ADRIAN CARMONA BERMUDEZ

THE ALPS FROM THE TOP

6th Red LHC workshop - Madrid IFT

athenea 3i

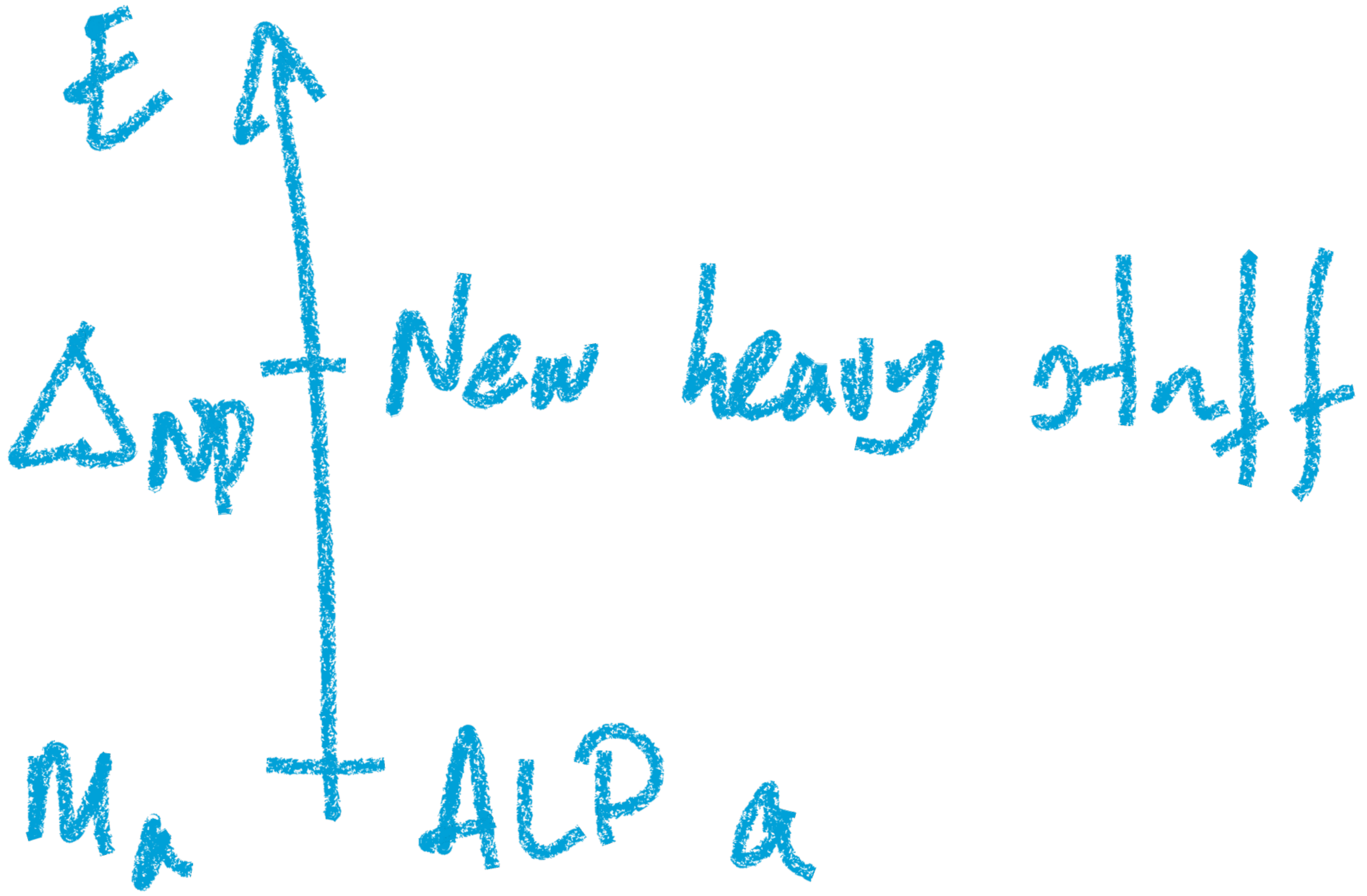
OFPI
Oficina de Proyectos Internacionales

UNIVERSITAS GRANATENSIS
PLUS ULTRA
1531
UNIVERSIDAD DE GRANADA

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



$a \to a + \theta$

ALP shift symmetry

ALP + SM EFT

ALP EFT above the electroweak scale

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

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

We assume the following EFT at the UV (CHARMING ALPS)

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

ALP + SM EFT

ALP EFT above the electroweak scale

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

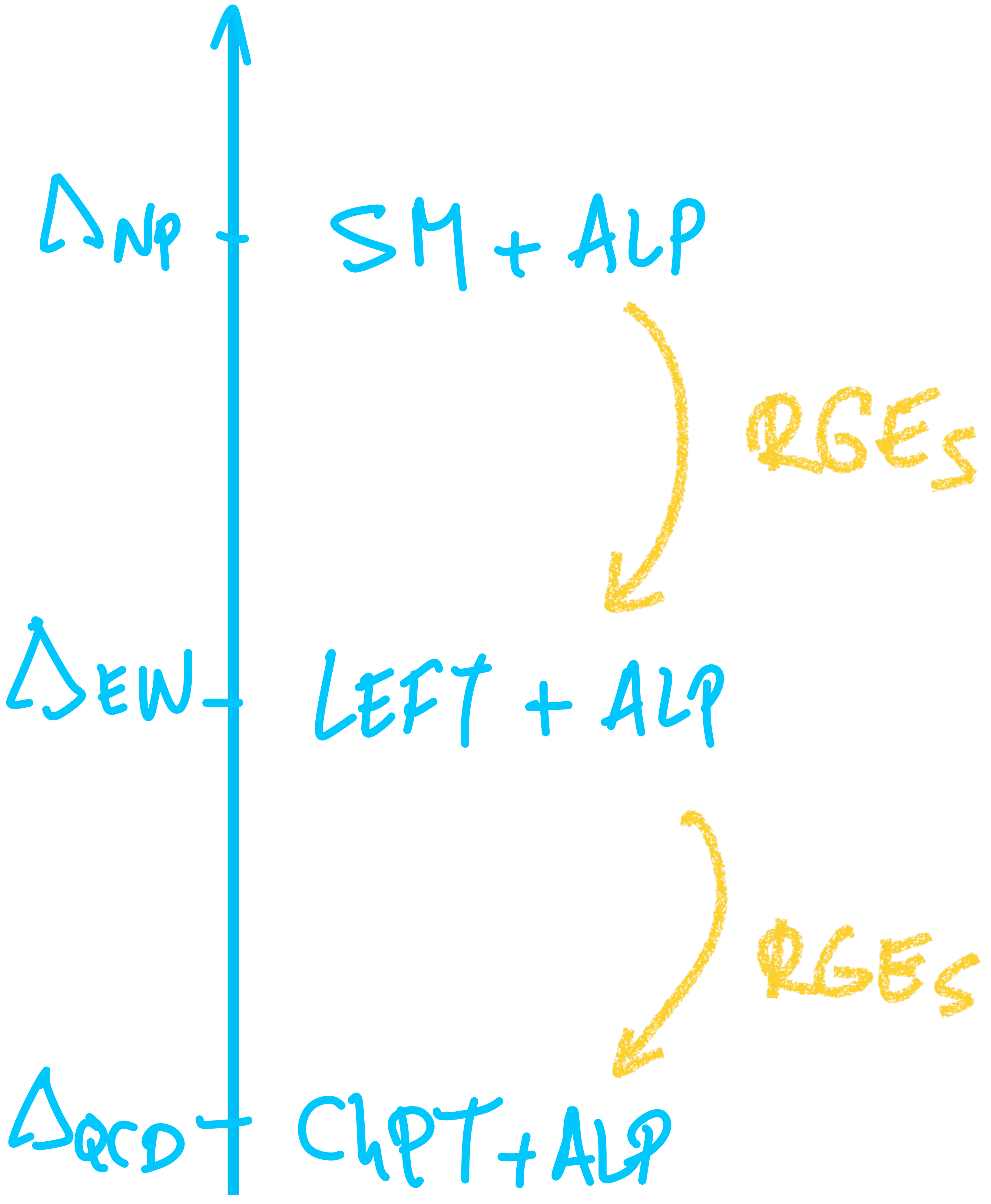
$$\mathscr{L} = \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{m_a^2}{2}a^2 + \frac{\partial_\mu a}{f_a}\sum_\psi \left(c_\psi\right)_{ij}\bar{\psi}_i\gamma^\mu\psi_j$$
$$-\frac{a}{f_a}\left[c_{GG}\frac{g_3^2}{32\pi^2}G^a_{\mu\nu}\tilde{G}^{a\,\mu\nu} + c_{WW}\frac{g_2^2}{32\pi^2}W^I_{\mu\nu}\tilde{W}^{I\,\mu\nu}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

We assume the following EFT at the UV (CHARMING ALPS)

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

$\leftarrow$ Dark QCD

ONE NEEDS TO RUN



Choi et al, 1708.00021
Chala et al, 2012.09017
Bauer et al, 2012.12272
Bonilla et al, 2107.11392

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!

ALPS PHENOMELOGY

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

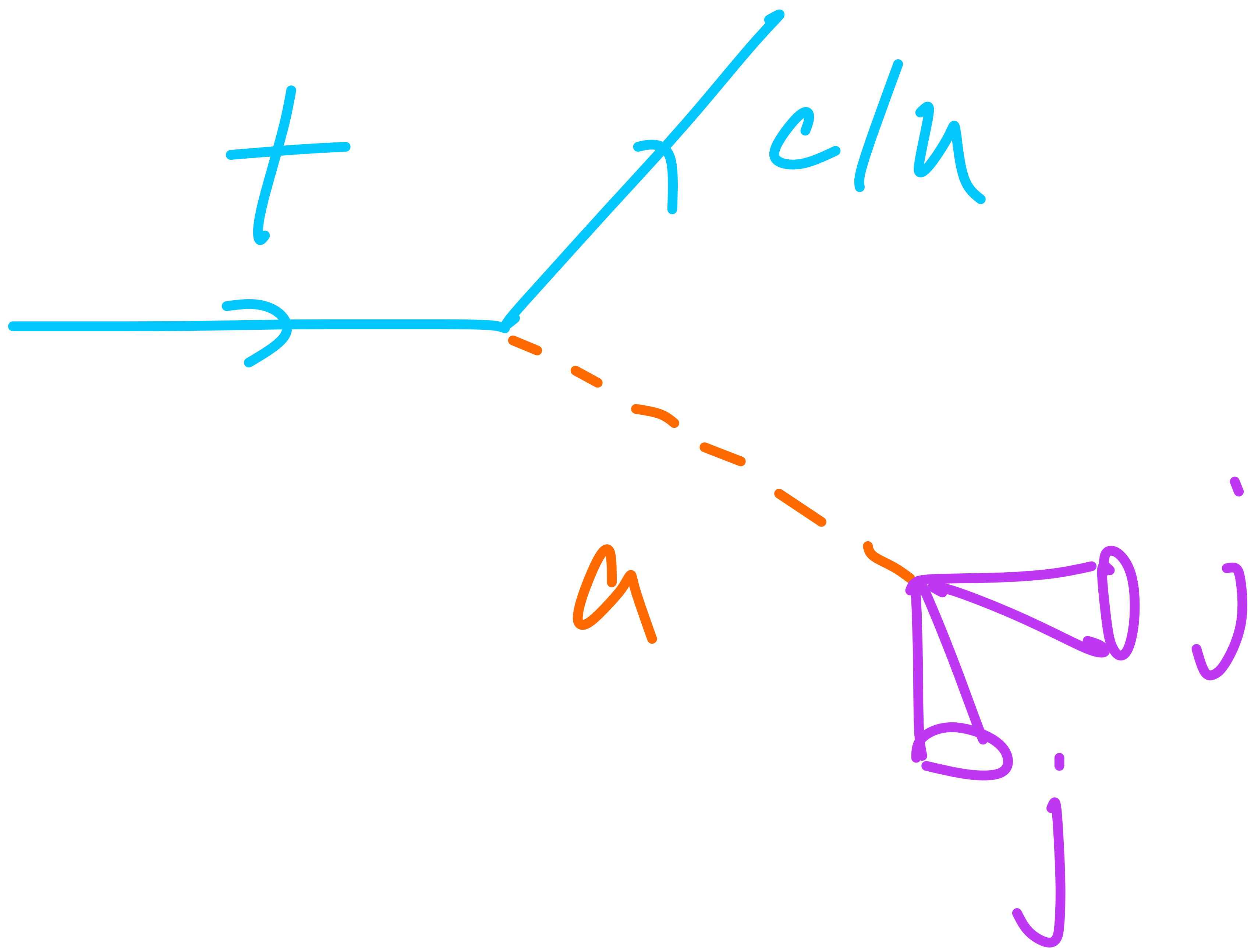
'Charming ALPs' AC, Scherb, Schwaller. JHEP 08 (2021) 121, arXiv: 2101.0783

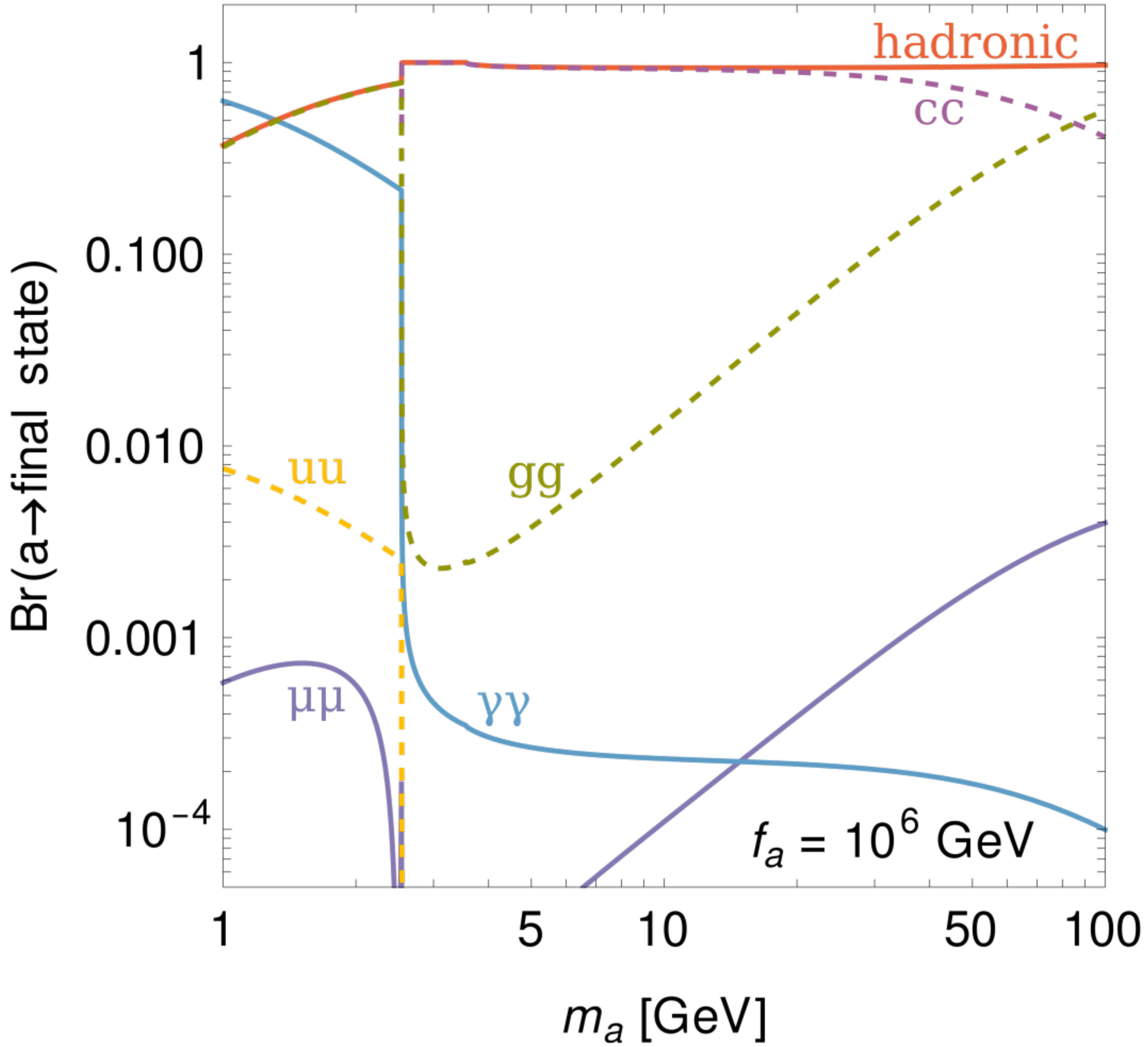
'The ALPs from the Top: Searching for long-lived axion-like particles from exotic top decays' AC, Elahi, Scherb, Schwaller. arXiv: 2202.0973

