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

(Dark) SMEFT and NP flavour structure

Xing-Bo Yuan (袁兴博)

Central China Normal University (华中师范大学)

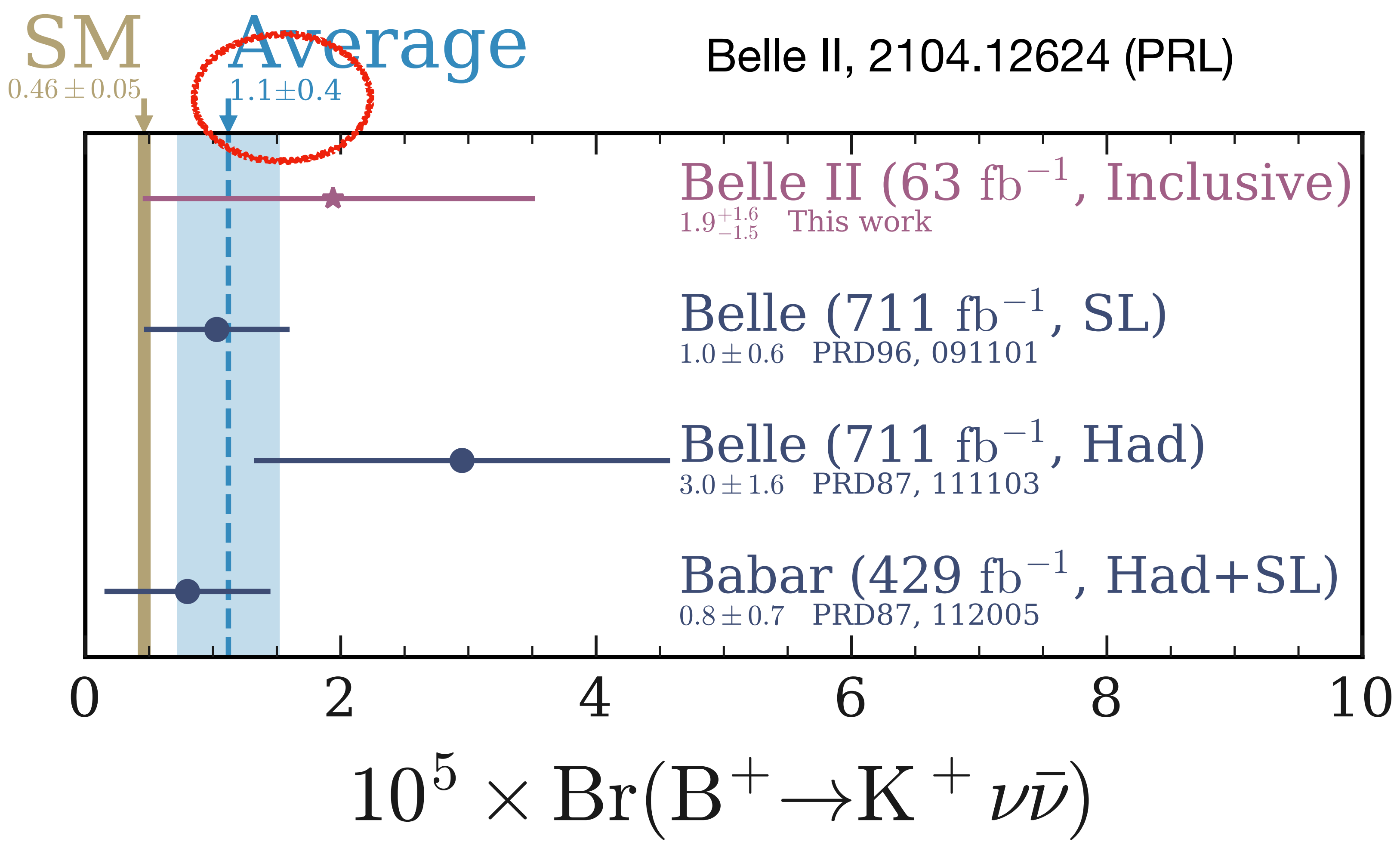
侯镖锋，李新强，沈萌，杨亚东，袁兴博, arXiv: 2402.19208 [JHEP]

高孟超，李新强，杨亚东，袁兴博，张欣, work in progress

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

▶ 2021 Apr

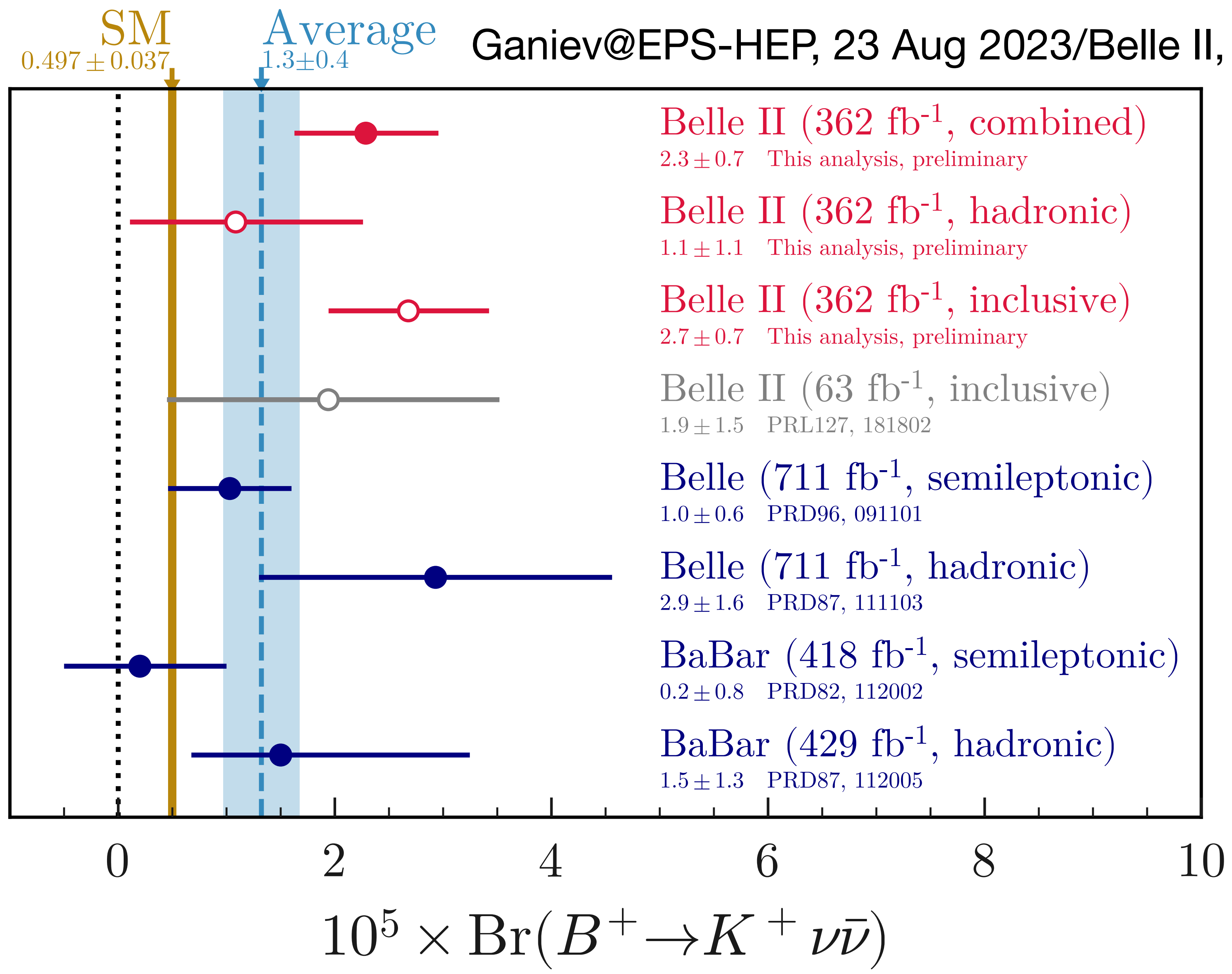
Belle II, 2104.12624 (PRL)



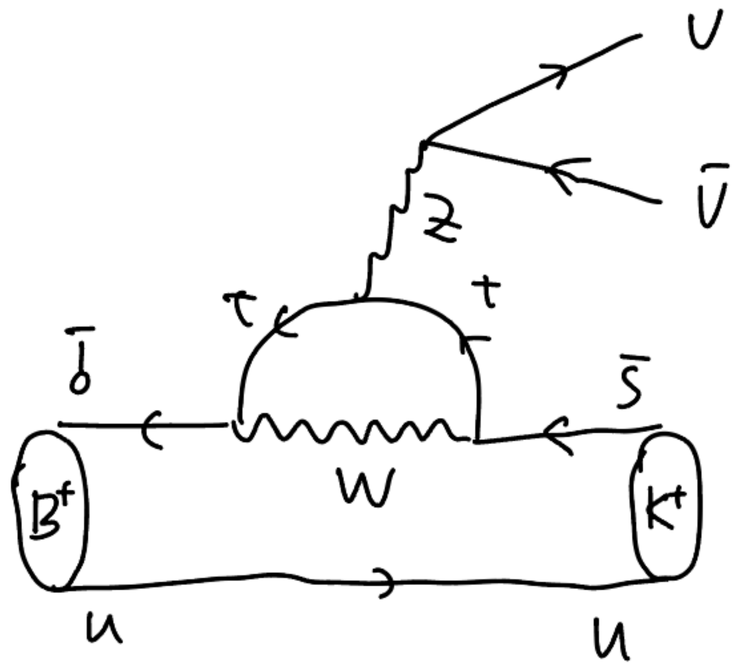
▶ 2023 Aug

see also 贾森's talk

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



▶ 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

NP/SM $\gtrsim 2$

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

▶ Theoretical prediction

form factor: 高婧，李东浩，沈月龙, WIP（see also 李东浩's talk）

Factorization

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

Wilson coef **quark current** **neutrino current**

theoretically, simple and clean

one of the cleanest channels in flavour physics

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

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

$\mathscr{O}_L = (\bar{s}P_L b)(\bar{\nu}P_L \nu)$ ✘

$\mathscr{O}_R = (\bar{s}P_R b)(\bar{\nu}P_R \nu)$ ✘

$\mathscr{O}_T = (\bar{s}\sigma_{\mu\nu} b)(\bar{\nu}\sigma^{\mu\nu} \nu)$ ✘

$\mathscr{O}_{T5} = (\bar{s}\sigma_{\mu\nu}\gamma_5 b)(\bar{\nu}\sigma^{\mu\nu} \nu)$ ✘

operator structure highly constrained by LH neutrino

Evidence for $B^+ \to K^+\nu\bar{\nu}$ decays #1

Belle-II Collaboration • I. Adachi et al. (Nov 24, 2023)

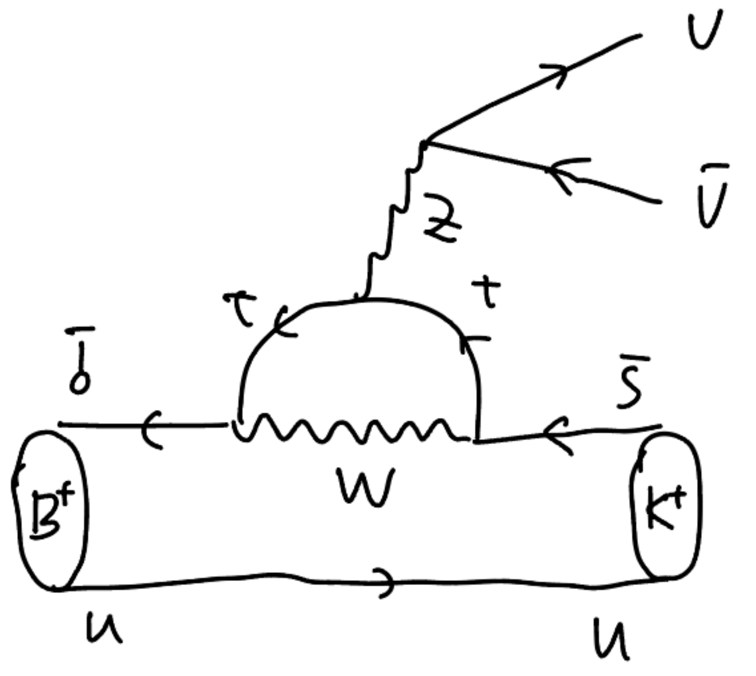
Published in: *Phys.Rev.D* 109 (2024) 11, 112006 • e-Print: 2311.14647 [hep-ex]

pdf DOI cite claim reference search 83 citations

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



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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**

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

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

operator structure highly constrained by Left-handed neutrino

μ_b

Minimal Flavour Violation

- Flavour symmetry without Yukawa

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

- Flavour symmetry breaking only from SM Yukawa

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

- 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 $G_{\rm QF}$

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

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

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

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

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 $\mathcal{O}(\lambda_d^2)$)

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

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**

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

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SMEFT

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$$\mathcal{Q}_{Hd} = \left(H^\dagger i \overleftrightarrow{D}_\mu H\right)\left(\bar{d}_p \gamma^\mu d_r\right),$$

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

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

forbidden by MFV

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

LEFT

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

one LEFT operator !
just the SM operator

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

μ_b

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

- **Prediction**

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Inconsistent →

$$\mathscr{B}(B^+ \to \pi^+\nu\bar{\nu})_{\rm SM} = (1.40 \pm 0.18) \times 10^{-7}$$
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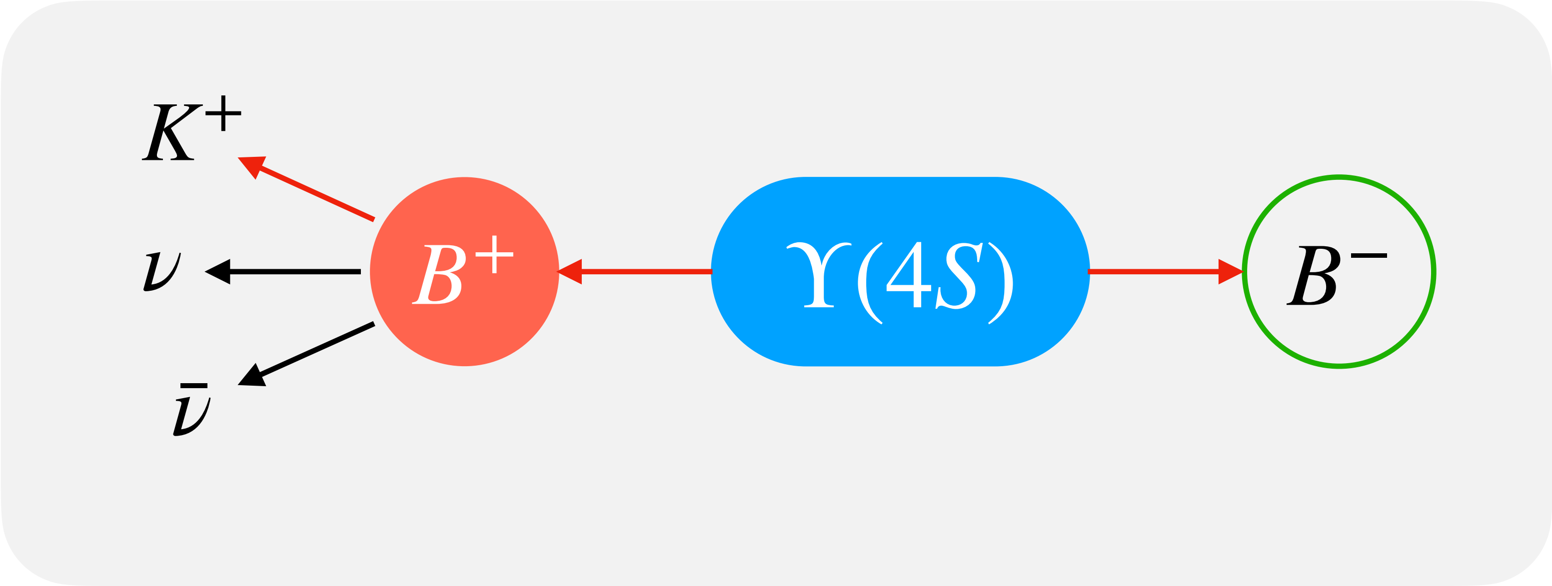
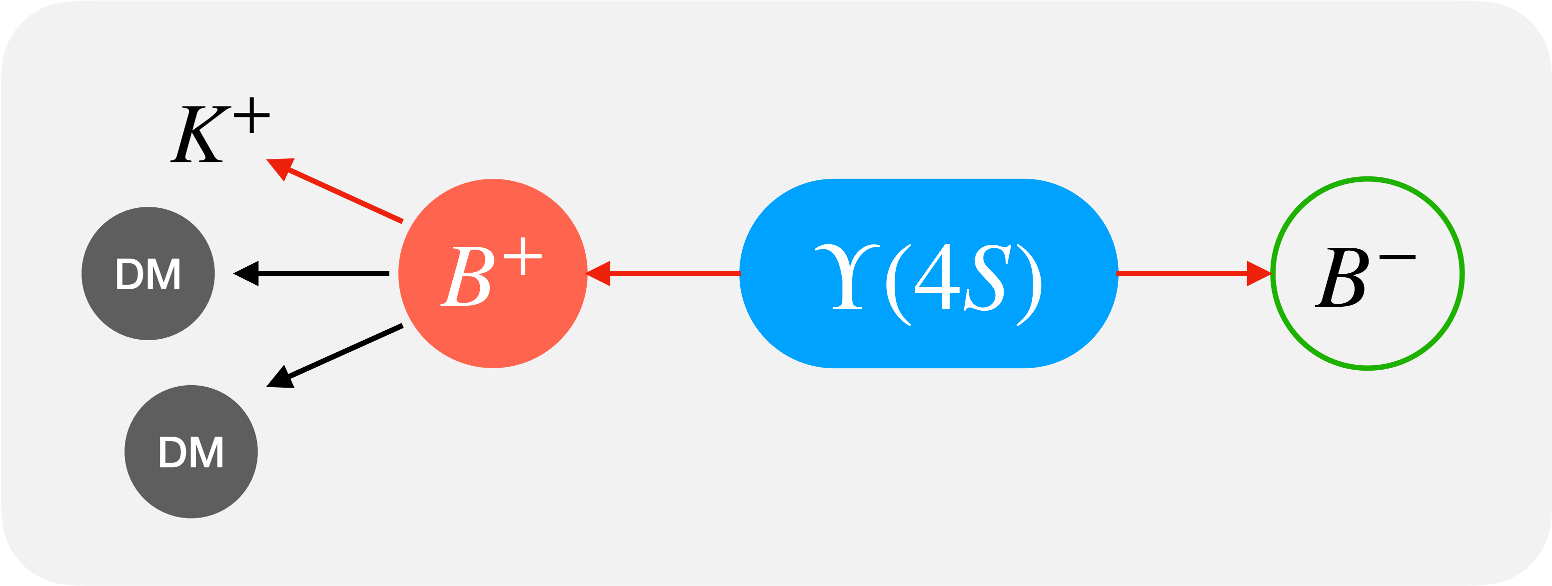
Belle II excess (if confirmed in the future) implies:
- impossible to explain in SMEFT with MFV
- NP flavour structure is highly non-trivial
- **NP structure in quark sector is beyond MFV**
- **flavour violation is beyond Yukawa coupling**

