New-Physics searches in *B*-meson decays

J. Martin Camalich

QCD for NPs searches at the precision frontier

September 30, 2015

Outline

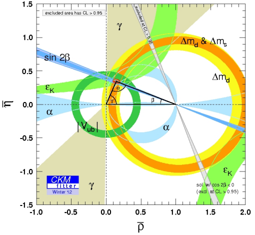
1. Intro flavor and NPs
2. Matching high- and low-energy EFTs for NPs
3. The $b \to s\ell\ell$ phenomenology and anomalies
   - $B_q \to \ell\ell$
   - $B \to K\ell\ell$ and the R_K anomaly
   - $B \to K^*\ell\ell$ and P_5' anomaly
4. New ideas: Rare decays of the B_s^*

Quark flavor changing in the SM

Yukawa sector of the SM

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

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



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

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

- **The structure of the CKM matrix is extremely hierarchical!**

Quark flavor changing in the SM

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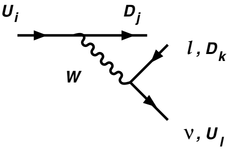
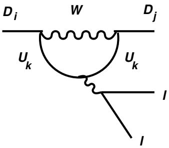
$$-\mathcal{L}_Y = \bar{q}_L Y_d d_R H + \bar{q}_L Y_u u_R \tilde{H} + \bar{\ell}_L Y_e e_R H + h.c.$$

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



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



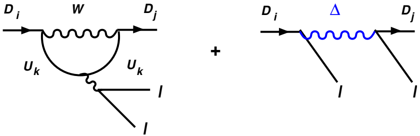
- $\mathcal{M} \sim G_F V_{ij} U^*_{kl}$,
  $V_{ij} U^*_{kl}$ can be $\mathcal{O}(1)$
- $\mathcal{M} \sim G_F \sum_k V_{ki} V^*_{kj} \frac{m_K^2}{m_W^2} \frac{\alpha}{4\pi}$,
  GIM and **loop** suppression
- In the SM, FCNCs are suppressed w.r.t. CC interactions: **"Rare" decays!**

Quark flavor changing in the SM

Yukawa sector of the SM

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

- **FCNC** $b \to s$: Very sensitive to exchange of new particles



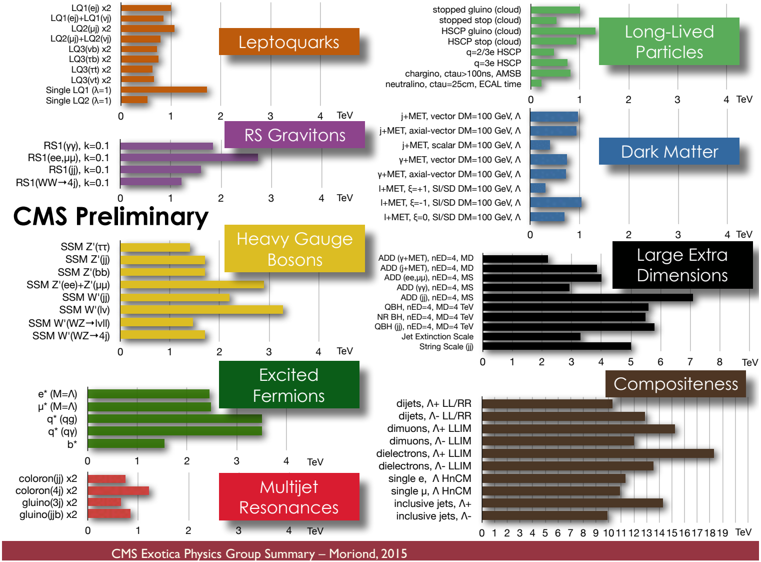
$$\mathcal{M} \sim G_F\, V_{tb} V_{ts}^* \frac{\alpha}{4\pi} \left(C^{\rm SM} + \frac{4\pi}{\alpha} \frac{1}{V_{tb} V_{ts}^*} \frac{v^2}{M^2} g^2 \right) \times \langle \bar{s} b \otimes \bar{\ell}\ell \rangle$$

