Flavour anomalies: status, new ideas and high-p$_T$ impact

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Cincinnati IPA 2018

Based on JHEP 1801 (2018) 093 and
M. Alguero, B. Capdevila, S. Descotes-Genon, P. Masjuan, J. Matias (arXiv:1809.08447).

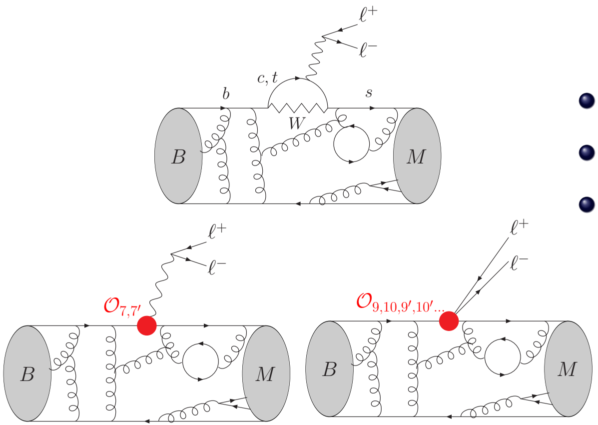
Outline

This talk will focus on the following questions:

- State-of-the-art of $b \to s\ell\ell$ anomalies.
  - The anomalies and their anatomy: LFD and LFUV.
  - Global fit (1D,2D,6D): what do we learn?
  - A new idea beyond NP versus hadronic: are we overlooking LFU? A new pattern.
- Brief state-of-the-art of $b \to c\tau\nu$ anomalies.
- Scales of New Physics and models
- Linking both anomalies: charged and (future) neutral with SMEFT.
- Impact of high-p$_T$ on flavour anomalies.

State-of-the-art of $b \to s\ell\ell$ anomalies

The framework: $b \to s\ell\ell$ effective Hamiltonian, **Wilson Coefficients**



$$b \to s\gamma^{(*)} : \mathcal{H}^{SM}_{\triangle F=1} \propto \sum V^*_{ts} V_{tb} \mathcal{C}_i \mathcal{O}_i + \ldots$$

separate short and long distances ($\mu_b = m_b$)

- $\mathcal{O}_7 = \frac{e}{16\pi^2} m_b \left(\bar{\mathbf{s}}\sigma^{\mu\nu}\mathbf{P_R b}\right) \mathbf{F}_{\mu\nu}$ [real or soft photon]
- $\mathcal{O}_9 = \frac{e^2}{16\pi^2} (\bar{\mathbf{s}}\gamma_\mu \mathbf{P_L b})\ (\bar{\ell}\gamma^\mu \ell)$
- $\mathcal{O}_{10} = \frac{e^2}{16\pi^2} (\bar{\mathbf{s}}\gamma_\mu \mathbf{P_L b})\ (\bar{\ell}\gamma^\mu \gamma_5 \ell)$

At the $\mu_b = 4.8$ GeV scale:

$$\mathcal{C}_7^{\rm SM} = -0.29,\ \mathcal{C}_9^{\rm SM} = 4.1,\ \mathcal{C}_{10}^{\rm SM} = -4.3$$

NP changes short-distance $\mathcal{C}_i = \mathcal{C}_i^{\rm SM} + \mathcal{C}_i^{\rm NP}$ for SM or involve additional operators $\mathcal{O}_i$

- Chirally flipped ($W \to W_R$) $\mathcal{O}_{7'} \propto (\bar{s}\sigma^{\mu\nu} P_L\, b) F_{\mu\nu}$, $\mathcal{O}_{9'} \propto (\bar{s}\gamma_\mu P_R\, b)(\bar{\ell}\gamma^\mu \ell)$ ....

If we find the right-scenario (NP in $\mathcal{C}_9$ or $\mathcal{C}_9 = -\mathcal{C}_{10}$ or ....) that is realized in Nature we will be able:

- To discard a large number of models and to focus on the right subset of models.

175 observables in total (LHCb, Belle, ATLAS and CMS, no CP-violating obs)

- $B \to K^*\mu\mu$ ($P_{1,2}, P'_{4,5,6,8}, F_L$ in 5 large-recoil bins + 1 low-recoil bin)+available electronic observables.

...April's update of $\mathrm{Br}(B \to K^*\mu\mu)$ showing now a deficit in muonic channel.

...April's new result from LHCb on R_K^*

- $B_s \to \phi\mu\mu$ ($P_1, P'_{4,6}, F_L$ in 3 large-recoil bins + 1 low-recoil bin)
- $B^+ \to K^+\mu\mu$, $B^0 \to K^0\ell\ell$ (BR) ($\ell = e, \mu$) (R_K is implicit)
- $B \to X_s\gamma$, $B \to X_s\mu\mu$, $B_s \to \mu\mu$ (BR).
- Radiative decays: $B^0 \to K^{*0}\gamma$ (A_I and $S_{K^*\gamma}$), $B^+ \to K^{*+}\gamma$, $B_s \to \phi\gamma$

▶ New Belle measurements for the isospin-averaged but lepton-flavour dependent ($Q_{4,5} = P'^{\mu}_{4,5} - P'^{e}_{4,5}$):

$$P'^{\,\ell}_i = \sigma_+ \, P'^{\,\ell}_i(B^+) + (1 - \sigma_+) \, P'^{\,\ell}_i(\bar{B}^0)$$

▶ New ATLAS and CMS measurements on P_i.

Frequentist approach: $\mathcal{C}_i = \mathcal{C}_i^{SM} + \mathcal{C}_i^{NP}$, with $\mathcal{C}_i^{NP}$ assumed to be real (no CPV)

$$\chi^2(C_i) = [O_{\text{exp}} - O_{\text{th}}(C_i^{NP})]_j \, [Cov^{-1}]_{jk} \, [O_{\text{exp}} - O_{\text{th}}(C_i^{NP})]_k$$

The anomalies and their anatomy.

First anomaly of $b \to s\mu^+\mu^-$ type (Lepton Flavour Dependent): P_5'

Framework: I-QCDF + SFF + KMPW+ power corrections

$$\frac{d^4\Gamma(\bar{B}_d \to K^*(\to K\pi)\mu^+\mu^-)}{dq^2\, d\cos\theta_\ell\, d\cos\theta_K\, d\phi} = \frac{9}{32\pi}\sum_i J_i(q^2) f_i(\theta_\ell, \theta_K, \phi)$$

P_5' was proposed in **DMRV, JHEP 1301(2013)048**

$$P_5' = J_5/2\sqrt{-J_{2s}J_{2c}} = P_5^\infty\left(1 + \mathcal{O}(\alpha_s \xi_\perp) + \text{p.c.}\right) .$$

Optimized observables:

SFF sensitivity α_s suppressed compared to non-optimized.

Impact of an improvement on KMPW-FF errors (50%):

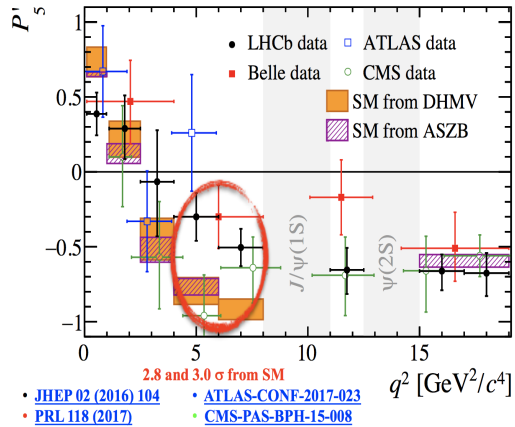
- Optimized observable P_5' (% present error size)

$$P'_{5\,[4,6]} = -0.82 \pm 0.08(\mathbf{10}\%) \to 0.06(\mathbf{8}\%)$$

$\longrightarrow$ interestingly BSZ-FF+full-FF approach finds 0.05

- Non-optimized observable S_5

$$S_{5\,[4,6]} = -0.35 \pm 0.12(\mathbf{34}\%) \to 0.06(\mathbf{17}\%)$$

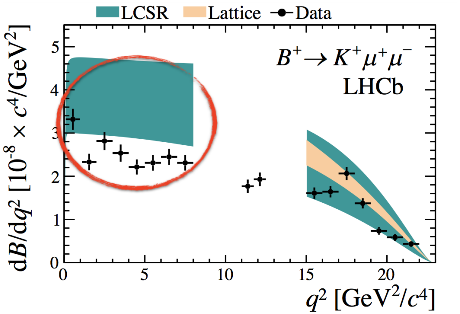


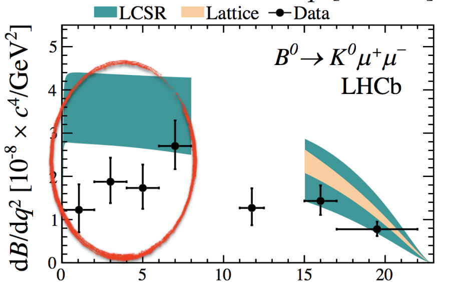
Experimentally: LHCb (1fb^{-1} 3.7σ and 3fb^{-1} 2 bins 3σ), Belle confirmed [4,8]. ATLAS and CMS first measurement.

