# Lepton Universality Violation in $B$-Meson Decays

## and Inclusive vs Exclusive $|V_{cb}|$

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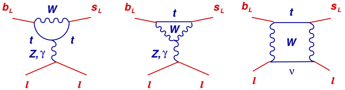
CERN Th Colloquium / Instant Workshop on B Physics Anomalies
CERN, 17 May, 2017

# Why the Excitement on Anomalies in $B$ decays?

## Slide for "executives"

The SM of EW intearctions predicts




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

- This is same for all lepton flavors: lepton univesality (LU)
- LU violation (LUV) reported by LHCb in $b \to s\mu\mu$ vs $b \to see$
- LUV could arise from new physics (NP):
  - At very short distances, with SM below scale $\Lambda \gg M_W$
  - Short distances at SM scale, $\Lambda \sim M_W$ (*e.g.*, strongly coupled EW symmetry breaking)
  - Long distances: new light particles
- Worse case scenario: $\Lambda \gg M_W$: $NP = \frac{g^2}{\Lambda^2}\, \bar{s}_L \gamma^\mu b_L\, \bar{\ell}\gamma_\mu(\gamma_5)\ell$
- Fits of reported LUV require

$$\frac{g^2}{\Lambda^2} \approx 0.25 \times G_F\, V_{tb}\, V_{ts}^* \frac{\alpha}{4\pi} C_{9(10)} \qquad \Rightarrow \qquad \frac{\Lambda}{g} \approx 28 \text{ TeV}$$

- Best argument to build VLHC! (or find NP sooner!!)

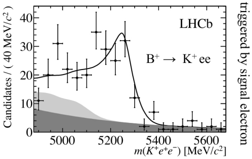
# Anomalies in $B$ decays?

## $b \to sll$

- **"$R_K$anomaly"** (**FCNC**)!

$$R_K = \left.\frac{\mathrm{Br}(B \to K\mu\mu)}{\mathrm{Br}(B \to Kee)}\right|_{[1,6]}$$

**LHCb PRL113(2014)151601**




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

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

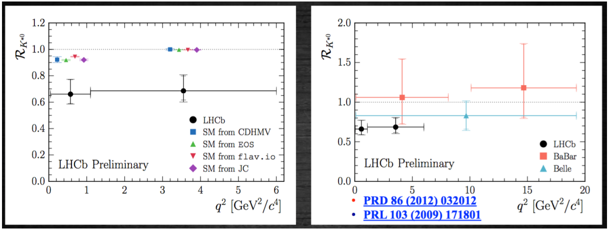
**Altmannshofer and Straub '14**

# Anomalies in $B$ decays?

## $b \to sll$ and decays to $\tau$

- **"$R_{K^*} = \mathbf{Br}(B \to K^* \mu\mu)/\mathbf{Br}(B \to K^* ee)$ anomaly" (FCNC)!**

Simone Banfi for LHCb, CERN seminar 2017-08-18

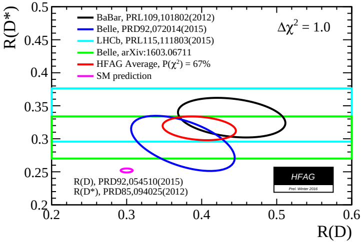



| LHCb Preliminary | low-$q^2$ | central-$q^2$ |
|---|---|---|
| $\mathcal{R}_{K^{*0}}$ | $0.660 \; ^{+\,0.110}_{-\,0.070} \pm 0.024$ | $0.685 \; ^{+\,0.113}_{-\,0.069} \pm 0.047$ |
| 95% CL | [0.517–0.891] | [0.530–0.935] |
| 99.7% CL | [0.454–1.042 ] | [0.462–1.100] |

- "Compatibility with **SM** 2.2-2.4$\sigma$ (low-$q^2$) 2.4-2.5$\sigma$ (central-$q^2$)"
- "Rare decays will largely benefit from the increase of energy (cross-section) and collected data ($\sim$ 5fb$^{-1}$ expected in LHCb) in Run 2"

- **"$R_{D^{(*)}}$ anomaly"** **(CC)**

$$R_{D^{(*)}} = \frac{\text{Br}(B \to D^{(*)}\tau\nu)}{\text{Br}(B \to D^{(*)}\ell\nu)}$$




- ***Excesses*** observed at more than $4\sigma$

| | $R(D)$ | $R(D^*)$ |
|---|---|---|
| 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

# Anomalies in $B$ decays

## Exclusive vs Inclusive determination of $|V_{cb}|$

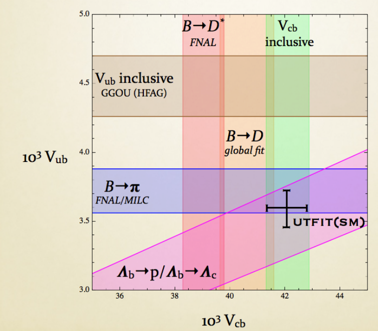
- $|V_{cb}|$ incl. vs $D^*$(FNAL/MILC) is $\sim 8\%(\sim 3\sigma)$
- RH currents won't do

$$|V_{cb}|_{\rm incl} = |V_{cb}|(1 + \tfrac{1}{2}\epsilon^2)$$
$$|V_{cb}|_{D^*} = |V_{cb}|(1 + \epsilon)$$
$$|V_{cb}|_{D} = |V_{cb}|(1 - \epsilon)$$

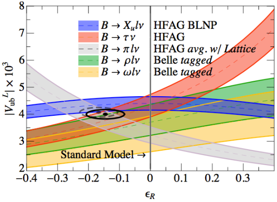
- More general NP dim-6 ops can't either

  Crivellin, Pokorski 1407.1320

- Tension decreased on $|V_{ub}|$ Bernlochner, Ligeti, Turczyk, PRD90(2014)094003




P. Gambino, Beauty 2016



# Anomalies in $B$ decays

(My?) problem is ...

- Exclusive vs Inclusive
  - NP won't do
  - Something wrong with our understanding, theory or experiment
- How can one accept $b \to sll$ and $b \to (u, c)\tau\nu$ anomalies if we can't explain exclusive vs inclusive anomalies?

# Outline

# Model-Independent Extraction of $|V_{cb}|$ from $\bar{B} \to D^* \ell \overline{\nu}$

New! No apologies: technical (4 slides).

