Links between EWP anomalies and semi-leptonic B decays

[speculations on the breaking of Lepton Flavor Universality in B decays]

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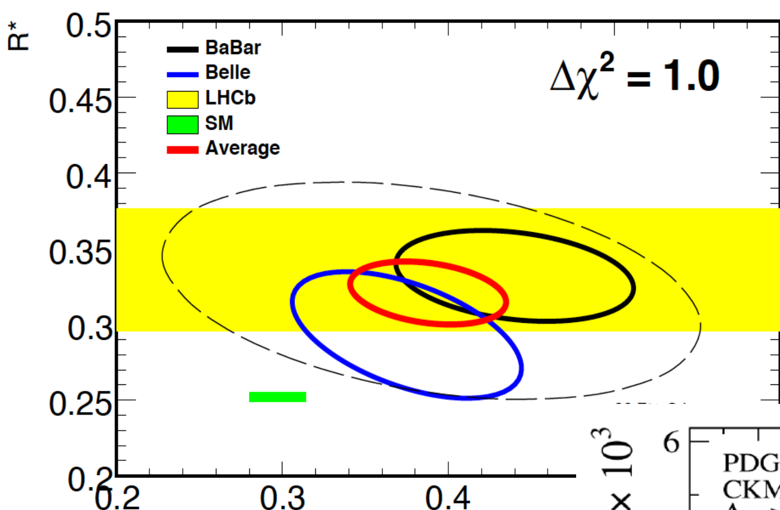
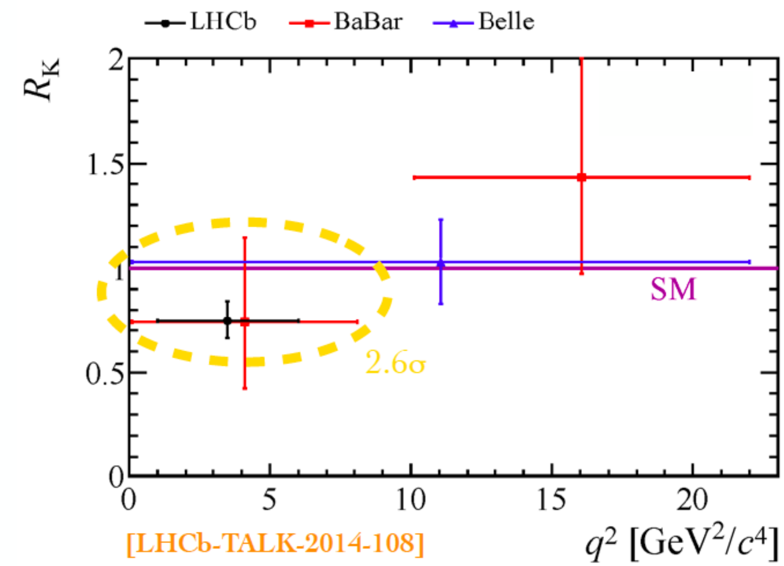
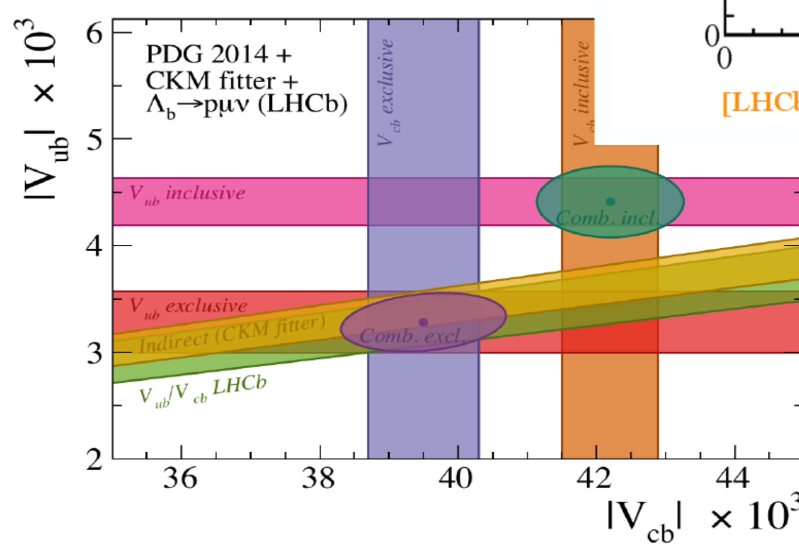
- On the anomalies
- Speculations on the breaking of Lepton Flavor Universality
- Conclusions

On the anomalies

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







This talk contains personal biases...!

I. The EWP anomalies in $B \to K^{(*)} \mu\mu$ / ee [LHCb]

The largest EWP anomaly is the "famous" deviation from SM in P_5' [$B \to K^{*}\mu\mu$]

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 + $\mu\mu$)]

