QCD systematics in current flavour anomalies

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Lepton-flavor symmetries hallmark of the SM

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

- **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 $\Longrightarrow$ $U(1)_\tau \times U(1)_\mu \times U(1)_e$ survives!*

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**

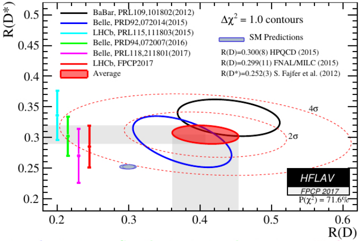
- Many experimental tests:

$$\begin{array}{llll} \mu \to e\gamma & \mathcal{O}(10^{-13}), & Z \to \ell\ell & \mathcal{O}(10^{-4}) \\ \tau \to \mu\gamma & \mathcal{O}(10^{-8}), & W \to \ell\nu & \mathcal{O}(10^{-4}) \\ \tau \to 3\mu & \mathcal{O}(10^{-8}), & \pi \to \ell\nu & \mathcal{O}(10^{-4}) \quad \ldots \end{array}$$

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

Lepton-universality ratios

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



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

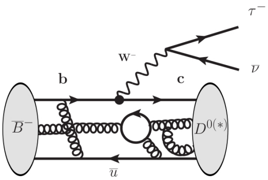
BaBar: Hadronic tag, leptonic τ LHCb: leptonic τ hadronic τ

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

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

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

Hadronic uncertainties (Form factors)



- **QCD is lepton universal!**
  - **However:** Important kinematic effects

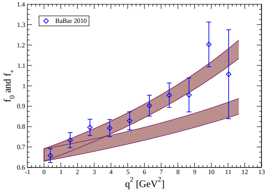
- **Fit Form Factors to experimental $B \to D^{(*)}(\mu, e)\nu$ data**

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

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

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

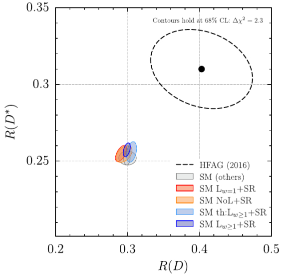
  - Scalar $f_0(q^2)$ enters rate $\propto m_\ell^2$
  - **CVC** implies $f_0(0) = f_+(0)$



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

Hadronic uncertainties (Form factors)

- Upcoming **LQCD calculation** of the $B \to D^*$ FFs at **non-zero recoil**!
- **Current prediction relies on HQET** relations including $\Lambda_{\rm QCD}/m_{c,b}$ corrections
  - Contribution to the $B \to D^* \tau \nu$ 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 $b \to c\tau\nu$

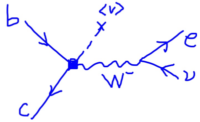
- Low-energy effective Lagrangian (no RH ν)

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

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}:

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

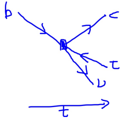


☛ RHC is lepton universal: $\epsilon_R^{\ell} \equiv \epsilon_R + \mathcal{O}(\frac{v^4}{\Lambda_{\rm NP}^4}) \Rightarrow$ **Cannot explain LUR $R_{D^{(*)}}$!**

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

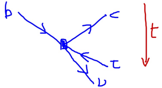
The constraint of the B_c-lifetime

- $B \to D^* \tau\nu$ 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,. . .

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

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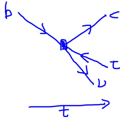

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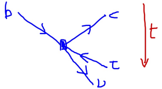
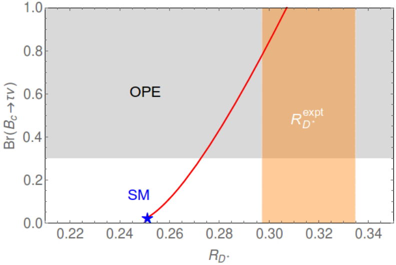


$$\frac{\mathrm{Br}(B_c^- \to \tau \bar{\nu}_\tau)}{\mathrm{Br}(B_c^- \to \tau \bar{\nu}_\tau)^{\mathrm{SM}}} = \left| 1 + \epsilon_L + \frac{m_{B_c}^2}{m_\tau (m_b + m_c)} \epsilon_P \right|^2$$



