Flavour Violating Higgs Yukawa Couplings

in

Minimal Flavour Violation

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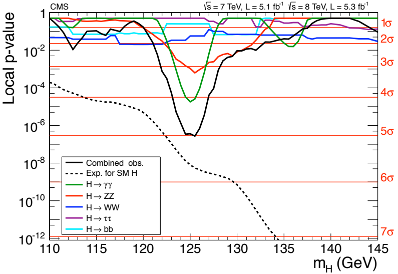
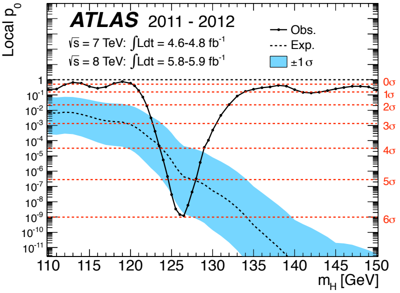
based on JHEP02(2019)007, in collaboration with Min He, Xiao-Gang He, XY, Jin-Jun Zhang

Higgs Discovery





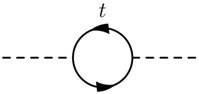
LHC Run I

- mass: $m_h \approx 125\,\mathrm{GeV}$ ☺
- spin ☺
- parity ☺
- Yukawa coupling ☺
- gauge coupling ☺
- self coupling ?

LHC Run II/HL/CEPC/ILC

Higgs After the Discovery

Hierarchy Problem

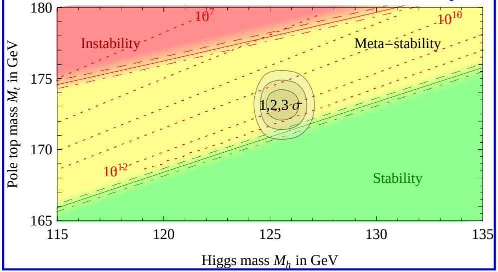


$$+ \ldots = \frac{c}{16\pi^2}\Lambda^2$$

fine-tuning

$$m_{h,0}^2 + \frac{c}{16\pi^2}\Lambda^2 = 125\,\mathrm{GeV}^2$$

Vacuum Stability

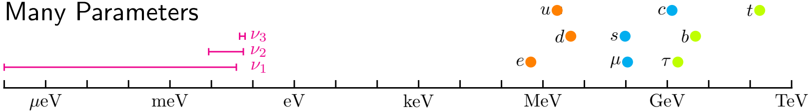


$$\Delta\mathcal{L}_H = +\mu^2\Phi^\dagger\Phi - \lambda\left(\Phi^\dagger\Phi\right)^2 + \left(2m_W^2 W_\mu^+ W^{-\mu} + m_Z^2 Z_\mu Z^\mu\right)\frac{h}{v} - m_i \bar{f}_i f_i \frac{h}{v}$$

$$+h\cdot X_{\mathrm{NP}} - \frac{1}{\sqrt{2}}\bar{f}_i(\lambda_{ij} + i\gamma_5\bar{\lambda}_{ij})f_j h + \ldots$$

S.Baek, XY, PLB, 2017

Many Parameters



Higgs FCNC: exp

e	μ	τ	
e^+e^-collider	$\mathcal{B} < 0.035\%$	$\mathcal{B} < 0.61\%$	e
	$\mu < 1.7$	$\mathcal{B} < 0.25\%$	μ
		$\mu = 1.09^{+0.27}_{-0.26}$	τ

u	c	t	
		$\mathcal{B} < 0.12\%$	u
	$\mu < 70$	$\mathcal{B} < 0.11\%$	c
		$\mu_{tth} = 1.3^{+0.3}_{-0.3}$	t

d	s	b	
			d
			s
		$\mu = 1.01^{+0.20}_{-0.20}$	b

◀ direct search

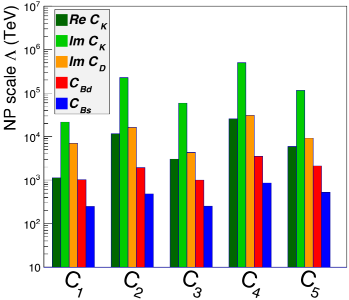
▼ indirect study

McWilliams, Li 1981
Shanker 1982
Barr, Zee 1990
Kanemura, Ota, Tsumura 2006
Davidson, Grenier 2010
Golowich et al 2011
Buras, Girrbach 2012
Blankenburg, Ellis, Isidori 2012
Harnik, Kopp, Zupan 2013
Gorbahn, Haisch 2014
Celis, Cirigliano, Passemar 2014
Chiang, He, Ye, XY 2017
... ...

