

Lepton-flavor Violation in B -meson decays

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101st Plenary ECFA meeting

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Outline

- 1 Introduction: Lepton flavor symmetries of the SM
- 2 LUV in $b \rightarrow c\tau\nu$ transitions
- 3 LUV $b \rightarrow ell$ transitions
- 4 Implications of anomalies for BSM
- 5 Conclusions

Lepton-flavor symmetries hallmark of the SM

$$\mathcal{L}_{\text{SM}} \supset \bar{L}_L^i i \not{D} L_L^i + \bar{e}_R^i i \not{D} e_R^i - \bar{L}_L^i (Y_e)_{ik} e_R^k H, \quad i, k = 1, 2, 3$$

- ▶ **Universality of gauge interactions:** Same “quantum numbers” under $SU(2)_L \times U(1)$
- ▶ **Yukawa interactions** are not lepton-flavor symmetric

Charged-lepton mass basis $\implies U(1)_\tau \times U(1)_\mu \times U(1)_e$ survives!*

* Up to tiny effects in charged-lepton processes produced by neutrino masses

Lepton Flavor Symmetries of the SM

- ▶ Interactions in the **SM** are **Charged-lepton flavor universal** up to ...
 - 1 **Higgs mediated** (Negligible)
 - 2 **Kinematic effects** due to different masses (process dependent)
- ▶ ... and **Charged-lepton flavor symmetric**

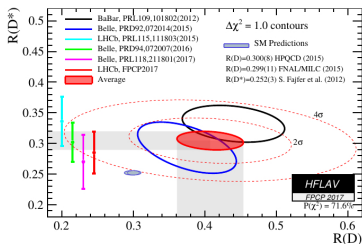
- Many experimental tests:

$\mu \rightarrow e\gamma$	$\mathcal{O}(10^{-13})$,	$Z \rightarrow \ell\ell$	$\mathcal{O}(10^{-4})$	
$\tau \rightarrow \mu\gamma$	$\mathcal{O}(10^{-8})$,	$W \rightarrow \ell\nu$	$\mathcal{O}(10^{-4})$	
$\tau \rightarrow 3\mu$	$\mathcal{O}(10^{-8})$,	$\pi \rightarrow \ell\nu$	$\mathcal{O}(10^{-4})$...

Lepton-universality violation in $b \rightarrow c\tau\nu$ decays

Lepton-universality ratios

$$R_{D^{(*)}} = \frac{\mathcal{B}(\bar{B} \rightarrow D^{(*)} \tau^- \bar{\nu})}{\mathcal{B}(\bar{B} \rightarrow D^{(*)} \ell^- \bar{\nu})} \quad \text{where } \ell = e, \mu$$



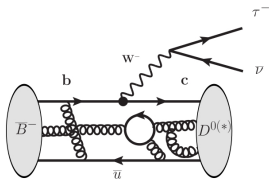
Belle: Hadronic tag, leptonic τ Semileptonic tag, leptonic τ Hadronic tag, hadronic τ
 BaBar: Hadronic tag, leptonic τ LHCb: leptonic τ hadronic τ

- Excesses** reported by **3 different experiments** in **2 channels** at $\sim 4\sigma$
 - 15% enhancement of the tau SM amplitude:

LUV in $b \rightarrow c\tau\nu$

$$\frac{\Lambda}{g} = \frac{v}{\sqrt{|V_{cb}|} \times 0.15} \sim 3 \text{ TeV}$$

Hadronic uncertainties (Form factors)



- **QCD is lepton universal!**

- ▶ **However:** Important kinematic effects

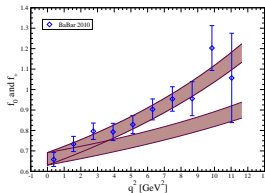
- **Fit Form Factors to experimental $B \rightarrow D^{(*)}(\mu, e)\nu$ data**

