The new physics implication for the recent Belle II observation of $B^+ \to K^+\nu\bar{\nu}$

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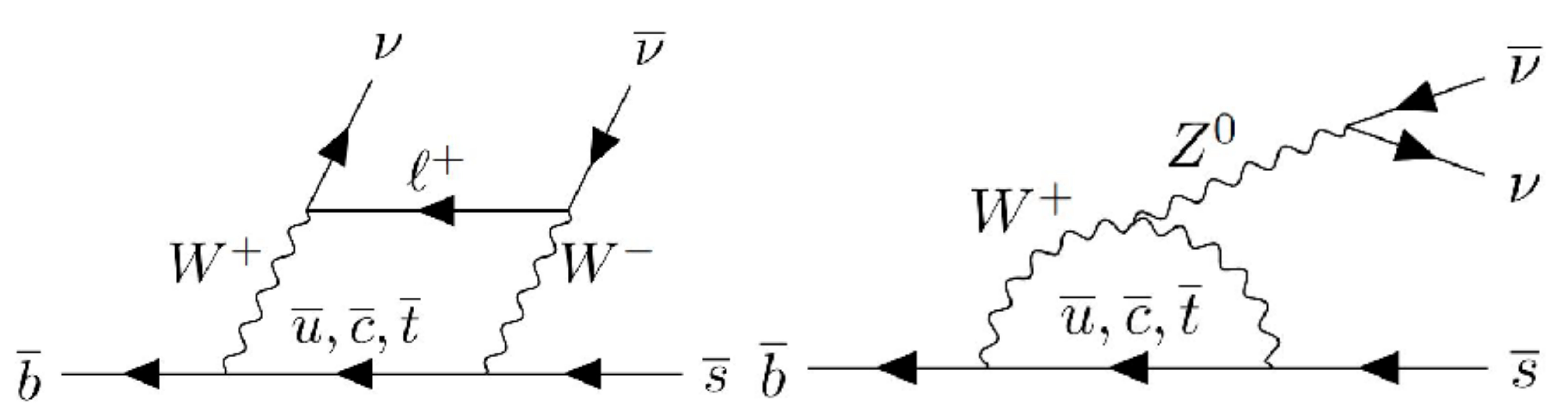
Outline

- Introduction
- New contribution to $B^+ \to K^+\nu\bar{\nu}$ from heavy mediator
- New decay modes involving new light states (sterile neutrinos or DM-like particles)
- Summary

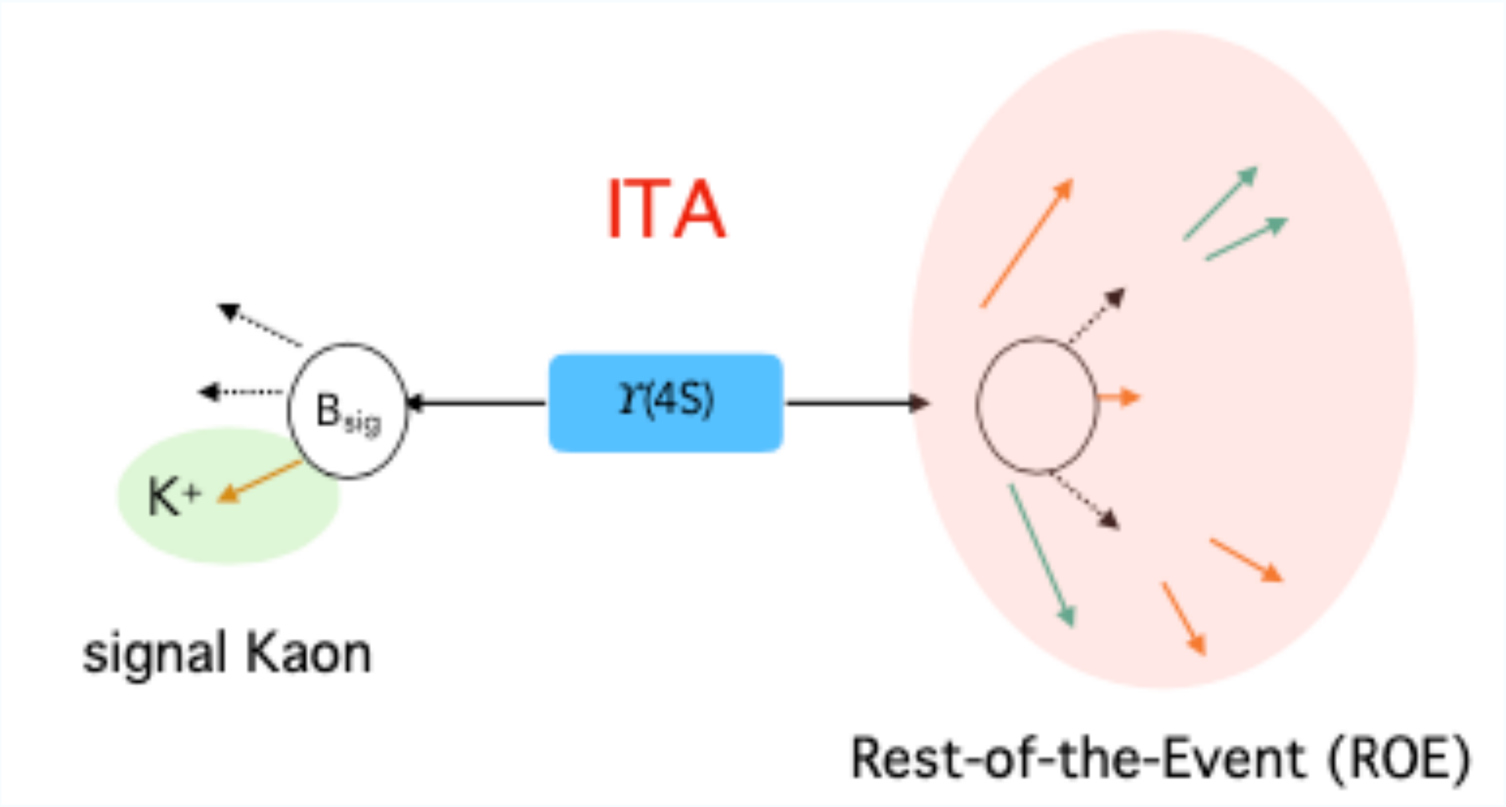
$B \to K^{(*)}\nu\bar{\nu}$ in the SM



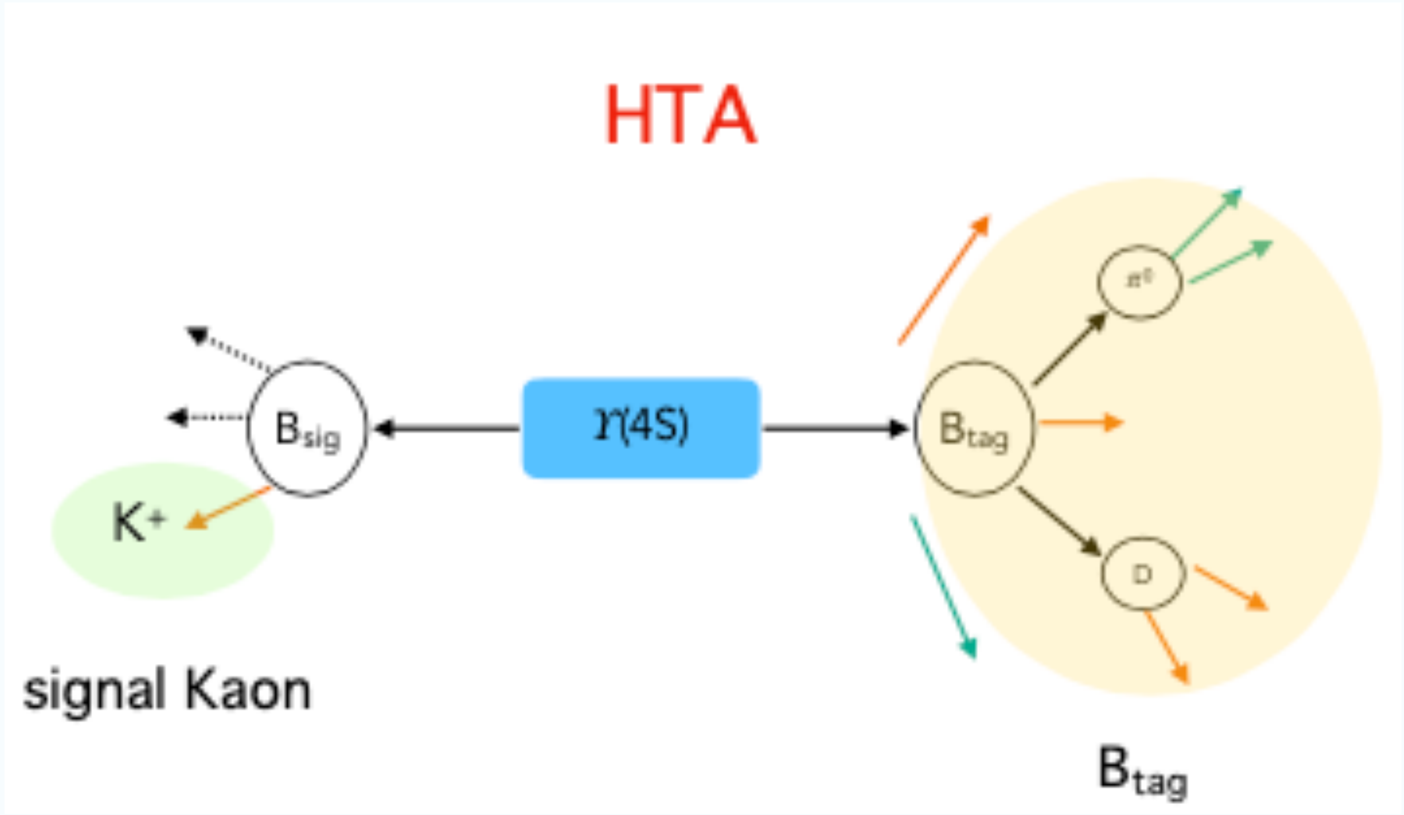
- Tree-level contribution is forbidden, suppressed by GIM mechanism at loop-level
- SM uncertainty is well-controlled, mainly from hadronic form factor
- SM prediction: $\mathscr{B}(B^+ \to K^+\nu\bar{\nu})_{\mathrm{SM}} = (4.43 \pm 0.31) \times 10^{-6}$
- $b \to s$ + missing are cleanest modes to search for new physics

Recent Belle II result

鄢文标’s talk



Inclusive Tag analysis (ITA)
more sensitive



Hadronic Tag analysis (HTA)
more conventional

- Combination: $\mathscr{B}(B^+ \to K^+ \nu\bar{\nu})_{\rm exp} = (2.4 \pm 0.7) \times 10^{-5}$

A. Glazov, talk @EPS-HEP2023
E. Ganiew,talk @EPS-HEP2023

- Combine Belle II 2021 data, $\mathscr{B}(B^+ \to K^+ \nu\bar{\nu})^{\rm ave}_{\rm exp} = (1.4 \pm 0.4) \times 10^{-5}$

- $2.8\,\sigma$ higher than SM prediction $\Rightarrow$ New physics possibility

Experimental results vs SM prediction

- Study ratios of experimental observation over SM prediction could bypass NP hidden in CKM

$$R_K^{\nu\nu} = \frac{\mathcal{B}(B^+ \to K^+\nu\bar{\nu})_{\mathtt{exp}}}{\mathcal{B}(B^+ \to K^+\nu\bar{\nu})_{\mathtt{SM}}} = 5.4 \pm 1.6.$$

$$R_{K^*}^{\nu\nu} = \frac{\mathcal{B}(B \to K^*\nu\bar{\nu})}{\mathcal{B}(B \to K^*\nu\bar{\nu})_{\mathtt{SM}}} \leq 2.7 \text{ or } 1.9.$$

- 2.7 $\Leftarrow$ combination of the charged and neutral modes
- 1.9 $\Leftarrow$ $\mathcal{B}(B^0 \to K^{0*}\nu\bar{\nu}) \leq 1.8 \times 10^{-5}\,(90\,\%\,\mathrm{CL})$ Belle, 1702.03224

The predictions for the charged and neutral modes are the same in many models

NP implication

New heavy mediators in the tree/loop, or new invisible particles in the final state

