Heavy flavour aspects in EFTs

Model-independent bounds on the Standard Model Effective Theory from Flavour Physics

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In collaboration with ***Luca Silvestrini***

UTA : A PRECISION TEST OF THE SM

From Unitarity of the CKM

$$(V^\dagger V)_{db} = 0 \;\leftrightarrow\; \text{apex: } (\bar\rho, \bar\eta)$$

Over-constrained global fit

$$\Delta m_{d,s} \;\leftrightarrow\; B\text{-}\bar{B} \text{ mixing}$$

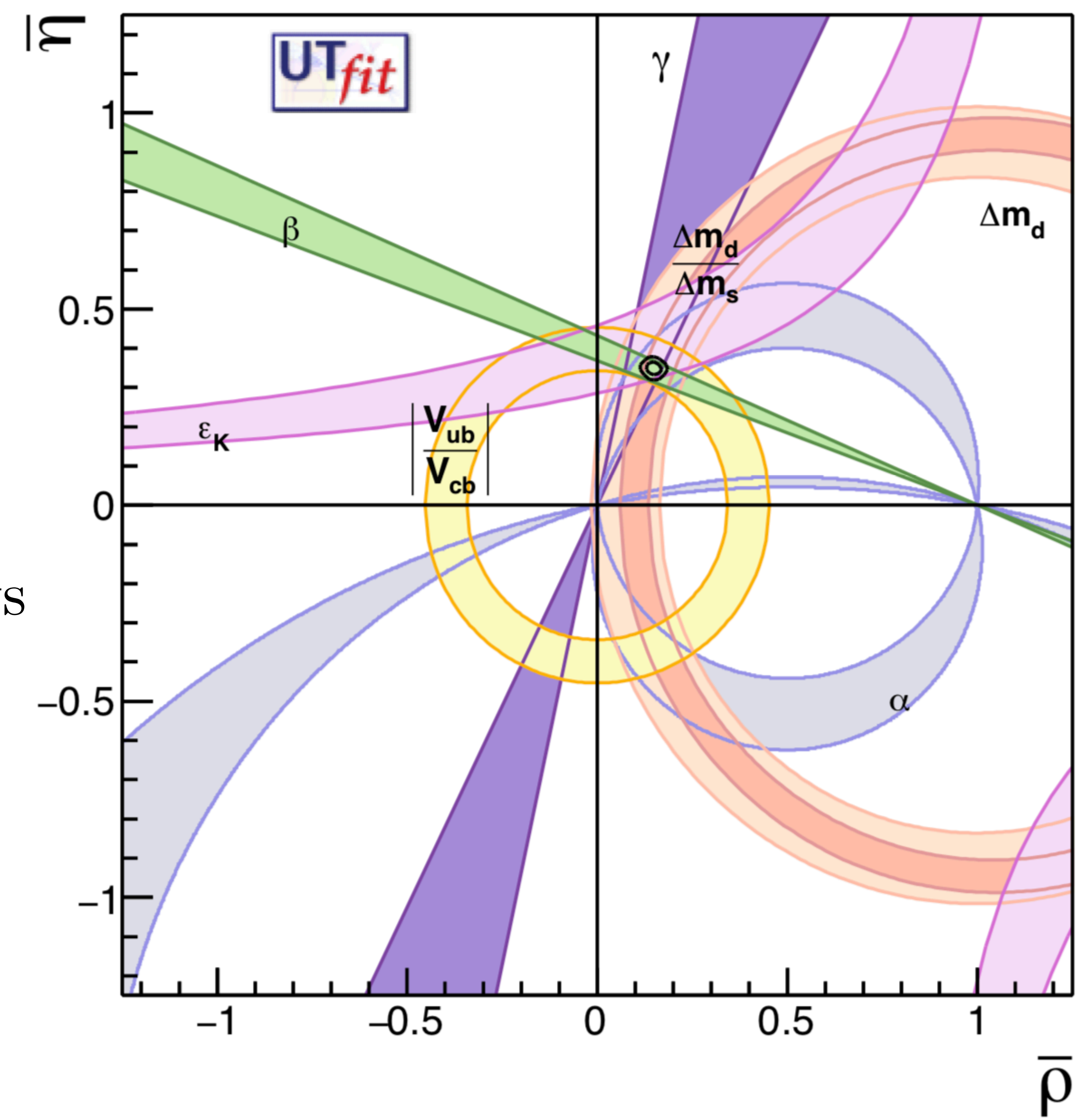
$$\epsilon_K \;\leftrightarrow\; K\text{-}\bar{K} \text{ mixing}$$

$$|V_{ub}/V_{cb}| \;\leftrightarrow\; \text{semileptonic } B \text{ decays}$$

$$\alpha, \beta, \gamma \;\leftrightarrow\; \text{hadronic } B \text{ decays}$$

$$\bar\rho = 0.148 \pm 0.013$$
$$\bar\eta = 0.348 \pm 0.010$$

http://www.utfit.org/UTfit



WHAT ABOUT NEW PHYSICS ?

No tree-level Flavor-Changing-Neutral-Current processes (FCNCs) in the SM.

Furthermore, suppression of FCNC amplitudes in the SM due to GIM.

⇨ $\Delta F = 2$ *: excellent probe of Physics Beyond the SM!*

The most general Weak Effective Hamiltonian for meson anti-meson mixing is:

[see, e.g., *M.Bona et al.* ***JHEP 03 (2008) 049***]

$$\mathcal{H}_{\rm eff}^{\Delta S=2} = \sum_{i=1}^{5} C_i O_i^{sd} + \sum_{i=1}^{3} \tilde{C}_i \tilde{O}_i^{sd}$$

$$\mathcal{H}_{\rm eff}^{\Delta C=2} = \sum_{i=1}^{5} C_i O_i^{cu} + \sum_{i=1}^{3} \tilde{C}_i \tilde{O}_i^{cu}$$

$$\mathcal{H}_{\rm eff}^{\Delta B=2} = \sum_{i=1}^{5} C_i O_i^{bq} + \sum_{i=1}^{3} \tilde{C}_i \tilde{O}_i^{bq}$$

where: $\tilde{O}_i \equiv O_i(L \leftrightarrow R)$

$$O_1^{q_i q_j} = \bar{q}_{jL}^{\alpha} \gamma_\mu q_{iL}^{\alpha} \, \bar{q}_{jL}^{\beta} \gamma^\mu q_{iL}^{\beta}$$ SM

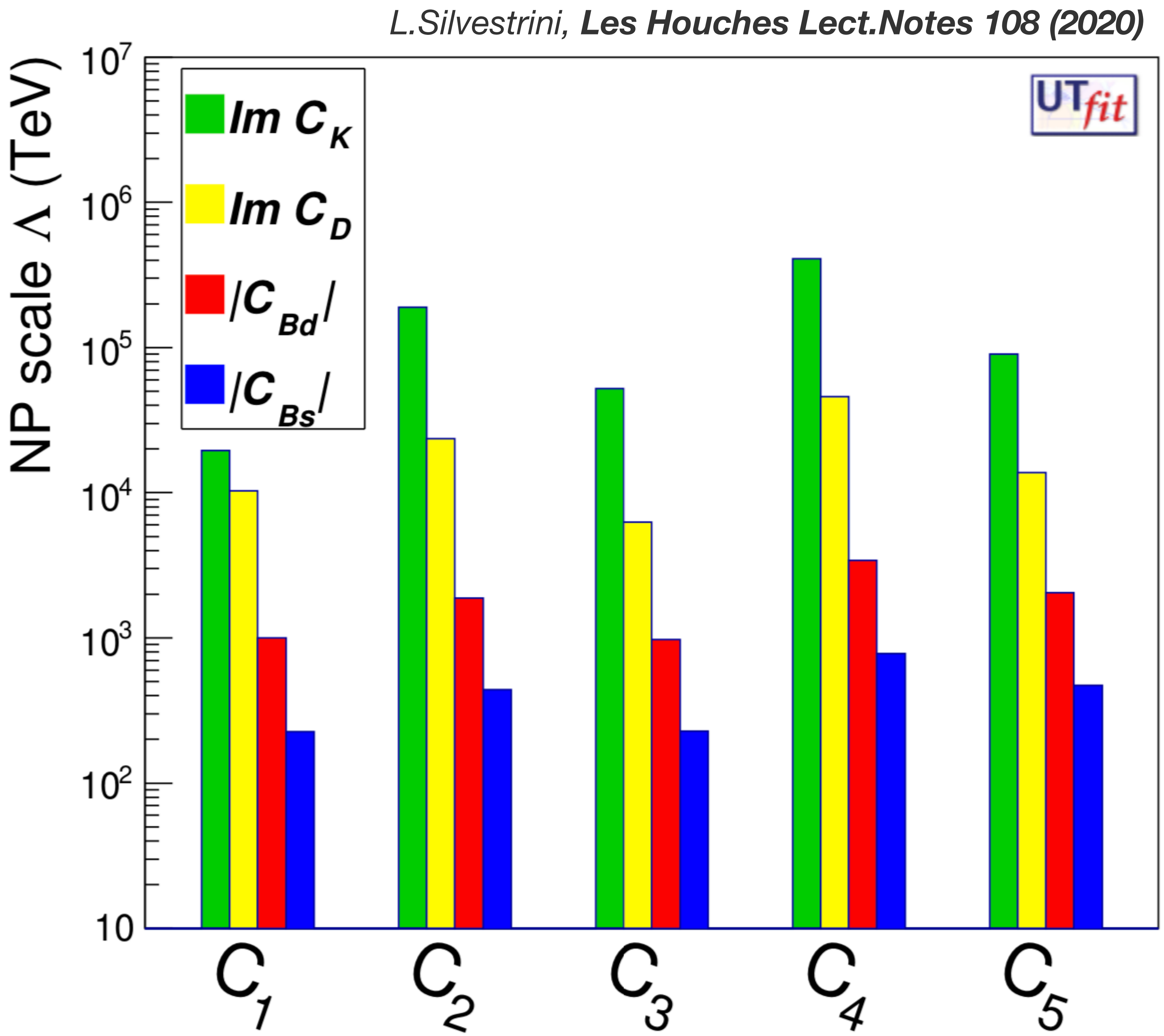
$$O_2^{q_i q_j} = \bar{q}_{jR}^{\alpha} q_{iL}^{\alpha} \, \bar{q}_{jR}^{\beta} q_{iL}^{\beta}$$

$$O_3^{q_i q_j} = \bar{q}_{jR}^{\alpha} q_{iL}^{\beta} \, \bar{q}_{jR}^{\beta} q_{iL}^{\alpha}$$

$$O_4^{q_i q_j} = \bar{q}_{jR}^{\alpha} q_{iL}^{\alpha} \, \bar{q}_{jL}^{\beta} q_{iR}^{\beta}$$

$$O_5^{q_i q_j} = \bar{q}_{jR}^{\alpha} q_{iL}^{\beta} \, \bar{q}_{jL}^{\beta} q_{iR}^{\alpha}$$

