# Aspects of $b \to s\ell\ell$ transitions

**J. Martin Camalich**

Novel aspects of $b \to s\ell\ell$ transitions: Investigating new channels

October 5, 2015

# Outline

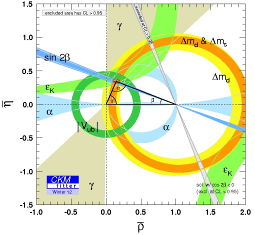
1. Matching high- and low-energy EFTs for NPs
   - $B_q \to \ell\ell$ and $R_K$
2. $B \to K^*\ell\ell$ and $P_5'$ anomaly
3. New ideas: Rare decays of the $B_s^*$
4. The shape of new physics
   - Lepton non-universal and lepton flavor conserving decays

# Quark flavor changing in the SM

## Yukawa sector of the SM

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

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




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

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

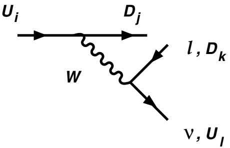
- **The structure of the CKM matrix is extremely hierarchical!**

# Quark flavor changing in the SM

## Yukawa sector of the SM

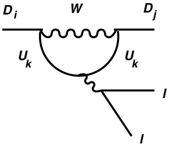
$$-\mathcal{L}_Y = \bar{q}_L Y_d d_R H + \bar{q}_L Y_u u_R \tilde{H} + \bar{\ell}_L Y_e e_R H + h.c.$$

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




- $\mathcal{M} \sim G_F V_{ij} U^*_{kl}$,
  $V_{ij} U^*_{kl}$ can be $\mathcal{O}(1)$

- **FCNC $D_i \to D_j$: 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

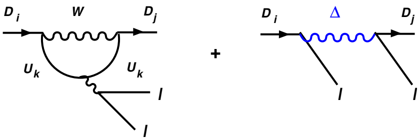
- In the SM, FCNCs are suppressed w.r.t. CC interactions: **"Rare" decays!**

# 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

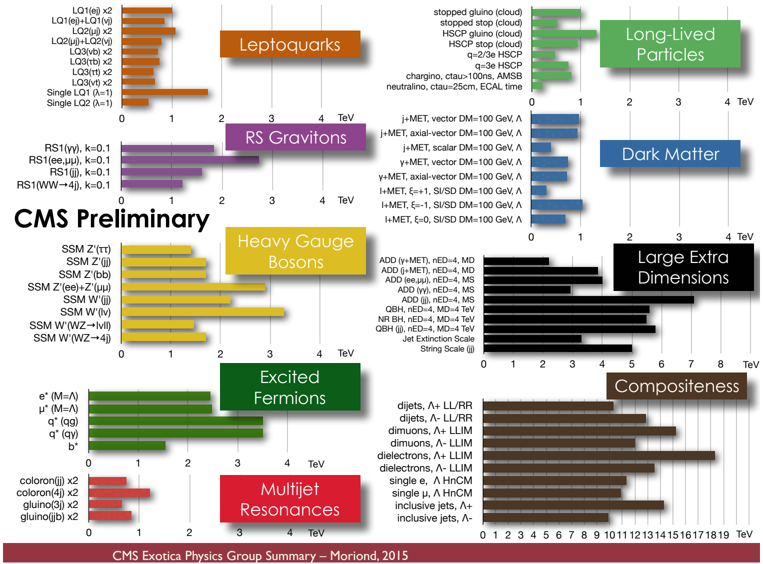



$$\mathcal{M} \sim G_F V_{tb} V_{ts}^* \frac{\alpha}{4\pi} \left( C^{\rm SM} + \frac{4\pi}{\alpha} \frac{1}{V_{tb} V_{ts}^*} \frac{v^2}{M^2} g_{il} g_{jl} \right) \times \langle \bar{s} b \otimes \bar{\ell} \ell \rangle$$

Rare $b$ decays sensitive to $M \sim 50$ TeV !!

