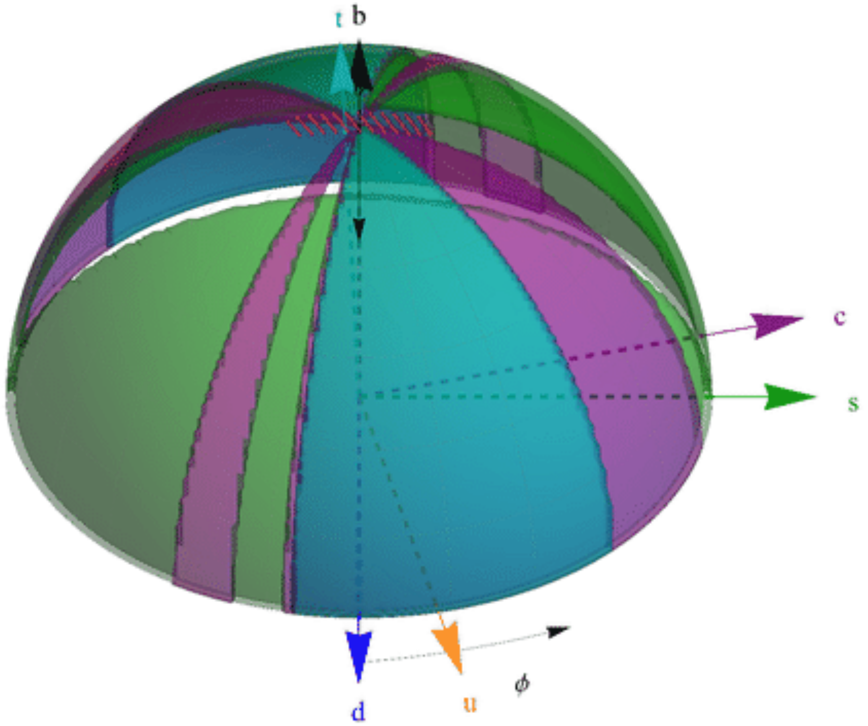
Rank-One Flavor Violation and B-anomalies

David Marzocca

INFN Trieste

Valerio Gherardi, D.M., Marco Nardecchia, Andrea Romanino

[1903.10954]



NPKI 2019, 13/05/2019

Neutral-Current B-anomalies

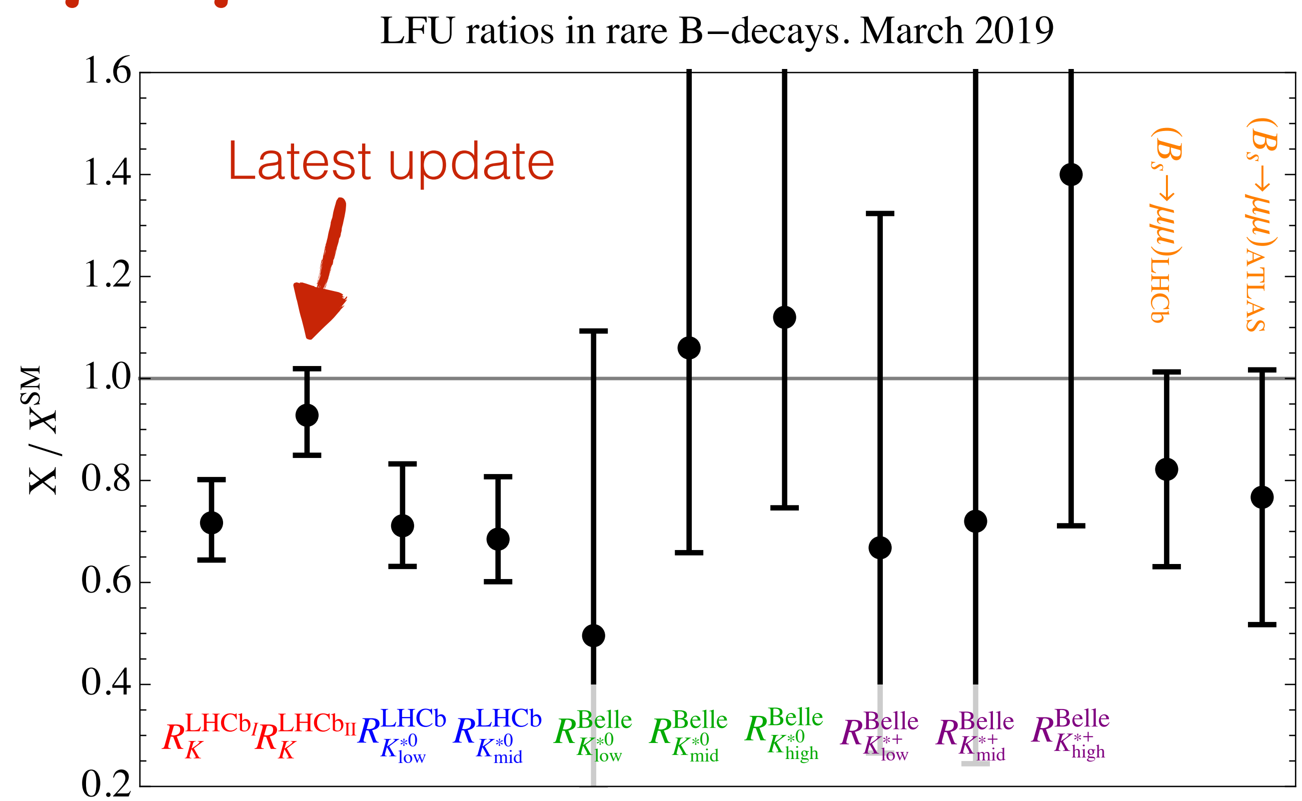
$b \to s\, \mu^+ \mu^-$

Lepton Flavor Universality ratios

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

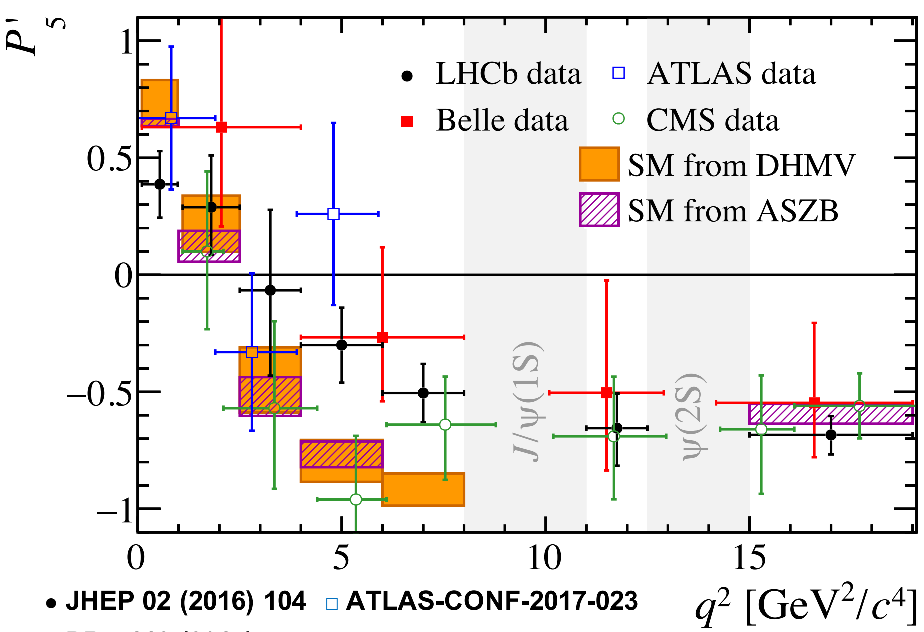
Clean SM prediction: 1 ± O(1%)

