From B-anomalies to Kaon physics

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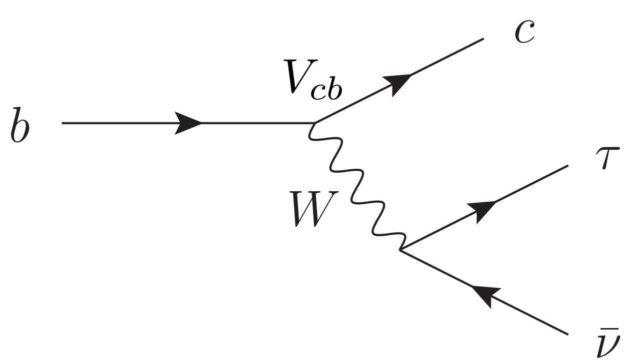
Outline

- Introduction on B-physics anomalies and EFT interpretations
- Implications of $R(D^{(*)})$: $U(2)^5$ flavor symmetry & $K\to\pi\nu\nu$
- Implications of $R(K^{(*)})$:
  1. *Rank-One Flavour Violation* (ROFV) assumption
  2. Constraints from $K_{L,S}\to\mu\mu$ and $K_L\to\pi^0\mu\mu$
- Summary

Charged-current anomalies



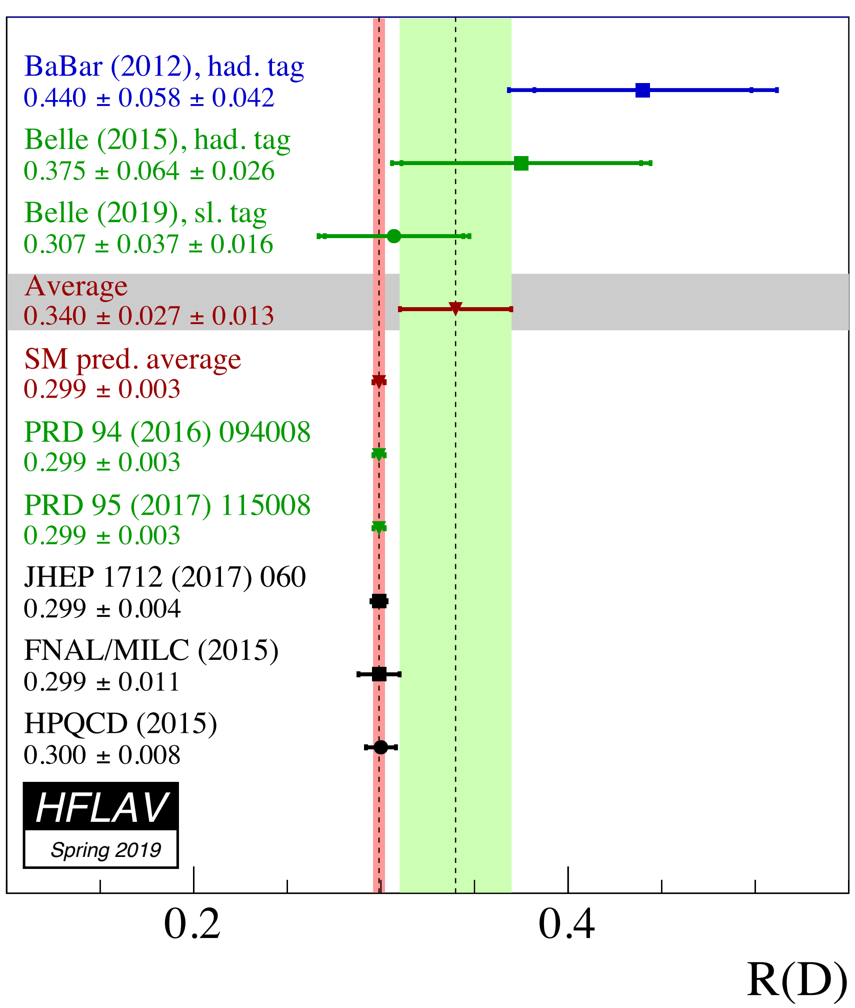
Tree-level SM process with V_{cb} suppression.

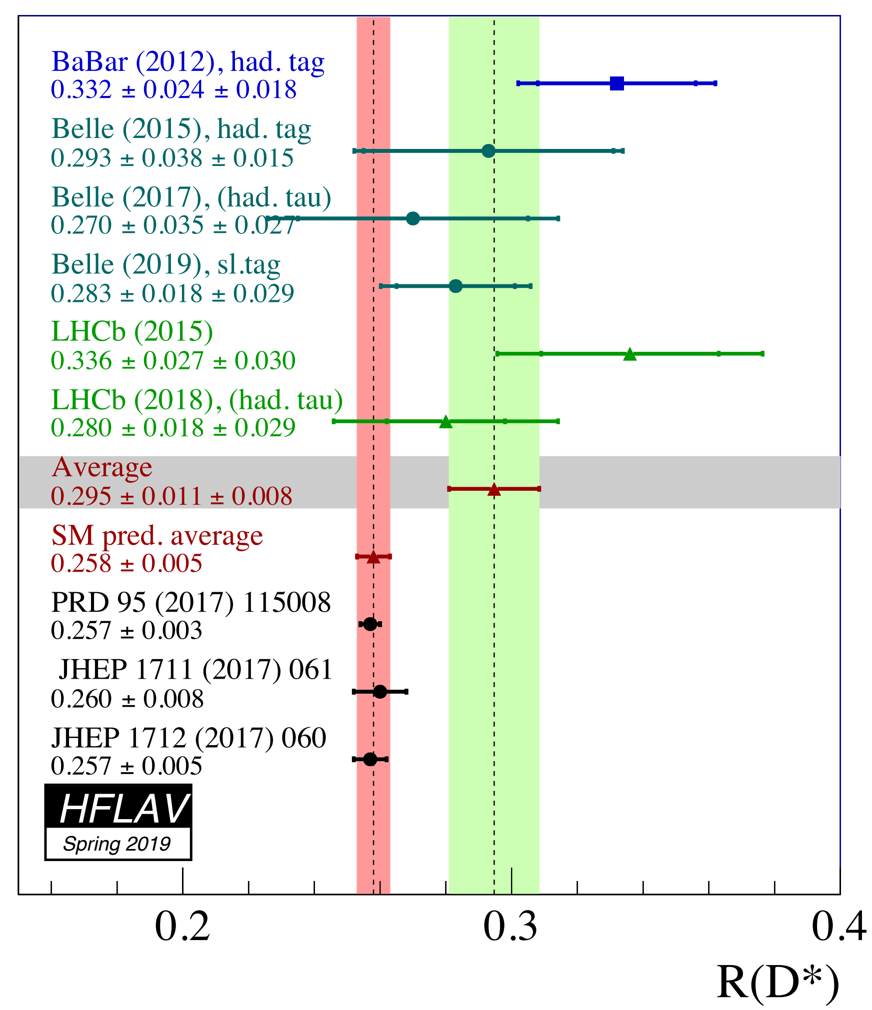
$b \to c\,\tau\,\nu$ vs. $b \to c\,\ell\,\nu$

$$R(D^{(*)}) \equiv \frac{\mathcal{B}(B^0 \to D^{(*)+}\tau\nu)}{\mathcal{B}(B^0 \to D^{(*)+}\ell\nu)},$$

$$\ell = \mu, e$$

All measurements since 2012 consistently above the SM predictions





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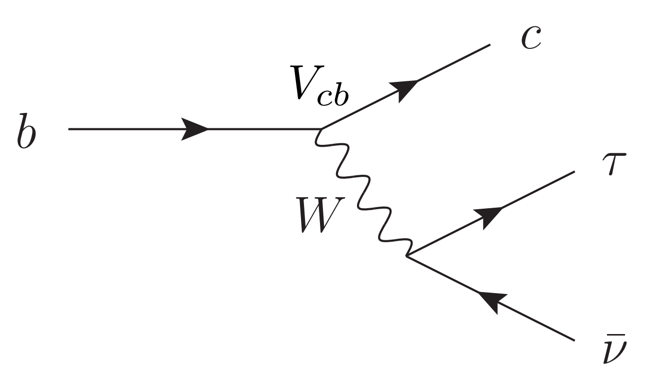

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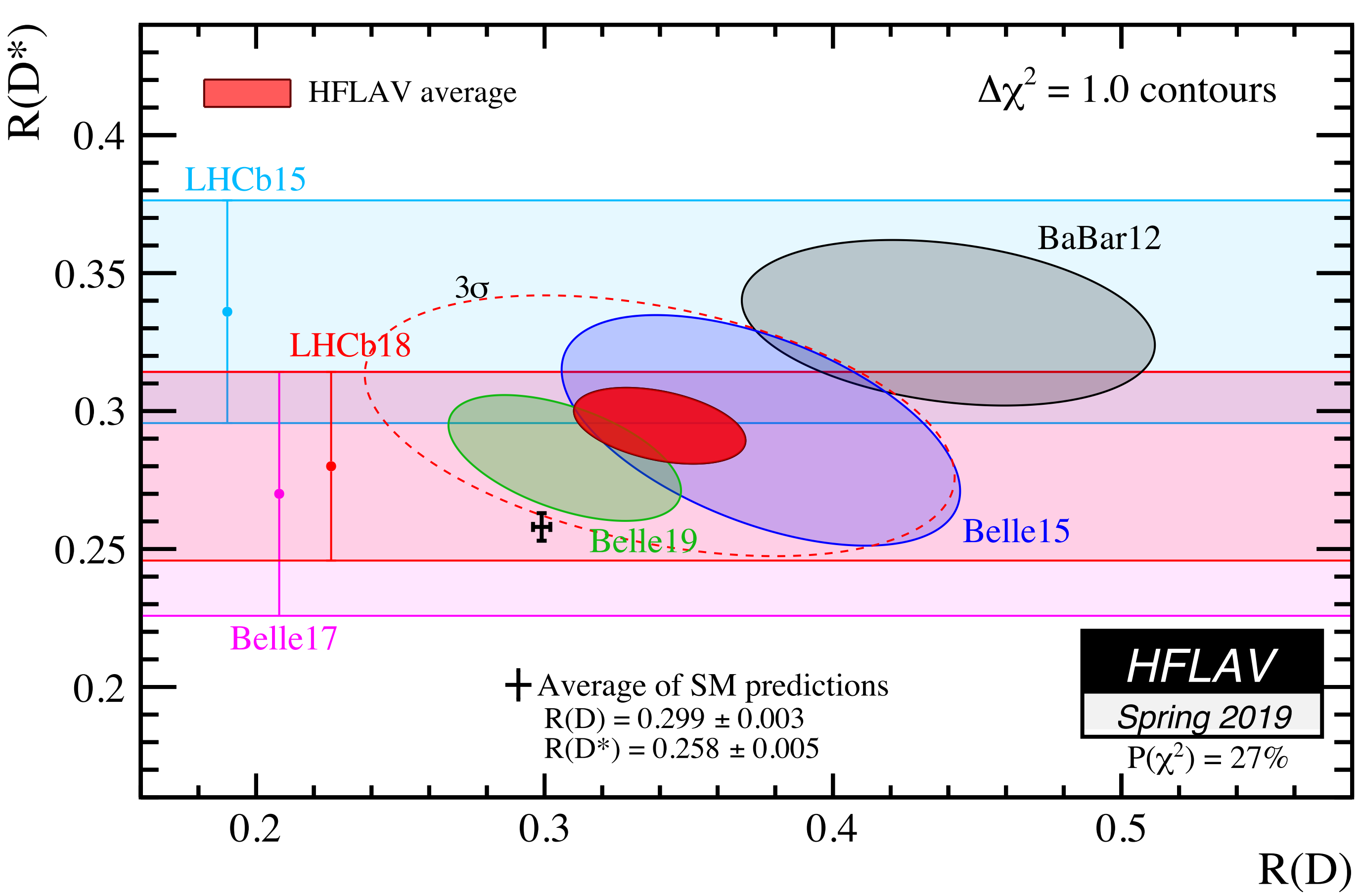
$$\ell = \mu, e$$

Assuming $R(D)=R(D^*)$: $\quad R(D^{(*)})/R(D^{(*)})_{\rm SM} = 1.142 \pm 0.038$



~ 14% enhancement from the SM

~ 3σ from the SM (3.7σ when combined)

While μ/e universality well tested

$$R(D)^{\mu/e} = 0.995 \pm 0.045$$

Belle - [1510.03657]