- Longstanding tension in exclusive vs inclusive determination HFAG 1612.07233

$$
\begin{aligned}
|V_{cb}| &= (39.18 \pm 0.99) \times 10^{-3} & (\bar{B} \to D\ell\overline{\nu}) \\
|V_{cb}| &= (38.71 \pm 0.75) \times 10^{-3} & (\bar{B} \to D^*\ell\overline{\nu}) \\
|V_{cb}| &= (42.19 \pm 0.78) \times 10^{-3} & (\bar{B} \to X_c\ell\overline{\nu},\ \text{kinetic scheme}) \\
|V_{cb}| &= (41.98 \pm 0.45) \times 10^{-3} & (\bar{B} \to X_c\ell\overline{\nu},\ \text{1S scheme})
\end{aligned}
$$

- Exclusive ($\bar{B} \to D^{(*)}\ell\overline{\nu}$): commonplace to use CLN Caprini, Lellouch, Neubert NPB 530 (1998)153
- CLN not a good fit to $B \to D\ell\nu$ data Bigi & Gambino PRD 94(2016)094008
- Fermilab Lattice and MILC collaborations: Phys. Rev.D92(2015)034506
  - Lattice $B \to D\ell\nu$ analysis, no CLN fits, errors not controlled
  - BGL can be used to obtain $|V_{cb}|$ for arbitrarily more precise uncertainties
- $\Lambda_{QCD}/m_Q$ in relations between form factors $\Rightarrow$ uncertainties in extracted $|V_{cb}|$ using CLN underestimated, perhaps Bernlochner *et al*, 1703.05330
- Can NP accomodate?
  - various opinions *e.g.*, Crivellin-Pokorski, PRL114(2015)011802 vs Colangelo-De Fazio, PRD95(2017)011701
  - not in SV limit, for *any* SM-EFT operators VS, SJNP47('88)511; BGM, PRD54('96)2081; BG unpub
- Is tension in Excl vs Incl from CLN?

# Model-Independent Extraction of $|V_{cb}|$ from $\bar{B} \to D^* \ell \overline{\nu}$, cont'd

- New Belle analysis released: **Abdesselam *et al* (Belle) 1702.01521**
  - Unfolded data, full correlation matrix
  - Large dataset, energy and angular distributions
  - CLN: $|V_{cb}| = (37.4 \pm 1.3) \times 10^{-3}$
- Two independent analyses using BGL:
  - Very consistent fits:

$$|V_{cb}| = (41.7\ {}^{+2.0}_{-2.1}) \times 10^{-3}$$ **Bigi, Gambino & Schacht, 1703.06124**

$$|V_{cb}| = (41.9\ {}^{+2.0}_{-1.9}) \times 10^{-3}$$ **BG & Kobach, 1703.08170**

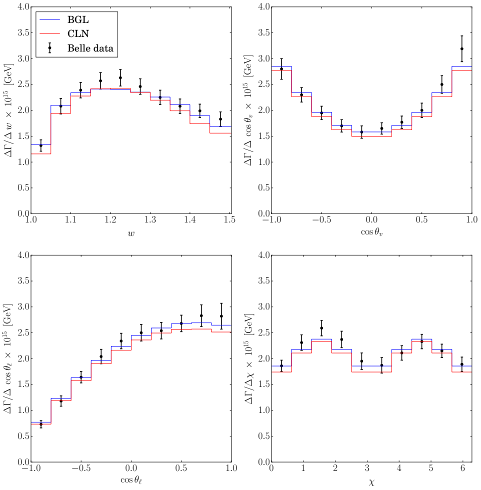
  - Robust: different numerical inputs
  - Likely culprit: independent form factors (no HQET symmerty)

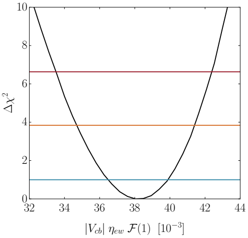
$$\begin{aligned} \langle D^*(\varepsilon, p')|\bar{c}\gamma^\mu b|\bar{B}(p)\rangle &= ig\epsilon^{\mu\nu\alpha\beta}\varepsilon^*_\nu p_\alpha p'_\beta, \\ \langle D^*(\varepsilon, p')|\bar{c}\gamma^\mu\gamma^5 b|\bar{B}(p)\rangle &= f\varepsilon^{*\mu} + (\varepsilon^*\cdot p)[a_+(p+p')^\mu + a_-(p-p')^\mu], \end{aligned}$$

Recall: BGL introduced $z$-parametrization, eg,

$$g(z) = \frac{1}{P_g(z)\phi_g(z)} \sum_{n=0}^{N} a_n z^n \quad \text{with} \quad \sum_n a_n^2 \leq 1 \quad \text{and} \quad 0 \leq z \leq z_{\max} = 0.056$$

with calculable outer function $\phi$ and Blaschke factor $P$
  - CLN uses BGL technique, but imposes HQET conditions




Fitted coefficients in ff expansion far from unitary bounds

Use $\eta_{ew} = 1.0066$ Sirlin, NPB196(1982)83, $\mathcal{F}(1) = 0.906 \pm 0.013$ FNAL/MILC PRD89(2014)114504

Work ahead:

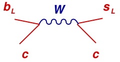
- Experiments: release unfolded data
- Experiments' next best alternative: do BGL fits
- Global analysts: do BGL fits, others (*e.g.*, polynomail in $q^2$)?
- Theorists: $\Lambda/m_c$ effects?
- Theorists: Is BGL better than polynomial for independent form factors?
- Can this affect $B \to D^{(*)}\tau\nu$
- ...

If I may be so bold: *problem solved*

- Retrospect: What went wrong?
  - The probelm was sociological!

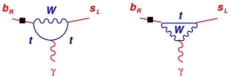
# Effective field theory approach to $b \to s\ell\ell$ decays

- **CC** (Fermi theory):

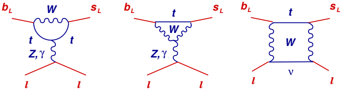



$$\Rightarrow \qquad G_F\, V_{cb}\, V_{cs}^*\, C_2\, \bar{c}_L \gamma^\mu b_L\, \bar{s}_L \gamma_\mu c_L$$

- **FCNC**:

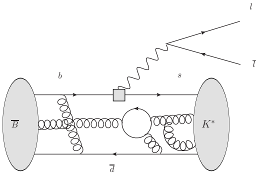



$$\Rightarrow \qquad \frac{e}{4\pi^2}\, G_F\, V_{tb}\, V_{ts}^*\, m_b\, C_7\, \bar{s}_L \sigma_{\mu\nu} b_R\, F^{\mu\nu}$$




