Flavor physics @ Run-I and Run-II prospects:

a personal, non-comprehensive, point of view...

Gino Isidori
[*University of Zürich*]

- Introduction
- Some interesting recent results (and "*anomalies*"...)
- Speculations on the breaking of Lepton Flavor Universality
- Conclusions

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

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Threefold
~~Twofold~~ role of low-energy physics
[*flavor-changing processes, EDMs, anomalous magnetic moments*]

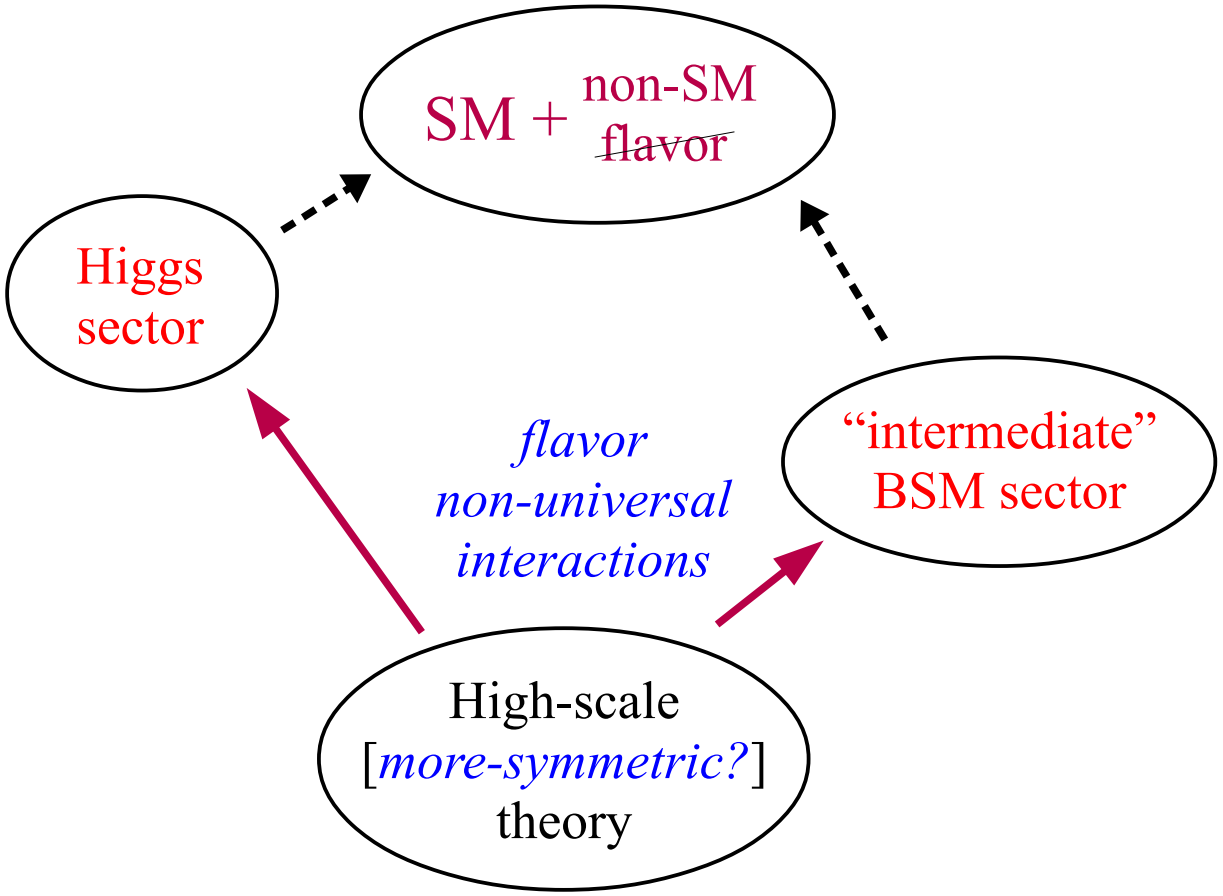
- Identify symmetries & symmetry-breaking patterns beyond those present in the SM
- Indirect probe of physics at energy scales not directly accessible at accelerators
- Learn more about QCD
(both perturbative & non-perturbative aspects)

NOT IN THIS TALK

Introduction

Twofold role of low-energy physics

- Identify symmetries and symmetry-breaking patterns beyond those present in the SM
- 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

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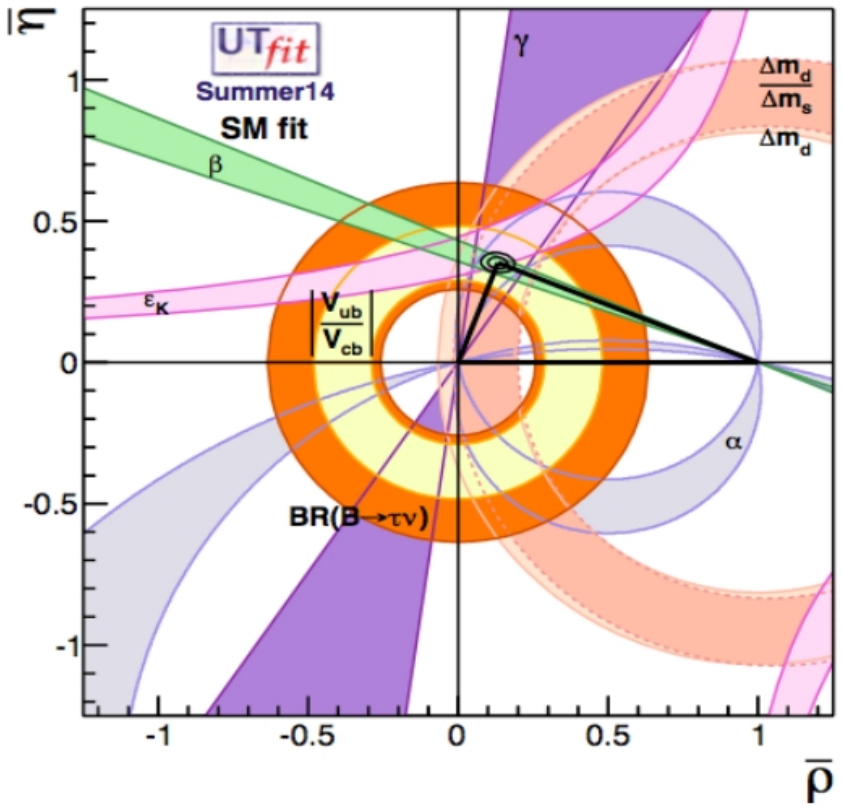

