Lepton-flavor Violation in meson decays

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Lepton-flavor symmetries in the SM

- $SU(3)_\ell \times SU(3)_e \times U(1)_L \times U(1)_{e-\ell}$ fulfilled by Gauge interactions ...
  ... but broken by the Yukawas in the SM
- Upon diagonalization of mass matrix $U(1)_\tau \times U(1)_\mu \times U(1)_e$ survives*

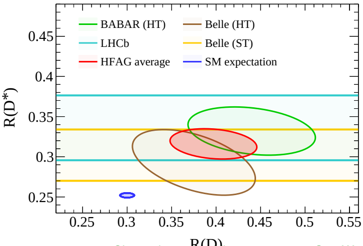
  * Up to tiny effects in charged-lepton processes produced by neutrino masses
- Interactions in the **SM** are **charged-lepton universal** up to ...
  1. **Higgs mediated** (Negligible)
  2. **Kinematic effects** (process dependent)
- ... and **charged-lepton flavor symmetric**

Lepton-universality and charged-lepton-flavor-conservation are a hallmark of the SM

Many experimental tests: $\mu \to e\gamma$, $\tau \to \mu\gamma$, $\mu \to 3e$, $Z \to \ell\ell$, $W \to \ell\nu$, $\pi \to \ell\nu$, $K \to \ell\nu$, $K \to \pi\ell\nu$ $\tau \to \ell\nu\nu$,...

Lepton Univ. violating new-physics in B CC decays? $R_{D^{(*)}}$ anomalies

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



Ciezarek *et al.* arXiv:1703.01766, Guy Worsmer's talk

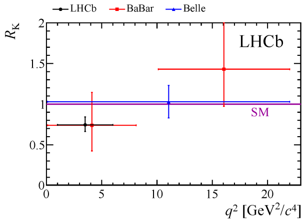
- ***Excesses*** reported by **3 different experiments** in **2 channels** at $\sim 4\sigma$
  - 15% enhancement of the tau SM amplitude:

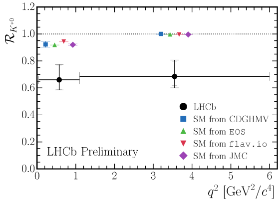
LUV in $b \to c\tau\nu$

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

Lepton Univ. violating new-physics in B FCNC decays? $R_{K^{(*)}}$ anomalies

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





- 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 $b \to s\ell\ell$

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

LUV in $b \to c\tau\nu$ decays

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

- Low-energy effective Lagrangian (no RH ν)

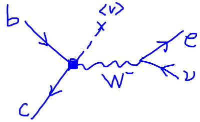
$$\mathcal{L}_{\rm eff}^{\ell}=-\frac{G_F V_{cb}}{\sqrt{2}}[(1+\epsilon_L^{\ell})\bar{\ell}\gamma_\mu(1-\gamma_5)\nu_\ell\cdot\bar{c}\gamma^\mu(1-\gamma_5)b+\epsilon_R^{\ell}\;\bar{\ell}\gamma_\mu(1-\gamma_5)\nu_\ell\;\;\bar{c}\gamma^\mu(1+\gamma_5)b$$

$$+\bar{\ell}(1-\gamma_5)\nu_\ell\cdot\bar{c}[\epsilon_S^{\ell}-\epsilon_P^{\ell}\gamma_5]b+\epsilon_T^{\ell}\;\bar{\ell}\sigma_{\mu\nu}(1-\gamma_5)\nu_\ell\cdot\bar{c}\sigma^{\mu\nu}(1-\gamma_5)b]+\text{h.c.},$$

Wilson coefficients: ϵ_Γ decouple as $\sim v^2/\Lambda_{\rm NP}^2$

- Matching to high-energy Lagrangian – SMEFT
  - Symmetry relations for ϵ_Γ
    - In charged-currents ϵ_R^{ℓ}:

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

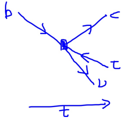


☛ RHC is lepton universal: $\epsilon_R^{\ell}\equiv\epsilon_R+\mathcal{O}(\frac{v^4}{\Lambda_{\rm NP}^4})\Rightarrow$ **Cannot explain LUR $R_{D^{(*)}}$!**