Bordone, Isidori, Pattori 2016



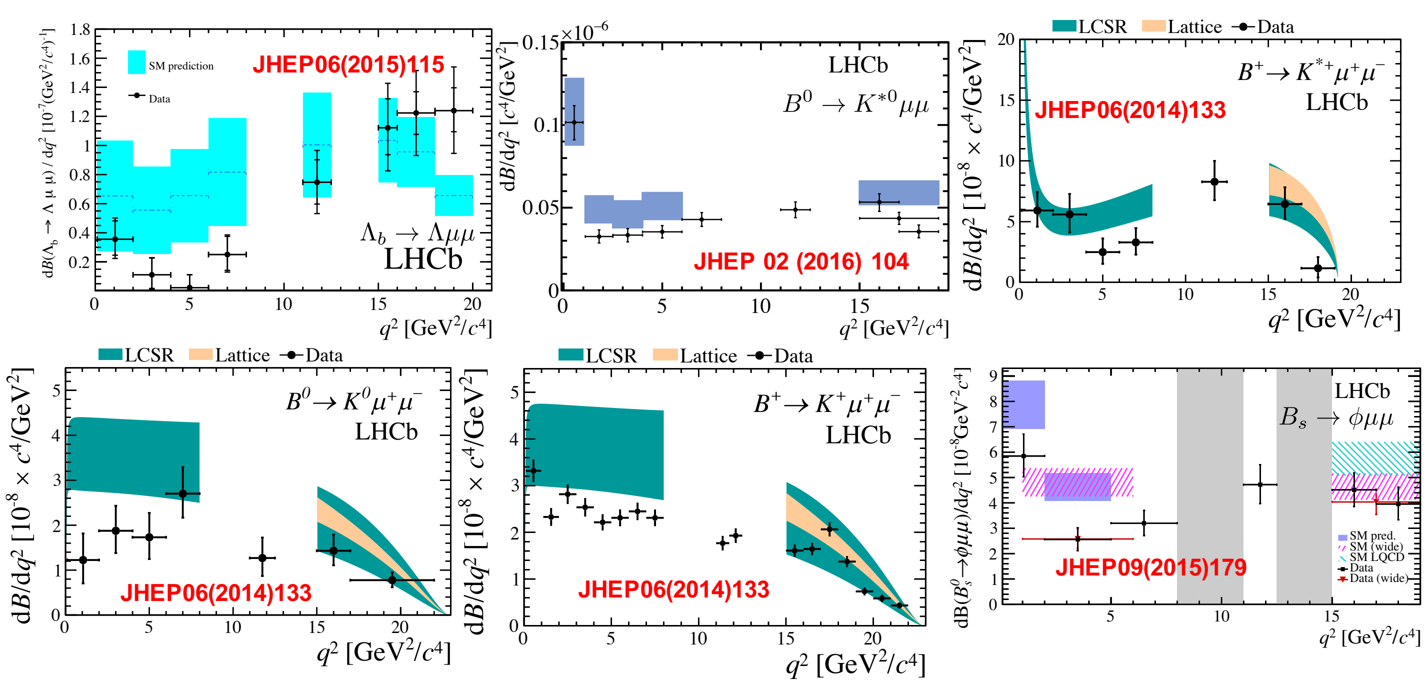
Angular distributions

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



- JHEP 02 (2016) 104
- PRL 118 (2017)
- ATLAS-CONF-2017-023
- CMS-PAS-BPH-15-008

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



Neutral-Current B-anomalies

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

If NP, then a contribution to this LH operator is necessary

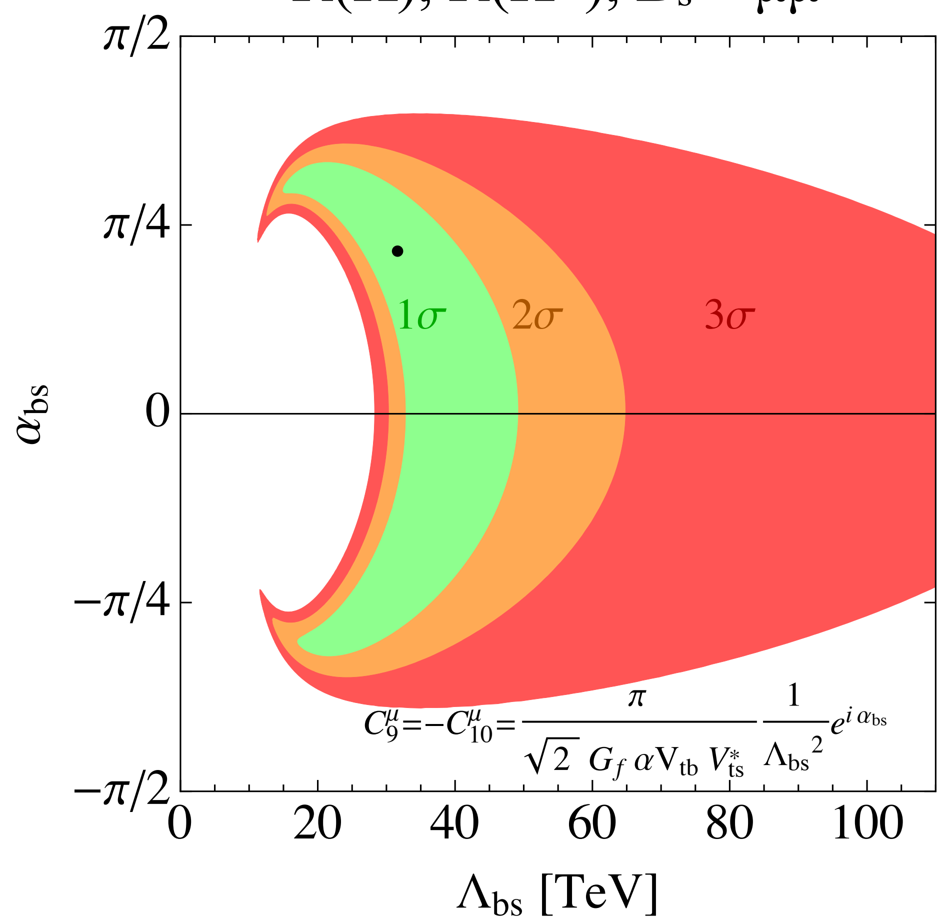
$$\boxed{\mathcal{L}_{\rm eff} \supset \frac{e^{i\alpha_{bs}}}{\Lambda_{bs}^2} (\bar{s}_L \gamma^\mu b_L)(\bar{\mu}_L \gamma_\mu \mu_L) + h.c.}$$

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

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

simplified fit of *clean observables*

R(K), R(K*), $B_s \to \mu\mu$



$$(\Lambda_{\rm bs})^{\text{best-fit}} \;\; (\alpha_{\rm bs}=0) \approx 38 \text{ TeV}$$

Adding also angular distributions and branching ratios:

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

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

A non-zero phase is compatible with data.

It implies a lower NP scale, the upper limit is due to a not large enough (destructive) interference with SM.

A new flavour structure

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

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

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

We are learning about C_{sb}. **What about the rest?**

What is the $SU(3)_q$ structure of this new flavor breaking term?

To answer, we need to find and study correlations with other flavor-violating transitions.

Directions in SU(3)$_q$ space

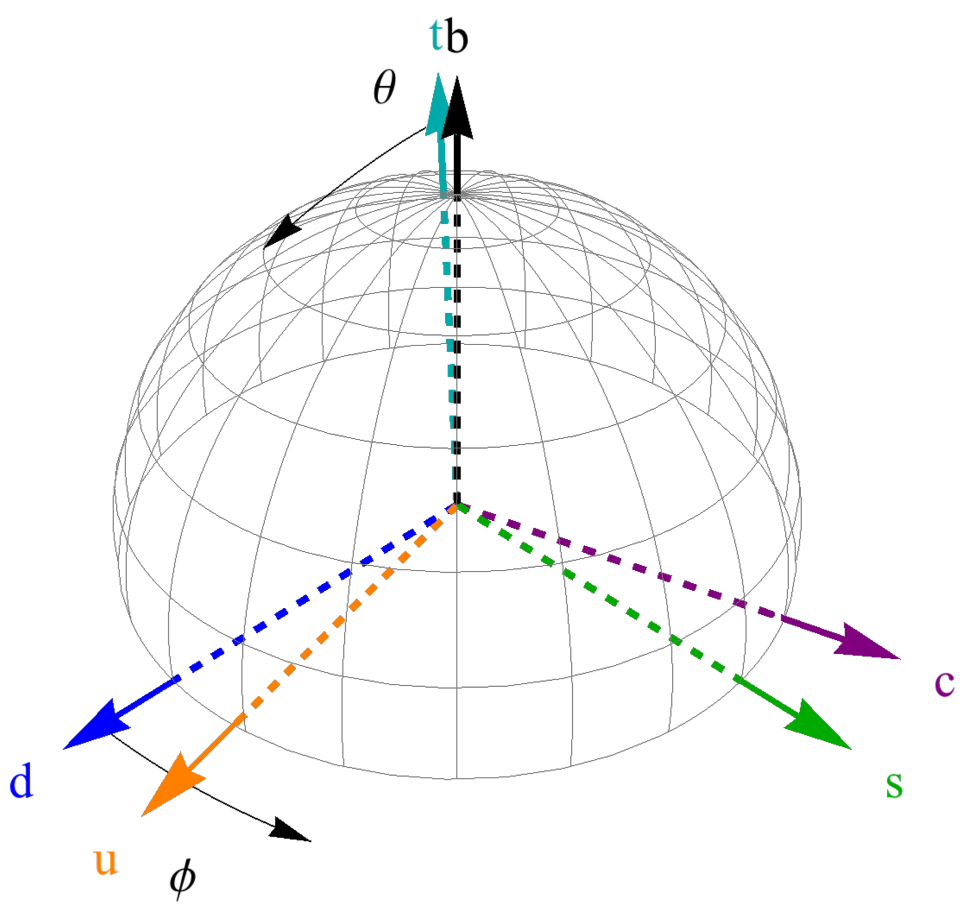
We can parametrise directions in SU(3)$_q$ as:

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

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

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

We assume that the **flavor matrix**

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

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

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

It selects a direction in that space.

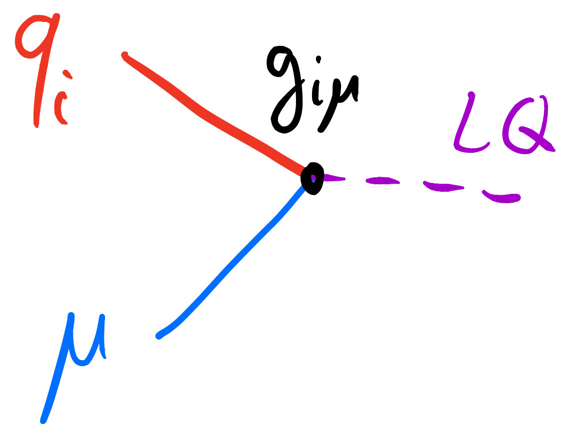
We aim to answer the following question

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

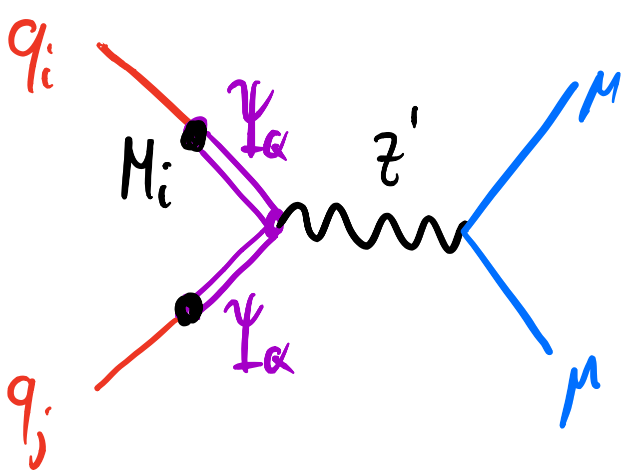
$$\mathcal{L} = \lambda_i \bar{q}_L^i \mathcal{O}_{\rm NP} + \text{h.c.}$$



Single leptoquark models

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

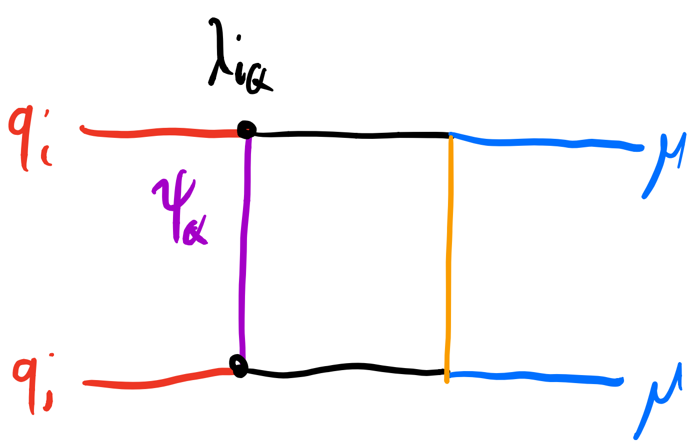
$$\hat{n}_i \propto g_{i\mu}$$



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

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

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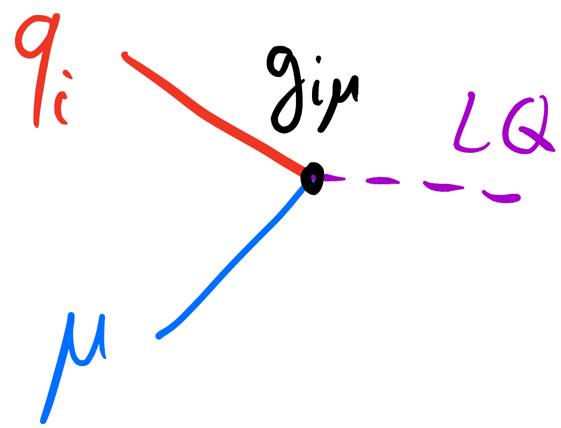

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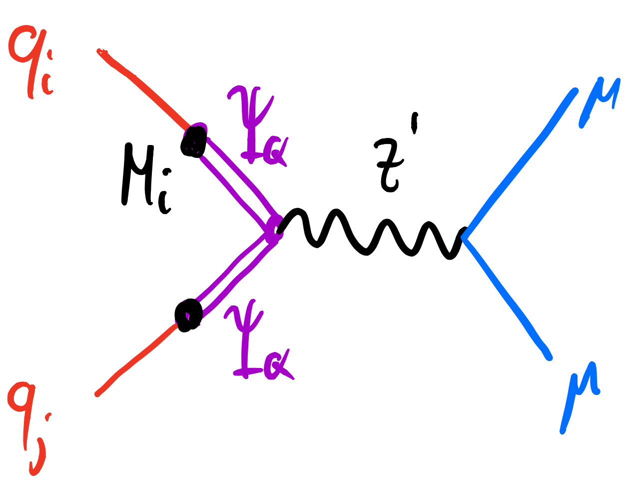

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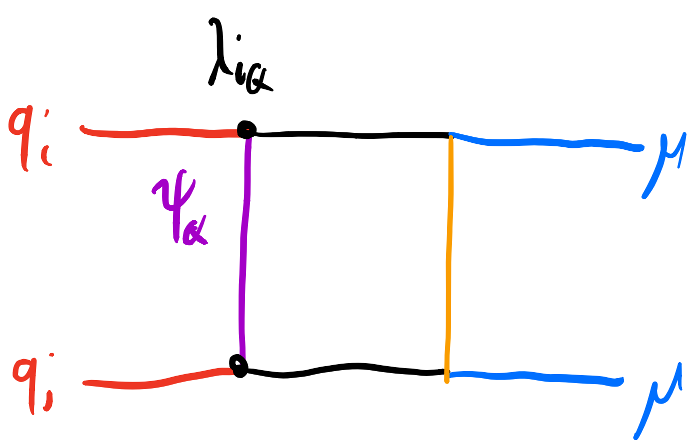

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Assuming B-anomalies are reproduced,
what are the experimentally allowed directions for $\hat{n}$?