Neutral-Current B-anomalies

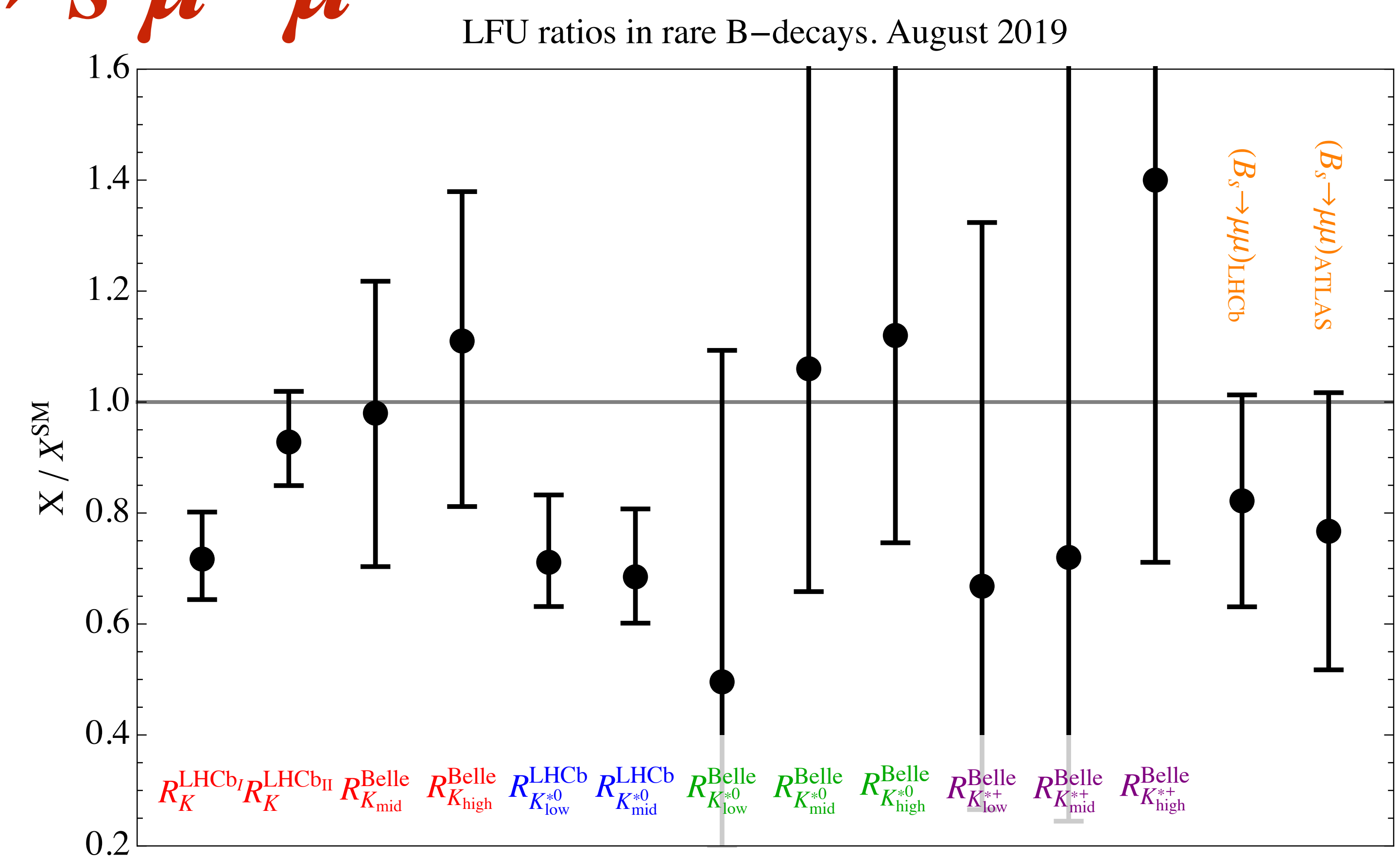
$b \to s \mu^+ \mu^-$

Lepton Flavor Universality ratios

$$R(K^{(*)}) = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)}$$

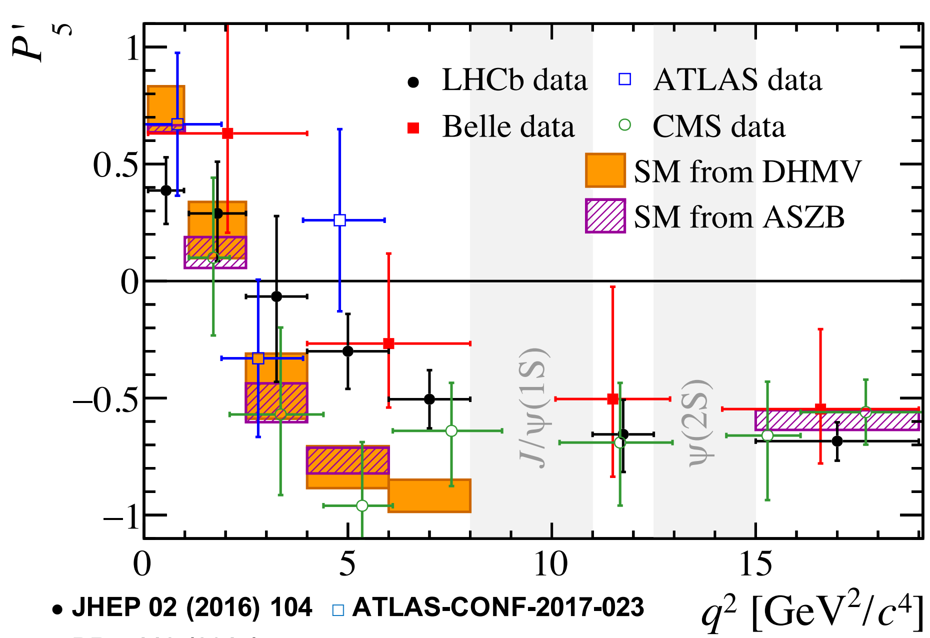
Clean SM prediction: 1 ± O(1%)

Bordone, Isidori, Pattori 2016



Angular distributions

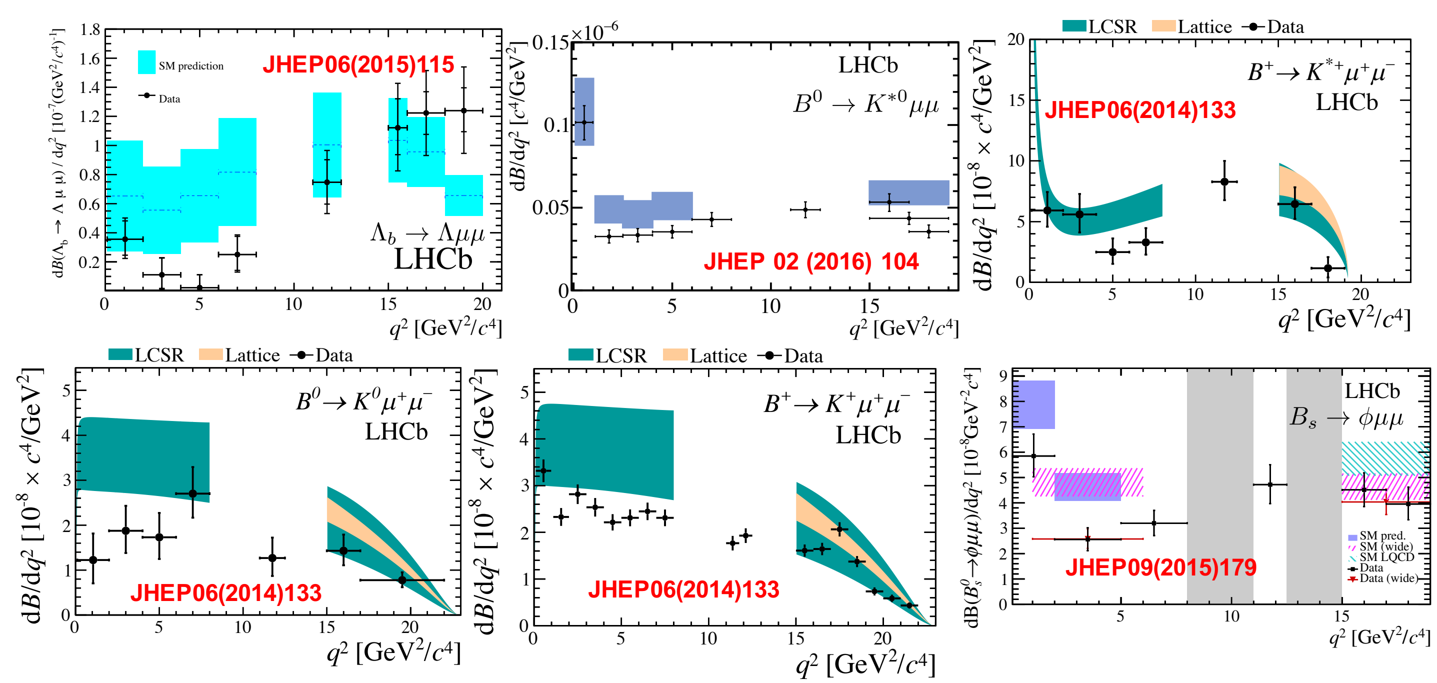
$B \to K^*(\to K\pi)\, \mu^+ \mu^-$



• JHEP 02 (2016) 104 □ ATLAS-CONF-2017-023

■ PRL 118 (2017) ○ CMS-PAS-BPH-15-008

Differential branching fractions in $q_{\mu\mu}^2$ in several channels.

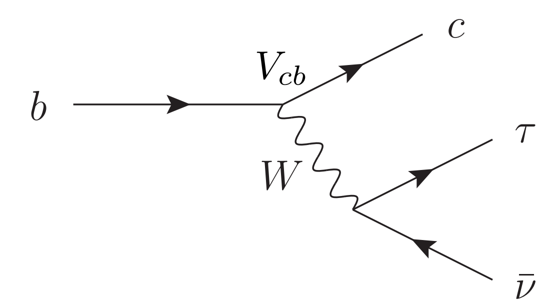


Low-energy interpretations

$b \rightarrow c\, \tau\, \nu$

$$\mathcal{L}_{\rm BSM} = \frac{2c}{\Lambda^2}(\bar{c}_L \gamma_\mu b_L)(\bar{\tau}_L \gamma^\mu \nu_\tau) + h.c.$$

$$\mathcal{H}_{\rm SM} = \frac{4G_F}{\sqrt{2}} V_{cb} (\bar{c}_L \gamma_\mu b_L)(\bar{\tau}_L \gamma^\mu \nu_\tau) + h.c.$$



if $c = 1$ $\rightarrow$ $\Lambda_{R(D)} \sim$ **4.5 TeV**

Freytsis et al. 2015, Angelescu et al. 1808.08179, Shi et al. 1905.08498, Murgui et al. 1904.09311, Bardhan, Ghosh 1904.10432, …

$b \rightarrow s\, \mu^+\, \mu^-$

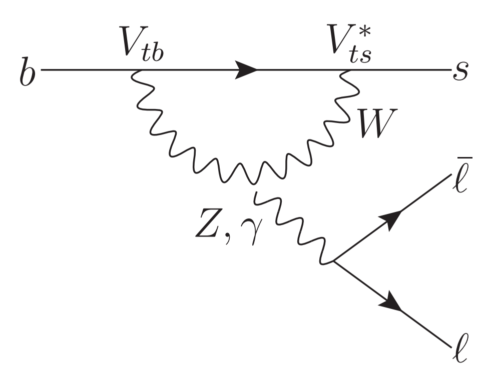
$$\mathcal{L}_{\rm eff} \supset \frac{e^{i\alpha_{bs}}}{\Lambda_{bs}^2}(\bar{s}_L \gamma^\mu b_L)(\bar{\mu}_L \gamma_\mu \mu_L) + h.c.$$

(if α_{bs}=0) $\Lambda_{R(K)} \sim$ **34 TeV**

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, …

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

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



Takeaway:

1) $\Lambda_{R(K)} \gg \Lambda_{R(D)}$

i.e.

Coupling to μ « Coupling to τ

2) Coupling to LH fields required

Combined Fit of B anomalies (SMEFT)

Buttazzo, Greljo, Isidori, DM 1706.07808

Adding SM $SU(2)_L$ gauge invariance:

$$\mathcal{L}_{\rm SMEFT} = \lambda^q_{ij}\lambda^\ell_{\alpha\beta}\left[C_T(\bar{Q}^i_L\gamma_\mu\sigma^a Q^j_L)(\bar{L}^\alpha_L\gamma^\mu\sigma^a L^\beta_L) + C_S(\bar{Q}^i_L\gamma_\mu Q^j_L)(\bar{L}^\alpha_L\gamma^\mu L^\beta_L)\right]$$

triplet operator *singlet operator*

Flavour Structure:

$$\lambda^q \sim \begin{pmatrix} 0 & \lambda^q_{sd} & \lambda_{bs}\frac{V_{ub}}{V_{cb}} \\ \lambda^q_{sd} & \lambda_{ss} & \lambda_{bs} \\ \lambda_{bs}\frac{V_{ub}}{V_{cb}} & \lambda_{bs} & 1 \end{pmatrix} \qquad \lambda_{bs} \sim O(V_{ts}) \qquad \lambda_{ss} \sim O(\lambda^2_{bs})$$

$$\lambda^\ell \sim \begin{pmatrix} 0 & 0 & 0 \\ 0 & \lambda_{\mu\mu} & \lambda_{\tau\mu} \\ 0 & \lambda_{\tau\mu} & 1 \end{pmatrix} \qquad \lambda_{\mu\mu} \sim O(\lambda^2_{\tau\mu})$$

Very good fit!

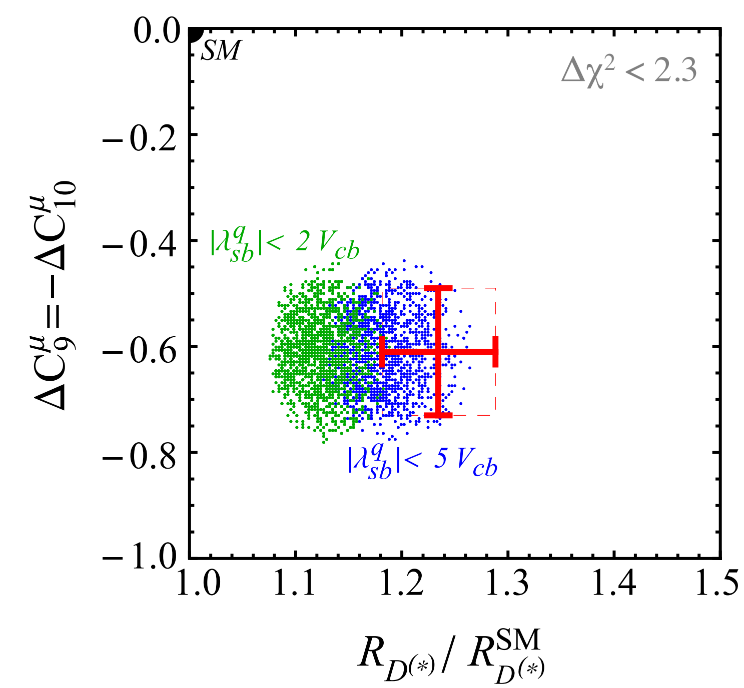
These values are compatible with a minimally-broken $SU(2)_q \times SU(2)_\ell$ flavour symmetry

$C_T \sim C_S \sim (1.7\ \text{TeV})^{-2}$

$\lambda^q_{bs} \gtrsim 3 V_{ts}$

$\lambda^\ell_{\mu\mu} \sim 10^{-2}$

$\lambda^\ell_{\tau\mu} \sim 10^{-1}$



Small $C_{T,S}$ to evade EWPT,
Large b-s coupling to fit $R(D^{(*)})$,
$C_T \sim C_S$ to evade $B \to K^* \nu\nu$.

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B-anomalies are driven by the 3-3 and 3-2 entries. λ^q_{bs}

Kaon physics depends instead on the 1-2 entry λ^q_{sd}

1) To correlate B and K physics, a **flavor assumption** is needed.

2) Given the low scale, explicit UV models are required and affect this EFT picture (e.g. additional RH couplings)

U(2)⁵ flavour symmetry

Keeping only the third-generation Yukawa couplings, the SM enjoys an approximate $U(2)^5$ flavor symmetry

$$U(2)^5 \equiv U(2)_q \times U(2)_\ell \times U(2)_u \times U(2)_d \times U(2)_e \qquad \psi_i = ((\psi_1 \;\; \psi_2)_{\mathbf{2}} \, (\psi_3)_{\mathbf{1}})$$

Assume this is minimally broken by the spurions:

$$\Delta Y_u = (\mathbf{2}, \bar{\mathbf{2}}, \mathbf{1}, \mathbf{1}, \mathbf{1}) \,, \quad \Delta Y_d = (\mathbf{2}, \mathbf{1}, \bar{\mathbf{2}}, \mathbf{1}, \mathbf{1}) \,, \quad \Delta Y_e = (\mathbf{1}, \mathbf{1}, \mathbf{1}, \mathbf{2}, \bar{\mathbf{2}})$$

$$V_q = (\mathbf{2}, \mathbf{1}, \mathbf{1}, \mathbf{1}, \mathbf{1}) \,, \quad V_l = (\mathbf{1}, \mathbf{1}, \mathbf{1}, \mathbf{2}, \mathbf{1})$$

The Yukawa matrices get this structure:

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

The **doublet spurions** regulate the mixing of the third generation with the lighter ones:

In the down-quark mass basis:

$$V_q = a_q \begin{pmatrix} V_{td}^* \\ V_{ts}^* \end{pmatrix}$$

Directly related to **CKM**

See e.g. [1909.02519]

Quark flavor matrix:

$$\lambda^q \sim \left(\begin{array}{c|c} V_q V_q^\dagger & V_q \\ \hline V_q^\dagger & 1 \end{array}\right) \qquad V_q \propto \begin{pmatrix} V_{td}^* \\ V_{ts}^* \end{pmatrix}$$

$$\lambda_{sd}^q \sim V_{ts}^* V_{td}$$
$$\lambda_{bs}^q \sim V_{ts}$$

b-s and s-d are correlated!

All is up to unknown O(1) factors!

