HIDDeν
Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

Looking for new physics through the exclusive $b \to s\nu\nu$ modes

HEP Seminar @ IJCLab

Salvador Rosauro-Alcaraz, 19/03/2024

Outline

- **Introduction**
- $B \to K^{(*)}\nu\nu$ **in the Standard Model**
  - Effective theory description
  - Sources of uncertainty
- **Belle-II results**
- **Implications for BSM physics**
    - LEFT
    - SMEFT
    - Light new physics
- **Summary and outlook**

Introduction

Flavor Physics

$$\mathscr{L}_{\text{Yukawa}} = -\bar{Q}Y_d H d_R - \bar{Q}Y_u \tilde{H} u_R - \bar{L}Y_\ell H e_R + \text{[redacted]} + h.c.$$

Most of the free parameters of the SM arise from $\mathscr{L}_{\text{Yukawa}}$ and need to be extracted from experiment

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Origin of neutrino masses?

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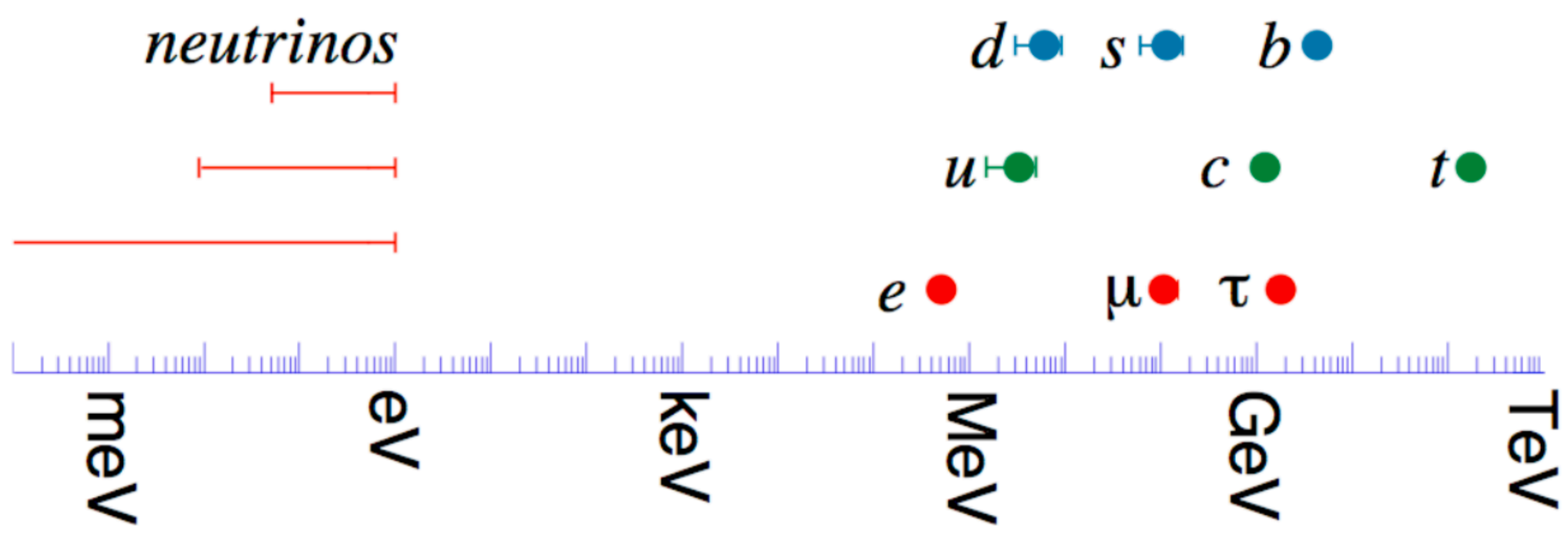
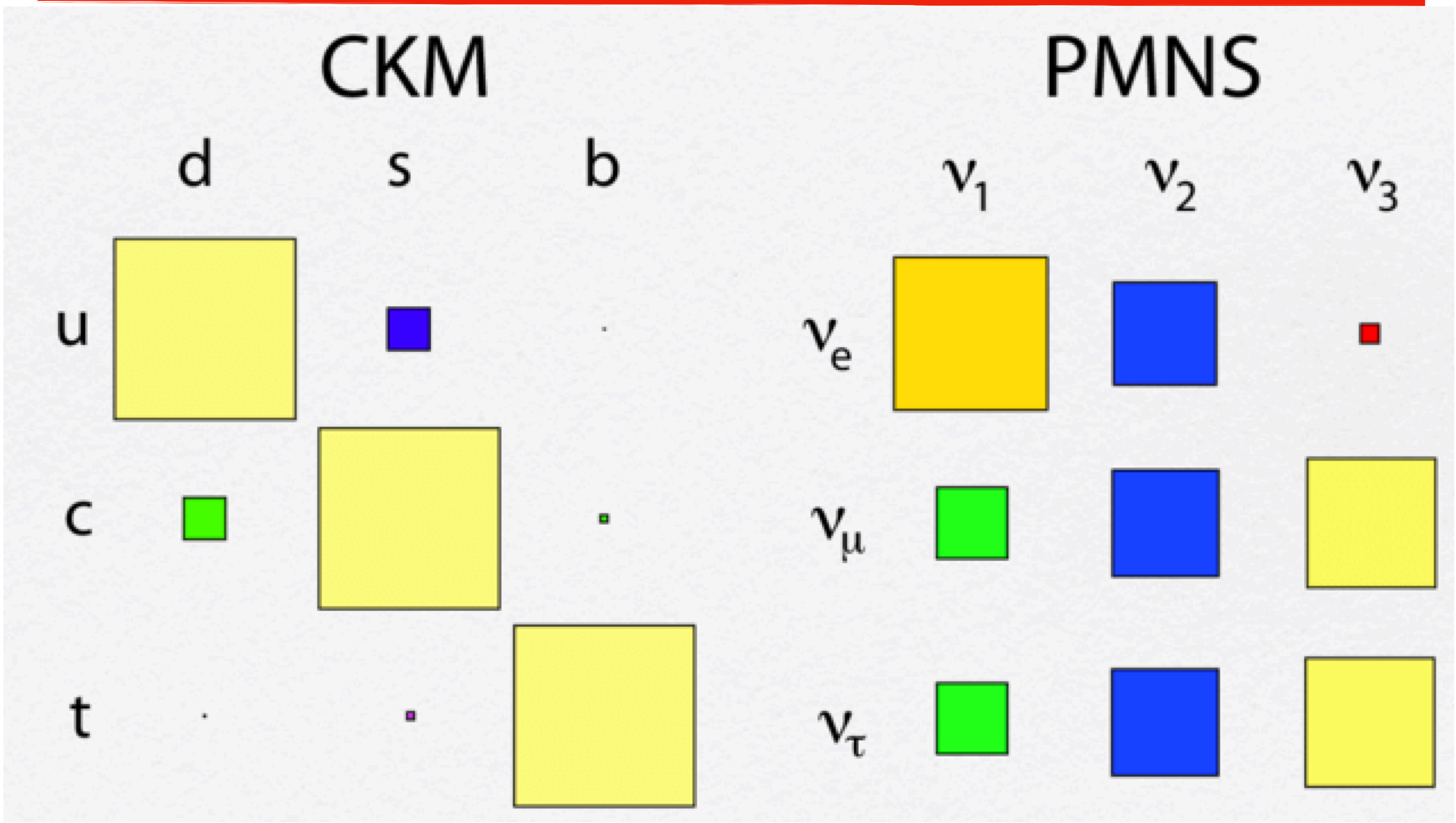
Fermion masses span ~ 5 orders of magnitude (not including m_ν)



Why is the quark mixing so different from the leptonic one?



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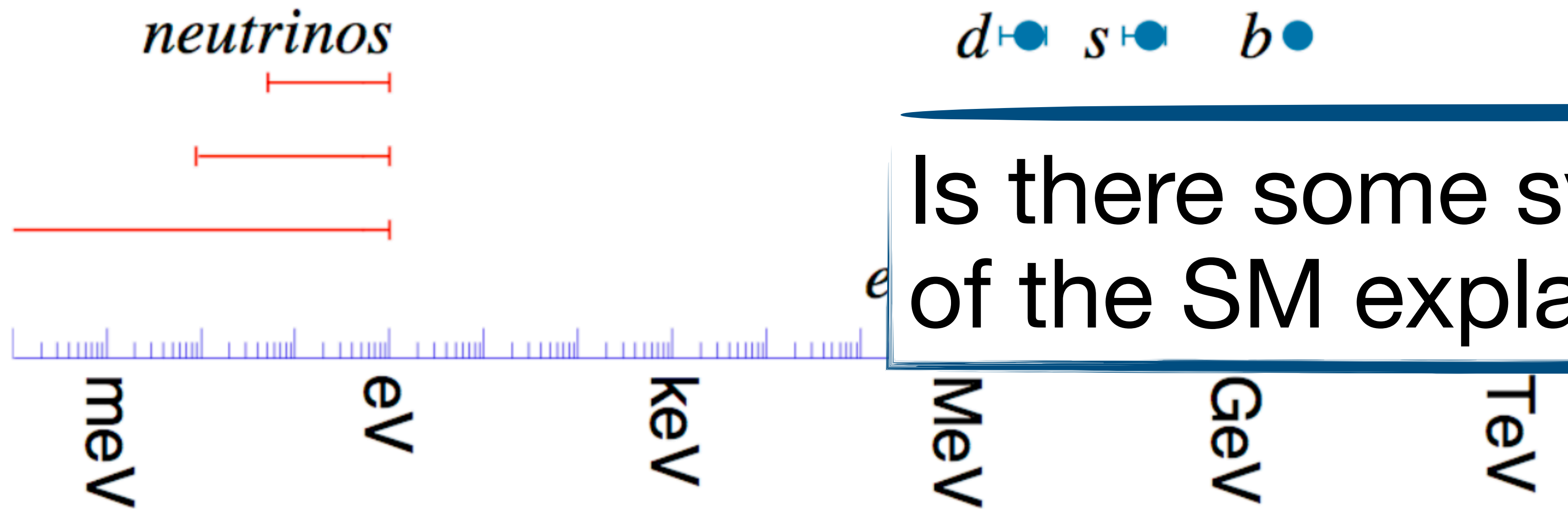

Is there some symmetry beyond those of the SM explaining this structure?

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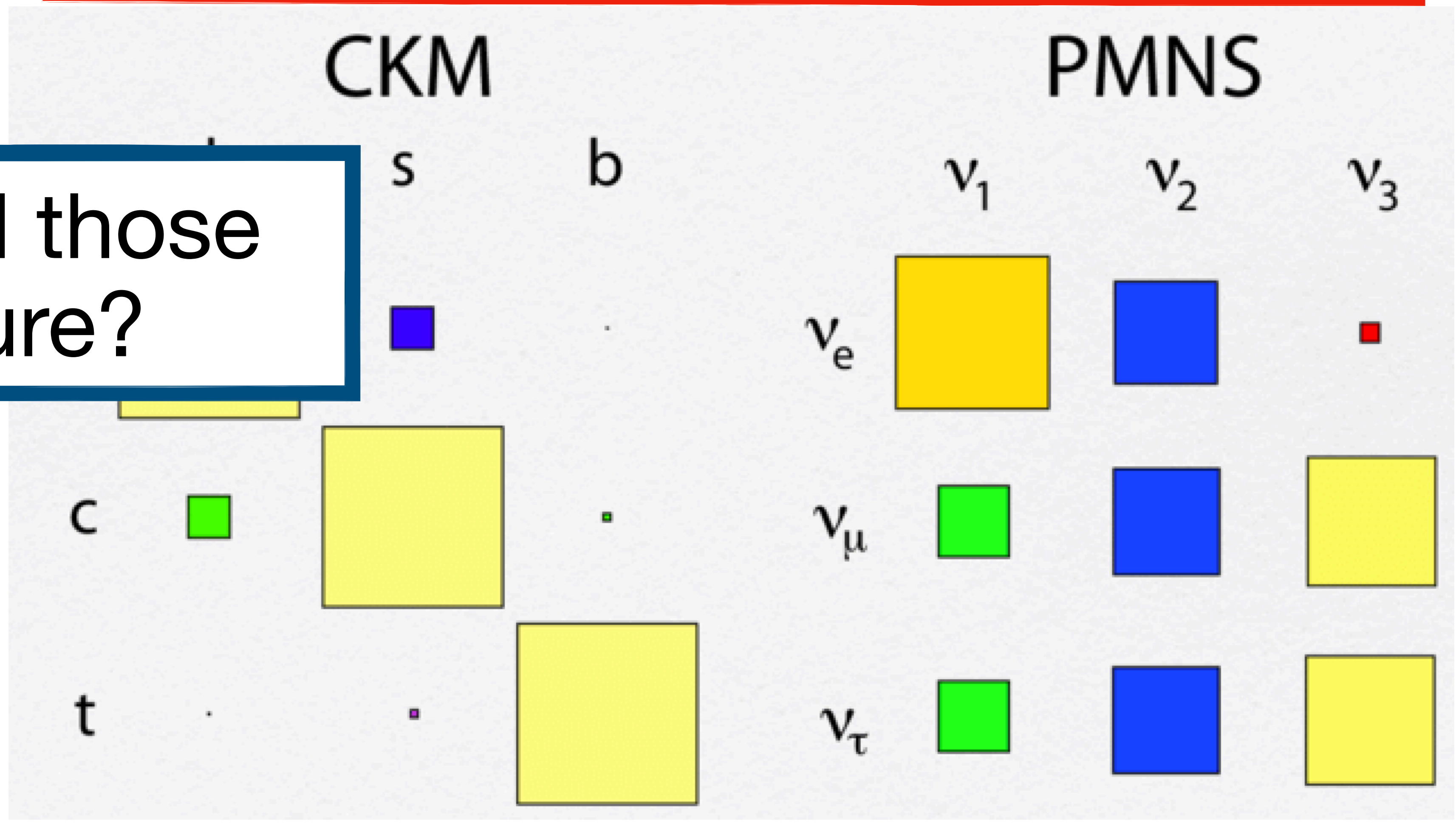

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Indirect searches for New Physics

We can look for rare/forbidden processes in the SM which would be sensitive to BSM physics effects

$$\mathcal{O}_{\text{exp}} = \mathcal{O}_{\text{SM}}(1+\delta_{\text{NP}})$$

Deviation with respect to the SM prediction

Need to be very precise!

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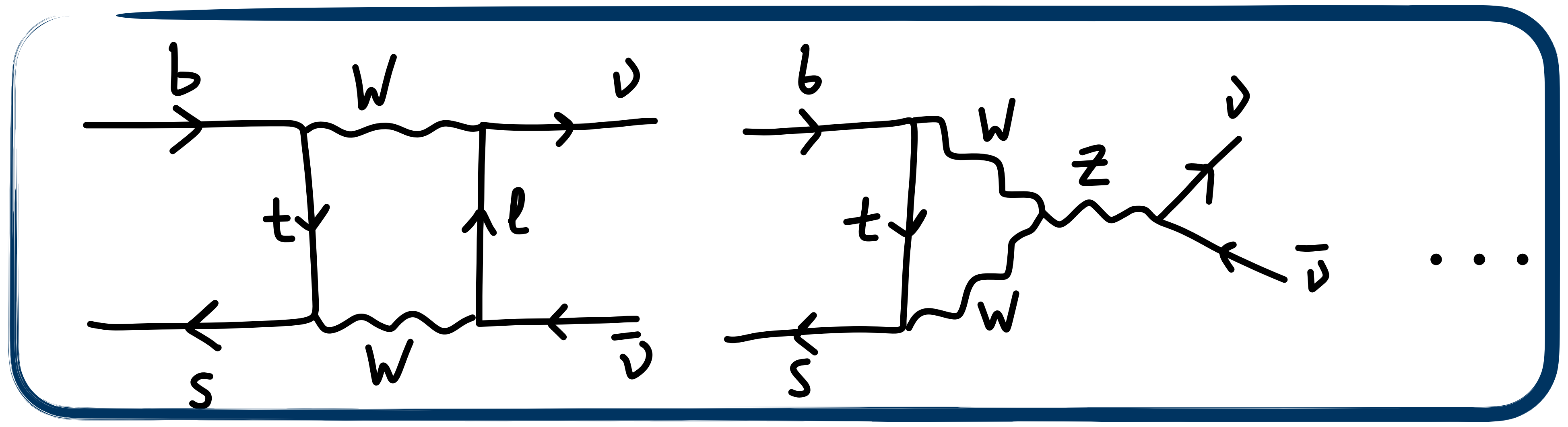
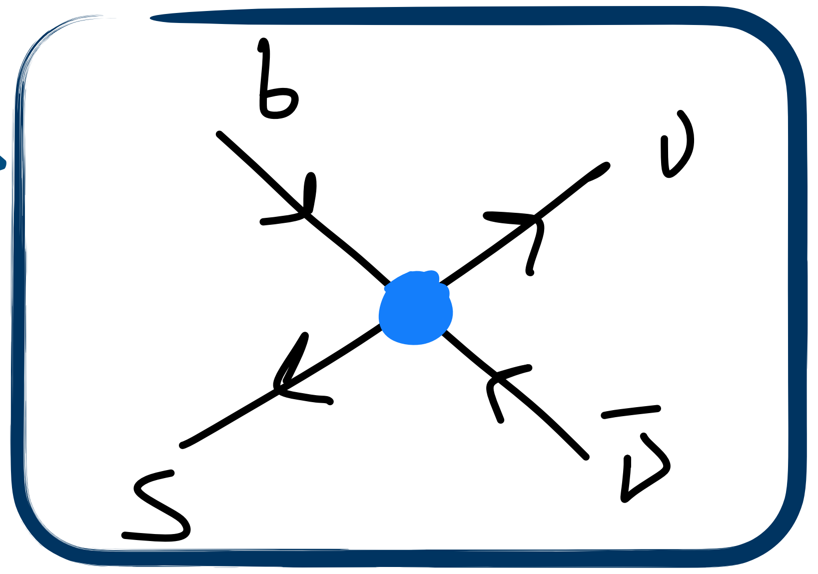
Rare B-meson decays



$E \ll M_{W,Z}$

At low energies we use an EFT



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

$B \to K^{(*)}\ell\ell$

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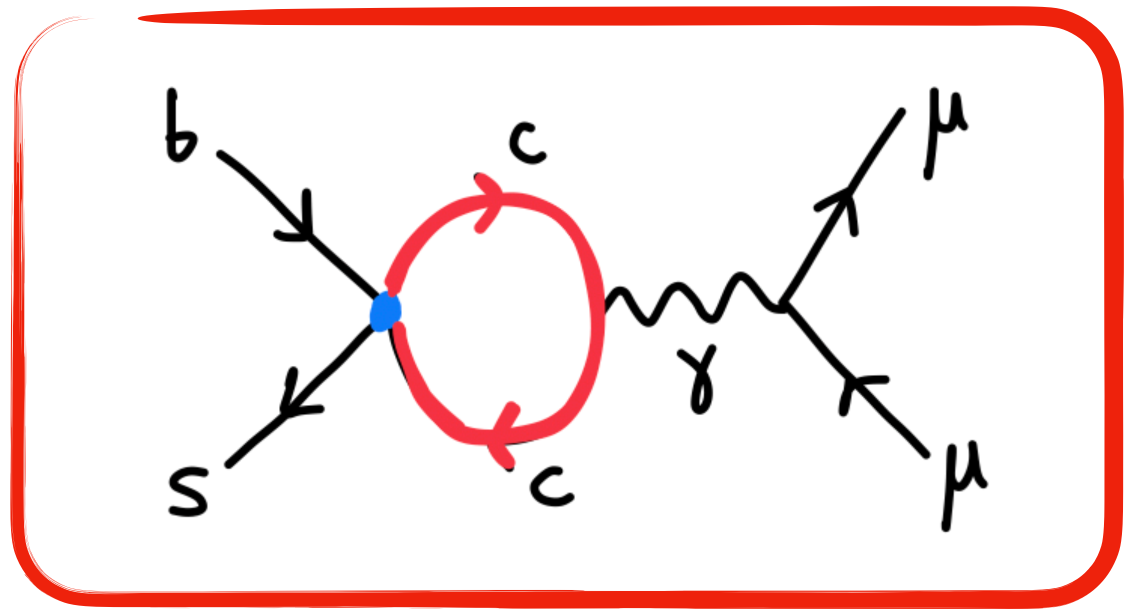
Rare B-meson decays

Advantage of $B \to K^{(*)}\nu\nu$ over the channel with charged leptons

Hadronic uncertainties might hinder their precise determination:

$b \to s\nu\nu$ is theoretically cleaner than $b \to s\mu\mu$, not affected by $c\bar{c}$-loops



$B \to K^{(*)}\nu\nu$ in the Standard Model

$$\mathcal{O}_{\rm exp} = \mathcal{O}_{\rm SM}(1+\delta_{\rm NP})$$

Effective lagrangian

$b \to s\nu\nu$

Effective description in the SM

See e.g. A. Buras *et al.*, 1409.4557

$$\mathscr{L}^{b\to s\nu\nu} = \frac{4G_F}{\sqrt{2}}\lambda_t \sum_a C_a \mathcal{O}_a + h.c.$$

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$$\mathcal{O}_L^{\nu_i\nu_j} = \frac{e^2}{(4\pi)^2}\left(\bar{s}_L\gamma_\mu b_L\right)\left(\bar{\nu}_i\gamma^\mu(1-\gamma_5)\nu_j\right)$$

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$$C_L^{\mathrm{SM}} = -6.32(7)$$

Flavor diagonal and universal

NLO QCD & 2-loop EW corrections

G. Buchalla & A. Buras, Nucl. Phys. B (1993)
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$$C_R^{\mathrm{SM}} = 0$$

Sources of uncertainty

CKM matrix element determination

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Inclusive vs exclusive

$$|\lambda_t| \times 10^3 = \begin{cases} 41.4 \pm 0.8, & B \to X_c \ell \bar{\nu} \\ 39.3 \pm 1.0, & B \to D \ell \bar{\nu} \\ 37.8 \pm 0.7, & B \to D^{(*)} \ell \bar{\nu} \end{cases}$$

HFLAV, arXiv:2206.07501

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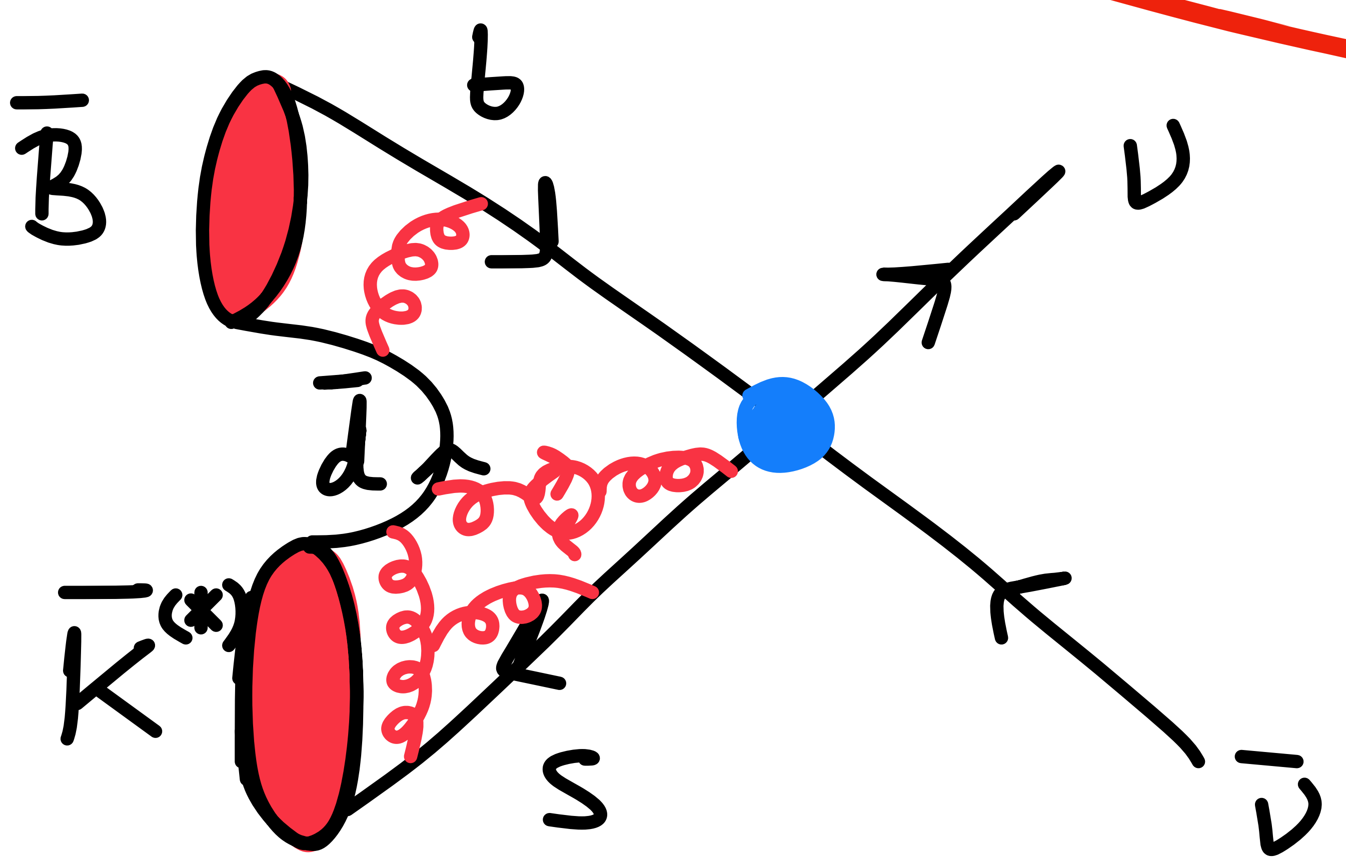