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

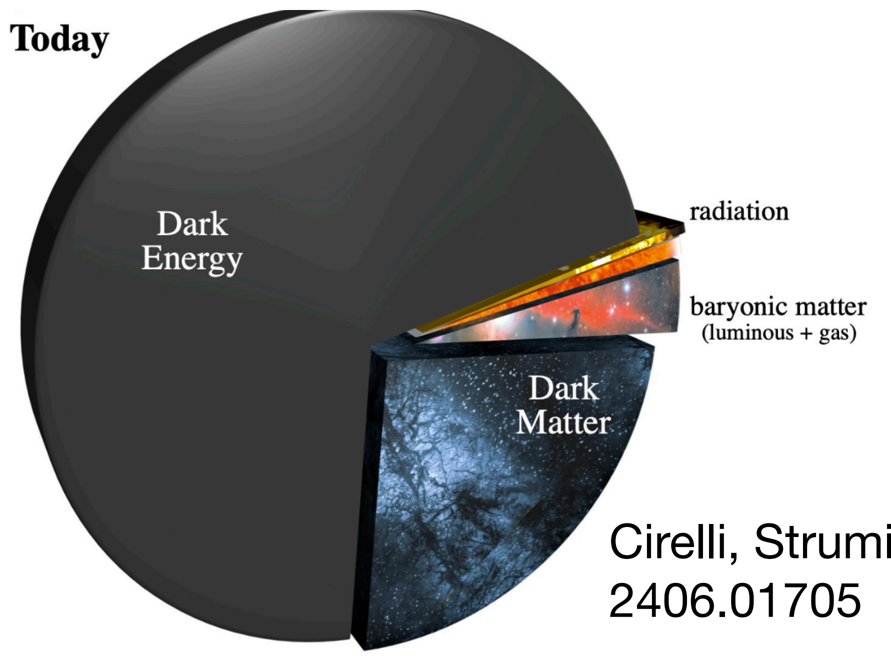
$b \to s\nu\bar{\nu}$: exp picture





Light DM: a bottom-up view

DM is electrically neutral ! $\Longrightarrow$ DM only have FC or FCNC couplings to quarks !



Cirelli, Strumia, Zupan
2406.01705

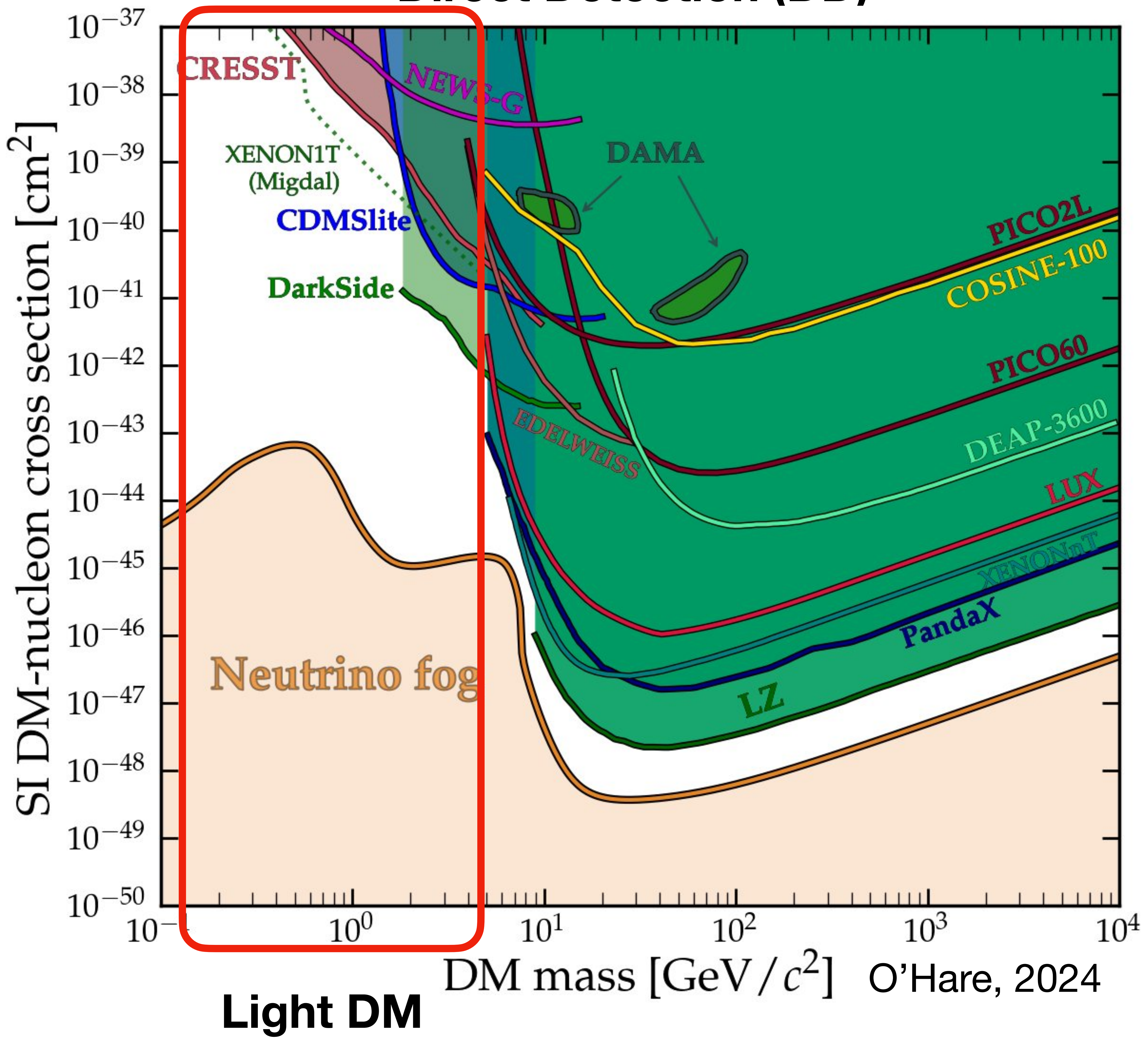
	d	s	b
d	DD	NA62/KOTO	Belle II
s		DD	Belle II
b			Belle II/LHC

	u	c	t
u	DD	BES/STCF	LHC
c		BES/STCF	LHC
t			LHC

example:
$B^+ \to K^+ +$ DM + DM
$K^+ \to \pi^+ +$ DM + DM
$D^0 \to \pi^0 +$ DM + DM

Blue box: means related to the DM relic density

Direct Detection (DD)



O'Hare, 2024

Effective Field Theory approach to combine the various experimental searches

In EFT, DM is a just singlet under the SM gauge group.

Dark SMEFT $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$, all the SM particles

example

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

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)

μ_{EW}

Dark LEFT $SU(3)_C \otimes U(1)_{\text{em}}$, W, Z, h, t have been integrated out

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

example

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

μ_b

μ_c

1 GeV

NRET/HDMET/Chiral EFT

$$\chi(x) = e^{-im_\chi v\cdot x}\left(\chi_v(x) + X_v(x)\right)$$

2011 Hill, Solon
2012 Fitzpatrick, Haxton, Katz, Lubbers, Xu
2013 Hill, Solon
2013 Anand, Fitzpatrick, Haxton
2016 Bishara, Brod, Grinstein, Zupan

$H_1 \to H_2 + \mathrm{DM}$ theoretical calculation and experimental searches

- $d_i \to d_j + \phi + \phi$

  2011 Kamenik, Smith
  2004 Bird, Jackson, Kowalewski, Pospelov
  2019 G.Li, J.Y. Su, Tandean
  $\Lambda \to n + \phi\phi$, $\Sigma^+ \to p + \phi\phi$, $\Xi^0 \to \Lambda + \phi\phi$, $\Xi^- \to \Sigma^-\phi\phi$, $\Omega^- \to \Sigma^- + \phi\phi$
  2020 X.G. He, X.D. Ma, Tandean, Valencia
  2020 C.Q.Geng, Tandean, $K \to \pi\pi + \phi\phi$
  2021 G. Li, T. Wang, J.B. Zhang, G.L. Wang
  2022 Kling, S. Li, H. Song, S. Su, W. Su

- $d_i \to d_j + \chi + \chi$

  2011 Kamenik, Smith
  2019 J.Y. Su, Tandean
  2020 G. Li, T. Wang, Y. Jiang, J.B. Zhang, G.L. Wang
  2021 Felkl, S. L. Li, Schmidt

- $d_i \to d_j + X + X$

  2011 Kamenik, Smith
  2021 G. Li, T. Wang, J.B. Zhang, G.L. Wang
  2022 X.G. He, X.D. Ma, Valencia

- $d_i \to d_j + a$

  2020 Camalich, Pospelov, Vuong, Ziegler, Zupan,
  2021 Bauer, Neubert, Renner, Schnubel, Thamm
  2022 Guerrera and S. Rigolin

- theoretically clean: $A \propto C \cdot \langle H_1 | O | H_2 \rangle$ (tiny LD contribution)
- no GIM suppression
- possibly two-body decay

} **enhancement**

Observable
$\mathcal{B}(B^+ \to K^+\nu\bar{\nu})$
$\mathcal{B}(B^0 \to K^0\nu\bar{\nu})$
$\mathcal{B}(B^+ \to K^{*+}\nu\bar{\nu})$
$\mathcal{B}(B^0 \to K^{*0}\nu\bar{\nu})$
$\mathcal{B}(B_s \to \phi\nu\bar{\nu})$
$\mathcal{B}(B^+ \to \pi^+\nu\bar{\nu})$
$\mathcal{B}(B^0 \to \pi^0\nu\bar{\nu})$
$\mathcal{B}(B^+ \to \rho^+\nu\bar{\nu})$
$\mathcal{B}(B^0 \to \rho^0\nu\bar{\nu})$
$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$
$\mathcal{B}(K_L \to \pi^0\nu\bar{\nu})$
$\mathcal{B}(B_s \to \nu\bar{\nu})$
$\mathcal{B}(B^0 \to \nu\bar{\nu})$

$\nu \to \mathrm{DM}$

- $c \to u + \mathrm{DM}$

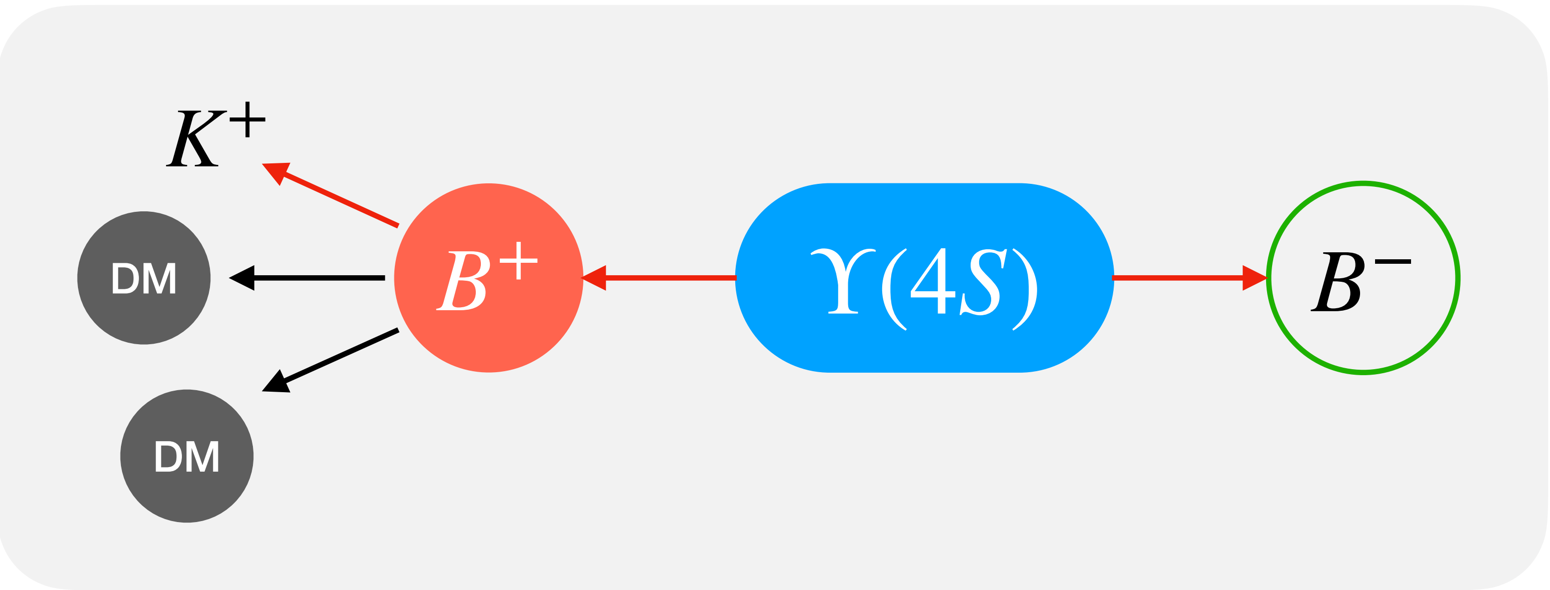
  2022 C.Q.Geng, G.Li
  2023 G.Li, Tandean

$D^0 \to \mathrm{s}\bar{\mathrm{s}}'$
$D^0 \to \gamma\mathrm{s}\bar{\mathrm{s}}'$
$D^0 \to \pi^0\mathrm{s}\bar{\mathrm{s}}'$
$D^+ \to \pi^+\mathrm{s}\bar{\mathrm{s}}'$
$D_s^+ \to K^+\mathrm{s}\bar{\mathrm{s}}'$
$D^0 \to \rho^0\mathrm{s}\bar{\mathrm{s}}'$
$D^+ \to \rho^+\mathrm{s}\bar{\mathrm{s}}'$
$D_s^+ \to K^{*+}\mathrm{s}\bar{\mathrm{s}}'$
$\Lambda_c^+ \to p\mathrm{s}\bar{\mathrm{s}}'$
$\Xi_c^+ \to \Sigma^+\mathrm{s}\bar{\mathrm{s}}'$
$\Xi_c^0 \to \Sigma^0\mathrm{s}\bar{\mathrm{s}}'$
$\Xi_c^0 \to \Lambda\mathrm{s}\bar{\mathrm{s}}'$

