

Flavours of the Standard Model :

precision , anomalies ,
and prospects

Diego Guadagnoli
CNRS , LAPTh Annecy

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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Charged LFV

MEG II Mu3e

Mu2e COMET

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Muon $g-2$ n^2 EDM

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Future!

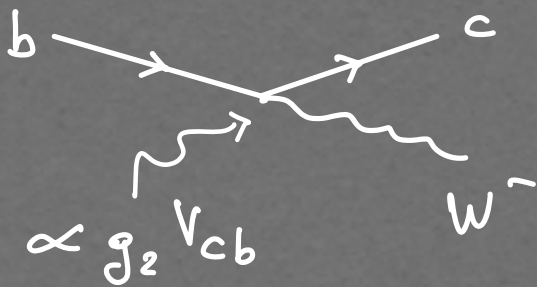
Flavour @ FCC-ee

SHIP

Pioneer ...

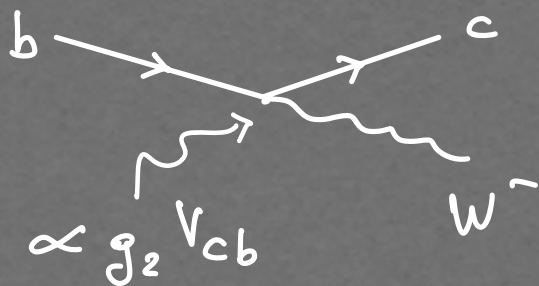
CKM : the V_{cb} case

SM: all quark flavour
from one vertex

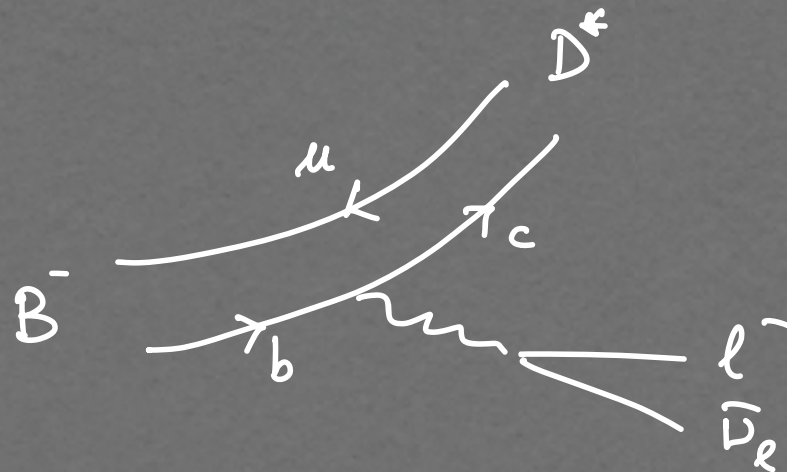


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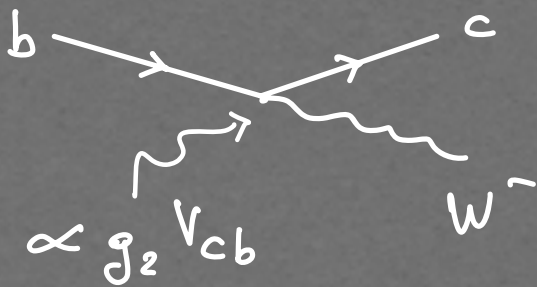


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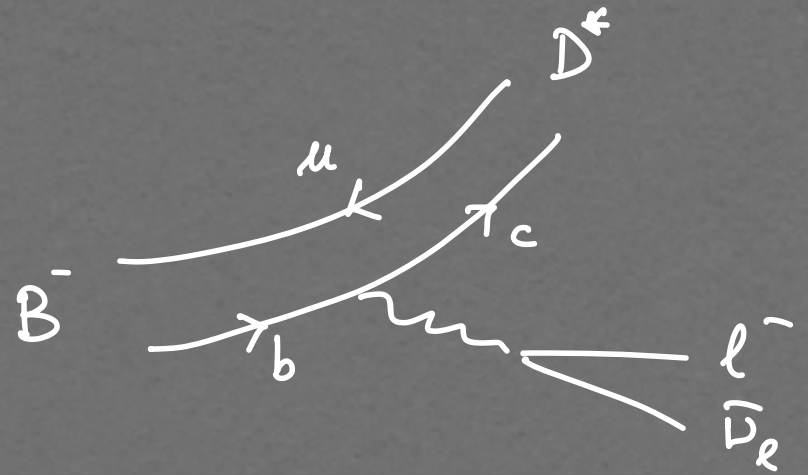


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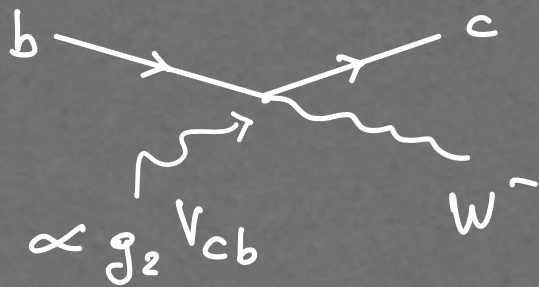
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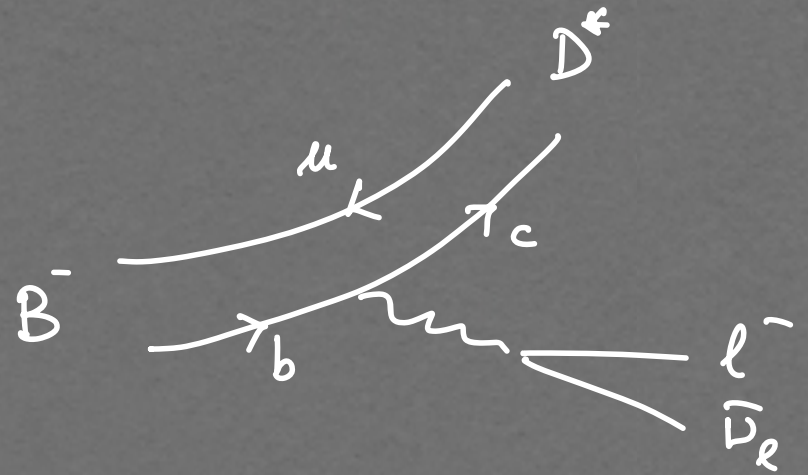
"Exclusive" modes :
rely on form factors
(lattice, sum rules, HQE)

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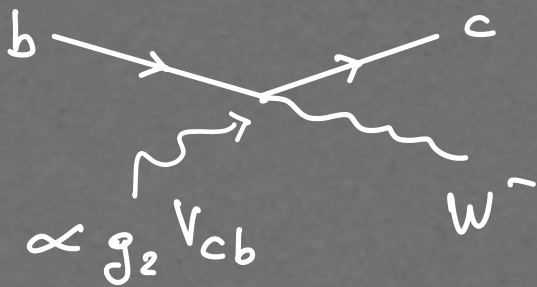
or use optical theorem

$$\text{Im } \mathcal{M}(B \rightarrow B)$$

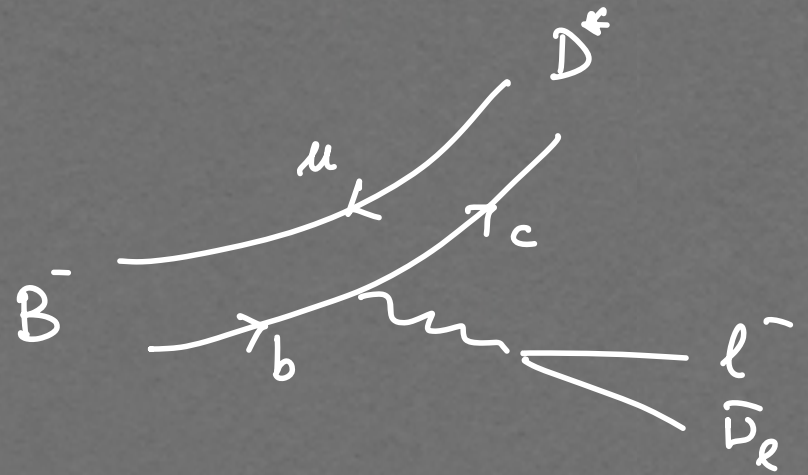
$$\propto \sum_i |\mathcal{M}(B \rightarrow X_{c,i})|^2$$

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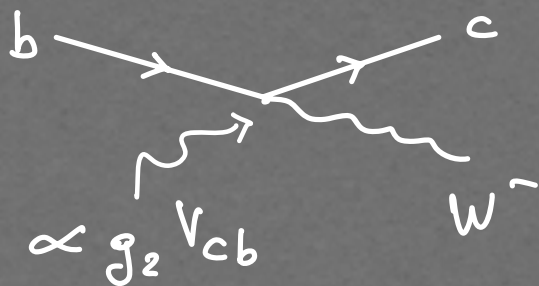
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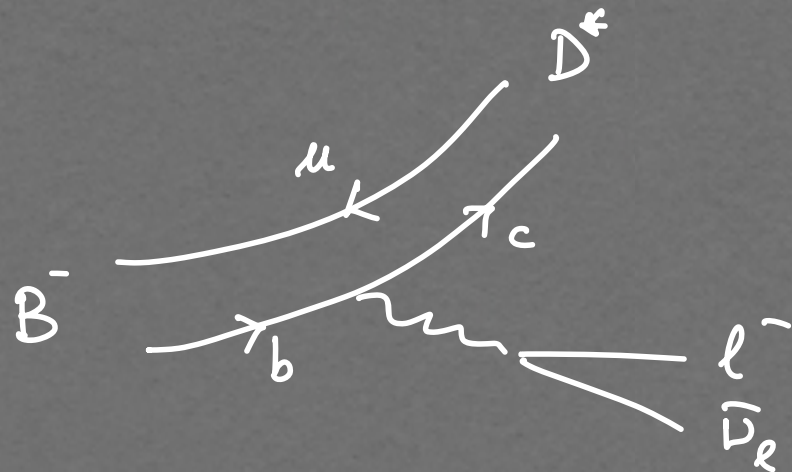
$$\frac{\Lambda_{\text{QCD}}}{m_b} \ll 1 \Rightarrow \text{local OPE}$$

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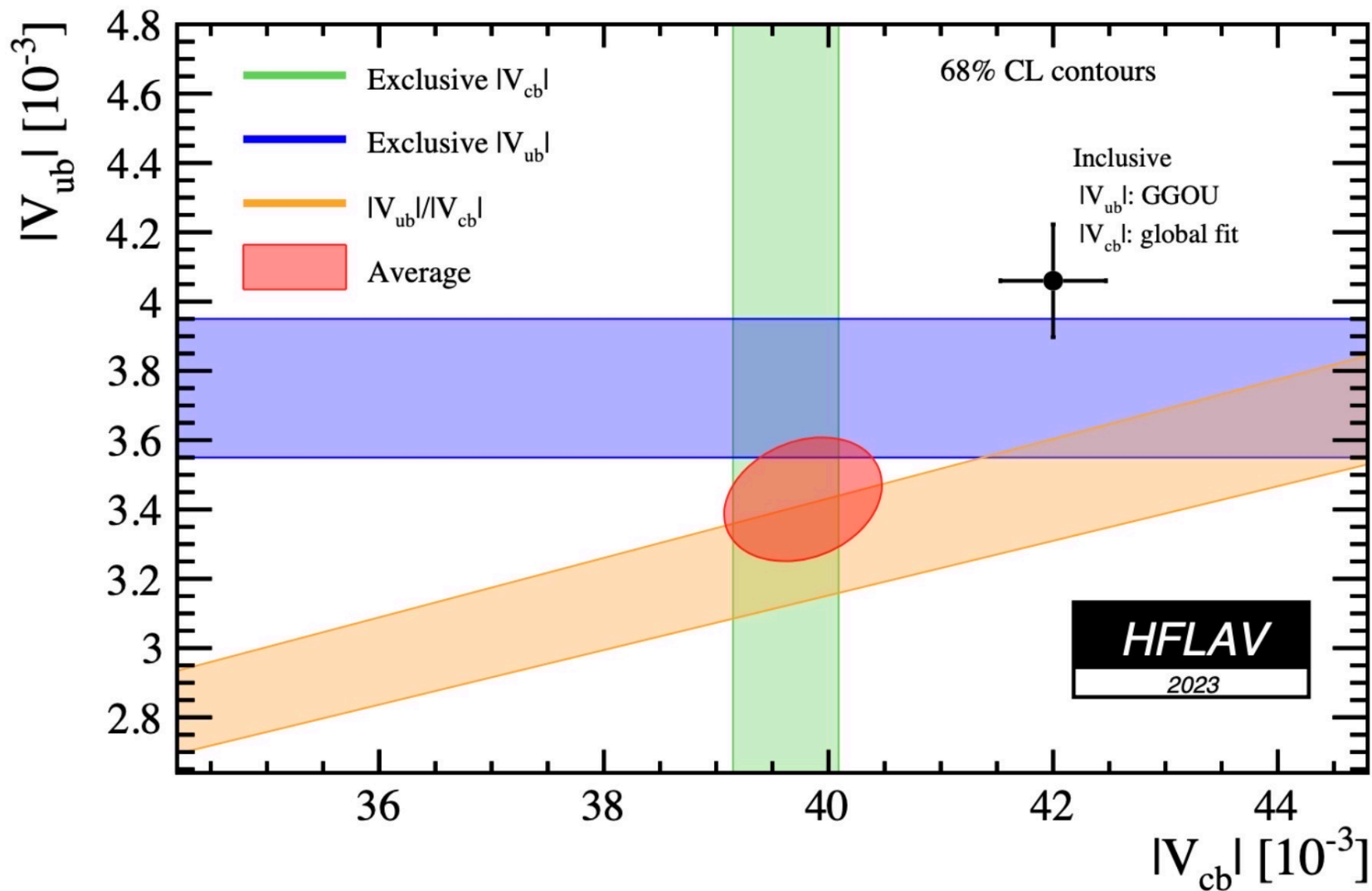
$$B^- \rightarrow X_c + l^- \bar{\nu}_e$$

all possible one-charmed
mesons

$$\frac{\Lambda_{\text{QCD}}}{m_b} \ll 1 \Rightarrow \text{local OPE}$$

doable at B-factories

V_{cb} vs. V_{ub} : a persistent tension



Lepton Flavour Universality : a test

$$R_{D^{(*)}} \equiv \frac{\text{BR}(B \rightarrow D^{(*)} \tau \bar{\nu})}{\text{BR}(B \rightarrow D^{(*)} \ell \bar{\nu})}$$

