On recent anomalies in flavor physics

Diego Guadagnoli
LAPTh Annecy (France)

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❶ + ❷ + ❸ ⇒ *There seems to be BSM LFNU and the effect is in μμ, not ee*

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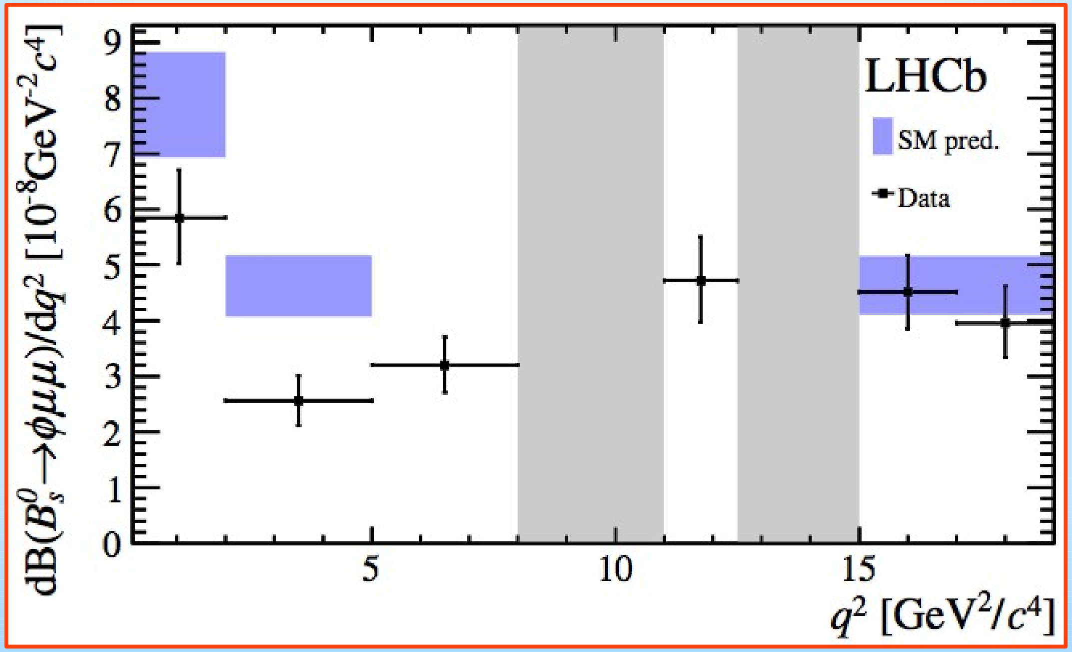

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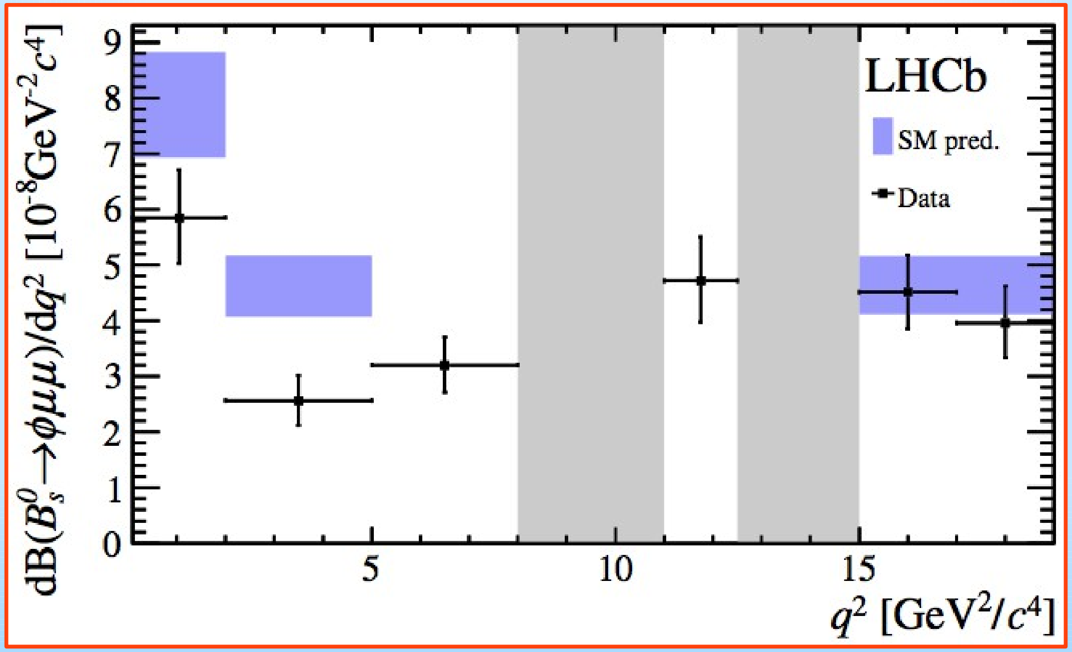

The measured branching fraction is compatible with the previous measurement [3] and lies below SM expectations. For the q^2 region $1.0 < q^2 < 6.0\,\mathrm{GeV}^2/c^4$ the differential branching fraction of $(2.58^{+0.33}_{-0.31} \pm 0.08 \pm 0.19) \times 10^{-8}\,\mathrm{GeV}^{-2}c^4$ is more than $3\,\sigma$ below the SM prediction of $(4.81 \pm 0.56) \times 10^{-8}\,\mathrm{GeV}^{-2}c^4$ [4,5,32].

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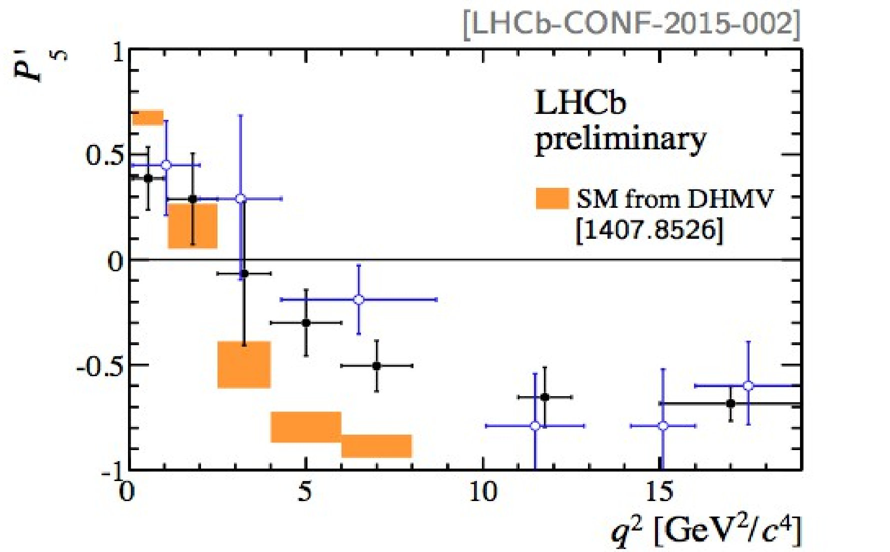

- Tension seen in P'_5 in [PRL 111, 191801 (2013)] confirmed
- $[4.0, 6.0]$ and $[6.0, 8.0]$ GeV^2/c^4 show deviations of 2.9σ each
- Naive combination results in a significance of 3.7σ
- Compatible with $1\,\mathrm{fb}^{-1}$ measurement

