Flavours of the Standard Model : precision , anomalies , and prospects

Diego Guadagnoli
CNRS , LAPTh Annecy

Sandra D'Amico

(Jan 30, 1951 – May 30, 2026)

In Memoriam

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Why flavour

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  - Example : small Kaon FCNC predicted charm years before discovery

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[Intensity & Energy frontiers :
two complementary programs]

The experimental landscape

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Heavy flavours

LHCb   Belle II

BES-III

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MEG II Mu3e

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NA62 KOTO

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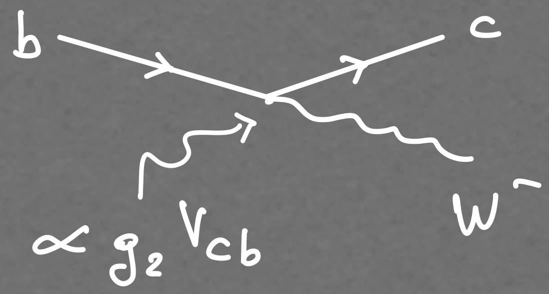
Future !

Flavour@FCC-ee SHiP Pioneer ...

CKM : the V_{cb} case

SM : all quark flavour
from one vertex



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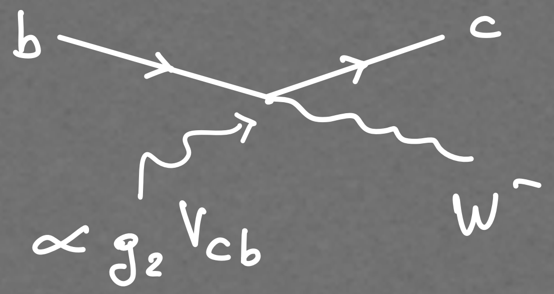

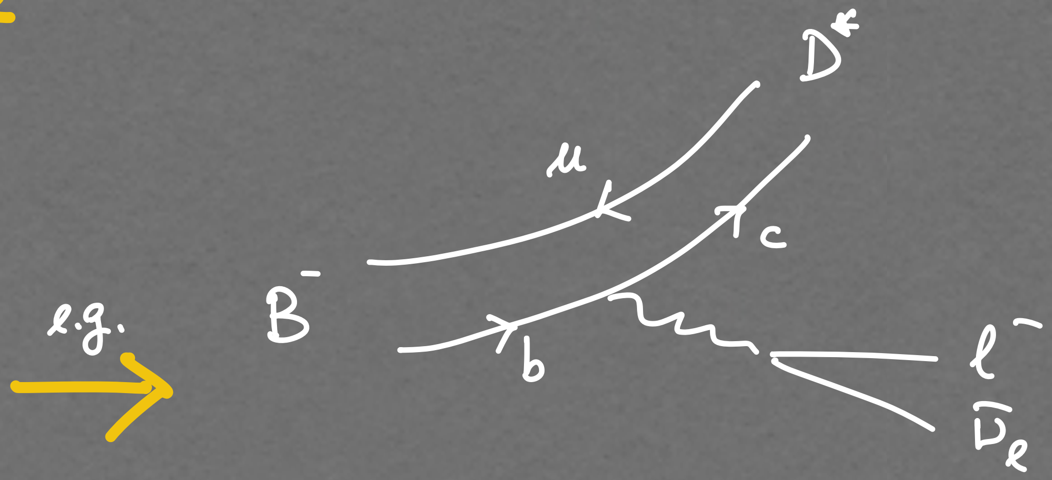

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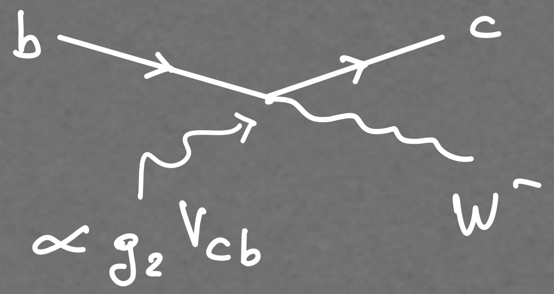

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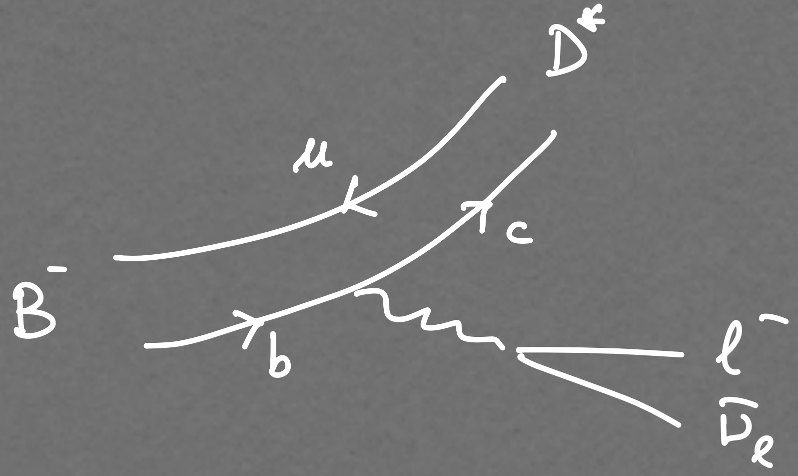

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rely on form factors
(lattice , sum rules, HQE)

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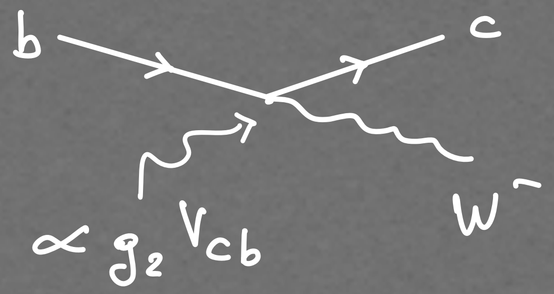

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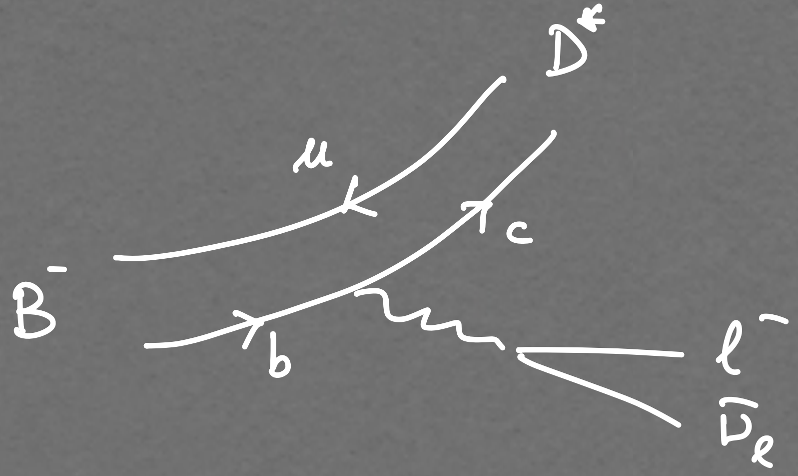

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or use optical theorem

$$\mathrm{Im}\,\mathcal{M}(B\to B)$$

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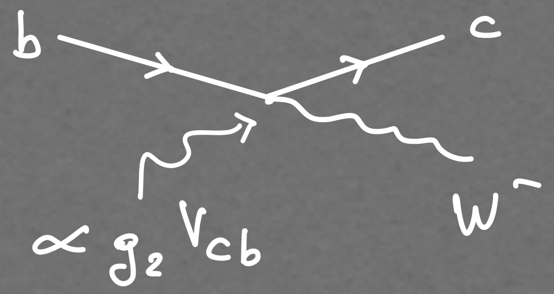

$\propto g_2 V_{cb}$

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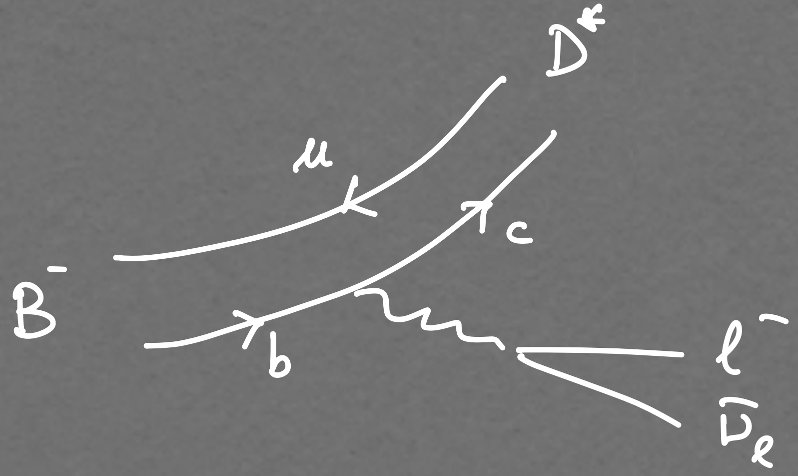

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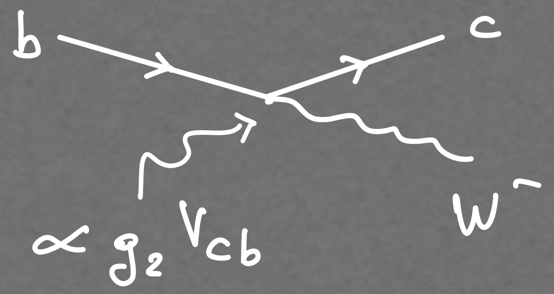

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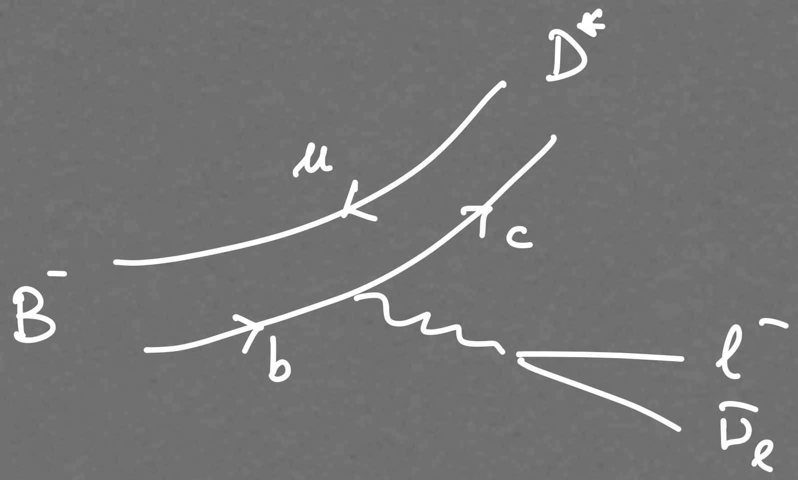

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→

$$B^- \to X_c + \ell^- \bar{\nu}_e$$

all possible one-charmed mesons

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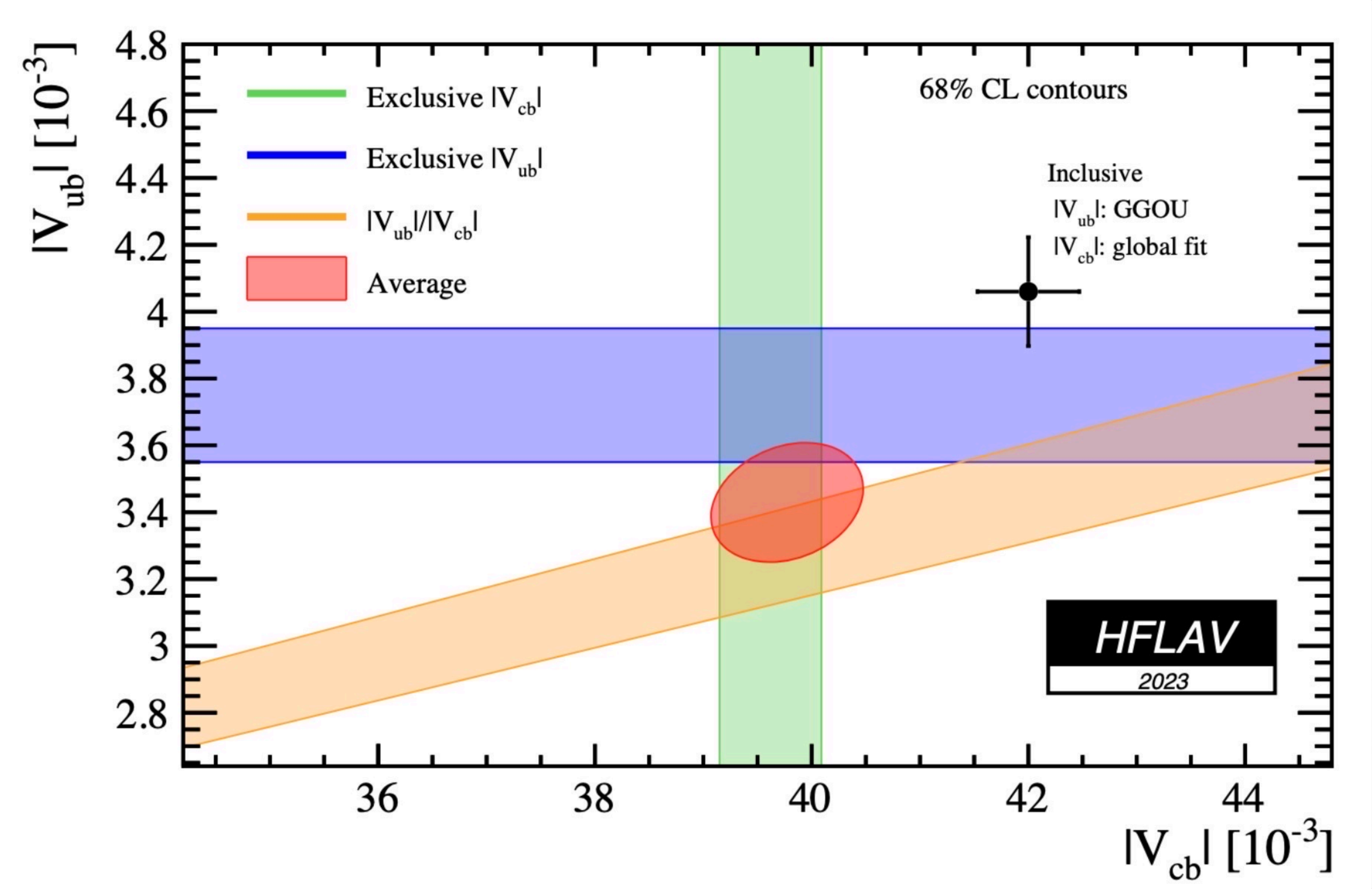
doable at B-factories