Kaon Physics and R(D(*))

- The flavor symmetry predicts larger NP effects in 3rd gen. leptons
- In Kaon physics the largest effects involve tau-neutrinos: $K\to\pi\nu\nu$
- The main correlation is with R(D(*))

For possible connections with R(K) see [Fajfer et al. 1802.00786]
For connections between B-anomalies and ε' see [Bobeth, Buras 1712.01295]

Contribution to $b \to c\tau\nu$:

$$\mathcal{L}^{\rm NP}_{R(D^{(*)})} = 2C_{R(D^{(*)})}\lambda^\ell_{\tau\tau}(\bar c_L\gamma_\mu b_L)(\bar\tau_L\gamma_\mu\nu_\tau) + h.c.$$

$$C_{R(D^{(*)})} \approx C_T\lambda^q_{bs} \qquad \lambda^q_{bs}\sim V_{ts}$$

Contribution to $s \to d\nu\nu$:

$$\mathcal{L}^{\rm NP}_{s\to d\nu\nu} = C_{sd\nu\nu}\left[\lambda^\ell_{\tau\tau}(\bar s_L\gamma_\mu d_L)(\bar\nu_\tau\gamma_\mu\nu_\tau) + \lambda^\ell_{\mu\mu}(\bar s_L\gamma_\mu d_L)(\bar\nu_\mu\gamma_\mu\nu_\mu)\right] + h.c.$$

$$\lambda^\ell_{\mu\mu} \ll \lambda^\ell_{\tau\tau} = 1$$

$$C_{sd\nu\nu} = (C_S - C_T)\lambda^q_{sd} \qquad \lambda^q_{sd}\sim V^*_{ts}V_{td}$$

Present status

Observable	Experimental value/bound	SM prediction	
$\mathrm{Br}(K^+\to\pi^+\nu_\mu\overline{\nu_\mu})$	$(17.3^{+11.5}_{-10.5})\times10^{-11}$	$(8.4\pm1.0)\times10^{-11}$	E949 '08, Buras et al. 1503.02693
$\mathrm{Br}(K_L\to\pi^0\nu_\mu\overline{\nu_\mu})$	$< 3.0\times10^{-9}$ (90% CL)	$(3.4\pm0.6)\times10^{-11}$	KOTO '18, Buras et al. 1503.02693

$$Br(K^+\to\pi^+\nu\bar\nu) < 2.44\times10^{-10}$$ NA62 2017 (preliminary)

Future Goals

SES for SM rate

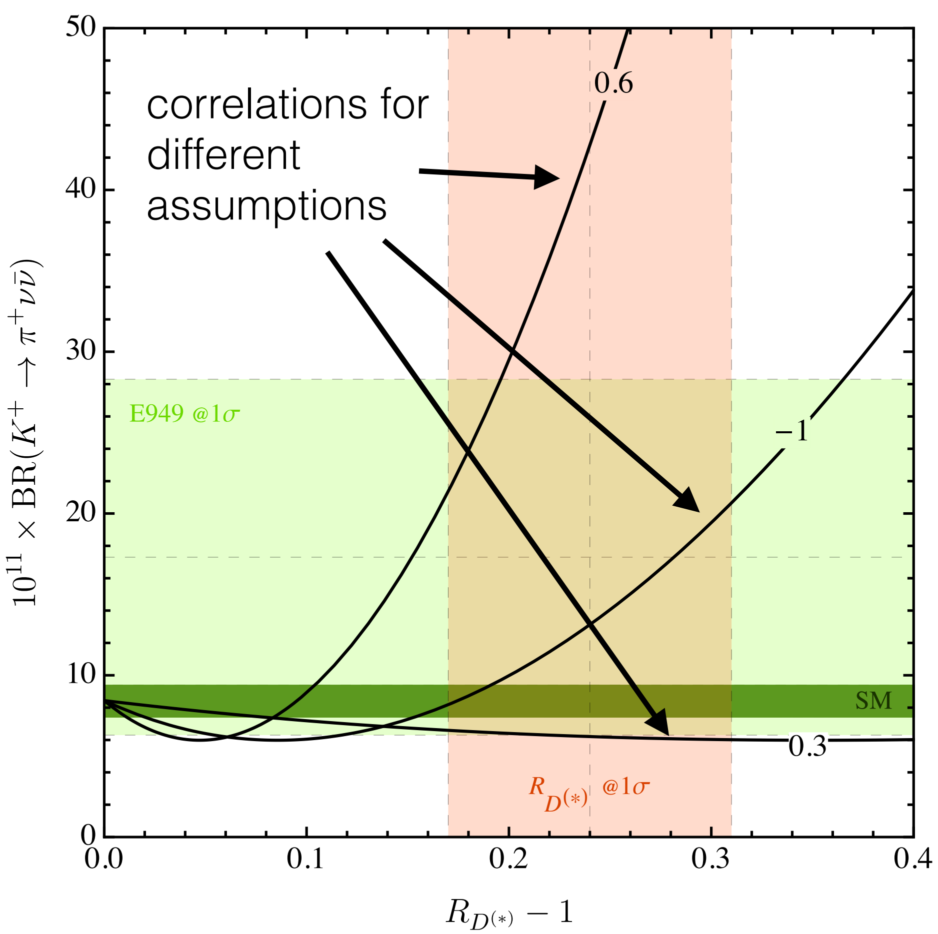
$\mathrm{Br}(K_L\to\pi^0\nu\nu)$	$\sim 1.8\times10^{-10}$	KOTO phase-I [7]
	20%	KOTO phase-II [7]
	20%	KLEVER
$\mathrm{Br}(K^+\to\pi^+\nu\nu)$	10%	NA62 goal

Kaon Physics and R(D(*))

- The flavor symmetry predicts larger NP effects in 3rd gen. leptons
- In Kaon physics the only chance is with tau-neutrino in $K\to\pi\nu\nu$
- The main correlation is with $R(D^{(*)})$
  For the connection with R(K) see [Fajfer et al. 1802.00786]

Connection in the SMEFT, assuming U(2)⁵ structure

[Bordone, Buttazzo, Isidori, Monnard 1705.10729]



While the precise correlation depends on the details of the model, it is clear that a future measurements by **NA62**, **KOTO**, and **KLEVER** will cover most of the parameter space.

For a complete analysis it is necessary to take into account the bounds from $B \to K^{(*)} \nu\nu$, $\Delta F=2$, LFV, LEP data, and direct searches.

Need a full UV model which can address the anomalies.

$S_1 + S_3$ model

Scalar Leptoquarks

$S_1 = (\bar{\mathbf{3}}, \mathbf{1}, 1/3)$,
$S_3 = (\bar{\mathbf{3}}, \mathbf{3}, 1/3)$,

Crivellin et al. 1703.09226; Buttazzo, Greljo, Isidori, DM 1706.07808;
D.M. 1803.10972; work in progress with V. Gherardi and E. Venturini

$$\mathcal{L}_{S_1+S_3} = \left(\bar{q}^c \lambda^{1L} \epsilon \ell + \bar{u}^c \lambda^{1R} e\right) S_1 + \bar{q}^c \lambda^{3L} \epsilon \sigma^I \ell S_3^I + h.c.$$

A very good fit of all data (including ΔF=2) can be achieved in this model.

work in progress with V. Gherardi and E. Venturini

The contributions to $R(D^{(*)})$ arise via a combination of (V-A) + (scalar) + (tensor) operators, uncorrelated with electroweak precision tests or B_s-mixing.

$$\mathcal{O}^\tau_{V_L} = (\bar{c}_L \gamma_\mu b_L)(\bar{\tau}_L \gamma^\mu \nu_\tau)\,, \quad \mathcal{O}^\tau_T = (\bar{c}_R \sigma_{\mu\nu} b_L)(\bar{\tau}_R \sigma^{\mu\nu} \nu_\tau)\,, \quad \mathcal{O}^\tau_{S_L} = (\bar{c}_R b_L)(\bar{\tau}_R \nu_\tau)$$

The coupling $(S_1\, c_R\, \tau_R)$ is a non-minimal breaking of the $U(2)^5$ flavor symmetry.

The correlation between B and Kaon physics is unchanged.

Since the model is fully renormalisable, all loop-generated observables can be computed and included in the fit.

A full NLO matching to the SMEFT and NLO analysis is in progress.

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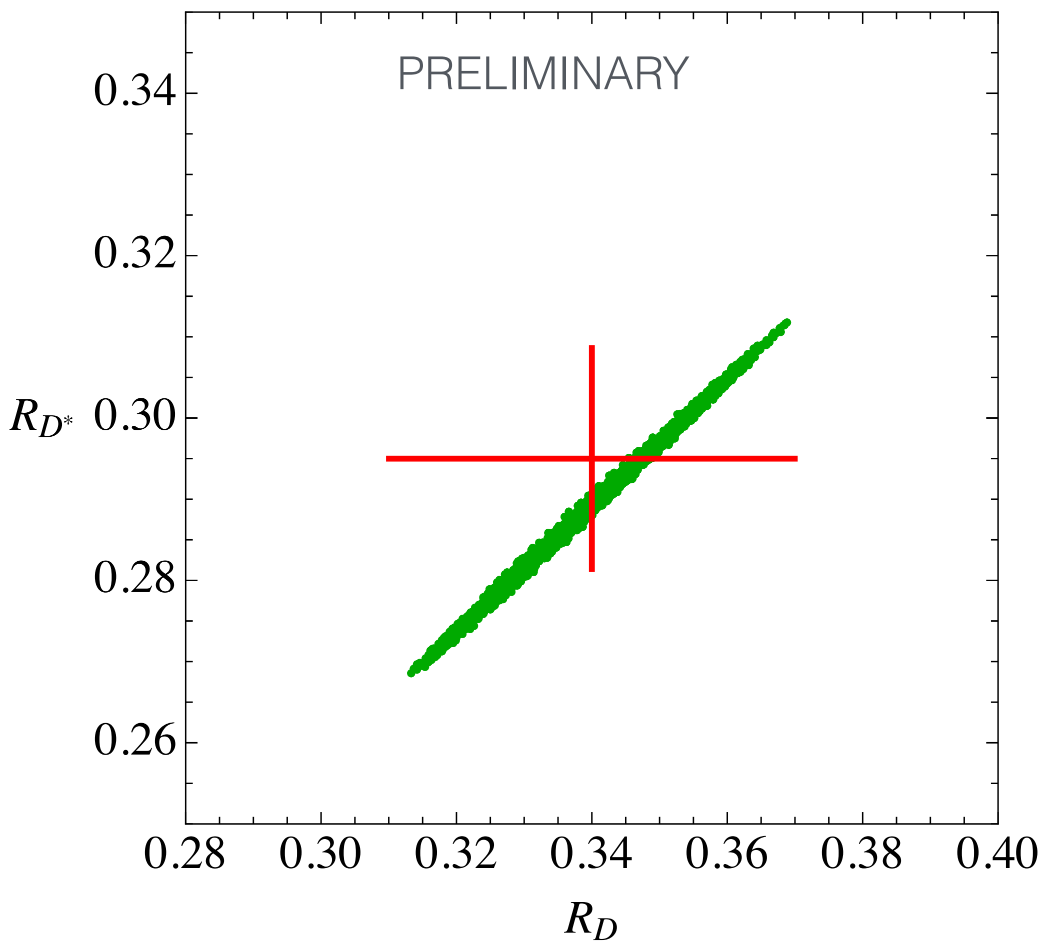
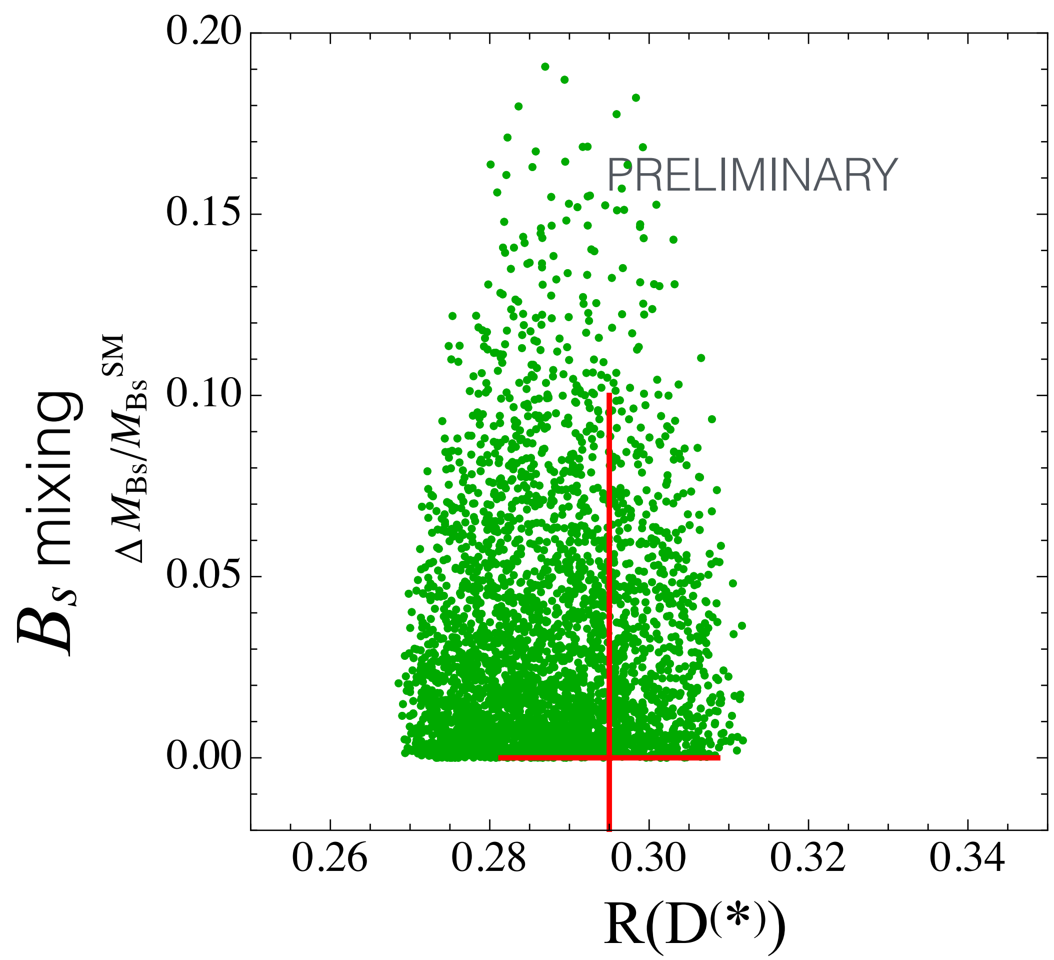




$M_{LQ} = 1.5$ TeV

This are ~3k points from a parameter scan,
each is within the 95%CL interval of the fit
(B-anomalies and all relevant constraints).

