Lepton Universality Violation in B-Meson Decays

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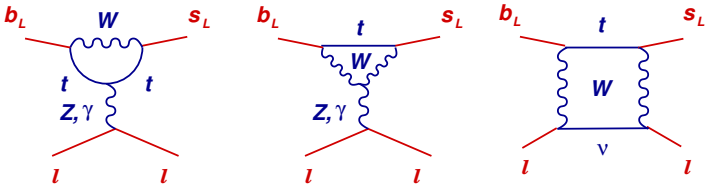
Outline

1. Executive Summary
2. Effective Field Theory Approach
3. The $b \to s\ell\ell$ anomalies
   - $B \to K\ell\ell$
   - $B \to K^*\ell\ell$
4. The shape of new physics
   - SMEFT and flavor
   - From Lepton flavor violation to MLFV **(time permitting)**
   - Applications to model-building
5. Conclusions

Why the Excitement on Anomalies in B decays?

Slide for non-specialist

The SM of EW intearctions predicts



$$\Rightarrow \qquad G_F\, V_{tb}\, V_{ts}^* \frac{\alpha}{4\pi}\, C_{9(10)}\, \bar{s}_L \gamma^\mu b_L\, \bar{\ell}\gamma_\mu(\gamma_5)\ell$$

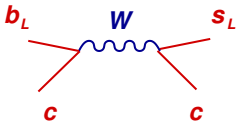
- This is same for all lepton flavors: lepton univesality (LU)
- LU violation (LUV) reported by LHCb in $b \to s\mu\mu$ vs $b \to see$
- LUV could arise from new physics (NP):
  - At very short distances, with SM below scale $\Lambda \gg M_W$
  - Short distances at SM scale, $\Lambda \sim M_W$ (*e.g.*, strongly coupled EW symmetry breaking)
  - Long distances: new light particles
- Worse case scenario: $\Lambda \gg M_W$: $NP = \frac{g^2}{\Lambda^2}\, \bar{s}_L \gamma^\mu b_L\, \bar{\ell}\gamma_\mu(\gamma_5)\ell$
- Fits of reported LUV require

$$\frac{g^2}{\Lambda^2} \approx 0.25 \times G_F\, V_{tb}\, V_{ts}^* \frac{\alpha}{4\pi}\, C_{9(10)} \quad \Rightarrow \quad \frac{\Lambda}{g} \approx 28 \text{ TeV}$$

- Best argument to build VLHC! (or find NP sooner!!)

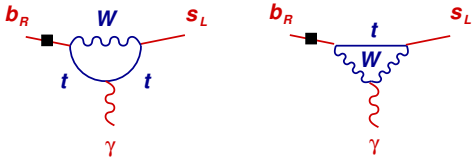
Effective field theory approach to $b \to s\ell\ell$ decays

- **CC** (Fermi theory):

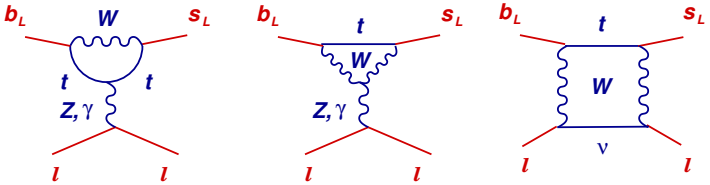


$$\Rightarrow \qquad G_F\, V_{cb}\, V_{cs}^*\, C_2\, \bar{c}_L \gamma^\mu b_L\, \bar{s}_L \gamma_\mu c_L$$

- **FCNC**:

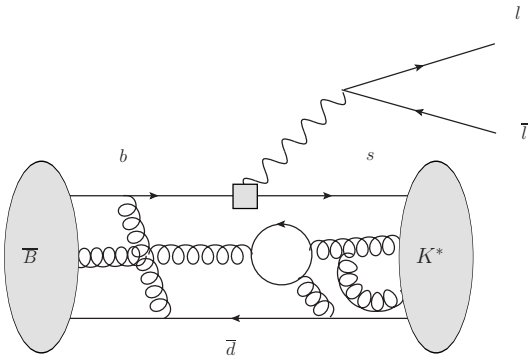


$$\Rightarrow \qquad \frac{e}{4\pi^2}\, G_F\, V_{tb}\, V_{ts}^*\, m_b\, C_7\, \bar{s}_L \sigma_{\mu\nu} b_R\, F^{\mu\nu}$$



$$\Rightarrow \qquad G_F\, V_{tb}\, V_{ts}^*\, \frac{\alpha}{4\pi}\, C_{9(10)}\, \bar{s}_L \gamma^\mu b_L\, \bar{\ell} \gamma_\mu (\gamma_5) \ell$$

- Wilson coefficients $C_k(\mu)$ calculated in P.T. at $\mu = m_W$ and rescaled to $\mu = m_b$



- Light fields active at long distances
  Nonperturbative QCD!
  - ★ Factorization of scales m_b *vs.* $\Lambda_{\rm QCD}$
    HQEFT, QCDF, SCET,...

Effective field theories: Bottom-up approach to new physics

Guiding principle

Construct $\mathcal{L}$ from most general local operators $\mathcal{O}_k$ made of $\phi \in u, d, s, c, b, l, \nu, F_{\mu\nu}, G_{\mu\nu}$, subject to Lorentz and $SU(3)_c \times U(1)_{em}$ invariance

- New physics manifest at the operator level through...
  - Different values of the Wilson coefficients $C_i^{\rm expt.} = C_i^{\rm SM} + \delta C_i$
  - New operators absent or very suppressed in the SM
    - ★ New chirally-flipped operators

$$\mathcal{O}'_{\mathbf{7}} = \frac{4G_F}{\sqrt{2}} \frac{e}{4\pi^{\mathbf{2}}} \hat{m}_b \, \bar{s}\sigma_{\mu\nu} P_L F^{\mu\nu} b; \qquad \mathcal{O}'_{\mathbf{9(10)}} = \frac{4G_F}{\sqrt{2}} \frac{\alpha}{4\pi} \bar{s}\gamma^\mu P_R b \, \bar{\ell}\gamma_\mu(\gamma_{\mathbf{5}})\ell$$

    - ★ **4** new scalar and pseudoscalar operators

$$\mathcal{O}_S^{(\prime)} = \frac{4G_F}{\sqrt{2}} \frac{\alpha}{4\pi} (\bar{s}P_{R,L}b)\,(\bar{\ell}\,\ell); \qquad \mathcal{O}_P^{(\prime)} = \frac{4G_F}{\sqrt{2}} \frac{\alpha}{4\pi} (\bar{s}P_{R,L}b)\,(\bar{\ell}\,\gamma_{\mathbf{5}}\,\ell)$$

    - ★ **2** new tensor operators

$$\mathcal{O}_{T(\mathbf{5})} = \frac{4G_F}{\sqrt{2}} \frac{\alpha}{4\pi} (\bar{s}\sigma^{\mu\nu} b)\,(\bar{\ell}\,\sigma_{\mu\nu}(\gamma_{\mathbf{5}})\ell).$$

