THE DARK SIDE OF THE ALPS

UNIVERSIDAD DE GRANADA

ADRIAN CARMONA BERMUDEZ - UNIVERSITY OF GRANADA

Pushing the Limits of Theoretical Physics - 10 years MITP Anniversary

8TH MAY 2023, MAINZ

BASED ON

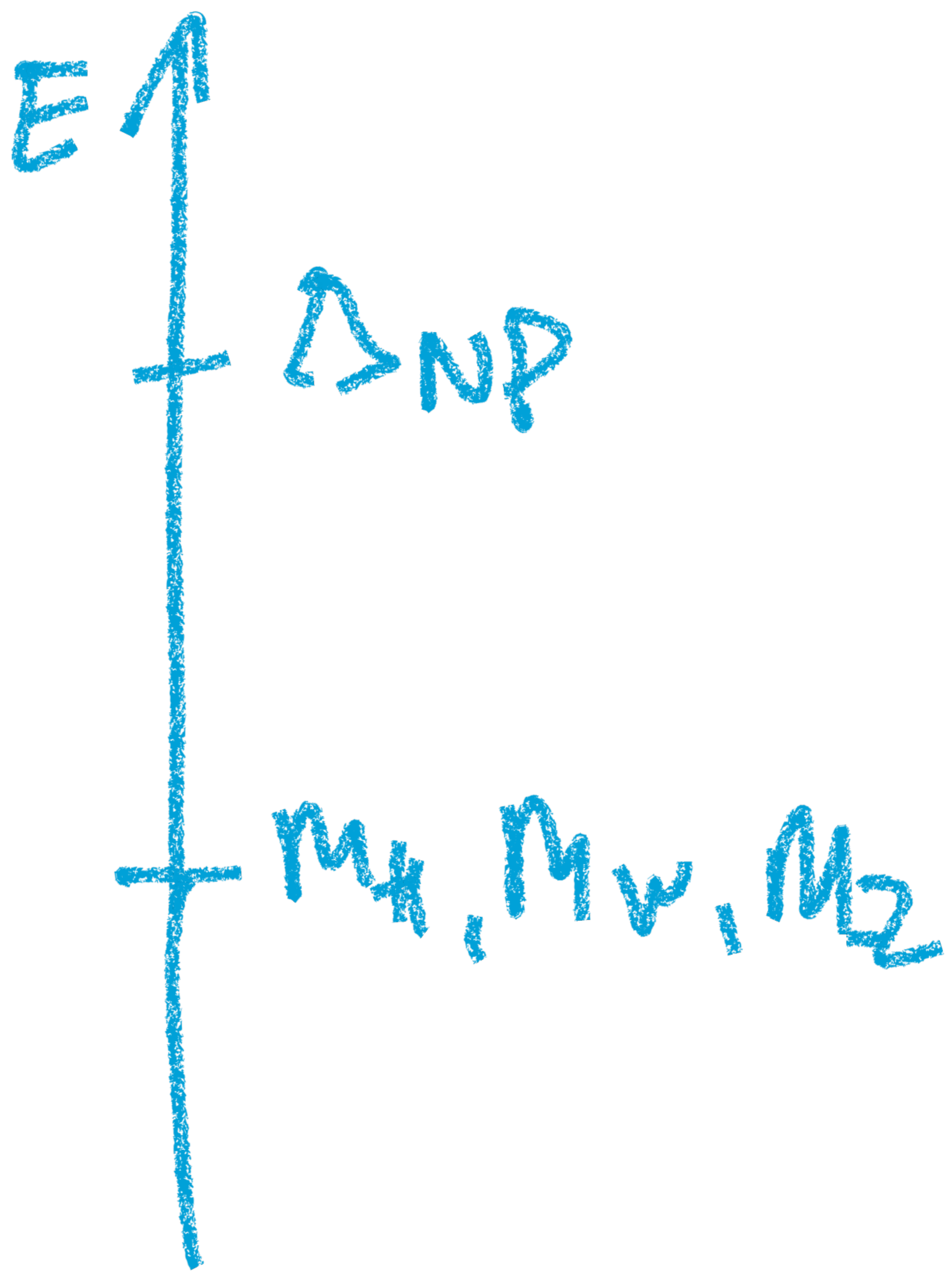
- ‘Charming ALPs’ AC, Scherb, Schwaller. JHEP 08 (2021) 121, arXiv: 2101.0783

- ‘The ALPs from the Top: Searching for long-lived axion-like particles from exotic top decays’ AC, Elahi, Scherb, Schwaller. JHEP 07 (2022) 122, arXiv: 2202.0973

- A couple of upcoming papers of AC, Elahi, Scherb, Schwaller (stay tuned!)

INTRODUCTION

NATURALLY LIGHT SCALARS



The scale of new physics seems to be rather heavy

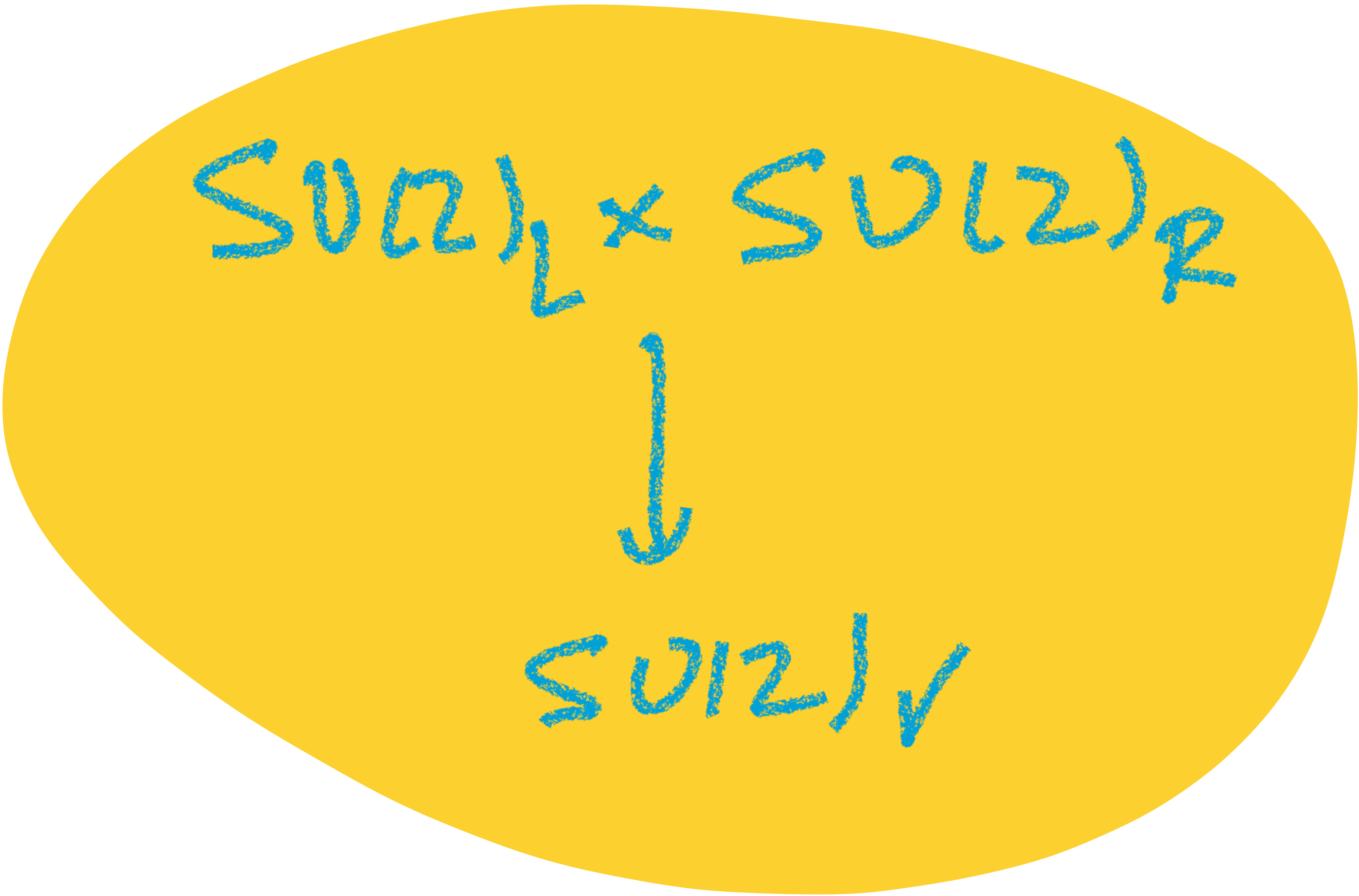
A natural way of obtaining light scalar degrees of freedom is through the Goldstone theorem

