ALP production in weak mesonic decays

Alfredo Walter Mario Guerrera and Stefano Rigolin, 2211.08343

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Motivation

ALPs and non-universal models

ALPs

- Dark Matter candidate
- Naturally decoupled from SM
- Scales beyond colliders reach

Motivation
ALPs and non-universal models

Non-universality

- Connection to SM flavour puzzle
- Relax bounds
- DFSZ-like 2HDM

Motivation

Focal Points

ALP production in weak mesonic decays

- Model Independent couplings
- Tree levels and penguins
- Pseudoscalars and vectors
- ALP masses in MeV-GeV range

ALPs searches

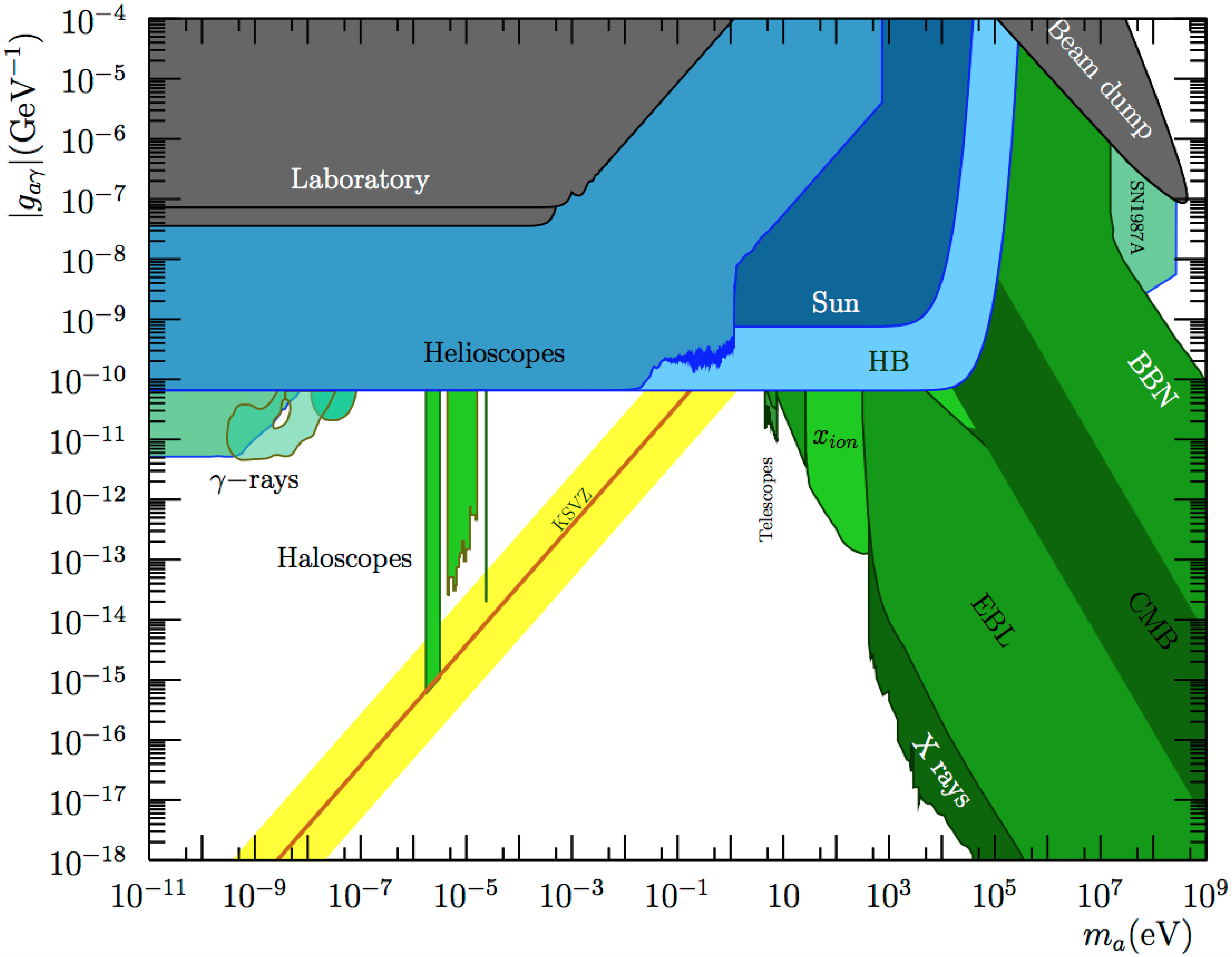

Figure is taken from [Irastorza Redondo, 2018].

Overview

ALP production in weak mesonic decays

- Axions and ALPs
- Hadronization of different channels
- Phenomenology of different searches
- Summary

LCSR for Mesogenesis

- Introduction on LCSR
- Form Factors & symmetries
- Results

Axions and ALPs

Theory Recap

Axions and ALPs
pseudo-Goldstone Bosons

Only need an extra $U(1)$ spontaneously broken at f_a

Axions	ALPs
• Solve the Strong CP problem • Mass and SSB scale are tied	• Do not solve Strong CP • Arbitrary mass and SSB scale

[Peccei Quinn, 77] [Wilczek, 77] [Weinberg, 77]

Axions and ALPs
pseudo-Goldstone Bosons

Weakly coupled

- Always enters as a/f_a
- Derivative couplings
- Neutral pseudoscalar boson

Axions and ALPs
Non-Universality

Low Energy Effective Couplings

- $\frac{\partial_\mu a}{2 f_a} \sum_{f=u,d,\ell} \bar{f} \gamma^\mu \left(C_V + C_A \gamma^5 \right) f$
- C_V and C_A matrices in flavour space
- Off-diagonal elements give FCNC

[Georgi Kaplan Randall, 86] [Bauer et al, 21]

Alfredo Walter Mario Guerrera [1]

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Axions and ALPs
Phenomenological Model

ALP physics at GeV scale:

Theory	Experiment
ALP EFT Bound states	Missing energy 2/3-body final states

Hadronization of different channel

Local and bi-local operators

Alfredo Walter Mario Guerrera [1]
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Hadronization of different channels
Phenomenological Model

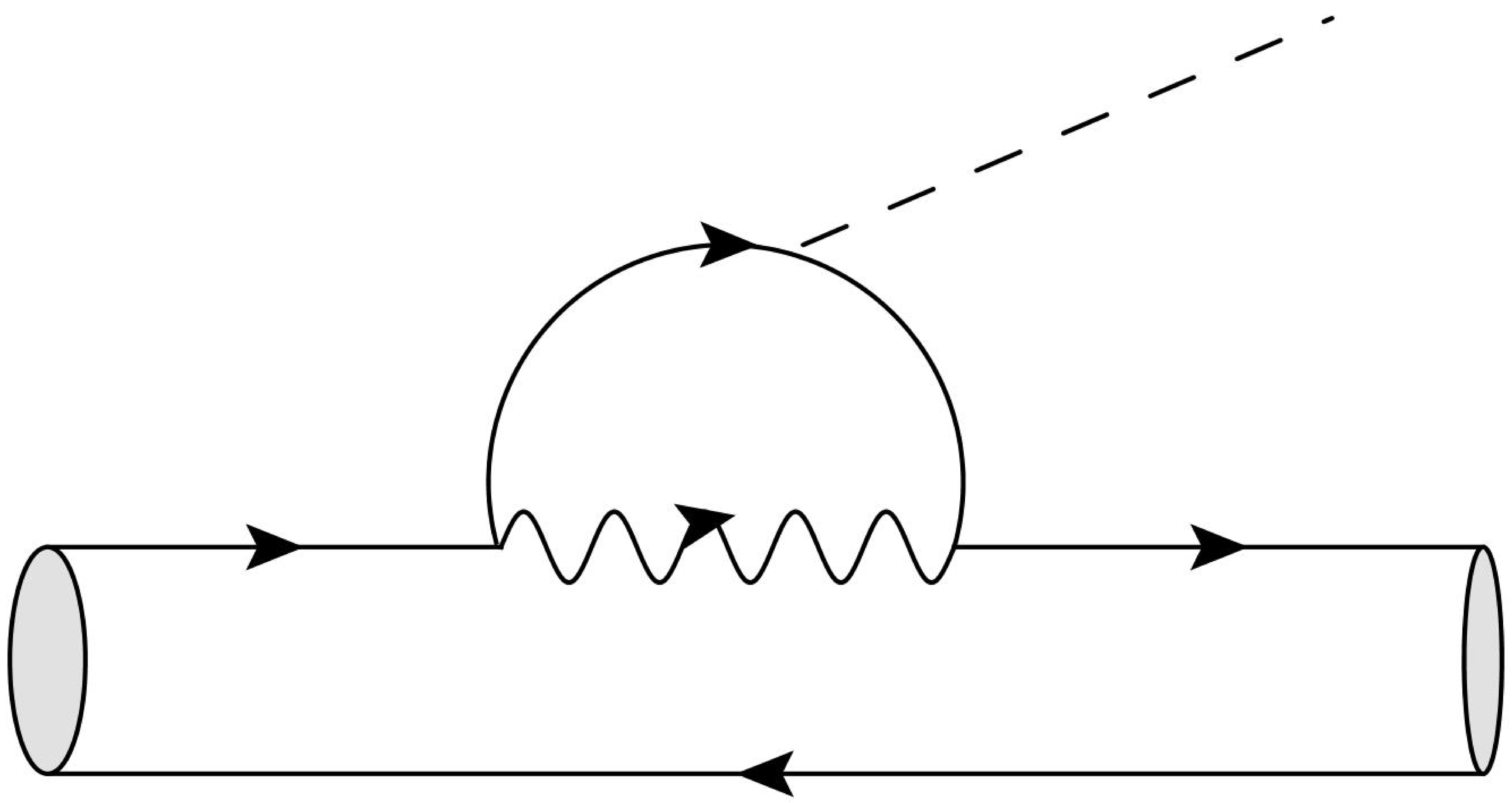
Hadronic matrix elements

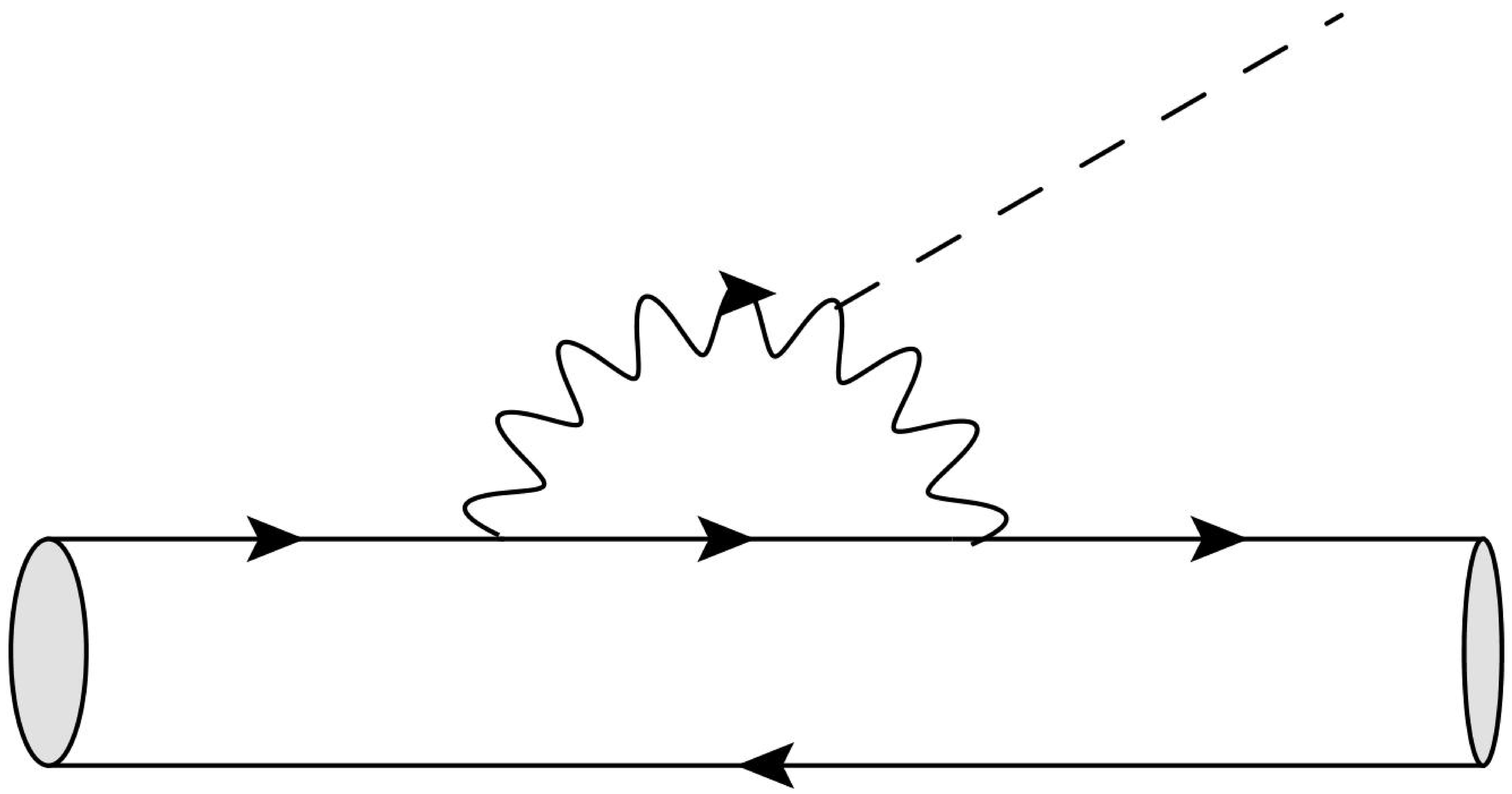
Lattice and Light Cone Sum Rules

Lattice QCD results for
local operators

[Carrasco et al, 16] [Ball Zwicky, 04]

Hadronization of different channels
Penguins Hadronization





Local Operators

$$\frac{G_F m_q^2}{2\sqrt{2}\pi^2}\sum_f V_{fi}V_{fj}^* c_f \frac{x_f}{x_q}\log\left(\frac{f_a^2}{m_f^2}\right)$$

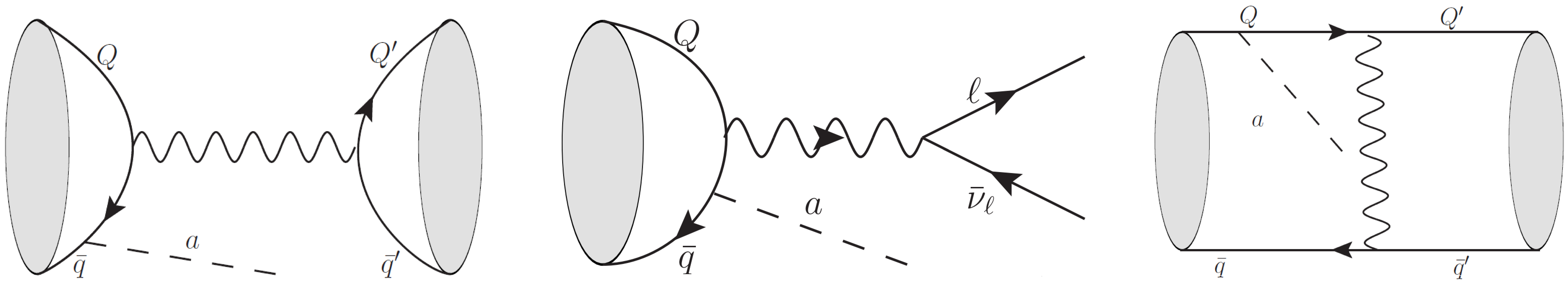
[Izaguirre Lin Shuve, 16] [Bauer Neubert Thamm, 17]

Hadronization of different channels
Phenomenological Model

Hadronic matrix elements

Brodsky-Lepage Hadronization

Used for bi-local operators



[Lepage Brodsky, 80] [Szczepaniak Henley Brodsky, 90]

Alfredo Walter Mario Guerrera [1]

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Hadronization of different channels
Brodsky-Lepage

Based on Distribution Amplitudes

Assumptions
Quark-Hadron duality High energy transfer

Allows one to compute meson-to-vacuum and meson-to-meson matrix elements

Phenomenology of different searches

Features and bounds

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Phenomenology of different searches

Meson-to-meson decay

Mesonic decays amplitudes

[AWMG Rigolin, 2211.08343]

Tree level $s-$channel

$$\mathcal{A}_{\mathrm{I}}^{(s)} \approx \frac{G_F V_{\mathrm{CKM}} f_I f_F}{2\sqrt{2} f_a} M_I^2 (c_q - c_Q)$$

Penguins

$$\left| \frac{\mathcal{M}_{\mathrm{T}}^{(s,t)}}{\mathcal{M}_{\mathrm{L}}} \right| \approx 2\pi^2 \frac{f_I f_F}{m_q^2} \left| \frac{V_{\mathrm{T}}^{\mathrm{CKM}}}{V_{\mathrm{L}}^{\mathrm{CKM}}} \right|$$

Phenomenology of different searches

Meson-to-meson decay

B-sector

[AWMG Rigolin, 2211.08343]

Channel	Tree–Level	Penguin
$B_c^\pm \to D_s^\pm a$	$(6 - 160) \times 10^{-11}$	2×10^{-6}
$B_c^\pm \to D^\pm a$	$(1 - 30) \times 10^{-11}$	3×10^{-7}
$B_c^\pm \to K^{*\pm} a$	$(2 - 70) \times 10^{-11}$	n.a.
$B_c^\pm \to \rho^\pm a$	$(4 - 100) \times 10^{-11}$	n.a.
$B_c^\pm \to K^\pm a$	$(8 - 230) \times 10^{-12}$	n.a.
$B_c^\pm \to \pi^\pm a$	$(3 - 85) \times 10^{-11}$	n.a.
$B^\pm \to D_s^\pm a$	$(5 - 30) \times 10^{-12}$	n.a.
$B^\pm \to D^\pm a$	$(1 - 7) \times 10^{-12}$	n.a.
$B^\pm \to K^{*\pm} a$	$(1 - 7) \times 10^{-12}$	4×10^{-6}
$B^\pm \to \rho^\pm a$	$(3 - 20) \times 10^{-12}$	4×10^{-7}
$B^\pm \to K^\pm a$	$(8 - 50) \times 10^{-13}$	2×10^{-6}
$B^\pm \to \pi^\pm a$	$(3 - 20) \times 10^{-12}$	3×10^{-7}

Phenomenology of different searches

Meson-to-meson decay

D-sector

[AWMG Rigolin, 2211.08343]

$D_s^\pm \to K^{*\pm} a$	$(1-60)\times 10^{-11}$	6×10^{-12}
$D_s^\pm \to \rho^\pm a$	$(3-170)\times 10^{-11}$	n.a.
$D_s^\pm \to K^\pm a$	$(6-300)\times 10^{-12}$	7×10^{-12}
$D_s^\pm \to \pi^\pm a$	$(2-120)\times 10^{-11}$	n.a.
$D^\pm \to K^{*\pm} a$	$(2-100)\times 10^{-12}$	n.a.
$D^\pm \to \rho^\pm a$	$(7-290)\times 10^{-12}$	3×10^{-12}
$D^\pm \to K^\pm a$	$(1-50)\times 10^{-12}$	n.a.
$D^\pm \to \pi^\pm a$	$(5-200)\times 10^{-12}$	6×10^{-12}

Phenomenology of different searches

Meson-to-meson decay

K-sector

[AWMG Rigolin, 2211.08343]

$K^{*\pm} \to K^{\pm} a$	$(5-25)\times 10^{-13}$	4×10^{-8}
$K^{*\pm} \to \pi^{\pm} a$	$(3-20)\times 10^{-12}$	3×10^{-9}
$\rho^{\pm} \to K^{\pm} a$	$(8-25)\times 10^{-12}$	2×10^{-9}
$\rho^{\pm} \to \pi^{\pm} a$	$(3-9)\times 10^{-11}$	4×10^{-10}
$K^{\pm} \to \pi^{\pm} a$	$(2-10)\times 10^{-12}$	5×10^{-10}

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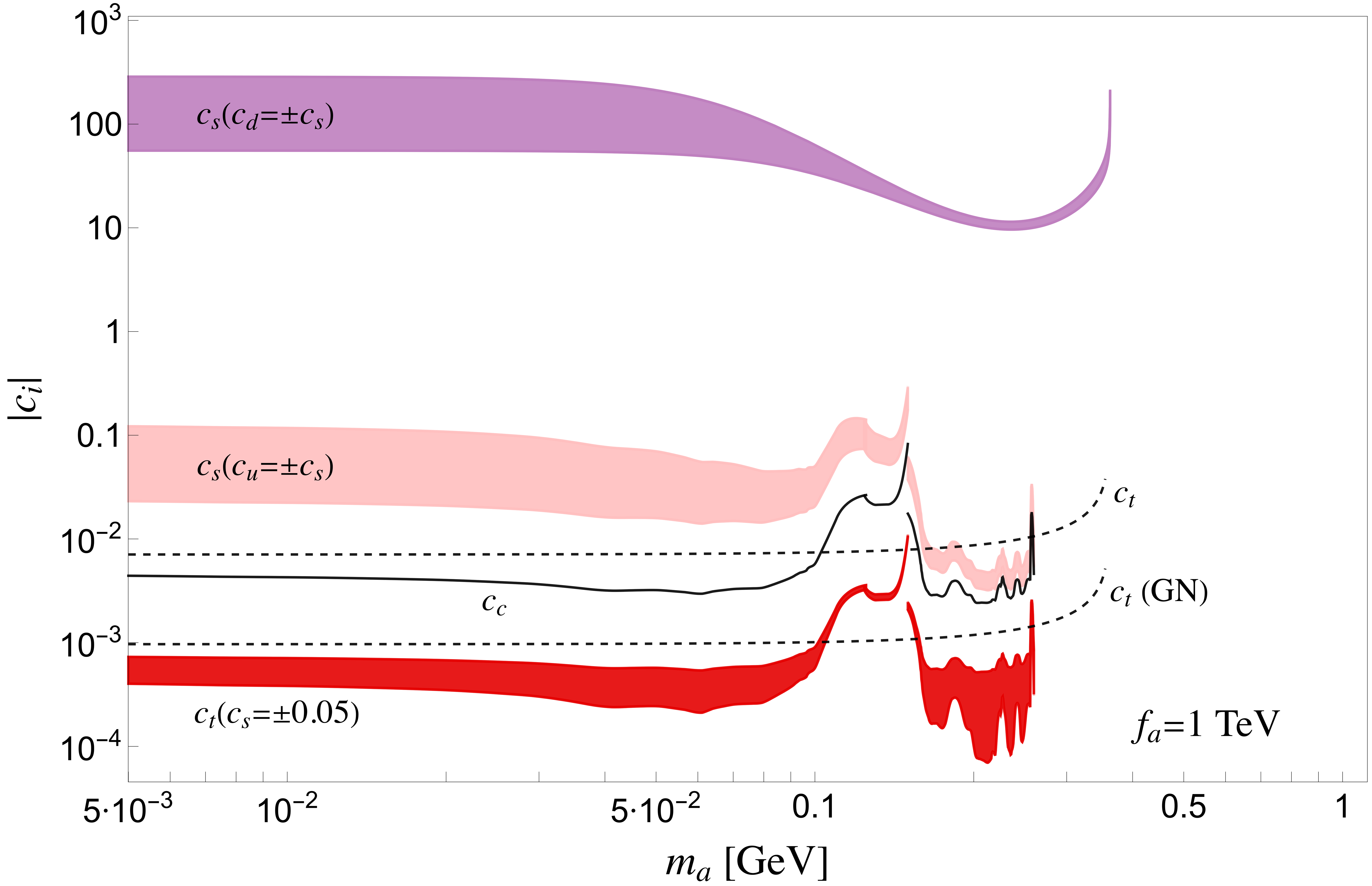
Phenomenology of different searches

Meson-to-meson decay

K-sector



Direct extension of $K^+ \to \pi^+\bar{\nu}\nu$ measurement and $K_L \to \pi^0\bar{\nu}\nu$

