Kaon physics implications from B-anomalies

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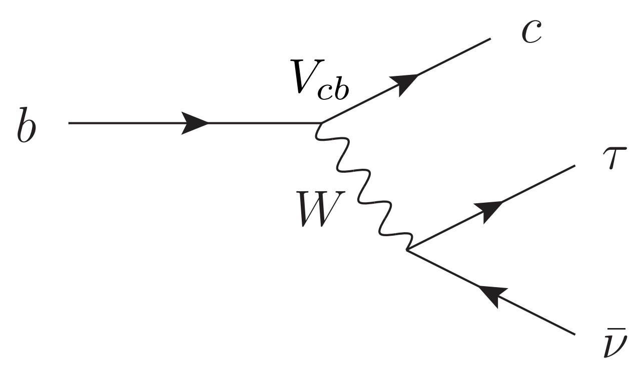
Outline

- Introduction on B-physics anomalies and EFT interpretations
- Implications of $R(D^{(*)})$: $SU(2)^n$ 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



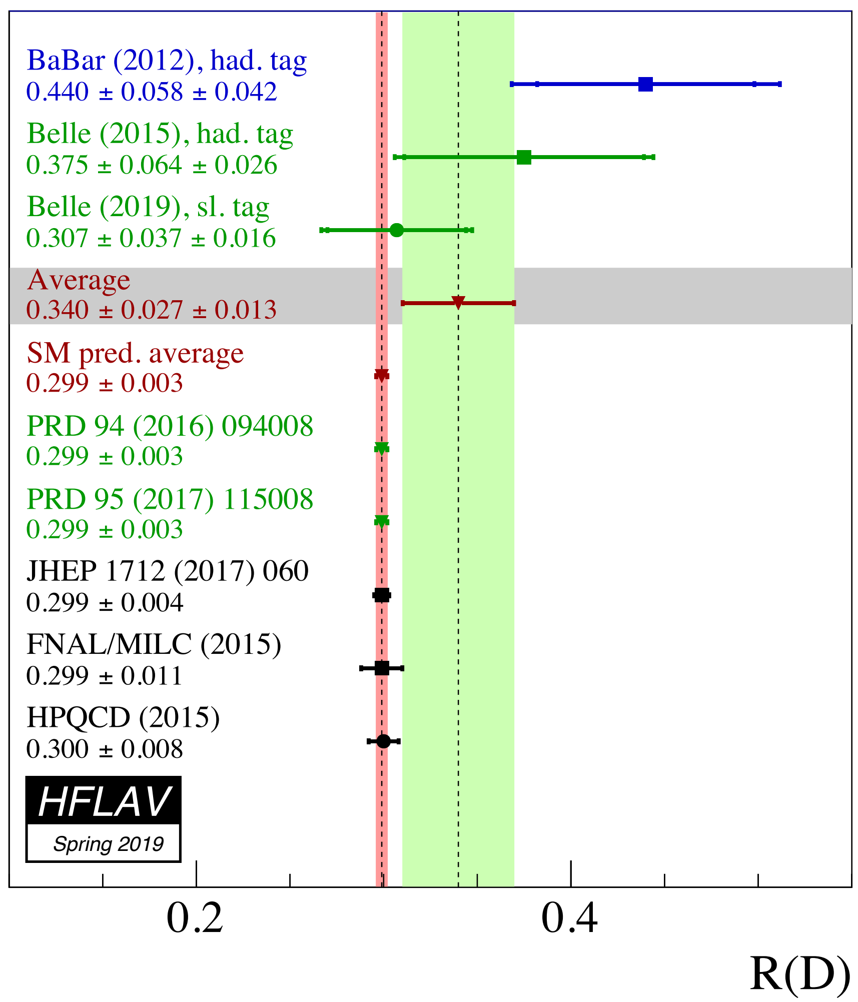
Tree-level SM process with V_{cb} suppression.

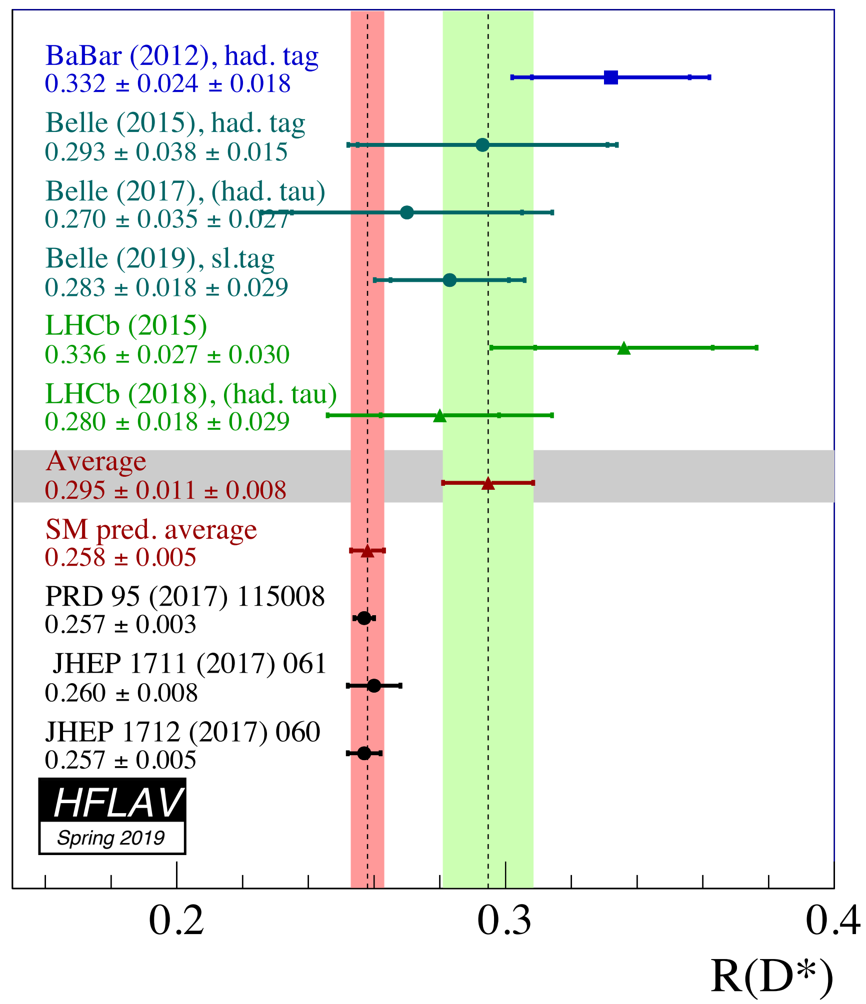
$b \to c\,\tau\,\nu$ vs. $b \to c\,\ell\,\nu$

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

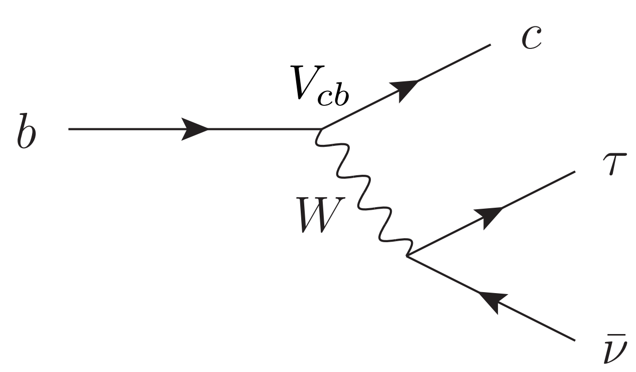
$$\ell = \mu, e$$

All measurements since 2012 consistently above the SM predictions





Charged-current anomalies



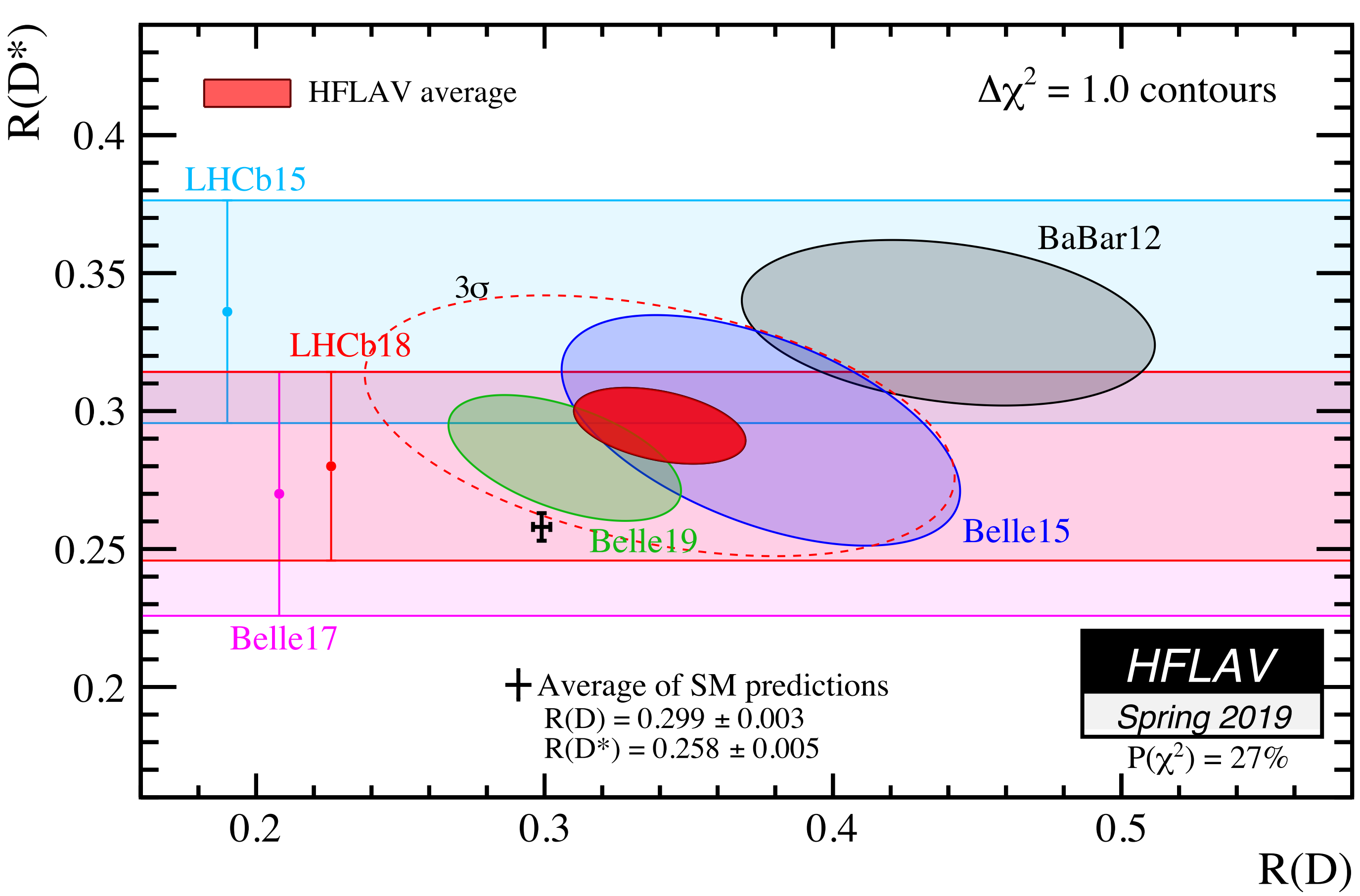
Tree-level SM process with V_{cb} suppression.