Vcb vs. Vub : a persistent tension



Lepton Flavour Universality : a test

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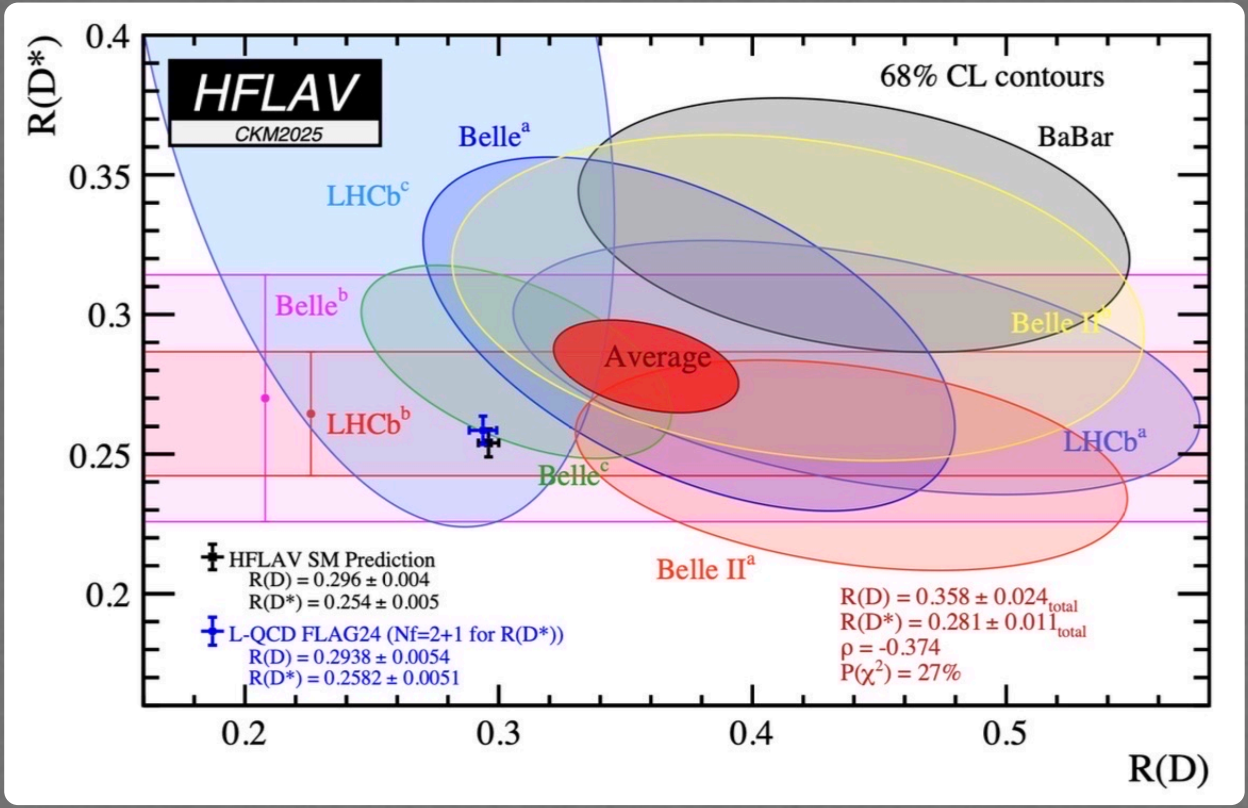

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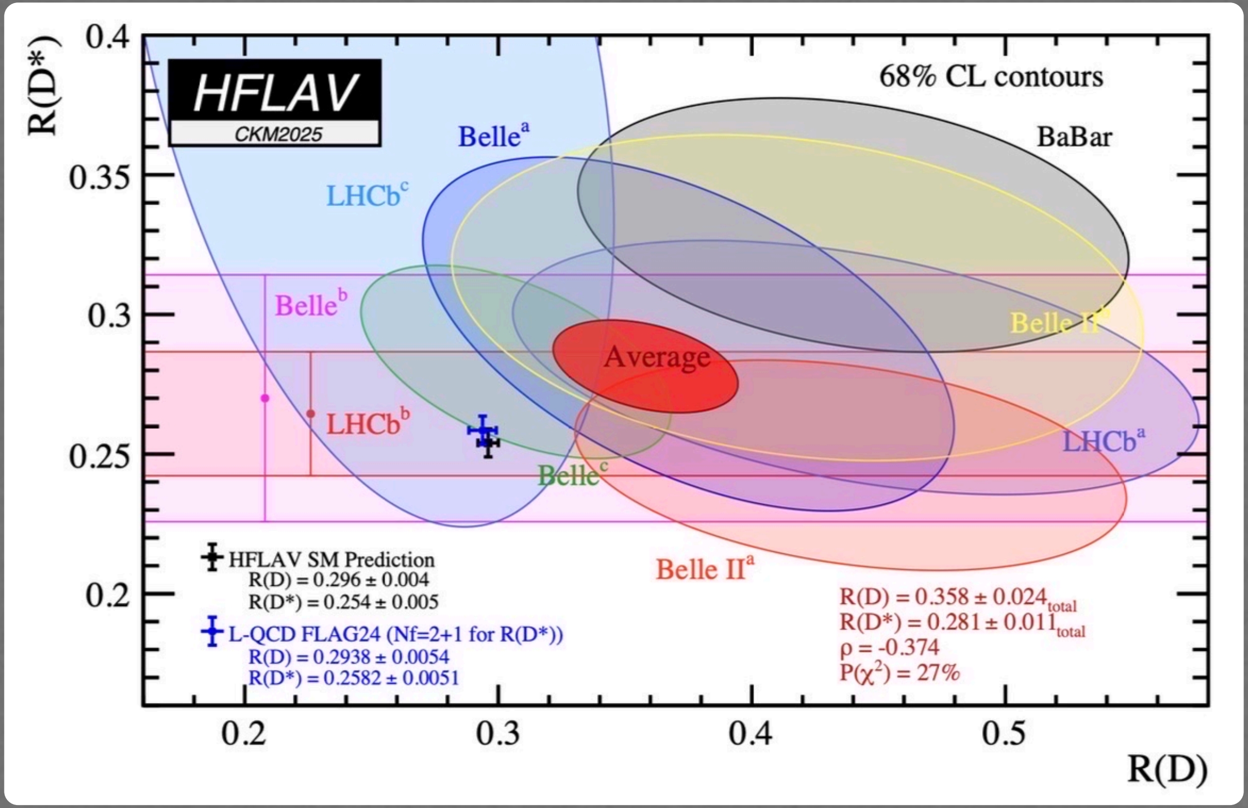
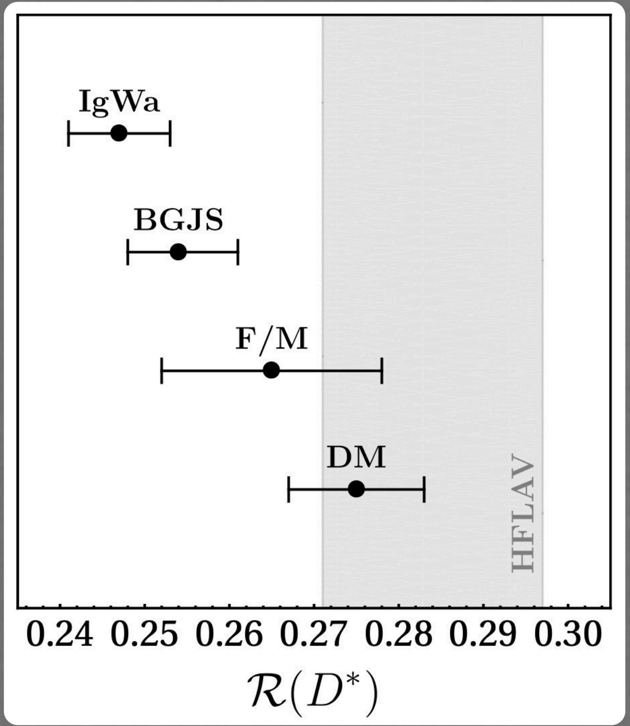
- in FNAL/MILC and "Dispersive Method" (Martinelli et al.) tension is absent





M. Blanke @ LHCb Impl. 2025

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[Freytsis, Ligeti, Ruderman, '15]

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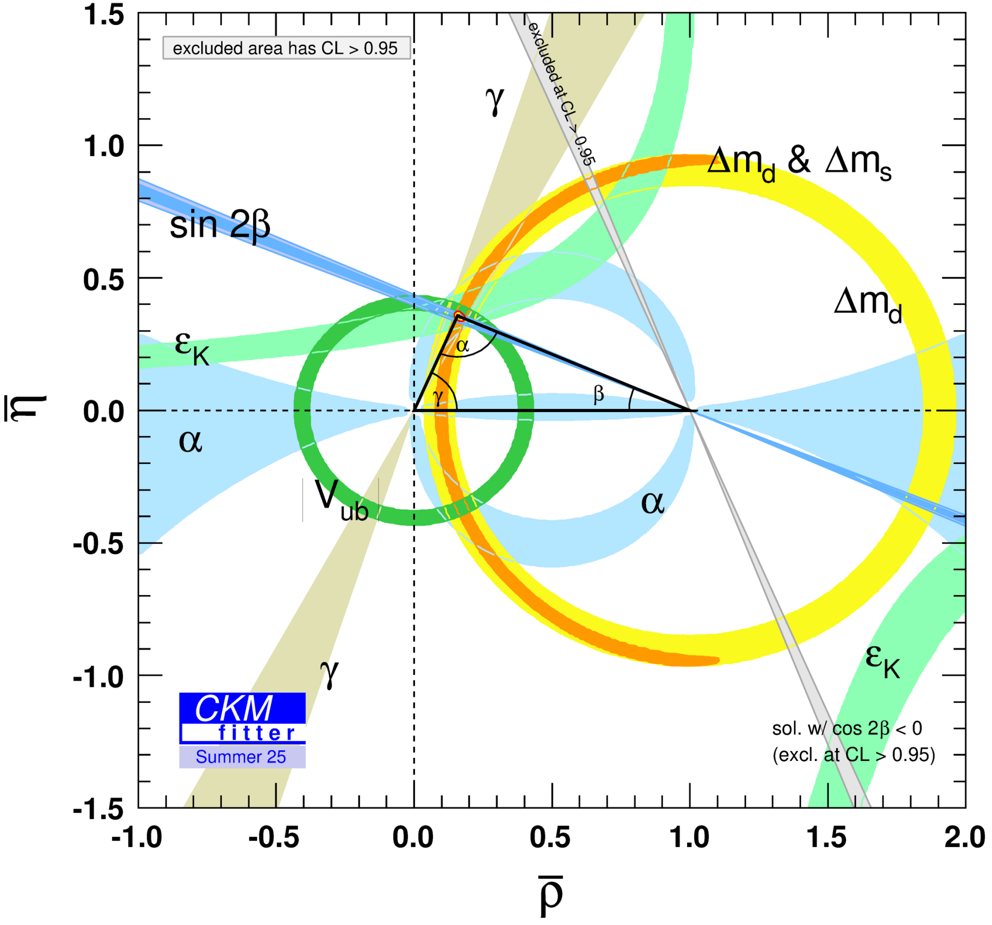
  Belle II & LHCb Upgrade II will provide final word

CKM picture : state of the union



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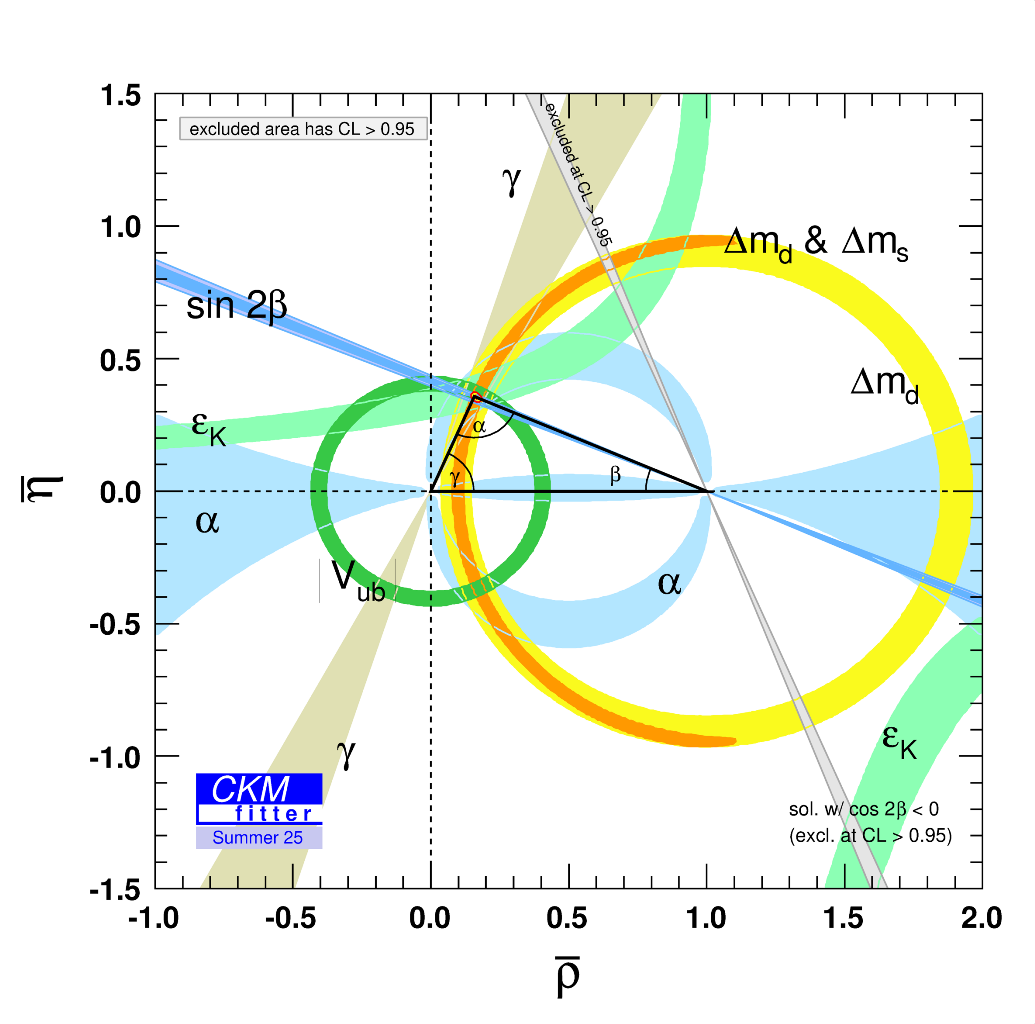