Hadronic matrix element

Lorentz structure

$$\langle K^{(*)}|\bar{s}_L\gamma^\mu b_L|B\rangle = \sum_i K_i^\mu \, \mathcal{F}_i(q^2)$$

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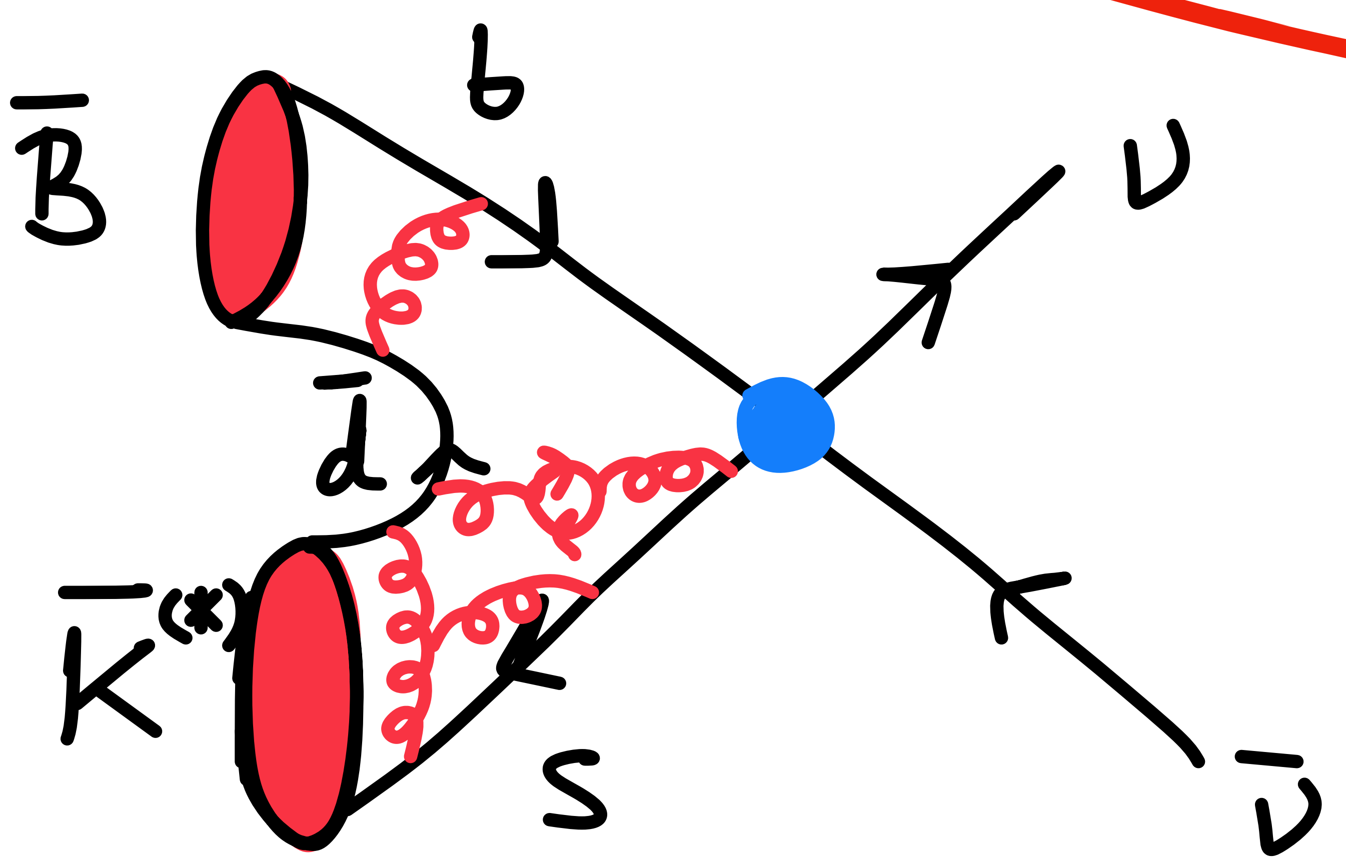

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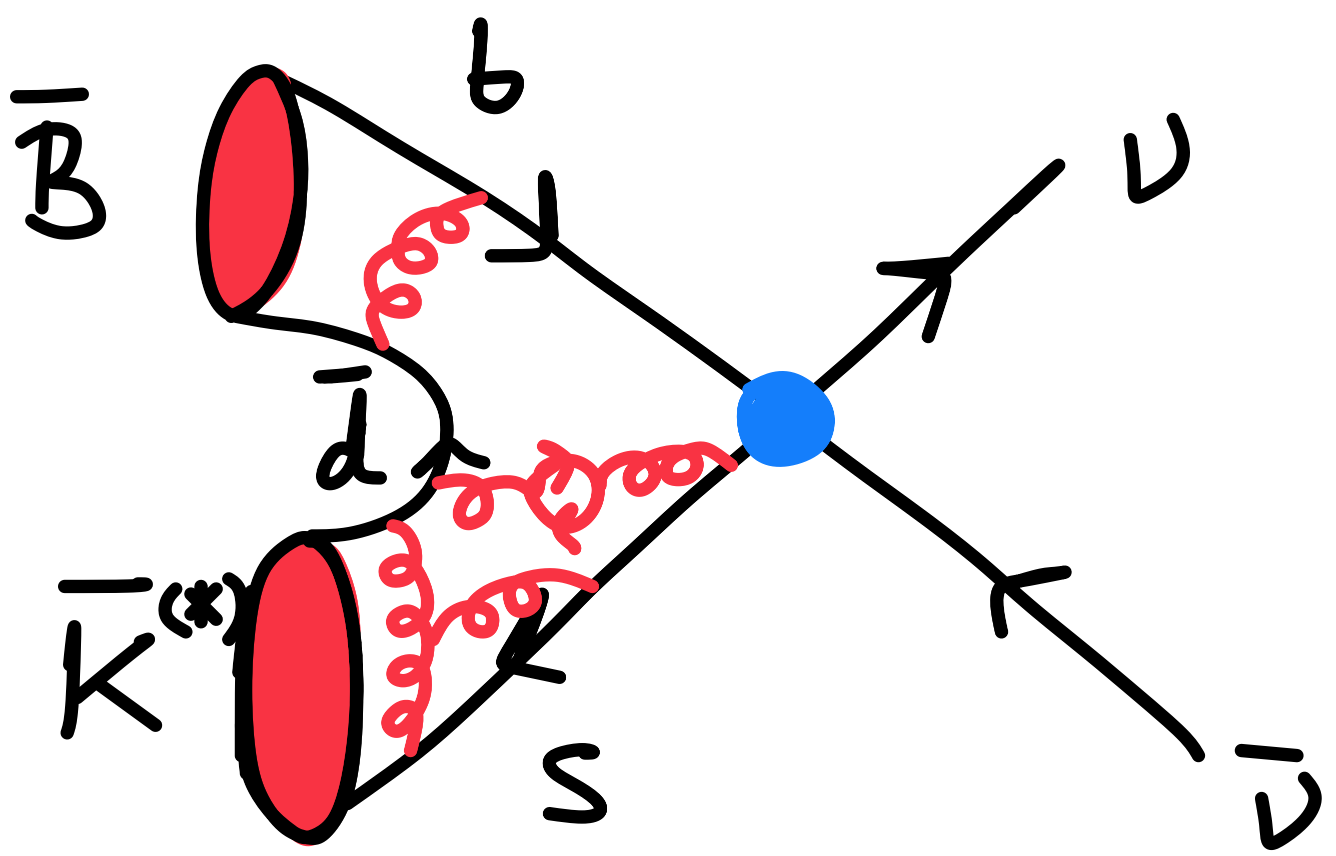

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Form factors

$B \to K\nu\bar{\nu}$

HPQCD, arXiv:2207.12468
FNAL/MILC, arXiv:1509.06235

Lattice determinations of the form factors (FF)

Only FF entering $\mathscr{B}\left(B \to K\nu\bar{\nu}\right)$

$$\langle \bar{K}(k) \,|\, \bar{s}\gamma^\mu b \,|\, \bar{B}(p) \rangle = \left[(p+k)^\mu - \frac{m_B^2 - m_K^2}{q^2} q^\mu \right] f_+(q^2) + q^\mu \frac{m_B^2 - m_K^2}{q^2} f_0(q^2)$$

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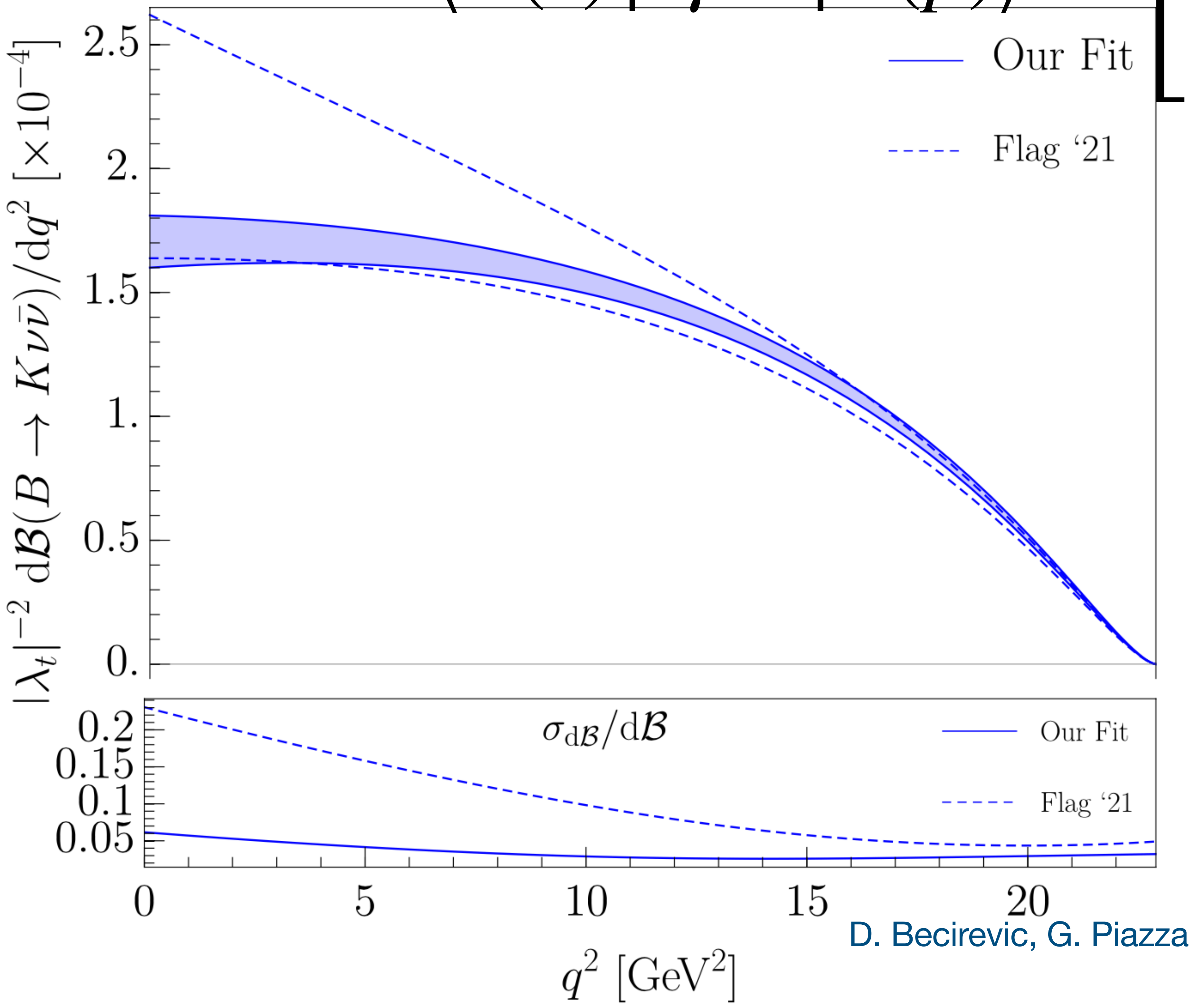

D. Becirevic, G. Piazza & O. Sumensari, arXiv:2301.06990

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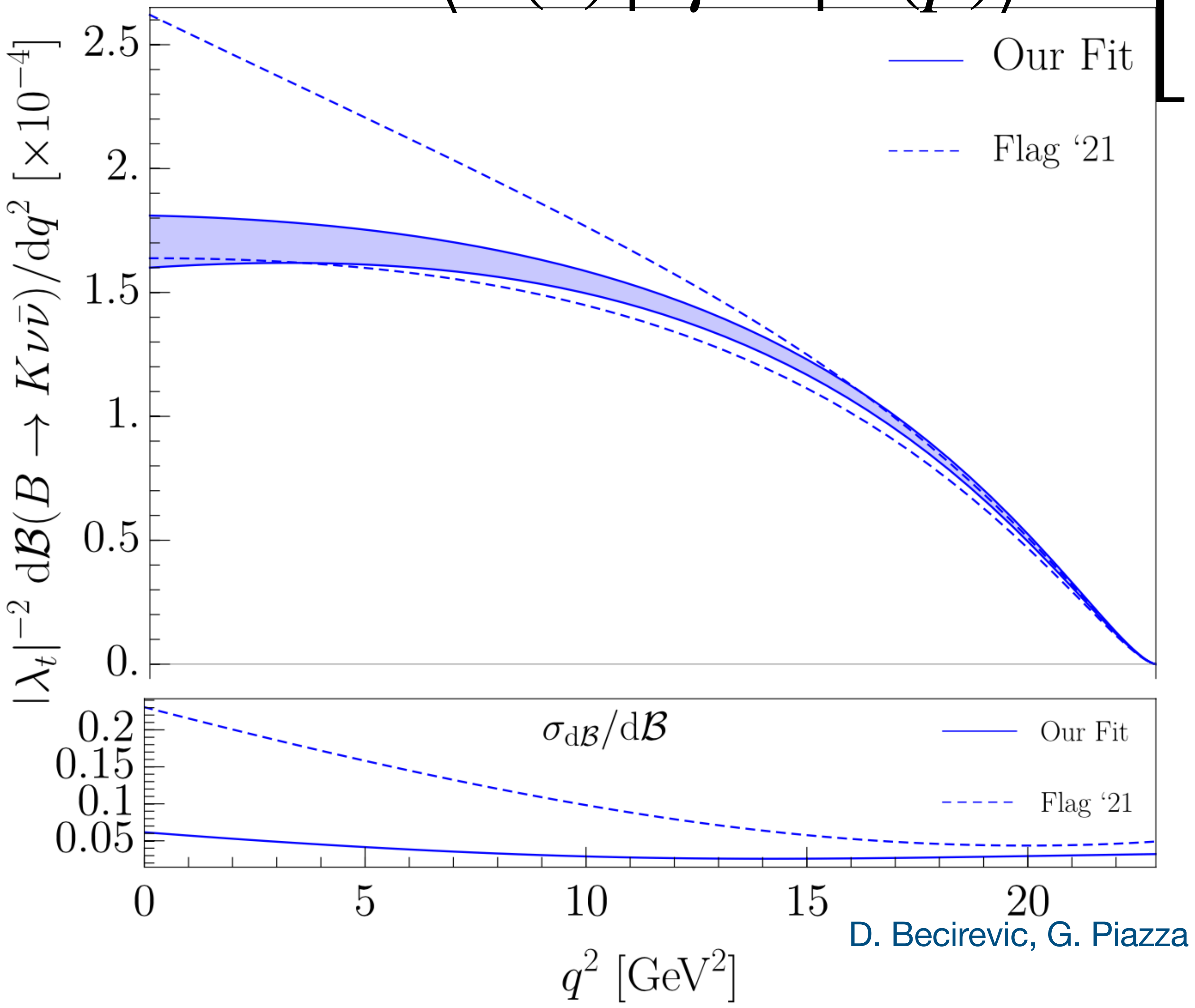

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Relative error related to FF determination $\lesssim \mathcal{O}(5\%)$

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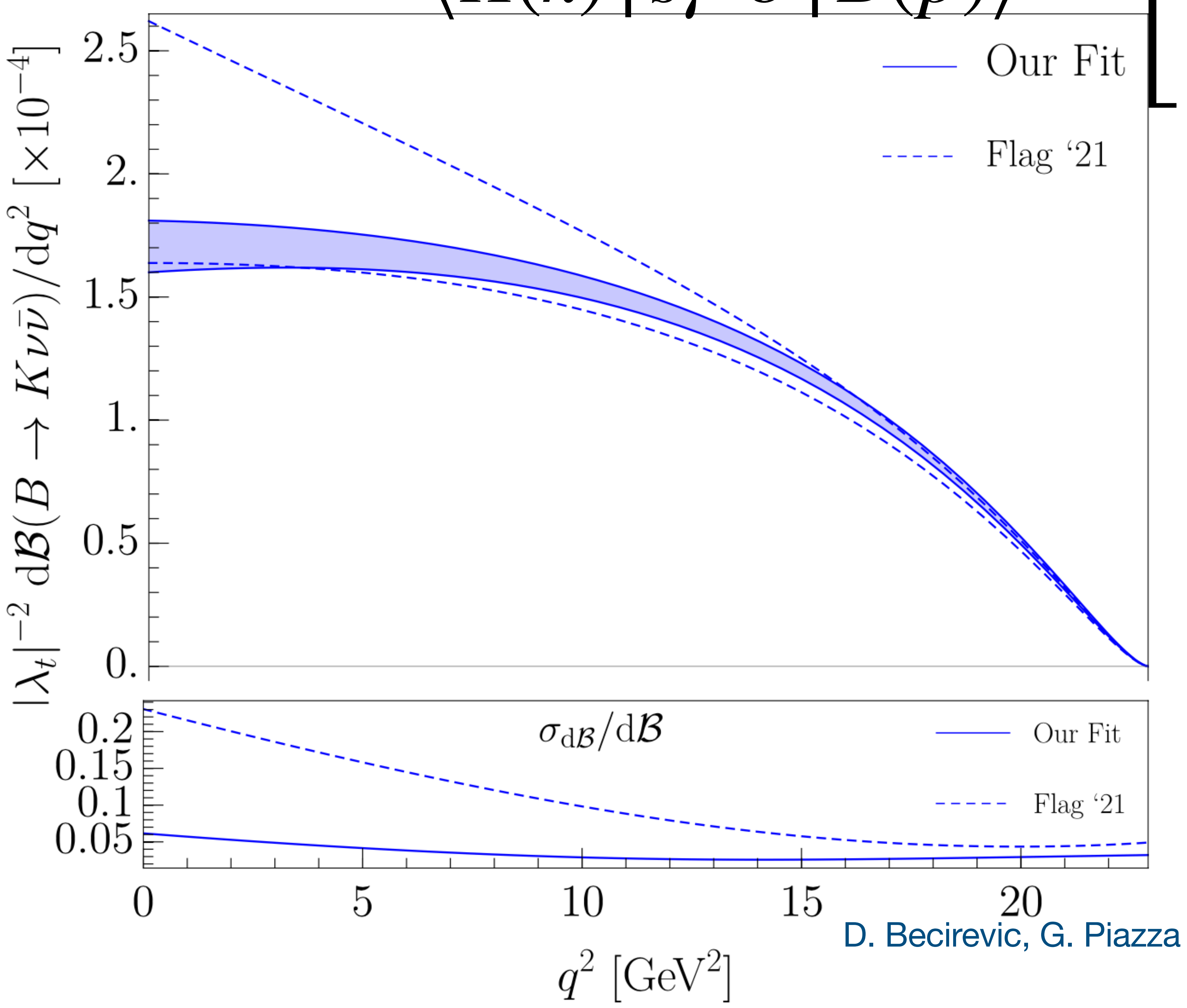

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Relative error related to FF determination $\lesssim \mathcal{O}(5\%)$

Final prediction

$$\mathcal{B}\left(B^\pm \to K^\pm \nu\bar{\nu}\right) = (4.44 \pm 0.30) \times 10^{-6}$$

$\mathcal{O}(7\%)$ error

*Only loop contribution

D. Becirevic, G. Piazza & O. Sumensari, arXiv:2301.06990

Form factors

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

Several FF enter into the decay rate, determined through the combination of one LQCD result & LCSR

R. R. Horgan *et al.*, arXiv:1310.3722
A. Bharucha, D. M. Straub & R. Zwicky, arXiv:1503.05534

$$\langle \bar{K}^*(k) | \bar{s}_L \gamma^\mu b_L | \bar{B}(p) \rangle = \epsilon_{\mu\nu\rho\sigma} \varepsilon^{*\nu} p^\rho k^\sigma \frac{2V(q^2)}{m_B + m_{K^*}} - i\varepsilon^*_\mu (m_B + m_{K^*}) A_1(q^2)$$

$$+ i(p+k)_\mu (\varepsilon^* \cdot q) \frac{A_2(q^2)}{m_B + m_{K^*}} + iq_\mu (\varepsilon^* \cdot q) \frac{2m_{K^*}}{q^2} \left[A_3(q^2) - A_0(q^2) \right]$$

