Interplay between LHC and flavor physics

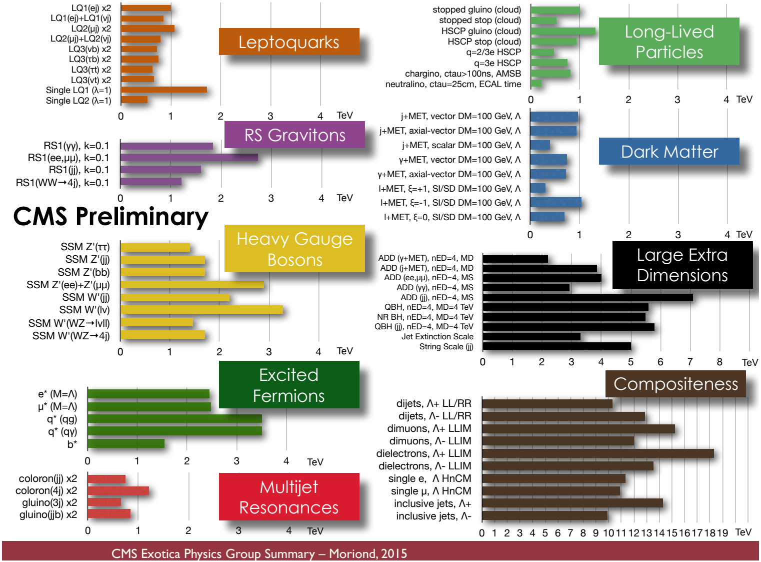
J. Martin Camalich

FPCP2015

May 26, 2015

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

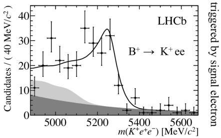
https://twiki.cern.ch/twiki/bin/view/CMSPublic/ https://twiki.cern.ch/twiki/bin/view/AtlasPublic/



CMS Exotica Physics Group Summary – Moriond, 2015

Anomalies in flavor physics

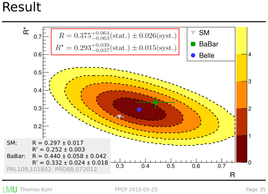
- **LUV** in $b \to s\ell\ell$!



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

C. Linn talk

- **LUV (?)** in $b \to c\ell\nu$!

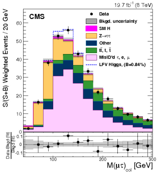

Result

SM: R = 0.297 ± 0.017
R' = 0.252 ± 0.003
BaBar: R = 0.440 ± 0.058 ± 0.042
R' = 0.332 ± 0.024 ± 0.018
PRL109,101802, PRD88,072012

LMU Thomas Kuhr FPCP 2015-05-25 Page 35

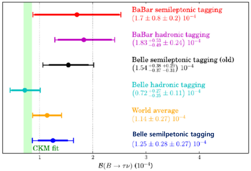
T. Kuhr and G. Ciezarek's talks

- **LFV** in Higgs decays!



CMS, arXiv:1502.07400

- Exc. *vs.* Inc. V_{ub} and $B \to \tau\nu$!



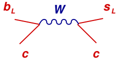
C. S. Park's talk

Outline

1. Bottom-up approach to new-phyics
2. $b \to s\ell\ell$ anomalies
   - $B_s \to \ell\ell$ and R_K
   - $b \to s\ell\ell$ and dynamics of EWSB
3. The shape of new physics
   - Lepton flavor violation vs. minimal flavor violation
   - Applications to model-building: LQs in MFV scenarios
4. Searches of NP in CCs
   - $s \to u\ell\nu$: Hyperon semileptonic decays *vs.* LHC

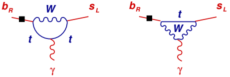
$$\log\left(\int d\Delta\, e^{i\,S[\phi,\Delta]}\right) = i\int dx^4\, \mathcal{L}_{\rm eff}[\phi] = i\int dx^4 \mathcal{L}_{d\leq 4} + i\int dx^4 \sum_k \frac{C_k(\mu)\mathcal{O}_k(x,\mu)}{M^{\dim(\mathcal{Q}_k)-4}}$$

- **CC** (Fermi theory):

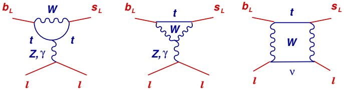


$\Rightarrow$ $G_F\, V_{cb}\, V_{cs}^*\, C_2\, \bar{c}_L\gamma^\mu b_L\, \bar{s}_L\gamma_\mu c_L$