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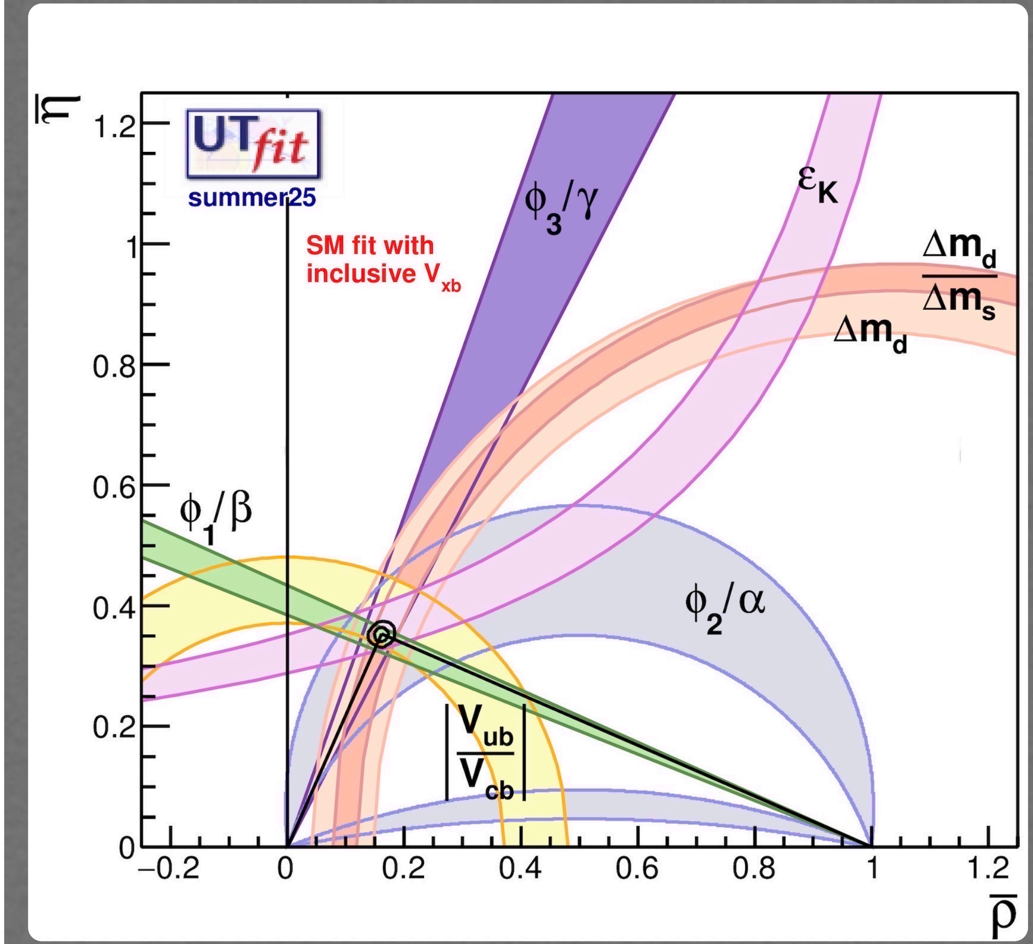

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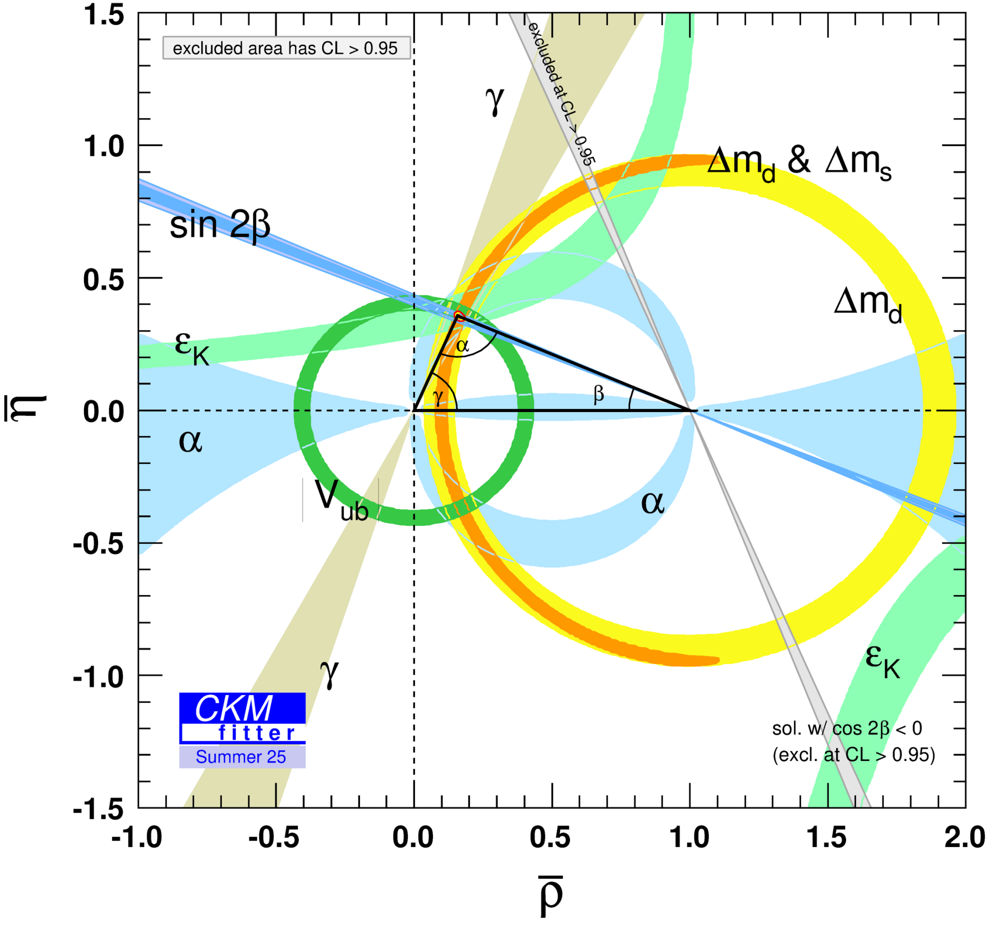

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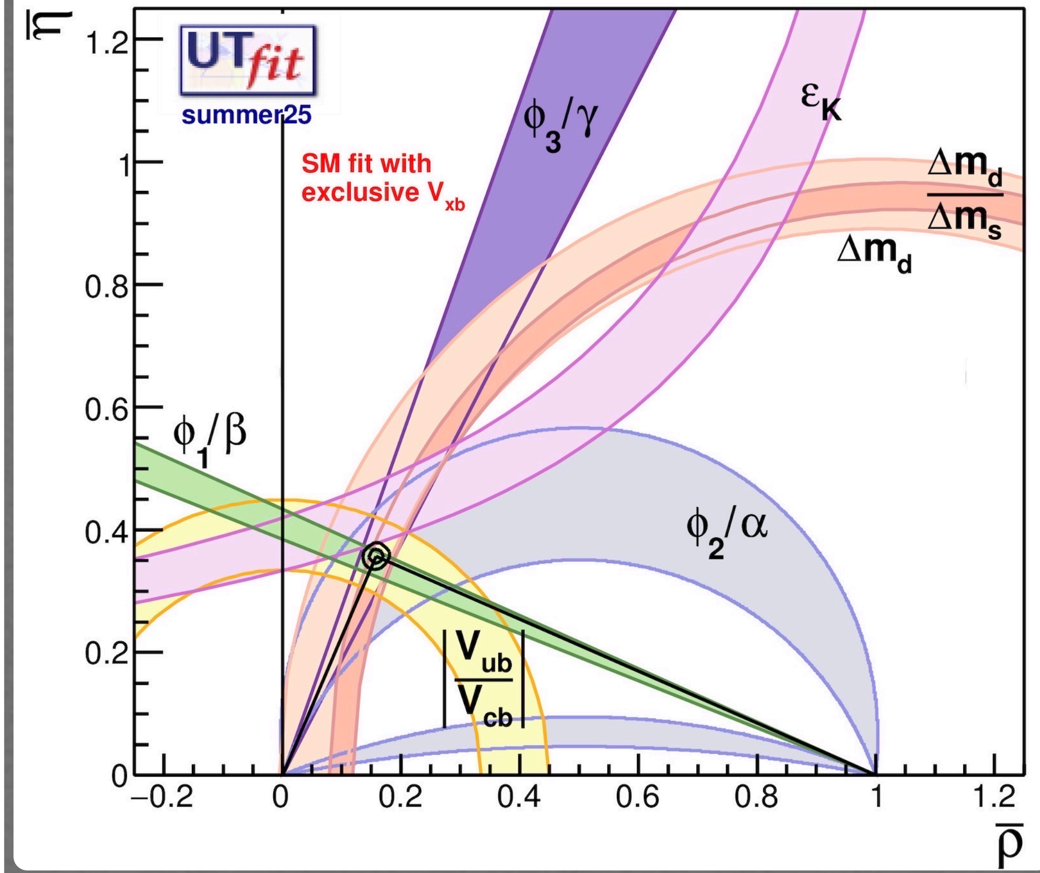
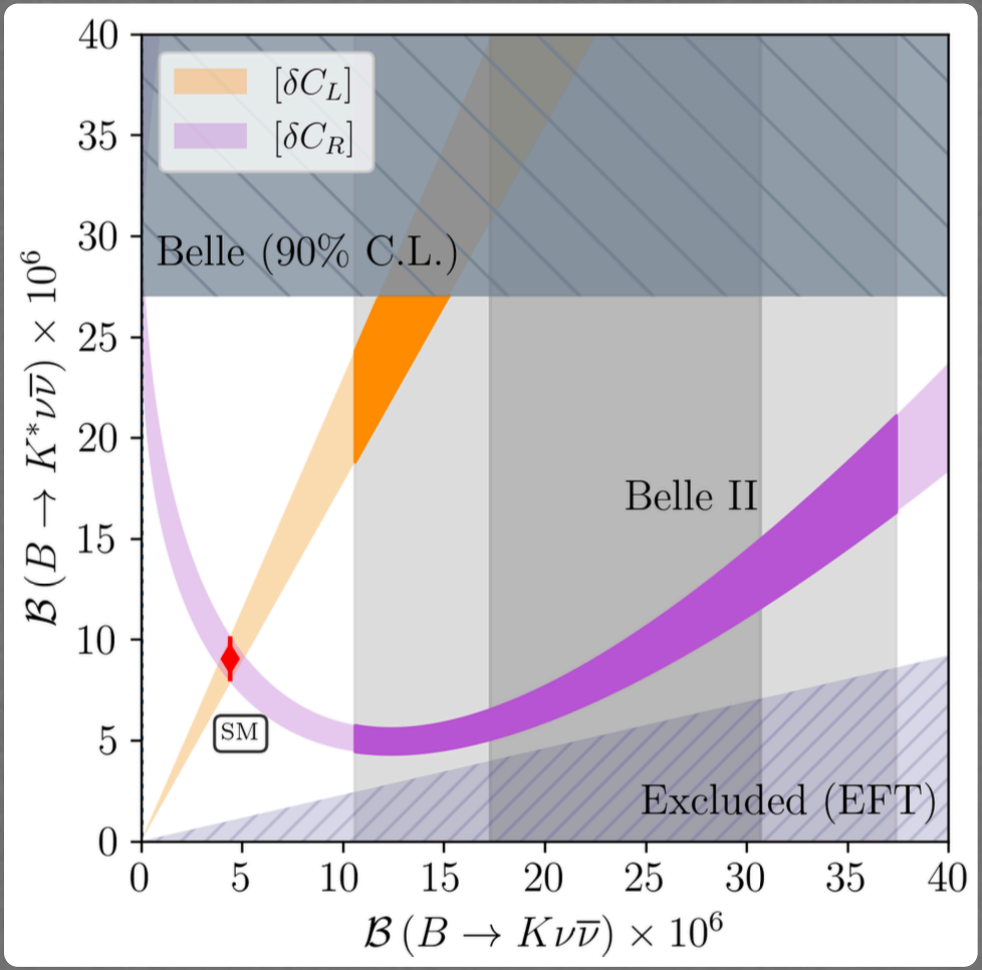


$B \to K^{(*)}\nu\bar{\nu}$



Allwicher et al., 2023

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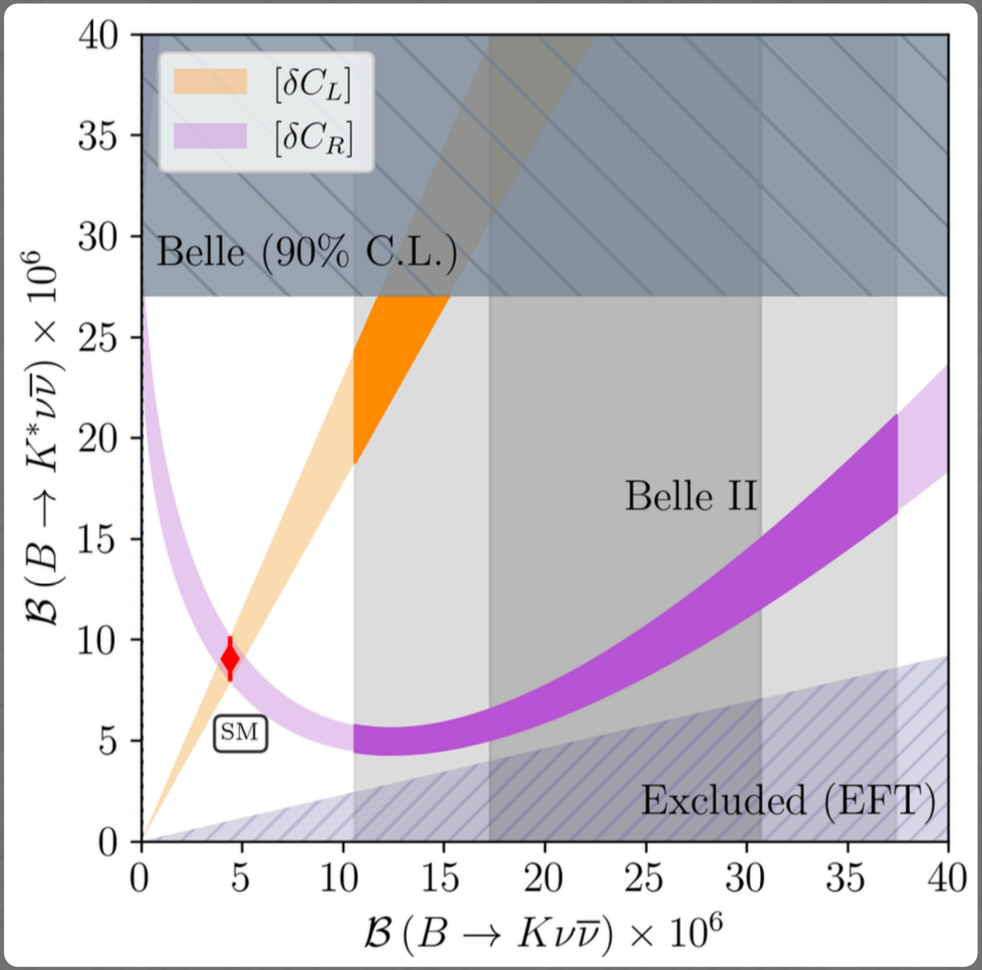
upper bound on K^* mode by Belle

