b $\rightarrow$ s : Theory Status

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CNRS, LAPTh Annecy

This talk assignment before Dec. 20, 2022

This talk assignment after Dec. 20, 2022

Before any anomaly

Why new physics in B decays

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- b $\rightarrow$ s transitions are the FCNCs closest to 3rd gen. physics

Take meson mixings as an example

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[Isidori-Nir-Perez, 1002.0900]

Operator	Bounds on Λ in TeV ($c_{ij}=1$) Re	Bounds on Λ in TeV ($c_{ij}=1$) Im	Bounds on c_{ij} ($\Lambda = 1$ TeV) Re	Bounds on c_{ij} ($\Lambda = 1$ TeV) Im	Observables
$(\bar{s}_L \gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	$\Delta m_K;\ \epsilon_K$
$(\bar{s}_R\, d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	$\Delta m_K;\ \epsilon_K$
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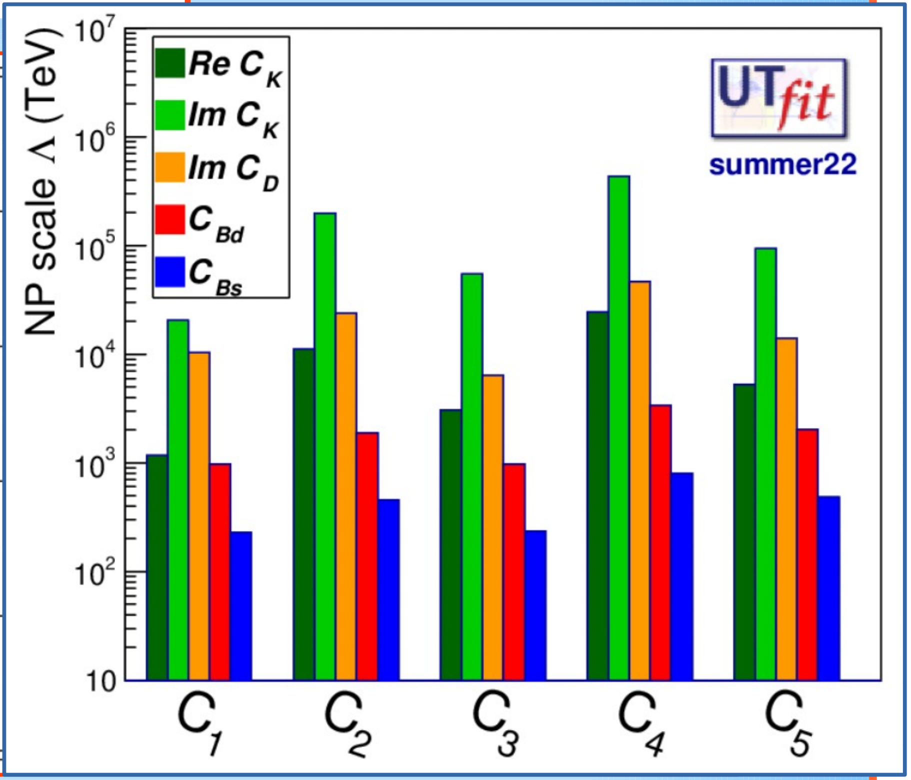

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- In either case, if focus is on the highest scales attainable, flavour observables remain among the deepest probes

Anomalies (?)

NP before Dec. 20

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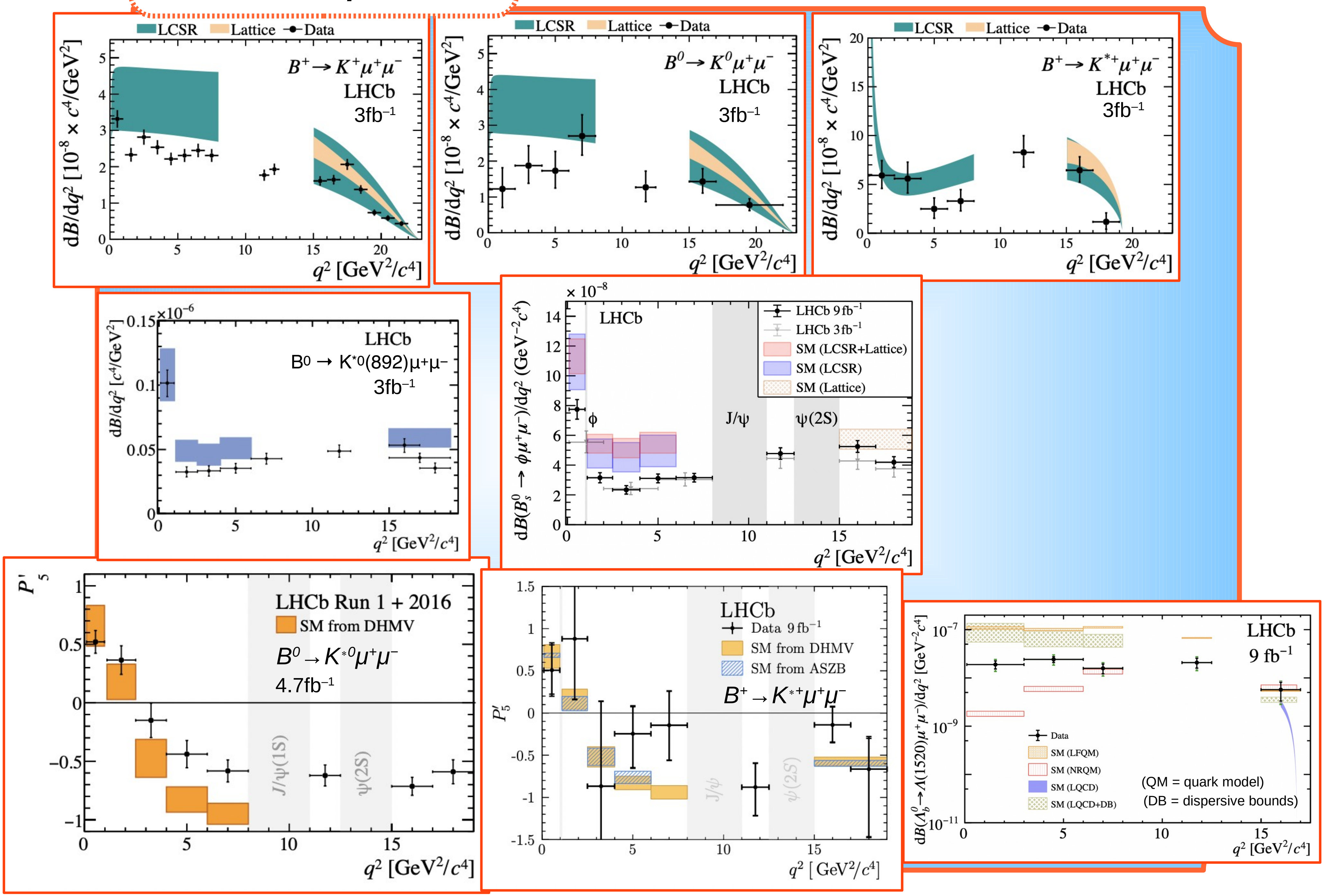
- But it was supported by a number of (less TH-clean) measurements
  - that in isolation displayed only mild disagreements
  - but in aggregate suggested a coherent picture

