Institute of Particle Physics
粒 子 物 理 研 究 所

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

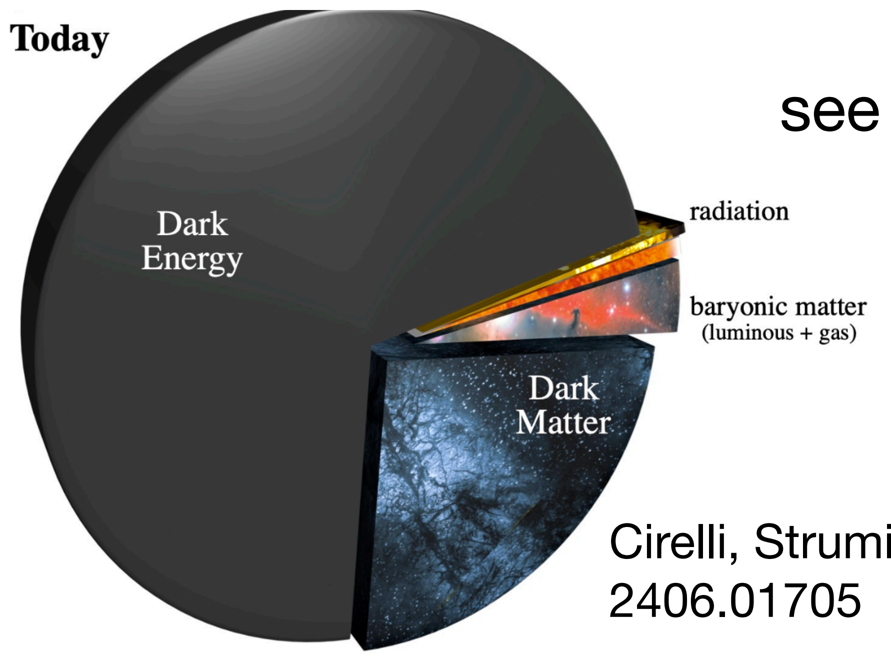
Xing–Bo Yuan (袁兴博)

Central China Normal University (华中师范大学)

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

高孟超，李新强，杨亚东，袁兴博，张　欣, work in progress

Light DM: a bottom-up view



see also 刘佐伟, 丁然's talk

Cirelli, Strumia, Zupan 2406.01705

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

	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/CEPC
c		BES/STCF	LHC/CEPC
t			LHC/CEPC

example:

$B^+ \to K^+$ + DM + DM

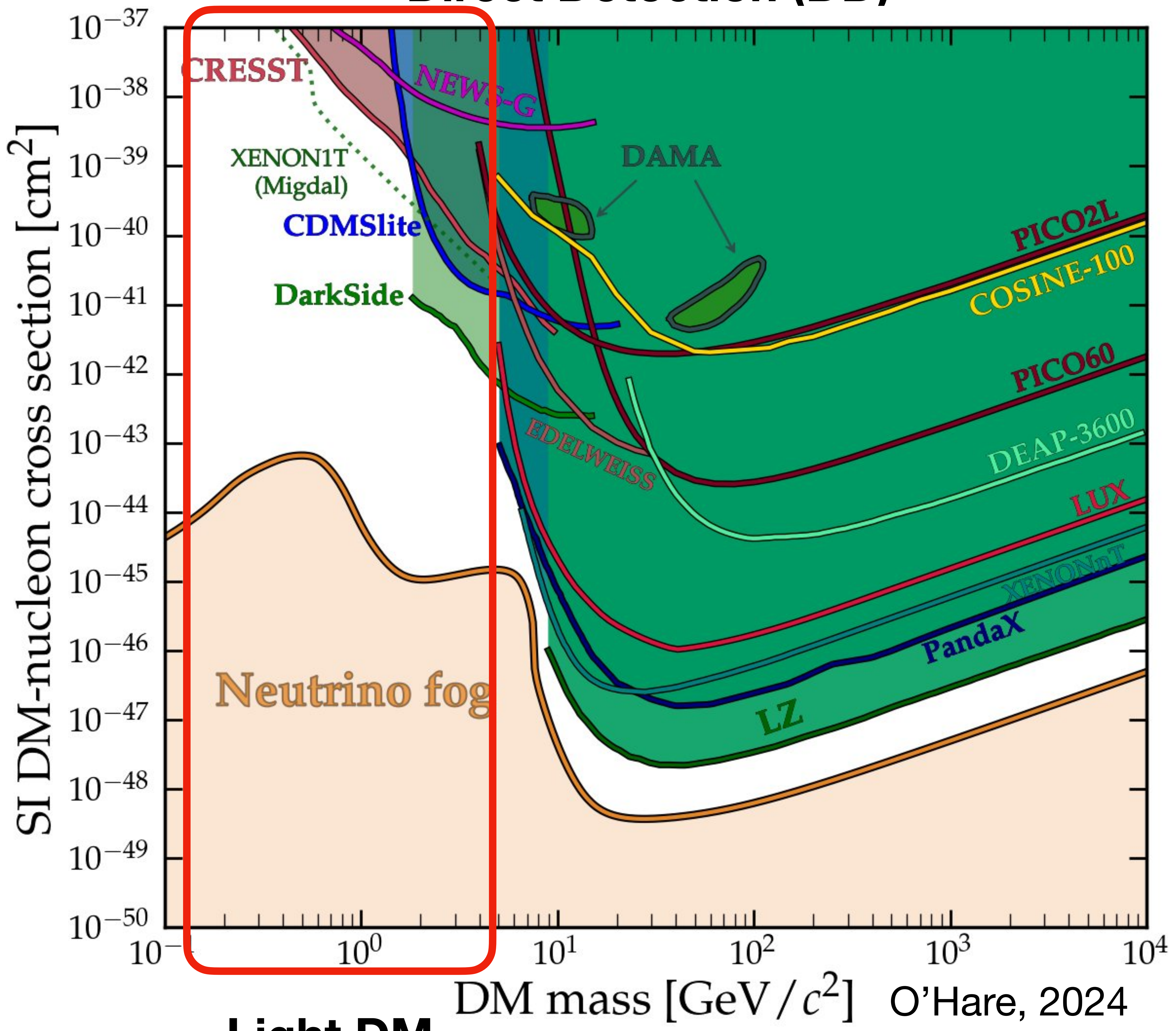
$K^+ \to \pi^+$ + DM + DM

$D^0 \to \pi^0$ + DM + DM

DD = Direct Detection

[blue box] means related to the DM relic density

Direct Detection (DD)



O'Hare, 2024

Light DM

Experimental Search

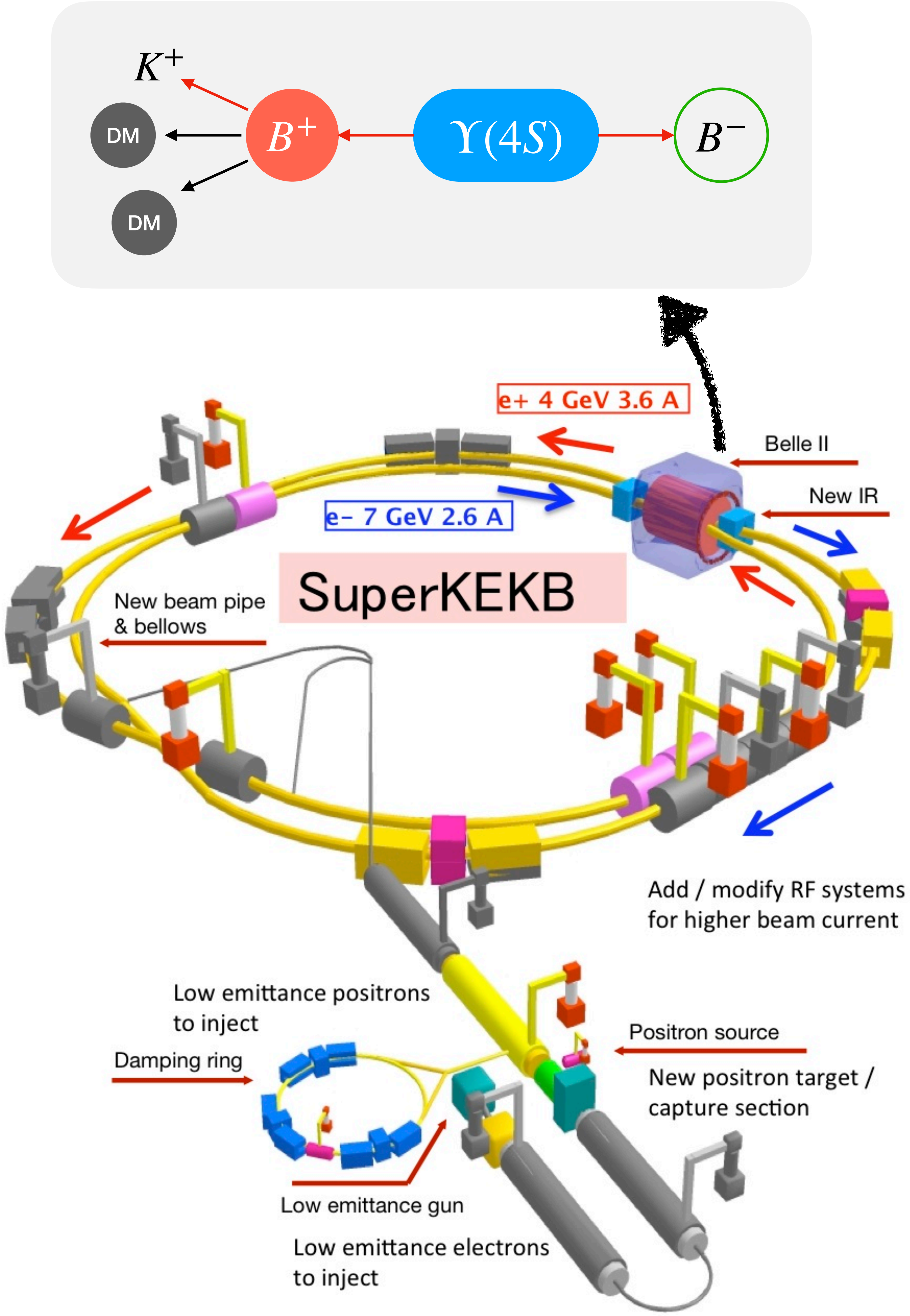
	Observable	SM	Exp	Unit
$b \to s$	$\mathcal{B}(B^+ \to K^+ \nu\bar{\nu})$	4.16 ± 0.57	$23 \pm 5^{+5}_{-4}$	10^{-6}
	$\mathcal{B}(B^0 \to K^0 \nu\bar{\nu})$	3.85 ± 0.52	< 26	10^{-6}
	$\mathcal{B}(B^+ \to K^{*+} \nu\bar{\nu})$	9.70 ± 0.94	< 61	10^{-6}
	$\mathcal{B}(B^0 \to K^{*0} \nu\bar{\nu})$	9.00 ± 0.87	< 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}

Belle II
CEPC

NA62
KOTO

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

BESIII
STCF



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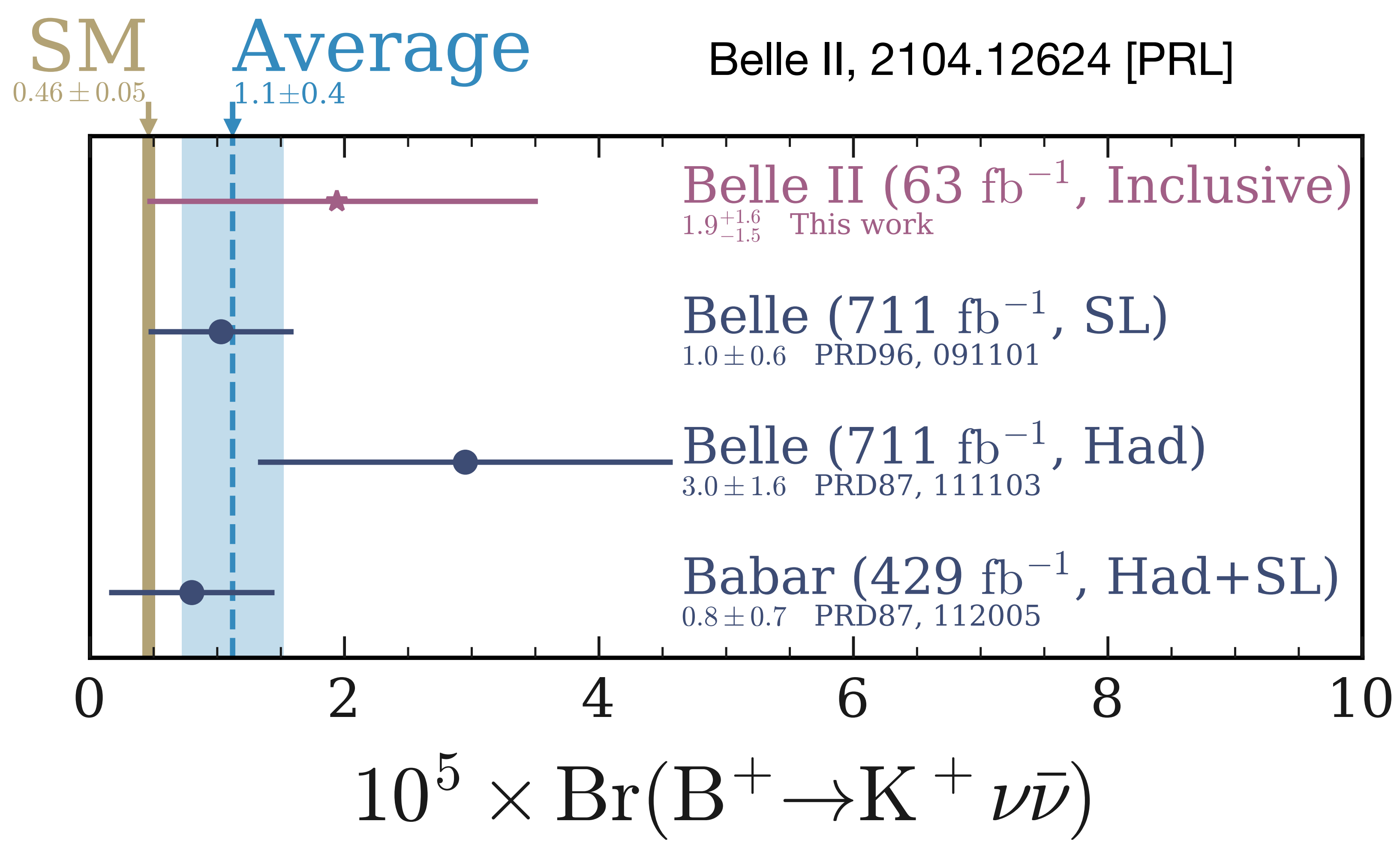
$c \to u$ $\quad D^+ \to \pi^+ + \text{inv}, D^0 \to \rho^0 + \text{inv}, \ldots \ldots$

BESIII
STCF

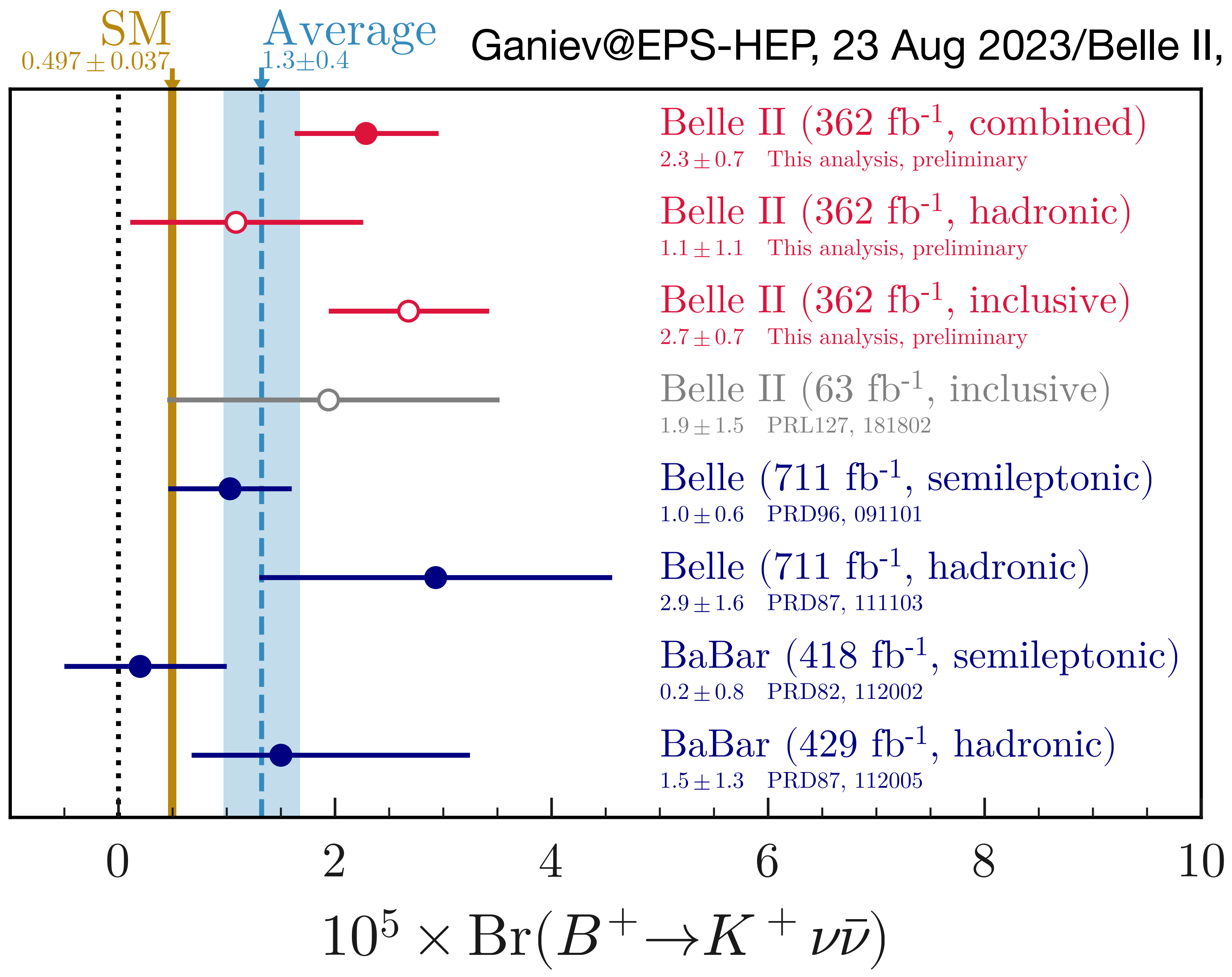
▶ 2021 Apr

Belle II, 2104.12624 [PRL]