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

- No **New Physics** at colliders (yet?) (Similar plots for ATLAS)

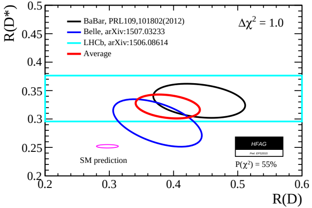
https://twiki.cern.ch/twiki/bin/view/CMSPublic/

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



Lepton universality violation in B decays?

- **"$R_{D^{(*)}}$ anomaly"** in $B \to D^{(*)}\ell\nu$! (**CC**) A. El-Khadra's talk on Monday



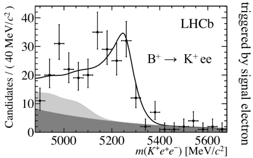
HFAG @ EPS-HEP 2015

- ***Excesses*** observed at $\sim 4\sigma$

	$R(D)$	$R(D^*)$
BaBar	$0.440 \pm 0.058 \pm 0.042$	$0.332 \pm 0.024 \pm 0.018$
Belle	$0.375^{+0.064}_{-0.063} \pm 0.026$	$0.293^{+0.039}_{-0.037} \pm 0.015$
LHCb		$0.336 \pm 0.027 \pm 0.030$
Exp. average	0.388 ± 0.047	0.321 ± 0.021
SM expectation	0.300 ± 0.010	0.252 ± 0.005
Belle II, 50 ab^{-1}	± 0.010	± 0.005

T. Freytsis *et al.* 1506.08896

- **"R_K anomaly"** in $B \to K\ell\ell$ (**FCNC**)! LHCb PRL113(2014)151601



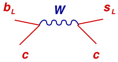
- Tension with **SM** $\sim 2.6\sigma$
- Other anomalies in $b \to s\mu\mu$
  - Branching fractions $B \to K\mu\mu$, $B_s \to \phi\mu\mu$
  - Angular analysis $B \to K^*\mu\mu$
- Up to 4σ in global fits

Altmannshofer and Straub '14

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

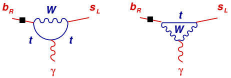
Effective field theory approach to $b \to s\ell\ell$ decays

- **CC** (Fermi theory):

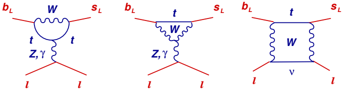


$$\Rightarrow \qquad G_F\, V_{cb}\, V_{cs}^*\, C_2\, \bar{c}_L\gamma^\mu b_L\, \bar{s}_L\gamma_\mu c_L$$

- **FCNC**:

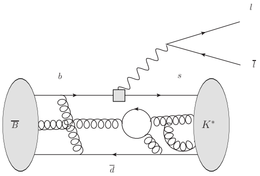


$$\Rightarrow \qquad \frac{e}{4\pi^2}\, G_F\, V_{tb}\, V_{ts}^*\, m_b\, C_7\, \bar{s}_L\sigma_{\mu\nu} b_R\, F^{\mu\nu}$$



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

  - 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.* $\Lambda_{\rm QCD}$
    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

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

  - The Wilson coefficients can be complex and introduce new sources of $C\!\!\!/P$

- 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 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, Cirigliano *et al.*'09'10, Grzadkowski *et al.*'10, V. Cirigliano's and M. Gonzalez-Alonso's talks

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

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

- Furthermore:

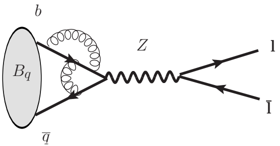
$$(\bar{d}_j\sigma_{\mu\nu}P_R d_i)(\bar{\ell}\sigma^{\mu\nu}P_L\ell) = 0$$

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

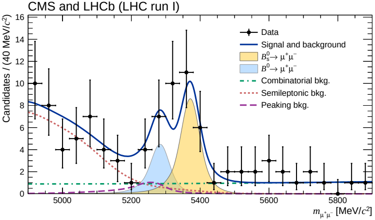
- From **4** scalar operators to only **2**!
- From **2** tensor operators to **none**!