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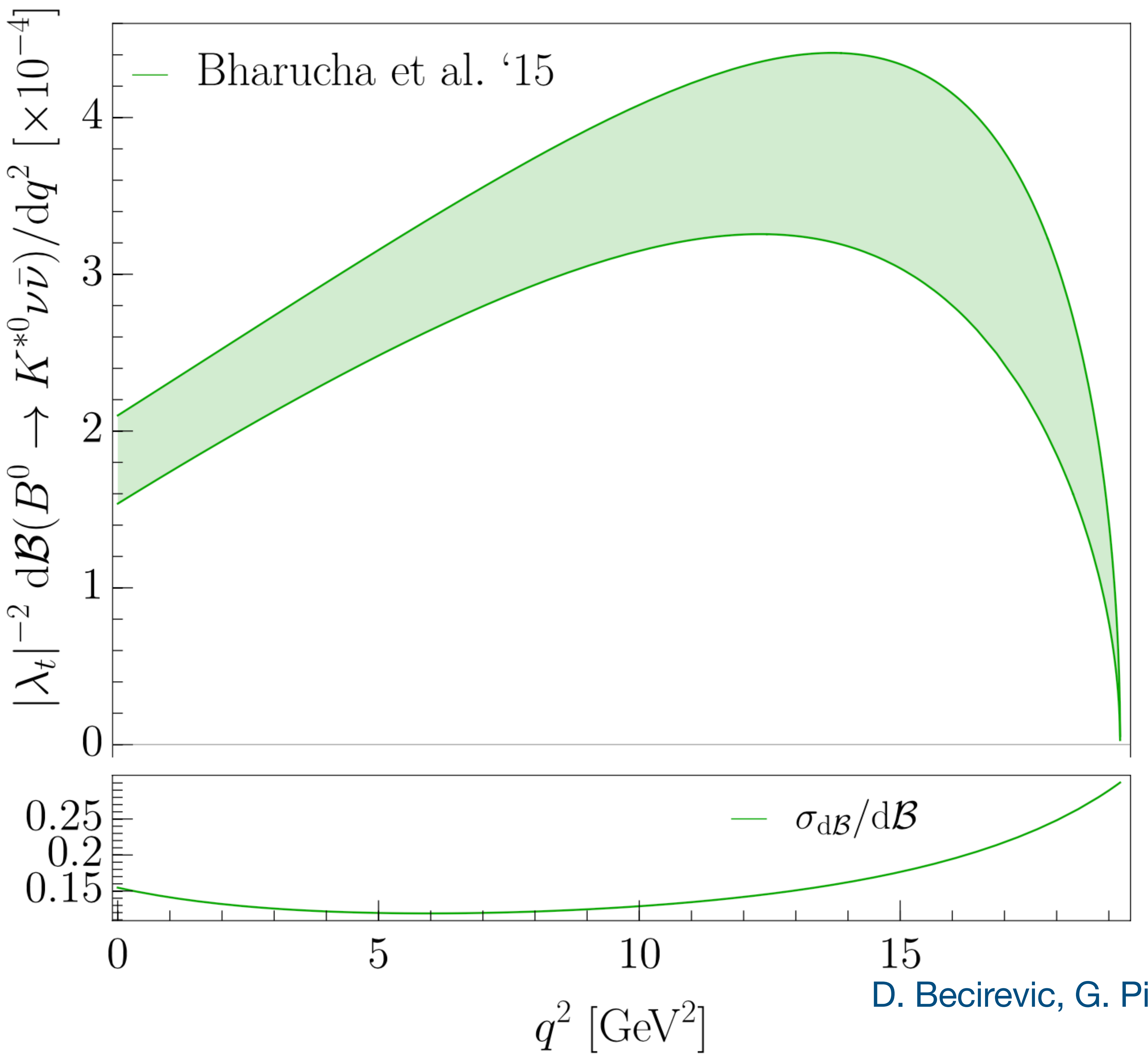

D. Becirevic, G. Piazza & O. Sumensari, arXiv:2301.06990

Relative error related to FF determination $\sim \mathcal{O}(15\%)$

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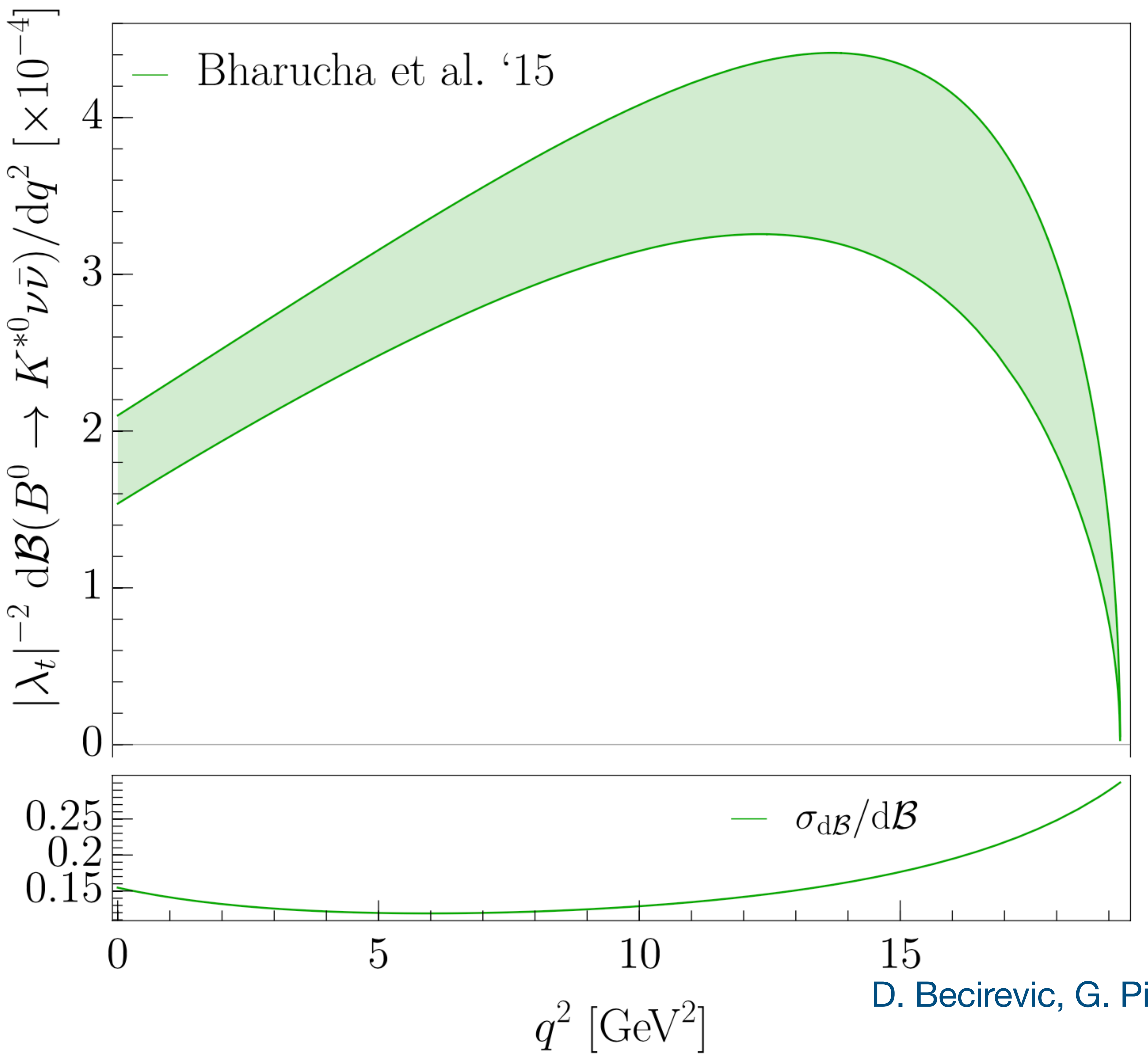

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Relative error related to FF determination $\sim \mathcal{O}(15\%)$

Final prediction

$$\mathcal{B}\left(B^\pm \to K^{\pm *} \nu \bar{\nu}\right) = (9.8 \pm 1.4) \times 10^{-6}$$

$\mathcal{O}(15\%)$ error

*Only loop contribution

Summary

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

Two main sources of uncertainty

Form factor determination

$$\langle K^{(*)} | \bar{s}_L \gamma^\mu b_L | B \rangle = \sum_i K_i^\mu \mathcal{F}_i(q^2)$$

Form factors (Lattice QCD, LCSR…)

CKM determination

CKM unitarity $|\lambda_t| \sim |V_{cb}|(1 + \mathcal{O}(\lambda^2))$

Inclusive vs exclusive?

Expected BR in the SM using exclusive $B \to D\ell\nu$ decays and available FF determinations as inputs

$$\mathcal{B}\left(B^\pm \to K^\pm \nu\bar{\nu}\right)\Big|_{\rm SM} = (4.44 \pm 0.30) \times 10^{-6}$$

$$\mathcal{B}\left(B^\pm \to K^{\pm *} \nu\bar{\nu}\right)\Big|_{\rm SM} = (9.8 \pm 1.4) \times 10^{-6}$$

Belle-II results

$$\mathcal{O}_{\text{exp}} = \mathcal{O}_{\text{SM}}\left(1+\delta_{\text{NP}}\right)$$

Belle-II experiment

Belle-II (SuperKEKB) is an e^+e^- collider operating at $\sqrt{s} \simeq m_{\Upsilon(4S)}$

BELLE-II Collaboration, arXiv:2311.14647

$$e^+e^- \to \Upsilon(4S) \to B^+B^-$$

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Tagged B

Tagging methods	Hadronic	Inclusive
Efficiency	0.5%	8 %
Backgrounds	Small	Large

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$$e^+e^- \to \Upsilon(4S) \to B^+B^-$$

Signal: $B^+ \to K^+\nu\nu$

Tagging methods	Hadronic	Inclusive
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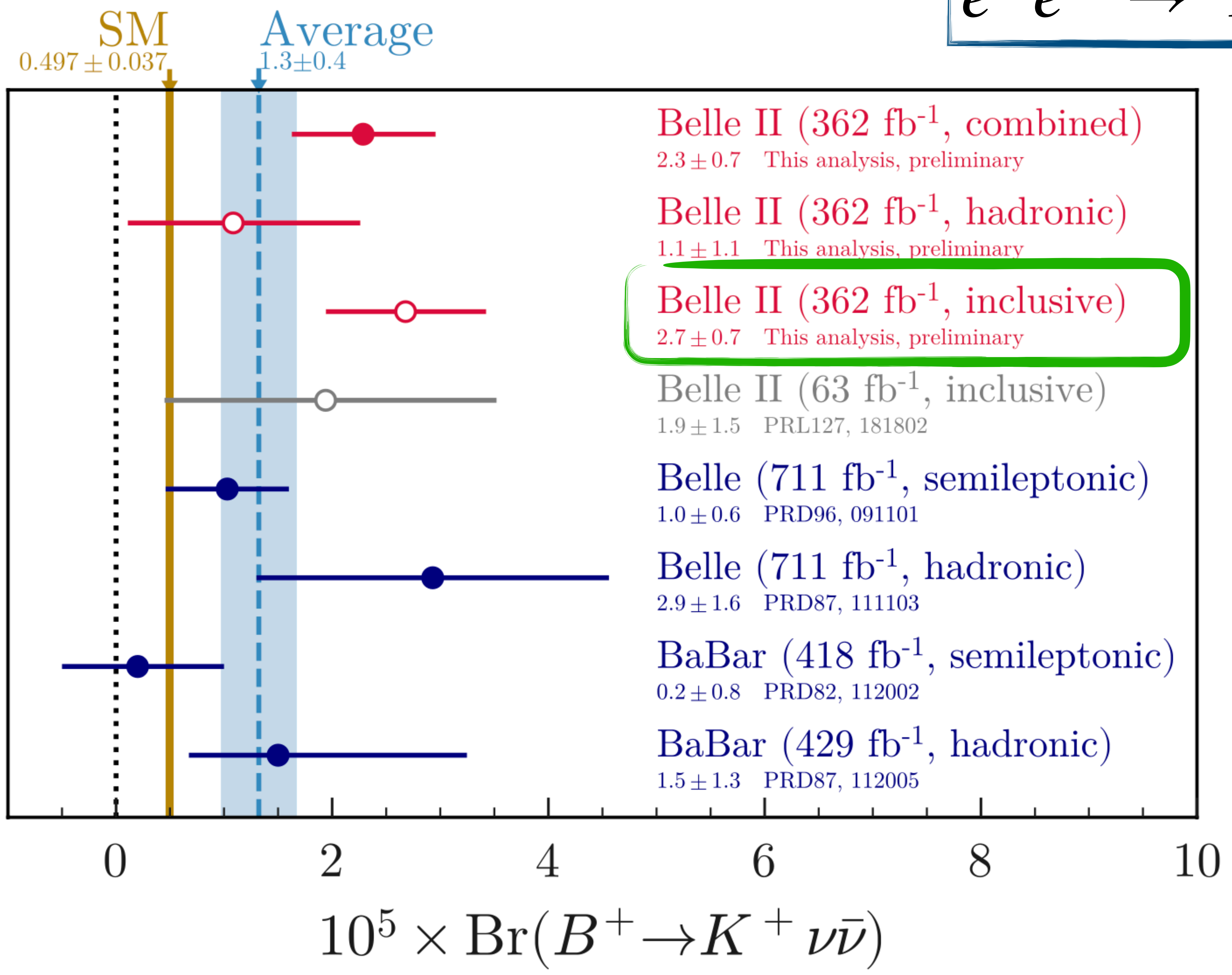

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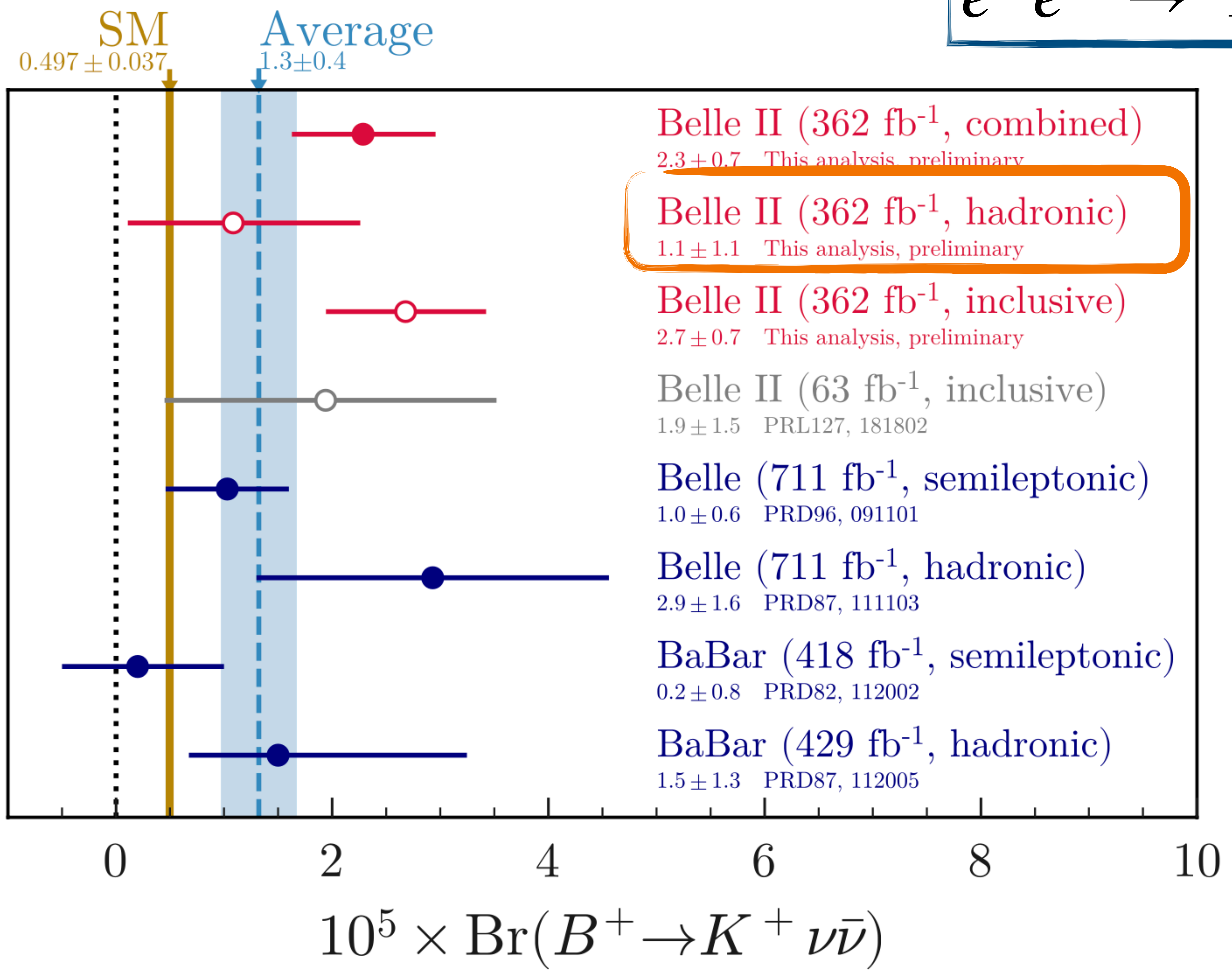

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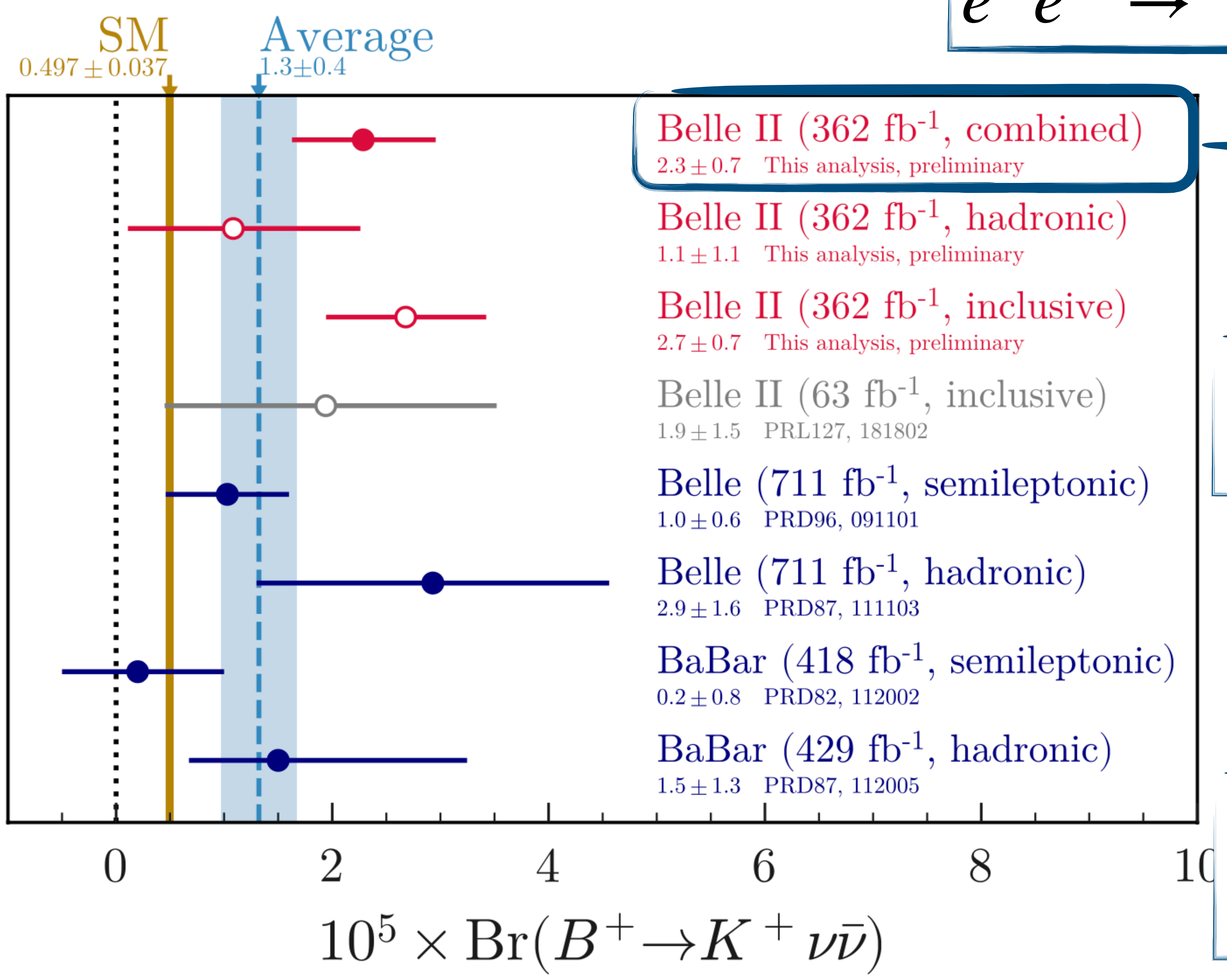

$$\mathcal{B}\left(B^+ \to K^+\nu\nu\right) = (2.3 \pm 0.7) \times 10^{-5}$$

About 3σ above the SM expectation

$$\mathcal{B}\left(B^+ \to K^+\nu\nu\right)\Big|_{\mathrm{SM}} = (4.44 \pm 0.30) \times 10^{-6}$$

Implications of $B \to K\nu\bar{\nu}$ for BSM

- LEFT
- SMEFT
- Light new physics

$$\mathcal{O}_{\text{exp}} = \mathcal{O}_{\text{SM}}\left(1 + \delta_{\text{NP}}\right)$$

BSM contributions

Low-energy EFT with SM neutrinos

Including BSM contributions we can write (w/o N_R)

$$\mathscr{L}^{b\to s\nu\nu} = \frac{4G_F}{\sqrt{2}}\lambda_t \sum_{i,j} \left(C_L^{\nu_i\nu_j}\mathcal{O}_L^{\nu_i\nu_j} + C_R^{\nu_i\nu_j}\mathcal{O}_R^{\nu_i\nu_j}\right) + h.c.$$

R. Bause, G. Hisbert & G. Hiller, arXiv:2309.00075
P. Athron, R. Martinez & C. Sierra, arXiv:2308. 13426
L. Allwicher, D. Becirevic, G. Piazza, **SRA** & O. Sumensari, arXiv:2309.02246

$$C_L^{\nu_i\nu_j} = C_L^{\text{SM}}\delta_{ij} + \delta C_L^{\nu_i\nu_j} \qquad C_R^{\nu_i\nu_j} = \delta C_R^{\nu_i\nu_j}$$

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L. Allwicher, D. Becirevic, G. Piazza, **SRA** & O. Sumensari, arXiv:2309.02246

$$\mathscr{B}\left(B\to K^{(*)}\nu\bar{\nu}\right) = \mathscr{B}\left(B\to K^{(*)}\nu\bar{\nu}\right)\Big|_{\text{SM}}\left(1+\delta\mathscr{B}_{K^{(*)}}\right)$$

All BSM contributions are contained here

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Low-energy EFT with SM neutrinos

Including BSM contributions we can write (w/o N_R)

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All BSM contributions are contained here

$$\delta\mathscr{B}_{K^{(*)}} = \sum_i \frac{2\text{Re}[C_L^{\text{SM}}(\delta C_L^{\nu_i\nu_i} + \delta C_R^{\nu_i\nu_i})]}{3|C_L^{\text{SM}}|^2}$$

$$+\sum_{i,j}\frac{|\delta C_L^{\nu_i\nu_j} + \delta C_R^{\nu_i\nu_j}|^2}{3|C_L^{\text{SM}}|^2} - \eta_V^{K^{(*)}}\sum_{i,j}\frac{\text{Re}[\delta C_R^{\nu_i\nu_j}(C_L^{\text{SM}}\delta_{ij} + \delta C_L^{\nu_i\nu_j})]}{3|C_L^{\text{SM}}|^2}$$

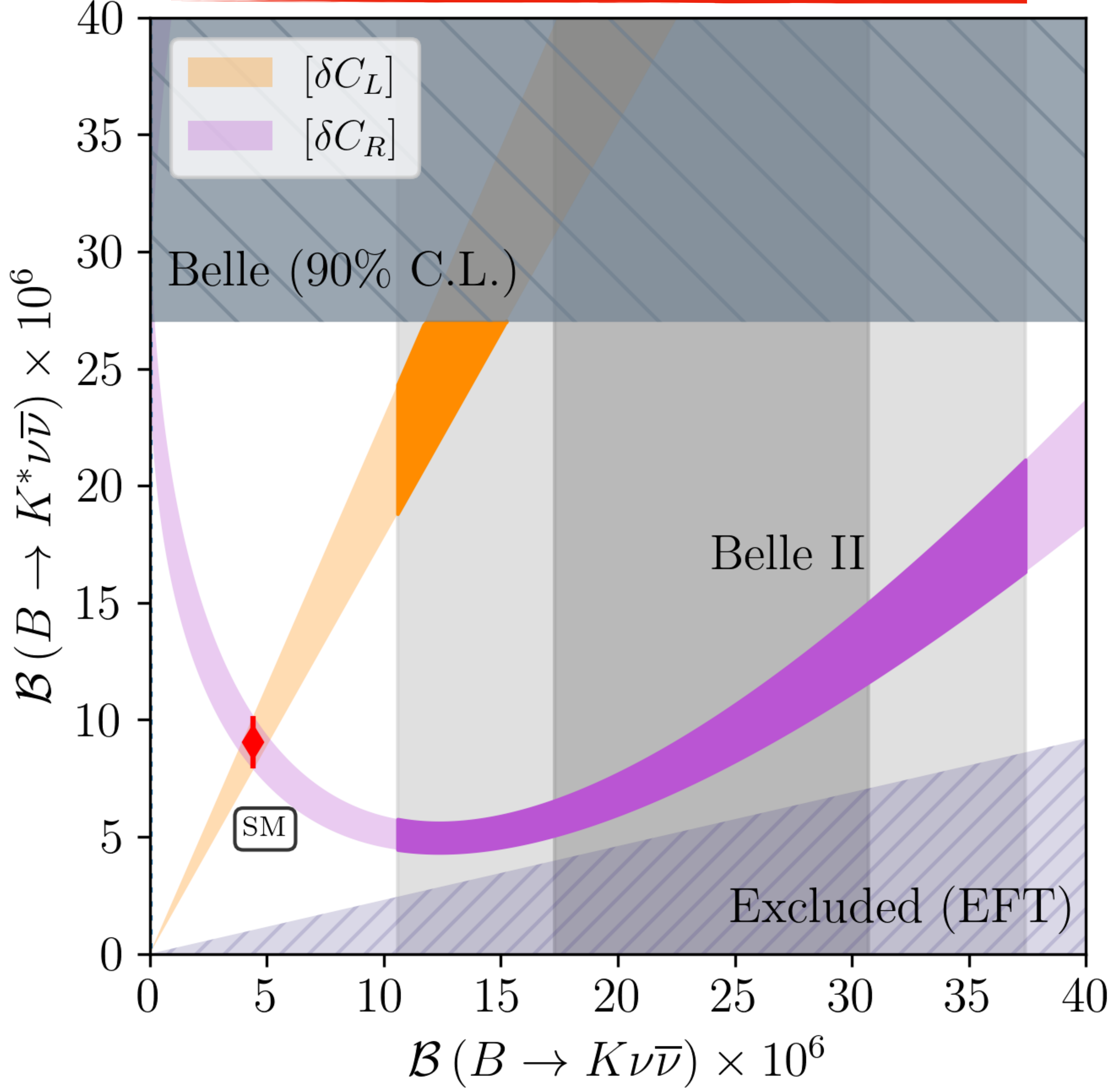
$$\eta_V^K = 0$$
$$\eta_V^{K^*} = 3.33 \pm 0.07$$

