Hints of breaking of Lepton Flavor Universality in B physics

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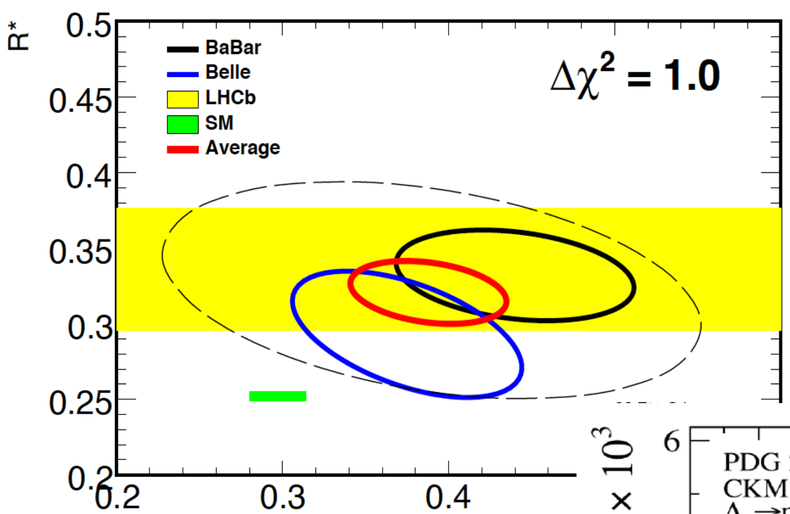
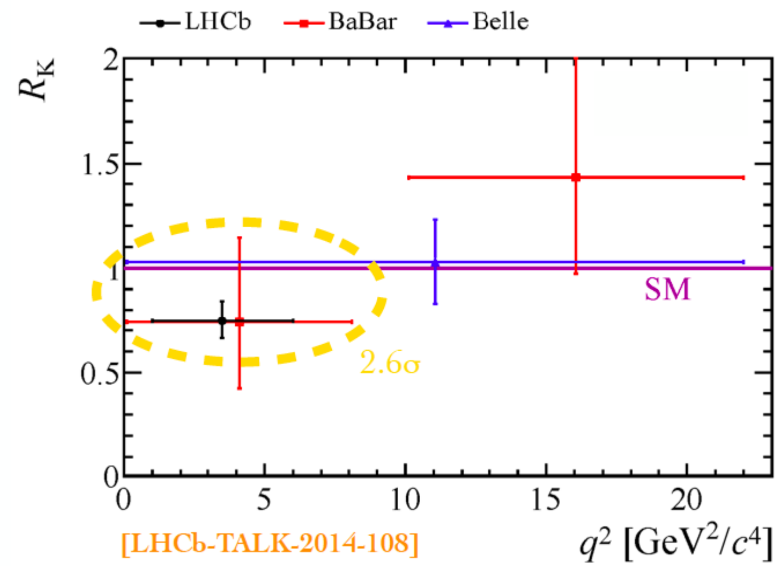
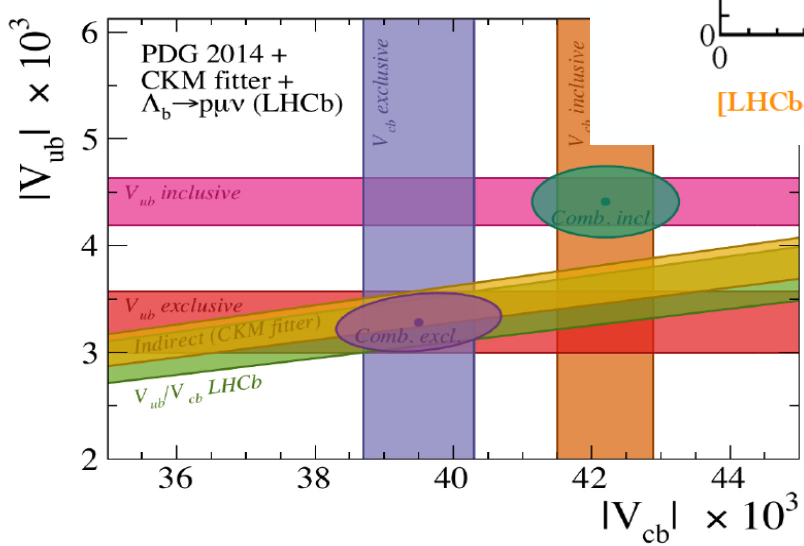
- On the anomalies
- Speculations on the breaking of Lepton Flavor Universality
- Conclusions

On the anomalies

[*i.e.where (and why) I start to think there is something interesting...*]







I. B → $D^{(*)}$ τν [LHCb, Belle]

Test of LFU in charged currents
[τ vs. light leptons (μ, e)]:

$$R(X) = \frac{\Gamma(B \to X\tau\bar{\nu})}{\Gamma(B \to X\ell\bar{\nu})}$$

		$R(D)$	$R(D^*)$	
	BaBar	$0.440 \pm 0.058 \pm 0.042$	$0.332 \pm 0.024 \pm 0.018$	
NEW →	Belle	$0.375^{+0.064}_{-0.063} \pm 0.026$	$0.293^{+0.039}_{-0.037} \pm 0.015$	
NEW →	LHCb		$0.336 \pm 0.027 \pm 0.030$	
	Average	0.388 ± 0.047	0.321 ± 0.021	
	SM expectation	0.300 ± 0.010 ~1.8σ	0.252 ± 0.005	~3.2σ

- SM prediction quite solid: f.f. uncertainty cancel (*to a good extent...*) in the ratio
- Consistent exp. results by 3 (very) different experiments

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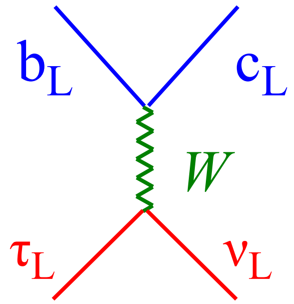
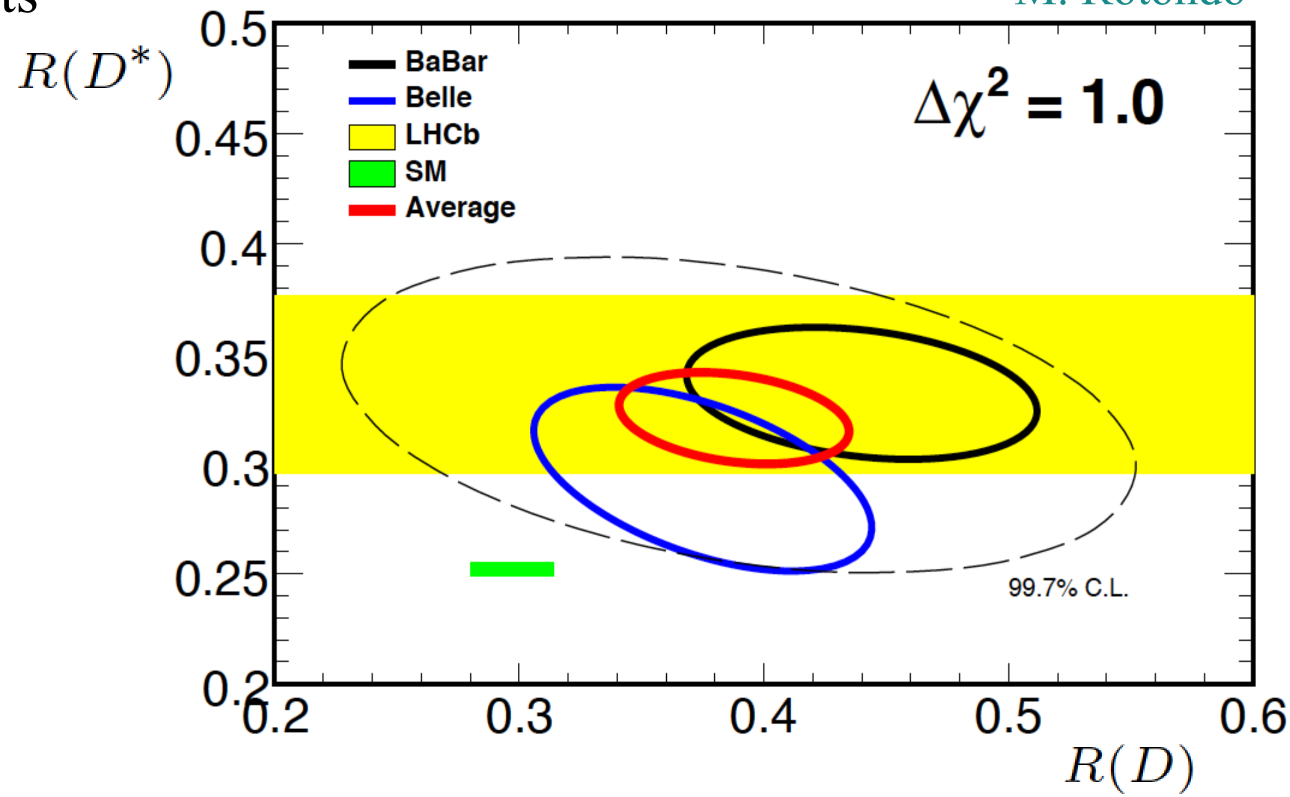


