Rank-One Flavor Violation and B-anomalies

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Valerio Gherardi, D.M., Marco Nardecchia, Andrea Romanino [\[1903.10954\]](https://arxiv.org/abs/1903.10954)

NPKI 2019, 13/05/2019

Neutral-Current B-anomalies ⁹ *,* Re*C^µ* ¹⁰) plane. We are particularly interested in the case weutral-Current B-anomalie. \mathcal{I} $b \rightarrow s \mu^{+} \mu^{-}$ \Box Π ull dog Fig. 8 shows the parameter Γ we most like the most like
We will not the most like the most like

If NP, then a contribution to this LH operator is necessary If NID than a contribution to this I H aparator is necessary \cdots in this work: related to the standard parameters of the standard parameter

$$
\mathcal{L}_{\text{eff}} \supset \frac{e^{i\alpha_{bs}}}{\Lambda_{bs}^2} (\bar{s}_L \gamma^\mu b_L) (\bar{\mu}_L \gamma_\mu \mu_L) + h.c. \qquad \qquad \frac{e^{-\Lambda_{bs}}}{\Lambda_{bs}^2} = \frac{G_F \alpha}{\sqrt{2}\pi} V_{tb} V_{ts}^* (\Delta C_9^\mu) \qquad \qquad \Lambda_{bs}^{\text{SM}} \approx 12 \text{ TeV}
$$

$$
\frac{e^{i\alpha_{bs}}}{\Lambda_{bs}^2} = \frac{G_F \alpha}{\sqrt{2}\pi} V_{tb} V_{ts}^* (\Delta C_9^{\mu} - \Delta C_{10}^{\mu})
$$

$$
\Lambda_{bs}^{\text{SM}} \approx 12 \text{ TeV}
$$

 (Λ_{bs}) best-fit $(\alpha_{bs}=0) \approx 38 \text{ TeV}$ $(\Lambda_{bs})^{\text{best-fit}}$ $(a_{bs}=0) \approx 38 \text{ TeV}$ $(4 \text{ } 105)$ $(400s - 0)$ $(2 \text{ } 100s - 0)$ $\frac{9}{2}$, the best-fit point assuming vanishing imaginary particles in assuming vanishing imaginary particles in $\frac{1}{2}$

also angular distributions and branching ratios:
 $\begin{bmatrix} 0 & 0 \\ 0 & -1 \end{bmatrix}$ \overline{B} is *Adding also angular* I recall g aloo angeler element is a fit brand ling redoo. Adding also angular distributions and branching ratios:

$$
(\Lambda_{bs})^{best\text{-fit}}\ \, (\alpha_{bs}=0)\,\approx 34\,\,TeV
$$

C
C sin 1903.09578, Algorio et al. 1903.09578, Al D'Amico et al. 1704.05438, Algueró et al. 1903.09578, Alok et al.
1903.09617, Ciuchini et al. 1903.09632, Aebischer et al 1903.10434 D'Amico et al. 1704.05438, Algueró et al. 1903.09578, Alok et al.
1903.09617, Ciuchini et al. 1903.09632, Aebischer et al 1903.10434 therefore include also these uncertainties and marginalise over the relevant parameters, this

*n n a***q (7)** *n a***q** (7) *n a***q** (7) *n a***q** (7) *n a***q** (7) *n a COURBE IS COURPERS WILL GATA.*
F lower NP scale, the upper limit is c A non-zero phase is compatible with data. $\frac{1}{1 - C_{10}^{\mu}} = \frac{\pi}{\sqrt{2}} e^{i \alpha_{bs}}$ It implies a lower NP scale, the upper limit is due to a ugh (destructive) interference with SM.
——————————————————— is however beyond the purpose of this work. Comparing the top-left panel in Fig. 8 with the not large enough (destructive) interference with SM.

A new flavour structure *Cdd Cds Cdb* r_1

The operator(s) responsible for the anomalies are part of an EFT involving all three families

$$
\mathcal{L}_{\mathrm{NP}}^{\mathrm{EFT}} = C_{ij} (\bar{d}_L^i \gamma_\mu d_L^i)(\bar{\mu}_L \gamma^\mu \mu_L)
$$

$$
\mathcal{C} = \begin{pmatrix} \mathcal{C}_{dd} & \mathcal{C}_{ds} & \mathcal{C}_{db} \\ \mathcal{C}_{ds}^* & \mathcal{C}_{ss} & \mathcal{C}_{sb} \\ \mathcal{C}_{db}^* & \mathcal{C}_{sb}^* & \mathcal{C}_{bb} \end{pmatrix}
$$

 Γ \overline{a} We are learning about C_{sb} **What about the rest?**

Cij = *C n* ˆ *in* ˆ⇤ avoi *b*iedring termi: What is the SU(3)_q structure of this new flavor breaking term?

⇠ *i d* answer, we need to mide
flavor-violating transitions. \overline{C} To answer, we need to find and study correlations with other

Directions in SU(3)_q space *D*irections in SU(3)_q space. \blacksquare *Cij S,T,R* = *CS,T,R n*ˆ*in*ˆ⇤ *^j ,* (4)

We can parametrise directions in SU(3)_q as: \overline{a} rtions in SU(3), as:

Via a U(1)_B phase redefinition we can always set $\hat{n_3}\!\!>\!\!0$

 $\theta \in [0, \frac{\pi}{2}]$ $\phi \in [0, 2\pi)$ $\alpha_{bd} \in [-\frac{\pi}{2}, \frac{\pi}{2}]$ $\alpha_{bc} \in [-\frac{\pi}{2}, \frac{\pi}{2}]$ *ts, V* ⇤ *tb*) 0*.*042 4*.*92 0*.*018 0*.*39 $\theta \in \left[0, \frac{\pi}{2}\right]$, $\phi \in \left[0, 2\pi\right)$, $\alpha_{bd} \in \left[-\frac{\pi}{2}, \frac{\pi}{2}\right]$, $\alpha_{bs} \in \left[-\frac{\pi}{2}, \frac{\pi}{2}\right]$ $\sqrt{ }$ 0*,* π 2 i $, \quad \phi \in [0, 2\pi)$, $\alpha_{bd} \in$ $\left[-\frac{\pi}{2}\right]$ *,* π 2 i $, \quad \alpha_{bs} \in$ $\left[-\frac{\pi}{2}\right]$ *,* π 2 $\overline{1}$

