University of Zurich[UZH]

Searching for New Physics in rare B decays

[Future opportunities in leptonic & semi-leptonic B (and τ) decays]

Gino Isidori
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- Introduction [*Where do we stand in the search for NP?*]
- The (still relevant) role of $B_{s,d} \to \mu\mu$
- The "new frontier": Lepton Flavor Universality
- Conclusions

Introduction (Where do we stand in the search for NP?)

The 1st run of the LHC has tested the validity of the SM in an un-explored range of energies, finding no significant deviations. The key results of the 1st LHC run can be summarized as follows:

- The Higgs boson (= last missing ingredient of the SM) has been found
- The Higgs boson is "light" ($m_h \sim 125$ GeV $\rightarrow$ not the heaviest SM particle)
- There is a "mass-gap" above the SM spectrum (i.e. no unambiguous sign of NP up to ~ 1 TeV)

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- There is a "mass-gap" above the SM spectrum (i.e. no unambiguous sign of NP up to ~ 1 TeV)

This is perfectly consistent with the (pre-LHC) indications coming from indirect NP searches (EWPO + flavor → light Higgs + mass gap above SM spectrum).

But all the problems of the SM (hierarchy problem, flavor pattern, dark-matter, U(1) charges,…) are still unsolved → the motivation for NP still there (even stronger than before....)

The key questions (*as in the pre-LHC era*) are:

- How large is the "mass gap"?
- Can we expect a non-minimal flavor pattern?

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...but the situation is changing rapidly thanks to a small DOSE (*Diphoton Over-excitement for a Small Excess*) of Run-II data and the "BURP" (*B-physics Under-estimated Rays of new Physics*) from the digestion of Run-I !

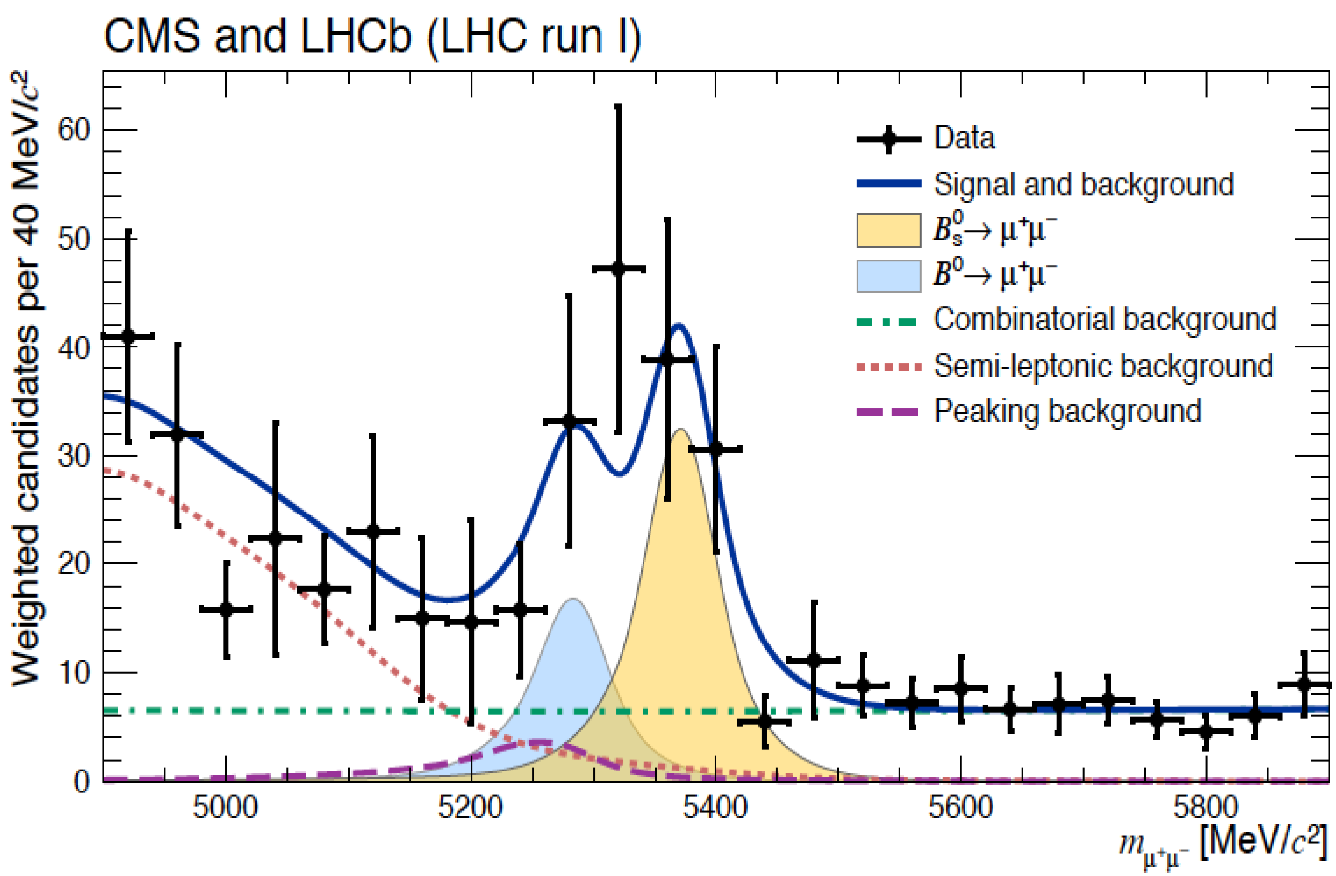
Jokes, apart:

- Direct bounds on NP exceed ~ 1 TeV only for new states colored and/or strongly coupled to 1st & 2nd generation of quarks
- Similarly, the tight indirect bounds from flavor physics always involve transitions with 1st & 2nd generation of quarks & leptons

⬇

NP models with (relatively) light NP and where 3rd generation of quarks & leptons have a special role are (still) very well-motivated → interplay of flavor-physics and high-pT physics extremely important → LFU studies are crucial !

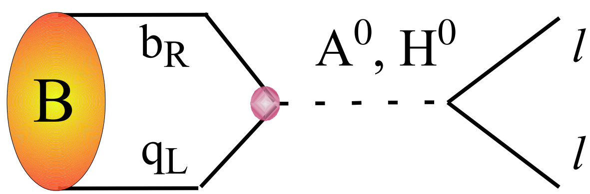
The role of $B_{s,d} \to \mu\mu$



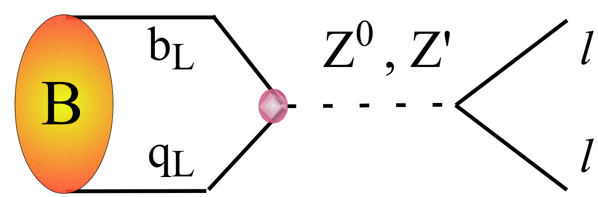
▶ *The (still relevant) role of $B_{s,d} \to \mu\mu$*

The whole set of $B_{s,d} \to l^+l^-$ decays (6 modes) remains a unique source of information about flavor physics beyond the SM:

- theoretically very clean (virtually no long-distance contributions)
- particularly sensitive to FCNC *scalar currents* and FCNC *Z penguins*



Possible large enhancements
(by now excluded by present data)



Relevant for BR = O(SM)

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-)_{\rm SM} = (3.66 \pm 0.23) \times 10^{-9}$$