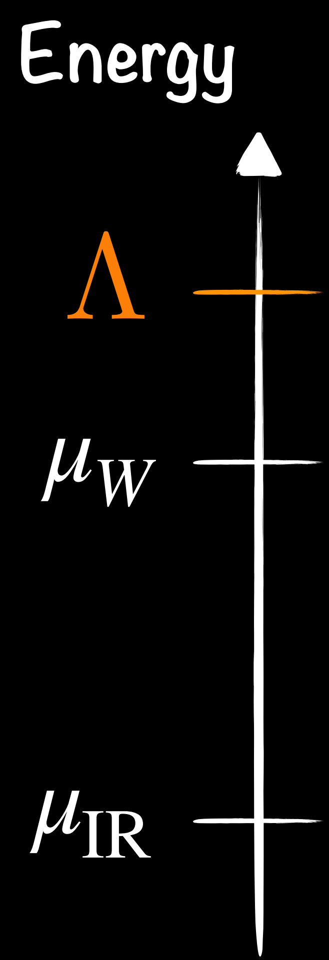
AMOUNT OF NP ALLOWED IN ΔF = 2



⚠️ New generic source of flavor / CP violation —> high NP scale

ΔF = 2 UNDER $SU(2)_L \times U(1)_Y$

ABOVE THE EW SCALE, WE MUST EXPLOIT **SM GAUGE SYMMETRY**



ΔF = 2 IN THE SMEFT

$$O^{QQ^{(1)}}_{ijij} = \bar{Q}_i \gamma_\mu Q_j \bar{Q}_i \gamma^\mu Q_j$$
$$O^{QQ^{(3)}}_{ijij} = \bar{Q}_i \gamma_\mu \tau^A Q_j \bar{Q}_i \gamma^\mu \tau^A Q_j$$
$$O^{qq}_{ijij} = \bar{q}_i \gamma_\mu q_j \bar{q}_i \gamma^\mu q_j$$
$$O^{Qq^{(1)}}_{ijij} = \bar{Q}_i \gamma_\mu Q_j \bar{q}_i \gamma^\mu q_j$$
$$O^{Qq^{(8)}}_{ijij} = \bar{Q}_i \gamma_\mu T^a Q_j \bar{q}_i \gamma^\mu T^a q_j$$

CAPITAL CASE

$SU(2)_L$ Doublets

LOWER CASE

$SU(2)_L$ singlets

See, e.g.:

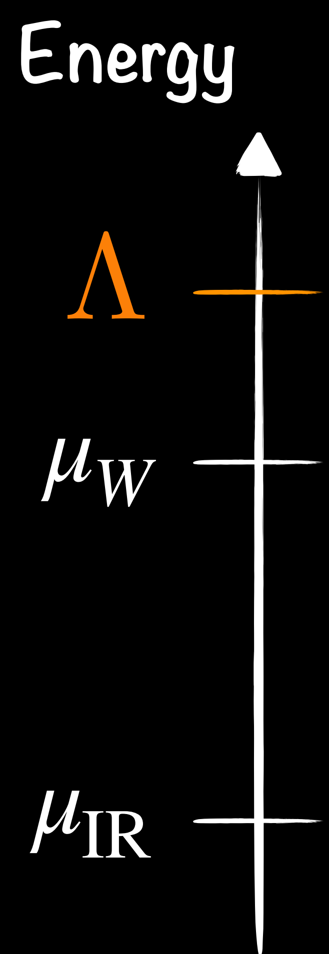
J.Aebischer et al. 1512.02830

A.Celis et al. 1704.04504

(q = u, d stands now on for RH fields ; $\boldsymbol{\tau}^A$ Pauli matrices ; $\boldsymbol{T}^a$ color ones)

$\Delta F = 2$ UNDER $SU(2)_L \times U(1)_Y$

ABOVE THE EW SCALE, WE MUST EXPLOIT **SM GAUGE SYMMETRY**



$\Delta F = 2$ MATCHING IN THE SMEFT

$$C_1(\mu_W) = -\left(C^{QQ^{(1)}}(\mu_W) + C^{QQ^{(3)}}(\mu_W)\right)/\Lambda^2$$

$$\tilde{C}_1(\mu_W) = -C^{qq}(\mu_W)/\Lambda^2$$

$$C_4(\mu_W) = C^{Qq^{(8)}}(\mu_W)/\Lambda^2$$

$$C_5(\mu_W) = \left(6C^{Qq^{(1)}}(\mu_W) - C^{Qq^{(8)}}(\mu_W)\right)/(3\Lambda^2)$$

$$\Rightarrow \quad C_2(\mu_W) = \tilde{C}_2(\mu_W) = C_3(\mu_W) = \tilde{C}_3(\mu_W) = 0$$

CAPITAL CASE

$SU(2)_L$ Doublets

LOWER CASE

$SU(2)_L$ singlets

See, e.g.:

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$\Delta F = 2$ BOUNDS — A modern view

95% BOUNDS $\mathbf{X}$ FROM MESON — ANTI-MESON MIXING AT THE EW SCALE IN $\mathbf{TeV^{-2}}$

		$\mathrm{Re\,X_1}$	$\mathrm{Im\,X_1}$	$\mathrm{Re\,X_4}$	$\mathrm{Im\,X_4}$	$\mathrm{Re\,X_5}$	$\mathrm{Im\,X_5}$
□	$s \leftrightarrow d$	$5.9 \cdot 10^{-7}$	$2.0 \cdot 10^{-9}$	$4.0 \cdot 10^{-9}$	$1.8 \cdot 10^{-11}$	$7.5 \cdot 10^{-8}$	$2.0 \cdot 10^{-10}$
◇	$c \leftrightarrow u$	$2.5 \cdot 10^{-7}$	$7.5 \cdot 10^{-9}$	$4.2 \cdot 10^{-8}$	$1.3 \cdot 10^{-9}$	$2.5 \cdot 10^{-7}$	$7.7 \cdot 10^{-9}$
△	$b \leftrightarrow d$	$9.5 \cdot 10^{-7}$	$8.0 \cdot 10^{-7}$	$2.0 \cdot 10^{-7}$	$1.5 \cdot 10^{-7}$	$5.0 \cdot 10^{-7}$	$4.8 \cdot 10^{-7}$
▽	$b \leftrightarrow s$	$2.0 \cdot 10^{-5}$	$6.7 \cdot 10^{-6}$	$5.8 \cdot 10^{-6}$	$2.0 \cdot 10^{-6}$	$1.3 \cdot 10^{-5}$	$4.5 \cdot 10^{-6}$

$$C_{\mathrm{NP}}\ [\mathrm{TeV}^{-2}] \leq \mathrm{X} \quad \Leftrightarrow \quad \Lambda_{\mathrm{NP}}\ [\mathrm{TeV}] \geq 1/\sqrt{\mathrm{X}}$$

ij	$C^{QQ^{(1,3)}}_{ijij}$	C^{dd}_{ijij}	C^{uu}_{ijij}	$C^{Qd^{(1)}}_{ijij}$	$C^{Qd^{(8)}}_{ijij}$	$C^{Qu^{(1)}}_{ijij}$	$C^{Qu^{(8)}}_{ijij}$
12	(Re , Im)	…	…	…	…	…	…
13	…	…	…	…	…	…	…
23	…	…	…	…	…	…	…

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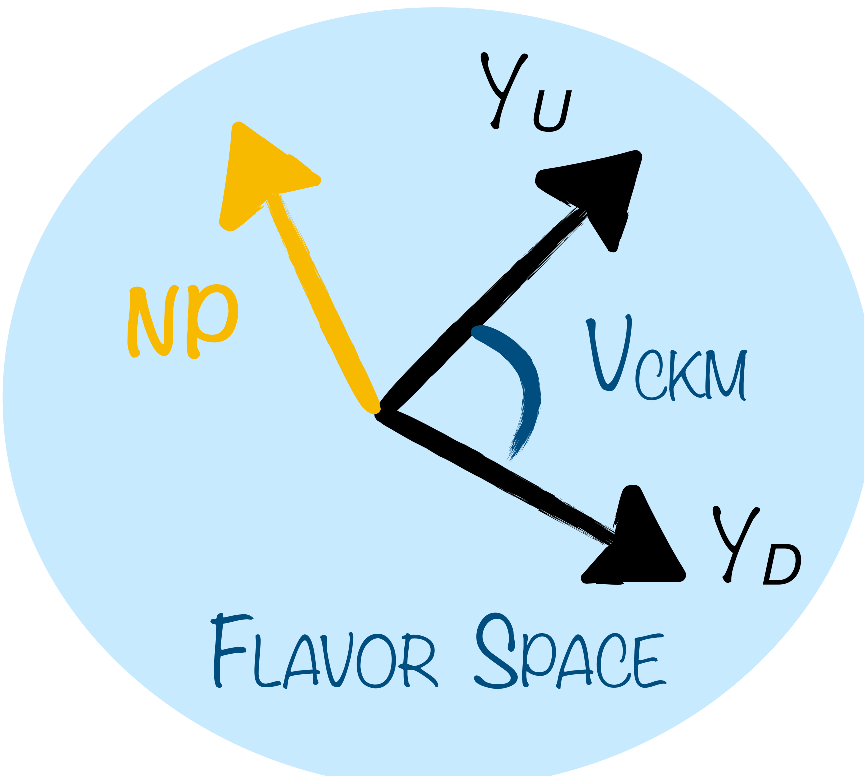
$\Delta F = 2$ BOUNDS — A modern view

$$U(3)_Q \times U(3)_u \times U(3)_d$$



Q: In which **basis** we are defining NP?

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_{i,d>4} \frac{C_i \mathcal{O}_i^{(d)}}{\Lambda_{\mathrm{NP}}^{d-4}}$$

Y_D diag $\xleftrightarrow{V_{\mathrm{CKM}}}$ Y_U diag

Basis where down-quark Yukawa matrix is diagonal

Basis where up-quark Yukawa matrix is diagonal

Orientation in Flavor space imprints NP phenomenology: *2 extremes at hand.*

Important point, since in the SMEFT up and down sectors are correlated!

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$\Delta F = 2$ BOUNDS — A modern view

Let's take for instance: $O^{QQ}_{1111} = (\bar{Q}_1 \gamma_\mu Q_1)^2$

$\rightarrow$ $\Delta F = 0$, still subject to Flavor constraints!