`HadronToNP`: a package to calculate decay of hadron to new particles
B.F. Hou, X.Q. Li, H.Yan, Y.D. Yang, **XBY** *to be finished*

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

Dark SMEFT

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

scalar: 4

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

fermion: 2

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

vector: 1+13

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

ALP: 2

μ_{EW}

Dark LEFT

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

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

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

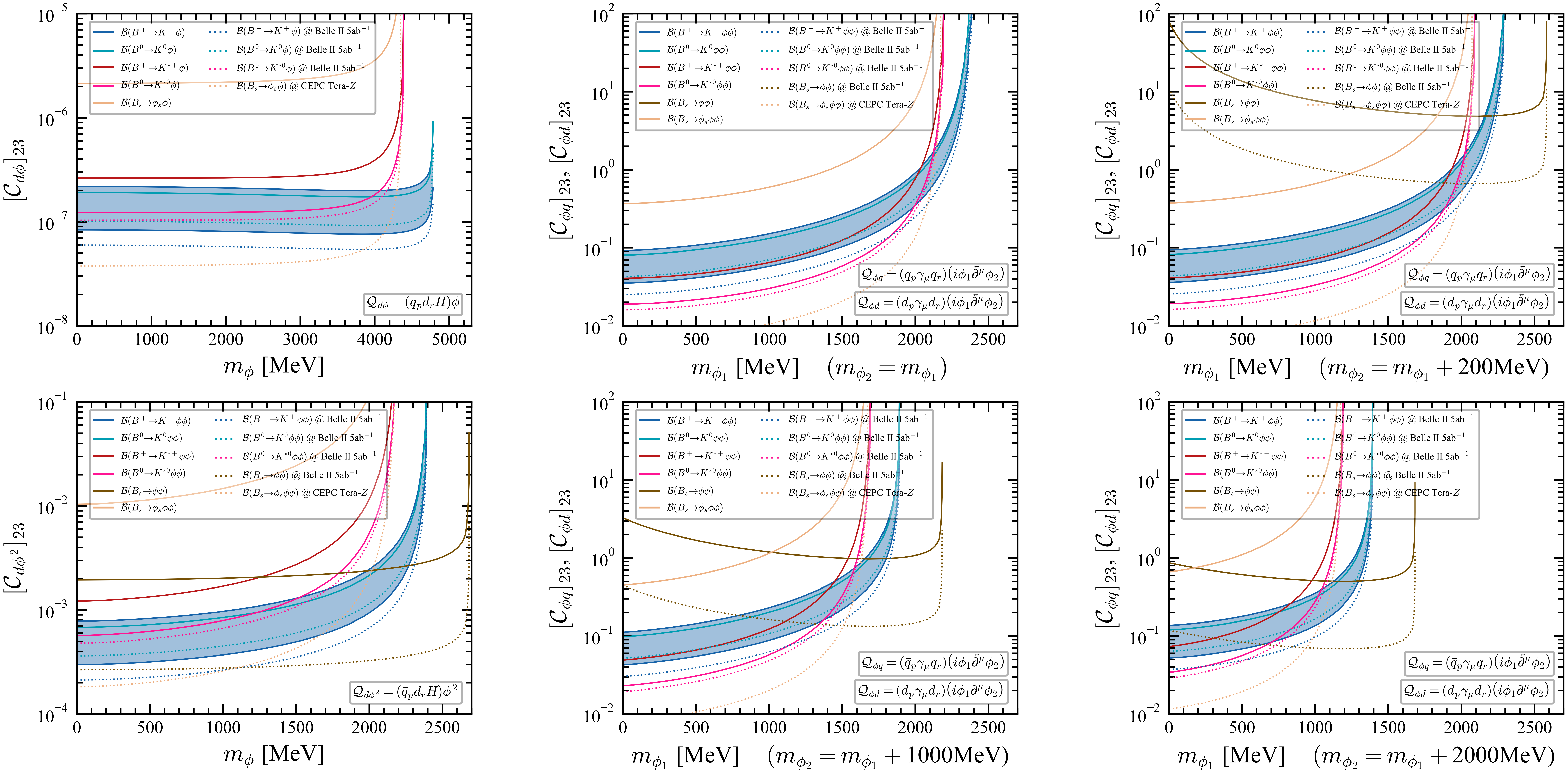
vector: 1+10

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

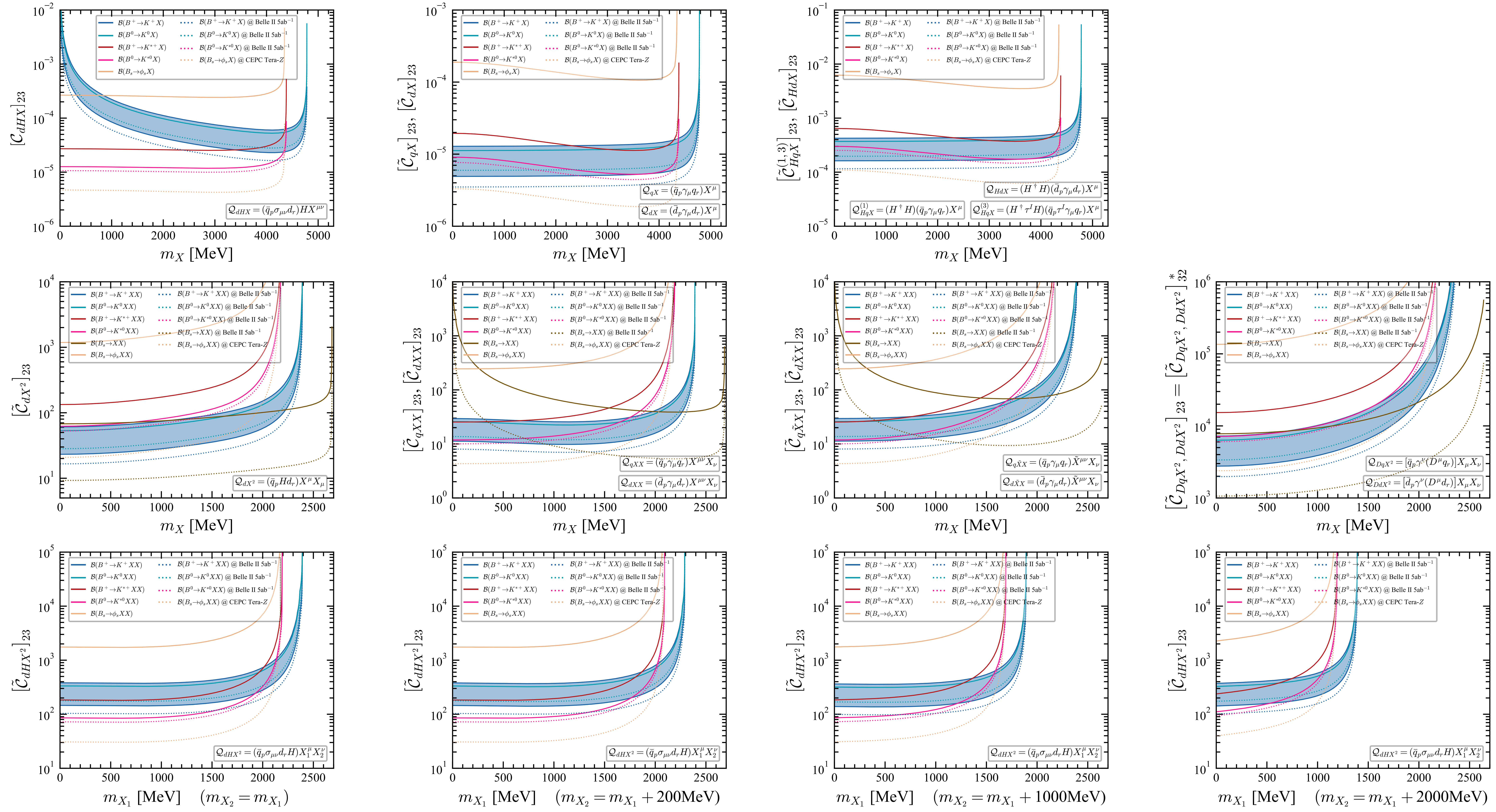
ALP: 2

μ_b

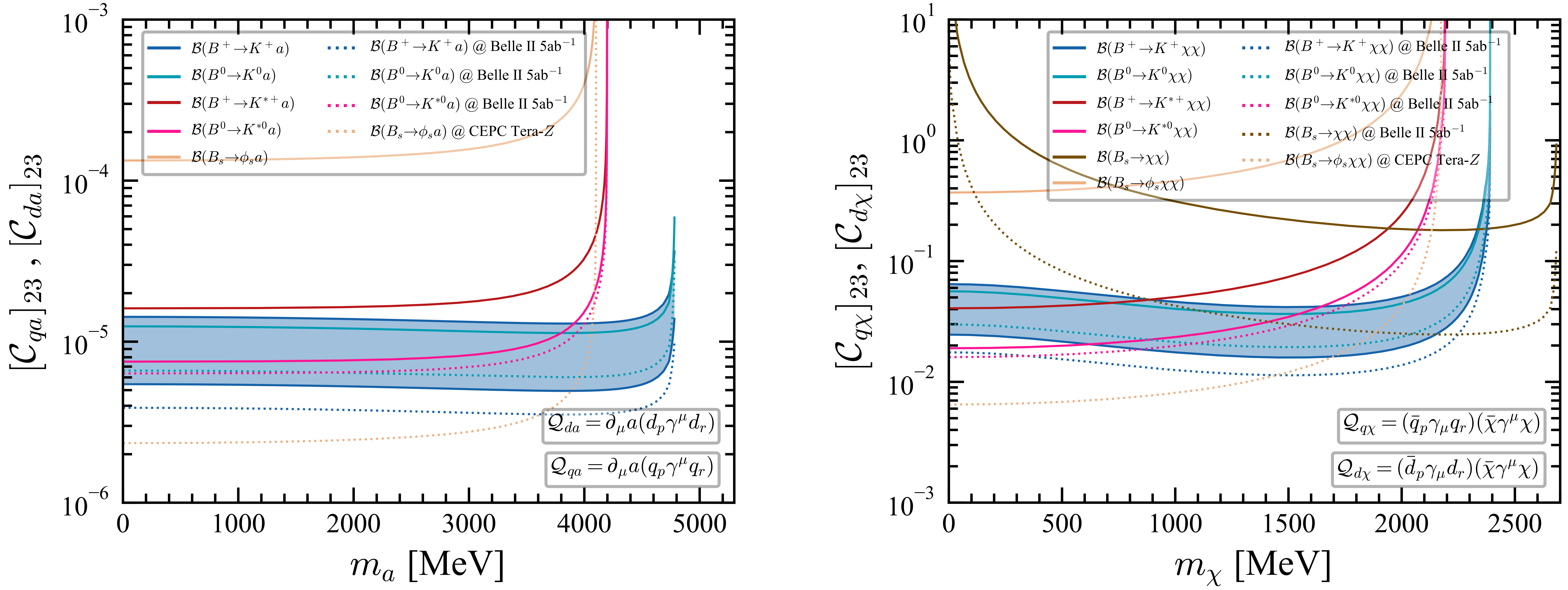
Dark SMEFT: Scalar



Dark SMEFT: Vector



Dark SMEFT: Fermion, ALP



All the operators survive from the constraints of the various FCNC decays.
In the future, all the parameter space to explain the Belle II anomaly can be covered by combing the Belle II (e.g., $B^0 \to K^0 + \text{inv}$) and CEPC (e.g., $B_s \to \phi + \text{inv}$ and $B_s \to \text{inv}$) measurements.

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

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

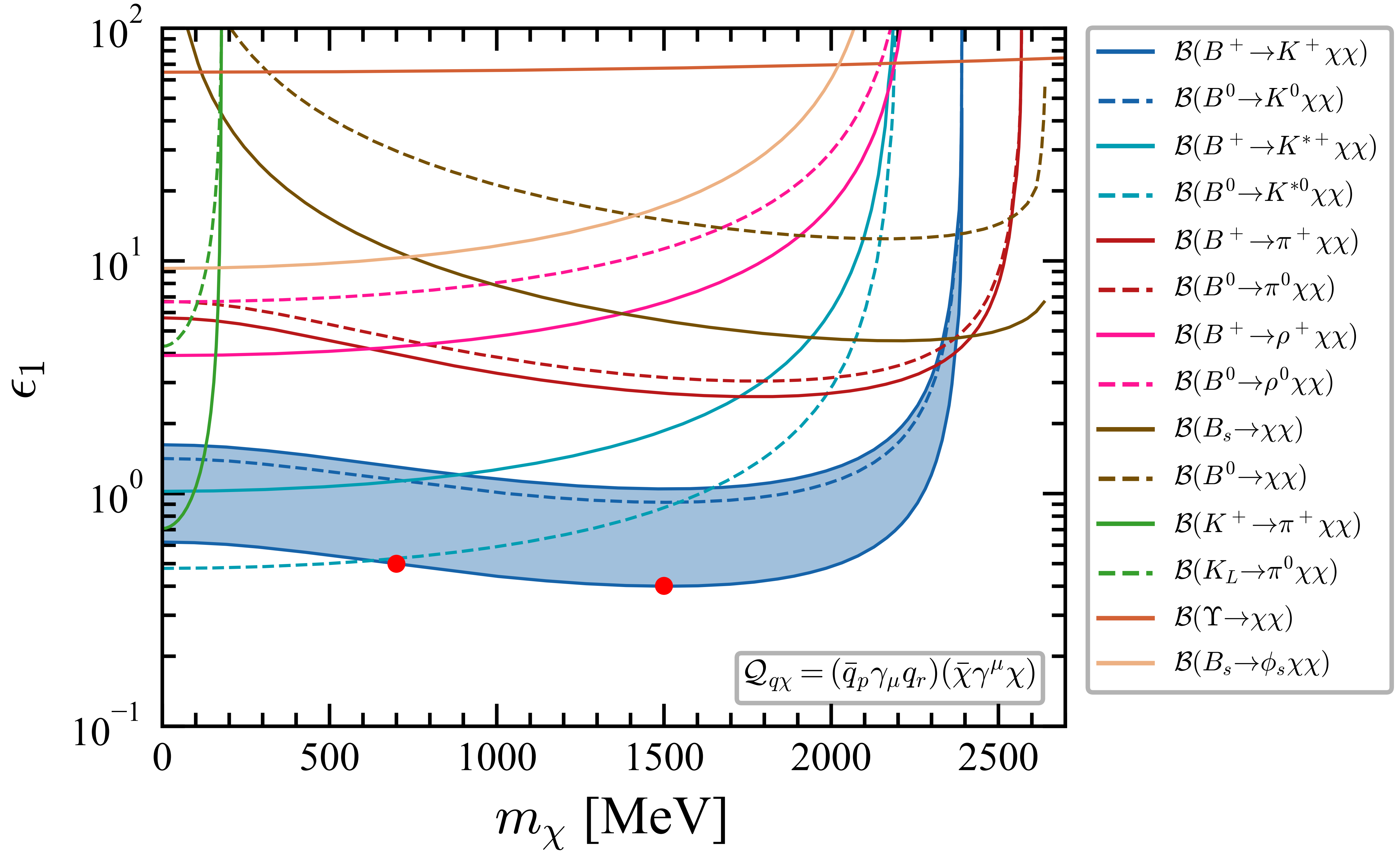
$$\Delta_q \hat{\lambda}_d = \begin{pmatrix} 0.0021 & -0.18 - 0.08i & 191.3 + 85.4i \\ -0.009 + 0.004i & 0.88 & -958.7 + 19.6i \\ 0.21 - 0.10i & -21.1 - 0.4i & 23728.1 \end{pmatrix} \times 10^{-6}$$