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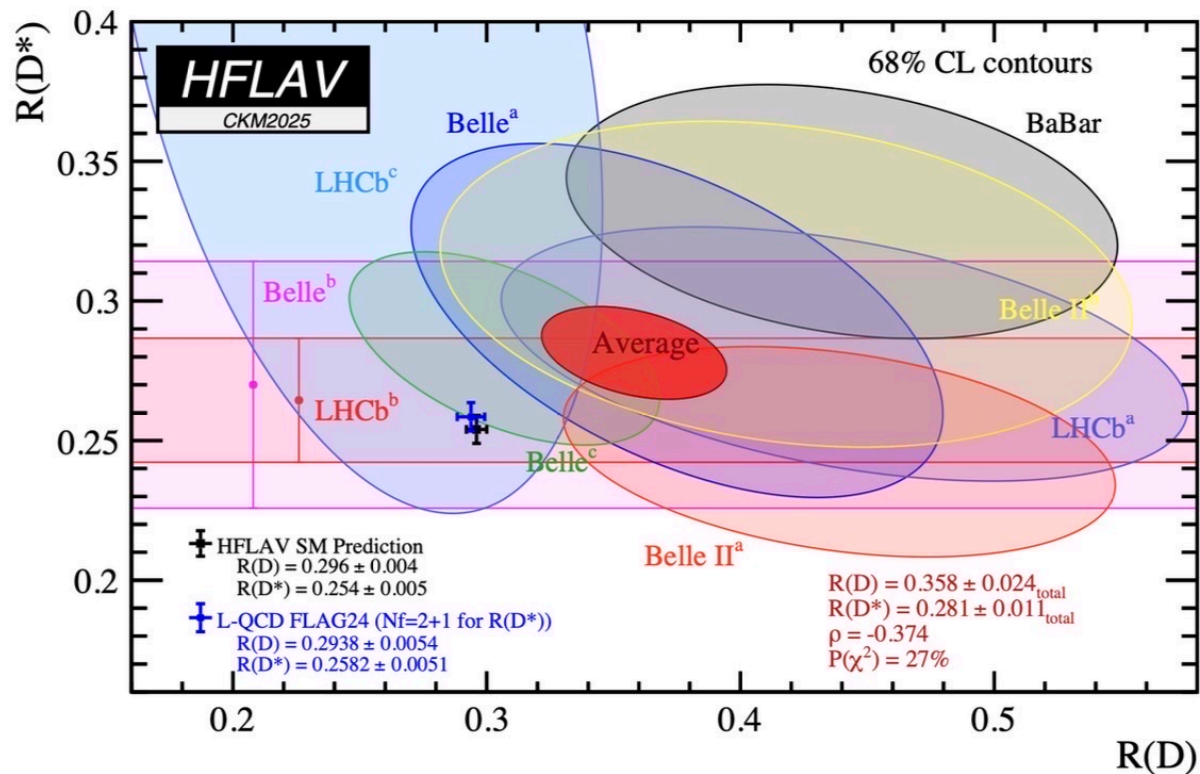
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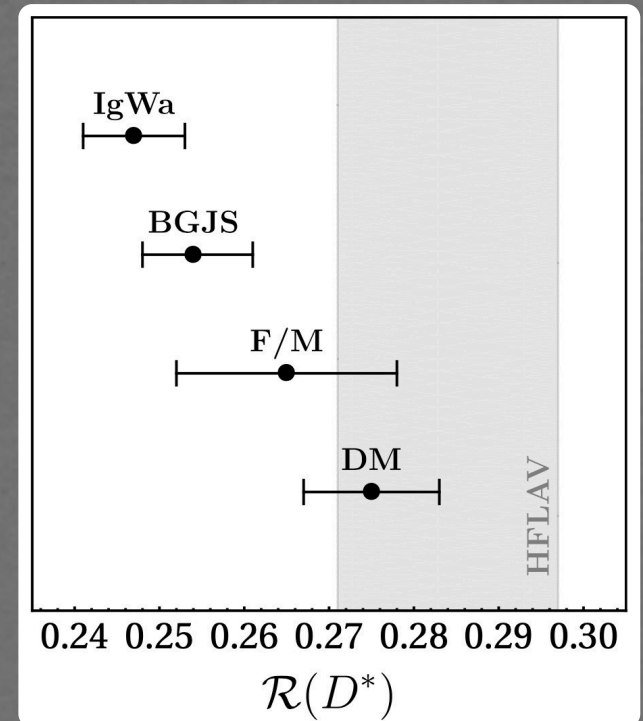
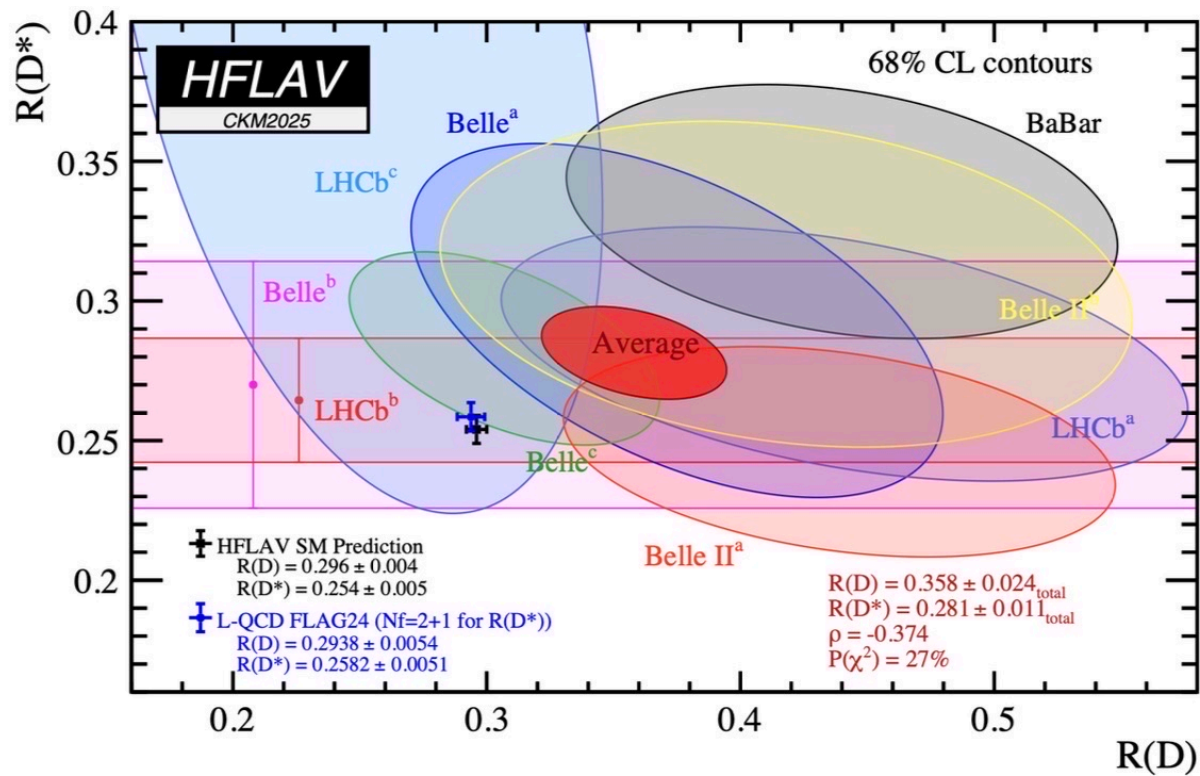
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- in FNAL/MILC and "Dispersive Method" (Martinelli et al.) tension is absent



M. Blake @ LHCb Impl. 2025

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[Freytsis, Ligeti, Rudeanu, '15]

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- Outlook

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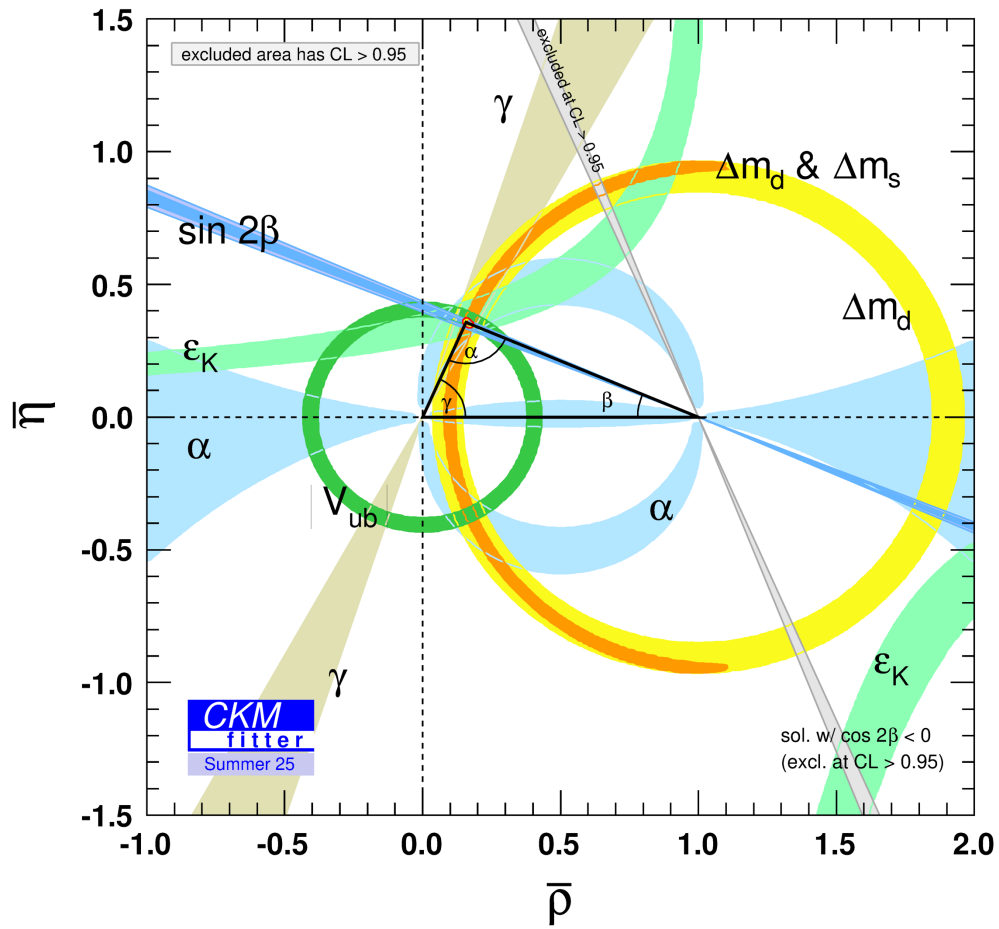
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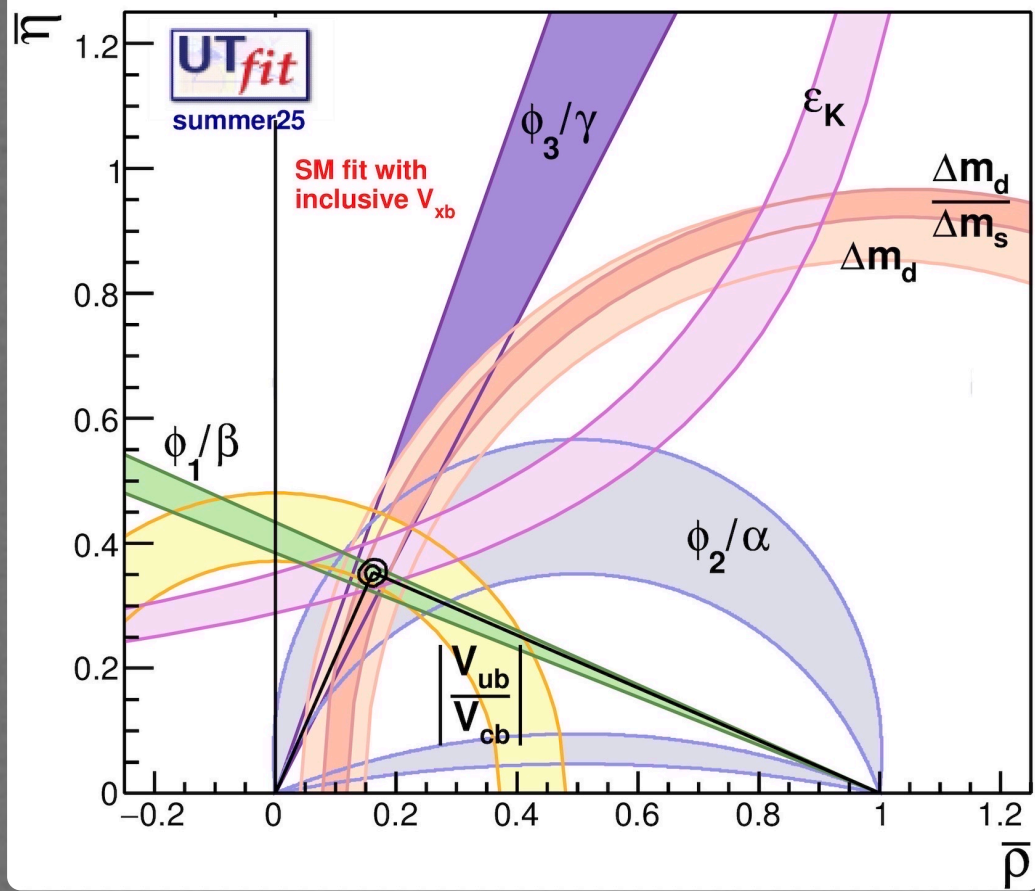
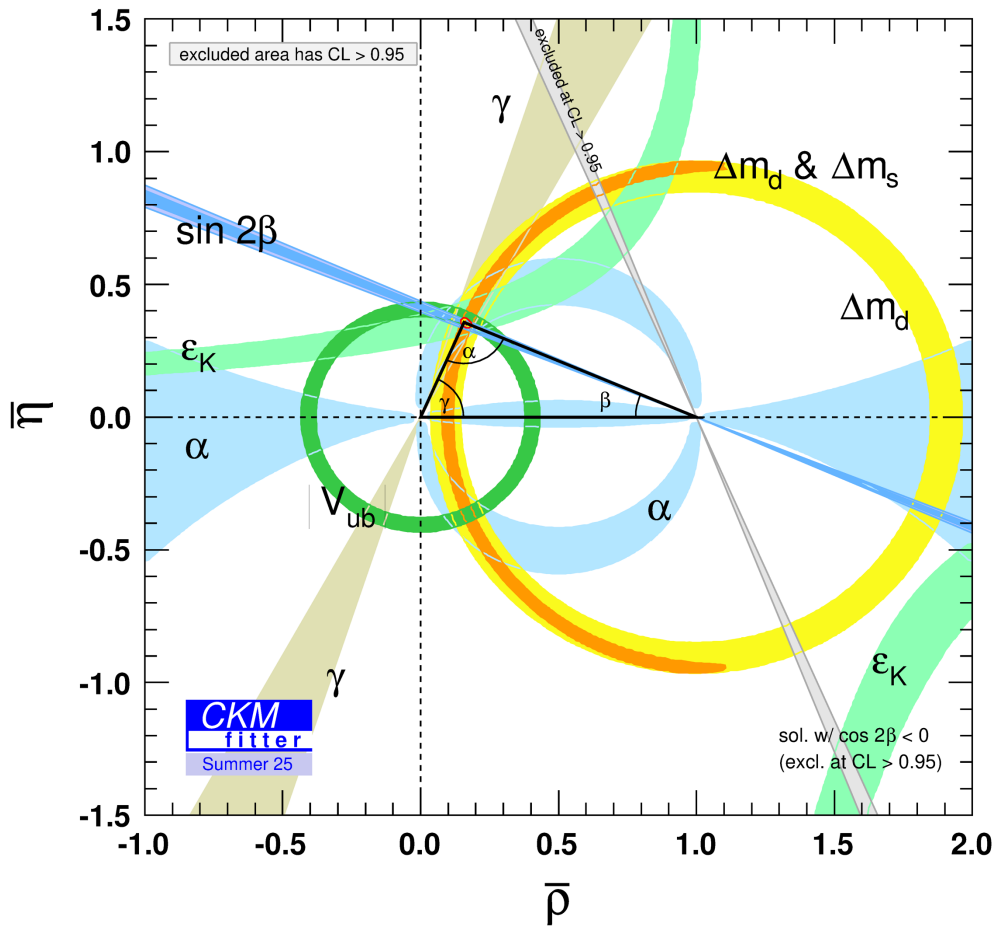
Belle II & LHCb Upgrade II will provide final word

