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

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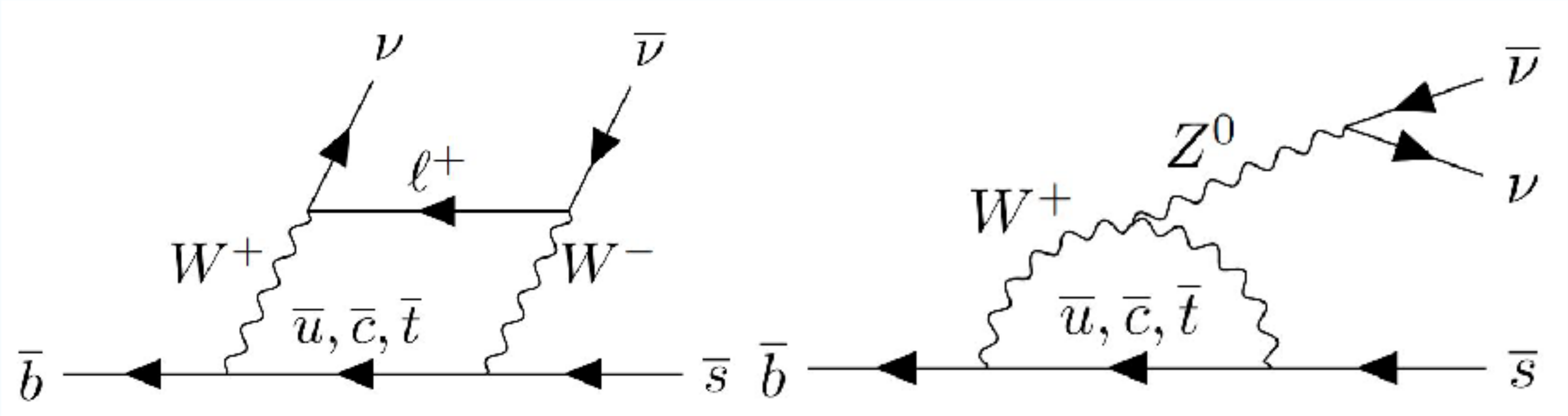
- X.G. He, XDM, G. Valencia, 2209.05223
- X.G. He, XDM, G. Valencia, 2309.12741
- X.G. He, XDM, M. A. Schmidt, G. Valencia, R. R. Volkas, 2403.12485

Outline

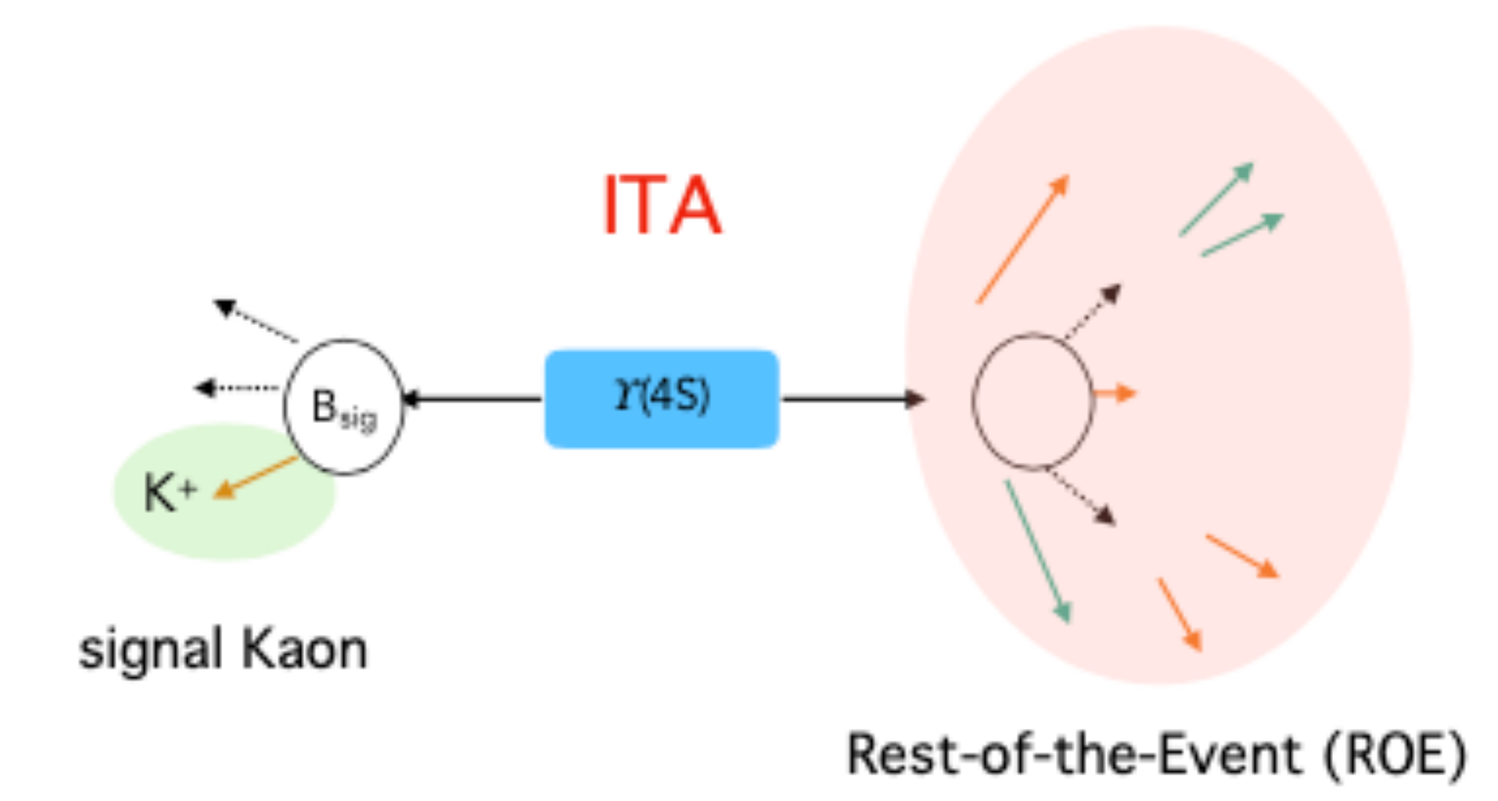
- **Introduction**
- **New contribution to $B^+ \to K^+\nu\bar{\nu}$ from heavy mediator**
- **New decay modes involving new light states**
- **A viable scalar DM model**
- **Summary**

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

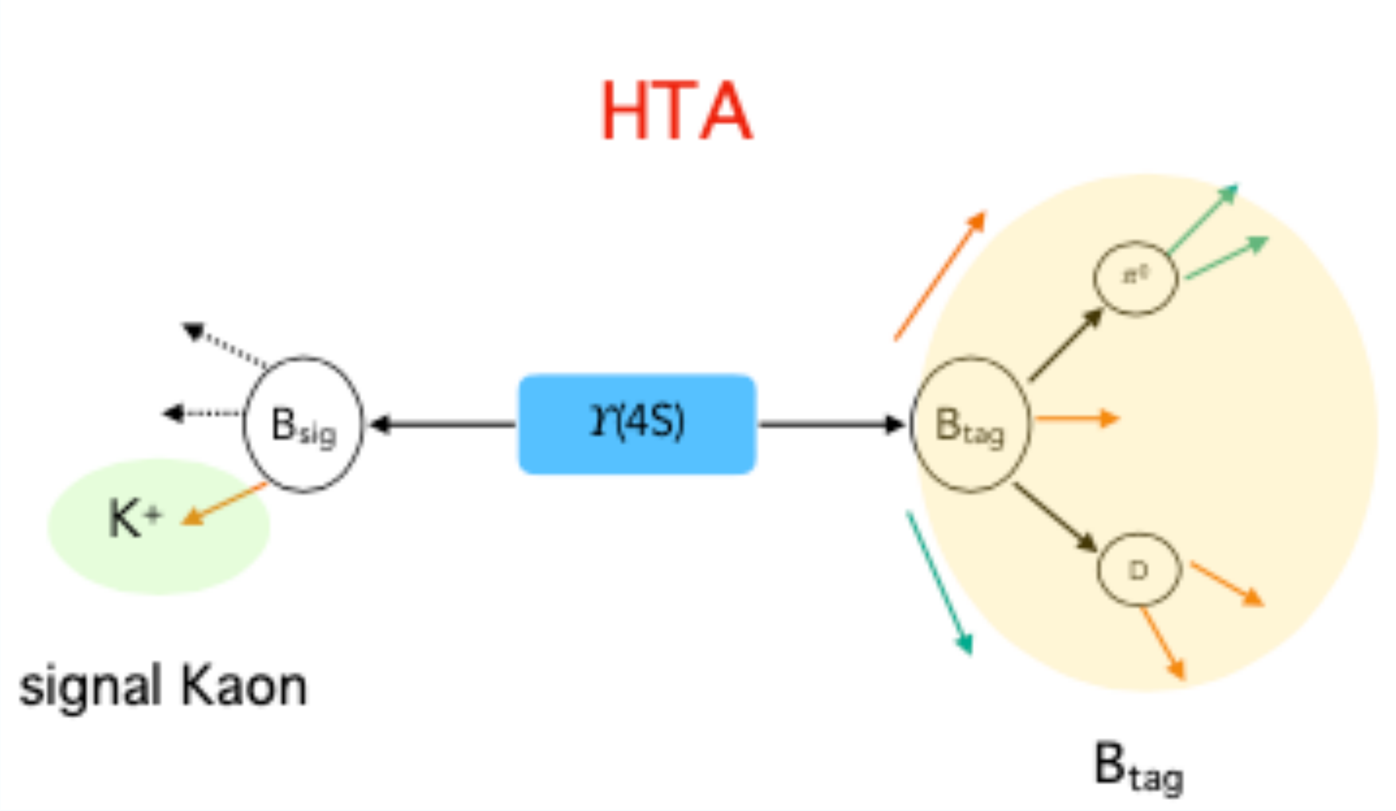


- Tree-level contribution is forbidden, suppressed by GIM mechanism at loop-level
- SM uncertainty is well-controlled, mainly from hadronic form factor
- SM prediction: $\mathscr{B}(B^+ \to K^+\nu\bar{\nu})_{\mathrm{SM}} = (4.43 \pm 0.31) \times 10^{-6}$ 2301.06990 [hep-ph]
- $b \to s$ + missing are cleanest modes to search for new physics

Recent Belle II result



Inclusive Tag analysis (ITA)
more sensitive



Hadronic Tag analysis (HTA)
more conventional

Belle-II Collaboration
2311.14647

- Combination: $\mathscr{B}(B^+ \to K^+\nu\bar{\nu})_{\rm exp} = (2.3 \pm 0.7) \times 10^{-5}$
- Combine Belle II 2021 data, $\mathscr{B}(B^+ \to K^+\nu\bar{\nu})^{\rm ave}_{\rm exp} = (1.3 \pm 0.4) \times 10^{-5}$
- $2.7\,\sigma$ higher than SM prediction $\Rightarrow$ New physics possibility

Experimental results vs SM prediction

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

$$R_K^{\nu\nu} = \frac{\mathcal{B}(B^+ \to K^+\nu\bar{\nu})_{\mathtt{exp}}}{\mathcal{B}(B^+ \to K^+\nu\bar{\nu})_{\mathtt{SM}}} = 5.3 \pm 1.7.$$

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

- 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: $B \to K^{(*)} + \phi(S)[X]$

- $B \to K^{(*)} + \nu_i \bar{\nu}_j$
  - P. Athron, R. Martinez, C. Sierra, 2308.13426
  - L. Allwicher, D. Becirevic, G. Piazza, S. Rosauro-Alcaraz, O. Sumensari, 2309.02246
  - R. Bause, H. Gisbert, G. Hiller, 2309.00075
  - X.G. He, **XDM**, G. Valencia, 2309.12741
  - C.H. Chen, C.W. Chiang, 2309.12904, 2403.02897
  - F.Z. Chen, Q.Y. Wen, F.R. Xu, 2401.11552
- $B \to K^{(*)} + \nu N, B \to K^{(*)} + N\bar{N}$
  - T. Felkl, A. Giri, R. Mohanta, M. A. Schmidt, 2309.02940
  - X.G. He, XDM, G. Valencia, 2309.12741
  - H. K. Dreiner, J. Y. Gunther, Z. S. Wang, 2309.03727
- $B \to K^{(*)} + \mathtt{DM} + \mathtt{DM}$
  - X.G. He, XDM, G. Valencia, 2209.05223, 2309.12741
  - X.G. He, XDM, M. A. Schmidt, G. Valencia, R. R. Volkas, 2403.12485
- $B \to K^{(*)} + \phi(S)[X]$
  - M. Abdughani, Y. Reyimuaji. 2309.03706
  - A. Berezhnoy, D. Melikhov, 2309.17191
  - A. Datta, D. Marfatia, 2310.15136
  - A. Datta, D. Marfatia, L. Mukherjee, 2310.15136
  - W. Altmannshofer, A. Crivellin, H. Haigh, G. Inguglia, J. M. Camalich, 2311.14629
  - E. Gabrielli, L. Marzola, K. Müürsepp, M. Raidal, 2402.05901
  - T. Li, Z.N. Qian, M. A. Schmidt, M. Yuan, 2402.14232
  - B.F. Hou, X.Q. Li, M. Shen, Y.D. Yang, X.B. Yuan, 2402.19208
  - D. Marzocca, M. Nardecchia, A. Stanzione, C. Toni 2404.06533
  - P. D. Bolton, S. Fajfer, J. F. Kamenik, M. Novoa-Brunet 2403.13887
  - D. Mckeen, J. N. Ng, D. Tuckler, 2312.00982
  - K. Fridell, M. Ghosh, T. Okui, K. Tobioka, 2312.12507
  - S.Y. Ho, J. Kim, P. Ko, 2401.10112