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

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

$$\ell = \mu, e$$

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



Before Moriond '19: $R_{D^{(*)}} \equiv R(D^{(*)})/R(D^{(*)})_{\rm SM} = 1.218 \pm 0.052$

~ 14% enhancement from the SM

~ 3.7σ from the SM (when combined)

While μ/e universality well tested

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

Belle - [1510.03657]

Neutral-Current B-anomalies

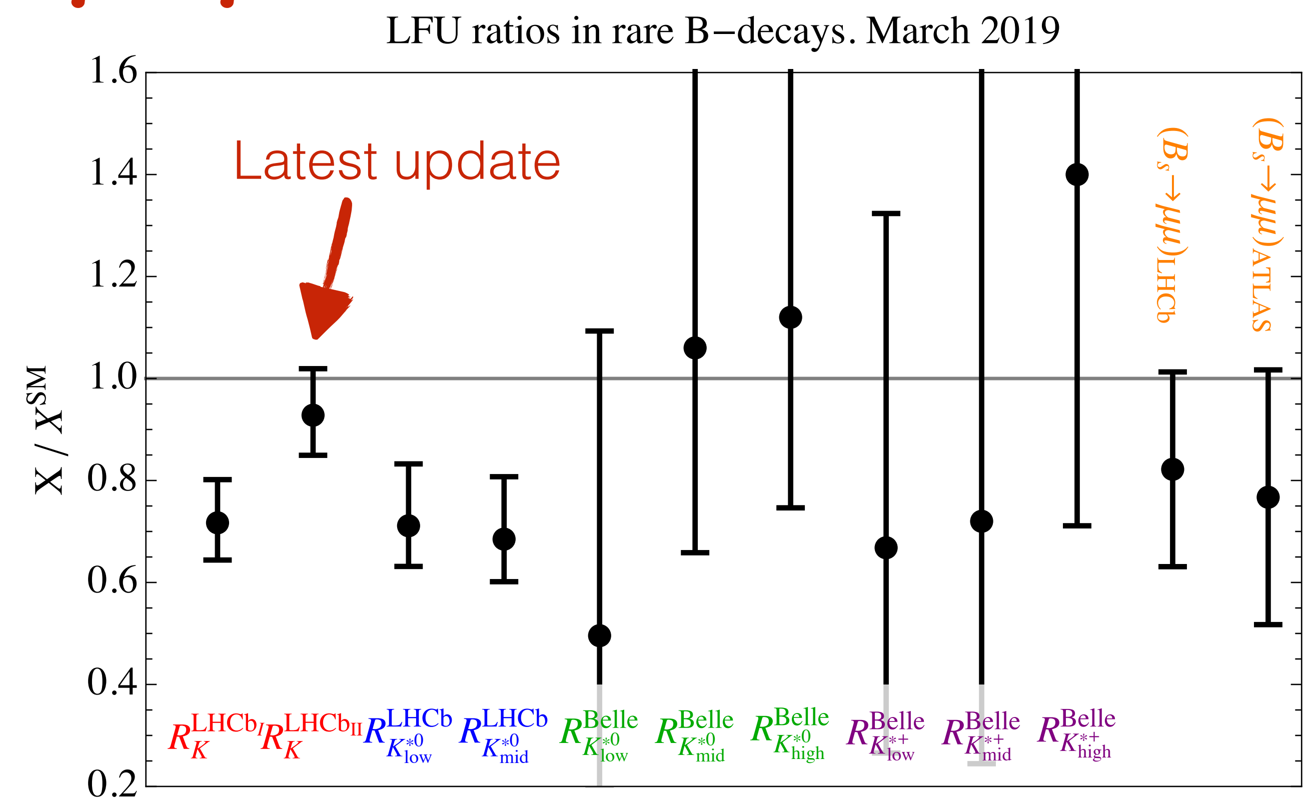
$b \rightarrow s\, \mu^+ \mu^-$

Lepton Flavor Universality ratios

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

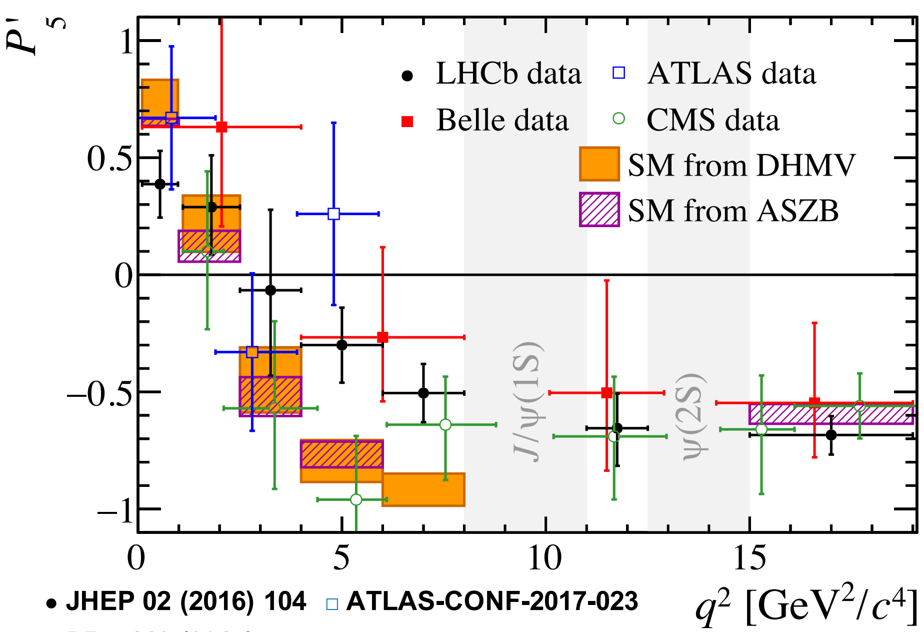
Clean SM prediction: $1 \pm O(1\%)$

Bordone, Isidori, Pattori 2016



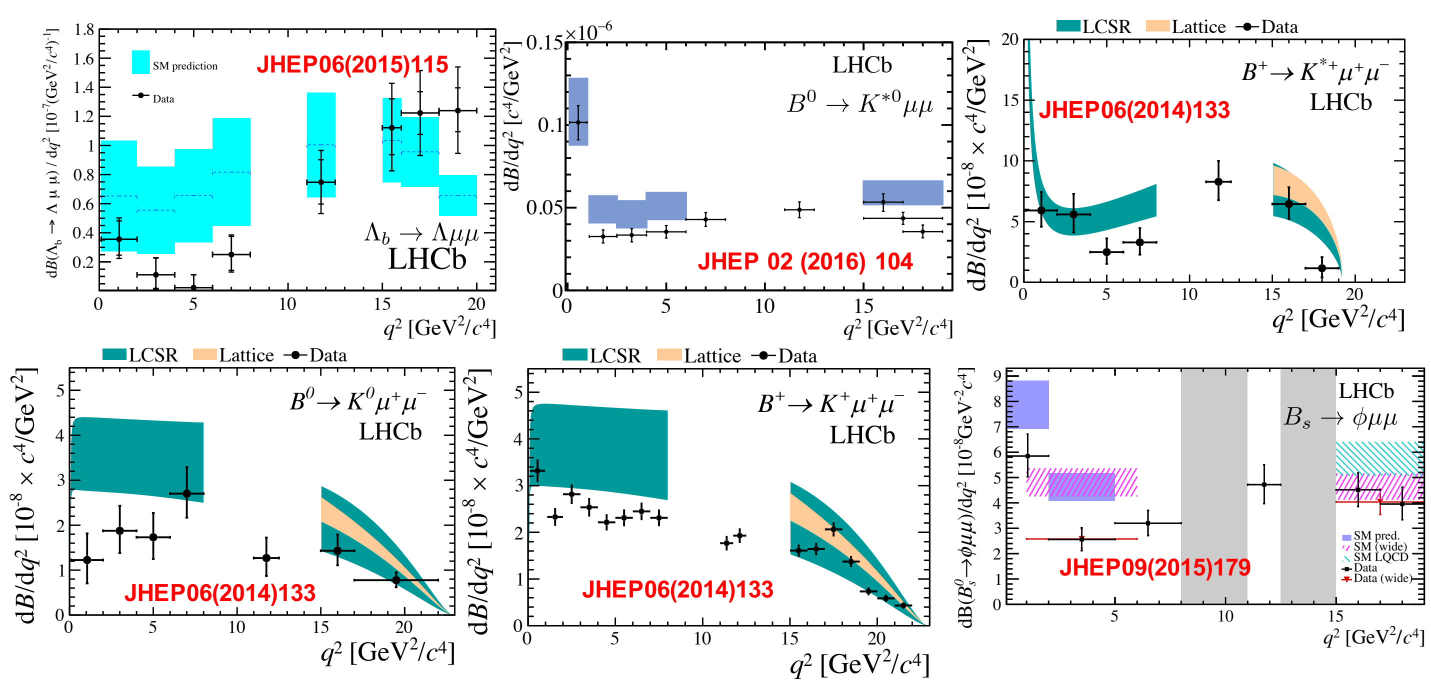
Angular distributions

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



- 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.

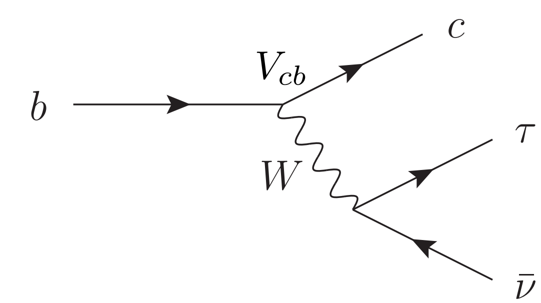


Low-energy interpretations

$b \to c\, \tau\, \nu$

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

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



if $c = 1$ $\quad\longrightarrow\quad$ $\Lambda \sim 4.5$ TeV

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

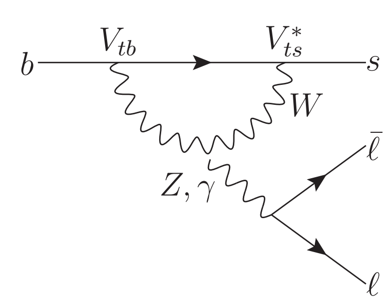
$b \to s\, \mu^+\, \mu^-$

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

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

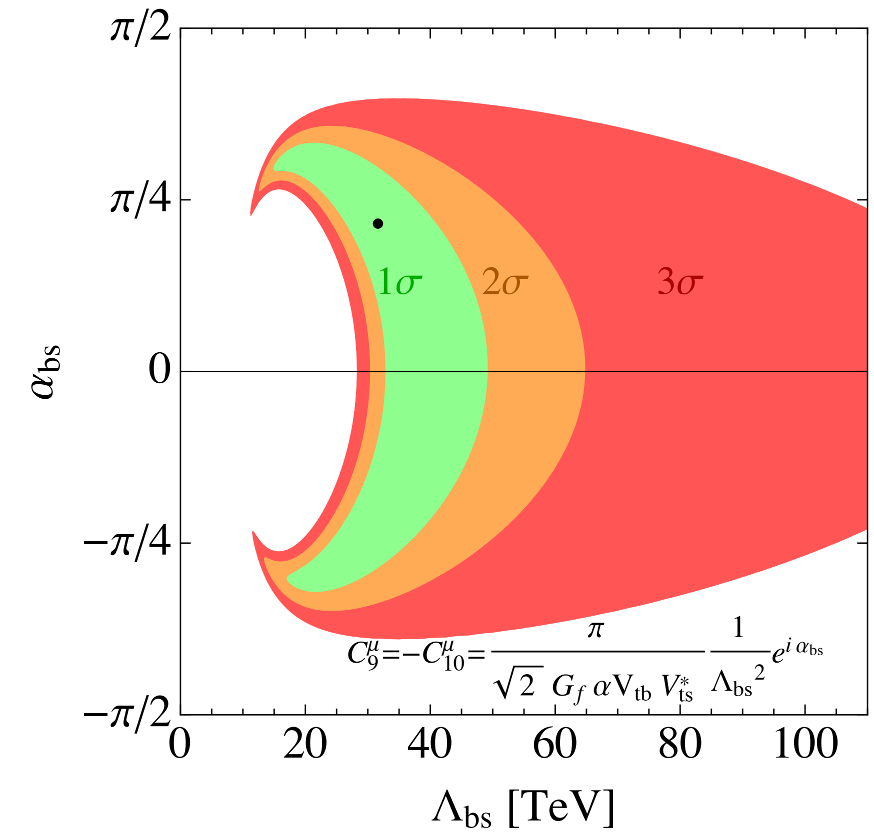
D'Amico et al. 1704.05438, Algueró et al. 1903.09578, Alok et al. 1903.09617, Ciuchini et al. 1903.09632, Aebischer et al 1903.10434, …

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



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

simplified fit of *clean observables*
R(K), R(K*), $B_s \to \mu\mu$



SM EFT fit (LH)

Buttazzo, Greljo, Isidori, DM 1706.07808

Adding SM SU(2)L gauge invariance:

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

triplet operator *singlet operator*

Flavour Structure:

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

B-anomalies are driven by the 3-3 and 3-2 entries. $\lambda^q{}_{bs}$

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

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

Kaon physics depends instead on the 1-2 entry $\lambda^q{}_{sd}$

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

Good fit for:

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

$\lambda^q{}_{bs} \gtrsim 3|V_{ts}|$

$\lambda^\ell{}_{\mu\mu} \sim 10^{-2}$

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

SU(2)^n flavour symmetry

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

$$G_F = \mathrm{SU}(2)_q \times \mathrm{SU}(2)_u \times \mathrm{SU}(2)_d \times \mathrm{SU}(2)_l \times \mathrm{SU}(2)_e \qquad \psi_i = (\overbrace{\psi_1 \ \ \psi_2}^{\mathbf{2}}\ \overbrace{\psi_3}^{\mathbf{1}})$$

Assume this is minimally broken
by the spurions:

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

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

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**

Quark flavor matrix:

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

$$\boxed{\begin{aligned} \lambda^q_{sd} &\sim V_{ts}^* V_{td} \\ \lambda^q_{bs} &\sim V_{ts} \end{aligned}}$$

All is up to unknown O(1) factors!