▶ 2023 Aug: first evidence

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



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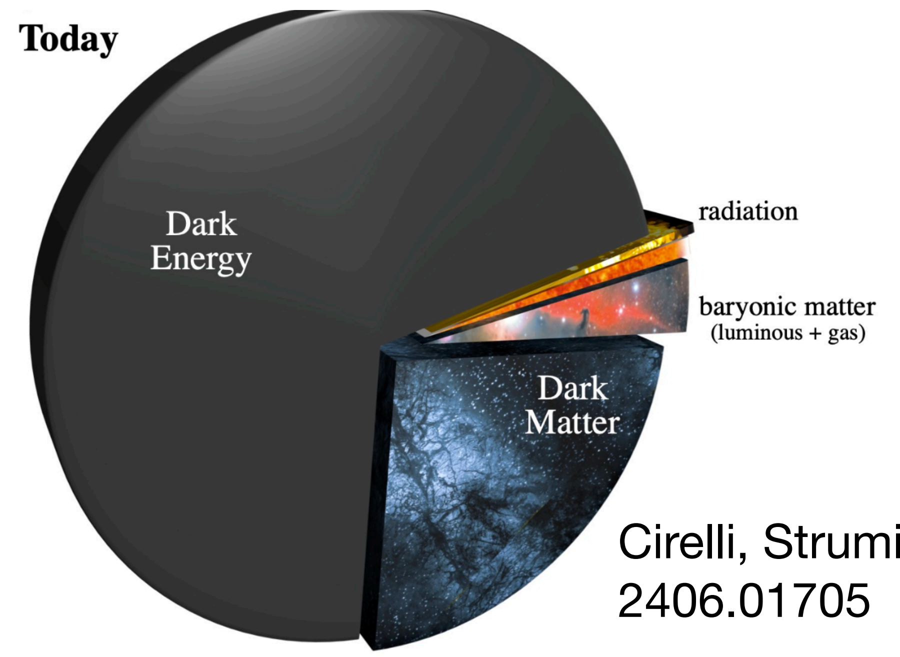

Cirelli, Strumia, Zupan
2406.01705

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example:
$B^+ \to K^+ +$ DM + DM
$K^+ \to \pi^+ +$ DM + DM
$D^0 \to \pi^0 +$ DM + 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 $10\,\%$

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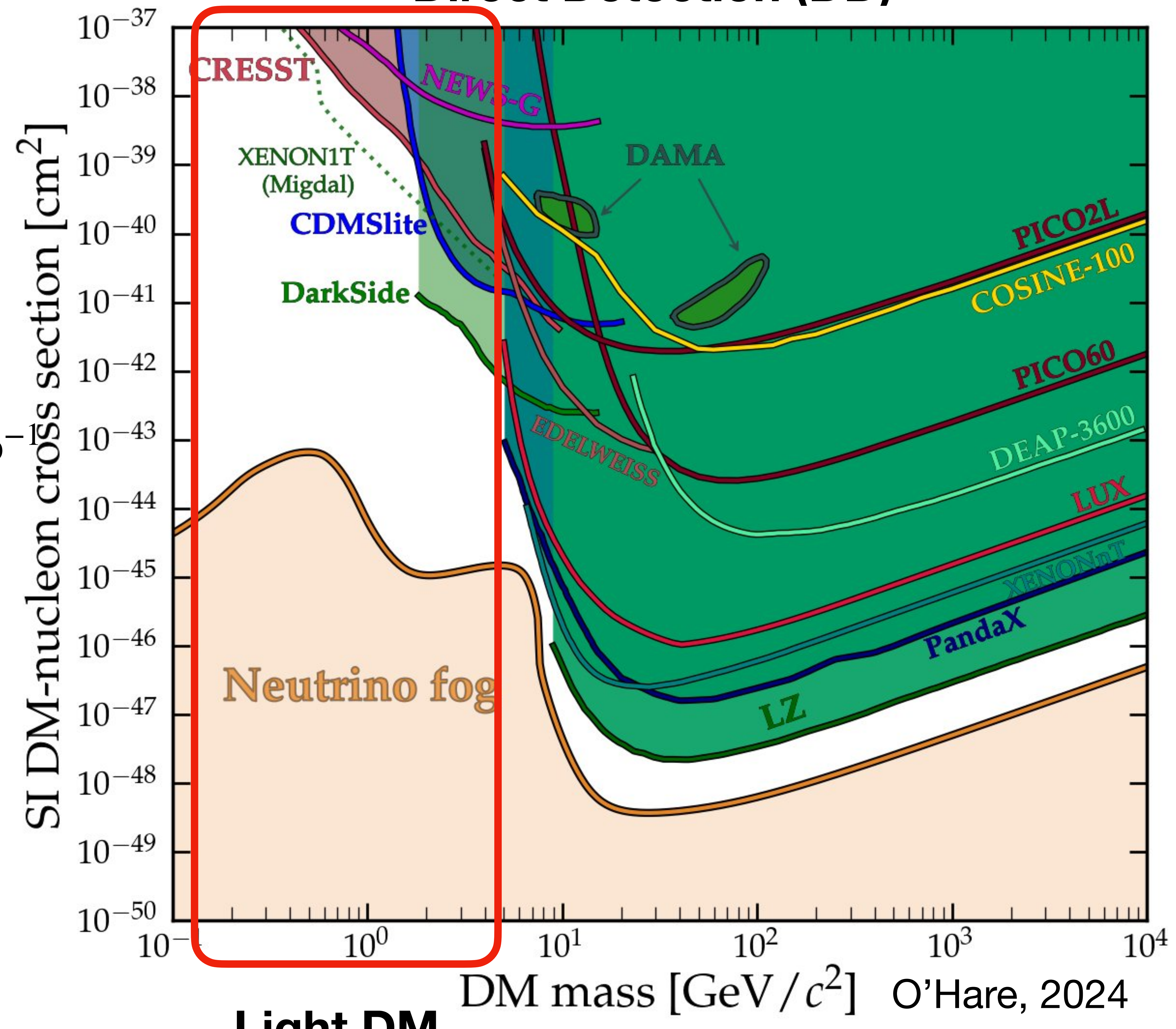
[blue box] means related to the DM relic density

Direct Detection (DD)



Light DM

O'Hare, 2024

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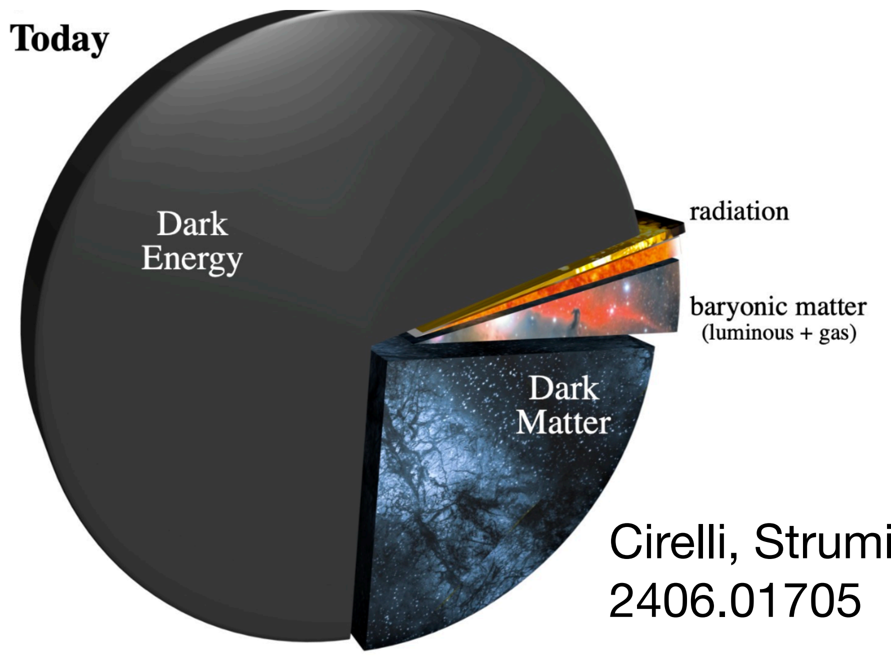

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example:
$B^+ \to K^+ + \mathrm{DM} + \mathrm{DM}$
$K^+ \to \pi^+ + \mathrm{DM} + \mathrm{DM}$
$D^0 \to \pi^0 + \mathrm{DM} + \mathrm{DM}$

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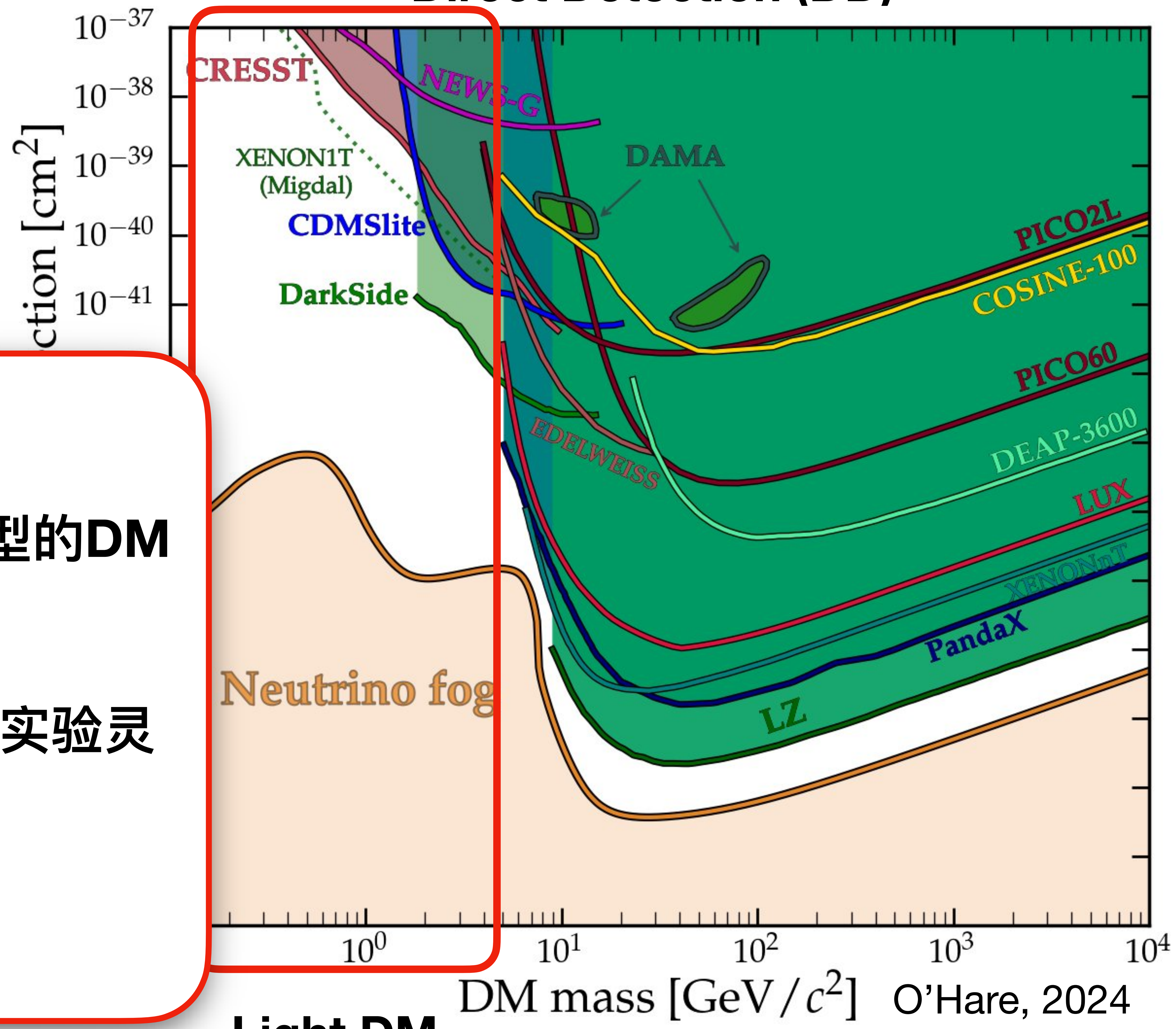


O'Hare, 2024

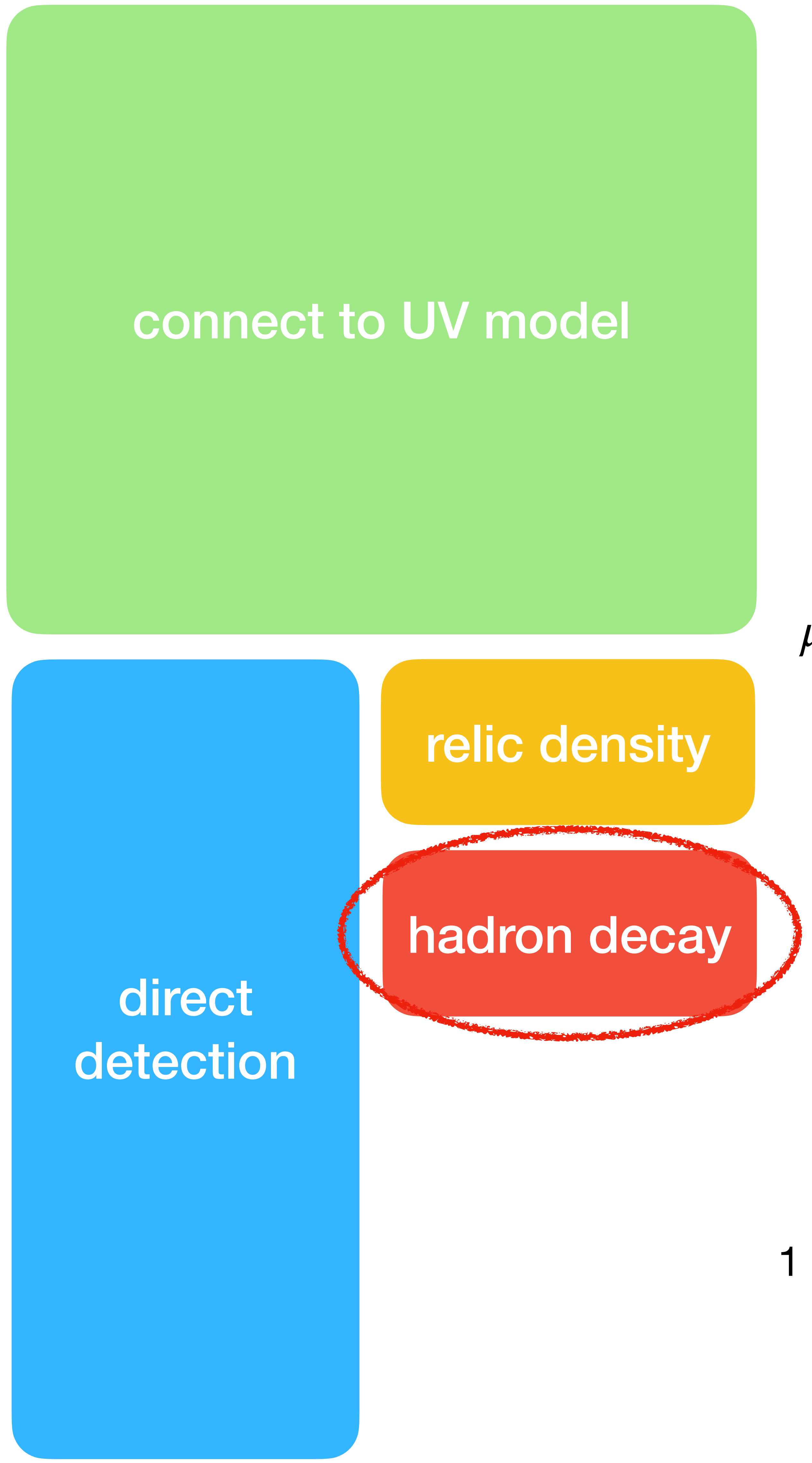
Light DM

一些问题：

1. 相对于DM直接探测，强子衰变探测DM有什么优势？对什么类型的DM更加敏感？能否给出额外的信息？
2. 能否构建出新物理模型，使得模型中的DM达到未来强子衰变的实验灵敏度，同时给出DM残余丰度并满足直接探测等限制？
3. 能否联合这些观测得到暗物质的味结构？

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**



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

$$\mathcal{O}_{d\phi^2} = (\bar{d}_{Lp} d_{Rr})\phi^2$$
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$$\mathcal{O}_{da}^{L} = (\bar{d}_{Lp}\gamma_\mu d_{Lr})\partial^\mu a$$

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

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

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
  - 2014 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
- $d_i \to d_j + X + X$
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  - 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: $A \propto C \cdot \langle H_1 | O | H_2 \rangle \cdot$ DM current (form factor)
- no GIM suppression
- possibly two-body decay

} **enhancement**

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

longitudinal polarization F_L

- $c \to u + \mathrm{DM}$
  - 2022 C.Q.Geng, G.Li
  - 2023 G.Li, Tandean

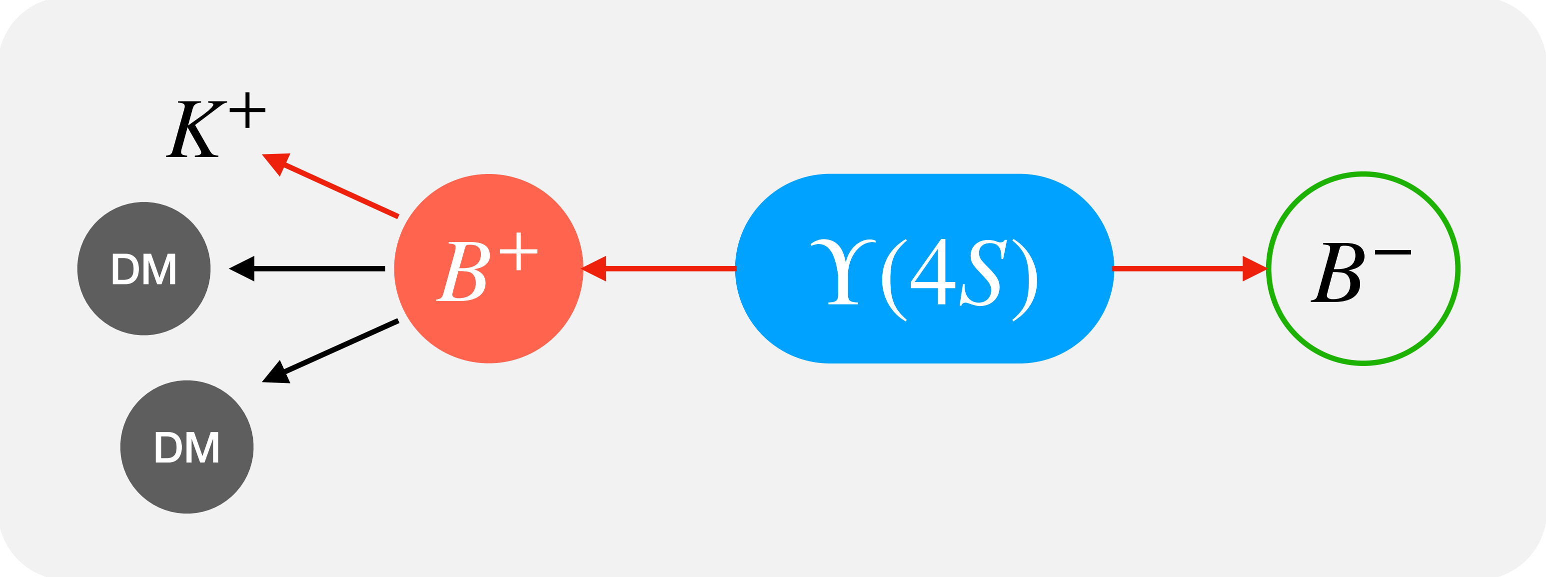
$D^0 \to \mathrm{s}\bar{\mathrm{s}}'$
$D^0 \to \gamma\mathrm{s}\bar{\mathrm{s}}'$
$D^0 \to \pi^0\mathrm{s}\bar{\mathrm{s}}'$
$D^+ \to \pi^+\mathrm{s}\bar{\mathrm{s}}'$
$D_s^+ \to K^+\mathrm{s}\bar{\mathrm{s}}'$
$D^0 \to \rho^0\mathrm{s}\bar{\mathrm{s}}'$
$D^+ \to \rho^+\mathrm{s}\bar{\mathrm{s}}'$
$D_s^+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

