Flavour Physics
– An Outlook

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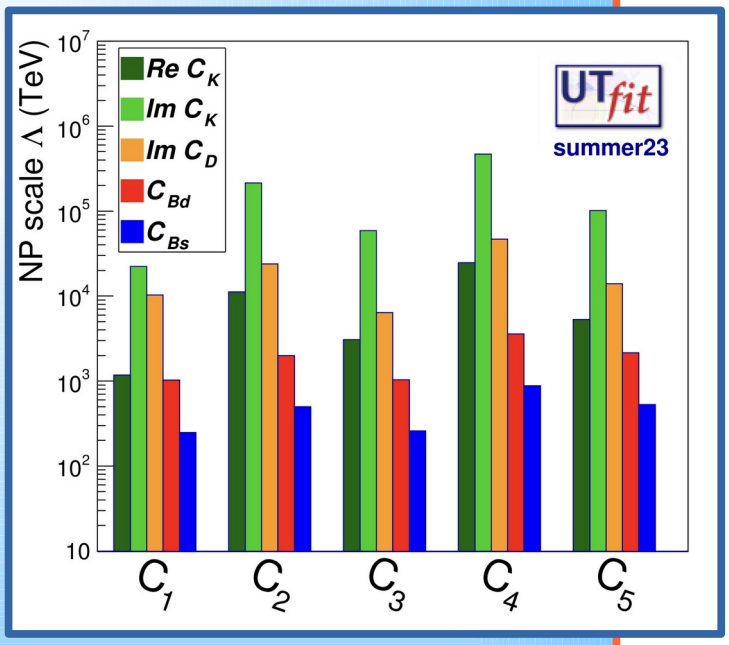

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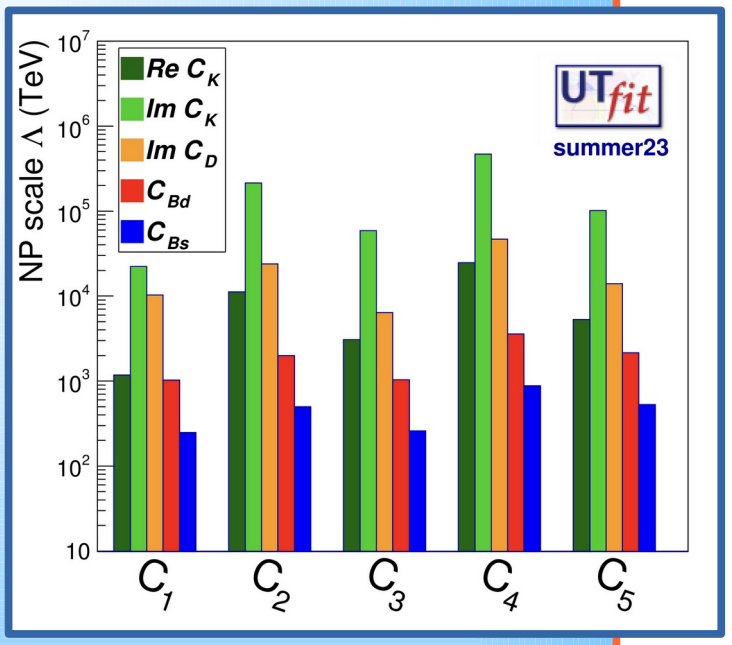

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  - Typical scales probed are ≳ 1000 TeV
  - TeV-scale effects require accidental symmetries

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If this BSM scale is not far from 10 TeV

Why do hundreds of flavour observables fit so well the SM predictions?

By the same logic

it is reasonable to expect

BSM dynamics to first emerge

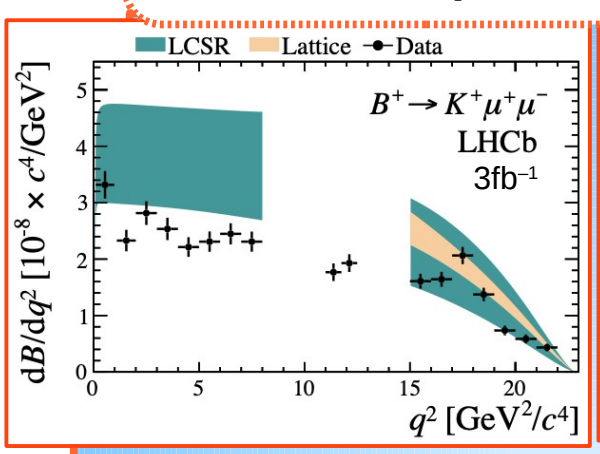
in the flavour sector

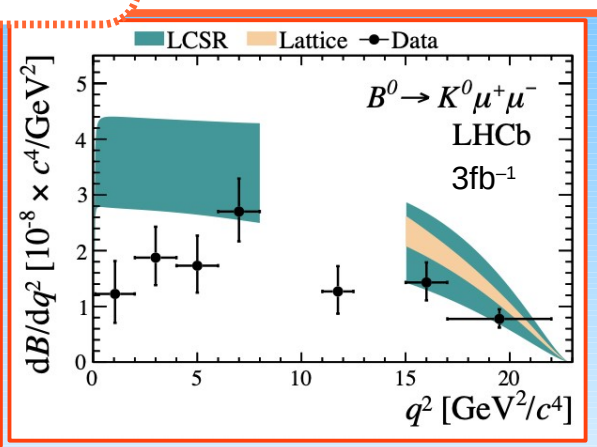
(historical precedents support this)

Flavour

Anomalies (?)

$b \to s$ discrepant data





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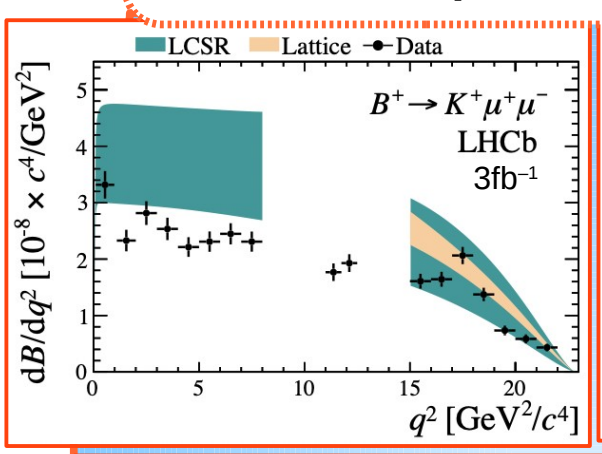

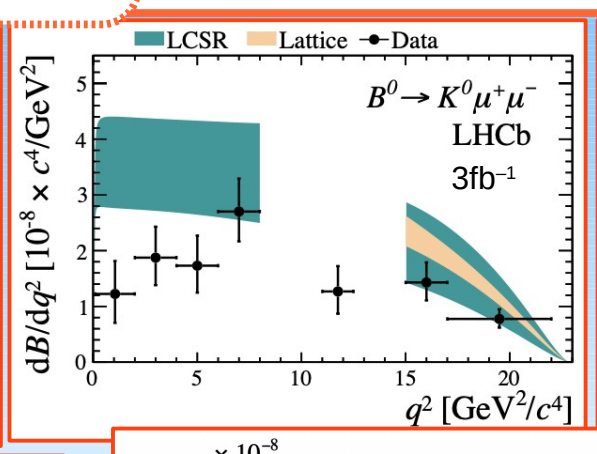

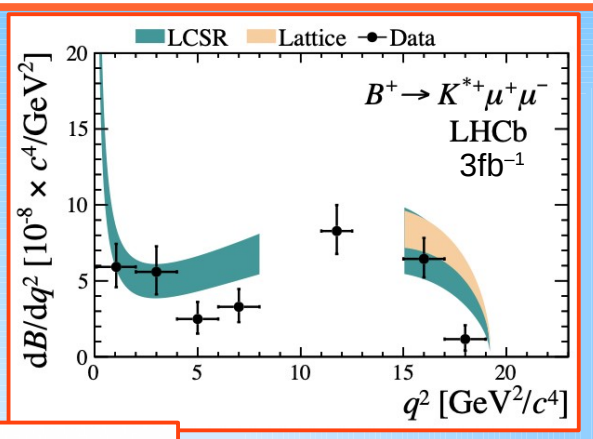

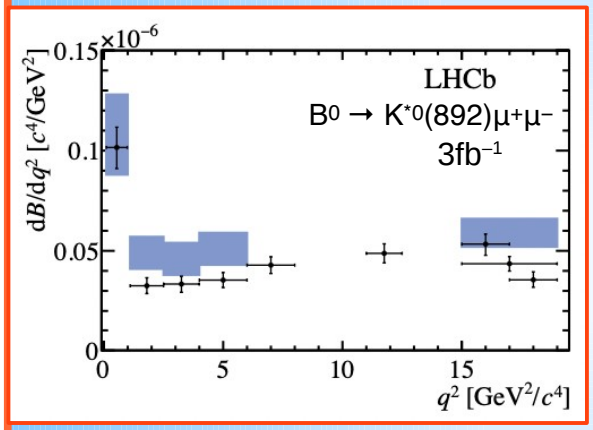

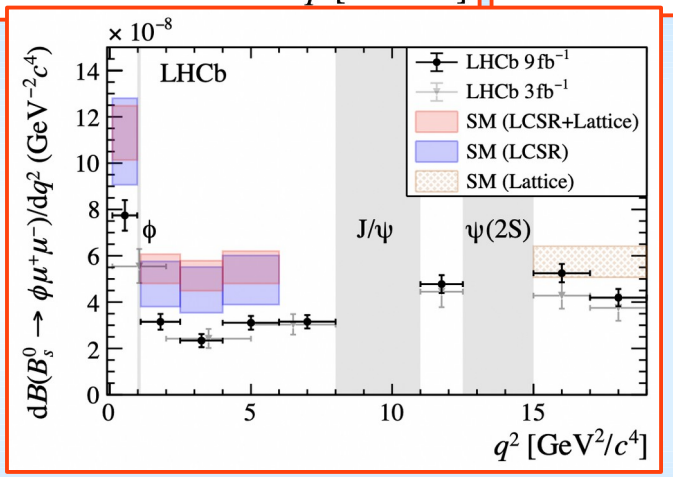

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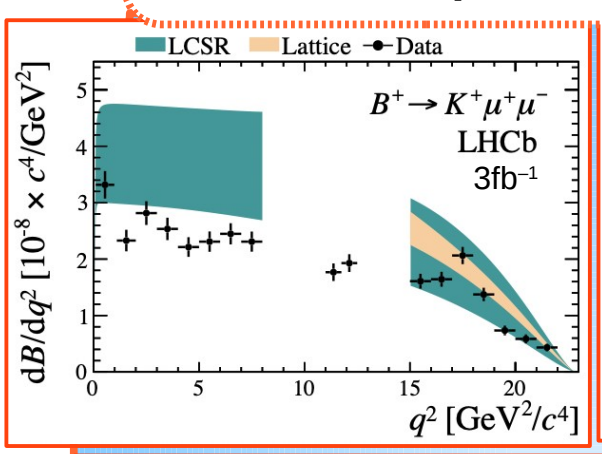