M. Rotondo



- SM prediction quite solid: f.f. uncertainty cancel (*to a good extent...*) in the ratio
- Consistent exp. results by 3 (very) different experiments
  - 4σ excess over SM (if D and D* combined)
  - The two channels are well consistent with a universal enhancement (~30%) of the SM $b_L \rightarrow c_L\ \tau_L\ \nu_L$ amplitude (*RH or scalar amplitudes disfavored*)

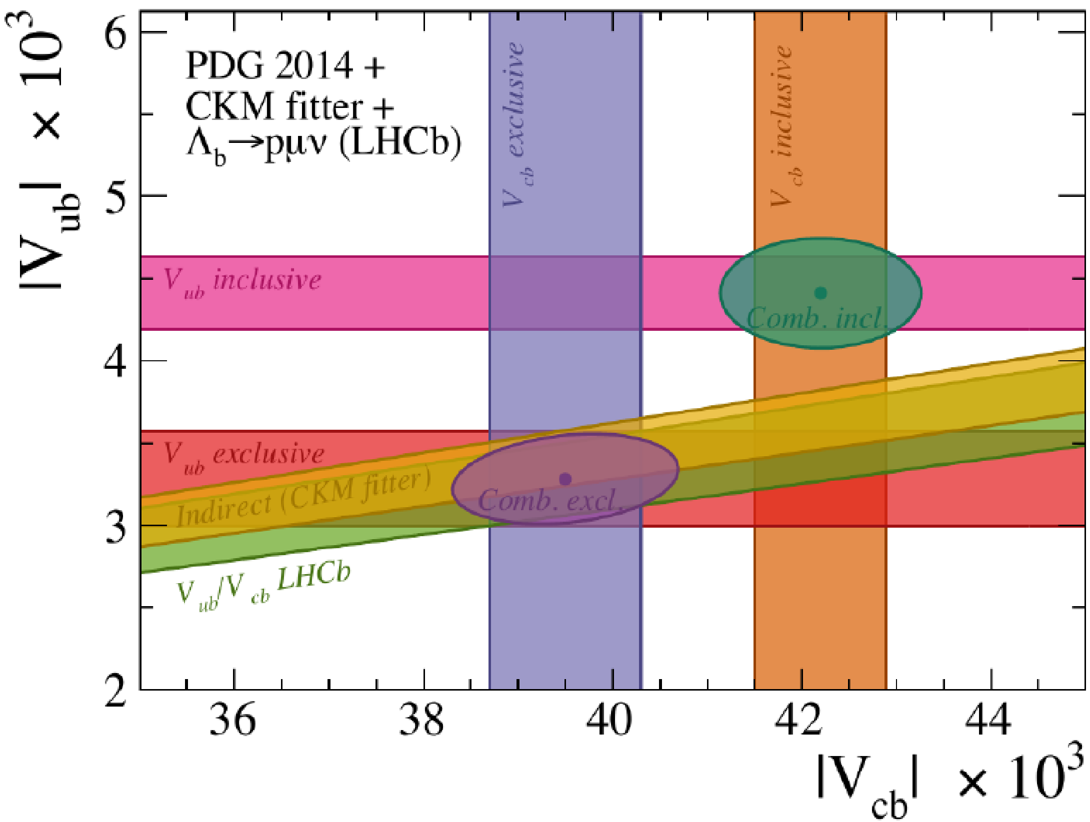
II. $|V_{ub}/V_{cb}|$ from $B(\Lambda_b \to p\mu\nu)/B(\Lambda_b \to \Lambda_c\mu\nu)$ [LHCb]

T. Gershon

Long-standing discrepancy between exclusive and inclusive determinations of both $|V_{ub}|$ & $|V_{cb}|$ (*again charged currents…*)

New ingredient: $|V_{ub}/V_{cb}|$ from $B(\Lambda_b \to p\mu\nu)/B(\Lambda_b \to \Lambda_c\mu\nu)$

→ small th. error given recent Lattice estimate of the *f.f.* [arXiv:1503.01421]



- Consistent with other exclusive data
- Increased tension between excl. & incl.

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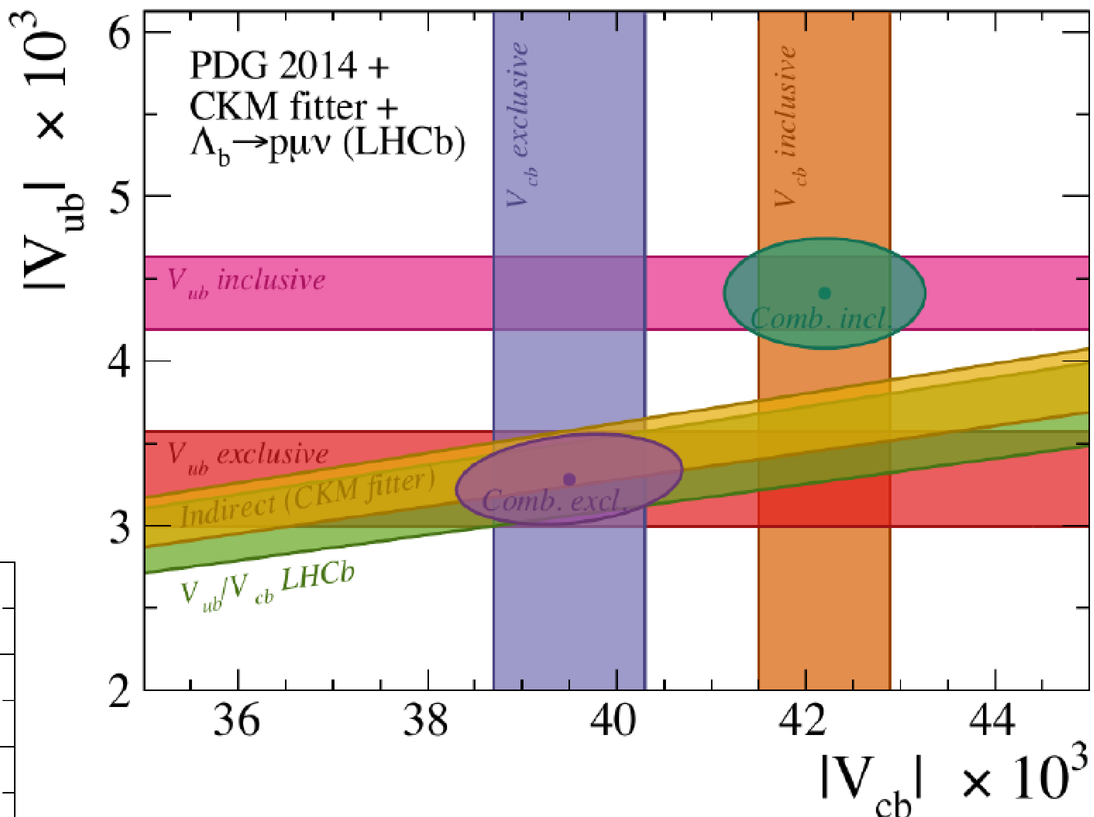