Orange: our th. framework with conserv. KMPW
Magenta: full-FF using BSZ (+dep. LCSR details)

Other $b \to s\mu^+\mu^-$ observables tensions show up:

Systematic deficit of muons at large-recoil but also at low-recoil:





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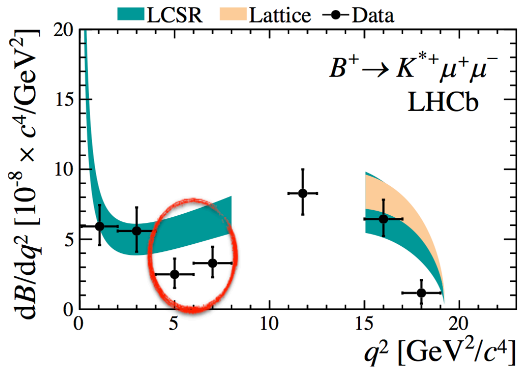
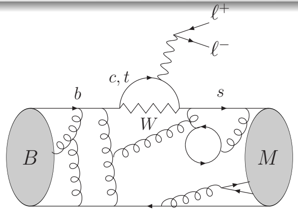


$b \to s\mu^+\mu^-$ $(\times 10^7)$	bin	SM	EXP	Pull
$\mathrm{BR}(B^0 \to K^0\mu^+\mu^-)$	[15,19]	0.91 ± 0.12	0.67 ± 0.12	+1.4
$\mathrm{BR}(B^0 \to K^{*0}\mu^+\mu^-)$	[16,19]	1.66 ± 0.15	1.23 ± 0.20	+1.7
$\mathrm{BR}(B^+ \to K^{*+}\mu^+\mu^-)$	[15,19]	2.59 ± 0.25	1.60 ± 0.32	**+2.5**
$\mathrm{BR}(B_s \to \phi\mu^+\mu^-)$	[15,18.8]	2.20 ± 0.17	1.62 ± 0.20	**+2.2**

First anomaly of Lepton Flavour Universality Violation (LFUV) type: R_K

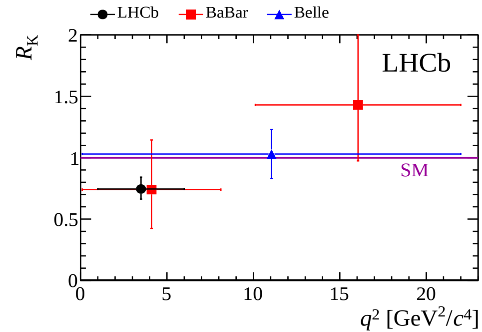


$$R_K = \frac{\text{Br}\,(B^+ \to K^+ \mu^+ \mu^-)}{\text{Br}\,(B^+ \to K^+ e^+ e^-)} = 0.745^{+0.090}_{-0.074} \pm 0.036$$

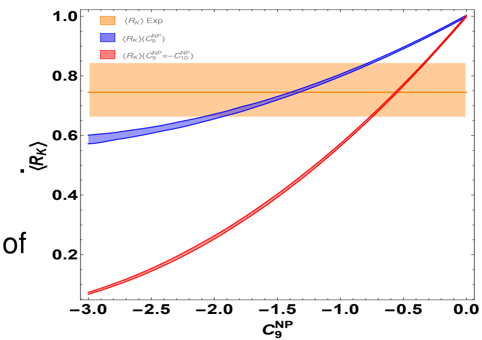
$\Rightarrow$ It deviates $\mathbf{2.6}\sigma$ from SM.

$\Rightarrow$ equals to 1 in SM (universality of lepton coupling).

$\Rightarrow$ NP coupling $\neq$ to μ and e.



1. **First signal of LFUV.**
   If experimental error reduces by 40% LFUV-fit $> 5\sigma$
2. Simple structure: $f_{+,0,T} \to$ one SFF (f_+) at large-recoil.
   $\to f_0$ lepton mass suppressed or arises in the presence of (pseudo)scalar while f_T suppressed by C_7^{eff}.
3. Tensions cannot be explained inside the SM by neither factorizable power corrections* nor long-distance charm*.



- In presence of NP also clean prediction

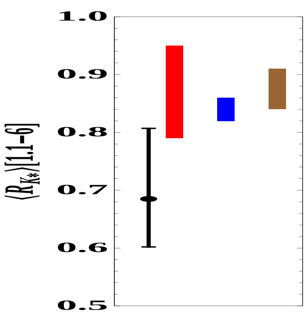
R_{K^*} plays a different league

$$R_{K^*} = \frac{Br(B^0 \to K^{*0}\mu^+\mu^-)}{Br(B^0 \to K^{*0}e^+e^-)}$$

pulls	$R_{K^*}^{[0.045,1.1]}$	$R_{K^*}^{[1.1,6]}$
Exp.	$0.66^{+0.113}_{-0.074}$	$0.685^{+0.122}_{-0.083}$
SM	0.92 ± 0.02	1.00 ± 0.01

$\mathbf{R_{K^*}}$: More complex structure, 6-8 Amplitudes and 7 form factors.
Impact of long-distance charm from KMPW on $B \to K^*$ larger than on $B \to K$.

- In presence of NP or for $q^2 < 1$ GeV^2 **hadronic uncertainties return.** Example: $(C_i^\mu - C_i^e)\delta FF$



Predictions R_{K^*}			
Bins	$[0.045, 1.1]$	$[1.1, 6.]$	$[15., 19.]$
Standard Model	0.916 ± 0.025	1.000 ± 0.006	0.998 ± 0.001
$\Leftarrow C_{9\mu}^{\rm NP} = -1.11$	0.897 ± 0.049	0.867 ± 0.080	0.788 ± 0.005
$C_{9\mu}^{\rm NP} = -1.76$	0.895 ± 0.084	0.827 ± 0.137	0.698 ± 0.009
$C_{9\mu}^{\rm NP} = -C_{10\mu}^{\rm NP} = -0.62$	0.866 ± 0.057	0.751 ± 0.027	0.714 ± 0.006

• 1st bin is expected to be SM-like. • $C_9 < 0$ gets near saturation at large-recoil.

KMPW-sch.1: $\xi_\perp = \mathbf{0.31^{+0.20}_{-0.10}}, \xi_\parallel = \mathbf{0.10^{+0.03}_{-0.02}}$

BSZ-sch.1 $\xi_\perp = \mathbf{0.32 \pm 0.03}, \xi_\parallel = 0.12 \pm 0.02$

JC-sch.2 $\xi_\perp = \mathbf{0.31 \pm 0.04}, \xi_\parallel = 0.10 \pm 0.02$

New category of LFUV observables: $Q_{4,5} = P'^{\mu}_{4,5} - P'^{e}_{4,5}$ (BELLE)

[S. Wehle et al. PRL118 (2017)]

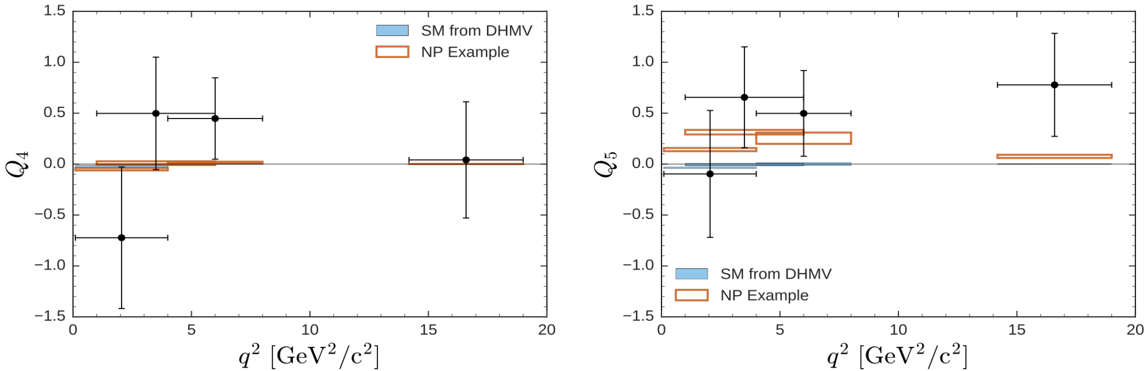


Figure 3: Q_4 and Q_5 observables with SM and favored NP "Scenario 1" from Ref. [6].

Table 2: Results for the lepton-flavor-universality-violating observables Q_4 and Q_5. The first uncertainty is statistical and the second systematic.

q^2 in GeV$^2/c^2$	Q_4	Q_5
[1.00, 6.00]	$0.498 \pm 0.527 \pm 0.166$	$0.656 \pm 0.485 \pm 0.103$
[0.10, 4.00]	$-0.723 \pm 0.676 \pm 0.163$	$-0.097 \pm 0.601 \pm 0.164$
[4.00, 8.00]	$0.448 \pm 0.392 \pm 0.076$	$0.498 \pm 0.410 \pm 0.095$
[14.18, 19.00]	$0.041 \pm 0.565 \pm 0.082$	$0.778 \pm 0.502 \pm 0.065$

Where we stand? Results 1D fits: All $b \to s\ell\ell$ and LFUV fit

⇒ Global fits test the **coherence** *of a set of deviations with a NP hypothesis versus SM hypothesis*

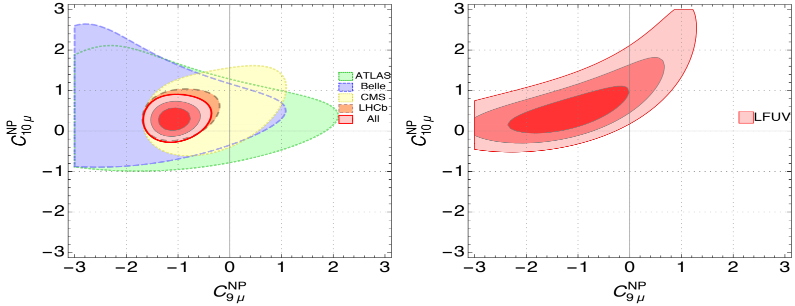
- Hypotheses "NP in some $\mathcal{C}_i$ only" (1D, 2D, 6D)