First evidence: 2023, Belle II



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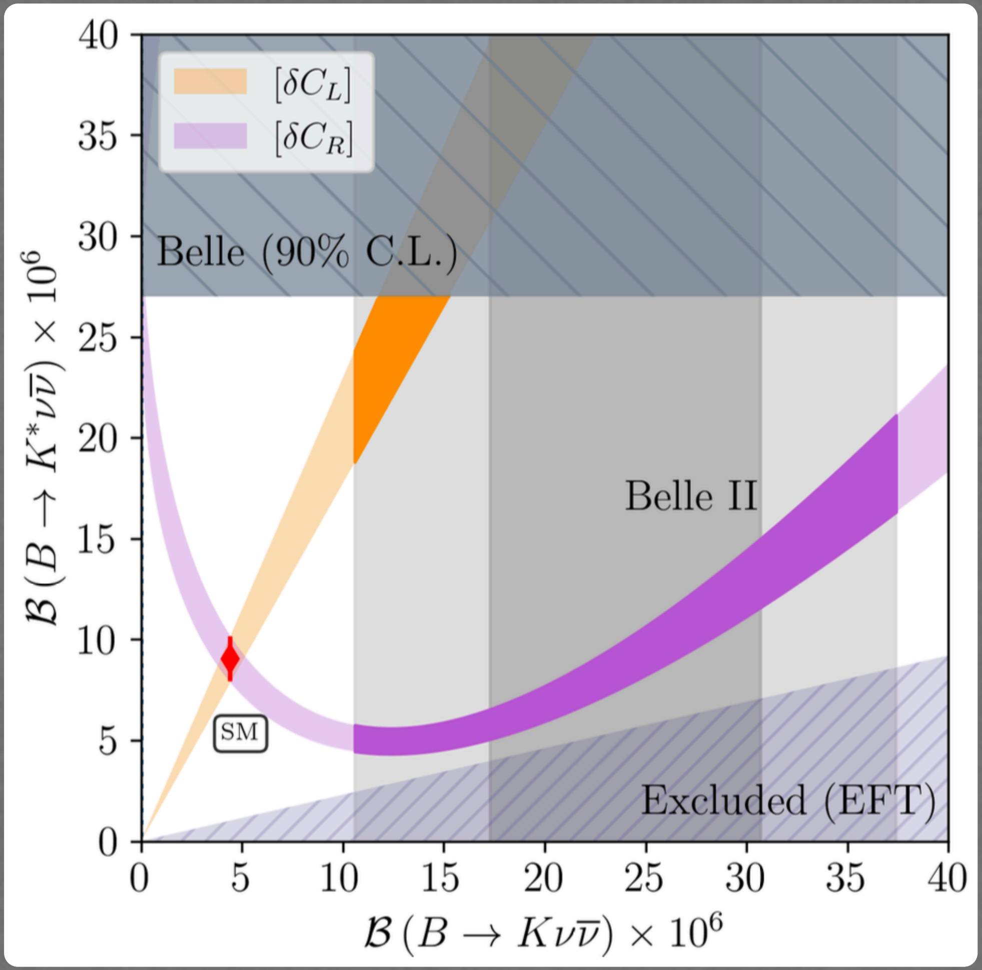

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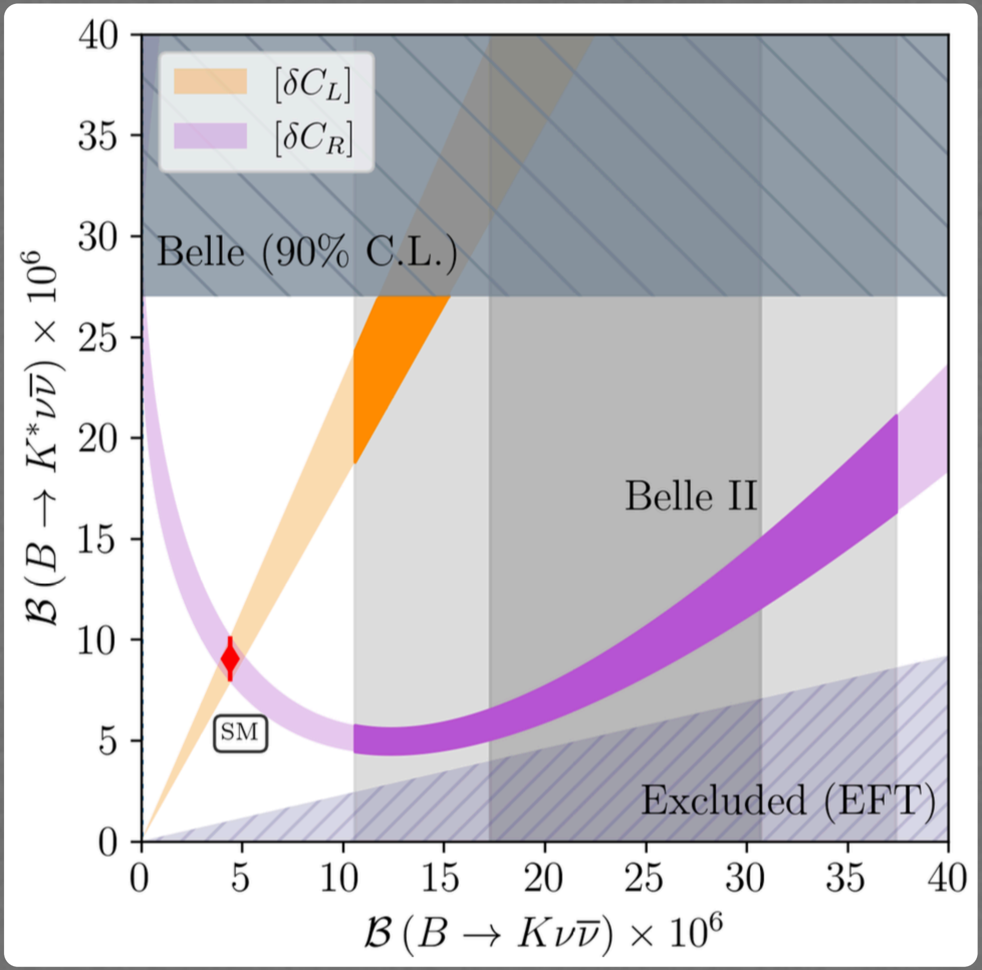

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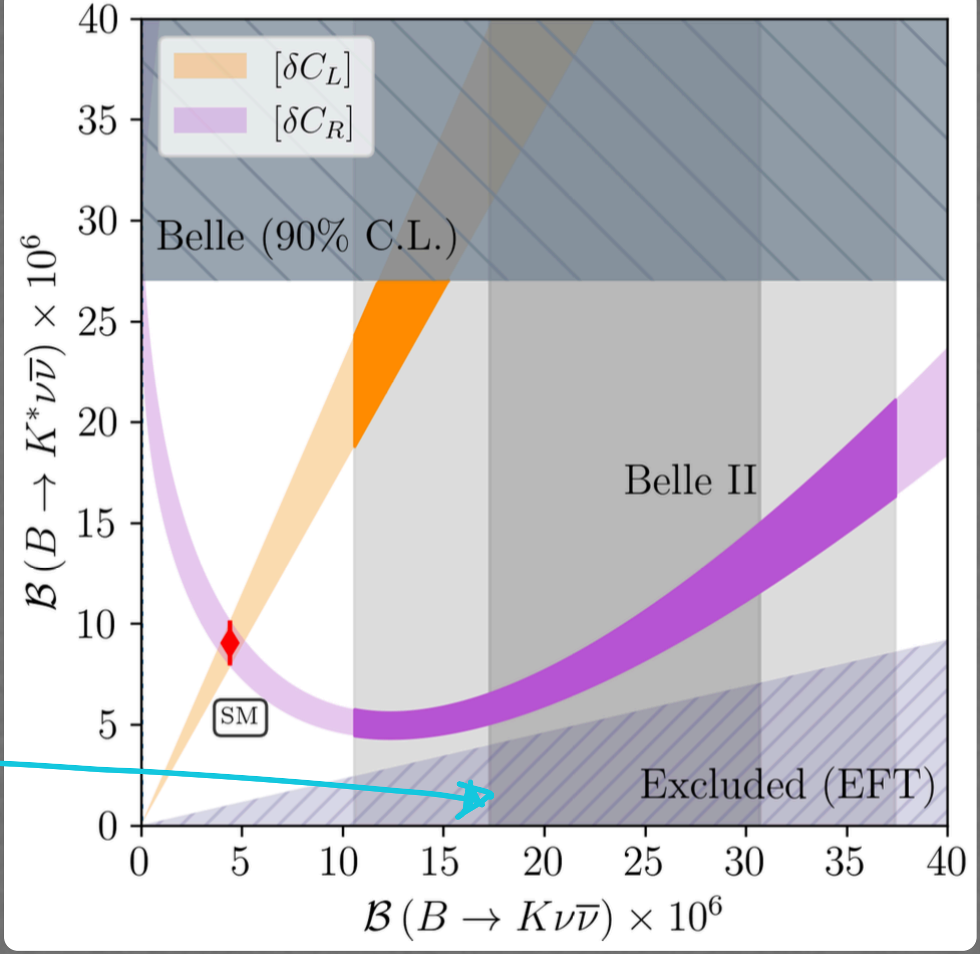

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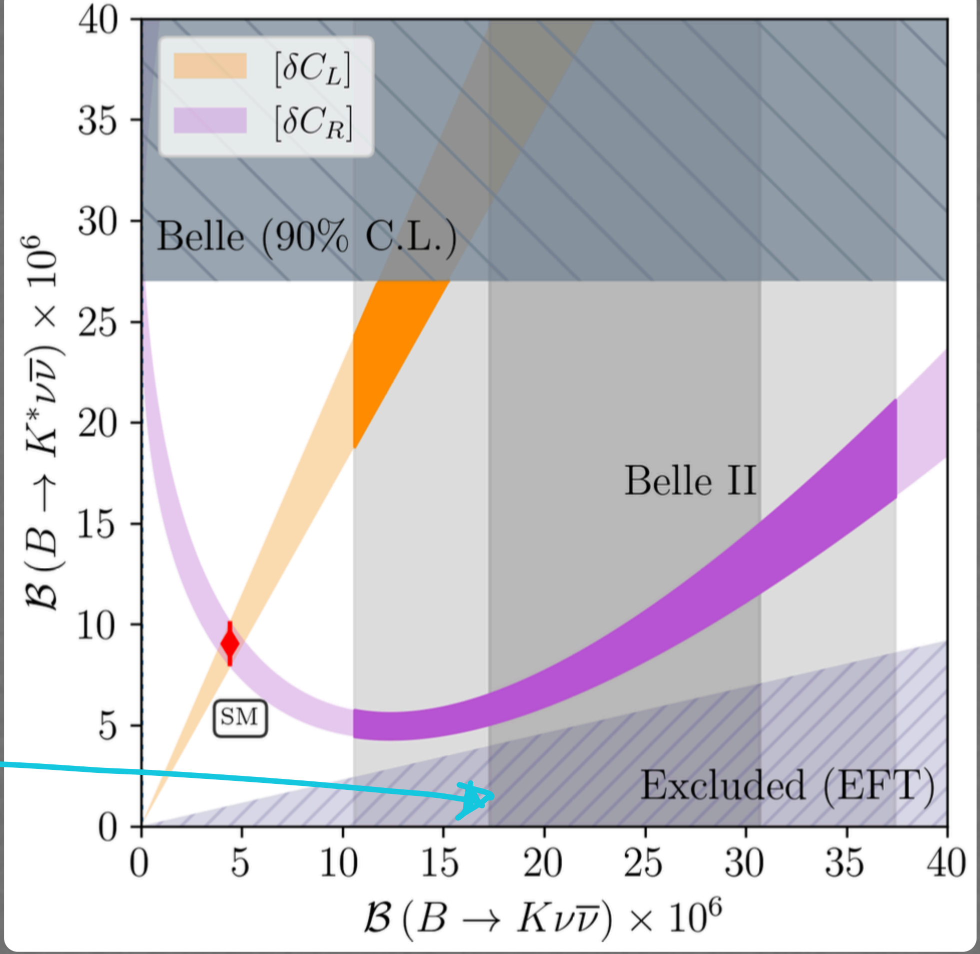

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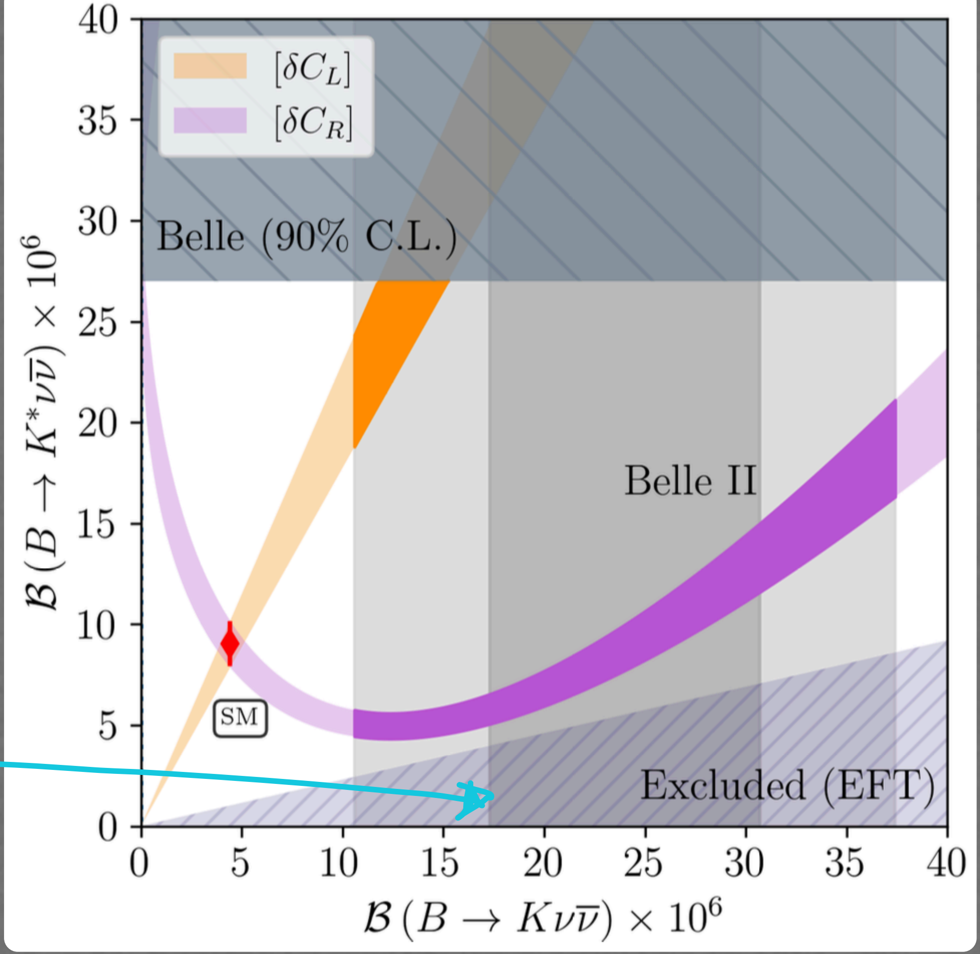