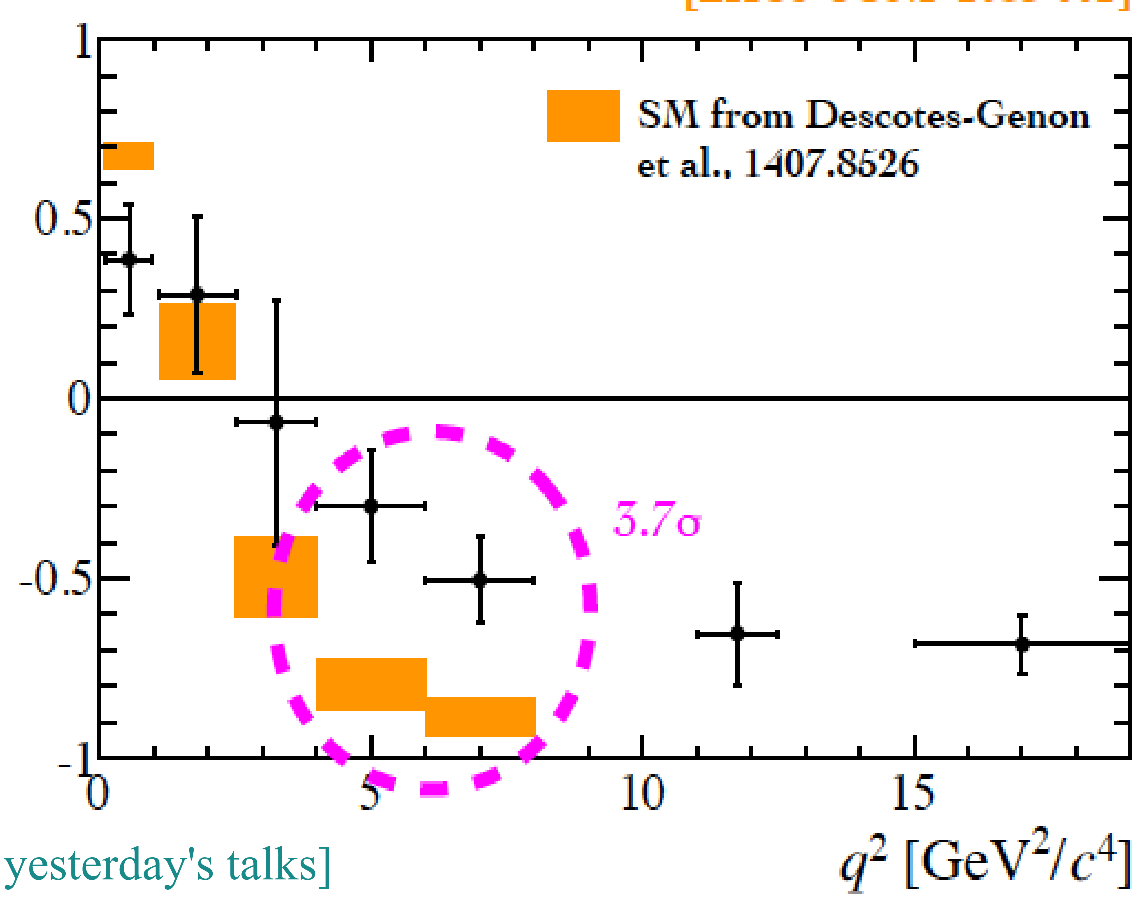
Pro NP:

- Reduced tension in all the observables with same set of non-standard short-distance Wilson coefficients (ΔC_9 or $\Delta C_9 = -\Delta C_{10}$)

Against NP:

- C_9 sensitive to charm re-scattering effects
- Significance reduced with conservative estimates of non-factorizable corrections

[LHCb-CONF-2015-002]



[→ yesterday's talks]

I. The EWP anomalies in $B \to K^{(*)} \mu\mu$ / ee [LHCb]

The most interesting aspect (*in my opinion*) is the 2.6σ deviation from the SM observed in the LFU ratio

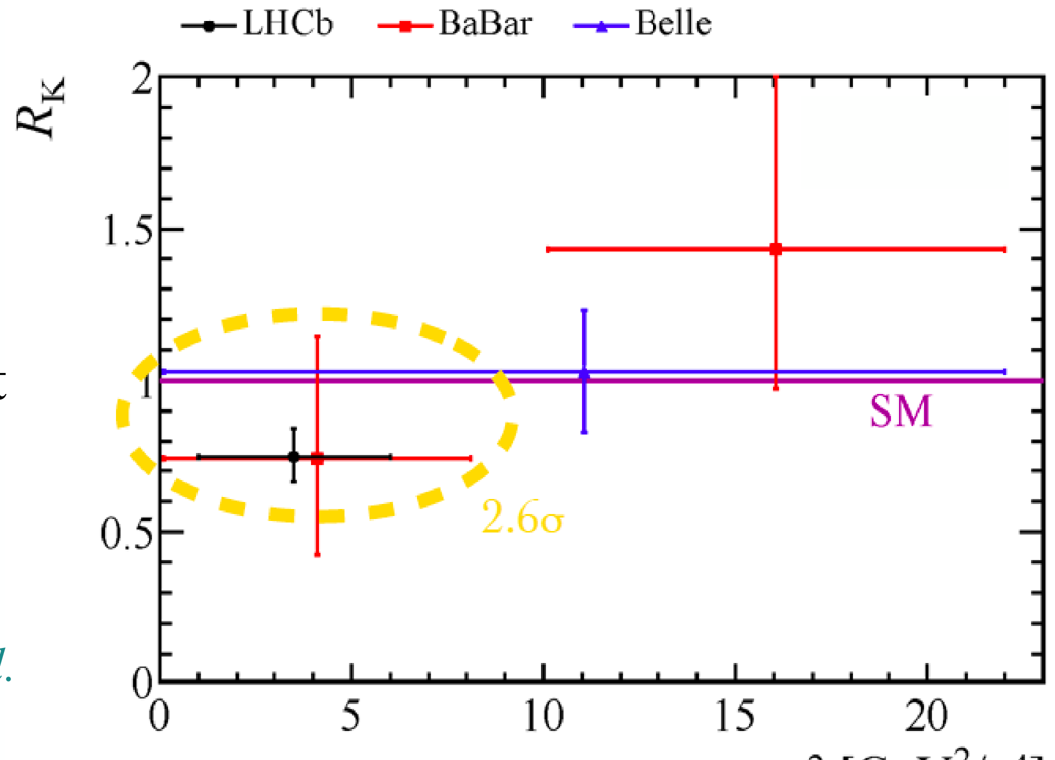
$$R_K = \frac{\int d\Gamma(B^+ \to K^+ \mu\mu)}{\int d\Gamma(B^+ \to K^+ ee)}$$