Boyd, Grinstein & Lebed '96, Caprini, Lellouch & Neubert'98

- **Example: $B \rightarrow D_T \nu$ with LQCD**

$$\langle D(k) | \bar{c} \gamma^\mu b | \bar{B}(\rho) \rangle = (\rho + k)^\mu f_+(q^2) + q^\mu \frac{m_B^2 - m_D^2}{q^2} (f_+(q^2) - f_0(q^2))$$

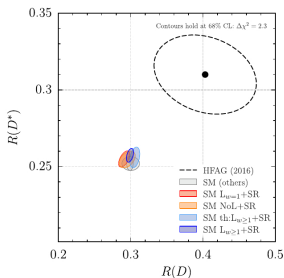
- ▶ Scalar $f_0(q^2)$ enters rate $\propto m_\ell^2$
- ▶ **CVC** implies $f_0(0) = f_+(0)$



Na *et al.* PRD92(2015)no.5,054510 (see also Bailey *et al.* PRD92,034506)

Hadronic uncertainties (Form factors)

- Upcoming **LQCD** calculation of the $B \rightarrow D^*$ FFs at **non-zero recoil!**
- **Current prediction relies on HQET** relations including $\Lambda_{\text{QCD}}/m_{c,b}$ corrections
 - ▶ Contribution to the $B \rightarrow D^* \tau \nu$ rate of (pseudo)scalar FF is small $\sim 10\%$!



Bernlocher *et al.* arXiv: 1703.05330

$$R_{D^*} = 0.257 \pm 0.003$$

Bernlocher *et al.* arXiv: 1703.05330

$$R_{D^*} = 0.260 \pm 0.008$$

Bigi *et al.* arXiv: 1707.09509

Hadronic uncertainties cannot explain the $R_{D^{(*)}}$ anomalies

EFT of new-physics in $b \rightarrow c\tau\nu$

- Low-energy effective Lagrangian (no RH ν)

$$\mathcal{L}_{\text{eff}}^{\ell} = -\frac{G_F V_{cb}}{\sqrt{2}} [(1 + \epsilon_L^{\ell}) \bar{\ell} \gamma_{\mu} (1 - \gamma_5) \nu_{\ell} \cdot \bar{c} \gamma^{\mu} (1 - \gamma_5) b + \epsilon_R^{\ell} \bar{\ell} \gamma_{\mu} (1 - \gamma_5) \nu_{\ell} \bar{c} \gamma^{\mu} (1 + \gamma_5) b \\ + \bar{\ell} (1 - \gamma_5) \nu_{\ell} \cdot \bar{c} [\epsilon_S^{\ell} - \epsilon_P^{\ell} \gamma_5] b + \epsilon_T^{\ell} \bar{\ell} \sigma_{\mu\nu} (1 - \gamma_5) \nu_{\ell} \cdot \bar{c} \sigma^{\mu\nu} (1 - \gamma_5) b] + \text{h.c.},$$

Wilson coefficients: ϵ_{Γ} decouple as $\sim v^2 / \Lambda_{\text{NP}}^2$

- Matching to high-energy Lagrangian – SMEFT

- ▶ Symmetry relations for ϵ_{Γ}

- ★ In charged-currents ϵ_R^{ℓ} :

$$\mathcal{O}_{Hud} = \frac{i}{\Lambda_{\text{NP}}^2} \left(\tilde{H}^{\dagger} D_{\mu} H \right) (\bar{u}_R \gamma^{\mu} d_R)$$

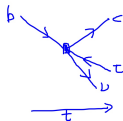


- RHC is lepton universal: $\epsilon_R^{\ell} \equiv \epsilon_R + \mathcal{O}\left(\frac{v^4}{\Lambda_{\text{NP}}^4}\right) \Rightarrow$ **Cannot explain LUR $R_{D^{(*)}}$!**

Down to 4 operators to explain $R_{D^{*}}$: $\epsilon_L, \epsilon_S, \epsilon_P, \epsilon_T$