In the mass eigenstate basis of down-quarks: *,* 2 [0*,* 2⇡) *,* ↵*bd* 2 The flavour structure of the semileptonic operators, Eq. (4), implies the existence of studying these can be summarized as follows: for a given direction ˆ*n*, we fix (some combina-

$$
q_L^i=\left(\begin{array}{c} V_{ji}^*u_L^i \\ d_L^i \end{array}\right)
$$

 \setminus

{qi

 $\sin\theta\cos\phi e^{i\alpha_{bd}}$

 $\sin\theta\sin\phi e^{i\alpha_{bs}}$

 $\cos\theta$

 $\hat{n}=% {\textstyle\sum\nolimits_{\alpha}} e_{\alpha}/2\pi\varepsilon_{0}$

 $\overline{1}$

 \overline{a}

|✏1*,*3*|* \overline{a} = (7) g phases **is described by the CKM matrix**. The misalignment between down- and up-quarks

^L} (1)

A *,* (5)

Rank-One Flavor Violation *Cdd Cds Cdb* **Flavor Violation**

Valerio Gherardi, D.M., Marco Nardecchia, Andrea Romanino [1903.10954]

$$
\mathcal{L}_{\rm NP}^{\rm EFT} = C_{ij} (\bar{d}_L^i \gamma_\mu d_L^i) (\bar{\mu}_L \gamma^\mu \mu_L)
$$

We assume that the *flavor matrix* $\frac{1}{2}$ **L**

*L*of the semi-leptonic couplings **to muons** is of **rank-one**: We assume that the flavor
of the semi-leptonic couplings to muo *L*) we may not the matrix α and β *L* and β *^L*EFT

$$
C_{ij} = C \,\hat{n}_i \hat{n}_j^*
$$

 \hat{n} is some (unknown) unitary vector in flavour space $SU(3)_q$.
It selects a direction in that space. It selects a direction in that space.
 nswer the following question

It selects a direction in that space. $1¹$

.
A air *We aim to answer the following question*

⇠

gµVcb What are the experimentally allowed directions for \hat{n} ? *^L*↵*µL*) (4) **Assuming B-anomalies are reproduced,**

Comment on UV realisations

This rank-1 condition is automatically realised in many UV scenarios

EQ

 $\frac{l}{l}$

 μ

 $\partial \gamma$

$$
\mathcal{L} = \lambda_i \bar{q}_L^i \mathcal{O}_{NP} + \text{h.c.}
$$

 $\hat{n}_i \propto g_{i\mu}$ $\tilde{\mathcal{L}} = \mathcal{L} \mathcal{L} \mathcal{L} \mathcal{L} \mathcal{L} \mathcal{L}$ $\frac{L}{L}$ $\frac{S}{L}$ ³ + *h.c.* (1) $\mathcal{L} \supset g_{i\mu} \, \bar{q}_L^i \gamma_\mu \ell_L^2 \, U_1^\mu + h.c.$ $\hat{n}_i \propto g_{i\mu}$ g_i _{μ} $\mathcal{L} \supset g_{i\mu} \, \bar{q}_L^i \gamma_\mu \ell_L^2 \, U_1^{\mu} + h.c.$ $q_i > q_i$ \blacktriangleright - \blacktriangleright Single leptoquark models \blacktriangleright \blacktriangleright $g_{i\mu} q_L^{\nu} \gamma_{\mu} \iota_L^{\nu} U_1^{\nu} + \iota \iota \iota \iota$.

Single vector-like quark mixing

 $\mathcal{L} \supset M_i \, \bar{q}^i_I$ ${}^{\imath}_{L}\Psi_{Q}$ $\hat{n}_i \propto M_i$ $\propto M_i$ $\mathcal{L} \supset M_i \, \bar{q}^i$ $\bar{q}_I^i \Psi_O$ $i \propto M_i$ $\mathcal{L} \supset M_i \, \overline{q}_L^i \Psi_Q$ NP ⁼ *^Cij* (¯ $u_i \propto I$ \overline{M} *i* $\hat{n}_i \propto M_i$

 $G_i \searrow \gamma$ assumptions, the operators in γ can be written assumptions, in γ can be written assumptions.

 λ_{ig} ii i
i $\frac{1}{\frac{1}{\sqrt{1-\frac{1}{\sqrt{$ $q_i \frac{\lambda_{ia}}{ab}$ *in* **and** $\frac{1}{2}$ and $\frac{1}{2}$ are $\frac{1}{2}$ and $\frac{1}{2}$ because $\frac{1}{2}$ because $\frac{1}{2}$

Roman Communication Commun

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 \mathcal{L} $=$ \mathcal{L}

See e.g. talk by M. Fedele and references therein

 $\mathcal{L} \supset \lambda_{iQ} \bar{q}_L^i \Psi_Q \Phi + h.c.$ $\hat{n}_i \propto \lambda_{iQ}$ *^j* (7) $\Phi + h.c.$ $n_i \propto \lambda_{iQ}$ *^j* (7) $n_i \propto \lambda_i Q$

⁷ *Lµdⁱ* \hat{c} **d**_{*i*} \hat{c} ˆ *in* ˆ⇤ θ (*x*) $\mathcal{L} \supset \lambda_{iQ} \bar{q}_L^i \Psi_Q \Phi + h.c.$ $\hat{n}_i \propto \lambda_{iQ}$

Comment on UV realisations

This rank-1 condition is automatically realised in many UV scenarios

$$
\mathcal{L} = \lambda_i \bar{q}_L^i \mathcal{O}_{\rm NP} + \text{h.c.}
$$

S,T,R = *CS,T,R n*ˆ*in*ˆ⇤ where C and C ² R and R and R is a unitary vector in the dimensional flavor space. We can see the dimensional flavor space. We can see the dimensional flavor space. We can see the dimensional flavor space. We ca Assuming B-anomalies are reproduced, what are the experimentally allowed directions for \hat{n} ?