Present th. error ~ 6%

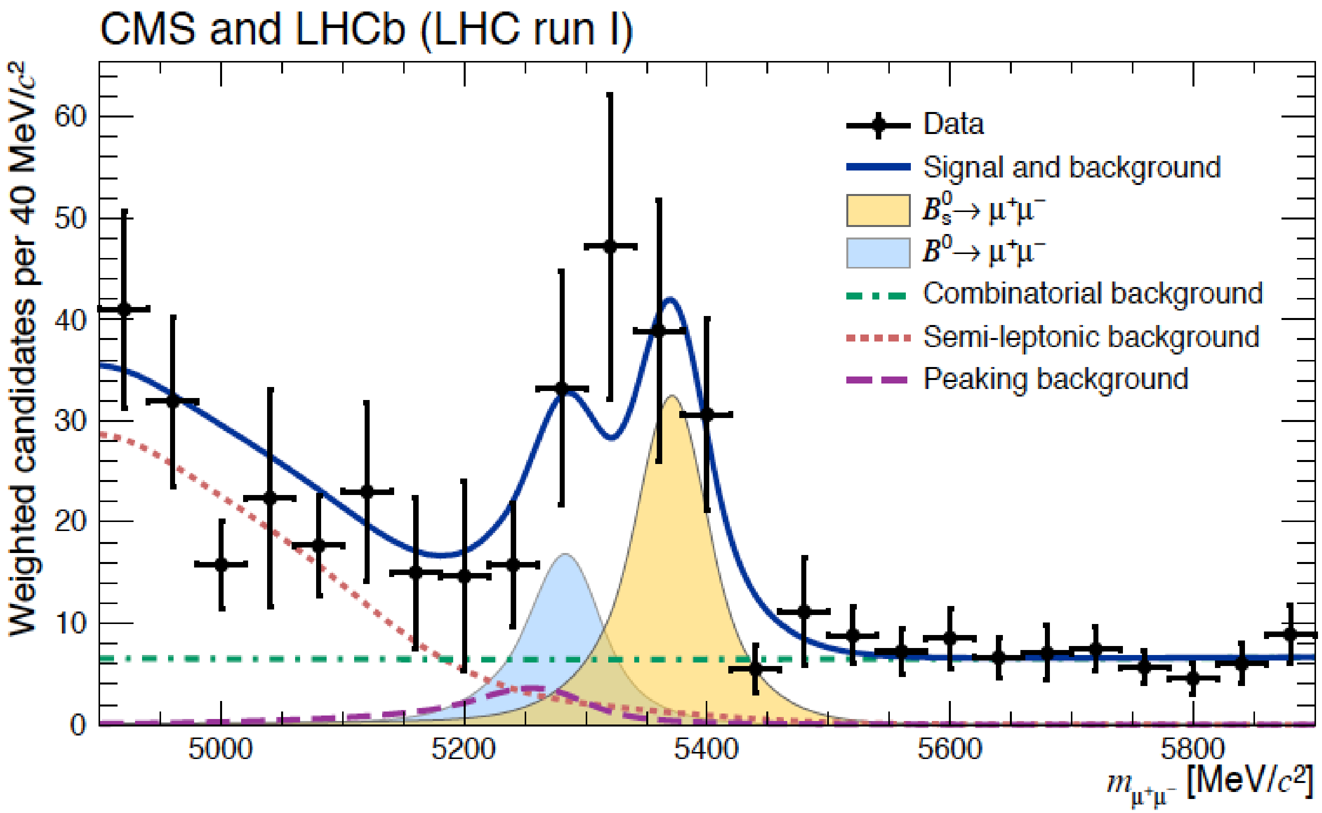
↓

likely to decrease to 2-3% in ~5 years (f_B from Lattice)

e channels suppressed by $(m_e/m_\mu)^2$

τ channels enhanced by $(m_\tau/m_\mu)^2$

▶ The (still relevant) role of $B_{s,d} \to \mu\mu$



At present there is perfect compatibility with the SM, but there is still large room for NP

N.B.: the allowed room for NP is ~ size of the effect observed in P_5' → fit of P_5' anomaly with $C_9=-C_{10}$ (pure left-handed interaction) works very well

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-)_{\rm SM} = (3.66 \pm 0.23) \times 10^{-9}$$

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.8\,^{+0.7}_{-0.6}) \times 10^{-9}$$

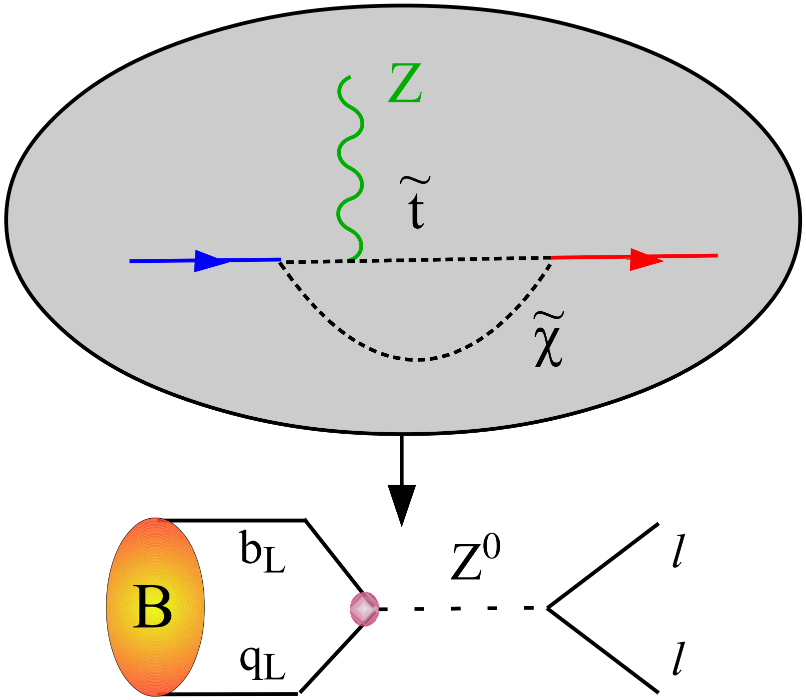
LHCb + CMS

The (still relevant) role of $B_{s,d} \to \mu\mu$

The fact we don't see large enhancements over the SM in $B_s \to \mu\mu$ does not mean the six $B_{s,d} \to ll$ decay modes are becoming less interesting.... !

We simply excluded scenarios with large scalar FCNC's, and we entered into a regime where different type of amplitudes (Z-penguins, Z', …) can affect these decays

E.g.: SUSY with relatively light stops (still allowed) and "disoriented A terms"



Possible O(±30%) corrections to the BR

Behring, Gross, Hiller, Schacht '12

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We simply excluded scenarios with large scalar FCNC's, and we entered into a regime where different type of amplitudes (Z-penguins, Z', …) can affect these decays → the good TH control over the BRs could allow to explore these scenarios in great detail with more statistics

⬇

No doubt these mode will be interesting in the future.
What is less clear is the outcome of the "competition" between LHCb and CMS (on $B_{s,d} \to \mu\mu$) in a high-lumi perspective

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Present th. error ~ 6% likely to decrease to 2-3% in ~5 years (f_B from Lattice)