D. Becirevic, G. Piazza & O. Sumensari, arXiv:2301.06990
L. Allwicher, D. Becirevic, G. Piazza, **SRA** & O. Sumensari, arXiv:2309.02246

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

Correlations between $B \to K\nu\bar{\nu}$ and $B \to K^*\nu\bar{\nu}$

Assuming $\delta C_{L(R)}^{\nu_i\nu_j} = \delta C_{L(R)}\delta_{ij}$



L. Allwicher, D. Becirevic, G. Piazza, **SRA** & O. Sumensari, arXiv:2309.02246

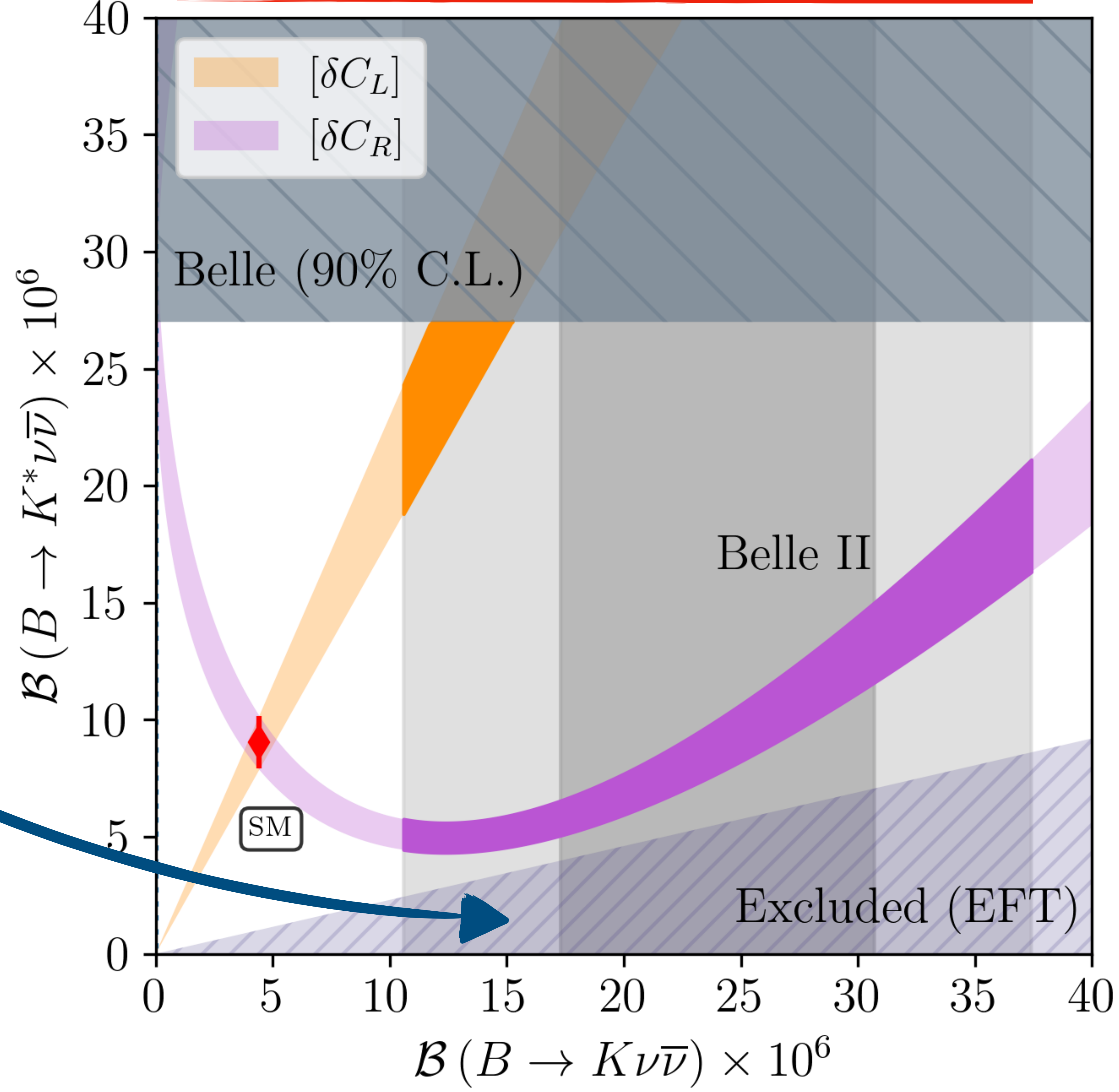
$B \to K^{(*)}\nu\bar{\nu}$ with heavy NP

Correlations between $B \to K\nu\bar{\nu}$ and $B \to K^*\nu\bar{\nu}$

One can find a lower bound for the validity of the EFT

$$\frac{\mathcal{B}(B \to K^*\nu\bar{\nu})}{\mathcal{B}(B \to K^*\nu\bar{\nu})_{\rm SM}} \geq \frac{\mathcal{B}(B \to K\nu\bar{\nu})}{\mathcal{B}(B \to K\nu\bar{\nu})_{\rm SM}} \left(1 - \frac{\eta_V^{K^*}}{4}\right)$$

Assuming $\delta C_{L(R)}^{\nu_i\nu_j} = \delta C_{L(R)}\delta_{ij}$



L. Allwicher, D. Becirevic, G. Piazza,
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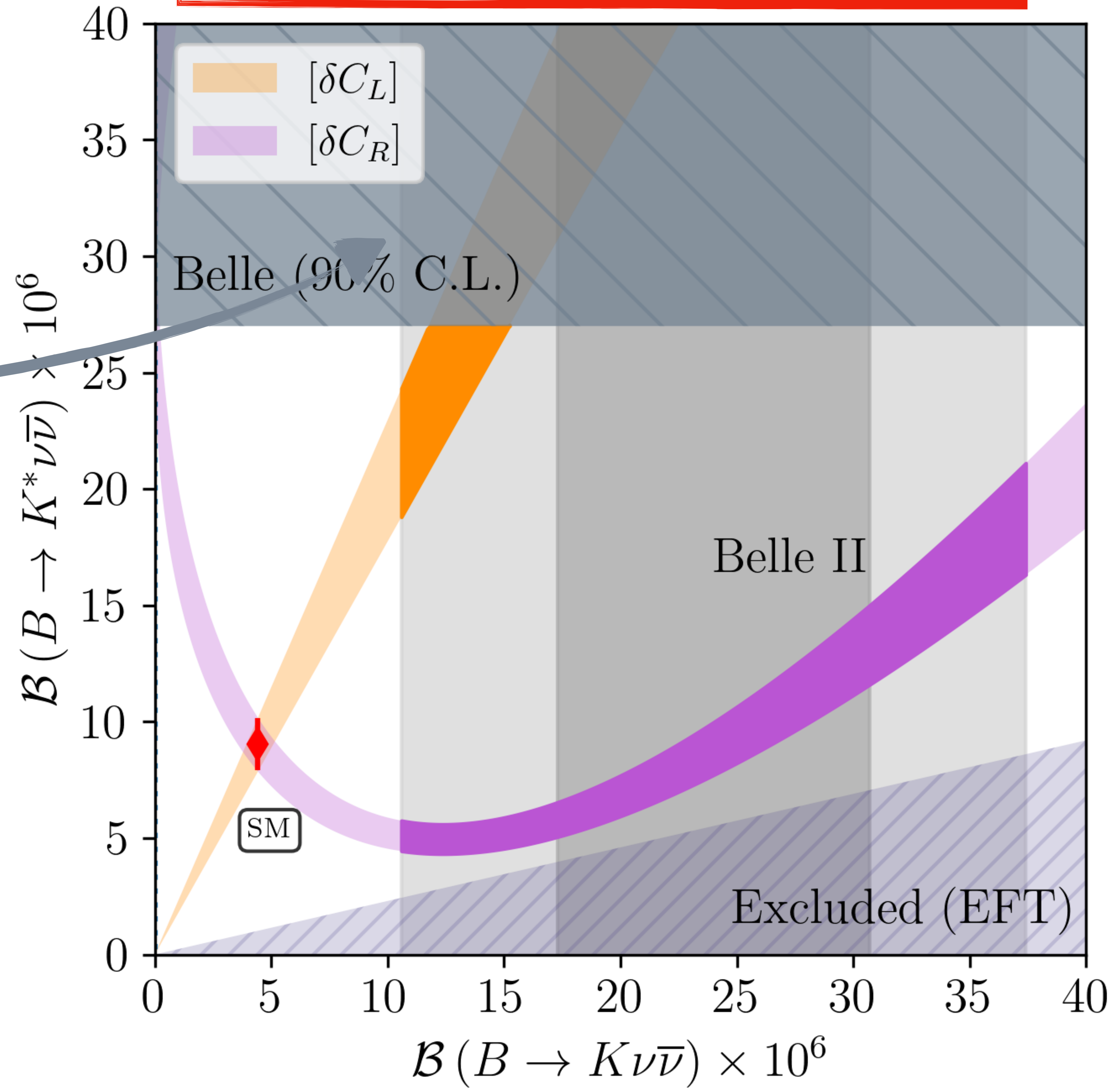
Belle bounds $\mathcal{B}(B \to K^*\nu\bar{\nu}) < 2.7 \times 10^{-5}$, constraining a solution only in terms of δC_L

Assuming $\delta C_{L(R)}^{\nu_i\nu_j} = \delta C_{L(R)}\delta_{ij}$



L. Allwicher, D. Becirevic, G. Piazza, **SRA** & O. Sumensari, arXiv:2309.02246

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

Correlations between $B \to K\nu\bar{\nu}$ and $B \to K^*\nu\bar{\nu}$

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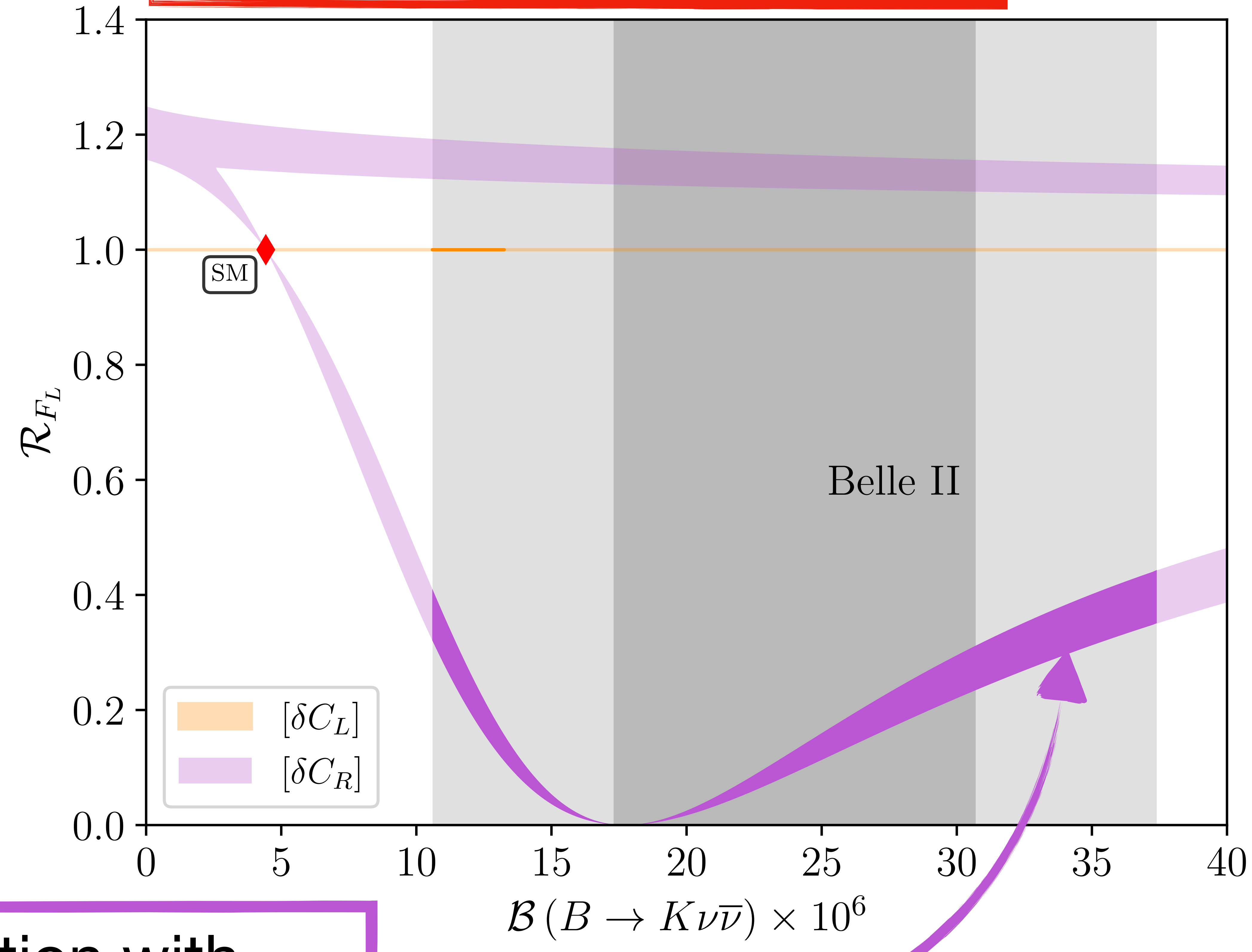
Belle bounds $\mathcal{B}(B \to K^*\nu\bar{\nu}) < 2.7 \times 10^{-5}$, constraining a solution only in terms of δC_L

Look for the fraction of longitudinally polarized K^*, F_L

$$\mathcal{R}_{F_L} = \frac{F_L}{F_L^{\mathrm{SM}}}$$

Assuming $\delta C_{L(R)}^{\nu_i\nu_j} = \delta C_{L(R)}\delta_{ij}$



Depletion with respect to the SM expectation

L. Allwicher, D. Becirevic, G. Piazza, **SRA** & O. Sumensari, arXiv:2309.02246

Implications of $B \to K\nu\bar{\nu}$ for BSM

- LEFT
- SMEFT
- Light new physics

$$\mathcal{O}_{\text{exp}} = \mathcal{O}_{\text{SM}}\left(1+\delta_{\text{NP}}\right)$$

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

Four fermion operators*

If the NP contribution is heavy enough, $\Lambda > v$, we can work in the SMEFT

$$\mathcal{L}^{(6)}_{\mathrm{SMEFT}} \supset \frac{1}{\Lambda^2}\Big\{\left(\mathcal{C}^{(1)}_{lq}+\mathcal{C}^{(3)}_{lq}\right)_{ij}(\bar{s}_L\gamma^\mu b_L)(\bar{e}_{Li}\gamma_\mu e_{Lj})+\left(\mathcal{C}^{(1)}_{lq}-\mathcal{C}^{(3)}_{lq}\right)_{ij}(\bar{s}_L\gamma^\mu b_L)(\bar{\nu}_{Li}\gamma_\mu \nu_{Lj})$$
$$+2V_{cs}\left[\mathcal{C}^{(3)}_{lq}\right]_{ij}(\bar{c}_L\gamma^\mu b_L)(\bar{e}_{Li}\gamma_\mu \nu_{Lj})+[\mathcal{C}_{ld}]_{ij}(\bar{s}_R\gamma^\mu b_R)\left[(\bar{\nu}_{Li}\gamma_\mu \nu_{Lj})+(\bar{e}_{Li}\gamma_\mu e_{Lj})\right]+\mathrm{h.c.}\Big\}$$

$$\left[\mathcal{O}^{(1)}_{LQ}\right]_{ijkl}=\left(\bar{L}_i\gamma^\mu L_j\right)\left(\bar{Q}_k\gamma_\mu Q_l\right) \qquad \left[\mathcal{O}^{(3)}_{LQ}\right]_{ijkl}=\left(\bar{L}_i\gamma^\mu\tau^I L_j\right)\left(\bar{Q}_k\gamma_\mu\tau^I Q_l\right) \qquad \left[\mathcal{O}_{Ld}\right]_{ijkl}=\left(\bar{L}_i\gamma^\mu L_j\right)\left(\bar{d}_k\gamma_\mu d_l\right)$$

L. Allwicher, D. Becirevic, G. Piazza, **SRA** & O. Sumensari, arXiv:2309.02246

* Operators with Higgs severely constrained!

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

Four fermion operators

If the NP contribution is heavy enough, $\Lambda > v$, we can work in the SMEFT

$$\mathcal{L}_{\text{SMEFT}}^{(6)} \supset \frac{1}{\Lambda^2}\Big\{ \Big(\mathcal{C}_{lq}^{(1)} + \mathcal{C}_{lq}^{(3)}\Big)_{ij} (\bar{s}_L\gamma^\mu b_L)(\bar{e}_{Li}\gamma_\mu e_{Lj}) + \Big(\mathcal{C}_{lq}^{(1)} - \mathcal{C}_{lq}^{(3)}\Big)_{ij} (\bar{s}_L\gamma^\mu b_L)(\bar{\nu}_{Li}\gamma_\mu \nu_{Lj})$$

$$+ 2\,V_{cs}\,\Big[\mathcal{C}_{lq}^{(3)}\Big]_{ij} (\bar{c}_L\gamma^\mu b_L)(\bar{e}_{Li}\gamma_\mu \nu_{Lj}) + [\mathcal{C}_{ld}]_{ij}\,(\bar{s}_R\gamma^\mu b_R)\,[(\bar{\nu}_{Li}\gamma_\mu \nu_{Lj}) + (\bar{e}_{Li}\gamma_\mu e_{Lj})] + \text{h.c.}\Big\}$$

Correlations between $b \to s\nu\nu$, $b \to s\ell_\alpha^-\ell_\beta^+$ and $b \to c\ell_\alpha\nu$

L. Allwicher, D. Becirevic, G. Piazza, **SRA** & O. Sumensari, arXiv:2309.02246

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

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$$+\, 2\,V_{cs}\left[\mathcal{C}^{(3)}_{lq}\right]_{ij} (\bar{c}_L\gamma^\mu b_L)(\bar{e}_{Li}\gamma_\mu \nu_{Lj}) + [\mathcal{C}_{ld}]_{ij}\, (\bar{s}_R\gamma^\mu b_R)\left[(\bar{\nu}_{Li}\gamma_\mu \nu_{Lj}) + (\bar{e}_{Li}\gamma_\mu e_{Lj})\right] + \mathrm{h.c.}\Big\}$$

Correlations between $b \to s\nu\nu$, $b \to s\ell^-_\alpha\ell^+_\beta$ and $b \to c\ell_\alpha\nu$

Matching to the low-energy NP couplings

$$\delta C_L^{\nu_i\nu_j} = \frac{\pi}{\alpha_{\mathrm{em}}\lambda_t}\frac{v^2}{\Lambda^2}\left\{\left[\mathcal{C}^{(1)}_{lq}\right]_{ij} - \left[\mathcal{C}^{(3)}_{lq}\right]_{ij}\right\}$$

$$\delta C_R^{\nu_i\nu_j} = \frac{\pi}{\alpha_{\mathrm{em}}\lambda_t}\frac{v^2}{\Lambda^2}\left[\mathcal{C}_{ld}\right]_{ij}$$

L. Allwicher, D. Becirevic, G. Piazza,
SRA & O. Sumensari, arXiv:2309.02246

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

Correlations between observables

If the NP contribution is heavy enough, $\Lambda > v$, we can work in the SMEFT

$$\mathcal{L}^{(6)}_{\text{SMEFT}} \supset \frac{1}{\Lambda^2}\Big\{\left(\mathcal{C}^{(1)}_{lq}+\mathcal{C}^{(3)}_{lq}\right)_{ij}(\bar{s}_L\gamma^\mu b_L)(\bar{e}_{Li}\gamma_\mu e_{Lj})+\left(\mathcal{C}^{(1)}_{lq}-\mathcal{C}^{(3)}_{lq}\right)_{ij}(\bar{s}_L\gamma^\mu b_L)(\bar{\nu}_{Li}\gamma_\mu \nu_{Lj})$$
$$+\,2\,V_{cs}\left[\mathcal{C}^{(3)}_{lq}\right]_{ij}(\bar{c}_L\gamma^\mu b_L)(\bar{e}_{Li}\gamma_\mu \nu_{Lj})+[\mathcal{C}_{ld}]_{ij}\,(\bar{s}_R\gamma^\mu b_R)\left[(\bar{\nu}_{Li}\gamma_\mu \nu_{Lj})+(\bar{e}_{Li}\gamma_\mu e_{Lj})\right]+\text{h.c.}\Big\}$$

- Coupling to muons are tightly constrained by $\mathscr{B}\left(B_s \to \mu\mu\right)$ and $R_{K^{(*)}}$
- Coupling to taus allowed, predicting

$$\frac{\mathscr{B}\left(B_s \to \tau\tau\right)}{\mathscr{B}\left(B_s \to \tau\tau\right)_{\text{SM}}} \simeq \frac{\mathscr{B}\left(B \to K^{(*)}\tau\tau\right)}{\mathscr{B}\left(B \to K^{(*)}\tau\tau\right)_{\text{SM}}} \simeq 10$$

L. Allwicher, D. Becirevic, G. Piazza,
SRA & O. Sumensari, arXiv:2309.02246

Examples for concrete models

- Z' coupled to RH quarks

$$\mathscr{L}_{Z'} \supset g_{bs}\left(\bar{s}_R\gamma^\mu b_R\right) Z'_\mu + g_{\tau\tau}\left(\bar{L}_3\gamma^\mu L_3\right) Z'_\mu$$

$B^0 - \bar{B}^0$ mixing constrain $|g_{sb}|/m_{Z'} \lesssim 2\times 10^{-3}\,\mathrm{TeV}^{-1}$

Cannot fit data with perturbative $g_{\tau\tau}$

- $\tilde{R}_2$ leptoquark

$$\mathscr{L}_{\tilde{R}_2} \supset y^R_{ij}\left(\bar{d}_{Ri}\tilde{R}_2 i\tau_2 L_j\right) + h.c.$$

Upper bound $m_{LQ} \lesssim 3\,\mathrm{TeV}$

Difficult to accommodate such a large excess, but possible

L. Allwicher, D. Becirevic, G. Piazza, **SRA** & O. Sumensari, arXiv:2309.02246

Implications of $B \to K\nu\bar{\nu}$ for BSM

- **LEFT**
- **SMEFT**
- **Light new physics**

$$\mathcal{O}_{\rm exp} = \mathcal{O}_{\rm SM}\left(1+\delta_{\rm NP}\right)$$

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

Include a light RH neutrino field

Only mass scale not set by the Higgs mechanism

$$\mathscr{L}_{\text{Yukawa}} = -\bar{Q}Y_d H d_R - \bar{Q}Y_u \tilde{H} u_R - \bar{L}Y_\ell H e_R + \bar{L}Y_\nu \tilde{H} N_R + \frac{1}{2}\bar{N}_R^c M N_R + h.c.$$