NP after Dec. 20

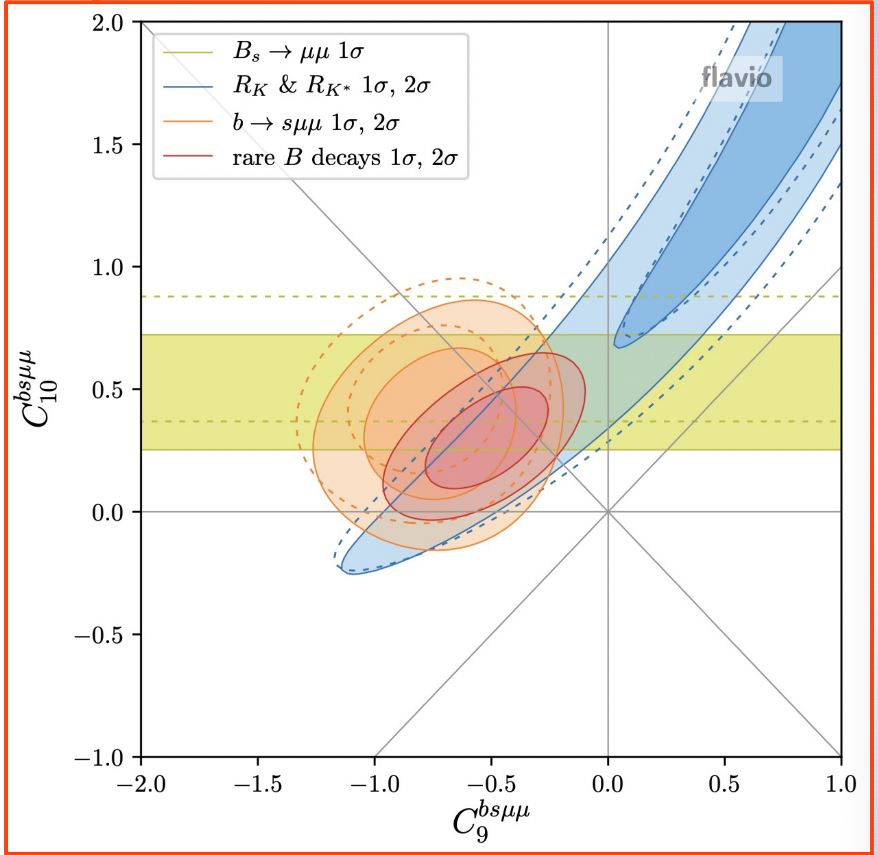
- The more (TH-)solid NP hints have disappeared – overnight.
- The remaining discrepancies (in $b \to s$ BRs and angular obs. & in $RD^{(*)}$) are debatable

$b \to s$ discrepant data



WET bounds

[Altmannshofer, Stangl, 2103.13370]



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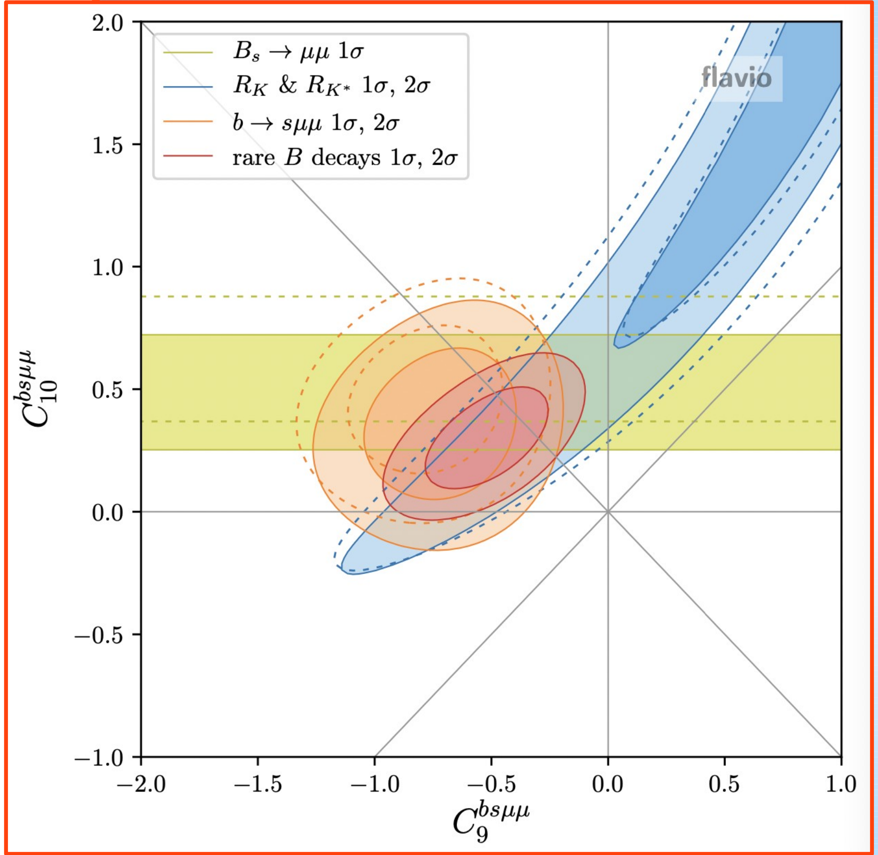
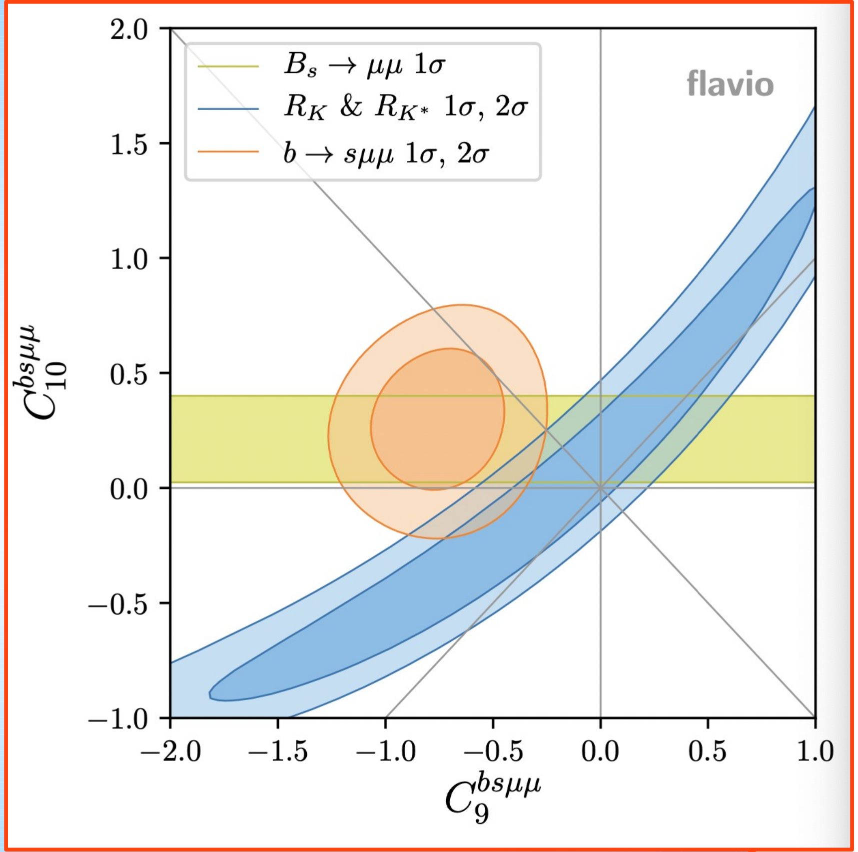