Implications for K→πνν

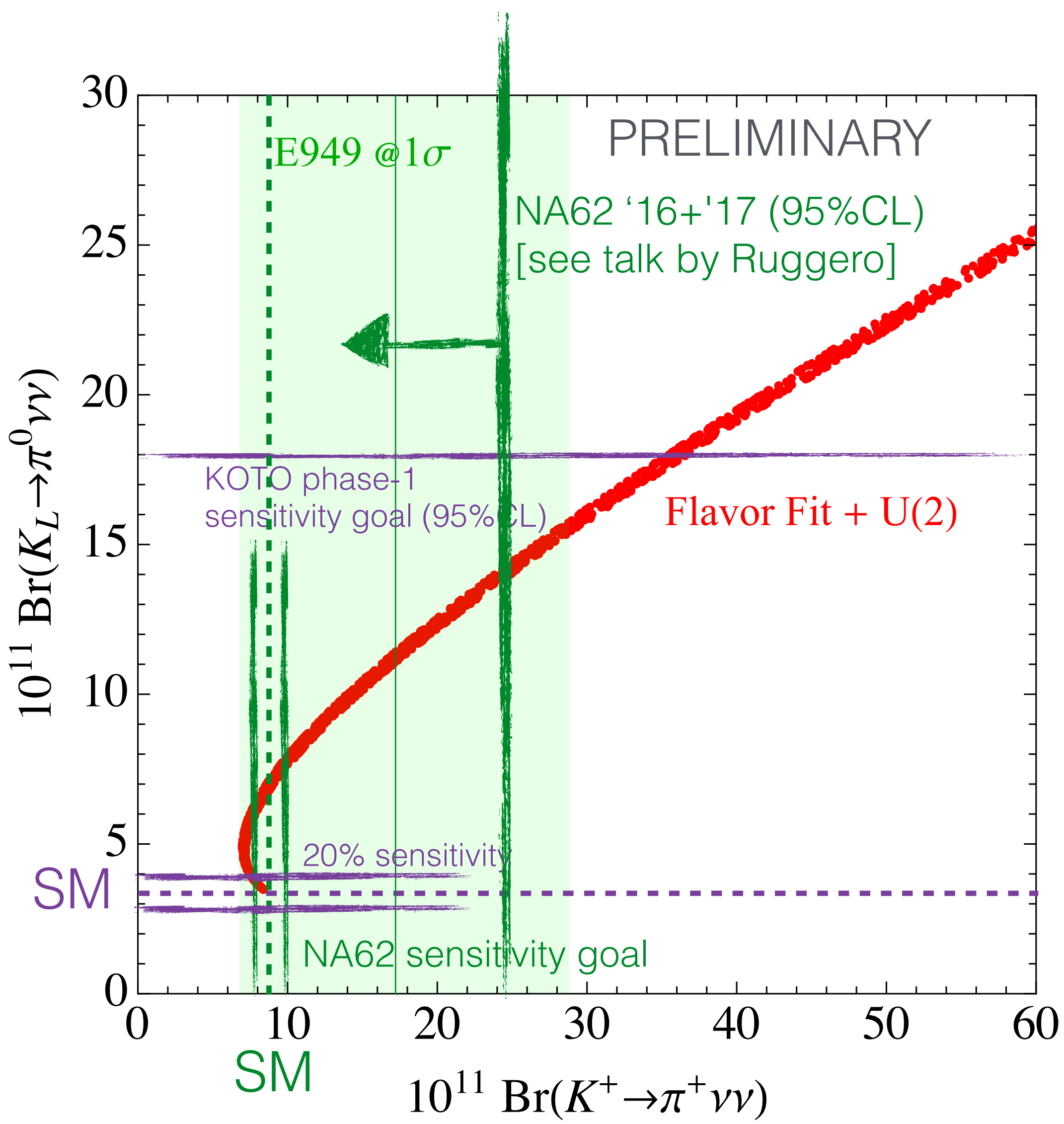
Work in progress with V. Gherardi and E. Venturini

$$\mathcal{L}_{S_1+S_3} = \left(\bar{q}^c \lambda^{1L} \epsilon \ell + \bar{u}^c \lambda^{1R} e\right) S_1 + \bar{q}^c \lambda^{3L} \epsilon \sigma^I \ell S_3^I + h.c.$$

Under U(2)[5] flavor symmetry assumption,
the LQ coupling to 1st ten is correlated with the one to 2nd gen:

$$\lambda_{d_L \tau_L} = \lambda_{s_L \tau_L} \frac{V_{td}^*}{V_{ts}^*}$$

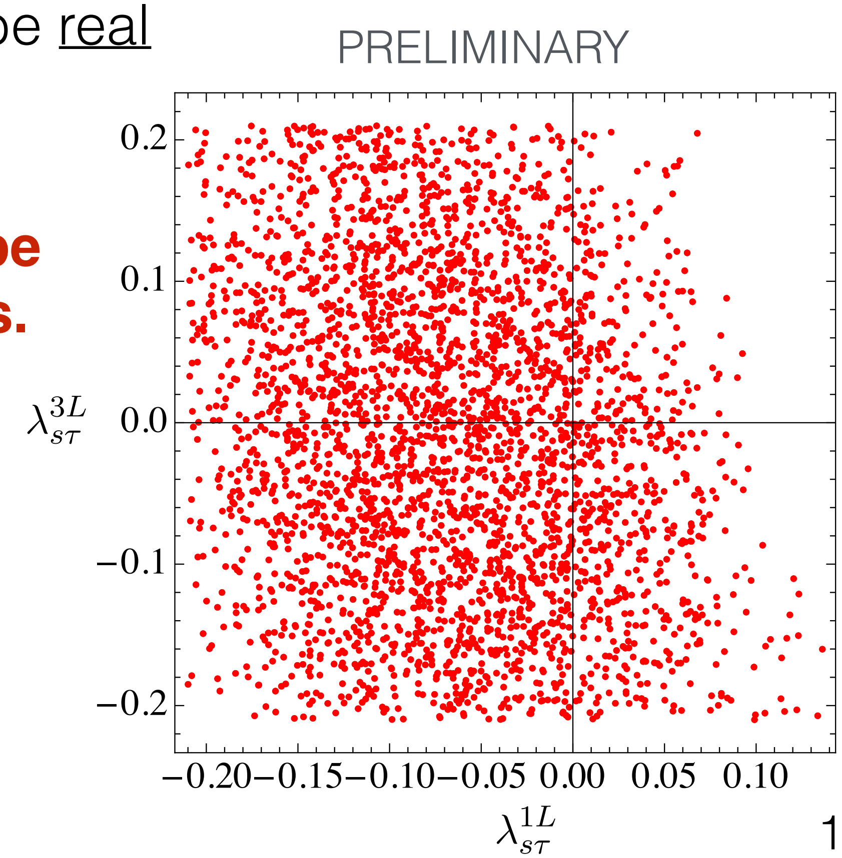
We can obtain a set of **predictions** for ***K⁺→π⁺νν*** and ***K_L→π⁰νν***.



The two are **very correlated** in this framework because there is only **one overall free phase**.

Here we chose $\lambda_{s_L \tau_L}$ to be real
(larger effect in R(D))

Many points can already be excluded by Kaon physics.



Kaon physics and R(K$^{(*)}$) ?

Under the U(2)^5 flavor symmetry: very small effect in kaon observables with muons.

$\Lambda_{R(K)} \sim$ 34 TeV $\lambda^{\ell}_{\mu\mu} \ll \lambda^{\ell}_{\tau\tau} = 1$ & $\lambda^{q}_{sd} \sim V^*_{ts} V_{td}$

To see an effect we need a more general flavor structure,
allowing for larger NP contributions in light quark generations.

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

$$\mathcal{L}^{\rm EFT}_{\rm NP} = C_{ij}(\bar{d}^i_L \gamma_\mu d^i_L)(\bar{\mu}_L \gamma^\mu \mu_L) \longrightarrow \mathcal{C} = \begin{pmatrix} \mathcal{C}_{dd} & \mathcal{C}_{ds} & \mathcal{C}_{db} \\ \mathcal{C}^*_{ds} & \mathcal{C}_{ss} & \mathcal{C}_{sb} \\ \mathcal{C}^*_{db} & \mathcal{C}^*_{sb} & \mathcal{C}_{bb} \end{pmatrix}$$

We need another motivated ansatz for the flavor structure of this matrix.

Directions in SU(3)$_q$ space

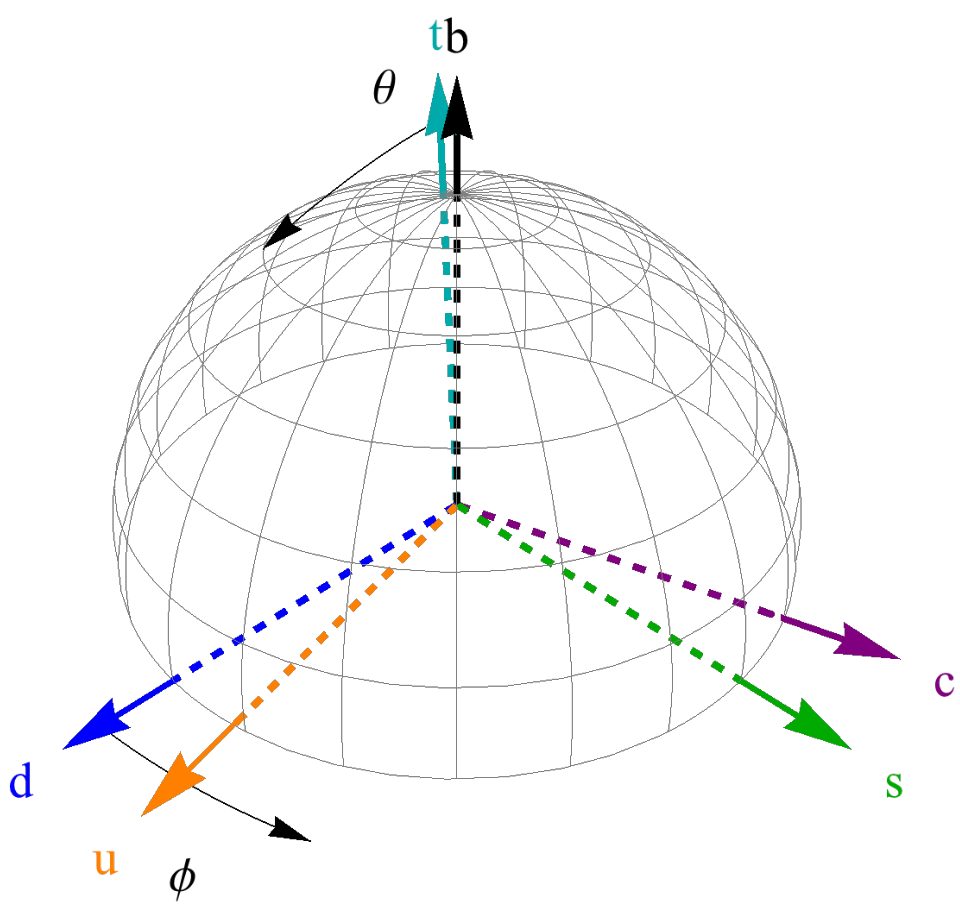
We can parametrise directions in SU(3)$_q$ as:

$$\hat{n} = \begin{pmatrix} \sin\theta\cos\phi e^{i\alpha_{bd}} \\ \sin\theta\sin\phi e^{i\alpha_{bs}} \\ \cos\theta \end{pmatrix}$$

Via a U(1)$_B$ phase redefinition we can always set $\hat{n}_3 > 0$

$$\theta \in \left[0, \frac{\pi}{2}\right] \;,\quad \phi \in [0, 2\pi) \;,\quad \alpha_{bd} \in \left[-\frac{\pi}{2}, \frac{\pi}{2}\right] \;,\quad \alpha_{bs} \in \left[-\frac{\pi}{2}, \frac{\pi}{2}\right]$$

In the mass eigenstate basis of down-quarks: $q_L^i = \begin{pmatrix} V_{ji}^* u_L^i \\ d_L^i \end{pmatrix}$



$\{q_L^i\}$ space, neglecting phases

quark	$\hat{n}$	ϕ	θ	α_{bd}	α_{bs}
down	$(1,0,0)$	0	$\pi/2$	0	0
strange	$(0,1,0)$	$\pi/2$	$\pi/2$	0	0
bottom	$(0,0,1)$	0	0	0	0
up	$e^{i\arg(V_{ub})}(V_{ud}^*, V_{us}^*, V_{ub}^*)$	0.23	1.57	-1.17	-1.17
charm	$e^{i\arg(V_{cb})}(V_{cd}^*, V_{cs}^*, V_{cb}^*)$	1.80	1.53	-6.2×10^{-4}	-3.3×10^{-5}
top	$e^{i\arg(V_{tb})}(V_{td}^*, V_{ts}^*, V_{tb}^*)$	4.92	0.042	-0.018	0.39

The misalignment between down- and up-quarks is described by the CKM matrix.

Rank-One Flavor Violation

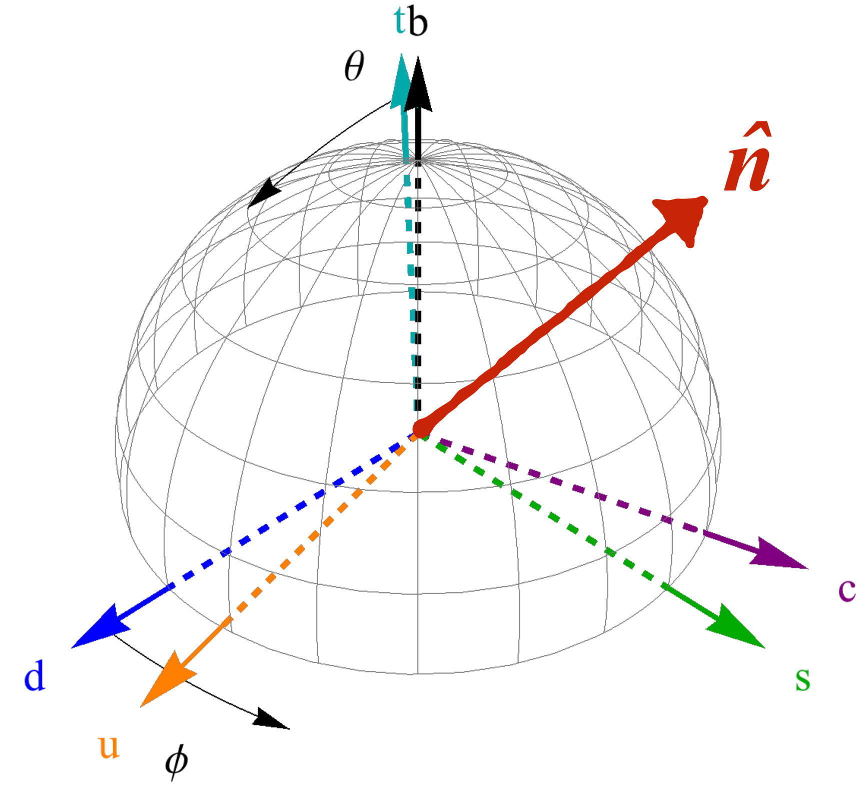
Valerio Gherardi, D.M., Marco Nardecchia, Andrea Romanino [1903.10954]

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

We assume that the **flavor matrix**

of the semi-leptonic couplings **to muons** is of **rank-one**:

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



$\hat{n}$ is some (arbitrary) unitary vector in flavour space $SU(3)_q$.

It selects a direction in that space.

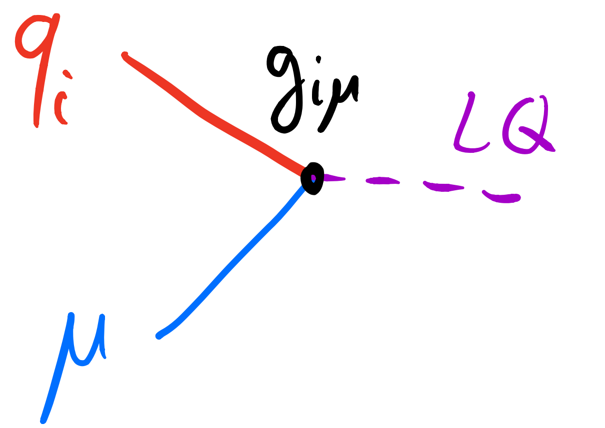
We aim to answer the following question

Assuming B-anomalies are reproduced, what are the experimentally allowed directions for $\hat{n}$?

