Theory of exclusive $b \to s\ell\ell$ decays

J. Martin Camalich

CKM 2016 (Mumbai)

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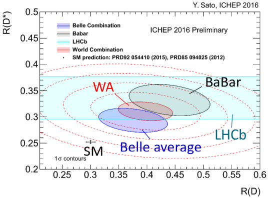
(Lepton universality violating) New-Physics in B decays?

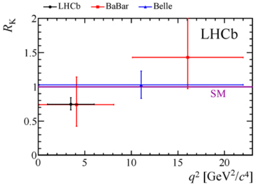
- **"$R_{D^{(*)}}$ anomaly"** in $B \to D^{(*)} \ell \nu$!



- ***Excesses*** observed at $\sim 4\sigma$ WG2 on Th.
- 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

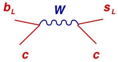


- Tension with **SM** $\sim$2.6σ WG3 on Tue.
- Other anomalies in $b \to s\mu\mu$
  - Branching fractions
  - Angular analysis $B \to K^* \mu\mu$
- Up to 4σ in global fits Javi Virto's talk
- $\Lambda_{\rm NP} \sim 10$ TeV

- **Anomalies addressed in many models of NP** (see e.g. V. Sudhir, J. Zupan's, S. Fajfer, ... talks)

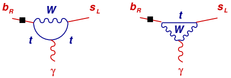
Effective field theory approach to $b \to s\ell\ell$ decays

- **CC** (Fermi theory):

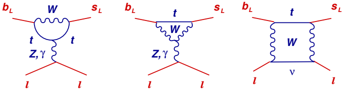


$$\Rightarrow \quad G_F\, V_{cb}\, V_{cs}^*\, C_2\, \bar{c}_L\gamma^\mu b_L\, \bar{s}_L\gamma_\mu c_L$$

- **FCNC**:

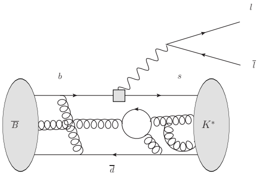


$$\Rightarrow \quad \frac{e}{4\pi^2}\, G_F\, V_{tb}\, V_{ts}^*\, m_b\, C_7\, \bar{s}_L\sigma_{\mu\nu} b_R\, F^{\mu\nu}$$



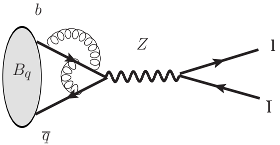
$$\Rightarrow \quad G_F\, V_{tb}\, V_{ts}^*\, \frac{\alpha}{4\pi}\, C_{9(10)}\, \bar{s}_L\gamma^\mu b_L\, \bar{\ell}\gamma_\mu(\gamma_5)\ell$$

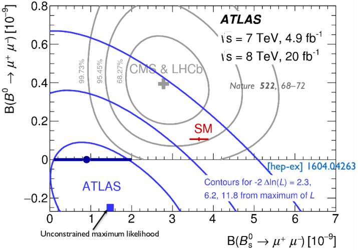
  - Wilson coefficients $C_k(\mu)$ calculated in P.T. @ $\mu = m_W$ and rescaled to $\mu = m_b$
  - Match NP to SMEFT @ $\mu = m_W$ Alonso, Grinstein, JMC, PRL113(2014)241802



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

$B_q^0 \to \ell\ell$





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

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

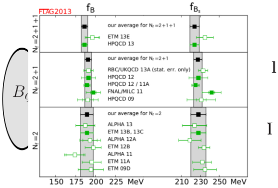
Bobeth *et al.* PRL112(2014)101801

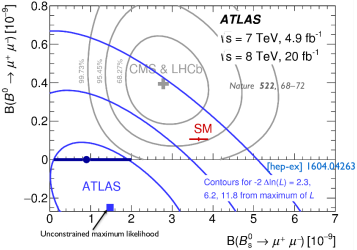
$$\overline{\mathcal{B}}_{s\mu}^{\mathrm{SM}} = 3.65(23) \times 10^{-9}$$
$$\overline{\mathcal{B}}_{s\mu}^{\mathrm{expt}} = 2.9(7) \times 10^{-9}$$

C_S and C_S', $\Lambda_S \sim 100$ TeV

Alonso, Grinstein, JMC, PRL113(2014)241802

$B_q^0 \to \ell\ell$





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

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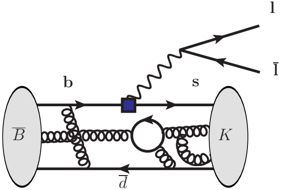
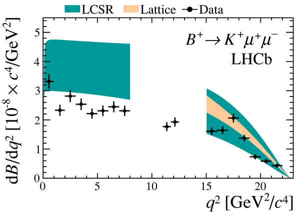
Phenomenological consequences: $B \to K\ell\ell$



LHCb JHEP06(2014)133, JHEP05(2014)082,PRL111 (2013)112003,...