C. Langenbruch (Warwick), Moriond EW 2015 | Rare decays from LHCb

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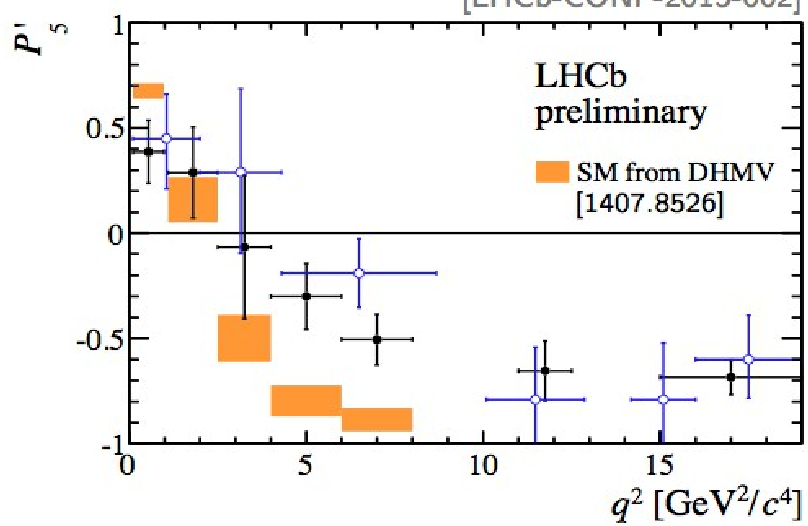
[LHCb-CONF-2015-002]



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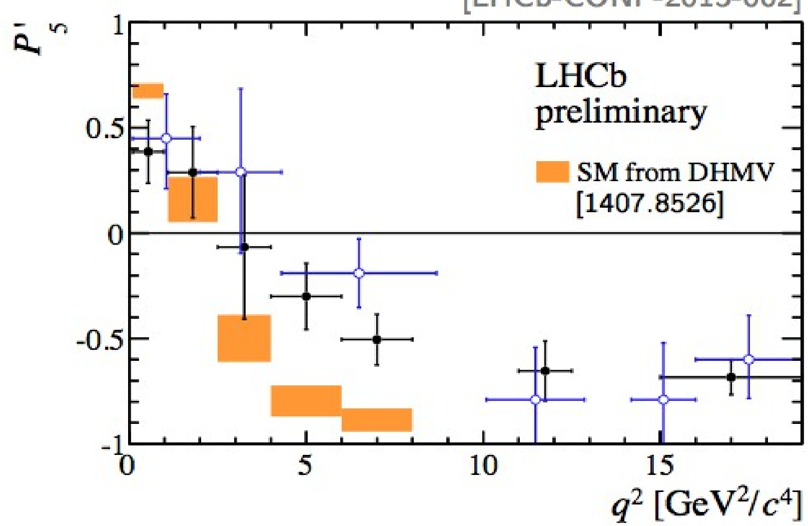

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  - What cancels is the dependence on the large-m_b form factors.
  - Debate on the role of
    - Subleading terms in $1/m_b$
    - $c\bar{c}$ loops and their resummation

See:
Jäger & Martin-Camalich, PRD 2016
Ciuchini *et al.*, 1512.07157

The P'$_5$ anomaly: *continued*

The above said, this anomaly remains interesting (and more and more so)

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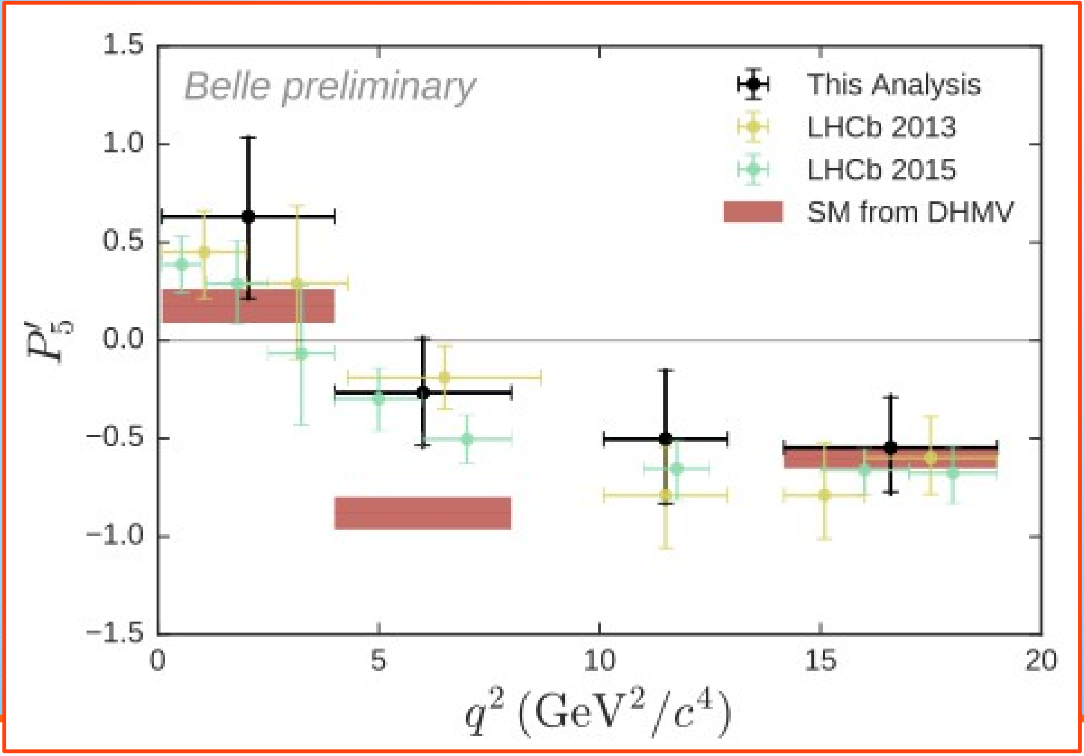

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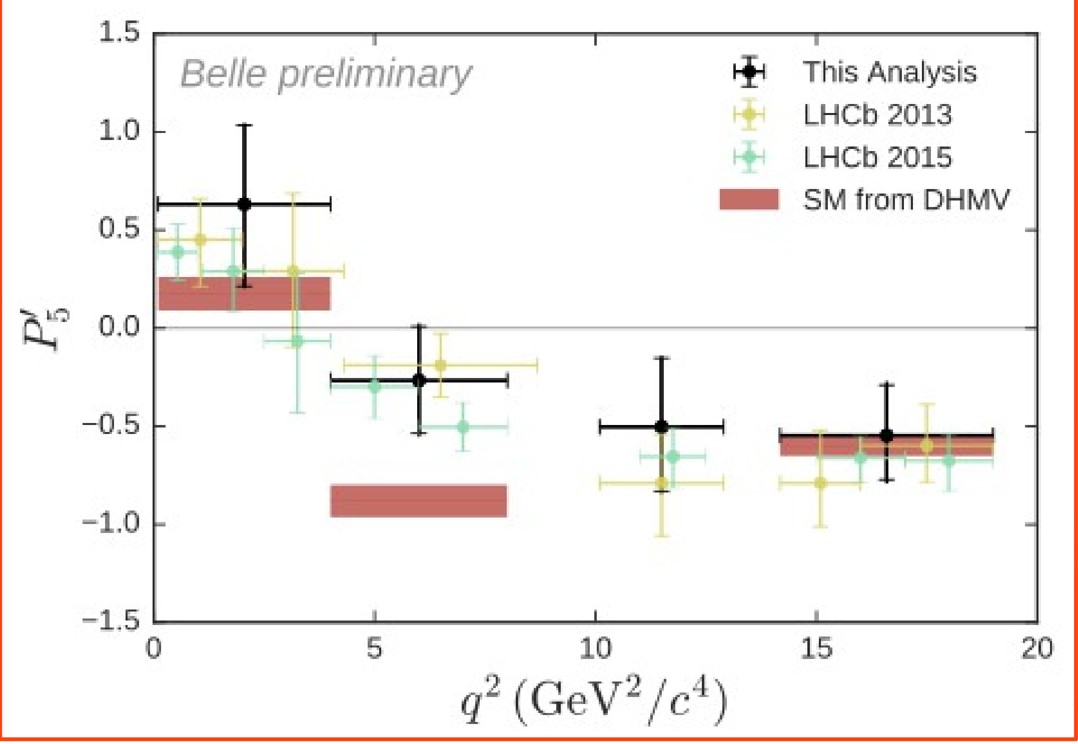

