Light dark matter contribution to lifetime difference of heavy neutral mesons

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BEACH 2024, Charleston

June 04, 2024

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UNIVERSITY OF South Carolina

Introduction

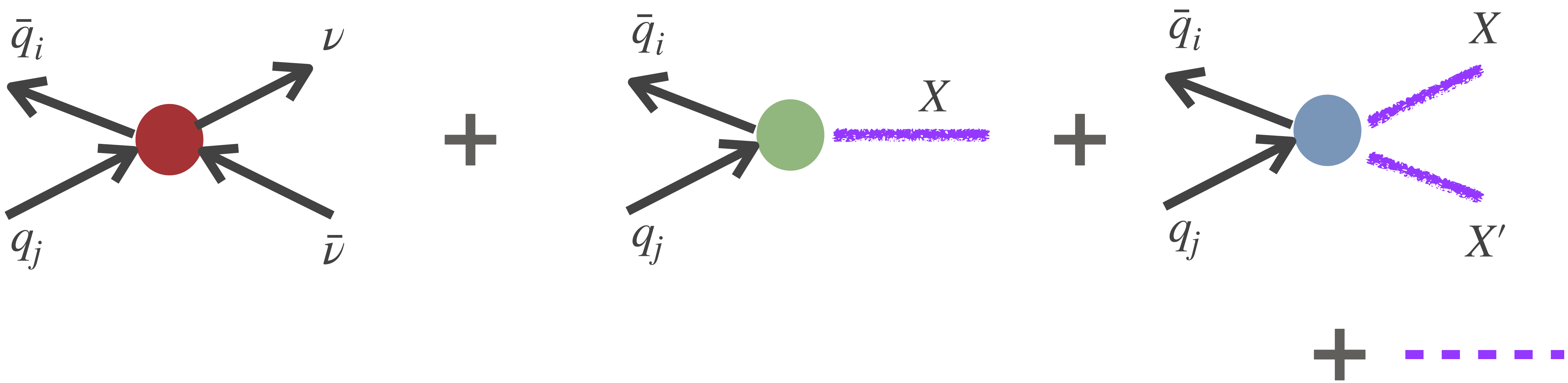
Dark matter probe in heavy meson decays with missing energy

$$M_i \to E_{\rm miss},\ M_i \to M_f E_{\rm miss}$$

Neutrinos are not seen in experiments, $E_{\rm miss}$ can also be carried away by exotic particles

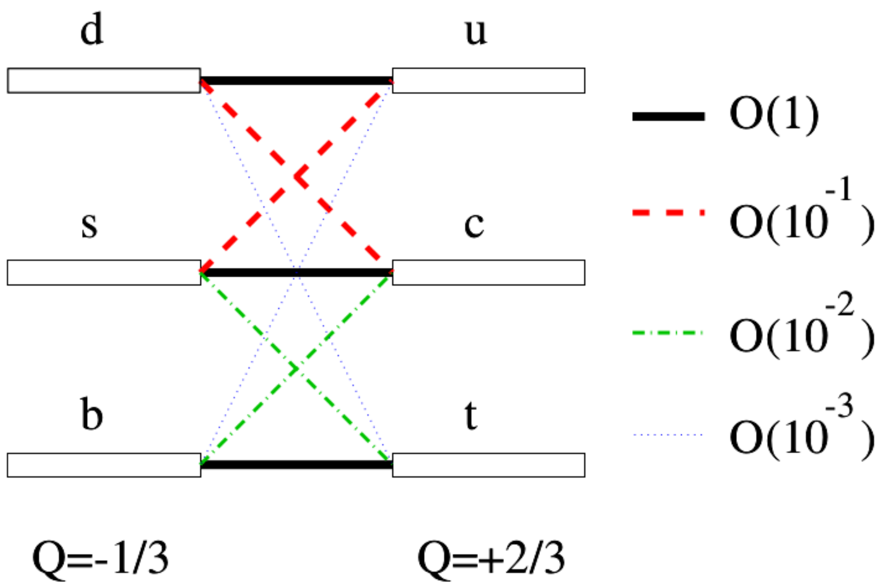
Standard Model

New Physics

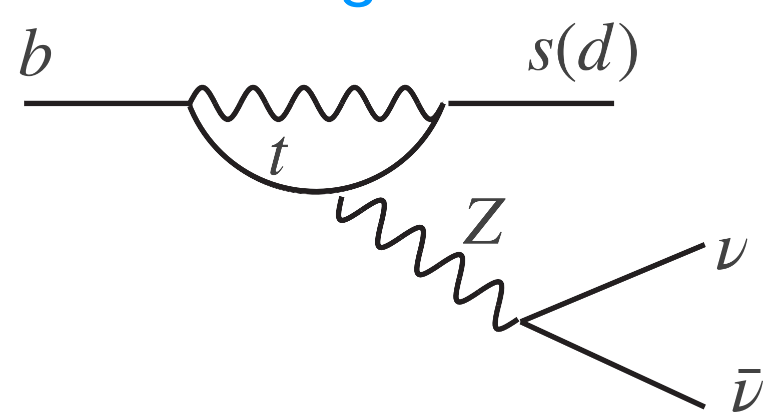


FCNC decays as probe of New physics

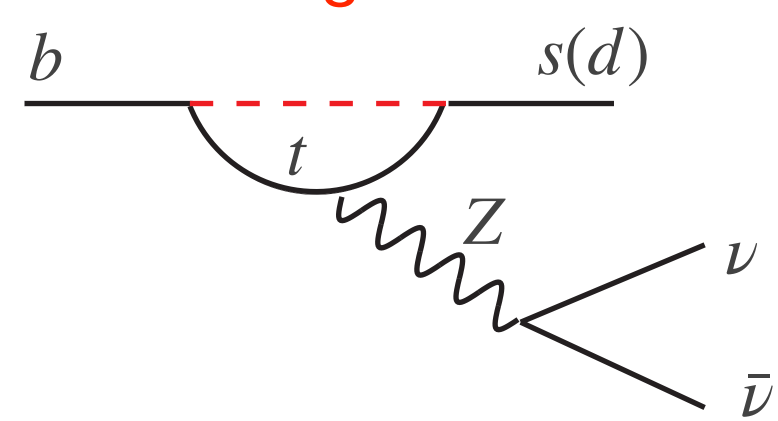
Flavor changing transitions are sensitive probe of SM/NP



SM diagram



NP diagram



SM amplitudes are highly suppressed

Dominated by the short-distance contributions

New particles can appear in competing diagrams and affect amplitudes.

di-neutrinos modes "**theoretically cleaner**"

⟶ Excellent indirect probes of NP!

Current experimental data

	Decay mode	SM prediction		Current bound	
$c \to u$	$D^0 \to E_{\text{miss}}$	$\sim 10^{-27}$	[BGP]	9.4×10^{-5}	Belle, 1611.09455
	$D^0 \to \pi^0 E_{\text{miss}}$	$\sim 10^{-16}$	[BGHP]	2.1×10^{-4}	BES III, 2112.14236
$b \to s$	$B^+ \to K^+ E_{\text{miss}}$	$(4.71 \pm 0.24) \times 10^{-6}$		$(2.3 \pm 0.7) \times 10^{-5}$	Belle-II, 2311.14647
	$B^0 \to K^0 E_{\text{miss}}$	$(4.35 \pm 0.21) \times 10^{-6}$		2.6×10^{-5}	Belle, 1702.03224
	$B^0 \to K^{*0} E_{\text{miss}}$	$(9.81 \pm 0.95) \times 10^{-6}$		1.8×10^{-5}	Belle 1702.03224
	$B^+ \to K^{*+} E_{\text{miss}}$	$(1.06 \pm 0.10) \times 10^{-5}$		4.0×10^{-5}	Belle 1303.3719
$b \to d$	$B^0 \to E_{\text{miss}}$	$\sim 10^{-16}$	[BGP]	2.4×10^{-5}	BaBar 1206.2543
	$B^0 \to \pi^0 E_{\text{miss}}$	$(6.52 \pm 0.78) \times 10^{-8}$		0.9×10^{-5}	Belle 1702.03224
	$B^+ \to \pi^+ E_{\text{miss}}$	$(1.40 \pm 0.16) \times 10^{-7}$		1.4×10^{-5}	Belle 1702.03224
	$B^0 \to \rho^0 E_{\text{miss}}$	$(1.88 \pm 0.35) \times 10^{-7}$		4.0×10^{-5}	Belle 1702.03224
	$B^+ \to \rho^+ E_{\text{miss}}$	$(4.06 \pm 0.73) \times 10^{-7}$		3.0×10^{-5}	Belle 1702.03224

[BGP]: Bhattacharya, Grant, Petrov, 1809.04606
[BGHP]: Burdman, Golowich, Hewitt, Pakvasa, hep-ph/0112235
Other SM predictions using FLAVIO (https://github.com/flav-io/flavio)

