Theoretical considerations on low-energy physics

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- Introduction
- Some interesting, intriguing, new results
- Speculations on the breaking of Lepton Flavor Universality
- Conclusions

Introduction

Introduction

Despite all its successes, the SM is likely to be an *effective theory*, i.e. the limit -*in the experimentally accessible range of energies and effective couplings*- of a more fundamental theory, with new degrees of freedom

We need to search for New Physics with a broad spectrum perspective given the lack of clear indications on the SM-EFT boundaries (*both in terms of energies and effective couplings*)

↓

Twofold role of low-energy physics

[*flavor-changing processes, EDMs, anomalous magnetic moments*]

↙ ↘

- Identify symmetries and symmetry-breaking patterns beyond those present in the SM
- Indirect probe of physics at energy scales not directly accessible at accelerators

Introduction

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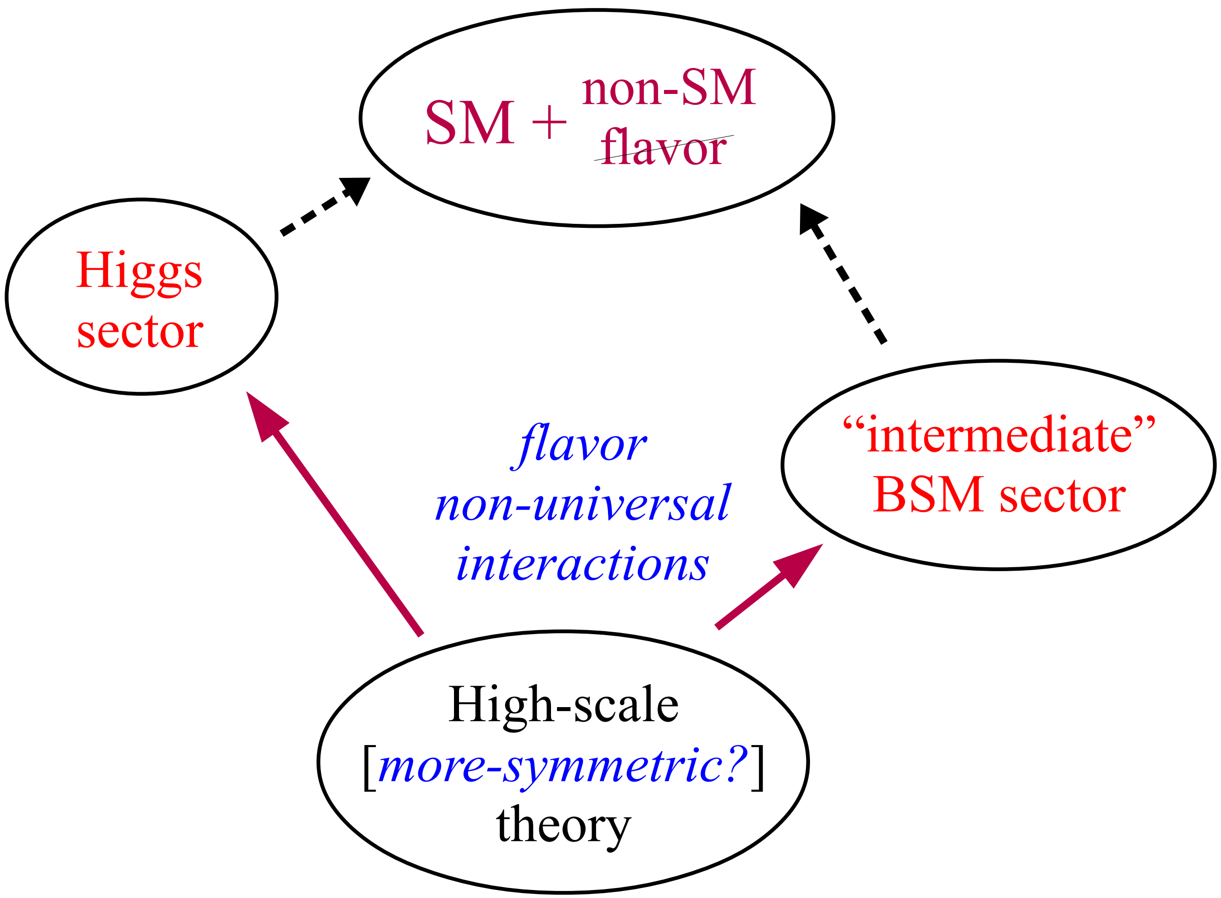
- Probe physics at energy scales not directly accessible at accelerators



Two key open questions:

- *Are there other sources of flavor symmetry breaking?*
- *What determines the observed pattern of quark & lepton mass matrices?*