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

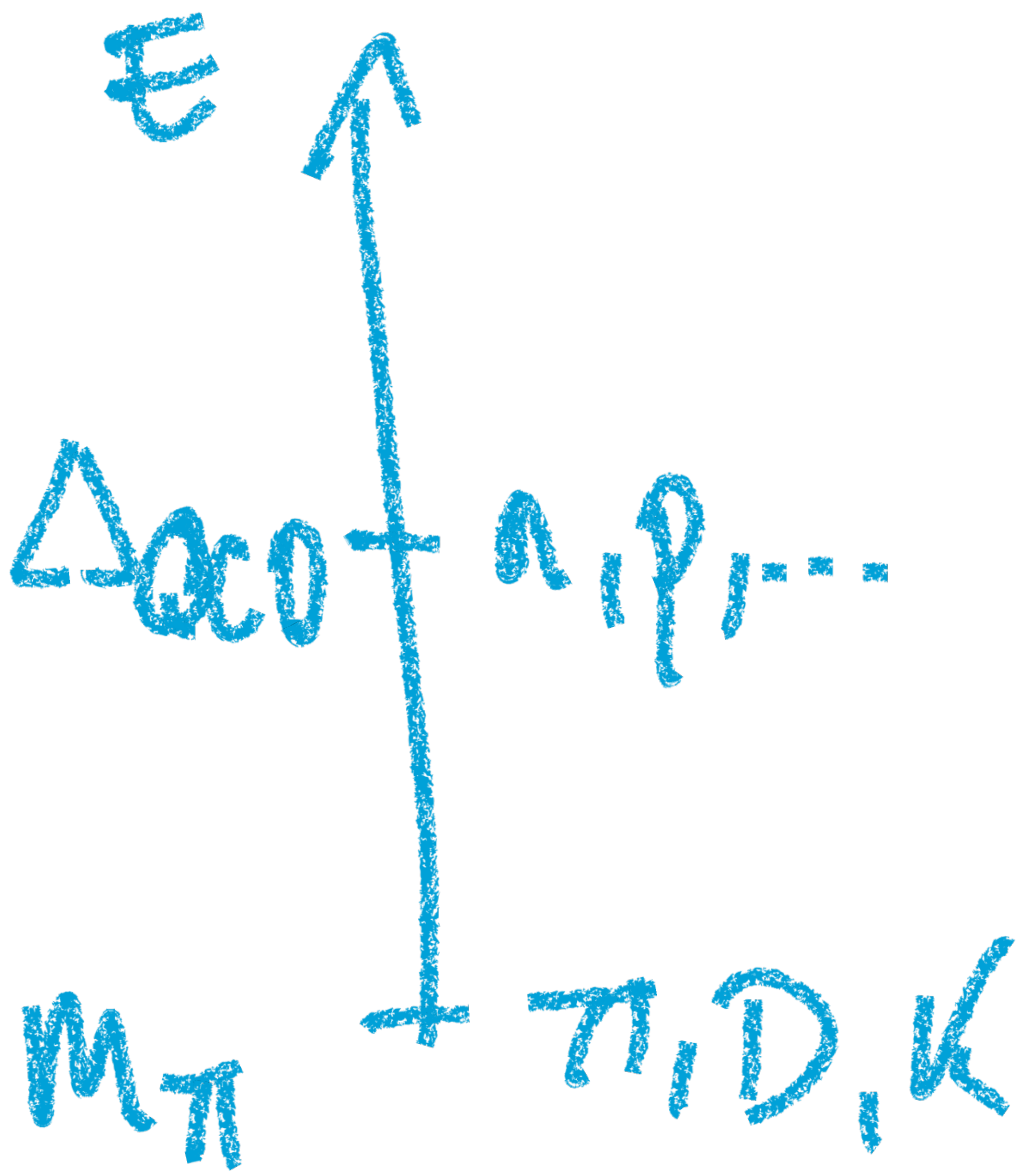
$$m_{\pi^i} \ll \Lambda_{NP}$$

NATURALLY LIGHT SCALARS

QCD gives us a beautiful example



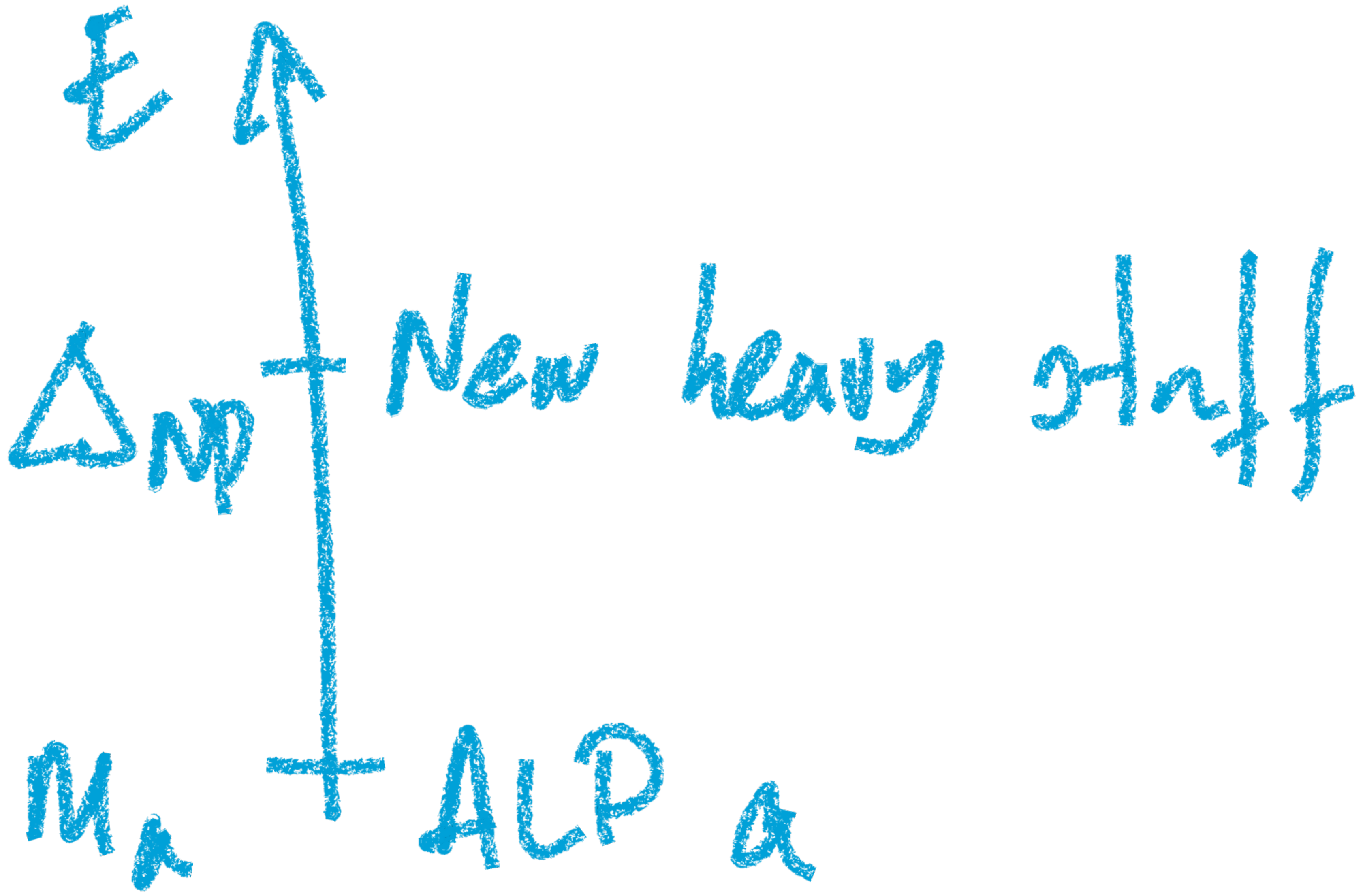
$$m_\pi \ll \Lambda_{QCD}$$



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



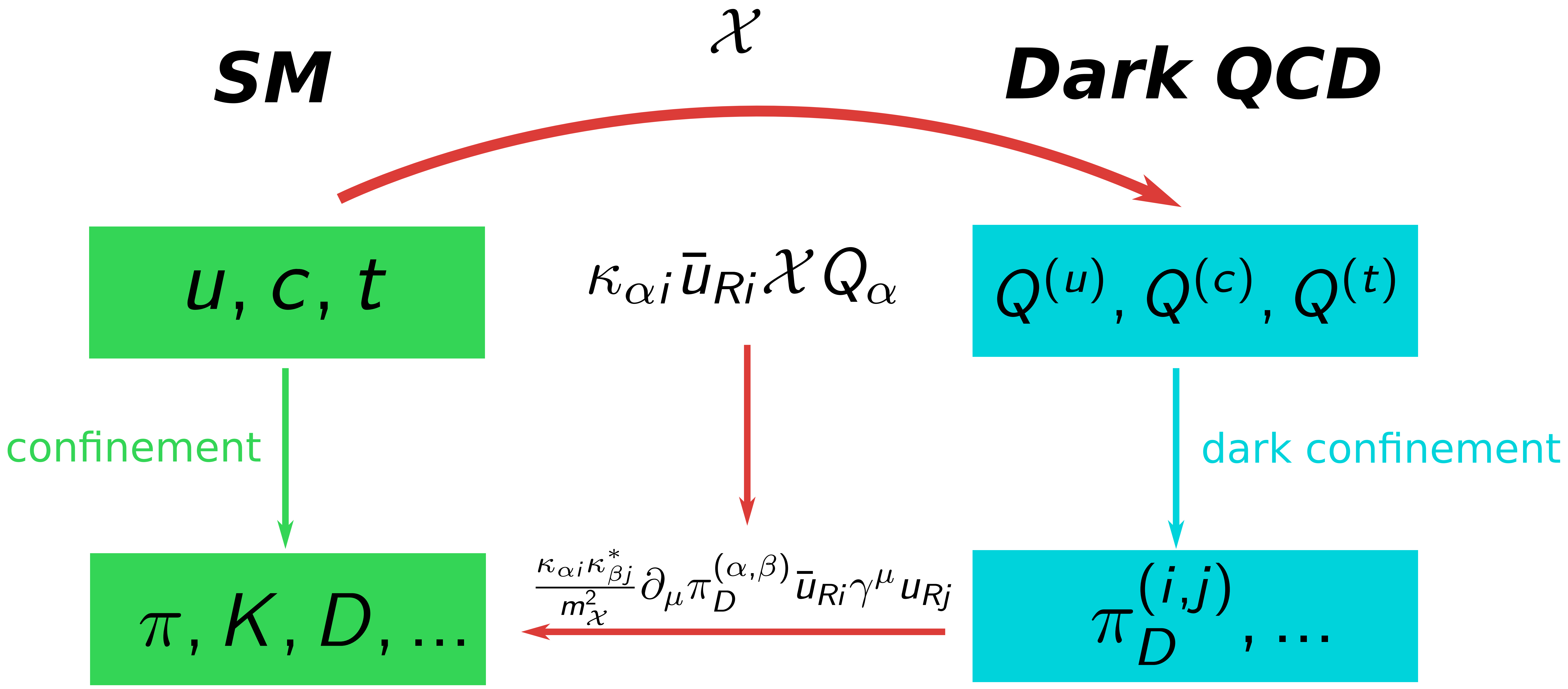
$$a \longrightarrow a + \theta$$

Shift symmetry

A QCD-LIKE DARK SECTOR

A QCD-LIKE DARK SECTOR

Schwaller, Bai, '14



* $SU(N_D)$ 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

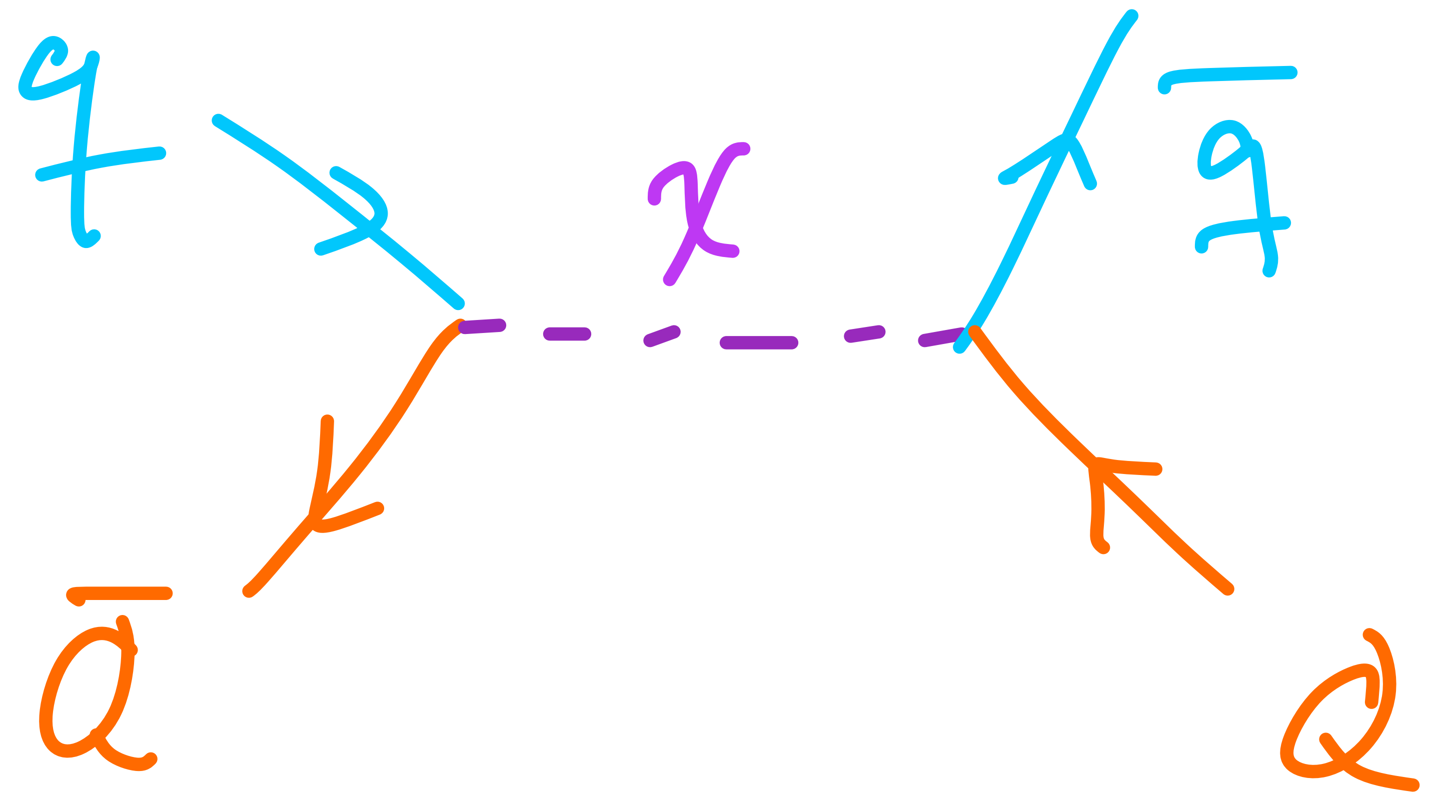
$\mathcal{X}$

SM | **Dark QCD**

u, c, t — $\kappa_{\alpha i}\bar{u}_{Ri}\mathcal{X}Q_{\alpha}$ → $Q^{(u)}, Q^{(c)}, Q^{(t)}$

confinement | dark confinement

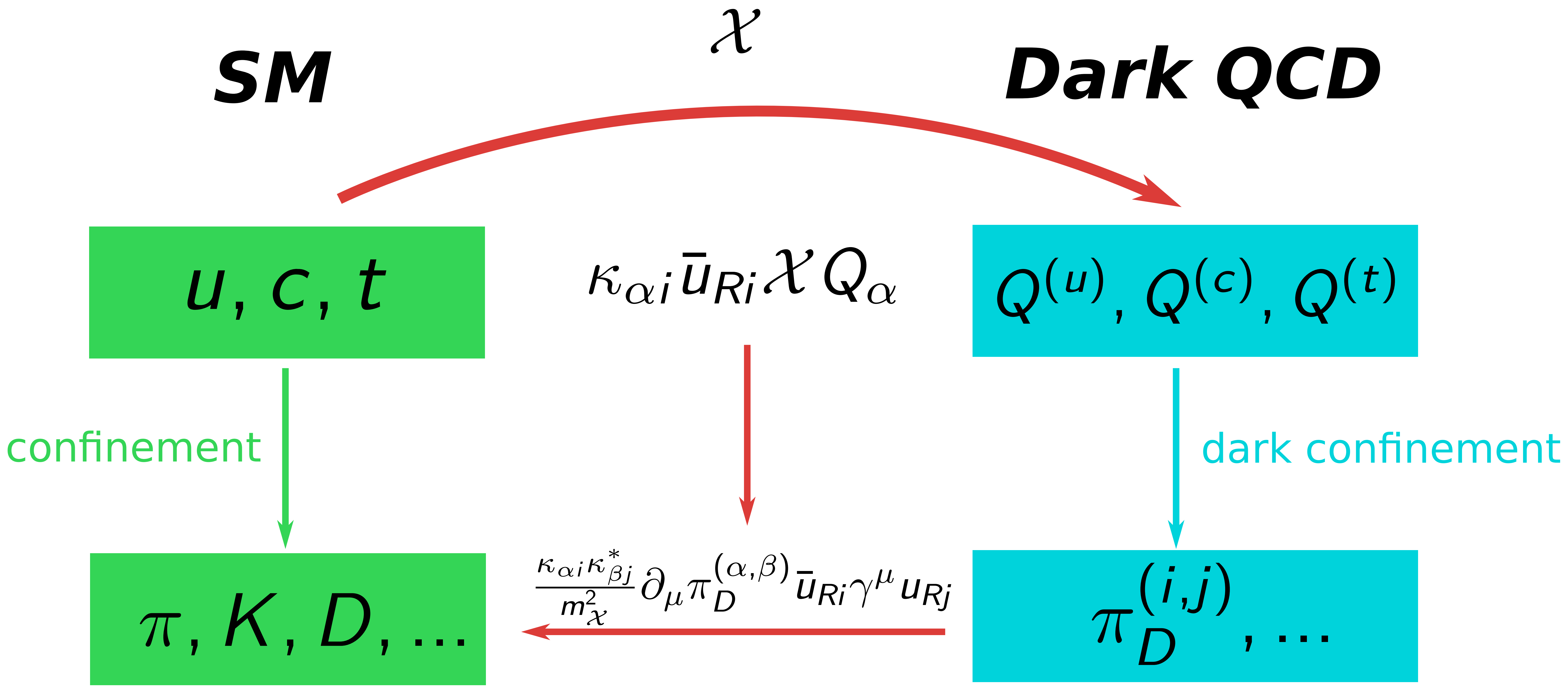
$\pi, K, D, \ldots$ ← $\frac{\kappa_{\alpha i}\kappa^{*}_{\beta j}}{m^2_{\mathcal{X}}}\partial_{\mu}\pi_D^{(\alpha,\beta)}\bar{u}_{Ri}\gamma^{\mu}u_{Rj}$ — $\pi_D^{(i,j)}, \ldots$

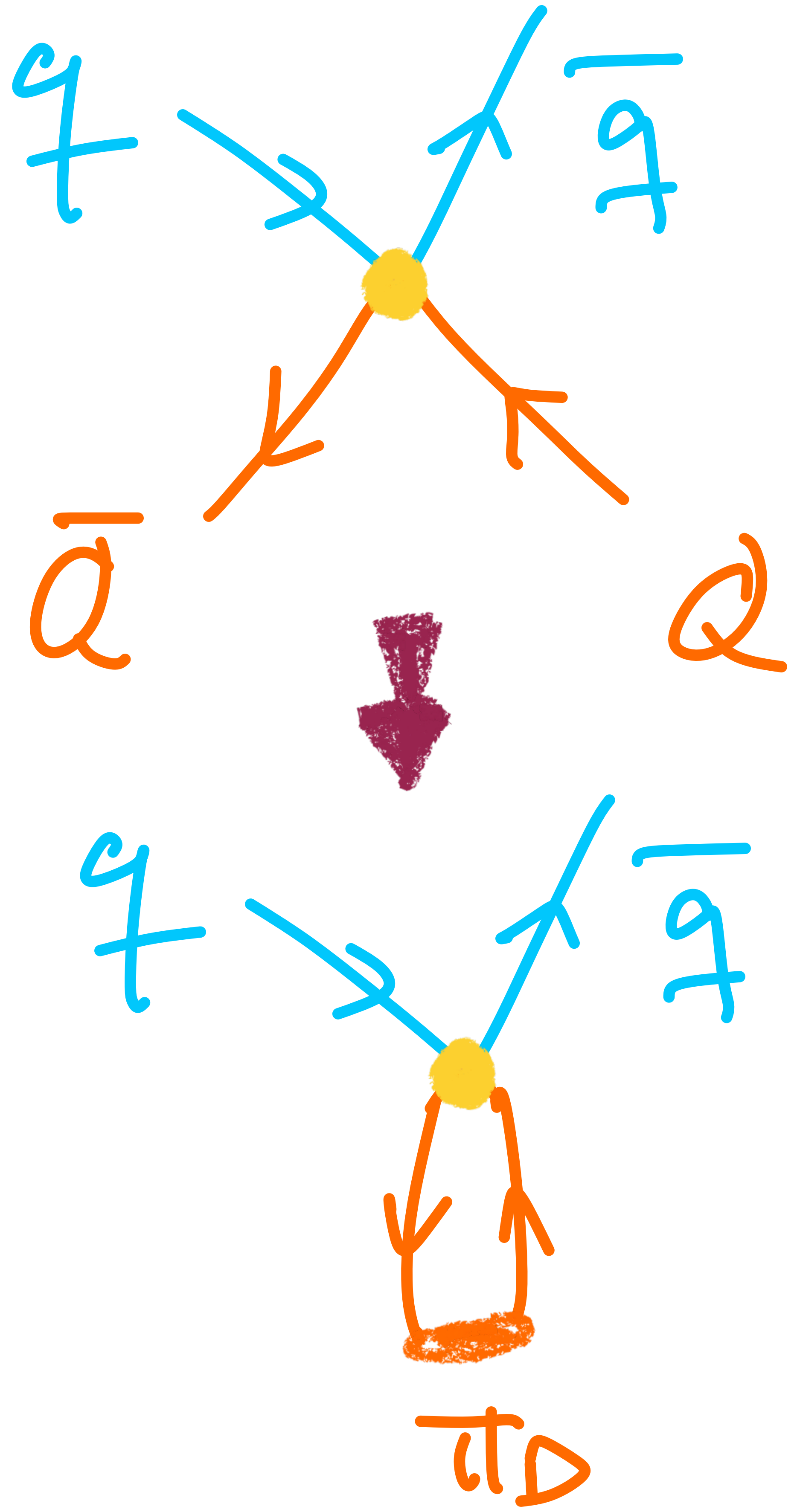


The SM couplings are fixed by the quantum numbers of χ, bifundamental of both strong gauge groups

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}	$1/\sqrt{6}\,[\bar{Q}_1 Q_1 + \bar{Q}_2 Q_2 - 2\bar{Q}_3 Q_3]$

$K = D \cdot U$

D diagonal

$$U = \begin{pmatrix} c_{12} & s_{12} e^{-i\delta} & 0 \\ -s_{12} e^{i\delta} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$C^{(a)}_{u_R} \sim K_{\alpha i} K^{\dagger}_{\beta j} (\lambda^a)_{\alpha\beta}$$

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

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

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

Schwaller, Renner '18

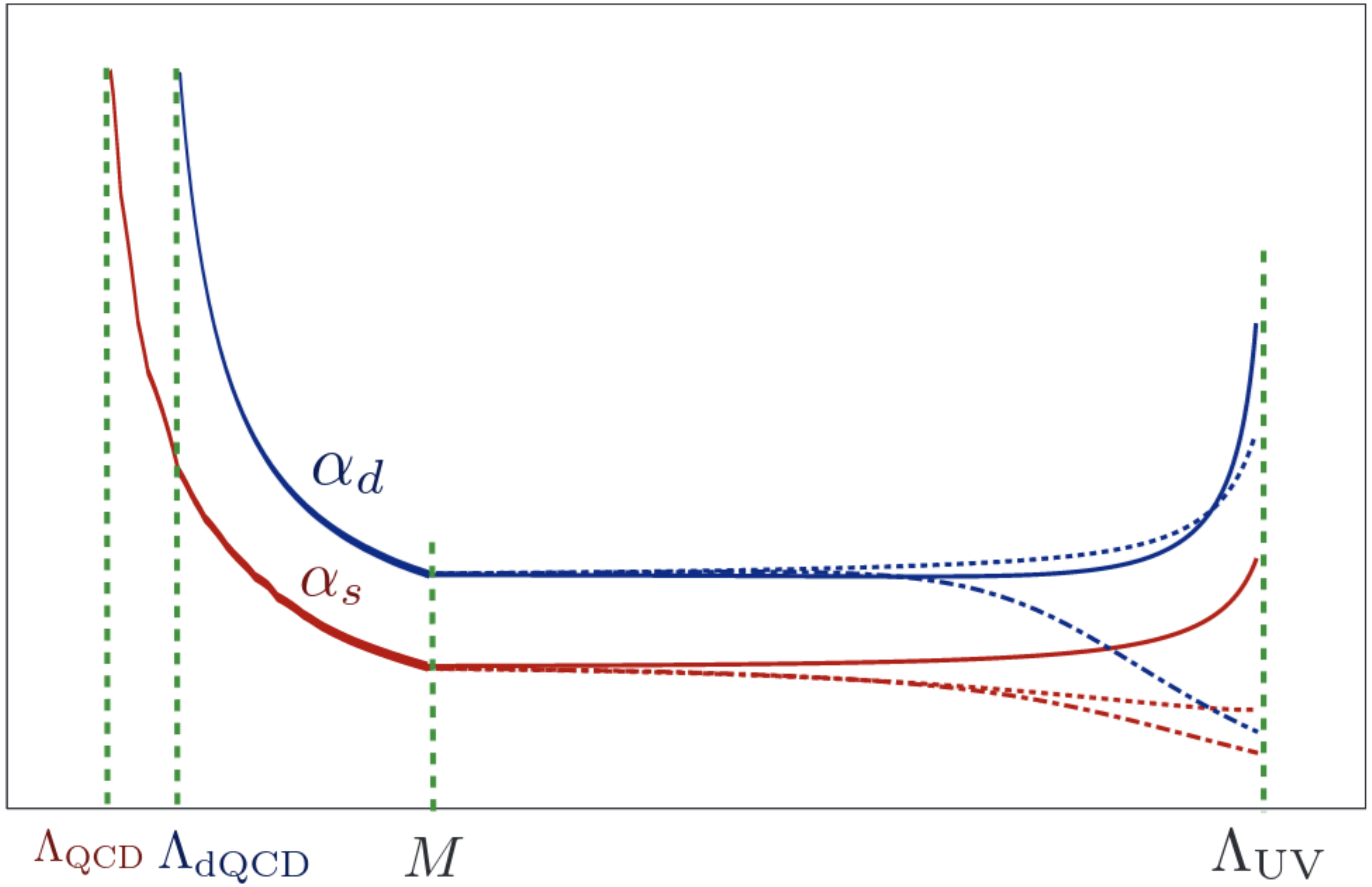
$$\chi \sim (3, \bar{3}, 1, -2/3) \qquad \mathcal{L}_{eff} \supset \frac{f_D^2}{m_\chi^2} \kappa_{\alpha i} \kappa^*_{\beta j} \partial_\mu \pi_D^{(\alpha,\beta)} \bar{u}_{Ri} \gamma^\mu u_{Rj}$$

AC, Scherb, Schwaller '21

A QCD-LIKE DARK SECTOR

Schwaller, Bai, ‘14

One motivation for these sectors is to get $\Lambda_{dQCD} = \mathcal{O}(\text{few})\Lambda_{QCD}$



This fits well with asymmetric DM

$$\Omega_{\text{DM}}/\Omega_B \approx 5$$

DM could also be made of dark pions which are stable (see later)

$SU(n_f) \otimes SU(n_f)$

$\downarrow$

$SU(n_f)$ $\quad n_f \geq 4$

CHARMING ALPS

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

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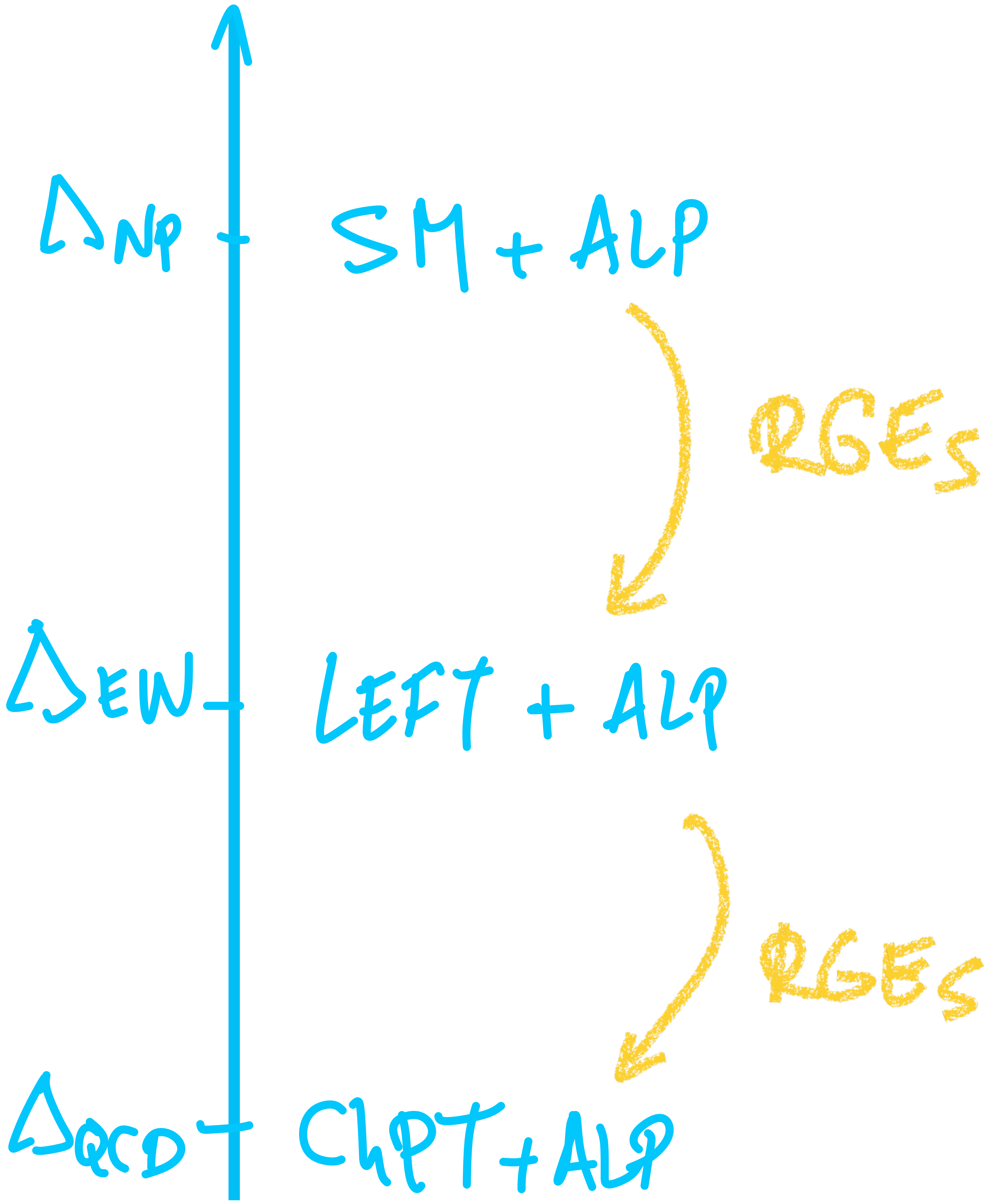
← Dark QCD