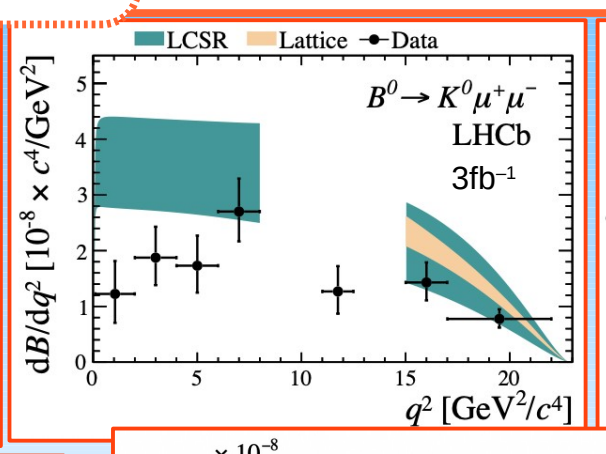

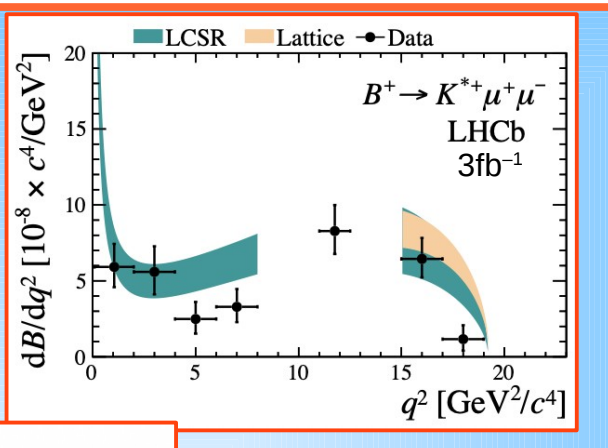

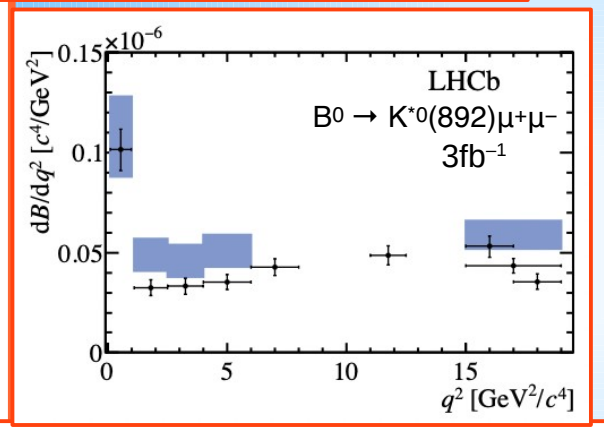

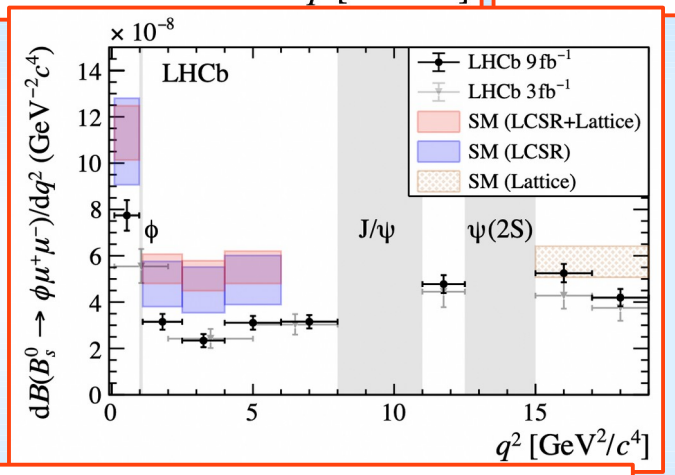

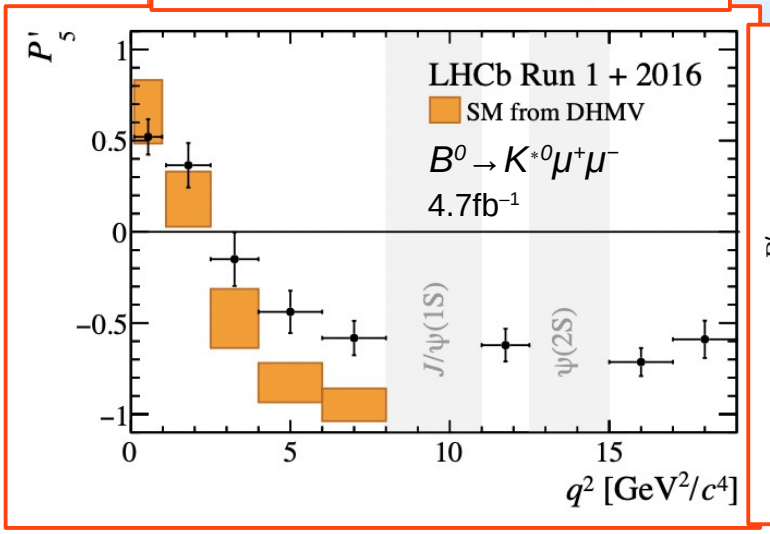

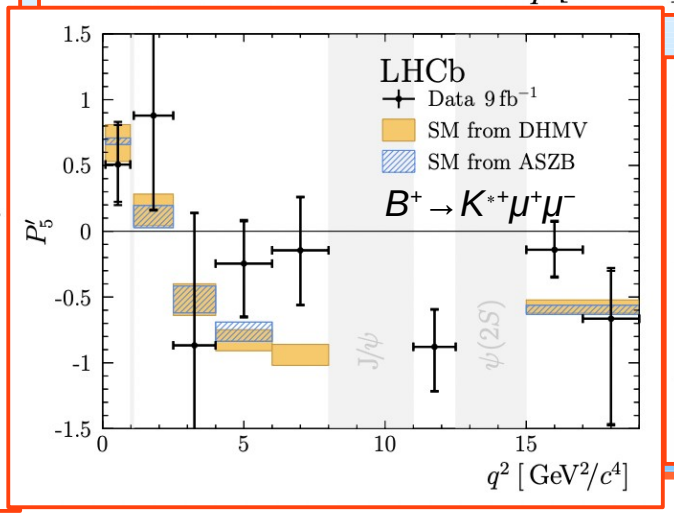

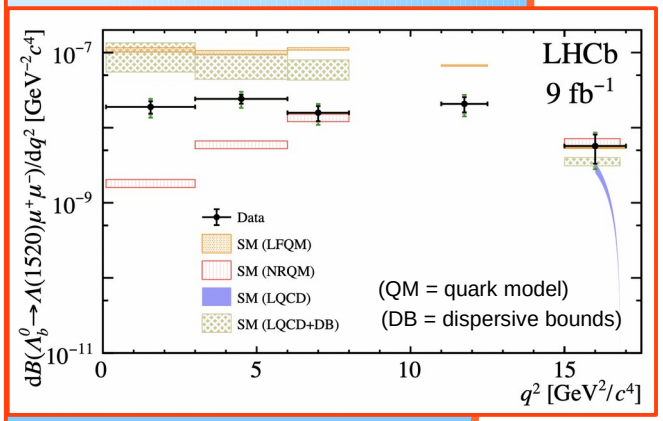

Weak Effective Theory bounds

A lepton-universal shift to the $(\bar{s}b)_L(\bar{\ell}\ell)_V$ coupling C_9 ?

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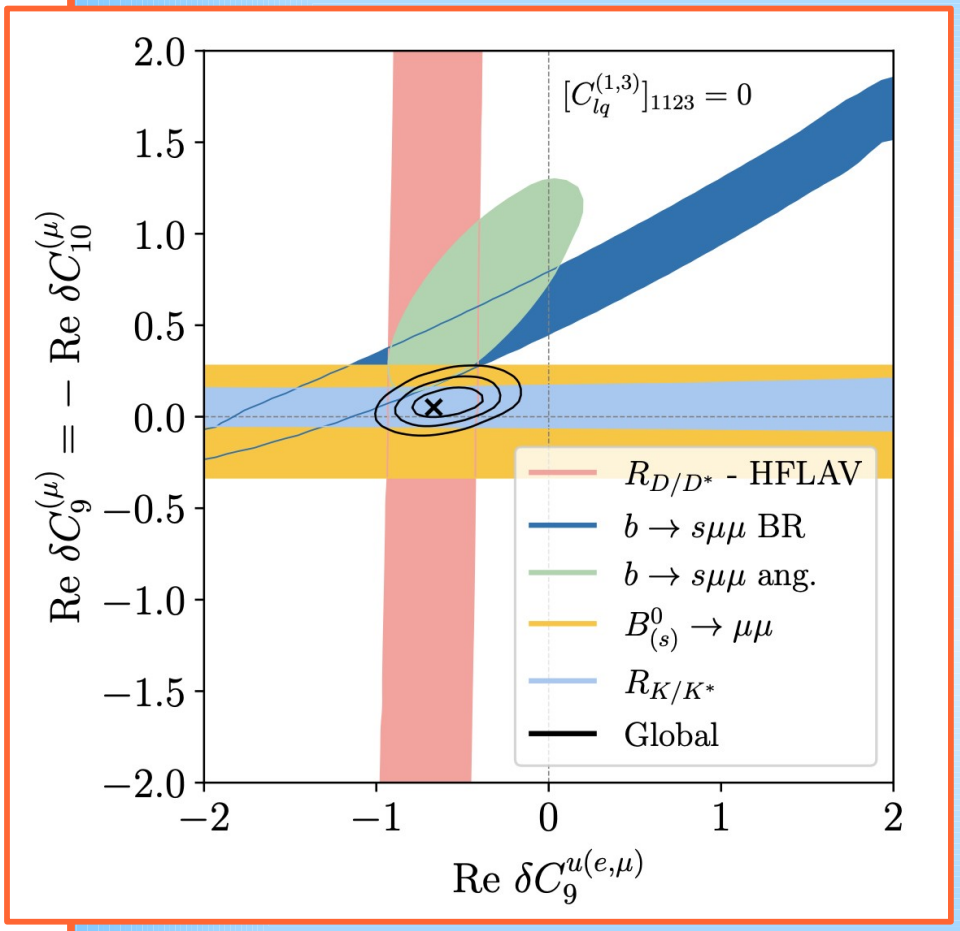

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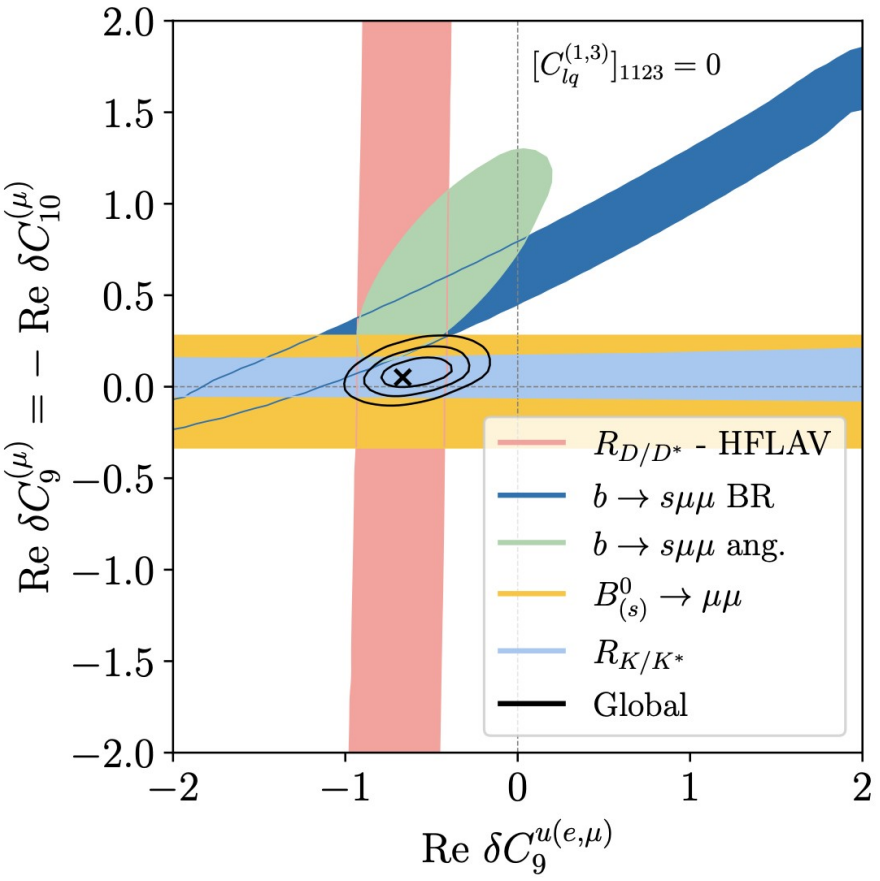

… or hadronic effects
difficult to assess by explicit calculation **(more later)**

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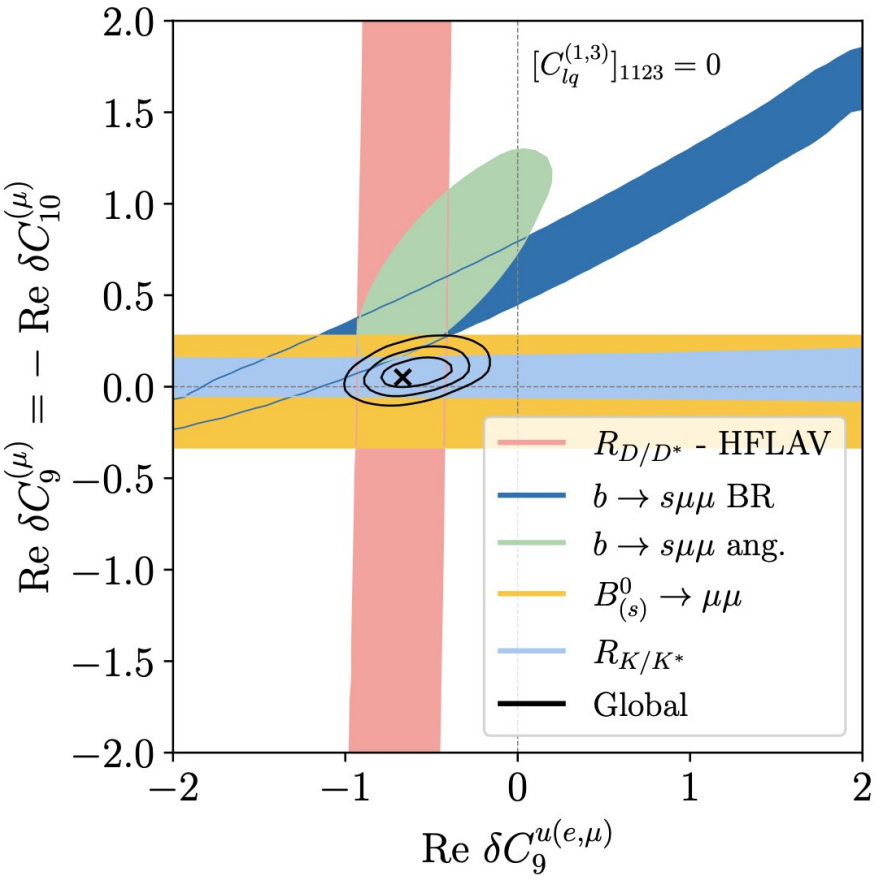
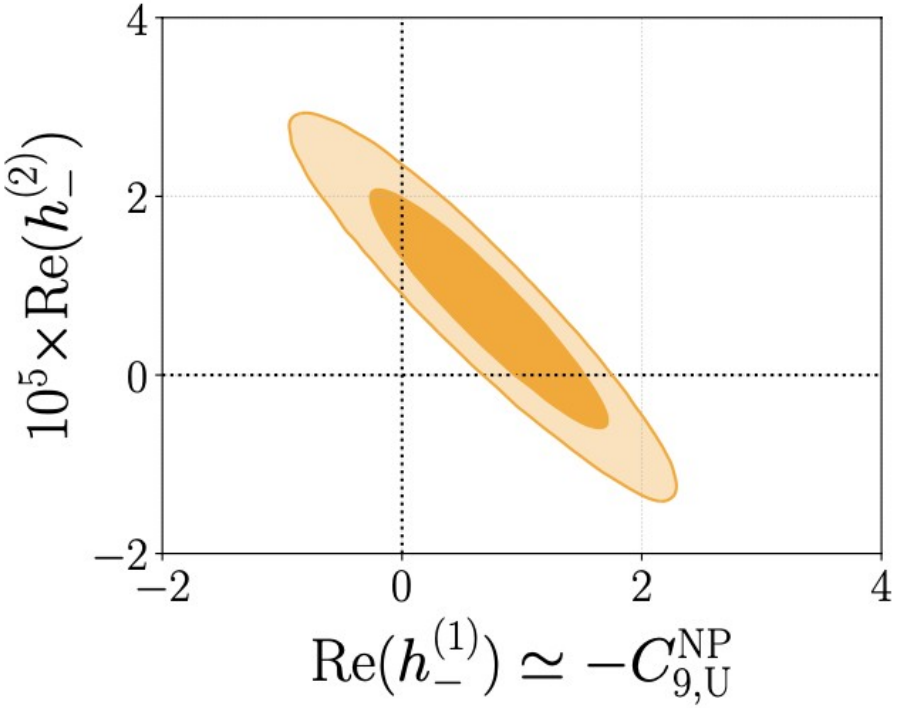


[Ciuchini et al., 2022]



$$H_V^- \propto \frac{m_B^2}{q^2}\left[\frac{2m_b}{m_B}\left(C_7^{\mathrm{SM}} + h_-^{(0)}\right)\widetilde{T}_{L-} - 16\pi^2 h_-^{(2)}\, q^4\right] + \left(C_9^{\mathrm{SM}} + h_-^{(1)}\right)\widetilde{V}_{L-}\,,$$

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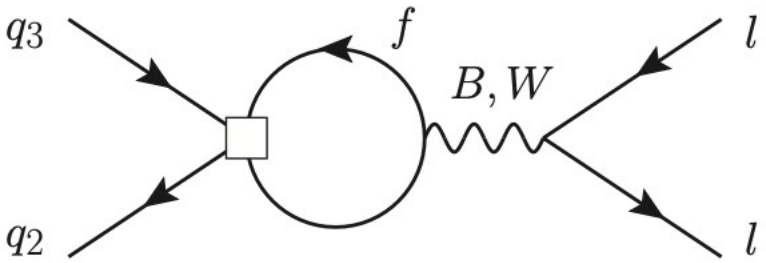
difficult to assess by explicit calculation **(more later)**

Connection with b → c anomalies from R(D$^{(*)}$) ?