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*

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

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



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$\mu_{\rm EW}$

μ_b

Dark SMEFT

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

scalar: 4

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

fermion: 2

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

vector: 1+13

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

ALP: 2

Dark LEFT

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

scalar: 4

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

fermion: 5

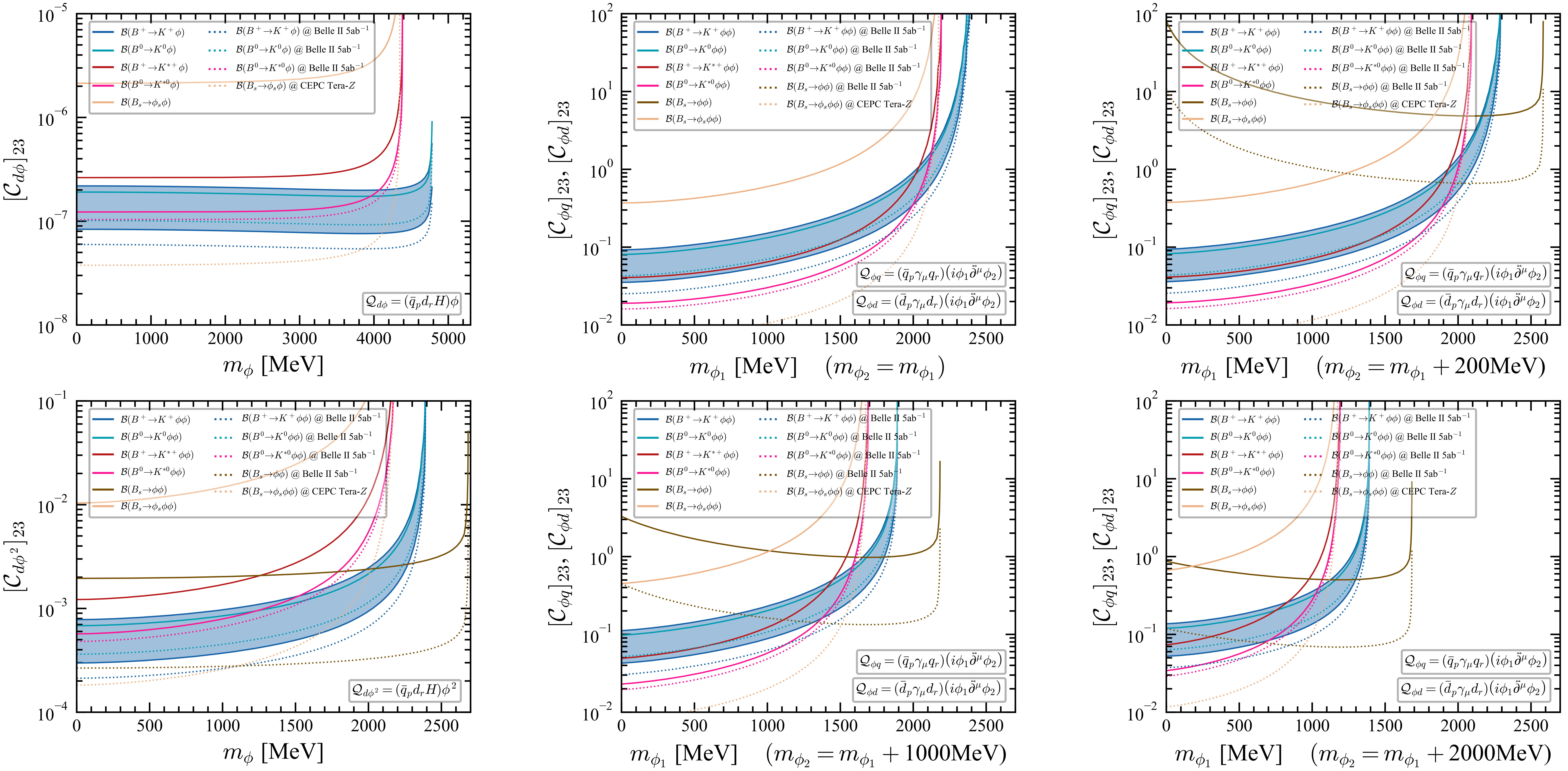
$$\mathcal{O}^T_{dX} = (\bar{d}_{Lp}\sigma_{\mu\nu} d_{Rr}) X^{\mu\nu}_a \qquad \mathcal{O}^L_{dXX} = (\bar{d}_{Lp}\gamma_\mu d_{Lr}) X^{\mu\nu} X_\nu$$

vector: 1+10

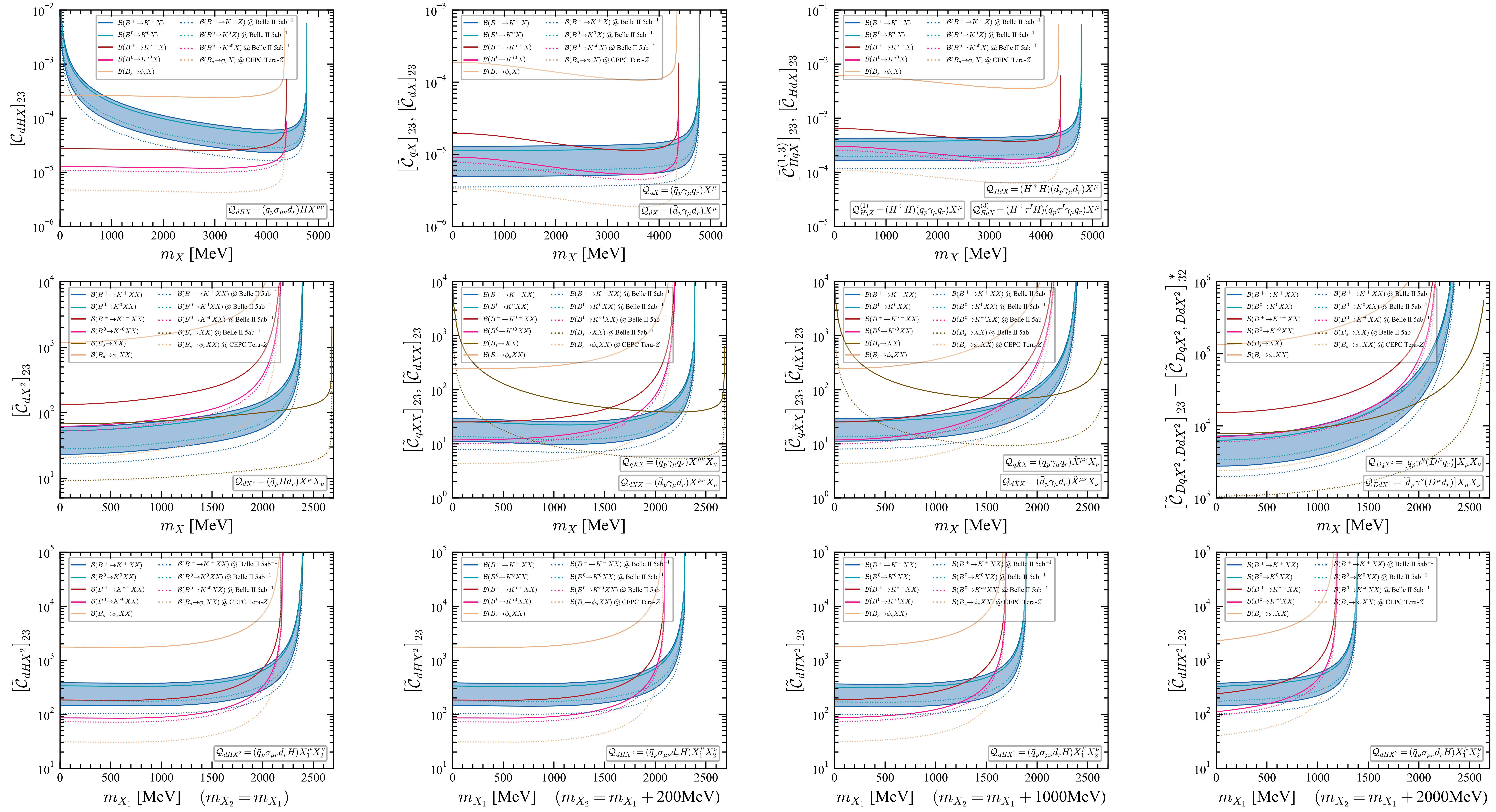
$$\mathcal{O}^L_{da} = (\bar{d}_{Lp}\gamma_\mu d_{Lr})\partial^\mu a, \qquad \mathcal{O}^R_{da} = (\bar{d}_{Rp}\gamma_\mu d_{Rr})\partial^\mu a$$

ALP: 2

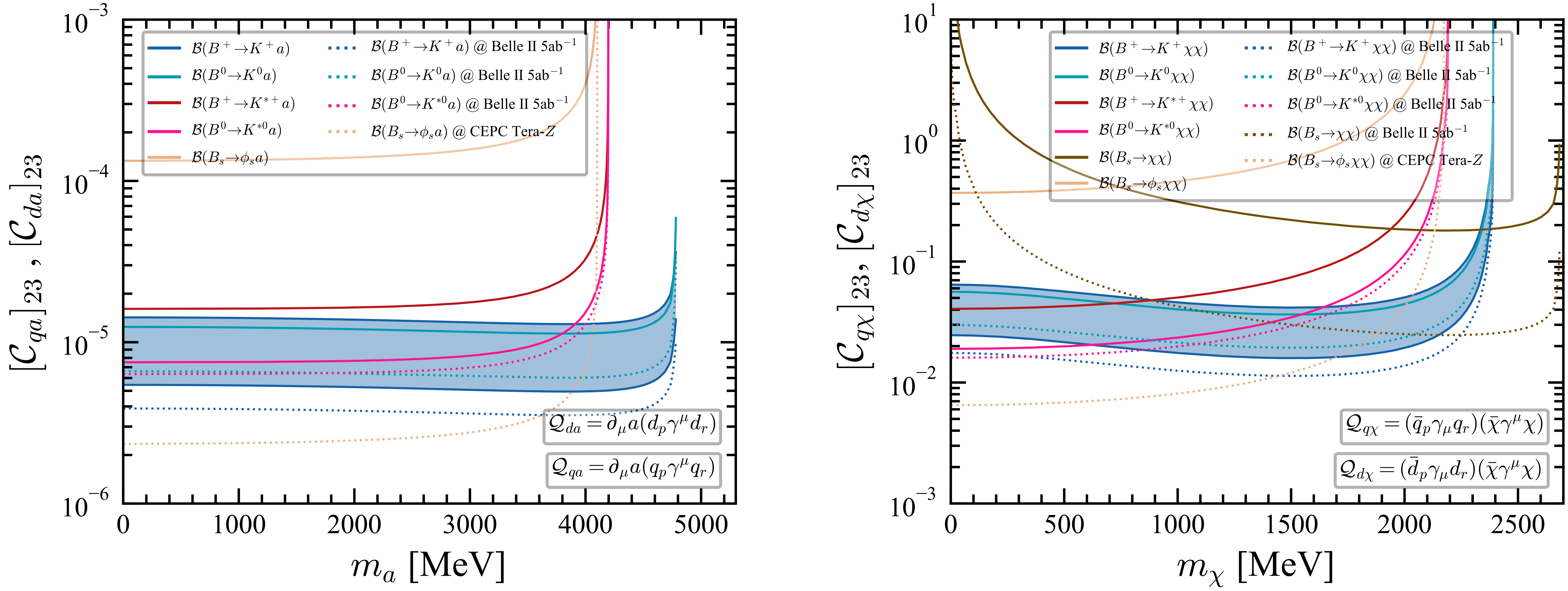
Dark SMEFT: Scalar



Dark SMEFT: Vector

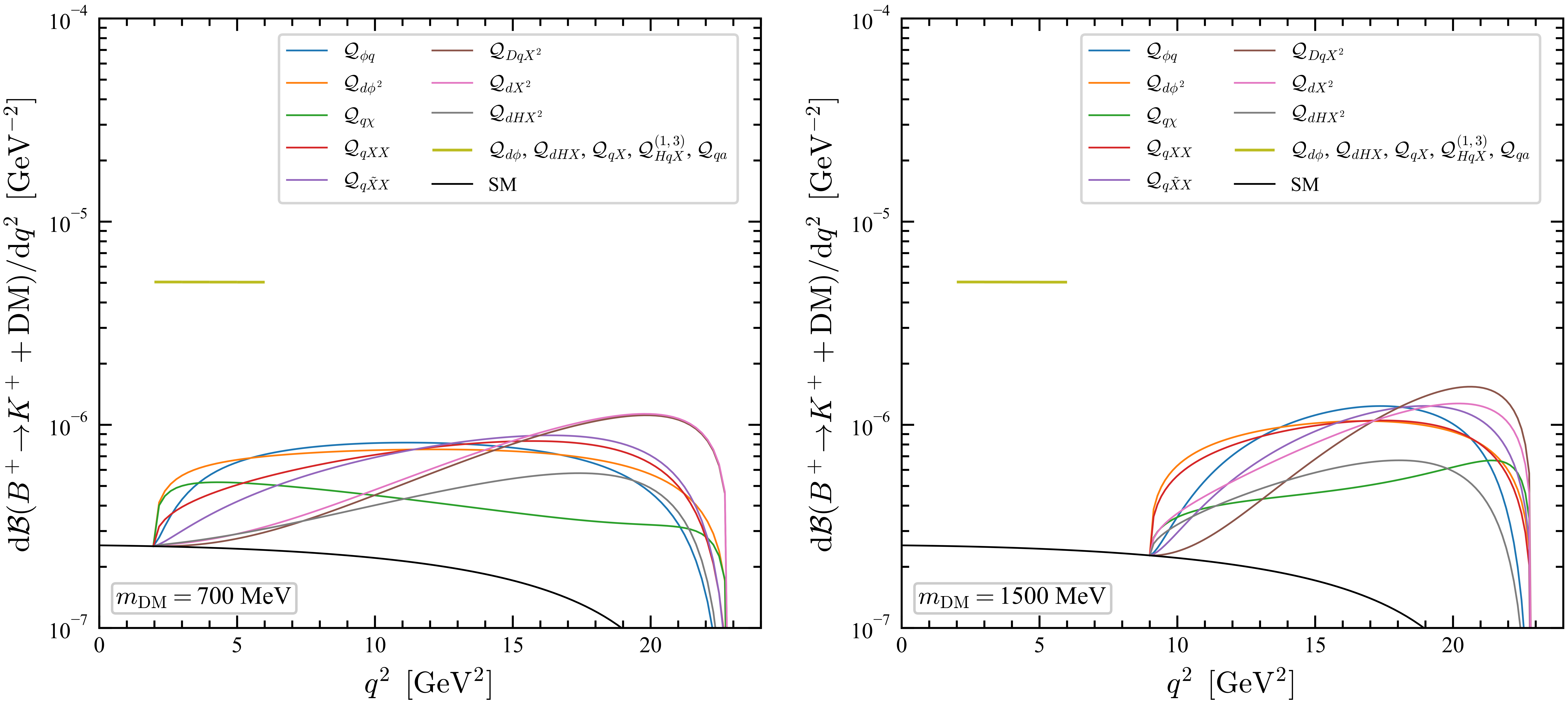


Dark SMEFT: Fermion, ALP



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

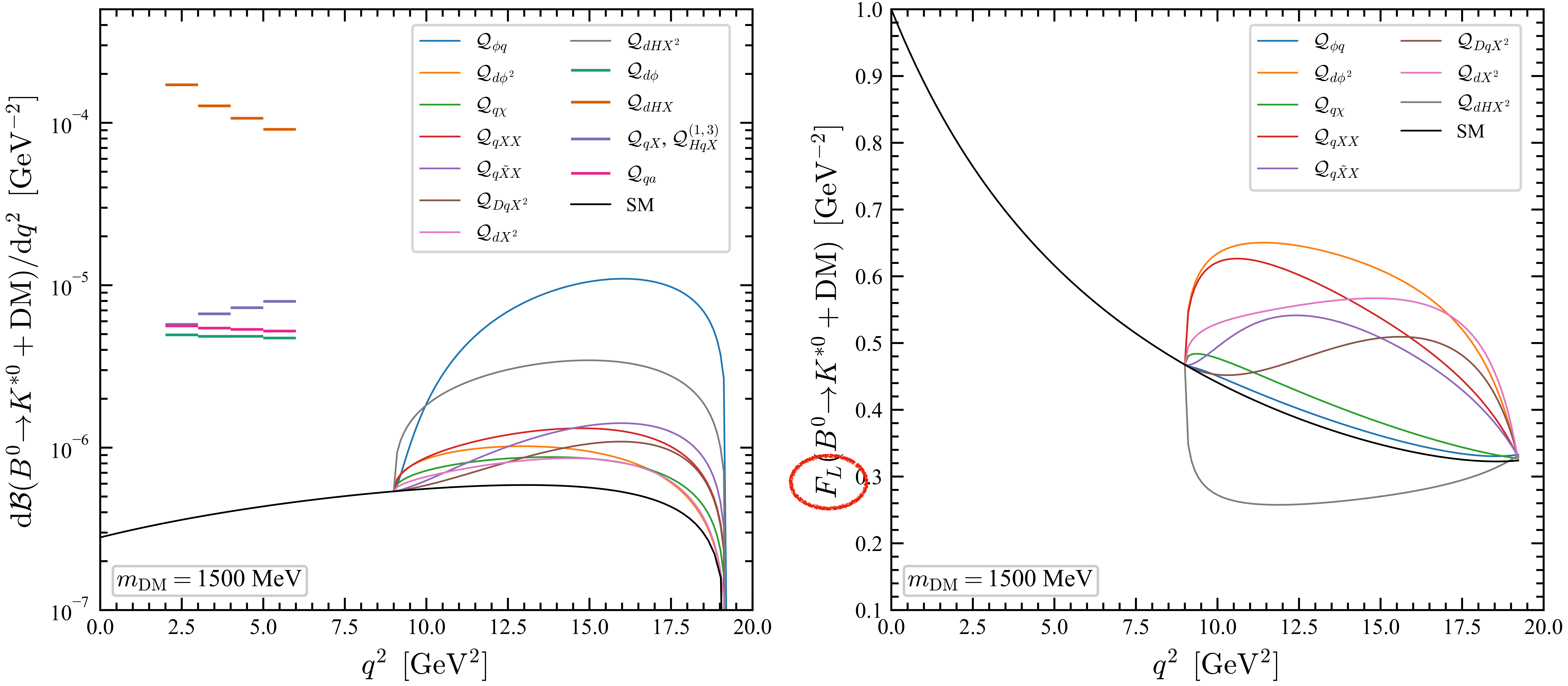
Dark SMEFT: $\mathrm{d}\mathcal{B}/\mathrm{d}q^2$