Comment on UV realisations

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

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

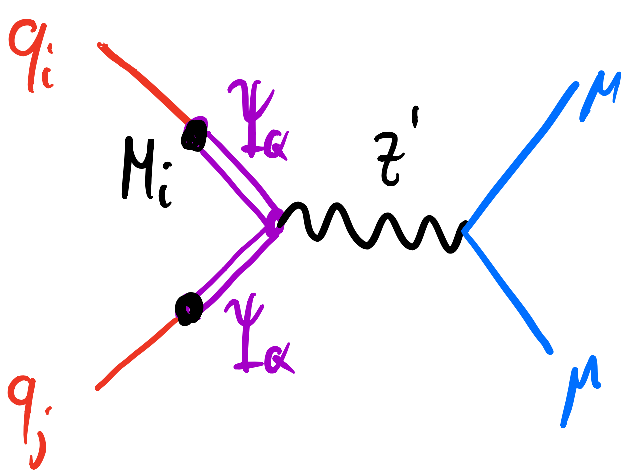


Single leptoquark models

$$\mathcal{L} \supset g_{i\mu}\, \bar{q}_L^i \gamma_\mu \ell_L^2\, U_1^\mu + h.c.$$

$$\hat{n}_i \propto g_{i\mu}$$

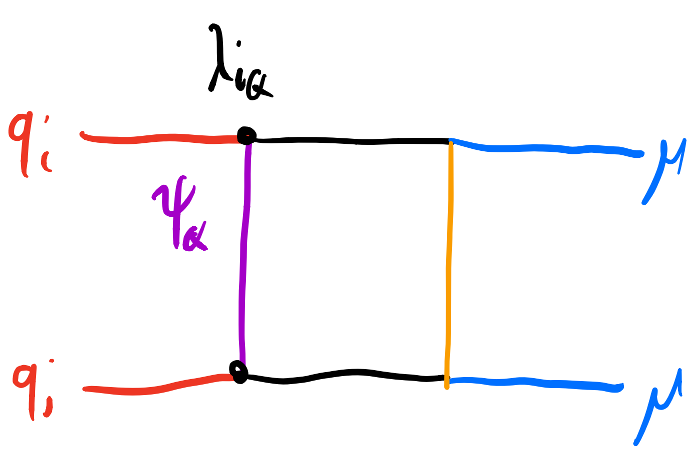
$$C_{ij} = C\, \hat{n}_i \hat{n}_j^*$$



Single vector-like quark mixing

$$\mathcal{L} \supset M_i\, \bar{q}_L^i \Psi_Q$$

$$\hat{n}_i \propto M_i$$



Loop models with 1 set of mediators

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

$$\mathcal{L} \supset \lambda_{iQ} \bar{q}_L^i \Psi_Q \Phi + h.c.$$

$$\hat{n}_i \propto \lambda_{iQ}$$

Constraints in ROFV

$$\mathcal{L}_{\rm NP}^{\rm EFT} = C\,\hat{n}_i\hat{n}_j^*(\bar{d}_L^i\gamma_\mu d_L^i)(\bar{\mu}_L\gamma^\mu\mu_L)$$

1) **Fix a direction $\hat{n}$.**

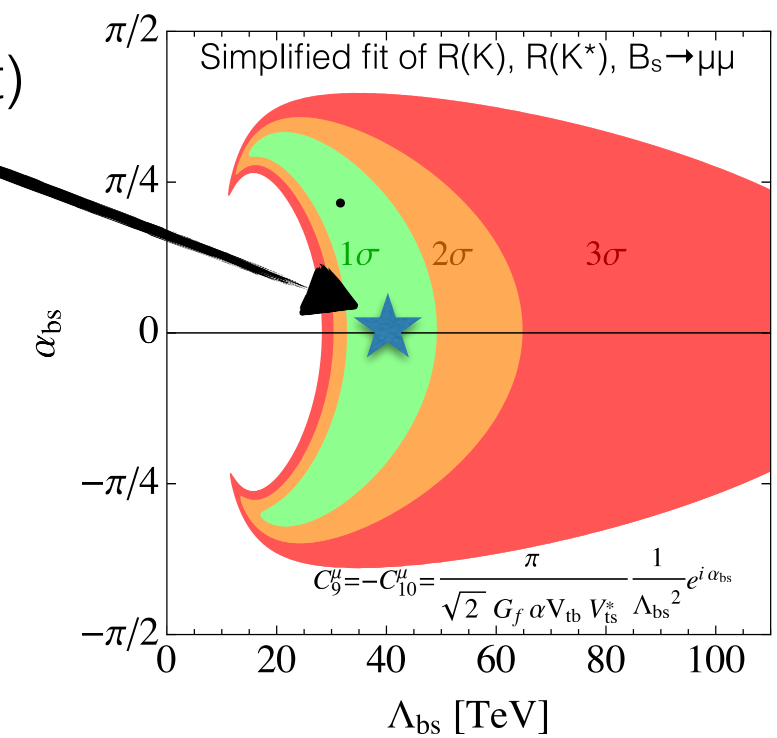
We fix the phases α_{bs}, α_{bd} and plot θ, φ.

$$\hat{n} = \begin{pmatrix} \sin\theta\cos\phi e^{i\alpha_{bd}} \\ \sin\theta\sin\phi e^{i\alpha_{bs}} \\ \cos\theta \end{pmatrix}$$

2) **Solve for C by imposing R(K$^{(*)}$)** (from the fit)

b → d μ⁺ μ⁻ $C_{sb} = C\sin\theta\cos\theta\sin\phi e^{i\alpha_{bs}} = \frac{e^{i\alpha_{bs}}}{\Lambda_{bs}^2}$ = (from fit)

$$C = C_{sb}^{\text{fit } R(K^{(*)})} e^{-i\alpha_{bs}}(\sin\theta\cos\theta\sin\phi)^{-1}$$



3) **Compute NP contribution for other flavor transitions:**

b → d μ⁺ μ⁻ $C_{db} = C\sin\theta\cos\theta\cos\phi e^{i\alpha_{bd}}$

s → d μ⁺ μ⁻ $C_{ds} = C\sin^2\theta\sin\phi\cos\phi e^{i(\alpha_{bd}-\alpha_{bs})}$

4) **Check if experimentally excluded or not.**

General correlations (LH)

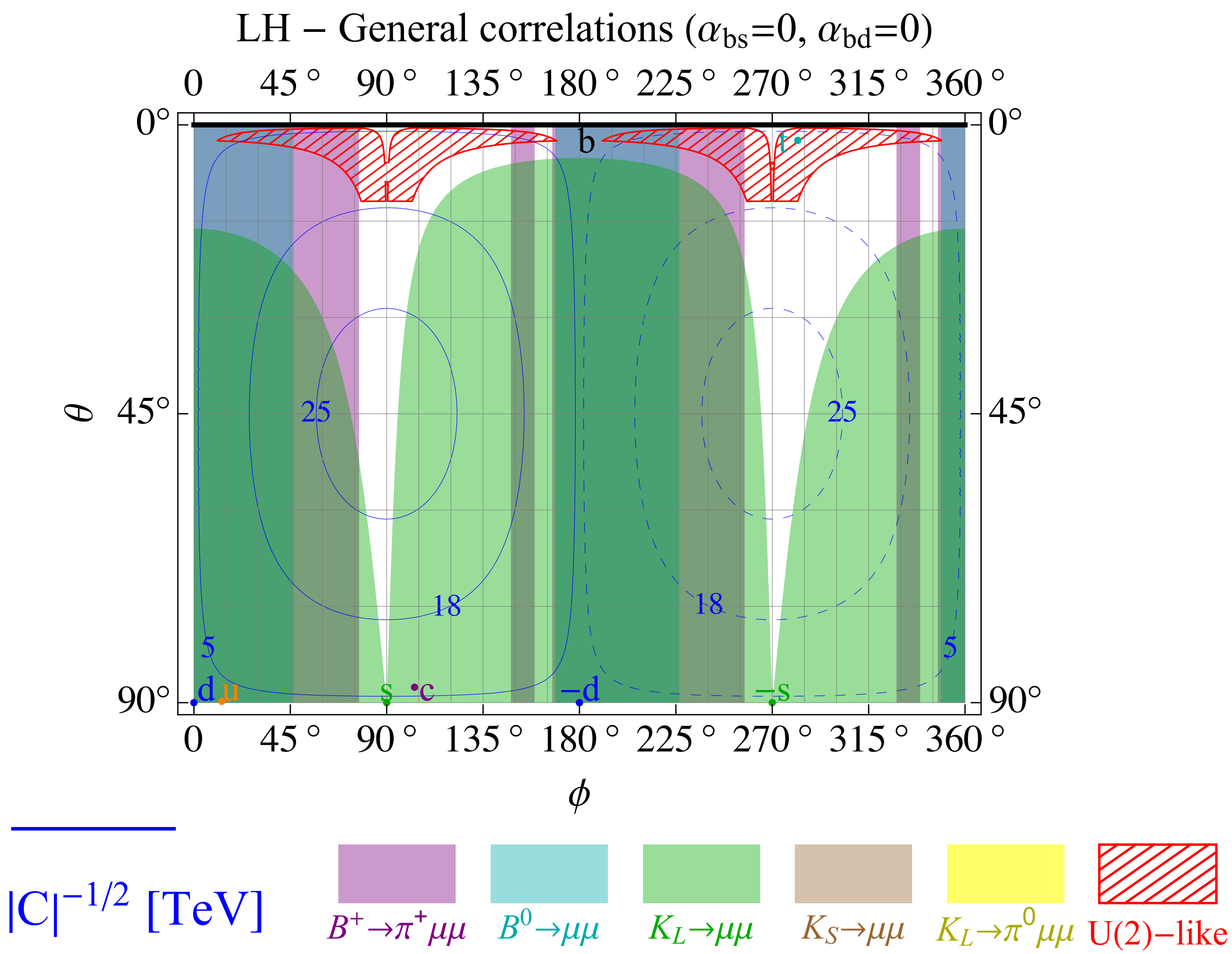
Direct correlations with other $d_i d_j \mu\mu$ observables

$$\mathcal{L}_{\rm NP}^{\rm EFT} = C\,\hat{n}_i \hat{n}_j^* (\bar{d}^i_L \gamma_\mu d^i_L)(\bar{\mu}_L \gamma^\mu \mu_L)$$

	Observable	Experimental value/bound	SM prediction	
C_{db}	$\mathrm{Br}(B_d^0 \to \mu^+\mu^-)$	$< 2.1 \times 10^{-10}$ (95% CL)	$(1.06 \pm 0.09) \times 10^{-10}$	ATLAS, LHCb
	$\mathrm{Br}(B^+ \to \pi^+\mu^+\mu^-)_{[1,6]}$	$(4.55^{+1.05}_{-1.00} \pm 0.15) \times 10^{-9}$	$(6.55 \pm 1.25) \times 10^{-9}$	LHCb
Im(C_{ds})	$\mathrm{Br}(K_S \to \mu^+\mu^-)$	$< 1.0 \times 10^{-9}$ (95% CL)	$(5.0 \pm 1.5) \times 10^{-12}$	LHCb
Re(C_{ds})	$\mathrm{Br}(K_L \to \mu^+\mu^-)_{\rm SD}$	$< 2.5 \times 10^{-9}$	$\approx 0.9 \times 10^{-9}$	E871, Isidori Unterdorfer '03
Im(C_{ds})	$\mathrm{Br}(K_L \to \pi^0\mu^+\mu^-)$	$< 3.8 \times 10^{-10}$ (90% CL)	$1.41^{+0.28}_{-0.26}(0.95^{+0.22}_{-0.21}) \times 10^{-11}$	KTEV

D'Ambrosio et al '98, Buchalla et al '03, Isidori et al '04, Mescia et al '06, Buras et al '17

Fix the phases and plot on the angles φ, θ (it's a semi-sphere in $SU(3)_q$)



Each colored region is excluded by the respective observable

General correlations (LH)

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

$$\mathcal{L}_{\rm NP}^{\rm EFT} = C\,\hat{n}_i \hat{n}_j^* (\bar{d}_L^i \gamma_\mu d_L^i)(\bar{\mu}_L \gamma^\mu \mu_L)$$

	Observable	Experimental value/bound	SM prediction
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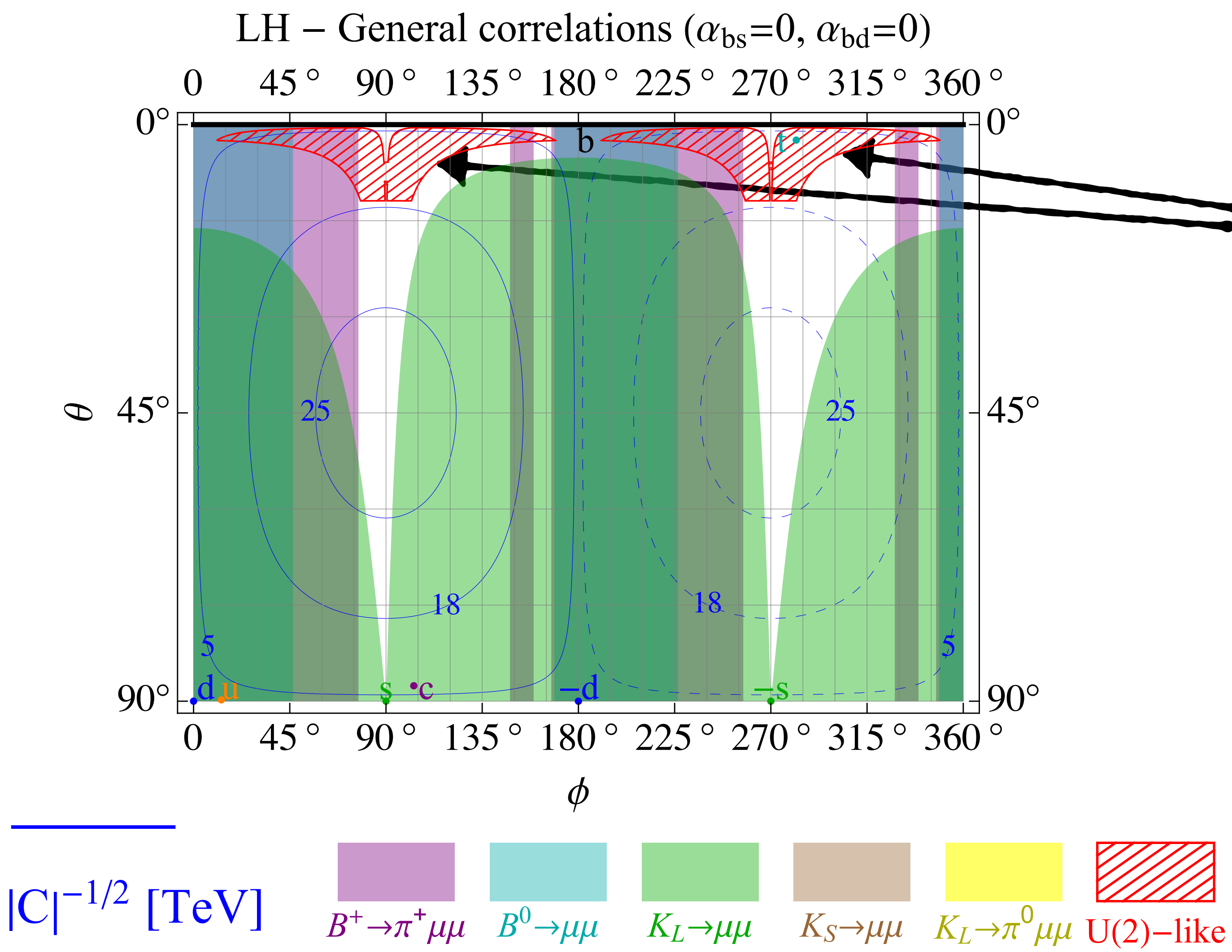
Fix the phases and plot on the angles φ, θ (it's a semi-sphere in SU(3)$_q$)