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



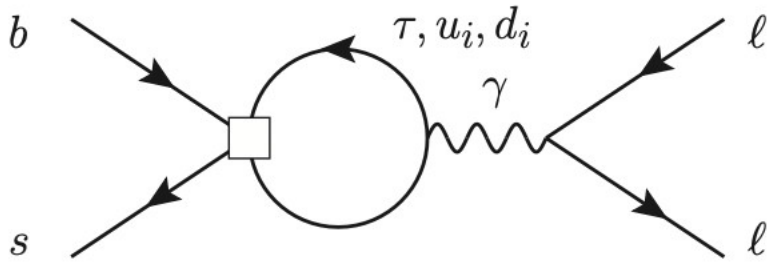


Figure 3: Diagrams inducing a contribution to C_9 through RG running above (left panel) and below (right panel) the EW scale. A sizeable contribution to C_9 is obtained when $f = u_{1,2}, d_{1,2,3}$ or l_3, see text for details.

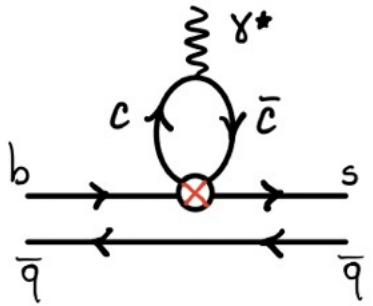
Beware: *using LQCD + unitarity, R(D$^{(*)}$) significance < 2σ*
[Martinelli, Simula, Vittorio, 2021+]

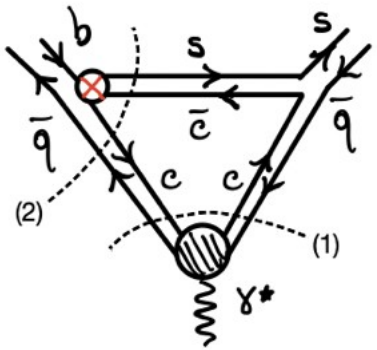
While waiting for updates of discrepant measurements,

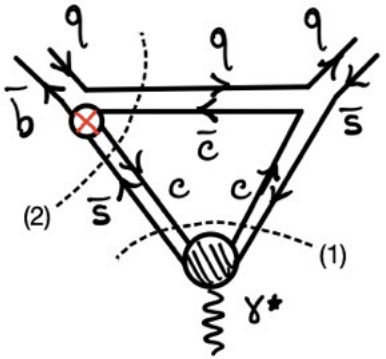
progress relies on a solid understanding of "non-local FFs" in b → s $\ell^+\ell^-$

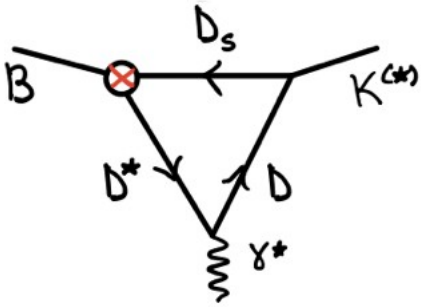
Anomalous thresholds in non-local FFs

[Ciuchini *et al.*, 2212.10516]









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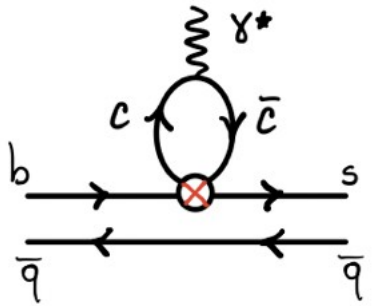

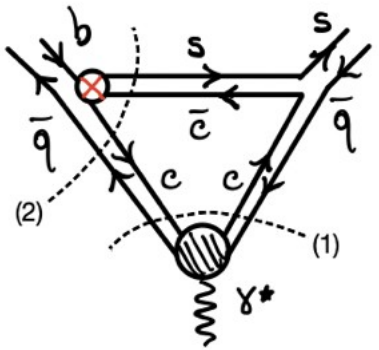

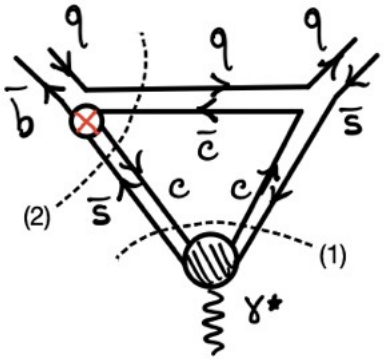

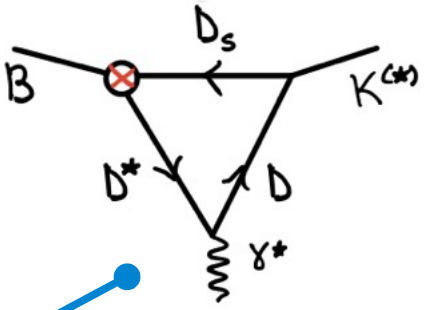

Anomalous-threshold effects in the physical region?

Anomalous thresholds: *general strategy*

[Mutke, Hoferichter, Kubis, 2024]

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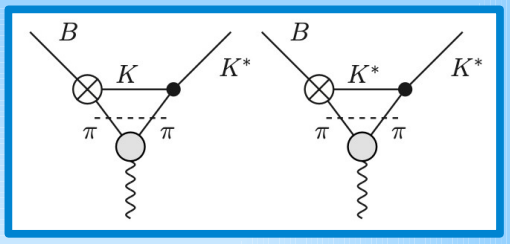
⇨ *Modify integration contour*
Decompose amplitude into covariant structures
And fix parameters from data

Anomalous thresholds: $A_0(B^+ \to K^{*+} \gamma^*)$ *w/* $\pi\pi$ *loop*

[Mutke, Hoferichter, Kubis, 2024]



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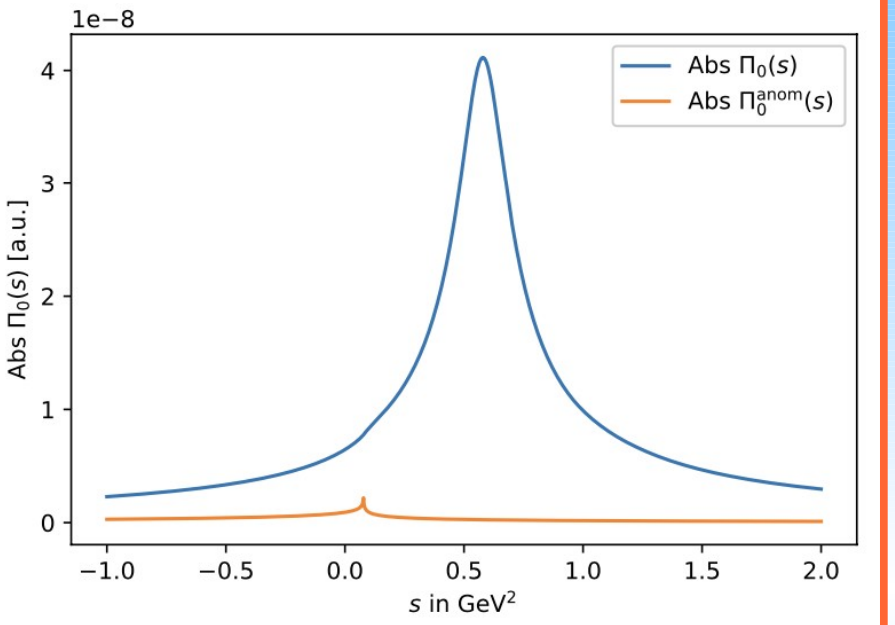

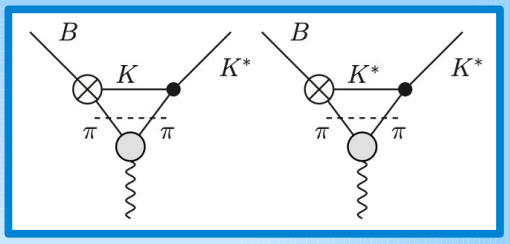

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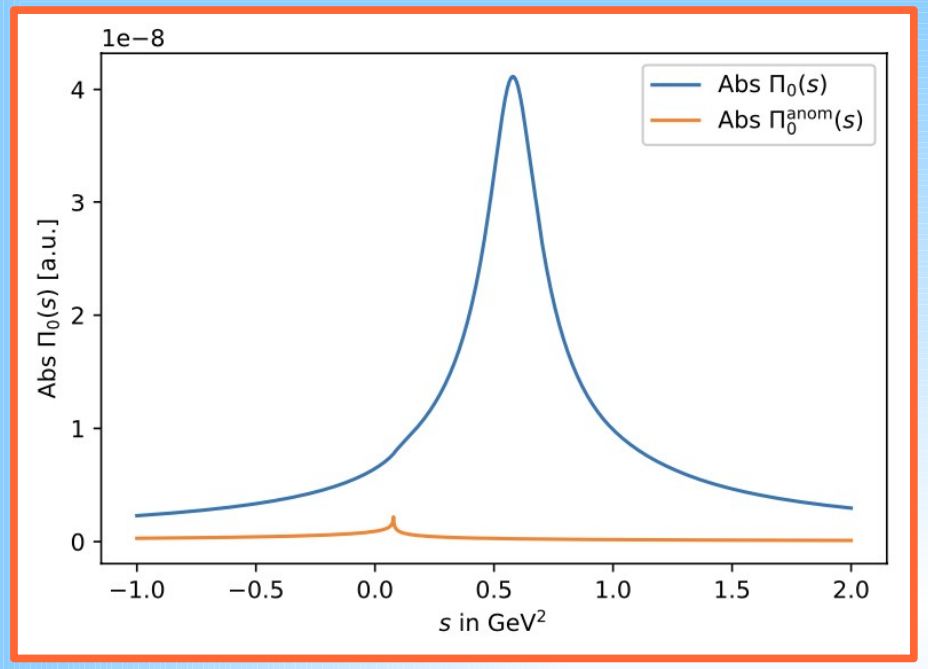

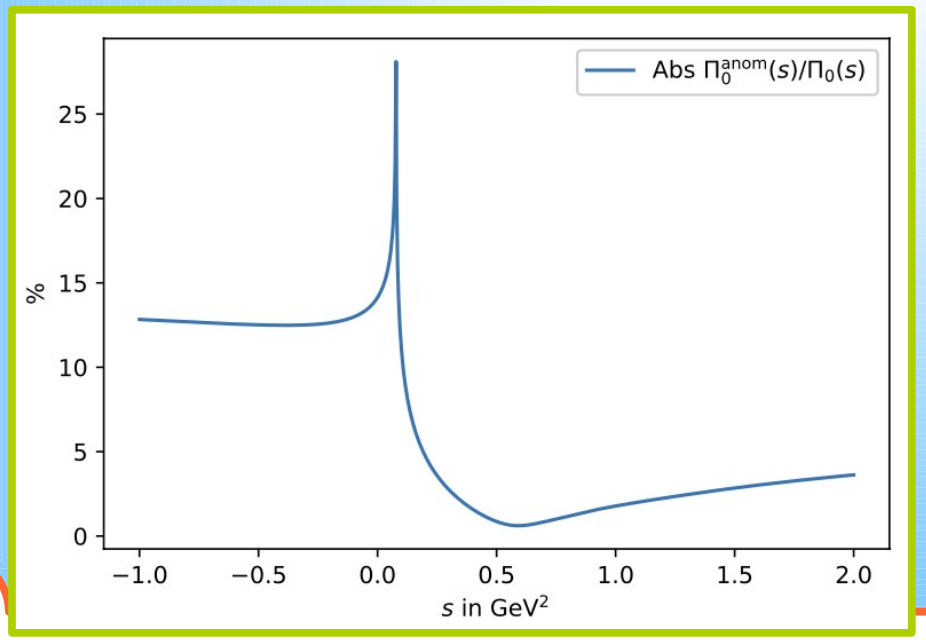

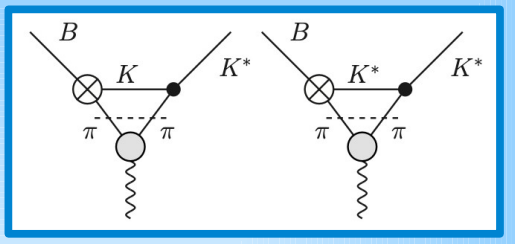

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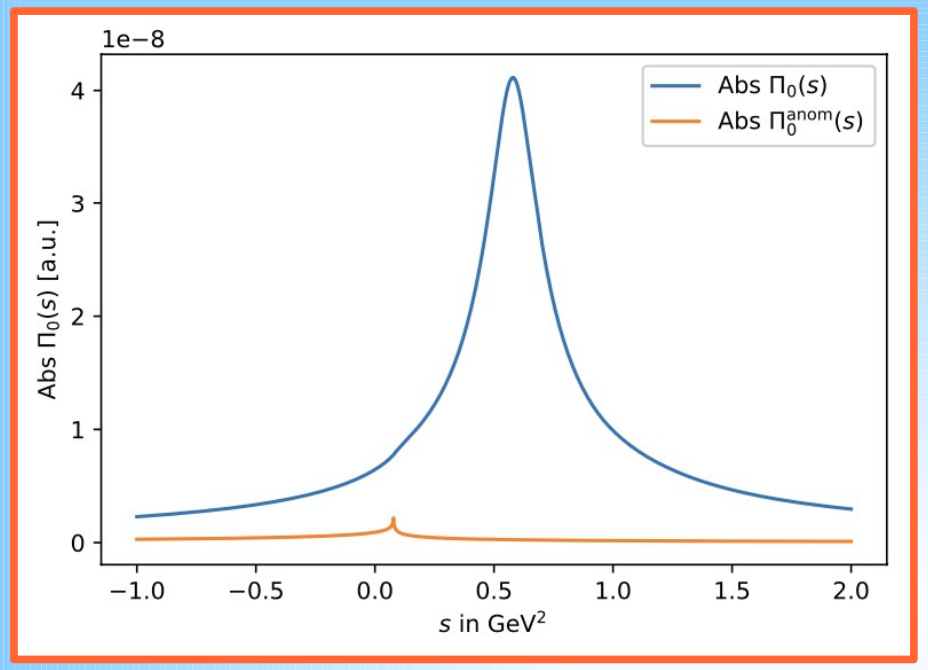