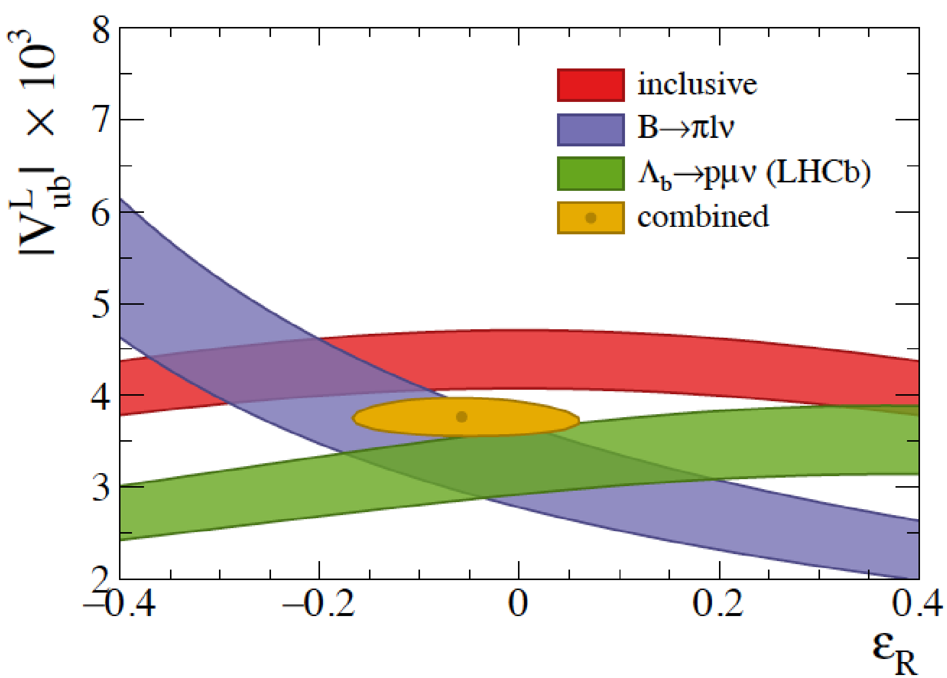

- Consistent with other exclusive data
- Increased tension between excl. & incl.
- Rules out RH currents as possible explanation of the tension

III. Anomalies in $B \to K^{(*)}\ \mu\mu$ / ee [LHCb]

The largest anomaly is the one [*obs. in 2013 and confirmed with higher stat. in 2015*] in the P_5' [$B \to K^*\mu\mu$] angular distribution.

But less significant anomalies present also in other $B \to K^*\mu\mu$ observables and also in other $b \to s\mu\mu$ channels [overall smallness of all BR($B \to$ Hadron + $\mu\mu$)]

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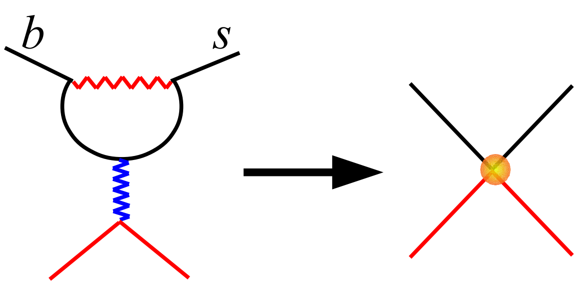
$B \to K^{(*)}\, ll$ are FCNC amplitudes ("natural" probes of physics beyond the SM):

- No SM tree-level contribution
- Strong suppression within the SM because of CKM hierarchy

Key point to be addressed: th. control of QCD effects

Three-step procedure to deal with the various scales of the problem:

I. Construction of a local eff. Hamiltonian at the electroweak scale



$$H_{\text{eff}} = \Sigma_i\, C_i(M_W)\, Q_i$$

- Heavy NP encoded in the $C_i(M_W)$
- No difference among all $b \to s\, ll$ decays

II. Evolution of $H_{\rm eff}$ down to low scales using RGE

FCNC operators (E.W. penguins)

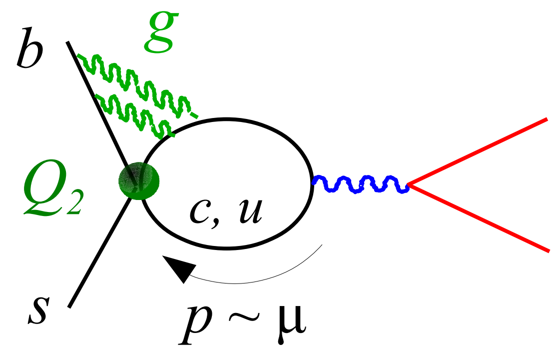
$$Q_9 = Q_f (b\,s)_{V-A} (l\,l)_V$$
$$Q_{10} = Q_f (b\,s)_{V-A} (l\,l)_A$$
$$\vdots$$

$$H_{\rm eff} = \Sigma_{\rm i}\, C_i(M_W)\, Q_i$$
$$\downarrow$$
$$H_{\rm eff} = \Sigma_{\rm i}\, C_i(\mu \sim m_b)\, Q_i$$

Four-quark (tree-level) ops.:

$$Q_1 = (b\,s)_{V-A} (c\,c)_{V-A}$$
$$Q_2 = (b\,c)_{V-A} (c\,s)_{V-A}$$
$$\vdots$$

Mixing of the four-quark Q_i into the FCNC Q_i
["dilution" of the potentially interesting NP]:



Negligible for Q_{10} [$B_{s,d} \to ll$ & $B \to K^{(*)} ll$]

Large for "photon penguins" Q_9 [$B \to K^{(*)} ll$ only]

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$$\vdots$$

III. Evaluation of the hadronic matrix elements

$$A(B \to f) = \Sigma_i\, C_i(\mu)\, \langle f |\, Q_i\, | B \rangle (\mu)$$

- sensitivity to long-distances (cc threshold...)
- distinction between different modes

non-perturbative effects...

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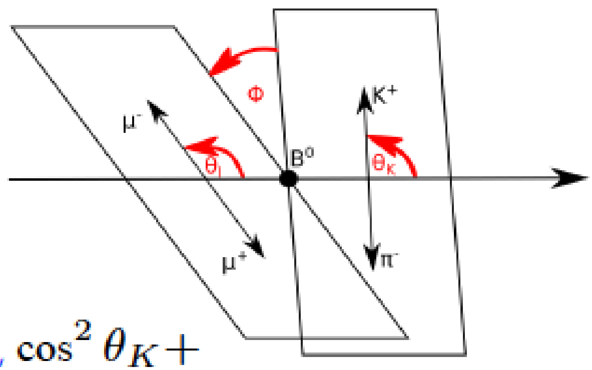
But less significant anomalies present also in other B → K*μμ observables and also in other b→sμμ channels [overall smallness of all BR(B → Hadron + μμ)]

Angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$



$$\frac{d^4(\Gamma+\bar{\Gamma})}{d\cos\theta_\ell\, d\cos\theta_K\, d\phi\, dq^2} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K +$$
$$\frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell - F_L\cos^2\theta_K\cos 2\theta_\ell +$$
$$S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi +$$
$$S_5\sin 2\theta_K\sin\theta_\ell\cos\phi + S_6\sin^2\theta_K\cos\theta_\ell +$$
$$S_7\sin 2\theta_K\sin\theta_\ell\sin\phi +$$
$$S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