	All				
1D Hyp.	Best fit	1 σ	2 σ	Pull$_{\rm SM}$	p-value
$\mathcal{C}_{9\mu}^{\rm NP}$	**-1.11**	$[-1.28, -0.94]$	$[-1.45, -0.75]$	**5.8**	68
$\mathcal{C}_{9\mu}^{\rm NP} = -\mathcal{C}_{10\mu}^{\rm NP}$	-0.62	$[-0.75, -0.49]$	$[-0.88, -0.37]$	**5.3**	58
$\mathcal{C}_{9\mu}^{\rm NP} = -\mathcal{C}'_{9\mu}$	-1.01	$[-1.18, -0.84]$	$[-1.34, -0.65]$	5.4	61
$\mathcal{C}_{9\mu}^{\rm NP} = -3\mathcal{C}_{9e}^{\rm NP}$	-1.07	[-1.24,-0.90]	[-1.40,-0.72]	5.8	70

	LFUV				
1D Hyp.	Best fit	1 σ	2 σ	Pull$_{\rm SM}$	p-value
$\mathcal{C}_{9\mu}^{\rm NP}$	**-1.76**	$[-2.36, -1.23]$	$[-3.04, -0.76]$	**3.9**	69
$\mathcal{C}_{9\mu}^{\rm NP} = -\mathcal{C}_{10\mu}^{\rm NP}$	-0.66	$[-0.84, -0.48]$	$[-1.04, -0.32]$	**4.1**	78
$\mathcal{C}_{9\mu}^{\rm NP} = -\mathcal{C}'_{9\mu}$	-1.64	$[-2.13, -1.05]$	$[-2.52, -0.49]$	3.2	32
$\mathcal{C}_{9\mu}^{\rm NP} = -3\mathcal{C}_{9e}^{\rm NP}$	-1.35	$[-1.82, -0.95]$	$[-2.38, -0.59]$	4.0	72

Pull$_{SM}$: how much the SM is disfavoured with respect to a New Physics hypothesis to explain data.
→ A scenario with a large SM-pull ⇒ big improvement over SM and better description of data.

Notice the difference of b.f.p. between all-fit and LFUV.



Allowed regions with all available data (upper) and only LFUV (lower) in good agreement. Constraints from $b \to s\gamma$ observables, $\mathcal{B}(B \to X_s \mu\mu)$ and $\mathcal{B}(B_s \to \mu\mu)$ always included. Experiments at 3σ.

Other analysis using BSZ [Altmannshofer et al.] finds 6.5σ.

We take all Wilson coefficients SM-like and chirally flipped as free parameters:
(neglect scalars and tensor operators)

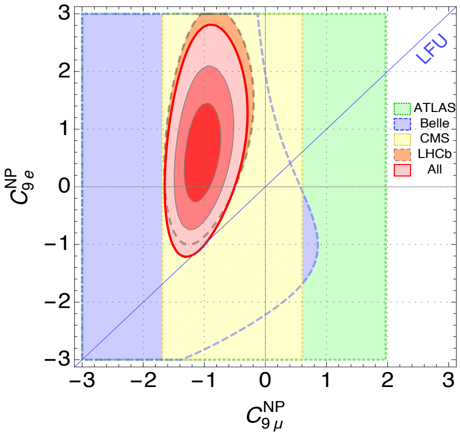
	$\mathcal{C}_7^{\rm NP}$	$\mathcal{C}_{9\mu}^{\rm NP}$	$\mathcal{C}_{10\mu}^{\rm NP}$	$\mathcal{C}_{7'}$	$\mathcal{C}_{9'\mu}$	$\mathcal{C}_{10'\mu}$
Best fit	+0.03	-1.12	+0.31	+0.03	+0.38	+0.02
1 σ	$[-0.01, +0.05]$	$[-1.34, -0.88]$	$[+0.10, +0.57]$	$[+0.00, +0.06]$	$[-0.17, +1.04]$	$[-0.28, +0.36]$
2 σ	$[-0.03, +0.07]$	$[-1.54, -0.63]$	$[-0.08, +0.84]$	$[-0.02, +0.08]$	$[-0.59, +1.58]$	$[-0.54, +0.68]$

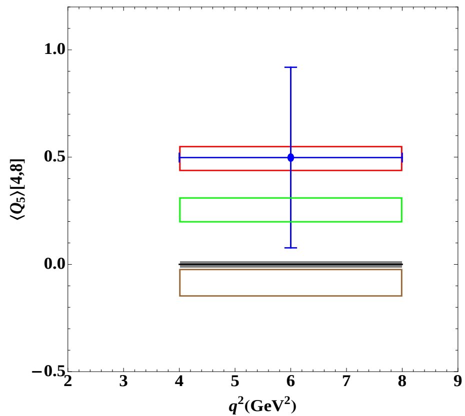
The SM pull moved from 3.6 $\sigma \to$ 5.0 σ (fit "All' with the latest CMS data at 8 TeV included)

Is there New Physics in electronic or muonic sector?

1 The independent analysis of $b \to s e^+ e^-$ and $b \to s \mu^+ \mu^-$ shows:

2017 with R_K^*





$$Q_5 = P_5^{\prime\mu} - P_5^{\prime e}$$

- Mainly in $\mu^\pm$ sector and marginally in $e^\pm$ sector [DHMV, AS, ...].
- Mainly in $e^\pm$ sector and marginally in $\mu^\pm$ sector [Ciuchini et al.]

Hyp: no RHC.

- $C_{9\mu} \sim -\mathcal{O}(1)$ with higher significance
- $C_{9e} \simeq 0$ compatible with SM albeit with large error bars.

1 NP solution of LFUV: only $C_{9\mu} = -1.76$ and $C_{ie} = 0$. $Q_5 \sim 0.49$

2 NP solution of all-fit: only $C_{9\mu} = -1.1$ and $C_{ie} = 0$. $Q_5 \sim 0.26$

3 NP solution of [Ciuchini et al.]: $C_{10\mu} = -0.12$, $C_{10e} = -1.22$. $Q_5 \sim -0.1$

$Q_5 > 0 \Rightarrow$ NP mainly in $\mu^\pm$ and marginally in $e^\pm$
$\hookrightarrow$+ moderate hadronic pollution

$Q_5 < 0 \Rightarrow$ NP mainly in $e^\pm$ and marginally in $\mu^\pm$
$\hookrightarrow$+ huge hadronic pollution

Are we overlooking something?

... a different perspective

[M. Algueró, B. Capdevila, S. Descotes-Genon, P. Masjuan, J.M, arXiv:1809.08447]

Let's remove assumptions and let's look beyond unfruitful discussions

Present situation: (standard assumption in the literature)

$\rightarrow$ All what we are observing is LFUV NP affecting LFUV observables and $b \rightarrow s\mu\mu$ ones.

$$C_{9\mu}^{\rm NP} = C_{9\mu}^{\rm V} \quad C_{10\mu}^{\rm NP} = C_{10\mu}^{\rm V}$$

and contributions to electrons are zero or small.

Even if non-small they are just another LFUV fit parameter constrained or not w.r.t. other leptons.

Our proposal: Instead let's be more precise on what New Physics means and take

$$\mathcal{C}_{i\ell}^{\rm NP} = \mathcal{C}_{i\ell}^{V} + \mathcal{C}_{i}^{U}$$

which means

$$\mathcal{C}_{9\mu}^{\rm NP} = \mathcal{C}_{9\mu}^{\rm V} + \mathcal{C}_{9}^{\rm U} \quad \mathcal{C}_{10\mu}^{\rm NP} = \mathcal{C}_{10\mu}^{\rm V} + \mathcal{C}_{10}^{\rm U}$$

which imposes a Universal contribution to electrons, muons and taus, different from the LFUV one.

1 A new mechanism to fulfill $\mathcal{B}(B_s \rightarrow \mu^+\mu^-) \propto |\mathcal{C}_{10}^{\rm V} + \mathcal{C}_{10}^{\rm U}|^2$ allowing for a large $\mathcal{C}_{10}^{\rm V} > 0$ and large $\mathcal{C}_{10}^{\rm U} < 0$

Implications

1 LFUV-observables explained by $\mathcal{C}_{i\mu}^{\rm V}$ (and very subleading contribution from LFU $\mathcal{C}_i^U$).

2 LFD-observables like P_5' explained by $\mathcal{C}_{i\mu}^{\rm V} + \mathcal{C}_i^{\rm U}$.

Our implicit assumption:

$\rightarrow$ hadronic uncertainties are well under control, i.e., we assume $\mathcal{C}_9^{\rm U}$ is of NP origin.