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				$\sim 2.6\sigma$ tension	See talk by Seema Choudhury
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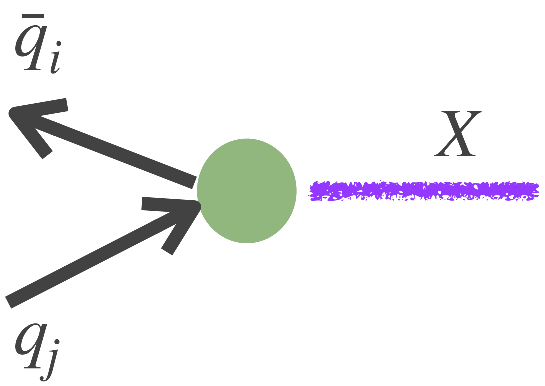
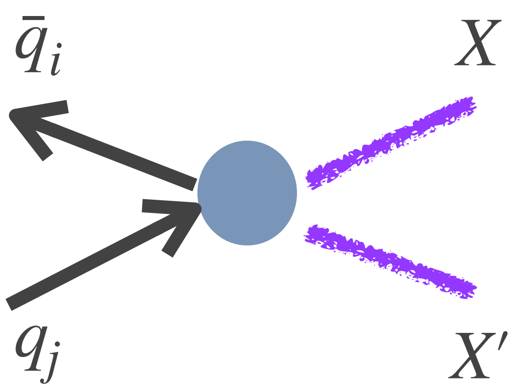
DM probe in meson decays



Bird et al hep-ph/0401195, Kamenik et al 1111.6402,
Li et al 2103.12921, 2306.05333, Geng et al 2212.04699,
Gabrielli et al 2402.05901, Bolton et al 2403.13887
…



Badin et al 1005.1277, Altmannshofer et al 0902.0160,
Kamenik et al 1111.6402, Tandean 1901.10447, Li et al 2004.10942,
Fajfer et al 2101.10712, Felkl et al 2111.04327, 2309.02940,
He et al 2209.05223, 2309.12741, Bolton et al 2403.13887,
Buras at al 2405.06742
…

Connection to meson-antimeson oscillations

$|\Delta F| = 1$ and $|\Delta F| = 2$ physics is related.

Off-diagonal element of meson mass matrix:

$$\left(M - \frac{i}{2}\Gamma\right)_{12}$$

$$= \frac{1}{2m_{M^0}} \langle \overline{M^0} | \mathscr{H}_{\text{eff}}^{|\Delta F|=2} | M^0 \rangle \quad + \quad \frac{1}{2m_{M^0}} \sum_n \frac{\langle \overline{M^0} | \mathscr{H}_{\text{eff}}^{|\Delta F|=1} | n \rangle \langle n | \mathscr{H}_{\text{eff}}^{|\Delta F|=1} | M^0 \rangle}{m_{M^0} - E_n + i\epsilon},$$

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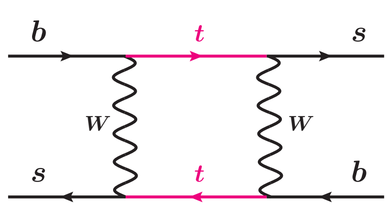
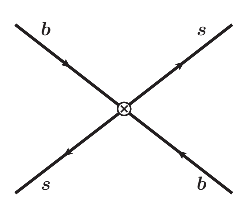
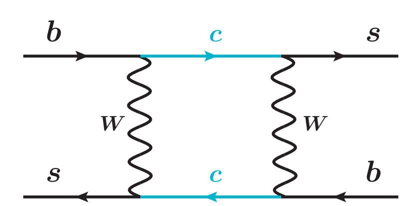
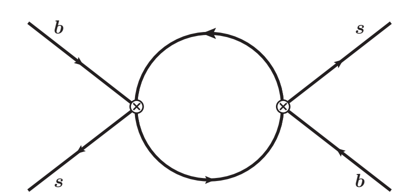
contributes to m_{12}

contributes to m_{12} and Γ_{12}









Local interaction at m_b

bi-local contributions connected by physical intermediate state

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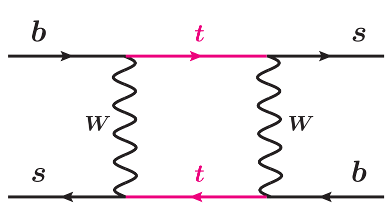
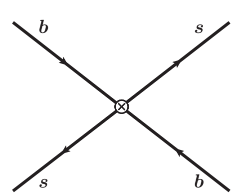
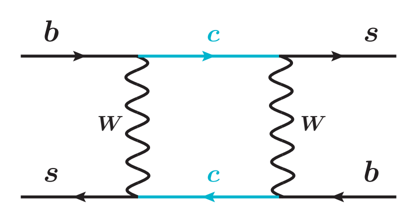
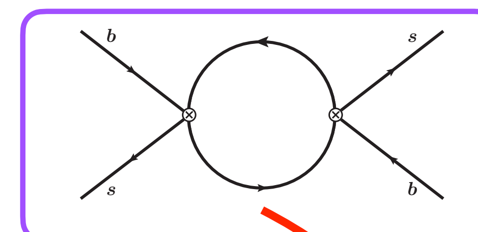




Local interaction at m_b

contributes to m_{12} and Γ_{12}





bi-local contributions connected by physical intermediate state

DM

$\Delta F = 1$ decays $b \to s, d$ DM DM, $c \to u$ DM DM affect lifetime-difference in meson-antimeson mixing

Effective interactions: scalar DM

Low-energy effective Hamiltonian

$SU(3)_c \times U(1)_{em}$
unbroken symmetry

$$\mathscr{H}_{\rm eff} = \sum_i \frac{C_i}{\Lambda^2} O_i$$

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Badin, Petrov 1005.1277; Lehmann, Profumo 2002.07809, He, Ma, Valencia 2209.05223

For complex scalar field:

$$O_S^{q_i q_j} = m_{q_j} (\bar{q}_i q_j)(\phi^\dagger \phi)$$

$$O_P^{q_i q_j} = m_{q_j} (\bar{q}_i i\gamma_5 q_j)(\phi^\dagger \phi)$$

$$O_V^{q_i q_j} = (\bar{q}_i \gamma^\mu q_j)(\phi^\dagger i\overleftrightarrow{\partial}_\mu \phi)$$

$$O_A^{q_i q_j} = (\bar{q}_i \gamma^\mu \gamma_5 q_j)(\phi^\dagger i\overleftrightarrow{\partial}_\mu \phi)$$

Notation: $\phi^\dagger \overleftrightarrow{\partial}_\mu \phi = \phi^\dagger (\partial_\mu \phi) - (\partial_\mu \phi^\dagger)\phi$

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For complex scalar field:	For real scalar field:
$O_S^{q_iq_j} = m_{q_j}(\bar{q}_i q_j)(\phi^\dagger \phi)$	✓
$O_P^{q_iq_j} = m_{q_j}(\bar{q}_i i\gamma_5 q_j)(\phi^\dagger \phi)$	✓
$O_V^{q_iq_j} = (\bar{q}_i \gamma^\mu q_j)(\phi^\dagger i\overleftrightarrow{\partial}_\mu \phi)$	✗
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Notation: $\phi^\dagger \overleftrightarrow{\partial}_\mu \phi = \phi^\dagger(\partial_\mu \phi) - (\partial_\mu \phi^\dagger)\phi$

Effective interactions: fermion DM

$$\mathscr{H}_{\text{eff}} = \sum_i \frac{C_i}{\Lambda^2} O_i$$

Badin, Petrov 1005.1277;

Lehmann, Profumo 2002.07809,

He, Ma, Valencia 2209.05223

Effective operators for Dirac Fermion:

$$O_{SS}^{q_i q_j} = (\bar{q}_i q_j)(\bar{\psi}\psi) \qquad O_{PS}^{q_i q_j} = (\bar{q}_i i\gamma_5 q_j)(\bar{\psi}\psi)$$

$$O_{SP}^{q_i q_j} = (\bar{q}_i q_j)(\bar{\psi} i\gamma_5 \psi) \qquad O_{PP}^{q_i q_j} = (\bar{q}_i \gamma_5 q_j)(\bar{\psi}\gamma_5\psi)$$

scalar interactions

$$O_{VV}^{q_i q_j} = (\bar{q}_i \gamma^\mu q_j)(\bar{\psi}\gamma_\mu\psi) \qquad O_{AV}^{q_i q_j} = (\bar{q}_i \gamma^\mu \gamma_5 q_j)(\bar{\psi}\gamma_\mu\psi)$$

$$O_{VA}^{q_i q_j} = (\bar{q}_i \gamma^\mu q_j)(\bar{\psi}\gamma_\mu\gamma_5\psi) \qquad O_{AA}^{q_i q_j} = (\bar{q}_i \gamma^\mu \gamma_5 q_j)(\bar{\psi}\gamma_\mu\gamma_5\psi)$$

vector interactions

$$O_{TT}^{q_i q_j} = (\bar{q}_i \sigma^{\mu\nu} q_j)(\bar{\psi}\sigma_{\mu\nu}\psi) \qquad O_{T\tilde{T}}^{q_i q_j} = (\bar{q}_i \sigma^{\mu\nu} q_j)(\bar{\psi}\sigma_{\mu\nu}\gamma_5\psi)$$

tensor interactions

Effective interactions: fermion DM

$$\mathcal{H}_{\text{eff}} = \sum_i \frac{C_i}{\Lambda^2} O_i$$

Badin, Petrov 1005.1277;

Lehmann, Profumo 2002.07809,

He, Ma, Valencia 2209.05223

Effective operators for Majorana Fermion:

$O_{SS}^{q_iq_j} = (\bar{q}_i q_j)(\bar{\psi}\psi)$ $\quad$ $O_{PS}^{q_iq_j} = (\bar{q}_i i\gamma_5 q_j)(\bar{\psi}\psi)$

$O_{SP}^{q_iq_j} = (\bar{q}_i q_j)(\bar{\psi} i\gamma_5\psi)$ $\quad$ $O_{PP}^{q_iq_j} = (\bar{q}_i \gamma_5 q_j)(\bar{\psi}\gamma_5\psi)$

scalar interactions

~~$O_{VV}^{q_iq_j} = (\bar{q}_i \gamma^\mu q_j)(\bar{\psi}\gamma_\mu\psi)$~~ $\quad$ ~~$O_{AV}^{q_iq_j} = (\bar{q}_i \gamma^\mu\gamma_5 q_j)(\bar{\psi}\gamma_\mu\psi)$~~

$O_{VA}^{q_iq_j} = (\bar{q}_i \gamma^\mu q_j)(\bar{\psi}\gamma_\mu\gamma_5\psi)$ $\quad$ $O_{AA}^{q_iq_j} = (\bar{q}_i \gamma^\mu\gamma_5 q_j)(\bar{\psi}\gamma_\mu\gamma_5\psi)$

vector interactions

~~$O_{TT}^{q_iq_j} = (\bar{q}_i \sigma^{\mu\nu} q_j)(\bar{\psi}\sigma_{\mu\nu}\psi)$~~ $\quad$ ~~$O_{T\tilde{T}}^{q_iq_j} = (\bar{q}_i \sigma^{\mu\nu} q_j)(\bar{\psi}\sigma_{\mu\nu}\gamma_5\psi)$~~

tensor interactions

Note: $\overline{\psi^c}\,\Gamma\,\psi^c = -\,\overline{\psi}\,\Gamma\,\psi$ for $\Gamma = \gamma^\mu, \sigma^{\mu\nu}, \sigma^{\mu\nu}\gamma_5$

Lifetime difference calculation

Decay width can be related to imaginary part of the forward scattering amplitude

$$\Gamma_{12} = \frac{1}{2m_{M^0}} \langle \overline{M^0} | \mathcal{T} | M^0 \rangle$$

$$\mathcal{T} = \mathrm{Im} \left\{ i \int d^4x T \left[\mathcal{H}_{\mathrm{eff}}^{\Delta F=1}(x) \mathcal{H}_{\mathrm{eff}}^{\Delta F=1}(0) \right] \right\}$$

Dominated by small distance contributions, compared to scale $1/m_q$

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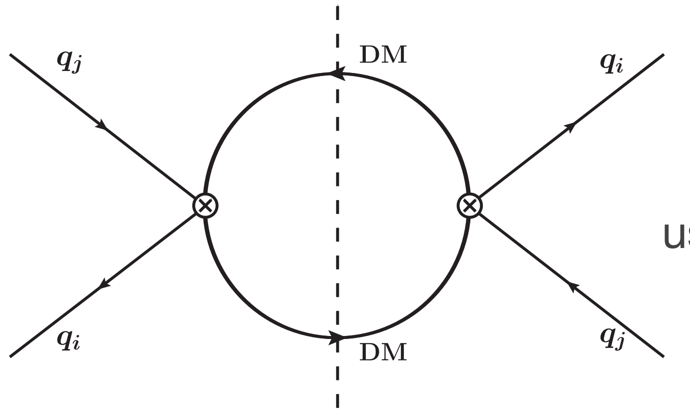
Example: consider operator $O_S^{q_i q_j} = m_{q_j} (\bar{q}_i q_j)(\phi^\dagger \phi)$



using Cutkosky rules

$$\Gamma_{12} = \frac{(C_S^{q_i q_j})^2 \, m_{q_j}^2 \beta_\phi}{32\pi \, m_{M^0}} \langle \overline{M^0} \,|\, (\bar{q}_i q_j)(\bar{q}_i q_j) \,|\, M^0 \rangle$$

$\Delta F = 2$ matrix elements

$$\beta_\phi = \sqrt{1 - 4m_\phi^2 / m_{M^0}^2}$$

See talk by William Jay

Making contact with experiments

$B_s^0 - \overline{B}_s^0$ system: $\Delta\Gamma_s = 2\,|\,\Gamma_{12}^{s,\mathrm{SM}} + \Gamma_{12}^{s,\mathrm{NP}}\,|\cos\phi_s$ $\phi_s = \arg(-M_{12}^s/\Gamma_{12}^s)$

$$\frac{\Gamma_{12}^s}{M_{12}^s} = 10^{-4}\left[c + a\frac{\lambda_u}{\lambda_t} + b\left(\frac{\lambda_u}{\lambda_t}\right)^2\right]$$

$\lambda_{u_i} = V_{u_i b}V_{u_i q}^*$ $c \approx -48,\ \ a \approx 12,\ \ b \approx 0.79$

Artuso, Borissov, Lenz 1511.09466

$(\Delta\Gamma_s)_{\mathrm{SM}} = (0.083 \pm 0.015)$ ps^{-1}

$(\Delta\Gamma_s)_{\mathrm{exp}} = (0.084 \pm 0.005)$ ps^{-1}

HFLAV, 2206.07501

Beneke et al hep-ph/9605259, Dighe et al hep-ph/0109088, Beneke et al hep-ph/9808385, hep-ph/0307344, Ciuchini et al hep-ph/0308029, Lenz et al hep-ph/0612167, ….Gerlach et al 2205.07907, Albrecht et al 2402.04224

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$B^0 - \overline{B}^0$ system: $c \approx -50,\ \ a \approx 12,\ \ b \approx 0.24$ Artuso, Borissov, Lenz 1511.09466

$(\Delta\Gamma_d)_{\mathrm{SM}} = (0.259 \pm 0.048) \times 10^{-2}$ ps^{-1} $(\Delta\Gamma_d/\Gamma_d)_{\mathrm{exp}} = 0.001 \pm 0.010$ HFLAV, 2206.07501

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Artuso, Borissov, Lenz 1511.09466

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$D^0 - \overline{D}^0$ system: $y_{12}^D = |\Gamma_{12}^D|/\Gamma$

$(\Gamma_{12}^D)_{\mathrm{SM}} = -\lambda_s^2(\Gamma_{ss}^D - 2\Gamma_{sd}^D + \Gamma_{dd}^D) + 2\lambda_s\lambda_s(\Gamma_{sd}^D - \Gamma_{dd}^D) - \lambda_b^2\Gamma_{dd}^D$ highly suppressed!

$\lambda_{d_i} = V_{cd_i}V_{ud_i}^*$ Lenz & Wilkinson 2011.04443

HFLAV, 2206.07501 $(y_{12}^D)_{\mathrm{exp}} = 0.641^{+0.024}_{-0.023}\ \%$

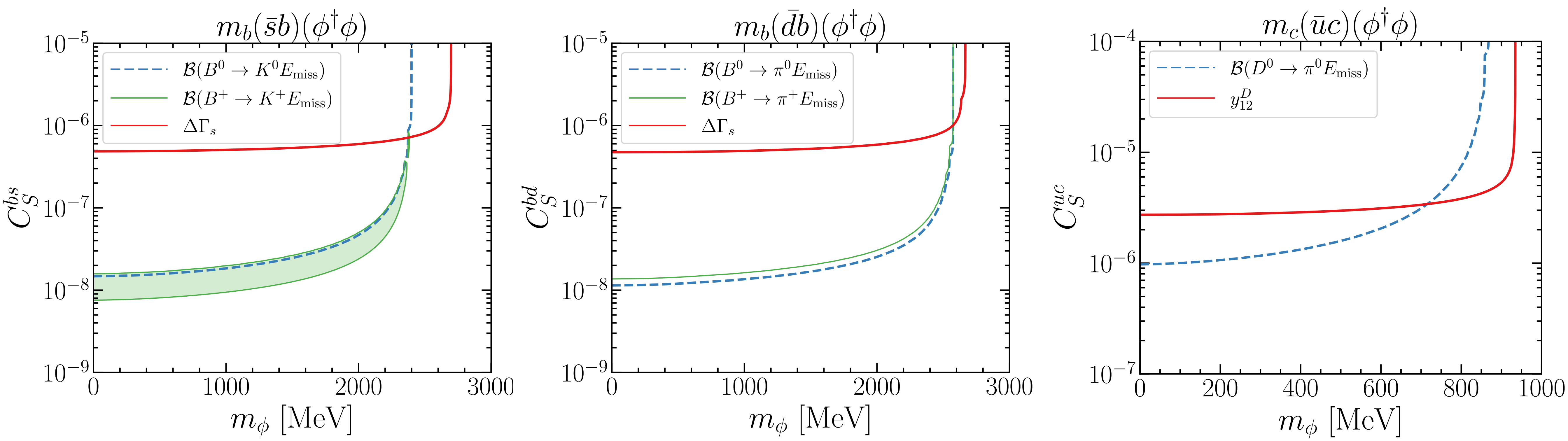
$(y_{12}^D)_{\mathrm{NP}} < (y_{12}^D)_{\mathrm{exp}}$