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

- Lepton flavor universality (LFU): same coupling to $\nu_e\bar{\nu}_e, \nu_\mu\bar{\nu}_\mu, \nu_\tau\bar{\nu}_\tau,$
- Lepton flavor conservation without universality: different coupling to $\nu_e\bar{\nu}_e, \nu_\mu\bar{\nu}_\mu, \nu_\tau\bar{\nu}_\tau,$
- Lepton flavor violation (LFV): $\nu_i\bar{\nu}_j$ with $i \neq j$ are open

* New invisible particles in the final state

- Sterile neutrino-like particle : $B \to K^{(*)} + \nu N, B \to K^{(*)} + N\bar{N}$
- DM/ dark sector particles: $B \to K^{(*)} + \mathtt{DM} + \mathtt{DM}$
- 2-body with dark scalar: $B \to K^{(*)} + \phi(S)$

- $B \to K^{(*)} + \nu_i \bar{\nu}_j$
  - Peter Athron, R. Martinez, Cristian Sierra, 2308.13426
  - L. Allwicher, D. Becirevic, G. Piazza, S. Rosauro- Alcaraz, O. Sumensari, 2309.02246
  - R. Bause, H. Gisbert, G. Hiller, 2309.00075
  - Xiao-Gang He, **XDM**, German Valencia, 2309.12741
  - Chuan-Hung Chen, Cheng-Wei Chiang, 2309.12904
- $B \to K^{(*)} + \nu N, B \to K^{(*)} + N\bar{N}$
  - T. Felkl, A. Giri, R. Mohanta, M. A. Schmidt, 2309.02940
  - Xiao-Gang He, **XDM**, German Valencia, 2309.12741
  - Herbert K. Dreiner, Julian Y. Gunther, Zeren Simon Wang, 2309.03727
- $B \to K^{(*)} + \mathrm{DM} + \mathrm{DM}$
  - Xiao-Gang He, **XDM**, German Valencia, 2209.05223
  - Xiao-Gang He, **XDM**, German Valencia, 2309.12741
- $B \to K^{(*)} + \phi(S)$
  - Murat Abdughani, Yakefu Reyimuaji. 2309.03706
  - Alexander Berezhnoy, Dmitri Melikhov, 2309.17191
  - Alakabha Datta, Danny Marfatia, 2310.15136

EFT vs model interpretation

* EFTs
  - SMEFT, νSMEFT
  - LEFT
  - DMEFT

$$\mathcal{O}_{lq}^{(1)} = (\bar{L}\gamma^{\mu}L)(\bar{Q}\gamma_{\mu}Q)$$

$$\mathcal{O}_{lq}^{(3)} = (\bar{L}\sigma^{I}\gamma^{\mu}L)(\bar{Q}\sigma^{I}\gamma_{\mu}Q)$$

$$\mathcal{O}_{ld} = (\bar{L}\gamma^{\mu}L)(\bar{d}\gamma_{\mu}d)$$

B. Grzadkowski, M. Iskrzynski, M. Misiak, J. Rosiek, 1008.4884

$$\mathcal{O}^{QN} = (\bar{Q}\gamma_{\mu}Q)(\bar{N}\gamma^{\mu}N)$$

$$\mathcal{O}^{dN} = (\bar{d}\gamma_{\mu}d)(\bar{N}\gamma^{\mu}N)$$

$$\mathcal{O}^{LNQd} = (\bar{L}^{\alpha}N)\epsilon_{\alpha\beta}(\bar{Q}^{\beta}d)$$

$$\mathcal{O}^{LNQd,\mathrm{T}} = (\bar{L}^{\alpha}\sigma_{\mu\nu}N)\epsilon_{\alpha\beta}(\bar{Q}^{\beta}\sigma^{\mu\nu}d)$$

Y. Liao, XDM, 1612.04527

* UV models
  - Non-universal U(1)′ models: $U(1)_{L_\mu - L_\tau}$′, etc
  - Leptoquarks: $S_0(\bar{3},1,1/3)$, $\tilde{S}_{1/2}(3,2,1/6)$, $S_1(\bar{3},3,1/3)$, $V_{1/2}(\bar{3},2,5/6)$, $V_1(3,3,2/3)$
  - R-parity violating SUSY
  - Scalar mediator coupling to DM particles

Other related modes or anomalies

* Modes give strong constraints

- R_K, R_{K*} in $b \to s\ell^+\ell^-, \ell = e, \mu$
- Neutral meson mixing: $B_s - \bar{B}_s, B_d - \bar{B}_d, K^0 - \bar{K}^0$
- $B_s \to \mu^+\mu^-$
- $B \to K^* + inv.$
- $B_s \to inv.$

- Strong interplay with $B \to K + inv.$
- Can be used to test some scenarios in the future measurements

* Other anomalies could be also included:

- $R(D), D(D^*)$ anomalies in $b \to c\tau\nu$: $R_D/R_D^{\rm SM} = 1.19(10), \quad R_{D*}/R_{D*}^{\rm SM} = 1.15(5)$
- The excess of electron-like events in the MiniBoone
- Muon g-2

HFAG & HFLAV, 2206.07501

New contributions to $b \to s\nu\bar{\nu}$ with heavy new mediators

The starting point is the WEF or LEFT:

$$\mathcal{H}_{\mathrm{NP}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^{\star} \frac{e^2}{16\pi^2} \sum_{ij} \left(C_L^{ij} \mathcal{O}_L^{ij} + C_R^{ij} \mathcal{O}_R^{ij} \right) + \mathrm{h.c.}, \quad \begin{aligned} \mathcal{O}_L^{ij} &= (\bar{s}\gamma_\mu P_L d)(\bar{\nu}_i \gamma^\mu P_L \nu_j) \\ \mathcal{O}_R^{ij} &= (\bar{s}\gamma_\mu P_R d)(\bar{\nu}_i \gamma^\mu P_L \nu_j) \end{aligned}$$

The SM contributes only to $C_{L,\mathrm{SM}}^{ii} = -X(x_t)/s_W^2, \quad X(x_t) = 1.46 \pm 0.017$

$$R_K^{\nu\nu} \approx 1 - 0.1\ \mathrm{Re} \sum_i \left(C_L^{ii} + C_R^{ii} \right) + 0.008 \sum_{ij} \left| C_L^{ij} + C_R^{ij} \right|^2,$$

$$R_{K^*}^{\nu\nu} \approx 1 + \mathrm{Re} \sum_i \left(-0.1\ C_L^{ii} + 0.07\ C_R^{ii} \right) + \sum_{ij} \left[0.008 \left(C_L^{ij\,2} + C_R^{ij\,2} \right) - 0.01 C_L^{ij} C_R^{ij} \right].$$

C_L^{ij} alone cannot satisfy both $3.8 \leq R_K^{\nu\nu} \leq 7$ and $R_{K^*}^{\nu\nu} \leq 2.7(1.9)$

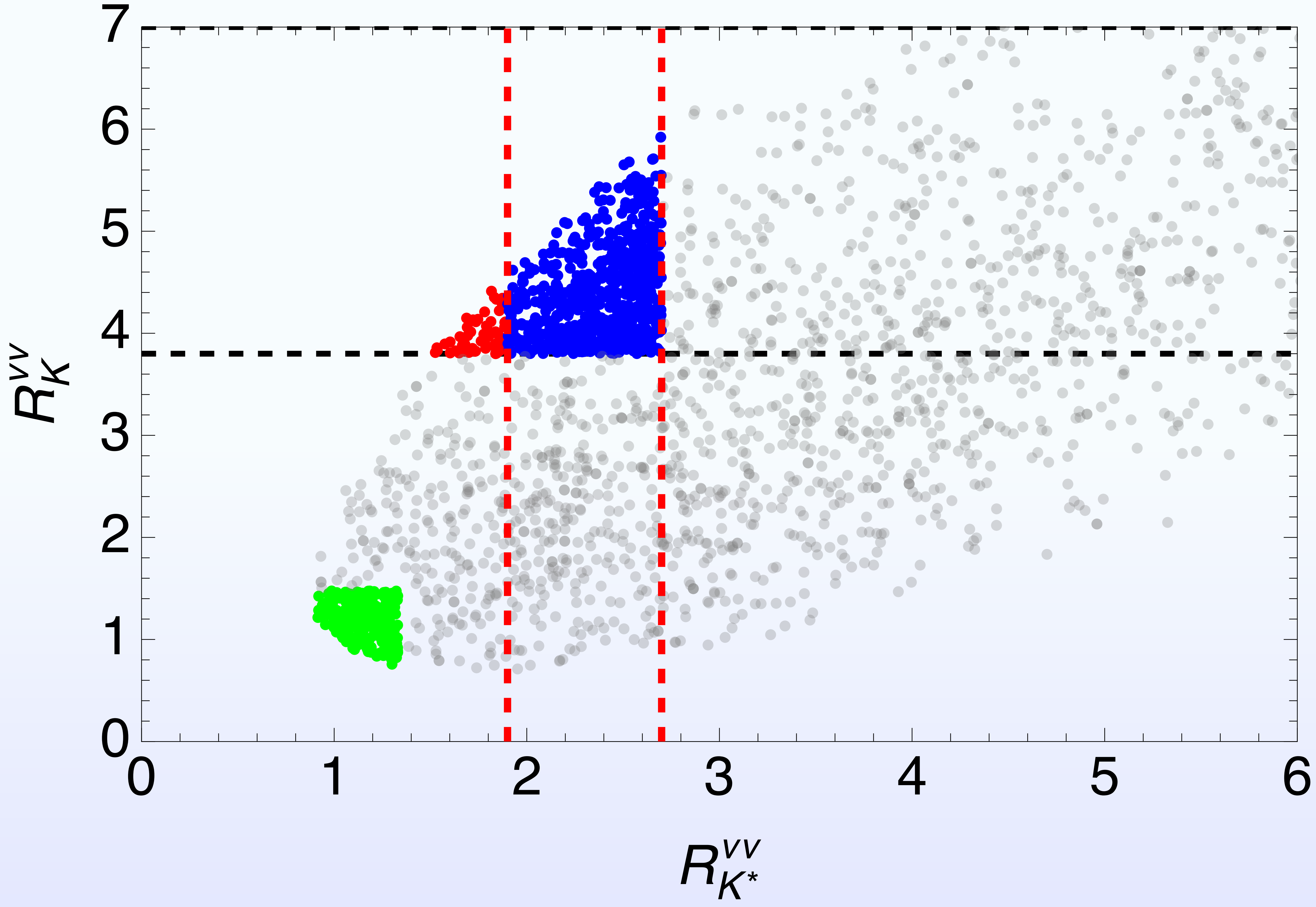
Models with only $S_0(\bar{3},1,1/3)$, $S_1(\bar{3},3,1/3)$, $V_1(3,3,2/3)$ are incompatible

