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

Theoretical perspective

Based on [2301.06990] & [2309.02246],
in collaboration with L. Allwicher, D. Becirevic, G. Piazza & O. Sumensari

GDR-InF, Strasbourg

Salvador Rosauro-Alcaraz, 06/11/2023

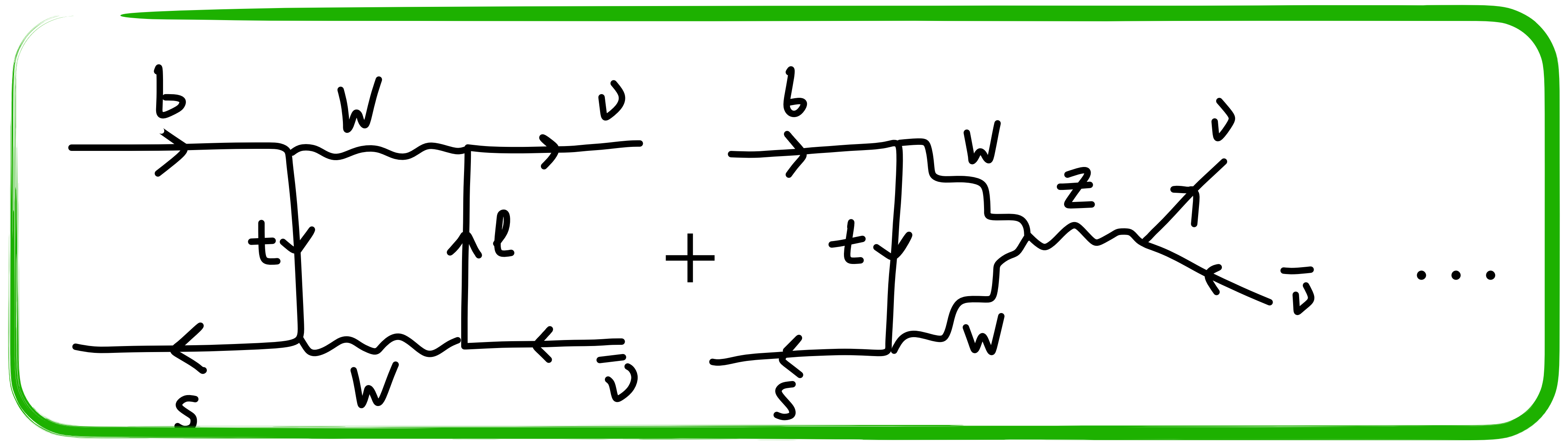
Plan for the talks

- **$B \to K^{(*)}\nu\bar{\nu}$ in the SM and theoretical uncertainties** — SRA
- **Search for the rare decay $B^+ \to K^+\nu\bar{\nu}$ decay at Belle II** — Jacopo Cerasoli & Lucas Martel
- **Consequences for New Physics of the Belle-II measurement** — SRA

Introduction

FCNC processes as probes of NP

Flavour Changing Neutral Current (FCNC) processes are good probes of New Physics as they are loop and CKM suppressed in the SM



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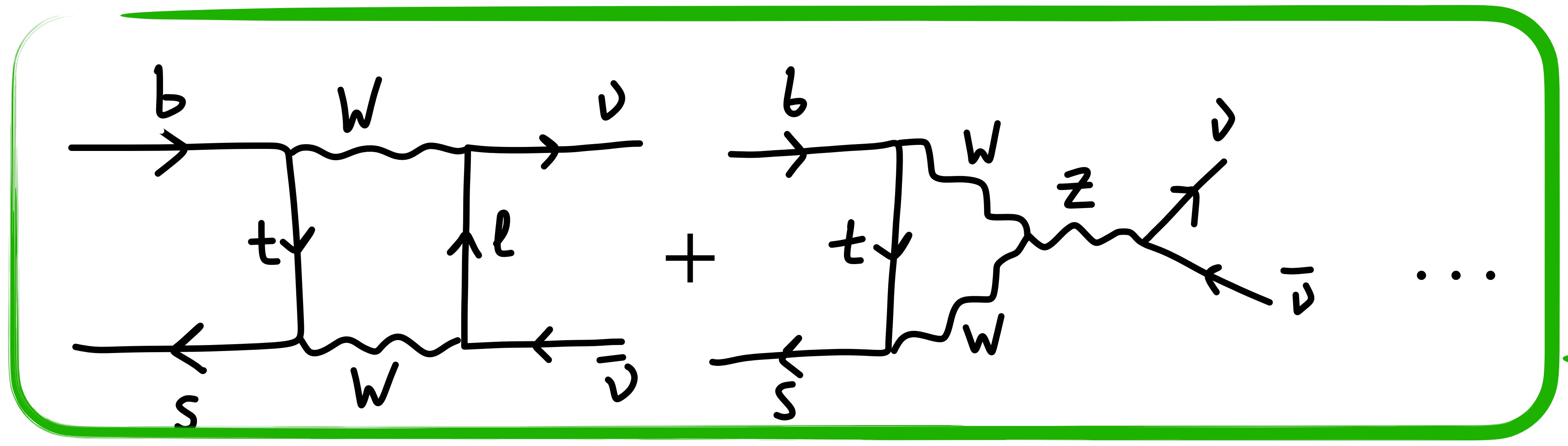
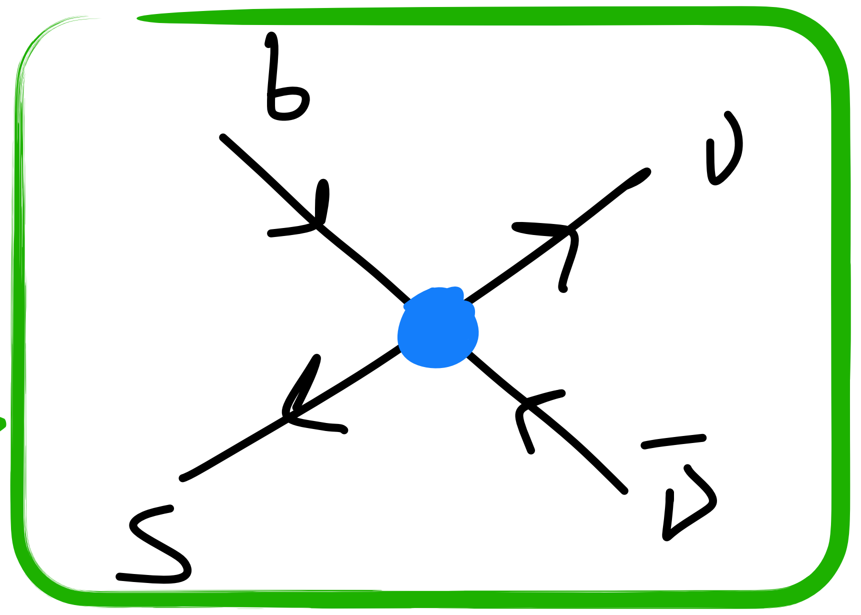


At low energies use an EFT



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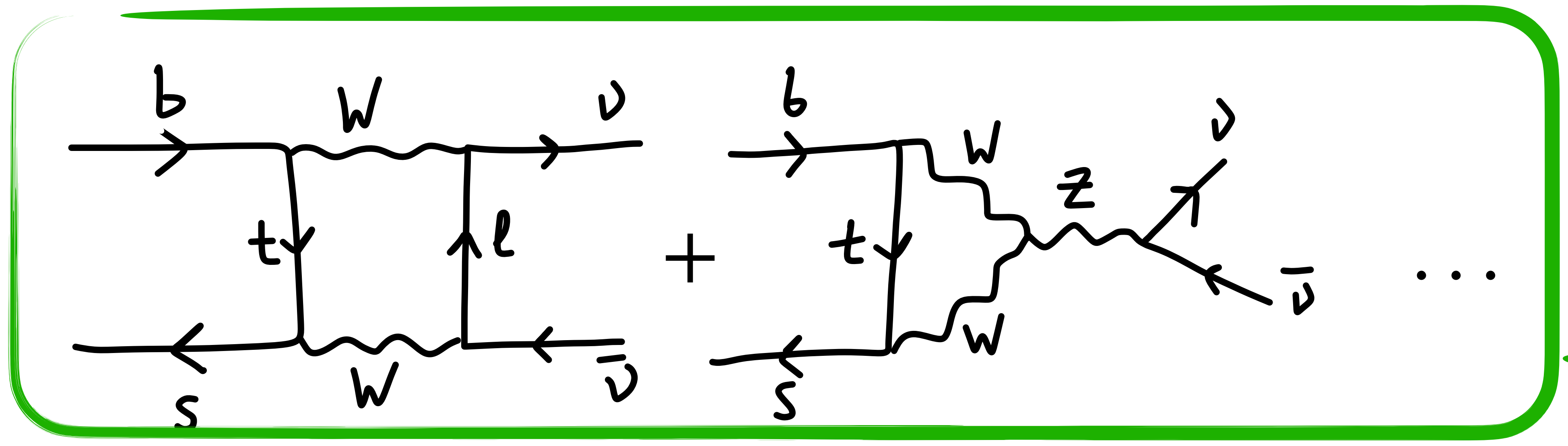

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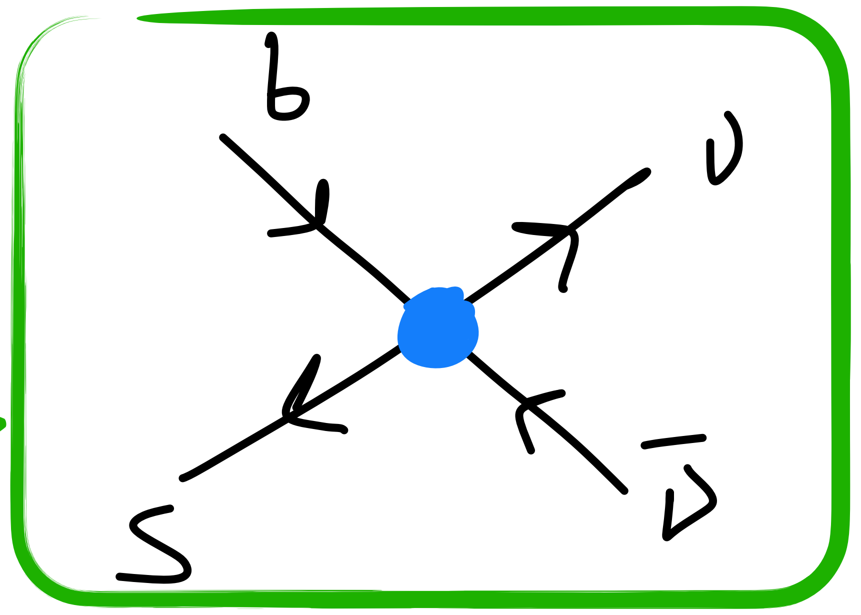
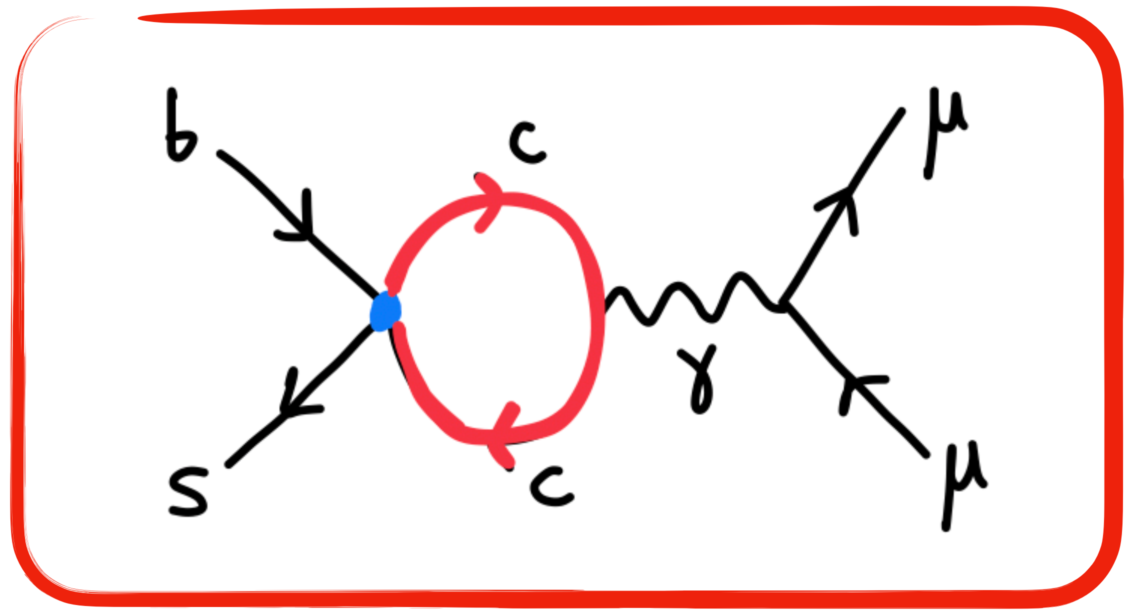