We will explore it by decreasing the order of complexity from:

4D: $(\mathcal{C}_{9\mu}^{\rm V}, \mathcal{C}_{10\mu}^{\rm V}, \mathcal{C}_{9e}^{\rm U} = \mathcal{C}_{9\mu}^{\rm U} = \mathcal{C}_{9\tau}^{\rm U}, \mathcal{C}_{10e}^{\rm U} = \mathcal{C}_{10\mu}^{\rm U} = \mathcal{C}_{10\tau}^{\rm U})$

	Best-fit point	1 σ CI	2 σ CI
$\mathcal{C}_{9\mu}^{\rm V}$	0.08	$[-0.72, 0.80]$	$[-1.69, 1.49]$
$\mathcal{C}_{10\mu}^{\rm V}$	1.14	$[0.66, 1.59]$	$[0.12, 2.03]$
$\mathcal{C}_9^{\rm U}$	-1.26	$[-1.92, -0.25]$	$[-2.43, 1.62]$
$\mathcal{C}_{10}^{\rm U}$	-0.91	$[-1.40, -0.40]$	$[-1.89, 0.16]$

SM excluded at 5.6 σ

3D: $(\mathcal{C}_{9\mu}^{\rm V} = -\mathcal{C}_{10\mu}^{\rm V}, \mathcal{C}_{9e}^{\rm U} = \mathcal{C}_{9\mu}^{\rm U} = \mathcal{C}_{9\tau}^{\rm U}, \mathcal{C}_{10e}^{\rm U} = \mathcal{C}_{10\mu}^{\rm U} = \mathcal{C}_{10\tau}^{\rm U})$

	Best-fit point	1 σ CI	2 σ CI
$\mathcal{C}_{9\mu}^{\rm V} = -\mathcal{C}_{10\mu}^{\rm V}$	-0.68	$[-0.96, -0.45]$	$[-1.28, -0.26]$
$\mathcal{C}_9^{\rm U}$	-0.37	$[-0.68, -0.03]$	$[-0.95, 0.35]$
$\mathcal{C}_{10}^{\rm U}$	-0.51	$[-0.86, -0.18]$	$[-1.24, 0.13]$

SM excluded at 5.7 σ

The unexpected and surprising result is the outcome of the fit:

$\mathcal{C}_9^{\rm U} \simeq \mathcal{C}_{10}^{\rm U}$ $\Leftarrow$ $\mathcal{C}_{10}^{\rm NP}$ can only be NP reinforcing the original assumption that $\mathcal{C}_9^{\rm U}$ is possibly also NP.

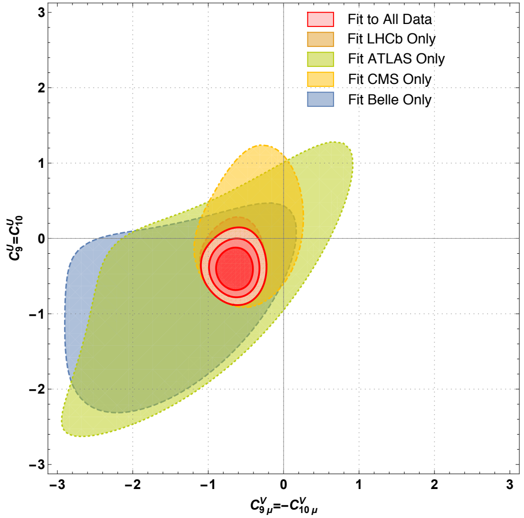
$\underline{\mathcal{C}^{\rm V}_{9\mu}, \mathcal{C}^{\rm V}_{10\mu}, \mathcal{C}^{\rm U}_{9} = \mathcal{C}^{\rm U}_{10}}$

	Best-fit point	1 σ CI	2 σ CI
$\mathcal{C}^{\rm NP}_{9\mu}$	-0.16	$[-0.94, 0.46]$	$[-2.05, 0.98]$
$\mathcal{C}^{\rm NP}_{10\mu}$	1.00	$[0.18, 1.59]$	$[-1.35, 2.06]$
$\mathcal{C}^{\rm NP}_{9U} = \mathcal{C}^{\rm NP}_{10U}$	-0.87	$[-1.43, -0.14]$	$[-1.91, 0.98]$

- SM excluded at 5.8 σ

$\underline{\mathcal{C}^{\rm V}_{9\mu} = -\mathcal{C}^{\rm V}_{10\mu}, \mathcal{C}^{\rm U}_{9} = \mathcal{C}^{\rm U}_{10}}$

	Best-fit point	1 σ CI	2 σ CI
$\mathcal{C}^{\rm V}_{9\mu} = -\mathcal{C}^{\rm V}_{10\mu}$	-0.64	$[-0.77, -0.51]$	$[-0.90, -0.39]$
$\mathcal{C}^{\rm U}_{9} = \mathcal{C}^{\rm U}_{10}$	-0.44	$[-0.58, -0.29]$	$[-0.71, -0.14]$



- SM excluded at **6.0** σ
- The two contributions are **uncorrelated**.
- **LFUV prefers a V-A structure and LFU prefers a V+A.**

Tension between b.f.p. $\mathcal{C}_9$ all-fit and LFUV

We found

	All				
1D Hyp.	Best fit	1 σ	2 σ	Pull_{SM}	p-value
$\mathcal{C}_{9\mu}^{\text{NP}}$	**-1.11**	$[-1.28, -0.94]$	$[-1.45, -0.75]$	**5.8**	68

	LFUV				
1D Hyp.	Best fit	1 σ	2 σ	Pull_{SM}	p-value
$\mathcal{C}_{9\mu}^{\text{NP}}$	**-1.76**	$[-2.36, -1.23]$	$[-3.04, -0.76]$	**3.9**	69

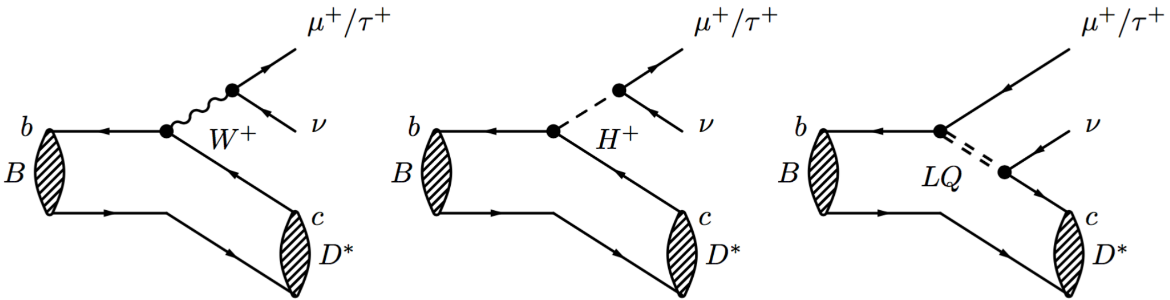
If LFUV and LFU NP are both allowed one finds:

	Best-fit point	1 σ CI	2 σ CI
$\mathcal{C}_{9\mu}^{\text{V}}$	-1.57	$[-2.14, -1.06]$	$[-2.75, -0.58]$
$\mathcal{C}_{9}^{\text{U}}$	0.56	$[0.01, 1.15]$	$[-0.51, 1.78]$

Table: 2D hyp. Top: Scenario 7: LFUV and LFU NP in $\mathcal{C}_9^{\text{NP}}$ only.

1. LFD observables are governed by $\mathcal{C}_{9\mu}^{\text{V}} + \mathcal{C}_9^{\text{U}} \simeq -1.57 + 0.56 = \mathbf{-1.01}$
2. LFUV observables driven by $\mathcal{C}_{9\mu}^{\text{V}} = \mathbf{-1.57}$ (subleading $\mathcal{C}_9^{\text{U}}$ responsible for difference).

Also LFUV anomalies in $b \to c\tau\nu$



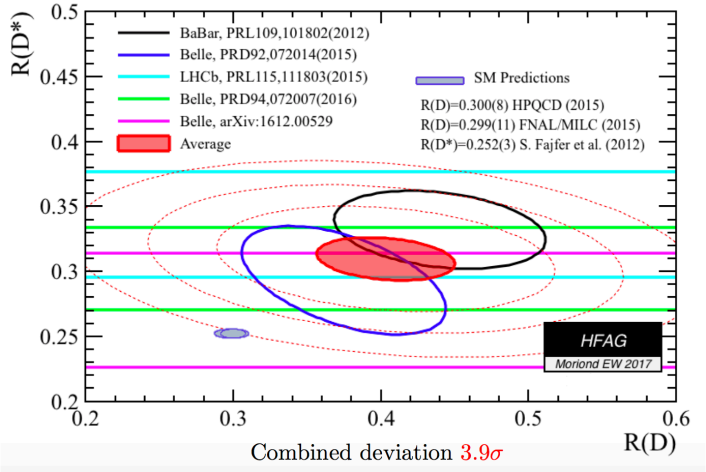
SM NP

Semi-tauonic B decays are charged current processes that can probe also New Physics.
Experimentally (in analogy to R_{K,K^*}) a LFUV ratio:

$$R_{D^{(*)}} = \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)}\ell^- \bar{\nu}_\ell)}$$

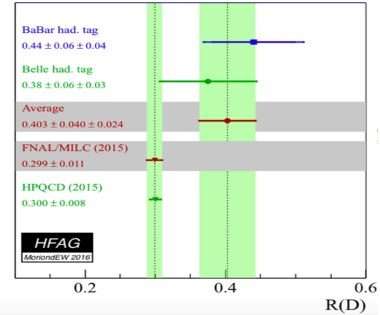
The ratio:

- differs in lepton mass: τ versus $\ell = \mu, e$ mass.
- cancels: form factors, V_{cb}, experimental systematics

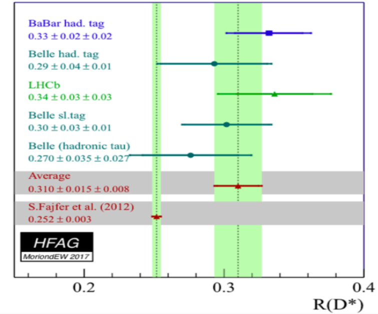


• Excess that becomes significant 3.9σ after combining experiments: Babar and Belle ($\ell = \mu, e$), LHCb ($\ell = \mu$).