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

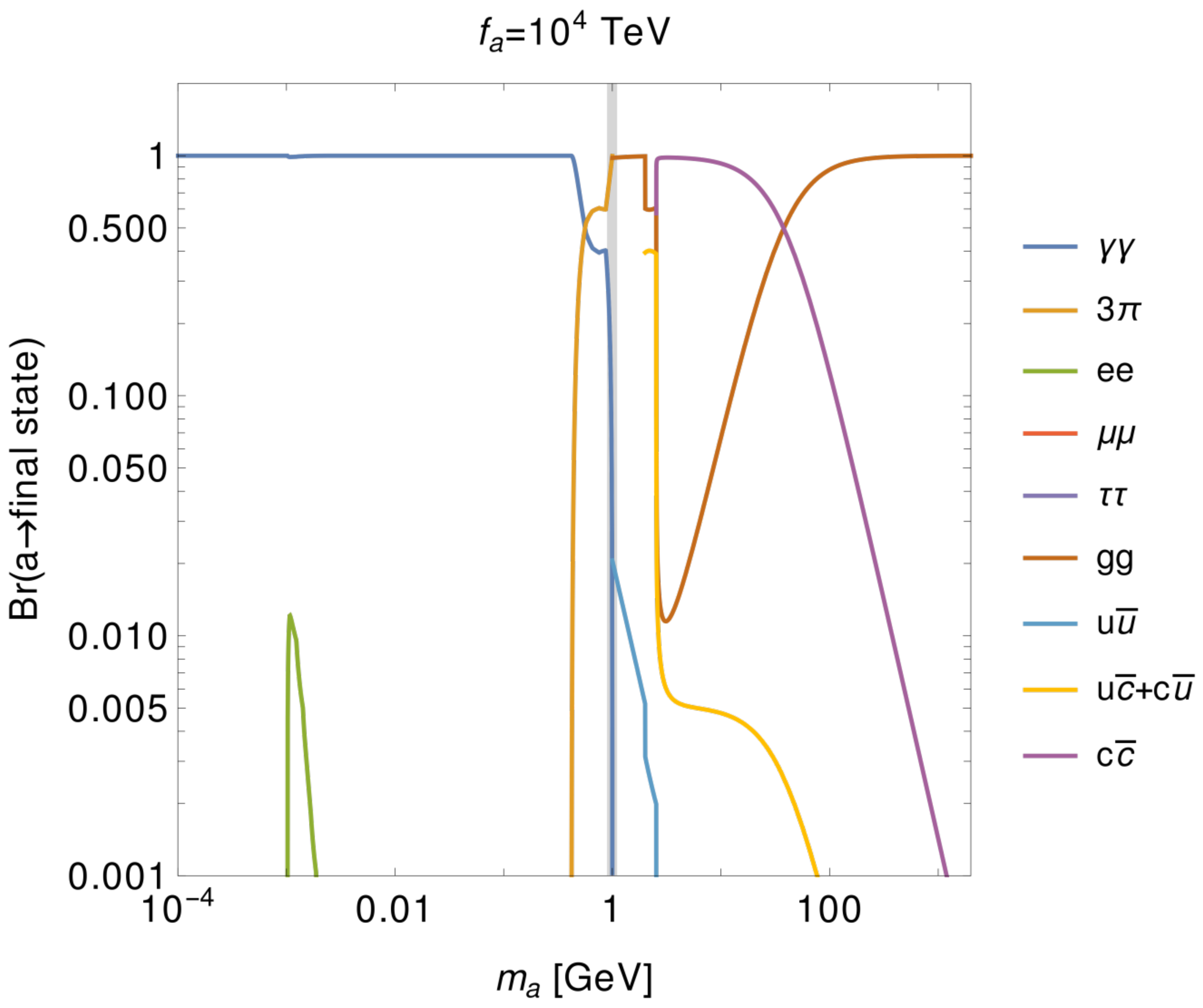
$$c_{q_L} = \frac{Y_u c_{u_R} Y_u}{32\pi^2} \ln\left(\frac{\Lambda_{NP}}{\mu^2}\right), \qquad c_H = \frac{3}{8\pi^2} \mathrm{Tr}\left(Y_u c_{u_R} Y_u\right) \ln\left(\frac{\Lambda_{NP}}{\mu^2}\right)$$

where

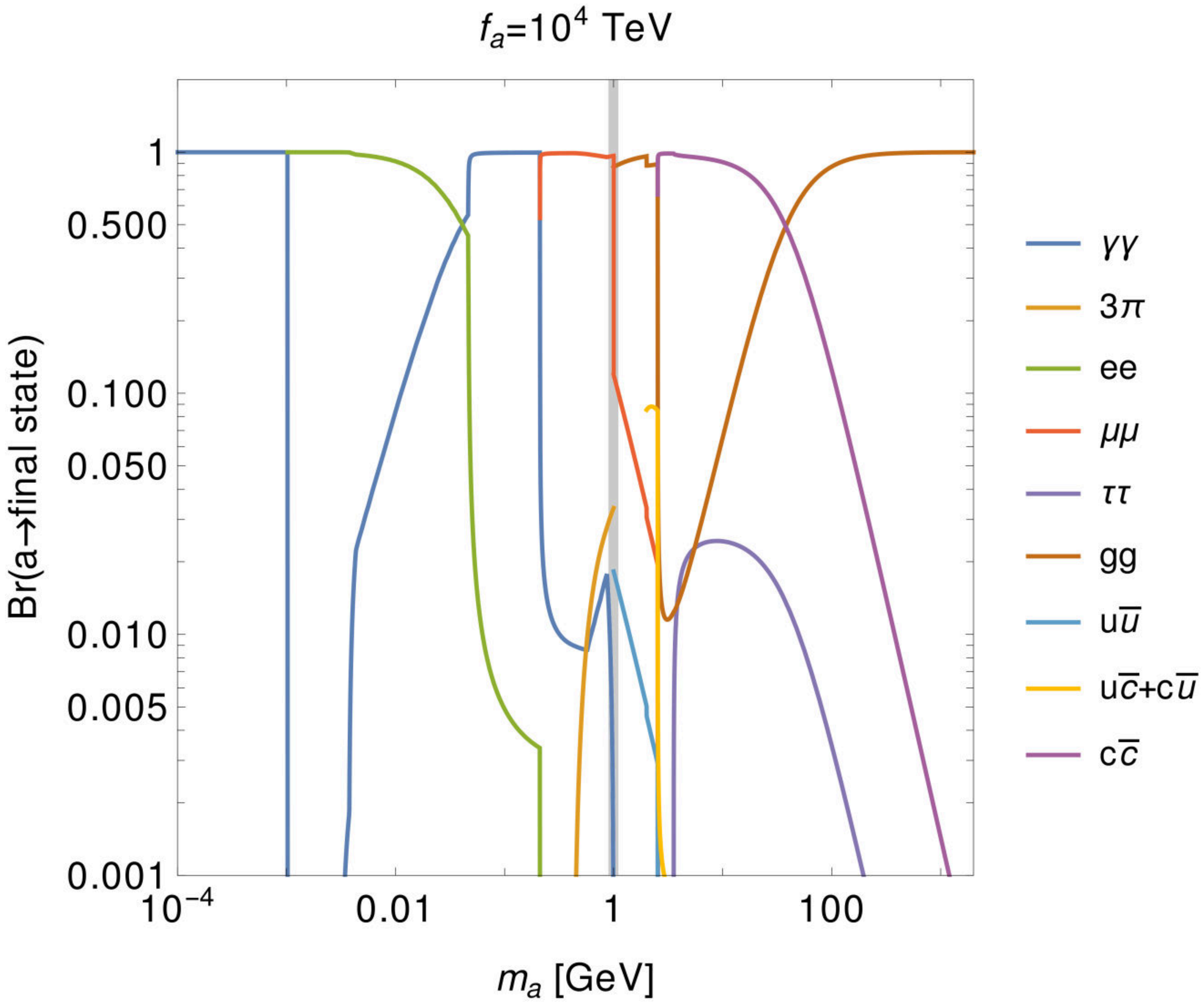
$$\left(\mathcal{O}_{q_L}\right)_{ij} = \frac{\partial_\mu a}{\Lambda_{NP}} \left(\bar{q}_{Li} \gamma^\mu q_{Lj}\right), \qquad \mathcal{O}_H = \frac{\partial_\mu a}{\Lambda_{NP}} \left(H^\dagger i \overleftrightarrow{D}^\mu H\right)$$

Top couplings will make a difference!

CHARMING ALPS



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



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

ALPS PHENOMELOGY

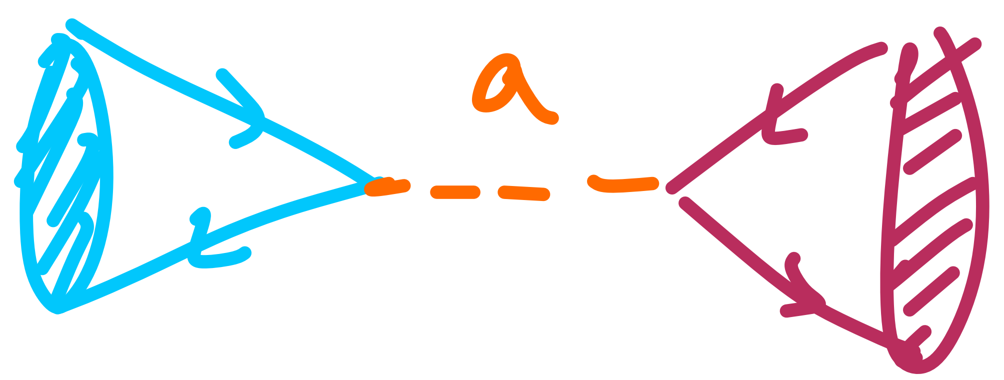
Flavor probes will compete or be complemented by astrophysical or cosmological bounds as well as by collider or fixed target experiments

'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

FLAVOR PROBES OF ALPS

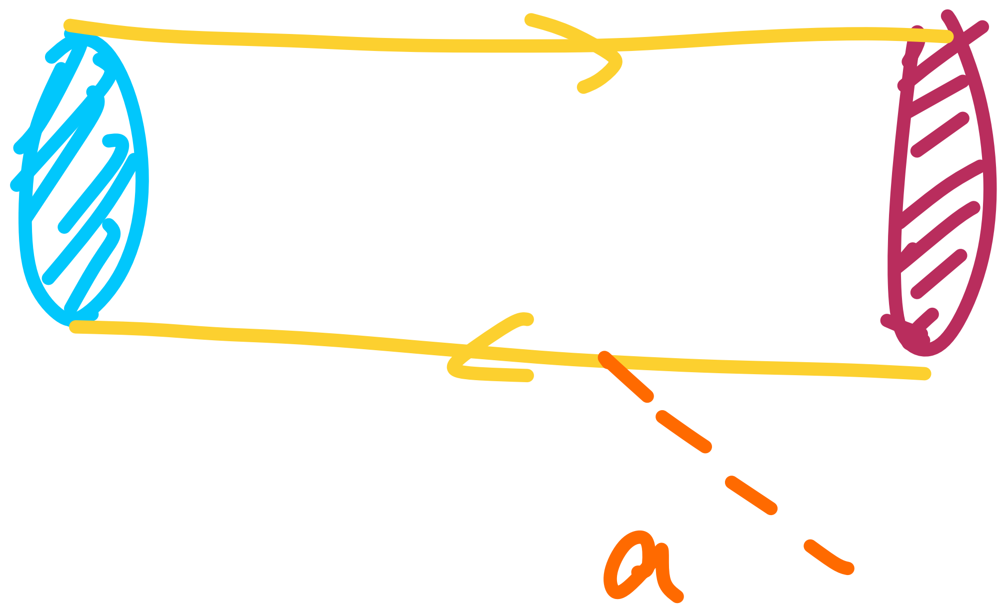
ΔF=2 Neutral meson mixing



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

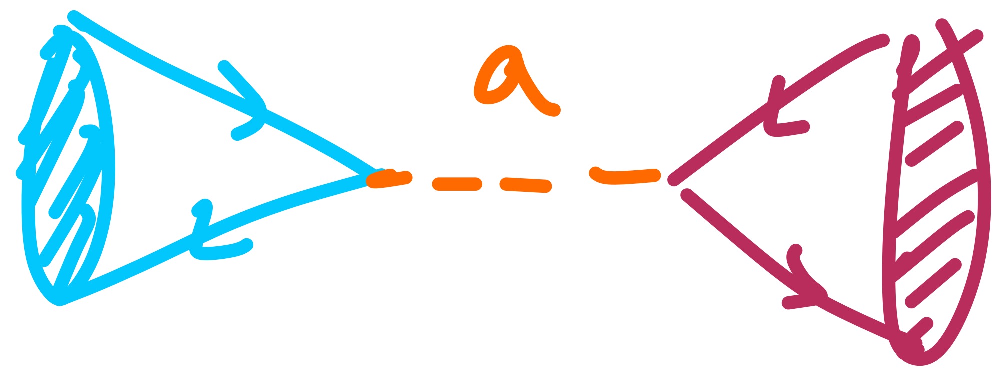
Depending on $m_a/m_{c,b}$ we might need to use OPE

ΔF=1 Rare meson decay

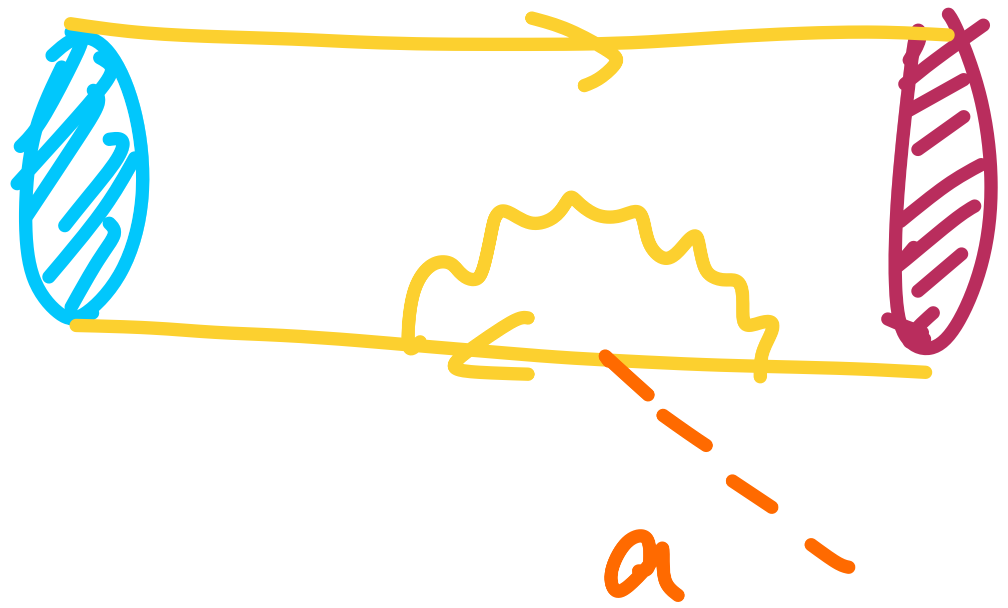


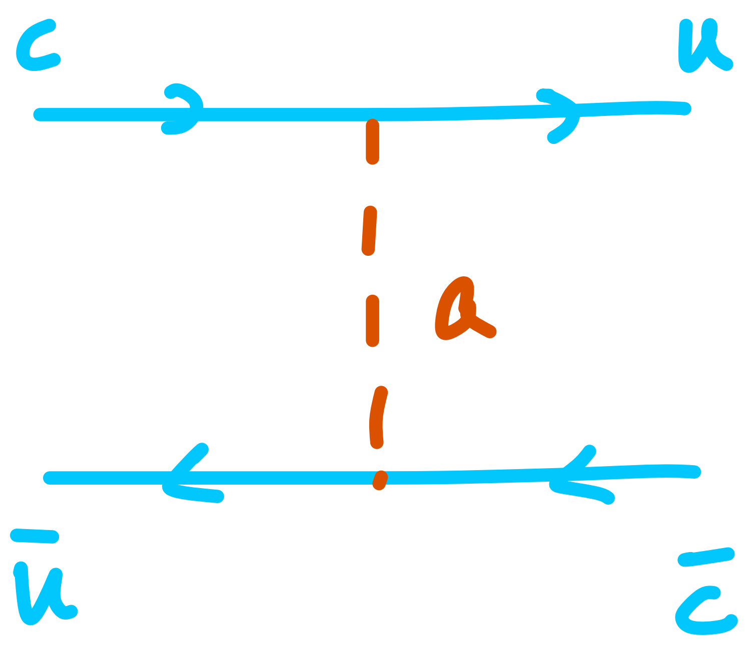
$D \to \pi a$, $B \to K a$, $B \to \pi a$, $K \to \pi a$, ...