Down to **4** operators to explain R_{D^*}: ϵ_L, ϵ_S, ϵ_P, ϵ_T

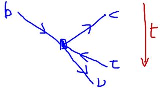
The constraint of the B_c-lifetime

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



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

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



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

- Use the lifetime of B_c
  - Very high experimental precision (1.5%):

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

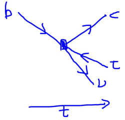
  - **QCD**: "Most of the B_c lifetime comes from $\bar{c} \to \bar{s}$ ($\sim$ 65%) and $b \to c$ ($\sim$ 30%)"

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

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

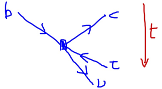
The constraint of the B_c-lifetime

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

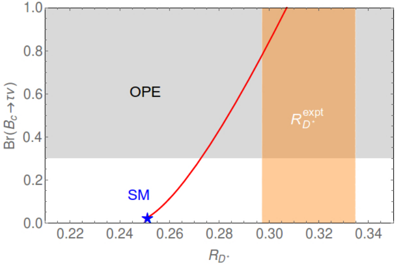


$$\epsilon_P \; \langle D^*(k,\epsilon)|\bar{c}\gamma_5 b|\bar{B}(p)\rangle = -\frac{2\epsilon_P \; m_{D^*}}{m_b + m_c} A_0(q^2)\epsilon^* \cdot q$$

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



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



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 with challenging UV completions

- Left-handed $\epsilon_L = 0.13$

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

  - If coupled predominantly to 3^{rd} generations

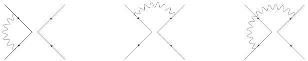
Warning

Radiatively LUV in τ and Z decays!

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

  - Need non-trivial flavor str. Crivellin *et al.* arXiv:1703.09226

- Tensor $\epsilon_T = 0.38$ (and scalars)
  - **EW corrections:** Large mixing tensor into scalars



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

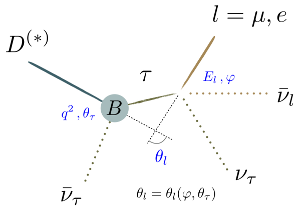
Gonzalez-Alonso, JMC & Mimouni arXiv: 1706.00410

  - **Tensors never come alone:** Important for the pheno!

UV models should be discovered soon at the LHC!

Discriminating power of kinematic distributions ($\tau^- \to \ell^- \bar{\nu}_\ell \nu_\tau$)

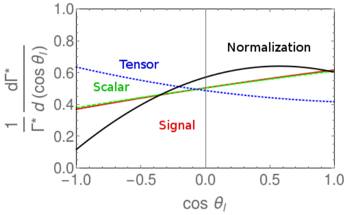
Alonso, Kobach, JMC, PRD94(2016)no.9,094021; Alonso, JMC, Westhoff, PRD95(2017)no.9,093006



- **Integrate** **analytically** **the τ and ν's angular phase-space:**

$$\frac{d^3\Gamma_5}{dq^2\, dE_\ell\, d(\cos\theta_\ell)} = \mathcal{B}[\tau_\ell]\ \mathcal{N}\ \left[I_0(q^2, E_\ell) + I_1(q^2, E_\ell)\cos\theta_\ell + I_2(q^2, E_\ell)\cos\theta_\ell^2\right]$$

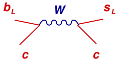
- Angular distribution help discriminate signal, **normalization**, NP



LUV in $b \to s\ell\ell$ decays

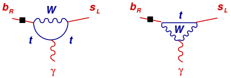
Effective field theory approach to $b \to s\ell\ell$ decays

- **CC** (Fermi theory):

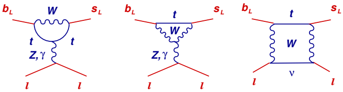


$$\Rightarrow \qquad G_F\, V_{cb}\, V_{cs}^*\, C_2\, \bar{c}_L\gamma^\mu b_L\, \bar{s}_L\gamma_\mu c_L$$

- **FCNC**:

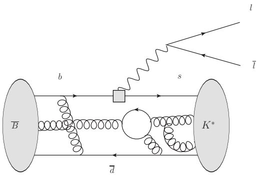


$$\Rightarrow \qquad \frac{e}{4\pi^2}\, G_F\, V_{tb}\, V_{ts}^*\, m_b\, C_7\, \bar{s}_L\sigma_{\mu\nu} b_R\, F^{\mu\nu}$$



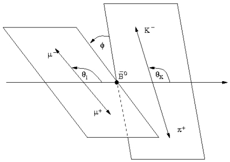
$$\Rightarrow \qquad G_F\, V_{tb}\, V_{ts}^*\, \frac{\alpha}{4\pi}\, C_{9(10)}\, \bar{s}_L\gamma^\mu b_L\, \bar{\ell}\gamma_\mu(\gamma_5)\ell$$

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



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

The complex example: $B \to K^{(*)}\ell\ell$



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

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

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

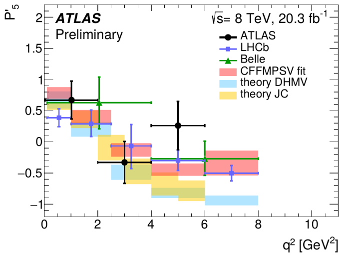
$$+ \quad I_7 \sin 2\theta_k \sin\theta_l \sin\phi + I_8 \sin 2\theta_k \sin 2\theta_l \sin\phi + I_9 \sin^2\theta_k \sin^2\theta_l \sin 2\phi)$$

- Anomalies in the angular observables ...

$$P_5' = \frac{I_5}{2\sqrt{-I_{2s}I_{2c}}}$$

- **Cancel leading theory uncertainties**

LHCb: JHEP 1602 (2016) 104



New physics?

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

Descotes-Genon *et al.* PRD88,074002

- **Interpretation blurred by hadronic uncertainties**

Anatomy of the amplitude in a nutshell

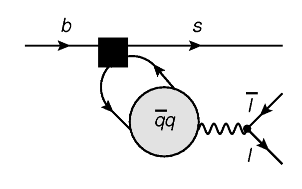
- Helicity amplitudes $\lambda = \pm 1, 0$

$$H_V(\lambda) = -iN\Big\{ \overbrace{\Big[C_9 \tilde{V}_{L\lambda} + \frac{m_B^2}{q^2} h_\lambda\Big]}^{C_9^{\rm eff}} - \frac{\hat{m}_b m_B}{q^2} C_7 \tilde{T}_{L\lambda} \Big\},$$

$$H_A(\lambda) = -iN C_{10} \tilde{V}_{L\lambda}$$

- Hadronic form factors: **7** independent q^2-dependent nonperturbative functions

"Charm" contribution



$$h_\lambda \propto \int d^4y e^{iq\cdot y} \langle \bar{K}^* | T\{j^{\rm em,had,\mu}(y), \mathcal{O}_{1,2}(0)\} | \bar{B}\rangle$$

- Charm and $\mathcal{O}_9$ are tied up by renormalization

Only $C_9^{\rm eff}$ is observable!

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 $B \to K\ell\ell$

$$\frac{d\Gamma_K}{dq^2} = \mathcal{N}_K |\vec{k}|^3 f_+(q^2)^2 \left(\left|C_{10}^\ell + C_{10}^{\prime\ell}\right|^2 + \left|C_9^\ell + C_9^{\prime\ell} + 2\frac{m_b}{m_B+m_K} C_7 \frac{f_T(q^2)}{f_+(q^2)} - 8\pi^2 h_K \right|^2 \right) + \mathcal{O}\left(\frac{m_\ell^4}{q^4}\right) + \ldots$$