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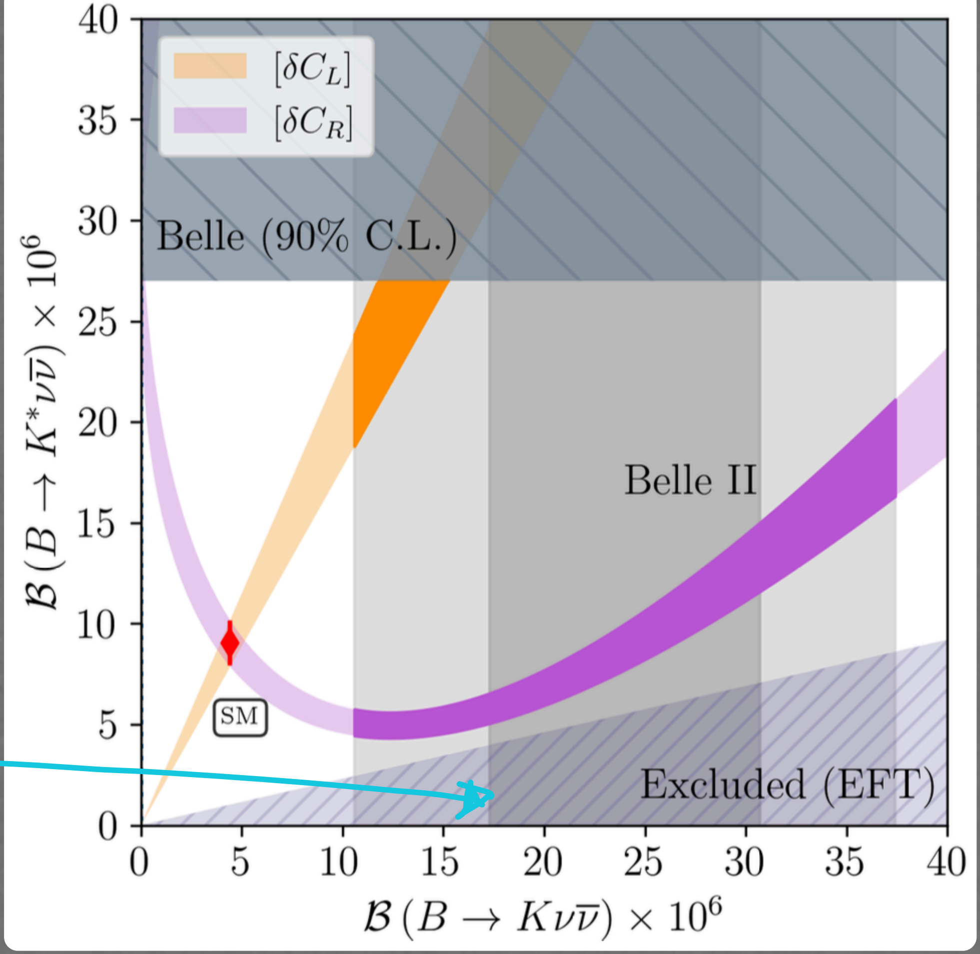

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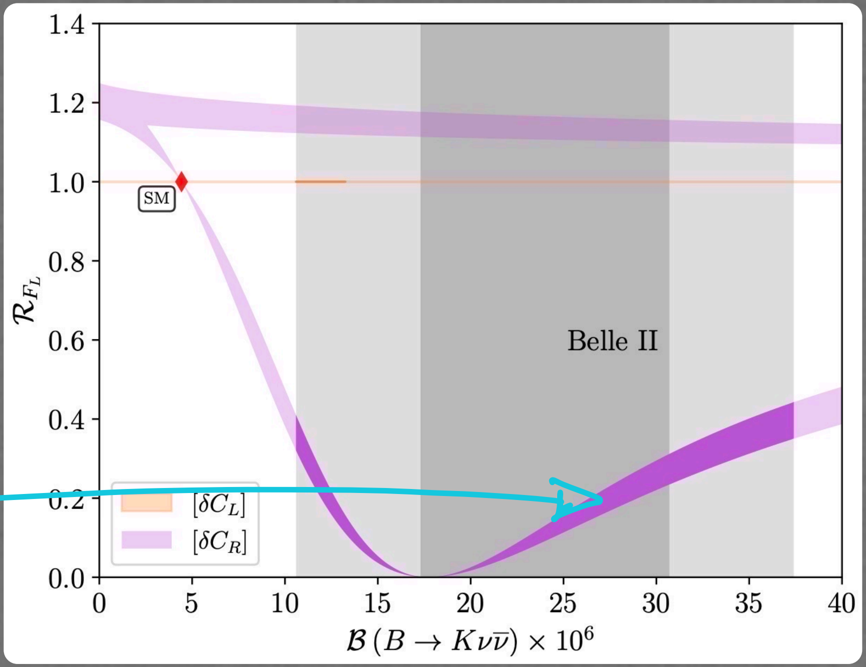

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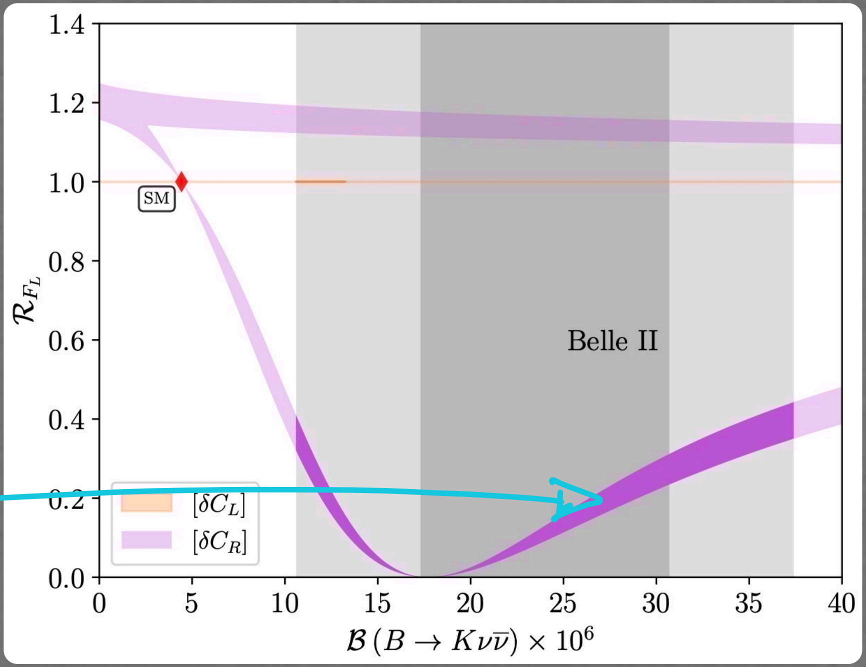

Allwicher et al., 2023

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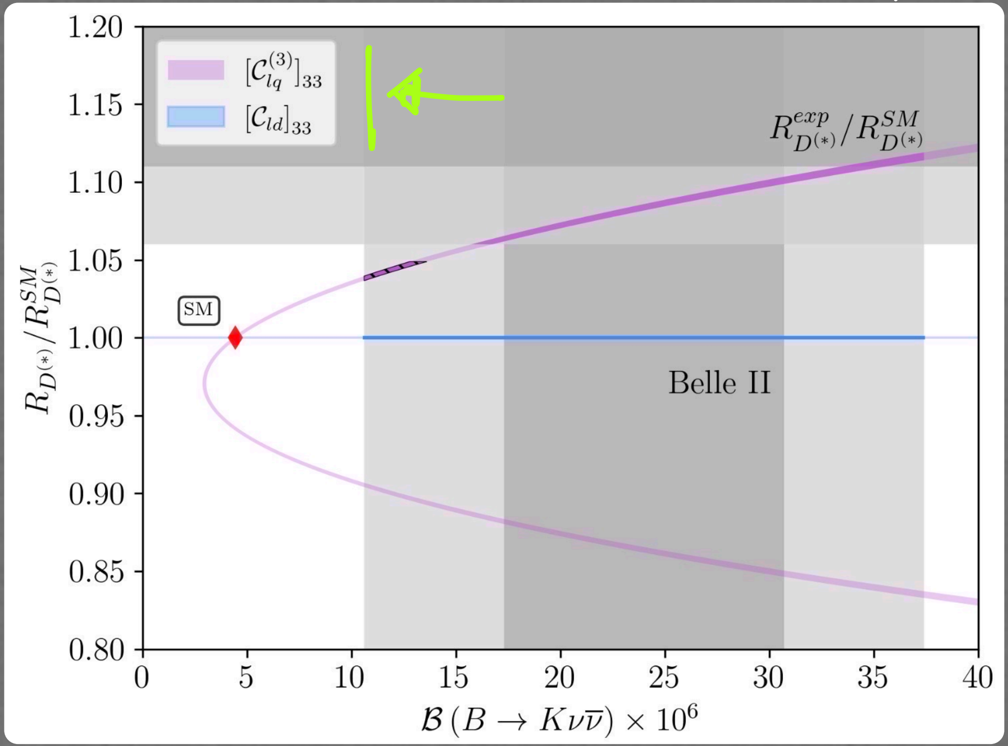

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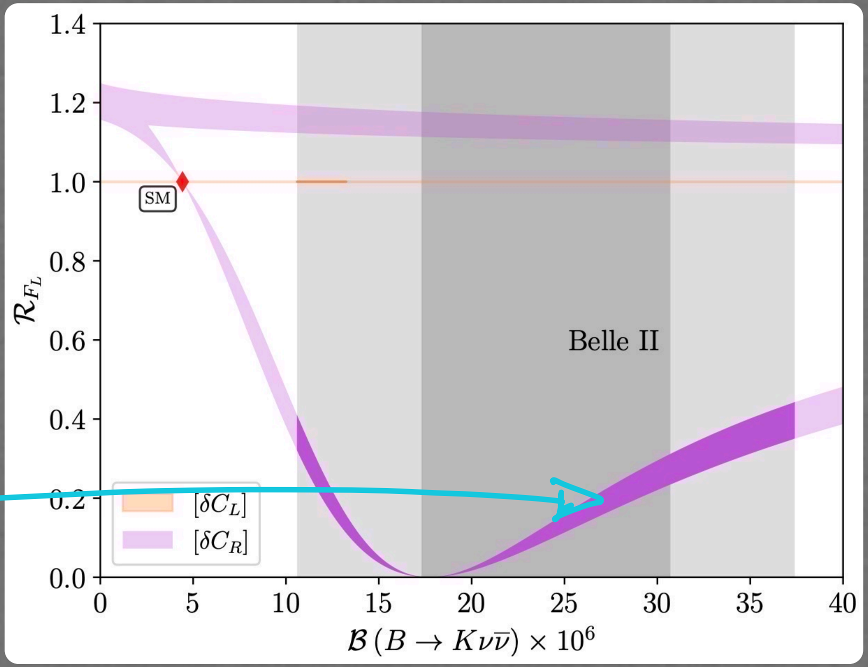

Allwicher et al., 2023

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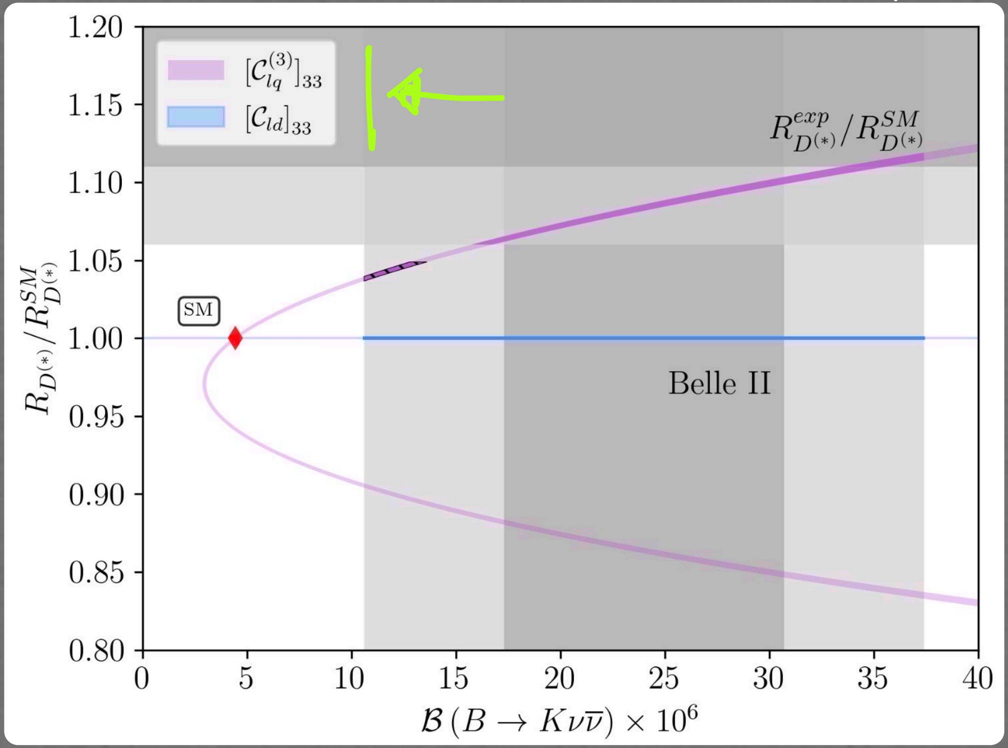
  Will imply sizable effects in $b \to s \tau\bar{\tau}$:

$$\frac{BR(b \to s \tau\bar{\tau})}{BR(b \to s \tau\bar{\tau})_{SM}} \sim 10$$



$B \to K \nu\bar{\nu}$ as a probe of light NP

- $B \to K \nu\bar{\nu}$ probes
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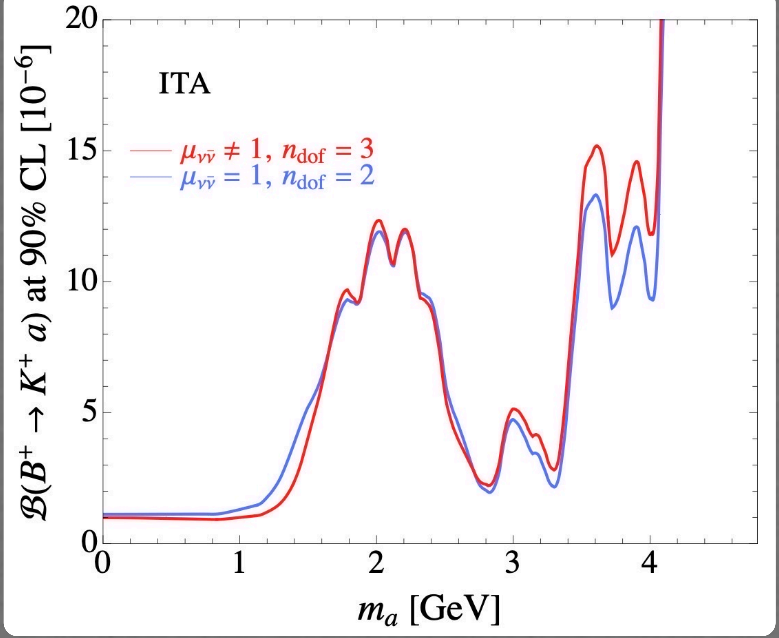
Abumusabh et al., 2025



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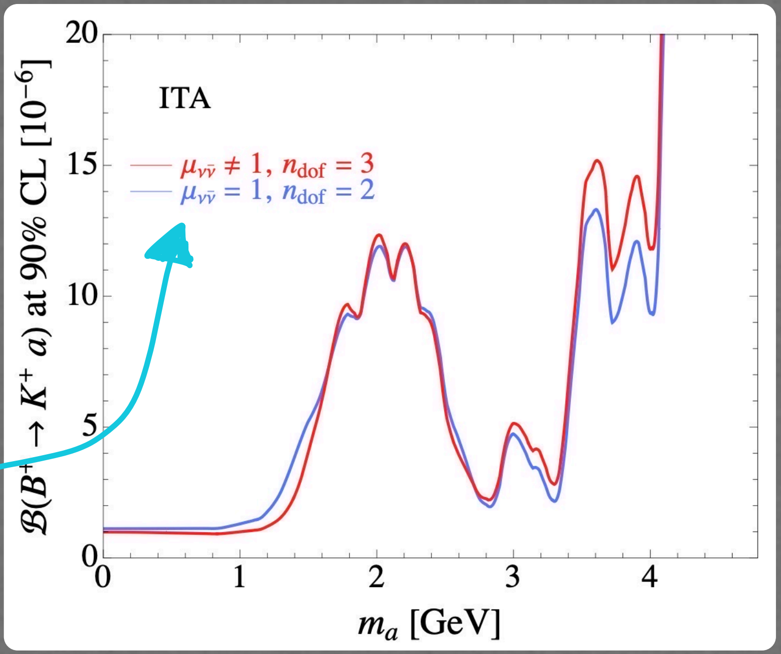

