ADRIAN CARMONA BERMUDEZ

ALPS AND FLAVOR

MITP PROGRAM - Flavor at the Crossroads

athenea 3i

OFPI Oficina de Proyectos Internacionales

UNIVERSIDAD DE GRANADA

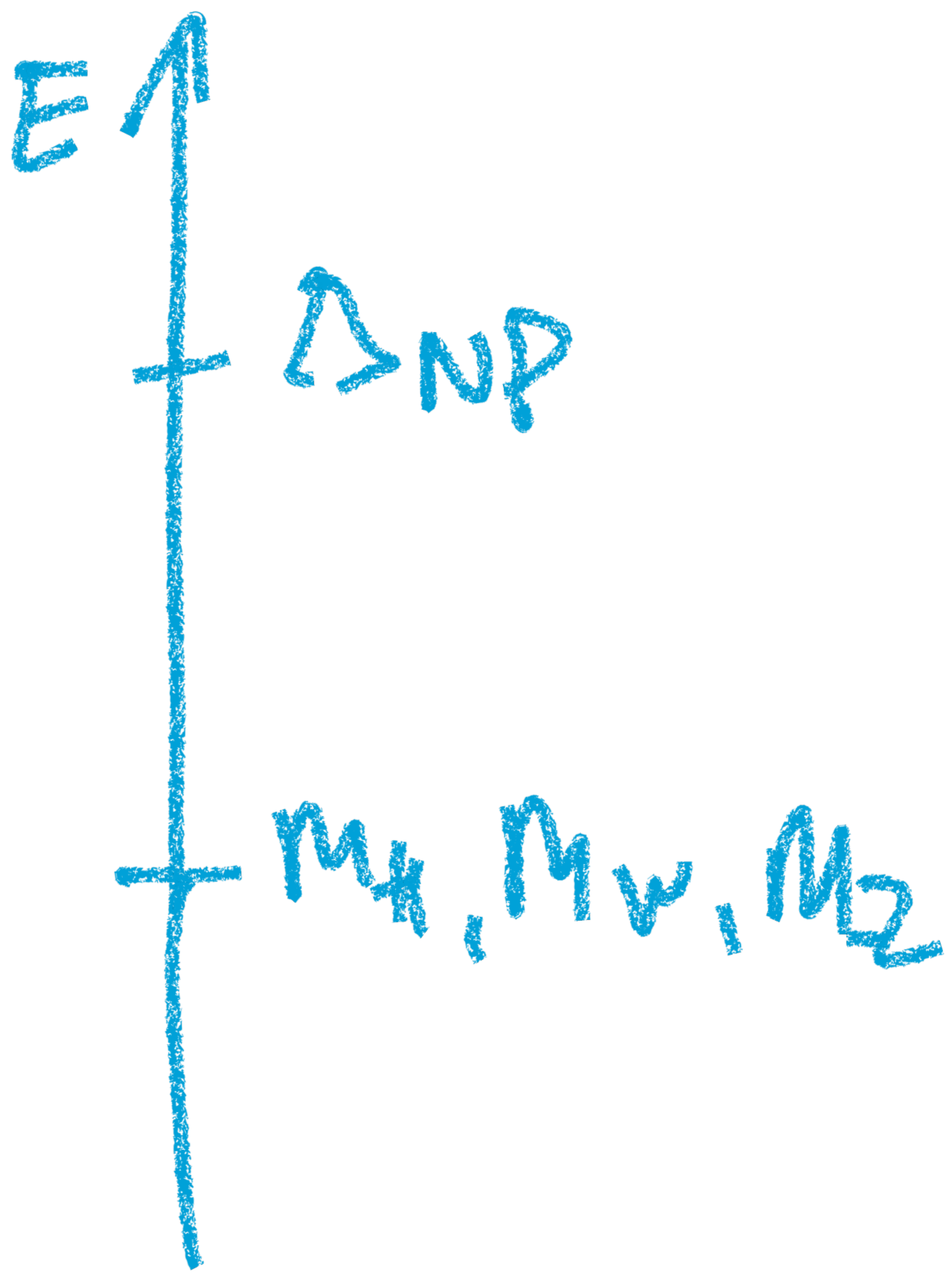
BASED ON

- ‘Charming ALPs’ AC, Scherb, Schwaller. JHEP 08 (2021) 121, arXiv: 2101.0783

- ‘The ALPs from the Top: Searching for long-lived axion-like particles from exotic top decays’ AC, Elahi, Scherb, Schwaller. arXiv: 2202.0973

INTRODUCTION

NATURALLY LIGHT SCALARS



The scale of new physics seems to be rather heavy

A natural way of obtaining light scalar degrees of freedom is through the Goldstone theorem

$$G \xrightarrow{\Lambda_{NP}} H \qquad \pi^i \in \mathrm{Alg}\{G/H\}$$

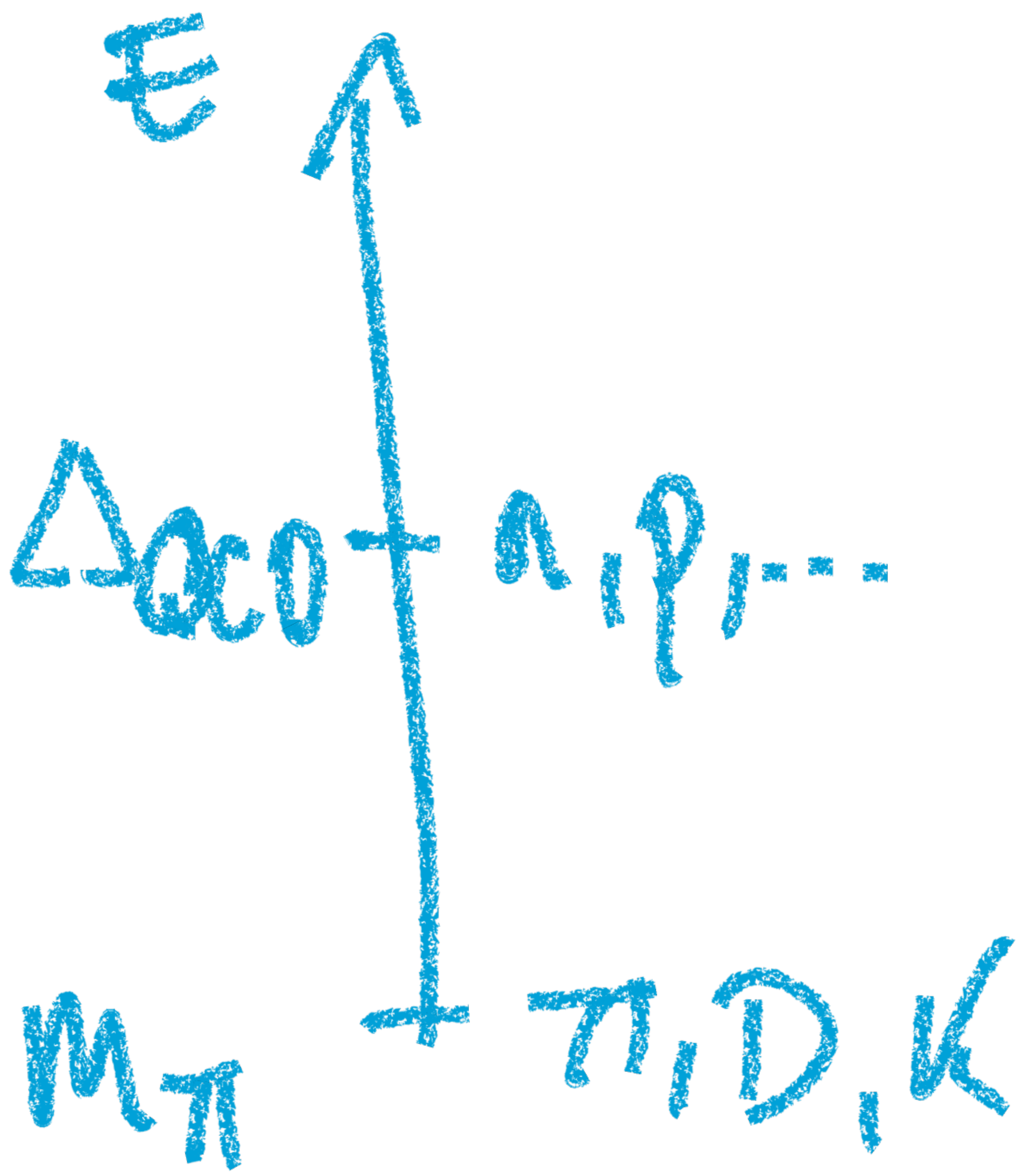
$$m_{\pi^i} \ll \Lambda_{NP}$$

NATURALLY LIGHT SCALARS

QCD gives us a beautiful example

$$SU(2)_L \times SU(2)_R \longrightarrow SU(2)_V$$

$$m_\pi \ll \Lambda_{QCD}$$



ALPS

Axion-like particles (ALPs) are pseudo-Nambu-Goldstone bosons (pNGBs) of a spontaneously broken global symmetry

One typically assumes that CP is a good symmetry and that the ALP is CP-odd

E

Δ_{NP} — New heavy stuff

m_a — ALP a

$a \to a + \theta$

ALP shift symmetry

ALP + SM EFT

ALP EFT above the electroweak scale

$\psi = q_L, l_L, u_R, d_R, e_R$

$$\mathscr{L} = \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{m_a^2}{2}a^2 + \frac{\partial_\mu a}{f_a}\sum_\psi \left(c_\psi\right)_{ij} \bar{\psi}_i \gamma^\mu \psi_j$$
$$-\frac{a}{f_a}\left[c_{GG}\frac{g_3^2}{32\pi^2}G^a_{\mu\nu}\tilde{G}^{a\,\mu\nu} + c_{WW}\frac{g_2^2}{32\pi^2}W^I_{\mu\nu}\tilde{W}^{I\,\mu\nu} + c_{BB}\frac{g_1^2}{32\pi^2}B_{\mu\nu}\tilde{B}^{\mu\nu}\right]$$

FCNCs are generated via c_{WW} at one loop Gavela et al, 1901.02031

SOME EXAMPLES

A QCD-LIKE DARK SECTOR

A QCD-LIKE DARK SECTOR

Schwaller, Bai, '14

u, c, t

$\Lambda_{QCD} \downarrow$

$\pi, K, D, \ldots$

$Q^{\alpha}, Q^{\beta}, Q^{\gamma}$

$\downarrow \Lambda_{DQCD}$

$\pi_D^{(\alpha,\beta)}$

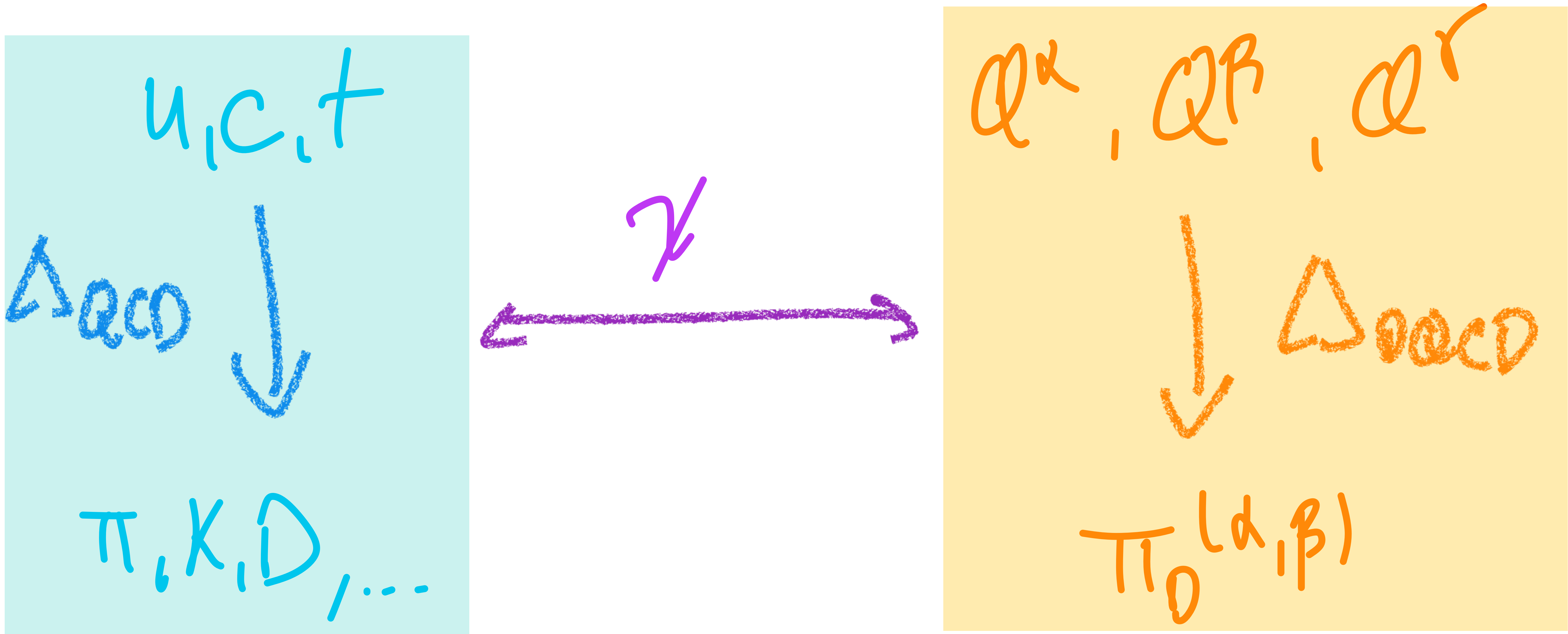
* $SU(N_D)$ gauge group
* n_f Dirac fermions
* $m_Q \ll \Lambda_{DQCD}$
* $SU(n_f) \otimes SU(n_f)$

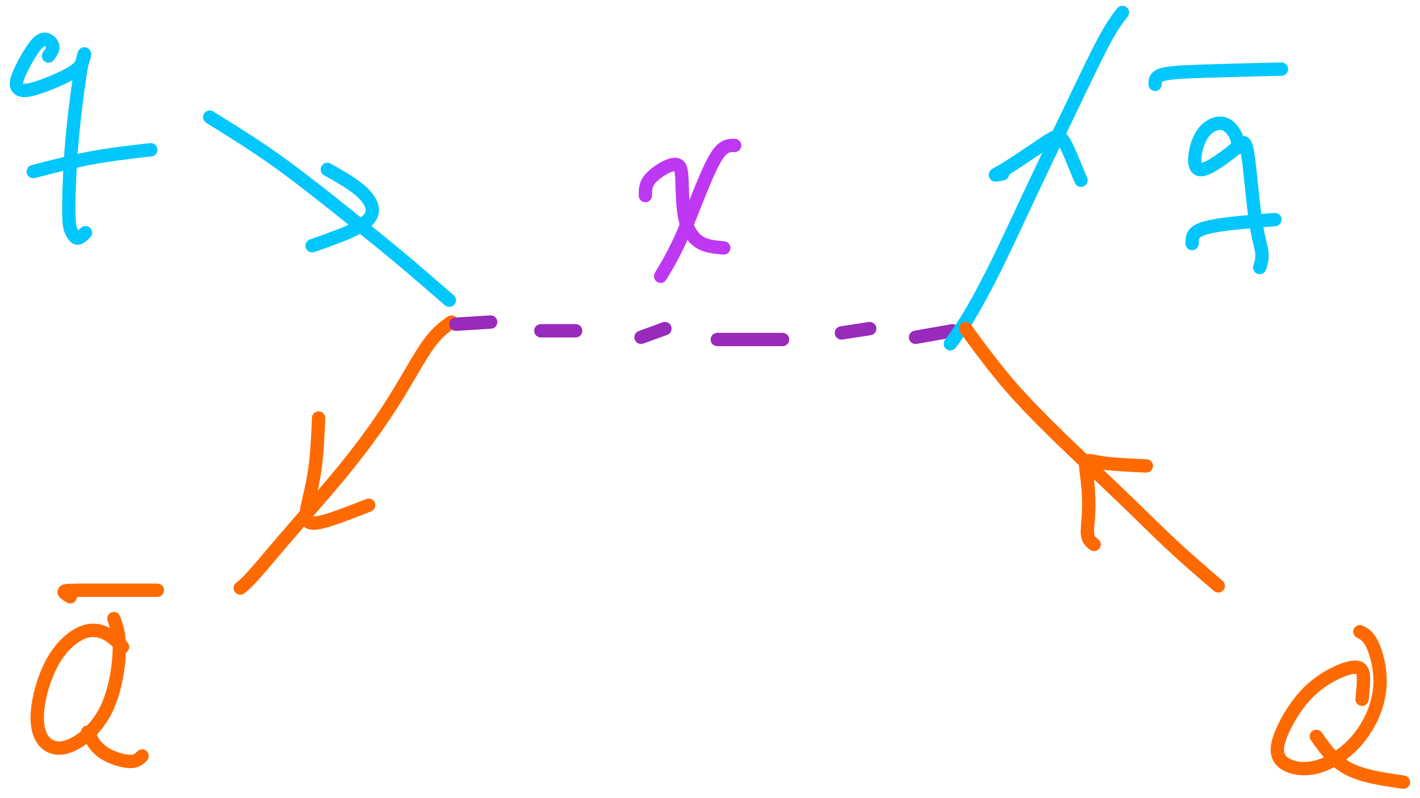
$\downarrow$

$SU(n_f)$

A QCD-LIKE DARK SECTOR

Schwaller, Bai, ‘14

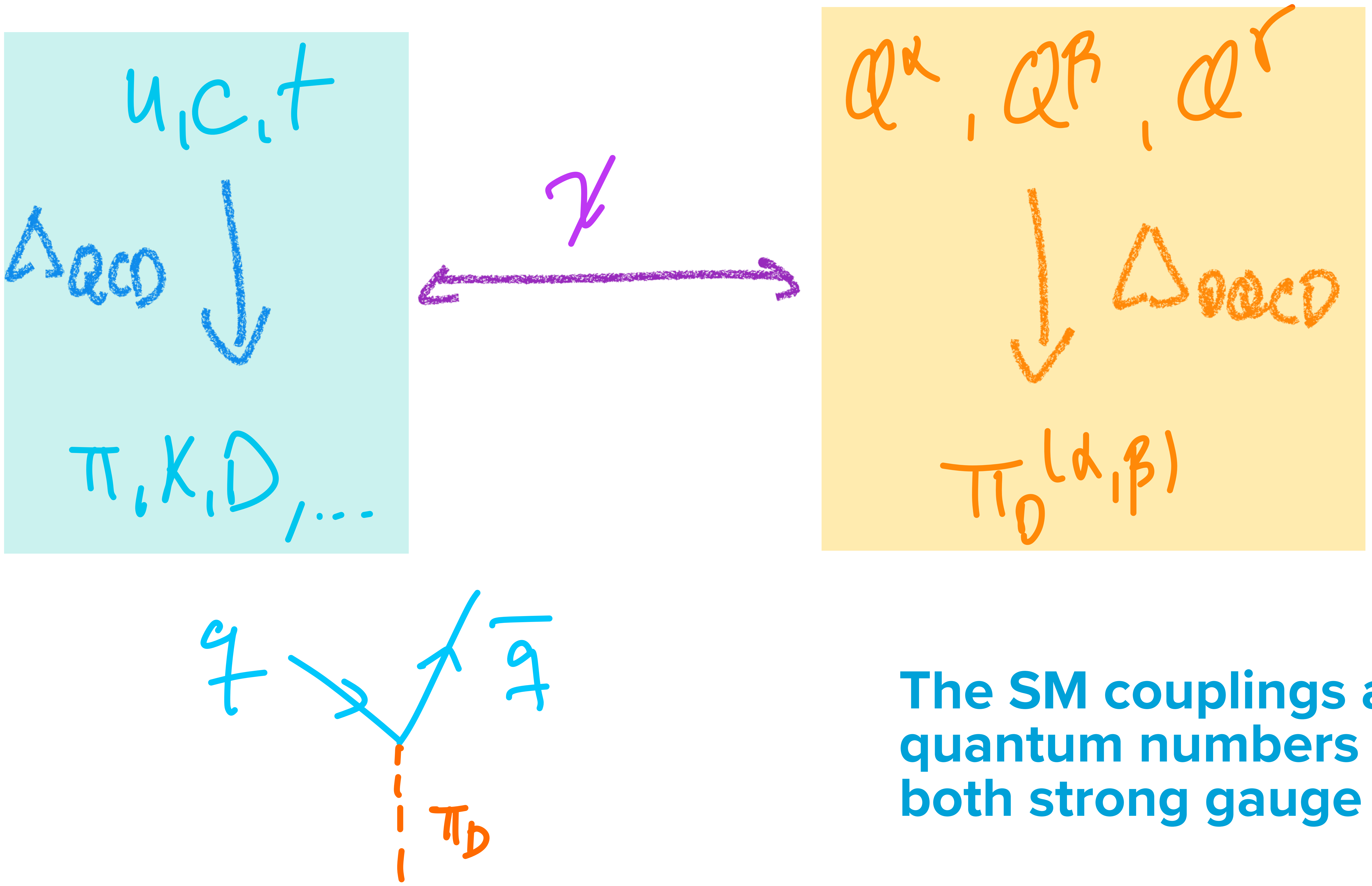




The SM couplings are fixed by the quantum numbers of χ, bifundamental of both strong gauge groups

