



Institute of Particle Physics
粒子物理研究所

B-meson FCNC decays as a probe of light Dark Matter

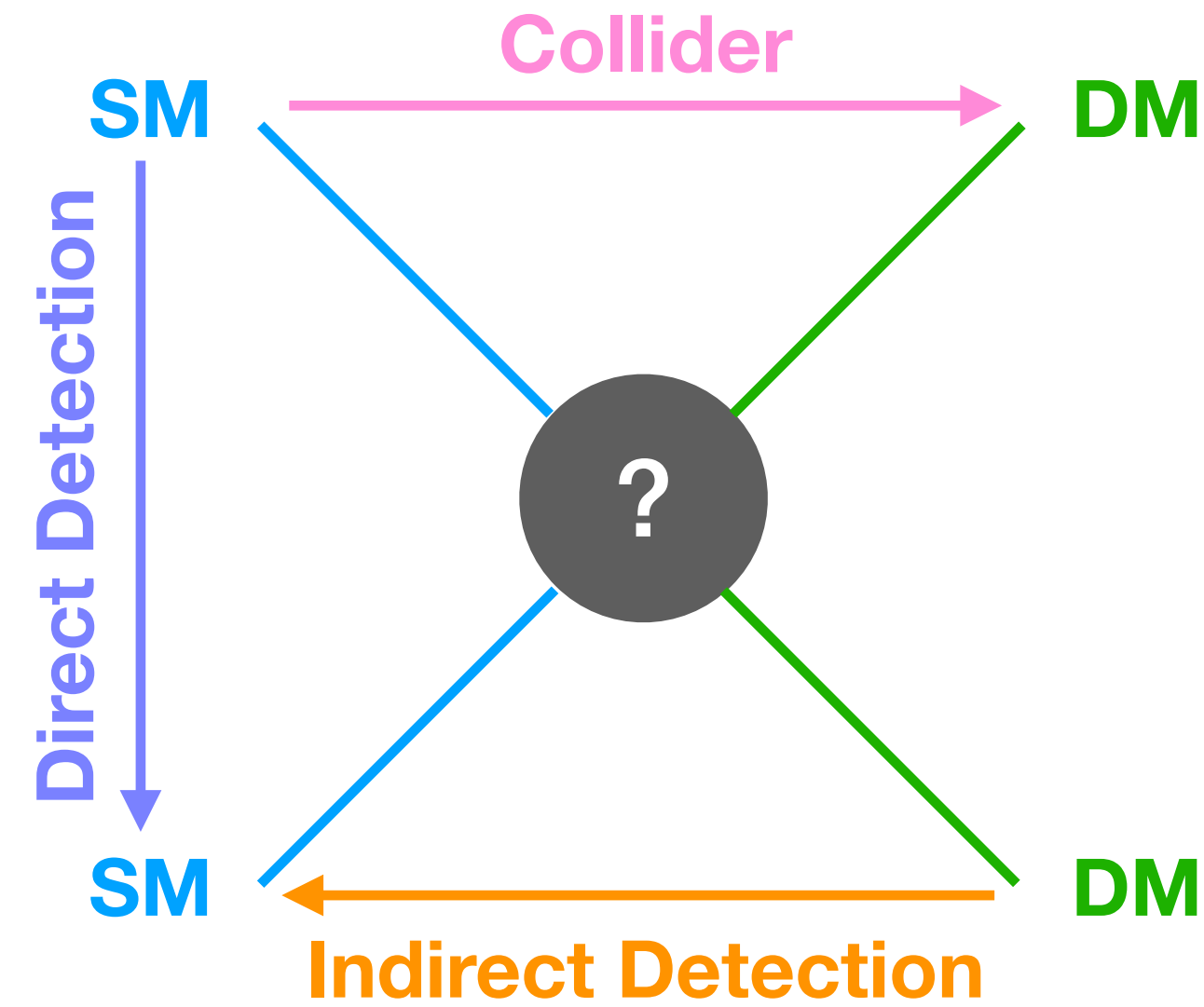
Xing-Bo Yuan (袁兴博)

Central China Normal University (华中师范大学)

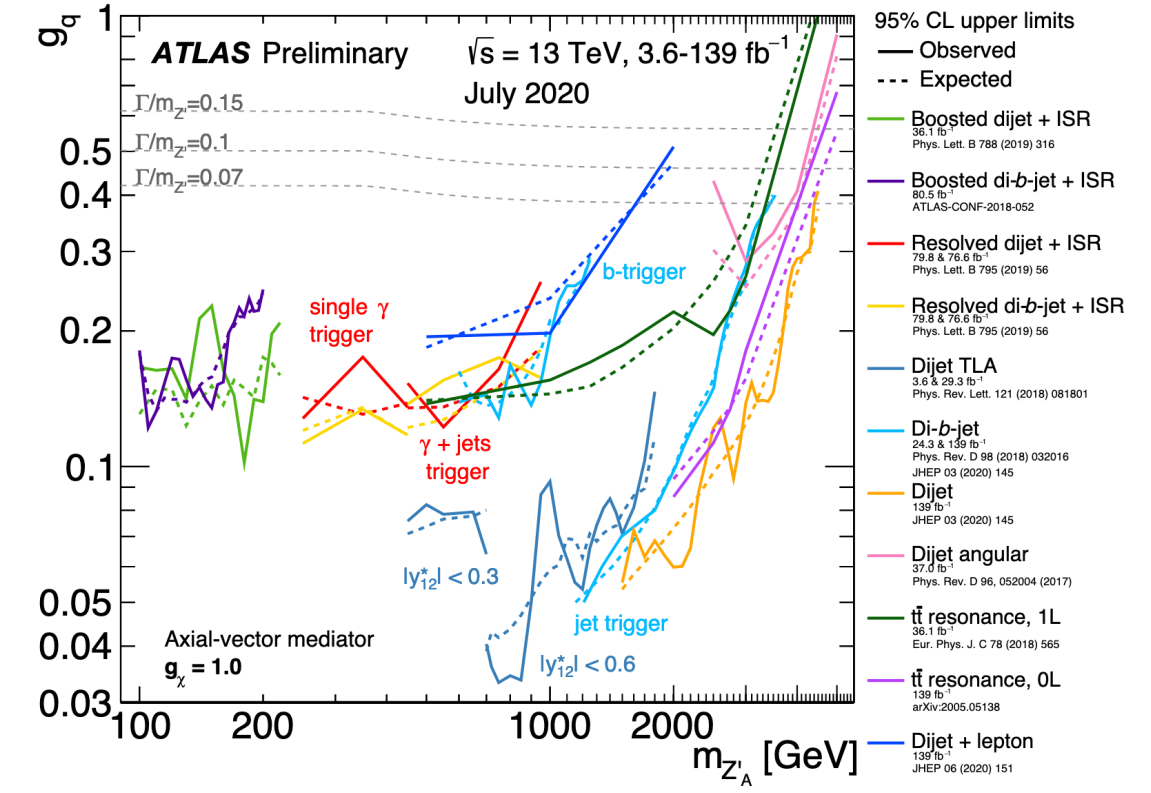
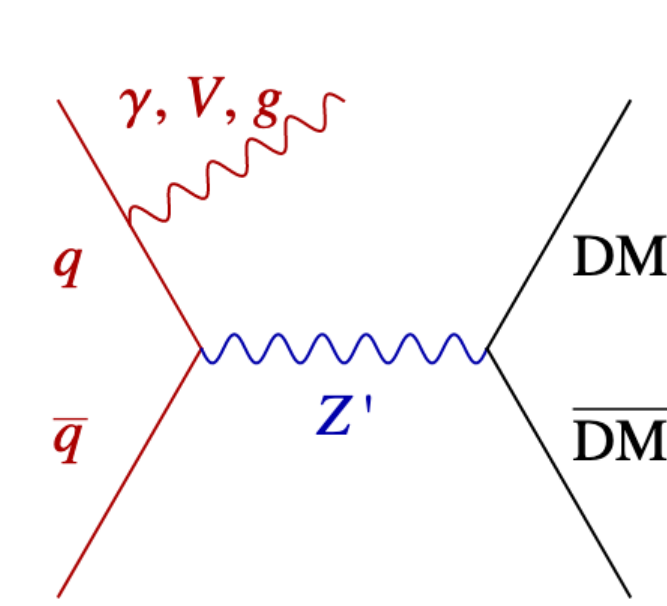
侯镖锋, 李新强, 沈 萌, 杨亚东, 袁兴博, JHEP06(2024)172

高孟超, 李新强, 杨亚东, 袁兴博, 张 欣, work in progress

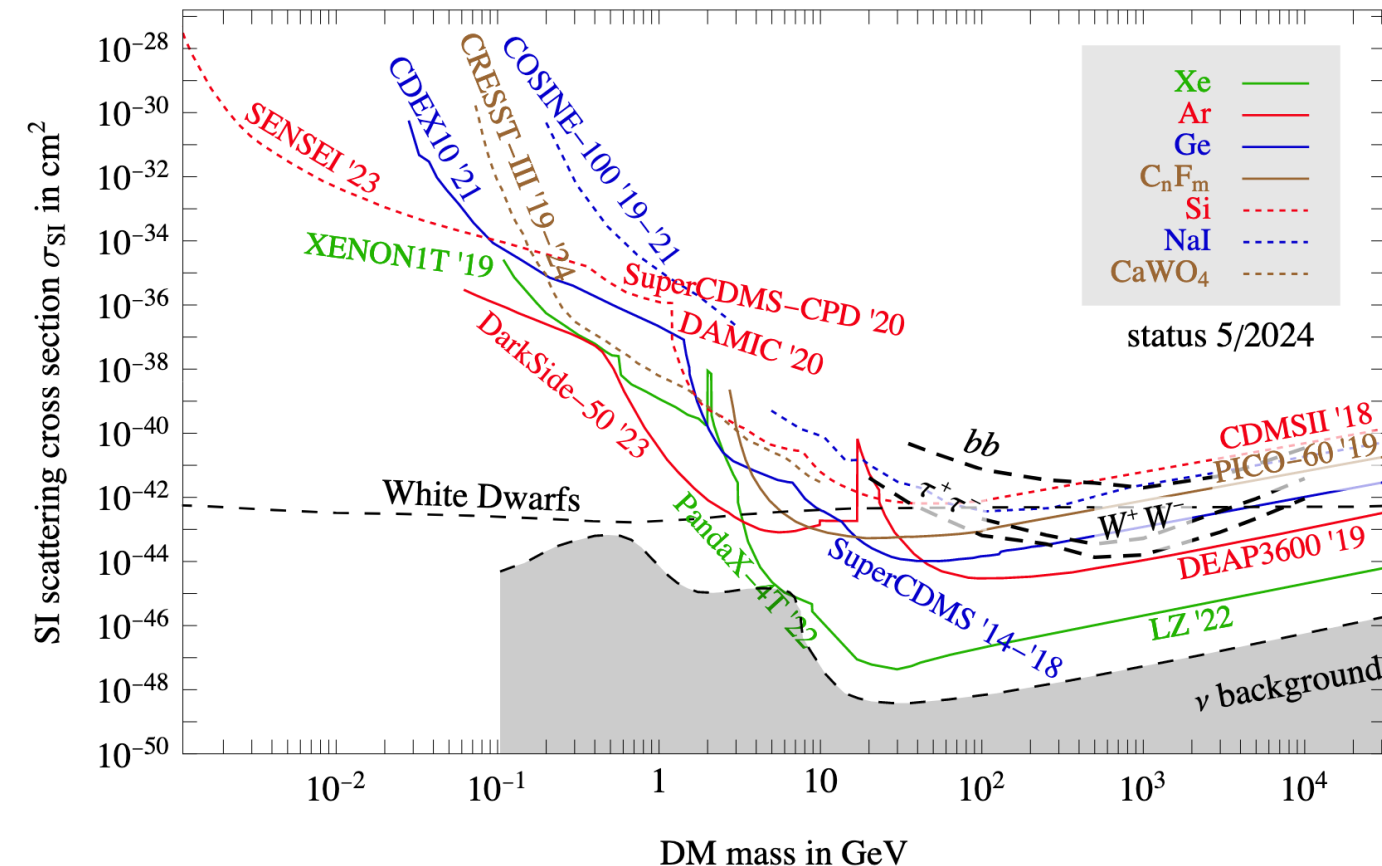
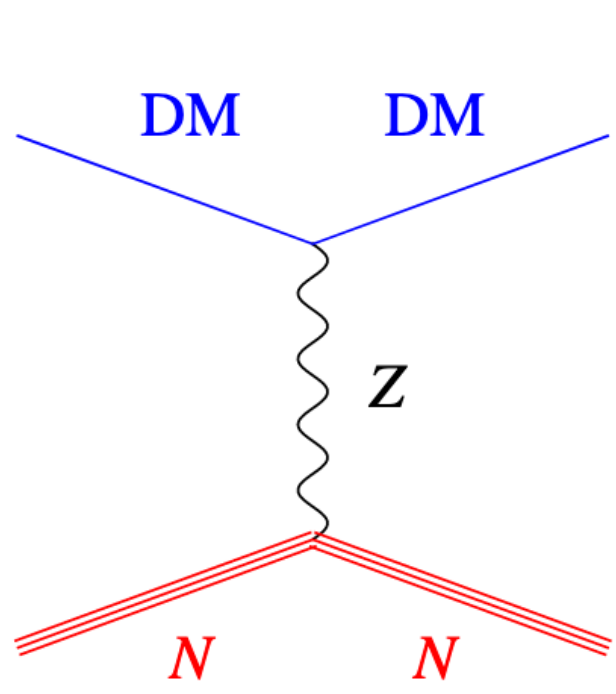
Dark Matter Detection



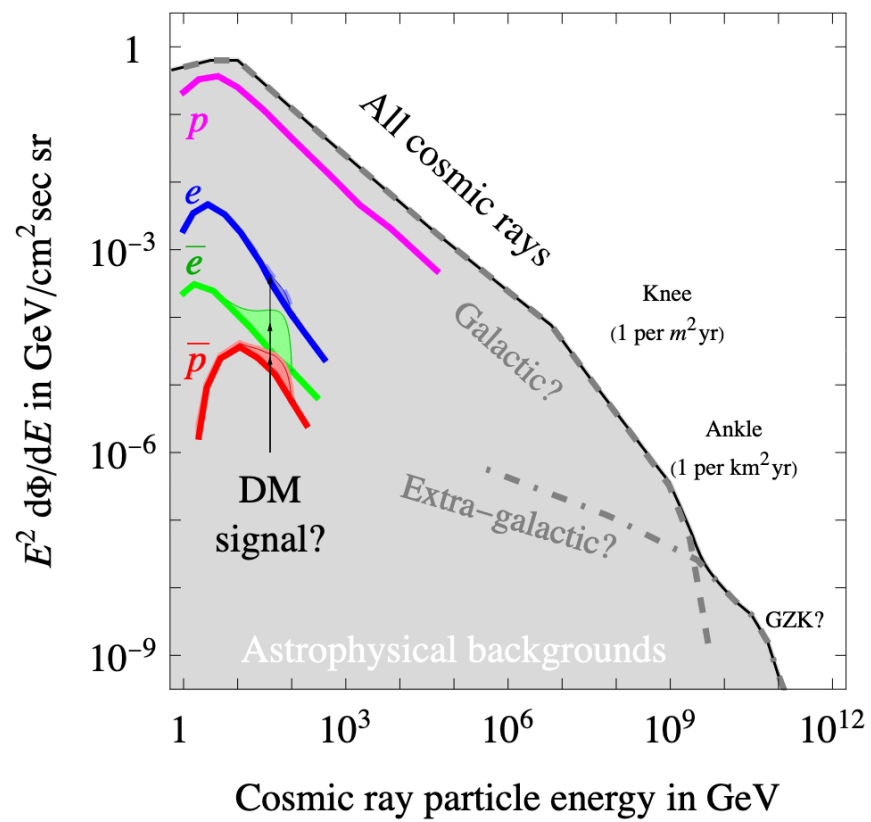
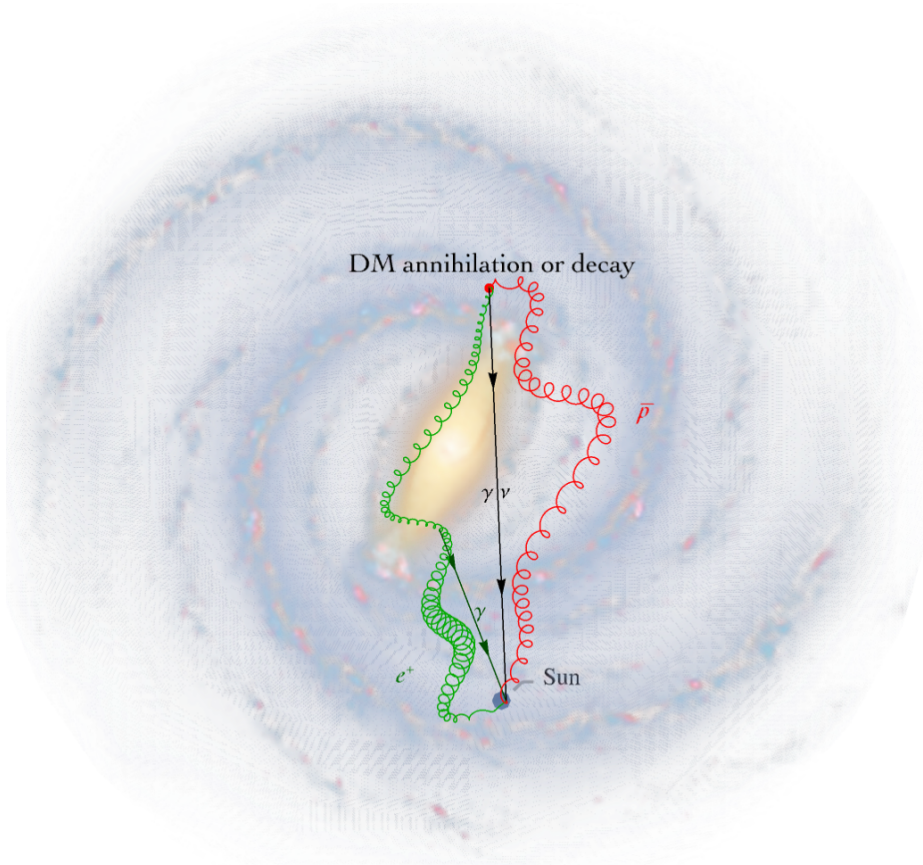
Collider



Direct Detection

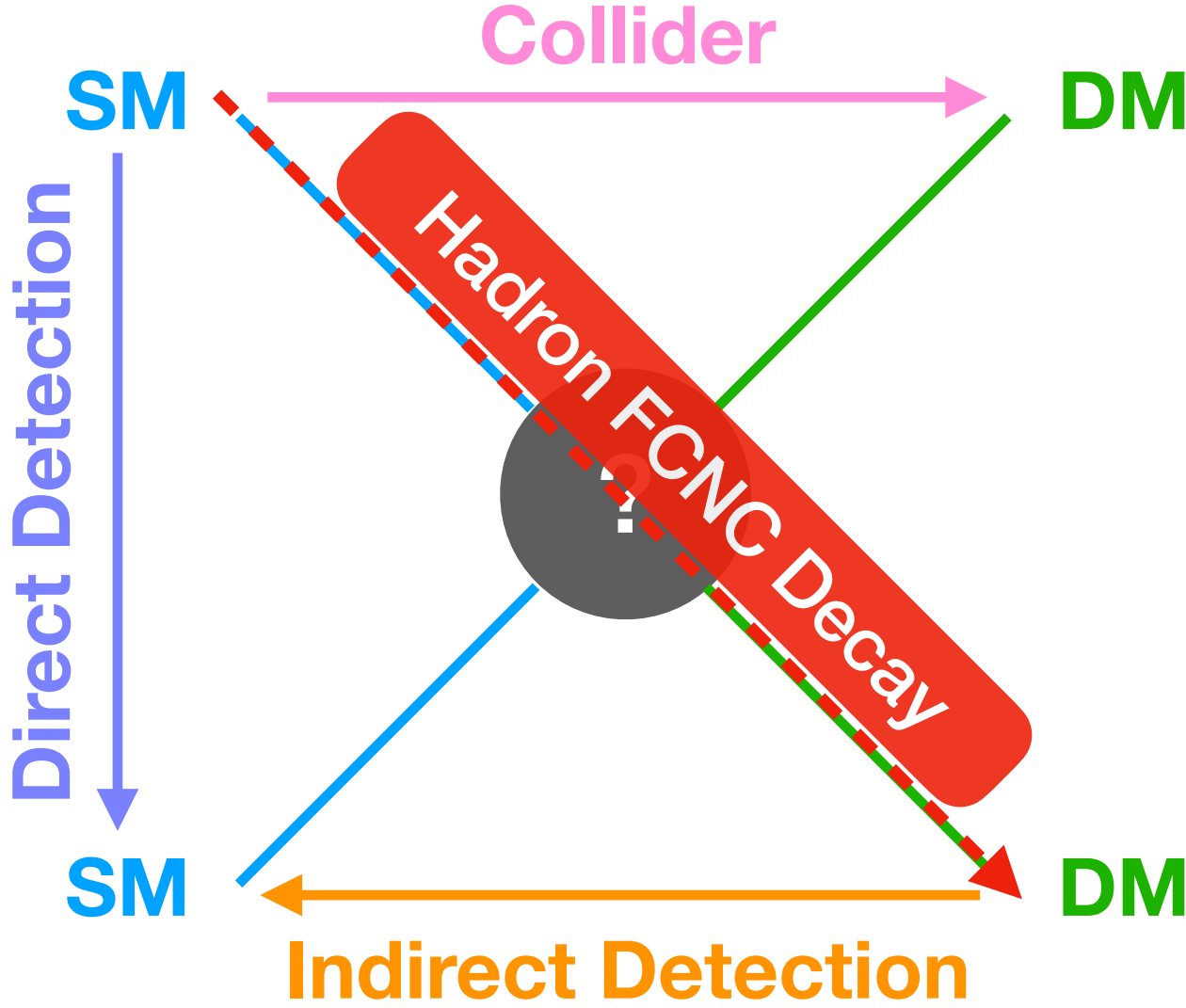
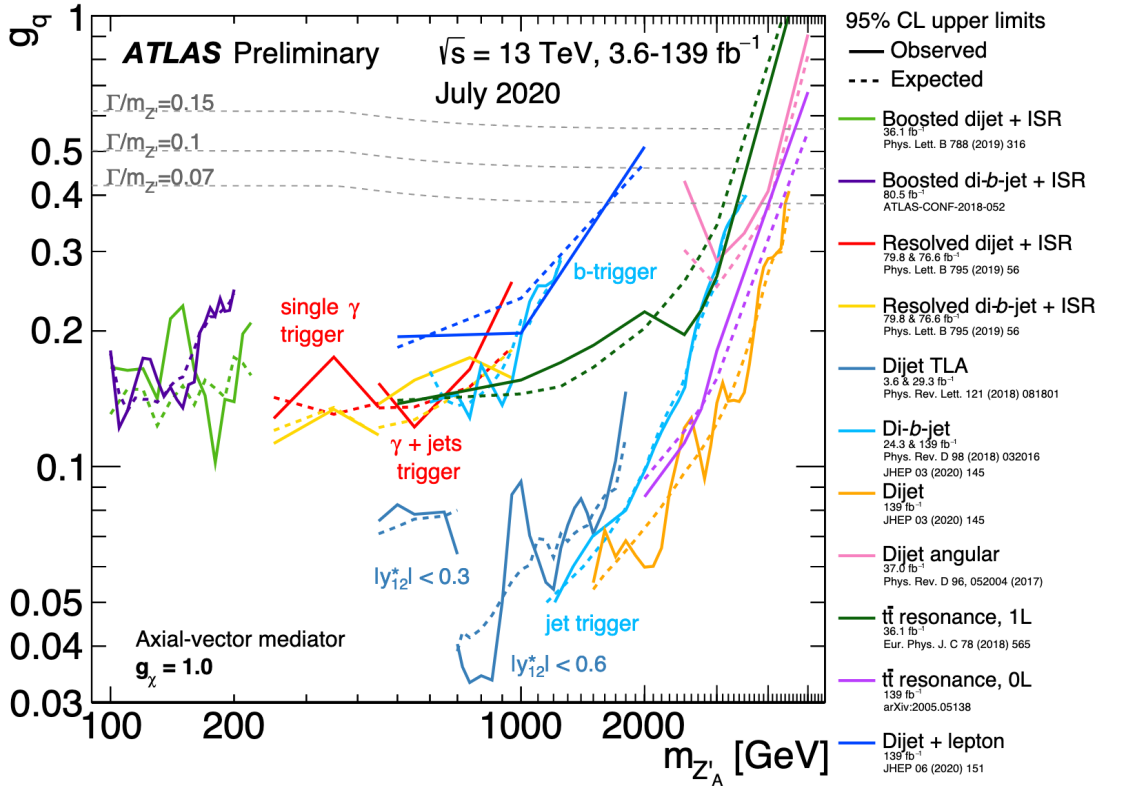
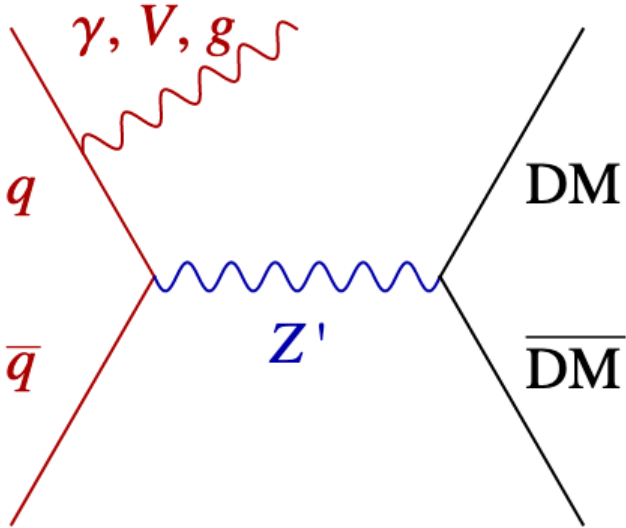


Indirect Detection

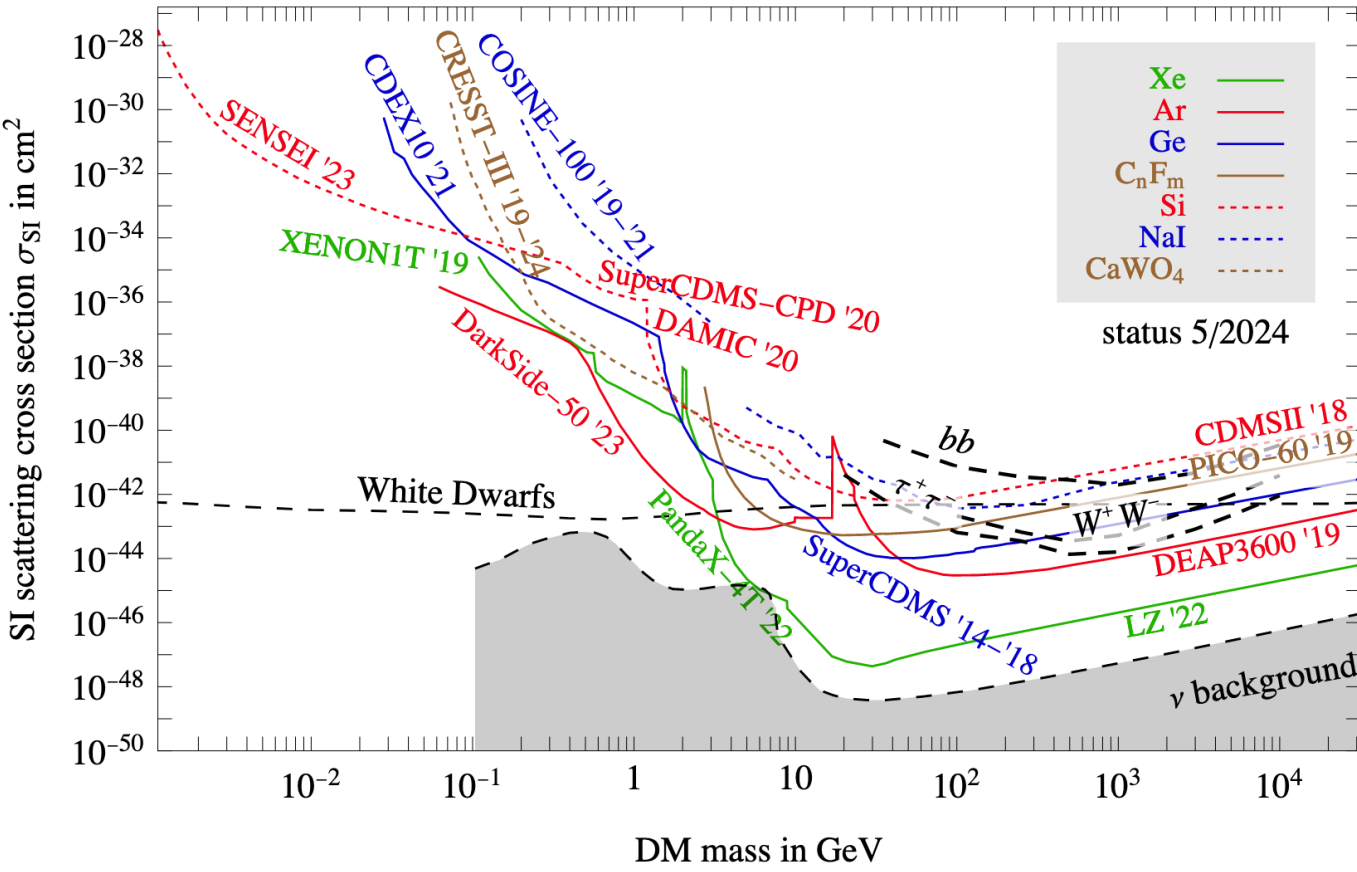
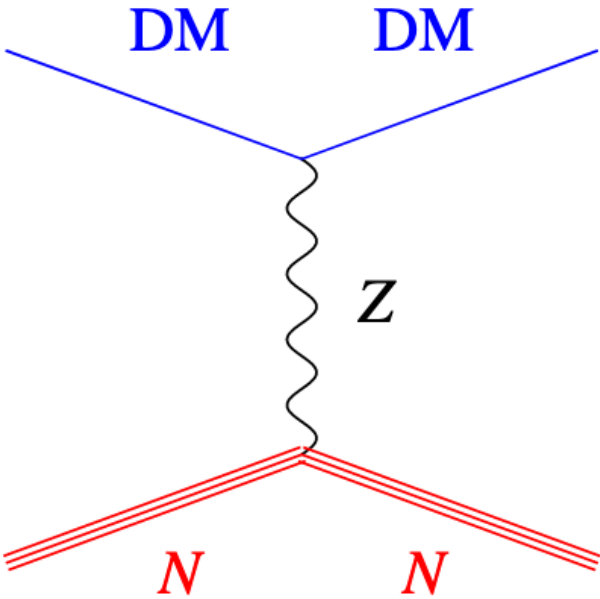


Dark Matter Detection

Collider



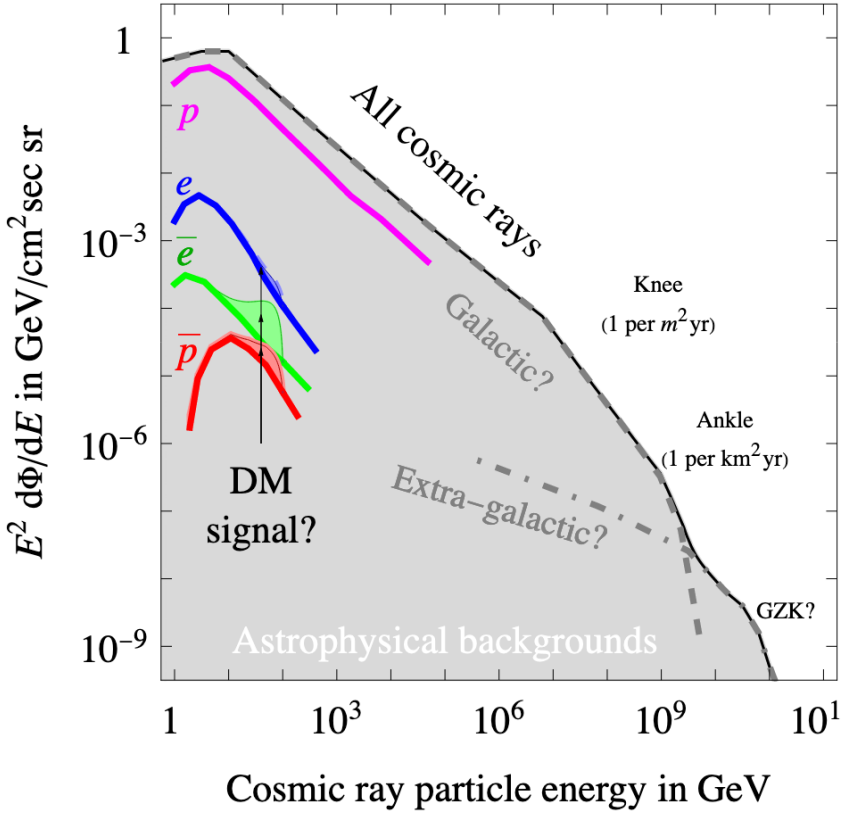
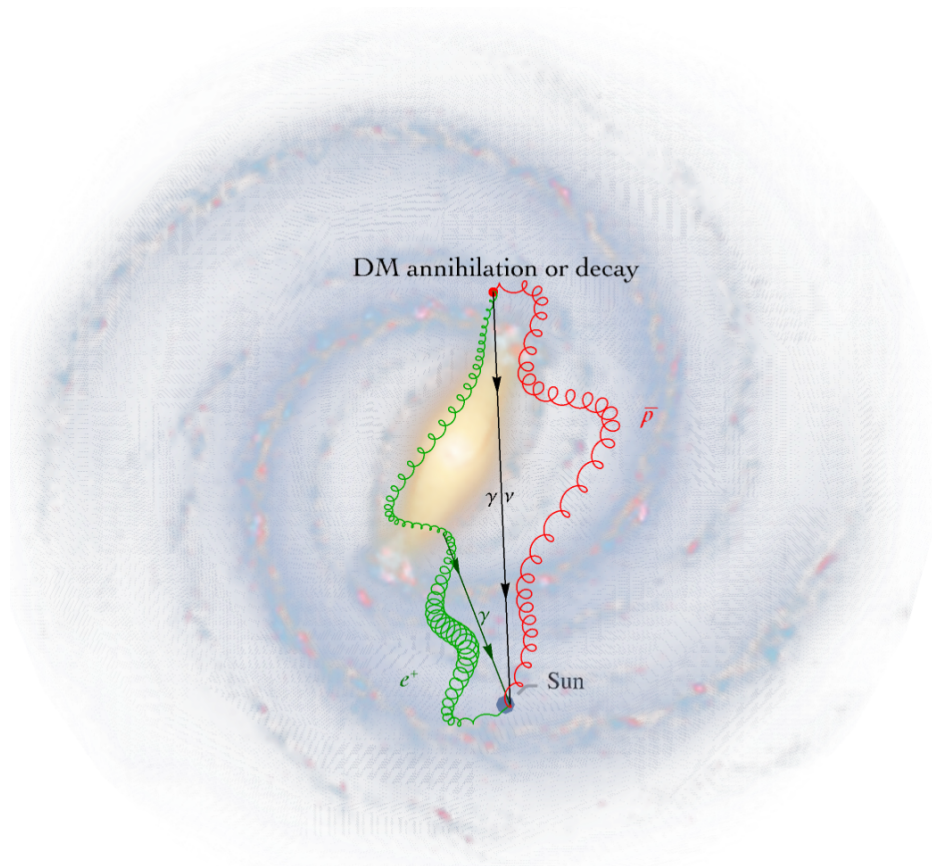
Direct
Detection



Hadron FCNC Decay

$$\begin{aligned} B^+ &\rightarrow K^+ + \text{DM} + \text{DM} \\ \Lambda_b &\rightarrow \Lambda + \text{DM} + \text{DM} \\ K^+ &\rightarrow \pi^+ + \text{DM} + \text{DM} \\ D^0 &\rightarrow \pi^0 + \text{DM} + \text{DM} \end{aligned}$$

Indirect
Detection



Theoretically cleanest processes in heavy flavour physics

$B_{s,d} - \bar{B}_{s,d}$ mixing

$b \rightarrow u(c)\ell\bar{\nu}$: $B \rightarrow D\ell\bar{\nu}$, $B \rightarrow D^*\ell\bar{\nu}$,

$b \rightarrow s(d)\gamma$: $B \rightarrow X_s\gamma$, $B \rightarrow K^*\gamma$,

$b \rightarrow s(d)\ell^+\ell^-$: $B_s \rightarrow \ell^+\ell^-$, $B \rightarrow K^*\ell^+\ell^-$,

$b \rightarrow s(d)\nu\bar{\nu}$: $B \rightarrow K\nu\bar{\nu}$, $K \rightarrow \pi\nu\bar{\nu}$, ...

