



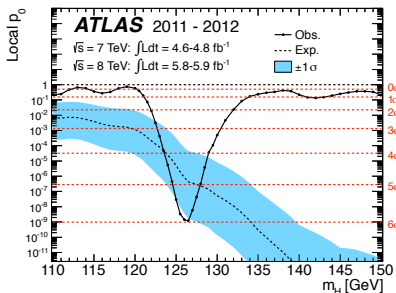
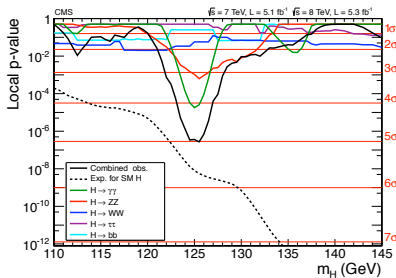
Flavor Violating Higgs Yukawa Couplings in Minimal Flavor Violation

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based on arXiv:1807.00921, in collaboration with Min He, Xiao-Gang He, XY, Jin-Jun Zhang

Higgs Discovery



LHC Run I

► mass: $m_h \approx 125 \text{ GeV}$

► spin

► parity

► Yukawa coupling

► gauge coupling

► self coupling

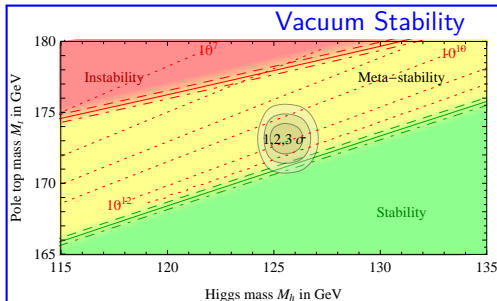
LHC Run II/HL/CEPC/ILC



Higgs After the Discovery

Hierarchy Problem

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

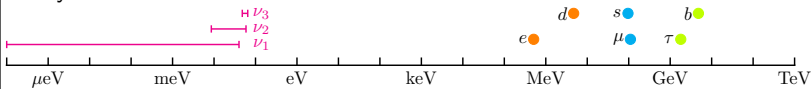


$$\Delta\mathcal{L}_H = +\mu^2\Phi^\dagger\Phi - \lambda(\Phi^\dagger\Phi)^2 + (2m_W^2W_\mu^+W^{-\mu} + m_Z^2Z_\mu Z^\mu)\frac{h}{v} - m_i\bar{f}_if_i\frac{h}{v}$$

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

S.Baek, XY, 2017

Many Parameters



Higgs FCNC: exp

e	μ	τ	
e^+e^- collider	$\mathcal{B} < 0.035\%$	$\mathcal{B} < 0.61\%$	e
	$\mu < 2.8$	$\mathcal{B} < 0.25\%$	μ
		$\mu = 1.1 \pm 0.2$	τ

u	c	t	
		$\mathcal{B} < 0.55\%$	u
		$\mathcal{B} < 0.40\%$	c
		$\mu_{tth} = 2.3^{+0.7}_{-0.6}$	t

d	s	b	
			d
			s
		$\mu = 0.70^{+0.29}_{-0.27}$	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, Girschbach 2012
- Blankenburg, Ellis, Isidori 2012
- Harnik, Kopp, Zupan 2013
- Gorbahn, Haisch 2014
- Celis, Cirigliano, Passemar 2014
- Chiang, He, Ye, XY 2017
- ...
- ...

Flavor Problem \implies MFV

Higgs FCNC in EFT

- ▶ Effective Field Theory

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

- ▶ 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

$$\mathcal{O}_{dH} = (H^\dagger H)(\bar{Q}_L H C_{dH} d_R),$$

$$\mathcal{O}_{uH} = (H^\dagger H)(\bar{Q}_L \tilde{H} C_{uH} u_R),$$

$$\mathcal{O}_{eH} = (H^\dagger H)(\bar{Q}_L H C_{eH} e_R),$$

- ▶ Yukawa interaction

Harnik, Kopp, Zupan, 2013

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

$$\bar{Y}_f = Y_f - \frac{1}{2} \frac{v^2}{\Lambda^2} C_{fH},$$

- ▶ FCNCs arise in the mass eigenstate

- ▶ Flavor symmetry without Yukawa

some $U(1)$'s

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

- ▶ Flavor symmetry breaking

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

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

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

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

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

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

- ▶ Higgs FCNC coupling

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

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

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

- ▶ Higgs FCNC coupling after resummation

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

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

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

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

- ▶ 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 \implies mass eigenstate

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

- ▶ Higgs Yukawa interaction in the mass eigenstate

$$\hat{\epsilon}_i^d \equiv (v^2/\Lambda^2) \epsilon_i^d$$

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

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

- ▶ 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 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 Casas, Ibarra, 2001