Working in the LEFT
(WEFT, WET,…)

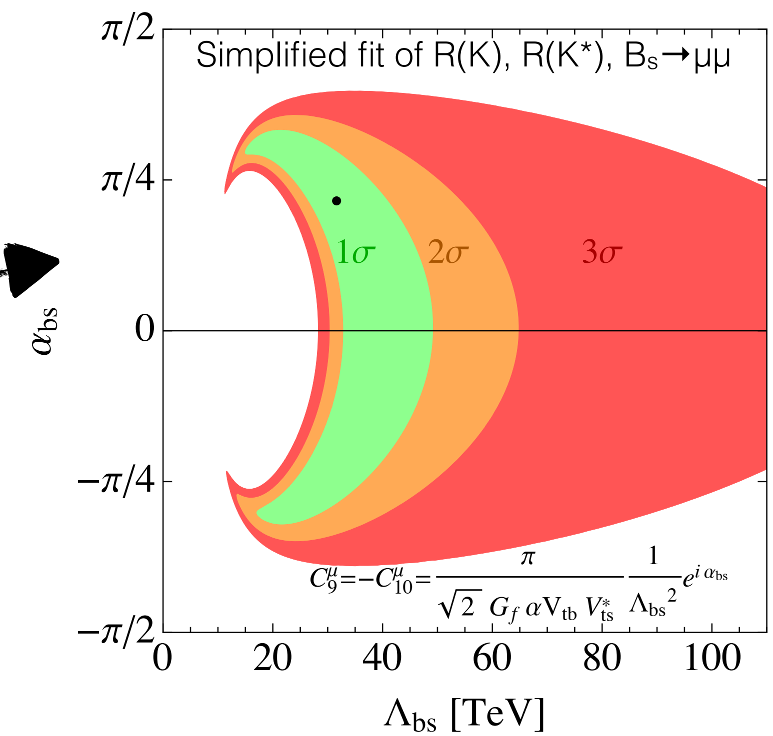
ROFV

$$\mathcal{L}_{\rm NP}^{\rm EFT} = C\, \hat{n}_i \hat{n}_j^* (\bar{d}_L^i \gamma_\mu d_L^i)(\bar{\mu}_L \gamma^\mu \mu_L) \qquad \hat{n} = \begin{pmatrix} \sin\theta\cos\phi e^{i\alpha_{bd}} \\ \sin\theta\sin\phi e^{i\alpha_{bs}} \\ \cos\theta \end{pmatrix}$$

The b-s element is fixed by the anomalies.

For any given $\hat{n}(\theta,\varphi,\alpha_{bs},\alpha_{bd})$,
we obtain the overall scale C by fitting the anomalies.

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



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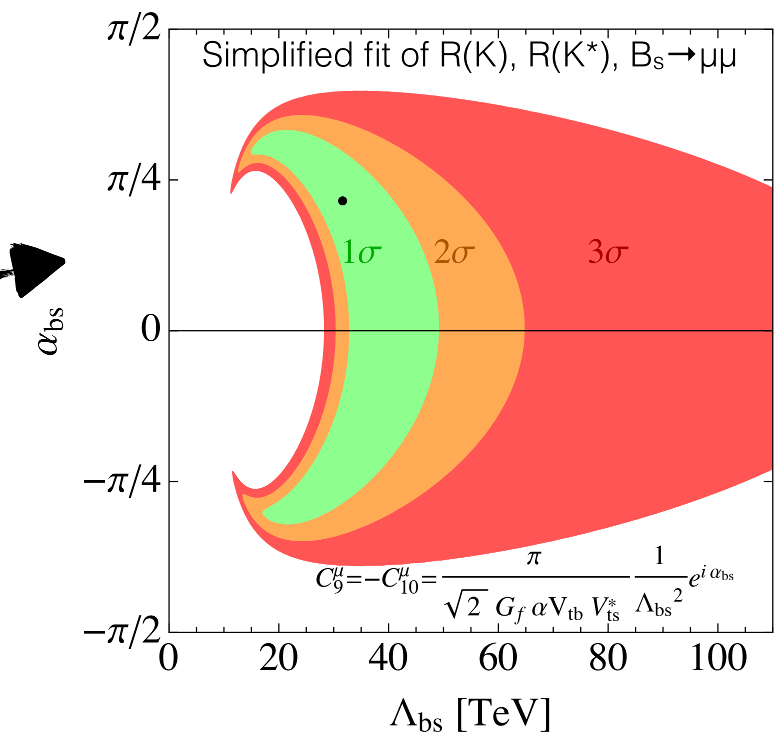

Once C is fixed (as a function of $\hat{n}$) we
predict all other flavor transitions:

$$C_{db} = C\sin\theta\cos\theta\cos\phi e^{i\alpha_{bd}}$$

$$C_{ds} = C\sin^2\theta\sin\phi\cos\phi e^{i(\alpha_{bd}-\alpha_{bs})}$$

We can check if the specific direction in $\mathrm{SU(3)_q}$ space $\hat{n}$
is experimentally allowed or excluded by observables testing these transitions.

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)	$(1.06 \pm 0.09) \times 10^{-10}$
	$\mathrm{Br}(B^+ \to \pi^+\mu^+\mu^-)_{[1,6]}$	$(4.55^{+1.05}_{-1.00} \pm 0.15) \times 10^{-9}$	$(6.55 \pm 1.25) \times 10^{-9}$
Im(C_{ds})	$\mathrm{Br}(K_S \to \mu^+\mu^-)$	$< 11 \times 10^{-9}$ (95% CL)	$(5.0 \pm 1.5) \times 10^{-12}$
Re(C_{ds})	$\mathrm{Br}(K_L \to \mu^+\mu^-)_{\rm SD}$	$< 2.5 \times 10^{-9}$	$\approx 0.9 \times 10^{-9}$
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 $SU(3)_q$)

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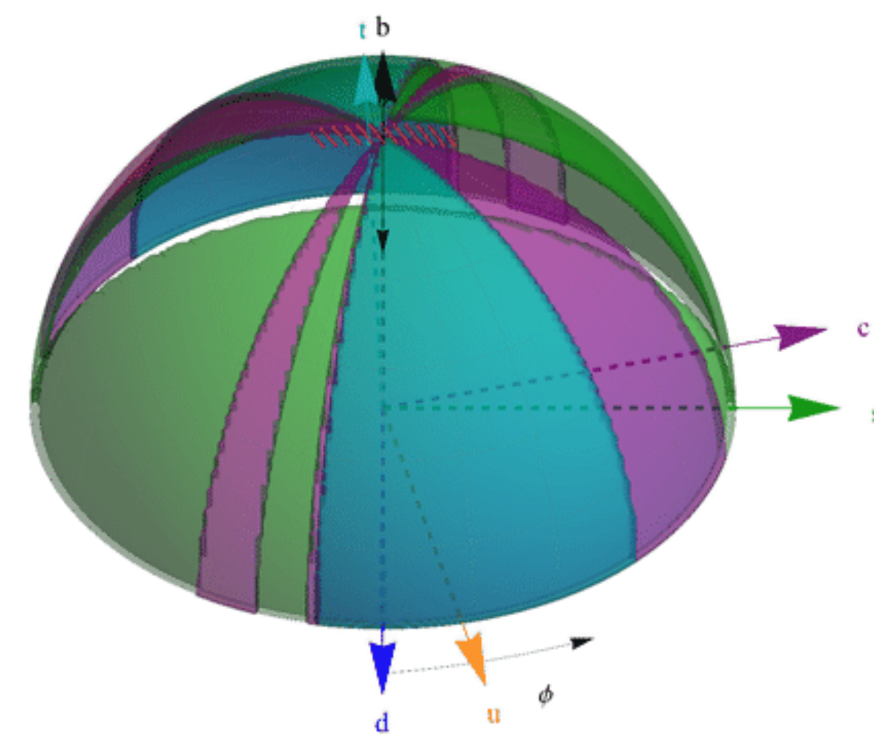
($\alpha_{\rm bs}$=0, $\alpha_{\rm bd}$=0)



Each colored region is excluded by the respective observable

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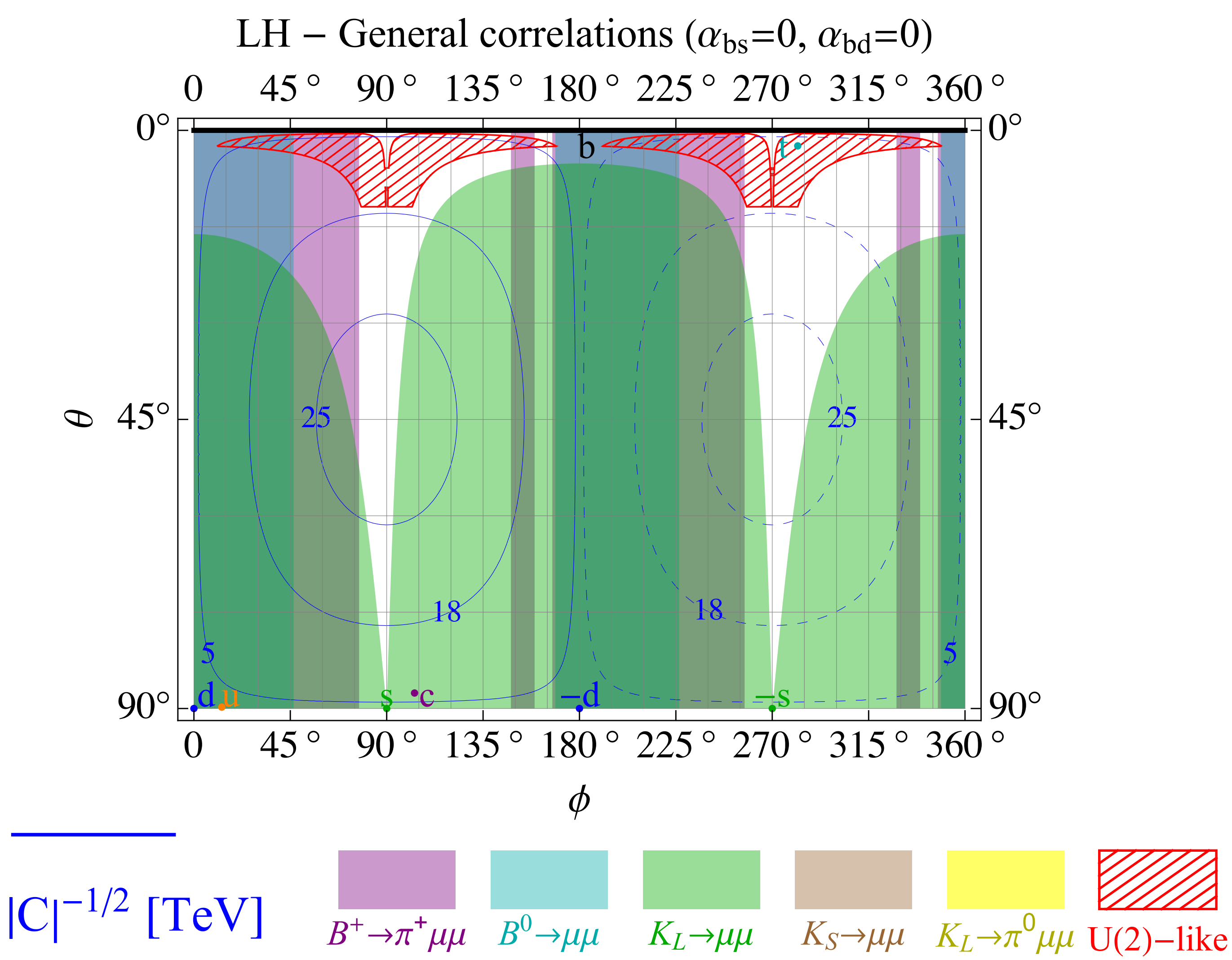