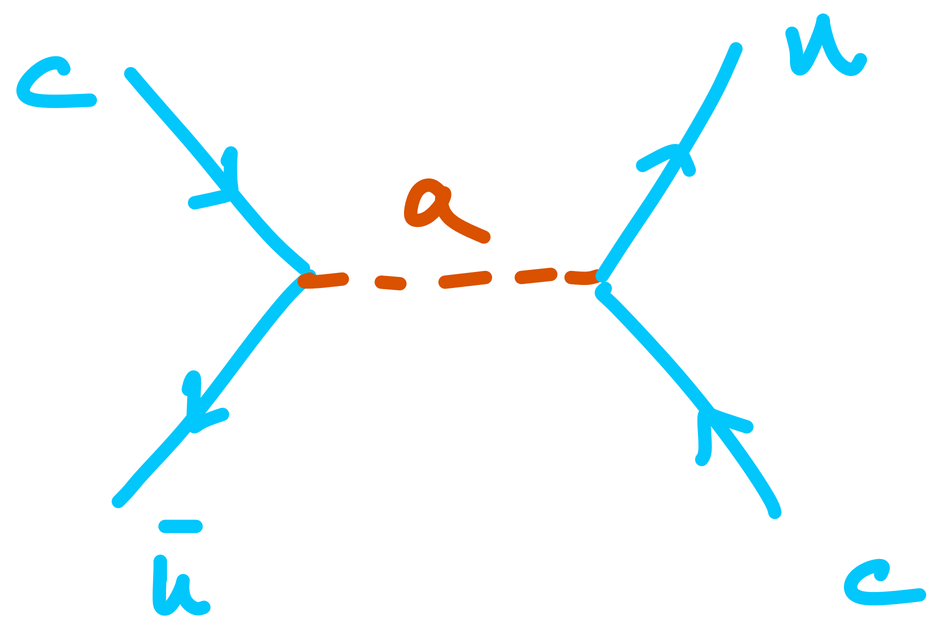
FLAVOR BOUNDS

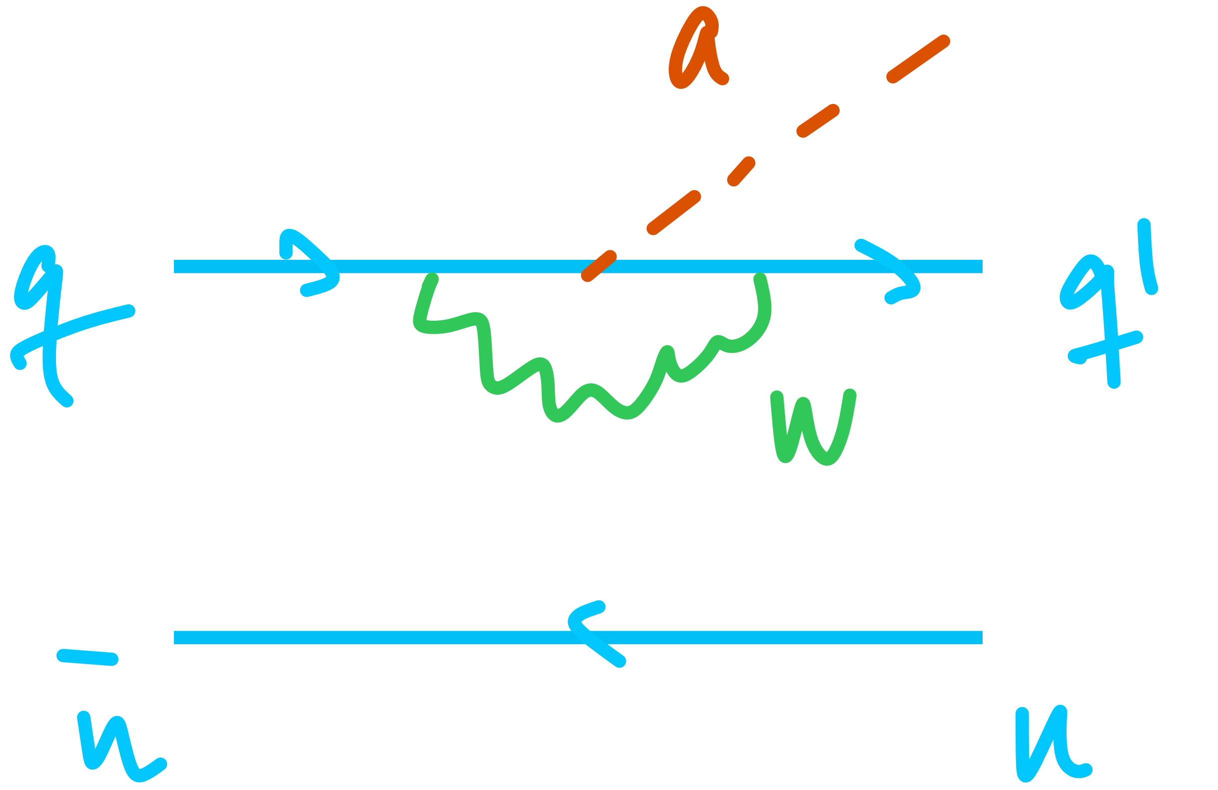


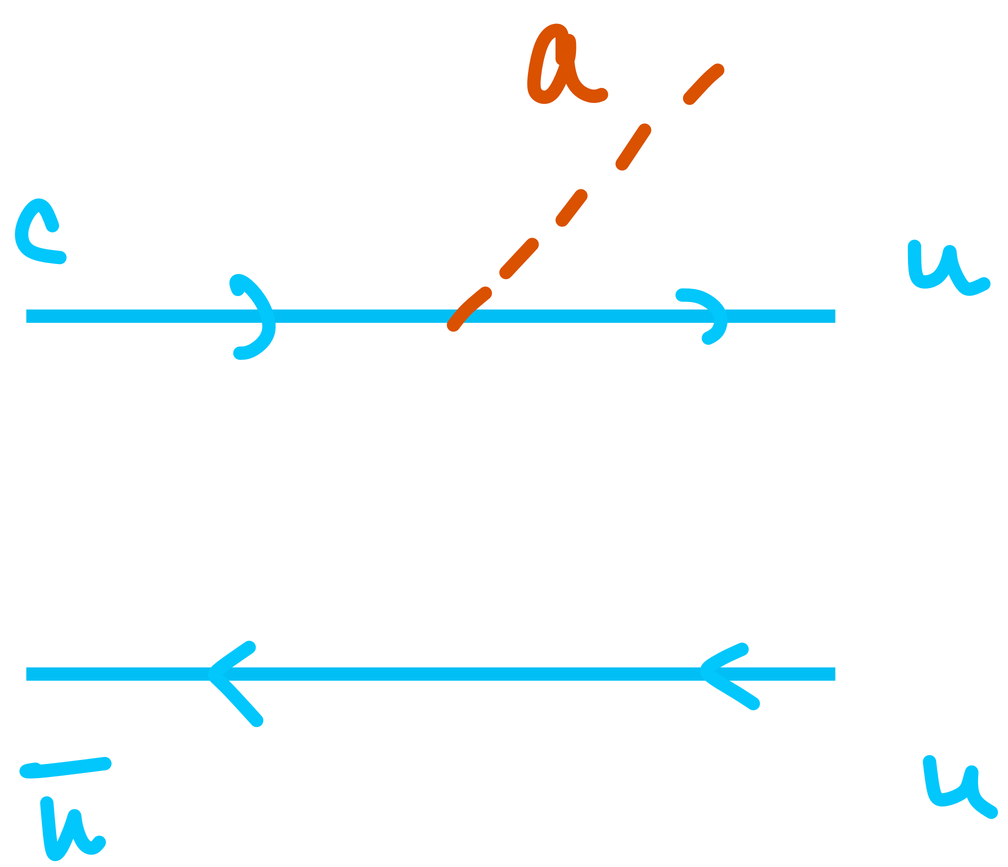
$D-\bar{D}$ mixing











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

$D \to \pi a$

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

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

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

SN1987a

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

Bremsstrahlung

$$N + N \rightarrow N + N + a$$

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

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

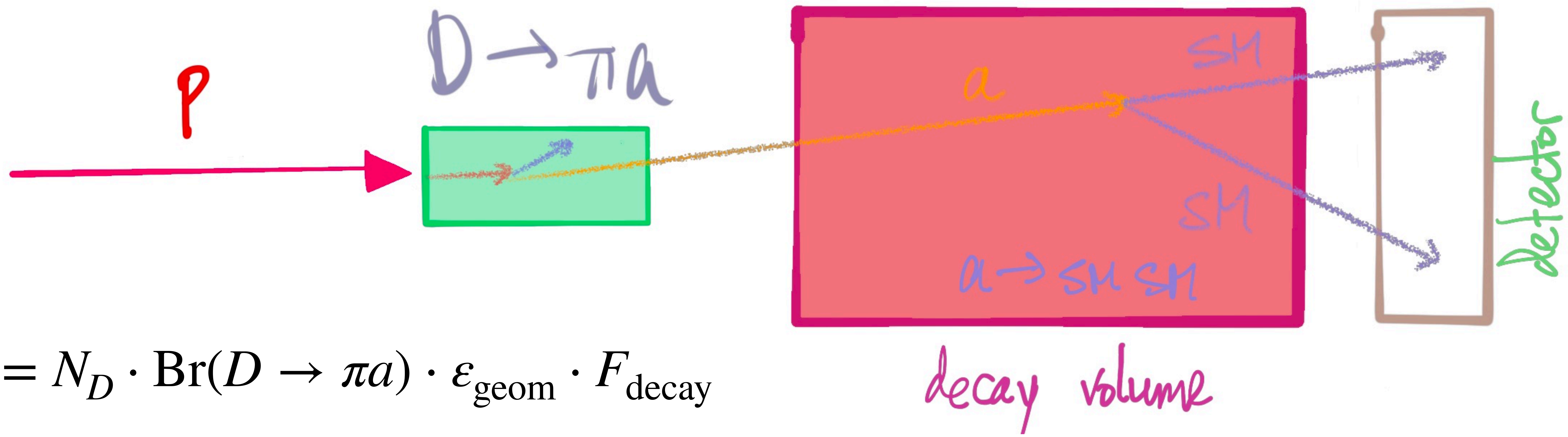
N_{eff}, distorsion of CMB, BBN, ...

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

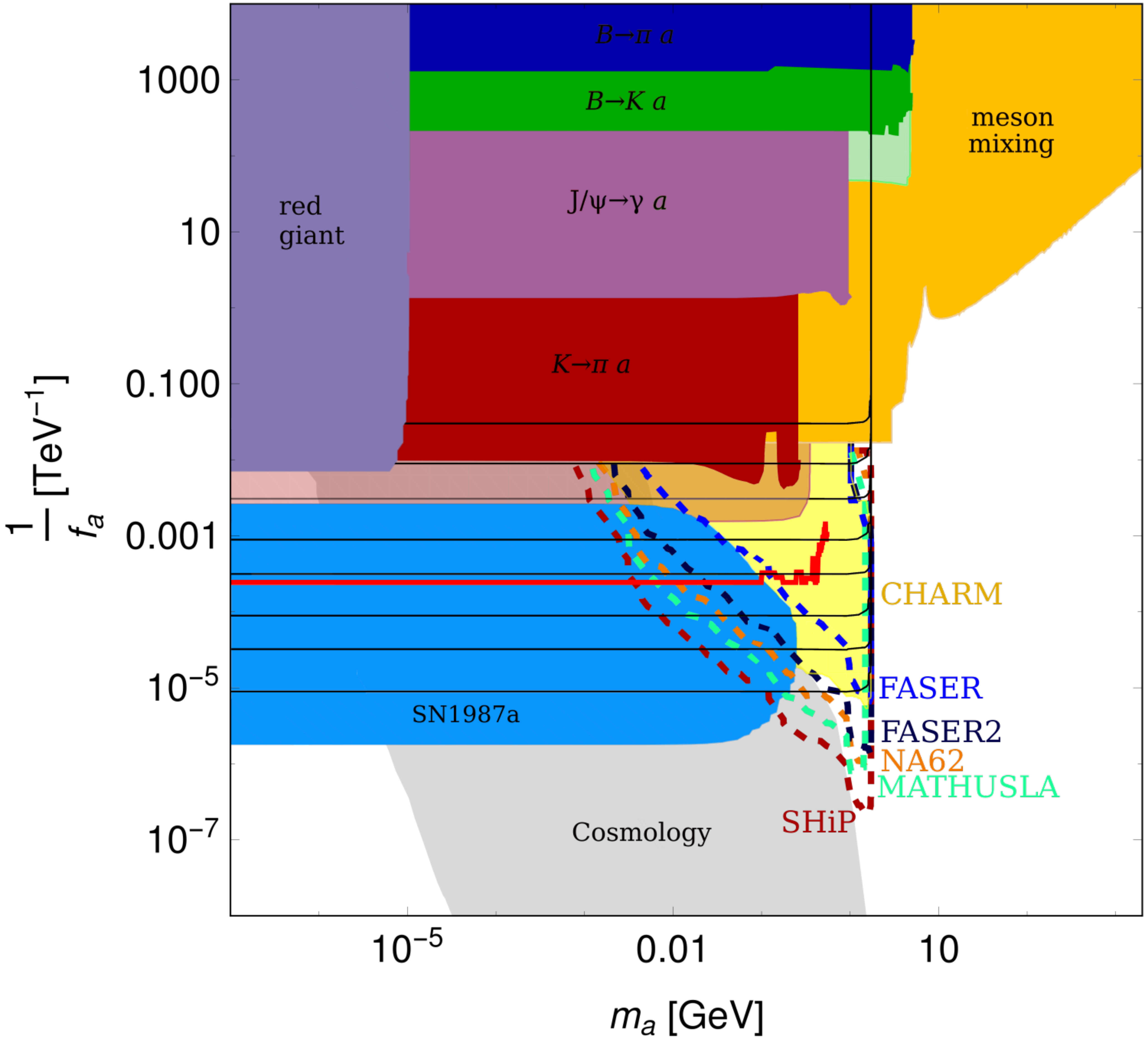


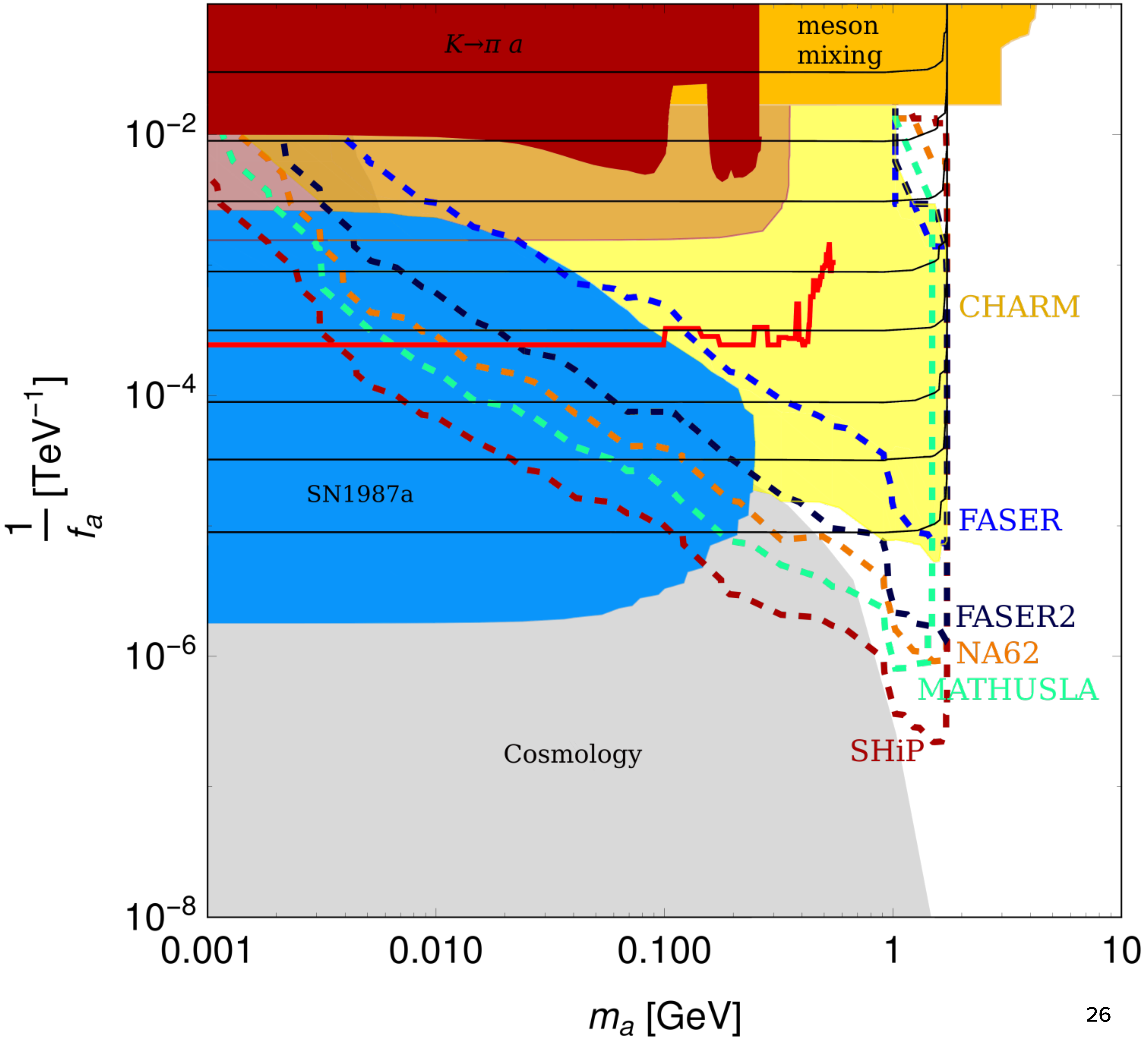
$$N_a = N_D \cdot \mathrm{Br}(D \to \pi a) \cdot \varepsilon_{\mathrm{geom}} \cdot F_{\mathrm{decay}}$$