Region suggested by U(2)^5 flavour symmetry or partial compositeness (close to third generation).

$$\hat{n} = (\mathcal{O}(V_{td}), \mathcal{O}(V_{ts}), \mathcal{O}(1))$$

Each colored region is excluded by the respective observable

General correlations (LH)

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

$$\mathcal{L}^{\rm EFT}_{\rm NP} = C\, \hat{n}_i \hat{n}^*_j (\bar{d}^i_L \gamma_\mu d^i_L)(\bar{\mu}_L \gamma^\mu \mu_L)$$

$$\hat{n} = \begin{pmatrix} \sin\theta\cos\phi e^{i\alpha_{bd}} \\ \sin\theta\sin\phi e^{i\alpha_{bs}} \\ \cos\theta \end{pmatrix}$$

	Observable	Experimental value/bound	SM prediction
C_{db}	$\text{Br}(B^0_d \to \mu^+\mu^-)$	$< 2.1 \times 10^{-10}$ (95% CL)	$(1.06 \pm 0.09) \times 10^{-10}$
	$\text{Br}(B^+ \to \pi^+\mu^+\mu^-)_{[1,6]}$	$(4.55^{+1.05}_{-1.00} \pm 0.15) \times 10^{-9}$	$(6.55 \pm 1.25) \times 10^{-9}$
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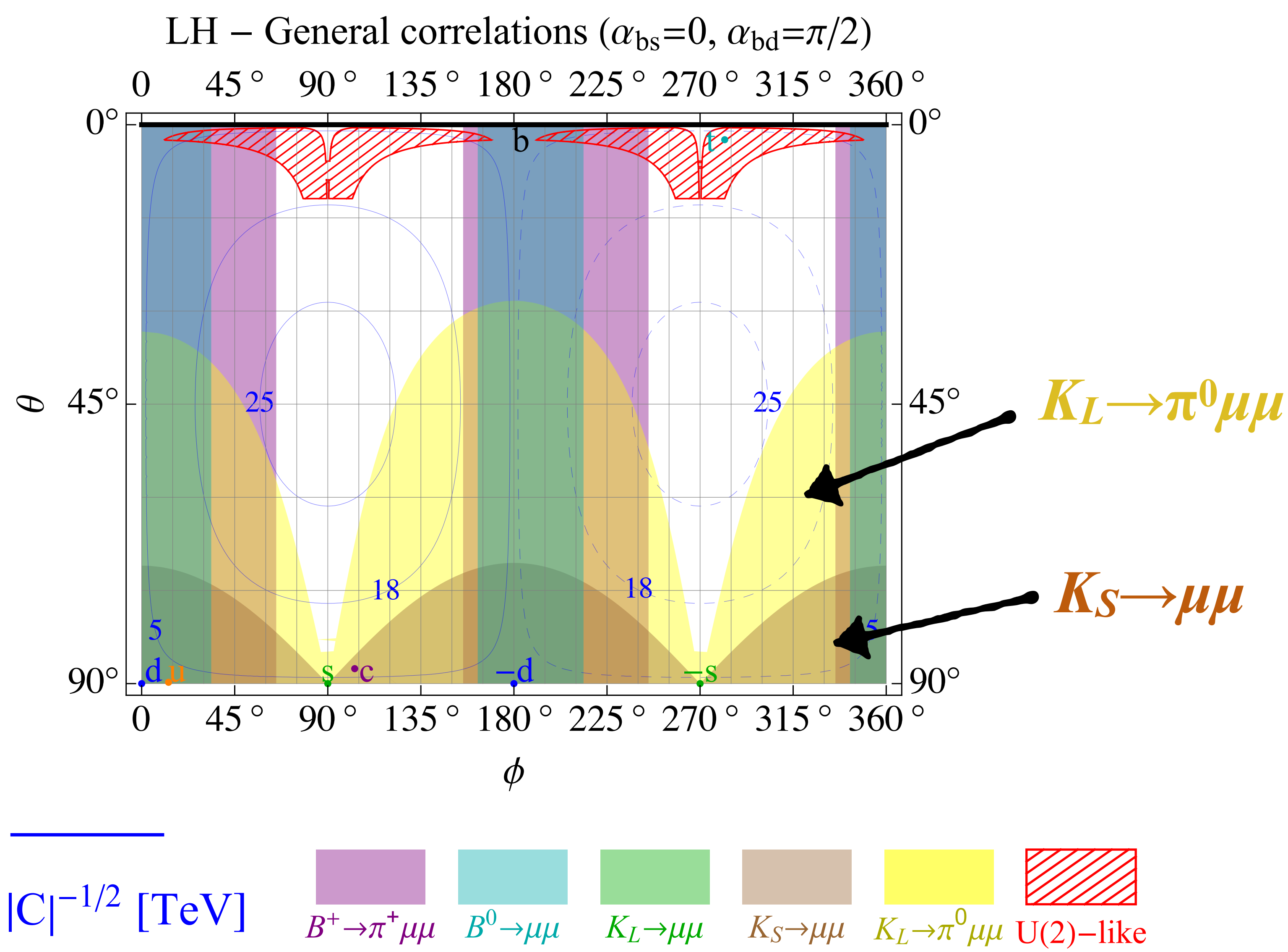
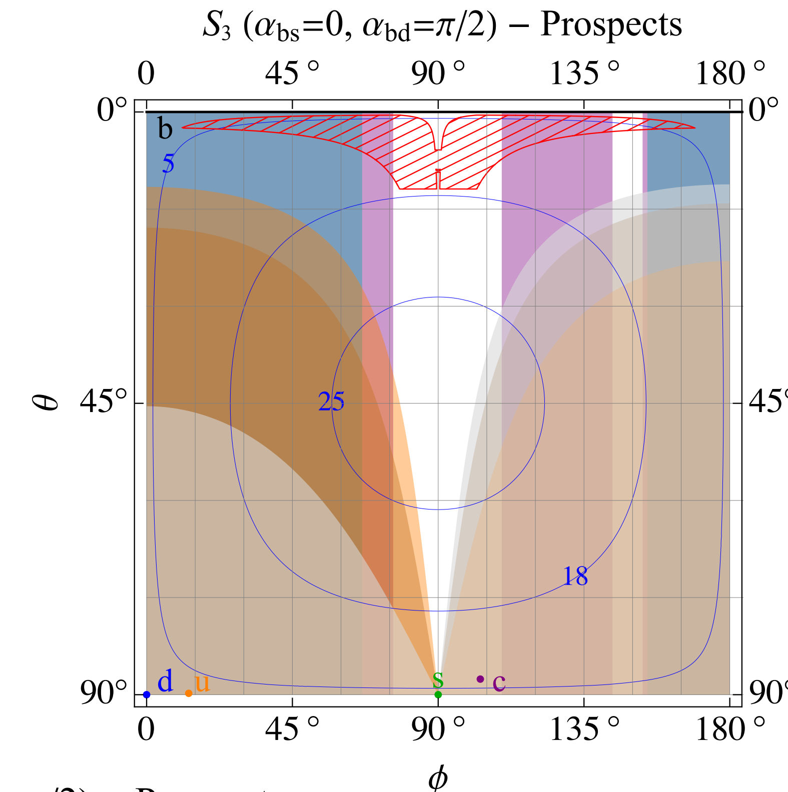


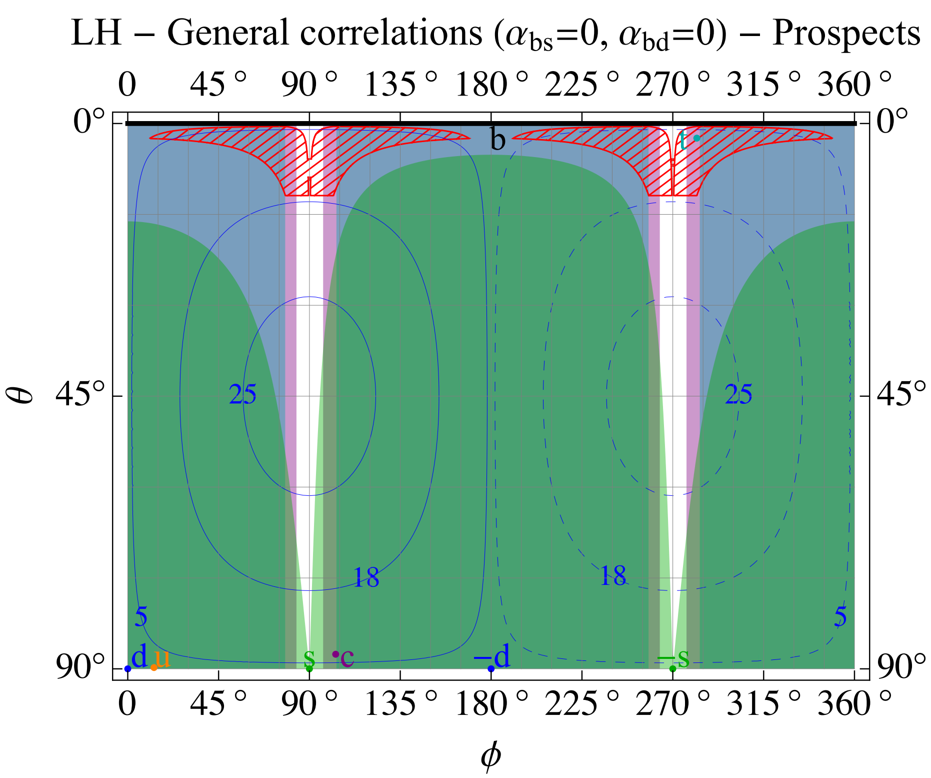
For complex coefficients, $K_L \to \pi^0\mu\mu$ and $K_S \to \mu\mu$ become important

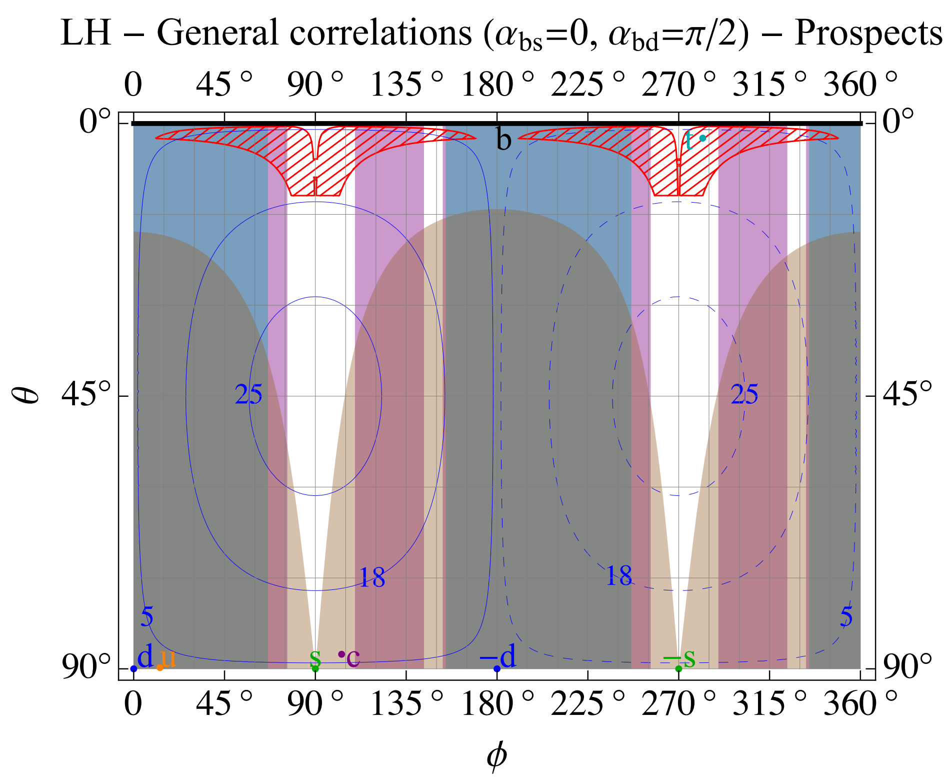
Prospects

Observable	Expected sensitivity	Experiment
R_K	0.7 (1.7)%	LHCb 300 (50) fb^{-1}
	3.6 (11)%	Belle II 50 (5) ab^{-1}
R_{K^*}	0.8 (2.0)%	LHCb 300 (50) fb^{-1}
	3.2 (10)%	Belle II 50 (5) ab^{-1}
R_π	4.7 (11.7)%	LHCb 300 (50) fb^{-1}
$\text{Br}(B_s^0 \to \mu^+\mu^-)$	4.4 (8.2)%	LHCb 300 (23) fb^{-1}
	7 (12)%	CMS 3 (0.3) ab^{-1}
$\text{Br}(B_d^0 \to \mu^+\mu^-)$	9.4 (33)%	LHCb 300 (23) fb^{-1}
	16 (46)%	CMS 3 (0.3) ab^{-1}
$\text{Br}(K_S \to \mu^+\mu^-)$	$\sim 10^{-11}$	LHCb 300fb^{-1}
	$\sim 1.8 \times 10^{-10}$	KOTO phase-I [6]
$\text{Br}(K_L \to \pi^0\nu\nu)$	20%	KOTO phase-II [6]
	20%	KLEVER
$\text{Br}(K^+ \to \pi^+\nu\nu)$	10%	NA62 goal

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







Summary

- The **B-physics anomalies** are one of the few experimental hints for NP at TeV scales. If confirmed, understanding the flavor structure of this new breaking of the SM flavor symmetries will be crucial.

- Specific flavor structures imply correlated effects in Kaon physics.

- In $U(2)^5$ flavor symmetry, $R(D^{(*)})$ is correlated with $K\to\pi\nu\nu$: **large** effects possible.

- The ***Rank-One Flavor Violation*** assumption, realised in several UV completions, allows to correlate $R(K^{(*)})$ with other Kaon observables, e.g. $K_{L,S}\to\mu\mu$ and $K_L\to\pi^0\mu\mu$, but also $K\to\pi\nu\nu$.

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

Grazie!