K→πνν and R(D^(*))

Contribution to s → dνν:

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

$$\lambda^{\ell}_{\mu\mu} \ll \lambda^{\ell}_{\tau\tau} = 1$$

$$C_{sd\nu\nu} = (C_S - C_T)\lambda^q_{sd}$$

Contribution to b → cτν:

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

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

If $C_S = C_T$, then the contribution to this channel vanishes (this happens for the U1 vector LQ).
Assuming instead $C_S - C_T \sim C_T$ then the NP coefficient of this operator is

$$C_{sd\nu\nu} \sim C_{R(D^{(*)})}\frac{\lambda^q_{sd}}{\lambda^q_{bs}} \approx \frac{1}{(4.5\ \mathrm{TeV})^2}\frac{\lambda^q_{sd}}{\lambda^q_{bs}}$$

$$\frac{\lambda^q_{sd}}{\lambda^q_{bs}} \sim \frac{V_{td}V_{ts}}{3V_{ts}} = V_{td}/3$$

We thus might expect a NP scale in this process of the order of:

$$\boxed{C_{sd\nu\nu} \sim (80\ \mathrm{TeV})^{-2}}$$

This must be compared with the experimental sensitivity

K→πνν and R(D(*))

$$\mathcal{L}^{\rm NP}_{s\to d\nu\nu} = C_{sd\nu\nu}(\bar{s}_L\gamma_\mu d_L)(\bar{\nu}_\tau\gamma_\mu\nu_\tau) + h.c. \qquad C_{sd\nu\nu} \sim (80\ \text{TeV})^{-2}$$

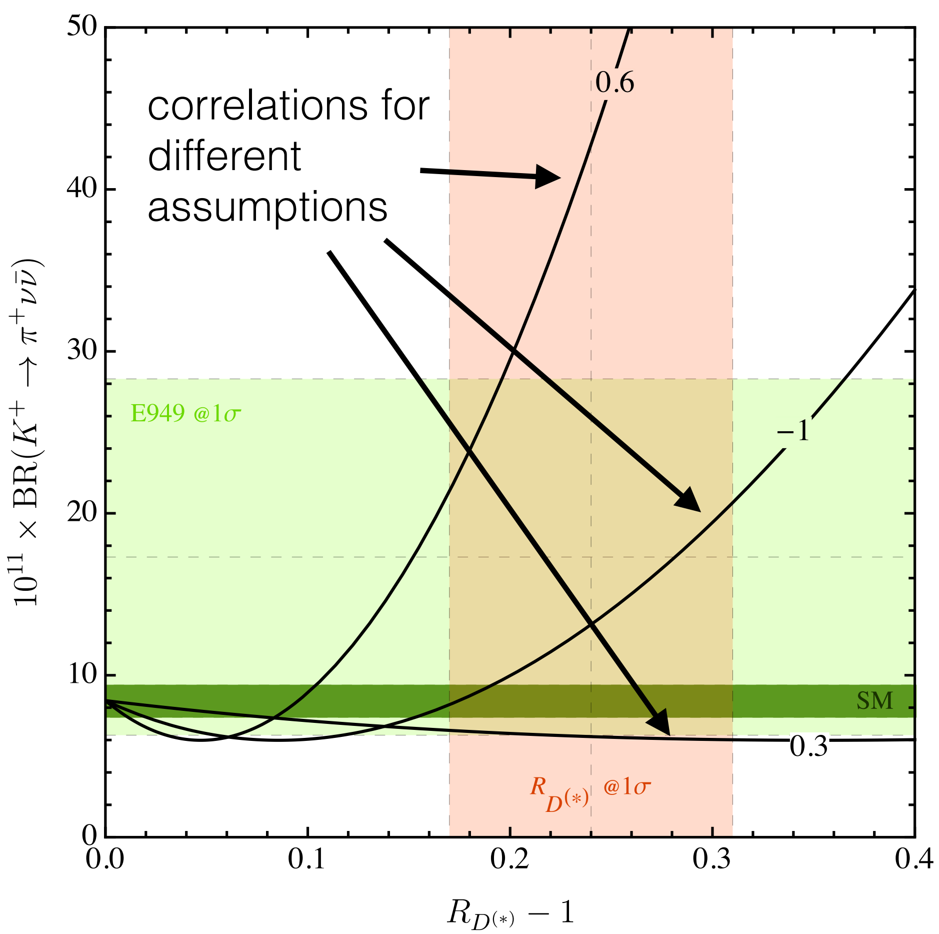
With these numbers I obtain:

$$\mathcal{B}(K^+\to\pi^+\nu\bar{\nu}) = 2\mathcal{B}(K^+\to\pi^+\nu_e\bar{\nu}_e)_{\rm SM} + \mathcal{B}(K^+\to\pi^+\nu_\tau\bar{\nu}_\tau)_{\rm SM}\left|1+\frac{C_{sd\nu\nu}}{C^{sd,\tau}_{\rm SM}}\right| \sim 20\times10^{-11}$$

$$\mathcal{B}(K^+\to\pi^+\nu\bar{\nu})_{\rm exp} = (17.3^{+11.5}_{-10.5})\times10^{-11}$$

O(1) effects possible

Bordone, Buttazzo, Isidori, Monnard 1705.10729



Analogously, I get $\mathcal{B}(K_L\to\pi^0\nu\bar{\nu}) \sim 4-7\times10^{-11}$

(depending on the NP phase)

$$\mathcal{B}(K_L\to\pi^0\nu\bar{\nu})_{\rm SM} = (3.4\pm0.6)\times10^{-11}$$

$$\mathcal{B}(K_L\to\pi^0\nu\bar{\nu})_{\rm exp} < 3.0\times10^{-9}$$

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.

Note: for a complete analysis it is important to take into account the bounds from $B\to K^{(*)}\nu\nu$, LEP data, and direct searches.

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

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

$$\lambda^{\ell}_{\mu\mu} \ll \lambda^{\ell}_{\tau\tau} = 1 \quad \& \quad \lambda^{q}_{sd} \sim V^*_{ts} V_{td}$$

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

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

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

Directions in SU(3)$_q$ space

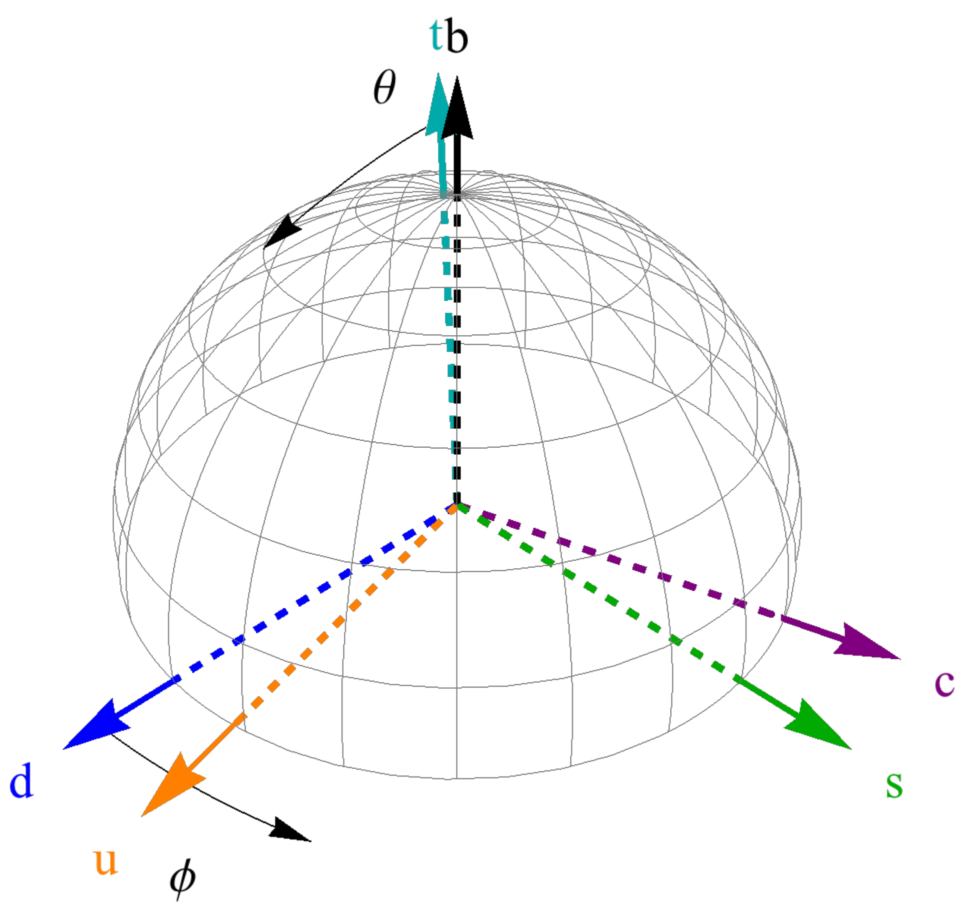
We can parametrise directions in SU(3)$_q$ as:

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

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

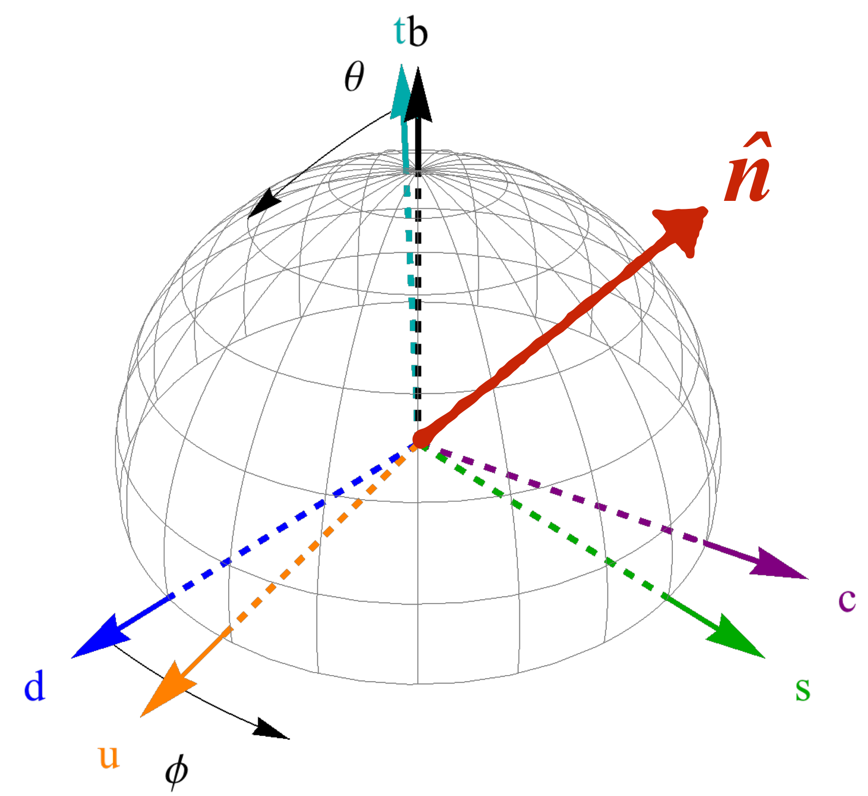
Valerio Gherardi, D.M., Marco Nardecchia, Andrea Romanino [1903.10954]

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

We assume that the **flavor matrix**

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

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



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

It selects a direction in that space.

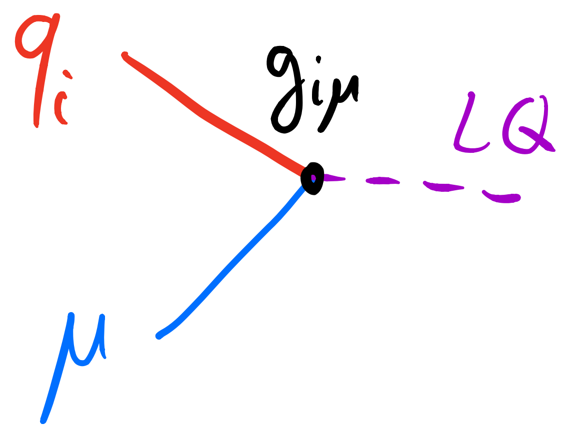
We aim to answer the following question

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

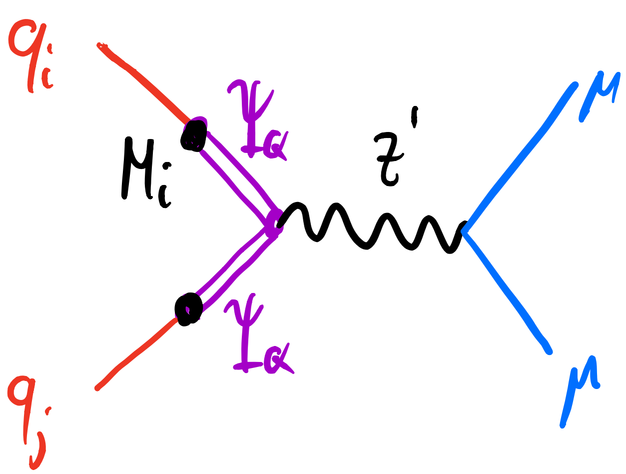
$$\mathcal{L} = \lambda_i \bar{q}_L^i \mathcal{O}_{\rm NP} + \text{h.c.}$$