1) If aligned with Y_U : $d_{L,i} \rightarrow V_{1j}\, d_{L,j}$ $\rightarrow$ $K - \bar{K}$

2) If aligned with Y_D : $u_{1,L} \rightarrow V^\dagger_{1j}\, u_{L,j}$ $\rightarrow$ $D - \bar{D}$

going to mass basis

$\Lambda_{\rm NP}^{QQ_{1111}} \gtrsim$ 1) 415 TeV 2) 267 TeV

Note that misalignment of NP in Flavor space is not relevant for fully right-handed quark operators.

$$O^{uu}_{ijkl} = \bar{u}_i \gamma_\mu u_j \bar{u}_k \gamma^\mu u_l$$

well constrained only in 1212

(independent of flavor alignment)

$ijkl$	$C^{QQ(1,3)}_{ijkl}$ [TeV^{-2}] Y_D diag	$C^{QQ(1,3)}_{ijkl}$ [TeV^{-2}] Y_U diag	C^{dd}_{ijkl} [TeV^{-2}] $Y_{D,U}$ diag
1111	$5.8^{\diamond}\ 10^{-6}$	$1.4^{\square}\ 10^{-5}$	$\varnothing$
1112	$(7.0^{\diamond}, 0.19^{\diamond})\ 10^{-7}$	$(17^{\square}, 0.051^{\square})\ 10^{-7}$	$(3.2^{\square}, 1.3^{\square})\ 10^{-3}$
1113	$(15^{\diamond}, 0.44^{\diamond})\ 10^{-6}$	$(39^{\triangle}, 0.12^{\square})\ 10^{-6}$	$(1.4^{\triangle}, 1.2^{\triangle})$
1122	$2.9^{\diamond}\ 10^{-6}$	$6.8^{\square}\ 10^{-6}$	$\varnothing$
1123	$(5.6^{\diamond}, 2.3^{\diamond})\ 10^{-6}$	$(1.5^{\square}, 3.4^{\square})\ 10^{-6}$	$(\varnothing, \varnothing)$
1133	$1.3^{\diamond}\ 10^{-4}$	$3.6^{\square}\ 10^{-5}$	$\varnothing$
1212	$(31^{\diamond}, 0.22^{\square})\ 10^{-8}$	$(28^{\diamond}, 0.25^{\square})\ 10^{-8}$	$(65^{\square}, 0.22^{\square})\ 10^{-8}$
1213	$(3.5^{\diamond}, 0.1^{\diamond})\ 10^{-6}$	$(15^{\square}, 0.3^{\square})\ 10^{-7}$	$(16^{\square}, 0.3^{\square})\ 10^{-4}$
1221	$2.9^{\diamond}\ 10^{-6}$	$6.8^{\square}\ 10^{-6}$	$\varnothing$
1222	$(7.0^{\diamond}, 0.19^{\diamond})\ 10^{-7}$	$(17^{\square}, 0.05^{\square})\ 10^{-7}$	$(3.2^{\square}, 1.3^{\square})\ 10^{-3}$
1223	$(15^{\diamond}, 0.44^{\diamond})\ 10^{-6}$	$(39^{\diamond}, 0.12^{\diamond})\ 10^{-6}$	$(\varnothing, \varnothing)$
1231	$(5.6^{\diamond}, 2.3^{\diamond})\ 10^{-6}$	$(1.5^{\square}, 3.4^{\square})\ 10^{-6}$	$(\varnothing, \varnothing)$
1232	$(1.3^{\diamond}, 2.2^{\diamond})\ 10^{-6}$	$(3.7^{\square}, 1.4^{\square})\ 10^{-7}$	$(7.2^{\square}, 2.9^{\square})\ 10^{-3}$
1233	$(3.1^{\diamond}, 6.2^{\diamond})\ 10^{-5}$	$(8.9^{\square}, 3.4^{\square})\ 10^{-6}$	$(\varnothing, \varnothing)$
1313	$(1.1^{\triangle}, 0.90^{\triangle})\ 10^{-6}$	$(1.1^{\triangle}, 0.95^{\triangle})\ 10^{-6}$	$(1.0^{\triangle}, 0.88^{\triangle})\ 10^{-6}$
1322	$(15^{\diamond}, 0.44^{\diamond})\ 10^{-6}$	$(39^{\diamond}, 0.12^{\diamond})\ 10^{-6}$	$(\varnothing, \varnothing)$
1323	$(3.3^{\diamond}, 0.1^{\diamond})\ 10^{-4}$	$(2.4^{\triangle}, 2.1^{\triangle})\ 10^{-6}$	$(6.3^{\triangle}, 5.3^{\triangle})\ 10^{-1}$
1331	$1.3^{\diamond}\ 10^{-4}$	$3.6^{\square}\ 10^{-5}$	$\varnothing$
1332	$(3.1^{\diamond}, 6.2^{\diamond})\ 10^{-5}$	$(8.9^{\square}, 3.4^{\square})\ 10^{-6}$	$(\varnothing, \varnothing)$
1333	$(6.7^{\diamond}, 15^{\diamond})\ 10^{-4}$	$(6.9^{\triangle}, 5.8^{\triangle})\ 10^{-5}$	$(1.4^{\triangle}, 1.2^{\triangle})$
2222	$5.8^{\diamond}\ 10^{-6}$	$1.4^{\square}\ 10^{-5}$	$\varnothing$
2223	$(5.7^{\diamond}, 2.3^{\diamond})\ 10^{-6}$	$(1.5^{\square}, 3.4^{\square})\ 10^{-6}$	$(3.0^{\triangledown}, 0.98^{\triangledown})\ 10^{-1}$
2233	$1.3^{\diamond}\ 10^{-4}$	$3.6^{\square}\ 10^{-5}$	$\varnothing$
2323	$(2.2^{\triangledown}, 0.75^{\triangledown})\ 10^{-5}$	$(2.1^{\triangle}, 0.80^{\triangle})\ 10^{-5}$	$(2.2^{\triangledown}, 0.74^{\triangledown})\ 10^{-5}$
2332	$1.3^{\diamond}\ 10^{-4}$	$3.6^{\square}\ 10^{-5}$	$\varnothing$
2333	$(2.2^{\diamond}, 2.8^{\diamond})\ 10^{-3}$	$(2.8^{\triangledown}, 0.94^{\triangledown})\ 10^{-4}$	$(3.0^{\triangledown}, 0.98^{\triangledown})\ 10^{-1}$
3333	$4.2^{\diamond}\ 10^{-1}$	$1.3^{\triangledown}\ 10^{-2}$	$\varnothing$

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$\Delta F = 2$ BOUNDS — A modern view

Along the same line, also remaining 4-quark operators are generally well probed by $\Delta F = 2$!

$$O_{ijkl}^{Qd^{(1,8)}}, O_{ijkl}^{Qu^{(1,8)}}$$

Strongest non-trivial bounds:

$$\Lambda_{\rm NP}^{\Delta F=1} \gtrsim 10^4\ \text{TeV}$$

$$\Lambda_{\rm NP}^{\Delta F=0} \gtrsim 10^2\ \text{TeV}$$

$ijkl$	$C_{ijkl}^{Qd^{(1)}}$ [TeV^{-2}] Y_D diag	$C_{ijkl}^{Qd^{(1)}}$ [TeV^{-2}] Y_U diag	$C_{ijkl}^{Qd^{(8)}}$ [TeV^{-2}] Y_D diag	$C_{ijkl}^{Qd^{(8)}}$ [TeV^{-2}] Y_U diag	$C_{ijkl}^{Qu^{(1)}}$ [TeV^{-2}] Y_D diag	$C_{ijkl}^{Qu^{(1)}}$ [TeV^{-2}] Y_U diag	$C_{ijkl}^{Qu^{(8)}}$ [TeV^{-2}] Y_D diag	$C_{ijkl}^{Qu^{(8)}}$ [TeV^{-2}] Y_U diag
1111	$11^\square$	$8.2^\square\,10^{-4}$	$3.3^\square$	$1.7^\square\,10^{-4}$	$3.7^\diamond\,10^{-1}$	$\varnothing$	$2.2^\diamond$	$\varnothing$
1112	$(1.9^\square, 0.81^\square)\,10^{-5}$	$(64^\square, 0.29^\square)\,10^{-9}$	$(5.5^\square, 2.3^\square)\,10^{-6}$	$(14^\square, 0.062^\square)\,10^{-9}$	$(6.0^\diamond, 0.18^\diamond)\,10^{-7}$	$(5.0^\diamond, 4.9^\diamond)$	$(14^\diamond, 0.45^\diamond)\,10^{-8}$	$(1.4^\diamond, 1.4^\diamond)$
1113	$(2.2^\triangle, 2.1^\triangle)\,10^{-3}$	$(7.7^\triangle, 0.77^\square)\,10^{-5}$	$(1.1^\triangle, 0.81^\triangle)\,10^{-3}$	$(3.4^\triangle, 0.16^\square)\,10^{-5}$	$(3.9^\diamond, 0.12^\diamond)\,10^{-2}$	$(\varnothing, 1.8^\square)$	$(24^\diamond, 0.74^\diamond)\,10^{-2}$	$(\varnothing, 5.5^\square)$
1122	$12^\square$	$8.2^\square\,10^{-4}$	$3.3^\square$	$1.7^\square\,10^{-4}$	$1.9^\diamond\,10^{-1}$	$\varnothing$	$1.4^\diamond\,10^{-1}$	$\varnothing$
1123	$(\varnothing, \varnothing)$	$(1.9^\square, 0.75^\square)\,10^{-3}$	$(7.4^\square, 7.4^\square)$	$(4.0^\square, 1.6^\square)\,10^{-4}$	$(7.9^\diamond, 6.5^\diamond)\,10^{-3}$	$(4.8^\square, 11^\square)\,10^{-2}$	$(5.9^\diamond, 4.9^\diamond)\,10^{-3}$	$(1.4^\square, 3.2^\square)\,10^{-1}$
1133	$\varnothing$	$\varnothing$	$\varnothing$	$10^\square$	$\varnothing$	$4.1^\square\,10^{-3}$	$\varnothing$	$1.2^\square\,10^{-2}$
1211	$(1.8^\square, 0.76^\square)\,10^{-4}$	$(2.0^\square, 0.76^\square)\,10^{-4}$	$(3.8^\square, 1.6^\square)\,10^{-5}$	$(4.3^\square, 1.6^\square)\,10^{-5}$	$(9.1^\diamond, 2.5^\diamond)\,10^{-2}$	$(\varnothing, \varnothing)$	$(5.4^\diamond, 1.5^\diamond)\,10^{-1}$	$(\varnothing, \varnothing)$
1212	$(140^\square, 0.63^\square)\,10^{-10}$	$(150^\square, 0.67^\square)\,10^{-10}$	$(30^\square, 0.14^\square)\,10^{-10}$	$(32^\square, 0.14^\square)\,10^{-10}$	$(14^\diamond, 0.43^\diamond)\,10^{-8}$	$(13^\diamond, 0.40^\diamond)\,10^{-8}$	$(3.3^\diamond, 0.1^\diamond)\,10^{-8}$	$(32^\diamond, 0.98^\diamond)\,10^{-9}$
1213	$(9.2^\square, 0.17^\square)\,10^{-5}$	$(6.4^\triangle, 1.8^\square)\,10^{-6}$	$(20^\square, 0.36^\square)\,10^{-6}$	$(36^\triangle, 3.8^\triangle)\,10^{-7}$	$(9.1^\diamond, 0.28^\diamond)\,10^{-3}$	$(\varnothing, 4.4^\diamond)\,10^{-1}$	$(5.5^\diamond, 0.17^\diamond)\,10^{-2}$	$(\varnothing, 5.2^\diamond)\,10^{-1}$
1221	$(1.2^\square, 1.2^\square)$	$(28^\square, 0.13^\square)\,10^{-8}$	$(2.5^\square, 2.7^\square)\,10^{-1}$	$(60^\square, 0.27^\square)\,10^{-9}$	$(26^\diamond, 0.8^\square)\,10^{-7}$	$(\varnothing, \varnothing)$	$(6.2^\diamond, 0.19^\diamond)\,10^{-7}$	$(\varnothing, \varnothing)$
1222	$(1.8^\square, 0.76^\square)\,10^{-4}$	$(2.0^\square, 0.77^\square)\,10^{-4}$	$(3.9^\square, 1.6^\square)\,10^{-5}$	$(4.3^\square, 1.6^\square)\,10^{-5}$	$(4.5^\diamond, 1.3^\diamond)\,10^{-2}$	$(\varnothing, 4.5^\diamond)\,10^{-2}$	$(3.4^\diamond, 0.95^\diamond)\,10^{-2}$	$(\varnothing, 1.3^\diamond)\,10^{-1}$
1223	$(4.6^\square, 2.1^\square)$	$(7.3^\triangledown, 2.5^\triangledown)\,10^{-4}$	$(9.8^\square, 4.4^\square)\,10^{-1}$	$(4.6^\triangledown, 1.6^\triangledown)\,10^{-4}$	$(3.4^\diamond, 2.8^\diamond)\,10^{-2}$	$(120^\square, 0.38^\square)\,10^{-2}$	$(2.6^\diamond, 2.1^\diamond)\,10^{-2}$	$(37^\square, 0.11^\square)\,10^{-1}$
1231	$(\varnothing, \varnothing)$	$(3.3^\triangle, 0.33^\square)\,10^{-4}$	$(\varnothing, \varnothing)$	$(15^\triangle, 0.71^\square)\,10^{-5}$	$(4.8^\square, 0.53^\diamond)\,10^{-2}$	$(\varnothing, \varnothing)$	$(14^\square, 3.2^\diamond)\,10^{-2}$	$(\varnothing, \varnothing)$
1232	$(4.1^\square, 1.7^\square)\,10^{-4}$	$(4.3^\square, 1.7^\square)\,10^{-4}$	$(8.7^\square, 3.6^\square)\,10^{-5}$	$(9.2^\square, 3.7^\square)\,10^{-5}$	$(3.8^\diamond, 1.1^\diamond)\,10^{-3}$	$(12^\square, 4.4^\square)\,10^{-3}$	$(2.8^\diamond, 0.82^\diamond)\,10^{-3}$	$(3.5^\square, 1.3^\square)\,10^{-2}$
1233	$(10^\square, 4.5^\square)$	$(12^\square, 4.3^\square)$	$(2.2^\square, 0.95^\square)$	$(2.5^\square, 0.95^\square)$	$(2.5^\square, 1.0^\square)\,10^{-1}$	$(9.9^\square, 3.8^\square)\,10^{-4}$	$(7.6^\square, 3.1^\square)\,10^{-1}$	$(3.0^\square, 1.1^\square)\,10^{-3}$
1311	$(1.8^\square, 0.80^\square)\,10^{-1}$	$(4.7^\square, 1.8^\square)\,10^{-3}$	$(3.0^\square, 1.4^\square)\,10^{-2}$	$(10^\square, 4.0^\square)\,10^{-4}$	$(1.8^\diamond, 0.6^\diamond)$	$(\varnothing, \varnothing)$	$(11^\diamond, 3.5^\diamond)$	$(\varnothing, \varnothing)$
1312	$(36^\square, 0.65^\square)\,10^{-7}$	$(8.6^\square, 0.16^\square)\,10^{-8}$	$(6.1^\square, 0.11^\square)\,10^{-7}$	$(18^\square, 0.34^\square)\,10^{-9}$	$(31^\diamond, 0.96^\diamond)\,10^{-7}$	$(3.6^\diamond, 0.11^\diamond)\,10^{-1}$	$(7.5^\diamond, 0.23^\diamond)\,10^{-7}$	$(9.4^\diamond, 0.29^\diamond)\,10^{-2}$
1313	$(2.6^\triangle, 2.5^\triangle)\,10^{-7}$	$(2.7^\triangle, 2.6^\triangle)\,10^{-7}$	$(1.5^\triangle, 1.1^\triangle)\,10^{-7}$	$(1.6^\triangle, 1.2^\triangle)\,10^{-7}$	$(20^\diamond, 0.63^\diamond)\,10^{-2}$	$(8.5^\triangle, 7.1^\triangle)$	$(12^\diamond, 0.38^\diamond)\,10^{-1}$	$(\varnothing, \varnothing)$
1321	$(5.2^\square, 5.2^\square)\,10^{-2}$	$(8.6^\square, 3.5^\square)\,10^{-8}$	$(1.1^\square, 1.1^\square)\,10^{-2}$	$(1.8^\square, 0.75^\square)\,10^{-8}$	$(5.2^\diamond, 12^\diamond)\,10^{-6}$	$(\varnothing, \varnothing)$	$(1.3^\diamond, 2.8^\diamond)\,10^{-6}$	$(\varnothing, \varnothing)$
1322	$(1.8^\square, 0.8^\square)\,10^{-1}$	$(4.7^\square, 1.8^\square)\,10^{-3}$	$(3.0^\square, 1.4^\square)\,10^{-2}$	$(10^\square, 4.0^\square)\,10^{-4}$	$(9.2^\diamond, 3.0^\diamond)\,10^{-1}$	$(\varnothing, 1.1^\square)$	$(7.0^\diamond, 2.2^\diamond)\,10^{-1}$	$(\varnothing, 3.2^\square)$
1323	$(3.2^\triangle, 3.1^\triangle)\,10^{-1}$	$(3.1^\triangledown, 1.1^\triangledown)\,10^{-5}$	$(1.8^\triangle, 1.4^\triangle)\,10^{-1}$	$(2.0^\triangledown, 0.67^\triangledown)\,10^{-5}$	$(7.4^\triangle, 6.2^\triangle)\,10^{-2}$	$(7.6^\triangle, 6.4^\triangle)\,10^{-2}$	$(2.2^\triangle, 1.9^\triangle)\,10^{-1}$	$(2.3^\triangle, 2.0^\triangle)\,10^{-1}$
1331	$(8.9^\triangle, 8.7^\triangle)$	$(2.2^\square, 0.94^\square)\,10^{-3}$	$(4.0^\triangle, 4.0^\triangle)$	$(4.7^\square, 2.0^\square)\,10^{-4}$	$(3.5^\diamond, 6.7^\triangle)\,10^{-1}$	$(\varnothing, \varnothing)$	$(2.1^\diamond, 2.0^\triangle)$	$(\varnothing, \varnothing)$
1332	$(4.0^\square, 2.7^\square)\,10^{-1}$	$(4.2^\square, 0.25^\square)\,10^{-3}$	$(6.9^\square, 3.0^\square)\,10^{-2}$	$(15^\square, 2.2^\square)\,10^{-4}$	$(15^\diamond, 4.7^\diamond)\,10^{-5}$	$(2.8^\square, 1.1^\square)\,10^{-1}$	$(11^\diamond, 3.5^\diamond)\,10^{-5}$	$(8.3^\square, 3.2^\square)\,10^{-1}$
1333	$(7.0^\triangle, 7.0^\triangle)\,10^{-1}$	$(7.1^\triangle, 2.8^\triangledown)\,10^{-1}$	$(4.0^\triangle, 3.0^\triangle)\,10^{-1}$	$(3.8^\triangle, 1.8^\triangledown)\,10^{-1}$	$(7.4^\triangle, 6.3^\triangle)\,10^{-3}$	$(7.6^\triangle, 6.4^\triangle)\,10^{-3}$	$(2.2^\triangle, 1.9^\triangle)\,10^{-2}$	$(2.3^\triangle, 2.0^\triangle)\,10^{-2}$
2211	$11^\square$	$8.3^\square\,10^{-4}$	$2.0^\square$	$1.8^\square\,10^{-4}$	$3.7^\diamond\,10^{-1}$	$\varnothing$	$2.2^\diamond$	$\varnothing$
2212	$(1.9^\square, 0.79^\square)\,10^{-5}$	$(64^\square, 0.29^\square)\,10^{-9}$	$(3.2^\square, 1.3^\square)\,10^{-6}$	$(140^\square, 0.62^\square)\,10^{-10}$	$(6.0^\diamond, 0.18^\diamond)\,10^{-7}$	$(3.2^\diamond, 3.2^\diamond)$	$(14^\diamond, 0.45^\diamond)\,10^{-8}$	$(8.5^\diamond, 8.4^\diamond)\,10^{-1}$
2213	$(4.8^\square, 2.1^\square)\,10^{-1}$	$(2.8^\triangle, 0.77^\square)\,10^{-5}$	$(8.1^\square, 3.6^\square)\,10^{-2}$	$(1.6^\square, 0.16^\square)\,10^{-5}$	$(4.0^\diamond, 0.12^\diamond)\,10^{-2}$	$(\varnothing, 1.8^\square)$	$(24^\diamond, 0.74^\diamond)\,10^{-2}$	$(\varnothing, 5.5^\square)$
2222	$11^\square$	$8.2^\square\,10^{-4}$	$2.0^\square$	$1.8^\square\,10^{-4}$	$1.9^\diamond\,10^{-1}$	$\varnothing$	$1.4^\diamond\,10^{-1}$	$\varnothing$
2223	$(1.2^\triangledown, 0.39^\triangledown)\,10^{-2}$	$(1.7^\triangledown, 0.57^\triangledown)\,10^{-4}$	$(6.1^\triangledown, 2.1^\triangledown)\,10^{-3}$	$(1.1^\triangledown, 0.36^\triangledown)\,10^{-4}$	$(16^\diamond, 4.7^\diamond)\,10^{-3}$	$(4.8^\square, 11^\square)\,10^{-2}$	$(12^\diamond, 3.5^\diamond)\,10^{-3}$	$(1.4^\square, 3.2^\square)\,10^{-1}$
2233	$\varnothing$	$4.5^\triangledown$	$\varnothing$	$2.9^\triangledown$	$\varnothing$	$4.1^\square\,10^{-3}$	$\varnothing$	$1.2^\square\,10^{-2}$
2311	$(4.9^\square, 4.9^\square)\,10^{-1}$	$(0.72^\square, 2.7^\square)\,10^{-2}$	$(8.3^\square, 8.4^\square)\,10^{-2}$	$(1.5^\square, 6.0^\square)\,10^{-3}$	$(\varnothing, 3.5^\diamond)$	$(\varnothing, \varnothing)$	$(\varnothing, \varnothing)$	$(\varnothing, \varnothing)$
2312	$(1.8^\square, 0.8^\square)\,10^{-2}$	$(39^\square, 0.68^\square)\,10^{-8}$	$(2.6^\square, 1.2^\square)\,10^{-3}$	$(8.3^\square, 0.15^\square)\,10^{-8}$	$(13^\diamond, 0.42^\diamond)\,10^{-6}$	$(\varnothing, \varnothing)$	$(3.2^\diamond, 0.10^\diamond)\,10^{-6}$	$(\varnothing, \varnothing)$
2313	$(2.4^\triangle, 2.3^\triangle)\,10^{-2}$	$(1.2^\triangle, 1.1^\triangle)\,10^{-6}$	$(1.5^\triangle, 1.1^\triangle)\,10^{-2}$	$(6.7^\triangle, 5.0^\triangle)\,10^{-7}$	$(8.9^\diamond, 0.27^\diamond)\,10^{-1}$	$(\varnothing, \varnothing)$	$(5.3^\diamond, 0.17^\diamond)$	$(\varnothing, \varnothing)$
2321	$(8.3^\square, 3.4^\square)\,10^{-7}$	$(2.0^\square, 0.81^\square)\,10^{-8}$	$(14^\square, 5.7^\square)\,10^{-8}$	$(8.3^\square, 1.7^\square)\,10^{-9}$	$(1.2^\diamond, 2.7^\diamond)\,10^{-6}$	$(1.4^\diamond, 3.1^\diamond)\,10^{-1}$	$(3.0^\diamond, 6.5^\diamond)\,10^{-7}$	$(3.6^\diamond, 8.2^\diamond)\,10^{-2}$
2322	$(1.9^\triangledown, 0.63^\triangledown)$	$(0.72^\square, 2.8^\square)\,10^{-2}$	$(8.3^\square, 4.0^\triangledown)\,10^{-2}$	$(1.5^\square, 6.0^\square)\,10^{-3}$	$(8.6^\triangledown, 1.8^\diamond)$	$(\varnothing, \varnothing)$	$(\varnothing, 1.3^\diamond)$	$(\varnothing, \varnothing)$
2323	$(7.0^\triangledown, 2.4^\triangledown)\,10^{-6}$	$(7.2^\triangledown, 2.4^\triangledown)\,10^{-6}$	$(4.4^\triangledown, 1.5^\triangledown)\,10^{-6}$	$(4.5^\triangledown, 1.6^\triangledown)\,10^{-6}$	$(3.6^\diamond, 1.2^\triangledown)\,10^{-1}$	$(3.3^\triangle, 1.2^\triangledown)\,10^{-1}$	$(2.7^\diamond, 3.2^\triangledown)\,10^{-1}$	$(10^\triangle, 3.7^\triangledown)\,10^{-1}$
2331	$(2.1^\square, 1.0^\square)\,10^{-2}$	$(5.1^\square, 2.2^\square)\,10^{-4}$	$(3.6^\square, 1.5^\square)\,10^{-3}$	$(11^\square, 4.7^\square)\,10^{-5}$	$(0.46^\diamond, 1.8^\diamond)\,10^{-1}$	$(\varnothing, \varnothing)$	$(4.8^\diamond, 11^\diamond)\,10^{-1}$	$(\varnothing, \varnothing)$
2332	$(7.4^\triangledown, 2.5^\triangledown)$	$(4.0^\triangledown, 1.1^\square)\,10^{-3}$	$(4.7^\triangledown, 1.6^\triangledown)$	$(2.5^\triangledown, 0.86^\triangledown)\,10^{-3}$	$(6.5^\diamond, 2.0^\diamond)\,10^{-4}$	$(5.7^\square, \varnothing)\,10^{-1}$	$(5.0^\square, 1.5^\square)\,10^{-4}$	$(1.7^\square, \varnothing)$
2333	$(1.9^\triangledown, 0.63^\triangledown)\,10^{-1}$	$(2.0^\triangledown, 0.65^\triangledown)\,10^{-1}$	$(1.2^\triangledown, 0.40^\triangledown)\,10^{-1}$	$(1.2^\triangledown, 0.42^\triangledown)\,10^{-1}$	$(3.4^\triangledown, 1.0^\triangledown)\,10^{-2}$	$(3.1^\triangledown, 1.0^\triangledown)\,10^{-2}$	$(9.1^\triangledown, 3.0^\triangledown)\,10^{-2}$	$(9.4^\triangledown, 3.1^\triangledown)\,10^{-2}$
3311	$\varnothing$	$2.7^\square\,10^{-1}$	$\varnothing$	$5.8^\square\,10^{-2}$	$\varnothing$	$\varnothing$	$\varnothing$	$\varnothing$
3312	$(8.0^\square, 3.4^\square)\,10^{-4}$	$(4.5^\square, 2.0^\square)\,10^{-7}$	$(12^\square, 5.0^\square)\,10^{-5}$	$(9.6^\square, 8.1^\square)\,10^{-8}$	$(2.7^\diamond, 6.1^\diamond)\,10^{-5}$	$(\varnothing, \varnothing)$	$(6.6^\diamond, 15^\diamond)\,10^{-6}$	$(\varnothing, \varnothing)$
3313	$(1.0^\triangle, 1.0^\triangle)\,10^{-3}$	$(3.3^\triangle, 3.2^\triangle)\,10^{-5}$	$(6.4^\triangle, 4.8^\triangle)\,10^{-4}$	$(1.9^\triangle, 1.4^\triangle)\,10^{-5}$	$(1.8^\diamond, 4.0^\diamond)$	$(\varnothing, \varnothing)$	$(\varnothing, 11^\diamond)$	$(\varnothing, \varnothing)$
3322	$\varnothing$	$2.7^\square\,10^{-1}$	$\varnothing$	$5.8^\square\,10^{-2}$	$\varnothing$	$\varnothing$	$\varnothing$	$\varnothing$
3323	$(5.3^\triangledown, 1.8^\triangledown)\,10^{-3}$	$(1.7^\triangledown, 0.58^\triangledown)\,10^{-4}$	$(3.6^\triangledown, 1.2^\triangledown)\,10^{-3}$	$(1.1^\triangledown, 0.37^\triangledown)\,10^{-4}$	$(1.5^\diamond, 1.8^\diamond)\,10^{-2}$	$(8.7^\triangledown, 2.9^\triangledown)$	$(1.1^\diamond, 1.3^\diamond)\,10^{-2}$	$(\varnothing, 8.7^\triangledown)$
3333	$\varnothing$	$4.5^\triangledown$	$\varnothing$	$2.9^\triangledown$	$\varnothing$	$7.3^\triangledown\,10^{-1}$	$\varnothing$	$2.2^\triangledown$