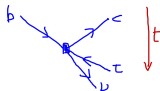
The constraint of the B_c -lifetime

- $B \rightarrow D^* \tau \nu$ receives a contribution from ϵ_P



$$\epsilon_P \langle D^*(k, \epsilon) | \bar{c} \gamma_5 b | \bar{B}(p) \rangle = -\frac{2\epsilon_P m_{D^*}}{m_b + m_c} A_0(q^2) \epsilon^* \cdot q$$

- $B_c \rightarrow \tau \nu$ **also** receives a **helicity-enhanced** contribution from ϵ_P !



$$\frac{\text{Br}(B_c^- \rightarrow \tau \bar{\nu}_\tau)}{\text{Br}(B_c^- \rightarrow \tau \bar{\nu}_\tau)^{\text{SM}}} = \left| 1 + \epsilon_L + \frac{m_{B_c}^2}{m_\tau (m_b + m_c)} \epsilon_P \right|^2$$

- Use the lifetime of B_c

- ▶ Very high experimental precision (1.5%):

$$\tau_{B_c} = 0.507(8) \text{ ps}$$

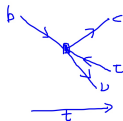
- ▶ **QCD**: “Most of the B_c lifetime comes from $\bar{c} \rightarrow \bar{s}$ ($\sim 65\%$) and $b \rightarrow c$ ($\sim 30\%$)”

Bigi PLB371 (1996) 105, Beneke *et al.* PRD53(1996)4991,...

$$\tau_{B_c}^{\text{OPE}} = 0.52_{-0.12}^{+0.18} \text{ ps}$$

The constraint of the B_c -lifetime

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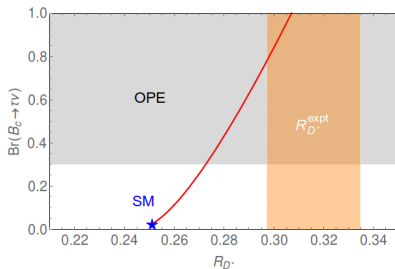


$$\epsilon_P \langle D^*(k, \epsilon) | \bar{c} \gamma_5 b | \bar{B}(p) \rangle = -\frac{2\epsilon_P m_{D^*}}{m_b + m_c} A_0(q^2) \epsilon^* \cdot q$$

- $B_c \rightarrow \tau \nu$ **also** receives a **helicity-enhanced** contribution from ϵ_P !



$$\frac{\text{Br}(B_c^- \rightarrow \tau \bar{\nu}_\tau)}{\text{Br}(B_c^- \rightarrow \tau \bar{\nu}_\tau)_{\text{SM}}} = \left| 1 + \epsilon_L + \frac{m_{B_c}^2}{m_\tau (m_b + m_c)} \epsilon_P \right|^2$$



Alonso, Grinstein&JMC, arXiv: 1611.06676

τ_{B_c} makes **highly implausible**
ANY “scalar solution”
 (e.g. 2HDM) to the R_{D^*} anomaly!

New-physics solutions and challenges

- Left-handed $\epsilon_L = 0.13$

SMEFT operators: $Q_{\ell q}^{(1)} = \frac{1}{\Lambda^2} (\bar{Q}_L \gamma^\mu Q_L) (\bar{L}_L \gamma_\mu L_L), \quad Q_{\ell q}^{(3)} = \frac{1}{\Lambda^2} (\bar{Q}_L \gamma^\mu \vec{\tau} Q_L) \cdot (\bar{L}_L \gamma_\mu \vec{\tau} L_L)$

- ▶ **Warning: Radiative LUV contributions in τ and Z decays!**

Ferruglio *et al.* PRL118 (2017), 011801



- ▶ **Problem with coupling to 3rd generation:** Non-trivial flavor str. [Buttazzo *et al.* arXiv:1706.07808](#)
- ▶ **Model dependence:** EFT only gives log parts (mixing)
- Tensor $\epsilon_T = 0.38$ (and scalars)