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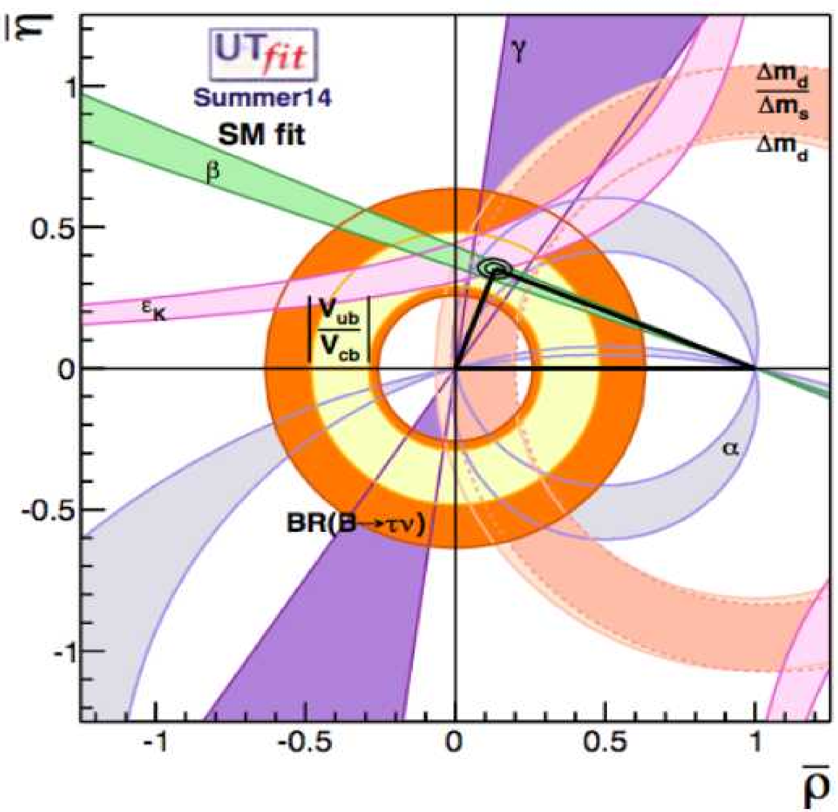
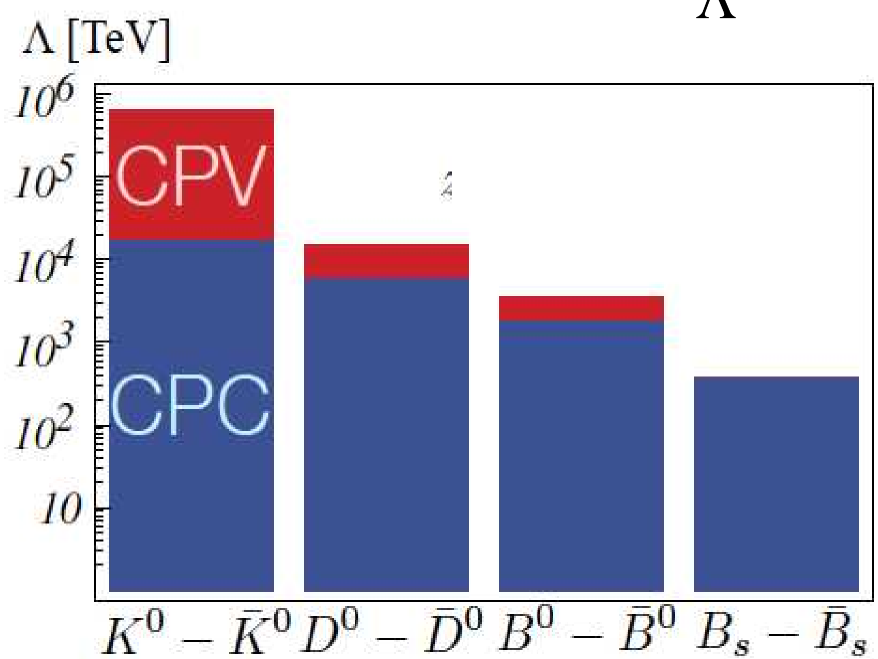
That's the question addressed by precision measurements (& searches) of flavor-changing processes of quarks & charged-leptons → So far everything seems to fit well with the SM→ Strong limits on NP



→

$$\mathscr{L}_{\text{eff}} = \mathscr{L}_{\text{SM}} + \frac{1}{\Lambda^2} O_{\Delta F=2}$$



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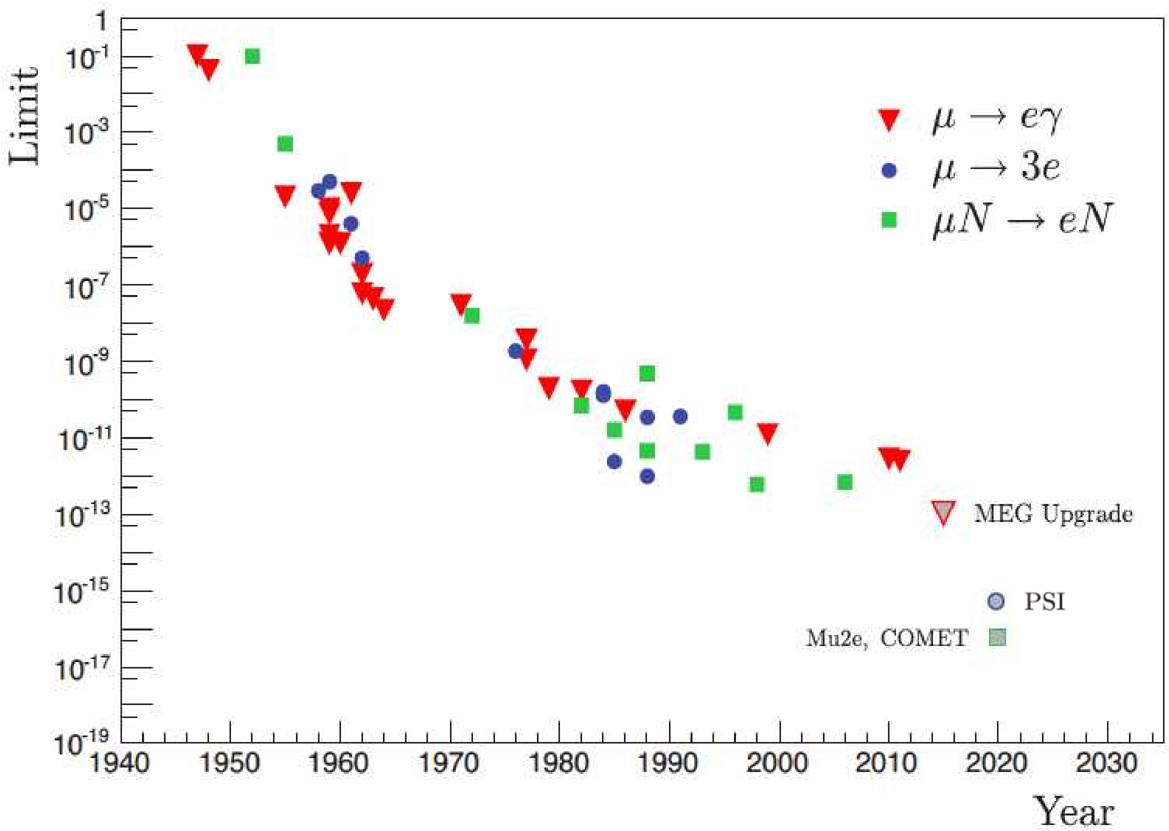