A QCD-LIKE DARK SECTOR

Schwaller, Bai, '14



The SM couplings are fixed by the quantum numbers of χ, bifundamental of both strong gauge groups

A QCD-LIKE DARK SECTOR

Schwaller, Bai, '14

When $m_Q \to 0,\ m_\chi \to \infty,\ SU(3)_{DL} \otimes SU(3)_{RD} \to SU(3)_{DV}$ by $\langle \bar{Q}_\alpha Q_\beta \rangle \sim \delta_{\alpha\beta} \Lambda^3_{DQCD}$ delivering 8 pNGB

Dark Pions	Dark Quark content
$\pi_D^{(1,2)}$	$\bar{Q}_2 Q_1$
$\pi_D^{(1,3)}$	$\bar{Q}_3 Q_1$
$\pi_D^{(2,3)}$	$\bar{Q}_3 Q_2$
π_{D3}	$1/\sqrt{2}\,[\bar{Q}_1 Q_1 - \bar{Q}_2 Q_2]$
π_{D8}	$1/\sqrt{6}\,[\bar{Q}_1 Q_1 + \bar{Q}_2 Q_2 - 2\bar{Q}_3 Q_3]$

A QCD-LIKE DARK SECTOR

Schwaller, Bai, '14

Depending of the quantum numbers of the heavy scalar we can have different low energy EFTs

$$SU(3)_c \times SU(3)_D \times SU(2)_L \times U(1)_Y$$

$$\chi \sim (3, \bar{3}, 1, 1/3) \qquad \mathcal{L}_{int} \supset -\kappa_{\alpha i} \bar{d}_{Ri} Q_{L\alpha} \chi + h.c$$

Schwaller, Renner '18

$$\chi \sim (3, \bar{3}, 1, -2/3) \qquad \mathcal{L}_{int} \supset -\kappa_{\alpha i} \bar{u}_{Ri} Q_{L\alpha} \chi + h.c$$

AC, Scherb, Schwaller '21

A QCD-LIKE DARK SECTOR

Schwaller, Bai, '14

Depending of the quantum numbers of the heavy scalar we can have different low energy EFTs

$$SU(3)_c \times SU(3)_D \times SU(2)_L \times U(1)_Y$$

$$\chi \sim (3, \bar{3}, 1, 1/3) \qquad \mathcal{L}_{eff} \supset \frac{f_D^2}{m_\chi^2} \kappa_{\alpha i} \kappa^*_{\beta j} \partial_\mu \pi_D^{(\alpha,\beta)} \bar{d}_{Ri} \gamma^\mu d_{Rj}$$

Schwaller, Renner '18

$$\chi \sim (3, \bar{3}, 1, -2/3) \qquad \mathcal{L}_{eff} \supset \frac{f_D^2}{m_\chi^2} \kappa_{\alpha i} \kappa^*_{\beta j} \partial_\mu \pi_D^{(\alpha,\beta)} \bar{u}_{Ri} \gamma^\mu u_{Rj}$$

AC, Scherb, Schwaller '21

FLAVONS

FLAVONS

Feng et al. '98

pNGBs of horizontal symmetries

$$\mathscr{L} = \frac{1}{f_a}\partial_\mu a^\alpha J^{\mu\alpha} = \frac{1}{f_a}\partial_\mu a^\alpha \bar{\psi}_i \gamma^\mu [f_L P_L + g_R P_R] T^\alpha_{ij} \psi_j$$

Consider e.g. a Froggatt-Nielsen (FN) model with charges

	S	H	q_L^i	d_R^i	u_R	c_R	t_R
$U(1)$	-1	0	0	0	2	1	0

Δ

f_a

$$S = \frac{1}{\sqrt{2}}(f_a + s)e^{ia/f_a}$$

$$\mathscr{L}_{eff} \supset -\lambda_u^{ij}\left(\frac{S}{\Delta}\right)^{n_j} \bar{q}_{Li} \tilde{H} u_{Rj}$$

COMPOSITE HIGGS MODELS

COMPOSITE HIGGS MODELS

See e.g. 1610.06591, 1902.06890

- The Higgs could be the pNGB from a strongly interacting sector

e.g. $SO(5) \to SO(4) \supseteq SU(2)_L \otimes U(1)_Y$ $\qquad 2_{1/2}$

- However, more ‘realistic’ models (aka UV complete) will give you a bunch of extra dof

$SU(5)/SO(5) \qquad 3_1 + 3_0 + 2_{1/2} + 1_0$

$SU(4)/Sp(4) \qquad 2_{1/2} + 1_0$

$SO(4) \times SU(4)/SU(4) \qquad 3_0 + 2_{1/2} + 2'_{1/2} + 1_1 + 1_0 + 1_0$

COMPOSITE HIGGS MODELS

See e.g. 1610.06591, 1902.06890

- One typically expects

$$\mathscr{L} = \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{m_a^2}{2}a^2 + iC_t \frac{m_t}{f_a} a\bar{t}\gamma_5 t$$
$$-\frac{a}{f_a}\left[c_{GG}\frac{g_3^2}{32\pi^2}G^a_{\mu\nu}\tilde{G}^{a\,\mu\nu} + c_{WW}\frac{g_2^2}{32\pi^2}W^I_{\mu\nu}\tilde{W}^{I\,\mu\nu} + c_{BB}\frac{g_1^2}{32\pi^2}B_{\mu\nu}\tilde{B}^{\mu\nu}\right]$$

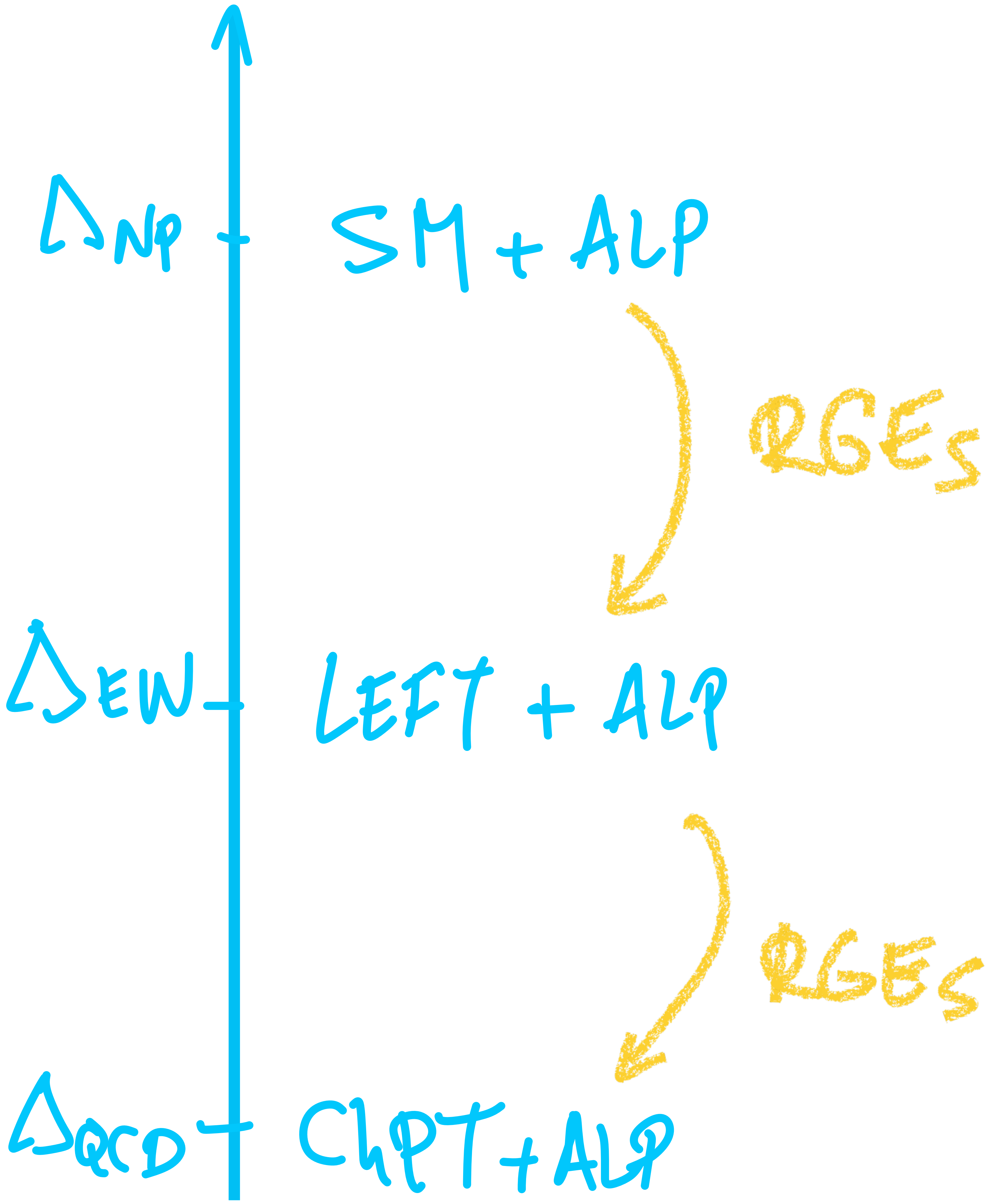
- RH quarks can be made composite more easily since they are custodially protected

- Partial compositeness comes with ‘top partners’

TAKE THE COUPLINGS AND RUN

ONE NEEDS TO RUN

Choi et al, 1708.00021
Chala et al, 2012.09017
Bauer et al, 2012.12272



Even if some Wilson coefficients are zero at the UV they will be generated via the RGEs. For instance

$$c_{q_L} = \frac{Y_u c_{u_R} Y_u}{32\pi^2} \ln\left(\frac{\Lambda_{NP}}{\mu^2}\right), \qquad c_H = \frac{3}{8\pi^2} \mathrm{Tr}\left(Y_u c_{u_R} Y_u\right) \ln\left(\frac{\Lambda_{NP}}{\mu^2}\right)$$

where

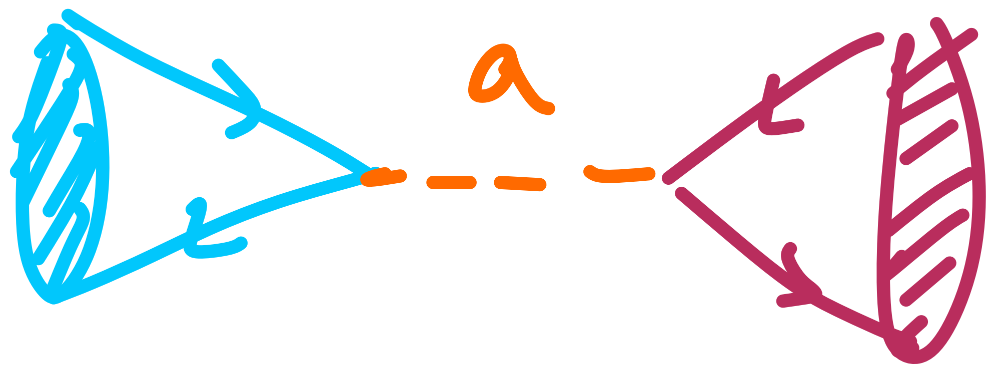
$$\left(\mathcal{O}_{q_L}\right)_{ij} = \frac{\partial_\mu a}{\Lambda_{NP}}\left(\bar{q}_{Li}\gamma^\mu q_{Lj}\right), \qquad \mathcal{O}_H = \frac{\partial_\mu a}{\Lambda_{NP}}\left(H^\dagger i \overleftrightarrow{D}^\mu H\right)$$

Top couplings will make a difference!

STANDARD FLAVOR PROBES

FLAVOR PROBES OF ALPS

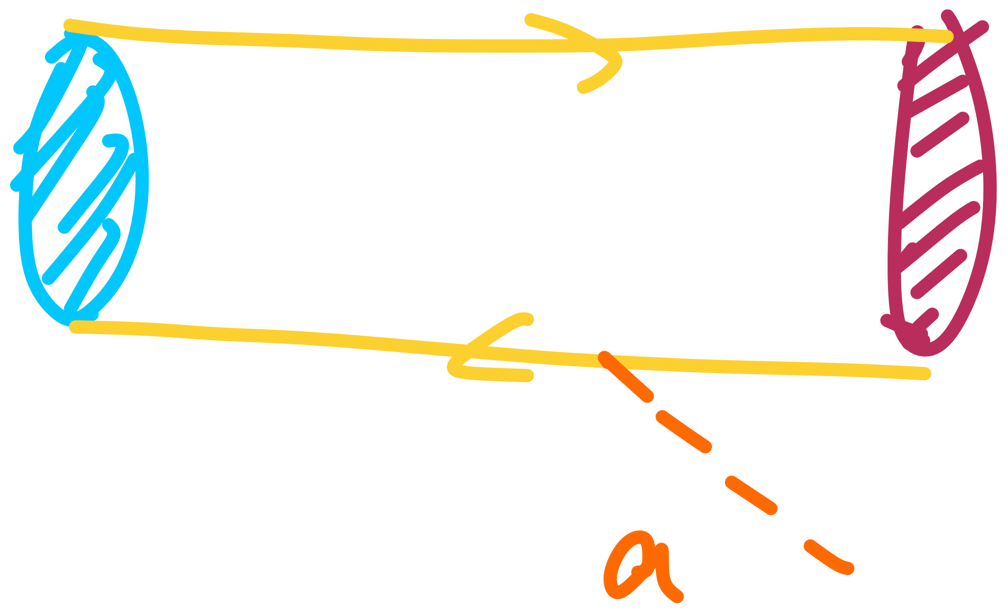
ΔF=2 Neutral meson mixing



B-$\bar{B}$ mixing / K-$\bar{K}$ mixing / D-$\bar{D}$ mixing

Depending on $m_a/m_{c,b}$ we might need to use OPE

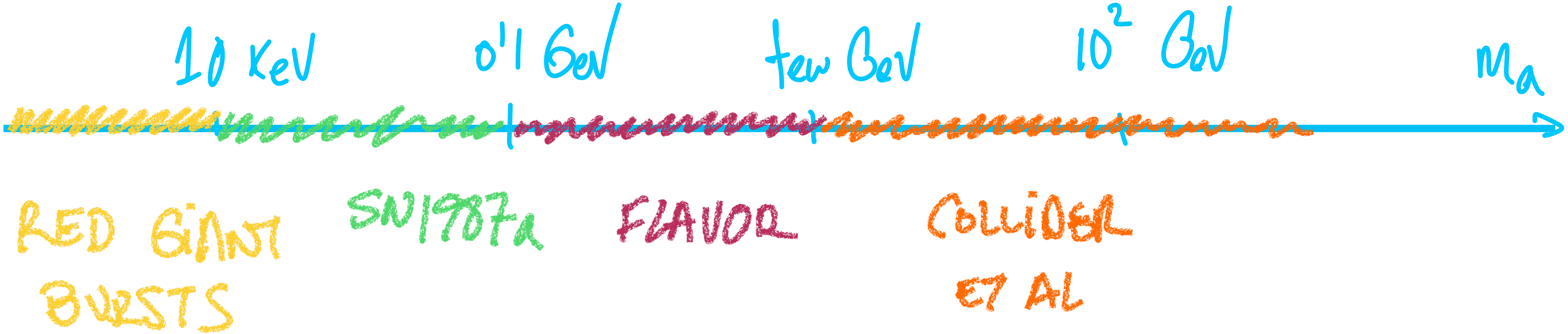
ΔF=1 Rare meson decay



$D \to \pi a$, $B \to K a$, $B \to \pi a$, $K \to \pi a$, ...