- ▶ **EW corrections:** Large mixing tensor into scalars

$$\begin{pmatrix} w_{ledq} \\ w_{lequ} \\ w_{lequ}^{(3)} \end{pmatrix}_{(\mu = m_Z)} = \begin{pmatrix} 1.19 & 0. & 0. \\ 0. & 1.20 & -0.185 \\ 0. & -0.00381 & 0.959 \end{pmatrix} \begin{pmatrix} w_{ledq} \\ w_{lequ} \\ w_{lequ}^{(3)} \end{pmatrix}_{(\mu = 1 \text{ TeV})}$$

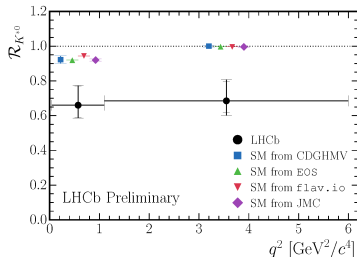
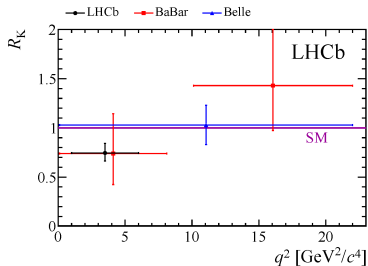
Gonzalez-Alonso, JMC & Mimouni arXiv: 1706.00410

- ▶ **Leptoquarks** can produce tensors and scalar upon mixing

Lepton-universality violation in $b \rightarrow sll$ decays

Lepton Universality Ratios

$$R_{K^{(*)}} = \frac{\mathcal{B}(\bar{B} \rightarrow K^{(*)} \mu^+ \mu^-)}{\mathcal{B}(\bar{B} \rightarrow K^{(*)} e^+ e^-)}$$



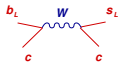
- Skewed μ -to- e ratios reported by **LHCb** in **2 channels** at $\sim 4\sigma$
 - ▶ Anomalies in **muonic BRs** and **angular observables**: **Global analyses** $\sim 5\sigma$
 - ▶ 25% deficit (enhancement) of the SM muon (electron) amplitude:

LUV in $b \rightarrow sll$

$$\frac{\Lambda}{g} = \frac{v}{\sqrt{|V_{ts}||V_{tb}|} \times \frac{\alpha_{em}}{4\pi}} \sim 30 \text{ TeV}$$

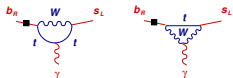
Effective field theory approach to $b \rightarrow sll$ decays

- **CC** (Fermi theory):

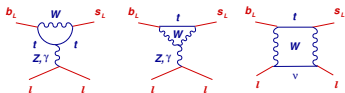

 \Rightarrow

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

- **FCNC**:

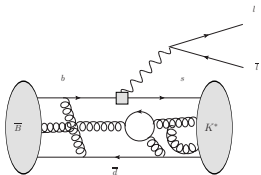

 \Rightarrow

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


 \Rightarrow

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

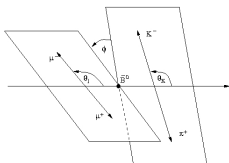
- ▶ **New-Physics** also in C_i or e.g. \mathcal{O}'_i obtained $P_L \rightarrow P_R$ in $\bar{s}_L b$



- ▶ Light fields active at long distances
Nonperturbative QCD!

- ★ Factorization of scales m_b vs. Λ_{QCD}
HQEFT, QCDF, SCET,...

The complex example: $B \rightarrow K^* \ell \bar{\ell}$



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

$$+ (I_2^S \sin^2 \theta_k + I_2^C \cos^2 \theta_k) \cos 2\theta_l + I_3 \sin^2 \theta_k \sin^2 \theta_l \cos 2\phi$$

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

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

- Anomalies in the angular observables ...

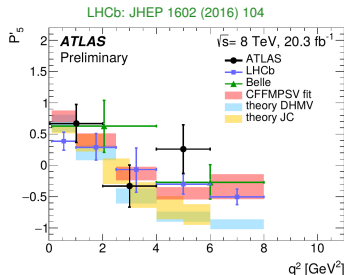
$$P'_5 = \frac{I_5}{2\sqrt{-I_{2S}I_{2C}}}$$

- ▶ Cancel leading theory uncertainties

New physics?