- **FCNC**:

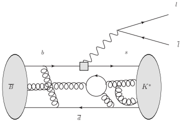


$\Rightarrow$ $\dfrac{e}{4\pi^2}\, G_F\, V_{tb}\, V_{ts}^*\, m_b\, C_7\, \bar{s}_L\sigma_{\mu\nu}b_R\, F^{\mu\nu}$



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

  - 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,…

C. Bobeth's talk

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. . .
  1. Different values of the Wilson coefficients $C_i^{\text{expt.}} = C_i^{\text{SM}} + \delta C_i$
  2. 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

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

  3. 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,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**!

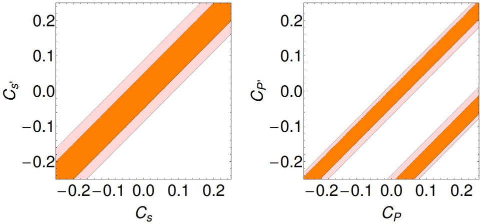
Alonso, Grinstein, JMC, PRL113(2014)241802

Phenomenological consequences $B_q \to \ell\ell$

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

CMS and LHCb Nature (2015), Bobeth *et al.* PRL112(2014)101801, De Bruyn *et al.* '12

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

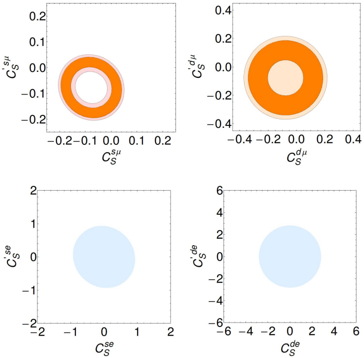


- $B_q \to \ell\ell$ blind to the orthogonal combinations $C_S + C'_S$ and $C_P + C'_P$
  Scalar operators unconstrained!

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
Λ [TeV]	79	130	36	49

Alonso, Grinstein, JMC, PRL113(2014)241802

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

- $SU(2)_L \times U(1)_Y$:
  - 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, *et al.*'14, Hiller *et al.*'14, Ghosh *et al.*'14, Straub *et al.*'14..., Hurth *et al.*'14

(Breaking of the relations)

What triggers electroweak symmetry breaking?

- **Weakly interacting**
  e.g. SUSY, with elementary scalars
- Different EFTs (think of **ChPT** in **QCD**)!!
- **Strongly interacting**
  e.g. Technicolor, with composite scalars (**QCD)**

1 scalar field

GBs

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \pi^1 + i\pi^2 \\ v + h + i\pi^3 \end{pmatrix}$$

gauge doublet

BEH scalar

2 scalar fields

$$\mathbf{U} = e^{i\pi^a \sigma^a / v} \qquad h$$

gauge singlet!

Brivio *et al.*JHEP 1403 (2014) 024, Buchalla *et al.* NPB880(2014)552,. . . Appelquist *et al.* PRD22(1980)200, Kaplan *et al.* PLB136(1984)152

(Breaking of the relations)

What triggers electroweak symmetry breaking?

- **Weakly interacting**
  e.g. SUSY, with elementary scalars
- **Strongly interacting**
  e.g. Technicolor, with composite scalars (**QCD)**
- Different EFTs (think of **ChPT** in **QCD**)!!
- In a nonlinear EFT there are more operators!

$$
\begin{aligned}
C_{S,P}^{(d)} &= \mathcal{N}_{\mathrm{NC}}^{(d)}\left[\pm c_S^{(d)} + \hat{c}_{Y1}\right] , &\quad C_{S,P}^{\prime(d)} &= \mathcal{N}_{\mathrm{NC}}^{(d)}\left[c_S^{\prime(d)} \pm \hat{c}'_{Y1}\right] , \\
C_T^{(d)} &= \mathcal{N}_{\mathrm{NC}}^{(d)}\left[\hat{c}_{Y2} + \hat{c}'_{Y2}\right] , &\quad C_{T5}^{(d)} &= \mathcal{N}_{\mathrm{NC}}^{(d)}\left[\hat{c}_{Y2} - \hat{c}'_{Y2}\right] ,
\end{aligned} \tag{10}
$$

Cata and Jung arXiv:1505.05804

- $\hat{c}_i$ new Wilson coefficients in the nonlinear theory

Breaking of the relations → dynamics of EWSB!