$$P'_{4,5} = \frac{S_{4,5}}{\sqrt{F_L(1-F_L)}}$$

observables designed to cancel f.f. dependence in the HQ limit

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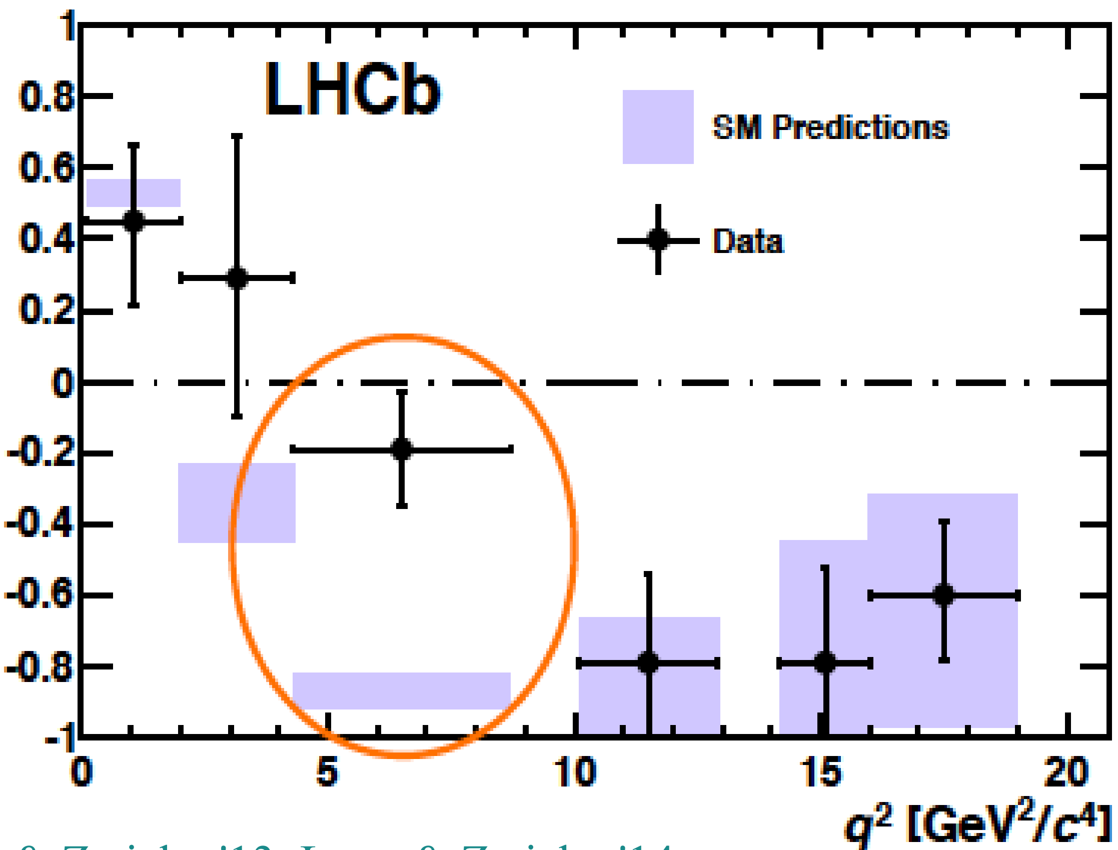
Pro NP:

- Reduced tension in <u>all the observables</u> with a unique fit of non-standard $C_i(M_W)$

Against NP:

- Main effect in P_5' not far from cc threshold
- "NP" mainly in C_9 ($\leftrightarrow$ *charm*)
- Significance reduced with conservative estimates of non-factorizable corrections



Jaeger *et al.* '12 Hambrock *et al.* '13, Hiller & Zwicky '13, Lyon & Zwicky '14

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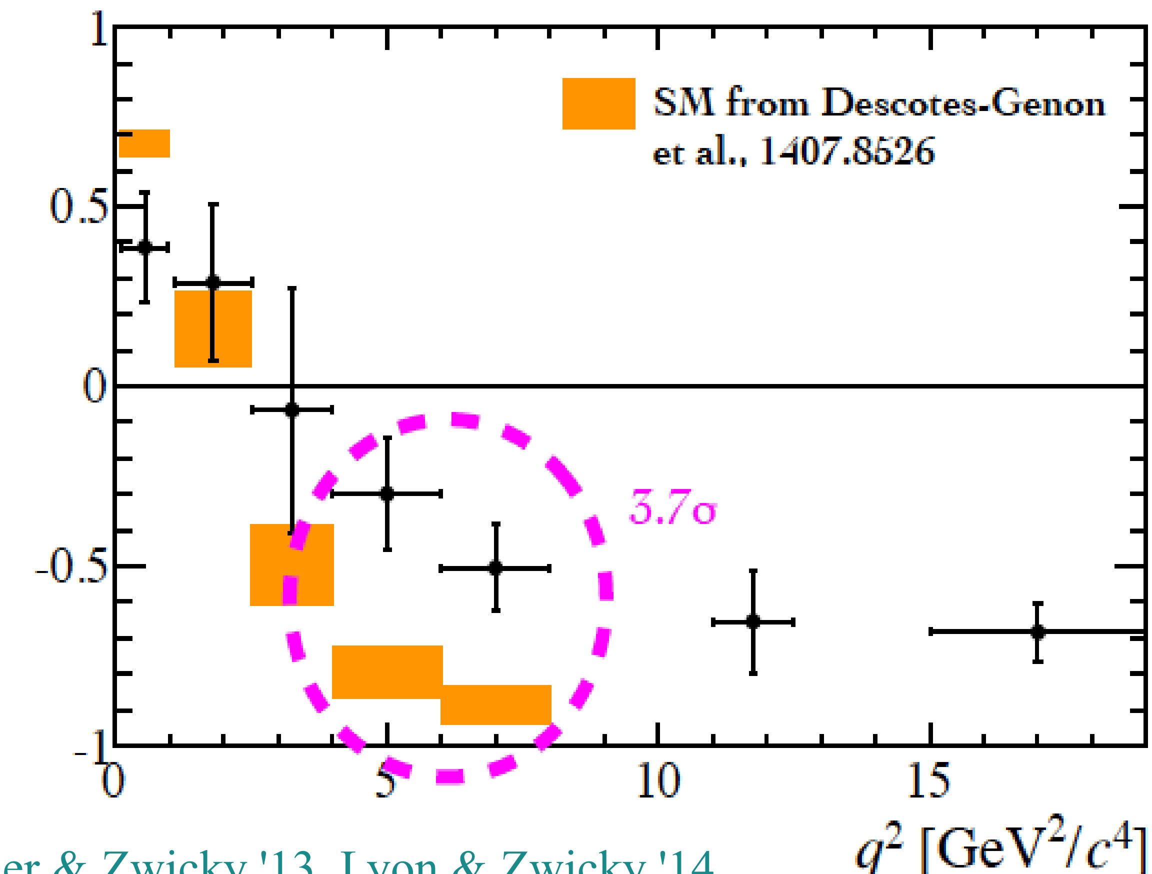
[LHCb-CONF-2015-002]



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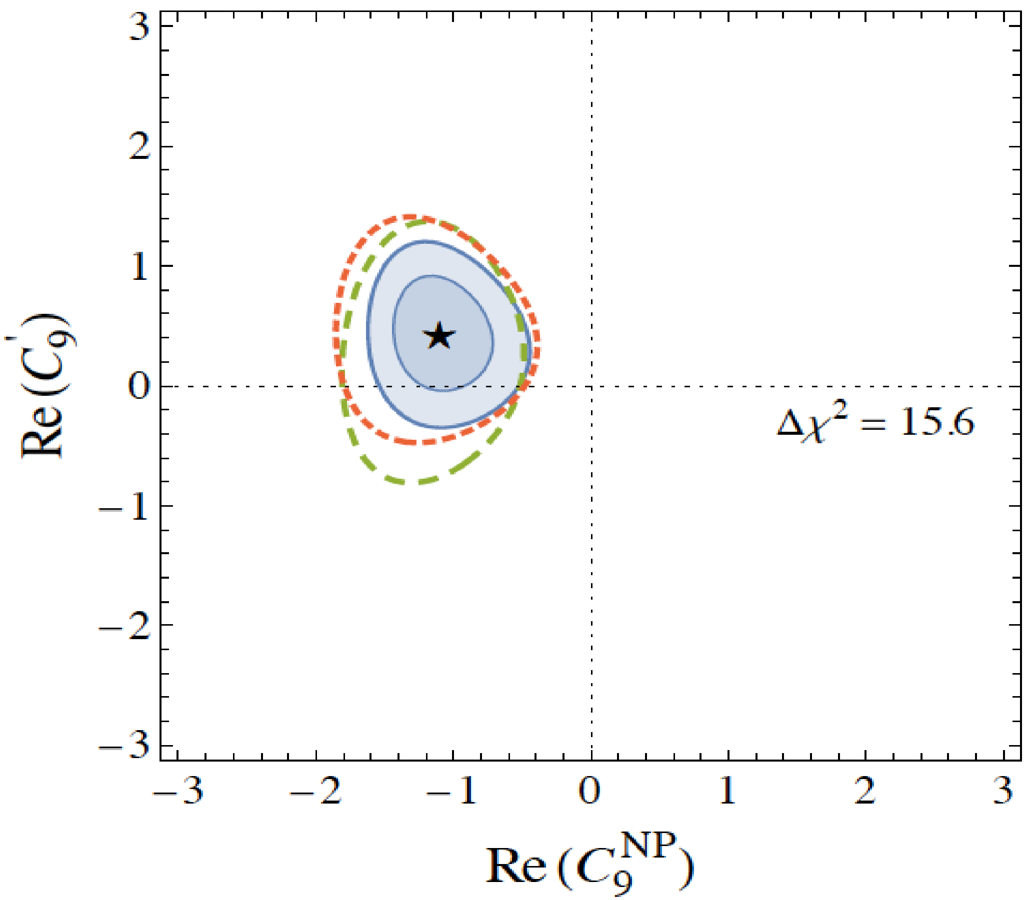
III. Anomalies in $B \to K^{(*)}\,\mu\mu$ / ee [LHCb]