- **Conclusion:**

  If it's new physics, it is expected to show up elsewhere in the $B \to K^* \mu\mu$ angular analysis.

  Run II will tell for sure

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- Exp error will go to: ~ 10% by end of Run II
  ~ 5% w/ LHCb upgrade

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b → c decays

There are long-standing discrepancies in b → c transitions as well.

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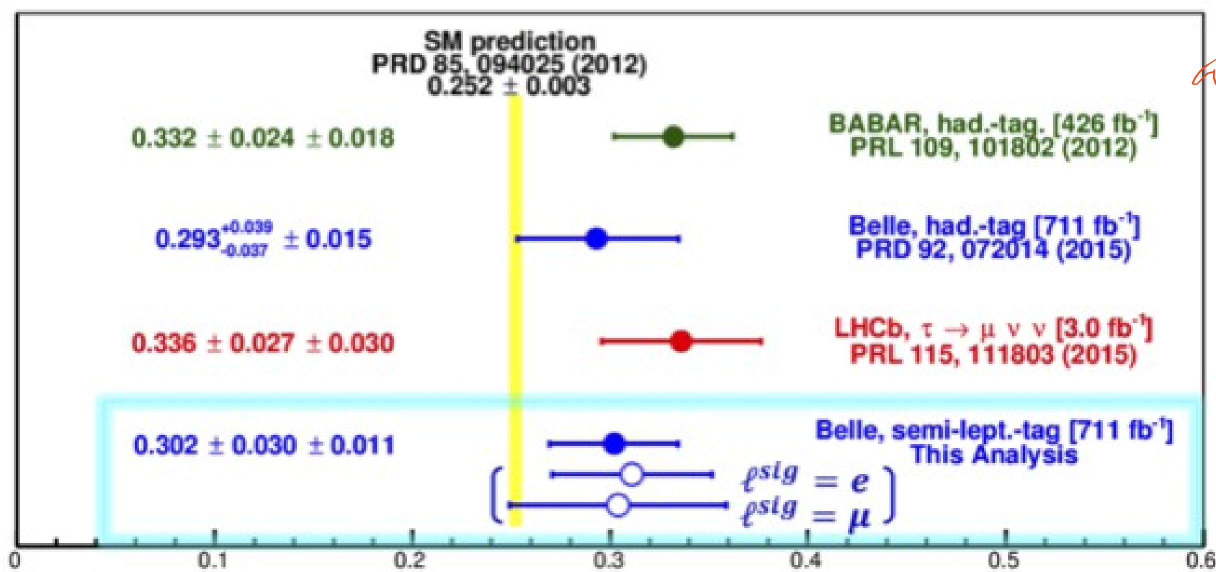

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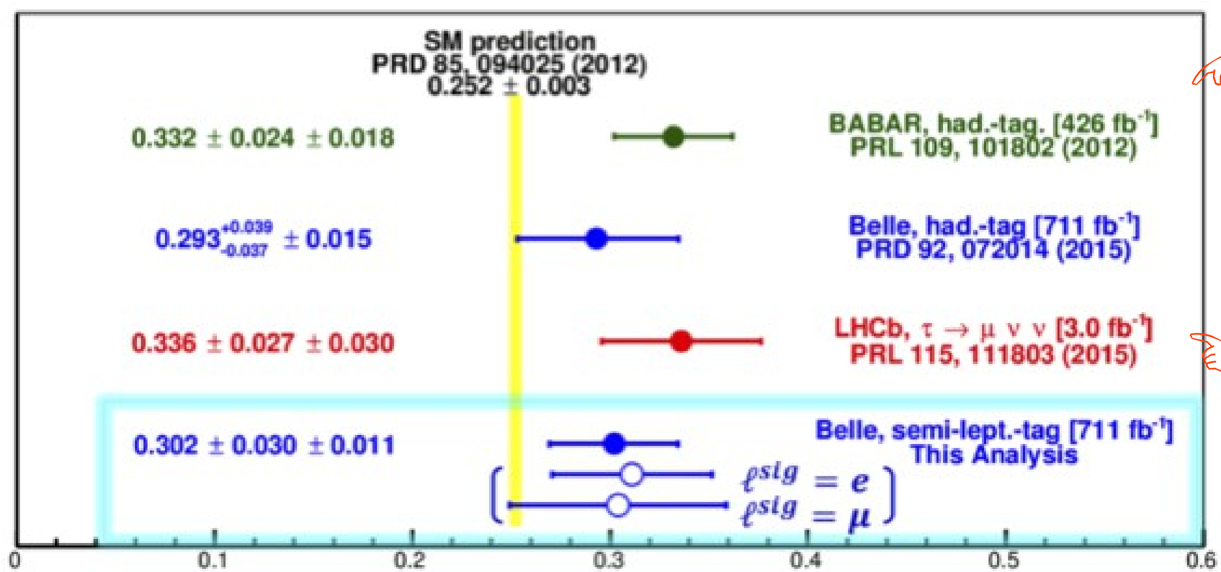