CKM picture : state of the union



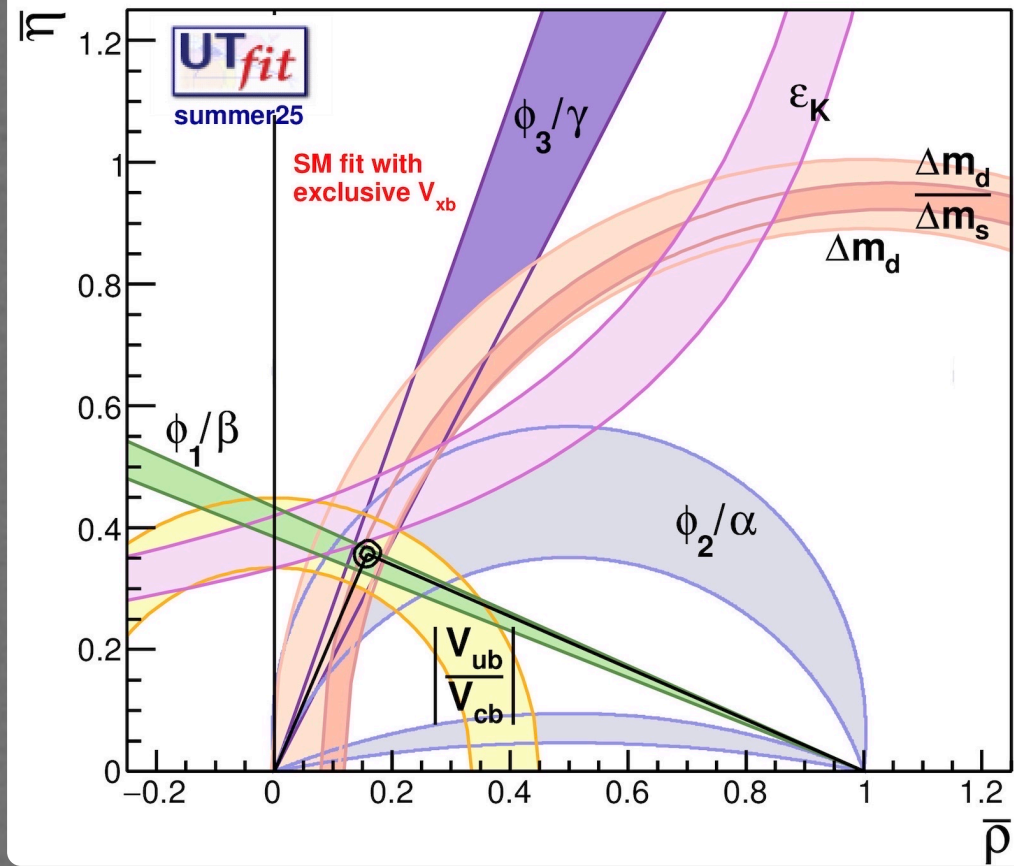
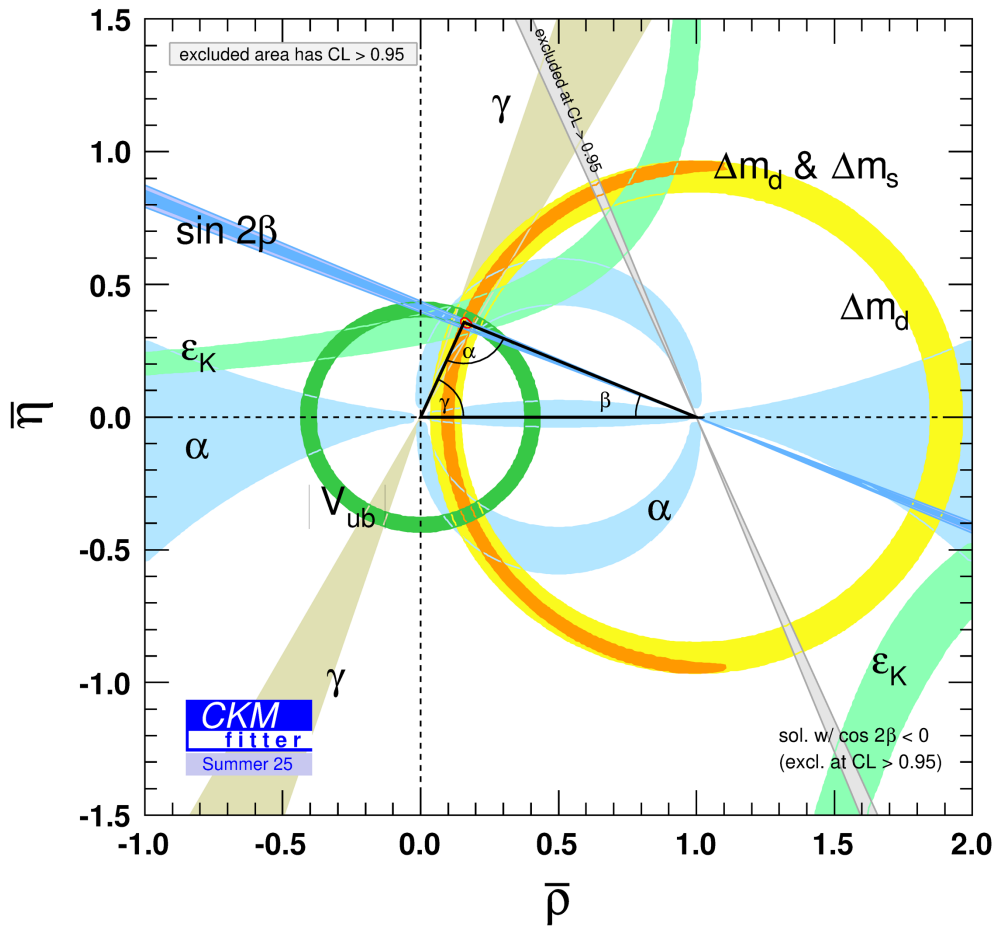
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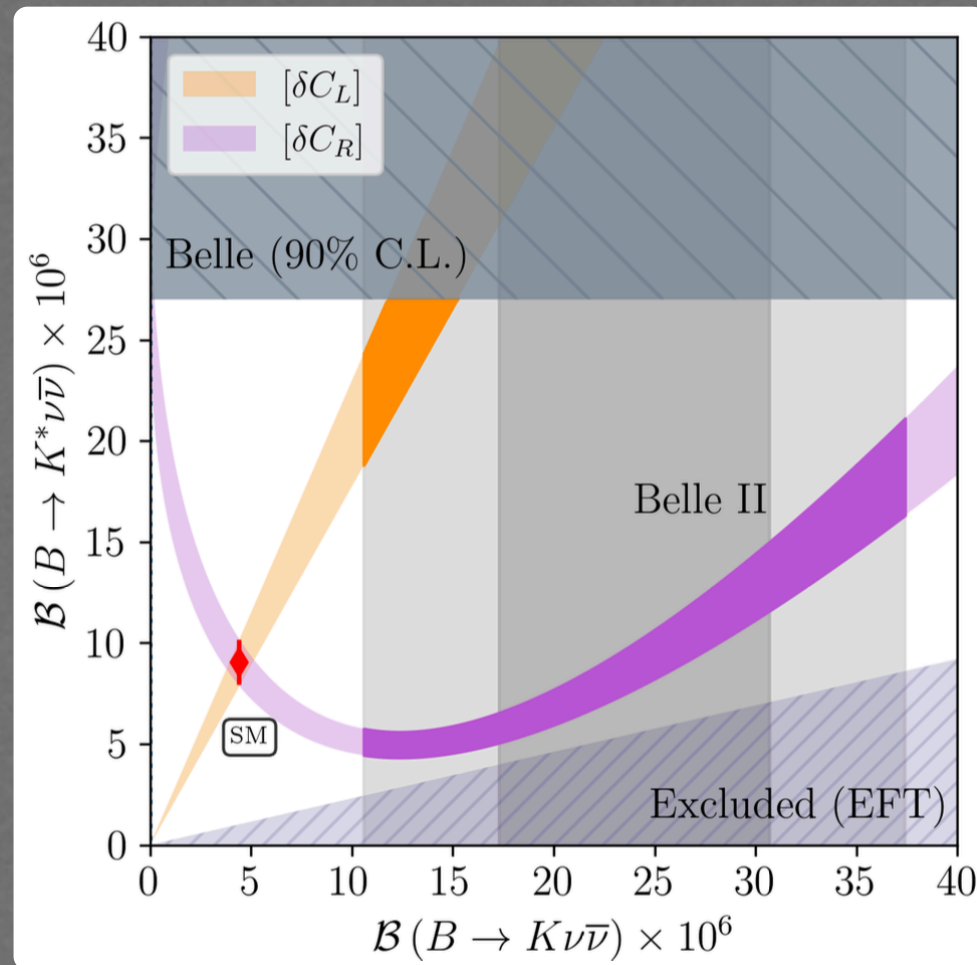
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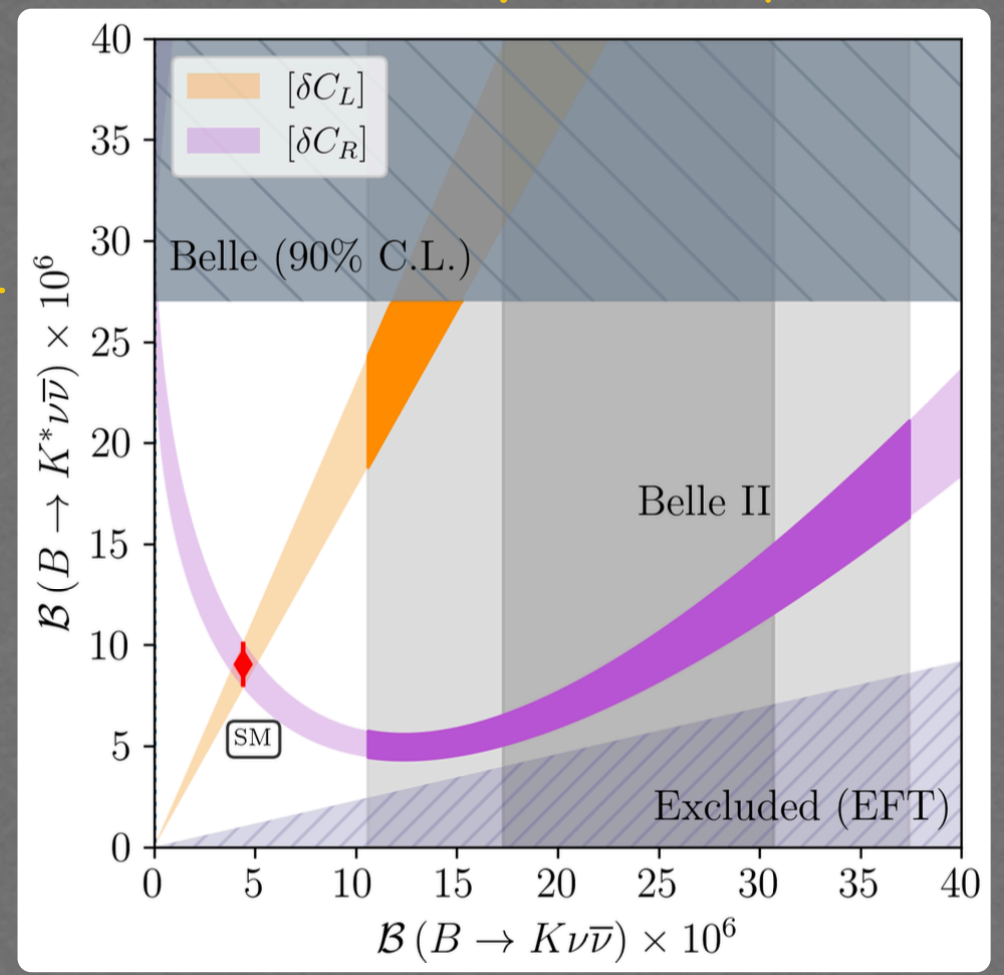