• Intriguing since this is a tree level process contrary to $b \to s\ell\ell$ related ones.



- (HFAG) $R_D^{exp} = 0.403 \pm 0.040 \pm 0.024$
- Lattice computation of $B \to D$ FF: F^+, F^0 (precise).
- (FLAG 2016): 0.300 ± 0.008
- Latest SM prediction: combined fit HQET (incl. $\mathcal{O}(\Lambda/m_{c,b}, \alpha_s)$)+ measured $B \to D\ell\nu$ distributions together with LQCD and QCDSR inputs: $R_D^{SM} = 0.299 \pm 0.003$ ([Bernlochner et al.'17]) ($\mathbf{2.2}\sigma$)

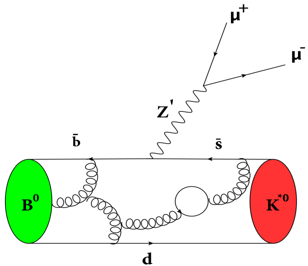


- (HFAG) $R_{D^*}^{exp} = 0.310 \pm 0.015 \pm 0.008$
- Lattice computation of $B \to D$ FF: V, $A_{0,1,2}$, $T_{1,2,3}$. (no non-zero recoil LQCD)
- Latest SM prediction: combined fit HQET (incl. $\mathcal{O}(\Lambda/m_{c,b}, \alpha_s)$)+ measured $B \to D^*\ell\nu$ distributions together with LQCD and QCDSR inputs: $R_{D^*}^{SM} = 0.257 \pm 0.003$ ([Bernlochner et al.'17]) ($\mathbf{3.1}\sigma$)

• EFT analyses of $R_{D(*)}$: • not too large contrib. to B_c lifetime+ q^2 $R_{D(*)}$ distributions favours NP contribution to SM operator: $[\bar{\mathbf{c}}\gamma^\mu \mathbf{P_L b}][\bar{\tau}\gamma_\mu \mathbf{P_L}\nu_\tau]$

Colourless vector $SU(2)_L$ triplets (W', B') or $U(1)'$ singlet

$$G \equiv SU(3)_c \times SU(2)_L \times U(1)_Y \times G_E$$

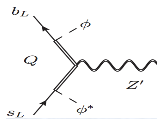


$G_E \equiv SU(2)_L$ could pot. explain anomalies ($R_K > 0.9$ & conflict with LHC searches)

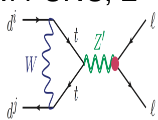
- $\bar{b}sZ'$ Quark FVC
- $Z'\ell\ell$ LFUV coupling

Generating Quark FV Coupling:

- Vector-like quarks: SM-VL couplings

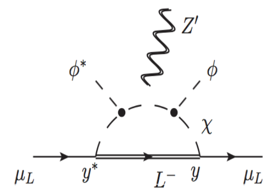


- Loop induced: SM FCNC, Z' penguins



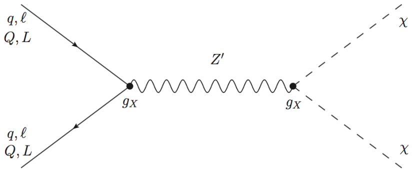
Generating Couplings to Leptons:

- Gauged $U(1)_{\mu-\tau}$ symmetry
- Loop induced with vector-like fermions



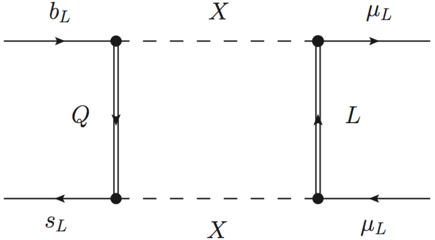
Link of $b \to s$ anomalies to dark matter:

- **Portal models:** Mediator for $b \to s\ell\ell$ anomalies also mediates dark matter production:

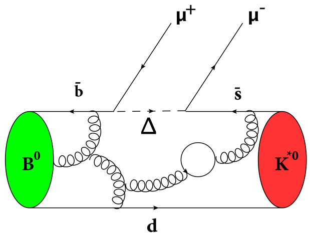


$\Rightarrow$ χ dark matter particle: scalar field.
$\Rightarrow$ $Q_{L,R}$ and $L_{L,R}$ vector-like fermions.
$\Rightarrow$ Left coupling same of $b \to s\ell\ell$ anomaly.

- **Loop models:** Models that induces the $b \to s$ transition via loops including the DM candidate. Two VL fermions Q and L and a complex scalar χ ($U(1)$ conserved $\Rightarrow$ χ stable)



Leptoquarks



- Spin 1 (vector) $SU(2)_L$ singlet or triplet leptoquarks
- Spin 0 (scalar) $SU(2)_L$ singlet or triplet leptoquarks

They mainly point in all versions to $C_9 = -C_{10}$ (left-handed structure like in the SM)

Important constraints:

- $b \to s\nu\bar{\nu}$ (two scalars LQ can do the job)
- direct bounds (from 0.5-1 TeV)

Colour triplet

Scalar LQ:

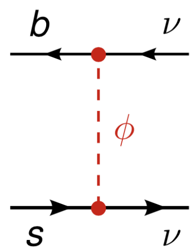
$S_1 \sim (\bar{3}, 1, 1/3)$

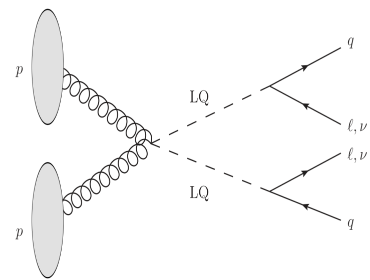
$S_3 \sim (\bar{3}, 3, 1/3)$

Vector LQ:

$\mathcal{U}_1^\mu \sim (3, 1, 2/3)$

$\mathcal{U}_3^\mu \sim (3, 3, 2/3)$





Flavour observables are sensitive to higher scales than direct searches at colliders

... if NP affects flavour it is not surprising that we detect it first.

What is the scale of NP for $b \to s\ell\ell$? Reescaling the Hamiltonian by $H_{eff}^{\rm NP} = \sum \frac{\mathcal{O}_i}{\Lambda_i^2}$

- Tree-level induced (semi-leptonic) with $\mathcal{O}(1)$ couplings ($\times\sqrt{g_{bs}\, g_{\mu\mu}}$):

$$\Lambda_i^{\rm Tree} = \frac{4\pi v}{s_w g} \frac{1}{\sqrt{2|V_{tb}V_{ts}^*|}} \frac{1}{|C_i^{\rm NP}|^{1/2}} \sim \frac{\mathbf{35}{\rm TeV}}{|C_i^{\rm NP}|^{1/2}}$$

- Loop level-induced (semi-leptonic) with $\mathcal{O}(1)$ couplings:

$$\Lambda_i^{\rm Loop} \sim \frac{35{\rm TeV}}{4\pi|C_i^{\rm NP}|^{1/2}} = \frac{\mathbf{2.8}{\rm TeV}}{|C_i^{\rm NP}|^{1/2}}$$

- MFV with CKM-SM, suppression $\sqrt{|V_{tb}V_{ts}^*|} \sim 1/5$: Tree level: $\frac{\mathbf{7\ TeV}}{|C_i^{\rm NP}|^{1/2}}$ and Loop: $\frac{\mathbf{0.6\ TeV}}{|C_i^{\rm NP}|^{1/2}}$

Solution $C_9^{\rm NP} \sim -1.1$ (scale is $\sim$ numerator) or $C_9^{\rm NP} = -C_{10}^{\rm NP} \sim -0.6$ (30 % higher scale).

Similar exercise for $b \to c\tau\nu$ taking a 15% enhancement over SM:

$$\Lambda^{\rm NP} \sim 1/(\sqrt{2}G_F|V_{cb}|0.15)^{1/2} \sim \mathbf{3.2}{\rm TeV}$$

- $\Lambda > v$.
- Dimension six 4-fermion interactions of 4 classes depending on chirality:

$$(\bar{L}L)(\bar{L}L),\ (\bar{R}R)(\bar{R}R),\ (\bar{R}R)(\bar{L}L),\ (\bar{L}L)(\bar{R}R)$$

$$\begin{aligned}
&\mathcal{L}^{\rm SMEFT} \supset \\
&\frac{c^{(3)}_{Q_{ij}L_{kl}}}{\Lambda^2}(\bar{Q}_i\gamma_\mu\sigma^a Q_j)(\bar{L}_k\gamma^\mu\sigma_a L_l) + \frac{c^{(1)}_{Q_{ij}L_{kl}}}{\Lambda^2}(\bar{Q}_i\gamma_\mu Q_j)(\bar{L}_k\gamma^\mu L_l) + \\
&\frac{c_{u_{ij}e_{kl}}}{\Lambda^2}(\bar{u}_i\gamma_\mu u_j)(\bar{e}_k\gamma^\mu e_l) + \frac{c_{d_{ij}L_{kl}}}{\Lambda^2}(\bar{d}_i\gamma_\mu d_j)(\bar{e}_k\gamma^\mu e_l) + \\
&\frac{c_{u_{ij}L_{kl}}}{\Lambda^2}(\bar{u}_i\gamma_\mu u_j)(\bar{L}_k\gamma^\mu L_l) + \frac{c_{d_{ij}L_{kl}}}{\Lambda^2}(\bar{d}_i\gamma_\mu d_j)(\bar{L}_k\gamma^\mu L_l) + \\
&\frac{c_{Q_{ij}e_{kl}}}{\Lambda^2}(\bar{Q}_i\gamma_\mu Q_j)(\bar{e}_k\gamma^\mu e_l)
\end{aligned}$$

$\rightarrow Q_i = (V^*_{ji}u^j_L, d^i_L)^T$ and $L_i = (\nu^i_L, \ell^i_L)^T$ are the SM left-handed quark and lepton weak doublets

$\rightarrow d_i,\ u_i,\ e_i$ are the right-handed singlets.