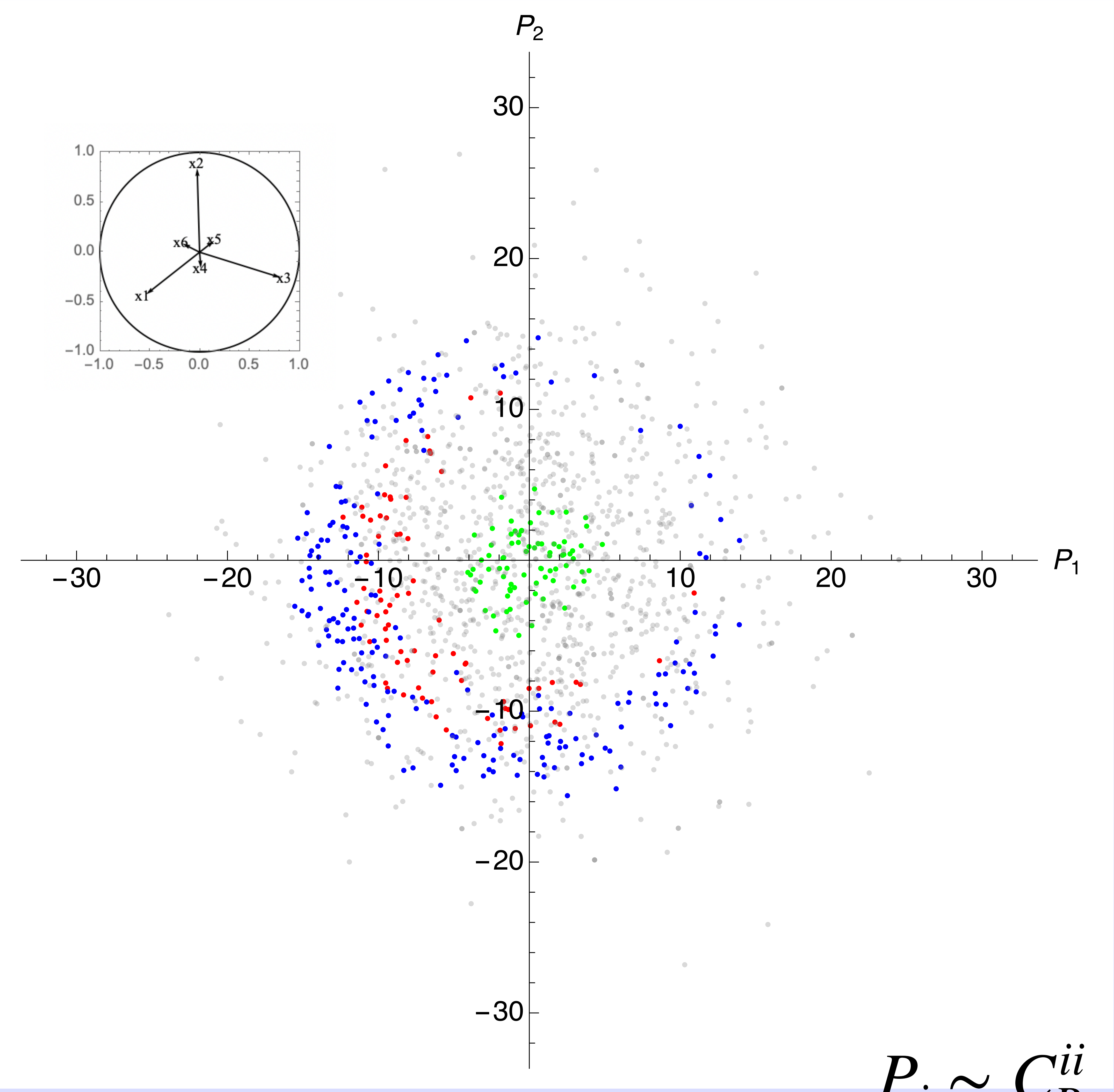
Leptoquark models

$$\mathcal{L}_S = \lambda_{LS_0}\overline{Q^c} i\tau_2 L S_0^\dagger + \lambda_{L\tilde{S}_{1/2}} \bar{d} L \tilde{S}_{1/2}^\dagger + \lambda_{LS_1}\overline{Q^c} i\tau_2 \vec{\tau}\cdot\vec{S}_1^\dagger L + \text{h.c.},$$

$$\mathcal{L}_V = \lambda_{LV_{1/2}}\overline{d^c}\gamma_\mu L V_{1/2}^{\dagger\mu} + \lambda_{LV_1}\bar{Q}\gamma_\mu\vec{\tau}\cdot\vec{V}_1^{\dagger\mu} L + \text{h.c.}.$$

C_R^{ij} can simultaneously satisfies the requirement of $R_K^{\nu\nu}$ and $R_{K*}^{\nu\nu}$





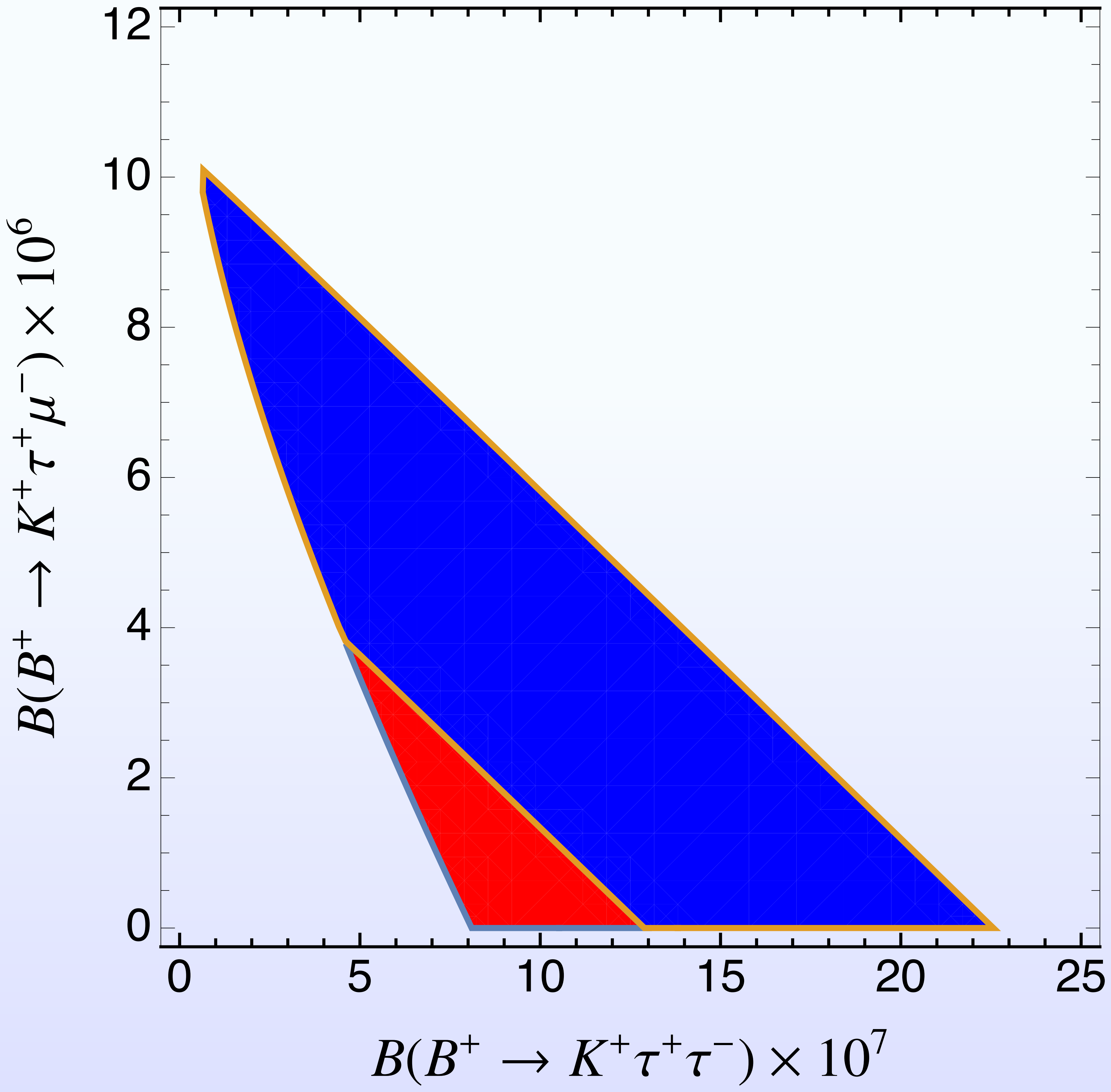
$P_i \sim C_R^{ii}$

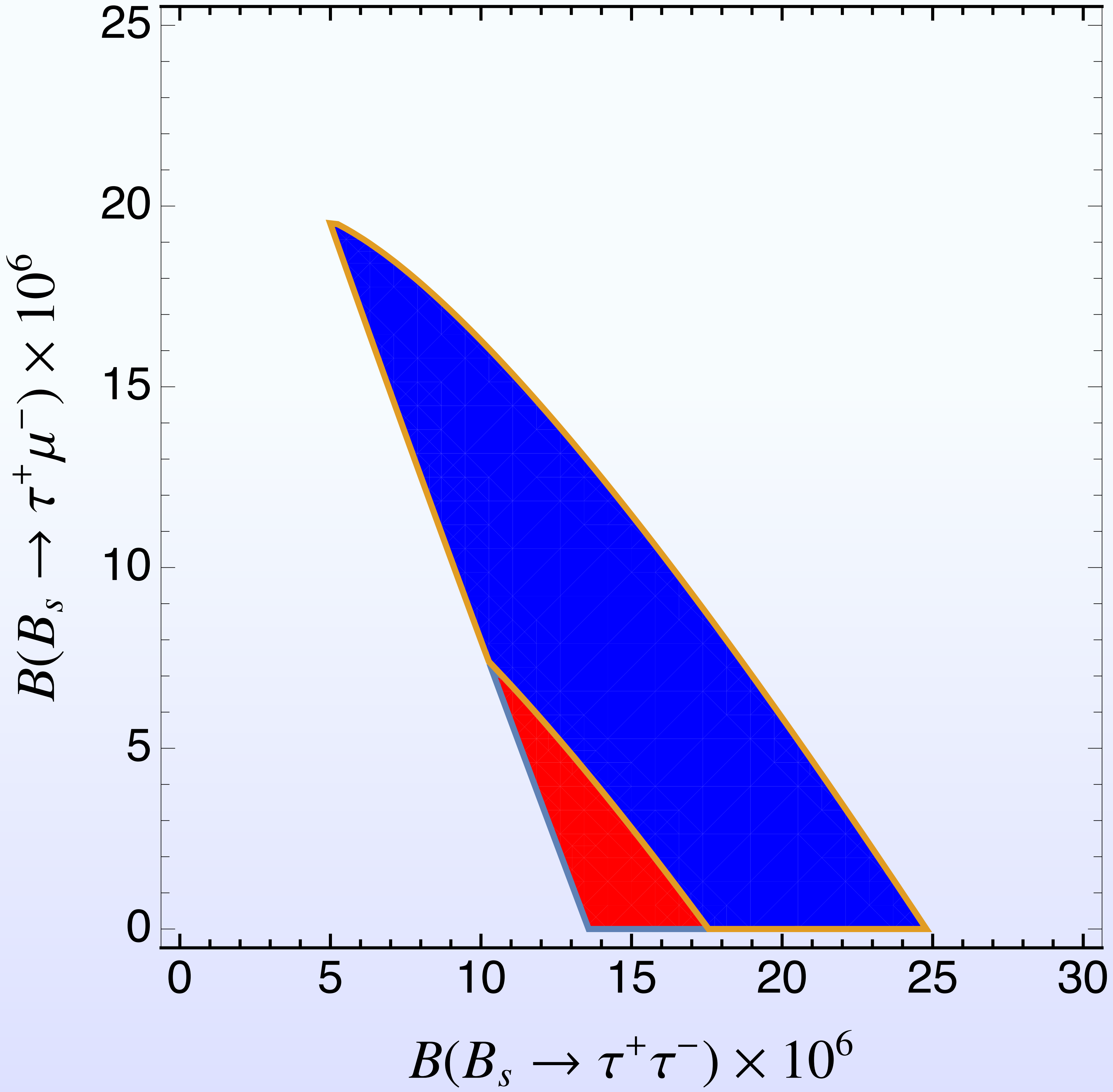
Imposing the constraints from $b \to s\ell^+\ell^-$

↓

The case with large $C_R^{\tau\tau}$ is the only viable solution → FLU violation

The WCs $C_R^{\tau\tau}$ and $C_R^{\mu\tau}$ generated by $\tilde{S}_{1/2}$ or $V_{1/2}$ imply large rates for other B decay modes





$\mathscr{B}(B^+ \to K^+\mu^-\tau^+)_{\texttt{PDG}} \leq 2.8\times 10^{-5}(90\,\%)$

$\mathscr{B}(B^+ \to K^+\tau^+\tau^-)_{\texttt{PDG}} \leq 2.25\times 10^{-3}(90\,\%)$