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

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

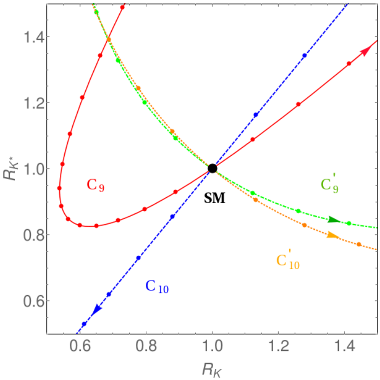
$$\frac{d\Gamma_0}{dq^2} = \mathcal{N}_{K^*0} |\vec{k}|^3 V_0(q^2)^2 \left(\left|C_{10}^\ell - C_{10}^{\prime\ell}\right|^2 + \left|C_9^\ell - C_9^{\prime\ell} + \frac{2m_b}{m_B} C_7 \frac{T_0(q^2)}{V_0(q^2)} - 8\pi^2 h_{K^*0} \right|^2 \right) + \mathcal{O}\left(\frac{m_\ell^2}{q^2}\right)$$

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

Wilson coefficients in the SM

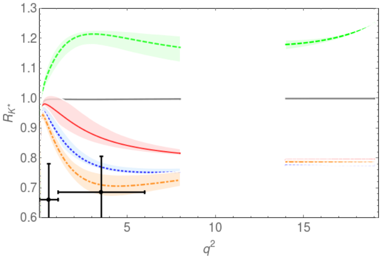
$C_9^{\rm SM}(m_b) \simeq -C_{10}^{\rm SM} = +4.27$ $\qquad$ $C_7^{\rm SM}(m_b) = -0.333$

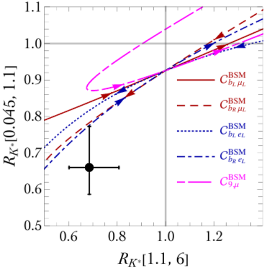
- **New physics in muons**



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)





SM; $\delta C_9^{\mu} = -1$; $\delta C_{10}^{\mu} = 1$; $\delta C_9^{\prime\mu} = -1$; $\delta C_L^{\mu} = -0.5$

D'Amico *et al.* 1704.05438

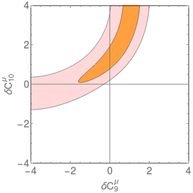
Obs.	Expt.	SM	$\delta C_L^{\mu} = -0.5$	$\delta C_9^{\mu} = -1$	$\delta C_{10}^{\mu} = 1$	$\delta C_9^{\prime\mu} = -1$
R_K [1, 6] GeV^2	0.745 ± 0.090	$1.0004^{+0.0008}_{-0.0007}$	$0.773^{+0.003}_{-0.003}$	$0.797^{+0.002}_{-0.002}$	$0.778^{+0.007}_{-0.007}$	$0.796^{+0.002}_{-0.002}$
R_{K^*} [0.045, 1.1]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

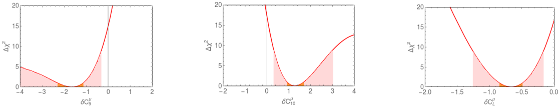
Very clean observables!

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

Fit 1: Only LUR

- We chose μ-specific for reference (e-specific obtained by $\delta C_i^e \simeq \delta C_i^\mu$)



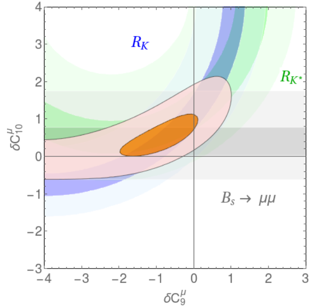


Coeff.	best fit	$\chi^2_{\rm min}$	p-value	SM exclusion $[\sigma]$	1σ range	3σ range
δC_9^μ	-1.64	4.52	0.104	3.87	[-2.31,-1.13]	[<-4, -0.31]
δC_{10}^μ	1.27	2.24	0.326	4.15	[0.91,1.70]	[0.31,3.04]
δC_L^μ	-0.66	2.93	0.231	4.07	[-0.85,-0.49]	[-1.26,-0.16]
Coeff.	best fit	$\chi^2_{\rm min}$	p-value	SM exclusion $[\sigma]$	parameter ranges	
$(\delta C_9^\mu, \delta C_{10}^\mu)$	(0.85, 2.69)	1.99	0.158	3.78	$C_9^\mu \in$ [-0.71, 1.38]	$C_{10}^\mu \in$ [0.61, >4]