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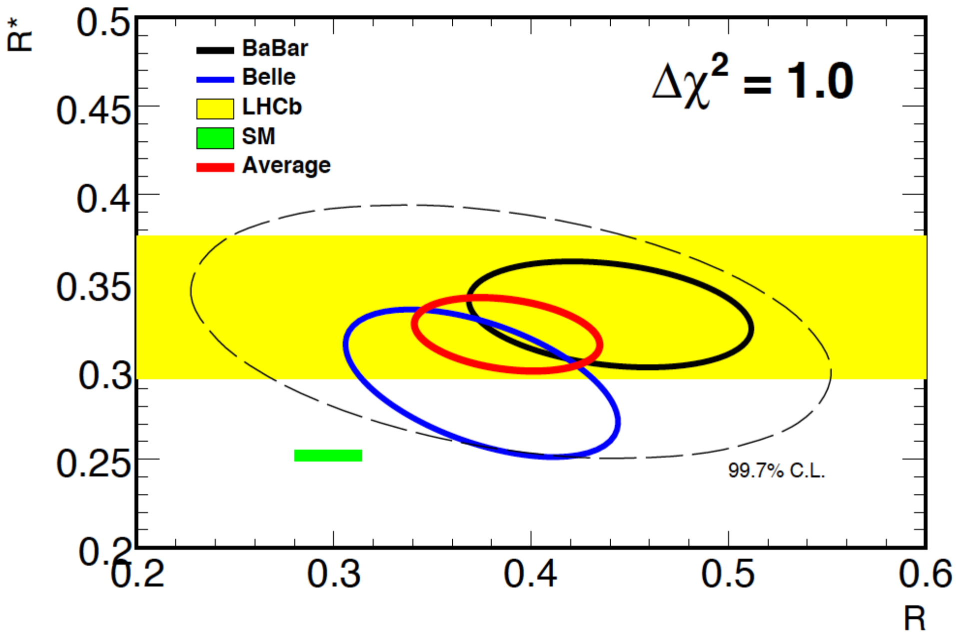
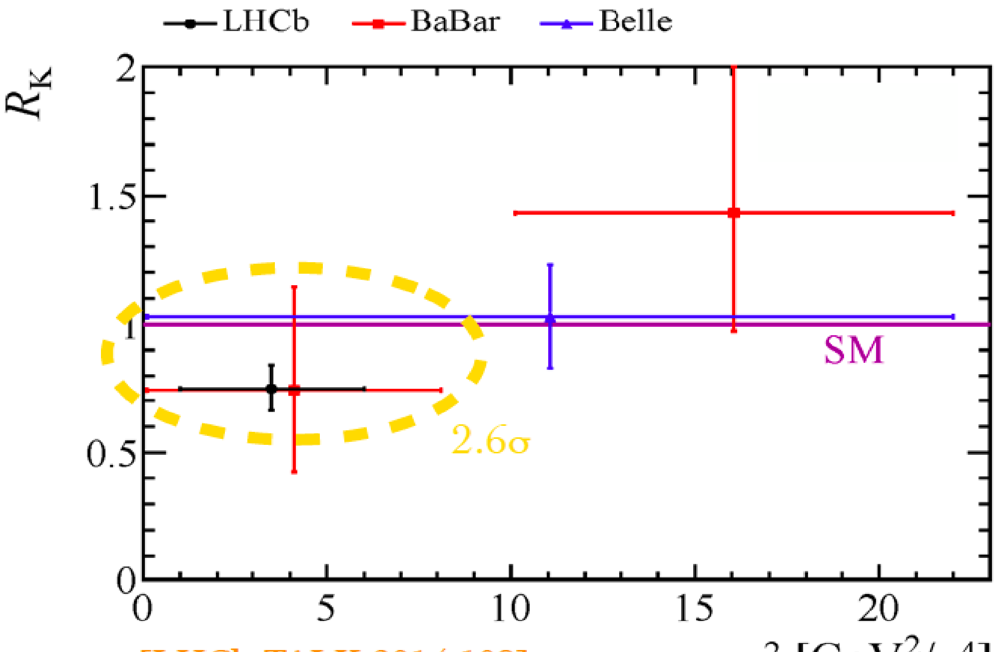
The "new frontier": Lepton Flavor Universality





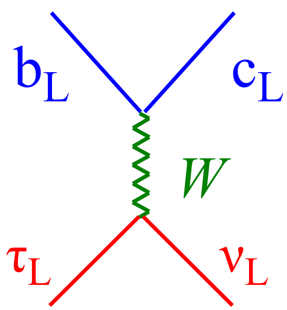
[LHCb-TALK-2014-108]

▶ *The "new frontier": Lepton Flavor Universality*

A renewed interest in possible violations of LFU has been triggered by two very different sets of observations:

I) LFU test in $b \to c$ 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	$0.440 \pm 0.058 \pm 0.042$		$0.332 \pm 0.024 \pm 0.018$	
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	$\sim 1.8\sigma$	0.321 ± 0.021	$\sim 3.2\sigma$
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