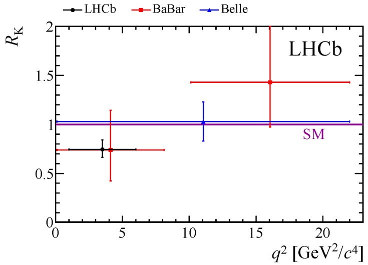
Alonso, Grinstein&JMC, arXiv: 1611.06676

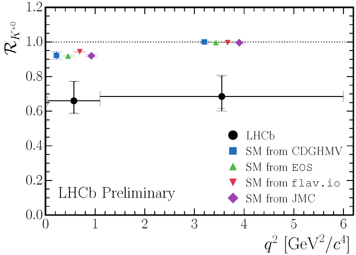
τ_{B_c} makes **highly implausible**
ANY "scalar solution"
(e.g. 2HDM) to the R_{D^*} anomaly!

Lepton-universality violation in $b \to s\ell\ell$ decays

Lepton Universality Ratios

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





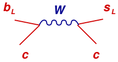
- Skewed μ-to-e ratios reported by **LHCb** in **2 channels** at $\sim 4\sigma$
  - Anomalies in **muonic BRs** and **angular observables**: **Global analyses** $\sim 5\sigma$
  - 25% deficit (enhancement) of the SM muon (electron) amplitude:

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

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

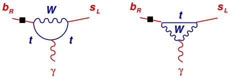
Effective field theory approach to $b \to s\ell\ell$ decays

- **CC** (Fermi theory):

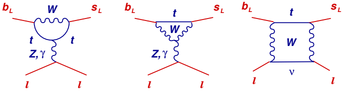


$$\Rightarrow \qquad G_F\, V_{cb}\, V_{cs}^*\, C_2\, \bar{c}_L \gamma^\mu b_L\, \bar{s}_L \gamma_\mu c_L$$

- **FCNC**:

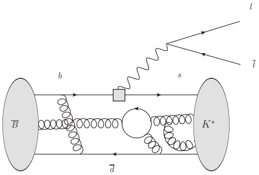


$$\Rightarrow \qquad \frac{e}{4\pi^2}\, G_F\, V_{tb}\, V_{ts}^*\, m_b\, C_7\, \bar{s}_L \sigma_{\mu\nu} b_R\, F^{\mu\nu}$$



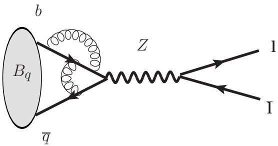
$$\Rightarrow \qquad G_F\, V_{tb}\, V_{ts}^*\, \frac{\alpha}{4\pi}\, C_{9(10)}\, \bar{s}_L \gamma^\mu b_L\, \bar{\ell} \gamma_\mu (\gamma_5) \ell$$

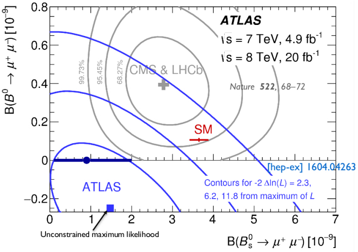
- **New-Physics** also in C_i or e.g. $\mathcal{O}_i'$ obtained $P_L \to P_R$ in $\bar{s}_L b$



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

The beautiful example: $B_q^0 \to \ell\ell$





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

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

Bobeth *et al.* PRL112(2014)101801

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

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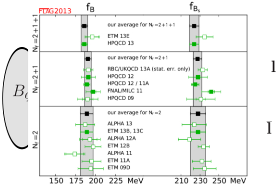