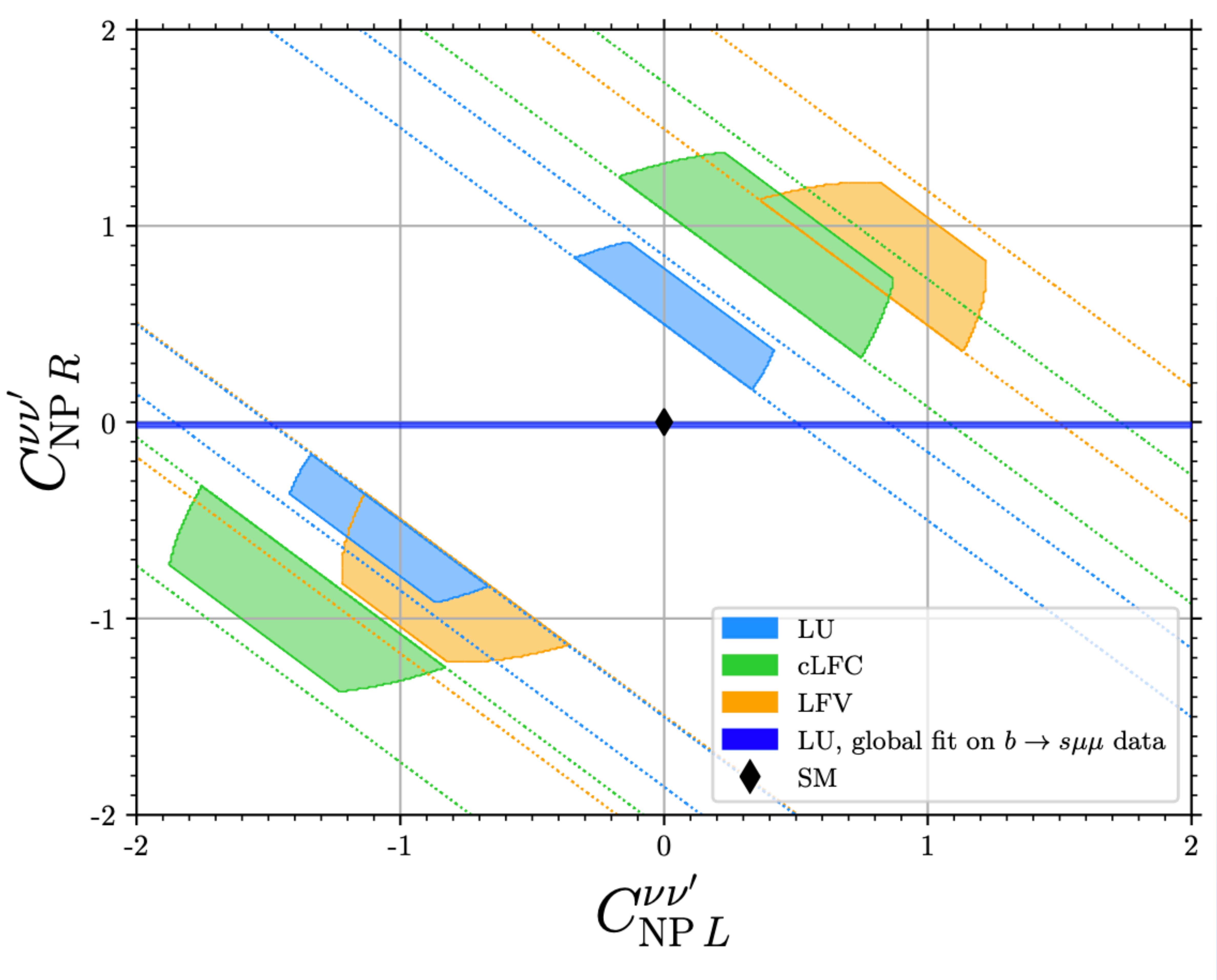
$\mathscr{B}(B_s \to \mu^-\tau^+)_{\texttt{PDG}} \leq 4.2\times 10^{-5}(95\,\%)$

$\mathscr{B}(B_s \to \tau^+\tau^-)_{\texttt{PDG}} \leq 6.8\times 10^{-3}(95\,\%)$

Other lepton flavor structure for the interpretation

R. Bause, H. Gisbert, and G. Hiller, 2309.00075

$$C^{\nu\nu'}_{\mathrm{NP}\,L} \sim C^{ij}_{L}, \quad C^{\nu\nu'}_{\mathrm{NP}\,R} \sim C^{ij}_{R}$$



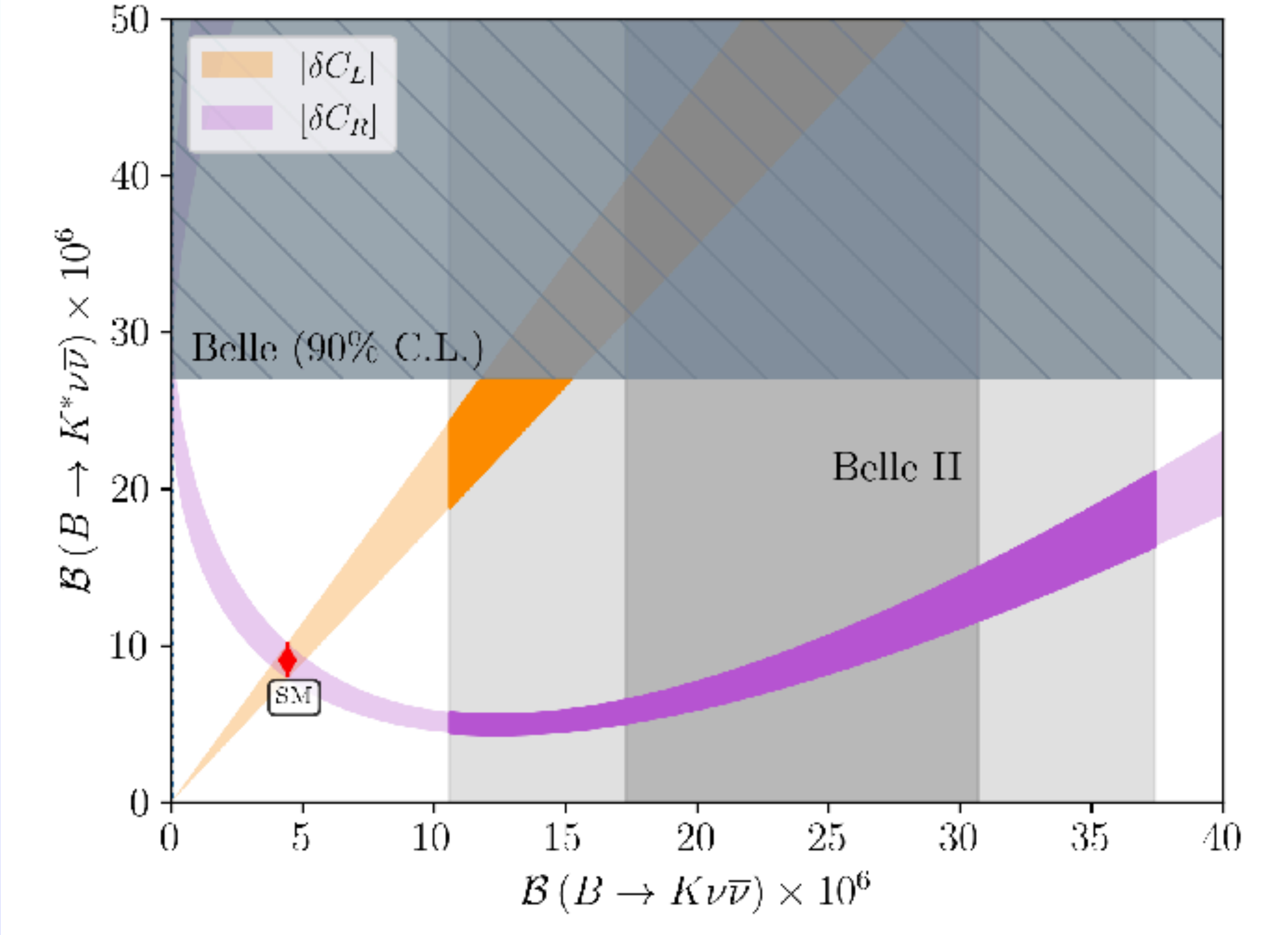
- Lepton universality (X)
- Lepton flavor conservation without universality
- Lepton flavor violation

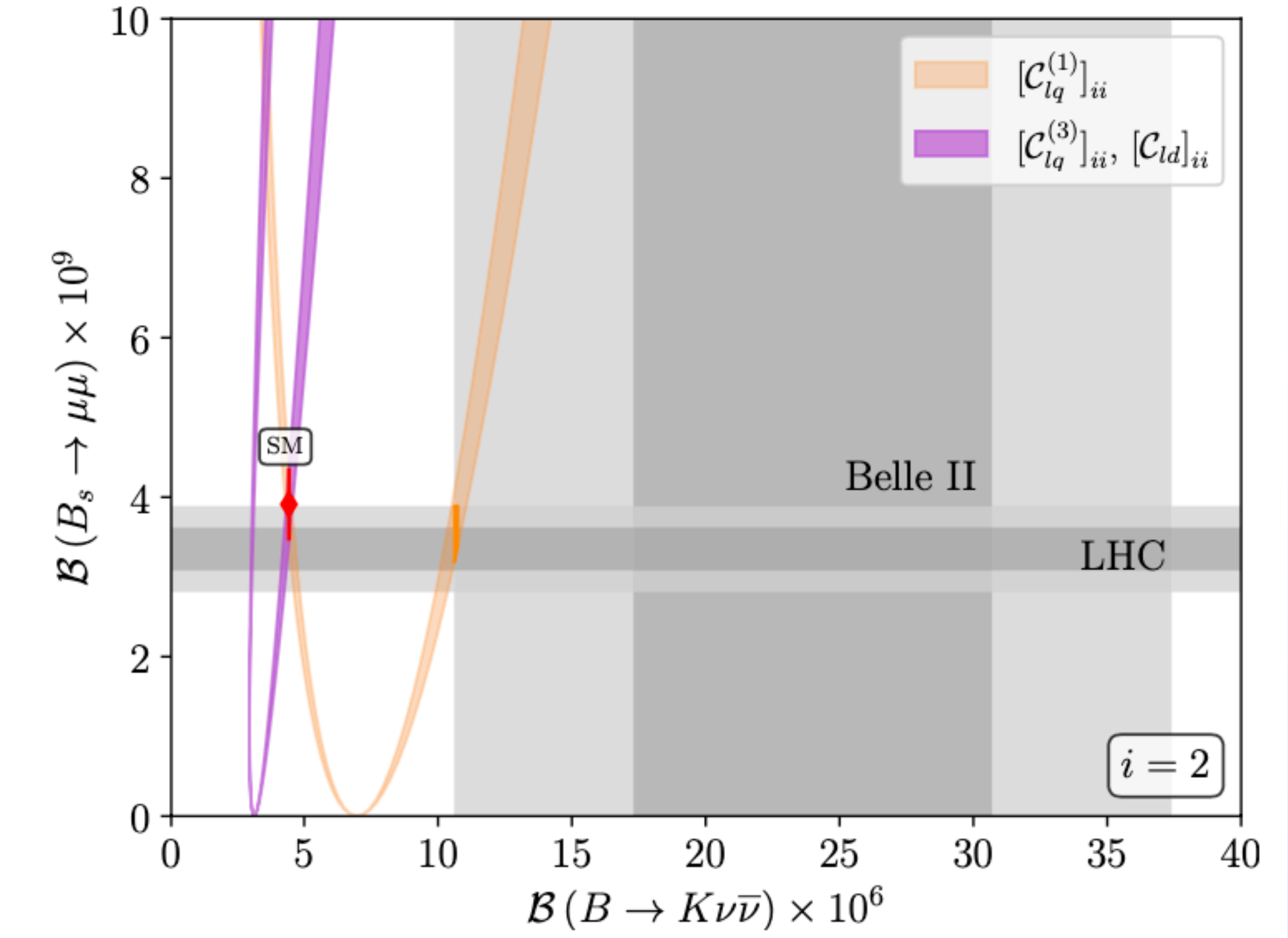
Models that feed only into one type of coupling cannot address the new Belle II result in full

Possible solutions:
— couple only to tau-flavors
— lepton flavor violating ones.

