Lepton Universality (Violation, and its consequences)

Diego Guadagnoli
LAPTh Annecy (France)

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

$B_s \to \varphi\ \mu\mu$

The R_K pattern, with data in the muon channel lower than the SM prediction, is supported by LHCb measurements of another b-to-s transition: $B_s \to \varphi\ \mu\mu$

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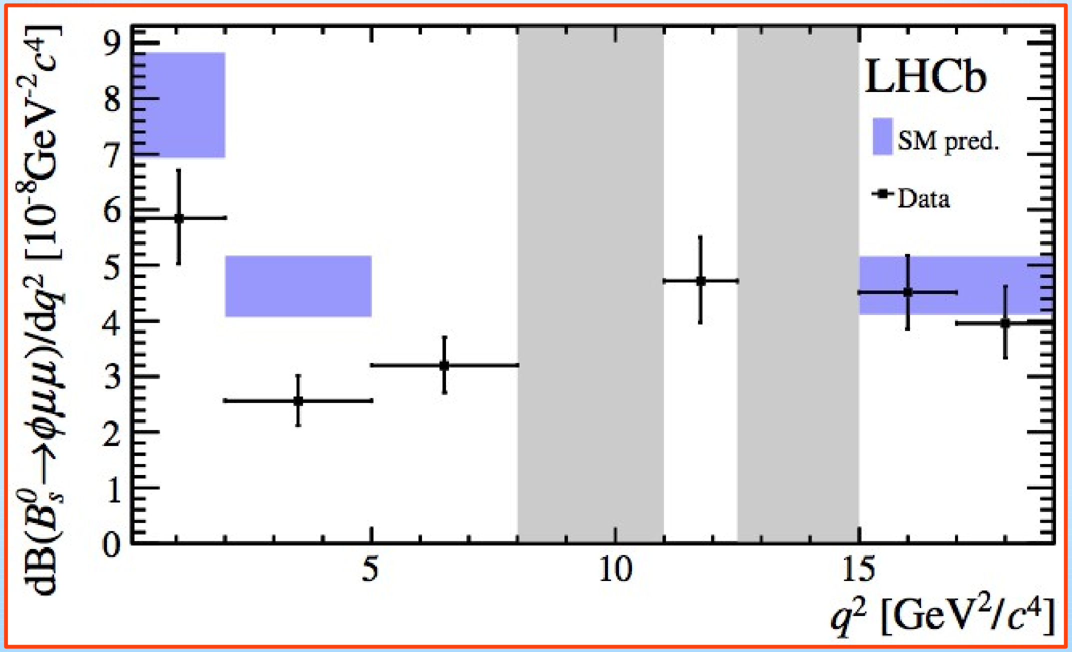

The measured branching fraction is compatible with the previous measurement [3] and lies below SM expectations. For the q^2 region $1.0 < q^2 < 6.0\,\mathrm{GeV}^2/c^4$ the differential branching fraction of $(2.58^{+0.33}_{-0.31} \pm 0.08 \pm 0.19) \times 10^{-8}\,\mathrm{GeV}^{-2}c^4$ is more than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

$B \to K^* \mu\mu$ angular analysis:

The P'_5 anomaly

LHCb can perform a fully angular analysis of the decay products in $B \to K^* \mu\mu$

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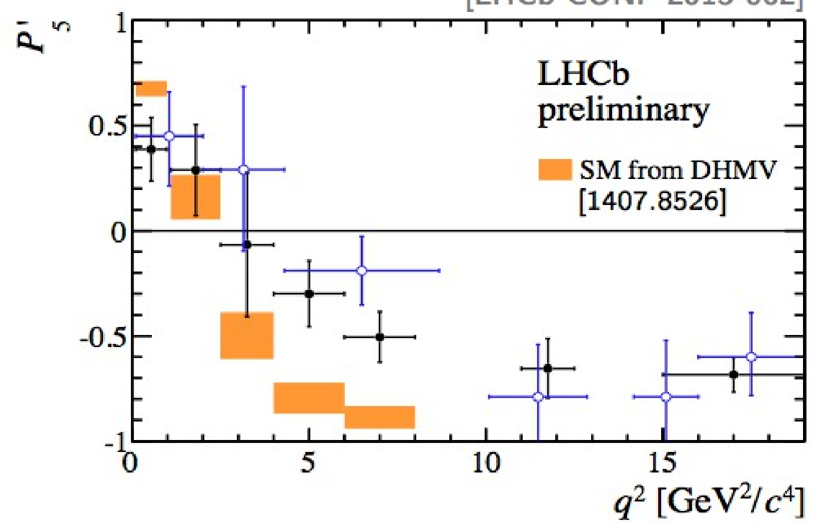