Picture from [AWMG Rigolin, 2211.08343]

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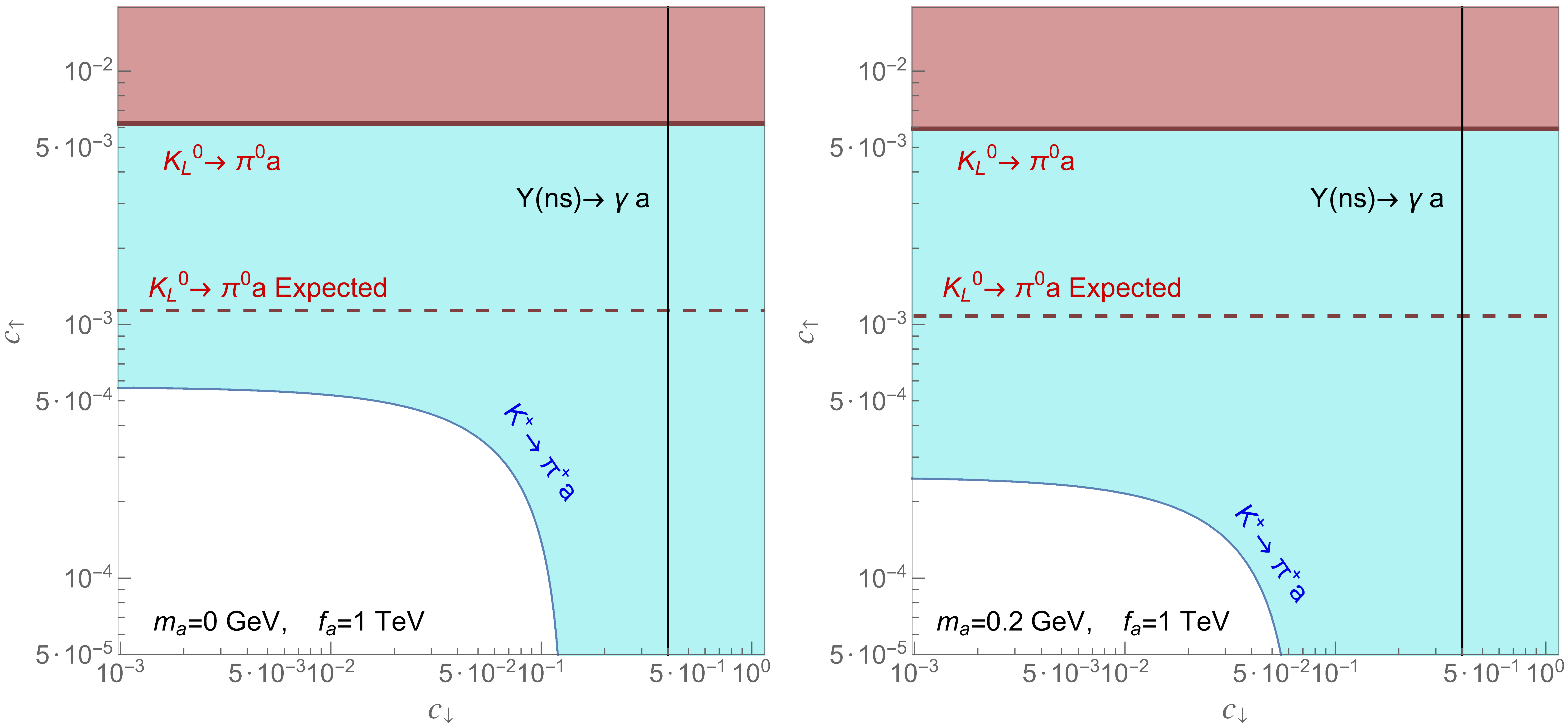
Phenomenology of different searches

Meson-to-meson decay

K-sector

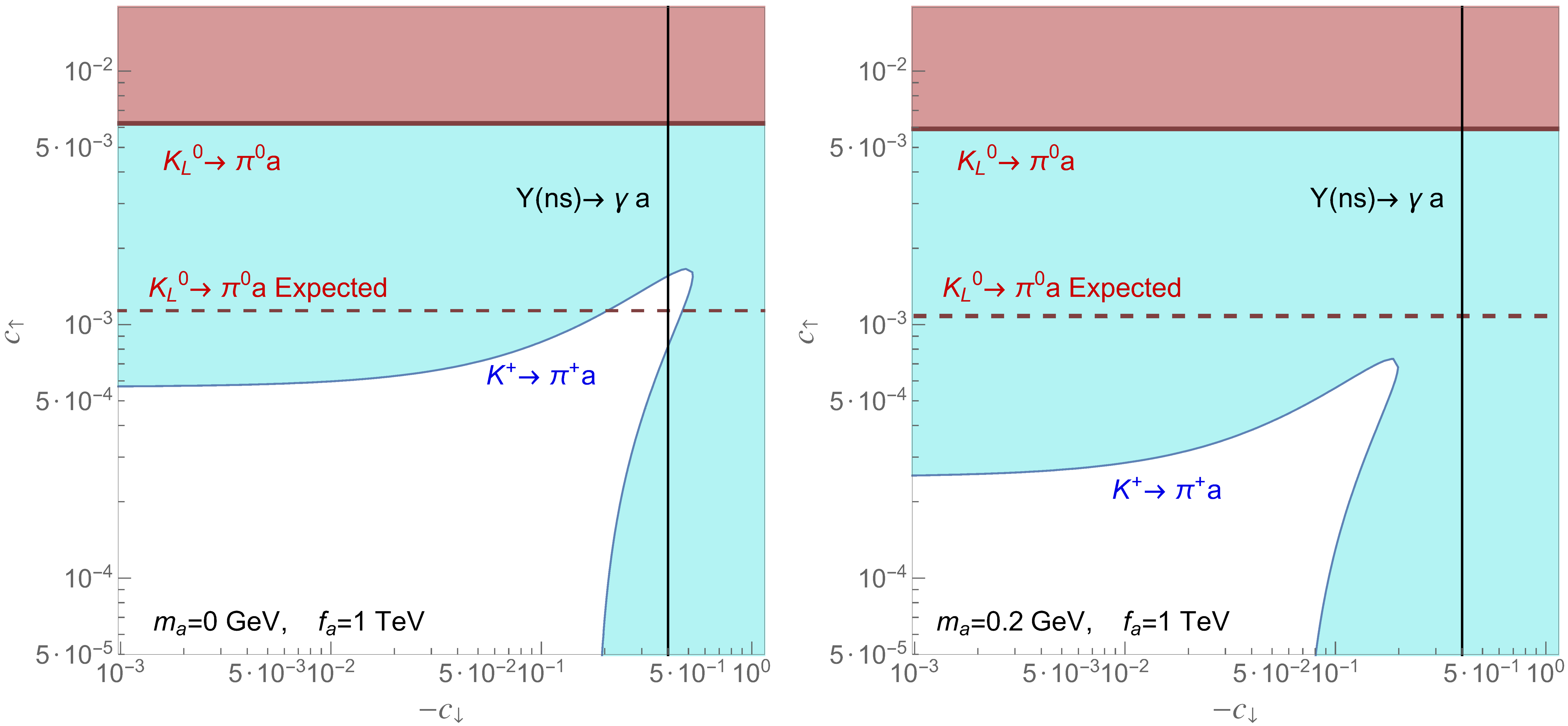


Picture from [AWMG Rigolin, 21]

Phenomenology of different searches

Meson-to-meson decay

K-sector



Picture from [AWMG Rigolin, 21]

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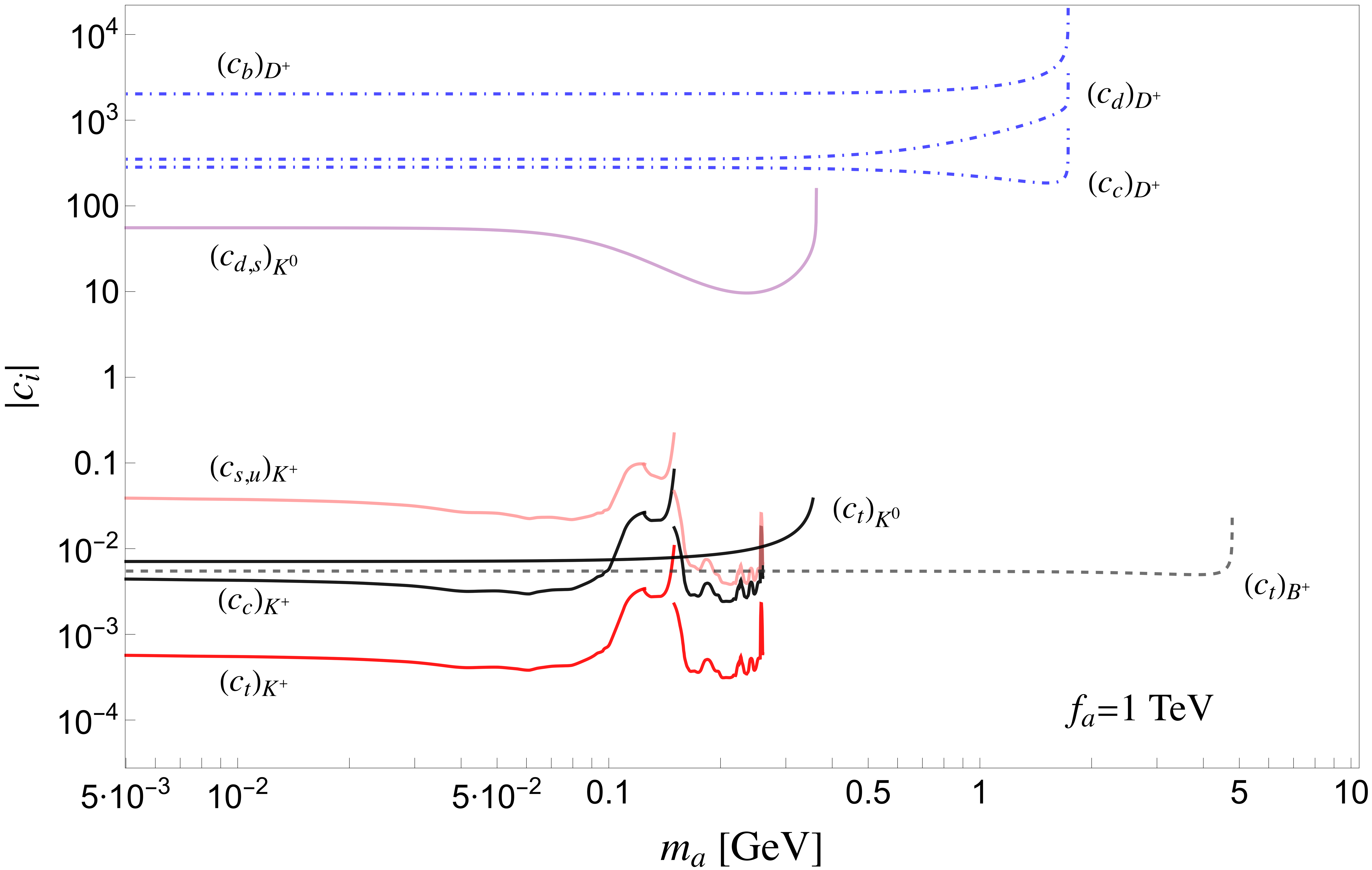
Phenomenology of different searches

Meson-to-meson decay

$$M_I \to M_F\, a$$



Picture from [AWMG Rigolin, 2211.08343]

Phenomenology of different searches

Leptonic decays

Three body Leptonic decay amplitude

Massless ALP limit

$$\mathcal{E}_h \approx \frac{iG_F V_{\mathrm{CKM}} f_M M_M^2}{\sqrt{2} f_a (k \cdot P_M)} \left(\bar{\ell}\, \not{k}\, P_L\, \nu_\ell \right) (c_q - c_Q)$$

ALP production in weak mesonic decays

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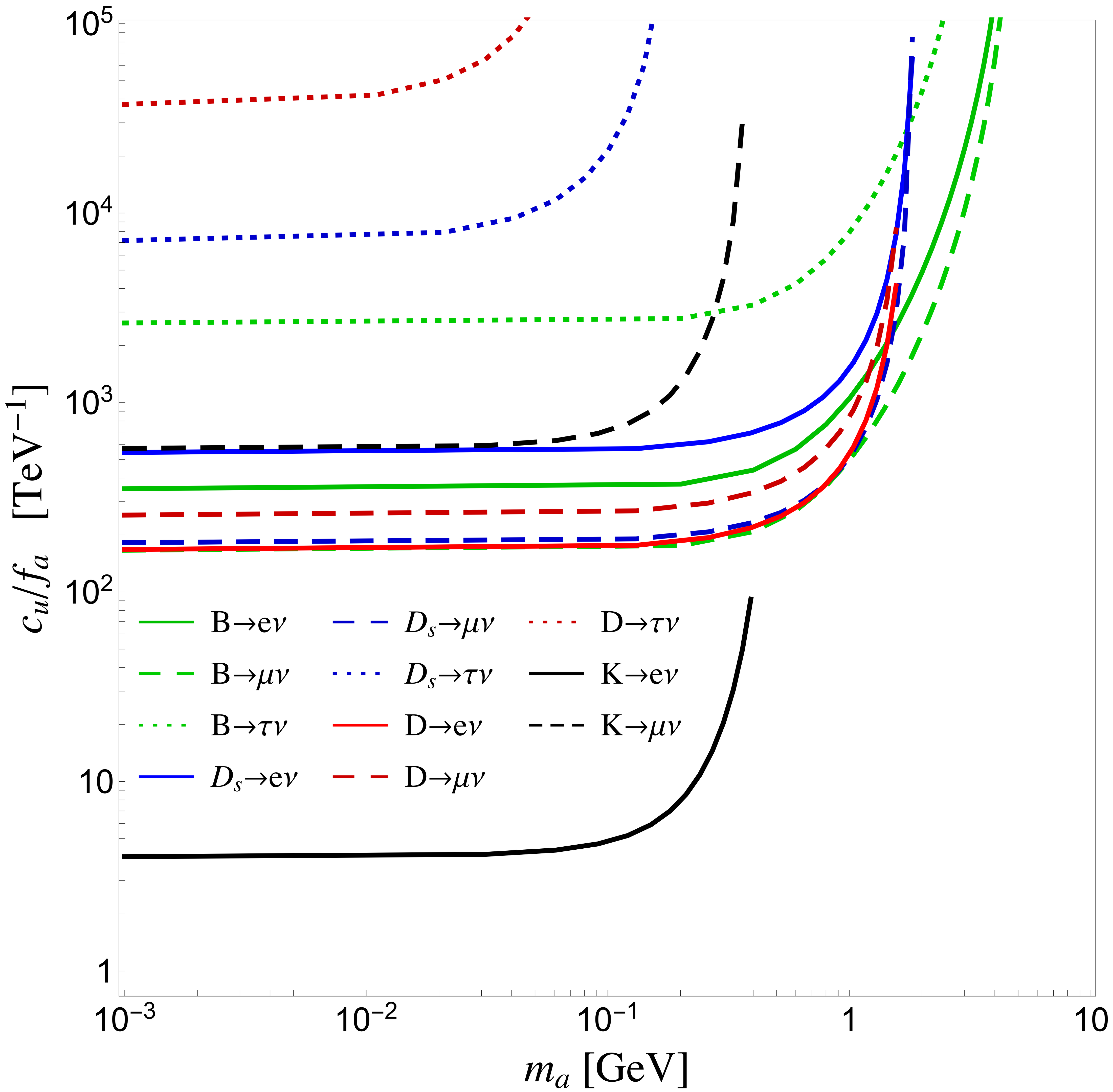
Phenomenology of different searches

Leptonic decays

$M \to \ell \bar{\nu}_\ell a$ three body decay



Channel	f_a [GeV] u-quark $m_a=0$	f_a [GeV] u-quark $m_a=\frac{M_M}{2}$
$B^\pm \to e^\pm \bar{\nu}_e$	2.8	0.079
$B^\pm \to \mu^\pm \bar{\nu}_\mu$	6	0.16
$B^\pm \to \tau^\pm \bar{\nu}_\tau$	0.38	0.006
$D^\pm \to e^\pm \bar{\nu}_e$	6	2.1
$D^\pm \to \mu^\pm \bar{\nu}_\mu$	4	1.3
$D^\pm \to \tau^\pm \bar{\nu}_\tau$	0.007	
$D_s^\pm \to e^\pm \bar{\nu}_e$	8	3
$D_s^\pm \to \mu^\pm \bar{\nu}_\mu$	5.5	2
$D_s^\pm \to \tau^\pm \bar{\nu}_\tau$	0.02	
$K^\pm \to e^\pm \bar{\nu}_e$	249.	87
$K^\pm \to \mu^\pm \bar{\nu}_\mu$	1.7	0.5

[Gallo AWMG Penaranda Rigolin, 2021]

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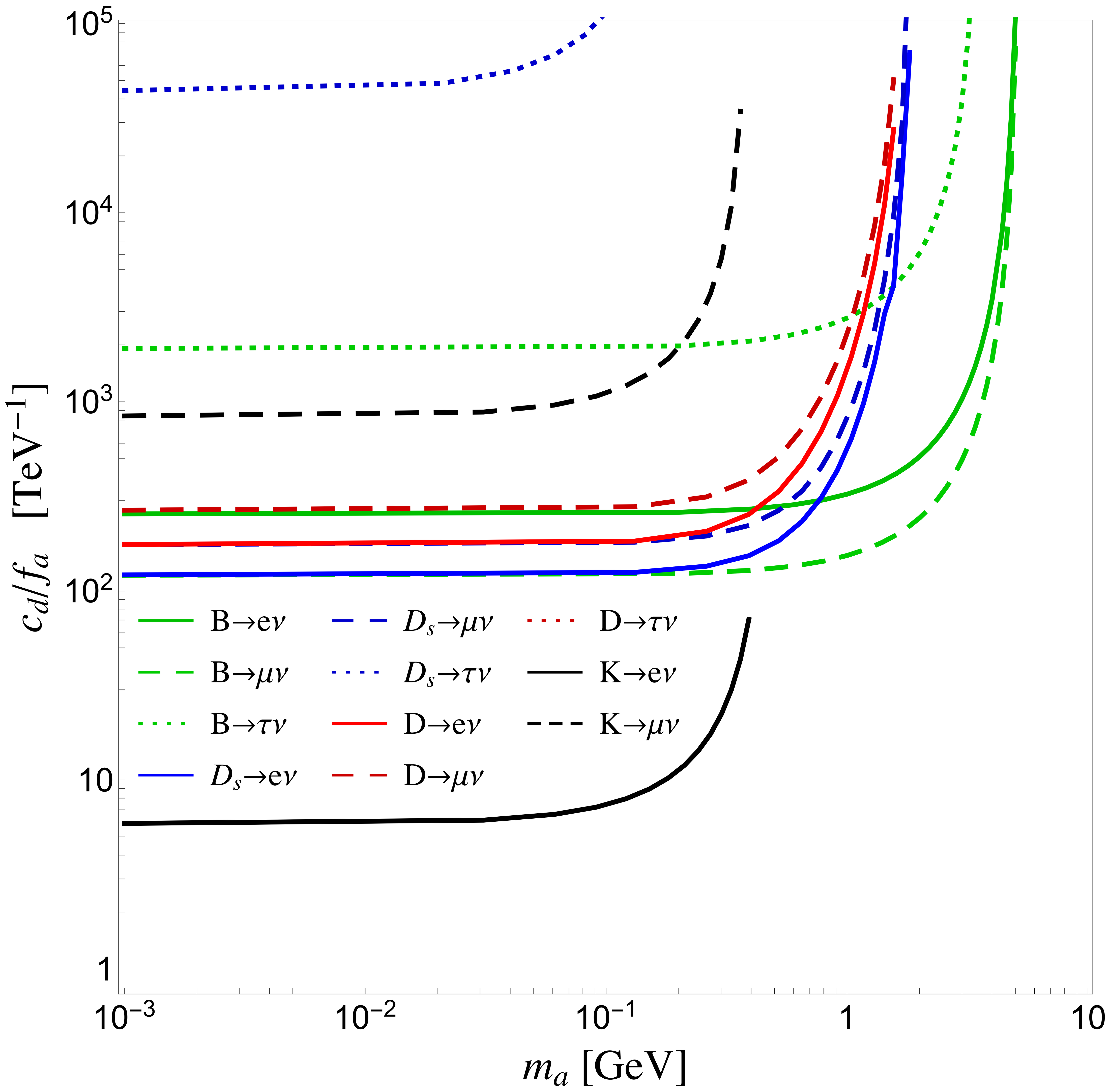
Phenomenology of different searches

Leptonic decays

$M \to \ell \bar{\nu}_\ell a$ three body decay



Channel	f_a [GeV] d-quark	
	$m_a=0$	$m_a=\frac{M_M}{2}$
$B^\pm \to e^\pm \bar{\nu}_e$	4	1.3
$B^\pm \to \mu^\pm \bar{\nu}_\mu$	8.3	2.7
$B^\pm \to \tau^\pm \bar{\nu}_\tau$	0.5	0.065
$D^\pm \to e^\pm \bar{\nu}_e$	5.7	0.86
$D^\pm \to \mu^\pm \bar{\nu}_\mu$	3.7	0.56
$D^\pm \to \tau^\pm \bar{\nu}_\tau$	0.007	
$D_s^\pm \to e^\pm \bar{\nu}_e$	8.2	1.9
$D_s^\pm \to \mu^\pm \bar{\nu}_\mu$	5.7	1.3
$D_s^\pm \to \tau^\pm \bar{\nu}_\tau$	0.01	
$K^\pm \to e^\pm \bar{\nu}_e$	170	10
$K^\pm \to \mu^\pm \bar{\nu}_\mu$	1.2	0.05

[Gallo AWMG Penaranda Rigolin, 2021]

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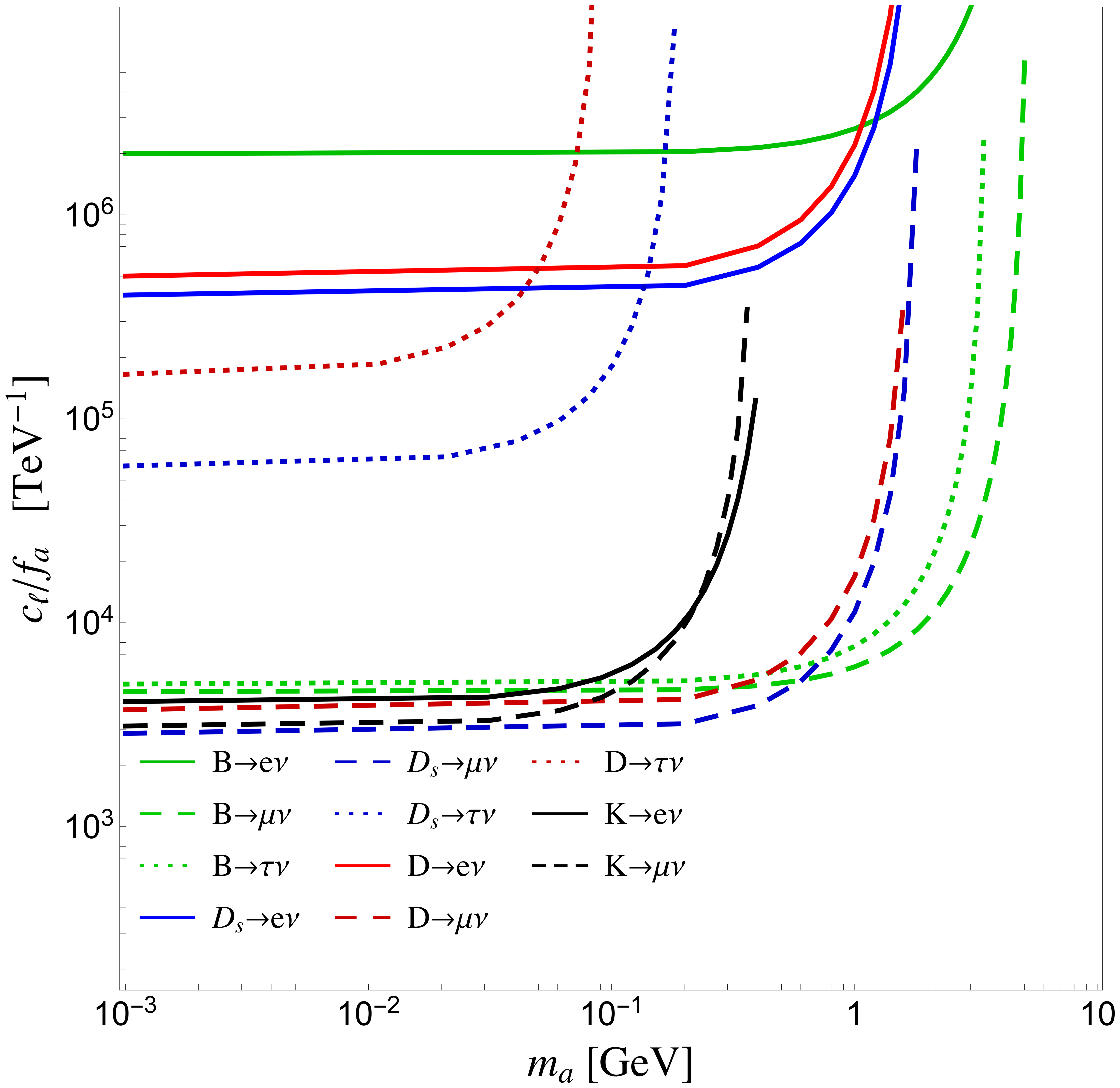
Phenomenology of different searches