[1-6] GeV^2

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

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

Bordone *et al.* work in prog.



[LHCb-TALK-2014-108]

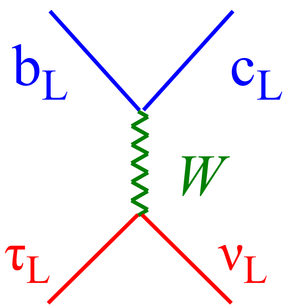
The anomaly is perfectly described assuming NP only in b→sμμ [*and not in* b→see] consistently with the various b→sμμ anomalies

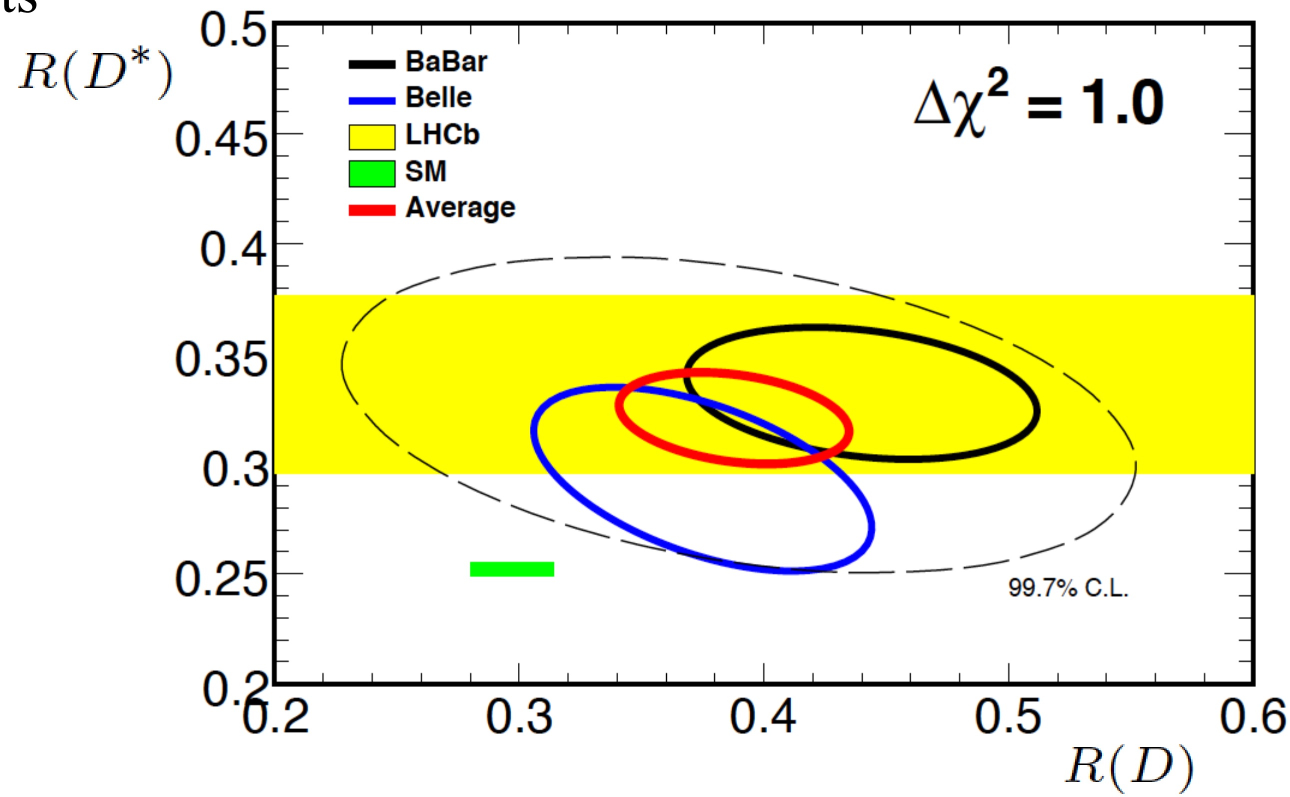
II. $B \to D^{(*)} \tau\nu$ [Babar, Belle, LHCb]

[→ today's talks]