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,
- DM models

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:

- $R(D), R(D^*)$ anomalies in $b \to c\tau\nu$: $R_D/R_D^{\mathrm{SM}} = 1.19(10), \quad R_{D*}/R_{D*}^{\mathrm{SM}} = 1.15(5)$
- 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:

$$\mathcal{H}_{\mathrm{NP}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^{\star} \frac{e^2}{16\pi^2} \sum_{ij} \left(C_L^{ij} \mathcal{O}_L^{ij} + C_R^{ij} \mathcal{O}_R^{ij} \right) + \text{h.c.},$$

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

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

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

$$R_K^{\nu\nu} = 1 + \frac{2C_{L\,\mathrm{SM}}}{3|C_{L\,\mathrm{SM}}|^2} \sum_i \mathrm{Re}(C_L^{ii} + C_R^{ii}) + \frac{1}{3|C_{L\,\mathrm{SM}}|^2} \sum_{ij} \left| C_L^{ij} + C_R^{ij} \right|^2,$$

$$R_{K^*}^{\nu\nu} = 1 + \frac{2C_{L\,\mathrm{SM}}}{3|C_{L\,\mathrm{SM}}|^2} \sum_i \mathrm{Re}\left(C_L^{ii}\right) + \frac{1}{3|C_{L\,\mathrm{SM}}|^2} \sum_{ij} \left(\left|C_L^{ij}\right|^2 + \left|C_R^{ij}\right|^2 \right) - 2\eta \left[\frac{C_{L\,\mathrm{SM}}}{3|C_{L\,\mathrm{SM}}|^2} \sum_i \mathrm{Re}\left(C_R^{ii}\right) + \frac{1}{3|C_{L\,\mathrm{SM}}|^2} \sum_{ij} \mathrm{Re}\left(C_L^{ij} C_R^{*ij} \right) \right],$$

$$R_K^{\nu\nu} - R_{K^*}^{\nu\nu} = 2(1+\eta)\left[\frac{C_{L\,\mathrm{SM}}}{3\,|C_{L\,\mathrm{SM}}|^2}\sum_i \mathrm{Re}\left(C_R^{ii}\right) + \frac{1}{3\,|C_{L\,\mathrm{SM}}|^2}\sum_{ij}\mathrm{Re}\left(C_L^{ij}C_R^{*ij}\right)\right]$$

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

↓

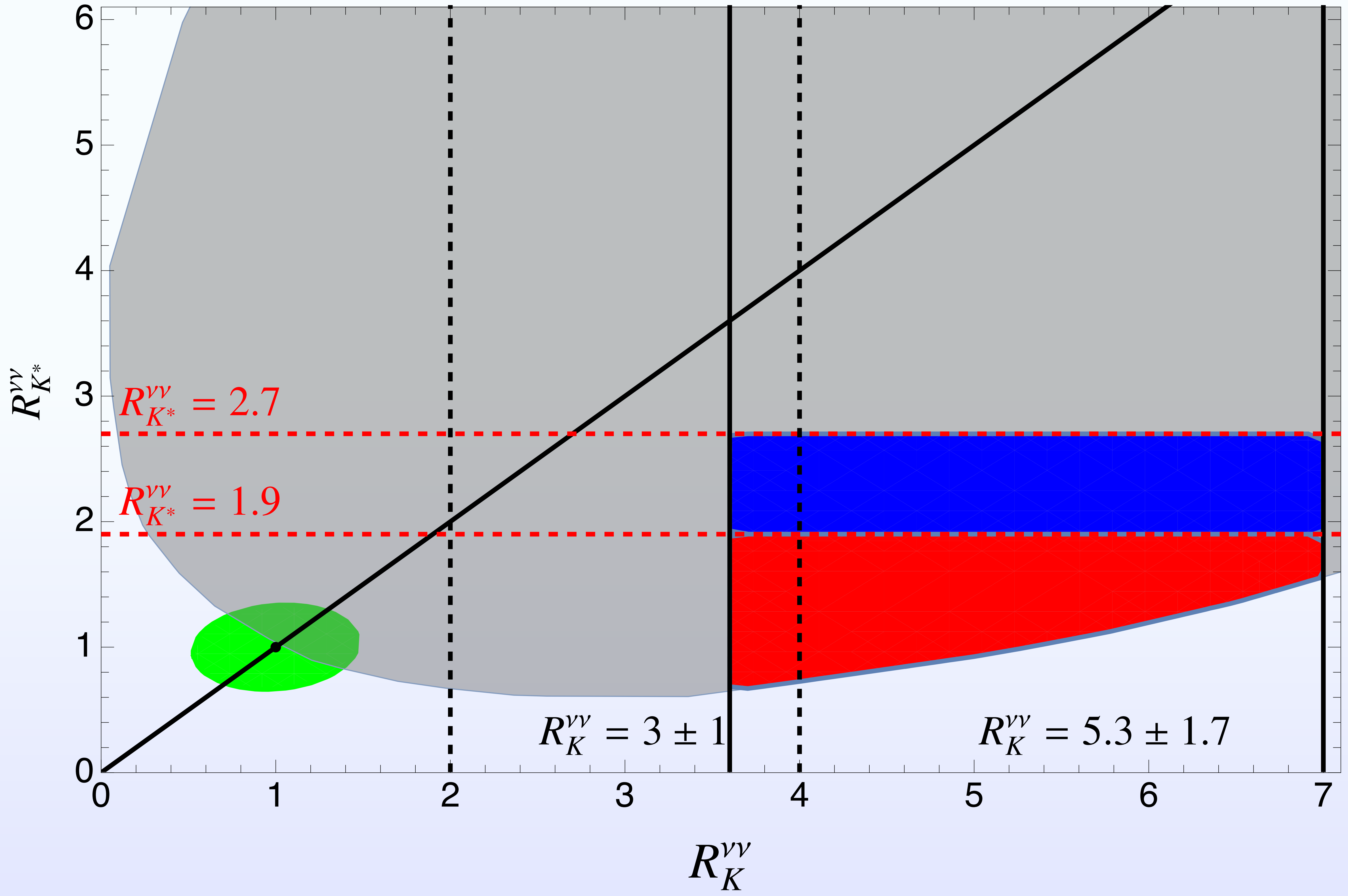
Models with only $S_0(\bar{3},1,1/3)$, $S_1(\bar{3},3,1/3)$, $V_1(3,3,2/3)$ are incompatible