NP Effects $< \mathcal{O}(20\%)$

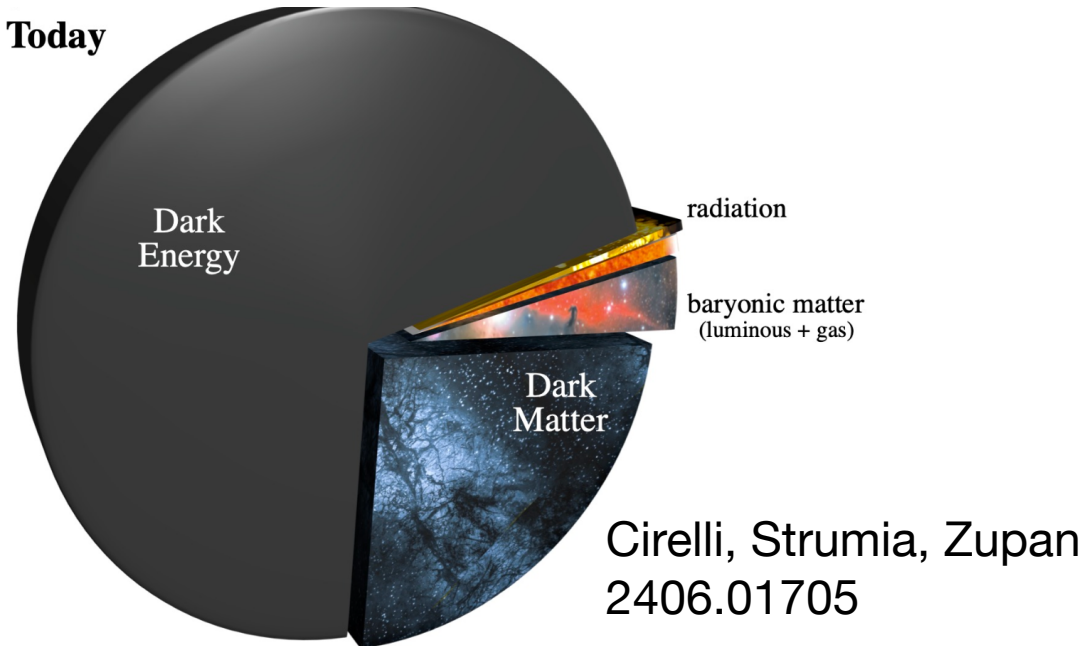
power corrections, e.g., QED corrections, ...

NOT measured yet !

$B \rightarrow K + \nu + \bar{\nu}$
 $B \rightarrow K + \text{DM} + \text{DM}$

Light DM: a bottom-up view

DM is electrically neutral ! $\implies$ DM only have FC or FCNC couplings to fermions !

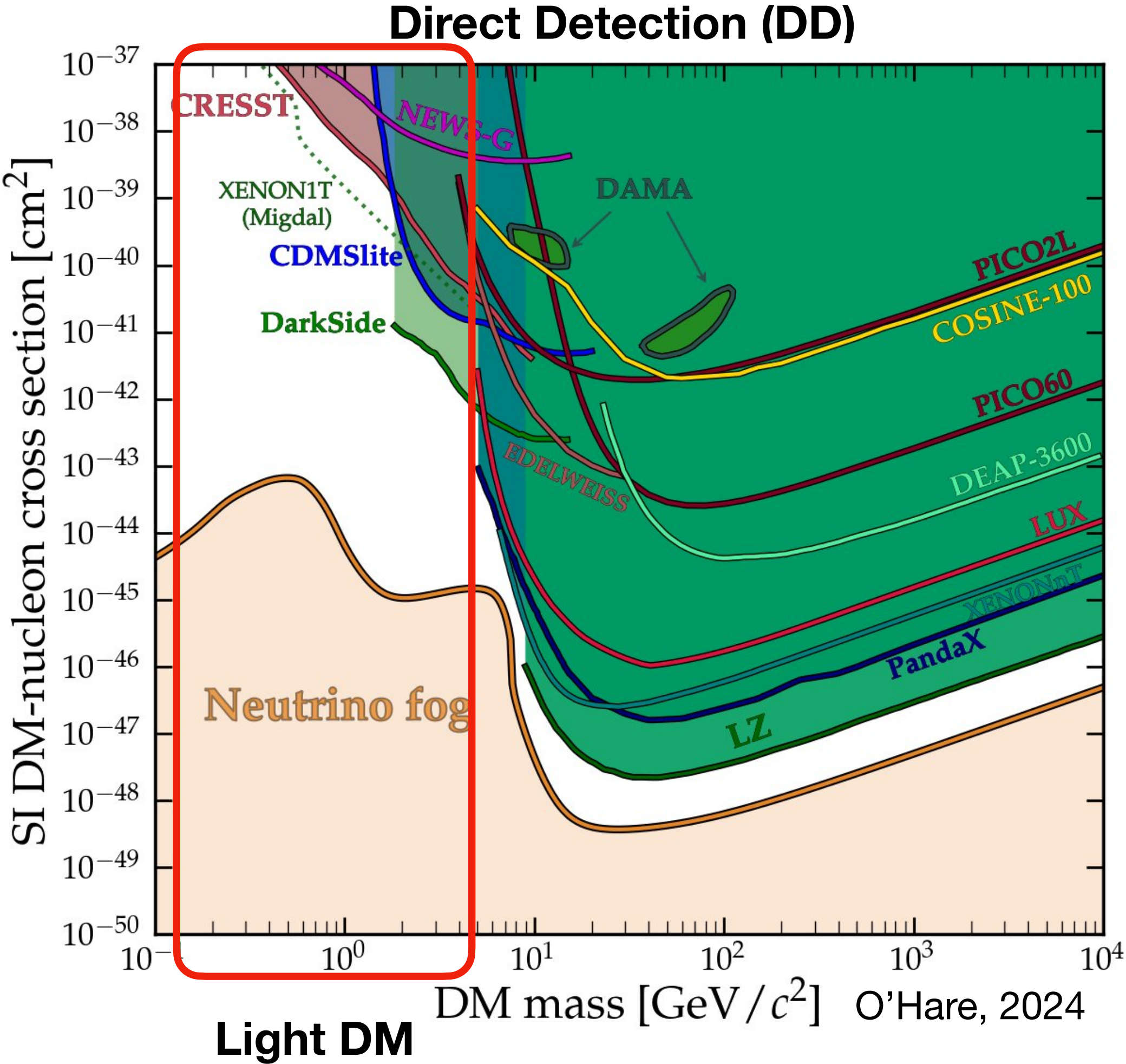


	<i>d</i>	<i>s</i>	<i>b</i>
<i>d</i>	DD	NA62/KOTO	Belle II
<i>s</i>		DD	Belle II
<i>b</i>			Belle II/LHC
	<i>u</i>	<i>c</i>	<i>t</i>
<i>u</i>	DD	BES/STCF	LHC/CEPC
<i>c</i>		BES/STCF	LHC/CEPC
<i>t</i>			LHC/CEPC

example:
 $B^+ \rightarrow K^+ + \text{DM} + \text{DM}$
 $K^+ \rightarrow \pi^+ + \text{DM} + \text{DM}$
 $D^0 \rightarrow \pi^0 + \text{DM} + \text{DM}$

DD = Direct Detection

 means related to the DM relic density



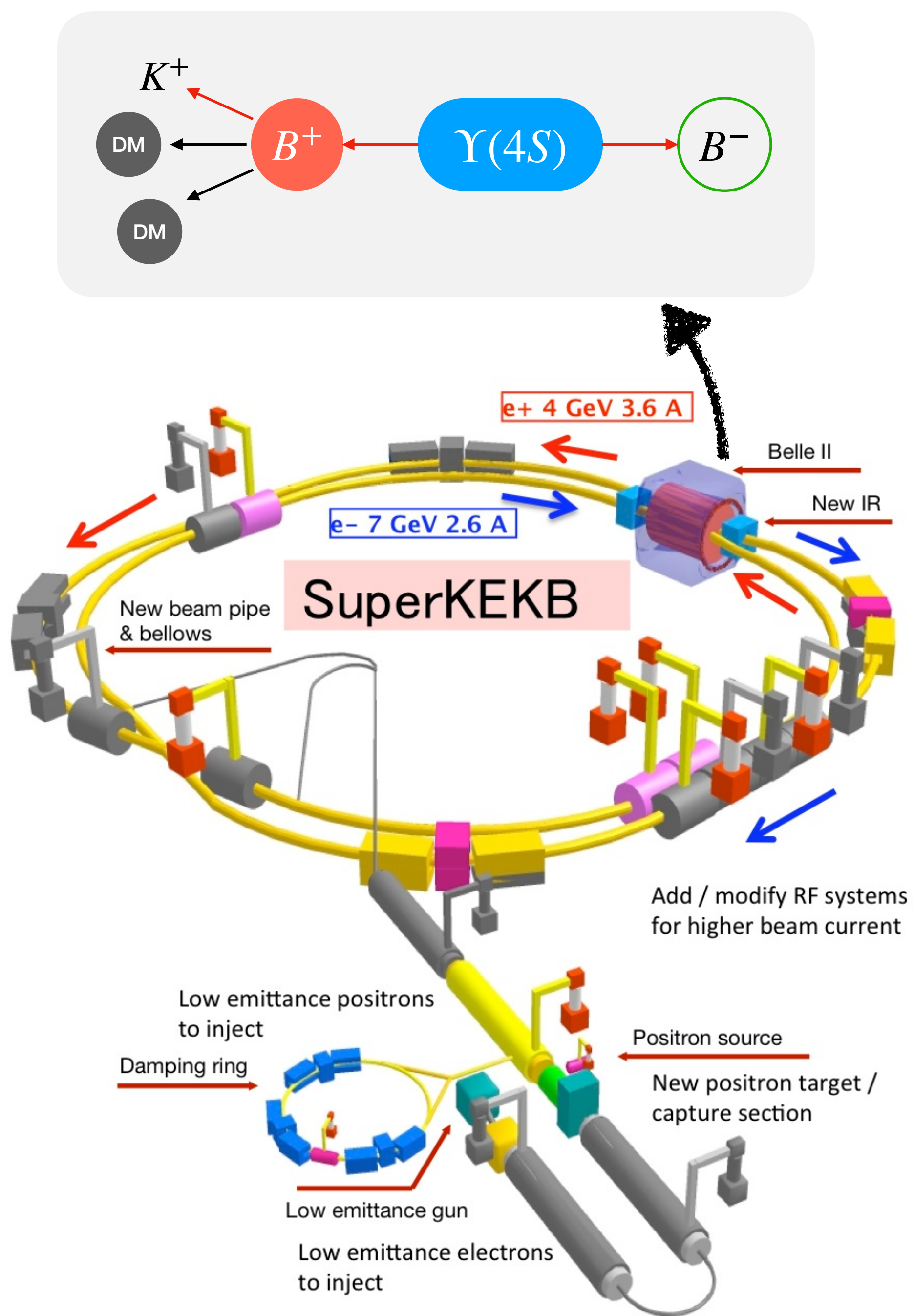
Experimental Search

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

Belle II
CEPC

NA62
KOTO

BESIII
STCF



Experimental Search

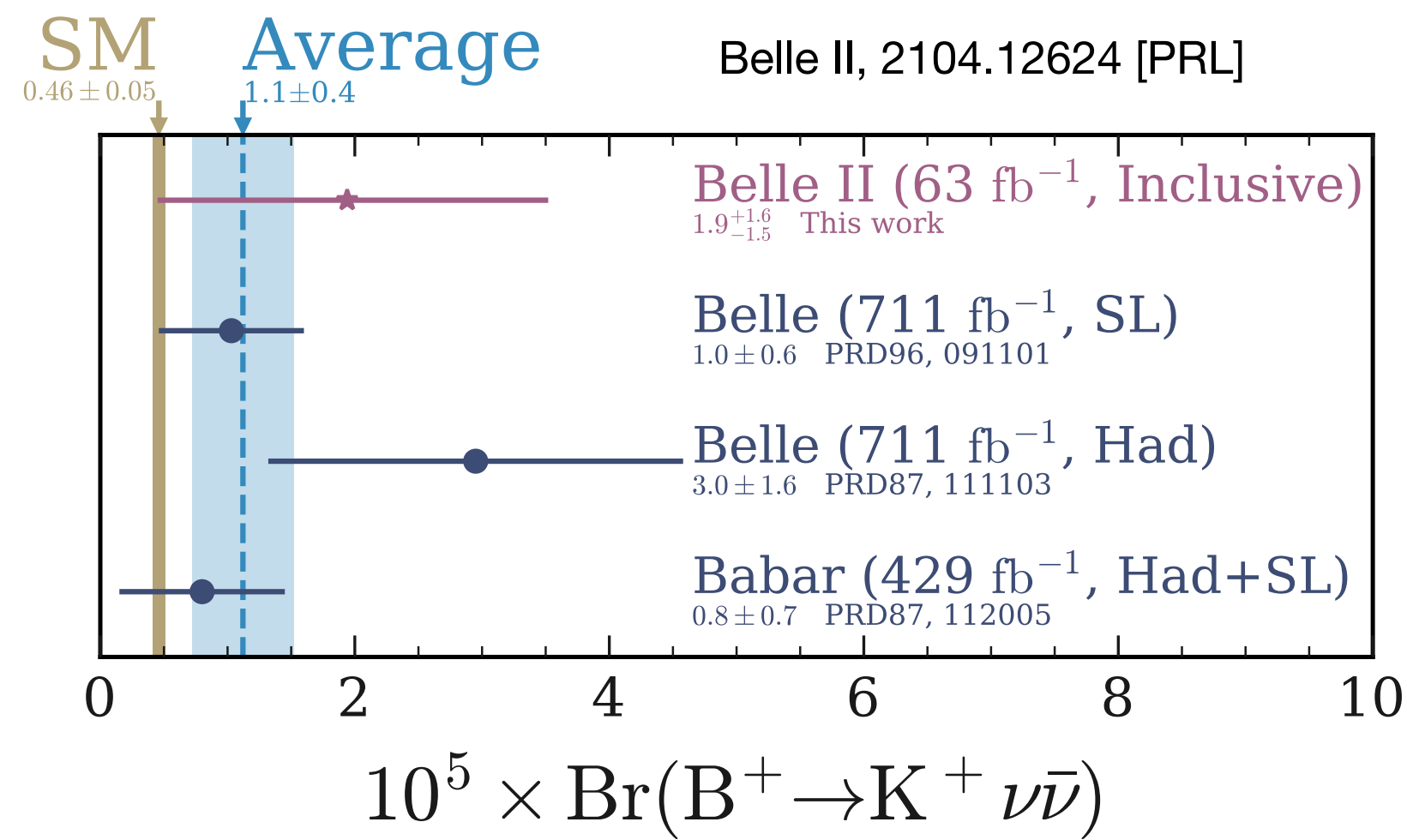
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$c \rightarrow u$ $D^+ \rightarrow \pi^+ + \text{inv}, D^0 \rightarrow \rho^0 + \text{inv}, \dots$				

**Belle II
CEPC**

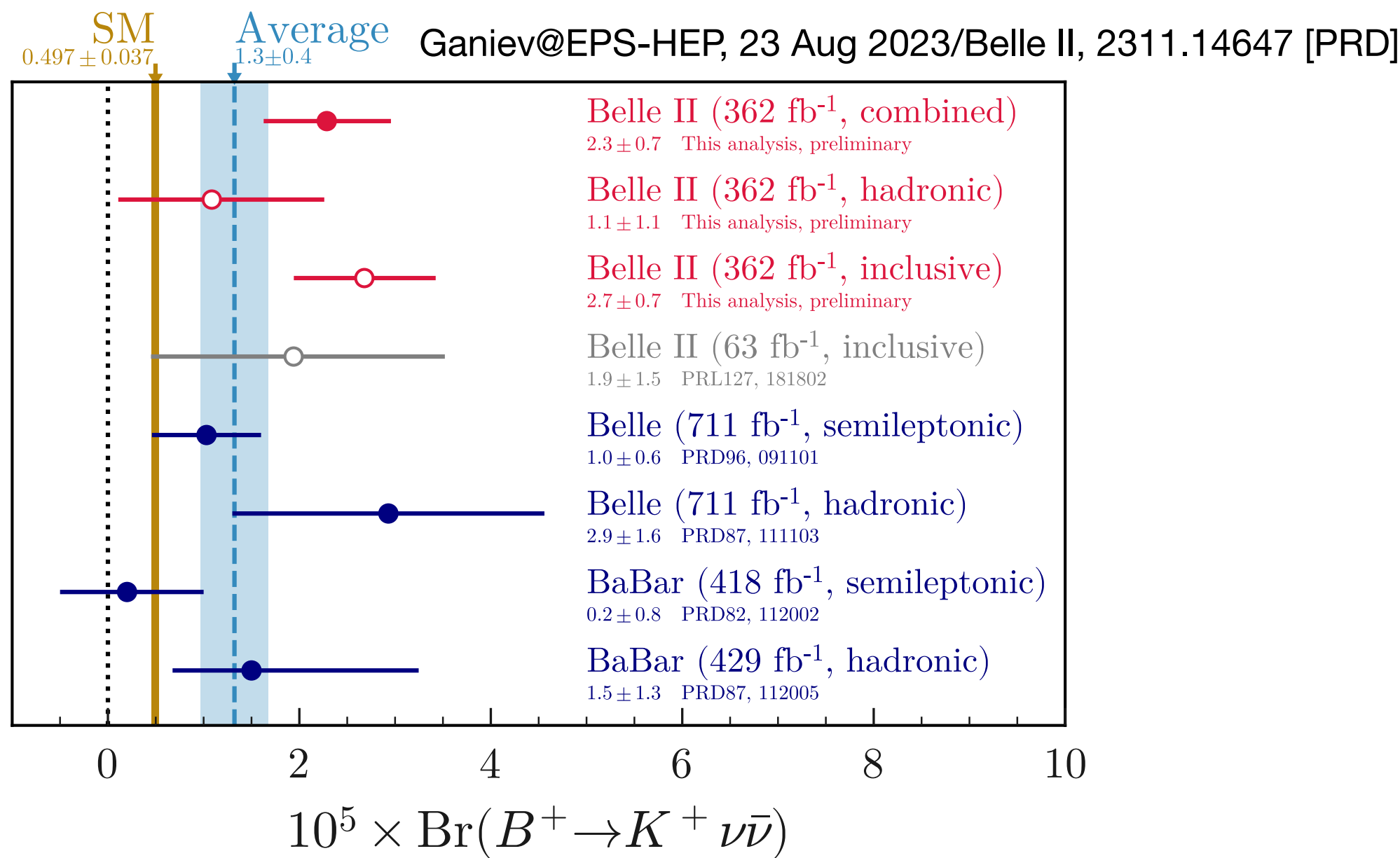
**NA62
KOTO**

**BESIII
STCF**

► 2021 Apr



► 2023 Aug: first evidence



Light DM: a bottom-up view

DM is electrically neutral ! $\implies$ DM only have FC or FCNC couplings to fermions !



	<i>d</i>	<i>s</i>	<i>b</i>
<i>d</i>	DD	NA62/KOTO	Belle II
<i>s</i>		DD	Belle II
<i>b</i>			Belle II/LHC
	<i>u</i>	<i>c</i>	<i>t</i>
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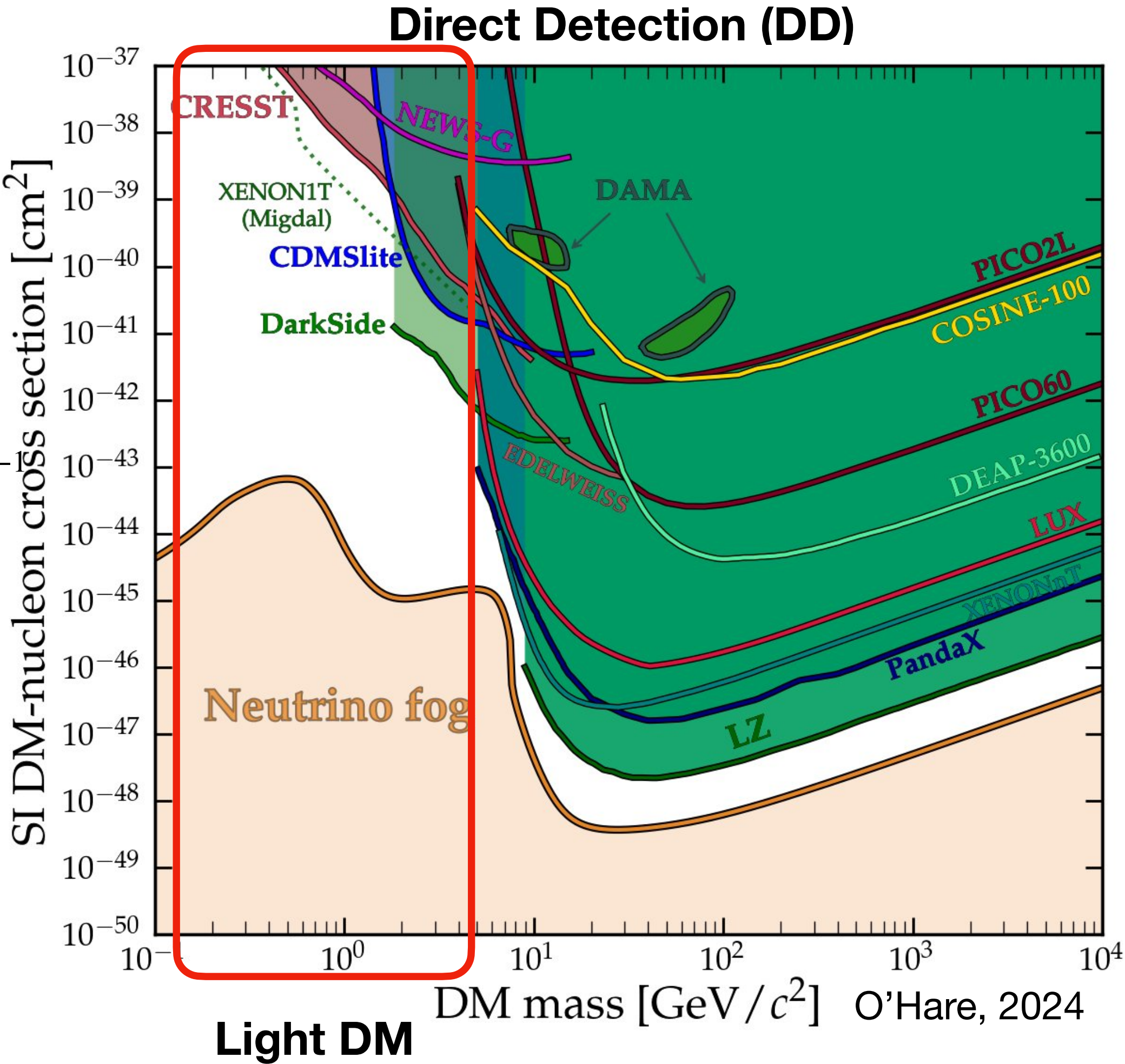
example:
 $B^+ \rightarrow K^+ + \text{DM} + \text{DM}$
 $K^+ \rightarrow \pi^+ + \text{DM} + \text{DM}$
 $D^0 \rightarrow \pi^0 + \text{DM} + \text{DM}$

future exp uncertainties:
 $\mathcal{O}(20 \sim 40\%)$ @Belle II with 5ab⁻¹
 $\mathcal{O}(2\%)$ @CEPC Tera-Z

future theo uncertainties:
less than 10 %

DD = Direct Detection

 means related to the DM relic density

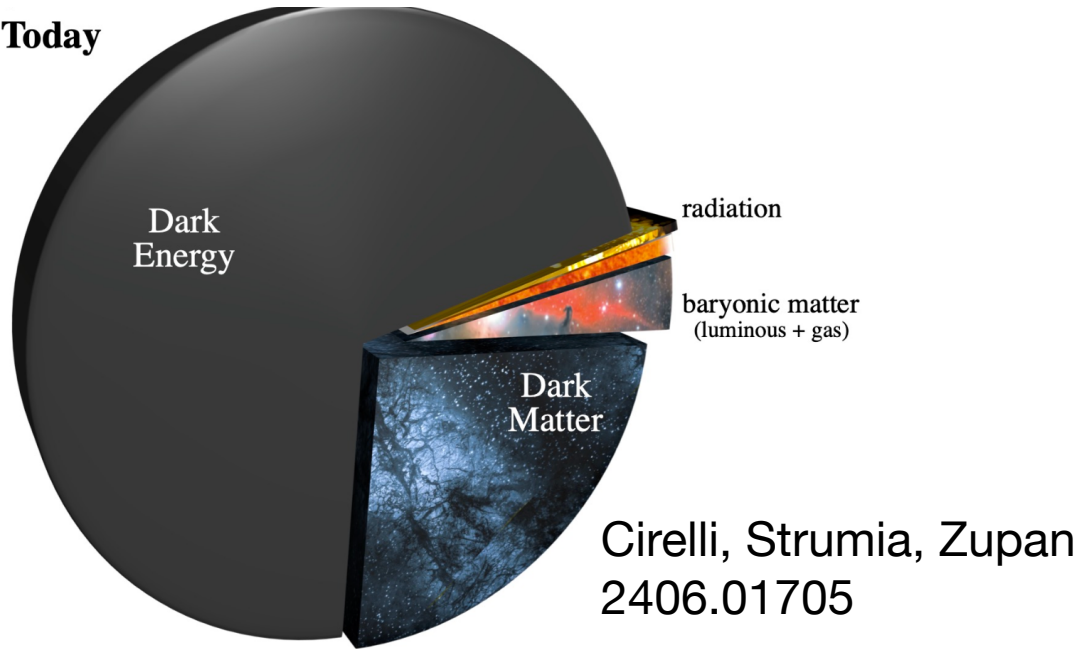


Light DM: a bottom-up view

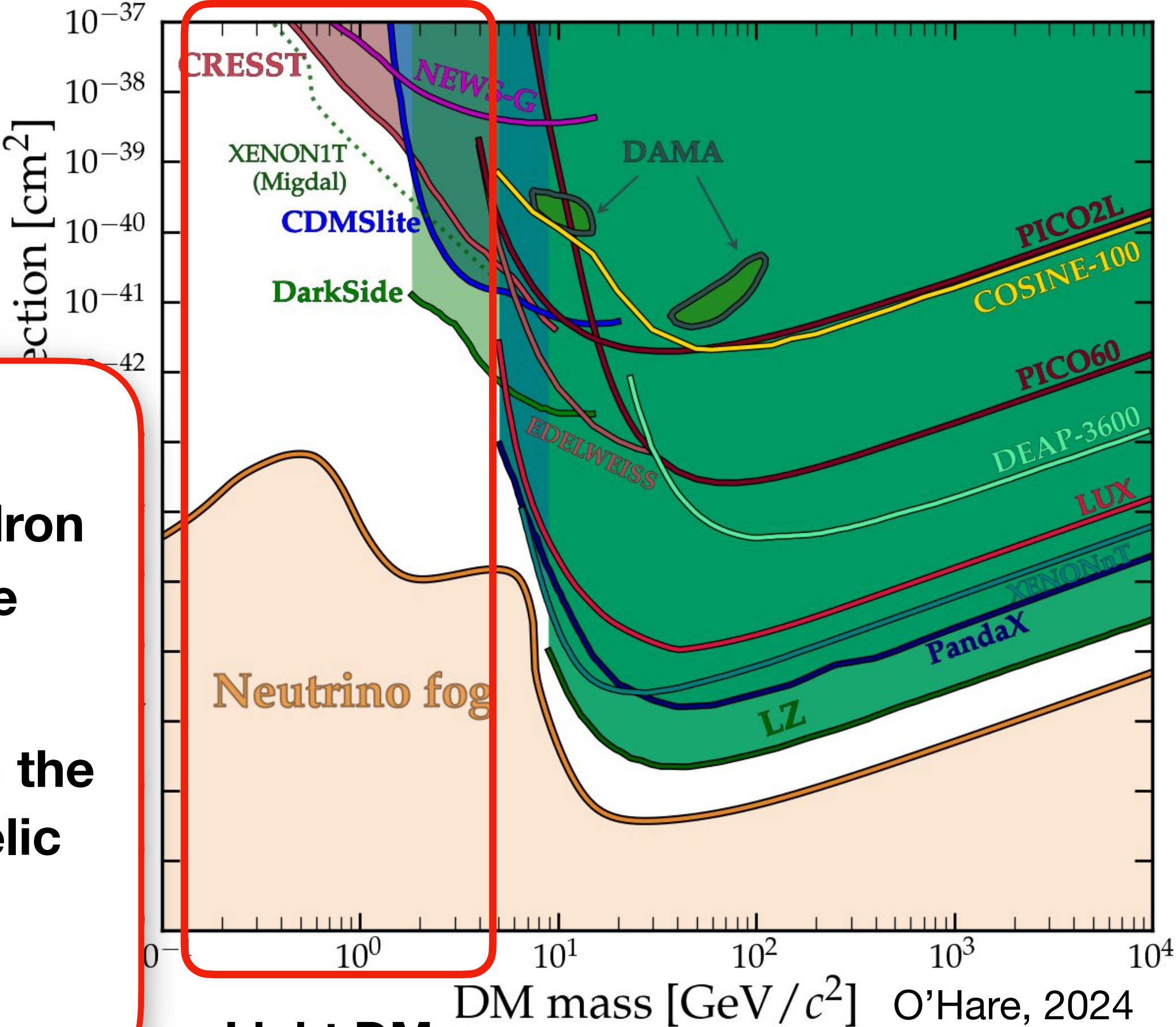
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	<i>d</i>	<i>s</i>	<i>b</i>
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Direct Detection (DD)



It's natural to ask:

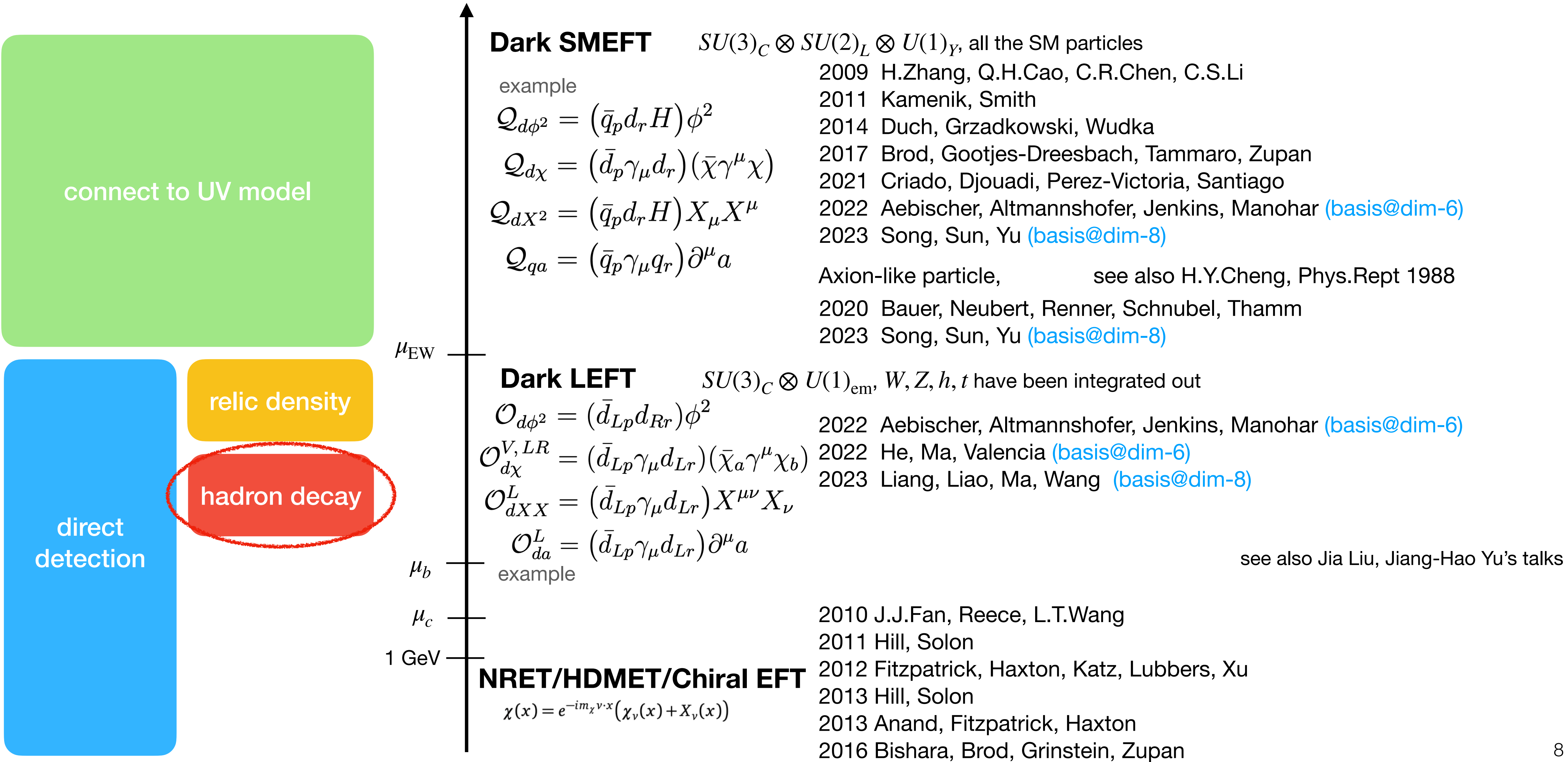
1. Compared to DM direct detection, what's the advantage of hadron decays ? which DM scenario is more sensitive to ? Can provide other information ?
2. Can we build NP model, in which hadron decays into DM reach the future Belle II/STCF sensitivities, while providing enough DM relic density and satisfying the bounds from DM direct detection ?
3. Is it possible to obtain the flavour structure of light DM ?