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

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



All the operators are distinguishable from each other by combing these observables

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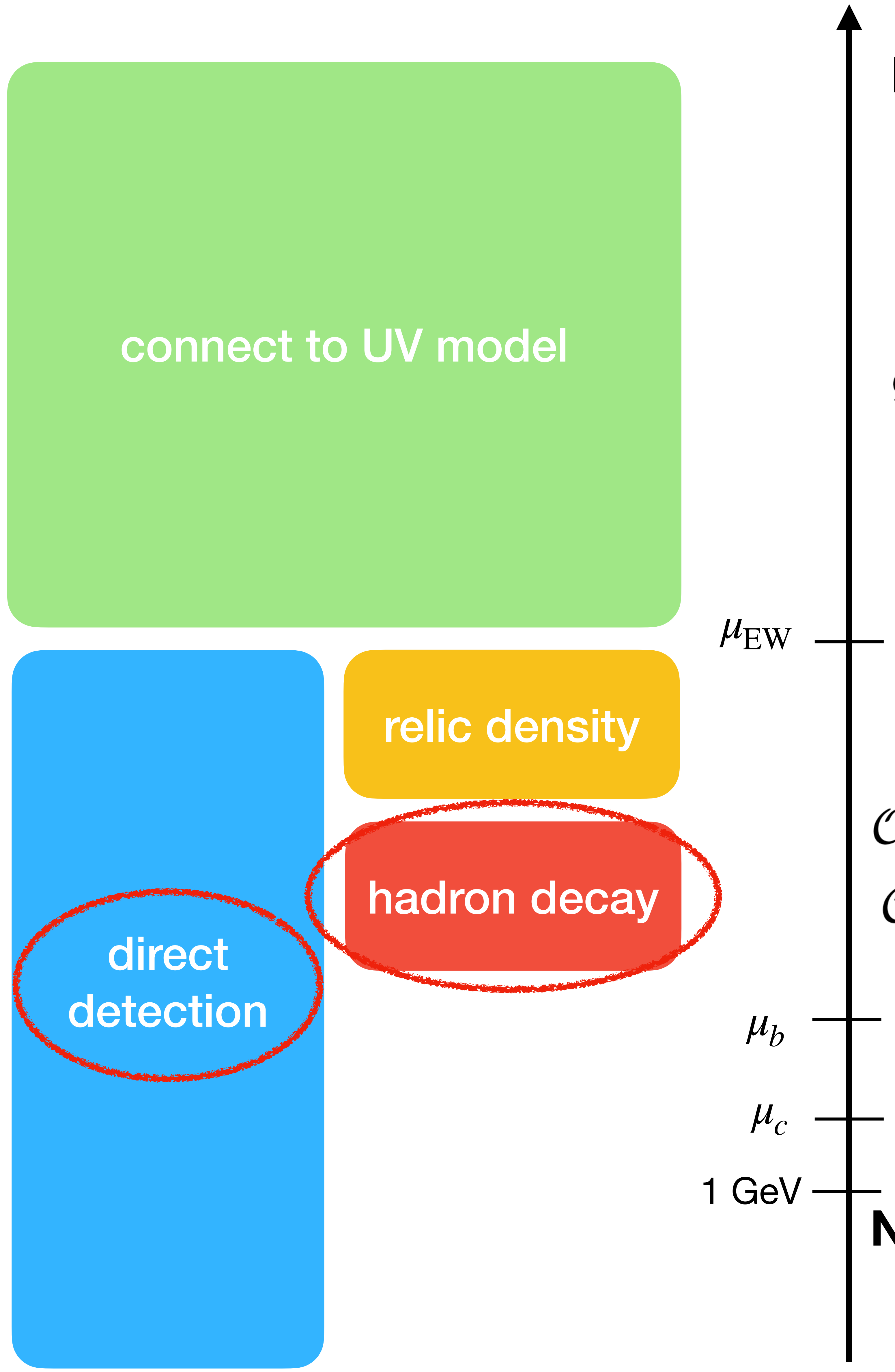
for light DM



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

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$$\mathcal{O}_{dXX}^{L} = \left(\bar{d}_{Lp}\gamma_\mu d_{Lr}\right)X^{\mu\nu}X_\nu$$
$$\mathcal{O}_{da}^{L} = \left(\bar{d}_{Lp}\gamma_\mu d_{Lr}\right)\partial^\mu a$$

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
2022 Yandong Liu, Bin Yan, Rui Zhang
… …

2019 ATLAS [JHEP05(2019)142]

$\mu_{\rm EW}$ — **Dark SMEFT** one-loop matching

μ_b — **Dark LEFT**

1 GeV

hadron decay

direct detection

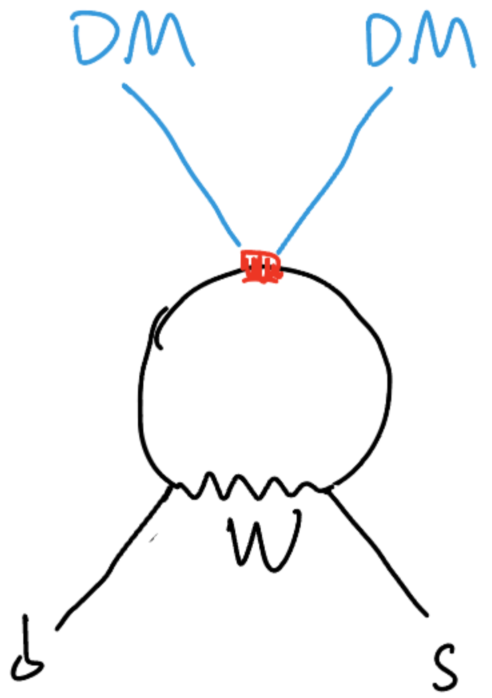
$$\mathcal{O}_{d\phi^2} = (\bar{d}_p P_R d_r)\phi^2$$

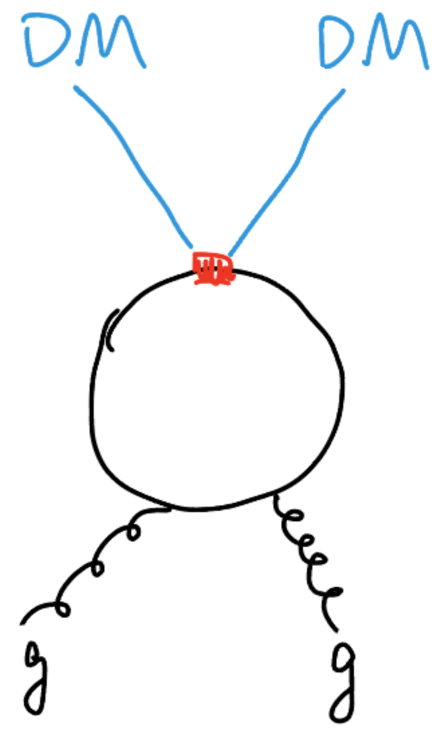
$$\mathcal{O}^{L}_{dXX} = (\bar{d}_p\gamma^\mu P_L d_r)X_{\mu\nu}X^\nu$$

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

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

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





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

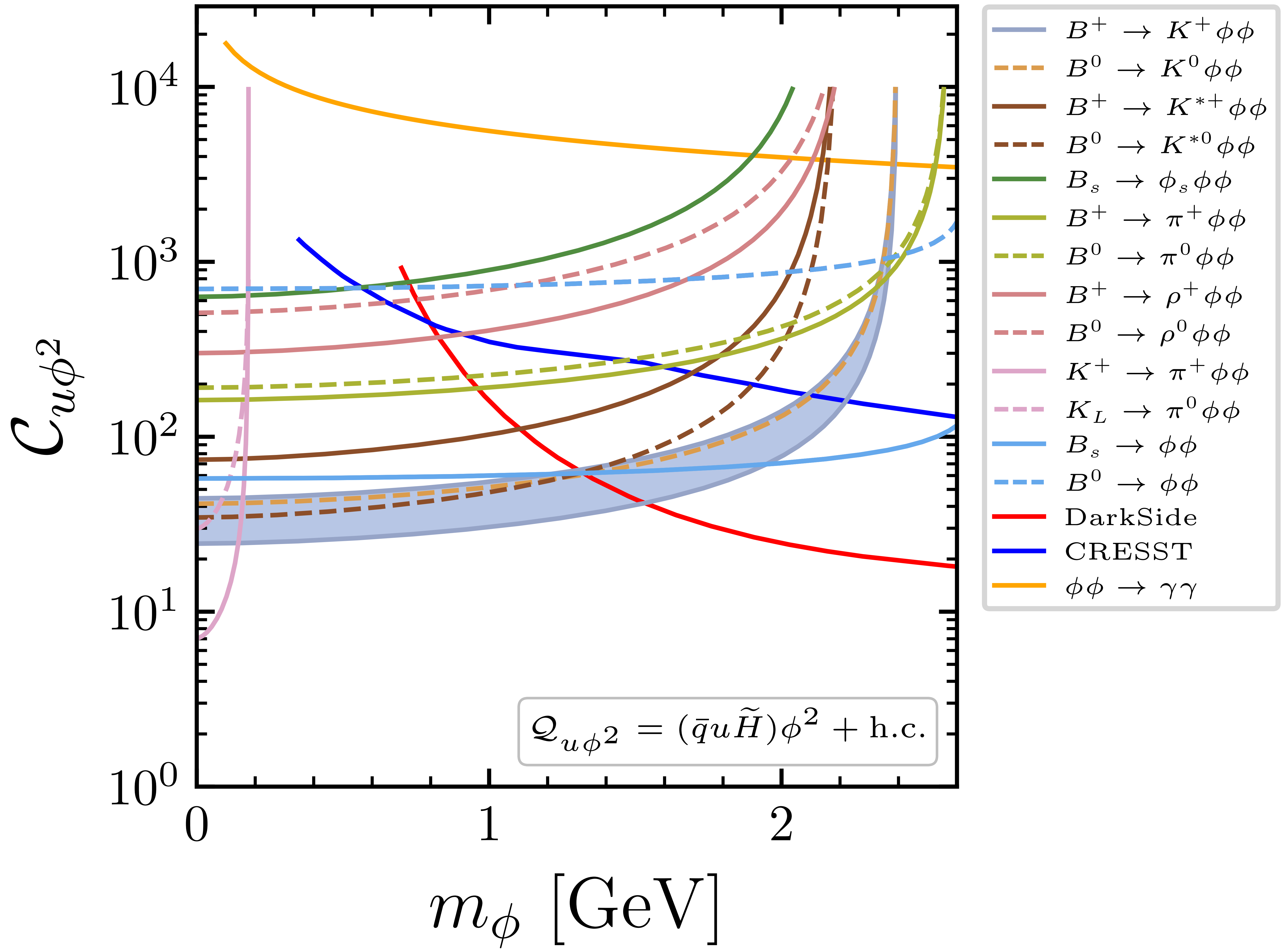
$$\mathcal{O}_{gX} = G^a_{\mu\nu}G^{\mu\nu,a}X_\rho X^\rho,$$

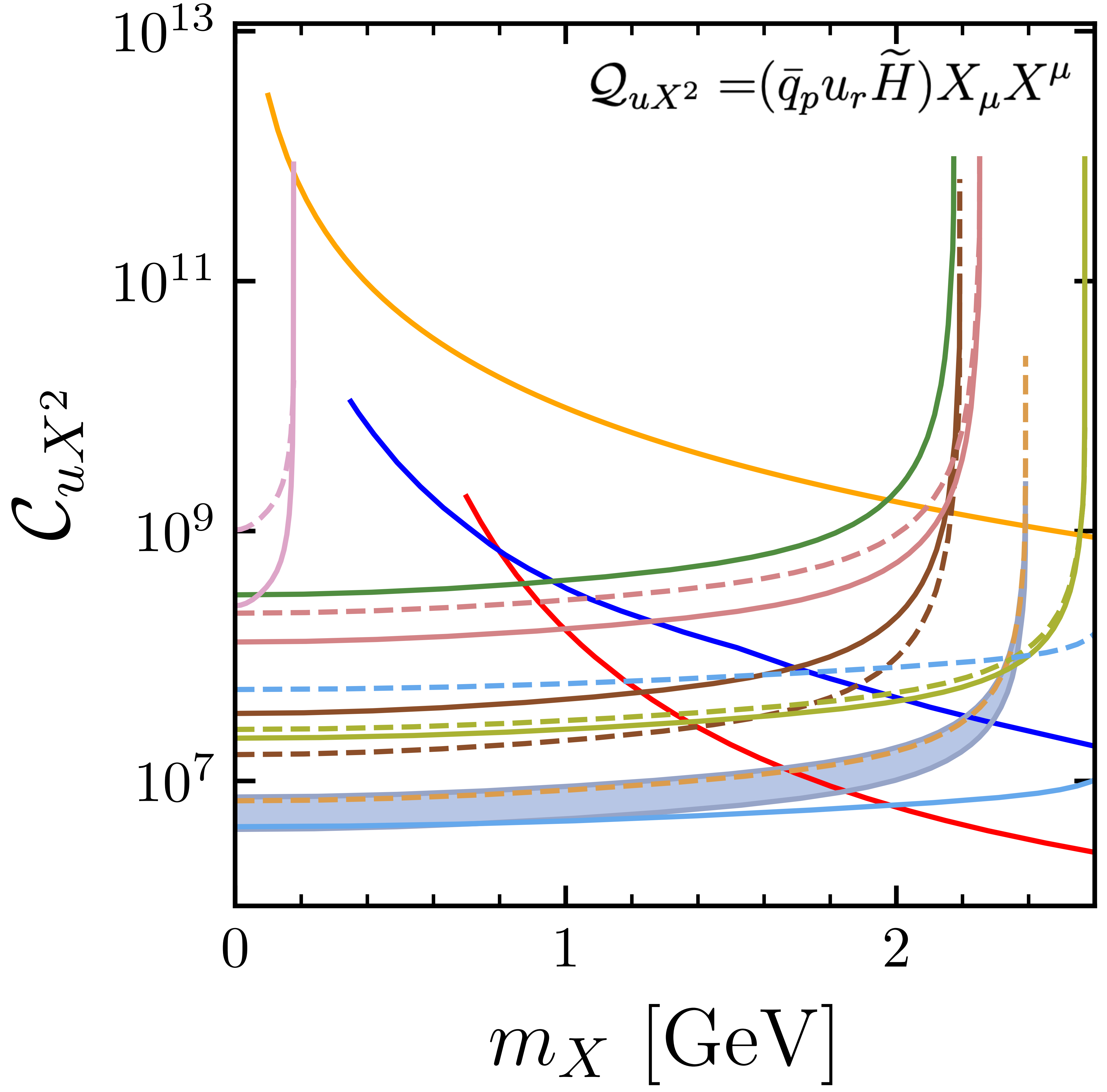
$$\mathcal{O}_{g\chi} = G^a_{\mu\nu}G^{\mu\nu,a}\bar{\chi}\chi$$