FLAVOR PROBES OF ALPS

Flavor probes will compete or be complemented by astrophysical or cosmological bounds as well as by collider or fixed target experiments



CHARMING ALPS

CHARMING ALPS

We assume the following EFT at the UV

$$\mathscr{L} = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_a^2}{2}a^2 + \frac{\partial_\mu a}{f_a}(c_{uR})_{ij}\left(\bar{u}_{Ri}\gamma^\mu u_{Rj}\right)$$

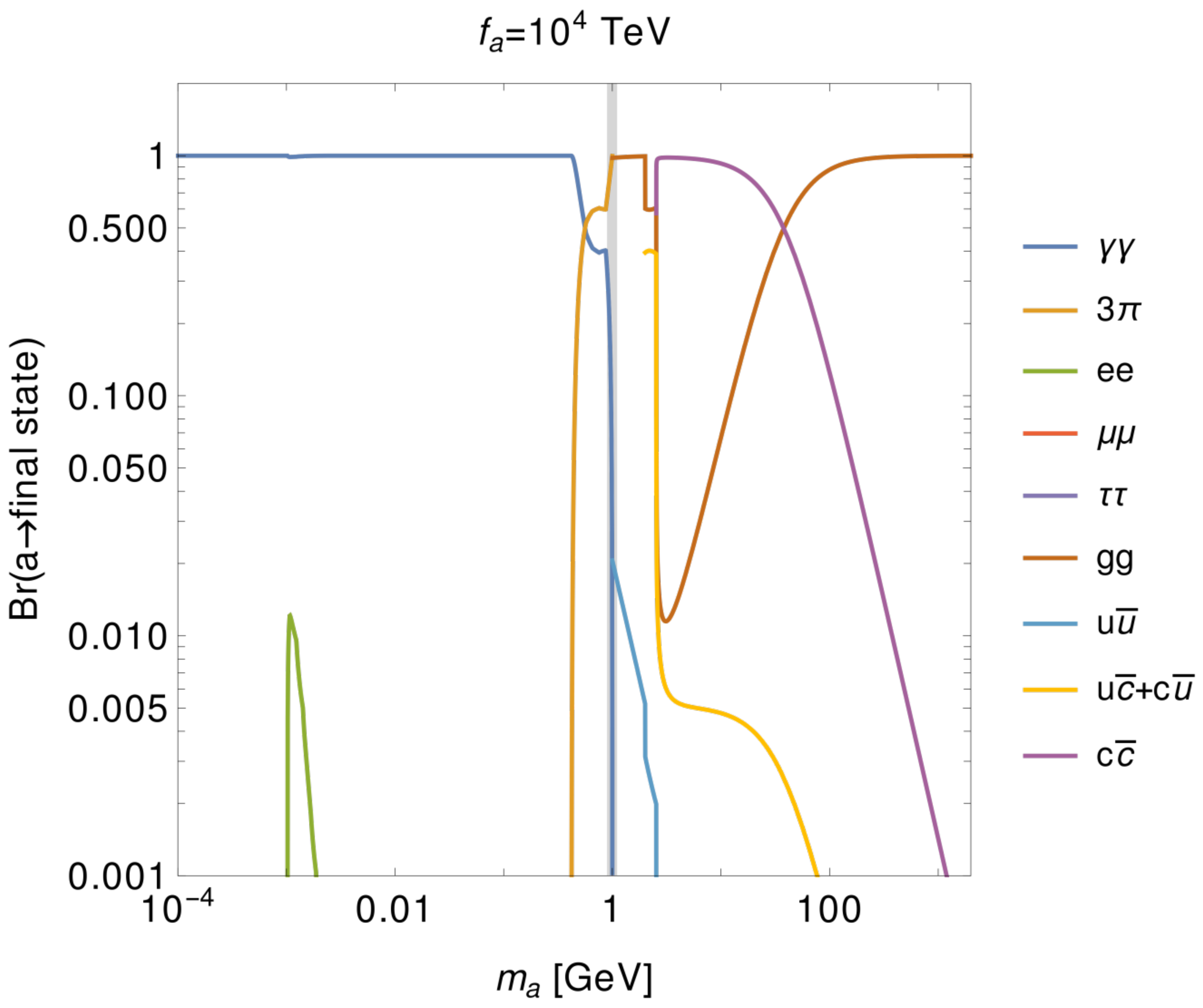
RGEs and heavy-quark loop induced processes will lead to

$$a \to \ell^+\ell^-,\ a \to \bar{d}_i d_j,\ a \to \gamma\gamma,\ a \to gg$$

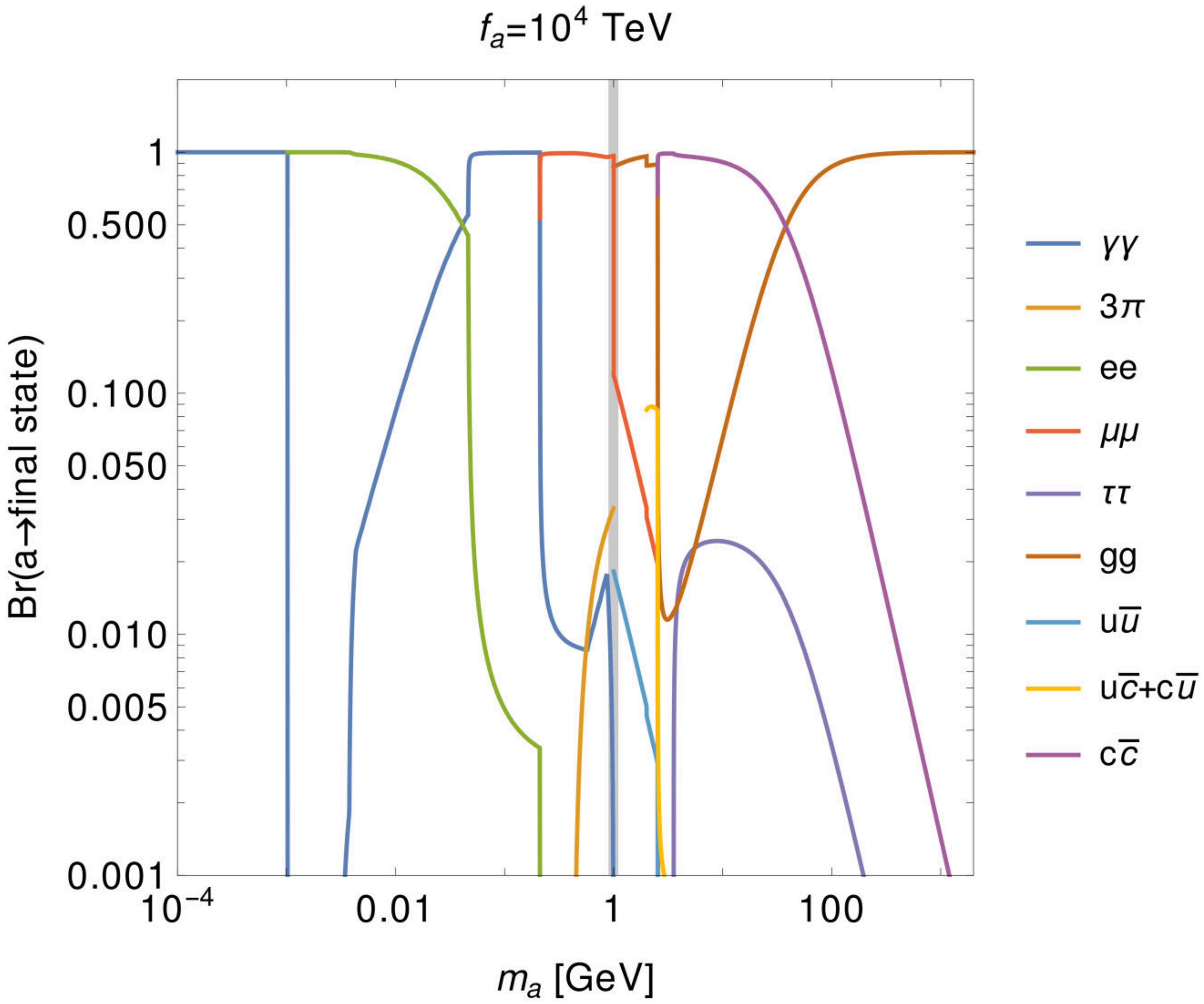
We consider several benchmarks motivated by the dark QCD model

$a = \pi_{D3},\ (c_{uR})_{33} = 0$ $\qquad$ $a = \pi_{D8},\ (c_{uR})_{33} \neq 0$

CHARMING ALPS

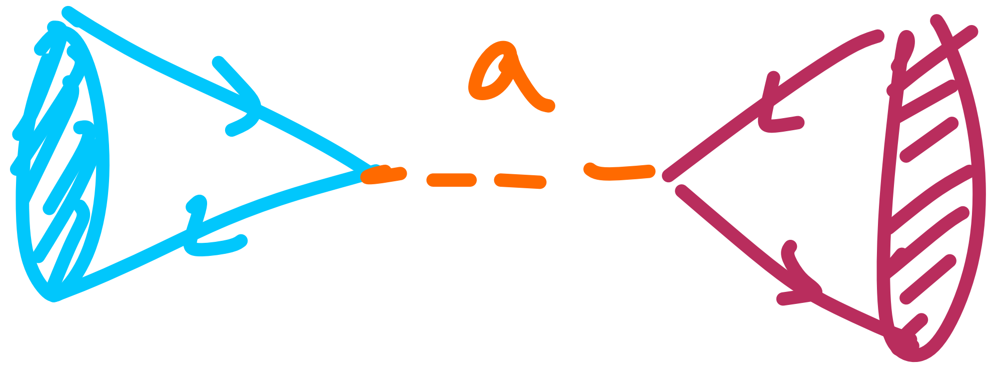


$$a = \pi_{D3},\ (c_{uR})_{33} = 0$$

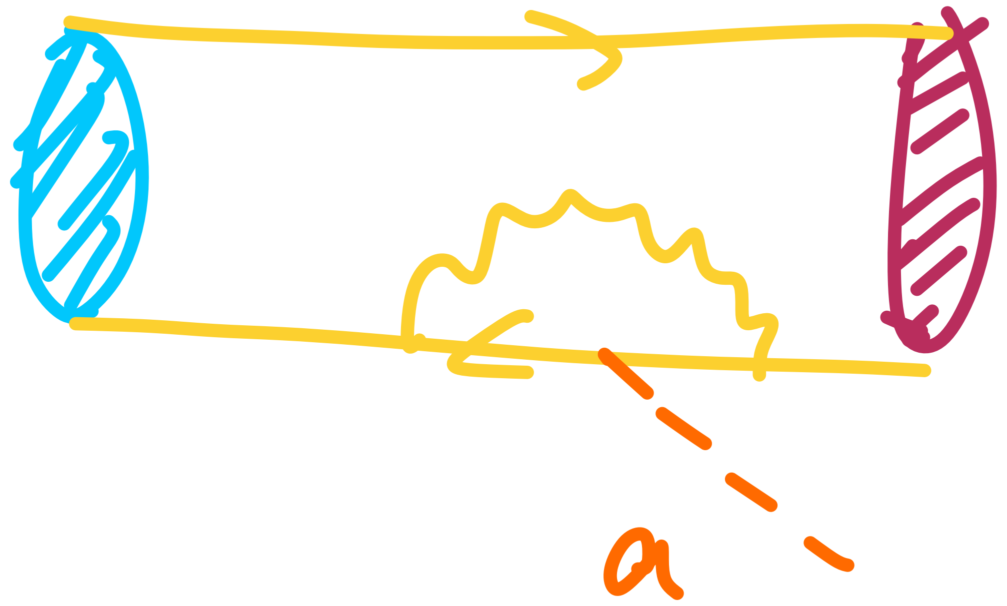


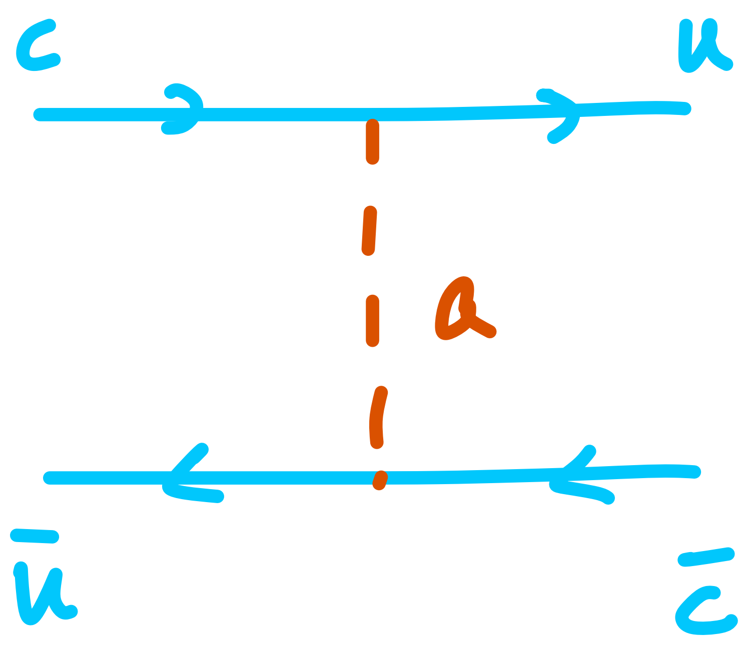
$$a = \pi_{D8},\ (c_{uR})_{33} \neq 0$$

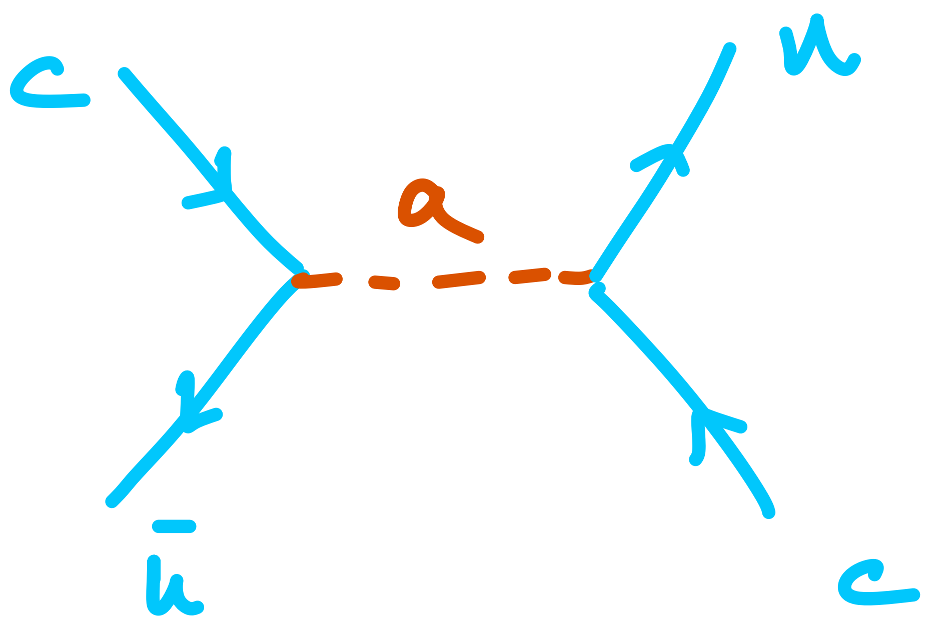
FLAVOR BOUNDS

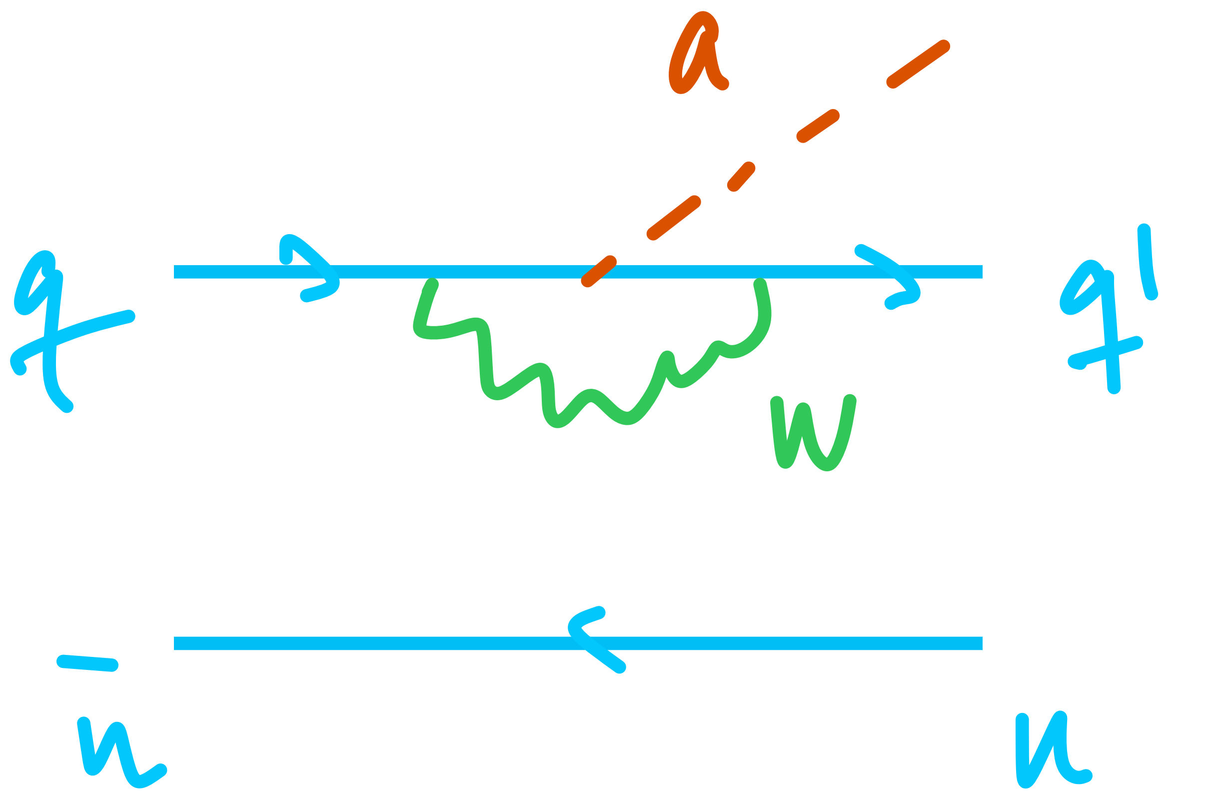


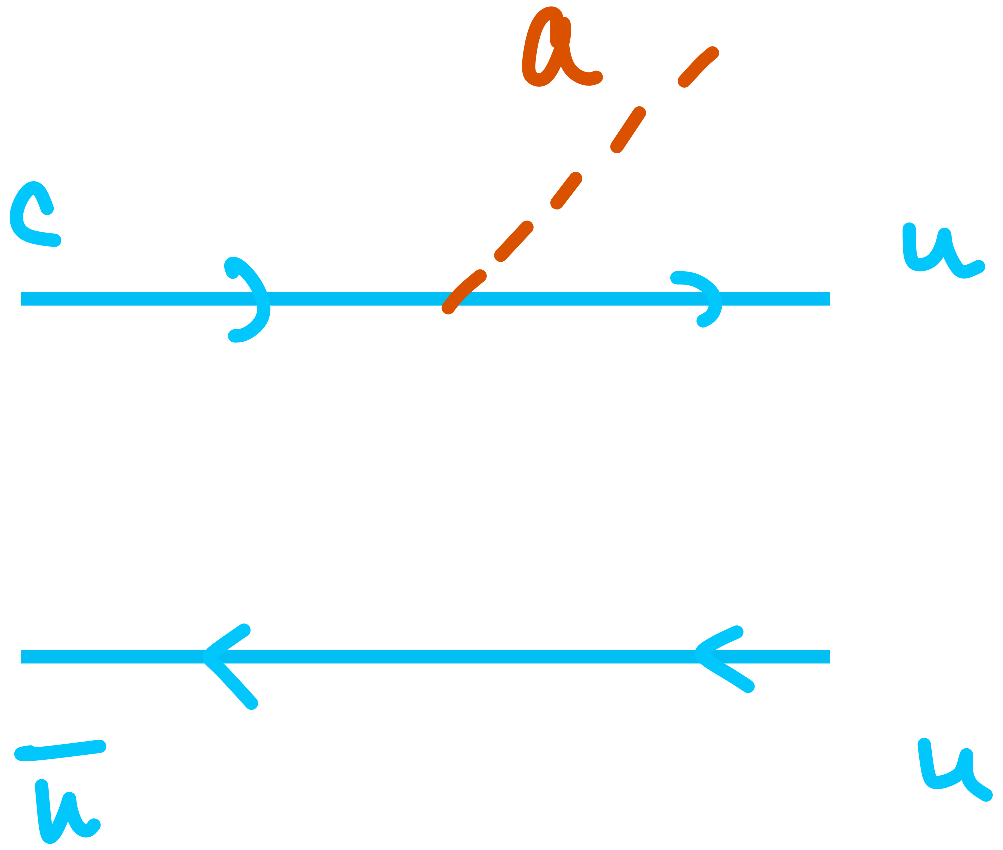
$D - \bar{D}$ mixing











$B \to K a$, $B \to \pi a$, $K \to \pi a$

$D \to \pi a$

FLAVOR BOUNDS

- $D^+ \to (\tau^+ \to \pi^+ \nu)\bar{\nu}$ recasted with $M^2_{\rm miss}$ for $D^+ \to \pi^+ a$ CLEO 0806.2112
- $B^+ \to K^+ \bar{\nu}\nu,\ B^0 \to K^0 \bar{\nu}\nu$ recasted with $s_B = k^2/m_B^2$ for $B \to Ka$ BaBar 1303.7465
- $B^+ \to \pi^+ \bar{\nu}\nu$ recasted with $\sqrt{\vec{p}_\pi^{\,2}}$ for $B \to \pi a$ BaBar hep-ex/0411061
- $K^+ \to \pi^+ a$ for $m_a > 0$ NA62 2011.11329
- $B^\pm \to K^\pm \bar{\nu}\nu$ expected at Belle II with $50\,\mathrm{ab}^{-1}$ and $K^\pm \to \pi^\pm \bar{\nu}\nu$ at NA62
- Recasts done with the CLs method