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

- ▶ Higgs Yukawa interaction

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

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

Higgs FCNC in EFT with MFV

- ▶ Higgs Yukawa interaction

$$Y_L = Y_R^\dagger$$

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

$$Y_R^d = (1 - \hat{\epsilon}_0^d) \lambda_d - \hat{\epsilon}_1^d V^\dagger \lambda_u^2 V \lambda_d$$

$$Y_R^u = (1 - \hat{\epsilon}_0^u) \lambda_u$$

$$Y_R^\ell = (1 - \hat{\epsilon}_0^\ell) \lambda_\ell - \hat{\epsilon}_1^\ell \mathbf{A}_\ell \lambda_\ell - \hat{\epsilon}_2^\ell \mathbf{A}_\ell^2 \lambda_\ell$$

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

hat suppressed

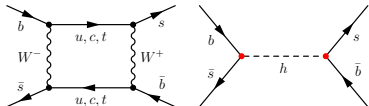
Constraints:

- ▶ $B_s - \bar{B}_s, B_d - \bar{B}_d, K^0 - \bar{K}^0$ mixing (ϵ_1^d)
- ▶ $h \rightarrow l_i l_j, l_i \rightarrow l_j \gamma, l_i \rightarrow l_j l_k \bar{l}_i, \mu \rightarrow e$ conversion in nuclei $(\epsilon_0^u, \epsilon_0^d, \epsilon_0^\ell, \epsilon_1^\ell, \epsilon_2^\ell)$
- ▶ Higgs data@LHC Run I $(\epsilon_0^u, \epsilon_0^d, \epsilon_0^\ell)$
- ▶ $B_s \rightarrow l_i l_j$ $(\epsilon_1^d, \epsilon_1^\ell, \epsilon_2^\ell)$

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

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

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



- Bound @95% CL

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

- Prediction @95% CL

$$\Gamma(h \rightarrow sd) < 7.4 \times 10^{-11} \text{ MeV}$$

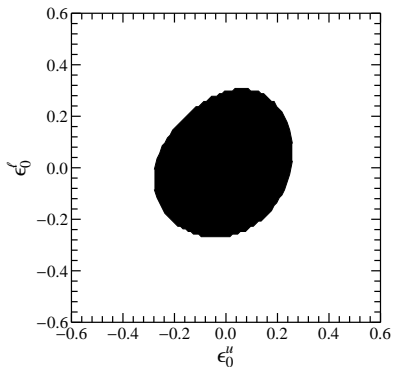
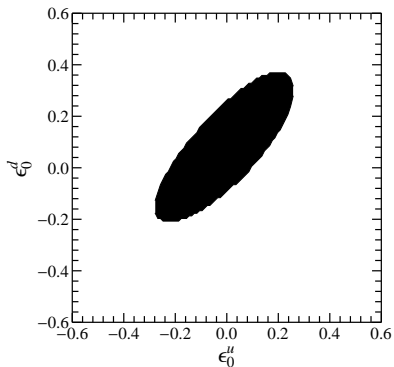
$$\Gamma(h \rightarrow sb) < 2.0 \times 10^{-3} \text{ MeV}$$

$$\Gamma(h \rightarrow db) < 9.4 \times 10^{-5} \text{ MeV}$$

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

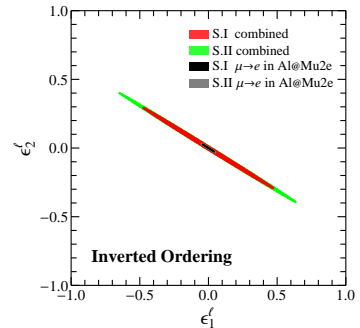
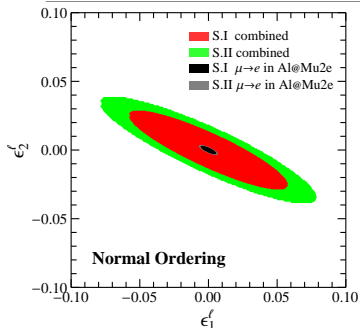
$$\mathcal{B}(h \rightarrow bj) \gtrsim 0.5\% \quad \text{with } j \text{ a light quark}$$

Constraints from Higgs data



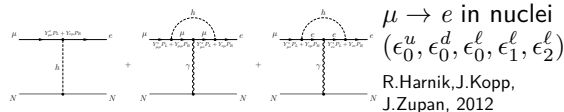
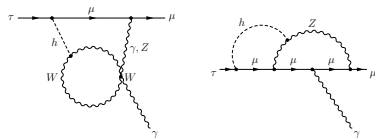
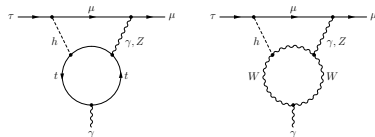
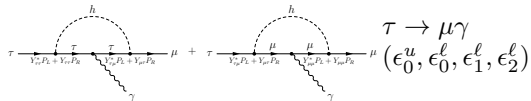
- ▶ 90% CL allowed regions of $(\epsilon_0^u, \epsilon_0^d, \epsilon_0^\ell)$
- ▶ LHC Run I data and Tevatron
- ▶ By Lilith package