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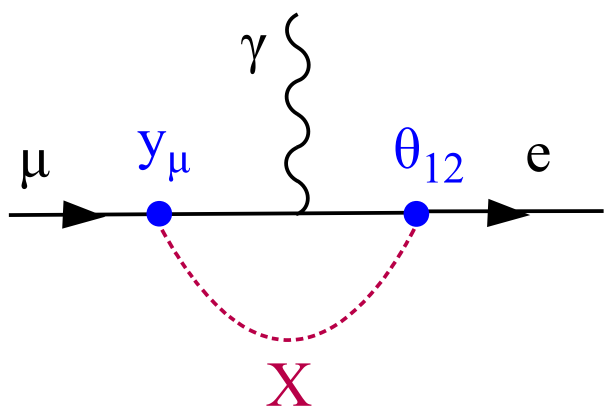
E.g.:



$$BR(\mu\to e\gamma)^{exp} < 5.7\times10^{-13}$$

MEG '13

$$M_X \gtrsim 200\ \text{TeV}$$

Either NP is <u>very heavy</u>...

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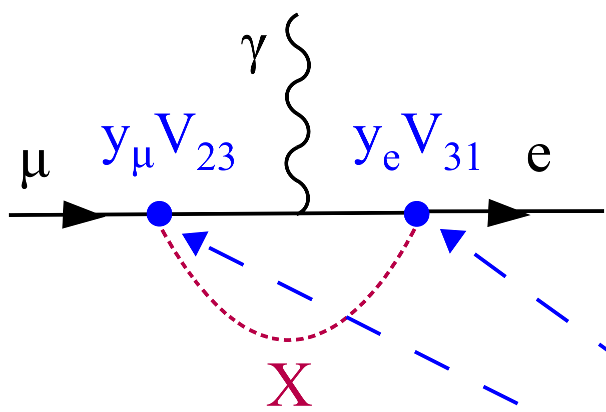

$BR(\mu\to e\gamma)^{exp} < 5.7\times10^{-13}$

MEG '13

$M_X \gtrsim 10$ GeV

Either NP is very heavy... or it has a non-trivial flavor-breaking pattern...

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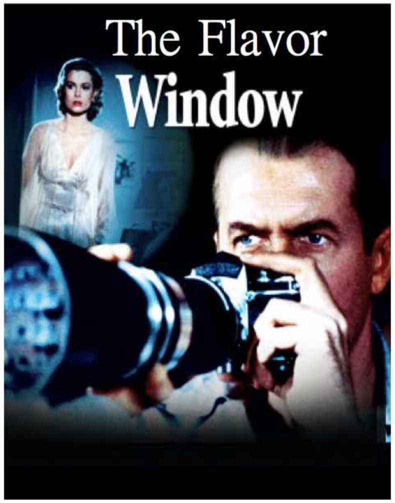
Either NP is very heavy... or it has a non-trivial flavor-breaking pattern...

There is still a wide (*possibly interesting...*) region of NP parameter space (*both in masses and couplings*) that is waiting to be explored yet...



Some interesting, intriguing, new results
[*on semi-leptonic B decays*]

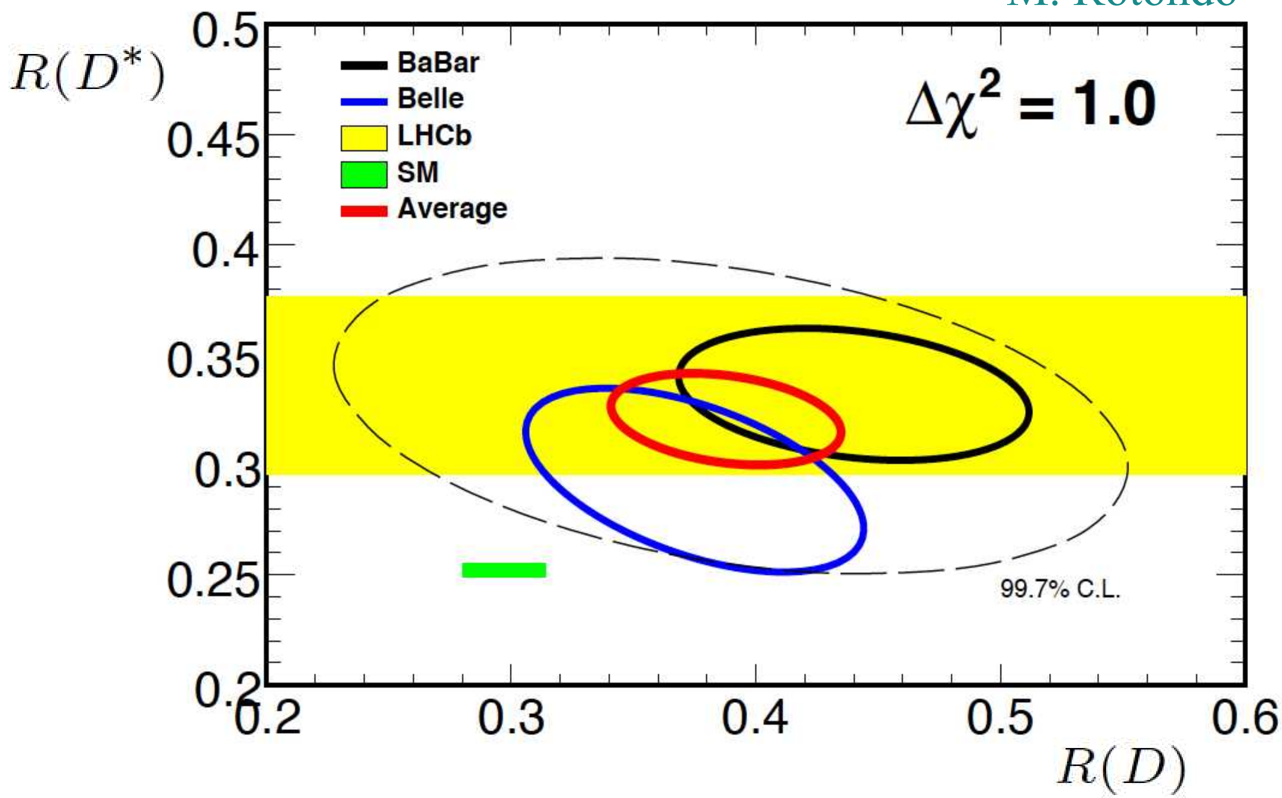
I. B → D$^{(*)}$ τν [LHCb, Belle]

