New signs of Supersymmetry: the R-axion

Bellazzini Mariotti Redigolo FS Serra, 1702.02152 + works in progress

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Take-home messages

Any other sign of SUSY to be looked for at colliders?

beyond gluino, stop, EWinos, extra Higgses,…

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Any other sign of SUSY to be looked for at colliders?

beyond gluino, stop, EWinos, extra Higgses,…

Spontaneously broken R-symmetry is quite generic

provides a naturally light state, the "R-axion" (whose pheno has been overlooked)

could be the first sign of SUSY at colliders

gives access to properties of the SUSY-breaking sector

opens new pheno & model-building avenues

Take-home messages

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provides a naturally light state, the "R-axion"

R symmetry: one slide recap

N = 1 SUSY always accompanied by a continuous $U(1)_R$ = "R-symmetry"

$$R: \ \theta_\alpha \to e^{i\epsilon}\,\theta_\alpha \qquad [R,Q] = -Q$$

R-charge assignments: $$\Phi = \phi + \sqrt{2}\theta\,\psi + \theta^2\,F$$

$$r_\phi = r_\Phi$$
$$r_\psi = r_\Phi - 1$$
$$r_F = r_\Phi - 2$$

Vector superfields are real $\Rightarrow$ gauginos have $r_\lambda = 1$

Lagrangian $\mathcal{L}$ R-symmetric $\Rightarrow R(W) = 2$

($\Leftarrow$ if Kahler canonical)

$$\mathcal{L} \supset \int d^2\theta\, W \,+\, \text{c.c.}$$

W superpotential

Why bothering with R-symmetry?

Nelson Seiberg hep-ph/9309299

i) SUSY broken in global minimum

ii) W generic
(i.e. contains all terms not forbidden by symmetries)

$\Rightarrow$ Lagrangian respects a $U(1)_R$

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1. gaugino masses
$\mathcal{L} \supset m_\lambda \lambda\lambda$

2. EW symmetry breaking & Higgsino masses
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Ways out?

- Break $U(1)_R$ spontaneously $\Longrightarrow$ Massless Goldstone in the spectrum R-axion a !
- Violate i) or ii) (e.g. SUSY broken in metastable vacuum) Intriligator Seiberg Shih 2006, 2007

  but then an analogous of Nelson Seiberg holds for an approximate $U(1)_R$

  $\longrightarrow$ the R-axion is a pseudo-Goldstone, gets small mass m_a

✓ Motivation

Setup

Phenomenology

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A general description

Least possible ingredients in the IR: SM a G

Goldstone from $U(1)_R$ breaking   Goldstino from SUSY breaking

Free parameters

f_a — $U(1)_R$ breaking scale, controls a pheno

F — SUSY breaking scale, controls G pheno

m_a

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m_a From small R-symmetry breaking, quite generic

→ from cosmological constant Bagger+ hep-ph/9405345

$$m_a^2 \sim (10\ \text{MeV})^2 \times \frac{M_{\text{SUSY}}}{10\ \text{TeV}} \times \frac{m_{3/2}}{\text{eV}}$$

→ we live in a metastable SUSY-breaking vacuum

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→ happens in many models

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Affleck Dine Seiberg 1985, …….
Dine+ 1612.05770, Bellazzini+ in progress

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Goh Ibe 0810.5773

Only mass range studied before our work

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The R-axion pheno Lagrangian-I

Komargodski Seiberg 0907.2441

Tool: constrained superfield formalism

$$X = \frac{G^2}{2\,F_X} + \sqrt{2}\theta\, G + \theta^2\, F_X$$

satisfy the constraints $\begin{cases} X^2 = 0 \\ X(R^\dagger R - 1) = 0 \end{cases}$

$$\mathcal{R} = e^{i\mathcal{A}/f_a} = e^{ia/f_a + O(a\,G,\ldots)}$$

~ analogous to ordinary Goldstones $U^\dagger U = 1 \quad U = e^{i\pi}$

Most general effective Lagrangian: $r_X = 2 \quad r_{\mathcal{R}} = 1$

$$\mathcal{L}_{G+a} = \int d^4\theta\,(X^\dagger X + f_a^2 \mathcal{R}^\dagger \mathcal{R}) + \int d^2\theta\,(F X + w_R \mathcal{R}^2) + \text{c.c.}$$