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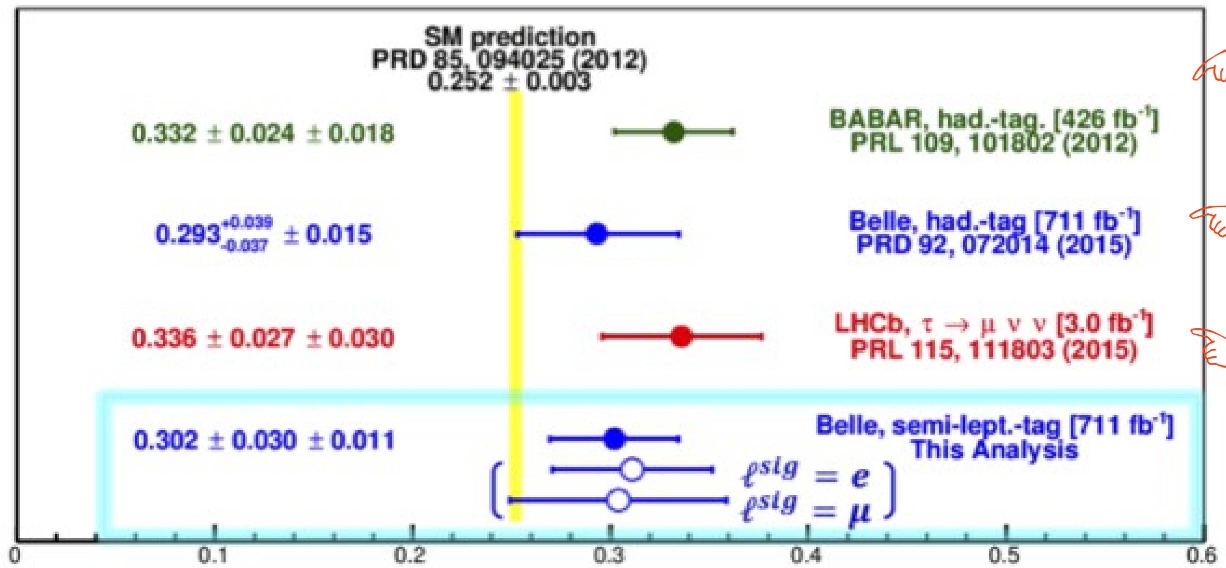

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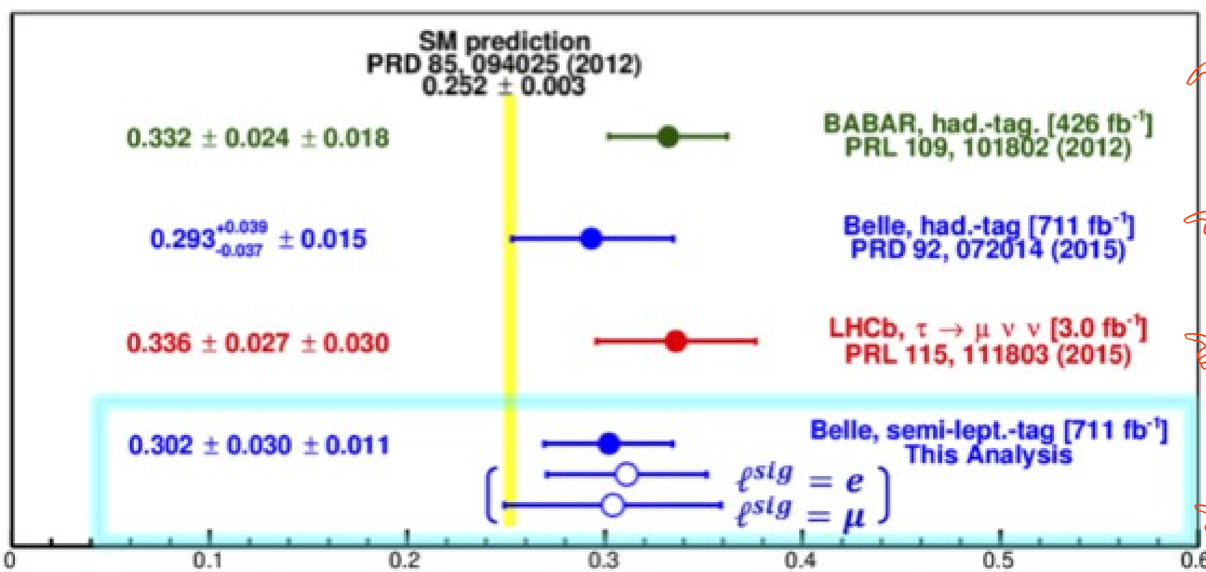

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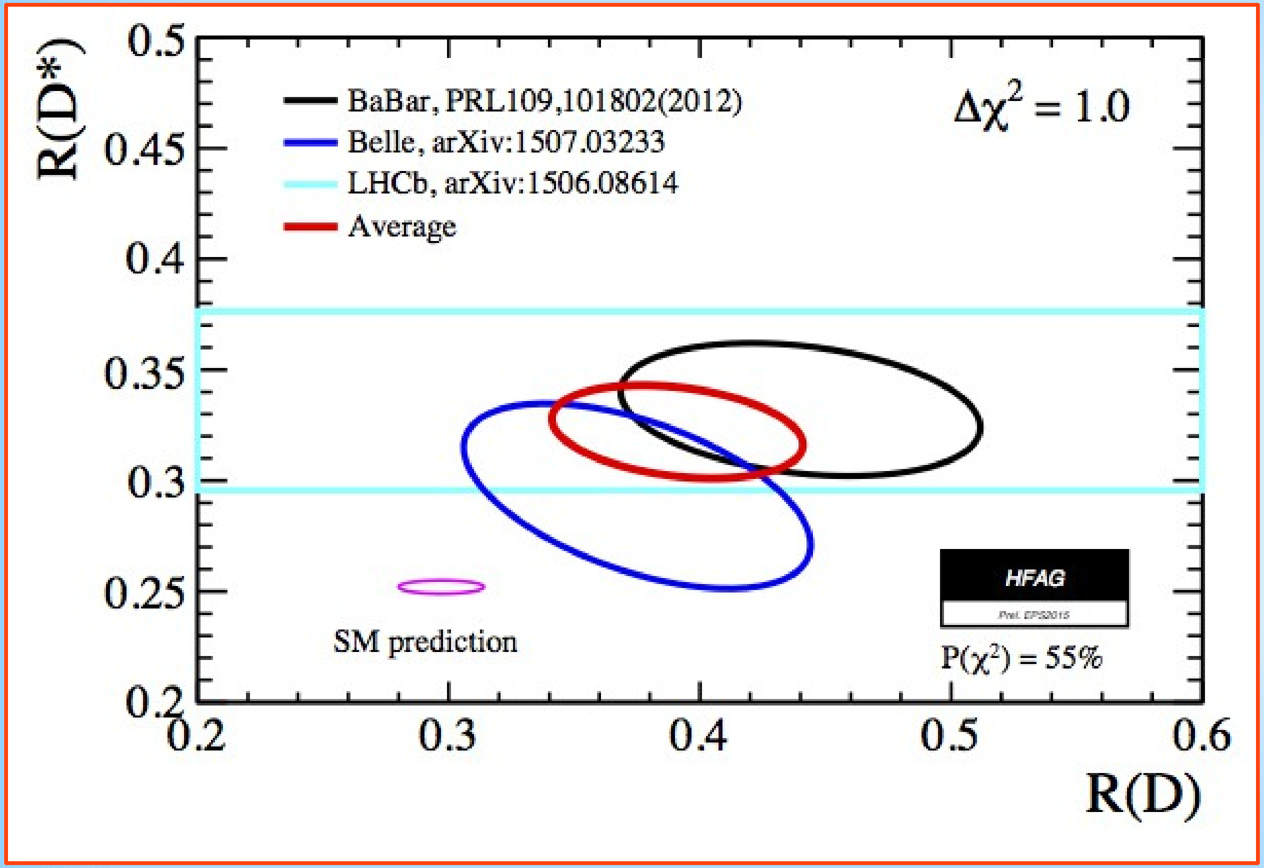