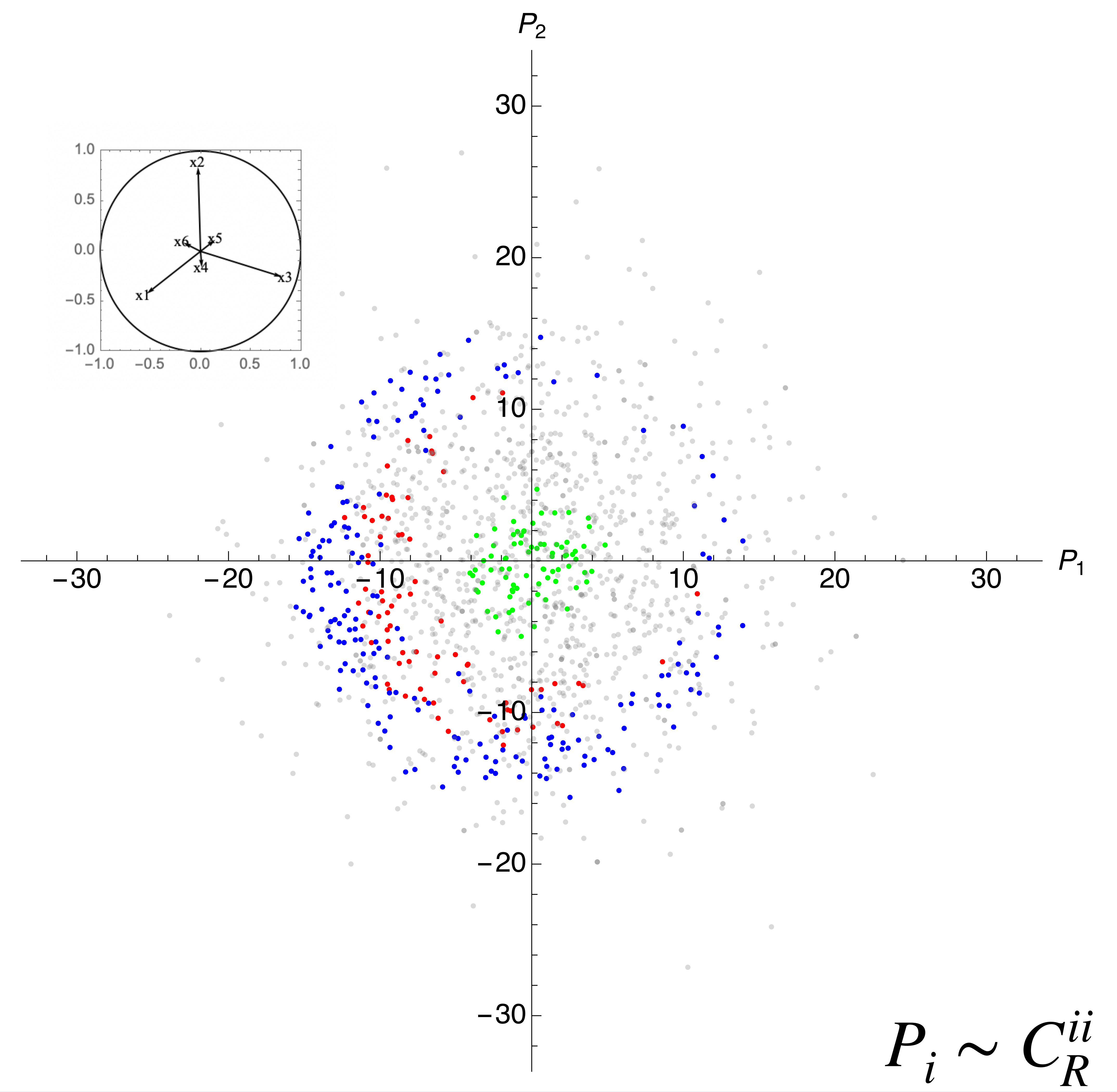
Leptoquark models

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

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

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



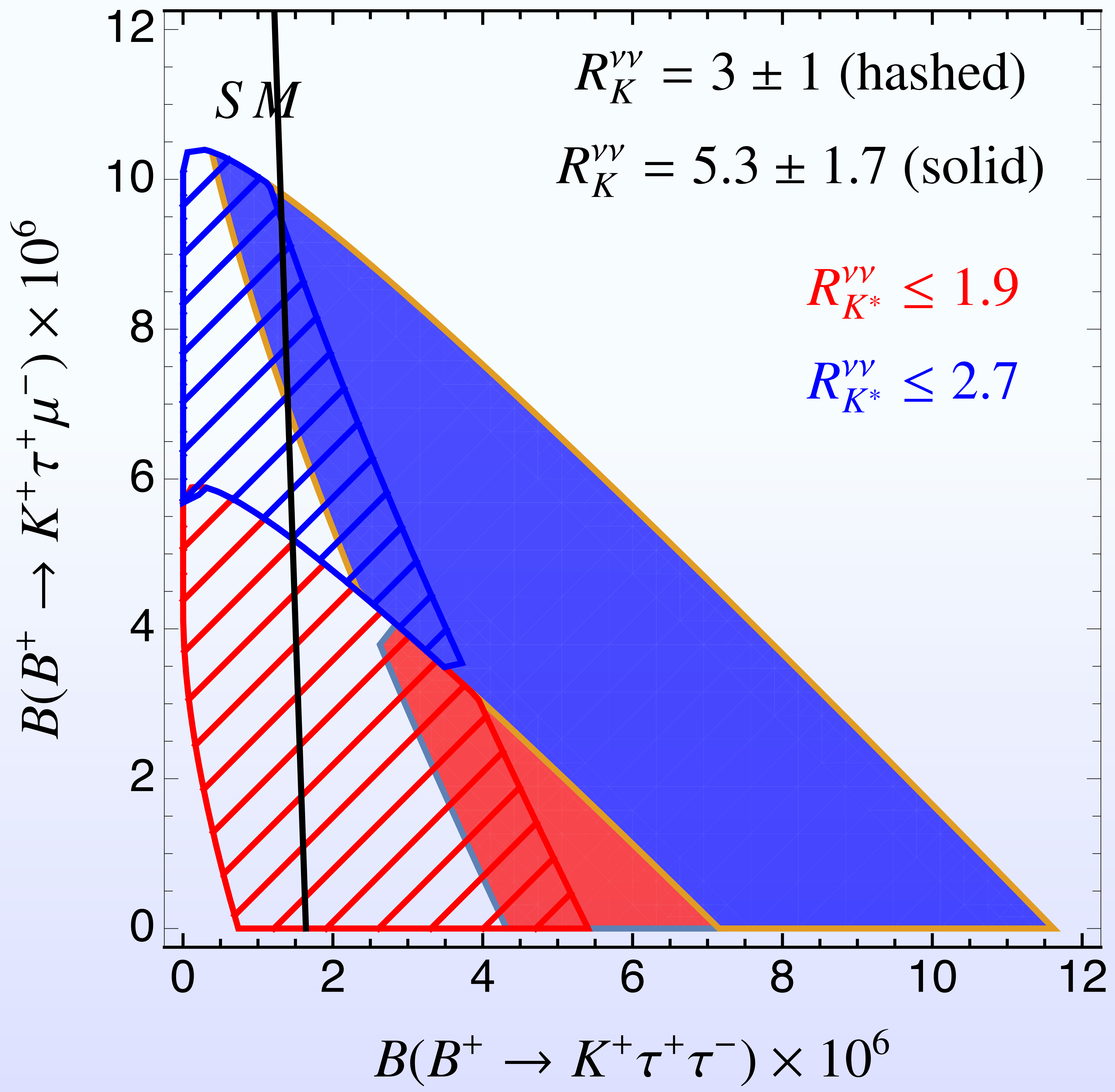


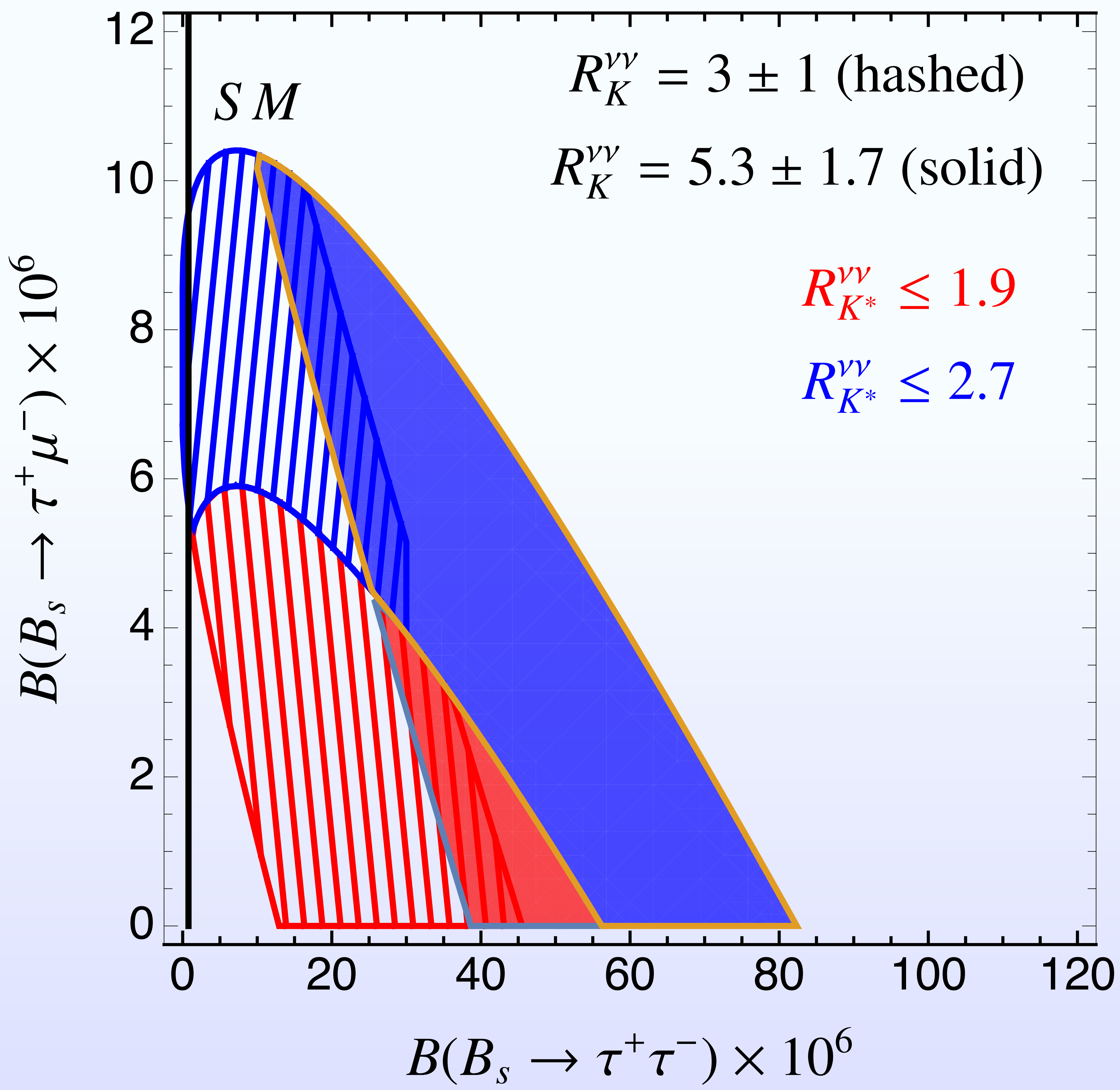
Imposing the constraints from $b \to s\ell^+\ell^-$

↓

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





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

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

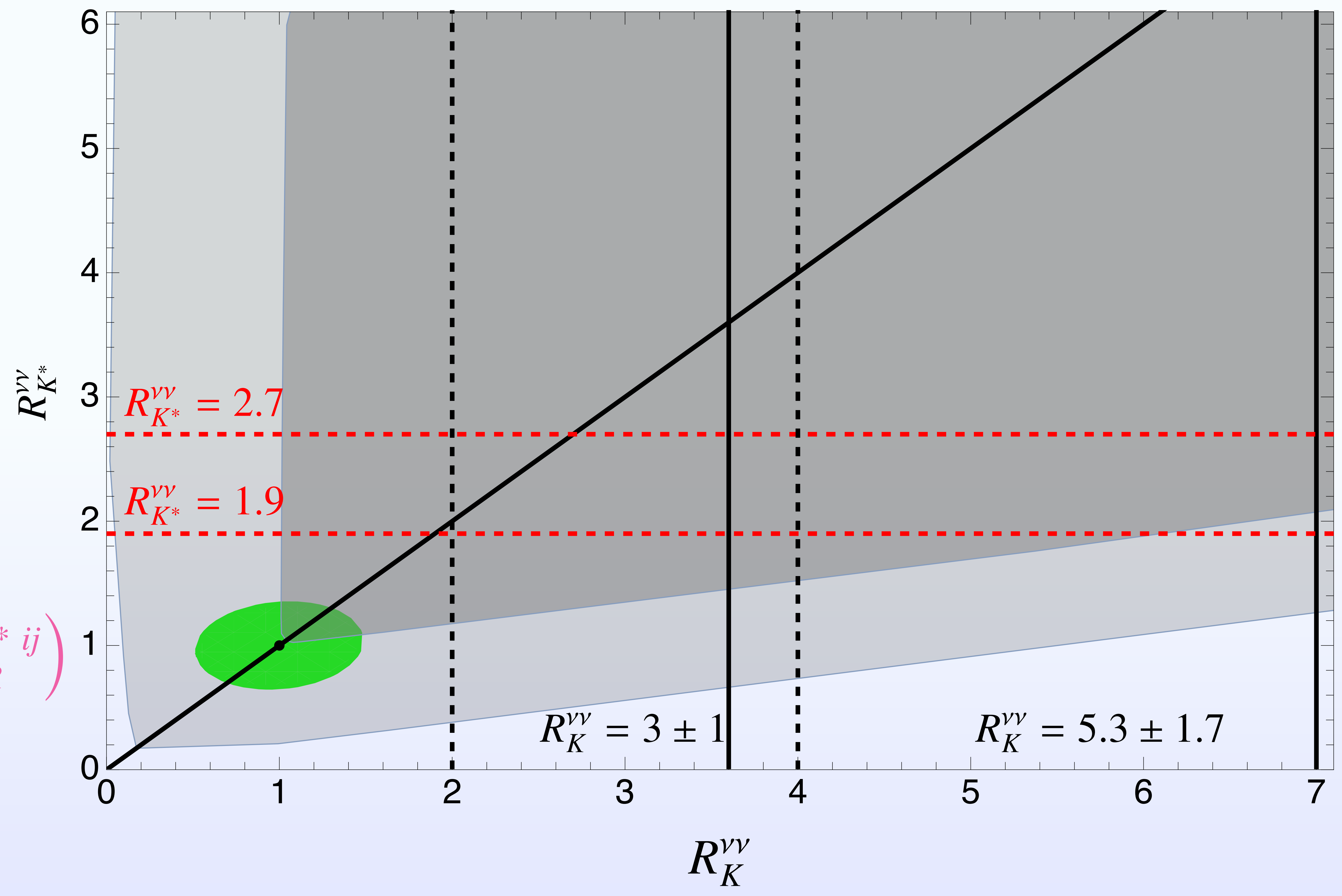
$\mathscr{B}(B_s \to \mu^-\tau^+)_{\text{PDG}} \leq 4.2 \times 10^{-5} (95\,\%)$

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

New decay modes with sterile neutrinos

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

$$R_K^{\nu\nu} = 1 + \frac{1}{3|C_{L\,\mathrm{SM}}|^2} \sum_{ij} \left| C'^{\,ij}_L + C'^{\,ij}_R \right|^2,$$
$$R_{K^*}^{\nu\nu} = 1 + \frac{1}{3|C_{L\,\mathrm{SM}}|^2} \sum_{ij} \left(\left|C'^{\,ij}_L\right|^2 + \left|C'^{\,ij}_R\right|^2 \right) - \frac{2\eta}{3|C_{L\,\mathrm{SM}}|^2} \sum_{ij} \mathrm{Re}\left(C'^{\,ij}_L C'^{*\,ij}_R \right)$$



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

Z' model

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

Scalar DM case

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

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

Fermion DM case

$$\mathcal{O}_{q\chi 1(2)}^{S,sb} = (\bar{s}b)(\bar{\chi}(i\gamma_5)\chi),$$

$$\mathcal{O}_{q\chi 1(2)}^{V,sb} = (\bar{s}\gamma^\mu b)(\bar{\chi}\gamma_\mu(\gamma_5)\chi), (\times)$$

$$\mathcal{O}_{q\chi 1(2)}^{T,sb} = (\bar{s}\sigma^{\mu\nu} b)(\bar{\chi}\sigma_{\mu\nu}(\gamma_5)\chi), (\times)$$

Vector DM case

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

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

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

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

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

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

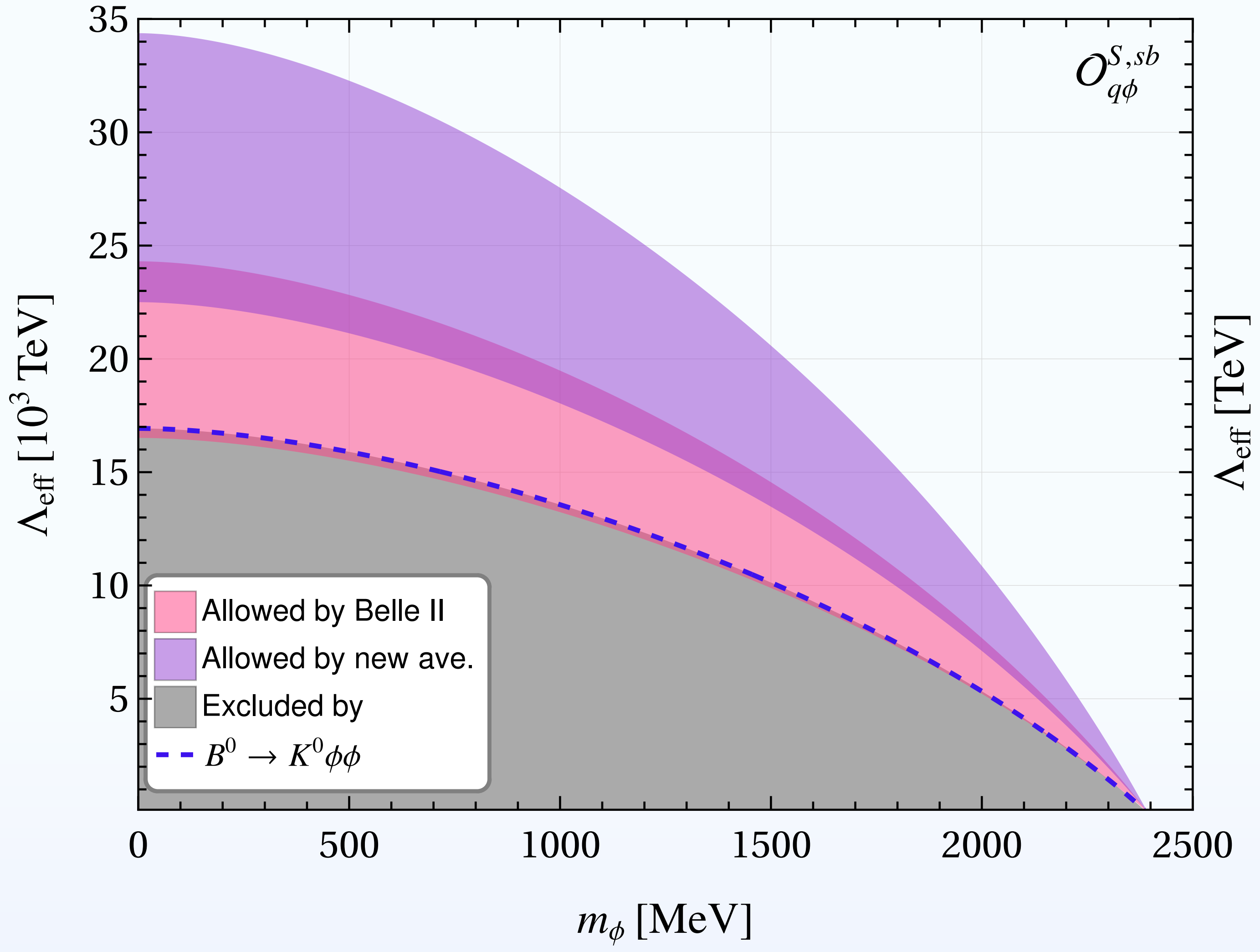
$$\mathcal{O}_{qX5}^{V,sb} = (\bar{s}\gamma_\mu b)i\partial_\nu(X^{\mu\dagger} X^\nu - X^{\nu\dagger} X^\mu), (\times)$$