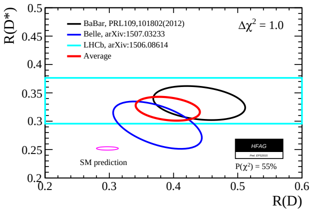
- No **New Physics** at colliders (yet?) (Similar plots for ATLAS)

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**)



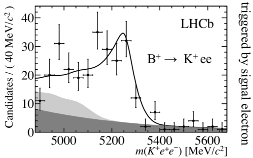

HFAG @ EPS-HEP 2015

- ***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 | $0.388 \pm 0.047$ | $0.321 \pm 0.021$ |
| SM expectation | $0.300 \pm 0.010$ | $0.252 \pm 0.005$ |
| Belle II, 50 ab$^{-1}$ | $\pm 0.010$ | $\pm 0.005$ |

T. Freytsis *et al.* 1506.08896

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



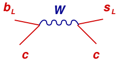

$$R_K = 0.745^{+0.090}_{-0.074}(\text{stat}) \pm 0.036(\text{syst})$$

- 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

Descotes-Genon *et al.*'13, Altmannshofer and Straub '13'14, Beaujean *et al.*'13

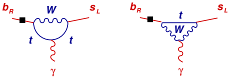
# Effective field theory approach to $b \to s\ell\ell$ decays

- **CC** (Fermi theory):

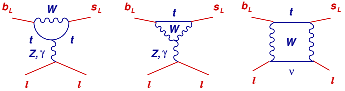



$$\Rightarrow \qquad G_F\, V_{cb}\, V_{cs}^*\, C_2\, \bar{c}_L \gamma^\mu b_L\, \bar{s}_L \gamma_\mu c_L$$

- **FCNC**:

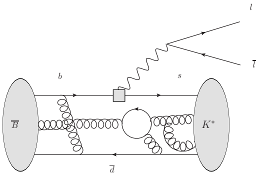



$$\Rightarrow \qquad \frac{e}{4\pi^2}\, G_F\, V_{tb}\, V_{ts}^*\, m_b\, C_7\, \bar{s}_L \sigma_{\mu\nu} b_R\, F^{\mu\nu}$$




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

- ▶ 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

- 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:

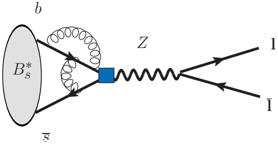
$$(\bar{d}_j \sigma_{\mu\nu} P_R d_i)(\bar{\ell} \sigma^{\mu\nu} P_L \ell) = 0$$

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

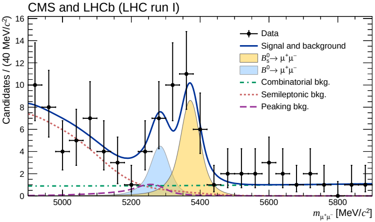
- From **4** scalar operators to only **2**!
- From **2** tensor operators to **none**!

Alonso, Grinstein, JMC, PRL113(2014)241802

# $B_q^0 \to \ell\ell$




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



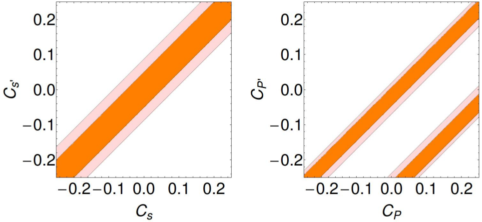

$$\mathcal{B}_{sl} \simeq \frac{G_F^2}{64\pi^3}\tau_{B_s} m_{B_s}^3 f_{B_s}^2 |V_{tb}V_{ts}^*|^2 \times \left\{ |C_S - C_S'|^2 + |C_P - C_P' + 2\frac{m_l}{m_{B_s}}(C_{10} - C_{10}')|^2 \right\}$$

# 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

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

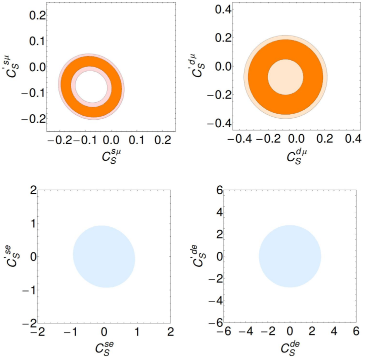



- $B_q \to \ell\ell$ blind to the orthogonal combinations $C_S + C_S'$ and $C_P + C_P'$
  Scalar operators unconstrained!

