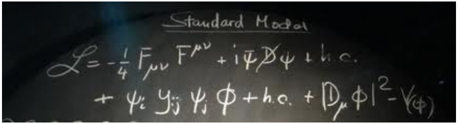
# The shape of (new) physics in *B* decays

J. Martin Camalich

FLASY2015

June 30, 2015

# The flavor puzzle of the Standard Model

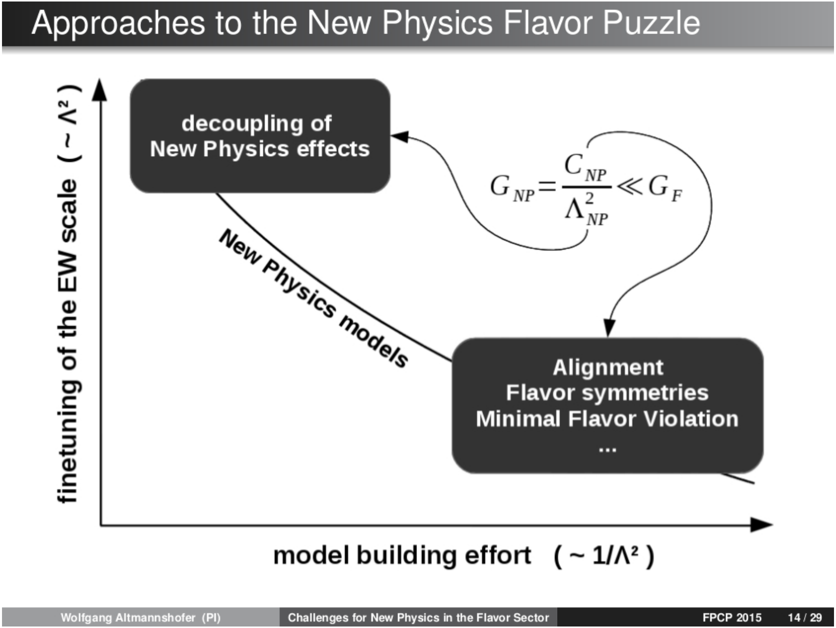



The **standard model** explains very successfully flavor transitions

**However** it does not explain . . .

- 3 families
- Hierarchy of the masses of the fermions
- Hierarchy in the mixing of the quark flavor
- Anarchy in the mixing of the lepton flavor

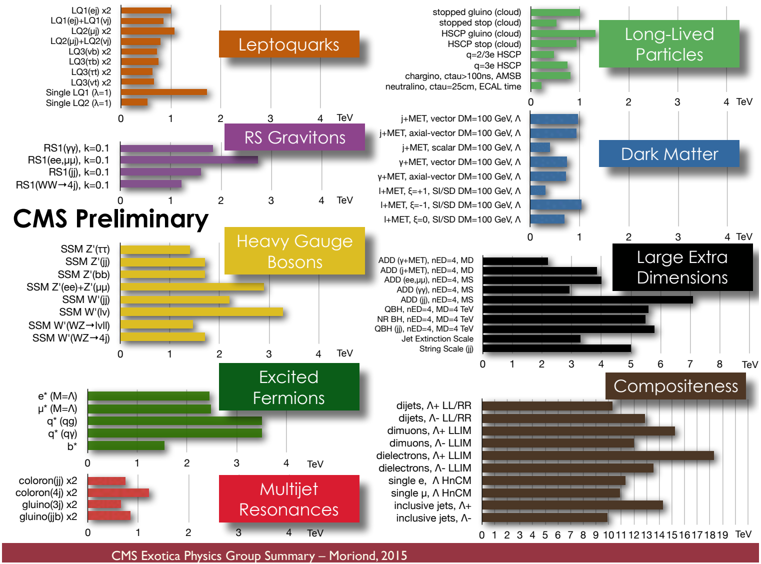
Answering these questions require physics beyond the SM




Ben Grinstein's talk

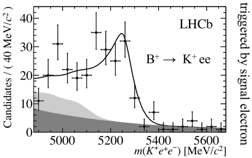
- No **New Physics** at colliders (yet?) (Similar plots for ATLAS)

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



# Lepton universality violation in $B$ decays?

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

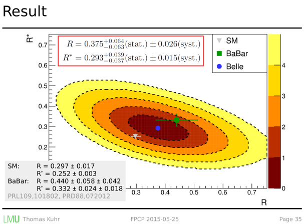



- Tension with **SM** $\sim 2.6\sigma$
- Other anomalies in $b \to s\mu\mu$
  - Branching fractions $B \to K\mu\mu$, $B_s \to \phi\mu\mu$
  - Angular analysis $B \to K^*\mu\mu$
- Up to $4\sigma$ in global fits

