$B^+ \to K^+ \nu\bar{\nu}$ excess@Belle II,

(Dark) SMEFT and NP flavour structure

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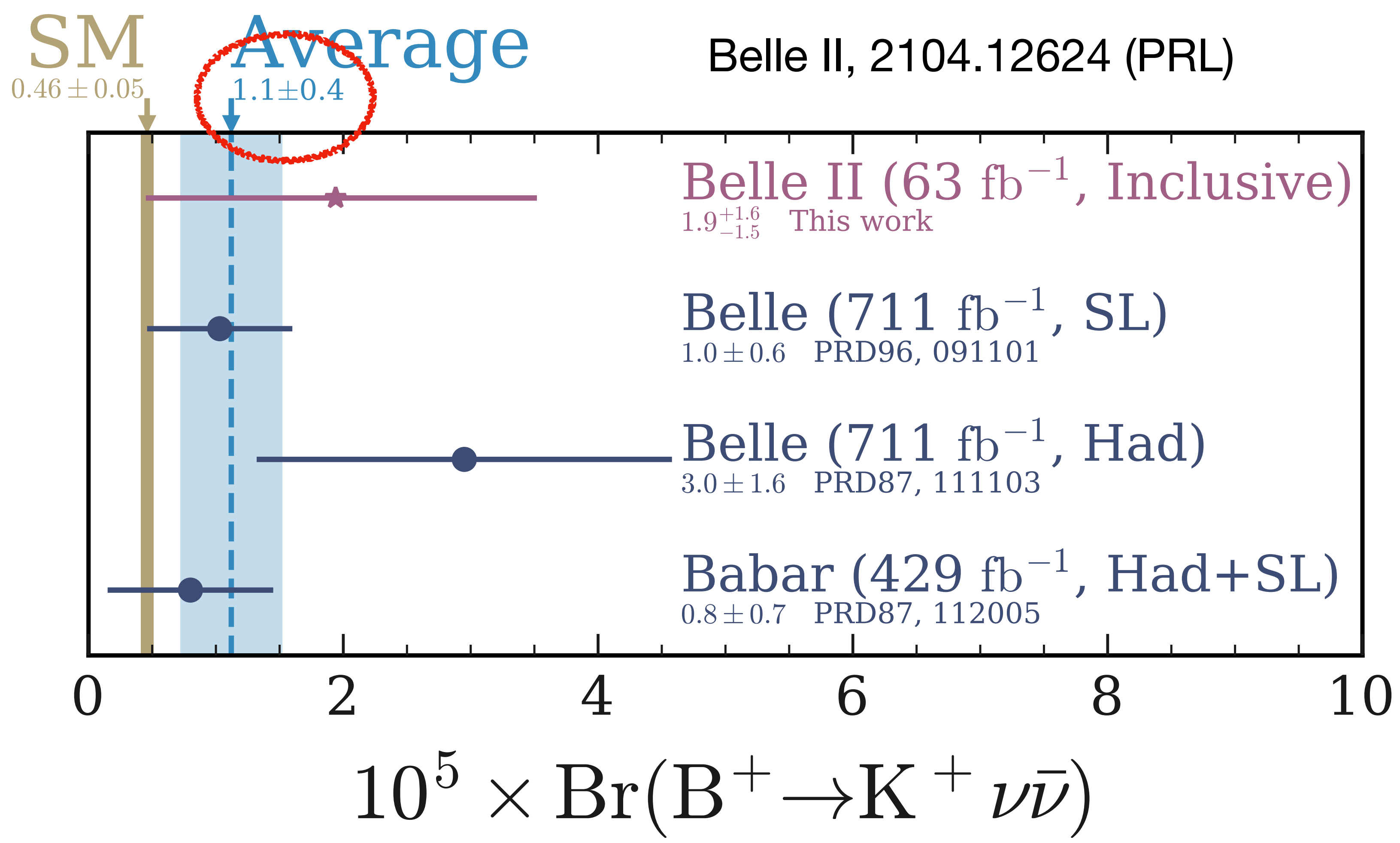
arXiv: 2402.19208，侯镖锋，李新强，沈萌，杨亚东，袁兴博

第六届 重味物理与量子色动力学研讨会

中国海洋大学丨山东大学，青岛，2024.04.22

$b \to s\nu\bar{\nu}$: exp & theory

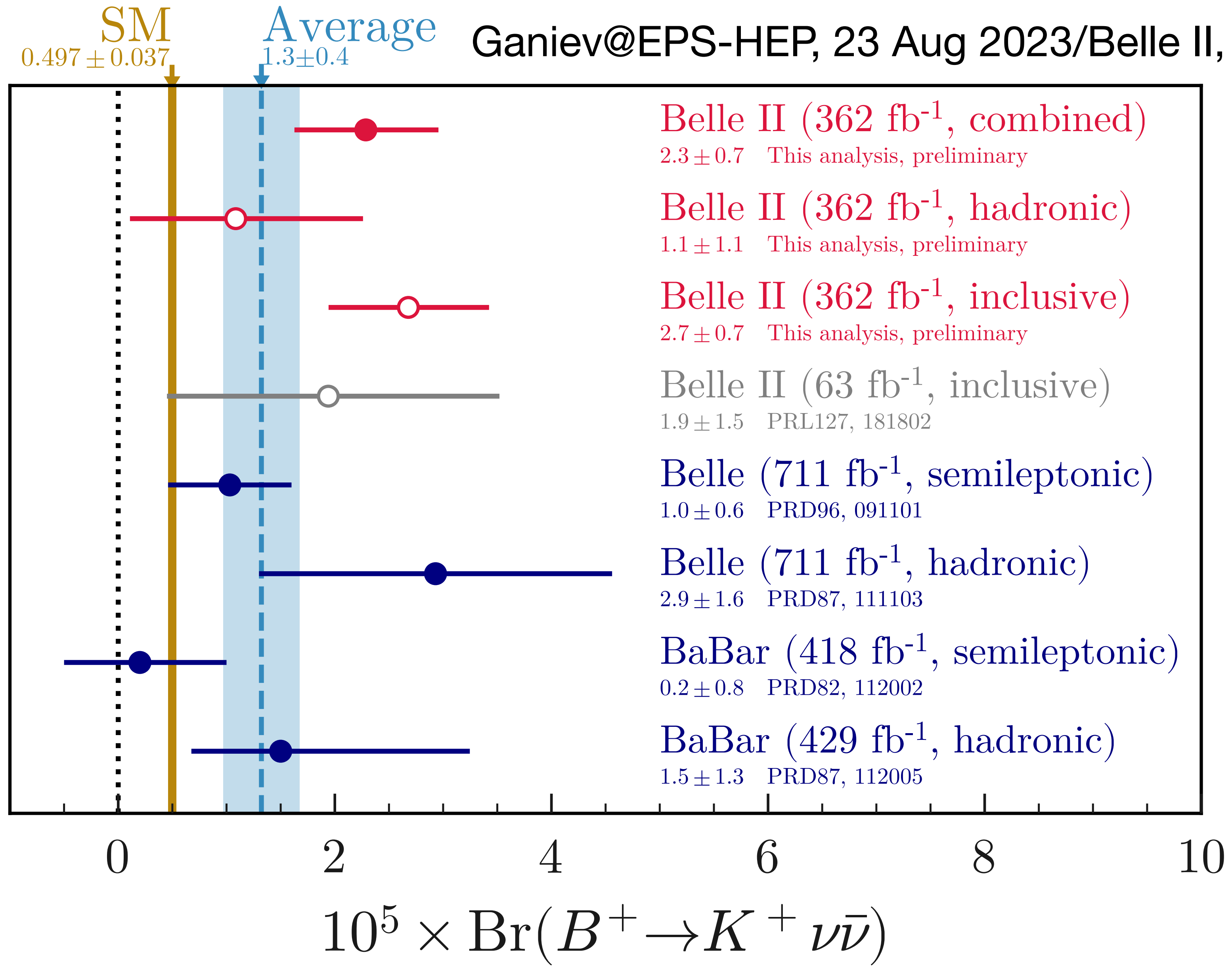
- **2021 Apr**



Belle II, 2104.12624 (PRL)

- **2023 Aug**

Ganiev@EPS-HEP, 23 Aug 2023/Belle II, 2311.14647



Impact of B→Kνν¯ measurements on beyond the Standard Model theories #69
Thomas E. Browder (Hawaii U.), Nilendra G. Deshpande (Oregon U.), Rusa Mandal (Siegen U.), Rahul Sinha (IMSc, Chennai and Bhubaneswar, Inst. Phys.) (Jul 2, 2021)
Published in: Phys.Rev.D 104 (2021) 5, 053007 • e-Print: 2107.01080 [hep-ph]
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A tale of invisibility: constraints on new physics in b → sνν #65
Tobias Felkl (New South Wales U.), Sze Lok Li (New South Wales U.), Michael A. Schmidt (New South Wales U.) (Nov 8, 2021)
Published in: JHEP 12 (2021) 118 • e-Print: 2111.04327 [hep-ph]
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Phenomenological study of a gauged L_μ - L_τ model with a scalar leptoquark #42
Chuan-Hung Chen (Taiwan, Natl. Cheng Kung U. and NCTS, Taipei), Cheng-Wei Chiang (Taiwan, Natl. Taiwan U. and NCTS, Taipei), Chun-Wei Su (Taiwan, Natl. Taiwan U.) (May 16, 2023)
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Explaining the $B^+ \to K^+\nu\bar{\nu}$ excess via a massless dark photon #16
E. Gabrielli, L. Marzola, K. Müürsepp, M. Raidal (Feb 8, 2024)
e-Print: 2402.05901 [hep-ph]
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Higgs portal interpretation of the Belle II $B^+ \to K^+\nu\nu$ measurement #29
David McKeen (TRIUMF), John N. Ng (TRIUMF), Douglas Tuckler (TRIUMF and Simon Fraser U.) (Dec 1, 2023)
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Decoding the $B \to K\nu\nu$ excess at Belle II: kinematics, operators, and masses #27
Kåre Fridell, Mitrajyoti Ghosh, Takemichi Okui, Kohsaku Tobioka (Dec 19, 2023)
e-Print: 2312.12507 [hep-ph]
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Light new physics in $B \to K^{(*)}\nu\bar{\nu}$? #30
Wolfgang Altmannshofer (UC, Santa Cruz, Inst. Part. Phys.), Andreas Crivellin (Zurich U.), Huw Haigh (Vienna, OAW), Gianluca Inguglia (Vienna, OAW), Jorge Martin Camalich (IAC, La Laguna) (Nov 24, 2023)
Published in: Phys.Rev.D 109 (2024) 7, 075008 • e-Print: 2311.14629 [hep-ph]
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Understanding the first measurement of $B(B \to K\nu\bar{\nu})$ #38
Lukas Allwicher (Zurich U.), Damir Becirevic (IJCLab, Orsay), Gioacchino Piazza (IJCLab, Orsay), Salvador Rosauro-Alcaraz (IJCLab, Orsay), Olcyr Sumensari (IJCLab, Orsay) (Sep 5, 2023)
Published in: Phys.Lett.B 848 (2024) 138411 • e-Print: 2309.02246 [hep-ph]
pdf DOI cite claim reference search 26 citations

$B \to K\nu\nu$, MiniBooNE and muon g - 2 anomalies from a dark sector #31
Alakabha Datta (Mississippi U. and SLAC and UC, Santa Cruz), Danny Marfatia (Hawaii U.), Lopamudra Mukherjee (Nankai U.) (Oct 23, 2023)
Published in: Phys.Rev.D 109 (2024) 3, L031701 • e-Print: 2310.15136 [hep-ph]
pdf DOI cite claim reference search 11 citations

Implications of an enhanced $B \to K\nu\bar{\nu}$ branching ratio #39
Rigo Bause (Tech. U., Dortmund (main)), Hector Gisbert (INFN, Padua and Padua U.), Gudrun Hiller (Tech. U., Dortmund (main) and Sussex U.) (Aug 31, 2023)
Published in: Phys.Rev.D 109 (2024) 1, 015006 • e-Print: 2309.00075 [hep-ph]
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$B \to K^* M_X$ vs $B \to K M_X$ as a probe of a scalar-mediator dark matter scenario #33
Alexander Berezhnoy (SINP, Moscow), Dmitri Melikhov (SINP, Moscow and Dubna, JINR and Vienna U.) (Sep 29, 2023)
Published in: EPL 145 (2024) 1, 14001 • e-Print: 2309.17191 [hep-ph]
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B meson anomalies and large $B^+ \to K^+\nu\bar{\nu}$ in non-universal U(1)′ models #40
Peter Athron (Nanjing Normal U.), R. Martinez (Colombia, U. Natl.), Cristian Sierra (Nanjing Normal U.) (Aug 25, 2023)
Published in: JHEP 02 (2024) 121 • e-Print: 2308.13426 [hep-ph]
pdf DOI cite claim reference search 22 citations

Flavor anomalies in leptoquark model with gauged $U(1)_{L_\mu - L_\tau}$ #34
Chuan-Hung Chen (Taiwan, Natl. Cheng Kung U. and Unlisted, TW), Cheng-Wei Chiang (Taiwan, Natl. Taiwan U. and Unlisted, TW) (Sep 22, 2023)
Published in: Phys.Rev.D 109 (2024) 7, 075004 • e-Print: 2309.12904 [hep-ph]
pdf DOI cite claim reference search 9 citations

SMEFT predictions for semileptonic processes #4
Siddhartha Karmakar, Amol Dighe, Rick S. Gupta (Apr 15, 2024)
e-Print: 2404.10061 [hep-ph]
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Revisiting models that enhance $B^+ \to K^+\nu\nu$ in light of the new Belle II measurement #35
Belle-II Collaboration • Xiao-Gang He (Tsung-Dao Lee Inst., Shanghai and Taiwan, Natl. Taiwan U.) et al. (Sep 22, 2023)
Published in: Phys.Rev.D 109 (2024) 7, 075019 • e-Print: 2309.12741 [hep-ph]
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Implications of $B \to K\nu\bar{\nu}$ under Rank-One Flavor Violation hypothesis #5
David Marzocca, Marco Nardecchia, Alfredo Stanzione, Claudio Toni (Apr 9, 2024)
e-Print: 2404.06533 [hep-ph]
pdf cite claim reference search 0 citations

