The shape of New Physics in *B*-meson decays

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VUB Workshop on flavour anomalies

March 29th 2018

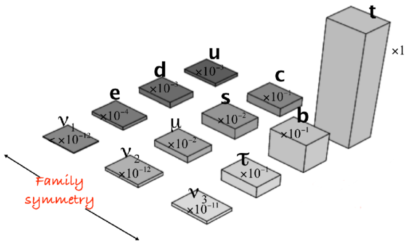
Outline

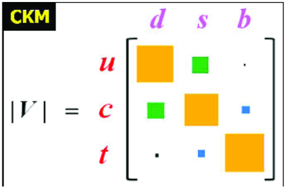
The flavor puzzle of the SM

- The matter content of the SM comes in **3 almost identical generations**
  - **Identical:** Same quantum numbers under $SU(3)_c \times SU(2)_L \times U(1)_Y$
  - **Almost:** Symmetry broken by Yukawa couplings!

$$-\mathcal{L}_Y = \bar{q}_L Y_d d_R H + \bar{q}_L Y_u u_R \tilde{H} + \bar{\ell}_L Y_e e_R H + h.c.$$

- **Masses** $M_u = L_u Y_u R_u^\dagger,\ M_d = L_d Y_d R_d^\dagger$ and **mixing**, $\mathbf{V_{CKM}} = L_u L_d^\dagger$ are **hierarchical!**





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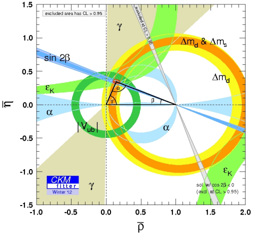
- Rotations are "not physical" in the SM ,only **masses** and $\mathbf{V_{CKM}}$

Where does flavor come from?

- **Geometrical:** *à la* Warped x-dimensions $\Lambda_{\rm NP} \sim \Lambda_{\rm Natural}$ Randall&Sundrum'98
- **Dynamical:** Horizontal symmetries $\Lambda_{\rm NP} \gg \Lambda_{\rm Natural}$ Froggat&Nielsen '78
- ...

Flavor BSM phenomenology

- Masses $\Rightarrow$ **9 parameters**
- Complex and Unitary matrix$\Rightarrow$ **3 angles** and **1 phase**



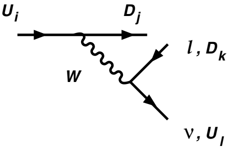
$$V_{CKM} \simeq \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

$$\lambda = 0.2253(7), \quad A = 0.808(22),$$
$$\bar{\rho} = 0.132(22), \quad \bar{\eta} = 0.341(13)$$

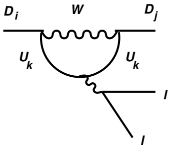
- Few parameters if we count the **thoudands of processes** they describe! (**PDG**)

Flavor BSM phenomenology

- **CC** $U_i \to D_j$: **Tree level**



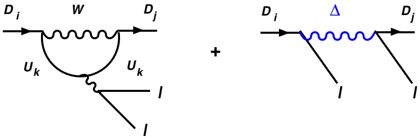
- **FCNC** $D_i \to D_j$: **Loop**



- $\mathcal{M} \sim G_F\, V_{ij} U^*_{kl}$,
  $V_{ij} U^*_{kl}$ can be $\mathcal{O}(1)$
- $\mathcal{M} \sim G_F \sum_k V_{ki} V^*_{kj} \frac{m_K^2}{m_W^2} \frac{\alpha}{4\pi}$,
  GIM and **loop** suppression
- In the SM, FCNCs are suppressed w.r.t. CC interactions: **“Rare” decays!**

Flavor BSM phenomenology

- Suppressed processes are very sensitive **to virtual exchange** of new particles!
- **Example: FCNC** $b \to s\ell\ell$:

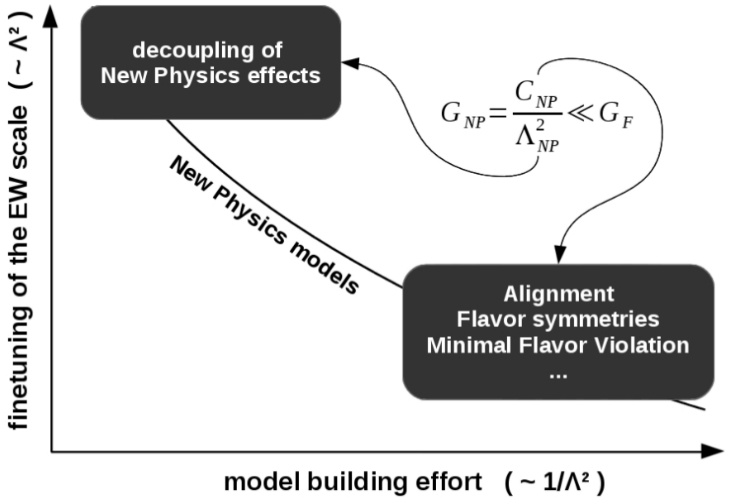


$$\mathcal{M} \sim G_F\, V_{tb} V_{ts}^* \frac{\alpha}{4\pi} \Big(C^{\rm SM} + \overbrace{\frac{4\pi}{\alpha} \frac{1}{V_{tb} V_{ts}^*}}^{\sim 200^2} \frac{v^2}{M^2} g^2 \Big) \times \langle \bar{s} b \otimes \bar{\ell}\ell \rangle$$

Rare b decays sensitive to $M \sim 100$ TeV !!

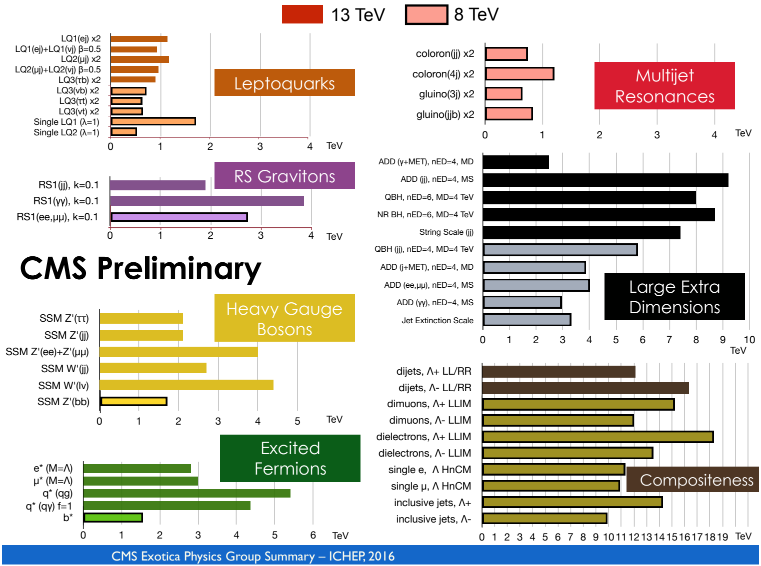
- Neutral meson mixing up to few 10^4 TeV!!

Approaches to the New Physics Flavor Puzzle

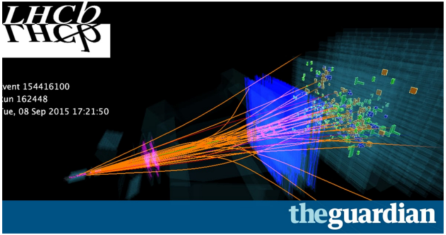


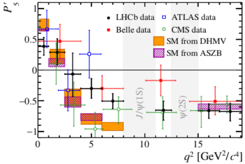
- No **New Physics** at colliders ...