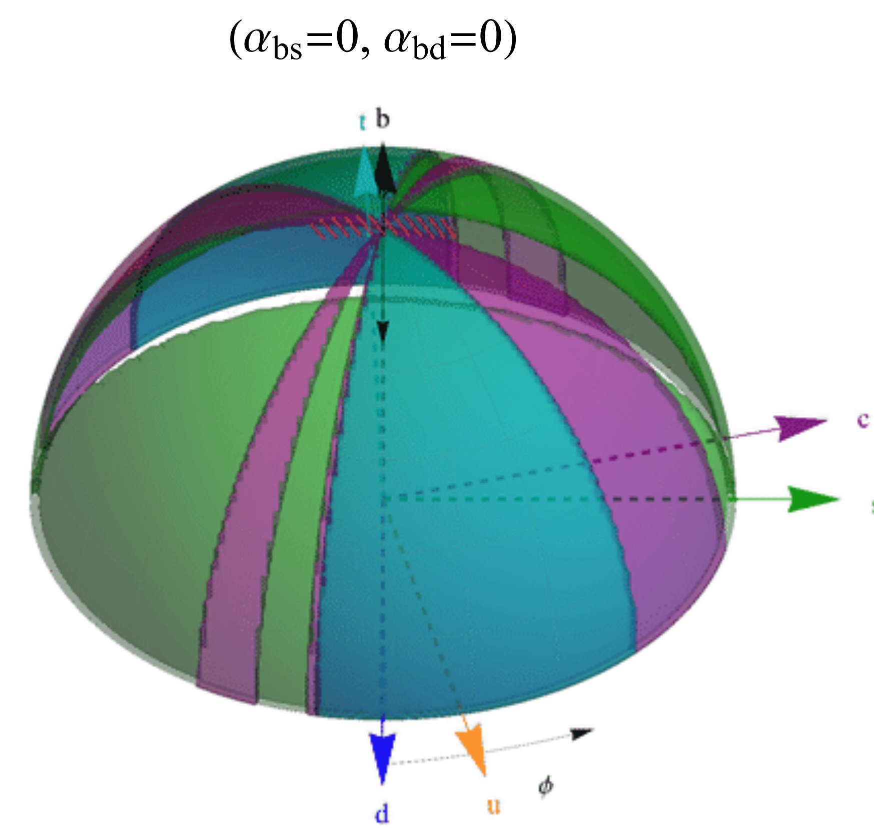

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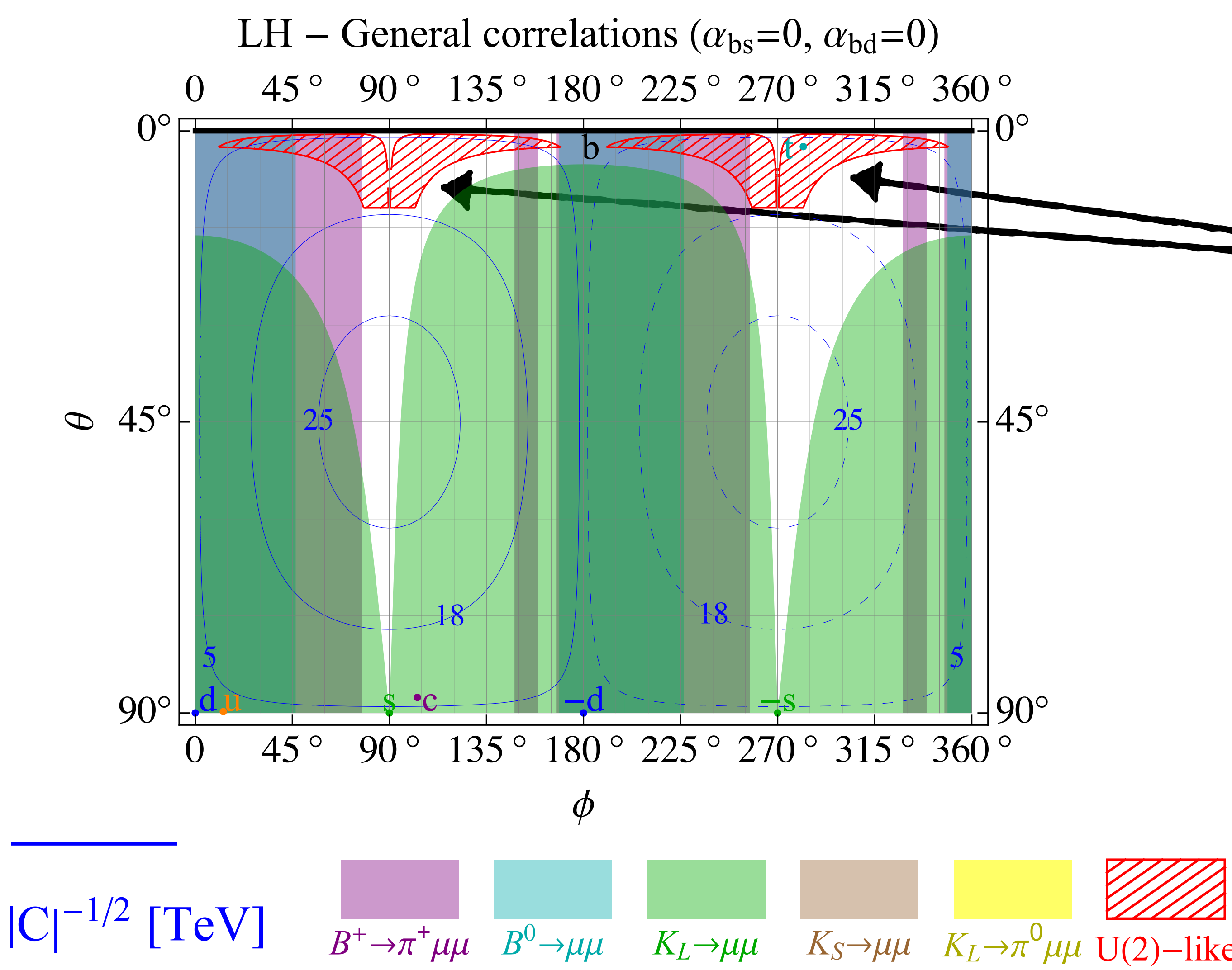

Region suggested by U(2) flavour symmetry or partial compositeness (close to third generation).

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

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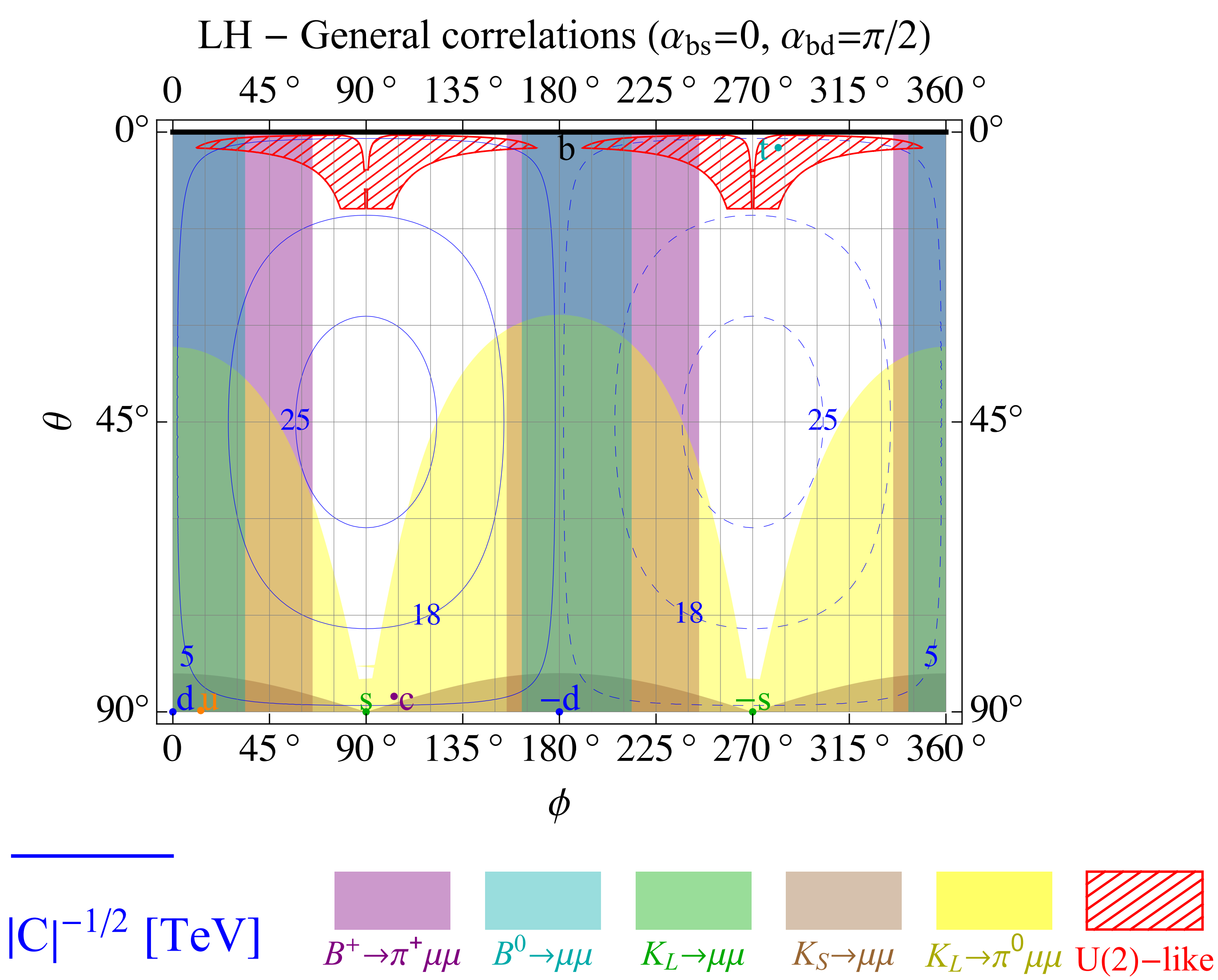

For complex coefficients, $K_L \to \pi^0 \mu\mu$ and $K_S \to \mu\mu$ become important

SMEFT case & mediators

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

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

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

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$d_i \to d_j \overline{\nu_\mu} \nu_\mu$	$C_S - C_T$
$u_i \to d_j \mu^+ \nu_\mu$	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 assumption is

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

Three overall coefficients

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

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Different processes depend on different combinations of the three overall coefficients

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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

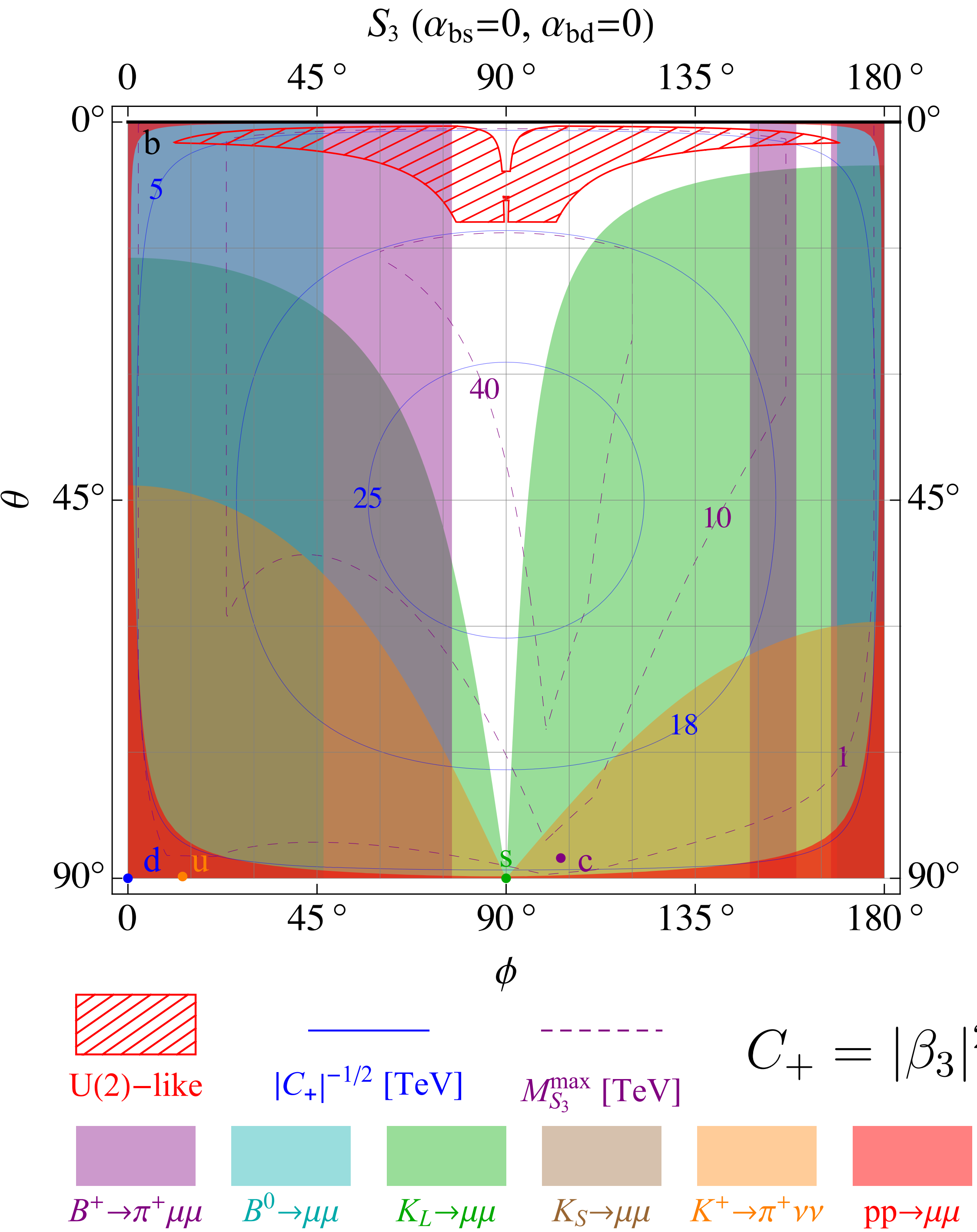
(backup slides)