Leptonic decays

$M \to \ell\bar{\nu}_\ell a$ three body decay



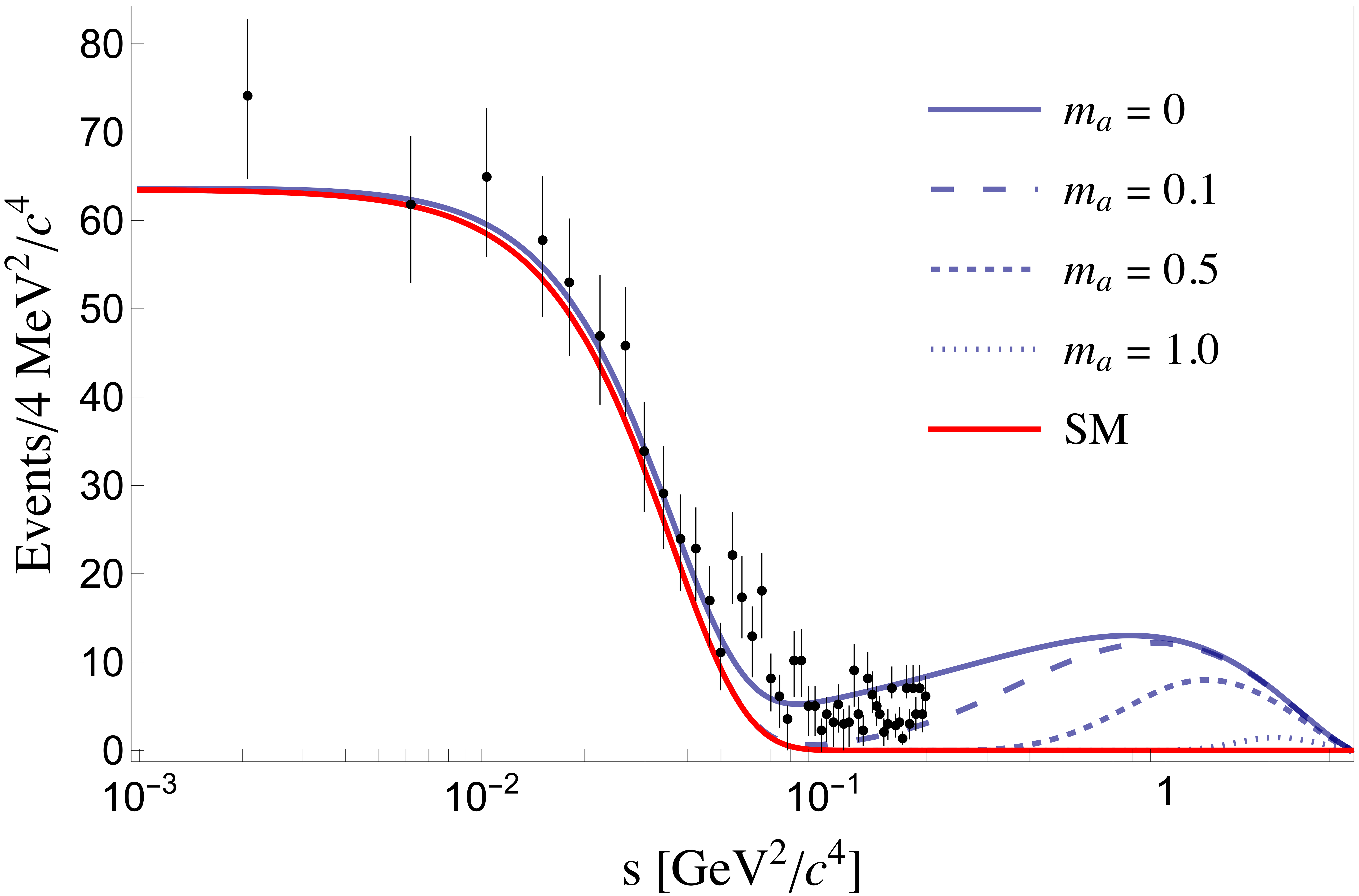
Channel	f_a [GeV] lepton $m_a=0$	f_a [GeV] lepton $m_a=\frac{M_M}{2}$
$B^\pm \to e^\pm\bar{\nu}_e$	$5\cdot10^{-4}$	$1.3\cdot10^{-4}$
$B^\pm \to \mu^\pm\bar{\nu}_\mu$	0.2	0.06
$B^\pm \to \tau^\pm\bar{\nu}_\tau$	0.2	0.05
$D^\pm \to e^\pm\bar{\nu}_e$	0.02	$5.3\cdot10^{-4}$
$D^\pm \to \mu^\pm\bar{\nu}_\mu$	0.27	0.070
$D^\pm \to \tau^\pm\bar{\nu}_\tau$	0.006	
$D_s^\pm \to e^\pm\bar{\nu}_e$	0.002	$6.6\cdot10^{-4}$
$D_s^\pm \to \mu^\pm\bar{\nu}_\mu$	0.3	0.09
$D_s^\pm \to \tau^\pm\bar{\nu}_\tau$	0.02	
$K^\pm \to e^\pm\bar{\nu}_e$	0.243	0.06
$K^\pm \to \mu^\pm\bar{\nu}_\mu$	0.32	0.06

[Gallo AWMG Penaranda Rigolin, 2021]

Phenomenology of different searches

Leptonic decays

$M \to \ell \bar{\nu}_\ell a$ three body decay

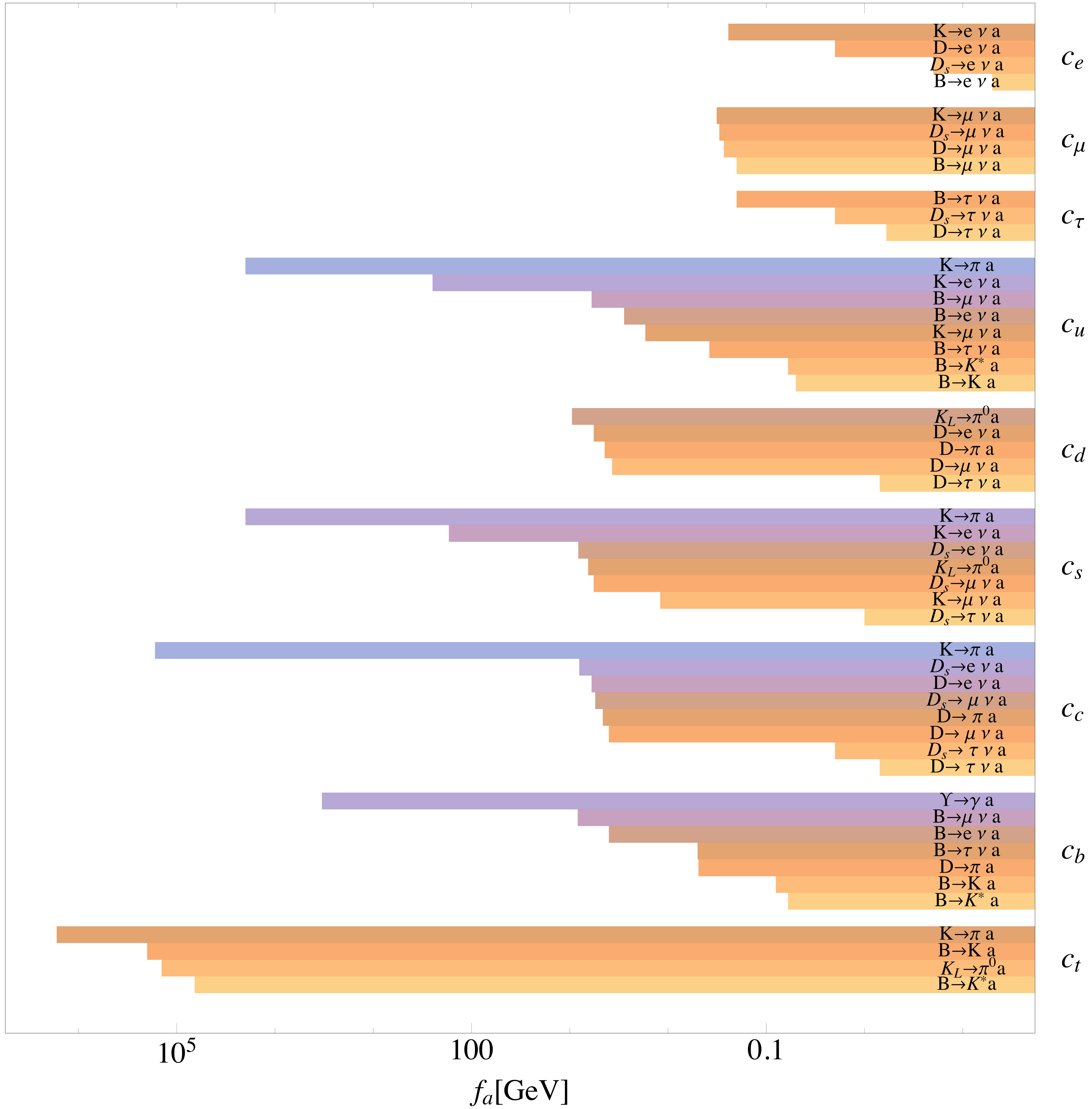


[Gallo AWMG Penaranda Rigolin, 2021]

Summary

Flavour Conserving Parameters

Summary on Flavor Conserving parameters



[AWMG Rigolin, 2211.08343]

Branching Fractions of B Meson Decays in Mesogenesis

Alfredo Walter Mario Guerrera and Gilly Elor, 2211.10553

LCSR & Mesogenesis

Alfredo Walter Mario Guerrera [1]
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Introduction

Mesogenesis

- CPV from Mesons systems
- Total baryon number is conserved
- Testable at colliders

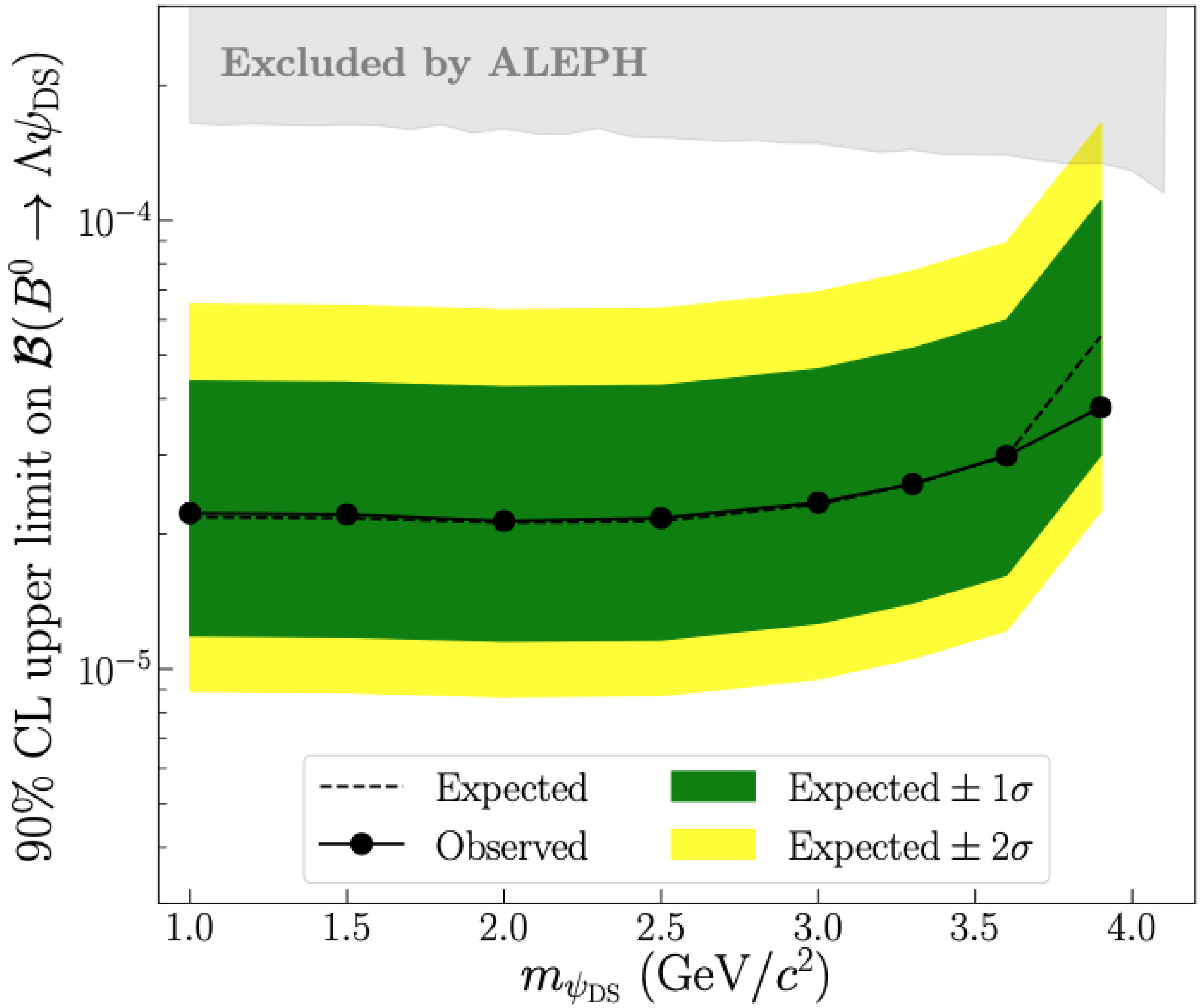
Operator and Decay	Initial State	Final State	ΔM (MeV)
$\mathcal{O}_{ud} = \psi\, b\, u\, d$, $\bar{b} \to \psi\, u\, d$	B_d	$\psi + n\,(udd)$	4340.1
	B_s	$\psi + \Lambda\,(uds)$	4251.2
	B^+	$\psi + p\,(duu)$	4341.0
	Λ_b	$\bar{\psi} + \pi^0$	5484.5
$\mathcal{O}_{us} = \psi\, b\, u\, s$, $\bar{b} \to \psi\, u\, s$	B_d	$\psi + \Lambda\,(usd)$	4164.0
	B_s	$\psi + \Xi^0\,(uss)$	4025.0
	B^+	$\psi + \Sigma^+\,(uus)$	4090.0
	Λ_b	$\bar{\psi} + K^0$	5121.9
$\mathcal{O}_{cd} = \psi\, b\, c\, d$, $\bar{b} \to \psi\, c\, d$	B_d	$\psi + \Lambda_c + \pi^-\,(cdd)$	2853.6
	B_s	$\psi + \Xi_c^0\,(cds)$	2895.0
	B^+	$\psi + \Lambda_c^+\,(dcu)$	2992.9
	Λ_b	$\bar{\psi} + \overline{D}^0$	3754.7
$\mathcal{O}_{cs} = \psi\, b\, c\, s$, $\bar{b} \to \psi\, c\, s$	B_d	$\psi + \Xi_c^0\,(csd)$	2807.8
	B_s	$\psi + \Omega_c\,(css)$	2671.7
	B^+	$\psi + \Xi_c^+\,(csu)$	2810.4
	Λ_b	$\bar{\psi} + D^- + K^+$	3256.2

LCSR & Mesogenesis

Introduction

Collider Tests

Belle-II Search $B^0 \to \Lambda\Psi_B$



ALP production in weak mesonic decays

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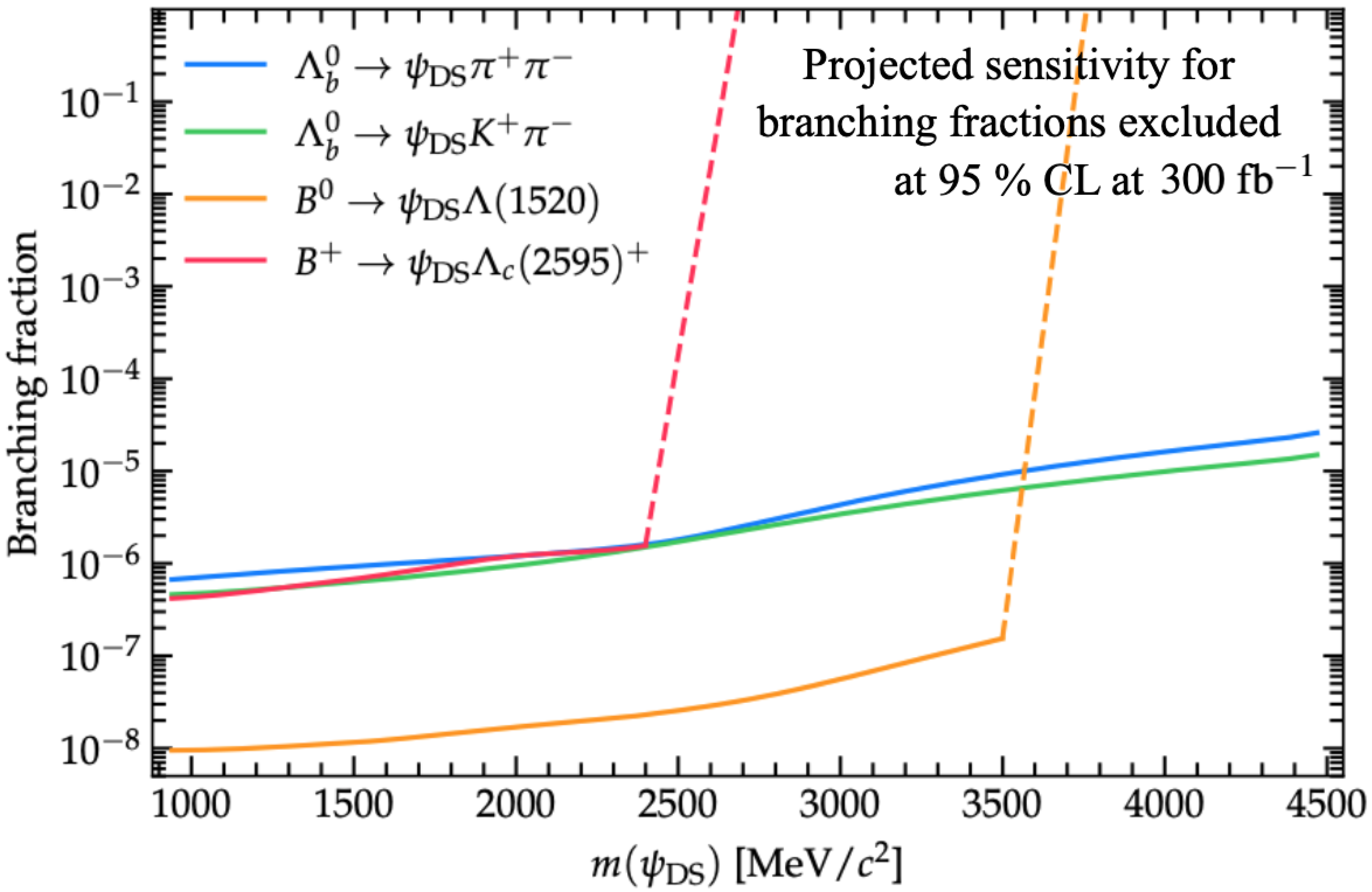
LCSR & Mesogenesis

Introduction

Collider Tests

LHCb proposal for many observables



Alfredo Walter Mario Guerrera [1]
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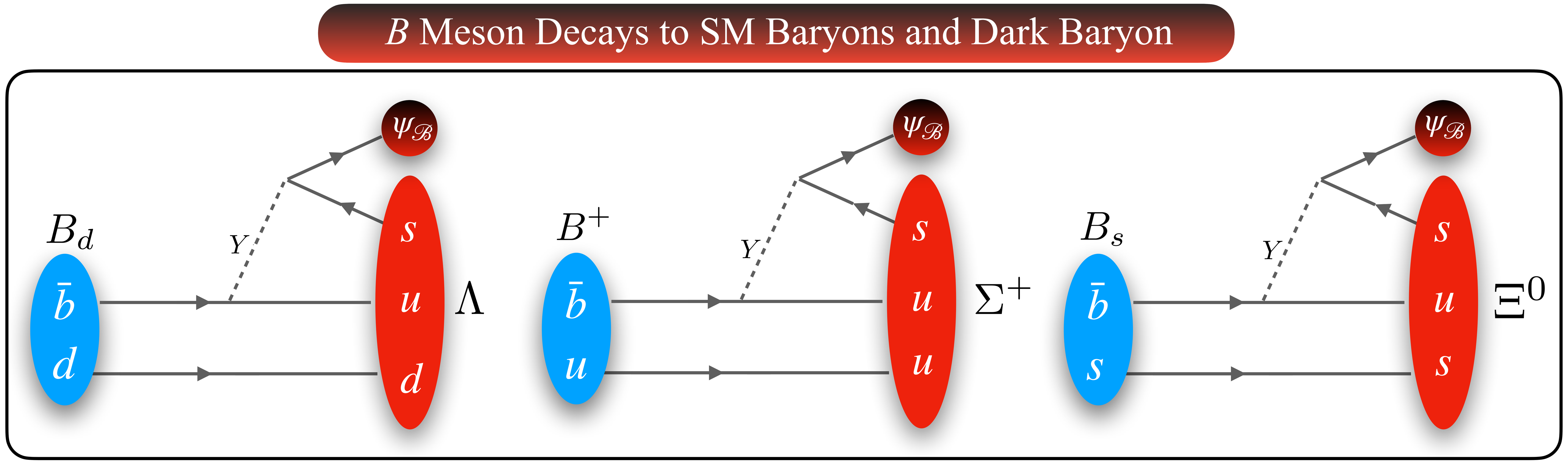
LCSR & Mesogenesis

Introduction



$\mathrm{Br}(B \to \mathcal{B}_{\mathrm{SM}} + \psi_{\mathcal{B}})$ challenging calculation

One can employ Light-Cone Sum Rules

ALP production in weak mesonic decays

Alfredo Walter Mario Guerrera [1]

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LCSR & Mesogenesis

Introduction

$$\int d^4x\ e^{i(P+q)\cdot x}\,\langle 0|\,\mathrm{T}\{j_B(x)\mathcal{O}_{d_iu_kd_j}\}\,|\mathcal{B}_{\mathrm{SM}}\rangle$$

Hadronic Dispersion Relation

$$\Pi_I((P+q)^2,q^2)\supset\int ds\frac{\rho_I(s,q^2)}{s-(P+q)^2}$$

Light-cone OPE

$$\Pi_I^{\mathrm{OPE}}((P+q)^2,q^2)=\frac{1}{\pi}\int ds\frac{\mathrm{Im}\{\Pi_I^{\mathrm{OPE}}(s,q^2)\}}{s-(P+q)^2}$$