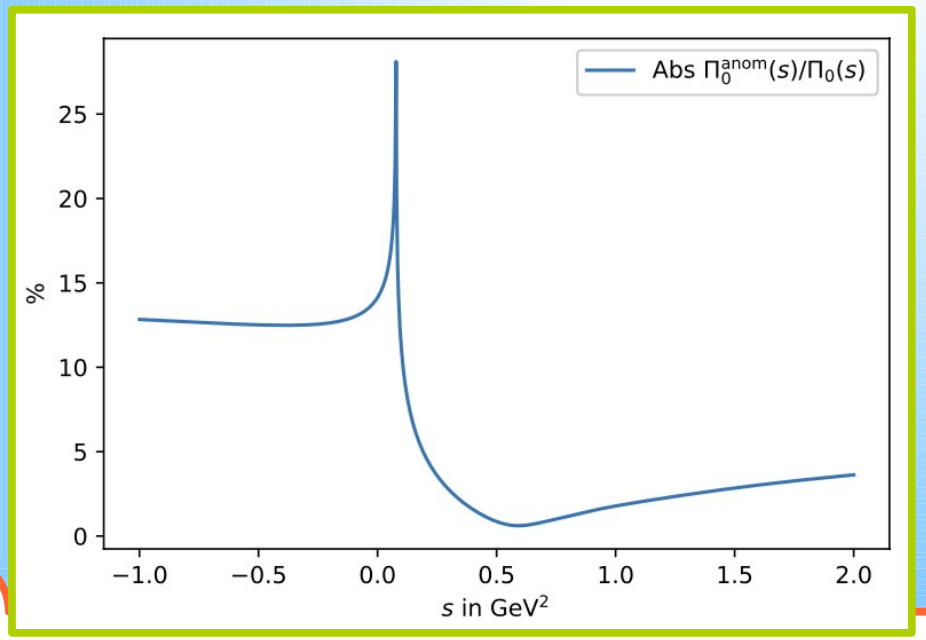

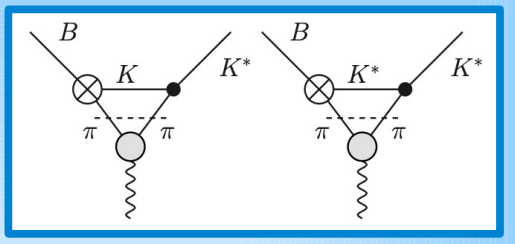

- *Effects ~ 10% off-resonance*
- *Impact of c-quark counterpart effects expected similar*

$B_s \to \mu\mu\gamma$ at high q^2

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- *Now measurable from $B_s \to \mu\mu$ & data-driven approach to bkgs*

[Dettori, DG, Reboud, 2017]

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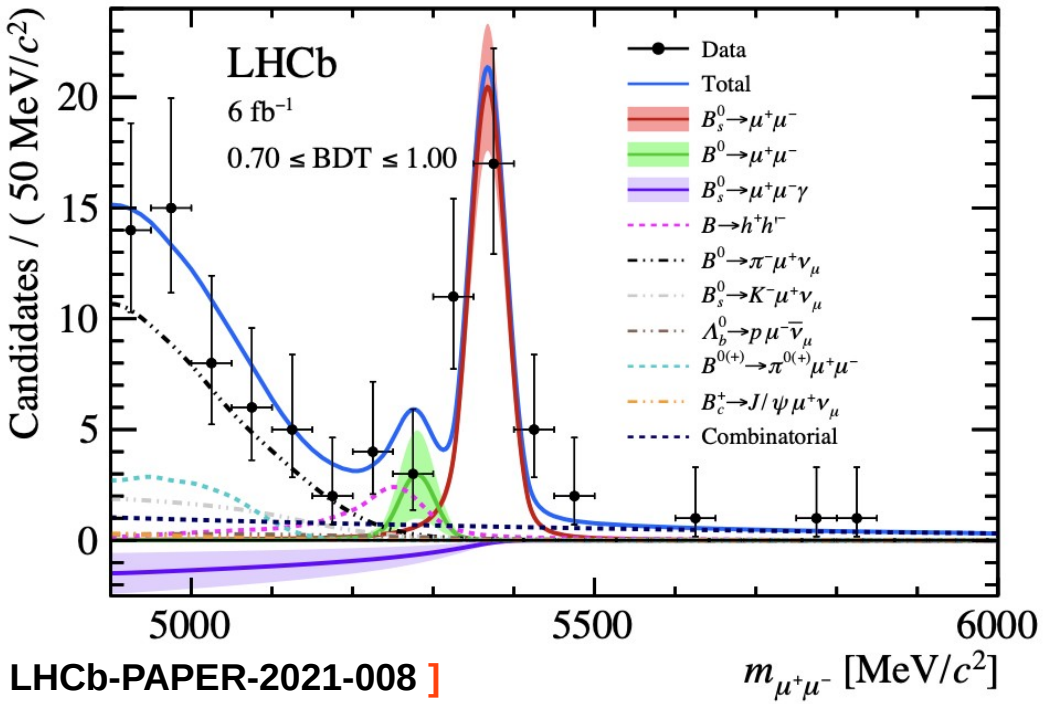
- *Recent LHCb "première"*



[LHCb-PAPER-2021-008]

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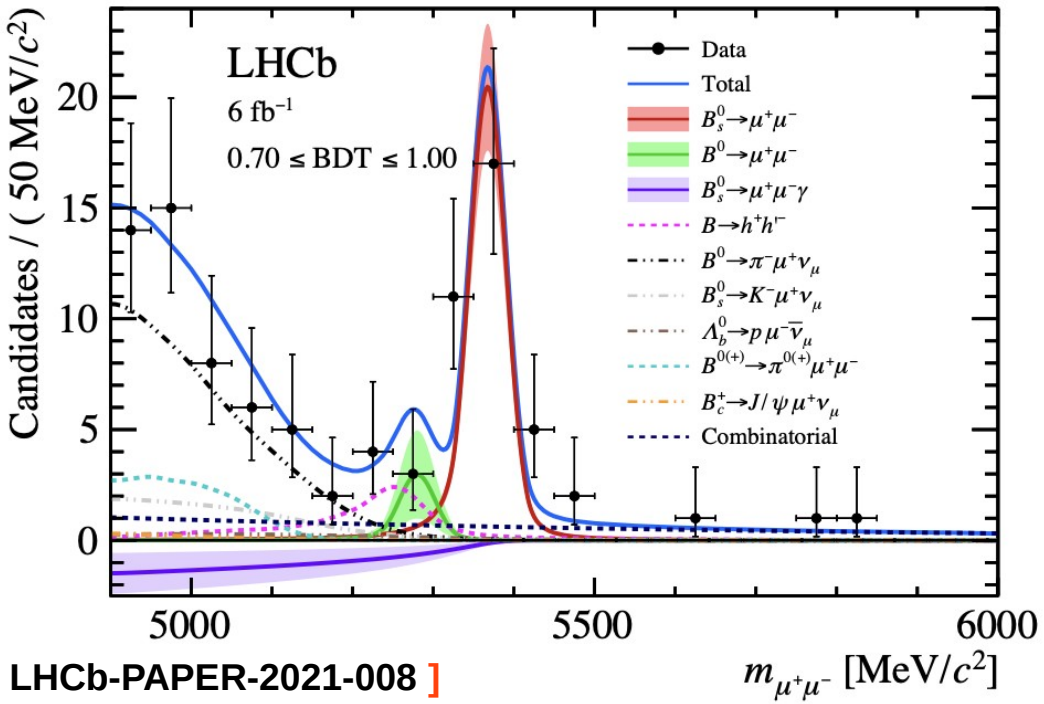

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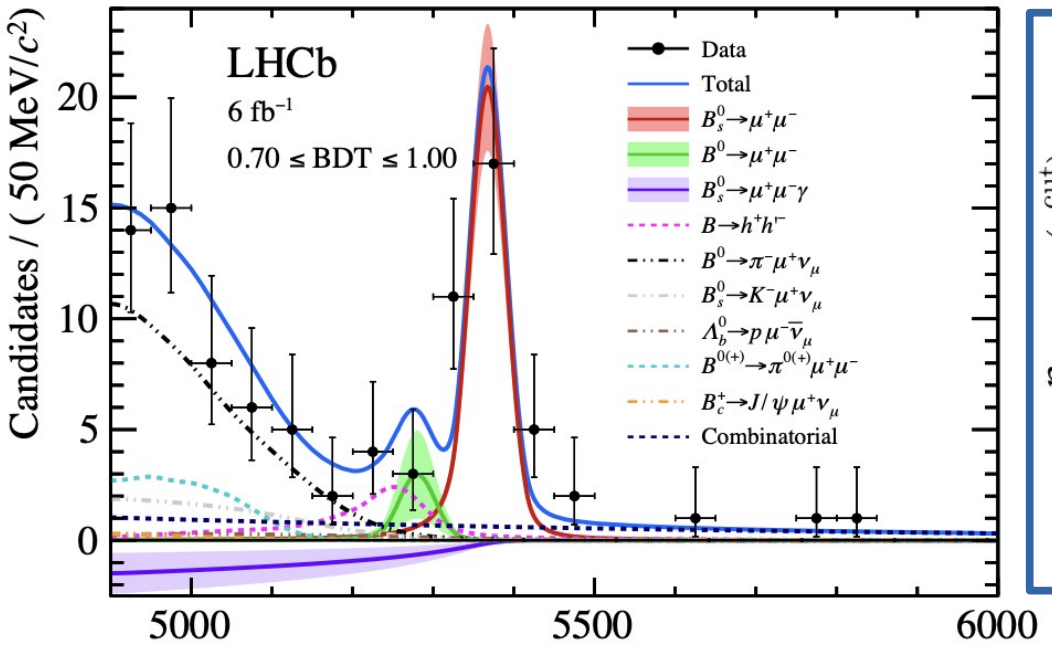

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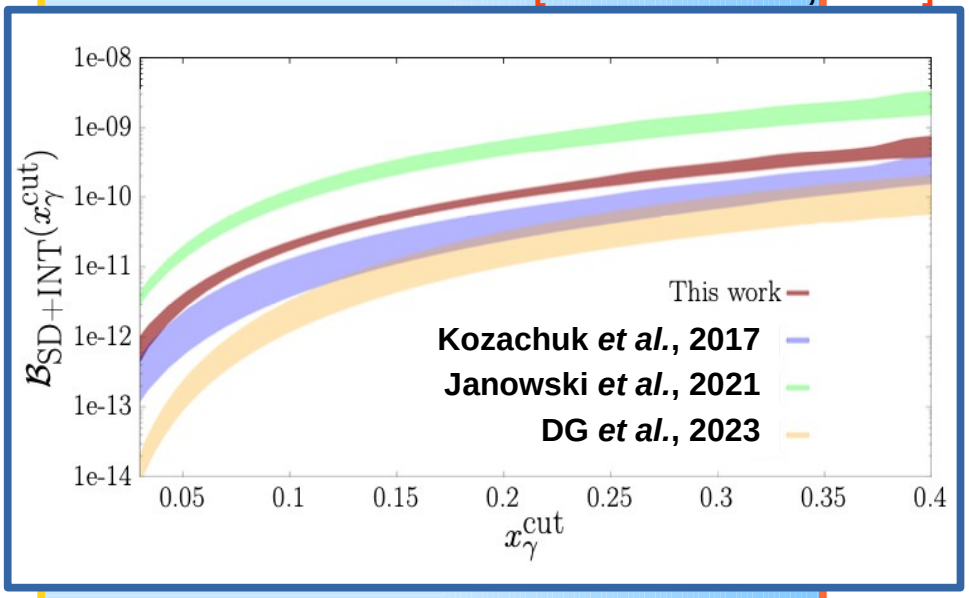
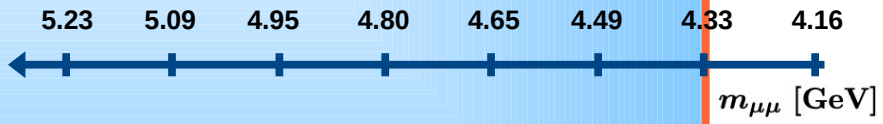
[Frezzotti et al., 2024]





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- Throughout, I advocate a Keynesian approach

When the facts change, I change my mind – what do you do, sir?