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

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





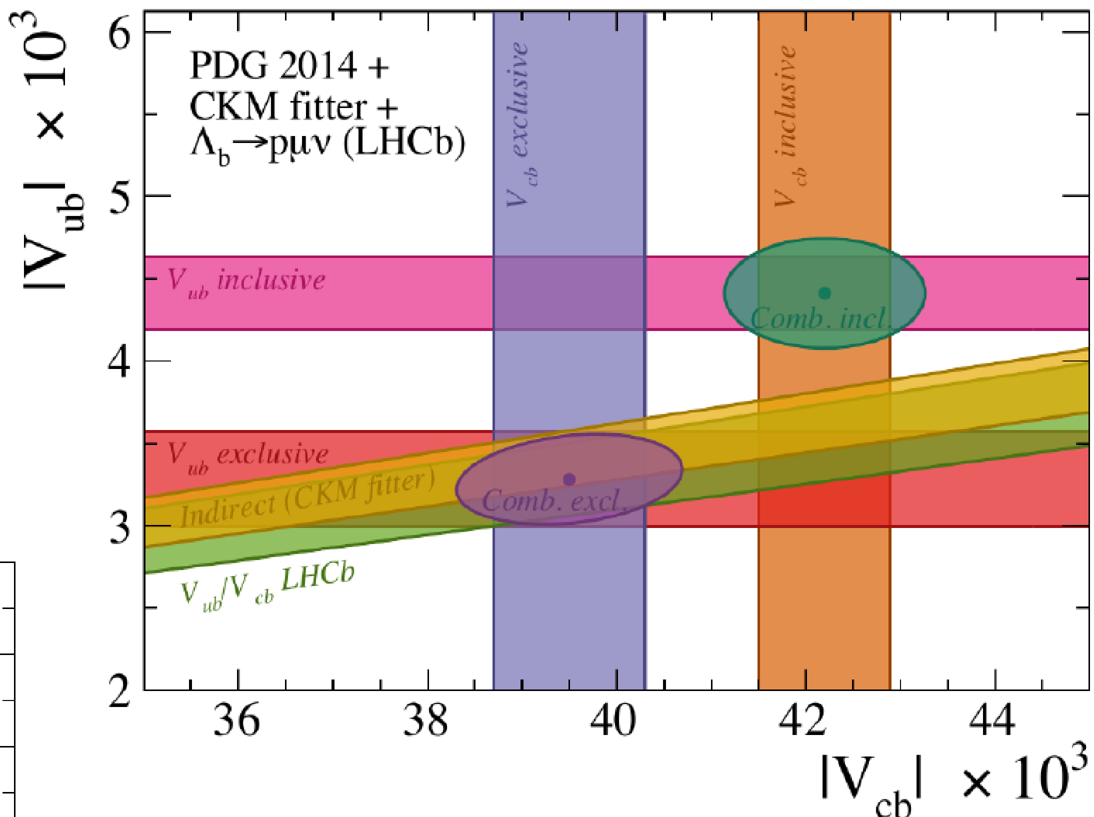
- SM prediction quite solid: f.f. uncertainty cancel (*to a good extent...*) in the ratio
- Consistent exp. results by 3 (very) different experiments
  - 3.9σ excess over SM (if D and D* combined)
  - The two channels are well consistent with a universal enhancement (~30%) of the SM $b_L \to c_L\ \tau_L\ \nu_L$ amplitude (*RH or scalar amplitudes disfavored*)

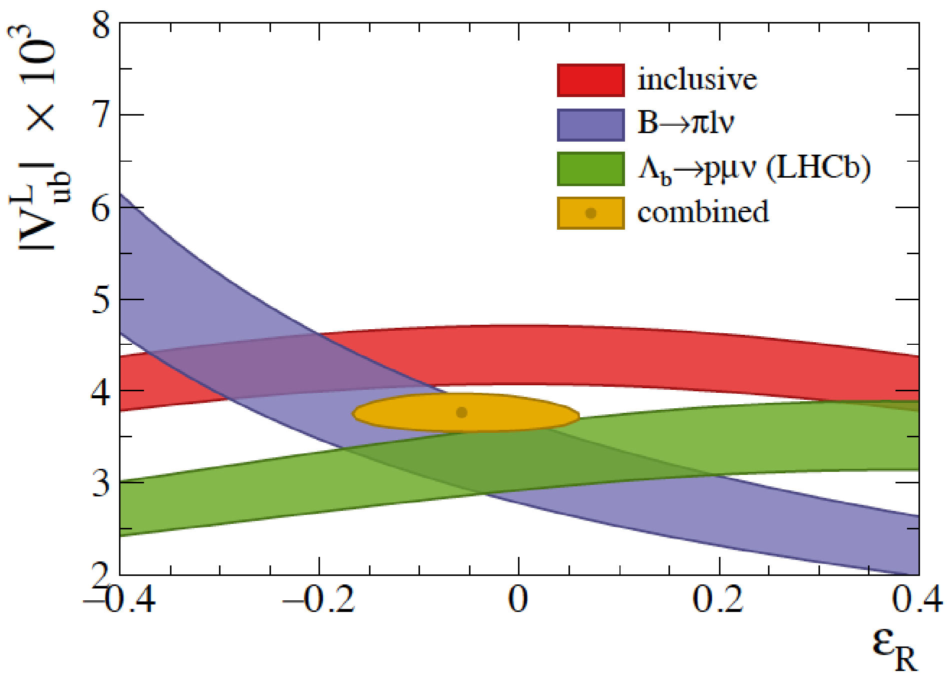
III. $|V_{ub}/V_{cb}|$ from $B(\Lambda_b \to p\mu\nu)/B(\Lambda_b \to \Lambda_c\mu\nu)$ [Babar, Belle, LHCb]

[→ today's talks]