Hadronic uncertainties might hinder their precise determination:

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



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

Effective lagrangian

$b \to s\nu\nu$

Effective description in the (B)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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Flavor diagonal

NLO QCD & 2-loop EW corrections

G. Buchalla & A. Buras, Nucl. Phys. B (1993)
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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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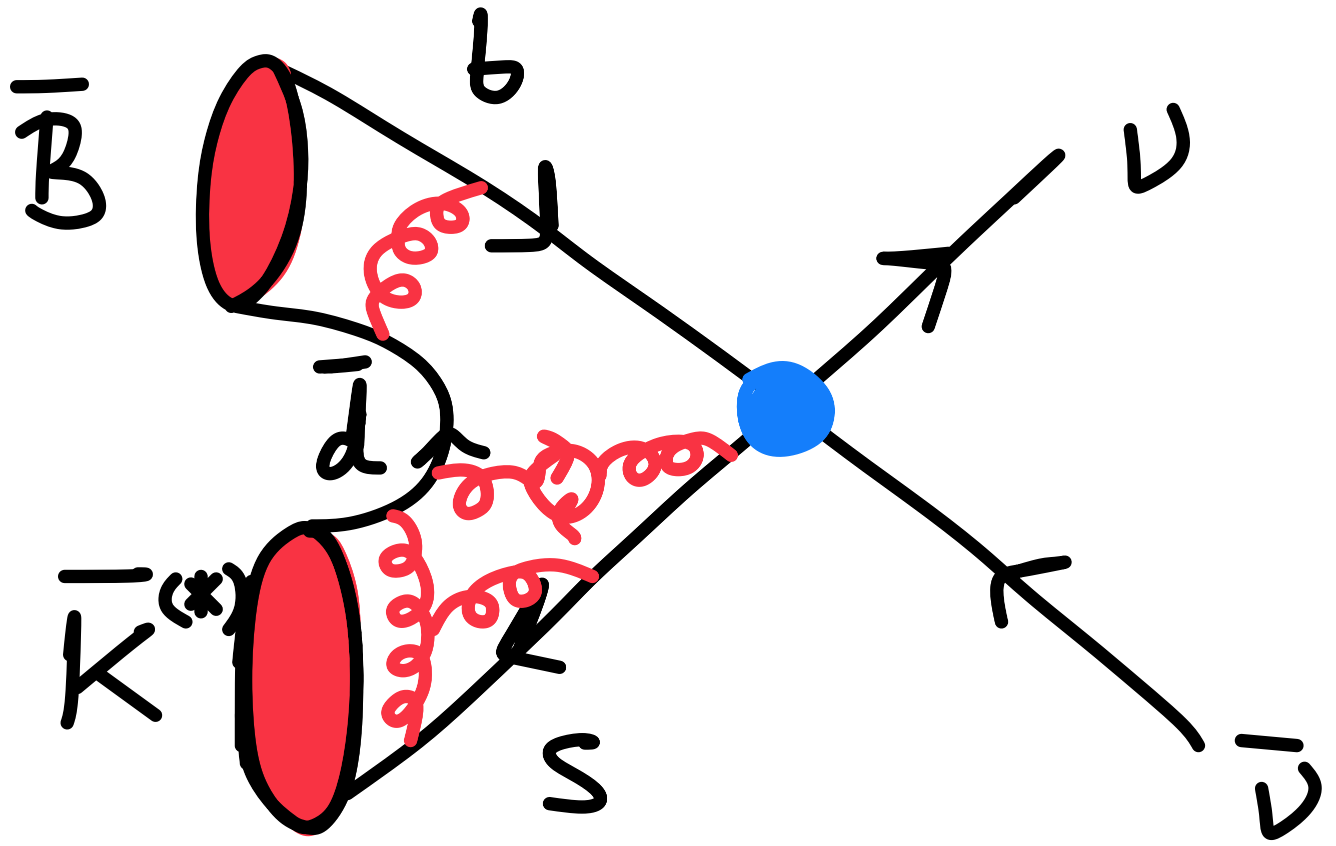

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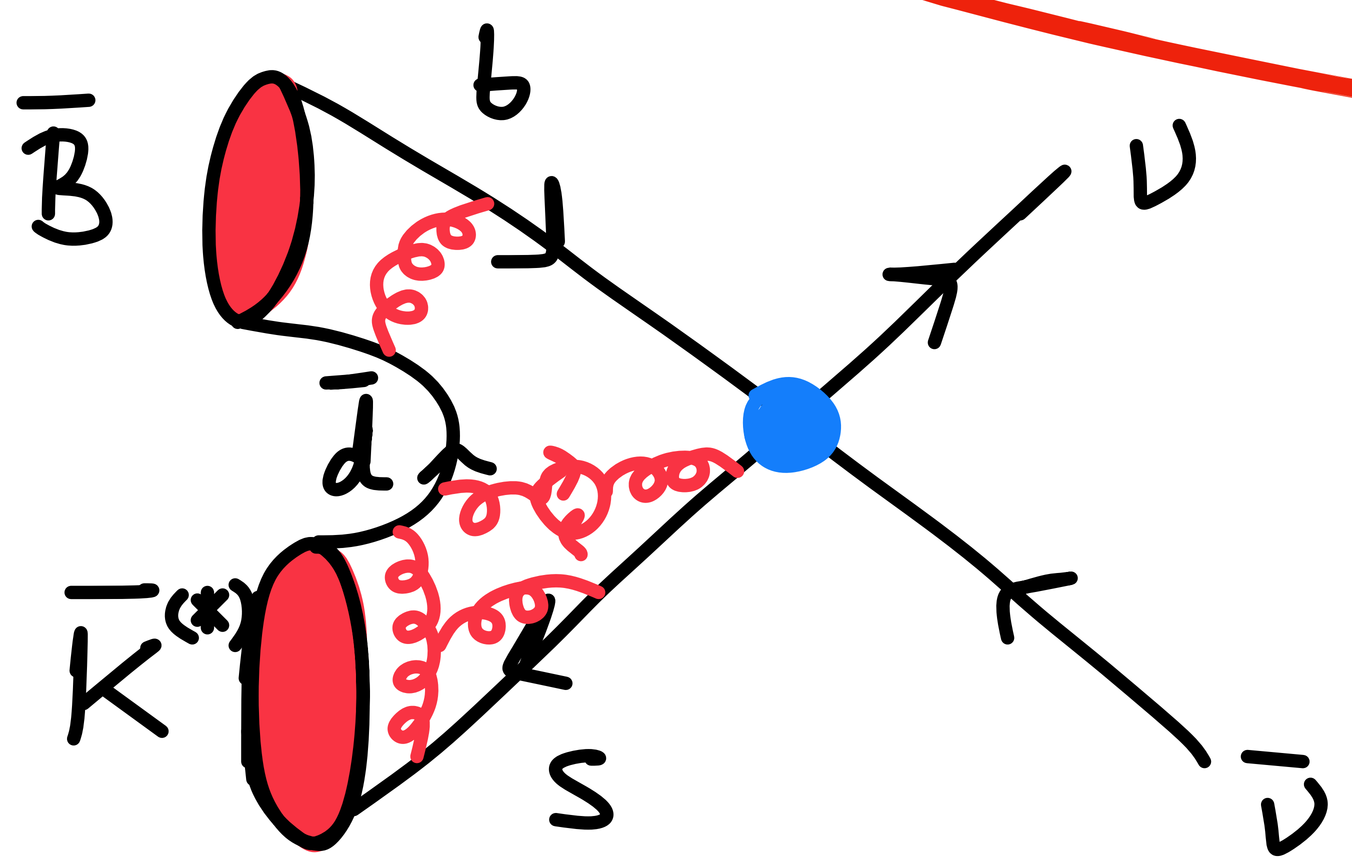

Hadronic matrix element

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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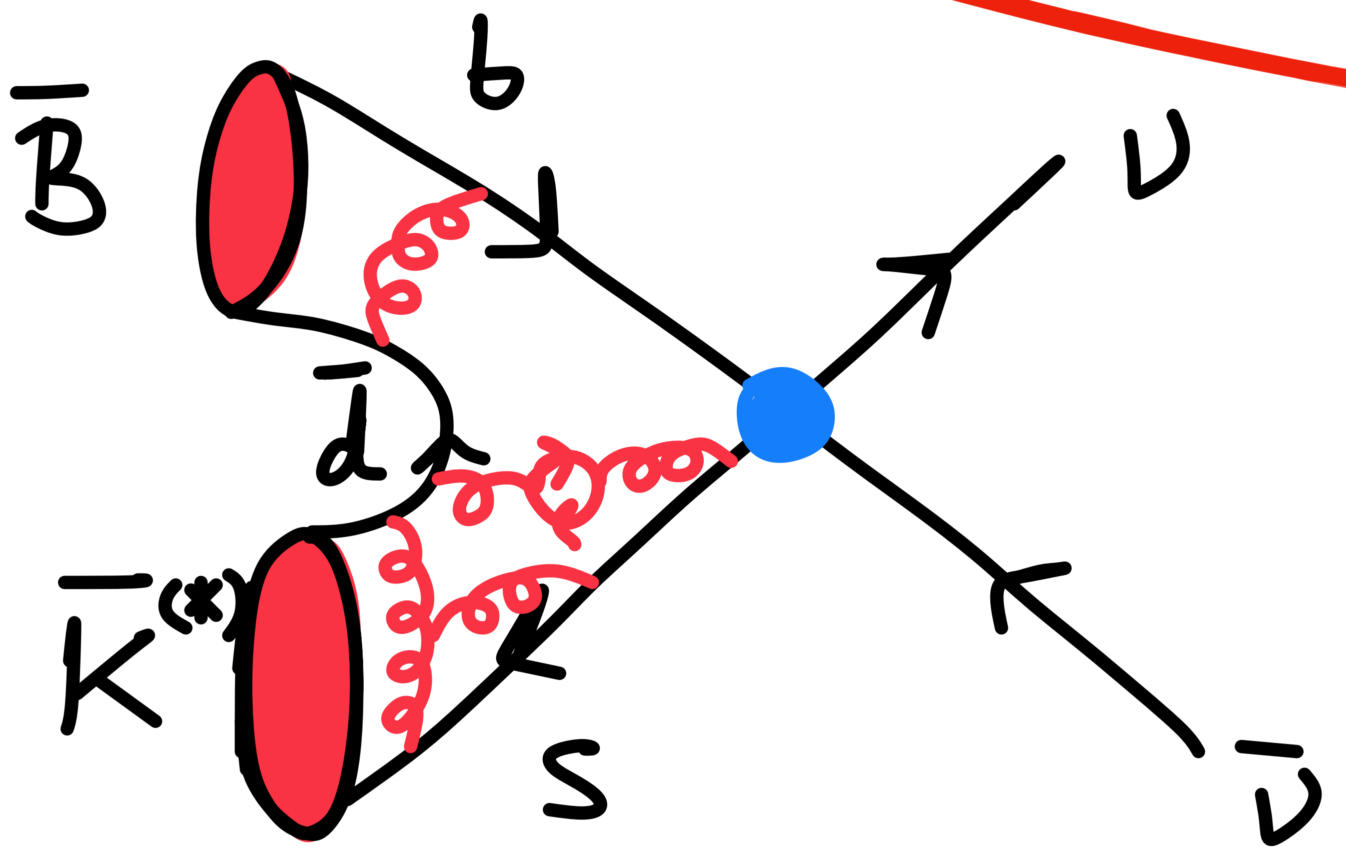