Pro NP:

- Reduced tension in all the observables with a unique fit of non-standard short-distance Wilson coefficients

Descotes-Genon, Matias, Virto '13, '15
Altmannshofer & Straub '13, '15
Beaujean, Bobeth, van Dyk '13
Horgan *et al.* '13



Altmannshofer & Straub '15

$$O_9^{(\prime)} \propto (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\mu}\gamma^\mu \mu)$$

muonic vector current

- ▶ NP contributions to C_9 give best description of the data

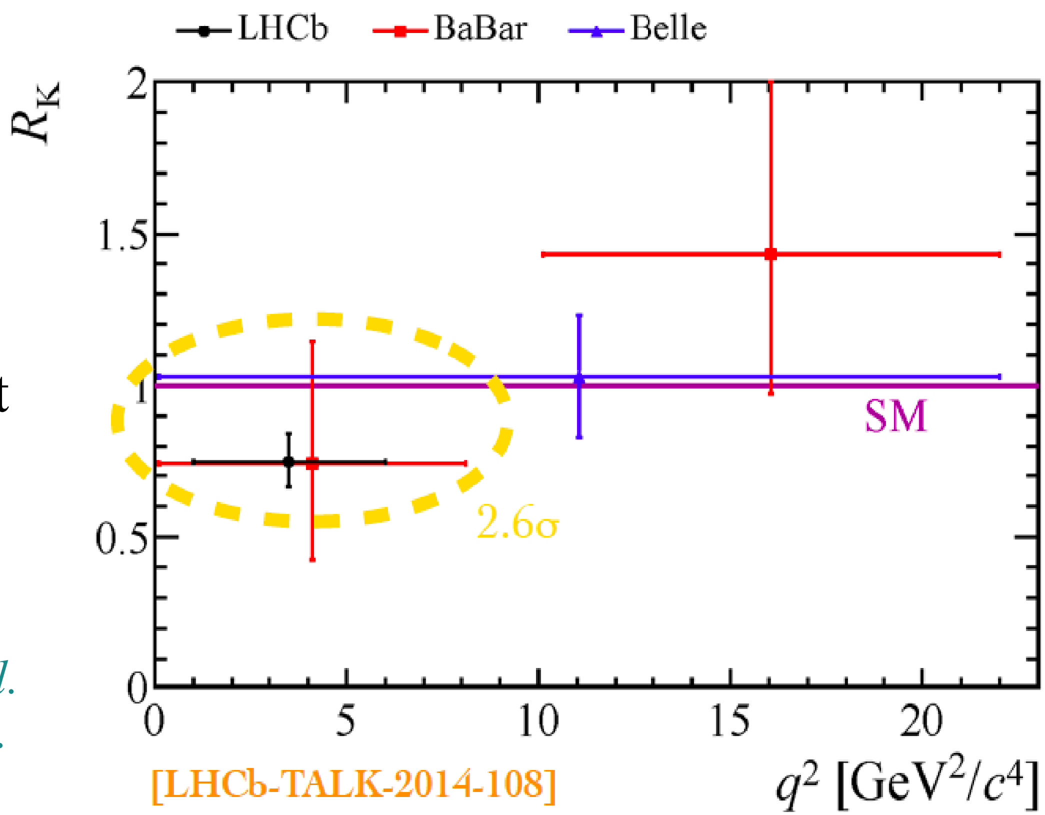
- ▶ (NP with $C_9 = -C_{10}$ works almost equally well)

III. Anomalies in $B \to K^{(*)} \mu\mu$ / ee [LHCb]

Last but not least, the most interesting effect in $b \to s\ell\ell$ transitions the 2.6σ deviation from the SM observed in the LFU ratio

$$R_K = \frac{\int d\Gamma(B^+ \to K^+\mu\mu)}{\int d\Gamma(B^+ \to K^+ee)}$$

$[1\text{-}6]\ \mathrm{GeV}^2$



[LHCb-TALK-2014-108]

- Negligible th. error → clean test of LFU (in neutral currents)

$$R_K = 1 \pm O(1\%)$$

Bordone *et al.* work in prog.

- This anomaly is perfectly described assuming NP only in $b \to s\mu\mu$ [*and not in* $b \to see$] consistently with the various $b \to s\mu\mu$ anomalies

Speculations on the breaking of Lepton Flavor Universality

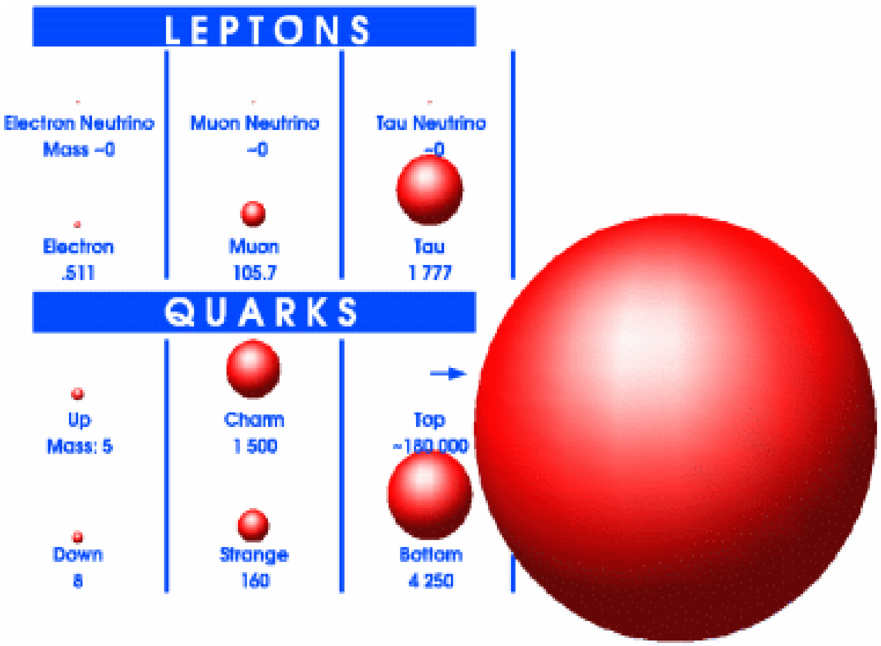
Speculations on the breaking of LFU

(Some of) these recent results have stimulated a lot of theoretical activity.

Most interesting aspect: possible breaking of LFU, both in charged currents ($b \to c\tau\nu$ vs. $b \to c\mu\nu$) and in neutral currents ($b \to s\mu\mu$ vs. $b \to see$)

A few general messages:

- LFU is not a fundamental symmetry of the SM Lagrangian (*accidental symmetry in the gauge sector, broken by Yukawas*)
- LFU tests at the Z peak are not too stringent (→ gauge sector)
- Most stringent tests of LFU involve only 1st-2nd gen. quarks & leptons



→ Natural to conceive NP models where LFU is violated more in processes with 3rd gen. quarks (↔ hierarchy in Yukawa coupl.)