S_3 scalar leptoquark

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

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

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



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

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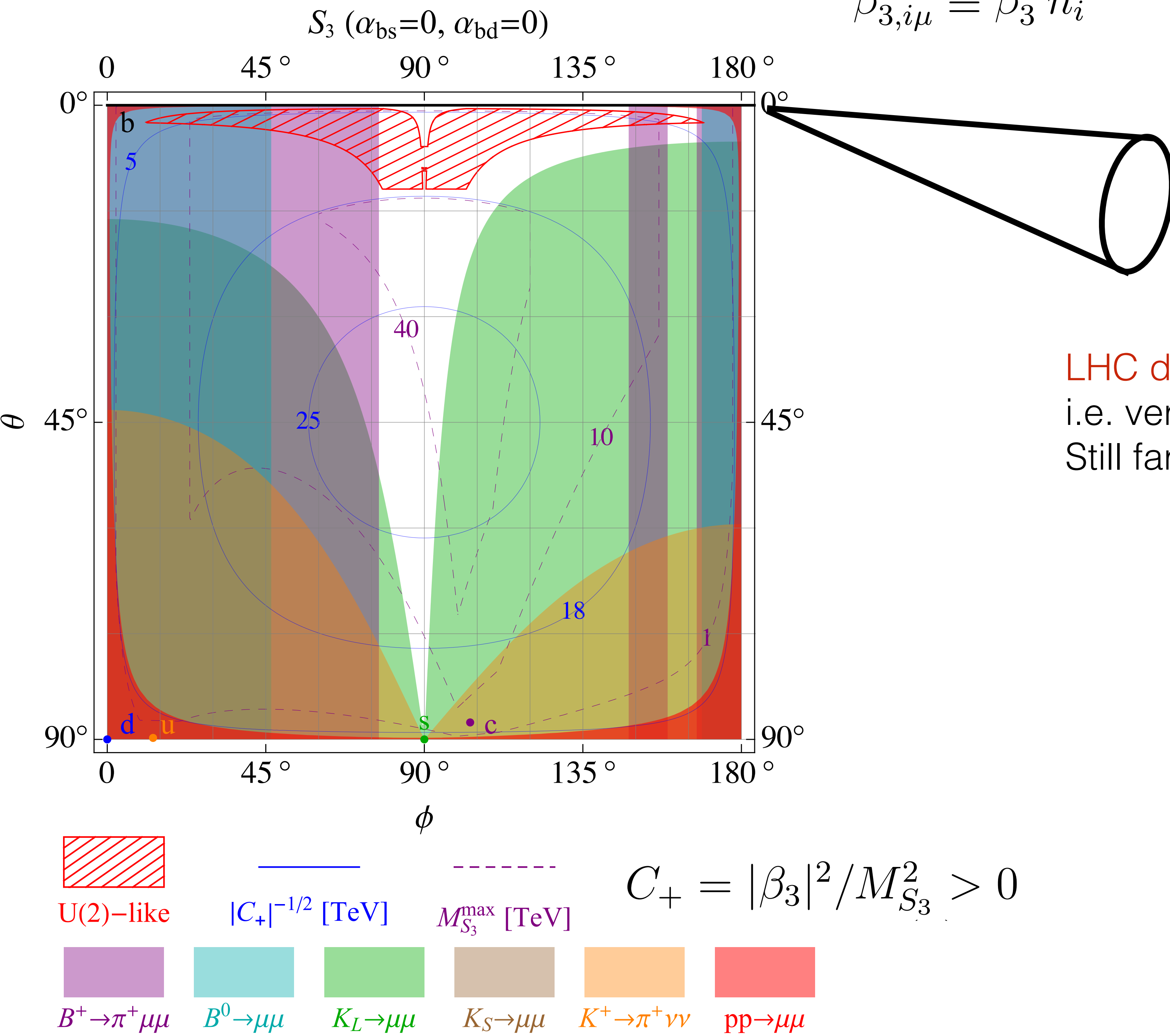

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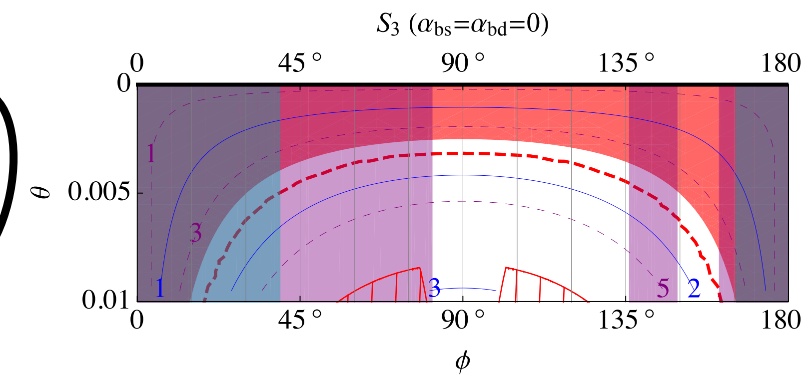
Zooming in on the small θ region



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]

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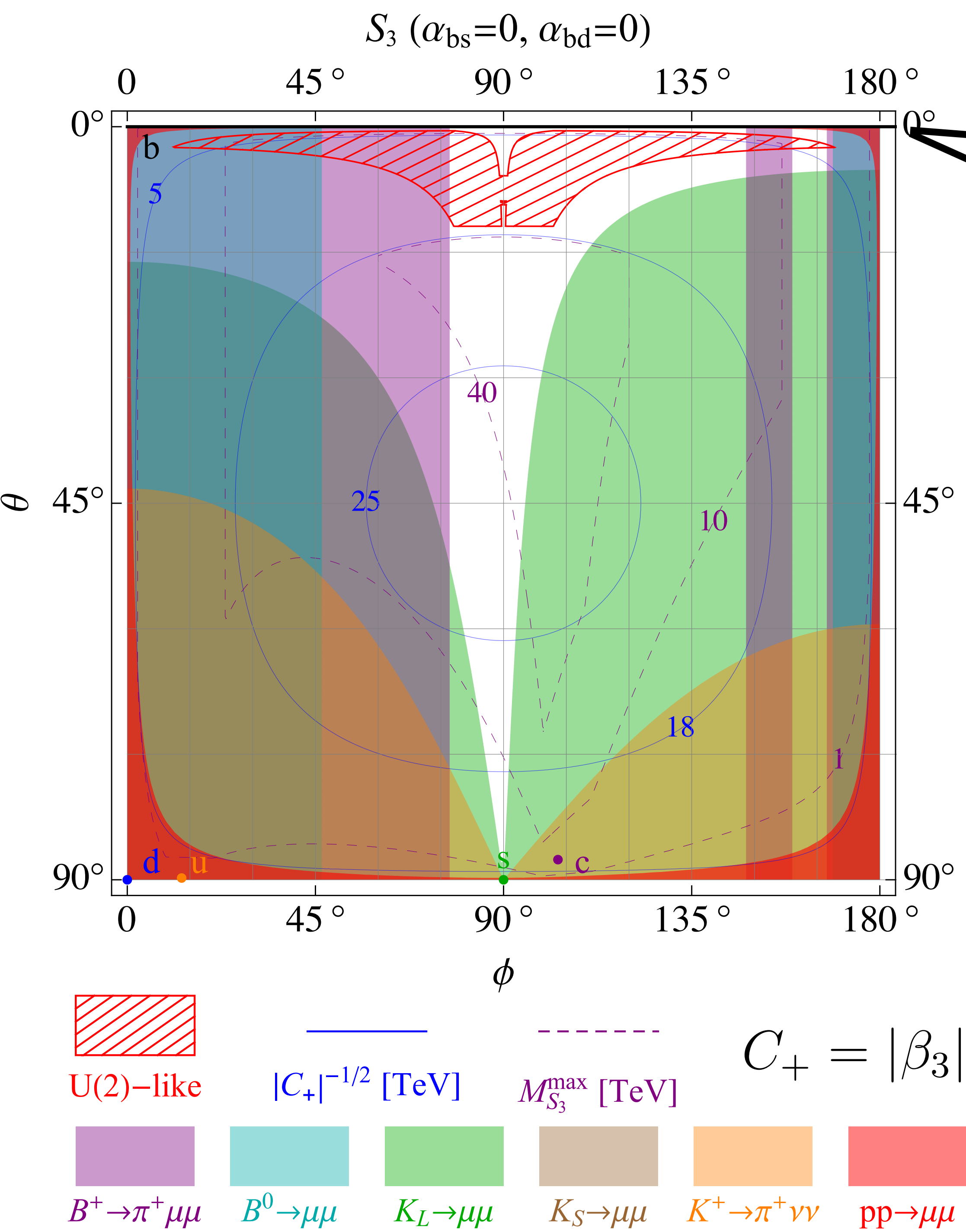

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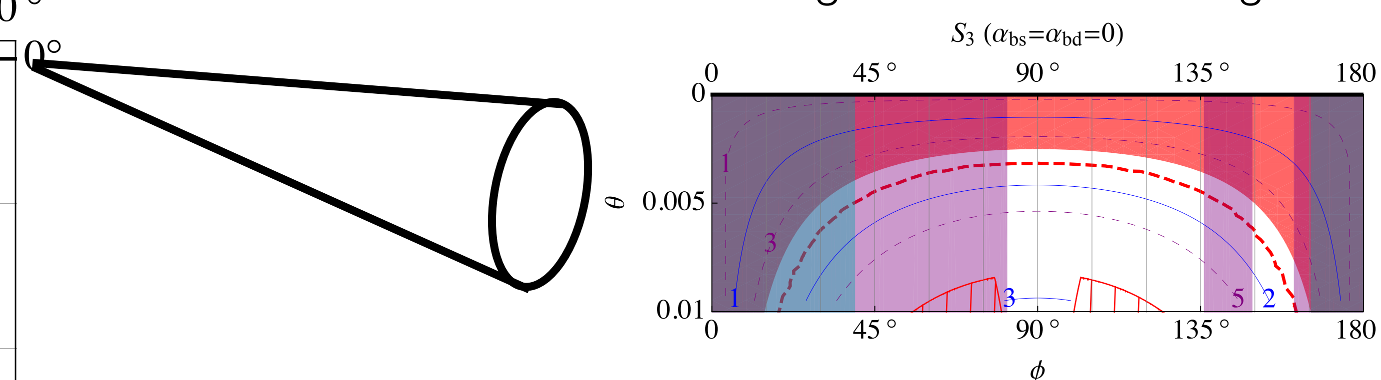

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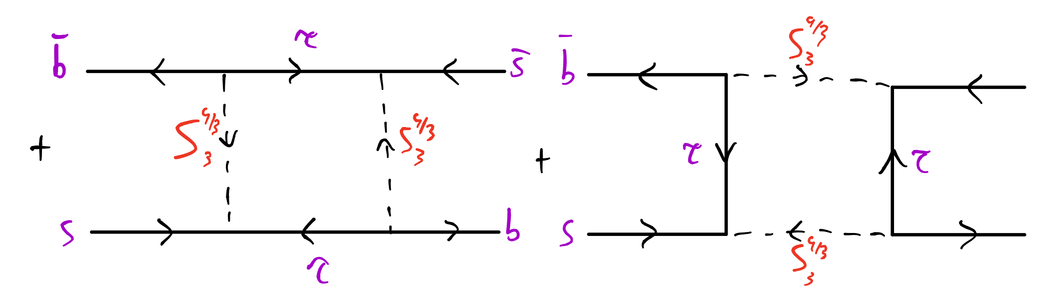