▶ The "new frontier": Lepton Flavor Universality

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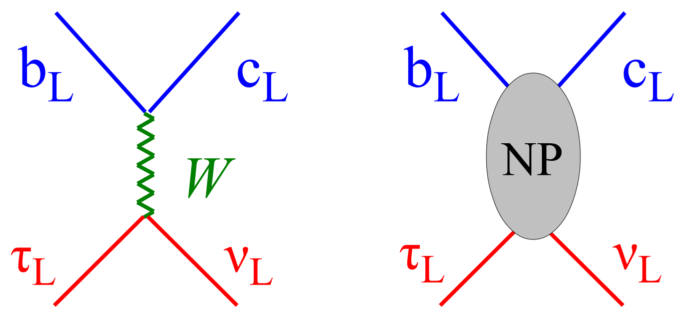
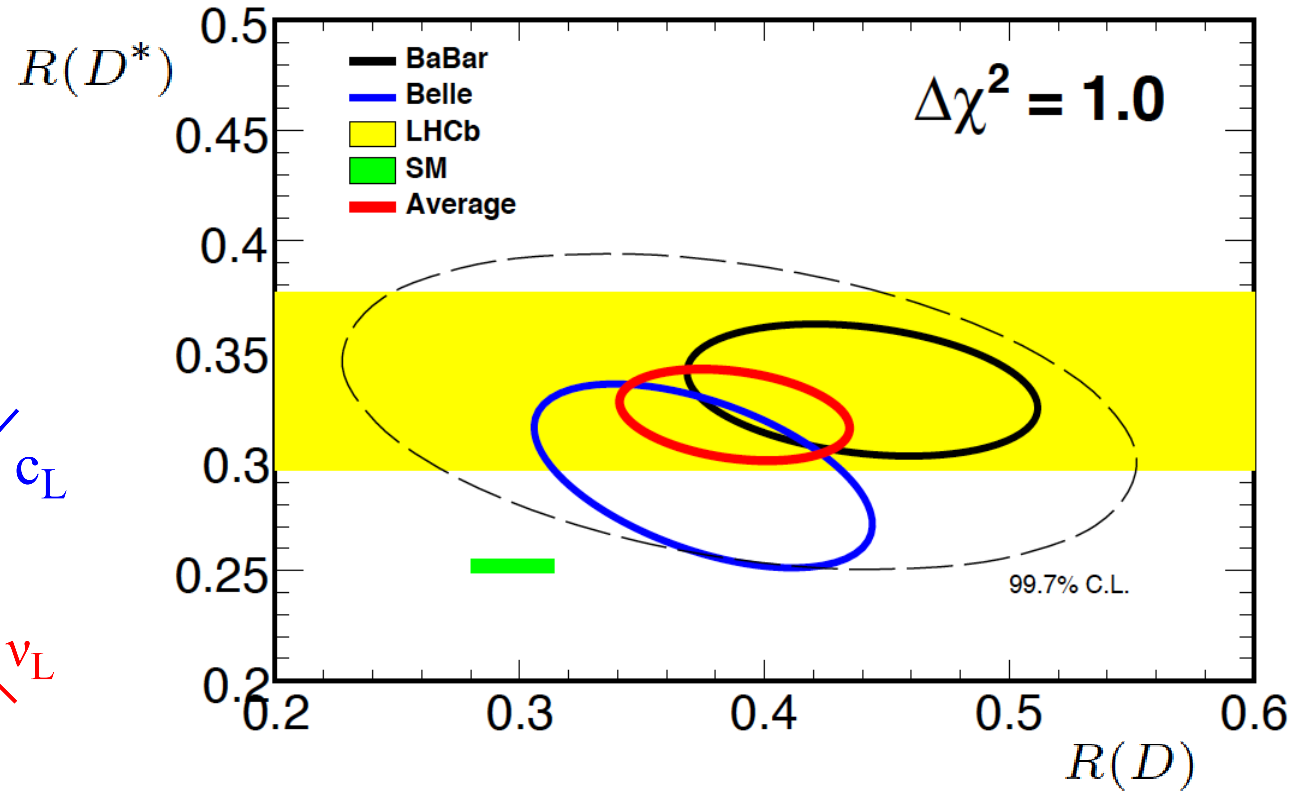




- SM prediction quite solid: f.f. uncertainty cancel (*to a good extent…*) in the ratio
- Consistent exp. results by 3 (very) different experiments
  - 4σ excess over SM (if D and D* combined)
  - The two channels are well consistent with a universal enhancement (~30%) of the SM $b_L \to c_L \tau_L \nu_L$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