Alfredo Walter Mario Guerrera [1]
[1]Università degli studi di Padova and INFN, sezione di Padova

LCSR & Mesogenesis

Form Factors and Symmetries

$$m_B^2 f_B F_I(q^2) e^{-m_B^2/M^2} = \frac{1}{\pi}\int_{m_b^2}^{s_0^B} ds\ e^{-s/M^2} \mathrm{Im}\{\Pi_I^{\mathrm{OPE}}(s,q^2)\},$$

Results

$$R_1(q^2) = \frac{m_b^3}{4m_B^2 f_B}\int_0^{\alpha_0^B} d\alpha\ \ e^{(m_B^2-s(\alpha))/M^2}\left\{\frac{\widetilde{V}(\alpha)}{(1-\alpha)^2}\left(1+\frac{(1-\alpha)^2 m_{\mathcal{B}_{\mathrm{SM}}}^2-q^2}{m_b^2}\right)\right\}$$

$$R_2(q^2) = \frac{m_b m_{\mathcal{B}_{\mathrm{SM}}}^2}{4m_B^2 f_B}\int_0^{\alpha_0^B} d\alpha\ \ e^{(m_B^2-s(\alpha))/M^2}\left(\widetilde{V}(\alpha)-3\frac{m_b}{m_{\mathcal{B}_{\mathrm{SM}}}}\frac{\widetilde{T}(\alpha)}{(1-\alpha)}\right)$$

$$R_3(q^2) = \frac{m_b^3}{4m_B^2 f_B}\int_0^{\alpha_0^B} d\alpha\ \ e^{(m_B^2-s(\alpha))/M^2}\left\{\left(1-\frac{q^2}{m_b^2}\right)\frac{\widetilde{V}(\alpha)}{(1-\alpha)^2}+3\frac{m_{\mathcal{B}_{\mathrm{SM}}}\widetilde{T}(\alpha)}{m_b\ (1-\alpha)}\right\}$$

$$\widetilde{L}_1(q^2) = \frac{m_b m_{\mathcal{B}_{\mathrm{SM}}}^2}{4m_B^2 f_B}\int_0^{\alpha_0^B} d\alpha\ \ \frac{\widetilde{V}(\alpha)}{(1-\alpha)}\ e^{(m_B^2-s(\alpha))/M^2}$$

ALP production in weak mesonic decays

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LCSR & Mesogenesis

Form Factors and Symmetries

$$m_B^2 f_B F_I(q^2) e^{-m_B^2/M^2} = \frac{1}{\pi} \int_{m_b^2}^{s_0^B} ds\; e^{-s/M^2} \mathrm{Im}\{\Pi_I^{\mathrm{OPE}}(s, q^2)\},$$

Input needed: Baryonic Distribution Amplitudes (DAs)

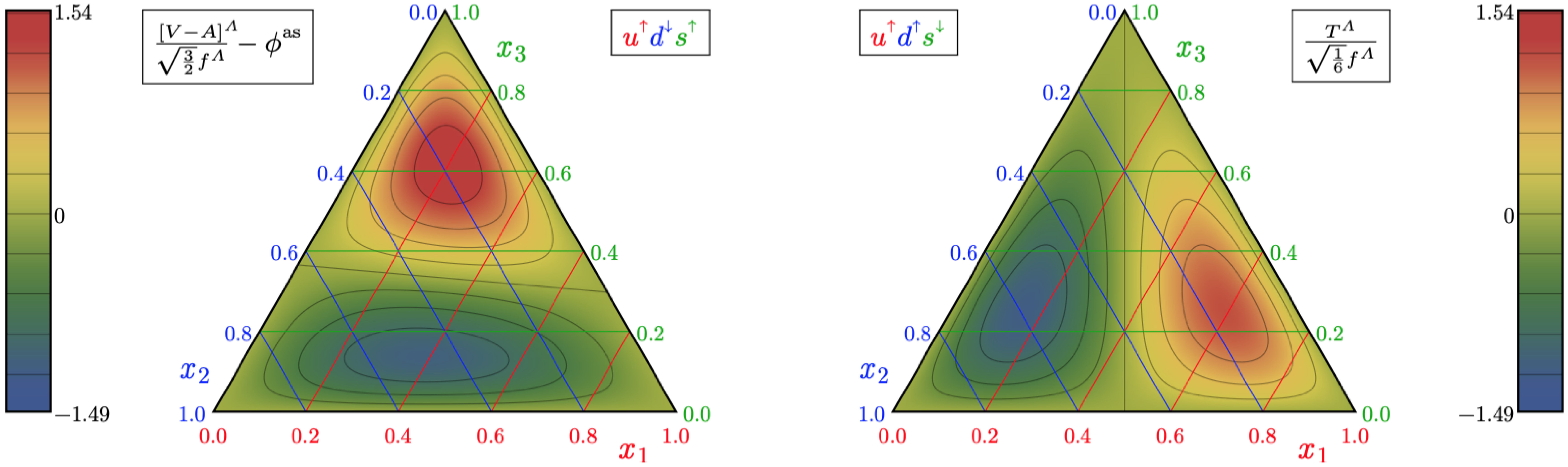


Figure taken from [Bali et al, 2019]

LCSR & Mesogenesis

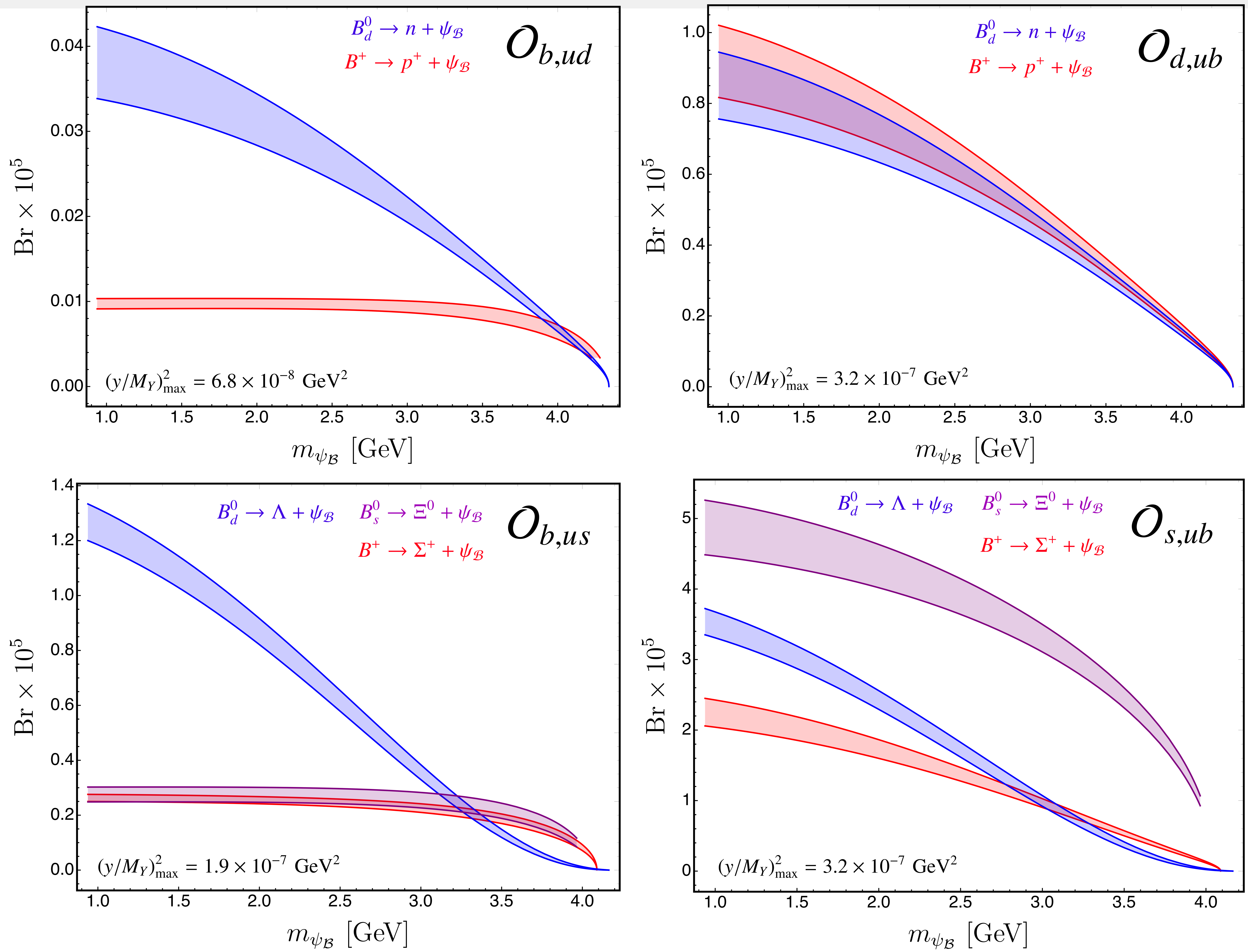
Results

Flavorful Operator	Decay Channel	$F_R^{\mathcal{O}}, \widetilde{F}_L^{\mathcal{O}}$ $\mathcal{O}=\mathcal{O}_{b,u_id_j}$	$F_R^{\mathcal{O}}, \widetilde{F}_L^{\mathcal{O}}$ $\mathcal{O}=\mathcal{O}_{d_k,u_ib}$	$\mathrm{Br}(B\to\mathcal{B}_{\mathrm{SM}}+\psi_{\mathcal{B}})$ $\mathcal{O}=\mathcal{O}_{b,u_id_j}$	$\mathrm{Br}(B\to\mathcal{B}_{\mathrm{SM}}+\psi_{\mathcal{B}})$ $\mathcal{O}=\mathcal{O}_{d_k,u_ib}$
$\psi_{\mathcal{B}}\,b\,u\,d$	$B_d\to\psi_{\mathcal{B}}+n$	R_1, 0	R_1, 0	$3.7_{\pm0.4}\cdot10^{-7}$	$8.3_{\pm0.9}\cdot10^{-6}$
	$B_s\to\psi_{\mathcal{B}}+\Lambda$	n.a.	n.a.	n.a	n.a.
	$B^+\to\psi_{\mathcal{B}}+p$	R_2, $\widetilde{L}_1$	R_1, 0	$9.6_{\pm0.6}\cdot10^{-8}$	$8.9_{\pm0.9}\cdot10^{-6}$
$\psi_{\mathcal{B}}\,b\,u\,s$	$B_d\to\psi_{\mathcal{B}}+\Lambda$	R_1, 0	R_1, 0	$1.2_{\pm0.06}\cdot10^{-5}$	$3.2_{\pm0.6}\cdot10^{-5}$
	$B_s\to\psi_{\mathcal{B}}+\Xi^0$	R_2, $\widetilde{L}_1$	R_3, $\widetilde{L}_1$	$2.6_{\pm0.1}\cdot10^{-6}$	$4.8_{\pm0.2}\cdot10^{-5}$
	$B^+\to\psi_{\mathcal{B}}+\Sigma^+$	R_2, $\widetilde{L}_1$	R_1, 0	$2.5_{\pm0.3}\cdot10^{-6}$	$2.1_{\pm0.2}\cdot10^{-5}$
$\psi_{\mathcal{B}}\,b\,c\,d$	$B_d\to\psi_{\mathcal{B}}+\Sigma_c^0$	R_2, $\widetilde{L}_1$	R_3, $\widetilde{L}_1$	$1.3_{\pm0.6}\cdot10^{-6}$	$2.7_{\pm1.5}\cdot10^{-4}$
	$B_s\to\psi_{\mathcal{B}}+\Xi_c^0$	R_2, $\widetilde{L}_1$	R_3, $\widetilde{L}_1$	$1.2_{\pm0.6}\cdot10^{-6}$	$2.3_{\pm1.3}\cdot10^{-4}$
	$B^+\to\psi_{\mathcal{B}}+\Sigma_c^+$	R_2, $\widetilde{L}_1$	R_3, $\widetilde{L}_1$	$1.4_{\pm0.7}\cdot10^{-6}$	$2.9_{\pm1.6}\cdot10^{-4}$
$\psi_{\mathcal{B}}\,b\,c\,s$	$B_d\to\psi_{\mathcal{B}}+\Xi_c^0$	R_2, $\widetilde{L}_1$	R_3, $\widetilde{L}_1$	$8.4_{\pm3.7}\cdot10^{-6}$	$3.2_{\pm1.7}\cdot10^{-4}$
	$B_s\to\psi_{\mathcal{B}}+\Omega_c$	R_2, $\widetilde{L}_1$	R_3, $\widetilde{L}_1$	$9.0_{\pm4.0}\cdot10^{-6}$	$4.4_{\pm2.0}\cdot10^{-4}$
	$B^+\to\psi_{\mathcal{B}}+\Xi_c^+$	R_2, $\widetilde{L}_1$	R_3, $\widetilde{L}_1$	$1.8_{\pm0.6}\cdot10^{-5}$	$3.5_{\pm1.9}\cdot10^{-4}$

ALP production in weak mesonic decays

Alfredo Walter Mario Guerrera [1]

[1]Università degli studi di Padova and INFN, sezione di Padova



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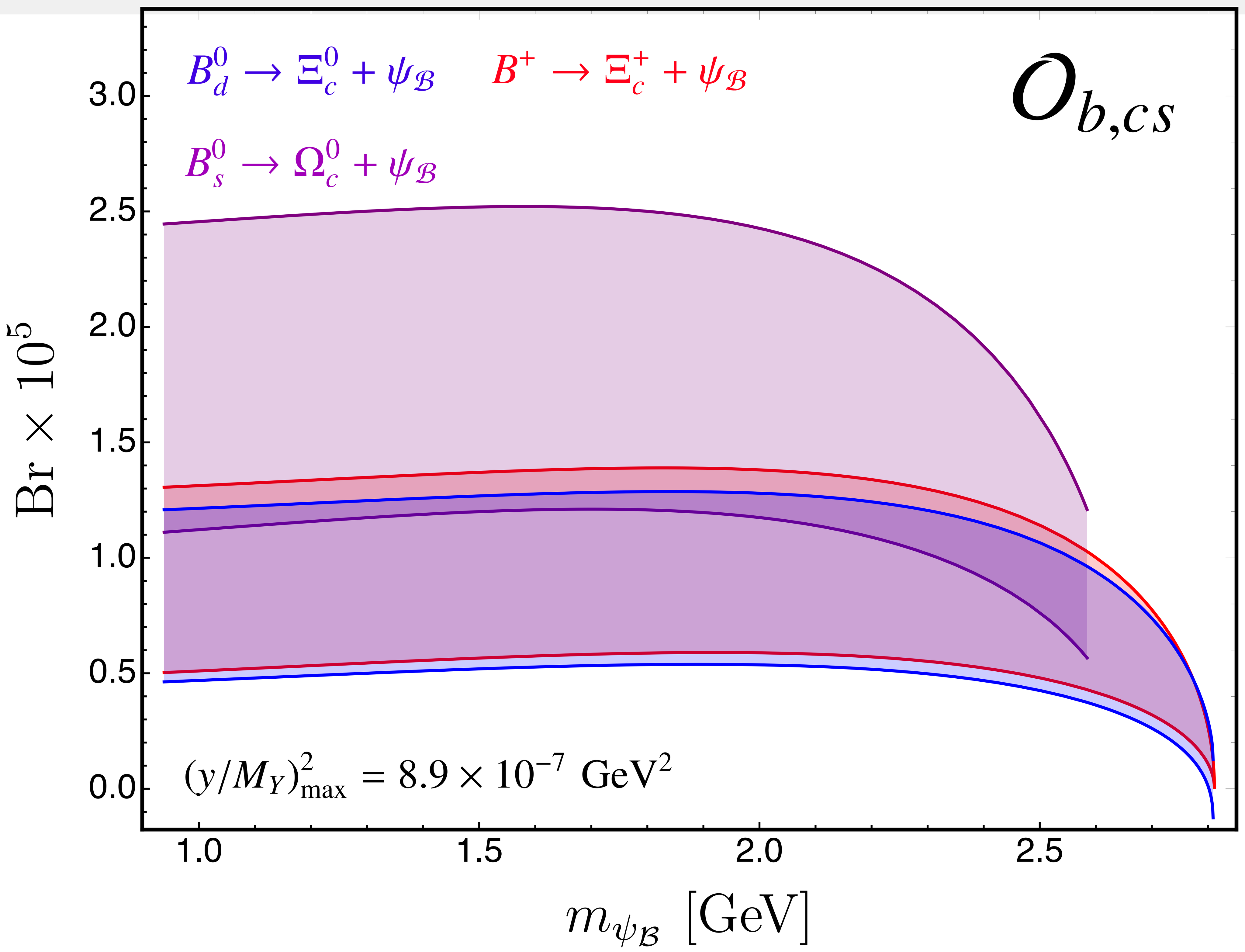