+ operators with u, d, s

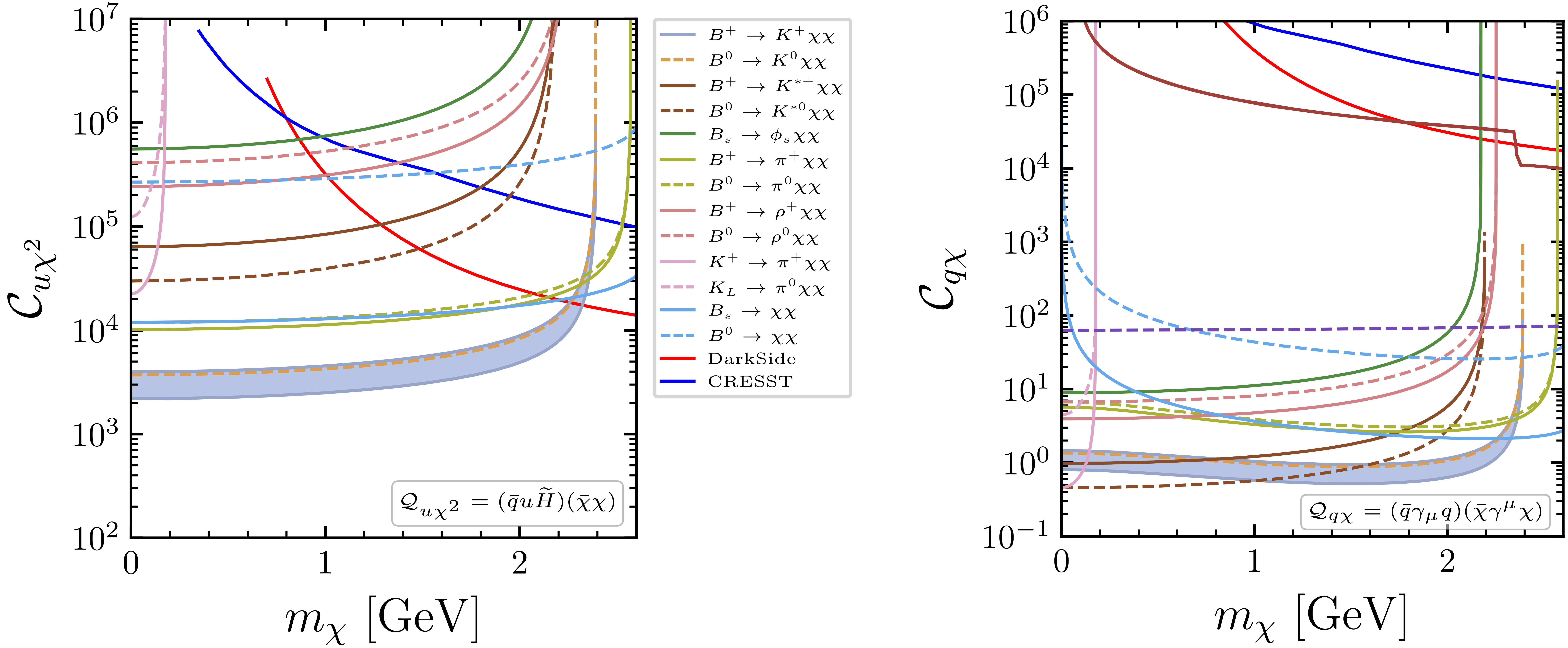
$$\langle N|\mathcal{O}_j|N\rangle$$

Hadron decay vs Direct detection

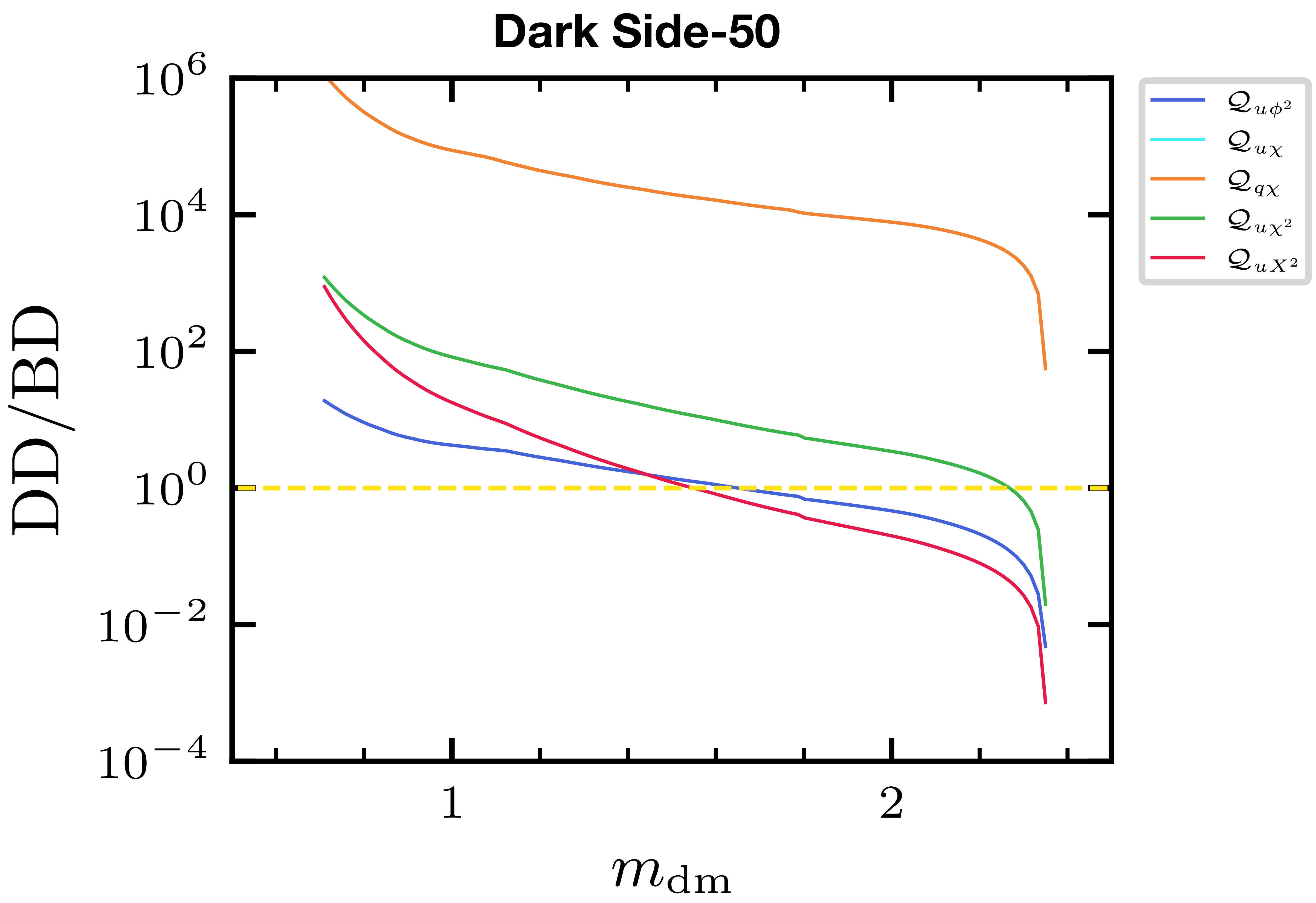


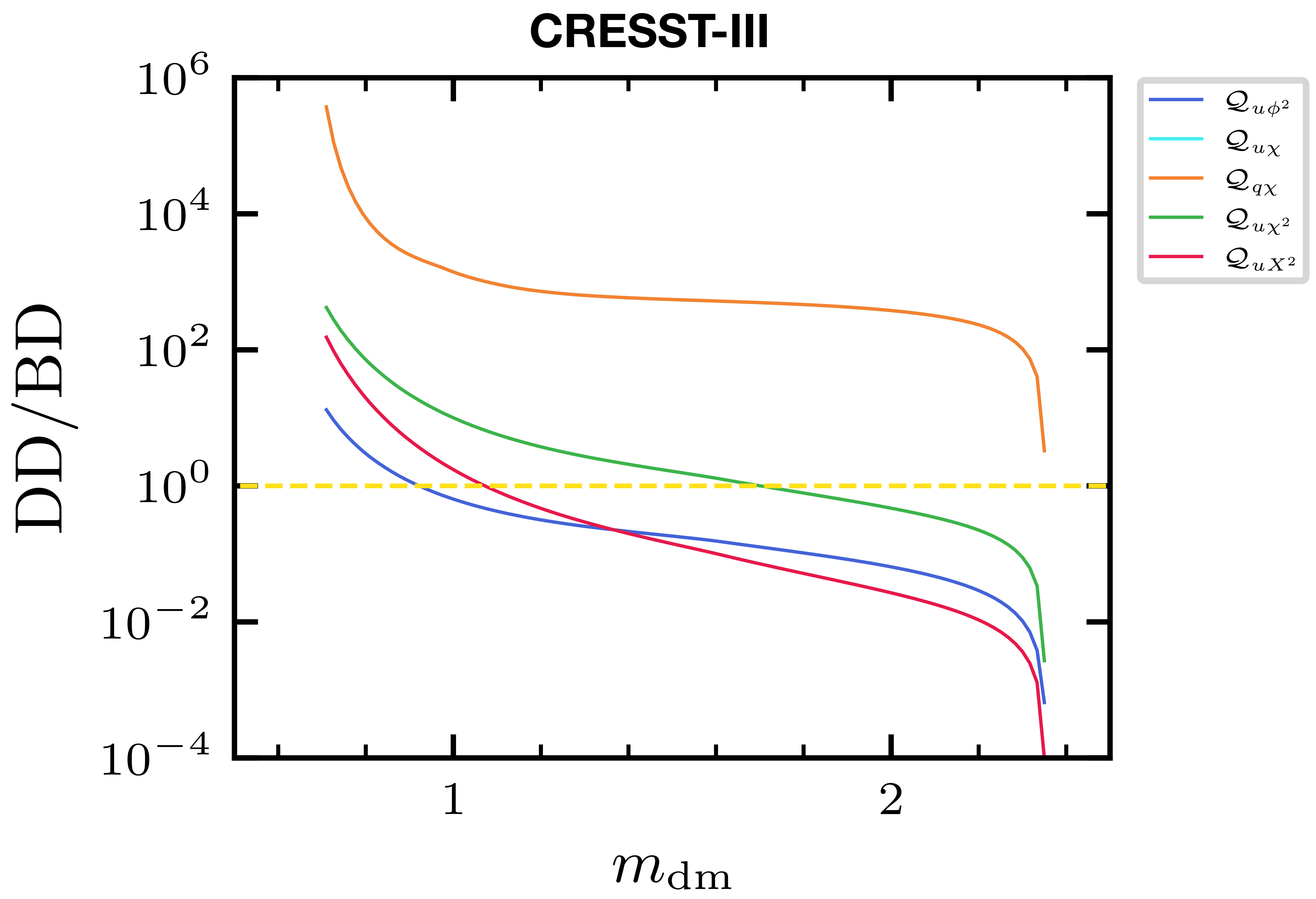


Hadron decay vs Direct detection



Hadron decay vs Direct detection



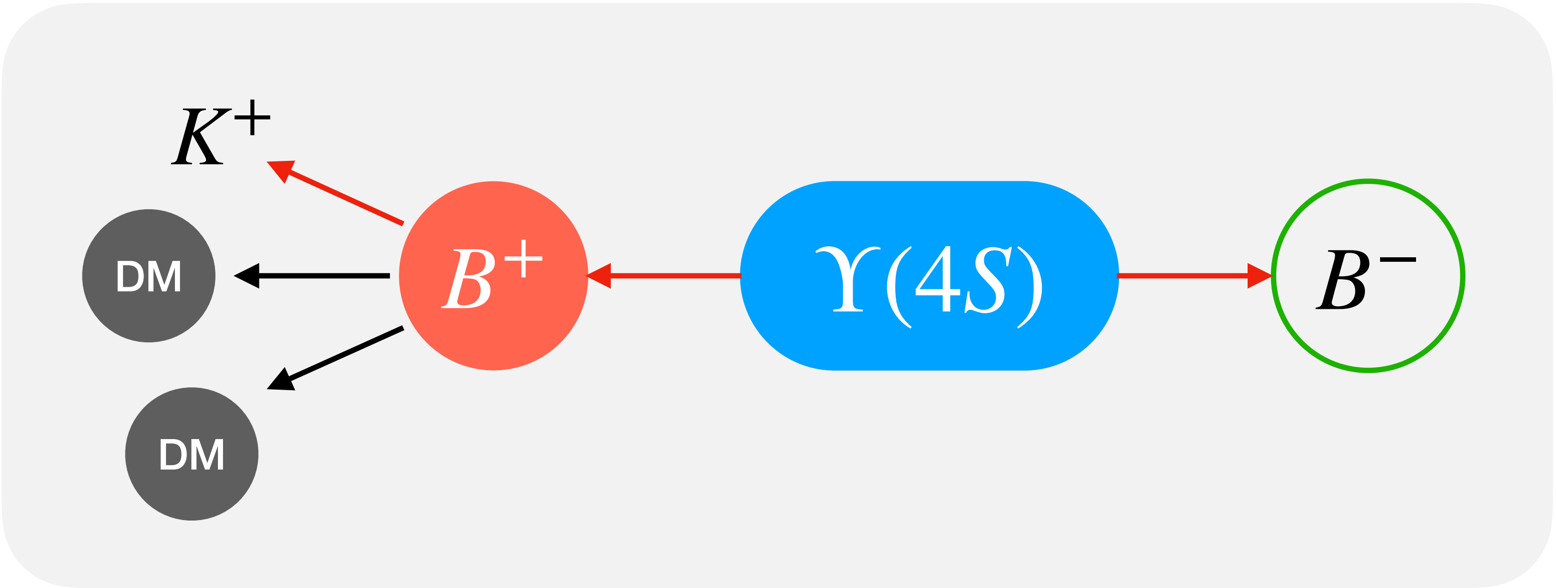


$$\frac{\textbf{upper bound from direct detection}}{\textbf{upper bound from B FCNC decay}}$$

Conclusion

一些问题：

1. 相对于DM直接探测，强子衰变探测DM有什么优势？对什么类型的DM更加敏感？能否给出额外的信息？
   角观测量可以提供相互作用的信息；top-flavored DM
2. 能否构建出新物理模型，使得模型中的DM达到未来强子衰变的实验灵敏度，同时给出DM残余丰度并满足直接探测等限制？
3. 能否联合这些观测得到暗物质的味结构？



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

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

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

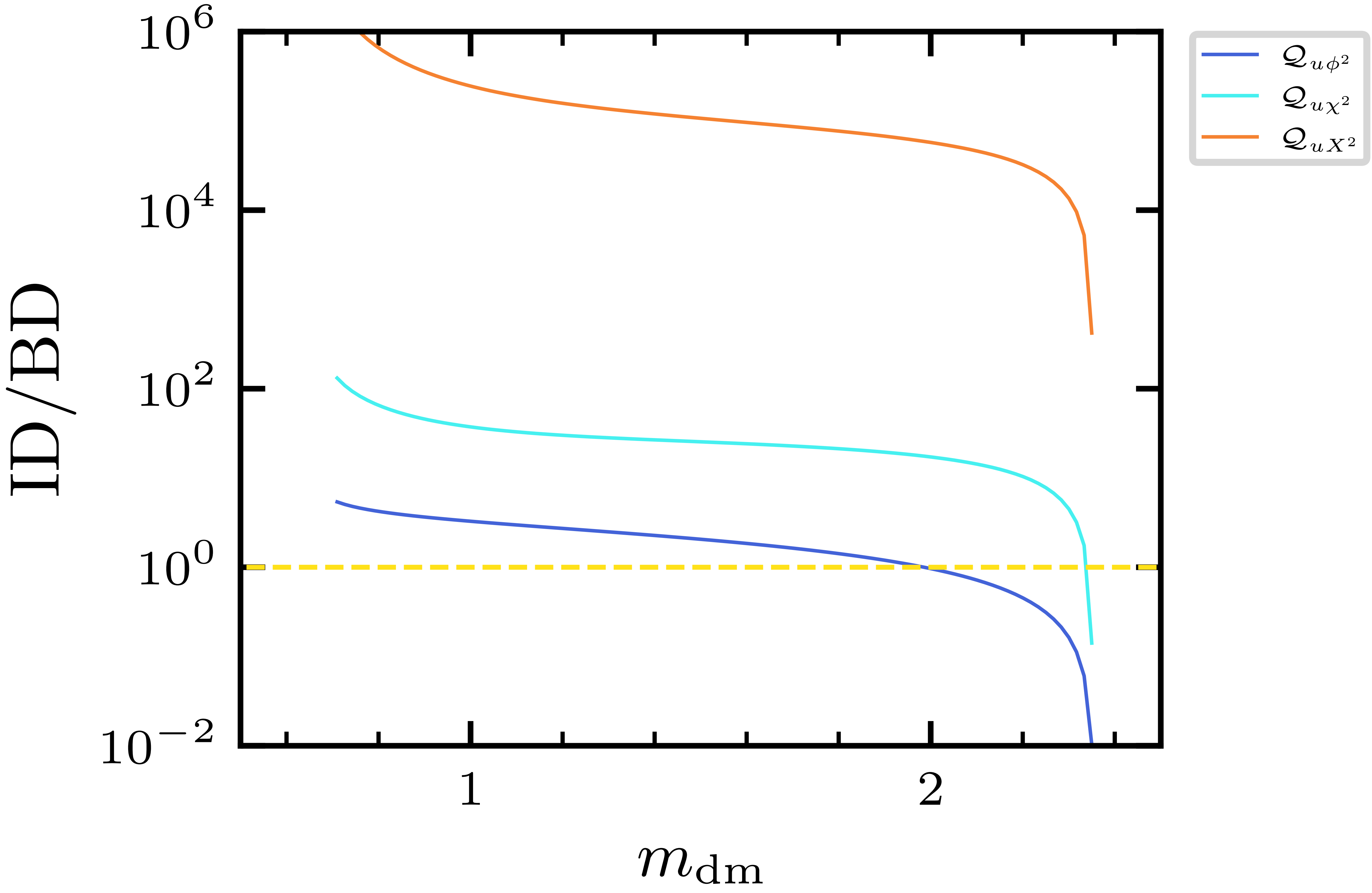
$D \to \pi + \mathrm{DM},\ D \to \rho + \mathrm{DM},\ \Xi_c \to \Xi + \mathrm{DM},\ J/\psi \to \mathrm{DM}, \ldots$

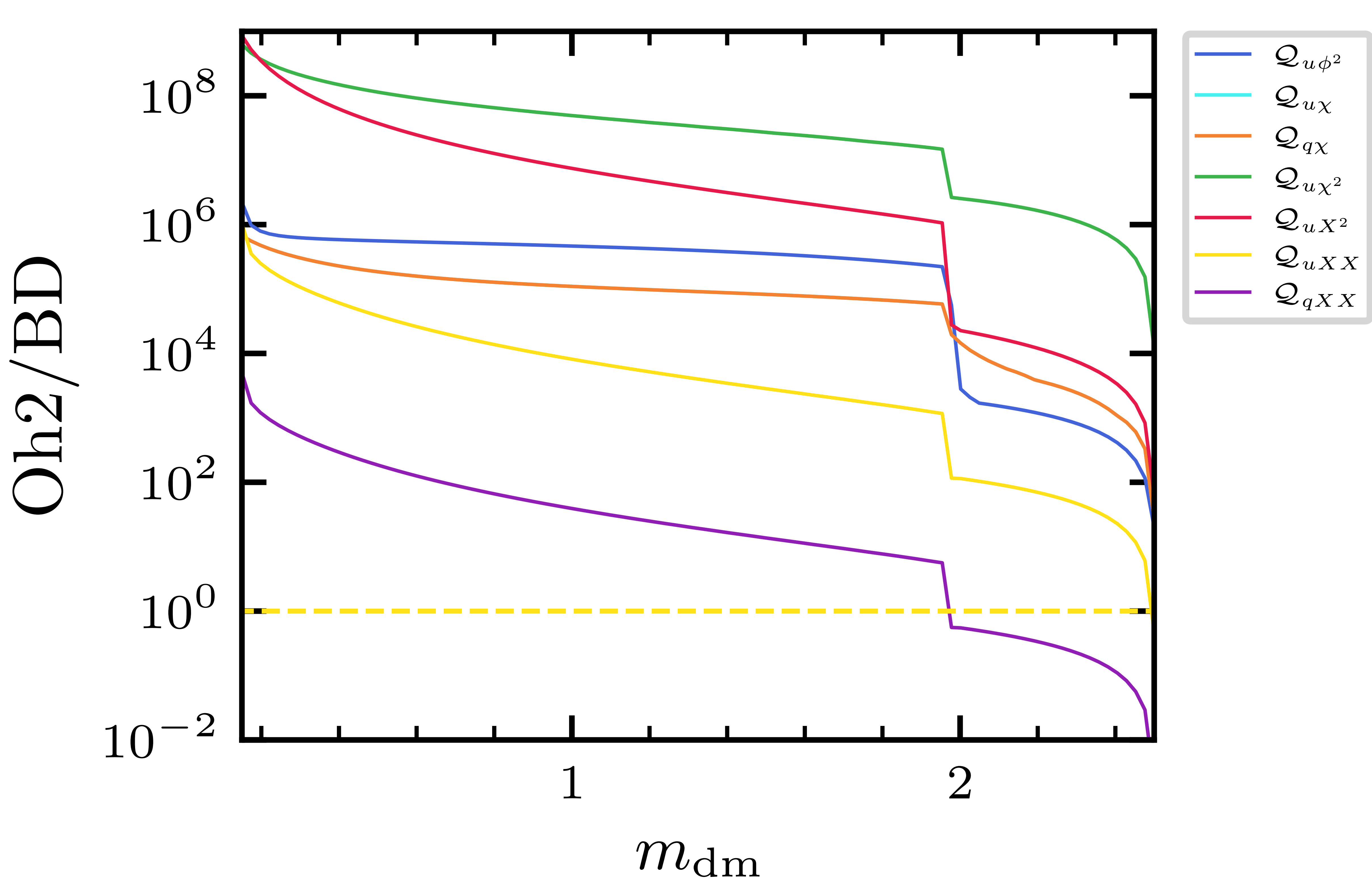
to be finished

Thank You !