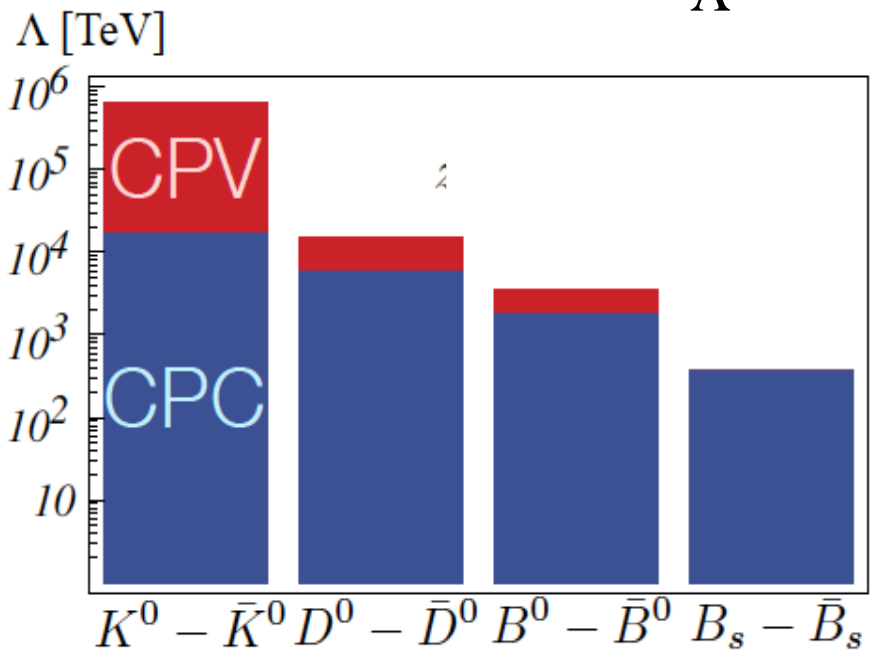

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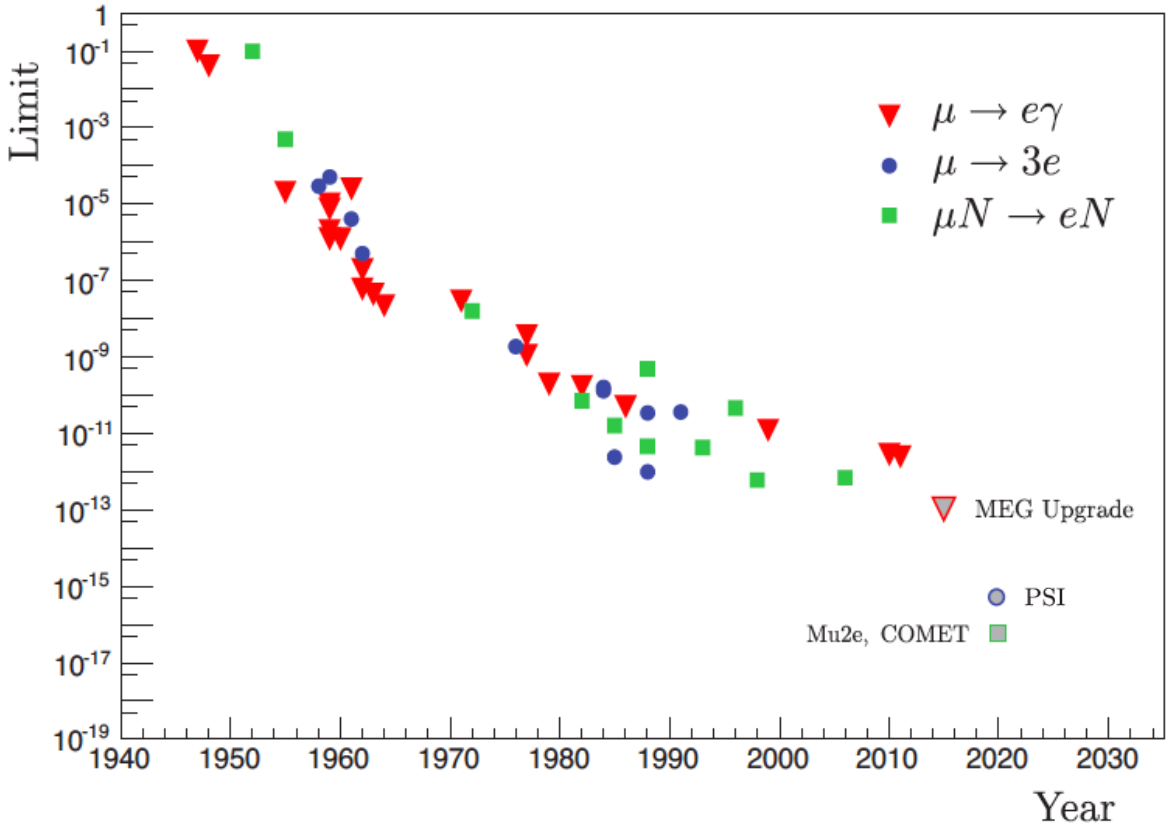

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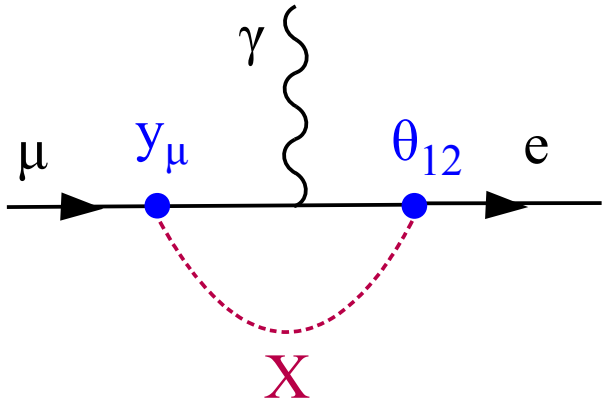

$BR(\mu \to e\gamma)^{exp} < 5.7\times10^{-13}$ MEG '13

$M_X \gtrsim 200$ TeV

Either NP is very heavy...

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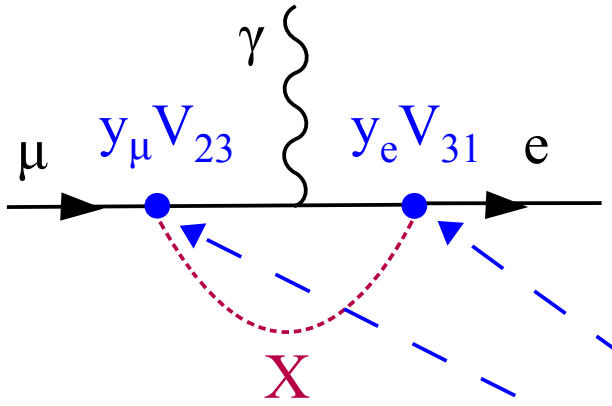