Flavor Problem $\Longrightarrow$ MFV

NP Flavor Problem and Minimal Flavor Violation

- bound from FCNC $\Longrightarrow \Lambda_{\mathrm{NP}} > \mathcal{O}(10^{2-5})\,\mathrm{TeV}$ UTfit 2018, Silvestrini, Valli 2018



$$\mathcal{L}_{\mathrm{full}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i^{d=6} + \ldots$$

$$\mathcal{O}_1 = \bar{Q}_L \gamma_\mu Q_L \bar{Q}_L \gamma^\mu Q_L$$

$\Lambda_{\mathrm{NP}} > 200\,\mathrm{TeV}$ from $B_s - \bar{B}_s$ mixing

NP flavor problem

- naturalness of the Higgs mass $\Longrightarrow \Lambda_{\mathrm{NP}} = \mathcal{O}(1)\,\mathrm{TeV}$
- An interesting solution to the NP flavor problem is the hypothesis of Minimal Flavor Violation: Yukawa couplings are the unique sources of flavour symmetry breaking beyond the SM.

Higgs FCNC in EFT

- Effective Field Theory — e.g., Yi Liao's talk

$$\mathcal{L}_{\rm full} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i^{d=6} + \dots$$

- Dim-4 operator in the SM

$$(\bar{Q}_L H Y_d d_R), \quad (\bar{Q}_L \tilde{H} Y_u u_R), \quad (\bar{Q}_L H Y_e e_R),$$

- Dim-6 operator in the EFT (Warsaw) — Grzadkowski, Iskrzynski, Misiak, Rosiek, 2010

$$\begin{aligned}
\mathcal{O}_{dH} &= (H^\dagger H)(\bar{Q}_L H C_{dH} d_R),\\
\mathcal{O}_{uH} &= (H^\dagger H)(\bar{Q}_L \tilde{H} C_{uH} u_R),\\
\mathcal{O}_{eH} &= (H^\dagger H)(\bar{Q}_L H C_{eH} e_R),
\end{aligned}$$

- Yukawa interaction — Harnik, Kopp, Zupan, 2013

$$\mathcal{L}_Y^f = -\frac{1}{\sqrt{2}}\bar{f}_L \bar{Y}_f f_R v - \frac{1}{\sqrt{2}}\bar{f}_L\left(\bar{Y}_f - \frac{v^2}{\Lambda^2}C_{fH}\right) f_R h + \text{h.c.}. \qquad \bar{Y}_f = Y_f - \frac{1}{2}\frac{v^2}{\Lambda^2}C_{fH},$$

- FCNCs arise in the mass eigenstate

Higgs FCNC in EFT with MFV

- Flavor symmetry without Yukawa — some $U(1)'\mathrm{s}$

$$G_{\mathrm{QF}} = SU(3)_{Q_L} \otimes SU(3)_{u_R} \otimes SU(3)_{d_R}$$

- Flavor symmetry breaking

$$-\mathcal{L}_Y = \bar{Q}_L H Y_d d_R + \bar{Q}_L \tilde{H} Y_u u_R + \mathrm{h.c.}$$

- Flavor symmetry recovering: Yukawa coupling $\Rightarrow$ spurion field

$$Y_u \sim (\mathbf{3}, \bar{\mathbf{3}}, \mathbf{1}) \qquad \text{and} \qquad Y_d \sim (\mathbf{3}, \mathbf{1}, \bar{\mathbf{3}}).$$

- EFT with Minimal Flavor Violation: dim-6 operators, constructed from SM and Yukawa spurion fields, are invariant under CP and G_{QF}.

D'Ambrosio, Giudice, G.Isidori, Strumia, 2009

$$\mathcal{O}_{dH} = (H^\dagger H)(\bar{Q}_L H C_{dH} d_R), \qquad \mathsf{A} \underset{(\mathbf{8}+\mathbf{1},\mathbf{1},\mathbf{1})}{=} Y_u Y_u^\dagger, \quad \mathsf{B} \underset{(\mathbf{8}+\mathbf{1},\mathbf{1},\mathbf{1})}{=} Y_d Y_d^\dagger$$

$$C_{dH} = f_d(\mathsf{A},\mathsf{B}) Y_d \equiv (\xi_0 \mathbb{1} + \xi_1 \mathsf{A} + \xi_2 \mathsf{B} + \xi_3 \mathsf{A}^2 + \xi_4 \mathsf{B}^2 + \xi_5 \mathsf{AB} + \xi_6 \mathsf{BA} + \ldots\ldots) Y_d$$

Higgs FCNC in EFT with MFV

- Higgs FCNC coupling

$$C_{dH} = f_d(\mathsf{A},\mathsf{B})Y_d \equiv (\xi_0 \mathbb{1} + \xi_1 \mathsf{A} + \xi_2 \mathsf{B} + \xi_3 \mathsf{A}^2 + \xi_4 \mathsf{B}^2 + \xi_5 \mathsf{AB} + \xi_6 \mathsf{BA} + \ldots\ldots)Y_d$$

- Cayley-Hamilton identity for 3×3 invertible matrix X

$$X^3 = \mathrm{Det}X \cdot \mathbb{1} + \frac{1}{2}[\mathrm{Tr}X^2 - (\mathrm{Tr}X)^2] \cdot X + \mathrm{Tr}X \cdot X^2$$