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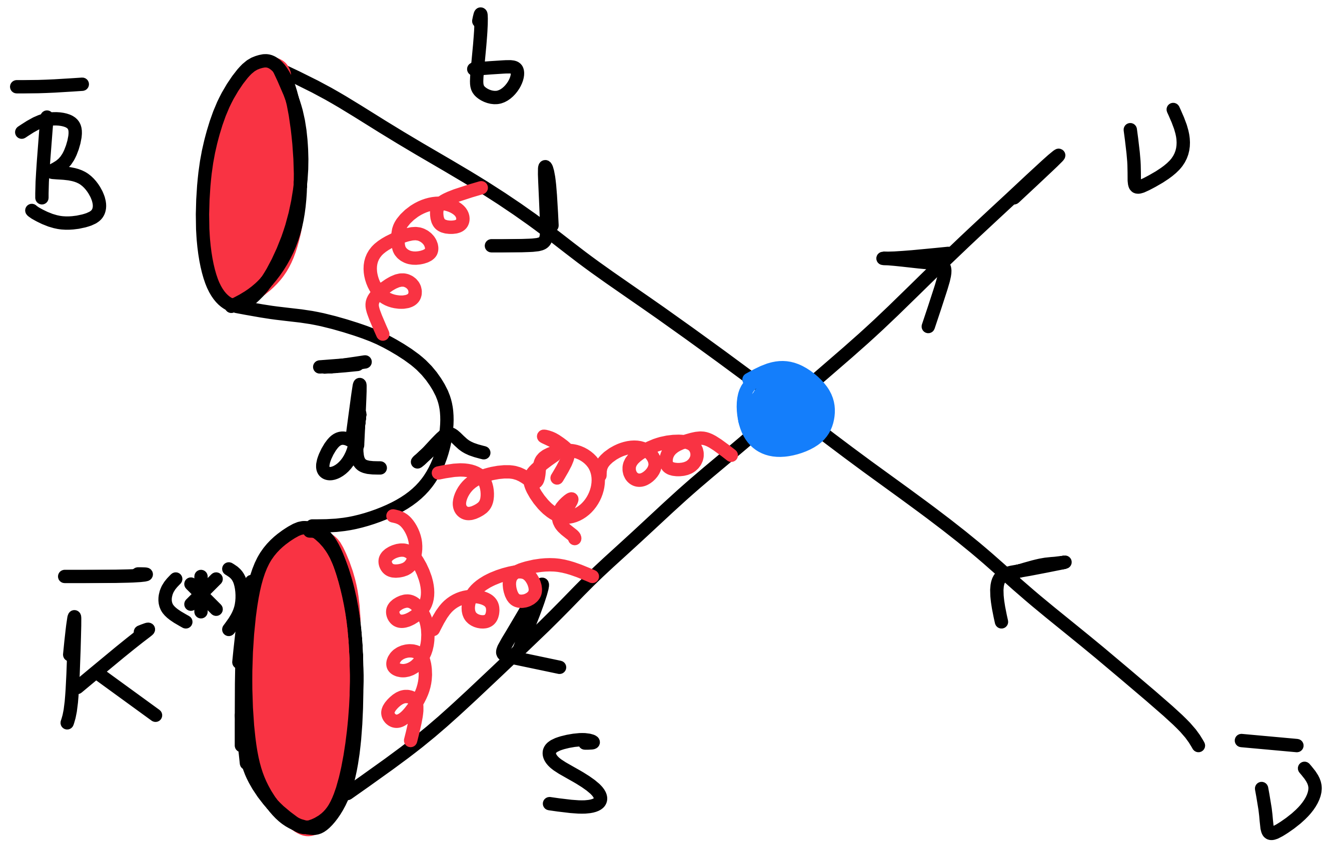

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Form factors

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

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

Lattice determinations of the form factors (FF)

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

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

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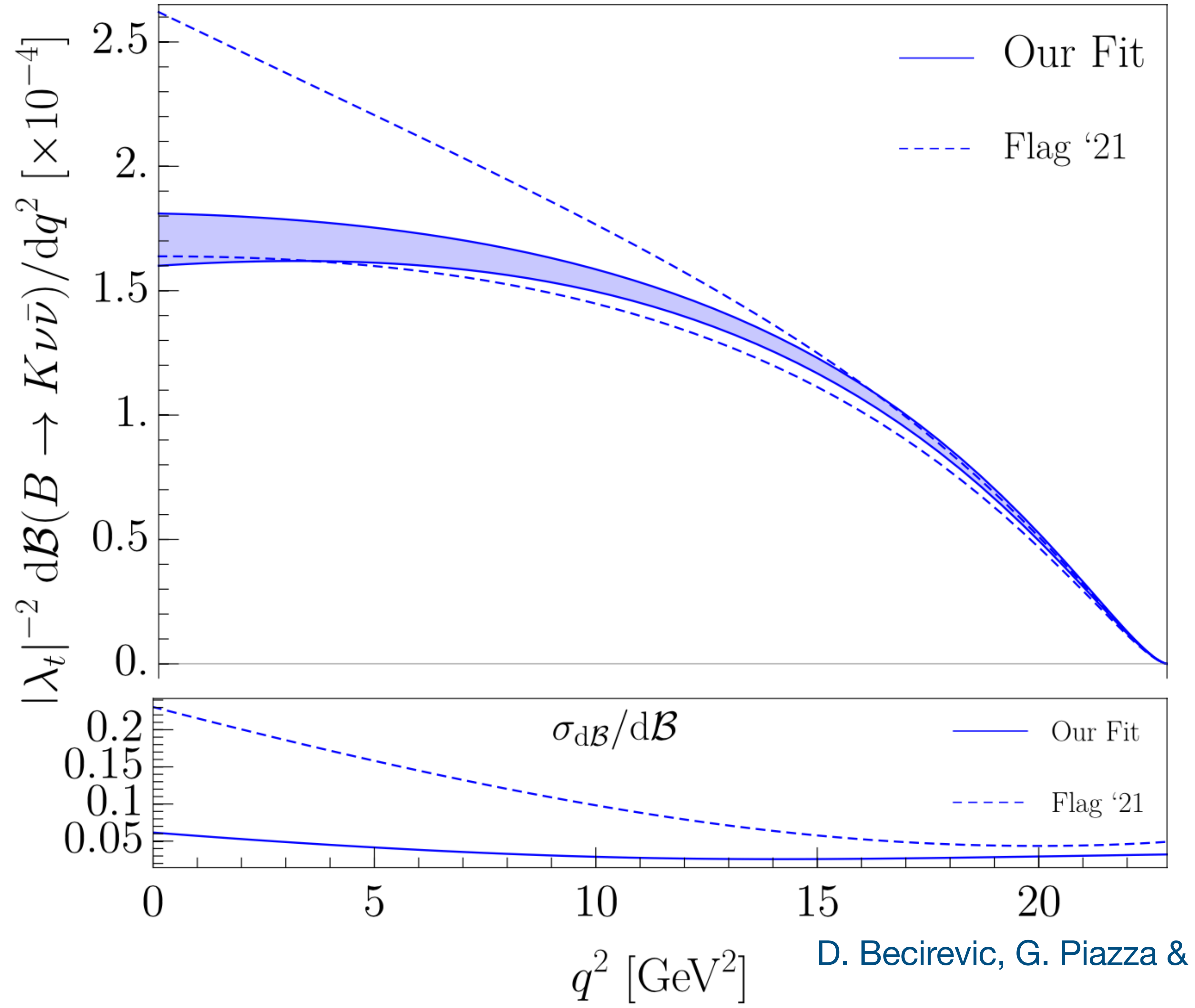

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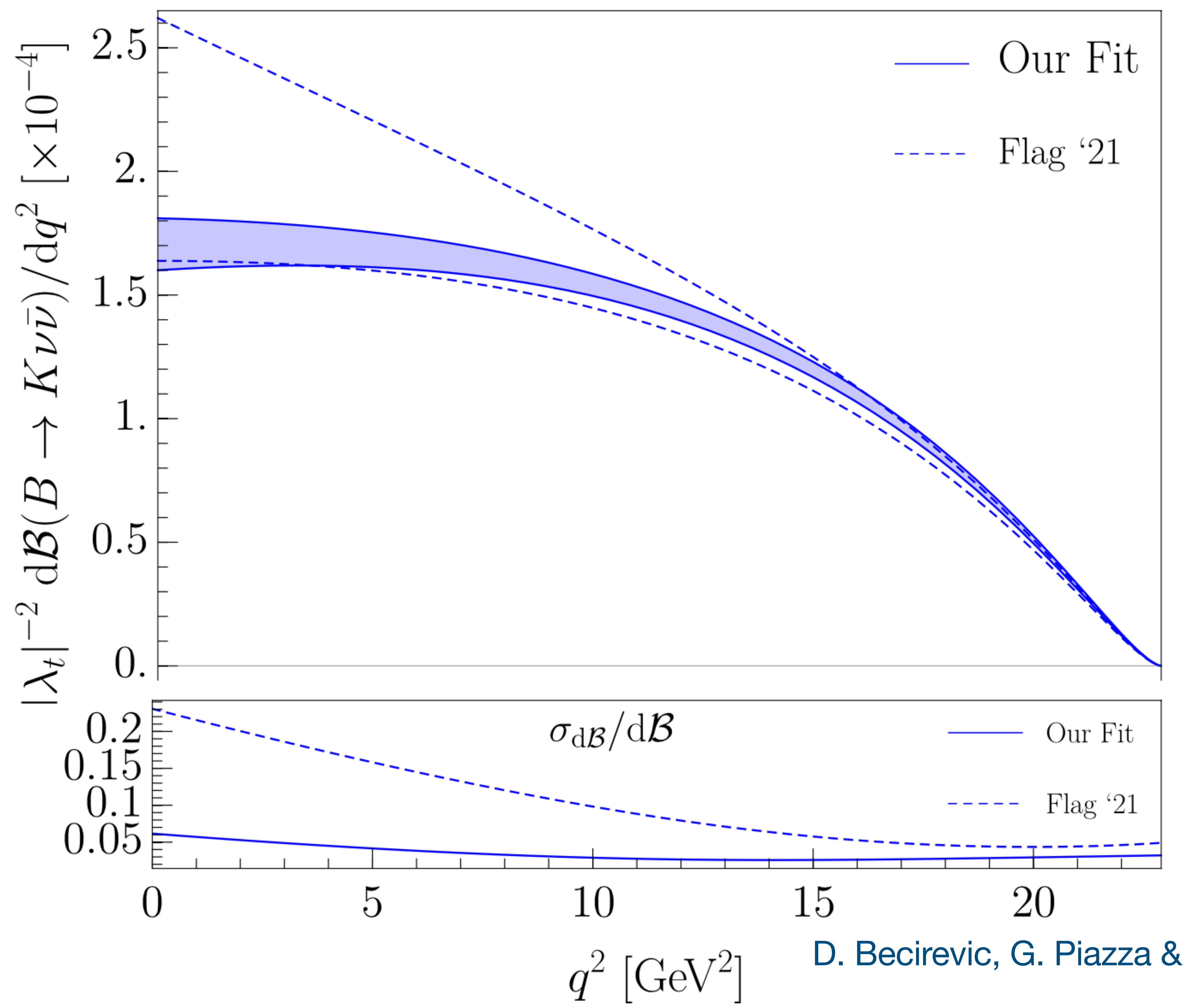

$$\frac{d\mathscr{B}}{dq^2} = \mathscr{N}_K(q^2)\ C_L^{SM\ 2}\ \lambda_t^{\ 2}\ \left[f_+(q^2)\right]^2$$

