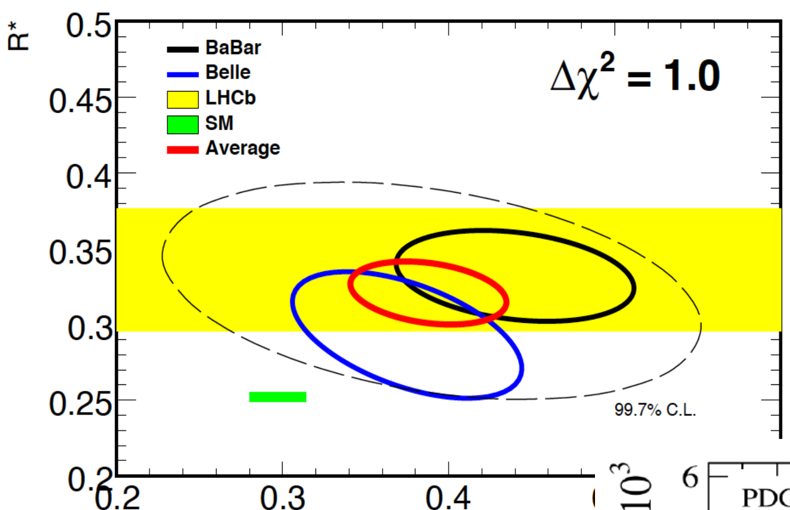
On the breaking of Lepton Flavor Universality in B decays

Gino Isidori
[*University of Zürich*]

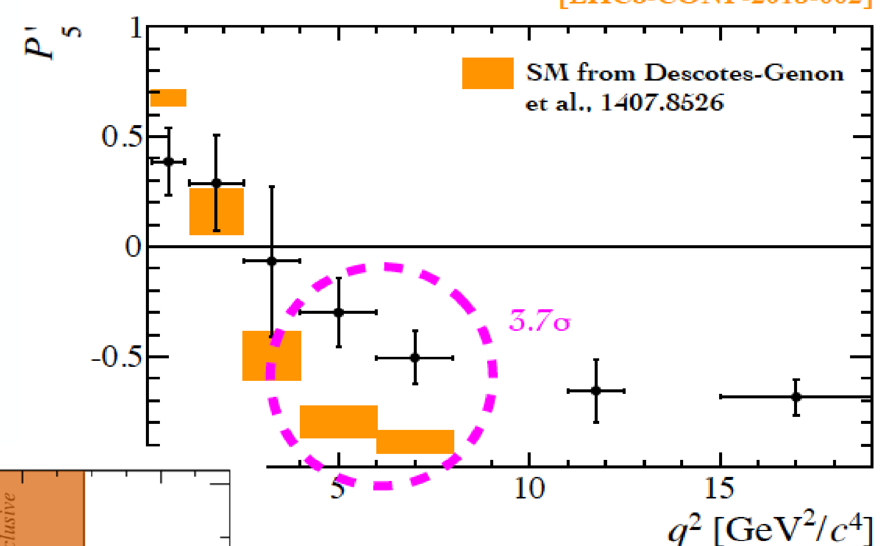
- Some interesting new (and old) anomalies in B physics
- Speculations on the breaking of Lepton Flavor Universality
- Conclusions

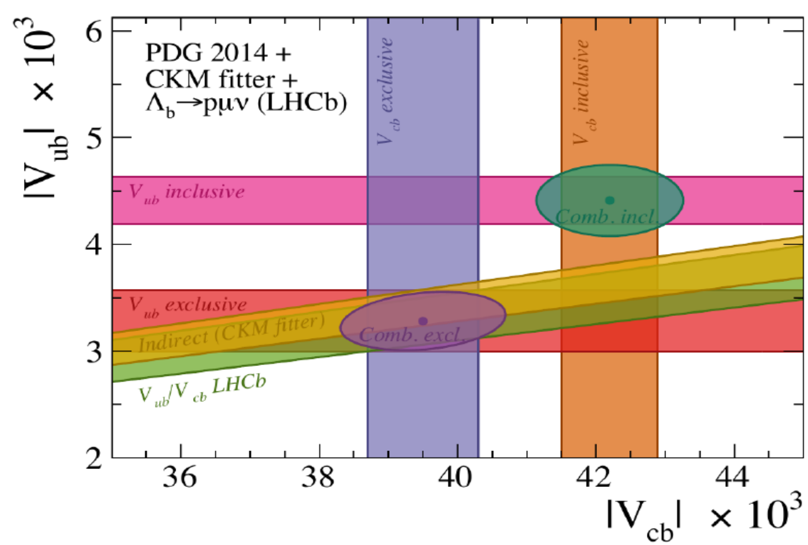
New and old anomalies in B physics

[*or better in semi-leptonic B decays…*]



[LHCb-CONF-2015-002]





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

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

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

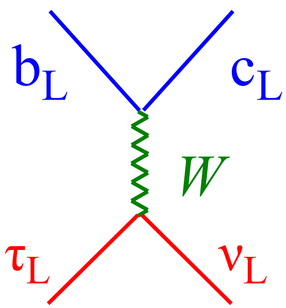
		$R(D)$		$R(D^*)$	
	BaBar	$0.440 \pm 0.058 \pm 0.042$		$0.332 \pm 0.024 \pm 0.018$	
NEW →	Belle	$0.375^{+0.064}_{-0.063} \pm 0.026$		$0.293^{+0.039}_{-0.037} \pm 0.015$	
NEW →	LHCb			$0.336 \pm 0.027 \pm 0.030$	
	Average	0.388 ± 0.047	~1.8σ	0.321 ± 0.021	~3.2σ
	SM expectation	0.300 ± 0.010		0.252 ± 0.005	