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

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





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

Speculations on the breaking of Lepton Flavor Universality

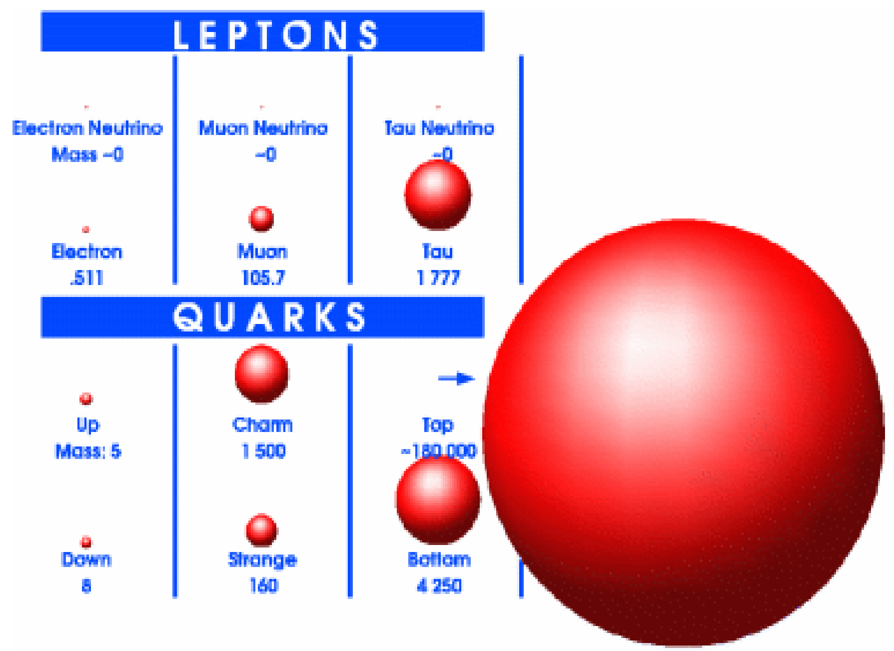
Speculations on the breaking of LFU

These anomalies have stimulated a lot of theoretical activity.

Most interesting aspect (*in my opinion*): 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 very interesting (→ 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

These anomalies 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 most attempts focused either on specific NP models (mainly for EWP anom.) or on "partial" EFT-type approaches (focused only on quark×lepton ops.).

Want I will discuss today is what happens if we try to describe all these effect within a simplified (rather general) dynamical model:

- low-energy correlations among quark×quark, quark×lepton, lepton×lepton
- correlation between low-energy and high-energy physics

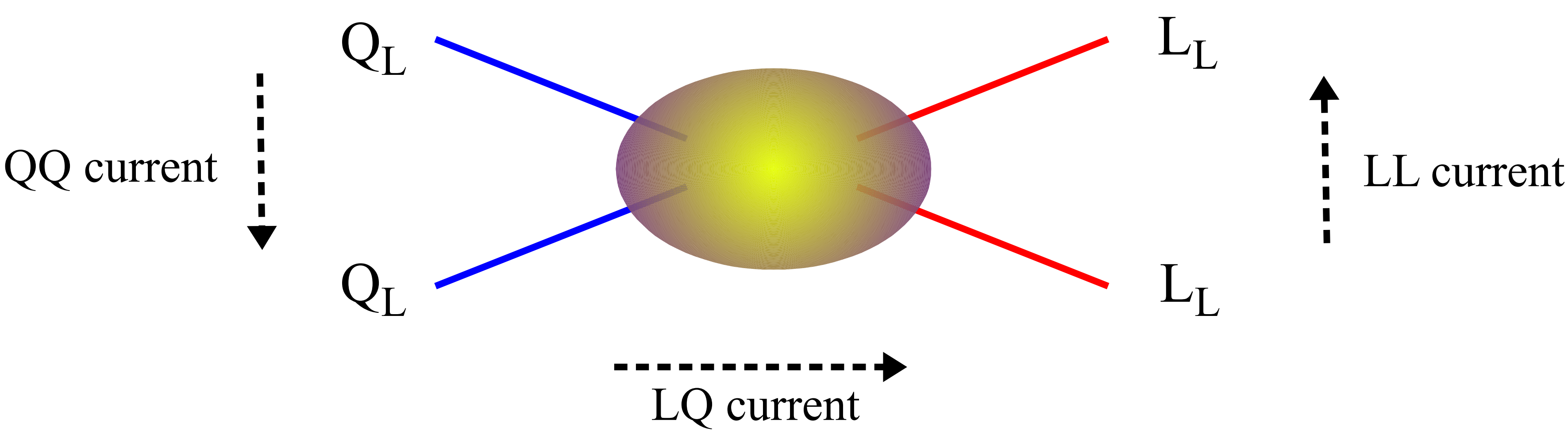
A "prototype data-inspired" model:

Main assumptions:

- NP in both charged & neutral currents + RH currents disfavored + $SU(2)_L \times U(1)_Y$ symmetry → $SU(2)_L$-triplet effective operator

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

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



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Greljo, GI, Marzocca '15

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

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

- → low-energy correlations among quark×quark, quark×lepton, lepton×lepton
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- Non-Universal flavor structure of the currents → mainly 3^{rd} generations

$$\lambda^{q,\ell}_{ij} = \delta_{i3}\delta_{3j}$$ + small corrections for 2^{nd} (& 1^{st}) generations (*hierarchy determined by CKM in the quark sector*)

A "prototype data-inspired" model:

A closer look to the flavor structure of the model:

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

→ 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 subleading terms in the Yukawa couplings