Light DM

Effective Field Theory approach to combine the various experimental searches

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

for light DM



$H_1 \rightarrow H_2 + \mathbf{DM}$ theoretical calculation and experimental searches

► $d_i \rightarrow d_j + \phi + \phi$

2011 Kamenik, Smith

2014 Bird, Jackson, Kowalewski, Pospelov

2019 G.Li, J.Y. Su, Tandean

$$\Lambda \rightarrow n + \phi\phi, \Sigma^+ \rightarrow p + \phi\phi, \Xi^0 \rightarrow \Lambda + \phi\phi,$$

$$\Xi^- \rightarrow \Sigma^- \phi\phi, \Omega^- \rightarrow \Sigma^- + \phi\phi$$

2020 X.G. He, X.D. Ma, Tandean, Valencia

2020 C.Q.Geng, Tandean, $K \rightarrow \pi\pi + \phi\phi$

2021 G. Li, T. Wang, J.B. Zhang, G.L. Wang

2022 Kling, S. Li, H. Song, S. Su, W. Su

► $d_i \rightarrow d_j + \chi + \chi$

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

► $d_i \rightarrow d_j + X + X$

2011 Kamenik, Smith

2021 G. Li, T. Wang, J.B. Zhang, G.L. Wang

2022 X.G. He, X.D. Ma, Valencia

► $d_i \rightarrow d_j + a$

2020 Camalich, Pospelov, Vuong, Ziegler, Zupan,

2021 Bauer, Neubert, Renner, Schnubel, Thamm

2022 Guerrera and S. Rigolin

see also 刘佳's talk

- theoretically clean: $A \propto C \cdot \langle H_2 | O | H_1 \rangle \cdot \text{DM current}$ ^{form factor}
 - no GIM suppression
 - possibly two-body decay
- } **enhancement**

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

$\nu \rightarrow \mathbf{DM}$

longitudinal polarization
 F_L

$\Lambda_b \rightarrow \Lambda + \mathbf{DM} + \mathbf{DM}$

► $c \rightarrow u + \mathbf{DM}$

2022 C.Q.Geng, G.Li

2023 G.Li, Tandean

$$D^0 \rightarrow s \bar{s}'$$

$$D^0 \rightarrow \gamma s \bar{s}'$$

$$D^0 \rightarrow \pi^0 s \bar{s}'$$

$$D^+ \rightarrow \pi^+ s \bar{s}'$$

$$D_s^+ \rightarrow K^+ s \bar{s}'$$

$$D^0 \rightarrow \rho^0 s \bar{s}'$$

$$D^+ \rightarrow \rho^+ s \bar{s}'$$

$$D_s^+ \rightarrow K^{*+} s \bar{s}'$$

$$\Lambda_c^+ \rightarrow p s \bar{s}'$$

$$\Xi_c^+ \rightarrow \Sigma^+ s \bar{s}'$$

$$\Xi_c^0 \rightarrow \Sigma^0 s \bar{s}'$$

$$\Xi_c^0 \rightarrow \Lambda s \bar{s}'$$

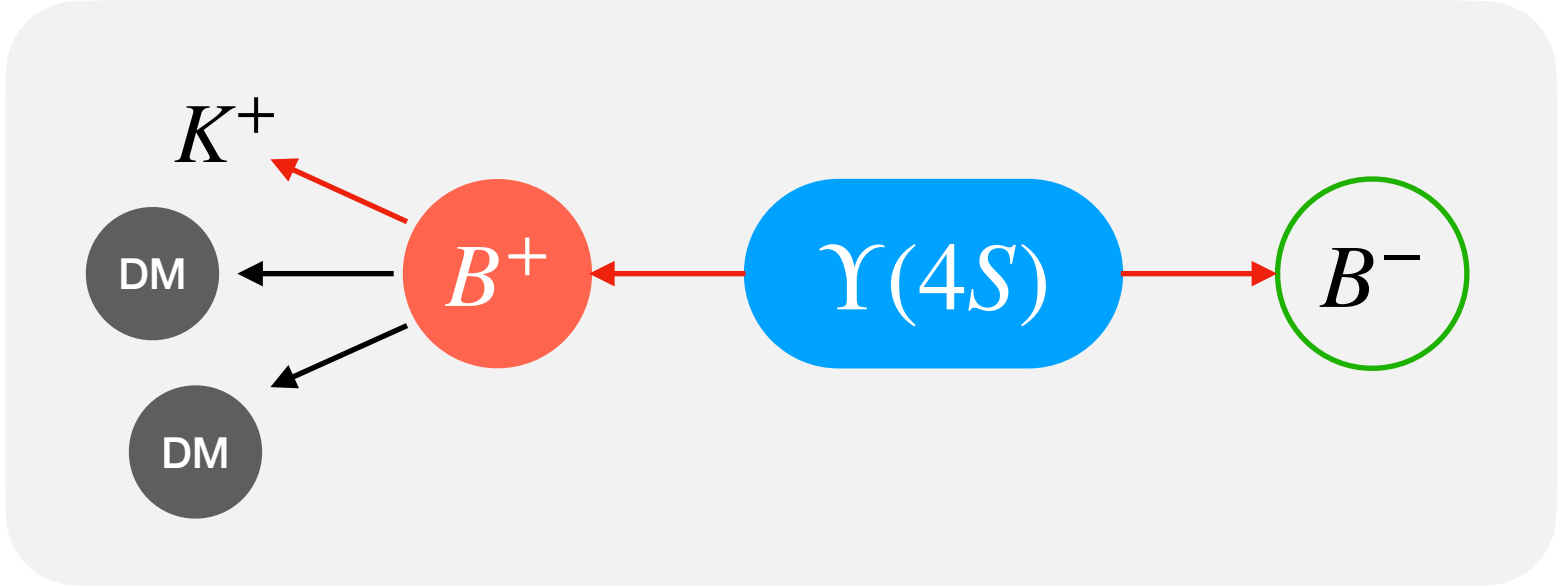
based on complete EFT basis (Dark LEFT)

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*

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

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

Observable	SM	Exp	Unit
$\mathcal{B}(B^+ \rightarrow K^+ \nu \bar{\nu})$	4.16 ± 0.57	$23 \pm 5^{+5}_{-4}$	10^{-6}
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Dark SMEFT

$$\mathcal{Q}_{d\phi} = (\bar{q}_p d_r H) \phi + \text{h.c.}, \quad \mathcal{Q}_{d\phi^2} = (\bar{q}_p d_r H) \phi^2 + \text{h.c.},$$
$$\mathcal{Q}_{\phi q} = (\bar{q}_p \gamma_\mu q_r) (i \phi_1 \overleftrightarrow{\partial}^\mu \phi_2), \quad \mathcal{Q}_{\phi d} = (\bar{d}_p \gamma_\mu d_r) (i \phi_1 \overleftrightarrow{\partial}^\mu \phi_2),$$
$$\mathcal{Q}_{q\chi} = (\bar{q}_p \gamma_\mu q_r) (\bar{\chi} \gamma^\mu \chi), \quad \mathcal{Q}_{d\chi} = (\bar{d}_p \gamma_\mu d_r) (\bar{\chi} \gamma^\mu \chi),$$
$$\mathcal{Q}_{dHX} = (\bar{q}_p \sigma_{\mu\nu} d_r) H X^{\mu\nu} \quad \mathcal{Q}_{dX^2} = (\bar{q}_p d_r H) X_\mu X^\mu$$
$$\mathcal{Q}_{qa} = (\bar{q}_p \gamma_\mu q_r) \partial^\mu a \quad \mathcal{Q}_{da} = (\bar{d}_p \gamma_\mu d_r) \partial^\mu a$$

scalar: 4

fermion: 2

vector: 1+13

ALP: 2

Dark LEFT

$$\mathcal{O}_{d\phi} = (\bar{d}_{Lp} d_{Rr}) \phi + \text{h.c.}, \quad \mathcal{O}_{\phi d}^L = (\bar{d}_{Lp} \gamma_\mu d_{Lr}) (i \phi_1 \overleftrightarrow{\partial}^\mu \phi_2),$$
$$\mathcal{O}_{d\chi}^{V,LR} = (\bar{d}_{Lp} \gamma_\mu d_{Lr}) (\bar{\chi}_a \gamma^\mu \chi_b), \quad \mathcal{O}_{d\chi}^{V,RR} = (\bar{d}_{Rp} \gamma_\mu d_{Rr}) (\bar{\chi}_a \gamma^\mu \chi_b),$$
$$\mathcal{O}_{dX}^T = (\bar{d}_{Lp} \sigma_{\mu\nu} d_{Rr}) X_a^{\mu\nu} \quad \mathcal{O}_{dXX}^L = (\bar{d}_{Lp} \gamma_\mu d_{Lr}) X^{\mu\nu} X_\nu$$
$$\mathcal{O}_{da}^L = (\bar{d}_{Lp} \gamma_\mu d_{Lr}) \partial^\mu a, \quad \mathcal{O}_{da}^R = (\bar{d}_{Rp} \gamma_\mu d_{Rr}) \partial^\mu a.$$

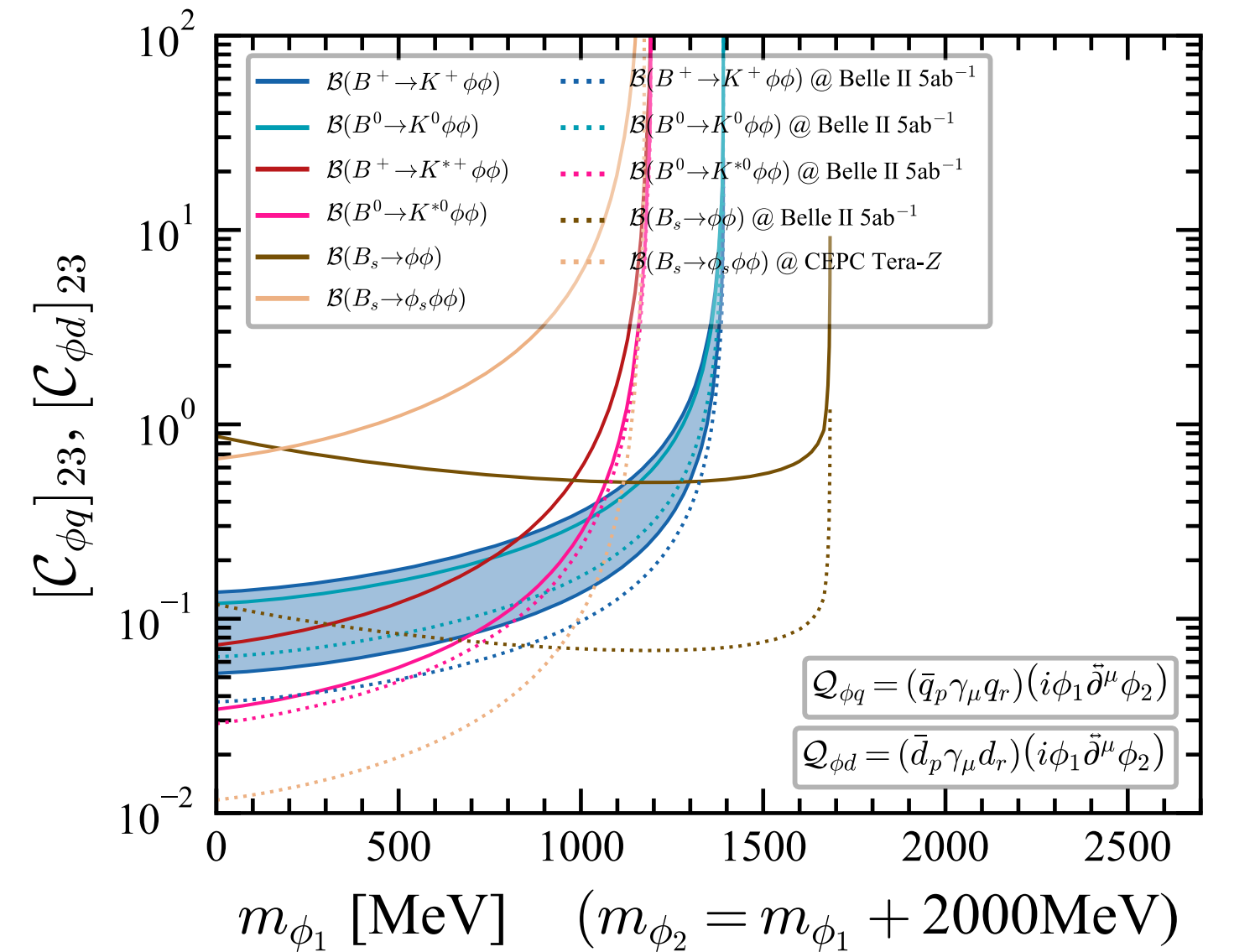
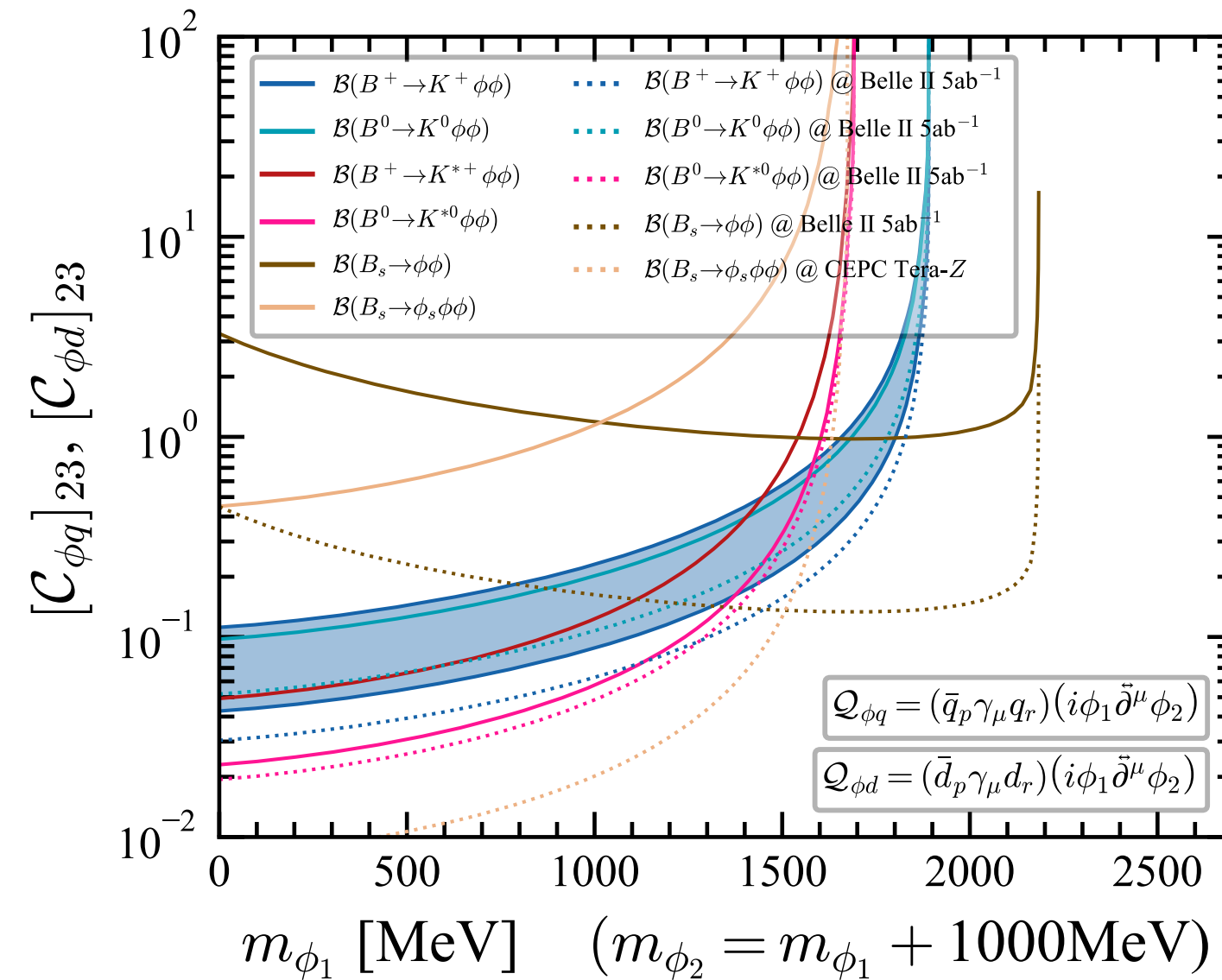
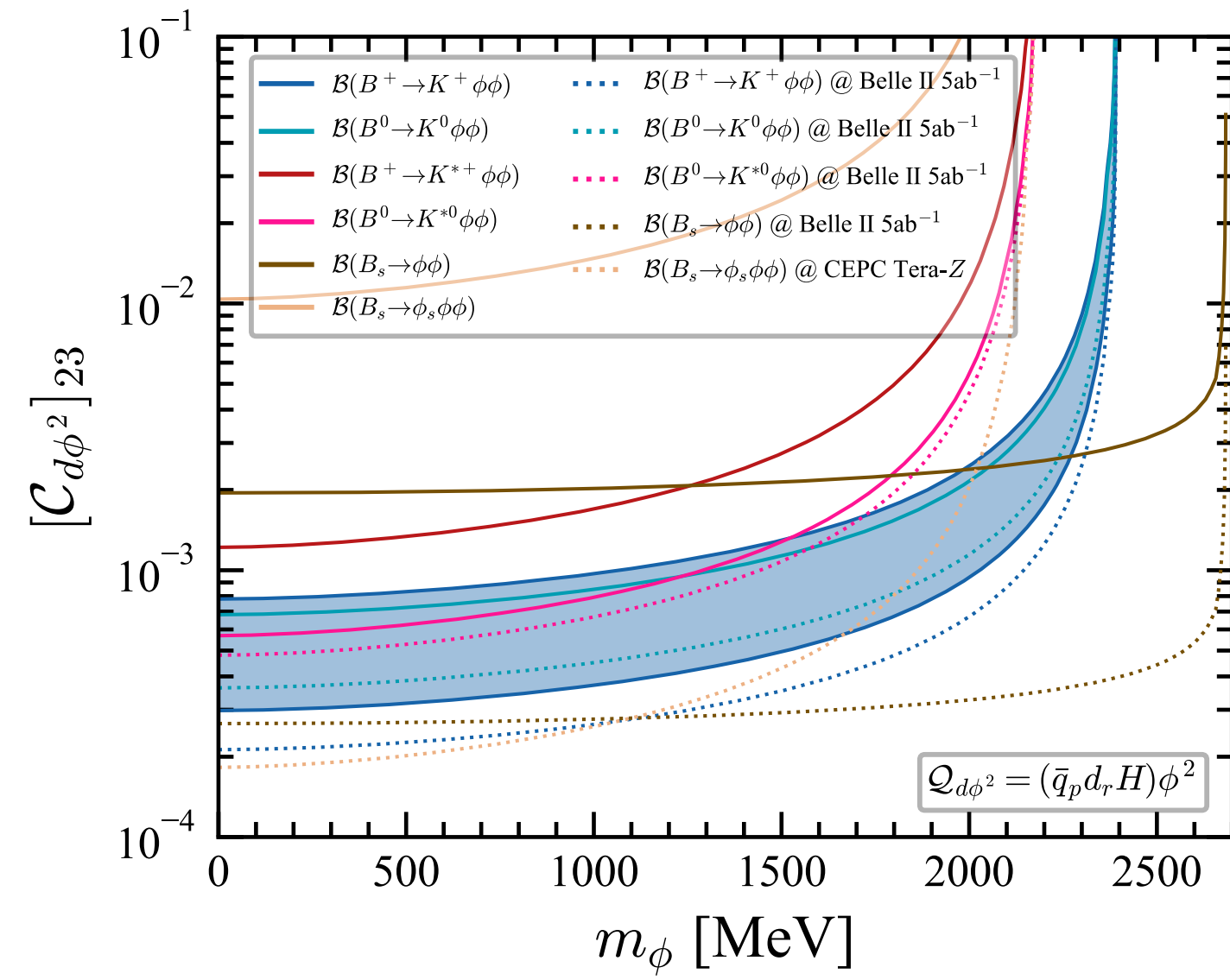
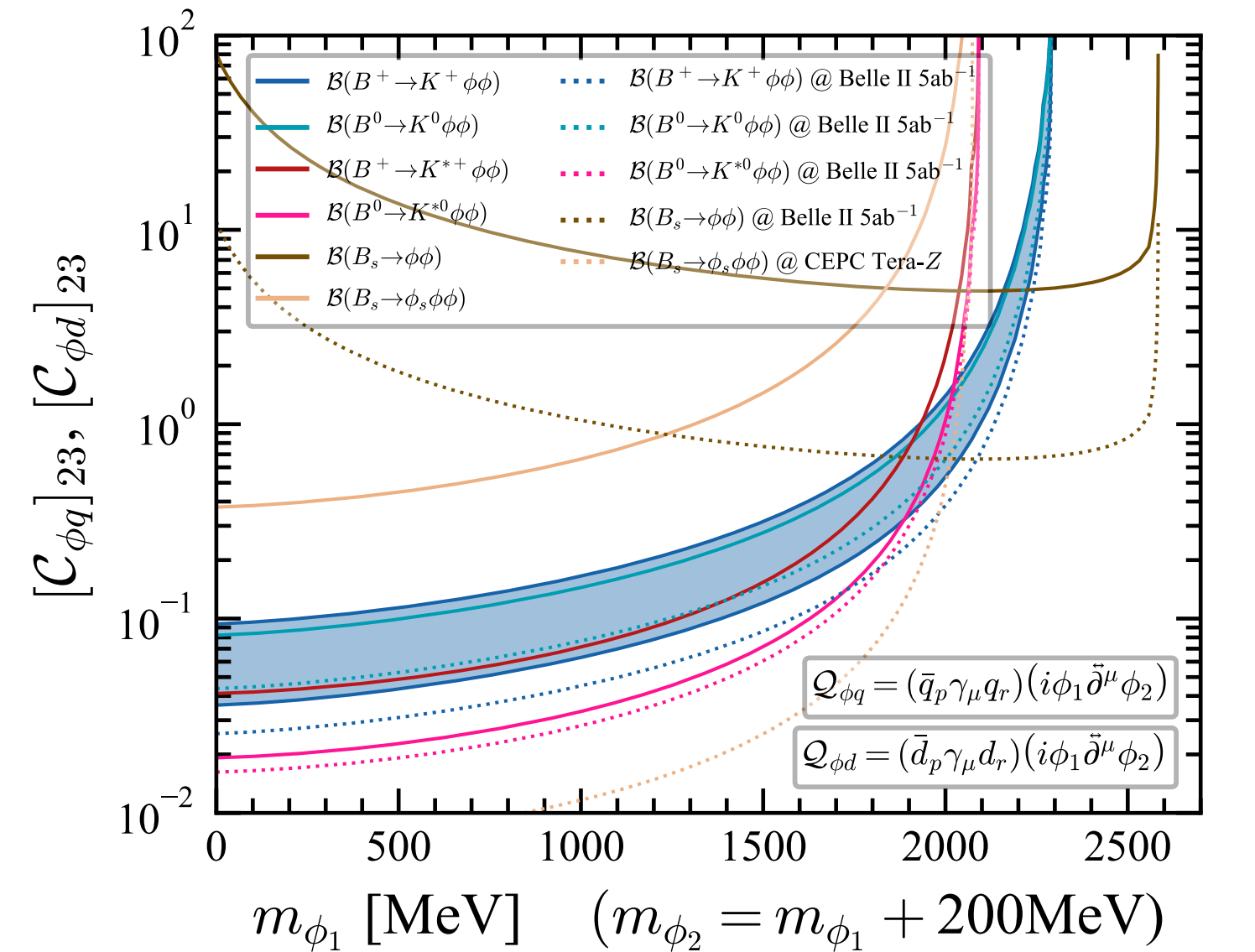
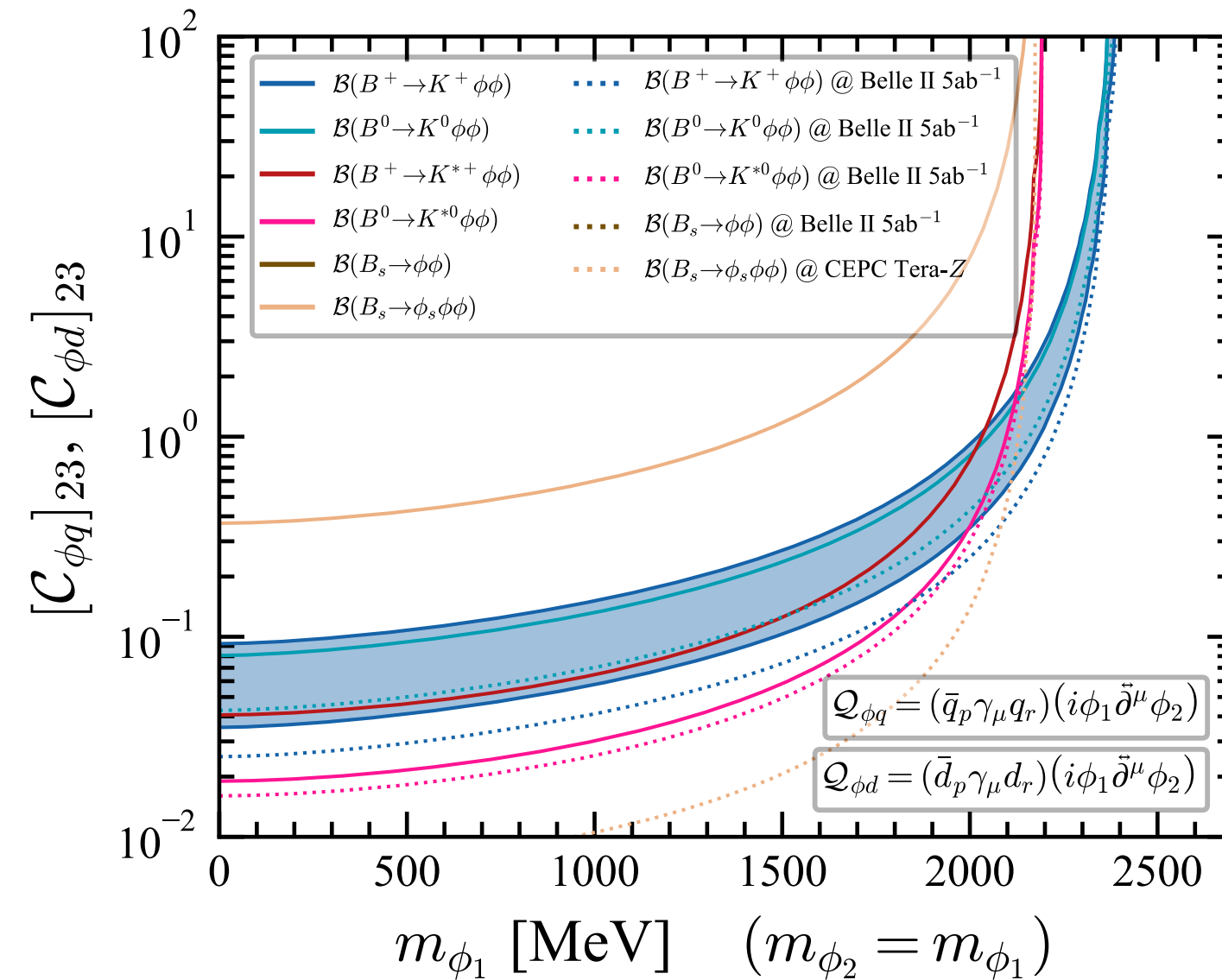
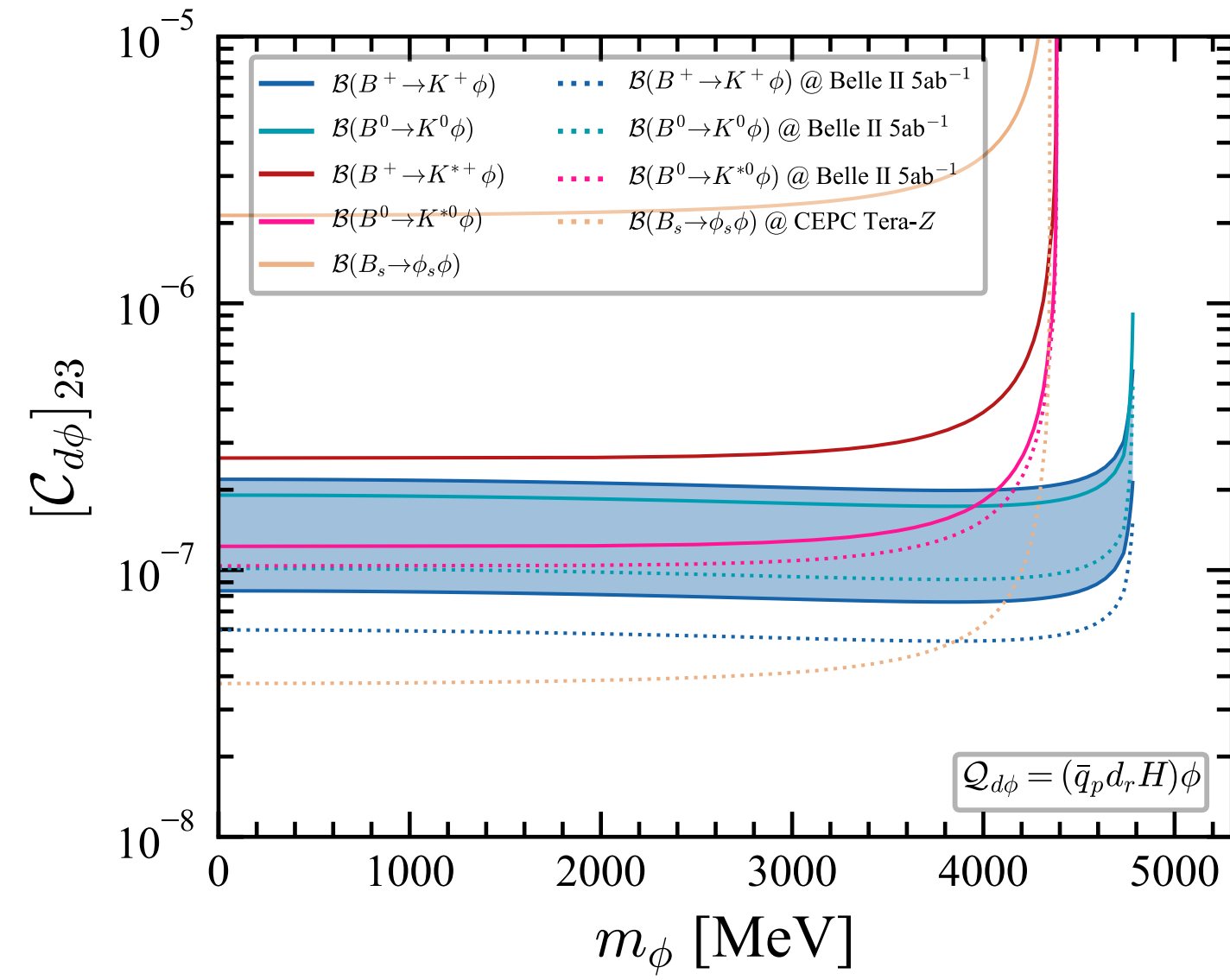
scalar: 4