▶ Speculations on the breaking of LFU

(Some of) these recent results have stimulated a lot of theoretical activity:

S. Fajfer, J. F. Kamenik, I. Nisandzic and J. Zupan, Phys. Rev. Lett. **109** (2012) 161801 [arXiv:1206.1872].

S. Descotes-Genon, J. Matias and J. Virto, Phys. Rev. D **88** (2013) 074002 [arXiv:1307.5683].

W. Altmannshofer and D. M. Straub, Eur. Phys. J. C **73** (2013) 2646 [arXiv:1308.1501].

A. Datta, M. Duraisamy and D. Ghosh, Phys. Rev. D **89** (2014) 7, 071501 [arXiv:1310.1937].

G. Hiller and M. Schmaltz, Phys. Rev. D **90** (2014) 054014 [arXiv:1408.1627]; JHEP **1502** (2015) 055

A. Crivellin and S. Pokorski, Phys. Rev. Lett. **114** (2015) 1, 011802 [arXiv:1407.1320].

S. L. Glashow, D. Guadagnoli and K. Lane, Phys. Rev. Lett. **114** (2015) 091801 [arXiv:1411.0565].

+ many others...

...but till last summer most attempts focused only on one set of anomalies (either charged or neutral currents)

Want I will discuss next are some general considerations if we try to describe all these effect within simplified (rather general) semi-dynamical models.

EFT-type considerations:

- Anomalies are seen only in semi-leptonic (quark×lepton) operators
- RR and scalar currents disfavored → LL current-current operators
- Necessity of at least one $SU(2)_L$-triplet effective operator (+ maybe a singlet one):

$$\frac{g_q g_\ell}{\Lambda^2} \lambda^q_{ij} \lambda^\ell_{kl} (\bar{Q}^i_L T^a \gamma_\mu Q^j_L)(\bar{L}^k_L T^a \gamma^\mu L^l_L)$$

Bhattacharya *et al.* '14
Alonso, Grinstein, Camalich '15
Greljo, GI, Marzocca '15

- Large coupling (competing with SM tree-level) in bc ($=33_{CKM}$) → $l_3\, \nu_3$
- Small non-vanishing coupling (competing with SM FCNC) in bs → $l_2\, l_2$

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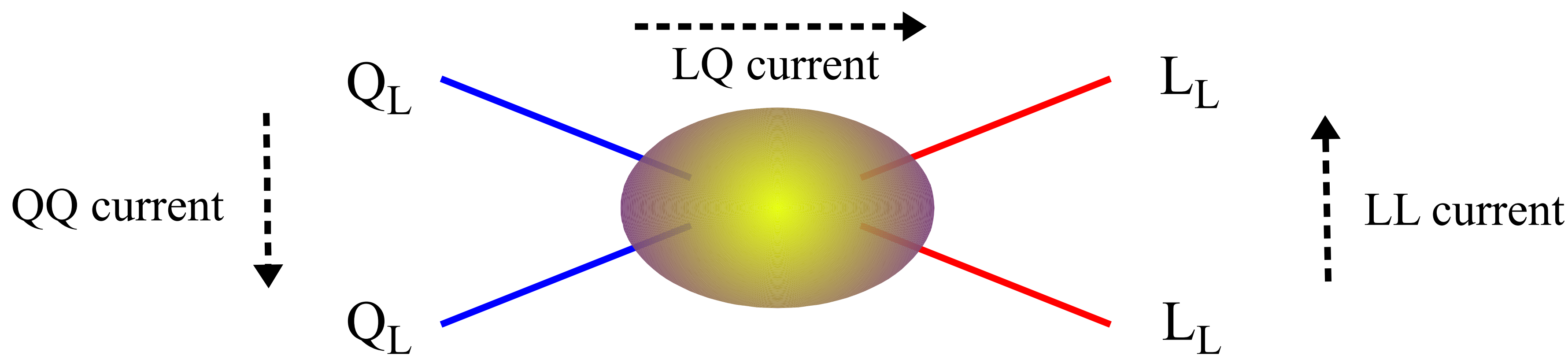

- Two natural classes of mediators, giving rise to different correlations among quark×lepton, (evidence) and quark×quark + lepton×lepton (bounds)

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⬇

$$\lambda^{q,\ell}_{ij} = \delta_{i3}\delta_{3j}$$ + small corrections for 2nd (& 1st) generations

General consequences in charged currents:

$$\frac{\mathcal{A}(b \to c\ \ell^i \bar{\nu}^i)_{\rm SM+NP}}{\mathcal{A}(b \to c\ \ell^i \bar{\nu}^i)_{\rm SM}} = 1 + \boxed{R_0} \lambda^\ell_{ii} \qquad R_0 \equiv \frac{g_\ell g_q}{g^2} \frac{m_W^2}{\Lambda^2}$$

I. From R(D*) & R(D) data [$\Gamma(b \to c\tau\nu)/\Gamma(b \to c\mu\nu)$] $\to$ $\boxed{R_0 = 0.14 \pm 0.04}$

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I. From R(D*) & R(D) data [Γ(b → cτν)/Γ(b → cμν)] → $R_0 = 0.14 \pm 0.04$

II. In principle, it should be possible to get a strong bound on the sub-leading leptonic coupling ($\lambda_{\mu\mu}$) from Γ(b → cμν)/Γ(b → ceν), but surprisingly it is not so stringent ($|\lambda_{\mu\mu}| \lesssim 0.1$) → *no dedicated studies @ B-facotries !*

✭ *General consequences in charged currents:*

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III. Even if it is hard to quantify [*work in prog.*], this breaking of LFU in c.c could decrease the tension between exclusive & inclusive determinations of $|V_{ub}|$ & $|V_{cb}|$:

$B \to X_{c,u}\, \tau\, \nu$

$\quad\quad\;\; \hookrightarrow \mu\nu\nu$

Irreducible bkg. for the inclusive meas. subtracted (at present) assuming SM-like $\Gamma(B \to X_{c,u}\tau\nu)$ → if $\Gamma(B \to X_{c,u}\tau\nu)$ is enhanced over the SM $\to |V_{c(u)b}|_{\rm incl.}$ are overestimated

A simplified dynamical model:

Main assumptions:

Greljo, GI, Marzocca '15

- We assume the effective triplet operator is the result of integrating-out a heavy triplet of vector bosons (W', Z') coupled to a single current:

$$J^a_\mu = g_q \boxed{\lambda^q_{ij}} \left(\bar{Q}^i_L \gamma_\mu T^a Q^j_L \right) + g_\ell \boxed{\lambda^\ell_{ij}} \left(\bar{L}^i_L \gamma_\mu T^a L^j_L \right) \longrightarrow \frac{1}{2m_V^2} J^a_\mu J^a_\mu$$

- Non-Universal flavor structure of the currents → mainly 3rd generations

→ Coupling to 3rd generations not suppressed [*dynamical assumption*]

→ Coupling to light generations controlled by small $U(2)_q \times U(2)_l$ breaking spurions related to sub-leading terms in the Yukawa couplings

Barbieri *et al.* '11

$$\lambda^q \simeq \begin{pmatrix} |\epsilon|^2 V^*_{3\alpha} V_{3\beta} & \epsilon^* V^*_{3\alpha} \\ \epsilon V_{3\beta} & 1 \end{pmatrix}_{\text{down-type mass basis}}$$

down-type mass basis

$$\lambda_{bd} \ll \lambda_{bs} \ll \lambda_{bb} = 1$$

$$\lambda_{ss} \sim \lambda^2_{bs}$$

A simplified dynamical model → low-energy global fit:

5 free parameters: $\epsilon_{\ell,q} \equiv \frac{g_{\ell,q}\, m_W}{g\, m_V} \approx g_{\ell,q} \frac{122\ \mathrm{GeV}}{m_V} \quad + \quad \lambda^q_{bs},\ \lambda^\ell_{\mu\mu},\ \lambda^\ell_{\tau\mu}$

several constraints:

- $R(D^*)$
- $R(D)$
- R_K
- $P_5'(B \to K^*\mu\mu)$

- $B(B \to K\nu\nu)$
- ΔM_{Bs} , ΔM_{Bd}
- CPV(D-$\underline{D}$)
- $\Gamma(B \to X\mu\nu)/\Gamma(B \to Xe\nu)$
- $\tau \to 3\mu$
- $\Gamma(\tau \to \mu\nu\nu)/\Gamma(\tau \to e\nu\nu)$