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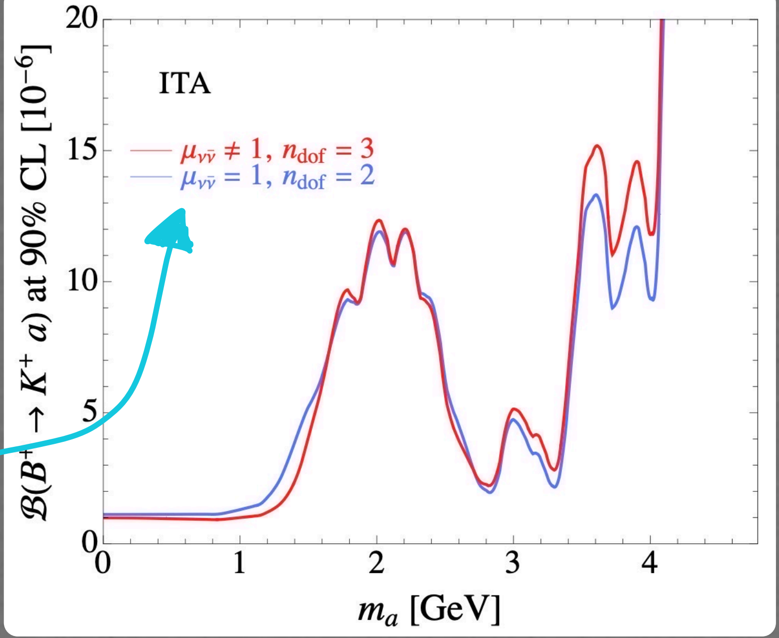

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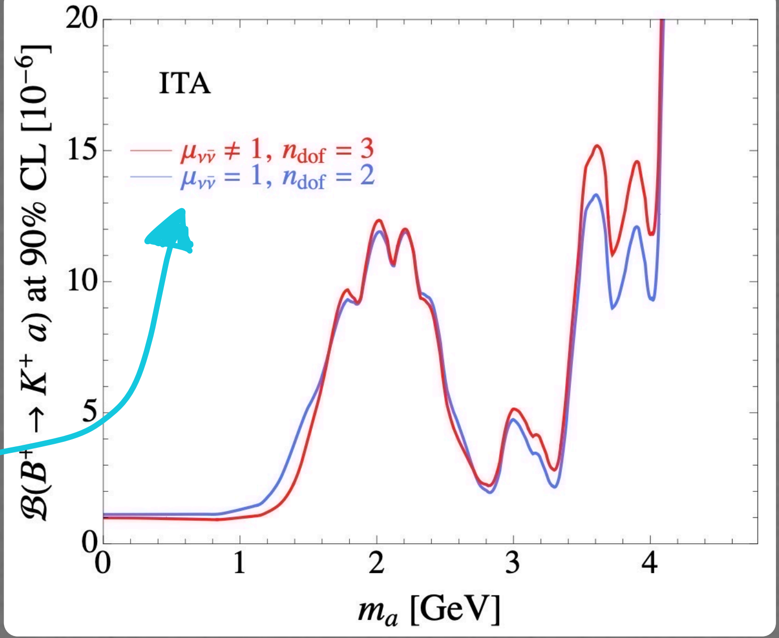
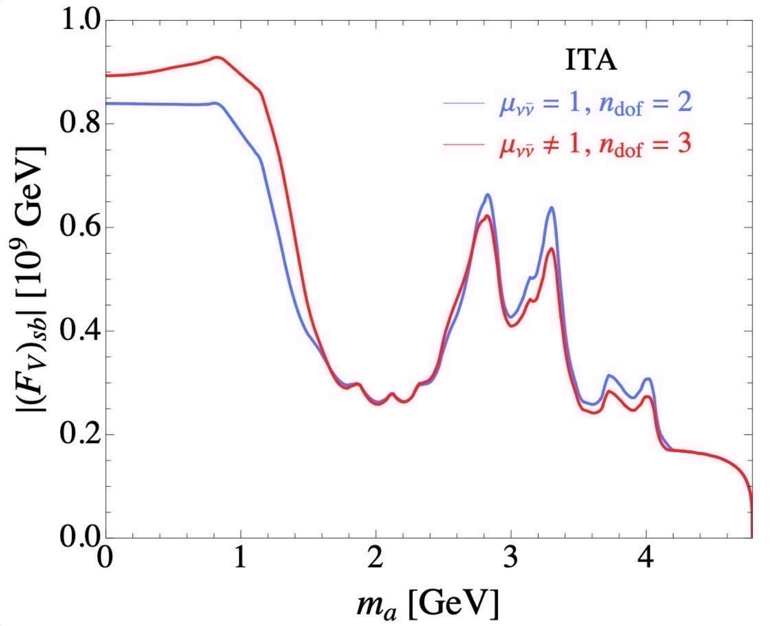
- Property only accessible if likelihood maximizes info on $q^2_{\nu\nu}$ → key discriminator

- Sensitivity to scales $\sim 10^9$ GeV!





$K \to \pi \nu \bar{\nu}$: the decay of the records

- short-dist. dominated && matrix elem. from $K^+ \to \pi^0 e^+ \nu$

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- CKM suppressed ($|V_{td}|^2$ rel. to $b \to s$)

  → Record sensitivity to $\Lambda_{NP} \sim 100$ TeV

$K \to \pi$ + axion (the QCD axion)

- $K \to \pi \nu \bar{\nu}$ data reinterpretable as $K \to \pi a$ at $\underset{m^2_{\text{miss}}}{\underset{\shortparallel}{m^2_{\nu\nu}}} = m_a^2$

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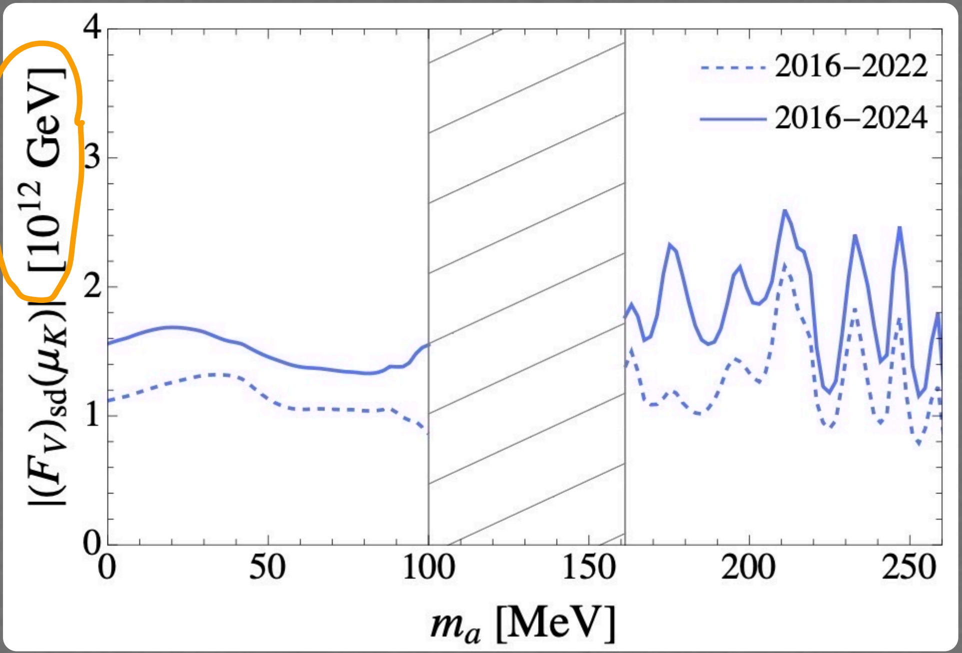
strongest accelerator-based constraint on axion



DG et al., 2025

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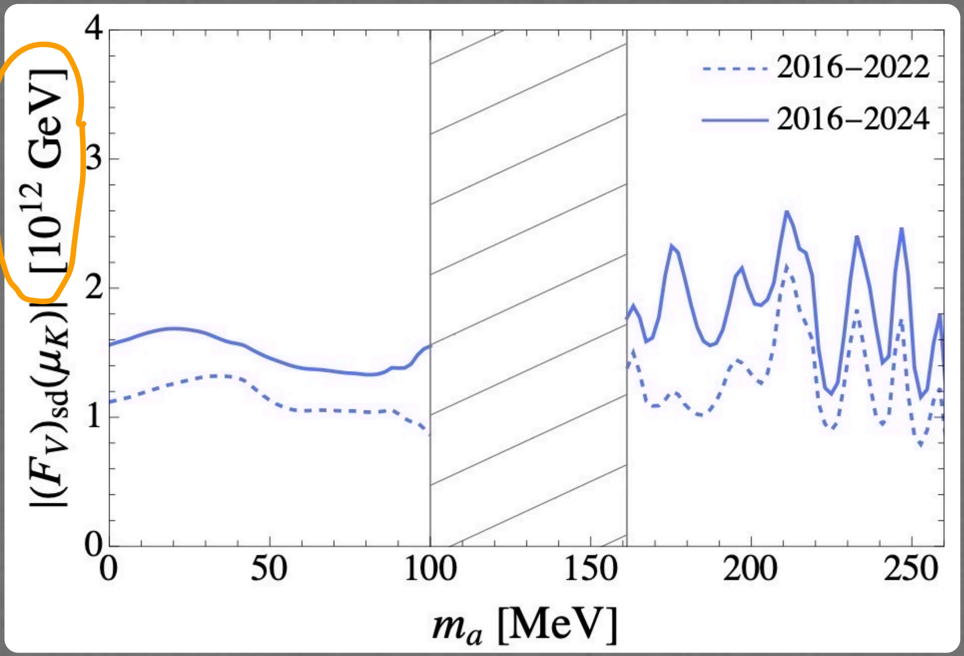

DG et al., 2025

- Two conceptually distinct bounds :

— Generic (= when strong ampl. dominates) : PQ scale $> 10^8 - 10^{12}$ GeV

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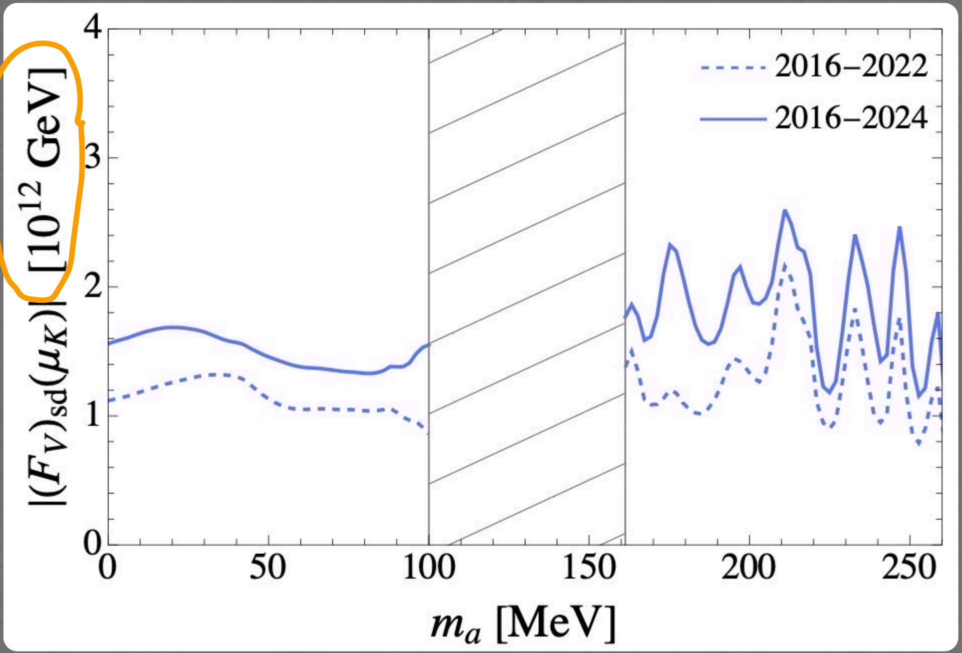

DG et al., 2025

- Two conceptually distinct bounds :

— Generic (= when strong ampl. dominates) : PQ scale $> 10^8 - 10^{12}$ GeV

— "Floor" (= accidental weak ampl. dominance) : ″ $> 5 \cdot 10^4$ GeV

Tensions in $b \to s \mu^+ \mu^-$ data

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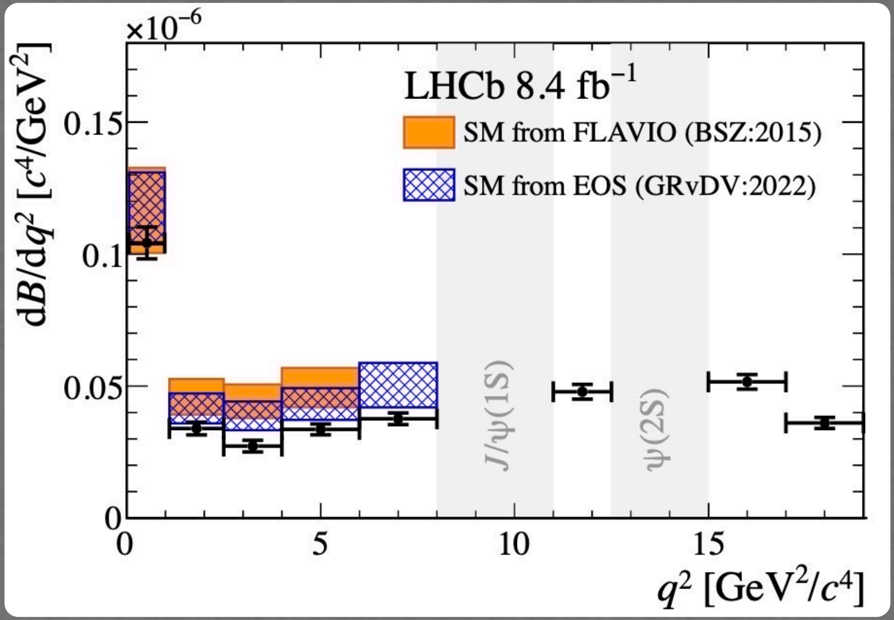
Branching Ratios