At 1-loop it generates ΔF=2 operators

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

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

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: $V_q \sim (\mathbf{2}, \mathbf{1}, \mathbf{1})$, $\Delta Y_u \sim (\mathbf{2}, \bar{\mathbf{2}}, \mathbf{1})$, $\Delta Y_d \sim (\mathbf{2}, \mathbf{1}, \bar{\mathbf{2}})$

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

The doublet is given by CKM elements up to corrections

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

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

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

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

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

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

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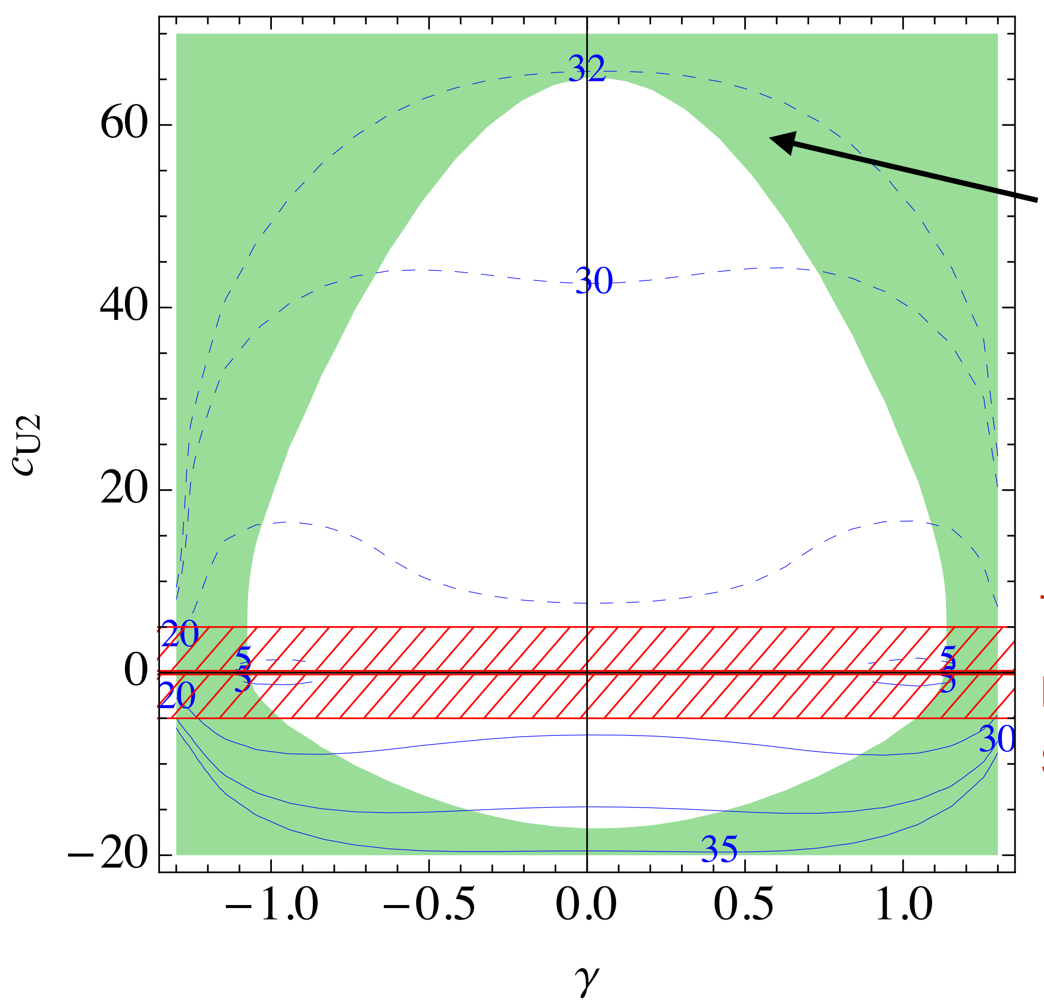
Imposing the ROFV structure we can also get **correlations with s-d transitions**:
only 2 free parameters: c_{U2}, γ.

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

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

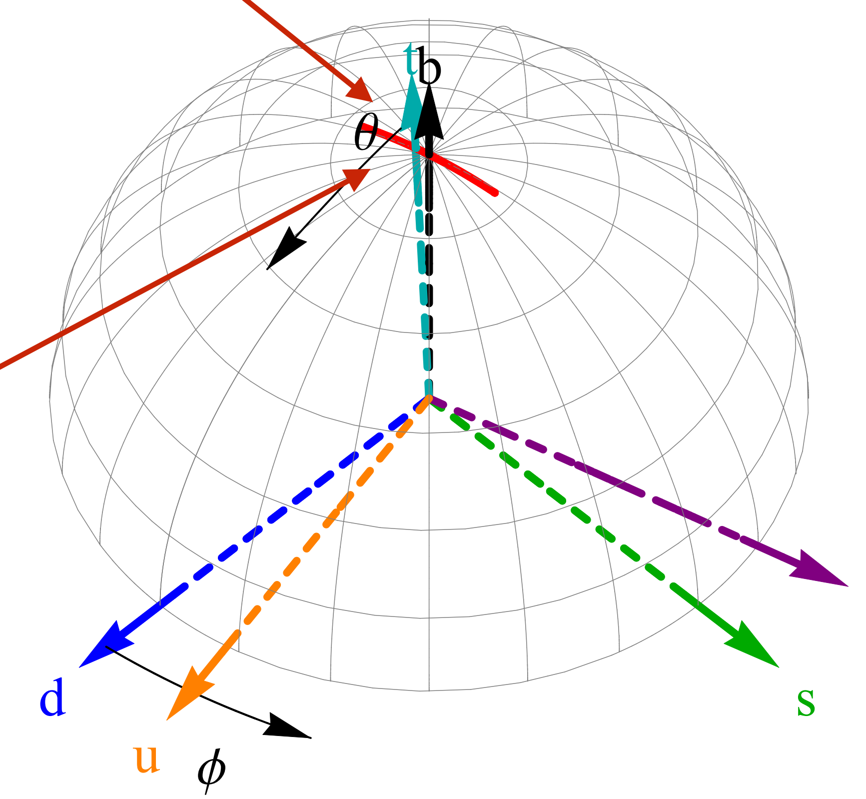
$$\hat{n} \propto \left(c_{U2} e^{i\gamma} V_{td}^*,\ c_{U2} e^{i\gamma} V_{ts}^*,\ 1\right)$$

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



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

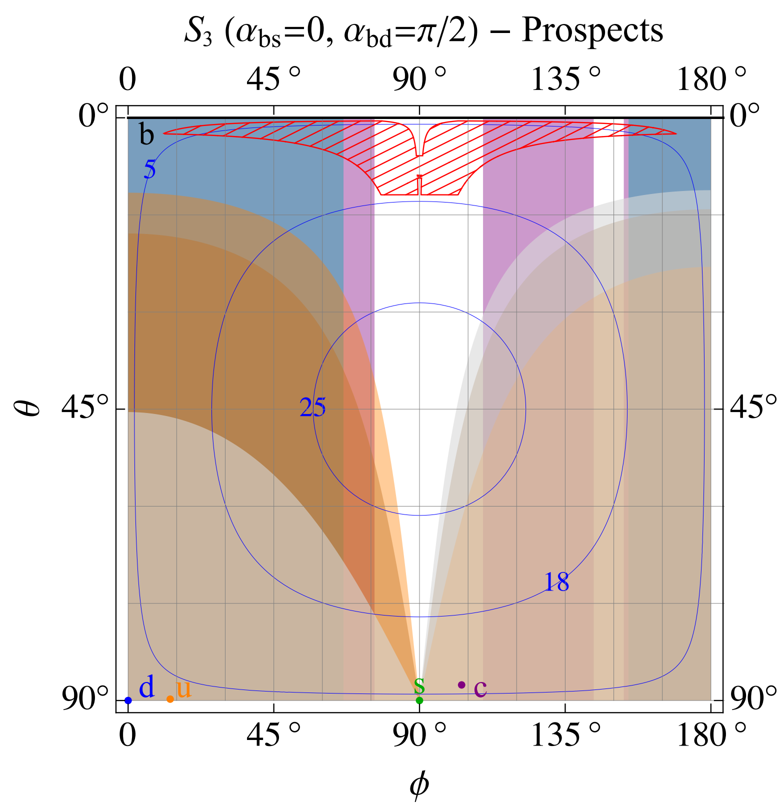
The region consistent with minimally broken U(2) symmetry is still not tested

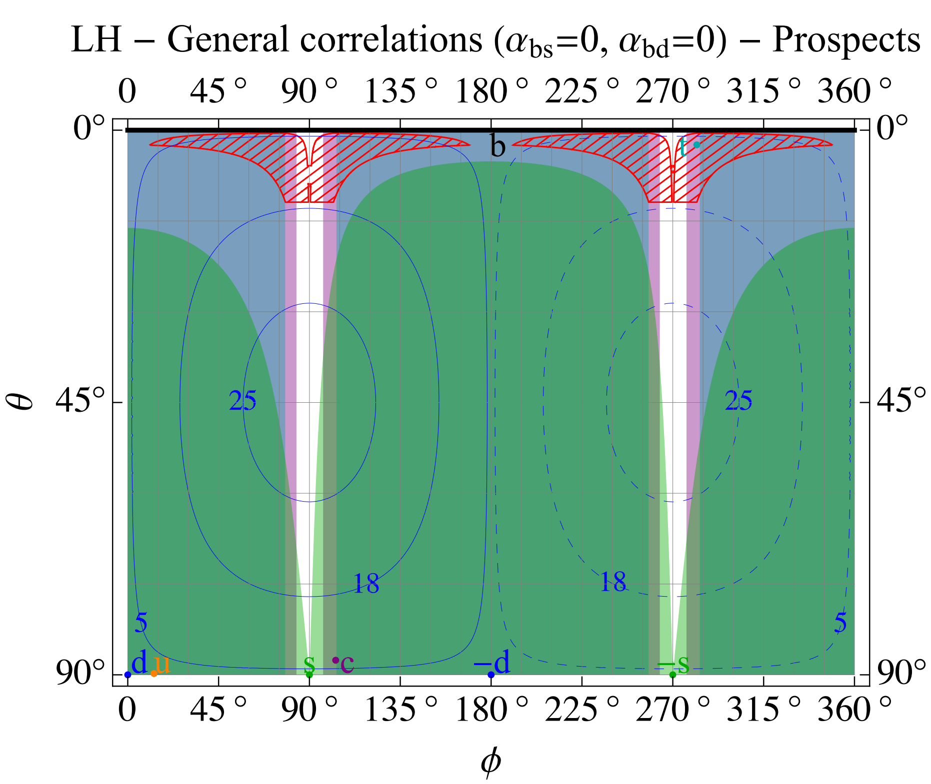


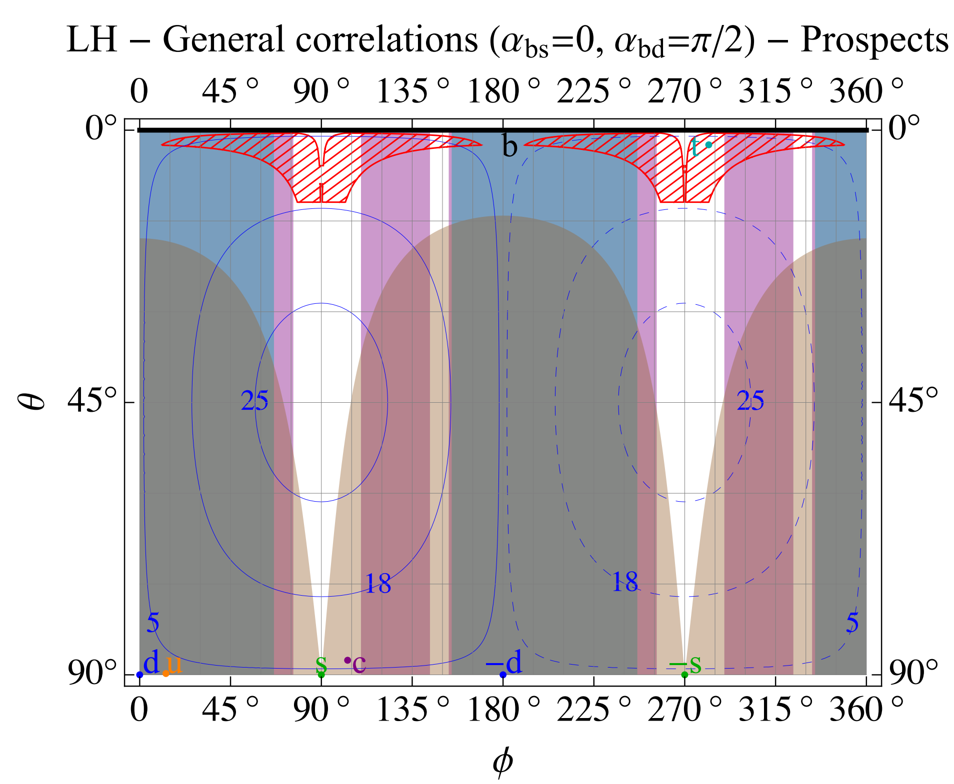
Prospects

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







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 $b \to s\mu\mu$ 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**.