Dark SMEFT with MFV: Scalar

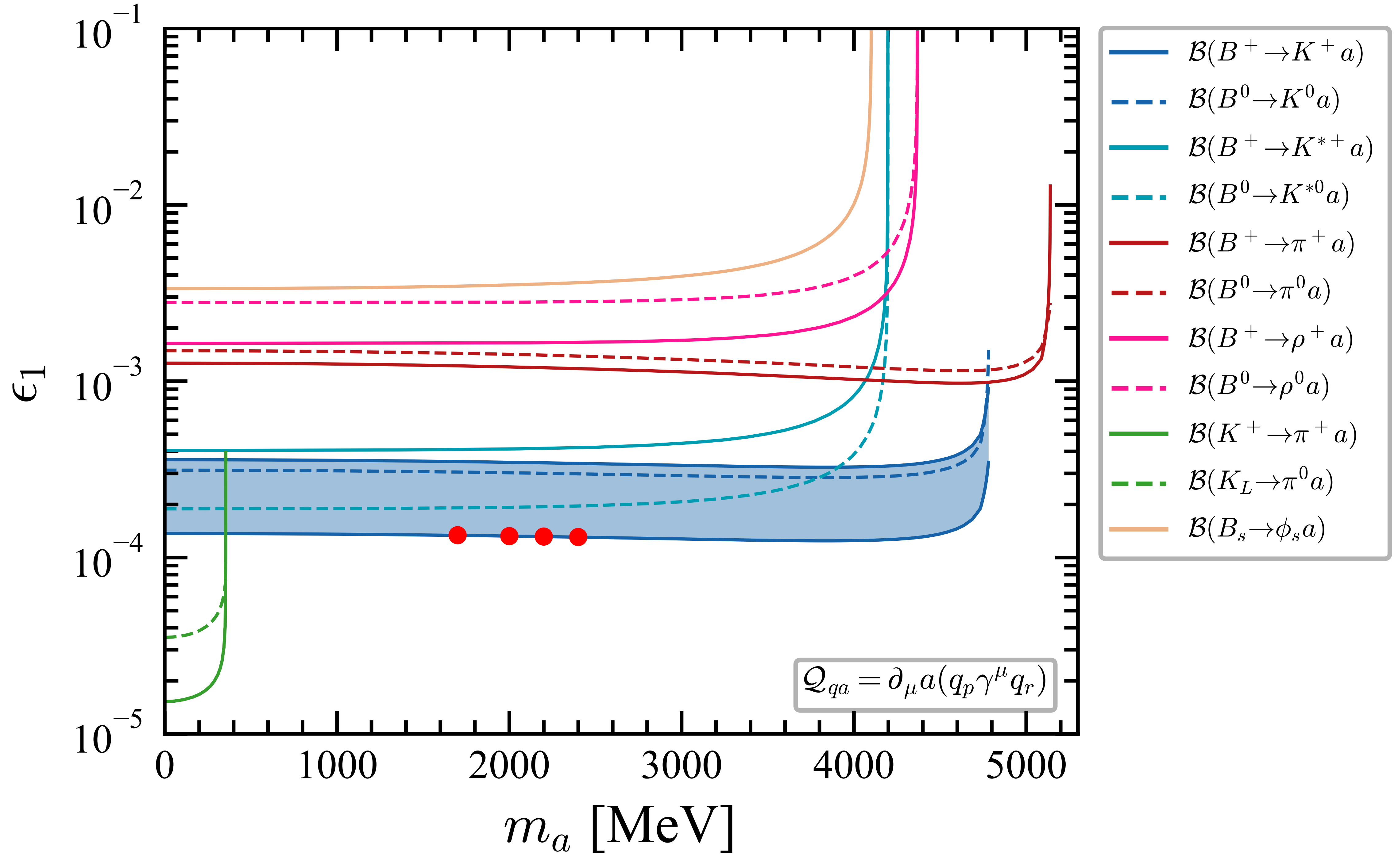
all the operators survive
some ones highly constrained

Dark SMEFT with MFV: Fermion, ALP

Fermion



Axion-like Particle

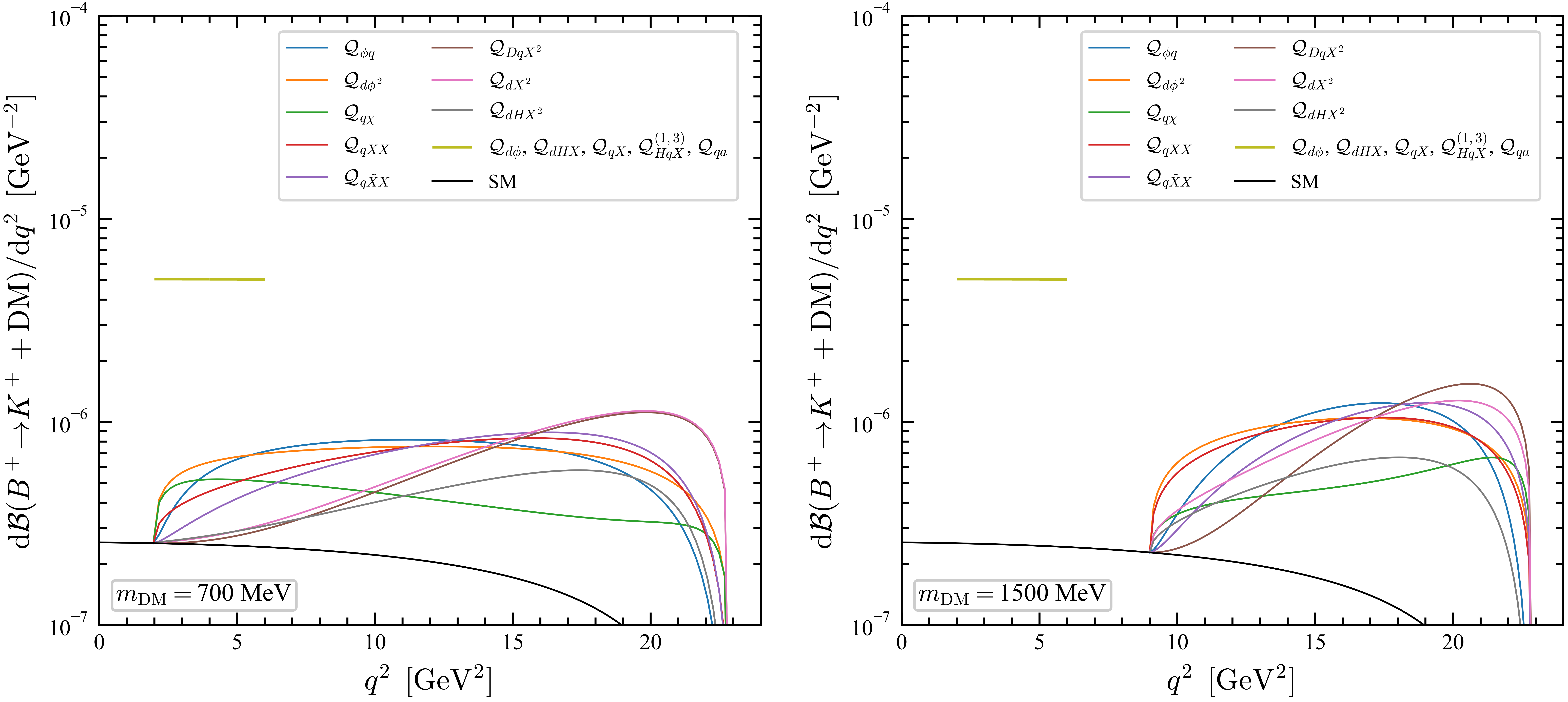


all the operators survive

Dark SMEFT with MFV: Vector

all the operators survive, some ones highly constrained

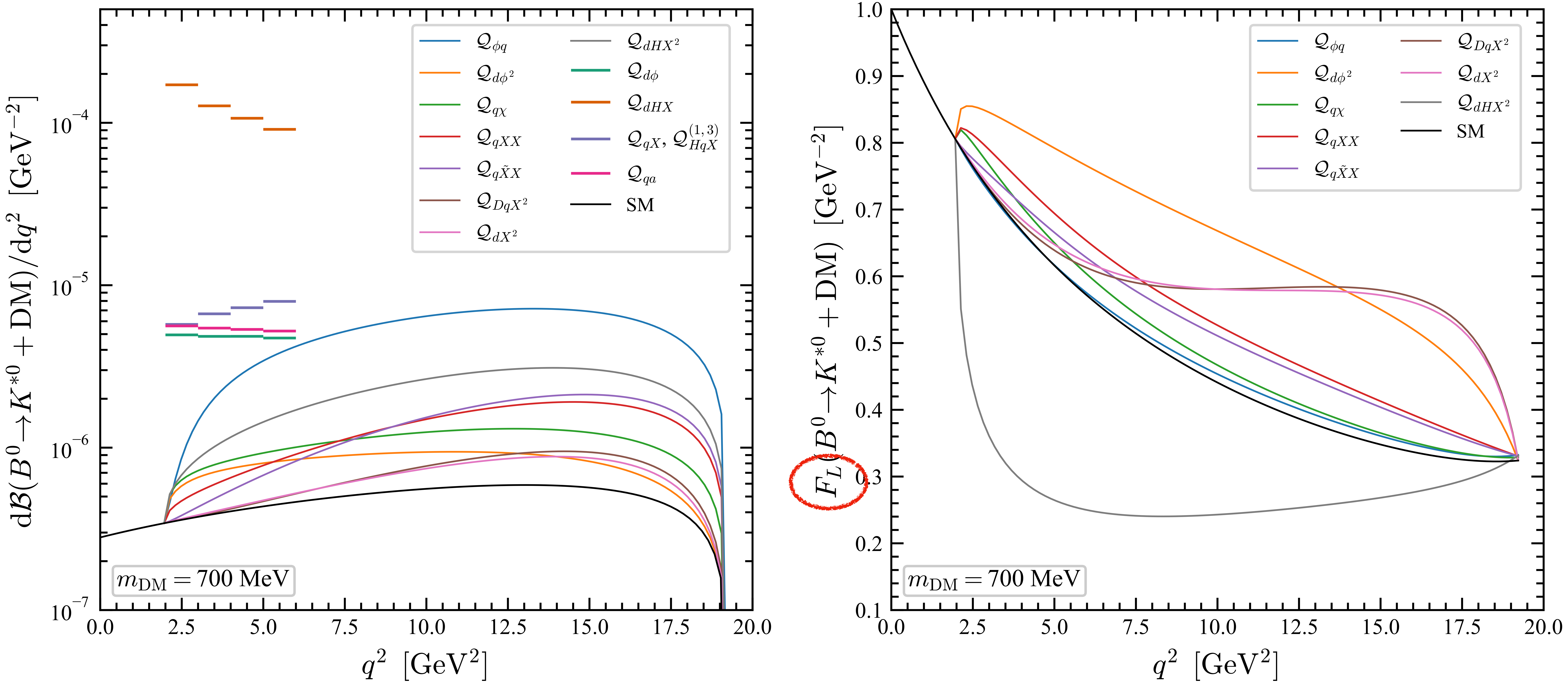
Dark SMEFT: $\mathrm{d}B/\mathrm{d}q^2$



Difficult to distinguish the DSMEFT operators by considering only the $B^+ \to K^+ \nu\bar{\nu}$ decay. However,

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

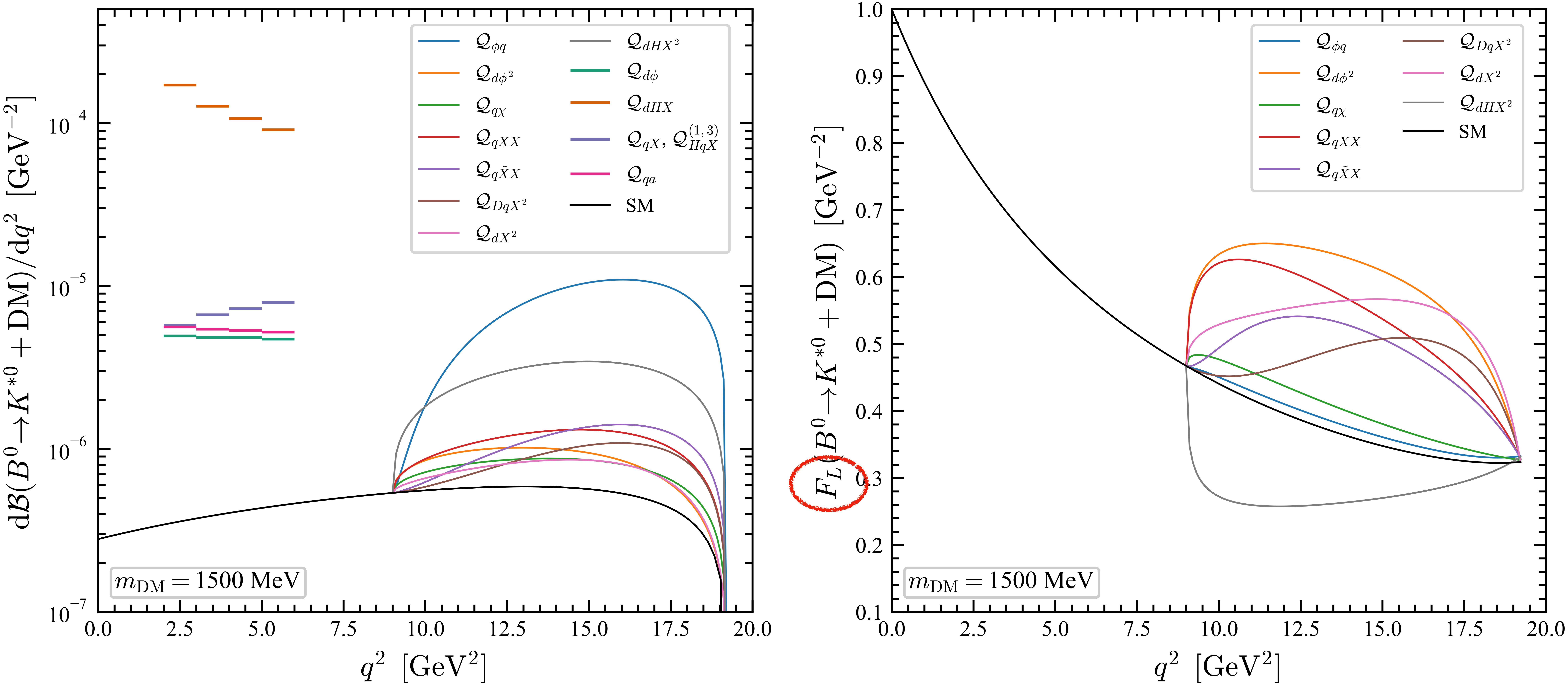
$m_{\mathrm{DM}} = 700\,\mathrm{MeV}$



All the operators are distinguishable from each other by combing these observables, except Q_{qXX} and $Q_{qX\tilde{X}}$, Q_{dX^2} and Q_{DqX}

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

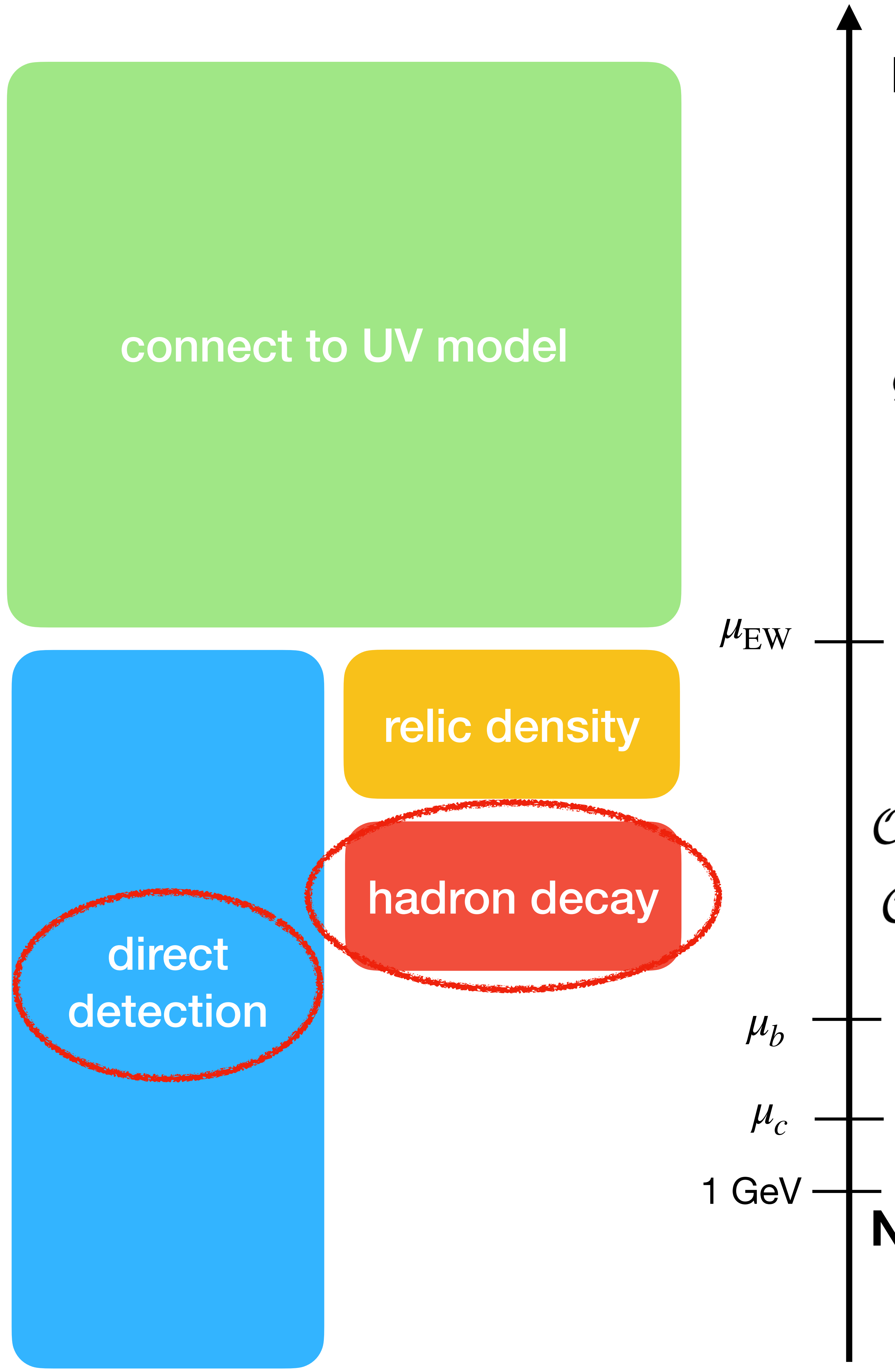
$m_{\rm DM}$ = 1500 MeV



All the operators are distinguishable from each other by combing these observables, except Q_{qXX} **and** $Q_{qX\tilde{X}}$, Q_{dX^2} **and** Q_{DqX}

Effective Field Theory approach to combine the various experimental searches

In EFT, DM is a just singlet under the SM gauge group.