Can we connect the $b \to c\tau\nu$ anomalies with future $b \to s\tau^+\tau^-$ anomalies?

NP contribution to SM operator $[\bar{\mathbf{c}}\gamma^\mu \mathbf{P_L b}][\bar{\tau}\gamma_\mu \mathbf{P_L}\nu_\tau]$ leads to (in agreement with current measurements):

$$R_{J/\psi}/R_{J/\psi}^{\rm SM} = R_D/R_D^{\rm SM} = R_{D^*}/R_{D^*}^{\rm SM}$$

Hypothesis: If NP at high scale, two SM-based $SU(2)_L$ invariant operators at dimension 6.

Constraints: EW precision data+direct searches
$+B \to K^{(*)}\nu\bar{\nu}$

$\Rightarrow b \to c\tau^-\nu_\tau$ and $b \to s\tau^+\tau^-$ generated together.

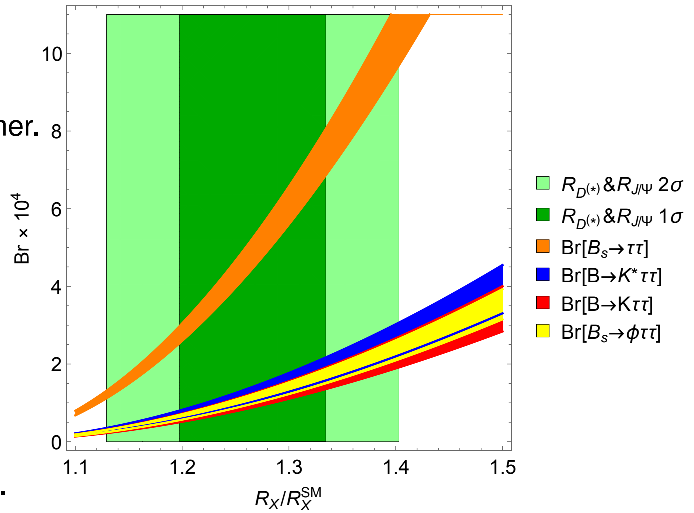
$$C_{9(10)\tau} \simeq C_{9,10}^{SM} - (+)\Delta$$

$$\Delta = 2\frac{\pi}{\alpha_{em}}\frac{V_{cb}}{V_{tb}V_{ts}^*}\left(\sqrt{\frac{R_X}{R_X^{SM}}} - 1\right) \simeq \mathcal{O}(100)$$

Consequently

$$\mathcal{B}^{\rm SM}_{B_s\to\tau^+\tau^-} \sim 10^{-7} \to \mathcal{B}_{B_s\to\tau^+\tau^-} \sim 10^{-4}$$

also $\mathcal{B}_{B\to K\tau^+\tau^-}$, $\mathcal{B}_{B\to K^*\tau^+\tau^-}$, $\mathcal{B}_{B_s\to\phi\tau^+\tau^-}$ all $\propto \Delta^2$.



Assume: Relevant dynamics outside LHC reach for on-shell production

$\Rightarrow$ EFT approach with 4-fermion opts. applicable to entire LHC range: p^2/Λ^2 deviations.

... complementary information on 4-fermion operators to flavour anomalies.

Observable: NP contributions to dilepton production via Drell-Yan in $pp \to \ell^+\ell^-$

$$R_{\mu^+\mu^-/e^+e^-} = \frac{d\sigma_{\mu\mu}}{dm_{\ell\ell}} / \frac{d\sigma_{ee}}{dm_{\ell\ell}}$$

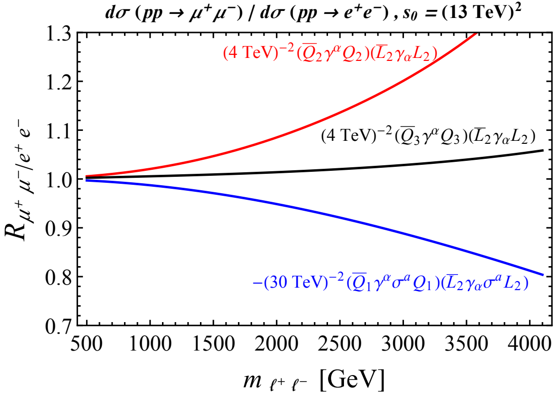
Constraints on: dimension 6 gauge-invariant coefficients c_X of opts (SMEFT)

$$\mathcal{A}(q^i_{p_1}\bar{q}^j_{p_2} \to \ell^-_{p'_1}\ell^+_{p'_2}) = i \sum_{q_L,q_R} \sum_{\ell_L,\ell_R} (\bar{q}^i\gamma^\mu q^j)(\bar{\ell}\gamma_\mu\ell)\, F_{q\ell}(p^2)\,,$$

where form factors can be expressed

$$F_{q\ell}(p^2) = \delta^{ij}\frac{e^2 Q_q Q_\ell}{p^2} + \delta^{ij}\frac{g_Z^q g_Z^\ell}{p^2 - m_Z^2 + i m_Z \Gamma_Z} + \frac{\epsilon^{q\ell}_{ij}}{v^2}$$

$\epsilon^{q\ell}_{ij} \leftrightarrow c_X$



if one assume that Nature is realized with our result: $\Delta C_9^\mu = -\Delta C_{10}^\mu = \mathbf{-0.62}$

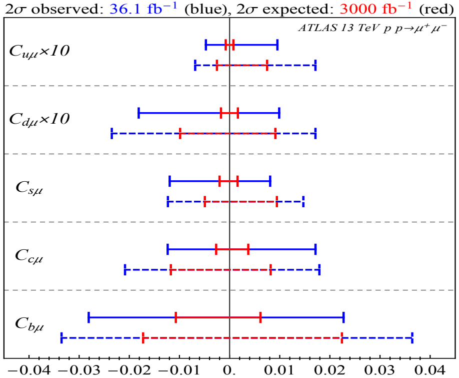
$\Downarrow$

Only $(\bar{L}L)(\bar{L}L)$ are considered:

$$\mathcal{L}^{\rm eff} \supset \frac{\mathbf{C}_{ij}^{U\mu}}{v^2}(\bar{u}_L^i\gamma_\mu u_L^j)(\bar{\mu}_L\gamma^\mu\mu_L) + \frac{\mathbf{C}_{ij}^{D\mu}}{v^2}(\bar{d}_L^i\gamma_\mu d_L^j)(\bar{\mu}_L\gamma^\mu\mu_L)\ ,$$

Flavour structure:

$$\mathbf{C}_{ij}^{U\mu} = \begin{pmatrix} C_{u\mu} & 0 & 0 \\ 0 & C_{c\mu} & 0 \\ 0 & 0 & C_{t\mu} \end{pmatrix}, \quad \mathbf{C}_{ij}^{D\mu} = \begin{pmatrix} C_{d\mu} & 0 & 0 \\ 0 & C_{s\mu} & C_{bs\mu}^* \\ 0 & C_{bs\mu} & C_{b\mu} \end{pmatrix}.$$



NP only in $C_{bs\mu}$ will **not be probed** at LHC:

$$\left|\Delta C_9^\mu = -\Delta C_{10}^\mu = \frac{\pi}{\alpha V_{tb}V_{ts}^*}C_{bs\mu}\right| < \mathbf{100\ (39)}\ ,$$

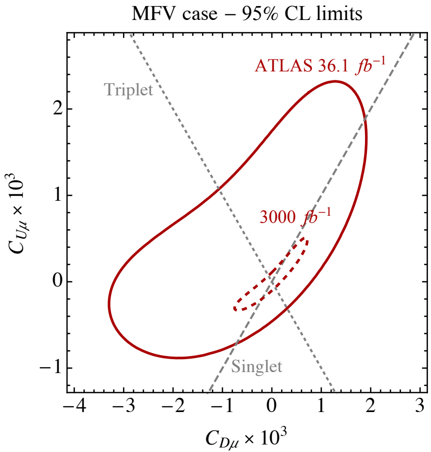
95% CL from 13 TeV ATLAS ($pp \to \mu^+\mu^-$) with 36 fb^{-1} (3000 fb^{-1}).