Thank you!

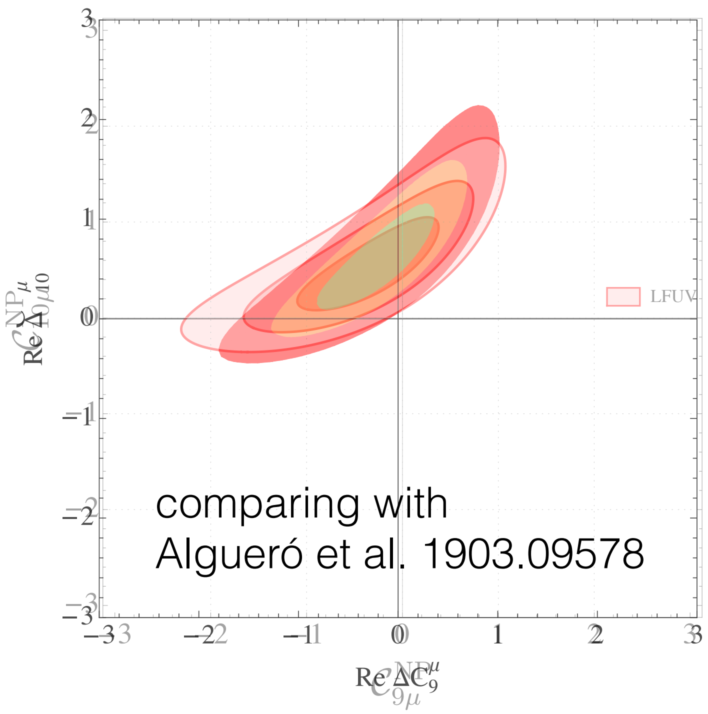
Backup

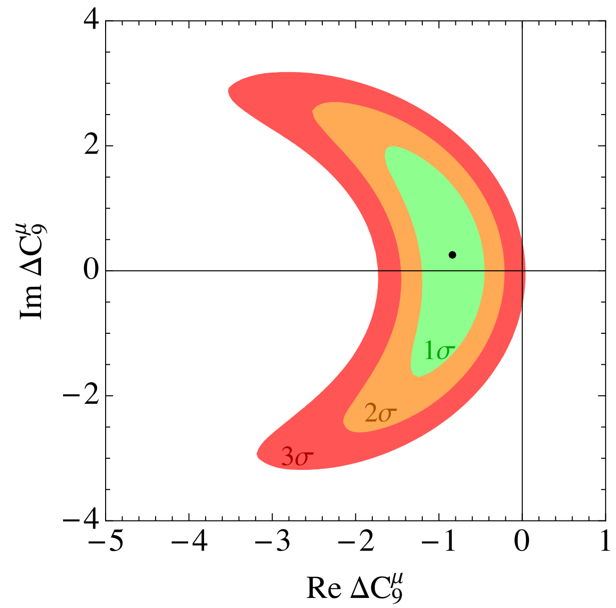
Simplified* fit of clean observables

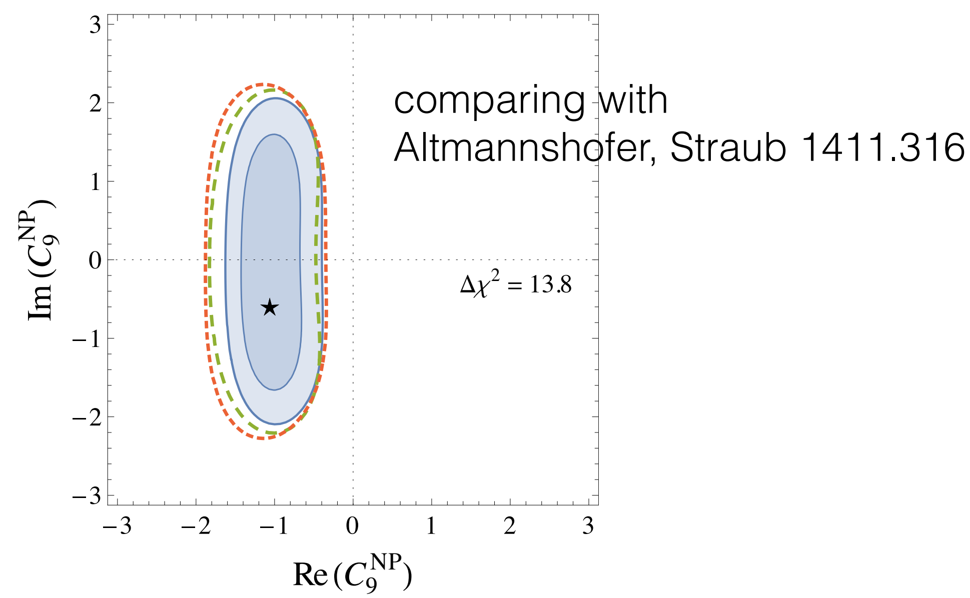
$$\mathcal{L}_{\text{eff}}^{\text{NP}} \supset \frac{G_F \alpha}{\sqrt{2}\pi} V_{tb} V_{ts}^* \left[\Delta C_9^\mu (\bar{s}_L \gamma^\mu b_L)(\bar{\mu}\gamma_\mu \mu) + \Delta C_{10}^\mu (\bar{s}_L \gamma^\mu b_L)(\bar{\mu}\gamma_\mu \gamma_5 \mu) \right] + h.c. \; .$$

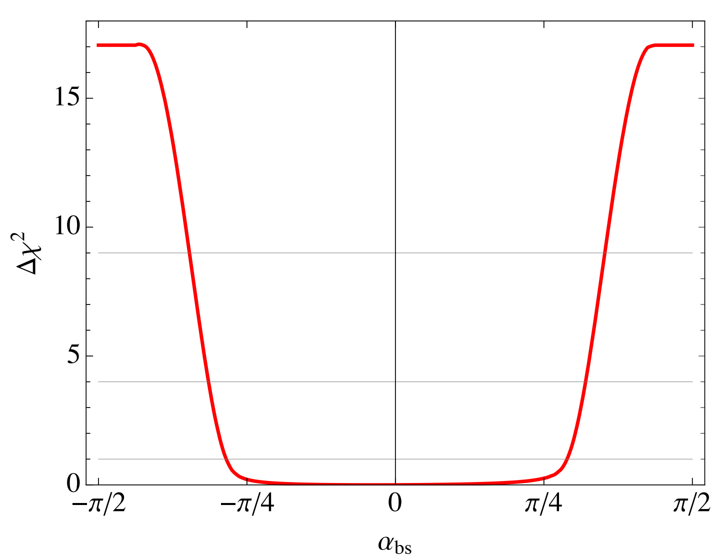
$$\mathcal{L}_{\text{eff}} \supset \frac{e^{i\alpha_{bs}}}{\Lambda_{bs}^2} (\bar{s}_L \gamma^\mu b_L)(\bar{\mu}_L \gamma_\mu \mu_L) + h.c.$$

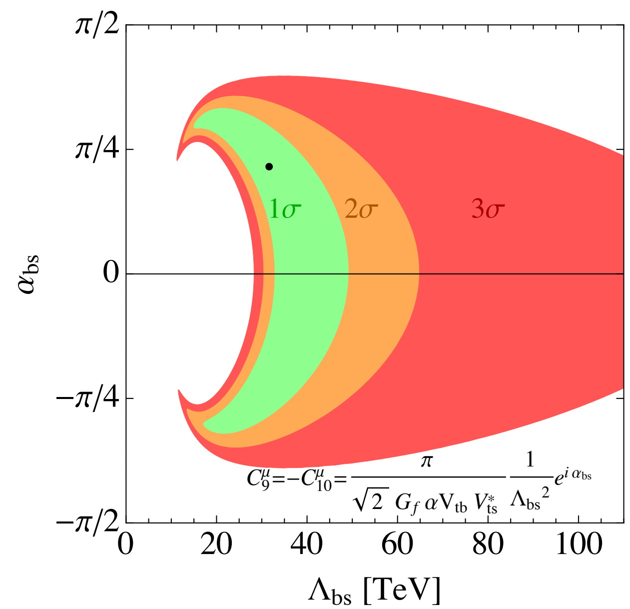
R_K $[1.1,\ 6]$ GeV^2	0.846 ± 0.062	LHCb [1, 2]
R_{K^*} $[0.045,\ 1.1]$ GeV^2	0.66 ± 0.11 $0.52^{+0.36}_{-0.26}$	LHCb [3] Belle [4]
R_{K^*} $[1.1,\ 6]$ GeV^2	0.69 ± 0.12 $0.96^{+0.45}_{-0.29}$	LHCb [3] Belle [4]
R_{K^*} $[15,\ 19]$ GeV^2	$1.18^{+0.52}_{-0.32}$	Belle [4]
$\text{Br}(B_s^0 \to \mu\mu)$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

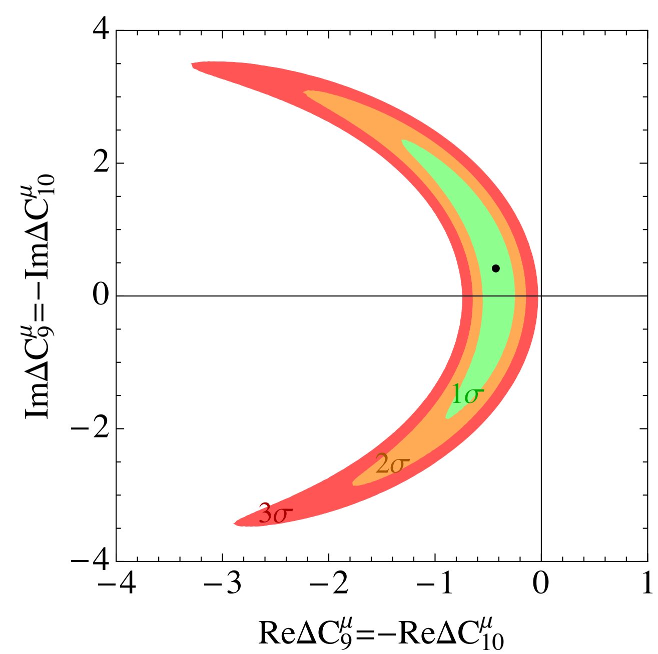












*Simplified = no theory uncertainties considered. Agrees well “enough" with full fits.