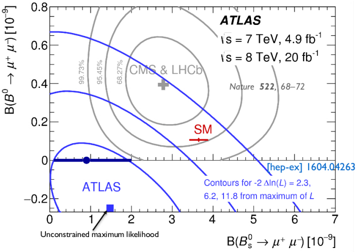

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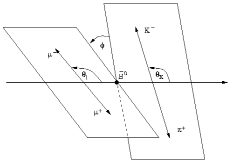
The complex example: $B \to K^* \ell\ell$



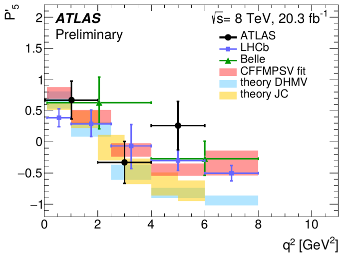
$$\frac{d^{(4)}\Gamma}{dq^2\, d(\cos\theta_l) d(\cos\theta_k) d\phi} = \frac{9}{32\pi}\left(I_1^s \sin^2\theta_k + I_1^c \cos^2\theta_k\right.$$
$$+ \quad (I_2^s \sin^2\theta_k + I_2^c \cos^2\theta_k)\cos 2\theta_l + I_3 \ \sin^2\theta_k \sin^2\theta_l \cos 2\phi$$
$$+ \quad I_4 \sin 2\theta_k \sin 2\theta_l \cos\phi + \mathbf{I_5} \sin 2\theta_k \sin\theta_l \cos\phi + I_6 \sin^2\theta_k \cos\theta_l$$
$$+ \quad \left. I_7 \sin 2\theta_k \sin\theta_l \sin\phi + I_8 \sin 2\theta_k \sin 2\theta_l \sin\phi + I_9 \ \sin^2\theta_k \sin^2\theta_l \sin 2\phi\right)$$

- 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

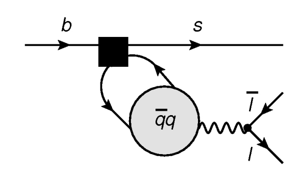
- Helicity amplitudes $\lambda = \pm 1, 0$

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

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

- 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 $B\to K\ell\ell$

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

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

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

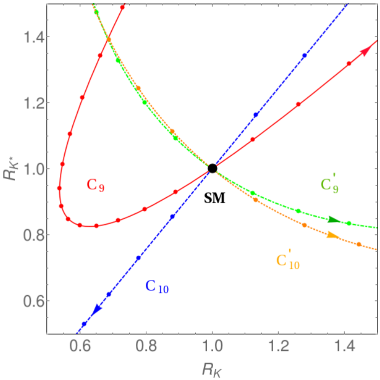
$$\frac{d\Gamma_0}{dq^2}=\mathcal{N}_{K^*0}|\vec{k}|^3 V_0(q^2)^2\left(\left|C_{10}^\ell-C_{10}^{\prime\ell}\right|^2+\left|C_9^\ell-C_9^{\prime\ell}+\frac{2m_b}{m_B}C_7\frac{T_0(q^2)}{V_0(q^2)}-8\pi^2 h_{K^*0}\right|^2\right)+\mathcal{O}\left(\frac{m_\ell^2}{q^2}\right)$$

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

Wilson coefficients in the SM

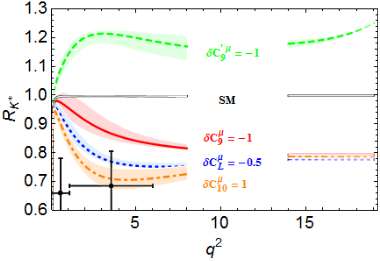
$C_9^{\rm SM}(m_b)\simeq -C_{10}^{\rm SM}=+4.27$ $\qquad$ $C_7^{\rm SM}(m_b)=-0.333$

- **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)