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$\Delta F = 2$ BOUNDS — RGE driven

ij	$C_{ij}^{HQ(1,3)}$ [TeV^{-2}] Y_D diag	Y_U diag
11	$\varnothing$	$4.1^{\square}\ 10^{-3}$
12	$(8.9^{\square}, 3.8^{\square})\ 10^{-4}$	$(9.9^{\square}, 3.8^{\square})\ 10^{-4}$
13	$(7.4^{\triangle}, 6.3^{\triangle})\ 10^{-3}$	$(7.6^{\triangle}, 6.4^{\triangle})\ 10^{-3}$
22	$\varnothing$	$4.1^{\square}\ 10^{-3}$
23	$(3.0^{\triangledown}, 1.0^{\triangledown})\ 10^{-2}$	$(3.1^{\triangledown}, 1.0^{\triangledown})\ 10^{-2}$
33	$\varnothing$	$7.3^{\triangle}\ 10^{-1}$

$\Rightarrow \Lambda_{\rm NP} \gtrsim 15$ TeV

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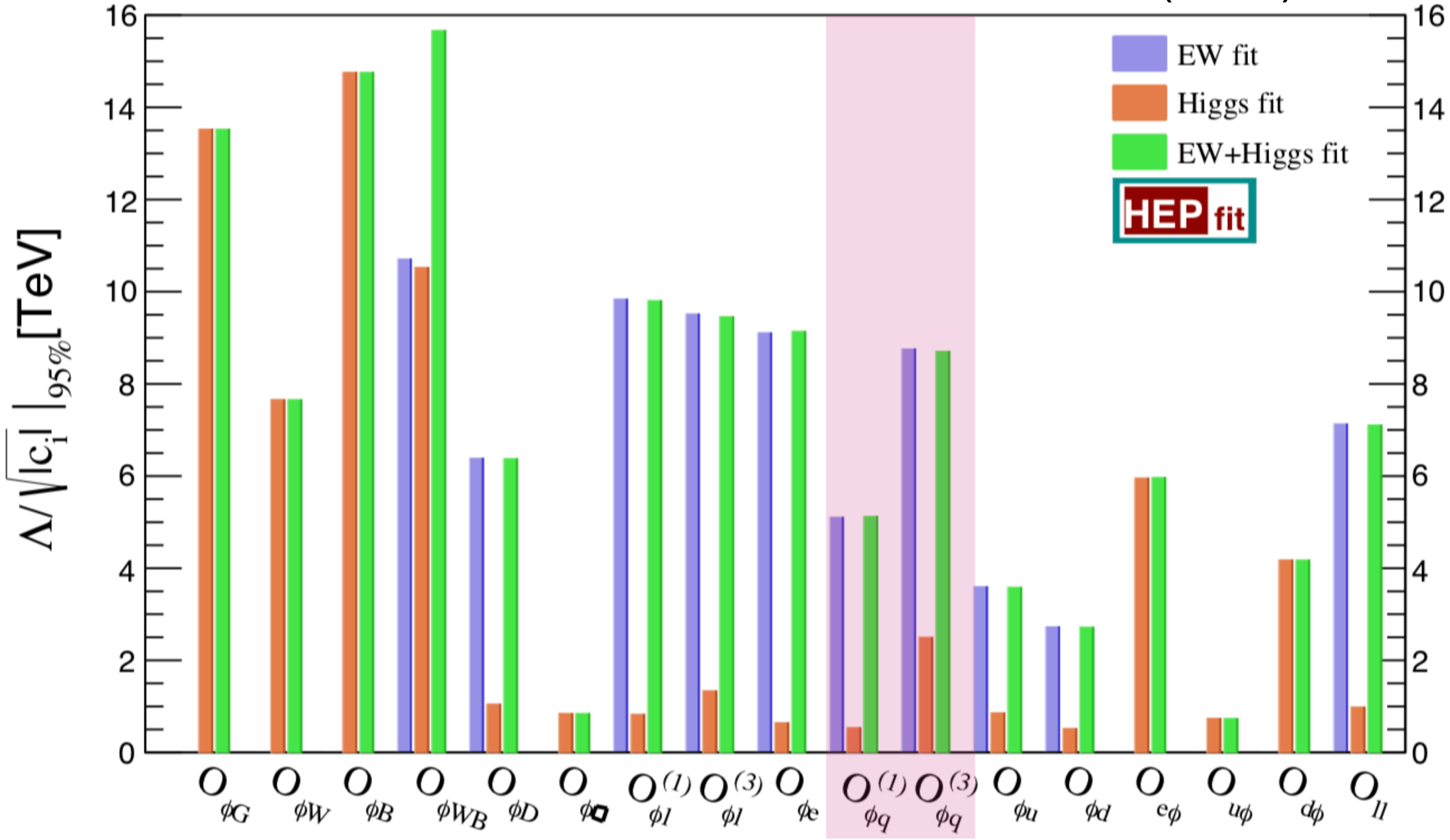