- $\chi^2_{\rm SM,min} = 19.51$ (3 d.o.f) which corresponds to a p-value of 2×10^{-4} (3.7σ)
- **Requires C_{10}:** $\chi^2_{\rm min}/{\rm d.o.f.} \simeq 1$
  Fit slighty tensed up by ultralow R_{K^*} bin

Fit 2: LUR+$B_s \to \mu\mu$

- **Need to assume NP is μ-specific**



Coeff.	best fit	$\chi^2_{\rm min}$	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	$\chi^2_{\rm min}$	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]

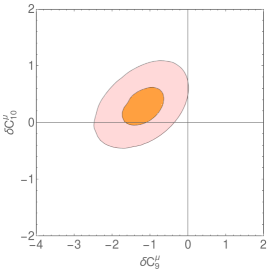
- **Deviation of the SM**: p-value of 3.7×10^{-4} (3.6σ)
- Best fit suggests a leptonic left-handed scenario δC_L^{μ}

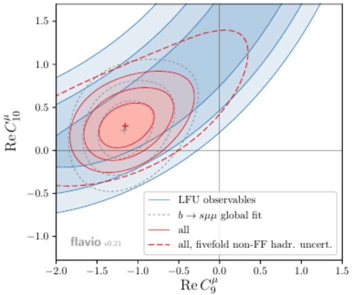
Fit 3: Global fit

Coeff.	best fit	$\chi^2_{\rm min}$	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	$\chi^2_{\rm min}$	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]

- The best fit is now driven by δC_9^μ!
- **However:** Remember that C_9 is subject to severe hadronic uncertainties!

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





Altmannshofer *et al.* arXiv:1704.05435

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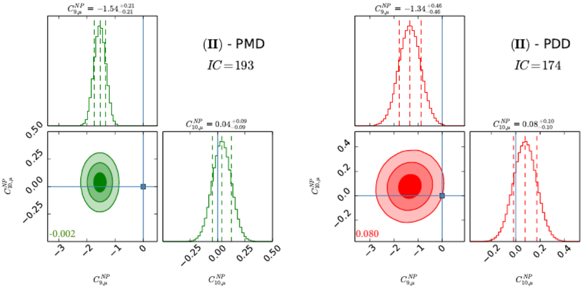
- Different treatment of hadronic uncertainties: **Significance can change** $3\sigma - 7\sigma$**!**



Ciuchini *et al.* arXiv:1704.05447

- **One group** claims $\gtrsim 5\sigma$ consistently in all global fits Capdevila *et al.* 1704.05340

Precision probes of lepton nonuniversal $C_{9,10}^{\ell}$

- Go to the angular analysis of $B \to K^* \ell\ell$...

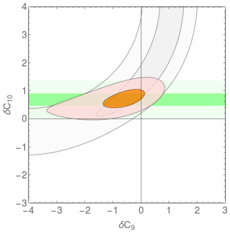
$$I_6^{(\ell)} = N C_{10}^{\ell} q^2 \beta_\ell^2(q^2)|\vec{k}| \left(\mathrm{Re}[H_{V-}^{(\ell)}(q^2)]V_-(q^2) + \mathrm{Re}[H_{V+}^{(\ell)}(q^2)\frac{H_{A+}^{(\ell)}(q^2)}{C_{10}^{\ell}}] \right)$$

  - The $H_{V,A+}$ amplitudes are suppressed unles we have primed operators!

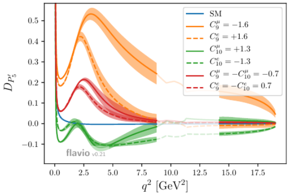
$$R_6[a,b] \approx \frac{C_{10}^{\mu}}{C_{10}^{e}} \times \frac{\int_a^b |\vec{k}|q^2\beta_\mu^2 \,\mathrm{Re}[H_{V-}^{(\mu)}(q^2)]V_-(q^2)}{\int_a^b |\vec{k}|q^2 \,\mathrm{Re}[H_{V-}^{(e)}(q^2)]V_-(q^2)}$$

R_6 is an optimal C_{10} LUV analyser!