Cdd Cds Cdb

1
1
1

Working in the LEFT (WEFT, WET,…)

parametrize ˆ*n* as follows¹: $ROFV$

 \overline{a}

$$
\mathcal{L}^{\rm EFT}_{\rm NP} = C\,\hat{n}_i \hat{n}_j^* (\bar{d}_L^i \gamma_\mu d_L^i) (\bar{\mu}_L \gamma^\mu \mu_L) \quad \hat{n} = \left(\frac{\sin \theta \cos \varphi e}{\sin \theta \sin \varphi e^{i \alpha_{bs}}} \right)
$$

 $\sqrt{2}$ \overline{a} $\sin\theta\cos\phi e^{i\alpha_{bd}}$ $\sin \theta \sin \phi e^{i\alpha_{bs}}$ $\cos\theta$ \setminus A *,* (5) $\left(\begin{array}{ccc} \cdot & 0 & \cdot & \cdot & 10 \\ 0 & 0 & \cdot & 100 \end{array} \right)$ *^j* (21)

The b-s element is fixed by the anomalies.

S,T,R = *CS,T,R n*ˆ*in*ˆ⇤ where C and C ² R and R and R is a unitary vector in the dimensional flavor space. We can see the dimensional flavor space. We can see the dimensional flavor space. We can see the dimensional flavor space. We ca Assuming B-anomalies are reproduced, what are the experimentally allowed directions for \hat{n} ?

Cdd Cds Cdb

1
1
1

Working in the LEFT (WEFT, WET,…)

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 \overline{a}

$$
\mathcal{L}_{\rm NP}^{\rm EFT} = C ~ \hat{n}_i \hat{n}_j^* (\bar{d}_L^i \gamma_\mu d_L^i) (\bar{\mu}_L \gamma^\mu \mu_L) \quad \hat{n} = \left(\frac{\sin \theta \cos \varphi \epsilon}{\sin \theta \sin \varphi e^{i \alpha_{bs}}} \right)
$$

 $\sqrt{2}$ \overline{a} $\sin\theta\cos\phi e^{i\alpha_{bd}}$ $\sin \theta \sin \phi e^{i\alpha_{bs}}$ $\cos\theta$ \setminus A *,* (5) $\left(\begin{array}{ccc} \cdot & 0 & \cdot & \cdot & 10 \\ 0 & 0 & \cdot & 100 \end{array} \right)$ *^j* (21)

The b-s element is fixed by the anomalies.

 T modition in bog*s j*q space n
Koluded by ebeervables testing these trensitions We can check if the specific direction in $\mathrm{SU}(3)_{\mathrm{q}}$ space \hat{n} is experimentally allowed or excluded by observables testing these transitions. Ω andwed of excluded by observables testing these trai
andwed or excluded by observables testing these trai

i ciations with other $a_i a_j \mu \mu$ obscreables

Direct correlations with other $d_id_j\mu\mu$ observables $\qquad {\cal L}_{\rm NP}^{\rm EFT}=C\,\hat n_i\hat n_j^*(\bar d_L^i\gamma_\mu d_L^i)(\bar\mu_L\gamma^\mu\mu_L)$ parametrize ˆ*n* as follows¹: relations with ather ddwyshes problem $\mathcal{C}^{\rm EFT} = \mathcal{C} \hat{\omega} \hat{\omega}^* (\vec{d}^i \approx d^i) (\vec{\omega})$

⇠ The flavour structure of the semileptonic operators, $\mathbb{E}_{\mathcal{A}}$, implies the existence of the exi **l** (it's a semi-sphere in SU(3)_q) and the strategy for R Fix the phases and plot on the angles φ , θ (it's a semi-sphere in SU(3)_q)

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 $\frac{1}{2}$ $(\alpha_{\text{bs}}=0, \alpha_{\text{bd}}=0)$ $(\alpha_{\text{bs}}=0, \alpha_{\text{bd}}=0)$

Each c
the res D lored region is excluded by
Dective observable Each colored region is excluded by the respective observable in the respective observable the phase ↵*bs* has an approximately flat direction in the range *|*↵*bs|* . ⇡*/*4. Since a non-zero

i ciations with other $a_i a_j \mu \mu$ obscreables

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Each c
the res م
د D lored region is excluded by
Dective observable Each colored region is excluded by

General correlations (LH) >: ⌘⇤ *µi* ⇠ 3*^q* ⌦ 3` *S*3*,* $\overline{P_{\text{EFT}}}$ $\alpha \land \alpha * \beta$ \overline{L} *^L*)(¯*µLµµL*) (1) with linear flavor violation $\mathcal{I}(\mathcal{I})$ $G \cap C \subset \{1, L\}$ *uⁱ* ! *djµ*⁺⌫*^µ C^T* Table 3: Dependencies of various semileptonic processes on the three coecients *CS,T,R* (cf.

Direct correlations with other $d_i d_j \mu \mu$ observables

 $\mathcal{L}_{\rm NP}^{\rm EFT} = C\,\hat{n}_i \hat{n}_j^* (\bar{d}_L^i \gamma_\mu d_L^i) (\bar{\mu}_L \gamma^\mu \mu_L)$ parametrize ˆ*n* as follows¹: relations with ather ddwyshes problem $\mathcal{C}^{\rm EFT} = \mathcal{C} \hat{\omega} \hat{\omega}^* (\vec{d}^i \approx d^i) (\vec{\omega})$

U(2) flavour symmetry or (close to third generation).
 Example 20 $\mathcal{L}=\mathcal{L}^{\mathcal{L}}$ ($\mathcal{L}^{\mathcal{L}}$) and $\mathcal{L}^{\mathcal{L}}$ ($\mathcal{L}^{\mathcal{L}}$) and $\mathcal{L}^{\mathcal{L}}$ ($\mathcal{L}^{\mathcal{L}}$) and $\mathcal{L}^{\mathcal{L}}$ T uar compositonic se

! ⇠ *^y* ¯SM SM ⁺ *...* (8) $160(T)$ $(20(T)$ $(20(T)$

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Direct correlations with other $d_id_j\mu\mu$ observables $\qquad {\cal L}_{\rm NP}^{\rm EFT}=C\,\hat n_i\hat n_j^*(\bar d_L^i\gamma_\mu d_L^i)(\bar\mu_L\gamma^\mu\mu_L)$ parametrize ˆ*n* as follows¹: relations with ather ddwyshes problem $\mathcal{C}^{\rm EFT} = \mathcal{C} \hat{\omega} \hat{\omega}^* (\vec{d}^i \approx d^i) (\vec{\omega})$