$BR(\mu \to e\gamma)^{exp} < 5.7\times10^{-13}$ MEG '13

$M_X \gtrsim 10$ GeV

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

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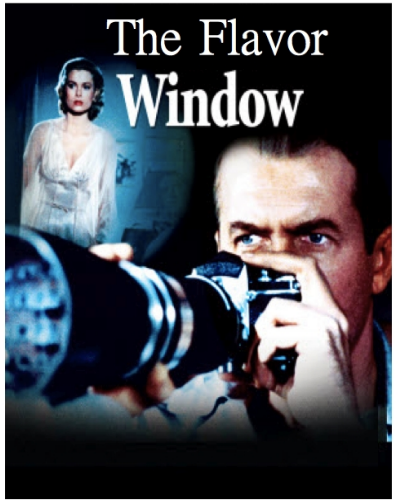
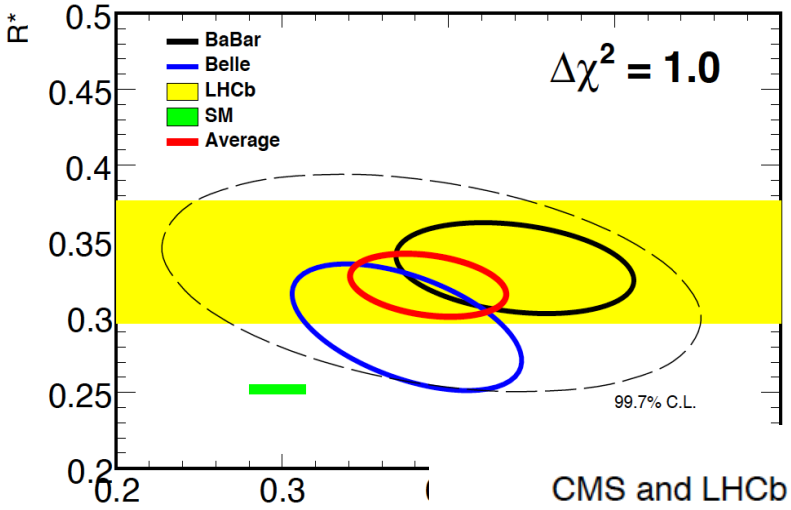
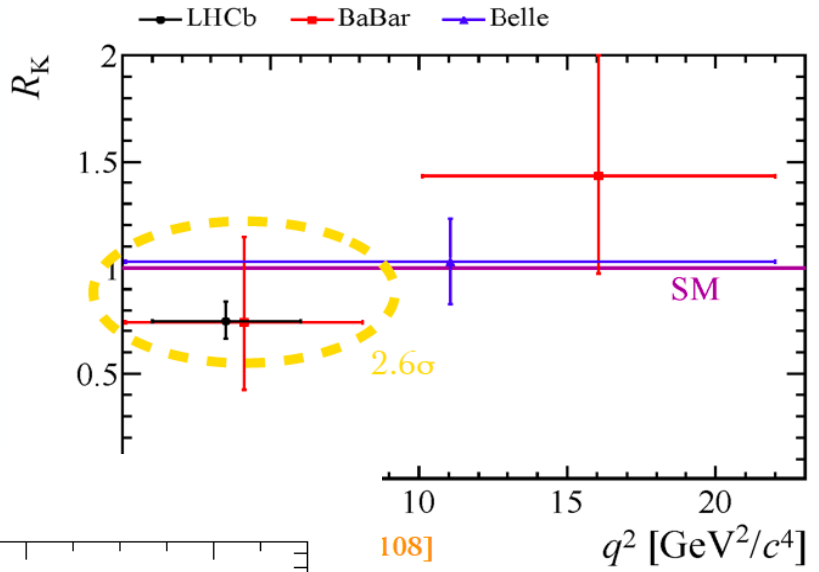
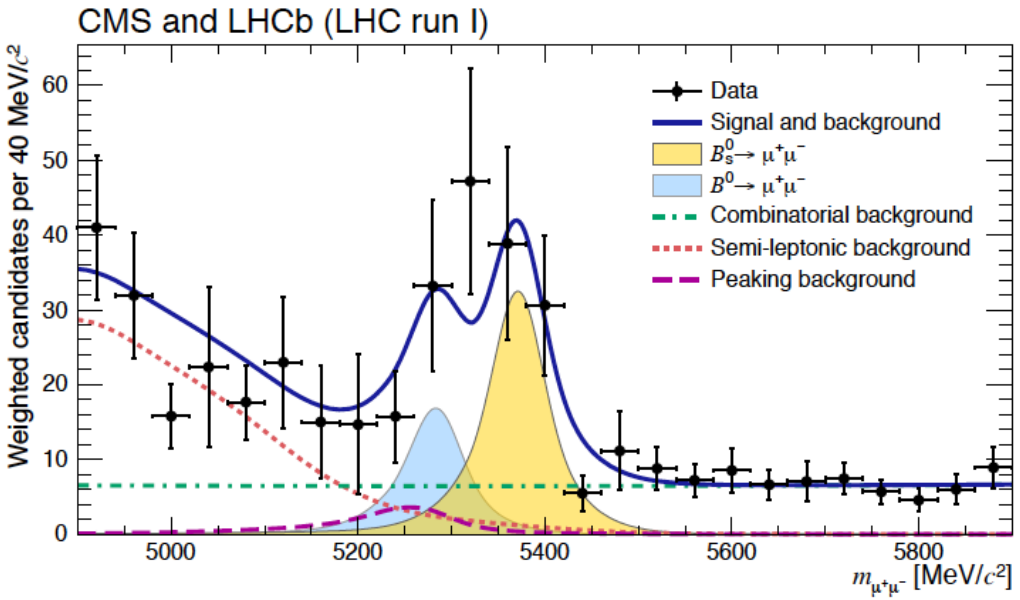
There is still a wide (*possibly interesting...*) region of NP parameter space (*both in masses and couplings*) that is waiting to be explored yet...



Some interesting recent results (and "*anomalies*"...)





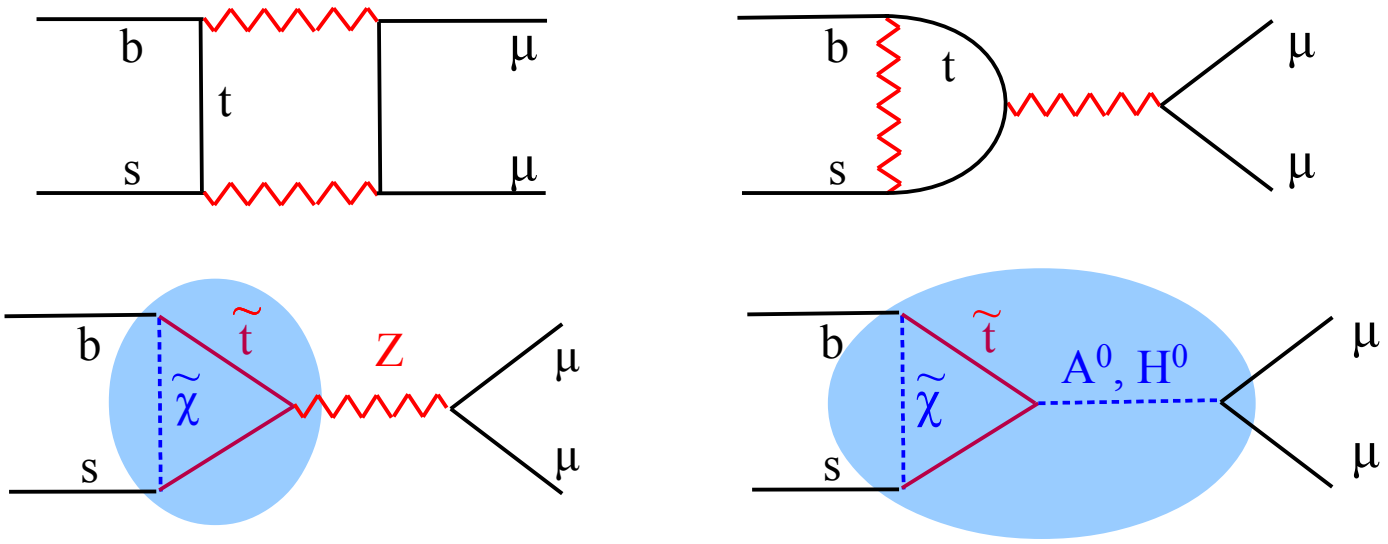


I. The b → s l^+l^- system

The exclusive FCNC decays of the type b→s μμ/ee represent a very interesting system