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



S.I: $(\epsilon_0^l, \epsilon_1^l, \epsilon_2^l)$,

S.II: $(\epsilon_0^u, \epsilon_0^d, \epsilon_0^l, \epsilon_1^l, \epsilon_2^l)$

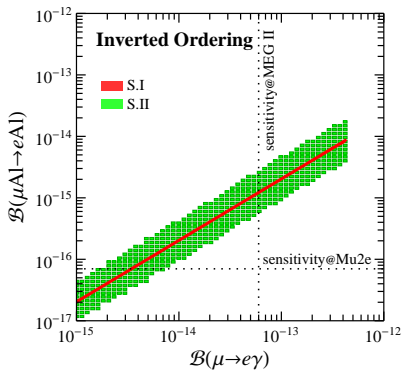
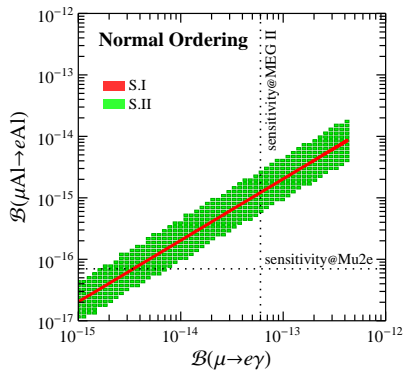


D.Chang, W.S.Hou, Y.Okada, 1993

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

► dominated by $\mu \rightarrow e\gamma$ at present
 $\mu \rightarrow e$ in Al in future

Predictions on $\mu \rightarrow e\gamma$ and $\mu \rightarrow e$ 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 $(Y_R^{qq}, Y_R^{e\mu})$
- ▶ see Tian-Yu Xing's talk on $\mu \rightarrow e$ conversion in COMET

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

- ▶ $h \rightarrow \ell_i \ell_j$ and $B_s \rightarrow \ell_i \ell_j$

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

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

		$\Gamma(h \rightarrow e\mu)$	$\Gamma(h \rightarrow e\tau)$	$\Gamma(h \rightarrow \mu\tau)$	$\mathcal{B}(B_s \rightarrow e\mu)$	$\mathcal{B}(B_s \rightarrow e\tau)$	$\mathcal{B}(B_s \rightarrow \mu\tau)$
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}

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

$$\mathcal{B}(B_d \rightarrow e\mu) < 1.3 \times 10^{-9}, \quad \mathcal{B}(B_s \rightarrow e\mu) < 6.3 \times 10^{-9},$$

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

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

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

- ▶ Using these constraints, predicted upper limits for $\mathcal{B}(h \rightarrow d_i d_j)$, $\mathcal{B}(h \rightarrow \ell_1 \ell_2)$, and $\mathcal{B}(B_s \rightarrow \ell_1 \ell_2)$ are much lower than the current experimental bounds.
- ▶ $\mathcal{B}(B_s \rightarrow \mu^+ \mu^-)$ 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 $\mu \rightarrow e\gamma$ decay and $\mu \rightarrow e$ conversion in AI 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

$$\delta m_h^2 = \text{---} \circlearrowleft \text{---} + \dots = \frac{c}{16\pi^2} \Lambda^2$$

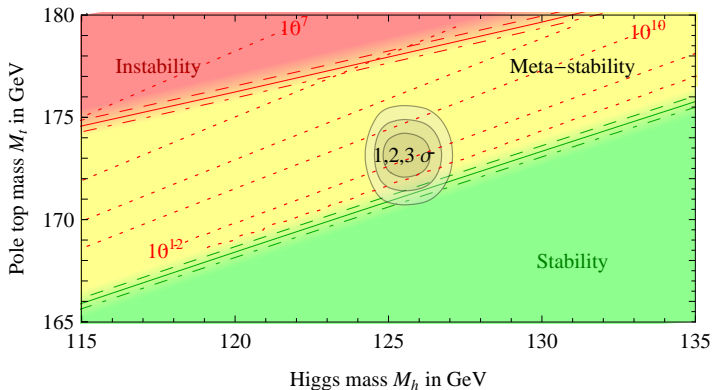
- ▶ Large cancellation regularization independent

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

fine-tuning

- ▶ 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 $M_h < 126$ GeV. ”