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

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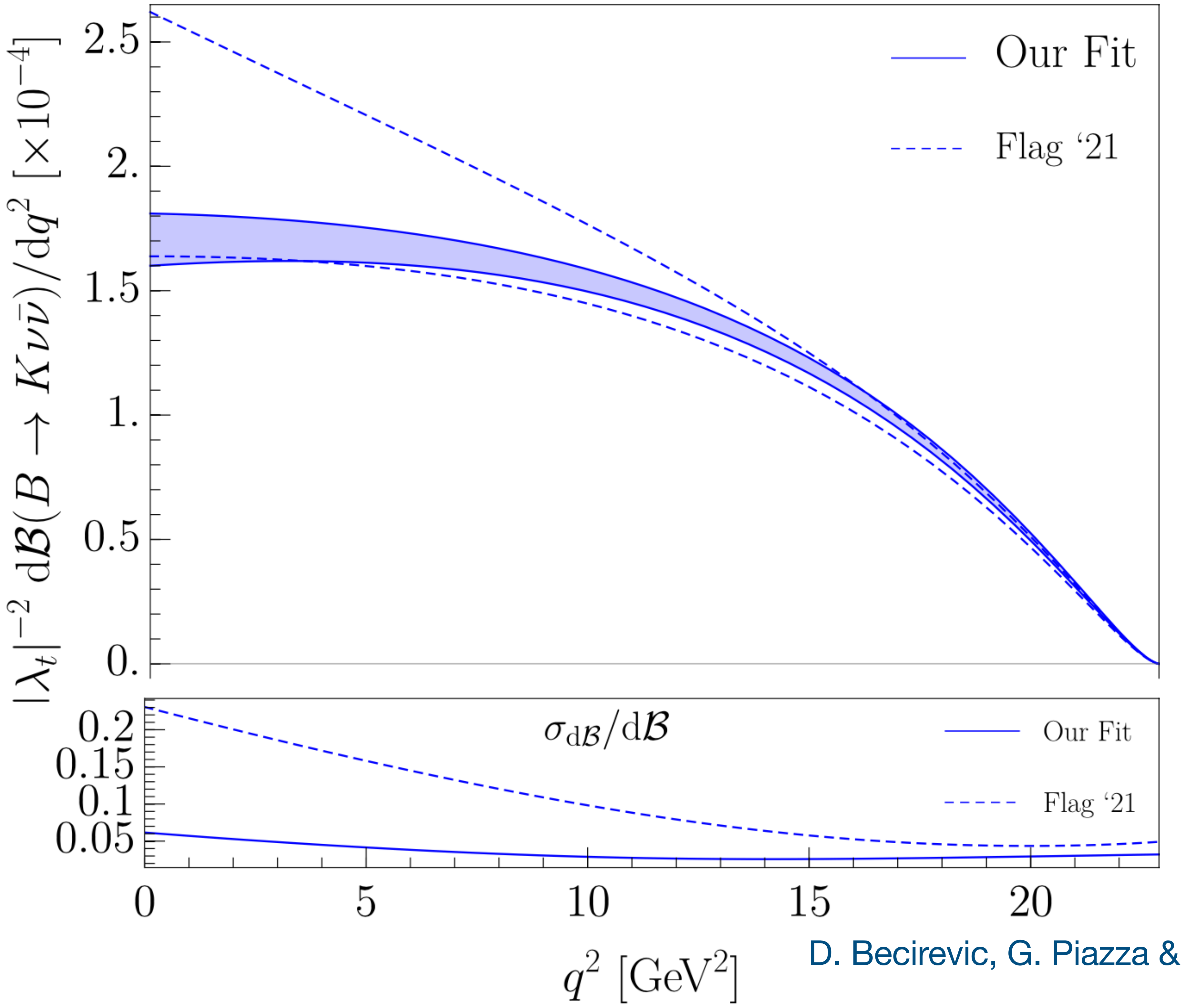

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Final prediction

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

$\mathcal{O}(7\%)$ 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 a Lattice QCD result & LCSR

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

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

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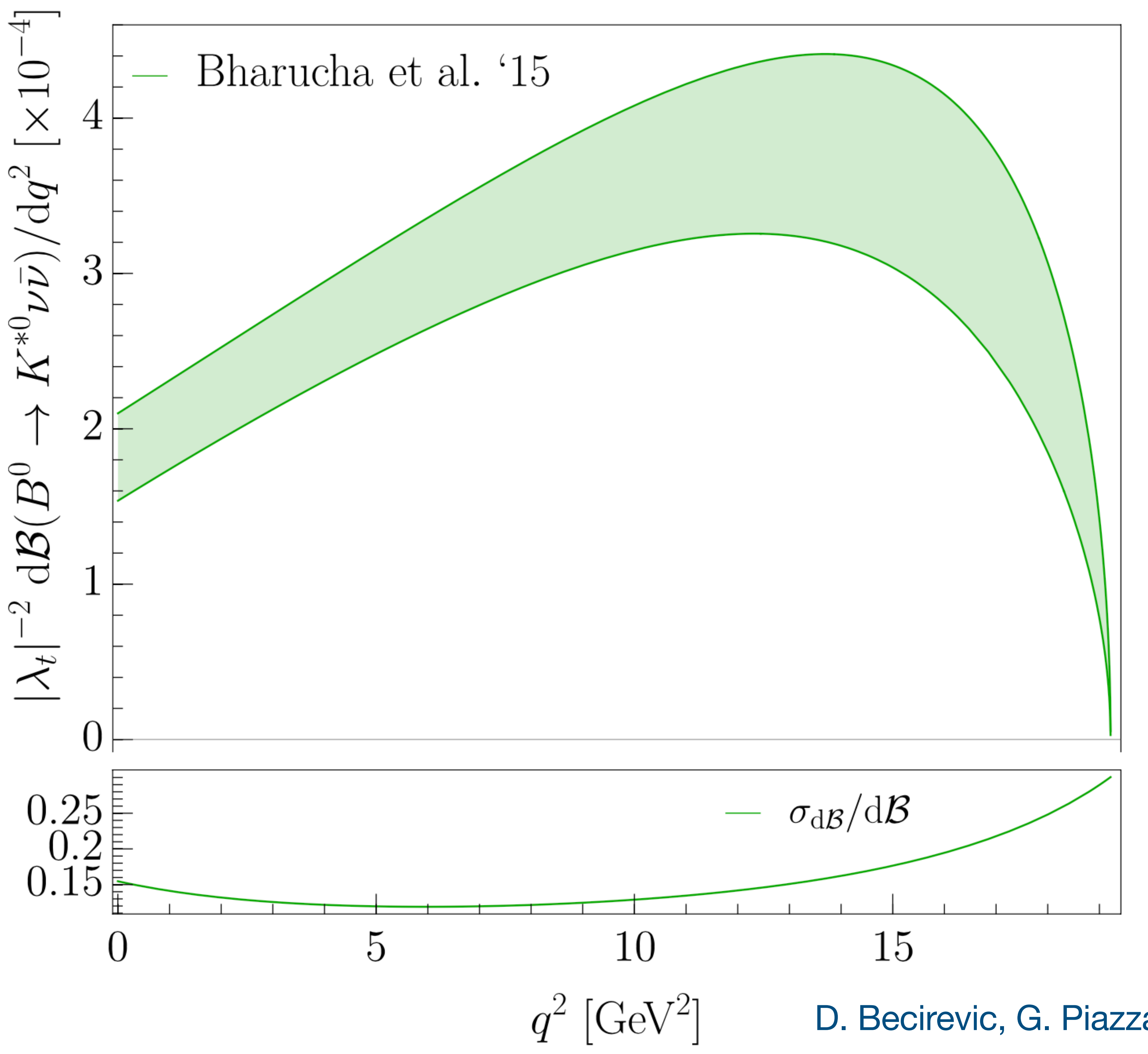

Relative error related to FF determination $\sim \mathcal{O}(15\%)$

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

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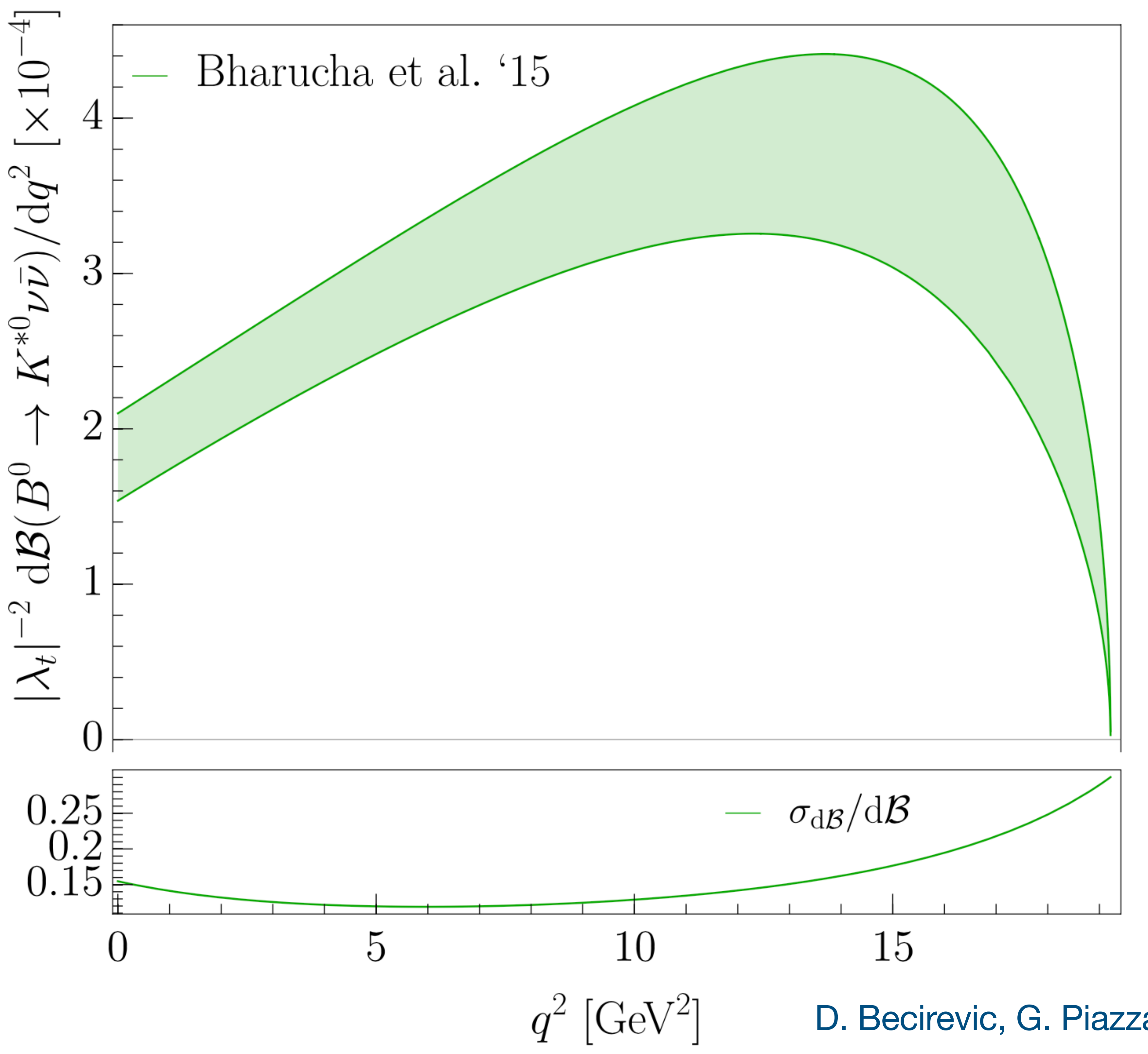