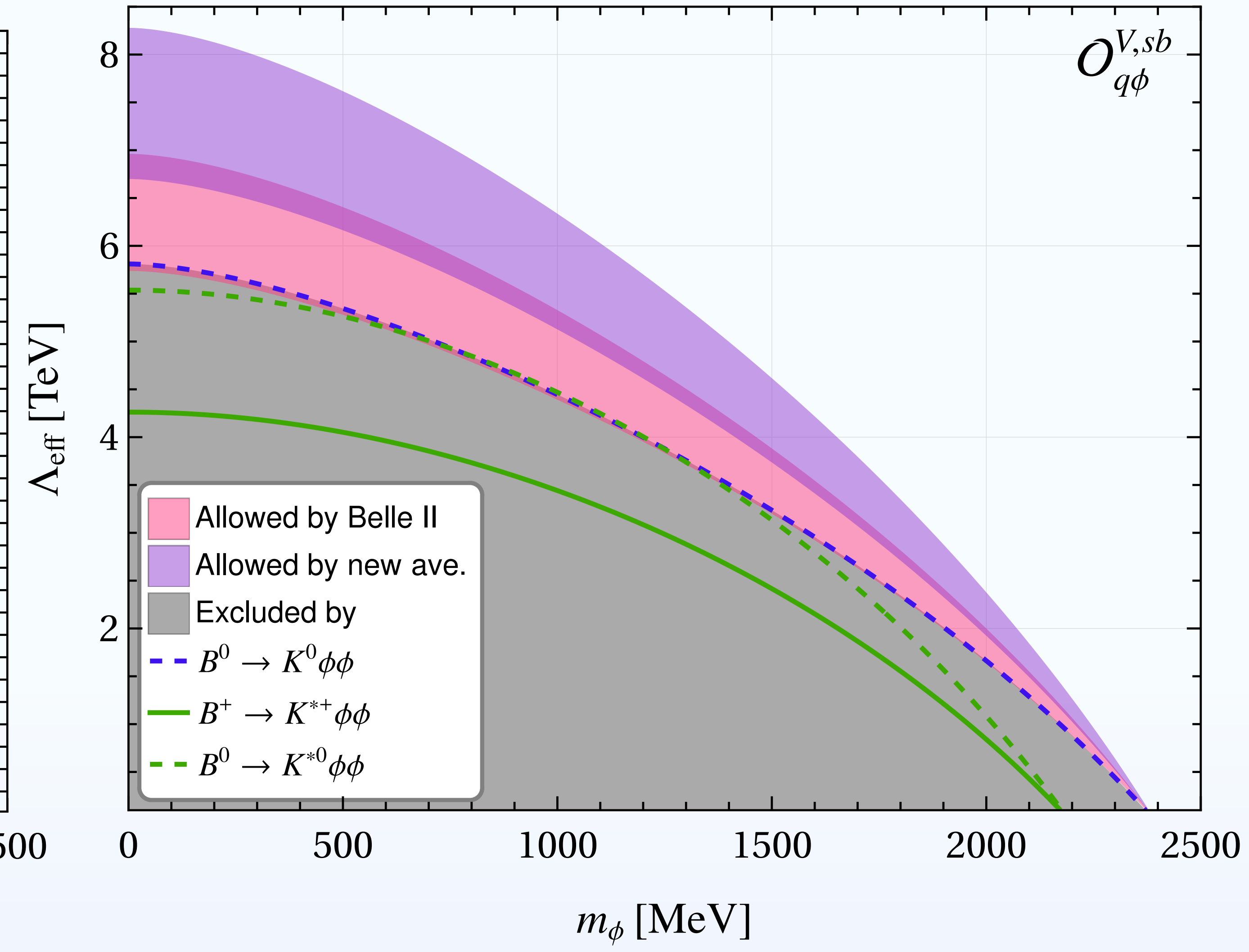
$$\mathcal{O}_{qX6}^{V,sb} = (\bar{s}\gamma_\mu b)i\partial_\nu(X_\rho^\dagger X_\sigma)\epsilon^{\mu\nu\rho\sigma}. (\times)$$

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

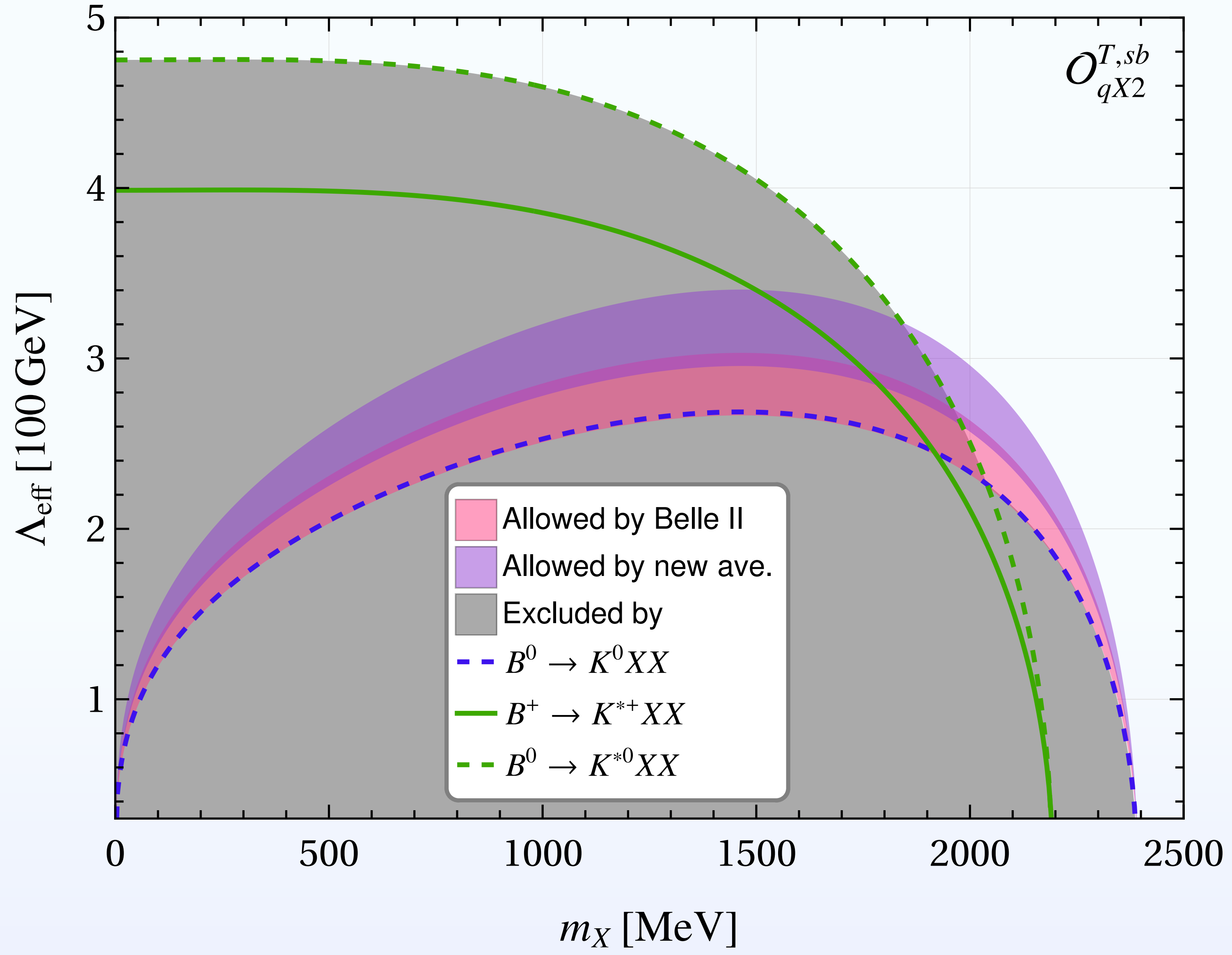
$b \to s + \text{DM} + \text{DM}$ in LEFT framework