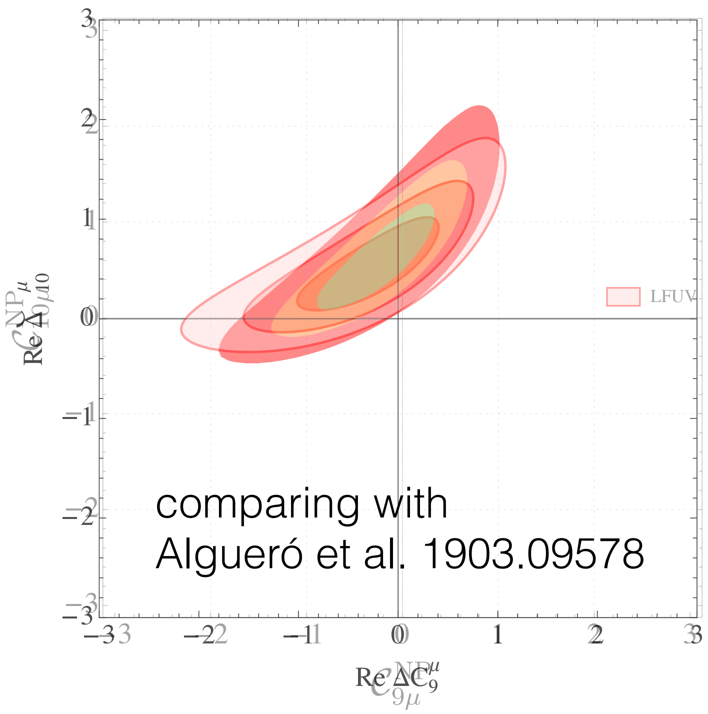
Backup

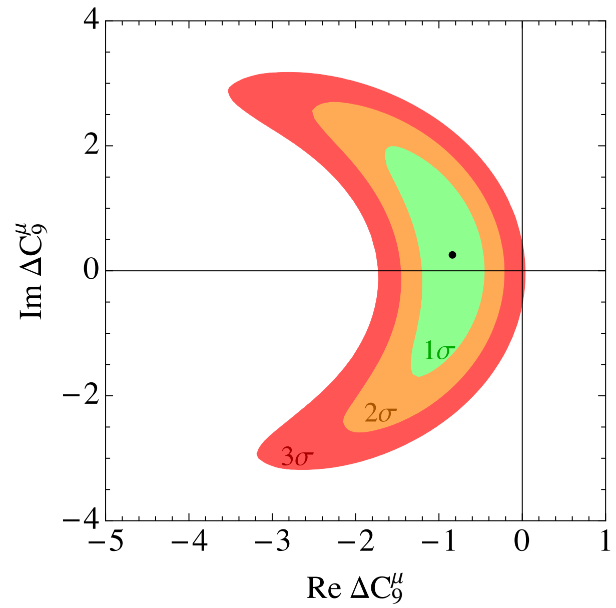
Simplified* fit of clean observables

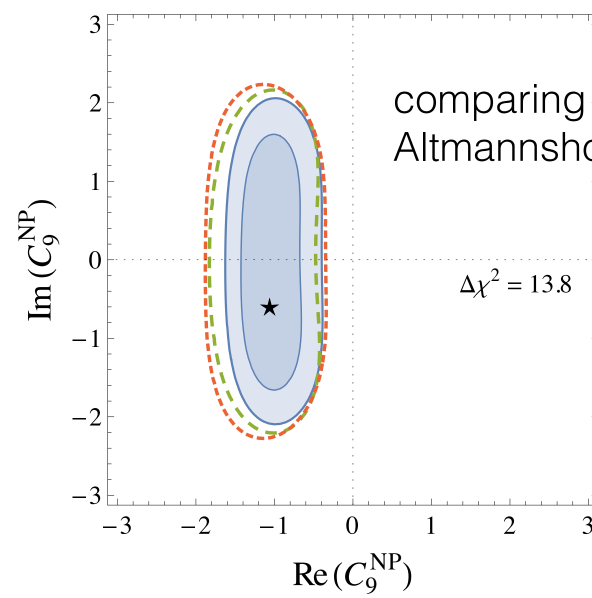
$$\mathcal{L}_{\rm eff}^{\rm NP} \supset \frac{G_F\alpha}{\sqrt{2}\pi} V_{tb}V_{ts}^* \left[\Delta C_9^\mu (\bar{s}_L\gamma^\mu b_L)(\bar\mu\gamma_\mu\mu) + \Delta C_{10}^\mu(\bar{s}_L\gamma^\mu b_L)(\bar\mu\gamma_\mu\gamma_5\mu)\right] + h.c. \,.$$

$$\mathcal{L}_{\rm eff} \supset \frac{e^{i\alpha_{bs}}}{\Lambda_{bs}^2}(\bar{s}_L\gamma^\mu b_L)(\bar\mu_L\gamma_\mu\mu_L) + h.c.$$

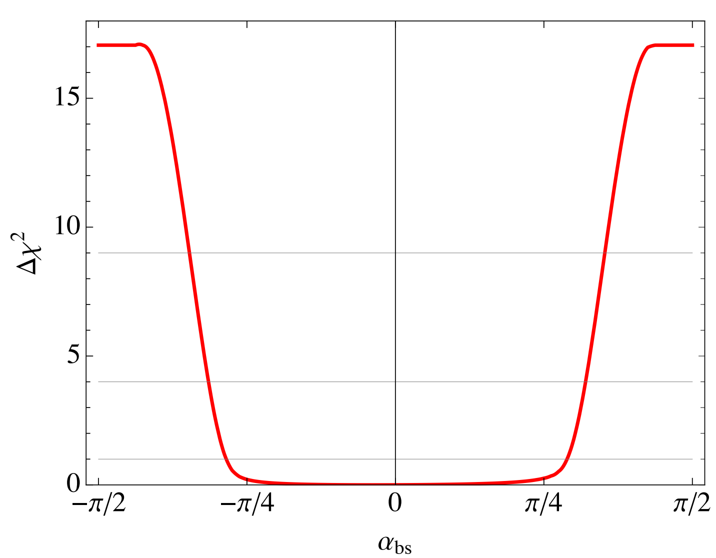
R_K $[1.1,\ 6]$ GeV^2	0.846 ± 0.062	LHCb [1, 2]
R_{K^*} $[0.045,\ 1.1]$ GeV^2	0.66 ± 0.11 $0.52^{+0.36}_{-0.26}$	LHCb [3] Belle [4]
R_{K^*} $[1.1,\ 6]$ GeV^2	0.69 ± 0.12 $0.96^{+0.45}_{-0.29}$	LHCb [3] Belle [4]
R_{K^*} $[15,\ 19]$ GeV^2	$1.18^{+0.52}_{-0.32}$	Belle [4]
${\rm Br}(B_s^0 \to \mu\mu)$	$(3.0^{+0.67}_{-0.63}) \times 10^{-9}$ $(2.8^{+0.8}_{-0.7}) \times 10^{-9}$	LHCb [9] ATLAS [10]

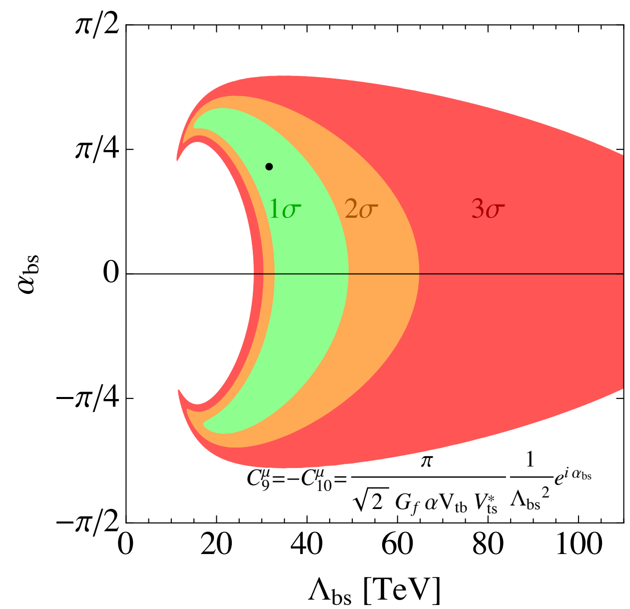


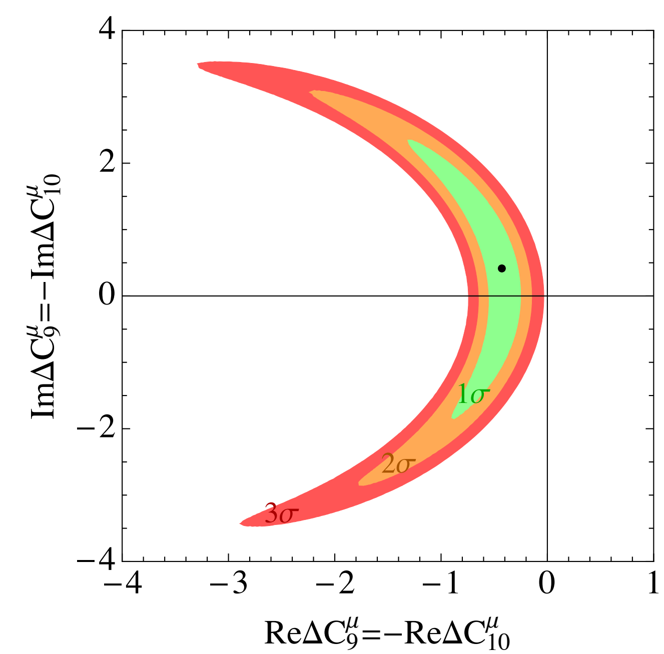




comparing with
Altmannshofer, Straub 1411.3161







*Simplified = no theory uncertainties considered. Agrees well “enough" with full fits.

SMEFT case & mediators

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

$$\mathcal{L}_{\rm NP}^{\rm SMEFT} = C_S^{ij}\left(\bar q_L^i \gamma_\mu q_L^j\right)\left(\bar\ell_L^2 \gamma^\mu \ell_L^2\right) + C_T^{ij}\left(\bar q_L^i \gamma_\mu \sigma^a q_L^j\right)\left(\bar\ell_L^2 \gamma^\mu \sigma^a \ell_L^2\right) + C_R^{ij}\left(\bar q_L^i \gamma_\mu q_L^j\right)\left(\mu_R \gamma^\mu \mu_R\right)$$

The ROFV assumption is

$$C_{S,T,R}^{ij} = C_{S,T,R}\, \hat n_i \hat n_j^*$$

Three overall coefficients

Channel	Coefficient dependencies
$d_i \to d_j \mu^+\mu^-$	$C_S + C_T,\ C_R$
$u_i \to u_j \overline{\nu_\mu}\nu_\mu$	$C_S + C_T$
$u_i \to u_j \mu^+\mu^-$	$C_S - C_T,\ C_R$
$d_i \to d_j \overline{\nu_\mu}\nu_\mu$	$C_S - C_T$
$u_i \to d_j \mu^+\nu_\mu$	C_T

Different processes depend on different combinations of the three overall coefficients

Assuming a *LH solution* ($C_R=0$):

$$C_+ \equiv C_S + C_T$$

This combination is fixed by the anomaly.
$d_i d_j\ \mu\mu$ transitions, are **directly correlated** with ***bs μμ***

$$C_- \equiv C_S - C_T$$

In general this is an independent parameter.
Must be fixed e.g. by assuming a specific mediator.

SMEFT case & mediators

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

$$\mathcal{L}_{\rm NP}^{\rm SMEFT} = C_S^{ij}\left(\bar{q}_L^i\gamma_\mu q_L^j\right)\left(\bar{\ell}_L^2\gamma^\mu\ell_L^2\right) + C_T^{ij}\left(\bar{q}_L^i\gamma_\mu\sigma^a q_L^j\right)\left(\bar{\ell}_L^2\gamma^\mu\sigma^a\ell_L^2\right) + C_R^{ij}\left(\bar{q}_L^i\gamma_\mu q_L^j\right)\left(\mu_R\gamma^\mu\mu_R\right)$$

The ROFV assumption is

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

Three overall coefficients

Channel	Coefficient dependencies
$d_i \to d_j\mu^+\mu^-$	$C_S + C_T,\ C_R$
$u_i \to u_j\overline{\nu_\mu}\nu_\mu$	$C_S + C_T$
$u_i \to u_j\mu^+\mu^-$	$C_S - C_T,\ C_R$
$d_i \to d_j\overline{\nu_\mu}\nu_\mu$	$C_S - C_T$
$u_i \to d_j\mu^+\nu_\mu$	C_T

Different processes depend on different combinations of the three overall coefficients

$K^+ \to \pi^+\nu\nu$ is important

We can ask what are the possible tree-level mediators which generate these operators.

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

Simplified model	Spin	SM irrep	(c_S, c_T, c_R)
S_3	0	$(\bar{3}, 3, 1/3)$	$(3/4, 1/4, 0)$
U_1	1	$(3, 1, 2/3)$	$(1/2, 1/2, 0)$
U_3	1	$(3, 3, 2/3)$	$(3/2, -1/2, 0)$
V'	1	$(1, 3, 0)$	$(0, 1, 0)$
$Z'_{(L)}$	1	$(1, 1, 0)$	$(1, 0, 0)$
$Z'_{(V)}$	1	$(1, 1, 0)$	$(1, 0, 1)$

As representative examples, we study:

S_3 U_1 Z'_V

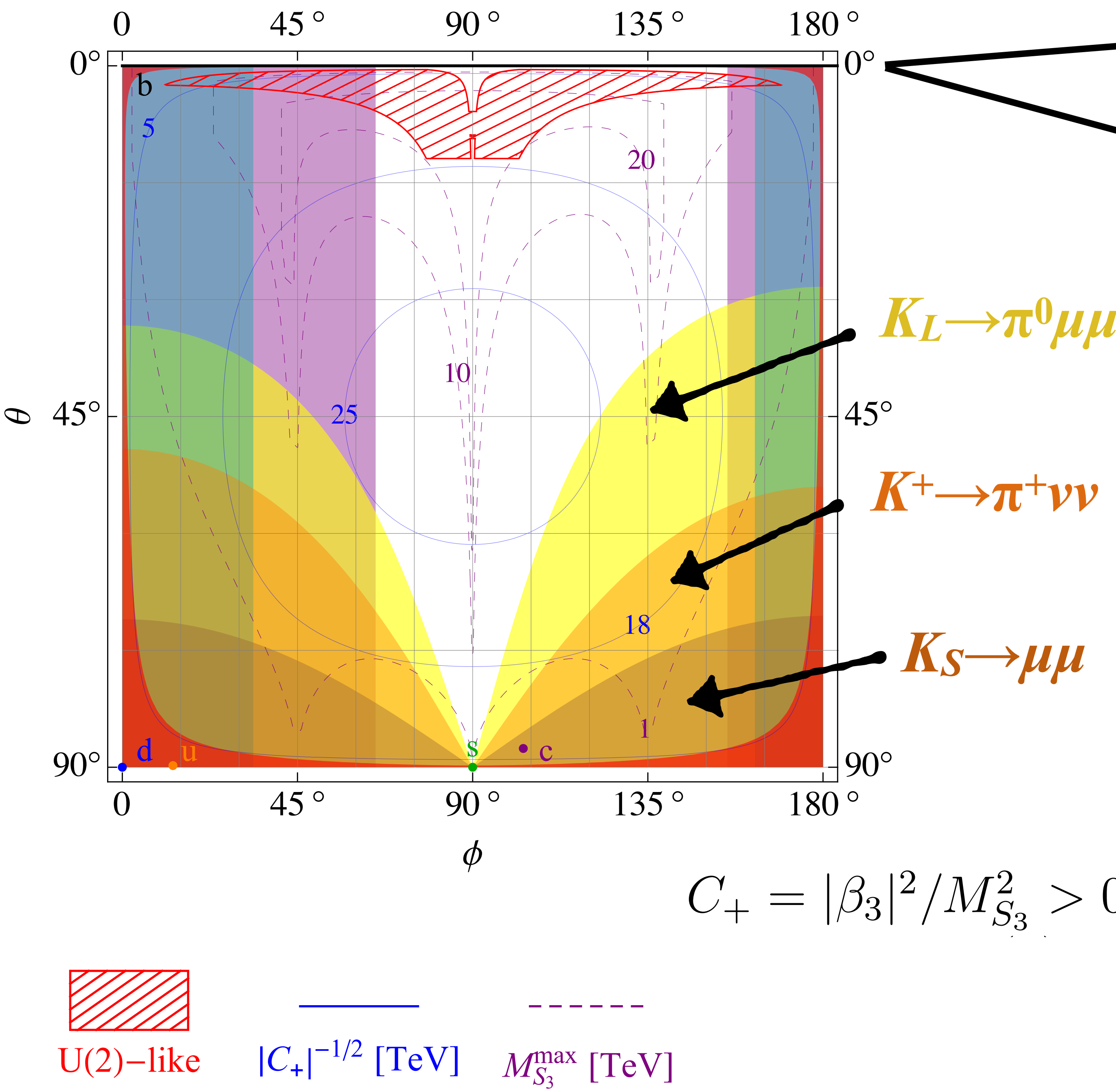
(backup slides)