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

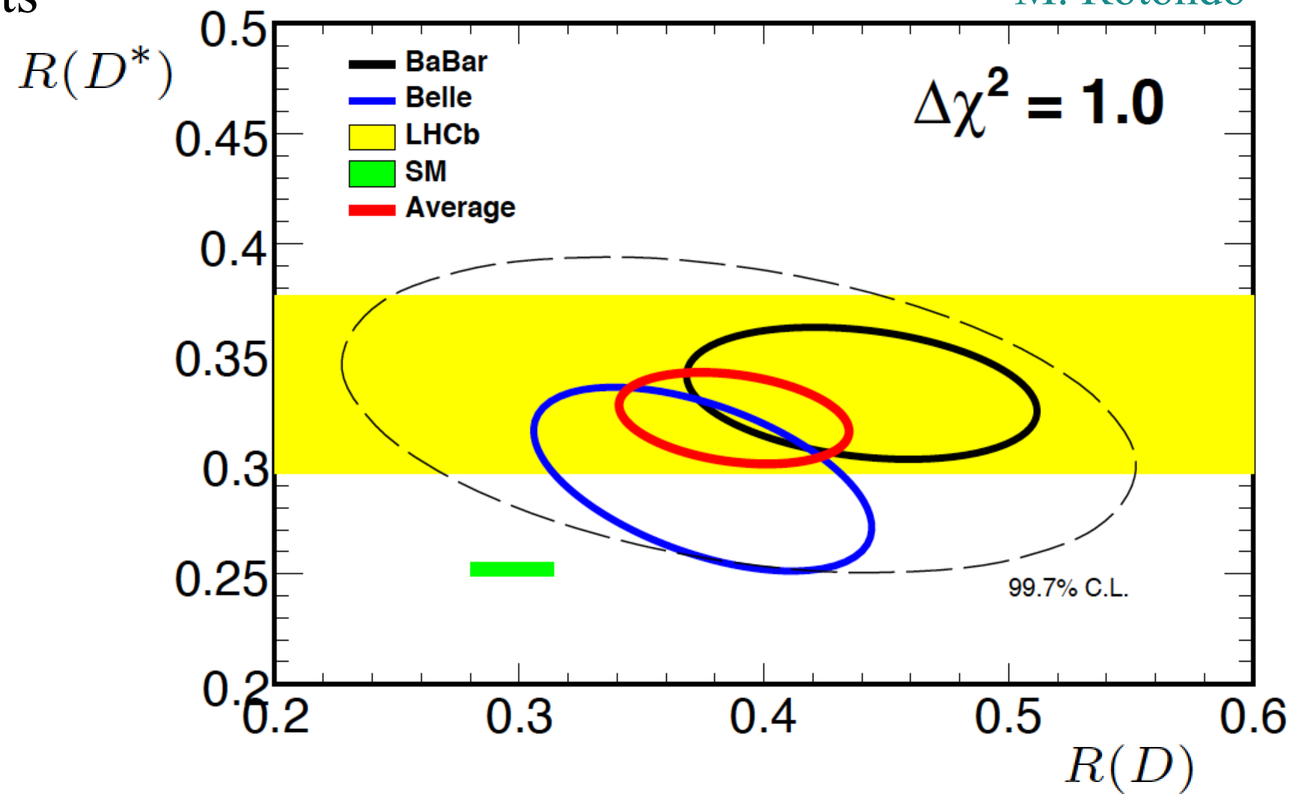
I. $B \to D^{(*)} \tau\nu$ [LHCb, Belle]

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

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



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 $b_L \to c_L\ \tau_L\ \nu_L$ amplitude (*RH or scalar amplitudes disfavored*)

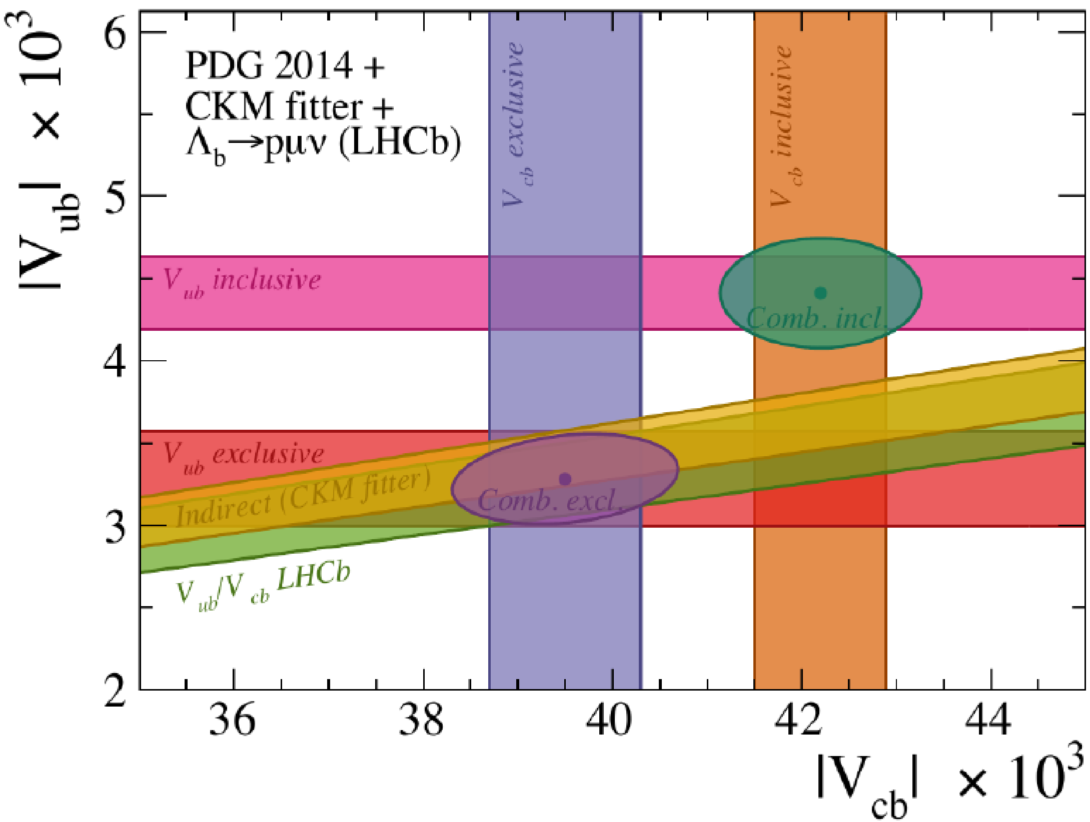
II. $|V_{ub}/V_{cb}|$ from $B(\Lambda_b \to p\mu\nu)/B(\Lambda_b \to \Lambda_c\mu\nu)$ [LHCb]

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]