ALPS FROM THE TOP

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

Probe charming ALPs above charm threshold

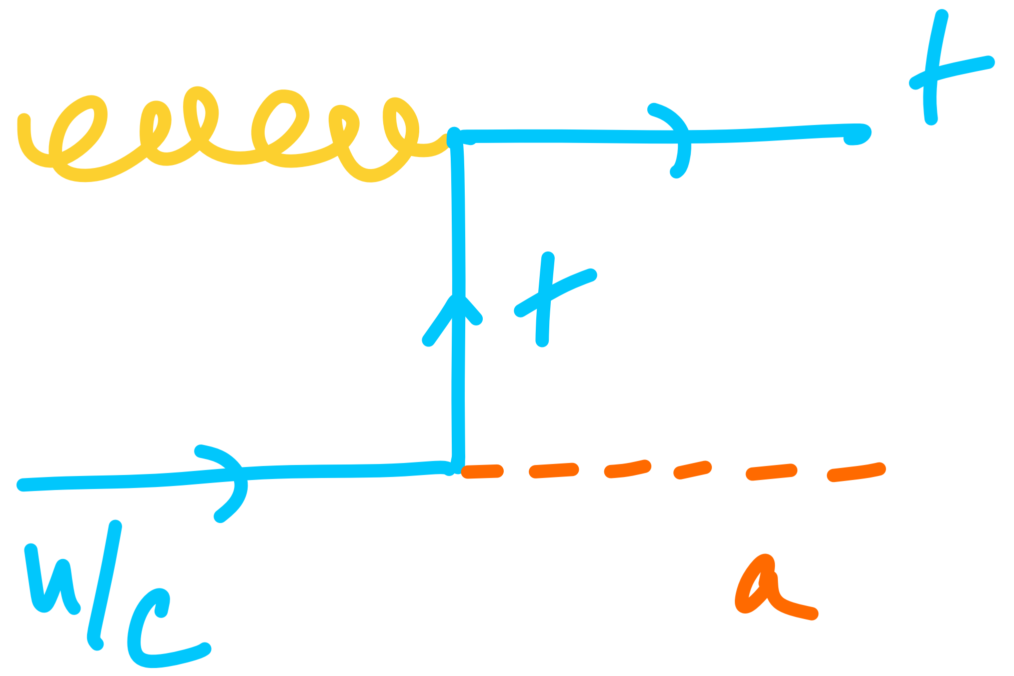


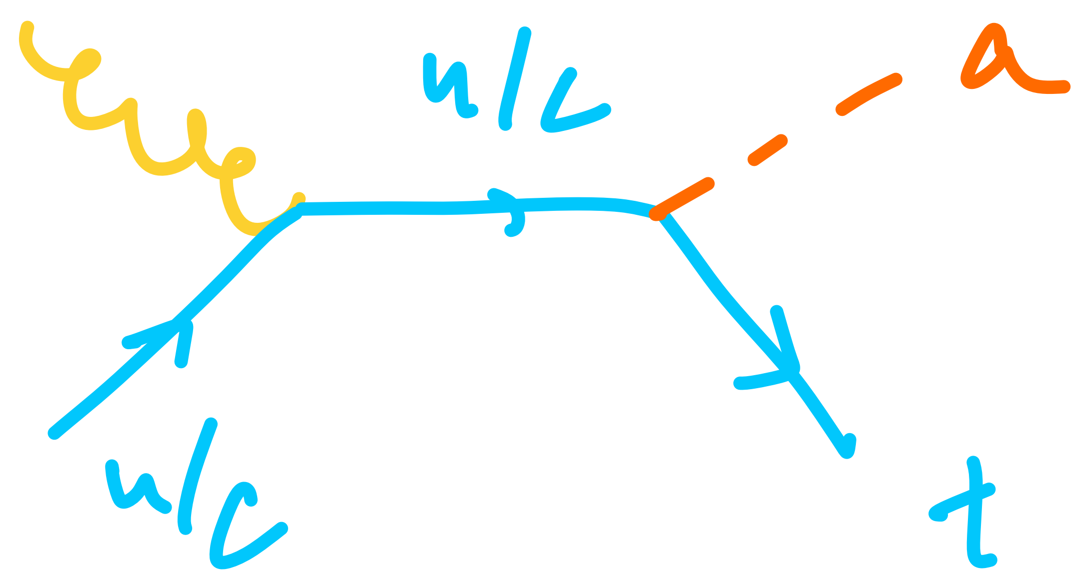


We trade diagonal and off-diagonal (equal) entries of c_{u_R} by $\mathrm{Br}(t \to a q_i)$ and $c\tau$

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

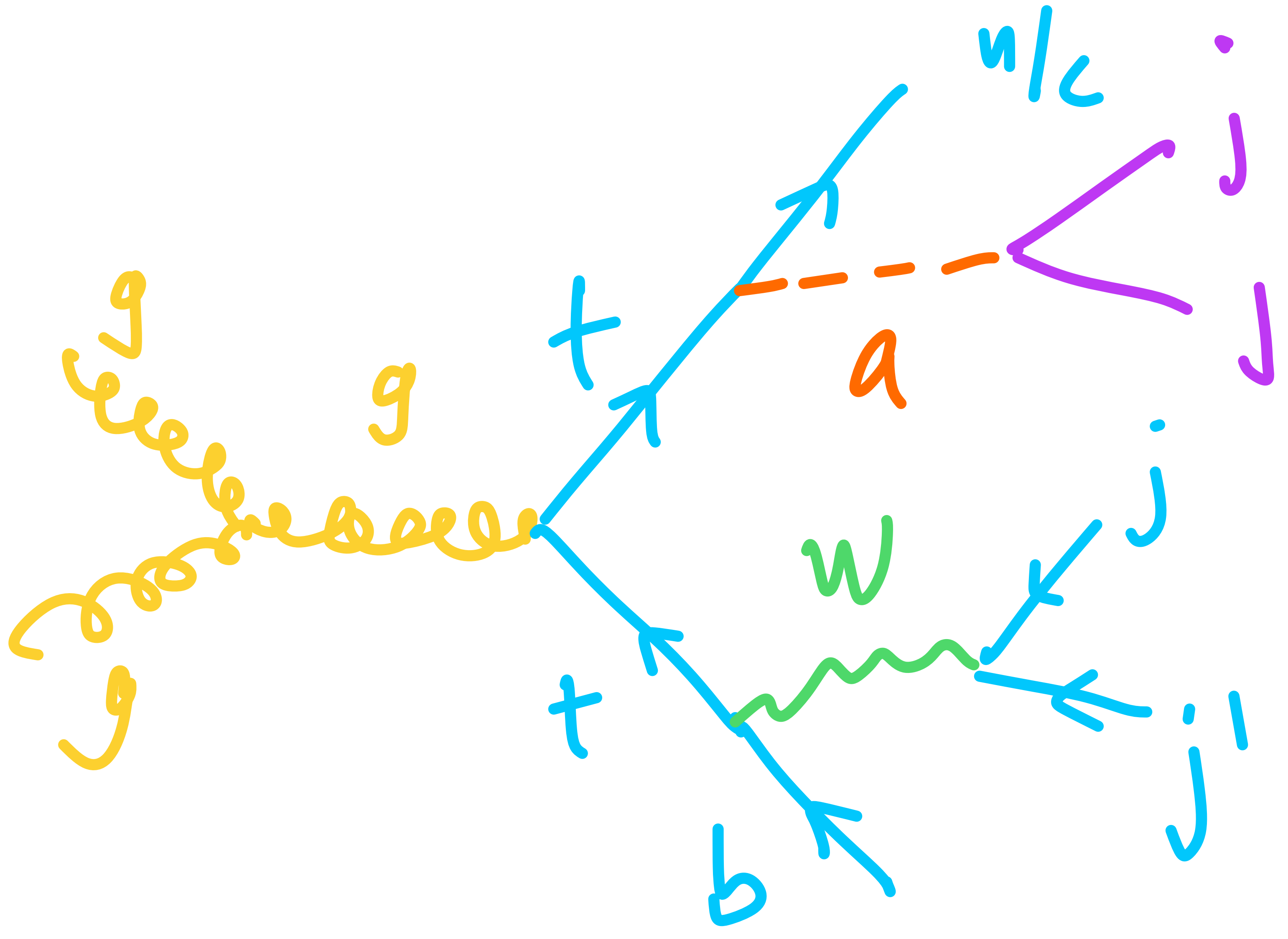
$$\int_{2.5\cdot 10^{-2}\,\mathrm{m}}^{2\,\mathrm{m}} (\gamma c\tau)^{-1} \exp\left(-\frac{ct}{\gamma c\tau}\right) d(ct)$$

'STABLE'

$c\tau \geq 10$ m

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

SIGNAL



We consider two benchmarks with ALP masses

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

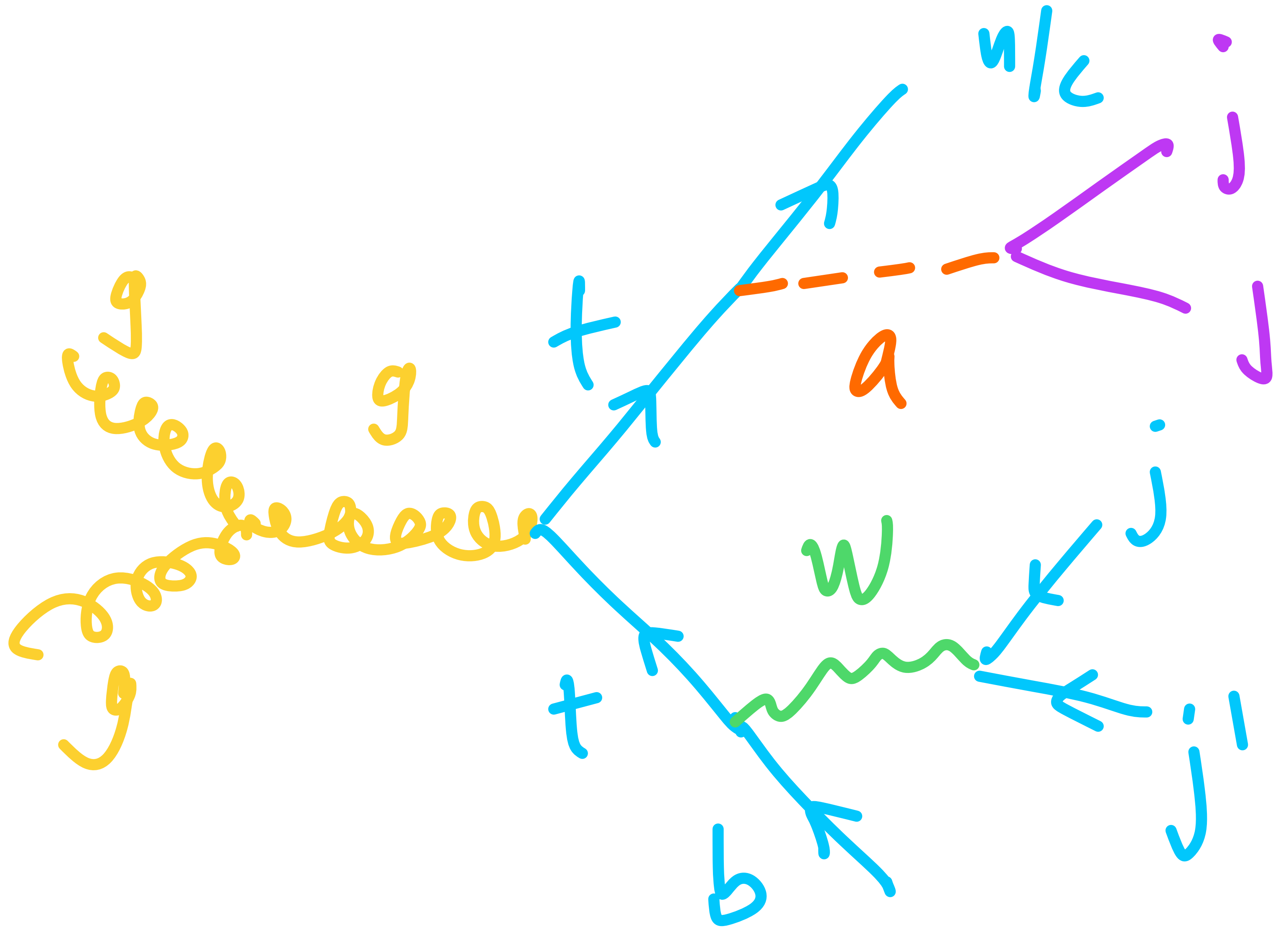
$$\sigma_{\text{signal}} = \sigma_{tt} \cdot \text{Br}(t \to Wb) \cdot \text{Br}(t \to aq)$$

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

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

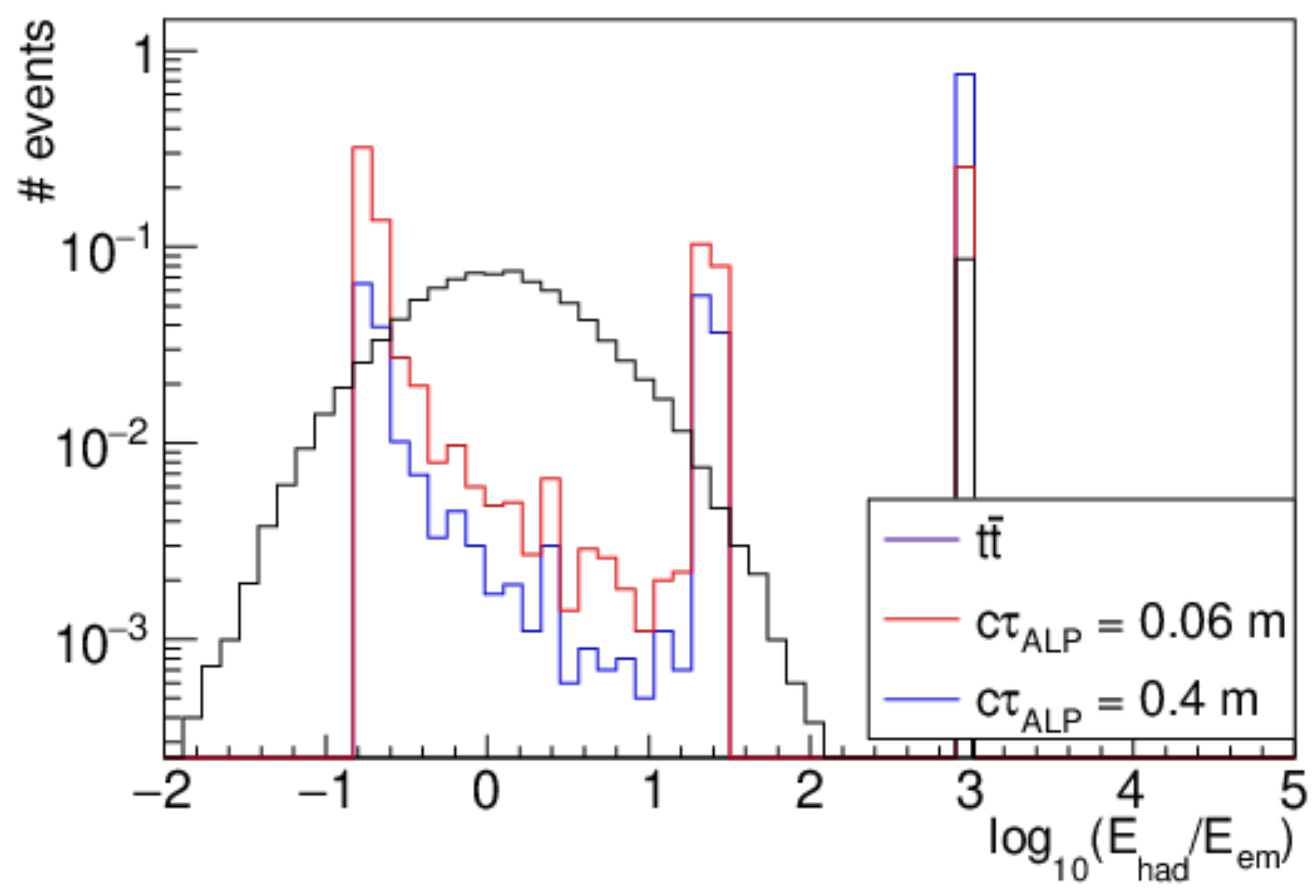
The ALP decay mostly in the ↗ hadronic calorimeter
↘ muon spectrometer