fermion: 5

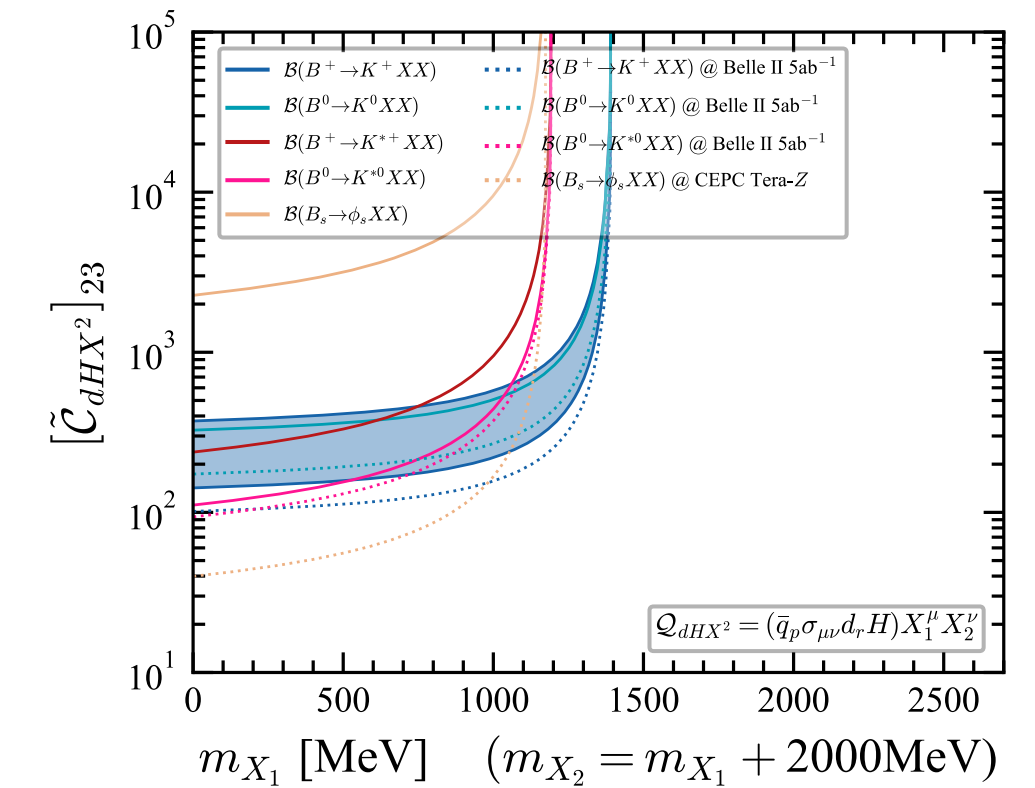
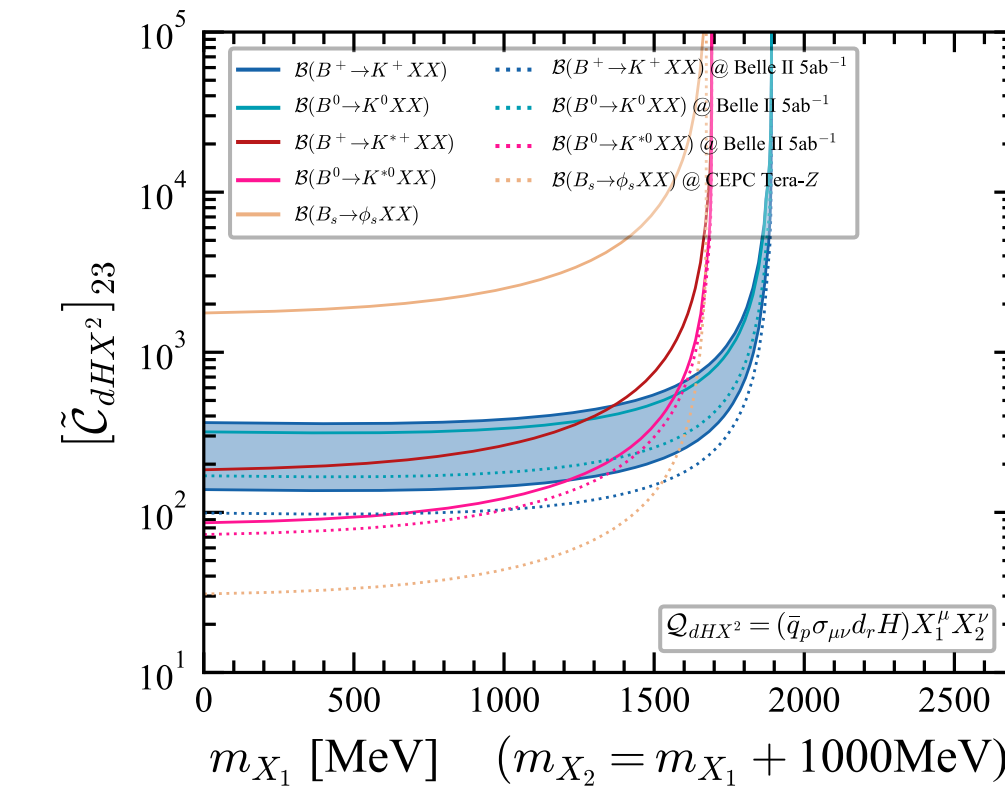
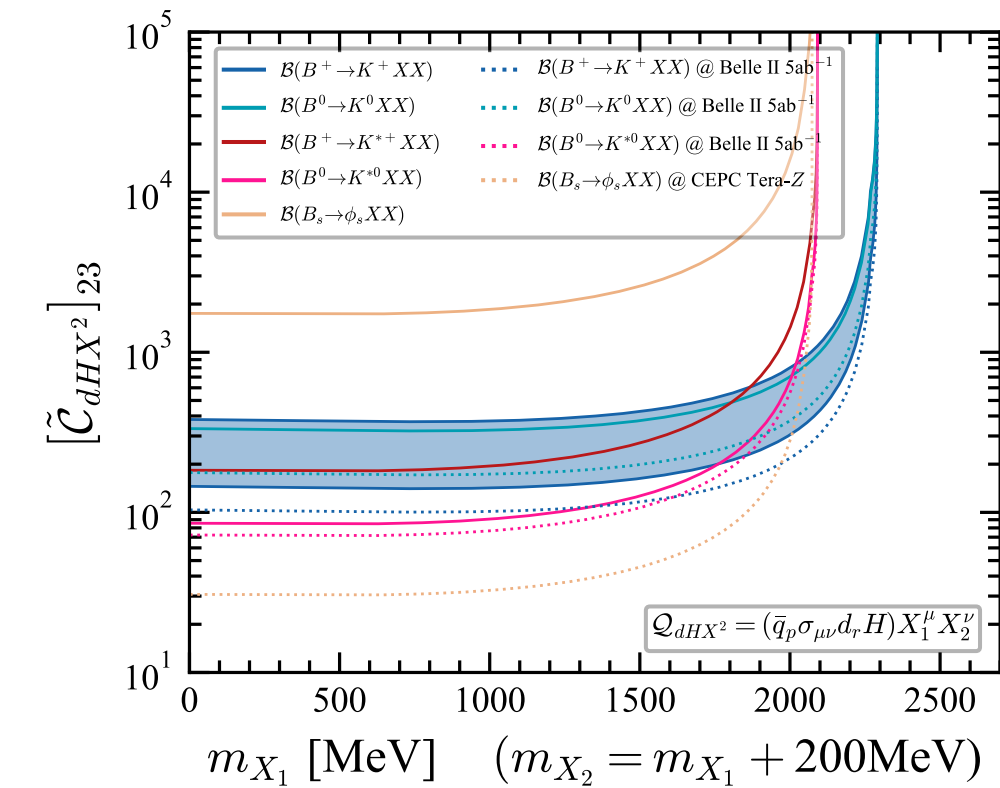
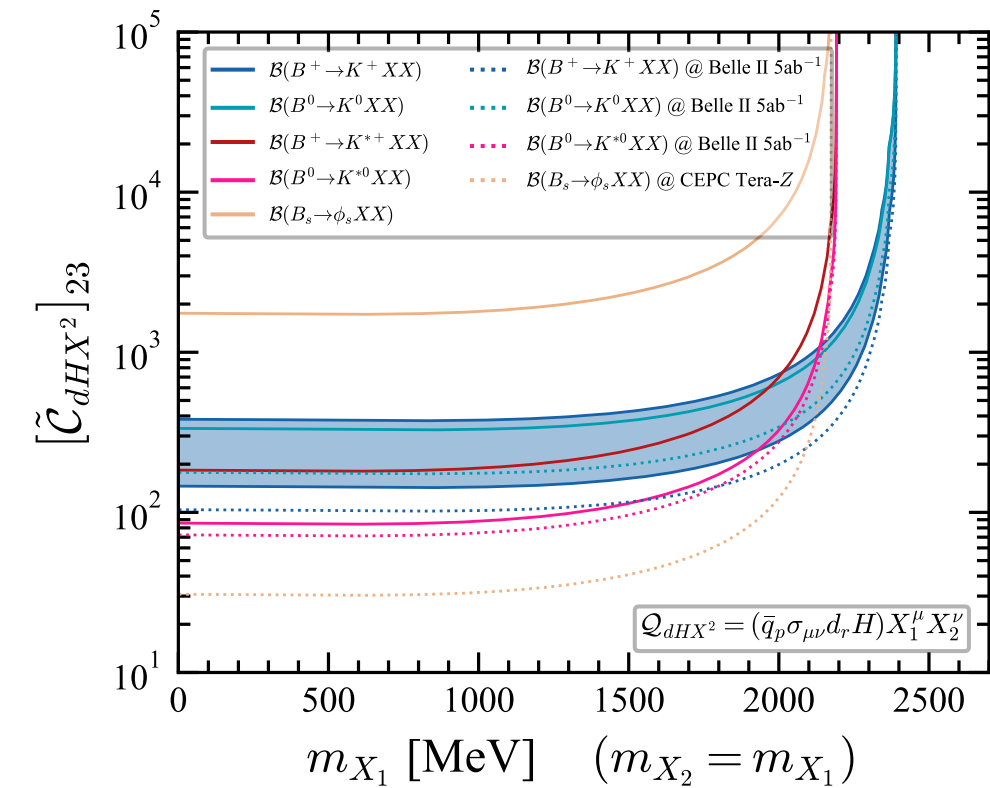
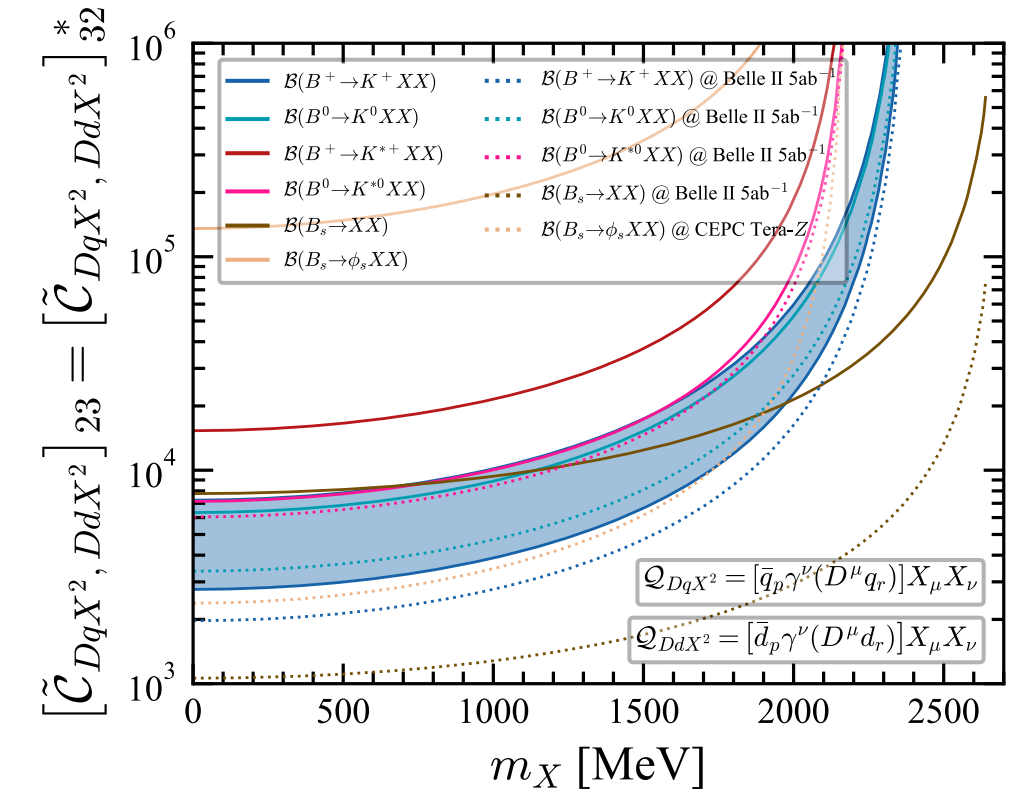
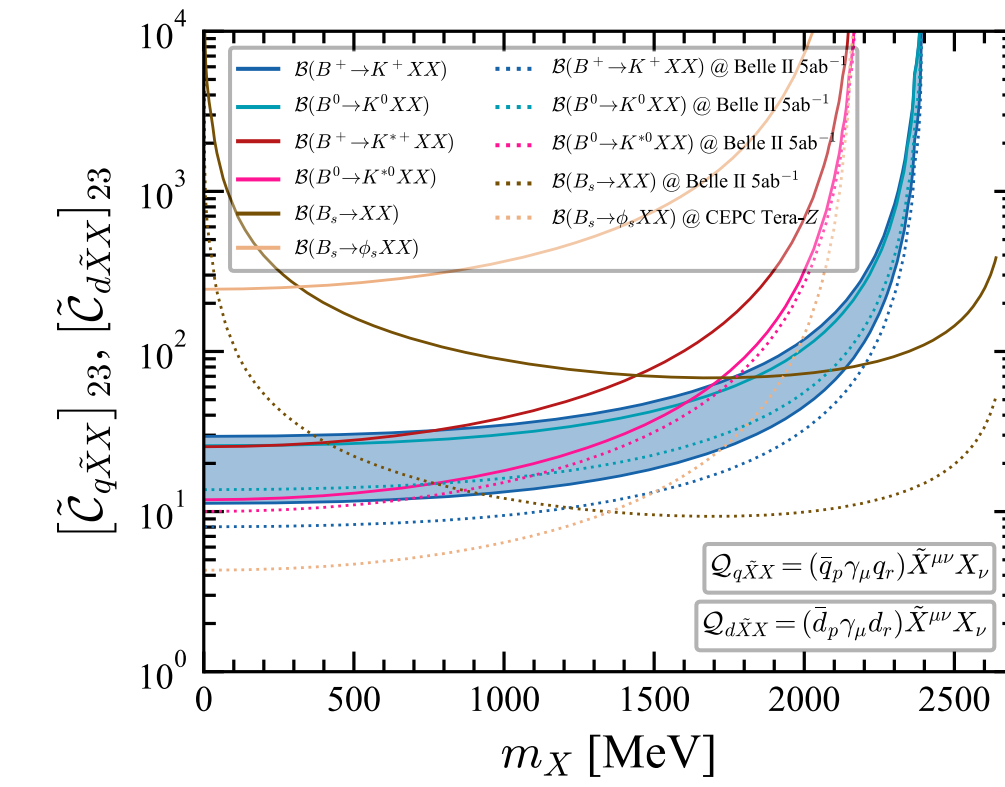
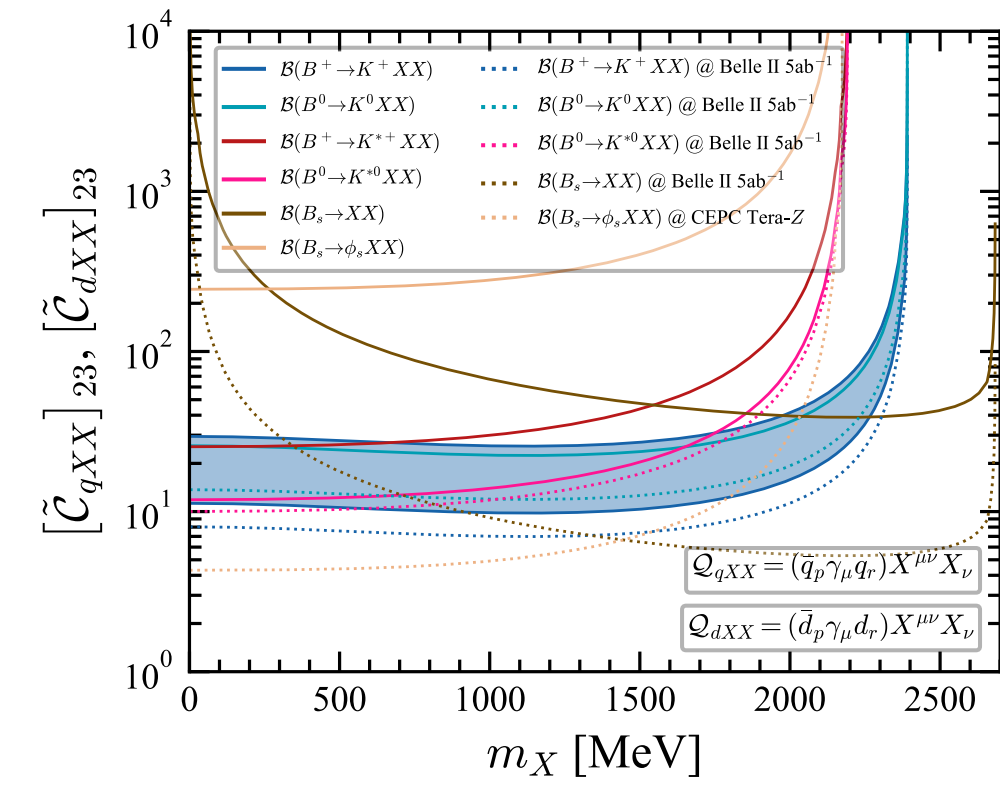
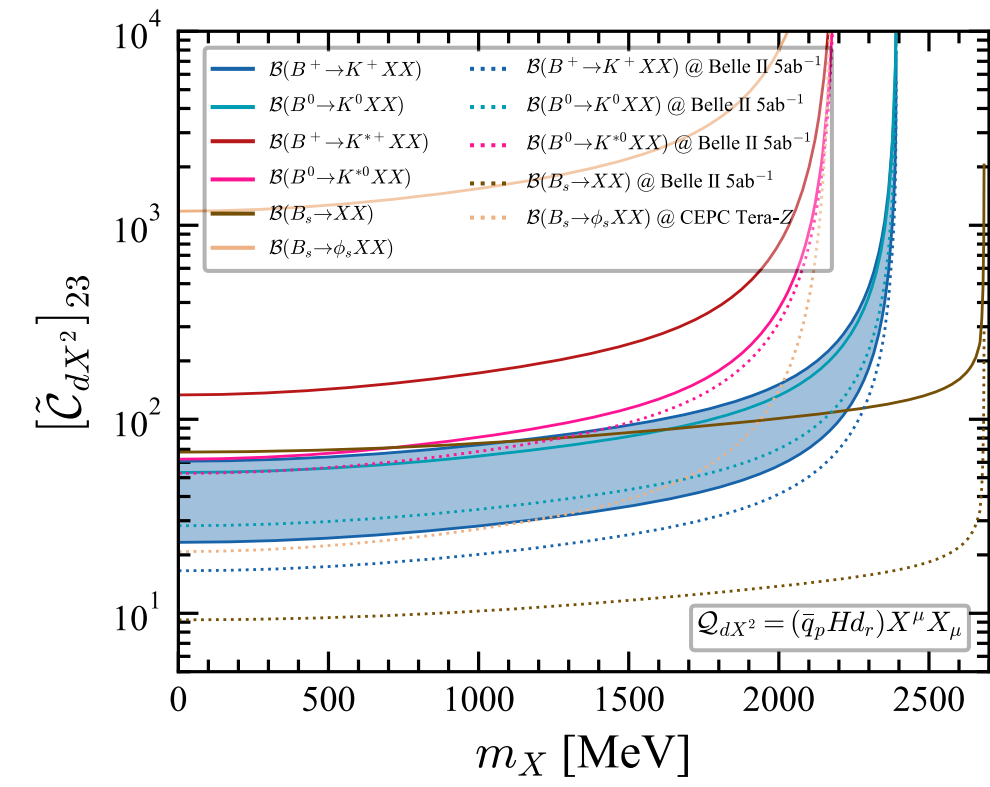
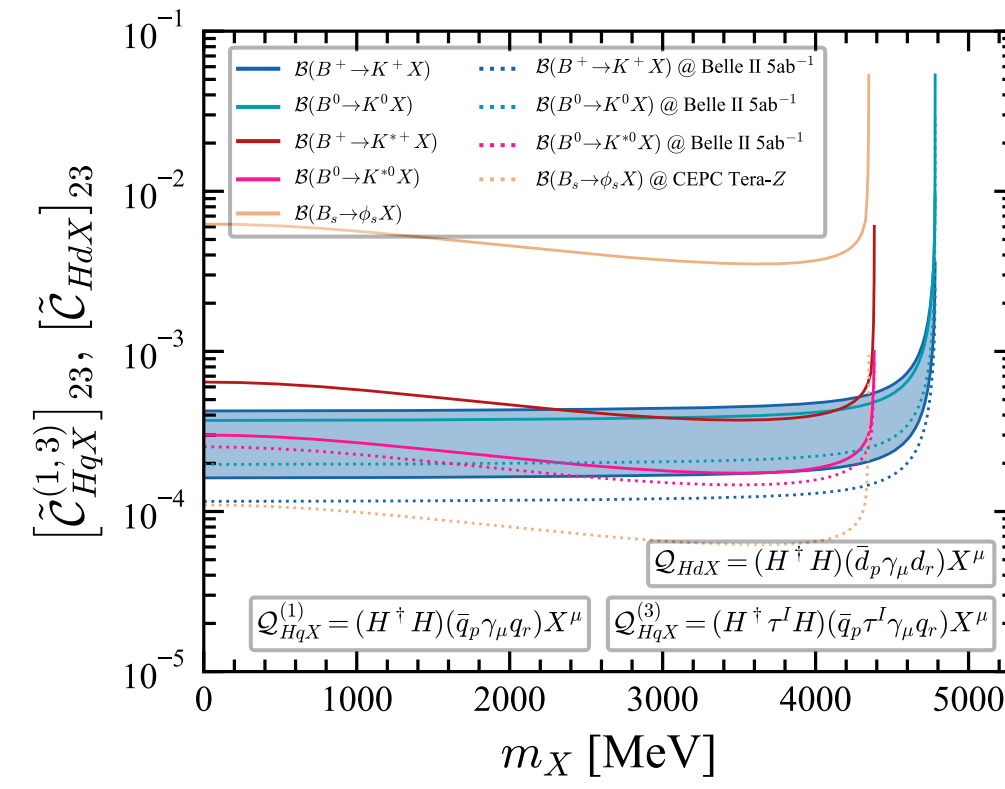
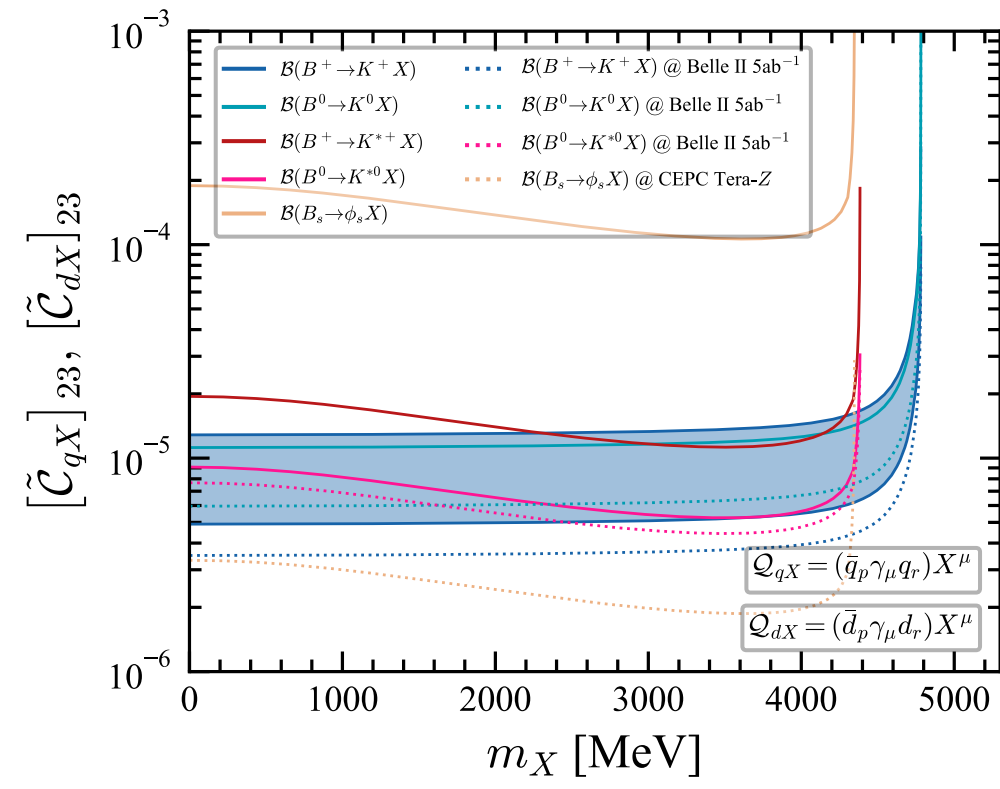
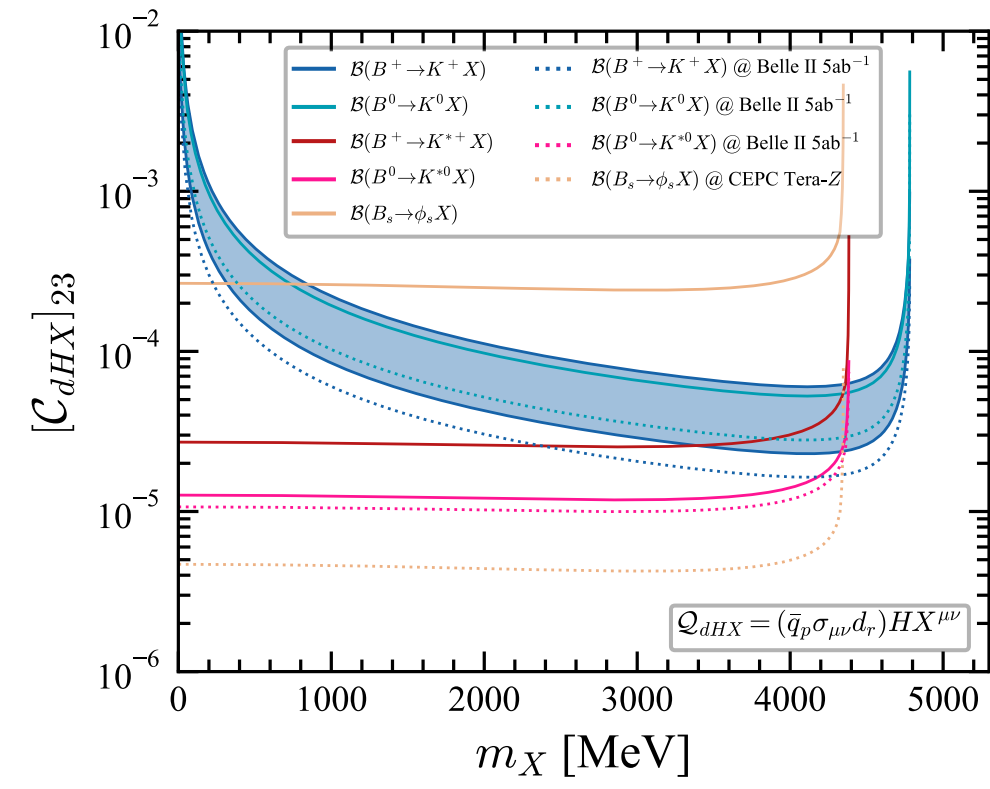
vector: 1+10

ALP: 2

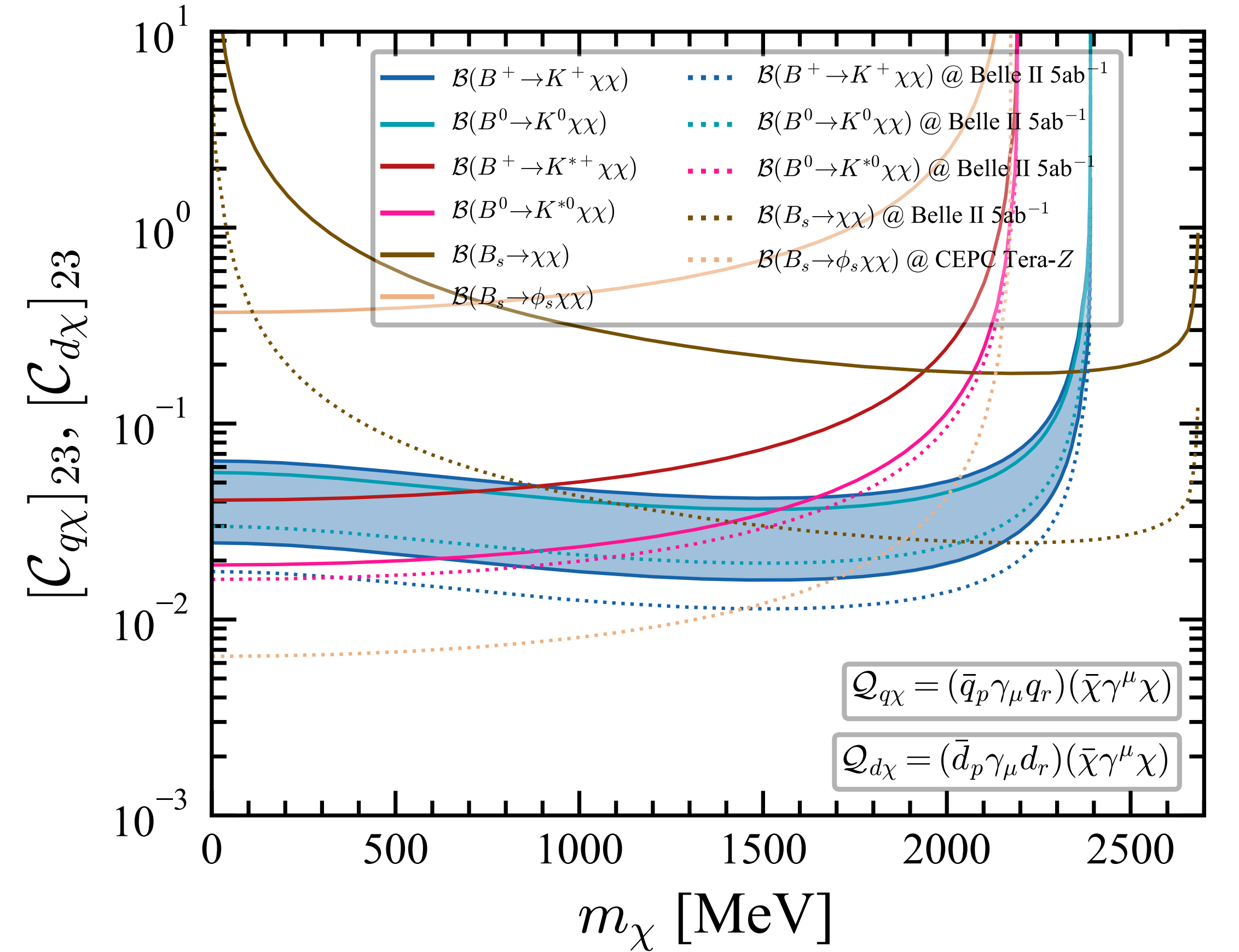
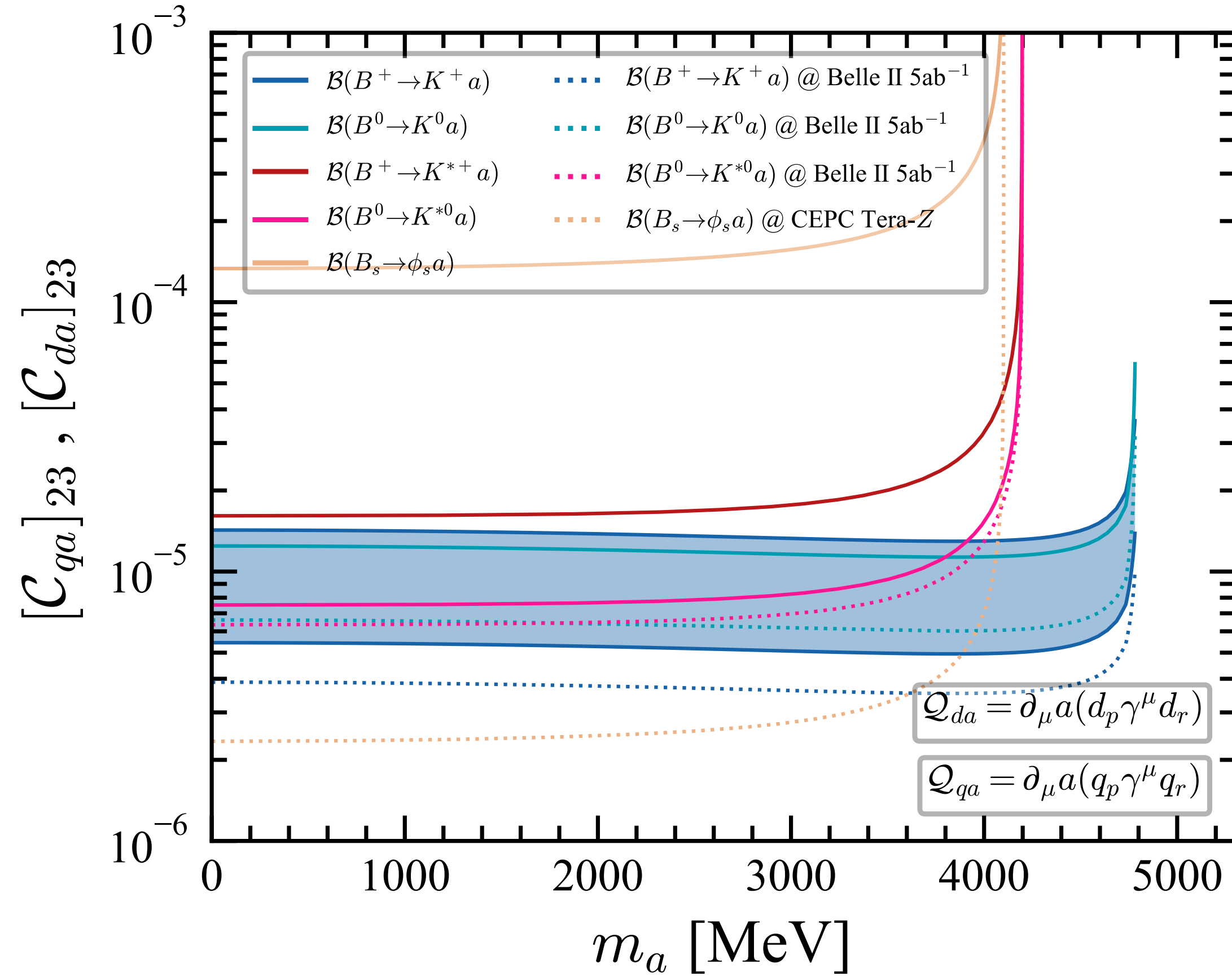
Dark SMEFT: Scalar



Dark SMEFT: Vector



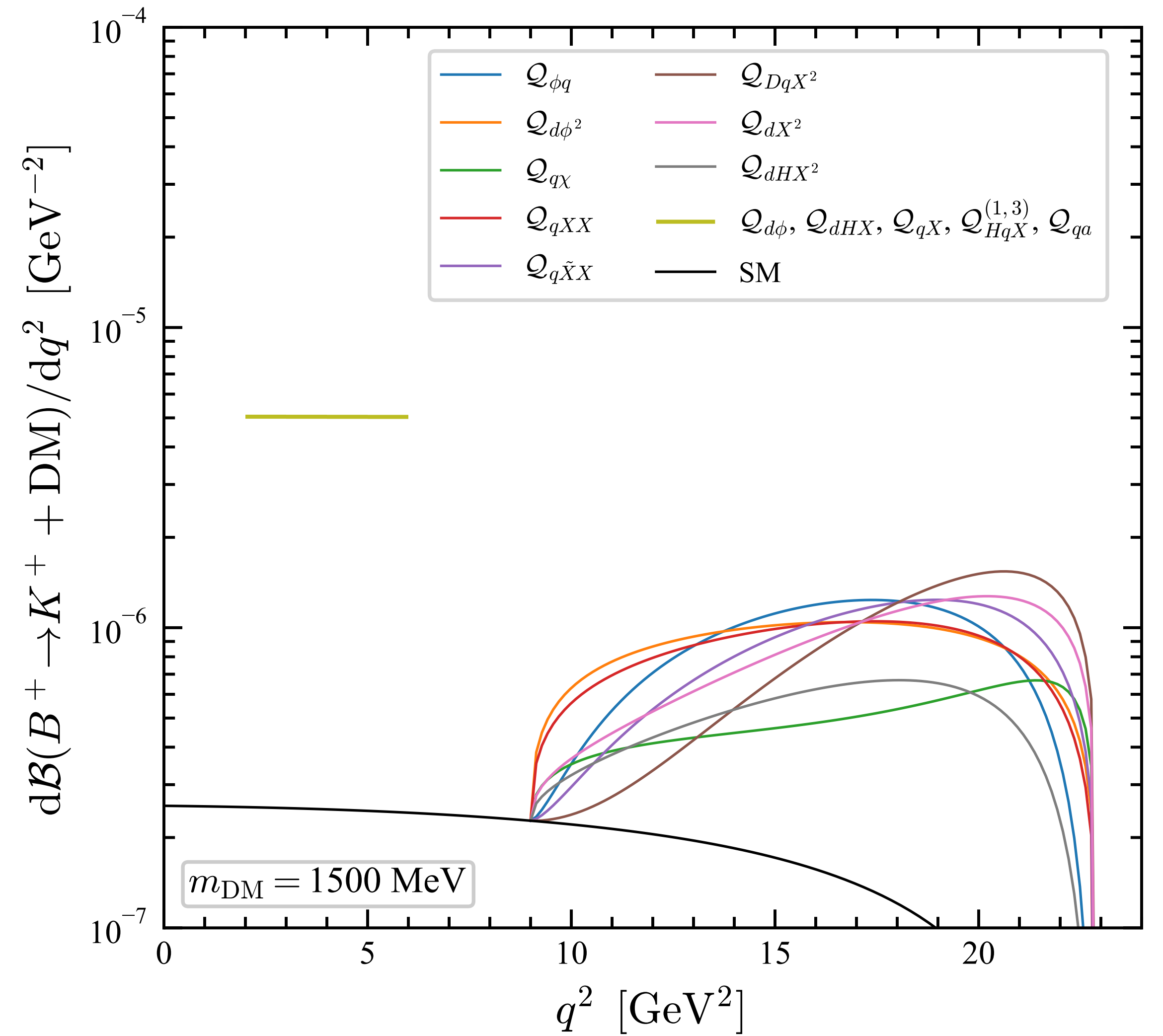
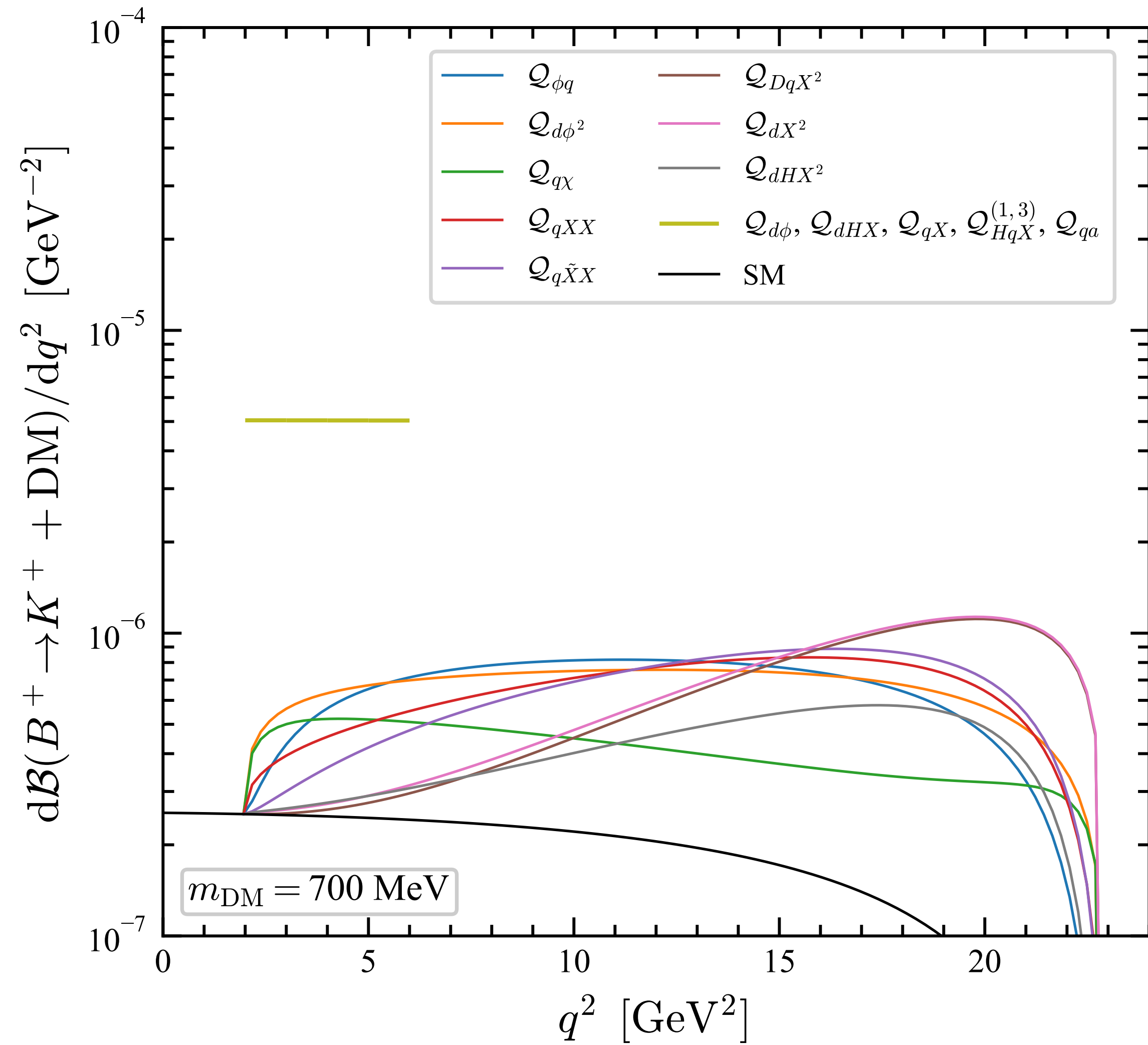
Dark SMEFT: Fermion, ALP



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 combining the Belle II (e.g., $B^0 \rightarrow K^0 + \text{inv}$) and CEPC (e.g., $B_s \rightarrow \phi + \text{inv}$ and $B_s \rightarrow \text{inv}$) measurements.