Dark SMEFT $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$, all the SM particles

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 $SU(3)_C \otimes U(1)_{\rm em}$, W, Z, h, t have been integrated out

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

example

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

NRET/HDMET/Chiral EFT

$$\chi(x) = e^{-im_\chi v\cdot x}\left(\chi_v(x) + X_v(x)\right)$$

2011 Hill, Solon
2012 Fitzpatrick, Haxton, Katz, Lubbers, Xu
2013 Hill, Solon
2013 Anand, Fitzpatrick, Haxton
2016 Bishara, Brod, Grinstein, Zupan

Top-flavored DM

- Dark SMEFT with 3rd generation@$\mu_{\rm EW}$

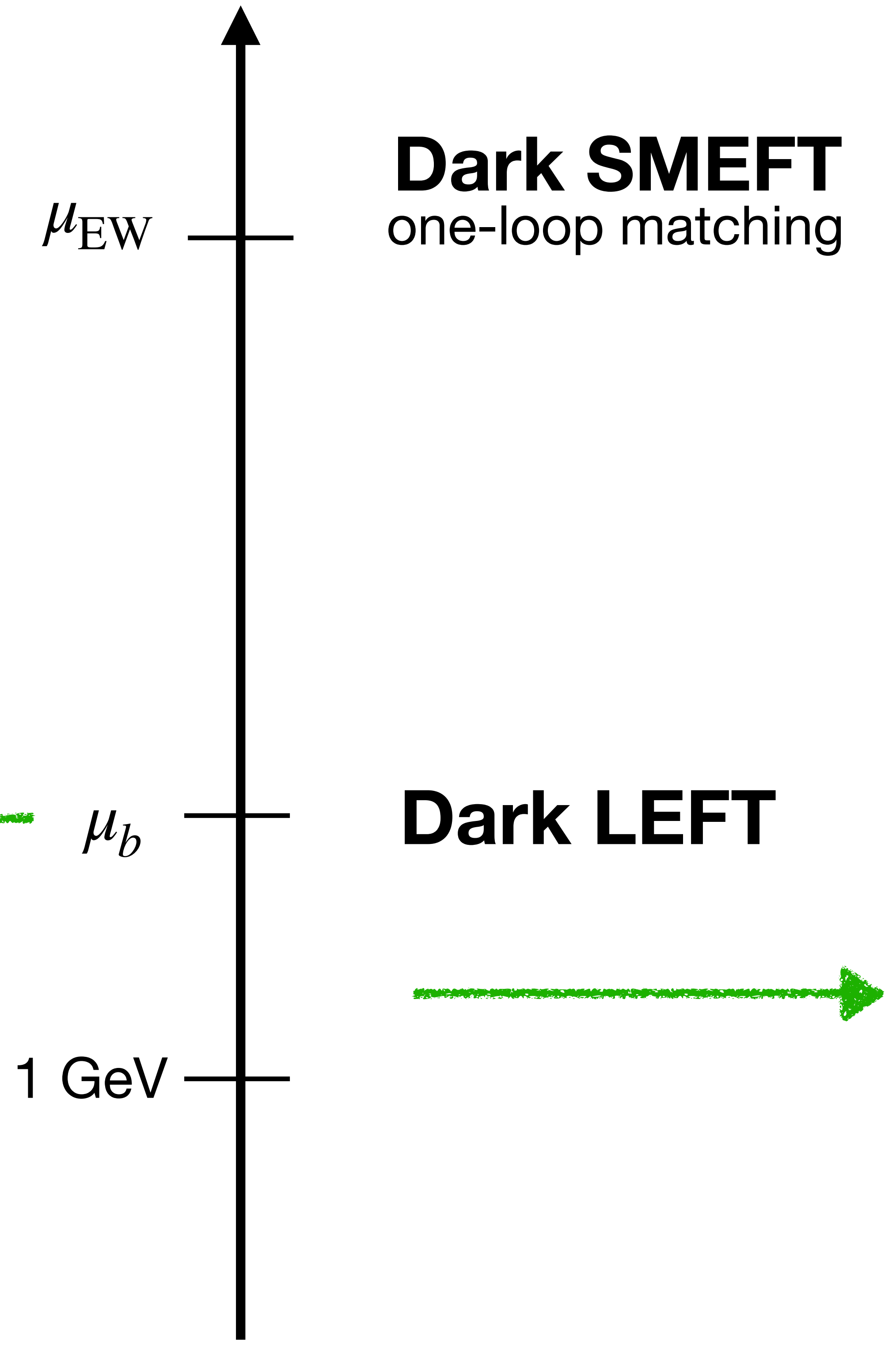
$$\mathcal{Q}_{u\chi} = (\bar{u}_p \gamma_\mu u_r)(\bar{\chi}\gamma^\mu \chi), \Longrightarrow (\bar{t}_R \gamma_\mu t_R)(\bar{\chi}\gamma^\mu \chi)$$

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

$$\mathcal{Q}_{u\chi^2} = (\bar{q}_p u_r \widetilde{H})(\bar{\chi}\chi), \qquad \mathcal{C} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} \mathcal{C}_{33}$$

2013 Tongyan Lin, Kolb, Lian-Tao Wang
2015 Kilic, Klimek, Jiang-Hao Yu
2015 Haisch, Re
2015 Boucheneb, Cacciapaglia, Deandrea, Fuks
2017 Blanke, Kast
2021 Blanke, Pani, Polesello, Rovelli
2021 Haisch, Polesello, Schulte
2021 Hermanna, Worek
… …

2019 ATLAS [JHEP05(2019)142]



Dark SMEFT
one-loop matching

Dark LEFT

hadron decay

direct detection

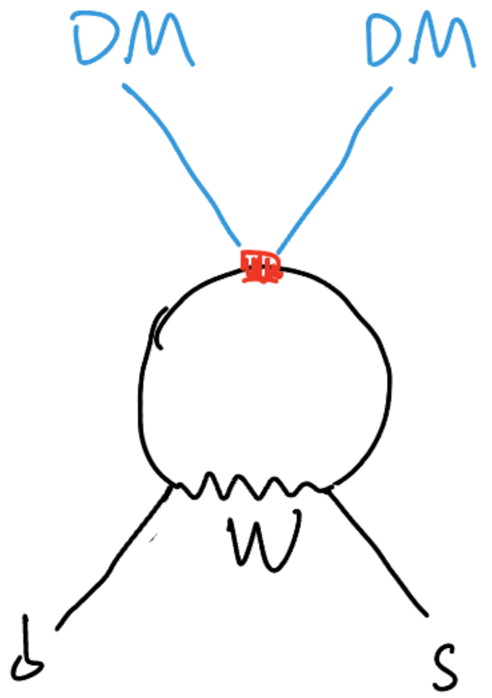
$$\mathcal{O}_{d\phi^2} = (\bar{d}_p P_R d_r)\phi^2$$

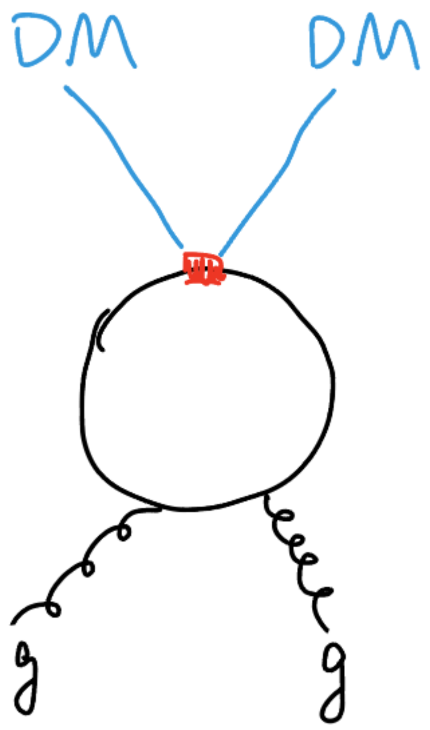
$$\mathcal{O}^{L}_{dXX} = (\bar{d}_p \gamma^\mu P_L d_r) X_{\mu\nu} X^\nu$$

$$\mathcal{O}^{V,LR}_{d\chi} = (\bar{d}_p \gamma_\mu P_L d_r)(\bar{\chi}\gamma^\mu \chi),$$

+ $\mathcal{O}(20)$ operators

$$\langle H_2 | \mathcal{O}_i | H_1 \rangle$$





$$\mathcal{O}_{g\phi} = G^a_{\mu\nu} G^{\mu\nu,a} \phi^2,$$

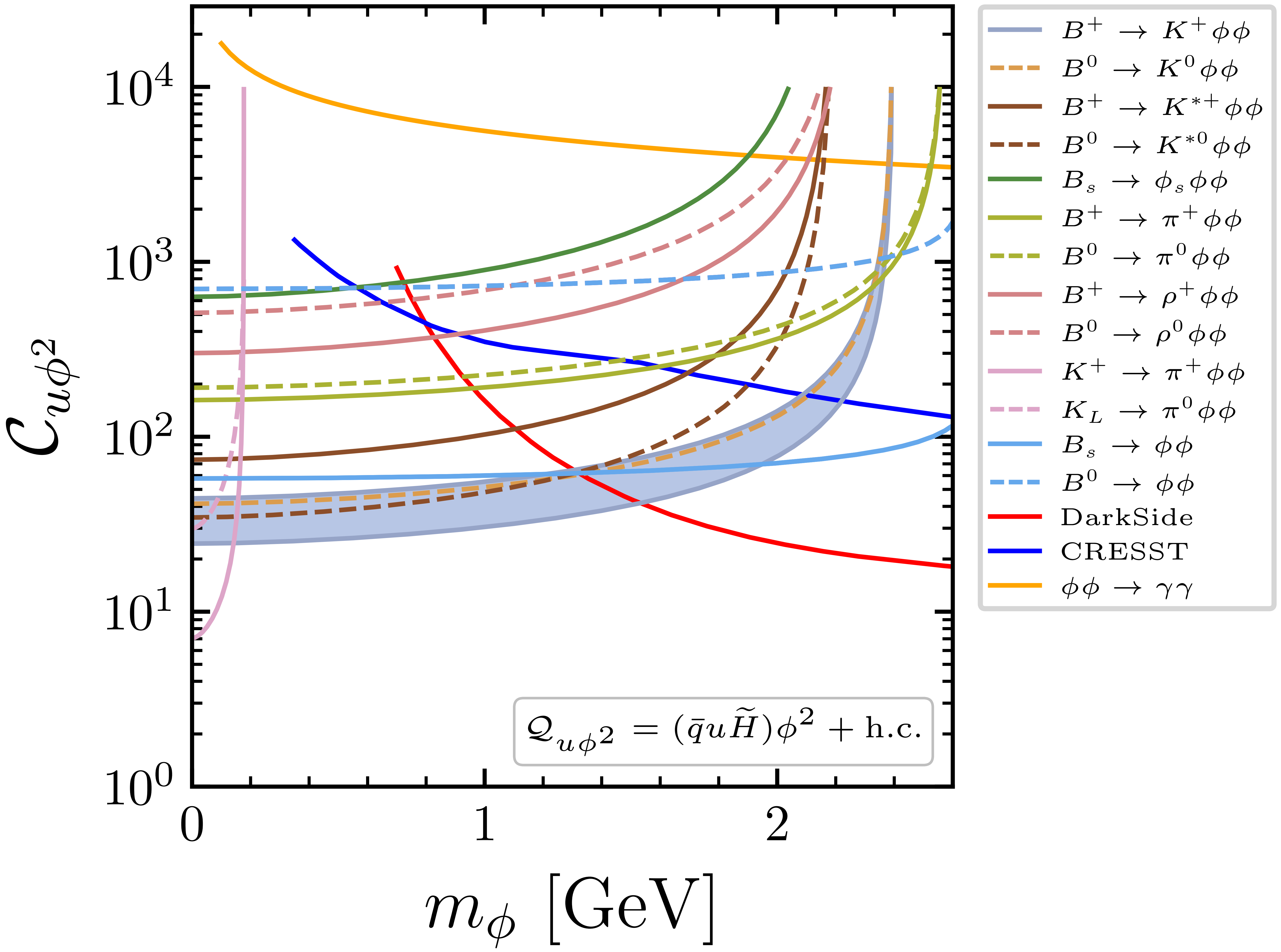
$$\mathcal{O}_{gX} = G^a_{\mu\nu} G^{\mu\nu,a} X_\rho X^\rho,$$

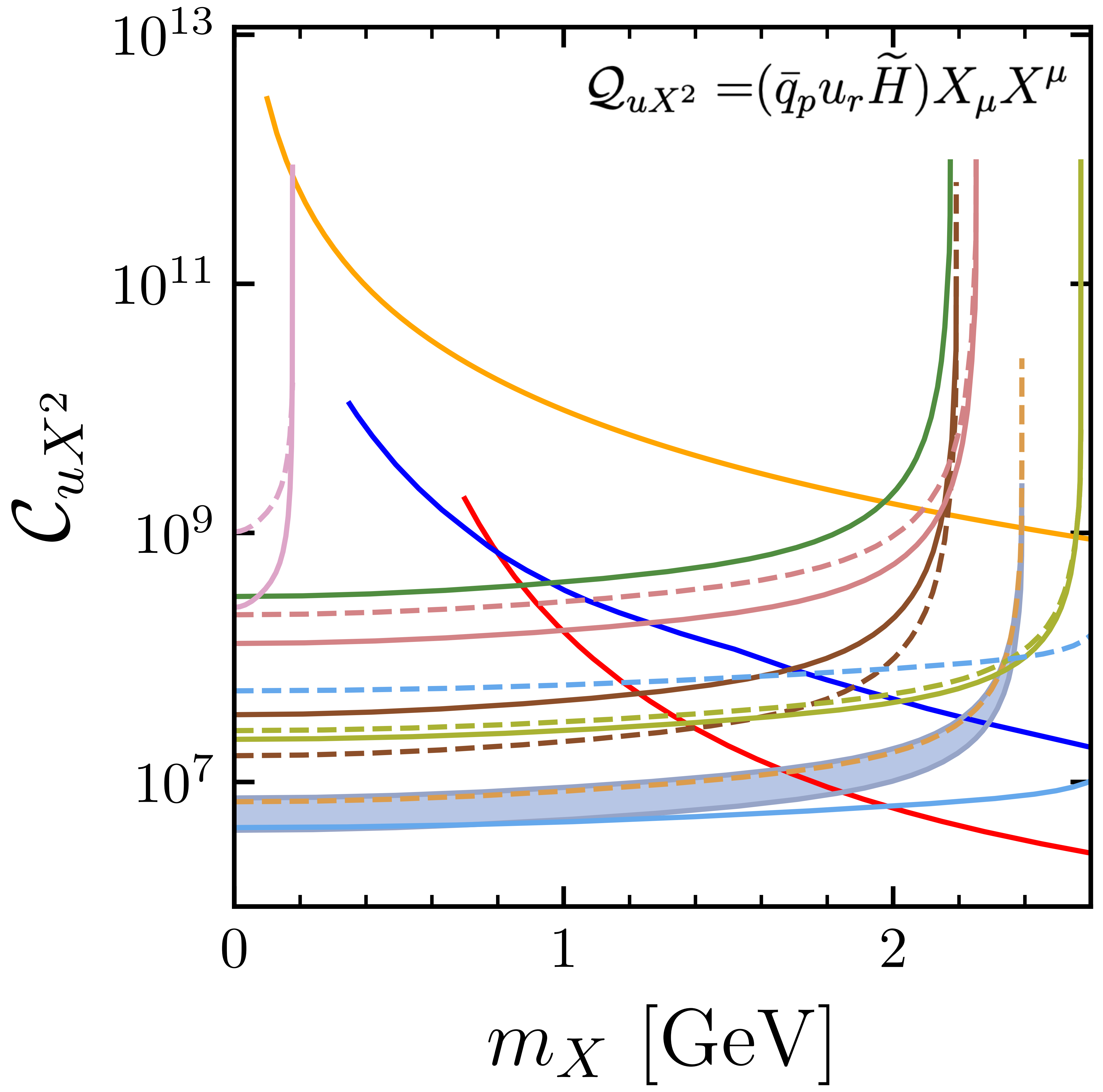
$$\mathcal{O}_{g\chi} = G^a_{\mu\nu} G^{\mu\nu,a} \bar{\chi}\chi$$

