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 $b \rightarrow s \ell \ell$ phenomenology and anomalies
   - $B_q \rightarrow \ell \ell$
   - $B \rightarrow K \ell \ell$ and the $R_K$ anomaly
   - $B \rightarrow K^* \ell \ell$ 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

\[ V_{\text{CKM}} \approx \begin{pmatrix} 1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} \]

- The structure of the CKM matrix is extremely hierarchical!

\[ \lambda = 0.2253(7), \quad A = 0.808(22), \quad \bar{\rho} = 0.132(22), \quad \bar{\eta} = 0.341(13) \]
Quark flavor changing in the SM

Yukawa sector of the SM

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

- **CC** $U_i \rightarrow D_j$: Tree level
  - $\mathcal{M} \sim G_F \, V_{ij} U_{kl}^*$
  - $V_{ij} U_{kl}^*$ can be $\mathcal{O}(1)$
  - In the SM, FCNCs are suppressed w.r.t. CC interactions: “Rare” decays!

- **FCNC** $D_i \rightarrow D_j$: Loop
  - $\mathcal{M} \sim G_F \sum_k V_{ki} V_{kj}^* \frac{m_k^2}{m_W^2} \frac{\alpha}{4\pi}$
  - GIM and loop suppression

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

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

Rare $b$ decays sensitive to $M \sim 100$ TeV !!
No New Physics at colliders (yet?) (Similar plots for ATLAS)

stopped gluino (cloud)
stopped stop (cloud)
HSCP gluino (cloud)
HSCP stop (cloud)
q=2/3e HSCP
q=3e HSCP
charged, ctau=100ns, AMSB
neutralino, ctau=25cm, ECAL time

RS1(γγ), k=0.1
RS1(ee, μμ), k=0.1
RS1(jj), k=0.1
RS1(WW→4j), k=0.1

0 1 2 3 4 TeV

CMS Preliminary

Heavy Gauge Bosons

SSM Z'(ττ)
SSM Z'(jj)
SSM Z'(bb)
SSM Z'(ee)+Z'(μμ)
SSM W'(jj)
SSM W'(lv)
SSM W'(WZ→lvll)
SSM W'(WZ→4j)

Excited Fermions

e* (M=Λ)
μ* (M=Λ)
q* (qg)
q* (qf)
b*

coloron(jj) x2
coloron(4j) x2
gluino(3j) x2
gluino(jj) x2

CMS Exotica Physics Group Summary – Moriond, 2015

Leptoquarks

100 GeV, Λ
100 GeV, Λ
100 GeV, Λ
100 GeV, Λ
100 GeV, Λ
100 GeV, Λ
100 GeV, Λ

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Lepton universality violation in $B$ decays?

- **“$R_{D(*)}$ anomaly”** in $B \to D(*)\ell\nu$ (CC) A. El-Khadra’s talk on Monday

### Excesses observed at $\sim 4\sigma$

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

HFAG @ EPS-HEP 2015

- **“$R_K$ 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 $4\sigma$ 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):
  \[ G_F V_{cb} V_{cs}^* C_2 \bar{c}_L \gamma_\mu b_L \bar{s}_L \gamma_\mu c_L \]

- **FCNC**:
  \[ \frac{e}{4\pi^2} G_F V_{tb} V_{ts}^* m_b C_7 \bar{s}_L \sigma_{\mu\nu} b_R F^{\mu\nu} \]
  \[ \Rightarrow \]
  \[ G_F V_{tb} V_{ts}^* \frac{\alpha}{4\pi} C_{9(10)} \bar{s}_L \gamma_\mu b_L \bar{\ell}_\mu (\gamma_5)\ell \]

- 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. $\Lambda_{QCD}$
      - 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
      $$\mathcal{O}_7' = \frac{4G_F}{\sqrt{2}} \frac{e}{4\pi^2} \bar{m}_b \bar{s} \sigma_{\mu\nu} P_L F_{\mu\nu} b; \quad \mathcal{O}_{9(10)}' = \frac{4G_F}{\sqrt{2}} \frac{\alpha}{4\pi} \bar{s} \gamma^\mu P_R b \bar{\ell} \gamma_\mu (\gamma_5) \ell$$
    - 4 new scalar and pseudoscalar operators
      $$\mathcal{O}_S^{(i)} = \frac{4G_F}{\sqrt{2}} \frac{\alpha}{4\pi} (\bar{s} P_{R,L} b) (\bar{\ell} \ell); \quad \mathcal{O}_P^{(i)} = \frac{4G_F}{\sqrt{2}} \frac{\alpha}{4\pi} (\bar{s} P_{R,L} b) (\bar{\ell} \gamma_5 \ell)$$
    - 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 $CP$
But hold on...  
▷ No evidence of new-particles *on-shell* at colliders up to $E \sim 1$ TeV...  
...except a scalar at $s \sim 125$ GeV that very much resembles the SM Higgs

