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Standard-Model Benchmarks for Higgs-Mediated Flavor Violation

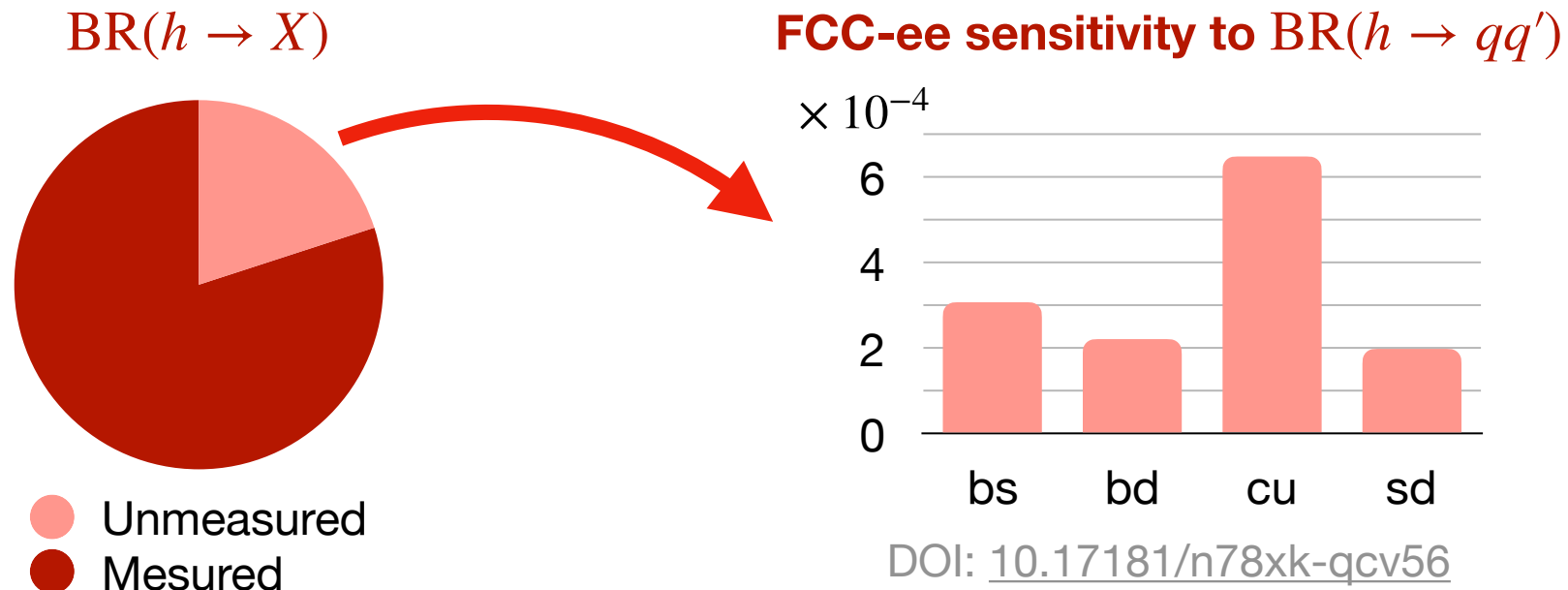
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BRDA 2026, October 15, 2026

Introduction and Motivation

10+ Years After the Higgs Discovery

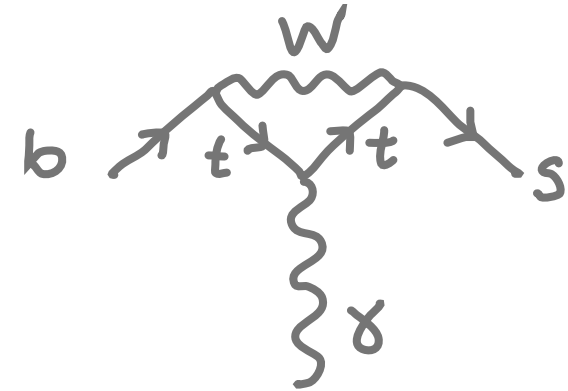
- Higgs (2012) completed SM
- Only a few couplings (t , W , Z , τ) precisely measured
- Light-quark and off-diagonal currently **unmeasured**
- Higgs factories (e.g. FCC-ee) → **sensitivity to** on off-diagonal