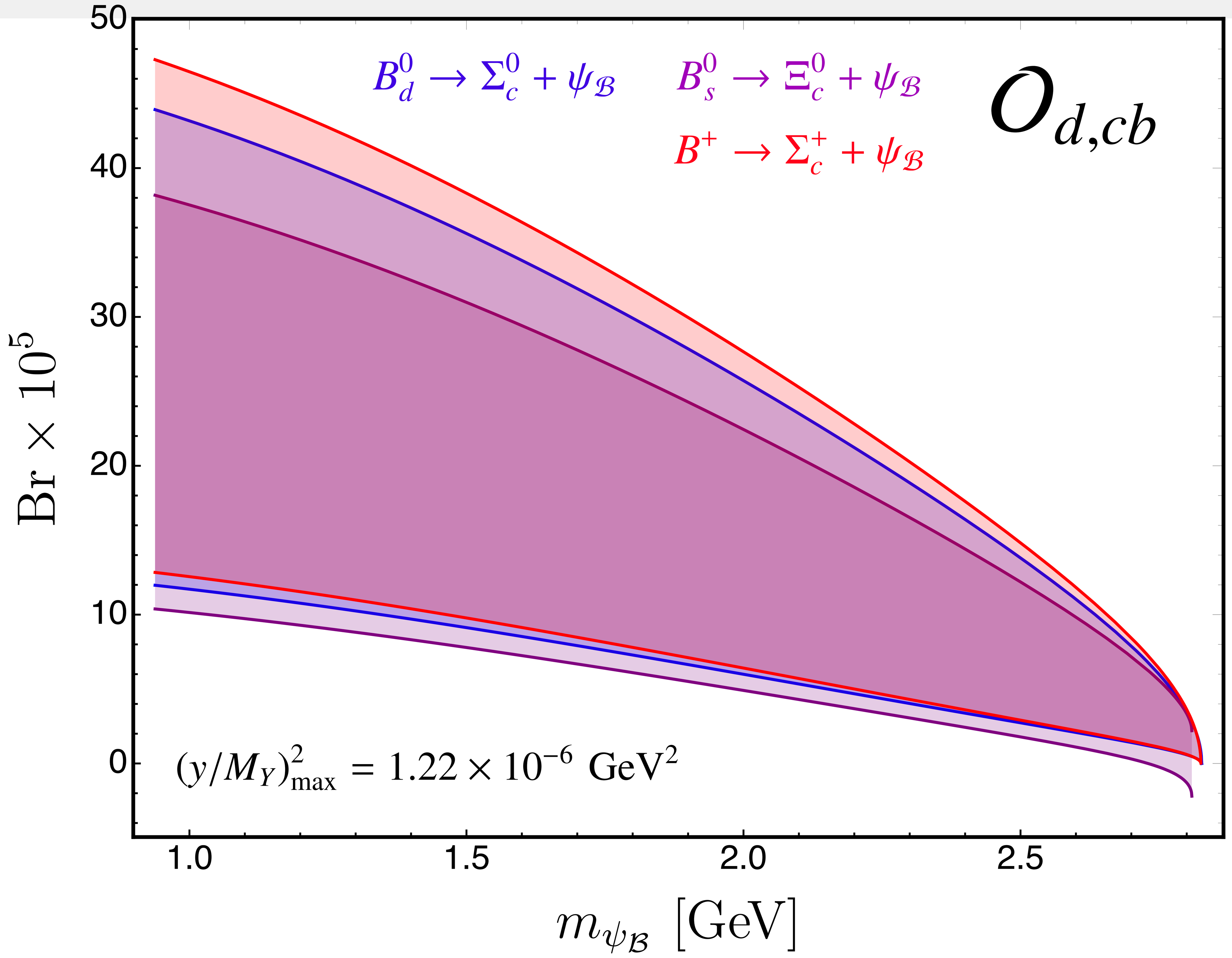

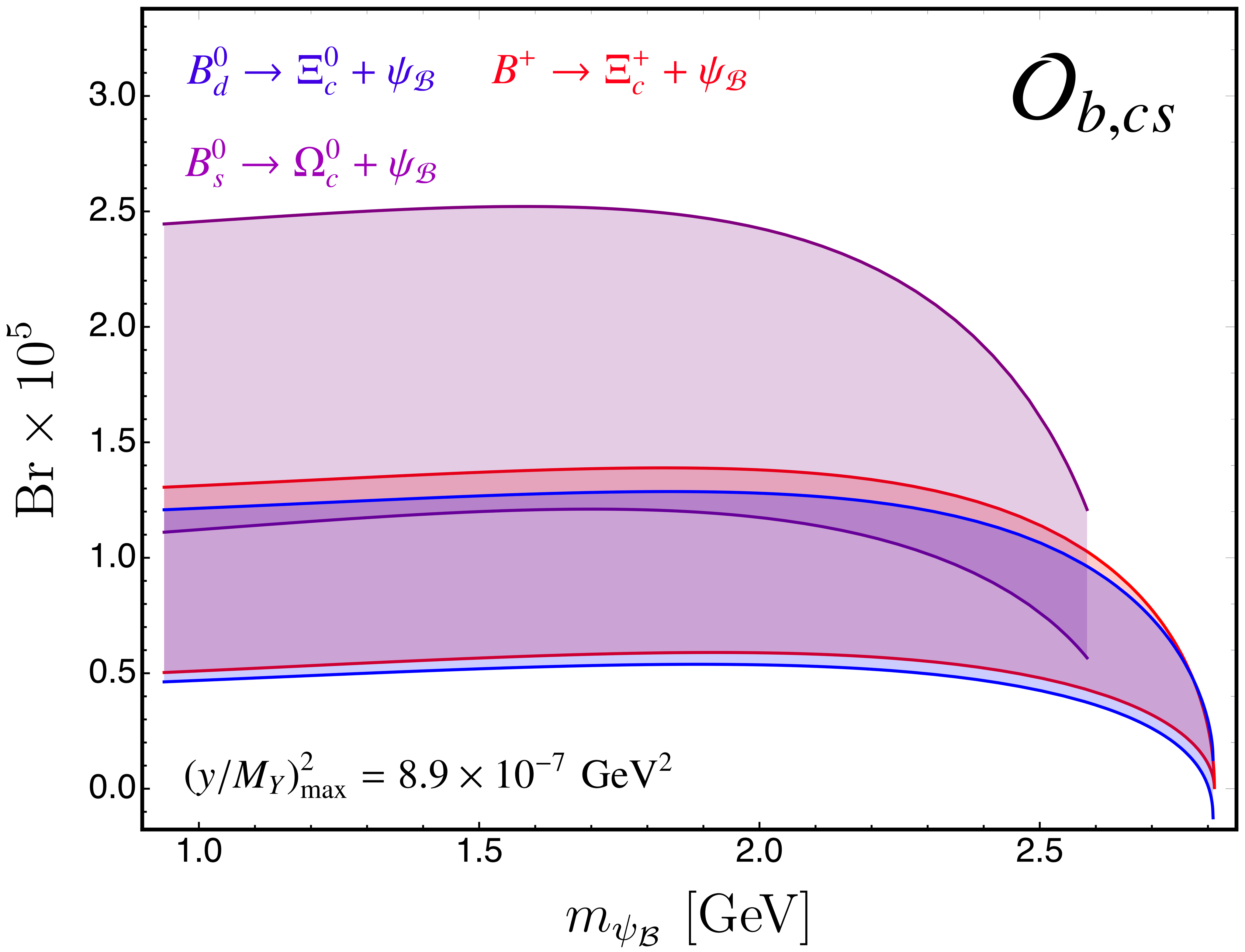

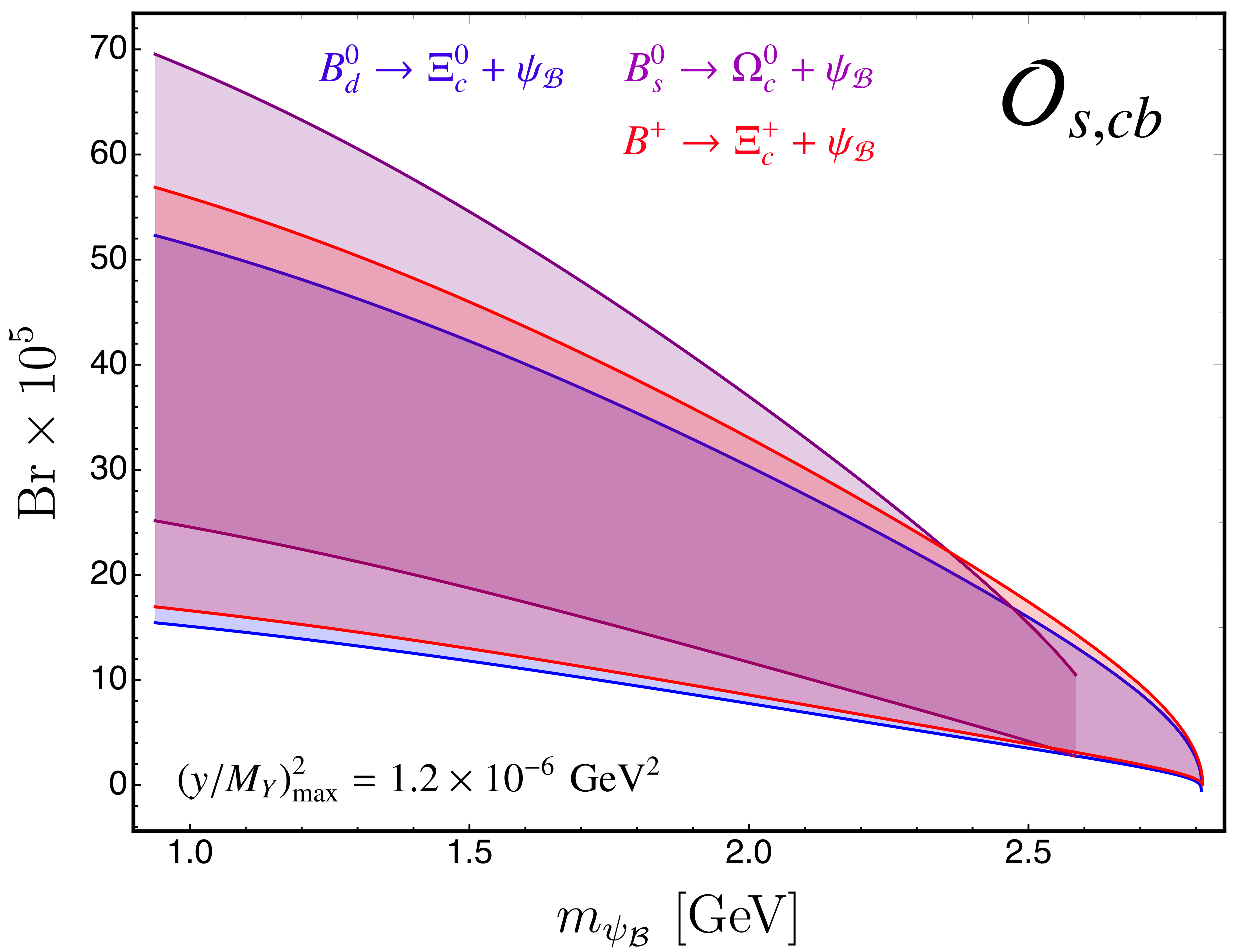

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Conclusions

Summary

Calculation for new s and t-channels contributions

Tree-level and loop amplitudes correlations

LCSR for mesogenesis predictions

Future projects

Visible ALP scenarios

More on non-universal axion

Different UV completions for mesogenesis operators

Different mesons in $M \to \mathcal{B}_{\rm SM} + \psi_{\mathcal{B}}$

Acknowledgements

Thank you for your time!

Backup slides

Refs and Extras

ALP production in weak mesonic decays

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Heavy/Light Axions

Models

How can one have heavier/lighter Axions?

Heavy Axion

Larger Confinig Group

QCD $\oplus$ QCD′

$$m_a^2 f_a^2 = m_\pi^2 f_\pi^2 + \Lambda'$$

[2001.05610]

Light Axion

Flatten The Axion Potential

N degenerate copies of SM result

$$m_a^2 f_a^2 = m_\pi^2 f_\pi^2 2^{-N}$$

[2102.00012]

Blurred lines between ALPs and Axions.

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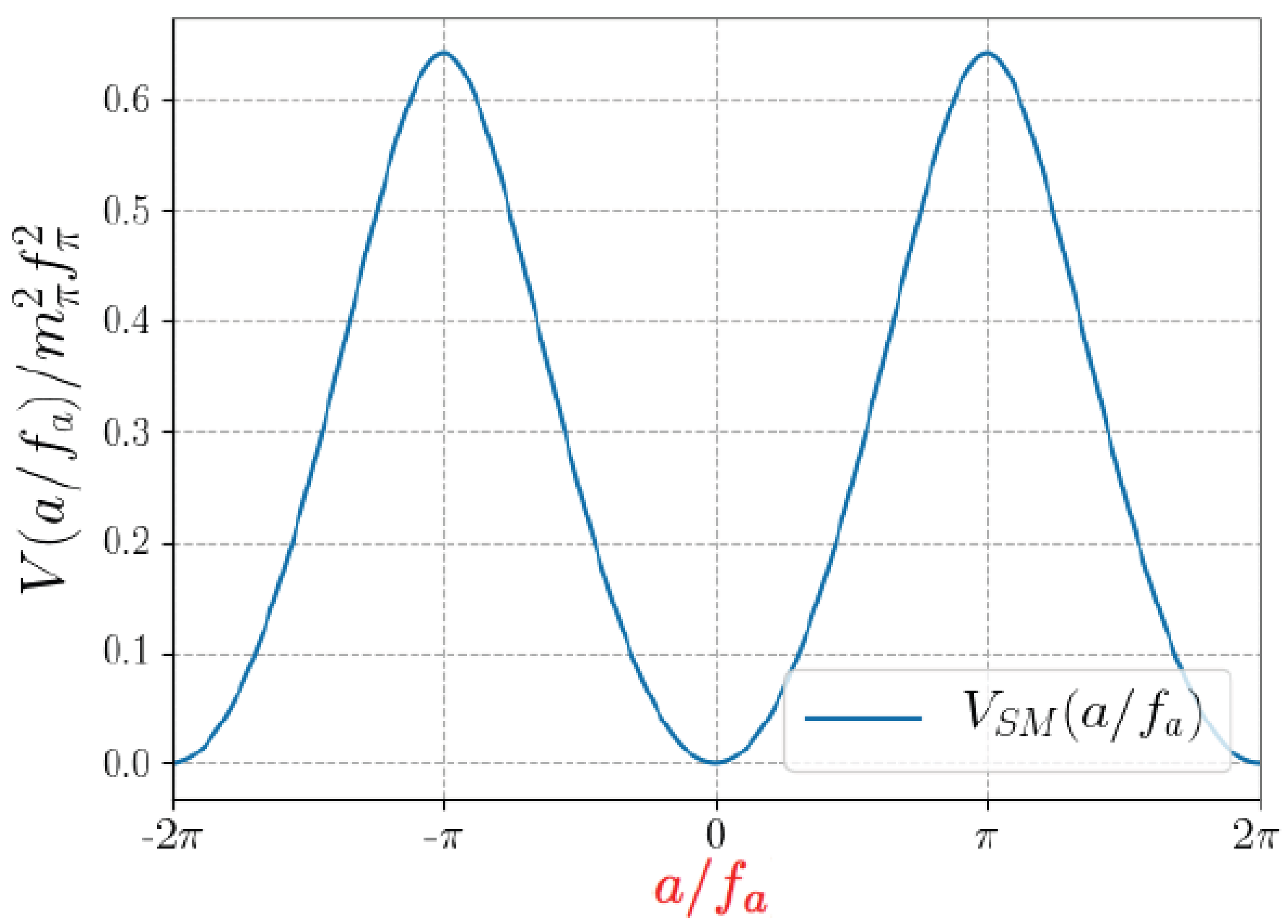
Axion Paradigm

Dynamical solution to the strong CP problem

$$\mathcal{L}_{\mathrm{QCD}} \supset G^a_{\mu\nu} G^{\mu\nu a} + \bar{\theta}\; G^a_{\mu\nu} \tilde{G}^{\mu\nu a}$$
$$\downarrow$$
$$\mathcal{L}_{\mathrm{QCD}} + \mathcal{L}_a \supset G^a_{\mu\nu} G^{\mu\nu a} + \left(\bar{\theta} + \frac{a}{f_a}\right) G^a_{\mu\nu} \tilde{G}^{\mu\nu a}$$

The coupling to $SU(3)_c$ gives the Axion a potential

$$V(a) = -m_\pi^2 f_\pi^2 \sqrt{1 - \frac{4 m_u m_d}{(m_u + m_d)^2} \sin^2\left(\frac{a}{f_a}\right)}$$
$$V(a) \approx \frac{1}{2}\left(m_\pi^2 f_\pi^2 \frac{m_u m_d}{f_a^2 (m_u + m_d)^2}\right) a^2$$



[Peccei+Quinn 77] [Weinberg, 78] [Wilczek, 78]

Axion Paradigm

UV Complete Models

The simplest way to implement the PQ mechanism was given by the Weinberg-Wilczek (WW) model.

W.W.

$$\Psi_L \to \chi_L,$$
$$H_{u,d} \to \chi_{u,d}.$$

Charges

Yukawa term imposes

$$\chi_u + \chi_d = 2\chi_{q_L} - \chi_{u_R} - \chi_{d_R}$$

The two higgs doublets are necessary for the charges to produce an axial anomaly.

The scale $f_a \simeq v$ excludes WW.

[Goldman Hoffman, 78]

"Invisible Axion" models are born

$$10^{-8} < m_a < 10^{-5} \quad \text{and} \quad 10^{9} < f_a < 10^{12} \quad \text{GeV}$$

Axion Paradigm

UV Complete Models

K.S.V.Z.

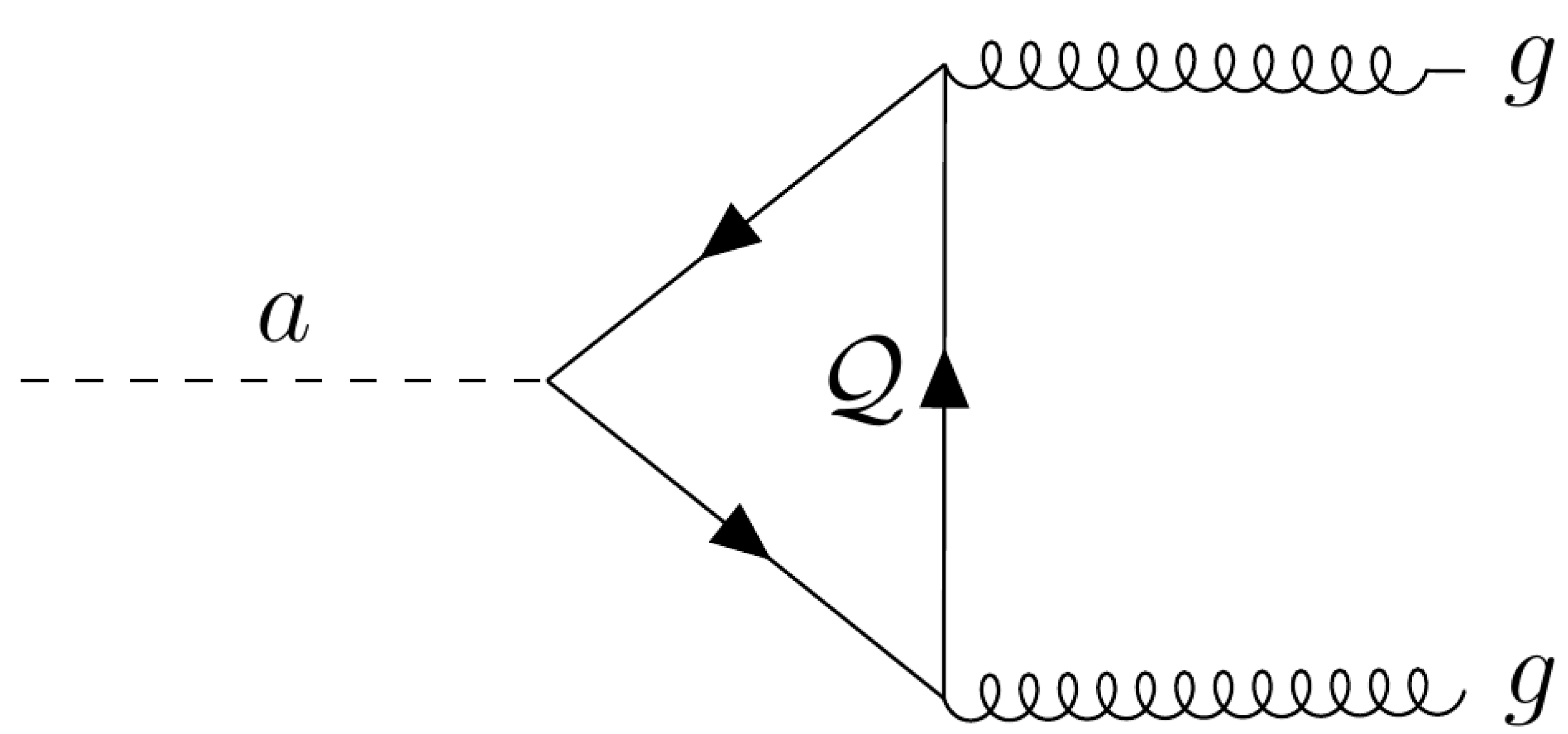
Heavy BSM fermions $\mathcal{Q}$
Complex Scalar Φ
$\downarrow$
$V(\Phi)$ for SSB
$\oplus$
Anomalous coupling
after rotating out the Axion.

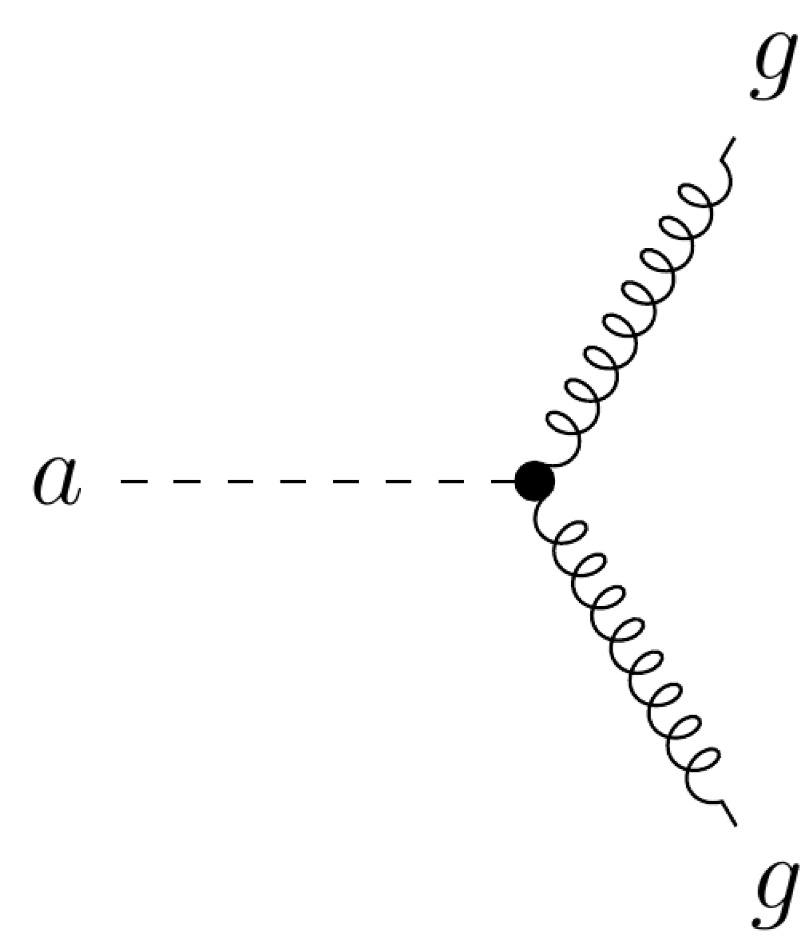
Charges

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$
$\mathcal{Q}$	3	1	0
Φ	1	1	0

PQ charges are determined by

$$\delta\mathcal{L} = -Y_Q \bar{\mathcal{Q}}_L \Phi \mathcal{Q}_R + \text{h.c.}$$





[Kim, 79] [Shifman Vainshtein Zakharov, 80]

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Axion Paradigm

UV Complete Models

D.F.S.Z.

2 Higgs doublets $(H_{u,d})$
Complex Scalar Φ
Breaking Pattern is:

$$U(1)_{H_u} \times U(1)_{H_d} \times U(1)_\Phi$$
$$\downarrow$$
$$U(1)_Y \times U(1)_{\mathrm{PQ}}$$

Charges

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$
H_u	1	2	-1/2
H_d	1	2	1/2
Φ	1	1	1

$$v^2 = v_u^2 + v_d^2$$

This model escapes esclusion thanks to

$$v_{\mathrm{PQ}} \simeq v_\Phi.$$

The ALP-fermion couplings depend on the single parameter

$$\tan\beta = v_u/v_d.$$

The anomalous couplings depend on which higgs doublet couples to leptons.

[Zhitnitsky, 80] [Dine Fischler Srednicki, 81]

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Axion Paradigm

UV Complete Models

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2 Higgs doublets ($H_{u,d}$)
Complex Scalar Φ
Breaking Pattern is:

$$U(1)_{H_u} \times U(1)_{H_d} \times U(1)_{\Phi}$$
$$\downarrow$$
$$U(1)_Y \times U(1)_{\mathrm{PQ}}$$

Charges

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$
H_u	1	2	-1/2
H_d	1	2	1/2
Φ	1	1	1

$$v^2 = v_u^2 + v_d^2$$

	Up	Down	Leptons	E/N
Model-I	$-1/3\cos^2\beta$	$-1/3\cos^2\beta$	$-1/3\cos^2\beta$	8/3
Model-II	$-1/3\cos^2\beta$	$-1/3\cos^2\beta$	$1/3\cos^2\beta$	2/3

where $\frac{\alpha}{8\pi}E/N$ is the ALP-photon coupling.

[Zhitnitsky, 80] [Dine Fischler Srednicki, 81]

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Benchmark Models

Axion

More on UV complete Axions

WW

QCD anomaly from SM quarks
Extra Higgs doublet
$f_a = \frac{v}{6}\sin 2\beta$
Axion couples too strongly

KSVZ

Heavy colored fermion
Complex scalar
Anomaly from Heavy sector
$U(1)_{\rm PQ}$ is SB at a scale $v_\phi \gg v$

DFSZ

Extended scalar sector
$U(1)^3 \to U(1)_Y \times U(1)_{\rm PQ}$
$U(1)_{\rm PQ}$ charges from Yukawas
Direct coupling to SM J^5_μ's.

Effective Field Theory

Basis

Higgs coupling redundant
Field dependent rotation changes interactions
Chiral conserv. $\leftrightarrow$ Chiral chang.

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Effective Lagrangian

Model Independent Description

The most general dimension 5 Lagrangian [Georgi Kaplan Randall, 86]

$$\mathcal{L}_a = \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{1}{2} m_a^2 a^2 + \sum_X c_X \frac{\alpha_X}{8\pi}\frac{a}{f_a} X_{\mu\nu}\tilde{X}^{\mu\nu} + \frac{\partial_\mu a}{f_a}\left(c_H H^\dagger i \overleftrightarrow{D}^\mu H + \sum_F \bar{\Psi}_F \gamma^\mu C_F \Psi_F \right).$$

At low energies, $E << v$,

$$\downarrow$$

$$\mathcal{L}'_a = \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{1}{2} m_a^2 a^2 + \frac{\alpha_s}{8\pi}\frac{a}{f_a} G^a_{\mu\nu}\tilde{G}^{\mu\nu a} + \frac{\alpha}{8\pi} c_\gamma \frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{\partial_\mu a}{2 f_a} \sum_{f=u,d,\ell} \bar{f}\gamma^\mu \left(C_V + C_A \gamma^5 \right) f.$$

Effective Couplings

C_V and C_A

are matrices in generation space

Flavor Violation

Off-diagonal elements

mix same charge fermions

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Effective Lagrangian

Model Independent Description

Disregard anomalous gauge couplings and off-diagonal fermionic couplings:

$$\mathcal{L}'_a = \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{1}{2}m_a^2 a^2 + \frac{\partial_\mu a}{2 f_a} \sum_{f=u,d,\ell} \bar{f}_i \gamma^\mu \left((C_V)_{ii} + (C_A)_{ii}\gamma^5 \right) f_i$$

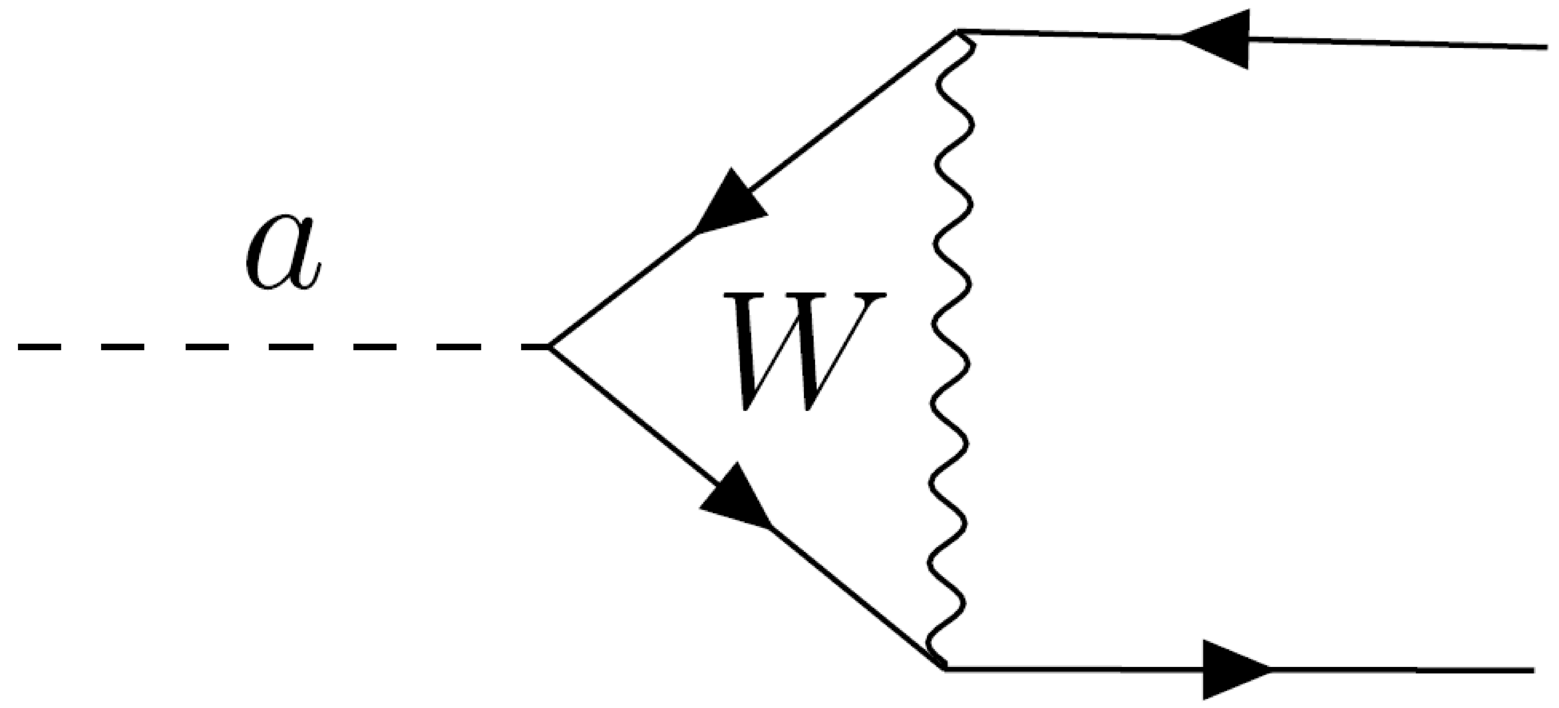
partial integration and conservation of $U(1)_{\mathrm{e.m.}}$ vector current implies:

$$\mathcal{L}'_a = \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{1}{2}m_a^2 a^2 + \frac{a}{f_a} \sum_{f=u,d,\ell} c_i \bar{f}_i m_i \gamma^5 f_i .$$

The parameters $c_i (= (C_A)_{ii})$ are all independent and non universal.