[Greljo *et al.*, 2212.10497]



Tension between LFU ratios (blue) and $b \to s\, \mu^+\mu^-$ data (orange)

WET bounds

[**Greljo *et al.*, 2212.10497**]

Tension solvable with LFU NP, in either the C_9 or the $C_9 = -C_{10}$ direction

$$C_9^{bsee} = C_9^{\text{univ.}} \qquad C_9^{bs\mu\mu} = C_9^{\text{univ.}} + \Delta C_9^{bs\mu\mu}$$

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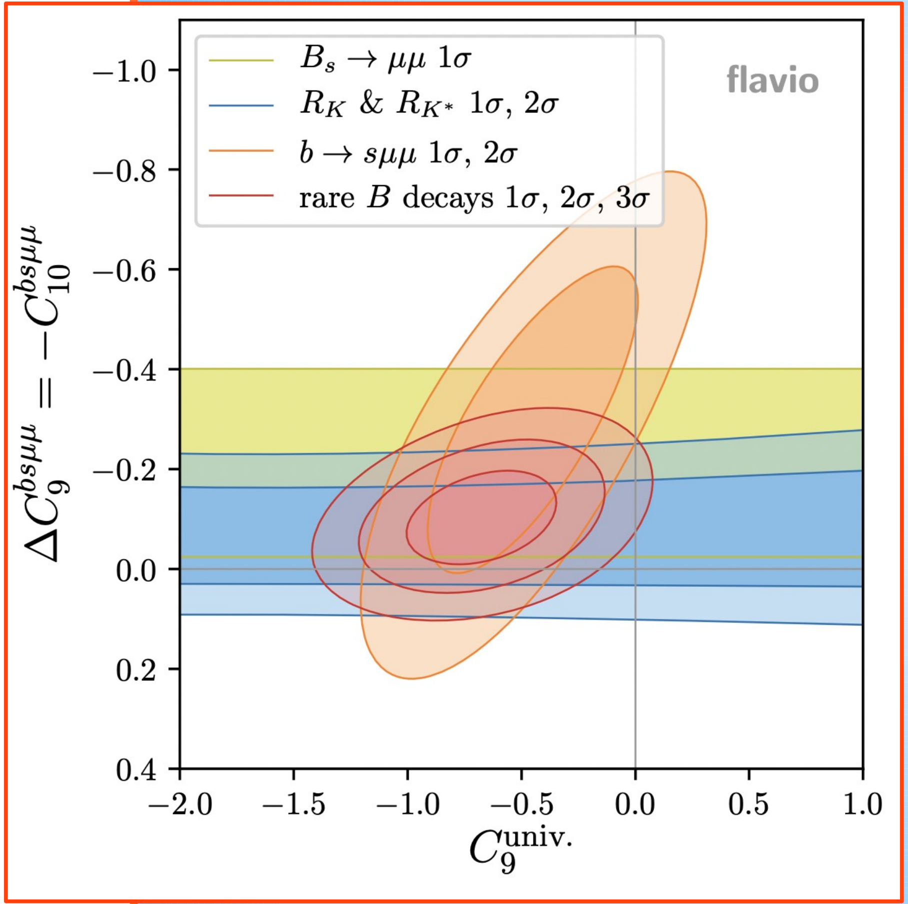

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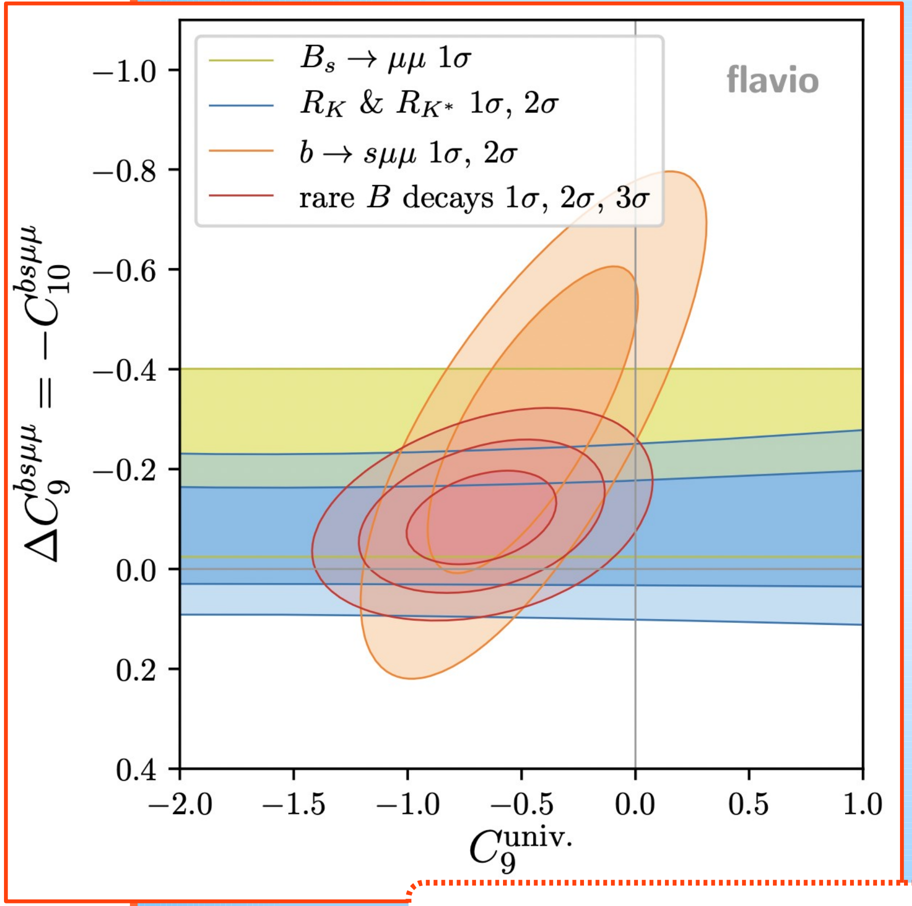