Results

Scalar dark matter

Constraint on scalar DM

$m_{q_j}(\bar{q}_i q_j)(\phi^\dagger \phi)$ $\quad$ $m_{q_j}(\bar{q}_i i\gamma_5 q_j)(\phi^\dagger \phi)$ $\quad$ $(\bar{q}_i \gamma^\mu q_j)(\phi^\dagger i\overleftrightarrow{\partial}_\mu \phi)$ $\quad$ $(\bar{q}_i \gamma^\mu \gamma_5 q_j)(\phi^\dagger i\overleftrightarrow{\partial}_\mu \phi)$

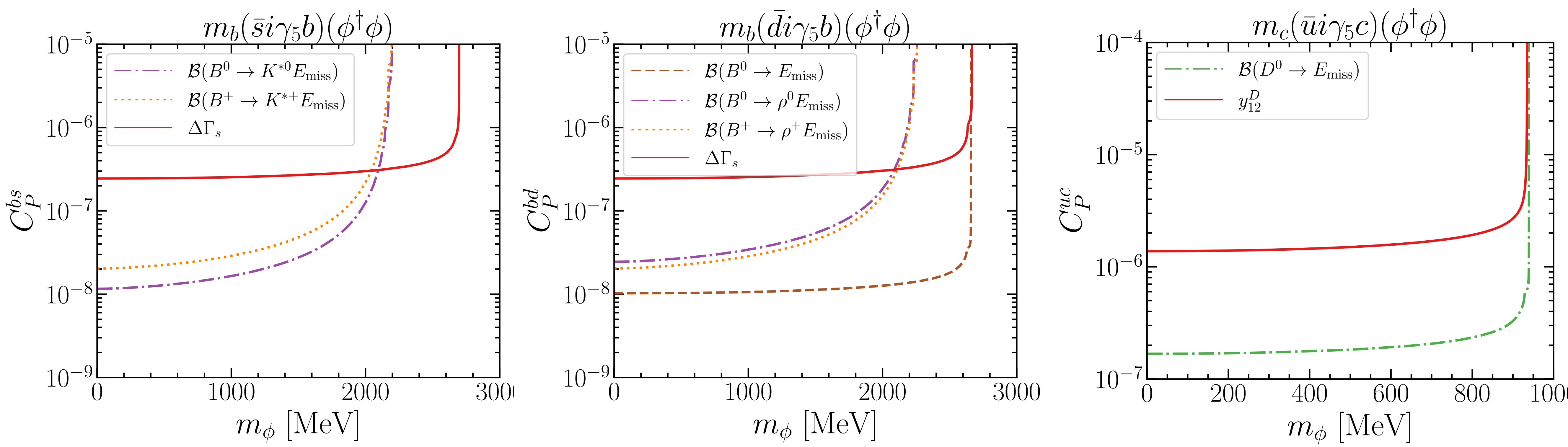


Recall: $\langle 0 | \overline{q}_i q_j | M^0 \rangle = \langle 0 | \overline{q}_i \gamma^\mu q_j | M^0 \rangle = 0$

$\langle P | \overline{q}_i \gamma^\mu \gamma_5 q_j | M_i \rangle = \langle P | \overline{q}_i \gamma_5 q_j | M_i \rangle = \langle V | \overline{q}_i q_j | M_i \rangle = 0$

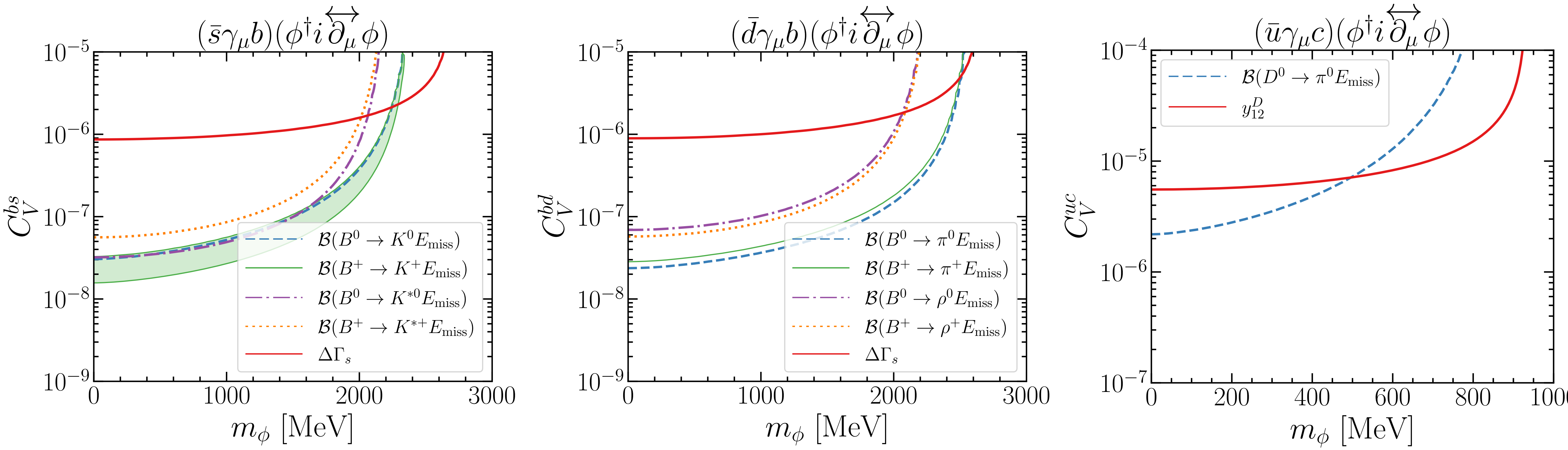
Constraint on scalar DM

$m_{q_j}(\bar{q}_i q_j)(\phi^\dagger\phi)$ $\quad$ $m_{q_j}(\bar{q}_i i\gamma_5 q_j)(\phi^\dagger\phi)$ $\quad$ $(\bar{q}_i\gamma^\mu q_j)(\phi^\dagger i\overleftrightarrow{\partial}_\mu\phi)$ $\quad$ $(\bar{q}_i\gamma^\mu\gamma_5 q_j)(\phi^\dagger i\overleftrightarrow{\partial}_\mu\phi)$