A new look at $b \to s$ observables in 331 models #18
Francesco Loparco (Jan 22, 2024)
e-Print: 2401.11999 [hep-ph]
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Scalar dark matter explanation of the excess in the Belle II B^+\to K^+ + \mbox{invisible} measurement #9
Xiao-Gang He, Xiao-Dong Ma, Michael A. Schmidt, German Valencia, Raymond R. Volkas (Mar 19, 2024)
e-Print: 2403.12485 [hep-ph]
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Correlating $B \to K^{(*)}\nu\bar{\nu}$ and flavor anomalies in SMEFT #19
Feng-Zhi Chen, Qiaoyi Wen, Fanrong Xu (Jan 21, 2024)
e-Print: 2401.11552 [hep-ph]
pdf cite claim reference search 8 citations

Status and prospects of rare decays at Belle-II #10
Elisa Manoni (Mar 12, 2024)
Published in: PoS WIFAI2023 (2024) 024 • Contribution to: WIFAI 2023, 024
pdf DOI cite claim reference search 0 citations

Recent $B^+ \to K^+\nu\bar{\nu}$ Excess and Muon $g-2$ Illuminating Light Dark Sector with Higgs Portal #20
Shu-Yu Ho, Jongkuk Kim, Pyungwon Ko (Jan 18, 2024)
e-Print: 2401.10112 [hep-ph]
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Rare B and K decays in a scotogenic model #11
Chuan-Hung Chen, Cheng-Wei Chiang (Mar 5, 2024)
e-Print: 2403.02897 [hep-ph]
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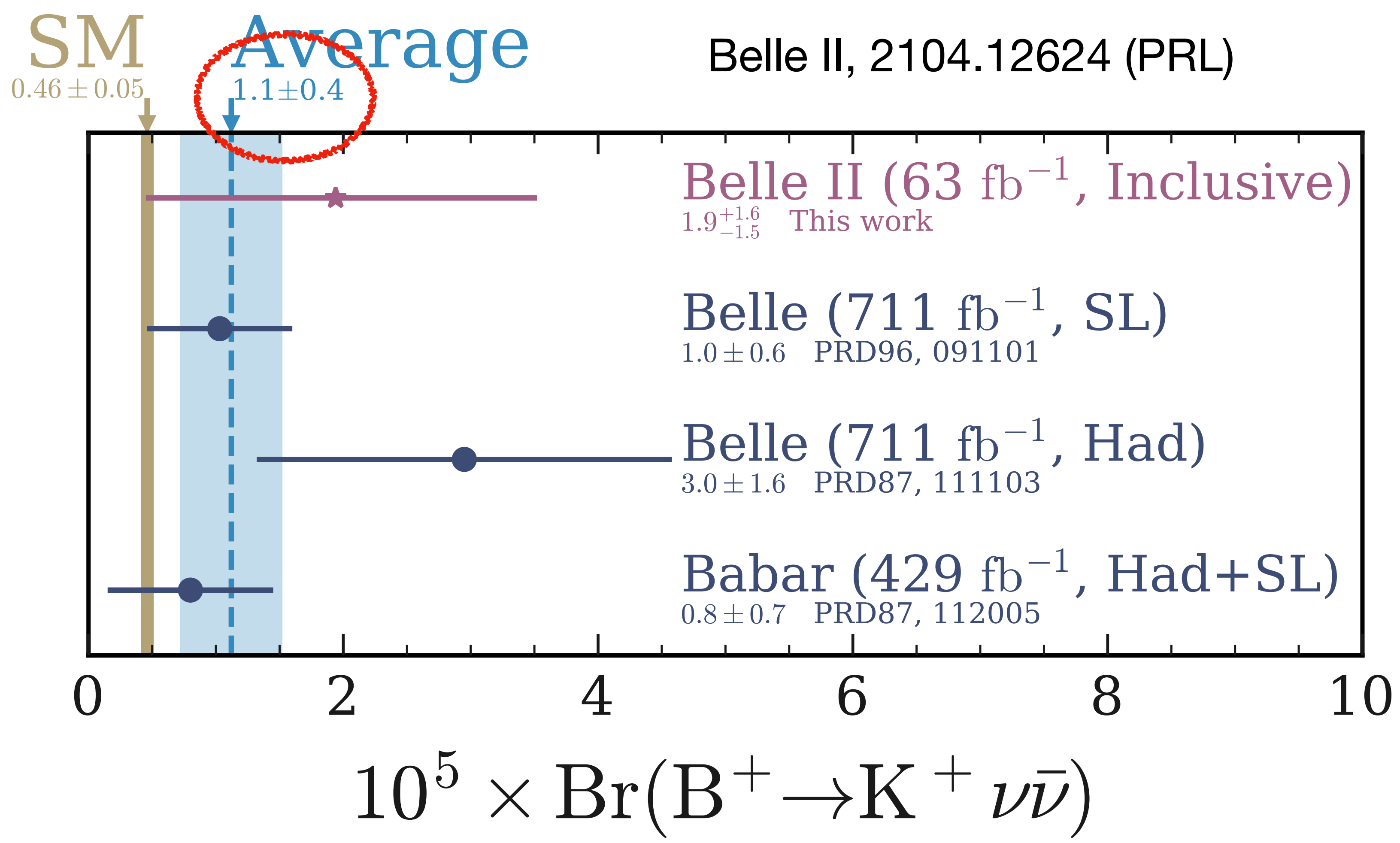
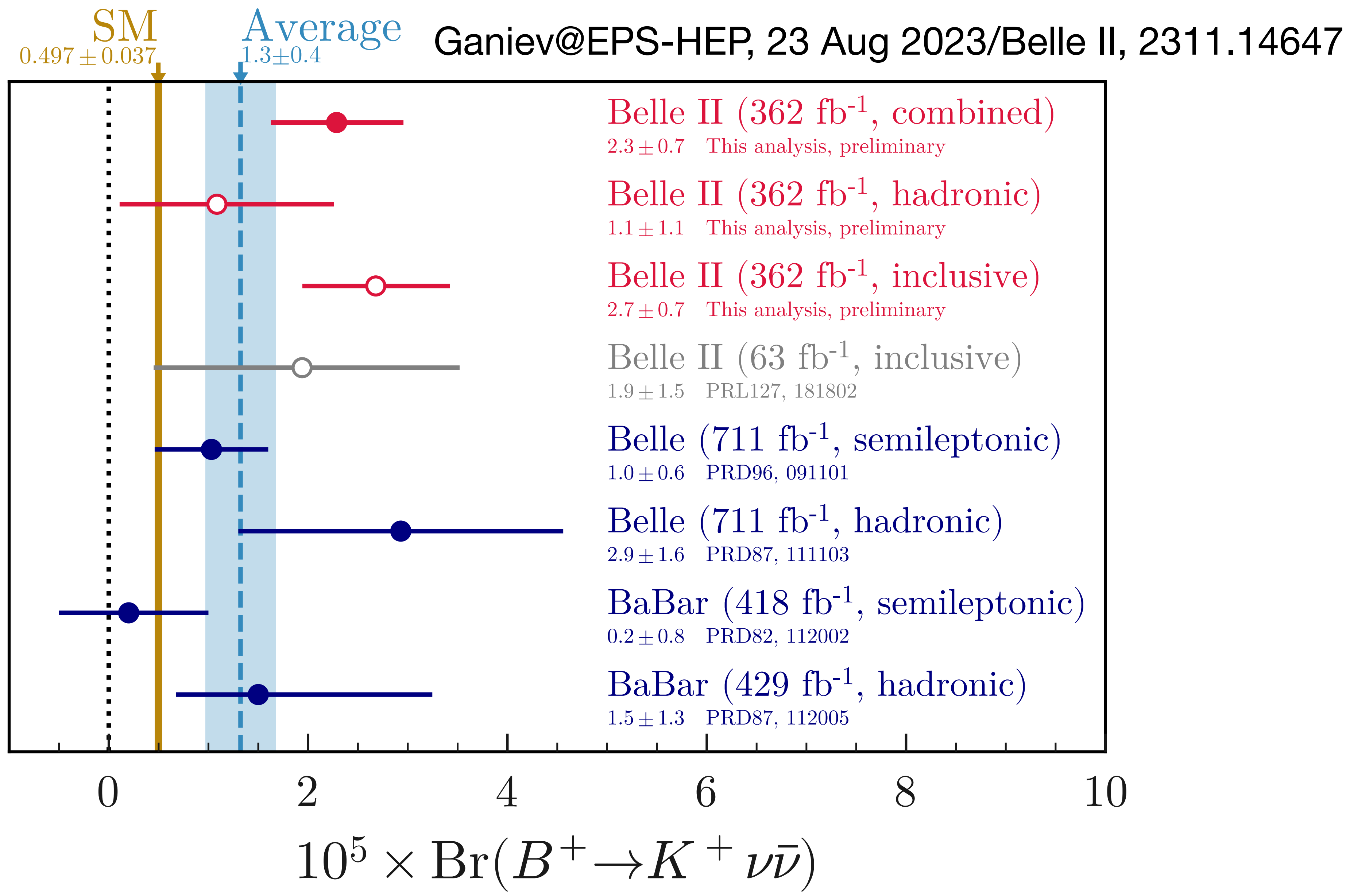
$b \to s\nu\bar{\nu}$: exp & theory

- **2021 Apr**



- **2023 Aug**



- **Exp vs SM** $[10^{-6}]$

$$\mathscr{B}(B^+ \to K^+\nu\bar{\nu})_{\rm SM} = 4.16 \pm 0.57$$

$$\mathscr{B}(B^+ \to K^+\nu\bar{\nu})_{\rm exp} = 23 \pm 7$$

$$\mathscr{B}(B^+ \to K^+\nu\bar{\nu})_{\rm exp} \gtrsim 10$$ (2σ lower bound)

2.7σ difference

- **Theoretical prediction**

$$\mathcal{O}_L = (\bar{s}\gamma_\mu P_L b)(\bar{\nu}\gamma^\mu P_L \nu)$$

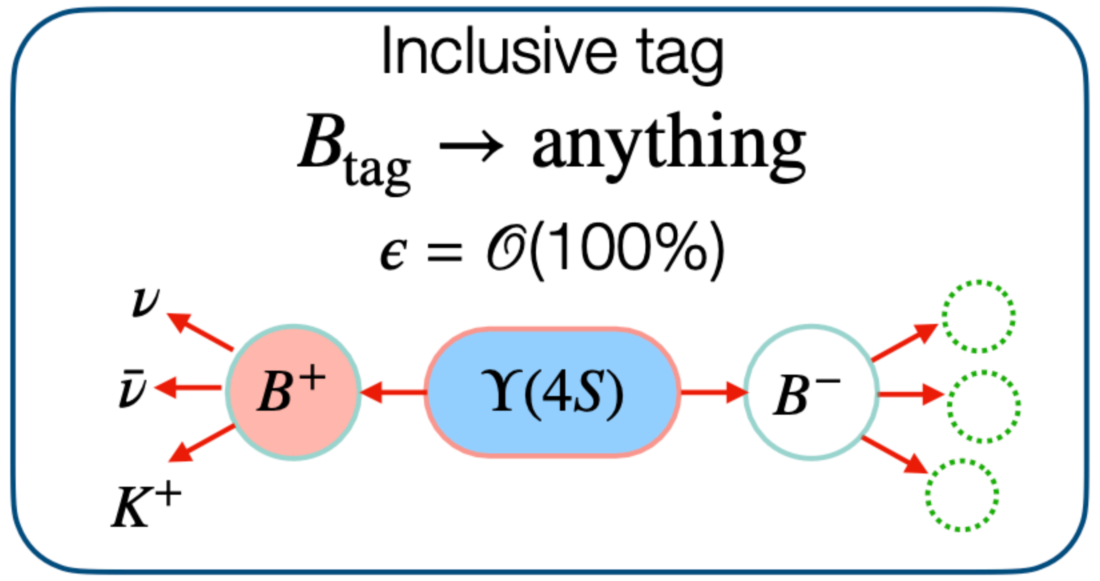
$$\mathcal{O}_R = (\bar{s}\gamma_\mu P_R b)(\bar{\nu}\gamma^\mu P_L \nu)$$

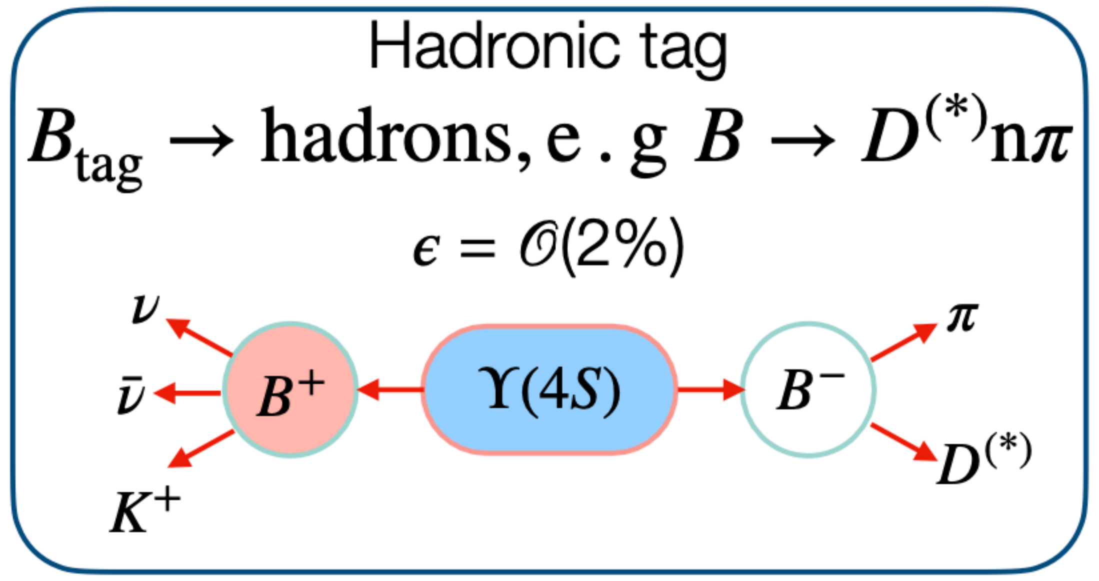
appear in BSM

Factorization

$$\mathscr{A} \propto C_L \cdot \langle K | \bar{s}\gamma^\mu b | \bar{B} \rangle$$

theoretically, simple and clean





$b \to s\nu\bar{\nu}$: exp & theory

	Observable	SM	Exp	Unit
$b \to s$	$\mathcal{B}(B^+ \to K^+\nu\bar{\nu})$	4.16 ± 0.57	$23 \pm 5^{+5}_{-4}$	10^{-6}
	$\mathcal{B}(B^0 \to K^0\nu\bar{\nu})$	3.85 ± 0.52	< 26	10^{-6}
	$\mathcal{B}(B^+ \to K^{*+}\nu\bar{\nu})$	9.70 ± 0.94	< 61	10^{-6}
	$\mathcal{B}(B^0 \to K^{*0}\nu\bar{\nu})$	9.00 ± 0.87	< 18	10^{-6}
	$\mathcal{B}(B_s \to \phi\nu\bar{\nu})$	9.93 ± 0.72	< 5400	10^{-6}
	$\mathcal{B}(B_s \to \nu\bar{\nu})$	≈ 0	< 5.9	10^{-4}
$b \to d$	$\mathcal{B}(B^+ \to \pi^+\nu\bar{\nu})$	1.40 ± 0.18	< 140	10^{-7}
	$\mathcal{B}(B^0 \to \pi^0\nu\bar{\nu})$	6.52 ± 0.85	< 900	10^{-8}
	$\mathcal{B}(B^+ \to \rho^+\nu\bar{\nu})$	4.06 ± 0.79	< 300	10^{-7}
	$\mathcal{B}(B^0 \to \rho^0\nu\bar{\nu})$	1.89 ± 0.36	< 400	10^{-7}
	$\mathcal{B}(B^0 \to \nu\bar{\nu})$	≈ 0	< 1.4	10^{-4}
$s \to d$	$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$	8.42 ± 0.61	$10.6^{+4.0}_{-3.4} \pm 0.9$	10^{-11}
	$\mathcal{B}(K_L \to \pi^0\nu\bar{\nu})$	3.41 ± 0.45	< 300	10^{-11}

Why such a large NP effect has not shown up
in other $b \to s$ decays ?
in $b \to d, s \to d$ decays ?