SMEFT framework

L. Allwicher, D. Becirevic, G. Piazza, S. Rosauro- Alcaraz, O. Sumensari, 2309.02246





$\mathcal{O}_{lq}^{(1)} = (\bar{L}\gamma^\mu L)(\bar{Q}\gamma_\mu Q)$, $\quad \mathcal{O}_{lq}^{(3)} = (\bar{L}\sigma^I\gamma^\mu L)(\bar{Q}\sigma^I\gamma_\mu Q)$ $\quad \mathcal{O}_{ld} = (\bar{L}\gamma^\mu L)(\bar{d}\gamma_\mu d)$

Our conclusions basically agree with those papers

Leptoquark model with gauged $U(1)_{L_\mu - L_\tau}$

Chuan-Hung Chen, Cheng-Wei Chiang, 2309.12904

$$-\mathscr{L}_Y \supset \left(\overline{u_L^{\mathtt{C}}}\mathbf{y}_L^q P_L \tau + \overline{u_R^{\mathtt{C}}}\mathbf{y}_R^u P_R \tau\right)\left(S_1^{-\frac{1}{3}}\right)^* - \overline{d_L^{\mathtt{C}}} V^T \mathbf{y}_L^q P_L \nu_\tau \left(S_1^{-\frac{1}{3}}\right)^* + \text{H.c.} \quad S_1(3,1,-1/3;1)$$

↓

$$\mathscr{H}_{d_i \to d_j \nu\bar{\nu}} = C_L^{\rm SM} V_{td_i}^* V_{td_j}\left(X_t + C_{L,ij}^{S_1}\delta_{\ell\tau}\right)\bar{d}_i \gamma_\mu P_L d_j \bar{\nu}_\ell \gamma^\mu P_L \nu_\ell$$

↓

$$\mathscr{B}(B \to M\nu\bar{\nu}) = \mathscr{B}(B \to M\nu\bar{\nu})^{\mathtt{SM}} R^\nu$$ → Same $R_{K^{(*)}}^{\nu\nu}$

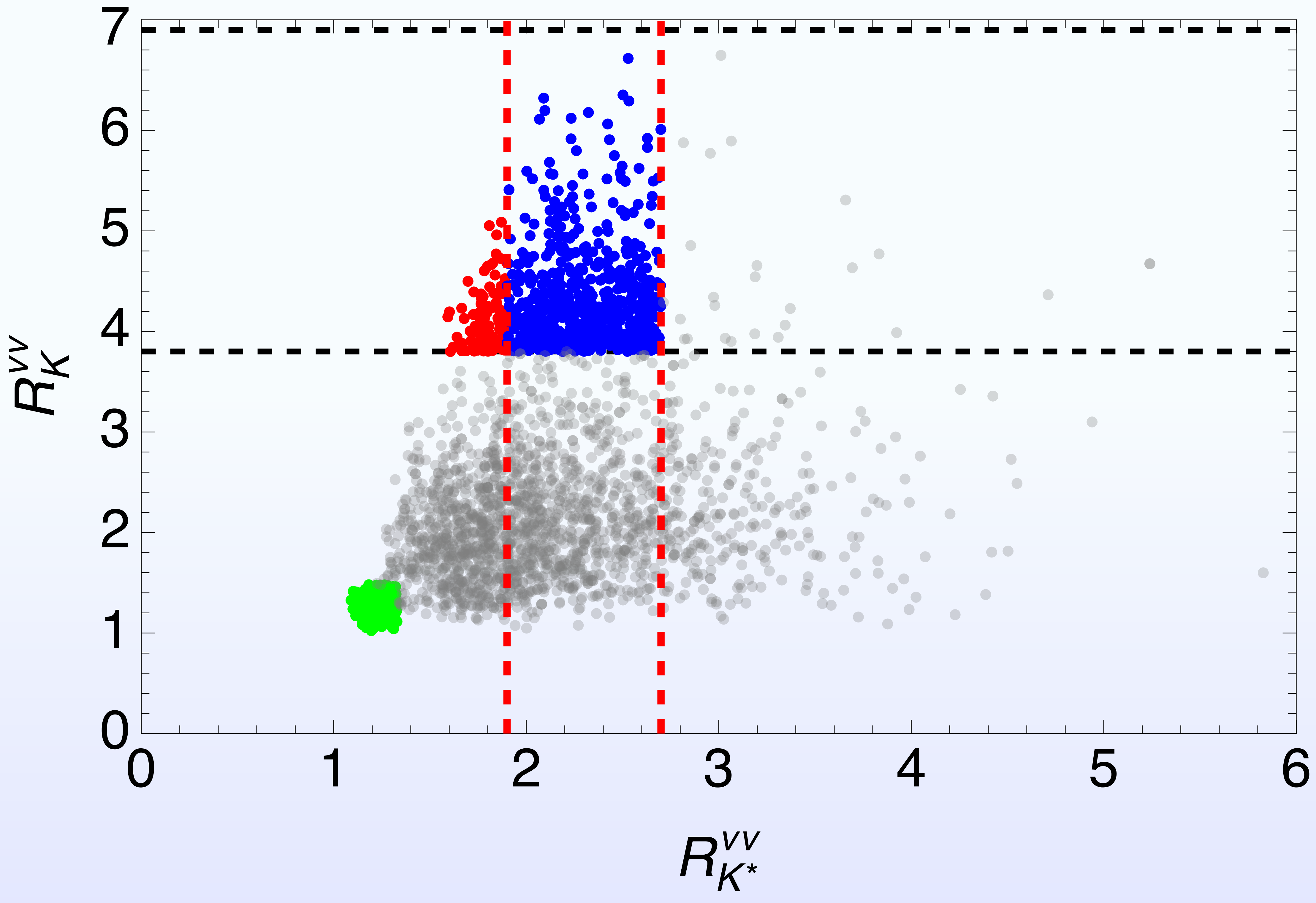
This scenario is in conflict with the $B \to K^* \nu\bar{\nu}$ constraints

New decay modes with sterile neutrinos

$$\mathcal{O}'^{ij}_L = (\bar{s}\gamma_\mu P_L d)(\bar{\nu}_i \gamma^\mu P_R \nu_j)$$
$$\mathcal{O}'^{ij}_R = (\bar{s}\gamma_\mu P_R d)(\bar{\nu}_i \gamma^\mu P_R \nu_j)$$

$$R_K^{\nu\nu} \approx 1 + 0.008 \sum_{ij} \left| C'^{ij}_L + C'^{ij}_R \right|^2,$$

$$R_{K^*}^{\nu\nu} \approx 1 + \sum_{ij} \left[0.008 \left(C'^{ij\,2}_L + C'^{ij\,2}_R \right) - 0.01 C'^{ij}_L C'^{ij}_R \right].$$



Both $C'^{\,ij}_L \neq 0$ and $C'^{\,ij}_R \neq 0$ are needed to deviate from $R_K^{\nu\nu} = R_{K^*}^{\nu\nu}$

Sterile Neutrinos in νSMEFT

T. Felkl, A. Giri, R. Mohanta, and M. A. Schmidt, 2309.02940

New decay mode involving sterile neutrino

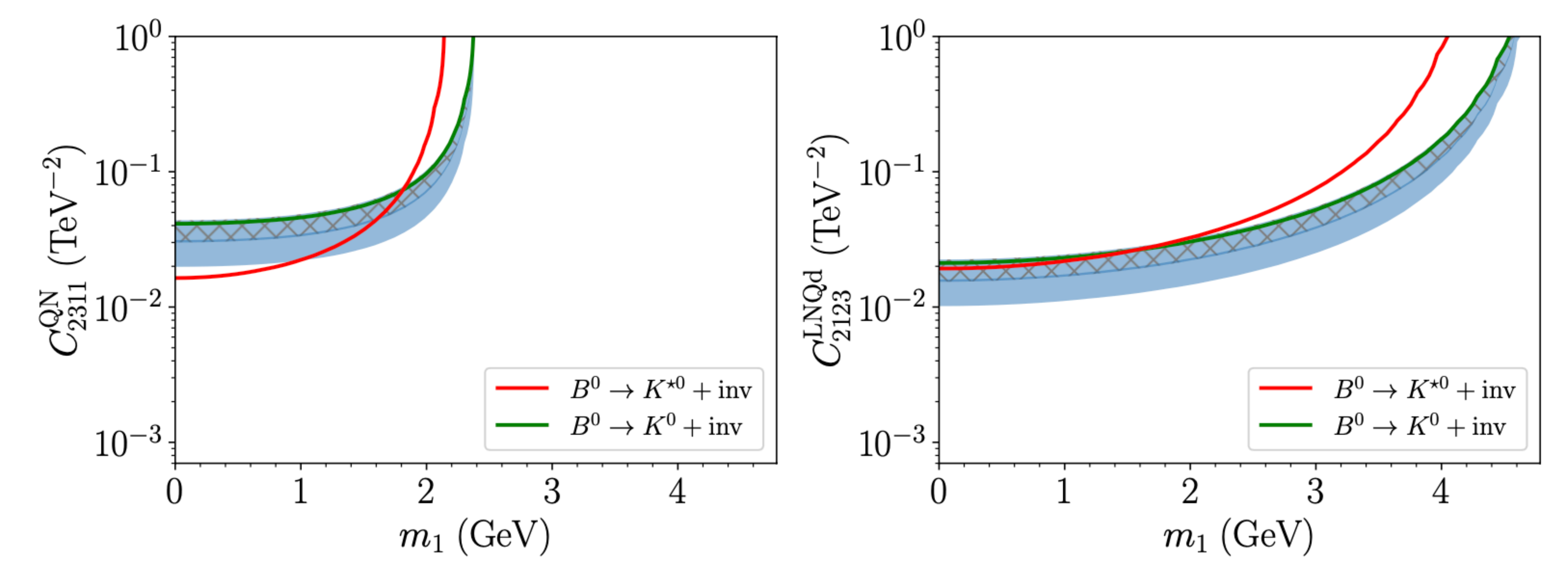
$C^{QN}(\bar{Q}\gamma_\mu Q)(\bar{N}\gamma^\mu N)$

$C^{dN}(\bar{d}\gamma_\mu d)(\bar{N}\gamma^\mu N)$

$C^{LNQd}(\bar{L}^\alpha N)\epsilon_{\alpha\beta}(\bar{Q}^\beta d)$

$C^{LNQd,\mathrm{T}}(\bar{L}^\alpha \sigma_{\mu\nu} N)\epsilon_{\alpha\beta}(\bar{Q}^\beta \sigma^{\mu\nu} d)$

Y. Liao, XDM, 1612.04527



UV completions

2nd EW scalar doublet, leptoquarks, etc

- Assumption with a single operator dominant
- Tensor operator is almost excluded by $B^0 \to K^{*0} + \mathtt{inv}$.
- The vector and scalar operators are viable

$b \to s + \mathrm{DM} + \mathrm{DM}$ in LEFT framework

Scalar DM case

$$\mathcal{O}^{S,sb}_{q\phi} = (\bar{s}b)(\phi^\dagger\phi),$$

$$\mathcal{O}^{V,sb}_{q\phi} = (\bar{s}\gamma^\mu b)(\phi^\dagger i\overleftrightarrow{\partial}_\mu\phi), (\times)$$

Fermion DM case

$$\mathcal{O}^{S,sb}_{q\chi1(2)} = (\bar{s}b)(\bar{\chi}(i\gamma_5)\chi),$$

$$\mathcal{O}^{V,sb}_{q\chi1(2)} = (\bar{s}\gamma^\mu b)(\bar{\chi}\gamma_\mu(\gamma_5)\chi), (\times)$$

$$\mathcal{O}^{T,sb}_{q\chi1(2)} = (\bar{s}\sigma^{\mu\nu}b)(\bar{\chi}\sigma_{\mu\nu}(\gamma_5)\chi), (\times)$$

Vector DM case

$$\mathcal{O}^{S,sb}_{qX} = (\bar{s}b)(X^\dagger_\mu X^\mu),$$

$$\mathcal{O}^{T,sb}_{qX1} = \frac{i}{2}(\bar{s}\sigma^{\mu\nu}b)(X^\dagger_\mu X_\nu - X^\dagger_\nu X_\mu), (\times)$$

$$\mathcal{O}^{T,sb}_{qX2} = \frac{1}{2}(\bar{s}\sigma^{\mu\nu}\gamma_5 b)(X^\dagger_\mu X_\nu - X^\dagger_\nu X_\mu), (\times)$$

$$\mathcal{O}^{V,sb}_{qX2} = (\bar{s}\gamma_\mu b)\partial_\nu(X^{\mu\dagger}X^\nu + X^{\nu\dagger}X^\mu),$$

$$\mathcal{O}^{V,sb}_{qX3} = (\bar{s}\gamma_\mu b)(X^\dagger_\rho\overleftrightarrow{\partial}_\nu X_\sigma)\epsilon^{\mu\nu\rho\sigma},$$

$$\mathcal{O}^{V,sb}_{qX4} = (\bar{s}\gamma^\mu b)(X^\dagger_\nu i\overleftrightarrow{\partial}_\mu X^\nu), (\times)$$