Single leptoquark models

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

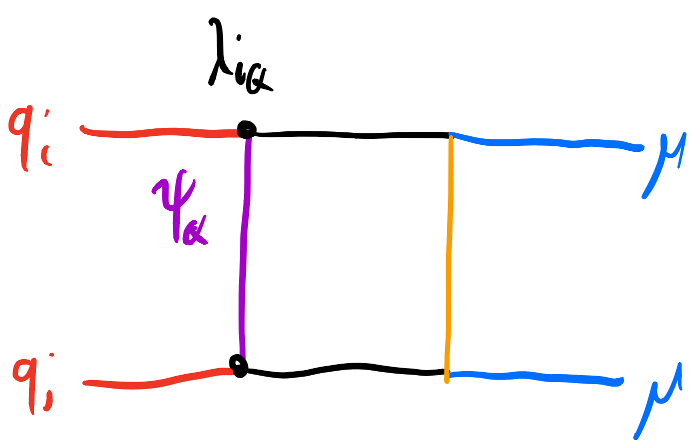
$$\hat{n}_i \propto g_{i\mu}$$



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

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

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

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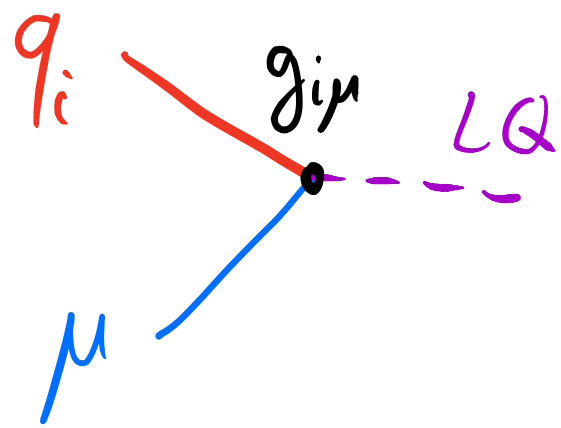

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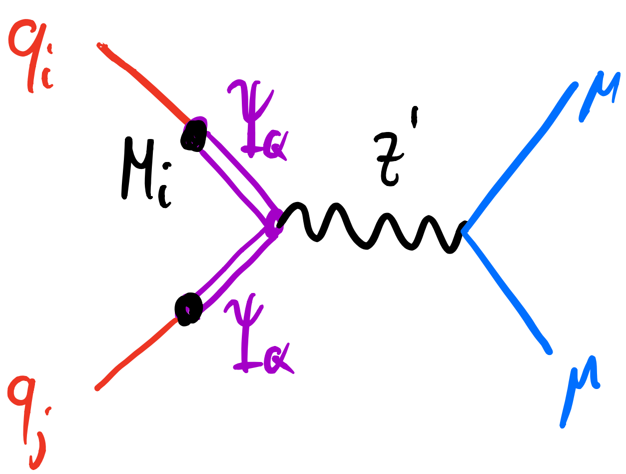
$$\hat{n}_i \propto g_{i\mu}$$

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



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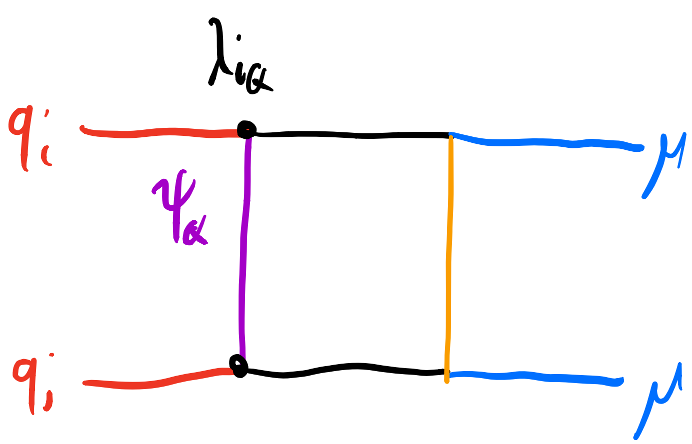

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$$\mathcal{L} \supset \lambda_{iQ} \bar{q}_L^i \Psi_Q \Phi + h.c.$$

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

Constraints in ROFV

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

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

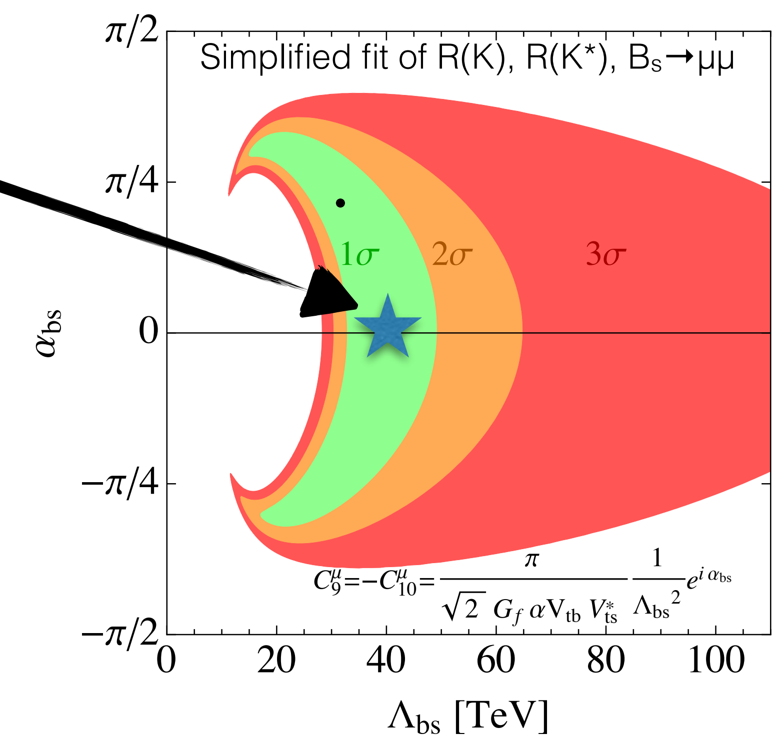
1) **Fix a direction $\hat{n}$.**

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

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

$$C_{sb} = C\sin\theta\cos\theta\sin\phi e^{i\alpha_{bs}} = \frac{e^{i\alpha_{bs}}}{\Lambda_{bs}^2} = \text{(from fit)}$$

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



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

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

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

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

General correlations (LH)

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

	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

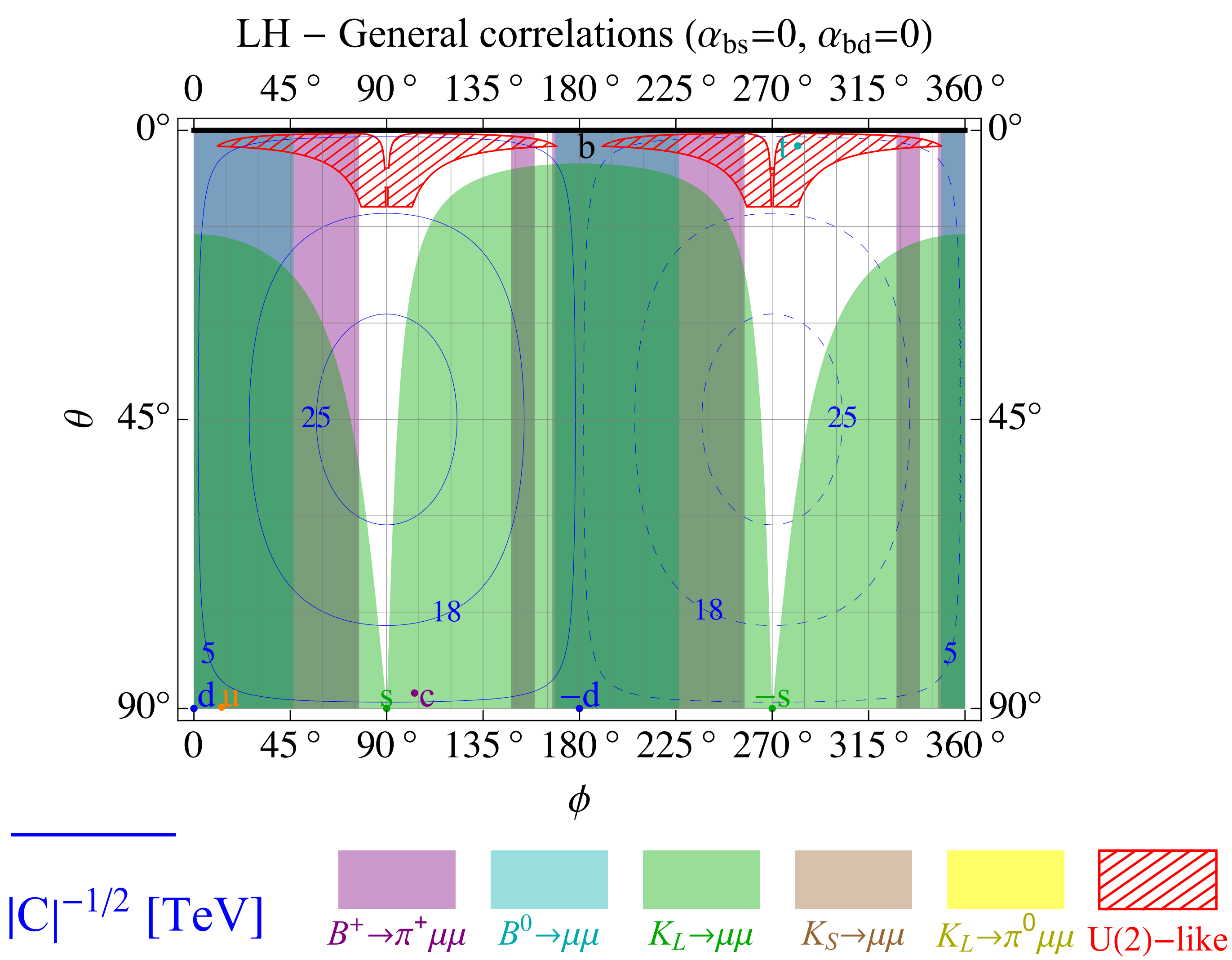
General correlations (LH)

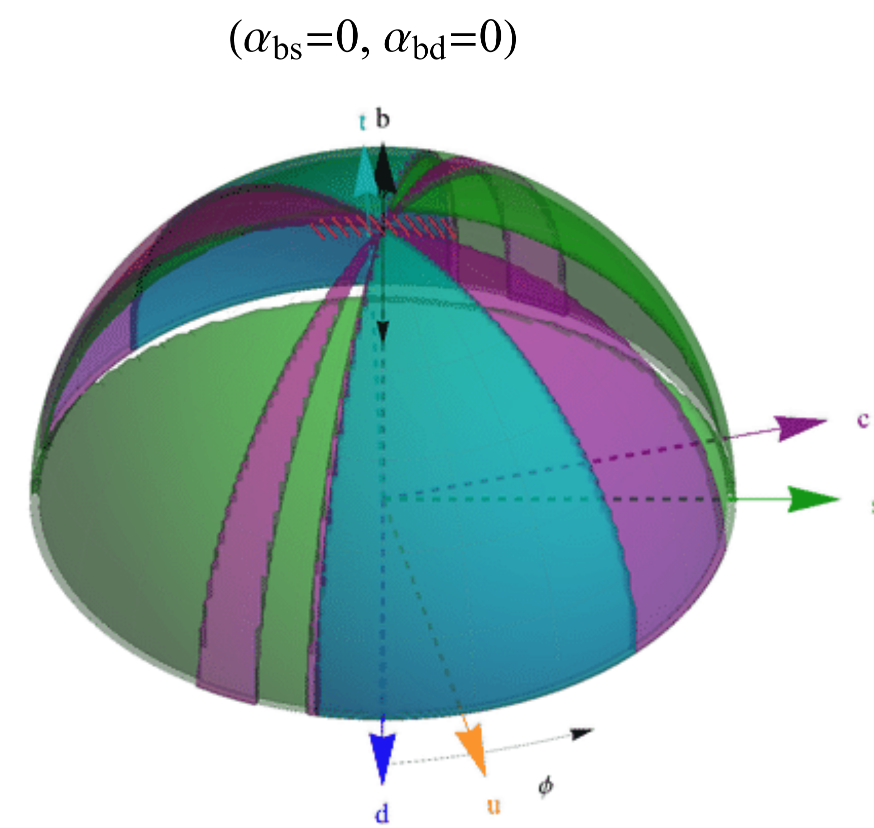
Direct correlations with other $d_i d_j \mu\mu$ observables