Flavor-Changing Neutral Currents

1. FCNCs are forbidden at tree level in SM

- Suppressed due to **GIM mechanism**
- Sensitive to New Physics (NP)
- Via loops $\rightarrow$ virtual heavy particles



2. Intensity vs. energy

- New particles modify effective couplings, even if too heavy to produce
- **Complementary to direct searches** at the energy frontier
- Rare processes $\rightarrow$ indirect search for new particles

Rare FCNC processes act as precision microscopes for heavy new physics. If we observe a Higgs-mediated FCNC, it's BSM.

What are we calculating?

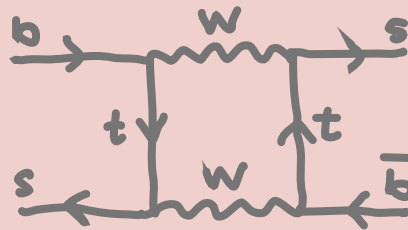
Effective flavor-changing
Yukawa couplings

$$h \rightarrow b\bar{s} + s\bar{b}$$



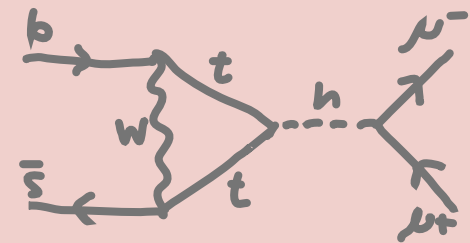
$\Delta B = 2$ “Wilson
coefficients”

$$B_s - \bar{B}_s$$



Rare decay $b \rightarrow s\mu^+\mu^-$
“Wilson coefficients”

$$B_s \rightarrow \mu^+\mu^-$$



SM 1 loop



UV cancellation/
gauge checks



effective
operators

Gauge-Invariant Setup

Gauge-Invariant Origin of Higgs FCNCs

- SMEFT:

$$Q_{d\varphi}^{ij} = (\varphi^\dagger \varphi)(\bar{q}_L^i \varphi d_R^j)$$

$$Q_{u\varphi}^{ij} = (\varphi^\dagger \varphi)(\bar{q}_L^i \tilde{\varphi} u_R^j)$$

$$\mathcal{L} \supset -\bar{q}_L Y_d \varphi d_R + \frac{C_{d\varphi}^{ij}}{\Lambda^2} Q_{d\varphi}^{ij} + \text{h.c.}$$

- After EWSB:

$$M_d = \frac{v}{\sqrt{2}} \left(Y_d - \frac{v^2}{2\Lambda^2} C_{d\varphi} \right), \quad Y_d^{(h)} = \frac{1}{\sqrt{2}} \left(Y_d - \frac{3v^2}{2\Lambda^2} C_{d\varphi} \right)$$

quark mass basis

$$\hat{Y}_d^{(h)} = \frac{\hat{M}_d}{v} - \frac{v^2}{\sqrt{2}\Lambda^2} \hat{C}_{d\varphi}$$