Exp vs SM $[10^{-6}]$

$$\mathscr{B}(B^+ \to K^+\nu\bar{\nu})_{\rm SM} = 4.16 \pm 0.57$$

$$\mathscr{B}(B^+ \to K^+\nu\bar{\nu})_{\rm exp} = 23 \pm 7$$

2.7σ difference

$$\mathscr{B}(B^+ \to K^+\nu\bar{\nu})_{\rm exp} \gtrsim 10 \text{ (}2\sigma\text{ lower bound)}$$

Theoretical prediction

$$\mathscr{O}_L = (\bar{s}\gamma_\mu P_L b)(\bar{\nu}\gamma^\mu P_L \nu)$$

$$\mathscr{O}_R = (\bar{s}\gamma_\mu P_R b)(\bar{\nu}\gamma^\mu P_L \nu)$$

appear in BSM

Factorization

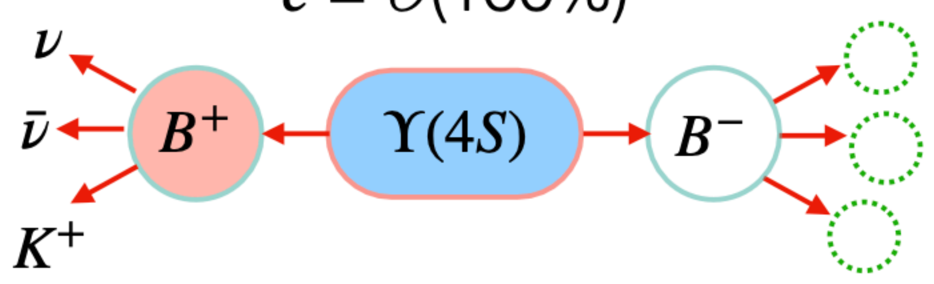
$$\mathscr{A} \propto C_L \cdot \langle K | \bar{s}\gamma^\mu b | \bar{B} \rangle$$

theoretically, simple and clean

Inclusive tag

$B_{\rm tag} \to$ anything

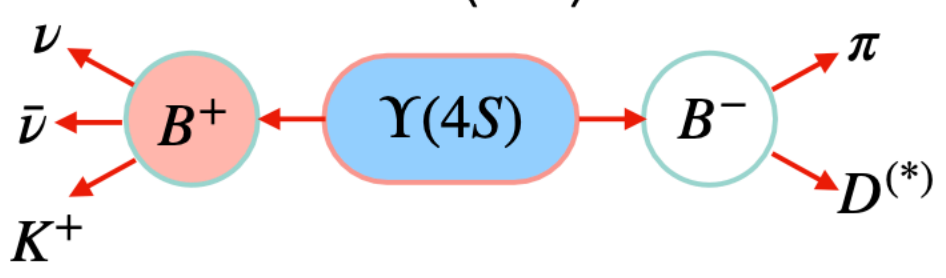
$\epsilon = \mathscr{O}(100\%)$



Hadronic tag

$B_{\rm tag} \to$ hadrons, e.g $B \to D^{(*)} n\pi$

$\epsilon = \mathscr{O}(2\%)$



$b \to s\nu\bar{\nu}$: SMEFT

SMEFT

$$\mathcal{Q}_{Hq}^{(1)} = \left(H^\dagger i \overleftrightarrow{D}_\mu H\right)\left(\bar{q}_p \gamma^\mu q_r\right),$$
$$\mathcal{Q}_{Hq}^{(3)} = \left(H^\dagger i \overleftrightarrow{D}^I_\mu H\right)\left(\bar{q}_p \tau^I \gamma^\mu q_r\right),$$
$$\mathcal{Q}_{Hd} = \left(H^\dagger i \overleftrightarrow{D}_\mu H\right)\left(\bar{d}_p \gamma^\mu d_r\right),$$
$$\mathcal{Q}_{ld} = \left(\bar{l}_p \gamma^\mu l_r\right)\left(\bar{d}_s \gamma_\mu d_t\right),$$
$$\mathcal{Q}_{lq}^{(1)} = \left(\bar{l}_p \gamma^\mu l_r\right)\left(\bar{q}_s \gamma_\mu q_t\right),$$
$$\mathcal{Q}_{lq}^{(3)} = \left(\bar{l}_p \gamma^\mu \tau^I l_r\right)\left(\bar{q}_s \tau^I \gamma_\mu q_t\right),$$

μ_{EW}

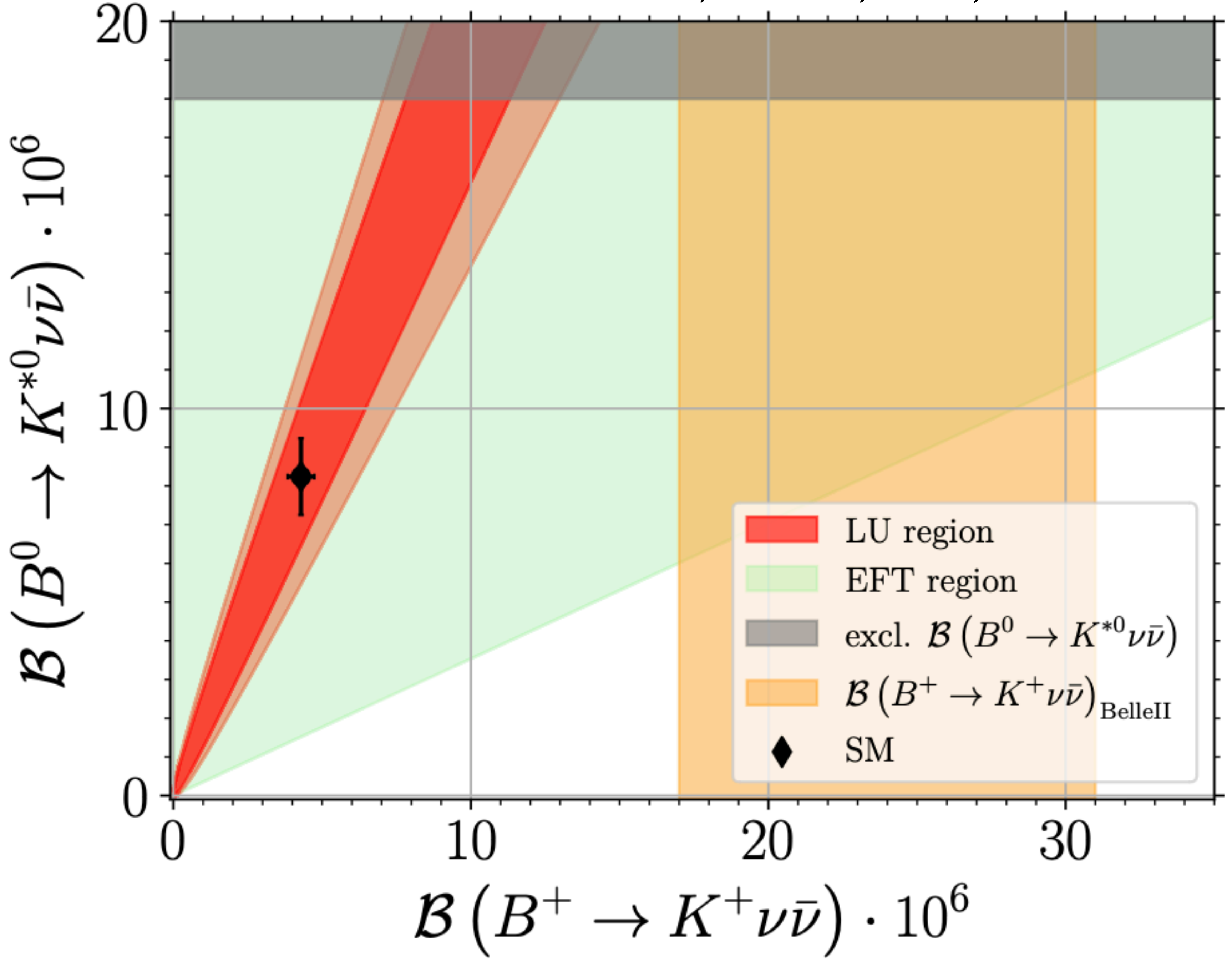
LEFT

$$\mathcal{O}_L^{\nu_i\nu_j} = \left(\bar{s}\gamma_\mu P_L b\right)\left(\bar{\nu}_i \gamma^\mu P_L \nu_j\right)$$
$$\mathcal{O}_R^{\nu_i\nu_j} = \left(\bar{s}\gamma_\mu P_R b\right)\left(\bar{\nu}_i \gamma^\mu P_L \nu_j\right)$$

μ_b

operator structure highly constrained by Left-handed neutrino

Bause, Gisbert, Hiller, 2309.00075



$$\mathcal{B}(B^+ \to K^+\nu\bar{\nu}) = A_+^{BK}\, x^+,$$
$$\mathcal{B}(B^0 \to K^{*0}\nu\bar{\nu}) = A_+^{BK^*}\, x^+ + A_-^{BK^*}\, x^-,$$
$$x^\pm = \sum_{\nu,\nu'} |C_L^{\nu\nu'} \pm C_R^{\nu\nu'}|^2,$$

Bause, Gisbert, Hiller, 2309.00075
Allwicher, Becirevic, Piazza, Rosauro-Alcaraz, Sumensari, 2309.02246
Chen, Wen, Xu, 2401.11552

$b \to s\nu\bar{\nu}$: SMEFT

SMEFT

$$\mathcal{Q}_{Hq}^{(1)} = \left(H^\dagger i \overleftrightarrow{D}_\mu H\right)\left(\bar{q}_p \gamma^\mu q_r\right),$$
$$\mathcal{Q}_{Hq}^{(3)} = \left(H^\dagger i \overleftrightarrow{D}^I_\mu H\right)\left(\bar{q}_p \tau^I \gamma^\mu q_r\right),$$
$$\mathcal{Q}_{Hd} = \left(H^\dagger i \overleftrightarrow{D}_\mu H\right)\left(\bar{d}_p \gamma^\mu d_r\right),$$

$$\mathcal{Q}_{ld} = \left(\bar{l}_p \gamma^\mu l_r\right)\left(\bar{d}_s \gamma_\mu d_t\right),$$

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$$\mathcal{Q}_{lq}^{(3)} = \left(\bar{l}_p \gamma^\mu \tau^I l_r\right)\left(\bar{q}_s \tau^I \gamma_\mu q_t\right),$$

$\mu_{\rm EW}$

LEFT

$$\mathcal{O}_L^{\nu_i\nu_j} = \left(\bar{s}\gamma_\mu P_L b\right)\left(\bar{\nu}_i \gamma^\mu P_L \nu_j\right)$$
$$\mathcal{O}_R^{\nu_i\nu_j} = \left(\bar{s}\gamma_\mu P_R b\right)\left(\bar{\nu}_i \gamma^\mu P_L \nu_j\right)$$

μ_b

operator structure highly constrained by Left-handed neutrino

	Observable	SM	Exp	Unit
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Why such a large NP effect has not shown up in other $b \to s$ decays ? in $b \to d, s \to d$ decays ? **NP flavour structure**

Minimal Flavour Violation

- Flavour symmetry without Yukawa

$$G_{\mathrm{QF}} = SU(3)_q \otimes SU(3)_u \otimes SU(3)_d$$

- Flavour symmetry breaking

$$-\mathcal{L}_Y = \bar{q}\, Y_d H d + \bar{q}\, Y_u \tilde{H} u + \mathrm{h.c.}$$

- Flavour symmetry recovering: Yukawa coupling $\Longrightarrow$ spurion field

$$Y_u \sim (\mathbf{3}, \bar{\mathbf{3}}, \mathbf{1}) \qquad Y_d \sim (\mathbf{3}, \mathbf{1}, \bar{\mathbf{3}})$$