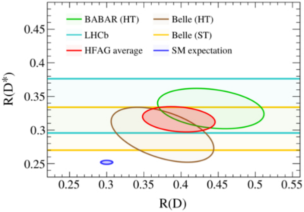
https://twiki.cern.ch/twiki/bin/view/CMSPublic/ https://twiki.cern.ch/twiki/bin/view/AtlasPublic/

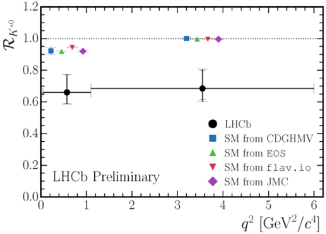


B-decay anomalies









“Evidence” for lepton-universality violation in *b*-quark decays!

Lepton-flavor symmetries is a hallmark of the SM

- **Universality of gauge interactions**: Same reps. under $SU(2)_L \times U(1)_Y$
- **Yukawa interactions** are not lepton-flavor symmetric

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

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

Lepton Flavor Symmetries of the SM

SM is **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:

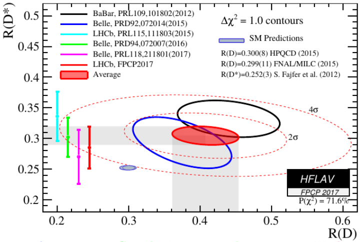
$$\mu \to e\gamma \qquad \mathcal{O}(10^{-13}), \quad Z \to \ell\ell \qquad \mathcal{O}(10^{-4})$$

$$\ldots$$

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

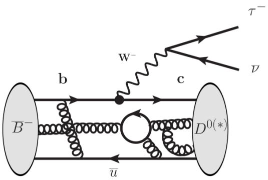
BaBar: Hadronic tag, leptonic τ LHCb: leptonic τ hadronic τ

- ***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)



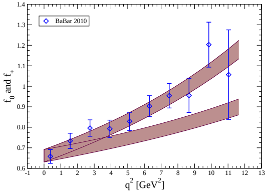
- **QCD is lepton universal!**
  - **However:** Important kinematic effects

- **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

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

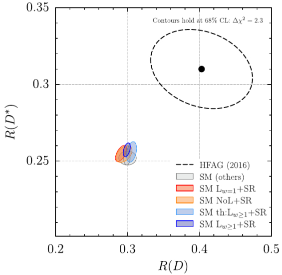


  - Scalar $f_0(q^2)$ enters rate $\propto m_\ell^2$
  - **CVC** implies $f_0(0) = f_+(0)$

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)

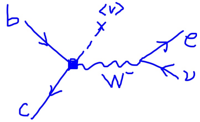
$$\mathcal{L}_{\rm eff}^{\ell}=-\frac{G_F V_{cb}}{\sqrt{2}}[(1+\epsilon_L^{\ell})\bar{\ell}\gamma_\mu(1-\gamma_5)\nu_\ell\cdot\bar{c}\gamma^\mu(1-\gamma_5)b+\epsilon_R^{\ell}\;\bar{\ell}\gamma_\mu(1-\gamma_5)\nu_\ell\;\bar{c}\gamma^\mu(1+\gamma_5)b$$

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

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}:

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

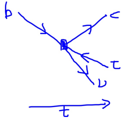


☛ RHC is lepton universal: $\epsilon_R^{\ell}\equiv\epsilon_R+\mathcal{O}(\frac{v^4}{\Lambda_{\rm NP}^4})\Rightarrow$ **Cannot explain LUR $R_{D^{(*)}}$!**

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

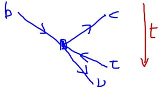
The constraint of the B_c-lifetime

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

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

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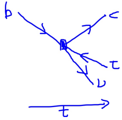

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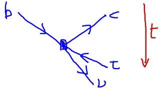

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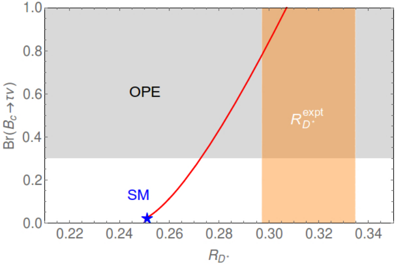


Alonso, Grinstein&JMC, arXiv: 1611.06676

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

- Bound $\mathrm{BR}(B_C \to \tau\nu)$ from LEP!