– John Maynard Keynes

$$B \to K^{(*)}\, \nu\bar{\nu}$$

$B \to K^{(*)} \nu\bar{\nu}$ – latest data

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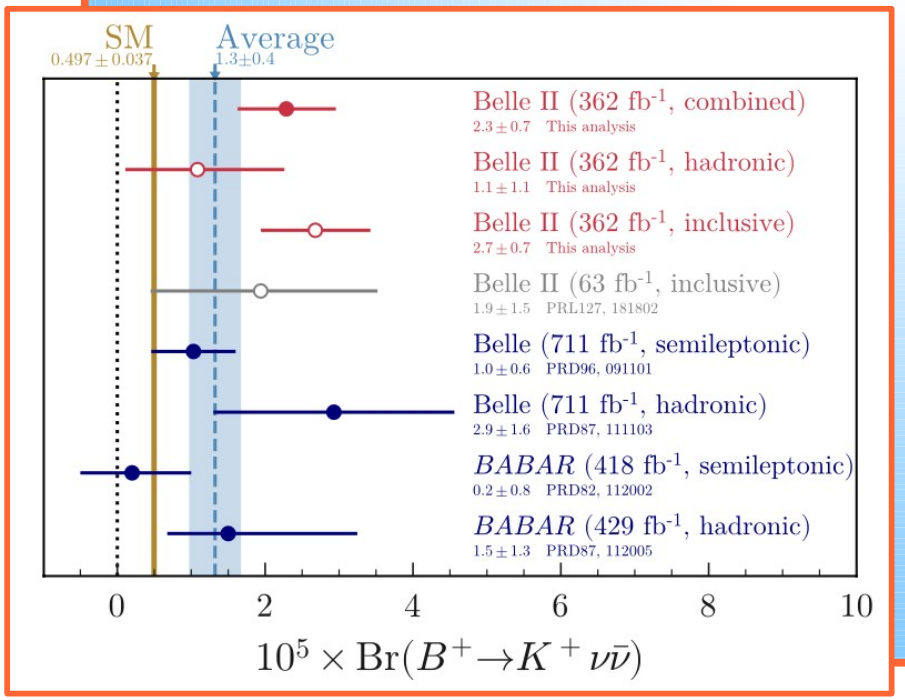

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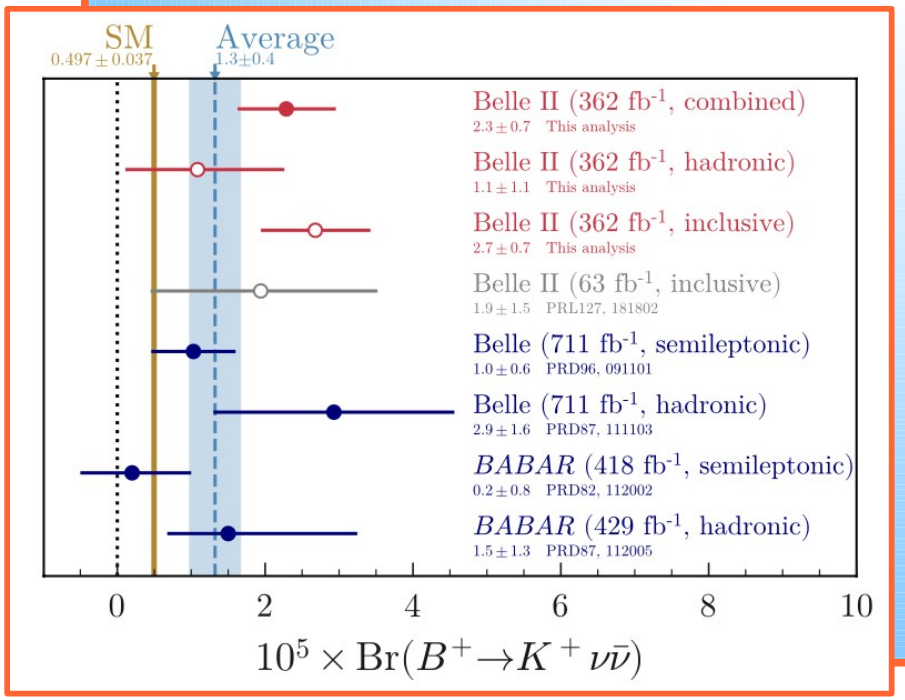

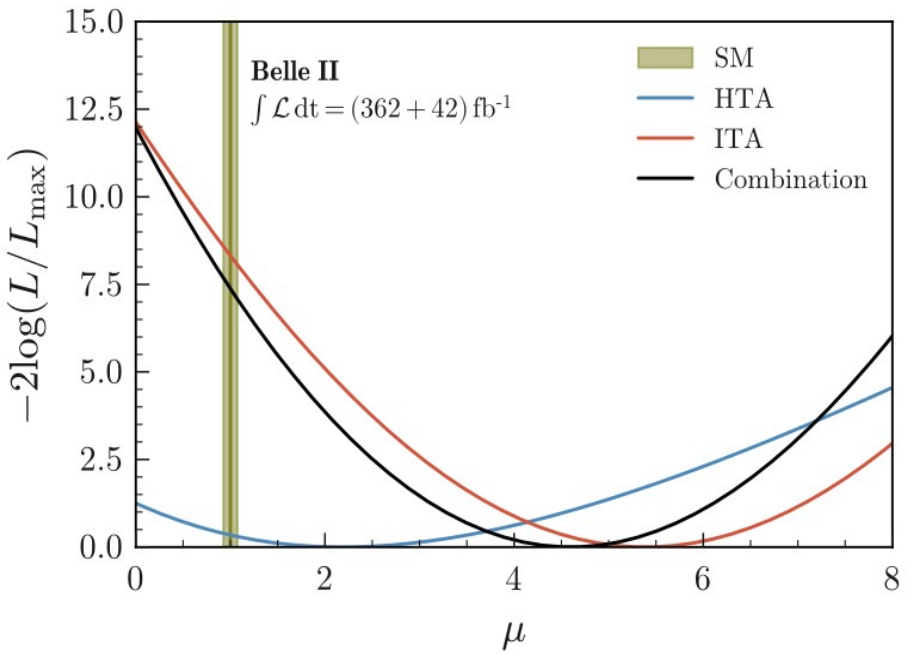

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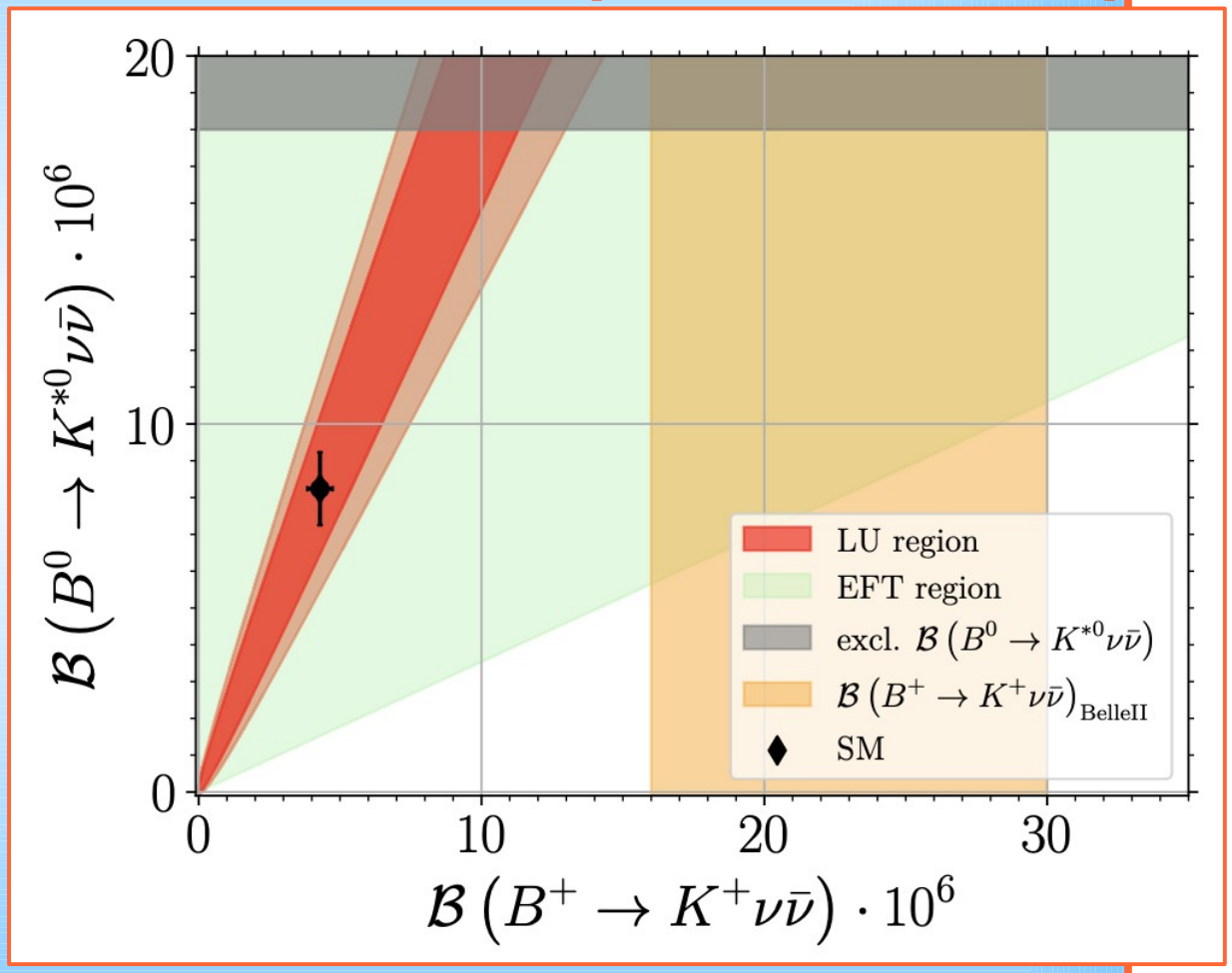

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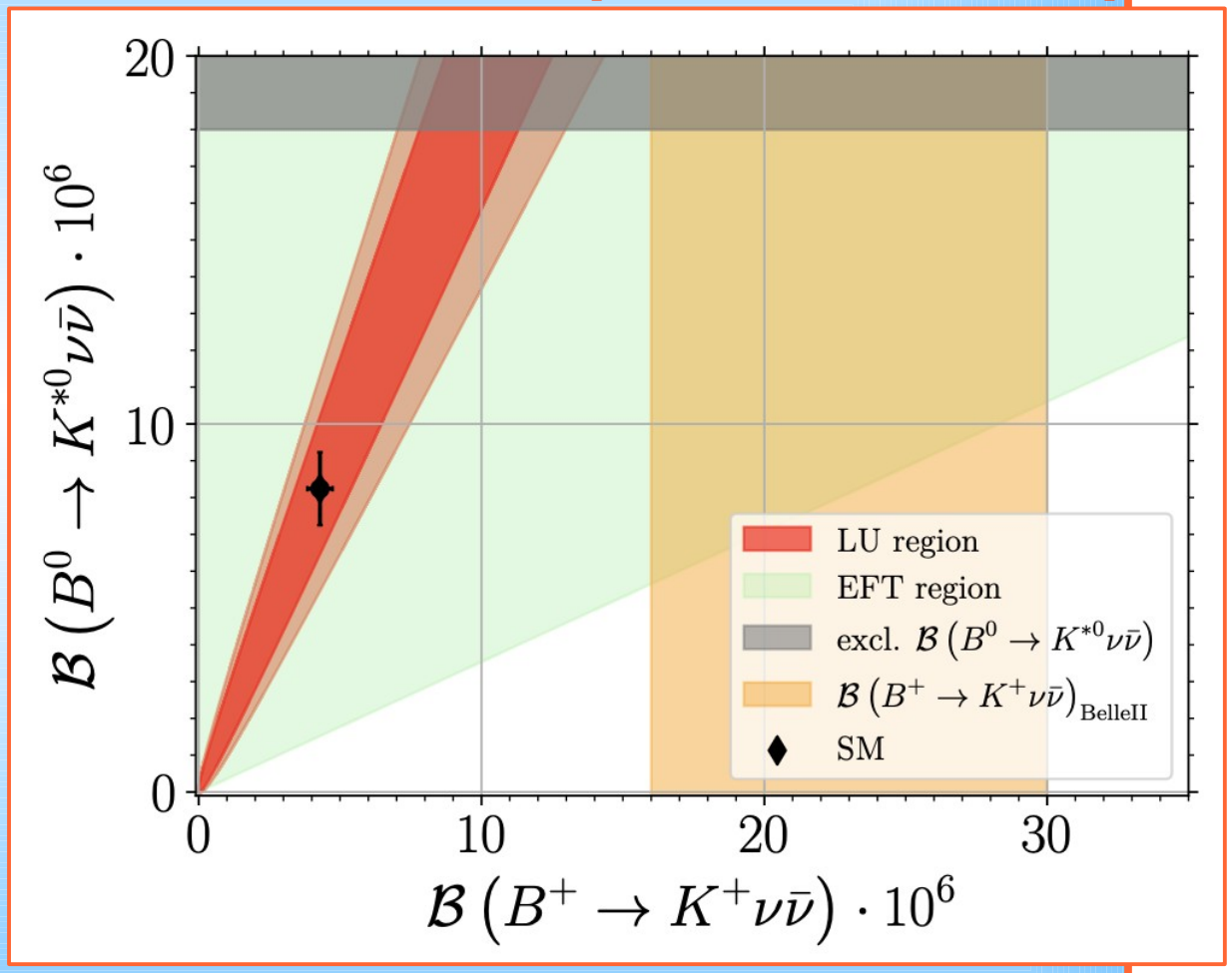