Relation between flavor and mass eigenstates

$$\nu_{L\alpha} = \sum_{i=1}^{4} U_{\alpha i} P_L n_i$$

$$N_R = \sum_{i=1}^{4} U_{si}^* P_R n_i$$

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

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E. Fernández-Martínez *et al.*, arXiv:2304.06772

Relation between flavor and mass eigenstates

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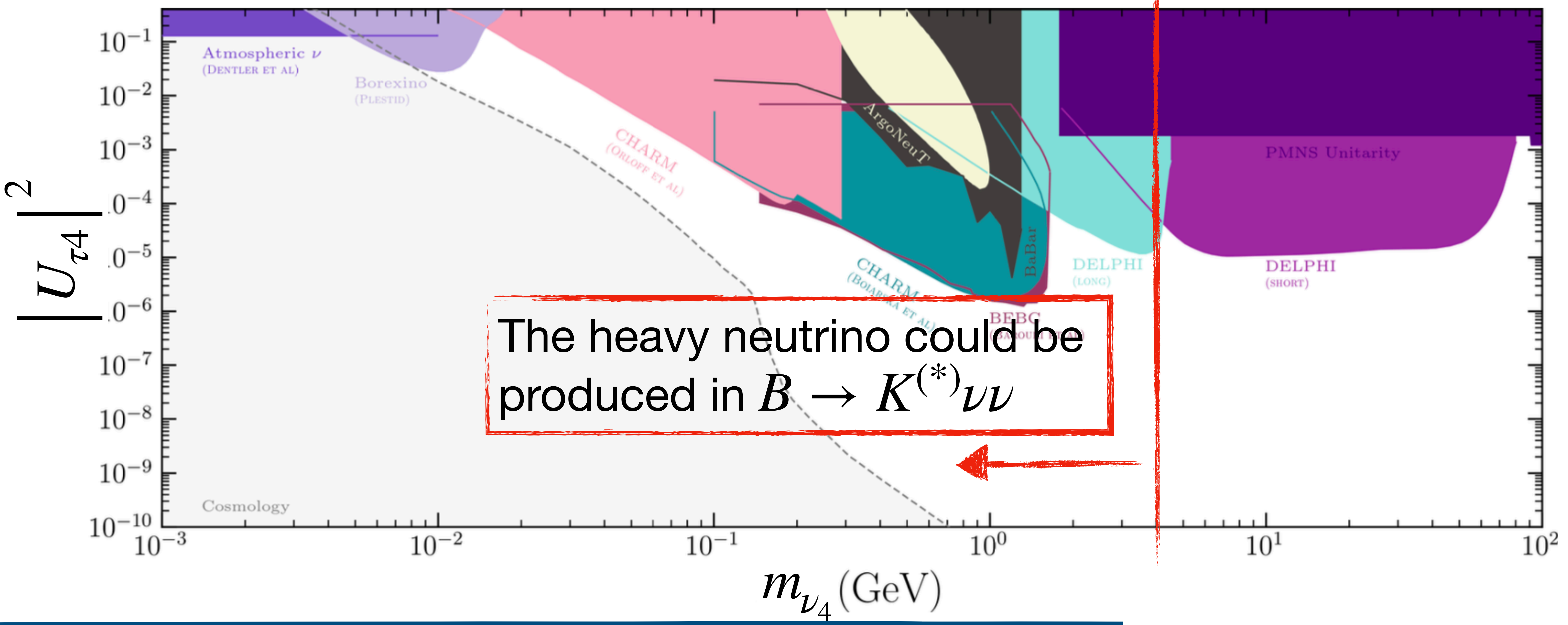
$$N_R = \sum_{i=1}^{4} U_{si}^* P_R n_i$$



The heavy neutrino could be produced in $B \to K^{(*)}\nu\nu$

Need to include N_R in the EFT description!

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

Include a light RH neutrino field

Many more contributions when having a light RH neutrino

See T. Felkl *et al.*, arXiv:2111.04327
& arXiv:2309.02940
L. Leal & **SRA**, work in progress

$$\mathcal{L}^{(6)}_{\nu SMEFT} \supset \frac{1}{\Lambda^2}\Big\{\mathcal{C}_{Nd}\left(\bar{s}_R\gamma_\mu b_R\right)\left(\bar{N}_R\gamma^\mu N_R\right) + \mathcal{C}_{NQ}\left(\bar{s}_L\gamma_\mu b_L\right)\left(\bar{N}_R\gamma^\mu N_R\right)$$
$$+ \left[\mathcal{C}_{LNQd}\right]_i\left(\bar{s}_L b_R\right)\left(\bar{\nu}_{Li}N_R\right) - V_{cs}\left[\mathcal{C}_{LNQd}\right]_i\left(\bar{c}_L b_R\right)\left(\bar{\ell}_{Li}N_R\right)$$
$$+ \left[\mathcal{C}_{LNQdT}\right]_i\left(\bar{s}_L\sigma^{\mu\nu}b_R\right)\left(\bar{\nu}_{Li}\sigma_{\mu\nu}N_R\right) - V_{cs}\left[\mathcal{C}_{LNQdT}\right]_i\left(\bar{c}_L\sigma^{\mu\nu}b_R\right)\left(\bar{\ell}_{Li}\sigma_{\mu\nu}N_R\right) + h.c\Big\}$$

Correlation between $b \to s\nu\nu$ and $b \to c\tau\nu$

In the LEFT we find additional operators

$$\mathcal{L}^{b\to s\nu\nu} = \frac{4G_F}{\sqrt{2}}\lambda_t\sum_a C_a\mathcal{O}_a + h.c.$$

$$\mathcal{O}_{V_{R(L)}} = \left(\bar{s}_L\gamma_\mu b_L\right)\left(n_i\gamma^\mu(1\pm\gamma_5)n_j\right)$$
$$\mathcal{O}_{S_{R(L)}} = \left(\bar{s}_L b_R\right)\left(n_i(1\pm\gamma_5)n_j\right)$$
$$\mathcal{O}_T = \left(\bar{s}_L\sigma_{\mu\nu}b_R\right)\left(n_i\sigma^{\mu\nu}n_j\right)$$

Also different kinematics when final state neutrino is massive $\to m_{\nu_4} \neq 0$

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

Include a light RH neutrino field

Many more contributions when having a light RH neutrino

See T. Felkl *et al.*, arXiv:2111.04327 & arXiv:2309.02940

L. Leal & **SRA**, work in progress

$$\mathcal{L}^{(6)}_{\nu SMEFT} \supset \frac{1}{\Lambda^2}\Big\{\mathcal{C}_{Nd}\,(\bar{s}_R\gamma_\mu b_R)\,(\bar{N}_R\gamma^\mu N_R) + \mathcal{C}_{NQ}\,(\bar{s}_L\gamma_\mu b_L)\,(\bar{N}_R\gamma^\mu N_R)$$
$$+ [\mathcal{C}_{LNQd}]_i\,(\bar{s}_L b_R)\,(\bar{\nu}_{Li}N_R) - V_{cs}\,[\mathcal{C}_{LNQd}]_i\,(\bar{c}_L b_R)\,(\bar{\ell}_{Li}N_R)$$
$$+ [\mathcal{C}_{LNQdT}]_i\,(\bar{s}_L\sigma^{\mu\nu}b_R)\,(\bar{\nu}_{Li}\sigma_{\mu\nu}N_R) - V_{cs}\,[\mathcal{C}_{LNQdT}]_i\,(\bar{c}_L\sigma^{\mu\nu}b_R)\,(\bar{\ell}_{Li}\sigma_{\mu\nu}N_R) + h.c\Big\}$$

Correlation between $b \to s\nu\nu$ and $b \to c\tau\nu$

Going from the νSMEFT to the LEFT with massive neutrinos

$$\nu_{L\alpha} = \sum_{i=1}^{4} U_{\alpha i}P_L n_i$$

$$N_R = \sum_{i=1}^{4} U^*_{si}P_R n_i$$

$$\mathcal{L}^{(6)}_{\nu\mathrm{SMEFT}} \sim \frac{1}{\Lambda^2}C_{Nd}\big(\bar{s}_L\gamma_\mu b_L\big)\big(\bar{N}_R\gamma^\mu(1+\gamma_5)N_R\big)$$

$$\mathcal{L}^{(6)}_{LEFT} \sim \frac{1}{\Lambda^2}\sum_{i,j} U_{si}C_{Nd}U^*_{sj}\big(\bar{s}_L\gamma_\mu b_L\big)\big(\bar{n}_i\gamma^\mu(1+\gamma_5)n_j\big)$$

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

Include a light RH neutrino field

Many more contributions when having a light RH neutrino

See T. Felkl *et al.*, arXiv:2111.04327 & arXiv:2309.02940

L. Leal & **SRA**, work in progress

$$\mathcal{L}^{(6)}_{\nu SMEFT} \supset \frac{1}{\Lambda^2}\Big\{\mathcal{C}_{Nd}\left(\bar{s}_R\gamma_\mu b_R\right)\left(\bar{N}_R\gamma^\mu N_R\right) + \mathcal{C}_{NQ}\left(\bar{s}_L\gamma_\mu b_L\right)\left(\bar{N}_R\gamma^\mu N_R\right)$$
$$+ \left[\mathcal{C}_{LNQd}\right]_i\left(\bar{s}_L b_R\right)\left(\bar{\nu}_{Li} N_R\right) - V_{cs}\left[\mathcal{C}_{LNQd}\right]_i\left(\bar{c}_L b_R\right)\left(\bar{\ell}_{Li} N_R\right)$$
$$+ \left[\mathcal{C}_{LNQdT}\right]_i\left(\bar{s}_L\sigma^{\mu\nu} b_R\right)\left(\bar{\nu}_{Li}\sigma_{\mu\nu} N_R\right) - V_{cs}\left[\mathcal{C}_{LNQdT}\right]_i\left(\bar{c}_L\sigma^{\mu\nu} b_R\right)\left(\bar{\ell}_{Li}\sigma_{\mu\nu} N_R\right) + h.c\Big\}$$

Correlation between $b \to s\nu\nu$ and $b \to c\tau\nu$

Going from the νSMEFT **Neglect active-heavy mixing!**

$$\nu_{L\alpha} \simeq \sum_{i=1}^{3} U_{\alpha i} P_L n_i$$

$$N_R \simeq P_R n_4$$

$$\mathscr{L}^{(6)}_{\nu\text{SMEFT}} \sim \frac{1}{\Lambda^2} C_{Nd}\left(\bar{s}_L\gamma_\mu b_L\right)\left(\bar{N}_R\gamma^\mu(1+\gamma_5)N_R\right)$$

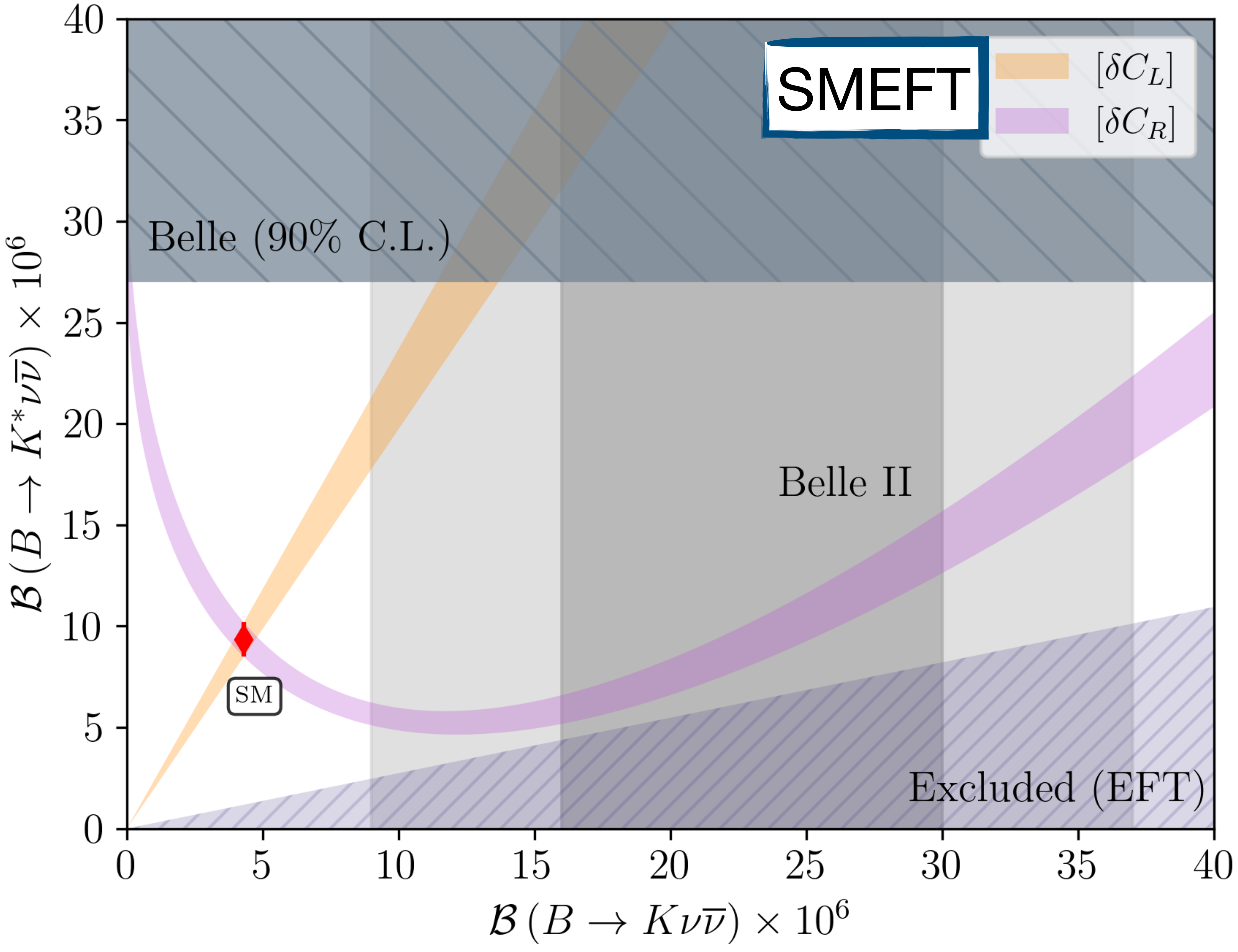
$$\mathscr{L}^{(6)}_{LEFT} \sim \frac{1}{\Lambda^2} C_{Nd}\left(\bar{s}_L\gamma_\mu b_L\right)\left(\bar{n}_4\gamma^\mu(1+\gamma_5)n_4\right)$$

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

Can we tell apart between SMEFT and νSMEFT?

For vector and tensor operators with (massless) RH neutrinos the EFT bound still applies

$$\frac{\mathscr{B}\left(B \to K^{*}\nu\bar{\nu}\right)}{\mathscr{B}\left(B \to K^{*}\nu\bar{\nu}\right)_{\text{SM}}} \geq \frac{\mathscr{B}\left(B \to K\nu\bar{\nu}\right)}{\mathscr{B}\left(B \to K\nu\bar{\nu}\right)_{\text{SM}}}\left(1 - \frac{\eta_V^{K^*}}{4}\right)$$



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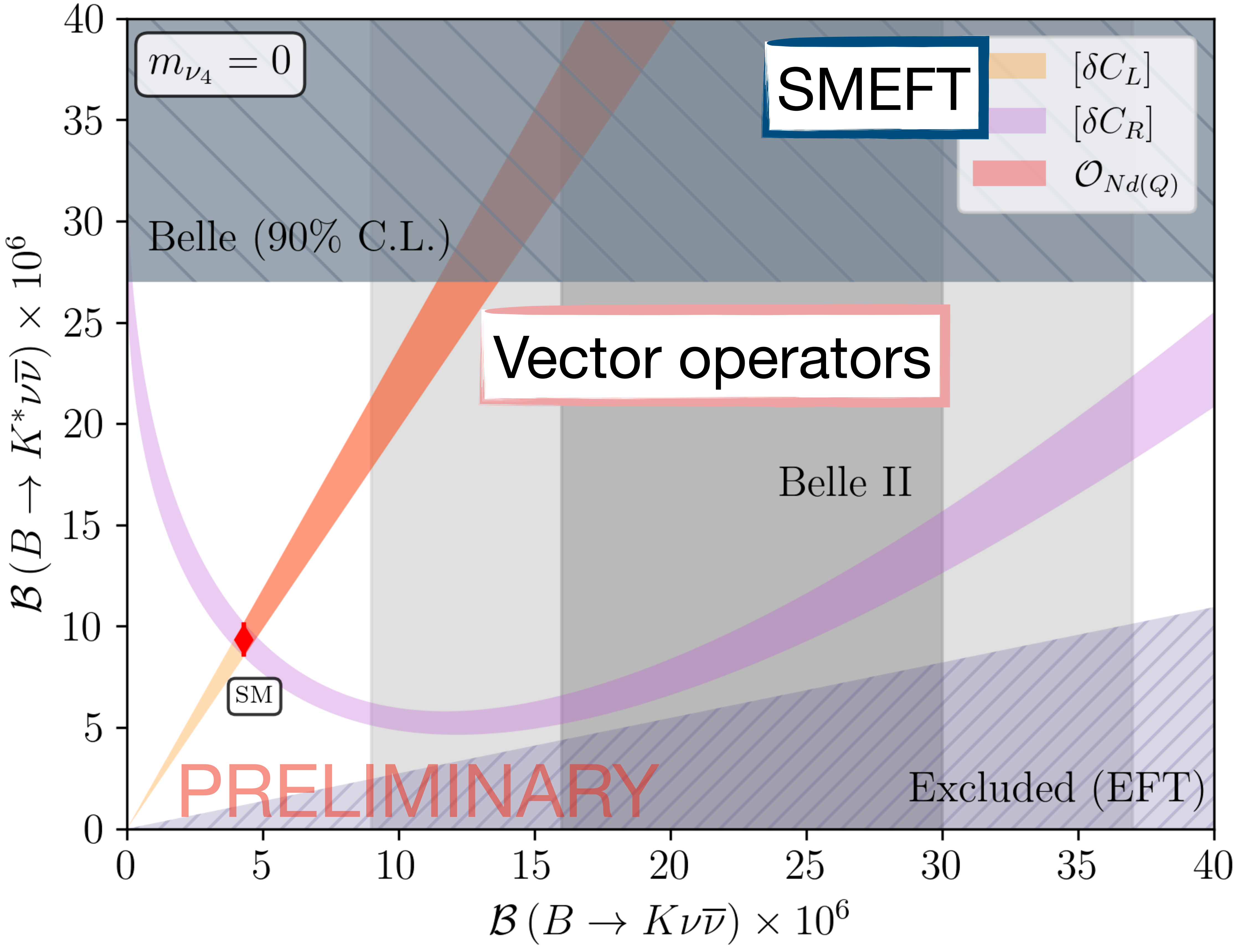

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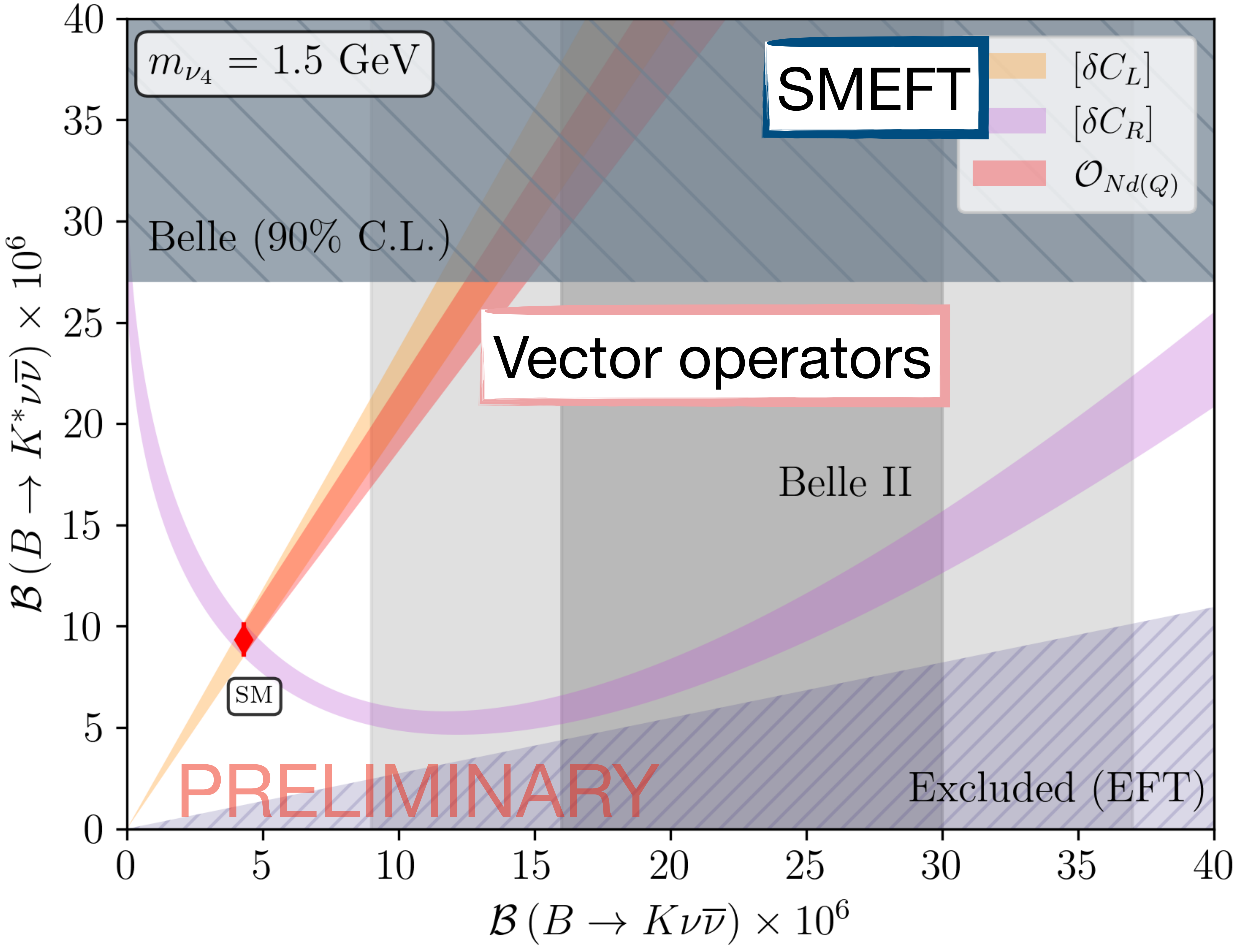
Having $m_{\nu_4} \neq 0$ suppresses $\mathscr{B}(B \to K^*\nu\nu)$