Allwicher et al., 2023



upper bound on
 K^* mode by Belle

First evidence:
2023, Belle II



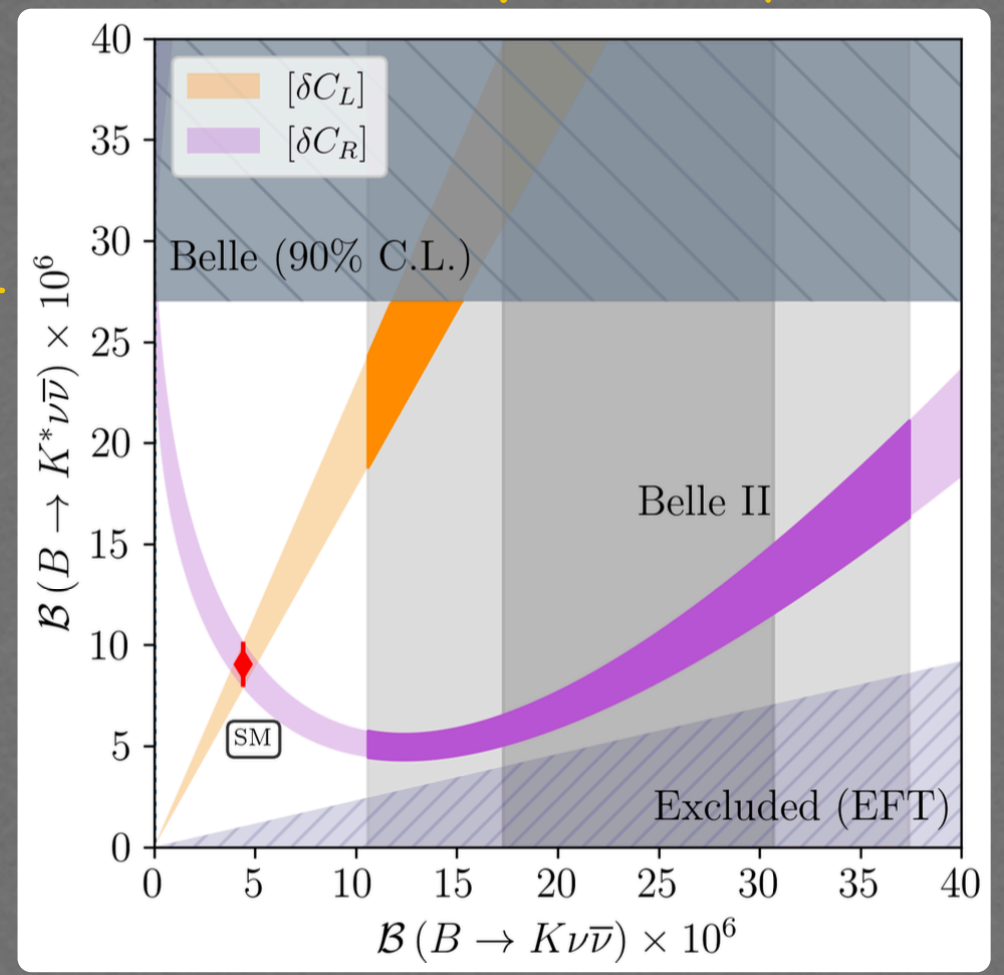
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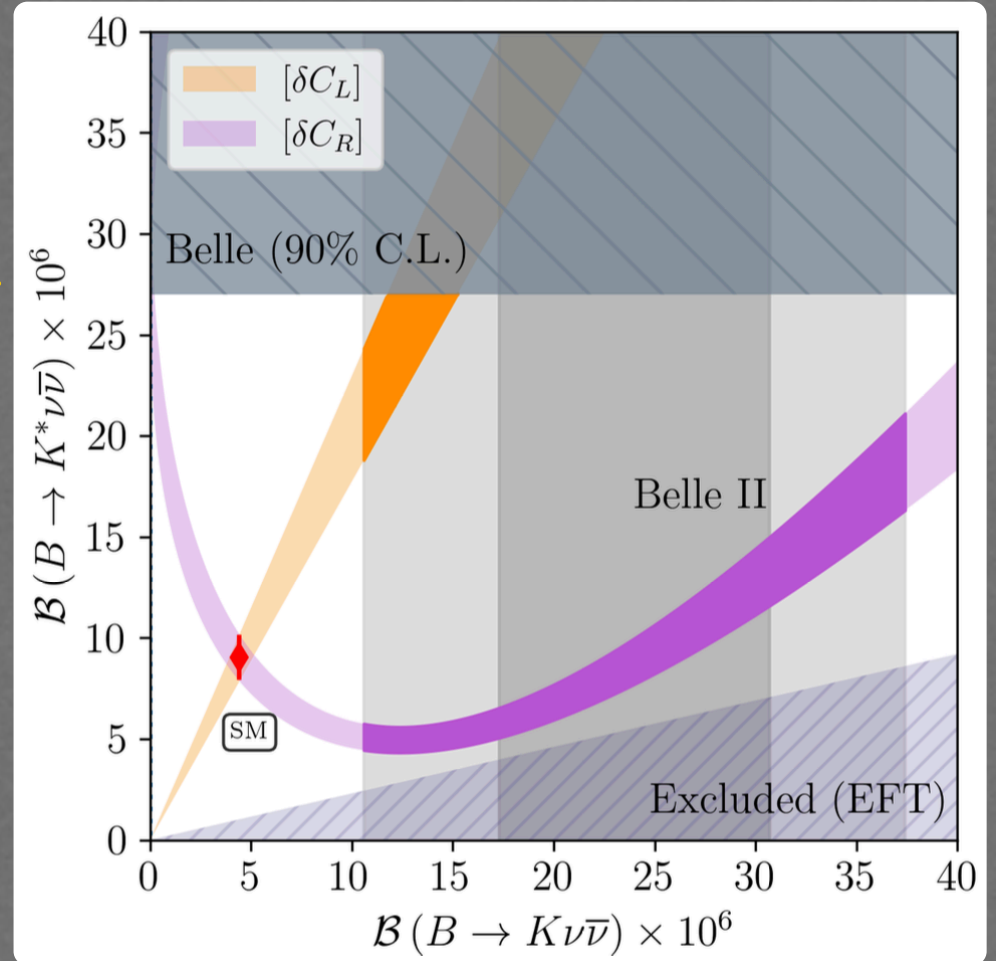


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$$g_{L,R}^{\nu\nu} \propto (\bar{s} \gamma_{L,R}^{\mu} b) \cdot (\bar{\nu} \gamma_{\mu L} \nu)$$

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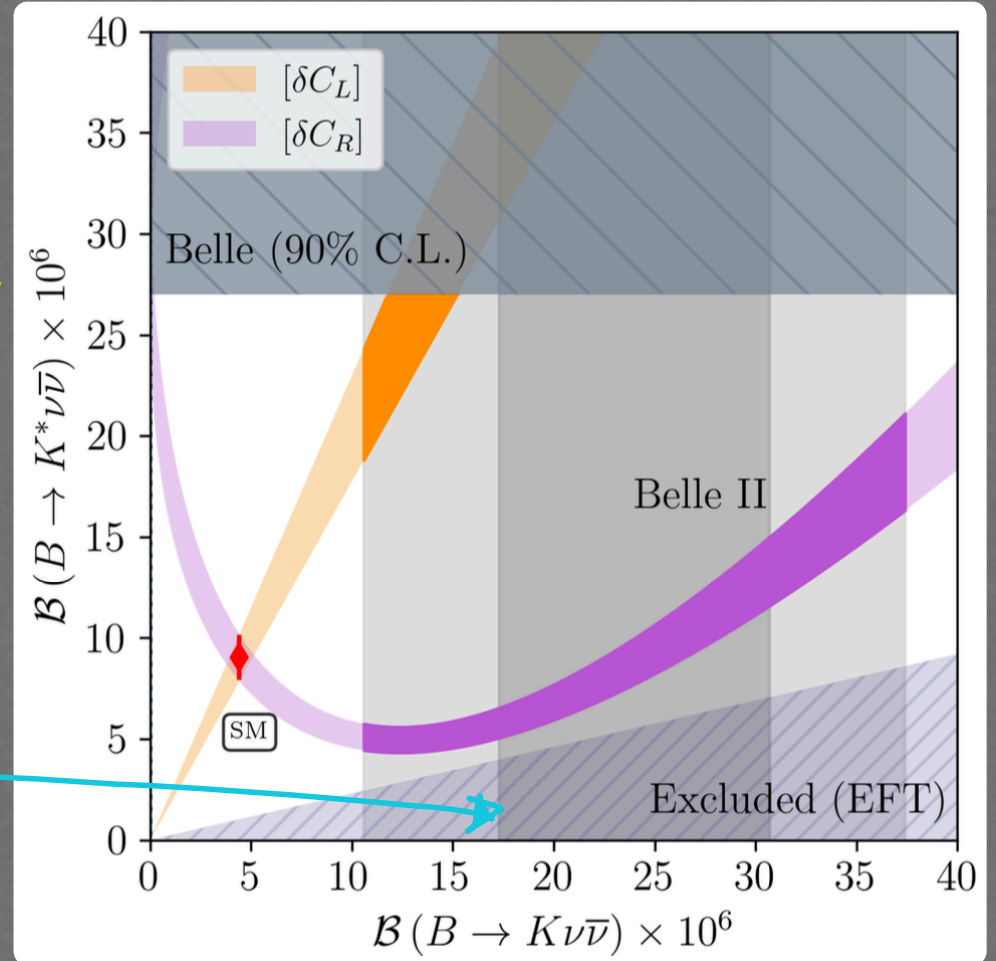
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Common dependence of K & K^* modes on $\mathcal{O}_{L,R}^{\nu\nu}$

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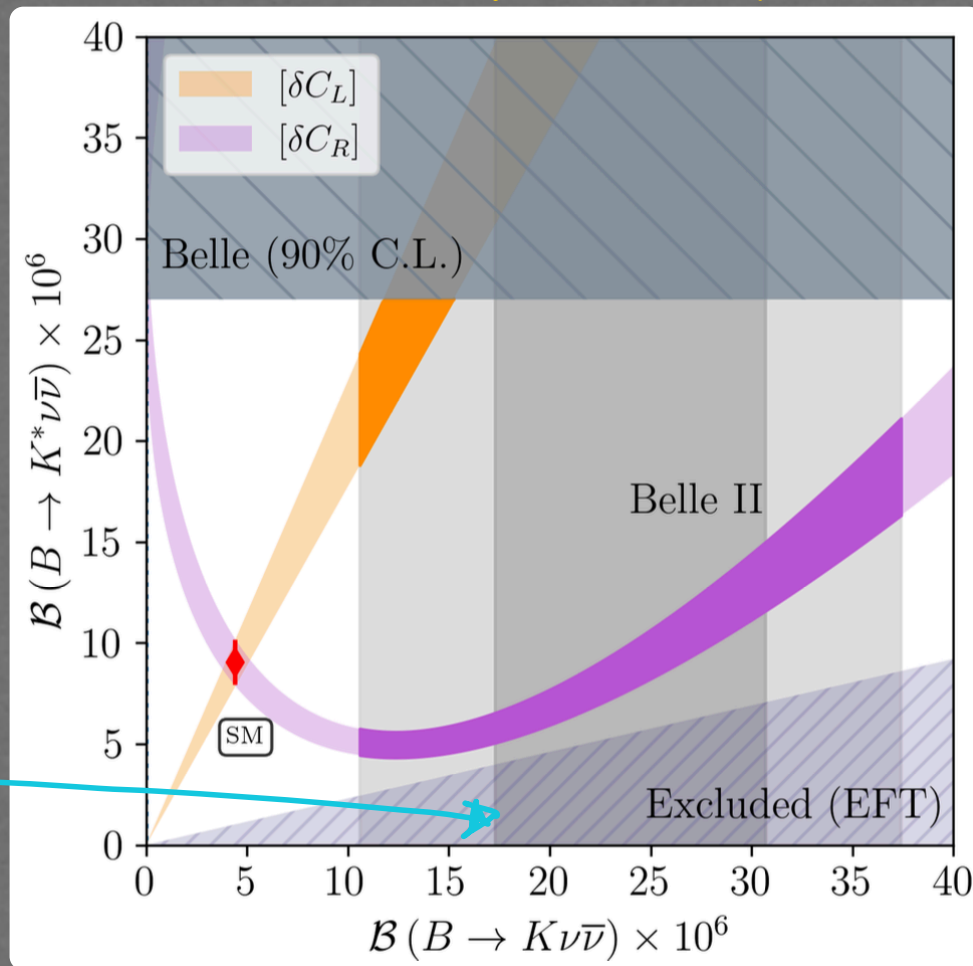
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Allwicher et al., 2023

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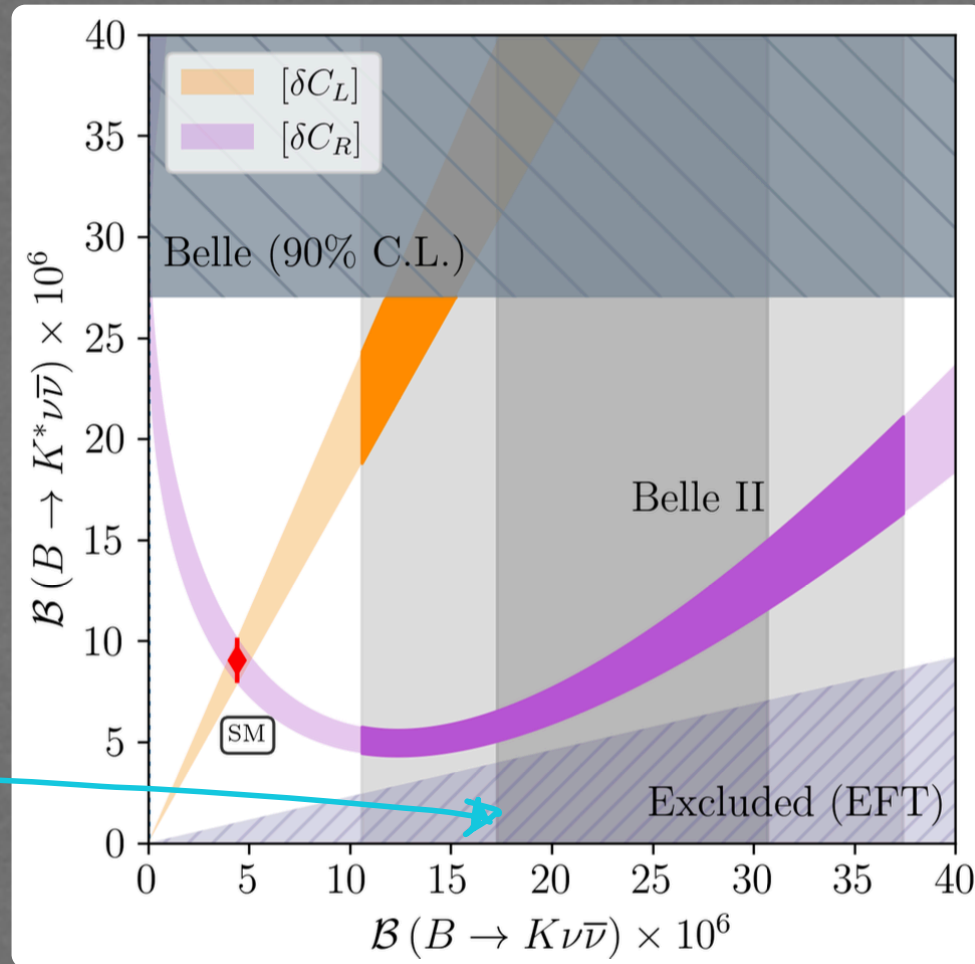
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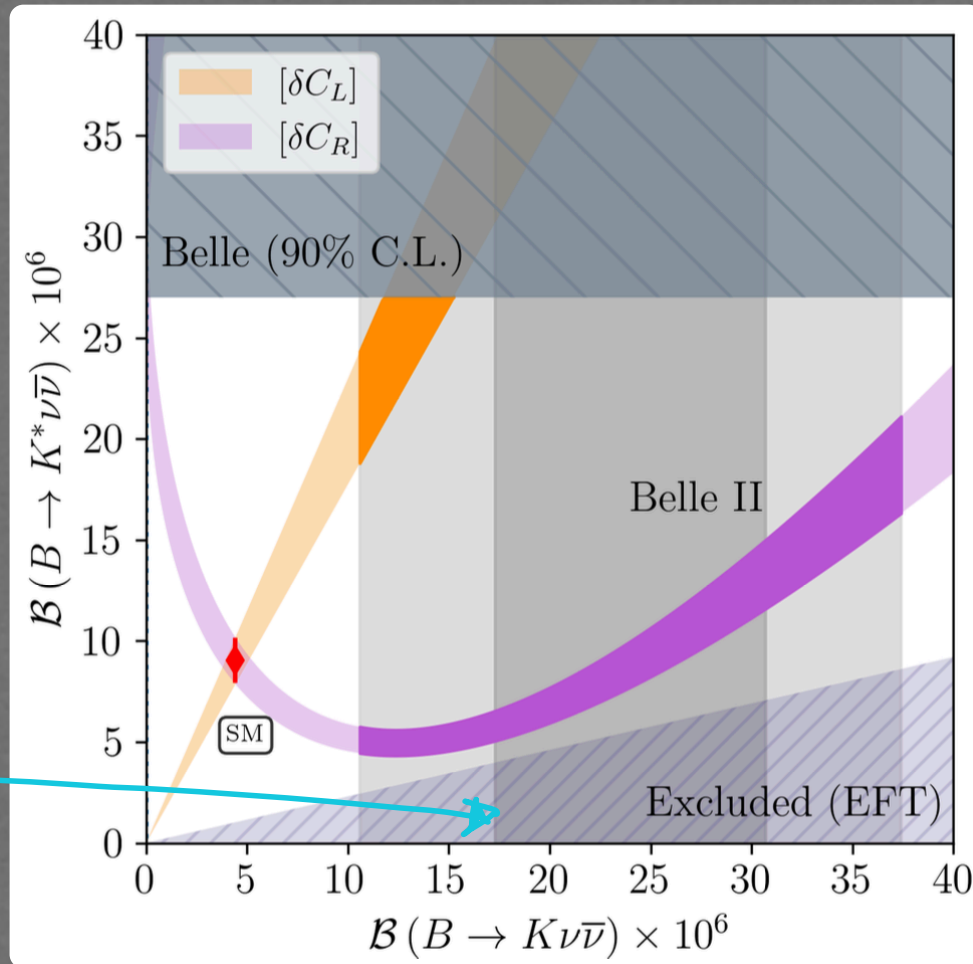
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Allwicher et al., 2023