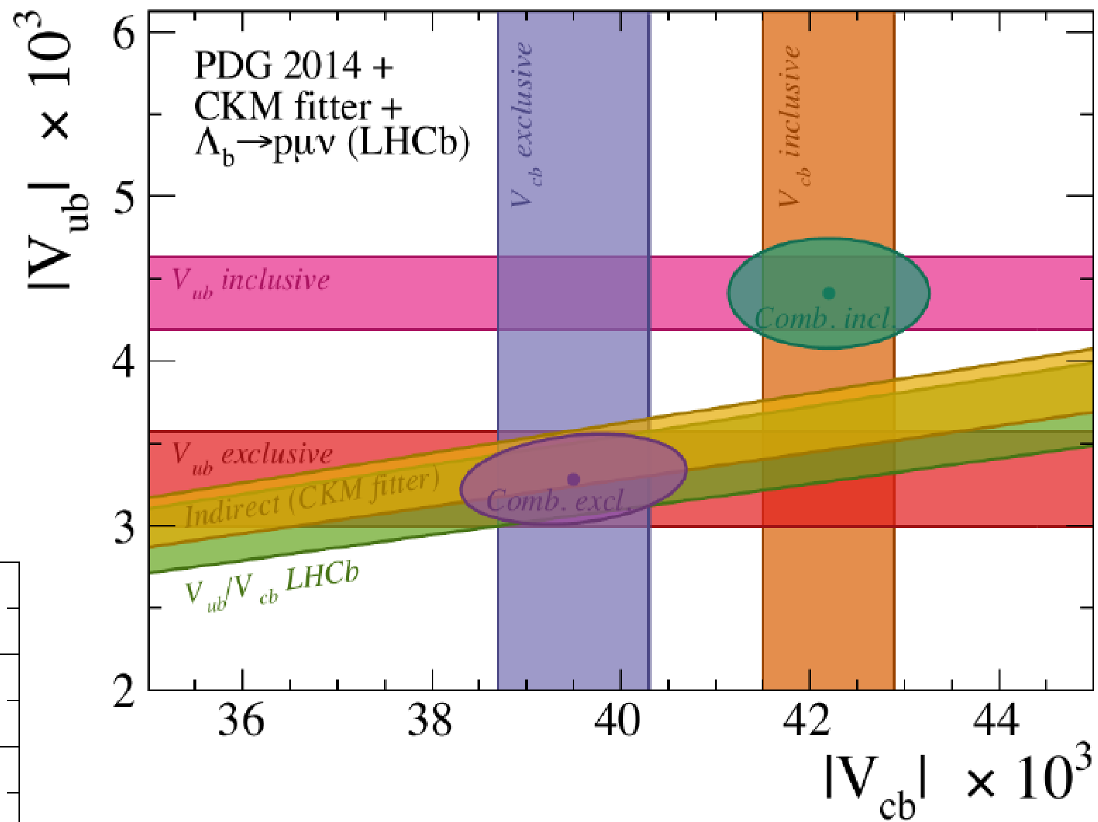
- Consistent with other exclusive data
- Increased tension between excl. & incl.

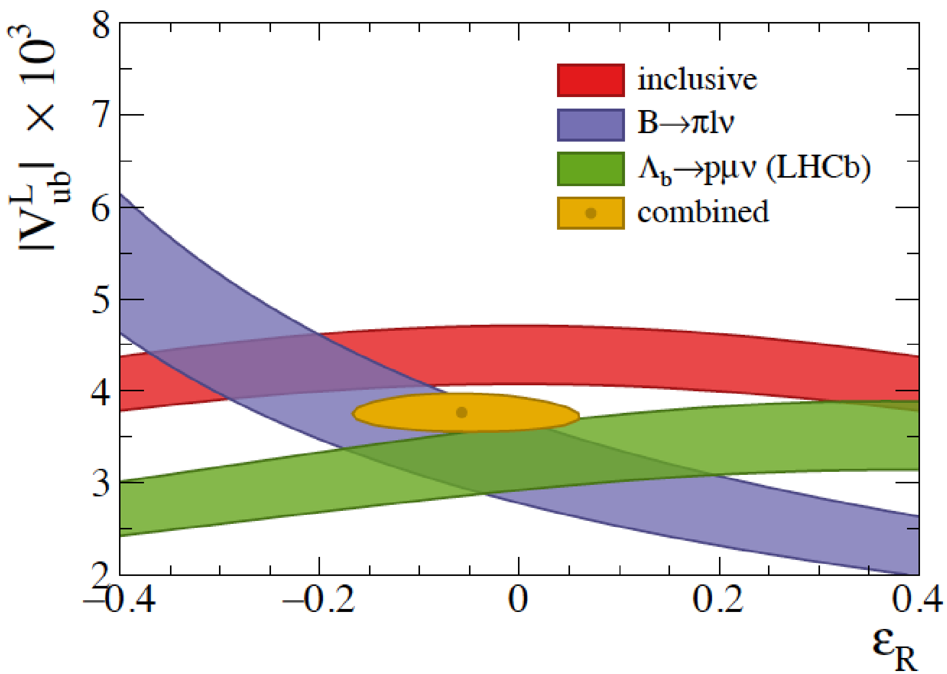
II. $|V_{ub}/V_{cb}|$ from $B(\Lambda_b \to p\mu\nu)/B(\Lambda_b \to \Lambda_c\mu\nu)$ [LHCb]

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 $B(\Lambda_b \to p\mu\nu)/B(\Lambda_b \to \Lambda_c\mu\nu)$





- 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.

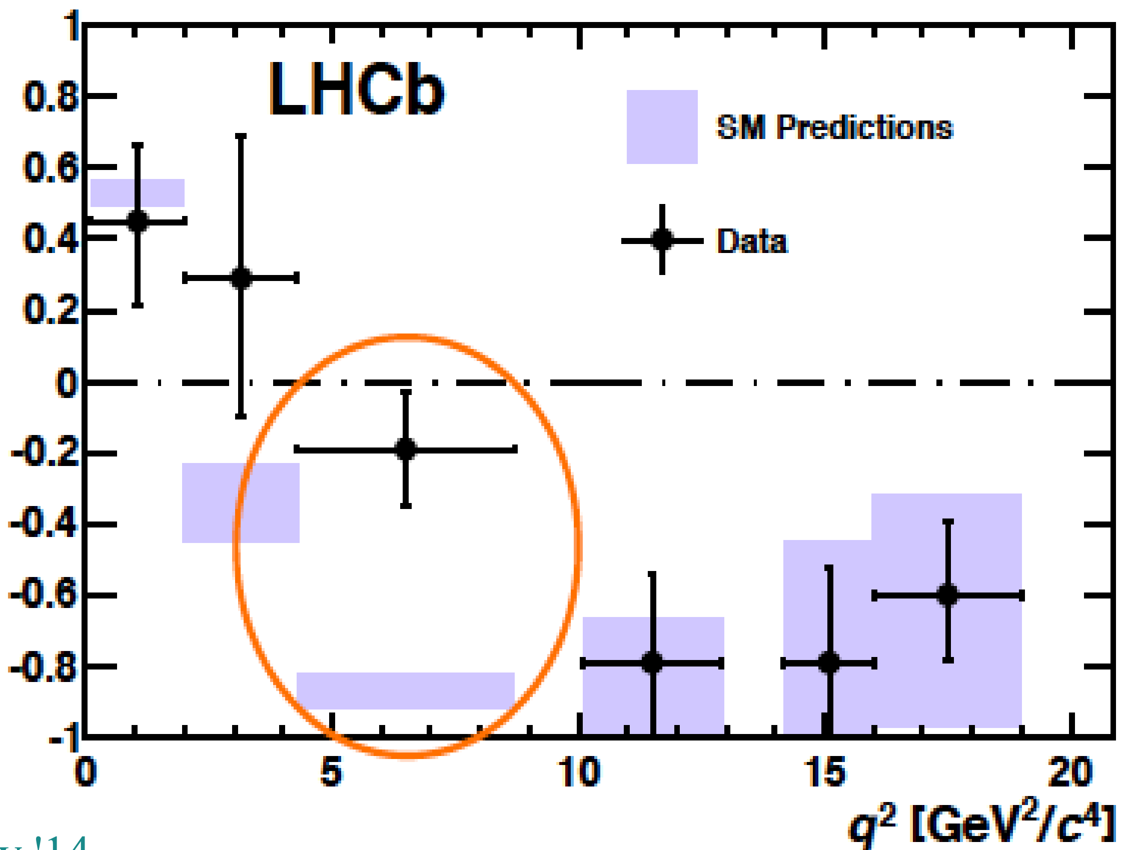
But less significant anomalies present also in other $B \to K^* \mu\mu$ observables and also in other $b \to s\mu\mu$ channels [overall smallness of all BR($B \to$ Hadron + $\mu\mu$)]