$ijkl$	C_{ijkl}^{LeQu} [TeV^{-2}] Y_D diag	C_{ijkl}^{LedQ} [TeV^{-2}] Y_U diag
2221	$(5.1^{\diamond}, 1.6^{\diamond})\ 10^{-1}$	$(4.2^{\square}, 0.13^{\square})\ 10^{-1}$
2222	$(22^{\diamond}, 6.8^{\diamond})\ 10^{-1}$	$(18^{\square}, 0.58^{\square})\ 10^{-1}$
2223	$(\varnothing, \varnothing)$	$(4.3^{\square}, 1.6^{\square})$
3321	$(3.0^{\diamond}, 0.93^{\diamond})\ 10^{-2}$	$(24^{\square}, 0.8^{\square})\ 10^{-3}$
3322	$(1.3^{\diamond}, 0.4^{\diamond})\ 10^{-1}$	$(10^{\square}, 0.34^{\square})\ 10^{-2}$
3323	$(3.1^{\diamond}, 3.6^{\diamond})$	$(2.5^{\square}, 0.9^{\square})\ 10^{-1}$
3331	$(\varnothing, 9.5^{\diamond})$	$(8.5^{\triangle}, 11^{\triangle})$
3332	$(\varnothing, \varnothing)$	$(\varnothing, 8.9^{\triangledown})$

$$O_{ijkl}^{LeQu} \equiv \bar{L}_i e_j \epsilon \bar{Q}_k u_l$$

mixes into ΔF = 2 operators in the up sector via $Y_U\, Y_L$ —> constraints from D-$\bar{\rm D}$ mixing only

$$O_{ijkl}^{LedQ} \equiv \bar{L}_i e_j \bar{d}_k Q_l$$

mixes into ΔF = 2 operators in the down sector via $Y_D\, Y_L$ —> constraints from K-$\bar{\rm K}$ & B-$\bar{\rm B}$ mixing only

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OTHER BOUNDS FROM RGE

$ijkl$	$C^{ud(1)}_{ijkl}$ [TeV^{-2}] Y_D diag	$C^{ud(1)}_{ijkl}$ [TeV^{-2}] Y_U diag	$C^{ud(8)}_{ijkl}$ [TeV^{-2}] Y_D diag	$C^{ud(8)}_{ijkl}$ [TeV^{-2}] Y_U diag
1112	$(\varnothing, 1.1^{\square})$	$(\varnothing, \varnothing)$	$(\varnothing, 0.10^{\square})$	$(\varnothing, \varnothing)$
1212	$(\varnothing, 2.5^{\square})\ 10^{-1}$	$(\varnothing, 2.5^{\square})\ 10^{-1}$	$(99^{\square}, 0.45^{\square})\ 10^{-1}$	$(99^{\square}, 0.45^{\square})\ 10^{-1}$
1213	$(\varnothing, \varnothing)$	$(\varnothing, \varnothing)$	$(\varnothing, 7.0^{\diamond})$	$(\varnothing, \varnothing)$
1221	$(360^{\square}, 0.95^{\square})\ 10^{-2}$	$(\varnothing, 4.6^{\square})$	$(38^{\square}, 0.17^{\square})\ 10^{-2}$	$(\varnothing, 8.3^{\square})\ 10^{-1}$
1222	$(\varnothing, 11^{\diamond})$	$(\varnothing, 11^{\diamond})$	$(\varnothing, 3.6^{\diamond})$	$(\varnothing, 3.6^{\diamond})$
1223	$(\varnothing, 4.7^{\diamond})$	$(\varnothing, \varnothing)$	$(\varnothing, 1.6^{\diamond})$	$(\varnothing, \varnothing)$
1231	$(2.4^{\triangle}, 2.3^{\triangle})$	$(\varnothing, \varnothing)$	$(1.9^{\triangle}, 1.4^{\triangle})$	$(\varnothing, \varnothing)$
1232	$(12^{\triangledown}, 5.0^{\triangledown})$	$(\varnothing, \varnothing)$	$(4.6^{\diamond}, 4.5^{\triangledown})$	$(4.6^{\diamond}, 10^{\diamond})$
1233	$(6.0^{\diamond}, \varnothing)$	$(\varnothing, \varnothing)$	$(2.0^{\diamond}, 4.5^{\diamond})$	$(\varnothing, \varnothing)$
1312	$(\varnothing, 5.7^{\square})$	$(11^{\square}, 0.21^{\square})\ 10^{-1}$	$(\varnothing, 1.0^{\square})$	$(21^{\square}, 0.37^{\square})\ 10^{-2}$
1313	$(2.2^{\triangle}, 2.1^{\triangle})$	$(2.2^{\triangle}, 2.1^{\triangle})$	$(1.7^{\triangle}, 1.3^{\triangle})$	$(1.7^{\triangle}, 1.3^{\triangle})$
1321	$(2.3^{\square}, 0.96^{\square})\ 10^{-3}$	$(12^{\square}, 4.7^{\square})\ 10^{-1}$	$(4.2^{\square}, 1.7^{\square})\ 10^{-4}$	$(2.0^{\square}, 0.84^{\square})\ 10^{-1}$
1331	$(2.1^{\triangle}, 2.0^{\triangle})\ 10^{-1}$	$(\varnothing, \varnothing)$	$(1.7^{\triangle}, 1.2^{\triangle})\ 10^{-1}$	$(\varnothing, \varnothing)$
1332	$(1.0^{\triangledown}, 4.3^{\triangledown})\ 10^{-1}$	$(\varnothing, \varnothing)$	$(8.9^{\triangledown}, 3.8^{\triangledown})\ 10^{-1}$	$(\varnothing, \varnothing)$
2212	$(83^{\square}, 0.22^{\square})\ 10^{-2}$	$(83^{\square}, 0.22^{\square})\ 10^{-2}$	$(89^{\square}, 0.4^{\square})\ 10^{-3}$	$(89^{\square}, 0.4^{\square})\ 10^{-3}$
2213	$(4.7^{\triangle}, 4.5^{\triangle})\ 10^{-1}$	$(\varnothing, \varnothing)$	$(3.7^{\triangle}, 2.8^{\triangle})\ 10^{-1}$	$(\varnothing, 11^{\square})$
2223	$(28^{\triangledown}, 9.7^{\triangledown})\ 10^{-1}$	$(\varnothing, \varnothing)$	$(25^{\triangledown}, 8.6^{\triangledown})\ 10^{-1}$	$(\varnothing, \varnothing)$
2312	$(\varnothing, 5.1^{\square})\ 10^{-2}$	$(11^{\square}, 0.19^{\square})\ 10^{-3}$	$(200^{\square}, 0.92^{\square})\ 10^{-2}$	$(11^{\square}, 0.33^{\square})\ 10^{-4}$
2313	$(1.9^{\triangle}, 1.9^{\triangle})\ 10^{-2}$	$(1.9^{\triangle}, 1.9^{\triangle})\ 10^{-2}$	$(1.5^{\triangle}, 1.2^{\triangle})\ 10^{-2}$	$(1.5^{\triangle}, 1.2^{\triangle})\ 10^{-2}$
2321	$(5.5^{\square}, 2.2^{\square})\ 10^{-4}$	$(5.5^{\square}, 2.2^{\square})\ 10^{-4}$	$(9.9^{\square}, 4.0^{\square})\ 10^{-5}$	$(9.9^{\square}, 4.0^{\square})\ 10^{-5}$
2323	$(1.2^{\triangledown}, 0.40^{\triangledown})\ 10^{-1}$	$(1.2^{\triangledown}, 0.40^{\triangledown})\ 10^{-1}$	$(1.0^{\triangledown}, 0.36^{\triangledown})\ 10^{-1}$	$(1.0^{\triangledown}, 0.36^{\triangledown})\ 10^{-1}$
2331	$(4.7^{\triangle}, 4.5^{\triangle})\ 10^{-2}$	$(\varnothing, 6.0^{\square})$	$(3.8^{\triangle}, 2.8^{\triangle})\ 10^{-2}$	$(2.5^{\square}, 1.1^{\square})$
2332	$(2.4^{\triangledown}, 0.82^{\triangledown})\ 10^{-1}$	$(\varnothing, \varnothing)$	$(2.1^{\triangledown}, 0.72^{\triangledown})\ 10^{-1}$	$(\varnothing, \varnothing)$
3311	$(\varnothing, \varnothing)$	$(\varnothing, \varnothing)$	$(\varnothing, \varnothing)$	$(4.8^{\square}, \varnothing)$
3312	$(13^{\square}, 5.1^{\square})\ 10^{-3}$	$(4.4^{\square}, 2.0^{\square})\ 10^{-5}$	$(2.3^{\square}, 0.92^{\square})\ 10^{-3}$	$(8.0^{\square}, 3.4^{\square})\ 10^{-6}$
3313	$(2.0^{\triangle}, 1.9^{\triangle})\ 10^{-3}$	$(2.0^{\triangle}, 1.9^{\triangle})\ 10^{-3}$	$(1.6^{\triangle}, 1.2^{\triangle})\ 10^{-3}$	$(1.6^{\triangle}, 1.2^{\triangle})\ 10^{-3}$
3322	$(\varnothing, \varnothing)$	$(\varnothing, \varnothing)$	$(\varnothing, \varnothing)$	$(4.8^{\square}, \varnothing)$
3323	$(10^{\triangledown}, 3.4^{\triangledown})\ 10^{-3}$	$(10^{\triangledown}, 3.4^{\triangledown})\ 10^{-3}$	$(8.7^{\triangledown}, 3.0^{\triangledown})\ 10^{-3}$	$(8.7^{\triangledown}, 3.0^{\triangledown})\ 10^{-3}$