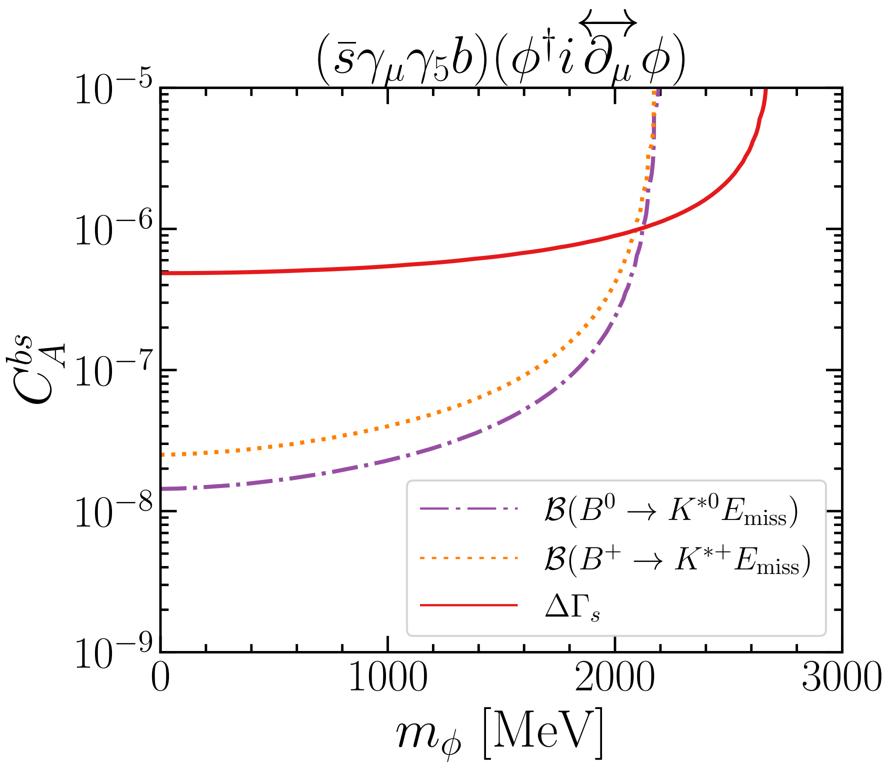
Constraint on scalar DM

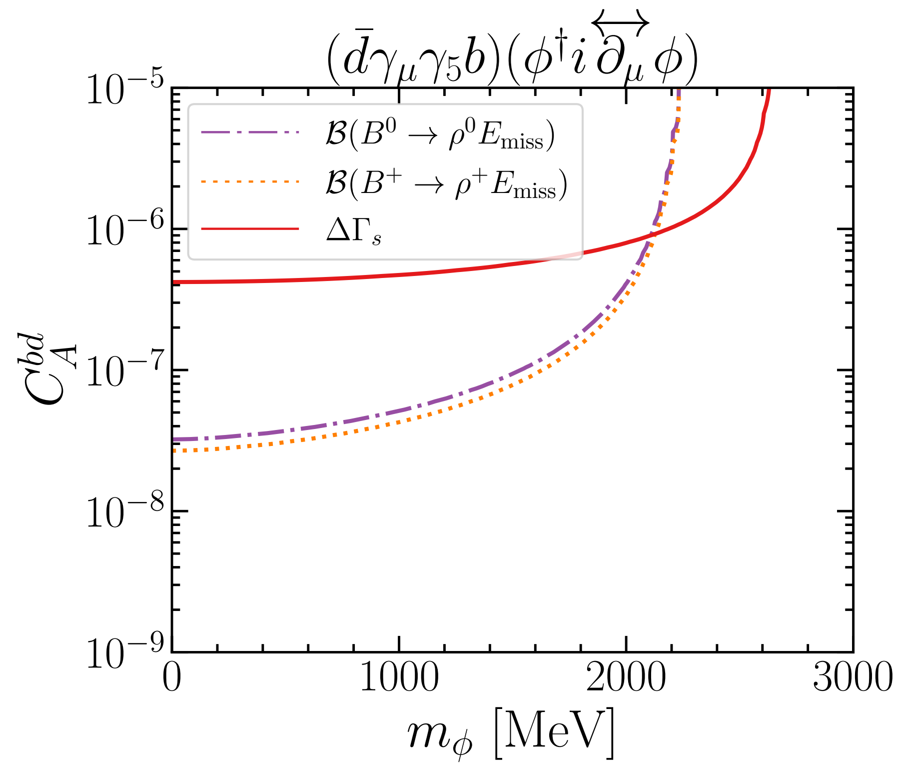
$m_{q_j}(\bar{q}_i q_j)(\phi^\dagger \phi)$ $\quad$ $m_{q_j}(\bar{q}_i i\gamma_5 q_j)(\phi^\dagger \phi)$ $\quad$ **$(\bar{q}_i \gamma^\mu q_j)(\phi^\dagger i\overleftrightarrow{\partial_\mu} \phi)$** $\quad$ $(\bar{q}_i \gamma^\mu \gamma_5 q_j)(\phi^\dagger i\overleftrightarrow{\partial_\mu} \phi)$

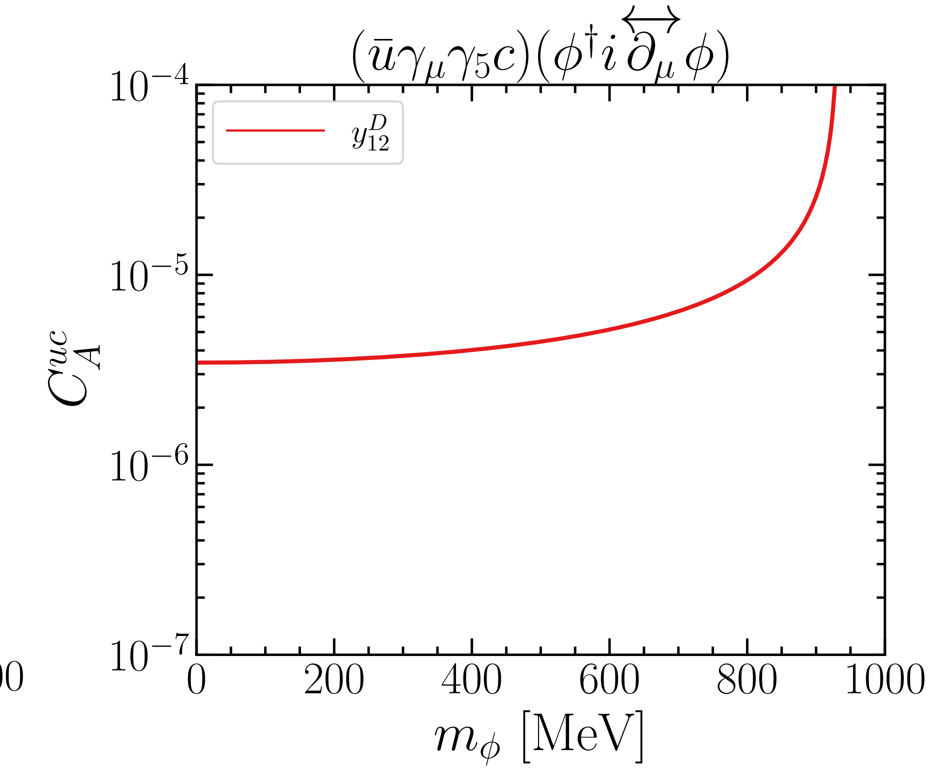


Constraint on scalar DM

$m_{q_j}(\bar{q}_i q_j)(\phi^\dagger \phi)$ $\quad$ $m_{q_j}(\bar{q}_i i\gamma_5 q_j)(\phi^\dagger \phi)$ $\quad$ $(\bar{q}_i \gamma^\mu q_j)(\phi^\dagger i\overleftrightarrow{\partial_\mu}\phi)$ $\quad$ $(\bar{q}_i \gamma^\mu \gamma_5 q_j)(\phi^\dagger i\overleftrightarrow{\partial_\mu}\phi)$