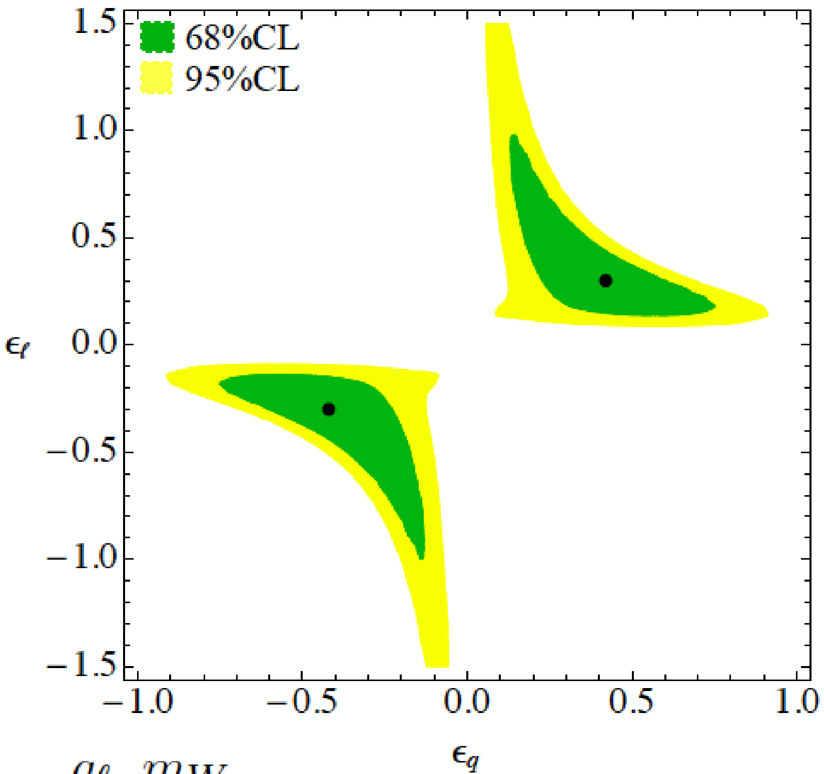
↓

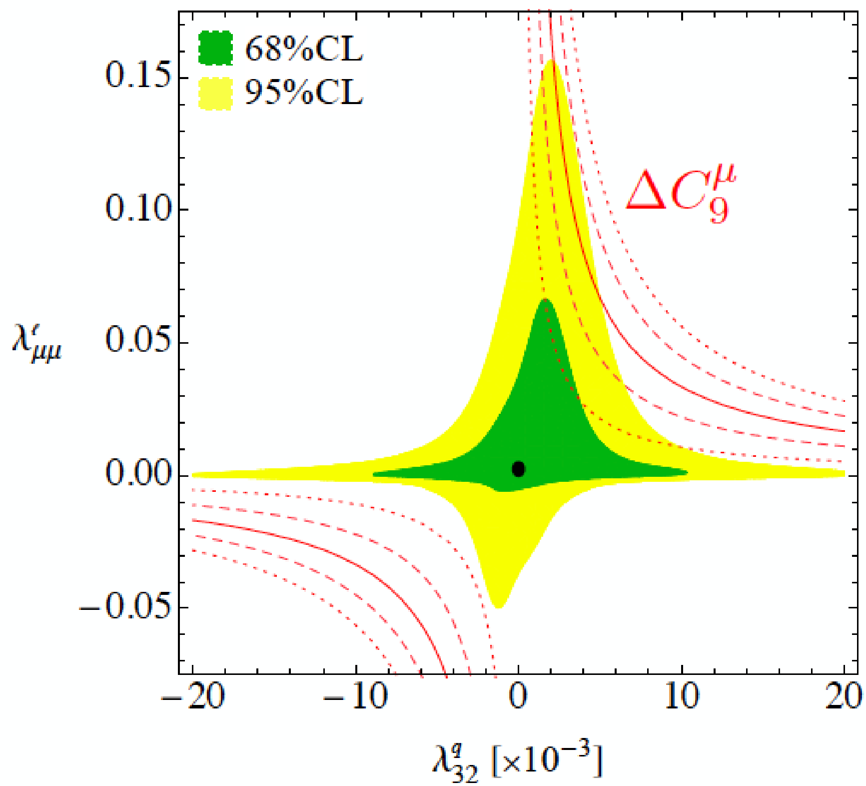
Overall good fit of low-energy data
(*non-trivial given tight constraints from ΔF=2 & LFV*)

Best fit point: $\epsilon_\ell \approx 0.37$, $\epsilon_q \approx 0.38$ p(SM) = 0.002

(flavor structure of the sub-leading terms not really probed)

✯ A simplified dynamical model → low-energy global fit:





$$\epsilon_{\ell,q} = \frac{g_{\ell,q} m_W}{g m_V}$$

$\varepsilon_\ell,\ \varepsilon_q \lesssim 1$

$\lambda_{\mu\mu} \lesssim 0.1$

$\lambda_{bs} \lesssim 0.015$

$\varepsilon_q > \varepsilon_\ell$ would improve $b \to s\mu\mu$

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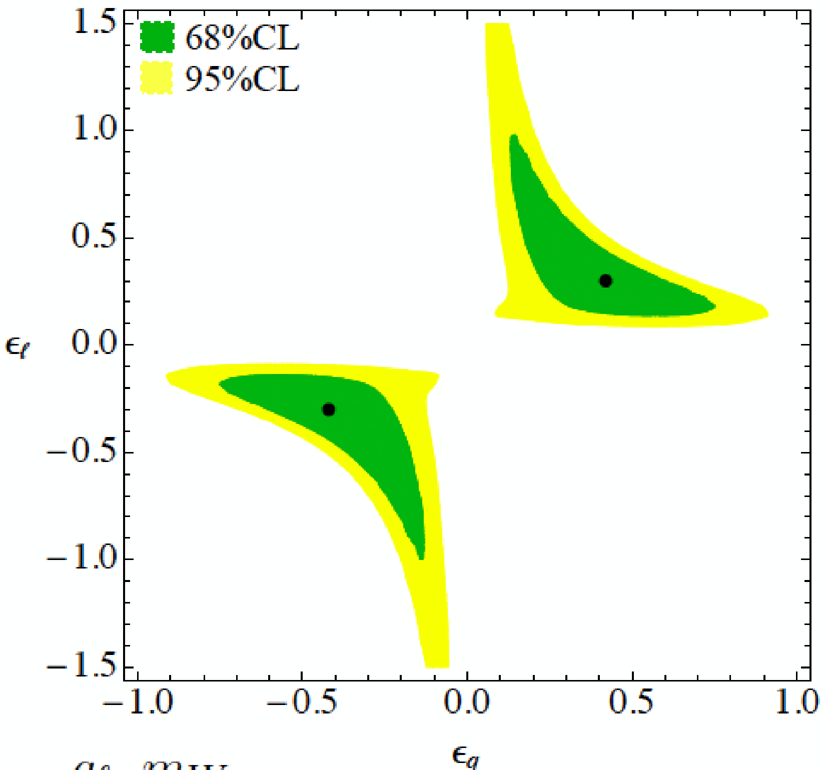