- Tension seen in P'_5 in [PRL 111, 191801 (2013)] confirmed
- $[4.0, 6.0]$ and $[6.0, 8.0]$ GeV$^2/c^4$ show deviations of 2.9σ each
- Naive combination results in a significance of 3.7σ
- Compatible with $1\,\text{fb}^{-1}$ measurement

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

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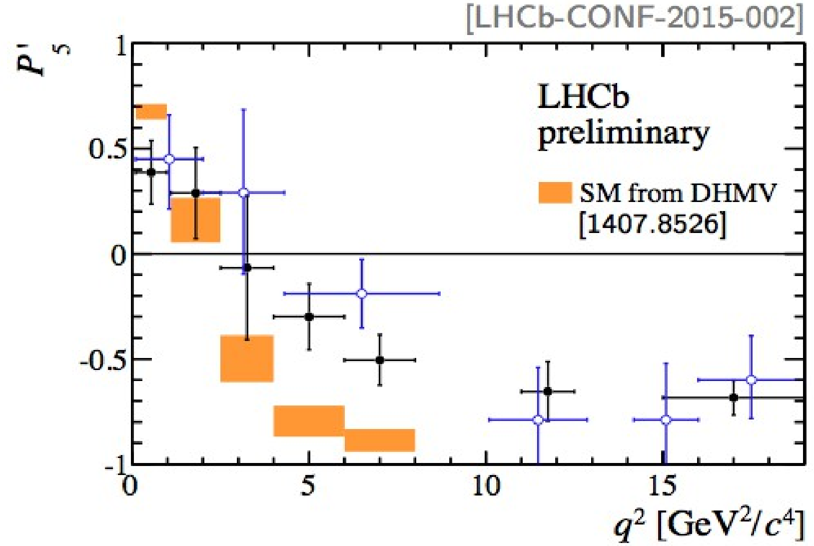

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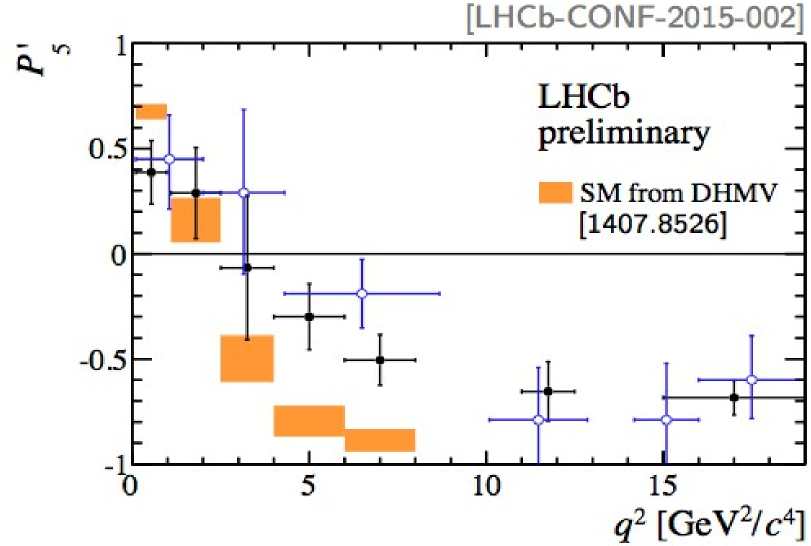

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  - Debate on the role of
    - Subleading terms in $1/m_b$
    - $c\bar{c}$ loops and their resummation