Altmannshofer and Straub '14

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

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




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

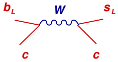
| | $R(D)$ | $R(D^*)$ |
|---|---|---|
| BaBar | $0.440 \pm 0.058 \pm 0.042$ | $0.332 \pm 0.024 \pm 0.018$ |
| Belle | $0.375^{+0.064}_{-0.063} \pm 0.026$ | $0.293^{+0.039}_{-0.037} \pm 0.015$ |
| LHCb | | $0.336 \pm 0.027 \pm 0.030$ |
| Exp. average | $0.388 \pm 0.047$ | $0.321 \pm 0.021$ |
| SM expectation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

T. Kuhr (Belle) @ FPCP2015

T. Freytsis *et al.* 1506.08896

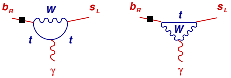
# Effective field theory approach to $b \to s\ell\ell$ decays

- **CC** (Fermi theory):

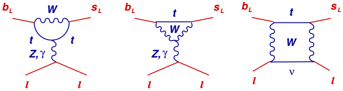



$$\Rightarrow \qquad G_F\, V_{cb}\, V_{cs}^*\, C_2\, \bar{c}_L \gamma^\mu b_L\, \bar{s}_L \gamma_\mu c_L$$

- **FCNC**:

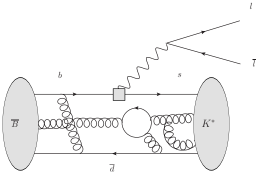



$$\Rightarrow \qquad \frac{e}{4\pi^2}\, G_F\, V_{tb}\, V_{ts}^*\, m_b\, C_7\, \bar{s}_L \sigma_{\mu\nu} b_R\, F^{\mu\nu}$$




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

  - 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 $C_i^{\rm expt.} = C_i^{\rm SM} + \delta C_i$
  - 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 $C\not{P}$

- 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,Grzadkowski *et al.*'10

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

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

- Furthermore:

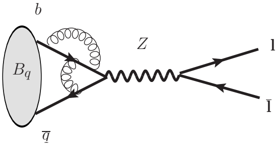
$$(\bar{d}_j\sigma_{\mu\nu}P_R d_i)(\bar{\ell}\sigma^{\mu\nu}P_L\ell) = 0$$

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

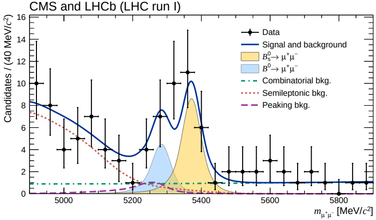
- From **4** scalar operators to only **2**!
- From **2** tensor operators to **none**!

Alonso, Grinstein, JMC, PRL113(2014)241802

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




CMS and LHCb combined arXiv: 1411.4413




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

- 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

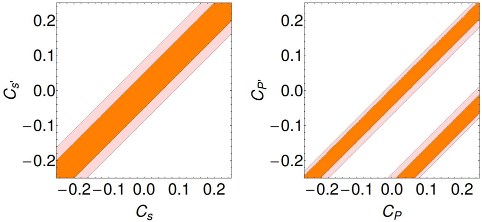
$$\overline{\mathcal{B}}_{s\mu}^{\rm SM} = 3.65(23) \times 10^{-9}$$
$$\overline{\mathcal{B}}_{s\mu}^{\rm expt} = 2.9(7) \times 10^{-9}$$

# 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

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

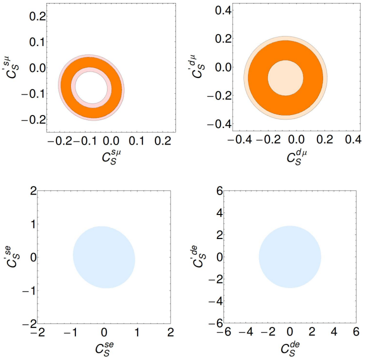



- $B_q \to \ell\ell$ blind to the orthogonal combinations $C_S + C_S'$ and $C_P + C_P'$
  Scalar operators unconstrained!