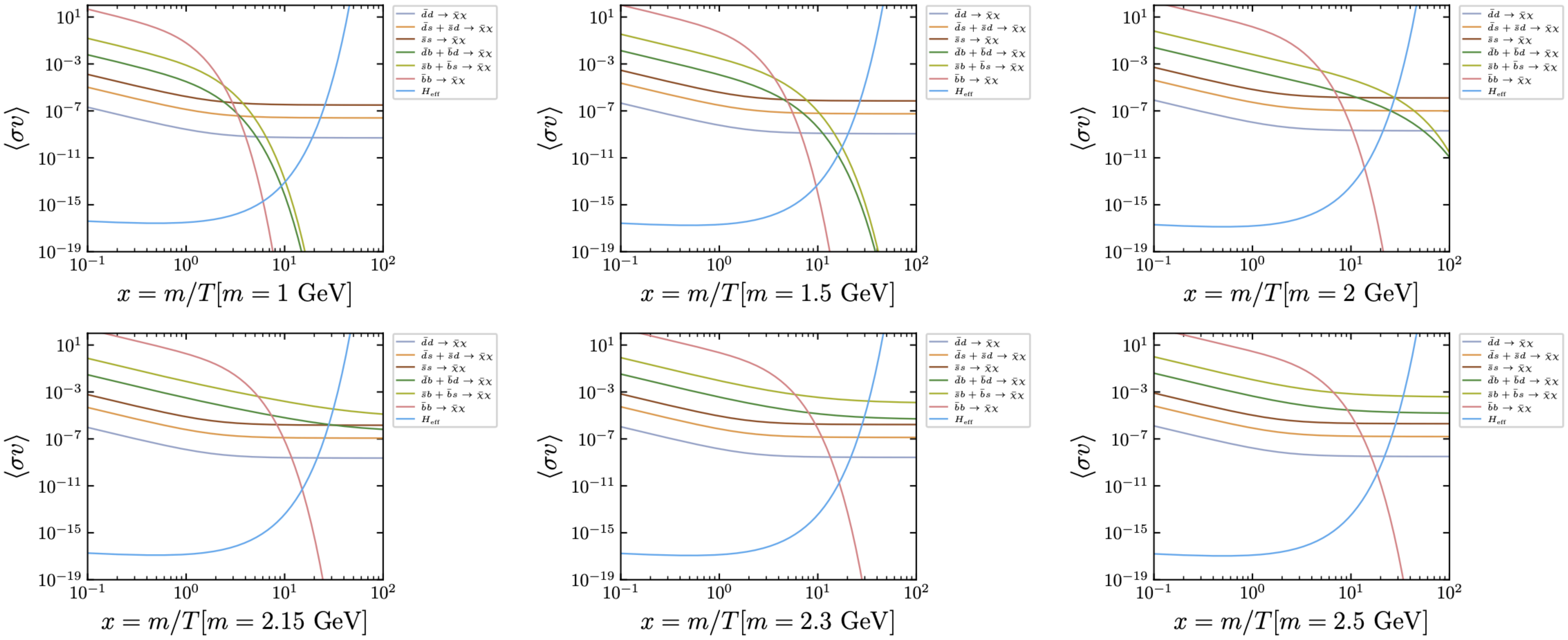
Backup

Hadron decay vs Relic density and Indirect detection



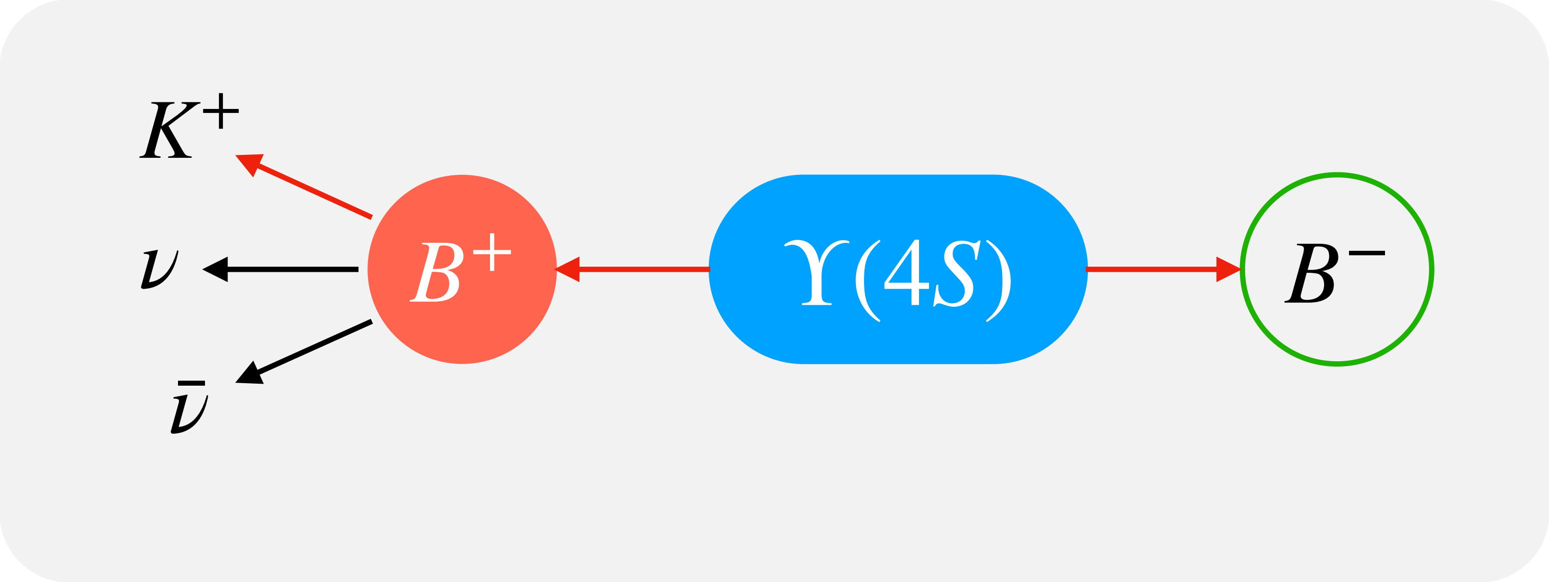


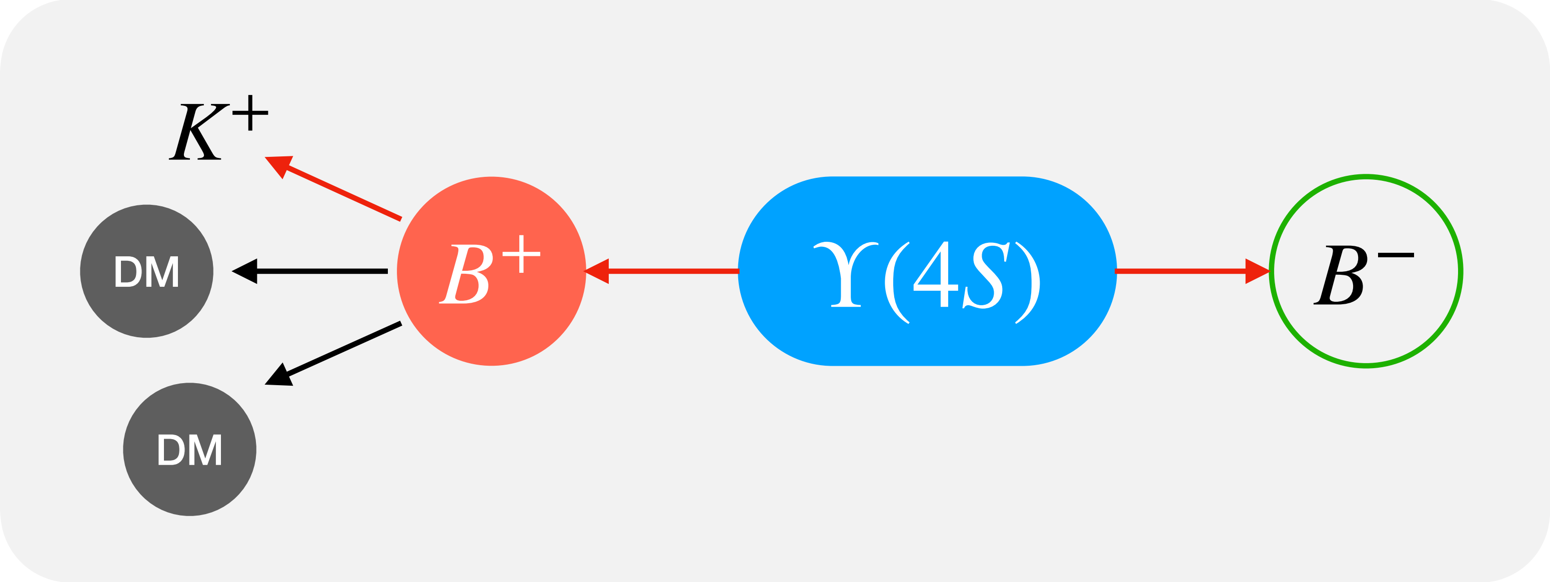
Hadron decay vs Relic density and Indirect detection



Conclusion

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





SMEFT | **Dark SMEFT**

μ_{EW}

LEFT | **Dark LEFT**

μ_b

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

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

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 Dark Matter

	d	s	b
d	DD	NA62/KOTO	Belle II
s		DD	Belle II
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	u	c	t
u	DD	BES/STCF	LHC/CEPC
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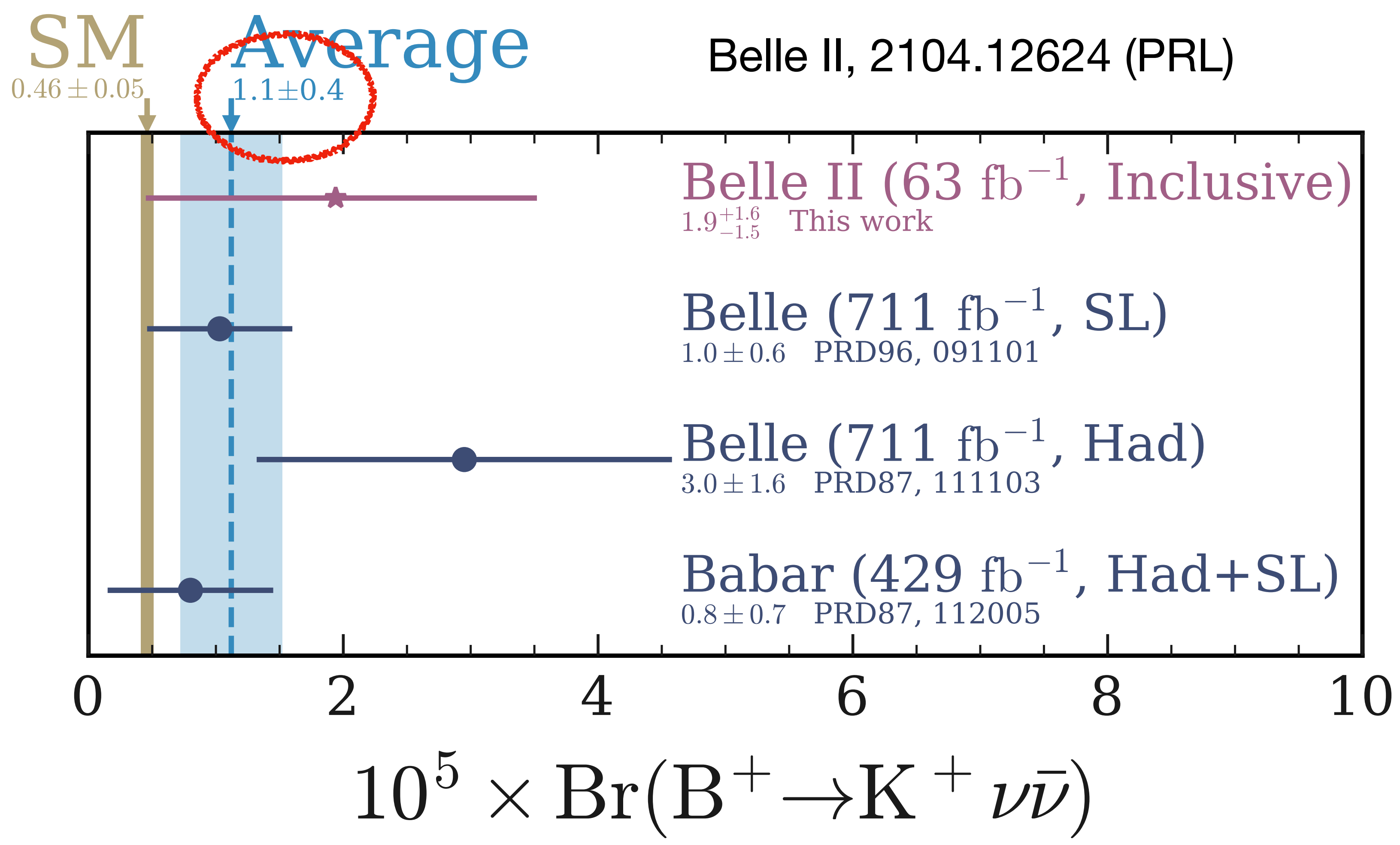
$b \to s\nu\bar{\nu}$: exp & theory

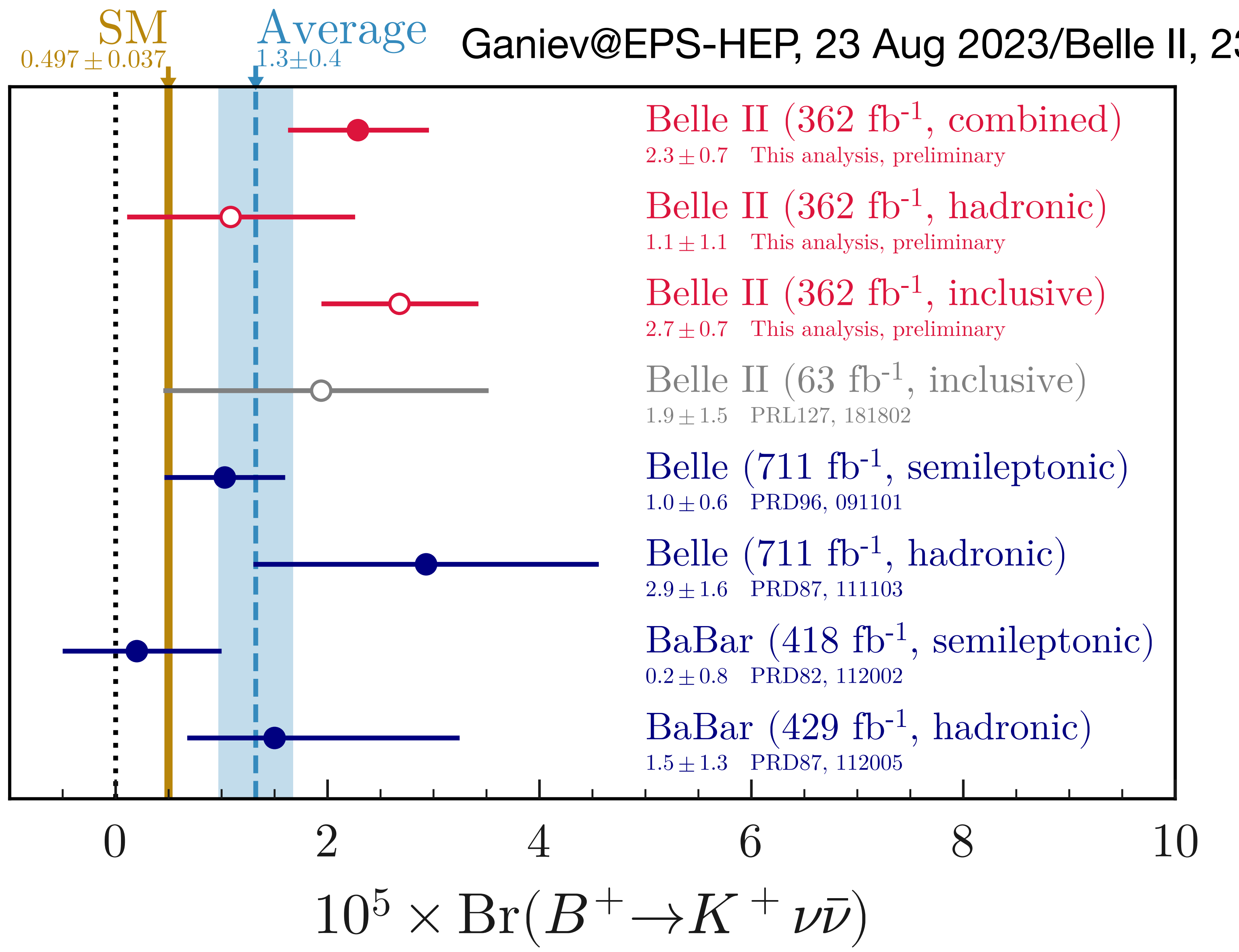
- **2021 Apr**

Belle II, 2104.12624 (PRL)

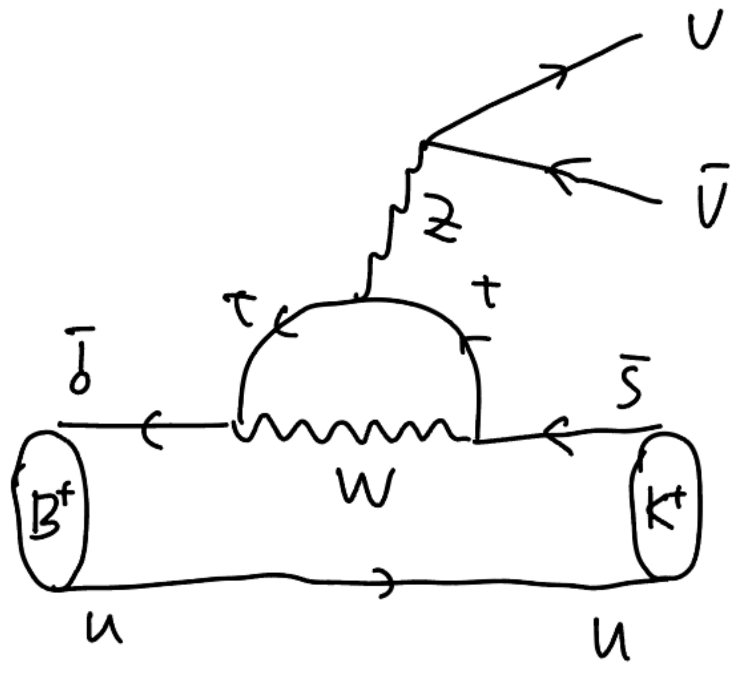


- **2023 Aug**

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



- **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 $\gtrsim 2$

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

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

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

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

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

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

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

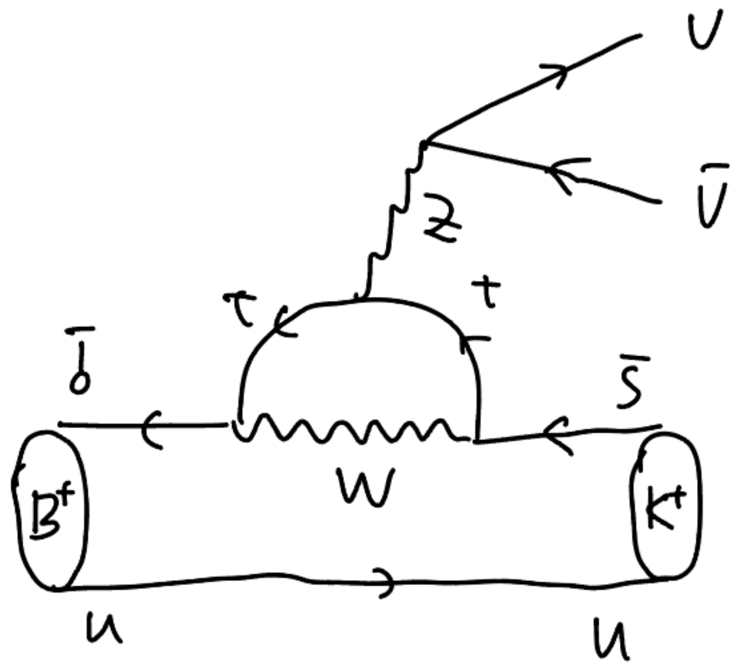
operator structure highly constrained by LH neutrino

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 ?