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

- ▶ 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 $\mathcal{L}$ from most general local operators $\mathcal{O}_k$ made of $\phi \in u, d, s, c, b, l, \nu, F_{\mu\nu}, G_{\mu\nu}$, subject to Lorentz and $SU(3)_c \times U(1)_{em}$ invariance

- New physics manifest at the operator level through...
  - Different values of the Wilson coefficients $C_i^{\mathrm{expt.}} = C_i^{\mathrm{SM}} + \delta C_i$
  - 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 non-SM-particles *on-shell* at colliders up to $E \simeq 1$ TeV...
    ...assuming the scalar at $s \simeq 125$ GeV is the SM Higgs

**Guiding principle** *(rewritten)*

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

Buchmuller *et al.*'86,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:

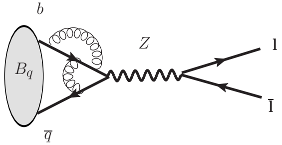
$$(\bar{q}_j\sigma_{\mu\nu}P_R d_i)(\bar{e}\sigma^{\mu\nu}P_L\ell) = 0$$

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

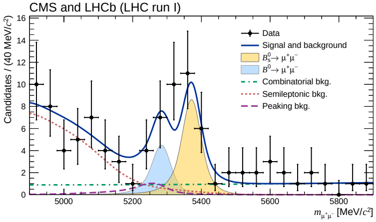
- From **4** scalar operators to only **2**!
- From **2** tensor operators to **none**!

Alonso, BG, Martin-Camalich, PRL113(2014)241802 ***Caveat:*** **Non-limearly relaized EW symmetry**

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




CMS and LHCb combined arXiv: 1411.4413




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

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

  FLAG averages Eur.Phys.J. C74 (2014) 2890

- Updated predictions:

  Bobeth *et al.* PRL112(2014)101801

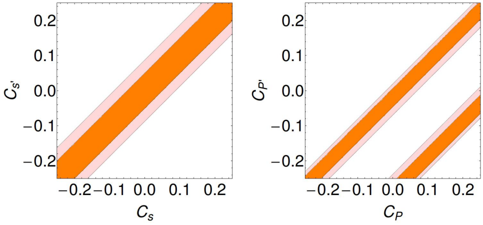
$$\overline{\mathcal{B}}_{s\mu}^{\rm SM} = 3.65(23) \times 10^{-9}$$
$$\overline{\mathcal{B}}_{s\mu}^{\rm expt} = 2.9(7) \times 10^{-9}$$

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

$$\overline{R}_{ql} = \frac{\overline{\mathcal{B}}_{ql}}{\left(\overline{\mathcal{B}}_{ql}\right)_{\rm SM}} = \frac{1 + \mathcal{A}^{ll}_{\Delta\Gamma}\, y_q}{1 + y_q} \left(|S|^2 + |P|^2\right),$$

De Bruyn *et al.* '12

$$S = \sqrt{1 - \frac{4m_l^2}{m_{B_q}^2}}\, \frac{m_{B_q}^2}{2m_l} \frac{C_S - C_S'}{(m_b + m_q) C_{10}^{\rm SM}}, \qquad P = \frac{C_{10} - C_{10}'}{C_{10}^{\rm SM}} + \frac{m_{B_q}^2}{2m_l} \frac{C_P - C_P'}{(m_b + m_q) C_{10}^{\rm SM}}$$



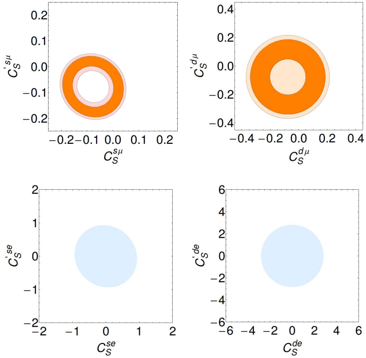

- $B_q \to \ell\ell$ blind to the orthogonal combinations $C_S + C_S'$ and $C_P + C_P'$

  Scalar operators unconstrained!

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

$$\overline{R}_{ql} = \frac{\overline{\mathcal{B}}_{ql}}{(\overline{\mathcal{B}}_{ql})_{\rm SM}} = \frac{1 + \mathcal{A}^{ll}_{\Delta\Gamma}\, y_q}{1 + y_q} \left(|S|^2 + |P|^2\right),$$

$$S = \sqrt{1 - \frac{4m_l^2}{m_{B_q}^2}} \frac{m_{B_q}^2}{2m_l} \frac{C_S - C_S'}{(m_b + m_q)C_{10}^{\rm SM}}, \qquad P = \frac{C_{10} - C_{10}'}{C_{10}^{\rm SM}} - \frac{m_{B_q}^2}{2m_l} \frac{C_S + C_S'}{(m_b + m_q)C_{10}^{\rm SM}}$$

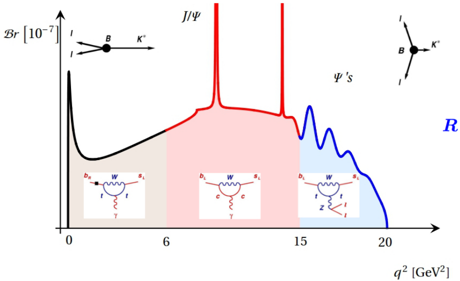


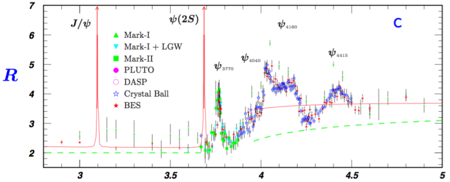

- $\Lambda_{\rm NP}$ (95%C.L.) RGE of QCD+EW+Yukawas

| 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, BG, Martin-Camalich, PRL113(2014)241802

# $b \to s\ell\ell$ anomalies: Hadronic complications

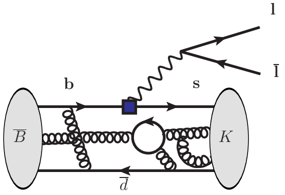


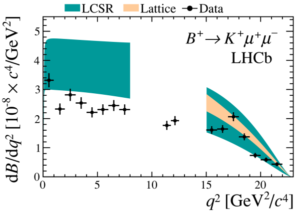




- **Large-recoil region** (low $q^2$)
  - Heavy to collinear light quark $\Rightarrow$ QCDf or SCET (power-corrections)
  - Dominant effect of the photon pole
- **Charmonium region**
  - Dominated by long-distance (hadronic) effects
  - Starting at the perturbative $c\bar{c}$ threshold $q^2 \simeq 6 - 7$ GeV$^2$
- **Low-recoil region** (high $q^2$)
  - Heavy quark EFT + Operator Product Expansion (OPE) (duality violation)
  - Dominated by semileptonic operators