Test of LFU in charged curr.:
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	$0.440 \pm 0.058 \pm 0.042$	$0.332 \pm 0.024 \pm 0.018$
Belle	$0.375^{+0.064}_{-0.063} \pm 0.026$	$0.293^{+0.039}_{-0.037} \pm 0.015$
LHCb		$0.336 \pm 0.027 \pm 0.030$
Average	0.388 ± 0.047	0.321 ± 0.021
SM expectation	0.300 ± 0.010	0.252 ± 0.005

M. Rotondo



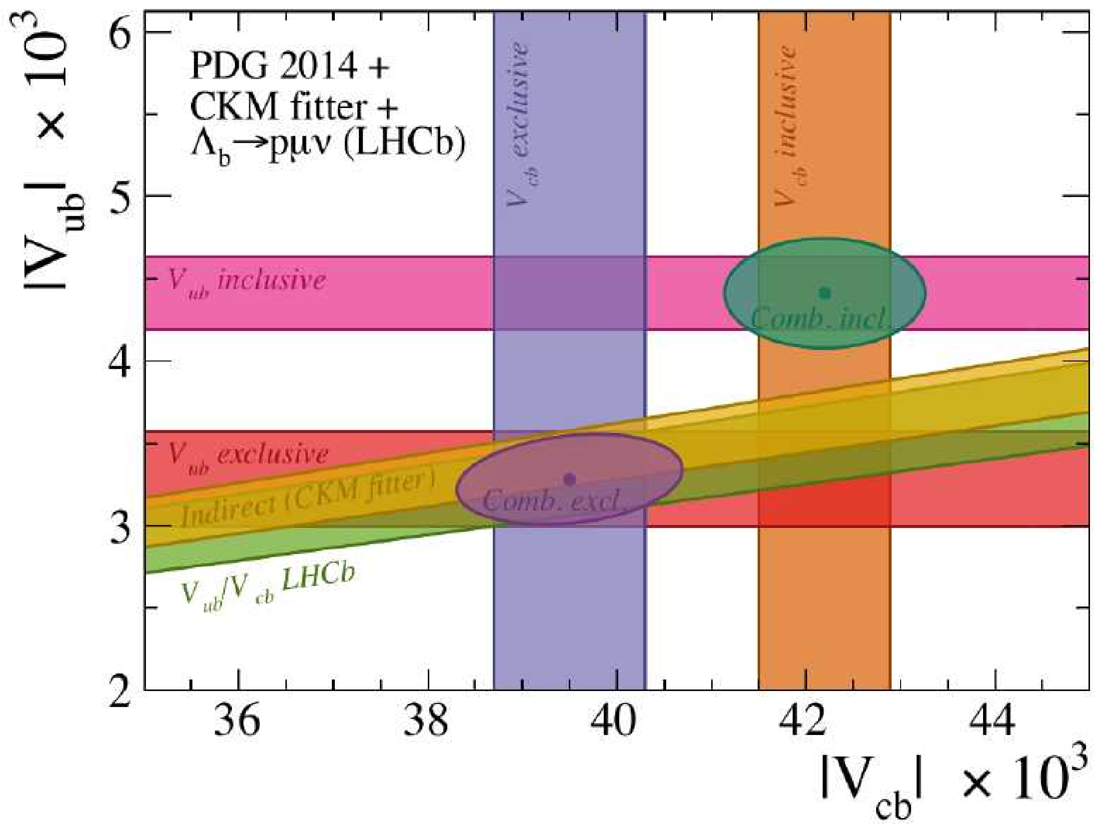
- SM prediction quite solid (f.f. cancel in the ratio)
- Consistent exp. results by the 3 experiments
- 4σ excess over SM

