The shape of new physics in *B* decays

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Rare B decays: Theory and experiment 2016 (Barcelona)

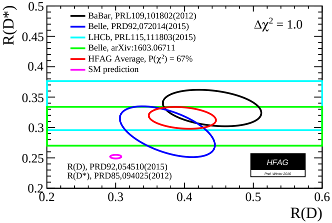
April 20, 2016

Outline

1. The SMEFT approach to the B-decay anomalies
2. $B_s^* \to \ell\ell$
3. $B \to D^{(*)}\tau^-(\to \ell^-\bar{\nu}_\ell\nu_\tau)\bar{\nu}_\tau$

(Lepton universality violating) New-Physics in B decays?

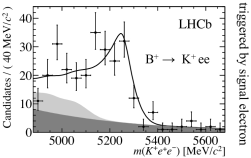
- **"$R_{D^{(*)}}$ anomaly"** in $B \to D^{(*)}\ell\nu$!



- ***Excesses*** observed at $\sim 4\sigma$
- Other "anomalies" in $b \to (u,c)\ell\nu$
  - Inclusive *vs.* Exclusive V_{ub} and V_{cb}
- $\Lambda_{\rm NP} \sim 2$ TeV

- **"R_K anomaly"** in $B \to K\ell\ell$ (**FCNC**)!

LHCb PRL113(2014)151601

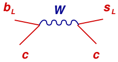


$$R_K = 0.745^{+0.090}_{-0.074}(\mathrm{stat}) \pm 0.036(\mathrm{syst})$$

- Tension with **SM** $\sim 2.6\sigma$
- Other anomalies in $b \to s\mu\mu$
  - Branching fractions
  - Angular analysis $B \to K^*\mu\mu$
- Up to 4σ in global fits
  Altmannshofer and Straub '14, Bobeth *et al.*'15,
  Descotes-Genon *et al.*'15, Hurth *et al.*'15 ...
- $\Lambda_{\rm NP} \sim 30$ TeV

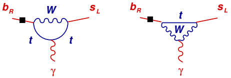
Effective field theory approach to $b \to s\ell\ell$ decays

- **CC** (Fermi theory):

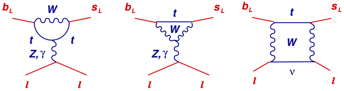


$$\Rightarrow \qquad G_F\, V_{cb}\, V_{cs}^*\, C_2\, \bar{c}_L\gamma^\mu b_L\, \bar{s}_L\gamma_\mu c_L$$

- **FCNC**:

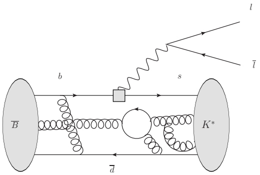


$$\Rightarrow \qquad \frac{e}{4\pi^2}\, G_F\, V_{tb}\, V_{ts}^*\, m_b\, C_7\, \bar{s}_L\sigma_{\mu\nu} b_R\, F^{\mu\nu}$$



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

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



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

Effective field theories: Bottom-up approach to new physics

Guiding principle

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

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

$$\mathcal{O}_7' = \frac{4G_F}{\sqrt{2}} \frac{e}{4\pi^2} \hat{m}_b \, \bar{s}\sigma_{\mu\nu} P_L F^{\mu\nu} b; \qquad \mathcal{O}_{9(10)}' = \frac{4G_F}{\sqrt{2}} \frac{\alpha}{4\pi} \bar{s}\gamma^\mu P_R b \, \bar{\ell}\gamma_\mu(\gamma_5)\ell$$

    - **4** new scalar and pseudoscalar operators

$$\mathcal{O}_S^{(\prime)} = \frac{4G_F}{\sqrt{2}} \frac{\alpha}{4\pi} (\bar{s}P_{R,L}b)\,(\bar{\ell}\,\ell); \qquad \mathcal{O}_P^{(\prime)} = \frac{4G_F}{\sqrt{2}} \frac{\alpha}{4\pi} (\bar{s}P_{R,L}b)\,(\bar{\ell}\,\gamma_5\,\ell)$$

    - **2** new tensor operators

$$\mathcal{O}_{T(5)} = \frac{4G_F}{\sqrt{2}} \frac{\alpha}{4\pi} (\bar{s}\sigma^{\mu\nu} b)\,(\bar{\ell}\,\sigma_{\mu\nu}(\gamma_5)\ell).$$