Pro NP:

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

Against NP:

- Main effect in P_5' not far from cc threshold
- Significance reduced with conservative estimates of non-factorizable corrections



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

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 + $\mu\mu$)]

Pro NP:

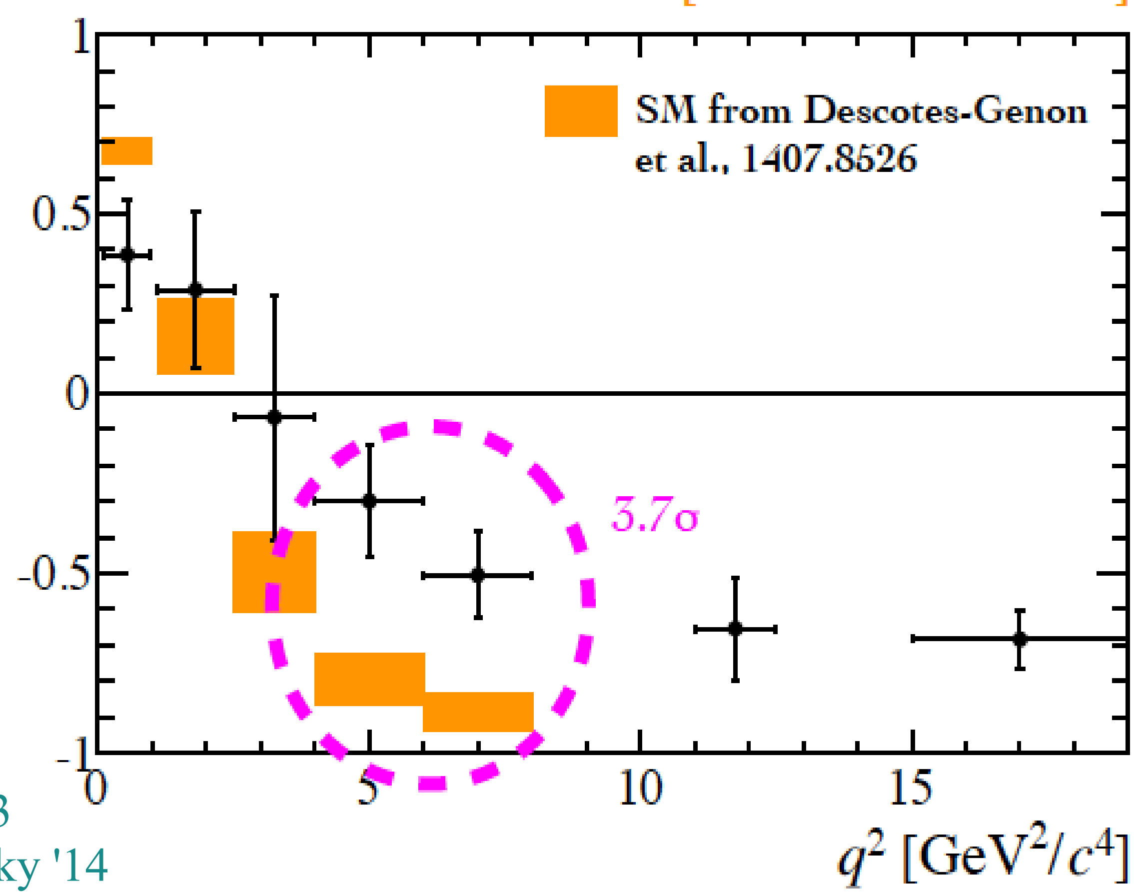
- Reduced tension in all the observables with a unique fit of non-standard short-distance Wilson coefficients

Against NP:

- ~~Main effect in P_5' not far from cc threshold~~
- Significance reduced with conservative estimates of non-factorizable corrections

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

[LHCb-CONF-2015-002]