ASTRO & COSMO BOUNDS

Red Giant bursts

$$\mathscr{L} \supset i a g_{a\ell\ell}(\bar{\ell}\gamma_5\ell), \quad g_{a\ell\ell} = \frac{3m_e}{8\pi v^2 f_a} \ln\left(\frac{f_a^2}{m_t^2}\right) \sum_{i=1}^{3} \left(\mathscr{M}_u\right)_{ii} \left(c_{u_R}\right)_{ii}$$

$g_{aee} < 1.6 \cdot 10^{-13}$

SN1987a

$$L_a \leq L_\nu = 3 \cdot 10^{52}\, \mathrm{erg}/s$$

Bremsstrahlung

$$N + N \to N + N + a$$

$$c_{app} = (c_{u_R})_{11}(0.75 \pm 0.03)$$

$$c_{ann} = (c_{u_R})_{11}(-0.51 \pm 0.03)$$

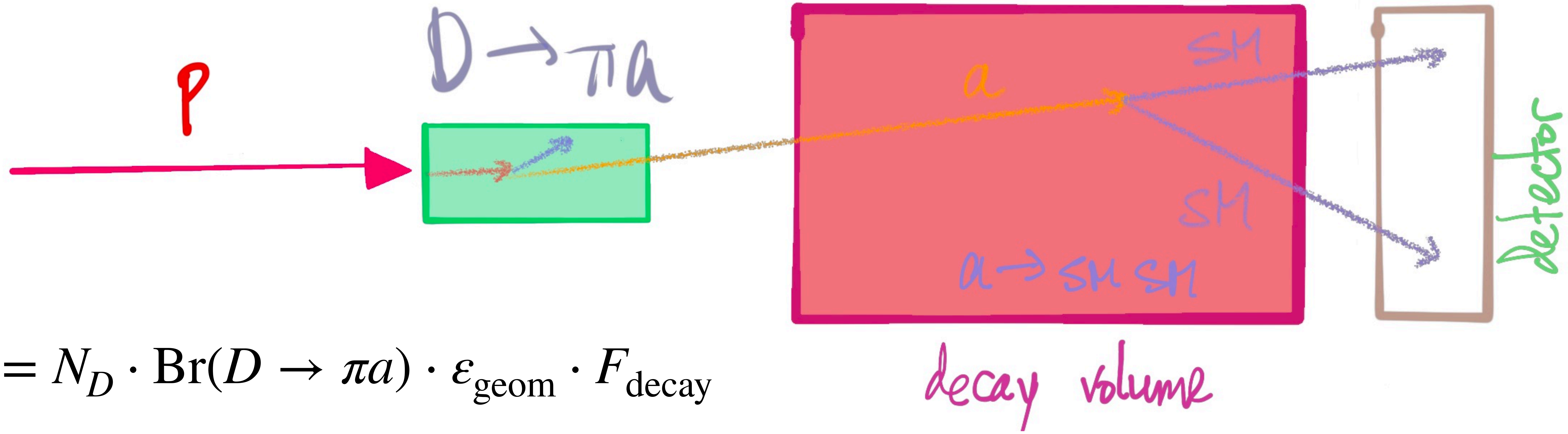
N_{eff}, distorsion of CMB, BBN, ...

Cadamuro, Redondo ‘12
Millea, Knox ‘15
Depta et al ‘20

Most of the bounds derived assumed only couplings to photons but they can still be recasted

COLLIDER AND FIXED TARGET EXPERIMEMTS

Fixed target experiments: NA62, SHiP, CHARM

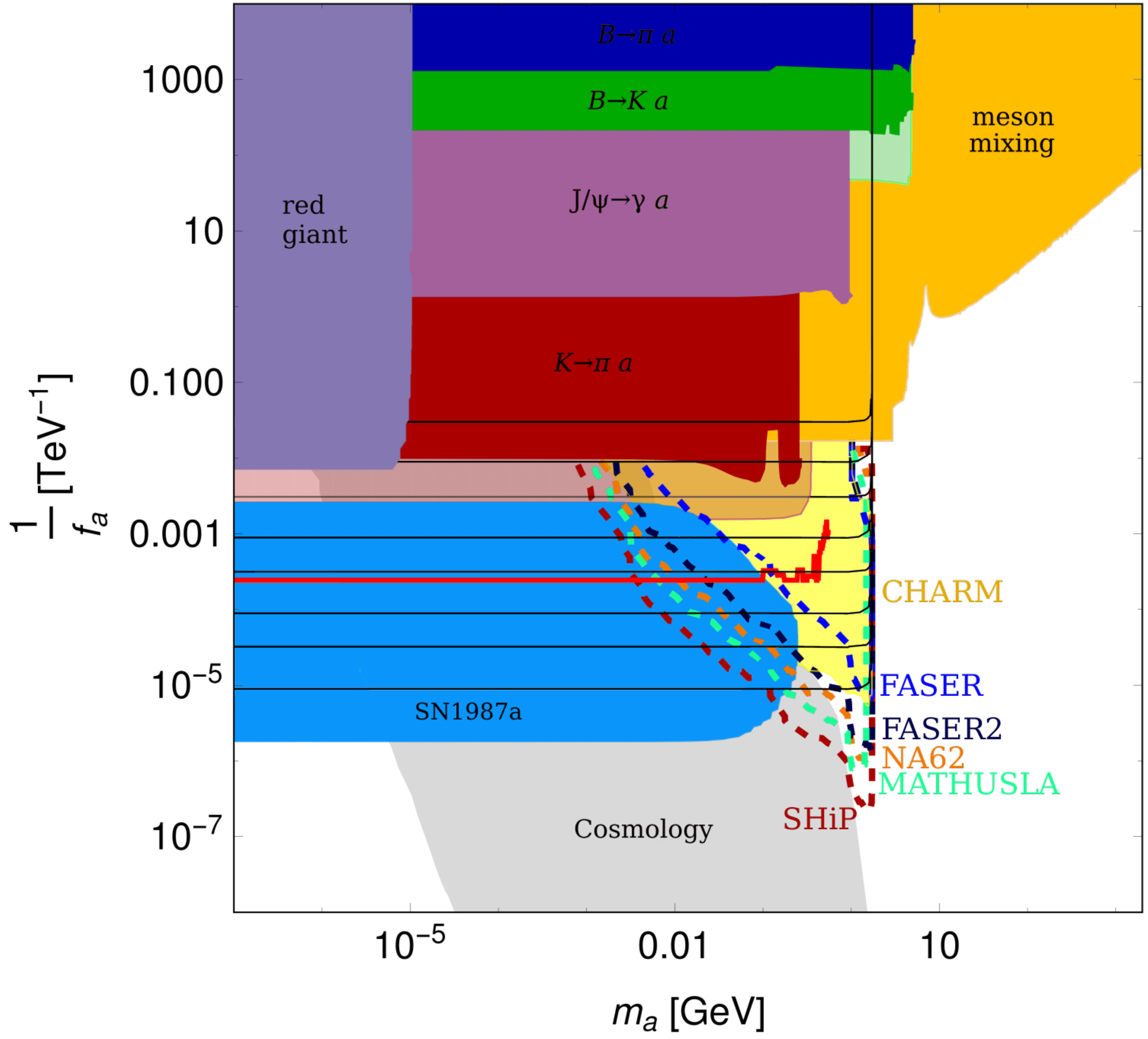


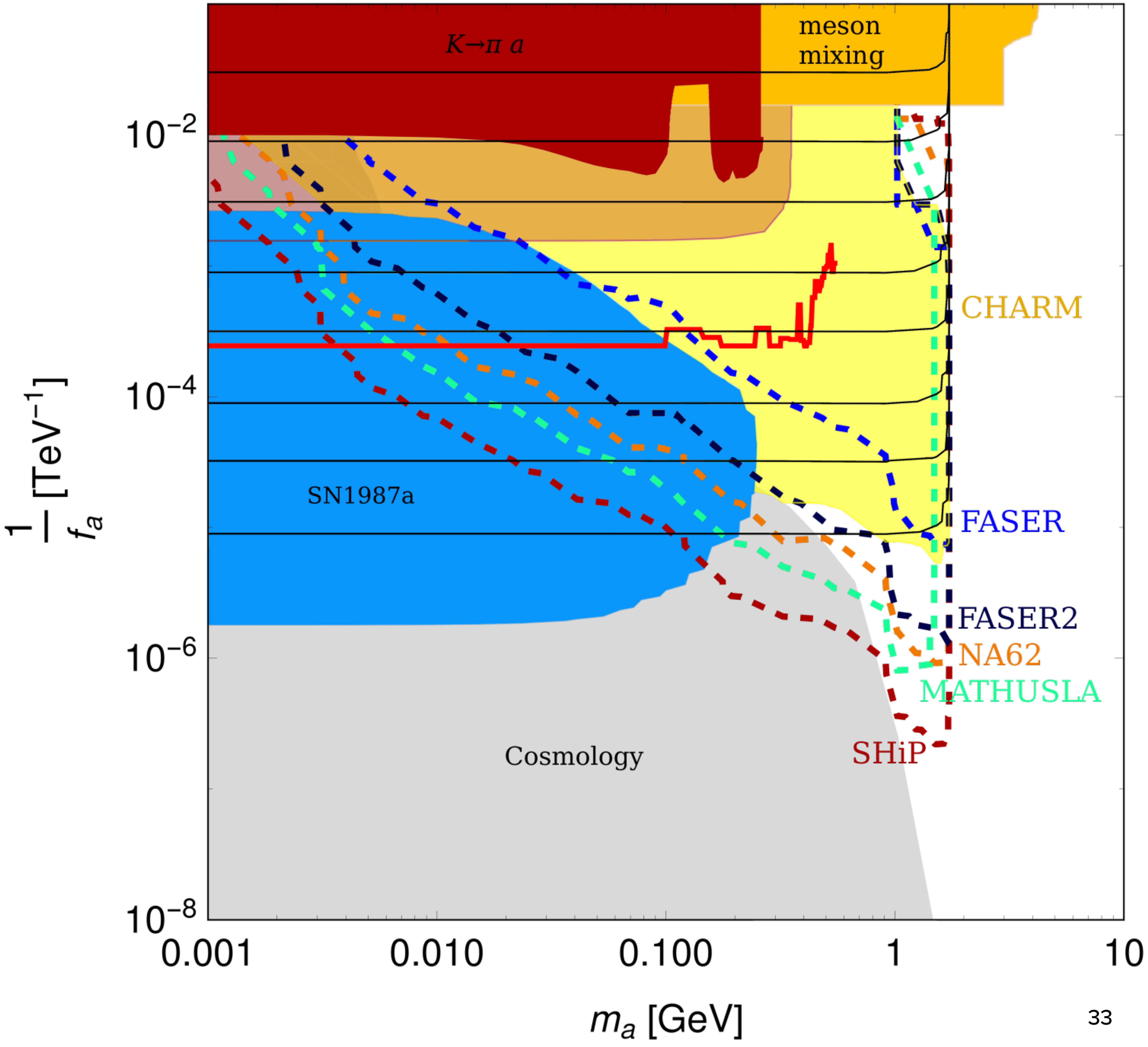
$$N_a = N_D \cdot \mathrm{Br}(D \to \pi a) \cdot \varepsilon_{\mathrm{geom}} \cdot F_{\mathrm{decay}}$$