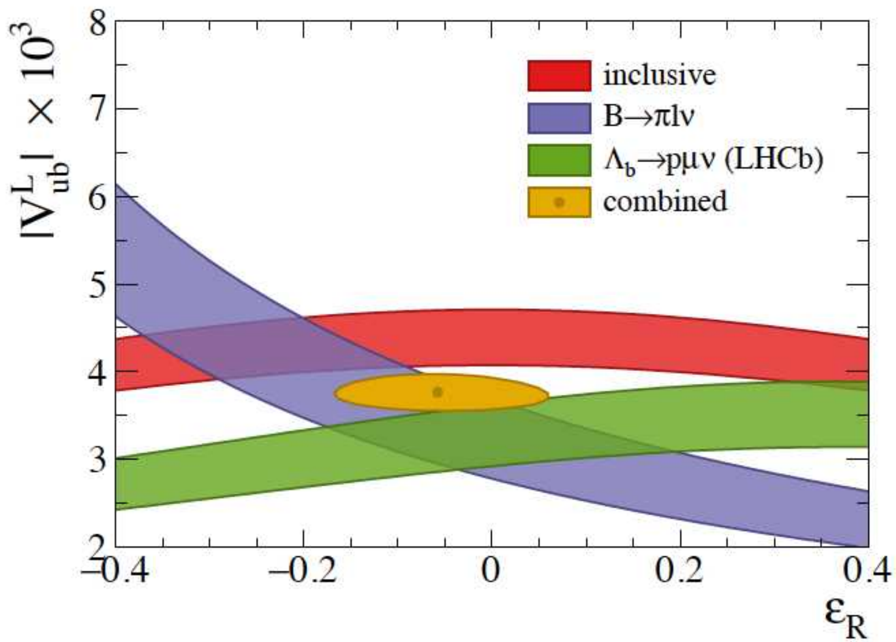
II. $|V_{ub}/V_{cb}|$ from $B(\Lambda_b \to p\mu\nu)/B(\Lambda_b \to \Lambda_c\mu\nu)$ [LHCb]

T. Gershon

Very different th. & exp. error compared to other available data on $|V_{ub}|$ & $|V_{cb}|$

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



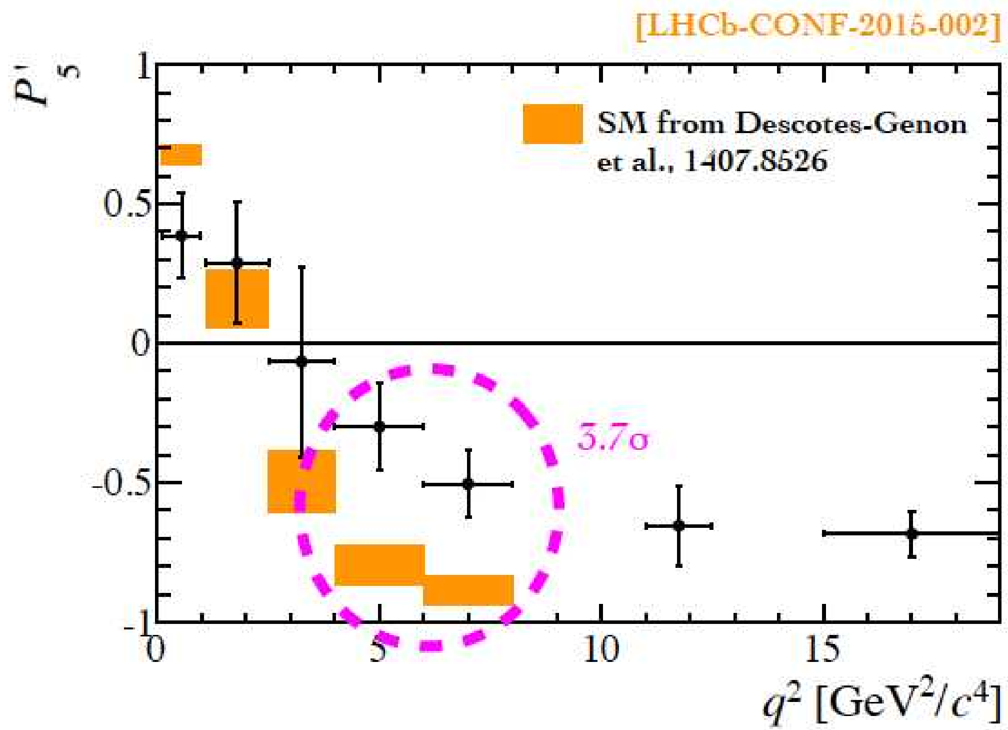


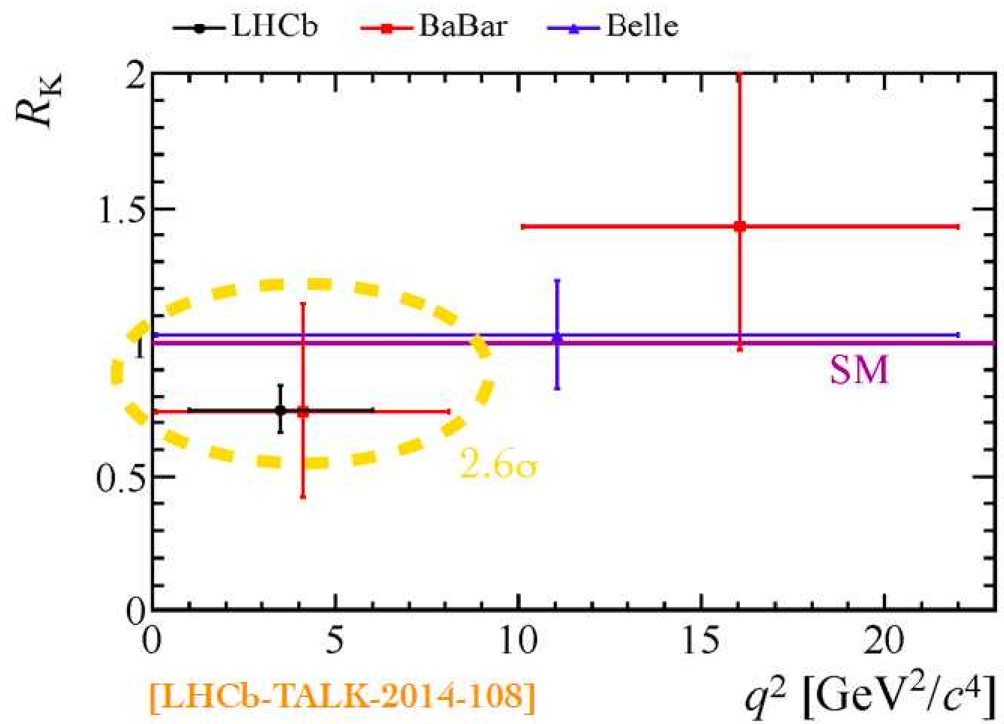
- Consistent with other exclusive data
- Increased tension between excl. & incl.
- Rules out RH curr. as possible explanation