Relative error related to FF determination $\sim \mathcal{O}(15\%)$

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

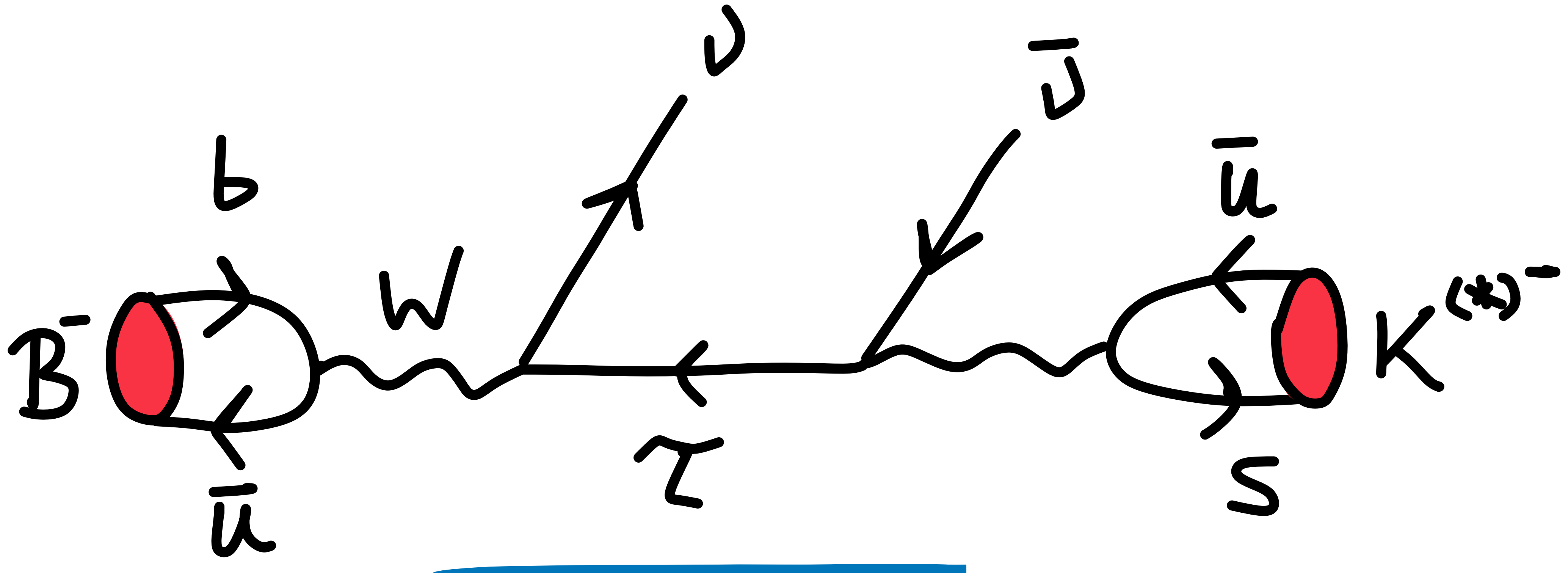
D. Becirevic, G. Piazza & O. Sumensari, arXiv:2301.06990

Tree-level contribution

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

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

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



$m_B > m_\tau > m_{K^{(*)}}$

Tree-level contribution

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

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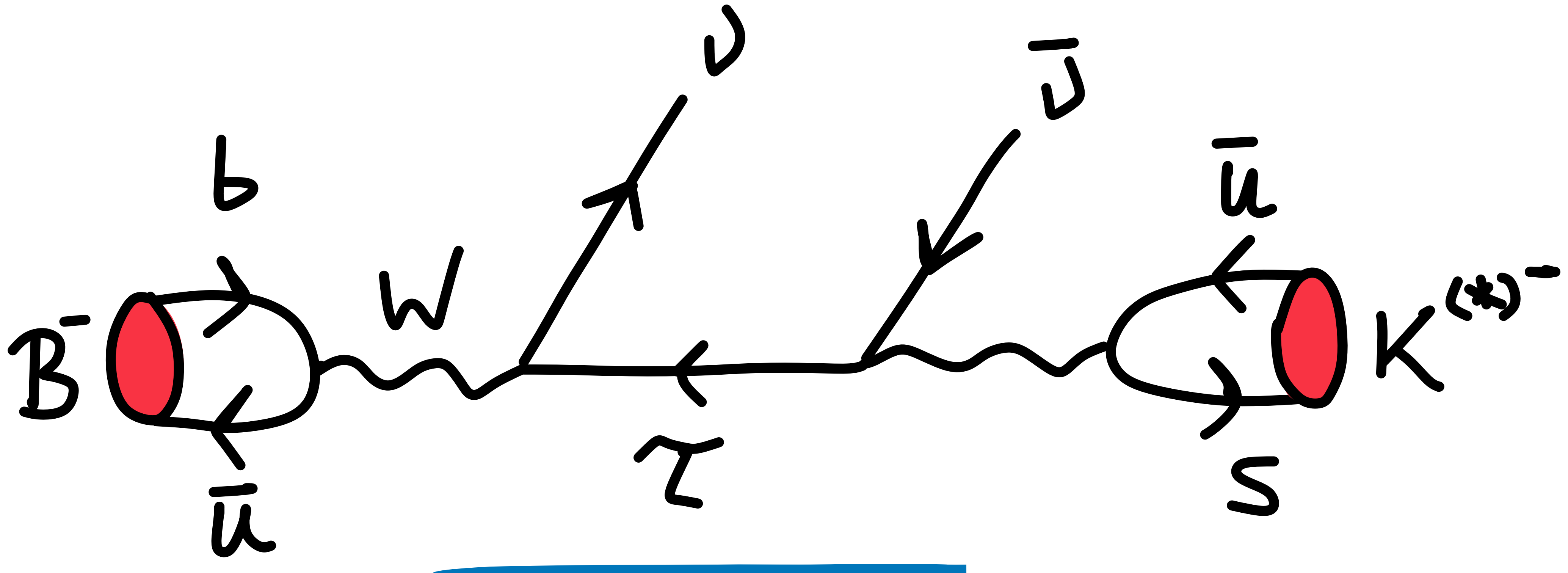

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Using the narrow width approximation

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

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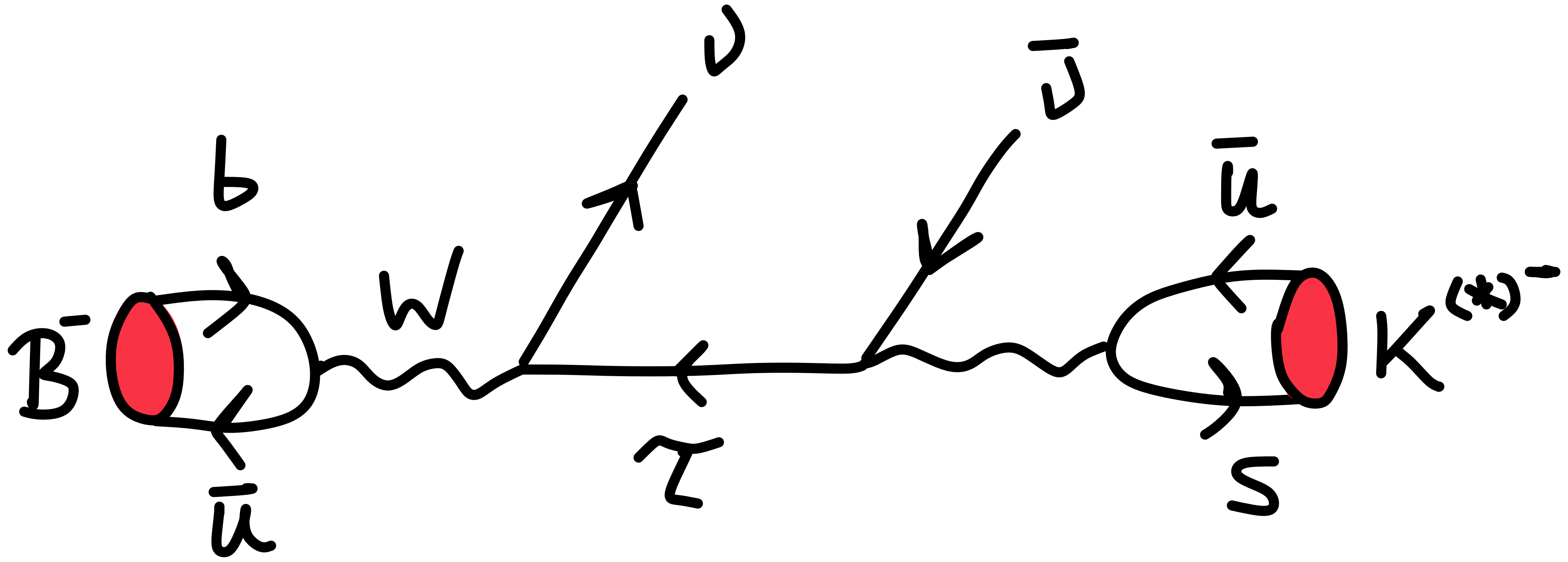

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$$\frac{\mathscr{B}\left(B \to K^{(*)}\nu\bar{\nu}\right)_{\text{tree}}}{\mathscr{B}\left(B \to K^{(*)}\nu\bar{\nu}\right)_{\text{loop}}} \simeq 14\,\%\,(11\%)$$

Non negligible contribution!