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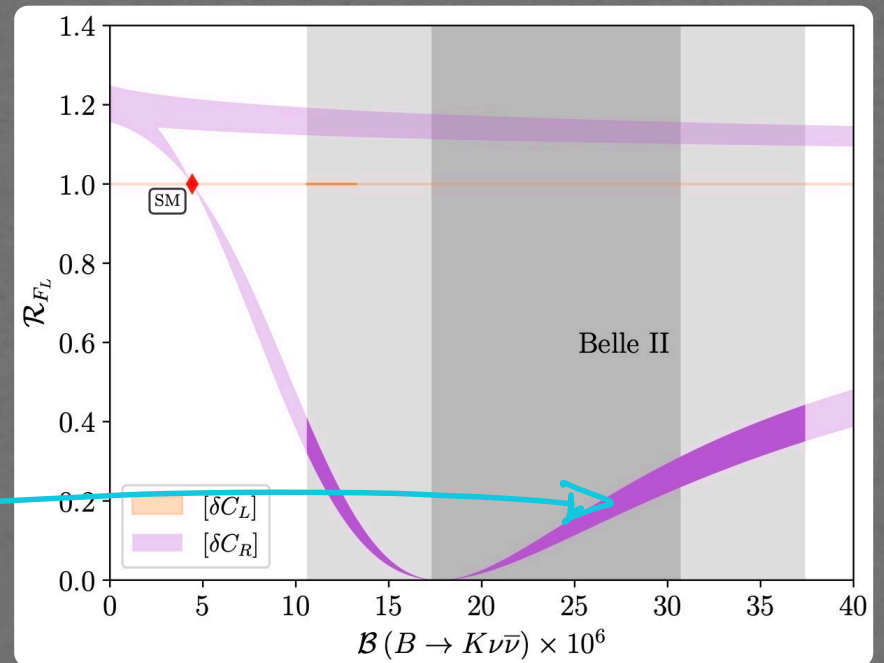
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δC_R viable

and testable

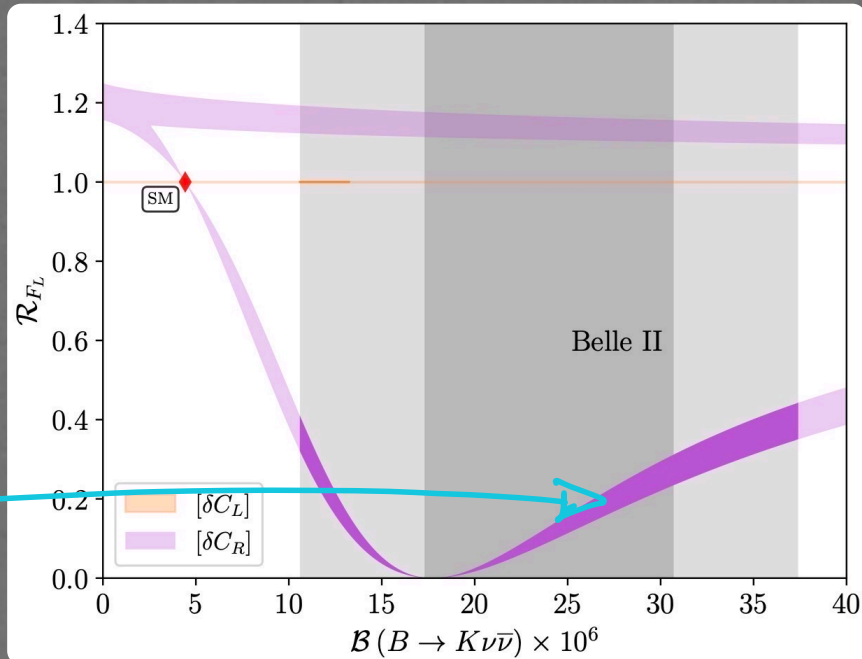


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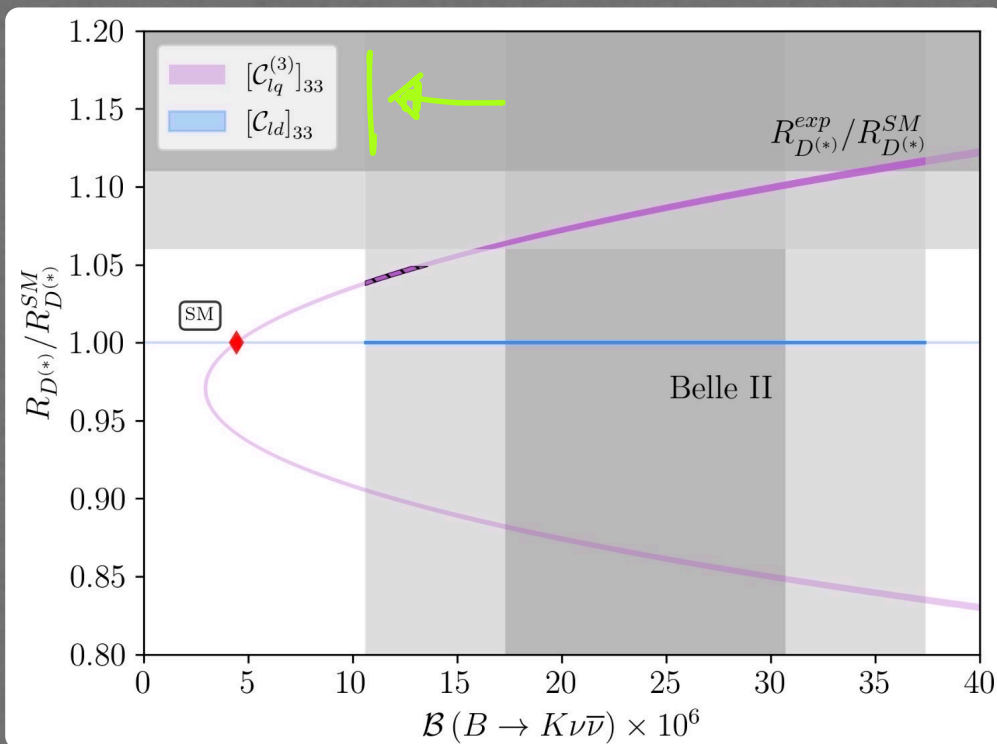
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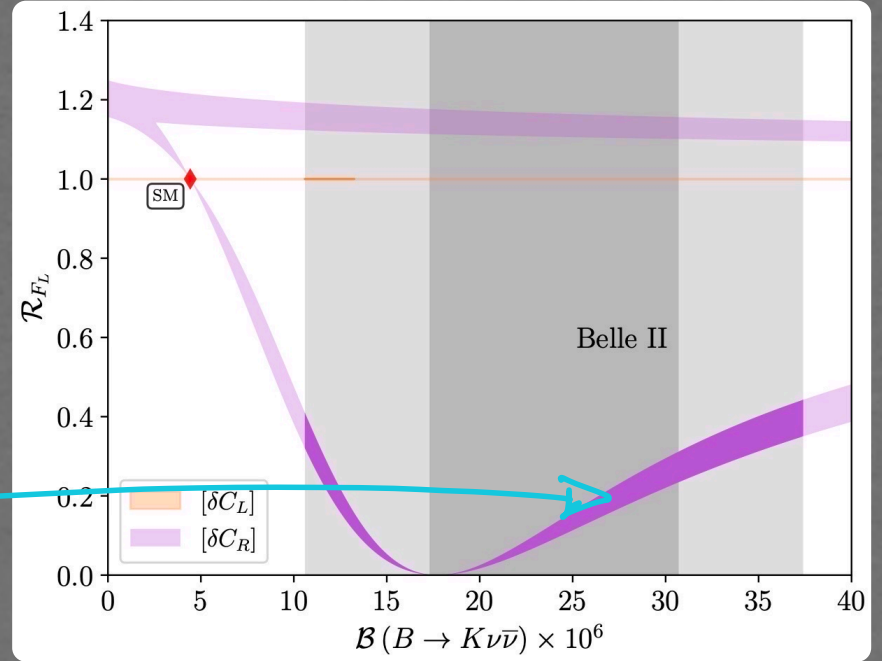


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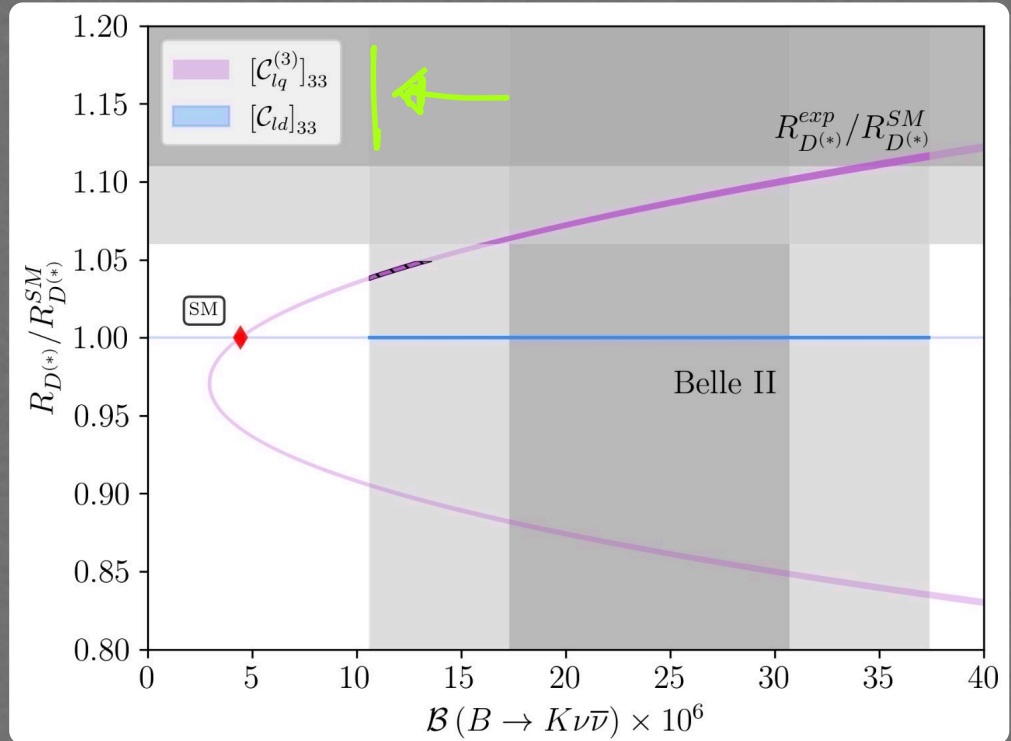
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Will imply sizable effects

in $b \rightarrow s \tau \bar{\tau}$:

$$\frac{BR(b \rightarrow s \tau \bar{\tau})}{BR(b \rightarrow s \tau \bar{\nu})} \sim 10$$

[Glashow, DG, Laure, '14]



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

o $B \rightarrow K \nu \bar{\nu}$ probes

— heavy NP via $\mu_{\nu\nu} \neq 1$

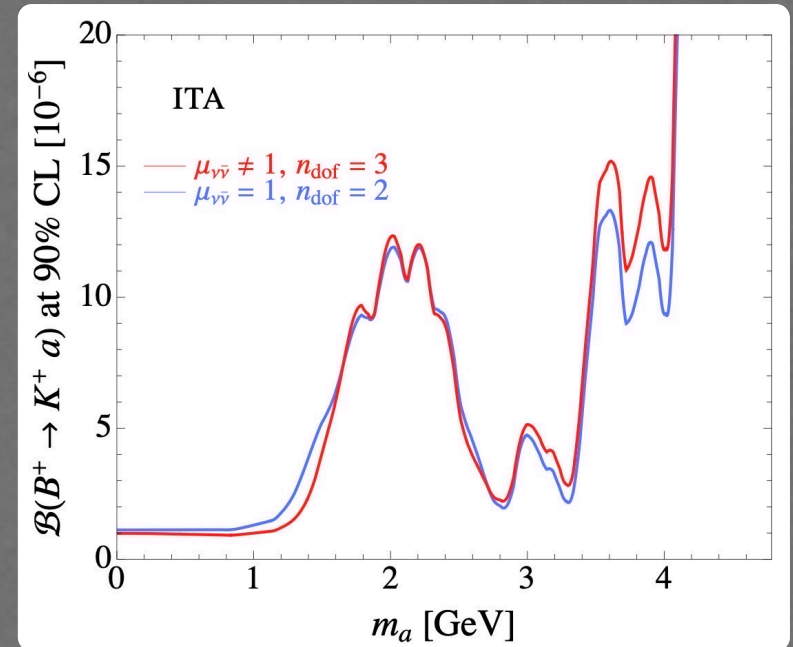
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Abumusa et al., 2025