The "new frontier": Lepton Flavor Universality

II) LFU test in b → s neutral currents: μ vs. e

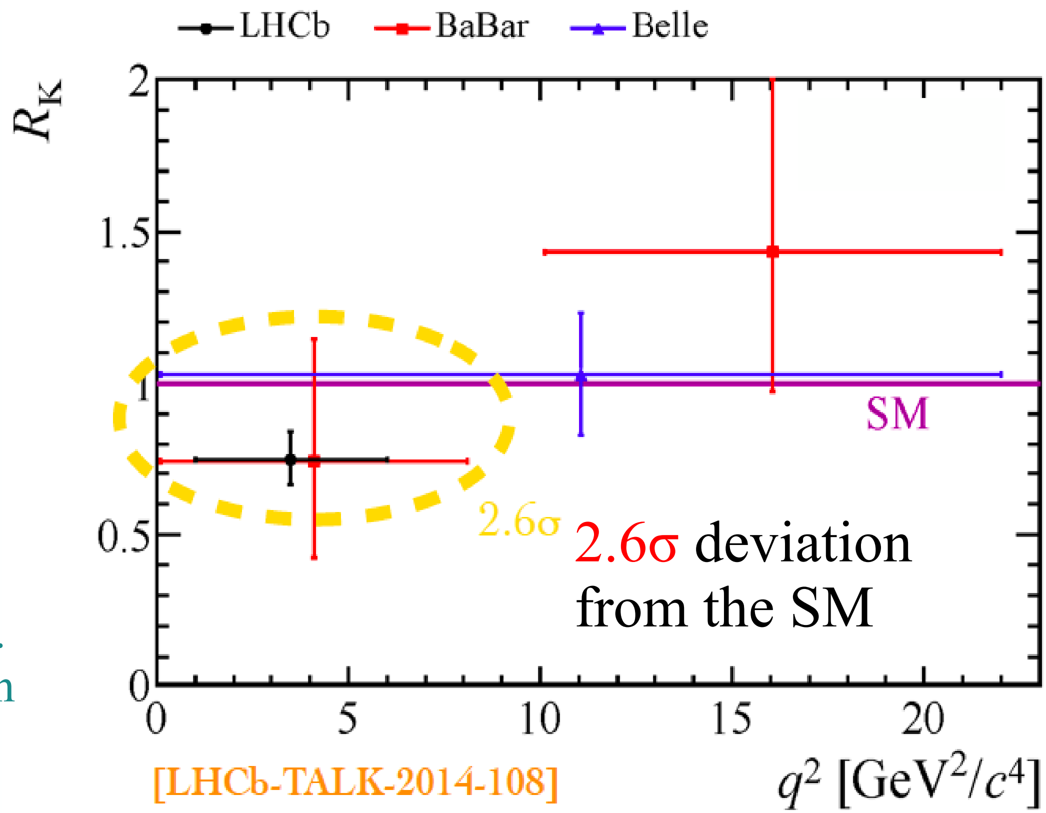
$$R_K = \frac{\int d\Gamma(B^+ \to K^+\mu\mu)}{\int d\Gamma(B^+ \to K^+ee)}$$

[1-6] GeV^2

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

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

Bordone *et al.* to appear soon



[LHCb-TALK-2014-108]

- The statistical significance of RK alone is small, but it increases a lot taking into account also the P5' anomaly and considering NP models that affects only (mainly) b→sμμ [*and not* b→see]

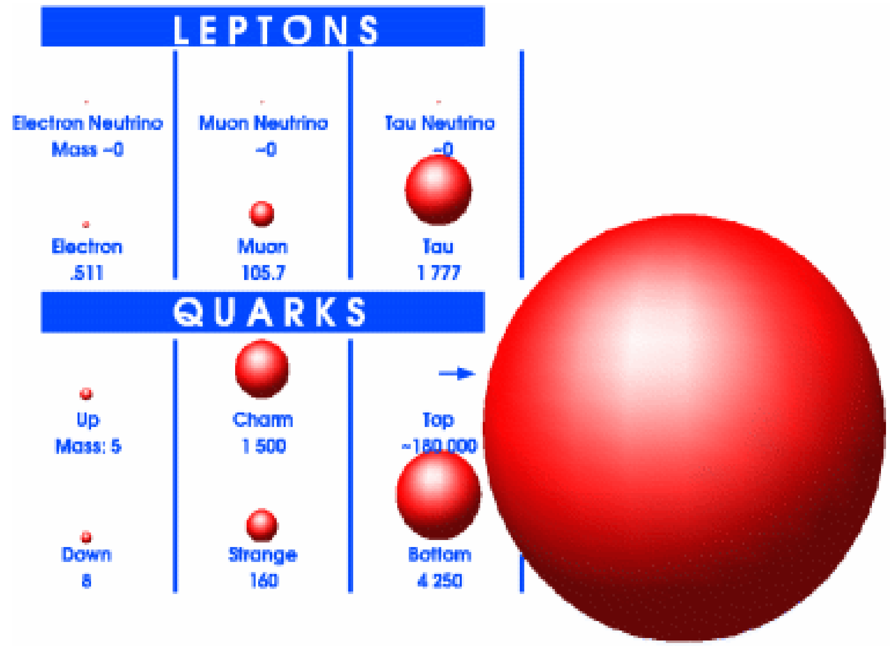
→ perfect consistency of the 2 anomalies under this (motivated) hypothesis

✭ *General considerations about the breaking of LFU*

These recent results have stimulated a significant amount 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.)

✭ General considerations about the breaking of LFU

These recent results have stimulated a significant amount 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 a few months agog most attempts focused only on one set of anomalies (either charged or neutral currents)

What I will discuss next are some general considerations in trying to describe both these effects 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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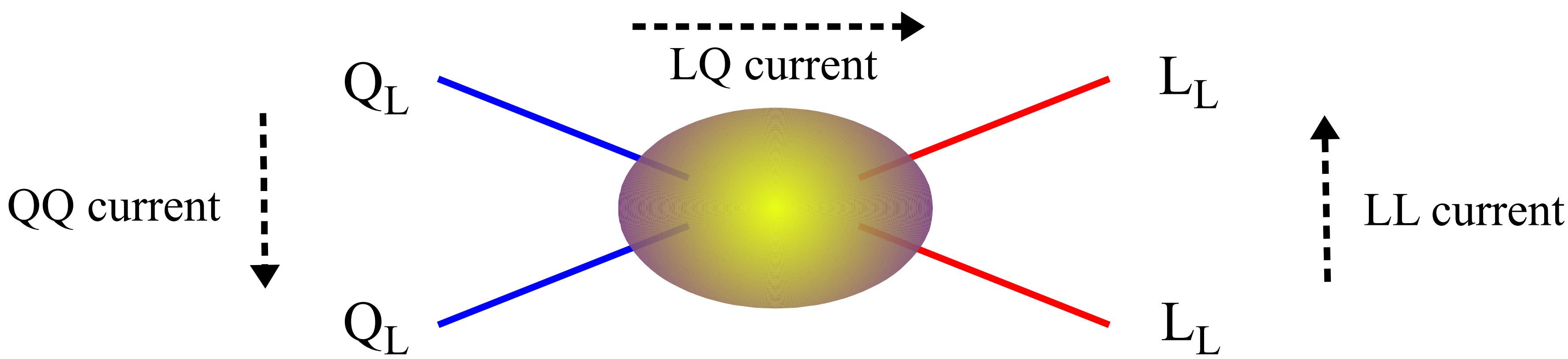