Mass-Yukawa
misalignment
↳ Higgs FCNCs

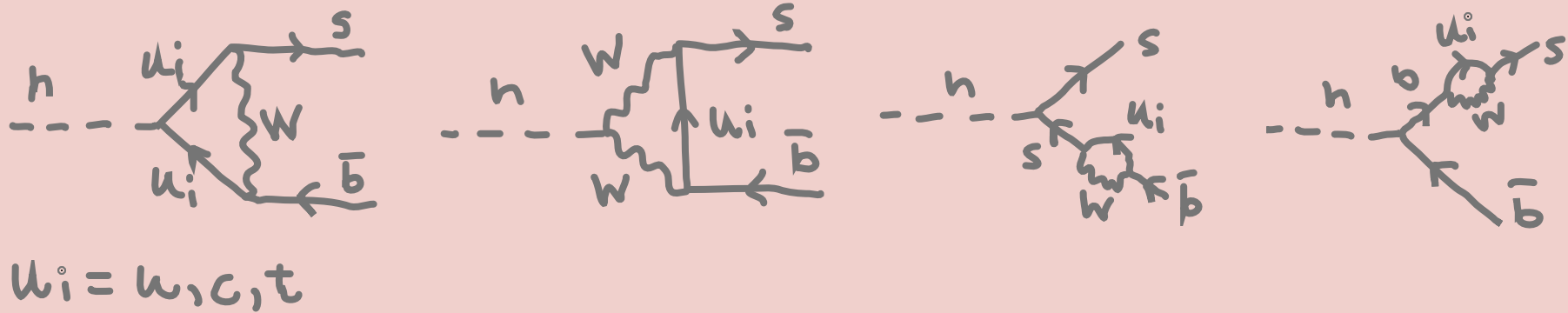
- Gauge-invariant completion:

$$\mathcal{L}_{\text{FCNC}} \supset \sum_{i \neq j} y_{ij} \bar{d}_L^i d_R^j \left(h + \frac{G^+ G^-}{v} \right) + \text{h.c.} + \dots$$

no linear
 G^0 term!

One-Loop Higgs FCNCs in the Standard Model

$$h \rightarrow s\bar{b}$$



$$i\mathcal{M}_{\text{SM}}(h \rightarrow s\bar{b}) = -i\bar{u}_s [(y_{bs}^{\text{SM}})^* P_L + y_{sb}^{\text{SM}} P_R] v_b$$

$$(y_{bs}^{\text{SM}})^* = \frac{g^3 m_s}{64\pi^2 m_W} \sum_{i=u,c,t} \lambda_i^{bs} f^{(i)}(m_s, m_b)$$

$$y_{sb}^{\text{SM}} = \frac{g^3 m_b}{64\pi^2 m_W} \sum_{i=u,c,t} \lambda_i^{bs} f^{(i)}(m_b, m_s)$$

chiral suppression

$$y_{bs}^{\text{SM}} \propto m_s, \quad y_{sb}^{\text{SM}} \propto m_b$$

GIM mechanism

$$\sum_{i=u,c,t} V_{ib} V_{is}^* = 0$$

→ UV finite & gauge independent

$h \rightarrow s\bar{b}$: UV Finiteness and Gauge Independence

Gauge independence

- Feynman Gauge: $W^\pm$, $G^\pm$



- Unitary Gauge: $W^\pm$



$$\mathcal{M}_{\text{Feynman}}^{\text{on-shell}} = \mathcal{M}_{\text{Unitary}}^{\text{on-shell}}$$

off-shell $h\bar{b}s$ vertex
is NOT gauge independent

Cancellation of UV divergences

- Individual diagrams are UV divergent
- Divergence in Feynman gauge:

$$i\mathcal{M}_i|_{\text{UV}} = \frac{ig^3}{64\pi^2 m_W} \frac{\lambda_i^{bs}}{\epsilon} \bar{u}_s (m_s P_L + m_b P_R) v_b$$

$$i\mathcal{M}|_{\text{UV}} \propto \sum_{i=u,c,t} V_{ib} V_{is}^*$$

$$\underbrace{\hspace{10em}}_{=0}$$

→ UV finite

$h \rightarrow s\bar{b}$: SM Predictions

$$\mathcal{B}_{qq'} \equiv \mathcal{B}(h \rightarrow q\bar{q}') + \mathcal{B}(h \rightarrow q'\bar{q}) \simeq \frac{3m_h}{8\pi\Gamma_h} \left(|y_{qq'}|^2 + |y_{q'q}|^2 \right)$$