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

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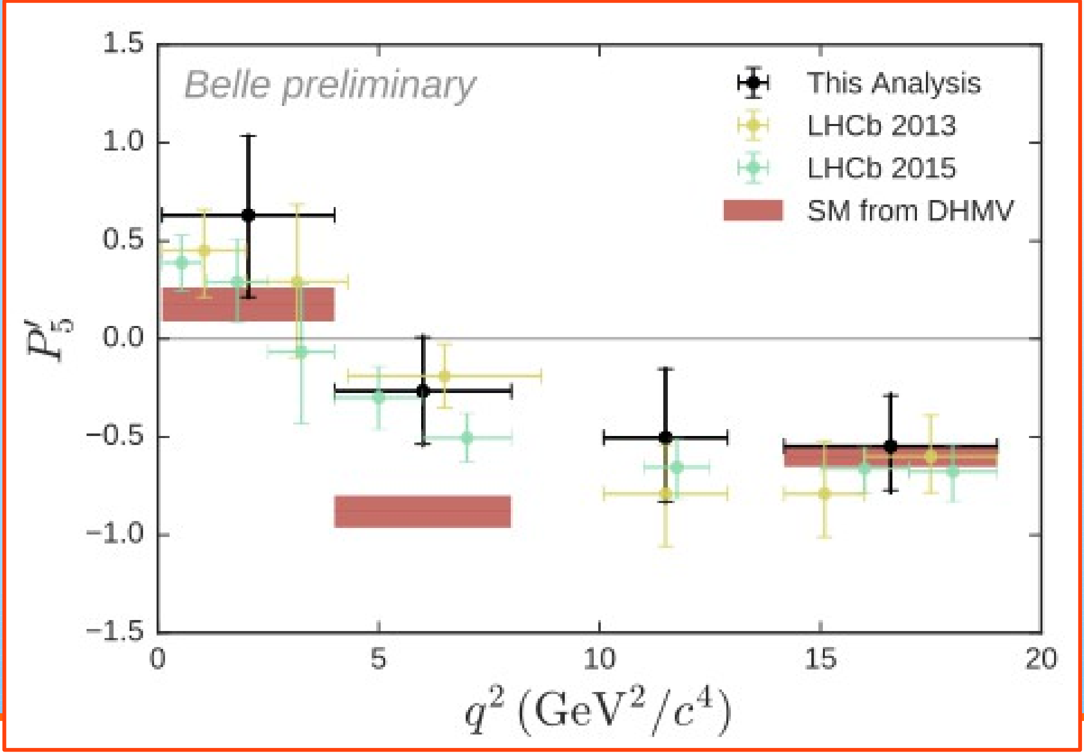

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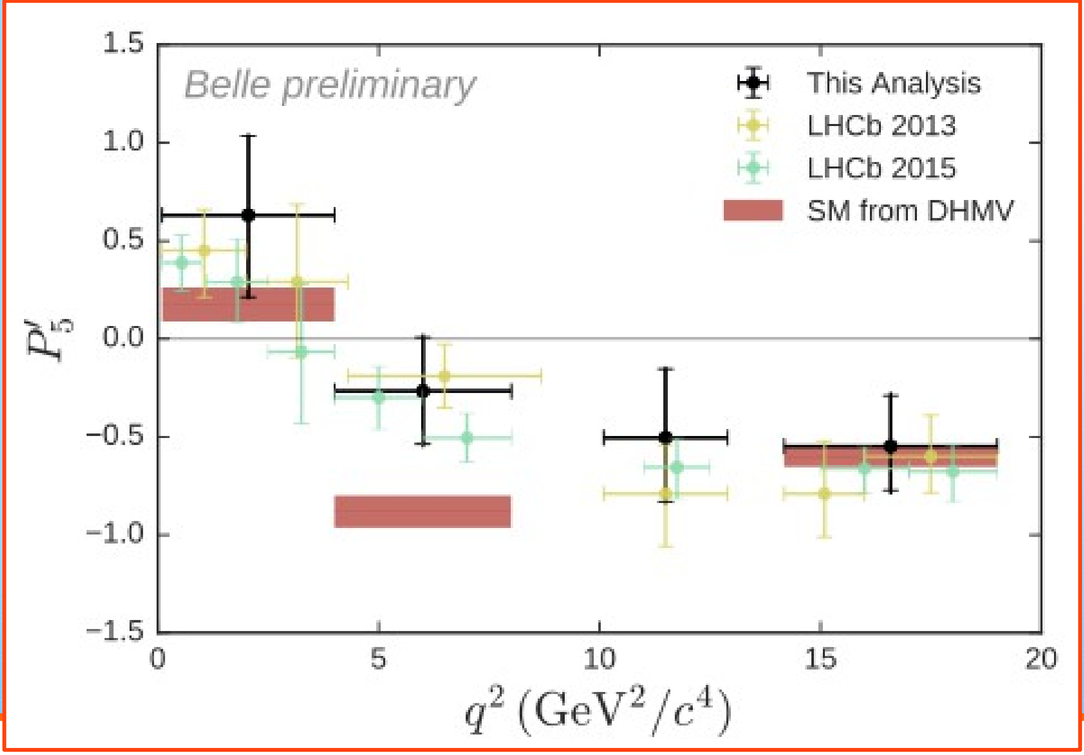