In flavour models usually:

flavour-violating couplings ($C_{bs\mu}$) $\leftrightarrow$ symmetry/dynamics $\leftrightarrow$ flavour-diagonal ones ($C_{i\mu}$)

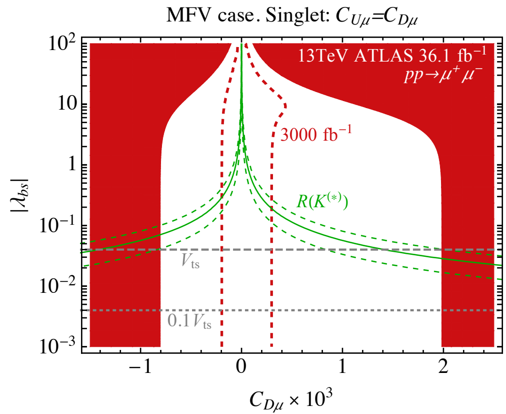
MFV case:

$$C_{u\mu} = C_{c\mu} = C_{t\mu} \equiv C_{U\mu} \; ,$$
$$C_{d\mu} = C_{s\mu} = C_{b\mu} \equiv C_{D\mu} \; ,$$



From $\lambda^q_{bs} \equiv C_{bs\mu}/C_{q\mu}$ [upper limit $C_{q\mu} \to$ lower bound λ^q_{bs}]

Assuming a singlet (or triplet) structure: 95% CL limit from $pp \to \mu^+\mu^-$



• Requiring $C_{bs\mu}$ to fit B decay anomalies disfavours MFV scenario ($\lambda_{bs} = V_{ts}$).

FVC is expected $|C_{bs\mu}| \sim |V_{tb} V^*_{ts} y_t^2 C_{D\mu}|$.
From $\Delta C_9^\mu = -\Delta C_{10}^\mu \to C_{bs\mu} \Rightarrow |C_{D\mu}| \sim 1.4 \times 10^{-3}$ already probed by ATLAS dimuon search!!!

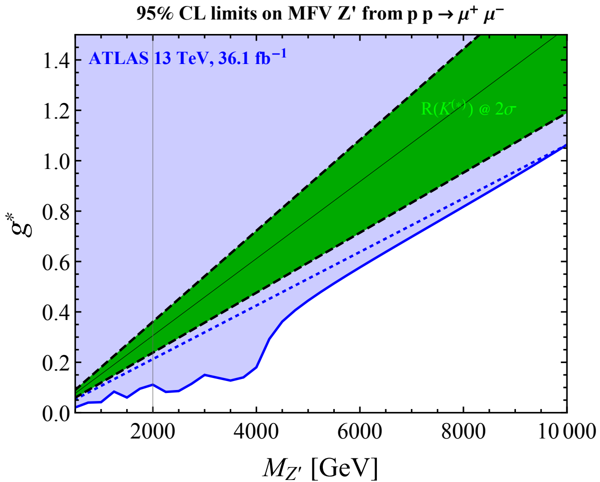
$$\mathcal{L} \supset Z'_\mu J_\mu$$

$$J_\mu = g_Q^{(1),ij} (\bar{Q}_i \gamma_\mu Q_j) + g_L^{(1),kl} (\bar{L}_k \gamma^\mu L_l) \ ,$$

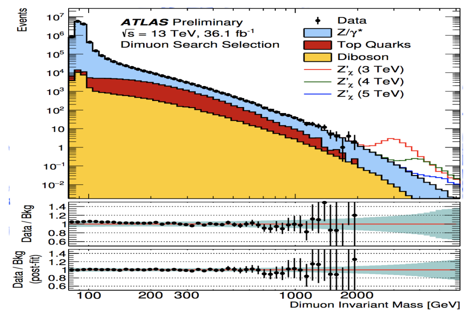
Assume singlet Z' with $g_Q^{(1),ii} = g_L^{(1),22} = g_*$ and MFV in quark sector $g_Q^{(1),23} = V_{ts} g_*$

$\Uparrow$ $\Uparrow$

required to explain flavour anomalies



$\Leftarrow$



green lines 2σ interval which reproduce the $b \to s\mu\mu$ flavour anomalies, showing how LHC dimuon searches already exclude such a scenario independently of the Z' mass.

Conclusions

- For the first time, we observe in particle physics a large set of **coherent deviations** in observables:

  $\boxed{1}$ in $b \to s\mu^+\mu^-$: P_5', $\mathcal{B}_{B^+\to K^{*+}\mu^+\mu^-}$, $\mathcal{B}_{B_s\to\phi\mu^+\mu^-}$ (low and large-recoil).

  $\boxed{2}$ in LFUV observables: R_K,R_{K^*}, $Q_{4,5}$

  pointing **in a global fit** to different patterns/scenarios of NP:

  • $\mathcal{C}_{9\mu} = -1.1$, $\mathcal{C}_{9e} = 0$ with **pull-SM 5.8σ** • $\mathcal{C}_{9\mu} = -\mathcal{C}_{10\mu} = -0.62$, $\mathcal{C}_{9e} = 0$ with pull-SM 5.3σ

- The fit using **only LFUV observables** finds Violations of LFU at the 3-4σ level.

- A scenario of NP allowing both LFU and LFUV NP opens new directions. While LFUV can accommodate a V-A structure, LFU prefers a V+A with a pull-SM 6σ.

- Under general assumptions in agreement with data we show that a very large enhancement w.r.t. SM of $b \to s\tau^+\tau^-$ processes (3 orders of magnitude) is expected if $R_D^{(*)}$ anomaly persists.

- High-p$_T$ measurements (in particular high-p$_T$ dilepton tails) can provide complementary information to the low-p$_T$ rare meson decays.

Back-up slides

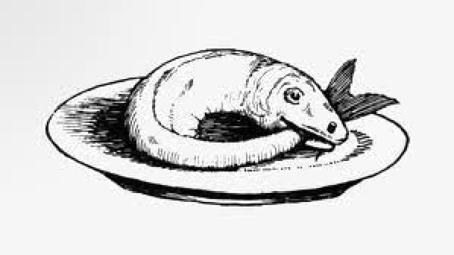
There has been a bit of (naive) discussion on:

$$C_{9i}^{\rm eff}(q^2) = \mathbf{C_{9\,SMpert}} + C_9^{\rm NP} + \mathbf{s_i \delta C_{9i}^{c\bar{c}LD}(q^2)} + C_9^{\rm unknown}(q^2).$$

The first three terms correspond to physically well defined contributions (from SM or NP model).

[Ciuchini, Paul, Silvestrini et al.] try to argue that $C_9^{\rm NP}$ $\nexists$ an instead $\exists$ a q^2 unknown contribution (no computation).

The naive question was (at the time of only R_K): Are the anomalies due to $C_9^{\rm NP}$ or $C_9^{\rm unknown}(q^2)$?



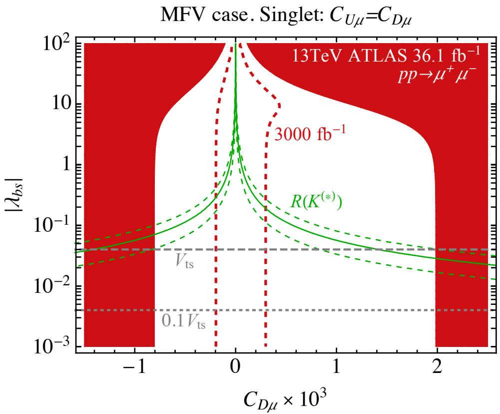
[Hadronic uncertainties] We showed using the fit that:

- LFUV observables cannot be explained by $C_9^{\rm unknown}$
- $C_9^{\rm unknown}(q^2)$ if exists is not q^2 dependent.
- analiticity properties or resonaces found no need for this $C_9^{\rm unknown}$

In flavour models usually:

flavour-violating couplings ($C_{bs\mu}$) $\leftrightarrow$ symmetry/dynamics $\leftrightarrow$ flavour-diagonal ones ($C_{i\mu}$)

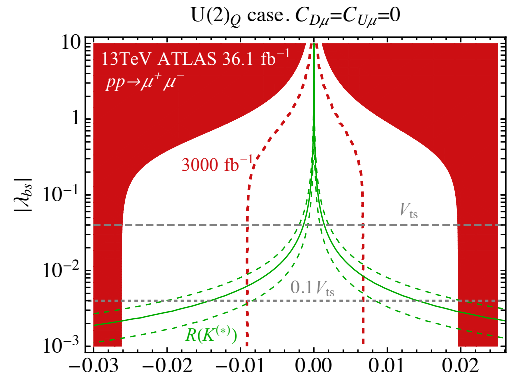
Two motivated flavour structures: $\lambda^q_{bs} \equiv C_{bs\mu}/C_{q\mu}$



$$C_{u\mu} = C_{c\mu} = C_{t\mu} \equiv C_{U\mu} \ ,$$
$$C_{d\mu} = C_{s\mu} = C_{b\mu} \equiv C_{D\mu} \ ,$$

FVC is expected $|C_{bs\mu}| \sim |V_{tb} V^*_{ts} y_t^2 C_{D\mu}|$.

• Requiring $C_{bs\mu}$ to fit B decay anomalies disfavours MFV scenario ($\lambda_{bs} = V_{ts}$).



$$C_{u\mu} = C_{c\mu} \equiv C_{U\mu} \ , \quad C_{d\mu} = C_{s\mu} \equiv C_{D\mu} \ ,$$
$$C_{b\mu}, \quad C_{bs\mu} \equiv \lambda_{bs} C_{b\mu} \ ,$$

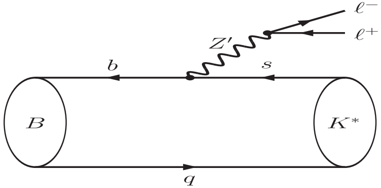
FVC expected $|\lambda_{bs}| \sim |V_{ts}|$.