Scalar DM case

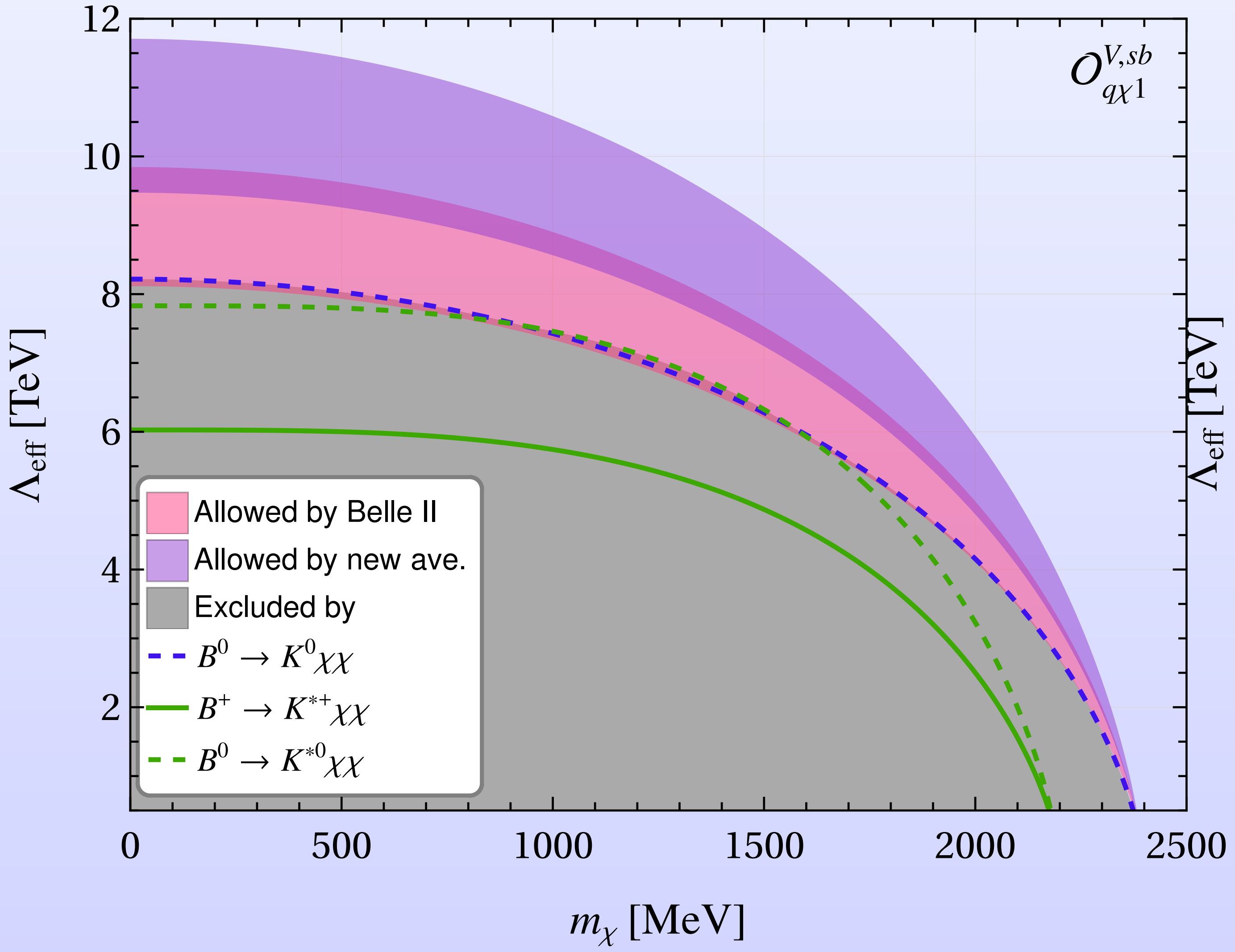


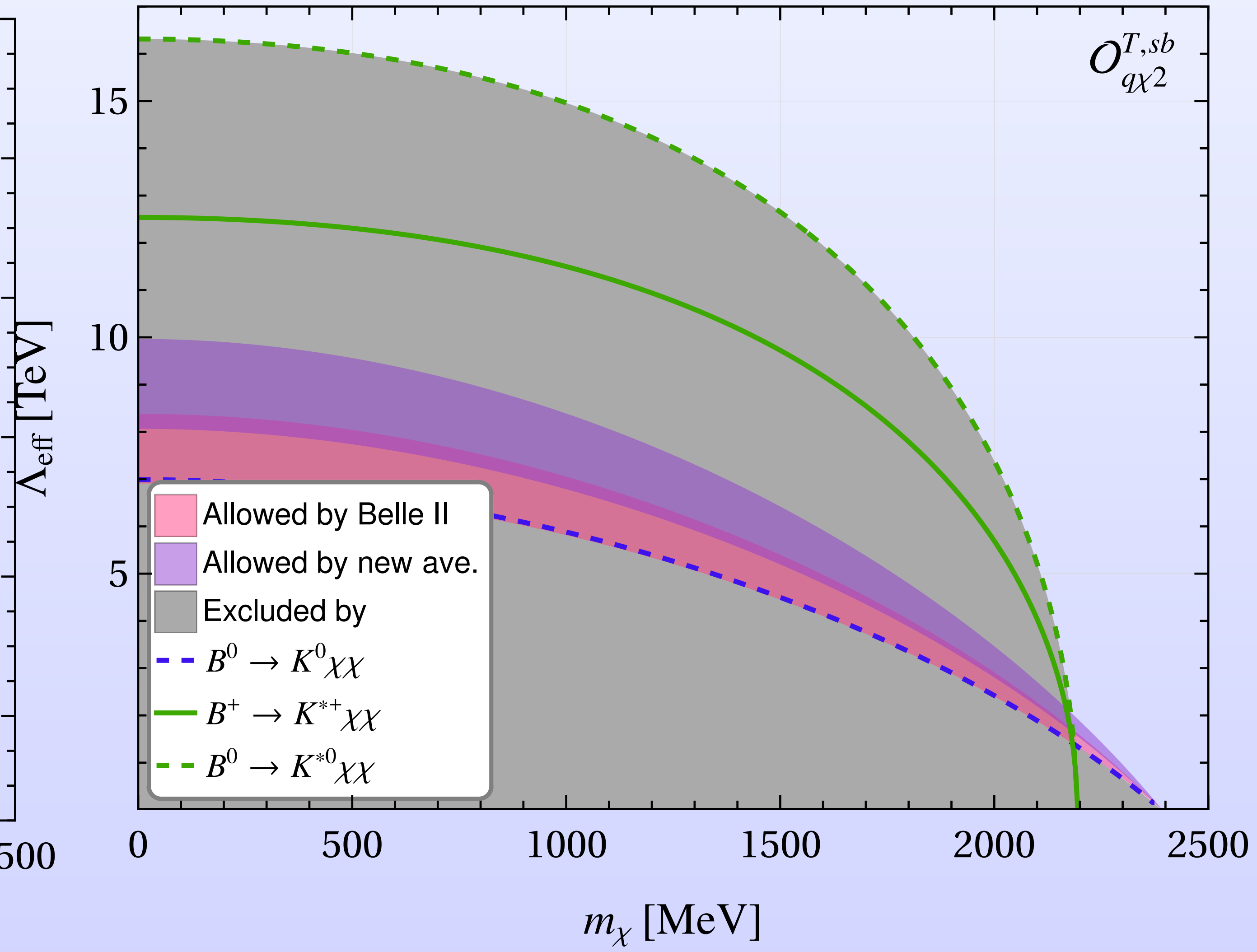


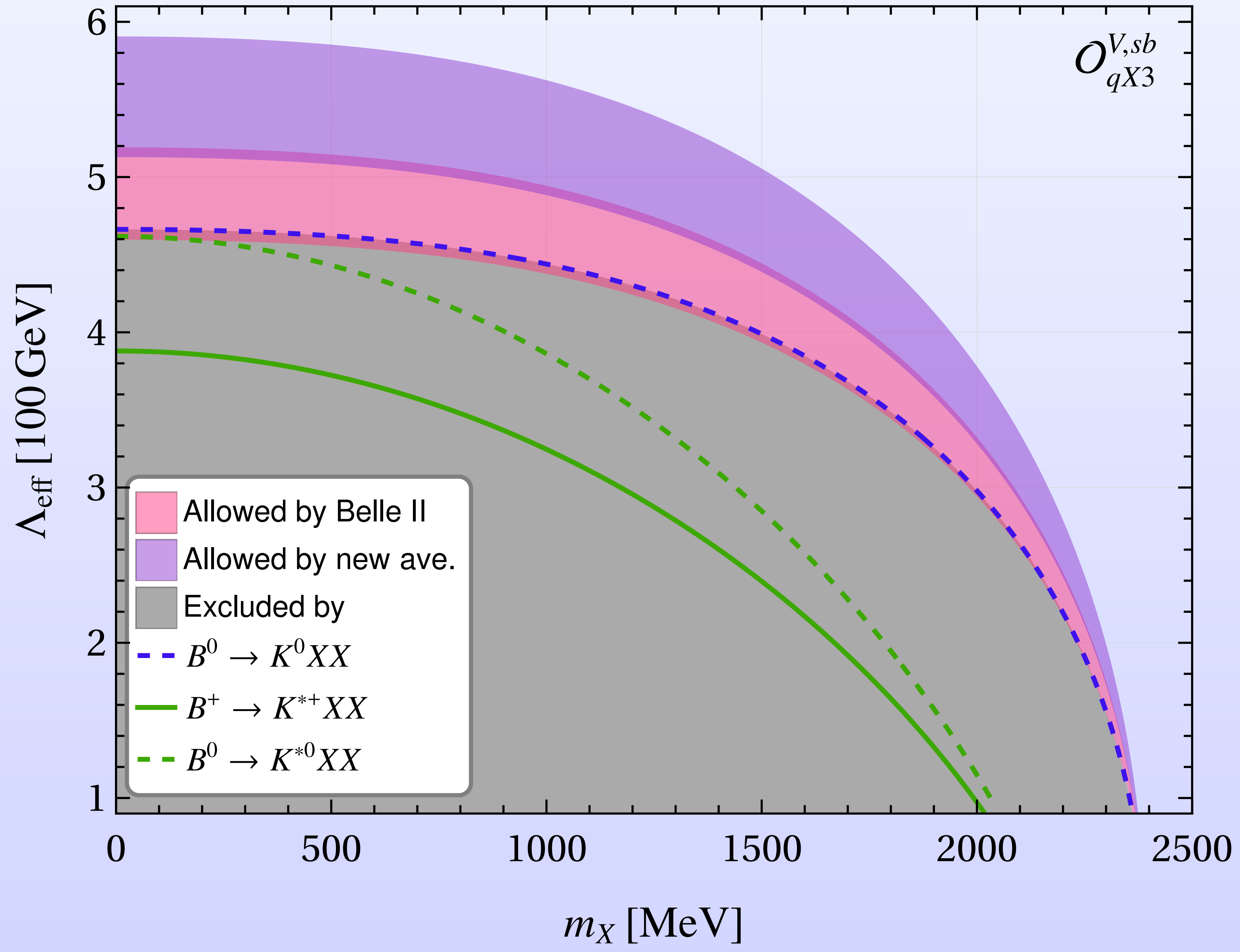
Vector DM case



Fermion DM case

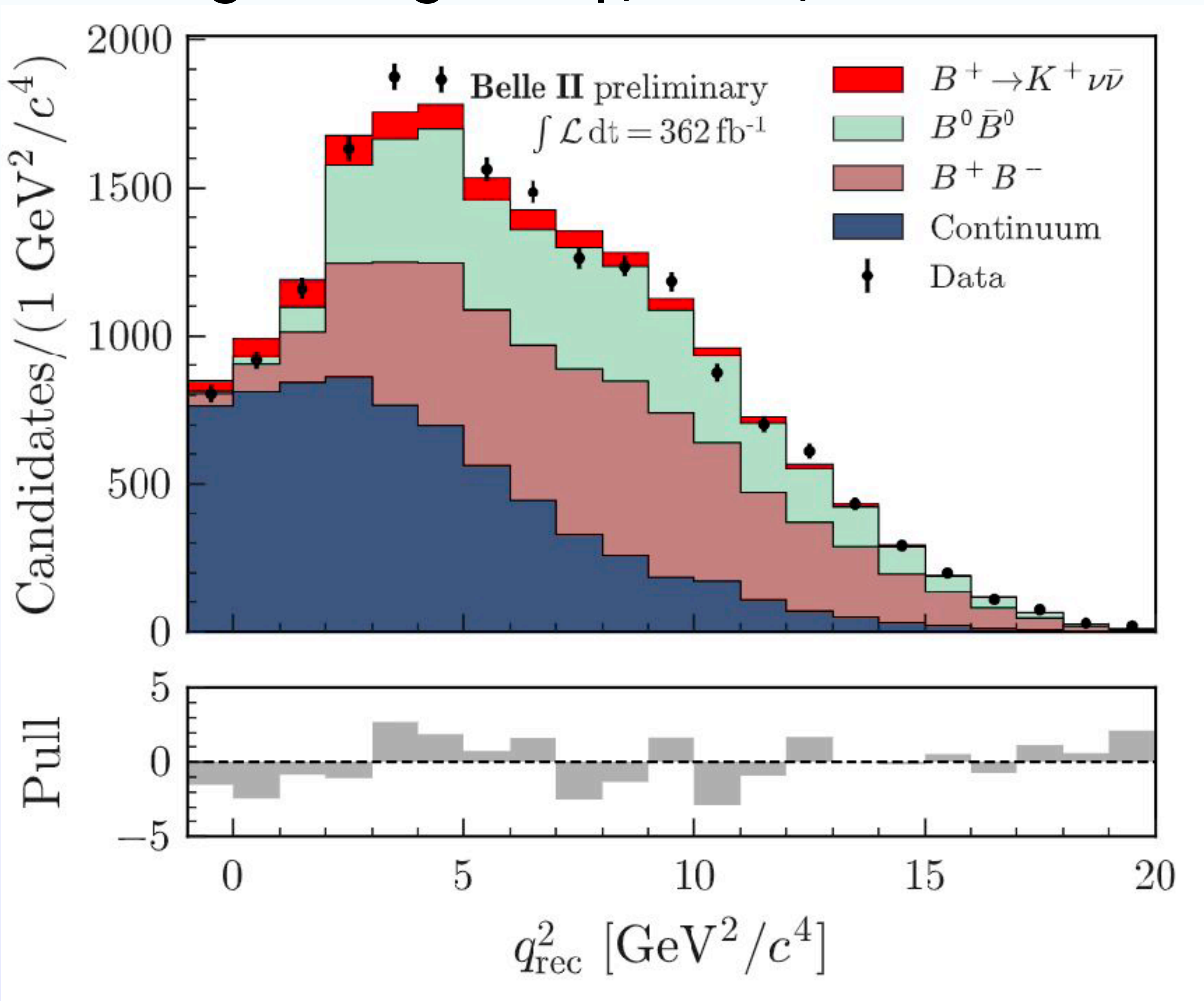




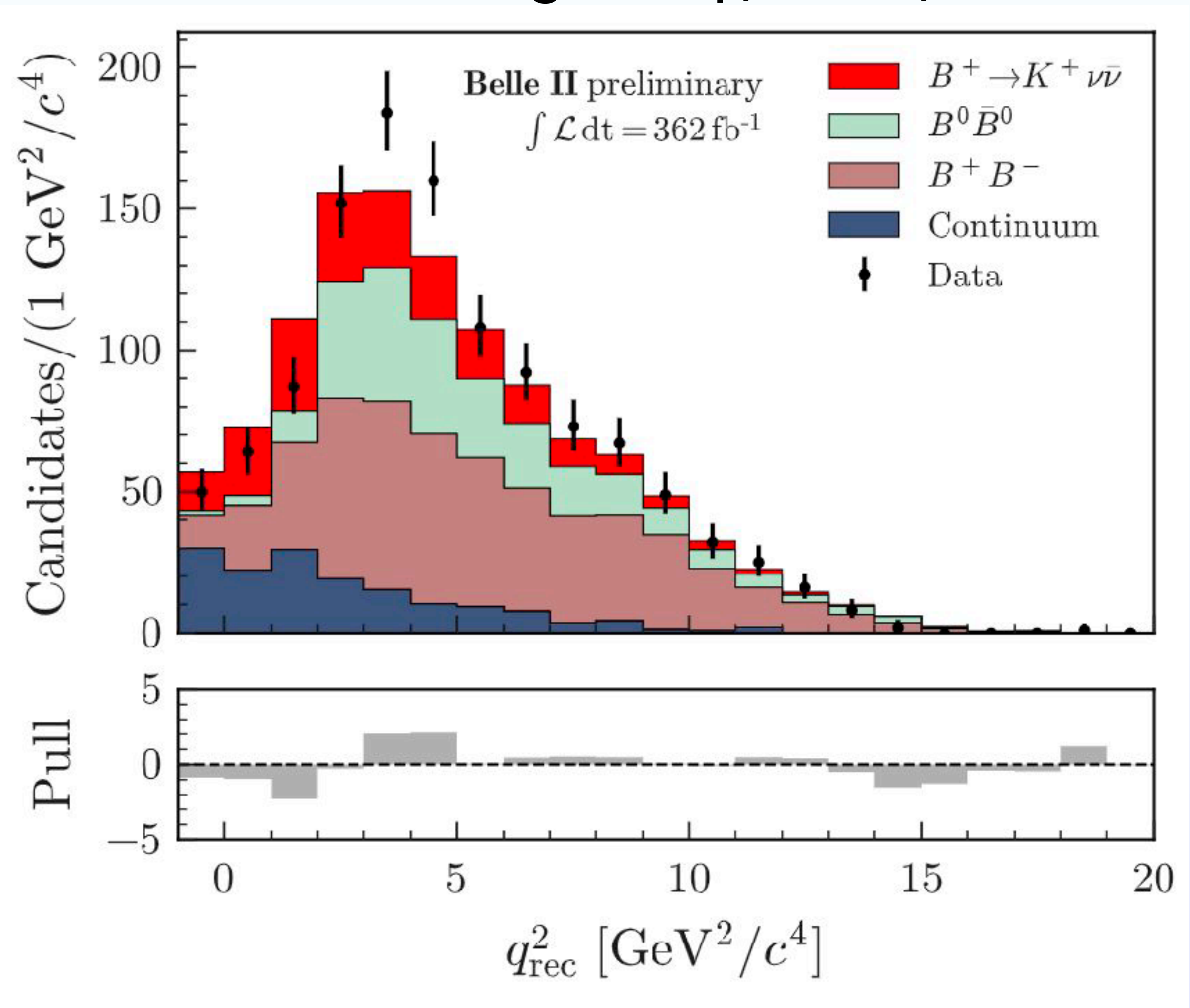


The q^2 distribution