SIGNAL : HADRONIC CALORIMETER

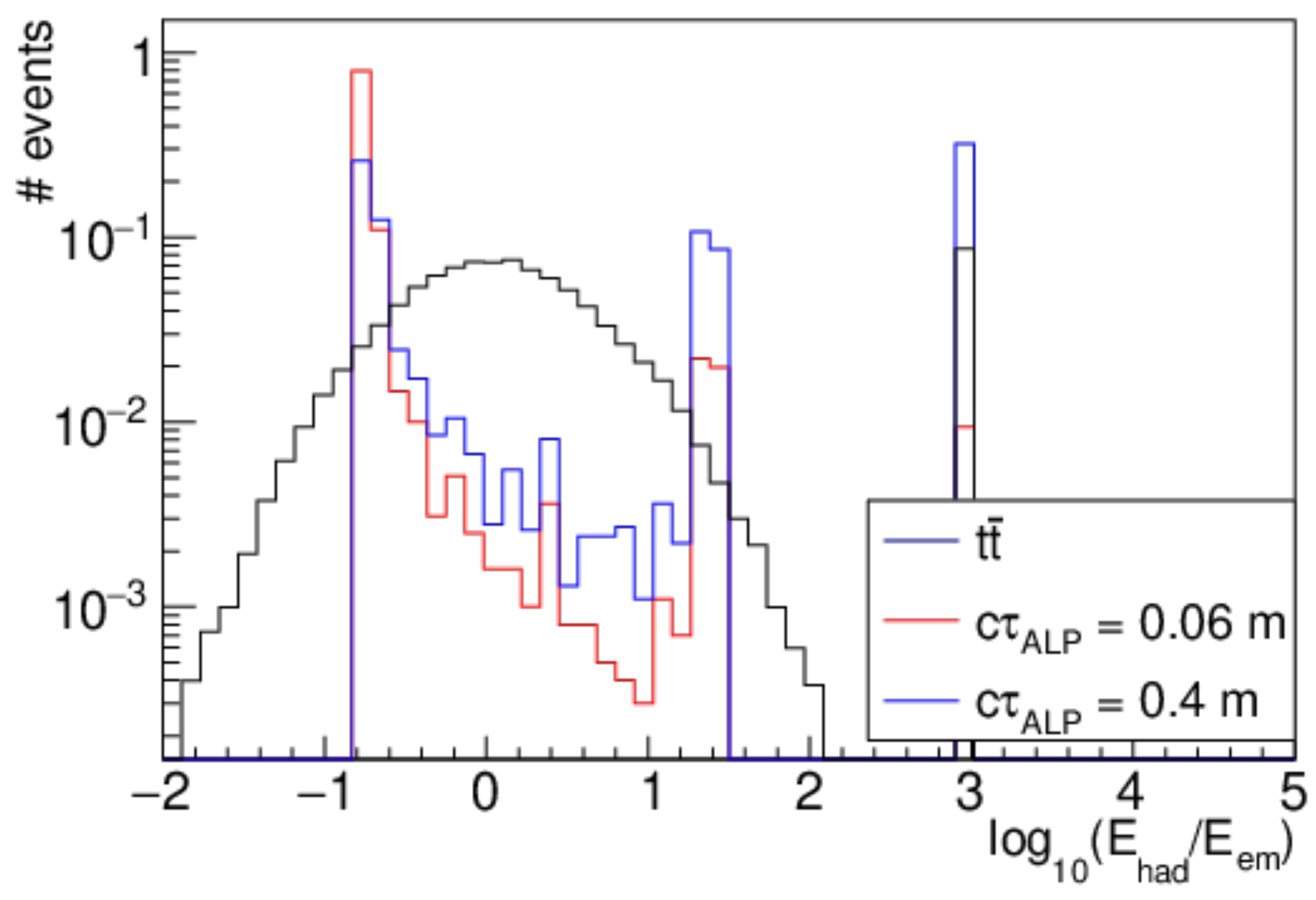


- Large Ehad/Ecal ratio
- No tracks in the displaced jet
- 3-5(6) jets with 1(2) displaced and another b-tagged

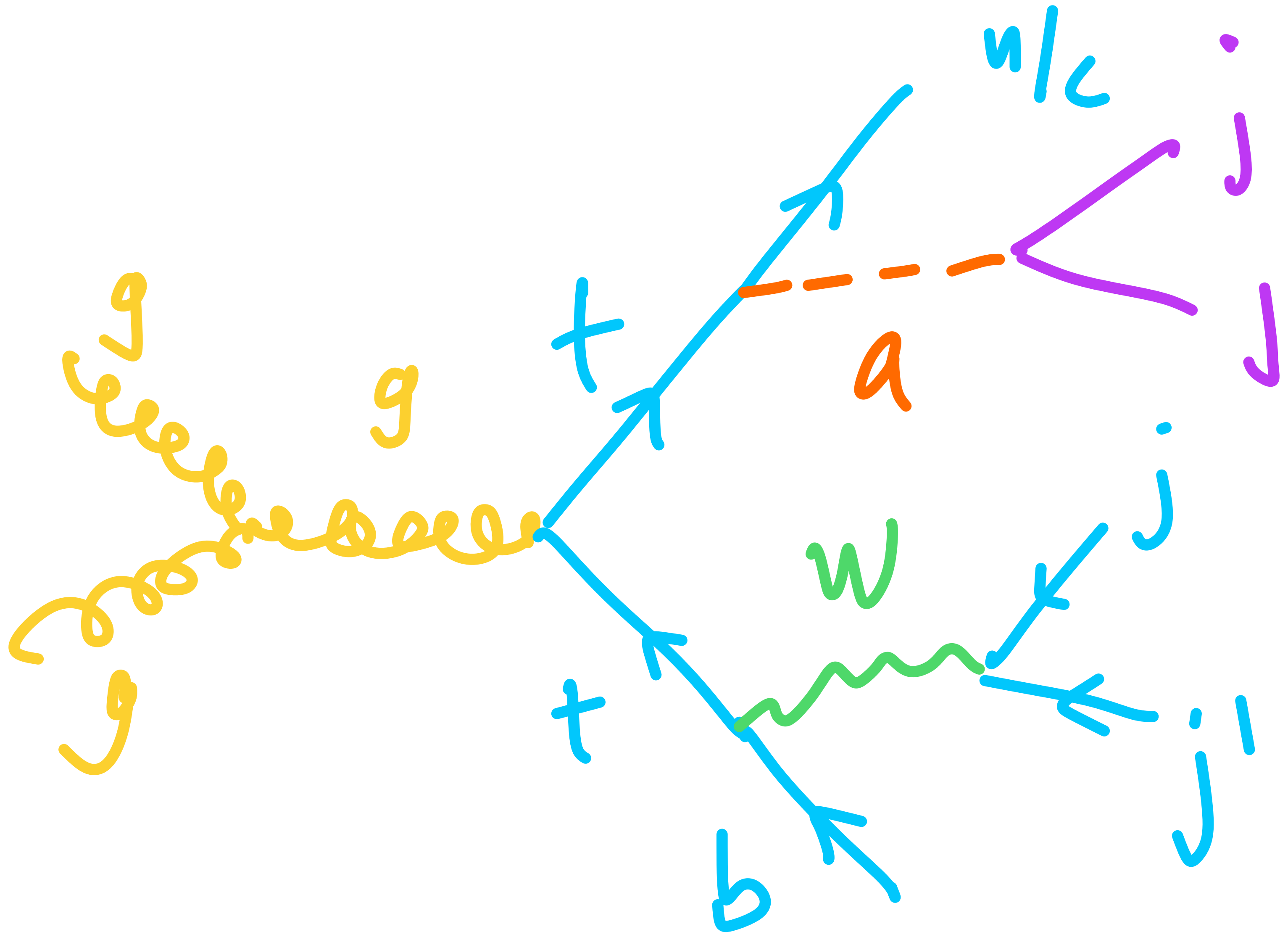
$m_a = 2$ GeV



$m_a = 10$ GeV

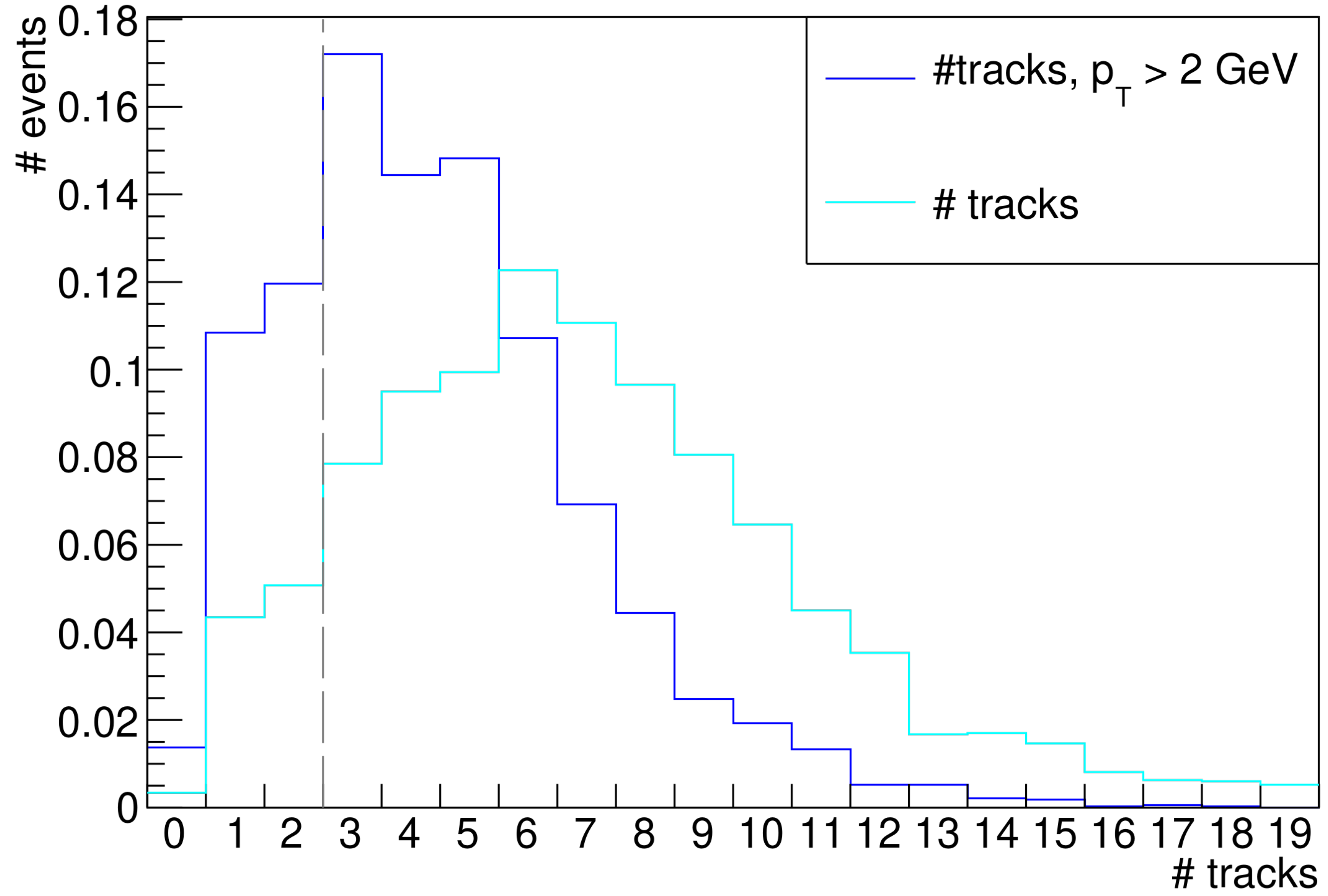


SIGNAL : HADRONIC CALORIMETER

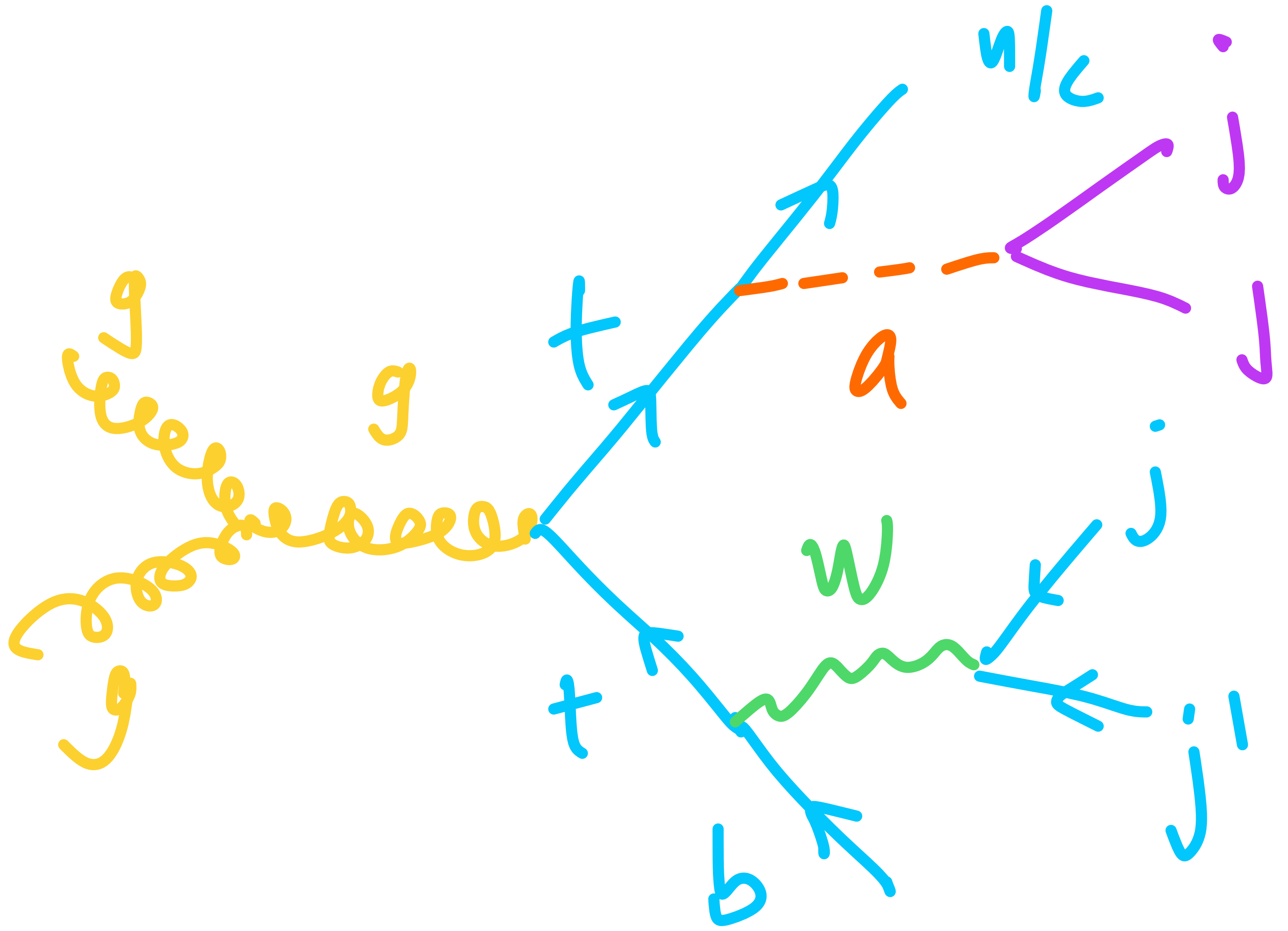


- Large Ehad/Ecal ratio
- No tracks in the displaced jet
- 3-5(6) jets with 1(2) displaced and another b-tagged