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

- Deviations from SM in kin. distrib. [P_5' & others] and overall rates in $B \to K^{(*)}\mu\mu$
  - Not easy to precisely determine th. erorr due to charm rescattering
  - Good fit with specific NP short-distance operators ($bs\mu\mu$)

- Deviations from SM in $R_K = B(B \to K\mu\mu)/B(B \to K\,ee)$
  - Negligible th. error → clean test of LFU in neutral currents
  - Consistent fit with same NP as above (only in μ channel)





Speculations on the breaking of Lepton Flavor Universality

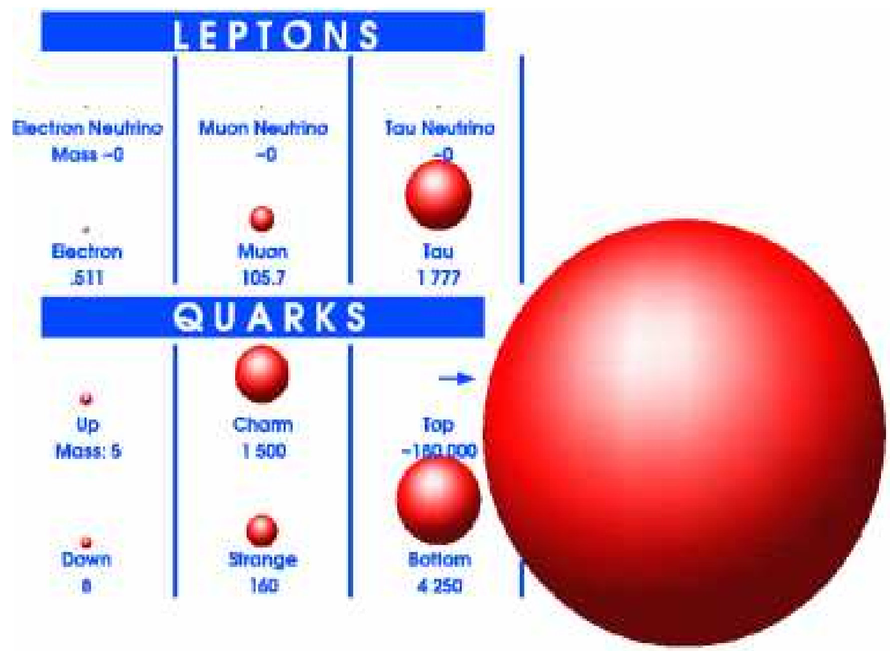
Speculations on the breaking of LFU

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 ($\to$ gauge sector)
- Most stringent tests of LFU involve only 1st-2nd gen. quarks & leptons



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

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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]

Very recent 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

Greljo, GI, Marzocca '15

Speculations on the breaking of LFU

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

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

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

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

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- 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*)

Speculations on the breaking of LFU

Global fit of 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
- $P_5'(B \to K^*\mu\mu)$

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

$\Downarrow$

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

Best fit point: $\epsilon_\ell \approx 0.37\ , \quad \epsilon_q \approx 0.38$

$\lambda^q_{bs} \approx 2.3 \times 10^{-3}\ , \quad \lambda^\ell_{\mu\mu} \approx 2.0 \times 10^{-2}\ , \quad \lambda^\ell_{\tau\mu} \approx 4.8 \times 10^{-2}$ $\quad p(\mathrm{SM}) = 0.002$

Speculations on the breaking of LFU

Several clear predictions for future low-energy data:

- $b \to c\, l\nu$ $R_D^{\tau/\ell} = R_{D*}^{\tau/\ell}$ $R_D^{\mu/e} \lesssim 10\% R_D^{\tau/\ell}$
- $b \to s\, \mu\mu$ $\Delta C_9^\mu = -\Delta C_{10}^\mu$ overall size of the anomaly should decrease
- $b \to s\, \tau\tau$ |NP| ~ |SM| → either large (~4) enhancement or strong suppression
- Meson mixing ~ 10% deviations from SM both in ΔM_{Bs} & ΔM_{Bd}
- τ decays $\tau \to 3\mu$ close to present exp. bound
- $\mu \to 3e$ no firm prediction (1st family), but potentially more interesting than $\mu \to e\gamma$

Speculations on the breaking of LFU

High-energy signatures of the simplified model:

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

$$g_{\ell,q} \sim 1 \ \to m_V \sim 250\text{GeV}$$
$$g_{\ell,q} \sim \sqrt{4\pi} \ \to m_V \lesssim 1\text{TeV}$$