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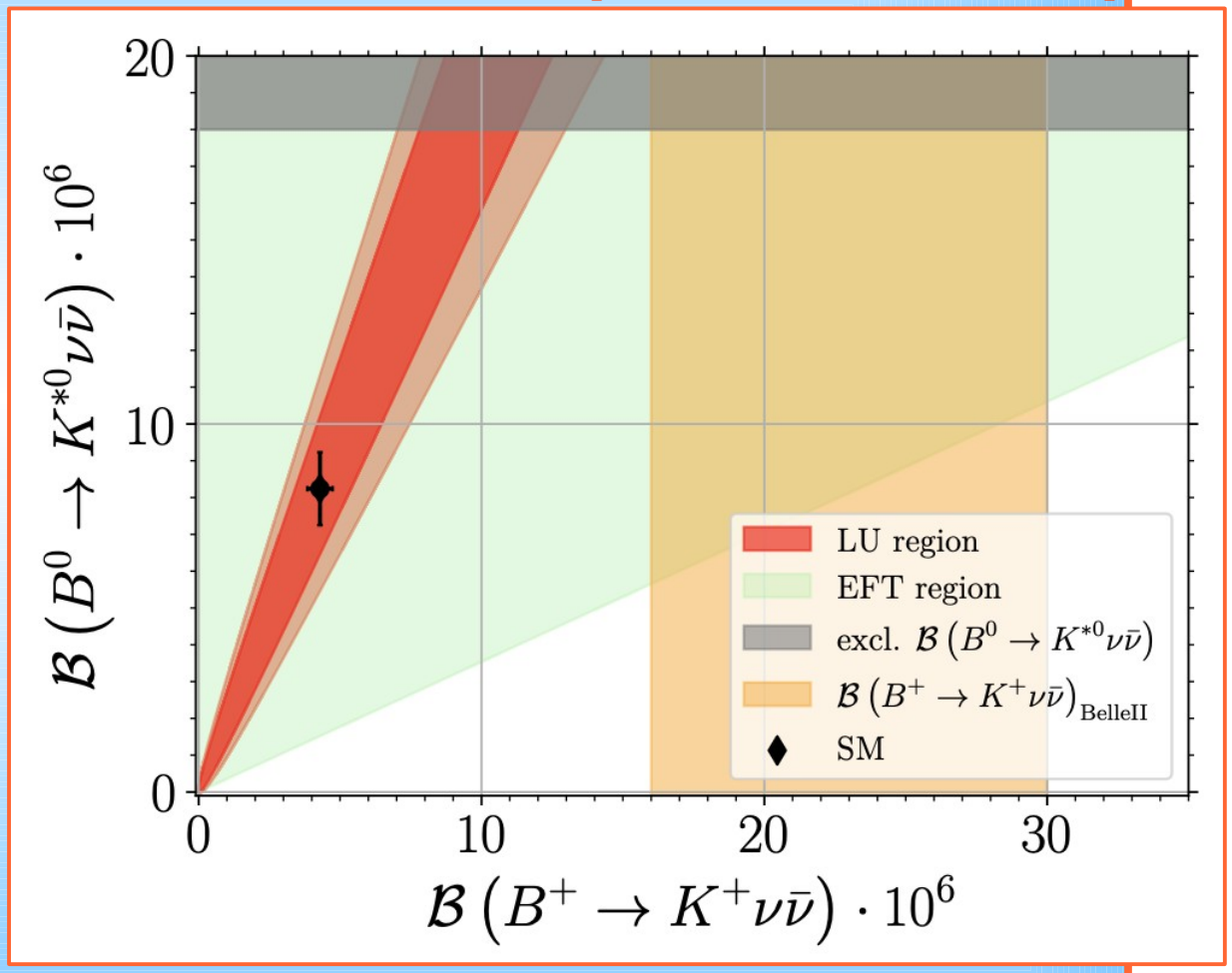

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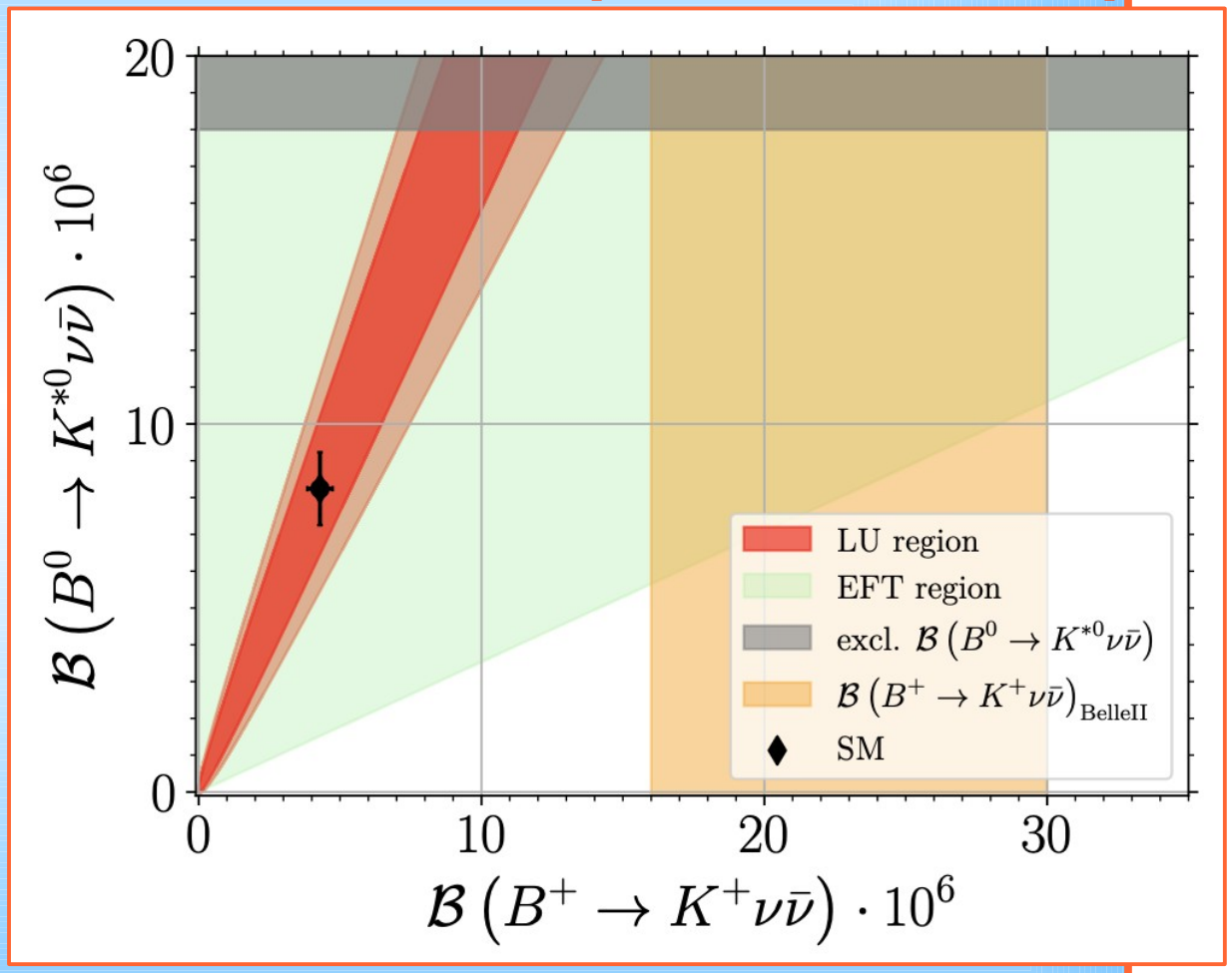

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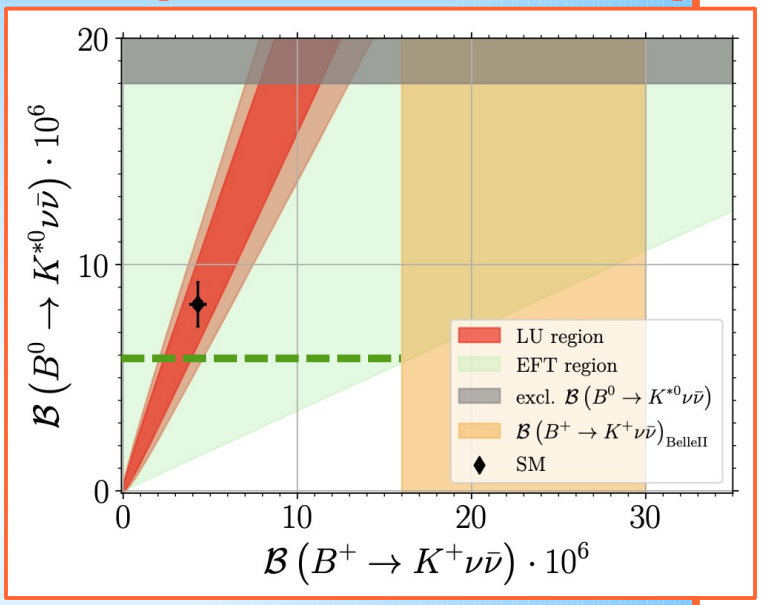

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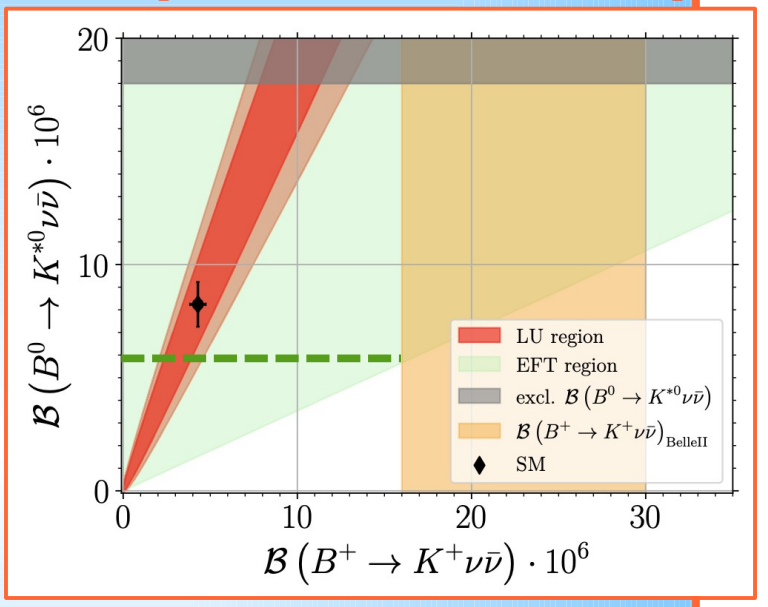

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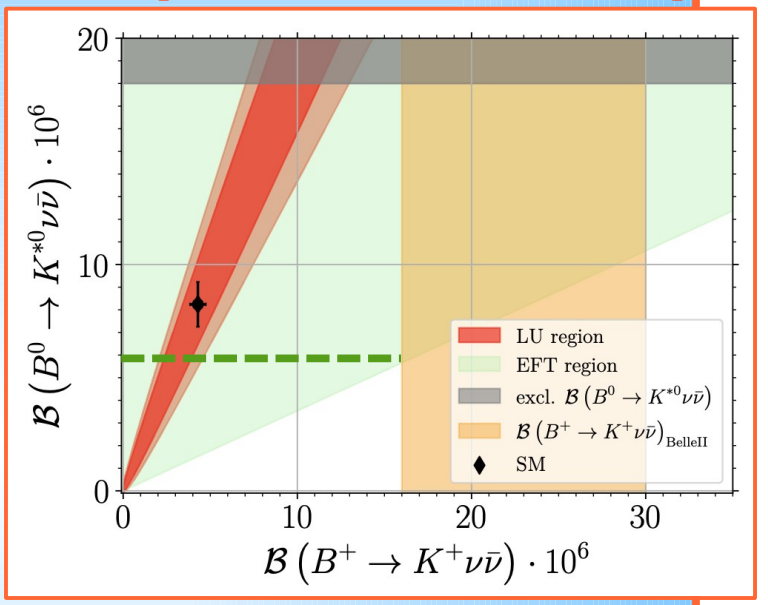

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At least one of these modes (or LFV ones) *has to* be affected [**Bause *et al.*, Allwicher *et al.***]

$$\mathcal{B}(B_s^0 \to \tau^+\tau^-) \lesssim 1.7 \cdot 10^{-5}$$

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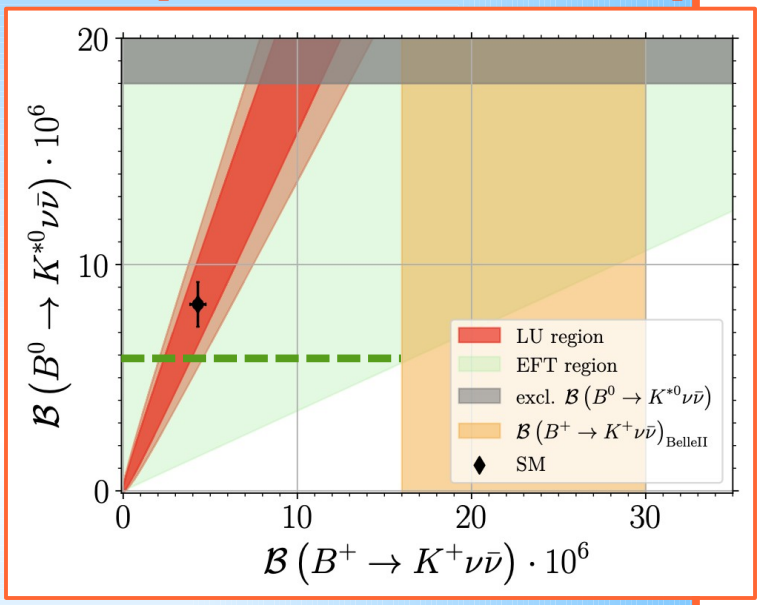

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- Else: light new dynamics, implying the relation

$$\mathcal{B}(B_s^0 \to \nu\bar{\nu})_{S,P} \approx 0.7\,\mathcal{B}(B^0 \to K^{*0}\nu\bar{\nu})_{S,P}$$

My take on

the ESPPU

(flavour)