sector	$ y_{qq'}^{\text{SM}} $	$ y_{q'q}^{\text{SM}} $	$\mathcal{B}_{\text{SM}}(h \rightarrow qq')$
bs	9.95×10^{-8}	5.31×10^{-6}	$(1.03 \pm 0.13) \times 10^{-7}$
bd	1.05×10^{-9}	1.11×10^{-6}	$(4.52 \pm 0.62) \times 10^{-9}$
sd	4.38×10^{-11}	8.71×10^{-10}	$(2.77 \pm 0.40) \times 10^{-15}$
cu	6.23×10^{-15}	3.22×10^{-12}	$(3.76 \pm 1.65) \times 10^{-20}$

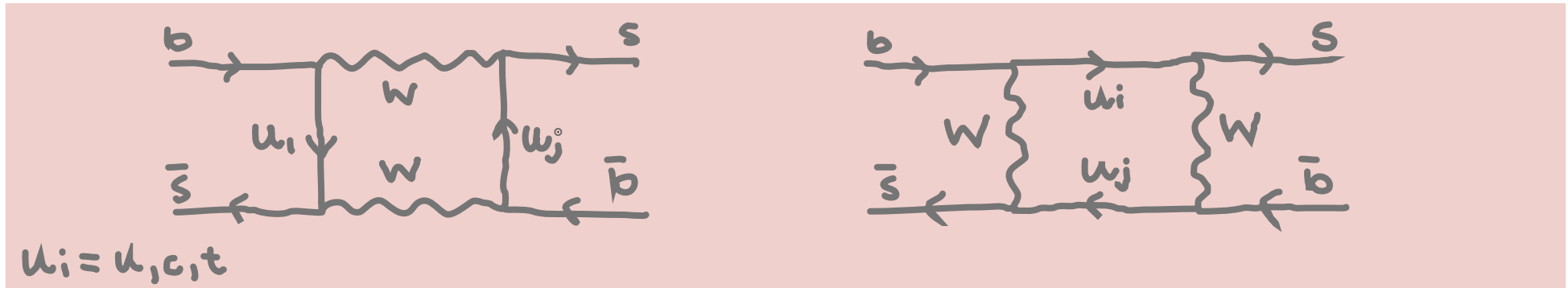
- For bs sector:

$$y_{bs}^{\text{SM}} = (-9.95 - 0.18i) \times 10^{-8}$$

$$y_{sb}^{\text{SM}} = (-5.31 + 0.10i) \times 10^{-6}$$

$$\left| \frac{y_{bs}^{\text{SM}}}{y_{sb}^{\text{SM}}} \right| \sim \frac{m_s}{m_b}$$

$B_s - \bar{B}_s$ Mixing: Subleading SM Corrections



$$\mathcal{M}_{\text{box}} = \mathcal{M}^{(0)} + m_b^2 \mathcal{M}^{(2)} + \dots$$