▶ Exp vs SM $[10^{-6}]$

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▶ Theoretical prediction

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

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

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

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

operator structure highly constrained by LH neutrino

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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

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

μ_{EW}

LEFT

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

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 $G_{\rm QF}$

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

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

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

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

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**

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

No Right-handed down-type FCNC !

- Numerics

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

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

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

- **Prediction**

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

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

- **prediction**

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

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

SMEFT

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

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

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

forbidden by MFV

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

$\mu_{\rm EW}$

LEFT

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

one LEFT operator !
just the SM operator

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

μ_b

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

- **Prediction**

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

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

- **prediction**

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

} **Inconsistent** →

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

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.

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

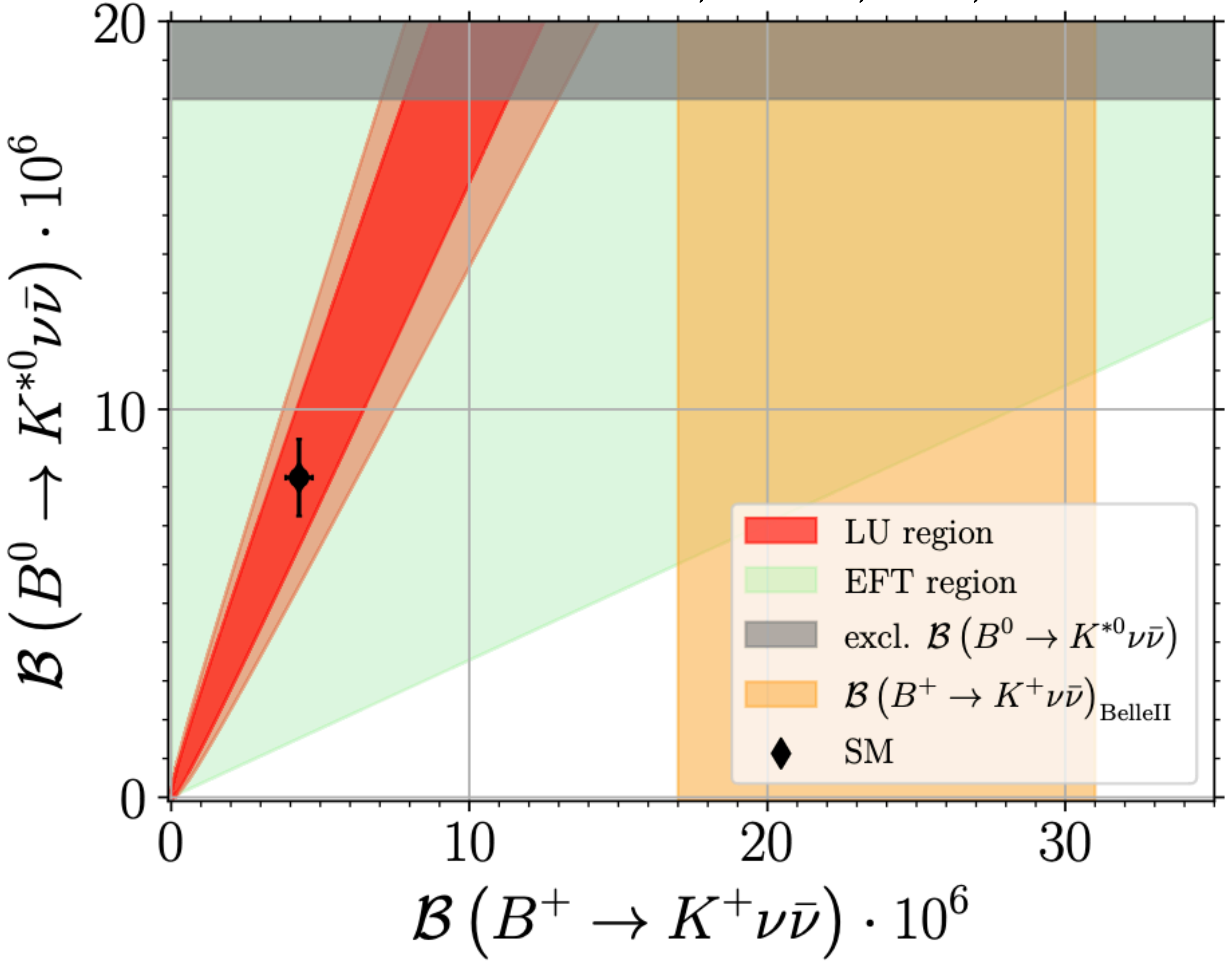
$$\mathcal{O}_L^{\nu_i \nu_j} = \left(\bar{s}\gamma_\mu P_L b\right)\left(\bar{\nu}_i \gamma^\mu P_L \nu_j\right)$$

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

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

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

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

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

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

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

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

$\mu_{\rm EW}$

LEFT

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

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

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 $b \to s\ell\ell$

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, **XBY**, 2402.19208

- **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 $R_{D^{(*)}}$**

- **$\mathcal{O}_{ld}$ 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.

SMEFT

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

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

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

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

$\mu_{\rm EW}$

LEFT

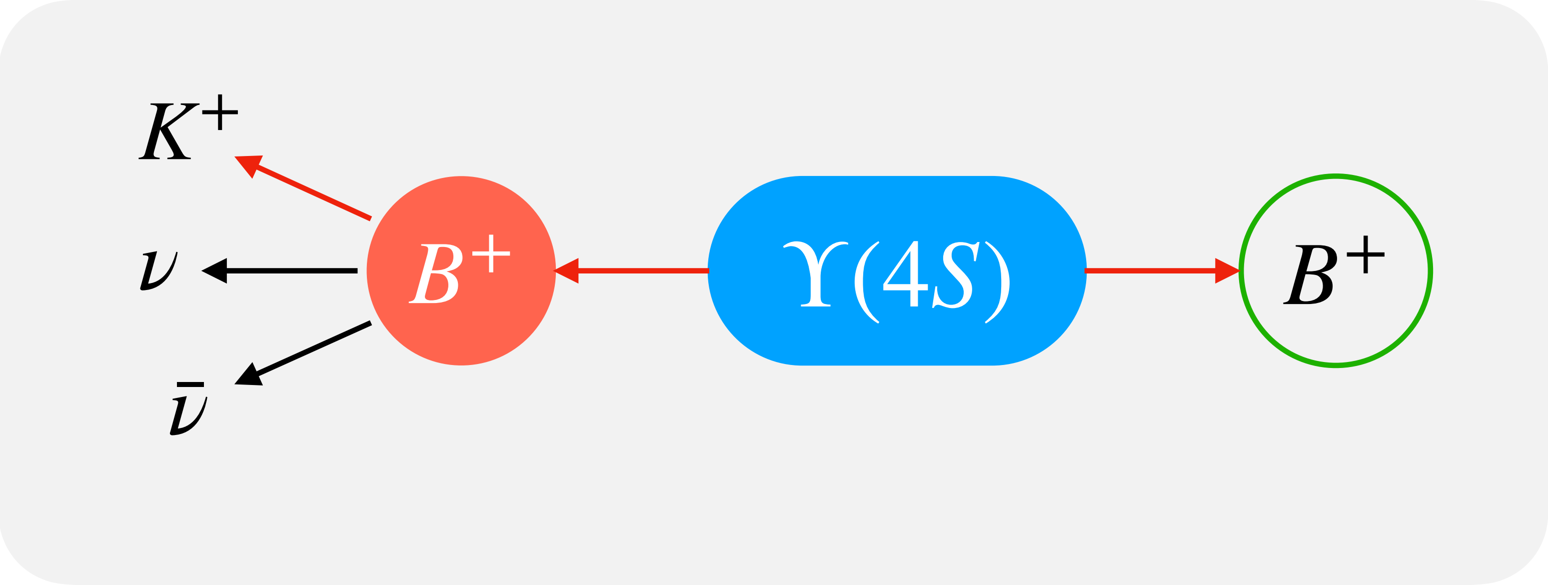
$$\mathcal{O}^{\nu_i\nu_j}_L = \left(\bar{s}\gamma_\mu P_L b\right)\left(\bar{\nu}_i \gamma^\mu P_L \nu_j\right)$$
$$\mathcal{O}^{\nu_i\nu_j}_R = \left(\bar{s}\gamma_\mu P_R b\right)\left(\bar{\nu}_i \gamma^\mu P_L \nu_j\right)$$

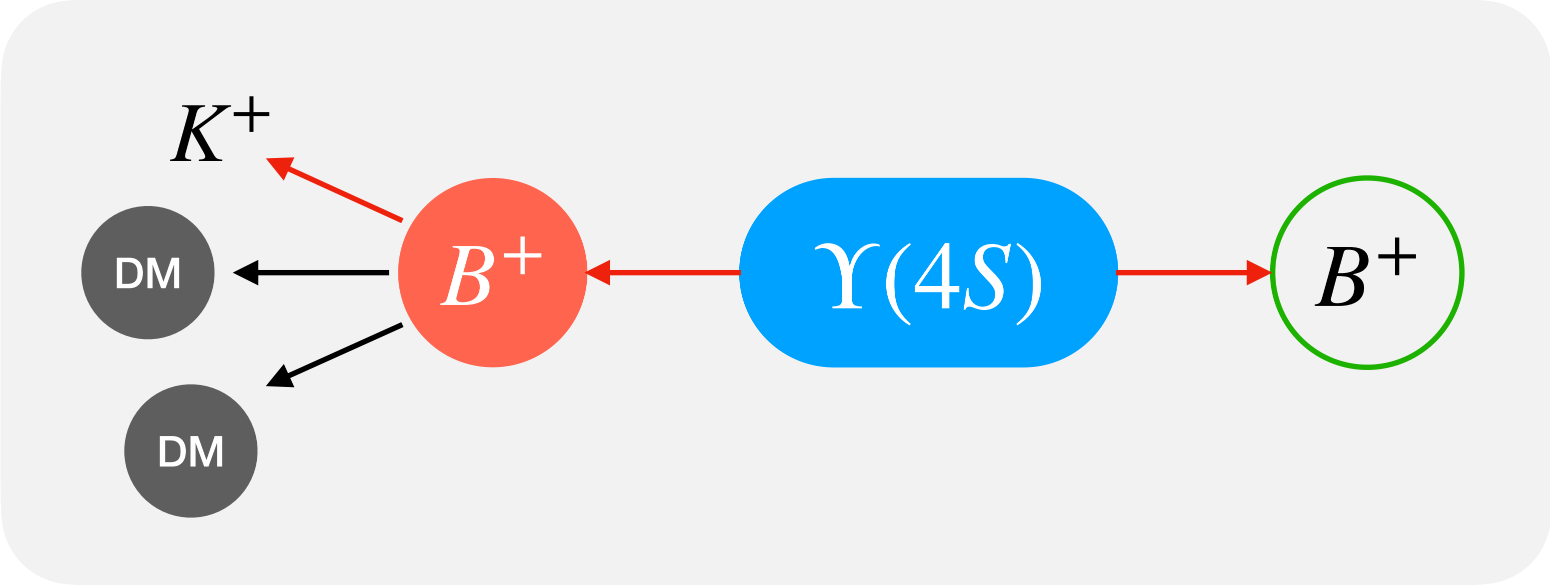
one LEFT operator !
just the SM operator

μ_b

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

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

Dark SMEFT with MFV

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

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

8 operators are eliminated

- Numerics

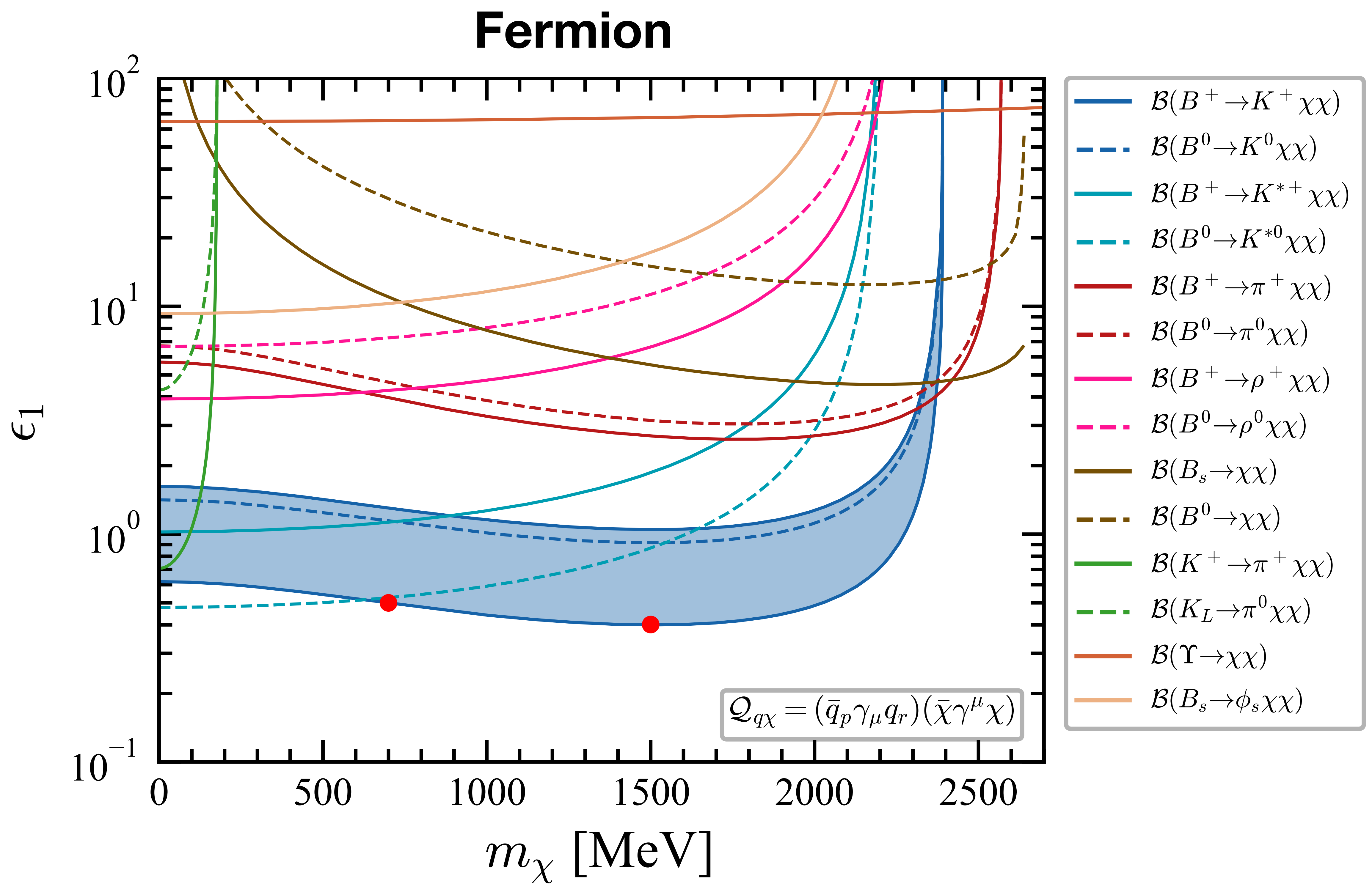
$$\Delta_q = \begin{pmatrix} 0.8 & -3.3 - 1.5i & 79.3 + 35.4i \\ -3.3 + 1.5i & 16.6 & -397.5 + 8.1i \\ 79.3 - 35.4i & -397.5 - 8.1i & 9839.0 \end{pmatrix} \times 10^{-4}$$

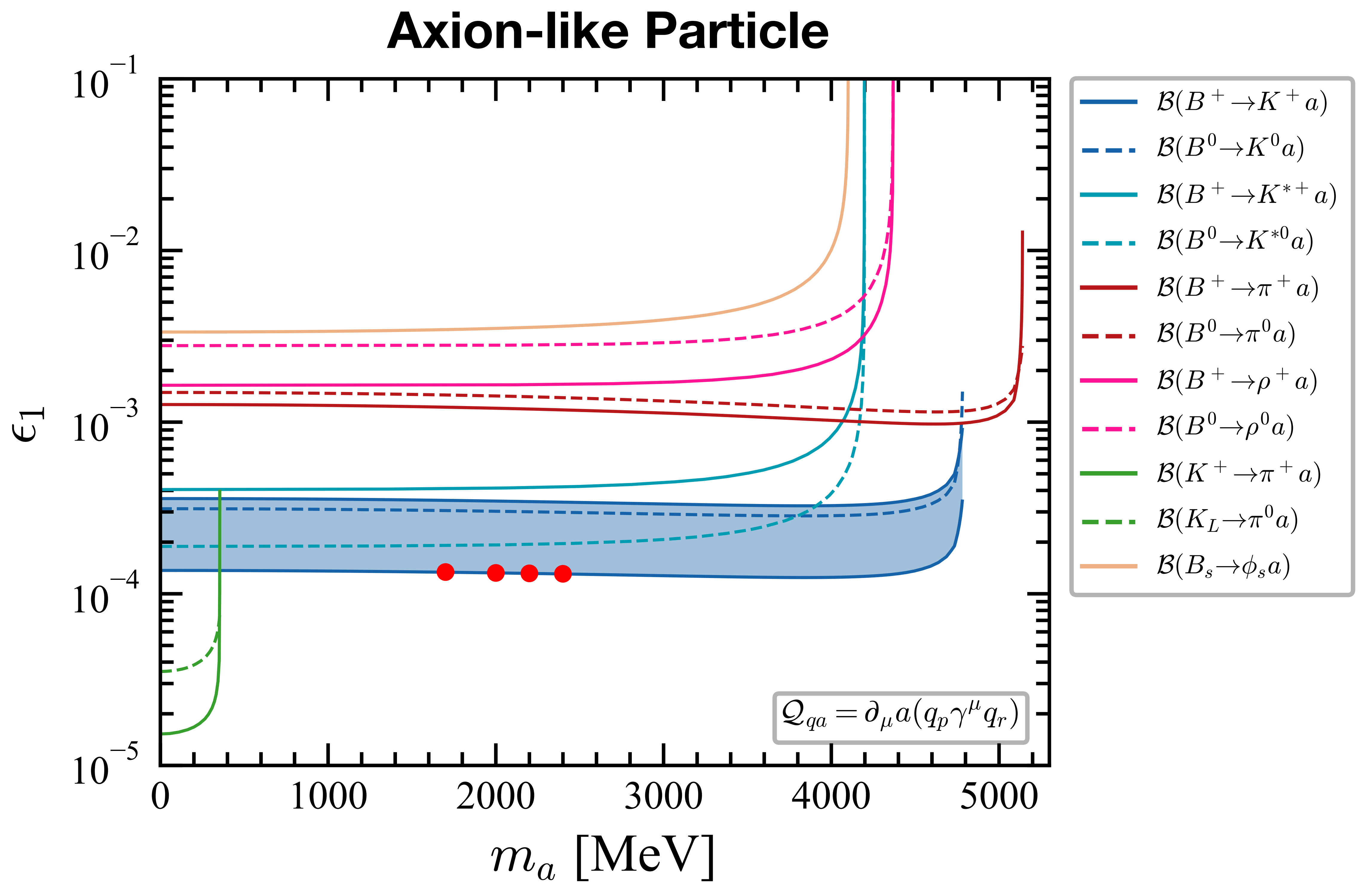
$$\Delta_q \hat{\lambda}_d = \begin{pmatrix} 0.0021 & -0.18 - 0.08i & 191.3 + 85.4i \\ -0.009 + 0.004i & 0.88 & -958.7 + 19.6i \\ 0.21 - 0.10i & -21.1 - 0.4i & 23728.1 \end{pmatrix} \times 10^{-6}$$