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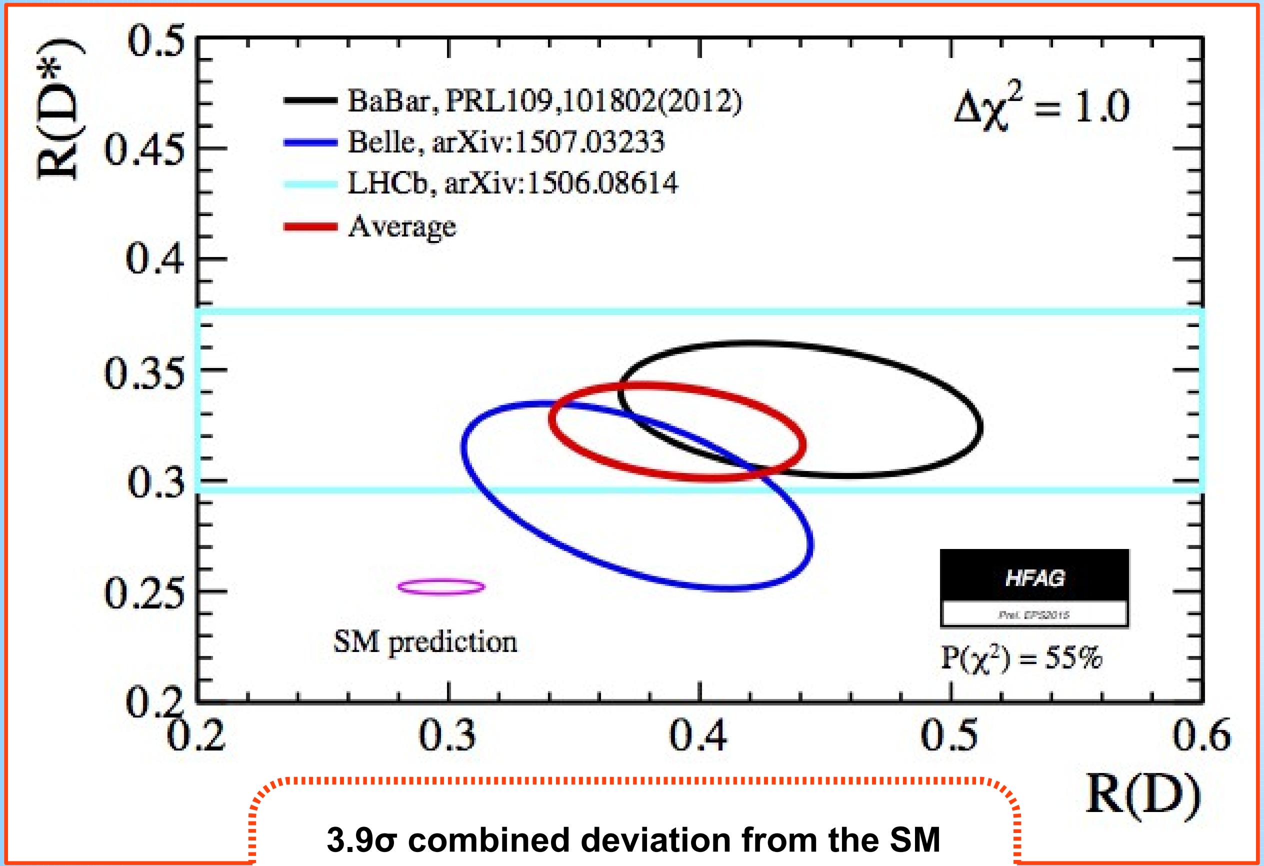

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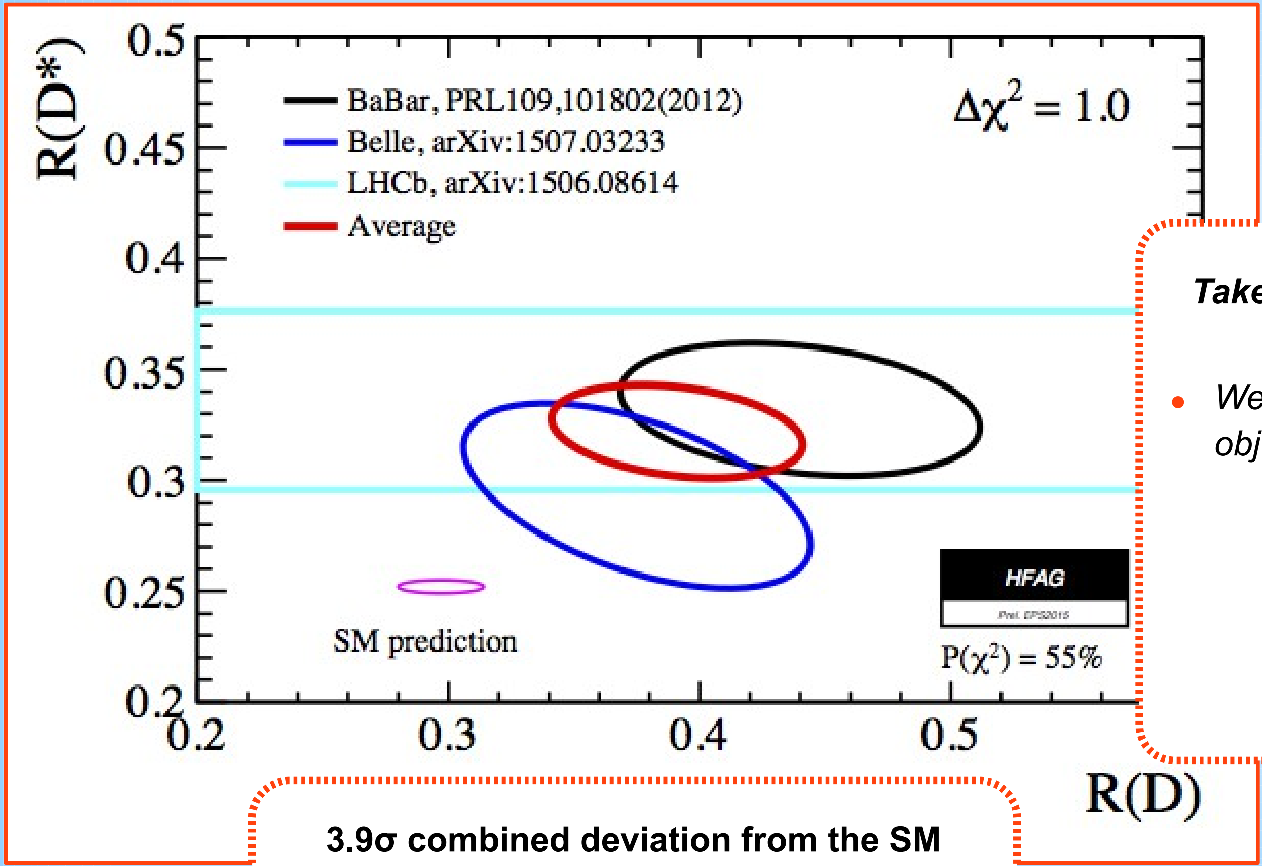