- But hold on...
  - No evidence of new-particles *on-shell* at colliders up to $E \simeq 1$ TeV...
    ...except a scalar at $s \simeq 125$ GeV that very much resembles to the SM Higgs

Guiding principle *(rewritten)*

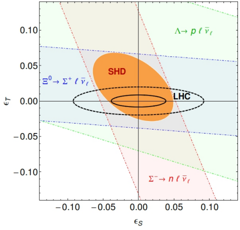
Construct the most general effective operators $\mathcal{O}_k$ built with ***all*** the SM fields and subject to the strictures of $SU(3)_c \times SU(2)_L \times U(1)_Y$

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

- **Example:** Application to searches of NP in baryon β decays (CC)

Cirigliano *et al.*'09'10,

$$\mathcal{L}_{\mathrm{c.c.}} \supset -\frac{G_F V_{us}}{\sqrt{2}} \Big[\epsilon_S (\bar{u}\, s)\, (\bar{e}(1-\gamma_5)\nu_e) + \epsilon_T (\bar{u}\sigma^{\mu\nu} s)\, (\bar{e}\sigma_{\mu\nu}(1-\gamma_5)\nu_e) \Big]$$



- Complementary between hyperon rates and LHC
- Bounds set of NP at $\Lambda_{\mathrm{NP}} \sim 2-4$ TeV

Chang, Gonzalez-Alonso and JMC, PRL114(2015)161802

Relations in FCNCs with dimension-6 operators

Fields	q_L	ℓ_L	u_R	d_R	e_R
Y	1/6	-1/2	2/3	-1/3	-1

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

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

- Furthermore:

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

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

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

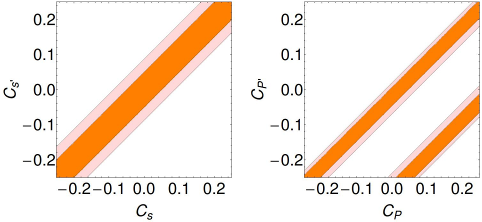
Alonso, Grinstein, JMC, PRL113(2014)241802

Phenomenological consequences $B_q \to \ell\ell$

$$\overline{R}_{ql} = \frac{\overline{\mathcal{B}}_{ql}}{(\overline{\mathcal{B}}_{ql})_{\rm SM}} \simeq \left(|S|^2 + |P|^2\right),$$

De Bruyn *et al.* '12

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



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

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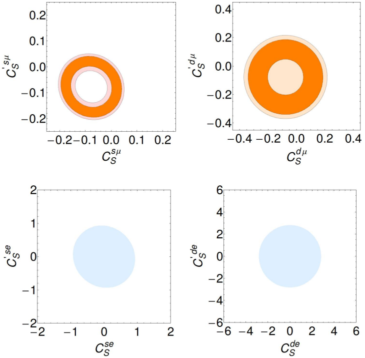


- $\Lambda_{\rm NP}$ (95%C.L.) RGE of QCD+EW+Yukawas

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

Alonso, Grinstein, JMC, PRL113(2014)241802

Phenomenological consequences: R_K

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

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

The R_K anomaly

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

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

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

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

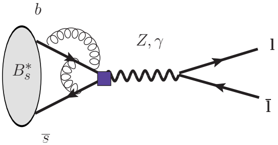
The effect must come from $\mathcal{O}^{(\prime)}_{9,10}$

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

Alonso, Grinstein, JMC, PRL113(2014)241802 (see also Hiller&Schmaltz'14,...)

$B_s^* \to \ell\ell$

B. Grinstein and JMC PRL116(2016)no.14,141801



- B_s^* is the $J^{PC} = 1^{++}$ partner of the B_s
  $m_{B_s^*} = 5415.4^{+2.4}_{-2.1}$ MeV ($m_{B_s^*} - m_{B_s} = 48.7$ MeV)

$$\mathcal{M}_{\ell\ell} = \frac{G_F}{2\sqrt{2}}\lambda_{ts}\frac{\alpha_{\rm em}}{\pi}\Bigg[\left(m_{B_s^*}\, f_{B_s^*}\, C_9 + 2\, f^T_{B_s^*}\, m_b\, C_7\right)\bar{\ell}\not{\varepsilon}\ell + f_{B_s^*}\, C_{10}\bar{\ell}\not{\varepsilon}\gamma_5\ell$$

$$- 8\pi^2\frac{1}{q^2}\sum_{i=1}^{6,8} C_i\,\langle 0|\mathcal{T}_i^\mu(q^2)|B_s^*(q,\varepsilon)\rangle\,\bar{\ell}\gamma_\mu\ell\Bigg],$$