# Phenomenological consequences $B_q \to \ell\ell$

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

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

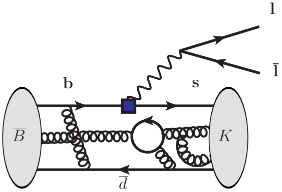



- $\Lambda_{\rm NP}$ (95%C.L.) RGE of QCD+EW+Yukawas

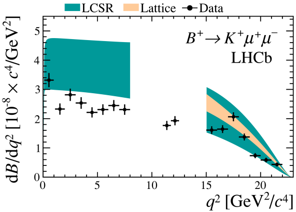
| Channels | $s\mu$ | $d\mu$ | $se$ | $de$ |
|---|---|---|---|---|
| $C_S^{(\prime)}(m_W)$ | 0.1 | 0.15 | 0.6 | 1.5 |
| $\Lambda$ [TeV] | 79 | 130 | 36 | 49 |

Alonso, Grinstein, JMC, PRL113(2014)241802

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




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




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

- 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 ($q^2$-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$^2$

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

**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

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

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

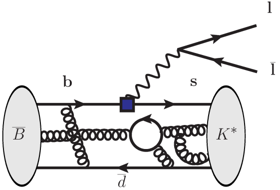
**The effect must come from $\mathcal{O}^{(\prime)}_{9,10}$**

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

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

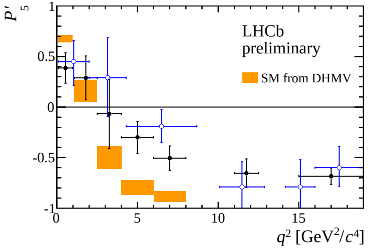
**Exceptions:** Non-linear realization of EWSB Cata and Jung arXiv:1505.05804, Beaujean *et al.* Eur.Phys.J. C75 (2015)

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

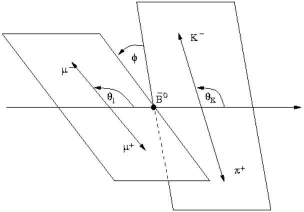



LHCb-CONF-2015-002, (also CDF, BaBar, Belle, CMS and ATLAS)

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




- **4-body decay**

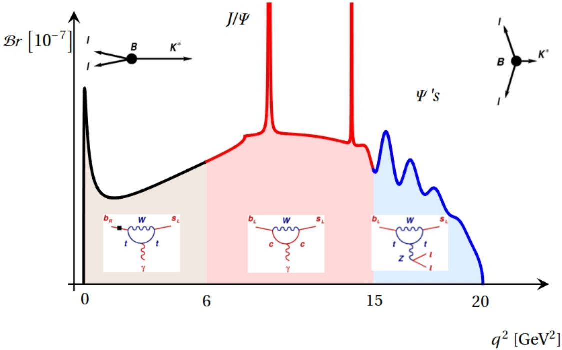



$$\frac{d^{(4)}\Gamma}{dq^2\, d(\cos\theta_l) d(\cos\theta_k) d\phi} = \frac{9}{32\pi} (I_1^s \sin^2\theta_k + I_1^c \cos^2\theta_k$$

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

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

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




- **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

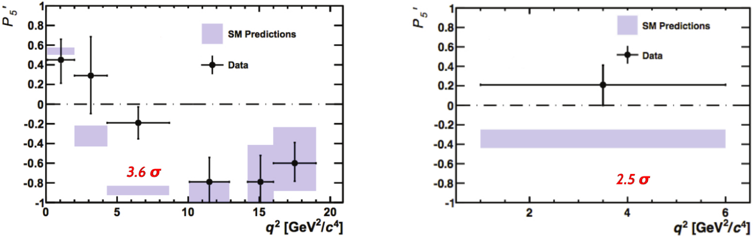
# The $P_5'$ anomaly at low $q^2$ (1 fb$^{-1}$)