Diagonal Couplings

Flavor Violation is loop induced
Can reproduce off-diagonal terms



[Izaguirre Lin Shuve, 2017] [Gavela et al. , 2019]

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Hadronization Techniques

Brodsky-Lepage

$s-$channel factorization:

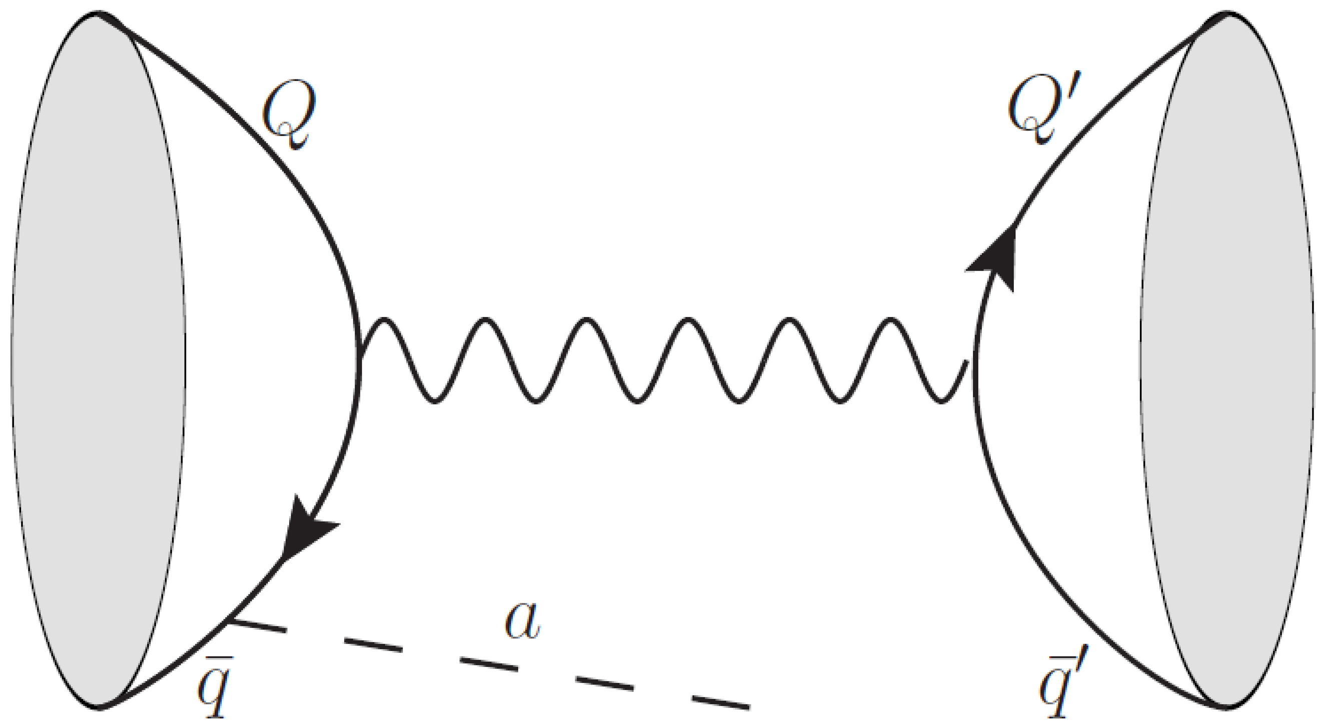
[AG Rigolin, 2021] [Gallo AG Penaranda Rigolin, 2021] [GA Rigolin, TBA]

Hadronization

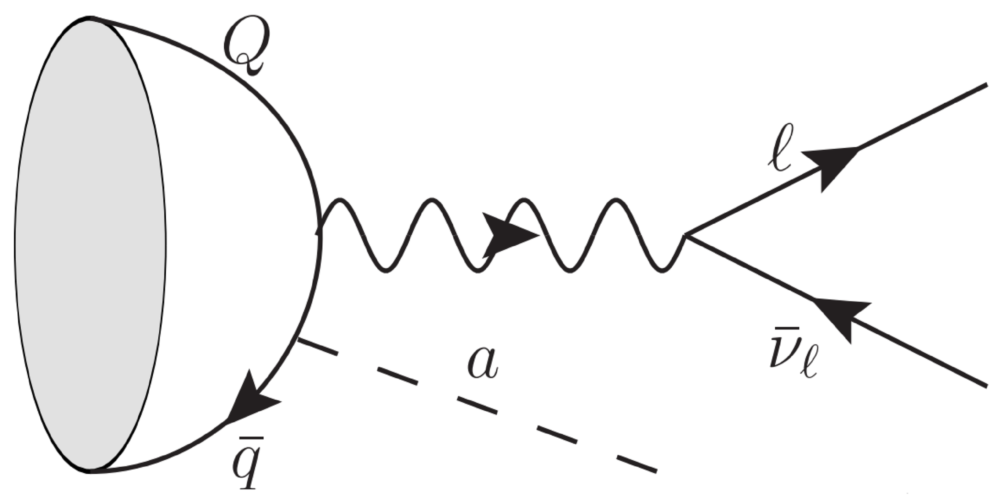
$$\langle 0|\left(\bar{q}\,\Gamma_\mu Q\right)|M\rangle$$

$$=$$

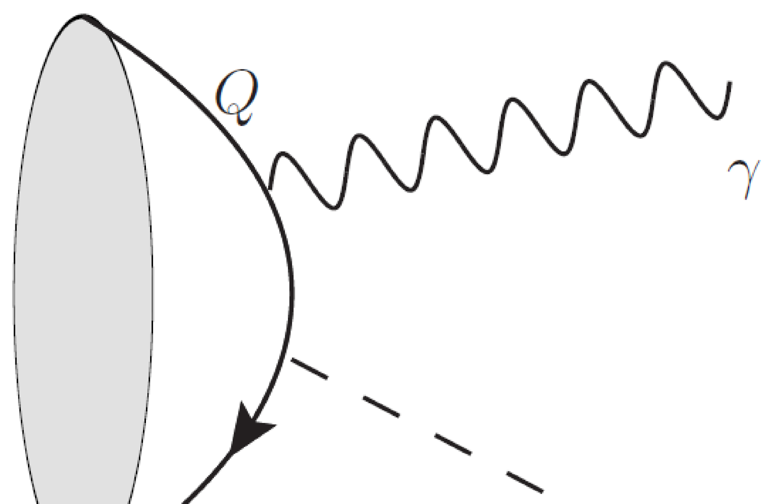
$$i f_M \int_0^1 dx \mathrm{Tr}[\Psi_M(x)\Gamma_\mu]$$



$M \to M'a$



$M \to \ell\bar{\nu}_\ell a$



$M \to \gamma a$

Hadronization Techniques

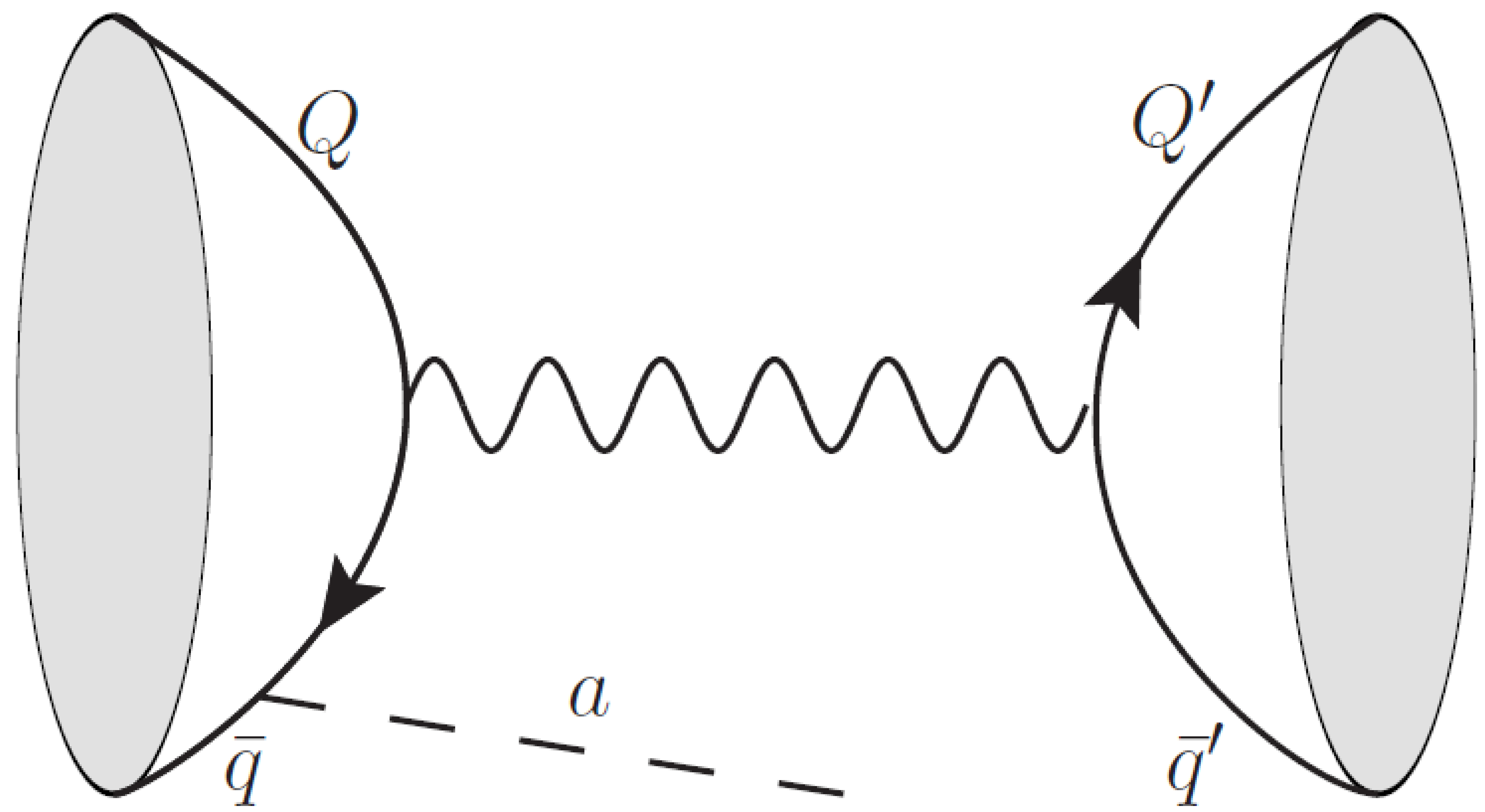
Brodsky-Lepage

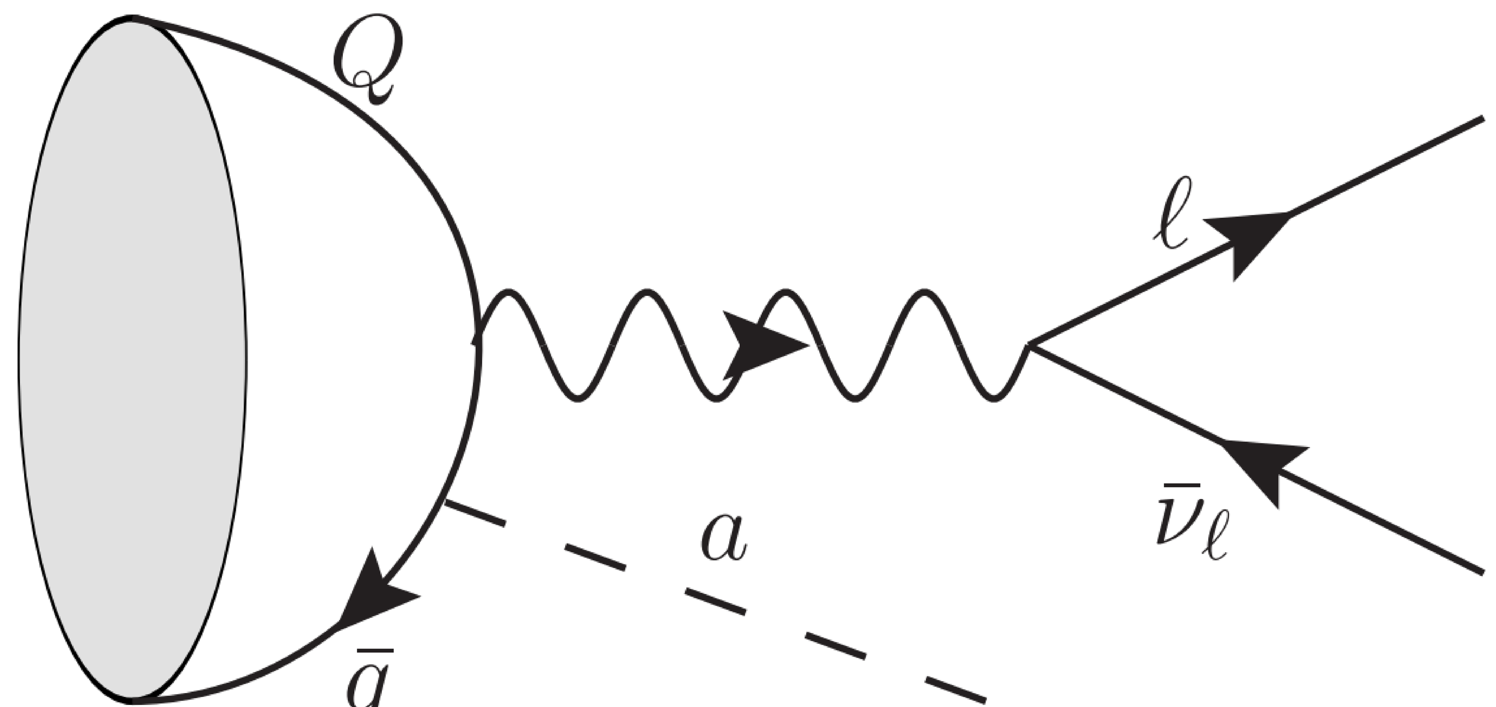
$s-$channel factorization:
$M_I \to M_F\, a$ and $M \to \ell \bar{\nu}_\ell a$

[AG Rigolin, 2021] [Gallo AG Penaranda Rigolin, 2021] [GA Rigolin, TBA]

Hadronization

$$\langle 0 | \left(\bar{q}\,\Gamma_\mu Q\right) | M \rangle$$
$$=$$
$$i f_M \int dx\, \mathrm{Tr}[\Psi_M(x)\Gamma_\mu]$$





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Hadronization Techniques

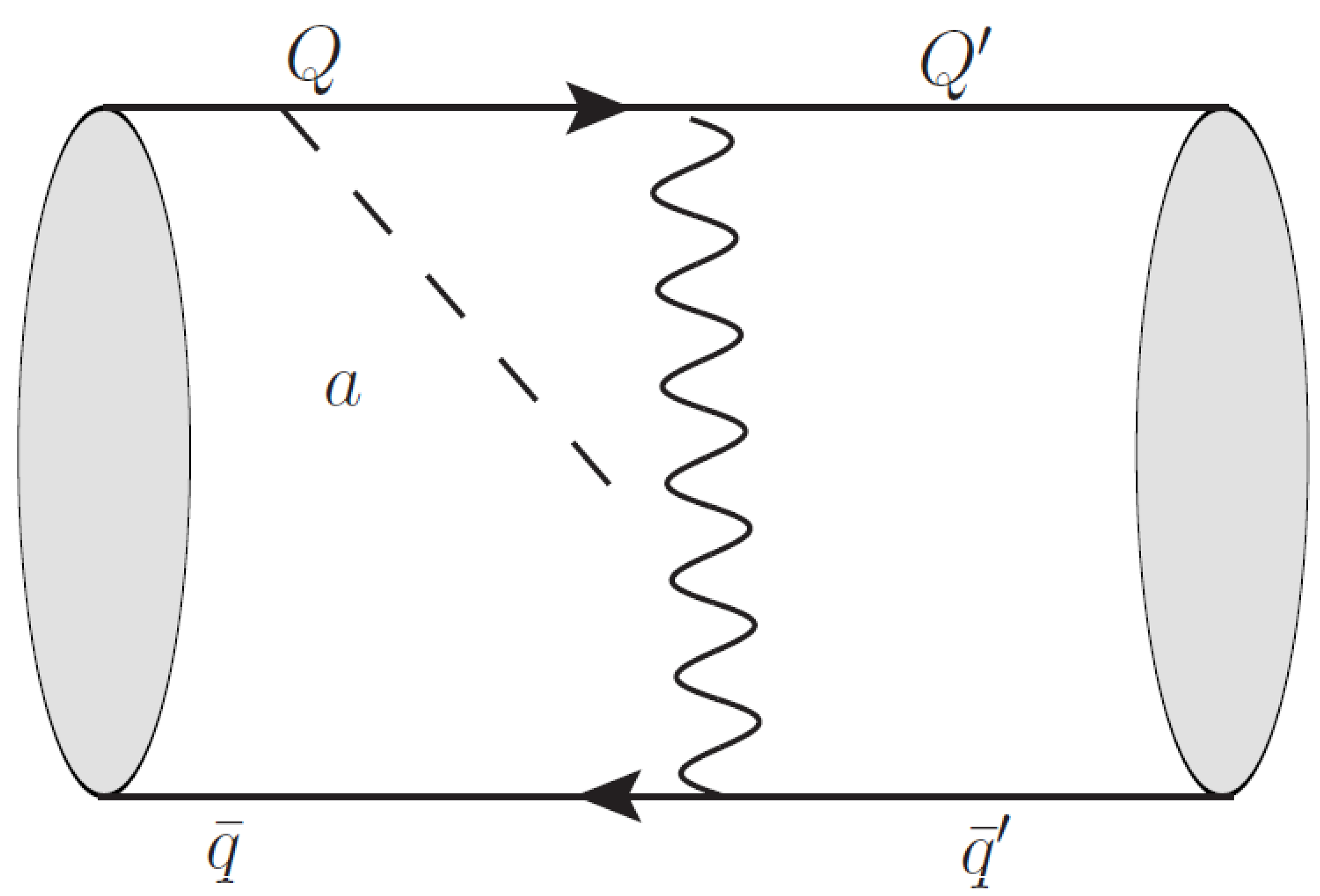
Brodsky-Lepage

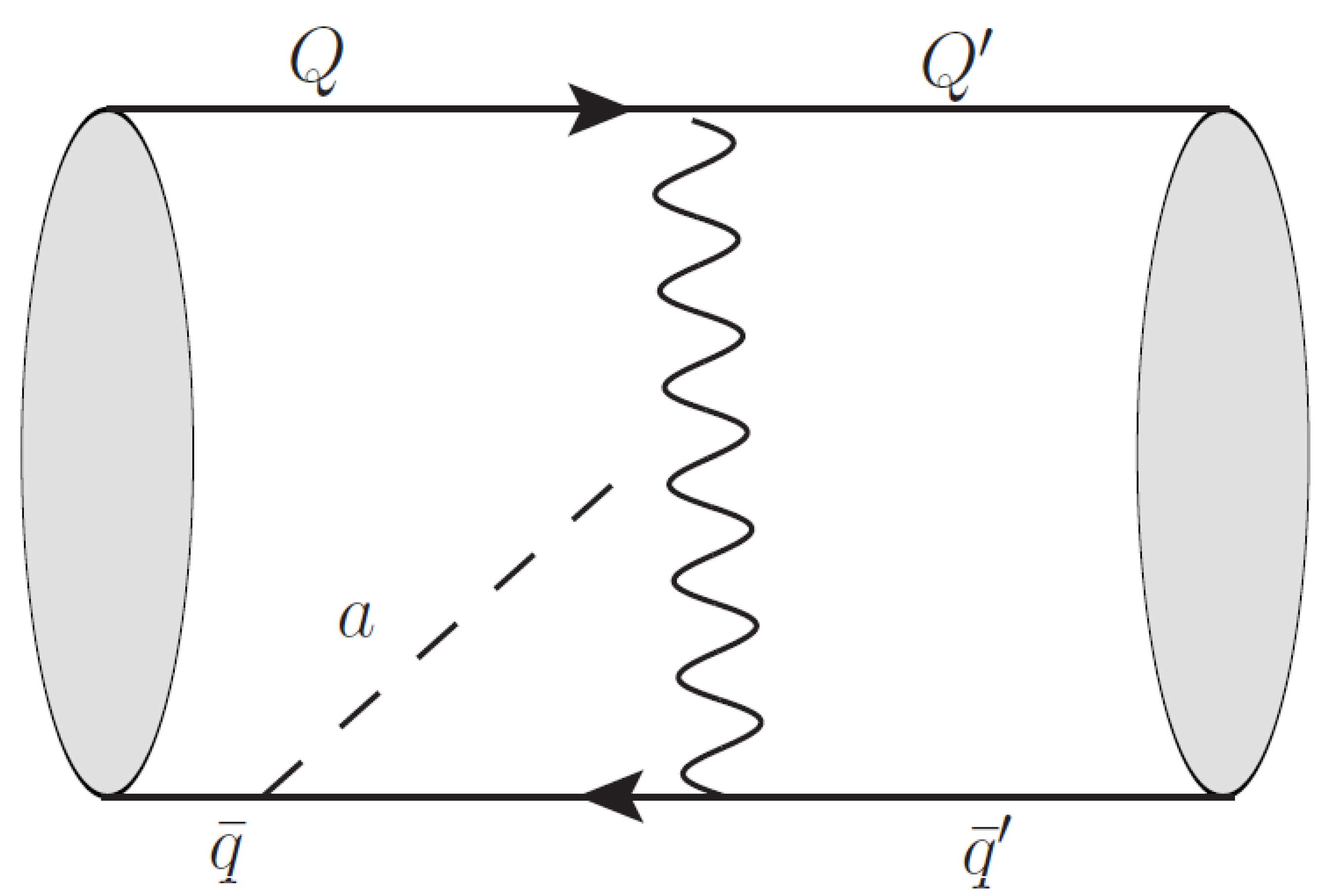
$t-$channel factorization:
Only for $M_I \to M_F\, a$

[AG Rigolin, 2021] [GA Rigolin, TBA]

Hadronization

$$\langle M_F|\,(\bar{Q}'\Gamma_\mu Q)(\bar{q}\Gamma'^\mu q')\,|M_I\rangle$$
$$=$$
$$-\frac{f_{M_F} f_{M_I}}{\sqrt{2}}\int dx\, dy \times$$
$$\mathrm{Tr}[\Psi_{M_I}(x)\Gamma'^\mu \Psi_{M_F}(y)\Gamma_\mu]$$





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Experimental Signatures

Stellar

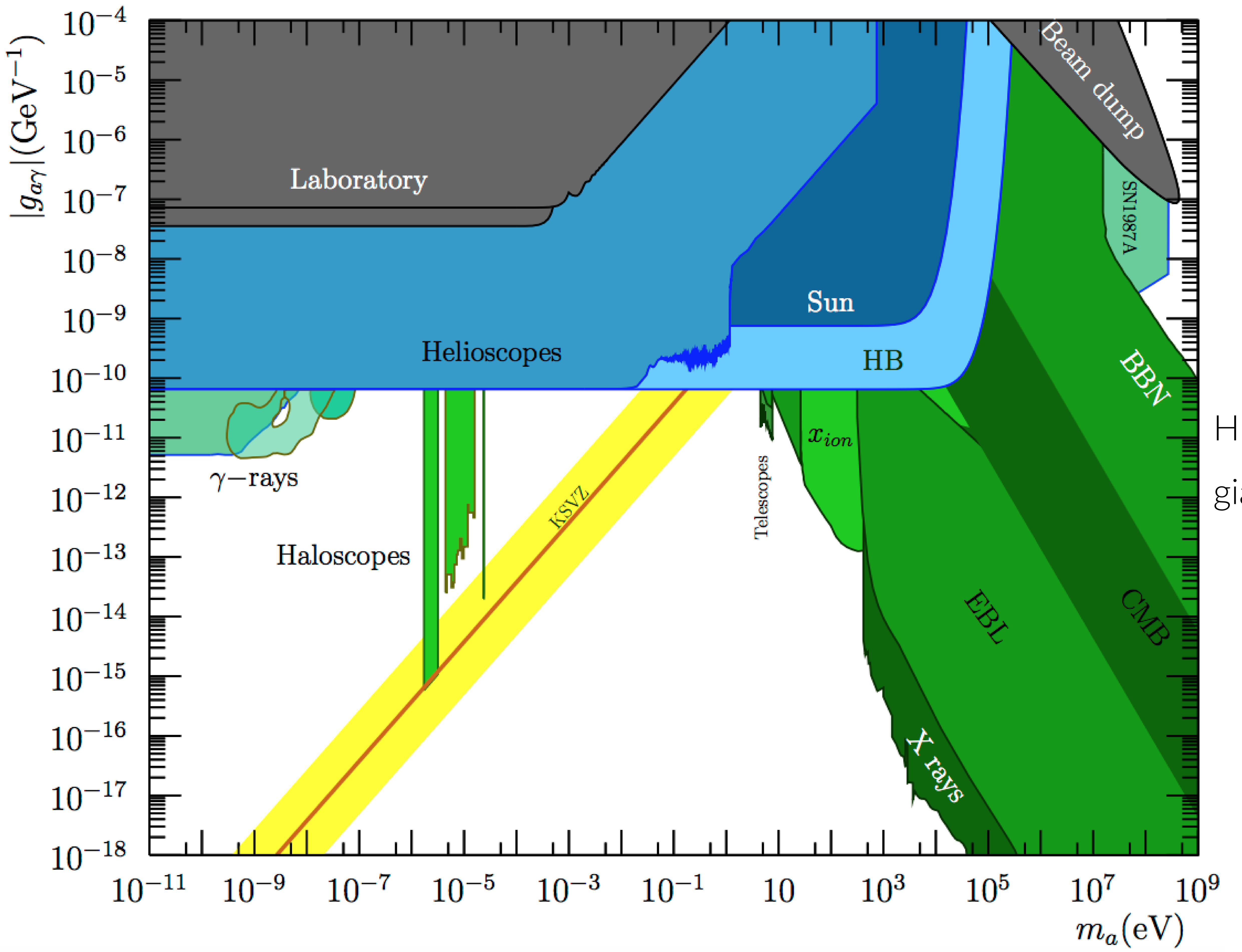

Figure is taken from [Irastorza Redondo, 2018].