- several accessible channels [B_s→μμ, B→K*μμ/ee, B→Kμμ/ee, B_s →ϕμμ/ee, ...]
- huge set of observables [BR & differential distributions]
- all controlled by the same basic short-distance dynamics

Non-perturbative QCD effects complicate a bit our life... but the richness of the system helps (*and this help with increase in the future...*) to disentangle short- and long-distance effects



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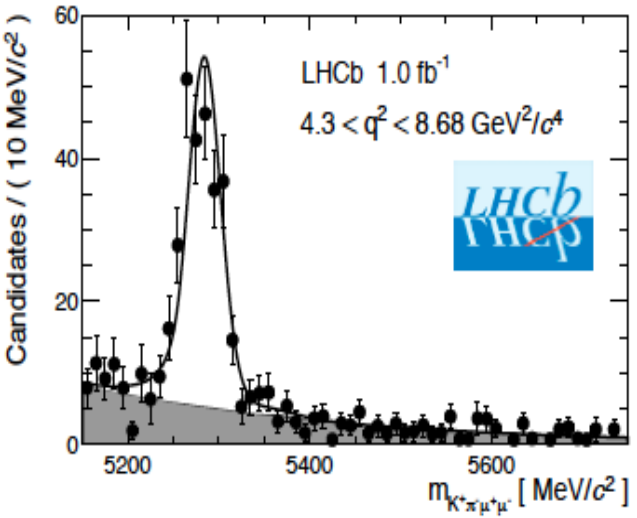
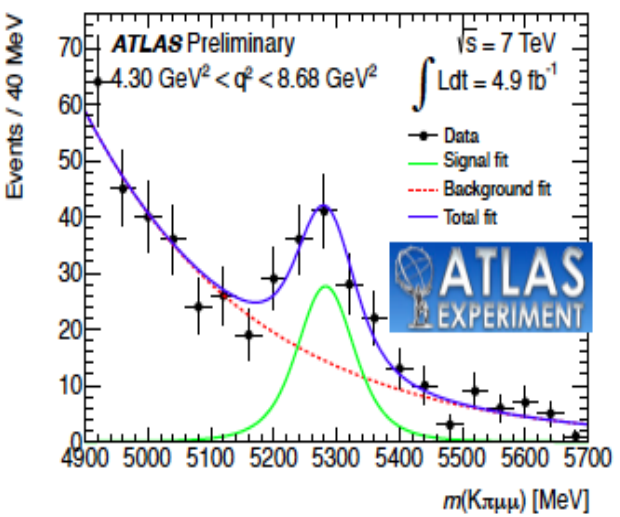
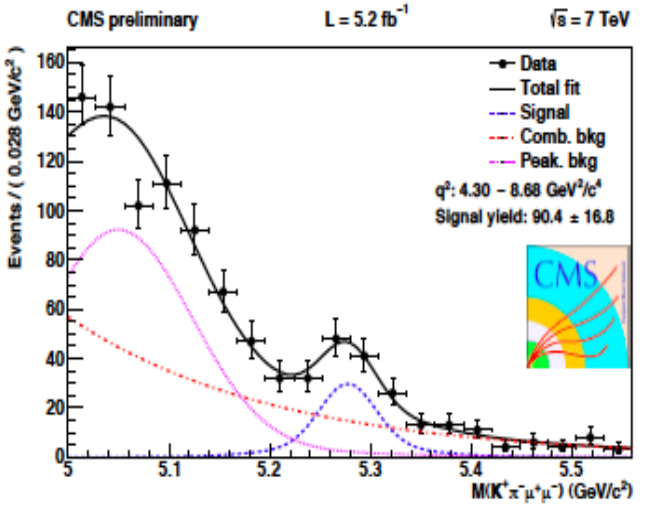
Non-perturbative QCD effects complicate a bit our life... but the richness of the system helps (*and this help with increase in the future...*) to disentangle short- and long-distance effects → *combination of results by different LHC experiments can be quite important in the future to gain statistics & reduce errors*

B → K*μμ signals from the 3 LHC experiments:







I. The b → s l^+l^- system

In such system some "puzzling" deviations from the SM are emerging.

The largest one [*observed in 2013 by LHCb & confirmed with higher stat. in 2015*] is the one in the P_5' [$B \to K^* \mu\mu$] angular distribution.

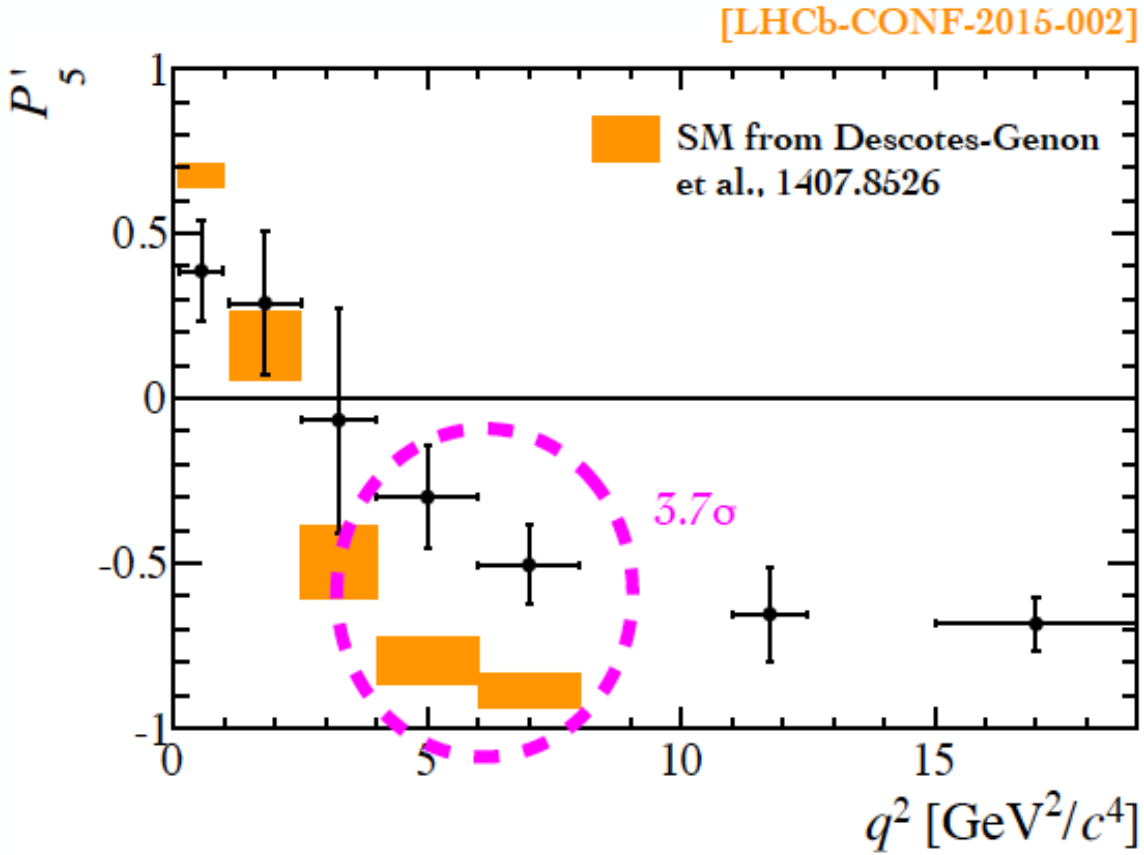
But less significant anomalies present also in other other b→sμμ channels [overall smallness of all BR(B → Hadron + μμ)]