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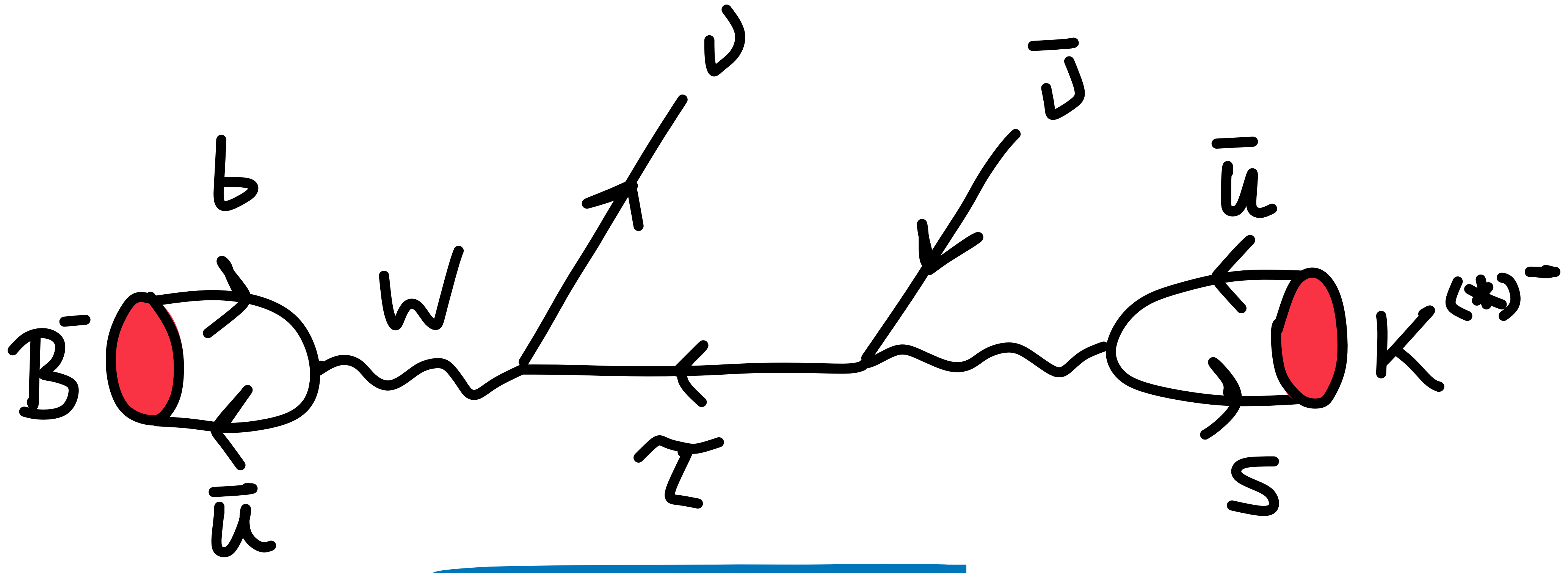

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Non negligible contribution!

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

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

Test of the extrapolated Lattice QCD form factors

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

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Test of the extrapolated Lattice QCD form factors

Independent of FF normalization and NP contributions (w/o ν_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

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

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

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

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

Possible improvements/checks

Ratio of BFs at low and high q^2 bins

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

Use high-q^2 bins to reduce FF uncertainty

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$B \to K^{(*)}\nu\bar{\nu}$ after Belle-II results

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

BSM contributions

E. Ganiev @ EPS

$$\mathscr{B}\left(B^+ \to K^+\nu\bar{\nu}\right)\Big|_{\mathrm{Belle-II}} = (2.4 \pm 0.7) \times 10^{-5}$$

Talk by J. Cerasoli & L. Martel

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Including BSM contributions we can write (w/o ν_R*)

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See T. Felkl *et al.*, arXiv:2309.02940
for the analysis with ν_R

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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

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All BSM contributions are contained here

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$$\delta\mathcal{B}_{K^{(*)}} = \sum_i \frac{2\mathrm{Re}[C_L^{\mathrm{SM}}(\delta C_L^{\nu_i\nu_i} + \delta C_R^{\nu_i\nu_i})]}{3\;\; C_L^{\mathrm{SM}} \;\;^2} + \sum_{i,j} \frac{\delta C_L^{\nu_i\nu_j} + \delta C_R^{\nu_i\nu_j} \;\;^2}{3\;\; C_L^{\mathrm{SM}} \;\;^2} - \eta_{K^{(*)}} \sum_{i,j} \frac{\mathrm{Re}[\delta C_R^{\nu_i\nu_j}(C_L^{\mathrm{SM}}\delta_{ij} + \delta C_L^{\nu_i\nu_j})]}{3\;\; C_L^{\mathrm{SM}} \;\;^2}$$

$$\eta_K = 0$$

$$\eta_{K^*} = 3.33 \pm 0.07$$

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 NP

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

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

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

R. Bause, G. Hisbert & G. Hiller, arXiv:2309.00075
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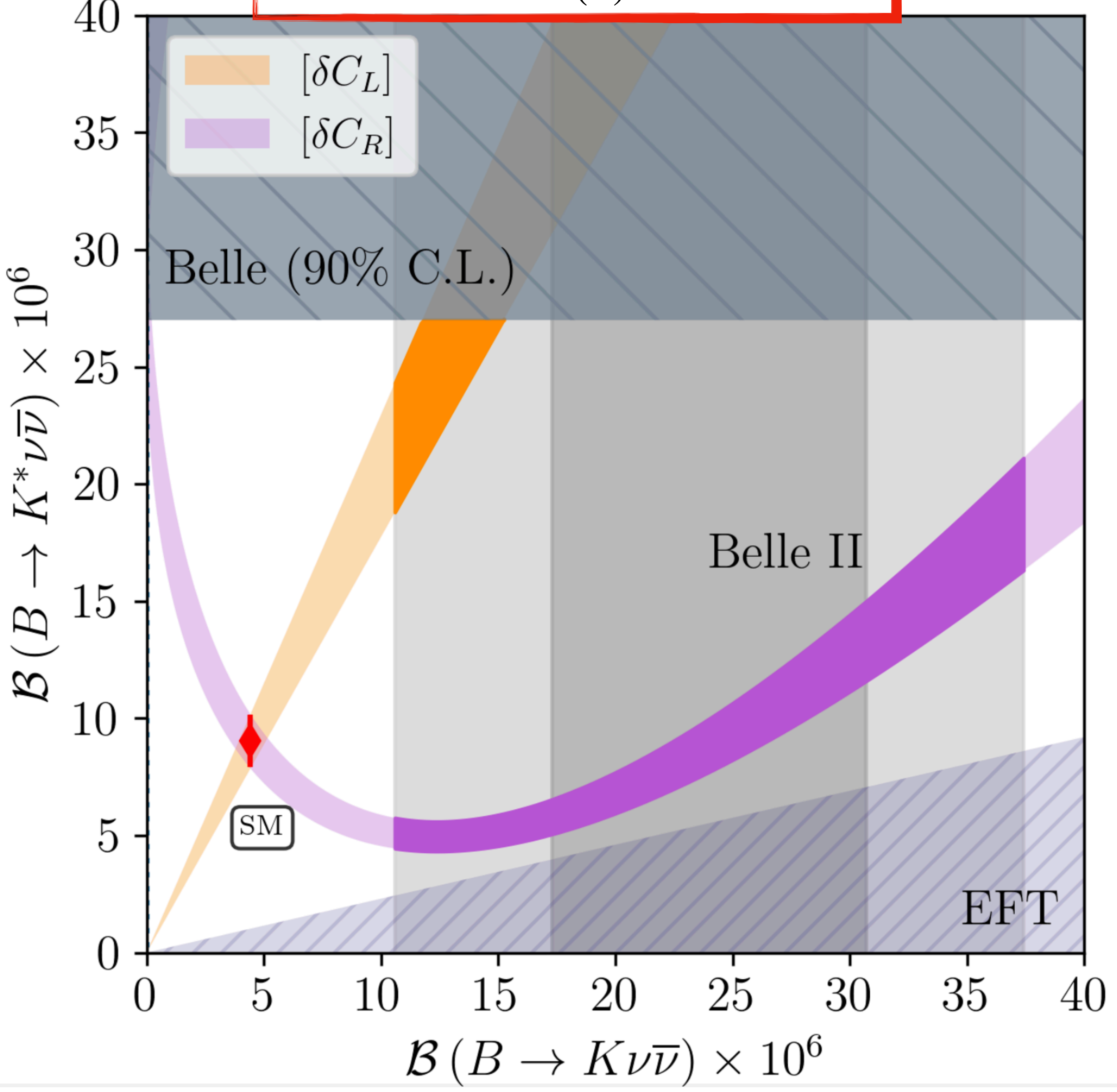
Assuming $\delta C^{\nu_i\nu_j}_{L(R)} = \delta C_{L(R)}\delta_{ij}$



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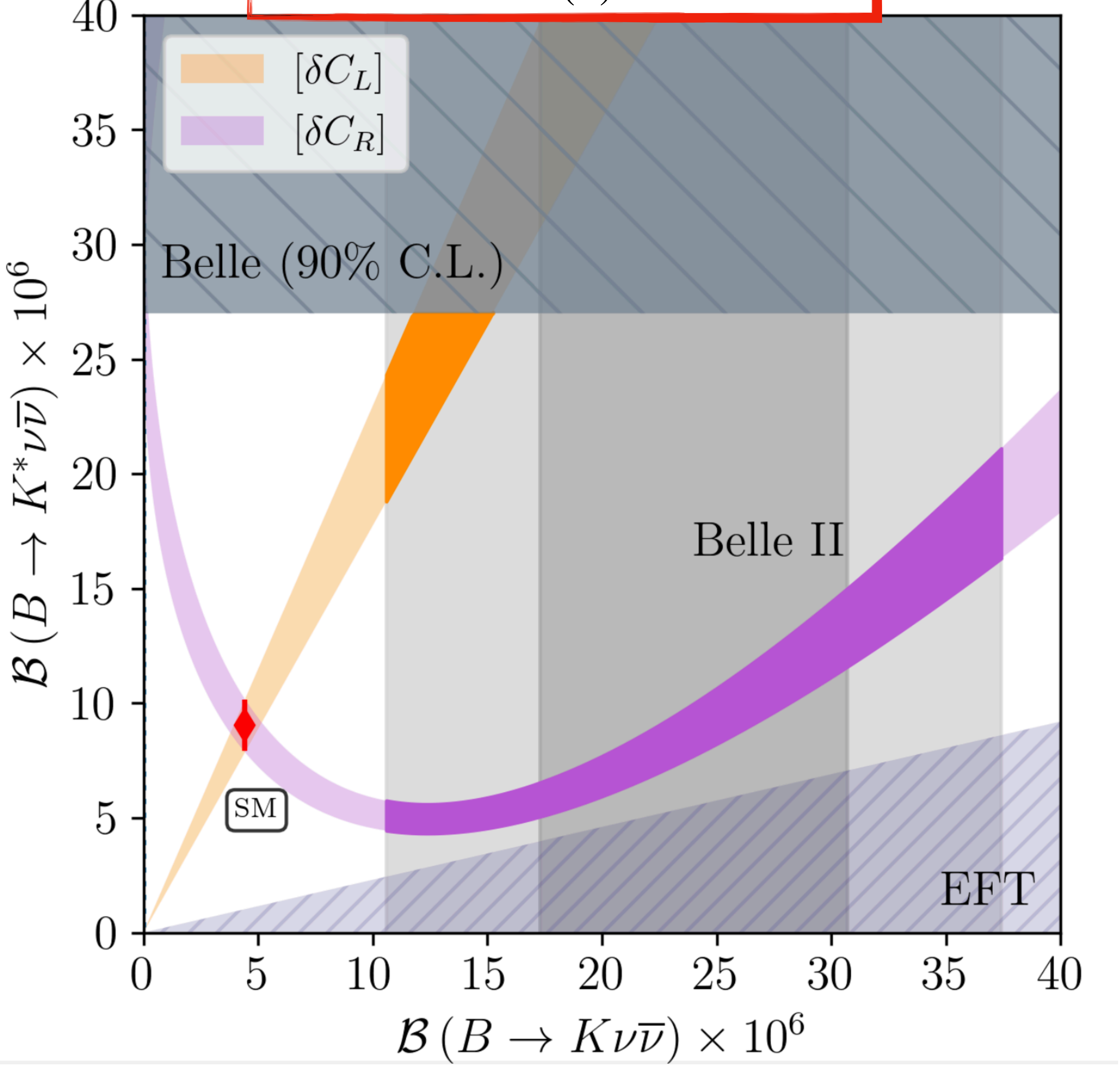
Belle bounds $\mathscr{B}(B \to K^*\nu\bar{\nu}) < 2.7 \times 10^{-5}$
constraining a solution only in terms of δC_L