Neglecting active-heavy neutrino mixing



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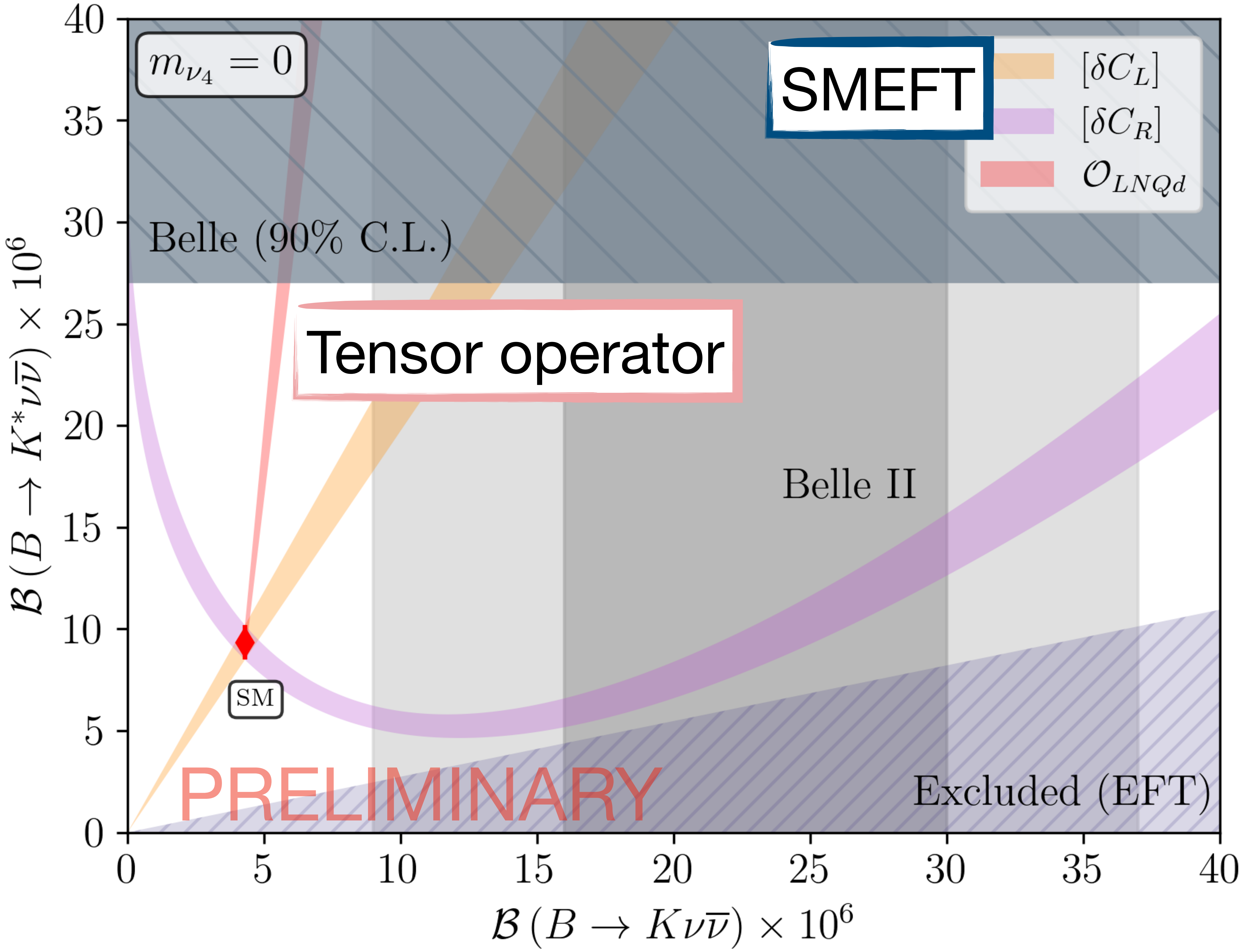
Only for $m_{\nu_4} \simeq (m_B - m_{K^*})$ the tensor operator is not ruled out

Neglecting active-heavy neutrino mixing



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One could however break this relation with scalar operators

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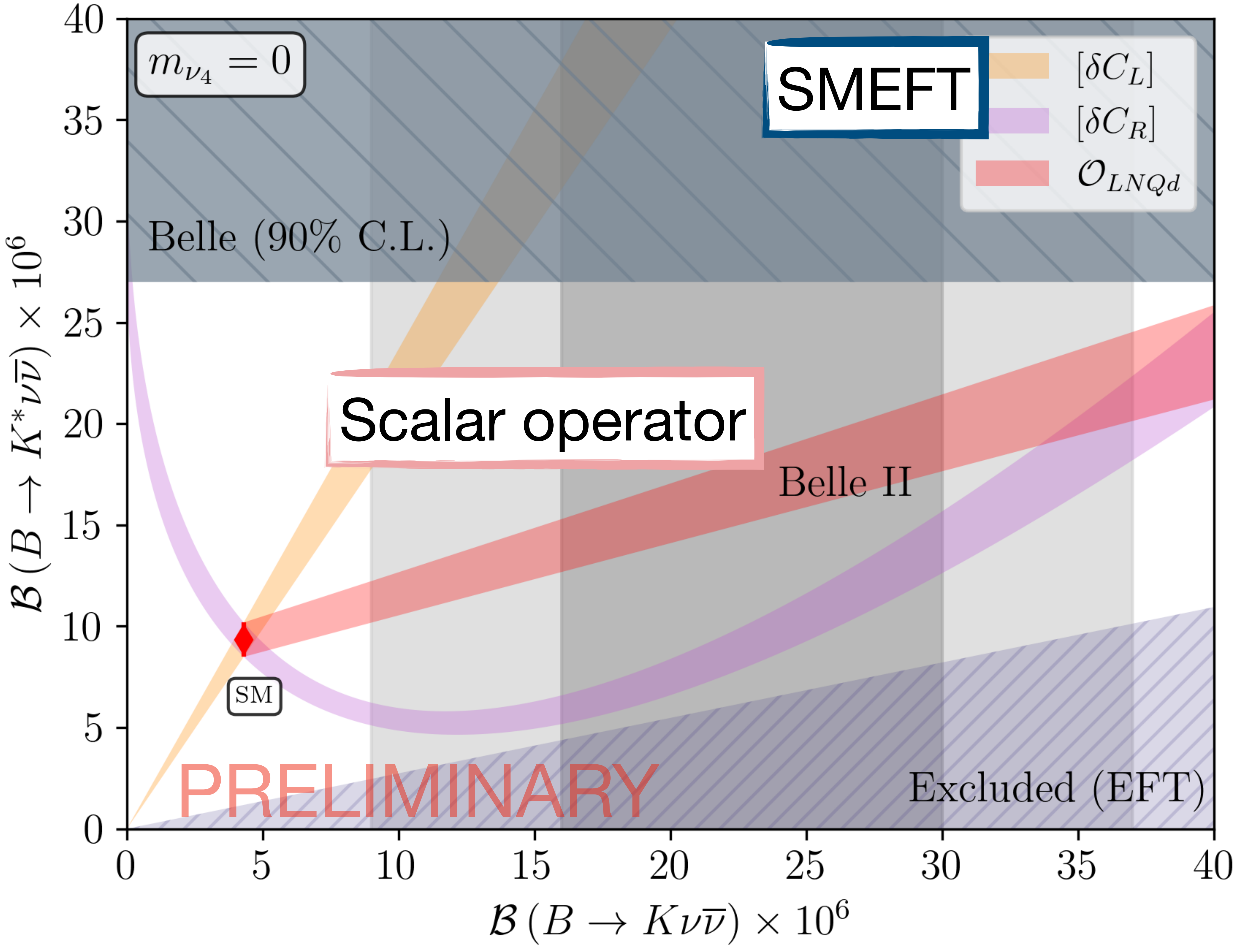

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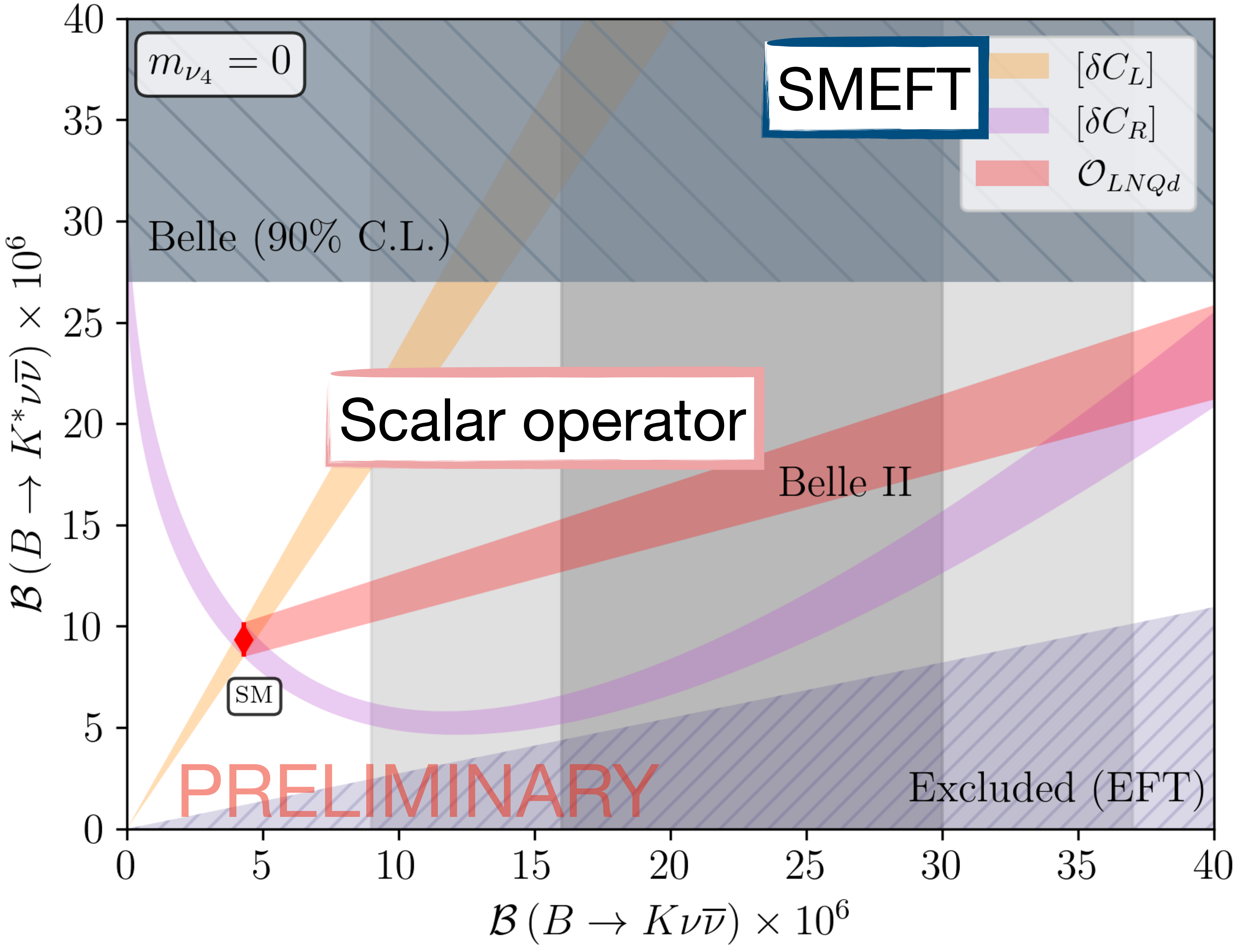
Only realized when

$$\frac{\mathscr{B}\left(B \to K\nu\bar{\nu}\right)}{\mathscr{B}\left(B \to K\nu\bar{\nu}\right)_{\rm SM}} \geq 11.4(5)$$

Experimentally excluded

Neglecting active-heavy neutrino mixing



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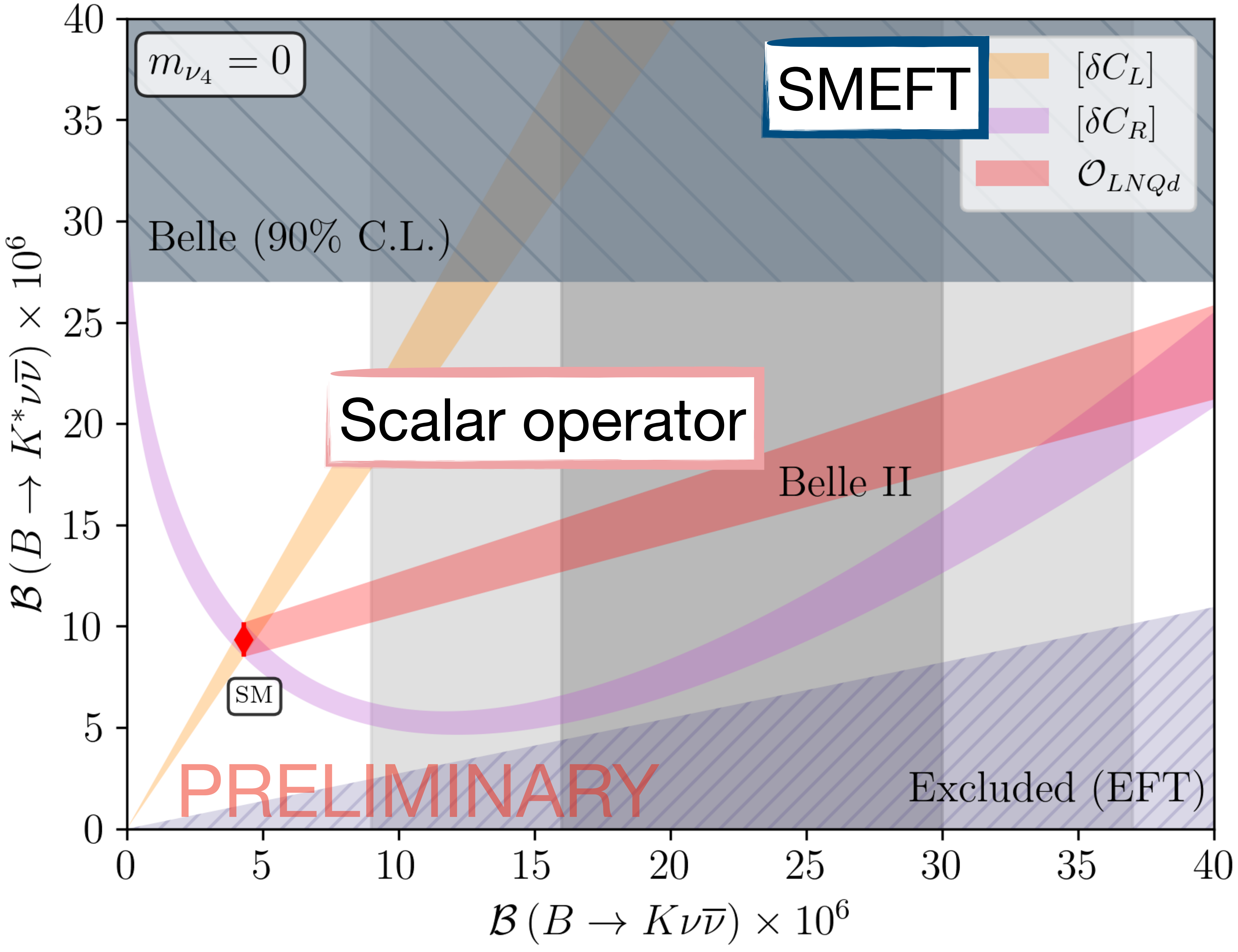
$$[\mathcal{C}_{LNQd}]_i (\bar{s}_L b_R)(\bar{\nu}_{Li} N_R) - V_{cs} [\mathcal{C}_{LNQd}]_i (\bar{c}_L b_R)(\bar{\ell}_{Li} N_R)$$

Effect of non-zero $U_{\alpha 4}$?

Impact on $R_D^{(*)}$

Neglecting active-heavy neutrino mixing



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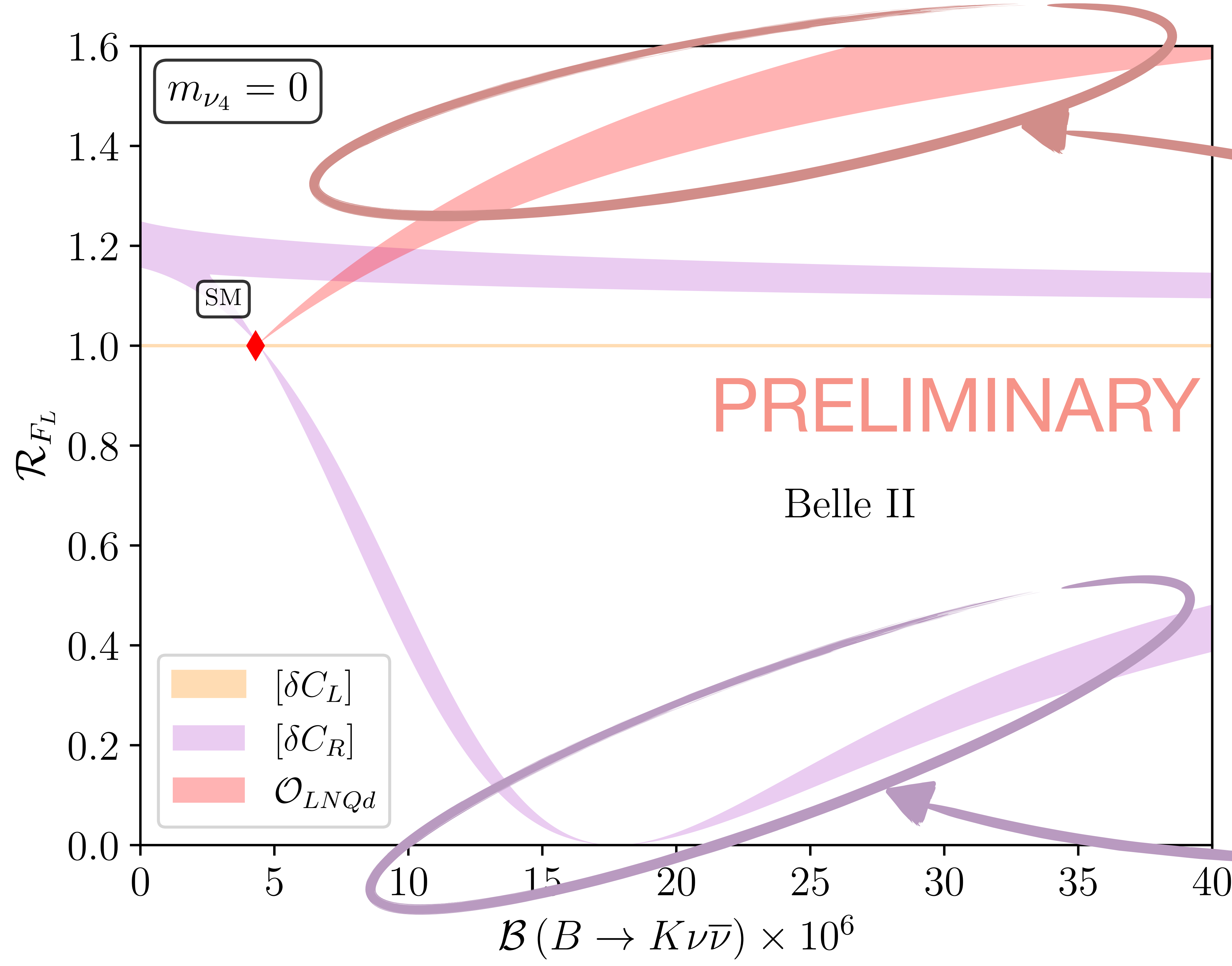
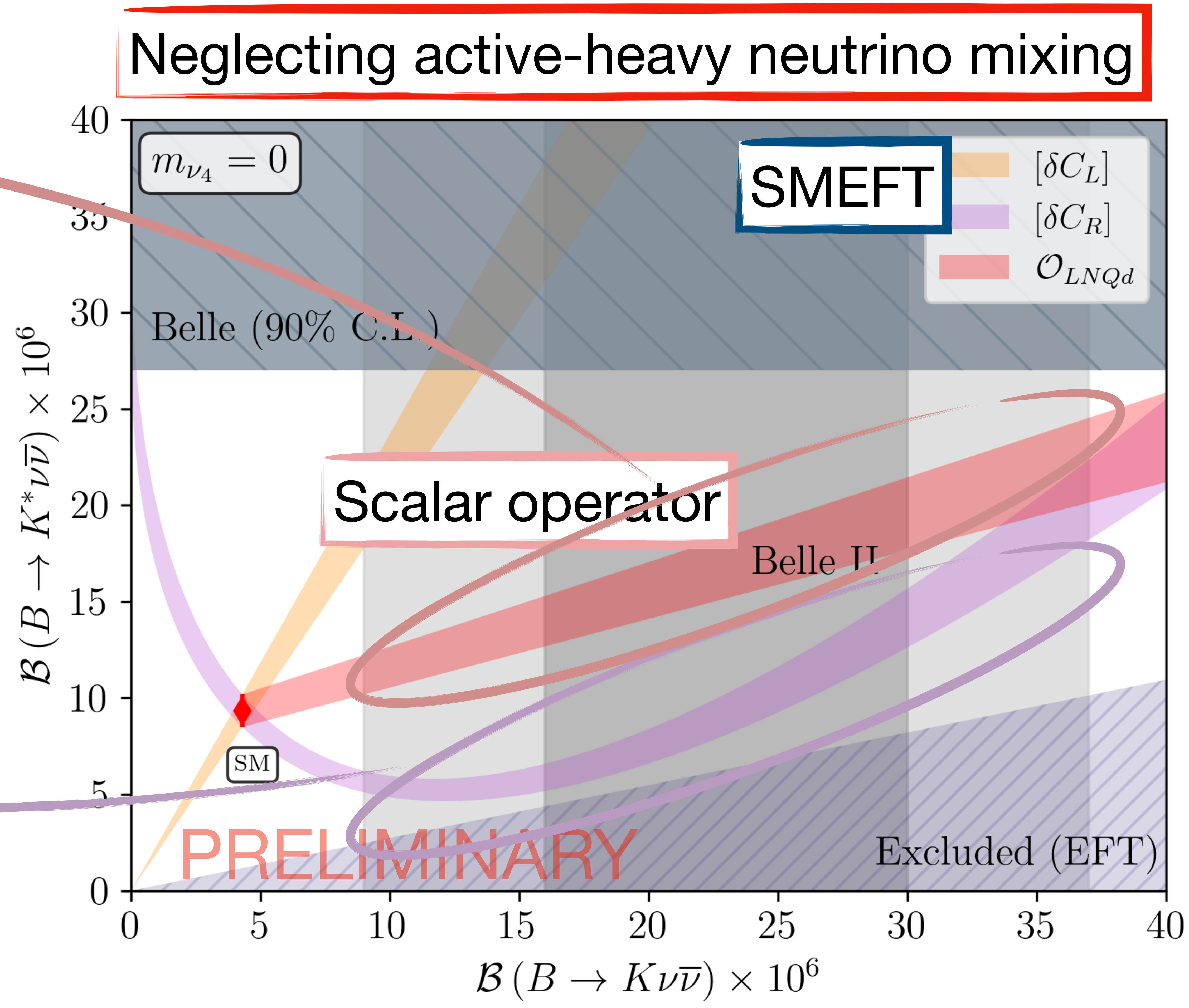




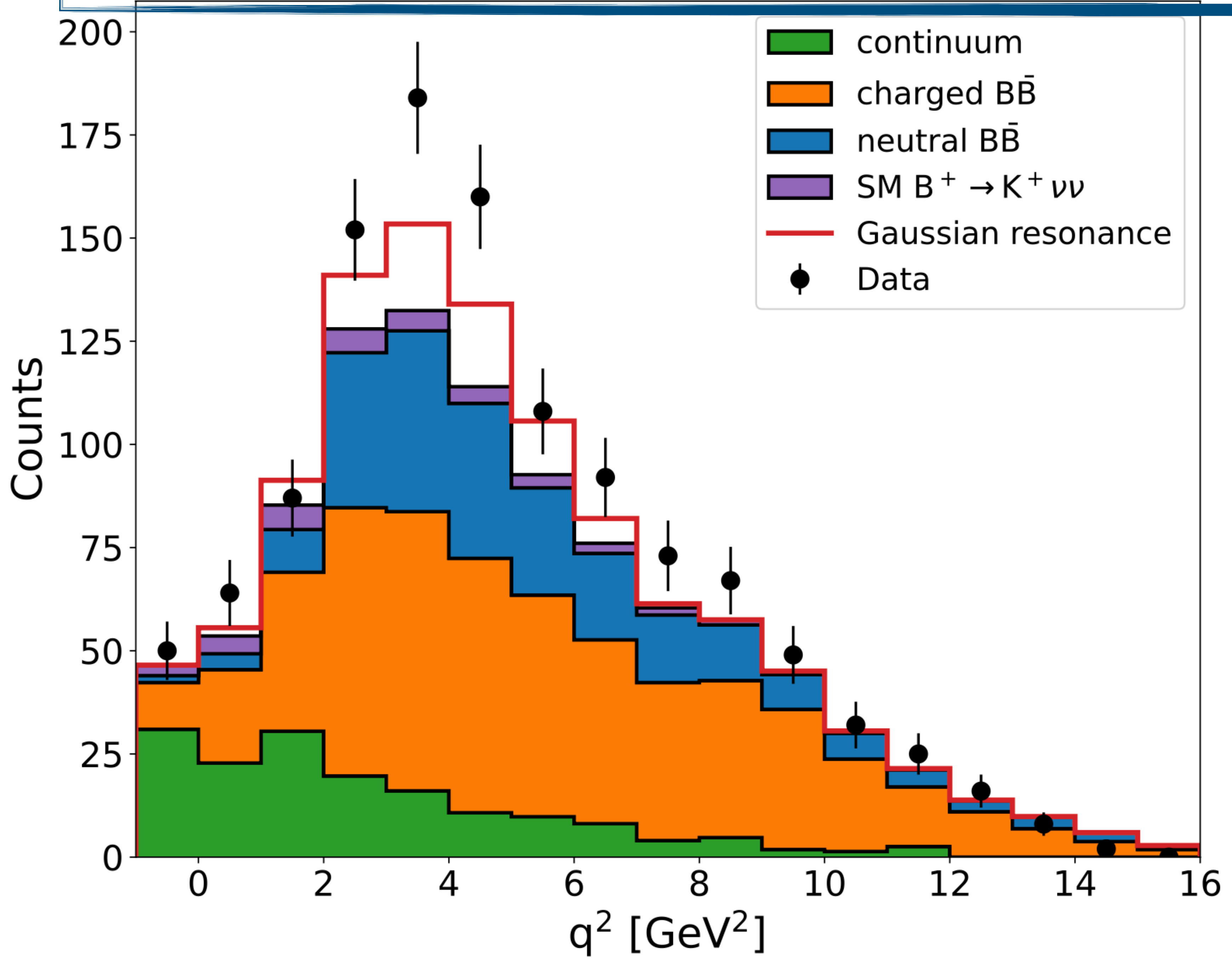
Light mediators?