Alonso, Grinstein, JMC, PRL113(2014)241802

$B_q^0 \to \ell\ell$



CMS and LHCb, Nature 522 (2015) 68-72



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

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

FLAG averages, A. El-Khadra's talk, Mon

- Updated predictions:

Bobeth *et al.* PRL112(2014)101801

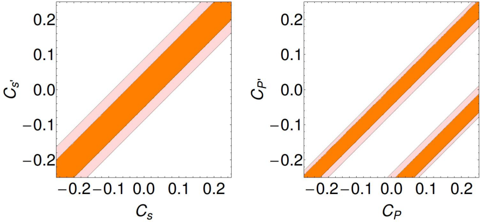
$$\overline{\mathcal{B}}_{s\mu}^{\rm SM} = 3.65(23) \times 10^{-9}$$
$$\overline{\mathcal{B}}_{s\mu}^{\rm expt} = 2.9(7) \times 10^{-9}$$

Phenomenological consequences $B_q \to \ell\ell$

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

De Bruyn *et al.* '12

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

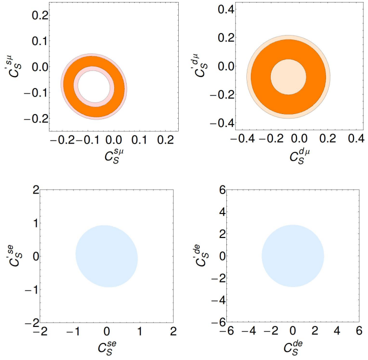


- $B_q \to \ell\ell$ blind to the orthogonal combinations $C_S + C_S'$ and $C_P + C_P'$
  Scalar operators unconstrained!

Phenomenological consequences $B_q \to \ell\ell$

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

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

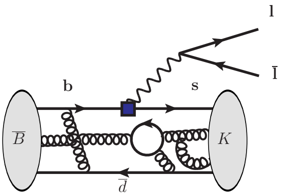


- Λ_{NP} (95%C.L.) RGE of QCD+EW+Yukawas

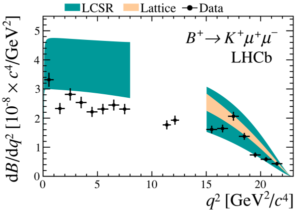
Channels	$s\mu$	$d\mu$	se	de
$C_S^{(\prime)}(m_W)$	0.1	0.15	0.6	1.5
Λ [TeV]	79	130	36	49

Alonso, Grinstein, JMC, PRL113(2014)241802

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



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



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

- 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 (q^2-dependent functions)
  - "Non-factorizable" contribution of 4-quark operators+EM current

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

- 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 $\mathcal{O}^{(\prime)}_{9,10}$

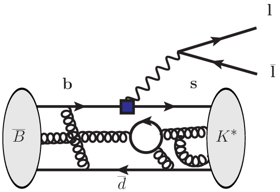
$$R_K \simeq 0.75 \text{ for } \delta C_9^\mu = -1$$

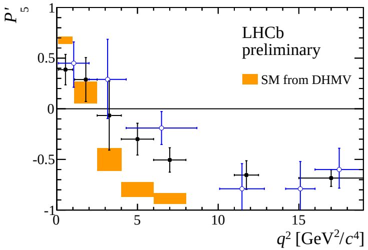
Alonso, Grinstein and JMC'14, Hiller and Schmaltz'14, Straub *et al*'14'15, Ghosh *et al*'14,...