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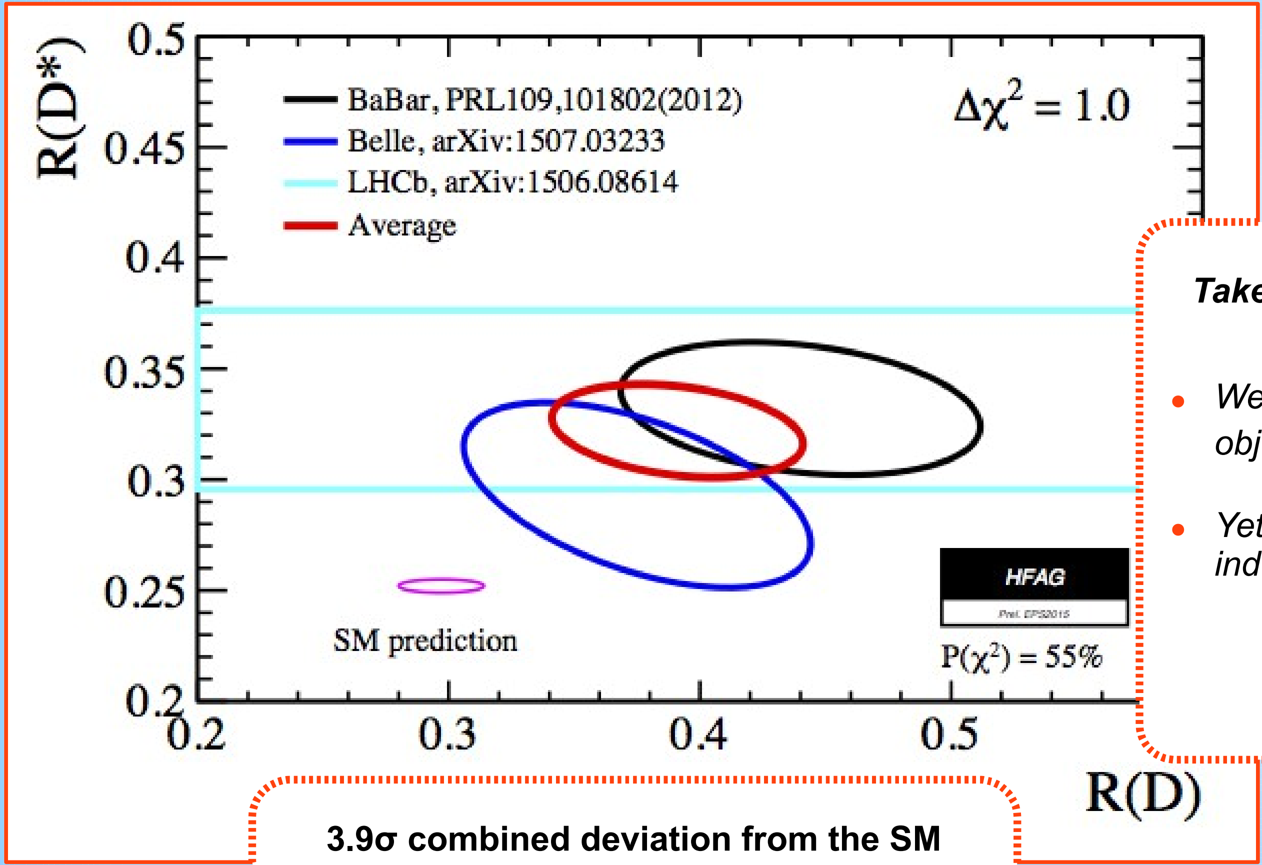

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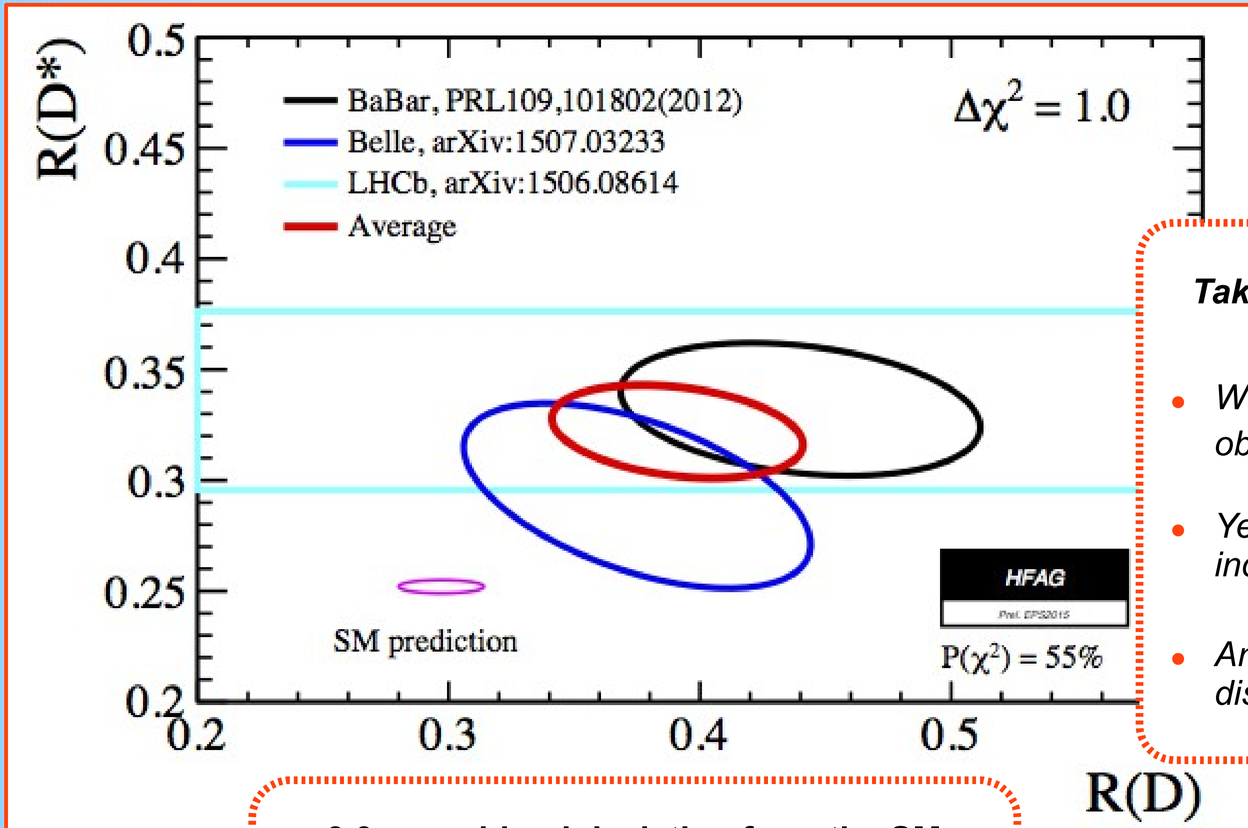

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- *Yet now the effect is seen by three independent experiments*
- *And the effect nicely fits the b → s discrepancies (see later)*

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  - **Q1:** *Can we (easily) make sense of* ❶ to ❺ ?
  - **Q2:** *What are the most immediate signatures to expect ?*

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  Namely, it's not the mass eigenbasis.
  (This basis doesn't yet even exist. We are above the EWSB scale.)

Concerning Q2: most immediate signatures to expect

Basic observation:

- *If R_K is signaling LFNU at a non-SM level, we may also expect LFV at a non-SM level.*

In fact:

- *Consider a new, LFNU interaction above the EWSB scale, e.g. with*

  new vector bosons: $\bar{\ell} Z' \ell$ *or* *leptoquarks:* $\bar{\ell} \varphi q$

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- *Rotating q and ℓ to the mass eigenbasis generates LFV interactions.*

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Can we (easily) make sense of data ❶ to ❺ ?