- Prospects for R_6 with a 5% precision



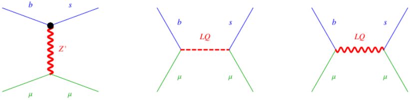
- $D_{P_5'} = P_5'^{\mu} - P_5'^{e}$



Altmannshofer *et al.* arXiv:1704.05435

Model-building

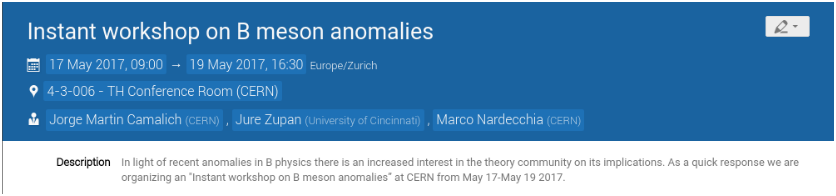
- **Most popular models:** Z' and Leptoquarks between 1 TeV and 100 TeV (perturbativity)



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

  - Also loop-mediated, compositeness, x-dim, flavor-gauged symmetries...
  - **ca. 250 papers ...**

- **All you ever wanted to know about *B*-decay anomalies but were afraid to ask**



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.

Conclusions

1. **"Evidence" for lepton universality violation in $b \to c\tau\nu$!**
   - Left-handed and tensor **tree-level** contributions $\Lambda \sim 1$TeV
   - **Warning:** Avoid effects at one-loop level
   - **Challenging UV completions:** Should appear soon at the LHC
2. **"Evidence" for lepton universality violation in $b \to s\ell\ell$**
   - 4σ tension of the data with LUV (SM)
   - **Clean** observables prefer C_L^ℓ-type of scenario

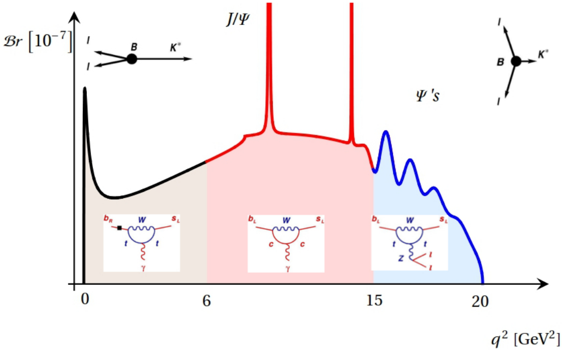
B. Grinstein @ *B*-decay anomalies workshop

- Fits of reported LUV require

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

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

Backup



- **Large-recoil region** (low q^2)
  - **No LQCD** (Sum Rules, models ...) and **QCDf** and **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)
  - **LQCD**+**HQEFT** + **OPE** (duality violation)
  - Dominated by semileptonic operators

Hadronic uncertainties (Form factors)

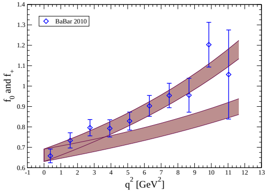
- Hadronic interactions are lepton universal⇒**Uncertainties largely cancel in R_{D^*}**
- **Fit** model-indep. parametrizations of FF to **experimental** $B \to D^{(*)}(\mu, e)\nu$ data

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

- **Example:** $B \to D\tau\nu$ with LQCD

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

  - 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)

- No non-zero recoil LQCD for $B \to D^*$: **HQET** (cont. from scalar FF is small)

  See: Bernlocher *et al.* arXiv: 1703.05330, Bigi *et al.* 1703.06124

Hadronic uncertainties (Form factors)

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- **Fit** model-indep. parametrizations of FF to **experimental** $B \to D^{(*)}(\mu, e)\nu$ data

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

SM predictions of $R_{D^{(*)}}$ seem to be well under control

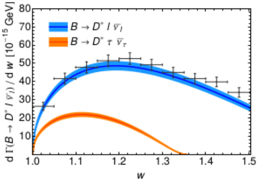
- LQCD calculations for $B \to D^* \ell\nu$ will test **HQET**

Hadronic uncertainties (Form factors)