Pro NP:

- Reduced tension in all the observables with same set of non-standard short-distance Wilson coeff. (C_9)

Against NP:

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

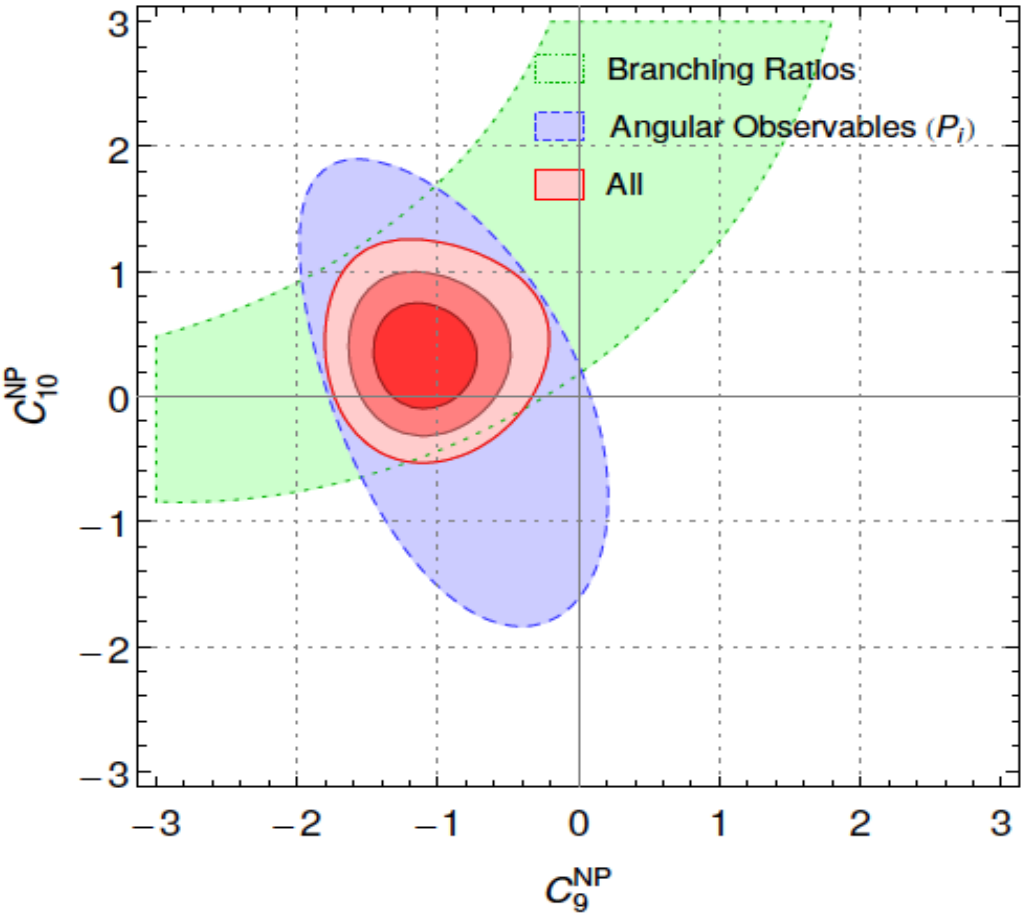


I. The b → s l^+l^- system

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



Descotes-Genon, Matias, Virto '13

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

muonic vector current

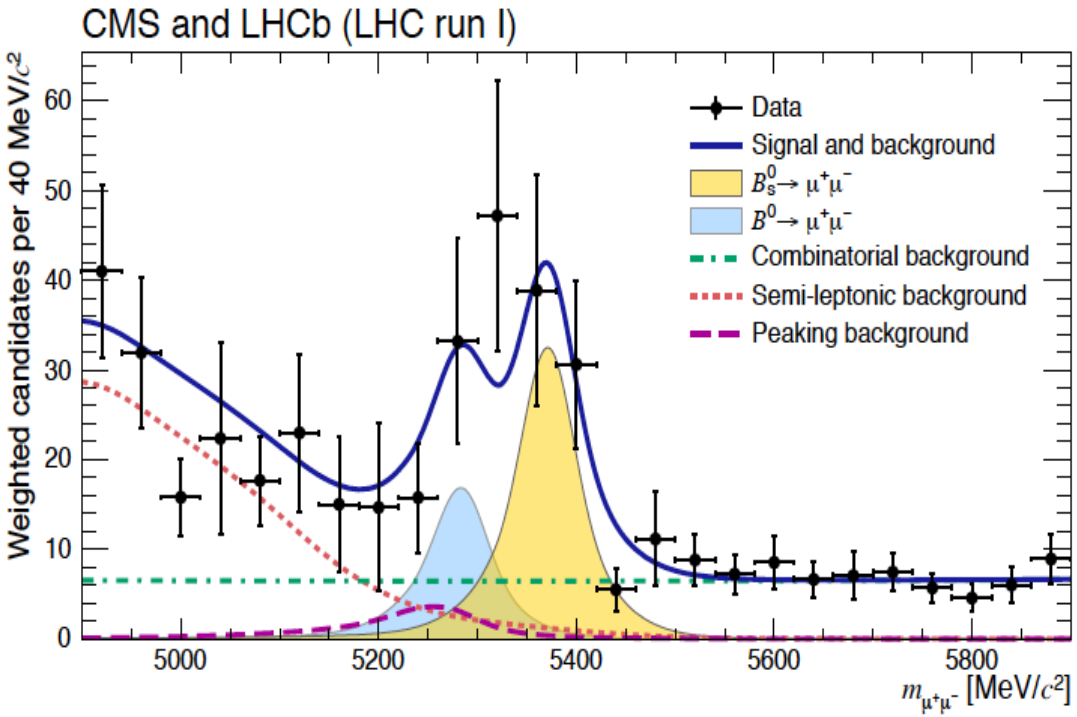
- NP contributions to C_9 give best description of the data
- (NP with $C_9 = -C_{10}$ works almost equally well)