- **Conclusion:**

  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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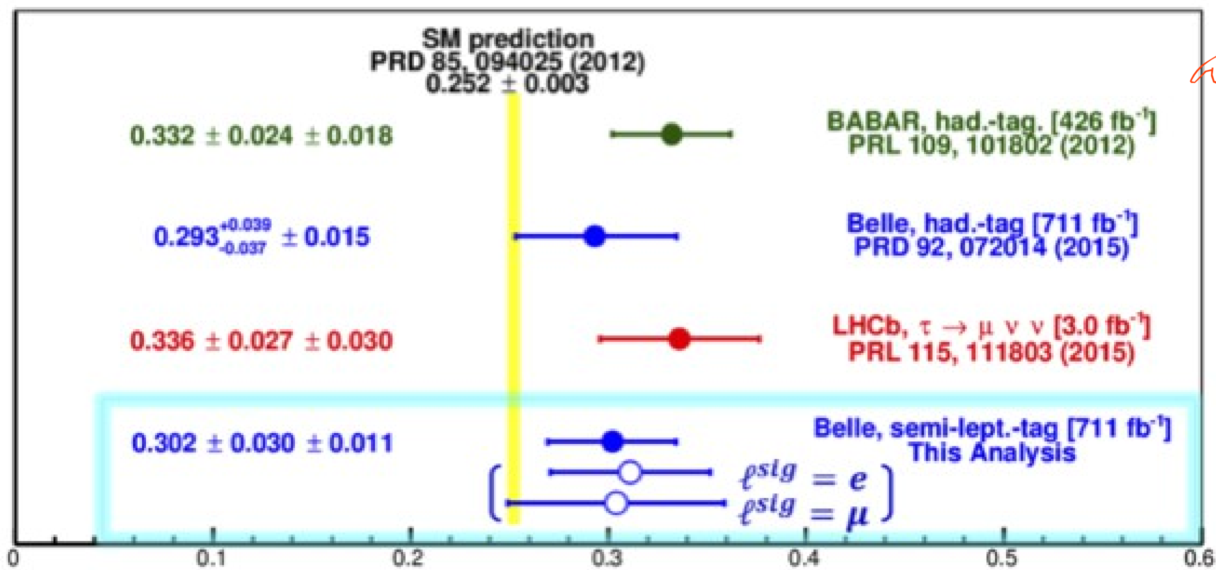

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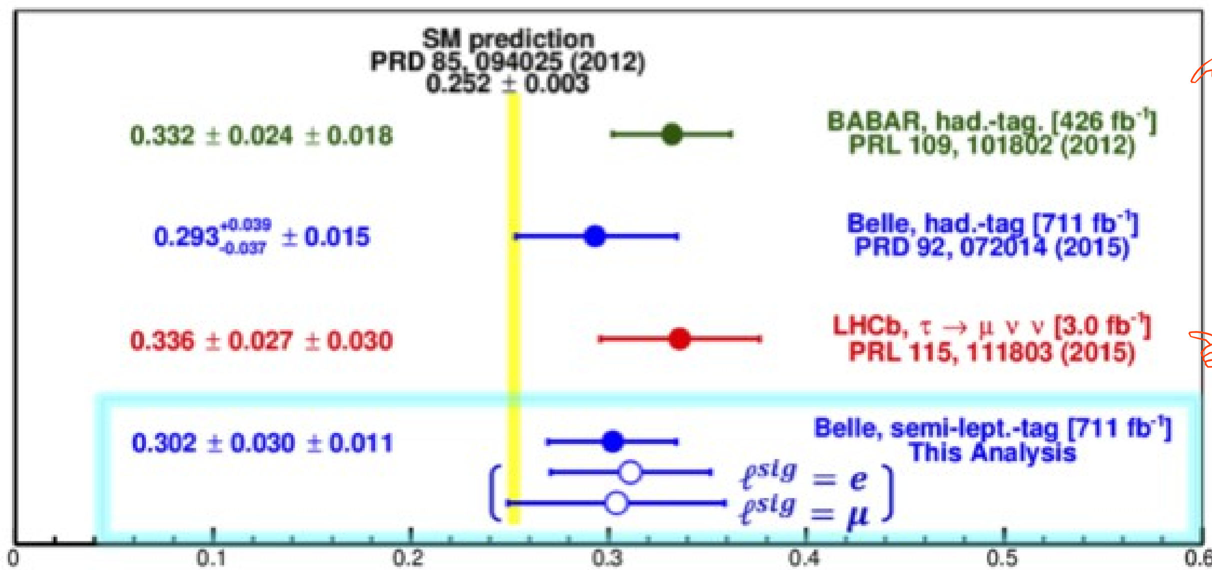