 $For complex coefficients,$ $K_L \rightarrow \pi^0 \mu \mu$ and $K_S \rightarrow \mu \mu$
become important become important ! ⇠ *^y* ¯SM SM ⁺ *...* (8)

natural framework for model independent studies of the anomalies is that of the Standard **SMILL EUGER ENDER THE THEORY (SMERT)** $\overline{}$ rank-one and proportional. This condition is automatically satisfied in all cases where $\overline{}$ the SM \vdash P \mathbf{a} SMEFT case & mediators

 $q_L^i = \left(V_{ji}^* u_L^j, d_L^i\right)$ \int_0^t

 $\mathcal{L}_{\rm NP}^{\rm SMEFT} = C_S^{ij}$ $\left(\bar{q}_L^i \gamma_\mu q_L^j\right)$ $\left(\bar{\ell}_L^2\gamma^\mu\ell_L^2\right)$ *L* $+ C_T^{ij}$ $\left(\bar{q}_L^i \gamma_\mu \sigma^a q_L^j\right)$ $\left(\bar{\ell}_L^2\gamma^\mu\sigma^a\ell_L^2\right)$ *L* $+ C_R^{ij}$ $\left(\bar{q}_L^i \gamma_\mu q_L^j\right)$ *L* ${\cal L}_{\rm NP}^{\rm SMEFT} = C_S^{ij} \left(\bar{q}_L^i \gamma_\mu q_L^j \right) \left(\bar{\ell}_L^2 \gamma^\mu \ell_L^2 \right) + C_T^{ij} \left(\bar{q}_L^i \gamma_\mu \sigma^a q_L^j \right) \left(\bar{\ell}_L^2 \gamma^\mu \sigma^a \ell_L^2 \right) + C_R^{ij} \left(\bar{q}_L^i \gamma_\mu q_L^j \right) \left(\mu_R \gamma^\mu \mu_R \right)$ in the charged-lepton and down quarks mass basis, and *V* is the CKM matrix. $C_{\scriptscriptstyle D}^{ij}$ ($\bar q'_I \gamma_{\mu} q'_I$) ($\mu_R \gamma^{\mu} \mu_R$) \mathbf{r} $\left(-\mathbf{b} + \mathbf{b} + \mathbf{c} \right)$ is specific to specific \mathbf{b}

 $C^{ij}_{S,T,R} = C_{S,T,R} \hat{n}_i \hat{n}_j^*$

Difforant processe donand with *B*-anomalies). of leptons is considered), which requires the Wilson coecient matrices *Cij*

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 E_{VOR} assuming a I H solution, the relative size of C_8 and C_7 is a free persmeter \Box coupled a single direction in the relative size of C_3 and C_4 is a fiee parameter. Even assuming a *LH solution*, the relative size of C_S and C_T is a free parameter. be rank-one and proportional. This condition is all cases where \sim and \sim and \sim

of leptons is considered), which requires the Wilson coecient matrices *Cij* $However,$ \overline{a} *,* u_j *,* ↵*bs* 2 ⇡ However, *didj µµ* transitions,

T_{eff} and allowing surful operators, with σ_{eff} and σ_{eff} *L* = *iq*¯ are **directly correlated** with *bs µµ*

(depend on the same complitation of C_S and C_T) and C_T for C_T and the escape sembination of C_1 and C_1 (depend on the same combination of C_S and C_T)

 $C_I = C_S + C_T \equiv C_+$ $CL - C_S + C_I - C_C + C$ $C_L = C_S + C_T \equiv C_+$

S,T,R in Eq. (2) to Also *uiuj νµνµ* transitions,

$\mu \mu$ and σ are **directly correlated** with *bs µµ*

First same compliance of C_5 and C_1 , and C_2 and C_3 and C_4 mediators and C_5 models and models are models in the same set of C_5 and C_6 and C_7 and C_8 and C_7 and C_8 and C_7 and C_8 and however no relevant bound exist (e.g. from $D \rightarrow \pi$ vv)

SMEFT case & mediators **SMILL EUGER ENDER THE THEORY (SMERT)** $\overline{}$ rank-one and proportional. This condition is automatically satisfied in all cases where $\overline{}$ the SM \vdash P \mathbf{a} q

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SMEFT case & mediators **SMILL EUGER ENDER THE THEORY (SMERT)** $\overline{}$ rank-one and proportional. This condition is automatically satisfied in all cases where $\overline{}$ the SM \vdash P \mathbf{a} *d*ⁱ*l*</sup>

 $q_L^i = \left(V_{ji}^* u_L^j, d_L^i\right)$ \int_0^t

 $\mathcal{L}_{\rm NP}^{\rm SMEFT} = C_S^{ij}$ $\left(\bar{q}_L^i \gamma_\mu q_L^j\right)$ $\left(\bar{\ell}_L^2\gamma^\mu\ell_L^2\right)$ *L* $+ C_T^{ij}$ $\left(\bar{q}_L^i \gamma_\mu \sigma^a q_L^j\right)$ $\left(\bar{\ell}_L^2\gamma^\mu\sigma^a\ell_L^2\right)$ *L* $+ C_R^{ij}$ $\left(\bar{q}_L^i \gamma_\mu q_L^j\right)$ *L* ${\cal L}_{\rm NP}^{\rm SMEFT} = C_S^{ij} \left(\bar{q}_L^i \gamma_\mu q_L^j \right) \left(\bar{\ell}_L^2 \gamma^\mu \ell_L^2 \right) + C_T^{ij} \left(\bar{q}_L^i \gamma_\mu \sigma^a q_L^j \right) \left(\bar{\ell}_L^2 \gamma^\mu \sigma^a \ell_L^2 \right) + C_R^{ij} \left(\bar{q}_L^i \gamma_\mu q_L^j \right) \left(\mu_R \gamma^\mu \mu_R \right)$ in the charged-lepton and down quarks mass basis, and *V* is the CKM matrix. $C_{\scriptscriptstyle D}^{ij}$ ($\bar q'_I \gamma_{\mu} q'_I$) ($\mu_R \gamma^{\mu} \mu_R$) \mathbf{r} $\left(-\mathbf{b} + \mathbf{b} + \mathbf{c} \right)$ is specific to specific \mathbf{b}

 $C^{ij}_{S,T,R} = C_{S,T,R} \hat{n}_i \hat{n}_j^*$

with *B*-anomalies). of leptons is considered), which requires the Wilson coecient matrices *Cij*

with *B*-anomalies). In the *R*_I we have the pecetion is the NP section is that the *R*_I sector and the components of the *R* We can ask what are the possible tree-level mediators which generate these operators.