  - The Wilson coefficients can be complex and introduce new sources of $\not{CP}$

- But hold on...
  - No evidence of non-SM-particles *on-shell* at colliders up to $E \simeq 1$ TeV...
    ...assuming the scalar at $s \simeq 125$ GeV is the SM Higgs

Guiding principle *(rewritten)*

Construct the most general $\mathcal{L}$ from operators $\mathcal{O}_k$ built with ***all*** the SM fields, subject to Lorentz and $SU(3)_c \times SU(2)_L \times U(1)_Y$ invariance

Buchmuller *et al.*'86, Grzadkowski *et al.*'10

- For **scalar** and **tensor** operators $\Gamma = \mathbb{I}, \sigma_{\mu\nu}$ we only have:

$$\frac{1}{\Lambda^2}\underbrace{(\bar{e}_R\,\Gamma\,\ell_L^a)}_{Y=1/2}\underbrace{(\bar{q}_L^a\,\Gamma\,d_R)}_{Y=-1/2} \qquad \frac{1}{\Lambda^2}\varepsilon^{ab}\underbrace{(\bar{\ell}_L^b\,\Gamma\,e_R)}_{Y=-1/2}\underbrace{(\bar{q}_L^a\,\Gamma\,u_R)}_{Y=1/2}$$

- Furthermore:

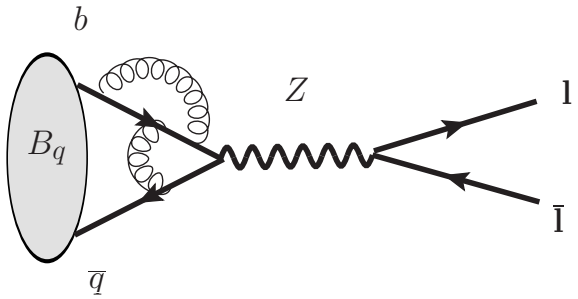
$$(\bar{q}_j\sigma_{\mu\nu}P_R d_i)(\bar{e}\sigma^{\mu\nu}P_L\ell) = 0$$

Constraints in $b \to s\ell\ell$ up to $\mathcal{O}(v^2/\Lambda^2)$

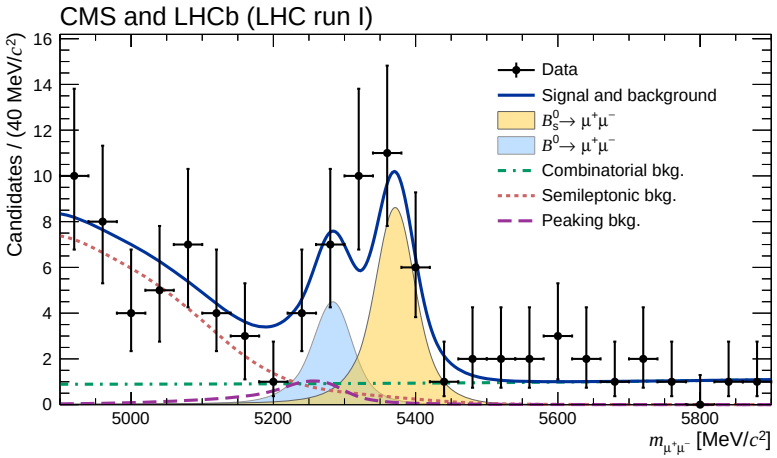
- From **4** scalar operators to only **2**!
- From **2** tensor operators to **none**!

Alonso, BG, Martin-Camalich, PRL113(2014)241802 ***Caveat:*** **Non-limearly relaized EW symmetry**

$B_q^0 \to \ell\ell$



CMS and LHCb combined arXiv: 1411.4413



$$\mathcal{B}_{sl} \simeq \frac{G_F^2 \alpha^2}{64\pi^3} \tau_{B_s} m_{B_s}^3 f_{B_s}^2 |V_{tb} V_{ts}^*|^2 \times \left\{ |C_S - C_S'|^2 + |C_P - C_P' + 2\frac{m_l}{m_{B_s}}(C_{10} - C_{10}')|^2 \right\}$$

- Decay is chirally suppressed: Very sensitive to (pseudo)scalar operators!
- Semileptonic decay **constants** f_{B_q} can be calculated in LQCD

  FLAG averages Eur.Phys.J. C74 (2014) 2890
- Updated predictions:

  Bobeth *et al.* PRL112(2014)101801

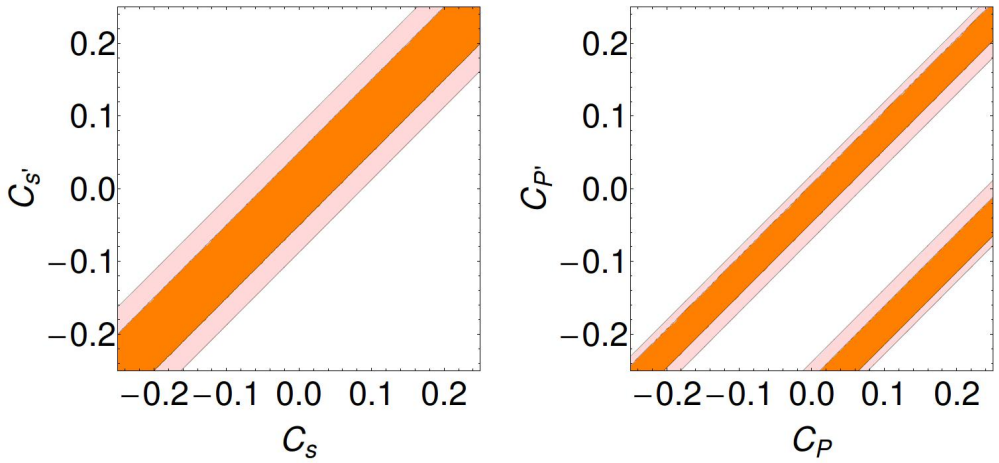
$$\overline{\mathcal{B}}_{s\mu}^{\rm SM} = 3.65(23) \times 10^{-9}$$
$$\overline{\mathcal{B}}_{s\mu}^{\rm expt} = 2.9(7) \times 10^{-9}$$

Phenomenological consequences $B_q \to \ell\ell$

$$\overline{R}_{ql} = \frac{\overline{\mathcal{B}}_{ql}}{\left(\overline{\mathcal{B}}_{ql}\right)_{\rm SM}} = \frac{1 + \mathcal{A}^{ll}_{\Delta\Gamma}\, y_q}{1 + y_q} \left(|S|^2 + |P|^2\right),$$