Signal region: η(BDT2) > 0.92



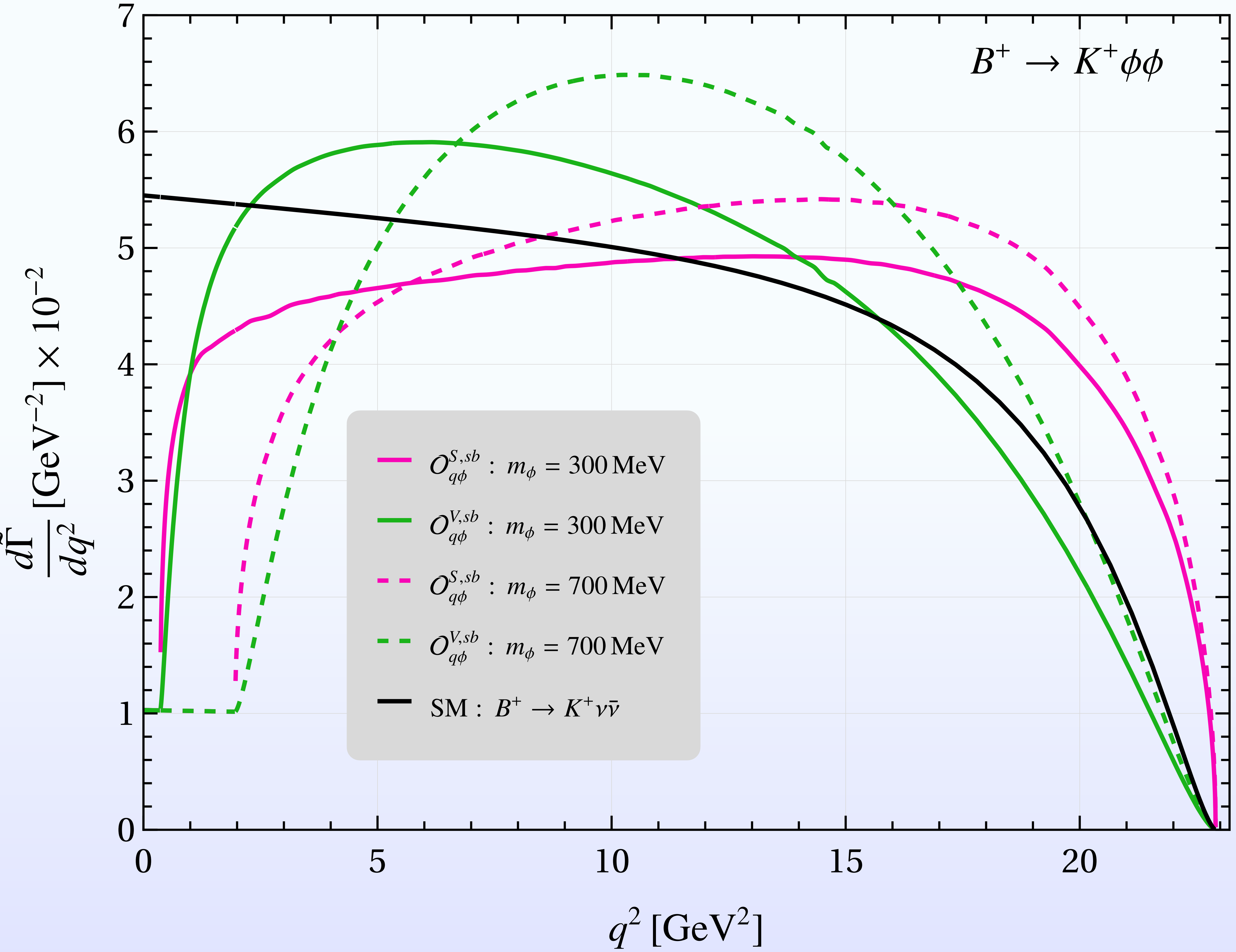
Most sensitive region: η(BDT2) > 0.98

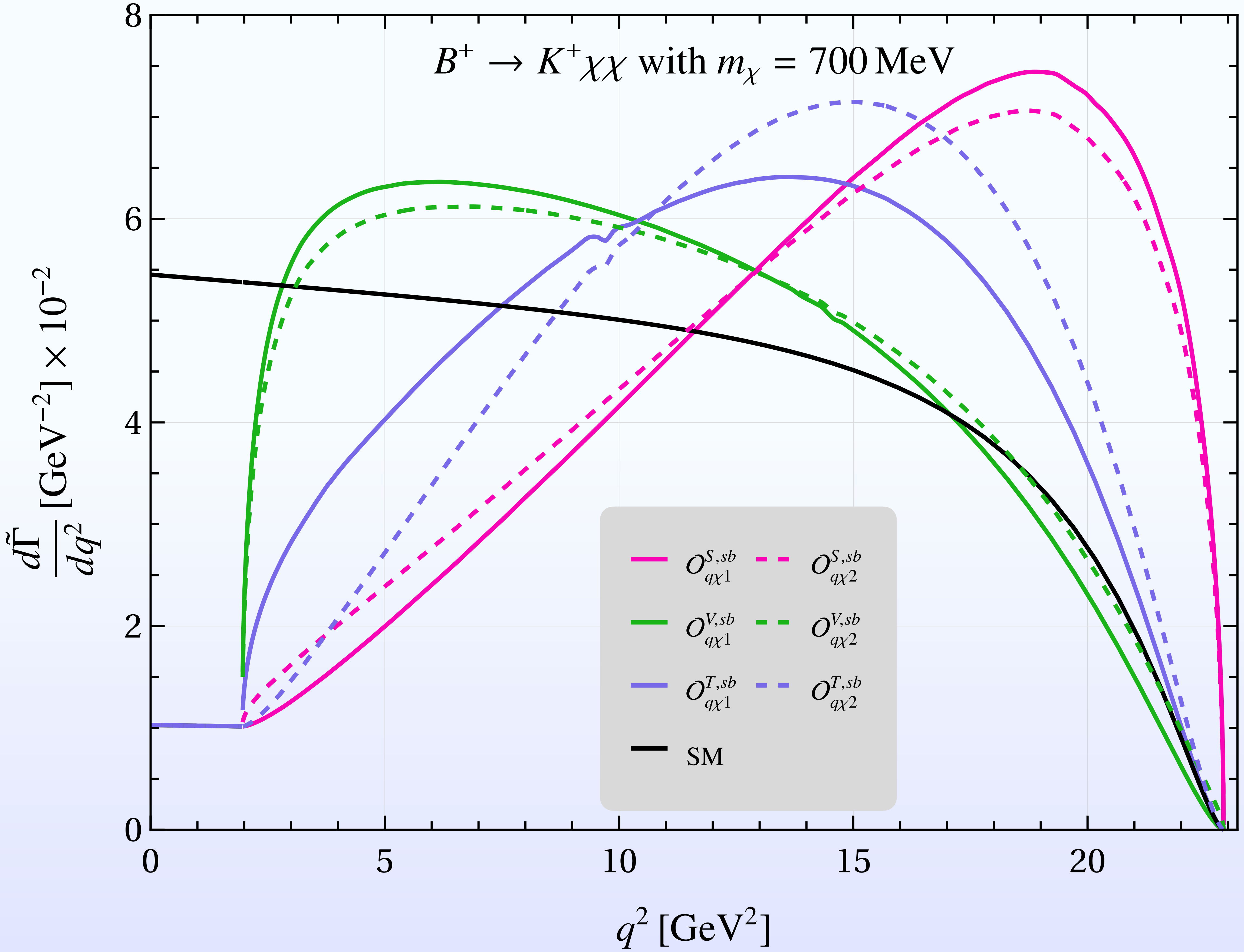


- **Excess between 3-7 GeV^2**
- **Not conclusive due to coarse binning choice, dictated from experimental resolution**