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$$-\frac{w_R}{f_a\, F^2}\Box a\, \bar{G} i\gamma_5 G$$

First pheno prediction (valid for any UV completion!):

R-axion decays to missing energy

$$w_R < \frac{1}{2} f_a F \quad \rightarrow \quad \Gamma_{a\to GG} < \frac{1}{32\pi}\frac{m_a^5}{F^2}$$

Dine Festuccia Komargodski 0910.2527
see also Bellazzini 1605.06111

The R-axion pheno Lagrangian-II

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$$\mathcal{L}_{\text{gauge}} = \int d^2\theta \left(\frac{1}{4} - i g_i^2 \, \frac{c_i^{\text{hid}}}{16\pi^2} \mathcal{A} \right) \mathcal{W}_i^2 - \int d^2\theta \frac{m_{\lambda_i}}{2F} X \mathcal{R}^{-2} \mathcal{W}_i^2 + \text{c.c.}$$

$$R_H \equiv r_{H_u} + r_{H_d}$$

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between a and MSSM pseudoscalar A

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$$-i\,a\,R_H \left(c_\beta^2 \frac{m_u}{f_a} \bar{u}\gamma_5 u + s_\beta^2 \frac{m_d}{f_a} \bar{d}\gamma_5 d + s_\beta^2 \frac{m_\ell}{f_a} \bar{\ell}\gamma_5 \ell \right)$$

$$\frac{\delta^2}{v} (\partial_\mu a)^2 h$$

(Here and in the following $m_A,\ m_{\tilde{f}} \gg m_a$)

A strongly coupled “UV" completion

Very low energy SUSY breaking F

motivated by:

Naturalness + Higgs mass Gherghetta Pomarol 1107.4697

+ LHC exclusions Buckley et al. 1610.08059

Gravitino cosmology Ibe Yanagida 1608.01610

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needs a strongly coupled sector

so that $m_{\lambda^i} \sim \frac{g_i^2}{g_*^2} m_*$ OK with LHC bounds

m_* mass gap of the hidden sector (e.g. mass of messengers in gauge mediation)

$g_* > 1$ coupling between hidden sector states

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m_*

$$m_{\rm soft} \approx \frac{g^2}{g_*^2} m_*$$

$$m_a \approx \sqrt{\epsilon_{R\!\!\!/}}\, m_*$$

$$m_G = \frac{F}{\sqrt{3} M_{Pl}}$$

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SUSY Naive Dimensional Analysis

$$M_{\rm SUSY} \sim m_* \sim g_* f \qquad f_a \sim f$$

$$F \sim g_* f^2 \qquad w_R \sim g_* f^3$$

inspired by
Cohen et al. 1997
Luty 1998
Giudice+ 2007

$a \to GG$ saturates the upper bound

✓ Motivation

✓ Setup

Phenomenology

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Pheno overview

We will focus on $2 \text{ GeV} < m_a < 2 \text{ TeV}$

just for definiteness

otherwise ~ not a pseudo Goldstone

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i.e. beyond reach of LHC14

$m_{\tilde{B}} \simeq 500\ \text{GeV} \quad m_{\tilde{W}} \simeq 1\ \text{TeV} \quad m_{\tilde{g}} \simeq 2.5\ \text{TeV}$ would correspond to $m_* \simeq 22\ \text{TeV} \left(\frac{g_*}{3}\right)^2$

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Value of their masses do not matter for R-axion pheno (as long as they are decoupled)

Example: $$\Gamma_{a\to gg} = k_{gg} \frac{\alpha_s^2}{16\pi^3} \frac{m_a^3}{f_a^2} \left| c_3^{\text{hid}} + 3\,\text{Loop}_{\tilde{g}} - \sum_{q=t,b,\ldots} r_q\, \text{Loop}_q \right|^2$$

$c_i^{\text{hid}} = -N_{\text{mess}}$

(messangers in $5+\bar{5}$ of $SU(5)$ with zero R-charge)

$\text{Loop}_{\tilde{g}} \xrightarrow{m_{\tilde{g}} \gg m_a/2} 1$

i.e. an anomaly

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Could the R-axion be the first SUSY sign at colliders?