De Bruyn *et al.* '12

$$S = \sqrt{1 - \frac{4m_l^2}{m_{B_q}^2}}\, \frac{m_{B_q}^2}{2m_l} \frac{C_S - C_S'}{(m_b + m_q) C_{10}^{\rm SM}}, \qquad P = \frac{C_{10} - C_{10}'}{C_{10}^{\rm SM}} + \frac{m_{B_q}^2}{2m_l} \frac{C_P - C_P'}{(m_b + m_q) C_{10}^{\rm SM}}$$

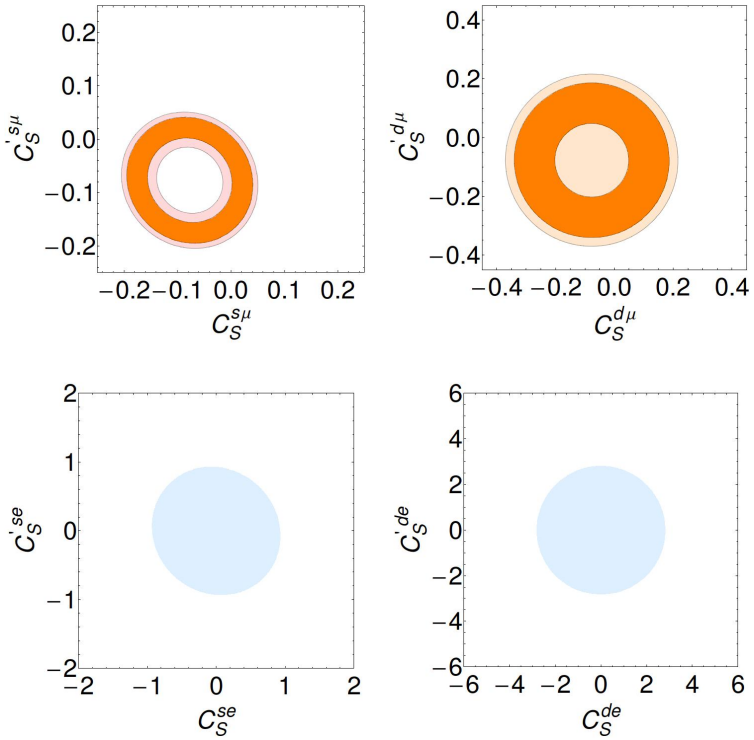


- $B_q \to \ell\ell$ blind to the orthogonal combinations $C_S + C_S'$ and $C_P + C_P'$
  Scalar operators unconstrained!

Phenomenological consequences $B_q \to \ell\ell$

$$\overline{R}_{ql} = \frac{\overline{\mathcal{B}}_{ql}}{\left(\overline{\mathcal{B}}_{ql}\right)_{\rm SM}} = \frac{1+\mathcal{A}^{ll}_{\Delta\Gamma}\, y_q}{1+y_q}\left(|S|^2+|P|^2\right),$$

$$S = \sqrt{1-\frac{4m_l^2}{m_{B_q}^2}}\,\frac{m_{B_q}^2}{2m_l}\,\frac{C_S - C_S'}{(m_b+m_q)C_{10}^{\rm SM}}, \qquad P = \frac{C_{10}-C_{10}'}{C_{10}^{\rm SM}} - \frac{m_{B_q}^2}{2m_l}\,\frac{C_S + C_S'}{(m_b+m_q)C_{10}^{\rm SM}}$$

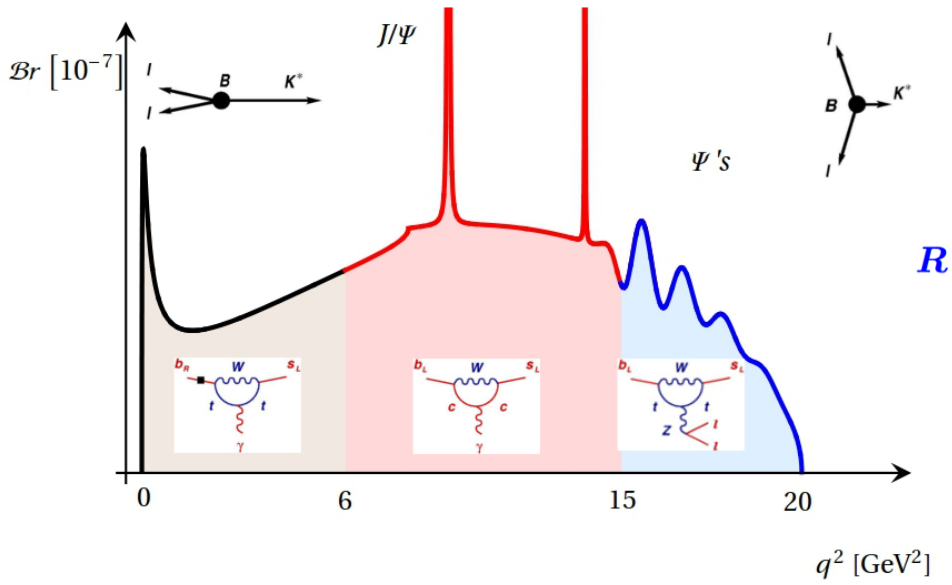


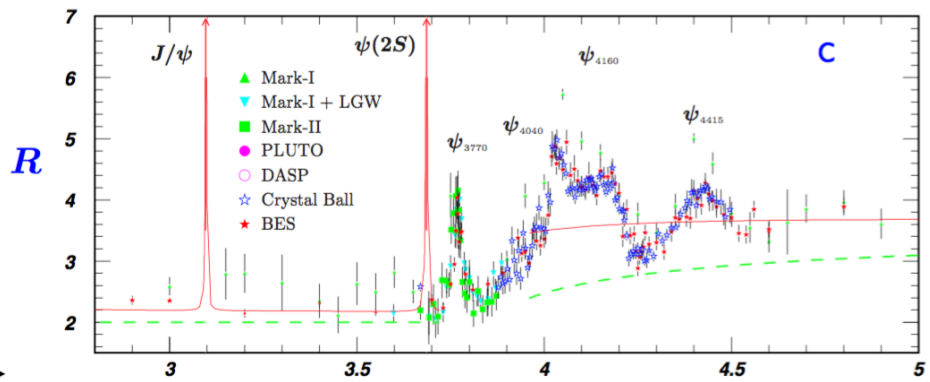
- $\Lambda_{\rm NP}$ (95%C.L.) RGE of QCD+EW+Yukawas

Channels	$s\mu$	$d\mu$	se	de
$C_S^{(\prime)}(m_W)$	0.1	0.15	0.6	1.5
Λ [TeV]	79	130	36	49