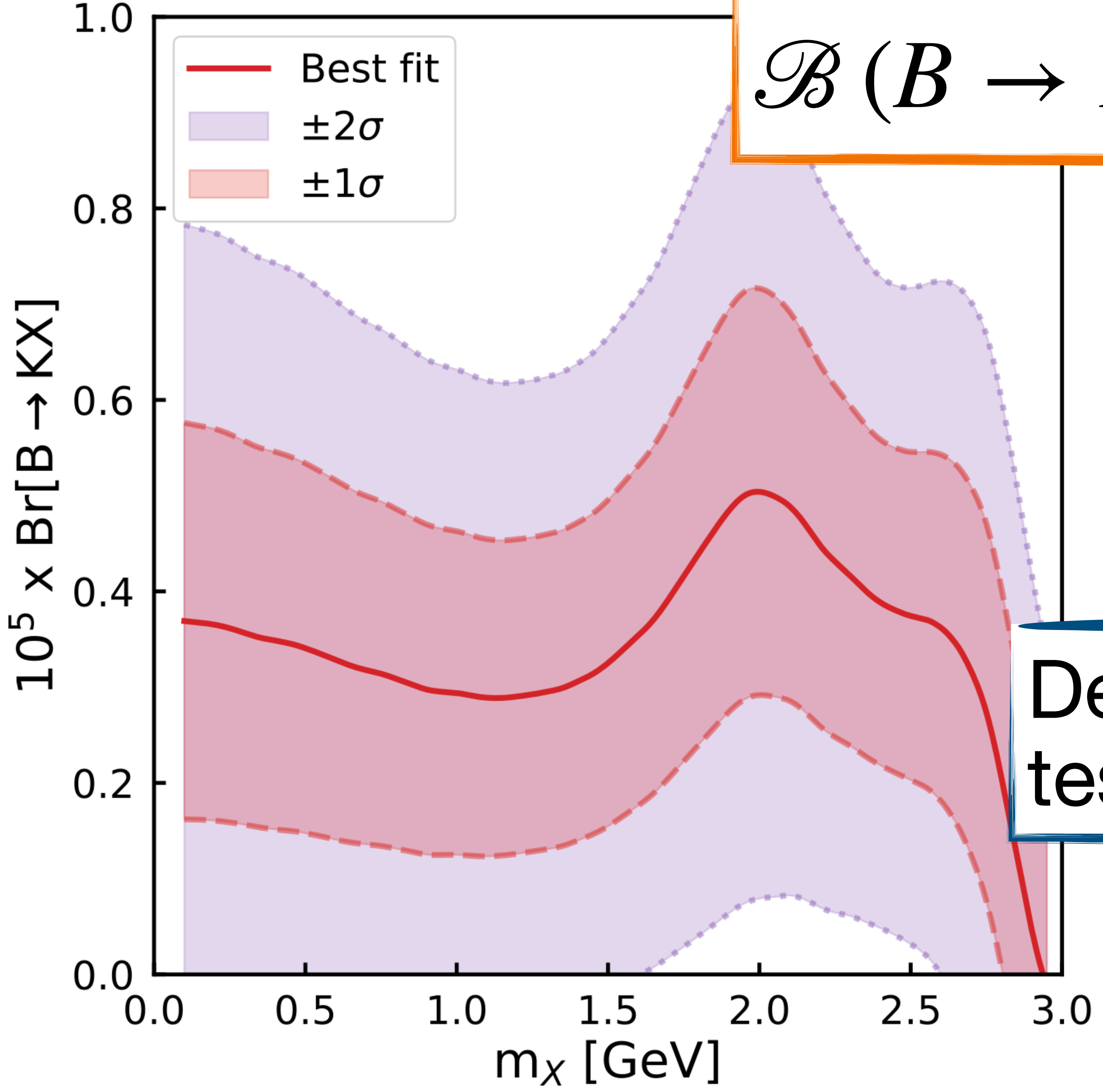
Effect of a light vector mediator

W. Altmannshofer *et al.*, arXiv:2311.14629

The excess is compatible with $B \to KX(\to \nu\nu)$ with X produced on-shell

Resonance in the q^2-distribution at $q^2 \simeq m_X^2$





Best fit: $m_X \simeq 2$ GeV

$\mathscr{B}(B \to KX) = \left(5.1 \pm 2.1\right) \times 10^{-6}$

Significance of 2.4σ

Dedicated searches could test this hypothesis!

Summary and outlook

Conclusions

$$\mathscr{B}\left(B^{\pm} \to K^{\pm}\nu\bar{\nu}\right)\Big|_{\rm SM} = (4.44 \pm 0.30) \times 10^{-6}$$

Theoretically cleaner than $B \to K^{(*)}\mu\mu$

Two main uncertainties from the theory side:

- CKM matrix element determination: **Inclusive vs exclusive** V_{cb}

Can change prediction by $\mathscr{O}(10\%)$

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- Form factor determination: $\begin{cases} B \to K\nu\bar{\nu} \\ B \to K^*\nu\bar{\nu} \end{cases}$

Error $\mathcal{O}(5\%)$

Error $\mathcal{O}(15\%)$

Eventually need to match the expected sensitivity by Belle-II

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$\mathscr{B}\left(B^{+} \to K^{+}\nu\bar{\nu}\right)\Big|_{\mathrm{Belle-II}} = (2.3 \pm 0.7) \times 10^{-5}$

$$\mathscr{L}^{b\to s\nu\nu} = \frac{4G_F}{\sqrt{2}}\lambda_t \sum_{i,j}\left(C_L^{\nu_i\nu_j}\mathscr{O}_L^{\nu_i\nu_j} + C_R^{\nu_i\nu_j}\mathscr{O}_R^{\nu_i\nu_j}\right) + h.c.$$

Contributions from only $C_L^{\nu_i\nu_j}$ are tightly constrained by Belle

Contributions from only $C_R^{\nu_i\nu_j}$ can explain $B \to K\nu\bar{\nu}$, correlated with $\mathscr{B}(B \to K^*\nu\bar{\nu})$ and F_L

Conclusions

SMEFT

- Couplings to μ constrained by $B_s \to \mu\mu$
- NP couplings allowed in τ leptons:

$$\frac{\mathscr{B}\left(B_s \to \tau\tau\right)_{\text{BSM}}}{\mathscr{B}\left(B_s \to \tau\tau\right)_{\text{SM}}} \sim 10$$

νSMEFT

- Scalar and tensor operators also contribute
- One can always suppress the NP effect on $B \to K^*\nu\nu$ with $m_{\nu_4} \sim (m_B - m_{K^*})$

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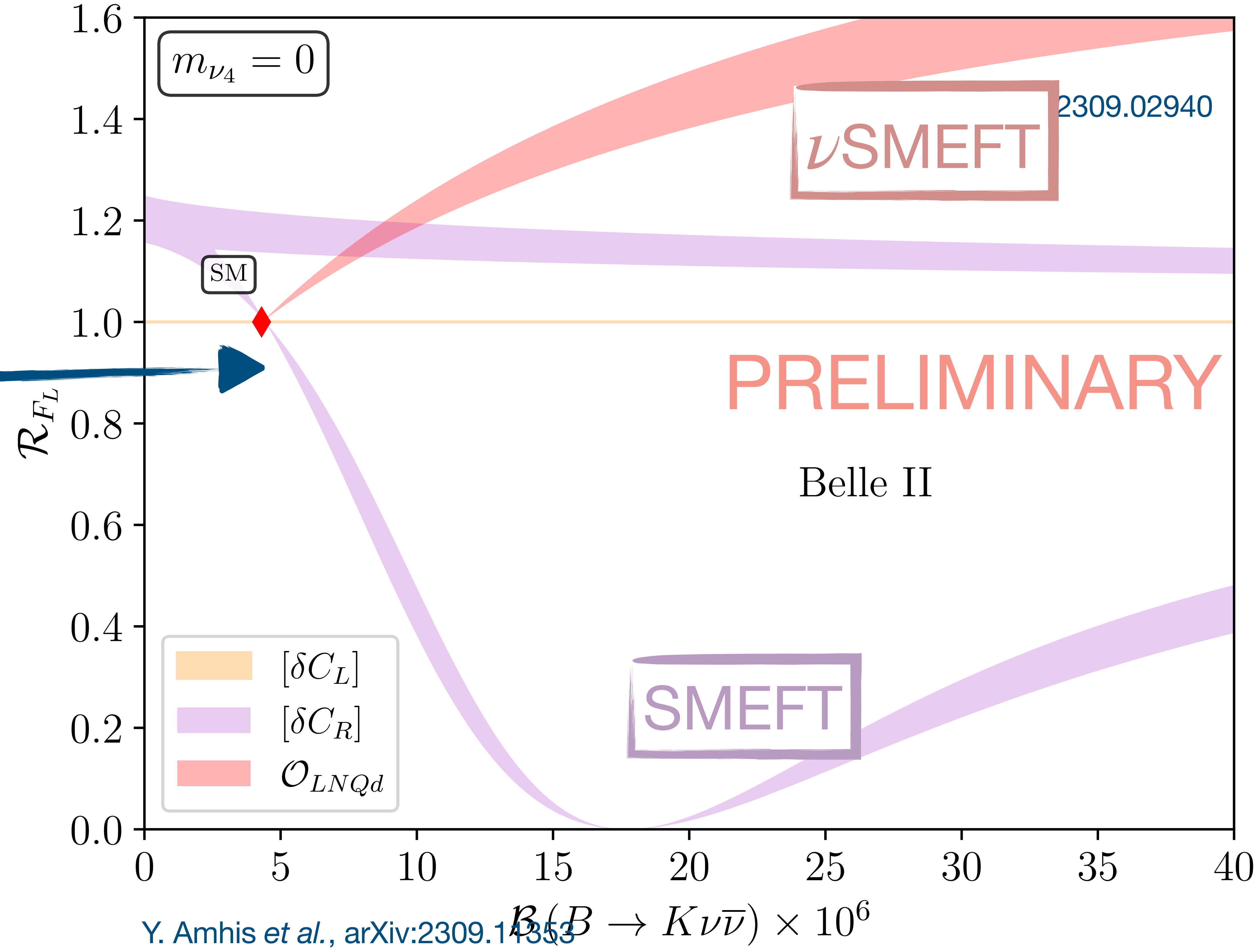
- **Measurement of F_L**
- $B_s \to \nu\nu$
- q^2-distribution of events
- High-p_T tails? Constraints on **sca**
- Complementary processes: B^0 –



Y. Amhis *et al.*, arXiv:2309.14353

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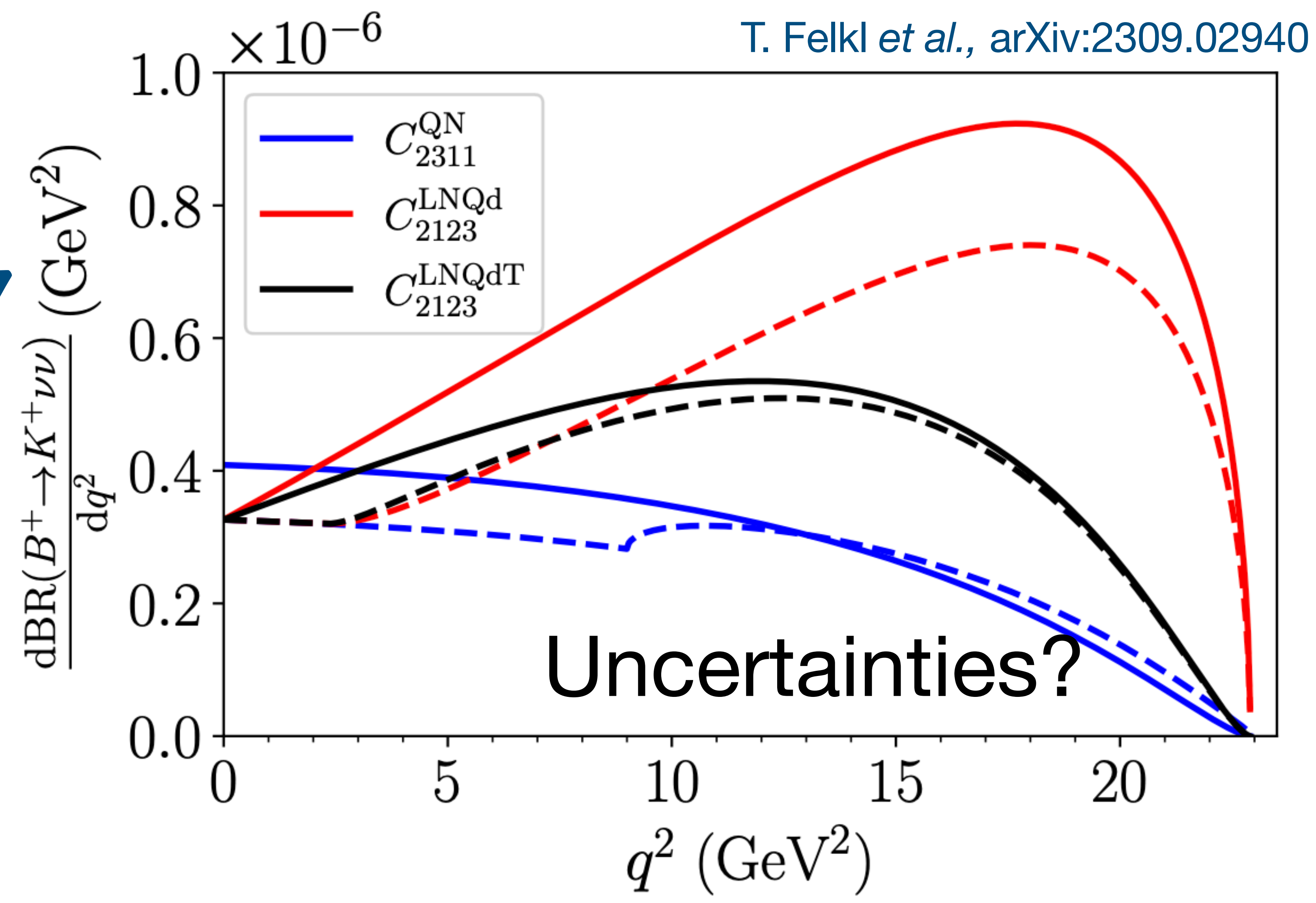

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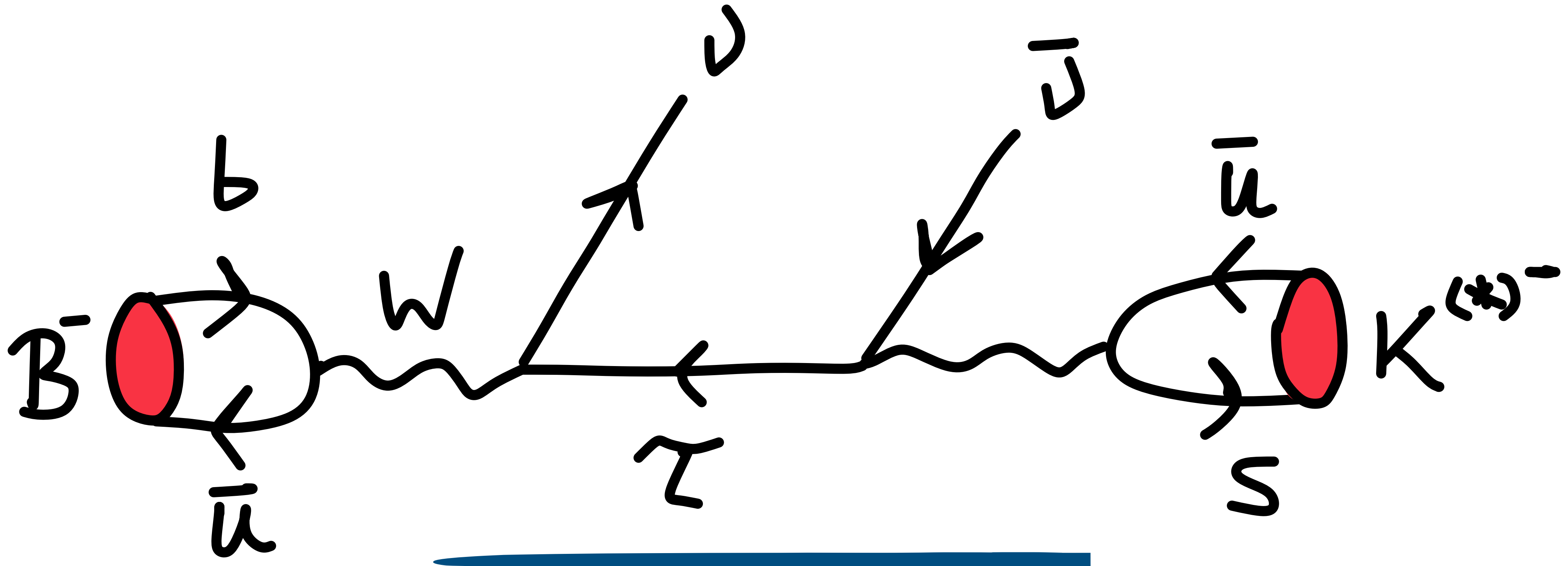
Thank you!

Back-up slides

Tree-level contribution

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



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J. F. Kamenik & C.Smith, arXiv:0908.1174

Charged meson decay modes have a tree-level contribution from the annihilation to an intermediate τ

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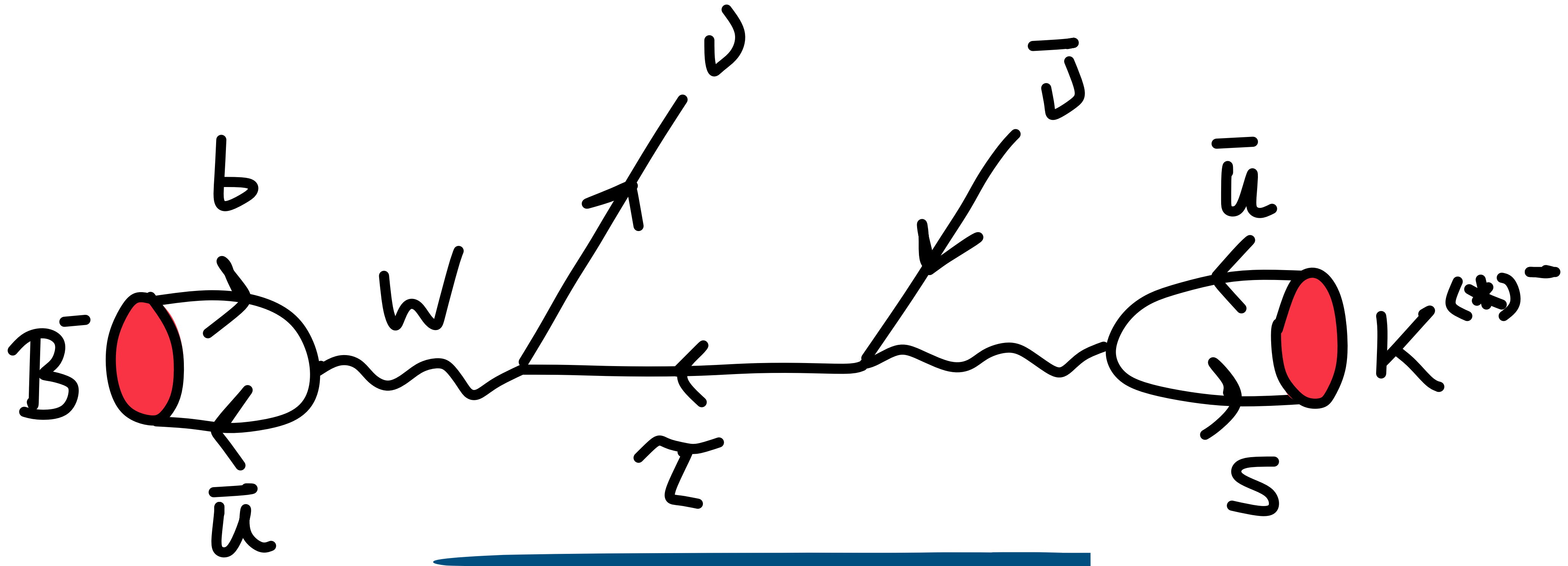

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Charged meson decay modes have a tree-level contribution from the annihilation to an intermediate τ

Using the narrow width approximation

$$\mathscr{B}\left(B^+ \to K^{(*)+}\nu\bar{\nu}\right) \sim \mathscr{B}\left(B^+ \to \tau^+\nu\right)\mathscr{B}\left(\tau^+ \to K^{(*)+}\bar{\nu}\right)$$

Tree-level contribution

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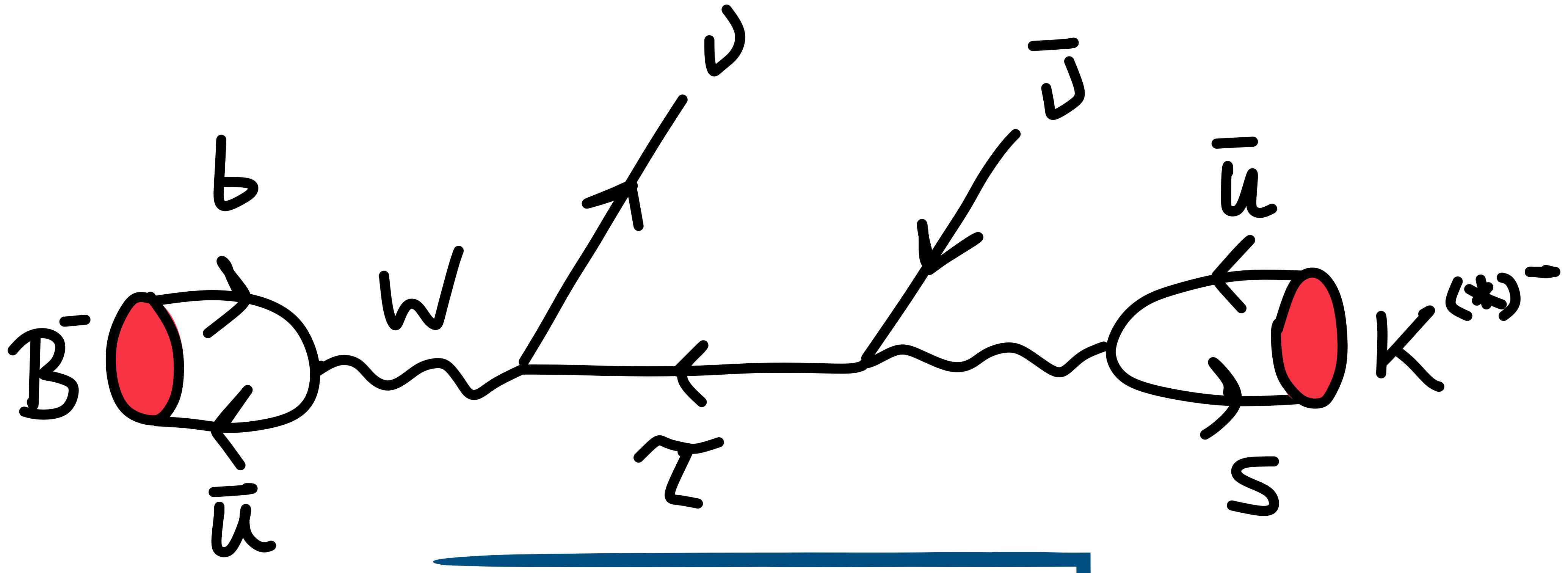

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$$\frac{\mathscr{B}\left(B \to K^{(*)}\nu\bar{\nu}\right)_{\text{tree}}}{\mathscr{B}\left(B \to K^{(*)}\nu\bar{\nu}\right)_{\text{loop}}} \simeq 14\,\%\,(11\%)$$

Non negligible contribution!