- Operators matched:
 - $\langle S_{RR} \rangle = 2iC_{S_{RR}} [(\bar{u}_s P_R v_b)(\bar{v}_s P_R u_b) - (\bar{u}_s P_R u_b)(\bar{v}_s P_R v_b)]$
 - $\langle V_{LL} \rangle = 2iC_{V_{LL}} [(\bar{u}_s \gamma^\mu P_L v_b)(\bar{v}_s \gamma_\mu P_L u_b) - (\bar{u}_s \gamma^\mu P_L u_b)(\bar{v}_s \gamma_\mu P_L v_b)]$
 - $\langle T_{RR} \rangle = 2iC_{T_{RR}} [(\bar{u}_s \sigma_{\mu\nu} P_R v_b)(\bar{v}_s \sigma^{\mu\nu} P_R u_b) - (\bar{u}_s \sigma^{\mu\nu} P_R u_b)(\bar{v}_s \sigma_{\mu\nu} P_R v_b)]$
 - $\langle O_7 \rangle = 2iC_{O_7} [(\bar{u}_s \not{p}_1 P_L v_b)(\bar{v}_s P_R u_b) - (\bar{u}_s P_R v_b)(\bar{v}_s \not{p}_3 P_L u_b) + m_b(\bar{u}_s P_R v_b)(\bar{v}_s P_R u_b) - (\bar{u}_s P_R u_b)(\bar{v}_s \not{p}_1 P_L v_b) + (\bar{u}_s \not{p}_3 P_L u_b)(\bar{v}_s P_R v_b) - m_b(\bar{u}_s P_R u_b)(\bar{v}_s P_R v_b)]$

$$O_7 = (\bar{s}_L \gamma^\mu b_L)(\bar{s}_L i \overleftrightarrow{D}_\mu b_L)$$

Leading

$$V_{LL}^{(0)}$$

Subleading

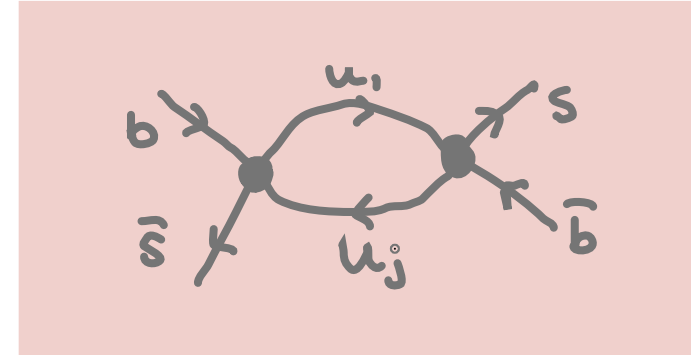
$$S_{RR}^{(2)}, V_{LL}^{(2)}, T_{RR}^{(2)}, O_7^{(1)}$$

$$C_i^{\text{Feyn.}} = C_i^{\text{Unit.}}$$

$B_s - \bar{B}_s$ Mixing: EFT Subtraction and EOM

- Double insertion of the $\Delta B = 1$ Lagrangian

$$\mathcal{L}_{\Delta B=1}^{(0)} = -\frac{4G_F}{\sqrt{2}} \sum_{i,j=u,c} V_{ib} V_{js}^* (\bar{s} \gamma_\mu P_L u_j) (\bar{u}_i \gamma^\mu P_L b) + \text{h.c.}$$



$c \ln\left(\frac{m_W^2}{\mu^2}\right)$
 $c \ln\left(-\frac{m_W^2}{m_b^2}\right)$

$\mathcal{M}_{\text{hard}}^{\Delta B=2} = \mathcal{M}_{\text{SM}}^{\text{box}} - \mathcal{M}_{\Delta B=1 \times \Delta B=1}$

$c \ln\left(\frac{m_W^2}{\mu^2}\right)$
 $c \ln\left(-\frac{\mu^2}{m_b^2}\right)$