Different ones generate different combinations of $C_{S,T,R}$. Different angle generate different cambi Different ones generate different combinations of $C_{S,T,R}$.

As representative examples, we study:

S3 scalar leptoquark category described by Eq. (3). Integrating out out out out out out out the e⊿ective operators in the e⊿ective o
Integrating out of the e⊿ective operators in the e⊿ective operators in the e⊿ective operators in the e⊿ective $E_{\rm c}$ *^L*NP 3*,iµ*(¯*qc i ^L* ✏*^a*` *^L*) *S^a* ³ + h*.*c*. ,* (18) IF I \bigoplus interaction interaction with \bigotimes \bigoplus \bigoplus \bigoplus is contained in \bigoplus in \bigoplus is contained for \bigoplus in \bigoplus is contained for \bigoplus in \bigoplus is contained for \bigoplus in \bigoplus is contained for category described by Eq. (3). Integrating out of the tree level, the e $\frac{1}{2}$ α SCalar leptoquark $S_3 = (\bar{3}, 3, 1/3)$ SM extensions), this is the *only* single-mediator simplified model for which a combined

S3 scalar leptoquark The relevant interaction of the *S*³ leptoquark with SM quarks and leptons can be described category described by Eq. (3). Integrating out out out out out out out the e⊿ective operators in the e⊿ective o
Integrating out of the e⊿ective operators in the e⊿ective operators in the e⊿ective operators in the e⊿ective $E_{\rm c}$ *^L*NP 3*,iµ*(¯*qc i ^L* ✏*^a*` *^L*) *S^a* ³ + h*.*c*. ,* (18) IF I \bigoplus interaction interaction with \bigotimes \bigoplus \bigoplus \bigoplus is contained in \bigoplus in \bigoplus is contained for \bigoplus in \bigoplus is contained for \bigoplus in \bigoplus is contained for \bigoplus in \bigoplus is contained for category described by Eq. (3). Integrating out of the tree level, the e $\frac{1}{2}$ $S_3 = (\bar{3}, 3, 1/3)$ 2.2 **Calar leptoquark** $S_3 = (\bar{3}, 3, 1/3)$ SM extensions), this is the *only* single-mediator simplified model for which a combined

S₃ scalar leptoquark S₃ = (3 The relevant interaction of the *S*³ leptoquark with SM quarks and leptons can be described 10 Supplement **S** $\mathbf{S} = (\mathbf{S}, \mathbf{S}, \mathbf{R})$ anomalies. category described by Eq. (3). Integrating out out out out out out out the e⊿ective operators in the e⊿ective o
Integrating out of the e⊿ective operators in the e⊿ective operators in the e⊿ective operators in the e⊿ective $E_{\rm c}$ *^L*NP 3*,iµ*(¯*qc i ^L* ✏*^a*` ³ + h*.*c*. ,* (18) IF I \bigoplus interaction interaction with \bigotimes \bigoplus \bigoplus \bigoplus is contained in \bigoplus in \bigoplus is contained for \bigoplus in \bigoplus is contained for \bigoplus in \bigoplus is contained for \bigoplus in \bigoplus is contained for category described by Eq. (3). Integrating out of the tree level, the e $\frac{1}{2}$ $S_3 = (\bar{3}, 3, 1/3)$ 2.2 **Calar leptoquark** $S_3 = (\bar{3}, 3, 1/3)$ SM extensions), this is the *only* single-mediator simplified model for which a combined

ROFV & U(2)³ symmetry **COF** *j* i v ⇣ 1 + *aYuY † ^u* + *bYdY † ^d* ⁺ *...*⌘ **discussion in Ref. (3)** in Ref. (3) THE G*FRANCI* SYMMETRY SYNG matrices. At leading order in the spurions and up to possible *O*(1) factors multiplying *l* & U(2)³ symmetry where \mathcal{L} is the case in \mathcal{L} of the flavon in \mathcal{L} and \mathcal{L} and \mathcal{L} is the flavon independent of the flavon in \mathcal{L}

Global quark [104] flavor symmetry

Global quark
flavor symmetry
$$
U(2)^3 = U(2)_q \times U(2)_u \times U(2)_d
$$
 $\psi_i = (\psi_1 \ \psi_2 \psi_3)$

$$
\psi_i=(\overline{(\psi_1\,\,\psi_2)}\overline{\psi_3})
$$

When *minimally broken*, the spurions are: $V_q \sim (\bf{2}, \bf{1}, \bf{1}) \ , \quad \Delta Y_u \sim (\bf{2}, \bf{\bar 2}, \bf{1}) \ ,$ When minimally broken the spurions are $V_c \sim (2, 1, 1)$ or $\Delta Y_c \sim (2, \overline{2}, 1)$ ✓ *Y^u V^q Value in the spurions are:* V_q *inimally broken, the spurions are:* $V_a \sim (\mathbf{2}, \mathbf{1}, \mathbf{1})$, $\Delta Y_u \sim (\mathbf{2}, \mathbf{\bar{2}}, \mathbf{1})$ *|Vtd|*

 $V_q \sim (2, 1, 1)$ When minimally broken, the spurions are: $V_q \sim (\bf{2},\bf{1},\bf{1}) \; , \quad \Delta Y_u \sim (\bf{2},\bf{\bar 2},\bf{1}) \; , \quad \Delta Y_d \sim (\bf{2},\bf{1},\bf{\bar 2})$ \sim $({\bf 2},{\bf 1},{\bf 1})\;,\quad \Delta$ *x* α the spurions are: $V_a \sim (2, 1, 1)$, $\Delta V_a \sim (2, \overline{2}, 1)$

$$
y_u \sim y_t \begin{pmatrix} \Delta Y_u & V_q \\ 0 & 1 \end{pmatrix}, \quad y_d \sim y_b \begin{pmatrix} \Delta Y_d & V_q \\ 0 & 1 \end{pmatrix}
$$