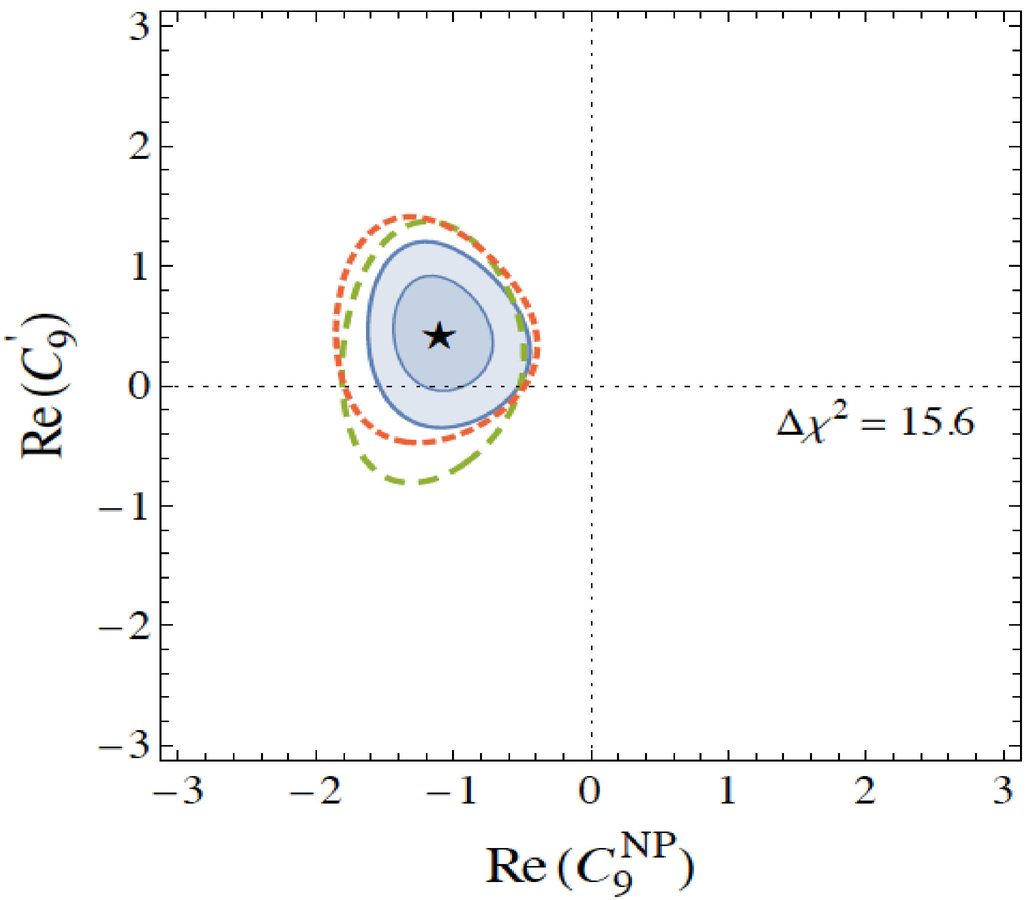


III. Anomalies in $B \to K^{(*)} \mu\mu$ / ee [LHCb]

Pro NP:

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

Descotes-Genon, Matias, Virto '13
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

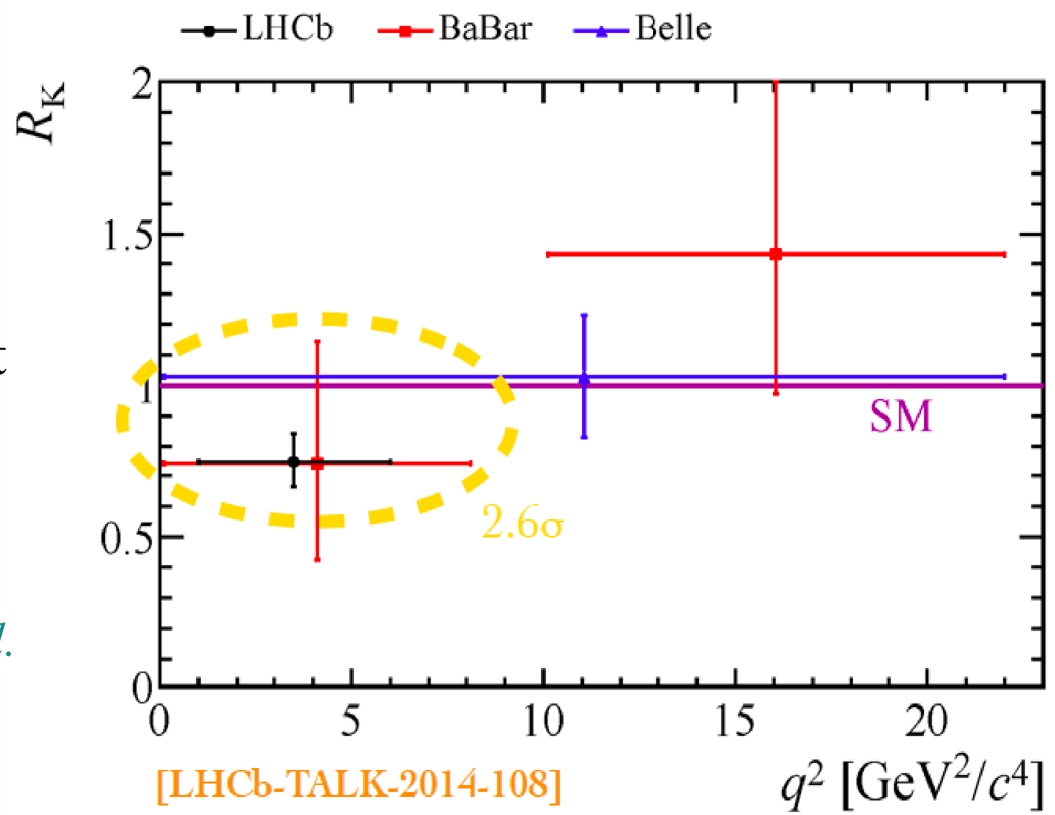
- NP contributions to C_9 give best description of the data
- (NP with $C_9 = -C_{10}$ works almost equally well)

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

Last but not least, a 2.6σ deviation from the SM is observed also in the LFU ratio

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

[1-6] GeV²



[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.

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

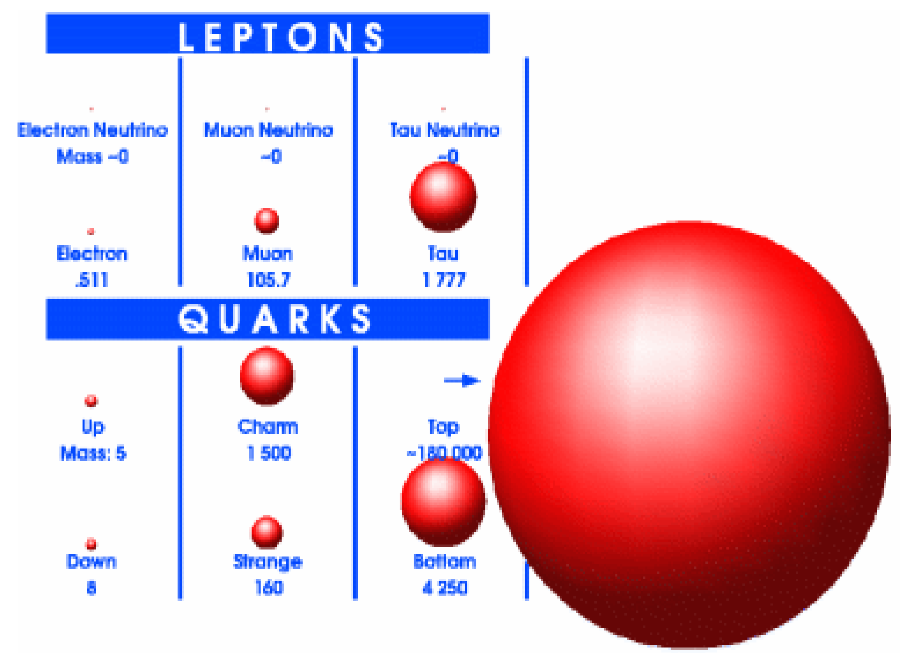
Most interesting aspect: possible breaking of LFU, both in charged currents ($b \to c\tau\nu$ vs. $b \to c\mu\nu$) and in neutral currents ($b \to s\mu\mu$ vs. $b \to see$)