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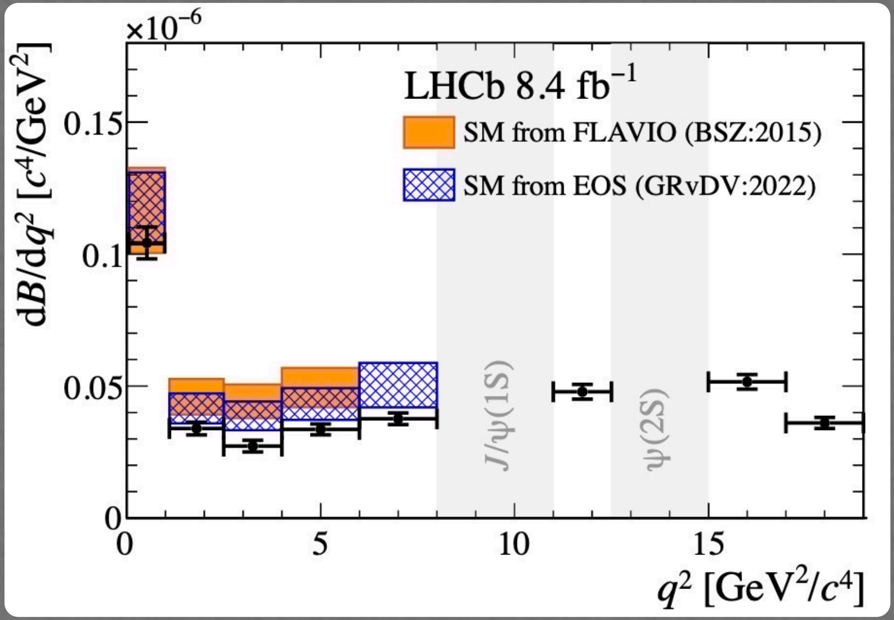
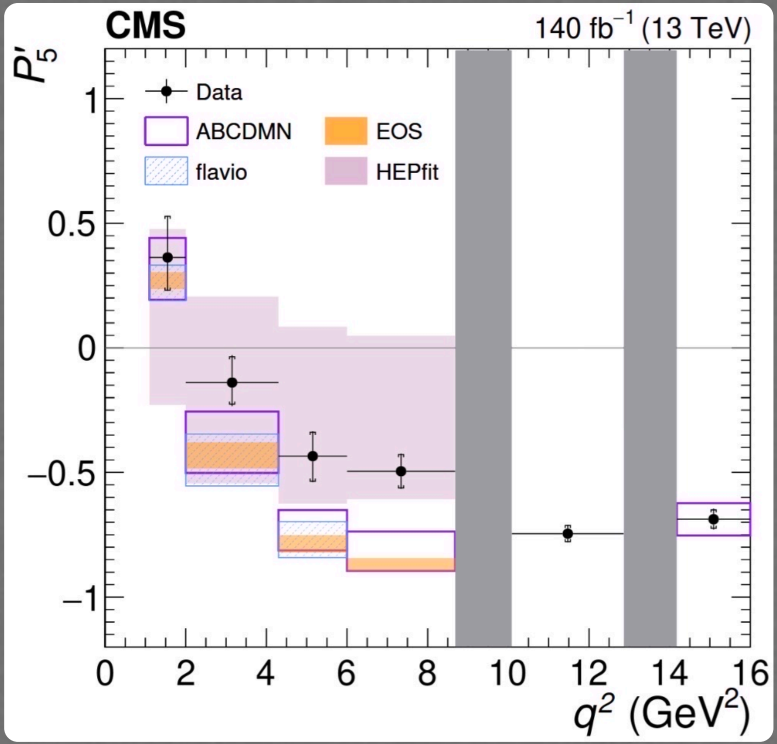
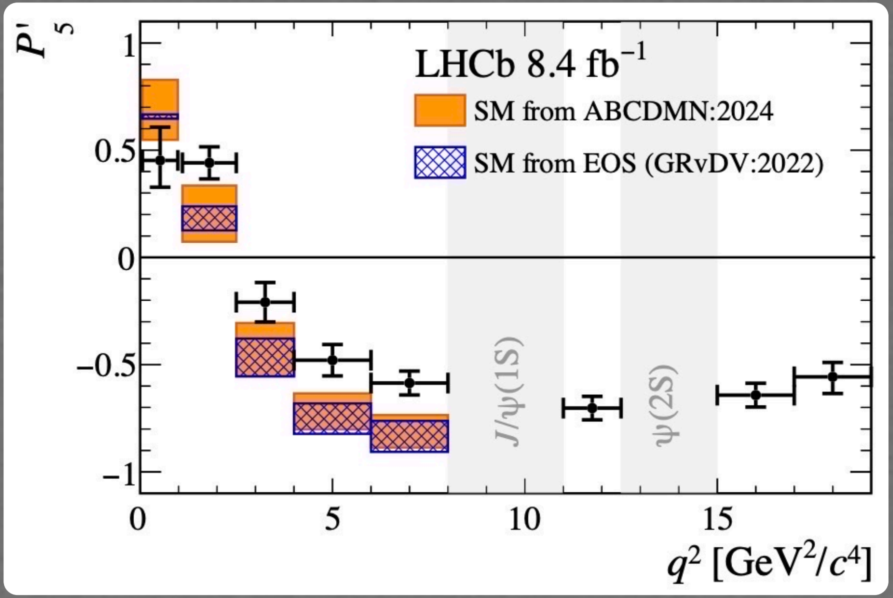


Angular Obs



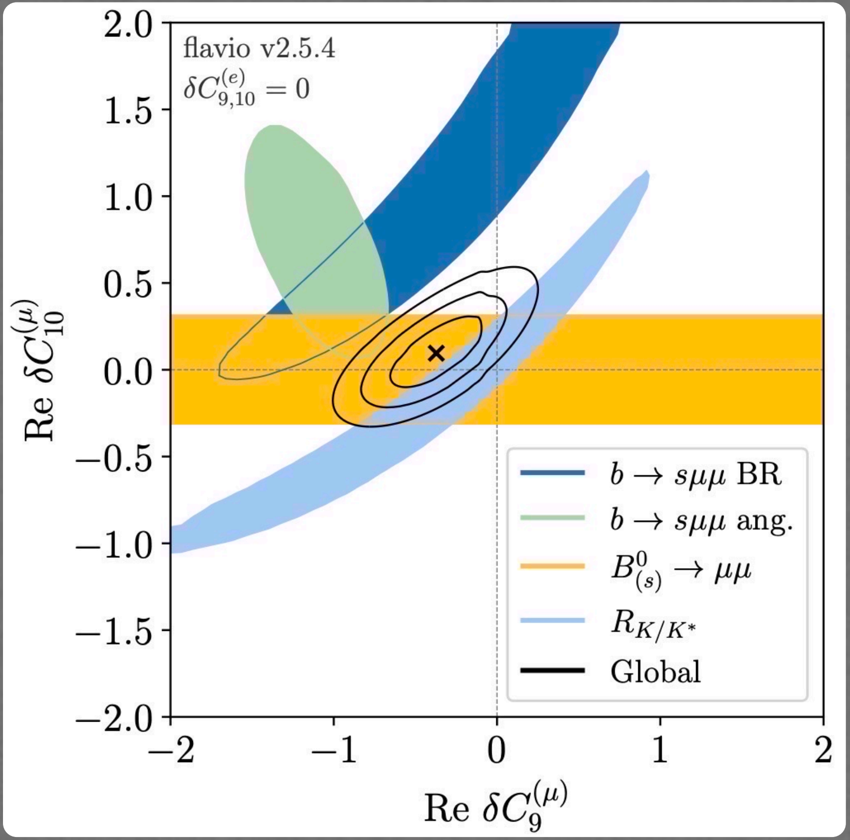


Main tension & possible solutions

$\delta C_9 (10)$:

vector (axial) leptonic current

DG, Normand, Simula, Vittorio, '23



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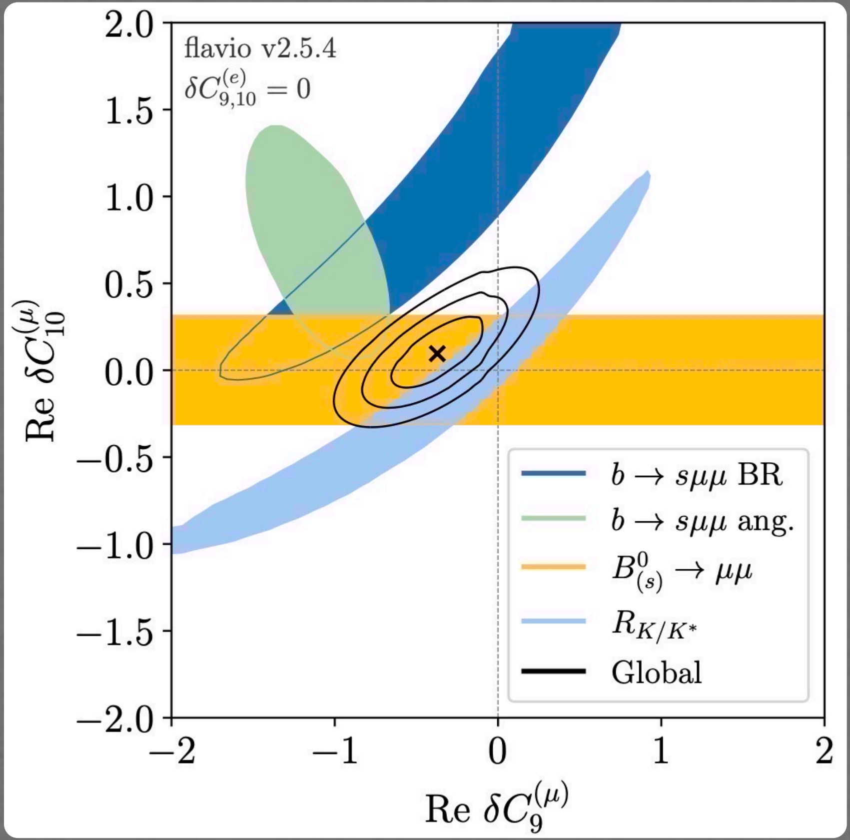

- R_{K/K^*} & $B_s \to \mu\mu$: SM-like

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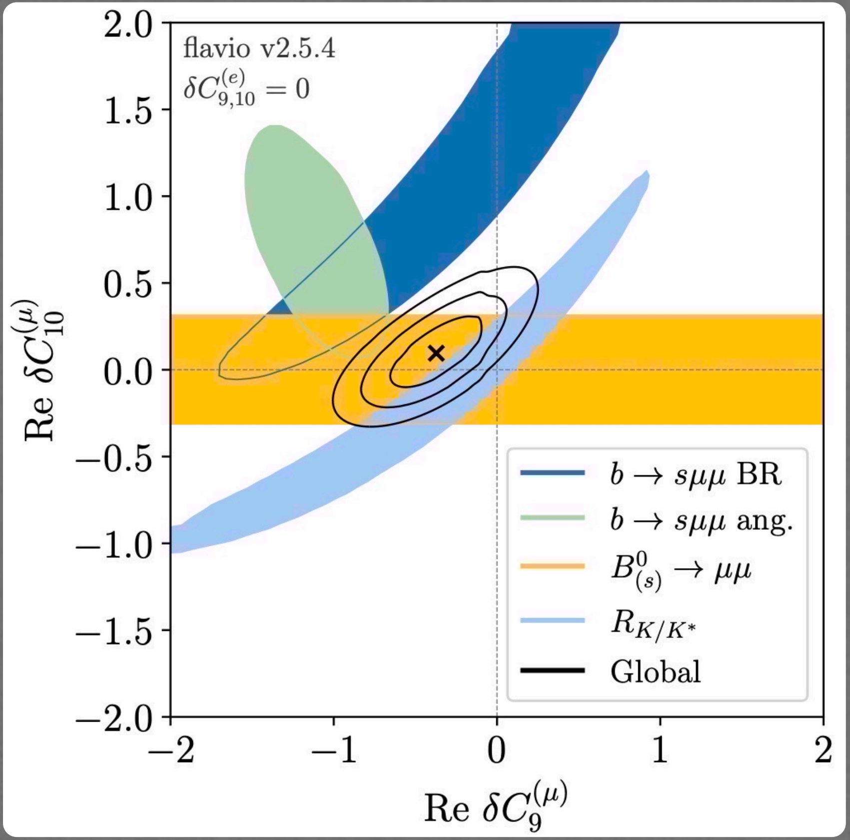

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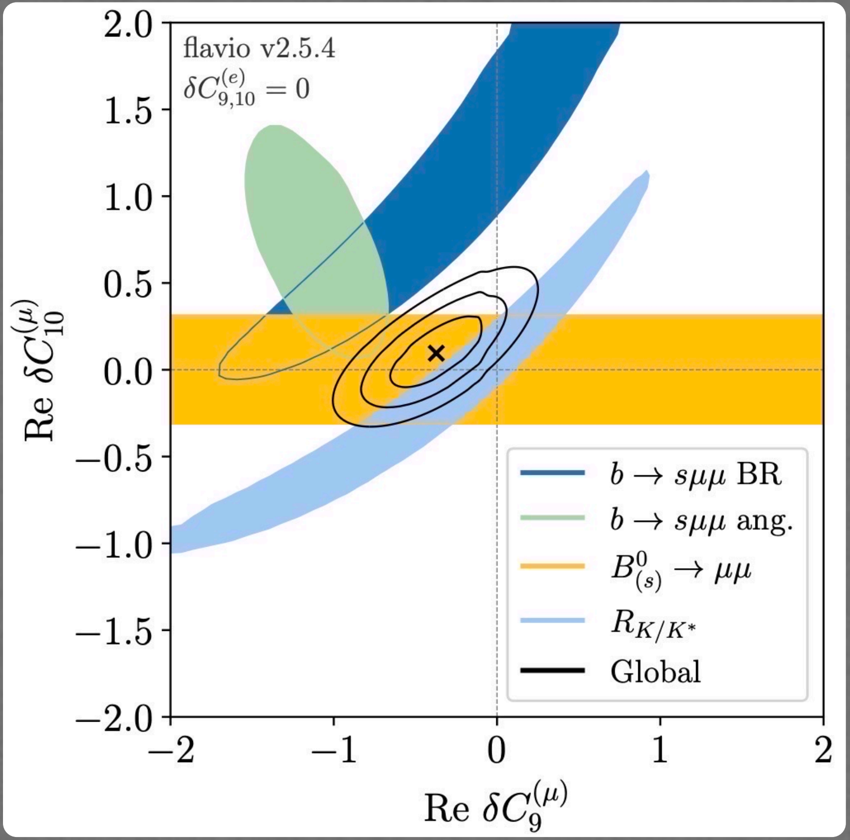