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

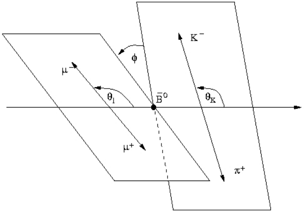
LHCb-CONF-2015-002, (also CDF, BaBar, Belle, CMS and ATLAS)

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

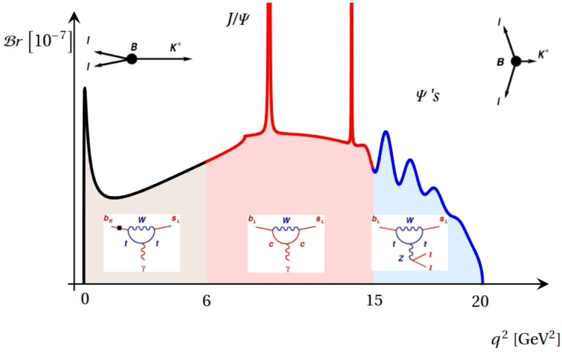




- **4-body decay**



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



- **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

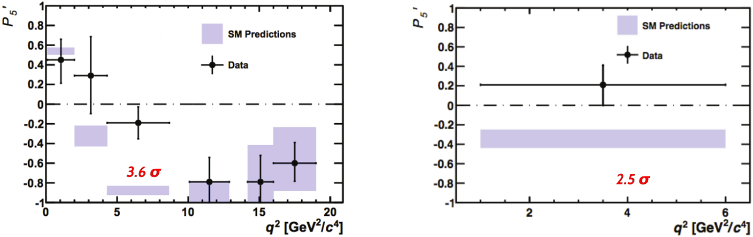
The P_5' anomaly at low q^2 (1 fb^{-1})

PRL **111,** 191801 (2013) PHYSICAL REVIEW LETTERS week ending 8 NOVEMBER 2013

Measurement of Form-Factor-Independent Observables in the Decay $B^0 \to K^{*0}\mu^+\mu^-$

R. Aaij *et al.**
(LHCb Collaboration)

(Received 9 August 2013; published 4 November 2013)



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

Descotes-Genon *et al.* PRD88,074002

Altmannshofer *et al.* Eur.Phys.J. C73 (2013) 2646

- **Tensions in the angular analysis have been ratified with 3 fb^{-1} !**

LHCb-CONF-2015-002

Connecting theory to experiment: The helicity amplitudes

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

$$H_V(\lambda) = -iN\Big\{C_9\,\tilde{V}_{L\lambda} - \frac{m_B^2}{q^2}\Big[\frac{2\,\hat{m}_b}{m_B}C_7\,\tilde{T}_{L\lambda} - 16\pi^2 h_\lambda\Big]\Big\},$$

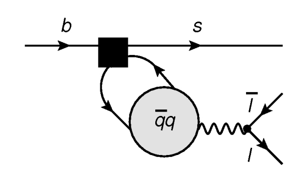
$$H_A(\lambda) = -iNC_{10}\,\tilde{V}_{L\lambda}, \qquad H_P = iN\frac{2\,m_l\hat{m}_b}{q^2}C_{10}\Big(\tilde{S}_L + \frac{m_s}{m_b}\tilde{S}_R\Big)$$

C_9 is exposed to various hadronic backgrounds

- Hadronic form factors

  7 independent q^2-dependent nonperturbative functions

  Bharucha *et al.*JHEP 1009 (2010) 090, Jäeger and JMC JHEP1305(2013)043



- "Non factorizable" contribution

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

  Calculable in **QCDf** at $q^2 \lesssim 6$ GeV^2

  Beneke *et al.*'01

Form Factors at low q^2

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

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

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

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

$$P_5' = \frac{I_5}{2\sqrt{-I_{2s}I_{2c}}} \simeq \frac{C_{10}\left(C_{9,\perp} + C_{9,\parallel}\right)}{\sqrt{(C_{9,\parallel}^2 + C_{10}^2)(C_{9,\perp}^2 + C_{10}^2)}}, \qquad \begin{cases} C_{9,\perp} = C_9^{\rm eff}(q^2) + \frac{2\,m_b\,m_B}{q^2}\,C_7^{\rm eff} \\ C_{9,\parallel} = C_9^{\rm eff}(q^2) + \frac{2\,m_b\,E}{q^2}\,C_7^{\rm eff} \end{cases}$$