- Two natural classes of mediators, giving rise to different correlations among quark×lepton, (evidence) and quark×quark + lepton×lepton (bounds)

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

→ fits well with the idea of approximate $U(2)^n$ flavor symmetry
(possible links with models explaining the "origin" of flavor)

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 [Γ(b → cτν)/Γ(b → cμν)] → $\boxed{R_0 = 0.14 \pm 0.04}$

Here only the dominat (3rd generation coupling) appears:

b → "u_b" (= V_{tb} t + V_{cb} c + V_{ub} u) → $l_3\, \nu_3$

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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 !*

⭑ *A simplified dynamical model (I):*

Greljo, GI, Marzocca '15

Main assumptions:

- 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:

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

- 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

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

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

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

✯ *A simplified dynamical model (I) → low-energy global fit:*

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

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-$\underline{D}$)
- $\Gamma(B \to X\mu\nu)/\Gamma(B \to Xe\nu)$
- $\tau \to 3\mu$
- $\Gamma(\tau \to \mu\nu\nu)/\Gamma(\tau \to e\nu\nu)$

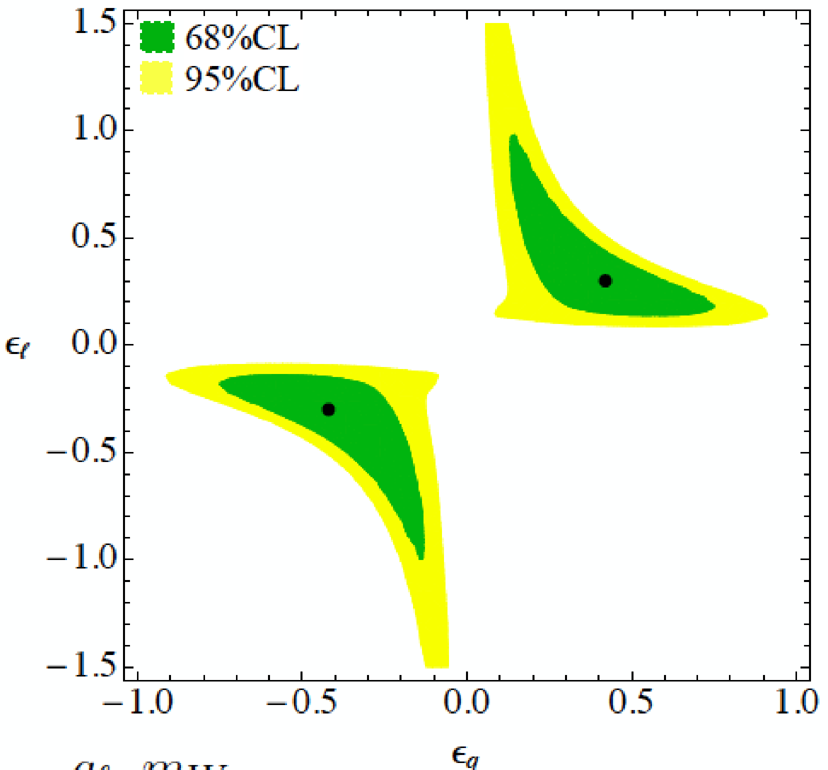
↓

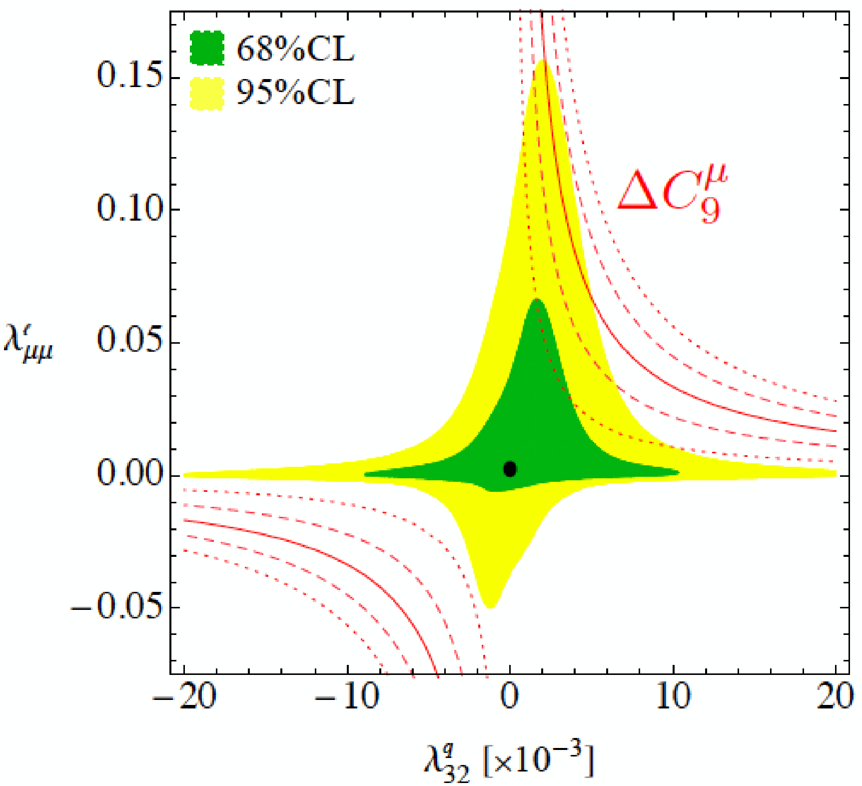
Overall good fit of low-energy data
(*non-trivial given tight constraints from ΔF=2 & LFV*)

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

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

✭ A simplified dynamical model (I) → low-energy global fit:





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

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

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

$\lambda_{bs} \lesssim 0.015$

A simplified dynamical model (I) → further low-energy tests:

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

works well...

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

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

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

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

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

- universal 20-30% enhancement of C.C. semi-lpetonic decays into tau leptons
- 1-2 % (universal) breaking of universality between muons & electrons (in leading CC modes)

✯ *A simplified dynamical model (I) → further low-energy tests:*

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

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  $= \ldots = BR(B_u \to \tau\nu)/BR_{SM}$ $\quad R^{\mu/e}(X) \sim 10\%\ R^{\tau/\mu}(X)$

- $b \to s\,\mu\mu$ $\quad \Delta C_9^\mu = -\Delta C_{10}^\mu$, 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

N.B: the deviations should be seen universally in all the hadronic modes: $B \to K^*\tau\tau$, $B \to K\tau\tau$, $\Lambda_b \to \Lambda\tau\tau$,...

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… 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