Dark SMEFT with MFV: Scalar

all the operators survive
some ones highly constrained

Dark SMEFT with MFV: Fermion, ALP





all the operators survive

Dark SMEFT with MFV: Vector

all the operators survive, some ones highly constrained

Backup

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

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

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

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

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

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

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

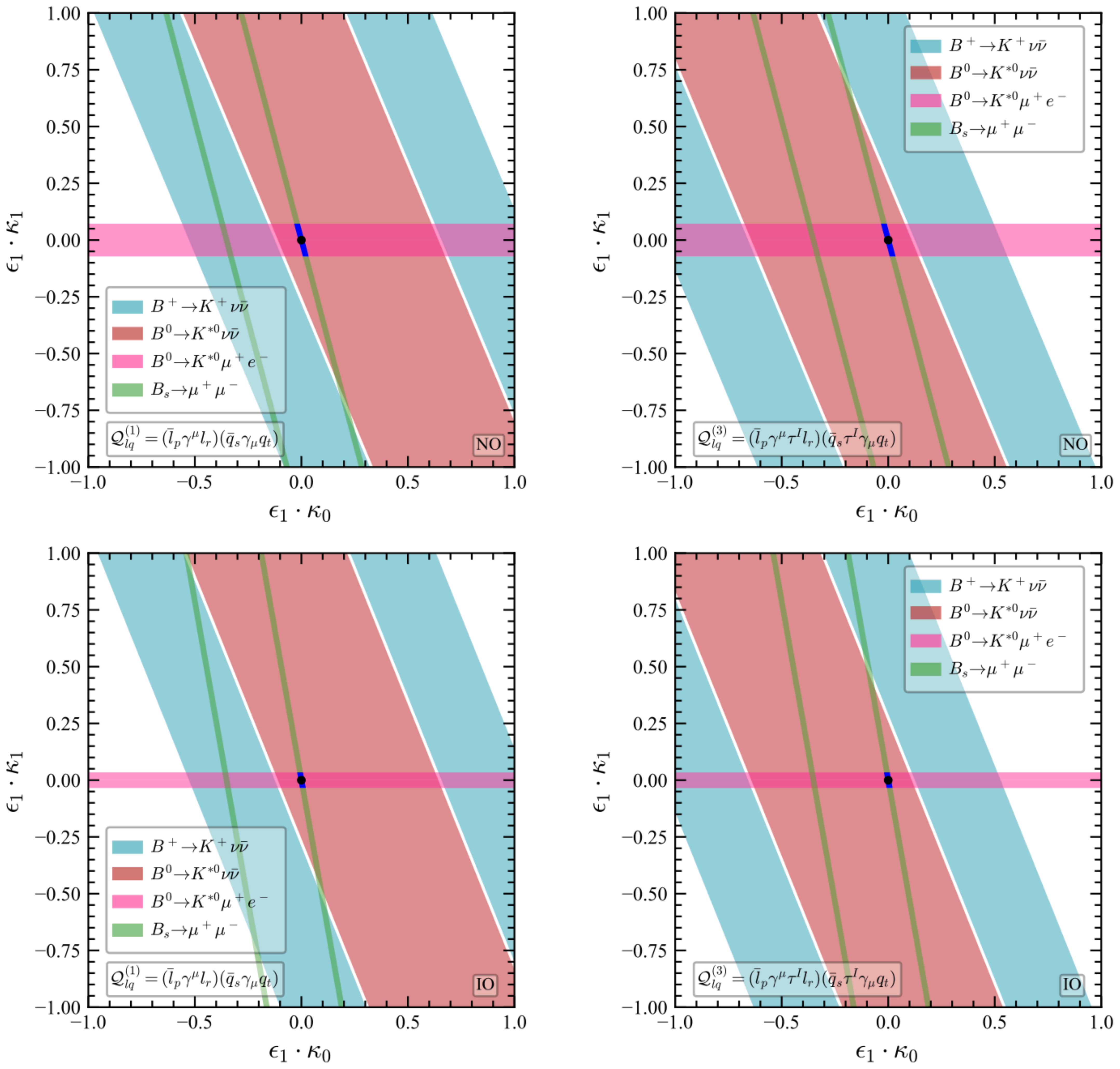
$$\mathcal{C}_{\rm MFV} \approx \kappa_0 + \kappa_1 \mathsf{A}_\ell + \kappa_2 \mathsf{A}_\ell^2, \tag{2.21}$$

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

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

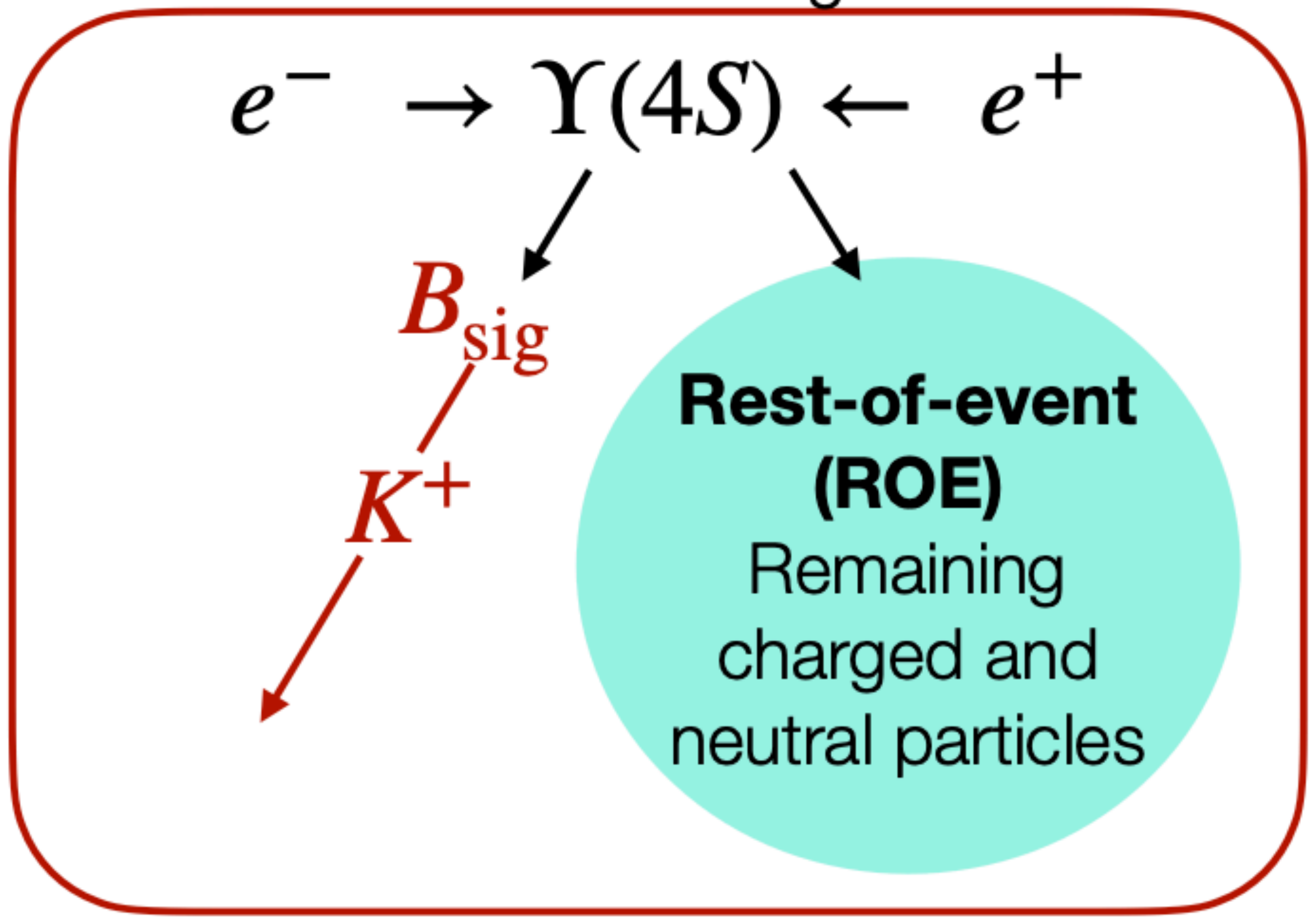


$$\Delta_\ell^{\rm NO} = \begin{pmatrix} -0.19-0.01i & -0.25-0.02i & 0.31-0.04i \\ 0.12+0.01i & 0.28-0.00i & 0.29+0.04i \\ -0.37-0.01i & 0.21-0.05i & -0.03+0.01i \end{pmatrix}, \quad \Delta_\ell^{\rm IO} = \begin{pmatrix} 0.21+0.09i & -0.34+0.05i & 0.03+0.11i \\ 0.31+0.12i & 0.19+0.00i & -0.15-0.14i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

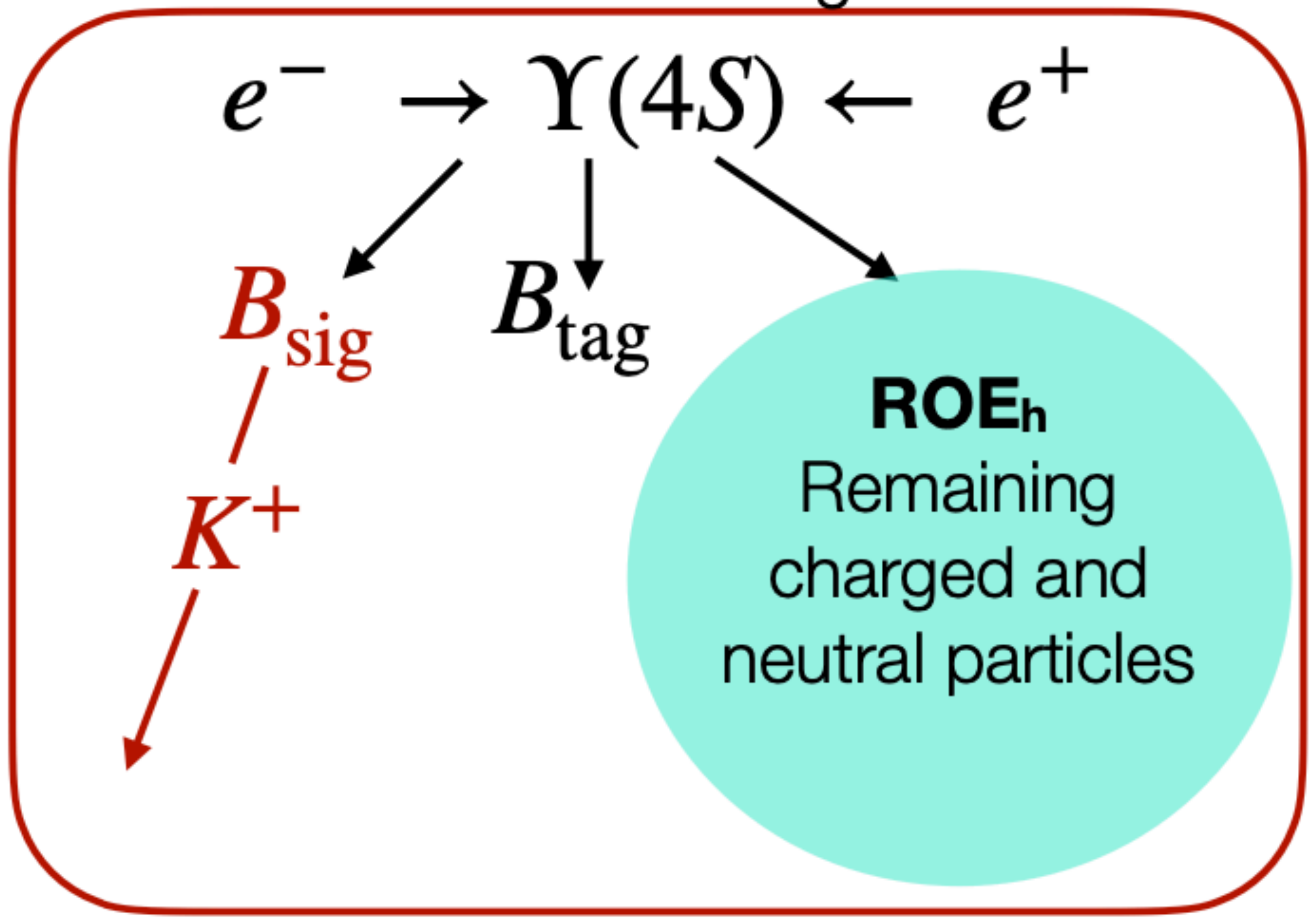
RECONSTRUCTION AND SELECTION

- 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

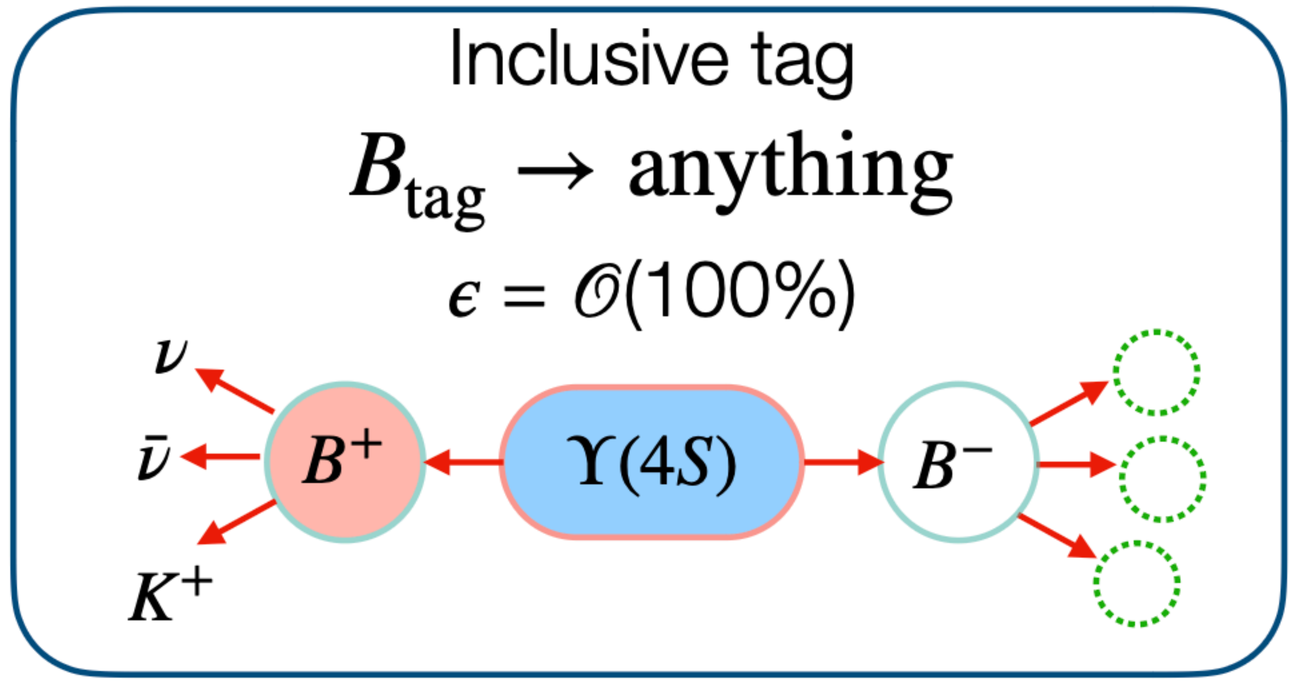
Inclusive-tag

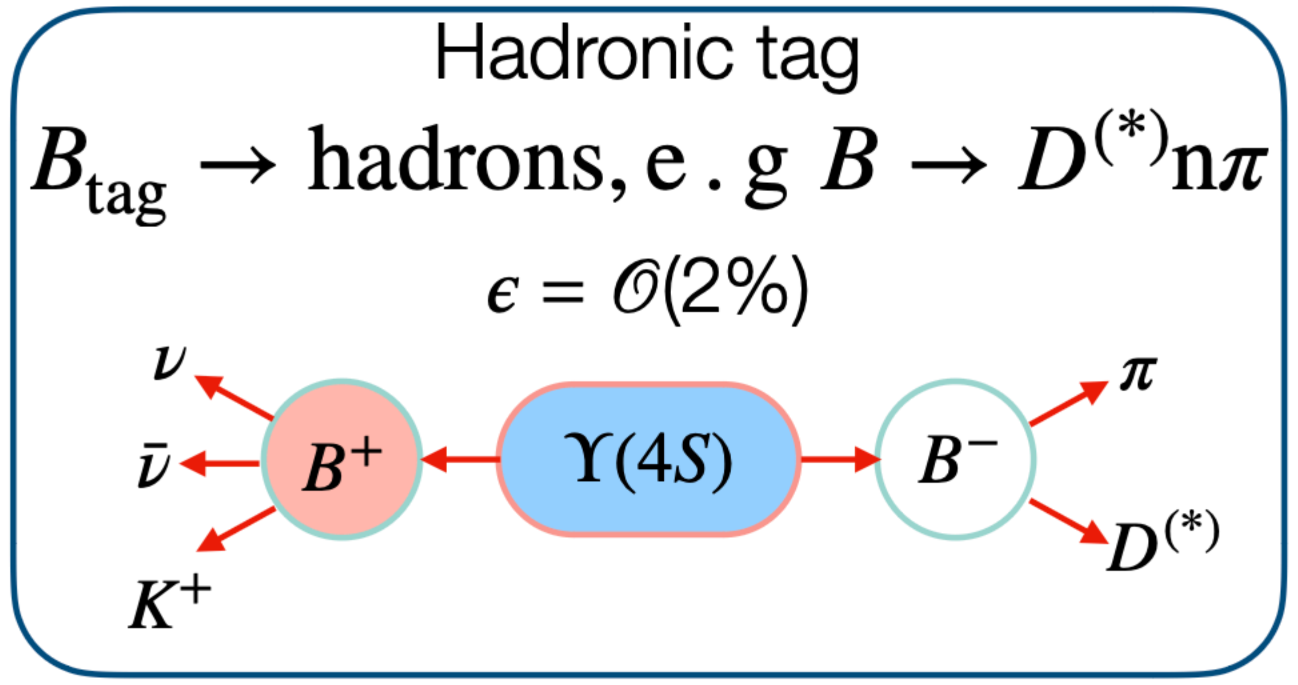


Hadronic-tag



In following, fo





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