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** ⇒ **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

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

$U(1)_\tau \times U(1)_\mu \times U(1)_e$ 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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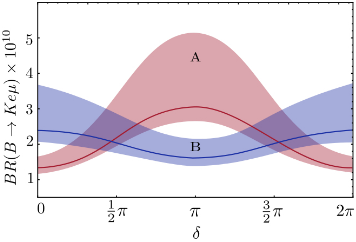
LFV in $b \to s\ell\ell'$!!

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

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!**

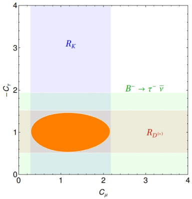
$$R_{D^{(*)}} = \frac{\mathcal{B}(\bar{B}\to D^{(*)}\tau\bar{\nu}_\tau)}{\mathcal{B}(\bar{B}\to D^{(*)}\mu\bar{\nu}_\mu)}$$

- ***Excess*** observed at 3.6σ

	SM	Expt.
R_D	0.297(17)	0.421(58)
R_{D^*}	0.252(3)	0.337(25)

Updates in yesterday talks!!

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



Alonso *et al.* arXiv:1505.05164

Survey of leptoquark models

- **Scalar** LQ

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

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

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

- **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.* arXiv:1505.05164

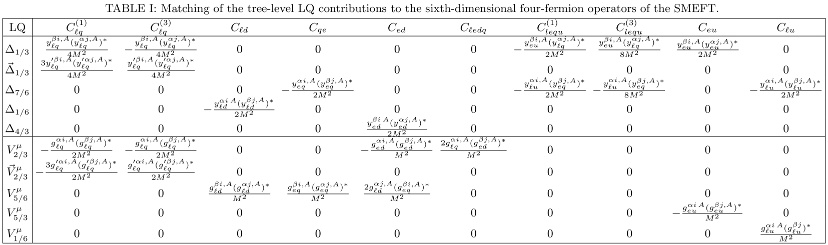


TABLE I: Matching of the tree-level LQ contributions to the sixth-dimensional four-fermion operators of the SMEFT.

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, 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

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

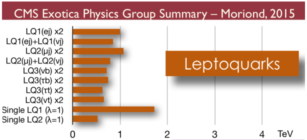
Hiller *et al.* PRD90(2014)054014, Gripaios *et al.* JHEP1505(2015)006, Sahoo *et al.* PRD91(2015)094019, Medeiros Varzielas *et al* arXiv:1503.01084, Becirevic *et al.* arXiv:1503.09024

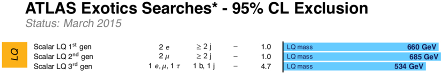
- Tauonic charged currents

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

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

Collider constraints





ATLAS Exotics Searches* - 95% CL Exclusion

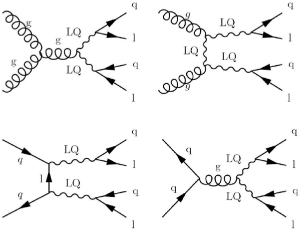
Status: March 2015

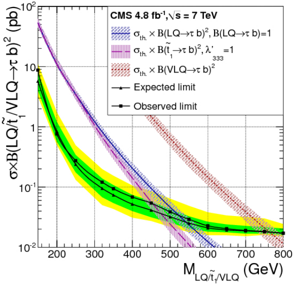
LQ	Scalar LQ 1st gen	2 e	≥ 2 j	–	1.0	LQ mass 660 GeV
	Scalar LQ 2nd gen	2 μ	≥ 2 j	–	1.0	LQ mass 685 GeV
	Scalar LQ 3rd gen	1 e, μ, 1 τ	1 b, 1 j	–	4.7	LQ mass 534 GeV

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

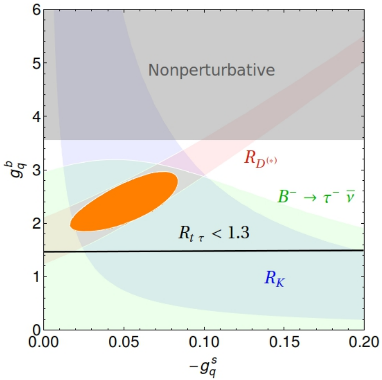
JHEP 1306 (2013) 033, . . .