G. Colangelo, E. Nikolidakis, C. Smith, 2009
L. Mercolli, C. Smith, 2009

- Higgs FCNC coupling after resummation

$$f_d(\mathsf{A},\mathsf{B}) = \kappa_1 \mathbb{1} + \kappa_2 \mathsf{A} + \kappa_5 \mathsf{B}^2 + \kappa_6 \mathsf{AB} + \kappa_8 \mathsf{ABA} + \kappa_{11} \mathsf{AB}^2 + \kappa_{13} \mathsf{A}^2\mathsf{B}^2 + \kappa_{15} \mathsf{B}^2\mathsf{AB} + \kappa_{16} \mathsf{AB}^2\mathsf{A}^2$$
$$+ \kappa_3 \mathsf{B} + \kappa_4 \mathsf{A}^2 + \kappa_7 \mathsf{BA} + \kappa_{10} \mathsf{BAB} + \kappa_9 \mathsf{BA}^2 + \kappa_{14} \mathsf{B}^2\mathsf{A}^2 + \kappa_{12} \mathsf{ABA}^2 + \kappa_{17} \mathsf{B}^2\mathsf{A}^2\mathsf{B}$$

- Approximation #1: neglect tiny imaginary parts of κ_i
- Approximation #2: $\mathsf{B} \approx 0$ due to highly suppressed down-type Yukawa couplings

$$f_u(\mathsf{A},\mathsf{B}) \approx \epsilon_0^u \mathbb{1} + \epsilon_1^u \mathsf{A} + \epsilon_2^u \mathsf{A}^2 \qquad f_d(\mathsf{A},\mathsf{B}) \approx \epsilon_0^d \mathbb{1} + \epsilon_1^d \mathsf{A} + \epsilon_2^d \mathsf{A}^2 \,.$$

Higgs FCNC in EFT with MFV

- Higgs Yukawa interaction in the interaction eigenstate

$$\mathcal{L}_Y^d = -\frac{1}{\sqrt{2}}\bar{d}_L \bar{Y}_d d_R v - \frac{1}{\sqrt{2}}\bar{d}_L\left(\bar{Y}_d - \frac{v^2}{\Lambda^2}C_{dH}\right)d_R h + \text{h.c.}$$

- Interaction eigenstate $\Longrightarrow$ mass eigenstate

$$\begin{aligned} C_{dH} &= \left[\epsilon_0^d\,\mathbb{1} + \epsilon_1^d Y_u Y_u^\dagger + \epsilon_2^d (Y_u Y_u^\dagger)^2\right] Y_d \\ &= \left[\epsilon_0^d\,\mathbb{1} + \epsilon_1^d \bar{Y}_u \bar{Y}_u^\dagger + \epsilon_2^d (\bar{Y}_u \bar{Y}_u^\dagger)^2\right] \bar{Y}_d + \mathcal{O}(v^2/\Lambda^2)\,. \end{aligned} \qquad \bar{Y}_f = Y_f - \frac{1}{2}\frac{v^2}{\Lambda^2}C_{fH}$$

- Higgs Yukawa interaction in the mass eigenstate $\qquad \hat{\epsilon}_i^d \equiv (v^2/\Lambda^2)\epsilon_i^d$

$$\begin{aligned} \mathcal{L}_Y^d &= -\frac{1}{\sqrt{2}}\bar{d}_L\left[(1-\hat{\epsilon}_0^d)\lambda_d - \hat{\epsilon}_1^d V^\dagger \lambda_u^2 V \lambda_d - \hat{\epsilon}_2^d V^\dagger \lambda_u^4 V \lambda_d\right] d_R h + \text{h.c.} \\ &\approx -\frac{1}{\sqrt{2}}\bar{d}_L\left[(1-\hat{\epsilon}_0^d)\lambda_d - \hat{\epsilon}_1^d V^\dagger \lambda_u^2 V \lambda_d\right] d_R h + \text{h.c.}\,, \end{aligned}$$

- Approximation: $(\hat{\epsilon}_1^d + \lambda_t^2 \hat{\epsilon}_2^d) \to \hat{\epsilon}_1^d$

Higgs FCNC in EFT with MFV

- Lepton MFV depends on the underlying mechanism for neutrino mass

  2005 V. Cirigliano, B. Grinstein, G. Isidori, M. B. Wise
  2006 V. Cirigliano, B. Grinstein
  2009 M. B. Gavela, T. Hambye, D. Hernandez, and P. Hernandez
  2011 R. Alonso, G. Isidori, L. Merlo, L. A. Munoz, and E. Nardi
  ... ...