$O^{ud^{1[8]}}_{ijkl}$

$\bar{u}_i\gamma_\mu[T^a]u_j\ \bar{d}_k\gamma^\mu[T^a]d_l$

$O^{QuQd^{1[8]}}_{ijkl}$

$\bar{Q}_i\gamma_\mu[T^a]u_j\epsilon\,\bar{Q}_l\gamma_\mu[T^a]d_j$

$ijkl$	$C^{QuQd(1)}_{ijkl}$ [TeV^{-2}] Y_D diag	$C^{QuQd(1)}_{ijkl}$ [TeV^{-2}] Y_U diag	$C^{QuQd(8)}_{ijkl}$ [TeV^{-2}] Y_D diag	$C^{QuQd(8)}_{ijkl}$ [TeV^{-2}] Y_U diag
1111	$(\varnothing, \varnothing)$	$(\varnothing, 4.8^{\square})$	$(\varnothing, \varnothing)$	$(\varnothing, \varnothing)$
1112	$(92^{\square}, 0.41^{\square})\ 10^{-1}$	$(9.5^{\square}, 0.31^{\square})$	$(\varnothing, 0.49^{\square})$	$(\varnothing, 1.6^{\square})$
1113	$(4.0^{\diamond}, 8.9^{\diamond})$	$(\varnothing, \varnothing)$	$(\varnothing, \varnothing)$	$(\varnothing, \varnothing)$
1121	$(\varnothing, 3.2^{\diamond})$	$(\varnothing, 1.1^{\square})$	$(\varnothing, \varnothing)$	$(\varnothing, \varnothing)$
1122	$(\varnothing, 0.71^{\diamond})$	$(\varnothing, 1.6^{\square})$	$(\varnothing, 8.6^{\diamond})$	$(\varnothing, \varnothing)$
1123	$(9.2^{\diamond}, 21^{\diamond})\ 10^{-1}$	$(\varnothing, \varnothing)$	$(11^{\diamond}, \varnothing)$	$(\varnothing, \varnothing)$
1211	$(5.1^{\diamond}, 1.6^{\diamond})$	$(95^{\square}, 0.43^{\square})\ 10^{-1}$	$(\varnothing, 8.3^{\diamond})$	$(\varnothing, 5.1^{\square})\ 10^{-1}$
1212	$(210^{\square}, 0.96^{\square})\ 10^{-2}$	$(22^{\square}, 0.1^{\square})\ 10^{-1}$	$(\varnothing, 1.1^{\square})\ 10^{-1}$	$(\varnothing, 1.2^{\square})\ 10^{-1}$
1213	$(8.9^{\triangle}, 3.6^{\diamond})$	$(\varnothing, \varnothing)$	$(\varnothing, \varnothing)$	$(\varnothing, \varnothing)$
1221	$(\varnothing, 11^{\diamond})$	$(220^{\square}, 0.99^{\square})\ 10^{-2}$	$(\varnothing, \varnothing)$	$(\varnothing, 1.2^{\square})\ 10^{-1}$
1222	$(3.1^{\diamond}, 2.3^{\diamond})\ 10^{-1}$	$(14^{\square}, 0.4^{\square})\ 10^{-2}$	$(\varnothing, 9.8^{\diamond})\ 10^{-1}$	$(10^{\square}, 0.53^{\square})\ 10^{-2}$
1223	$(22^{\diamond}, 0.69^{\diamond})\ 10^{-1}$	$(\varnothing, \varnothing)$	$(\varnothing, 4.3^{\diamond})\ 10^{-1}$	$(\varnothing, \varnothing)$
1231	$(3.4^{\diamond}, 1.4^{\diamond})$	$(\varnothing, 0.23^{\square})$	$(\varnothing, 8.2^{\diamond})$	$(\varnothing, 2.8^{\square})$
1232	$(4.0^{\diamond}, 1.7^{\diamond})\ 10^{-2}$	$(6.5^{\square}, 15^{\square})\ 10^{-2}$	$(2.4^{\diamond}, 1.1^{\diamond})\ 10^{-1}$	$(1.2^{\square}, 2.6^{\square})\ 10^{-2}$
1233	$(9.0^{\diamond}, 1.5^{\diamond})\ 10^{-3}$	$(\varnothing, \varnothing)$	$(11^{\diamond}, 4.4^{\diamond})\ 10^{-2}$	$(\varnothing, \varnothing)$
1311	$(\varnothing, \varnothing)$	$(11^{\square}, 4.3^{\square})\ 10^{-3}$	$(\varnothing, \varnothing)$	$(13^{\square}, 5.2^{\square})\ 10^{-2}$
1312	$(\varnothing, 2.2^{\square})\ 10^{-1}$	$(470^{\square}, 8.5^{\square})\ 10^{-4}$	$(\varnothing, 2.6^{\square})$	$(5.6^{\square}, 0.1^{\square})\ 10^{-1}$
1313	$(3.7^{\triangle}, 2.8^{\triangle})\ 10^{-1}$	$(3.9^{\triangle}, 2.9^{\triangle})\ 10^{-1}$	$(2.2^{\triangle}, 2.1^{\triangle})$	$(2.4^{\triangle}, 2.3^{\triangle})$
1321	$(\varnothing, \varnothing)$	$(2.4^{\square}, 0.11^{\square})\ 10^{-3}$	$(\varnothing, \varnothing)$	$(2.9^{\square}, 1.2^{\square})\ 10^{-2}$
1322	$(\varnothing, \varnothing)$	$(21^{\square}, 0.37^{\square})\ 10^{-2}$	$(\varnothing, \varnothing)$	$(41^{\square}, 0.74^{\square})\ 10^{-3}$
1323	$(\varnothing, \varnothing)$	$(4.5^{\triangle}, 4.3^{\triangle})\ 10^{-1}$	$(\varnothing, \varnothing)$	$(3.4^{\triangle}, 2.6^{\triangle})\ 10^{-1}$
1331	$(\varnothing, \varnothing)$	$(5.5^{\square}, 2.3^{\square})\ 10^{-2}$	$(\varnothing, \varnothing)$	$(6.7^{\square}, 2.8^{\square})\ 10^{-1}$
1332	$(\varnothing, \varnothing)$	$(5.0^{\square}, 0.16^{\square})\ 10^{-4}$	$(\varnothing, \varnothing)$	$(5.9^{\square}, 0.12^{\square})\ 10^{-4}$
1333	$(\varnothing, \varnothing)$	$(1.7^{\triangle}, 2.3^{\triangle})\ 10^{-1}$	$(\varnothing, \varnothing)$	$(2.0^{\triangle}, 2.7^{\triangle})\ 10^{-1}$
2111	$(\varnothing, 3.15^{\diamond})$	$(\varnothing, 1.1^{\square})$	$(\varnothing, \varnothing)$	$(\varnothing, \varnothing)$
2112	$(\varnothing, 7.1^{\diamond})\ 10^{-1}$	$(\varnothing, 3.2^{\square})$	$(\varnothing, 8.6^{\diamond})$	$(\varnothing, 9.4^{\square})$
2113	$(9.2^{\diamond}, 21^{\diamond})\ 10^{-1}$	$(\varnothing, \varnothing)$	$(11^{\diamond}, \varnothing)$	$(\varnothing, \varnothing)$
2121	$(\varnothing, 2.4^{\square})\ 10^{-1}$	$(\varnothing, 2.6^{\square})\ 10^{-1}$	$(\varnothing, 2.9^{\square})$	$(\varnothing, 3.1^{\square})$
2122	$(5.3^{\diamond}, 0.17^{\diamond})$	$(5.1^{\diamond}, 0.16^{\diamond})$	$(\varnothing, 2.0^{\diamond})$	$(\varnothing, 1.9^{\diamond})$
2123	$(2.1^{\diamond}, 4.7^{\diamond})\ 10^{-1}$	$(2.0^{\diamond}, 4.5^{\diamond})\ 10^{-1}$	$(2.6^{\diamond}, 5.7^{\diamond})$	$(2.4^{\diamond}, 5.4^{\diamond})$
2131	$(\varnothing, \varnothing)$	$(\varnothing, 6.0^{\square})$	$(\varnothing, \varnothing)$	$(\varnothing, \varnothing)$
2132	$(\varnothing, 3.7^{\diamond})$	$(\varnothing, \varnothing)$	$(\varnothing, \varnothing)$	$(\varnothing, \varnothing)$
2133	$(4.8^{\diamond}, 10^{\diamond})$	$(\varnothing, \varnothing)$	$(\varnothing, \varnothing)$	$(\varnothing, \varnothing)$
2211	$(\varnothing, 8.0^{\diamond})$	$(22^{\square}, 0.1^{\square})\ 10^{-1}$	$(\varnothing, \varnothing)$	$(\varnothing, 1.2^{\square})\ 10^{-1}$
2212	$(1.9^{\diamond}, 0.527^{\diamond})$	$(2.3^{\square}, 0.11^{\square})\ 10^{-2}$	$(1.4^{\diamond}, 1.3^{\diamond})$	$(28^{\square}, 0.13^{\square})\ 10^{-1}$
2213	$(\varnothing, 8.6^{\diamond})\ 10^{-1}$	$(8.0^{\triangle}, 10^{\triangle})$	$(9.0^{\diamond}, 0.28^{\diamond})$	$(\varnothing, \varnothing)$
2221	$(48^{\square}, 0.22^{\square})\ 10^{-2}$	$(51^{\square}, 0.23^{\square})\ 10^{-2}$	$(58^{\square}, 0.26^{\square})\ 10^{-1}$	$(61^{\square}, 0.27^{\square})\ 10^{-1}$
2222	$(12^{\diamond}, 7.0^{\diamond})\ 10^{-1}$	$(8.3^{\square}, 0.38^{\square})\ 10^{-2}$	$(6.1^{\diamond}, 2.4^{\diamond})$	$(4.3^{\square}, 0.16^{\square})\ 10^{-1}$
2223	$(9.7^{\diamond}, 0.30^{\diamond})$	$(\varnothing, 7.1^{\triangledown})$	$(\varnothing, 3.4^{\diamond})$	$(\varnothing, \varnothing)$
2231	$(\varnothing, 2.2^{\square})$	$(31^{\square}, 0.53^{\square})\ 10^{-1}$	$(\varnothing, \varnothing)$	$(\varnothing, 0.64^{\square})$
2232	$(1.8^{\diamond}, 0.72^{\diamond})\ 10^{-1}$	$(2.8^{\square}, 1.3^{\square})\ 10^{-1}$	$(11^{\diamond}, 4.3^{\diamond})\ 10^{-1}$	$(5.0^{\square}, 11^{\square})\ 10^{-2}$
2233	$(3.9^{\diamond}, 0.64^{\diamond})\ 10^{-2}$	$(\varnothing, \varnothing)$	$(4.7^{\diamond}, 1.9^{\diamond})\ 10^{-1}$	$(\varnothing, \varnothing)$
2311	$(\varnothing, \varnothing)$	$(2.4^{\square}, 1.1^{\square})\ 10^{-3}$	$(\varnothing, \varnothing)$	$(2.9^{\square}, 1.2^{\square})\ 10^{-2}$
2312	$(\varnothing, \varnothing)$	$(10^{\square}, 0.2^{\square})\ 10^{-3}$	$(\varnothing, \varnothing)$	$(5.9^{\square}, 0.1^{\square})\ 10^{-2}$
2313	$(\varnothing, \varnothing)$	$(8.9^{\triangle}, 6.7^{\triangle})\ 10^{-2}$	$(\varnothing, \varnothing)$	$(4.4^{\triangle}, 3.7^{\triangle})\ 10^{-1}$
2321	$(5.3^{\square}, 2.2^{\square})\ 10^{-4}$	$(5.7^{\square}, 2.3^{\square})\ 10^{-4}$	$(6.4^{\square}, 2.6^{\square})\ 10^{-3}$	$(6.8^{\square}, 2.8^{\square})\ 10^{-3}$
2322	$(\varnothing, \varnothing)$	$(48^{\square}, 0.83^{\square})\ 10^{-3}$	$(\varnothing, \varnothing)$	$(57^{\square}, 1.0^{\square})\ 10^{-2}$
2323	$(5.7^{\triangledown}, 2.0^{\triangledown})\ 10^{-1}$	$(3.9^{\triangle}, 2.1^{\triangledown})\ 10^{-1}$	$(3.1^{\triangledown}, 1.1^{\triangledown})$	$(2.3^{\triangle}, 1.1^{\triangledown})$
2331	$(5.3^{\square}, 2.3^{\square})\ 10^{-1}$	$(13^{\square}, 5.4^{\square})\ 10^{-3}$	$(6.4^{\square}, 2.7^{\square})$	$(15^{\square}, 6.5^{\square})\ 10^{-2}$
2332	$(\varnothing, \varnothing)$	$(25^{\square}, 0.7^{\square})\ 10^{-4}$	$(\varnothing, \varnothing)$	$(25^{\square}, 0.51^{\square})\ 10^{-4}$
2333	$(\varnothing, \varnothing)$	$(5.0^{\triangledown}, 1.7^{\triangledown})\ 10^{-1}$	$(\varnothing, \varnothing)$	$(6.2^{\triangledown}, 2.1^{\triangledown})\ 10^{-1}$
3112	$(\varnothing, \varnothing)$	$(6.2^{\square}, \varnothing)$	$(\varnothing, \varnothing)$	$(\varnothing, \varnothing)$
3121	$(\varnothing, \varnothing)$	$(\varnothing, 6.0^{\square})$	$(\varnothing, \varnothing)$	$(\varnothing, \varnothing)$
3122	$(\varnothing, 3.7^{\diamond})$	$(\varnothing, \varnothing)$	$(\varnothing, \varnothing)$	$(\varnothing, \varnothing)$
3123	$(4.8^{\diamond}, 11^{\diamond})$	$(\varnothing, \varnothing)$	$(\varnothing, \varnothing)$	$(\varnothing, \varnothing)$
3211	$(\varnothing, \varnothing)$	$(\varnothing, 0.23^{\square})$	$(\varnothing, 5.5^{\diamond})$	$(\varnothing, 2.8^{\square})$
3212	$(4.8^{\diamond}, 2.1^{\diamond})\ 10^{-1}$	$(2.9^{\square}, 6.6^{\square})\ 10^{-3}$	$(16^{\diamond}, 6.6^{\diamond})\ 10^{-2}$	$(1.8^{\square}, 4.0^{\square})\ 10^{-2}$
3213	$(3.6^{\diamond}, 1.0^{\diamond})\ 10^{-2}$	$(\varnothing, \varnothing)$	$(4.3^{\diamond}, 0.6^{\diamond})\ 10^{-2}$	$(\varnothing, \varnothing)$
3221	$(\varnothing, 2.2^{\square})$	$(31^{\square}, 0.54^{\square})\ 10^{-1}$	$(\varnothing, \varnothing)$	$(\varnothing, 0.64^{\square})\ 10^{-1}$
3222	$(2.1^{\diamond}, 0.85^{\diamond})$	$(1.3^{\square}, 2.7^{\square})\ 10^{-2}$	$(7.1^{\diamond}, 2.9^{\diamond})\ 10^{-1}$	$(0.80^{\square}, 2.4^{\square})\ 10^{-1}$
3223	$(15^{\diamond}, 4.8^{\diamond})\ 10^{-2}$	$(\varnothing, \varnothing)$	$(1.9^{\diamond}, 0.28^{\diamond})\ 10^{-1}$	$(\varnothing, \varnothing)$
3231	$(4.6^{\triangle}, 3.5^{\triangle})\ 10^{-1}$	$(4.6^{\triangle}, 3.5^{\triangle})\ 10^{-1}$	$(2.8^{\triangle}, 2.7^{\triangle})$	$(2.8^{\triangle}, 2.7^{\triangle}$
3232	$(3.1^{\triangledown}, 1.1^{\triangledown})$	$(0.3^{\square}, 1.1^{\triangledown})$	$(\varnothing, 5.8^{\triangledown})$	$(3.6^{\square}, 5.8^{\square})$
3233	$(4.0^{\diamond}, 5.9^{\diamond})\ 10^{-1}$	$(\varnothing, \varnothing)$	$(2.4^{\diamond}, 3.1^{\diamond})$	$(\varnothing, \varnothing)$
3311	$(\varnothing, \varnothing)$	$(5.5^{\square}, 2.3^{\square})\ 10^{-2}$	$(\varnothing, \varnothing)$	$(6.6^{\square}, 2.8^{\square})\ 10^{-1}$
3312	$(\varnothing, \varnothing)$	$(12^{\square}, 0.26^{\square})\ 10^{-5}$	$(\varnothing, \varnothing)$	$(1.5^{\square}, 3.5^{\square})\ 10^{-3}$
3313	$(\varnothing, \varnothing)$	$(4.3^{\triangle}, 5.7^{\triangle})\ 10^{-2}$	$(\varnothing, \varnothing)$	$(5.2^{\triangle}, 5.7^{\triangle})\ 10^{-1}$
3321	$(5.3^{\square}, 2.3^{\square})\ 10^{-1}$	$(13^{\square}, 5.4^{\square})\ 10^{-3}$	$(6.4^{\square}, 2.7^{\square})$	$(15^{\square}, 6.2^{\square})\ 10^{-2}$
3322	$(\varnothing, \varnothing)$	$(5.2^{\square}, 0.11^{\square})\ 10^{-4}$	$(\varnothing, \varnothing)$	$(0.62^{\square}, 1.3^{\square})\ 10^{-2}$
3323	$(\varnothing, \varnothing)$	$(1.3^{\triangledown}, 0.44^{\triangledown})\ 10^{-1}$	$(\varnothing, \varnothing)$	$(1.2^{\triangledown}, 0.41^{\triangledown})$
3331	$(4.7^{\triangle}, 3.5^{\triangle})\ 10^{-2}$	$(4.7^{\triangle}, 3.5^{\triangle})\ 10^{-2}$	$(2.8^{\triangle}, 2.7^{\triangle})\ 10^{-1}$	$(2.8^{\triangle}, 2.7^{\triangle})\ 10^{-1}$
3332	$(2.6^{\triangledown}, 0.9^{\triangledown})\ 10^{-1}$	$(7.1^{\square}, 2.7^{\square})\ 10^{-4}$	$(1.4^{\triangledown}, 0.49^{\triangledown})$	$(3.8^{\square}, 1.4^{\square})\ 10^{-3}$
3333	$(\varnothing, \varnothing)$	$(2.4^{\triangledown}, 0.83^{\triangledown})$	$(\varnothing, \varnothing)$	$(10^{\triangledown}, 3.6^{\triangledown})$