Plot Legend

Helioscopes: primakoff conversion from Axion sun fluxes

Sun: Neutrino Flux and Helioseismology

HB: Ratio of Horizontal Branch to red giants, ratio decreses with Primakoff

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Experimental Signatures

Cosmological

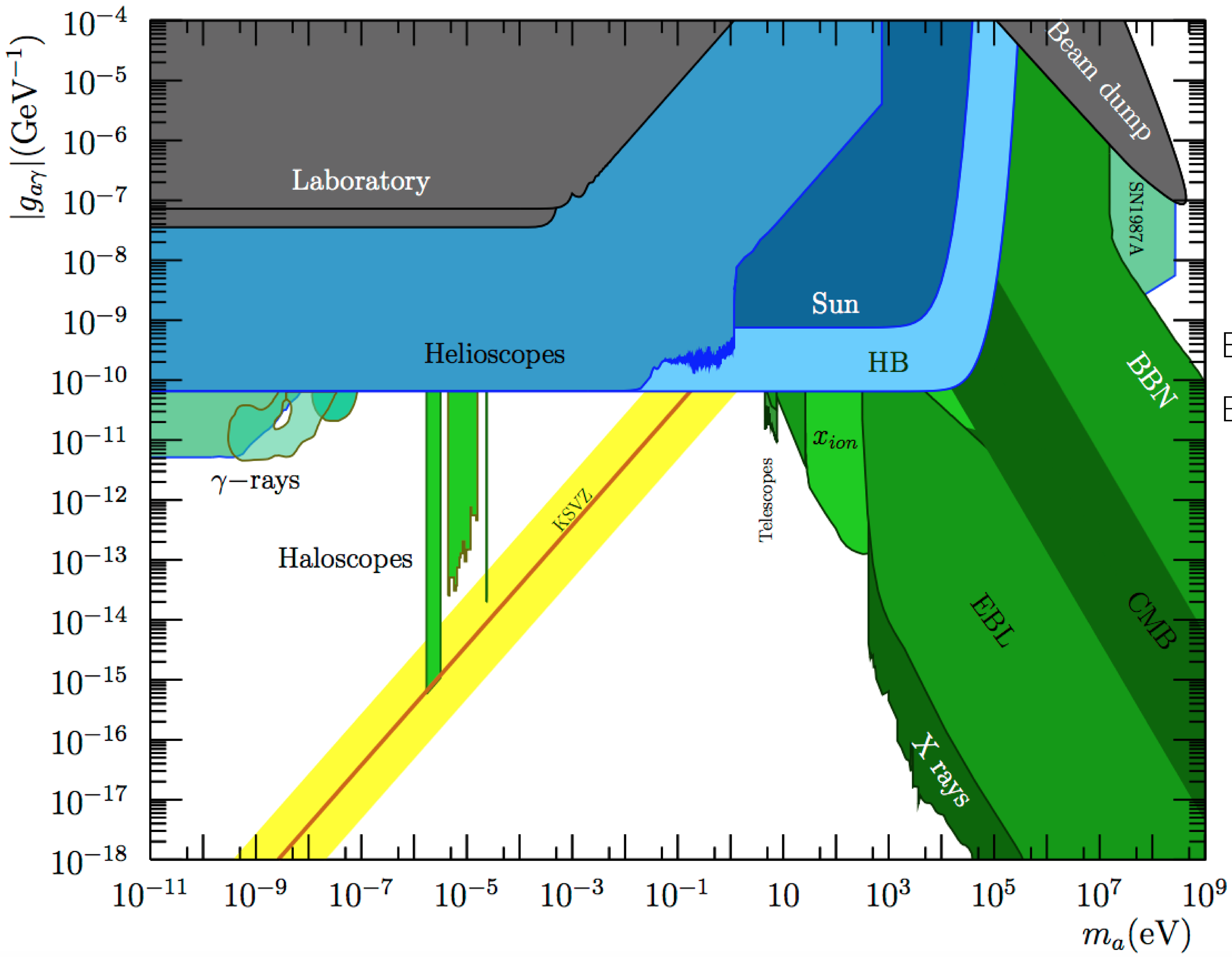

Figure is taken from [Irastorza Redondo, 2018].

Plot Legend

Monochromatic lines of photons from ALP 2 body decay

Extragalactic Background Light (EBL),

BBN, CMB, X-Rays

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Phenomenology of different searches

Meson-to-meson decay

Charged Mesonic decays amplitudes

[AWMG Rigolin, 2211.08343]

Tree level $s-$channel

$$
\begin{aligned}
\mathcal{A}_{\mathrm{I}}^{(s)} =& \frac{G_F V_{CKM} f_I f_F (k \cdot P_F)}{\sqrt{2} f_a} M_I \\
& \int dx\, g_I(x) \left[\frac{c_q m_q}{m_a^2 - 2k \cdot P_I(1-x)} - \frac{c_Q m_Q}{m_a^2 - 2k \cdot P_I x} \right] \phi_I(x) \\
\mathcal{B}_{\mathrm{I}}^{(s)} =& \frac{G_F V_{CKM} f_I f_F (k \cdot \epsilon(P_F))}{\sqrt{2} f_a} M_I M_F \\
& \int dx\, g_I(x) \left[\frac{c_q m_q}{m_a^2 - 2k \cdot P_I(1-x)} - \frac{c_Q m_Q}{m_a^2 - 2k \cdot P_I x} \right] \phi_I(x)
\end{aligned}
$$

Channel	Tree–Level	Penguin
$B_c^\pm \to D_s^\pm a$	$(6-160)\times 10^{-11}$	2×10^{-6}
$B_c^\pm \to D^\pm a$	$(1-30)\times 10^{-11}$	3×10^{-7}
$B_c^\pm \to K^{*\pm} a$	$(2-70)\times 10^{-11}$	n.a.
$B_c^\pm \to \rho^\pm a$	$(4-100)\times 10^{-11}$	n.a.
$B_c^\pm \to K^\pm a$	$(8-230)\times 10^{-12}$	n.a.
$B_c^\pm \to \pi^\pm a$	$(3-85)\times 10^{-11}$	n.a.
$B^\pm \to D_s^\pm a$	$(5-30)\times 10^{-12}$	n.a.
$B^\pm \to D^\pm a$	$(1-7)\times 10^{-12}$	n.a.
$B^\pm \to K^{*\pm} a$	$(1-7)\times 10^{-12}$	4×10^{-6}
$B^\pm \to \rho^\pm a$	$(3-20)\times 10^{-12}$	4×10^{-7}
$B^\pm \to K^\pm a$	$(8-50)\times 10^{-13}$	2×10^{-6}
$B^\pm \to \pi^\pm a$	$(3-20)\times 10^{-12}$	3×10^{-7}
$D_s^\pm \to K^{*\pm} a$	$(1-60)\times 10^{-11}$	6×10^{-12}
$D_s^\pm \to \rho^\pm a$	$(3-170)\times 10^{-11}$	n.a.
$D_s^\pm \to K^\pm a$	$(6-300)\times 10^{-12}$	7×10^{-12}
$D_s^\pm \to \pi^\pm a$	$(2-120)\times 10^{-11}$	n.a.
$D^\pm \to K^{*\pm} a$	$(2-100)\times 10^{-12}$	n.a.
$D^\pm \to \rho^\pm a$	$(7-290)\times 10^{-12}$	3×10^{-12}
$D^\pm \to K^\pm a$	$(1-50)\times 10^{-12}$	n.a.
$D^\pm \to \pi^\pm a$	$(5-200)\times 10^{-12}$	6×10^{-12}
$K^{*\pm} \to K^\pm a$	$(5-25)\times 10^{-13}$	4×10^{-8}
$K^{*\pm} \to \pi^\pm a$	$(3-20)\times 10^{-12}$	3×10^{-9}
$\rho^\pm \to K^\pm a$	$(8-25)\times 10^{-12}$	2×10^{-9}
$\rho^\pm \to \pi^\pm a$	$(3-9)\times 10^{-11}$	4×10^{-10}
$K^\pm \to \pi^\pm a$	$(2-10)\times 10^{-12}$	5×10^{-10}

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Phenomenology of different searches

Meson-to-meson deca

Channel	Tree–Level	Penguin
$B_c^\pm \to D_s^\pm a$	$(6-160)\times 10^{-11}$	2×10^{-6}
$B_c^\pm \to D^\pm a$	$(1-30)\times 10^{-11}$	3×10^{-7}
$B_c^\pm \to K^{*\pm} a$	$(2-70)\times 10^{-11}$	n.a.
$B_c^\pm \to \rho^\pm a$	$(4-100)\times 10^{-11}$	n.a.
$B_c^\pm \to K^\pm a$	$(8-230)\times 10^{-12}$	n.a.
$B_c^\pm \to \pi^\pm a$	$(3-85)\times 10^{-11}$	n.a.
$B^\pm \to D_s^\pm a$	$(5-30)\times 10^{-12}$	n.a.
$B^\pm \to D^\pm a$	$(1-7)\times 10^{-12}$	n.a.
$B^\pm \to K^{*\pm} a$	$(1-7)\times 10^{-12}$	4×10^{-6}
$B^\pm \to \rho^\pm a$	$(3-20)\times 10^{-12}$	4×10^{-7}
$B^\pm \to K^\pm a$	$(8-50)\times 10^{-13}$	2×10^{-6}
$B^\pm \to \pi^\pm a$	$(3-20)\times 10^{-12}$	3×10^{-7}

Charged Mesonic decays amplitudes

[AWMG Rigolin, 2211.08343]

Tree level $s-$channel

$$\mathcal{A}_{\rm I}^{(s)} \approx \frac{G_F V_{\rm CKM} f_I f_F}{2\sqrt{2} f_a} M_I^2 (c_q - c_Q)$$

$$\mathcal{B}_{\rm I}^{(s)} \approx i\frac{G_F V_{\rm CKM} f_I f_F M_F (k\cdot\epsilon(P_F))}{2\sqrt{2} f_a (k\cdot P_I)} M_I^2 (c_q - c_Q)$$

Phenomenology of different searches

Meson-to-meson decay

Neutral Mesonic decays amplitudes

[AWMG Rigolin, 2211.08343]

Tree level $t-$channel

$$\mathcal{C}_{\rm I}^{(t)} = -i\frac{G_F V_{CKM} f_I f_F}{2 f_a}\epsilon^\alpha(P_I) P_I^\beta (k^\beta P_F^\alpha - k^\alpha P_F^\beta)$$
$$\int_0^1 dx \left[\frac{c_Q m_Q\,\theta(x-\delta_a^M)}{m_a^2 - 2k\cdot P_I x} - \frac{c_q m_q\,\theta(1-x-\delta_a^M)}{m_a^2 - 2k\cdot P_I(1-x)}\right]\phi_I(x)$$

$$\mathcal{D}_{\rm I}^{(t)} = i\frac{G_F V_{CKM} f_I f_F}{2 f_a}\epsilon^\alpha(P_I)\epsilon^\delta(P_F) P_I^\beta M_F$$
$$\int_0^1 dx \left[\frac{c_Q m_Q\,\theta(x-\delta_a^M)}{m_a^2 - 2k\cdot P_I x}(\varepsilon_{\alpha\beta\delta\rho}k^\rho - ik^\beta g^{\alpha\delta} + ik^\alpha g^{\beta\delta}) + \frac{c_q m_q\,\theta(1-x-\delta_a^M)}{m_a^2 - 2k\cdot P_I(1-x)}(\varepsilon_{\alpha\beta\delta\rho}k^\rho - ik^\alpha g^{\beta\delta} + ik^\beta g^{\alpha\delta})\right]\phi_I(x)$$

Channel	Tree–Level	Penguins
$B_s^0 \to D_s^0 a$	n.a.	4×10^{-7}
$B_s^0 \to D^0 a$	$(7-70)\times10^{-12}$	n.a.
$B_s^0 \to K^{*0} a$	n.a.	4×10^{-6}
$B_s^0 \to \rho^0 a$	$(4-50)\times10^{-13}$	n.a.
$B_s^0 \to K_L^0 a$	n.a.	3×10^{-7}
$B^0 \to K^{*0} a$	n.a.	4×10^{-6}
$B^0 \to D^0 a$	$(3-30)\times10^{-11}$	n.a.
$B^0 \to \rho^0 a$	$(2-20)\times10^{-12}$	6×10^{-7}
$B^0 \to K_L^0 a$	n.a.	4×10^{-6}
$B^0 \to \pi^0 a$	$(1-10)\times10^{-12}$	5×10^{-7}
$D^0 \to K^{*0} a$	$(7-300)\times10^{-12}$	n.a.
$D^0 \to \rho^0 a$	$(5-200)\times10^{-12}$	4×10^{-12}
$D^0 \to K_L^0 a$	$(7-270)\times10^{-13}$	n.a.
$D^0 \to \pi^0 a$	$(2-100)\times10^{-12}$	3×10^{-12}
$K^{*0} \to K^0 a$	$(2-6)\times10^{-12}$	3×10^{-9}
$K^{*0} \to \pi^0 a$	$(1-2)\times10^{-11}$	3×10^{-9}
$\rho^0 \to K^0 a$	$(1-3)\times10^{-11}$	2×10^{-9}
$\rho^0 \to \pi^0 a$	$(2-7)\times10^{-11}$	3×10^{-9}
$K_L^0 \to \pi^0 a$	$(4-20)\times10^{-15}$	1×10^{-10}

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Phenomenology of different searches

Meson-to-meson decay

Charged Mesonic decays amplitudes

[AWMG Rigolin, 2211.08343]

Penguins

$$R_{\mathrm{T/L}} = \left|\frac{\mathcal{M}_{\mathrm{T}}^{(s,t)}}{\mathcal{M}_{\mathrm{L}}}\right| \approx 2\pi^2 \frac{f_I f_F}{m_q^2} \left|\frac{V_{\mathrm{T}}^{\mathrm{CKM}}}{V_{\mathrm{L}}^{\mathrm{CKM}}}\right|$$

Channel	Tree–Level	Penguin
$B_c^\pm \to D_s^\pm a$	$(6-160)\times 10^{-11}$	2×10^{-6}
$B_c^\pm \to D^\pm a$	$(1-30)\times 10^{-11}$	3×10^{-7}
$B_c^\pm \to K^{*\pm} a$	$(2-70)\times 10^{-11}$	n.a.
$B_c^\pm \to \rho^\pm a$	$(4-100)\times 10^{-11}$	n.a.
$B_c^\pm \to K^\pm a$	$(8-230)\times 10^{-12}$	n.a.
$B_c^\pm \to \pi^\pm a$	$(3-85)\times 10^{-11}$	n.a.
$B^\pm \to D_s^\pm a$	$(5-30)\times 10^{-12}$	n.a.
$B^\pm \to D^\pm a$	$(1-7)\times 10^{-12}$	n.a.
$B^\pm \to K^{*\pm} a$	$(1-7)\times 10^{-12}$	4×10^{-6}
$B^\pm \to \rho^\pm a$	$(3-20)\times 10^{-12}$	4×10^{-7}
$B^\pm \to K^\pm a$	$(8-50)\times 10^{-13}$	2×10^{-6}
$B^\pm \to \pi^\pm a$	$(3-20)\times 10^{-12}$	3×10^{-7}
$D_s^\pm \to K^{*\pm} a$	$(1-60)\times 10^{-11}$	6×10^{-12}
$D_s^\pm \to \rho^\pm a$	$(3-170)\times 10^{-11}$	n.a.
$D_s^\pm \to K^\pm a$	$(6-300)\times 10^{-12}$	7×10^{-12}
$D_s^\pm \to \pi^\pm a$	$(2-120)\times 10^{-11}$	n.a.
$D^\pm \to K^{*\pm} a$	$(2-100)\times 10^{-12}$	n.a.
$D^\pm \to \rho^\pm a$	$(7-290)\times 10^{-12}$	3×10^{-12}
$D^\pm \to K^\pm a$	$(1-50)\times 10^{-12}$	n.a.
$D^\pm \to \pi^\pm a$	$(5-200)\times 10^{-12}$	6×10^{-12}
$K^{*\pm} \to K^\pm a$	$(5-25)\times 10^{-13}$	4×10^{-8}
$K^{*\pm} \to \pi^\pm a$	$(3-20)\times 10^{-12}$	3×10^{-9}
$\rho^\pm \to K^\pm a$	$(8-25)\times 10^{-12}$	2×10^{-9}
$\rho^\pm \to \pi^\pm a$	$(3-9)\times 10^{-11}$	4×10^{-10}
$K^\pm \to \pi^\pm a$	$(2-10)\times 10^{-12}$	5×10^{-10}

Phenomenology of different searches

Meson-to-meson decay

Neutral Mesonic decays amplitudes

[AWMG Rigolin, 2211.08343]

Tree level $t-$channel

$$|\mathcal{C}_{\rm I}^{(t)}| \approx \frac{G_F V_{\rm CKM} f_I f_F}{4 f_a} M_I^2 (c_Q - c_q)$$

$$|\mathcal{D}_{\rm I}^{(t)}| \approx \frac{G_F V_{\rm CKM} f_I f_F M_I^2}{4 f_a} \sqrt{(c_Q - c_q)^2 + 4\frac{M_F^2}{M_I^2}(c_Q^2 + c_q^2)}$$

Channel	Tree–Level	Penguins
$B_s^0 \to D_s^0 a$	n.a.	4×10^{-7}
$B_s^0 \to D^0 a$	$(7-70) \times 10^{-12}$	n.a.
$B_s^0 \to K^{*0} a$	n.a.	4×10^{-6}
$B_s^0 \to \rho^0 a$	$(4-50) \times 10^{-13}$	n.a.
$B_s^0 \to K_L^0 a$	n.a.	3×10^{-7}
$B^0 \to K^{*0} a$	n.a.	4×10^{-6}
$B^0 \to D^0 a$	$(3-30) \times 10^{-11}$	n.a.
$B^0 \to \rho^0 a$	$(2-20) \times 10^{-12}$	6×10^{-7}
$B^0 \to K_L^0 a$	n.a.	4×10^{-6}
$B^0 \to \pi^0 a$	$(1-10) \times 10^{-12}$	5×10^{-7}
$D^0 \to K^{*0} a$	$(7-300) \times 10^{-12}$	n.a.
$D^0 \to \rho^0 a$	$(5-200) \times 10^{-12}$	4×10^{-12}
$D^0 \to K_L^0 a$	$(7-270) \times 10^{-13}$	n.a.
$D^0 \to \pi^0 a$	$(2-100) \times 10^{-12}$	3×10^{-12}
$K^{*0} \to K^0 a$	$(2-6) \times 10^{-12}$	3×10^{-9}
$K^{*0} \to \pi^0 a$	$(1-2) \times 10^{-11}$	3×10^{-9}
$\rho^0 \to K^0 a$	$(1-3) \times 10^{-11}$	2×10^{-9}
$\rho^0 \to \pi^0 a$	$(2-7) \times 10^{-11}$	3×10^{-9}
$K_L^0 \to \pi^0 a$	$(4-20) \times 10^{-15}$	1×10^{-10}

ALP production in weak mesonic decays

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Phenomenology of different searches

Leptonic decay of mesons

Three body Leptonic decay amplitude

Channel	f_a [GeV] up-quark		f_a [GeV] down-quark		f_a [GeV] lepton	
	$m_a = 0$	$m_a = M_M/2$	$m_a = 0$	$m_a = M_M/2$	$m_a = 0$	$m_a = M_M/2$
$B^\pm \to e^\pm \bar{\nu}_e$	2.8	0.079	4	1.3	0.0005	0.00013
$B^\pm \to \mu^\pm \bar{\nu}_\mu$	6	0.16	8.3	2.7	0.2	0.06
$B^\pm \to \tau^\pm \bar{\nu}_\tau$	0.38	0.006	0.5	0.065	0.2	0.05
$D^\pm \to e^\pm \bar{\nu}_e$	6	2.1	5.7	0.86	0.02	0.00053
$D^\pm \to \mu^\pm \bar{\nu}_\mu$	4	1.3	3.7	0.56	0.27	0.070
$D^\pm \to \tau^\pm \bar{\nu}_\tau$	0.007		0.007		0.006	
$D_s^\pm \to e^\pm \bar{\nu}_e$	8	3	8.2	1.9	0.002	0.00066
$D_s^\pm \to \mu^\pm \bar{\nu}_\mu$	5.5	2	5.7	1.3	0.3	0.09
$D_s^\pm \to \tau^\pm \bar{\nu}_\tau$	0.02		0.01		0.02	
$K^\pm \to e^\pm \bar{\nu}_e$	249.	87	170	10	0.243	0.06
$K^\pm \to \mu^\pm \bar{\nu}_\mu$	1.7	0.5	1.2	0.05	0.32	0.06

Table from [Gallo AWMG Penaranda Rigolin, 2021]