Alonso, BG, Martin-Camalich, PRL113(2014)241802

$b \to s\ell\ell$ anomalies: Hadronic complications

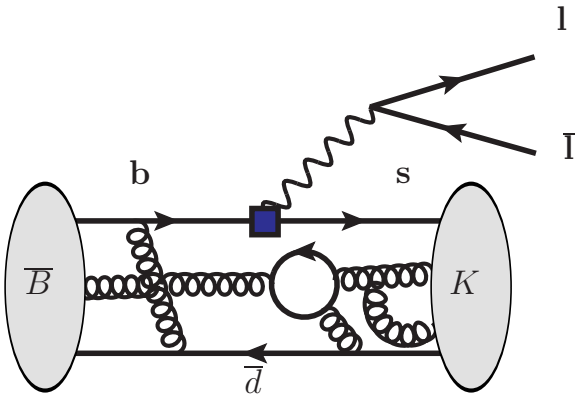


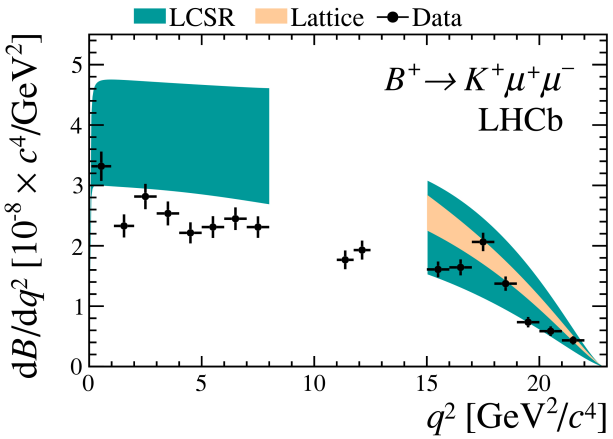


- **Large-recoil region** (low q^2)
  - Heavy to collinear light quark $\Rightarrow$ QCDf or SCET (power-corrections)
  - Dominant effect of the photon pole
- **Charmonium region**
  - Dominated by long-distance (hadronic) effects
  - Starting at the perturbative $c\bar{c}$ threshold $q^2 \simeq 6 - 7$ GeV^2
- **Low-recoil region** (high q^2)
  - Heavy quark EFT + Operator Product Expansion (OPE) (duality violation)
  - Dominated by semileptonic operators

$B \to K\ell\ell$

LHCb JHEP06(2014)133, JHEP05(2014)082, PRL111 (2013)112003,...





$$\frac{d\Gamma}{dq^2} = \frac{G_F^2\,\alpha^2|V_{tb}V_{ts}^*|^2}{1536\pi^5}\, f_+^2 \left(|C_9 + C_9' + 2\frac{\mathcal{T}_K}{f_+}|^2 + |C_{10} + C_{10}'|^2 \right) + \mathcal{O}(\frac{m_\ell^4}{q^4})$$

Note: in this talk I won't show corresponding Eq for K^*: similar but C_7 matters and $C_n' \to -C_n'$

- Phenomenologically rich (3-body decay)
  - Decay rate is a function of dilepton invariant mass $q^2 \in [4m_\ell^2, (m_B - m_K)^2]$
  - **1 angle**: Angular analysis sensitive only to scalar and tensor operators

    Bobeth *et al.*, JHEP 0712 (2007) 040
- **However:** Very complicated nonperturbative problem
  - Hadronic form factors (q^2-dependent functions)
  - "Non-factorizable" contribution of 4-quark operators+EM current

$B \to K\ell\ell$

- Then in the SM for $q^2 \gtrsim 1$ GeV^2

$$R_K \equiv \frac{\mathrm{Br}\left(B^+ \to K^+\mu^+\mu^-\right)}{\mathrm{Br}\left(B^+ \to K^+e^+e^-\right)} = 1 + \mathcal{O}(10^{-4})$$

The R_K anomaly

$$\langle R_K \rangle_{[1,6]} = 0.745^{+0.090}_{-0.074}(\mathrm{stat}) \pm 0.036(\mathrm{syst})$$

LHCb, Phys.Rev.Lett.113(2014)151601

- 2.6σ discrepancy with the SM $\langle R_K \rangle_{[1,6]} = 1.0003(1)$
- Linearly realized $SU(2)_L \times U(1)_Y$ EFT:
  - No tensors
  - Scalar operators constrained by $B_s \to \ell\ell$ alone:

$$R_K \in [0.982, 1.007] \text{ at } 95\% \text{ CL}$$

The effect must come from $\mathcal{O}^{(\prime)}_{9,10}$

$R_K \simeq 0.75$ for $\delta C_9^\mu = -\delta C_{10}^\mu = -0.5$

Alonso, BG, Martin-Camalich, PRL113(2014)241802

$B \to K^* \ell\ell$: R_{K^*}

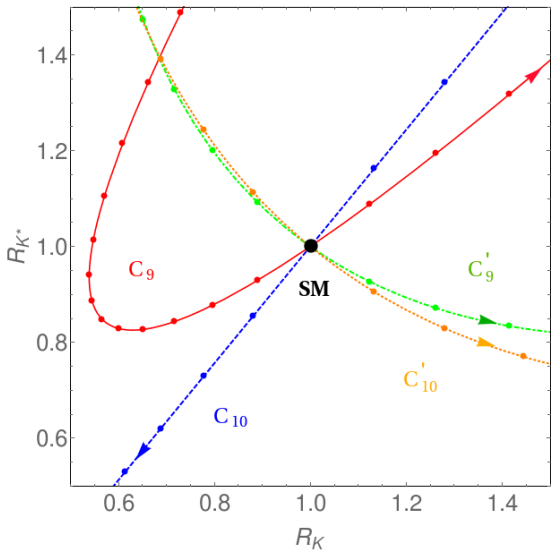
The R_{K^*} anomaly

$$\langle R_{K^*} \rangle_{[0.045,1.1]} = 0.660^{+0.110}_{-0.070}(\mathrm{stat}) \pm 0.024(\mathrm{syst})$$

$$\langle R_{K^*} \rangle_{[1.1,6]} = 0.685^{+0.113}_{-0.069}(\mathrm{stat}) \pm 0.047(\mathrm{syst})$$