P_5' "hadronic independent" at $\mathcal{O}(\alpha_s^0, (\frac{\Lambda}{m_b})^0)$

- α_s corrections can be computed to any order in QCDf or SCET

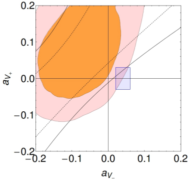
  Beneke *et al.* NPB592(2001)3, NPB612(2001)25, NPB685(2004)249, Bauer *et al.* PRD63(2001)114020,...

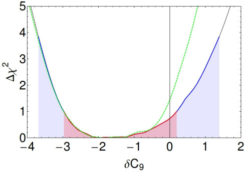
- Power-corrections (Λ/m_b) non calculable
  - Use light-cone sum rules Altmannshofer *et al.*, Descotes-Genon *et al.*
  - Parametrize PCs model-independently and include in th. errors Jäger and JMC

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

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

Jäger and JMC, arXiv: 1412.3183





- **LCSR** lead to PC parameters implying a higher significance (blue box)

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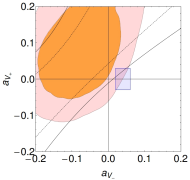

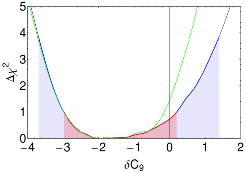

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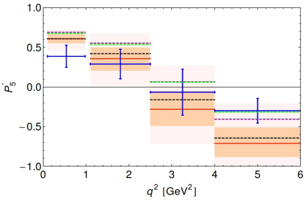


- 3.6σ tension with the SM in **LCSR** LHCb-CONF-2015-002
- Ongoing analysis in the **HQ+PC**
- Effect depends on q^2? Altmannshofer&Straub, arXiv:1503.06199

What about the high q^2 region?

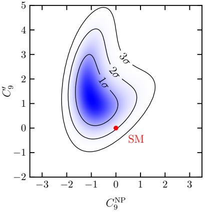
- Especially suited for determining C_9
- Theoretical approach based on **OPE+HQET**

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

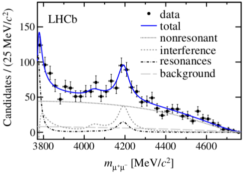
Grinstein *et al.* PRD70(2004)114005, Bobeth *et al.* JHEP1007(2010)098, Beylich *et al* EPJC71(2011)1635

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

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



- **However:** Duality violations!!

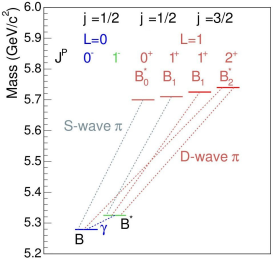


No satisfactory (model-independent) solution (yet?)

Weak decays of “unstable” *b*-mesons

Grinstein and JMC arXiv: 1509.05049

- The *b*-mesons have a rich spectrum of states

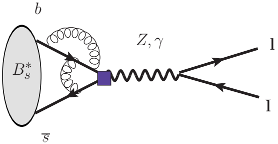


- Degenerate doublets in the HQ limit $\Delta M \simeq \Lambda^2/m_B$
- “Unstable” under **EM** or **Strong** interactions
- **Short life-times:** $\tau^* \lesssim 10^{-17}s$ ($\tau_B \sim 10^{-12}$) Do not live long enough to do weak physics!

However ...