D'Ambrosio, Giudice, Isidori, Strumia, 2009

- EFT with MFV: operators, constructed from SM and Yukawa spurion fields, are invariant under CP and G_{QF}

$$\mathcal{C}^{\mathrm{MFV}} = \begin{cases} f(\mathsf{A},\mathsf{B}) & \text{for } \bar{q}\gamma^\mu \mathcal{C} q, \\ f(\mathsf{A},\mathsf{B}) Y_d & \text{for } \bar{q}\mathcal{C} d,\ \bar{q}\sigma^{\mu\nu}\mathcal{C} d, \\ \epsilon_0 \mathbb{1} + Y_d^\dagger g(\mathsf{A},\mathsf{B}) Y_d & \text{for } \bar{d}\gamma^\mu \mathcal{C} d, \end{cases}$$

$$f(\mathsf{A},\mathsf{B}) = \epsilon_0 1 + \epsilon_1 \mathsf{A} + \epsilon_2 \mathsf{B} + \epsilon_3 \mathsf{A}^2 + \epsilon_4 \mathsf{B}^2 + \epsilon_5 \mathsf{AB} + \ldots$$

$$\mathsf{A} = Y_u Y_u^\dagger$$

$$\mathsf{B} = Y_d Y_d^\dagger$$

Minimal Flavour Violation

- Spurion function

$$f(\mathsf{A},\mathsf{B}) = \epsilon_0 1 + \epsilon_1 \mathsf{A} + \epsilon_2 \mathsf{B} + \epsilon_3 \mathsf{A}^2 + \epsilon_4 \mathsf{B}^2 + \epsilon_5 \mathsf{AB} + \ldots\ldots$$

- Cayley-Hamilton identity for 3×3 invertible matrix X

$$X^3 = \mathrm{Det}X \cdot \mathbb{1} + \frac{1}{2}[\mathrm{Tr}X^2 - (\mathrm{Tr}X)^2] \cdot X + \mathrm{Tr}X \cdot X^2$$

- Spurion function after resummation

Colangelo, Nikolidakis, Smith, 2009
Mercolli, Smith, 2009

$$\begin{aligned} f(\mathsf{A},\mathsf{B}) = \epsilon_0 \mathbb{1} &+ \epsilon_1 \mathsf{A} + \epsilon_3 \mathsf{A}^2 + \epsilon_5 \mathsf{AB} + \epsilon_7 \mathsf{ABA} + \epsilon_{10} \mathsf{AB}^2 + \epsilon_{12} \mathsf{A}^2\mathsf{B}^2 + \epsilon_{14} \mathsf{B}^2\mathsf{AB} + \epsilon_{15} \mathsf{AB}^2\mathsf{A}^2 \\ &+ \epsilon_2 \mathsf{B} + \epsilon_4 \mathsf{B}^2 + \epsilon_6 \mathsf{BA} + \epsilon_9 \mathsf{BAB} + \epsilon_8 \mathsf{BA}^2 + \epsilon_{13} \mathsf{B}^2\mathsf{A}^2 + \epsilon_{11} \mathsf{ABA}^2 + \epsilon_{16} \mathsf{B}^2\mathsf{A}^2\mathsf{B}. \end{aligned}$$

- assumption #1: neglect tiny imaginary parts of ϵ_i
- assumption #2: neglect spurion B (suppressed by $\mathcal{O}(\lambda_d)$)

$$f(\mathsf{A},\mathsf{B}) \approx \epsilon_0 \mathbb{1} + \epsilon_1 \mathsf{A} + \epsilon_2 \mathsf{A}^2$$

Minimal Flavour Violation

- MFV coupling **FCNC controlled by CKM**

$$C^{\mathrm{MFV}} = \begin{cases} \epsilon_0 1 + \epsilon_1 \Delta_q & \text{for } \bar{d}_L \gamma^\mu C d_L \\ \epsilon_0 \hat{\lambda}_d + \epsilon_1 \Delta_q \hat{\lambda}_d & \text{for } \bar{d}_L C d_R,\ \bar{d}_L \sigma^{\mu\nu} C d_R \\ \epsilon_0 1 & \text{for } \bar{d}_R \gamma^\mu C d_R \end{cases} \qquad \Delta_q = V^\dagger \hat{\lambda}_u^2 V$$

No Right-handed down-type FCNC !

- Numerics

$$\Delta_q = \begin{pmatrix} 0.8 & -3.3 - 1.5i & 79.3 + 35.4i \\ -3.3 + 1.5i & 16.6 & -397.5 + 8.1i \\ 79.3 - 35.4i & -397.5 - 8.1i & 9839.0 \end{pmatrix} \times 10^{-4}$$

$$\Delta_q \hat{\lambda}_d = \begin{pmatrix} 0.0021 & -0.18 - 0.08i & 191.3 + 85.4i \\ -0.009 + 0.004i & 0.88 & -958.7 + 19.6i \\ 0.21 - 0.10i & -21.1 - 0.4i & 23728.1 \end{pmatrix} \times 10^{-6}$$

$b \to s\nu\bar{\nu}$: SMEFT with MFV

- **Prediction**

$$\frac{\mathcal{B}(B^+ \to K^+\nu\bar{\nu})}{\mathcal{B}(B^0 \to K^{*0}\nu\bar{\nu})} = \frac{\mathcal{B}(B^+ \to K^+\nu\bar{\nu})_{\rm SM}}{\mathcal{B}(B^0 \to K^{*0}\nu\bar{\nu})_{\rm SM}} = 0.46 \pm 0.07$$

$$\frac{\mathcal{B}(B^+ \to K^+\nu\bar{\nu})}{\mathcal{B}(B^+ \to \pi^+\nu\bar{\nu})} = \frac{\mathcal{B}(B^+ \to K^+\nu\bar{\nu})_{\rm SM}}{\mathcal{B}(B^+ \to \pi^+\nu\bar{\nu})_{\rm SM}} = 29.7 \pm 5.6$$

- **prediction**

$$\mathscr{B}(B^0 \to K^{*0}\nu\bar{\nu})_{\rm SM} = (9.00 \pm 0.87) \times 10^{-6}$$
$$\mathscr{B}(B^0 \to K^{*0}\nu\bar{\nu})_{\rm MFV} = \left(50^{+17}_{-16}\right) \times 10^{-6}$$
$$\mathscr{B}(B^0 \to K^{*0}\nu\bar{\nu})_{\rm exp} < 18 \times 10^{-6}$$

$$\mathscr{B}(B^+ \to \pi^+\nu\bar{\nu})_{\rm SM} = (1.40 \pm 0.18) \times 10^{-7}$$
$$\mathscr{B}(B^+ \to \pi^+\nu\bar{\nu})_{\rm MFV} = \left(7.8^{+2.8}_{-2.6}\right) \times 10^{-7}$$
$$\mathscr{B}(B^+ \to \pi^+\nu\bar{\nu})_{\rm exp} < 140 \times 10^{-7}$$

SMEFT

$$\mathcal{Q}^{(1)}_{Hq} = \left(H^\dagger i \overleftrightarrow{D}_\mu H\right)\left(\bar{q}_p \gamma^\mu q_r\right),$$
$$\mathcal{Q}^{(3)}_{Hq} = \left(H^\dagger i \overleftrightarrow{D}^I_\mu H\right)\left(\bar{q}_p \tau^I \gamma^\mu q_r\right),$$
$$\mathcal{Q}_{Hd} = \left(H^\dagger i \overleftrightarrow{D}_\mu H\right)\left(\bar{d}_p \gamma^\mu d_r\right),$$

induce $\bar{s}bZ$ interaction, Thus, universally affect $b \to s e^+e^-, \mu^+\mu^-, \tau^+\tau^-$

$$\mathcal{Q}_{ld} = \left(\bar{l}_p \gamma^\mu l_r\right)\left(\bar{d}_s \gamma_\mu d_t\right),$$

forbidden by MFV

$$\mathcal{Q}^{(1)}_{lq} = \left(\bar{l}_p \gamma^\mu l_r\right)\left(\bar{q}_s \gamma_\mu q_t\right),$$
$$\mathcal{Q}^{(3)}_{lq} = \left(\bar{l}_p \gamma^\mu \tau^I l_r\right)\left(\bar{q}_s \tau^I \gamma_\mu q_t\right),$$

$\mu_{\rm EW}$

LEFT

$$\mathcal{O}^{\nu_i\nu_j}_L = \left(\bar{s}\gamma_\mu P_L b\right)\left(\bar{\nu}_i \gamma^\mu P_L \nu_j\right)$$

one LEFT operator !

$$\mathcal{O}^{\nu_i\nu_j}_R = \left(\bar{s}\gamma_\mu P_R b\right)\left(\bar{\nu}_i \gamma^\mu P_L \nu_j\right)$$

μ_b

$b \to s\nu\bar{\nu}$: SMEFT with MFV

- **Prediction**

$$\frac{\mathcal{B}(B^+ \to K^+\nu\bar{\nu})}{\mathcal{B}(B^0 \to K^{*0}\nu\bar{\nu})} = \frac{\mathcal{B}(B^+ \to K^+\nu\bar{\nu})_{\rm SM}}{\mathcal{B}(B^0 \to K^{*0}\nu\bar{\nu})_{\rm SM}} = 0.46 \pm 0.07$$

$$\frac{\mathcal{B}(B^+ \to K^+\nu\bar{\nu})}{\mathcal{B}(B^+ \to \pi^+\nu\bar{\nu})} = \frac{\mathcal{B}(B^+ \to K^+\nu\bar{\nu})_{\rm SM}}{\mathcal{B}(B^+ \to \pi^+\nu\bar{\nu})_{\rm SM}} = 29.7 \pm 5.6$$

- **prediction**

$$\mathscr{B}(B^0 \to K^{*0}\nu\bar{\nu})_{\rm SM} = (9.00 \pm 0.87) \times 10^{-6}$$

$$\mathscr{B}(B^0 \to K^{*0}\nu\bar{\nu})_{\rm MFV} = \left(50^{+17}_{-16}\right) \times 10^{-6}$$

$$\mathscr{B}(B^0 \to K^{*0}\nu\bar{\nu})_{\rm exp} < 18 \times 10^{-6}$$

Inconsistent →

Belle II excess (if confirmed in the future) implies:
- impossible to explain in SMEFT with MFV
- NP flavour structure is highly non-trivial
- **NP structure in quark sector is beyond MFV**
- **flavour violation is beyond Yukawa coupling**

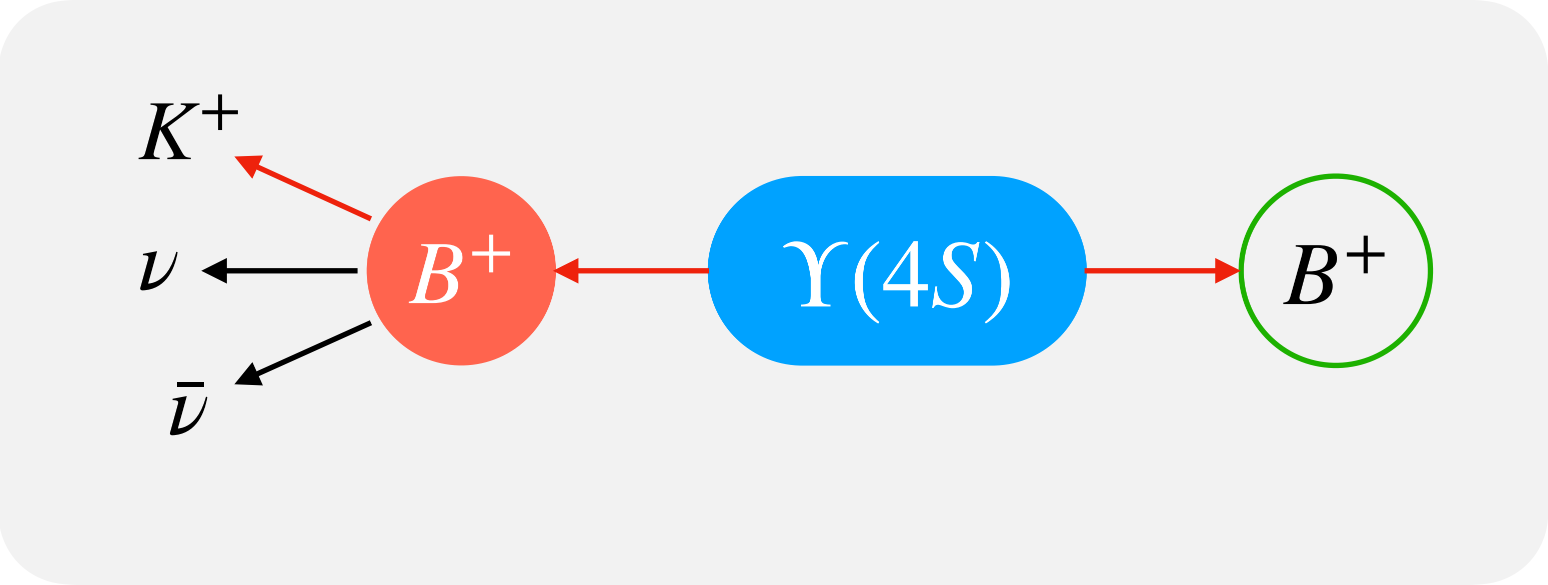
$$\mathscr{B}(B^+ \to \pi^+\nu\bar{\nu})_{\rm SM} = (1.40 \pm 0.18) \times 10^{-7}$$

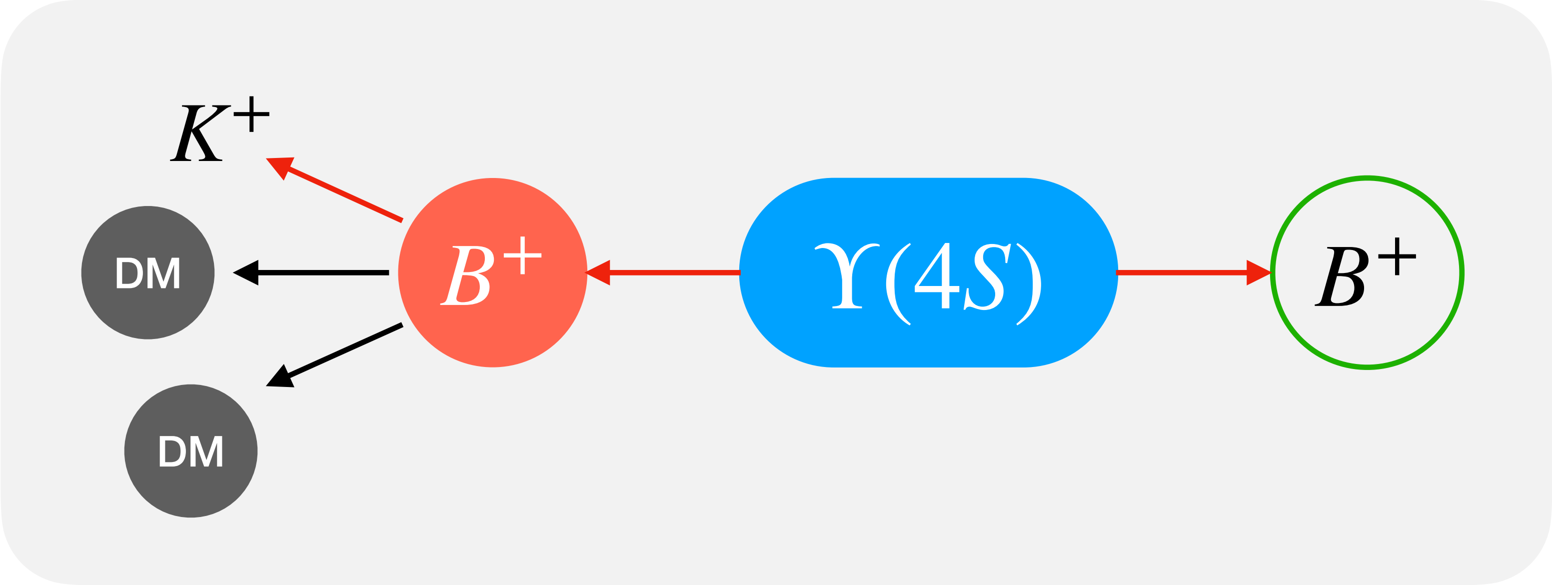
$$\mathscr{B}(B^+ \to \pi^+\nu\bar{\nu})_{\rm MFV} = \left(7.8^{+2.8}_{-2.6}\right) \times 10^{-7}$$

$$\mathscr{B}(B^+ \to \pi^+\nu\bar{\nu})_{\rm exp} < 140 \times 10^{-7}$$

This conclusion only assumes the quark MFV.
No lepton flavour structure is assumed.