$$\frac{d\Gamma}{dq^2} = \frac{G_F^2\,\alpha^2 |V_{tb}V_{ts}^*|^2}{1536\pi^5}\, f_+^2 \left(|C_9 + C_9' + 2\frac{\mathcal{T}_K}{f_+}|^2 + |C_{10} + C_{10}'|^2 \right) + \mathcal{O}(\frac{m_\ell^4}{q^4})$$

- Phenomenologically richer (3-body decay)
  - Decay rate is a function of dilepton invariant mass $q^2 \in [4m_\ell^2, (m_B - m_K)^2]$
  - **1 angle**: Angular analysis sensitive only to scalar and tensor operators

    Bobeth *et al.*, JHEP 0712 (2007) 040
- **However:** Very complicated nonperturbative problem
  - **3** hadronic form factors
  - "Charm" contribution

Phenomenological consequences: R_K

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

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

The R_K anomaly

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

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:

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

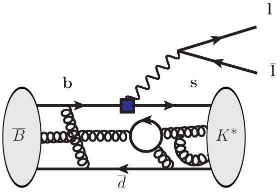
The effect must come from $\mathcal{O}^{(\prime)}_{9,10}$

$$R_K \simeq 0.75 \text{ for } \delta C_9^\mu = -1$$

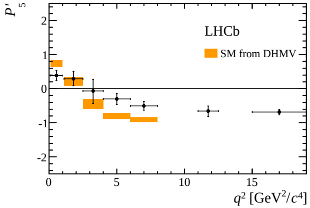
Alonso, Grinstein, JMC, PRL113(2014)241802 (see also Hiller&Schmaltz'14,. . .)

$\bar{B} \to \bar{K}^* \ell^+ \ell^-$

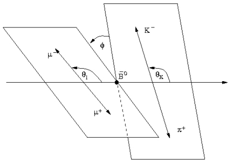
LHCb, JHEP 1602 (2016) 104, (see also Belle, arXiv:1604.04042)



Descotes-Genon *et al.* JHEP 1412 (2014) 125



- **4-body decay**



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

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

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

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

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

Descotes-Genon *et al.* PRD88,074002

Connecting theory to experiment: The helicity amplitudes

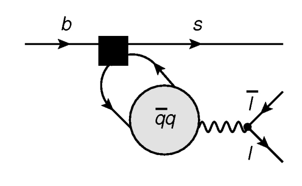
- Helicity amplitudes $\lambda = \pm 1, 0$

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

$$H_A(\lambda) = -iNC_{10}\,\tilde{V}_{L\lambda}, \qquad H_P = iN\frac{2\,m_l \hat{m}_b}{q^2} C_{10}\Big(\tilde{S}_L + \frac{m_s}{m_b}\tilde{S}_R\Big)$$

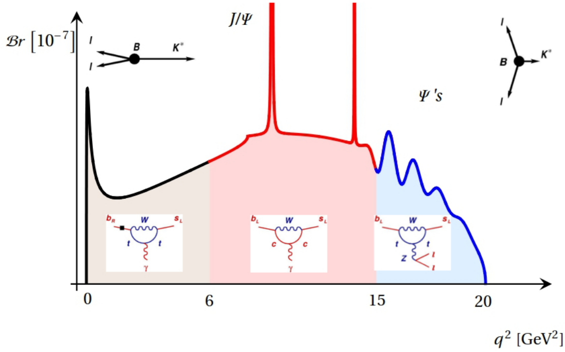
- Hadronic form factors: **7** independent q^2-dependent nonperturbative functions

"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!



- **Large-recoil region** (low q^2)
  - **LCSR+QCDf/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

Form Factors at low q^2

- **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' Descotes-Genon *et al.*'12

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

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

- **"Factorizable power corrections"** ($\Lambda_{\rm QCD}/m_b$)**:** Jäger&JMC, JHEP1305(2013)043

$$F^{\rm p.c.} = \pm a_F \pm b_F \frac{q^2}{m_B^2}$$

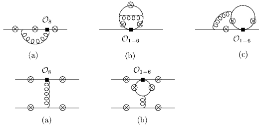
1. **Identify soft- with QCD-FFs:** E.g. $[T_-(q^2),\ S(q^2)]$ or $[V_-(q^2),\ V_0(q^2)]$
   (Scheme dependence?) Hofer *et al.*, JHEP1412(2014)125
2. **QCD exact relations** $\Longrightarrow a_{T_+} = 0$ and $a_{V_0} = a_S$
3. **PC's estimated dim. analysis:** $\Lambda/m_b = 10\%$

Charm at low q^2

- We start from **QCDf** Beneke, Feldmann&Seidel, NPB612(2001)25

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

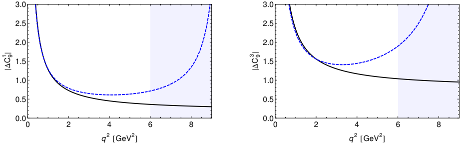
Below $c\bar{c}$ threshold! $q^2 \leq 6$ GeV^2

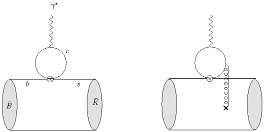


- PCs estimated with **soft-gluon** cont.