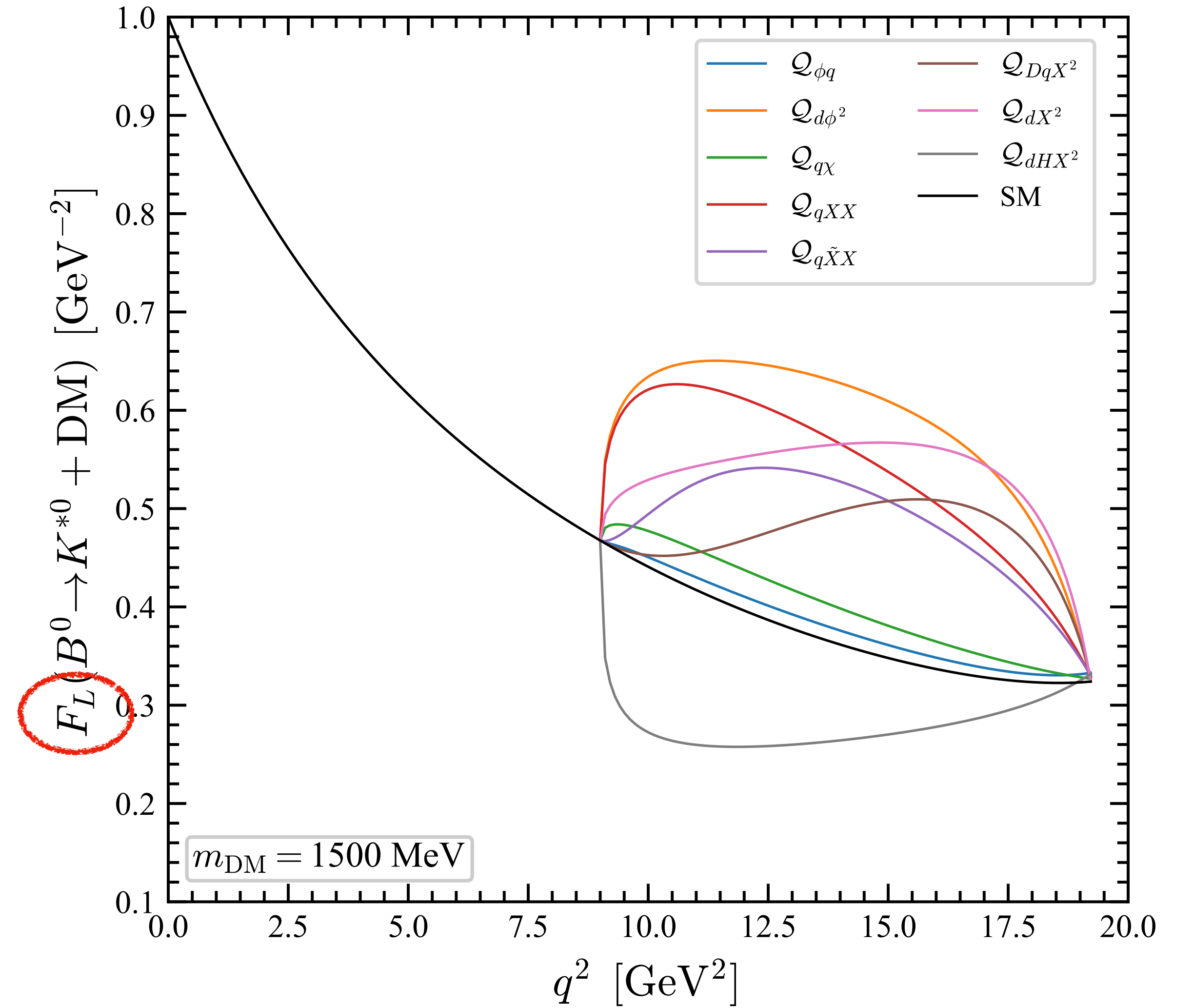
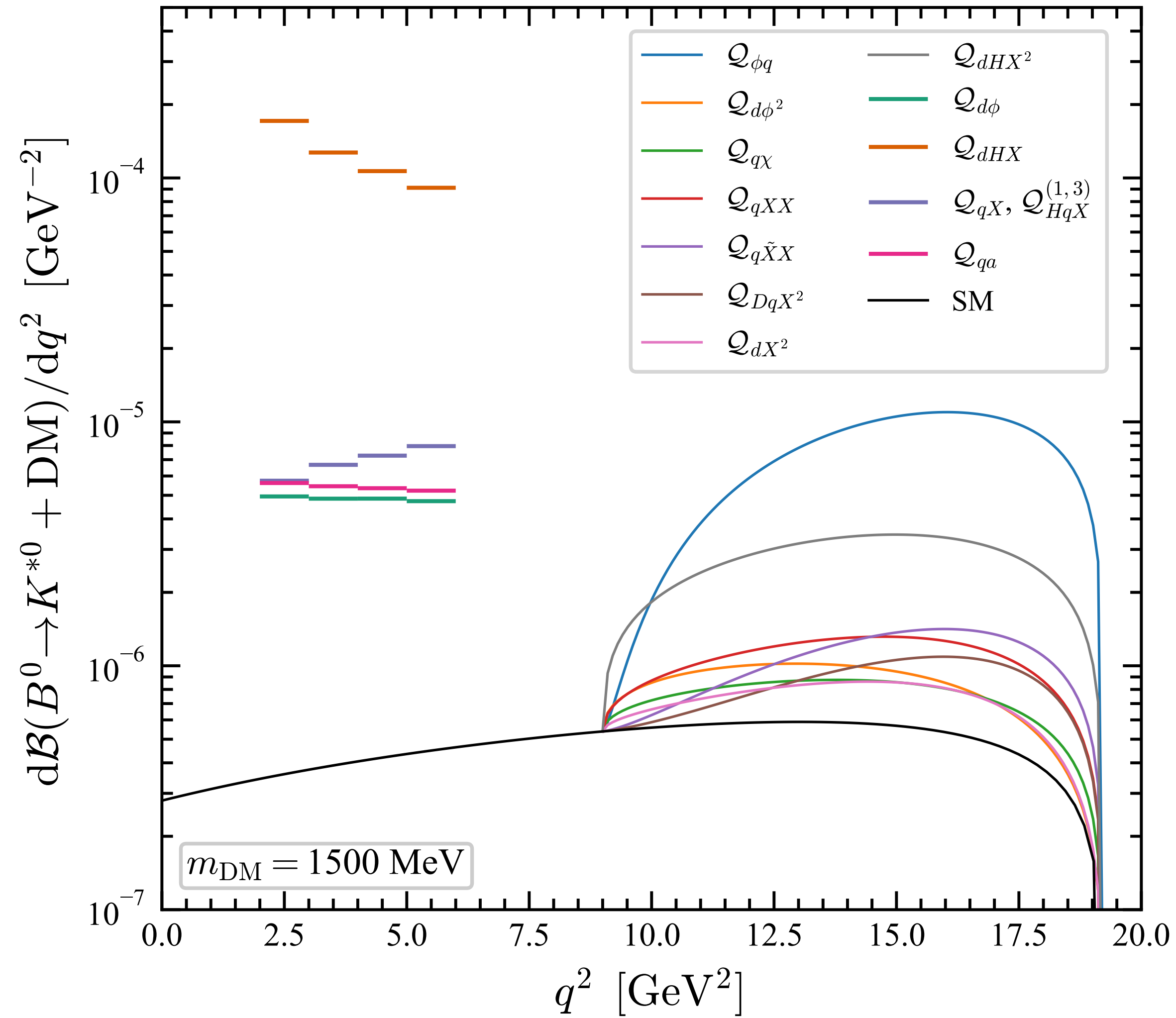
Dark SMEFT: $\mathrm{d}B/\mathrm{d}q^2$



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

Dark SMEFT: $dB/dq^2, F_L$

$m_{\text{DM}} = 1500 \text{ MeV}$

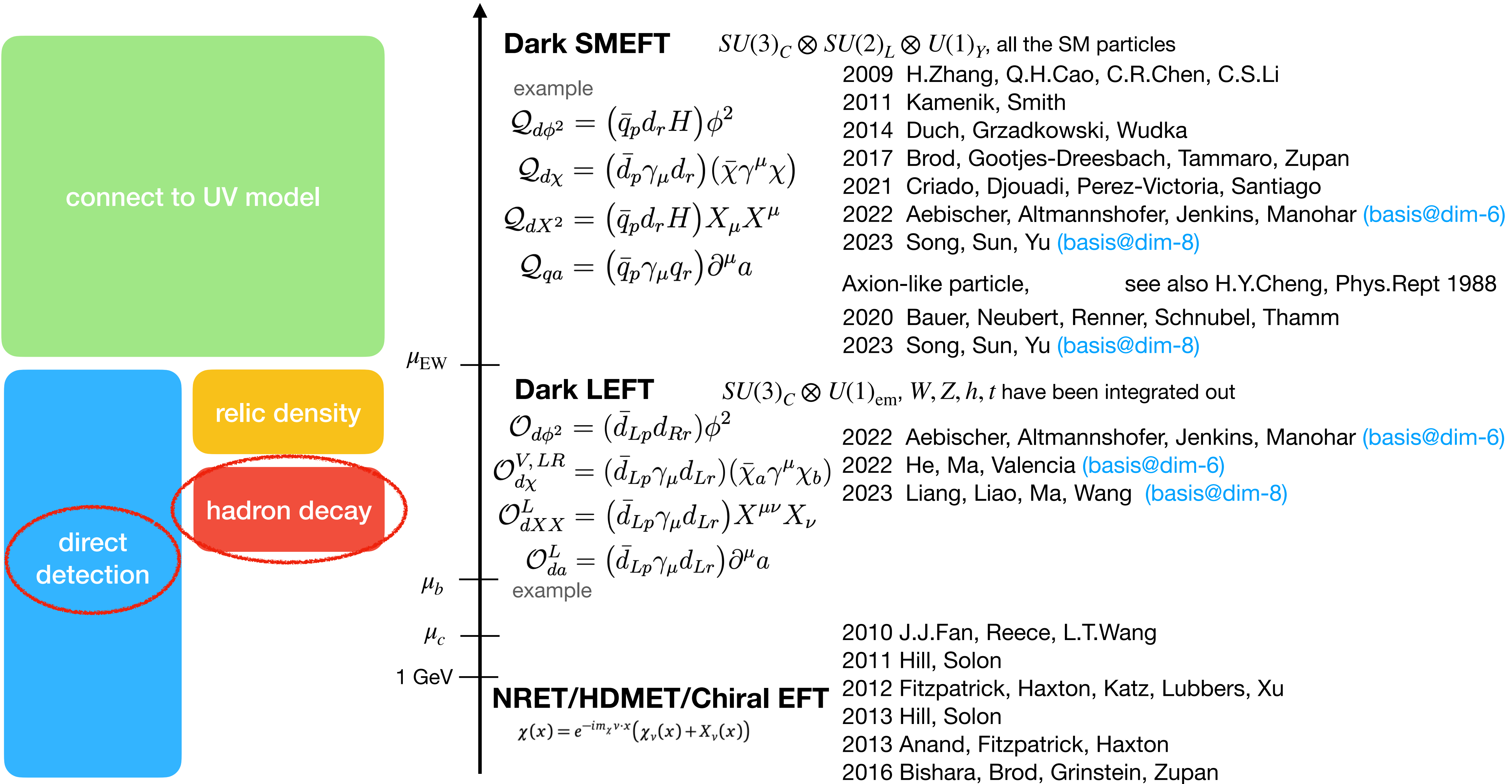


All the operators are **distinguishable** from each other by combining these observables

Effective Field Theory approach to combine the various experimental searches

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

for light DM



Top-flavored DM

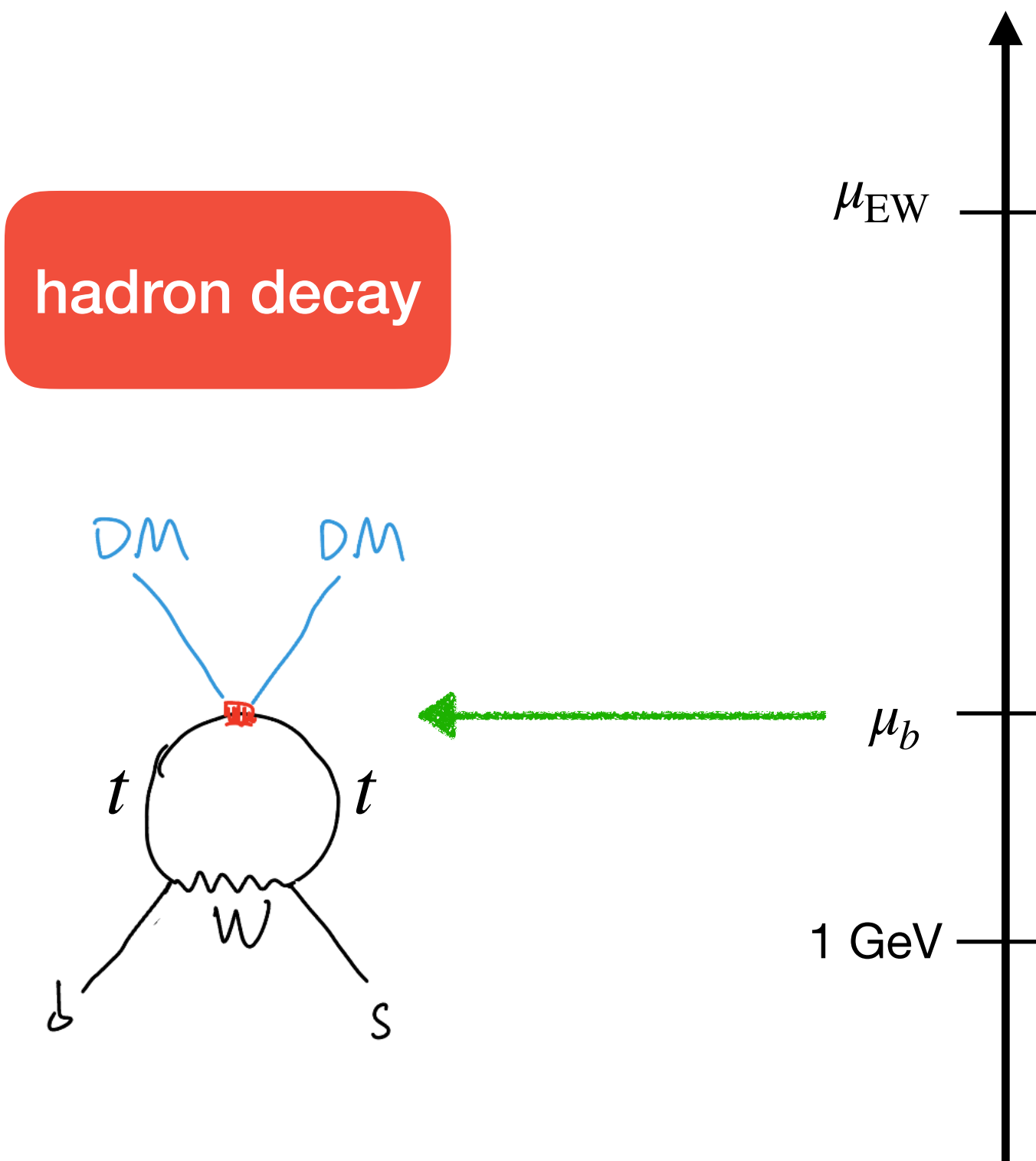
► Dark SMEFT with 3rd generation@ μ_{EW}

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

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

$$\begin{aligned}\mathcal{Q}_{q\chi} &= (\bar{q}_p \gamma_\mu q_r)(\bar{\chi} \gamma^\mu \chi), \\ \mathcal{Q}_{u\chi^2} &= (\bar{q}_p u_r \tilde{H})(\bar{\chi} \chi),\end{aligned}\quad \mathcal{C} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} \mathcal{C}_{33}$$

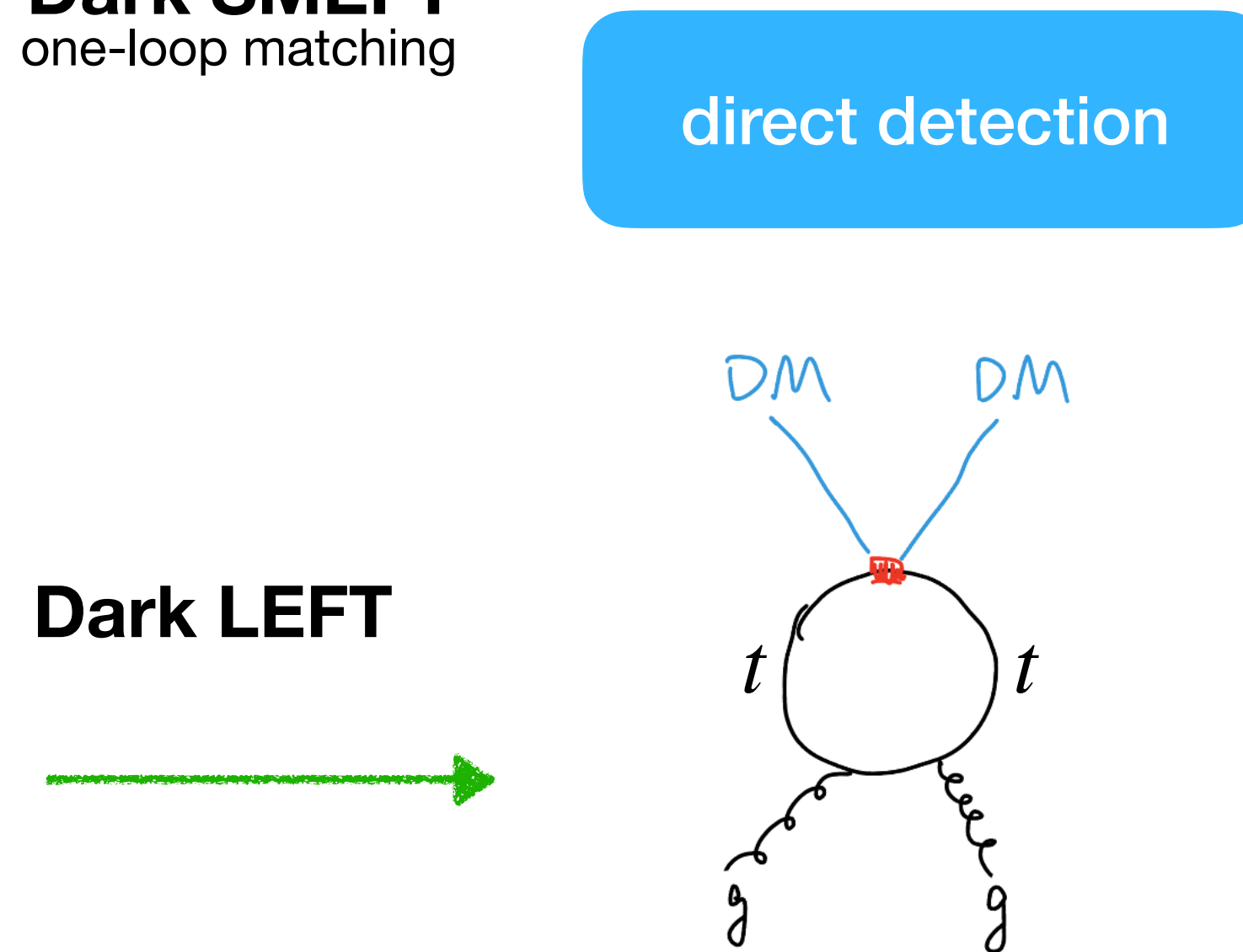
$$\begin{aligned}\mathcal{O}_{d\phi^2} &= (\bar{d}_p P_R d_r) \phi^2 \\ \mathcal{O}_{dXX}^L &= (\bar{d}_p \gamma^\mu P_L d_r) X_{\mu\nu} X^\nu \\ \mathcal{O}_{d\chi}^{V,LR} &= (\bar{d}_p \gamma_\mu P_L d_r) (\bar{\chi} \gamma^\mu \chi), \\ &+ \mathcal{O}(20) \text{ operators} \\ &\langle H_2 | \mathcal{O}_i | H_1 \rangle\end{aligned}$$



Dark SMEFT

one-loop matching

Dark LEFT



$$\begin{aligned}\mathcal{O}_{g\phi} &= G_{\mu\nu}^a G^{\mu\nu,a} \phi^2, \\ \mathcal{O}_{gX} &= G_{\mu\nu}^a G^{\mu\nu,a} X_\rho X^\rho, \\ \mathcal{O}_{g\chi} &= G_{\mu\nu}^a G^{\mu\nu,a} \bar{\chi}\chi \\ &+ \text{operators with } u, d, s \\ &\langle N | \mathcal{O}_i | N \rangle\end{aligned}$$

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
2022 Yandong Liu, Bin Yan, Rui Zhang
... ..

2019 ATLAS [JHEP05(2019)142]

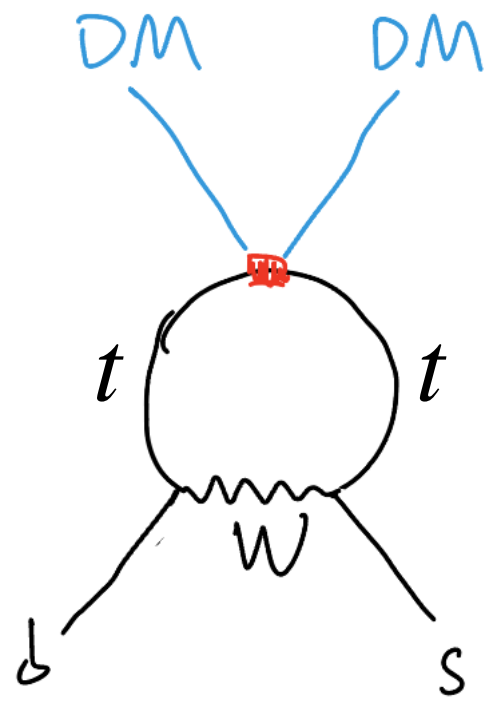
One-Loop Matching between Dark SMEFT and Dark LEFT

► Dark SMEFT

$$\mathcal{L}_{\text{DSMEFT}} \supset \sum_i \mathcal{C}_i \mathcal{Q}_i^{(4)} + \boxed{\frac{1}{\Lambda} \sum_j \mathcal{C}_j \mathcal{Q}_j^{(5)}} + \boxed{\frac{1}{\Lambda^2} \sum_k \mathcal{C}_k \mathcal{Q}_k^{(6)}} + \boxed{\frac{1}{\Lambda^3} \sum_l \mathcal{C}_l \mathcal{Q}_l^{(7)}}$$

$\mathcal{Q}_{u\phi^2} = (\bar{q}_p u_r \tilde{H}) \phi^2 + \text{h.c.}$	$\mathcal{Q}_{\phi u} = (\bar{u}_p \gamma_\mu u_r) (i\phi_1 \overleftrightarrow{\partial}^\mu \phi_2)$	$\mathcal{Q}_{\phi q} = (\bar{q}_p \gamma_\mu q_r) (i\phi_1 \overleftrightarrow{\partial}^\mu \phi_2)$	...	scalar
$\mathcal{Q}_{u\chi^2} = (\bar{q}_p u_r \tilde{H}) (\chi^T C \chi)$	$\mathcal{Q}_{u\chi} = (\bar{u}_p \gamma_\mu u_r) (\bar{\chi} \gamma^\mu \chi)$	$\mathcal{Q}_{q\chi} = (\bar{q}_p \gamma_\mu q_r) (\bar{\chi} \gamma^\mu \chi)$	...	fermion
$\mathcal{Q}_{qXX} = (\bar{q}_p \gamma_\mu q_r) X^{\mu\nu} X_\nu$	$\mathcal{Q}_{u\tilde{X}X} = (\bar{u}_p \gamma_\mu u_r) \tilde{X}^{\mu\nu} X_\nu$	$\mathcal{Q}_{uX^2} = (\bar{q}_p u_r \tilde{H}) X_\mu X^\mu + \text{h.c.}$	...	vector

► Matching



► Dark LEFT: **hadron detection**

$$\mathcal{L}_{\text{DLEFT}} \supset \sum_k L_k \mathcal{O}_k^{(4)} + \boxed{\frac{1}{v} \sum_i L_i \mathcal{O}_i^{(5)}} + \boxed{\frac{1}{v^2} \sum_j L_j \mathcal{O}_j^{(6)}} + \boxed{\frac{1}{v^3} \sum_l L_l \mathcal{O}_l^{(7)}}$$

$\mathcal{O}_{\phi d}^R = (\bar{d}_p \gamma_\mu P_R d_r) (i\phi_1 \overleftrightarrow{\partial}^\mu \phi_2)$	$\mathcal{O}_{d\phi^2} = (\bar{d}_p P_R d_r) \phi^2$	...	scalar
$\mathcal{O}_{d\chi}^{V,RR} = (\bar{d}_p \gamma_\mu P_R d_r) (\bar{\chi} \gamma^\mu \chi)$	$\mathcal{O}_{d\chi}^{V,LR} = (\bar{d}_p \gamma_\mu P_L d_r) (\bar{\chi} \gamma^\mu \chi)$	...	fermion
$\mathcal{O}_{dXX}^R = (\bar{d}_p \gamma^\mu P_R d_r) X_{\mu\nu} X^\nu$	$\mathcal{O}_{dXX}^L = (\bar{d}_p \gamma^\mu P_L d_r) X_{\mu\nu} X^\nu$	...	vector

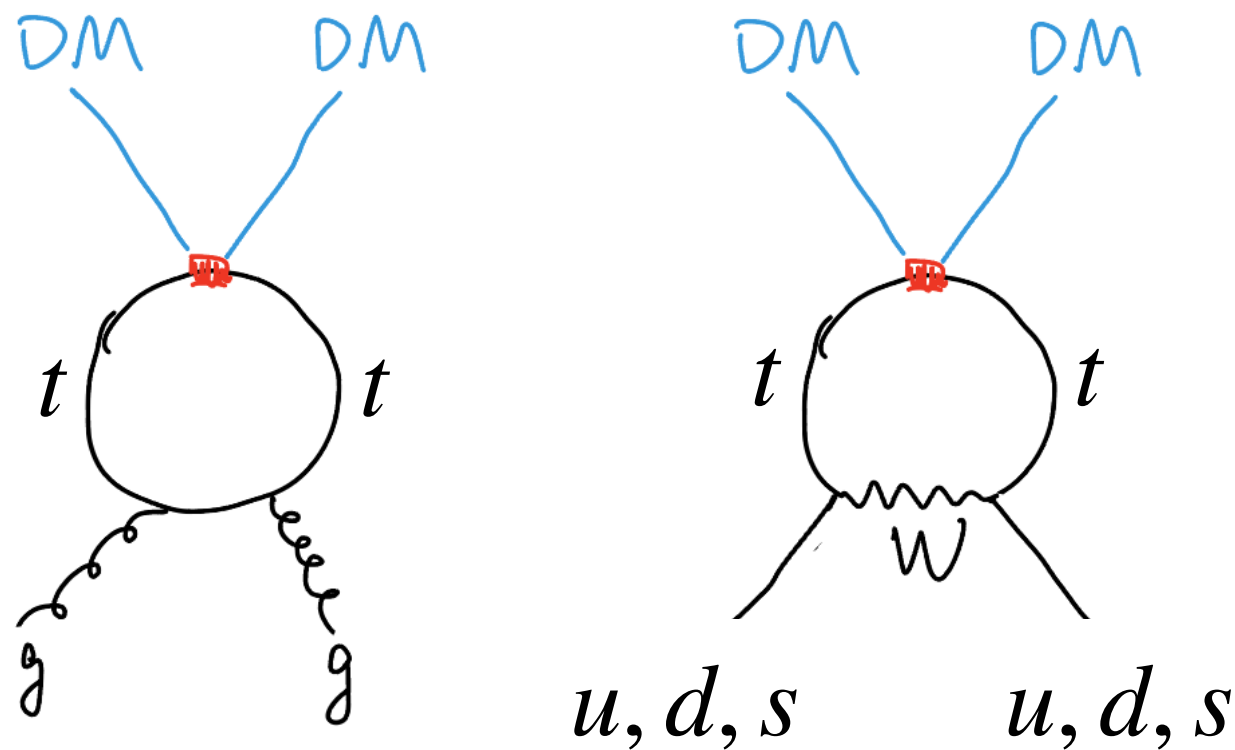
One-Loop Matching between Dark SMEFT and Dark LEFT

► Dark SMEFT

$$\mathcal{L}_{\text{DSMEFT}} \supset \sum_i c_i \mathcal{Q}_i^{(4)} + \boxed{\frac{1}{\Lambda} \sum_j c_j \mathcal{Q}_j^{(5)}} + \boxed{\frac{1}{\Lambda^2} \sum_k c_k \mathcal{Q}_k^{(6)}} + \boxed{\frac{1}{\Lambda^3} \sum_l c_l \mathcal{Q}_l^{(7)}}$$

$\mathcal{Q}_{u\phi^2} = (\bar{q}_p u_r \tilde{H}) \phi^2 + \text{h.c.}$	$\mathcal{Q}_{\phi u} = (\bar{u}_p \gamma_\mu u_r) (i\phi_1 \overleftrightarrow{\partial}^\mu \phi_2)$	$\mathcal{Q}_{\phi q} = (\bar{q}_p \gamma_\mu q_r) (i\phi_1 \overleftrightarrow{\partial}^\mu \phi_2)$	...	scalar
$\mathcal{Q}_{u\chi^2} = (\bar{q}_p u_r \tilde{H}) (\chi^T C \chi)$	$\mathcal{Q}_{u\chi} = (\bar{u}_p \gamma_\mu u_r) (\bar{\chi} \gamma^\mu \chi)$	$\mathcal{Q}_{q\chi} = (\bar{q}_p \gamma_\mu q_r) (\bar{\chi} \gamma^\mu \chi)$	...	fermion
$\mathcal{Q}_{qXX} = (\bar{q}_p \gamma_\mu q_r) X^{\mu\nu} X_\nu$	$\mathcal{Q}_{u\tilde{X}X} = (\bar{u}_p \gamma_\mu u_r) \tilde{X}^{\mu\nu} X_\nu$	$\mathcal{Q}_{uX^2} = (\bar{q}_p u_r \tilde{H}) X_\mu X^\mu + \text{h.c.}$	...	vector