ΔF = 2 observables (and ε'/ε)

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

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

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

$q = u, d, s, c$

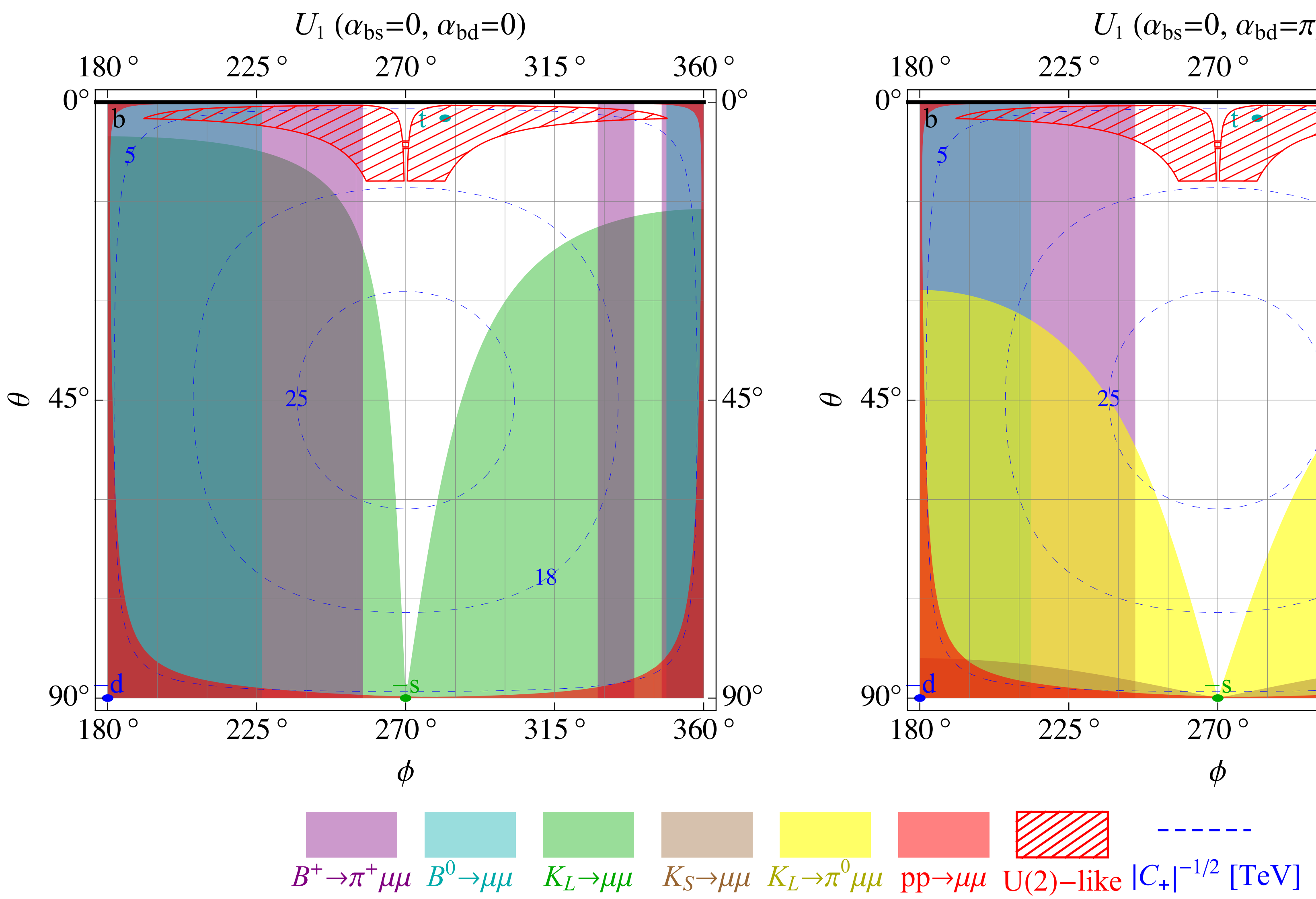
[Aebisher et al. 1807.02520, 1808.00466]

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

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

U_1 vector leptoquark

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



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

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

Z' & vector-like couplings to μ

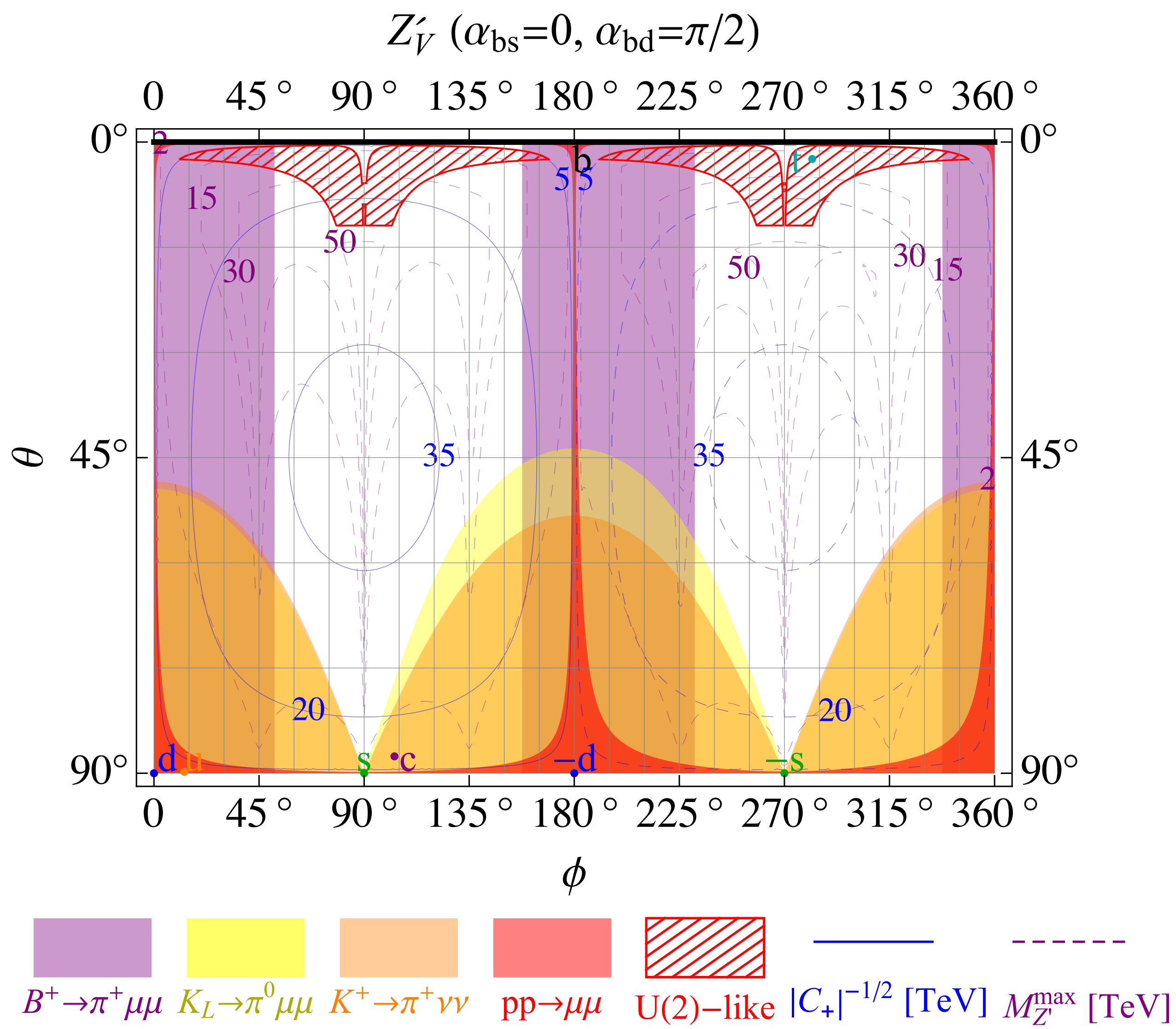
For example see the gauged U(1)$_{L\mu-L\tau}$ model with 1 vector-like quark.

[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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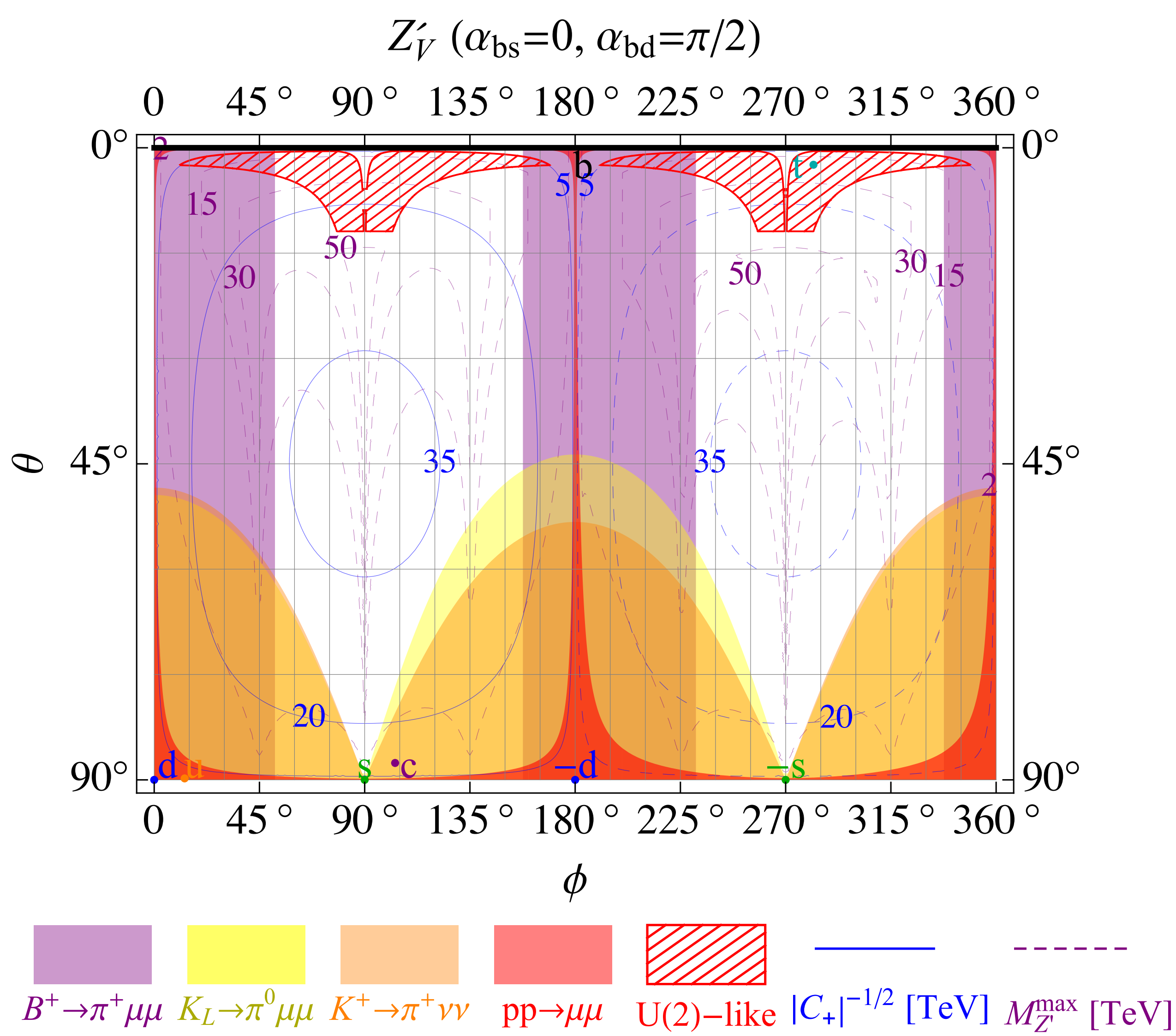

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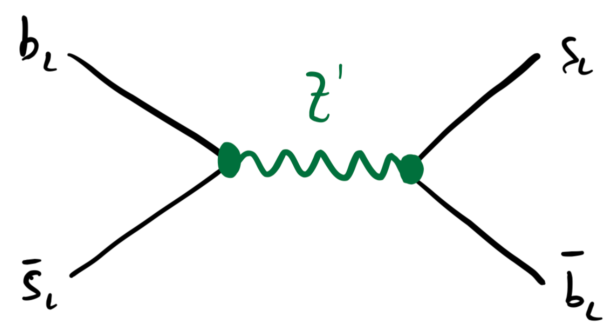

ΔF=2 operators are generated at the tree level.

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

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

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