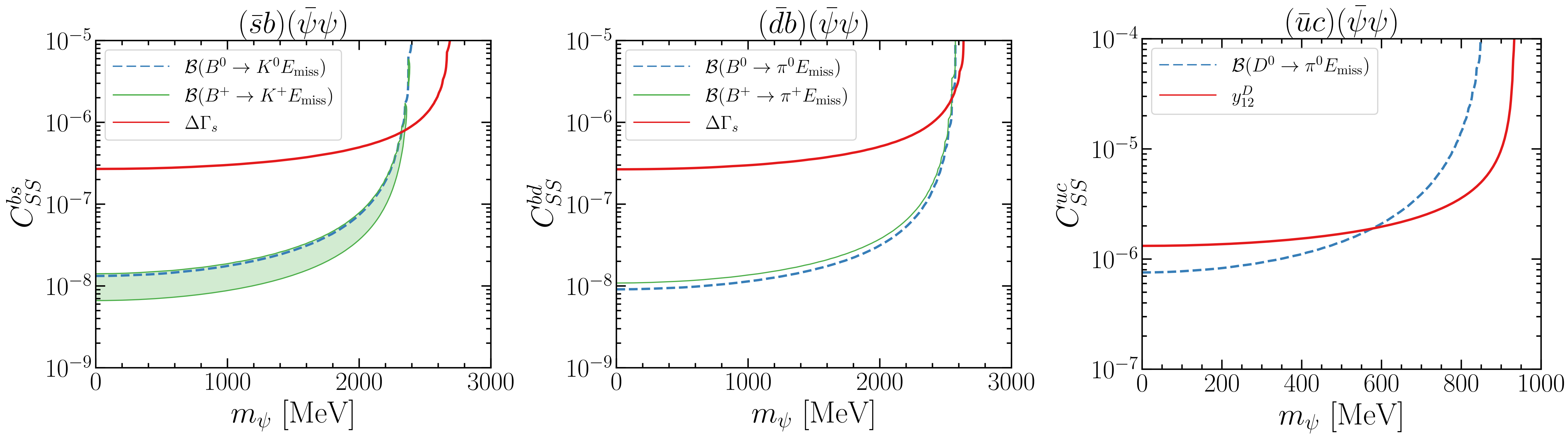


Results

Fermionic dark matter

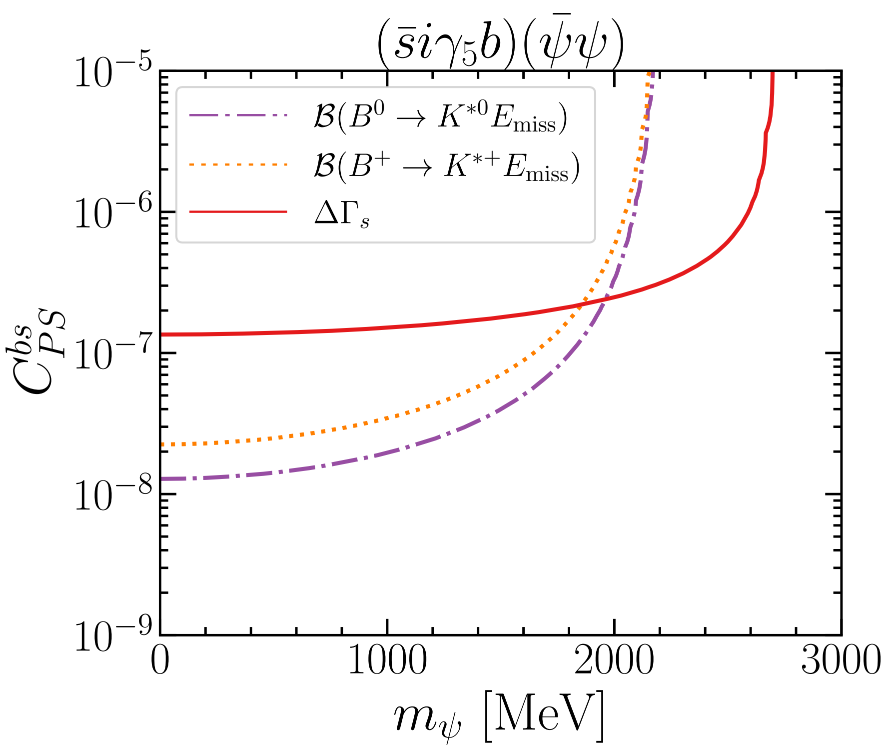
Constraint on fermion DM

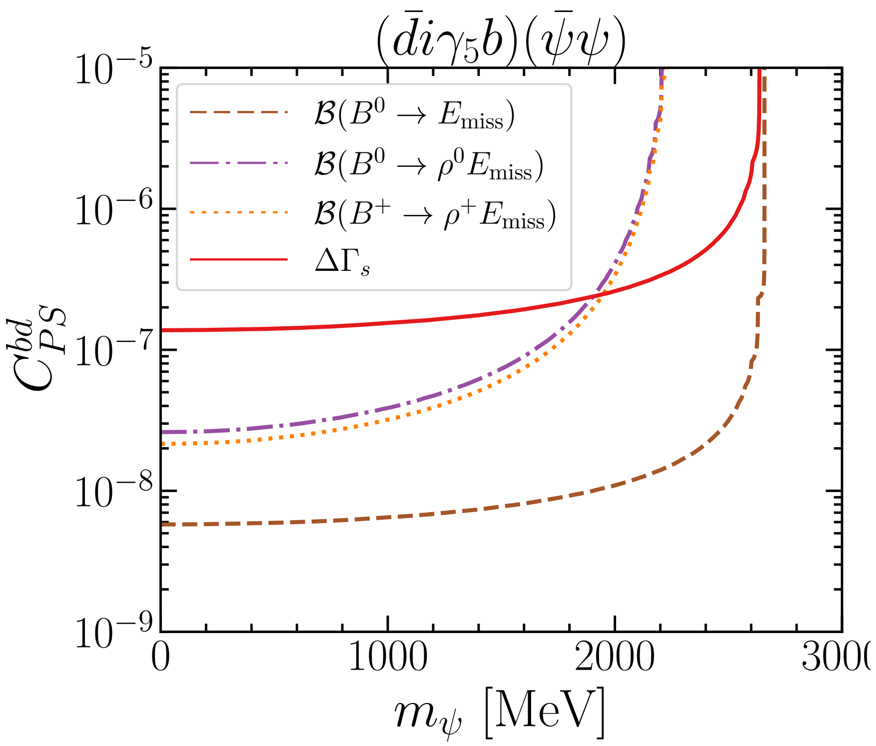
Scalar current: $(\bar{q}_i q_j)(\bar{\psi}\psi)$, $(\bar{q}_i i\gamma_5 q_j)(\bar{\psi}\psi)$, $(\bar{q}_i q_j)(\bar{\psi} i\gamma_5 \psi)$, $(\bar{q}_i \gamma_5 q_j)(\bar{\psi}\gamma_5\psi)$

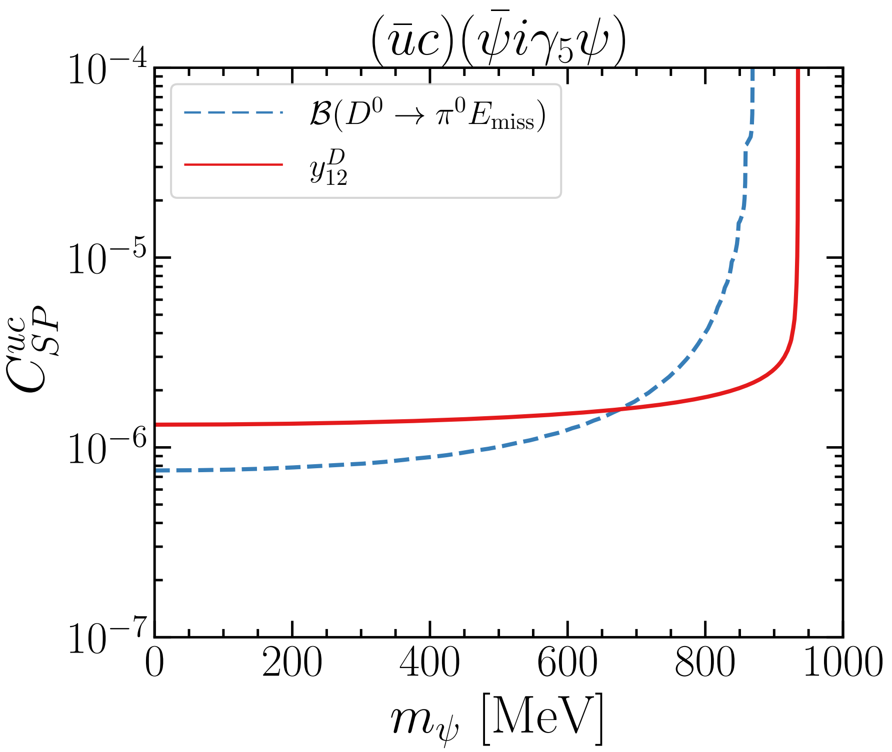


Constraint on fermion DM

Scalar current: $(\bar{q}_i q_j)(\bar{\psi}\psi)$, $(\bar{q}_i i\gamma_5 q_j)(\bar{\psi}\psi)$, $(\bar{q}_i q_j)(\bar{\psi} i\gamma_5 \psi)$, $(\bar{q}_i \gamma_5 q_j)(\bar{\psi}\gamma_5\psi)$

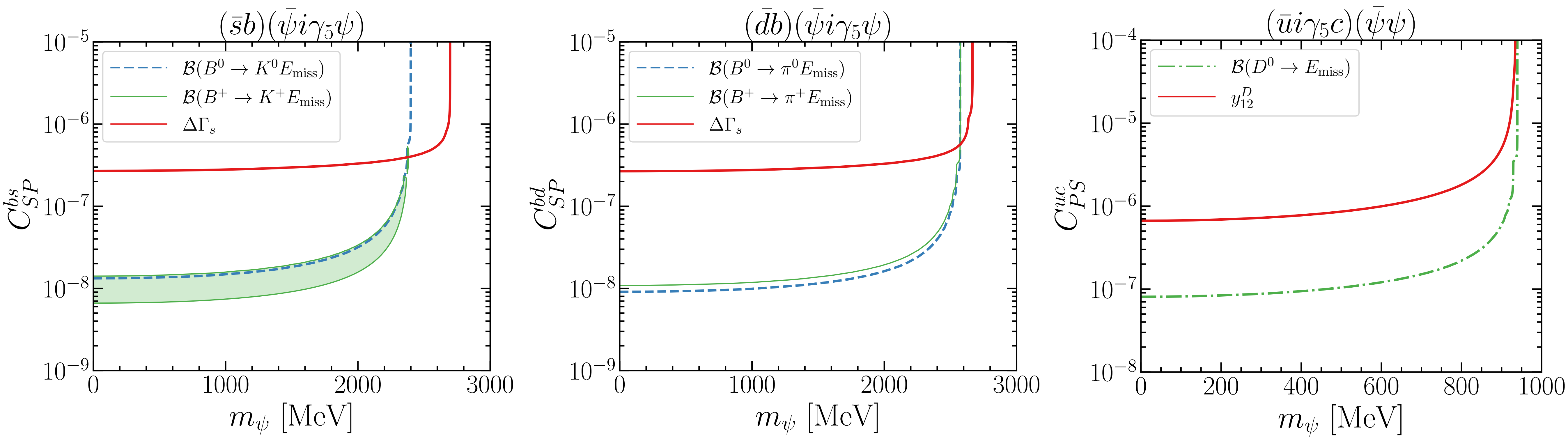






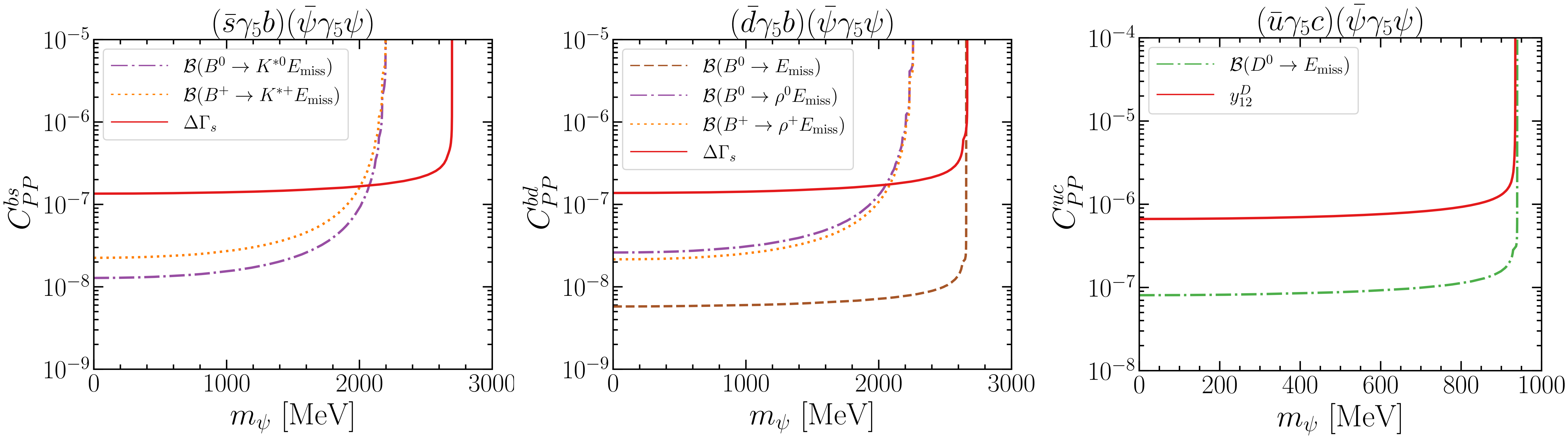
Constraint on fermion DM

Scalar current: $(\bar{q}_i q_j)(\bar{\psi}\psi)$, $(\bar{q}_i i\gamma_5 q_j)(\bar{\psi}\psi)$, $(\bar{q}_i q_j)(\bar{\psi} i\gamma_5 \psi)$, $(\bar{q}_i \gamma_5 q_j)(\bar{\psi}\gamma_5\psi)$