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

Descotes-Genon *et al.* PRD88,074002



- ▶ Interpretation blurred by hadronic uncertainties

The lepton-universality ratios...

- **QCD interactions are lepton universal***

▶ * EM corrections are lepton-dependent but at \sim % level Bordone et al. EPJC76(2016),8,440

- ... In $B \rightarrow K\ell\ell$

$$\frac{d\Gamma_K}{dq^2} = \mathcal{N}_K |\vec{k}|^3 f_+(q^2)^2 \left(|C_{10}^\ell + C_{10}'^\ell|^2 + |C_9^\ell + C_9'^\ell + 2 \frac{m_b}{m_B + m_K} C_7 \frac{f_T(q^2)}{f_+(q^2)} - 8\pi^2 h_K|^2 \right) + \mathcal{O}\left(\frac{m_\ell^2}{q^2}\right) + \dots$$

- ... in $B \rightarrow K^*\ell\ell$

$$\frac{d\Gamma_{K^*}}{dq^2} = \frac{d\Gamma_\perp}{dq^2} + \frac{d\Gamma_0}{dq^2}$$

$$\frac{d\Gamma_0}{dq^2} = \mathcal{N}_{K^*0} |\vec{k}|^3 V_0(q^2)^2 \left(|C_{10}^\ell - C_{10}'^\ell|^2 + |C_9^\ell - C_9'^\ell + \frac{2m_b}{m_B} C_7 \frac{T_0(q^2)}{V_0(q^2)} - 8\pi^2 h_{K^*0}|^2 \right) + \mathcal{O}\left(\frac{m_\ell^2}{q^2}\right)$$

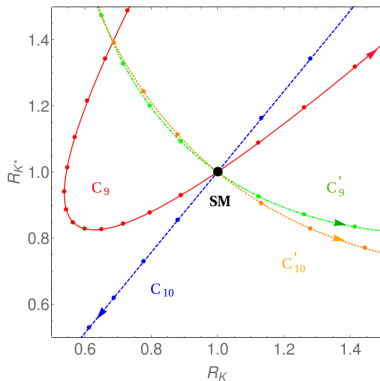
$$\frac{d\Gamma_\perp}{dq^2} = \mathcal{N}_{K^*\perp} |\vec{k}|^2 V_\perp(q^2)^2 \left(|C_{10}^\ell|^2 + |C_9'^\ell|^2 + |C_{10}'^\ell|^2 + |C_9^\ell + \frac{2m_b m_B}{q^2} C_7 \frac{T_\perp(q^2)}{V_\perp(q^2)} - 8\pi^2 h_{K^*\perp}|^2 \right) + \mathcal{O}\left(\frac{m_\ell^2}{q^2}\right)$$

Wilson coefficients in the SM

$$C_9^{\text{SM}}(m_b) \simeq -C_{10}^{\text{SM}} = +4.27$$

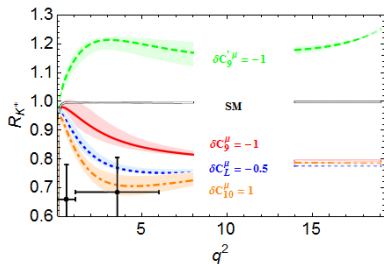
$$C_7^{\text{SM}}(m_b) = -0.333$$

- **New physics in muons**

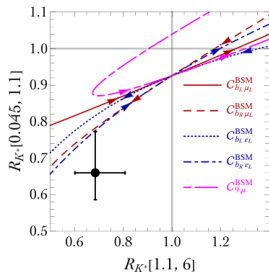


Geng, Grinstein, Jäger, Martin Camalich, Ren, Shi, arXiv: 1704.05446

- Nodes indicate steps of $\Delta C^\mu = +0.5$
 - ▶ **Primed operators** $C'_{9,10}$: Monotonically decreasing dependence $R_{K^*}(R_K)$!
- **New physics in electrons** \sim mirror image of above (see D'Amico *et al.* 1704.05438)