+ operators with u, d, s

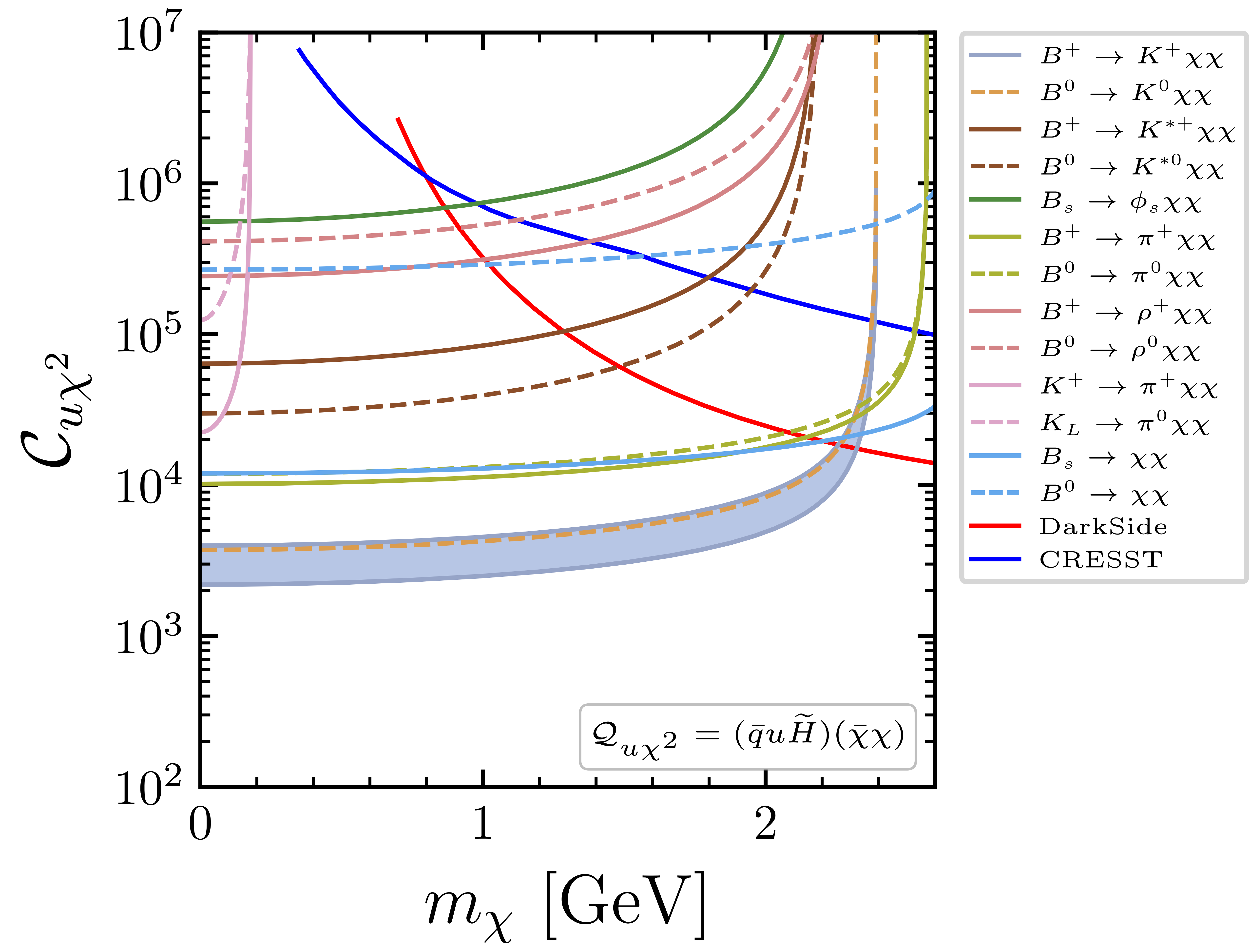
$$\langle N | \mathcal{O}_j | N \rangle$$

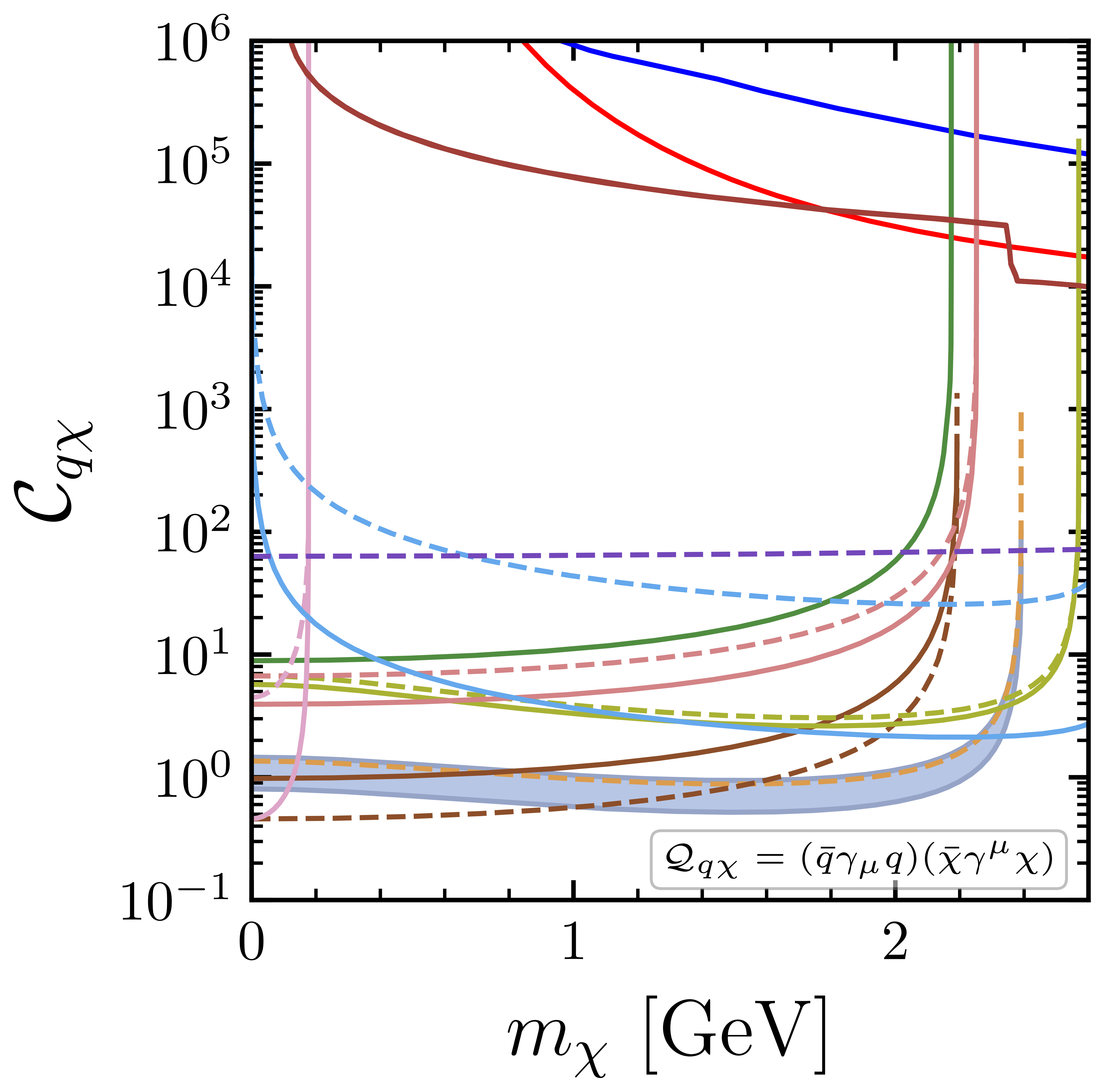
Hadron decay vs direct detection





Hadron decay vs direct detection





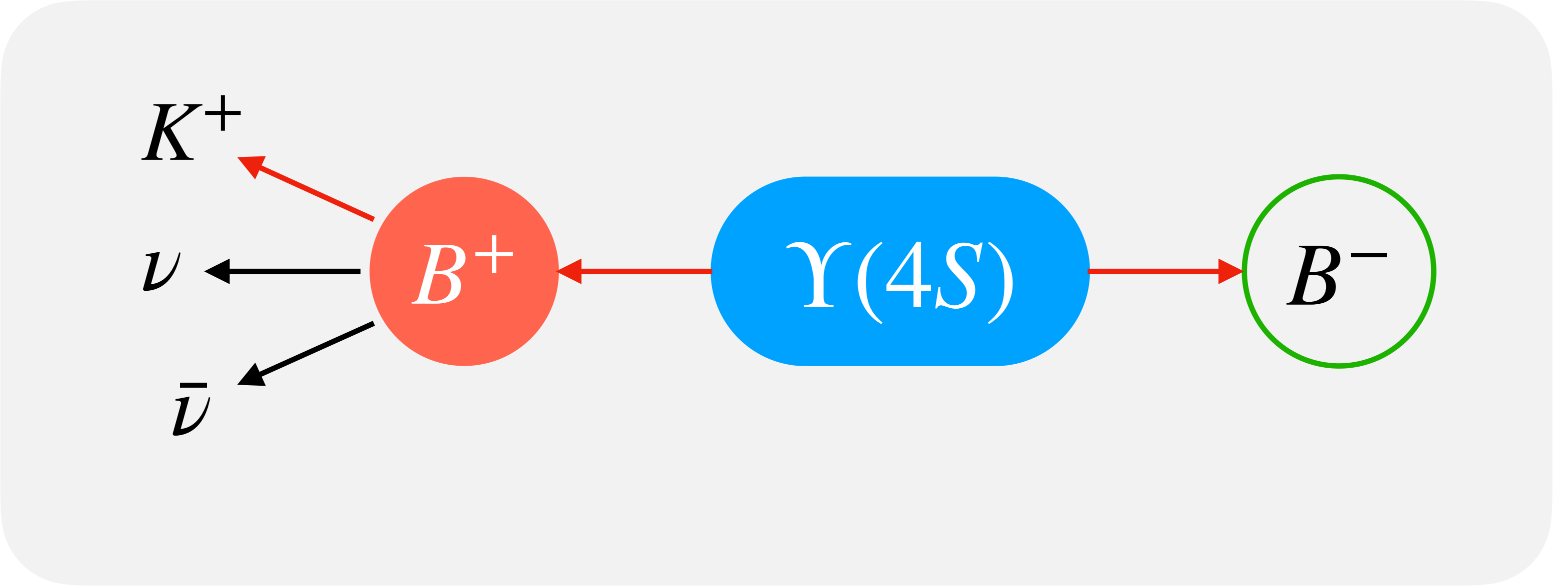
Conclusion

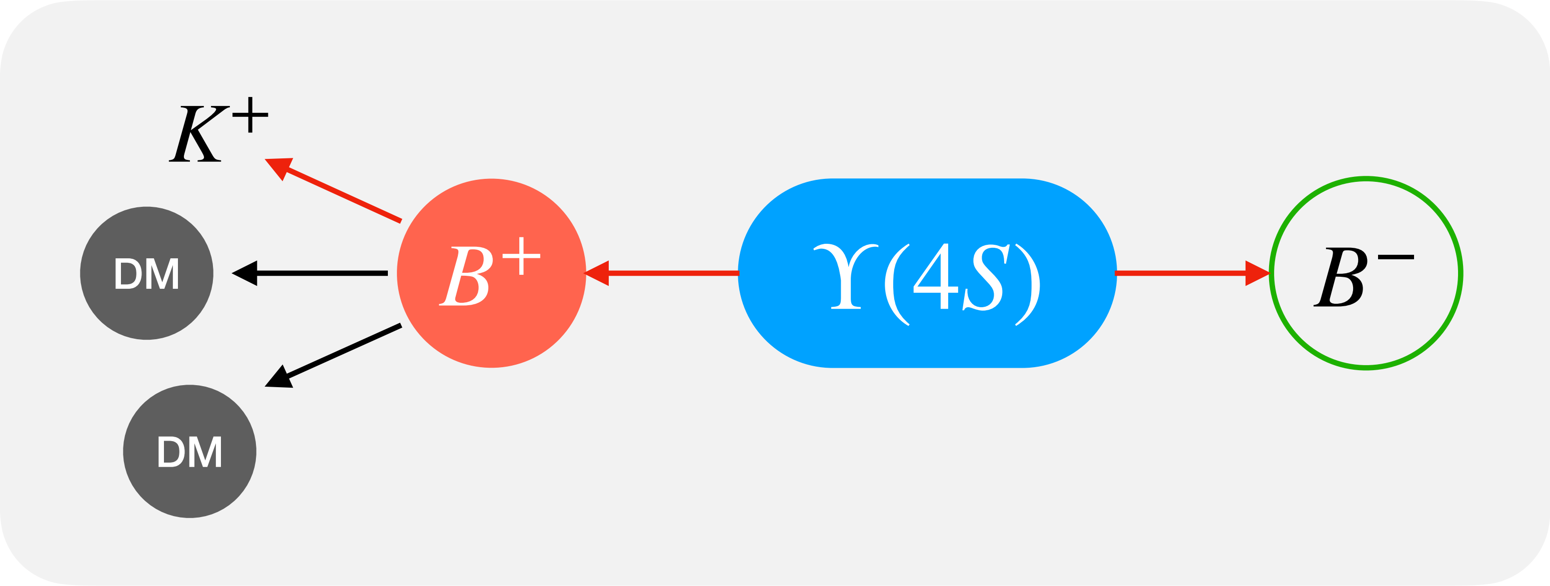
`HadronToNP`: a package to calculate decay of hadron to new particles