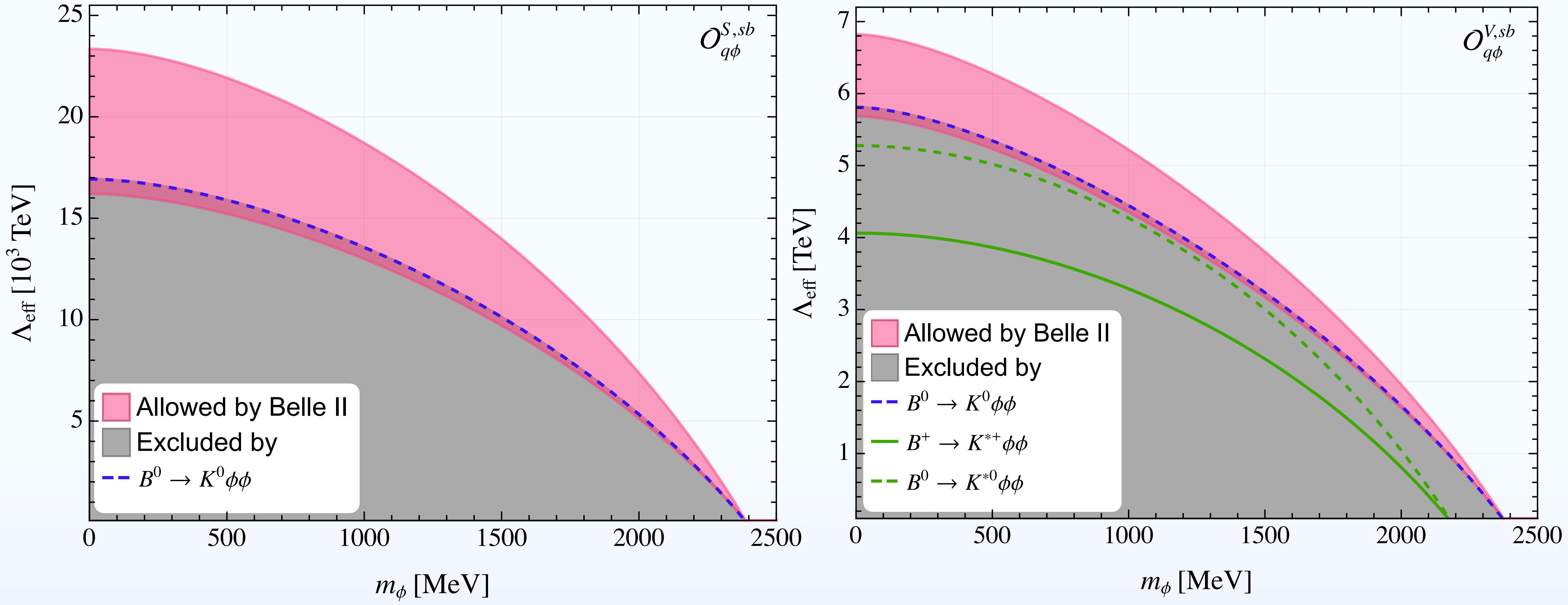
$$\mathcal{O}^{V,sb}_{qX5} = (\bar{s}\gamma_\mu b)i\partial_\nu(X^{\mu\dagger}X^\nu - X^{\nu\dagger}X^\mu), (\times)$$

$$\mathcal{O}^{V,sb}_{qX6} = (\bar{s}\gamma_\mu b)i\partial_\nu(X^\dagger_\rho X_\sigma)\epsilon^{\mu\nu\rho\sigma}. (\times)$$

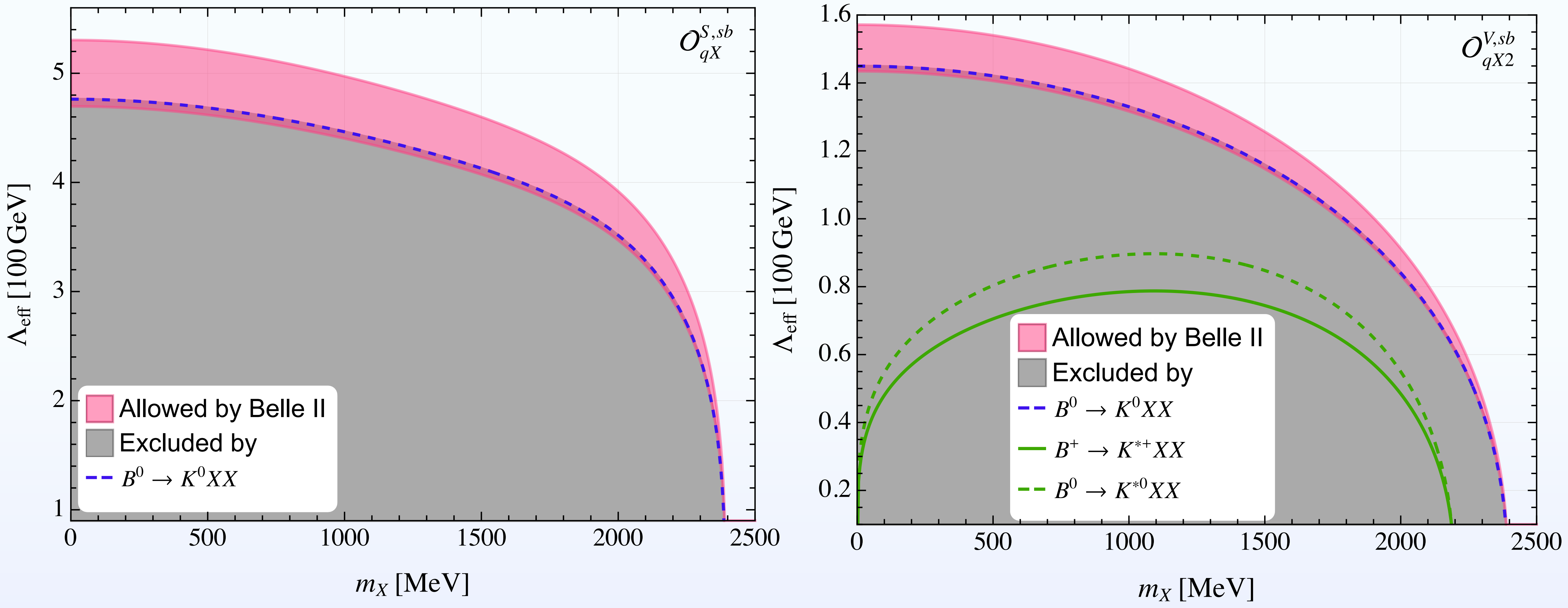
✸ The (X) stands for the interactions vanishes for “real” field

$b \to s + \mathrm{DM} + \mathrm{DM}$ in LEFT framework

Scalar DM case



Vector DM case



Fermion DM case

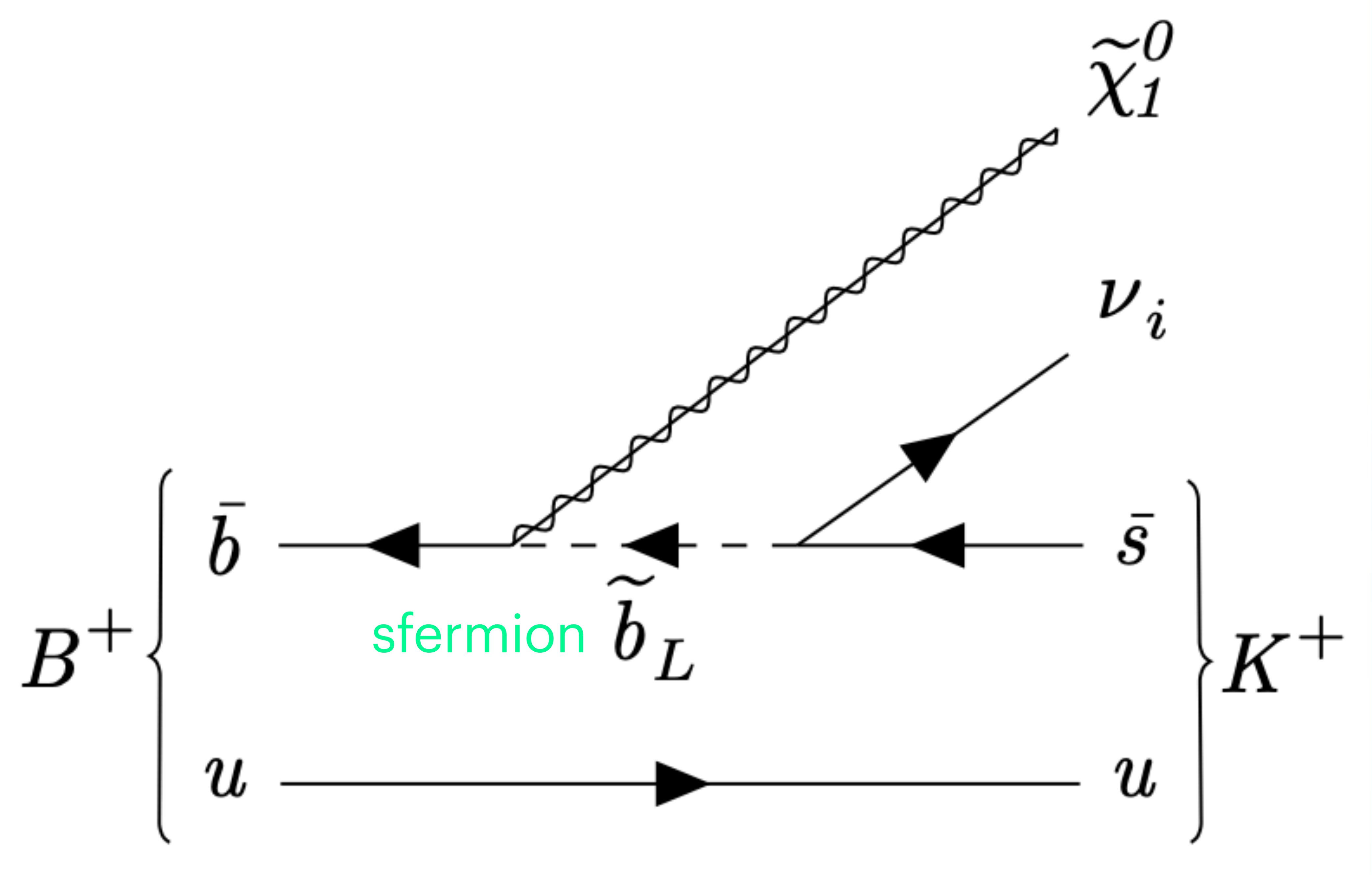
Massless Bino in R-parity-violating Supersymmetry

Herbert K. Dreiner, Julian Y. Gunther, Zeren Simon Wang, arXiv:2309.03727

Super potential $W_{\Delta L \neq 0} = \lambda'_{ijk} L_i Q_j \bar{D}_k$

$B^+ \to K^+ \nu(\bar{\nu}) \tilde{\chi}^0_1$: a single lightest neutralino, tree level

$B^+ \to K^+ \tilde{\chi}^0_1 \tilde{\chi}^0_1$: negligible contribution from 1-loop



$B^+ \to K^+ \nu \tilde{\chi}^0_1$, λ'_{i32}, λ'_{i12}, λ'_{i22}

$B^+ \to K^+ \bar{\nu} \tilde{\chi}^0_1$, λ'_{i23}, λ'_{i13}, λ'_{i33}

suppressed by CKM elements

$$\Gamma(B^+ \to K^+ \nu_i(\bar{\nu}_i) \tilde{\chi}^0_1) = \frac{0.0038\,\text{GeV}^5}{\tilde{m}^4} |V_{u_j b} \lambda'_{ij2}|^2 (|V_{u_j s} \lambda'_{ij3}|^2)$$

Large parts of the parameter space for $\lambda'_{i23/i32}$ and the degenerate sfermion mass $\tilde{m}$ can explain the latest Belle II measurement