Glashow *et al.* '14

Barbieri *et al.* '11

Connection to CKM matrix in the quark sector:

$$\lambda^q \simeq \begin{pmatrix} |\epsilon|^2 V^*_{3\alpha} V_{3\beta} & \epsilon^* V^*_{3\alpha} \\ \epsilon V_{3\beta} & 1 \end{pmatrix}$$

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

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

down-type
mass basis

$$\epsilon \lesssim 1$$

Effects in charged currents:

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

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

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

II. In principle, it should be possible to get a strong bound on the sub-leading leptonic coupling ($\lambda_{\mu\mu}$) from $\Gamma(b \to c\mu\nu)/\Gamma(b \to ce\nu)$ but it turns out to be not so stringent ($|\lambda_{\mu\mu}| \lesssim 0.1$ *no dedicated studies @ B-facotries*)

Effects 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 $|V_{ub}|$ & $|V_{cb}|$:

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

$\quad\llcorner\!\!\longrightarrow \mu\nu\nu$

Irreducible bkg. for the inclusive meas. subtracted (at present) assuming SM-like $\Gamma(B \to X_{c,u}\tau\nu)$ $\to$

if $\Gamma(B \to X_{c,u}\tau\nu)$ is enhanced over the SM $\to |V_{c(u)b}|_{\rm incl.}$ are overestimated

Global fit to low-energy data:

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

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-<u>D</u>)
- $\Gamma(B \to X\mu\nu)/\Gamma(B \to Xe\nu)$
- $\tau \to 3\mu$
- $\Gamma(\tau \to \mu\nu\nu)/\Gamma(\tau \to e\nu\nu)$

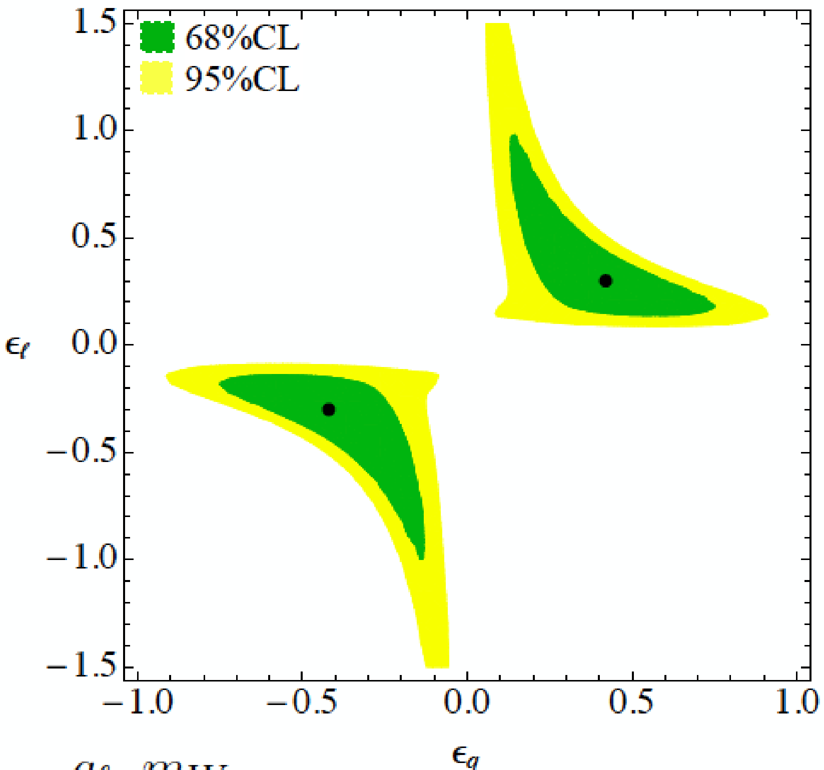
↓

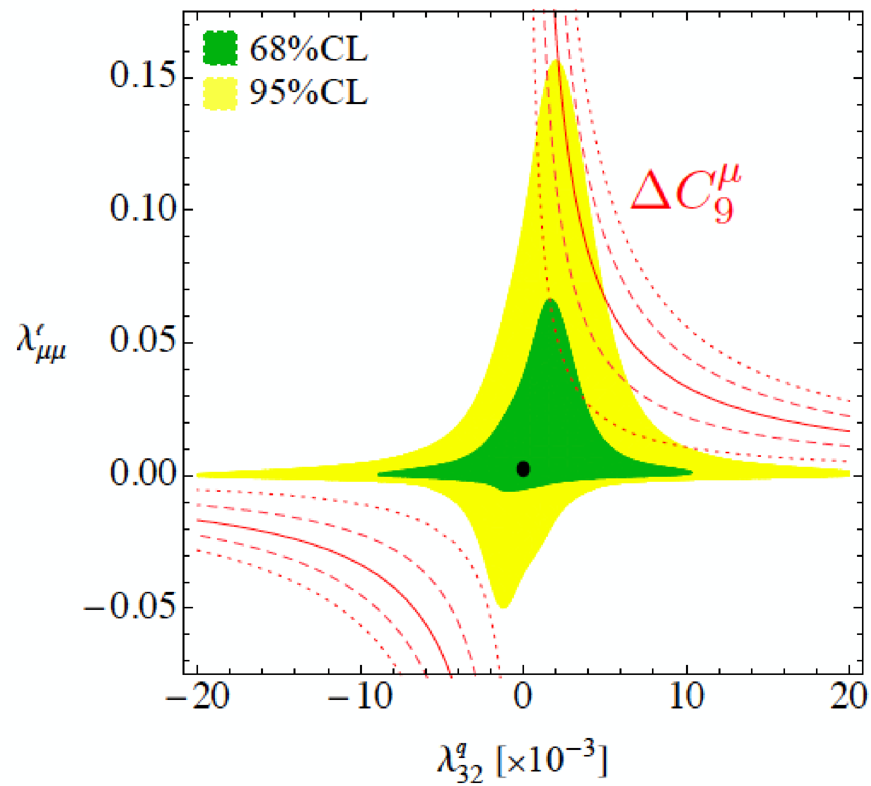
Overall good fit of low-energy data
(*non-trivial given tight constraints from ΔF=2 & LFV*)