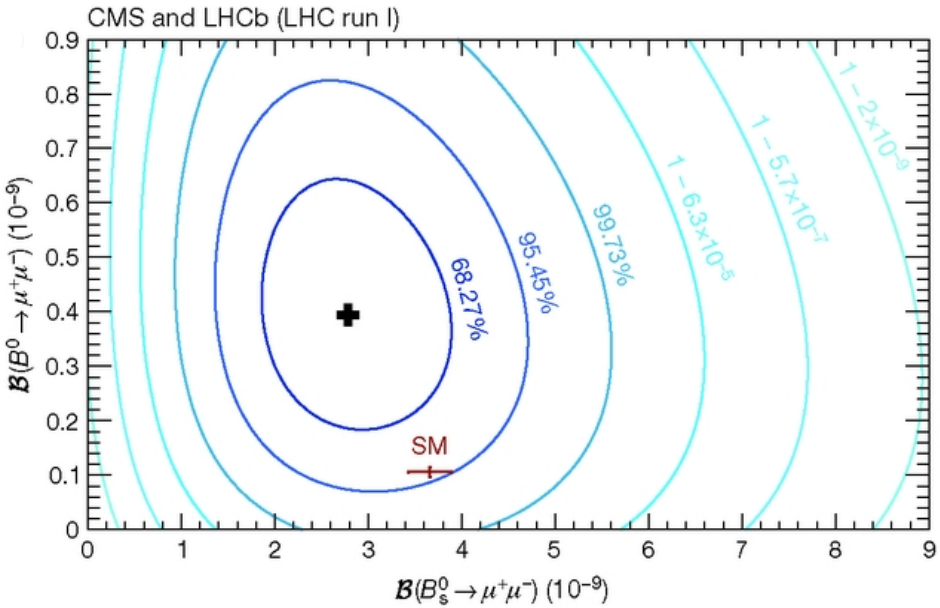
I. The b → s l^+l^- system

Pro NP:

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

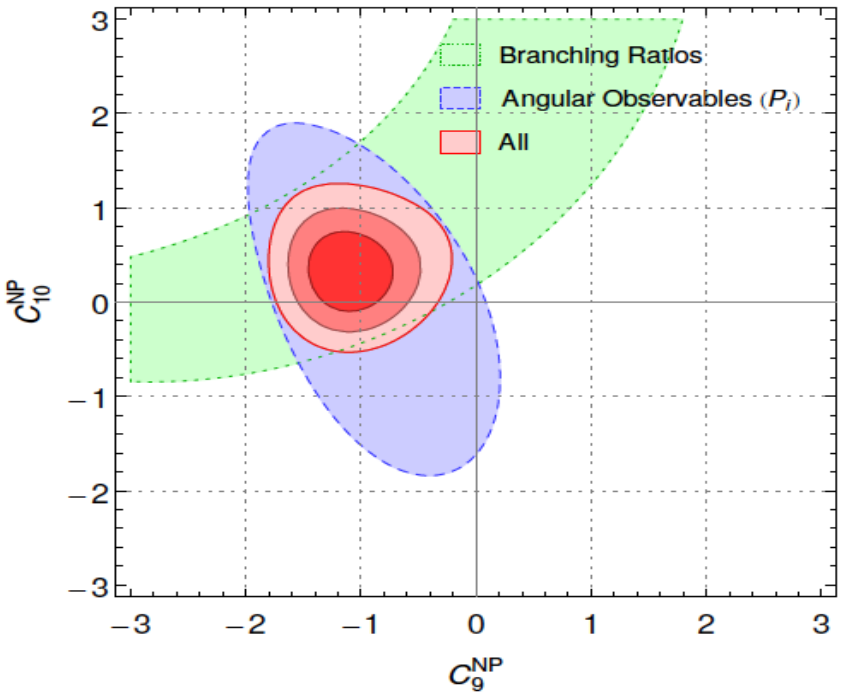
My (*and not only my....*) hope, is that the deviation from the SM will become clear also in C_{10} ↔ BR($B_s \to \mu\mu$)

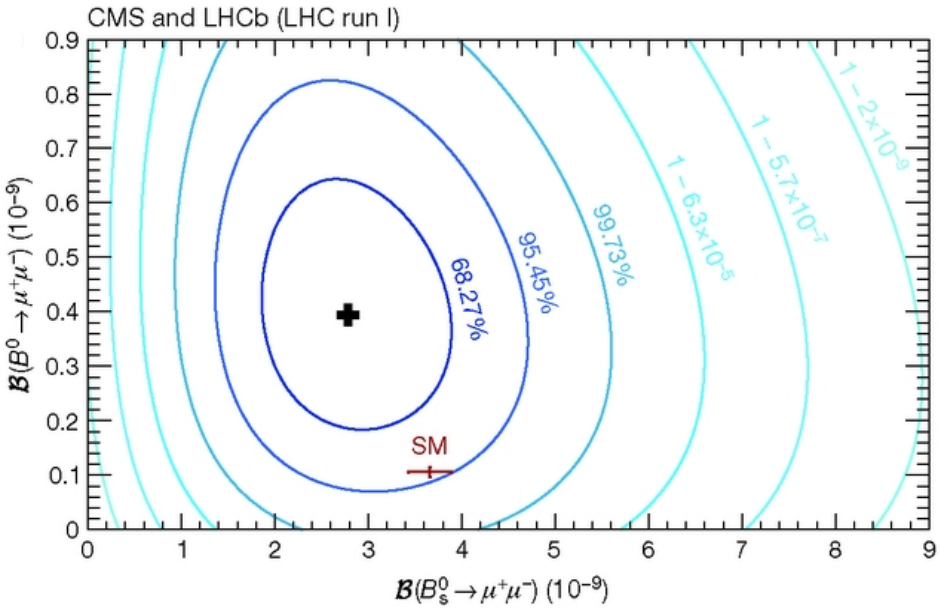




[Nature 522(2015)]

"*Intermezzo*": how to present and combine data





→ important to avoid (or at least provide only as additional/complementary results...) combination/presentation of results that contain sizable theoretical biases (e.g. form factor uncertainties)

I. The b → s l^+l^- system

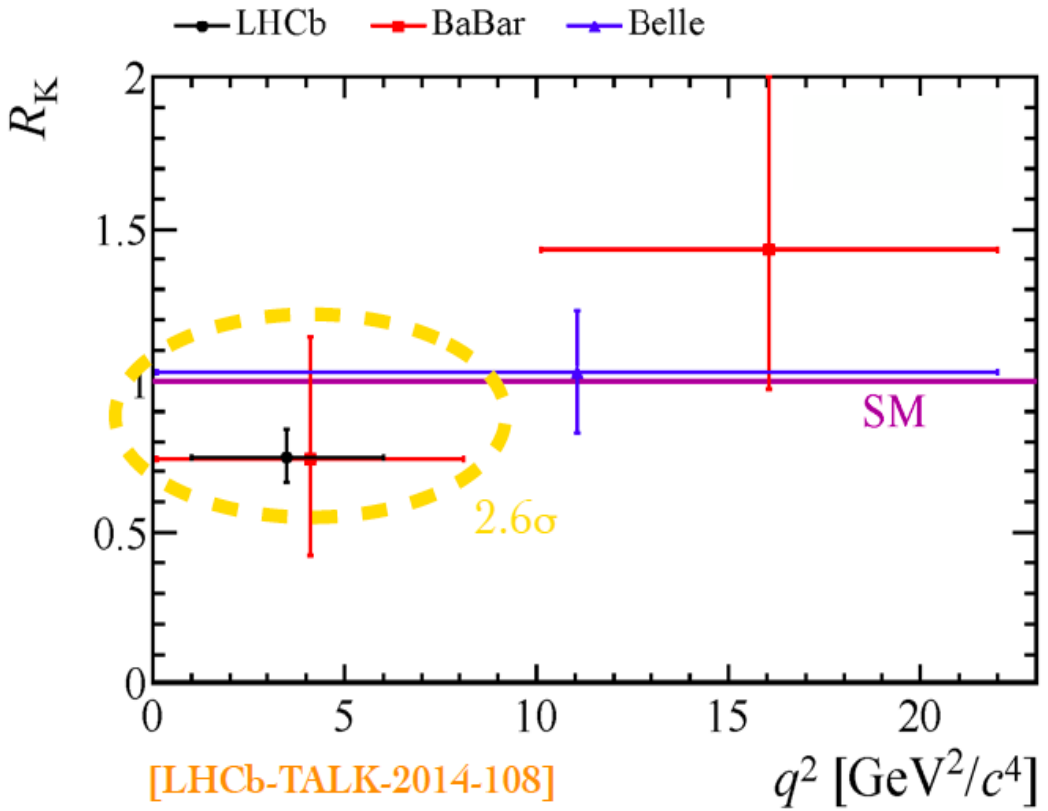
What makes present data in the b → s l^+l^- system even more interesting is the 2.6σ deviation from the SM observed in the LFU ratio