LHC forward detectors: FASER, FASER II, MATUSHLA

CHARMING ALPS PARAMETER SPACE

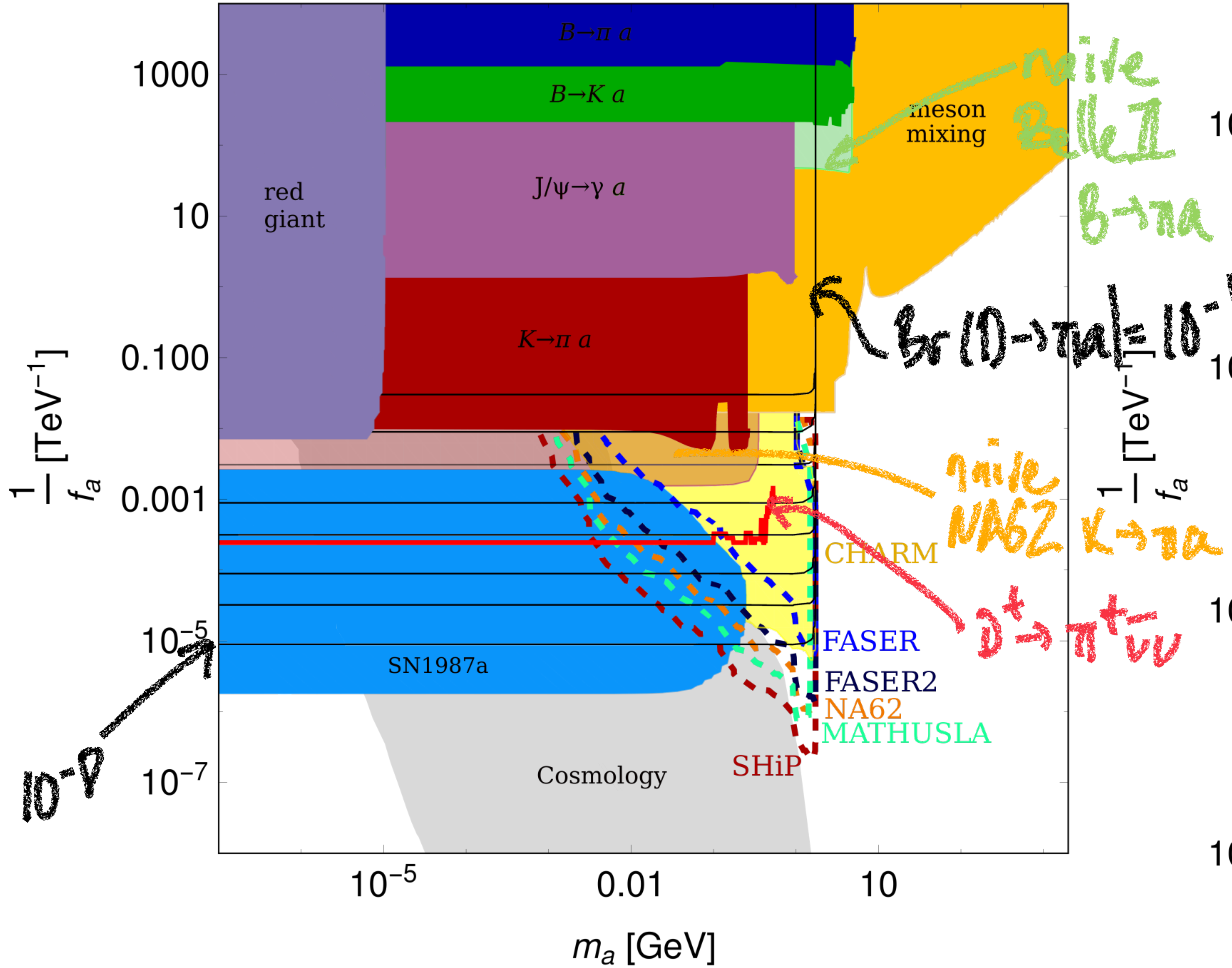
$$a = \pi_{D_3},\ (c_{u_R})_{33} = 0$$

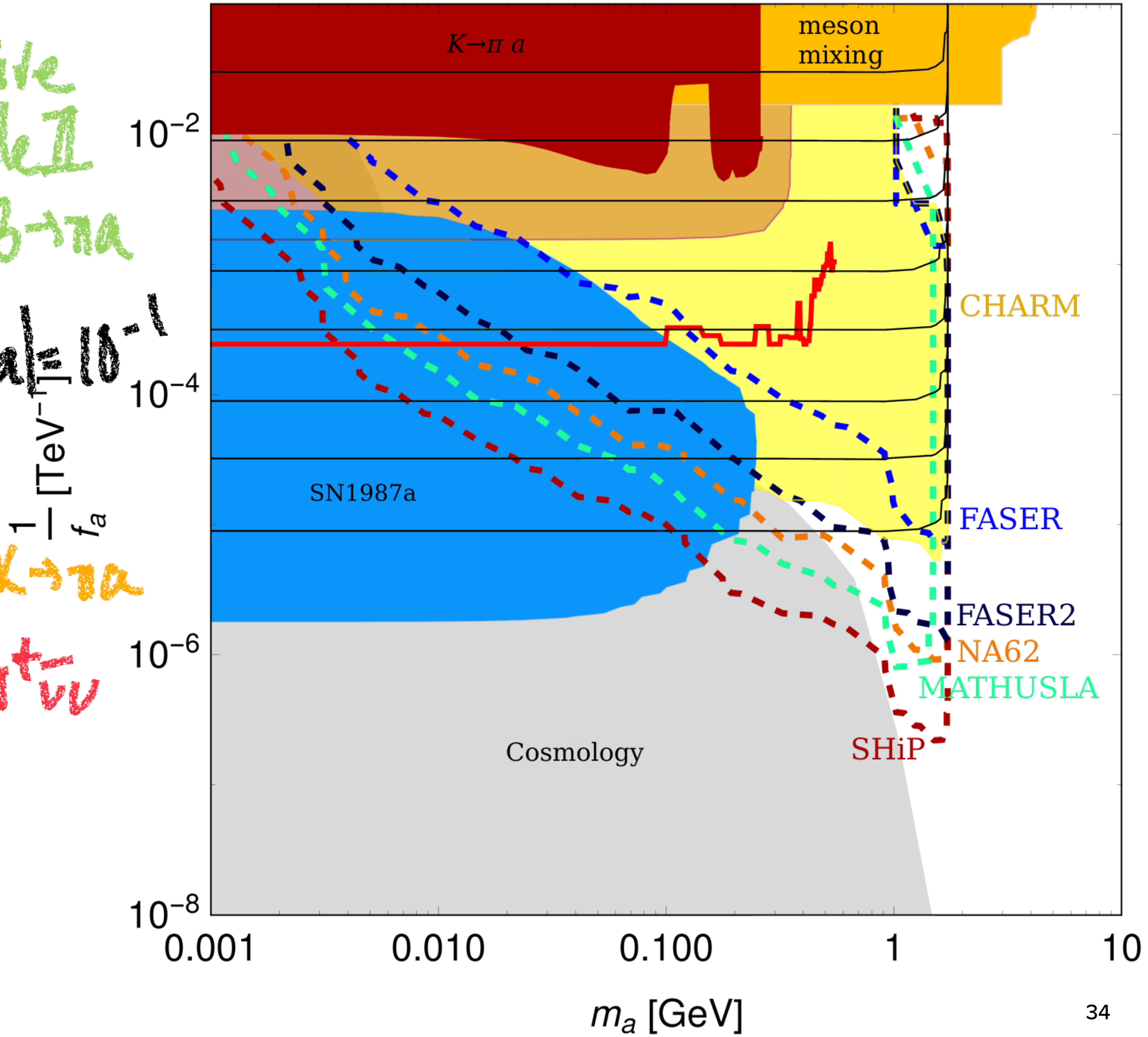




CHARMING ALPS PARAMETER SPACE

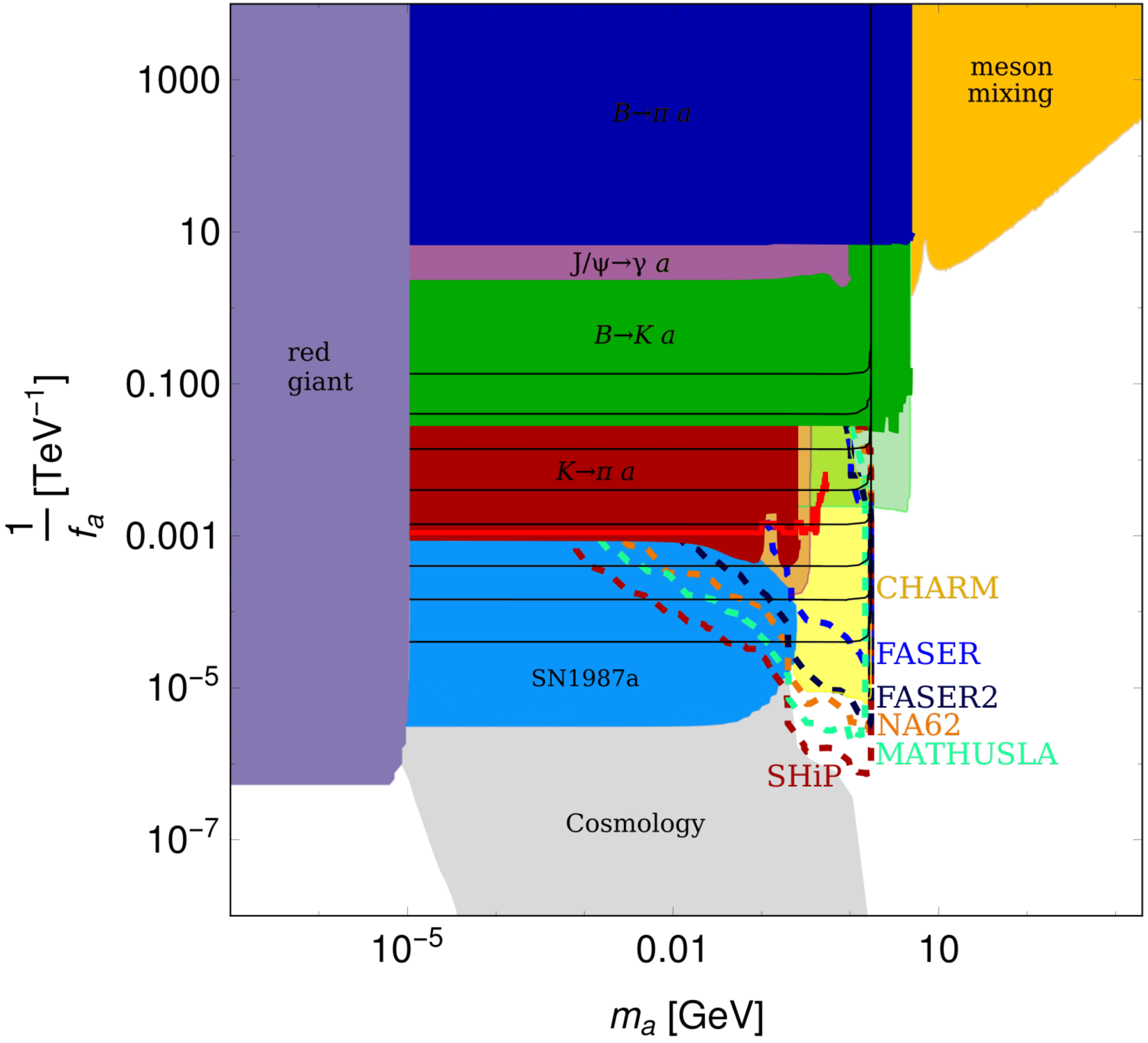
$$a = \pi_{D_3},\ (c_{u_R})_{33} = 0$$

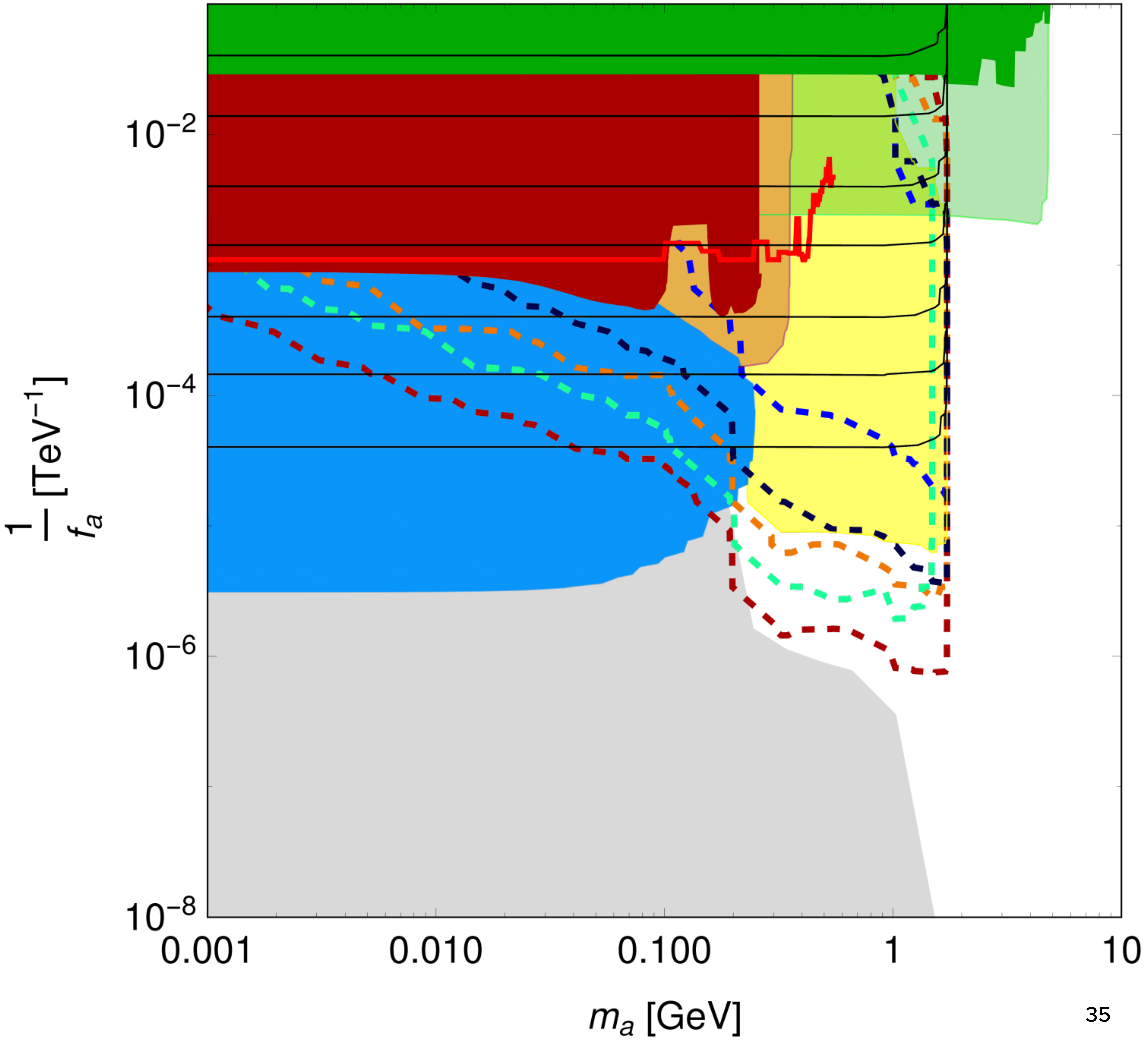




CHARMING ALPS PARAMETER SPACE

$$a = \pi_{D_8},\ (c_{u_R})_{33} \neq 0$$



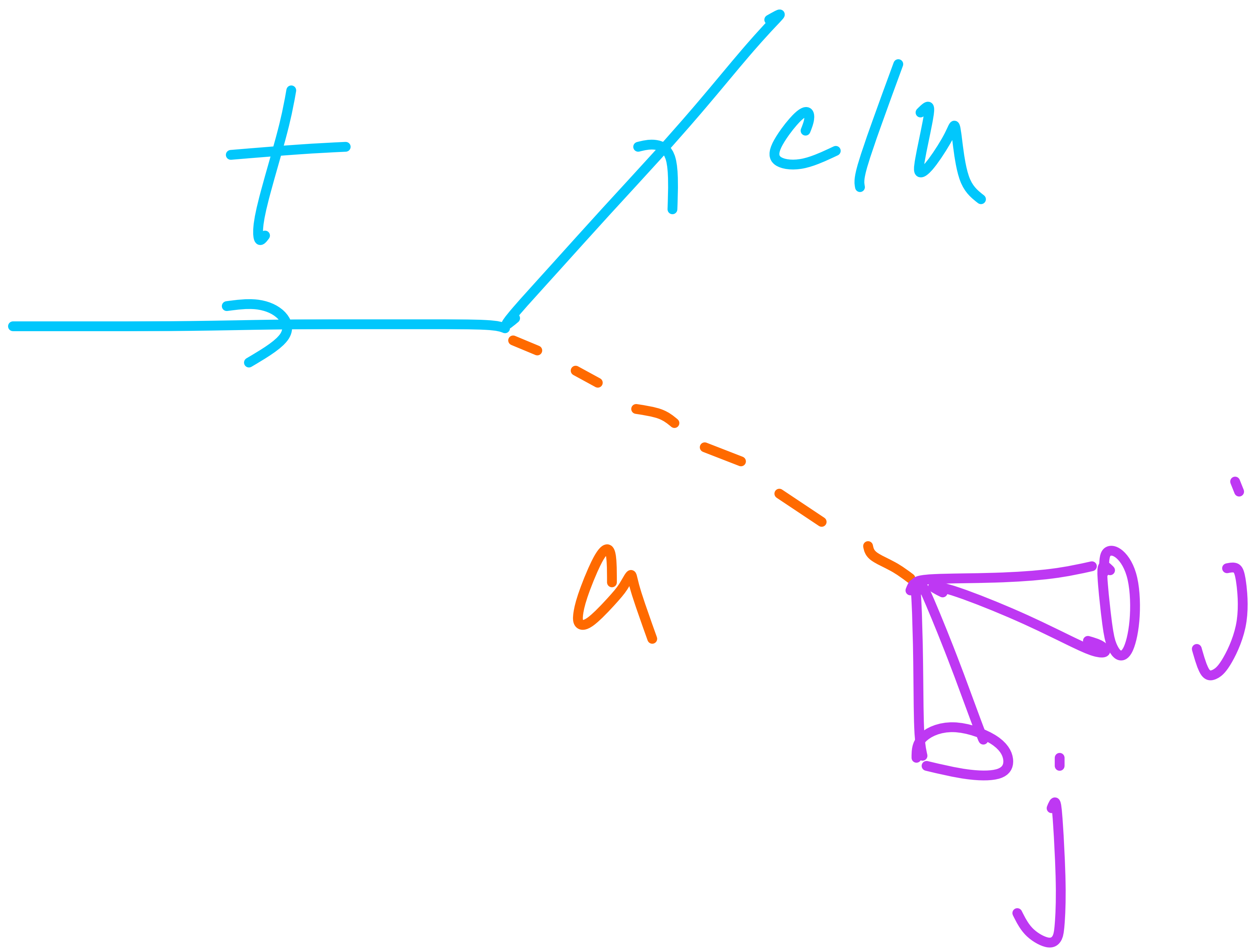


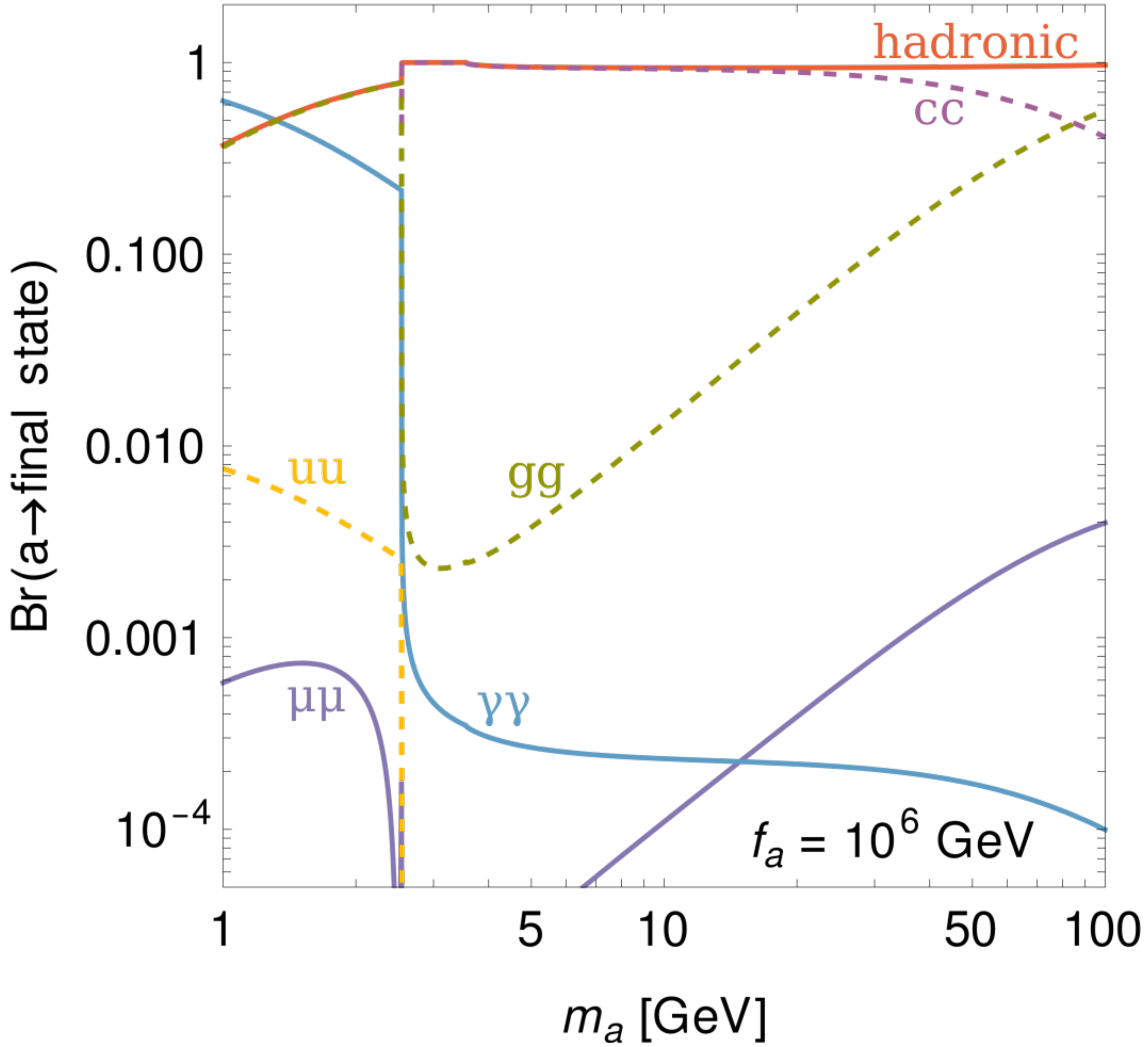
ALPS FROM THE TOP

Searching for long-lived particles from exotic top decays, 2202.0973

ALPS FROM THE TOP

- **Probe charming ALPs above charm threshold**

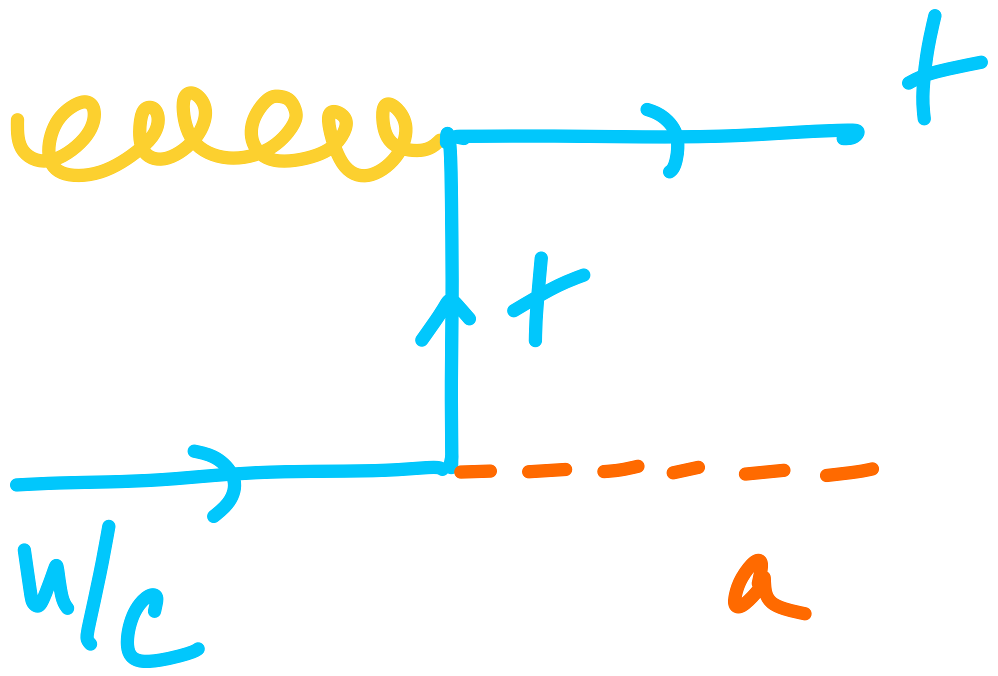


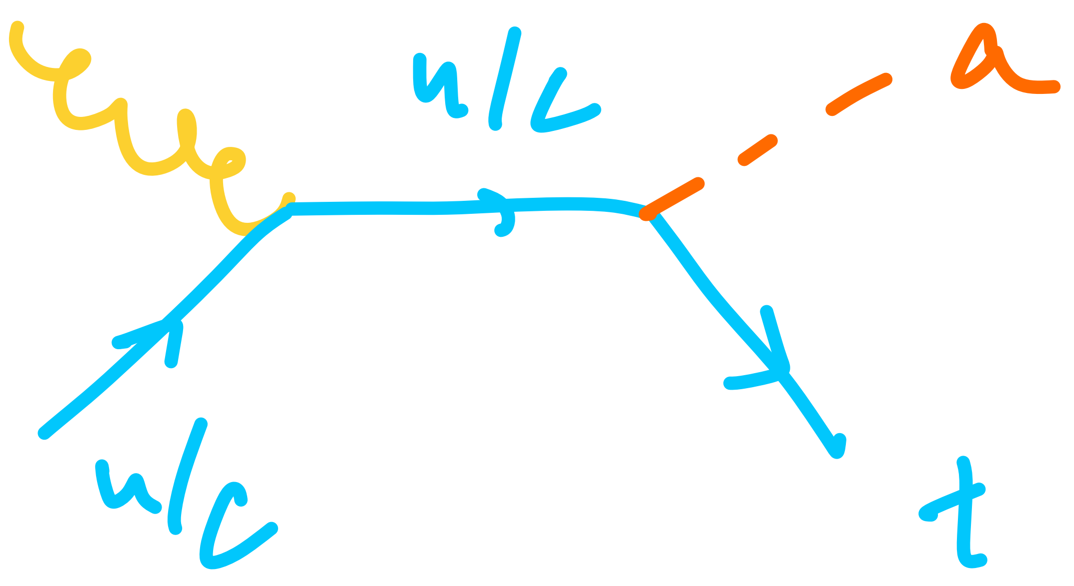


We trade diagonal and off-diagonal (equal) entries of c_{u_R} by $\mathrm{Br}(t \to a q_i)$ and $c\tau$

ALPS FROM THE TOPS: CONSTRAINTS

We recast searches from exotic top decays





PROMPT

$r < 0'01$ cm