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)

Global fit to low-energy data:





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

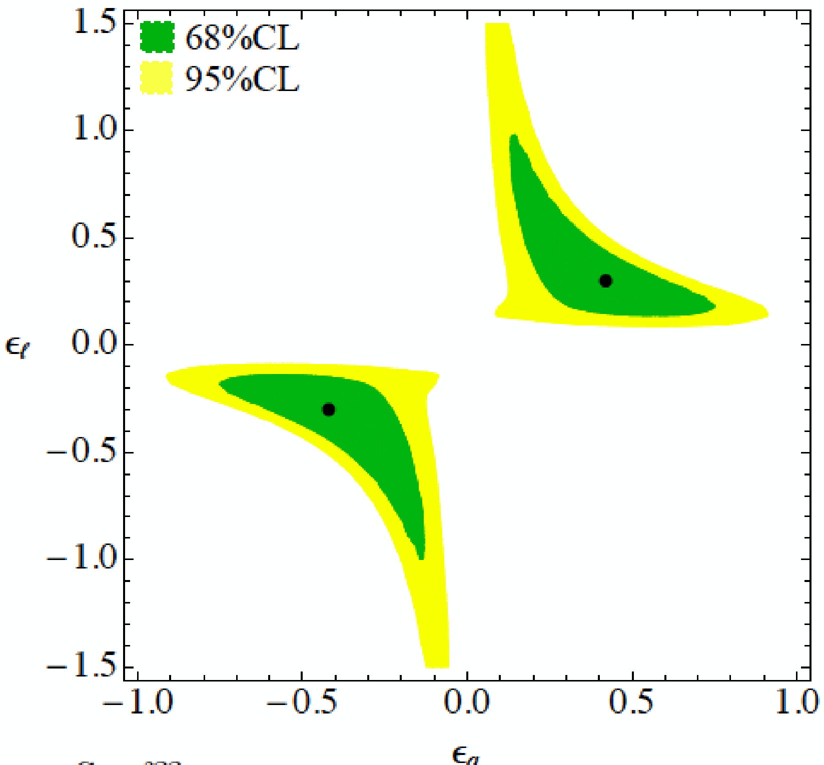
$\varepsilon_\ell,\ \varepsilon_q \lesssim 1$

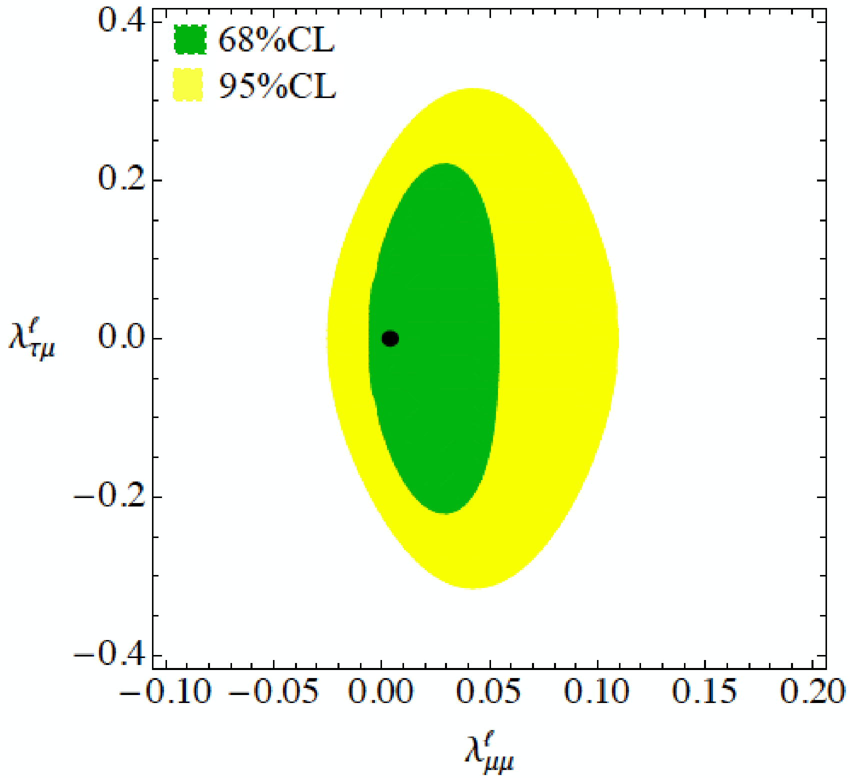
$\lambda_{\mu\mu} \lesssim 0.1$

$\lambda_{bs} \lesssim 0.015$

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

Global fit to low-energy data:





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

Future low-energy tests:

$$\mathscr{L}_{\rm eff} = -\frac{1}{2m_V^2} J_\mu^a J_\mu^a$$

works well...