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

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

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

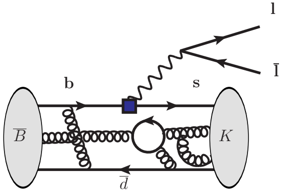



- $\Lambda_{\rm NP}$ (95%C.L.) RGE of QCD+EW+Yukawas

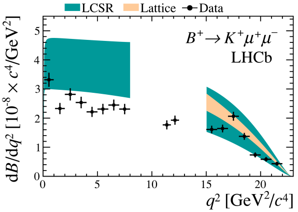
| Channels | $s\mu$ | $d\mu$ | $se$ | $de$ |
|---|---|---|---|---|
| $C_S^{(\prime)}(m_W)$ | 0.1 | 0.15 | 0.6 | 1.5 |
| $\Lambda$ [TeV] | 79 | 130 | 36 | 49 |

Alonso, 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$^2$

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

**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 $\langle R_K \rangle_{[1,6]} = 1.0003(1)$
- $SU(2)_L \times U(1)_Y$:
  - No tensors
  - Scalar operators constrained by $B_s \to \ell\ell$ alone:

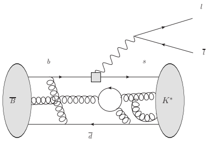
$$R_K \in [0.982, 1.007] \text{ at } 95\% \text{ CL}$$

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

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

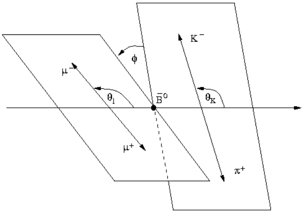
Alonso, Grinstein, JMC, PRL113(2014)241802

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




| | |
|---|---|
| **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 $\text{fb}^{-1}$) LHCb-CONF-2015-002 |
| **LHCb ($e$)** | 128 ([0.0004, 1] $\text{GeV}^2$) JHEP 1504(2015)064 |

- **4-body decay**

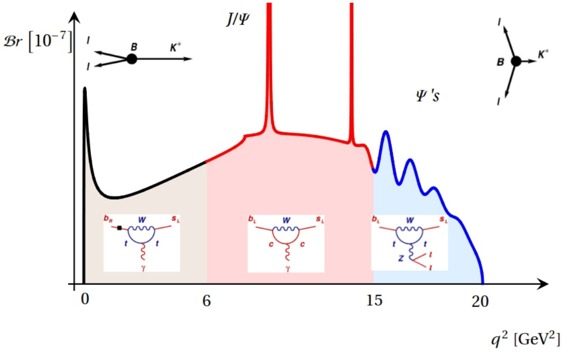



$$\frac{d^{(4)}\Gamma}{dq^2\, d(\cos\theta_l) d(\cos\theta_k) d\phi} = \frac{9}{32\pi} \left( I_1^s \sin^2\theta_k + I_1^c \cos^2\theta_k \right.$$

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

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

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



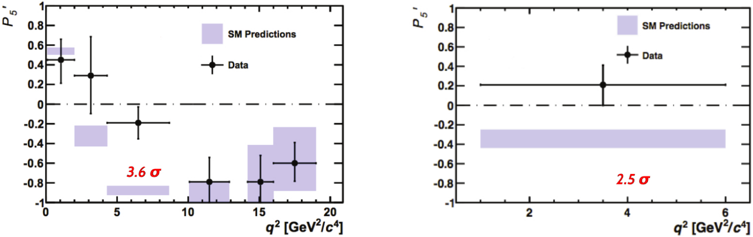

- **Large-recoil region** (low $q^2$)
  - Heavy to collinear light quark $\Rightarrow$ QCDf or SCET (power-corrections)
  - Dominant effect of the photon pole
- **Charmonium region**
  - Dominated by long-distance (hadronic) effects
  - Starting at the perturbative $c\bar{c}$ threshold $q^2 \simeq 6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

# 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

- Consistent with $R_K$!

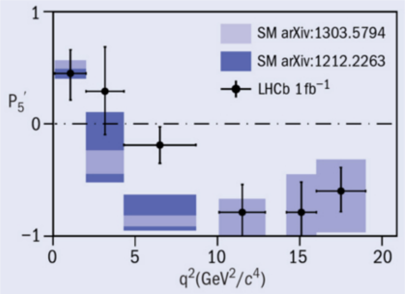
Alonso, Grinstein, JMC, PRL113(2014)241802

# The $P_5'$ anomaly: New Physics?

**CERN COURIER**

Nov 20, 2013

## LHCb and theorists chart a course for discovery




Jäger and JMC, JHEP 1305 (2013) 043

- Larger SM uncertainties in the predictions

**QUESTION:** Do we really understand the hadronic effects?

# Connecting theory to experiment: The helicity amplitudes

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

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

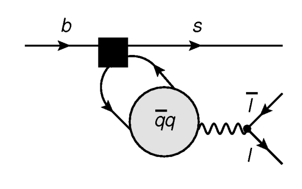
$$H_A(\lambda) = -iNC_{10}\,\tilde{V}_{L\lambda}, \qquad H_P = iN\frac{2\,m_l\hat{m}_b}{q^2}C_{10}\Big(\tilde{S}_L + \frac{m_s}{m_b}\tilde{S}_R\Big)$$