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

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

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

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

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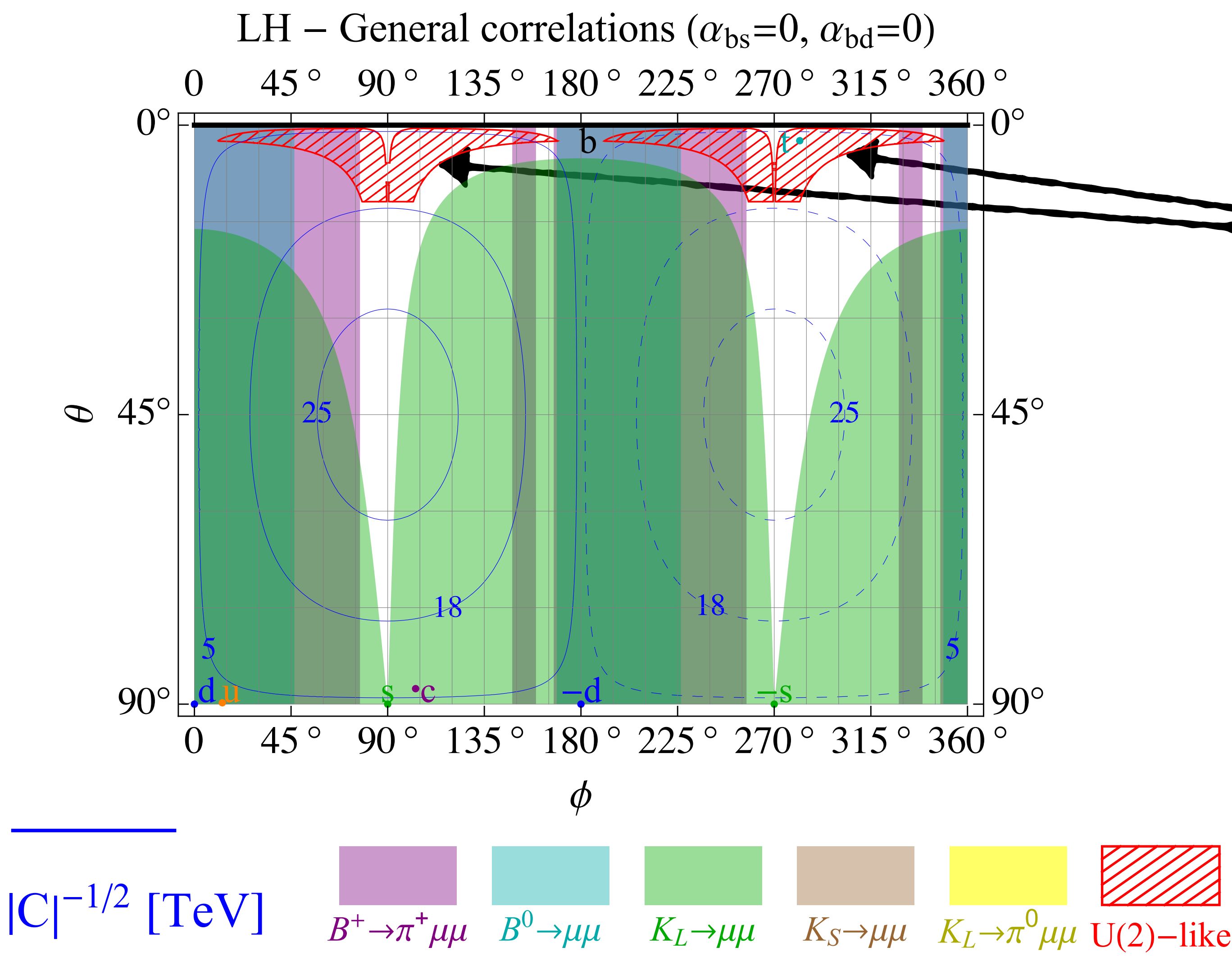
$\mathrm{Im}(C_{ds})$	$\mathrm{Br}(K_L \to \pi^0\mu^+\mu^-)$	$< 3.8 \times 10^{-10}$ (90% CL)	$1.41^{+0.28}_{-0.26}(0.95^{+0.22}_{-0.21}) \times 10^{-11}$

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



Region suggested by SU(2)ⁿ 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

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

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

	Observable	Experimental value/bound	SM prediction
C_{db}	$\mathrm{Br}(B_d^0 \to \mu^+\mu^-)$	$< 2.1 \times 10^{-10}$ (95% CL)	$(1.06 \pm 0.09) \times 10^{-10}$
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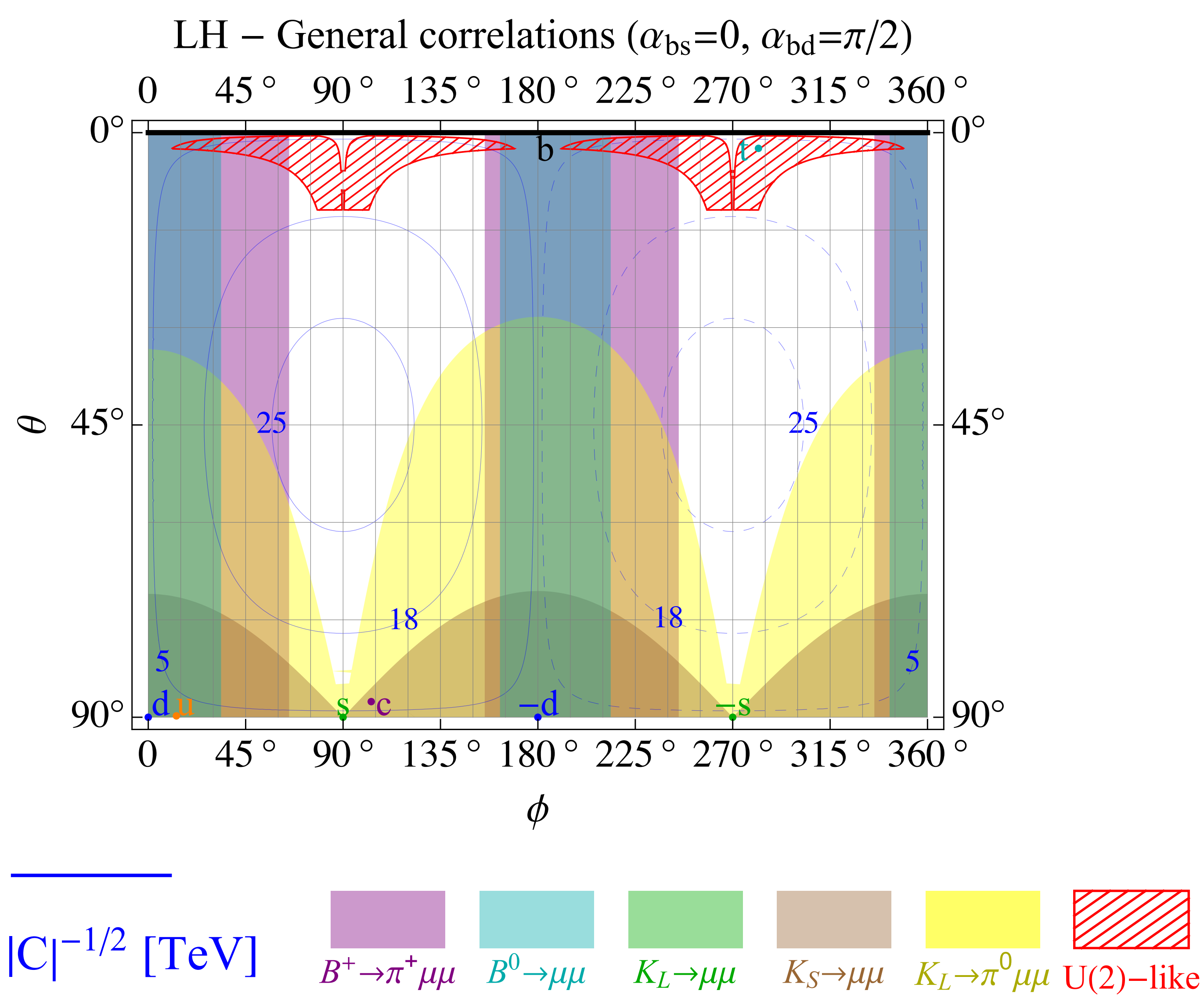

For complex coefficients, $K_L \to \pi^0\mu\mu$ and $K_S \to \mu\mu$ become important

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

Different processes depend on different combinations of the three overall coefficients

Even assuming a *LH solution*, the relative size of C_S and C_T is a free parameter.

However, $d_i d_j\, \mu\mu$ transitions,
are **directly correlated** with $bs\ \mu\mu$
(depend on the same combination of C_S and C_T)

$$C_L = C_S + C_T \equiv C_+$$

Also $u_i u_j\ \nu_\mu \nu_\mu$ transitions,
are **directly correlated** with $bs\ \mu\mu$
however no relevant bound exist
(e.g. from $D \to \pi\, \nu\nu$)

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 structure gives

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

Three overall coefficients

Channel	Coefficient dependencies
$d_i \to d_j\mu^+\mu^-$	$\boxed{C_S + C_T,\ C_R}$
$u_i \to u_j\overline{\nu_\mu}\nu_\mu$	$C_S + C_T$
$u_i \to u_j\mu^+\mu^-$	$C_S - C_T,\ C_R$
$d_i \to d_j\overline{\nu_\mu}\nu_\mu$	$\boxed{C_S - C_T}$
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Different processes depend on different combinations of the three overall coefficients

K→πνν is important

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 structure gives

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

Three overall coefficients

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

Different processes depend on different combinations of the three overall coefficients

K→πνν 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***

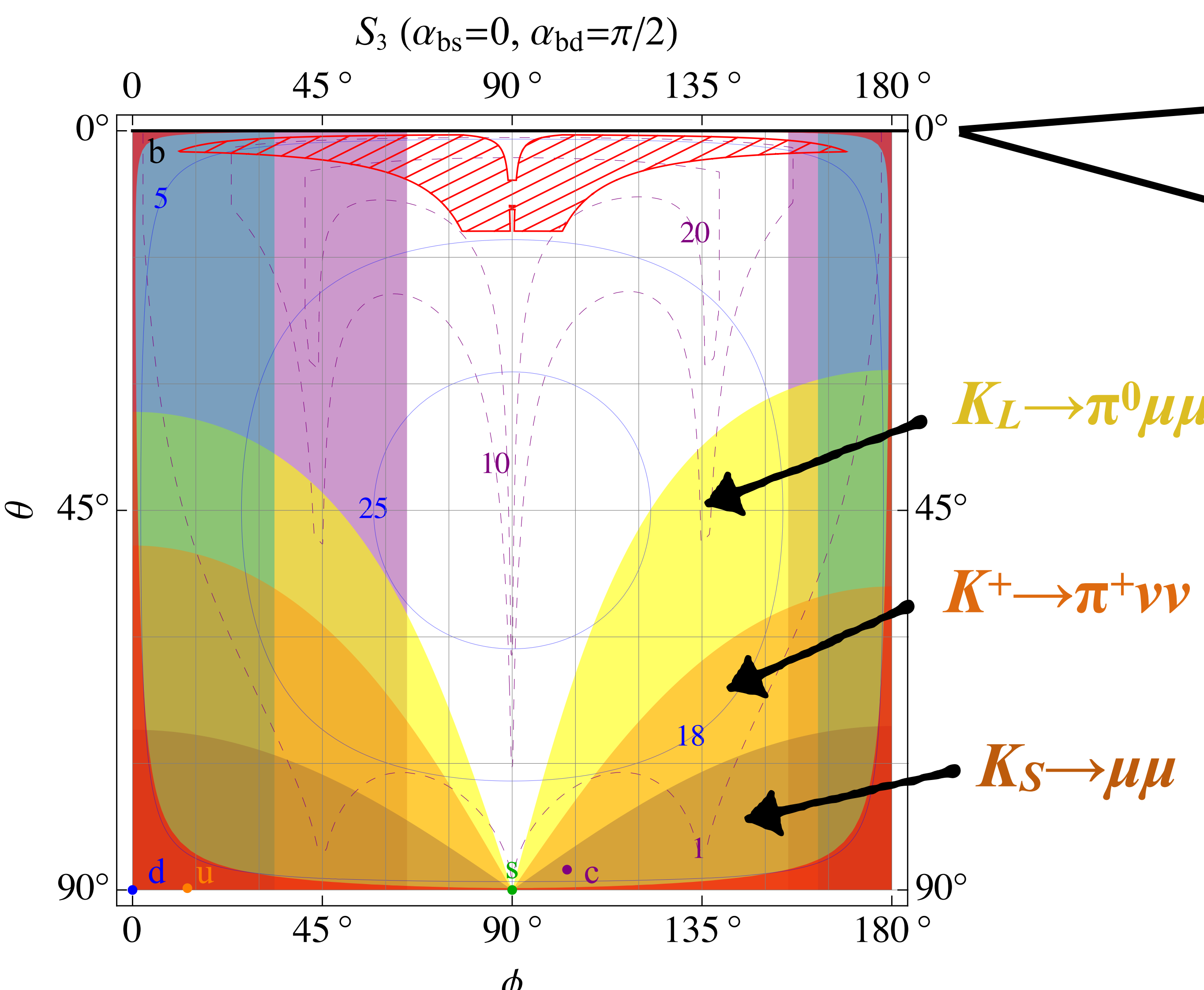
(backup slides)