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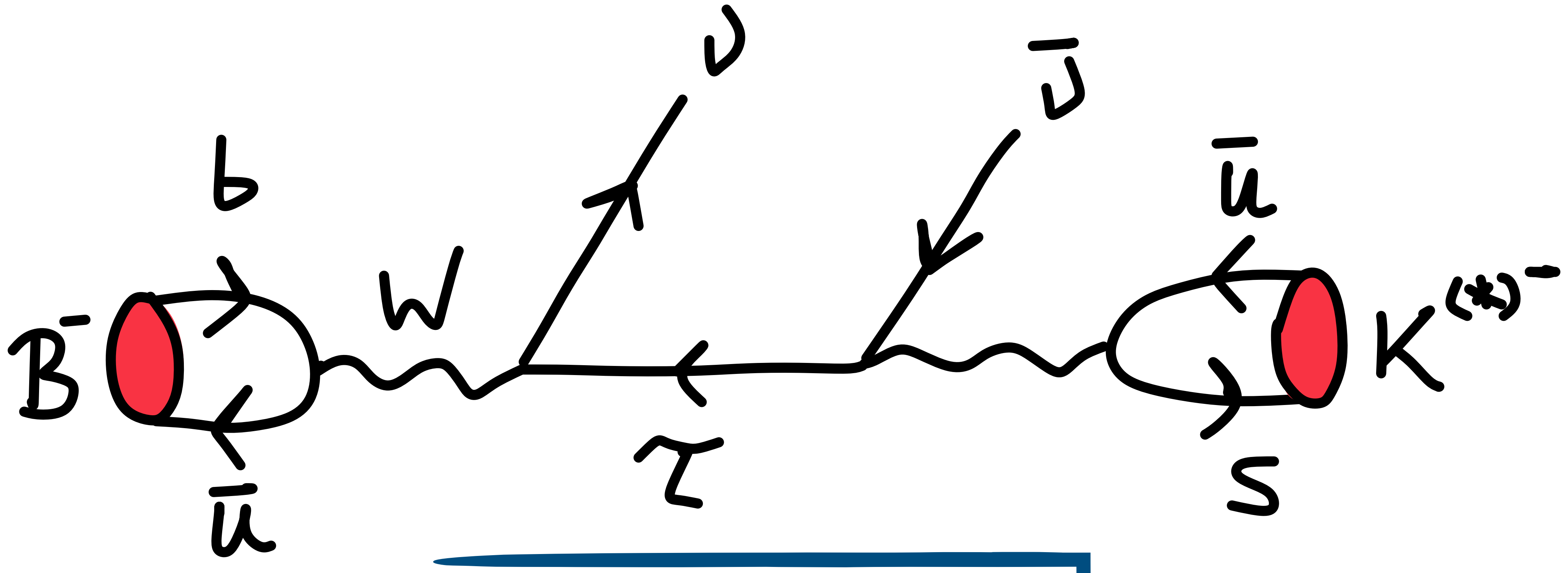

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Non negligible contribution!

Belle-II can in principle disentangle these two contributions

Reduction of uncertainties

Ratio between low and high-q^2 regions

D. Becirevic, G. Piazza & O. Sumensari, arXiv:2301.06990

Binned information would allow one to study the following CKM-free ratio

$$r_{\text{low/high}} \equiv \frac{\mathscr{B}\left(B \to K^{(*)}\nu\bar{\nu}\right)_{\text{low}-q^2}}{\mathscr{B}\left(B \to K^{(*)}\ell\ell\right)_{\text{high}-q^2}}$$

Test of the extrapolated Lattice QCD form factors

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Test of the extrapolated Lattice QCD form factors

Independent of FF normalization and NP contributions (w/o N_R)

Take bins $(0, q^2_{\text{max}}/2)$ and $(q^2_{\text{max}}/2, q^2_{\text{max}})$:

$$r_{\text{low/high}} = 1.91 \pm 0.06$$

Using previous FLAG average

$$r_{\text{low/high}} = 2.15 \pm 0.26$$

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Partial branching fractions integrated in the same q^2 range

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FF uncertainties significantly reduced if $q^2 \gg m_\ell^2$

Choosing the q^2 region away from $c\bar{c}$-resonances, $[q_0^2, q_1^2] \to [1.1, 6]\,\mathrm{GeV}^2$

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Using perturbative calculations for the $c\bar{c}$-loops one finds

$$\mathcal{R}_K^{(\nu/\mu)}[1.1,6] = 7.58 \pm 0.04$$

$\lesssim \mathcal{O}(1\%)$ uncertainty

$$\mathcal{R}_{K^*}^{(\nu/\mu)}[1.1,6] = 8.6 \pm 0.3$$

$\lesssim \mathcal{O}(5\%)$ uncertainty

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D. Becirevic, G. Piazza & O. Sumensari, arXiv:2301.06990

Binned information would allow one to study the following CKM-free ratio

$$\mathcal{R}_{K^{(*)}}^{(\nu/\ell)}[q_0^2, q_1^2] \equiv \left.\frac{\mathcal{B}\left(B \to K^{(*)}\nu\bar{\nu}\right)}{\mathcal{B}\left(B \to K^{(*)}\ell\ell\right)}\right|_{[q_0^2,q_1^2]}$$

Partial branching fractions integrated in the same q^2 range

FF uncertainties significantly reduced if $q^2 \gg m_\ell^2$

Choosing the q^2 region away from $c\bar{c}$-resonances, $[q_0^2, q_1^2] \to [1.1,6]\,\mathrm{GeV}^2$

But we can use this ratio to extract C_9!

$$\left.\frac{1}{\mathcal{R}_K^{\nu/\mu}[1.1,6]}\right|_{\mathrm{SM}} \simeq \left[7.5 - 0.45 C_9^{\mathrm{eff}} + 0.42 \cdot \left(C_9^{\mathrm{eff}}\right)^2\right]$$

Correlations between observables

Coupling to muons only

One can relate $B \to K\nu\bar{\nu}$ with $B_s \to \mu\mu$

$$\mathscr{B}\left(B_s \to \mu\mu\right) = \left(3.35 \pm 0.27\right) \times 10^{-9}$$

ATLAS, arXiv:1812.03017
LHCb, arXiv:2108.09283
CMS,arXiv:2212.10311

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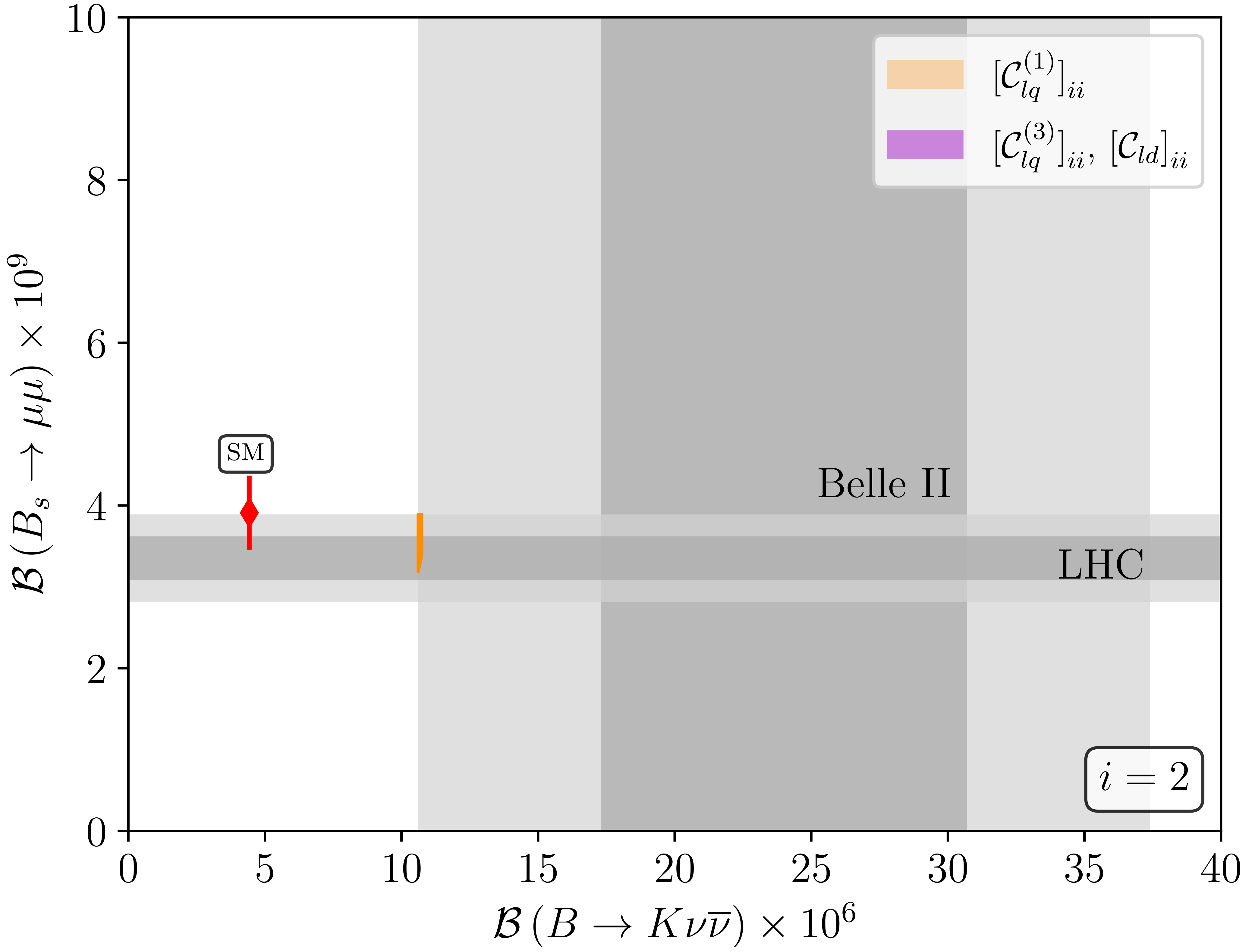
$$\mathcal{O}_{10} = \frac{e^2}{(4\pi)^2}\left(\bar{s}_L\gamma^\mu b_L\right)\left(\bar{\ell}\gamma_\mu\gamma_5\ell\right)$$

$$\delta C_{10}^{\ell_i\ell_i} = \frac{\pi}{\alpha_{\rm em}\lambda_t}\frac{v^2}{\Lambda^2}\left\{\left[\mathcal{C}_{ld}\right]_{ii} - \left[\mathcal{C}_{lq}^{(1)}\right]_{ii} - \left[\mathcal{C}_{lq}^{(3)}\right]_{ii}\right\}$$



L. Allwicher, D. Becirevic, G. Piazza,
SRA & O. Sumensari, arXiv:2309.02246

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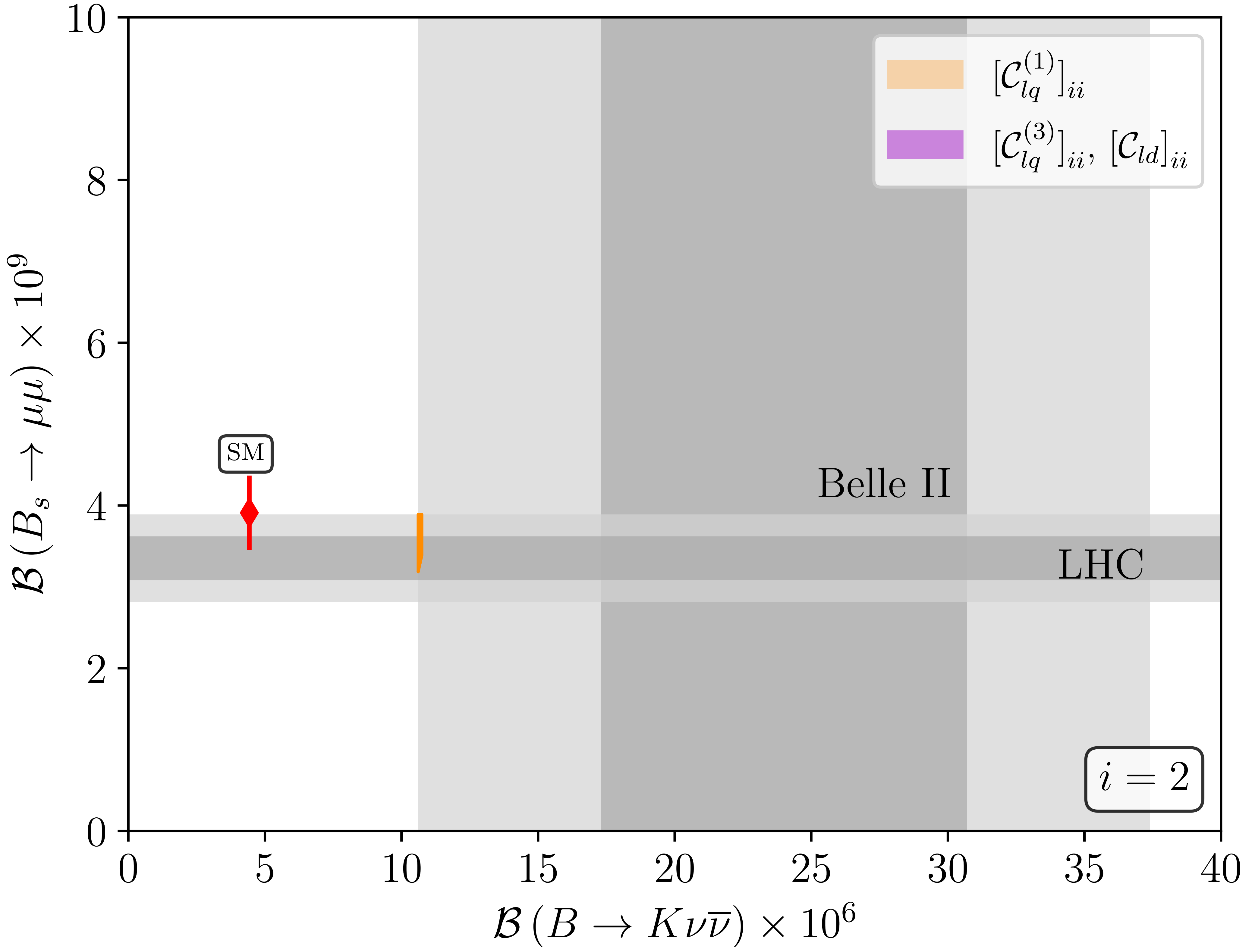

Note that one could also use $R_{K^{(*)}}$ now as well as a constrain

$$R_{K^{(*)}} = \frac{\mathscr{B}(B \to K^{(*)}\mu\mu)}{\mathscr{B}(B \to K^{(*)}ee)}$$

NP coupled to muons cannot explain Belle-II

L. Allwicher, D. Becirevic, G. Piazza, **SRA** & O. Sumensari, arXiv:2309.02246

Correlations between observables

Coupling to tau leptons

Can we introduce NP to simultaneously explain the Belle-II result and $R_D^{(*)}$?

$$R_{D^{(*)}} = \frac{\mathscr{B}\left(B \to D^{(*)}\tau\bar{\nu}\right)}{\mathscr{B}\left(B \to D^{(*)}\ell\bar{\nu}\right)}, \text{with } \ell = e, \mu$$

HFLAV, arXiv:2206.07501

$$R^{\mathrm{exp}}_{D^{(*)}}/R^{\mathrm{SM}}_{D^{(*)}} = 1.16 \pm 0.05$$

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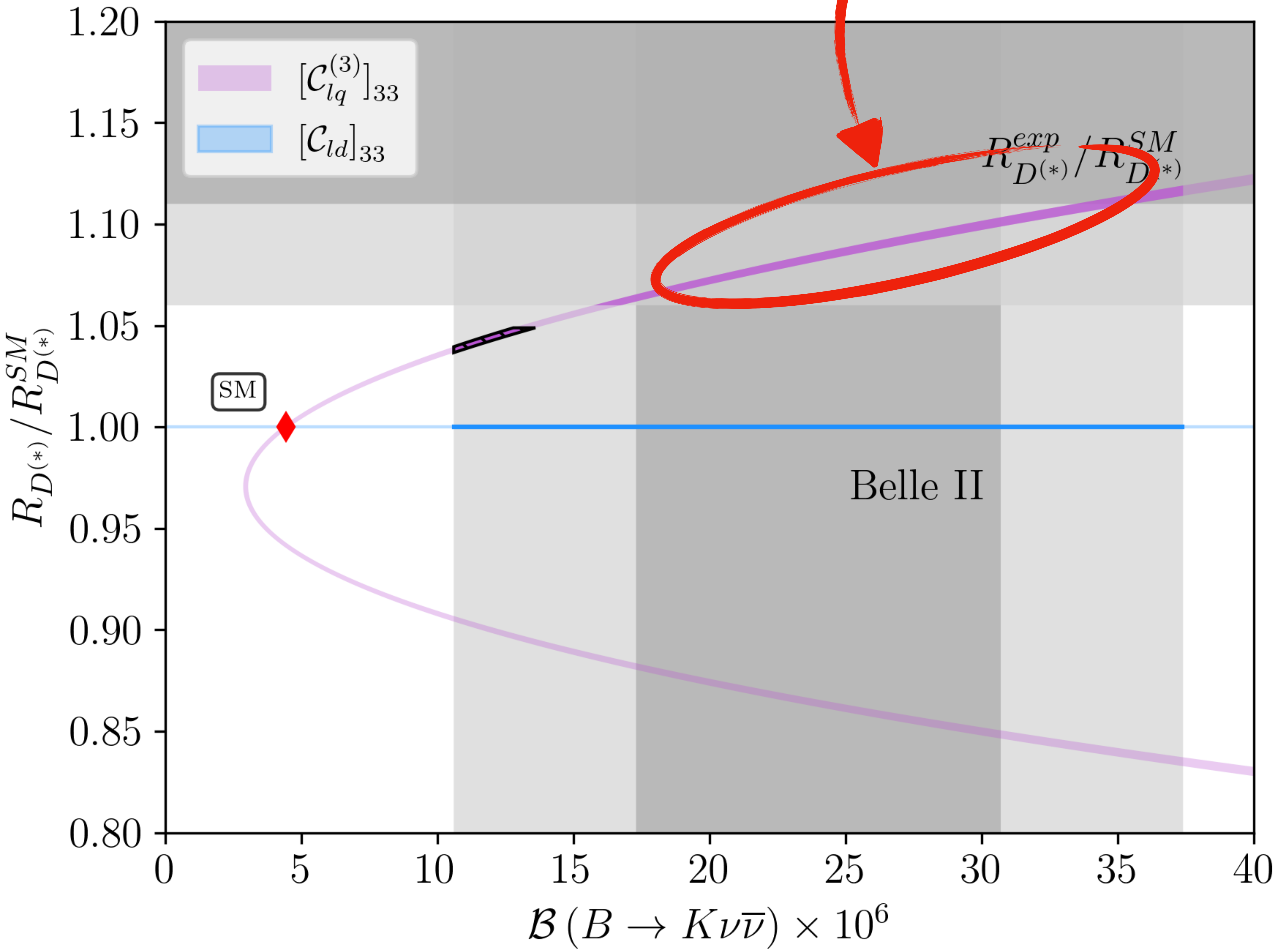
BSM contributions to this process given by

$$\frac{R_{D^{(*)}}}{R_{D^{(*)}}^{\text{SM}}} = \left(1 - \frac{v^2}{\Lambda^2}\frac{V_{cs}}{V_{cb}}\mathcal{C}_{lq}^{(3)}\right)^2$$

Excluded by $\mathcal{B}(B \to K^*$



L. Allwicher, D. Becirevic, G. Piazza, **SRA** & O. Sumensari, arXiv:2309.02246

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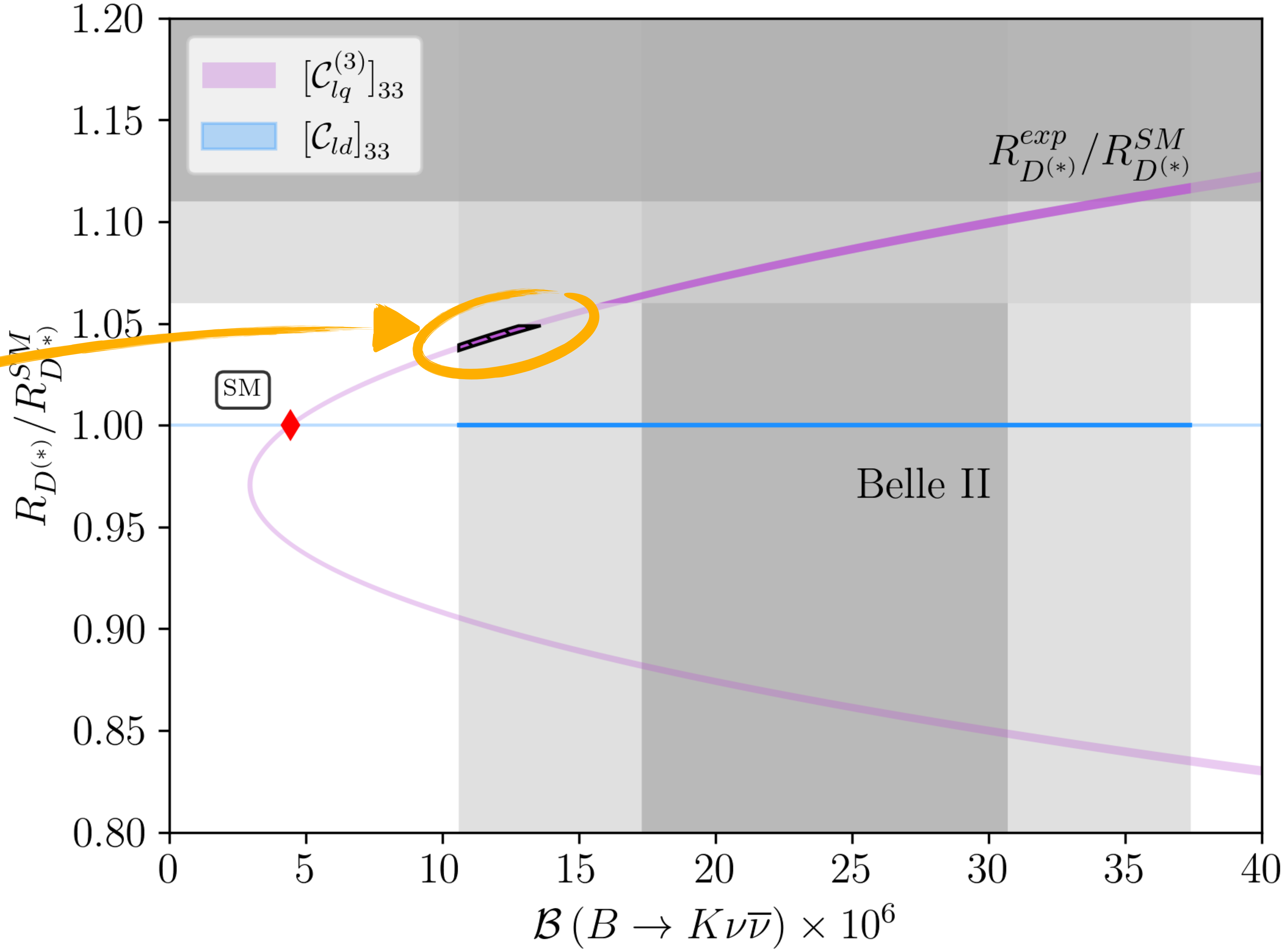
In this region $\mathcal{B}\left(B \to K^*\nu\bar{\nu}\right)$ is ok and we expect for example

$$\frac{\mathcal{B}\left(B_s \to \tau\tau\right)_{BSM}}{\mathcal{B}\left(B_s \to \tau\tau\right)_{\text{SM}}} \simeq 10$$



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