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



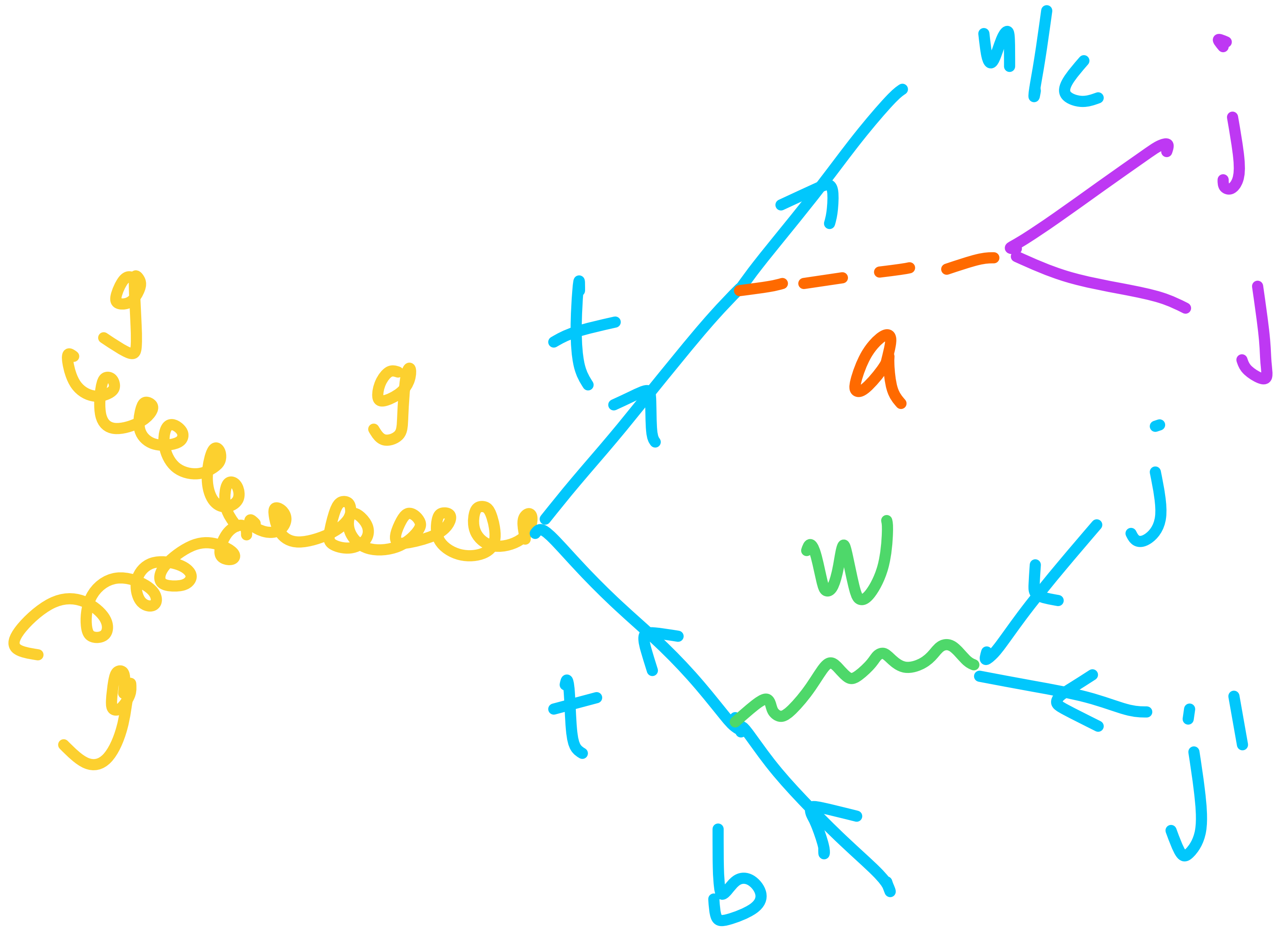
SIGNAL : HADRONIC CALORIMETER



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

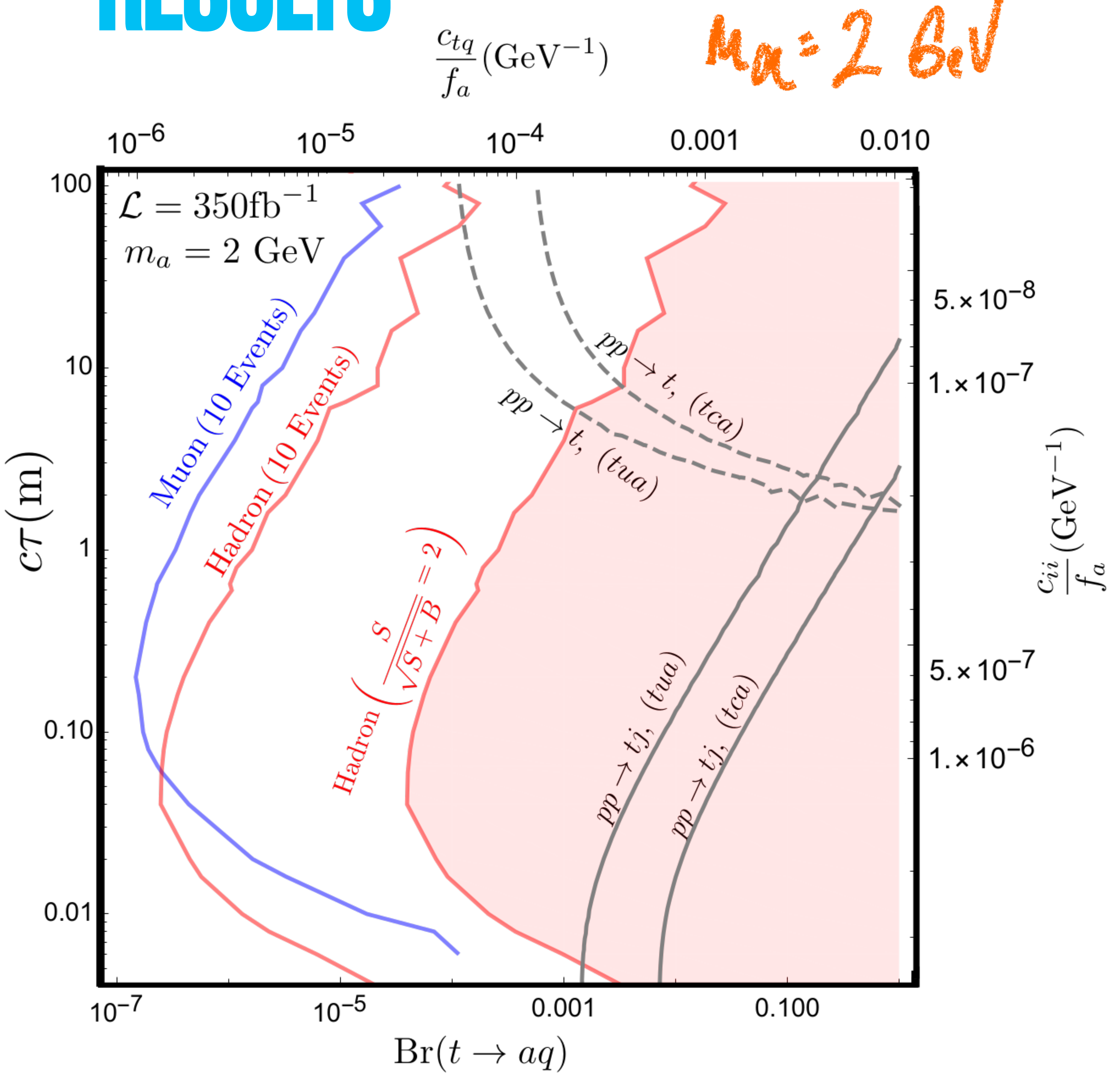
	$\mathbf{m_a = 2\ GeV}$	$\mathbf{m_a = 10\ GeV}$	$\mathbf{t\bar{t}}$
total	$(1)\ 2.79 \times 10^5$	$(1)\ 2.79 \times 10^5$	$(1)\ 2.91 \times 10^8$
3 – 6 jets with $\mathbf{p_T > 40\ GeV\ \&\ \lvert\eta\rvert < 2.5}$	$(0.8439)\ 2.35 \times 10^5$	$(0.8414)\ 2.35 \times 10^5$	$(0.71801)\ 2.09 \times 10^8$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