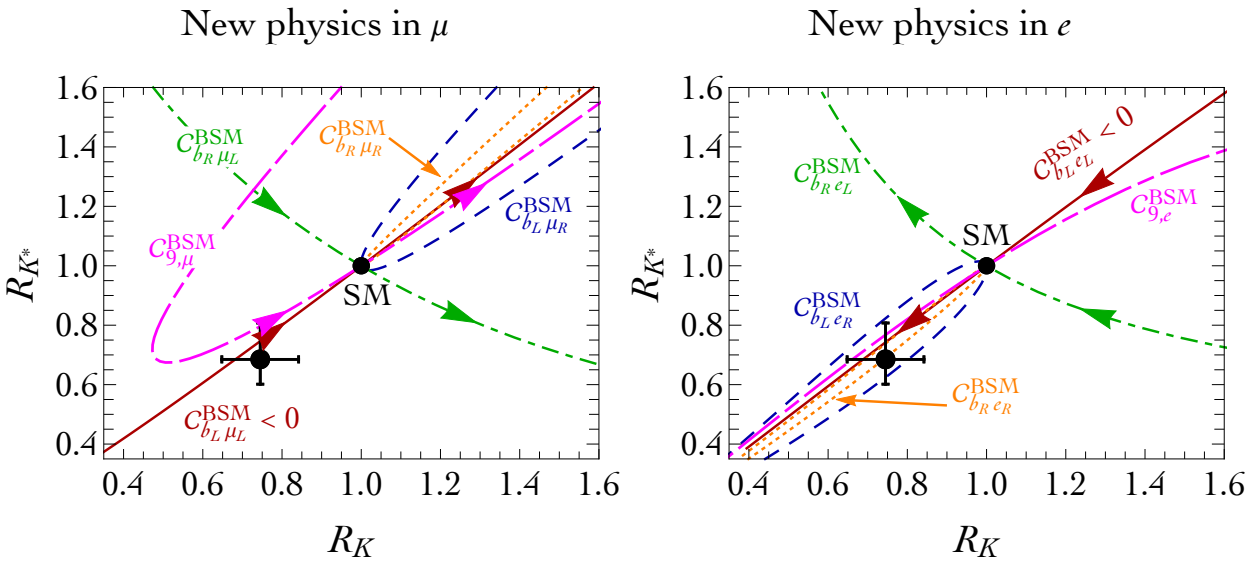
Theoretical interpretation (mostly in pictures)

Bernat Capdevila, Andreas Crivellin, Sébastien Descotes-Genon, Joaquim Matias, Javier Virto, 1704.05340
Wolfgang Altmannshofer, Peter Stangl, David M. Straub, 1704.05435
G. D'Amico, M. Nardecchia, Paolo Panci, Francesco Sannino, Alessandro Strumia, Riccardo Torre, Alfredo Urbano, 1704.05438
Gudrun Hiller, Ivan Nišandžić, 1704.05444
Marco Ciuchini, António M. Coutinho, Marco Fedele, Enrico Franco, Ayan Paul, Luca Silvestrini, Mauro Valli, 1704.05447
Alejandro Celis, Javier Fuentes-Martín, Avelino Vicente, Javier Virto, 1704.05672
Li-Sheng Geng, BG, Sebastian Jäger, Jorge Martin Camalich, Xiu-Lei Ren, Rui-Xiang Shi, 1704.05446

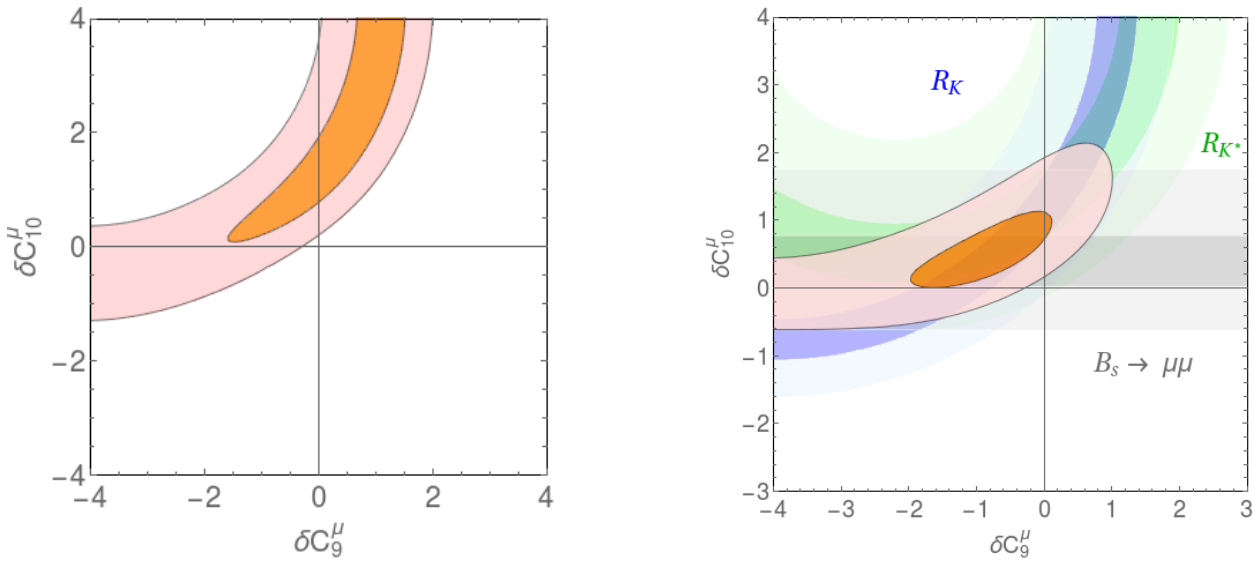


- Recall $C_9^{SM} \approx -C_{10}^{SM} \approx 4.5$
- These are $\delta C_i = C_i^{NP}$, in μ
- Arrows: increasing δC
- Dots: intervals of $\Delta(\delta C) = 0.5$
- Central Value (R_K, R_{K^*}) on blue line
- Not C_9', C_{10}' (ie, not $V + A$)

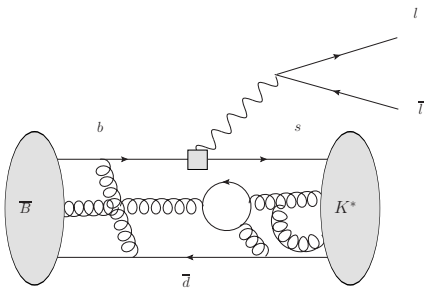
μ vs e



Fit to R_K and R_{K^*}, and these plus $B_s \to \mu\mu$

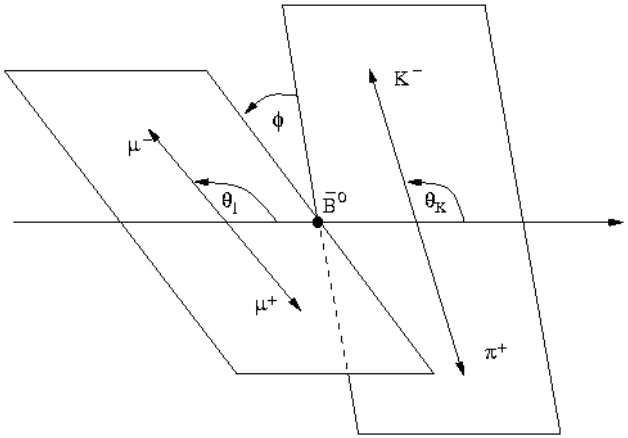


$\bar{B} \to \bar{K}^* \ell^+ \ell^-$: angular



CDF	100	PRL106(2011)161801
BaBar	150	PRD86(2012)032012
Belle	200	PRL103(2009)171801
CMS	400	PLB727(2013)77
ATLAS	500	arXiv:1310.4213
LHCb (μ)	3000 (3 fb^{-1})	JHEP 1602 (2016) 104
LHCb (e)	128 ([0.0004, 1] GeV^2)	JHEP 1504(2015)064