Geng, Grinstein, Jäger, Martin Camalich, Ren, Shi, arXiv: 1704.05446



D'Amico *et al.* 1704.05438

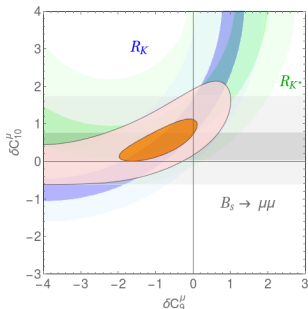
Obs.	Expt.	SM	$\delta C_L^\mu = -0.5$	$\delta C_9^\mu = -1$	$\delta C_{10}^\mu = 1$	$\delta C_9^{\prime\mu} = -1$
$R_K [1, 6] \text{ GeV}^2$	0.745 ± 0.090	$1.0004_{-0.0007}^{+0.0008}$	$0.773_{-0.003}^{+0.003}$	$0.797_{-0.002}^{+0.002}$	$0.778_{-0.007}^{+0.007}$	$0.796_{-0.002}^{+0.002}$
$R_{K^*} [0.045, 1.1] \text{ GeV}^2$	0.66 ± 0.12	$0.920_{-0.006}^{+0.007}$	$0.88_{-0.02}^{+0.01}$	$0.91_{-0.02}^{+0.01}$	$0.862_{-0.011}^{+0.016}$	$0.98_{-0.03}^{+0.03}$
$R_{K^*} [1.1, 6] \text{ GeV}^2$	0.685 ± 0.120	$0.996_{-0.002}^{+0.002}$	$0.78_{-0.01}^{+0.02}$	$0.87_{-0.03}^{+0.04}$	$0.73_{-0.04}^{+0.03}$	$1.20_{-0.03}^{+0.02}$
$R_{K^*} [15, 19] \text{ GeV}^2$	—	$0.998_{-0.001}^{+0.001}$	$0.776_{-0.002}^{+0.002}$	$0.793_{-0.001}^{+0.001}$	$0.787_{-0.004}^{+0.004}$	$1.204_{-0.008}^{+0.007}$

Very clean null-tests of the SM!

- **Warning:** Central Value at ultralow- q^2 is difficult to accommodate with UV physics

Fits with clean observables only

- Assume NP is μ -specific



Coeff.	best fit	χ^2_{\min}	p -value	SM exclusion [σ]	1σ range	3σ range
δC_9^μ	-1.64	5.65	0.130	3.87	[-2.31, -1.12]	[<-4, -0.31]
δC_{10}^μ	0.91	4.98	0.173	3.96	[0.66, 1.18]	[0.20, 1.85]
δC_L^μ	-0.61	3.36	0.339	4.16	[-0.78, -0.46]	[-1.14, -0.16]
Coeff.	best fit	χ^2_{\min}	p -value	SM exclusion [σ]	parameter ranges	
$(\delta C_9^\mu, \delta C_{10}^\mu)$	(-0.76, 0.54)	3.31	0.191	3.76	$C_9^\mu \in [-1.50, -0.16]$	$C_{10}^\mu \in [0.18, 0.92]$

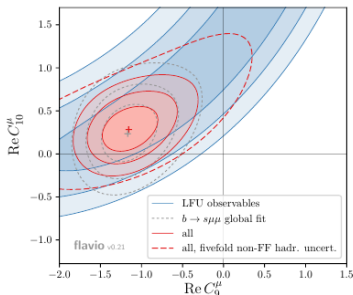
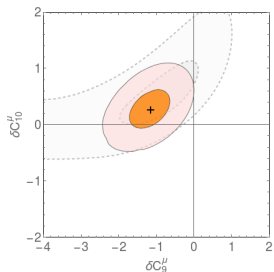
- Deviation of the SM: p -value of 3.7×10^{-4} (3.6σ)
- Best fit suggests a leptonic left-handed scenario δC_L^μ