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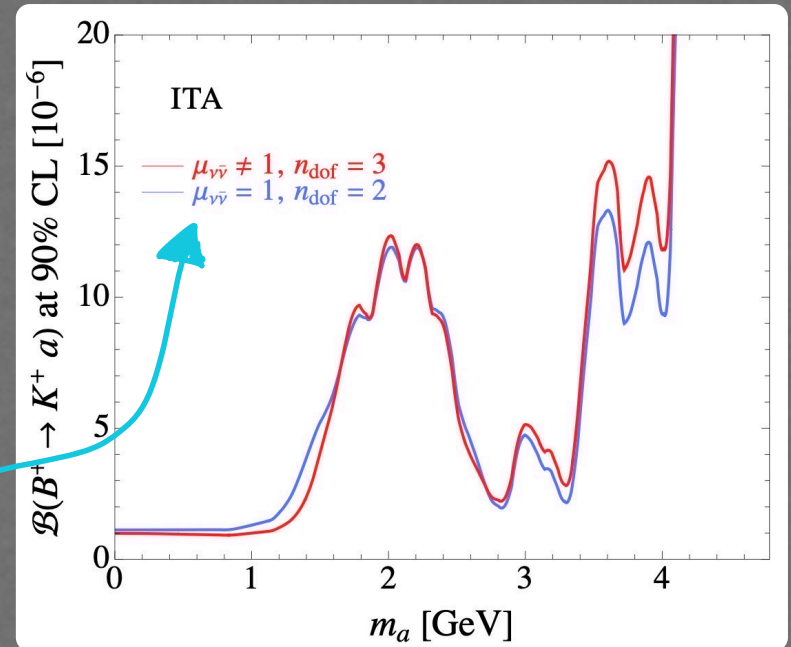
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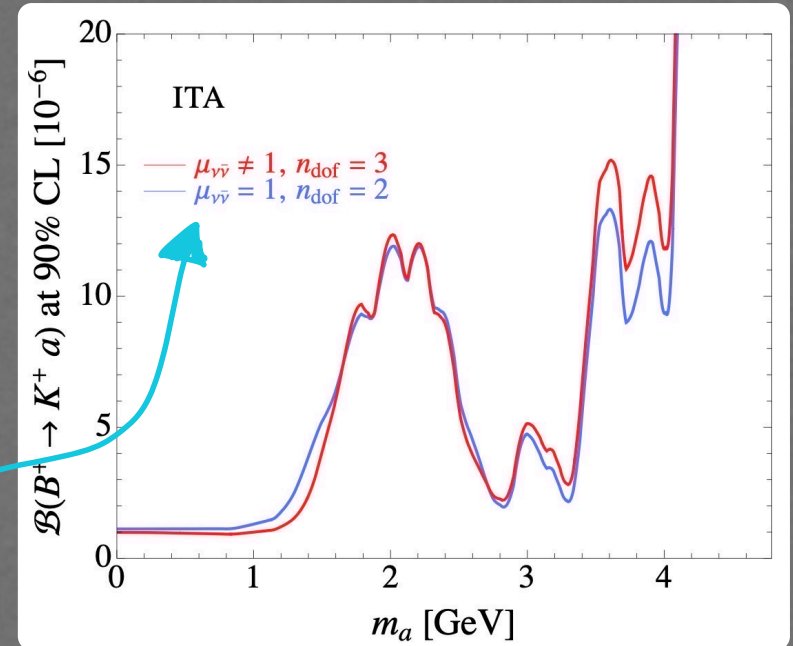
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maximizes info on $q_{\nu\bar{\nu}}^2 \rightarrow$ key discriminator



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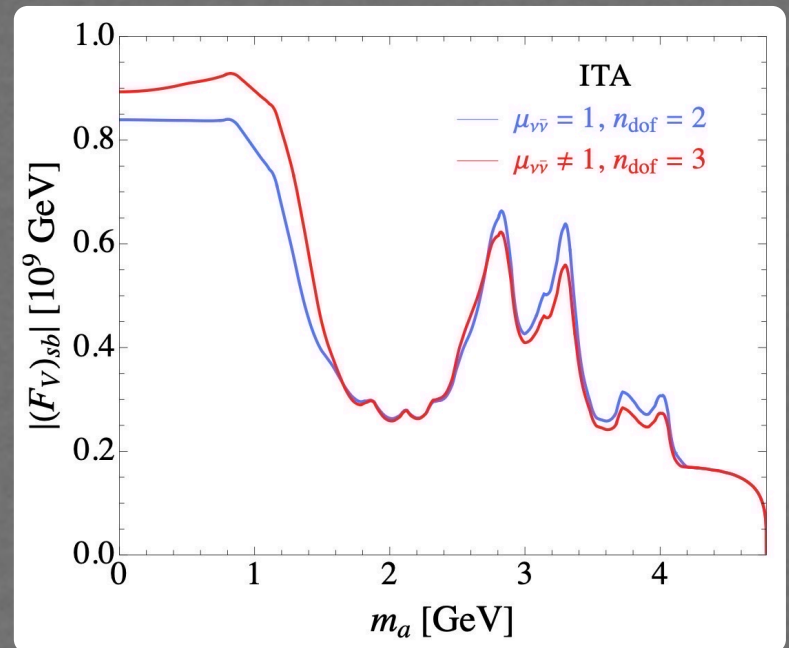
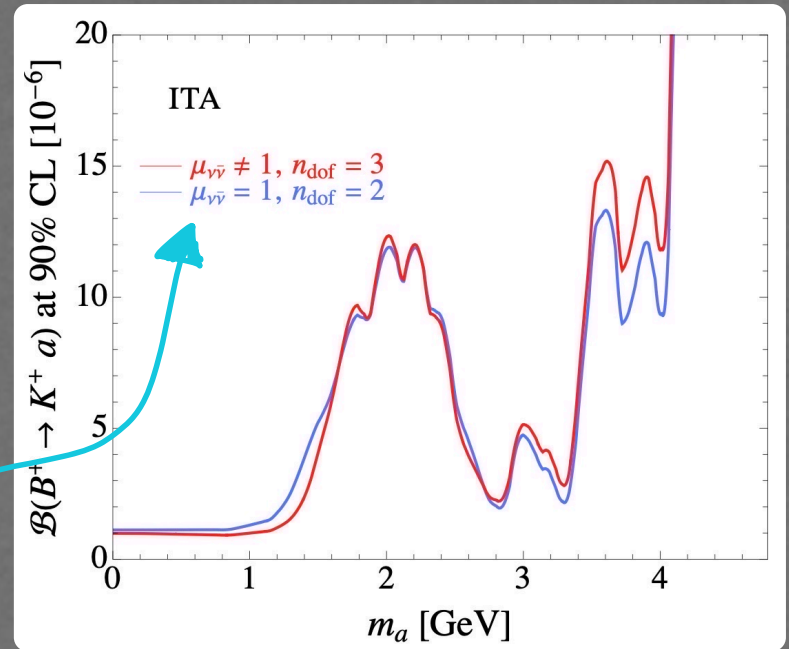
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- Sensitivity to scales $\sim 10^9$ GeV!



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(Grossman - Nir bound)
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- CKM suppressed ($|V_{td}|^2$ rel. to $b \rightarrow s$)
→ Record sensitivity to $\Lambda_{NP} \sim 100$ TeV

$K \rightarrow \pi + \text{axion}$ (the QCD axion)

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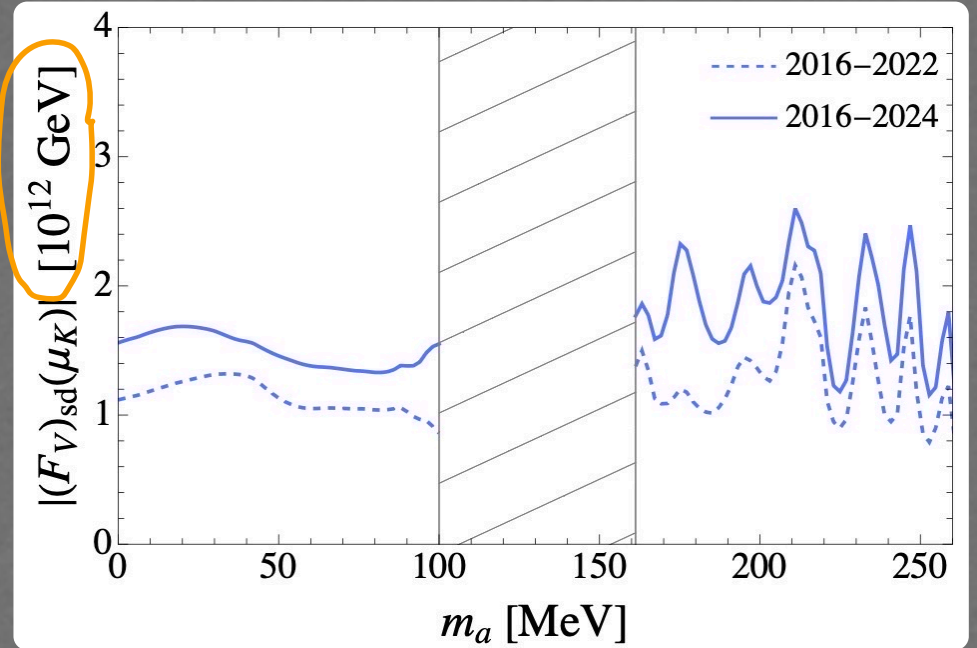
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 Strongest accelerator-based constraint on axion

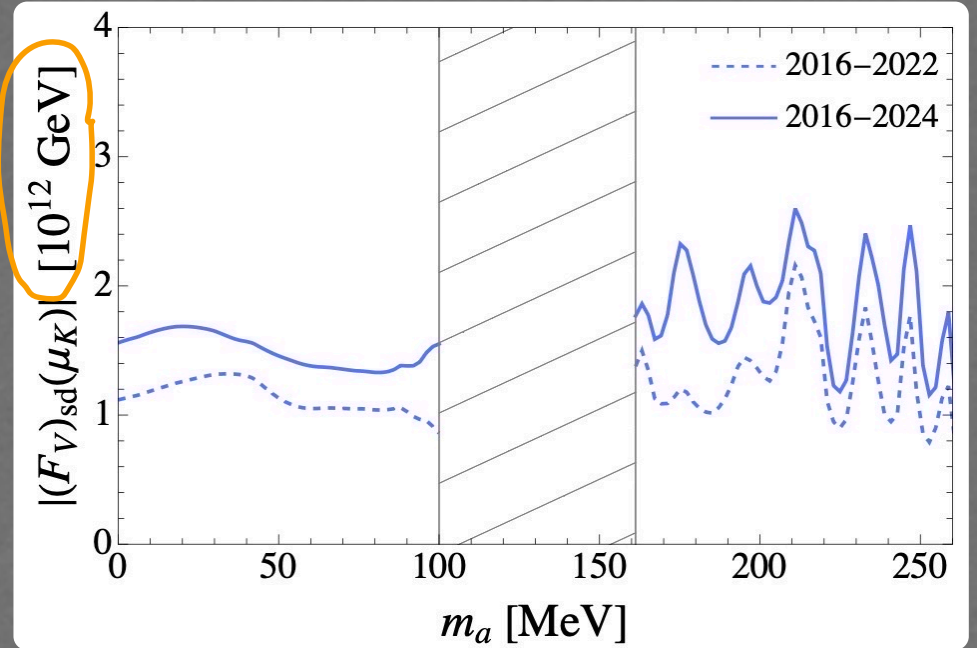


DG et al., 2025

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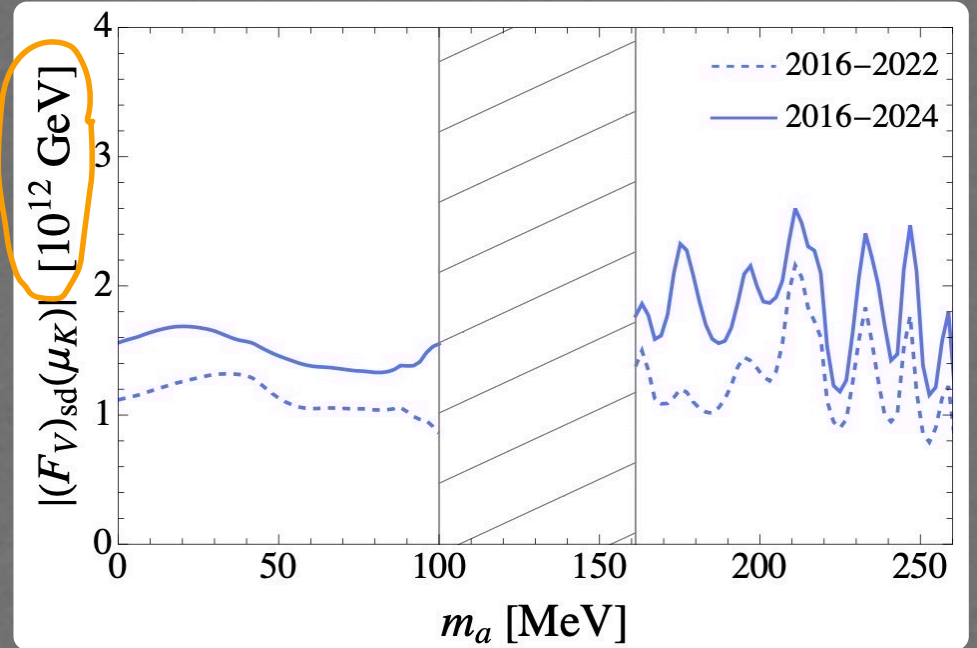
- Two conceptually distinct bounds:

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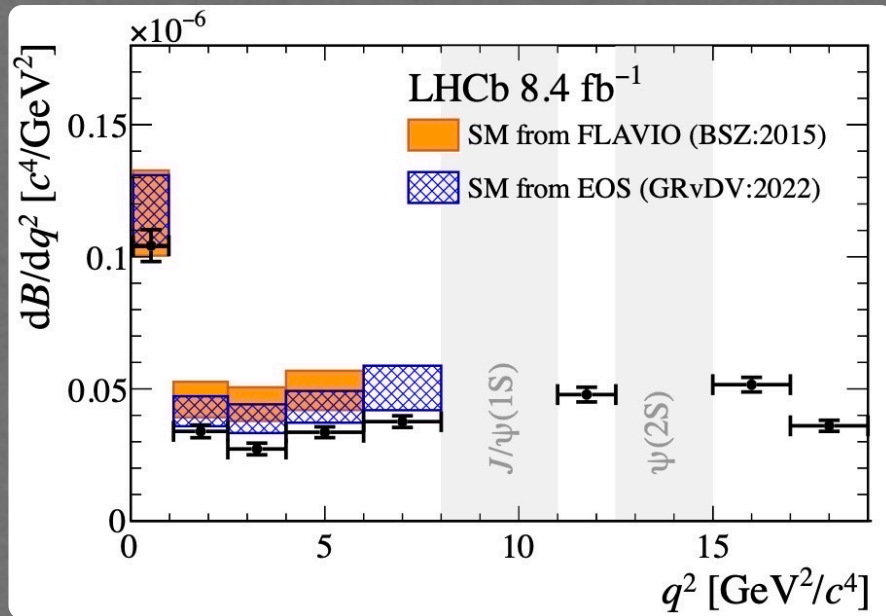
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Tensions in $b \rightarrow s \mu^+ \mu^-$ data