► Matching

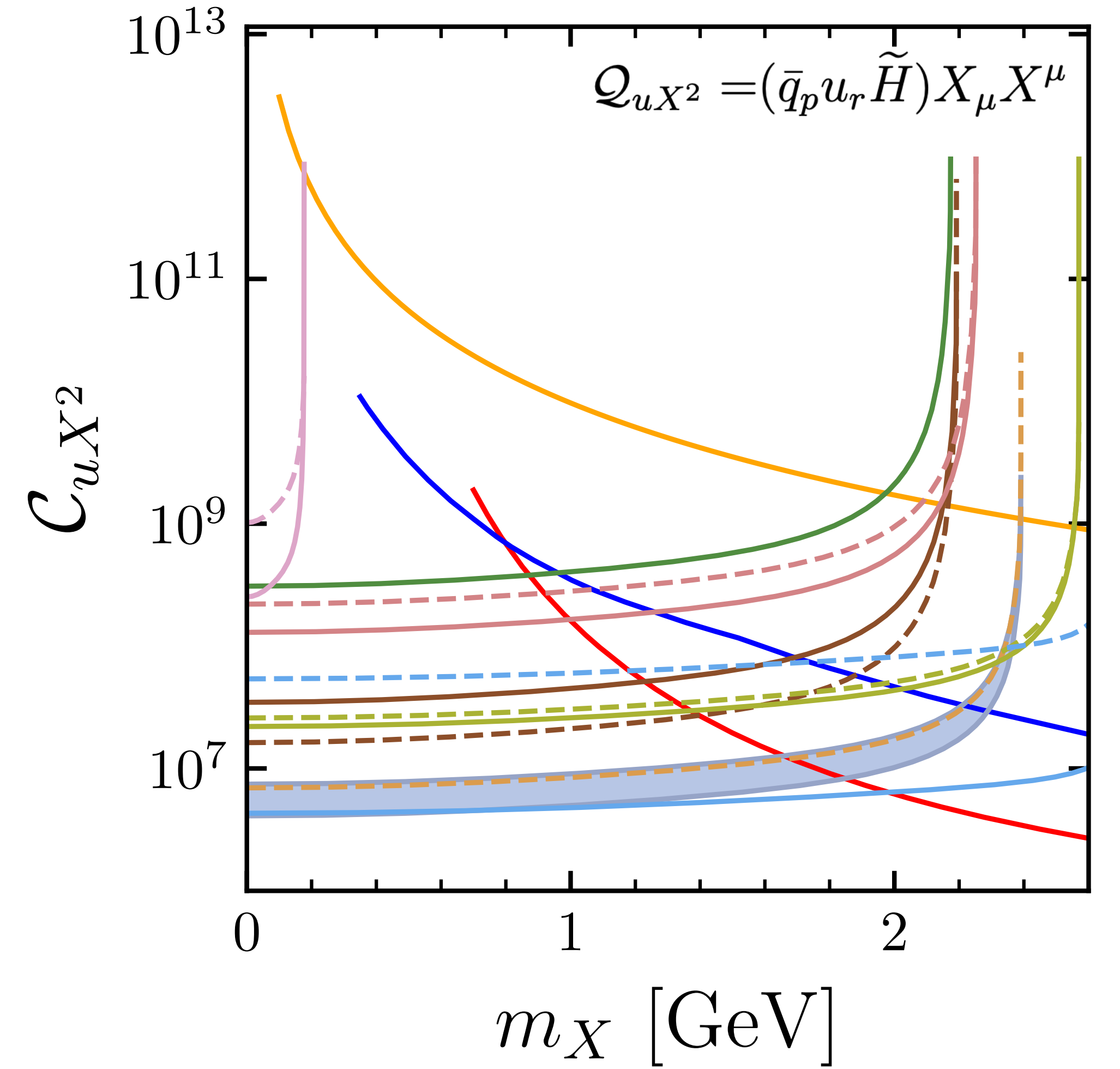
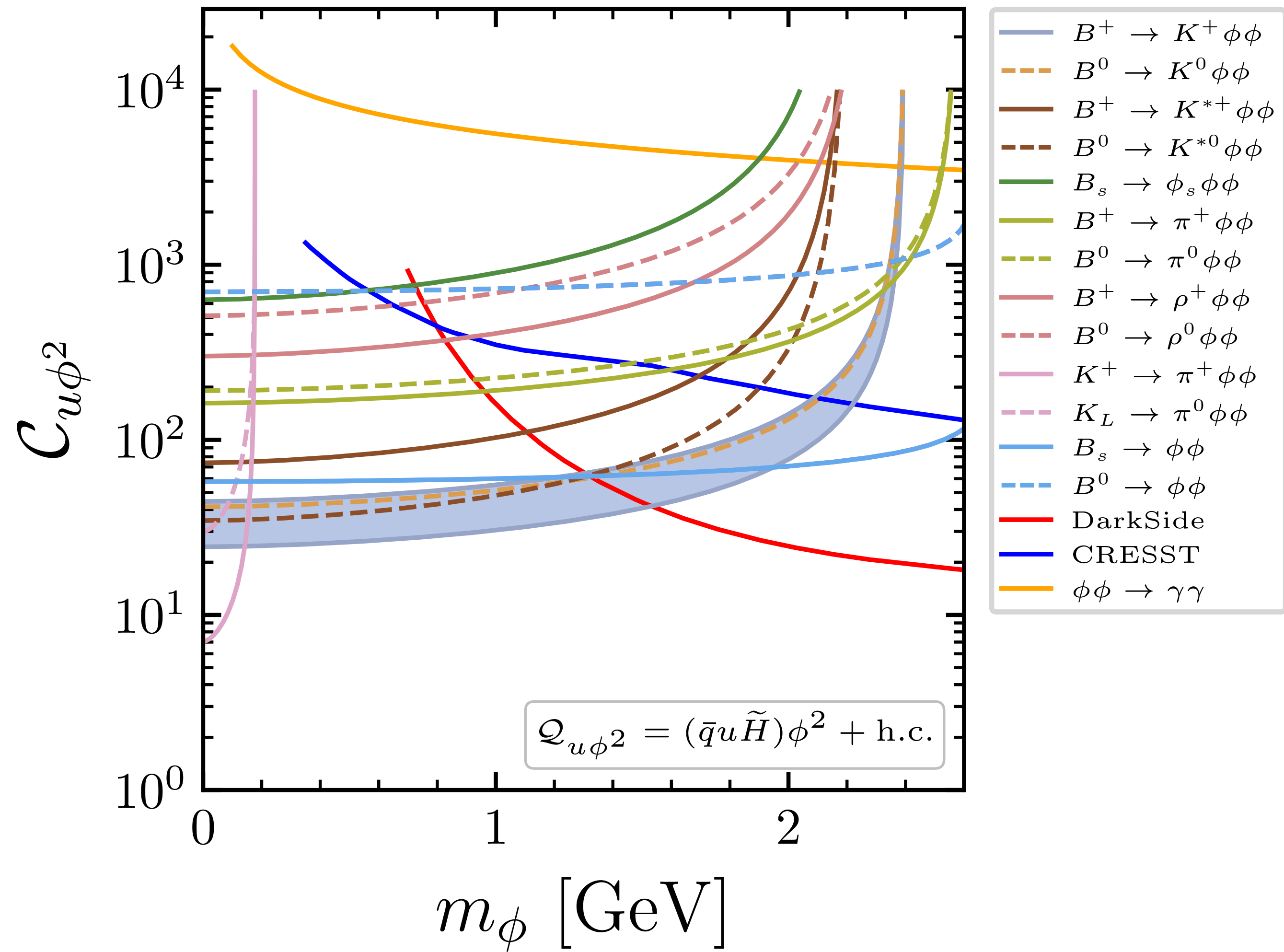


► Dark LEFT: **direct detection**

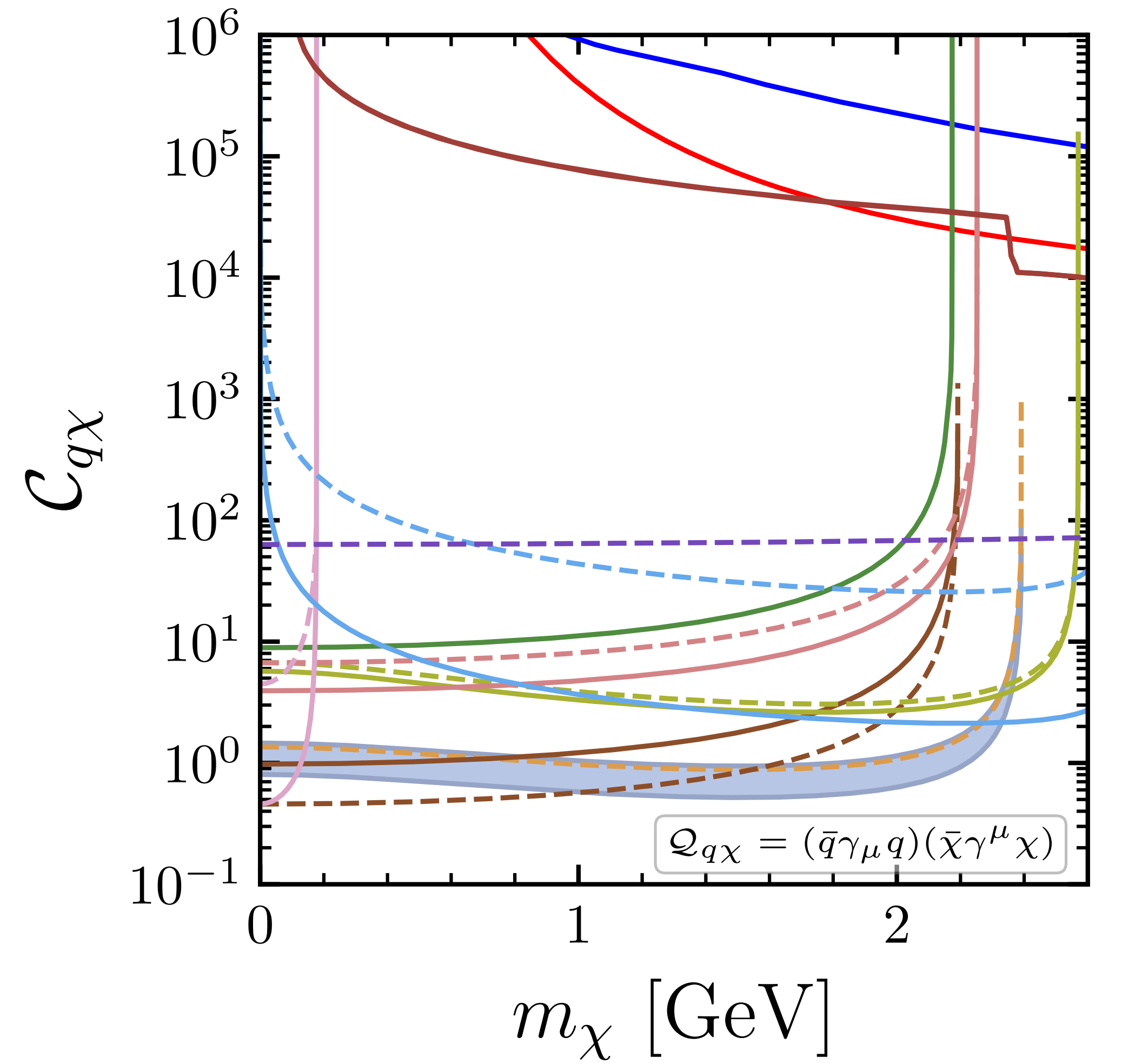
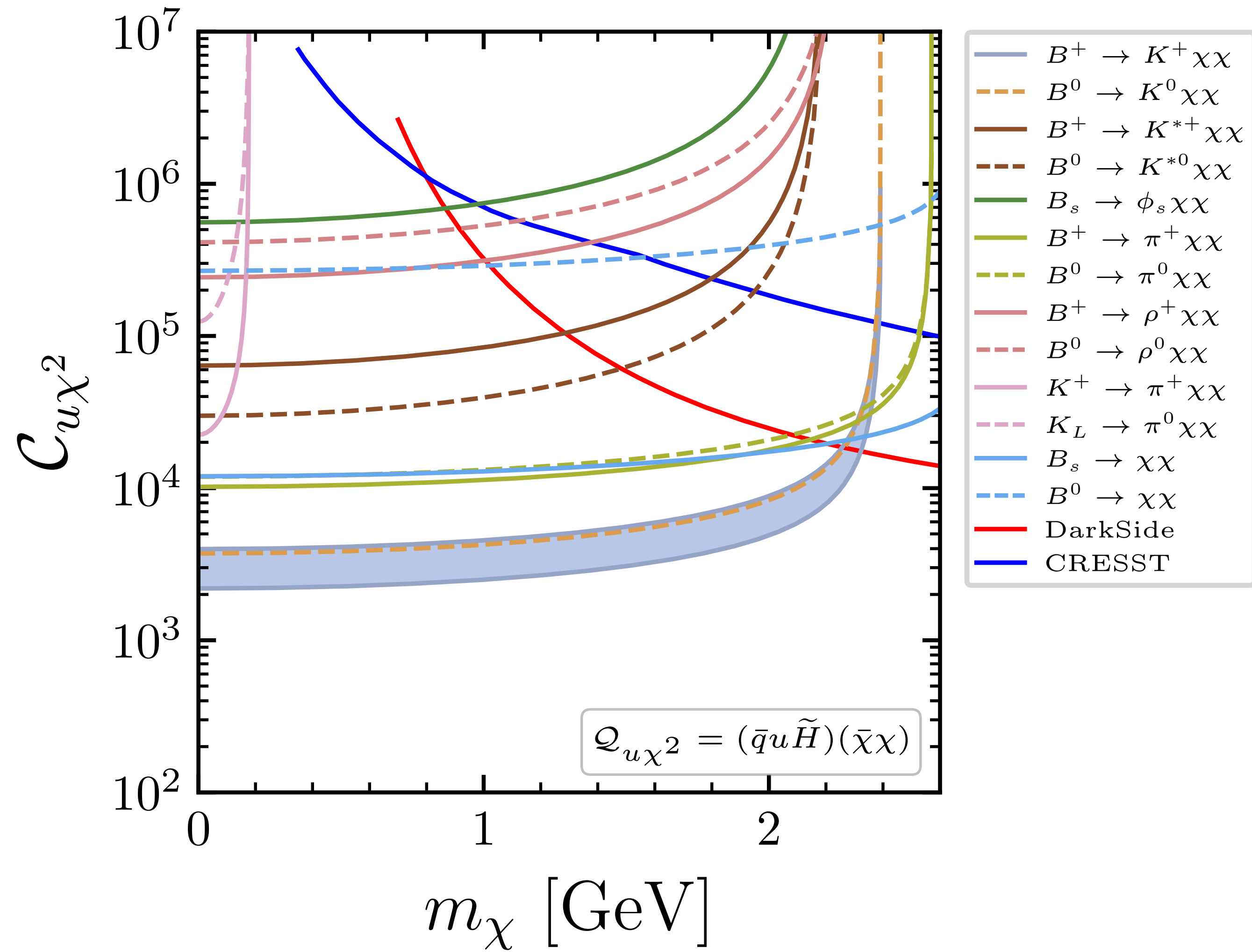
$$\mathcal{L}_{\text{DLEFT}} \supset \sum_k L_k \mathcal{O}_i^{(4)} + \boxed{\frac{1}{v} \sum_i L_i \mathcal{O}_i^{(5)}} + \boxed{\frac{1}{v^2} \sum_j L_j \mathcal{O}_j^{(6)}} + \boxed{\frac{1}{v^3} \sum_l L_l \mathcal{O}_l^{(7)}}$$

$\mathcal{O}_{g\phi} = G_{\mu\nu}^a G^{\mu\nu,a} \phi^2$	$\mathcal{O}_{d\phi^2} = (\bar{d}_p P_R d_r) \phi^2$	...	scalar
$\mathcal{O}_{g\chi} = G_{\mu\nu}^a G^{\mu\nu,a} \bar{\chi} \chi$	$\mathcal{O}_{d\chi}^{V,LR} = (\bar{d}_p \gamma_\mu P_L d_r) (\bar{\chi} \gamma^\mu \chi)$	...	fermion
$\mathcal{O}_{gX} = G_{\mu\nu}^a G^{\mu\nu,a} X_\rho X^\rho$	$\mathcal{O}_{dXX}^L = (\bar{d}_p \gamma^\mu P_L d_r) X_{\mu\nu} X^\nu$	...	vector

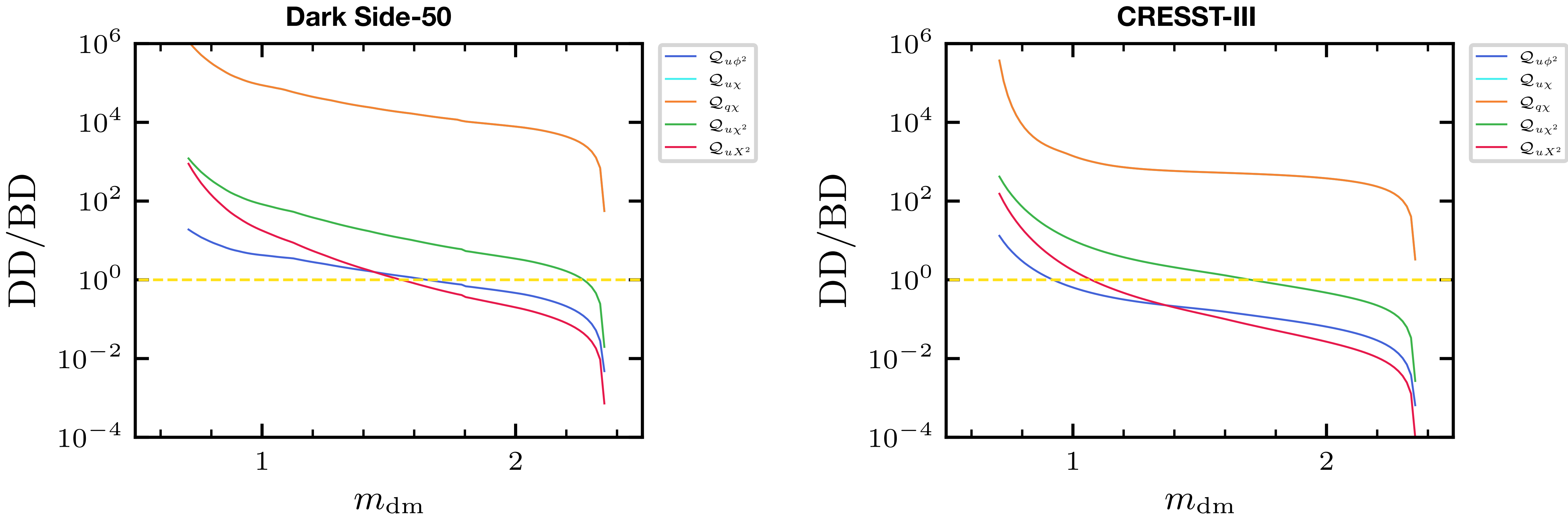
Hadron decay vs Direct detection



Hadron decay vs Direct detection



Hadron decay vs Direct detection



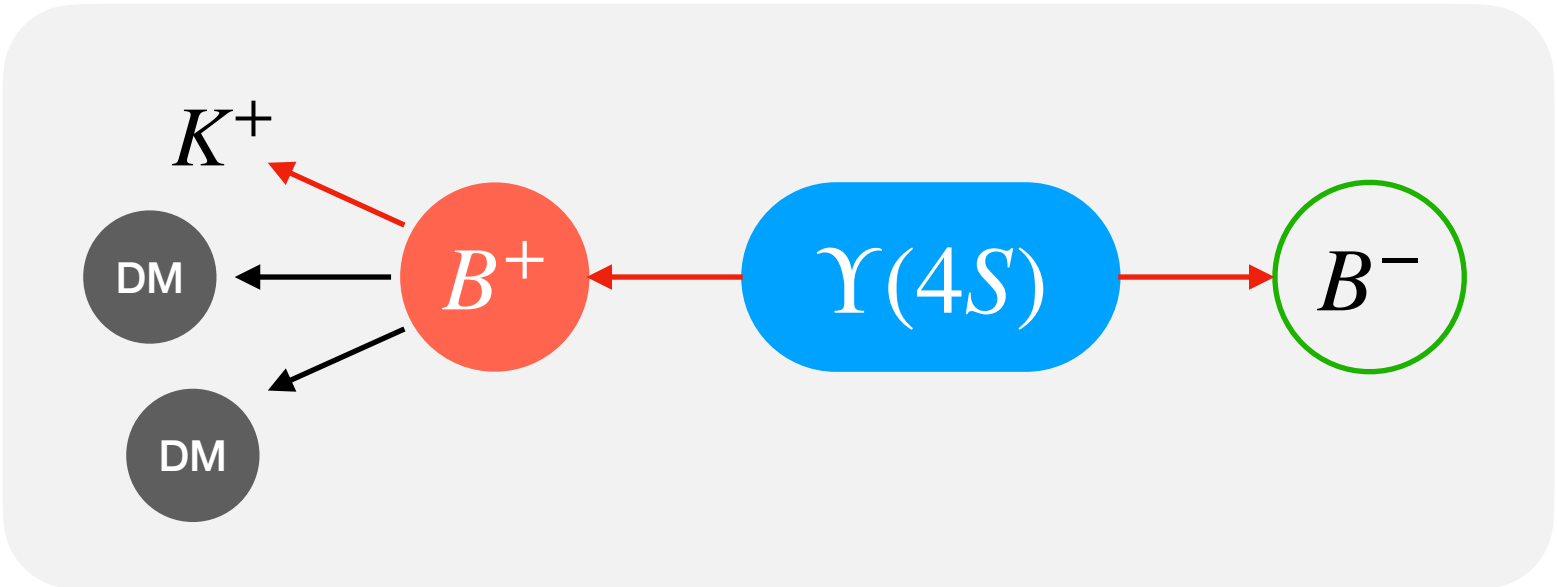
upper bound from **direct detection**
upper bound from **B FCNC decay**

Conclusion

It's natural to ask:

- 1. Compared to DM direct detection, what's the advantage of hadron decays? which DM scenario is **more sensitive** to ? Can provide **other information** ?
- 2. Can we build NP model, in which hadron decays into DM reach the future Belle II/STCF sensitivities, while providing enough DM relic density and satisfying the bounds from DM direct detection ?
- 3. Is it possible to obtain the flavour structure of light DM ?

HadronToNP: a package to calculate decay of hadron to new particles
 $B \rightarrow K + \text{DM}, B \rightarrow \rho + \text{DM}, \Lambda_b \rightarrow \Lambda + \text{DM}, \Upsilon \rightarrow \text{DM}, \dots$
 $D \rightarrow \pi + \text{DM}, D \rightarrow \rho + \text{DM}, \Xi_c \rightarrow \Xi + \text{DM}, J/\psi \rightarrow \text{DM}, \dots$ *to be finished*



A Possible Flavour Path to Dark Matter

	<i>d</i>	<i>s</i>	<i>b</i>
<i>d</i>	DD	NA62/KOTO	Belle II
<i>s</i>		DD	Belle II
<i>b</i>			Belle II/LHC
	<i>u</i>	<i>c</i>	<i>t</i>
<i>u</i>	DD	BES/STCF	LHC/CEPC
<i>c</i>		BES/STCF	LHC/CEPC
<i>t</i>			LHC/CEPC

Thank You !

Backup

$$\mathcal{C} = \begin{cases} \mathcal{C}_t & \text{for } \bar{u}_L \gamma^\mu \mathcal{C} u_L, u_R \gamma^\mu \mathcal{C} u_R, \bar{u}_L \mathcal{C} u_R, \bar{u}_L \sigma^{\mu\nu} \mathcal{C} u_R, \\ V^\dagger \mathcal{C}_t V & \text{for } \bar{d}_L \gamma^\mu \mathcal{C} d_L, \\ V^\dagger \mathcal{C}_t & \text{for } \bar{d}_L \mathcal{C} u_R, \bar{d}_L \sigma^{\mu\nu} \mathcal{C} u_R, \end{cases}$$

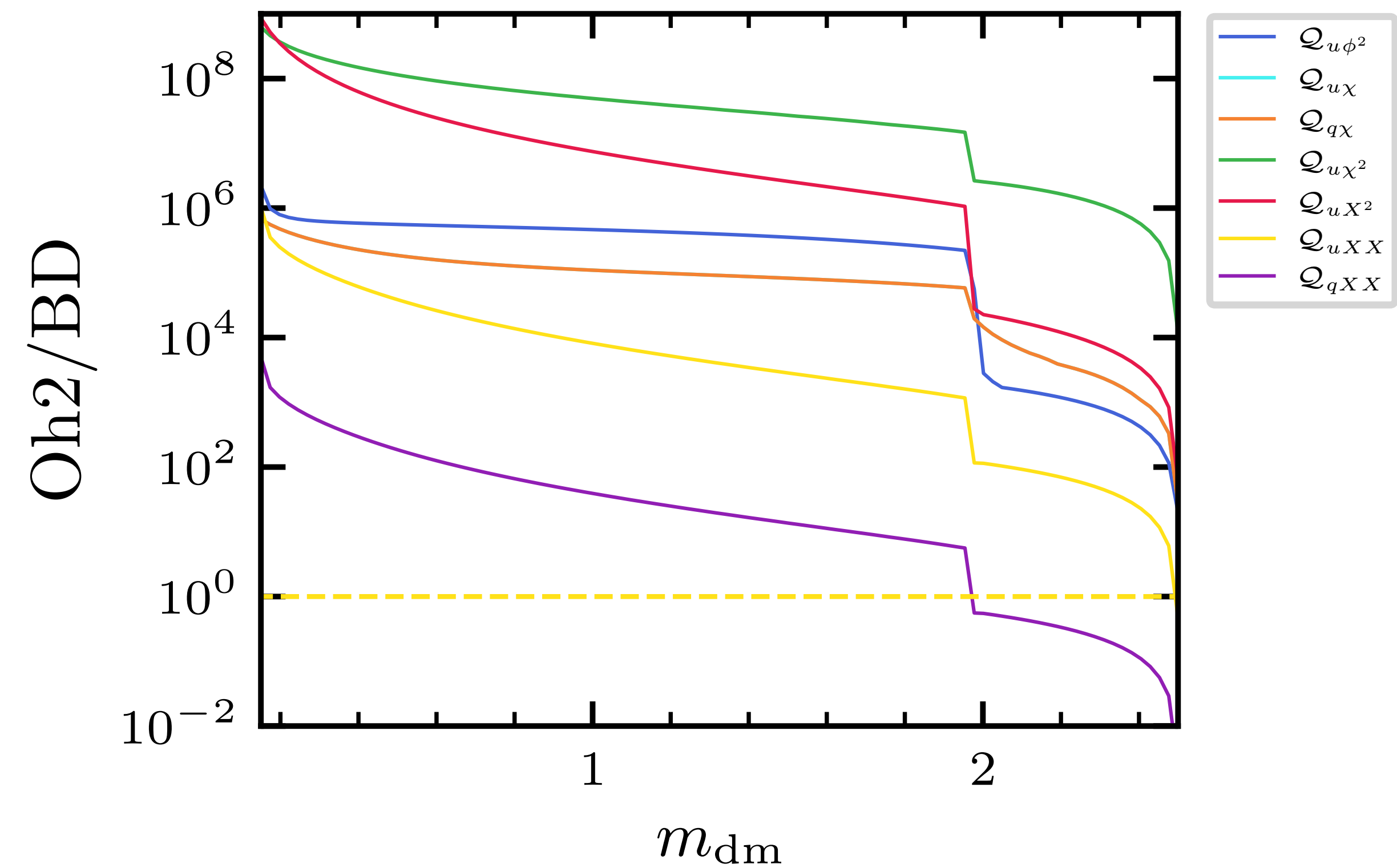
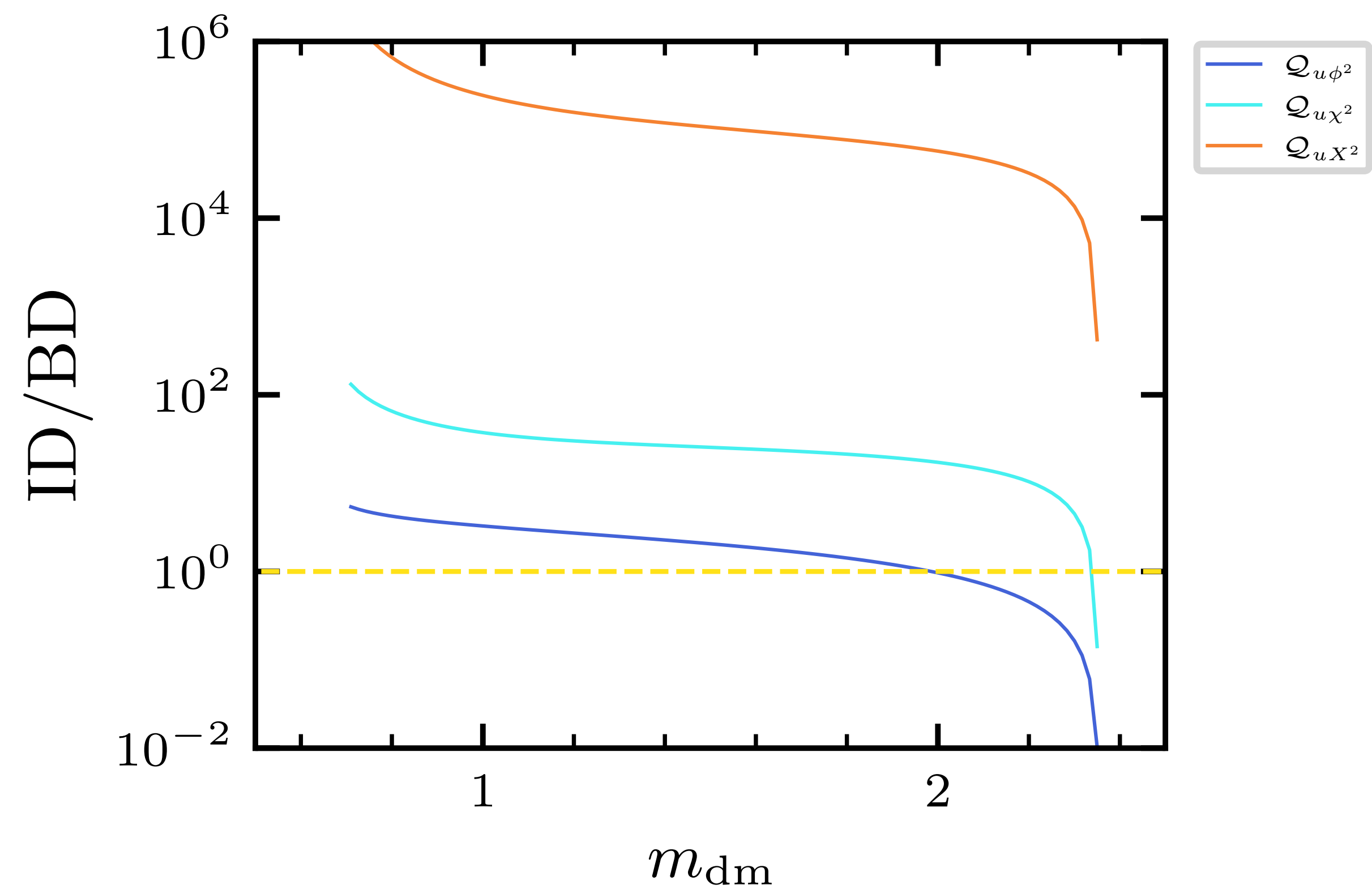
$$V^\dagger \mathcal{C}_t V = \mathcal{C}_{33} \begin{pmatrix} V_{td}^* V_{td} & V_{td}^* V_{ts} & V_{td}^* V_{tb} \\ V_{ts}^* V_{td} & V_{ts}^* V_{ts} & V_{ts}^* V_{tb} \\ V_{tb}^* V_{td} & V_{tb}^* V_{ts} & V_{tb}^* V_{tb} \end{pmatrix} \quad \mathcal{C}_t \equiv \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \mathcal{C}_{33} \end{pmatrix}$$

$$= \mathcal{C}_{33} \begin{pmatrix} 0.71 & -3.09 - 1.45i & 76.81 + 34.29i \\ -3.09 + 1.45i & 16.43 & -404.93 + 7.87i \\ 76.81 - 34.29i & -404.93 - 7.87i & 9982.86 \end{pmatrix} \times 10^{-4}$$

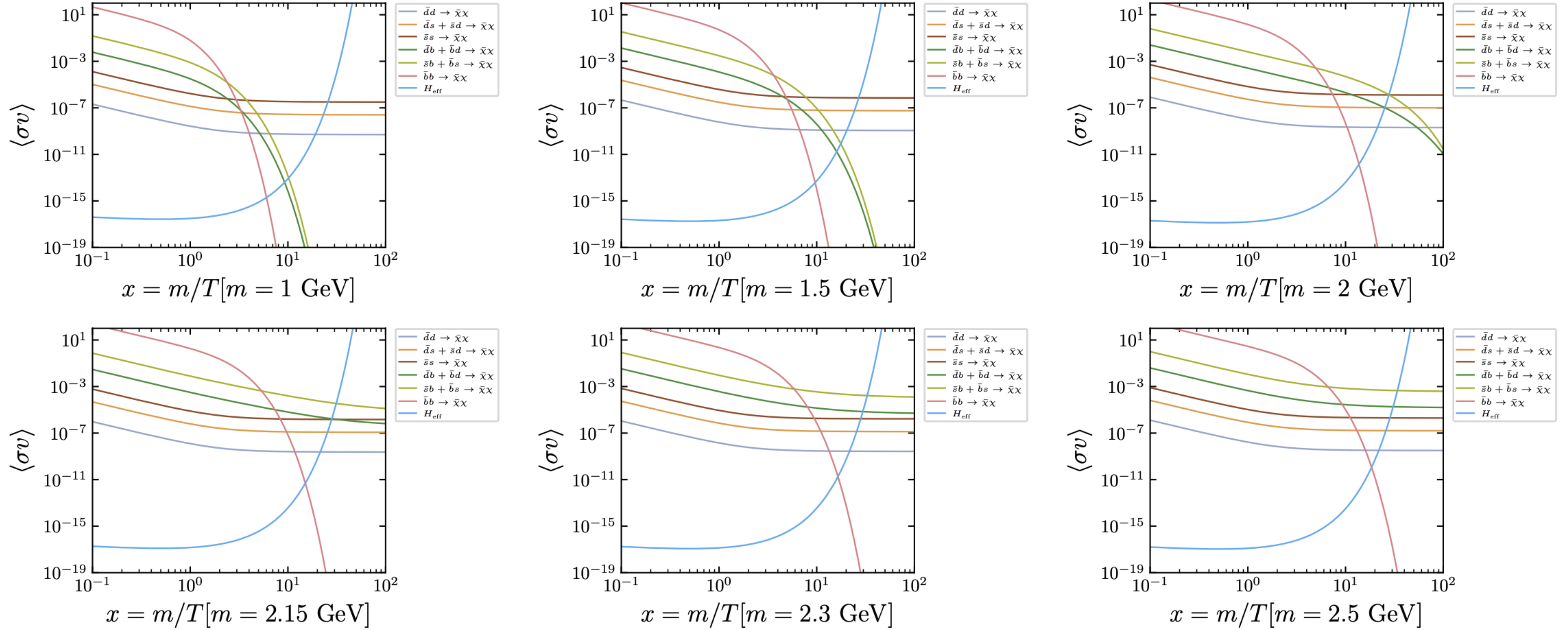
$$V^\dagger \mathcal{C}_t = \mathcal{C}_{33} \begin{pmatrix} 0 & 0 & V_{td}^* \\ 0 & 0 & V_{ts}^* \\ 0 & 0 & V_{tb}^* \end{pmatrix} = \mathcal{C}_{33} \begin{pmatrix} 0 & 0 & 0.77 + 0.34i \\ 0 & 0 & -4.05 + 0.08i \\ 0 & 0 & 99.91 \end{pmatrix} \times 10^{-2}$$

$$\mathcal{C}_i = \begin{cases} \mathcal{C}_t^i & \text{for } \mathcal{Q}_i = \mathcal{Q}_{\phi u}, \mathcal{Q}_{u\chi}, \mathcal{Q}_{uX}, \mathcal{Q}_{HuX}, \mathcal{Q}_{uXX}, \mathcal{Q}_{u\tilde{X}X}, \mathcal{Q}_{DuX^2}, \mathcal{Q}_{ua}, \\ (\mathcal{C}_t^i, V^\dagger \mathcal{C}_t^i) & \text{for } \mathcal{Q}_i = \mathcal{Q}_{u\phi}, \mathcal{Q}_{u\phi^2}, \mathcal{Q}_{u\chi^2}, \mathcal{Q}_{qu\chi l}, \mathcal{Q}_{uHX}, \mathcal{Q}_{uX^2}, \mathcal{Q}_{uHX^2}, \\ (\mathcal{C}_t^i, V^\dagger \mathcal{C}_t^i V) & \text{for } \mathcal{Q}_i = \mathcal{Q}_{\phi q}, \mathcal{Q}_{q\chi}, \mathcal{Q}_{qX}, \mathcal{Q}_{HqX}^{(1,3)}, \mathcal{Q}_{qXX}, \mathcal{Q}_{q\tilde{X}X}, \mathcal{Q}_{DqX^2}, \mathcal{Q}_{qa}, \end{cases}$$