## $C_9$ is exposed to various hadronic backgrounds

- Hadronic form factors

  7 independent $q^2$-dependent nonperturbative functions

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




- "Non factorizable" contribution

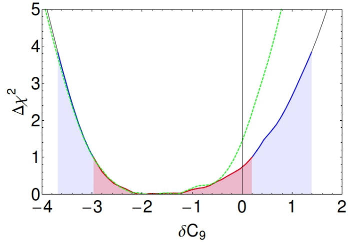
$$h_\lambda \propto \int d^4y e^{iq\cdot y}\langle\bar{K}^*|j^{\mathrm{em,had},\mu}(y)\mathcal{H}^{\mathrm{had}}(0)|\bar{B}\rangle\epsilon^*_\mu$$

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

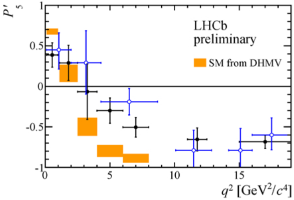
  Beneke *et al.*'01

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

Jäger and JMC, arXiv:1412.3183




- LHCb just released preliminar angular analysis with 3 fb$^{-1}$ LHCb-CONF-2015-002




- 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!

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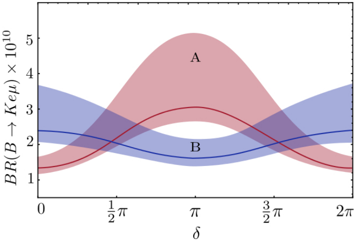
- **However:** Any new source of flavor violation will lead to LF violation. . .

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

**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



# 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

- . . . 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 $b \to s\tau\tau$!**

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

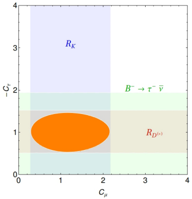
2. **Very strong constraint from $b \to s\nu_\tau\nu_\tau$**
3. **Sizable effects in CC tauonic $B$ decays!**

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

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

| | 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

# 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 $V^\mu_{-2/3}$ can work with (our) **MFV**! Alonso *et al.* arXiv:1505.05164

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

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

# 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, Grinstein *et al.* JHEP 1011 (2010) 067, Alonso *et al.* arXiv:1505.05164

- $V^\mu_{-2/3}$ 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

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

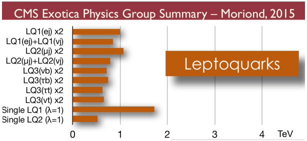
Hiller *et al.* PRD90(2014)054014, Gripaios *et al.* JHEP1505(2015)006, Sahoo *et al.* PRD91(2015)094019, Medeiros Varzielas *et al* arXiv:1503.01084, Becirevic *et al.* arXiv:1503.09024

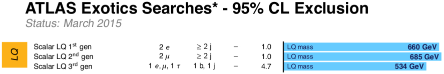
- Tauonic charged currents

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

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

# Collider constraints

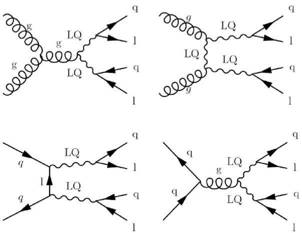


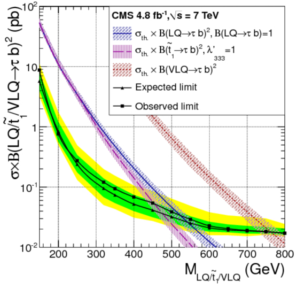




PRL110(2013)081801, PLBB739 (2014)229 . . .

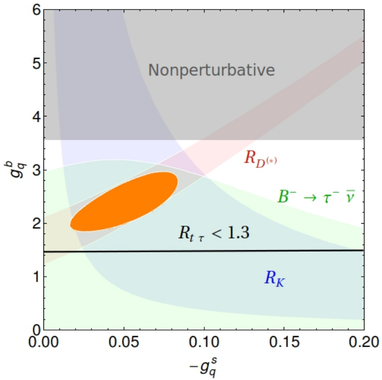
JHEP 1306 (2013) 033, . . .

- **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**

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

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

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

Discussion of $Z'$ models: Avelino's talk

# 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 $B \to K^*\mu\mu$
3. **The shape of new physics**
   - Left-handed-left-handed scenario seems favored
   - **LFV** or **MLFV**? Both scenarios have testable consequences
   - Impact on charged current tauonic $B$ decays: The $R_{D^{(*)}}$ anomalies

With the LHC run2 very exciting times ahead!