$b \to s\nu\bar{\nu}$: exp picture





SMEFT

$$\mathcal{Q}_{Hq}^{(1)} = \left(H^\dagger i \overleftrightarrow{D}_\mu H\right)\left(\bar{q}_p \gamma^\mu q_r\right),$$
$$\mathcal{Q}_{Hq}^{(3)} = \left(H^\dagger i \overleftrightarrow{D}^I_\mu H\right)\left(\bar{q}_p \tau^I \gamma^\mu q_r\right),$$
$$\mathcal{Q}_{Hd} = \left(H^\dagger i \overleftrightarrow{D}_\mu H\right)\left(\bar{d}_p \gamma^\mu d_r\right),$$

$$\mathcal{Q}_{ld} = \left(\bar{l}_p \gamma^\mu l_r\right)\left(\bar{d}_s \gamma_\mu d_t\right),$$

$$\mathcal{Q}_{lq}^{(1)} = \left(\bar{l}_p \gamma^\mu l_r\right)\left(\bar{q}_s \gamma_\mu q_t\right),$$
$$\mathcal{Q}_{lq}^{(3)} = \left(\bar{l}_p \gamma^\mu \tau^I l_r\right)\left(\bar{q}_s \tau^I \gamma_\mu q_t\right),$$

μ_{EW}

LEFT

$$\mathcal{O}_L^{\nu_i\nu_j} = \left(\bar{s}\gamma_\mu P_L b\right)\left(\bar{\nu}_i \gamma^\mu P_L \nu_j\right)$$
$$\mathcal{O}_R^{\nu_i\nu_j} = \left(\bar{s}\gamma_\mu P_R b\right)\left(\bar{\nu}_i \gamma^\mu P_L \nu_j\right)$$

μ_b

Dark SMEFT

example

$$\mathcal{Q}_{d\phi^2} = \left(\bar{q}_p d_r H\right)\phi^2$$
$$\mathcal{Q}_{d\chi} = \left(\bar{d}_p \gamma_\mu d_r\right)\left(\bar{\chi}\gamma^\mu \chi\right)$$
$$\mathcal{Q}_{dX^2} = \left(\bar{q}_p d_r H\right)X_\mu X^\mu$$
$$\mathcal{Q}_{qa} = \left(\bar{q}_p \gamma_\mu q_r\right)\partial^\mu a$$

2011 Kamenik, Smith
2014 Duch, Grzadkowski, Wudka
2017 Brod, Gootjes-Dreesbach, Tammaro, Zupan
2021 Criado, Djouadi, Perez-Victoria, Santiago
2022 Aebischer, Altmannshofer, Jenkins, Manohar (basis@dim-6)
2023 Song, Sun, Yu (basis@dim-8)

Axion-like particle, see also H.Y.Cheng, Phys.Rept 1988

2020 Bauer, Neubert, Renner, Schnubel, Thamm
2023 Song, Sun, Yu (basis@dim-8)

Dark LEFT

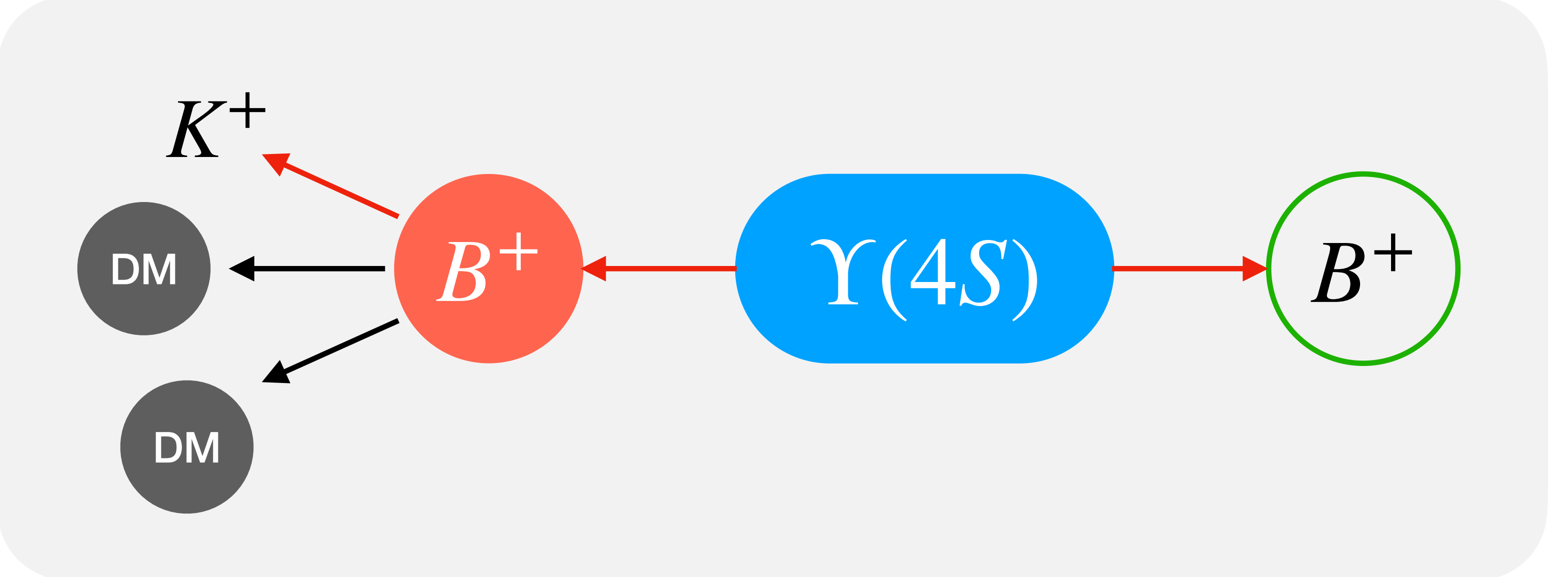
$$\mathcal{O}_{d\phi^2} = \left(\bar{d}_{Lp} d_{Rr}\right)\phi^2$$
$$\mathcal{O}_{d\chi}^{V,LR} = \left(\bar{d}_{Lp}\gamma_\mu d_{Lr}\right)\left(\bar{\chi}_a \gamma^\mu \chi_b\right)$$
$$\mathcal{O}_{dXX}^{L} = \left(\bar{d}_{Lp}\gamma_\mu d_{Lr}\right)X^{\mu\nu}X_\nu$$
$$\mathcal{O}_{da}^{L} = \left(\bar{d}_{Lp}\gamma_\mu d_{Lr}\right)\partial^\mu a$$

example

2022 Aebischer, Altmannshofer, Jenkins, Manohar (basis@dim-6)
2022 He, Ma, Valencia (basis@dim-6)
2023 Liang, Liao, Ma, Wang (basis@dim-8)

$b \to s\nu\bar{\nu}$: DSMEFT

Can DSMEFT operators explain the Belle II excess, while satisfy other $b \to s$ bounds ?



Observable	SM	Exp	Unit
$\mathcal{B}(B^+ \to K^+\nu\bar{\nu})$	4.16 ± 0.57	$23 \pm 5^{+5}_{-4}$	10^{-6}
$\mathcal{B}(B^0 \to K^0\nu\bar{\nu})$	3.85 ± 0.52	< 26	10^{-6}
$\mathcal{B}(B^+ \to K^{*+}\nu\bar{\nu})$	9.70 ± 0.94	< 61	10^{-6}
$\mathcal{B}(B^0 \to K^{*0}\nu\bar{\nu})$	9.00 ± 0.87	< 18	10^{-6}
$\mathcal{B}(B_s \to \phi\nu\bar{\nu})$	9.93 ± 0.72	< 5400	10^{-6}
$\mathcal{B}(B_s \to \nu\bar{\nu})$	≈ 0	< 5.9	10^{-4}
$\mathcal{B}(B^+ \to \pi^+\nu\bar{\nu})$	1.40 ± 0.18	< 140	10^{-7}
$\mathcal{B}(B^0 \to \pi^0\nu\bar{\nu})$	6.52 ± 0.85	< 900	10^{-8}
$\mathcal{B}(B^+ \to \rho^+\nu\bar{\nu})$	4.06 ± 0.79	< 300	10^{-7}
$\mathcal{B}(B^0 \to \rho^0\nu\bar{\nu})$	1.89 ± 0.36	< 400	10^{-7}
$\mathcal{B}(B^0 \to \nu\bar{\nu})$	≈ 0	< 1.4	10^{-4}
$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$	8.42 ± 0.61	$10.6^{+4.0}_{-3.4} \pm 0.9$	10^{-11}
$\mathcal{B}(K_L \to \pi^0\nu\bar{\nu})$	3.41 ± 0.45	< 300	10^{-11}

$\mu_{\rm EW}$

Dark SMEFT

$$\mathcal{Q}_{d\phi} = (\bar{q}_p d_r H)\phi + \text{h.c.}, \qquad \mathcal{Q}_{d\phi^2} = (\bar{q}_p d_r H)\phi^2 + \text{h.c.},$$
$$\mathcal{Q}_{\phi q} = (\bar{q}_p \gamma_\mu q_r)(i\phi_1 \overleftrightarrow{\partial}^\mu \phi_2), \qquad \mathcal{Q}_{\phi d} = (\bar{d}_p \gamma_\mu d_r)(i\phi_1 \overleftrightarrow{\partial}^\mu \phi_2),$$

scalar: 4

$$\mathcal{Q}_{q\chi} = (\bar{q}_p \gamma_\mu q_r)(\bar{\chi}\gamma^\mu \chi), \qquad \mathcal{Q}_{d\chi} = (\bar{d}_p \gamma_\mu d_r)(\bar{\chi}\gamma^\mu \chi),$$

fermion: 2

$$\mathcal{Q}_{dHX} = (\bar{q}_p \sigma_{\mu\nu} d_r) H X^{\mu\nu} \qquad \mathcal{Q}_{dX^2} = (\bar{q}_p d_r H) X_\mu X^\mu$$

vector: 1+13

$$\mathcal{Q}_{qa} = (\bar{q}_p \gamma_\mu q_r)\partial^\mu a \qquad \mathcal{Q}_{da} = (\bar{d}_p \gamma_\mu d_r)\partial^\mu a$$

ALP: 2

Dark LEFT

$$\mathcal{O}_{d\phi} = (\bar{d}_{Lp} d_{Rr})\phi + \text{h.c.}, \qquad \mathcal{O}^L_{\phi d} = (\bar{d}_{Lp}\gamma_\mu d_{Lr})(i\phi_1 \overleftrightarrow{\partial}^\mu \phi_2),$$

scalar: 4

$$\mathcal{O}^{V,LR}_{d\chi} = (\bar{d}_{Lp}\gamma_\mu d_{Lr})(\bar{\chi}_a \gamma^\mu \chi_b), \mathcal{O}^{V,RR}_{d\chi} = (\bar{d}_{Rp}\gamma_\mu d_{Rr})(\bar{\chi}_a \gamma^\mu \chi_b),$$

fermion: 5

$$\mathcal{O}^T_{dX} = (\bar{d}_{Lp}\sigma_{\mu\nu} d_{Rr}) X^{\mu\nu}_a \qquad \mathcal{O}^L_{dXX} = (\bar{d}_{Lp}\gamma_\mu d_{Lr}) X^{\mu\nu} X_\nu$$