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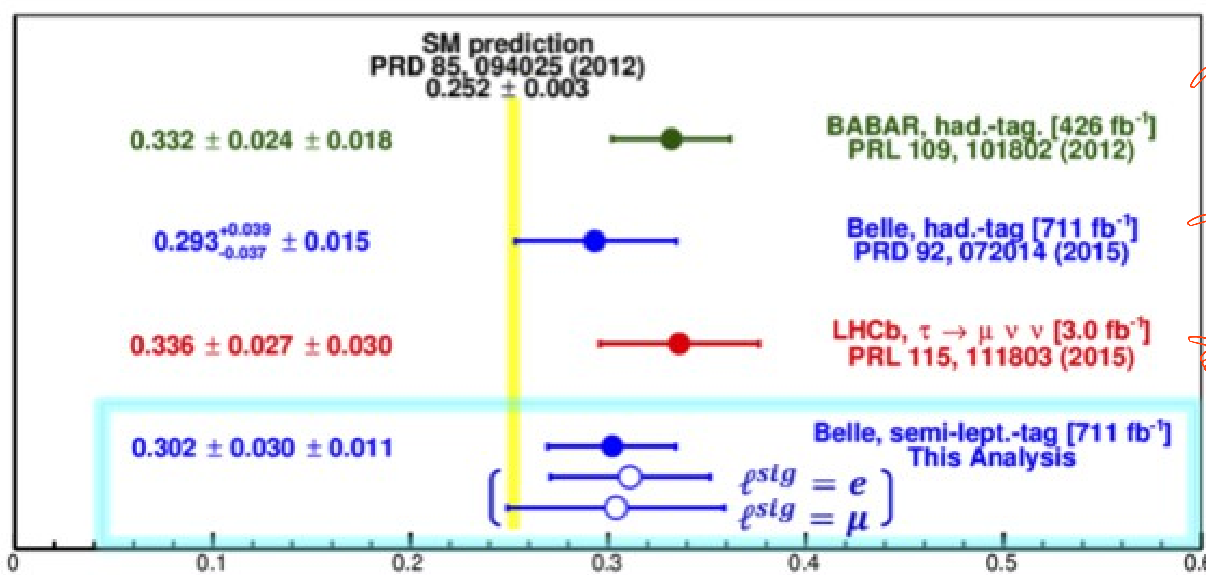

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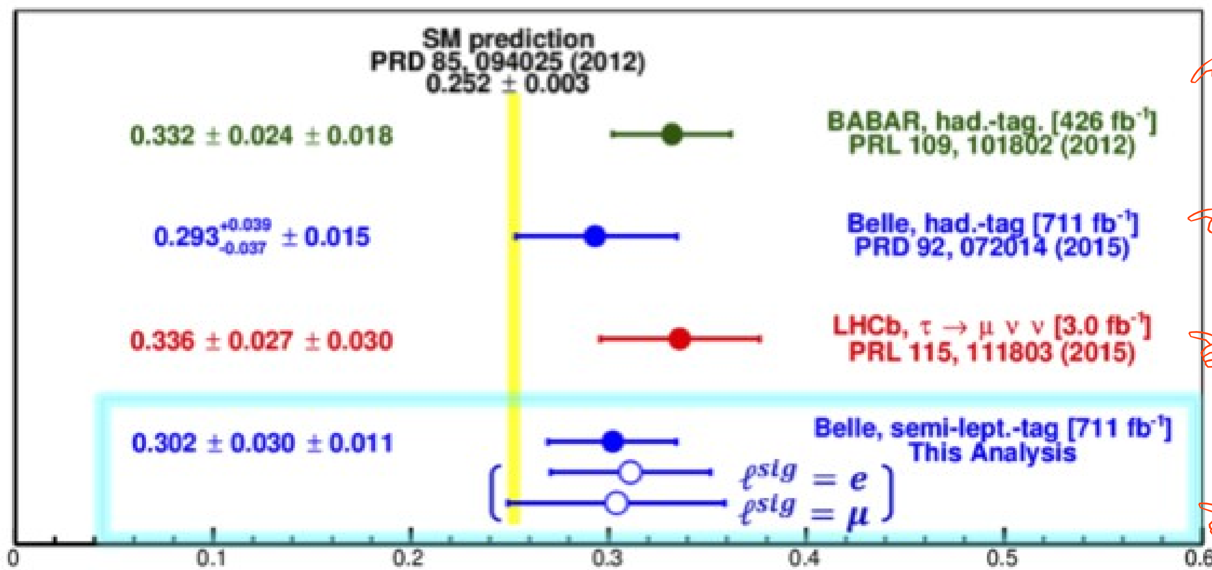

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2016: Belle also starts to See an R(D*) excess (semi-lep. tau)

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- *Yet, focusing (for the moment) on the $b \to s$ discrepancies*

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

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

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

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- *Advocating the same (V – A) x (V – A) structure also for the corrections to $C_{9,10}^{SM}$ (in the μμ-channel only!) would account for:*
  - *R_K lower than 1*
  - *$B \to K\,\mu\mu$ & $B_s \to \mu\mu$ BR data below predictions*
  - *the P_5' anomaly in $B \to K^*\,\mu\mu$*

Concerning Q1: can we easily make theoretical sense of these data?