- Type-I Seesaw $\quad O$: complex orthogonal matrix, $\hat{m}_\nu = \text{diag}(m_1, m_2, m_3)$

$$m_\nu = -\frac{v^2}{2} Y_\nu M_N^{-1} Y_\nu^T = U \hat{m}_\nu U^T, \quad Y_\nu = \frac{i\sqrt{2}}{v} U \hat{m}_\nu^{1/2} O M_N^{1/2}$$

- Lepton MFV in Type-I Seesaw $\quad$ Casas, Ibarra, 2001

$$\mathsf{A}_\ell = \frac{2\mathcal{M}}{v^2} U \hat{m}_\nu^{1/2} O O^\dagger \hat{m}_\nu^{1/2} U^\dagger$$

- Higgs Yukawa interaction

$$\mathcal{L}_Y^\ell = -\frac{1}{\sqrt{2}} \bar{\ell}_L \left[(1 - \hat{\epsilon}_0^\ell) \lambda_\ell - \hat{\epsilon}_1^\ell \mathsf{A}_\ell \lambda_\ell - \hat{\epsilon}_2^\ell \mathsf{A}_\ell^2 \lambda_\ell \right] \ell_R h \,,$$

In numerical analysis, $\mathcal{M} = 10^{15}\,\text{GeV}$, $m_{1(3)} = 0$, and real matrix O

Higgs FCNC in EFT with MFV

- Higgs Yukawa interaction $Y_L = Y_R^\dagger$

$$\mathcal{L}_Y = -\frac{1}{\sqrt{2}}\bar{f}(Y_L P_L + Y_R P_R) f h$$

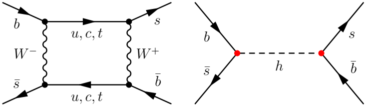
$$Y_R^d = (1-\hat{\epsilon}_0^d)\lambda_d - \hat{\epsilon}_1^d V^\dagger \lambda_u^2 V \lambda_d$$
$$Y_R^u = (1-\hat{\epsilon}_0^u)\lambda_u$$
$$Y_R^\ell = (1-\hat{\epsilon}_0^\ell)\lambda_\ell - \hat{\epsilon}_1^\ell \mathsf{A}_\ell \lambda_\ell - \hat{\epsilon}_2^\ell \mathsf{A}_\ell^2 \lambda_\ell$$

- Higgs FCNC in up-sector is highly suppressed by λ_d^2
- 6 free real parameter: $\left(\epsilon_0^u,\ \epsilon_0^d,\ \epsilon_1^d,\ \epsilon_0^\ell,\ \epsilon_1^\ell,\ \epsilon_2^\ell\right)$ hat suppressed

Constraints:

- $B_s - \bar{B}_s$, $B_d - \bar{B}_d$, $K^0 - \bar{K}^0$ mixing (ϵ_1^d)
- $h \to \ell_i \ell_j$ $\ell_i \to \ell_j \gamma$, $\ell_i \to \ell_j \ell_k \bar{\ell}_l$, $\mu \to e$ conversion in nuclei $(\epsilon_0^u, \epsilon_0^d, \epsilon_0^\ell, \epsilon_1^\ell, \epsilon_2^\ell)$
- Higgs data@LHC Run I $(\epsilon_0^u, \epsilon_0^d, \epsilon_0^\ell)$
- $B_s \to \ell_i \ell_j$ $(\epsilon_1^d, \epsilon_1^\ell, \epsilon_2^\ell)$

Constraints from $B_s - \bar{B}_s$ mixing



- Observables: Δm_d, Δm_s, ϕ_s, Δm_K, ϵ_K

$$\Delta m_s^{\rm SM} = 19.196^{+1.377}_{-1.341}, \quad \Delta m_s^{\rm exp} = 17.757 \pm 0.021, \qquad \text{in unit of ps}^{-1}$$

- Bound @95% CL

$$|\epsilon_1^d| < 0.59$$

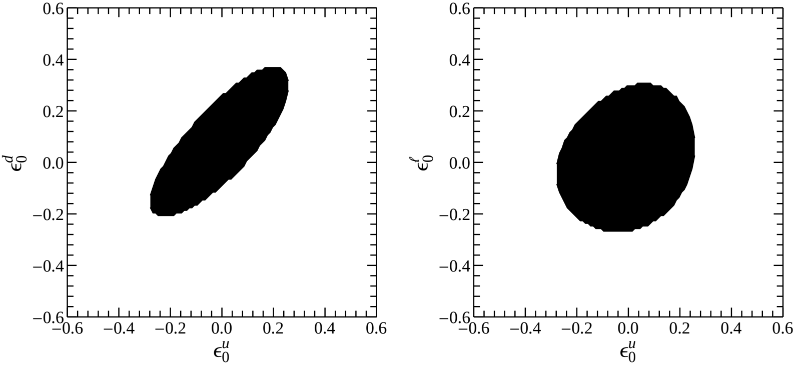
- Prediction @95% CL

$$\Gamma(h \to sd) < 7.4 \times 10^{-11}\,\text{MeV}$$
$$\Gamma(h \to sb) < 2.0 \times 10^{-3}\ \text{MeV}$$
$$\Gamma(h \to db) < 9.4 \times 10^{-5}\ \text{MeV}$$