SMEFT: A FLAVORFUL SUMMARY

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SMEFT RGE

$O^{HQ(1[3])}_{jk}$ $(H^\dagger i \overleftrightarrow{D}^{[A]}_\mu H)\,(\bar{Q}_j\gamma^\mu\,[\tau^A]\,Q_k)$	O^{LedQ}_{jjkl} $(\bar{L}_j e_j)\,(\bar{d}_k Q_l)$	O^{LeQu}_{jjkl} $(\bar{L}_j e_j) i\tau^2\,(\bar{Q}_k u_l)$	$O^{ud(1[8])}_{jklm}$ $(\bar{u}_j\gamma_\mu[T^a]u_k)\,(\bar{d}_l\gamma^\mu[T^a]d_m)$	$O^{QuQd(1[8])}_{jklm}$ $(\bar{Q}_j\gamma_\mu[T^a]u_k) i\tau^2\,(\bar{Q}_l\gamma^\mu[T^a]d_m)$
$O^{QQ(1[3])}_{jklm}$ $(\bar{Q}_j\gamma_\mu[\tau^A]Q_k)\,(\bar{Q}_l\gamma^\mu[\tau^A]Q_m)$	O^{uu}_{jklm} $(\bar{u}_j\gamma_\mu u_k)\,(\bar{u}_l\gamma^\mu u_m)$	O^{dd}_{jklm} $(\bar{d}_j\gamma_\mu d_k)\,(\bar{d}_l\gamma^\mu d_m)$	$O^{Qd(1[8])}_{jklm}$ $(\bar{Q}_j\gamma_\mu[T^a]Q_k)\,(\bar{d}_l\gamma^\mu[T^a]d_m)$	$O^{Qu(1[8])}_{jklm}$ $(\bar{Q}_j\gamma_\mu[T^a]Q_k)\,(\bar{u}_l\gamma^\mu[T^a]u_m)$

poorly constrained

FLAVOR MISALIGNMENT

Interesting future directions ahead:

—> IMPACT OF OTHER FLAVOR MEASUREMENTS (e.g., $\Delta F = 1$ FCNCs)

See recent work in: 2003.05432 (R.Aoude et al.) , 2005.05366 (D.A.Faroughy et al.) , 2009.07276 (J.Aebischer et al.) , 2101.07273 (S.Bruggisser et al.)

—> INTERPLAY WITH DI-BOSON SEARCHES / EW PRECISION / HIGGS / TOP PHYSICS

See previous talks by David Marzocca and by Gudrun Hiller!

BACK-UP

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$\Delta F = 2$ BOUNDS — A modern view

Leading-log RGE effects may be also relevant …

Let's compare bounds in the SMEFT on ΔF = 1 operators that run into ΔF = 2 via RGE:

$$\mathcal{A}_{\rm NP}^{\Delta F=2} \lesssim \mathcal{A}_{\rm SM}^{\Delta F=2} \varepsilon_{\Delta F=2} \qquad \Bigg| \qquad \mathcal{A}_{\rm NP}^{\Delta F=1} \lesssim \mathcal{A}_{\rm SM}^{\Delta F=1} \varepsilon_{\Delta F=1}$$

$\mathcal{A}$ being short-distance amplitude, $\varepsilon_{\Delta F=i}$ amount of NP allowed in $\Delta F = i$

$$\mathcal{A}_{\rm SM}^{\Delta F=2} \sim \frac{(Y_{\rm SM} Y_{\rm SM}^\dagger)^2}{\Lambda_{\rm EW}^2}\,,\quad \mathcal{A}_{\rm NP}^{\Delta F=2} \sim \frac{C_{\rm NP}^{\Delta F=2}}{\Lambda_{\rm NP}^2} \qquad \Bigg| \qquad \mathcal{A}_{\rm SM}^{\Delta F=1} \sim \frac{Y_{\rm SM} Y_{\rm SM}^\dagger}{\Lambda_{\rm EW}^2}\,,\quad \mathcal{A}_{\rm NP}^{\Delta F=1} \sim \frac{C_{\rm NP}^{\Delta F=1}}{\Lambda_{\rm NP}^2}$$

ΔF = 2 BOUND ON NEW PHYSICS SCALE IS STRONGER IFF:

$$\frac{C_{\rm NP}^{\Delta F=2}\,\Lambda_{\rm EW}^2}{(Y_{\rm SM} Y_{\rm SM}^\dagger)^2 \varepsilon_{\Delta F=2}} \gtrsim \frac{C_{\rm NP}^{\Delta F=1}\,\Lambda_{\rm EW}^2}{Y_{\rm SM} Y_{\rm SM}^\dagger \varepsilon_{\Delta F=1}}$$

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RGE in the SMEFT implies:

$$C_{\rm NP}^{\Delta F=2} = Y_{\rm SM}Y_{\rm SM}^\dagger\, C_{\rm NP}^{\Delta F=1}\,\mathcal{R} \equiv \frac{1}{16\pi^2}\log\left(\frac{\Lambda_{\rm NP}}{\Lambda_{\rm EW}}\right) \sim \mathcal{O}(\%)$$

THEN, ΔF = 2 BOUND RELEVANT IFF $\mathcal{R} \gtrsim \varepsilon_{\Delta F=2}/\varepsilon_{\Delta F=1}$