- It is sensitive to C_9!!
- Very clean!
  1. Decay constants: **HQ** limit and **LQCD**...
  2. "Non-factorizable": **OPE** at $q^2 = m_{B_s^*}^2 = 28$ GeV^2 well above charmonium states
     Duality violation is not a concern!!

$$\boxed{\Gamma_{\ell\ell} = 1.12(5)(7)\times 10^{-18}\ \text{GeV}}$$

Branching fraction and prospects for measurement

- Our **weak** decay has to compete with the **EM** $B_s^* \to B_s\gamma$

$$\mathcal{M}_\gamma = \langle B_s(q-k)|j^\mu_{\rm e.m.}|B_s^*(q,\,\varepsilon)\rangle\eta^*_\mu = e\,\mu_{bs}\,\epsilon^{\mu\nu\rho\sigma}\eta^*_\mu q_\nu k_\rho \varepsilon_\sigma$$

μ_{bs} can be computed in HMχPT Cho&Georgi'92, Amundson *et al.*'92

$$\Gamma(B_s^{*0} \to B_s^0\gamma) = 0.10(5)\text{KeV}$$

$$\boxed{\mathcal{B}^{\rm SM}(B_s^* \to \ell\ell) = (0.7-2.2)\times 10^{-11}}$$

- **LQCD** calculations of μ_{bs} are necessary! Becirevic *et al.* EPJC71,1743, Donald *et al.* PRL112,212002

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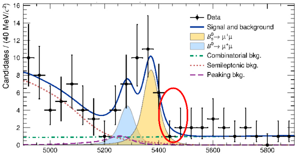


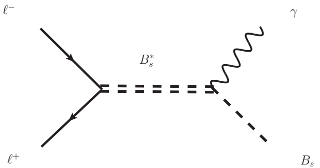
- Small peak in $B_q \to \mu\mu$ measurents
- ~ 10 (~ 100) events @ end of run III (HL-LHC)
- Can be also produced in resonant $\ell^+\ell^-$ scattering!

B. Grinstein and JMC PRL116(2016)no.14,141801

B_s^* production in $\ell^+\ell^-$ scattering

B. Grinstein and JMC PRL116(2016)no.14,141801 (see also Khodjamirian *et al.* JHEP 1511 (2015) 142)

- Resonant enhancement compensates for CKM and loop suppression



$$\sigma(s)=\frac{24\pi\, m_{B_s^*}^2}{s}\left(\frac{s-m_{B_s}^2}{m_{B_s^*}^2-m_{B_s}^2}\right)^3\frac{\Gamma_{\ell\ell}\Gamma}{(s-m_{B_s^*}^2)^2+m_{B_s^*}^2\Gamma^2}$$

- At the pole: $s=m_{B_s^*}^2$

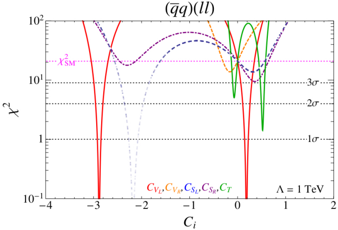
$$\sigma_0=\frac{24\pi}{m_{B_s^*}^2}\mathcal{B}(B_s^*\to\ell\ell)=(7-22)\,\text{fb}$$

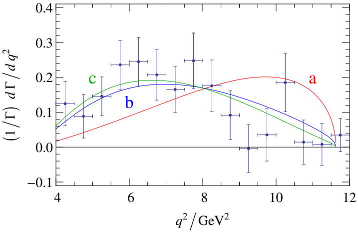
νN scattering experiments at ~ 10 fb!!

- **Energy spread** of accelerator essential:

$$\bar{\sigma}\sim\frac{\pi}{4}\frac{\Gamma}{\Delta E}\sigma_0$$

$B \to D^{(*)} \tau^- \bar{\nu}_\tau$





Freytsis *et al.*, PRD92(2015)no.5,054018 (Becirevic&Tayduganov'12, Fajfer *et al.*'12, Crivellin *et al.*'12,. . .)