A scalar-mediator dark matter/sector scenario

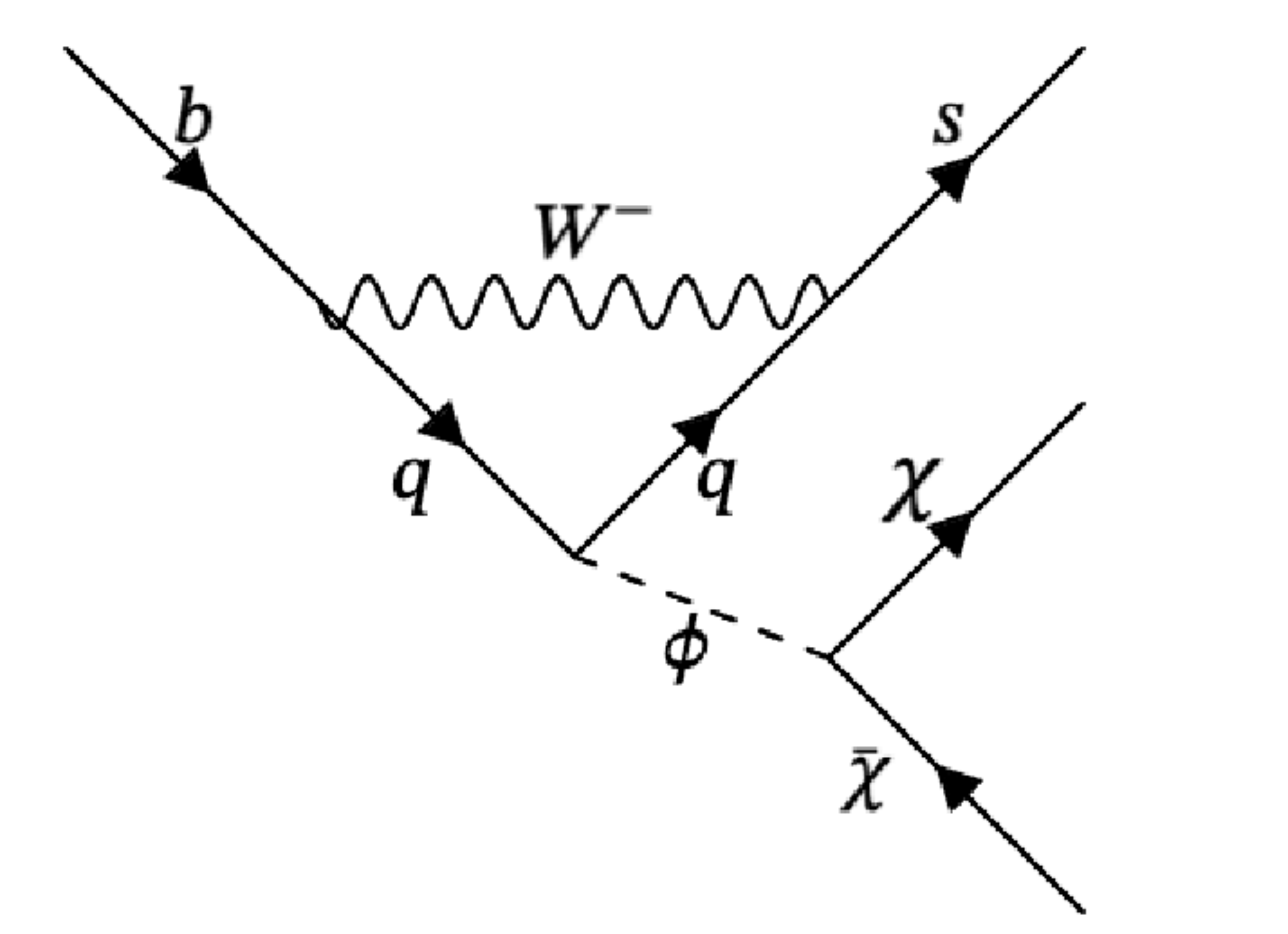
The scalar mediator couples mainly to top quark:

Murat Abdughani, Yakefu Reyimuaji. 2309.03706
Alexander Berezhnoy, Dmitri Melikhov, 2309.17191
Alakabha Datta, Danny Marfatia, 2310.15136

$$\mathscr{L}_{\text{int}} = -\frac{y m_t}{v}\phi \bar{t} t - \kappa \phi \bar{\chi}\chi$$

$$\mathscr{L}_{b\to s\phi} = g_{b\to s\phi}\phi \bar{s}_L b_R + \text{h.c.}$$

$$g_{b\to s\phi} = \frac{y m_b}{v}\frac{3\sqrt{2}G_F m_q^2 V_{qs}^* V_{qb}}{16\pi^2}$$



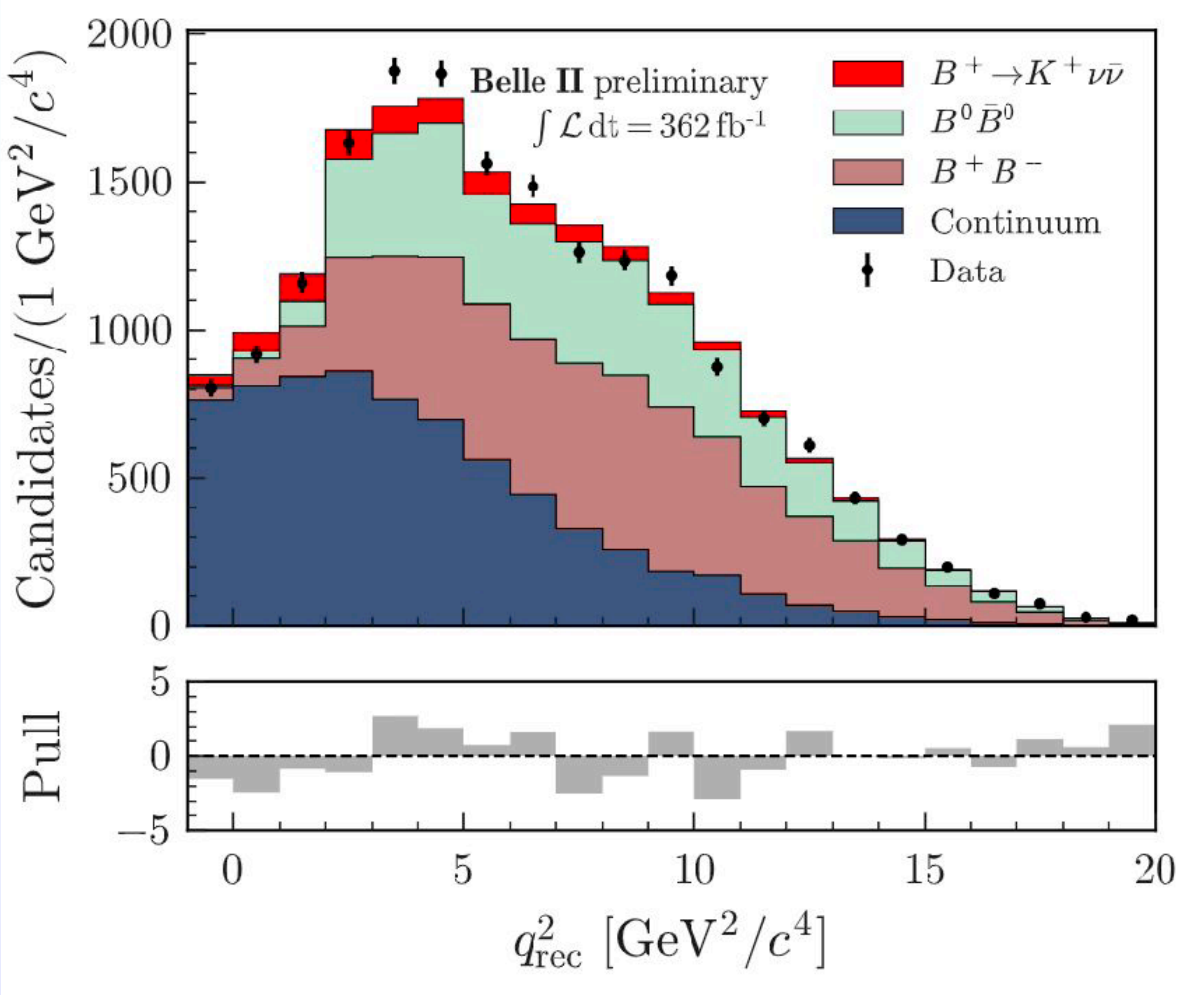
$$B \to K^+\phi \to K^+\chi\chi$$

Extensions of such model could also accommodate other excesses or anomalies:

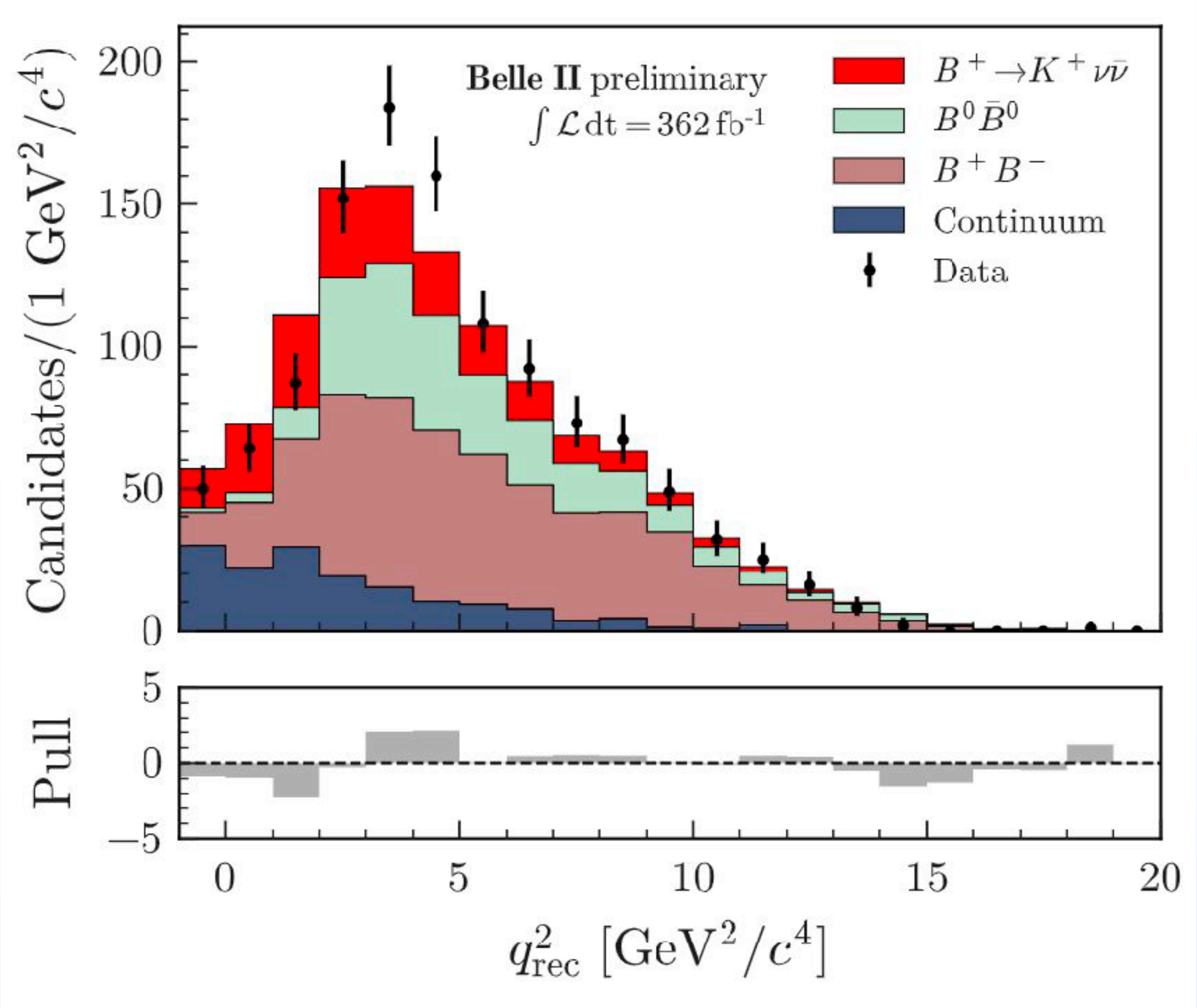
Muon g-2, MiniBooNE electron-like events