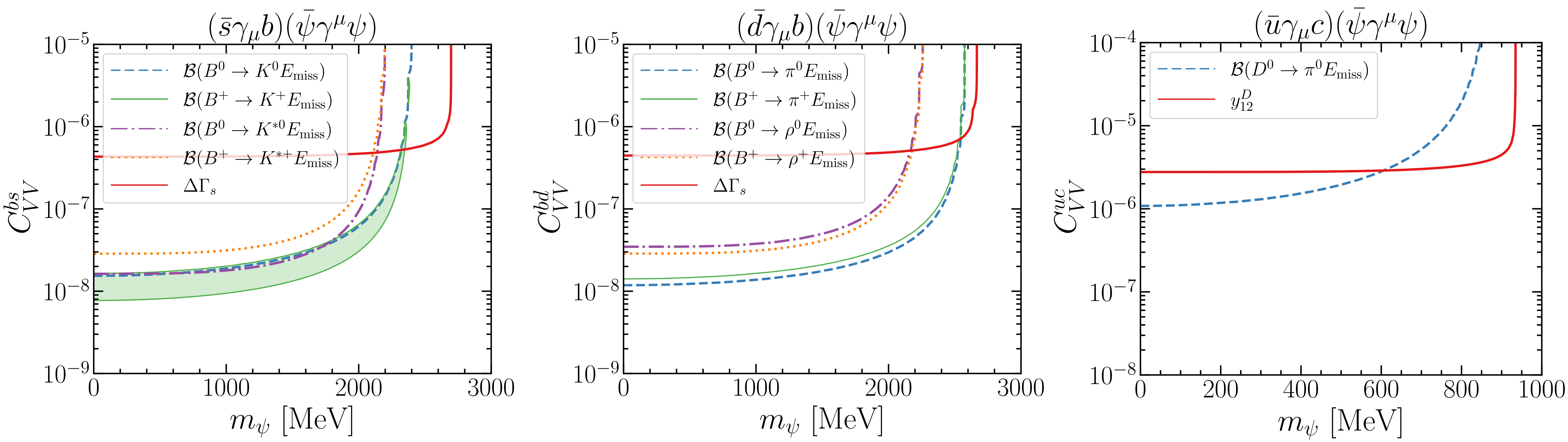
Constraint on fermion DM

Scalar current: $(\bar{q}_i q_j)(\bar{\psi}\psi)$, $(\bar{q}_i i\gamma_5 q_j)(\bar{\psi}\psi)$, $(\bar{q}_i q_j)(\bar{\psi} i\gamma_5\psi)$, $(\bar{q}_i \gamma_5 q_j)(\bar{\psi}\gamma_5\psi)$



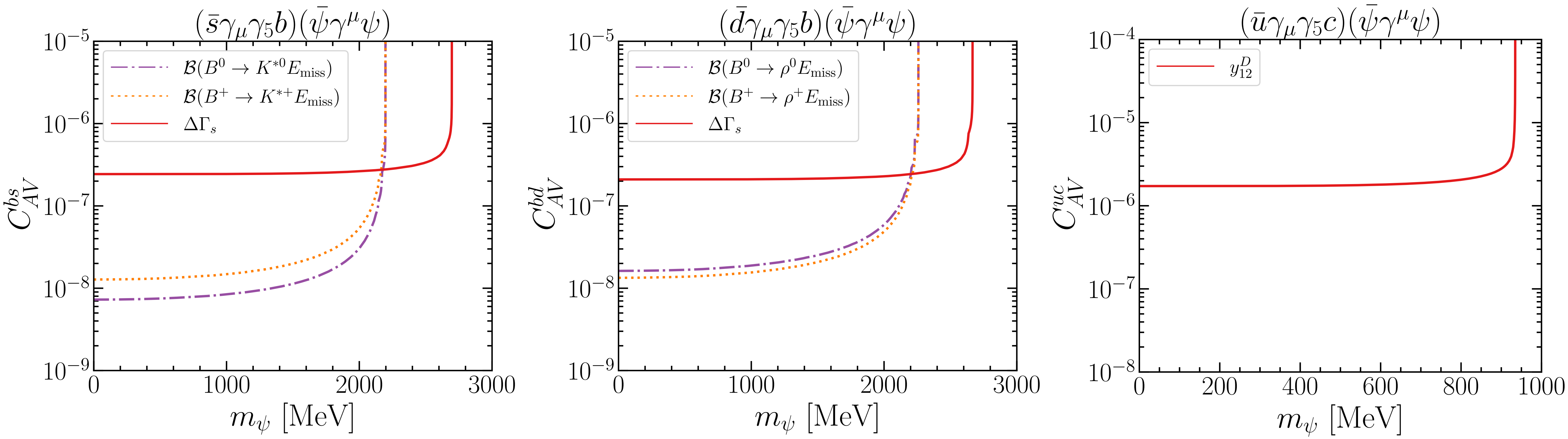
Constraint on fermion DM

Vector current: $(\bar{q}_i\gamma^\mu q_j)(\bar{\psi}\gamma_\mu\psi)$, $(\bar{q}_i\gamma^\mu\gamma_5 q_j)(\bar{\psi}\gamma_\mu\psi)$, $(\bar{q}_i\gamma^\mu q_j)(\bar{\psi}\gamma_\mu\gamma_5\psi)$, $(\bar{q}_i\gamma^\mu\gamma_5 q_j)(\bar{\psi}\gamma_\mu\gamma_5\psi)$



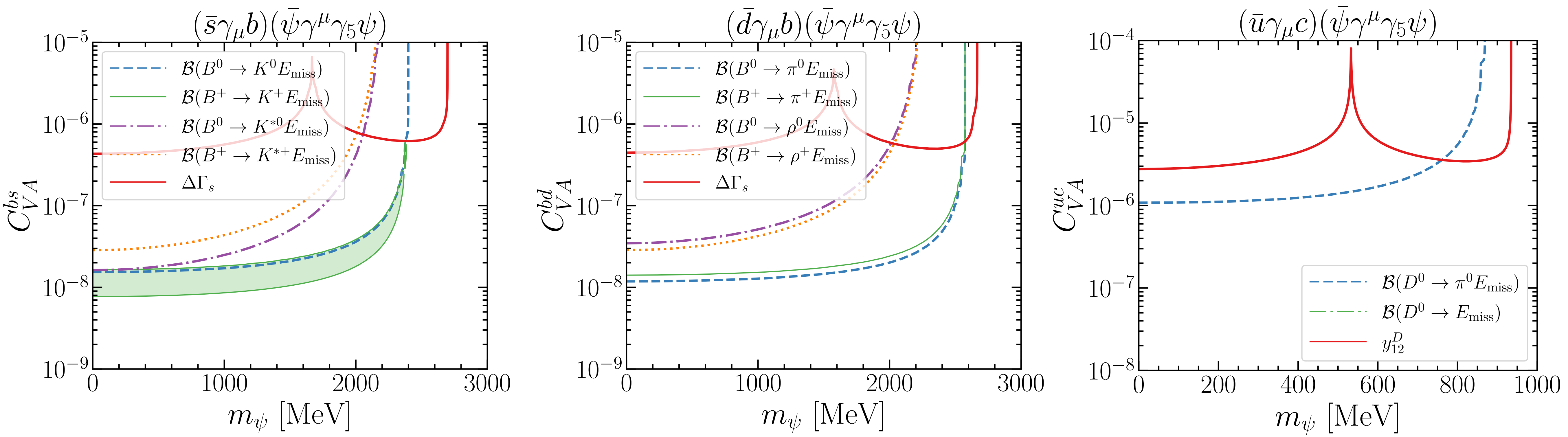
Constraint on fermion DM

Vector current: $(\bar{q}_i\gamma^\mu q_j)(\bar{\psi}\gamma_\mu\psi)$, $(\bar{q}_i\gamma^\mu\gamma_5 q_j)(\bar{\psi}\gamma_\mu\psi)$, $(\bar{q}_i\gamma^\mu q_j)(\bar{\psi}\gamma_\mu\gamma_5\psi)$, $(\bar{q}_i\gamma^\mu\gamma_5 q_j)(\bar{\psi}\gamma_\mu\gamma_5\psi)$



Constraint on fermion DM

Vector current: $(\bar{q}_i\gamma^\mu q_j)(\bar{\psi}\gamma_\mu\psi)$, $(\bar{q}_i\gamma^\mu\gamma_5 q_j)(\bar{\psi}\gamma_\mu\psi)$, $(\bar{q}_i\gamma^\mu q_j)(\bar{\psi}\gamma_\mu\gamma_5\psi)$, $(\bar{q}_i\gamma^\mu\gamma_5 q_j)(\bar{\psi}\gamma_\mu\gamma_5\psi)$