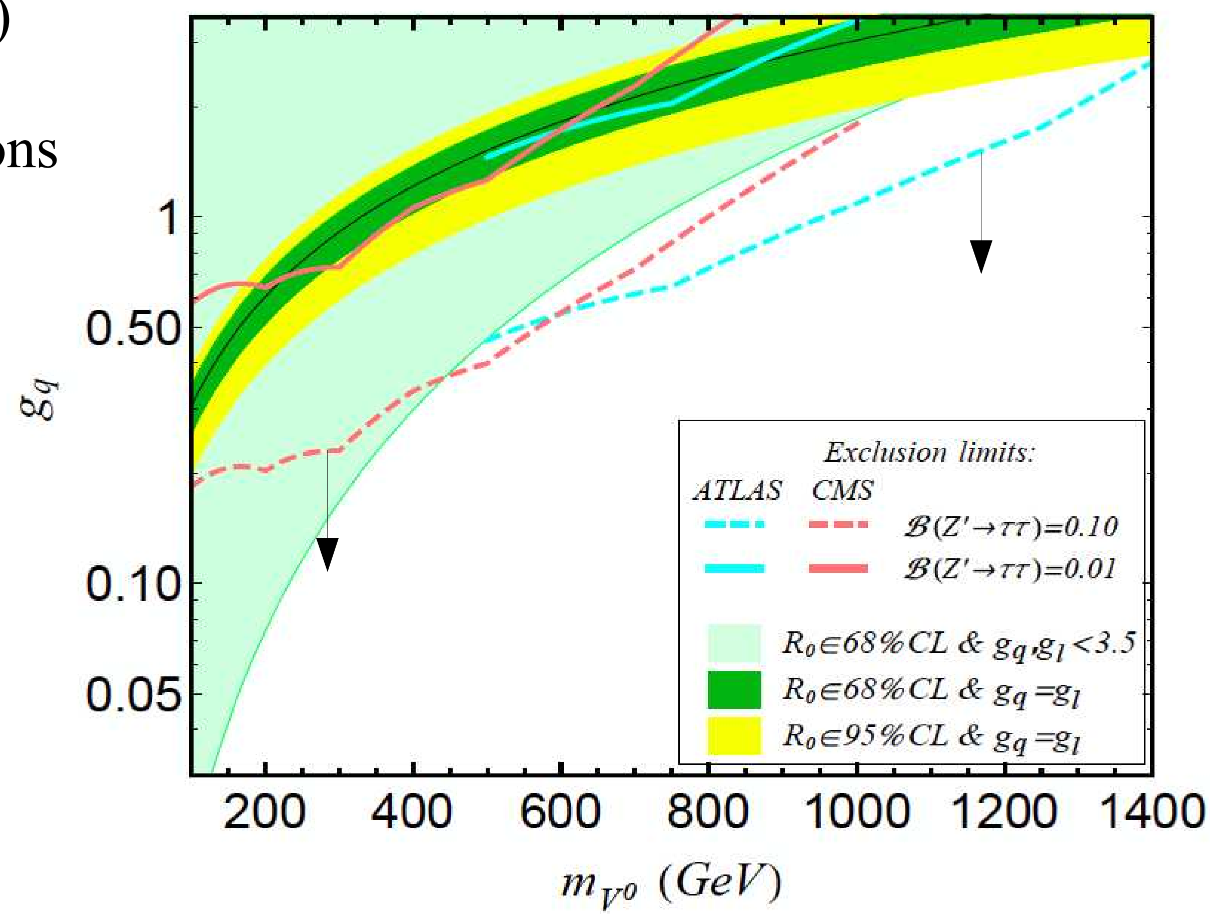
- Produced mainly from 3rd gen. quarks (bb → Z', bc → W', bb → W' tt)
- Decaying mainly in 3rd generations quarks or leptons

↓

Most stringent constraints from Z' → ττ

↓

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



Conclusions

- Low-energy physics represent a "unique window" on BSM physics → *There is still a lot to learn & explore, also in view of HL-LHC.*
- Intriguing hints of LF non Universality in recent semi-leptonic B decay 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

Heavy Vector Triplet

These 4-fermion operators can naturally be generated by integrating out a heavy Vector Boson, triplet of SU(2)$_L$:

[Pappadopulo, Thamm, Torre, Wulzer 1402.4431]

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

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

Coupling to the Higgs current

The dimension-6 operators obtained by integrating it out are:

$$\mathcal{L}_{\text{eff}}^{d=6} = \boxed{-\frac{1}{2m_V^2} J_\mu^a J_\mu^a} - \boxed{\frac{g_H^2}{2m_V^2} (H^\dagger T^a i \overleftrightarrow{D}_\mu H)(H^\dagger T^a i \overleftrightarrow{D}_\mu H)} - \boxed{\frac{g_H}{m_V^2} (H^\dagger T^a i \overleftrightarrow{D}_\mu H) J_\mu^a}$$

4-fermion op. $\quad$ Z, W masses, hVV couplings $\quad$ Zff and $Zhff$ couplings

Possible solution to V_{ub} & V_{cb} puzzle?

Processes of the kind $\quad \bar{B} \to X_{c(u)}\, \tau\, \bar{\nu}$

$$\tau \to \ell\, \nu\, \bar{\nu}$$

are are part of the background for the inclusive analysis $\quad \bar{B} \to X_{c(u)}\, \ell\, \bar{\nu}$

Presently this is taken into account by assuming SM rates.