S_3 scalar leptoquark

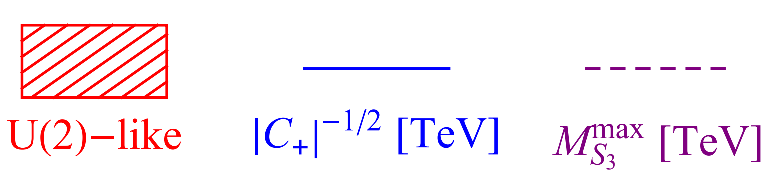
$S_3 = (\bar{\mathbf{3}}, \mathbf{3}, 1/3)$

$$\mathcal{L}_{\rm NP} \supset \beta_{3,i\mu} (\bar{q}^{c\,i}_L \epsilon \sigma^a \ell^2_L)\, S^a_3 + \text{h.c.} \longrightarrow C^{ij}_S = \frac{3}{4}\frac{\beta^*_{3,i\mu}\beta_{3,j\mu}}{M^2_{S_3}}\,, \quad C^{ij}_T = \frac{1}{4}\frac{\beta^*_{3,i\mu}\beta_{3,j\mu}}{M^2_{S_3}}\,, \quad C^{ij}_R = 0$$

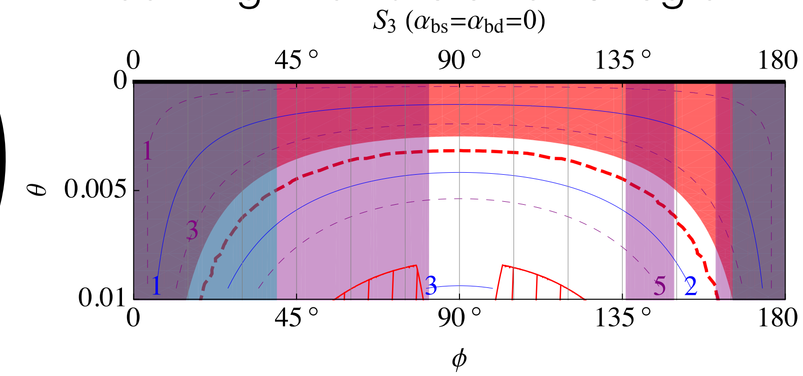
$$\beta^*_{3,i\mu} \equiv \beta^*_3\, \hat{n}_i$$



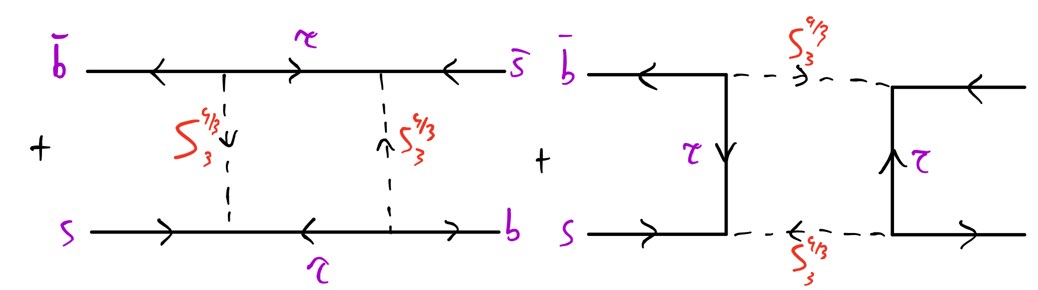
$$C_+ = |\beta_3|^2/M^2_{S_3} > 0$$



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

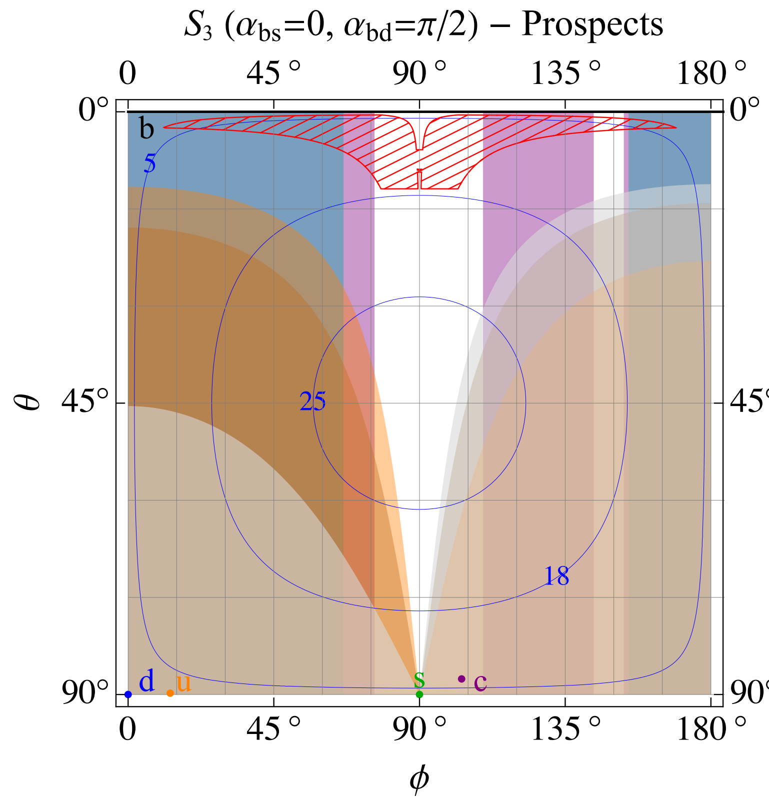
$$\Delta\mathcal{L}_{\Delta F=2} = -\frac{5|\beta_3|^4}{128\pi^2 M^2_{S_3}} \left[(\hat{n}_i \hat{n}^*_j \bar{d}^i_L \gamma^\alpha d^j_L)^2 + (V_{ik}\hat{n}_k \hat{n}^*_l V^*_{jl}\, \bar{u}^i_L \gamma^\alpha u^j_L)^2 \right]$$

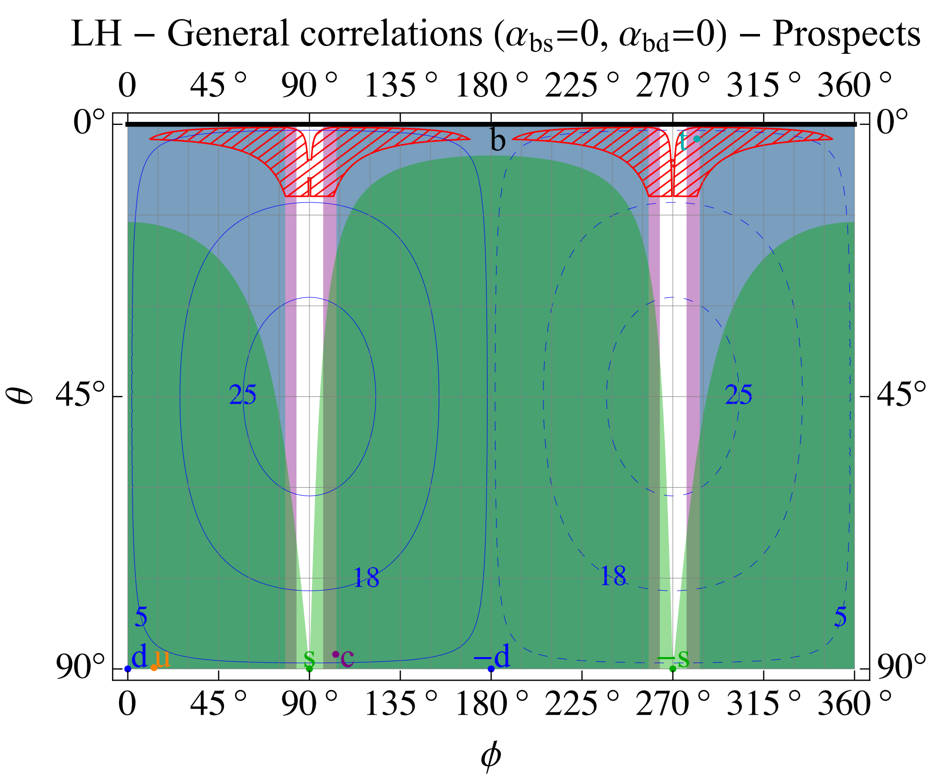
Limits on D-$\bar{D}$, K-$\bar{K}$, B_d-$\bar{B}_d$, B_s-$\bar{B}_s$ give an upper limit on the leptoquark mass

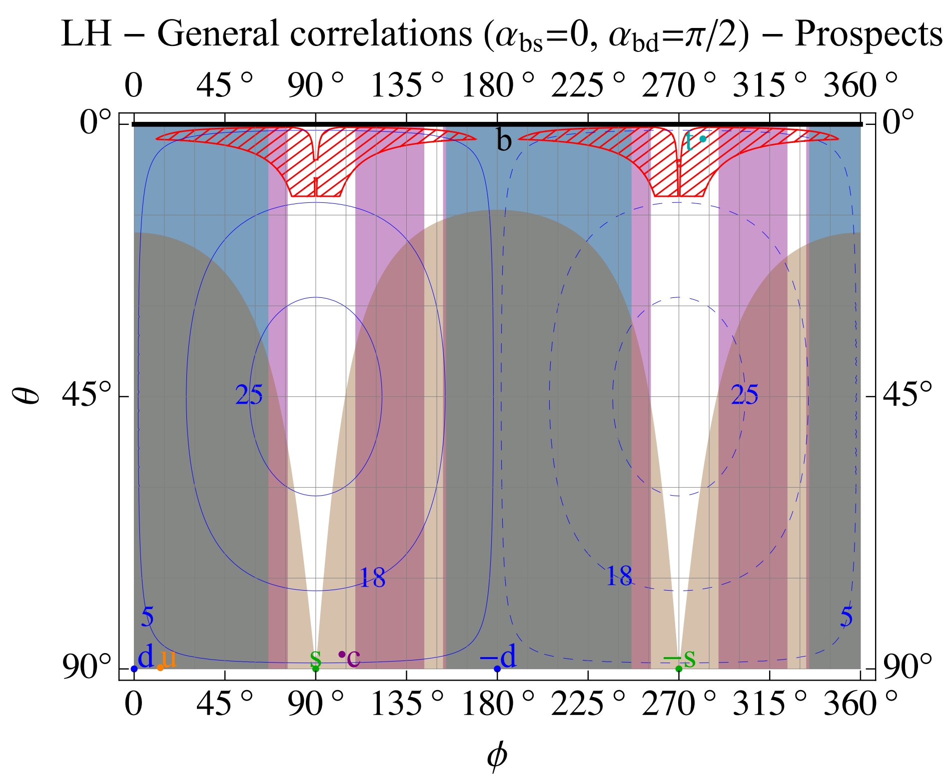
Prospects

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

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}
$\mathrm{Br}(B_s^0 \to \mu^+\mu^-)$	4.4 (8.2)%	LHCb 300 (23) fb^{-1}
	7 (12)%	CMS 3 (0.3) ab^{-1}
$\mathrm{Br}(B_d^0 \to \mu^+\mu^-)$	9.4 (33)%	LHCb 300 (23) fb^{-1}
	16 (46)%	CMS 3 (0.3) ab^{-1}
$\mathrm{Br}(K_S \to \mu^+\mu^-)$	$\sim 10^{-11}$	LHCb 300fb^{-1}
$\mathrm{Br}(K_L \to \pi^0\nu\nu)$	$\sim 30\%$	KOTO phase-I
	20%	KLEVER
$\mathrm{Br}(K^+ \to \pi^+\nu\nu)$	10%	NA62 goal







$K_L\to\mu\mu$
(present bound)

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 $SU(2)^n$ flavor symmetry, $R(D^{(*)})$ is correlated with $K\to\pi\nu\nu$: $O(1)$ 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!