LHC forward detectors: FASER, FASER II, MATUSHLA

CHARMING ALPS PARAMETER SPACE

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





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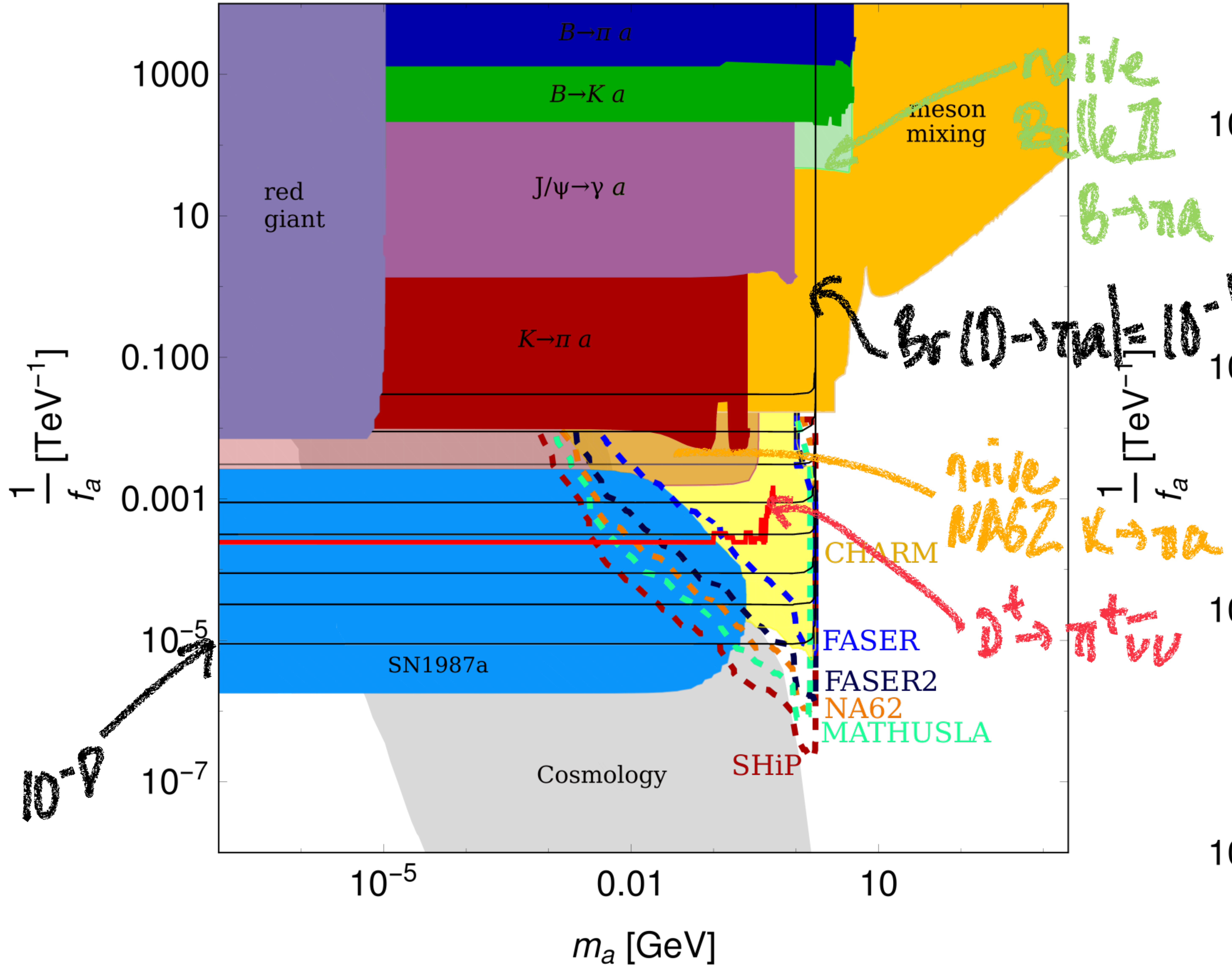
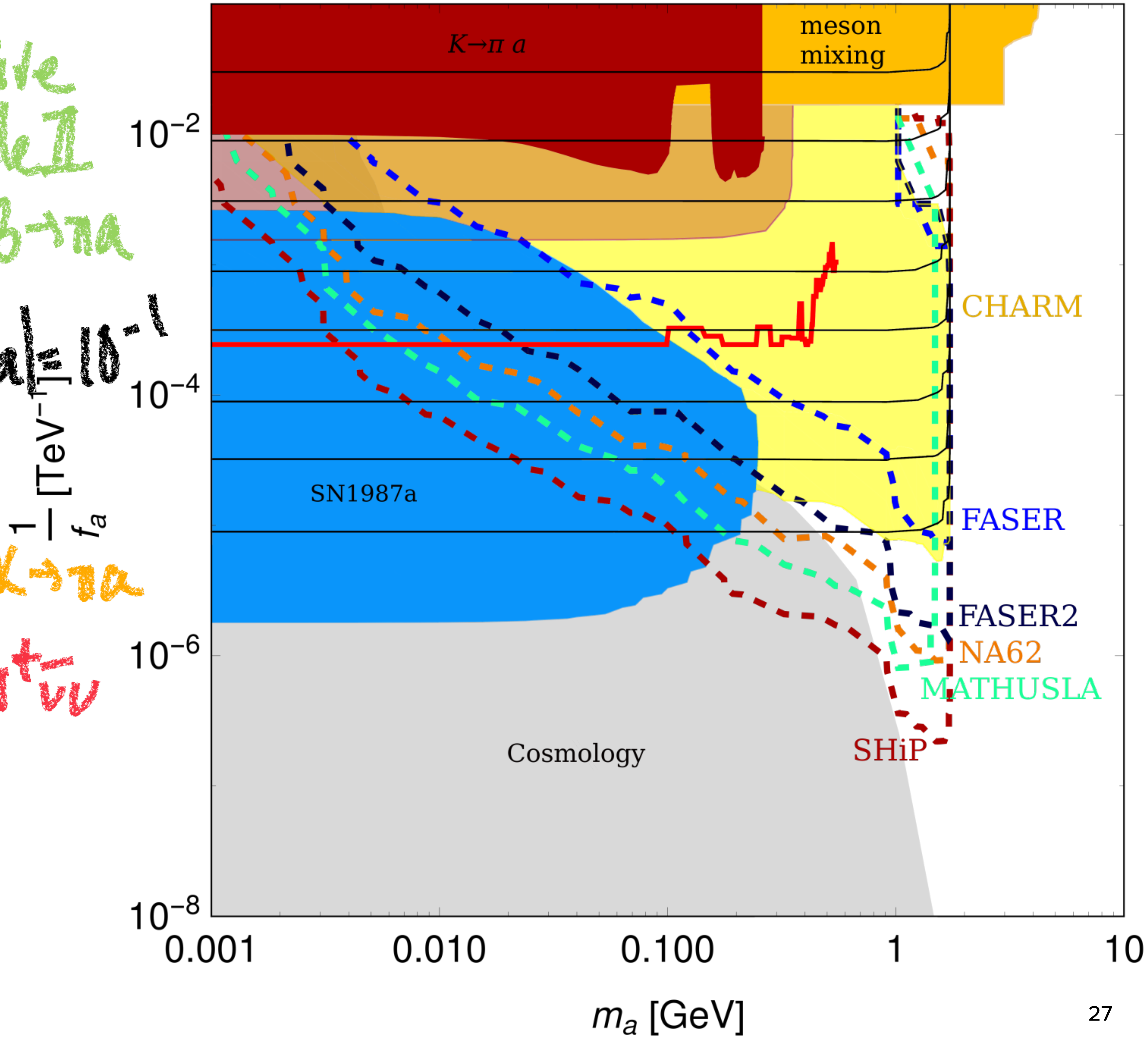
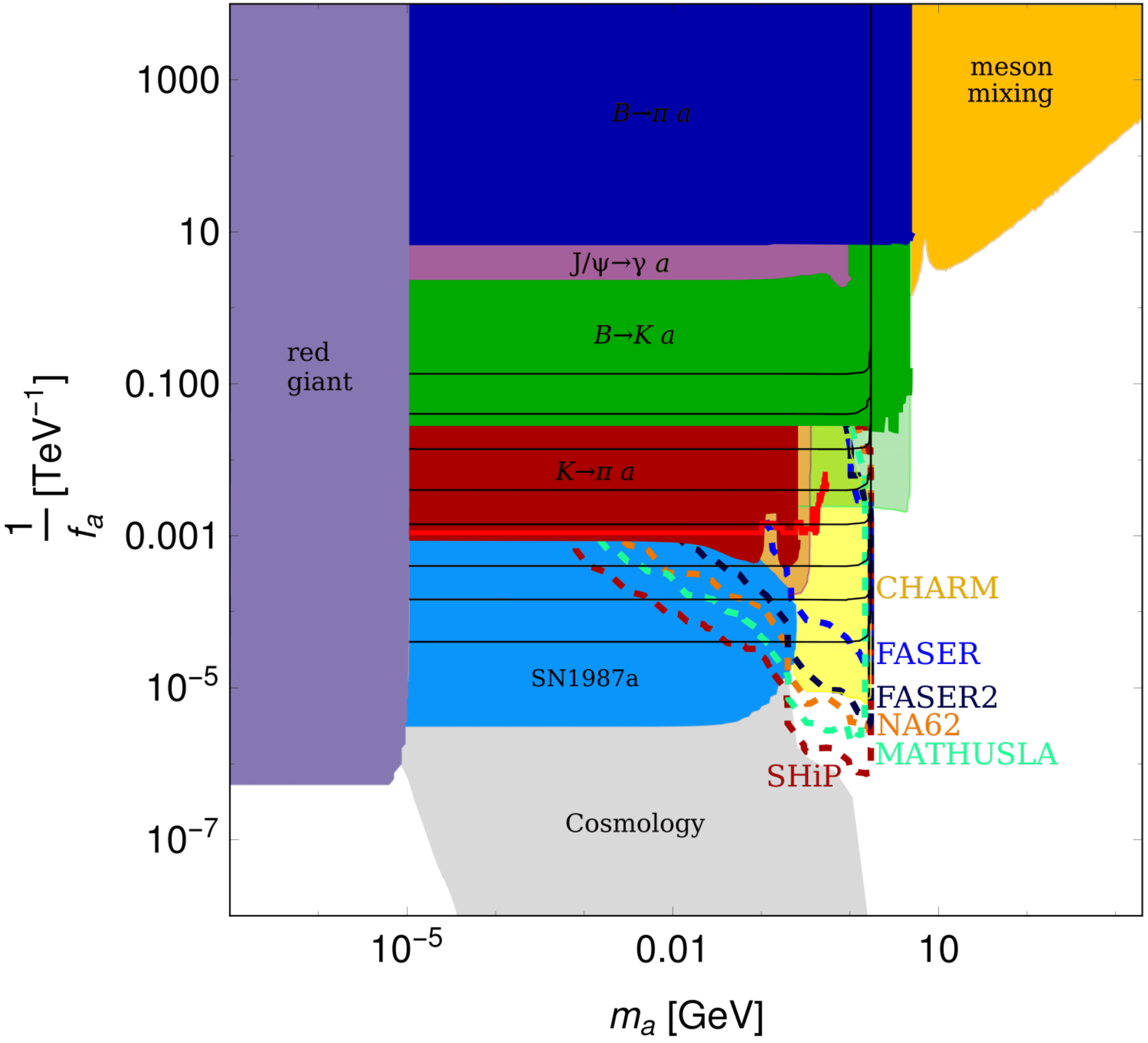
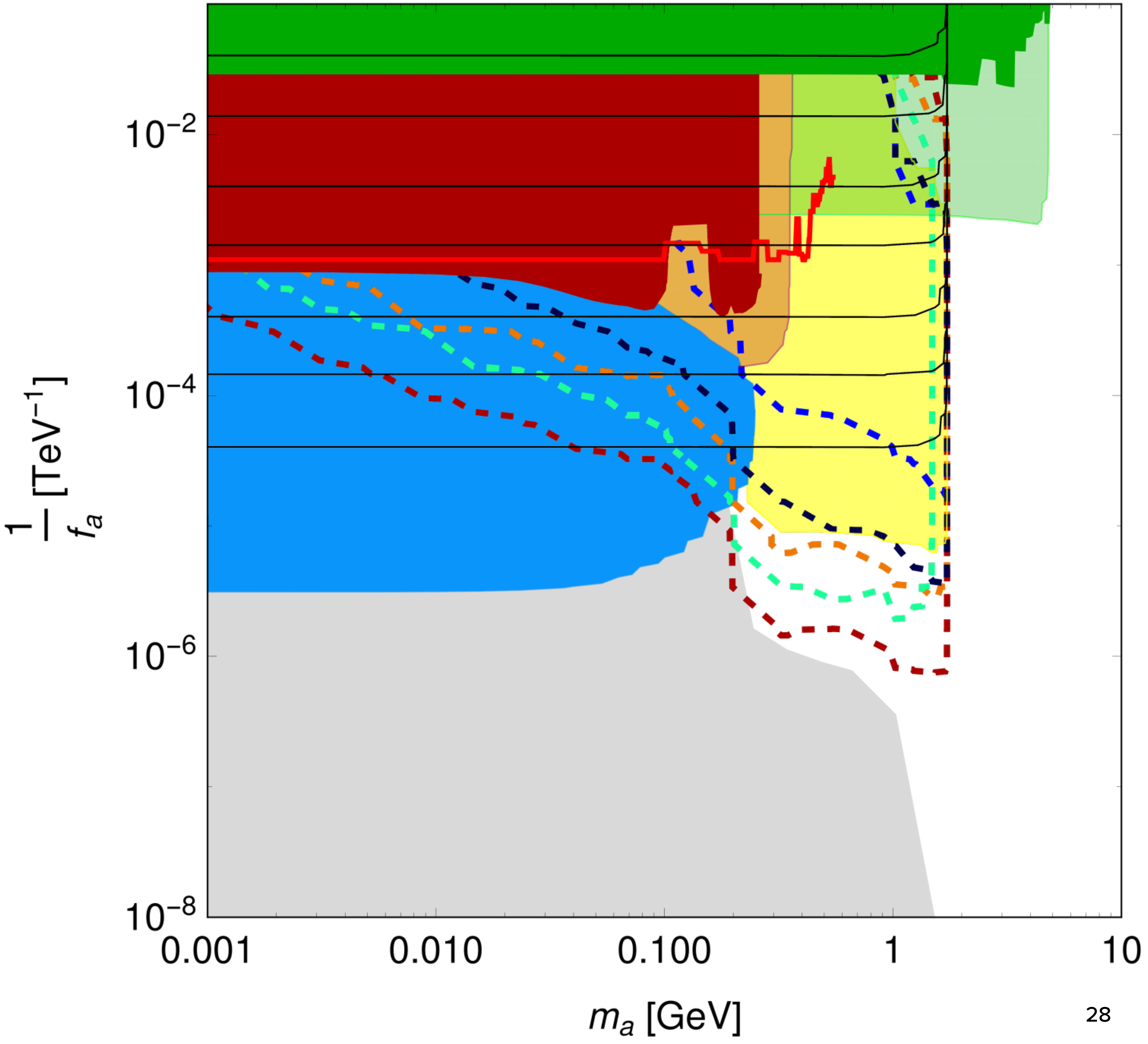




CHARMING ALPS PARAMETER SPACE

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

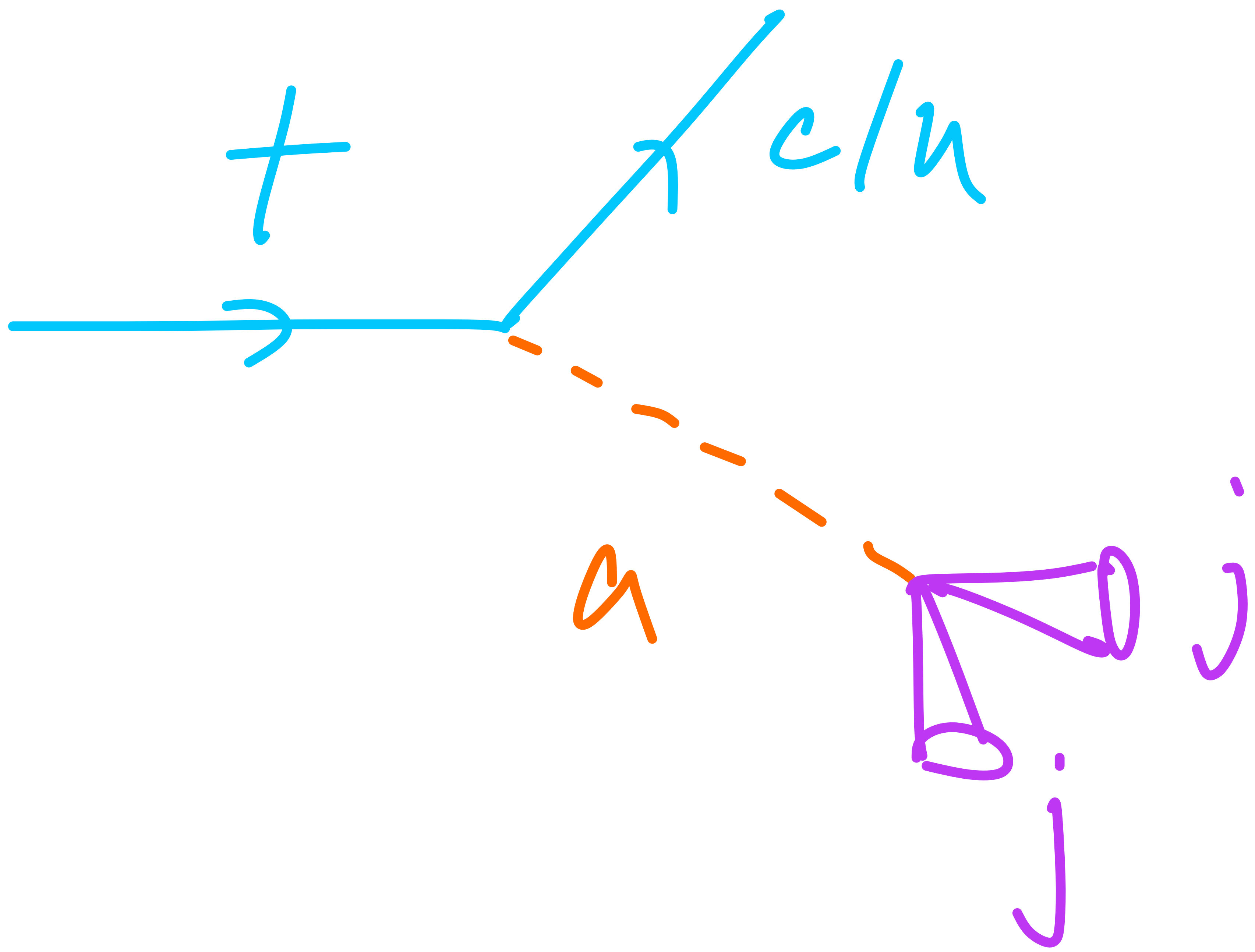


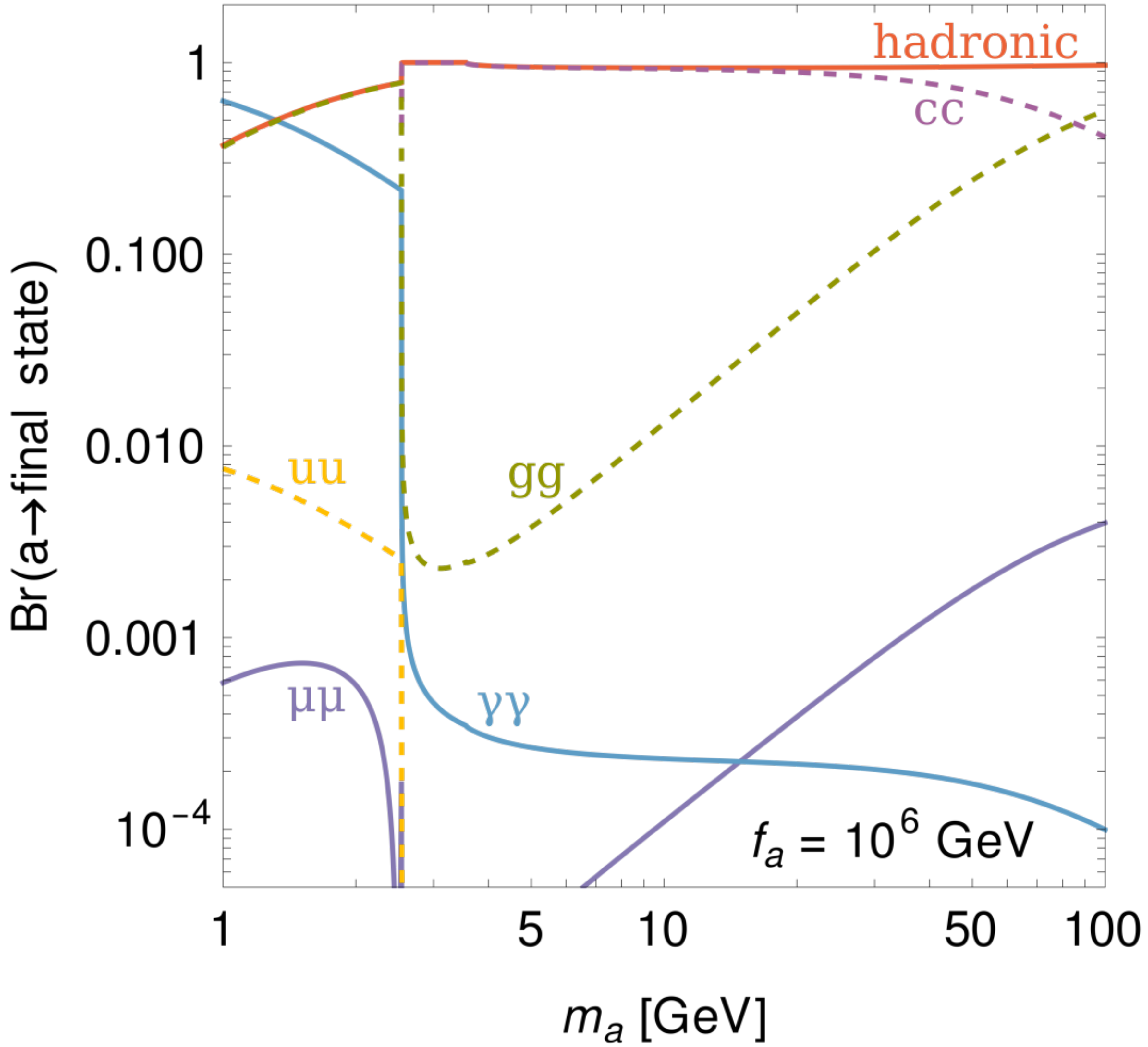


ALPS FROM THE TOP

‘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 (single top and single top + jets)

CMS tqg: leptonic top + 1/2 jets ∧ 1 fails
b-tagging secondary vertex algorithm $0'01\,cm < r < 2'5\,cm$

ATLAS single top: one jet, one lepton + $\not{E}_T$
Caveat m_T distribution changes