G. Degrandi, et. al. JHEP 12

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

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

► SM prediction

Bobeth et al. 2013, with updated inputs

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

► Exp data

$$\overline{\mathcal{B}}(B_s \rightarrow \mu^+ \mu^-)_{\text{LHCb2017}} = (3.0 \pm 0.6_{-0.2}^{+0.3}) \times 10^{-9}$$

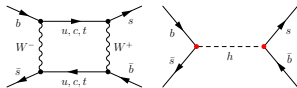
$$\overline{\mathcal{B}}(B_s \rightarrow \mu^+ \mu^-)_{\text{CMS2013}} = (3.0_{-0.9}^{+1.0}) \times 10^{-9}$$

$$\overline{\mathcal{B}}(B_s \rightarrow \mu^+ \mu^-)_{\text{avg.}} = (3.0 \pm 0.5) \times 10^{-9}$$

- 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

$$\mathcal{O}_1^{\text{VLL}} = (\bar{b}^\alpha \gamma_\mu P_L s^\alpha) (\bar{b}^\beta \gamma^\mu P_L s^\beta),$$

$$\mathcal{O}_1^{\text{LR}} = (\bar{b}^\alpha \gamma_\mu P_L s^\alpha) (\bar{b}^\beta \gamma^\mu P_R s^\beta),$$

$$\mathcal{O}_1^{\text{VRR}} = (\bar{b}^\alpha \gamma_\mu P_R s^\alpha) (\bar{b}^\beta \gamma^\mu P_R s^\beta),$$

$$\mathcal{O}_2^{\text{LR}} = (\bar{b}^\alpha P_L s^\alpha) (\bar{b}^\beta P_R s^\beta),$$

$$\mathcal{O}_1^{\text{SLL}} = (\bar{b}^\alpha P_L s^\alpha) (\bar{b}^\beta P_L s^\beta),$$

$$\mathcal{O}_2^{\text{SLL}} = (\bar{b}^\alpha \sigma_{\mu\nu} P_L s^\alpha) (\bar{b}^\beta \sigma^{\mu\nu} P_L s^\beta),$$

$$\mathcal{O}_1^{\text{SRR}} = (\bar{b}^\alpha P_R s^\alpha) (\bar{b}^\beta P_R s^\beta),$$

$$\mathcal{O}_2^{\text{SRR}} = (\bar{b}^\alpha \sigma_{\mu\nu} P_R s^\alpha) (\bar{b}^\beta \sigma^{\mu\nu} P_R s^\beta).$$

► Wilson coefficients from the Higgs FCNC

$$C_1^{\text{SLL, NP}} = -\frac{1}{2} \kappa (Y_{bs} - i\bar{Y}_{bs})^2,$$

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

$$C_2^{\text{LR, NP}} = -\kappa (Y_{bs}^2 + \bar{Y}_{bs}^2),$$

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

$B_s - \bar{B}_s$ mixing

- ▶ Mass difference

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

- ▶ SM prediction

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

- ▶ Exp data

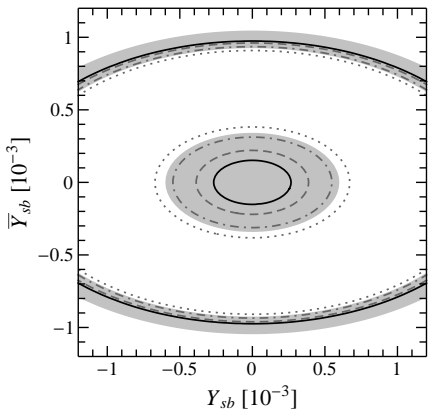
$$\Delta m_s^{\text{exp}} = (17.757 \pm 0.021) \text{ps}^{-1}$$

- ▶ 95% CL bound

complex Y

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

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

$h \rightarrow f_1 f_2$ decay

► Decay width

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

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

► $h \rightarrow \mu\tau$

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

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

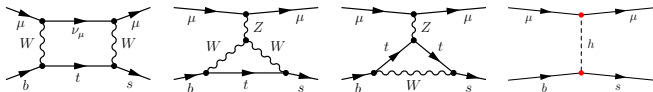
$$\mathcal{B}(h \rightarrow \mu\tau)_{\text{CMS17}} < 0.25\% \quad \text{at 95\% CL}$$

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

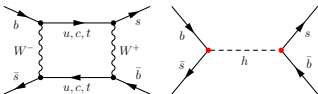
Constraints and Predictions

Constraints:

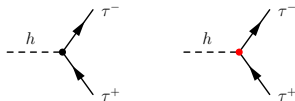
► $B_s \rightarrow \mu^+ \mu^-$



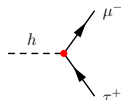
► $B_s - \bar{B}_s$



► $h \rightarrow \tau\tau$



► $h \rightarrow \mu\tau$



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