- *Yes we can. Consider the following Hamiltonian*

About equal size & opposite sign in the SM (at the m_b scale)

$$H_{\mathrm{SM+NP}}(\bar{b} \to \bar{s}\,\mu\,\mu) = -\frac{4\,G_F}{\sqrt{2}} V_{tb}^* V_{ts} \frac{\alpha_{\mathrm{em}}}{4\pi} \left[\bar{b}_L \gamma^\lambda s_L \cdot \left(\boxed{C_9^{(\mu)}} \bar{\mu} \gamma_\lambda \mu + \boxed{C_{10}^{(\mu)}} \bar{\mu} \gamma_\lambda \gamma_5 \mu \right) \right]$$

- *Advocating the same (V – A) x (V – A) structure also for the corrections to $C_{9,10}^{SM}$ (in the μμ-channel only!) would account for:*
  - *R_K lower than 1*
  - *$B \to K\,\mu\mu$ & $B_s \to \mu\mu$ BR data below predictions*
  - *the P_5' anomaly in $B \to K^*\,\mu\mu$*

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

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]

For analogous conclusions, see also [Ghosh, Nardecchia, Renner, JHEP '14]

Model example:
Glashow, DG, Lane, PRL 2015

- *As we saw before, all $b \to s$ data are explained at one stroke if:*
  - $C_9^{(\ell)} \approx -C_{10}^{(\ell)}$ *(V – A structure)*
  - $\left|C_{9,\mathrm{NP}}^{(\mu)}\right| \gg \left|C_{9,\mathrm{NP}}^{(e)}\right|$ *(LFNU)*

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

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Explaining b → s data

- *Recalling our full Hamiltonian*

$$H_{\mathrm{SM+NP}}(\bar{b} \to \bar{s}\mu\mu) = -\frac{4G_F}{\sqrt{2}} V_{tb}^* V_{ts} \frac{\alpha_{\mathrm{em}}}{4\pi} \left[\bar{b}_L \gamma^\lambda s_L \cdot \left(C_9^{(\mu)} \bar{\mu} \gamma_\lambda \mu + C_{10}^{(\mu)} \bar{\mu} \gamma_\lambda \gamma_5 \mu \right) \right]$$

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

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

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

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

Explaining b → s data

- *So, in the above setup*

$$R_K \approx \frac{|C_9^{(\mu)}|^2 + |C_{10}^{(\mu)}|^2}{|C_9^{(e)}|^2 + |C_{10}^{(e)}|^2} \simeq \frac{2|C_{10}^{\mathrm{SM}} + \delta C_{10}|^2}{2|C_{10}^{\mathrm{SM}}|^2}$$

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

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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

LFV model signatures

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

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

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

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☑ *An analogous argument holds for purely leptonic modes*

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Reminder:

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

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More on LFV model signatures

DG, Melikhov, Reboud, 2016

- *Bottom line: we can reasonably expect one of the $B \to K \ell \ell'$ decays in the 10^{-8} ballpark and one of the $B \to \ell \ell'$ decays in the 10^{-10} one, namely ~ 5% of $BR(B_s \to \mu\mu)$*

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  - *γ = "hard" photon*

    (hard = outside of the di-lepton Invariant-mass signal window)

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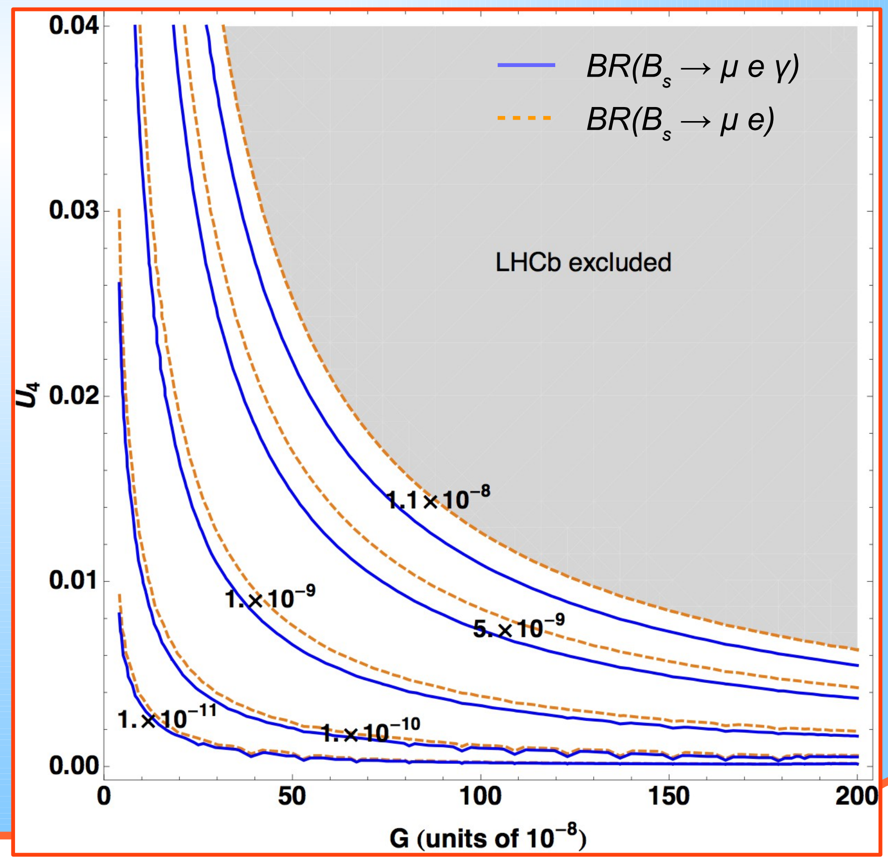
Enhancement by ~ 30%