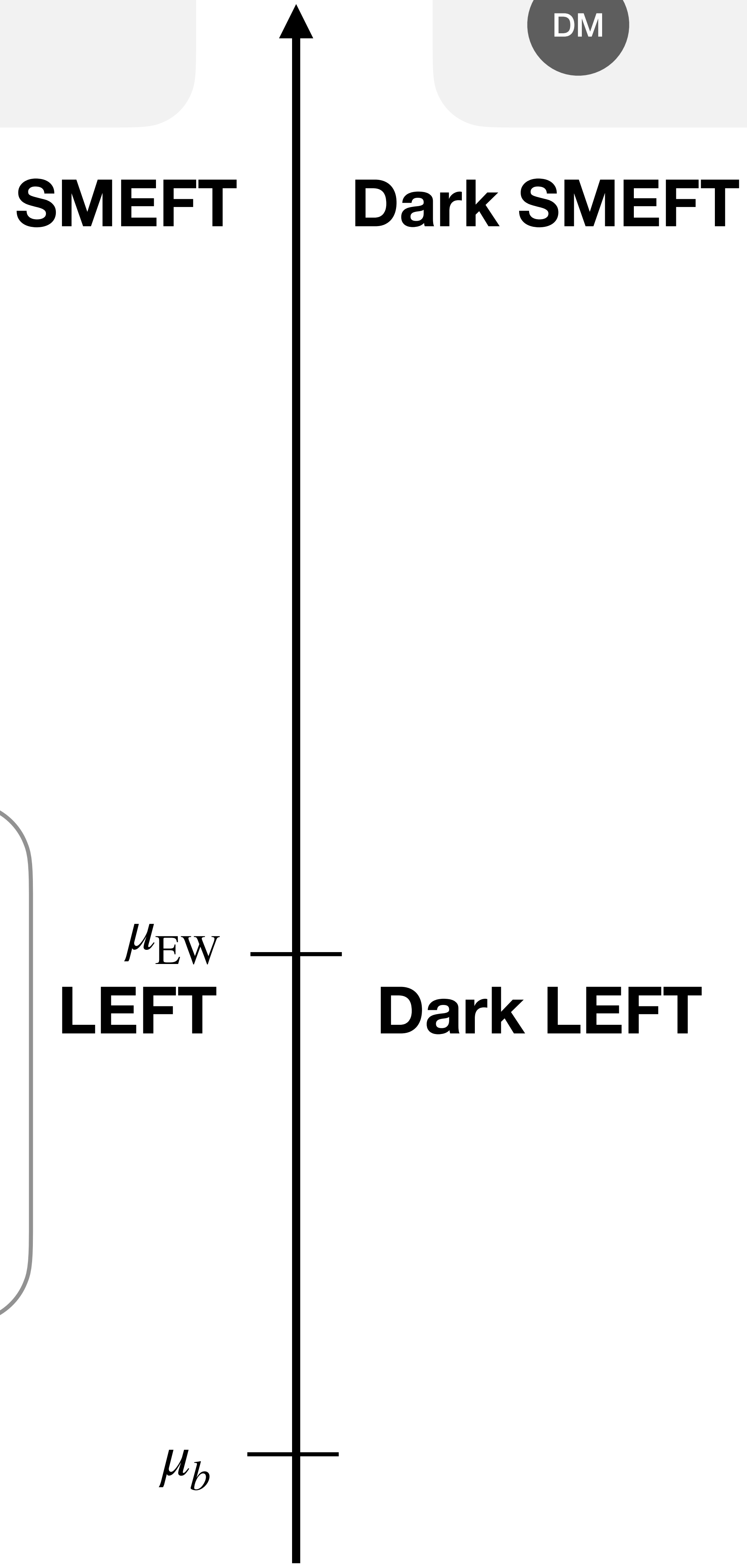
$B \to K + \mathrm{DM},\ B \to \rho + \mathrm{DM},\ \Lambda_b \to \Lambda + \mathrm{DM}, \Upsilon \to \mathrm{DM}, \ldots$

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

to be finished







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

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

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**

A Possible Flavour Path to New Physics

	d	s	b
d	DD	NA62/KOTO	Belle II
s		DD	Belle II
b			Belle II/LHC

	u	c	t
u	DD	BES/STCF	LHC
c		BES/STCF	LHC
t			LHC

Backup

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

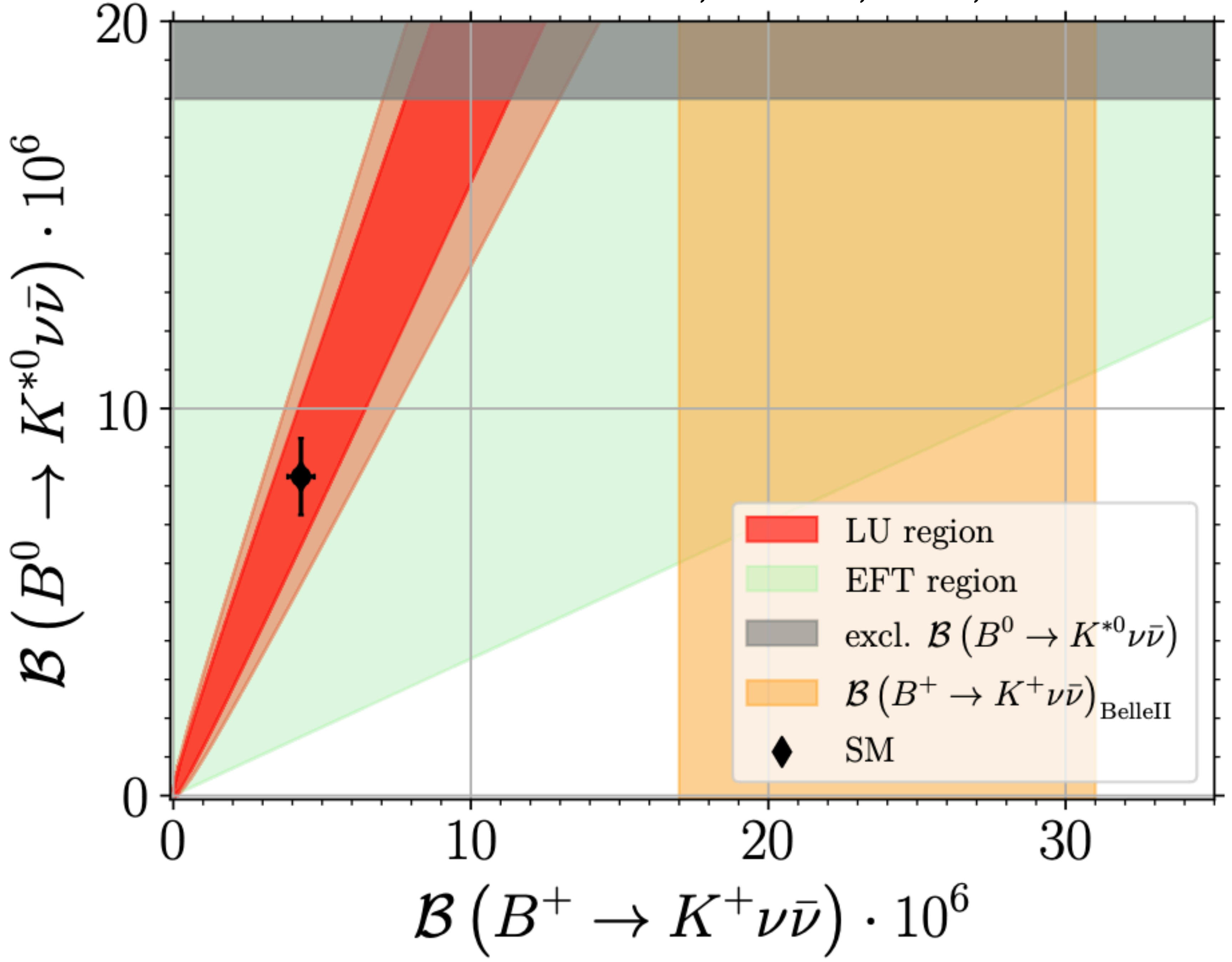
$$\mathcal{O}_L^{\nu_i\nu_j} = \left(\bar{s}\gamma_\mu P_L b\right)\left(\bar{\nu}_i \gamma^\mu P_L \nu_j\right)$$

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

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

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

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

	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 ? **NP flavour structure**

$b \to s\nu\bar{\nu}$ and $b \to s\ell\ell$

B.F.Hou, X.Q.Li, M.Shen, Y.D.Yang, **XBY**, 2402.19208

SMEFT notation: $l = \begin{pmatrix} \nu \\ e \end{pmatrix}_L, q = \begin{pmatrix} u \\ d \end{pmatrix}_L, d = d_R$

- **Prediction**

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

- **prediction**

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

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

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

conflict

- **Only $\mathcal{O}^{(3)}_{lq}$ is relevant with $R_{D^{(*)}}$**

SMEFT

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

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

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

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

$\mu_{\rm EW}$

LEFT

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

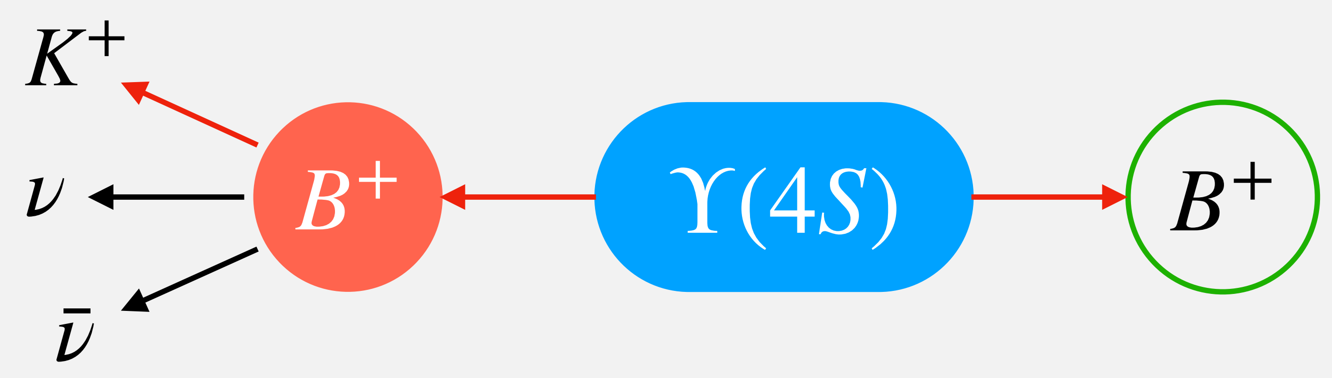
one LEFT operator !
just the SM operator

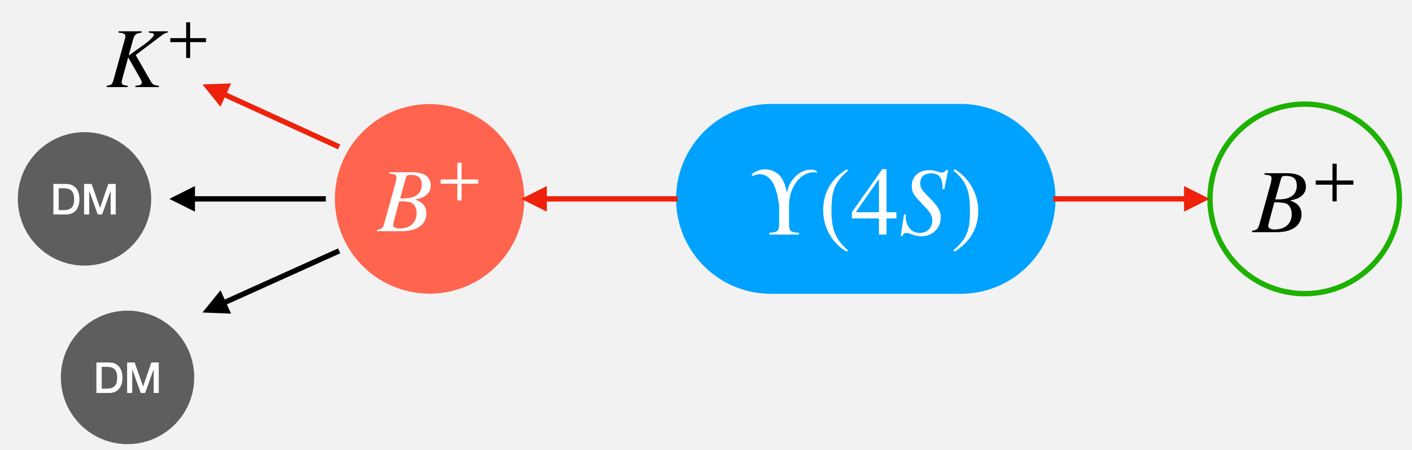
μ_b

- **$\mathcal{O}_{ld}$ can explain the $B^+ \to K^+\nu\bar{\nu}$ data**
- **$\mathcal{O}_{ld}$ also induce $O'_{9,ij}$ and $O'_{10,ij}$**
- **They can't improve the $b \to s\ell\ell$ fit**
  - O'_{9e} and $O'_{10\mu}$ worsen the fit. weird (LFV, $\tau\tau \gg ee, \mu\mu$)
  - $O'_{9,ij}$ and $O'_{10,ij}$ with $i = j = \tau$ has no effect.
  - $O'_{9,ij}$ and $O'_{10,ij}$ with $i \neq j$ (i.e. LFV) has no effect.

$$O'_{9,ij} = (\bar{b}\gamma^\mu P_R s)(\bar{\ell}_i \gamma_\mu \ell_j)$$
$$O'_{10,ij} = (\bar{b}\gamma^\mu P_R s)(\bar{\ell}_i \gamma_\mu \gamma_5 \ell_j)$$

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





SMEFT

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

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

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

μ_{EW}

LEFT

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

μ_b

Dark SMEFT

example

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

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

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

example

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

Backup

$$\mathcal{Q}_{d\phi} = \big(\bar{q}_p d_r H\big)\phi + \text{h.c.}, \qquad \mathcal{Q}_{d\phi^2} = \big(\bar{q}_p d_r H\big)\phi^2 + \text{h.c.},$$
$$\mathcal{Q}_{\phi q} = \big(\bar{q}_p \gamma_\mu q_r\big)\big(i\phi_1 \overleftrightarrow{\partial^\mu} \phi_2\big), \qquad \mathcal{Q}_{\phi d} = \big(\bar{d}_p \gamma_\mu d_r\big)\big(i\phi_1 \overleftrightarrow{\partial^\mu} \phi_2\big), \tag{4.2}$$

$$\mathcal{Q}_{q\chi} = \big(\bar{q}_p \gamma_\mu q_r\big)(\bar{\chi}\gamma^\mu \chi\big), \qquad \mathcal{Q}_{d\chi} = \big(\bar{d}_p \gamma_\mu d_r\big)(\bar{\chi}\gamma^\mu \chi\big), \tag{4.3}$$

$$\mathcal{Q}_{dHX} = \big(\bar{q}_p \sigma_{\mu\nu} d_r\big) H X^{\mu\nu} + \text{h.c.}, \tag{4.4}$$

$$\mathcal{Q}_{dX} = \big(\bar{d}_p \gamma_\mu d_r\big) X^\mu, \qquad \mathcal{Q}_{HdX} = \big(H^\dagger H\big)\big(\bar{d}_p \gamma^\mu d_r\big) X_\mu,$$
$$\mathcal{Q}_{qX} = \big(\bar{q}_p \gamma_\mu q_r\big) X^\mu, \qquad \mathcal{Q}^{(1)}_{HqX} = \big(H^\dagger H\big)\big(\bar{q}_p \gamma^\mu q_r\big) X_\mu,$$
$$\mathcal{Q}_{dX^2} = \big(\bar{q}_p d_r H\big) X_\mu X^\mu + \text{h.c.}, \qquad \mathcal{Q}^{(3)}_{HqX} = \big(H^\dagger \tau^I H\big)\big(\bar{q}_p \tau^I \gamma^\mu q_r\big) X_\mu,$$
$$\mathcal{Q}_{qXX} = \big(\bar{q}_p \gamma_\mu q_r\big) X^{\mu\nu} X_\nu\,, \qquad \mathcal{Q}_{dXX} = \big(\bar{d}_p \gamma_\mu d_r\big) X^{\mu\nu} X_\nu,$$
$$\mathcal{Q}_{q\tilde{X}X} = \big(\bar{q}_p \gamma_\mu q_r\big) \tilde{X}^{\mu\nu} X_\nu\,, \qquad \mathcal{Q}_{d\tilde{X}X} = \big(\bar{d}_p \gamma_\mu d_r\big) \tilde{X}^{\mu\nu} X_\nu\,,$$
$$\mathcal{Q}_{DqX^2} = i\big(\bar{q}_p \gamma^\mu D^\nu q_r\big) X_\mu X_\nu + \text{h.c.}, \qquad \mathcal{Q}_{DdX^2} = i\big(\bar{d}_p \gamma^\mu D^\nu d_r\big) X_\mu X_\nu + \text{h.c.},$$
$$\mathcal{Q}_{dHX^2} = (\bar{q}_p \sigma_{\mu\nu} d_r H) X_1^\mu X_2^\nu + \text{h.c.}, \tag{4.5}$$

$$\mathcal{C}_i = \tilde{\mathcal{C}}_i \cdot \begin{cases} (m_X/\Lambda)^2 & \text{for } \mathcal{Q}_i = \mathcal{Q}_{dX^2}, \mathcal{Q}_{DdX^2}, \mathcal{Q}_{DqX^2}, \mathcal{Q}_{dHX^2}, \\ (m_X/\Lambda) & \text{for } \mathcal{Q}_i = \text{others.} \end{cases}$$

$$\mathcal{Q}_{qa} = \big(\bar{q}_p \gamma_\mu q_r\big)\partial^\mu a, \qquad \mathcal{Q}_{da} = \big(\bar{d}_p \gamma_\mu d_r\big)\partial^\mu a, \tag{4.7}$$