- The vector partner of the B_q meson is specially attractive!
  - As a vector $B_0^* \to \ell\ell$ is not chirally suppressed!
  - It decays EM and is a very narrow resonance $\Gamma \lesssim 1$ KeV
  - Hadronic matrix elements related to those of the *B* in the HQ limit!

$B_s^* \to \ell\ell$



- 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)

In the SM:

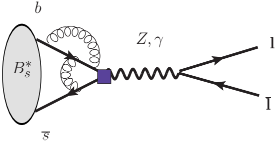
$$\mathcal{M}_{\ell\ell} = \frac{G_F}{2\sqrt{2}}\lambda_{ts}\frac{\alpha_{\rm em}}{\pi}\Big[\Big(m_{B_s^*}\, f_{B_s^*}\, C_9 + 2\, f^T_{B_s^*}\, m_b\, C_7\Big)\,\bar\ell\not\epsilon\ell + f_{B_s^*}\, C_{10}\bar\ell\not\epsilon\gamma_5\ell$$
$$- 8\pi^2\frac{1}{q^2}\sum_{i=1}^{6,8} C_i\,\langle 0|\mathcal{T}_i^\mu(q^2)|B_s^*(q,\varepsilon)\rangle\;\bar\ell\gamma_\mu\ell\Big],$$

- It is sensitive to C_9!!
- Very clean!
  1. Decay constants: **HQ** limit and **LQCD**...

     $$f_{B_s^*} = f_{B_s}\left(1 - \frac{2\alpha_s}{3\pi}\right), \qquad f^T_{B_s^*} = f_{B_s}\left[1 + \frac{2\alpha_s}{3\pi}\left(\log\left(\frac{m_b}{\mu}\right) - 1\right)\right]$$

  2. “Non-factorizable”: **OPE** at $q^2 = m^2_{B_s^*} = 28$ GeV^2 well above charmonium states
     Duality violation is much less of a concern!!

$B_s^* \to \ell\ell$



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- The decay rate can then be predicted accurately in the SM

HPQCD Collab., Colquhoun *et al.*, PRD91, 114504 for the LQCD input on $f_{B_s^*}$

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

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

  - Using $\Gamma(D^{*\pm}\to D^\pm\gamma) = \Gamma(D^{*\pm})\times\mathcal{B}(D^{*\pm}\to D^\pm\gamma) = 1.33(33)$ KeV

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

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

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

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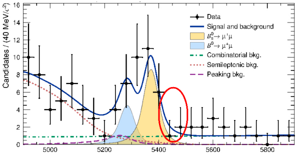

- Small peak in $B_q \to \mu\mu$ measurents
- $\sigma(pp \to b\bar{b}) \simeq 10^{12}$ fb @ 14 TeV
- We estimate that ~ 10 (~ 100) $B_s^* \to \mu\mu$ events by the end of run III (HL-LHC)

Conclusions

1. EFT approach very efficient method to investigate anomalies
   - Connect low- and high-energy information in a systematic fashion
   - Constraints between low-energy operators
     - **2** out of **4** independent **scalar** operators and **no tensors** in $d_i \to d_j \ell\ell$
2. The $b \to s\ell\ell$ anomalies
   - $B_q \to \ell\ell$
   - R_K in $B \to K\ell\ell$
   - The P_5' anomaly in $B \to K^* \mu\mu$
     Strong interplay between **QCD** and **NPs**
3. **New Ideas:** Weak decays of unstable b-mesons
   - Clean window to C_9
   - Support from the **LQCD** is essential (μ_{bs}, $f_{B_s^*}$, $f_{B_s^*}^T$)
   - Experimental challenging but plausible at **LHC**
   - **No time to talk about ...** Probe **NPs** is $\ell^+\ell^- \to B_s^* \to B_s\gamma$ scattering experiments

Grinstein and JMC arXiv: 1509.05049

With the LHC run2 very exciting times ahead!