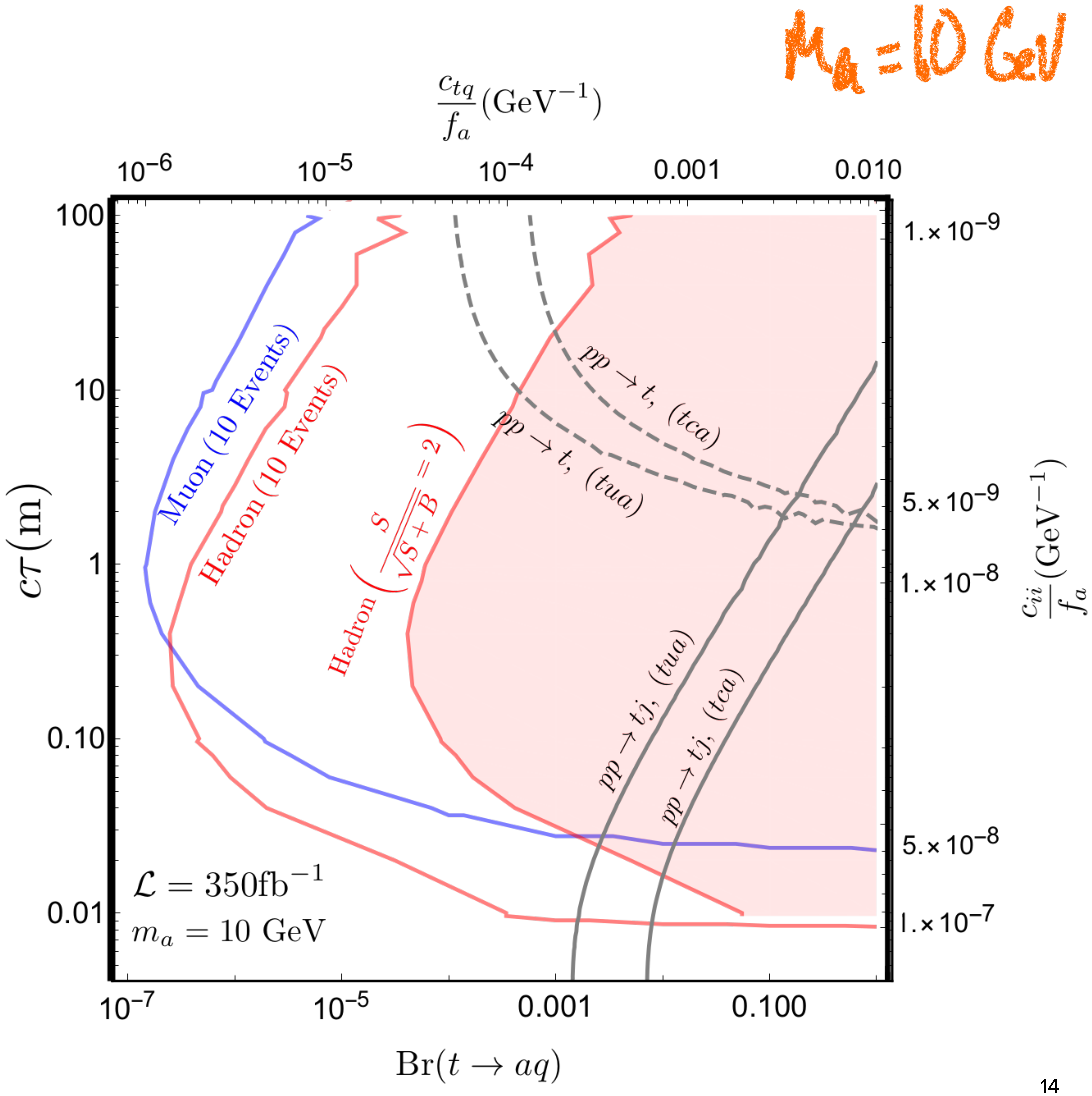
SIGNAL : MUON SPECTROMETER



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

RESULTS

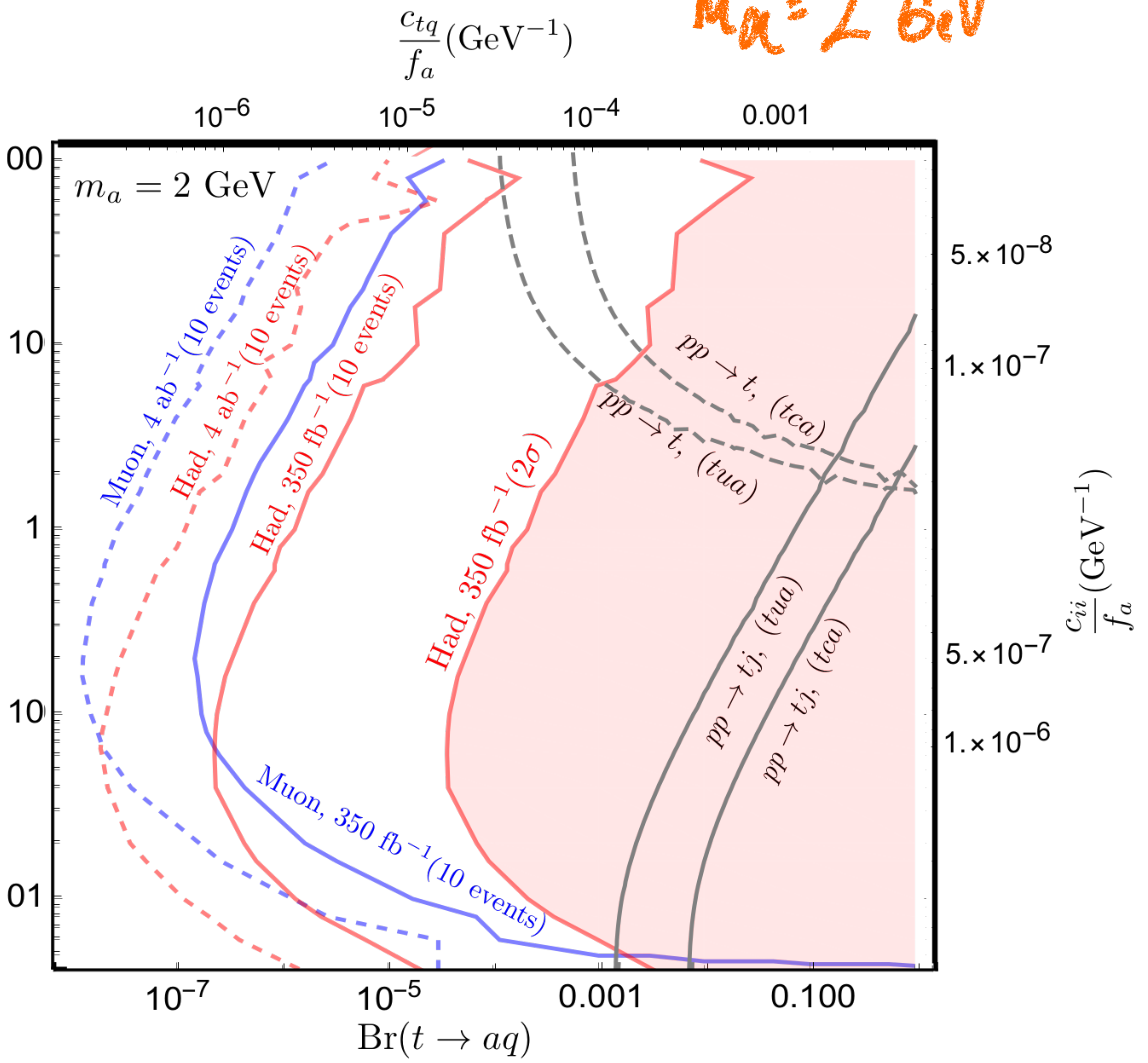

$m_a = 2$ GeV
$\frac{c_{tq}}{f_a}(\mathrm{GeV}^{-1})$
$\mathcal{L} = 350\mathrm{fb}^{-1}$
$m_a = 2$ GeV
Muon (10 Events)
Hadron (10 Events)
Hadron $\left(\frac{S}{\sqrt{S+B}} = 2\right)$
$pp \to t, (tca)$
$pp \to t, (tua)$
$pp \to tj, (tua)$
$pp \to tj, (tca)$
$c\tau\,(\mathrm{m})$
$\mathrm{Br}(t \to aq)$
$\frac{c_{ii}}{f_a}(\mathrm{GeV}^{-1})$

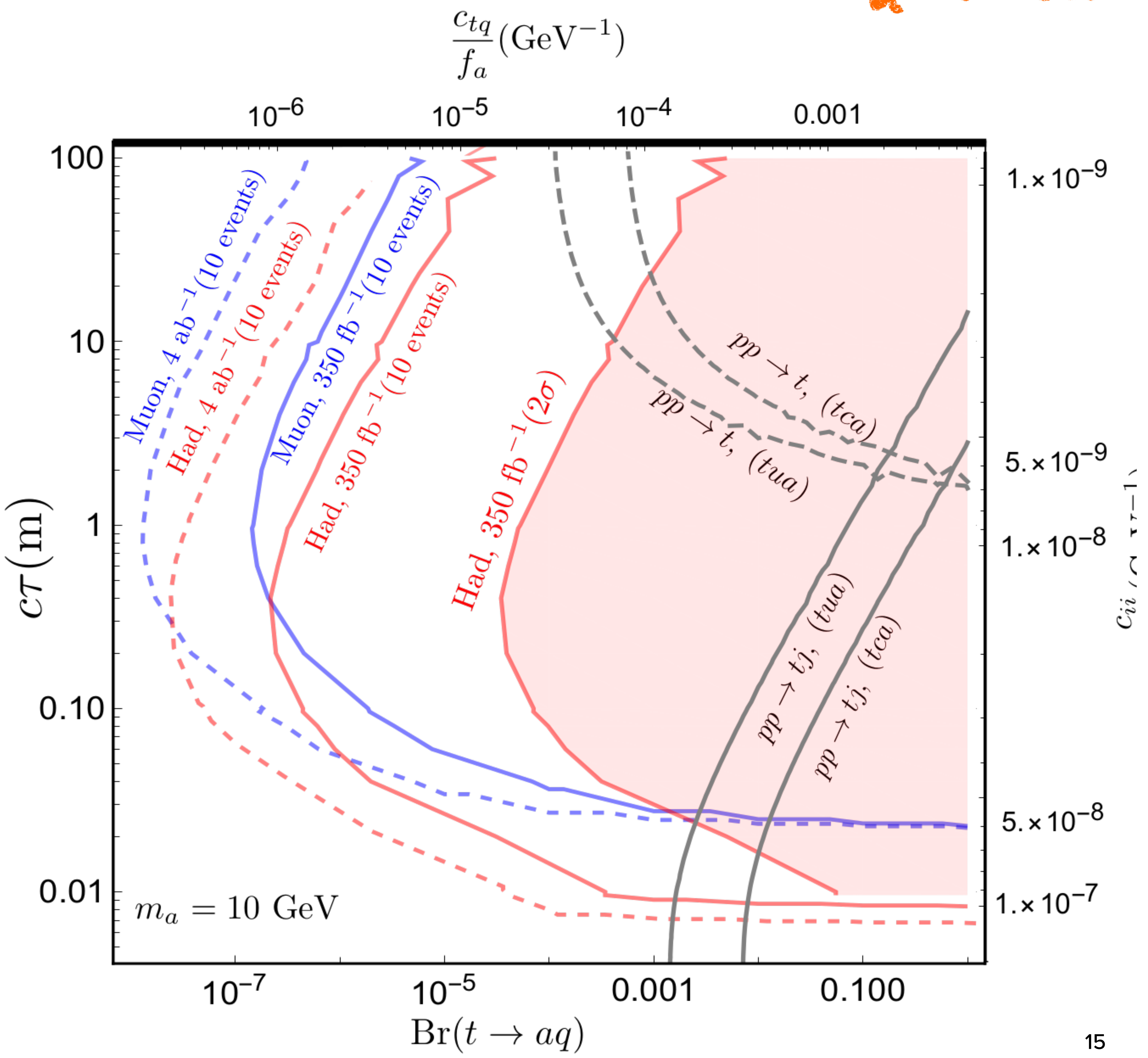

$m_a = 10$ GeV
$\frac{c_{tq}}{f_a}(\mathrm{GeV}^{-1})$
$\mathcal{L} = 350\mathrm{fb}^{-1}$
$m_a = 10$ GeV
Muon (10 Events)
Hadron (10 Events)
Hadron $\left(\frac{S}{\sqrt{S+B}} = 2\right)$
$pp \to t, (tca)$
$pp \to t, (tua)$
$pp \to tj, (tua)$
$pp \to tj, (tca)$
$c\tau\,(\mathrm{m})$
$\mathrm{Br}(t \to aq)$
$\frac{c_{ii}}{f_a}(\mathrm{GeV}^{-1})$

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
- 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

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.

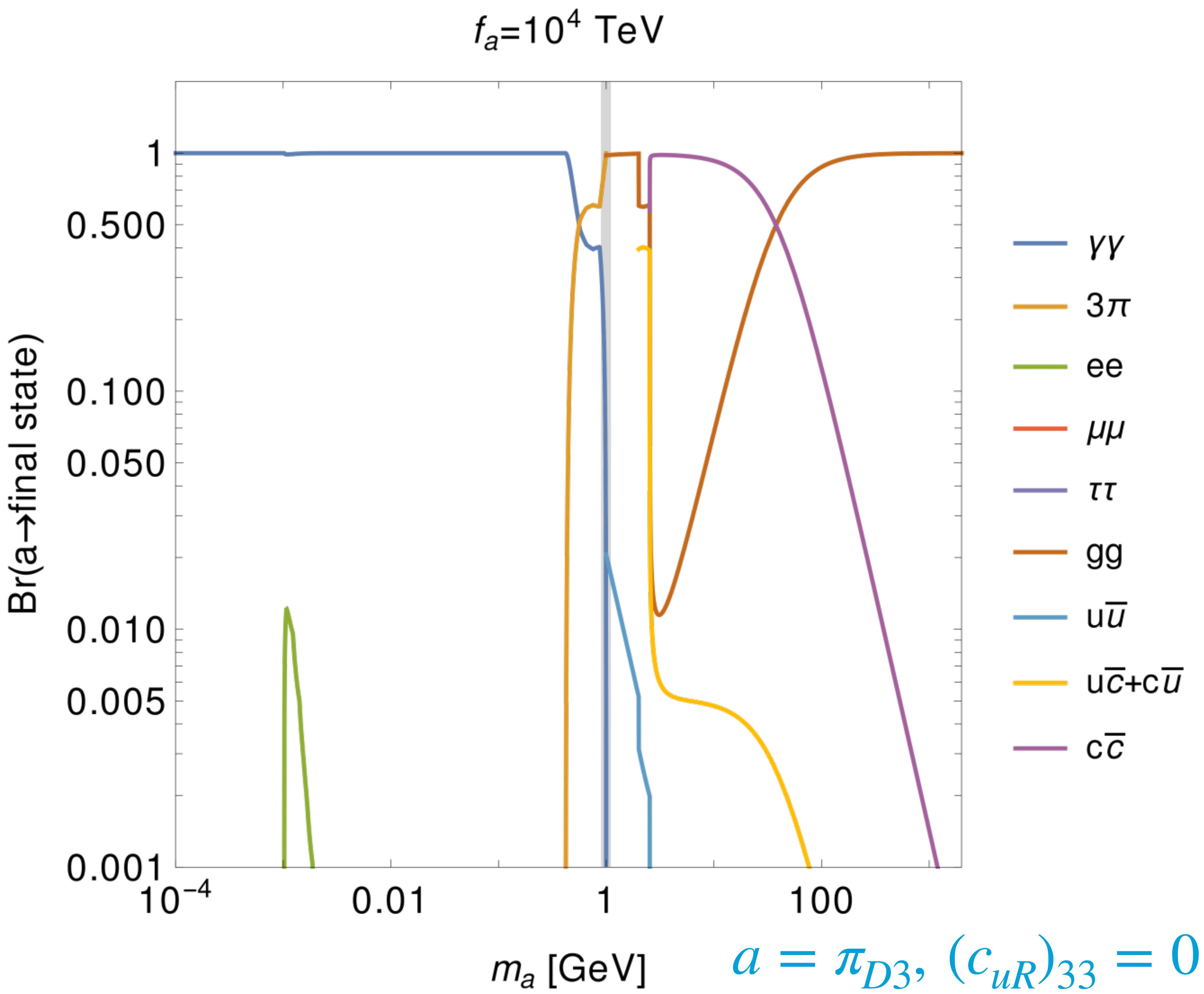
This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement and UGR Research and Knowledge Transfer Found – Athenea3i