$$\int_0^{10^{-4}\,\mathrm{m}} (\gamma c\tau)^{-1} \exp\left(-\frac{ct}{\gamma c\tau}\right) d(ct)$$

LONG-LIVED

$2'5$ cm $< r < 2$ m

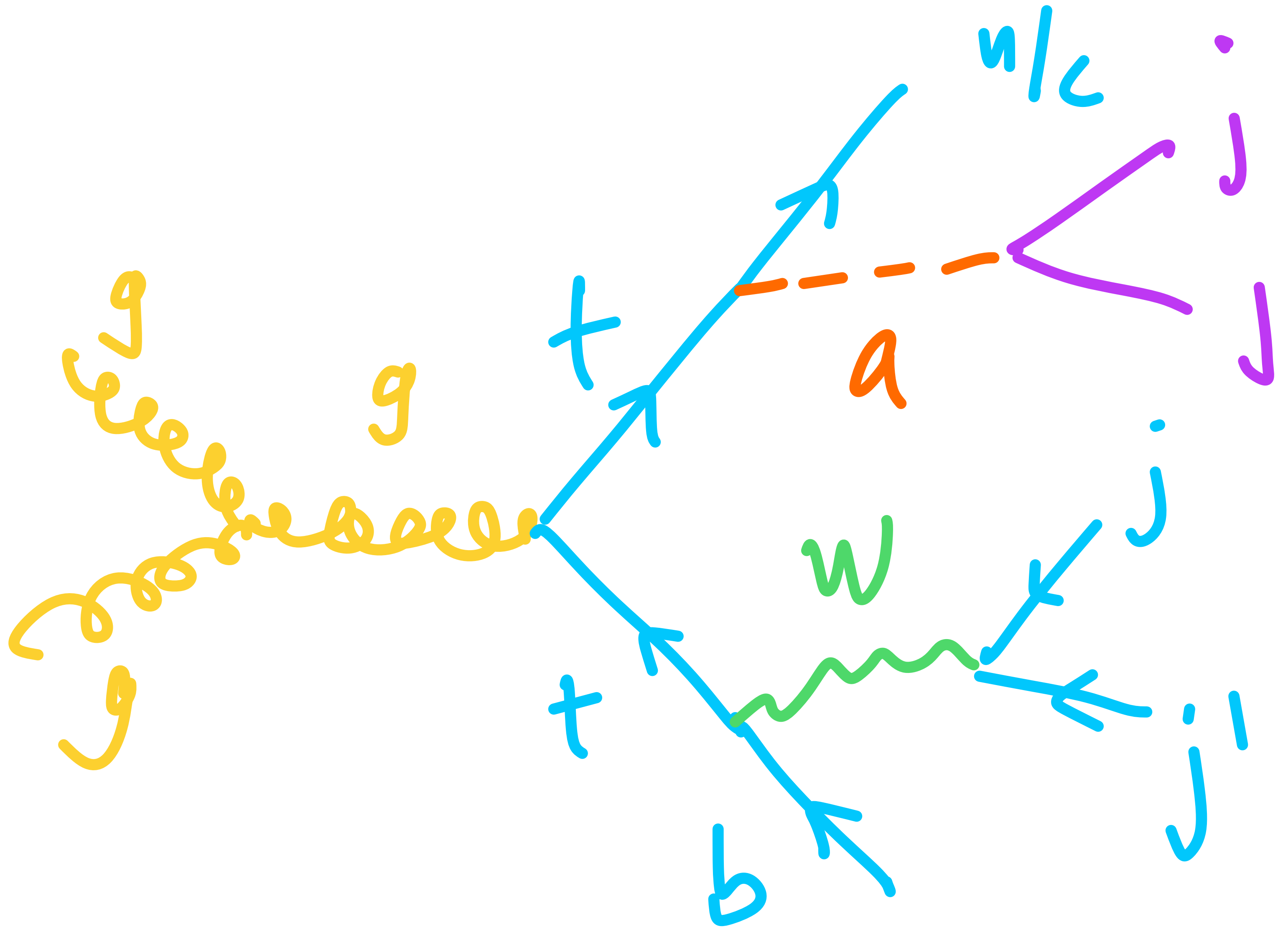
$$\int_{2.5\cdot 10^{-2}\,\mathrm{m}}^{2\,\mathrm{m}} (\gamma c\tau)^{-1} \exp\left(-\frac{ct}{\gamma c\tau}\right) d(ct)$$

‘STABLE’

$c\tau \geq 10$ m

$$\exp\left(-\frac{10\,\mathrm{m}}{\gamma c\tau}\right)$$

SIGNAL



We consider two benchmarks with ALP masses

$$m_a = 2\,\text{GeV}, \quad m_a = 10\,\text{GeV}$$

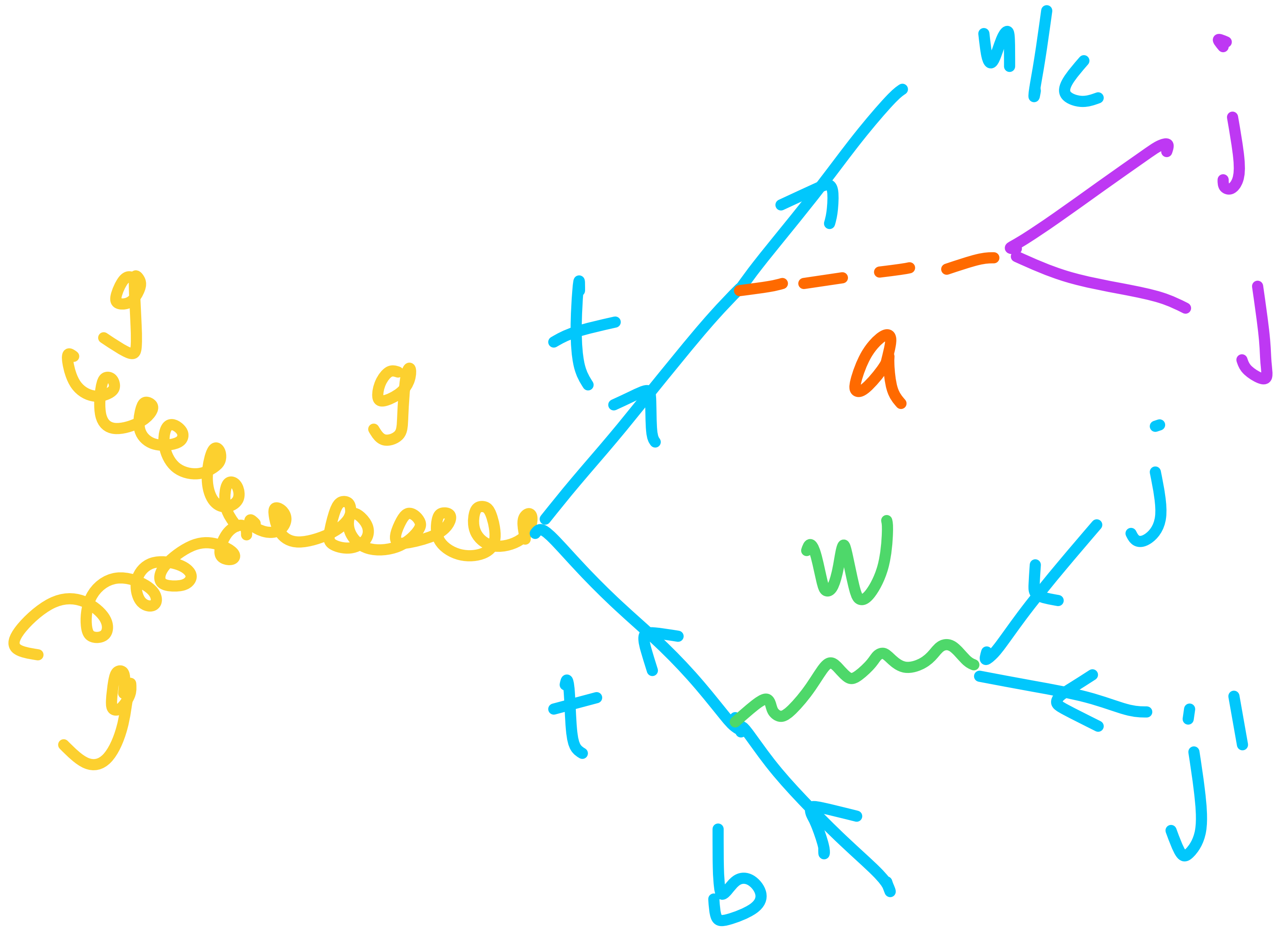
$$\sigma_{\text{signal}} = \sigma_{tt} \cdot \text{Br}(t \to Wb) \cdot \text{Br}(t \to aq)$$

$$(c_{u_R})_{ij} = \mathcal{O}(1), \quad f_a = \mathcal{O}(10^5 - 10^9)\,\text{GeV} \;\Rightarrow\; c\tau \sim 1\,\text{mm} - 100\,\text{m}$$

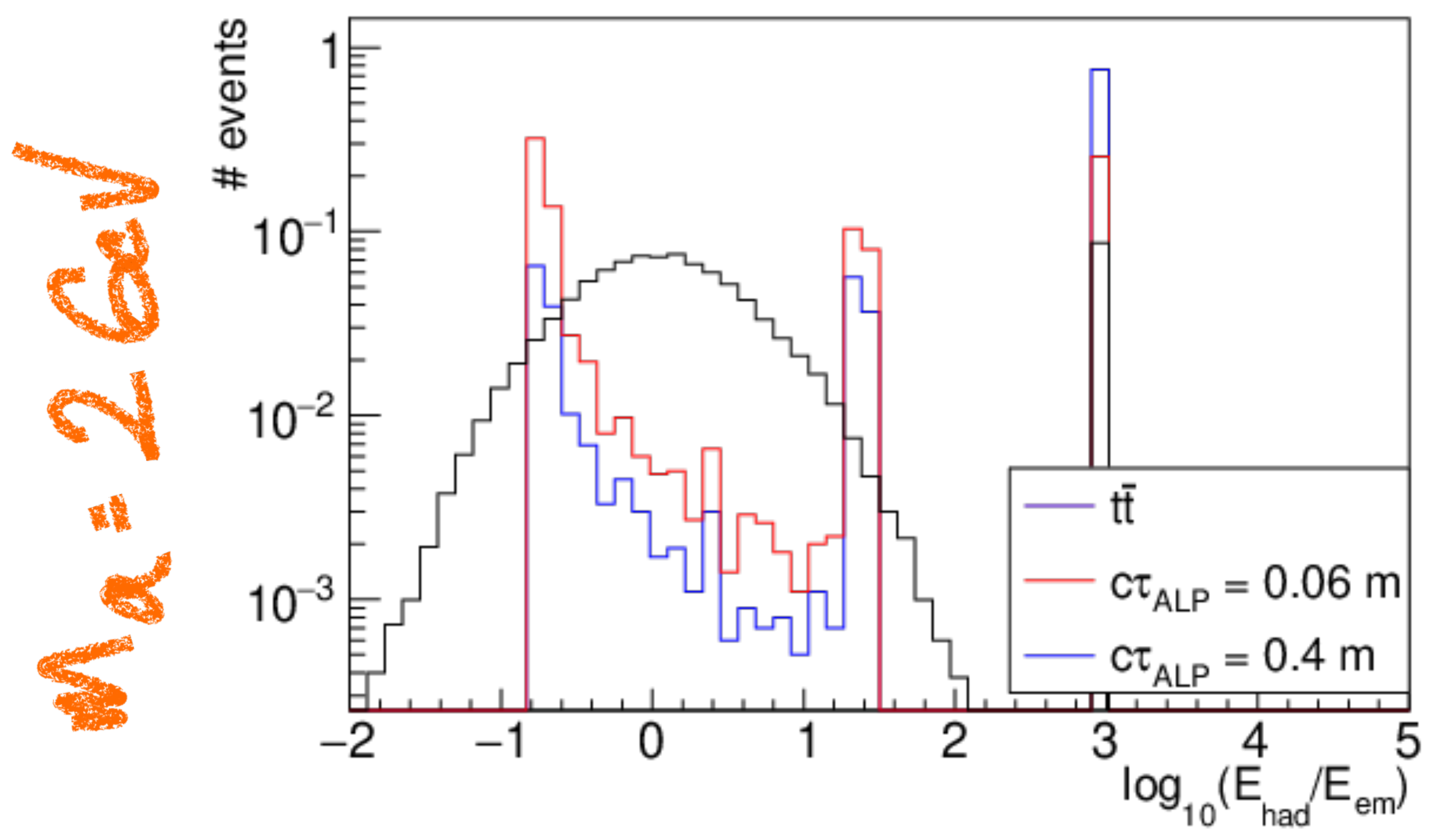
while having $\text{Br}(t \to aq) \lesssim 10^{-3}$

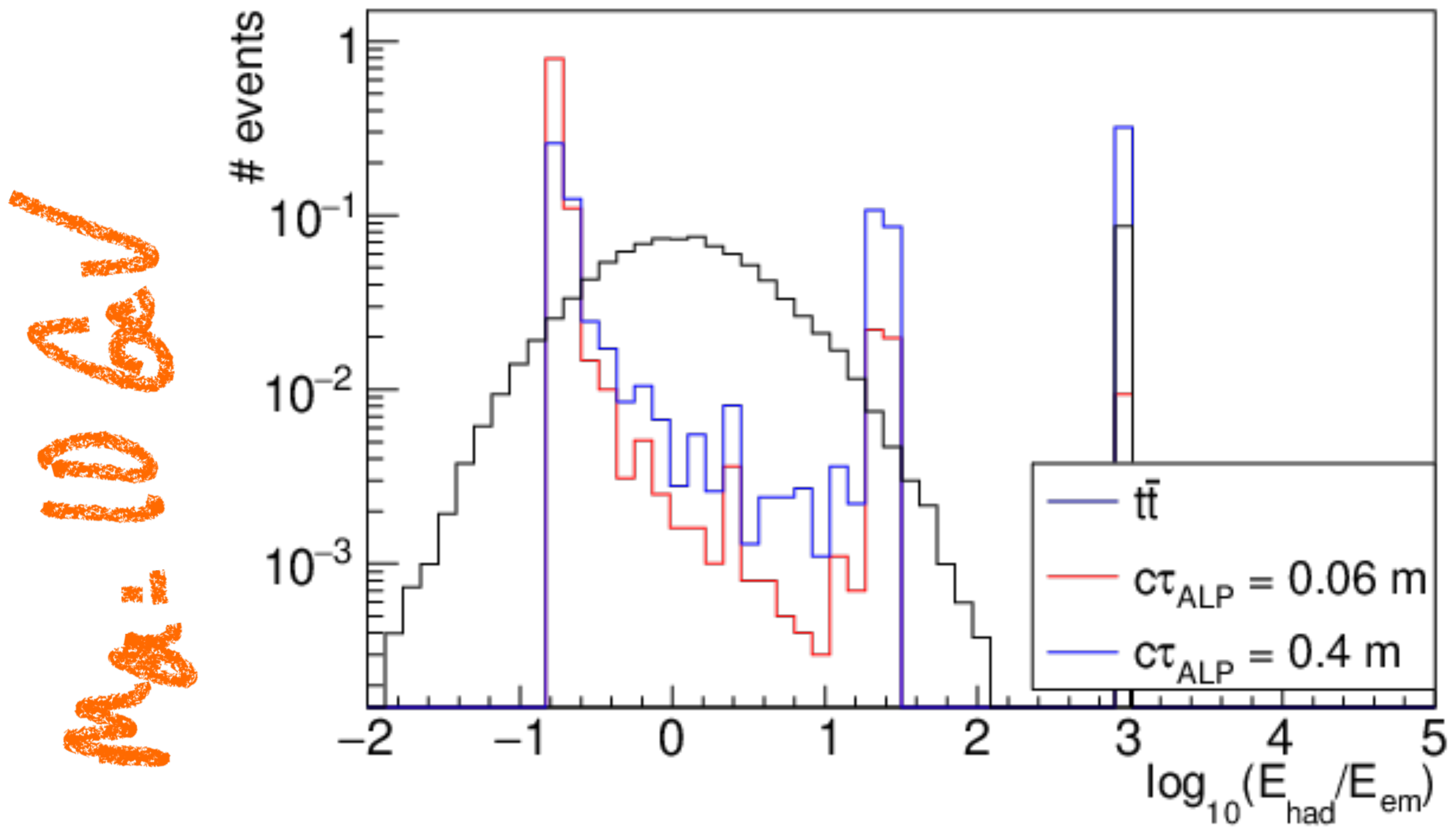
The ALP decay mostly in the hadronic calorimeter / muon spectrometer