Akeroyd&Chen, 1708.04072

The left-handed operator

- Left-handed $\epsilon_L = 0.13$: *Universal* enhancement of the $b \to c\tau\nu$ rates by 30%

  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 3^{rd} generation:** Non-trivial flavor str. Buttazzo *et al.* arXiv:1706.07808
  - **Model dependence:** EFT only gives log parts (mixing)

- It can also solve $b \to s\ell\ell$ anomaly! Bhattacharya et al. '14, Alonso, JMC & Grinstein. '15, ...
  - **Lepton flavor structure:**
    - ★ Large enhancements $\tilde{C}_{\tau\tau} \gg \tilde{C}_{\mu\mu}$ ruled out by $B \to K^{(*)}\nu\nu$ unless $C_{\tau\tau}^{(1)} \simeq C_{\tau\tau}^{(3)}$
    - ★ **Vector Leptoquark** U_1^μ ($\overline{3}$,1,2/3) produces this! Alonso, JMC & Grinstein. '15, Barbieri *et al.* '15, ...

- More on Dario's talk!

Tensor and scalar operators

- Mixing in $H^3\psi^2$ operators that **modify Yukawas** Jenkins *et al.*, arXiv: 1310.4838

- Tensor $\epsilon_T = 0.38$
  - **EW+QED corrections:** Large mixing tensor into scalars

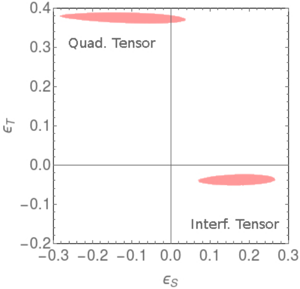
$$\begin{pmatrix} w_{ledq} \\ w_{\ell equ} \\ w^{(3)}_{\ell equ} \end{pmatrix}_{(\mu=m_Z)} = \begin{pmatrix} 1.19 & 0. & 0. \\ 0. & 1.20 & -0.185 \\ 0. & -0.00381 & 0.959 \end{pmatrix} \begin{pmatrix} w_{ledq} \\ w_{\ell equ} \\ w^{(3)}_{\ell equ} \end{pmatrix}_{(\mu=1\text{ TeV})}$$

Gonzalez-Alonso, JMC & Mimouni arXiv: 1706.00410

  - **No explicit models** that give *only* tensor operators

- Tensor & Scalar

- Fit to current values of $R_{D^{(*)}}$



- **New solution:** ϵ_T interferes constructively in R_{D^*}
  - ★ **Best Fit:** $\epsilon_S = 0.17$, $\epsilon_T = -0.04$
  - ★ **Scalar Leptoquark** S_1 ($\bar{3}$,1,1/3) produces

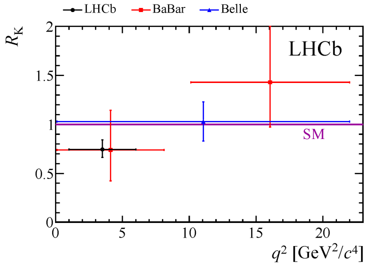
$$\epsilon_T(M) = -\frac{\epsilon_{S_L}(M)}{4}$$

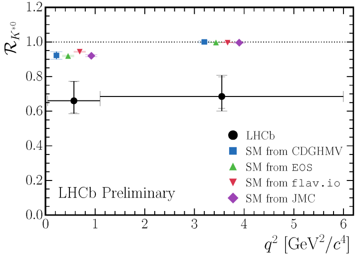
  - ★ $\epsilon_P \sim 0.2$ produces BR($B_c \to \tau\nu$) $\sim$ 6%

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

Lepton Universality Ratios

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





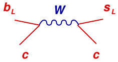
- Skewed μ-to-e ratios reported by **LHCb** in **2 channels** at $\sim 4\sigma$
  - Anomalies in **muonic BRs** and **angular observables**: **Global analyses** $\sim 5\sigma$
  - 25% deficit (enhancement) of the SM muon (electron) amplitude:

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

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

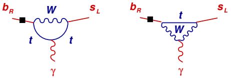
Effective field theory approach to $b \to s\ell\ell$ decays

- **CC** (Fermi theory):

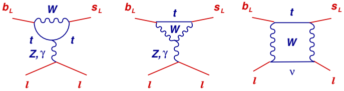


$$\Rightarrow \qquad G_F\, V_{cb}\, V_{cs}^{*}\, C_2\, \bar{c}_L \gamma^{\mu} b_L\, \bar{s}_L \gamma_{\mu} c_L$$

- **FCNC**:

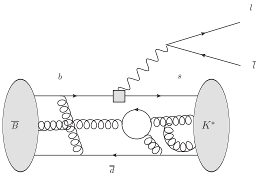


$$\Rightarrow \qquad \frac{e}{4\pi^2}\, G_F\, V_{tb}\, V_{ts}^{*}\, m_b\, C_7\, \bar{s}_L \sigma_{\mu\nu} b_R\, F^{\mu\nu}$$



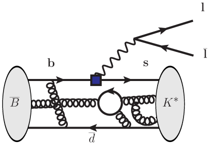
$$\Rightarrow \qquad G_F\, V_{tb}\, V_{ts}^{*}\, \frac{\alpha}{4\pi}\, C_{9(10)}\, \bar{s}_L \gamma^{\mu} b_L\, \bar{\ell} \gamma_{\mu} (\gamma_5) \ell$$

  - **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.* Λ_{QCD}
      HQEFT, QCDF, SCET,...

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



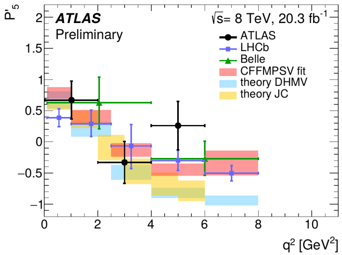
$$\frac{d^{(4)}\Gamma}{dq^2\, d(\cos\theta_l) d(\cos\theta_k) d\phi} = \frac{9}{32\pi} (I_1^s \sin^2\theta_k + I_1^c \cos^2\theta_k$$
$$+ \quad (I_2^s \sin^2\theta_k + I_2^c \cos^2\theta_k) \cos 2\theta_l + I_3 \sin^2\theta_k \sin^2\theta_l \cos 2\phi$$
$$+ \quad I_4 \sin 2\theta_k \sin 2\theta_l \cos\phi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

- 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



- **Interpretation blurred by hadronic uncertainties**

New physics?

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

Descotes-Genon *et al.* PRD88,074002

Anatomy of the amplitude in a nutshell

Jäger and JMC, PRD93 (2016) no.1, 014028

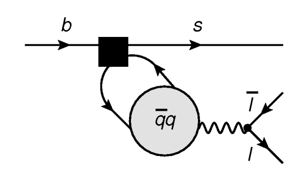
- Helicity amplitudes $\lambda = \pm 1, 0$

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

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

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

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

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

Wilson coefficients in the SM

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

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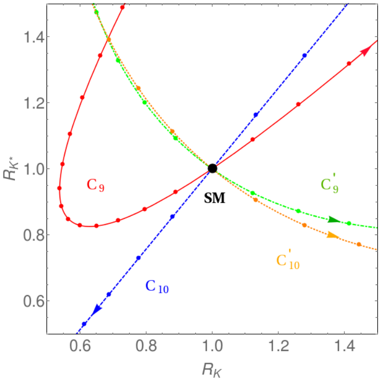
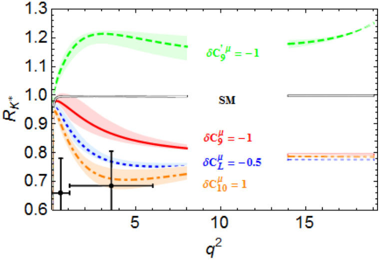
- **New physics in muons**