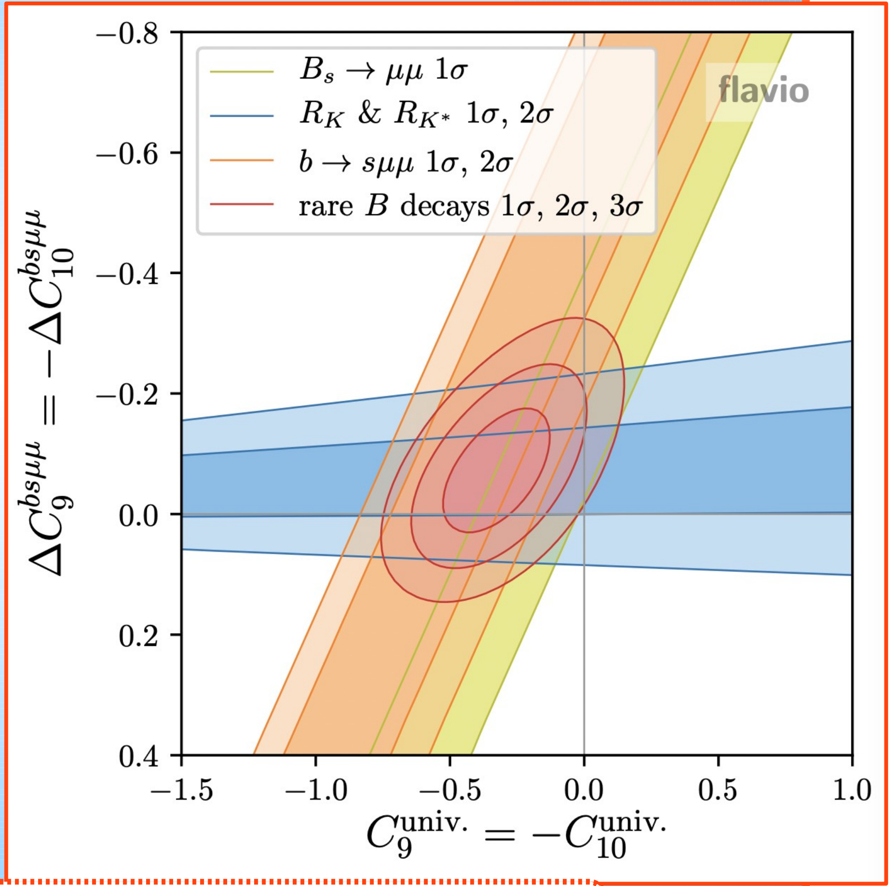

- *Purely muonic shift consistent with 0*
- *Univ. contrib. O(13%) for C_9-only, or half as much for C_L*

Connection with b → c ?

- $C_9^{\text{univ.}}$ of the correct size can be generated through RGE effects
  [Bobeth-Haisch, 2011][Crivellin *et al.*, 2018][Aebischer *et al.*, 2019]

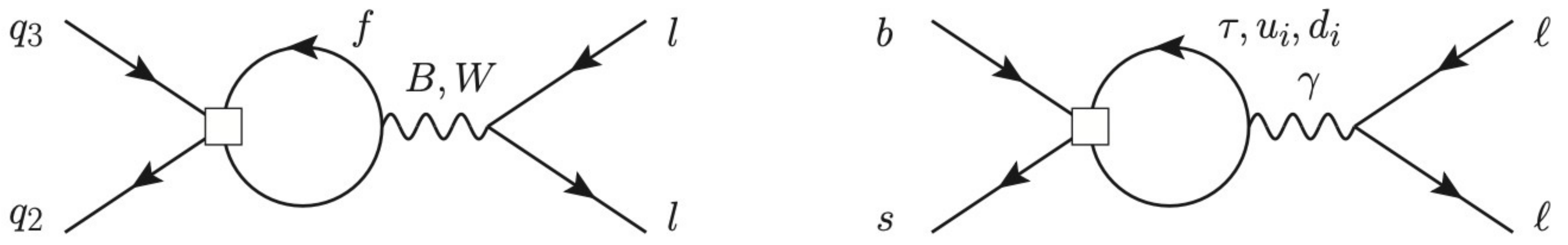

Figure 3: Diagrams inducing a contribution to C_9 through RG running above (left panel) and below (right panel) the EW scale. A sizeable contribution to C_9 is obtained when $f = u_{1,2}, d_{1,2,3}$ or l_3, see text for details.

Connection with $b \to c$ after Dec. 20?

Exercise not yet done quantitatively AFAIK. But it will probably work:

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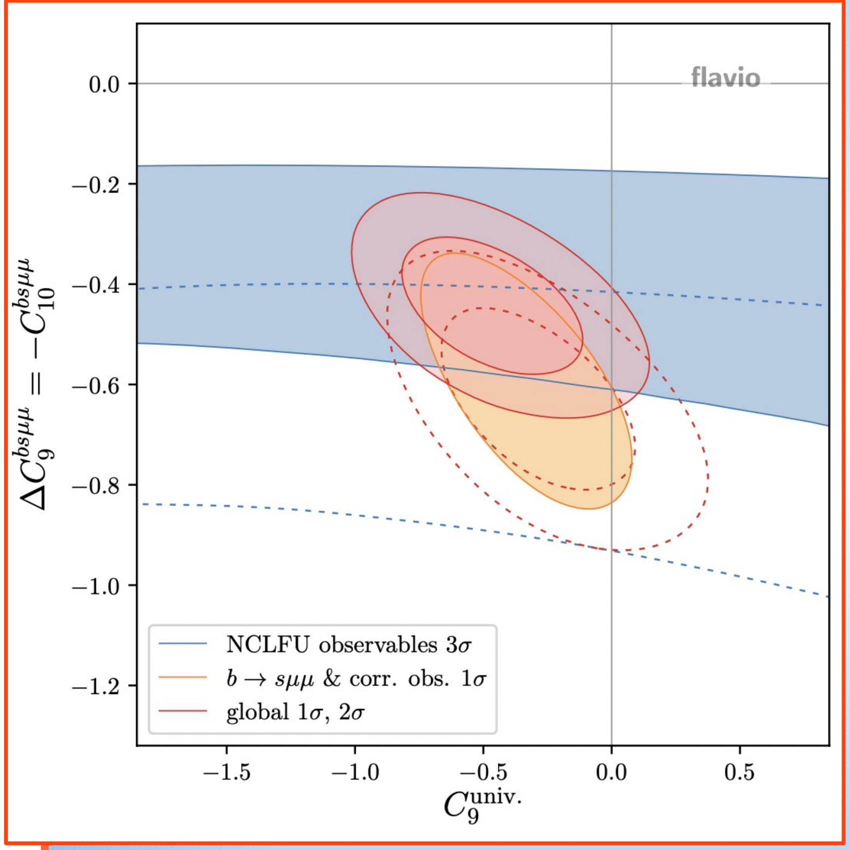

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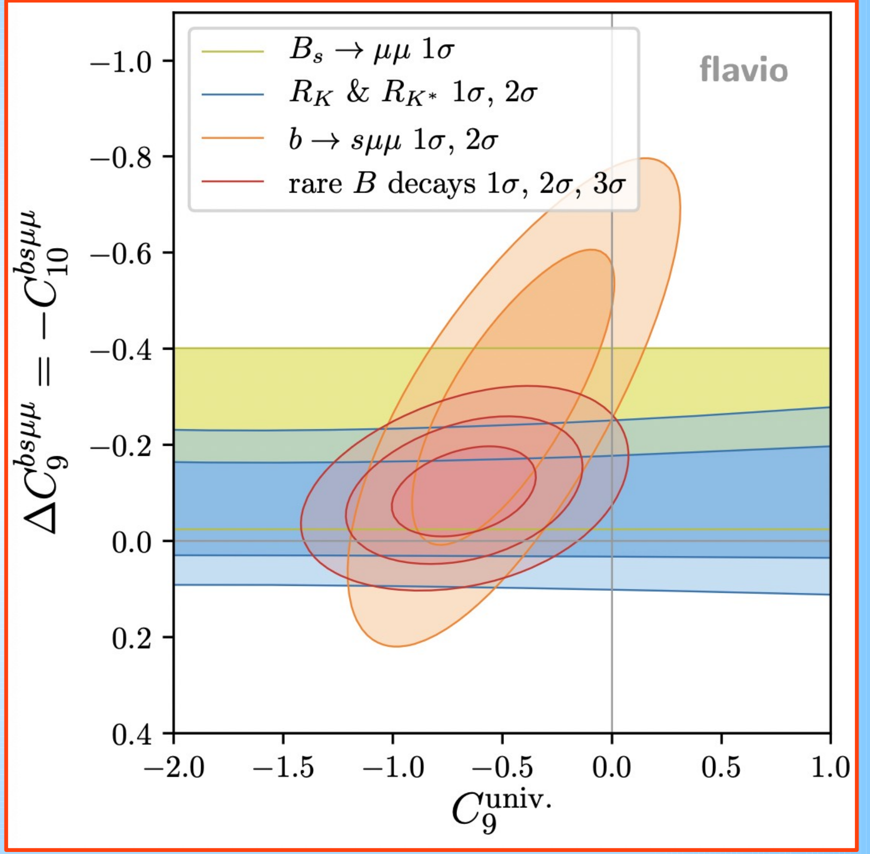