SIGNAL : HADRONIC CALORIMETER

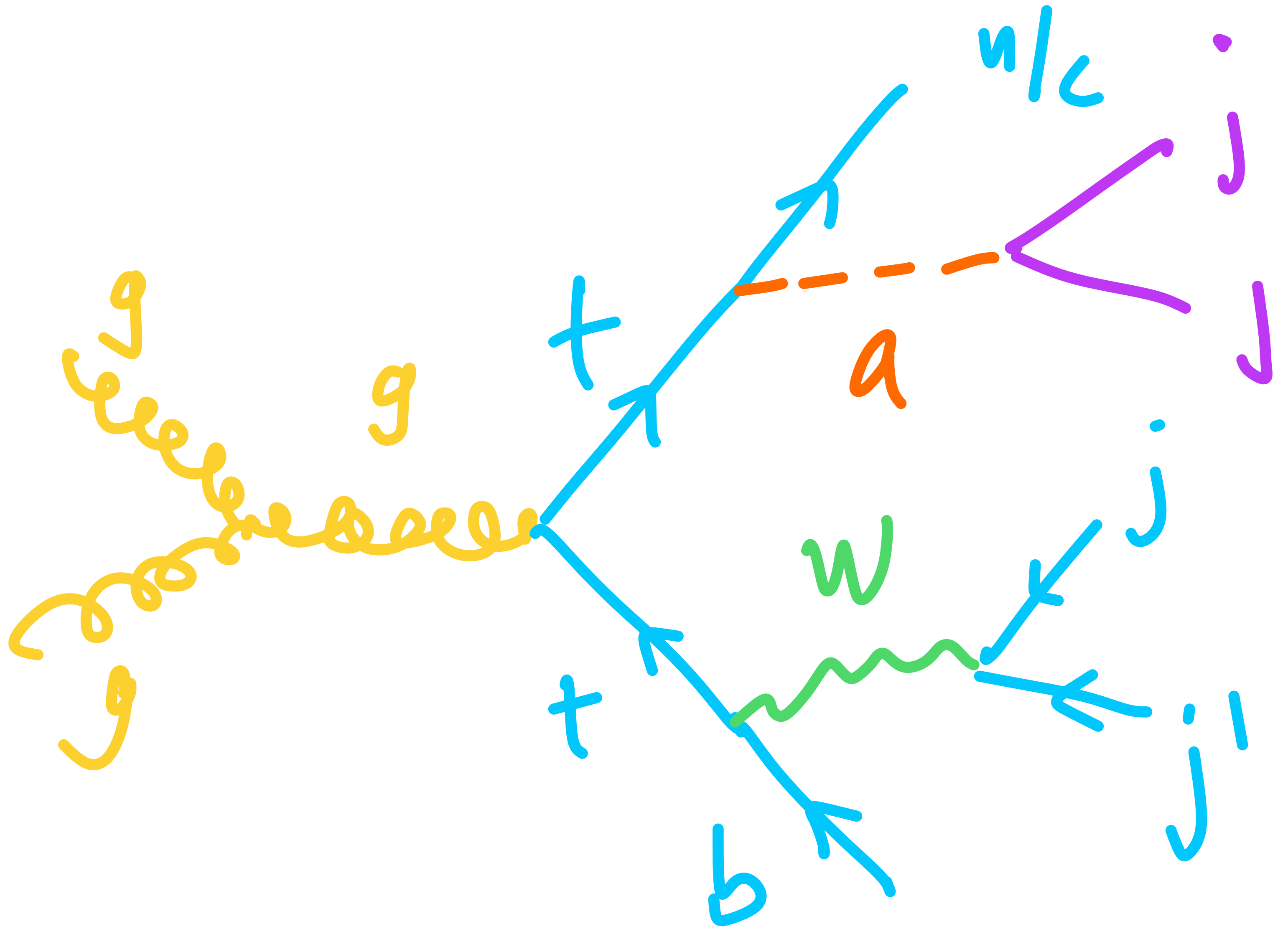


- Large Ehad/Ecal ratio
- No tracks in the displaced jet
- 3-5(6) jets with 1(2) displaced and another b-tagged



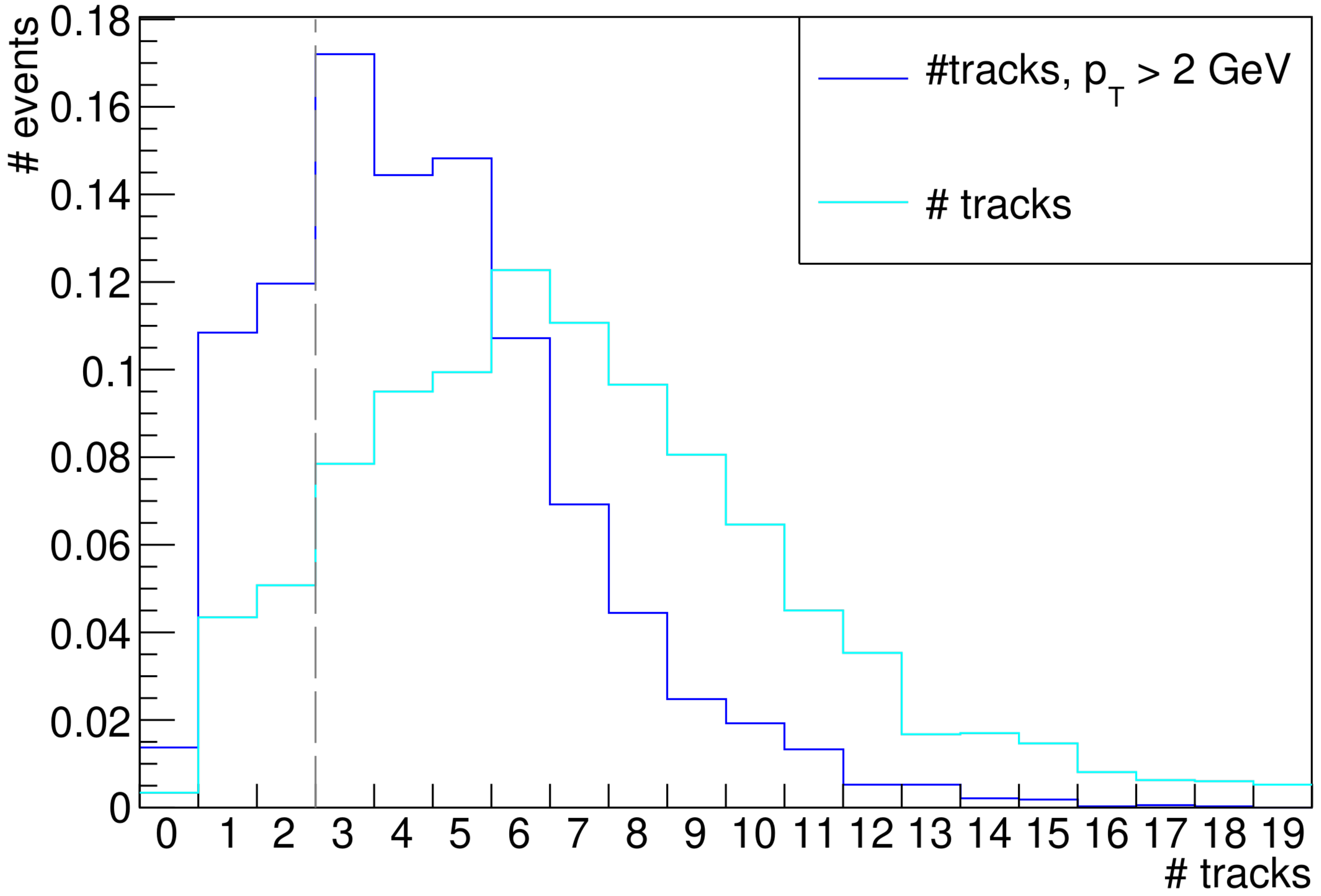


SIGNAL : HADRONIC CALORIMETER

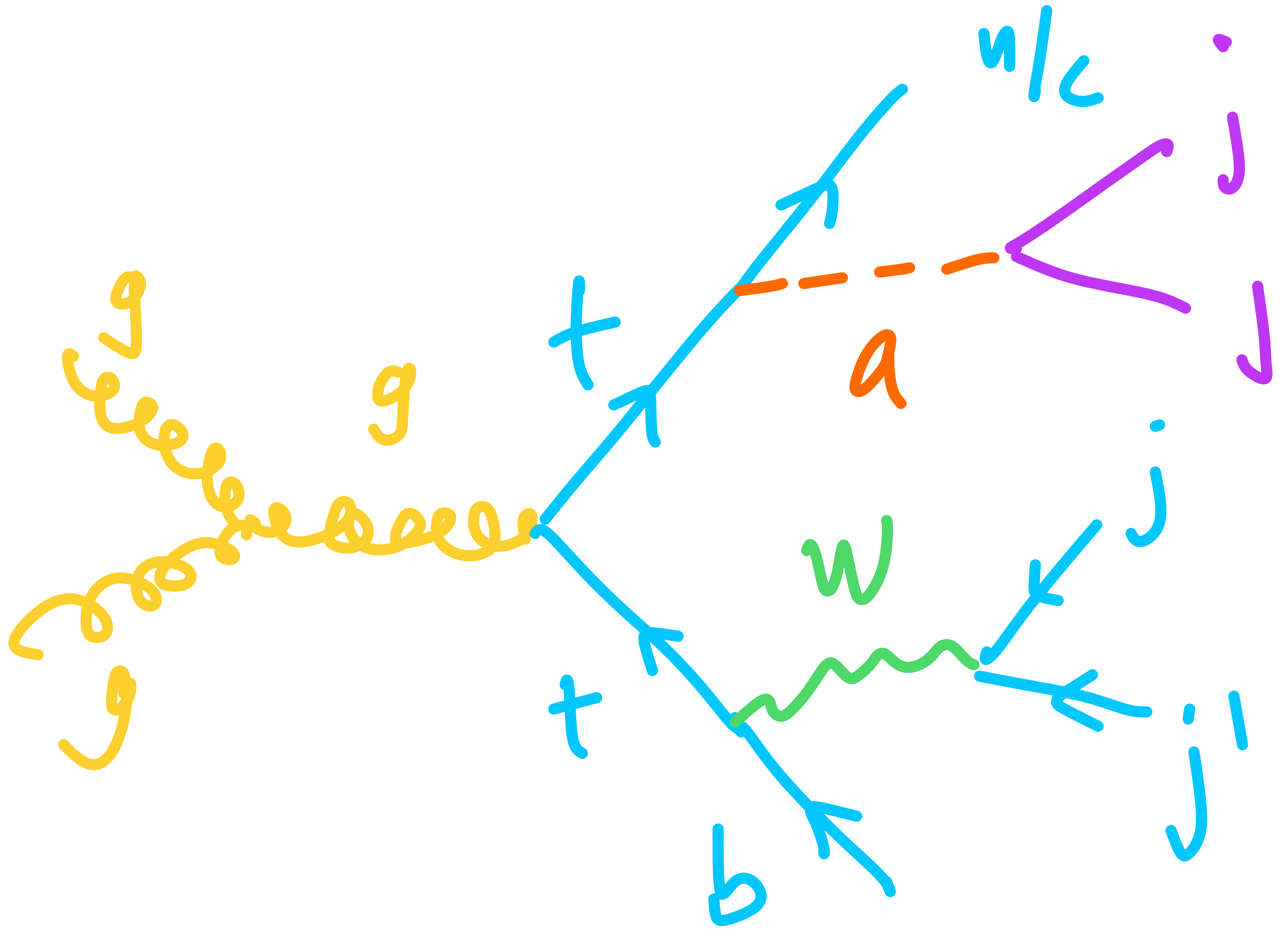


- Large Ehad/Ecal ratio
- No tracks in the displaced jet
- 3-5(6) jets with 1(2) displaced and another b-tagged

For $t\bar{t}$ with $\log_{10}(E_{had}/E_{cal}) > 1.2 \Rightarrow$



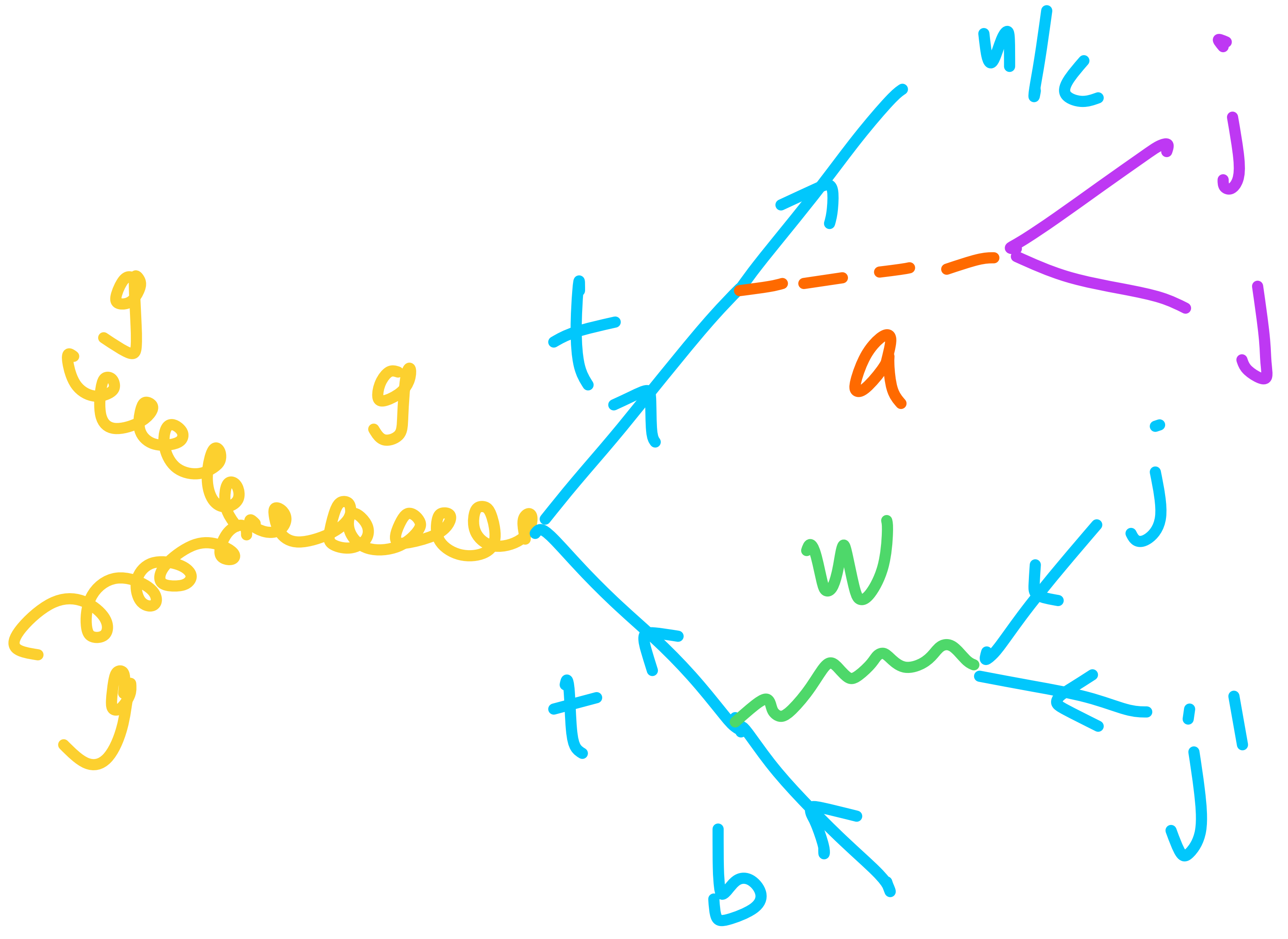
SIGNAL : HADRONIC CALORIMETER



- Large Ehad/Ecal ratio
- No tracks in the displaced jet
- 3-5(6) jets with 1(2) displaced and another b-tagged

	$\mathbf{m_a = 2\ GeV}$	$\mathbf{m_a = 10\ GeV}$	$\mathbf{t\bar{t}}$
total	$(1)\ 2.79 \times 10^5$	$(1)\ 2.79 \times 10^5$	$(1)\ 2.91 \times 10^8$
$3 - 6$ jets with $p_T > 40$ GeV & $\lvert\eta\rvert < 2.5$	$(0.8439)\ 2.35 \times 10^5$	$(0.8414)\ 2.35 \times 10^5$	$(0.71801)\ 2.09 \times 10^8$
1 jet with $\log_{10}\left(\frac{E_{had}}{E_{em}}\right) > 1.2$	$(0.1436)\ 4.00 \times 10^4$	$(0.0775)\ 2.16 \times 10^4$	$(0.01244)\ 3.61 \times 10^6$
displaced jet has ≤ 2 tracks with $p_T > 2$ GeV	$(0.1436)\ 4.00 \times 10^4$	$(0.0775)\ 2.16 \times 10^4$	$(0.00022)\ 6.39 \times 10^4$