- **Include 70-100 observables**

Coeff.	best fit	χ^2_{\min}	p -value	SM exclusion [σ]	1σ range	3σ range
δC_9^μ	-1.37	61.98 [64 dof]	0.548	4.37	[-1.70, -1.03]	[-2.41, -0.41]
δC_{10}^μ	0.60	71.72 [64 dof]	0.237	3.06	[0.40, 0.82]	[-0.01, 1.28]
δC_L^μ	-0.59	63.62 [64 dof]	0.490	4.18	[-0.74, -0.44]	[-1.05, -0.16]
Coeff.	best fit	χ^2_{\min}	p -value	SM exclusion [σ]	parameter ranges	
$(\delta C_9^\mu, \delta C_{10}^\mu)$	(-1.15, 0.28)	60.33 [63 dof]	0.572	4.17	$C_9^\mu \in [-1.54, -0.81]$	$C_{10}^\mu \in [0.06, 0.50]$

- C_9 in global fits is subject to hadronic uncertainties!

- ▶ Results in the $(\delta C_9^\mu, \delta C_{10}^\mu)$ plane



Altmannshofer *et al.* arXiv:1704.05435

Combined explanations of R_{D^*} and R_{K^*} anomalies

- **New physics** in $C_{9,10}$

SMEFT operators: $Q_{\ell q(ijkl)}^{(1)} = \frac{1}{\Lambda^2} (\bar{Q}_L^i \gamma^\mu Q_L^j) (\bar{L}_L^k \gamma_\mu L_L^l), \quad Q_{\ell q(ijkl)}^{(3)} = \frac{1}{\Lambda^2} (\bar{Q}_L^i \gamma^\mu \vec{\tau} Q_L^j) \cdot (\bar{L}_L^k \gamma_\mu \vec{\tau} L_L^l)$

- ▶ Same operators as ϵ_L solution to $R_{D^{(*)}}$ anomalies!

- **Suggestive of a combined explanation*** Bhattacharya et al. '14, Alonso et al. '15, Greljo et al. '15, ...

* Here we are assuming the same tree-level mediator; alternatives with tree vs. loop Bauer Neubert'15

- ▶ **Reduce the NP scale** of $b \rightarrow s\mu\mu$

$$\Lambda < 9 \text{ TeV}$$

Luzio & Nardecchia '17

- ▶ **Quark flavor structure:** B decays from pure $C_{ij} \sim \delta_{i3}\delta_{j3}$ ruled out by τ and Z decays!

Ferruglio et al. '16

- ▶ **Lepton flavor structure:**

- ★ Large enhancements $\tilde{C}_{\tau\tau} \gg \tilde{C}_{\mu\mu}$ ruled out by $B \rightarrow K^{(*)}\nu\nu$ unless $C_{\tau\tau}^{(1)} \simeq C_{\tau\tau}^{(3)}$
- ★ **Charged-lepton flavor violation!** in e.g. $B \rightarrow K^{(*)}\tau\mu$ unless there is "flavor alignment"

Glashow et al. '14, Alonso et al. '15, ...

Combined explanations of R_{D^*} and R_{K^*} anomalies

- **New physics** in $C_{9,10}$

SMEFT operators: $Q_{\ell q}^{(1)}(ijkl) = \frac{1}{\Lambda^2} (\bar{Q}_L^i \gamma^\mu Q_L^j) (\bar{L}_L^k \gamma_\mu L_L^l)$, $Q_{\ell q}^{(3)} = \frac{1}{\Lambda^2} (\bar{Q}_L^i \gamma^\mu \vec{T} Q_L^j) \cdot (\bar{L}_L^k \gamma_\mu \vec{T} L_L^l)$

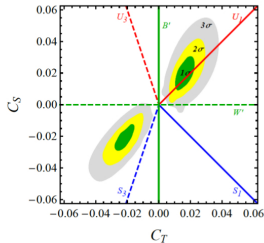
▶ Same operators as ϵ_L solution to R_{D^*} anomalies!