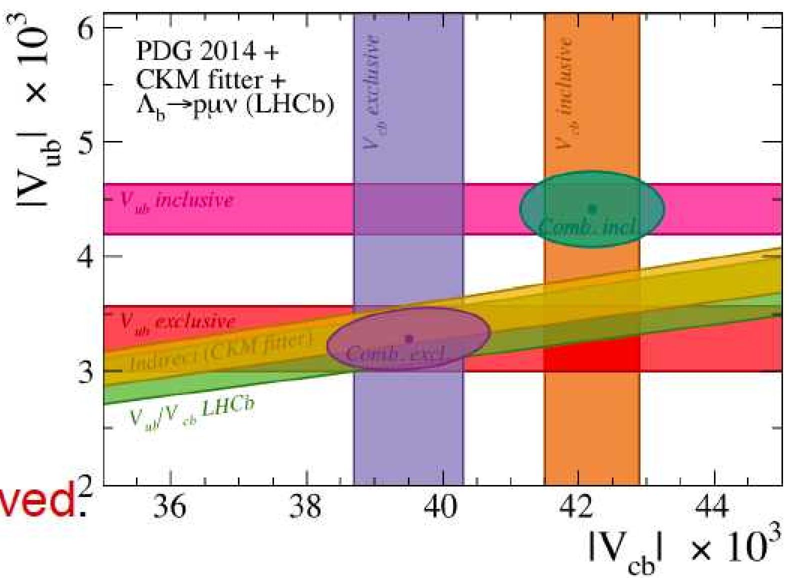
An excess in $\bar{B} \to D^{(*)}\, \tau\, \bar{\nu}$

↓

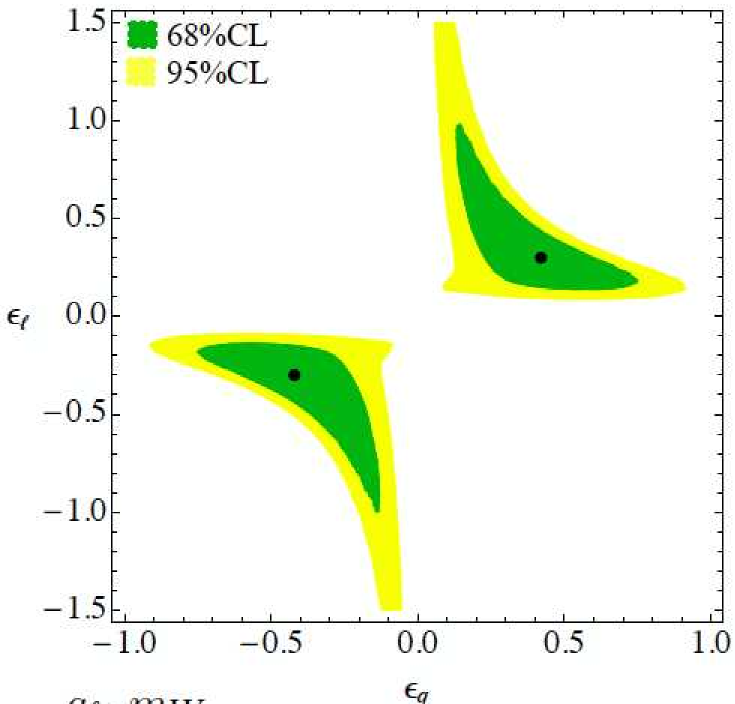
higher event rate

↓

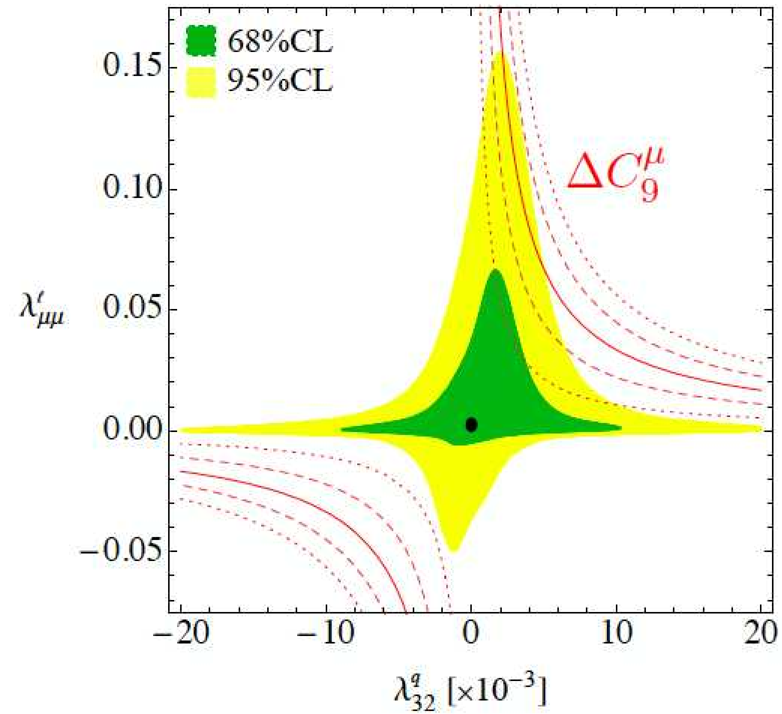
higher value of $V_{c(u)b}$ extracted, as observed?



Fit of the model



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



ε_ℓ, $\varepsilon_q \lesssim 1$

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

$\lambda_{bs} \lesssim 0.015$

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

Direct Searches

Most relevant couplings: $Z'_\mu \, \overline{b}_L \gamma^\mu b_L$, $Z'_\mu \, \overline{t}_L \gamma^\mu t_L$,
$Z'_\mu \, \overline{\tau}_L \gamma^\mu \tau_L$, $Z'_\mu \, \overline{\nu}_\tau \gamma^\mu \nu_\tau$

$W'_\mu \, \overline{\tau}_L \gamma^\mu \nu_\tau$, $W'_\mu \, \overline{t}_L \gamma^\mu b_L$, $V_{cb} W'_\mu \, \overline{c}_L \gamma^\mu b_L$

Production cross section

Z' via bb

W' via cb
suppressed by V_{cb}

No meaningful bound.