# $B \to K\ell\ell$

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




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

**Note: in this talk I won't show corresponding Eq for $K^*$: similar but $C_7$ matters and $C_n' \to -C_n'$**

- Phenomenologically rich (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
  - Hadronic form factors ($q^2$-dependent functions)
  - "Non-factorizable" contribution of 4-quark operators+EM current

# $B \to K\ell\ell$

- 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

- $2.6\sigma$ discrepancy with the SM $\langle R_K\rangle_{[1,6]} = 1.0003(1)$
- Linearly realized $SU(2)_L \times U(1)_Y$ EFT:
  - 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 $\mathcal{O}^{(\prime)}_{9,10}$**

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

Alonso, BG, Martin-Camalich, PRL113(2014)241802

# $B \to K^*\ell\ell$: $R_{K^*}$

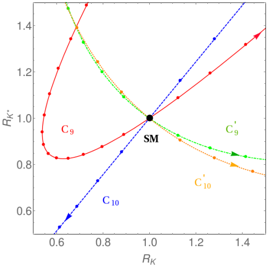
## The $R_{K^*}$ anomaly

$$\langle R_{K^*}\rangle_{[0.045,1.1]} = 0.660^{+0.110}_{-0.070}(\text{stat}) \pm 0.024(\text{syst})$$

$$\langle R_{K^*}\rangle_{[1.1,6]} = 0.685^{+0.113}_{-0.069}(\text{stat}) \pm 0.047(\text{syst})$$

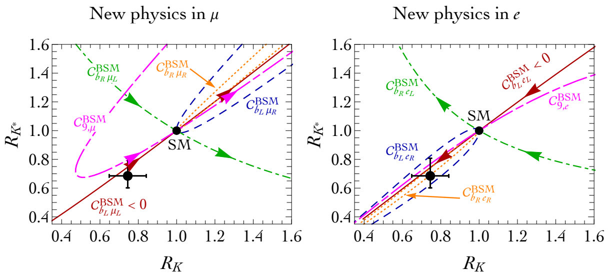
Theoretical interpretation (mostly in pictures)

**Bernat Capdevila, Andreas Crivellin, Sébastien Descotes-Genon, Joaquim Matias, Javier Virto, 1704.05340**
**Wolfgang Altmannshofer, Peter Stangl, David M. Straub, 1704.05435**
**G. D'Amico, M. Nardecchia, Paolo Panci, Francesco Sannino, Alessandro Strumia, Riccardo Torre, Alfredo Urbano, 1704.05438**
**Gudrun Hiller, Ivan Nišandžić, 1704.05444**
**Marco Ciuchini, António M. Coutinho, Marco Fedele, Enrico Franco, Ayan Paul, Luca Silvestrini, Mauro Valli, 1704.05447**
**Alejandro Celis, Javier Fuentes-Martín, Avelino Vicente, Javier Virto, 1704.05672**
**Li-Sheng Geng, BG, Sebastian Jäger, Jorge Martin Camalich, Xiu-Lei Ren, Rui-Xiang Shi, 1704.05446**

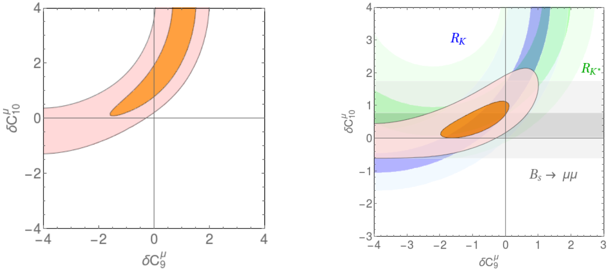



- Recall $C_9^{SM} \approx -C_{10}^{SM} \approx 4.5$
- These are $\delta C_i = C_i^{NP}$, in $\mu$
- Arrows: increasing $\delta C$
- Dots: intervals of $\Delta(\delta C) = 0.5$
- Central Value $(R_K, R_{K^*})$ on blue line
- Not $C'_9, C'_{10}$ (ie, not $V + A$)

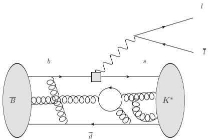
$\mu$ vs $e$




Fit to $R_K$ and $R_{K^*}$, and these plus $B_s \to \mu\mu$

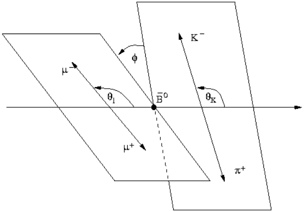


# $\bar{B} \to \bar{K}^* \ell^+ \ell^-$: angular




| | | |
|---|---|---|
| **CDF** | 100 | PRL106(2011)161801 |
| **BaBar** | 150 | PRD86(2012)032012 |
| **Belle** | 200 | PRL103(2009)171801 |
| **CMS** | 400 | PLB727(2013)77 |
| **ATLAS** | 500 | arXiv:1310.4213 |
| **LHCb ($\mu$)** | 3000 (3 $\text{fb}^{-1}$) | JHEP 1602 (2016) 104 |
| **LHCb ($e$)** | 128 ([0.0004, 1] $\text{GeV}^2$) | JHEP 1504(2015)064 |

- **4-body decay**




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

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

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

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

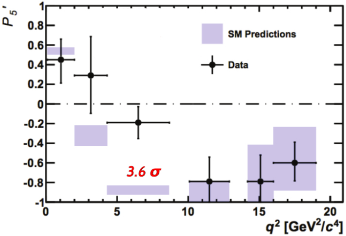
# The $P_5'$ anomaly at low $q^2$ (1 fb$^{-1}$)

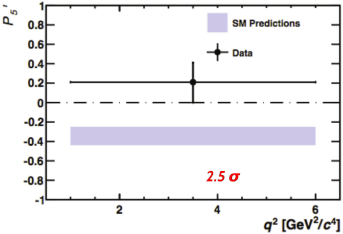
PRL **111**, 191801 (2013) PHYSICAL REVIEW LETTERS week ending 8 NOVEMBER 2013