Elisa Manoni's Talk @CERN EP seminar, 2023

Scalar and fermion DM cases

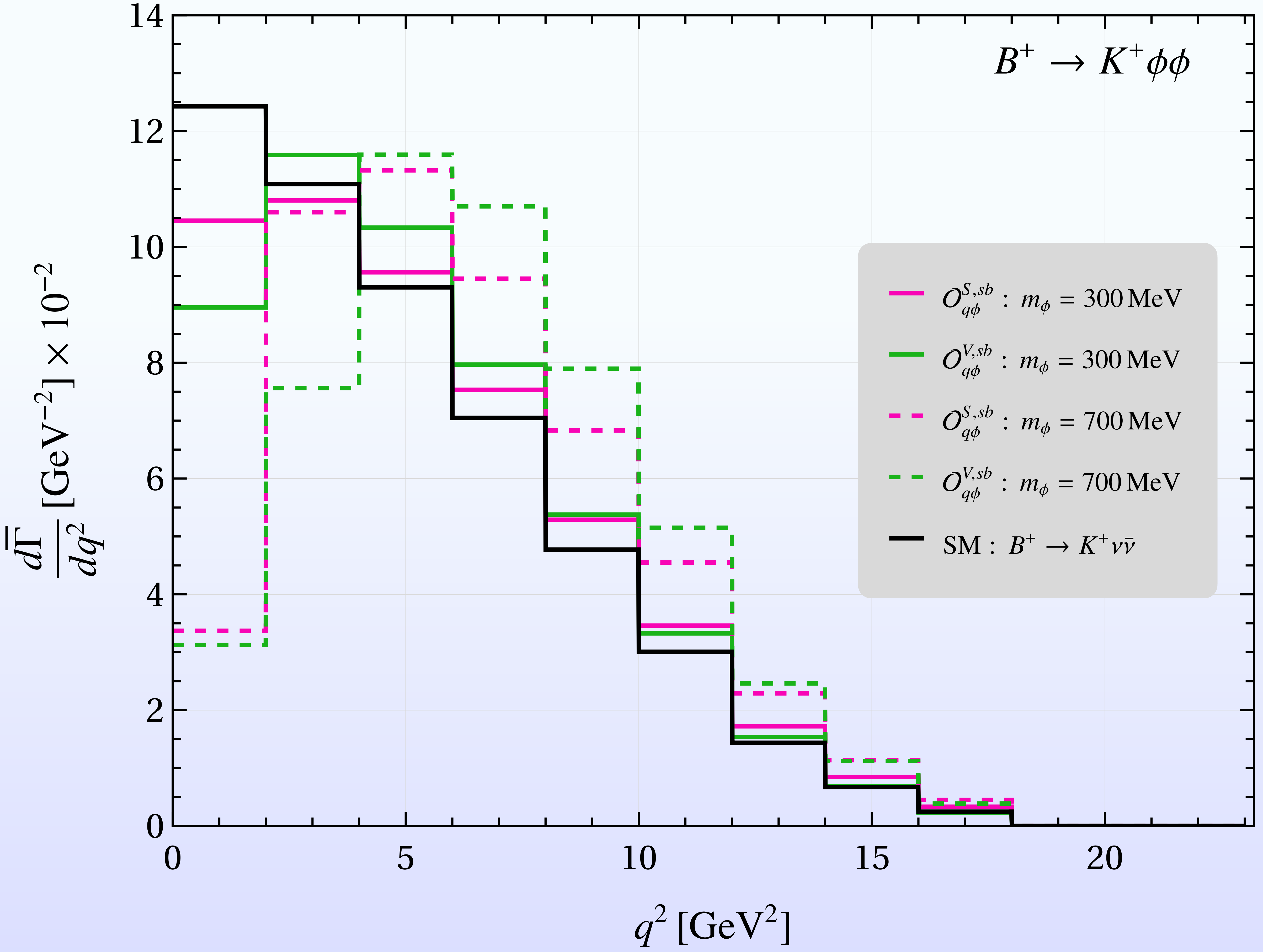


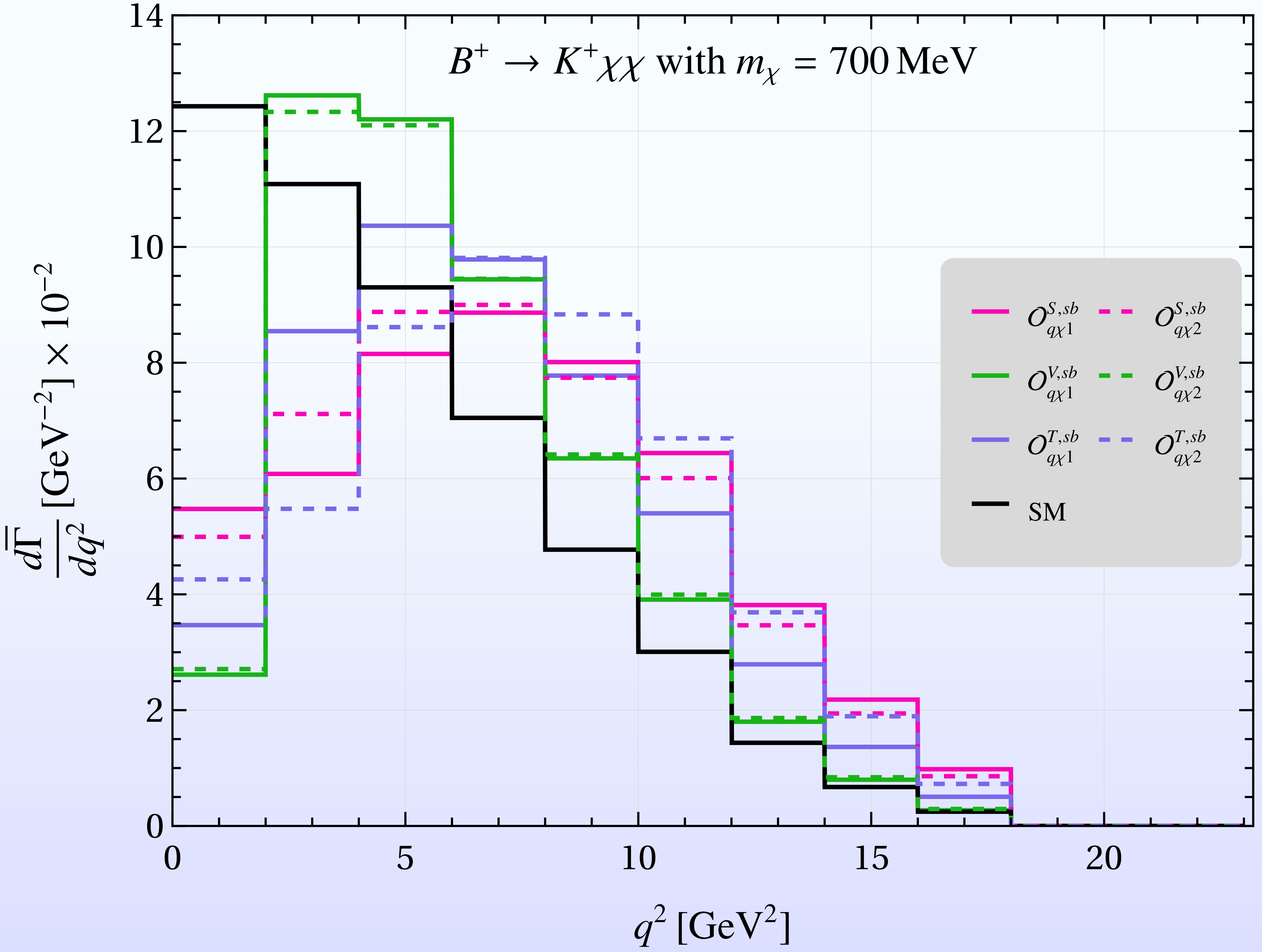


The vector current operators with scalar or vector DM particles with masses in the hundreds of MeV can match the anomaly.

All cases in vector DM case cannot match !

Influence of experimental efficiency





Scalar DM model

SM + a real scalar ϕ (DM)+ two vector-like quarks Q (q_L), $D(d_R)$

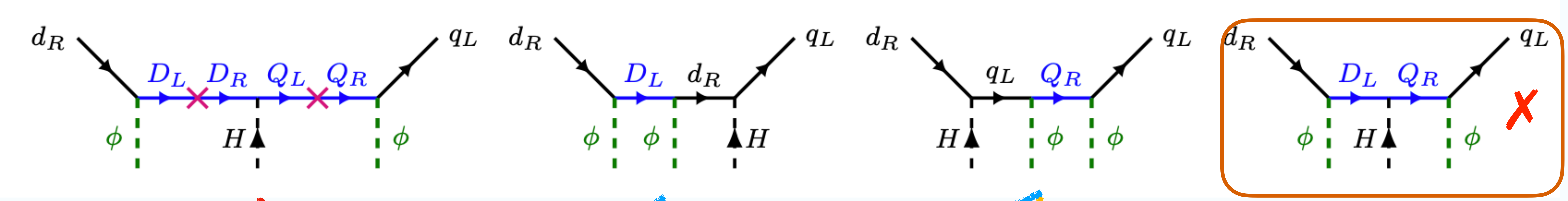
$\mathbb{Z}_2$ symmetry: odd of new particles

$$\mathcal{L}^{\rm NP}_{\tt kinetic} = \bar{Q} i \not{D} Q - m_Q \bar{Q} Q + \bar{D} i \not{D} D - m_D \bar{D} D + \frac{1}{2}\partial_\mu \phi \partial^\mu \phi - \frac{1}{2} m_\phi^2 \phi^2,$$

$$\mathcal{L}^{\rm NP}_{\tt Yukawa} = y_q^p \bar{q}_{Lp} Q_R \phi + y_d^p \bar{D}_L d_{Rp} \phi - \boxed{y_1 \bar{Q}_L D_R H} - y_2 \bar{Q}_R D_L H + \text{h.c.} \,,$$

$$V^{\rm NP}_{\tt potential} = \frac{1}{4}\lambda_\phi \phi^4 + \frac{1}{2}\kappa\, \phi^2 H^\dagger H \,,$$

$B \to K + \phi\phi$



$$\frac{1}{2}C^{S,ij}_{d\phi}(\bar{d}_i d_j)\phi^2 + \frac{1}{2}C^{P,ij}_{d\phi}(\bar{d}_i i\gamma_5 d_j)\phi^2 + \frac{1}{2}C^{S,ij}_{u\phi}(\bar{u}_i u_j)\phi^2 + \frac{1}{2}C^{P,ij}_{u\phi}(\bar{u}_i i\gamma_5 u_j)\phi^2$$

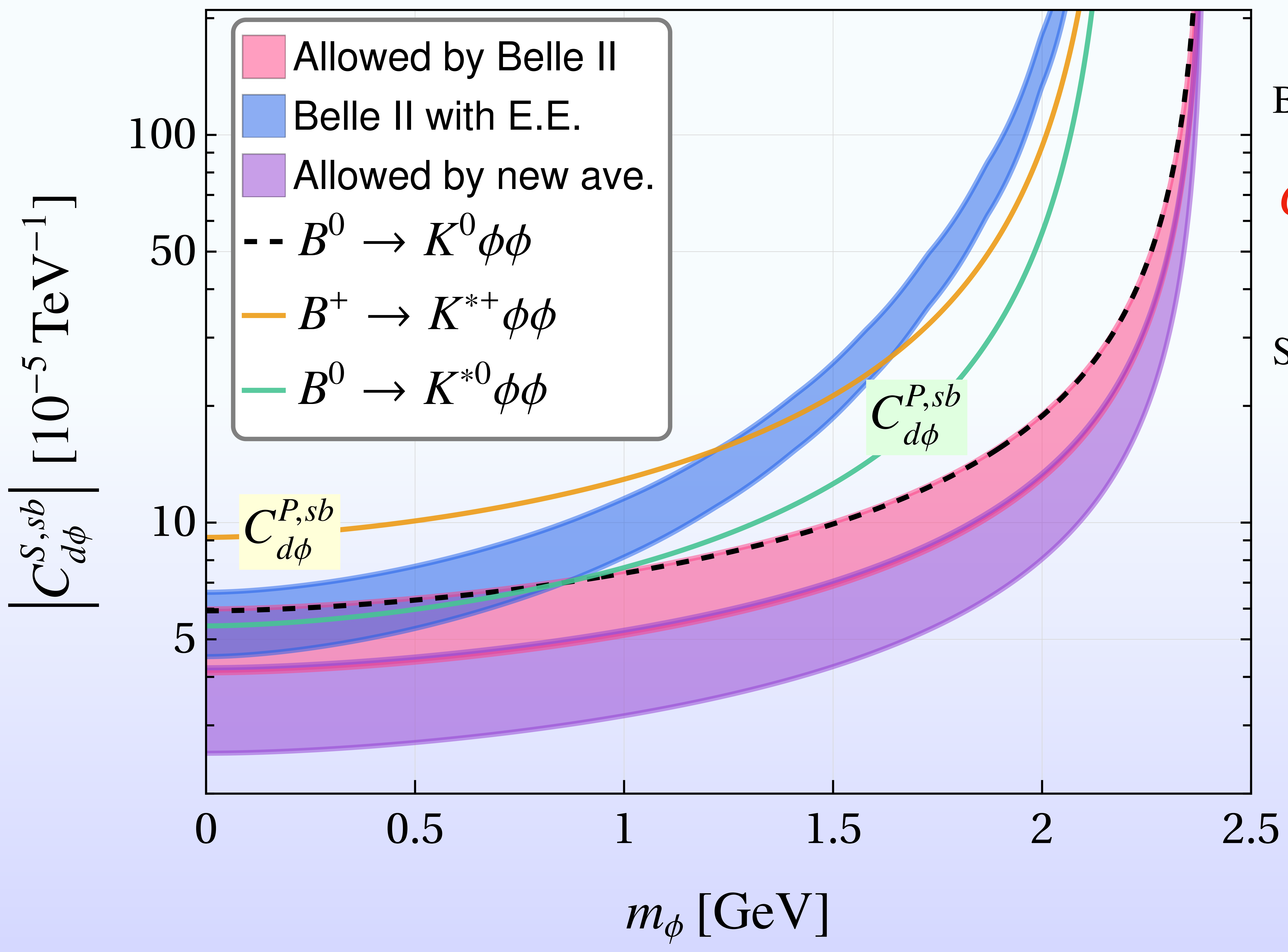
$$C^{S,ij}_{d\phi} = \frac{(y_q^i y_d^j y_1 + y_q^{j*} y_d^{i*} y_1^*)v}{\sqrt{2}m_Q m_D} + \left(\frac{y_q^i y_q^{j*}}{2m_Q^2} + \frac{y_d^{i*} y_d^j}{2m_D^2}\right)(m_{d_i} + m_{d_j}),$$

$$iC^{P,ij}_{d\phi} = \frac{(y_q^i y_d^j y_1 - y_q^{j*} y_d^{i*} y_1^*)v}{\sqrt{2}m_Q m_D} - \left(\frac{y_q^i y_q^{j*}}{2m_Q^2} - \frac{y_d^{i*} y_d^j}{2m_D^2}\right)(m_{d_i} - m_{d_j}),$$

Dominant ones

$$C^{S,ij}_{u\phi} = \frac{\tilde{y}_q^i \tilde{y}_q^{j*}}{2m_Q^2}(m_{u_i} + m_{u_j}),$$

$$iC^{P,ij}_{u\phi} = -\frac{\tilde{y}_q^i \tilde{y}_q^{j*}}{2m_Q^2}(m_{u_i} - m_{u_j}),$$



Belle II anomaly:

$C^{S,sb}_{d\phi} \sim (3-8)/(10^5\,\text{TeV})$

Signal selection efficiency impact:

$$\omega(m) = \frac{\sum_i \tilde{\Gamma}_{i,\text{SM}}\epsilon_i}{\sum_i \tilde{\Gamma}_{i,\text{NP}}(m)\epsilon_i}.$$