- $C_9^{univ.}$ *has slightly increased in central value from pre- to post-Dec. 20*

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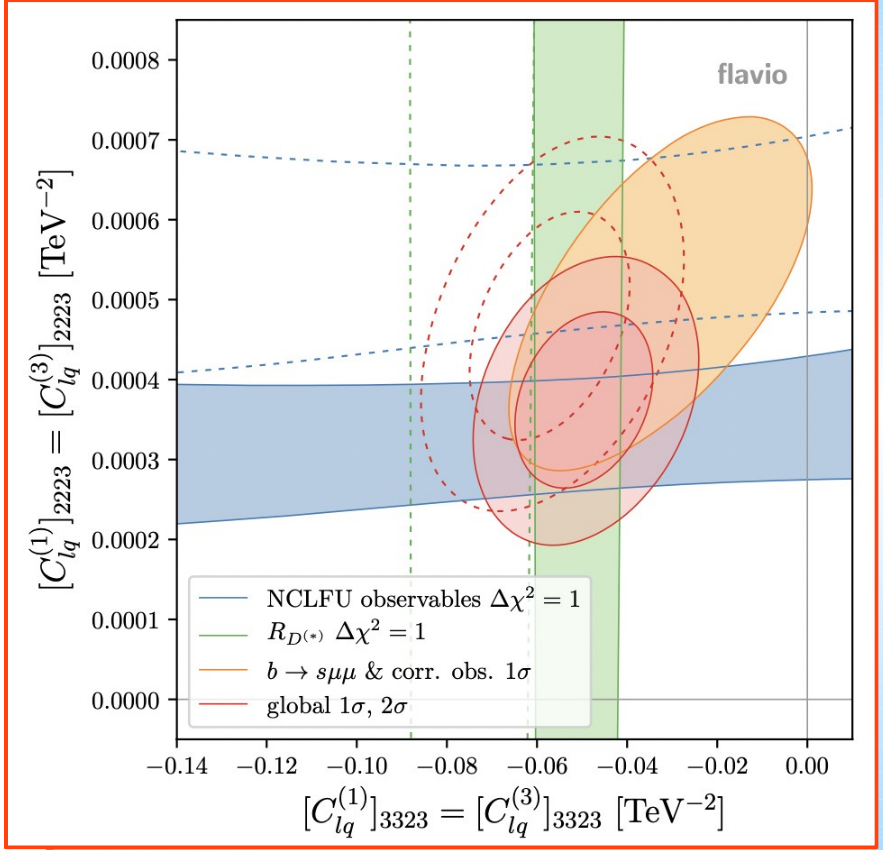

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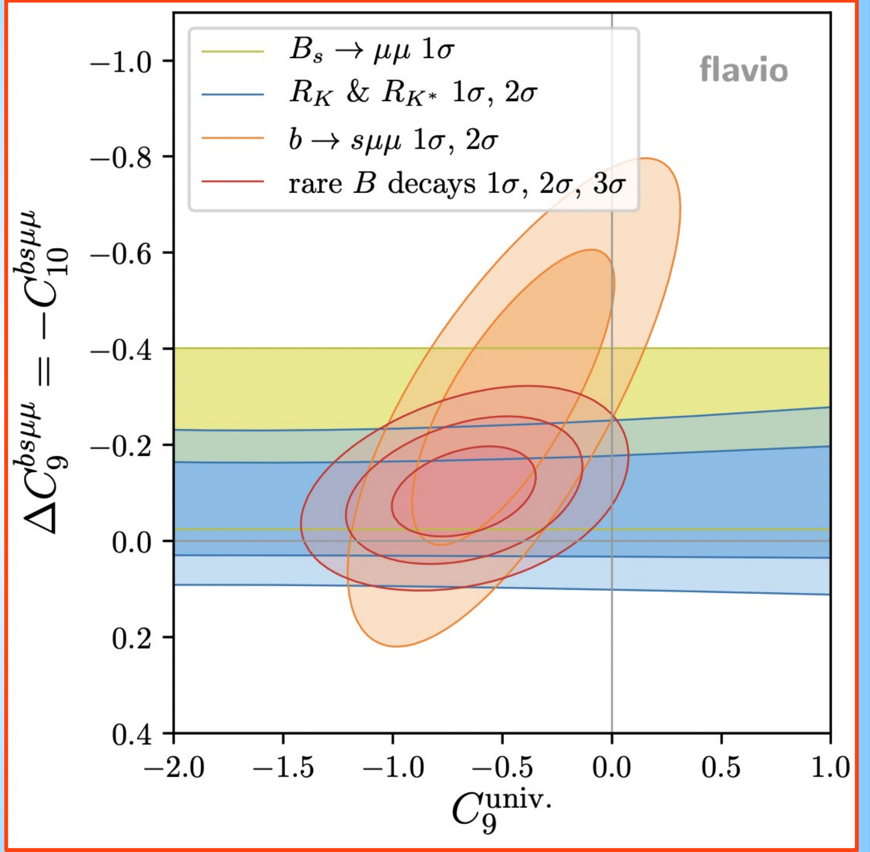

- *But RD$^{(*)}$ prefers the part of the yellow ellipse closer to zero (in the y-axis direction)*

Connection with b → c ?

Beware: *properly using LQCD + unitarity, $R(D^{(*)})$ significance ~ 1.4σ*

[**Martinelli, Simula, Vittorio, 2021**]

Models

[**Greljo *et al.*, 2212.10497**]

Post-Dec. 20 exercise:
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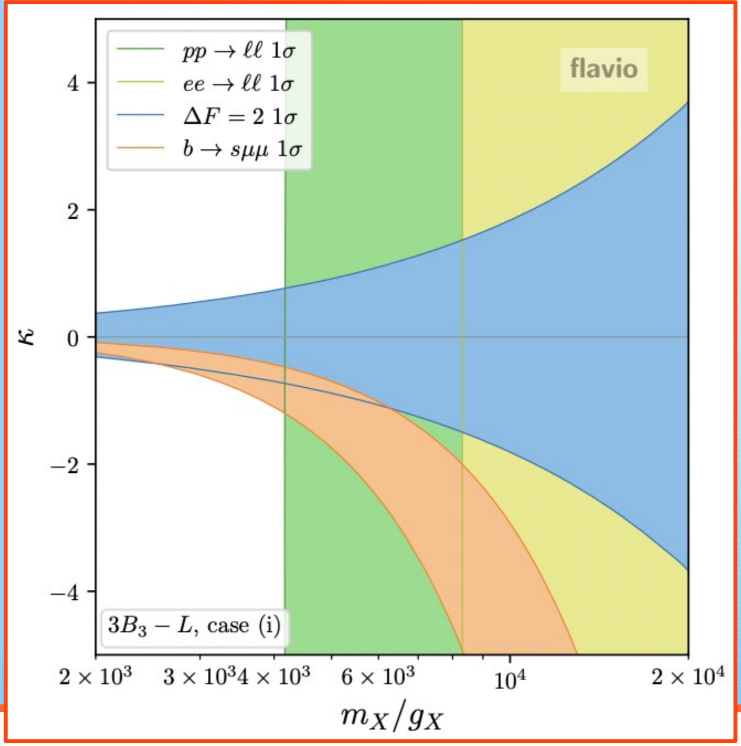
  ⇨ challenged by $\Delta F = 2$ & pp, ee $\to \ell\ell$