The q^2 distribution

Signal region: η(BDT2) > 0.92



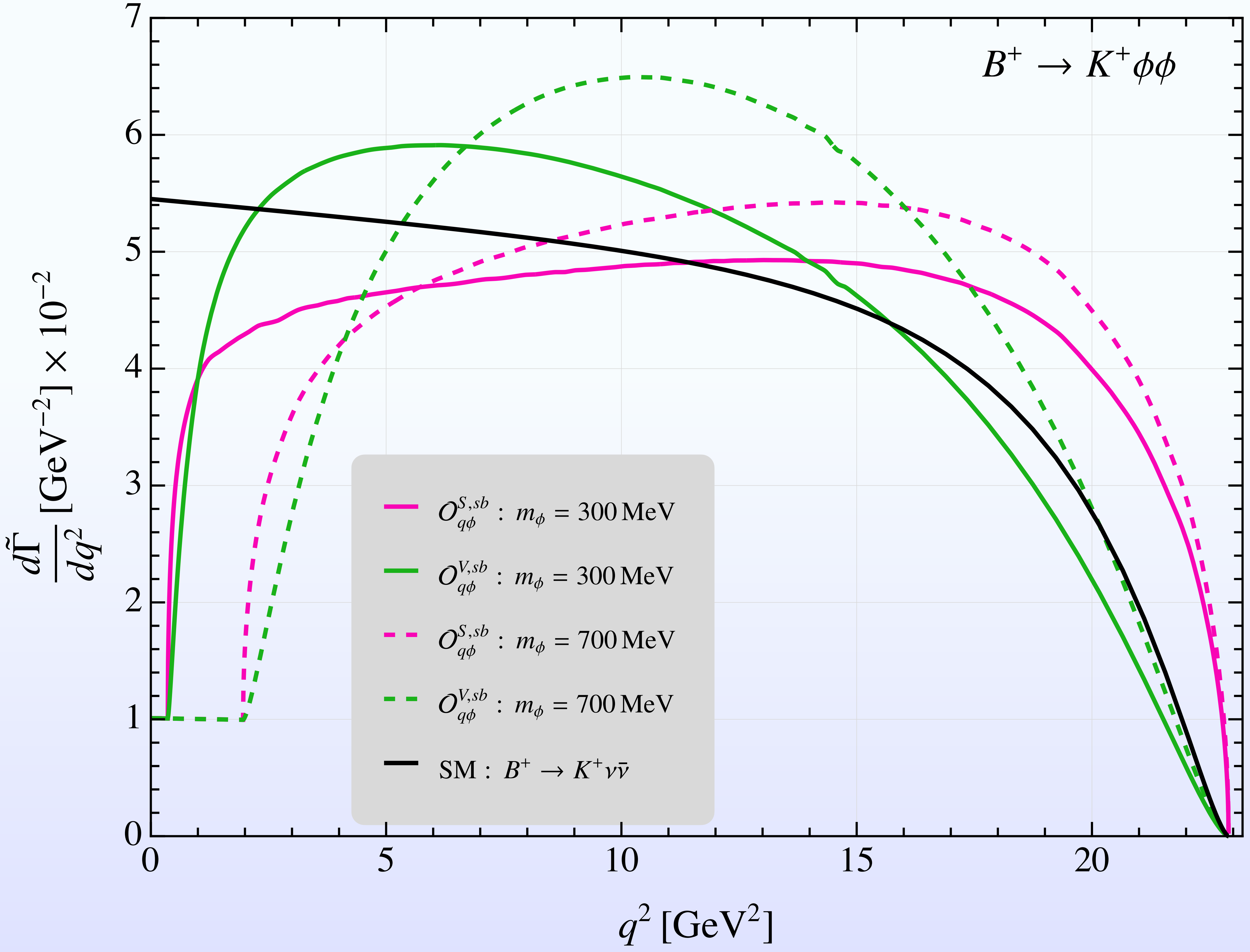
Most sensitive region: η(BDT2) > 0.98

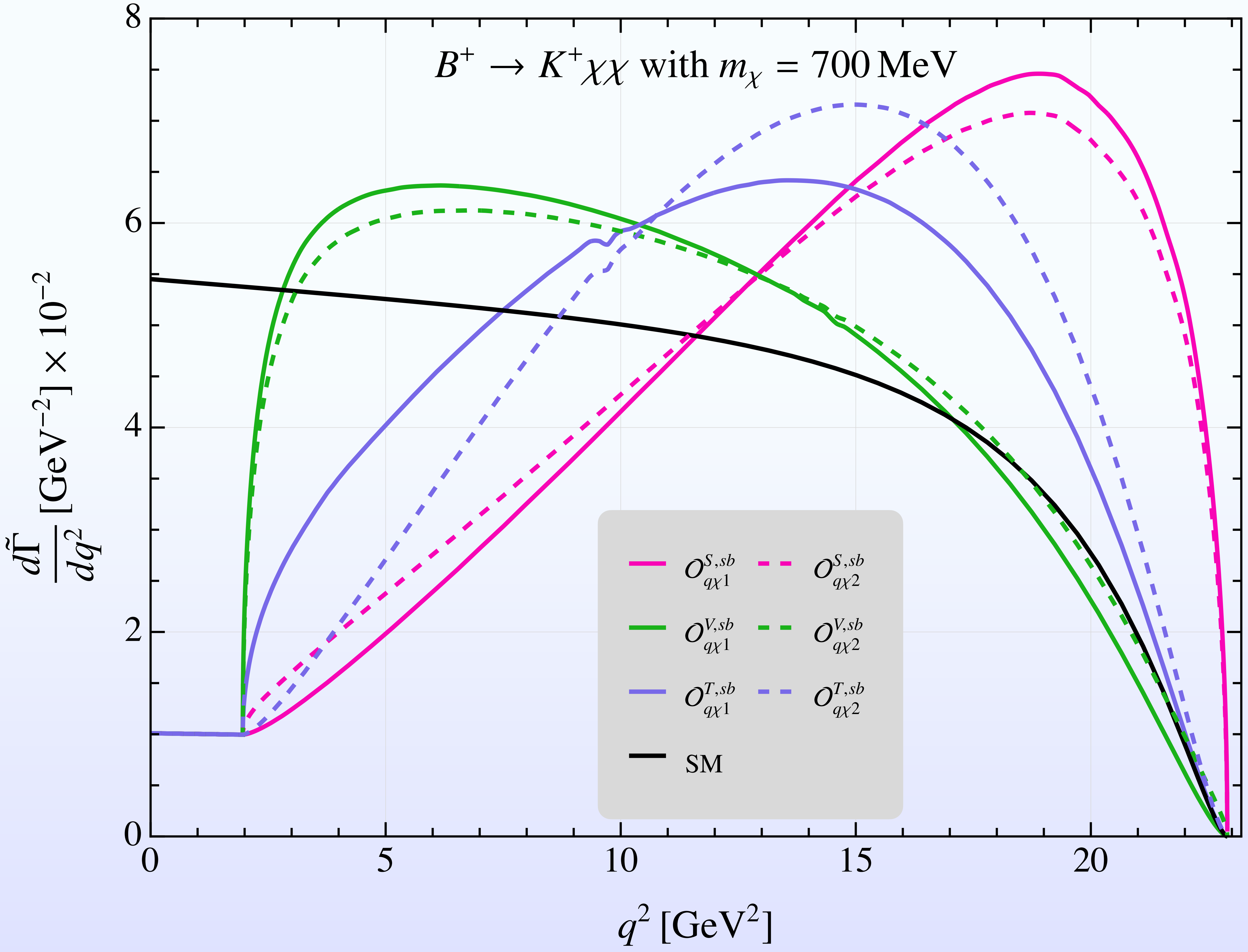


- **Excess between 3-7 GeV^2**
- **Not conclusive due to coarse binning choice, dictated from experimental resolution**

Elisa Manoni's Talk @CERN EP seminar, 2023

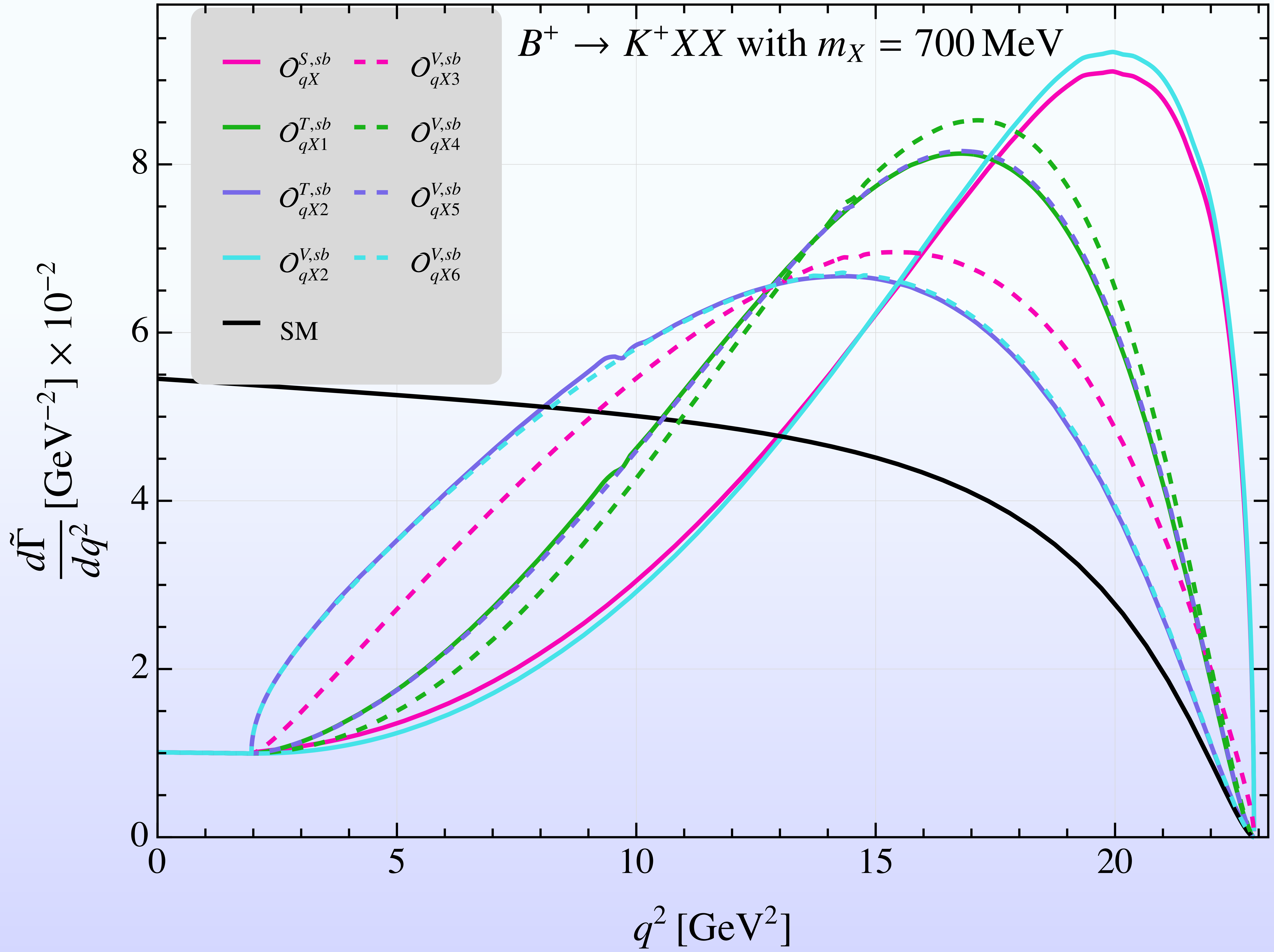
Scalar and fermion DM cases





The vector current operators with scalar or vector DM particles with masses in the hundreds of MeV can match the anomaly.

Vector DM case



All cases cannot match!

Conclusion

- Several interesting scenarios that could accommodate the recent Belle II anomaly are reviewed, including heavy mediators and new decay modes;
- For heavy mediator case, the viable explanations are mediators that couple only to tau-flavors and/or LFV ones;
- The EFT consideration involves new light states are also possible;
- $B \to K^* + inv.$, $B_s \to inv.$ and other rare B decay modes can be simultaneously to probe or constrain those NP scenarios;
- The future significantly improved data from Belle II can be expected to shed light on this anomaly.

Thank you for your time!