**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)



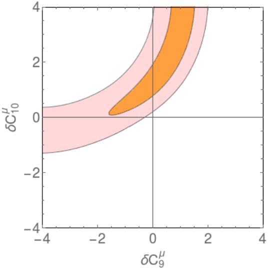



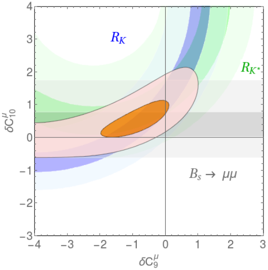

$$\delta C_9^\mu \simeq -1$$

Descotes-Genon *et al.* PRD88,074002

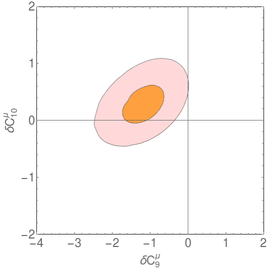
Altmannshofer *et al.* Eur.Phys.J. C73 (2013) 2646

We have seen: Fit to $R_K$ and $R_{K^*}$, and these plus $B_s \to \mu\mu$




And now including all "dirty" observables




- Not $C'$
- Not purely $C^e$
- New LUV observables (no time to discuss)

# The shape of the new physics

- Assume hereafter: $R_{K,K^*}$ and $P_5'$ are NP
- Stick to SM-EFT

**Simplest example: chiral solution**

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

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 $\Rightarrow$ new correlations,** *i.e.*,**:**
   - 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.* PLB742(2015)370

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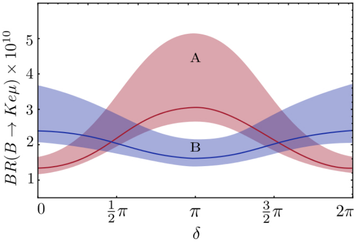
Glashow *et al.* PRL114(2015)091801, Bhattacharya *et al.* PLB742(2015)370

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

**Assume, eg, NP is LF-diagonal in interaction basis:**

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




Boucenna *et al.* PLB750(2015)367

# Lepton flavor symmetries in the SM

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

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

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

  Glashow *et al.* PRL114(2015)091801, Bhattacharya *et al.* PLB742(2015)370

- ...unless it is "aligned" with the Yukawas (e.g. Lee *et al.* JHEP1508(2015)123, Crivellin *et al.* PRL114(2015)151801, Celis *et al.* PRD92(2015)015007

## 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 $\epsilon_e \sim (0,-2)$

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

Very generic observations:

**Hierarchic leptonic couplings (no LFV)**

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

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

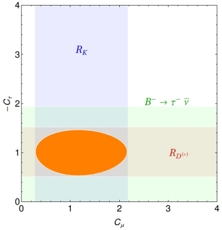
$$\mathcal{B}(B\to K\tau^-\tau^+)\simeq 2\times 10^{-4},\qquad \mathcal{B}(B^+\to K^+\tau\tau)^{\rm expt}<3.3\times 10^{-3}$$

2. **Very strong constraint from $b\to s\nu_\tau\nu_\tau$**
   - $\Lambda_{NP}\simeq 3$ TeV
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 more than $4\sigma$

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




Alonso *et al.* JHEP1510(2015)184

# Applications to model-building

Refs: apologies!

Scratching the surface of large and growing literature, just to give a sense

- Approaches:
  - Short distance: decoupling particles, heavier than EW, weak coupling (tree level)
    - $Z'$
      - ★ LUV: couple (typically) to $L_\mu - L_\tau$, strength $g_{\mu\mu}$
      - ★ FCNC: non-diag coupling to $\bar{s}b$, strength $g_{bs}$; $B_s$-mixing $\Rightarrow$ $g_{bs}/M_{Z'} < 5 \times 10^{-3}$ TeV$^{-1}$
      - ★ B-anomalies: $g_{\mu\mu}/M_{Z'} > 1/(3.7\text{ TeV})$, or $M_{Z'} < 13$ TeV for $g_{\mu\mu} < \sqrt{4\pi}$
      - ★ Need to address LFV (eg, $\mu \to e\gamma$) and other quark FCNC
    - Leptoquarks $\to$ see next slide
  - Non-decoupling, EW scale
    - **SM-EFT analysis does not necessarily apply**
    - Loop mediators — Arnan et al, 1608.07832; Gripaios et al, JHEP1606(2016)083; Kamenik et al, 1704.06005
    - Composites, partial composites — eg Gripaios et al, JHEP1505(2015)006
  - Long distance, lighter than EW — Sala & Straub, 1704.06188, Bishara et al, 1705.03465, ...
- Is Q&L flavor fundamental to the NP?
  - No, small numbers look fine tuned just as in CKM model
  - Yes, this is a window to flavodynamics, e.g., gauged flavor — Crivellin et al, PRD91(2015)075006

# Survey of leptoquark models

- **Scalar** LQ

$$\mathcal{L}_\Delta = \left(y_{\ell u}\,\bar\ell_L\, u_R + y_{eq}\,\bar e_R\, i\tau_2\, q_L\right)\Delta_{-7/6} + y_{\ell d}\,\bar\ell_L\, d_R\,\Delta_{-1/6} + \left(y_{\ell q}\,\bar\ell_L^c i\tau_2\, q_L + y_{eu}\bar e_R^c\, u_R\right)\Delta_{1/3} + y_{ed}\,\bar e_R^c\, d_R\,\Delta_{4/3} + y'_{\ell q}\,\bar\ell_L^c i\tau_2\vec\tau q_L\cdot\vec\Delta'_{1/3}$$

- **Vector** LQ

$$\mathcal{L}_V = \left(g_{\ell q}\,\bar\ell_L\gamma_\mu q_L + g_{ed}\,\bar e_R\gamma_\mu d_R\right)V^\mu_{-2/3} + g_{eu}\,\bar e_R\gamma_\mu u_R\, V^\mu_{5/3} + g'_{\ell q}\,\bar\ell_L\gamma_\mu\vec\tau q_L\cdot\vec V'^\mu_{-2/3} + \left(g_{\ell d}\,\bar\ell_L\gamma_\mu d_R^c + g_{eq}\,\bar e_R\gamma_\mu q_L^c\right)V^\mu_{-5/6} + g_{\ell u}\,\bar\ell_L\gamma_\mu u_R^c\, V^\mu_{1/6}$$

**Büchmuller and Wyler'87, Davidson *et al.*'94,...**

- Assume $M_{LQ} \gg v$: Only $\vec\Delta'_{1/3}$, $V^\mu_{-2/3}$, $\vec V^\mu_{-2/3}$ can work.
  - (x)MSSM? Only $\Delta_{1/6}$, the doublet squark (with R-parity breakaing); does not work.