- 3rd-(quark)-gen-philic variant: $3\, B_3 - L$



⇨ *pp $\to \ell\ell$ gets less stringent, but tension w/ ee $\to \ell\ell$ persists*

Models

[Greljo *et al.*, 2212.10497]

Post-Dec. 20 exercise:
generate O(10%), lepton universal effects in $b \to s\, \ell^+ \ell^-$

Scalar LQs

- Three "leptonic flavours" of S ~ ($\bar{\mathbf{3}}$, **3**, 1/3)

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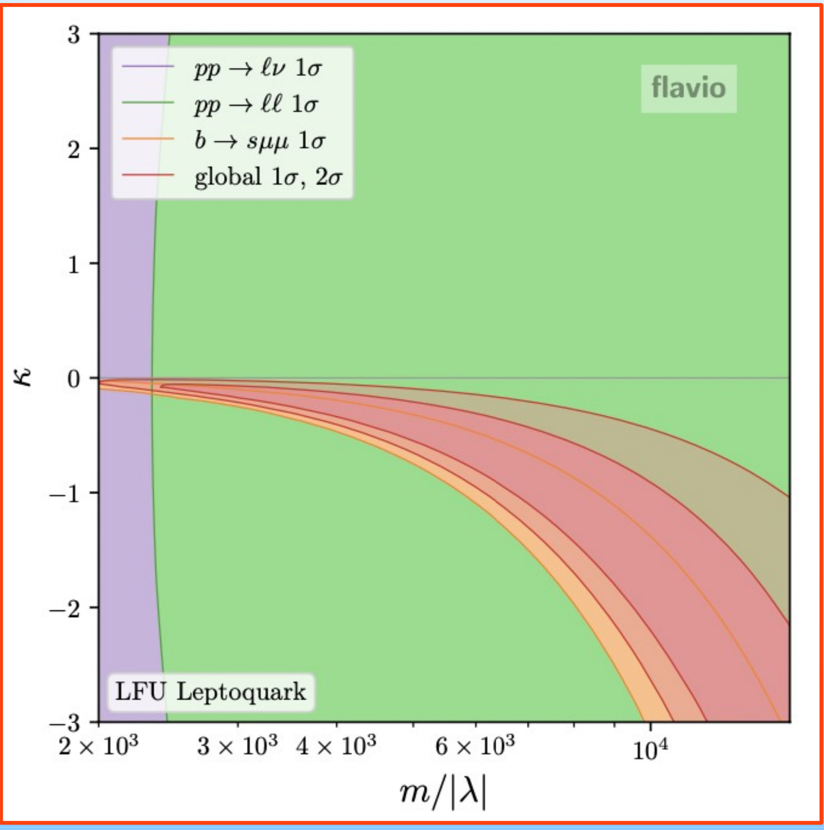
  Semilep at tree level, but ΔF = 2 & ee $\to \ell\ell$ only at loop level



The important work ahead

(= long-distance)

NP after Dec. 20

Main points

① The TH-cleaner bits (LUV observables; $B_s \to \mu^+\mu^-$) are gone

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② Remaining hints suggest:

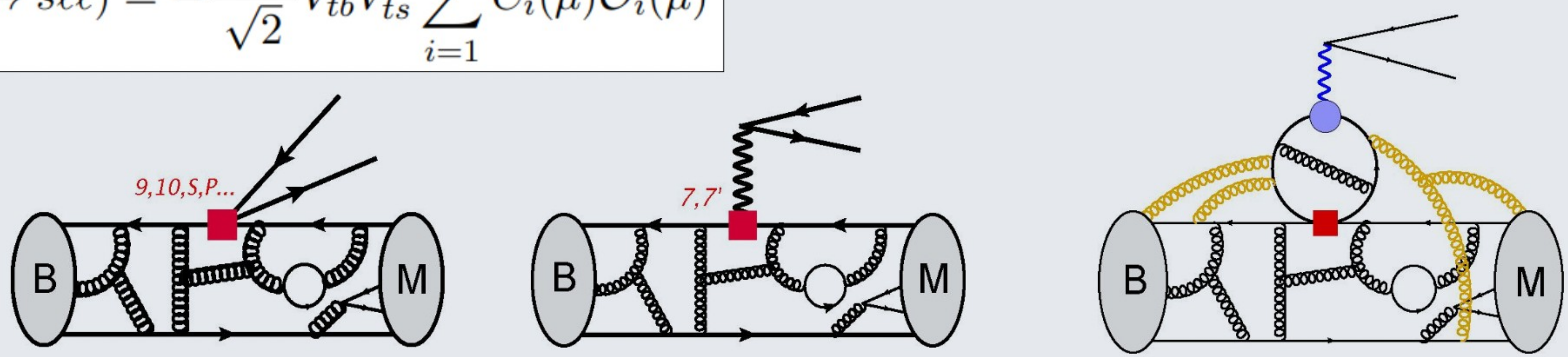
- C_9^{NP} (or C_L^{NP}) at low q^2, but not at high q^2 ?
- C_9^{NP} (or C_L^{NP}) in di-muons, and also in di-electrons?

While waiting for updates of discrepant measurements,
progress relies on a solid understanding of “non-local FFs” in $b \to s\, \ell^+\ell^-$
(because of ①)

Per aspera (= long-distance contributions) ad astra

Form factors in b → $s\ell\ell$

$$\mathcal{H}(b \to s\ell\ell) = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_{i=1}^{10} C_i(\mu) \mathcal{O}_i(\mu)$$



$$\mathcal{A}_\lambda^{L,R}(B \to M_\lambda \ell\ell) = \mathcal{N}_\lambda \left\{ (C_9 \mp C_{10}) \mathcal{F}_\lambda(q^2) + \frac{2 m_b M_B}{q^2} \left[C_7 \mathcal{F}_\lambda^T(q^2) - 16\pi^2 \frac{M_B}{m_b} \mathcal{H}_\lambda(q^2) \right] \right\}$$

$$\mathcal{H}_\mu(k,q) = i \int d^4x \, e^{iq\cdot x} \langle \bar{M}(k) | T\{ \mathcal{J}_\mu^{\text{em}}(x), \mathcal{C}_i \mathcal{O}_i \} | \bar{B}(q+k) \rangle$$

Non-local form-factors

→ Main contributions: the **"charm-loops"** $\mathcal{O}^c_{2(1)} = \left(\bar{s}_L \gamma_\mu (T^a) c_L\right)\left(\bar{c}_L \gamma^\mu (T^a) b_L\right)$