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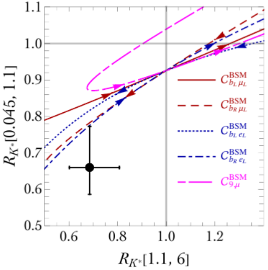


D'Amico *et al.* 1704.05438

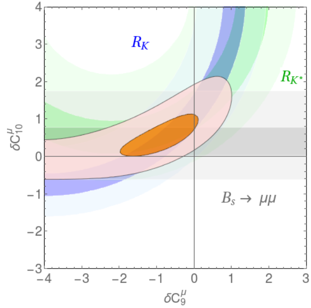
Obs.	Expt.	SM	$\delta C_L^{\mu} = -0.5$	$\delta C_9^{\mu} = -1$	$\delta C_{10}^{\mu} = 1$	$\delta C_9'^{\mu} = -1$
R_K [1, 6] GeV^2	0.745 ± 0.090	$1.0004^{+0.0008}_{-0.0007}$	$0.773^{+0.003}_{-0.003}$	$0.797^{+0.002}_{-0.002}$	$0.778^{+0.007}_{-0.007}$	$0.796^{+0.002}_{-0.002}$
R_{K^*} [0.045, 1.1] GeV^2	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 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	$\chi^2_{\min}$	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	$\chi^2_{\min}$	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}

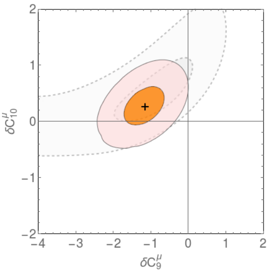
Global fits

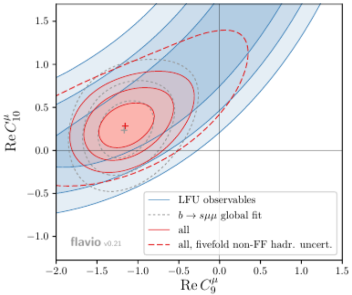
- **Include 70-100 observables**

Coeff.	best fit	χ^2_{min}	p-value	SM exclusion $[\sigma]$	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 $[\sigma]$	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

Global fits

- **Include 70-100 observables**

Coeff.	best fit	$\chi^2_{\rm min}$	p-value	SM exclusion $[\sigma]$	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]
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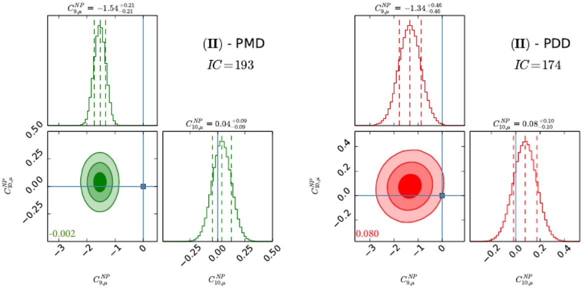
- Different treatment of hadronic uncertainties: **Significance can change** $3\sigma - 6\sigma$**!**



Ciuchini *et al.* arXiv:1704.05447

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

“Extraordinary claims require Extraordinary evidence”
– C. Sagan

1. **“Evidence” for lepton universality violation in $b \to c\tau\nu$!**
   - Left-handed and tensor **tree-level** contributions $\Lambda \sim 1$ TeV
2. **“Evidence” for lepton universality violation in $b \to s\ell\ell$**
   - **Clean** observables prefer C_L^ℓ-type of scenario

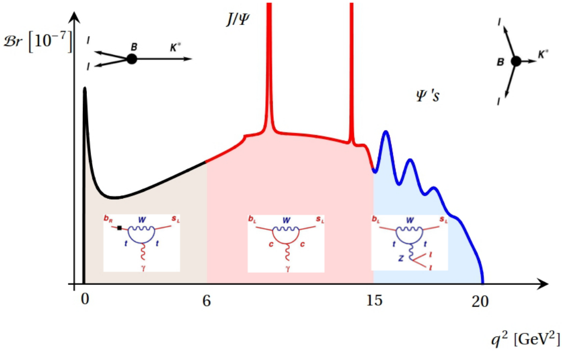
B. Grinstein @ Instant workshop on *B*-decay anomalies