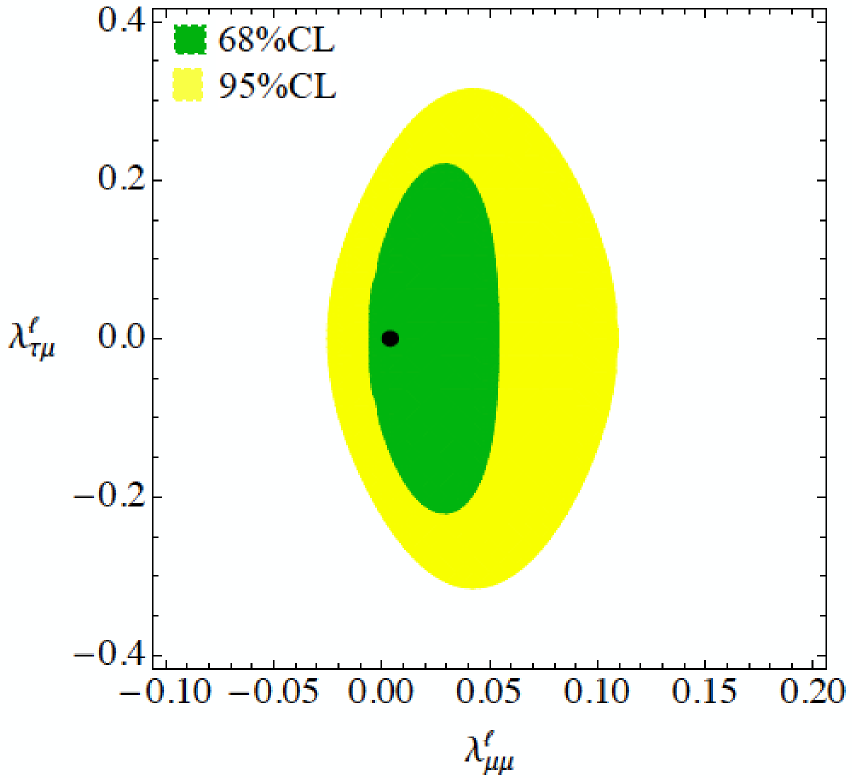

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A simplified dynamical model → further low-energy tests:

$$\mathcal{L}_{\text{eff}} = -\frac{1}{2m_V^2} J^a_\mu J^a_\mu$$

works well...

… and gives several clear predictions for future low-energy data:

- $b \to c(u)\, l\nu$ — $BR(B \to D^* \tau\nu)/BR_{SM} = BR(B \to D\tau\nu)/BR_{SM} = BR(\Lambda_b \to \Lambda_c \tau\nu)/BR_{SM}$ $= \ldots = BR(B_u \to \tau\nu)/BR_{SM}$ $R^{\mu/e}(X) \sim 10\%\, R^{\tau/\mu}(X)$

- $b \to s\, \mu\mu$ — $\Delta C_9^\mu = -\Delta C_{10}^\mu$, but overall size of the anom. should decrease
- $b \to s\, \tau\tau$ — $|NP| \sim |SM| \to$ large enhancement ($\sim BR\times 4$) or strong suppr.
- $b \to s\, \nu\nu$ — $\sim \pm 50\%$ deviation from SM in the rate

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- Meson mixing — $\sim 10\%$ deviations from SM both in ΔM_{Bs} & ΔM_{Bd}
- τ decays — $\tau \to 3\mu$ not far from present exp. bound

A simplified dynamical model → high-energy constraints:

The dynamical model

$$\mathcal{L}_V = -\frac{1}{4} D_{[\mu} V^a_{\nu]} D^{[\mu} V^{\nu]a} + \frac{m_V^2}{2} V^a_\mu V^{\mu a} + g_H V^a_\mu (H^\dagger T^a i \overleftrightarrow{D}_\mu H) + V^a_\mu J^a_\mu$$

The "heavy vector triplet" eff. Lagrangian [Pappadopulo, Tham, Torre, Wulzer, '14] in a rather peculiar parameter range:

- W' and Z' resonances in the mass range:

$$g_{\ell,q} \sim 1 \ \rightarrow m_V \sim 250\text{GeV}$$

$$g_{\ell,q} \sim \sqrt{4\pi} \ \rightarrow m_V \lesssim 1\text{TeV}$$

- Strong constraint on g_H from e.w. precisions tests:

$$\epsilon_{\ell,q} = \frac{g_{\ell,q} m_W}{g m_V} \approx 0.3 \qquad\qquad \epsilon_H = \frac{g_H\, m_W}{g m_V} \lesssim 0.01$$

A simplified dynamical model → high-energy constraints:

- The heavy vectors are produced mainly from 3rd gen. quarks (bb → Z', bc → W') and decay mainly in 3rd generations quarks or leptons (Z' → ττ,bb,tt, W' →tb, τν)

↓

- Not a very easy signature...

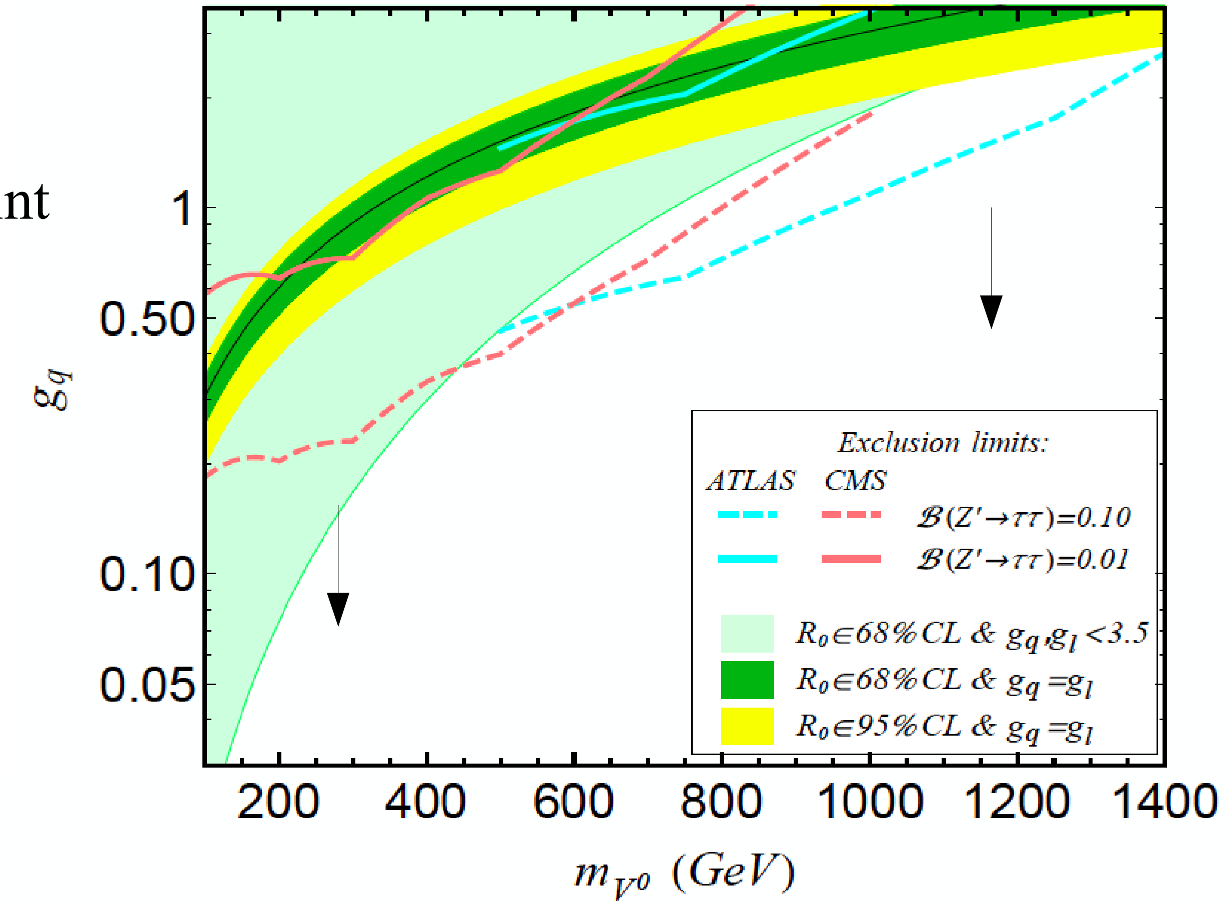
The only really stringent constraint comes from Z' → ττ

↓

Minimal version of the model
(*no exotic decay channels*)
ruled out by direct searches

$$BR(Z' \to \bar{\tau}\tau) = \frac{g_\ell^2}{2g_\ell^2 + 6g_q^2 + \text{extra}}$$

Greljo, GI, Marzocca '15



Conclusions

- Intriguing hints of LF non Universality in recent semi-leptonic B-physics data, but picture far form being clear → more data can help to clarify the situation

- Main messages of these recent anomalies:
  - (re)analyze B physics data without assuming LFU
  - conceive more low-energy tests of LFU (especially in B decays)
  - the search for LFV in charged leptons is extremely well motivated
  - the bounds on NP coupled mainly to 3rd generation are still relatively weak
  - the interplay of low- and high-energy searches is essential