- **Suggestive of a combined explanation*** Bhattacharya et al. '14, Alonso et al. '15, Greljo et al. '15, ...

* Here we are assuming the same tree-level mediator; alternatives with tree vs. loop Bauer Neubert'15

Three main options
(for the combined explanation):

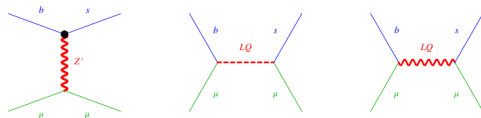
	SU(2) _L	
	singlet	triplet
Vector LQ:	U_1	U_3
Scalar LQ:	S_1	S_3
Colorless vector:	B'	W'



G. Isidori at LHCb Implication workshop 2017, Buttazzo et al. '17

Mediators in simplified models

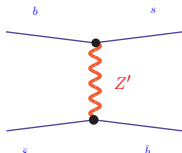
- **Most popular models:** Z' and **Leptoquarks** between 1 TeV and 90 TeV



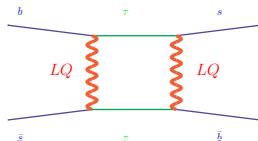
(see D'Amico *et al.* 1704.05438)

- **Extra bounds from low energy** e.g. B_S - \bar{B}_S mixing

▶ Z' exchange at tree level



▶ LQ exchanges at loop level

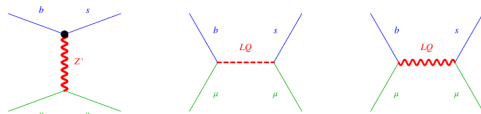


- ★ Require small Z' bs coupling! (e.g. **MFV**)
 $M_{Z'} \lesssim 10$ TeV or nonperturbative $Z' \mu\mu$

- ★ Important for LQs addressing $R_{D^{(*)}}$

Mediators in simplified models

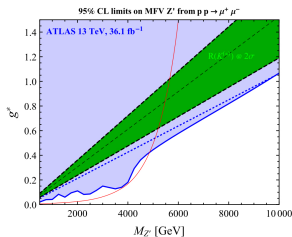
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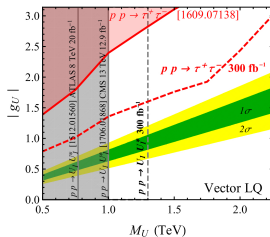
- **Implications for high p_T physics**

- ▶ **MFV Z' in kinematic tails of $pp \rightarrow \mu\mu$**



Greljo&Marzocca'17

- ▶ **3rd gen. VLQs in $pp \rightarrow \tau\tau$**



Buttazzo et al. '17

Efforts from the TH community

- “Instant” workshop at CERN last May

Instant workshop on B meson anomalies

📅 17 May 2017, 09:00 → 19 May 2017, 16:30 Europe/Zurich

📍 4-3-006 - TH Conference Room (CERN)

👤 Jorge Martin Camalich (CERN) , Jure Zupan (University of Cincinnati) , Marco Nardecchia (CERN)

Description In light of recent anomalies in B physics there is an increased interest in the theory community on its implications. As a quick response we are organizing an “Instant workshop on B meson anomalies” at CERN from May 17-May 19 2017.

CERN-TH Institute programmed for the next year

“From flavor anomalies to direct discovery of New Physics”

Oct. 22nd to Nov. 2nd 2018 (tentative)

Conclusions

① “Evidence” for lepton universality violation in $b \rightarrow c\tau\nu$!

- ▶ Left-handed and tensor tree-level contributions $\Lambda \sim 1\text{TeV}$
- ▶ **Warning:** Avoid effects at one-loop level
- ▶ **Challenging UV completions:** Should appear soon at the LHC

② “Evidence” for lepton universality violation in $b \rightarrow s\ell\ell$

- ▶ 4σ tension of the data with LUV (SM)
- ▶ **Clean** observables prefer C_L^ℓ -type of scenario

B. Grinstein @ B -decay anomalies workshop

- Fits of reported LUV require

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

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