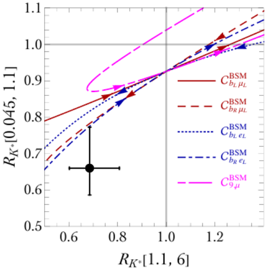


Geng, Grinstein, Jäger, Martin Camalich, Ren, Shi, arXiv: 1704.05446

- 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



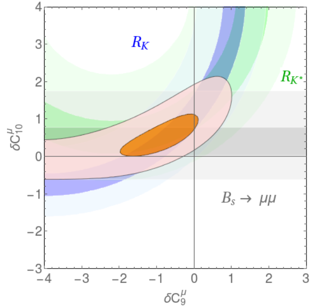
D'Amico *et al.* 1704.05438

Very clean null-tests of the SM!

- **Warning** ☠**:** 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	$\chi^2_{\rm min}$	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

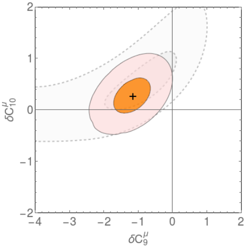
Global fits

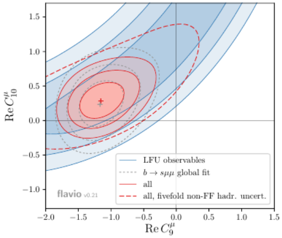
- **Include 70-100 observables**

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]

- 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

- More on Nazila's talk!

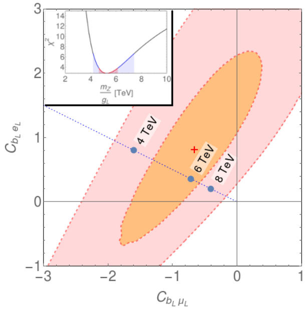
Top-down approach: Knocking on the flavor-puzzle's door?

- **Gauged flavor symmetries** Altmannshofer *et al.* arXiv:1403.1269, Alonso *et al.* arXiv:1704.08158,...
  - **Gauge** $SU(3)_L \times SU(3)_R$ Cline&JMC arXiv:1706.08510
    - ★ Dynamically generate Flavor and UV consistent (no Landau poles)
    - ★ *Baroque* field content for gauge anomalies/SSB-structure

- Couplings to the leptons

$$V_l^L\, T^8\, V_l^{L\dagger} \cong \frac{1}{2\sqrt{3}} \begin{pmatrix} 1 & \epsilon_1 & \epsilon_2 \\ \epsilon_1^* & -2 & \epsilon_3 \\ \epsilon_2^* & \epsilon_3^* & 1 \end{pmatrix}$$

Coupling to both electrons and muons!



- Couplings to electrons opens up much more stringent phenomenology!

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.

- **Check recordings @** `https://indico.cern.ch/event/633880/`

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

"Extraordinary claims require Extraordinary evidence"
– C. Sagan

- **Looking (indirectly) for the Extraordinary Evidence!**
  1. **More data on the measured channels!** $\Rightarrow 5\sigma$ in a single measurement!
     - ★ 5σ-evidence should be soon available in single measurements of $R_{D^{(*)}}$ and $R_{K^{(*)}}$
  2. **Measure NEW channels:** Different channels, different backgrounds
     - ★ Many new channels will be soon available at **LHCb**: $R_{J/\Psi}$, R_{Λ_c}, ...
  3. **Measure NEW observables:** Consistency, different sensitivities to NP
     - ★ New observables will be soon available at **Belle II**: Polarizations, distributions, ...
  4. **Look ELSEWHERE**: Low energy & **High p_T signatures**
     - ★ New flavor sectors at reach: $b \to s\nu\nu$, $b \to d\mu\mu$, $b \to s\tau\tau$

Indirect discovery or Ruling-out of the *B*-anomalies in 5-10 yrs!

IF true $\Longrightarrow$ **THEN Discovery case** for next-generation collider (FCC-ee, FCC-hh, ...)