- Discovery sensitivity@500GeV ILC with $4000\ \text{fb}^{-1}$ D.Barducci, A.J.Helmboldt, 2017

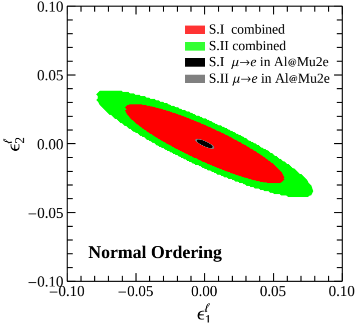
$$\mathcal{B}(h \to bj) \gtrsim 0.5\% \qquad \text{with } j \text{ a light quark}$$

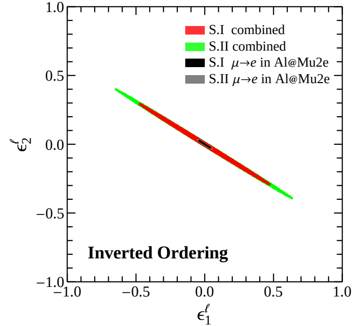
Constraints from Higgs data



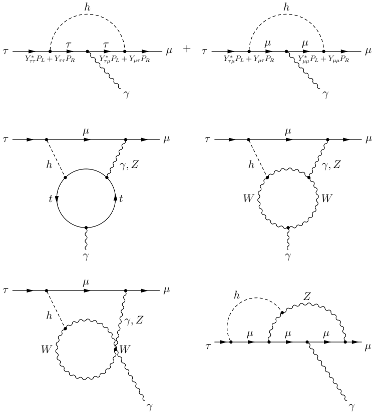
- 90% CL allowed regions of $(\epsilon_0^u,\, \epsilon_0^d,\, \epsilon_0^\ell)$
- LHC Run I data and Tevatron
- By `Lilith` package

Constraints from $\mu \to e\gamma$ and $\mu \to e$ in nuclei



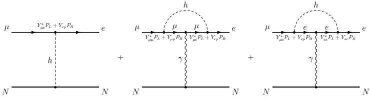


S.I: $(\epsilon_0^\ell, \epsilon_1^\ell, \epsilon_2^\ell)$, **S.II:** $(\epsilon_0^u, \epsilon_0^d, \epsilon_0^\ell, \epsilon_1^\ell, \epsilon_2^\ell)$



$\tau \to \mu\gamma$
$(\epsilon_0^u, \epsilon_0^\ell, \epsilon_1^\ell, \epsilon_2^\ell)$

D.Chang, W.S.Hou, Y.Okada, 1993

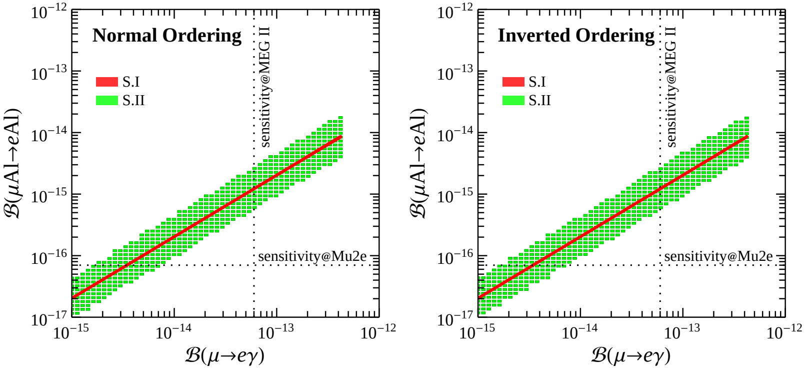


$\mu \to e$ in nuclei
$(\epsilon_0^u, \epsilon_0^d, \epsilon_0^\ell, \epsilon_1^\ell, \epsilon_2^\ell)$

R.Harnik, J.Kopp, J.Zupan, 2012

- dominated by $\mu \to e\gamma$ at present
  $\mu \to e$ in Al in future

Predictions on $\mu \to e\gamma$ and $\mu \to e$ in nuclei



- strong and similar correlations in NO and IO cases
- scenario I: $Y_R^{e\mu}$ vs $Y_R^{e\mu}$
- scenario II: $(Y_L^{tt}, Y_R^{e\mu})$ vs $(Y_R^{qq}, Y_R^{e\mu})$

Predictions on $h \to \ell_i \ell_j$ and $B_s \to \ell_i \ell_j$

- $h \to \ell_i \ell_j$ and $B_s \to \ell_i \ell_j$

$$\frac{\mathcal{B}(B_s \to \ell_1 \ell_2)}{\mathcal{B}(h \to \ell_1 \ell_2)} \approx 2.1 |\bar{Y}_{sb}|^2$$