| LQ | $C_9$ | $C_{10}$ | $C'_9$ | $C'_{10}$ | $C_S$ | $C_\nu$ | $C'_\nu$ |
|---|---|---|---|---|---|---|---|
| $\vec\Delta'_{1/3}$ | $y'^{\beta i,A}_{\ell q}(y'^{\alpha j,A}_{\ell q})^*$ | $-y'^{\beta i,A}_{\ell q}(y'^{\alpha j,A}_{\ell q})^*$ | 0 | 0 | 0 | $-\frac{1}{2}y'^{\beta i,A}_{\ell q}(y'^{\alpha j,A}_{\ell q})^*$ | 0 |
| $\Delta_{7/6}$ | $-\frac{1}{2}y^{\alpha i,A}_{eq}(y^{\beta j,A}_{eq})^*$ | $-\frac{1}{2}y^{\alpha i,A}_{eq}(y^{\beta j,A}_{eq})^*$ | 0 | 0 | 0 | 0 | 0 |
| $\Delta_{1/6}$ | 0 | 0 | $-\frac{1}{2}y^{\alpha i,A}_{\ell d}(y^{\beta j,A}_{\ell d})^*$ | $\frac{1}{2}y^{\alpha i,A}_{\ell d}(y^{\beta j,A}_{\ell d})^*$ | 0 | 0 | $-\frac{1}{2}y^{\alpha i,A}_{\ell d}(y^{\beta j,A}_{\ell d})^*$ |
| $\Delta_{4/3}$ | 0 | 0 | $\frac{1}{2}y^{\beta i,A}_{ed}(y^{\alpha j,A}_{ed})^*$ | $\frac{1}{2}y^{\beta i,A}_{ed}(y^{\alpha j,A}_{ed})^*$ | 0 | 0 | 0 |
| $V^\mu_{2/3}$ | $-g^{\alpha i,A}_{\ell q}(g^{\beta j,A}_{\ell q})^*$ | $g^{\alpha i,A}_{\ell q}(g^{\beta j,A}_{\ell q})^*$ | $-g^{\alpha i,A}_{ed}(g^{\beta j,A}_{ed})^*$ | $-g^{\alpha i,A}_{ed}(g^{\beta j,A}_{ed})^*$ | $2g^{\alpha i,A}_{\ell q}(g^{\beta j,A}_{ed})^*$ | 0 | 0 |
| $\vec V^\mu_{2/3}$ | $-g'^{\alpha i,A}_{\ell q}(g'^{\beta j,A}_{\ell q})^*$ | $g'^{\alpha i,A}_{\ell q}(g^{\beta j,A}_{\prime\ell q})^*$ | 0 | 0 | 0 | $-2\,g'^{\alpha i,A}_{\ell q}(g'^{\beta j,A}_{\ell q})^*$ | 0 |
| $V^\mu_{5/6}$ | $g^{\beta i,A}_{eq}(g^{\alpha j,A}_{eq})^*$ | $g^{\beta i,A}_{eq}(g^{\alpha j,A}_{eq})^*$ | $g^{\beta i,A}_{\ell d}(g^{\alpha j,A}_{\ell d})^*$ | $-g^{\beta i,A}_{\ell d}(g^{\alpha j,A}_{\ell d})^*$ | $2g^{\alpha j,A}_{\ell d}(g^{\beta i,A}_{eq})^*$ | 0 | $g^{\beta i,A}_{\ell d}(g^{\alpha j,A}_{\ell d})^*$ |

- Assume, in addition, MLFV: $B\to K\nu\bar\nu \;\Rightarrow\; C_\nu \lesssim 10$, 3rd gen has $\times(m_\tau/m_\mu)^2$

**Alonso *et al.* JHEP 1510 (2015) 184**

  - Only $V^\mu_{-2/3}$ can work!

# Conclusions

1. Inclusive vs Exclusive determination of $|V_{cb}|$
   - Lesson: Use extrapolation with controlled errors (eg, BGL)
   - Not a problem anymore
2. EFT approach very efficient method to investigate anomalies
   - Assumptions: New Physics is heavy and EW is linearly realized
   - Constraints between low-energy operators
     - **2** out of **4** independent **scalar** operators and **no tensors** in $d_i \to d_j \ell\ell$
     - $B_q \to \ell\ell$: remove **scalar** operators
3. The $b \to s\ell\ell$ anomalies
   - The $P_5'$ anomaly in $B \to K^*\mu\mu$: prefer NP in $C_9^{(\prime)}$ in $\mu$-sector
   - $R_{K,K^*}$ in $B \to K^{(*)}\ell\ell$: (slightly) prefer NP in $C_{10}$, then $C_9$ (no $C'_{9,10}$)
   - Global fit: $\delta C_9$ and $\delta C_{10}$, attractively chiral: $\delta C_9 = -\delta C_{10}$ $(V-A)\otimes(V-A)$
4. New Physics
   - Heavy/medium/light? $M_{NP} < 50$ TeV; VLHC territory!
   - Does NP come with more/less symmetry? Does it lead to **LFV** vs **MLFV**?
   - Connection to charged current tauonic $B$ decays: The $R_{D^{(*)}}$ anomalies?

With the LHC run2 and Belle II, very exciting times ahead!

# The End

Backup slides

# Connecting theory to experiment: The helicity amplitudes

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

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

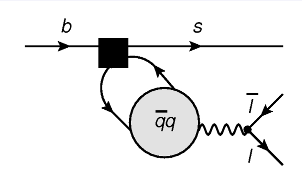
$$H_A(\lambda) = -iN\, C_{10}\, \tilde{V}_{L\lambda}, \qquad H_P = iN\frac{2\, m_l\, \hat{m}_b}{q^2} C_{10}\Big(\tilde{S}_L + \frac{m_s}{m_b}\tilde{S}_R\Big)$$

## $C_9$ 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 Martin-Camalich JHEP1305(2013)043**




- "Non factorizable" contribution

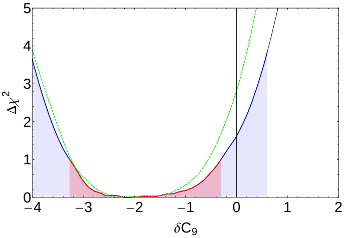
$$h_\lambda \propto \int d^4y e^{iq\cdot y} \langle \bar{K}^* | j^{\mathrm{em,had},\mu}(y)\mathcal{H}^{\mathrm{had}}(0)|\bar{B}\rangle \epsilon^*_\mu$$

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

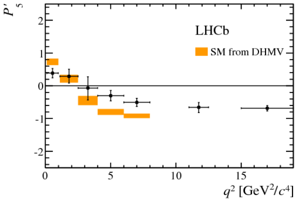
  **Beneke *et al.*'01**

- Analysis of the angular observables of $B \to K^* \mu\mu$ with 1 $\text{fb}^{-1}$
- Use only EFT for QCD (SCET)+model independent constraints

**Jäger and Martin-Camalich, Phys.Rev. D93 (2016) no.1, 014028**




- LHCb angular analysis with 3 $\text{fb}^{-1}$ **LHCb, JHEP 1602 (2016) 104**



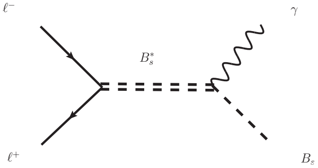

- $3.6\sigma$ using "QCD form factors" (LCSRs)
- Ongoing (QCD) model-independent analysis
- Effect depends on $q^2$? **Straub at Moriond'15**

  Stay tuned! Turbulences ahead!