 $V_q = a_q$

 $\frac{1}{2}$

 $\left(V_{td}^* \right)$

The doublet is given by $V_q = a_q \begin{pmatrix} V_{td}^* \ V_{ts}^* \end{pmatrix}$
CKM elements up to $V_q = a_q \begin{pmatrix} V_{td}^* \ V_{ts}^* \end{pmatrix}$ CKM elements up to The doublet is given by $V_q = a_q \left(\begin{array}{c} V_{td}^* \ V_{ts}^* \end{array} \right)$ The doublet is given by corrections CKM elements up to $V_q = a_q \left(\begin{array}{c} u \\ V^* \end{array} \right)$ Another interesting point is that, with interesting point is that, with λ \rightarrow λ \rightarrow

 $\mathcal{O}(m_s/m_b)$ $\mathcal{O}(m_s/m_b)$

ROFV & U(2)³ symmetry **COF** *j* i v ⇣ 1 + *aYuY † ^u* + *bYdY † ^d* ⁺ *...*⌘ **FIUTV & U(Z)³ Symmetry** discussion in Ref. \mathcal{S} is imposed at the matrix level. If also the scalar HC matrices. At leading order in the spurions and up to possible *O*(1) factors multiplying *l* & U(2)³ symmetry where \mathcal{L} is the case in \mathcal{L} of the flavon in \mathcal{L} and \mathcal{L} and \mathcal{L} is the flavon independent of the flavon in \mathcal{L}

Global quark [104] flavor symmetry

Global quark
flavor symmetry
$$
U(2)^3 = U(2)_q \times U(2)_u \times U(2)_d \qquad \psi_i = (\psi_1 \ \psi_2 \overline{\psi_3})
$$

$$
\psi_i=(\overline{(\psi_1\,\,\psi_2)}\overline{\psi_3})
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When *minimally broken*, the spurions are: $V_q \sim (\bf{2}, \bf{1}, \bf{1}) \; , \quad \Delta Y_u \sim (\bf{2}, \bf{\bar 2}, \bf{1}) \; ,$ **Bread of the spurions are:** I $\overline{\mathbf{s}}$ as When minimally broken the spurions are $V_c \sim (2, 1, 1)$ or $\Delta Y_c \sim (2, \overline{2}, 1)$ ✓ *Y^u V^q Value in the spurions are:* V_q *inimally broken, the spurions are:* $V_a \sim (\mathbf{2}, \mathbf{1}, \mathbf{1})$, $\Delta Y_u \sim (\mathbf{2}, \mathbf{\bar{2}}, \mathbf{1})$ *|Vtd|*

 $Y_q \sim (\mathbf{2},\mathbf{1},\mathbf{1}) \,\,, \quad \Delta Y_u \sim (\mathbf{2},\mathbf{\bar{2}},\mathbf{1}) \,\,, \quad \Delta Y_d \sim 1$ $V_q \sim (2, 1, 1)$ When minimally broken, the spurions are: $V_q \sim (\bf{2},\bf{1},\bf{1}) \; , \quad \Delta Y_u \sim (\bf{2},\bf{\bar 2},\bf{1}) \; , \quad \Delta Y_d \sim (\bf{2},\bf{1},\bf{\bar 2})$ \sim $({\bf 2},{\bf 1},{\bf 1})\;,\quad \Delta$ *x* α the spurions are: $V_a \sim (2, 1, 1)$, $\Delta V_a \sim (2, \overline{2}, 1)$

 \mathbf{a}

ei↵*bs*

$$
y_u \sim y_t \begin{pmatrix} \Delta Y_u & V_q \\ 0 & 1 \end{pmatrix} , \quad y_d \sim y_b \begin{pmatrix} \Delta Y_d & V_q \\ 0 & 1 \end{pmatrix}
$$

CKM elements up to The doublet is given by corrections

 \sum_{s} and \sum_{s}^{V} of a sumption $V_q = a_q \left(\begin{array}{c} V_{td} \\ V_{ts}^* \end{array} \right)$ The doublet is given by $V_q = a_q \left(\begin{array}{c} V_{td}^* \ V_{ts}^* \end{array} \right)$ = 0*.*70 *±* 0*.*30*,* (32) $\frac{1}{2}$ $V_q = a_q$ $\left(V_{td}^* \right)$ The doublet is given by $V_q = a_q \left(\begin{array}{c} V_{td}^* \ V_{ts}^* \end{array} \right)$ CKM elements up to $V_q = a_q \left(\begin{array}{c} u \\ V^* \end{array} \right)$ Another interesting point is that, with interesting point is that, with λ \rightarrow λ \rightarrow

 β/m_b) $\mathcal{O}(m_s/m_b)$ $\mathcal{O}(m_s/m_b)$

One can **predict** (up to O(2%) corrections) $s_n = s_{n+1}$ for s_{n+1} and s_{n+1} and s_{n+1} prediction, normalism, *Ci*je can **predict** (up to $O(2\%)$ corrections) *^j* (8) where *a^q* is an *O*(1) parameter. As shown in Section 5, in order to fit the flavour anomalies **One can predict** (up to O(2%) corrections) $\frac{M}{M}$, $\frac{M}{M}$,

Br(*B* ! ⇡*µ*⁺*µ*)[1*,*6]

Br(*B* ! *Me*⁺*e*)[1*,*6]

$$
R_K \approx R_{\pi} \qquad \frac{\text{Br}(B_s^0 \to \mu^+ \mu^-)}{\text{Br}(B_s^0 \to \mu^+ \mu^-)^{\text{SM}}} \approx \frac{\text{Br}(B^0 \to \mu^+ \mu^-)}{\text{Br}(B^0 \to \mu^+ \mu^-)^{\text{SM}}}
$$

⇣

These predictions of minimally broken U(2)3 ⇠ will be tested with future data (see prospects slide). Another prediction of this setup is for the branching ratio of *B*⁰ ! *µ*⁺*µ* with respect to *gµVcb* ⇤² (¯*bL*↵*cL*)(¯⌫*^µ ^L*↵*µL*) (10) *C* = @ *C*⇤ *ds Css Csb* Br(*B* ! ⇡*µ*⁺*µ*)SM [1*,*6]