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

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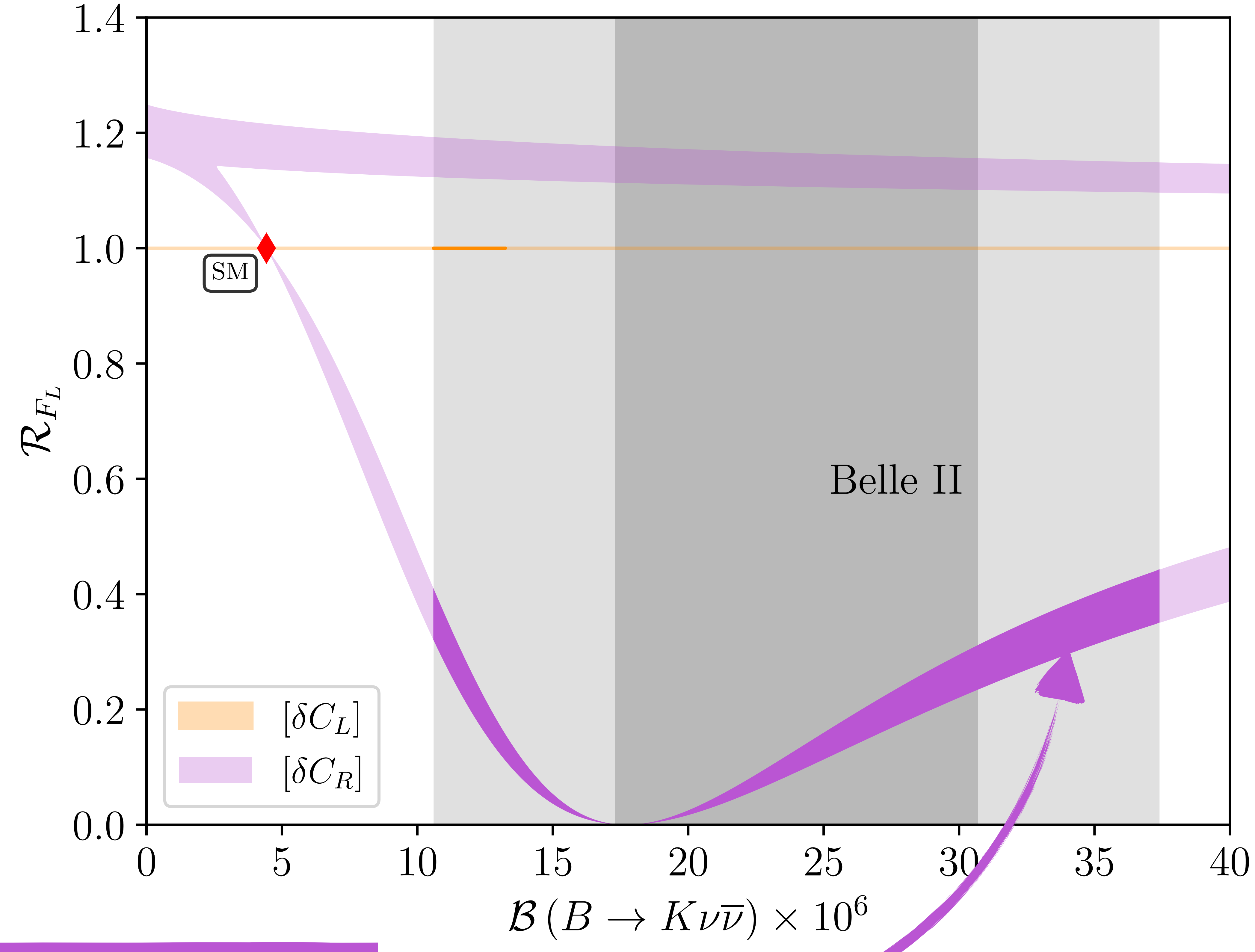
Look for the fraction of longitudinally polarized K^*, F_L

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

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



After imposing the Belle bound, we find $F_L \in [0, 0.21]$ for δC_R

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

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

Four fermion operators

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

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

L. Allwicher, D. Becirevic, G. Piazza,
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Matching to the low-energy NP couplings

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

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

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Contributions to $B \to K\nu\bar{\nu}$ will have an impact on observables with charged leptons!

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

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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ATLAS, arXiv:1812.03017
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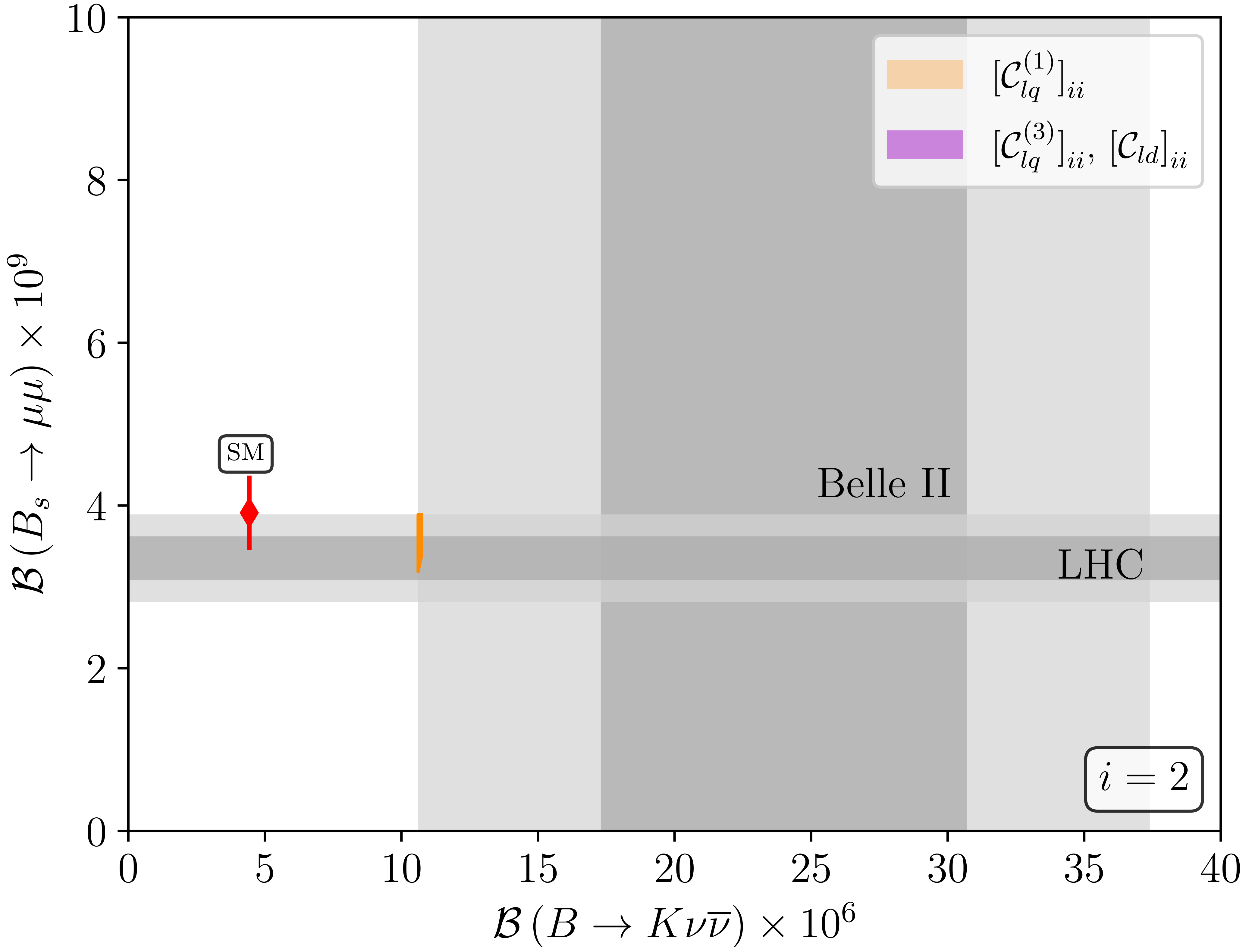
$$\mathcal{O}_{10} = \frac{e^2}{(4\pi)^2}\left(\bar{s}_L \gamma^\mu b_L\right)\left(\bar{\ell}\gamma_\mu \gamma_5 \ell\right)$$

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



L. Allwicher, D. Becirevic, G. Piazza,
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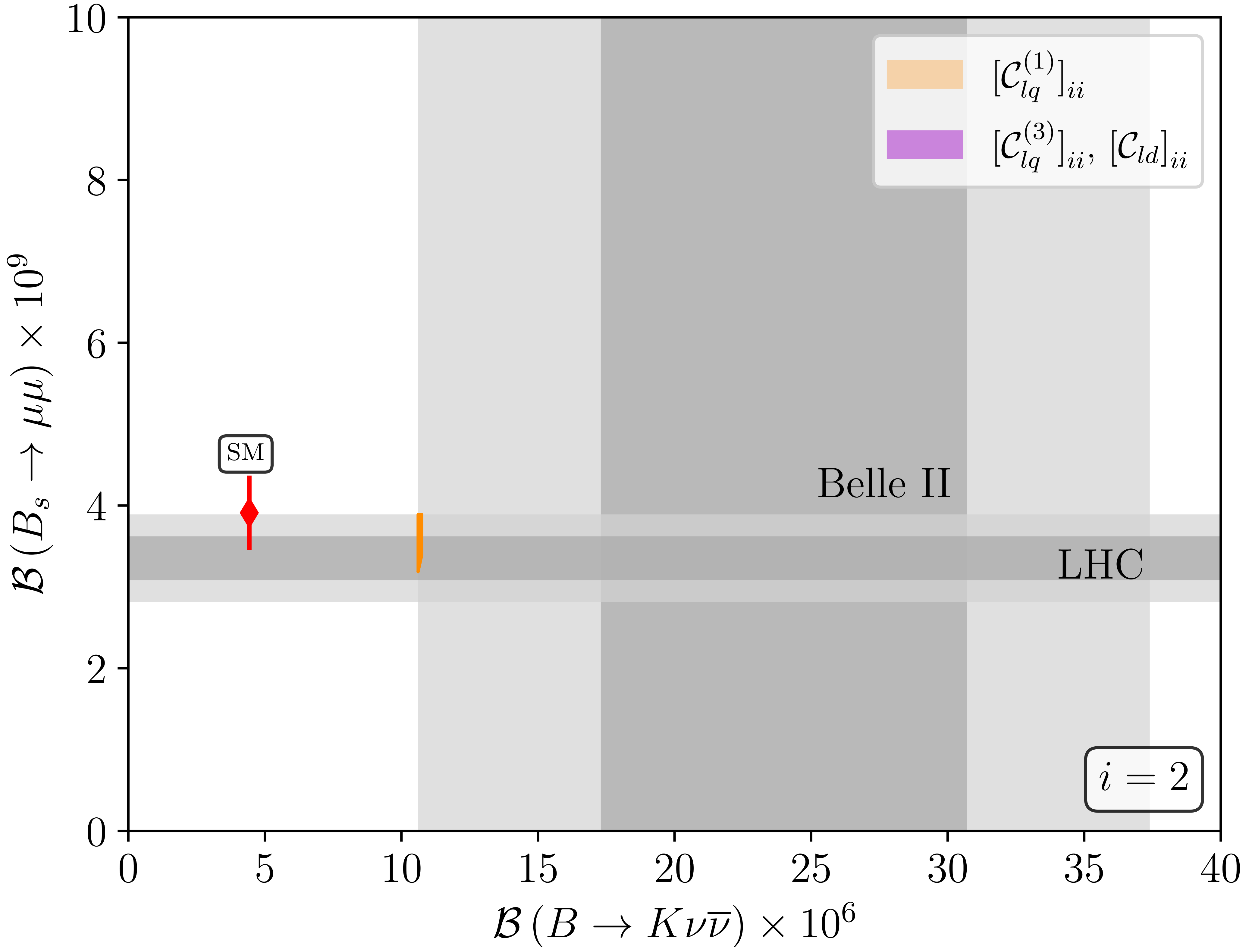
Note that one could also use $R_{K^{(*)}}$ now as well as a constrain