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

**BG and Martin-Camalich PRL116(2016)no.14,141801 (see also Khodjamirian *et al.* JHEP 1511 (2015) 142)**

- Resonant enhancement compensates for CKM and loop suppression




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

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

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

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

- **Energy spread** of accelerator essential:

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

# Survey of leptoquark models

- **Scalar** LQ

$$\mathcal{L}_\Delta = \left( y_{\ell u}\, \bar{\ell}_L\, u_R + y_{eq}\, \bar{e}_R\, i\tau_2\, q_L \right) \Delta_{-7/6}$$

$$+ y_{\ell d}\, \bar{\ell}_L\, d_R\, \Delta_{-1/6} + \left( y_{\ell q}\, \bar{\ell}^c_L i\tau_2\, q_L + y_{eu} \bar{e}^c_R\, u_R \right) \Delta_{1/3}$$

$$+ y_{ed} \bar{e}^c_R\, d_R\, \Delta_{4/3} + y'_{\ell q}\, \bar{\ell}^c_L i\tau_2 \vec{\tau} q_L \cdot \vec{\Delta}'_{1/3}$$

- **Vector** LQ

$$\mathcal{L}_V = \left( g_{\ell q}\, \bar{\ell}_L \gamma_\mu q_L + g_{ed}\, \bar{e}_R \gamma_\mu d_R \right) V^\mu_{-2/3}$$

$$+ g_{eu}\, \bar{e}_R \gamma_\mu u_R\, V^\mu_{5/3} + g'_{\ell q}\, \bar{\ell}_L \gamma_\mu \vec{\tau} q_L \cdot \vec{V}'^\mu_{-2/3}$$

$$+ \left( g_{\ell d}\, \bar{\ell}_L \gamma_\mu d^c_R + g_{eq}\, \bar{e}_R \gamma_\mu q^c_L \right) V^\mu_{-5/6} + g_{\ell u}\, \bar{\ell}_L \gamma_\mu u^c_R\, V^\mu_{1/6}$$

**Büchmuller and Wyler'87, Davidson *et al.*'94,...**

- Assume $M_{LQ} \gg v$: Only $V^\mu_{-2/3}$ can work with (our) **MFV**! **Alonso *et al.* JHEP 1510 (2015) 184**

TABLE I: Matching of the tree-level LQ contributions to the sixth-dimensional four-fermion operators of the SMEFT.

| LQ | $C^{(1)}_{\ell q}$ | $C^{(3)}_{\ell q}$ | $C_{\ell d}$ | $C_{qe}$ | $C_{ed}$ | $C_{\ell edq}$ | $C^{(1)}_{lequ}$ | $C^{(3)}_{lequ}$ | $C_{eu}$ | $C_{\ell u}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| $\Delta_{1/3}$ | $\frac{y^{\beta i,A}_{\ell q}(y^{\alpha j,A}_{\ell q})^*}{4M^2}$ | $-\frac{y^{\beta i,A}_{\ell q}(y^{\alpha j,A}_{\ell q})^*}{4M^2}$ | 0 | 0 | 0 | 0 | $-\frac{y^{\beta i,A}_{eu}(y^{\alpha j,A}_{\ell q})^*}{2M^2}$ | $\frac{y^{\beta i,A}_{eu}(y^{\alpha j,A}_{\ell q})^*}{8M^2}$ | $\frac{y^{\beta i,A}_{eu}(y^{\alpha j,A}_{eu})^*}{2M^2}$ | 0 |
| $\vec{\Delta}_{1/3}$ | $\frac{3y'^{\beta i,A}_{\ell q}(y'^{\alpha j,A}_{\ell q})^*}{4M^2}$ | $\frac{y'^{\beta i,A}_{\ell q}(y'^{\alpha j,A}_{\ell q})^*}{4M^2}$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| $\Delta_{7/6}$ | 0 | 0 | 0 | $-\frac{y^{\alpha i,A}_{eq}(y^{\beta j,A}_{eq})^*}{2M^2}$ | 0 | 0 | $-\frac{y^{\alpha i,A}_{\ell u}(y^{\beta j,A}_{eq})^*}{2M^2}$ | $-\frac{y^{\alpha i,A}_{\ell u}(y^{\beta j,A}_{eq})^*}{8M^2}$ | 0 | $-\frac{y^{\alpha i,A}_{\ell u}(y^{\beta j,A}_{\ell u})^*}{2M^2}$ |
| $\Delta_{1/6}$ | 0 | 0 | $-\frac{y^{\alpha i\ A}_{\ell d}(y^{\beta j,A}_{\ell d})^*}{2M^2}$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| $\Delta_{4/3}$ | 0 | 0 | 0 | 0 | $\frac{y^{\beta i\ A}_{ed}(y^{\alpha j,A}_{ed})^*}{2M^2}$ | 0 | 0 | 0 | 0 | 0 |
| $V^\mu_{2/3}$ | $-\frac{g^{\alpha i,A}_{\ell q}(g^{\beta j,A}_{\ell q})^*}{2M^2}$ | $-\frac{g^{\alpha i,A}_{\ell q}(g^{\beta j,A}_{\ell q})^*}{2M^2}$ | 0 | 0 | $-\frac{g^{\alpha i,A}_{ed}(g^{\beta j,A}_{ed})^*}{M^2}$ | $\frac{2g^{\alpha i,A}_{\ell q}(g^{\beta j,A}_{ed})^*}{M^2}$ | 0 | 0 | 0 | 0 |
| $\vec{V}^\mu_{2/3}$ | $-\frac{3g'^{\alpha i,A}_{\ell q}(g'^{\beta j,A}_{\ell q})^*}{2M^2}$ | $\frac{g'^{\alpha i,A}_{\ell q}(g'^{\beta j,A}_{\ell q})^*}{2M^2}$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| $V^\mu_{5/6}$ | 0 | 0 | $\frac{g^{\beta i,A}_{\ell d}(g^{\alpha j,A}_{\ell d})^*}{M^2}$ | $\frac{g^{\beta i,A}_{eq}(g^{\alpha j,A}_{eq})^*}{M^2}$ | $\frac{2g^{\alpha j,A}_{\ell d}(g^{\beta i,A}_{eq})^*}{M^2}$ | 0 | 0 | 0 | 0 | 0 |
| $V^\mu_{5/3}$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | $-\frac{g^{\alpha i\ A}_{eu}(g^{\beta j,A}_{eu})^*}{M^2}$ | 0 |
| $V^\mu_{1/6}$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | $\frac{g^{\alpha i\ A}_{\ell u}(g^{\beta j}_{\ell u})^*}{M^2}$ |