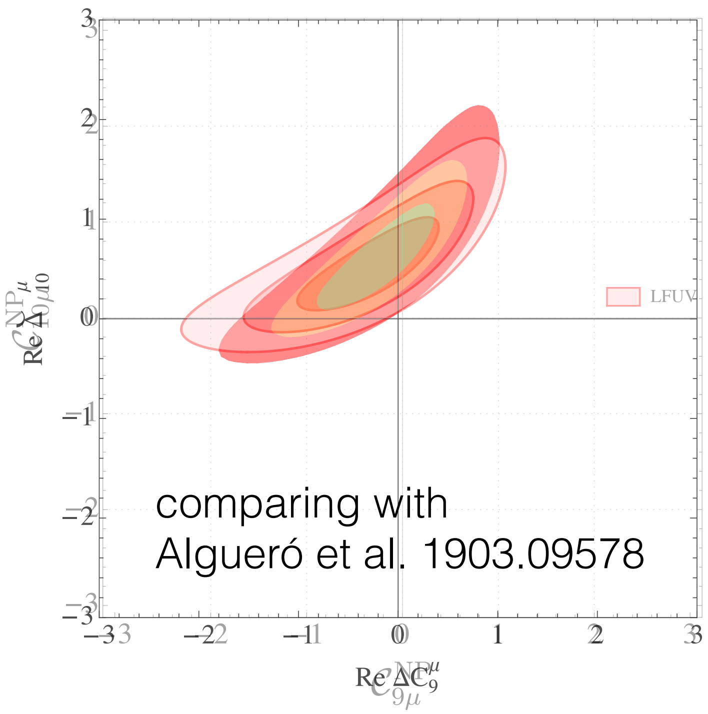
Backup

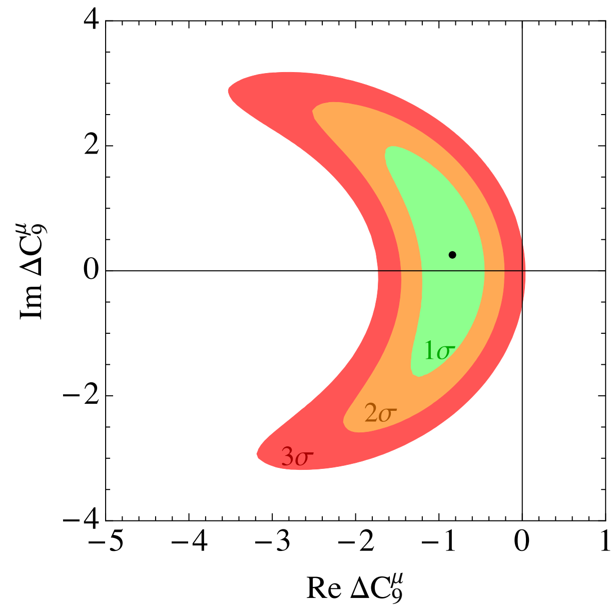
Simplified* fit of clean observables

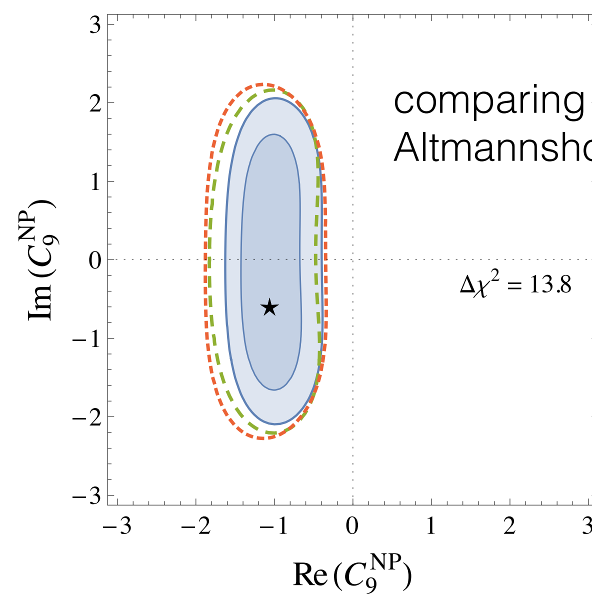
$$\mathcal{L}_{\rm eff}^{\rm NP} \supset \frac{G_F\alpha}{\sqrt{2}\pi} V_{tb}V_{ts}^* \left[\Delta C_9^\mu (\bar{s}_L\gamma^\mu b_L)(\bar\mu\gamma_\mu\mu) + \Delta C_{10}^\mu(\bar{s}_L\gamma^\mu b_L)(\bar\mu\gamma_\mu\gamma_5\mu)\right] + h.c. \; .$$

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

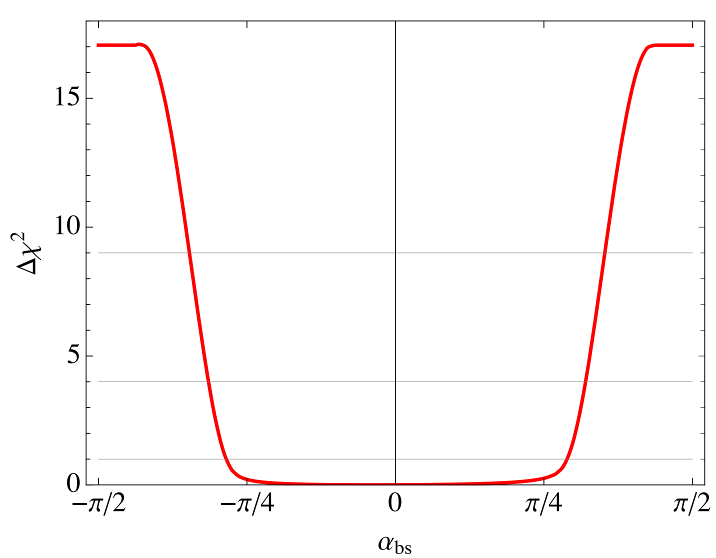
R_K [1.1, 6] GeV^2	0.846 ± 0.062	LHCb [1, 2]
R_{K^*} [0.045, 1.1] GeV^2	0.66 ± 0.11 $0.52^{+0.36}_{-0.26}$	LHCb [3] Belle [4]
R_{K^*} [1.1, 6] GeV^2	0.69 ± 0.12 $0.96^{+0.45}_{-0.29}$	LHCb [3] Belle [4]
R_{K^*} [15, 19] GeV^2	$1.18^{+0.52}_{-0.32}$	Belle [4]
$\mathrm{Br}(B_s^0 \to \mu\mu)$	$(3.0^{+0.67}_{-0.63})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

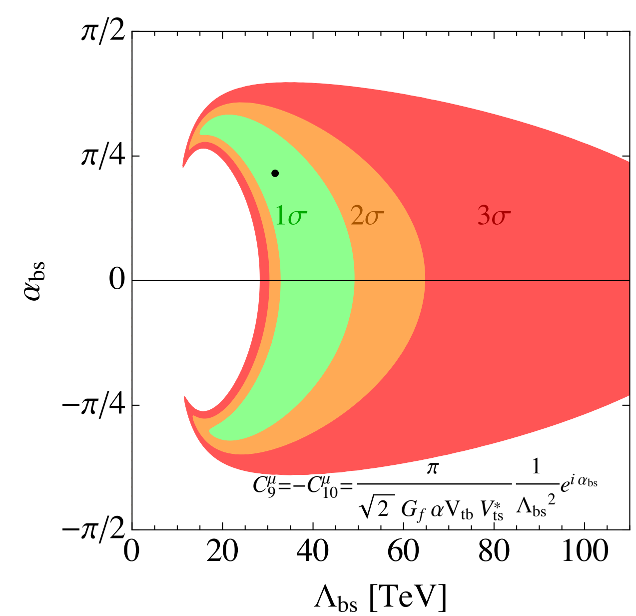


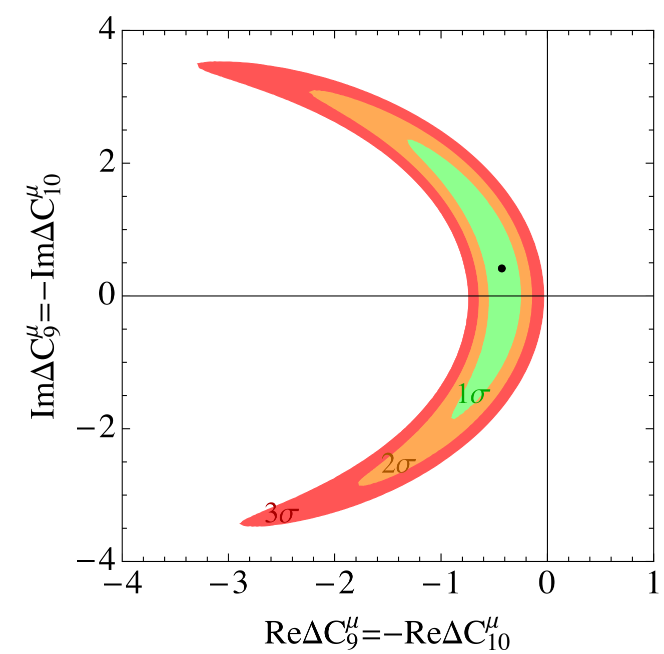




comparing with
Altmannshofer, Straub 1411.3161







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

ΔF = 2 observables (and ε'/ε)

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

$$\mathcal{L}_{\Delta\mathrm{F}=2}^{\mathrm{NP}} = C_{ij}(\bar{q}_L^i \gamma_\mu q_L^j)^2$$

[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 $(\bar{s}\gamma_\mu P_L d)(\bar{q}\gamma^\mu P_L q)$

$q = u, d, s, c$

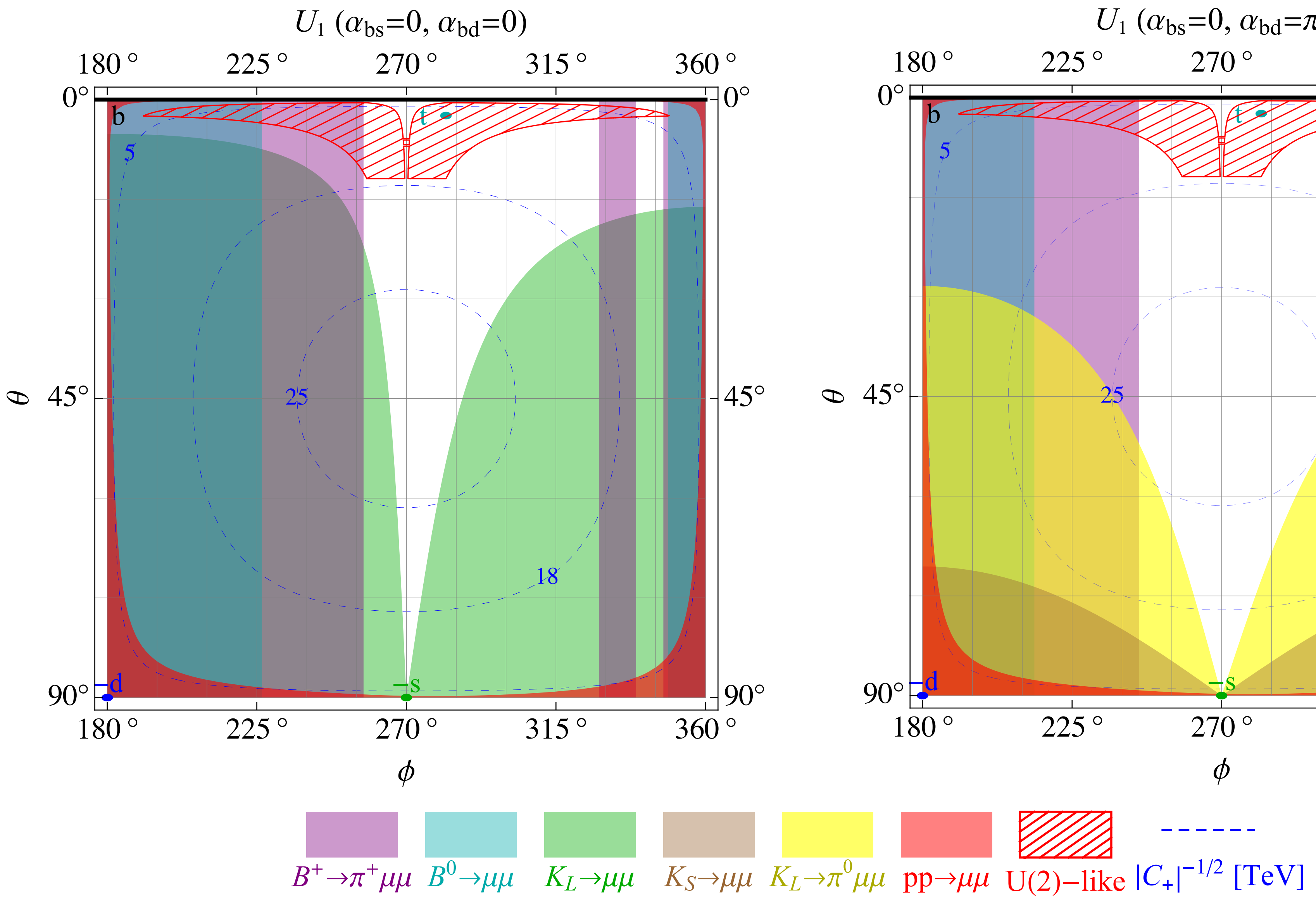
[Aebisher et al. 1807.02520, 1808.00466]