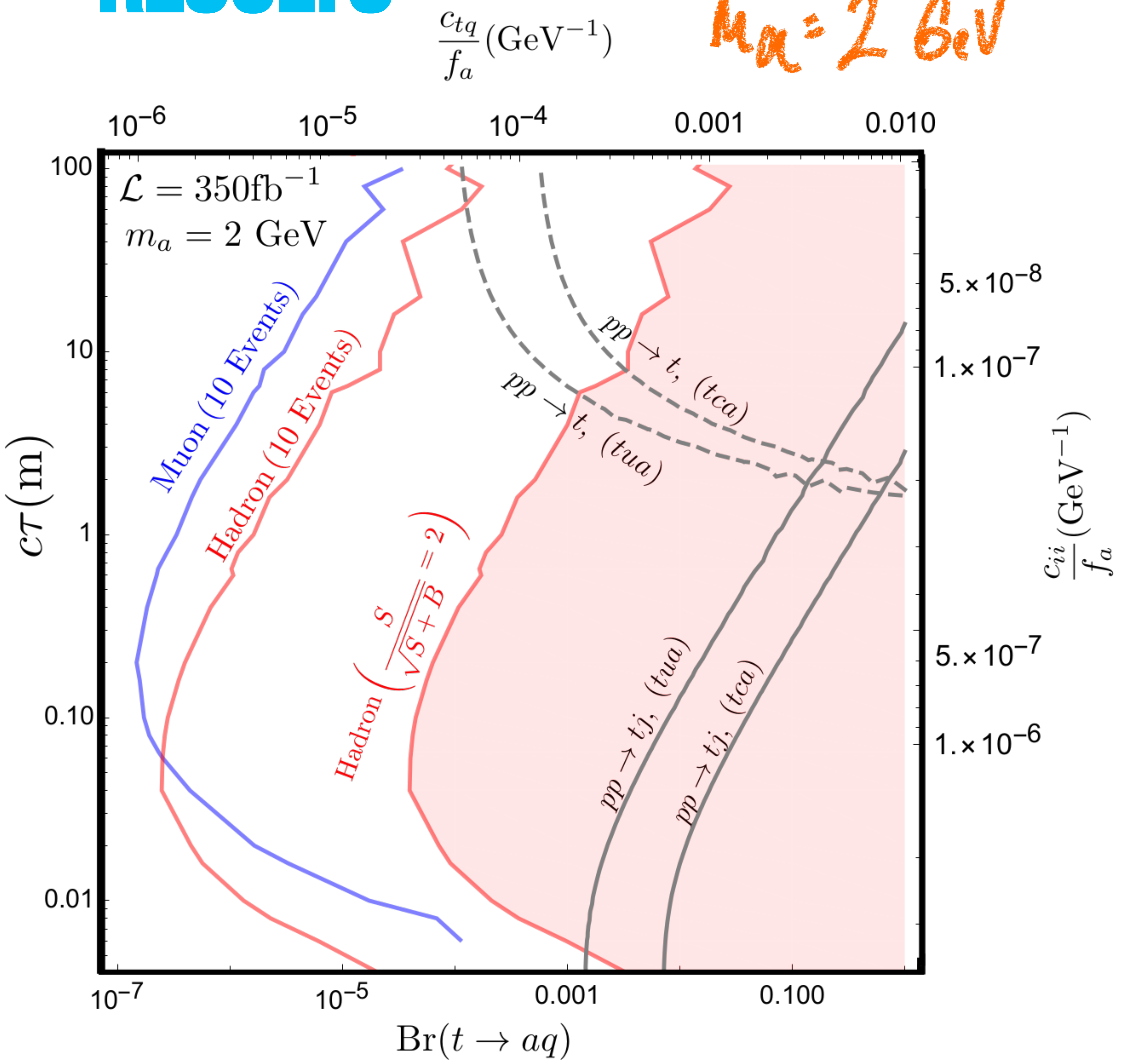
SIGNAL : MUON SPECTROMETER



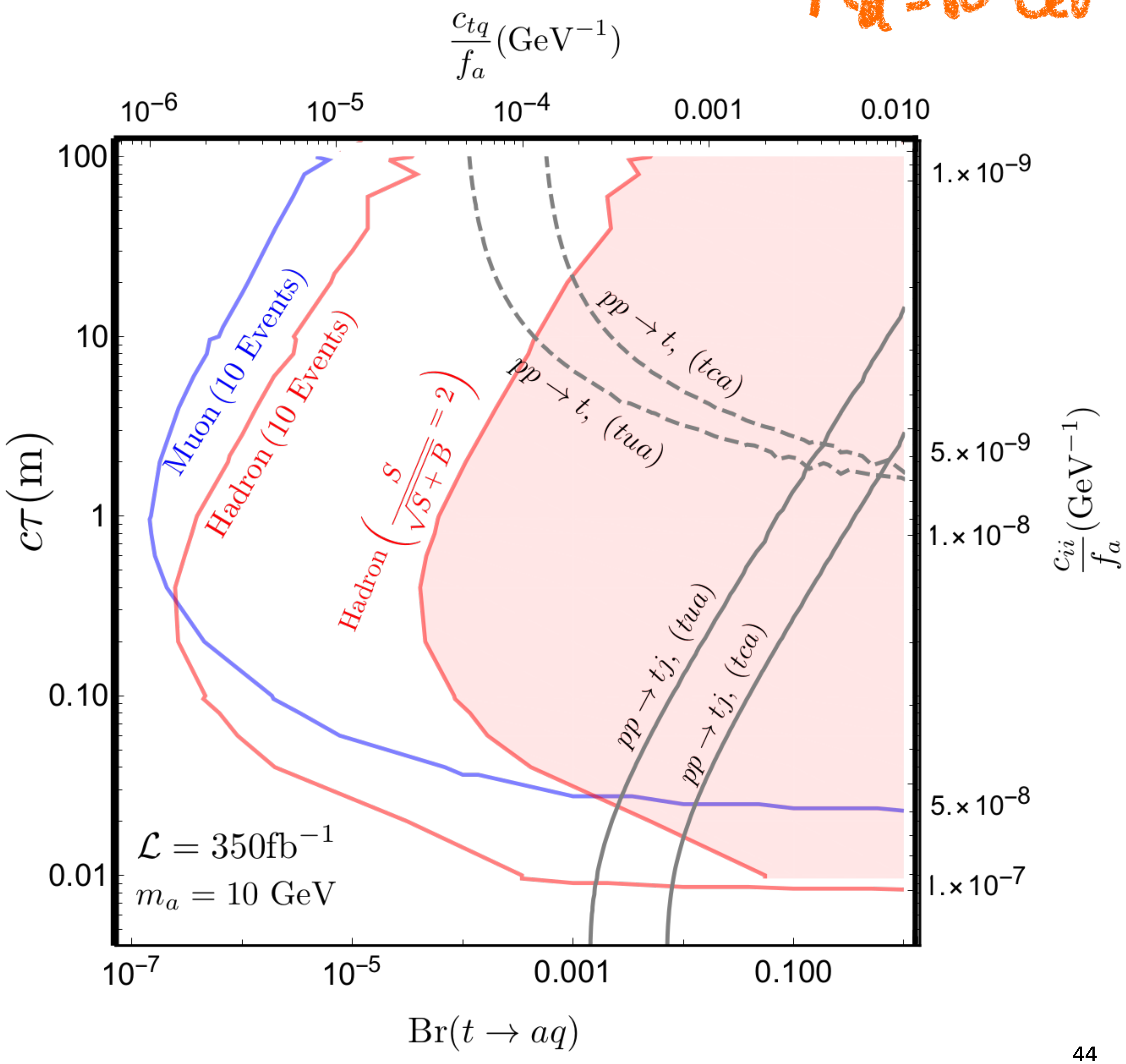
- Event in the muon system
- No associated track pointing to the primary vertex
- 2-4(5) jets
- Signal is background free

RESULTS

$m_a = 2$ GeV

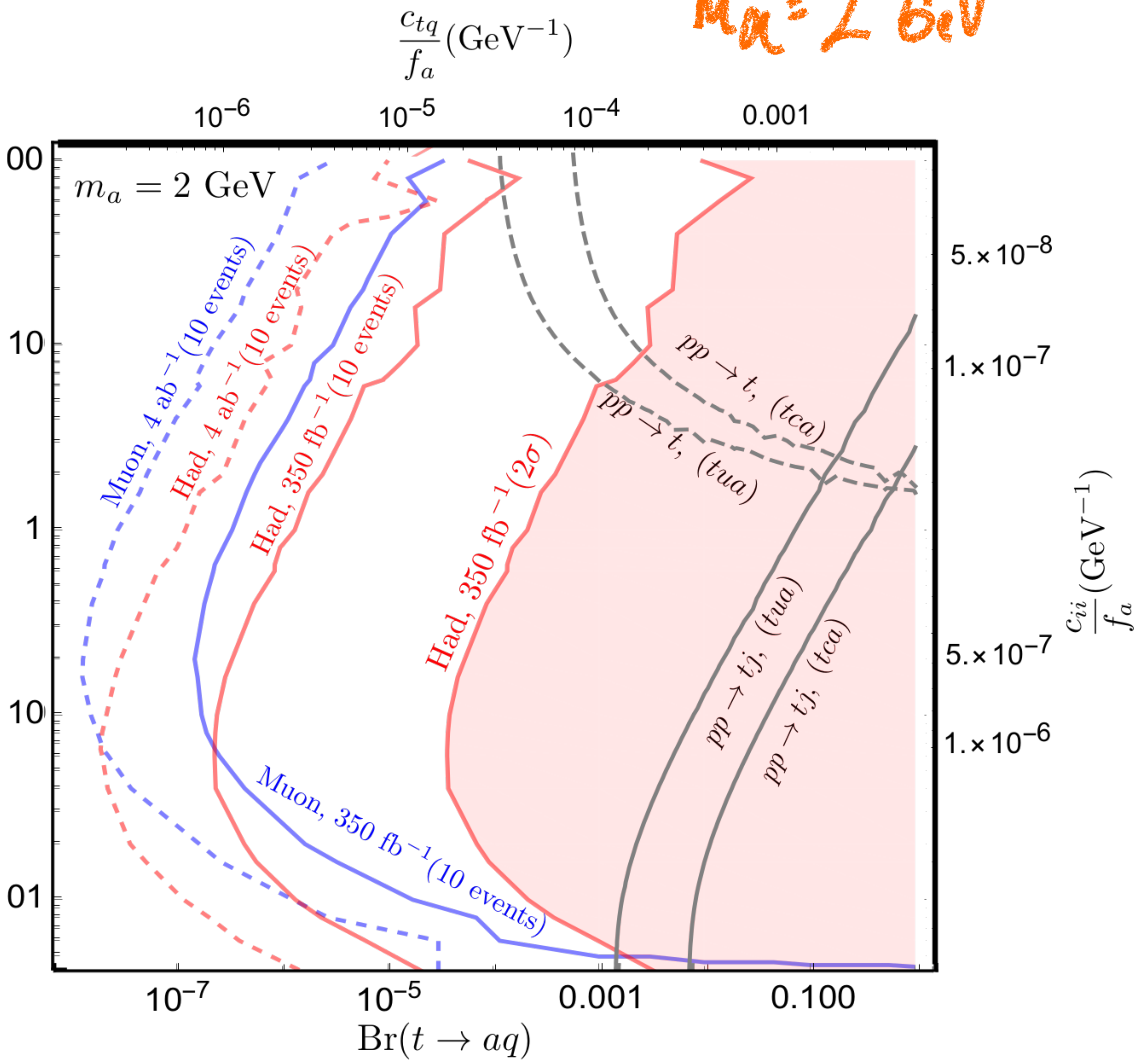


$m_a = 10$ GeV

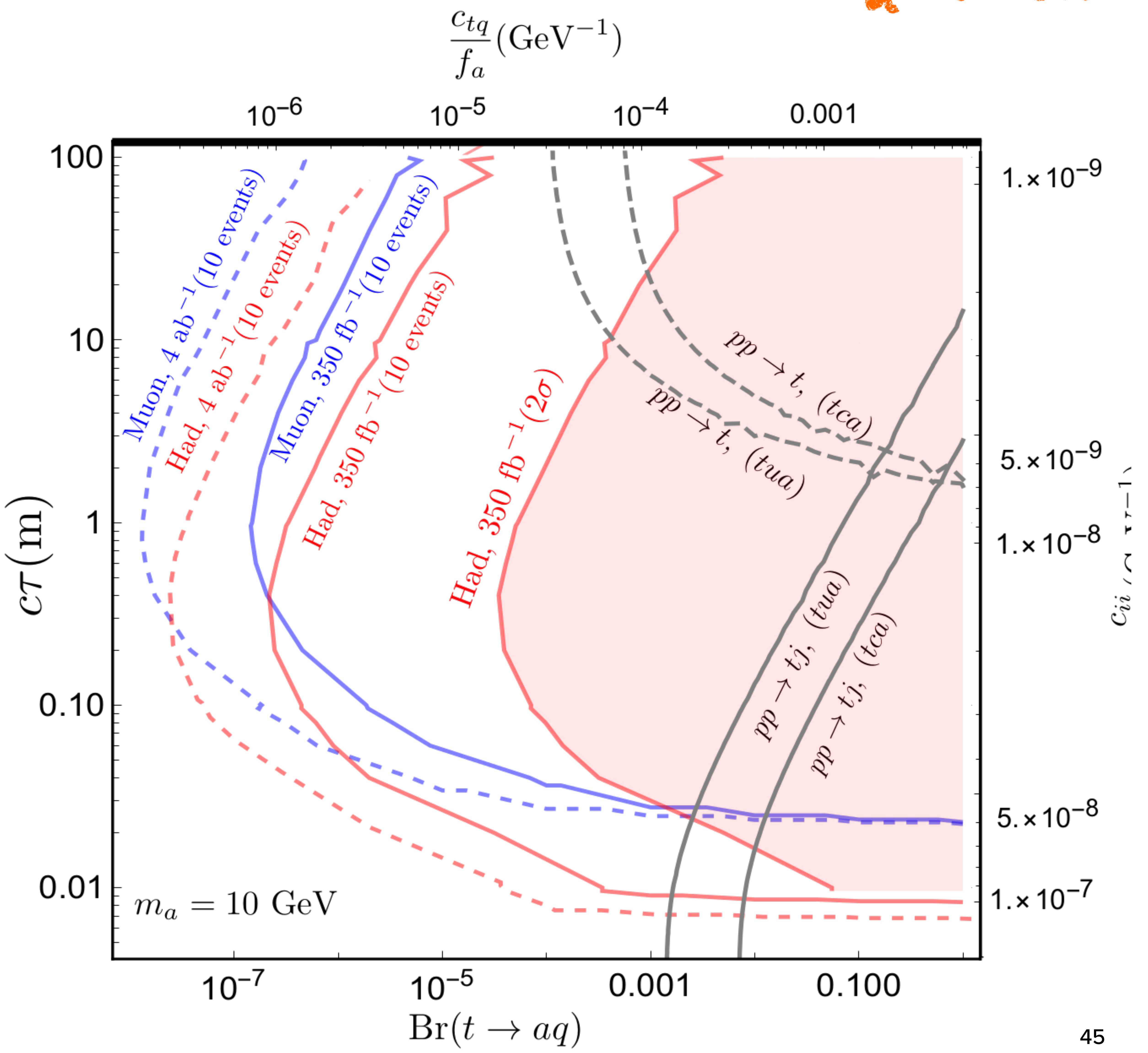


RESULTS

$m_a = 2$ GeV



$m_a = 10$ GeV



CONCLUSIONS

CONCLUSIONS

- ALPs are ubiquitous in beyond the SM physics
- They can be probed by very different and complementary experiments
- Interesting models of Dark Matter and/or Flavor can lead to ALP mediated FCNC
- A direct measurement of $D \to \pi a$ can provide a complementary test of charming ALPS
- Exotic top decays provide a unique way of probing ALPs above the charm threshold
- We can probe $\mathrm{Br}(t \to aq) \lesssim 10^{-4}$ and there is room for improvement!

15 - 17 JUNE 2022

HEFT 2022

[HTTPS://FTAE.UGR.ES/HEFT2022](https://ftae.ugr.es/heft2022)

Register!!

Wed 20 Apr

FTAE High Energy Theory

Speakers | Committee | Program | Participants | Registration | Code of Conduct | Previous editions

HIGGS AND EFFECTIVE FIELD THEORY - HEFT 2022

15-17 June 2022

Salon de Actos del Carmen de la Victoria, Cuesta del Chapiz, 9 (Granada)

HEFT is an annual workshop focusing on the use of effective field theories to search for physics beyond the Standard Model. A broad range of topics are encouraged, ranging from collider phenomenology and formal aspects to the latest experimental updates on dedicated searches. The meeting aims to foster discussions between theorists and phenomenologists from varied backgrounds as well as with experimental colleagues.

We would like to achieve a balance of senior and junior speakers, enhancing the visibility of younger scientists while keeping some overview talks.

This year's edition is organized by (and will be held in) the Dpto. Física Teórica y del Cosmos of the Universidad de Granada. The format of the event will be in-person only.

The workshop will begin on June 15th morning and end after lunch on June 17th.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement and UGR Research and Knowledge Transfer Found – Athenea3i

BACK UP

SN1986A

$$L_a = \int_{r\le R_\nu} dV \int_{m_a}^{\infty} d\omega \left(\frac{dP_a}{dV\,d\omega}\right) e^{-\sigma}$$

$R_\nu \sim O(40\,\text{Km})$

for $r \geq R_\nu$ ν free stream

$R_{far} \sim O(100-1000\,\text{Km})$

for $r \geq R_{far}$ ν are not produced efficiently

$e^{-\sigma}$: probability for an ALP produced with $r < R_\nu$ to reach R_{far}

Otherwise, their energy is converted back to ν

SN1986A

$$L_a = \int_{r \le R_\nu} dV \int_{m_a}^{\infty} d\omega \left(\frac{dP_a}{dV d\omega} \right) e^{-\sigma} \qquad \frac{dP_a}{dV d\omega} = \frac{1}{2\pi^2} \omega^3 \Gamma_a e^{-\omega/T} \beta^2$$

$$\beta = \sqrt{1 - m_a^2/\omega} \qquad \Gamma_a = \Gamma_a^{pp} + \Gamma_a^{nn} + \Gamma_a^{pn} + \Gamma_a^{np} \quad \text{with}$$

$$\Gamma_a^{NN'} = \frac{C_{aNN'}^2 Y_N Y_{N'}}{4 f_a^2} \frac{\omega}{2} \frac{n_B^2 \sigma_{np\pi}}{\omega^2} \gamma_f \gamma_p \gamma_h \qquad n_B = \rho / m_N$$

$\sigma_{np\pi} = 4 \alpha_\pi^2 \sqrt{\pi T / m_N^5}$ $\quad \gamma_f, \gamma_p, \gamma_h$ correction factors $\quad \rho(r), T(r)$

COSMO BOUNDS

- Bounds can be directly applied when the decay to electron pairs dominate
- When the decay to pair of muons dominate, the limits are conservative since muon decays also heat the neutrino bath, reducing the impact of N_{eff}
- When $a \to 3\pi$ dominates, bounds from $^4\mathrm{He}$ overproduction (the dominant bound in this region) still holds, since only a minimal amount of charged pions is enough for this bound to apply
- For even larger masses, ALP decays into hadrons will eventually make its lifetime shorter than a second, making nucleosynthesis constraints harmless

FIXED TARGET EXPERIMENTS

Experiment	distance from IP	length of decay volume	radius/opening angle	N_D
FASER	480 m	1.5 m	0.1 m	1.1×10^{15}
FASER2	480 m	5 m	1 m	2.2×10^{16}
MATHUSLA	68 m downstream, 60 m above	100 m	25 m high	2.2×10^{16}
NA62	80 m	65 m	$\theta_{\max} = 0.05$	2×10^{15}
SHiP	60 m	50 m	2.5 m	6.8×10^{17}
CHARM	480 m	35 m	$0.0068 < \theta < 0.0126$	4.08×10^{15}