- $b \to s\, \tau\tau$ — $|NP| \sim |SM|$ → large enhancement (~ BR×4) or strong suppr.
- $b \to s\, \nu\nu$ — ~ ± 50% deviation from SM in the rate

- Meson mixing — ~ 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 (II):

Barbieri, GI, Pattori, Senia '15

Main assumptions:

- We assume the effective triplet operator is the result of integrating-out Lepto-Quark fields
- Non-Universal flavor structure of the current, based again on approximate $U(2)_q \times U(2)_l$ flavor symmetry
- Both Vector and Scalar LQ tried → Vector LQ, $SU(2)_L$-singlets, produce a very good fit to data (*essentially as good as in model I*)

↓

- Some differences with respect to model I in other observables:
  - No differences in CC
  - Much larger effects possible in $b \to s\,\tau\tau$ & $b \to s\,\nu\nu$
  - Naturally smaller effects in $\tau \to 3\mu$

UV completions & high-energy bounds:

In both cases (heavy vector triplets & vector LQ) we should address two basic questions:

- Are these models compatible with high-energy (direct) searches?
- Can we find meaningful UV completions?

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- Are these models compatible with high-energy (direct) searches? Yes

  In both cases no real problem provided we are in a regime of strong-coupling [large couplings → heavy (~ 1 TeV) masses].

  E.g.: the heavy vectors should have a mass ~ 1.4-1.8 TeV (not easily detectable due to small coupling to light quarks & large width)

- Can we find meaningful UV completions?

⋆ *UV completions & high-energy bounds:*

In both cases (heavy vector triplets & vector LQ) we should address two basic questions:

- Are these models compatible with high-energy (direct) searches? Yes
- Can we find meaningful UV completions?

An attractive possibility is that of composite models, that would allow also a to build a natural link to the possible 750 GeV di-photon "bump" (*if it is there...*)

A concrete example [Buttazo, Greljo, GI, Marzocca, to appear next week] can be build with a proper set of vector-like (techni-)fermions, charged under a new strong dynamics and mixed with 3rd gen. SM quarks & leptons

→ "new spectroscopy" that include:

X(750) ~ "techni-π^0" (decaying to 2γ via the anomaly)

Heavy Vectors ~ "techni-ρ" (responsible for the B-physics anomalies)

Conclusions

- We entered in a very special era in particle physics: the SM is a successful theory that has no intrinsic energy limitations.

- Motivations for NP still there (*including the puzzling structure of quark and lepton masses matrices, or the origin of flavor...*) → flavor physics remains very interesting, and we must search for NP with an "open-mind" perspective, given the lack of a clear preferred direction in "model space".

- While "classical studies" of rare B (→ muon) decays remains well motivated, recent data have helped us to identify a very rich "new frontier" in flavor physics: the study of LFU (*whose interest will remain high even if present anomalies will disappear*) → possible improved performances on tau & e modes (even non-rare) should be carefully investigated in view of possible LHCb upgrades.