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 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

(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 most attempts based on EFT approaches and focused only on semi-leptonic operators [quark×lepton]

Want I will discuss today is a proposal to describe all these effect within a simplified 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:

Greljo, GI, Marzocca '15

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

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

▶ A "prototype data-inspired" model:

Greljo, GI, Marzocca '15

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

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

- 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
- correlation between low-energy and high-energy physics

A "prototype data-inspired" model:

Greljo, GI, Marzocca '15

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

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

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

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

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

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

A "prototype data-inspired" model:

A closer look to the flavor structure of the model:

$$J_\mu^a = g_q \lambda_{ij}^q \left(\bar{Q}_L^i \gamma_\mu T^a Q_L^j \right) + g_\ell \lambda_{ij}^\ell \left(\bar{L}_L^i \gamma_\mu T^a L_L^j \right)$$

→ 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

Barbieri *et al.* '11

Connection to CKM matrix in the quark sector:

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

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

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

down-type mass basis

$$\epsilon \lesssim 1$$

▶ *Effects in charged currents:*

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

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

Effects in charged currents:

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

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

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 surprisingly it is not so stringent ($|\lambda_{\mu\mu}| \lesssim 0.1$) $\to$ *no dedicated studies @ B-facotries !*

▶ *Effects in charged currents:*

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

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

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 surprisingly it is not so stringent ($|\lambda_{\mu\mu}| \lesssim 0.1$) $\to$ *no dedicated studies @ B-facotries !*

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

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

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

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

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

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

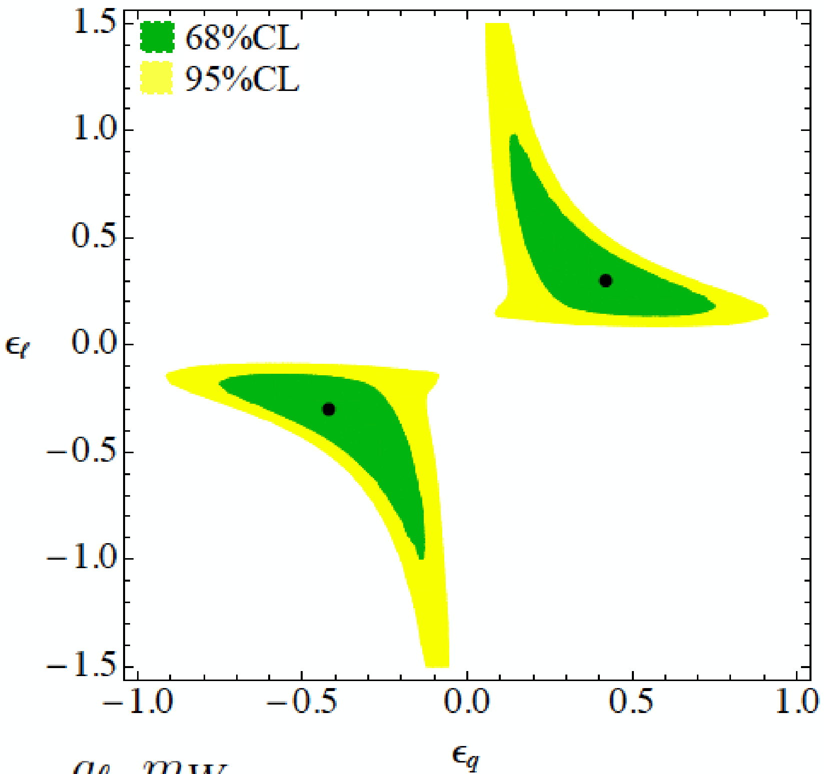
↓

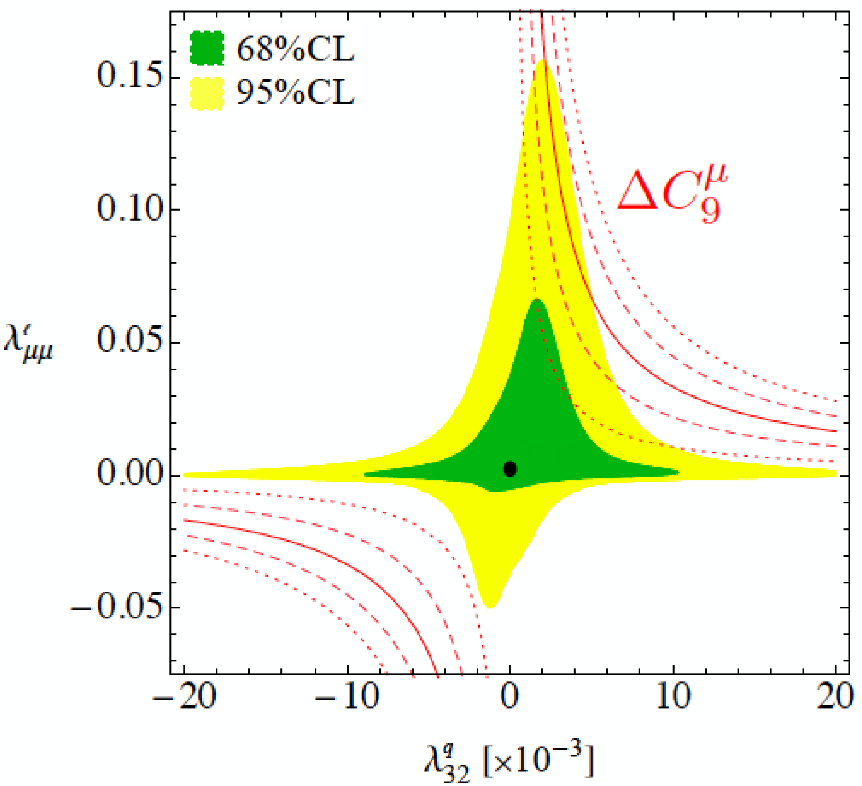
Overall good fit of low-energy data
(*non-trivial given tight constraints from ΔF=2 & LFV*)

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:





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

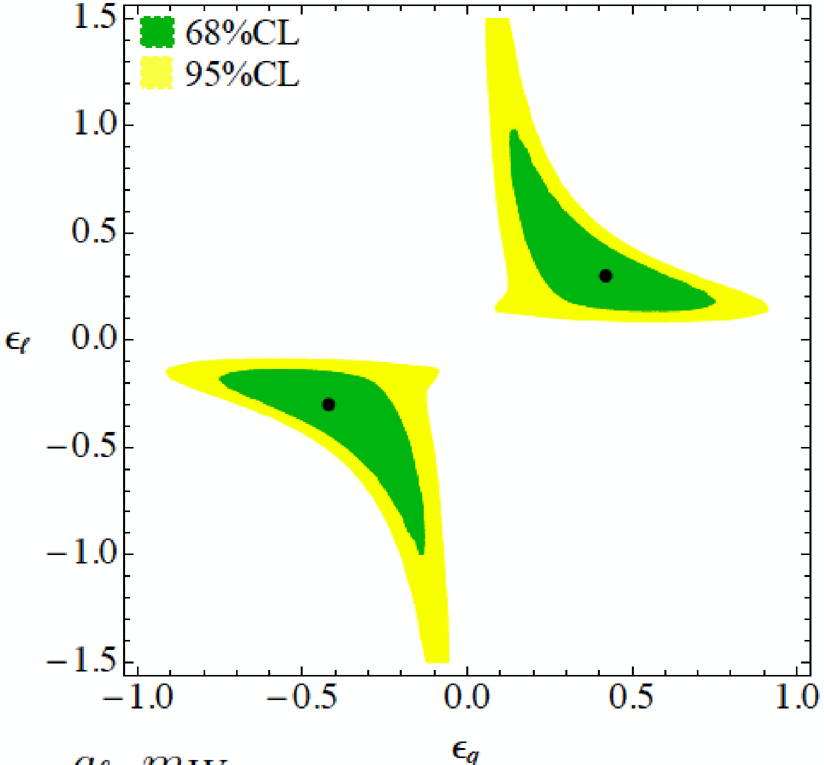
$\varepsilon_\ell, \varepsilon_q \lesssim 1$

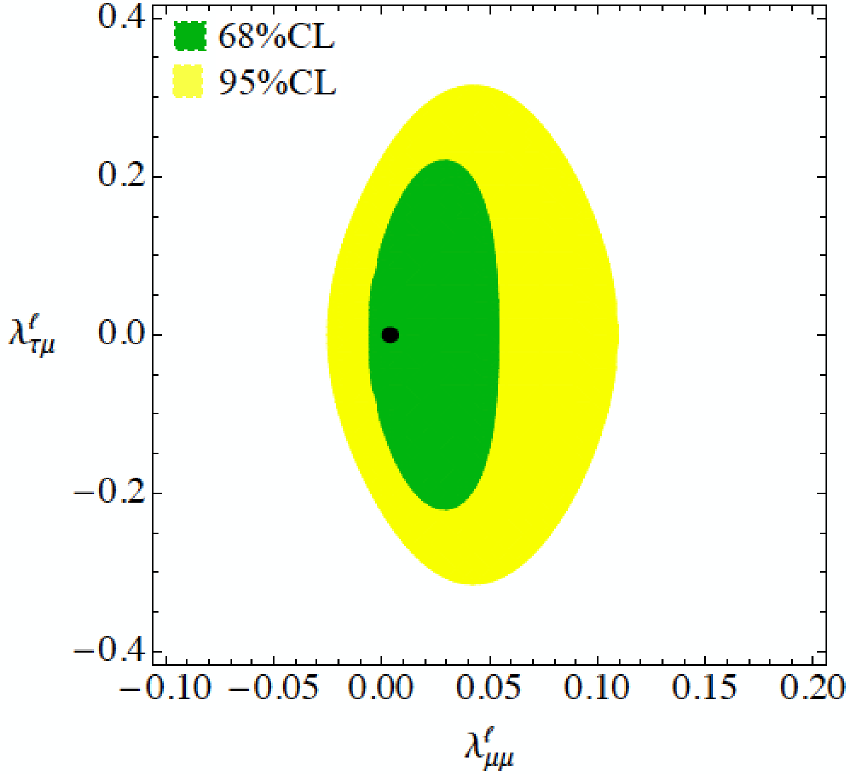
$\lambda_{\mu\mu} \lesssim 0.1$

$\lambda_{bs} \lesssim 0.015$

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

▶ *Global fit to low-energy data:*





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

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

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

$\lambda_{bs} \lesssim 0.015$

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

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:

- $b \to c\, l\nu$ $\qquad R_D^{\tau/\ell} = R_{D*}^{\tau/\ell} \qquad R_D^{\mu/e} \lesssim 10\% R_D^{\tau/\ell}$
- $b \to s\, \mu\mu$ $\qquad \Delta C_9^\mu = -\Delta C_{10}^\mu$ overall size of the anomaly should decrease
- $b \to s\, \tau\tau$ $\qquad$ |NP| ~ |SM| $\to$ either large (~4) enhancement or strong suppression
- Meson mixing $\qquad$ ~ 10% deviations from SM both in ΔM_{Bs} & ΔM_{Bd}
- τ decays $\qquad \tau \to 3\mu$ close to 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:

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

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

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

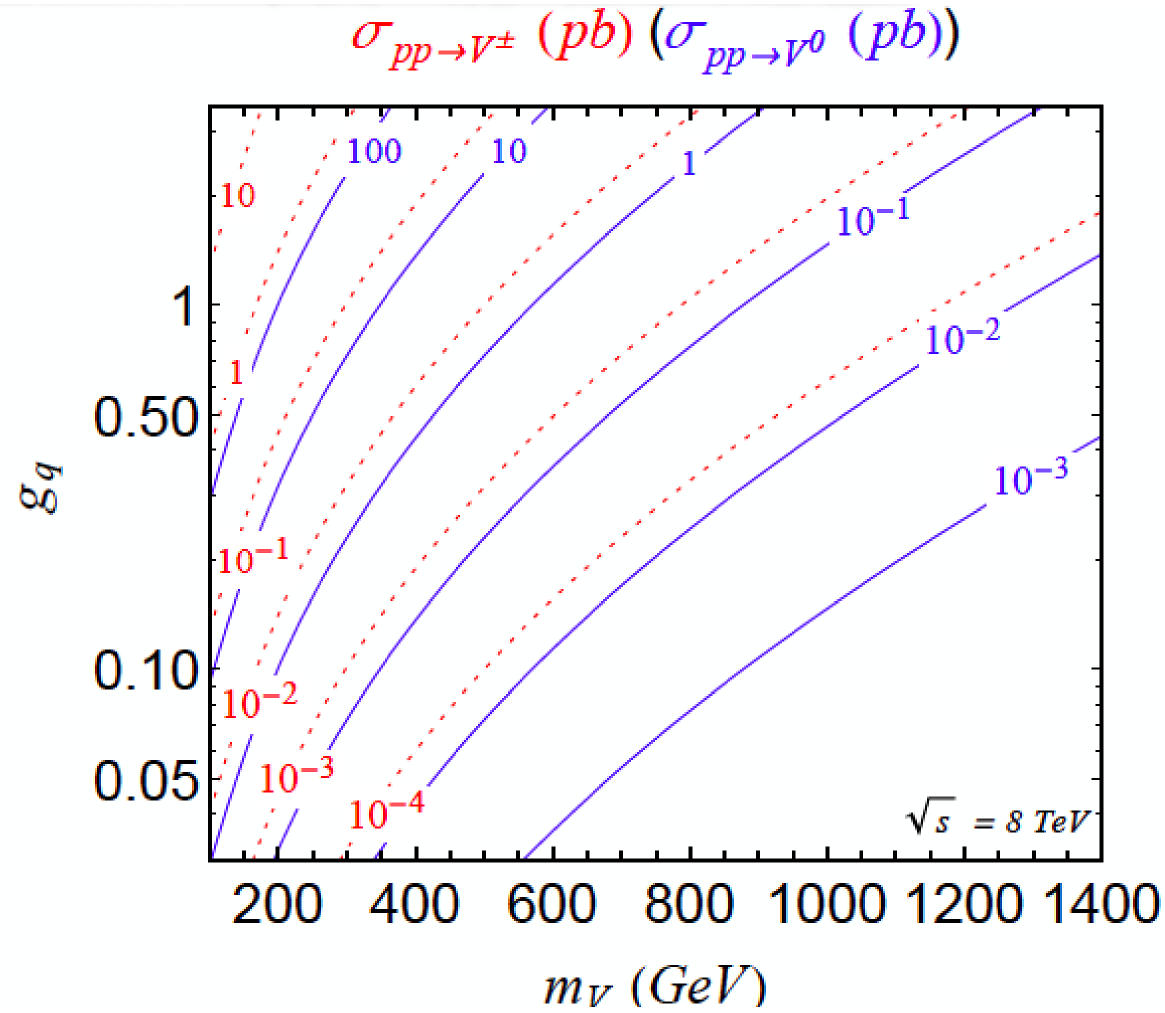
$$\epsilon_{\ell,q} = \frac{g_{\ell,q} m_W}{g m_V} \approx 0.3 \qquad\qquad \epsilon_H = \frac{g_H m_W}{g m_V} \lesssim 0.01$$

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...



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)

↓

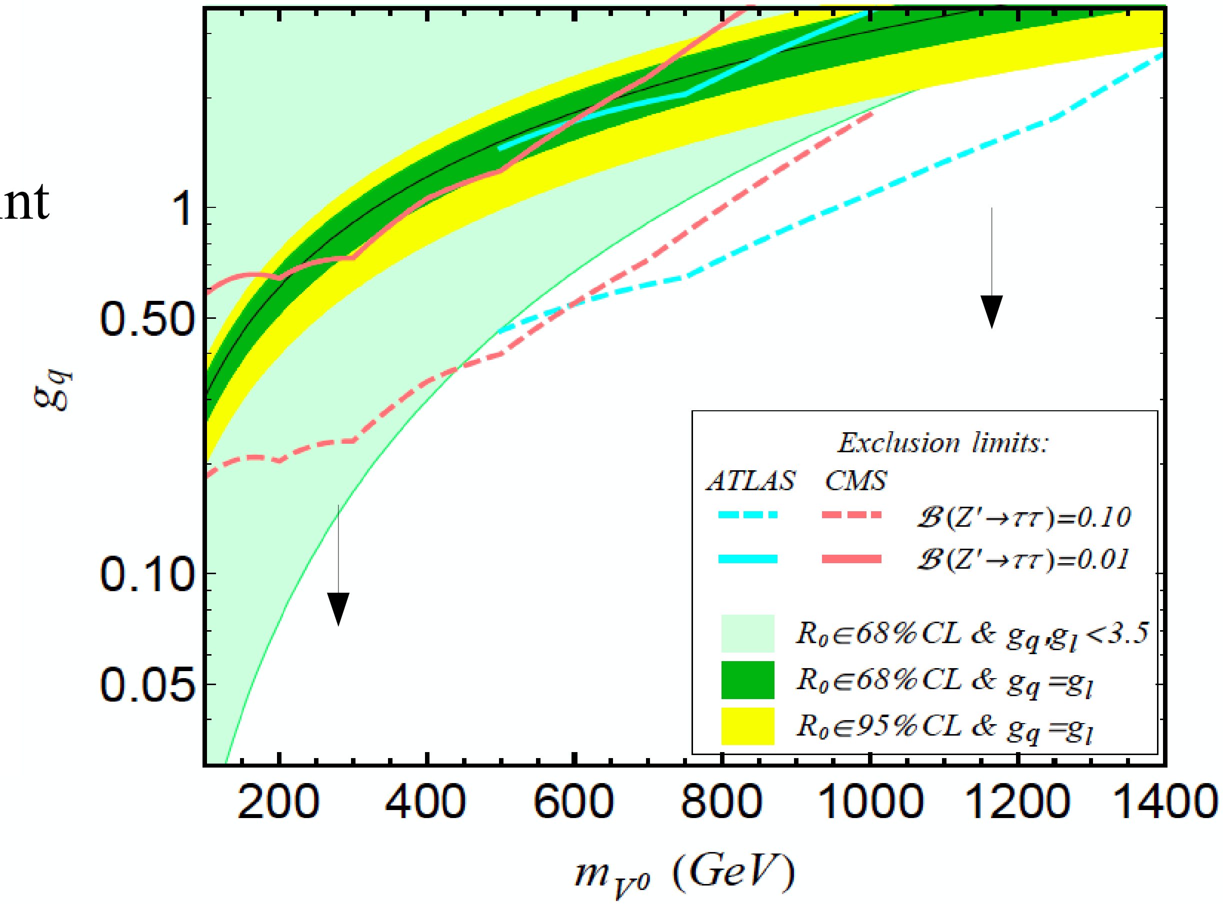
- Not a very easy signature...

The only really stringent constraint comes from Z' → ττ

↓

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

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

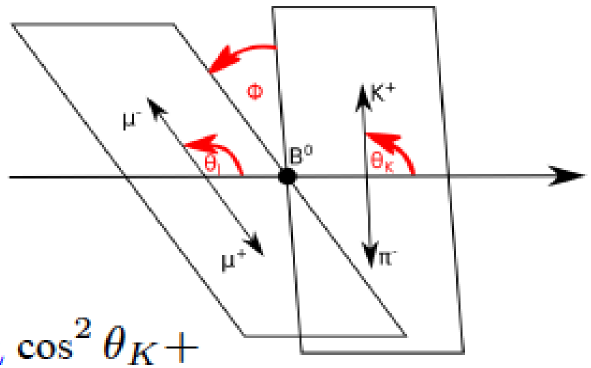


Conclusions

- 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


Backup

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



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

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