- Predicted upper bounds on $\Gamma(h \to \ell_i \ell_j)$ [MeV] and $\mathcal{B}(B_s \to \ell_i \ell_j)$

		$\Gamma(h \to e\mu)$	$\Gamma(h \to e\tau)$	$\Gamma(h \to \mu\tau)$	$\mathcal{B}(B_s \to e\mu)$	$\mathcal{B}(B_s \to e\tau)$	$\mathcal{B}(B_s \to \mu\tau)$
NO	S.I	1.2×10^{-8}	1.3×10^{-5}	9.0×10^{-5}	2.4×10^{-16}	2.6×10^{-13}	1.8×10^{-12}
NO	S.II	2.2×10^{-8}	2.4×10^{-5}	1.7×10^{-4}	4.6×10^{-16}	5.0×10^{-13}	3.5×10^{-12}
IO	S.I	1.2×10^{-8}	4.7×10^{-6}	7.1×10^{-5}	2.4×10^{-16}	9.6×10^{-14}	1.4×10^{-12}
IO	S.II	2.2×10^{-8}	8.7×10^{-6}	1.3×10^{-4}	4.5×10^{-16}	1.8×10^{-13}	2.6×10^{-12}

- $\mathcal{B}(B_s \to \mu^+ \mu^-)$ can't deviate from the SM prediction by more than 1%
- Experimental upper limits @ 95% CL, L.Sun's talk & LHCb 2018, CMS 2016, 2017

$$\mathcal{B}(B_d \to e\mu) < 1.3 \times 10^{-9}, \qquad \mathcal{B}(B_s \to e\mu) < 6.3 \times 10^{-9},$$
$$\mathcal{B}(B_d \to \mu\tau) < 1.4 \times 10^{-5}, \qquad \mathcal{B}(B_s \to \mu\tau) < 4.2 \times 10^{-5},$$

$$\mathcal{B}(h \to e\mu) < 3.5 \times 10^{-4}, \quad \mathcal{B}(h \to e\tau) < 6.1 \times 10^{-3}, \quad \mathcal{B}(h \to \mu\tau) < 2.5 \times 10^{-3},$$

Summary

- Higgs FCNC Yukawa couplings in the EFT + type-I seesaw with MFV
- All the Yukawa couplings are described by 6 parameter $(\epsilon_0^u, \epsilon_0^d, \epsilon_1^d, \epsilon_0^\ell, \epsilon_1^\ell, \epsilon_2^\ell)$
- Constraints

$$\begin{aligned} \epsilon_0^u, \epsilon_0^d, \epsilon_0^\ell &: \text{constrained by Higgs data} \\ \epsilon_1^\ell, \epsilon_2^\ell &: \text{constrained by } \mu \to e\gamma \qquad (\mu \to e \text{ in Al in future}) \\ \epsilon_1^d &: \text{constrained by } B_s - \bar{B}_s \text{ mixing} \end{aligned}$$

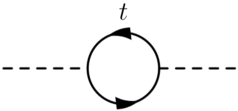
- Using these constraints, predicted upper limints for $\mathcal{B}(h \to d_i d_j)$, $\mathcal{B}(h \to u_i u_j)$, $\mathcal{B}(h \to \ell_1 \ell_2)$, and $\mathcal{B}(B_s \to \ell_1 \ell_2)$ are much lower than the current experimental bounds.
- $\mathcal{B}(B_s \to \mu^+ \mu^-)$ can't deviate from the SM prediction by more than 1%
- However, with the improved measurements at the future MEG II and Mu2e experiments, searches for the LFV Higgs couplings in the $\mu \to e\gamma$ decay and $\mu \to e$ conversion in Al are very promising.

Thank You !

Backup

Higgs After the Discovery: 1. Hierarchy Problem

- If SM is an effective theory below Λ
- Higgs mass receives quadratically divergent radiative corrections

$\delta m_h^2 =$  $+ \ldots = \dfrac{c}{16\pi^2}\,\Lambda^2$

- Large cancellation

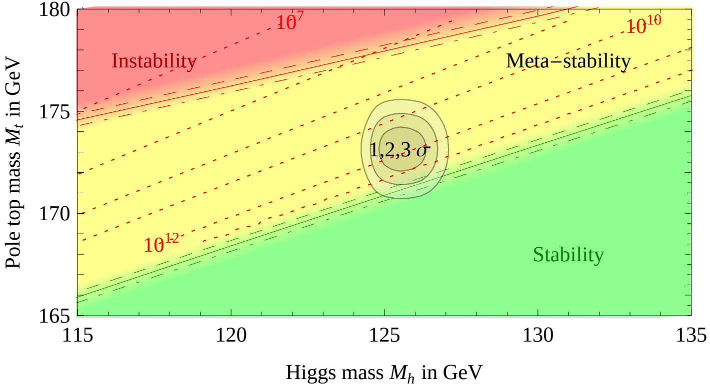
regularization independent

fine-tuning

$$m_h^2 = m_{h,0}^2 + \frac{c}{16\pi^2}\,\Lambda^2 = 126\,\mathrm{GeV}^2$$

- Possible answer: New Physics
  - SUSY
  - Extra Dimensions
  - Dynamical Symmetry Breaking
  - Compositeness
  - . . . . . .