- **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**

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

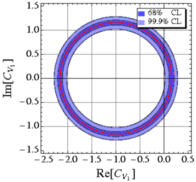
- **CDF** measured $R_{t\tau} = \frac{\Gamma(t\to\tau\nu q)}{\Gamma(t\to\tau\nu q)^{\rm SM}} < 5.2$ at 95% C.L. PLB639(2006)172

Semileptonic top decays correlated with LUV anomalies!

Discussion of Z' models: W. Altmannshofer talk

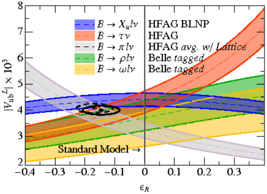
Model-independent analyses of CC decays

- R_{D^*} anomalies



Sasaki *et al.* arXiv:1412.3761. See also Fajfer *et al.*'12, Becirevic *et al.*'12

- $b \to u\ell\nu$ and V_{ub}



Bernlochner *et al.* PRD90(2014)9,094003 See also Crivellin'09, . . .

- EFT technology applied systematically in $d \to u\ell\nu$ transitions
  - β-decays and π decays
  - **LHC bounds** from $pp \to \ell^{\pm} + ME + X$

Bhattacharya *et al.* PRD85(2012)054512

Interplay between low energies and LHC!

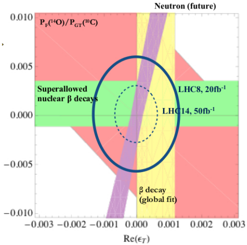
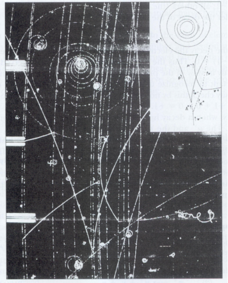
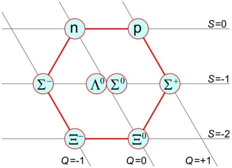
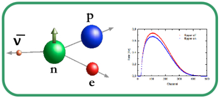


Illustration: Semileptonic hyperon decays







$$\mathcal{L}_{\rm cc} \supset -\frac{G_F V_{us}}{\sqrt{2}} \sum_{\ell=e,\mu}\left[\bar\ell(1-\gamma_5)\nu_\ell\cdot\bar u\left[\epsilon_S-\epsilon_P\gamma_5\right]s+\epsilon_T\,\bar\ell\sigma_{\mu\nu}(1-\gamma_5)\nu_\ell\cdot\bar u\sigma^{\mu\nu}(1-\gamma_5)s\right]+\text{h.c.}$$

- Scalar ($\epsilon_{S,P}$) and tensor (ϵ_T) contributions interfere with the SM $\propto m_\ell/\sqrt{q^2}$
- 6 form factors in the SM $\Rightarrow$ $SU(3)_F$ app. symmetry of QCD
  - Expansion in $\delta = \Delta M/M \sim 10 - 20\%$

$$\Gamma_e \simeq \frac{G_F^2\,|V_{us}\,f_1(0)|^2\,\Delta^5}{60\,\pi^3}\left[\left(1-\frac{3}{2}\delta\right)+3\left(1-\frac{3}{2}\delta\right)\frac{g_1(0)^2}{f_1(0)^2}\right]+\mathcal{O}(5\%)$$

Cabibbo *et al.* Ann.Rev.Nucl.Part.Sci. 53 (2003) 39-75

$$R^{\mu e}=\frac{\Gamma(B_1\to B_2\,\mu^-\,\bar{\nu}_\mu)}{\Gamma(B_1\to B_2\,e^-\,\bar{\nu}_e)}\qquad\qquad(\Delta=M_2-M_1)$$

$R^{\mu e}_{\rm SM}$ only depend on phase space up to $\mathcal{O}(\delta^2)$!

$$R^{\mu e}_{\rm SM}=\sqrt{1-\frac{m_\mu^2}{\Delta^2}}\left(1-\frac{9}{2}\frac{m_\mu^2}{\Delta^2}-4\frac{m_\mu^4}{\Delta^4}\right)+\frac{15}{2}\frac{m_\mu^4}{\Delta^4}\,\mathrm{arctanh}\left(\sqrt{1-\frac{m_\mu^2}{\Delta^2}}\right)$$