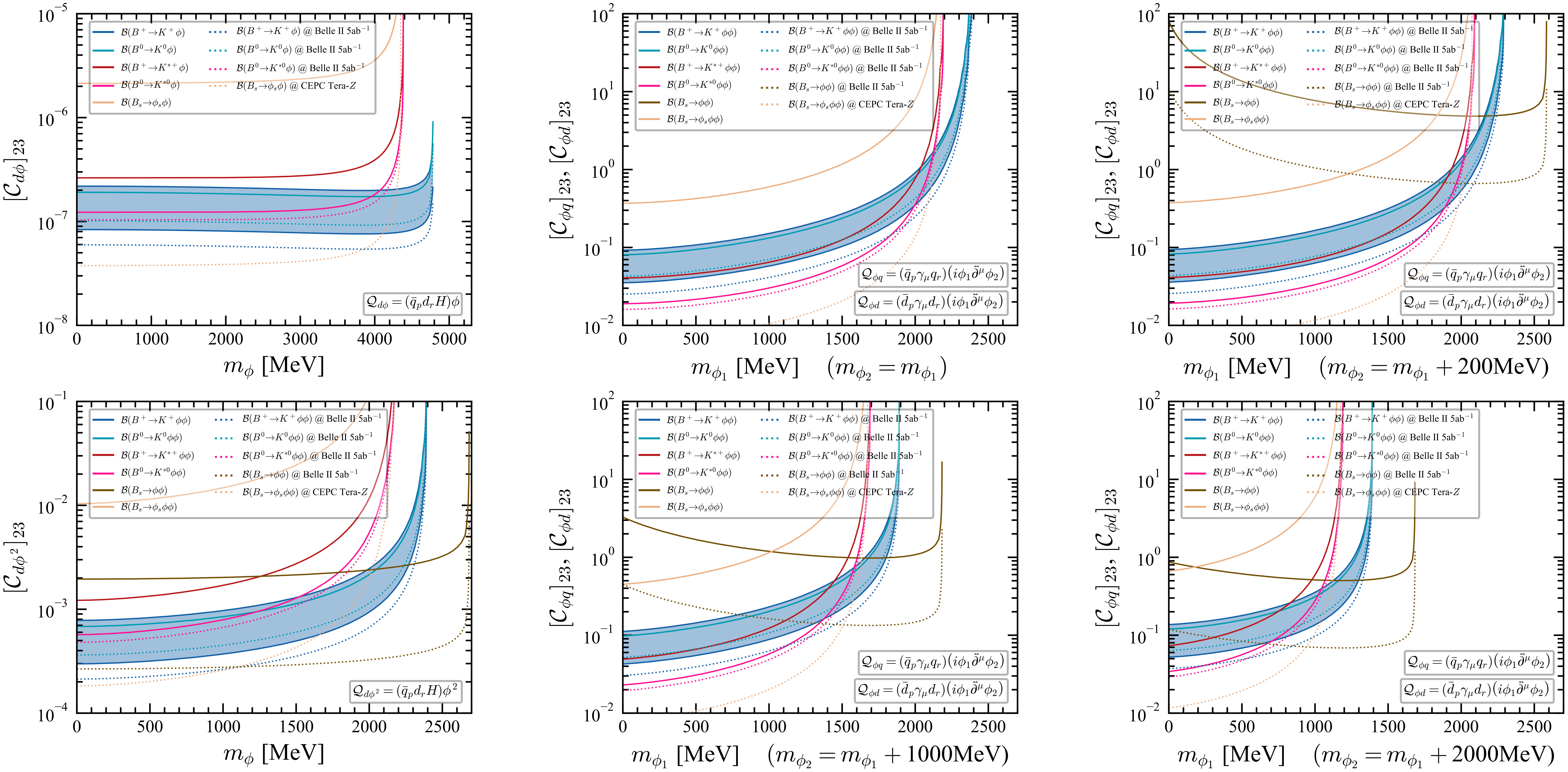
vector: 1+10

$$\mathcal{O}^L_{da} = (\bar{d}_{Lp}\gamma_\mu d_{Lr})\partial^\mu a, \qquad \mathcal{O}^R_{da} = (\bar{d}_{Rp}\gamma_\mu d_{Rr})\partial^\mu a$$

ALP:

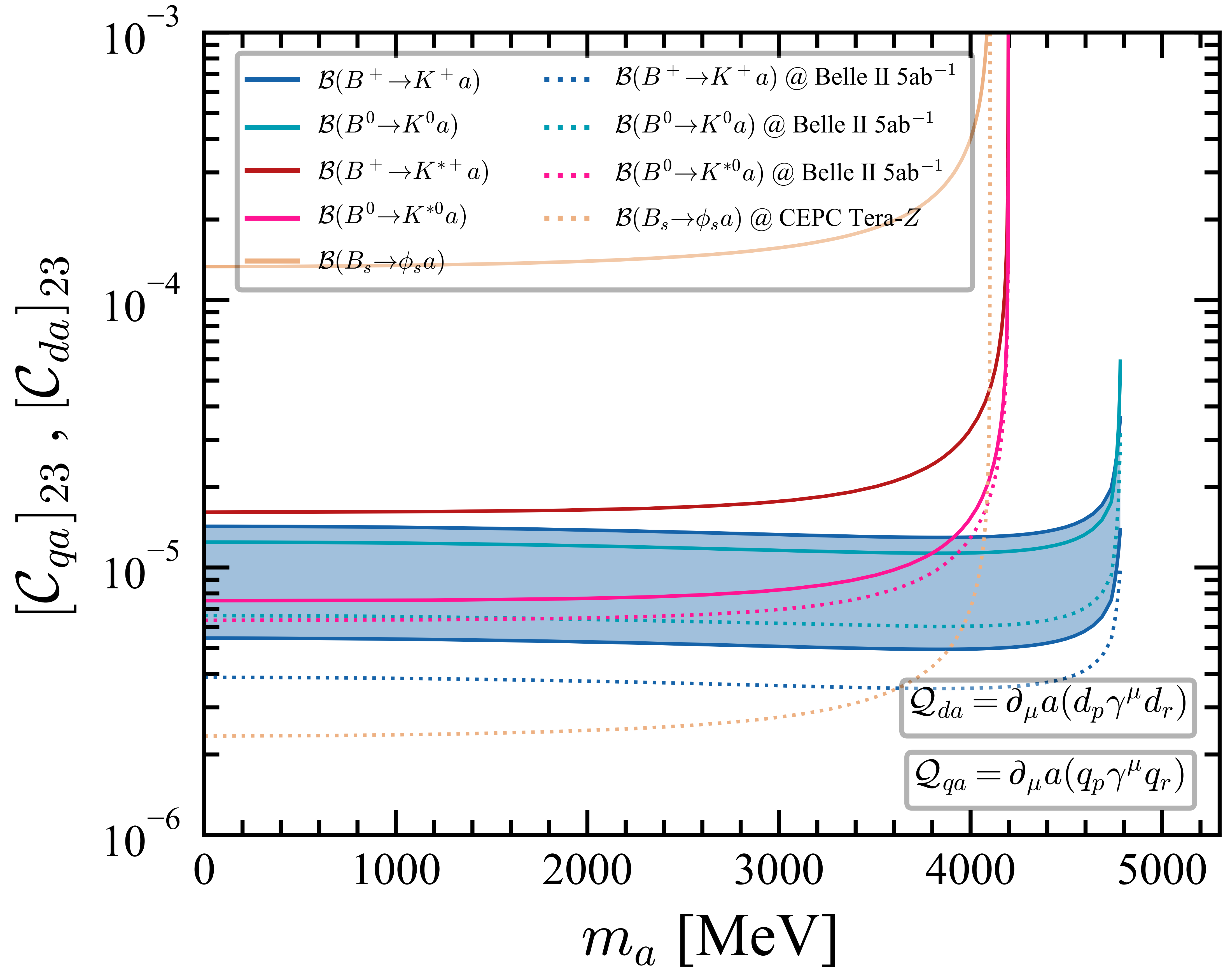
μ_b

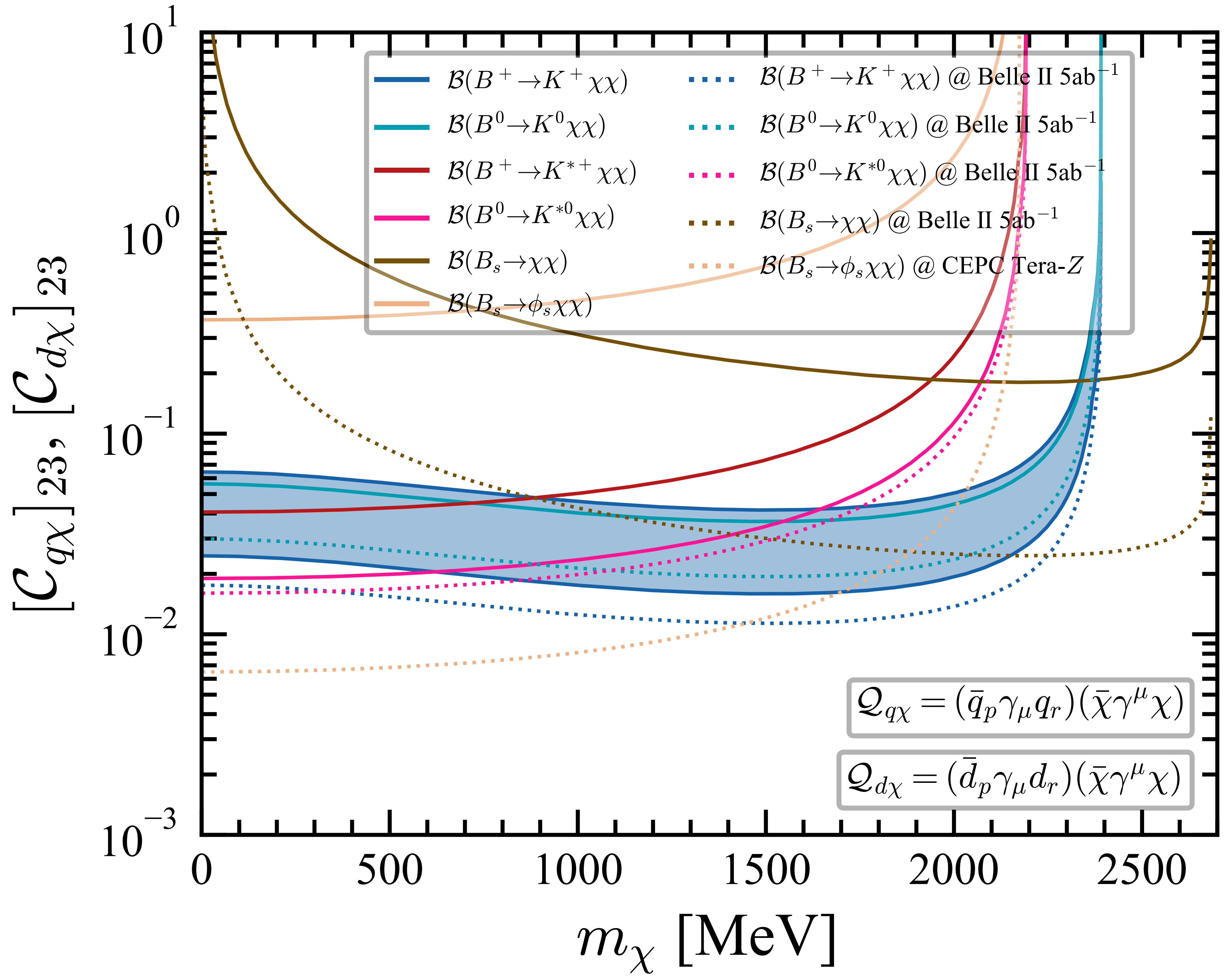
Dark SMEFT: Scalar



all the operators survive

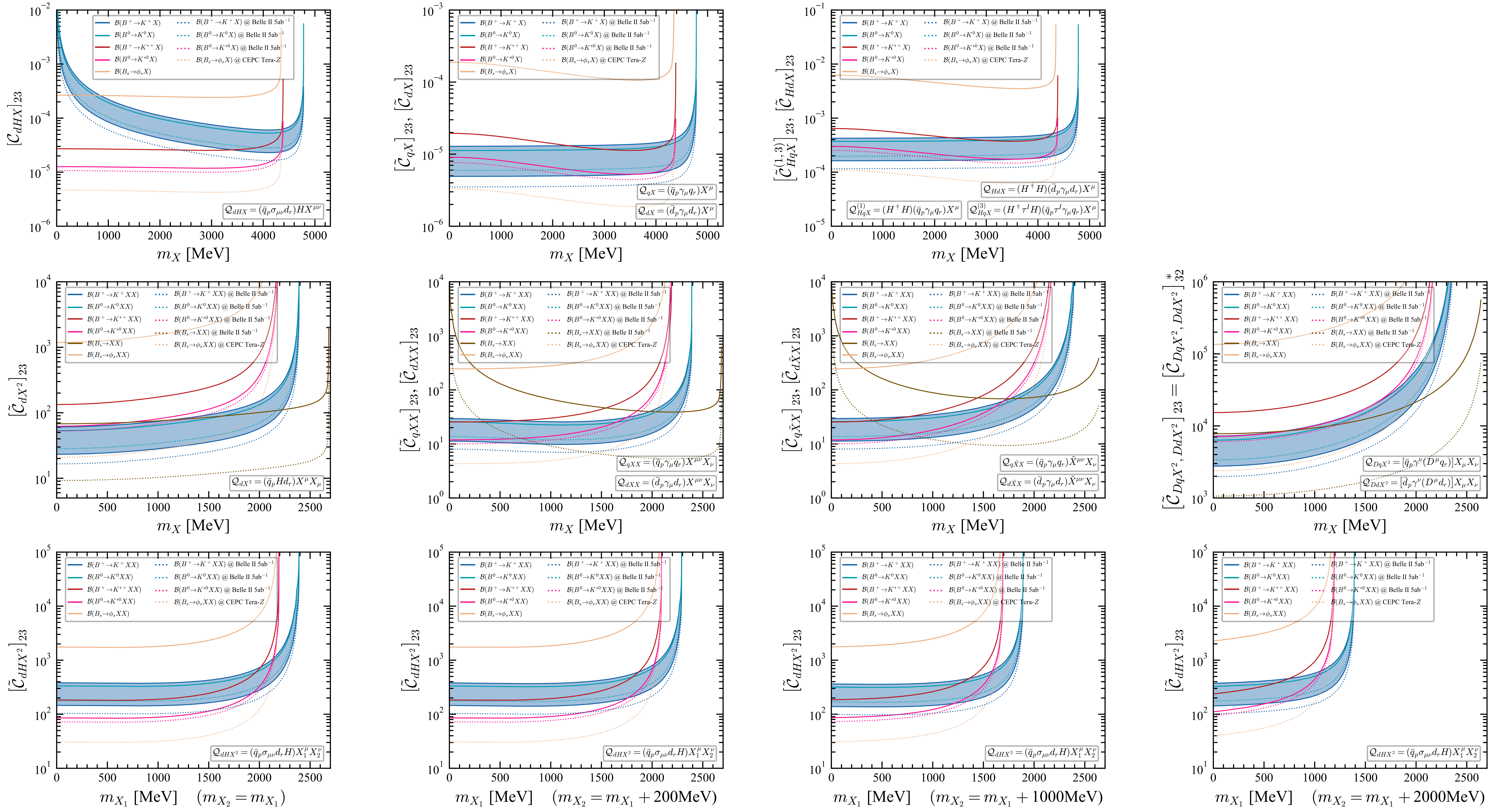
Dark SMEFT: Fermion, ALP





all the operators survive

Dark SMEFT: Vector



all the operators survive

Dark SMEFT with MFV

- MFV coupling **$b \to s, b \to d, s \to d$ are connected with each other.**

$$\mathcal{C}_i^{\text{MFV}} = \begin{cases} \epsilon_0^i \hat{\lambda}_d + \epsilon_1^i \Delta_q \hat{\lambda}_d & \text{for } \mathcal{Q}_i = \mathcal{Q}_{d\phi}, \mathcal{Q}_{d\phi^2}, \mathcal{Q}_{dHX}, \mathcal{Q}_{dHX^2}, \mathcal{Q}_{dX^2}, \\ \epsilon_0^i \mathbb{1} + \epsilon_1^i \Delta_q & \text{for } \mathcal{Q}_i = \mathcal{Q}_{\phi q}, \mathcal{Q}_{q\chi}, \mathcal{Q}_{qXX}, \mathcal{Q}_{q\tilde{X}X}, \mathcal{Q}_{DqX^2}, \mathcal{Q}_{qX}, \mathcal{Q}_{HqX}^{(1,3)}, \mathcal{Q}_{qa}, \\ \epsilon_0^i \mathbb{1} & \text{for } \mathcal{Q}_i = \mathcal{Q}_{\phi d}, \mathcal{Q}_{d\chi}, \mathcal{Q}_{dXX}, \mathcal{Q}_{d\tilde{X}X}, \mathcal{Q}_{DdX^2}, \mathcal{Q}_{dX}, \mathcal{Q}_{HdX}, \mathcal{Q}_{da}, \end{cases}$$