It is highly non-trivial that a simple consistent BSM picture exists to describe the above data ❶ *to* ❺

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Let's assume the above V – A structure to hold also beyond the SM, namely

$$C_9^{(\ell)} \approx -C_{10}^{(\ell)} \qquad \textit{with} \qquad C_{9,10}^{(\ell)} = C_{9,10}^{\mathrm{SM}} + C_{9,10}^{(\ell),\mathrm{NP}}$$

Our main motivation is phenomenological: it fits the data.
However, there is more: see later

Cf. discussion in Hiller, Schmaltz, PRD 14

Model example:
Glashow, DG, Lane, PRL 2015

- *Our model requirements are:*
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Explaining b → s data

- *Recalling our full Hamiltonian*

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the shift to the C_9 Wilson coeff. in the μμ-channel becomes

$$k_{\mathrm{SM}}\, C_9^{(\mu)} = k_{\mathrm{SM}}\, C_{9,\mathrm{SM}} + \frac{G}{2} (U_L^d)_{33}^* (U_L^d)_{32} |(U_L^\ell)_{32}|^2$$

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The NP contrib. in the ee-channel is negligible, as

$$\left|\left(U_L^\ell\right)_{31}\right|^2 \ll \left|\left(U_L^\ell\right)_{32}\right|^2$$

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$$0.77 \pm 0.20 = \frac{BR(B_s \to \mu\mu)_{\rm exp}}{BR(B_s \to \mu\mu)_{\rm SM}} = \frac{BR(B_s \to \mu\mu)_{\rm SM+NP}}{BR(B_s \to \mu\mu)_{\rm SM}} = \frac{|C_{10}^{\rm SM} + \delta C_{10}|^2}{|C_{10}^{\rm SM}|^2}$$

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implying (within our model) the correlations

$$\frac{BR(B_s \to \mu\mu)_{\rm exp}}{BR(B_s \to \mu\mu)_{\rm SM}} \simeq R_K \simeq \frac{BR(B^+ \to K^+ \mu\mu)_{\rm exp}}{BR(B^+ \to K^+ \mu\mu)_{\rm SM}}$$

Another good reason to pursue accuracy in the $B_s \to \mu\mu$ measurement

See also Hiller, Schmaltz, PRD 14

Explaining b → s data

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- *A fully quantitative test requires a global fit.*

  See in particular [Ghosh, Nardecchia, Renner, JHEP '14] and [Altmannshofer, Straub, EPJC '15]

new physics contributions to the Wilson coefficients. We find that the by far largest decrease in the χ^2 can be obtained either by a negative new physics contribution to C_9 (with $C_9^{\rm NP} \sim -30\% \times C_9^{\rm SM}$), or by new physics in the $SU(2)_L$ invariant direction $C_9^{\rm NP} = -C_{10}^{\rm NP}$, (with $C_9^{\rm NP} \sim -12\% \times C_9^{\rm SM}$). A positive NP contribution to C_{10} alone would also improve the fit, although to a lesser extent. [Altmannshofer, Straub, EPJC '15]

LFV model signatures

As mentioned: if R_K is signaling BSM LFNU, then expect BSM LFV as well

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LFV model signatures

As mentioned: if R_K is signaling BSM LFNU, then expect BSM LFV as well

☑ $$\frac{BR(B^+ \to K^+ \mu e)}{BR(B^+ \to K^+ \mu\mu)} = \boxed{\frac{|\delta C_{10}|^2}{|C_{10}^{SM} + \delta C_{10}|^2}} \cdot \frac{|(U_L^\ell)_{31}|^2}{|(U_L^\ell)_{32}|^2} \cdot \boxed{2}$$

$= 0.159^2$ according to R_K

$\mu^+ e^-$ & $\mu^- e^+$ modes

$$BR(B^+ \to K^+ \mu e) < 2.2 \times 10^{-8} \cdot \frac{|(U_L^\ell)_{31}|^2}{|(U_L^\ell)_{32}|^2}$$

The current BR(B+ → K+ μe) limit yields the weak bound

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☑ *There is even an interesting signature outside B physics: K → (π) ℓ ℓ'*
It is measurable at NA62, that just started taking data

More signatures

For a recent discussion:
Alonso, Grinstein, Martin-Camalich,
PRL 14

- *Being defined above the EWSB scale, our assumed operator* $G\,\bar{b}'_L \gamma^\lambda b'_L\, \bar{\tau}'_L \gamma_\lambda \tau'_L$ *must actually be made invariant under* $SU(3)_c \times SU(2)_L \times U(1)_Y$

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See:
Bhattacharya, Datta, London, Shivashankara, PLB 15

$$\bar{b}'_L \gamma^\lambda b'_L\, \bar{\tau}'_L \gamma_\lambda \tau'_L \quad \xrightarrow[\text{inv.}]{SU(2)_L} \quad \begin{cases} \bar{Q}'_L \gamma^\lambda Q'_L\, \bar{L}'_L \gamma_\lambda L'_L & \text{[neutral-current int's only]} \\ \bar{Q}'^i_L \gamma^\lambda Q'^j_L\, \bar{L}'^j_L \gamma_\lambda L'^i_L & \text{[also charged-current int's]} \end{cases}$$

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- *Thus, the generated structures are all of:*

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- *After rotation to the mass basis (unprimed), the last structure contributes to* $\Gamma(b \to c\, \tau\, \bar{\nu}_i)$

Can explain BaBar + Belle + LHCb deviations on $R(D^{(*)}) = \dfrac{BR(\bar{B} \to D^{(*)+} \tau^- \bar{\nu}_\tau)}{BR(\bar{B} \to D^{(*)+} \ell^- \bar{\nu}_\ell)}$

Some models explaining R_K and $R(D^*)$

Bauer-Neubert, PRL 2016

- *Introduce one single leptoquark scalar, transforming as (**3**, **1**, –1/3) under $SU(3)_c \times SU(2)_L \times U(1)_Y$*
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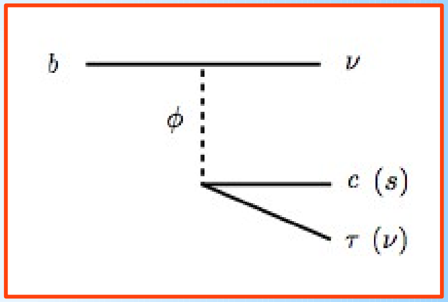

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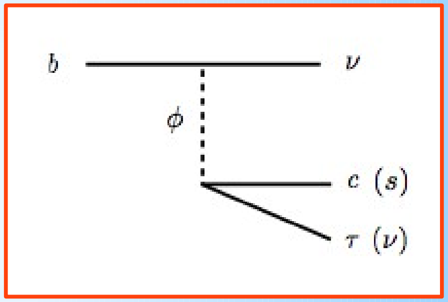

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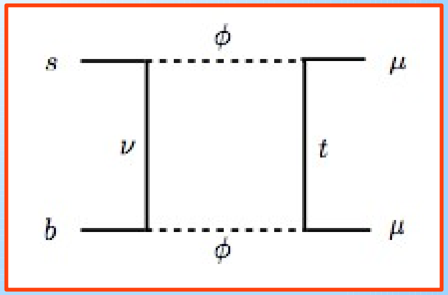