ROFV & U(2)³ symmetry **COF** *j* i v ⇣ 1 + *aYuY † ^u* + *bYdY † ^d* ⁺ *...*⌘ *i d i i y i x i* condition *||n* ˆ*||*² = 1. The area in the (*,* ✓) plane corresponding to values *|abs,bd|* 2 $\mathsf{P} \cup \mathsf{P} \times \mathsf{P} \cup \mathsf{P$

Global quark flavor symmetry $\begin{bmatrix} 0 & 2 \end{bmatrix}$

Global quark
\nflavor symmetry

\n
$$
U(2)^3 = U(2)_q \times U(2)_u \times U(2)_d
$$
\n
$$
\psi_i = (\psi_1 \psi_2 \psi_3)
$$

$$
\psi_i = (\overbrace{(\psi_1 \ \psi_2)}^{\hspace*{1pt}1} \overline{(\psi_3)})
$$

When *minimally broken*, the spurions are: $V_q \sim (\bf{2}, \bf{1}, \bf{1}) \ , \quad \Delta Y_u \sim (\bf{2}, \bf{\bar 2}, \bf{1}) \ ,$ $V_q \sim (2, 1, 1)$ $\frac{1}{2}$ $V_q\sim({\bf 2},{\bf 1},{\bf 1})\;,\quad \Delta Y_u\sim({\bf 2},{\bf \bar 2},{\bf 1})\;,\quad \Delta Y_d\sim({\bf 2},{\bf 1},{\bf \bar 2})$ • In some cases, the above correlation between ˆ*n* and the CKM matrix becomes precise

re we can also ge *C*⇤ Imposing the ROFV structure we can also get **correlations with s-d transitions**:

correlations with s-α transitive
only 2 free parameters: *cu₂*, *γ*.

Imposing the ROFV structure we can also get\n
$$
C_{ij} = C \hat{n}_i \hat{n}_j^*
$$
\n
$$
C_{ij} = C \hat{n}_i \hat{n}_j^*
$$
\n
$$
C_{ij} = C \hat{n}_i \hat{n}_j^*
$$
\n
$$
\hat{n} \sim 1 + 2q \sim (c_{U2} V_q^T, 1)^T
$$
\n
$$
\hat{n} \propto (c_{U2} e^{i\gamma} V_{td}^*, c_{U2} e^{i\gamma} V_{ts}^*, 1)
$$
\n
$$
C_{U2} \sim O(1)
$$
\n
$$
C_{V2} \sim O(1)
$$
\n
$$
C_{V2} \sim O(1)
$$
\n
$$
K_L \rightarrow \mu^+ \mu^-
$$
\n
$$
C_{V2} \sim O(1)
$$
\n
$$
K_L \rightarrow \mu^+ \mu^-
$$
\n
$$
C_{V2} \sim O(1)
$$
\

Lµdⁱ

Prospects

Future improvements in the measurements of these observables will allow to cover the majority of the parameter space

Summary

The **B-physics anomalies** will be throughly tested in the next few years. If confirmed, understanding the flavor structure of this new breaking of the SM flavor symmetries will be crucial.

The *Rank-One Flavor Violation* assumption is realised in several UV completions. It allows to correlate b→sµµ processes with other flavor observables involving muons (or muon neutrinos).

Already now a sizeable part of parameter space is **tested** and **future measurements will cover the majority of the framework**.

*Simplified = no theory uncertainties considered. Agrees well "enough" with full fits. $\frac{1}{20}$

$\Delta F = 2$ observables (and ε'/ε) $\Delta I = L$ UNJURVANIGJ α

 $\boxed{\text{Limits on } \Delta F = 2 \text{ coefficients } [\text{GeV}^{-2}]}$ $\text{Re}C_K^1 \in [-6.8, 7.7] \times 10^{-13}$, $\text{Im}C_K^1 \in [-1.2, 2.4] \times 10^{-15}$ $\left[\text{Re} C_D^1 \in \left[-2.5, 3.1 \right] \times 10^{-13} , \text{ Im} C_D^1 \in \left[-9.4, 8.9 \right] \times 10^{-15} \right]$ $\mathcal{L}_{\Delta F = 2}^{\text{NP}}$ $|C_{B_d}^1|$ < 9.5 \times 10⁻¹³ $|C_{B_s}^1|$ < 1.9 \times 10⁻¹¹ $\frac{1}{\text{Re} C_V^1 \in [-6.8, 7.7] \times 10^{-13} }$, Im $C_V^1 \in [-1.2, 2.4] \times 10^{-15}$ analyses. Writing Company

$$
\mathcal{L}^{\rm NP}_{\Delta \rm F=2} = C_{ij} (\bar{q}^i_L \gamma_\mu q^j_L)^2
$$

[UTfit 0707.0636, update by L. Silvestrini @ La Thuile '18] !
ε′′

CQij^L / $a_i n_j d_{iL} \gamma^{\alpha} d_{jL}$ ² + $(V_{ik}n)$ For example, the Z' contribution is: $\Delta \mathcal{L}_{\Delta F=2} = -\frac{g_q^2}{2M}$ *q* $2M_{Z'}^2$ $\left[(\hat{n}_i\hat{n}_j^*\overline{d_{iL}}\gamma^\alpha d_{jL})^2 + (V_{ik}\hat{n}_k\hat{n}_l^*V_{jl}^*\;\overline{u_{iL}}\gamma^\alpha u_{jL})^2\right]$ ⇤ *.* (24) \overline{C} ibution $\Delta{\cal L}_{\Delta F=2} =$ a^2

des a p *s*2 \overline{a} \cdot ntial C *cons V* ⇤ *tsVtd X*` *c* $\ddot{}$ on the coefficient of (*X*¹,02520, 1808,00466 **1** $(Y/\mu L u)(q/\gamma L u)$ σ tial constrain on the coefficient of $(\bar{s}\gamma_\mu P_I d)(\bar{q}\gamma^\mu P_I q)$ α constrain on the coemercin of α β μ ² μ 3 Also ε'/ε provides a potential constrain on the coefficient of $(\bar{s}\gamma_\mu P_L d)(\bar{q}\gamma^\mu P_L q)$ $q = u, d, s, c$ also s'/s provides a potential constrain on the coefficient of are the extension of the electronical condition in the edemologie of [Aebisher et al. 1807.02520, 1808.00466]