**Guiding principle (rewritten)**

Construct the most general effective operators $O_k$ 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 $\Gamma = I, \sigma_{\mu\nu}$ we only have:

$$
\frac{1}{\Lambda^2} \left( \bar{e}_R \Gamma \ell^a_L \right) \left( \bar{q}^a_R \Gamma d_R \right)_{Y=1/2}
\quad
\frac{1}{\Lambda^2} \left( \bar{\ell}^b_L \Gamma e_R \right) \left( \bar{q}^a_L \Gamma u_R \right)_{Y=1/2}
$$

- Furthermore:

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

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

- From 4 scalar operators to only 2!
- From 2 tensor operators to none!
\[ B^0_q \rightarrow \ell\ell \]

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

- 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

\[
\overline{B}_{s\mu}^{\text{SM}} = 3.65(23) \times 10^{-9} \\
\overline{B}_{s\mu}^{\text{expt}} = 2.9(7) \times 10^{-9}
\]
Phenomenological consequences $B_q \rightarrow \ell\ell$

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

De Bruyn et al. ’12

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

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

$$\bar{R}_q = \frac{\bar{B}_q}{(\bar{B}_q)_{SM}} \simeq \left( |S|^2 + |P|^2 \right),$$

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

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

<table>
<thead>
<tr>
<th>Channels</th>
<th>$s_\mu$</th>
<th>$d_\mu$</th>
<th>$se$</th>
<th>$de$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_S^{(r)}(m_W)$</td>
<td>0.1</td>
<td>0.15</td>
<td>0.6</td>
<td>1.5</td>
</tr>
<tr>
<td>Λ [TeV]</td>
<td>79</td>
<td>130</td>
<td>36</td>
<td>49</td>
</tr>
</tbody>
</table>

Alonso, Grinstein, JMC, PRL113(2014)241802
Phenomenological consequences: $B \rightarrow K\ell\ell$

\[ \frac{d\Gamma}{dq^2} = \frac{G_F^2 \alpha^2 |V_{tb} V_{ts}^*|^2}{1536 \pi^5} f_+^2 \left( |C_9 + C'_9 + 2 \frac{T_K}{f_+}|^2 + |C_{10} + C'_{10}|^2 \right) + O\left( \frac{m_\ell^4}{q^4} \right) \]

- 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: $B \rightarrow K\ell\ell$

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

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

The $R_K$ anomaly

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

- $2.6\sigma$ 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 $B_s \rightarrow \ell\ell$ alone:

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

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

$$R_K \simeq 0.75 \text{ for } \delta C_{9}^{\ell} = -1$$

Alonso, Grinstein and JMC’14, Hiller and Schmaltz’14, Straub et al’14’15, Ghosh et al’14,…
\[ B \rightarrow \bar{K}^* \ell^+ \ell^- \]

- 4-body decay

\[
\frac{d^{(4)}\Gamma}{dq^2 \; d(\cos \theta_I) \; d(\cos \theta_K) d\phi} = \frac{9}{32 \pi} \left( l_1^s \sin^2 \theta_k + l_1^c \cos^2 \theta_k \right) \\
+ \left( l_2^s \sin^2 \theta_k + l_2^c \cos^2 \theta_k \right) \cos 2\theta_I + l_3 \sin^2 \theta_k \sin^2 \theta_I \cos 2\phi \\
+ l_4 \sin 2\theta_k \sin 2\theta_I \cos \phi + l_5 \sin 2\theta_k \sin \theta_I \cos \phi + l_6 \sin^2 \theta_k \cos \theta_I \\
+ l_7 \sin 2\theta_k \sin \theta_I \sin \phi + l_8 \sin 2\theta_k \sin 2\theta_I \sin \phi + l_9 \sin^2 \theta_k \sin^2 \theta_I \sin 2\phi
\]
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 $q^2 \simeq 6 - 7 \text{ GeV}^2$

Low-recoil region (high $q^2$)

- LQCD+HQEFT + OPE (duality violation)
- Dominated by semileptonic operators
The $P'_5$ anomaly at low $q^2 (1 \text{ fb}^{-1})$

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)

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\[ \delta C^\mu_9 \simeq -1 \]

Descotes-Genon et al. PRD88,074002

- Tensions in the angular analysis have been ratified with 3 fb$^{-1}$!
Connecting theory to experiment: The helicity amplitudes

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

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

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

$C_9$ is exposed to various hadronic backgrounds

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


- “Non factorizable” contribution

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

Calculable in $\text{QCDf}$ at $q^2 \lesssim 6 \text{ GeV}^2$

Beneke et al. '01
Form Factors at low $q^2$

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

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


- The observable $P'_5$ Matias *et al.*'12

$$P'_5 = \frac{l_5}{2\sqrt{-l_2l_2l_c}} \cong \frac{C_{10} \left( C_{9,\perp} + C_{9,\parallel} \right)}{\sqrt{(C_{9,\parallel}^2 + C_{10}^2)(C_{9,\perp}^2 + C_{10}^2)}},$$

$$\left\{ \begin{array}{l} C_{9,\perp} = C_{9}^{\text{eff}}(q^2) + \frac{2m_b}{q^2} \frac{m_B}{C_{7}^{\text{eff}}} \\ C_{9,\parallel} = C_{9}^{\text{eff}}(q^2) + \frac{2m_b}{q^2} \frac{E}{C_{7}^{\text{eff}}} \end{array} \right.$$  