Hadron decay vs Relic density and Indirect detection

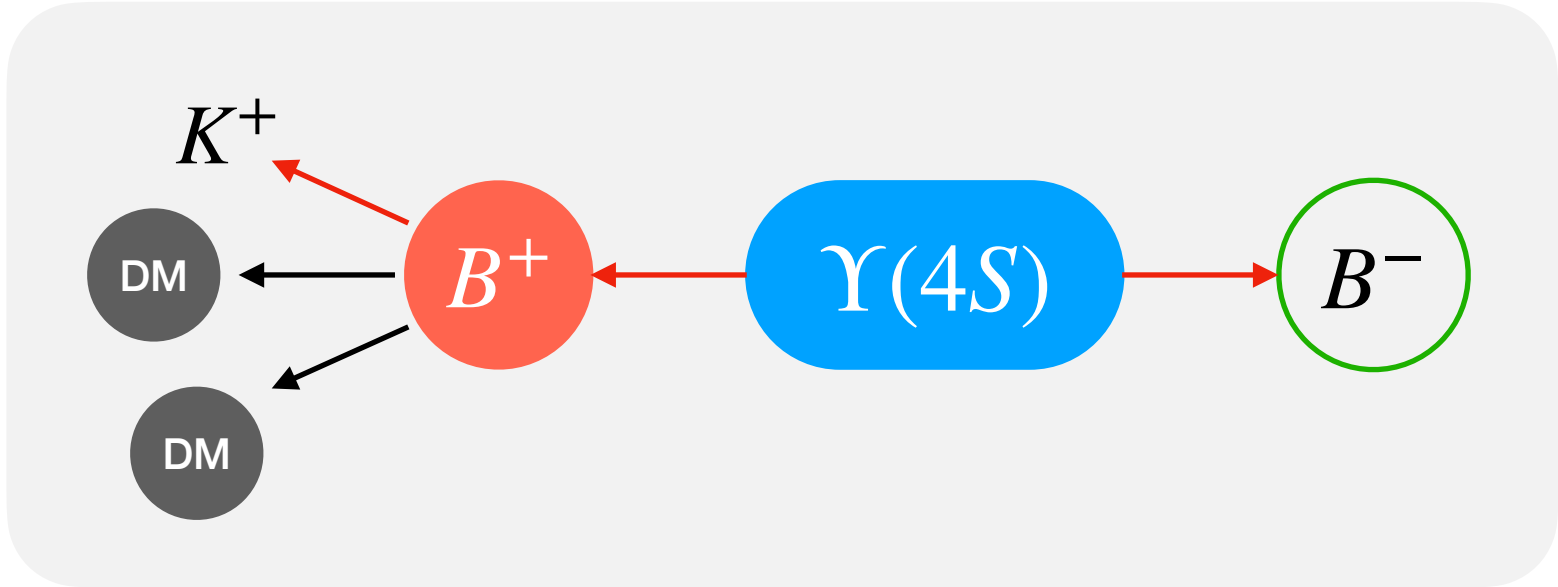
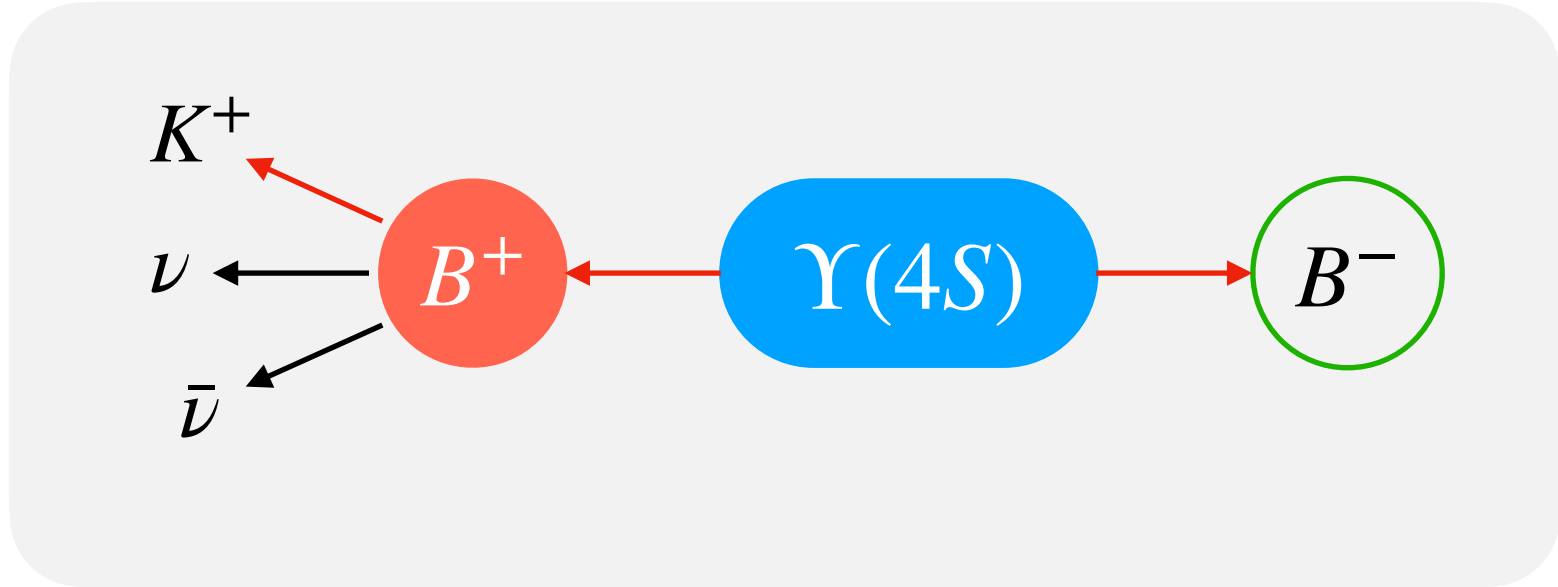


Hadron decay vs Relic density and Indirect detection



Conclusion

HadronToNP: a package to calculate decay of hadron to new particles
 $B \rightarrow K + \text{DM}, B \rightarrow \rho + \text{DM}, \Lambda_b \rightarrow \Lambda + \text{DM}, \Upsilon \rightarrow \text{DM}, \dots$ *to be finished*
 $D \rightarrow \pi + \text{DM}, D \rightarrow \rho + \text{DM}, \Xi_c \rightarrow \Xi + \text{DM}, J/\psi \rightarrow \text{DM}, \dots$



SMEFT

Dark SMEFT

$$\frac{\mathcal{B}(B^+ \rightarrow K^+ \nu \bar{\nu})}{\mathcal{B}(B^0 \rightarrow K^{*0} \nu \bar{\nu})} = \frac{\mathcal{B}(B^+ \rightarrow K^+ \nu \bar{\nu})_{\text{SM}}}{\mathcal{B}(B^0 \rightarrow K^{*0} \nu \bar{\nu})_{\text{SM}}} = 0.46 \pm 0.07$$
$$\frac{\mathcal{B}(B^+ \rightarrow K^+ \nu \bar{\nu})}{\mathcal{B}(B^+ \rightarrow \pi^+ \nu \bar{\nu})} = \frac{\mathcal{B}(B^+ \rightarrow K^+ \nu \bar{\nu})_{\text{SM}}}{\mathcal{B}(B^+ \rightarrow \pi^+ \nu \bar{\nu})_{\text{SM}}} = 29.7 \pm 5.6$$

- 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 Dark Matter

	d	s	b
d	DD	NA62/KOTO	Belle II
s		DD	Belle II
b			Belle II/LHC
u	DD	BES/STCF	LHC/CEPC
c		BES/STCF	LHC/CEPC
t			LHC/CEPC

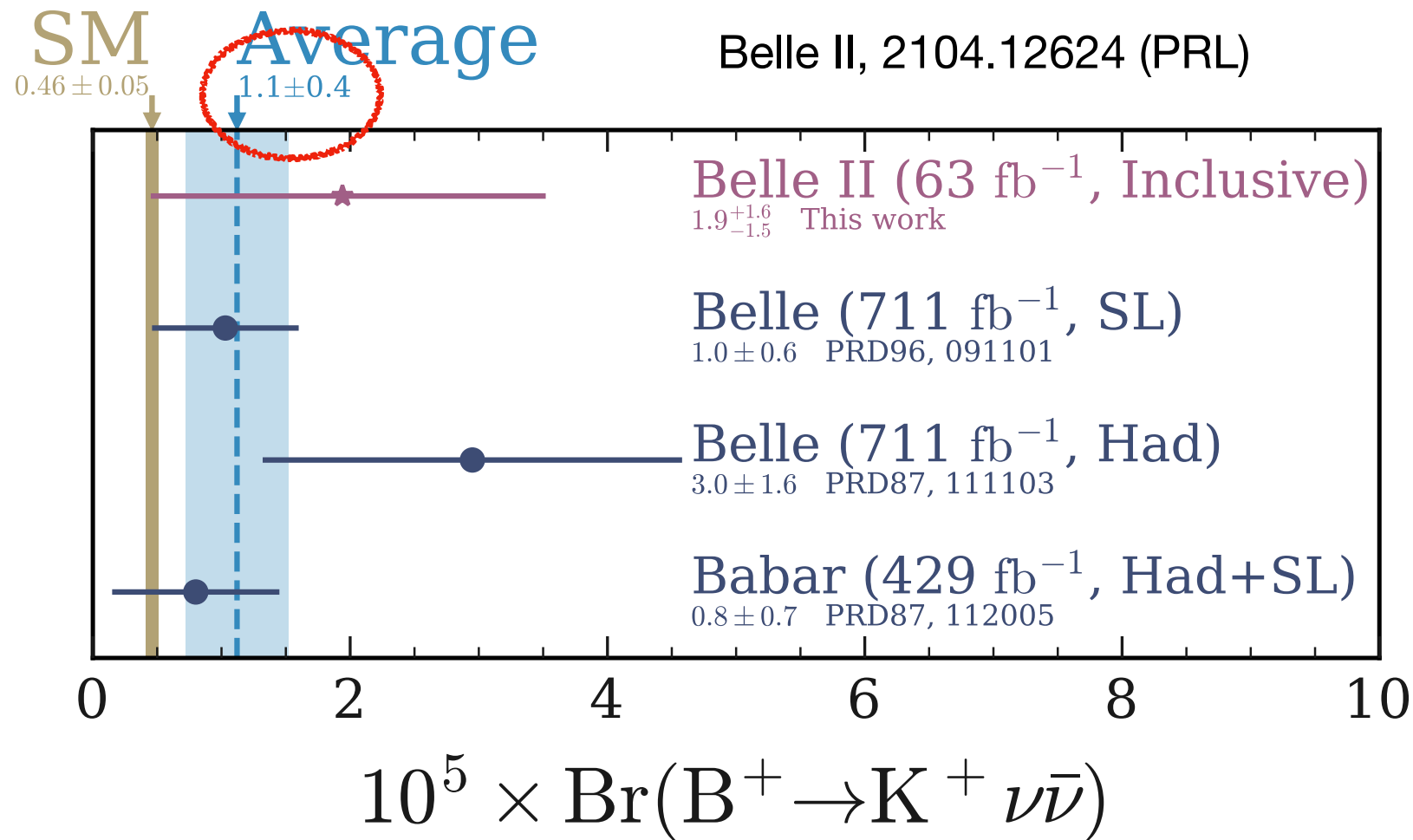
μ_{EW}
LEFT

Dark LEFT

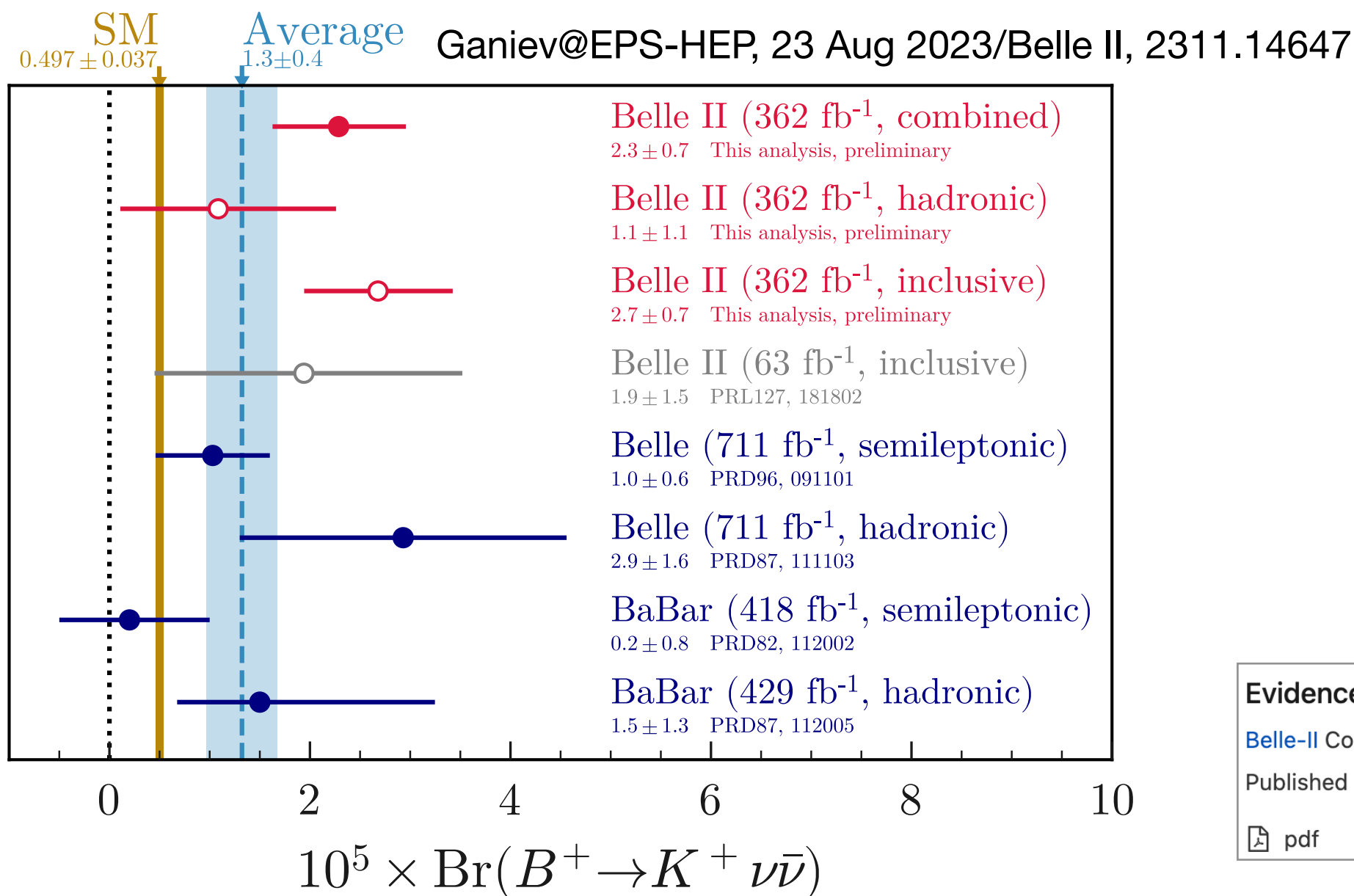
μ_b

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

► 2021 Apr



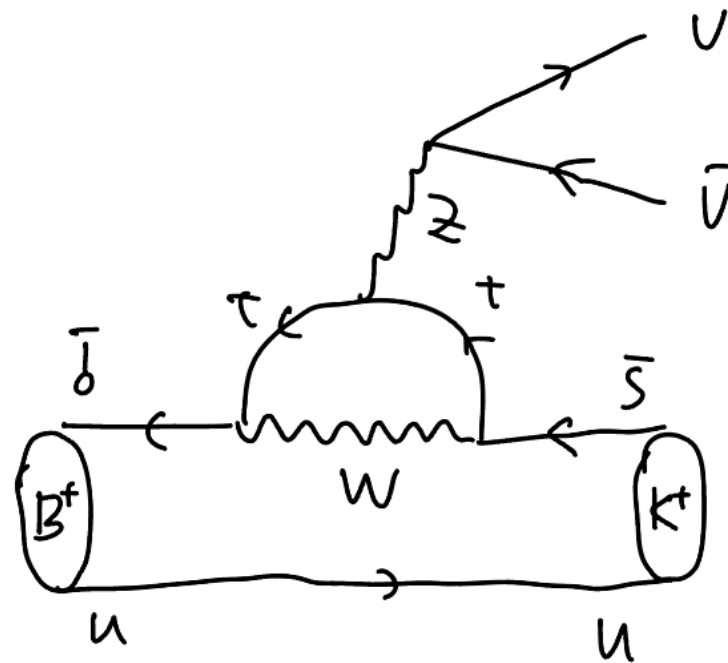
► 2023 Aug



► Exp vs SM [10⁻⁶]

$$\left. \begin{aligned} \mathcal{B}(B^+ \rightarrow K^+ \nu \bar{\nu})_{\text{SM}} &= 4.16 \pm 0.57 \\ \mathcal{B}(B^+ \rightarrow K^+ \nu \bar{\nu})_{\text{exp}} &= 23 \pm 7 \end{aligned} \right\} \text{2.7}\sigma \text{ difference} \\ \text{NP/SM} \gtrsim 2$$

$\mathcal{B}(B^+ \rightarrow K^+ \nu \bar{\nu})_{\text{exp}} \gtrsim 10$ (2 σ lower bound)



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

Factorization

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

Wilson coef quark current neutrino current

theoretically, simple and clean
one of the cleanest channels in
flavour physics

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

$$\mathcal{O}_L = (\bar{s} P_L b)(\bar{\nu} P_L \nu) \times$$

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

$$\mathcal{O}_R = (\bar{s} P_R b)(\bar{\nu} P_R \nu) \times$$

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

operator structure highly
constrained by LH neutrino

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

Evidence for $B^+ \rightarrow K^+ \nu \bar{\nu}$ decays

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

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83 citations



83 citations

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

$b \rightarrow s$

Observable	SM	Exp	Unit
$\mathcal{B}(B^+ \rightarrow K^+ \nu \bar{\nu})$	4.16 ± 0.57	$23 \pm 5^{+5}_{-4}$	10^{-6}
$\mathcal{B}(B^0 \rightarrow K^0 \nu \bar{\nu})$	3.85 ± 0.52	< 26	10^{-6}
$\mathcal{B}(B^+ \rightarrow K^{*+} \nu \bar{\nu})$	9.70 ± 0.94	< 61	10^{-6}
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$\mathcal{B}(B_s \rightarrow \phi \nu \bar{\nu})$	9.93 ± 0.72	< 5400	10^{-6}
$\mathcal{B}(B_s \rightarrow \nu \bar{\nu})$	≈ 0	< 5.9	10^{-4}

$b \rightarrow d$

$\mathcal{B}(B^+ \rightarrow \pi^+ \nu \bar{\nu})$	1.40 ± 0.18	< 140	10^{-7}
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$s \rightarrow d$

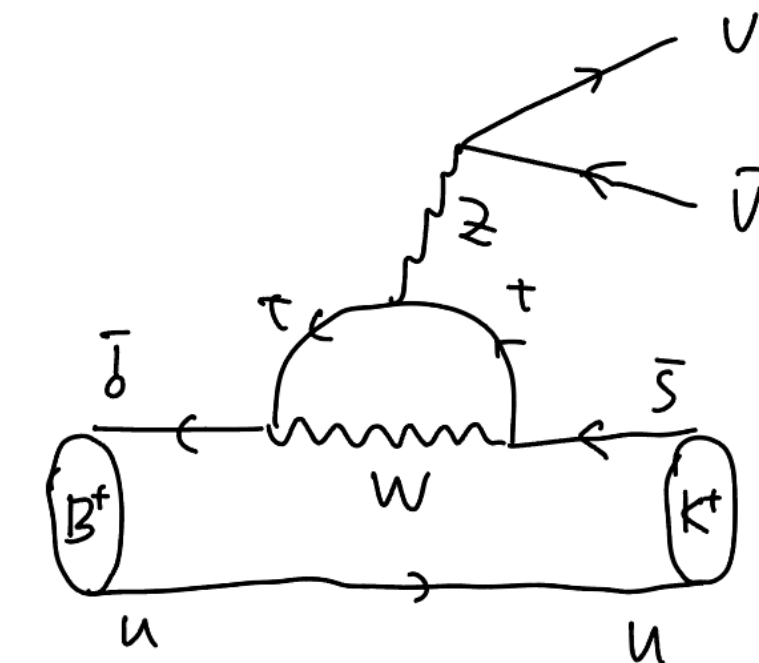
$\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$	8.42 ± 0.61	$10.6^{+4.0}_{-3.4} \pm 0.9$	10^{-11}
$\mathcal{B}(K_L \rightarrow \pi^0 \nu \bar{\nu})$	3.41 ± 0.45	< 300	10^{-11}

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

► Exp vs SM [10⁻⁶]

$$\left. \begin{aligned} \mathcal{B}(B^+ \rightarrow K^+ \nu \bar{\nu})_{\text{SM}} &= 4.16 \pm 0.57 \\ \mathcal{B}(B^+ \rightarrow K^+ \nu \bar{\nu})_{\text{exp}} &= 23 \pm 7 \end{aligned} \right\} \begin{array}{l} \text{2.7}\sigma \text{ difference} \\ \text{NP/SM} \gtrsim 2 \end{array}$$

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



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

Factorization

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

Wilson coef

quark current

neutrino current

theoretically, simple and clean
one of the cleanest channels in flavour physics

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

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

$$\mathcal{O}_L = (\bar{s} P_L b)(\bar{\nu} P_L \nu) \text{ X}$$

$$\mathcal{O}_R = (\bar{s} P_R b)(\bar{\nu} P_R \nu) \text{ X}$$

$$\mathcal{O}_T = (\bar{s} \sigma_{\mu\nu} b)(\bar{\nu} \sigma^{\mu\nu} \nu) \text{ X}$$

$$\mathcal{O}_{T5} = (\bar{s} \sigma_{\mu\nu} \gamma_5 b)(\bar{\nu} \sigma^{\mu\nu} \nu) \text{ X}$$

operator structure highly
constrained by LH neutrino

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

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in $b \rightarrow d, s \rightarrow d$ decays ? **NP flavour structure**

SMEFT

$$\mathcal{Q}_{Hq}^{(1)} = (H^\dagger i \overleftrightarrow{D}_\mu H) (\bar{q}_p \gamma^\mu q_r),$$

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

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

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

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

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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

operator structure highly
constrained by Left-handed neutrino

Minimal Flavour Violation

- ▶ Flavour symmetry without Yukawa

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

- ▶ 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 $\implies$ spurion field

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

D'Ambrosio, Giudice, Isidori, Strumia, 2009

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

$$\mathcal{C}^{\text{MFV}} = \begin{cases} f(A, B) & \text{for } \bar{q} \gamma^\mu \mathcal{C} q, \\ f(A, B) Y_d & \text{for } \bar{q} \mathcal{C} d, \bar{q} \sigma^{\mu\nu} \mathcal{C} d, \\ \epsilon_0 \mathbb{1} + Y_d^\dagger g(A, B) Y_d & \text{for } \bar{d} \gamma^\mu \mathcal{C} d, \end{cases} \quad \begin{aligned} f(A, B) &= \epsilon_0 \mathbb{1} + \epsilon_1 A + \epsilon_2 B + \epsilon_3 A^2 + \epsilon_4 B^2 + \epsilon_5 AB + \dots \\ A &= Y_u Y_u^\dagger \\ B &= Y_d Y_d^\dagger \end{aligned}$$

Minimal Flavour Violation

- ▶ Spurion function

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

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

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

- ▶ Spurion function after resummation

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

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

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

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

Minimal Flavour Violation

- ▶ MFV coupling FCNC controlled by CKM

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

No Right-handed down-type FCNC !

- ▶ Numerics

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

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

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

► Prediction

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

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► prediction

$$\mathcal{B}(B^0 \rightarrow K^{*0} \nu \bar{\nu})_{\text{SM}} = (9.00 \pm 0.87) \times 10^{-6}$$

$$\mathcal{B}(B^0 \rightarrow K^{*0} \nu \bar{\nu})_{\text{MFV}} = (50_{-16}^{+17}) \times 10^{-6}$$

$$\mathcal{B}(B^0 \rightarrow K^{*0} \nu \bar{\nu})_{\text{exp}} < 18 \times 10^{-6}$$

$$\mathcal{B}(B^+ \rightarrow \pi^+ \nu \bar{\nu})_{\text{SM}} = (1.40 \pm 0.18) \times 10^{-7}$$

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SMEFT

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

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

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

forbidden by MFV

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

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one LEFT operator !
just the SM operator

μ_b

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

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$$\mathcal{B}(B^+ \rightarrow \pi^+ \nu \bar{\nu})_{\text{SM}} = (1.40 \pm 0.18) \times 10^{-7}$$

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$$\mathcal{B}(B^+ \rightarrow \pi^+ \nu \bar{\nu})_{\text{exp}} < 140 \times 10^{-7}$$

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.

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

SMEFT

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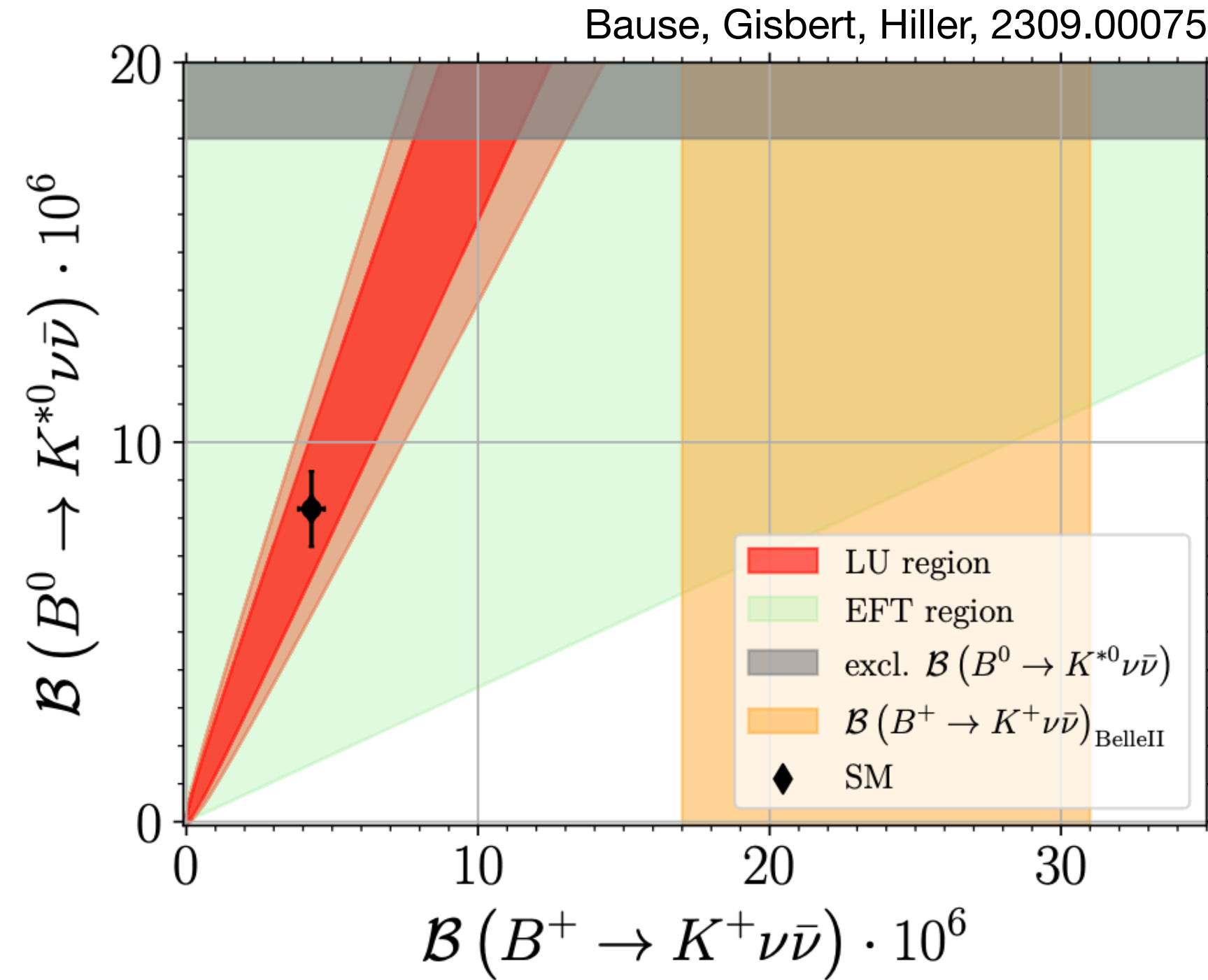
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μ_b

operator structure highly
constrained by Left-handed neutrino



$$\mathcal{B}(B^+ \rightarrow K^+ \nu \bar{\nu}) = A_+^{BK} x^+,$$

$$\mathcal{B}(B^0 \rightarrow K^{*0} \nu \bar{\nu}) = A_+^{BK^*} x^+ + A_-^{BK^*} x^-,$$

$$x^\pm = \sum_{\nu, \nu'} |C_L^{\nu \nu'} \pm C_R^{\nu \nu'}|^2,$$

Bause, Gisbert, Hiller, 2309.00075

Allwicher, Becirevic, Piazza, Rosauero-Alcaraz, Sumensari, 2309.02246

Chen, Wen, Xu, 2401.11552

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

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$b \rightarrow d$

$s \rightarrow d$

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in $b \rightarrow d, s \rightarrow d$ decays ? **NP flavour structure**

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

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

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

► Prediction

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$$\mathcal{B}(B^0 \rightarrow K^{*0} \nu \bar{\nu})_{\text{SMEFT}} = (50^{+17}_{-16}) \times 10^{-6} \quad \text{conflict}$$

$$\mathcal{B}(B^0 \rightarrow K^{*0} \nu \bar{\nu})_{\text{exp}} < 18 \times 10^{-6}$$

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

► $\mathcal{O}_{ld}$ can explain the $B^+ \rightarrow K^+ \nu \bar{\nu}$ data

► $\mathcal{O}_{ld}$ also induce $O'_{9,ij}$ and $O'_{10,ij}$

► They can't improve the $b \rightarrow s\ell\ell$ 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.

SMEFT

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

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induce $\bar{s}bZ$ interaction,
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μ_{EW}

LEFT

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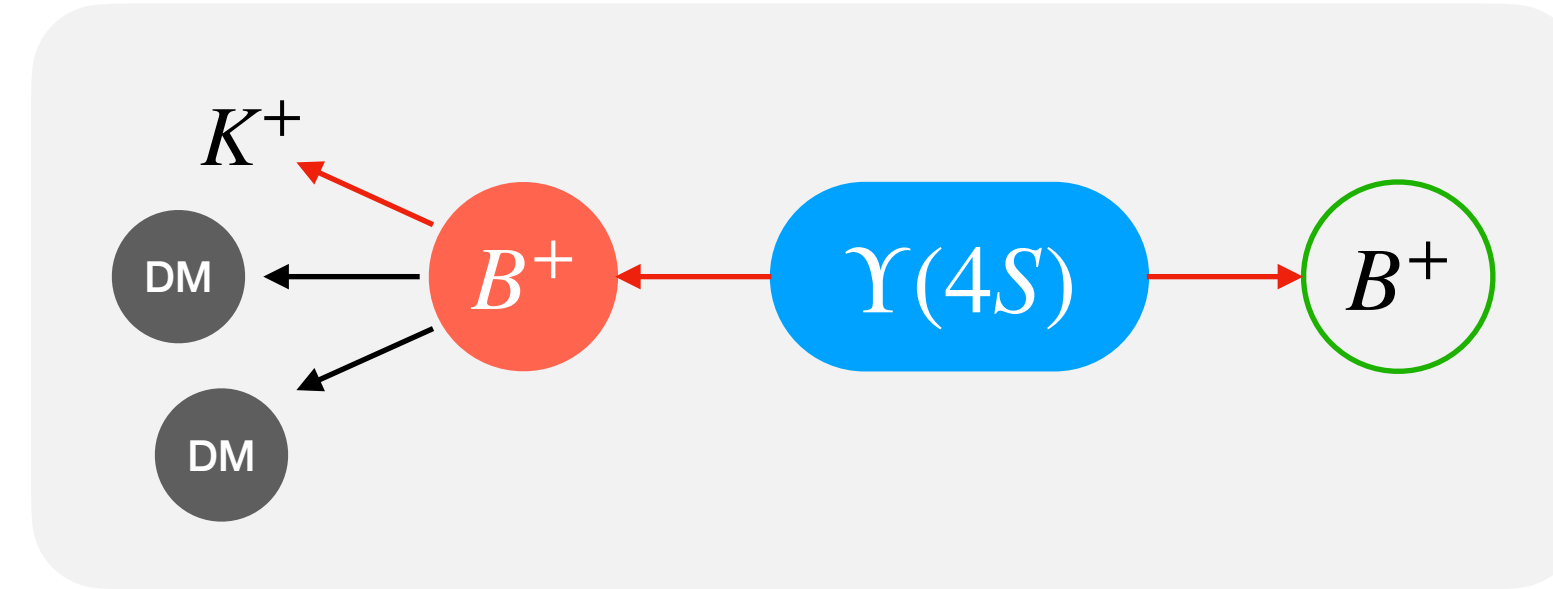
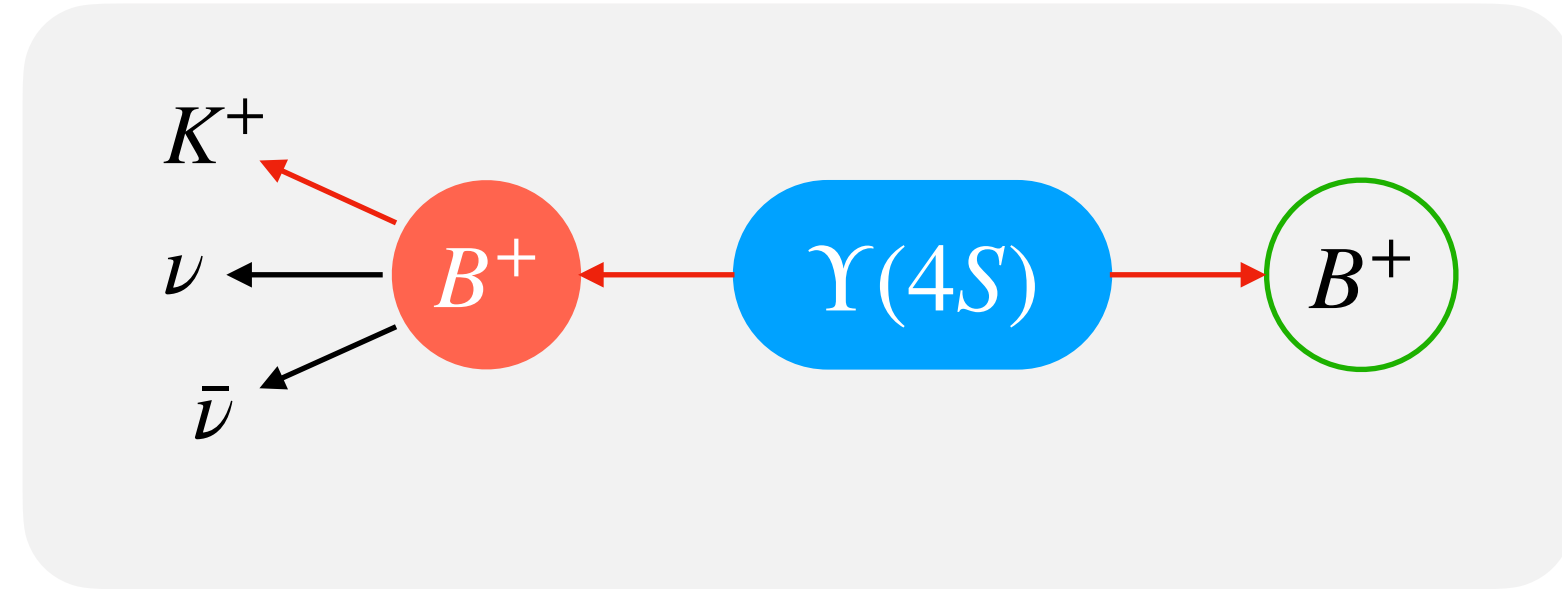
one LEFT operator !
just the SM operator

μ_b

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

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

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



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

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

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

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

SMEFT

Dark SMEFT

example

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

- 2011 Kamenik, Smith
- 2014 Duch, Grzadkowski, Wudka
- 2017 Brod, Gootjes-Dreesbach, Tamaro, 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}
LEFT

Dark LEFT

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

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

Dark SMEFT with MFV

- ▶ MFV coupling $b \rightarrow s, b \rightarrow d, s \rightarrow d$ are connected with each other.