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



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

$$R_{D^{(*)}}^{\text{exp}}/R_{D^{(*)}}^{\text{SM}} = 1.16 \pm 0.05$$

Correlations between observables

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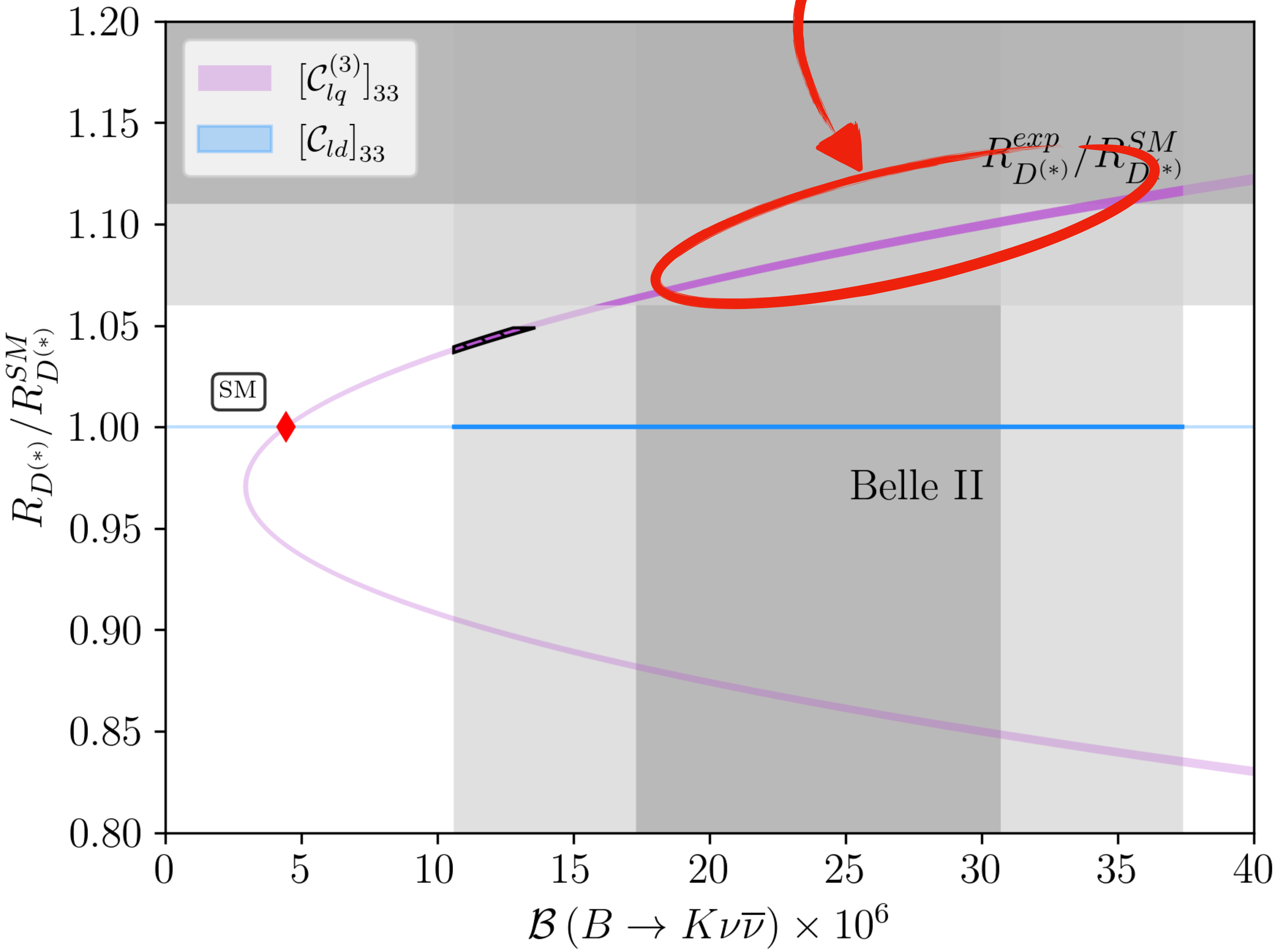
HFLAV, arXiv:2206.07501

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

BSM contributions to this process given by

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

Excluded by $\mathscr{B}\left(B \to K^*\nu\bar{\nu}\right)$



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

Correlations between observables

Coupling to tau leptons

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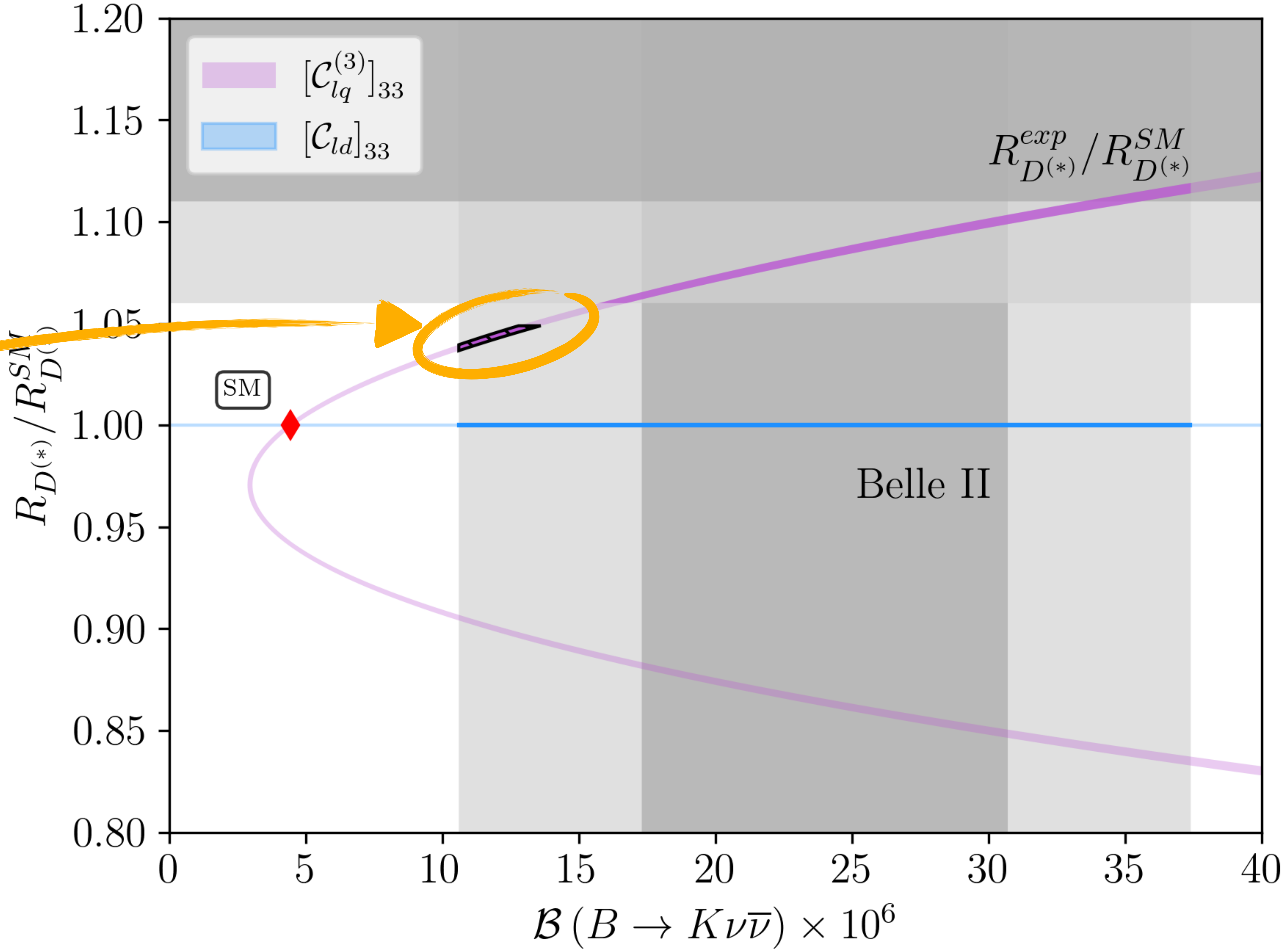
$$R^{\text{exp}}_{D^{(*)}}/R^{\text{SM}}_{D^{(*)}} = 1.16 \pm 0.05$$

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

$$\frac{\mathcal{B}\left(B_s \to \tau\tau\right)_{BSM}}{\mathcal{B}\left(B_s \to \tau\tau\right)_{\text{SM}}} \in [44,157]$$



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Conclusions

SM predictions

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

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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- CKM matrix element determination: **Inclusive vs exclusive** V_{cb} — Can change prediction by $\mathcal{O}(10\%)$

- Form factor determination:
  - $B \to K\nu\bar{\nu}$ has several Lattice determinations — Error $\mathcal{O}(5\%)$
  - $B \to K^{*}\nu\bar{\nu}$ with one Lattice determination + LCSR — Error $\mathcal{O}(15\%)$

Eventually need to match expected sensitivity by Belle-II

Conclusions

BSM contributions

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$$\mathcal{B}\left(B^{+} \to K^{+}\nu\bar{\nu}\right)\Big|_{\text{Belle-II}} = (2.4 \pm 0.7) \times 10^{-5}$$

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

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

Contributions from only $C_R^{\nu_i\nu_j}$ can explain $B \to K\nu\bar{\nu}$, correlated with $\mathcal{B}\left(B \to K^*\nu\bar{\nu}\right)$ compared to SM

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In the context of SMEFT → Correlation between neutrino decay modes and those involving charged leptons

NP coupled to muons only fail to explain Belle-II taking into account $\mathscr{B}\left(B_s \to \mu\mu\right)$

NP coupled to 3rd generation explain Belle-II, but additional operators would be needed to explain $R_{D^{(*)}}$

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Thank you!

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Back-up slides

Reduction of uncertainties

Combination with $B \to K^{(*)}\mu\mu$

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

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

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

Partial branching fractions integrated in the same q^2 range

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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

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

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

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

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

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But we can use this ratio to extract C_9!

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