Searches for $B_c \to \tau\nu$ at LEP

- BR($B_c \to \tau\nu$) measured in a e^+e^- collider at the Z pole Akeroyd&Chen, 1708.04072
  - Searches of $B^- \to \tau^-\nu$ above $B_c\,\bar{B}_c$ threshold really measure

    Mangano&Slabospitsky, PLB410(1997)299

$$\overbrace{\text{BR}_{\text{eff}}}^{\text{LEP}} = \overbrace{\text{BR}(B \to \tau\nu)}^{\text{Belle \& BaBar}} + \overbrace{\frac{f_c}{f_u}}^{\text{TH.input}} \text{BR}(B_c \to \tau\nu)$$

  - B_c contribution suppressed by $f_c/f_u \sim 10^{-3}$-10^{-2} but enhanced by $\frac{|V_{cb}|^2}{|V_{ub}|^2}\frac{f_{B_c}^2}{f_B^2} \sim$ **700**

- f_c/f_u: Fraction of hadronization into B_c over B
  - Traded by experimental data and **computable TH. input**

$$R_\ell = \frac{f_c}{f_u}\frac{\text{BR}(B_c \to J/\psi\mu\nu)}{B \to J/\psi K}$$

  - R_ℓ measured by **CDF** and reconstructed from **LHCb** data

Searches for $B_c \to \tau\nu$ at LEP

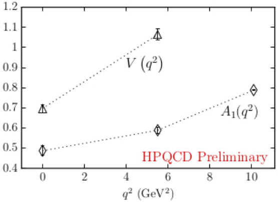
- **Model calculations** predict BR($B_c \to J/\psi\mu\nu$) $\in 1 - 7\%$!

	pQCD	WSL[9]	EFG[7]	ISK[6]	HNV[5]	DV[4]
$V^{B_c\to J/\Psi}$	0.42	0.74	0.49	0.83	0.61	0.91
$A_0^{B_c\to J/\Psi}$	0.59	0.53	0.40	0.57	0.45	0.58
$A_1^{B_c\to J/\Psi}$	0.46	0.50	0.50	0.56	0.49	0.63
$A_2^{B_c\to J/\Psi}$	0.64	0.44	0.73	0.54	0.56	0.74

Wang, Fang&Xiao, arXiv: 1212.5903

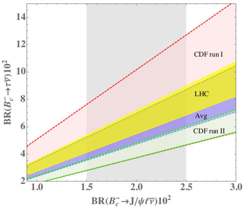
- **Ongoing efforts in LQCD!**

  - **Preliminary** results to select models



HPQCD Collaboration, PoS LATTICE2016 (2016) 281

  - Constrains BR($B_c \to \tau\nu$) $< 10\%$



Akeroyd&Chen, 1708.04072

Adding new channels: $B_c \to J/\psi\tau\nu$

$$R_{J/\psi}^{\rm LHCb} = 0.71 \pm 0.17 \pm 0.18$$

Greg's talk yesterday

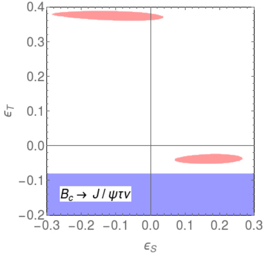
- Comparison with SM **NOW** is subtle because of **model dependence**

Mode	This paper	[8, 30]	[11]	[15]	[16]	[31]	[32]
$B_c^- \to J/\psi\ell\nu$	$6.7^{+2.1+1.0+0.9}_{-1.2-0.4-0.6}$	1.9	2.37	1.5	1.49	1.20	2.07
$B_c^- \to J/\psi\tau\nu$	$0.52^{+0.16+0.08+0.08}_{-0.09-0.03-0.05}$	0.48	0.65	0.4	0.37	0.34	0.49

Qiao&Zhu, 1208.5916

$$R_{J/\psi}^{\rm SM^*} \sim 0.24 - 0.29$$

- Goes in the *right* direction of NP but effect is **large**



- For the LH solution one predicts

$$R_{J/\psi}^{\rm LH^*} \sim 0.35 - 0.4$$

(see also Watanabe, arXiv: 1709.08644)

- Besides more data, **LQCD input urgently needed!**