8 operators are eliminated

- Numerics

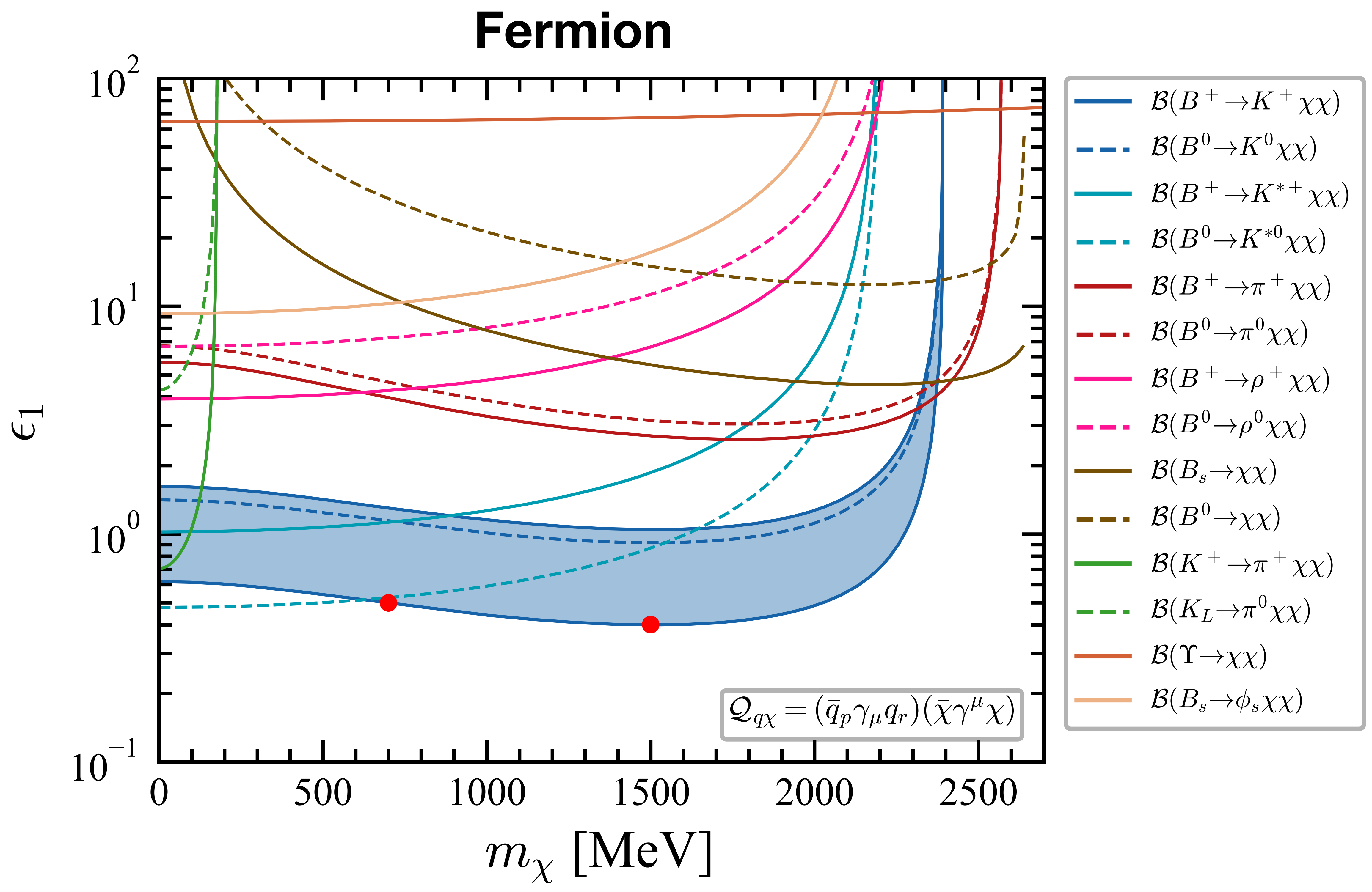
$$\Delta_q = \begin{pmatrix} 0.8 & -3.3 - 1.5i & 79.3 + 35.4i \\ -3.3 + 1.5i & 16.6 & -397.5 + 8.1i \\ 79.3 - 35.4i & -397.5 - 8.1i & 9839.0 \end{pmatrix} \times 10^{-4}$$

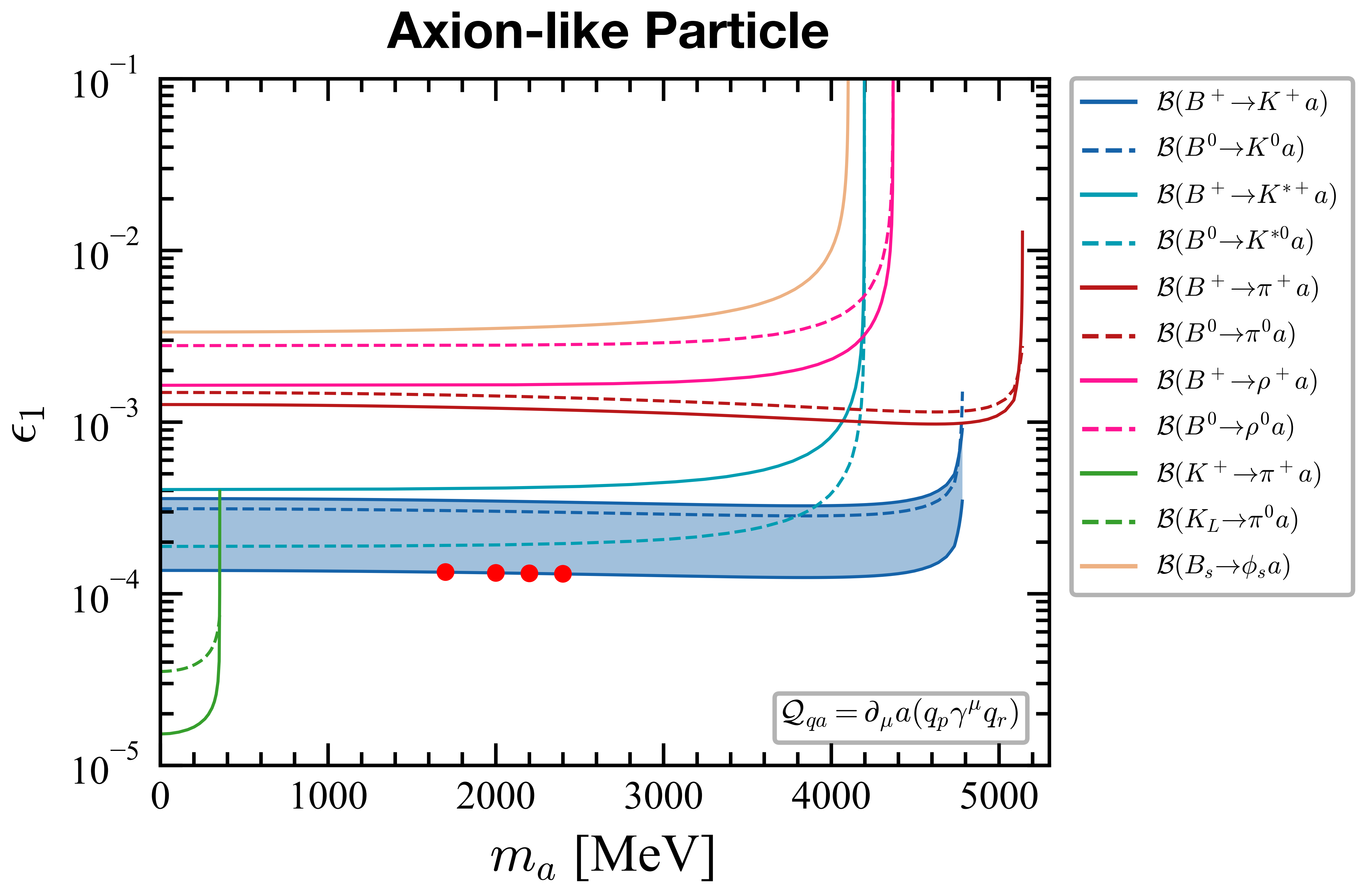
$$\Delta_q \hat{\lambda}_d = \begin{pmatrix} 0.0021 & -0.18 - 0.08i & 191.3 + 85.4i \\ -0.009 + 0.004i & 0.88 & -958.7 + 19.6i \\ 0.21 - 0.10i & -21.1 - 0.4i & 23728.1 \end{pmatrix} \times 10^{-6}$$