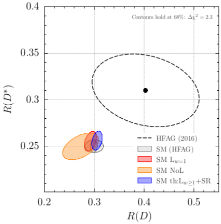
- Hadronic interactions are lepton universal⇒**Uncertainties largely cancel in** R_{D^*}
- **However,** τ **is heavy:** phase-space and kinematic effects are important
- **Strategy:** Fit parametrizations of FF to **experimental** $B \to D^{(*)}\ell\nu$ data
  - Use HQEFT
  - Use LQCD (only for $B \to D\tau\nu$ mode)
  - Employ parametrizations of the q^2 dependence constrained by analyticity and unitarity

    Boyd, Grinstein & Lebed '96, Caprini, Lellouch & Neubert'98
- **Non-zero recoil LQCD** for $B \to D^*\tau\nu$ not available yet

  Prediction relies on **HQET relations** neglecting $\mathcal{O}((\Lambda_{QCD}/m_{c,b})^2, \alpha_s \times \Lambda_{QCD}/m_{c,b}, \alpha_s^2)$



Bernlocher *et al.* arXiv: 1703.05330



$\tau^- \to \pi^- \nu_\tau$ as a τ polarimeter: P_L

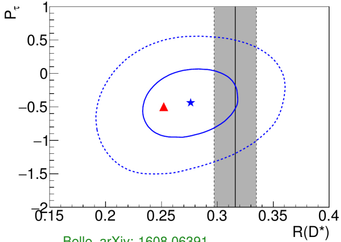
$$\frac{dP_L}{dq^2} = \frac{d\Gamma_{B,+}/dq^2 - d\Gamma_{B,-}/dq^2}{d\Gamma_B/dq^2}$$

Slope in E_π of $d\Gamma_4 \Rightarrow$ **Longitudinal Polarization**

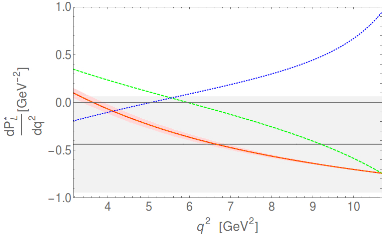
$$\frac{d^2\Gamma_4}{dq^2 dE_\pi} = \frac{\mathcal{B}[\tau_\pi]}{|\vec{p}_\tau|}\frac{d\Gamma_B}{dq^2}\left[1 + \xi(E_\pi, q^2)\frac{dP_L}{dq^2}\right], \quad \xi(E_\pi, q^2) = \frac{1}{\beta_\tau}\left(2\frac{E_\pi}{E_\tau} - 1\right)$$

M. Davier *et al.* PLB306, 411 (1993), Tanaka&Watanabe, PRD82, 034027 (2010)

- Applied to the BD^* channel by *Belle*



Belle, arXiv: 1608.06391



$\tau^- \to \pi^- \nu_\tau$ as a τ polarimeter: $P_\perp$ (and A^τ_{FB}!)

Alonso, JMC & Westhoff, arXiv:1702.02773

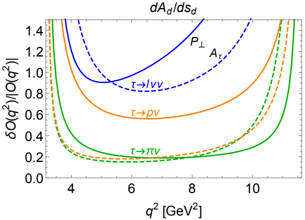
- $P_\perp$ probes **interference between τ polarization states**

$$d\Gamma\, dP_\perp = \frac{(2\pi)^4\, d\Phi_3}{2 m_B} 2\mathrm{Re}\left[\mathcal{M}_{B+}\mathcal{M}^\dagger_{B-}\right]$$

$$\frac{d^2 A^d_{FB}}{dq^2 dE_d} = \mathcal{B}[\tau_d]\left[f^d_{FB}(E_d, q^2)\frac{dA_\tau}{dq^2} + f^d_\perp(E_d, q^2)\frac{dP_\perp}{dq^2}\right]$$

$$f^\pi_{FB} = -\frac{\left(2E_\pi E_\tau - m_\tau^2\right)\left(E_\tau - |\vec{p}_\tau| - 2E_\pi\right)}{2|\vec{p}_\tau|^3 E_\pi} \qquad f^\pi_\perp = -\frac{4E_\pi^2 - 4E_\pi E_\tau + m_\tau^2}{\pi\, E_\pi |\vec{p}_\tau|^3 m_\tau}$$

- Prospects at Belle (II)



- Sensitivity to NP