- 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

Description at low q^2 using QCD factorization

- **Heavy-quark** and **large-recoil** (K^*) limit only **2** independent "soft form factors"

$$T_+ = V_+ = 0, \qquad T_- = V_- = \frac{2E}{m_B}\xi_\perp, \qquad T_0 = V_0 = S = \xi_\parallel$$

Dugan *et al.* PLB255(1991)583, Charles *et al.* PRD60(1999)014001

- The observable P_5' Matias *et al.*'12

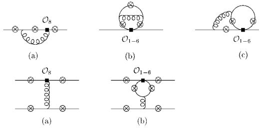
$$P_5'|_\infty = \frac{I_5}{2\sqrt{-I_{2s}I_{2c}}} \simeq \frac{C_{10}\left(C_{9,\perp}+C_{9,\parallel}\right)}{\sqrt{(C_{9,\parallel}^2+C_{10}^2)(C_{9,\perp}^2+C_{10}^2)}},$$

$$\begin{cases} C_{9,\perp} = C_9^{\rm eff}(q^2) + \frac{2\,m_b\,m_B}{q^2}C_7^{\rm eff} \\ C_{9,\parallel} = C_9^{\rm eff}(q^2) + \frac{2\,m_b\,E}{q^2}C_7^{\rm eff} \end{cases}$$

- For the charm Beneke, Feldmann&Seidel, NPB612(2001)25

$$\langle \ell^+\ell^-\bar{K}_a^*|\mathcal{H}_{\rm w}|\bar{B}\rangle = C_a\xi_a + \Phi_B\otimes T_a\otimes\Phi_{K^*} + \mathcal{O}(\Lambda_{\rm QCD}/m_b)$$

Below $c\bar{c}$ threshold! $q^2 \leq 6$ GeV^2



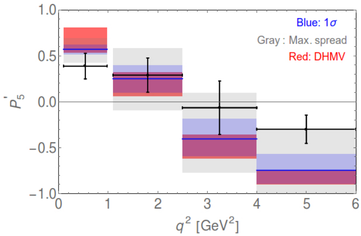
No model-independent treatment for Λ/m_b corrections

$$P_5' = P_5'|_\infty \left(1 + \frac{a_{V_-} - a_{T_-}}{\xi_\perp} \frac{m_B}{|\vec{k}|} \frac{m_B^2}{q^2} C_7^{\rm eff} \frac{C_{9,\perp} C_{9,\parallel} - C_{10}^2}{(C_{9,\perp}^2 + C_{10}^2)(C_{9,\perp} + C_{9,\parallel})} + \frac{a_{V_0} - a_{T_0}}{\xi_\parallel} 2\, C_7^{\rm eff} \frac{C_{9,\perp} C_{9,\parallel} - C_{10}^2}{(C_{9,\parallel}^2 + C_{10}^2)(C_{9,\perp} + C_{9,\parallel})} \right.$$

$$\left. + 8\pi^2 \frac{\tilde{h}_-}{\xi_\perp} \frac{m_B}{|\vec{k}|} \frac{m_B^2}{q^2} \frac{C_{9,\perp} C_{9,\parallel} - C_{10}^2}{C_{9,\perp} + C_{9,\parallel}} + \dots \right) + \mathcal{O}(\Lambda^2/m_B^2)$$

Jäger and JMC, PRD93(2016)no.1,014028

- **Predictions** for $P_i^{(\prime)}$ observables strongly depend on theoretical assumptions



Better understanding of had. uncert. desirable!

- **Use models of QCD, sum rules, etc ...?**
- **Charm under control?** Ciuchini *et al.* arXiv:1512.07157, Bobeth *et al.* arXiv:1707.07305