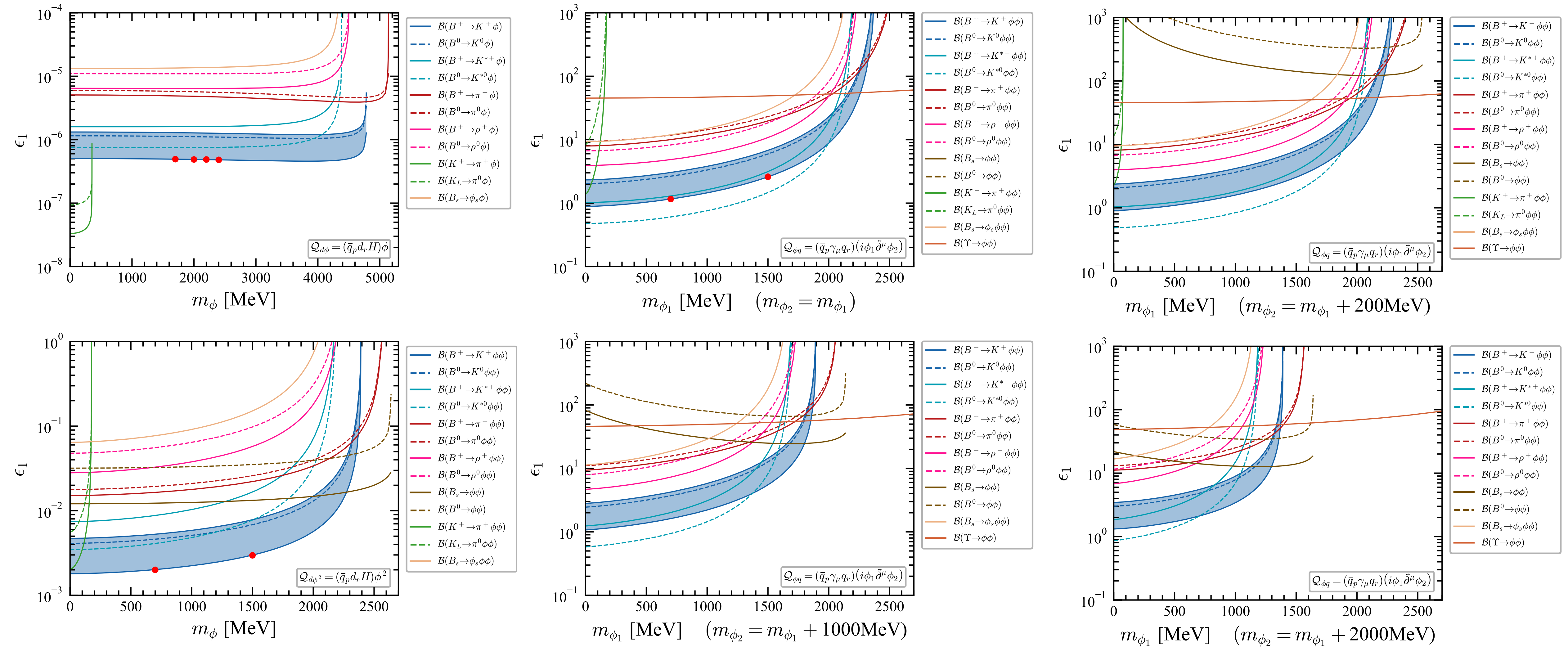
$$c_i^{\text{MFV}} = \begin{cases} \epsilon_0^i \hat{\lambda}_d + \epsilon_1^i \Delta_q \hat{\lambda}_d & \text{for } \mathcal{Q}_i = \mathcal{Q}_{d\phi}, \mathcal{Q}_{d\phi^2}, \mathcal{Q}_{dHX}, \mathcal{Q}_{dHX^2}, \mathcal{Q}_{dX^2}, \\ \epsilon_0^i \mathbb{1} + \epsilon_1^i \Delta_q & \text{for } \mathcal{Q}_i = \mathcal{Q}_{\phi q}, \mathcal{Q}_{q\chi}, \mathcal{Q}_{qXX}, \mathcal{Q}_{q\tilde{X}X}, \mathcal{Q}_{DqX^2}, \mathcal{Q}_{qX}, \mathcal{Q}_{HqX}^{(1,3)}, \mathcal{Q}_{qa}, \\ \epsilon_0^i \mathbb{1} & \text{for } \mathcal{Q}_i = \mathcal{Q}_{\phi d}, \mathcal{Q}_{d\chi}, \mathcal{Q}_{dXX}, \mathcal{Q}_{d\tilde{X}X}, \mathcal{Q}_{DdX^2}, \mathcal{Q}_{dX}, \mathcal{Q}_{HdX}, \mathcal{Q}_{da}, \end{cases} \quad \text{8 operators are eliminated}$$

- ▶ Numerics

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

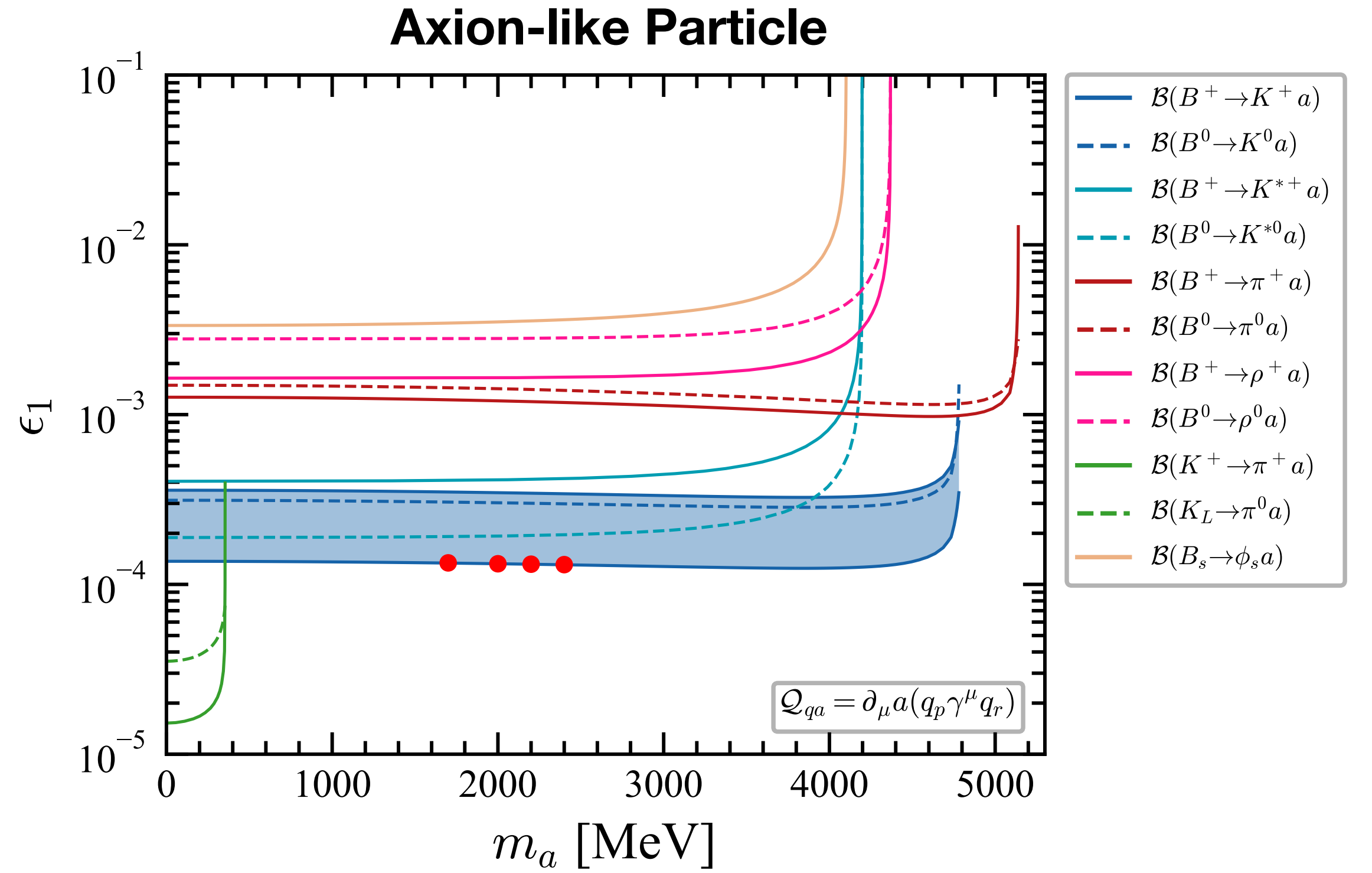
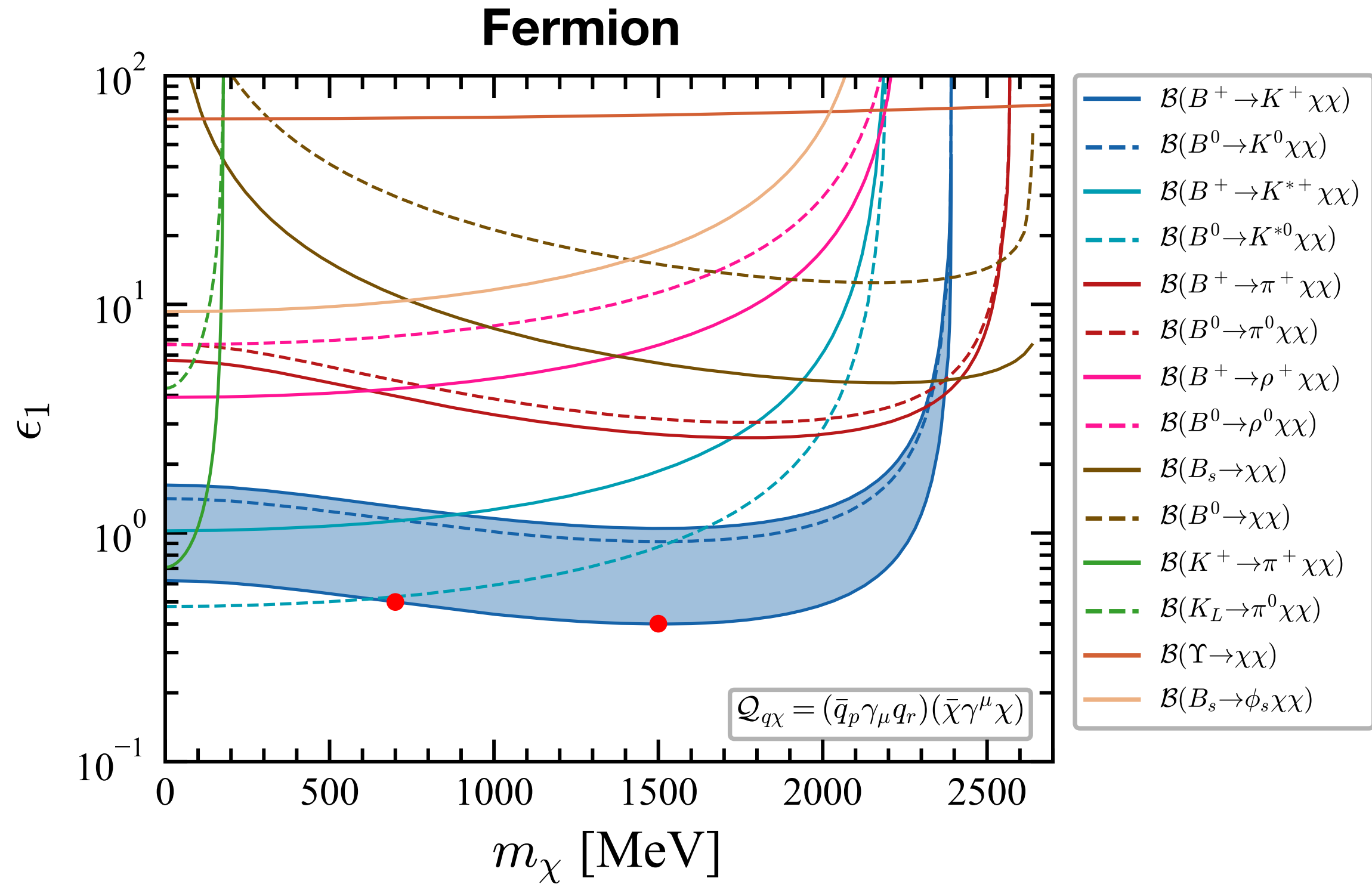
$$\Delta_q \hat{\lambda}_d = \begin{pmatrix} 0.0021 & -0.18 - 0.08i & 191.3 + 85.4i \\ -0.009 + 0.004i & 0.88 & -958.7 + 19.6i \\ 0.21 - 0.10i & -21.1 - 0.4i & 23728.1 \end{pmatrix} \times 10^{-6}$$

Dark SMEFT with MFV: Scalar



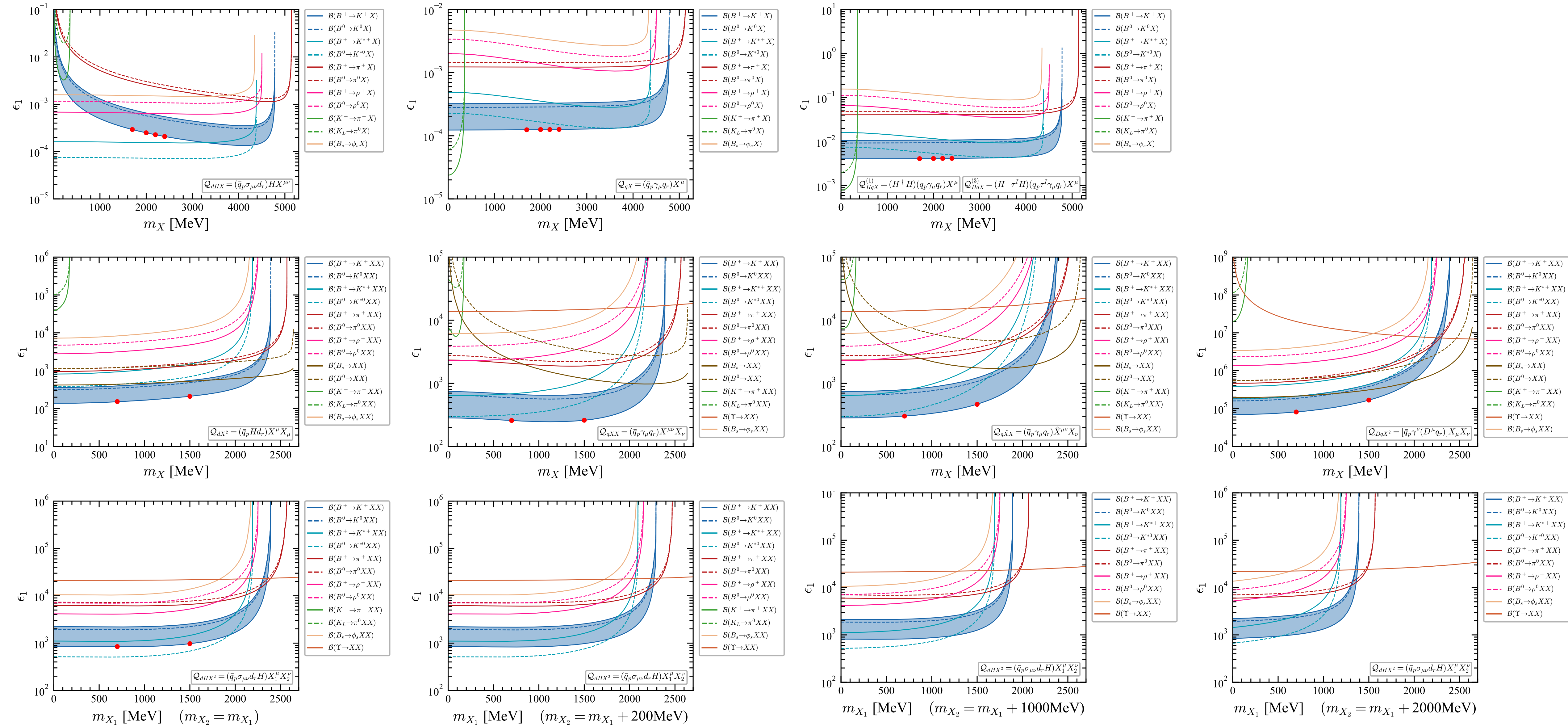
all the operators survive
some ones highly constrained

Dark SMEFT with MFV: Fermion, ALP



all the operators survive

Dark SMEFT with MFV: Vector



all the operators survive, some ones highly constrained

Backup

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

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

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

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

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

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

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

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

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. Λ_{LN} denotes the breaking scale of the lepton number symmetry $U(1)_{\text{LN}}$. 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

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

finite polynomial of $\mathbf{A}_\ell$ and $\mathbf{B}_\ell$. After neglecting all the terms involving $\mathbf{B}_\ell$, which are suppressed by the small lepton Yukawa couplings Y_e , we obtain

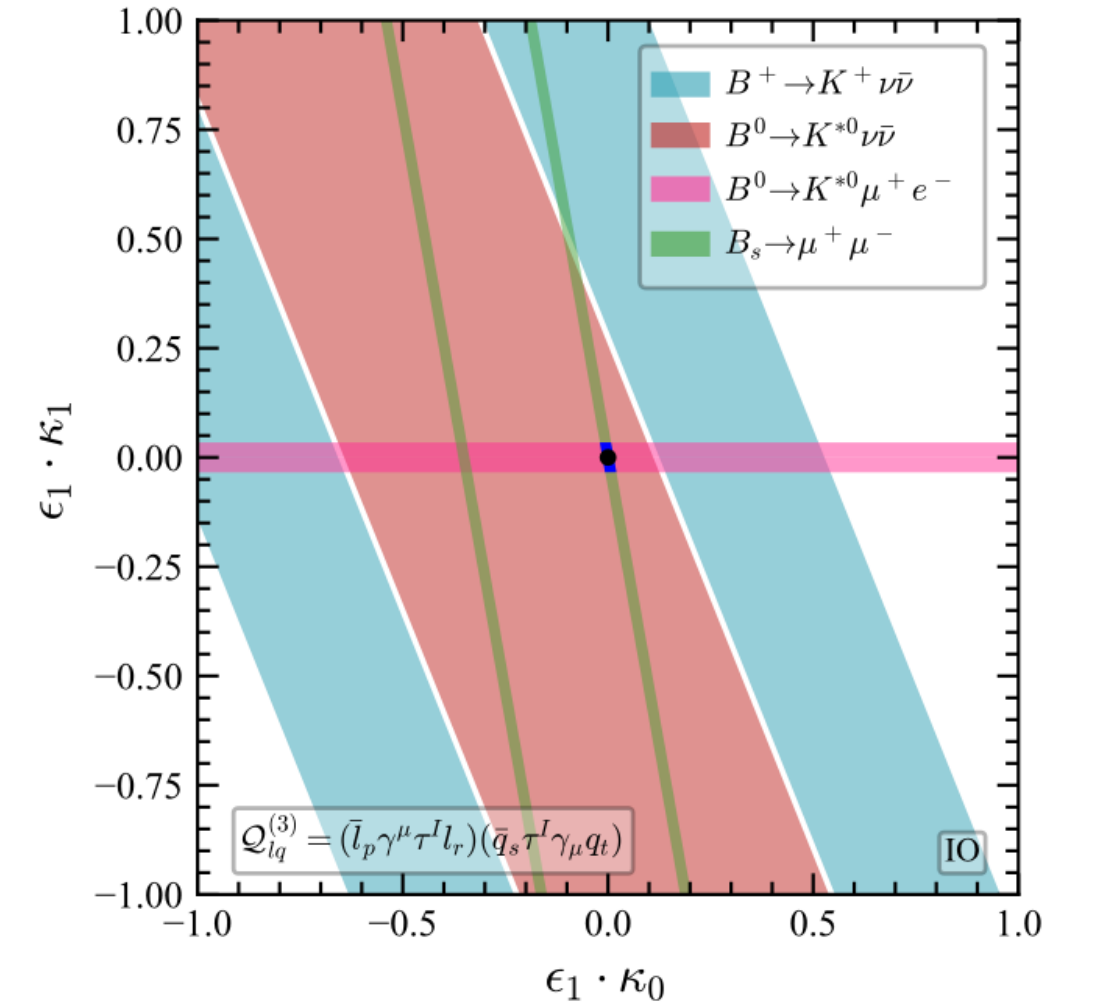
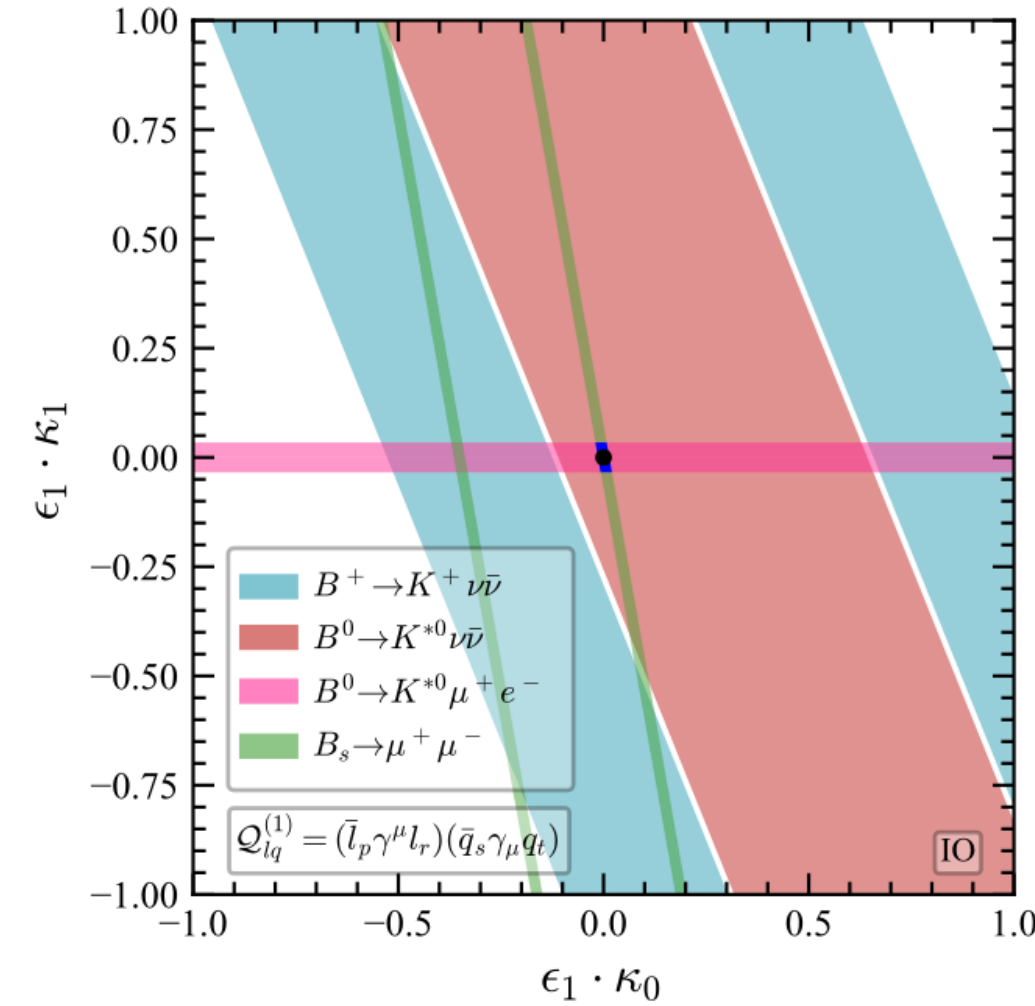
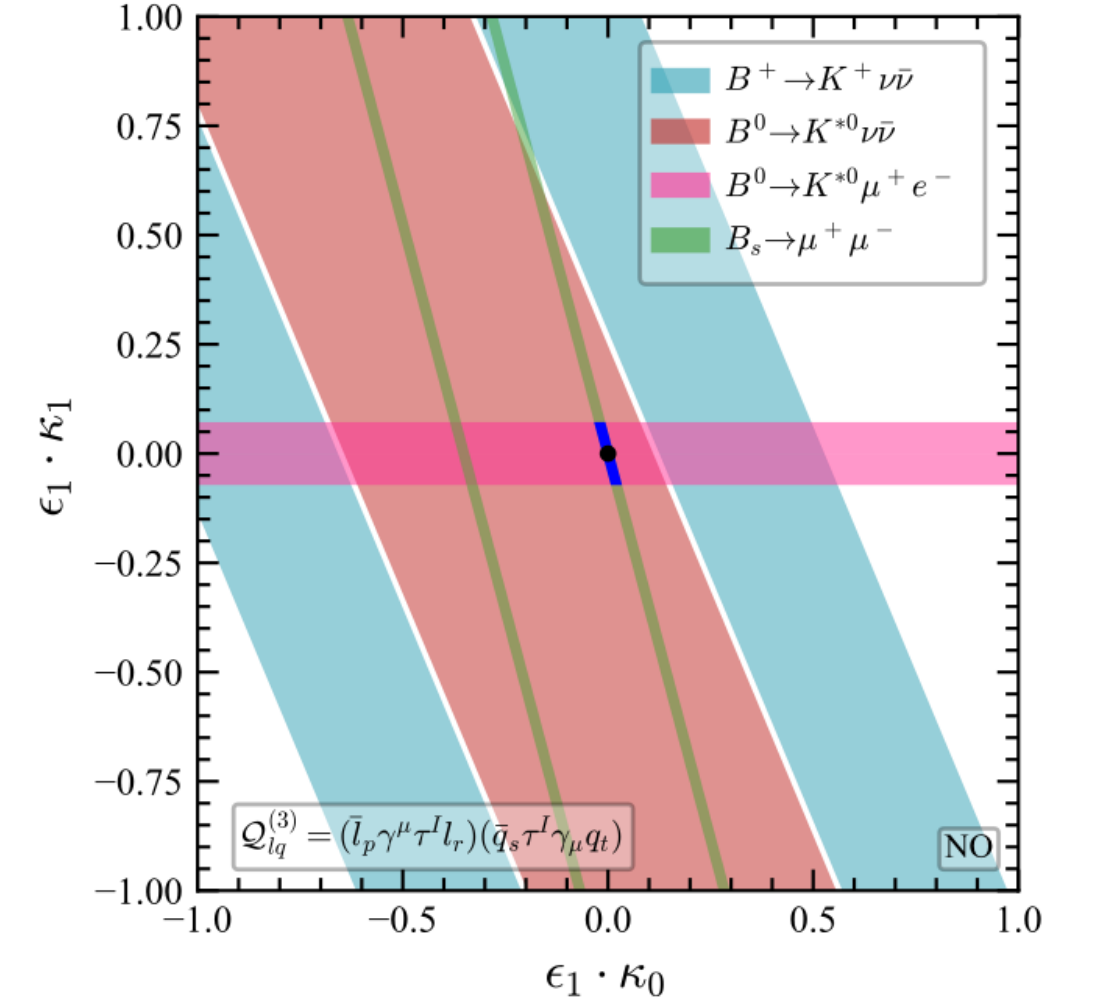
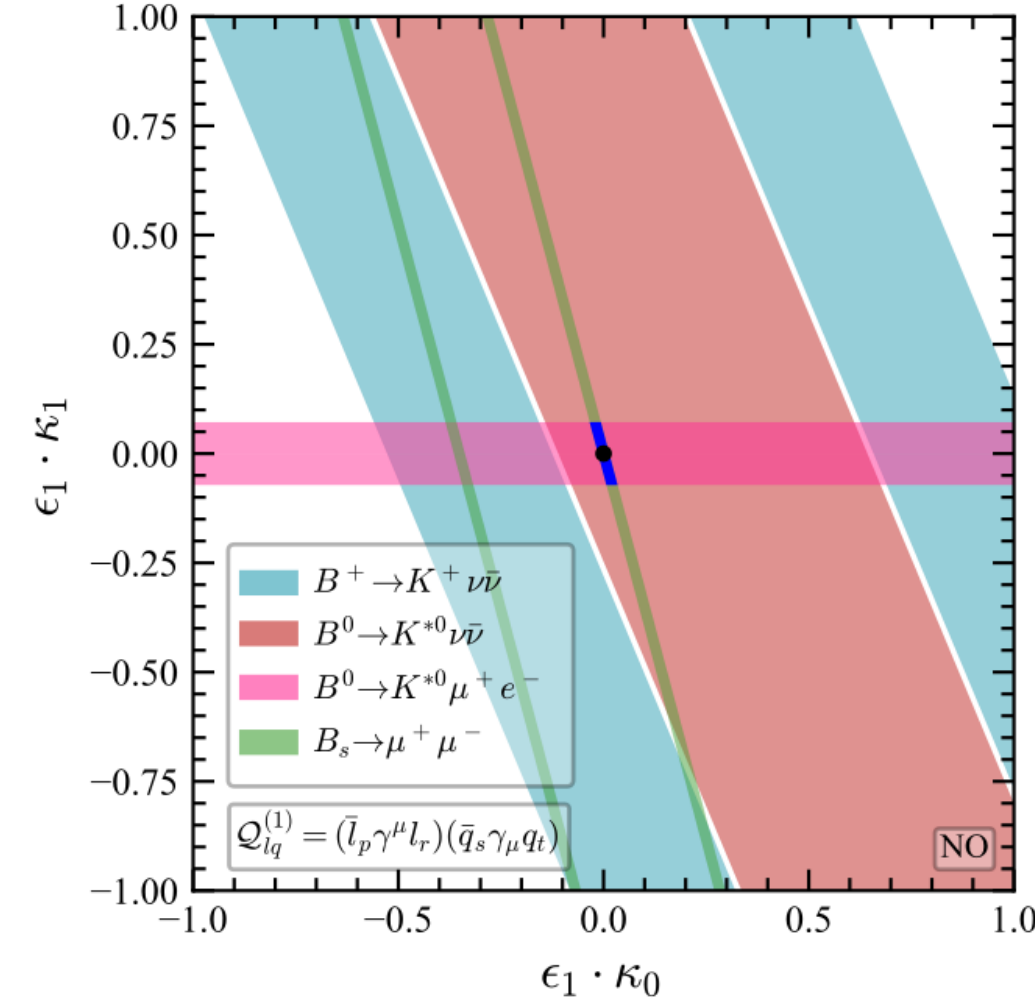
$$\mathcal{C}_{\text{MFV}} \approx \kappa_0 + \kappa_1 \mathbf{A}_\ell + \kappa_2 \mathbf{A}_\ell^2, \quad (2.21)$$

where the coefficients $\kappa_{0,1,2}$ are free real parameters. In the numerical analysis, we keep only the leading lepton flavour violation term $\mathbf{A}_\ell$ 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:

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

where the basic LFV coupling Δ_ℓ can be obtained from $\mathbf{A}_\ell$ and takes the form

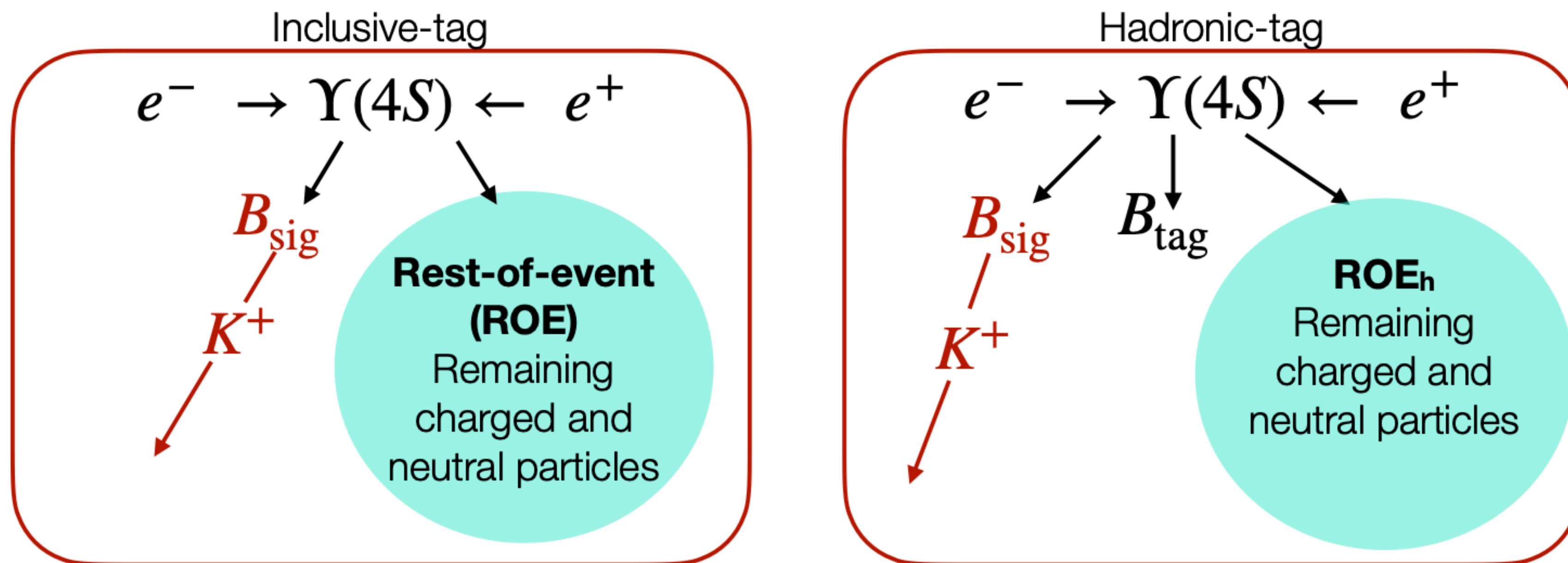
$$\Delta_\ell = U \hat{\lambda}_\nu^2 U^\dagger, \quad (2.23)$$



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

RECONSTRUCTION AND SELECTION

- Charged particles: $p_T > 100$ MeV/c, close to collision point, in the central part of the detector
- Neutral particles: $E > 100$ MeV, in the central part of the detector
- Signal kaon candidates reconstructed applying kaon-enriching selection



In following, for