Backup

One can also apply the MFV hypothesis to the lepton sector. However, since the mechanism of neutrino mass generation is still unknown, there are different approaches to formulate the leptonic MFV [73–79]. Here, we consider the realization of leptonic MFV within the so-called minimal field content [73, 74], in which the neutrino masses are generated by the Weinberg operator. In this case, the Yukawa interactions in the lepton sector can be written as

$$-\Delta\mathcal{L} = \bar{e}\,Y_e H^\dagger l + \frac{1}{2\Lambda_{\rm LN}}\left(\bar{l}^c \tau_2 H\right) Y_\nu \left(H^T \tau_2 l\right) + \text{h.c.}, \tag{2.18}$$

where l denotes the left-handed lepton doublet with the charge conjugated field given by $l^c = -i\gamma_2 l^*$, and e is the right-handed charged lepton singlet. $\Lambda_{\rm LN}$ denotes the breaking scale of the lepton number symmetry $U(1)_{\rm LN}$. Y_e and Y_ν stand for the 3×3 Yukawa coupling matrices in flavour space. In the absence of these Yukawa couplings, the lepton sector respects the flavour symmetry

$$G_{\rm LF} = SU(3)_l \otimes SU(3)_e. \tag{2.19}$$

finite polynomial of A_ℓ and B_ℓ. After neglecting all the terms involving B_ℓ, which are suppressed by the small lepton Yukawa couplings Y_e, we obtain

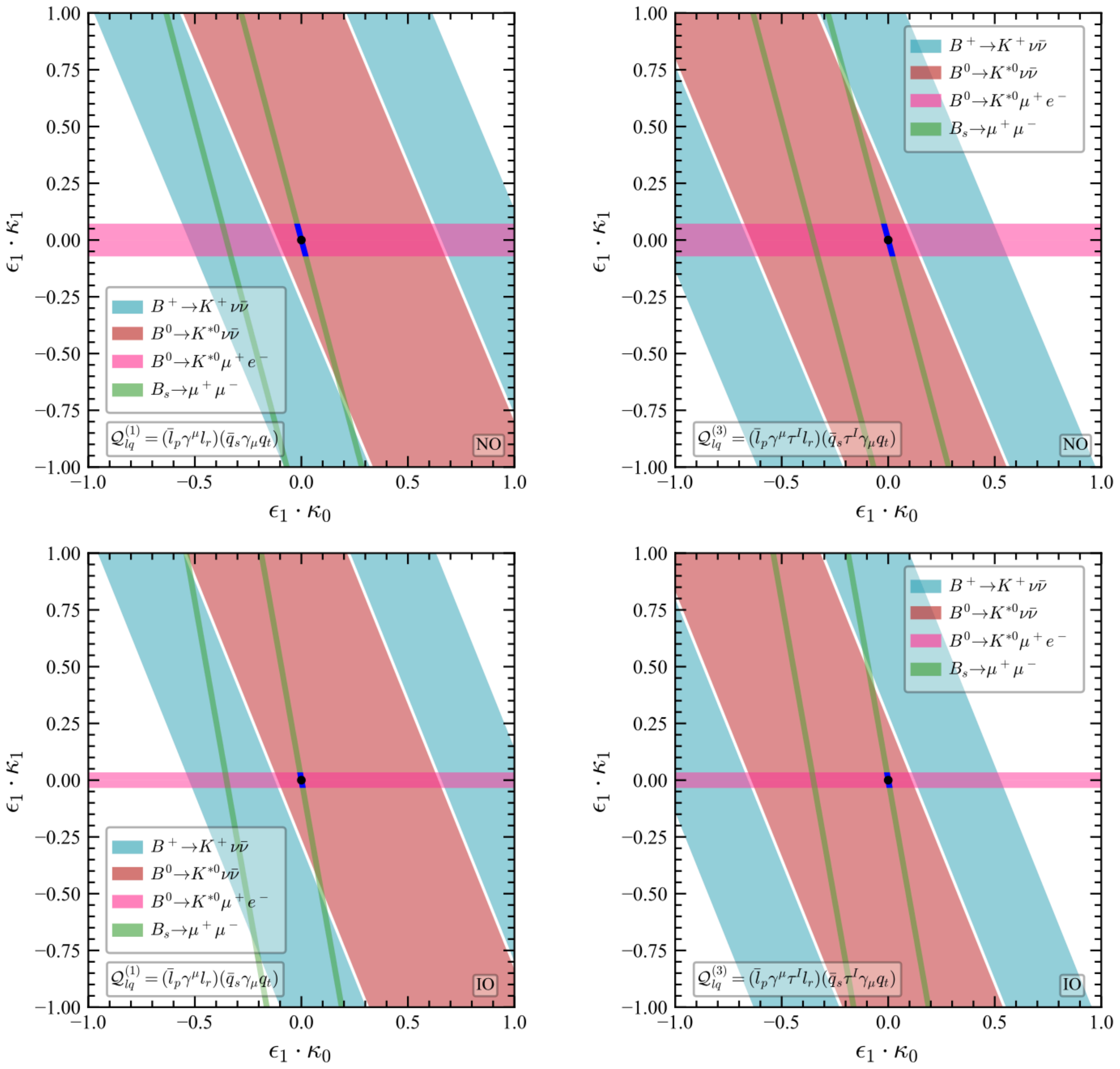
$$\mathcal{C}_{\rm MFV} \approx \kappa_0 + \kappa_1 \mathsf{A}_\ell + \kappa_2 \mathsf{A}_\ell^2, \tag{2.21}$$

where the coefficients $\kappa_{0,1,2}$ are free real parameters. In the numerical analysis, we keep only the leading lepton flavour violation term A_ℓ for simplicity, i.e., $\kappa_2 = 0$. Turning to the lepton mass eigenbasis, the current $\bar{l}\gamma^\mu \mathcal{C} l$ gives in the MFV hypothesis the following interactions:

$$\bar{e}_L \gamma^\mu (\kappa_0 \mathbb{1} + \kappa_0 \Delta_\ell) e_L + \bar{\nu}_L \gamma^\mu (\kappa_0 \mathbb{1} + \kappa_0 \hat{\lambda}_\nu^2) \nu_L, \tag{2.22}$$

where the basic LFV coupling Δ_ℓ can be obtained from A_ℓ and takes the form

$$\Delta_\ell = U \hat{\lambda}_\nu^2 U^\dagger, \tag{2.23}$$

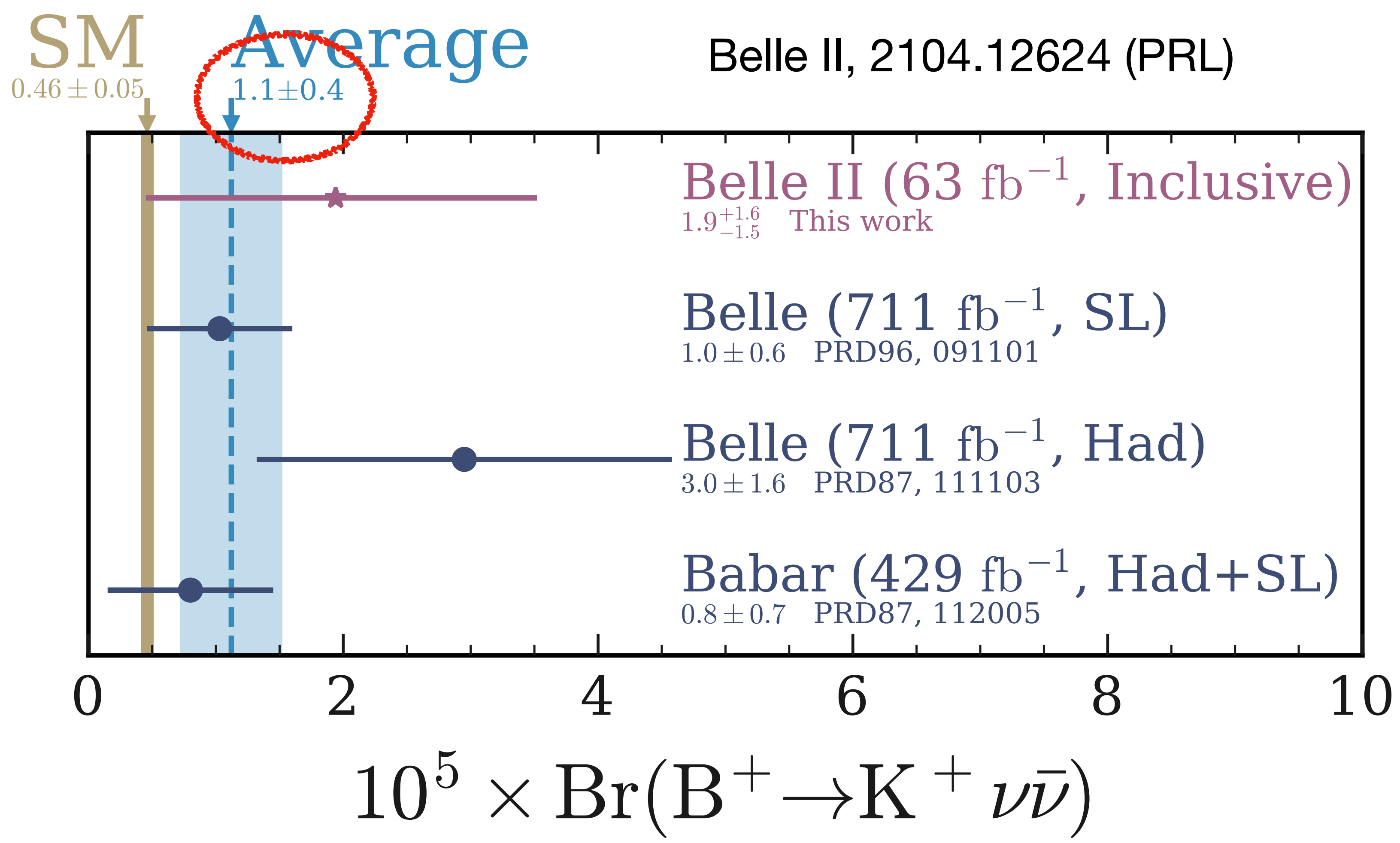


$$\Delta_\ell^{\rm NO} = \begin{pmatrix} -0.19-0.01i & -0.25-0.02i & 0.31-0.04i \\ 0.12+0.01i & 0.28-0.00i & 0.29+0.04i \\ -0.37-0.01i & 0.21-0.05i & -0.03+0.01i \end{pmatrix}, \quad \Delta_\ell^{\rm IO} = \begin{pmatrix} 0.21+0.09i & -0.34+0.05i & 0.03+0.11i \\ 0.31+0.12i & 0.19+0.00i & -0.15-0.14i \\ 0.12-0.02i & 0.04-0.19i & 0.34-0.10i \end{pmatrix}$$

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

▶ 2021 Apr

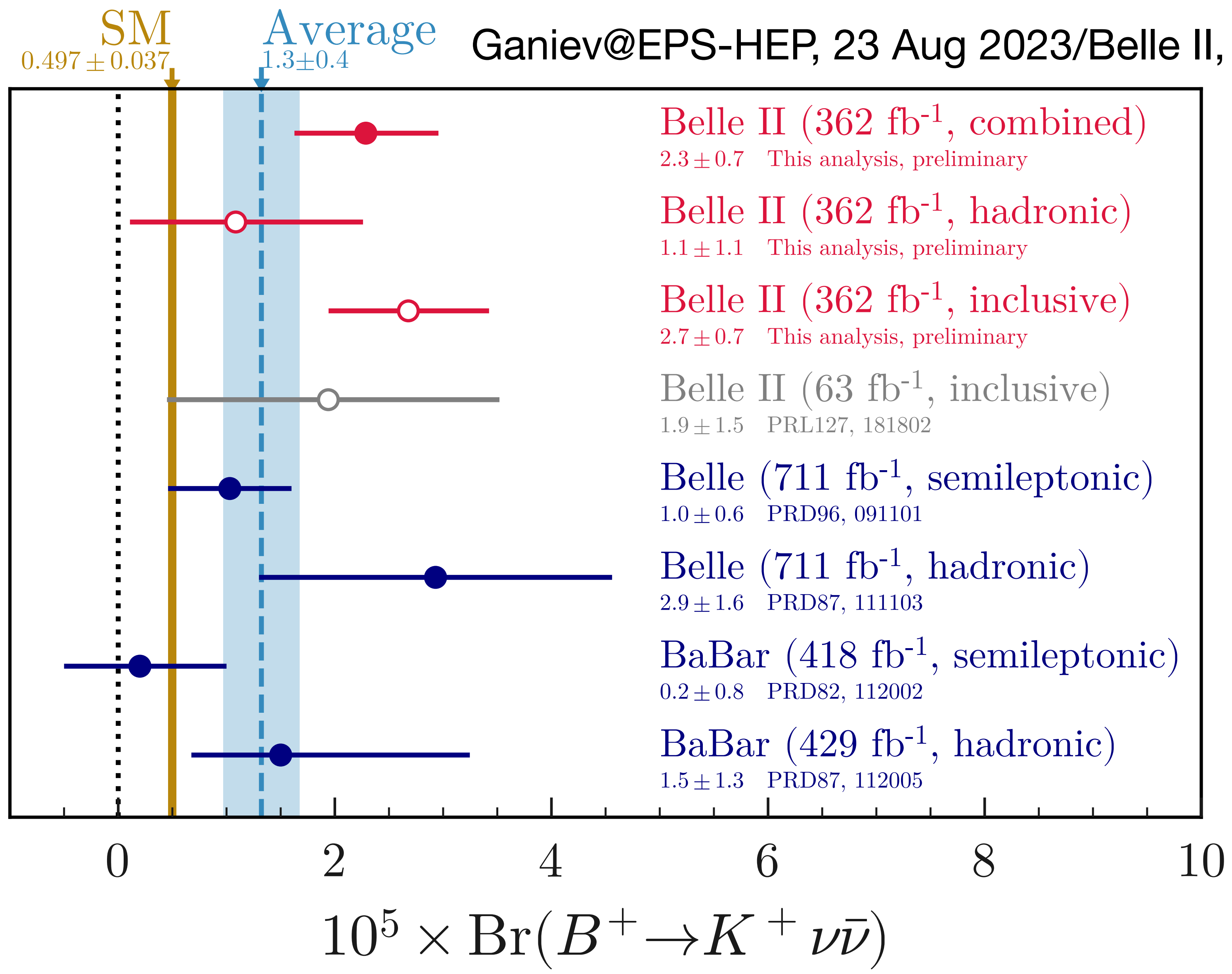
Belle II, 2104.12624 (PRL)



▶ 2023 Aug

see also 贾森's talk

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



30+ theory papers !

Impact of B→Kνν̄ 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]
pdf DOI cite claim reference search 34 citations

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)
Published in: Phys.Rev.D 109 (2024) 5, 5 • e-Print: 2305.09256 [hep-ph]
pdf DOI cite claim reference search 3 citations

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)
Published in: Phys.Rev.D 109 (2024) 7, 075006 • e-Print: 2312.00982 [hep-ph]
pdf DOI cite claim reference search 10 citations

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]
pdf DOI cite claim reference search 15 citations

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

$B \to K^*M_X$ vs $B \to KM_X$ 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]
pdf DOI cite claim reference search 10 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

Revisiting models that enhance $B^+ \to K^+\nu\bar{\nu}$ 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]
pdf DOI cite claim reference search 16 citations

A new look at $b \to s$ observables in 331 models #18
Francesco Loparco (Jan 22, 2024)
e-Print: 2401.11999 [hep-ph]
pdf cite claim reference search 1 citation

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

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]
pdf cite claim reference search 4 citations

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]
pdf DOI cite claim reference search 24 citations

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]
pdf cite claim reference search 4 citations

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]
pdf cite claim reference search 10 citations

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

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]
pdf DOI cite claim reference search 31 citations

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

SMEFT predictions for semileptonic processes #4
Siddhartha Karmakar, Amol Dighe, Rick S. Gupta (Apr 15, 2024)
e-Print: 2404.10061 [hep-ph]
pdf cite claim reference search 0 citations

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]
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The quark flavor-violating ALPs in light of B mesons and hadron colliders #20
Tong Li (Nankai U.), Zhuoni Qian (Hangzhou Normal U.), Michael A. Schmidt (Sydney U. and New South Wales U.), Man Yuan (Nankai U.) (Feb 21, 2024)
Published in: JHEP 05 (2024) 232 • e-Print: 2402.14232 [hep-ph]
pdf DOI cite claim reference search 3 citations

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]
pdf cite claim reference search 2 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

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]
pdf cite claim reference search 2 citations