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

Beaujean *et al.* arXiv: 1310.2478

- **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 $\lambda = \pm 1, 0$

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

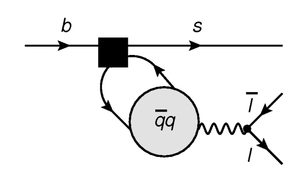
$$H_A(\lambda) = -iNC_{10}\,\tilde{V}_{L\lambda}, \qquad H_P = iN\frac{2\,m_l\hat{m}_b}{q^2}C_{10}\Big(\tilde{S}_L + \frac{m_s}{m_b}\tilde{S}_R\Big)$$

## $C_9$ 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-local" 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 **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"

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

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 $\mathcal{O}(\alpha_s^0, (\frac{\Lambda}{m_b})^0)$

- $\alpha_s$ 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 ($\Lambda/m_b$) 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

# Model-independent parameterization of power corrections

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

Jäger and JMC'12,'14, Descotes-Genon *et al.* '14

1. **Identify soft- with QCD-FFs:** E.g. $[T_-(q^2),\ S(q^2)]$ or $[V_-(q^2),\ V_0(q^2)]$
2. **At $q^2 = 0$:** Use models and consistent with $B \to K^*\gamma$ (fits $C_7^{(\prime)}$ input)

$$\xi_\perp(0) = 0.31(4), \qquad \xi_\parallel(0) = 0.31(6)$$

3. **QCD exact relations** $\Longrightarrow a_{T_+} = 0$ and $a_{V_0} = a_S$
4. **$q^2$ dependence:** Use modified HQ/LE limit scaling + models ($\alpha_X$)

$$\xi_X(q^2)=\xi_X(0)\left(\frac{1}{1-q^2/m_B^2}\right)^{2+\alpha_X}, \qquad X=\perp,\parallel$$

Charles *et al.*, Beneke and Feldmann'01, Jäger and JMC'14

5. **PC's estimated with power counting:** $\Lambda/m_b = 10\%$ where ...
   - ...for $a_F$ is based on $\xi_X(0)$
   - ... for $b_F$ is based on $d\xi_X(q^2)/dq^2$

- Errors of $P_i^{(\prime)}$ are almost independent of $\xi_X$
- Dependence on different parametrizations?

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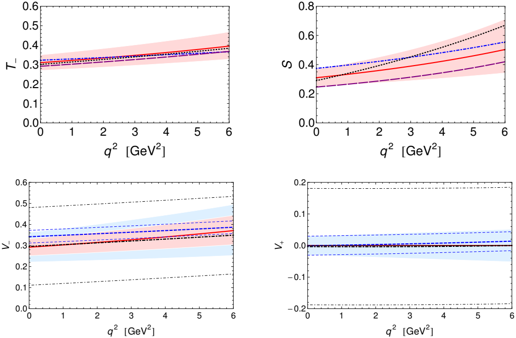
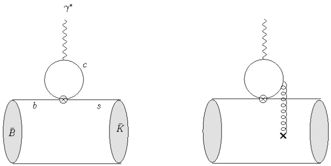


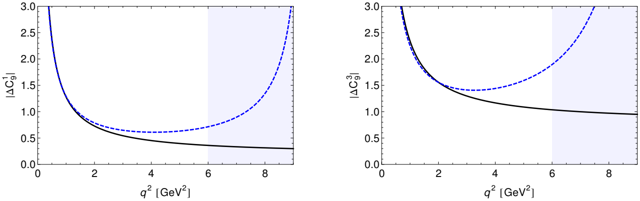

- **Light-cone SRs** (Ball&Zwicky'05, Khodjamirian *et al.*'10)
- **Dyson-Schwinger** (Ivanov *et al.*'07)

# Charm-loop at low $q^2$




- **QCDF**: Can be computed at leading-power perturbatively in $\alpha_s$
- Long-distance in **light-cone OPE + SRs**: As large as $\Lambda^2/(4m_c^2)$ Khodjamirian *et al.*'10

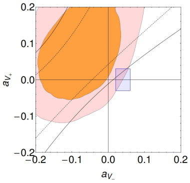
$$\Delta C_9^i = (2\, m_b\, m_B/q^2\, \delta_{i1} + \delta_{i2})\, e^{i\phi_i}$$