The intensity frontier

- **Strategy:**

Use large datasets of some of the rarest processes

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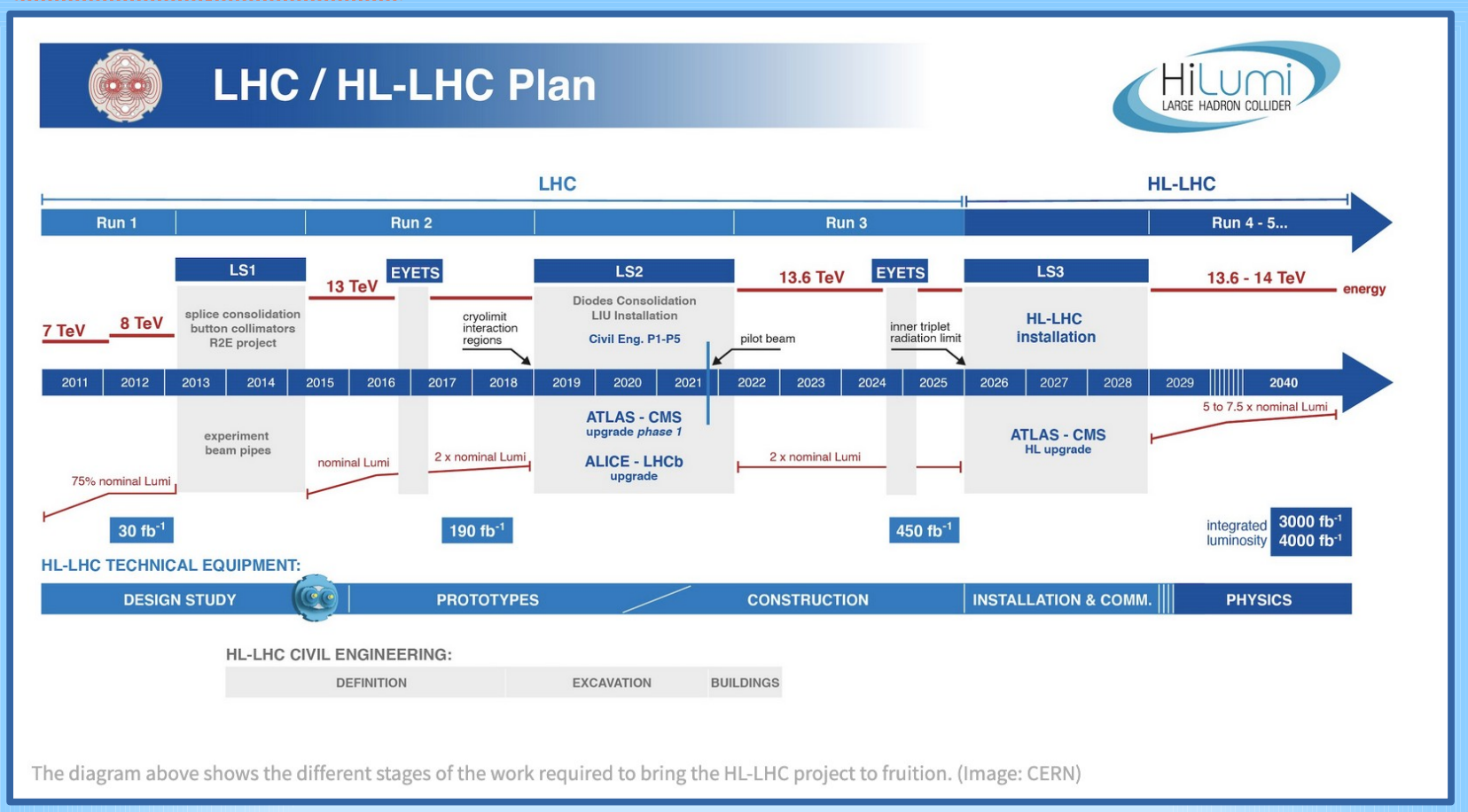
Large facilities



The diagram above shows the different stages of the work required to bring the HL-LHC project to fruition. (Image: CERN)

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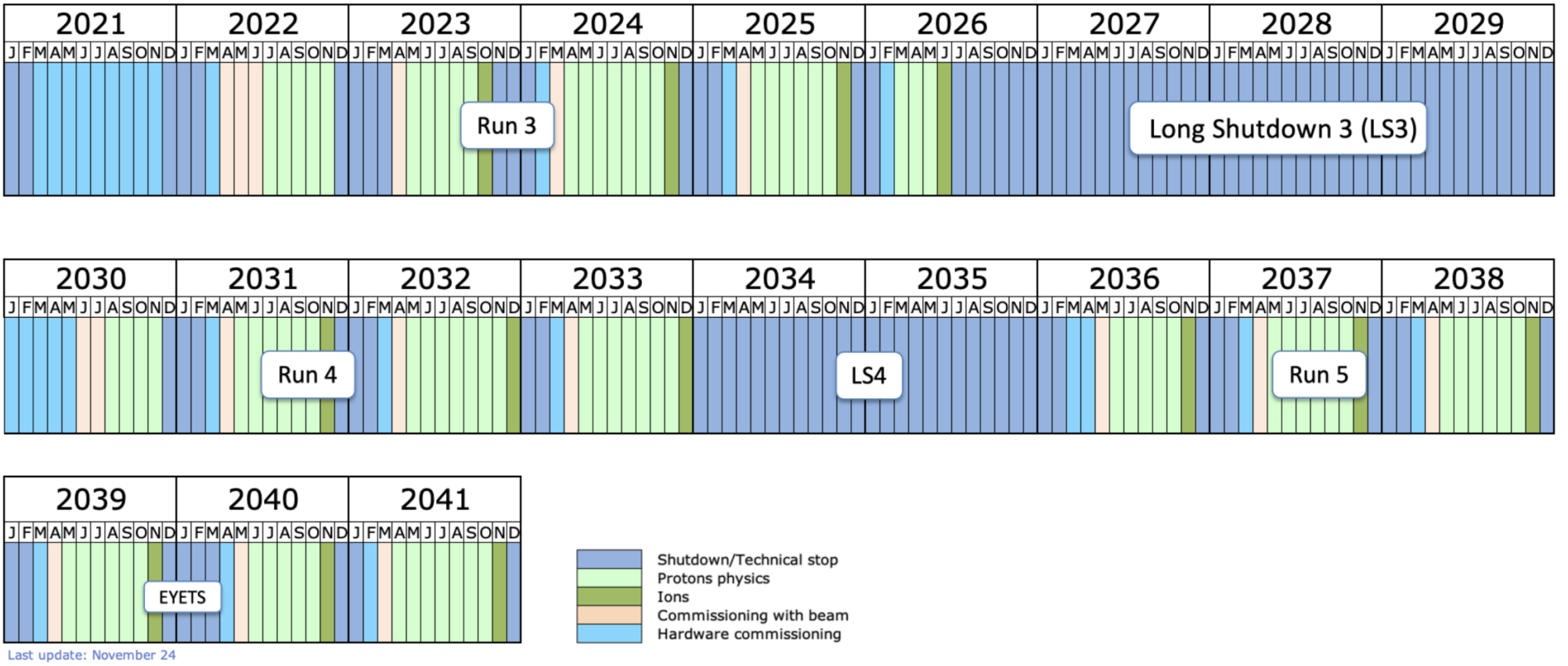

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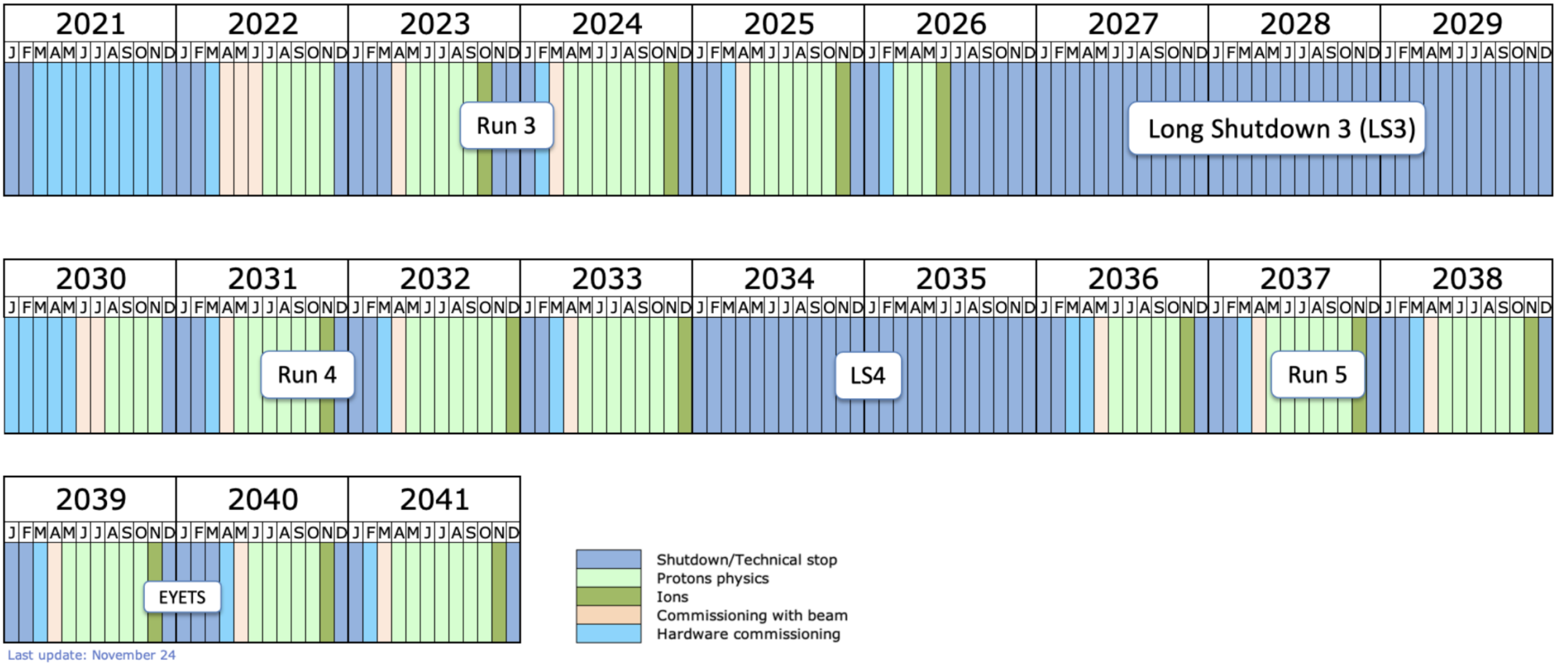

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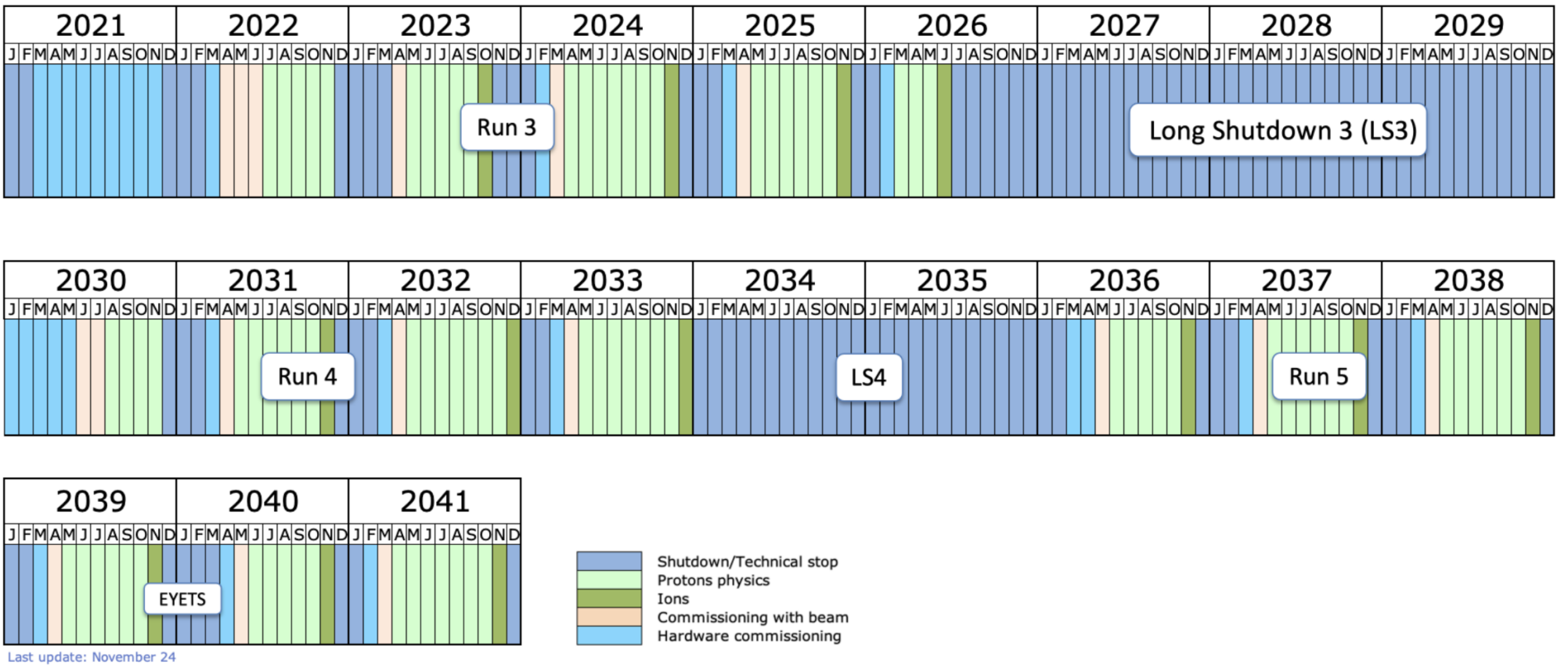