- **4-body decay**



$$\frac{d^{(4)}\Gamma}{dq^2\, d(\cos\theta_l)\, d(\cos\theta_k)\, d\phi} = \frac{9}{32\pi}\Big(I_1^s \sin^2\theta_k + I_1^c \cos^2\theta_k$$

$$+ \quad (I_2^s \sin^2\theta_k + I_2^c \cos^2\theta_k)\cos 2\theta_l + I_3 \sin^2\theta_k \sin^2\theta_l \cos 2\phi$$

$$+ \quad I_4 \sin 2\theta_k \sin 2\theta_l \cos\phi + I_5 \sin 2\theta_k \sin\theta_l \cos\phi + I_6 \sin^2\theta_k \cos\theta_l$$

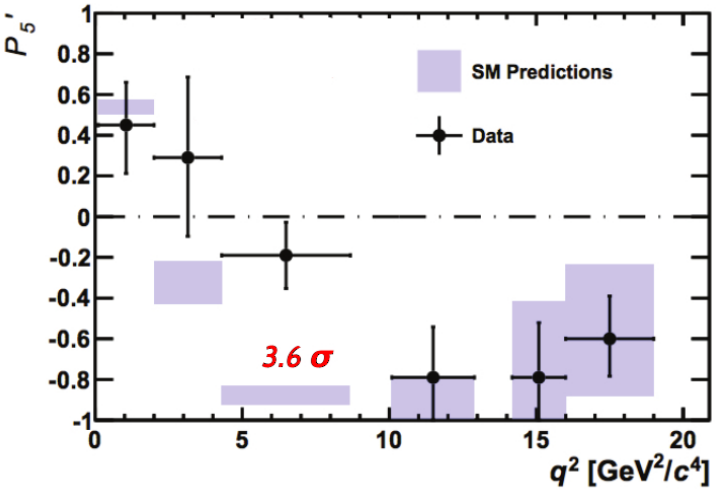
$$+ \quad I_7 \sin 2\theta_k \sin\theta_l \sin\phi + I_8 \sin 2\theta_k \sin 2\theta_l \sin\phi + I_9 \sin^2\theta_k \sin^2\theta_l \sin 2\phi\Big)$$

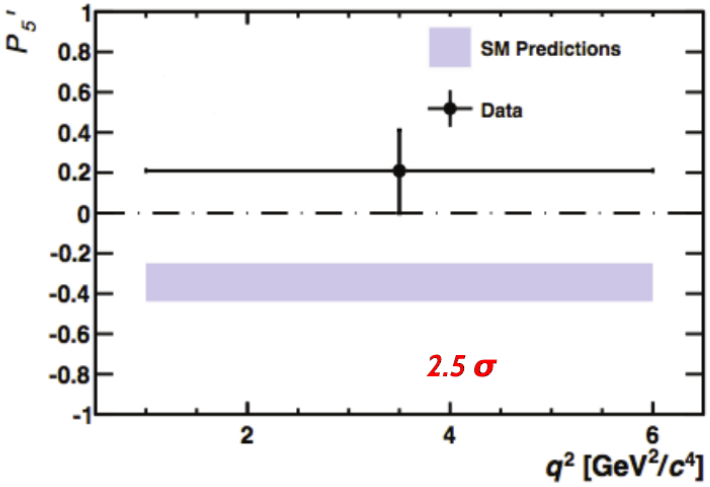
The P_5' anomaly at low q^2 (1 fb^{-1})

PRL **111,** 191801 (2013) PHYSICAL REVIEW LETTERS week ending 8 NOVEMBER 2013

Measurement of Form-Factor-Independent Observables in the Decay $B^0 \to K^{*0}\mu^+\mu^-$

R. Aaij *et al.**
(LHCb Collaboration)
(Received 9 August 2013; published 4 November 2013)



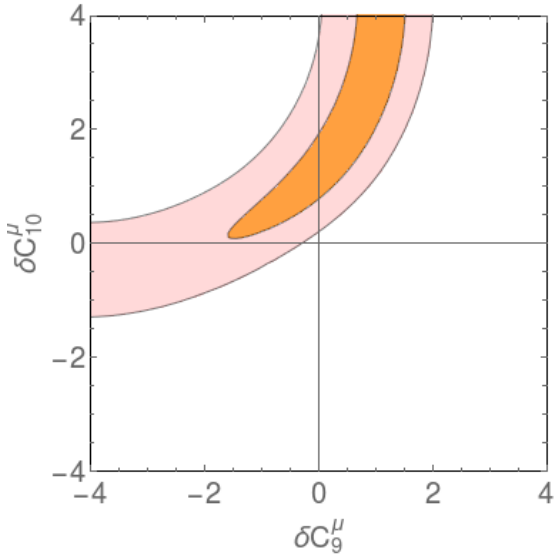


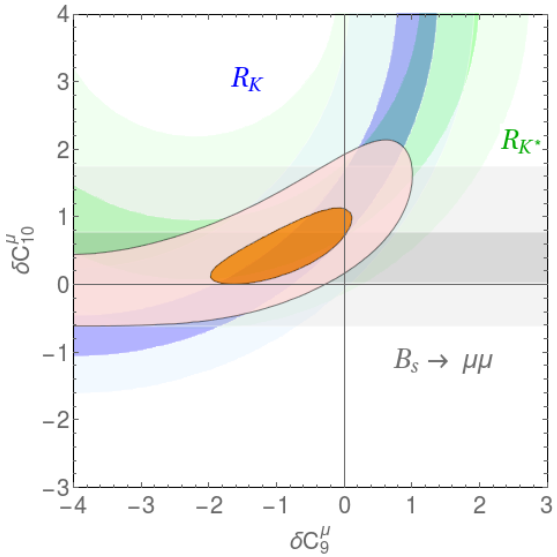
$$\delta C_9^\mu \simeq -1$$

Descotes-Genon *et al.* PRD88,074002

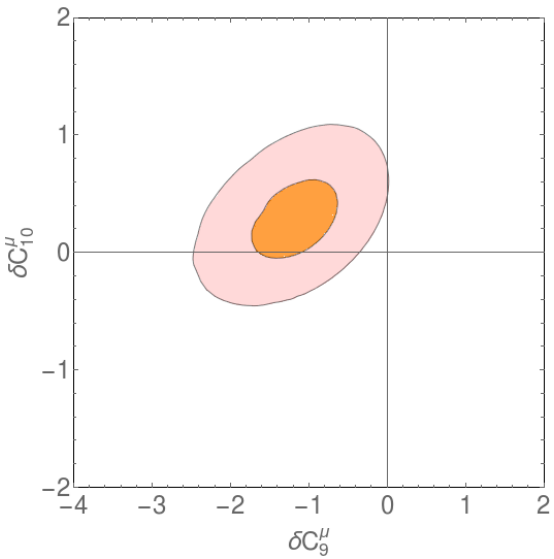
Altmannshofer *et al.* Eur.Phys.J. C73 (2013) 2646

We have seen: Fit to R_K and R_{K^*}, and these plus $B_s \to \mu\mu$





And now including all "dirty" observables



- Not C'
- Not purely C^e
- New LUV observables (no time to discuss)

The shape of the new physics

- Assume hereafter: R_{K,K^*} and P_5' are NP
- Stick to SM-EFT

Simplest example: chiral solution

$$\delta C_9^\mu = -\delta C_{10}^\mu = -0.5$$
$$\delta C_9^e = \delta C_{10}^e = 0$$

Hiller and Schmaltz'14, Straub *et al*'14'15, Ghosh *et al*'14,...