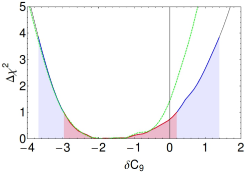


$$P_5' = P_5'|_\infty \left( 1 + \frac{a_{V_-} - a_{T_-}}{\xi_\perp} \frac{m_B}{|\vec{k}|} \frac{m_B^2}{q^2} C_7^{\rm eff} \frac{C_{9,\perp} C_{9,\parallel} - C_{10}^2}{(C_{9,\perp}^2 + C_{10}^2)(C_{9,\perp} + C_{9,\parallel})} + \frac{a_{V_0} - a_{T_0}}{\xi_\parallel} \, 2\, C_7^{\rm eff} \frac{C_{9,\perp}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

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

Jäger and JMC, arXiv: 1412.3183

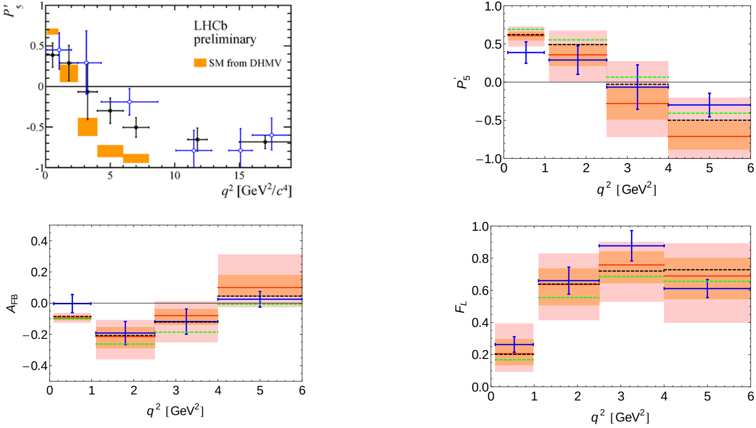



- Analysis using 1 fb$^{-1}$ and the ***R-fit method*** Höcker *et al.* EPJC21,225(2001)
- **LCSR** lead to PC parameters implying a higher significance (blue box)
- Extra th. constraints? Bharucha *et al.* arXiv:1503.05534
  - e.o.m.'s in **LCSRs**
  - **LQCD** data at high $q^2$ (too early?)
  - $z$-parametrization of form factors
  - ...

# Comparison with 3 fb$^{-1}$

- Internal Band: Gaussian distributions $1\sigma$
- External Band: Flat distributions max. spread
- Two scenarios: (a): $\delta C_9 = -1$; **(b)** 10% power corrections in $V_\pm$




- $q^2$-dependence of the effect (charm loop?) Lyon *et al.* arXiv:1406.0566, Altmannshofer *et al.* arXiv:1503.06199

# What about the high $q^2$ region?

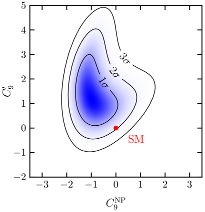
- Especially suited for determining $C_9$
- Theoretical approach based on **OPE+HQET**

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

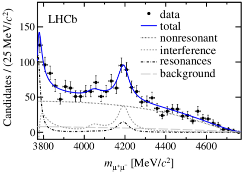
Grinstein *et al.* PRD70(2004)114005, Bobeth *et al.* JHEP1007(2010)098, Beylich *et al* EPJC71(2011)1635

- 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!!

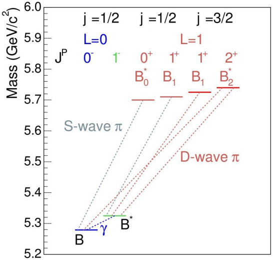



No satisfactory (model-independent) solution (yet?)