Tensions in $b \rightarrow s \pi^+ \pi^-$ data

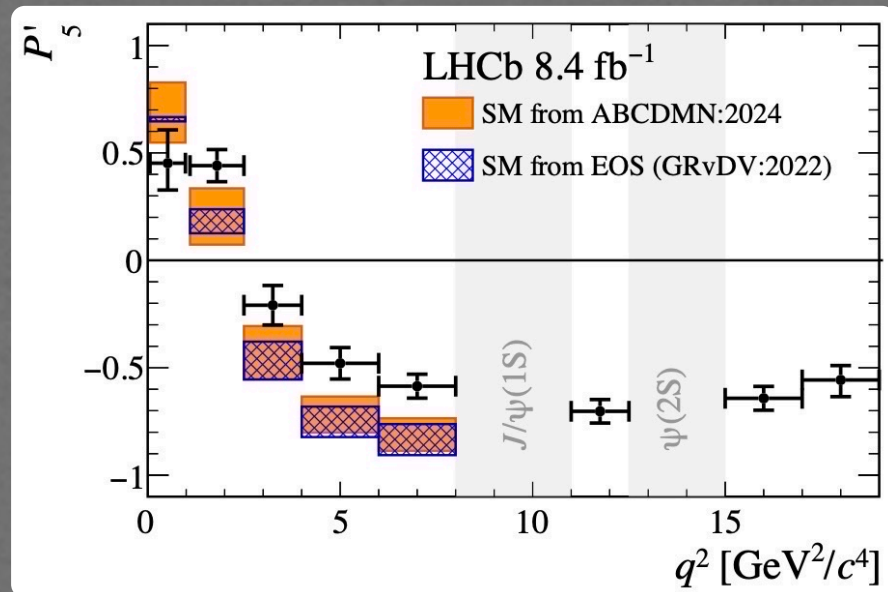
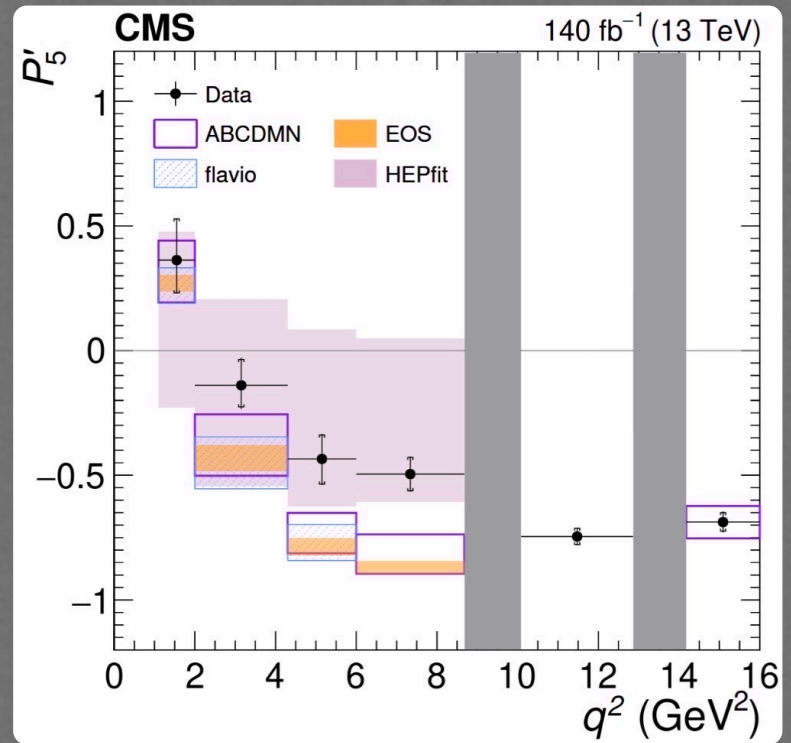
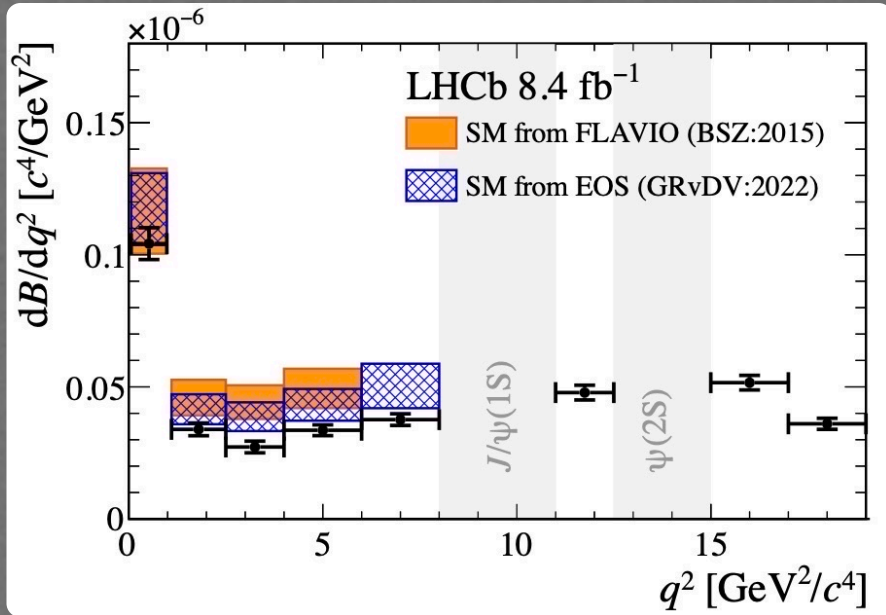
Branching Ratios



Tensions in $b \rightarrow s \pi^+ \pi^-$ data

Angular Obs

Branching Ratios

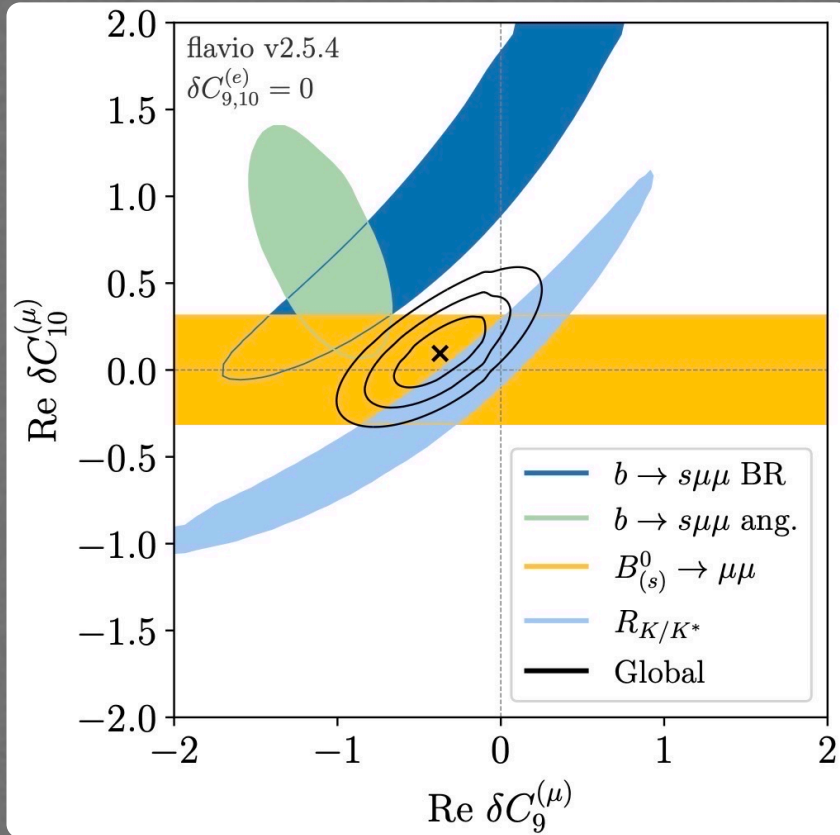


Main tension & possible solutions

$\delta C_9(10)$:

vector (axial) leptonic current

ΔS , Narwand, Simuk, Vittasio, 123

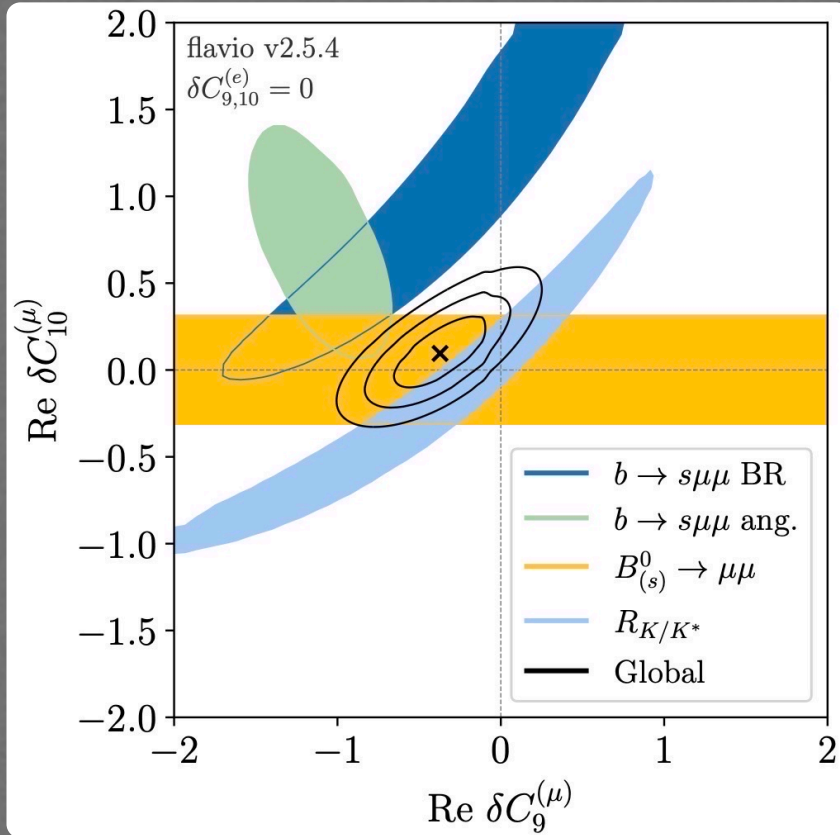


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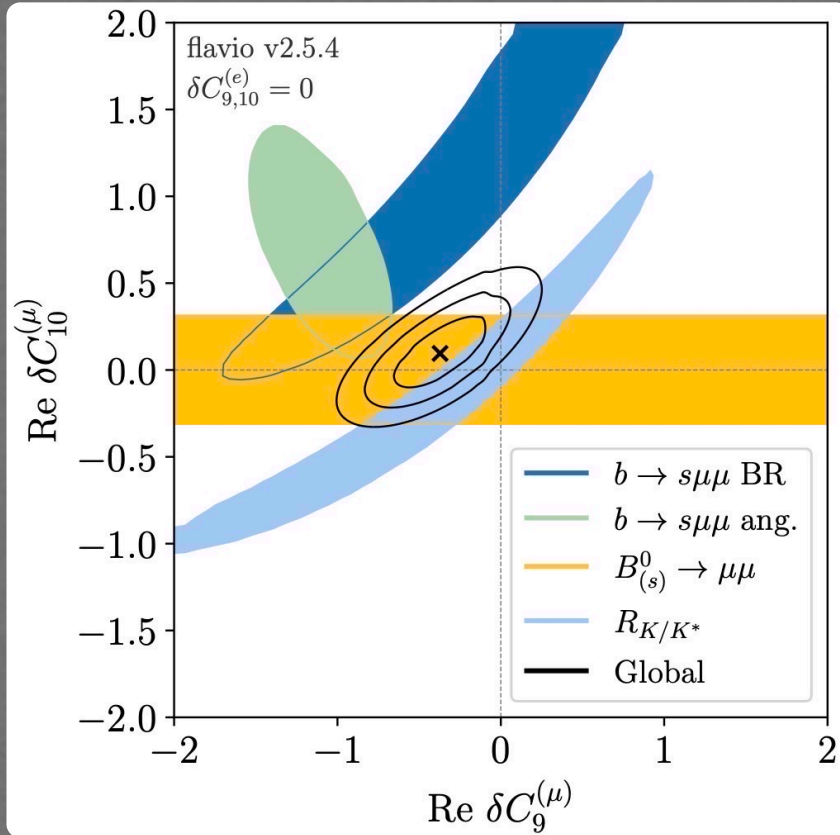
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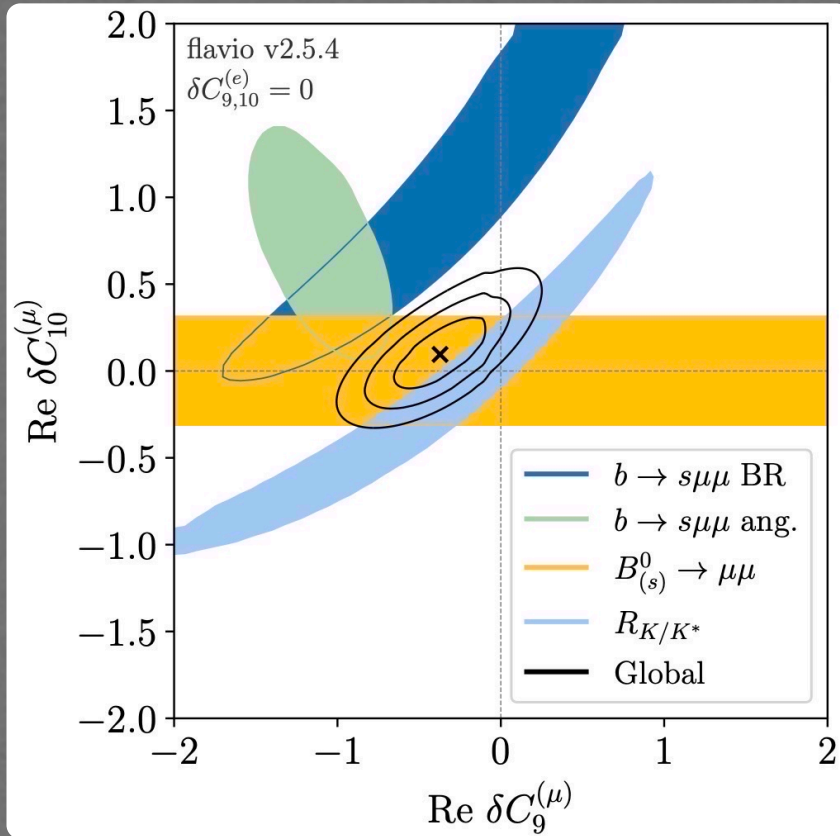
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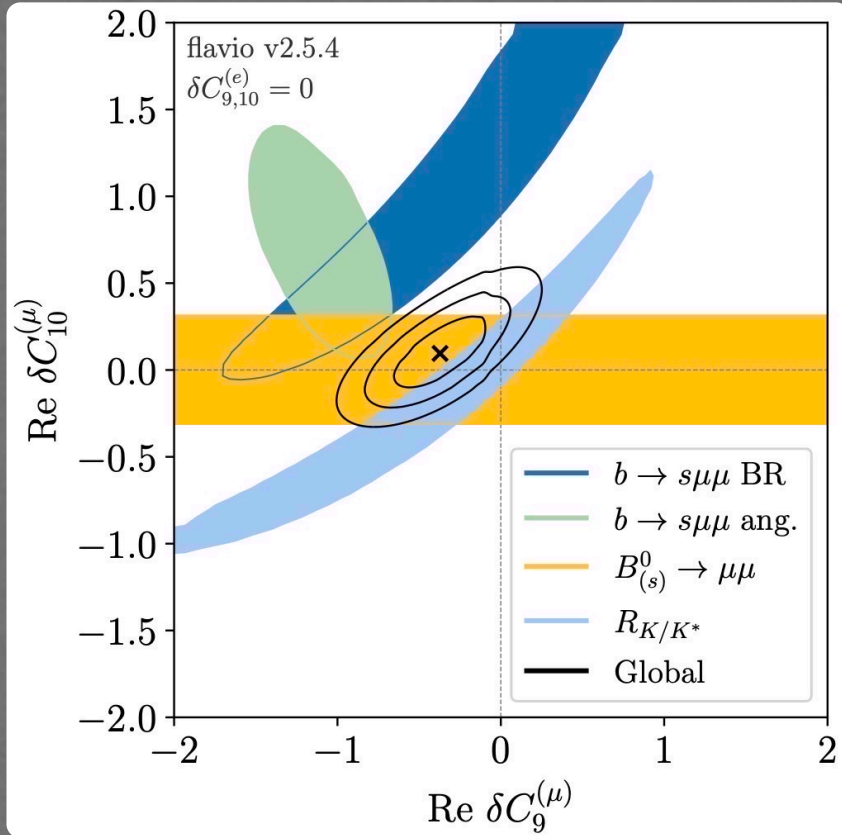
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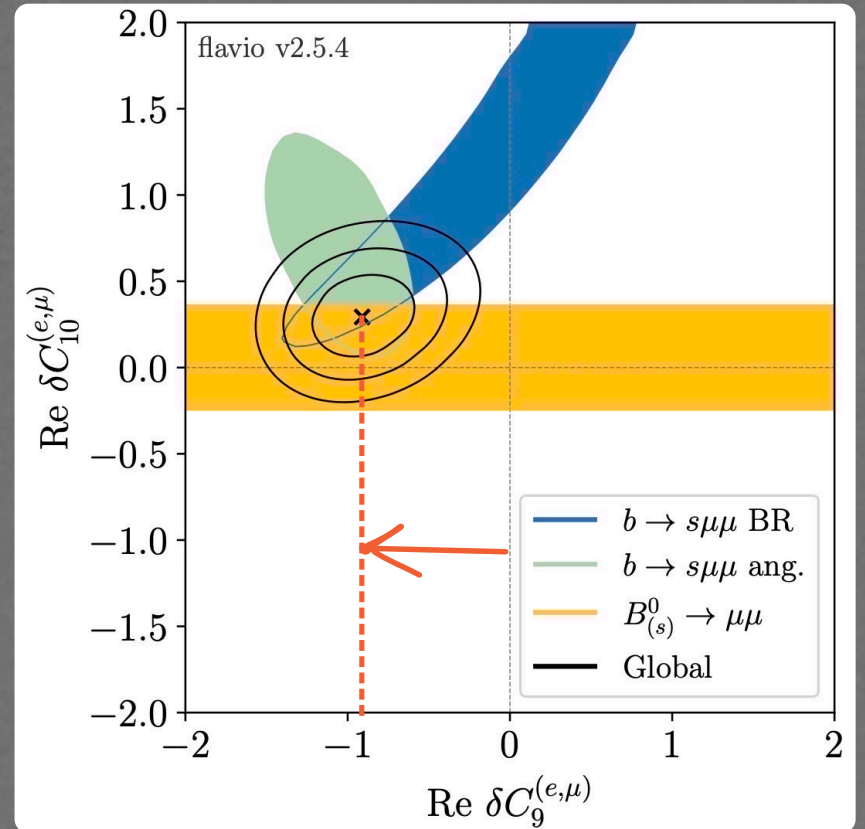
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Possible solution 1