Higgs After the Discovery: 2. Vacuum Stability



"While λ (Higgs quartic coupling) at the Planck scale is remarkably close to zero, absolute stability of the Higgs potential is excluded at 98% C.L. for $M_h < 126\,\mathrm{GeV}$. "

G. Degrassi, et. al. JHEP 12

Why $\lambda \approx 0 @ \Lambda_{\mathrm{Planck}}$?

$B_s \to \mu^+\mu^-$ decay: SM and exp

- SM prediction

Bobeth et al. 2013, with updated inputs

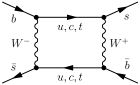
$$\overline{\mathcal{B}}(B_s \to \mu^+\mu^-)_{\rm SM} = \big(3.44 \pm 0.19\big) \times 10^{-9}$$

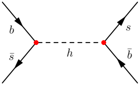
- Exp data

$$\overline{\mathcal{B}}(B_s \to \mu^+\mu^-)_{\rm LHCb2017} = \big(3.0 \pm 0.6^{+0.3}_{-0.2}\big) \times 10^{-9}$$
$$\overline{\mathcal{B}}(B_s \to \mu^+\mu^-)_{\rm CMS2013} = \big(3.0^{+1.0}_{-0.9}\big) \times 10^{-9}$$
$$\overline{\mathcal{B}}(B_s \to \mu^+\mu^-)_{\rm avg.} = \big(3.0 \pm 0.5\big) \times 10^{-9}$$

- Consistent within 1σ. We can use it to constrain possible NP effects.
- However, experimental central value is $\sim 13\%$ lower than the SM one. NP effects may address such a discrepancy, though the error bars are still too large to call for such a solution.

$B_s - \bar{B}_s$ mixing





- Effective Hamiltonian

$$\mathcal{H}^{\Delta B=2} = \frac{G_F^2}{16\pi^2} m_W^2 (V_{tb}^* V_{ts})^2 \sum_i C_i \mathcal{O}_i + h.c..$$

- Effective operator

RGE: Buras et al. 2001

$$\mathcal{O}_1^{\rm VLL} = (\bar{b}^\alpha \gamma_\mu P_L s^\alpha)(\bar{b}^\beta \gamma^\mu P_L s^\beta), \qquad \mathcal{O}_1^{\rm LR} = (\bar{b}^\alpha \gamma_\mu P_L s^\alpha)(\bar{b}^\beta \gamma^\mu P_R s^\beta),$$
$$\mathcal{O}_1^{\rm VRR} = (\bar{b}^\alpha \gamma_\mu P_R s^\alpha)(\bar{b}^\beta \gamma^\mu P_R s^\beta), \qquad \mathcal{O}_2^{\rm LR} = (\bar{b}^\alpha P_L s^\alpha)(\bar{b}^\beta P_R s^\beta),$$
$$\mathcal{O}_1^{\rm SLL} = (\bar{b}^\alpha P_L s^\alpha)(\bar{b}^\beta P_L s^\beta), \qquad \mathcal{O}_2^{\rm SLL} = (\bar{b}^\alpha \sigma_{\mu\nu} P_L s^\alpha)(\bar{b}^\beta \sigma^{\mu\nu} P_L s^\beta),$$
$$\mathcal{O}_1^{\rm SRR} = (\bar{b}^\alpha P_R s^\alpha)(\bar{b}^\beta P_R s^\beta), \qquad \mathcal{O}_2^{\rm SRR} = (\bar{b}^\alpha \sigma_{\mu\nu} P_R s^\alpha)(\bar{b}^\beta \sigma^{\mu\nu} P_R s^\beta).$$

- Wilson coefficients from the Higgs FCNC

$$C_1^{\rm SLL,NP} = -\frac{1}{2}\kappa (Y_{bs} - i\bar{Y}_{bs})^2,$$
$$C_1^{\rm SRR,NP} = -\frac{1}{2}\kappa (Y_{bs} + i\bar{Y}_{bs})^2,$$
$$C_2^{\rm LR,NP} = -\kappa (Y_{bs}^2 + \bar{Y}_{bs}^2),$$

$$\kappa = \frac{8\pi^2}{G_F^2} \frac{1}{m_h^2 m_W^2} \frac{1}{(V_{tb}^* V_{ts})^2},$$

$B_s - \bar{B}_s$ mixing

- Mass difference

$$\Delta m_s = 2|\langle \bar{B}_s|\mathcal{H}^{\Delta B=2}|B_s\rangle| = \frac{G_F^2}{8\pi^2} m_W^2 |V_{tb}^* V_{ts}|^2 \sum \left| C_i \langle \bar{B}_s \left| \mathcal{O}_i \right| B_s \rangle \right|,$$