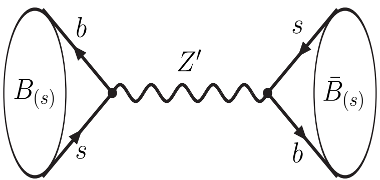
• A much lower bound is found than the natural value, important for certain U(2) flavour models requiring $\lambda_{bs} < |V_{ts}|$

In [DMV'13] we proposed to explain the anomaly in $B \to K^* \mu\mu$ with a Z' **gauge boson** contributing to

$$\mathcal{O}_9 = e^2/(16\pi^2)\,(\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)\,,$$

with specific couplings as a possible explanation of the anomaly in P_5'.





$$\mathcal{L}^q = \left(\bar{s}\gamma_\nu P_L b \Delta_L^{sb} + \bar{s}\gamma_\nu P_R b \Delta_R^{sb} + h.c.\right) Z'^\nu \quad \mathcal{L}^{lep} = \left(\bar{\mu}\gamma_\nu P_L \mu \Delta_{\mathbf{L}}{}^{\mu\bar{\mu}} + \bar{\mu}\gamma_\nu P_R \mu \Delta_{\mathbf{R}}{}^{\mu\bar{\mu}} + ...\right) Z'^\nu$$

The Wilson coefficients of the semileptonic operators are:

$$\mathcal{C}^{\rm NP}_{\{9,10\}} = -\frac{1}{s_W^2 g_{SM}^2}\frac{1}{M_{Z'}^2}\frac{\Delta_L^{sb}\Delta^{\mu\mu}_{\{\mathbf{V},\mathbf{A}\}}}{\lambda_{ts}}\,, \quad \mathcal{C}^{\rm NP}_{\{9',10'\}} = -\frac{1}{s_W^2 g_{SM}^2}\frac{1}{M_{Z'}^2}\frac{\Delta_R^{sb}\Delta^{\mu\mu}_{\{\mathbf{V},\mathbf{A}\}}}{\lambda_{ts}}\,,$$

with the vector and axial couplings to muons: $\Delta^{\mu\mu}_{\mathbf{V},\mathbf{A}} = \Delta^{\mu\mu}_{\mathbf{R}} \pm \Delta^{\mu\mu}_{\mathbf{L}}$.

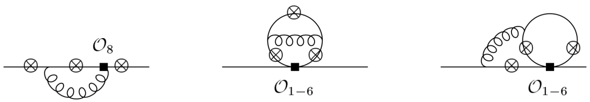
Δ_L^{sb} with same phase as $\lambda_{ts} = V_{tb}V_{ts}^*$ (to avoid ϕ_s) like in MFV. Main constraint from ΔM_{B_s} ($\Delta_{L,R}^{sb}$).

A closer look to the theory behind $B \to K^* \mu^+ \mu^-$ in a nutshell: Factorizable & Non-factorizable contributions

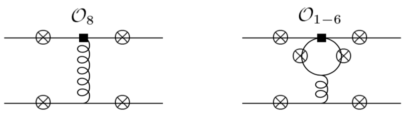
Theoretical framework: QCDF/SCET+**robust large-recoil symmetries** +breaking (pert+non-pert)
$\hookrightarrow$ independent of LCSR details

$$\mathcal{T}_a = \xi_{\mathbf{a}} \left(C_a^{(0)} + \frac{\alpha_s C_F}{4\pi} C_a^{(1)} \right) + \frac{\pi^2}{N_c} \frac{f_B f_{K^*,a}}{M_B} \Sigma_a \sum_{\pm} \int \frac{d\omega}{\omega} \Phi_{B,\pm}(\omega) \int_0^1 du \Phi_{K^*,a}(u) T_{a,\pm}(u,\omega). \quad \mathbf{a} = \perp, \parallel$$

$\Downarrow$ $\Downarrow$



(c) (d) (e)



(a) (b)

- Diagrams involving the $b \to s$ transition only

Hard spectator scattering (T_a)

$$C_{9i}^{\rm eff}(q^2) = \mathbf{C_9}_{\,\rm SMpert} + C_9^{\rm NP} + \mathbf{s_i} \delta \mathbf{C_{9i}^{c\bar{c}LD}}(\mathbf{q^2}).$$

Perturbative: $\mathbf{C_9}_{\,\rm SMpert} = C_9^{\rm SM} + Y(q^2)$

with $Y(q^2)$ stemming from one-loop matrix elements of 4-quark operators O_{1-6}.

...$\mathcal{O}(\alpha_s)$ corrections to $C_{7,9}^{\rm eff}$ of $Y(q^2)$ included via $C_{\perp,\parallel}^{1\,(\rm nf)}$ but only $O_{1,2}$ (previous slide)

THE ONLY REAL COMPUTATION IN LITERATURE (Khodjamirian, Mannel, Pivovarov, Wang).

⇒ long-distance effect by current- current operators $O_{1,2}$ together with the c-quark e.m. current:

$$\mathcal{H}_\mu^{B\to K^*}(p,q) = i\int d^4x e^{iqx}\langle K^*(p)|T\left\{\bar{c}(x)\gamma_\mu c(x)[C_1O_1+C_2O_2]\right\}|B(p+q)\rangle$$

$$O_1 = (\bar{s}_L\gamma_\rho c_L)(\bar{c}_L\gamma^\rho b_L), \quad O_2 = (\bar{s}^j_L\gamma_\rho c^i_L)(\bar{c}^i_L\gamma^\rho b^j_L)$$

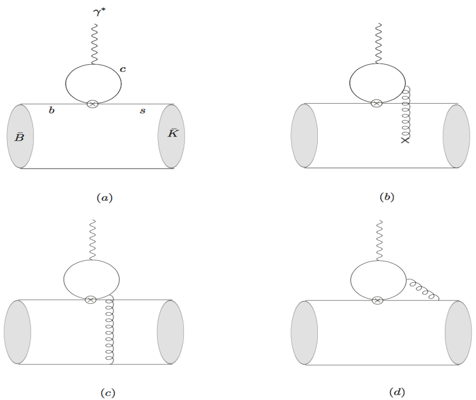
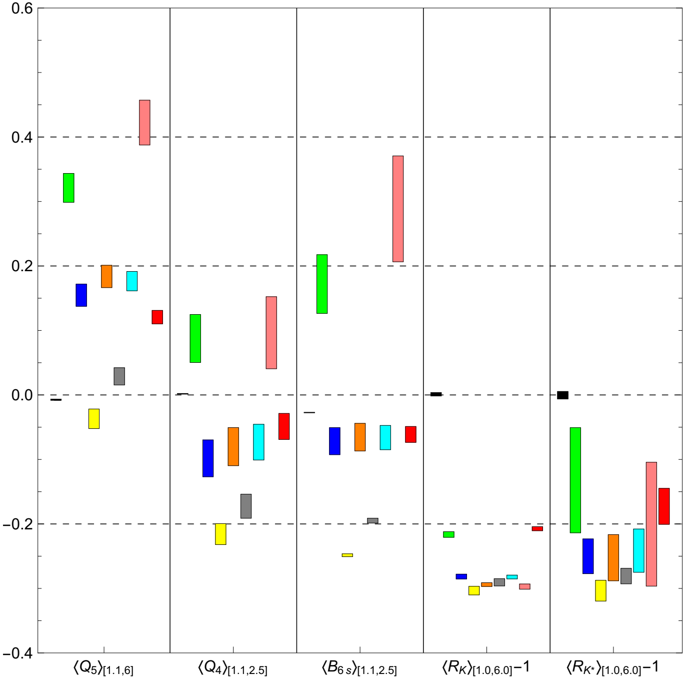


Figure 1: *Charm-loop effect in $B \to K^{(*)}\ell^+\ell^-$: (a)-the leading-order factorizable contribution; (b) nonfactorizale soft-gluon emission, (c),(d)-hard gluon exchange.*

⇐ emission of one soft gluon (with low virtuality but nonvanishing momentum) from the c-quark loop. **Only real part computed!**

- dispersion relation is used to extend it to all region.
- hadronic matrix elements uses LCSR with B-meson DA (we consistently use them for all obs except $B_s \to \phi$, not available).



$$Q_i = P_i^{\mu} - P_i^{e}.$$

- SM (black)
- Sc.1 (green): $\mathcal{C}_9^{\rm V}$
- Sc.2 (blue): $\mathcal{C}_9^{\rm V} = -\mathcal{C}_{10}^{\rm V}$
- Sc.3 (yellow): $\mathcal{C}_{9\mu}^{\rm V}, \mathcal{C}_{10\mu}^{\rm V}, \mathcal{C}_9^{\rm U}, \mathcal{C}_{10}^{\rm U}$
- Sc.4 (orange): $\mathcal{C}_{9\mu}^{\rm V} = -\mathcal{C}_{10\mu}^{\rm V}, , \mathcal{C}_9^{\rm U}, \mathcal{C}_{10}^{\rm U}$
- Sc.5 (brown): $\mathcal{C}_{9\mu}^{\rm V}, \mathcal{C}_{10\mu}^{\rm V}, \mathcal{C}_9^{\rm U} = \mathcal{C}_{10}^{\rm U}$
- Sc.6 (light blue): $\mathcal{C}_{9\mu}^{\rm V} = -\mathcal{C}_{10\mu}^{\rm V}, \mathcal{C}_9^{\rm U} = \mathcal{C}_{10}^{\rm U}$
- Sc.7: $\mathcal{C}_{9\mu}^{\rm V}, \mathcal{C}_9^{\rm U}$
- Sc.8 (red): $\mathcal{C}_{9\mu}^{\rm V} = -\mathcal{C}_{10\mu}^{\rm V}, \mathcal{C}_9^{\rm U}$