$P'_5$ “hadronic independent” at $O(\alpha_s^0, \left(\frac{\Lambda}{m_b}\right)^0)$

- $\alpha_s$ corrections can be computed to any order in QCDf or SCET


- Power-corrections ($\Lambda/m_b$) 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
\[ P'_5 = P'_5 \bigg|_{\infty} \left( 1 + \frac{a_{V_0} - a_T}{\xi} \right) \frac{m_B}{|k|} \frac{m_B^2}{q^2} C_7^{\text{eff}} \frac{c_{9, \perp} c_{9, \parallel} - c_{10}^2}{(c_{9, \perp} + c_{10}^2)(c_{9, \perp} + c_{9, \parallel})} \right) + \mathcal{O}(\Lambda^2 / m_B^2) \]

Jäger and JMC, arXiv: 1412.3183

- **LCSR** lead to PC parameters implying a higher significance (blue box)
\[ P'_5 = P'_5 \bigg|_{\infty} \left( 1 + \frac{a_{V_\perp} - a_{\tau_\perp}}{\xi_\perp} \frac{m_B}{|k|} \frac{m_B^2}{q^2} C_7^{\text{eff}} \frac{c_{9, \perp} c_{9, \parallel} - c_{10}^2}{(c_{9, \perp} + c_{9, \parallel})(c_{9, \perp} + c_{9, \parallel})} + \frac{a_{V_\parallel} - a_{\tau_\parallel}}{\xi_\parallel} 2 \frac{c_{7}^{\text{eff}}}{(c_{9, \parallel} + c_{9, \parallel})(c_{9, \perp} + c_{9, \parallel})} \right) + O(\Lambda^2/m_B^2) \]

\[ + 8\pi^2 \frac{\bar{m}_B}{\xi_\perp} \frac{m_B^2}{|k|} \frac{m_B^2}{q^2} \frac{c_{9, \perp} c_{9, \parallel} - c_{10}^2}{c_{9, \perp} + c_{9, \parallel}} \ldots \]  

Jäger and JMC, arXiv: 1412.3183

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

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


- Up to $O(\Lambda^2/m_b^2) \sim 1\%$ “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

![Mass vs. J^P](image)

- Degenerate doublets in the HQ limit
  \[ \Delta M \approx \frac{\Lambda^2}{m_B} \]

- “Unstable” under EM or Strong interactions

- Short life-times: $\tau^* \lesssim 10^{-17} \text{s}$ ($\tau_B \sim 10^{-12}$)
  Do not live long enough to do weak physics!

However ...

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

- $B_s^*$ 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:

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

- It is sensitive to $C_9$!!
- Very clean!

1. **Decay constants**: HQ limit and LQCD...

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

2. **“Non-factorizable”**: OPE at $q^2 = m_{B_s^*}^2 = 28$ GeV$^2$ well above charmonium states

Duality violation is much less of a concern!!
$B_s^* \rightarrow \ell\ell$

- $B_s^*$ is the $J^{PC} = 1^{++}$ partner of the $B_s$

\[
m_{B_s^*} = 5415.4_{-2.1}^{+2.4} \text{ MeV (} m_{B_s^*} - m_{B_s} = 48.7 \text{ MeV)}
\]

In the SM:

\[
\mathcal{M}_{\ell\ell} = \frac{G_F}{2\sqrt{2}} \lambda_{ts} \frac{\alpha_{em}}{\pi} \left[ \left( m_{B_s^*} f_{B_s^*} C_9 + 2 f_{B_s^*}^T m_b C_7 \right) \bar{\ell} \ell + f_{B_s^*} C_{10} \bar{\ell} \gamma_5 \ell \right]
\]

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

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

$\Gamma_{\ell\ell} = 1.12(5)(7) \times 10^{-18} \text{ GeV}$
Branching fraction and prospects for measurement

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

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

$\mu_{bs}$ can be computed in HM$\chi$PT Cho&Georgi’92, Amundson et al.’92

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

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

\[
B^{\text{SM}}(B_s^* \to \ell\ell) = (0.7 - 2.2) \times 10^{-11}
\]

- **LQCD** calculations of $\mu_{bs}$ are necessary! Becirevic et al. EPJC71,1743, Donald et al. PRL112,212002
Branching fraction and prospects for measurement

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

- Small peak in $B_q \rightarrow \mu\mu$ measurements

- $\sigma(pp \rightarrow b\bar{b}) \simeq 10^{12} \text{ fb} @ 14 \text{ TeV}$

- We estimate that $\sim 10$ ($\sim 100$) $B_s^* \rightarrow \mu\mu$ 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 ($\mu_{bs}, f_{B_s^*}, f_{B_s^{T*}}$)
   - 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!