- SM prediction

$$\Delta m_s^{\rm SM} = (18.64^{+2.40}_{-2.27}) {\rm ps}^{-1}$$

- Exp data

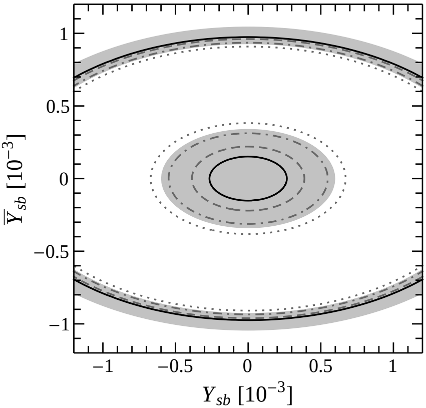
$$\Delta m_s^{\rm exp} = (17.757 \pm 0.021) {\rm ps}^{-1}$$

- 95% CL bound

complex Y

$$0.76 < \left| 1 - \left(0.7\, Y_{sb}^2 + 2.1\, \bar{Y}_{sb}^2 \right) \times 10^6 \right| < 1.29$$

Bounds from $B_s - \bar{B}_s$ mixing



- dark region: 95% CL allowed
- black: exp central value
- dashed: $\Delta m_s^{\text{exp}}/\Delta m_s^{\text{theo}} = 0.9$
- dot-dashed: $\Delta m_s^{\text{exp}}/\Delta m_s^{\text{theo}} = 0.8$
- dotted: $\Delta m_s^{\text{exp}}/\Delta m_s^{\text{theo}} = 0.7$

- constructive: $Y_{sb}, \bar{Y}_{sb} \sim 0$
- destructive: other

$h \to f_1 f_2$ decay

- Decay width

$S = 1$ $(1/2)$ for $f_1 \neq f_2$ $(f_1 = f_2)$

$$\Gamma(h \to f_1 f_2) = S N_c \frac{m_h}{8\pi} \left(\left|Y_{f_1 f_2}\right|^2 + \left|\bar{Y}_{f_1 f_2}\right|^2 \right)$$

- $h \to \mu\tau$

$\sqrt{|Y_{\mu\tau}|^2 + |\bar{Y}_{\mu\tau}|^2} < 1.43 \times 10^{-3}$ at 95% CL

$$\mathcal{B}(h \to \mu\tau)_{\rm CMS15} = (0.84^{+0.39}_{-0.37})\%$$

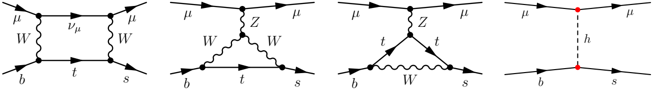
$$\mathcal{B}(h \to \mu\tau)_{\rm CMS17} < 0.25\% \qquad \text{at 95\% CL}$$

$$\mathcal{B}(h \to \mu\tau)_{\rm ATLAS16} < 1.43\% \qquad \text{at 95\% CL}$$

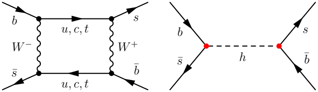
Constraints and Predictions

Constraints:

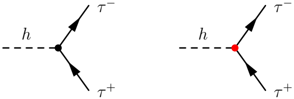
- $B_s \to \mu^+\mu^-$



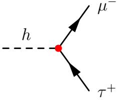
- $B_s - \bar{B}_s$



- $h \to \tau\tau$

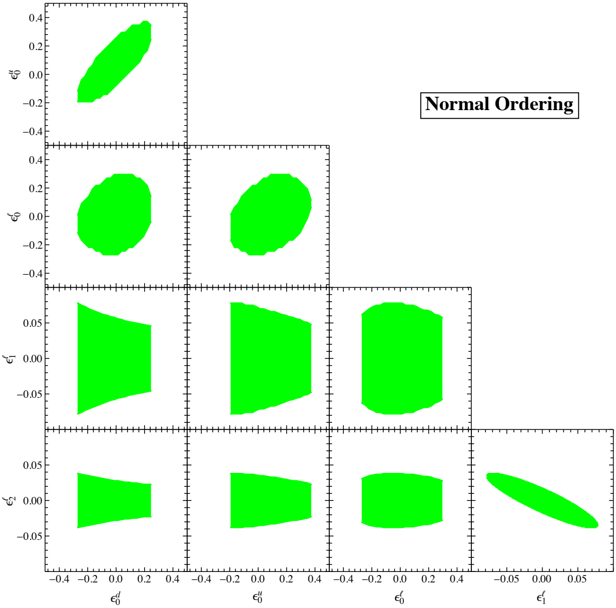


- $h \to \mu\tau$



Predictions: $\mathcal{B}(B_s \to \mu\tau)$, $\mathcal{B}(B_s \to \tau\tau)$, ...

Allowed parameter space



Allowed parameter space