ALPS FROM THE TOPS: CONSTRAINTS

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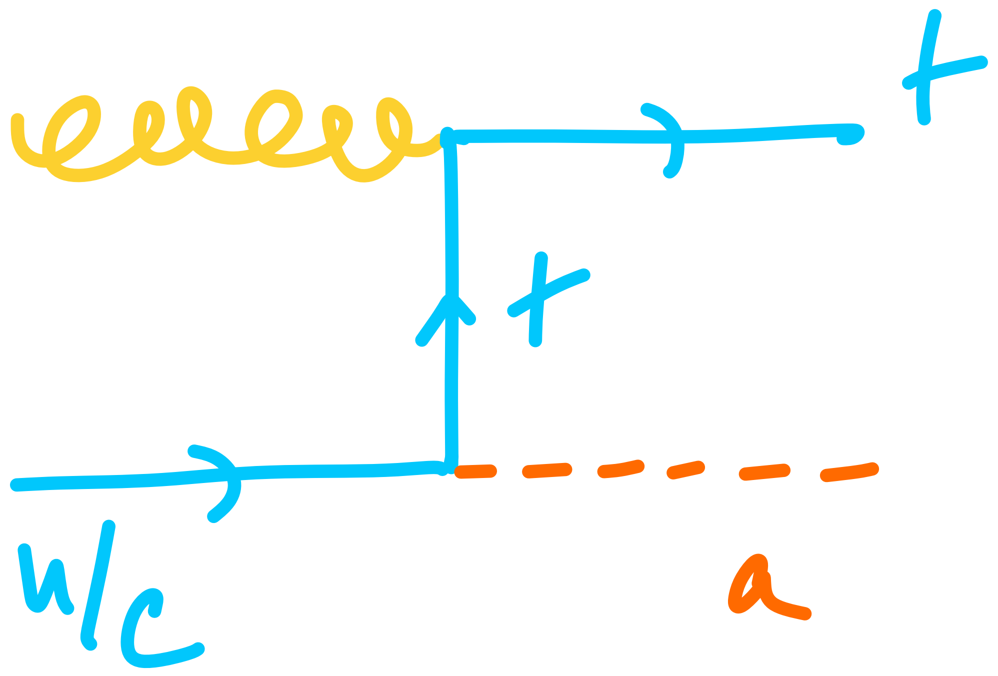
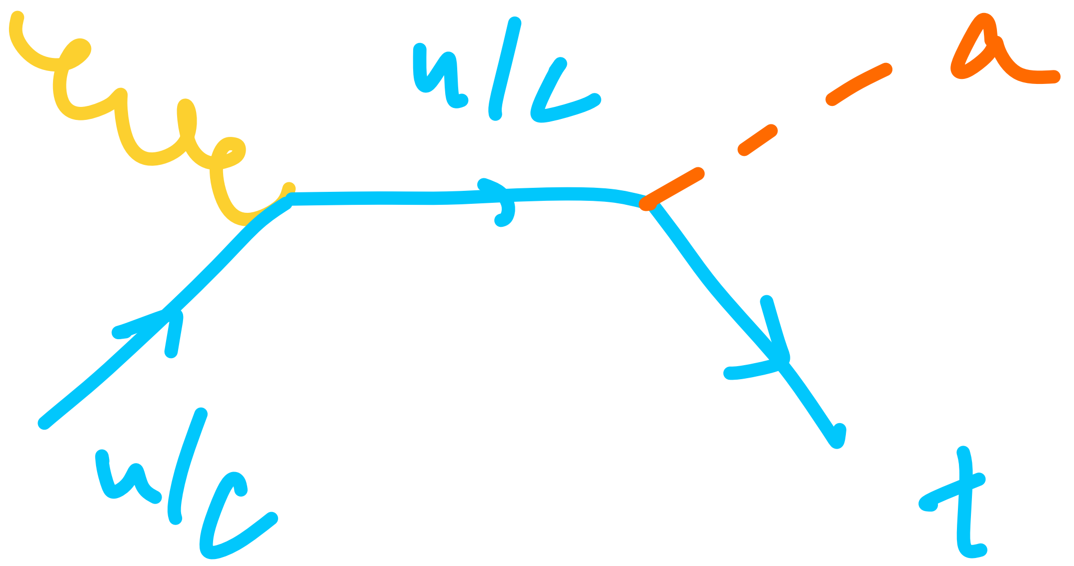




PROMPT

r < 0'01 cm

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

CMS top+jet

LONG-LIVED

2'5 cm < r < 2 m

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

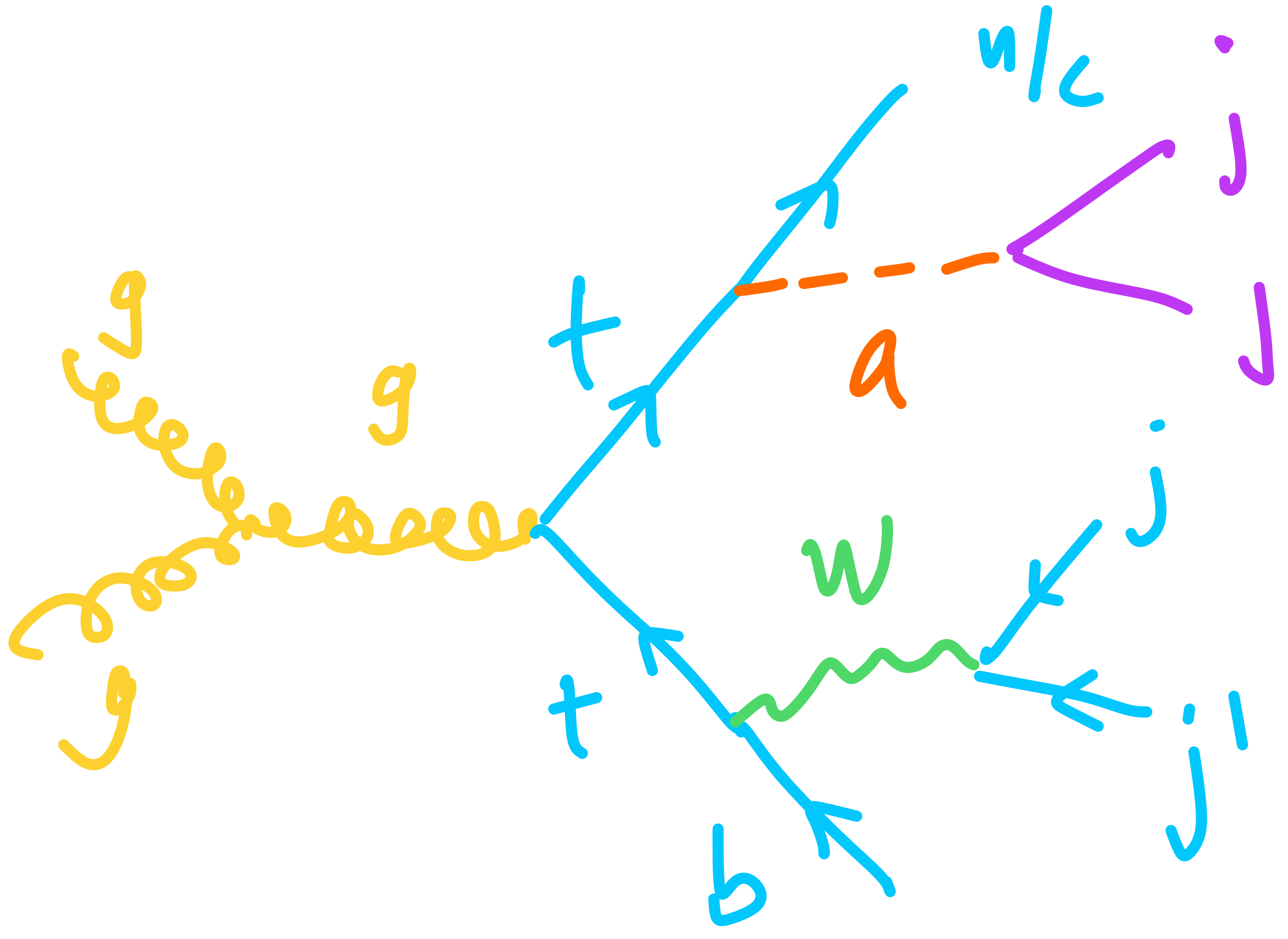
'STABLE'

$c\tau \geq 10$ m

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

ATLAS single top

SIGNAL



We consider two benchmarks with ALP masses

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

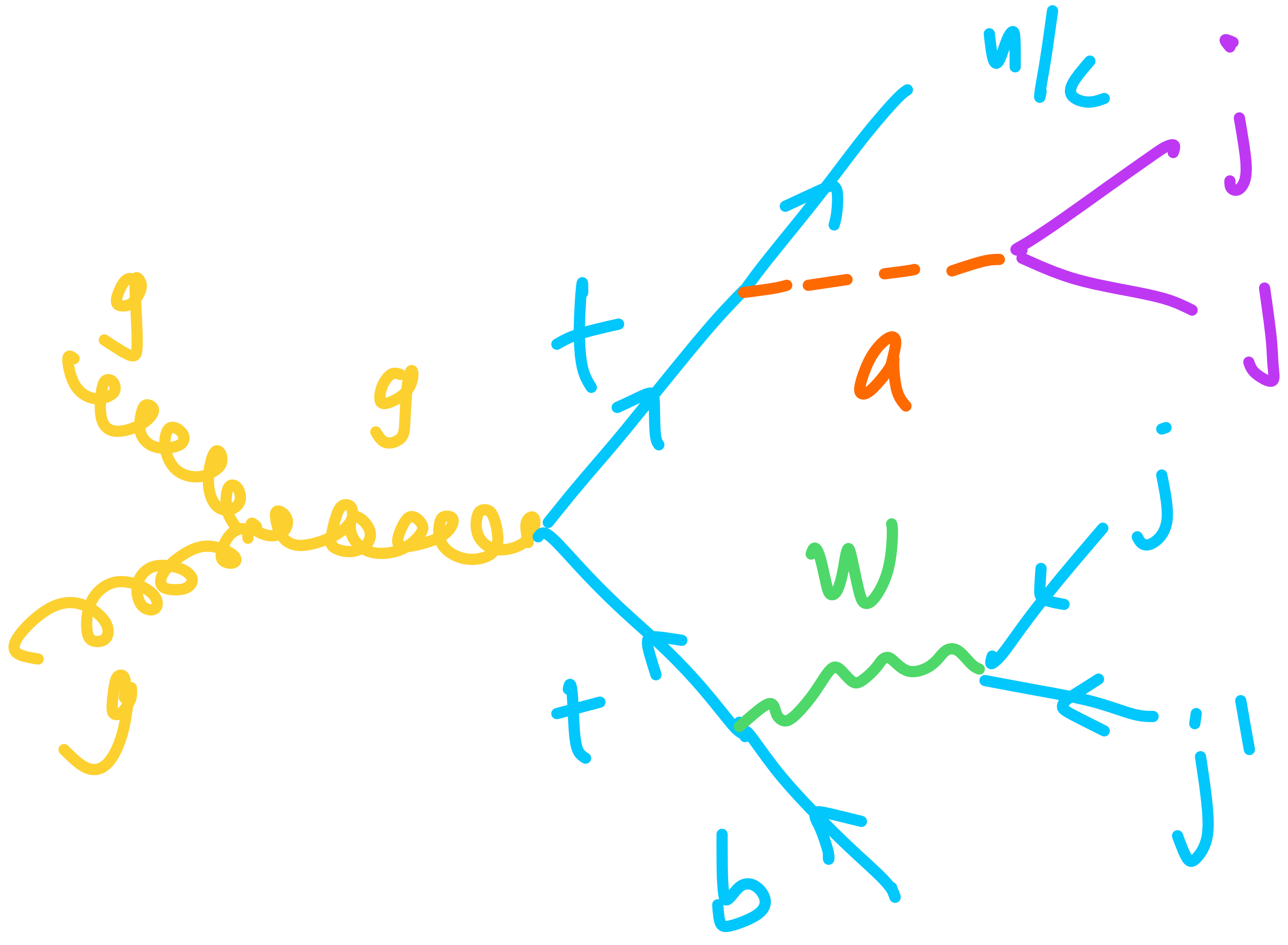
$$\sigma_{\text{signal}} = \sigma_{tt} \cdot \text{Br}(t \to Wb) \cdot \text{Br}(t \to aq)$$

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

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

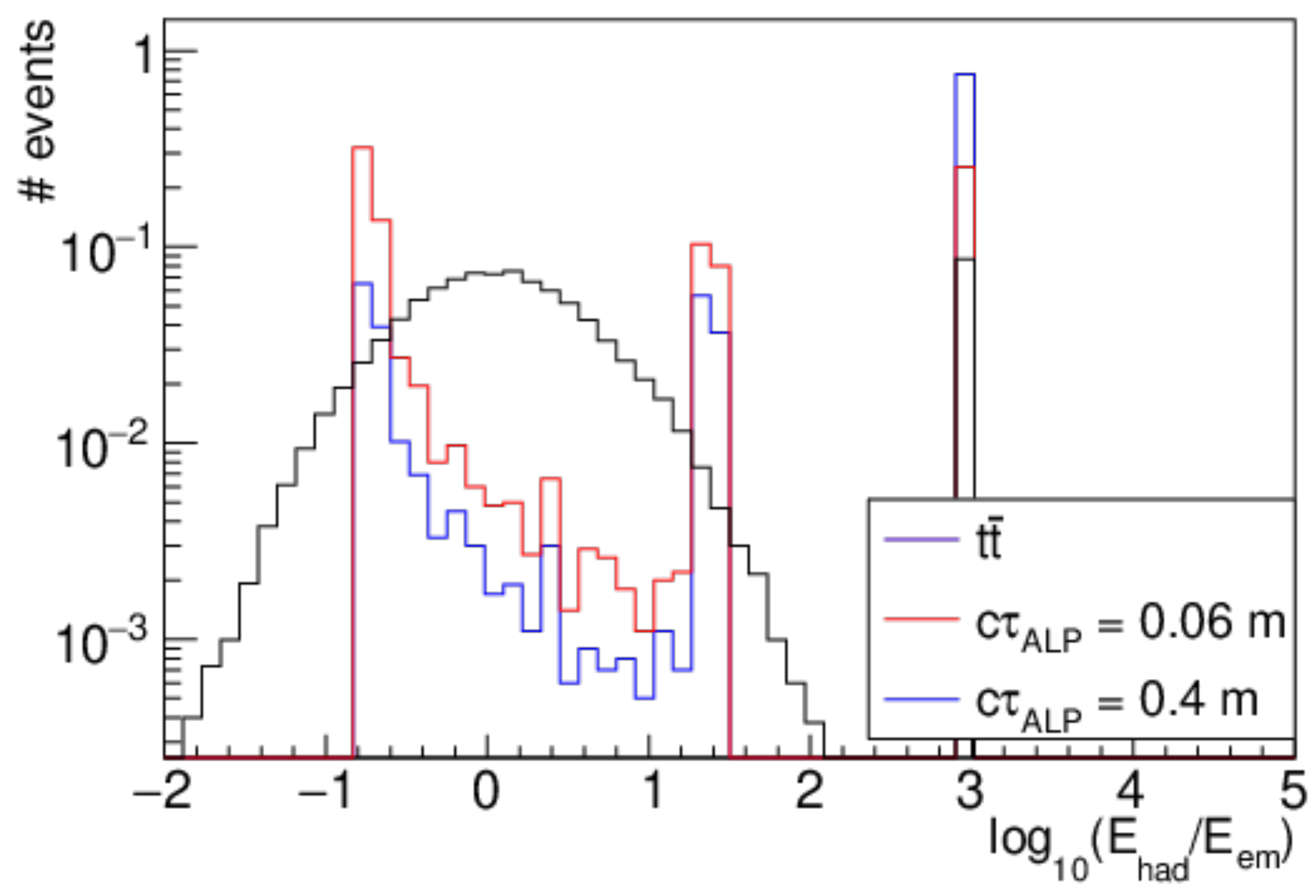
The ALP decay mostly in the → hadronic calorimeter
→ muon spectrometer

SIGNAL : HADRONIC CALORIMETER

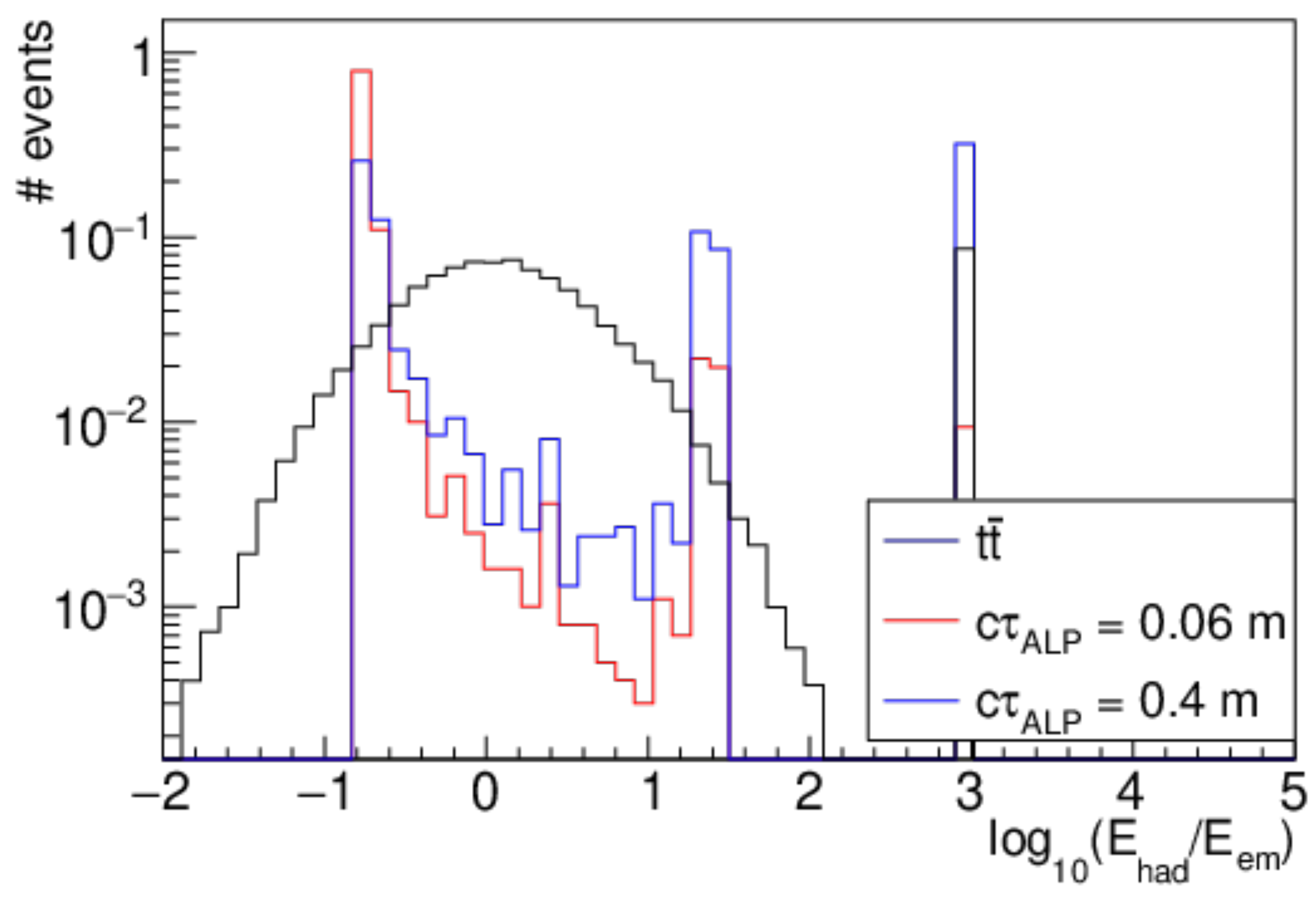


- 3-5(6) jets with 1(2) displaced and another b-tagged
- Large Ehad/Ecal ratio
- No tracks in the displaced jet