- Only 2 dim-6 $SU(2)_L \times U(1)_Y$-invariant operators

$$Q_{\ell q}^{(1)} = \frac{1}{\Lambda^2}(\bar{q}_L \gamma^\mu q_L)(\bar{\ell}_L \gamma_\mu \ell_L) \qquad Q_{\ell q}^{(3)} = \frac{1}{\Lambda^2}(\bar{q}_L \gamma^\mu \vec{\tau} q_L)\cdot(\bar{\ell}_L \gamma_\mu \vec{\tau} \ell_L)$$

1. **Lepton Universality Violation $\Rightarrow$ Lepton flavor Violation?**
2. **Operators with $SU(2)_L$ quark doublets $\Rightarrow$ new correlations, *i.e.*,:**
   - FCNC with neutrinos and/or up quarks
   - $V-A$ Contributions CC ($b \to c\ell\bar{\nu}$, $t \to b\bar{\ell}\nu\ldots$)

A liitle more theory: Lepton flavor symmetries in the SM

$$SU(3)_\ell \times SU(3)_e \times U(1)_L \times U(1)_{e-\ell}\,, \qquad \ell_L \sim (3,1)_{1,-1}\,, \qquad e_R \sim (1,3)_{1,1}$$

Broken **only** by the Yukawas in the SM

$$-\mathcal{L}_Y \supset \epsilon_e\, \bar{\ell}_L \hat{Y}_e e_R H + h.c., \qquad (Y_e = \epsilon_e\, \hat{Y}_e,\ \mathrm{tr}(\hat{Y}_e\, \hat{Y}_e^\dagger) = 1)$$

$U(1)_\tau \times U(1)_\mu \times U(1)_e$ survives

- **However:** Any new source of flavor violation will lead to LF violation...

  Glashow *et al.* PRL114(2015)091801, Bhattacharya *et al.* PLB742(2015)370

LFV in $b \to s\ell\ell'$!!

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LFV in $b \to s\ell\ell'$!!

- ...unless it is "aligned" with the Yukawas (e.g. Lee *et al.* JHEP1508(2015)123, Crivellin *et al.* PRL114(2015)151801, Celis *et al.* PRD92(2015)015007)

Minimal flavor violation

The only source of lepton flavor structure in the new physics *are* the Yukawas

Chivukula *et al*'87s, D'Ambrosio *et al*'02, Cirigliano *et al*'05

Introduce spurions $\hat{Y}_e \sim (3,\bar{3})$ and $\epsilon_e \sim (0,-2)$

$$\mathcal{L}^{\rm NP} = \frac{1}{\Lambda^2}\left[(\bar q'_L\, C_q^{(1)}\gamma^\mu q'_L)(\bar\ell'_L\, \hat Y_e\, \hat Y_e^\dagger \gamma_\mu \ell'_L) + (\bar q'_L\, C_q^{(3)}\gamma^\mu \vec\tau q'_L)\cdot(\bar\ell'_L\, \hat Y_e\, \hat Y_e^\dagger \gamma_\mu \vec\tau \ell'_L)\right]$$

Very generic observations:

Hierarchic leptonic couplings (no LFV)

Interactions $\sim \delta_{\alpha\beta} m_\alpha^2/m_\tau^2$

1. **Boost of 10^3 in $b \to s\tau\tau$!**

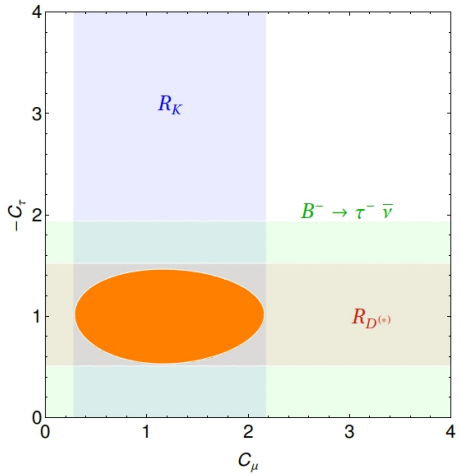
$$\mathcal{B}(B \to K\tau^-\tau^+) \simeq 2\times 10^{-4}, \qquad \mathcal{B}(B^+ \to K^+\tau\tau)^{\rm expt} < 3.3\times 10^{-3}$$

2. **Very strong constraint from $b \to s\nu_\tau\nu_\tau$**
   - $\Lambda_{NP} \simeq 3$ TeV
3. **Sizable effects in CC tauonic B decays!**

$$R_{D^{(*)}} = \frac{\mathcal{B}(\bar B \to D^{(*)}\tau\bar\nu_\tau)}{\mathcal{B}(\bar B \to D^{(*)}\mu\bar\nu_\mu)}$$

- ***Excess*** observed at more than 4σ

	SM	Expt.
R_D	0.300(10)	0.388(47)
R_{D^*}	0.252(5)	0.321(21)



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Applications to model-building

Refs: apologies!

Scratching the surface of large and growing literature, just to give a sense

- Approaches:
  - Short distance: decoupling particles, heavier than EW, weak coupling (tree level)
    - Z'
      - ★ LUV: couple (typically) to $L_\mu - L_\tau$, strength $g_{\mu\mu}$
      - ★ FCNC: non-diag coupling to $\bar{s}b$, strength g_{bs}; B_s-mixing $\Rightarrow$ $g_{bs}/M_{Z'} < 5 \times 10^{-3}$ TeV^{-1}
      - ★ B-anomalies: $g_{\mu\mu}/M_{Z'} > 1/(3.7 \text{ TeV})$, or $M_{Z'} < 13$ TeV for $g_{\mu\mu} < \sqrt{4\pi}$
      - ★ Need to address LFV (eg, $\mu \to e\gamma$) and other quark FCNC
    - Leptoquarks $\to$ see next slide
  - Non-decoupling, EW scale
    - **SM-EFT analysis does not necessarily apply**
    - Loop mediators Arnan et al, 1608.07832; Gripaios et al, JHEP1606(2016)083; Kamenik et al, 1704.06005
    - Composites, partial composites eg Gripaios et al, JHEP1505(2015)006
  - Long distance, lighter than EW Sala & Straub, 1704.06188, Bishara et al, 1705.03465, ...
- Is Q&L flavor fundamental to the NP?
  - No, small numbers look fine tuned just as in CKM model
  - Yes, this is a window to flavodynamics, e.g., gauged flavor Crivellin et al, PRD91(2015)075006