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

- $b \to c(u)\ l\nu$

$BR(B \to D^* \tau\nu)/BR_{SM} = BR(B \to D\tau\nu)/BR_{SM} = BR(\Lambda_b \to \Lambda_c \tau\nu)/BR_{SM}$

$= \ldots = BR(B_u \to \tau\nu)/BR_{SM}$

$R^{\mu/e}(X) \sim 10\%\ R^{\tau/\mu}(X)$

→ universal ~ 30% enhancement of C.C. semi-lpetonic decays into tau leptons

→ ~1-2 % (universal) breaking of universality between muons & electron (in CC modes)

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

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

Future low-energy tests:

$$\mathscr{L}_{\rm eff} = -\frac{1}{2m_V^2} J_\mu^a J_\mu^a$$

works well...

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

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

- b → s μμ — $\Delta C_9^\mu = -\Delta C_{10}^\mu$, but overall size of the anom. should decrease
- b → s ττ — |NP| ~ |SM| → large enhancement (~ BR×4) or strong suppr.
- b → s νν — ~ ± 50% deviation from SM in the rate

- Meson mixing — ~ 10% deviations from SM both in ΔM_{Bs} & ΔM_{Bd}
- τ decays — τ → 3μ not far from present exp. bound

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:

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

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

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

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

High-energy constraints:

- The heavy vectors are produced mainly from 3rd gen. quarks ($bb \to Z'$, $bc \to W'$) and decay mainly in 3rd generations quarks or leptons ($Z' \to \tau\tau, bb, tt$, $W' \to tb, \tau\nu$)

↓

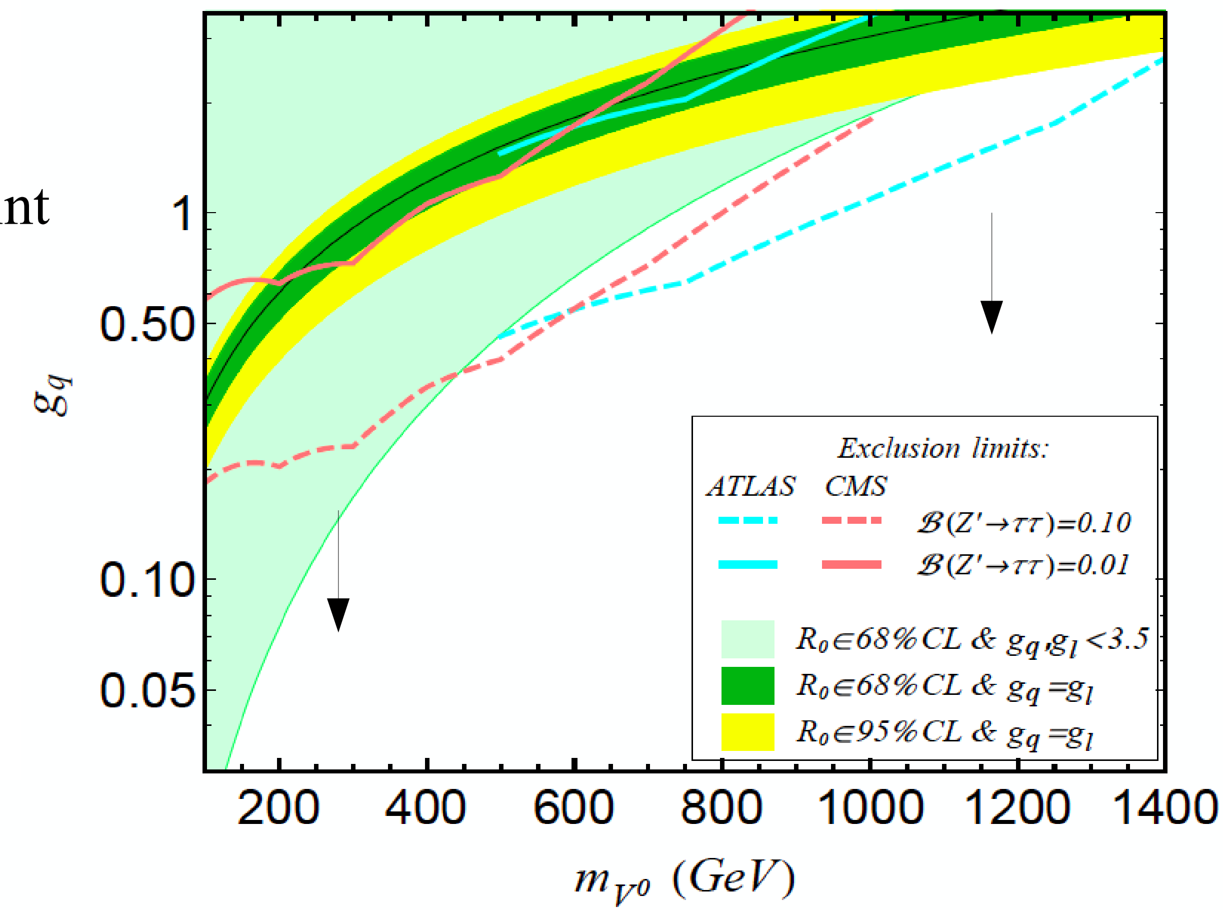
- Not a very easy signature...

The only really stringent constraint comes from $Z' \to \tau\tau$

↓

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

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



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