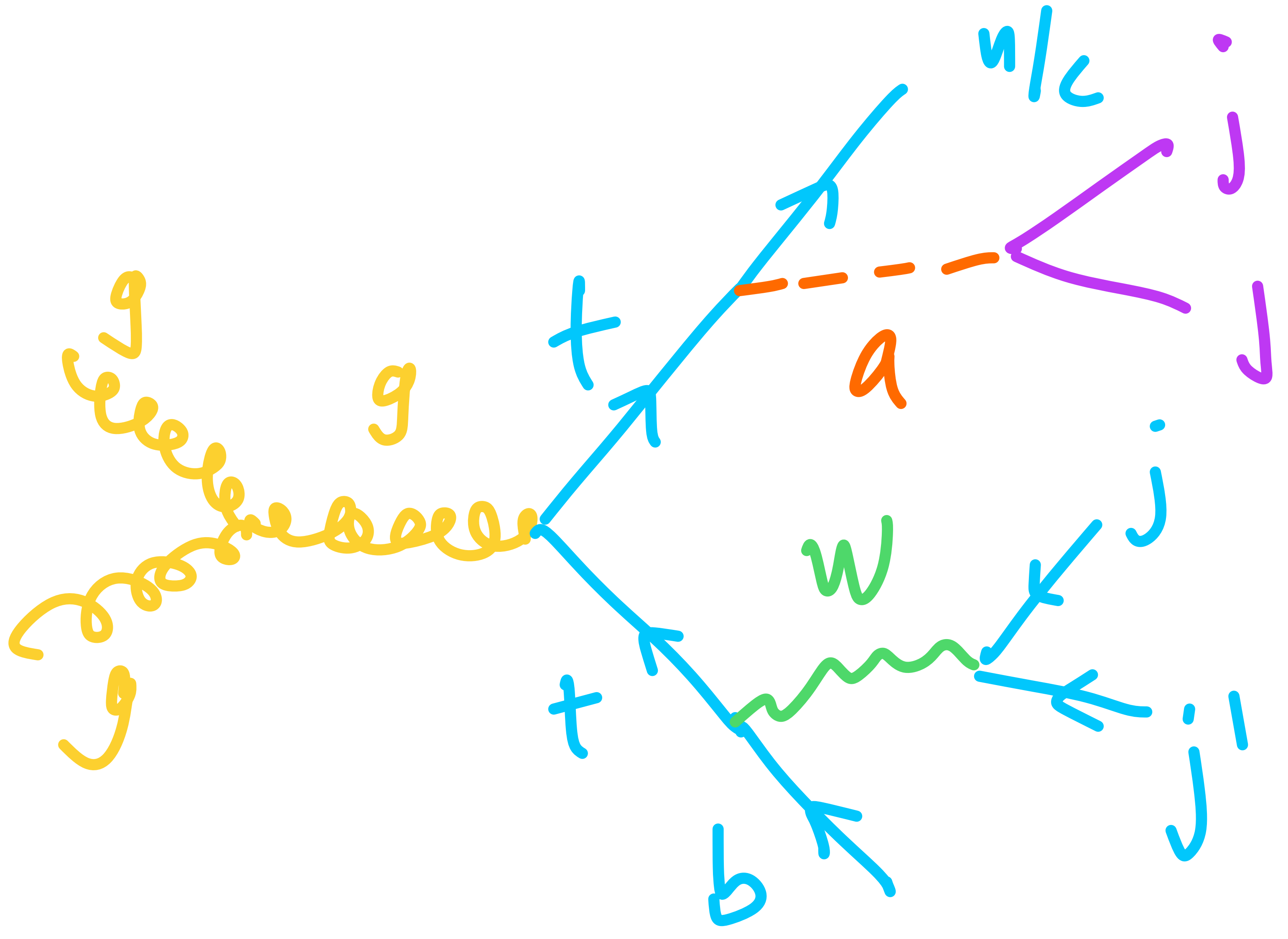
$m_a = 2$ GeV



$m_a = 10$ GeV

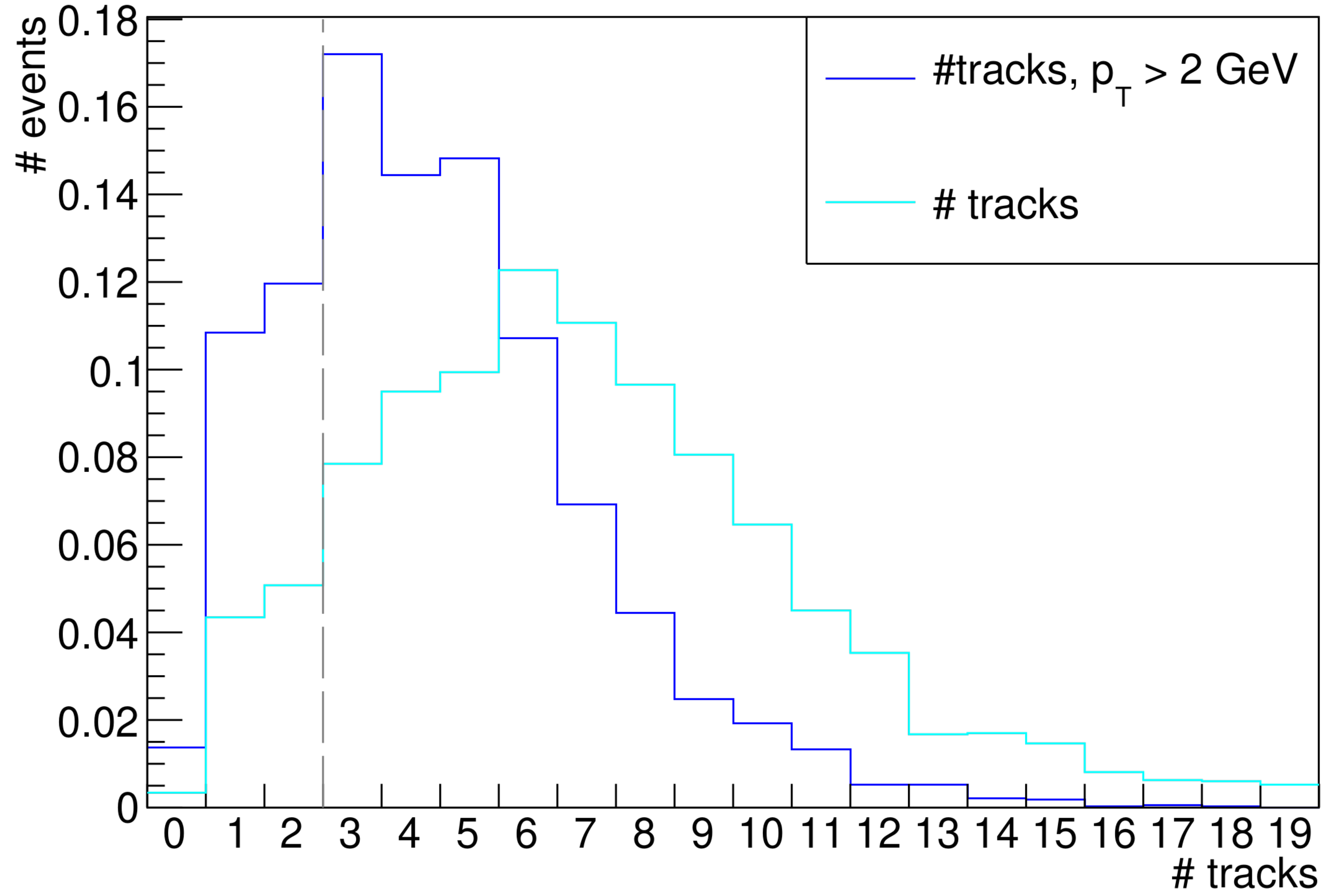


SIGNAL : HADRONIC CALORIMETER

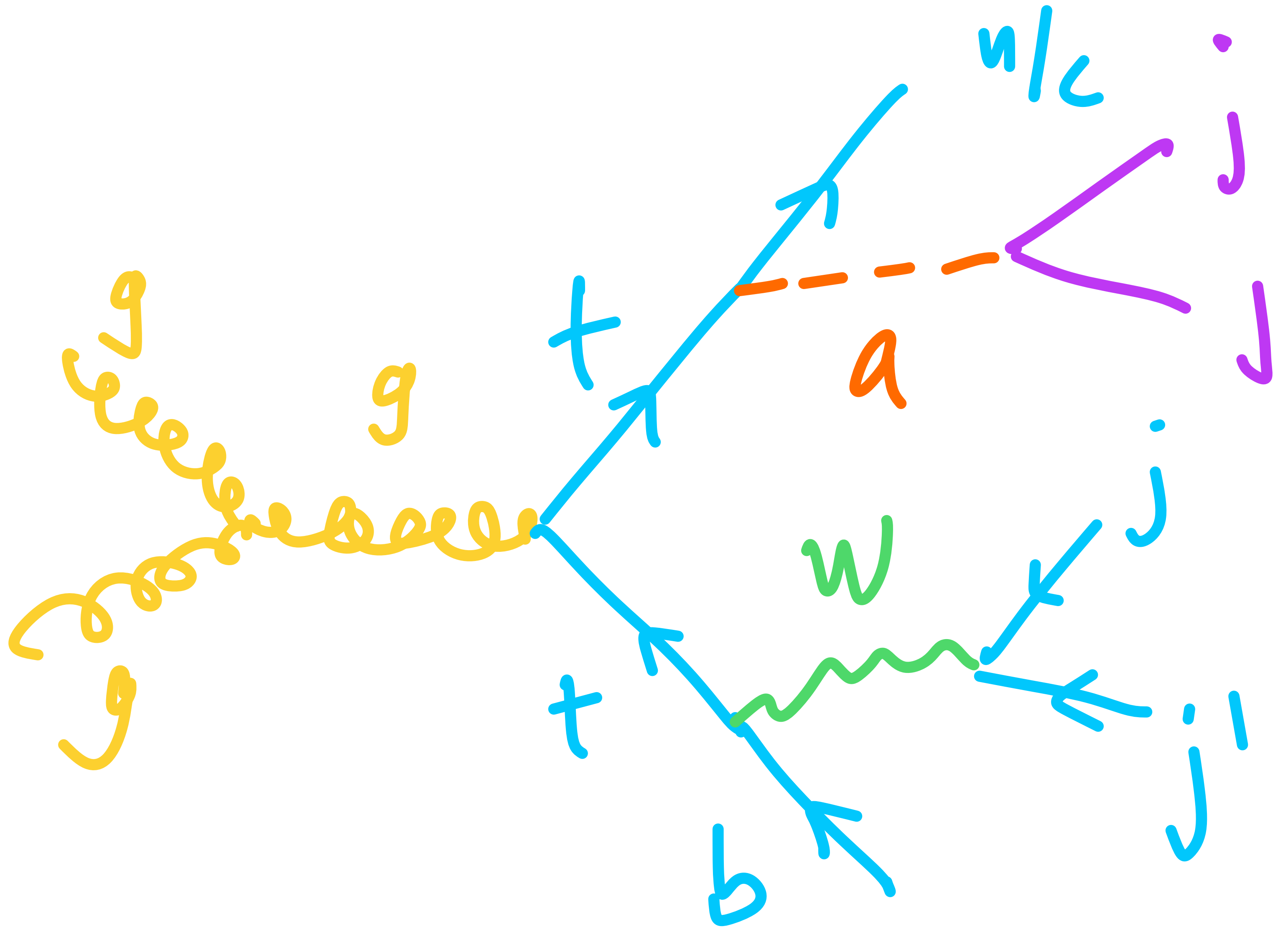


- 3-5(6) jets with 1(2) displaced and another b-tagged
- Large Ehad/Ecal ratio
- No tracks in the displaced jet

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



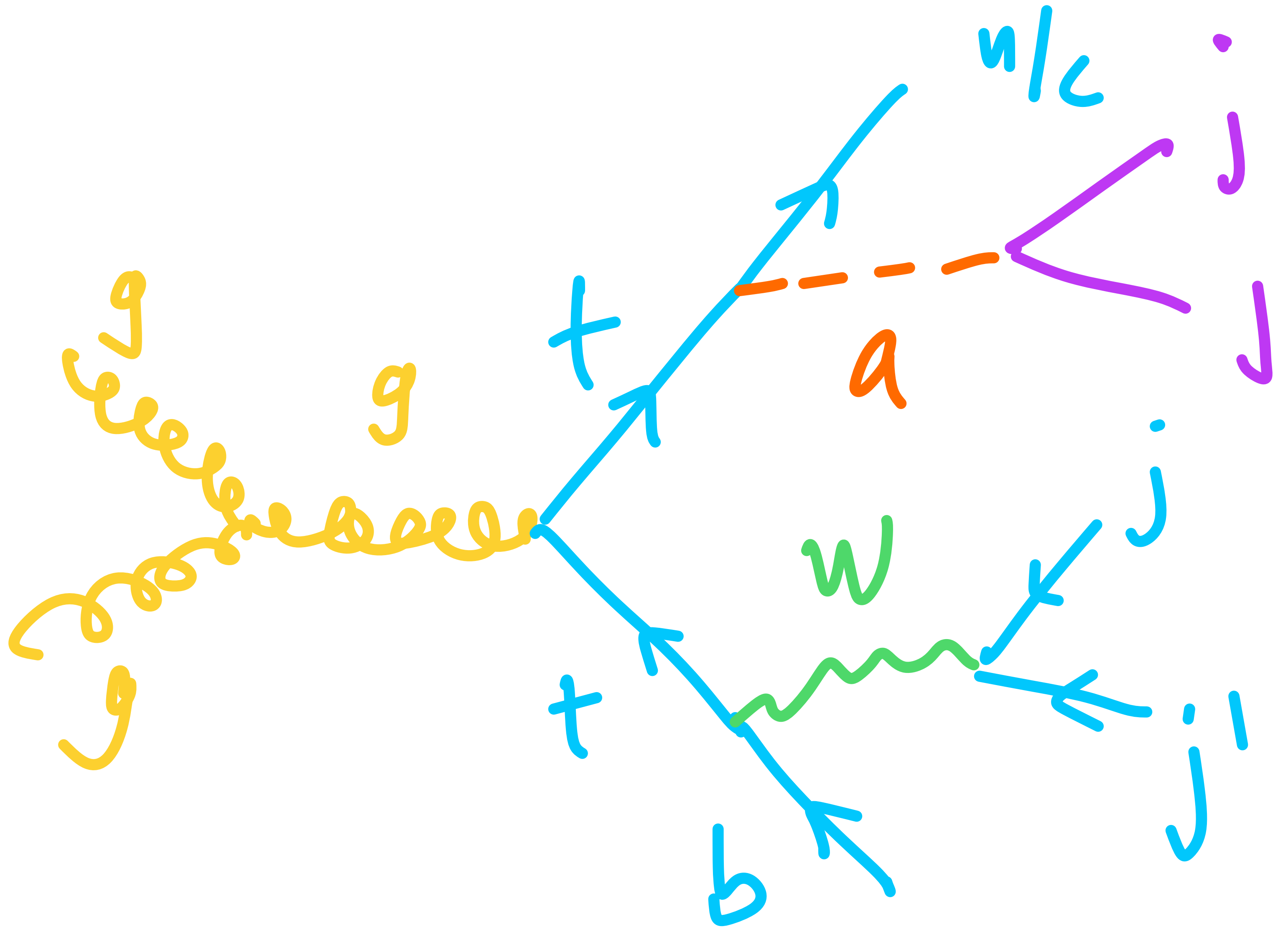
SIGNAL : HADRONIC CALORIMETER



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

	$\mathbf{m_a = 2\ GeV}$	$\mathbf{m_a = 10\ GeV}$	$\mathbf{t\bar{t}}$
total	$(1)\ 2.79 \times 10^5$	$(1)\ 2.79 \times 10^5$	$(1)\ 2.91 \times 10^8$
3 – 6 jets with $\mathbf{p_T > 40\ GeV\ \&\ \|\eta\| < 2.5}$	$(0.8439)\ 2.35 \times 10^5$	$(0.8414)\ 2.35 \times 10^5$	$(0.71801)\ 2.09 \times 10^8$
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 $\mathbf{p_T > 2\ GeV}$	$(0.1436)\ 4.00 \times 10^4$	$(0.0775)\ 2.16 \times 10^4$	$(0.00022)\ 6.39 \times 10^4$