BACK UP

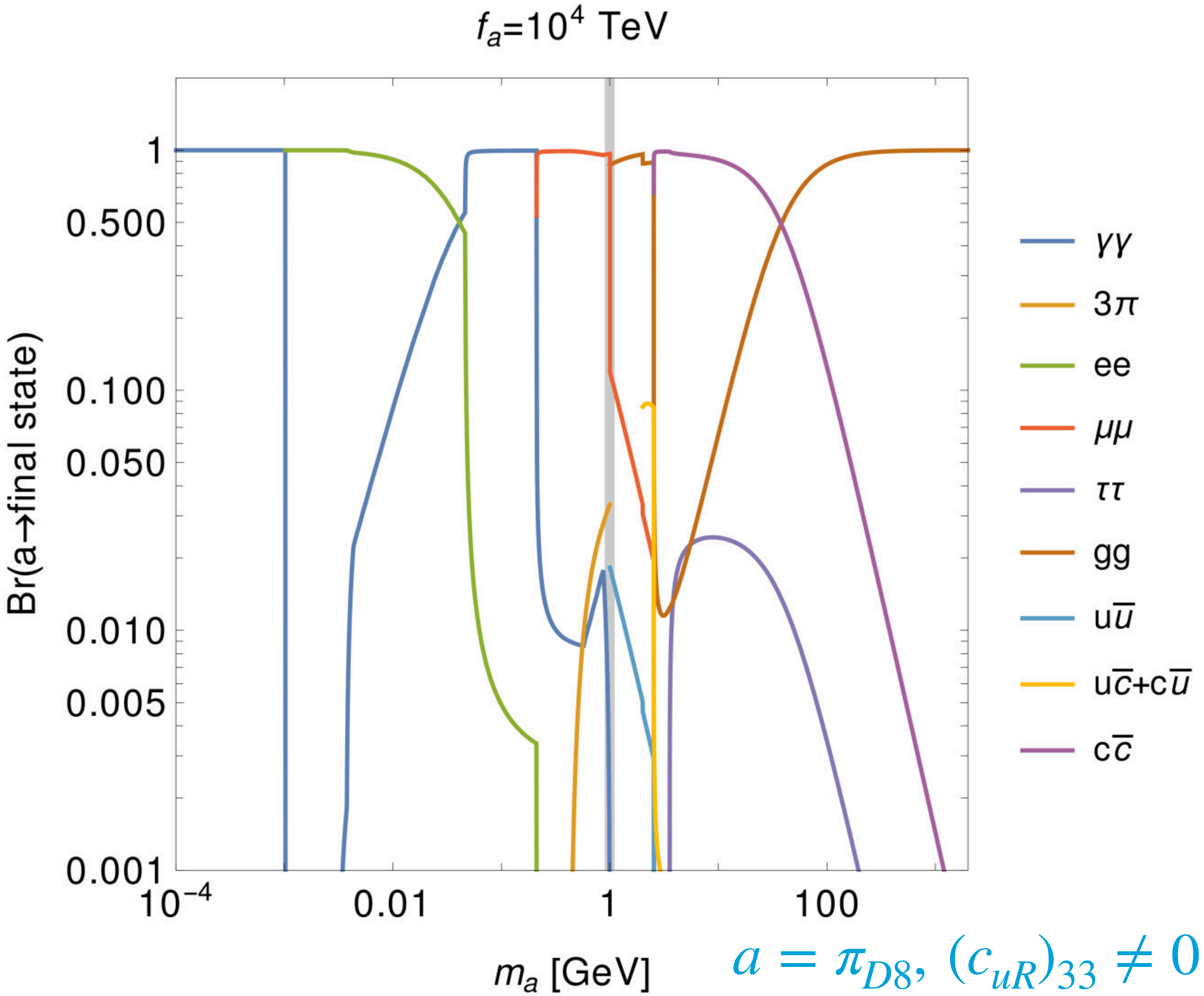
CHARMING ALPS

RGEs and heavy-quark loop induced processes will lead to

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

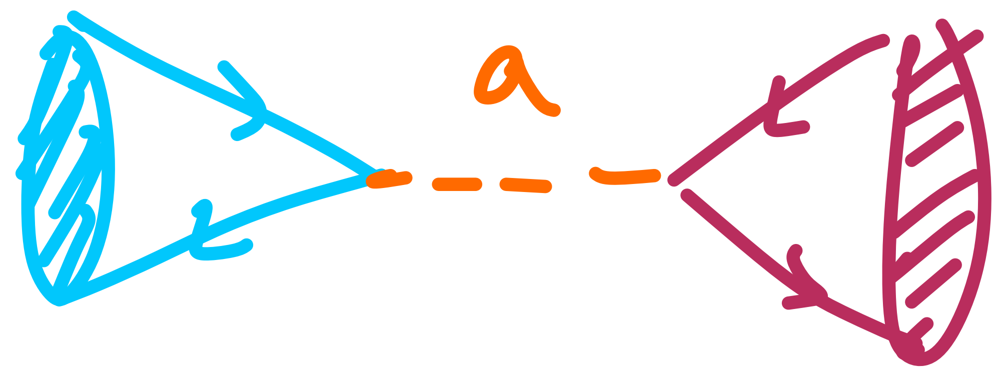


$a = \pi_{D3},\ (c_{uR})_{33} = 0$

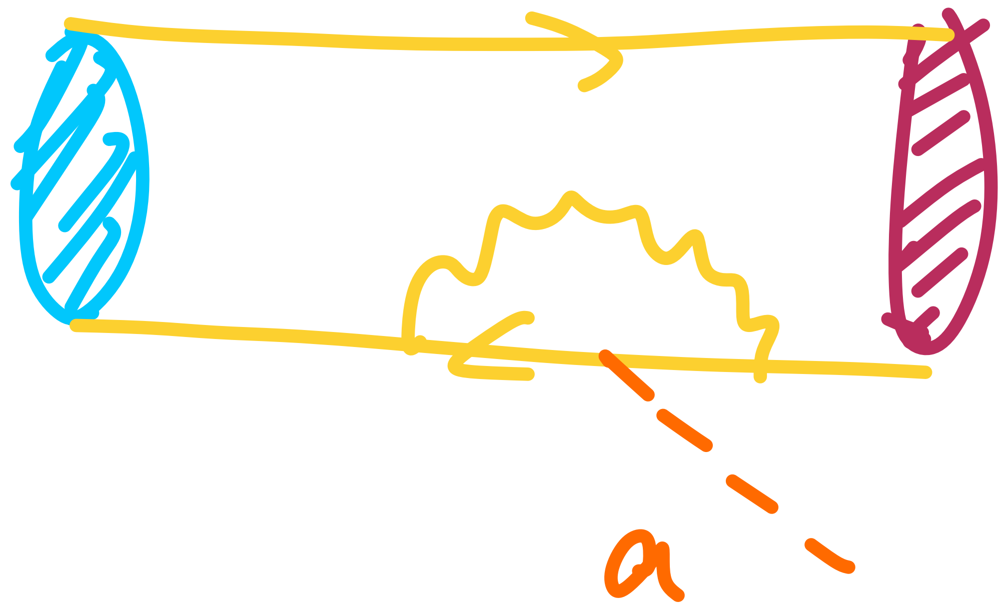


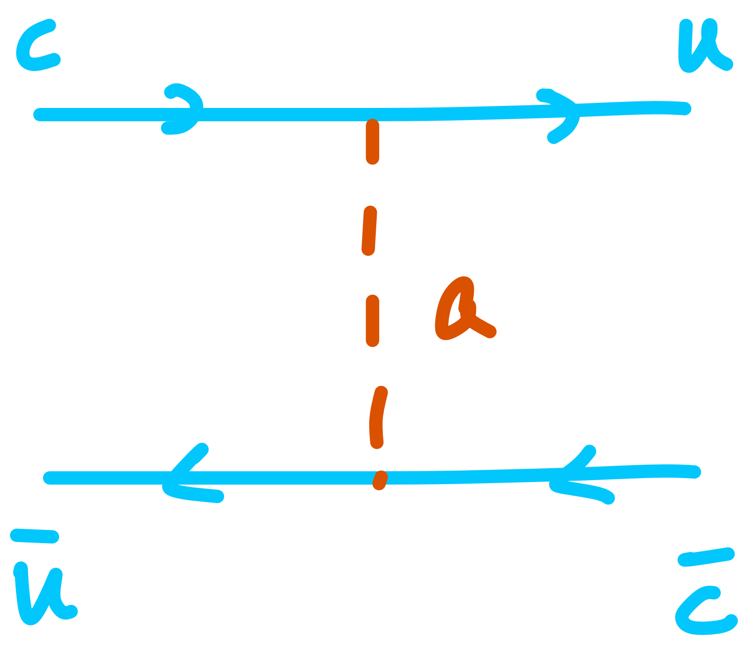
$a = \pi_{D8},\ (c_{uR})_{33} \neq 0$

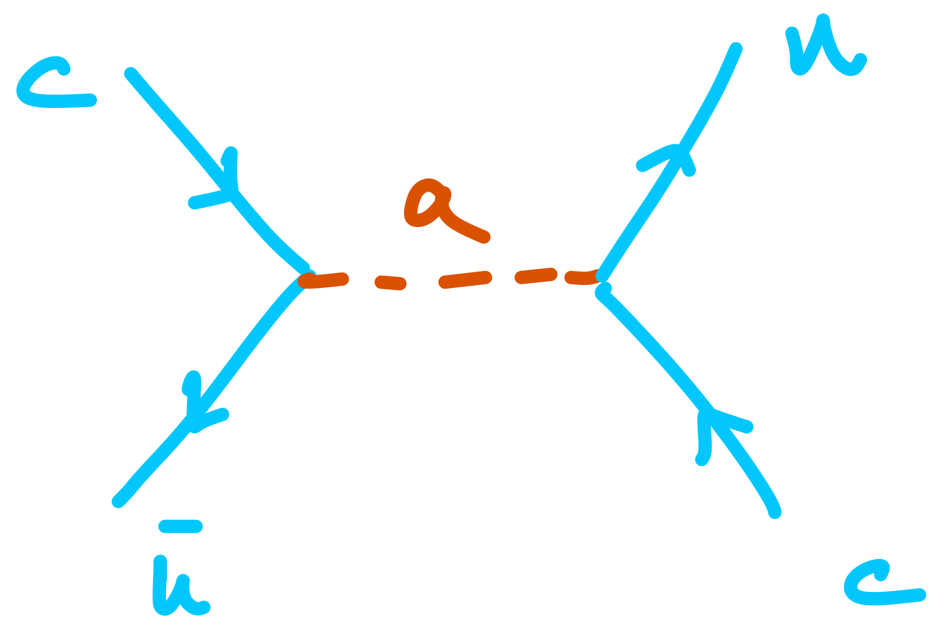
FLAVOR BOUNDS

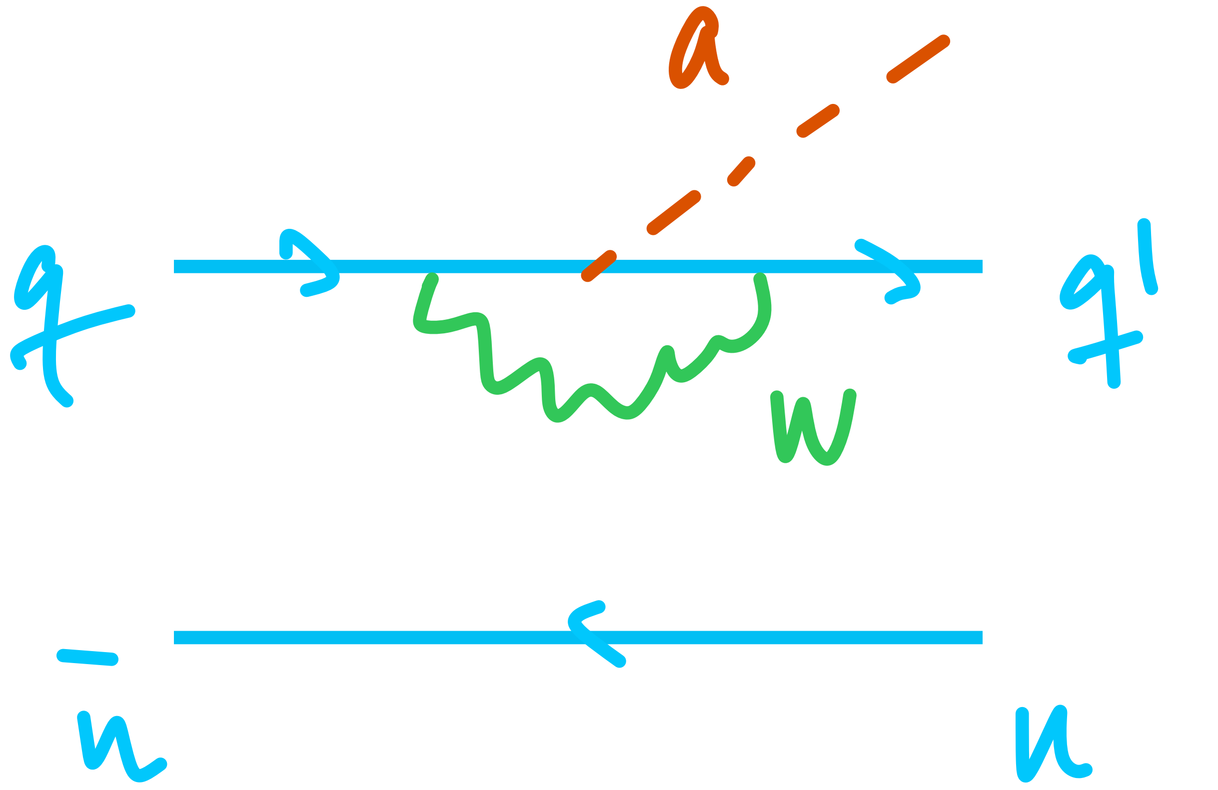


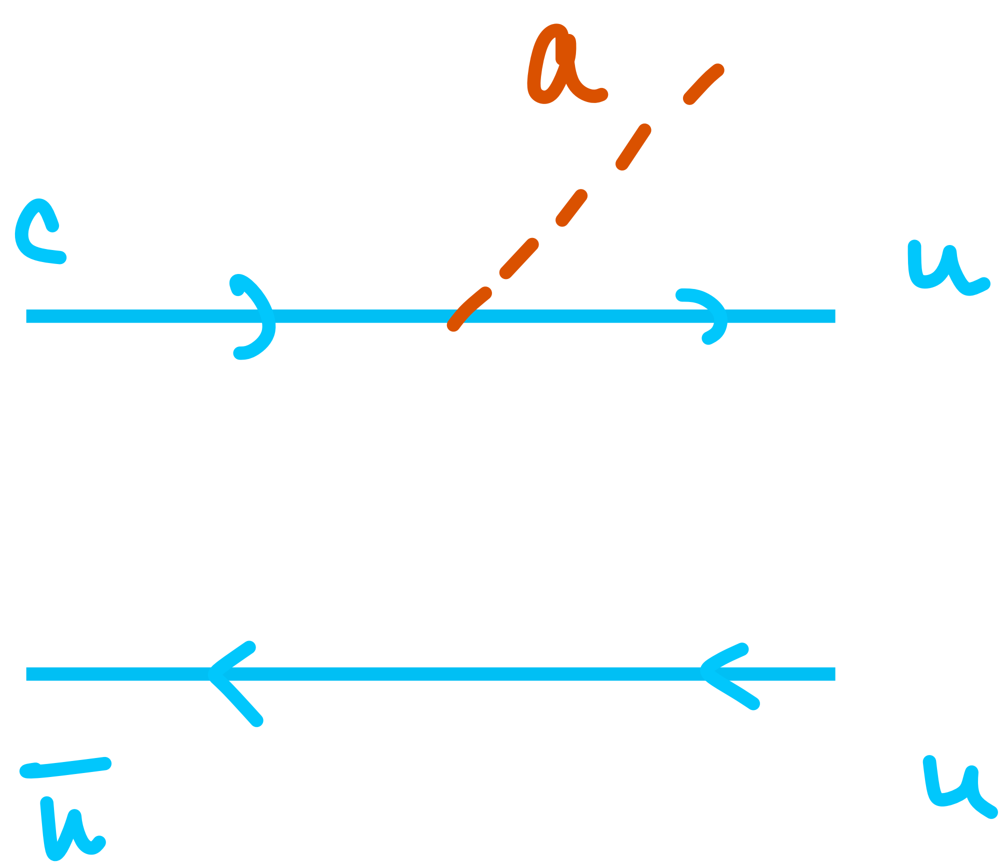
$D - \bar{D}$ mixing











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

$D \to \pi a$

FLAVOR BOUNDS

- $D^+ \to (\tau^+ \to \pi^+ \nu)\bar{\nu}$ recasted with M^2_{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 $50\,\text{ab}^{-1}$ and $K^\pm \to \pi^\pm \bar{\nu}\nu$ at NA62
- Recasts done with the CLs method