tension ⚡

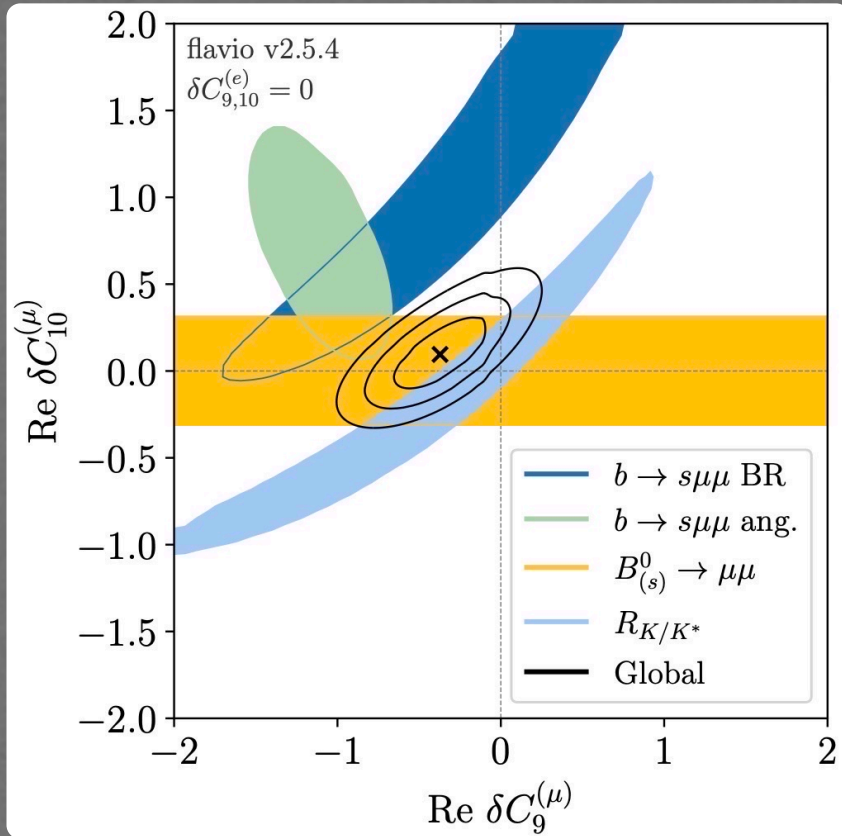
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lepton - universal
shift to vector
leptonic current

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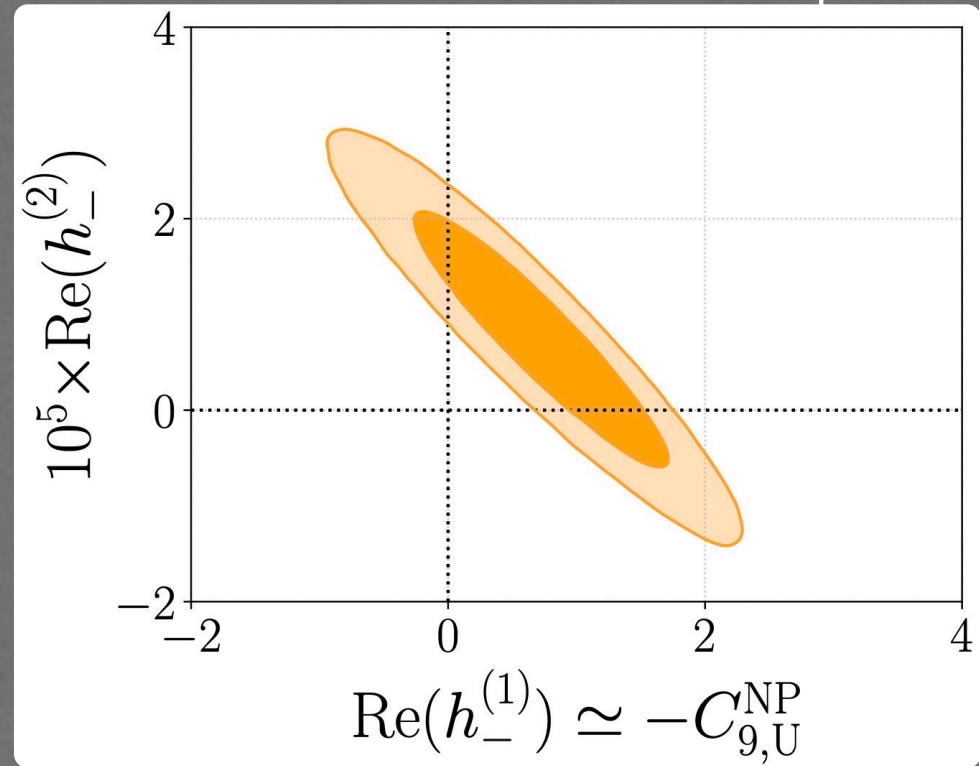
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Possible solution 2

Ciuchini et al., '22



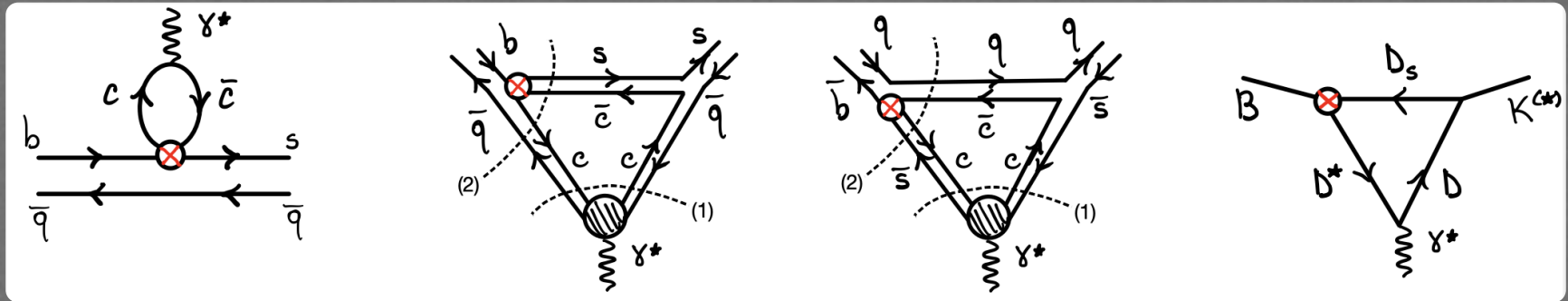
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Hadronic effects
(difficult to assess
by direct calculation)

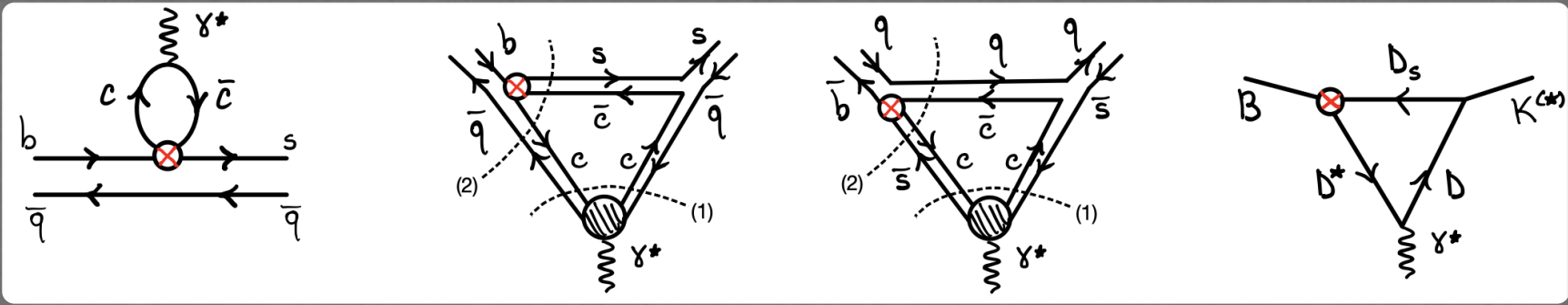
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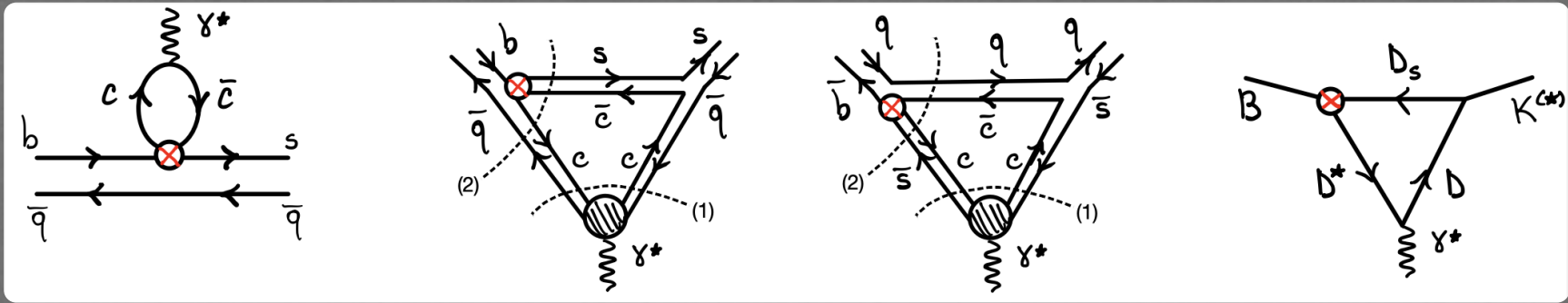
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Triangle diags: • not only "normal" cuts
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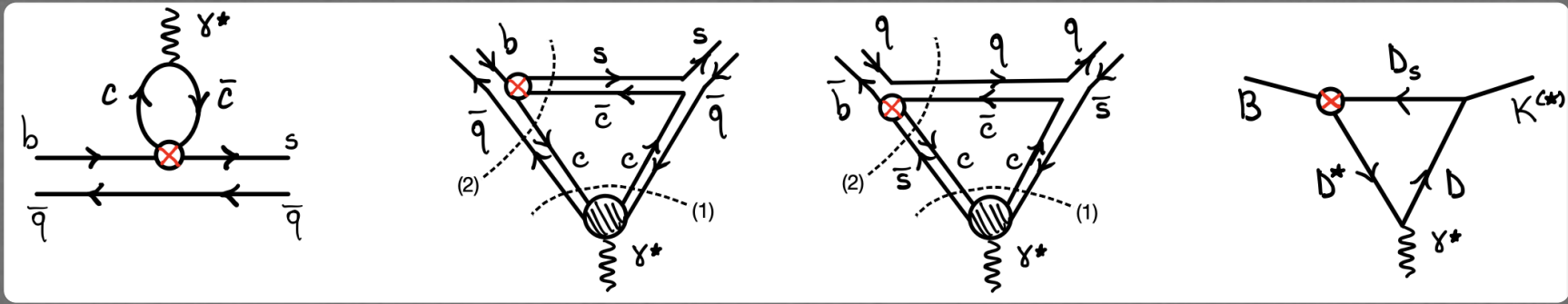
Triangle diags :

- not only "normal" cuts
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- also "anomalous" cuts
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[see Mutke, Hoferichter, Kobis ;
Isler, Polonski, Tinsari, '24]

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[see Mutke, Hoferichter, Kobis;
 Isobri, Polonski, Tinsari, '24]

Alternative solution: go to different q^2 region

e.g. $B_s \rightarrow \tau \tau \gamma$ [DG et al., 2017+]

Prospects

(besides the exciting FCC)

Upgrade-era flavour : 2030-2040s

o LHCb: $50/\text{fb}$ Run 4 $\rightarrow > 300/\text{fb}$ w/ Upgrade II

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- charged b, c (and $s!$) decays
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Unique
for

- Ξ , neutrals, inclusive modes, τ LFV
- $R(D^*) \sim 1\%$; $B \rightarrow K \nu \bar{\nu} \sim 8\%$; $\tau \rightarrow 3\pi \sim 10^{-10}$

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• Atlas/CMS HL-LHC :

Indep. &
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• Tests of CKM & LFU & FCNCs & CPV
w/ O.E.M. improved precision