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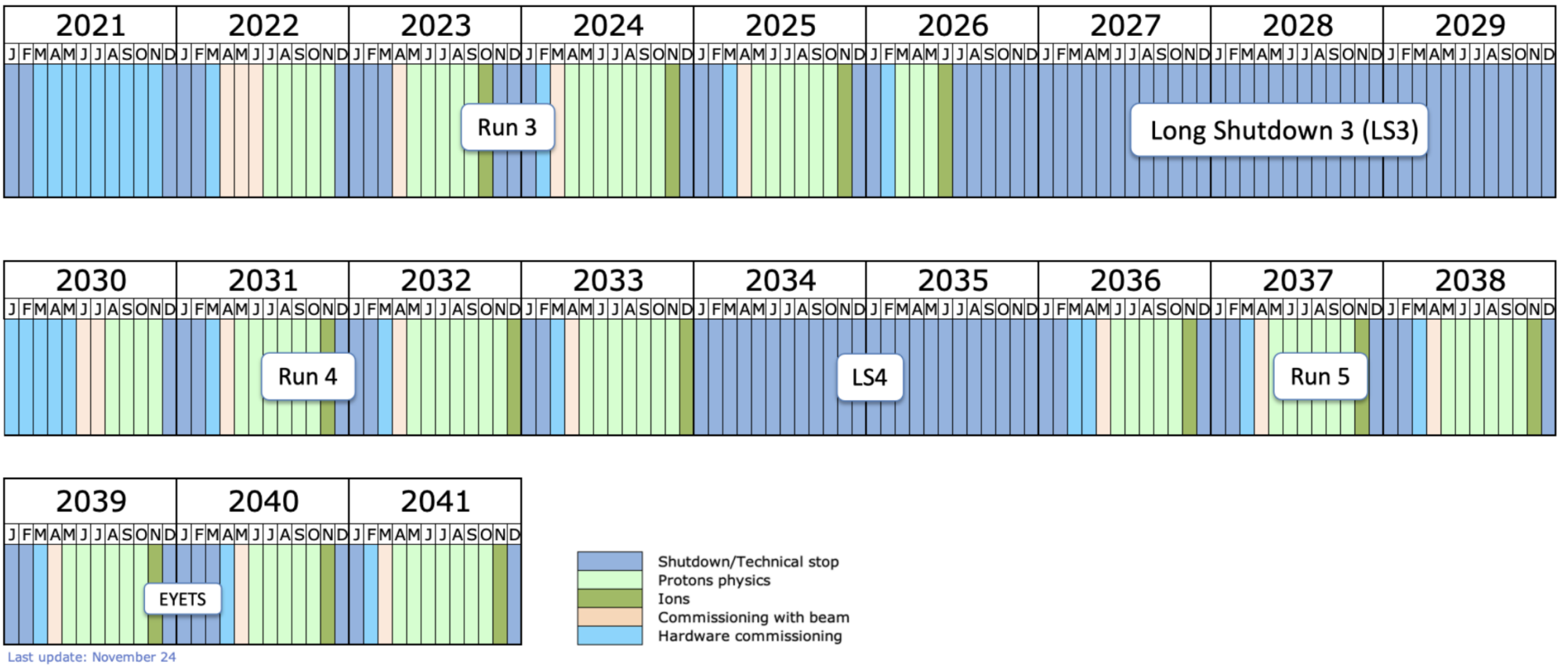

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- Proposed Belle II Upgrade ~2032
- After HL-LHC (2030 onward) & Belle II

⇨ e^+e^- collider at the Z pole (10^{12} Z)

The many uses of ultrarare K decays

- *K* decays are the most severe manifestation of the flavour problem:
  Generic new dynamics cannot be below **10^4 – 10^5 TeV**

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- *K* decays also excruciating probes of well-motivated light NP
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$$\mathcal{L}_{aff} = \frac{\partial_\mu a}{f_a}\left(\bar{q}\,\gamma_L^\mu\,\hat{k}_L(a)\,q + \bar{q}\,\gamma_R^\mu\,\hat{k}_R(a)\,q\right)$$ + leptonic analogue

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axion-mediated
d ↔ s FCNCs

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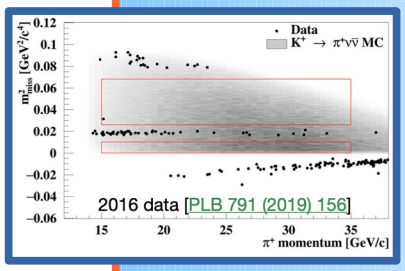
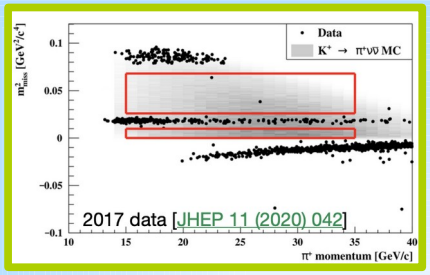
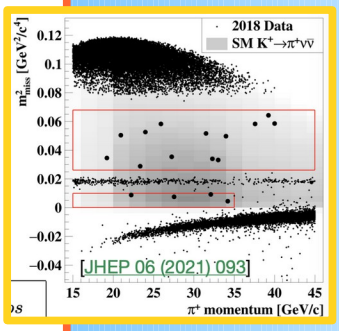
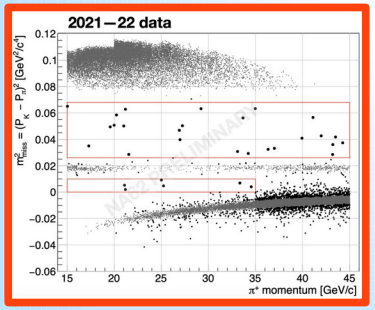




2016-2022 dataset





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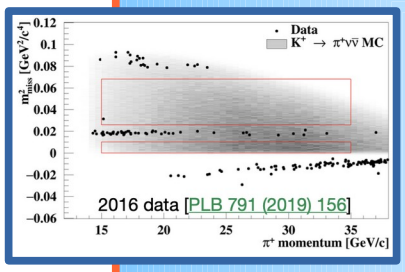
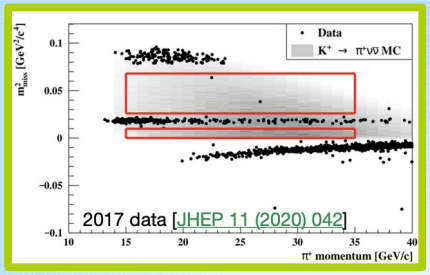
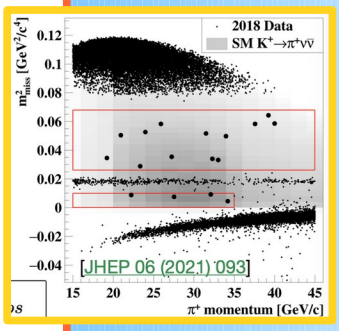
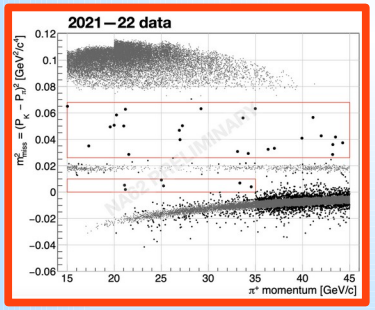
[DG, Iohner, Lazzeroni, Martinez-Santos, Swallow, Toni, 2025]

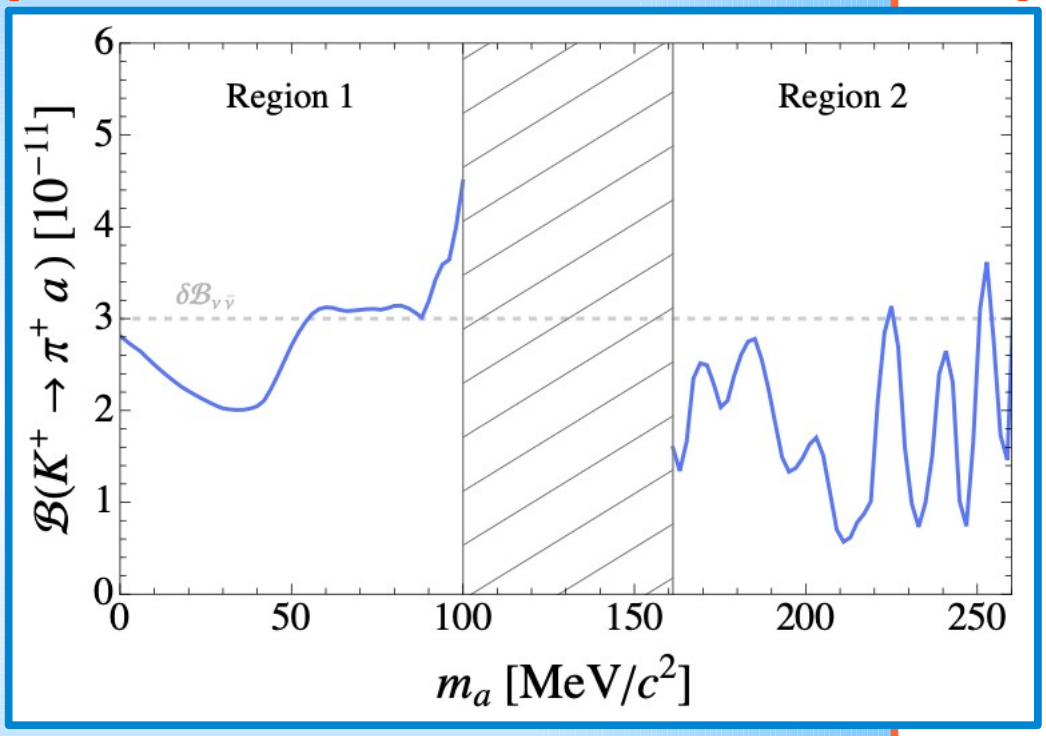




2016-2022 dataset



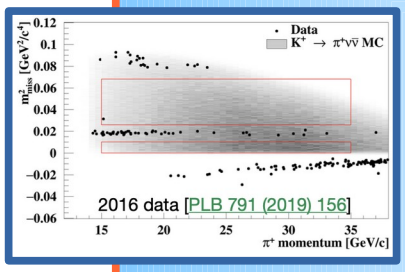


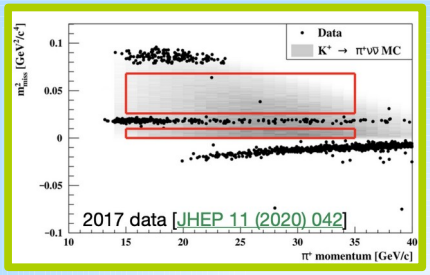


NA62 $K \to \pi\,(\pi)\,\nu\bar{\nu}$ data

- *The NA62 dataset for $K \to \pi\,(\pi)\,\nu\bar{\nu}$, recast as $K \to \pi\,(\pi)\,a$,* sets world-leading bounds on the above couplings

[DG, Iohner, Lazzeroni, Martinez-Santos, Swallow, Toni, 2025]





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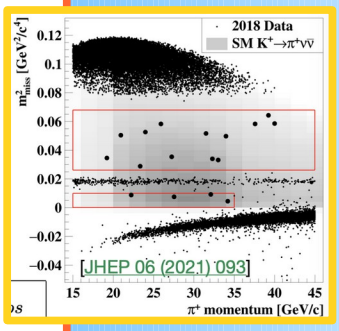

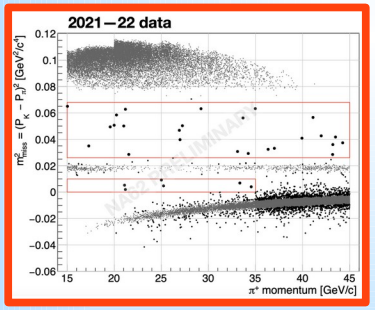

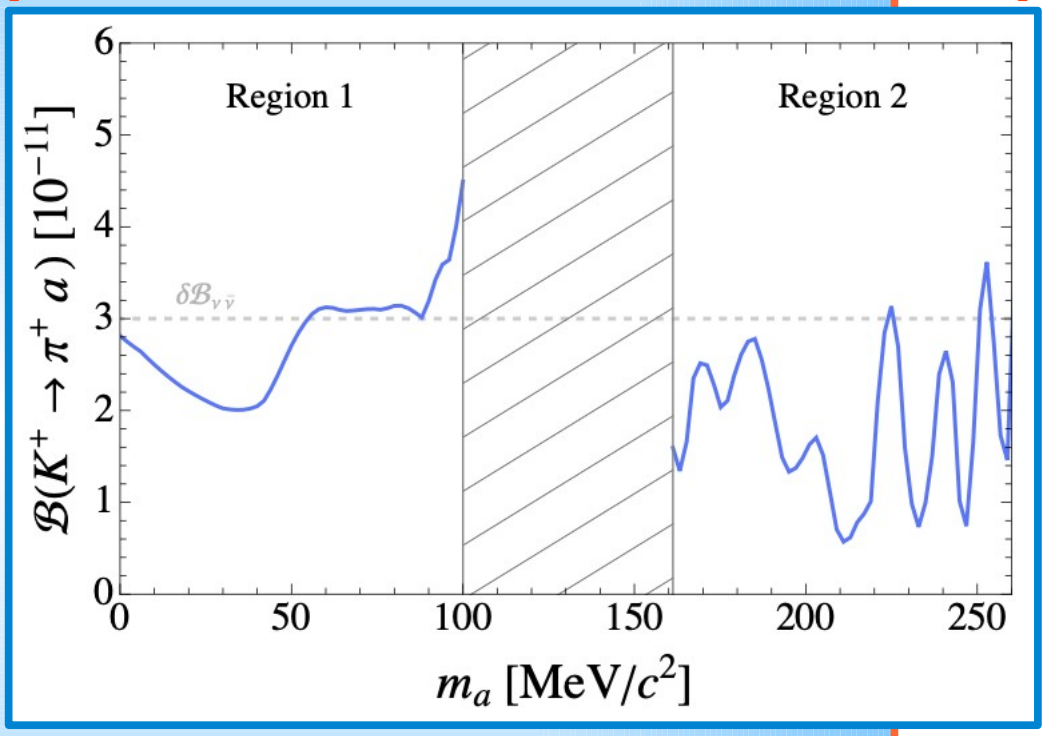

$$\frac{2f_a}{(k_V)_{23}} > 1.1 \times 10^9 \text{ TeV} \qquad \frac{2f_a}{(k_A)_{23}} > 1.0 \times 10^5 \text{ TeV}$$

Conclusions

Even if some of the outstanding SM problems lie in the gauge sector – i.e., not in the Yukawa sector

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Also, the interactions of longitudinal gauge bosons may be probed through their direct production at high energies

BUT

They also enter in e.g. "penguin" diagrams

[See e.g. "$B_s \to \mu\mu$ as an electroweak precision test", DG & Isidori, 2013]

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Flavour has demonstrably the largest reach

and Kaons have the largest reach within flavour