ASTRO & COSMO BOUNDS

Red Giant bursts

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

$g_{aee} < 1'6 \cdot 10^{-13}$

SN1987a

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

Bremsstrahlung

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

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

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

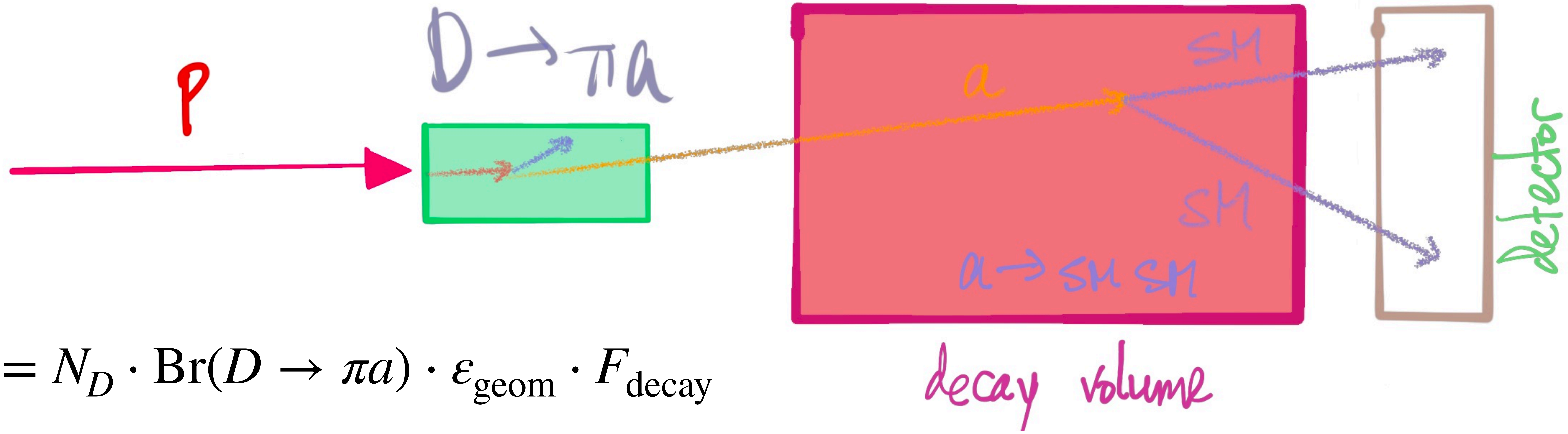
N_{eff}, distorsion of CMB, BBN, …

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

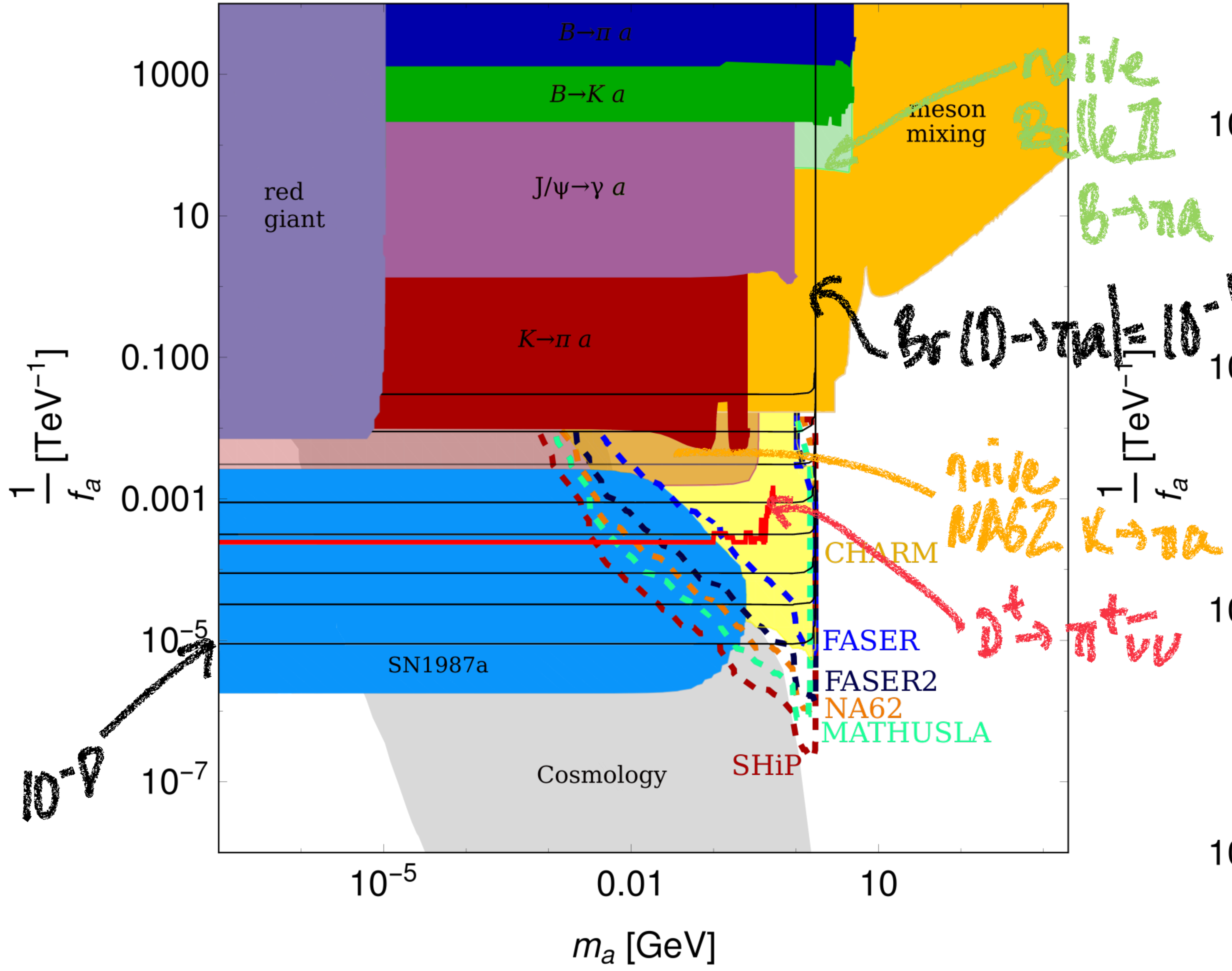


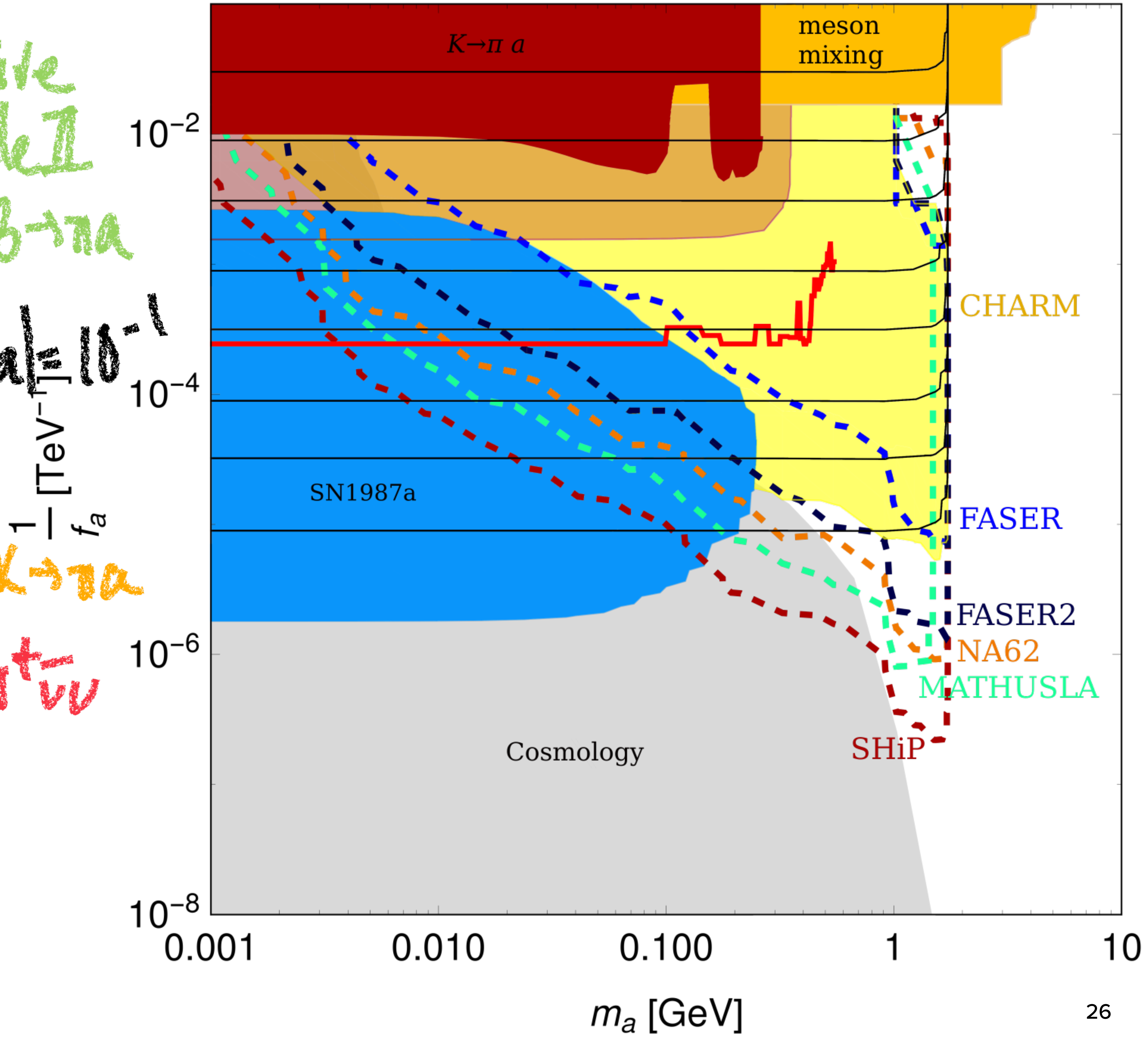
$$N_a = N_D \cdot \mathrm{Br}(D \to \pi a) \cdot \varepsilon_{\mathrm{geom}} \cdot F_{\mathrm{decay}}$$