S_3 scalar leptoquark

$S_3 = (\bar{\mathbf{3}}, \mathbf{3}, 1/3)$

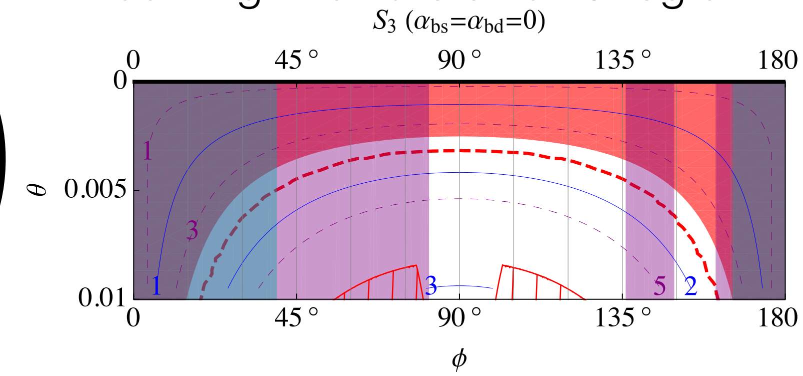
$$\mathcal{L}_{\rm NP} \supset \beta_{3,i\mu}(\bar{q}_L^{c\,i}\epsilon\sigma^a\ell_L^2)\,S_3^a + {\rm h.c.} \longrightarrow C_S^{ij} = \frac{3}{4}\frac{\beta^*_{3,i\mu}\beta_{3,j\mu}}{M^2_{S_3}}\,, \quad C_T^{ij} = \frac{1}{4}\frac{\beta^*_{3,i\mu}\beta_{3,j\mu}}{M^2_{S_3}}\,, \quad C_R^{ij} = 0$$

$$\beta^*_{3,i\mu} \equiv \beta^*_3\,\hat{n}_i$$

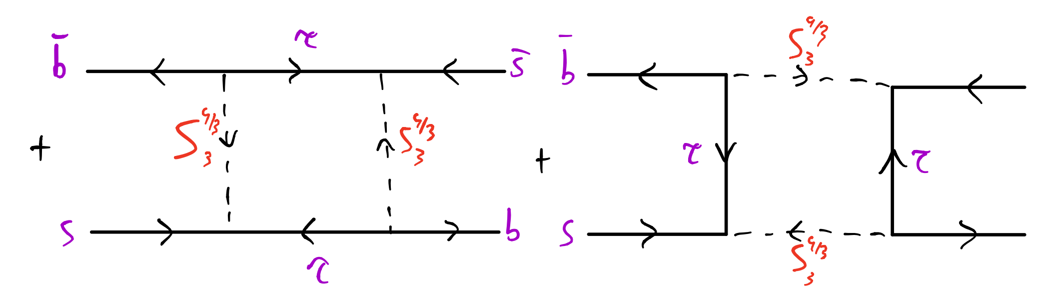


$$C_+ = |\beta_3|^2/M^2_{S_3} > 0$$

Zooming in on the small θ region



LHC dimuon searches are relevant only for *small θ*, i.e. very close to the 3rd generation.
Still far from testing U(2) hypothesis [Greljo, D.M. 1704.09015]



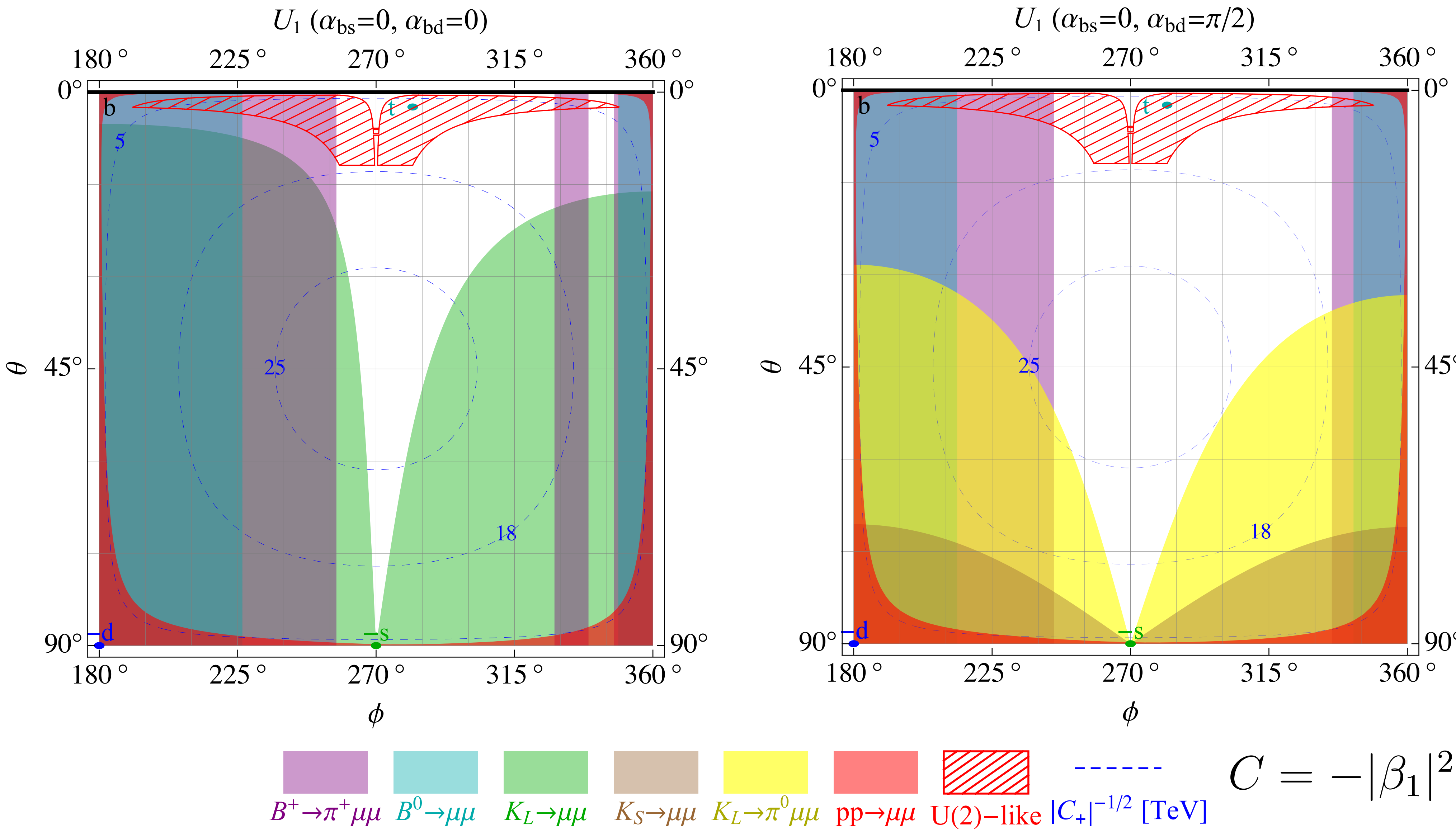
At 1-loop it generates ΔF=2 operators

$$\Delta\mathcal{L}_{\Delta F=2} = -\frac{5|\beta_3|^4}{128\pi^2 M^2_{S_3}}\left[(\hat{n}_i\hat{n}_j^*\bar{d}_L^i\gamma^\alpha d_L^j)^2 + (V_{ik}\hat{n}_k\hat{n}_l^* V^*_{jl}\,\bar{u}_L^i\gamma^\alpha u_L^j)^2\right]$$

Limits on D-$\bar{D}$, K-$\bar{K}$, B_d-$\bar{B}_d$, B_s-$\bar{B}_s$ give an upper limit on the leptoquark mass

U_1 vector leptoquark

$$\mathcal{L}_{\rm NP} \supset \beta_{1,i\mu}(\bar{q}^i_L \gamma_\alpha \ell^2_L)\, U_1^\alpha + {\rm h.c.} \quad \xrightarrow[\beta_{1,i\mu} \equiv \beta_1\, \hat{n}_i]{} \quad C_S^{ij} = -\frac{1}{2}\frac{\beta_{1,i\mu}\beta^*_{1,j\mu}}{M^2_{U_1}}\,, \quad C_T^{ij} = -\frac{1}{2}\frac{\beta_{1,i\mu}\beta^*_{1,j\mu}}{M^2_{U_1}}\,, \quad C_R^{ij} = 0$$



$$C = -|\beta_1|^2/M^2_{U_1} < 0$$

ΔF=2 loops are divergent, need a UV completion.

Z’ & vector-like couplings to μ

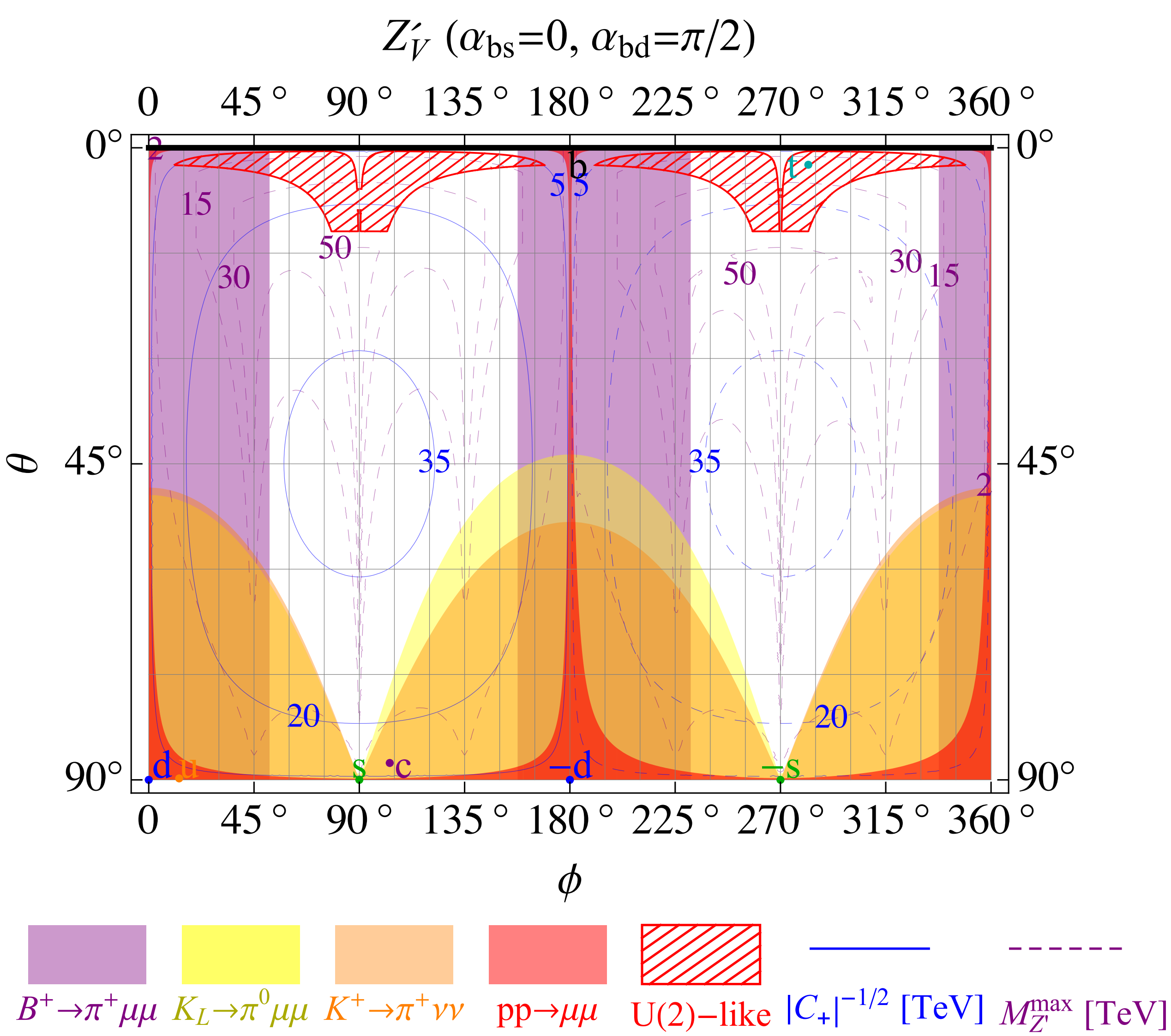
For example see the gauged $U(1)_{L\mu-L\tau}$ model with 1 vector-like quark.

[Altmannshofer, Gori, et al 1403.1269, 1609.04026]

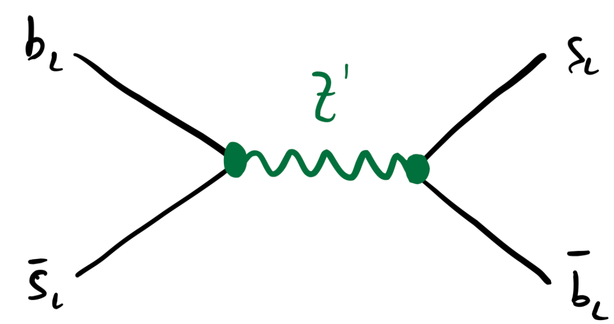
$$\mathcal{L} \supset M_i \, \bar{q}_L^i \Psi_Q$$

$$\hat{n}_i \propto M_i$$

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



$$C_+ = -g_q g_\mu / (M_{Z'}^2)$$



ΔF=2 operators are generated at the tree level.

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

We can put upper limits on $r_{q\mu}=g_q/g_\mu$,
or for a given maximum g_μ,
an upper limit on the Z’ mass

$$M_{Z'}^{\rm lim} = \sqrt{\frac{r_{q\mu}^{\rm lim}}{4|C|}} |g_\mu^{\rm max}|$$

ΔF = 2 observables (and ε'/ε)

Limits on $\Delta F = 2$ coefficients $[\,\mathrm{GeV}^{-2}]$
$\mathrm{Re}C_K^1 \in [-6.8, 7.7] \times 10^{-13}$, $\mathrm{Im}C_K^1 \in [-1.2, 2.4] \times 10^{-15}$
$\mathrm{Re}C_D^1 \in [-2.5, 3.1] \times 10^{-13}$, $\mathrm{Im}C_D^1 \in [-9.4, 8.9] \times 10^{-15}$
$\lvert C_{B_d}^1\rvert < 9.5 \times 10^{-13}$
$\lvert C_{B_s}^1\rvert < 1.9 \times 10^{-11}$

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

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

For example, the Z' contribution is: $\Delta\mathcal{L}_{\Delta F=2} = -\frac{g_q^2}{2M_{Z'}^2}\left[(\hat{n}_i\hat{n}_j^*\overline{d_{iL}}\gamma^\alpha d_{jL})^2 + (V_{ik}\hat{n}_k\hat{n}_l^* V_{jl}^*\,\overline{u_{iL}}\gamma^\alpha u_{jL})^2\right]$

Also ε'/ε provides a potential constrain on the coefficient of $(\bar{s}\gamma_\mu P_L d)(\bar{q}\gamma^\mu P_L q)$

$q = u, d, s, c$

[Aebisher et al. 1807.02520, 1808.00466]

$$\left(\frac{\varepsilon'}{\varepsilon}\right)_{\mathrm{BSM}} = \sum_i P_i(\mu_{\mathrm{ew}})\ \mathrm{Im}\left[C_i(\mu_{\mathrm{ew}}) - C_i'(\mu_{\mathrm{ew}})\right] \lesssim 10\times10^{-4}$$

In this framework, this constraint is not competitive with ΔF = 2