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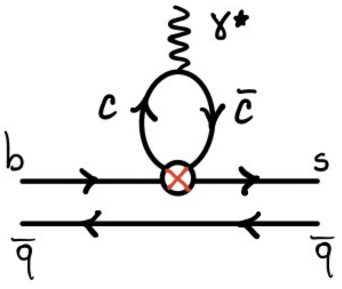
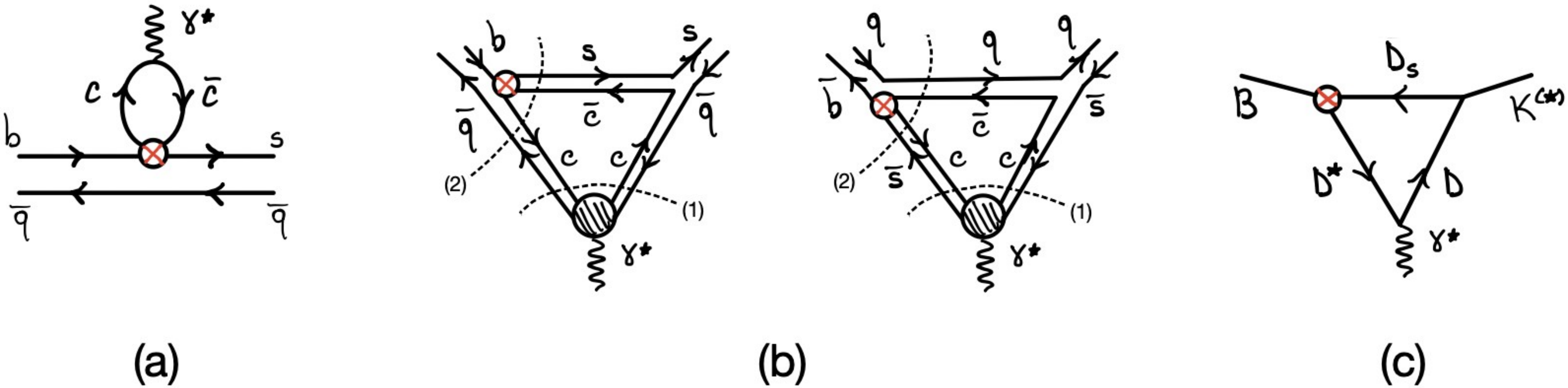
Per aspera (= long-distance contributions) ad astra



Per aspera (= long-distance contributions) *ad astra*

[Ciuchini *et al.*, 2212.10516]



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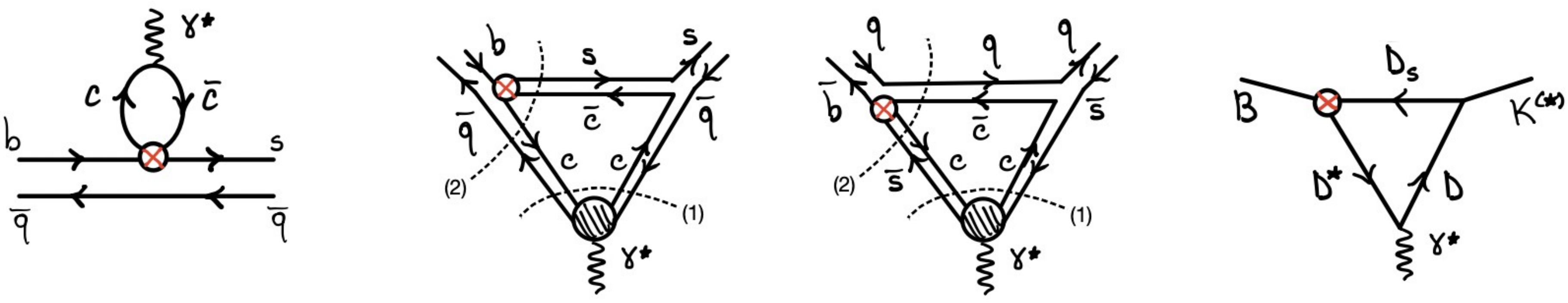

(a) (b) (c)

What about contribs. (b)?

In principle, well-known to be there, e.g.

▶ On-shell cuts in the variable $(q+k)^2$ (the "forward" or "decay" channel) include branch cuts from intermediate states such as $B \to \bar{D}D_s \to K^*\ell^+\ell^-$. The physical point $(q+k)^2 = M_B^2$ lies on these cuts, which implies that the functions $\mathcal{H}_\lambda(q^2)$ are complex-valued for all values of q^2. But this imaginary part is not associated with any singularity in the variable q^2. Thus, one can write $\mathcal{H}_\lambda(q^2) = \mathcal{H}_\lambda^{(\mathrm{re})}(q^2) + i\,\mathcal{H}_\lambda^{(\mathrm{im})}(q^2)$, with $\mathcal{H}_\lambda^{(\mathrm{re,im})}(q^2)$ satisfying the analytic properties of the previous point as functions of q^2, and obeying the same dispersion relation.

[Bobeth *et al.*, 2017]

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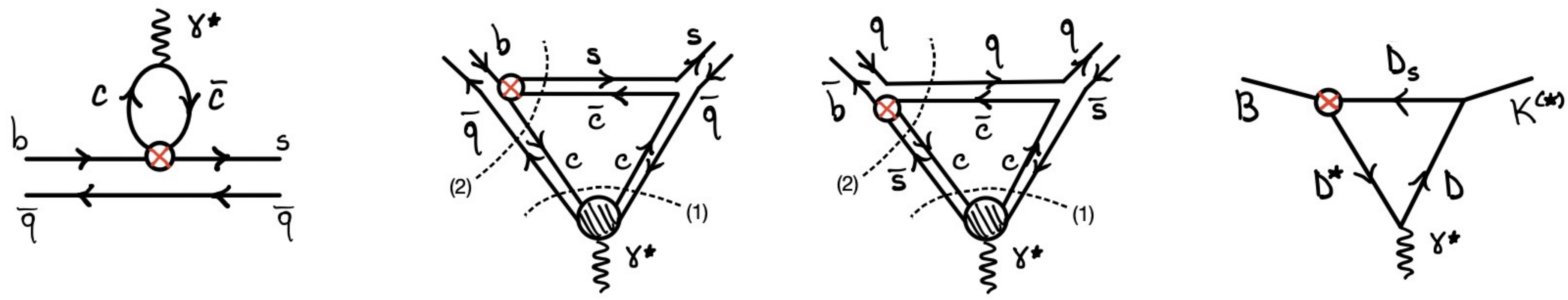

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[Bobeth *et al.*, 2017]

In practice, however...

to this kind of contributions, but the analytic structure of triangle diagrams is quite involved, depending on the values of external momenta and internal masses. A dispersion relation in q^2 of the kind used in refs. [43, 45–48], based on the cut denoted by (1) in Fig. 1 **(b)**, could be written if the B invariant mass were below the threshold for the production of charmed intermediate states. However, when the B invariant mass raises above the threshold for cut (2), an additional singularity moves into the q^2 integration domain, requiring a nontrivial deformation of the path (see for example the detailed discussion in ref. [94]). Another possibility would be to get an

[Ciuchini *et al.*, 2212.10516]

Looking elsewhere in q^2:

Effects?