# Weak decays of “unstable” $b$-mesons

Grinstein and JMC arXiv: 1509.05049

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

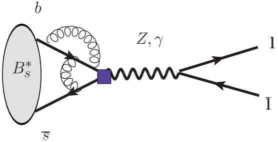



- Degenerate doublets in the HQ limit $\Delta M \simeq \Lambda^2/m_B$
- “Unstable” under **EM** or **Strong** interactions
- **Short life-times:** $\tau^* \lesssim 10^{-17}s$ ($\tau_B \sim 10^{-12}$) Do not live long enough to do weak physics!

**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:

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

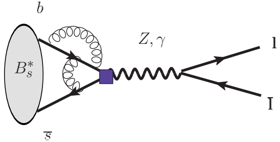
$$- 8\pi^2\frac{1}{q^2}\sum_{i=1}^{6,8} C_i\,\langle 0|\mathcal{T}_i^{\mu}(q^2)|B_s^*(q,\varepsilon)\rangle\;\bar{\ell}\gamma_\mu\ell\Big],$$

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

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

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

# $B_s^* \to \ell\ell$

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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** $B_s^* \to B_s\gamma$

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

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

- Using $\Gamma(D^{*\pm} \to D^\pm\gamma) = \Gamma(D^{*\pm}) \times \mathcal{B}(D^{*\pm} \to D^\pm\gamma) = 1.33(33)$ 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 $\mu_{bs}$ are necessary! Becirevic *et al.* EPJC71,1743, Donald *et al.* PRL112,212002

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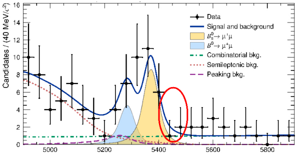
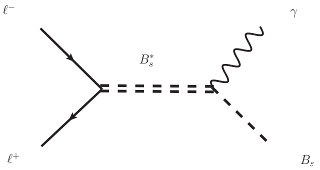



- Small peak in $B_q \to \mu\mu$ measurents
- $\sigma(pp \to b\bar{b}) \simeq 10^{12}$ fb @ 14 TeV
- We estimate that $\sim 10$ ($\sim 100$) $B_s^* \to \mu\mu$ events by the end of run III (HL-LHC)

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

Grinstein and JMC arXiv: 1509.05049

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

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

$\nu N$ scattering experiments at $\sim$ 10 fb!!

- **Energy spread** of accelerator essential:

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

# The shape of the (new) physics

**Let's assume $R_K$ and $P_5'$ are NP**

$$\delta C_9^{\mu} = -\delta C_{10}^{\mu} = -0.5$$
$$\delta C_9^{e} = \delta C_{10}^{e} = 0$$

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

- Only 2 dim-6 $SU(2)_L \times U(1)_Y$-invariant operators

$$Q_{\ell q}^{(1)} = \frac{1}{\Lambda^2}(\bar{q}_L \gamma^{\mu} q_L)(\bar{\ell}_L \gamma_{\mu} \ell_L) \qquad Q_{\ell q}^{(3)} = \frac{1}{\Lambda^2}(\bar{q}_L \gamma^{\mu} \vec{\tau} q_L) \cdot (\bar{\ell}_L \gamma_{\mu} \vec{\tau} \ell_L)$$

1. **Lepton Universality Violation** $\Rightarrow$ **Lepton flavor Violation**?
2. **Operators with $SU(2)_L$ quark doublets**
   - FCNC with neutrinos and/or up quarks
   - $V - A$ Contributions CC ($b \to c\ell\bar{\nu}$, $t \to b\bar{\ell}\nu \ldots$)

# Lepton flavor symmetries in the SM

$$SU(3)_\ell \times SU(3)_e \times U(1)_L \times U(1)_{e-\ell}\,, \qquad \ell_L \sim (3,1)_{1,-1}\,, \qquad e_R \sim (1,3)_{1,1}$$

Broken **only** by the Yukawas in the SM

$$-\mathcal{L}_Y \supset \epsilon_e\,\bar{\ell}_L\,\hat{Y}_e e_R H + h.c., \qquad (Y_e = \epsilon_e\,\hat{Y}_e,\ \mathrm{tr}(\hat{Y}_e\,\hat{Y}_e^\dagger) = 1)$$

$U(1)_\tau \times U(1)_\mu \times U(1)_e$ survives

- **However:** Any new source of flavor violation will lead to LF violation. . .