*X*¹ *x x*

$$
\left(\frac{\varepsilon'}{\varepsilon}\right)_{\text{BSM}} = \sum_{i} P_i(\mu_{\text{ew}}) \operatorname{Im} \left[C_i(\mu_{\text{ew}}) - C_i'(\mu_{\text{ew}})\right] \le 10 \times 10^{-4}
$$

etitive with ΔF = 2 $\overline{}$ In this framework, this constraint is not competitive with $\Delta F = 2$

U1 vector leptoquark The interaction lagrangian of the vector leptoquark *U*¹ is *ain* Figure 3: Limits in the plane (*,* ✓) for the vector leptoquark *U*¹ and two choices of the

ΔF=2 loops are divergent, need a UV completion. $\Delta F = 2$ loops are divergent,

Z' & vector-like couplings to μ \sim simplified model. In general such UV completions contains to the contributions of the cont \mathbf{z} and \mathbf{z} be taken into a count scenarios see e.g. \mathbf{z} $Lilz \sim \Omega$ quark doublet *Q* in the form ³ + *h.c.* (1) *n*ˆ*ⁱ* / ⇤ *iµ* (2) *i* **0** μ

For example see the gauged U(1)_{Lμ-Lτ} model with 1 vector-like quark. Let us consider a heavy singlet vector *Z*⁰ with couplings: $\mathcal{L} \supset M_i \, \bar{q}_L^i \Psi_Q$ (see e.g. []). In such a case, ˆ*nⁱ* / *M*⇤ $\hat{n}_i \propto M_i$ [Altmannshofer, Gori, et al 1403.1269, 1609.04026] $L^u L^v Q$ $\mathcal{L} \supset M_i \, \bar{q}_I^i$ $\bar{g}_L^i \Psi_Q$

$$
\mathcal{L}_{\rm NP} \supset \left[g_q \hat{n}_i \hat{n}_j^* (\bar{q}_L^i \gamma^\alpha q_L^j) + g_\mu (\bar{\ell}_L^2 \gamma^\alpha \ell_L^2 + \bar{\mu}_R \gamma^\alpha \mu_R) \right] Z_\alpha' \quad \Longleftrightarrow \qquad C_S^{ij} = -\frac{g_q g_\mu}{M_{Z'}^2} \hat{n}_i \hat{n}_j^* \ , \quad C_T^{ij} = 0 \ , \quad C_R^{ij} = -\frac{g_q g_\mu}{M_{Z'}^2} \hat{n}_i \hat{n}_j^* \ .
$$

Z' & vector-like couplings to μ \sim simplified model. In general such UV completions contains to the contributions of the cont \mathbf{z} and \mathbf{z} be taken into a count scenarios see e.g. \mathbf{z} limits on the *Z*⁰ mass [TeV] from *F* = 2 processes using Eq. (26). limits on the *Z*⁰ mass [TeV] from *F* = 2 processes using Eq. (26). quark doublet *Q* in the form quark doublet *Q* in the form *^L iµ ^qi c ^L a*`² *^L S^a* ³ + *h.c.* (1) *n*ˆ*ⁱ* / ⇤ *iµ* (2) *i* **0** μ

For example see the gauged U(1)_{Lμ-Lτ} model with 1 vector-like quark. Let us consider a heavy singlet vector *Z*⁰ with couplings: $\mathcal{L} \supset M_i \, \bar{q}_L^i \Psi_Q$ (see e.g. []). In such a case, ˆ*nⁱ* / *M*⇤ $\hat{n}_i \propto M_i$ (see e.g. []). In such a case, ˆ*nⁱ* / *M*⇤ $\hat{n}_i \propto M_i$ is given by the set of t [Altmannshofer, Gori, et al 1403.1269, 1609.04026] $L^u L^v Q$ $\hat{n}_i \propto M_i$ $\mathcal{L} \supset M_i \, \bar{q}_I^i$ $\bar{g}_L^i \Psi_Q$

$$
\mathcal{L}_{\rm NP} \supset [g_q \hat{n}_i \hat{n}_j^* (\bar{q}_L^i \gamma^\alpha q_L^j) + g_\mu (\bar{\ell}_L^2 \gamma^\alpha \ell_L^2 + \bar{\mu}_R \gamma^\alpha \mu_R)] Z'_\alpha \qquad \qquad \mathcal{L}_{S}^{ij} = -\frac{g_q g_\mu}{M_{Z'}^2} \hat{n}_i \hat{n}_j^* , \quad C_T^{ij} = 0 , \quad C_R^{ij} = -\frac{g_q g_\mu}{M_{Z'}^2} \hat{n}_i \hat{n}_j^*
$$

 $\Delta F=2$ operators are $K_{\rm H}^{\rm H}$ ⁺³ $K_{\rm H}^{\rm H}$ and $K_{\rm H}^{\rm H}$ and $K_{\rm H}^{\rm H}$ are shown in Fig. 4.1 the tree level This model also generates at the tree-level four quark operators which contribute to generated at the tree level. **Example 145°** △F=2 operators are This model also generates at the tree-level four quark operators which contribute to ⇤² (¯*bL*↵*cL*)(¯⌫*^µ gµVcb*

$$
\Delta \mathcal{L}_{\Delta F=2} = -\frac{g_q^2}{2M_{Z'}^2} \left[(\hat{n}_i \hat{n}_j^* \; \bar{d}_L^i \gamma^\alpha d_L^j)^2 + (V_{ik} \hat{n}_k \hat{n}_l^* V_{jl}^* \; \bar{u}_L^i \gamma^\alpha u_L^j)^2 \right]
$$

 $\frac{1}{5^{\circ}360^{\circ}}$ We can put upper limits on $r_{qu} = g_q/g_\mu$, α or for a given maximum g_{μ} , $\frac{1}{2}$ an upper limit on the Z' mass $\frac{1}{200}$ and $\frac{1}{20}$ is the put apper in the strain $\frac{1}{4}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2} \text{ units on } \frac{r_{\text{qu}}}{g} = \frac{g}{g}/g_{\mu},$ \mathbb{Z}' mass

$$
C_{\pm} |^{-1/2} \text{ [TeV]} \, M_Z^{\text{max}} \text{ [TeV]} \qquad \qquad M_{Z'}^{\text{lim}} = \sqrt{\frac{r_{q\mu}^{\text{lim}}}{4|C|}} |g_{\mu}^{\text{max}}|
$$