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

[1-6] GeV^2

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

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



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

II. $B \to D^{(*)} \tau\nu$

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	0.252 ± 0.005

~1.8σ ~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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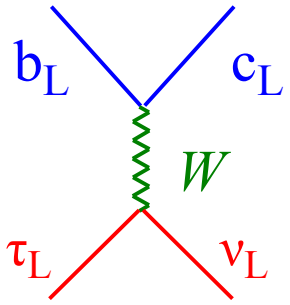
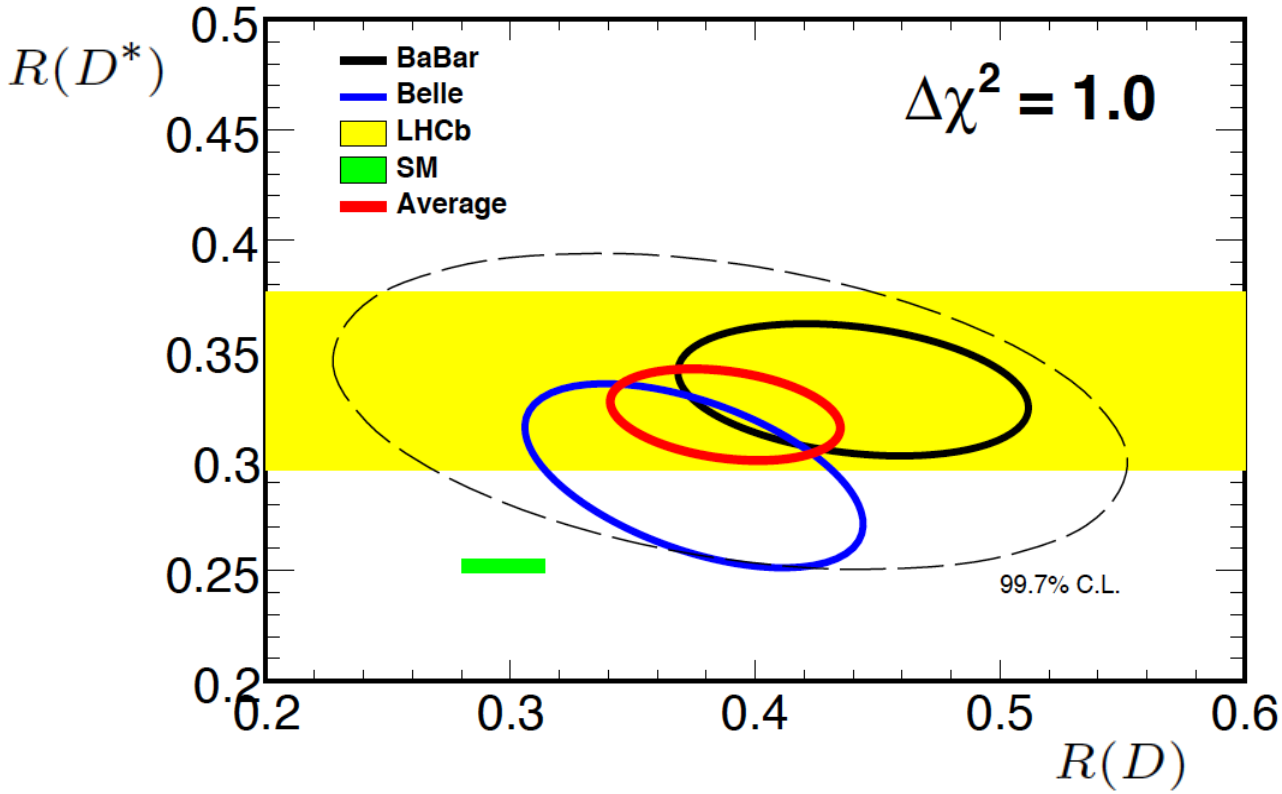




- SM prediction quite solid: f.f. uncertainty cancel (*to a good extent...*) in the ratio
- Consistent exp. results by 3 (very) different experiments
  - 4σ excess over SM (if D and D* combined)
  - The two channels are well consistent with a universal enhancement (~30%) of the SM $b_L \to c_L\, \tau_L\,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

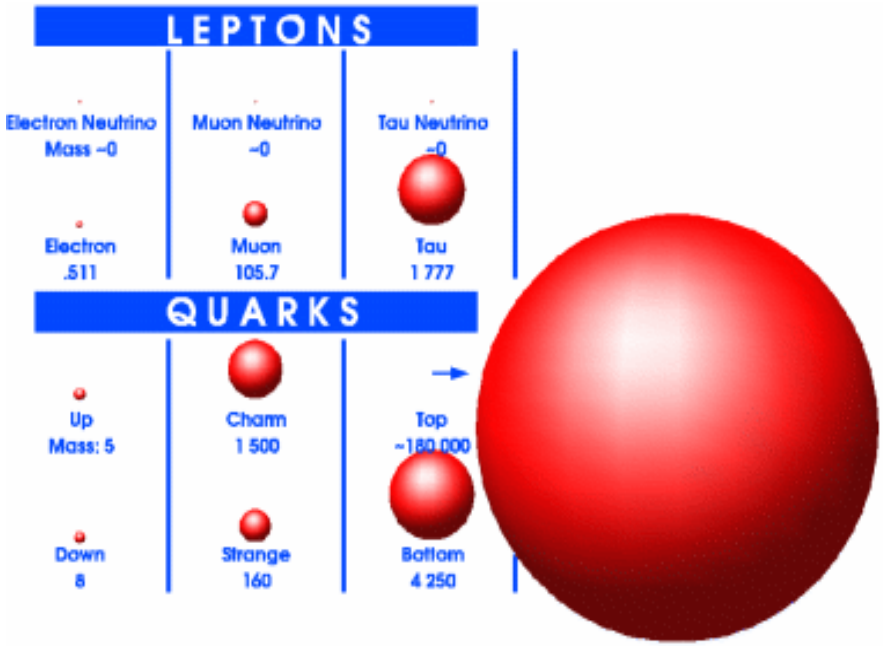
Speculations on the breaking of Lepton Flavor Universality

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

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

What I will discuss next (*mainly for illustrative purposes*) 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