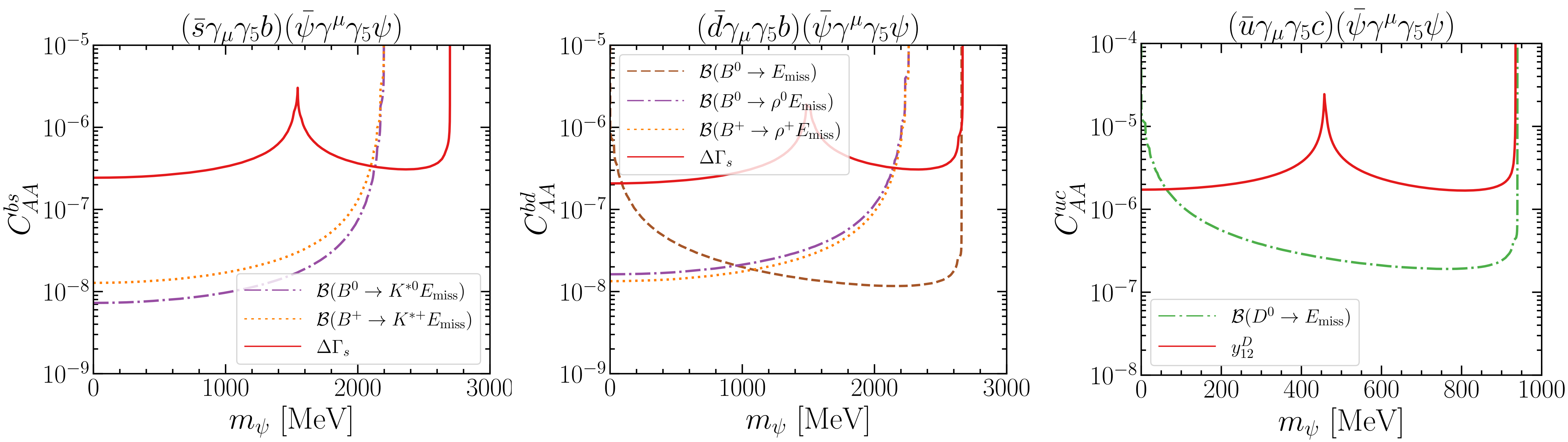


Cancellation between terms:

$$(\Gamma_{12})_{VA}^{q_iq_j,\psi} = -\frac{(c_{VA}^{q_iq_j})^2\,\beta_\psi}{24\pi\, m_{M_{ij}^0}} \left\{(1+2x_\psi)m_{q_j}^2\langle\overline{M_{ij}^0}\,|\,(\bar{q}_iq_j)(\bar{q}_iq_j)\,|\,M_{ij}^0\rangle + (\beta_\psi)^2\, m_{M_{ij}^0}^2\langle\overline{M_{ij}^0}\,|\,(\bar{q}_i\gamma^\mu q_j)(\bar{q}_i\gamma_\mu q_j)\,|\,M_{ij}^0\rangle\right\}$$

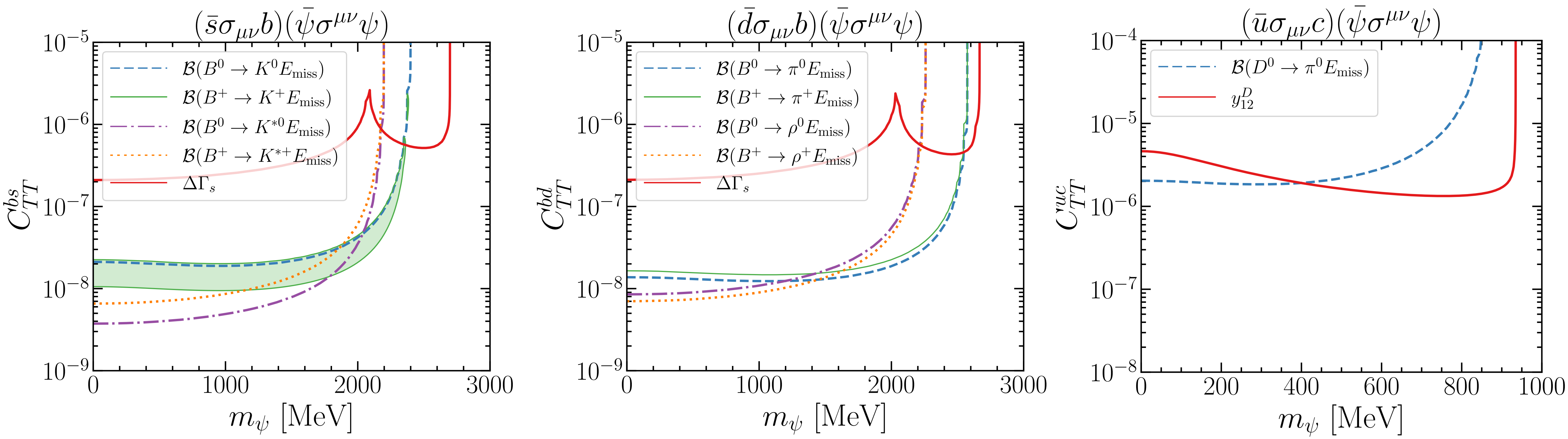
Constraint on fermion DM

Vector current: $(\bar{q}_i\gamma^\mu q_j)(\bar{\psi}\gamma_\mu\psi)$, $(\bar{q}_i\gamma^\mu\gamma_5 q_j)(\bar{\psi}\gamma_\mu\psi)$, $(\bar{q}_i\gamma^\mu q_j)(\bar{\psi}\gamma_\mu\gamma_5\psi)$, $(\bar{q}_i\gamma^\mu\gamma_5 q_j)(\bar{\psi}\gamma_\mu\gamma_5\psi)$



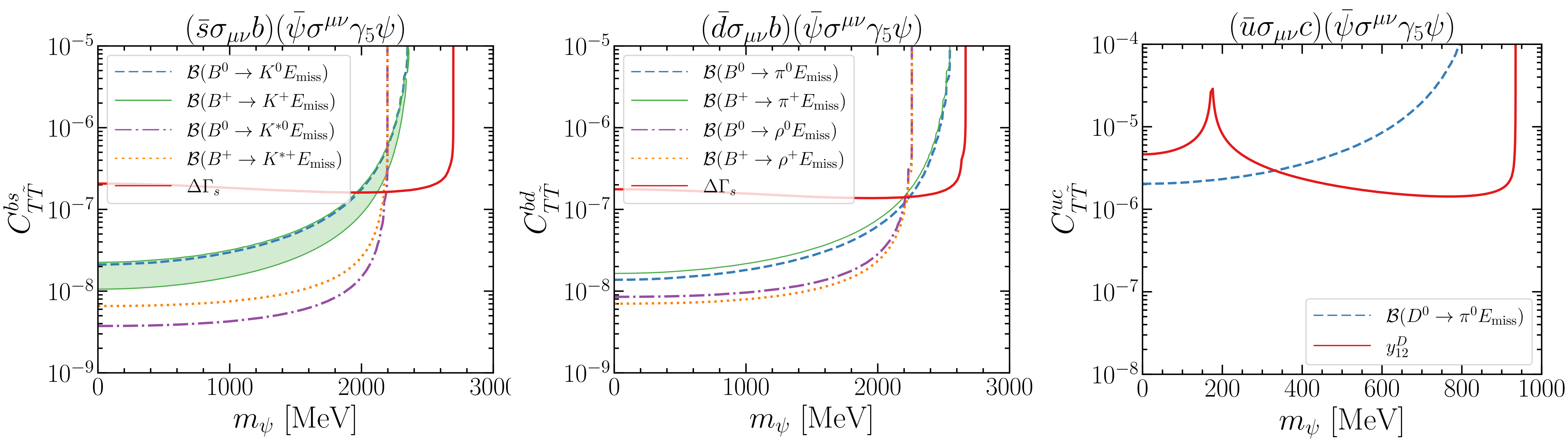
Constraint on fermion DM

Tensor current: $(\bar{q}_i\sigma^{\mu\nu}q_j)(\bar{\psi}\sigma_{\mu\nu}\psi)$, $(\bar{q}_i\sigma^{\mu\nu}q_j)(\bar{\psi}\sigma_{\mu\nu}\gamma_5\psi)$



Constraint on fermion DM

Tensor current: $(\bar{q}_i\sigma^{\mu\nu}q_j)(\bar{\psi}\sigma_{\mu\nu}\psi)$, $(\bar{q}_i\sigma^{\mu\nu}q_j)(\bar{\psi}\sigma_{\mu\nu}\gamma_5\psi)$



Summary

Light DM can be searched in decays of meson decays!

SM background with neutrino final state, but theoretically under control

We consider low-energy EFTs for spin 0 and 1/2 light DM and calculate contribution to lifetime difference of neutral mesons

Constraints on quark-DM interactions:

Beauty systems: constraints on complementary to those from decays

Charm system: new constraints on operators from lifetime difference