Inclusion of the radiative mode more-than-doubles statistics of the non-radiative



LFV in K decays

- *The interaction advocated in Glashow et al.*

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

can also manifest itself in $K \to (\pi)\, \ell\, \ell'$, for example

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- *Exp limits*

$$\frac{\Gamma(K_L^0 \to e^\pm \mu^\mp)}{\Gamma(K^+ \to \mu^+ \nu_\mu)} < 1.7 \times 10^{-12}$$

BNL E871 Collab., PRL 1998

$$\frac{\Gamma(K^+ \to \pi^+ \mu^+ e^-)}{\Gamma(K^+ \to \pi^0 \mu^+ \nu_\mu)} < 3.9 \times 10^{-10}$$

BNL E865 Collab., PRD 2005

LFV in K decays

- *Defining the basic quantity*

$$\beta^{(K)} = \frac{G\left(U_L^d\right)^*_{32}\left(U_L^d\right)_{31}\left(U_L^\ell\right)^*_{31}\left(U_L^\ell\right)_{32}}{\frac{4\,G_F}{\sqrt{2}}V_{us}^*} \quad \Rightarrow \quad \left|\beta^{(K)}\right|^2 = 2.15\times 10^{-14}$$

(*within "model A" of DG, Lane, PLB 2015*)

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I obtain

$$\frac{\Gamma\left(K_L^0 \to e^\pm \mu^\mp\right)}{\Gamma\left(K^+ \to \mu^+ \nu_\mu\right)} = \left|\beta^{(K)}\right|^2$$

LFV in K decays

- *Defining the basic quantity*

$$\beta^{(K)} = \frac{G\,(U_L^d)^*_{32}(U_L^d)_{31}(U_L^\ell)^*_{31}(U_L^\ell)_{32}}{\frac{4\,G_F}{\sqrt{2}}\,V^*_{us}} \quad \Rightarrow \quad \left|\beta^{(K)}\right|^2 = 2.15\times 10^{-14}$$

(*within "model A" of DG, Lane, PLB 2015*)

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with

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$$\mathrm{BR}(K^+ \to \pi^+ \mu^\pm e^\mp) \approx 3 \times 10^{-15}$$

with

$$\mathrm{BR}(K^+ \to \pi^0 \mu^+ \nu_\mu) \approx 3\,\%$$

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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- *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* $R(D^{(*)}) = \dfrac{BR(\bar{B} \to D^{(*)+} \tau^- \bar{\nu}_\tau)}{BR(\bar{B} \to D^{(*)+} \ell^- \bar{\nu}_\ell)}$

But this coin has a flip side

Feruglio, Paradisi, Pattori, 2016

- *Properly taking into account RGE running from the NP scale to the scale(s) of the low-energy processes, one finds non-trivial constraints from:*
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- *Also LFV decays of leptons are generated, and they provide sensitive probes.*

  E.g.:

$$\mathrm{BR}(\tau \to 3\mu) \;\&\; \mathrm{BR}(\tau \to \mu\rho) \sim 5\times 10^{-8}$$

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

Bauer-Neubert, PRL 2016

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

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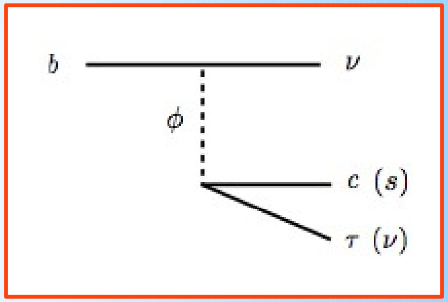

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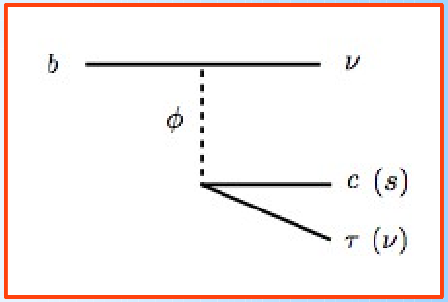