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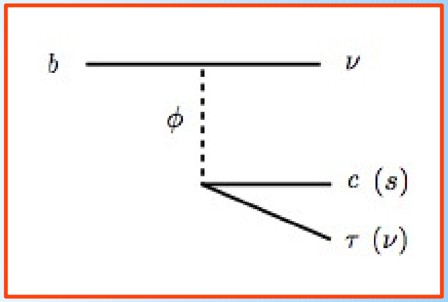

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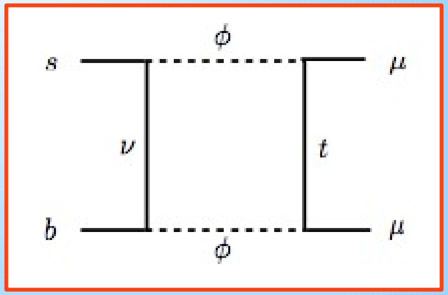

- *With $M_\phi \sim 1$ TeV and O(1) generation-diagonal couplings, contributions are just the right size*

One model explaining all flavor anomalies and the diphoton resonance

Buttazzo, Greljo, Isidori, Marzocca
1604.03940

- *New non-Abelian strongly interacting sector with N_{TC} new "techni-fermions" (TC fermions).*

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⇒ *One of the pNGB is the 750-GeV state seen by Atlas & CMS*
It couples to 2 gluons and decays to 2γ via the anomaly

One model explaining all flavor anomalies and the diphoton resonance: continued

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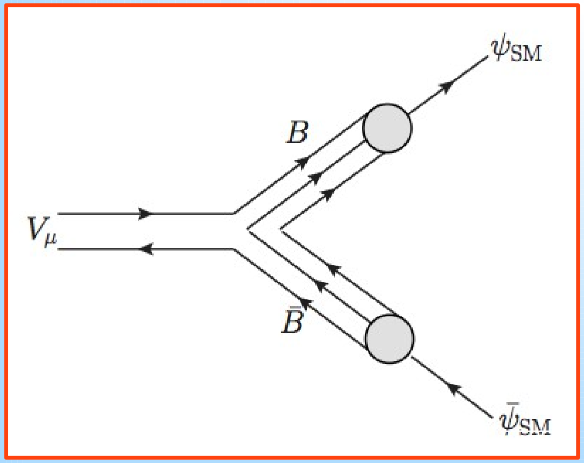

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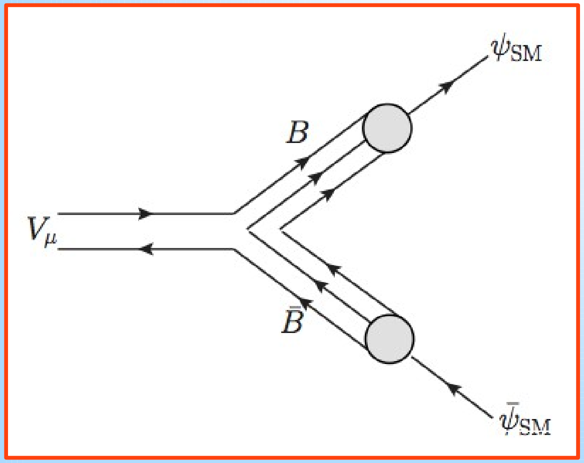

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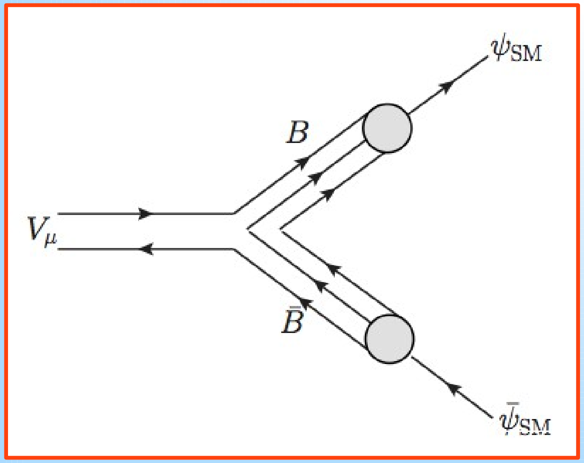

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- *Integrating out the vector mesons then yields automatically (among the others) the effective operator*

$$H_{NP} = G\, \bar{b}'_L \gamma^\lambda b'_L\, \bar{\tau}'_L \gamma_\lambda \tau'_L$$

proposed in [Glashow, DG, Lane, PRL 15]

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- *Most promising theory direction (to me): Seeking for a correlated explanation of the diphoton excess and of the flavor anomalies.*

Spares

Frequently made objection:
what about the SM? It has LFNU, but no LFV

Take the SM with zero ν masses.

- *Charged-lepton Yukawa couplings are LFNU, but they are diagonal in the mass eigenbasis (hence no LFV)*

Or more generally, take the SM plus a minimal mechanism for ν masses.

- *Physical LFV will appear in W couplings, but it's suppressed by powers of $(m_\nu / m_W)^2$*

Bottom line: in the SM+ν there is LFNU, but LFV is nowhere to be seen (in decays)

- *But nobody ordered that the reason (=tiny m_ν) behind the above conclusion be at work also beyond the SM*

So, BSM LFNU $\Rightarrow$ BSM LFV (i.e. not suppressed by m_ν)

More quantitative LFV predictions

Reminder:

$$(U_L^\ell)^\dagger \, Y_\ell \, U_R^\ell = \hat{Y}_\ell$$

- *More quantitative LFV predictions require knowledge of the U_L^ℓ*
- *One approach:* *DG, Lane, 1507.01412*
  - *Appelquist-Bai-Piai ansatz:*
    the flavor-SU(3) rotations are not all independent. Choosing 3 to be the independent ones allows to predict one SM Yukawa in terms of the other two.
  - *One can thereby determine Y_ℓ in terms of Y_u and Y_d*
  - *But we don't know Y_u and Y_d entirely, so we take an (independently motivated) model for them, reproducing quark masses and the CKM matrix [Martin-Lane, PRD 2005].*
- *Another approach:* *Boucenna, Valle, Vicente, PLB 2015*
  - *One has $(U_L^\ell)^\dagger \, U_L^\nu$ = PMNS matrix*
  - *Taking $U_L^\nu = 1$, U_L^ℓ can be univocally predicted*

More quantitative LFV predictions

LFV predictions in one of the two scenarios of [DG, Lane]

	$B^+ \to K^+ \mu^\pm \tau^\mp$	$B^+ \to K^+ e^\pm \tau^\mp$	$B^+ \to K^+ e^\pm \mu^\mp$
	1.14×10^{-8}	3.84×10^{-10}	0.52×10^{-9}
Exp:	$< 4.8 \times 10^{-5}$	$< 3.0 \times 10^{-5}$	$< 9.1 \times 10^{-8}$

	$B_s \to \mu^\pm \tau^\mp$	$B_s \to e^\pm \tau^\mp$	$B_s \to e^\pm \mu^\mp$
	1.37×10^{-8}	4.57×10^{-10}	1.73×10^{-12}
Exp:	—	—	$< 1.1 \times 10^{-8}$

All predictions are phase-space corrected.