Long-distance issues at low vs. high q^2 are different

whereas above-EWSB new effects are the same

Inclusive b → s $\ell^+\ell^-$

[Isidori *et al.*, 2305.03076]

- Look for proxies of the inclusive b → s $\ell^+\ell^-$ rate at high q^2

Inclusive b $\to$ s $\ell^+\ell^-$

[Isidori *et al.*, 2305.03076]

- Look for proxies of the inclusive b $\to$ s $\ell^+\ell^-$ rate at high q^2
  - For q^2 = 15 GeV^2, rate dominated by 3 modes (B $\to$ K(*) & B $\to$ Kπ)

Inclusive b $\to$ s $\ell^+\ell^-$

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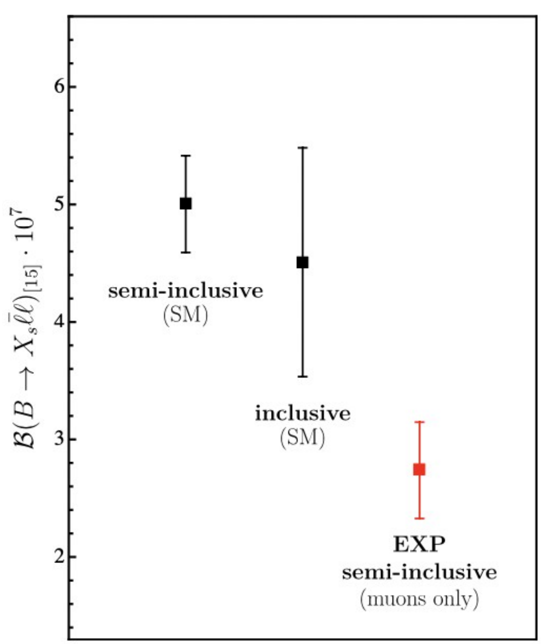

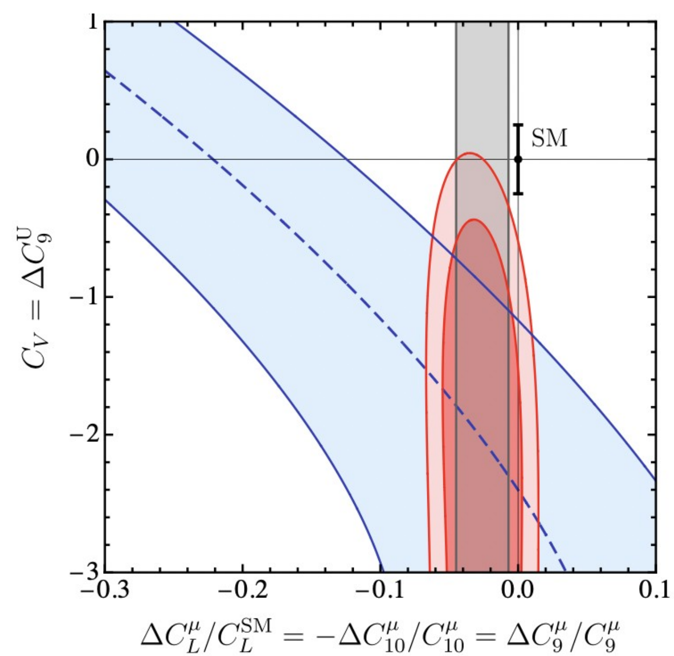

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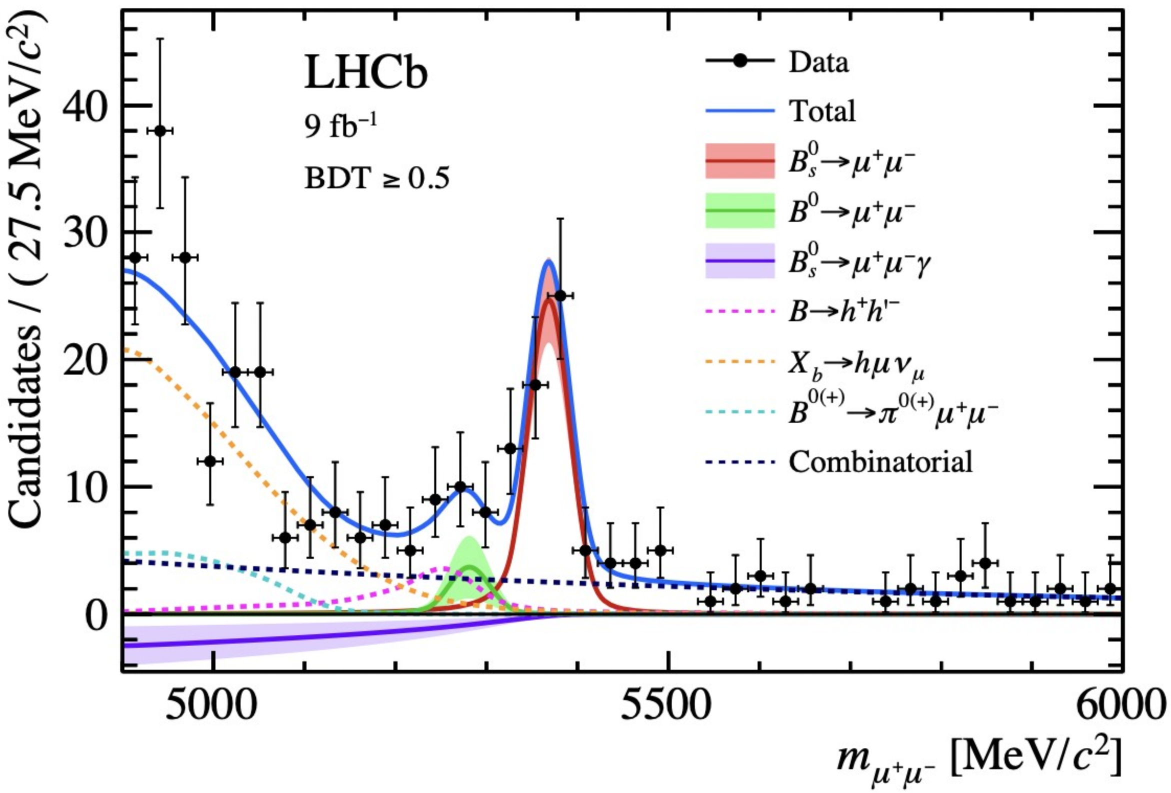
[thanks F. Dettori]



[LHCb-PAPER-2021-007] [LHCb-PAPER-2021-008]

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(3.09\,^{+\,0.46\,+\,0.15}_{-\,0.43\,-\,0.11}\right) \times 10^{-9}$$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) = \left(1.2\,^{+\,0.8}_{-\,0.7} \pm 0.1\right) \times 10^{-10} < 2.6 \times 10^{-10}$$

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)_{m_{\mu\mu}>4.9\,\mathrm{GeV}} = (-2.5 \pm 1.4 \pm 0.8) \times 10^{-9} < 2.0 \times 10^{-9}$$

No significant signal for $B^0 \to \mu^+\mu^-$ and $B_s^0 \to \mu^+\mu^-\gamma$, upper limits at 95%

First world limit on $B_s^0 \to \mu^+\mu^-\gamma$ decay

Conclusions

- *Possible hints of NP in $b \to s\mu\mu$ transitions persist*
  but only on observables for which certain possibly sizeable,
  long-distance contributions, are not known quantitatively

- *To make progress, we have to address the size of such contributions*

- *Or we may look in other kinematic regions not affected*
  by such theory uncertainty