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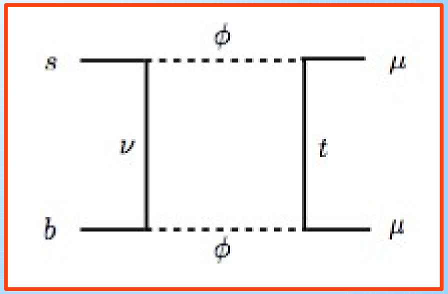

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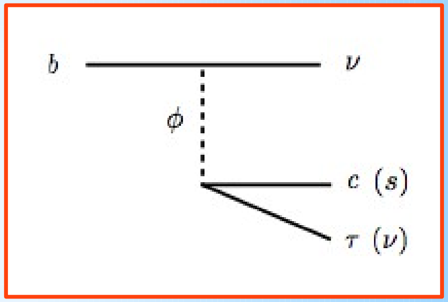

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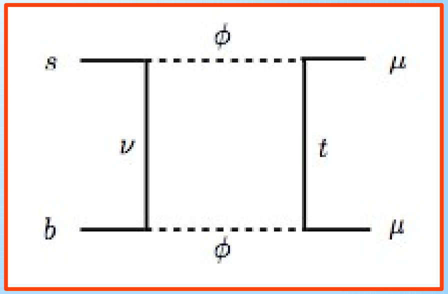

- *With M_ϕ ~ 1 TeV and O(1) generation-diagonal couplings, contributions are just the right size*

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

Buttazzo, Greljo, Isidori, Marzocca 1604.03940

- *There are also vector mesons, like QCD's rho.*
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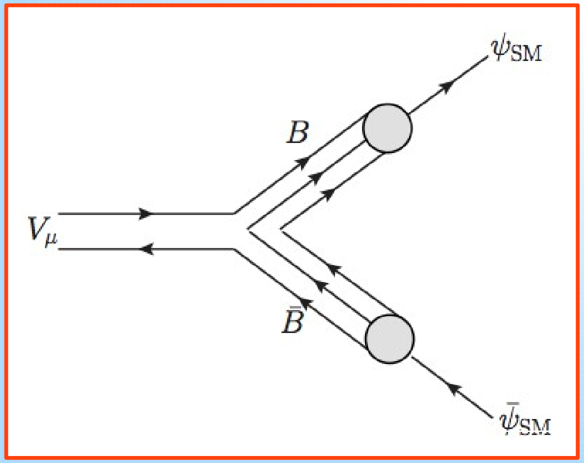

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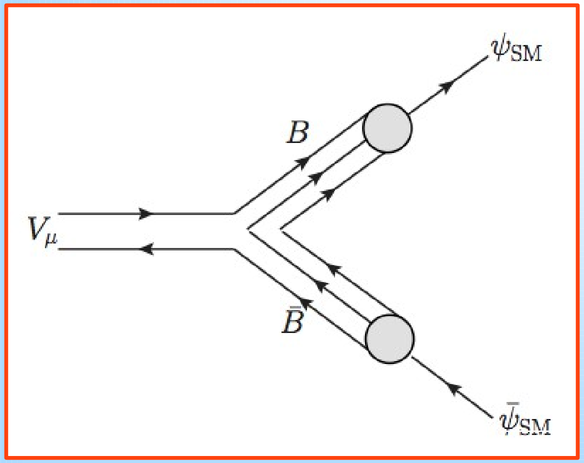

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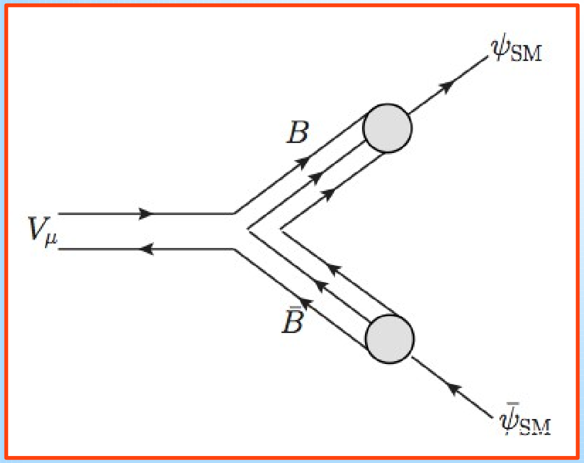

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- *Integrating out the vector mesons then yields automatically (among the others) the effective operator*

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

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

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  Their most convincing aspects are the following:

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- *Early to draw conclusions. But Run II will provide a definite answer*

- *Timely to propose further tests. One promising direction is that of LFV.*
  Plenty of channels, many of which largely untested.