LHC forward detectors: FASER, FASER II, MATUSHLA

CHARMING ALPS PARAMETER SPACE

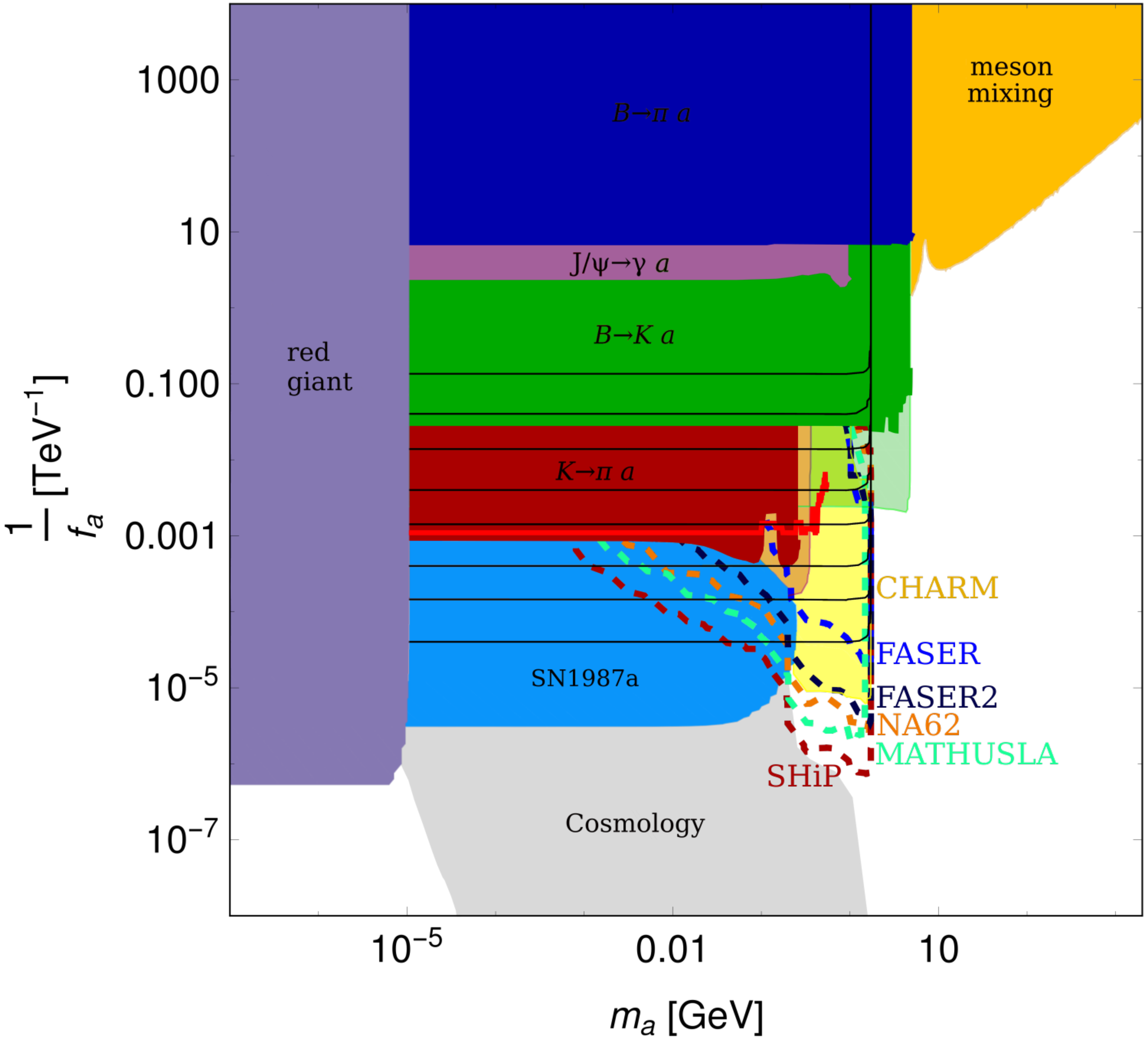
$$a = \pi_{D_3},\ (c_{u_R})_{33} = 0$$

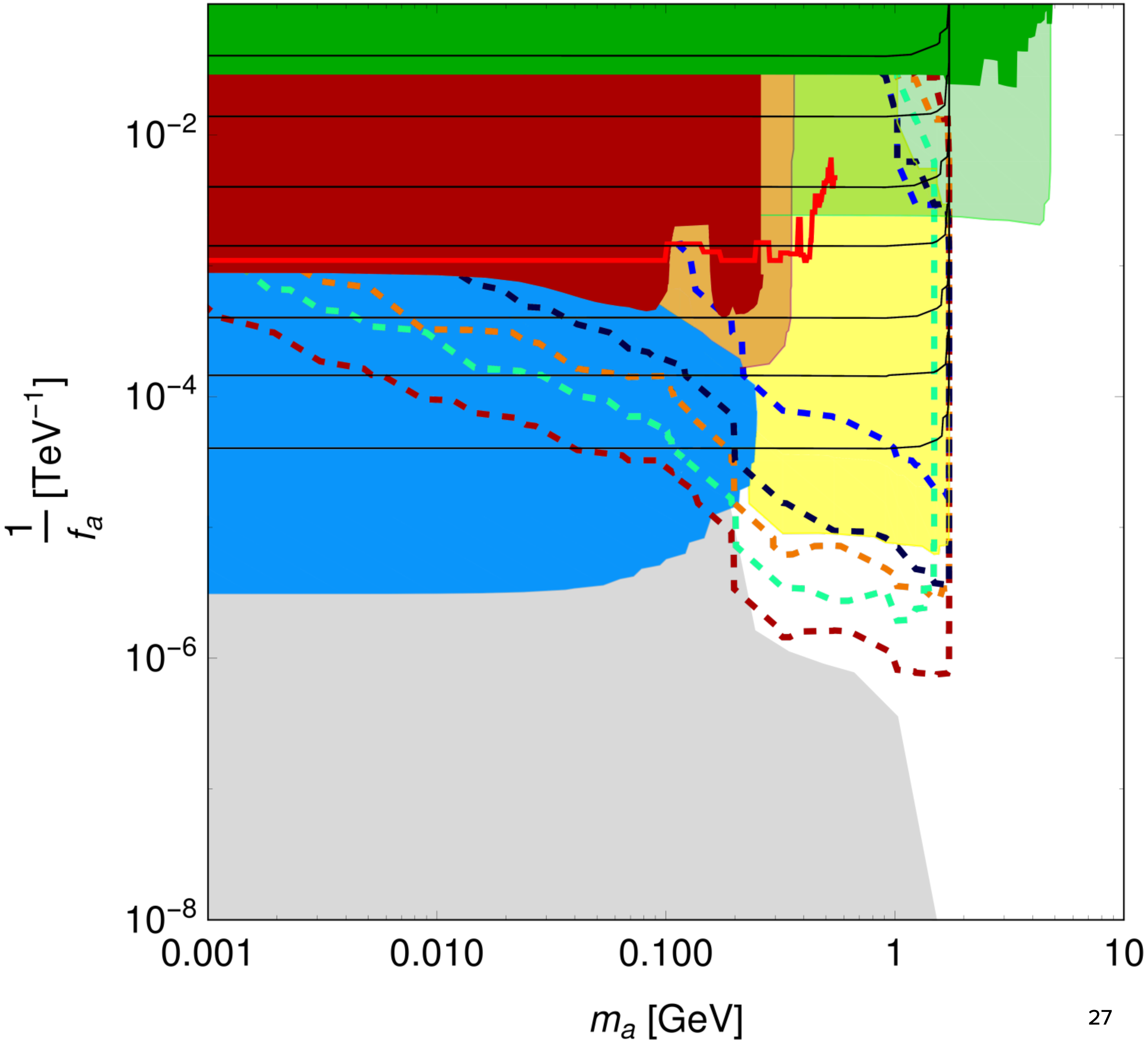




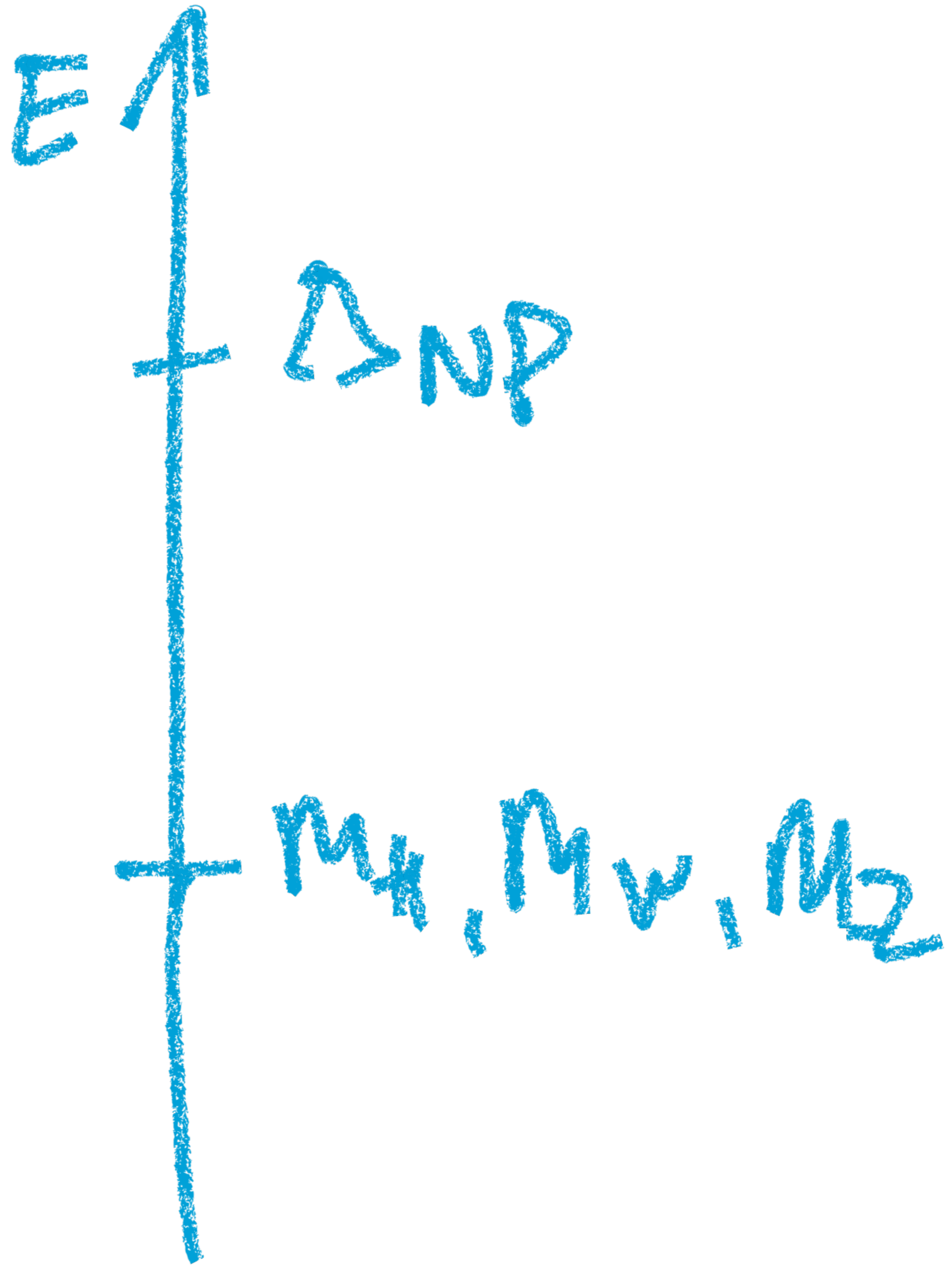
CHARMING ALPS PARAMETER SPACE

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





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

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

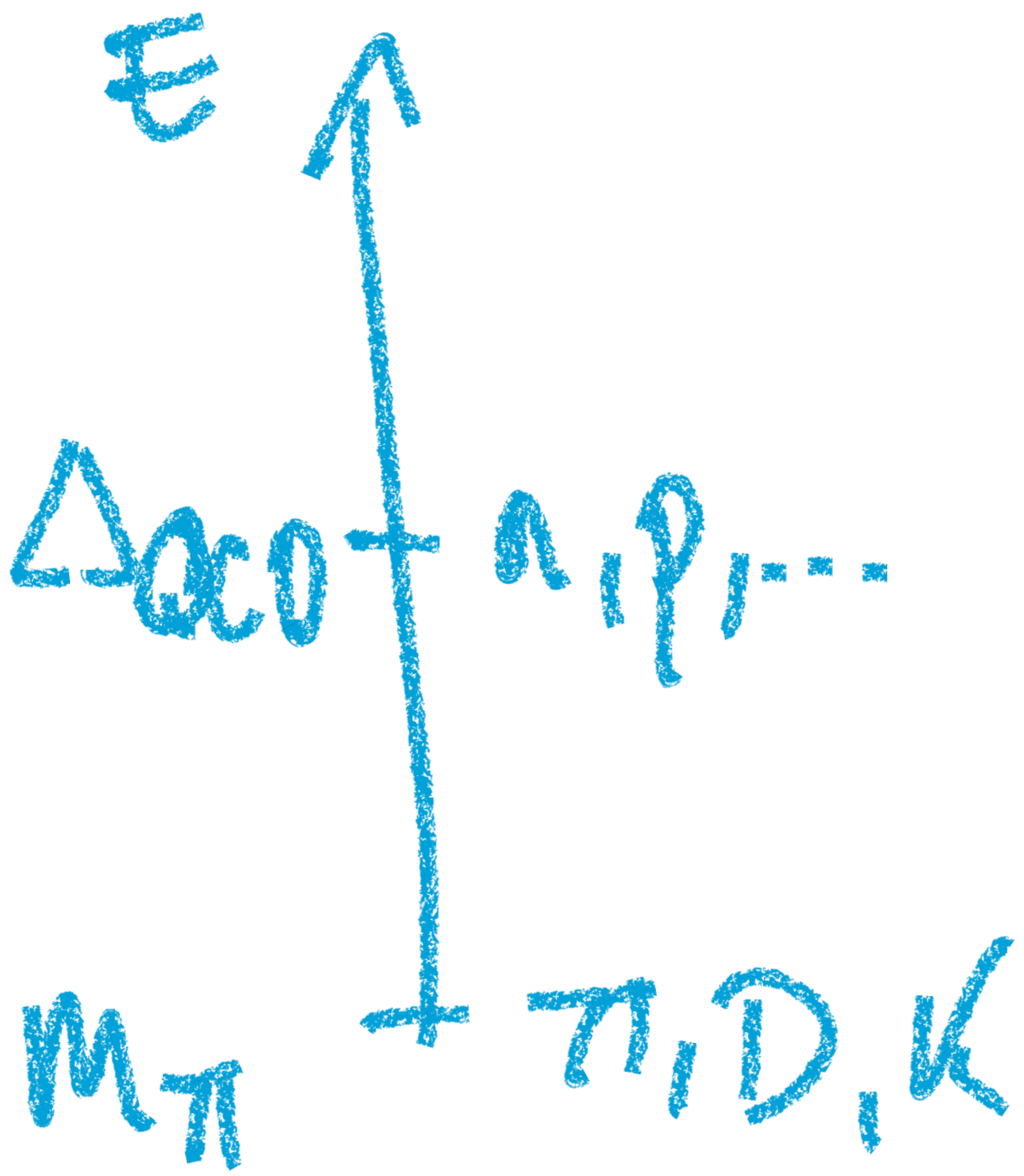
$$m_{\pi^i} \ll \Lambda_{NP}$$

NATURALLY LIGHT SCALARS

QCD gives us a beautiful example

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

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



A QCD-LIKE DARK SECTOR

A QCD-LIKE DARK SECTOR

Schwaller, Bai, '14

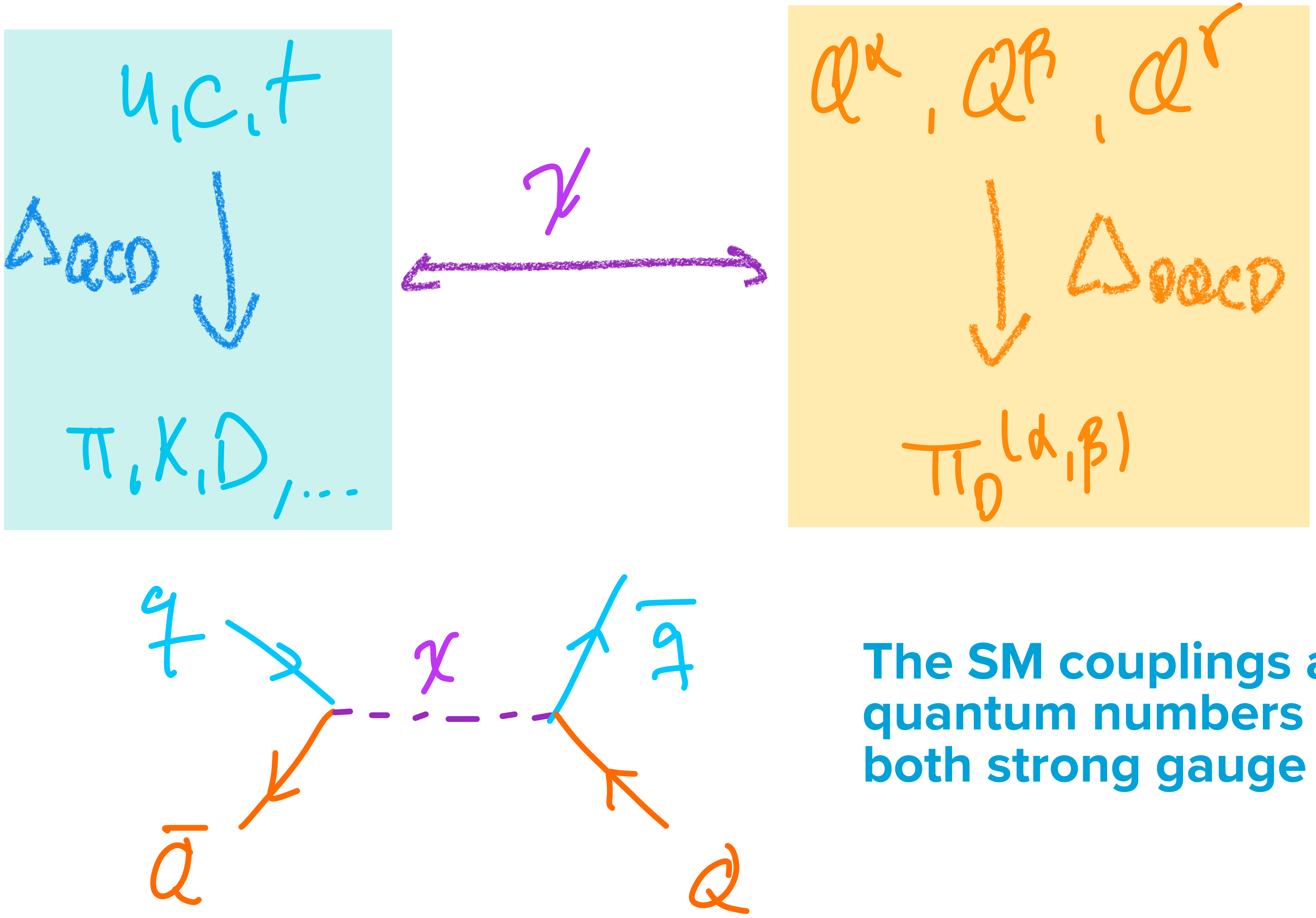
$$u, c, t \xrightarrow{\Lambda_{QCD}} \pi, K, D, \ldots$$

$$Q^{\alpha}, Q^{\beta}, Q^{\gamma} \xrightarrow{\Lambda_{DQCD}} \pi_D^{(\alpha,\beta)}$$

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

A QCD-LIKE DARK SECTOR

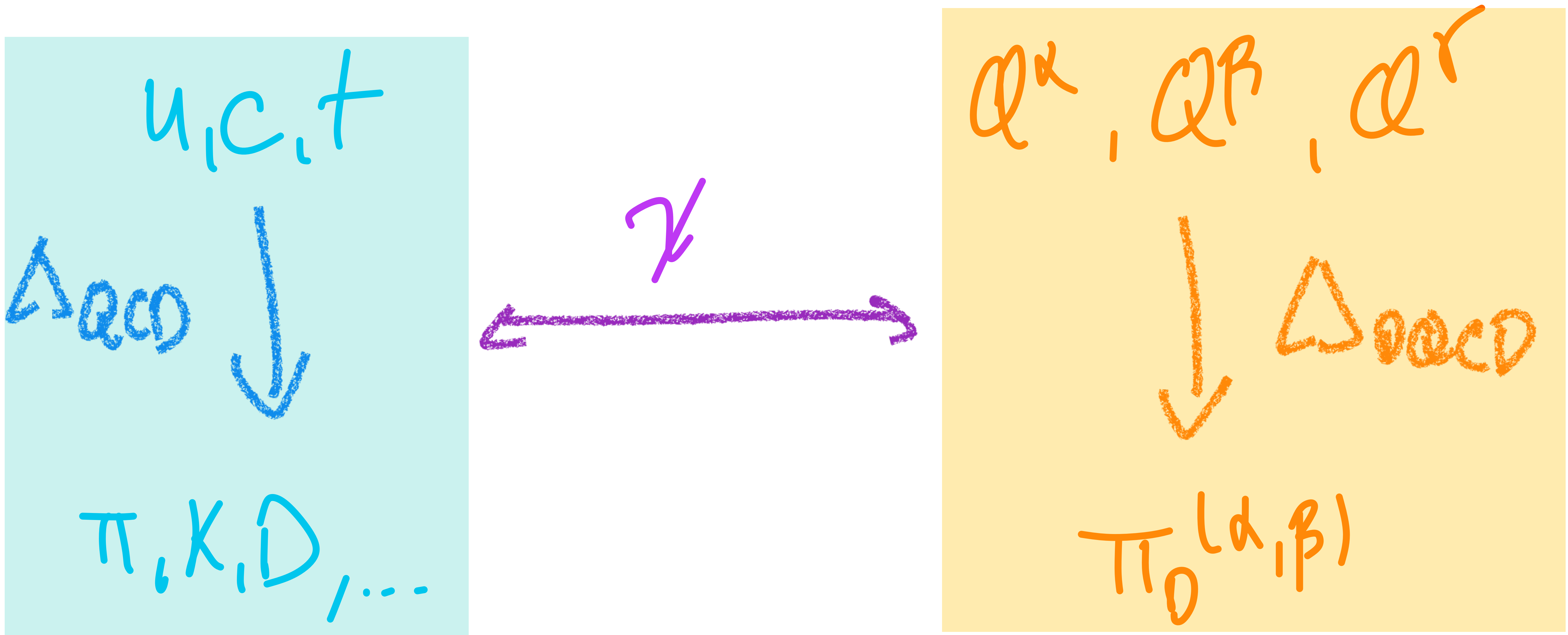
Schwaller, Bai, ‘14

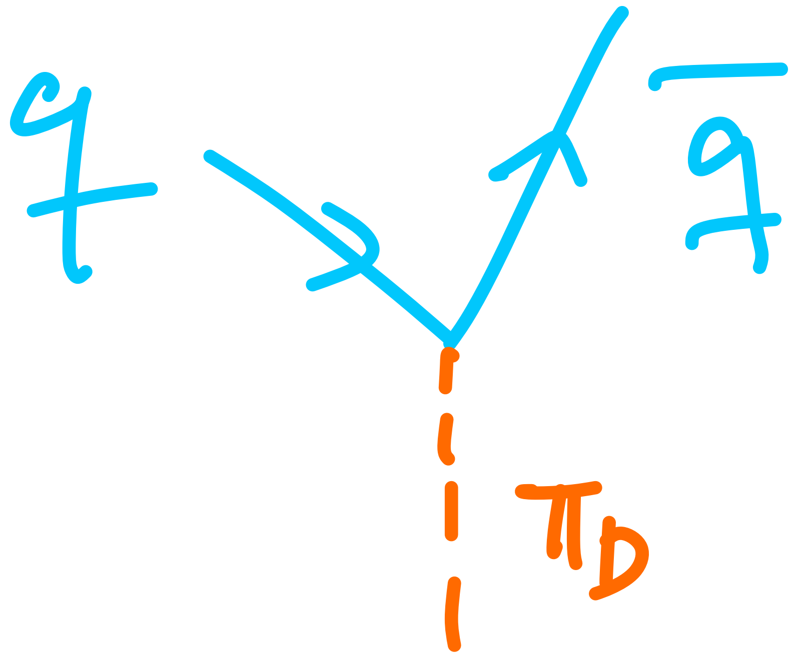


The SM couplings are fixed by the quantum numbers of χ, bifundamental of both strong gauge groups

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