UV divergent $\overline{\text{MS}}$

$\left| \frac{m_b^2 V_{ub} V_{ts}}{V_{cb} V_{cs}} \right| \sim 0.03\%$

- EOM reduction

doesn't change
EFT power
counting

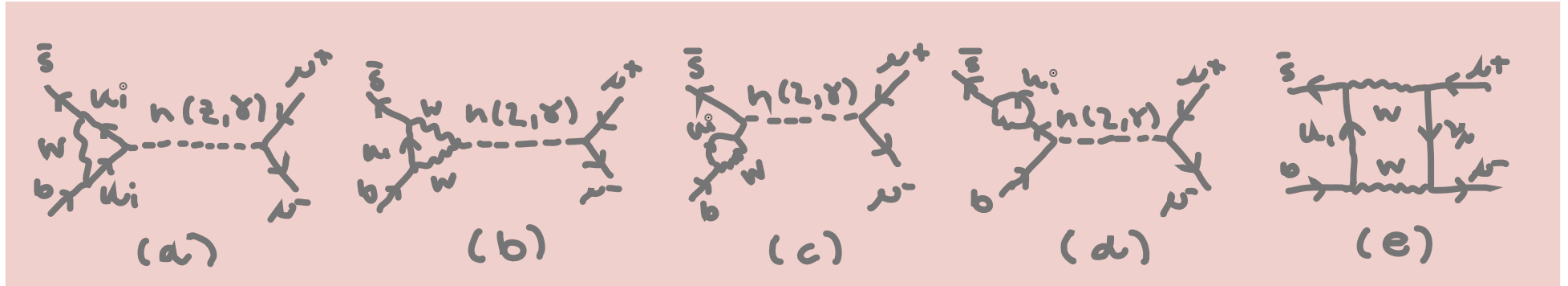
$\mathcal{O}_{D^2}^{(8)} \xrightarrow{\text{EOM}} m_b^2 \mathcal{O}^{(6)} + \dots$

Example:

$$\mathcal{O}_{RR}^{(8)} = (\bar{s} P_R (i \not{D})^2 b) (\bar{s} P_R b)$$

$\hookrightarrow \text{EOM: } m_b^2 \mathcal{O}_{RR}^{(6)}$

$B_s \rightarrow \mu^+ \mu^-$: One-Loop SM Calculation



$$\mathcal{M}_{\text{SM}} = \mathcal{M}_a + \mathcal{M}_b + \mathcal{M}_c + \mathcal{M}_d + \mathcal{M}_e$$

- Operators matched:

- Scalar S_{RR}, S_{RL}
- Vector: V_{LL}, V_{LR}
- Tensor: T_{RR}
- Dim 7: $O_{\mu\mu sbD1}, O_{\mu\mu sbD2}, O_{sb\mu\mu D1}, O_{bs\mu\mu D1}^\dagger$

$$\mathcal{M}_{1\text{-loop}} \xrightarrow{\text{EOM, Dirac identities, Fierz}} \{V, S, T, \mathcal{O}_D\}$$

safe D=4 limit

$B_s \rightarrow \mu^+ \mu^-$: Current Status

- UV finiteness ✓
- IR finiteness ✓

- **ISSUE: leading order limit in ρ** $\nearrow m \rightarrow \mathcal{E} m, (s, t, u) \rightarrow \mathcal{E}^2(s, t, u)$

$$C_A^{(0)} = \frac{V_{LR}^{(0)} - V_{LL}^{(0)}}{2} = -\frac{g^4 \lambda_t}{32\pi^2 m_W^2} \left(Y_0(x_t) + \underbrace{\frac{x_t}{192}}_{222} \right),$$

$$Y_0(x) = \frac{x}{8} \left[\frac{4-x}{1-x} + \frac{3x \ln x}{(1-x)^2} \right] \leftarrow \begin{matrix} 222 \\ \vdots \end{matrix}$$

- Suspect: package X using $D = 4$ specific identities
- **SOLUTION: trying to use a different package**

Conclusions & Outlook

1. Flavor-changing Higgs decays

- Complete one-loop calculation
- UV finite and gauge independent
- SM branching fractions obtained

2. $B_s - \bar{B}_s$ mixing

- Subleading m_b^2 -suppressed box amplitudes calculated
- Feynman / unitary gauge agreement
- EFT subtraction and EOM / RG subtleties

3. $B_s \rightarrow \mu^+ \mu^-$

- One-loop unitary-gauge calculation
- UV and IR cancellations verified
- Final operator matching and comparison with the known SM result still under investigation

GOAL: Reliable SM benchmarks for future constraints on flavor-changing Higgs couplings.