- EFT Lagrangian:

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

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

- Only total rates ($R_{D^{(*)}}$) and q^2 spectra are studied to discriminate for NPs
  - Angular analysis based on θ_τ not accessible

Study the full **observable** kinematic distributions of the 5-body decay

See also Nierste, Trine and Westhoff, PRD78 (2008) 015006 and Bordone, Van Dyk and Isidori, arXiv:1603.02974

$B \to D^{(*)}\tau^-(\to \ell^-\bar{\nu}_\ell\nu_\tau)\bar{\nu}_\tau$

Alonso, Kobach, JMC, arXiv: 1602.07671

- Since *(1)* $m_\tau \gg \Gamma_\tau$; and *(2)* integrating 3-ν phase space ($\sim$trivial)

$$d\Gamma = \tau_\tau \sum_{\lambda_\tau=\pm 1/2} d\Gamma_{B,\lambda_\tau} \times d\Gamma_{\tau,\lambda_\tau}$$

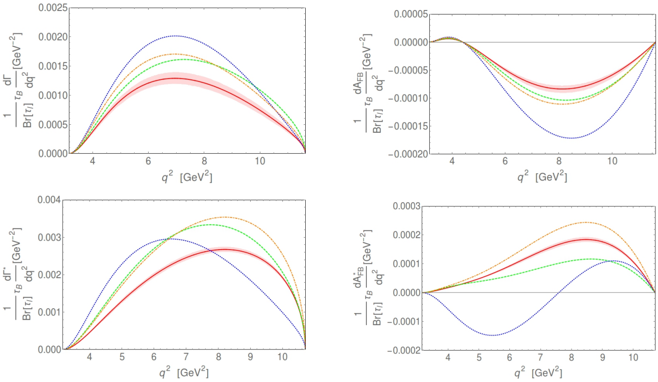
- **Integrate analytically τ angular phase-space:** (nontrivial)

$$\frac{d^3\Gamma_5}{dq^2\, dE_\ell\, d(\cos\theta_\ell)} = \mathcal{B}[\tau_\ell]\, \frac{G_F^2 |V_{cb}|^2 \eta_{\mathrm{EW}}^2}{32\pi^3} \frac{|\vec{k}|}{m_B^2} \left(1 - \frac{m_\tau^2}{q^2}\right)^2 \frac{E_\ell^2}{m_\tau^3} \times \left[I_0(q^2, E_\ell) + I_1(q^2, E_\ell)\cos\theta_\ell + I_2(q^2, E_\ell)\cos\theta_\ell^2\right]$$

  - $\cos\theta_\ell$ defined as for the normalization mode (w.r.t recoiling $D^{(*)}$ in the q rest frame)
  - $I_{0,2}(q^2, E_\ell)$ accessed in $R_{D^{(*)}}$
  - $I_1(q^2, E_\ell)$ accessible only with a FB leptonic asymmetry!

$$\frac{d^2 A_{FB}(q^2, E_\ell)}{dq^2\, dE_\ell} = \left(\int_0^1 d(\cos\theta_\ell) - \int_{-1}^0 d(\cos\theta_\ell)\right) \frac{d^3\Gamma_5}{dq^2\, dE_\ell\, d(\cos\theta_\ell)}$$

$$R_{FB}^{(*)} = \frac{1}{\mathcal{B}[\tau_\ell]} \frac{1}{\Gamma_{\mathrm{norm.}}} A_{FB},$$



- FB-asymmetry can be useful to discriminate and confirm NP!

	R_D	R_{FB}	R_{D*}	R^*_{FB}
SM	0.310(19)	−0.0166(9)	0.252(4)	0.0143(5)
Current	0.410	−0.0219	0.333	0.0189
Scalar	0.400	−0.0205	0.315	0.0093
Tensor	0.467	−0.0315	0.346	−0.0030
Expt.	0.391(41)(28)	–	0.322(18)(12)	–

- E_ℓ and double $(E_\ell,\, q^2)$ spectra can also be studied (v2)

Conclusions

- **High-energy EFT**
  1. Connect low- and high-energy information in a systematic fashion
  2. Constraints between low-energy operators
- New processes/observables
  - $B_s^* \to \ell\ell$
    - Very clean probe of C_9^ℓ
    - Experimentally very challenging
  - NP in kinematic distributions of $B \to D^{(*)}\tau^-(\to \ell^-\bar{\nu}_\ell\nu_\tau)\bar{\nu}_\tau$
    - Full 3-fold 5-body decay rate obtained **analytically**
    - **New** angular observables
    - Clear targer for **Belle(2)**. Applications to **LHCb**? (6-body decays)
    - Other τ decays?

With the LHC run2 (and Belle2) very exciting times ahead!