DM relic density

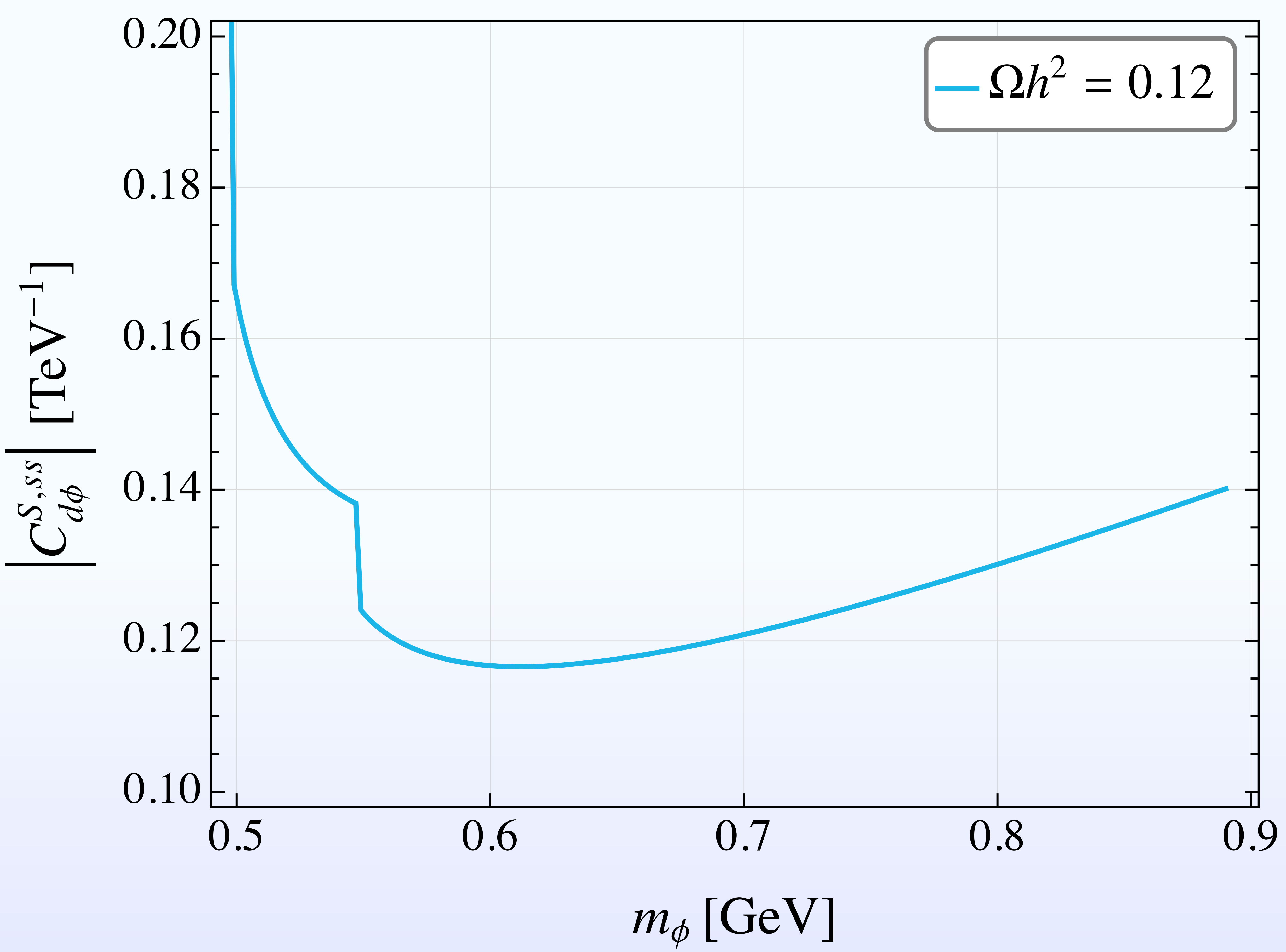
- Neglect Higgs portal coupling ($h \to \text{inv}$)
- Thermal freeze-out mechanism
- Neglect $C^{S,uu}_{u\phi}, y^{d}_{q,d}$
- $500\,\text{MeV} < m_\phi < 900\,\text{MeV}$
- Main channels: $\phi\phi \to K^+K^-, K^0\bar{K}^0, \eta\eta$
- $\langle \sigma v \rangle \simeq 2.4 \times 10^{-26} \dfrac{\text{cm}^3\text{s}^{-1}}{(\hbar c)^2 c} = 2.2 \times 10^{-9}\,\text{GeV}^{-2}$

ChPT

$$\mathscr{L}_{\phi P} \ni -\sqrt{2} B F_0 \,\text{tr}\left[p\Phi\right] - B\,\text{tr}\left[s\Phi^2\right] + \mathcal{O}(\phi^2 P^3)$$

$$\langle \sigma v(\phi\phi \to K^+K^-, K^0\bar{K}^0)\rangle = \frac{B^2 |C_{d\phi}^{S,ss}|^2 \eta(x, z_K)}{64\pi m_\phi^2},$$

$$\langle \sigma v(\phi\phi \to \eta\eta)\rangle = \frac{B^2 |C_{d\phi}^{S,ss}|^2 \eta(x, z_\eta)}{72\pi m_\phi^2},$$

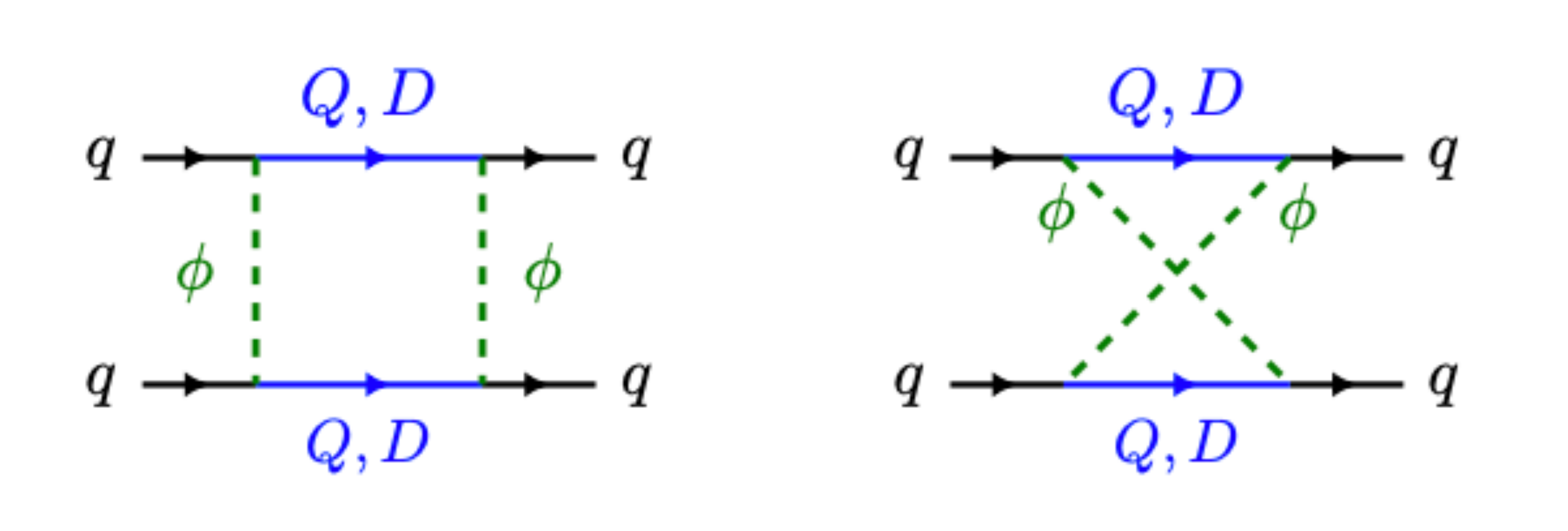


A large 10^3 hierarchy is required between the strange and bottom couplings

1. DM indirect detection constraints is negligible $\Leftarrow$ loop induced $\phi^2 F_{\mu\nu}F^{\mu\nu}$
2. Sub-GeV scale DM also is safe for direct detection;

Other constraints or implications

- $B \to X_s\gamma$: $O_{d\gamma}^{ij} = \bar{d}_i \sigma^{\mu\nu} P_R d_j F_{\mu\nu}$
- $B_s - \bar{B}_s$: has no contribution at dim-6 order



- $B \to \text{inv}$: Indued by $\mathcal{O}_{d\phi}^{P,sb}$ with $\mathscr{B}(B_s \to \phi\phi) \sim 4 \times 10^{-5}$

2310.13043 [hep-ph]

$\mathscr{B}(B_s \to \text{inv}) < 5.4 \times 10^{-4}$

- $D^0 \to \text{inv}$, $D^0 \to \pi^0 + \text{inv}$: $C_{u\phi}^{S(P),uc} \,|/m_c \lesssim 2.06(0.25)/\text{TeV}^2$

1611.09455 [hep-ex].
2112.14236 [hep-ex].

$\mathscr{B}(D^0 \to \text{inv}) < 9.4 \times 10^{-5}$

$\mathscr{B}(D^0 \to \pi^0 \nu\bar{\nu}) < 2.1 \times 10^{-4}$

- LHC search for vector-like quarks: > 1.5 TeV by ATLAS and CMS

2212.05263 [hep-ex].
2209.07327 [hep-ex].

$$y_q^i \equiv |y_q^i| e^{-i\alpha_i}, \quad y_d^i \equiv |y_d^i| e^{-i\beta_i}$$

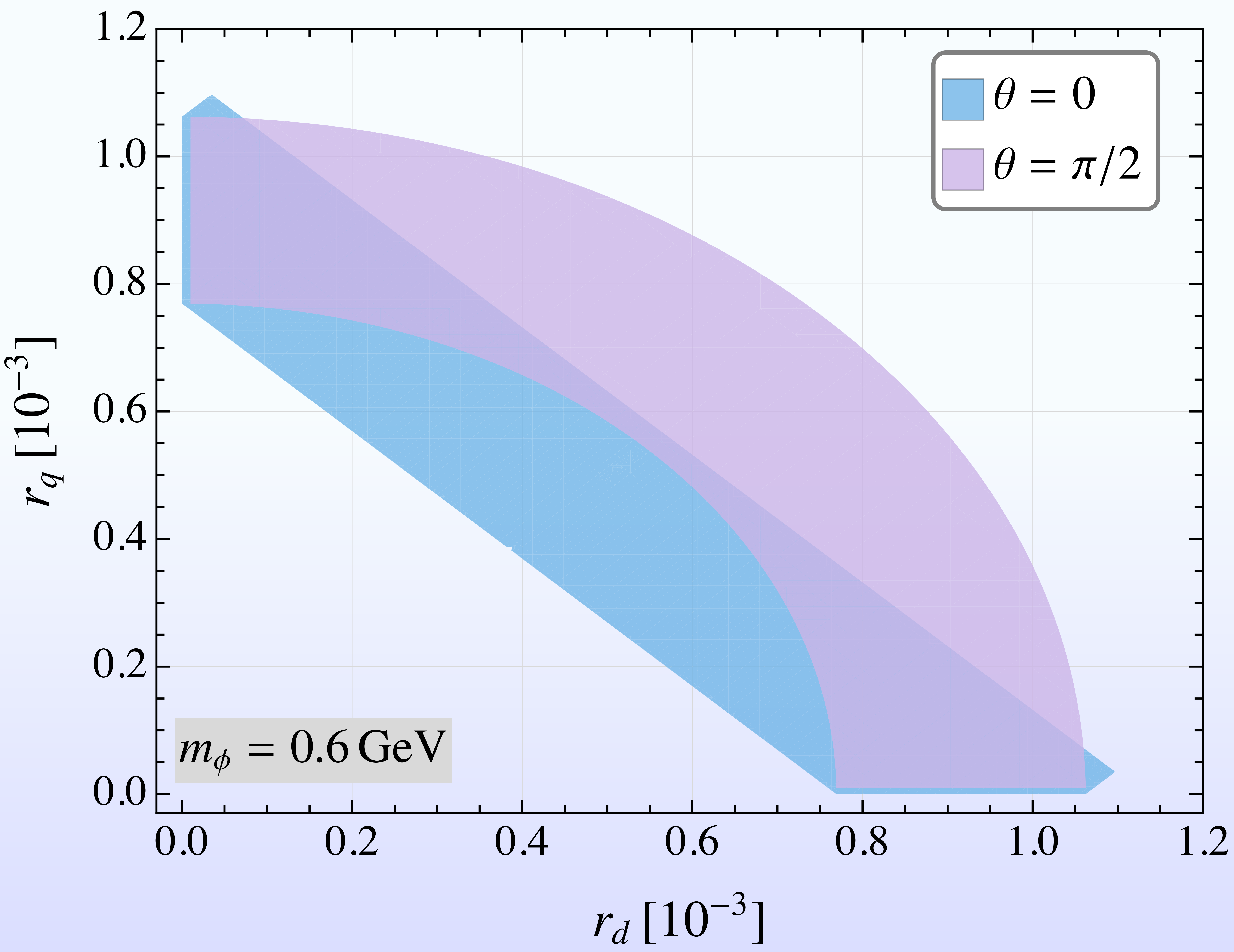
$$\alpha_s + \beta_s = \rho, \quad \alpha_b + \beta_b + \rho \equiv \theta$$

$$|y_d^b| / |y_d^s| \equiv r_d, \quad |y_q^b| / |y_q^s| \equiv r_q\,.$$

$$|C_{d\phi}^{S,ss}| \approx \frac{|y_q^s||y_d^s| y_1 v}{\sqrt{2} m_Q m_D} \left|1 + e^{i2\rho}\right|,$$

$$|C_{d\phi}^{S(P),sb}| \approx \frac{|y_q^s||y_d^s| y_1 v}{\sqrt{2} m_Q m_D} \left|r_d \pm r_q e^{i\theta}\right|.$$

$$m_Q = m_D = 3\,\text{TeV}$$
$$|y_d^s| = |y_q^s| = 2$$



Conclusion

- Several scenarios that could accommodate the recent Belle II anomaly are discussed, 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;
- For new light states, a viable scalar DM model is proposed to explain the anomaly and DM relic density;
- $B \to K^* + inv.$, $B_s \to inv.$ 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!