# Dressing the chosen one ...

$$\Delta\mathcal{L}_V = \left(g_q \bar{\ell}_L \hat{Y}_e \gamma_\mu q_L + g_d\, \varepsilon_e^*\, \bar{e}_R \gamma_\mu d_R\right)\, V^\mu_{-2/3} + \text{h.c.}$$

Davidson *et al.* JHEP 1011 (2010) 073, BG, Redi, Villadoro JHEP 1011 (2010) 067, Alonso *et al.* JHEP 1510 (2015) 184

- $V^\mu_{-2/3}$ flavored under $SU(3)_\ell \times SU(3)_e \times U(1)_L \times U(1)_{\ell-e}$
  - $V^\mu_{-2/3} \sim (3,1)_{1,-1}$
  - $g_q^i$, $i \equiv d, s, b$ vector in quark-flavor space
  - $g_d$ contribution naturally suppressed by $|\varepsilon_e|$

- $b \to s\mu\mu$ anomalies

$$\frac{\alpha_e}{\pi}\lambda_{ts}\delta C_9^\mu = -\frac{v^2}{M^2}\left(\frac{m_\mu}{m_\tau}\right)^2 (g_q^s)^* g_q^b$$

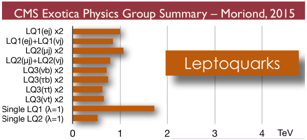
Hiller *et al.* PRD90(2014)054014
Gripaios *et al.* JHEP1505(2015)006
Sahoo *et al.* PRD91(2015)094019
Medeiros Varzielas *et al* arXiv:1503.01084
Becirevic *et al.* arXiv:1503.09024

- Tauonic charged currents

$$\epsilon_L^{kj,\tau} = \frac{1}{2}\frac{v^2}{M^2}\sum_k \frac{V_{ik}}{V_{ij}}(g_q^k)^* g_q^j$$

Sakaki *et al.* PRD88(2013)9,094012, arXiv:1412.3761

# Collider constraints




**ATLAS Exotics Searches* - 95% CL Exclusion**

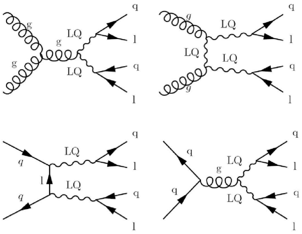
*Status: March 2015*

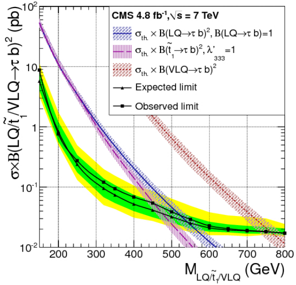
| | | | | | | |
|---|---|---|---|---|---|---|
| LQ | Scalar LQ 1st gen | 2 e | ≥ 2 j | – | 1.0 | LQ mass 660 GeV |
| | Scalar LQ 2nd gen | 2 μ | ≥ 2 j | – | 1.0 | LQ mass 685 GeV |
| | Scalar LQ 3rd gen | 1 e, μ, 1 τ | 1 b, 1 j | – | 4.7 | LQ mass 534 GeV |

PRL110(2013)081801, PLBB739 (2014)229 . . .

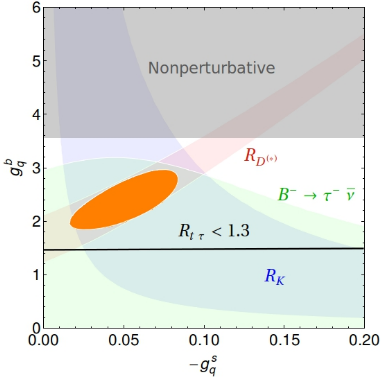
JHEP 1306 (2013) 033, . . .

- **CMS** Searched for vector (scalar) LQs using **4.8 fb**$^{-1}$ (19.7 fb$^{-1}$)




- Vector LQs with 1/2 coupling to $\tau\, b$: $M_{LQ} \gtrsim 600$ GeV at 95% CL




- LQ mass set at $M_{LQ} = 750$ GeV
- **Perturbativity bound:** $g_q^i \leqslant \sqrt{4\pi}$
- **Interplay** between LHC searches, FCNC and CC $b$ decays

- Can be tested **model-independently** with **top decays**

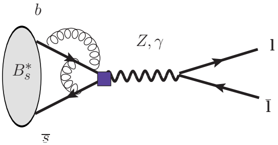
$$\mathcal{L}_{\mathrm{c.c.}} \supset -\frac{G_F V_{tb}}{\sqrt{2}}(1+\epsilon_L^{tb})(\bar{b}\,\gamma^\mu\, t_L)\,(\bar{\nu}_L \gamma_\mu \tau) \quad \text{with} \quad \epsilon_L^{tb,\tau} \simeq \frac{1}{2}\frac{v^2}{M^2}|g_q^b|^2$$

- **CDF** measured $R_{t\tau} = \frac{\Gamma(t\to\tau\nu q)}{\Gamma(t\to\tau\nu q)^{\mathrm{SM}}} < 5.2$ at 95% C.L. PLB639(2006)172

**Semileptonic top decays** correlated with LUV anomalies!

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

BG and Martin-Camalich PRL116(2016)no.14,141801




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

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

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

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

# 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

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

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

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

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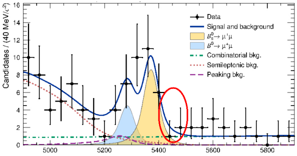


- Won't show as small peak in $B_q \to \mu\mu$ measurments
- $\sim 10$ ($\sim 100$) events @ end of run III (HL-LHC)
- **Impossible!** LHCb private communication
- Alternative: $\ell^+\ell^- \to B_s^* \to B_s\gamma$, $\sigma_0 \sim 10$ fb

**End digression**