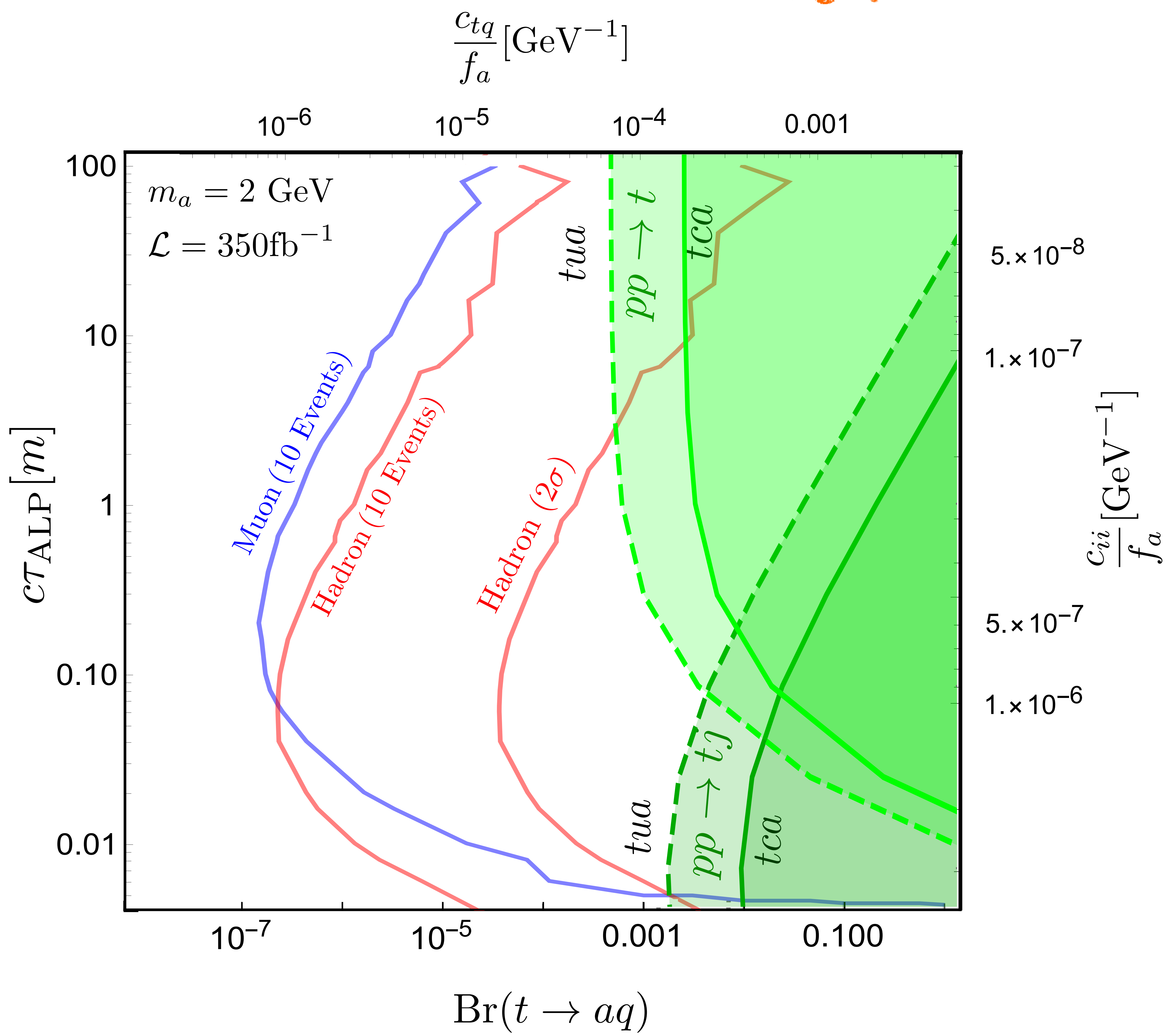
SIGNAL : MUON SPECTROMETER



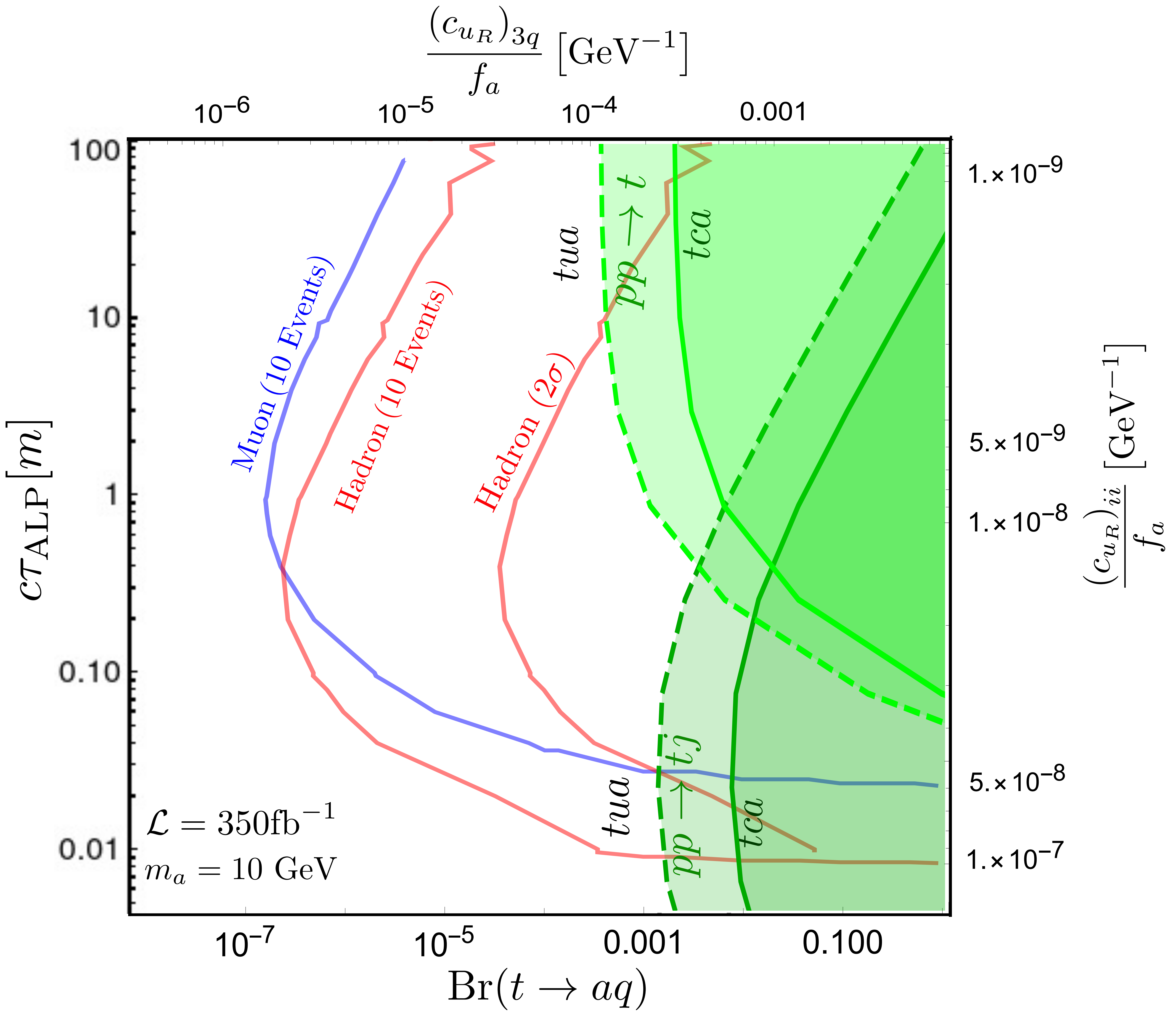
- Event in the muon system
- No associated track pointing to the primary vertex
- 2-4(5) jets
- Signal is background free

RESULTS

$m_a = 2$ GeV



$m_a = 10$ GeV



DARK MATTER AS DARK PIONS

AC, Elahi, Scherb, Schwaller (upcoming!)

If $n_f \geq 4$ then we will have stable dark pions

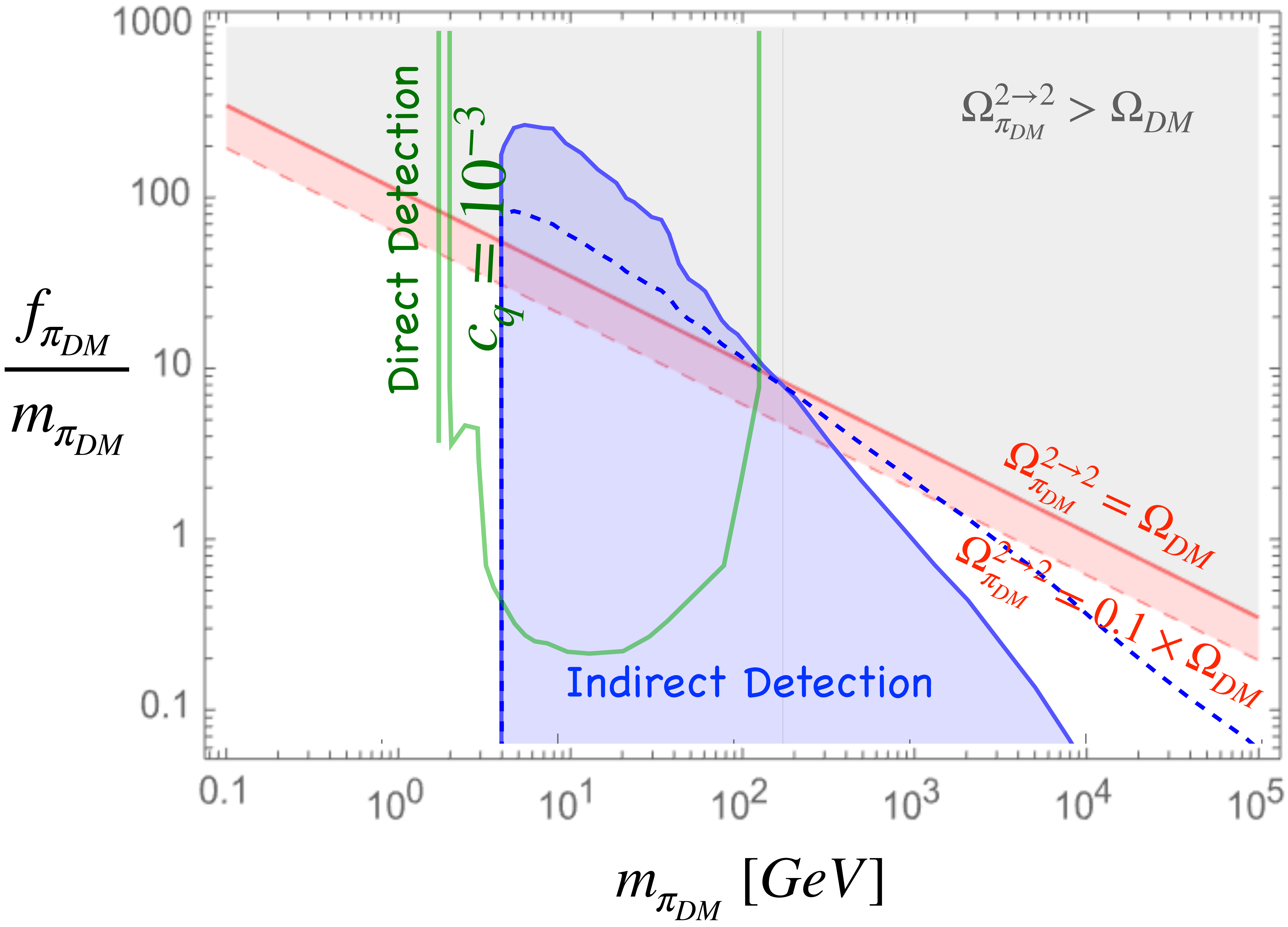
Since $n_f \geq 3$ we will have also a WZW term

$$\mathscr{L}^{(5)}_{\rm SI} = \frac{2N_d}{15\pi^2 f_D^5}\epsilon^{\mu\nu\rho\sigma} \sum_{a<b<c<d<e} \pi^a \partial_\mu \pi^b \partial_\nu \pi^c \partial_\rho \pi^d \partial_\sigma \pi^e T_{abcde}$$

However the 2-2 processes are more efficient then the 3-2 processes and the relic abundance is dominated by the former

DARK MATTER AS DARK PIONS

AC, Elahi, Scherb, Schwaller (upcoming!)



$$C_q \equiv \frac{(\kappa_{\alpha q}\kappa^*_{\beta q}c_{\alpha\beta})\max(f_D, m_{\pi_D})^2}{m_\chi^2}$$

Indirect detection: FERMI-LAT

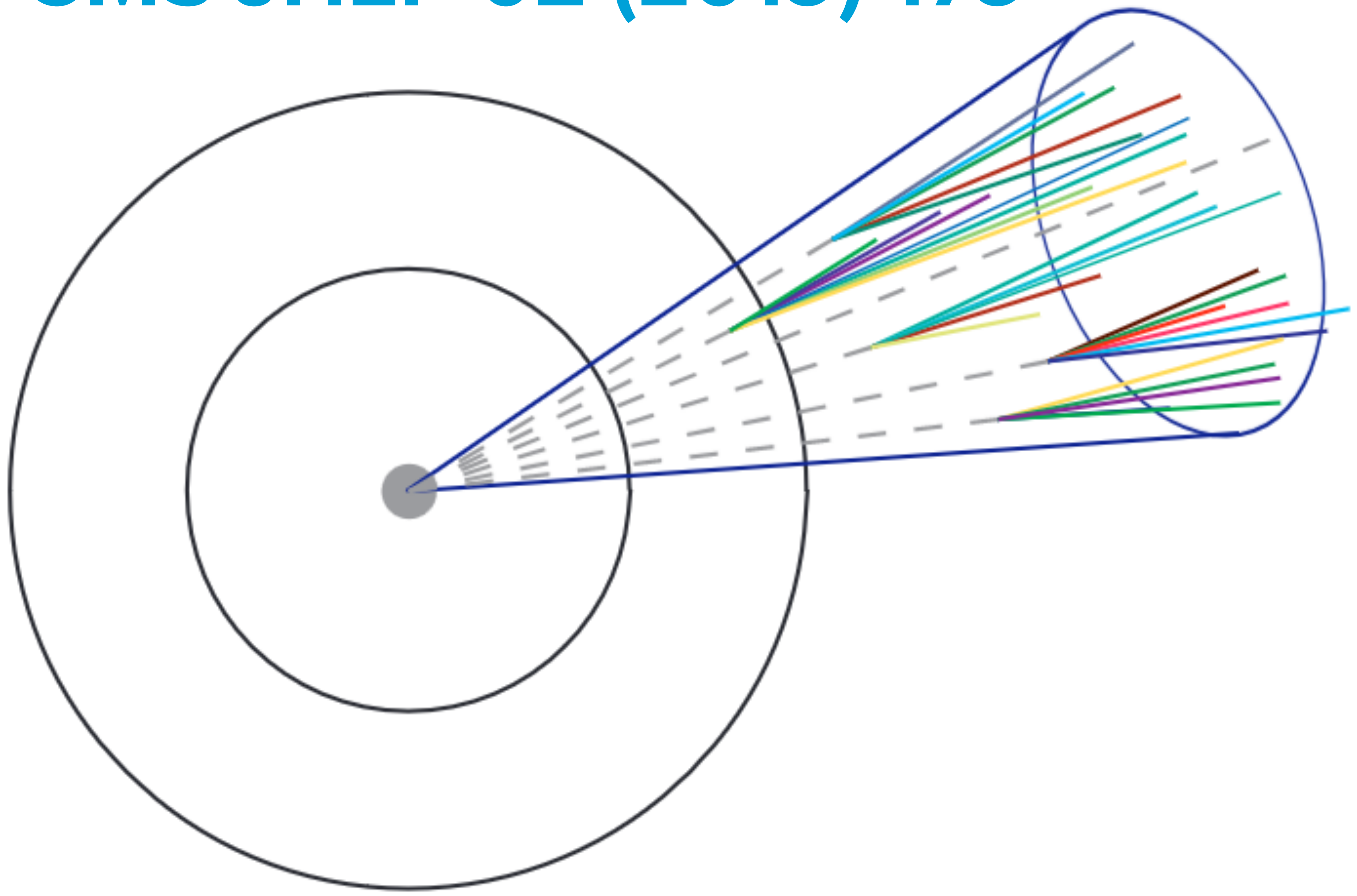
Direct detection: LUX

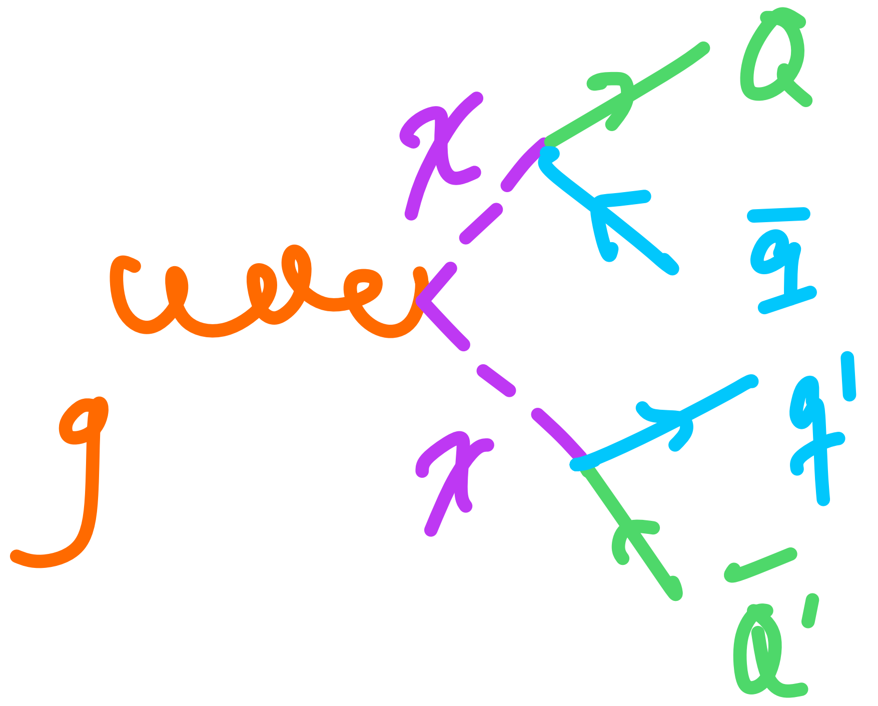
VERY PRELIMINARY!

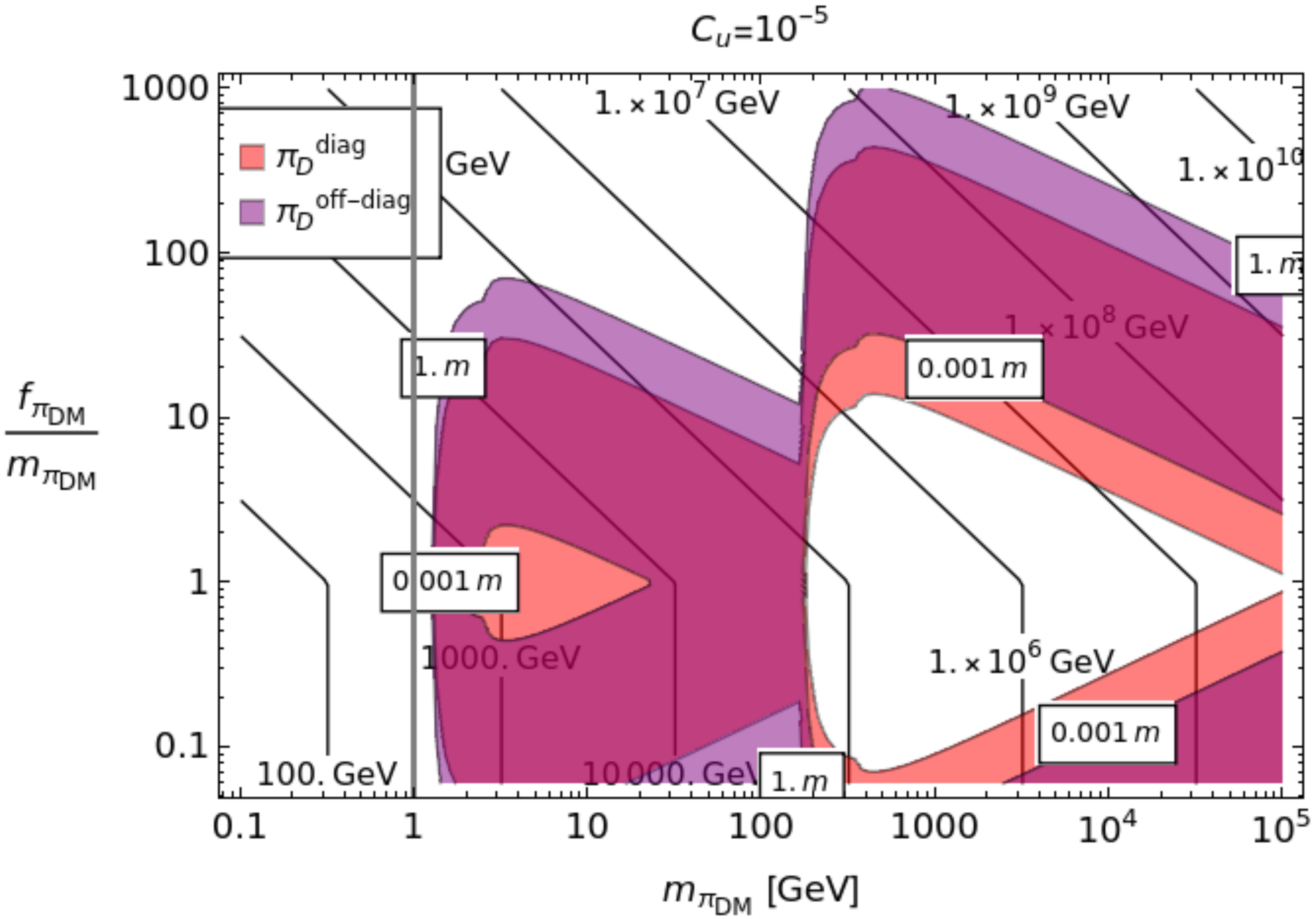
DARK MATTER AS DARK PIONS

AC, Elahi, Scherb, Schwaller (upcoming!)

CMS JHEP 02 (2019) 179







VERY PRELIMINARY!

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!

BACK UP

SN1986A

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

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

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

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

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

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

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

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

ALPS FROM THE TOPS: CONSTRAINTS

We recast searches from exotic top decays (single top and single top + jets)

CMS tqg: leptonic top + 1/2 jets ∧ 1 fails
b-tagging secondary vertex algorithm 0'01 cm < r < 2'5 cm

ATLAS single top: one jet, one lepton + E_T
Caveat m_T distribution changes

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}

RESULTS

$m_a = 2$ GeV

$m_a = 10$ GeV