  Glashow *et al.* PRL114(2015)091801, Bhattacharya *et al.* arXiv:1505.04692, Lee *et al.* arXiv:1505.04692

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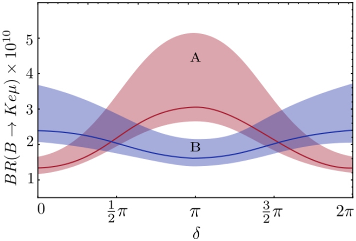
**LFV** in $b \to s\ell\ell'$!!

$$\begin{aligned}
\mathrm{BR}(B \to K e^\pm \mu^\mp) &\in [1.2, 1.7] \times 10^{-10} \\
\mathrm{BR}(B \to K e^\pm \tau^\mp) &\in [1.9, 5.8] \times 10^{-10} \\
\mathrm{BR}(B \to K \mu^\pm \tau^\mp) &\in [3.4, 7.2] \times 10^{-9}\,.
\end{aligned}$$




Boucenna *et al.* arXiv:1503.07099

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- ...unless it is "aligned" with the Yukawas (e.g. Crivellin *et al.* PRL114(2015)151801, Celis *et al.* arXiv:1505.03079)

**Minimal flavor violation**

The only source of lepton flavor structure in the new physics *are* the Yukawas

Chivukula *et al*'87s, D'Ambrosio *et al*'02, Cirigliano *et al*'05

Introduce spurions $\hat{Y}_e \sim (3,\bar{3})$ and $\epsilon_e \sim (-1,1)$

Alonso, Grinstein and JMC arXiv:1505.05164

$$\mathcal{L}^{\rm NP}=\frac{1}{\Lambda^2}\left[(\bar q'_L\, C_q^{(1)}\gamma^\mu q'_L)(\bar\ell'_L\, \hat Y_e\, \hat Y_e^\dagger \gamma_\mu \ell'_L)+(\bar q'_L\, C_q^{(3)}\gamma^\mu \vec\tau q'_L)\cdot(\bar\ell'_L\, \hat Y_e\, \hat Y_e^\dagger \gamma_\mu \vec\tau \ell'_L)\right]$$

**Hierarchic leptonic couplings (no LFV)**

Interactions $\sim \delta_{\alpha\beta} m_\alpha^2/m_\tau^2$

1. **Boost of $10^3$ in $b \to s\tau\tau$!**

$$\mathcal{B}(B\to K\tau^-\tau^+)\simeq 2\times 10^{-4},\qquad \mathcal{B}(B^+\to K^+\tau\tau)^{\rm expt}<3.3\times 10^{-3}$$

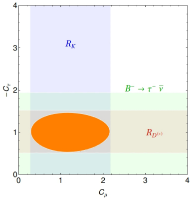
2. **Very strong constraint from $b \to s\nu_\tau\nu_\tau$**
3. **Sizable effects in CC tauonic $B$ decays!**

$$R_{D^{(*)}}=\frac{\mathcal{B}(\bar B\to D^{(*)}\tau\bar\nu_\tau)}{\mathcal{B}(\bar B\to D^{(*)}\mu\bar\nu_\mu)}$$

- ***Excess*** observed at $3.6\sigma$

| | SM | Expt. |
|---|---|---|
| $R_D$ | 0.300(10) | 0.388(47) |
| $R_{D^*}$ | 0.252(5) | 0.321(21) |

- $\Lambda_{NP} \simeq 3$ TeV




Alonso *et al.* arXiv:1505.05164

# 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 $d_i \to d_j \ell\ell$
   - Efficient interpretation of $R_K$ anomaly
2. The $P_5'$ anomaly
   - Strong interplay between **QCD** and **NPs**
   - Model-independent parameterization of power corrections
   - **Understand differences between different groups!**
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**
   - Probe **NPs** is $\ell^+\ell^- \to B_s^* \to B_s\gamma$ scattering experiments
4. The shape of new physics
   - Lepton non-universal but flavor-conserving scenarios

With the LHC run2 very exciting times ahead!