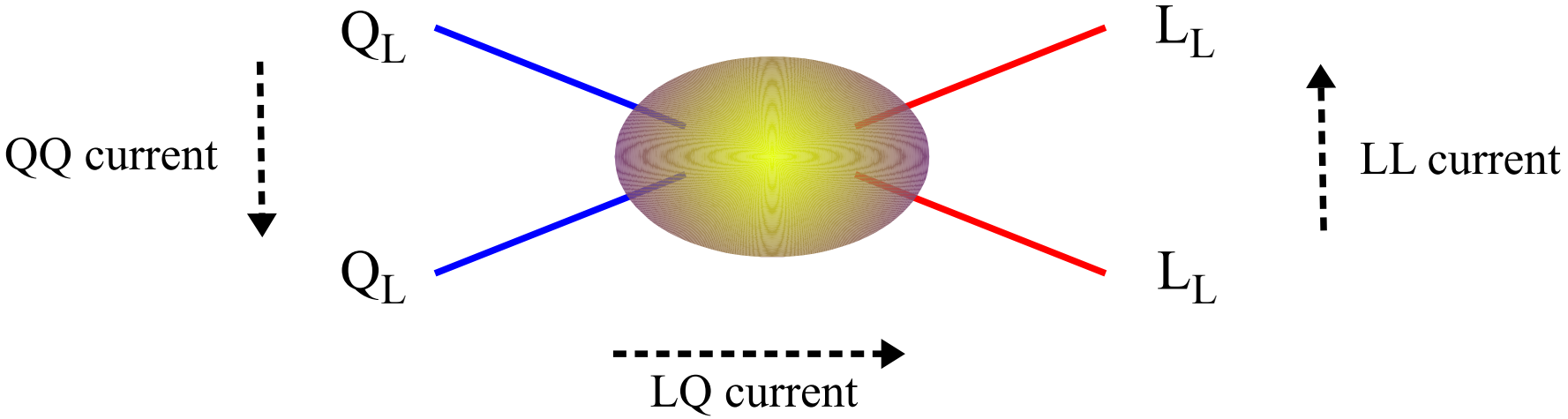
A "prototype data-inspired" model:

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:

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

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

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

(*hierarchy determined by CKM in the quark sector*)

Global fit to low-energy data:

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

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)

Future low-energy tests:

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

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

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

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

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

  - universal ~ 30% enhancement of C.C. semi-lpetonic decays into tau leptons (τ/μ)
  - ~1-2 % (universal) breaking of universality between muons & electron CC modes (μ/e)

N.B.: so far neither PDG nor HFAG provide a clear answer to the following question:

"how large are possible deviations of e/μ universality in semi-leptonic B decays?"

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

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

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

$$= \ldots = \text{BR}(B_u \to \tau\nu)/\text{BR}_{\text{SM}} \qquad R^{\mu/e}(X) \sim 10\%\, R^{\tau/\mu}(X)$$

- $b \to s\,\mu\mu$

$\Delta C_9^\mu = -\Delta C_{10}^\mu$, but overall size of the anom. should decrease

The effect should become visible in $\text{BR}(B_s\to\mu\mu)$

[*key role of future LHC combined analysis*]

Future low-energy tests:

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

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

- b → c(u) *lν*

  BR(B→D*τν)/BR$_{SM}$ = BR(B→Dτν)/BR$_{SM}$ = BR($\Lambda_b \to \Lambda_c \tau\nu$)/BR$_{SM}$

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

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

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

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)

↓

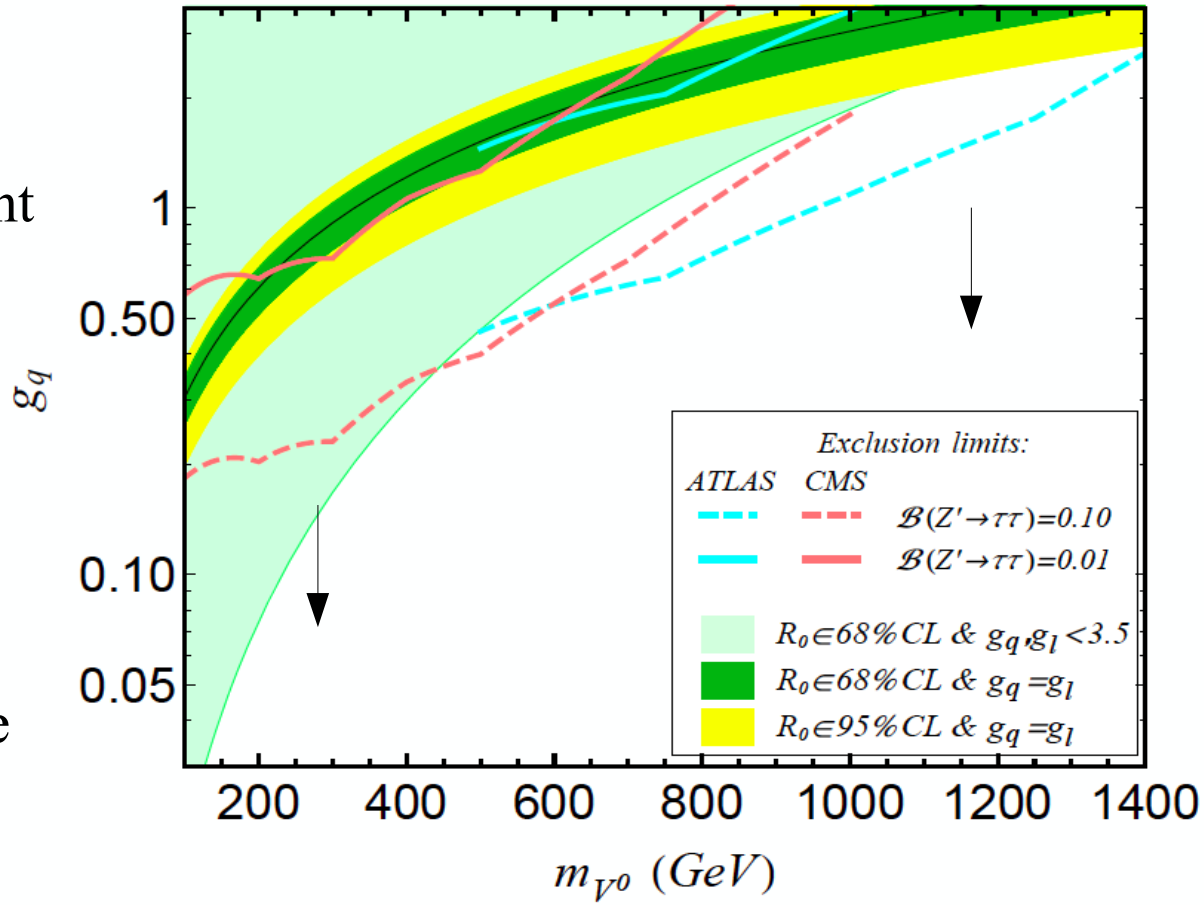
- Not a very easy signature...

The only really stringent constraint (so far) comes from Z' → ττ

↓

Minimal version of the model (*no exotic decay channels*) ruled out by direct searches, but less-minimal versions survive

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



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 → combination of different LHC exp. can be very important in this respect
- 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