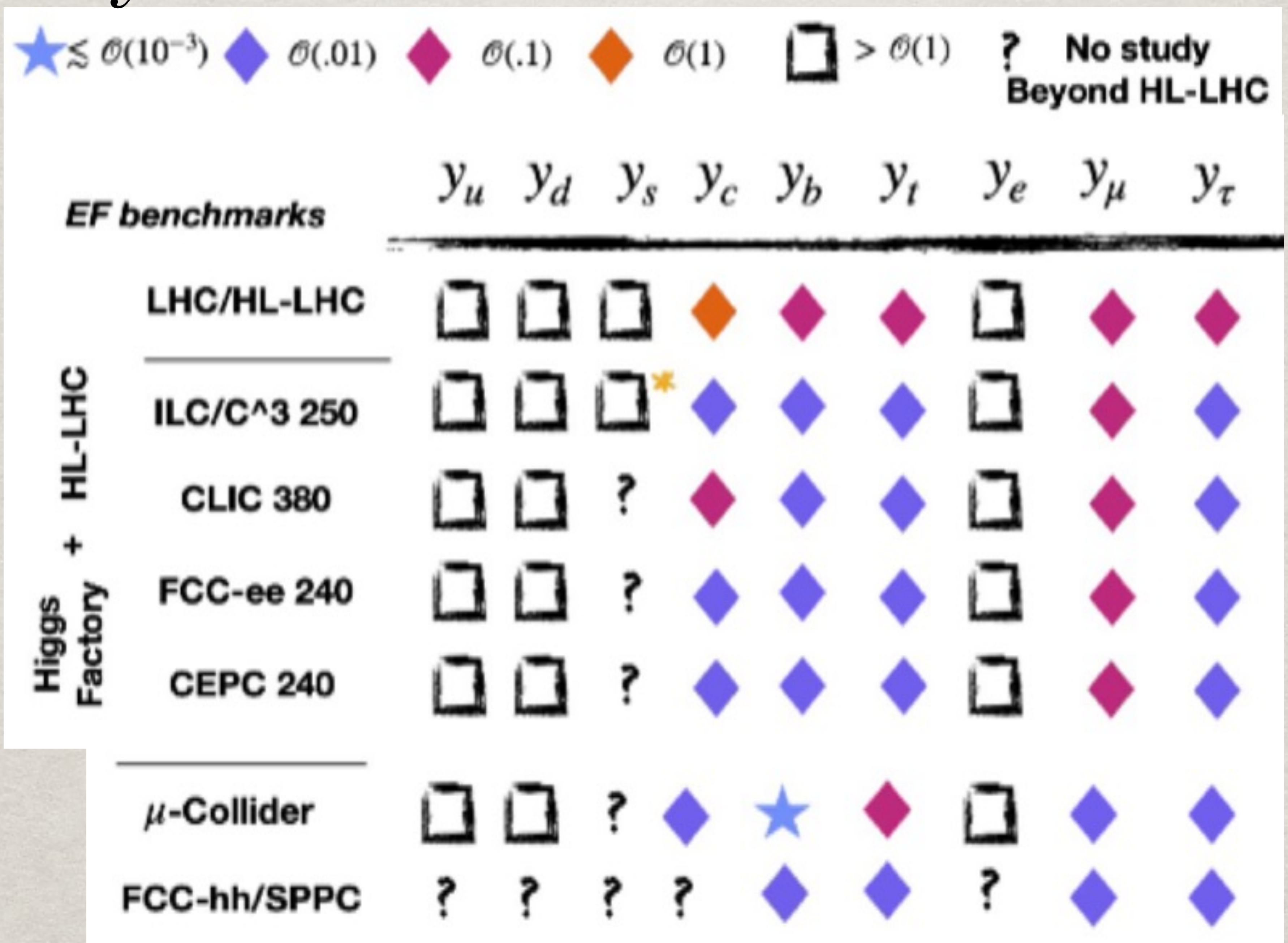
At 30 TeV: $\delta\kappa_\mu \sim$ 1% - 4%, corresponding to $\Lambda \sim$ 30 TeV – 100 TeV.

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.

Sensitivities to Yukawa couplings at future colliders

Achieving percentage/sub-percentage level!

Symbols of sensitivities:



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

Conclusions:

- Higgs couplings to fermions most mysterious:
  least understood in theory, but rich phenomenology!
- Continue to search for more Higgses, Z', T' …
- Must look for rare Higgs decays:
  flavor changing, invisible channels …
- Measuring Higgs Yukawa couplings: indispensable
- SMEFT sets a target: $\delta\kappa_f \sim Y_1 \frac{v^2}{\Lambda^2} \sim O(\text{a few}\%)$
- HEFT could be close by: $\delta\kappa_f \sim Y_1 \frac{H}{v} \sim O(1)$
- Immediate targets on Yukawa couplings:
  ttH@high scale; 2nd generations $H\mu\mu$ & Hcc !

Push for the next discovery for NP from HP!