Dark SMEFT with MFV: Scalar, ALP

all the operators survive

Dark SMEFT with MFV: Fermion, ALP





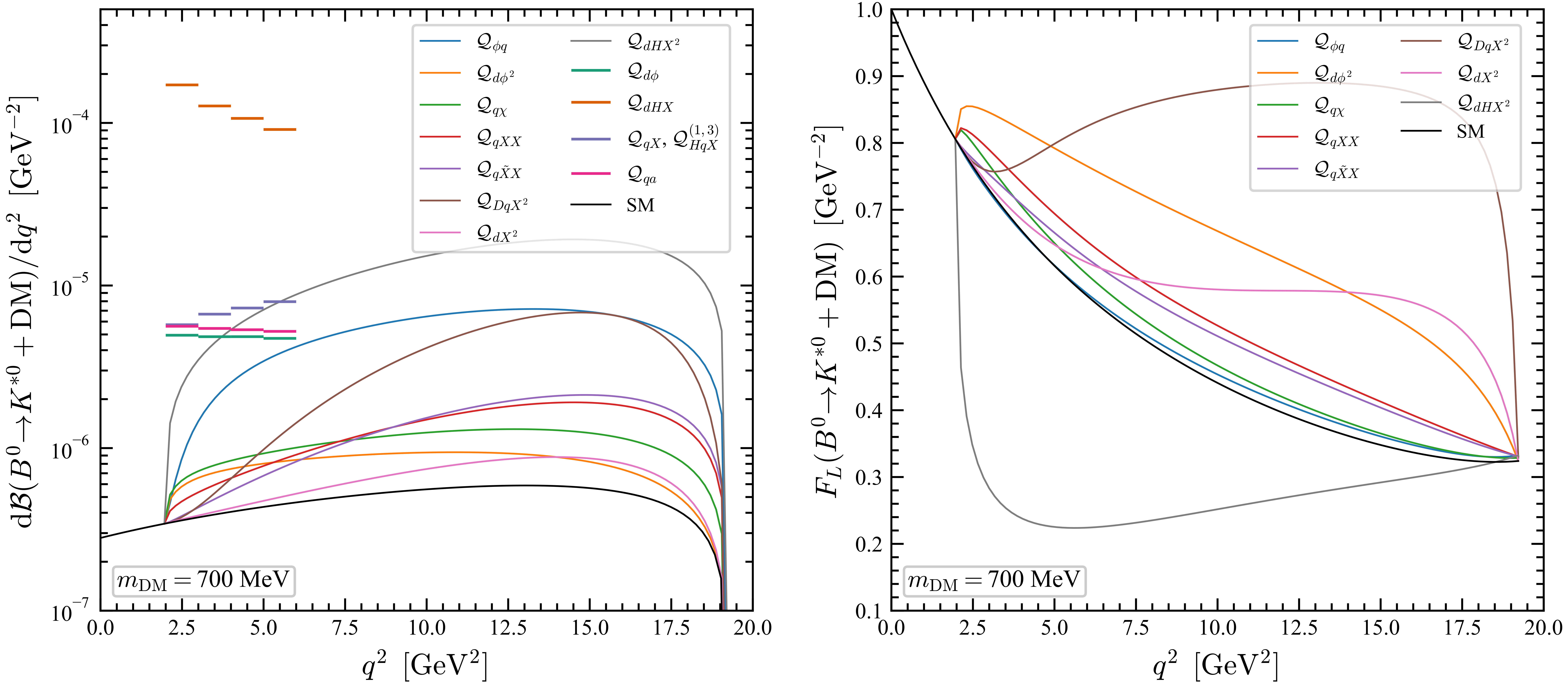
all the operators survive

Dark SMEFT with MFV: Vector

all the operators survive

Dark SMEFT: $\mathrm{d}B/\mathrm{d}q^2$, F_L

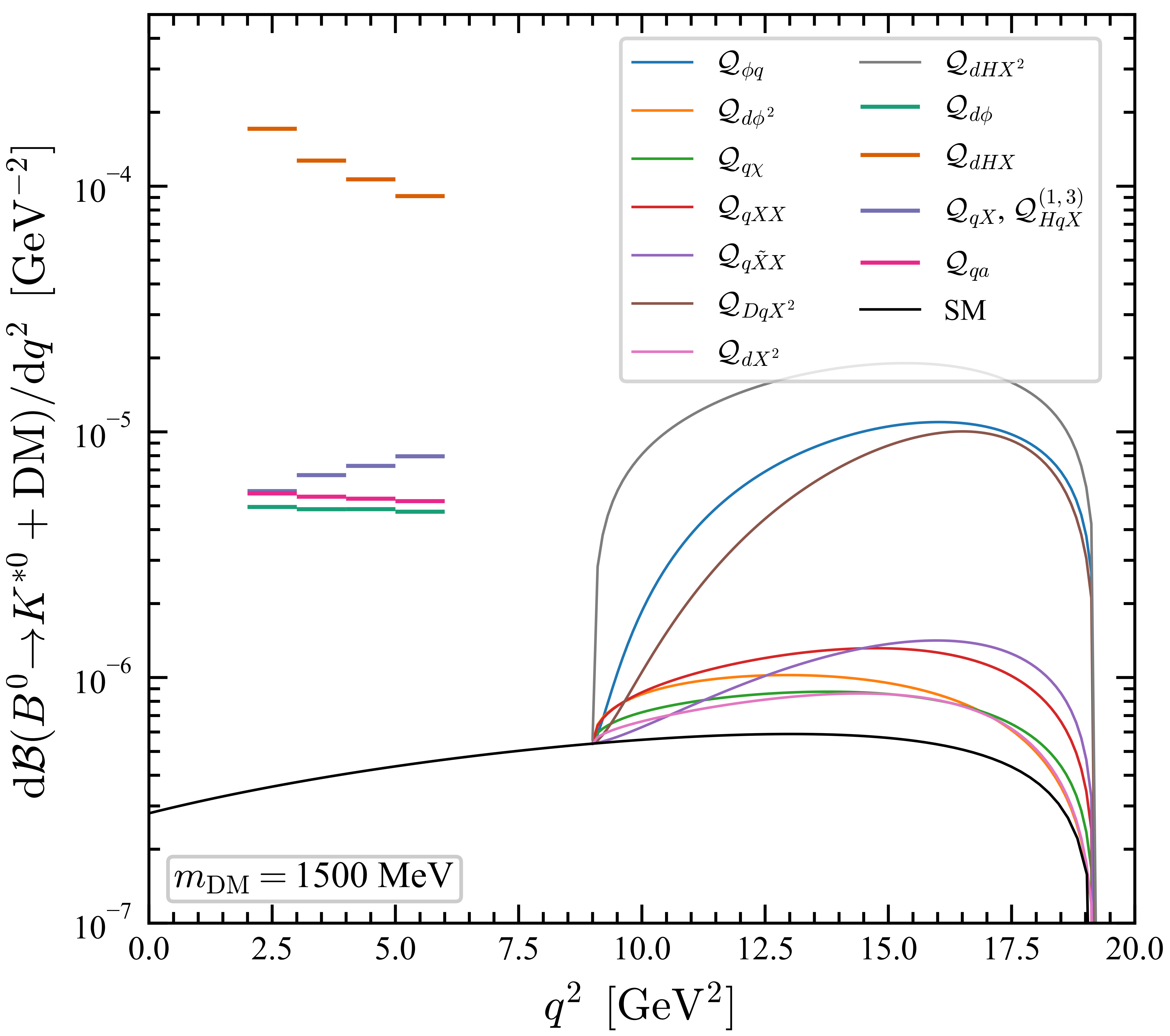
$m_{\mathrm{DM}} = 700\,\mathrm{MeV}$

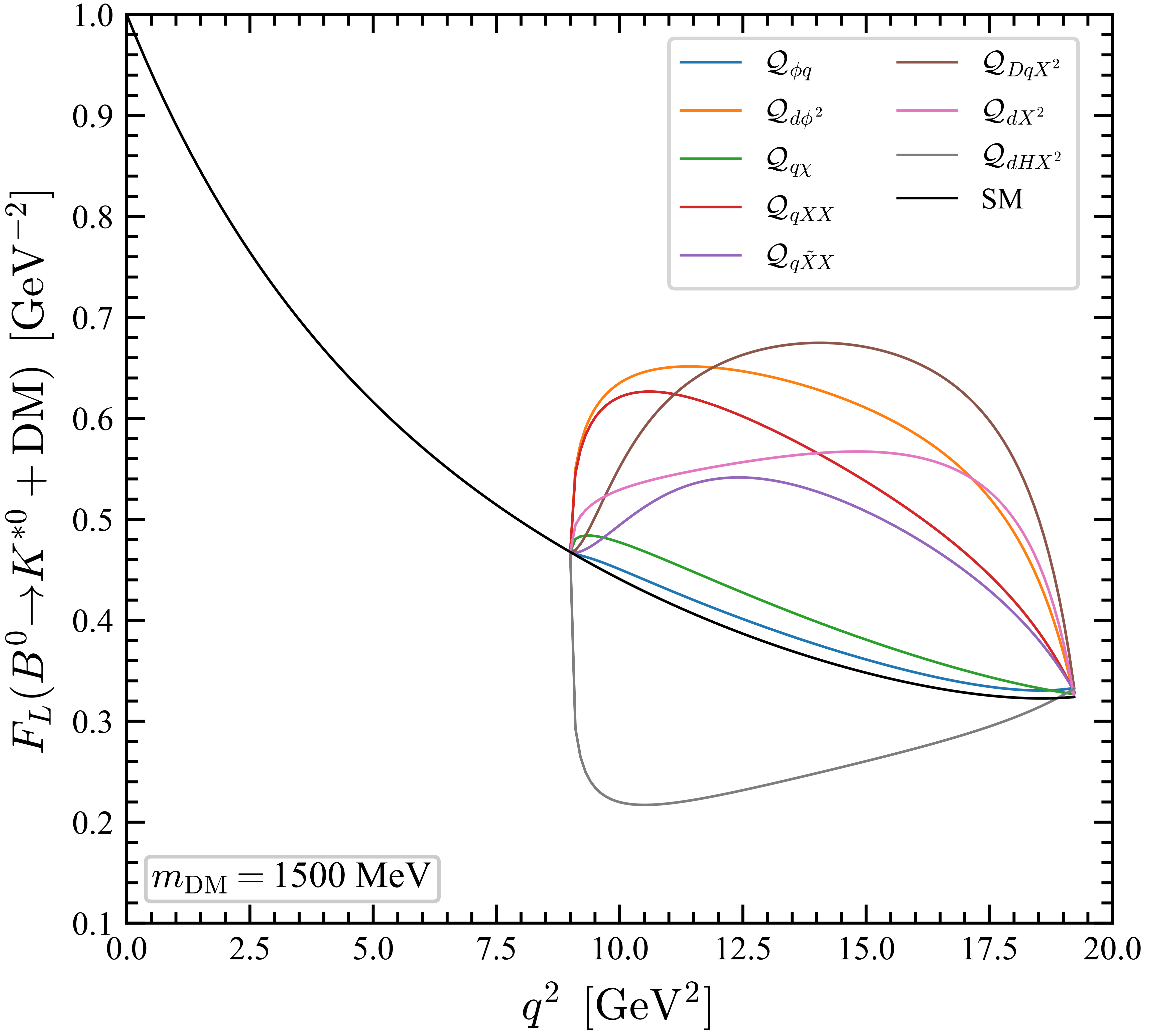


All the operators are distinguishable from each other by combing these observables, except Q_{qXX} and $Q_{qX\tilde{X}}$

Dark SMEFT: $\mathrm{d}B/\mathrm{d}q^2$, F_L

$m_{\mathrm{DM}} = 1500\,\mathrm{MeV}$





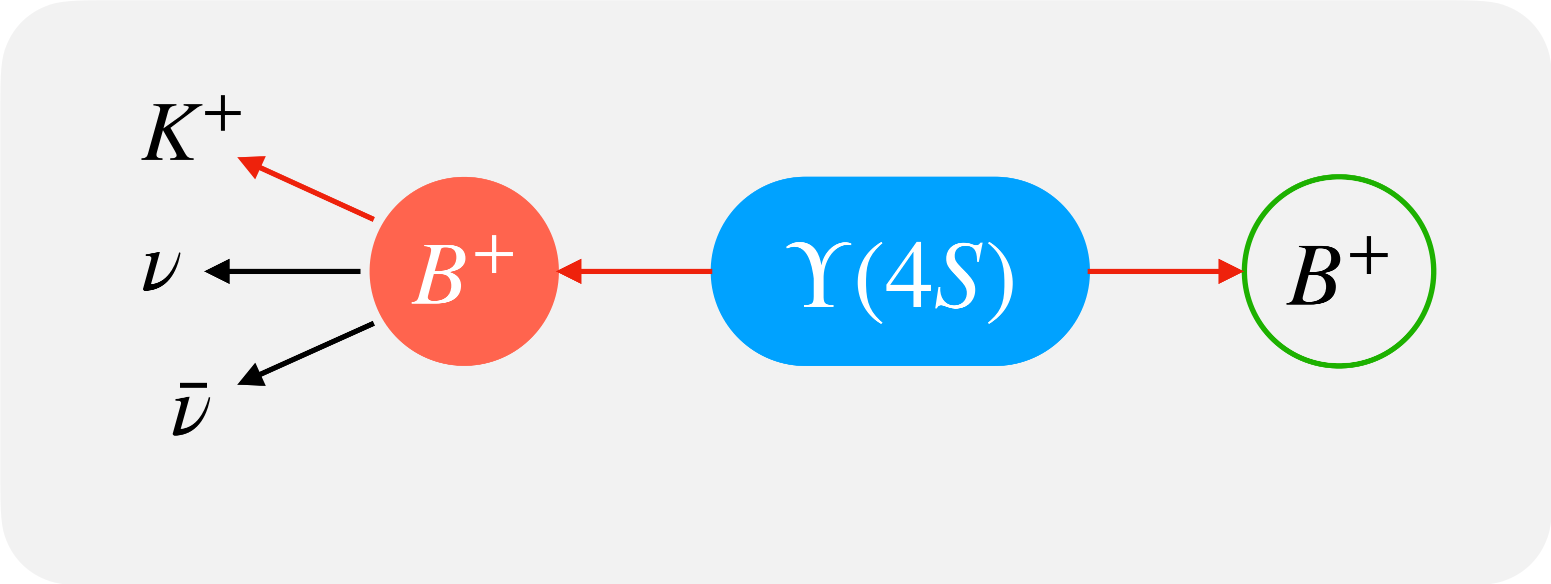
All the operators are distinguishable from each other by combing these observables, ~~except Q_{qXX} and $Q_{qX\tilde{X}}$~~

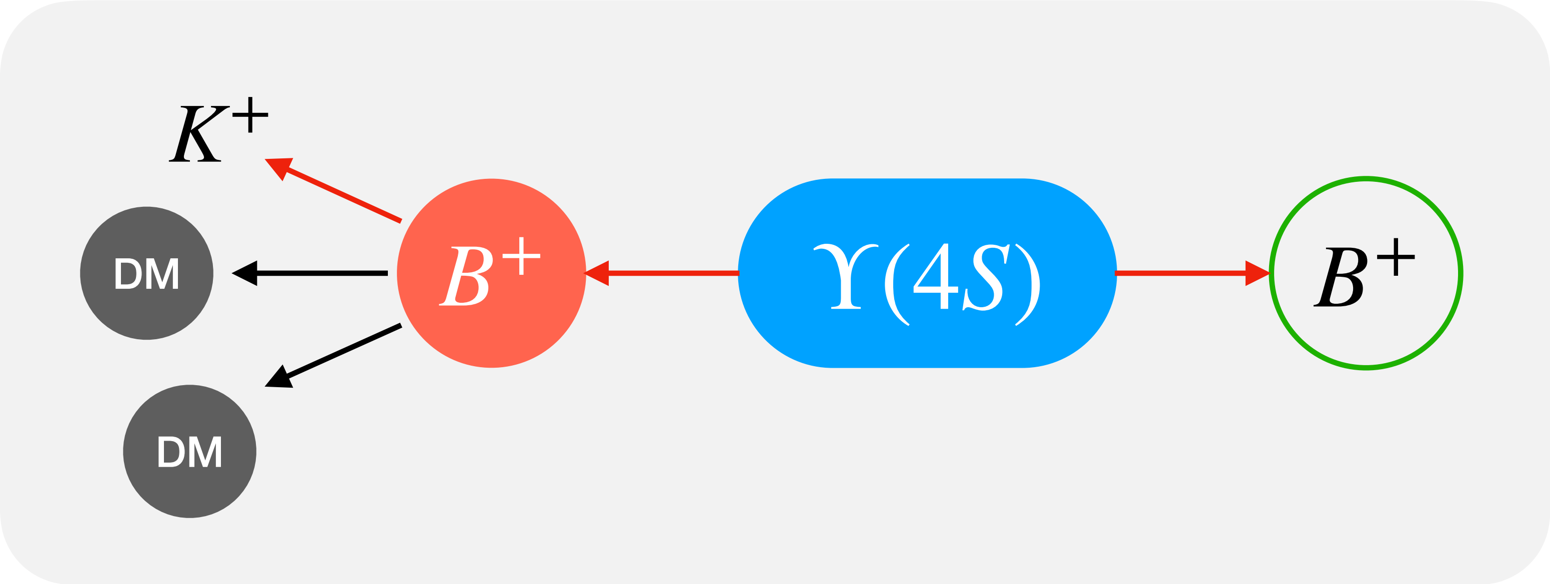
Conclusion

`HadronToNP`: a package to calculate decay of hadron to new particles

$B \to K + \mathrm{DM},\ B \to \rho + \mathrm{DM},\ \Lambda_b \to \Lambda + \mathrm{DM},\ \Upsilon \to \mathrm{DM}, \ldots$

$D \to \pi + \mathrm{DM},\ D \to \rho + \mathrm{DM},\ \Xi_c \to \Xi + \mathrm{DM},\ J/\psi \to \mathrm{DM}, \ldots$





SMEFT | **Dark SMEFT**

$$\frac{\mathcal{B}(B^+ \to K^+\nu\bar{\nu})}{\mathcal{B}(B^0 \to K^{*0}\nu\bar{\nu})} = \frac{\mathcal{B}(B^+ \to K^+\nu\bar{\nu})_{\rm SM}}{\mathcal{B}(B^0 \to K^{*0}\nu\bar{\nu})_{\rm SM}} = 0.46 \pm 0.07$$

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$\mu_{\rm EW}$

LEFT | **Dark LEFT**

μ_b

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- impossible to explain in SMEFT with MFV
- NP flavour structure is highly non-trivial
- **NP structure in quark sector is beyond MFV**
- **flavour violation is beyond Yukawa coupling**

All DSMEFT operators survive in general and MFV

$\mathrm{d}B/\mathrm{d}q^2$ and F_L are useful to distinguish them