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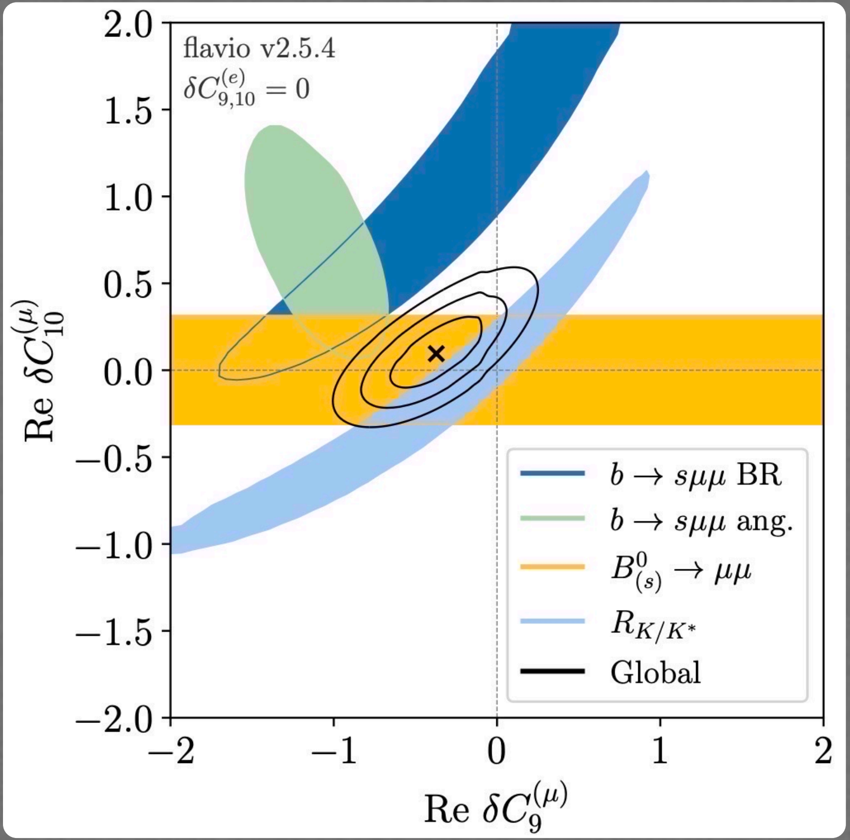
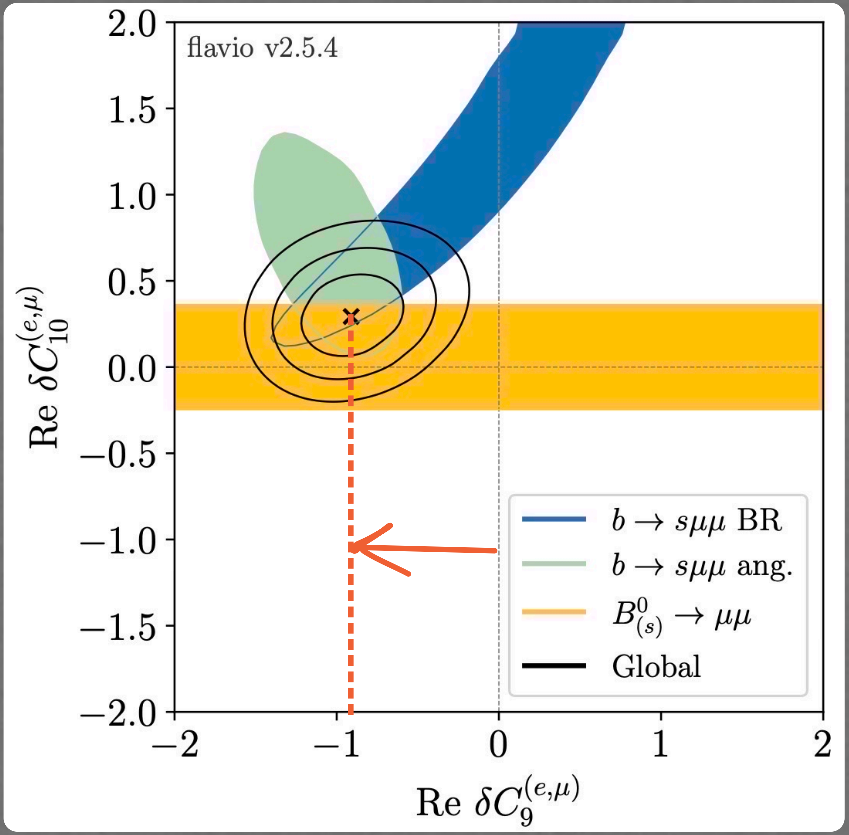


Possible solution 1



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lepton-universal shift to vector leptonic current

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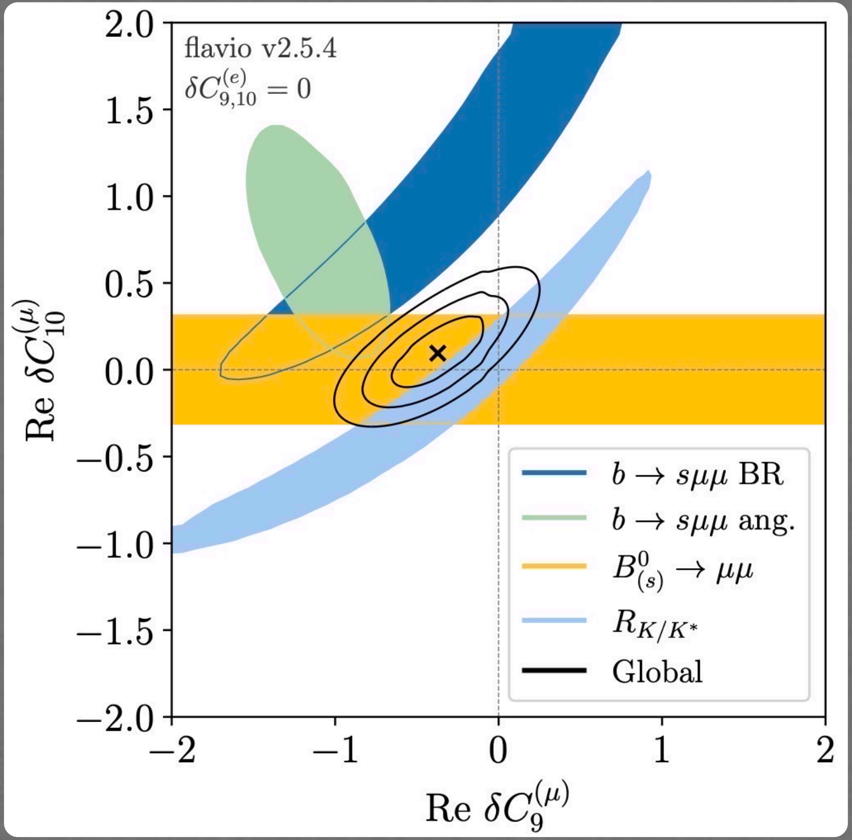
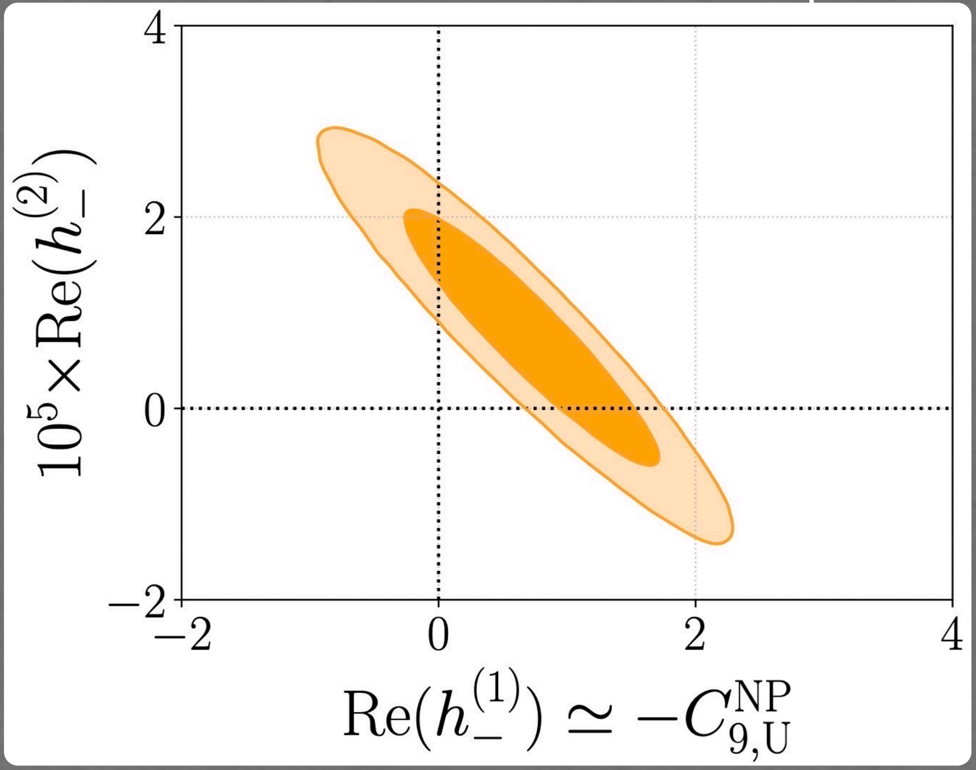


Possible solution 2

Ciuchini et al., '22



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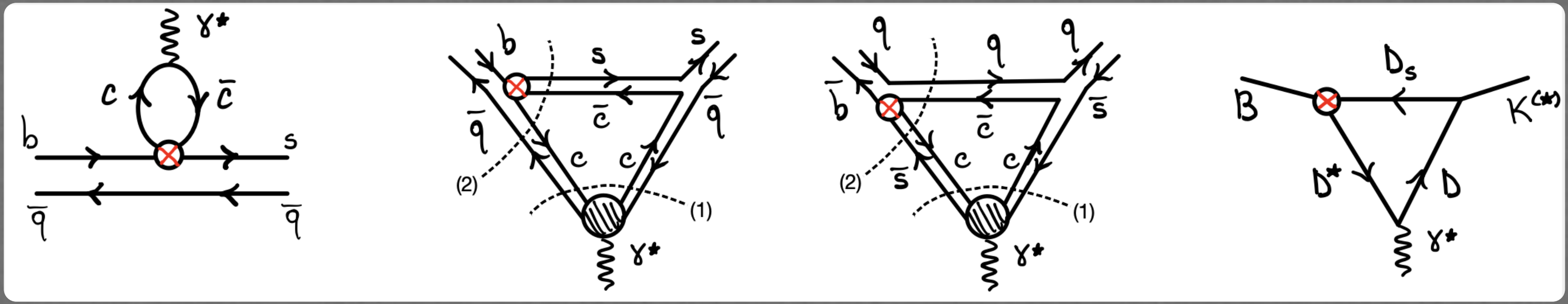
Hadronic effects
(difficult to assess
by direct calculation)

Why hadronic-effect solution difficult to assess

Ciuchini et al., '22



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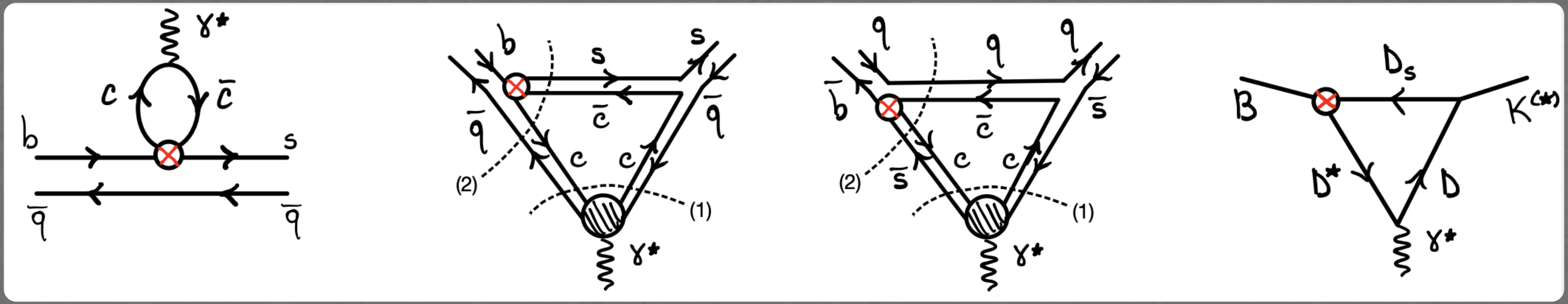

Triangle diags :

- not only "normal" cuts
  (= √ branch point)

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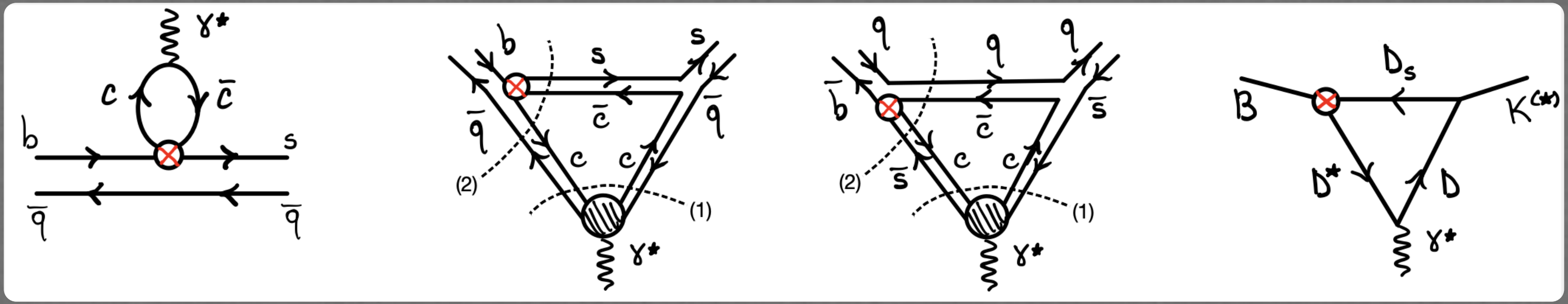

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[see Mutke, Hoferichter, Kubis; Isidori, Polonski, Tinari, '24]

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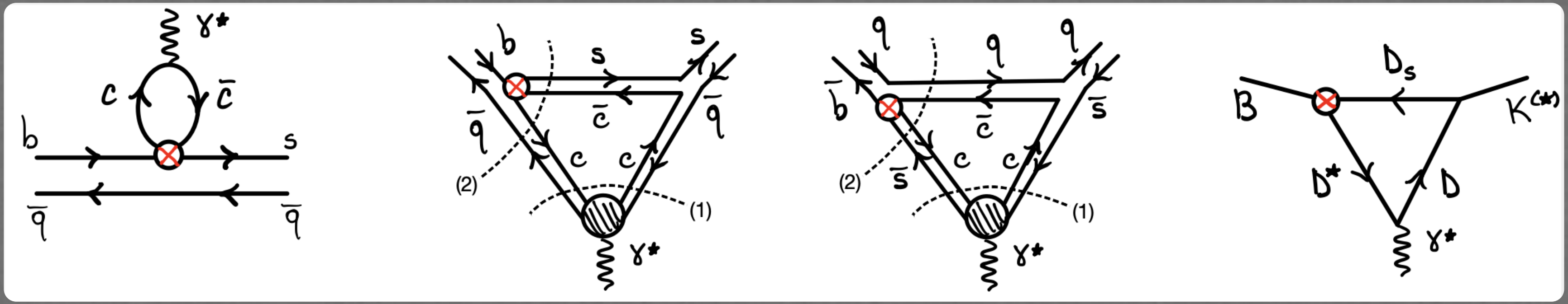

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[see Mutke, Hoferichter, Kubis; Isidori, Polonski, Tinari, '24]

Alternative solution: go to different q^2 region

e.g. $B_s \to \mu\mu\gamma$ [DG et al., 2017+]

Prospects

(besides the exciting FCC)

Upgrade-era flavour : 2030 – 2040s

- LHCb : 50/fb Run 4 → > 300/fb w/ Upgrade II

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Unique for

- $\not{E}$, neutrals, inclusive modes, τ LFV
- $R(D^*) \sim 1\%$; $B \to K \nu \bar{\nu} \sim 8\%$; $\tau \to 3\mu \sim 10^{-10}$

Upgrade-era flavour : 2030–2040s

- Atlas/CMS HL-LHC :

Indep. & competitive in many modes

— 3000/fb !

— muonic final states

— $\phi_s \sim 3$ mrad ; $B_{s,d} \to \mu^+\mu^-$

$b \to s\mu\mu$ angular obs.

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Take-home :

- Built-in complementarity

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Take-home :

- Built-in complementarity
- Tests of CKM & LFU & FCNCs & CPV
  w/ o.o.m. improved precision