Survey of leptoquark models

- **Scalar** LQ

$$\mathcal{L}_\Delta = \left(y_{\ell u}\,\bar{\ell}_L\,u_R + y_{eq}\,\bar{e}_R\,i\tau_2\,q_L\right)\Delta_{-7/6}$$
$$+ y_{\ell d}\,\bar{\ell}_L\,d_R\,\Delta_{-1/6} + \left(y_{\ell q}\,\bar{\ell}^c_L i\tau_2\,q_L + y_{eu}\bar{e}^c_R\,u_R\right)\Delta_{1/3}$$
$$+ y_{ed}\bar{e}^c_R\,d_R\,\Delta_{4/3} + y'_{\ell q}\,\bar{\ell}^c_L i\tau_2\vec{\tau}q_L\cdot\vec{\Delta}'_{1/3}$$

- **Vector** LQ

$$\mathcal{L}_V = \left(g_{\ell q}\,\bar{\ell}_L\gamma_\mu q_L + g_{ed}\,\bar{e}_R\gamma_\mu d_R\right)V^\mu_{-2/3}$$
$$+ g_{eu}\,\bar{e}_R\gamma_\mu u_R\,V^\mu_{5/3} + g'_{\ell q}\,\bar{\ell}_L\gamma_\mu\vec{\tau}q_L\cdot\vec{V}'^\mu_{-2/3}$$
$$+ \left(g_{\ell d}\,\bar{\ell}_L\gamma_\mu d^c_R + g_{eq}\,\bar{e}_R\gamma_\mu q^c_L\right)V^\mu_{-5/6} + g_{\ell u}\,\bar{\ell}_L\gamma_\mu u^c_R\,V^\mu_{1/6}$$

Büchmuller and Wyler'87, Davidson *et al.*'94,...

- Assume $M_{LQ} \gg v$: Only $\vec{\Delta}'_{1/3}, V^\mu_{-2/3}, \vec{V}^\mu_{-2/3}$ can work.
  - (x)MSSM? Only $\Delta_{1/6}$, the doublet squark (with R-parity breakaing); does not work.

LQ	C_9	C_{10}	C'_9	C'_{10}	C_S	C_ν	C'_ν
$\vec{\Delta}'_{1/3}$	$y'^{\beta i,A}_{\ell q}(y'^{\alpha j,A}_{\ell q})^*$	$-y'^{\beta i,A}_{\ell q}(y'^{\alpha j,A}_{\ell q})^*$	0	0	0	$-\frac{1}{2}y'^{\beta i,A}_{\ell q}(y'^{\alpha j,A}_{\ell q})^*$	0
$\Delta_{7/6}$	$-\frac{1}{2}y^{\alpha i,A}_{eq}(y^{\beta j,A}_{eq})^*$	$-\frac{1}{2}y^{\alpha i,A}_{eq}(y^{\beta j,A}_{eq})^*$	0	0	0	0	0
$\Delta_{1/6}$	0	0	$-\frac{1}{2}y^{\alpha i,A}_{\ell d}(y^{\beta j,A}_{\ell d})^*$	$\frac{1}{2}y^{\alpha i,A}_{\ell d}(y^{\beta j,A}_{\ell d})^*$	0	0	$-\frac{1}{2}y^{\alpha i,A}_{\ell d}(y^{\beta j,A}_{\ell d})^*$
$\Delta_{4/3}$	0	0	$\frac{1}{2}y^{\beta i,A}_{ed}(y^{\alpha j,A}_{ed})^*$	$\frac{1}{2}y^{\beta i,A}_{ed}(y^{\alpha j,A}_{ed})^*$	0	0	0
$V^\mu_{2/3}$	$-g^{\alpha i,A}_{\ell q}(g^{\beta j,A}_{\ell q})^*$	$g^{\alpha i,A}_{\ell q}(g^{\beta j,A}_{\ell q})^*$	$-g^{\alpha i,A}_{ed}(g^{\beta j,A}_{ed})^*$	$-g^{\alpha i,A}_{ed}(g^{\beta j,A}_{ed})^*$	$2g^{\alpha i,A}_{\ell q}(g^{\beta j,A}_{ed})^*$	0	0
$\vec{V}^\mu_{2/3}$	$-g'^{\alpha i,A}_{\ell q}(g'^{\beta j,A}_{\ell q})^*$	$g'^{\alpha i,A}_{\ell q}(g^{\beta j,A}_{\prime\ell q})^*$	0	0	0	$-2\,g'^{\alpha i,A}_{\ell q}(g'^{\beta j,A}_{\ell q})^*$	0
$V^\mu_{5/6}$	$g^{\beta i,A}_{eq}(g^{\alpha j,A}_{eq})^*$	$g^{\beta i,A}_{eq}(g^{\alpha j,A}_{eq})^*$	$g^{\beta i,A}_{\ell d}(g^{\alpha j,A}_{\ell d})^*$	$-g^{\beta i,A}_{\ell d}(g^{\alpha j,A}_{\ell d})^*$	$2g^{\alpha j,A}_{\ell d}(g^{\beta i,A}_{eq})^*$	0	$g^{\beta i,A}_{\ell d}(g^{\alpha j,A}_{\ell d})^*$

- Assume, in addition, MLFV: $B \to K\nu\bar{\nu} \;\Rightarrow\; C_\nu \lesssim 10$, 3rd gen has $\times(m_\tau/m_\mu)^2$

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  - Only $V^\mu_{-2/3}$ can work!

Conclusions

1. EFT approach very efficient method to investigate anomalies
   - Assumptions: New Physics is heavy and EW is linearly realized
   - Constraints between low-energy operators
     - ★ **2** out of **4** independent **scalar** operators and **no tensors** in $d_i \to d_j \ell\ell$
     - ★ $B_q \to \ell\ell$: remove **scalar** operators
2. The $b \to s\ell\ell$ anomalies
   - The P_5' anomaly in $B \to K^* \mu\mu$: prefer NP in $C_9^{(\prime)}$ in μ-sector
   - R_{K,K^*} in $B \to K^{(*)}\ell\ell$: (slightly) prefer NP in C_{10}, then C_9 (no $C'_{9,10}$)
   - Global fit: δC_9 and δC_{10}, attractively chiral: $\delta C_9 = -\delta C_{10}$ $(V-A) \otimes (V-A)$
3. New Physics
   - Heavy/medium/light? $M_{NP} < 50$ TeV; VLHC territory!
   - Does NP come with more/less symmetry? Does it lead to **LFV** vs **MLFV**?
   - Connection to charged current tauonic B decays: The $R_{D^{(*)}}$ anomalies?

With the LHC run2 and Belle II, very exciting times ahead!

The End