Khodjamirian, Mannel, Pivovarov&Wang, JHEP1009(2010)089

$$\Delta C_9^i = (2\, m_b\, m_B / q^2\ \delta_{i1} + \delta_{i2})\ e^{i\phi_i}$$





- **Fit "intrinsic" charm:** Add $\delta_{i3} \frac{q^2}{m_B^2}$ to ΔC_9^i and fit it to data! *(Not done here)*

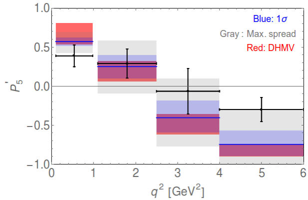
Ciuchini et*al.* JHEP 1606 (2016) 116

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

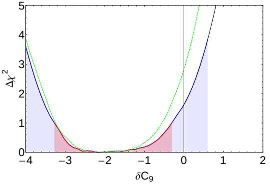
$$\left. + 8\pi^2 \frac{\tilde{h}_-}{\xi_\perp} \frac{m_B}{|\vec{k}|} \frac{m_B^2}{q^2} \frac{C_{9,\perp} C_{9,\parallel} - C_{10}^2}{C_{9,\perp} + C_{9,\parallel}} + \ldots \right) + \mathcal{O}(\Lambda^2/m_B^2)$$

Jäger and JMC, PRD93(2016)no.1,014028

- **Predictions** for P_5'



- **R-fit** to 1 fb^{-1} $P_i^{(\prime)}$'s [1, 6] GeV^2



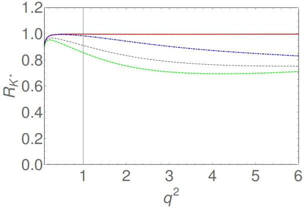
Better understanding of had. uncert. desirable!

- **Learn from LCSR** Bharucha, Straub and Zwicky, arXiv: 1503.05534
- **Charm under control?** Lyon *et al.* arXiv:1406.0566, Ciuchini *et al.* JHEP 1606 (2016)

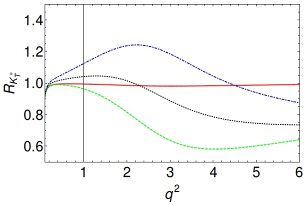
LUV ratios with $B \to K^* \ell\ell$

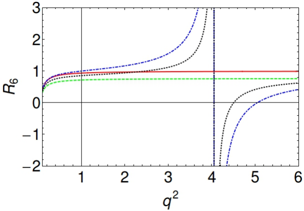
Jäger and JMC, PRD93(2016)no.1,014028

- Solid: SM
- Dotted-Dashed: $\delta C_9^\mu = -1$
- Dashed: $\delta C_{10}^\mu = +1$
- Dotted: $\delta C_9^\mu = -\delta C_{10}^\mu = -0.5$



- The "zero-crossing" of H_V (C_7 vs. C_9) offers powerful interplay:





LUV in angular observables: Capdevila *et al.* JHEP 1610 (2016) 075 (see also Q. Matia's talk)

What about the high q^2 region?

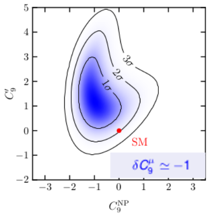
- Theoretical approach based on **OPE+HQET**

$$\lim_{x\to 0}\int d^4x\,\frac{e^{iq\cdot x}}{q^2}\,T\{j^{\mathrm{em,had},\mu}(x),\mathcal{H}^{\mathrm{had}}(0)\} = \sum_n C_{3,n}\,\mathcal{O}_{3,n}(q^2) + 0 + \mathcal{O}(\mathrm{dim}{>}4)$$

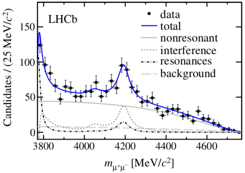
Chay *et al.* PLB247(1990)399-405, Grinstein *et al.* PRD70(2004)114005

- Up to $\mathcal{O}(\Lambda^2/m_b^2)$ $\sim 1\%$ **"charm"** described by **form factors**

  - FFs in **LQCD**!! Horgan *et al.* PRL112(2014)212003



  - **However:** Duality violations!!



Pheno approach: Braß *et al.* arXiv:1606.00775

No satisfactory (model-independent) solution (yet?)

Conclusions

"Extraordinary claims require Extraordinary evidence"
– C. Sagan

1. We find new particles at the LHC
   - Modelling their flavor structure should explain anomalies+new predictions!
2. We do not find new particles but we confirm LUV
   - Reading the shape with more sophisticated (angular) observables
     - Take LUV ratios between angular observables in $B \to K^* \ell\ell$
   - **Bottom-up model-building:** Path for discovery at LHC or beyond!
3. No new particles+No LUV
   - More data needed to confirm or rule out q^2-dependence of the effect
   - Tackling theoretical errors **systematically** will require a **theoretical breakthrough**
   - **New ideas:** e.g. $B_s^* \to \ell\ell$ (Grinstein&JMC, Phys.Rev.Lett. 116 (2016) no.14, 141801)