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

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

U_1 vector leptoquark

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



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

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

Z' & vector-like couplings to μ

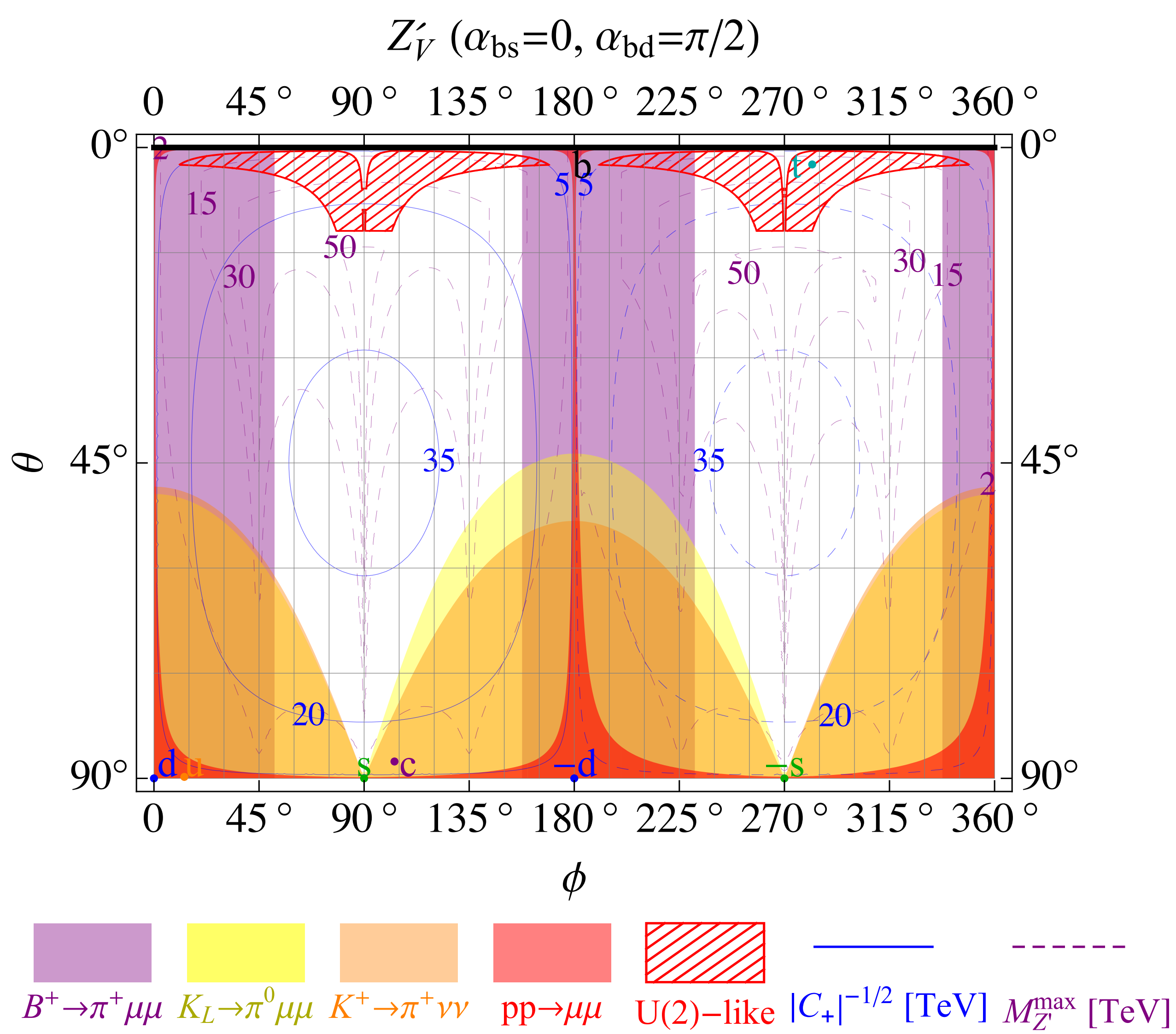
For example see the gauged U(1)$_{L\mu-L\tau}$ model with 1 vector-like quark.

[Altmannshofer, Gori, et al 1403.1269, 1609.04026]

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

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

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



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

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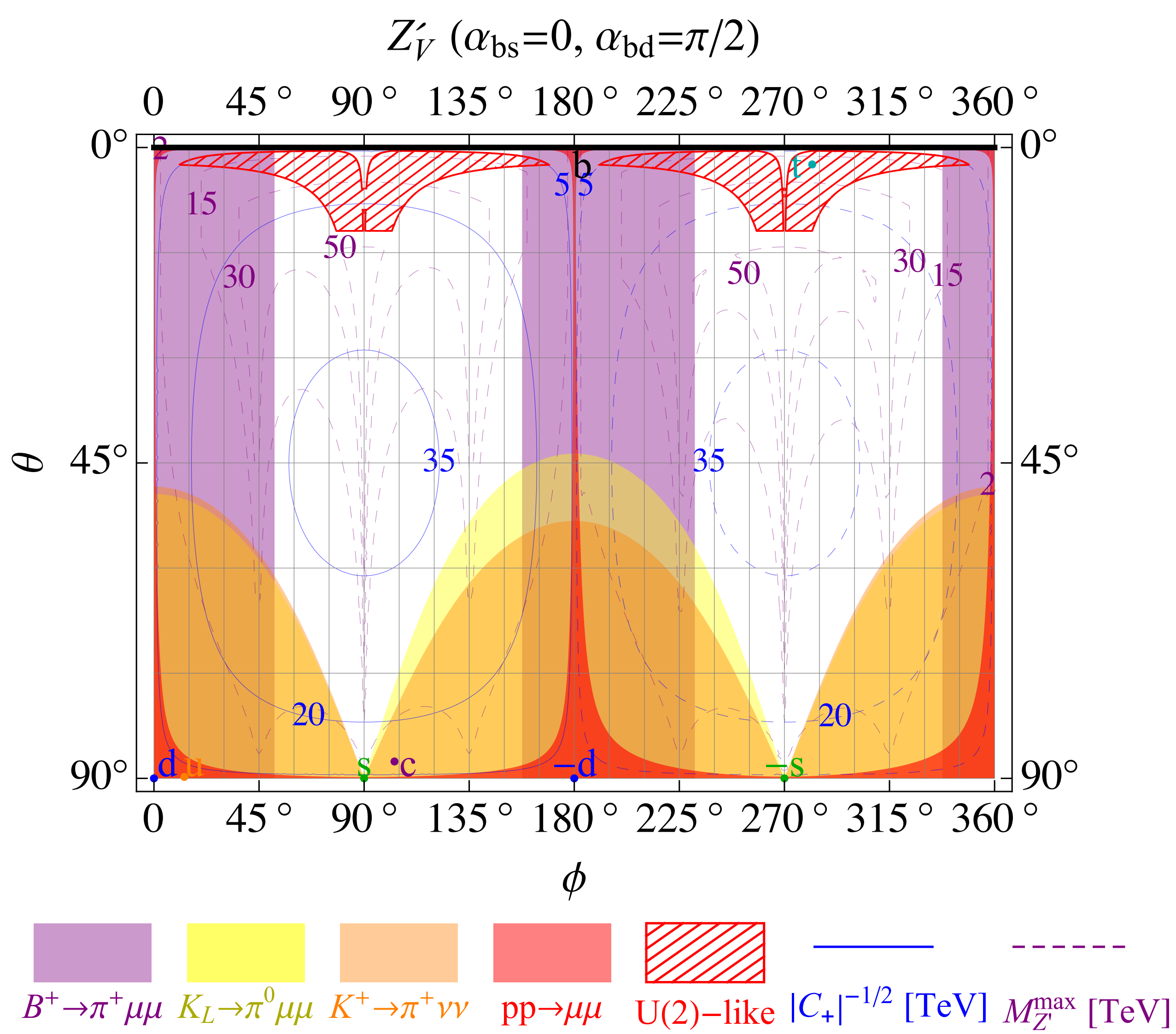
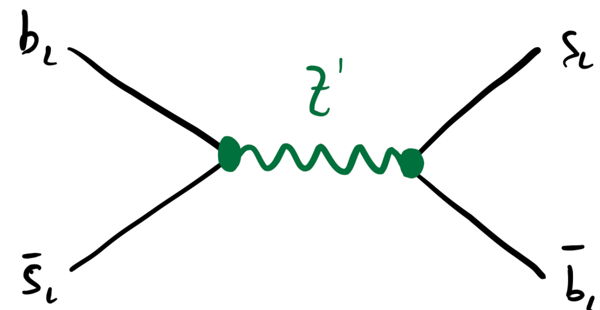
$$\hat{n}_i \propto M_i$$

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



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



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

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

ROFV & U(2)³ symmetry

Global quark flavor symmetry

$$\boxed{\mathrm{U}(2)^3 = \mathrm{U}(2)_q \times \mathrm{U}(2)_u \times \mathrm{U}(2)_d}$$

$$\psi_i = (\overbrace{\psi_1 \;\; \psi_2}^{\mathbf{2}} \; \overbrace{\psi_3}^{\mathbf{1}})$$

When *minimally broken*, the spurions are: $V_q \sim (\mathbf{2},\mathbf{1},\mathbf{1})\ ,\quad \Delta Y_u \sim (\mathbf{2},\bar{\mathbf{2}},\mathbf{1})\ ,\quad \Delta Y_d \sim (\mathbf{2},\mathbf{1},\bar{\mathbf{2}})$

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

The doublet is given by CKM elements up to corrections

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

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

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When *minimally broken*, the spurions are: $V_q \sim (\mathbf{2}, \mathbf{1}, \mathbf{1})$, $\Delta Y_u \sim (\mathbf{2}, \bar{\mathbf{2}}, \mathbf{1})$, $\Delta Y_d \sim (\mathbf{2}, \mathbf{1}, \bar{\mathbf{2}})$

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

The doublet is given by CKM elements up to corrections $\mathcal{O}(m_s/m_b)$

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

One can **predict** (up to O(2%) corrections)

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

These predictions of minimally broken U(2)³ will be tested with future data (see prospects slide).

ROFV & U(2)³ symmetry

Global quark flavor symmetry

$$\boxed{\mathrm{U}(2)^3 = \mathrm{U}(2)_q \times \mathrm{U}(2)_u \times \mathrm{U}(2)_d}$$

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When *minimally broken*, the spurions are: $V_q \sim (\mathbf{2},\mathbf{1},\mathbf{1})\ , \quad \Delta Y_u \sim (\mathbf{2},\bar{\mathbf{2}},\mathbf{1})\ , \quad \Delta Y_d \sim (\mathbf{2},\mathbf{1},\bar{\mathbf{2}})$

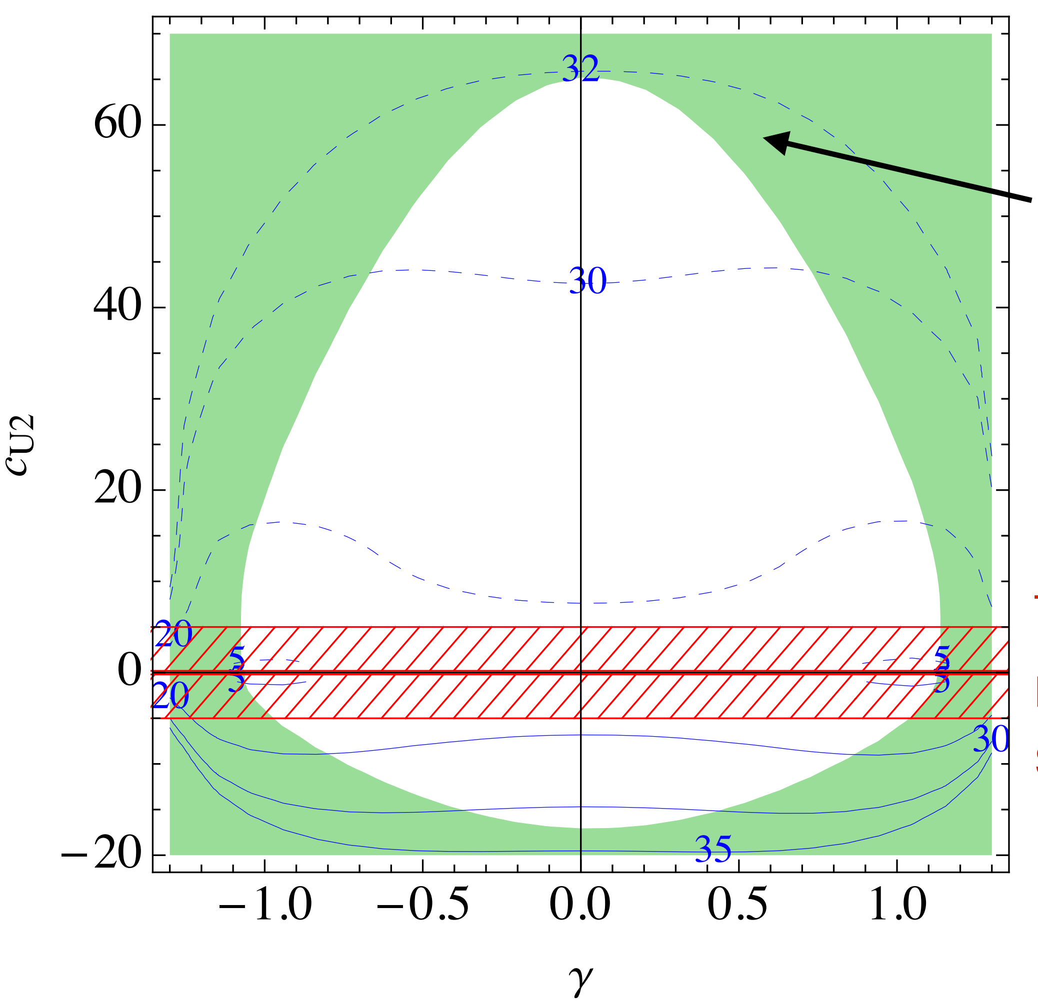
Imposing the ROFV structure we can also get **correlations with s-d transitions**:
only 2 free parameters: c_{U2}, γ.

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

$$\hat{n} \sim \mathbf{1} + \mathbf{2}_q \sim \left(c_{U2} V_q^T, 1\right)^T$$

$$\hat{n} \propto \left(c_{U2} e^{i\gamma} V_{td}^*,\ c_{U2} e^{i\gamma} V_{ts}^*,\ 1\right)$$

$c_{U2} \sim O(1)$



Main constraint from $K_L \to \mu^+\mu^-$

The region consistent with minimally broken U(2) symmetry is still not tested