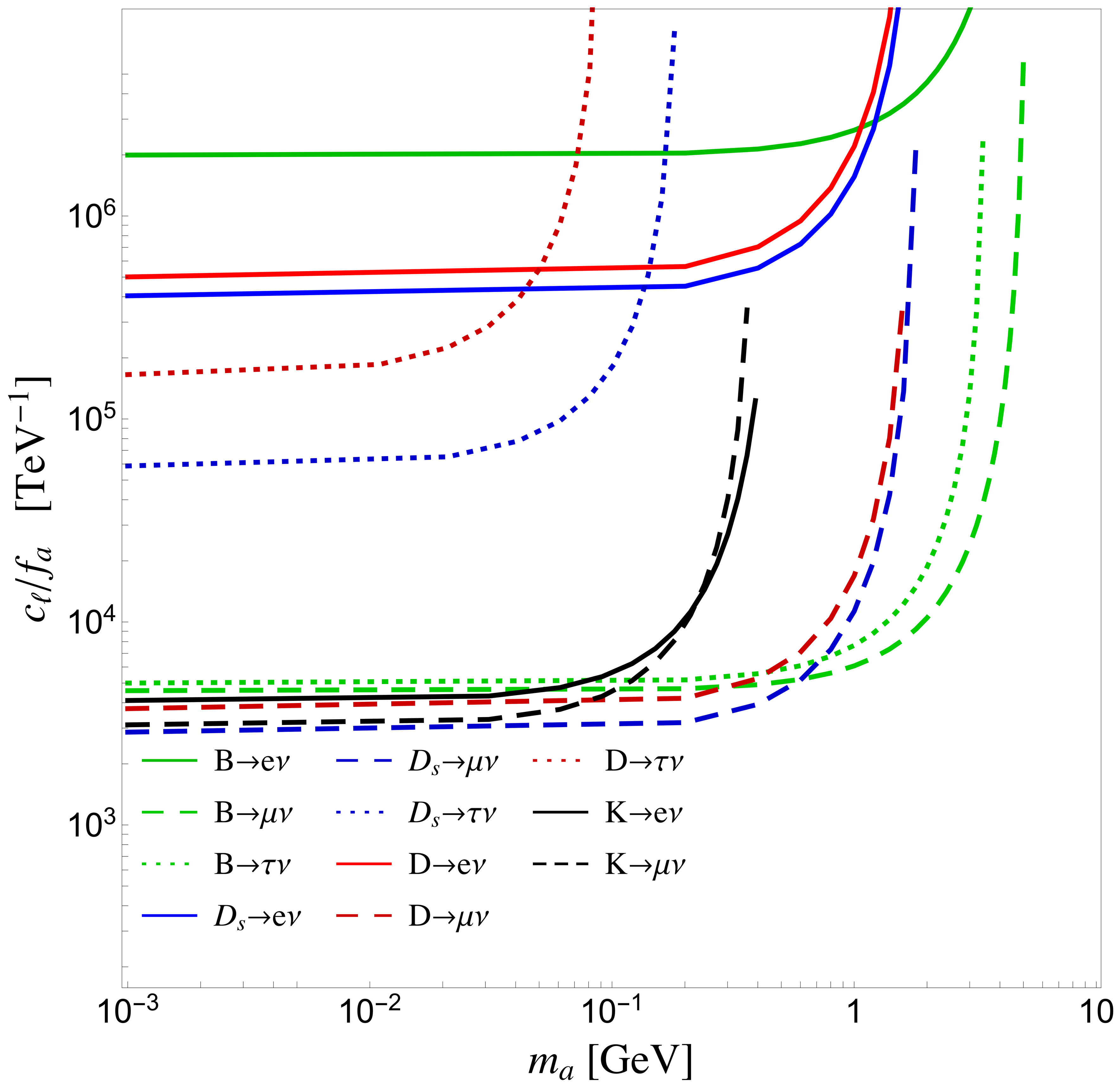
Massless ALP limit

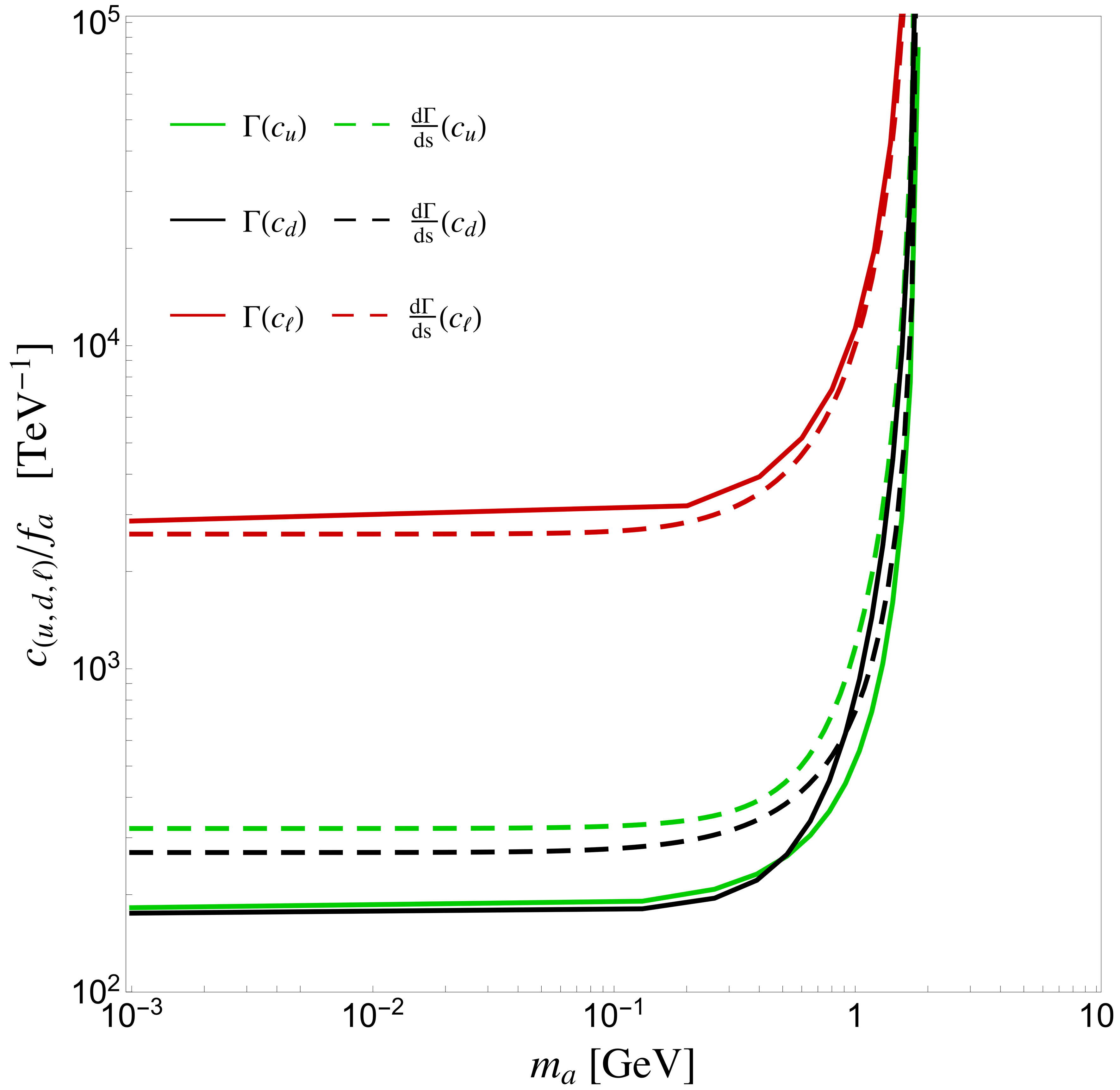
$$\mathcal{E}_h \approx \frac{i G_F V_{\mathrm{CKM}} f_M M_M^2}{\sqrt{2} f_a (k \cdot P_M)} \left(\bar{\ell} \not{k} \, P_L \, \nu_\ell \right) (c_q - c_Q)$$

Phenomenology of different searches

Semileptonic decay

$M \to \ell \bar{\nu}_\ell a$ three body decay





Limits on ALP-leptons couplings

$D_s \to \mu\, \nu_\mu\, a$ with BR and M_M^2 distribution

[Gallo AWMG Penaranda Rigolin, 2021]

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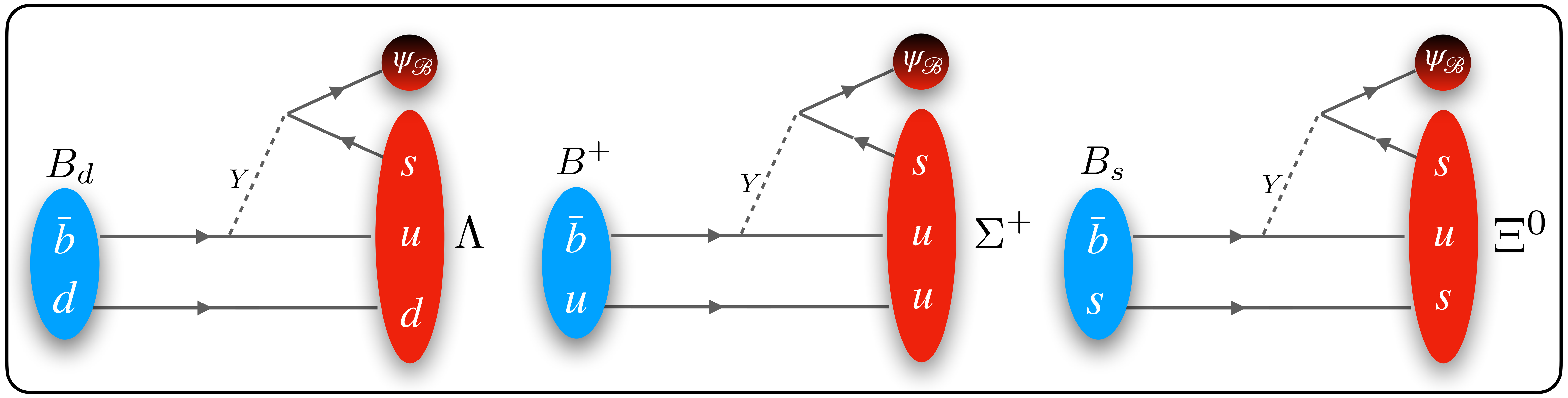
LCSR & Mesogenesis

Introduction

B Meson Decays to SM Baryons and Dark Baryon



$\mathrm{Br}(B \to \mathcal{B}_{\mathrm{SM}} + \psi_{\mathcal{B}})$ challenging calculation

Correlation function $\int d^4x e^{i(P+q)\cdot x} \langle 0 | \mathrm{T}\{j_B(x), \mathcal{O}_{d_i u_k d_j}\} | \mathcal{B}_{\mathrm{SM}} \rangle$

Dispersion Relation

$$\Pi_I((P+q)^2, q^2) \supset \int ds \frac{\rho_I(s, q^2)}{s - (P+q)^2}$$

OPE

$$\Pi_I^{\mathrm{OPE}}((P+q)^2, q^2) = \frac{1}{\pi} \int ds \frac{\mathrm{Im}\{\Pi_I^{\mathrm{OPE}}(s, q^2)\}}{s - (P+q)^2}$$

LCSR & Mesogenesis

Introduction

How to generate a matter/antimatter asymmetry

$$\boxed{Y_B^{obs} \equiv \frac{n_B - n_{\bar{B}}}{s} \sim 8 \times 10^{-11} \quad \text{(CMB, BBN)}}$$

Image: Stolen from the Internet

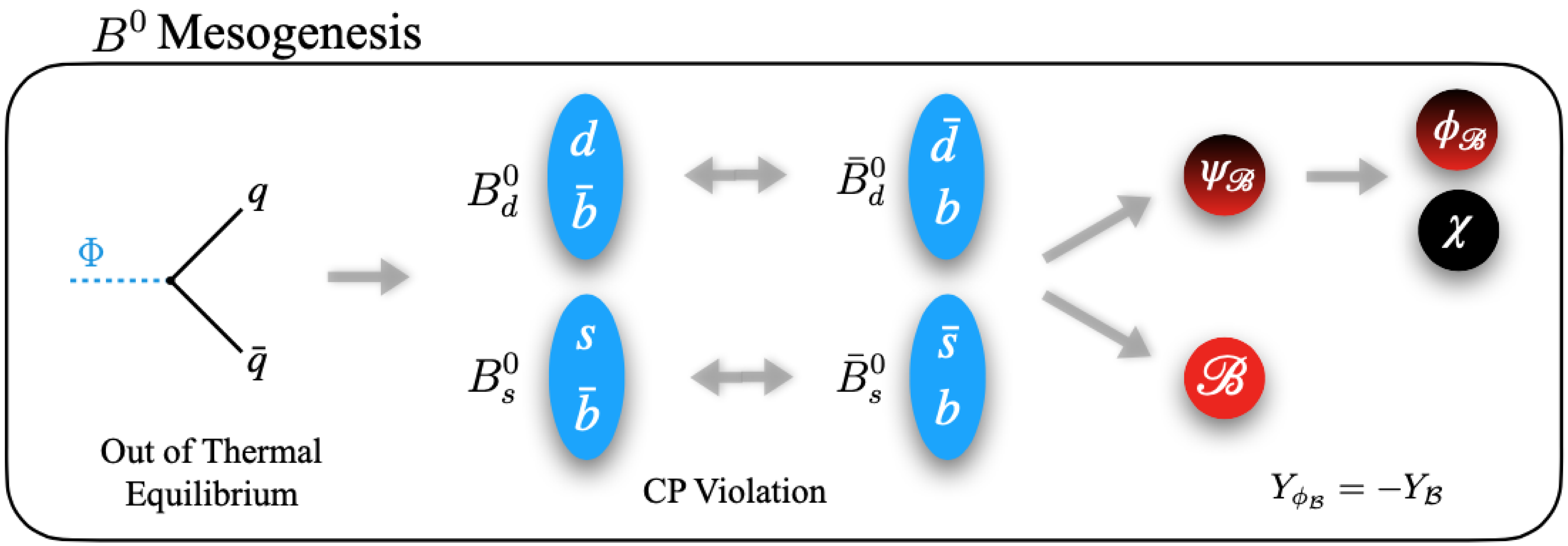
The Sakharov conditions (1967):

- Out of thermal equilibrium: Late decays of "inflaton" field to SM Mesons.
- CP Violation: In SM Meson systems.
- "Baryon number violation": SM Meson decays to dark leptons or baryons.

G. Elor

LCSR & Mesogenesis

Introduction



GE, M. Escudero, A. E. Nelson, PRD, [1810.00880]
G. Alonso-Alvarez, GE, A. E. Nelson, H. Xiao, JHEP, [1907.10612]
GE, R. McGehee, PRD [2011.06115]
G. Alonso-Alvarez, GE. M. Escudero, PRD, [2101.02706]
F. Elahi, GE, R. McGehee, [2109.09751]
G. Alonso-Alvarez, GE, M. Escudero, B. Fornal, B. Grinstein, J.M. Camalich [arXiv:2111.12712]

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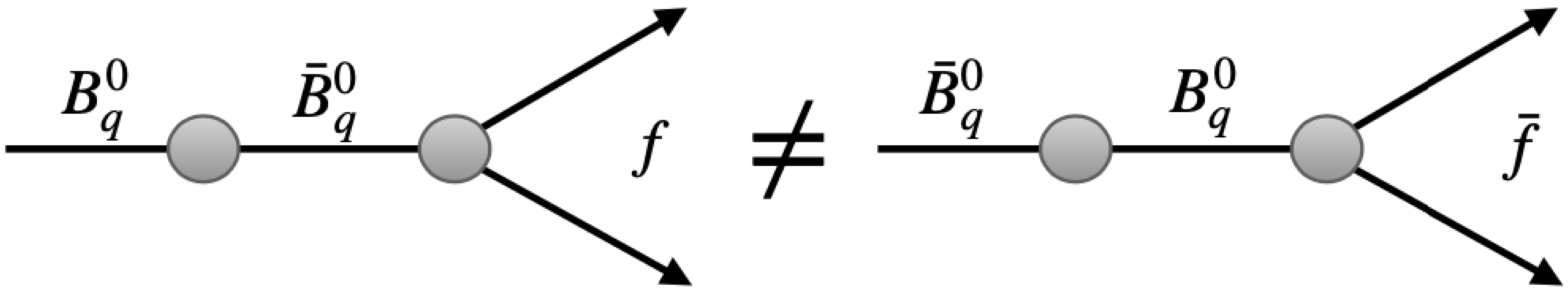
LCSR & Mesogenesis

Introduction

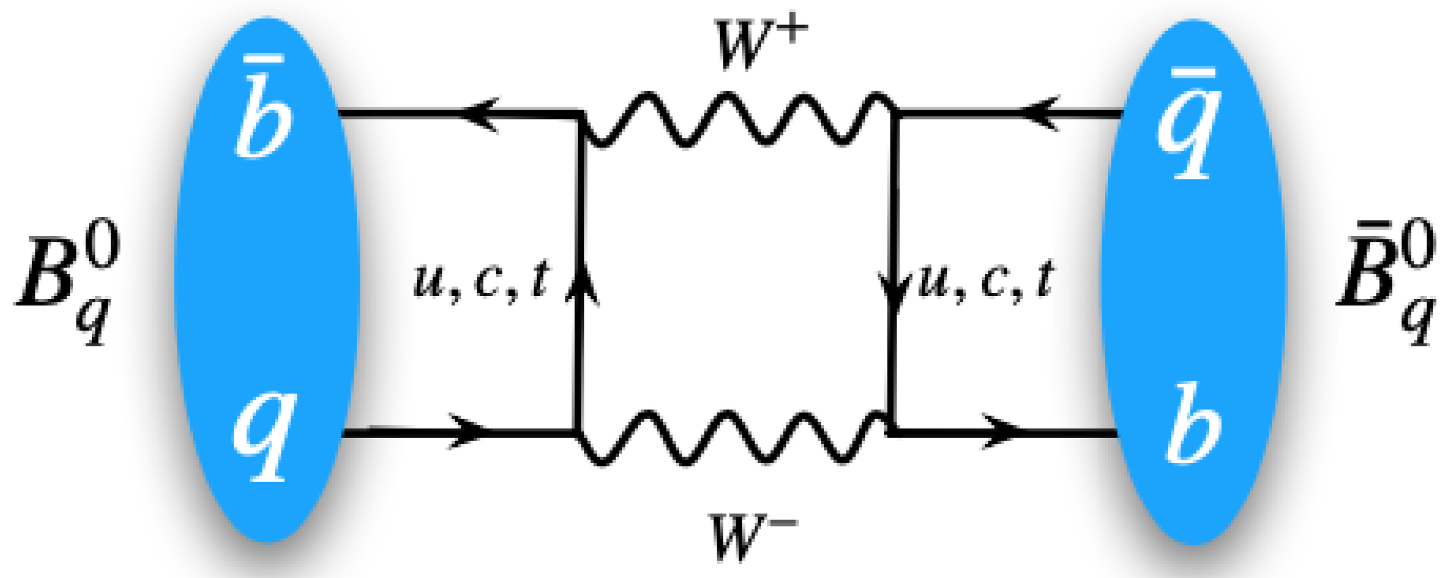
B meson/anti-meson mixing has sizable CP violation



Experimental Observable:

$$A_{\rm SL}^q = \frac{\Gamma\left(\bar{B}_q^0 \to B_q^0 \to f\right) - \Gamma\left(B_q^0 \to \bar{B}_q^0 \to \bar{f}\right)}{\Gamma\left(\bar{B}_q^0 \to B_q^0 \to f\right) + \Gamma\left(B_q^0 \to \bar{B}_q^0 \to \bar{f}\right)}$$

e.g. in Standard Model



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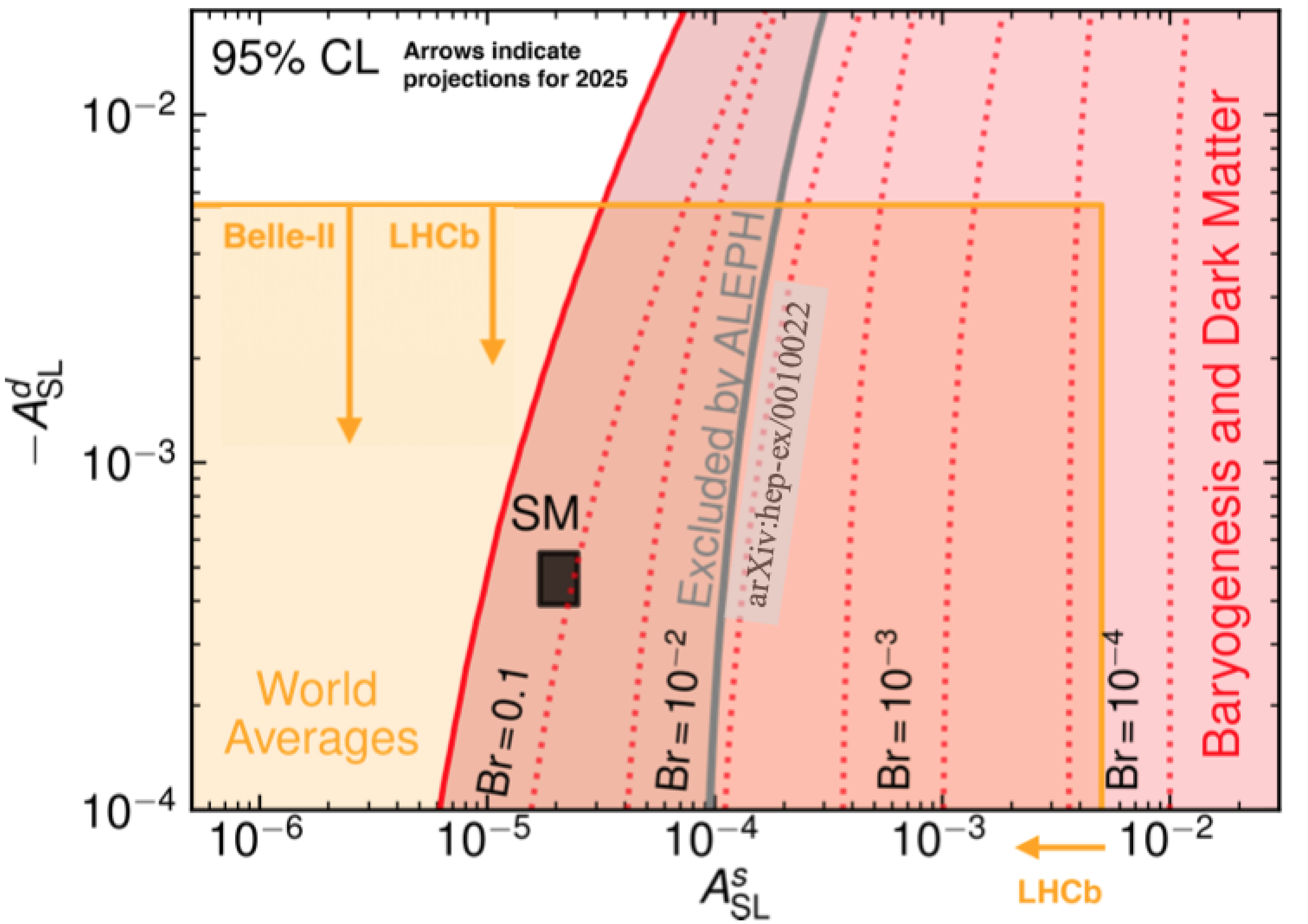
The Semi-Leptonic Asymmetry



$\lesssim 10^{-3}$

$$Y_{\mathcal{B}} \simeq 8.7 \times 10^{-11} \frac{\mathrm{Br}\,(B \to \psi \mathcal{B} \mathcal{M})}{10^{-2}} \sum_{q=s,d} \alpha_q \frac{A^q_{\mathrm{SL}}}{10^{-4}}$$

for baryogenesis

$$\mathrm{Br}(B \to \psi\, \mathcal{B}\, \mathcal{M}) \gtrsim 10^{-4}$$

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