Chang, Gonzalez-Alonso and JMC PRL114(2015)16,161802

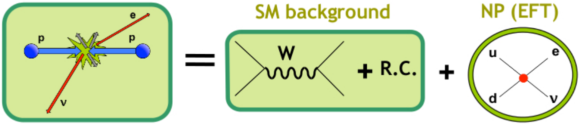
	$\Lambda\to p$	$\Sigma^-\to n$	$\Xi^0\to\Sigma^+$	$\Xi^-\to\Lambda$
Expt.	0.189(41)	0.442(39)	0.0092(14)	0.6(5)
SM-NLO	0.153(8)	0.444(22)	0.0084(4)	0.275(14)

$$R^{\mu e}_{\rm NP}\simeq\frac{\left(\epsilon_S\,\frac{f_S(0)}{f_1(0)}+12\,\epsilon_T\,\frac{g_1(0)}{f_1(0)}\,\frac{f_T(0)}{f_1(0)}\right)}{(1-\frac{3}{2}\,\delta)\left(1+3\,\frac{g_1(0)^2}{f_1(0)^2}\right)}\,\Pi(\Delta,m_\mu)$$

- Most of the data is very old (60's-70's): $\frac{\delta Br}{Br}\sim 10\%-100\%$
- $\frac{f_T(0)}{f_1(0)}$ (**models – LQCD?**) and $\frac{f_S(0)}{f_1(0)}$ (**CVC**) are channel-dependent
- Non-LUV contributions can modify the "LUV" ratio!

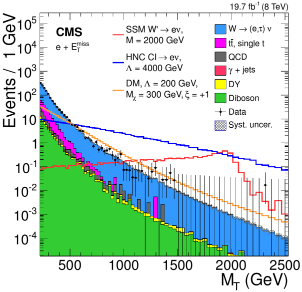
See e.g. Becirevic *et al.* PLB716(2012)208 for the R_D anomalies

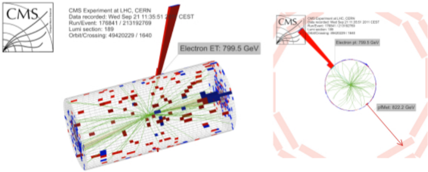
LHC limits of $\epsilon_{S,T}$



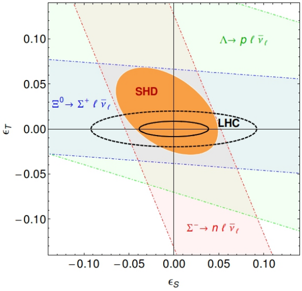
$$N_{pp\to\ell\nu X}(m_T^2 > m_{T,cut}^2) = \varepsilon \times L \times \left(\sigma_W + \sigma_S \epsilon_S^2 + \sigma_T^2 \epsilon_T^2\right)$$

Bhattacharya *et al.* PRD85 (2012) 054512, Cirigliano *et al.* JHEP1302(2013)046





$$m_T \equiv \sqrt{2E_T^e E_T^\nu (1 - \cos \Delta\phi_{e\nu})}$$



Chang *et al.* PRL114(2015)16,161802

- Bounds on NP @ 3-4 TeV
- Hyperons suffice to constrain ϵ_S and ϵ_T
  Very old decay data!
- Quadratic **LHC** *vs.* linear (**hyperons**)

Successful proof of concept!

1. More data in hyperon decays? (NA62, PANDA, J-PARC, . . .) ?
2. Systematic analysis of $s \to u\ell\nu$ transitions including **kaon decays**
3. Extension to rare hyperon decays?
4. **Get creative** using low- and high-energy synergies! (**EFT!**)

Conclusions

- **High-energy EFT**
  1. Connect low- and high-energy information in a systematic fashion
  2. Constraints between low-energy operators
  3. **Address fundamental questions: EWSB dynamics!**
- **The $b \to s\ell\ell$ anomalies**
  - $B_q \to \ell\ell$ and R_K
  - LFV, correlation between CC tauonic *B* and top decays
  - Signatures at the **LHC**: E.g. Leptoquarks
  - **Learn: Non trivial correlations involving lepton flavor breaking!**
- **Charged current decays:** More interplay between LHC and flavor

  E.g. Hyperons *vs.* LHC

With the LHC run2 very exciting times ahead!