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Resonant production @ LHC

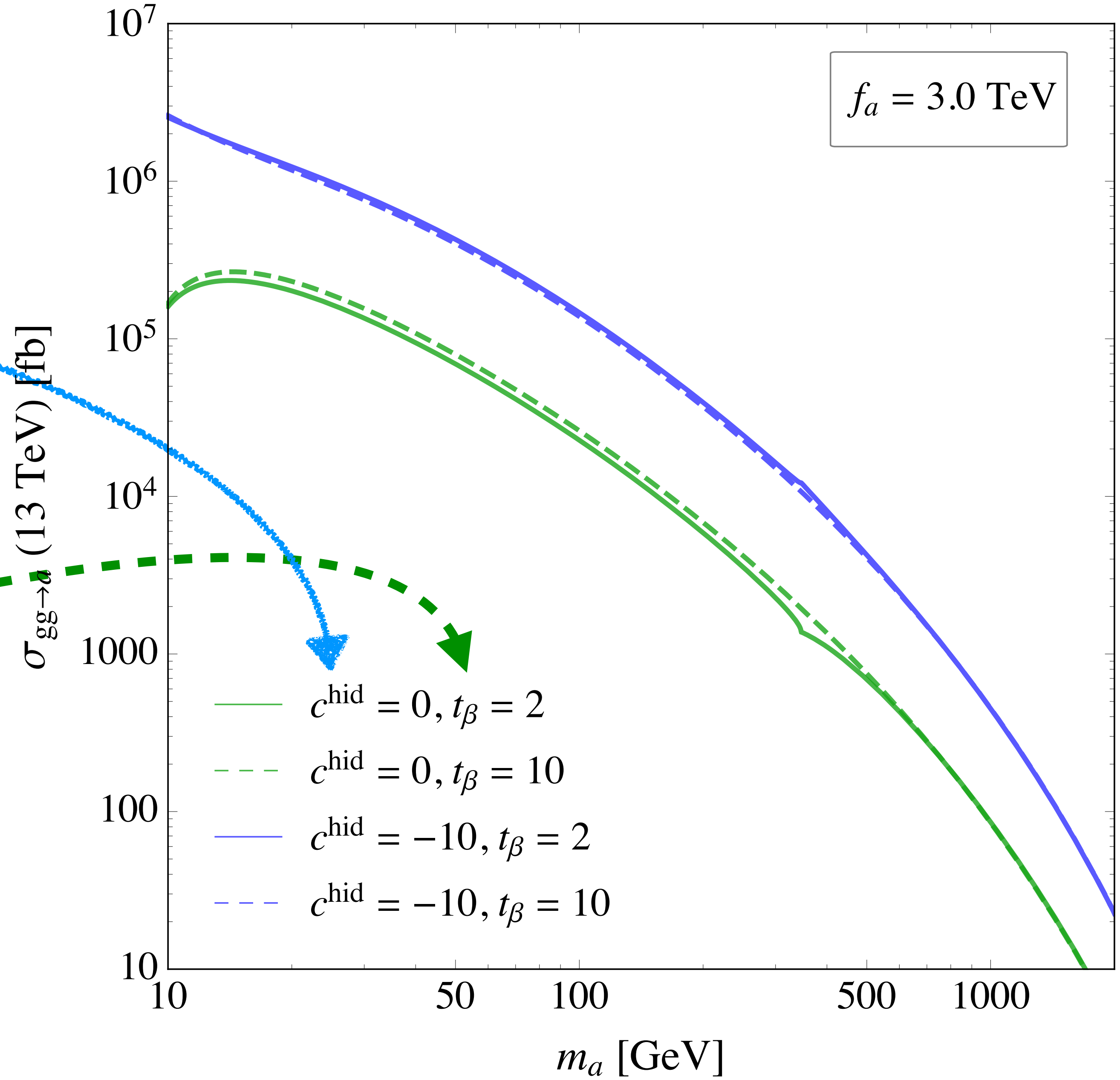
3 contributions to $a\, G^a_{\mu\nu} \tilde{G}^{a,\mu\nu}$ vertex:

UV anomaly

gluino loop

quark loops

$$r_H\, c_\beta^2\, \frac{m_t}{f_a}\, a\, \bar{t}\gamma_5 t$$



a from decays of h, Υ and B

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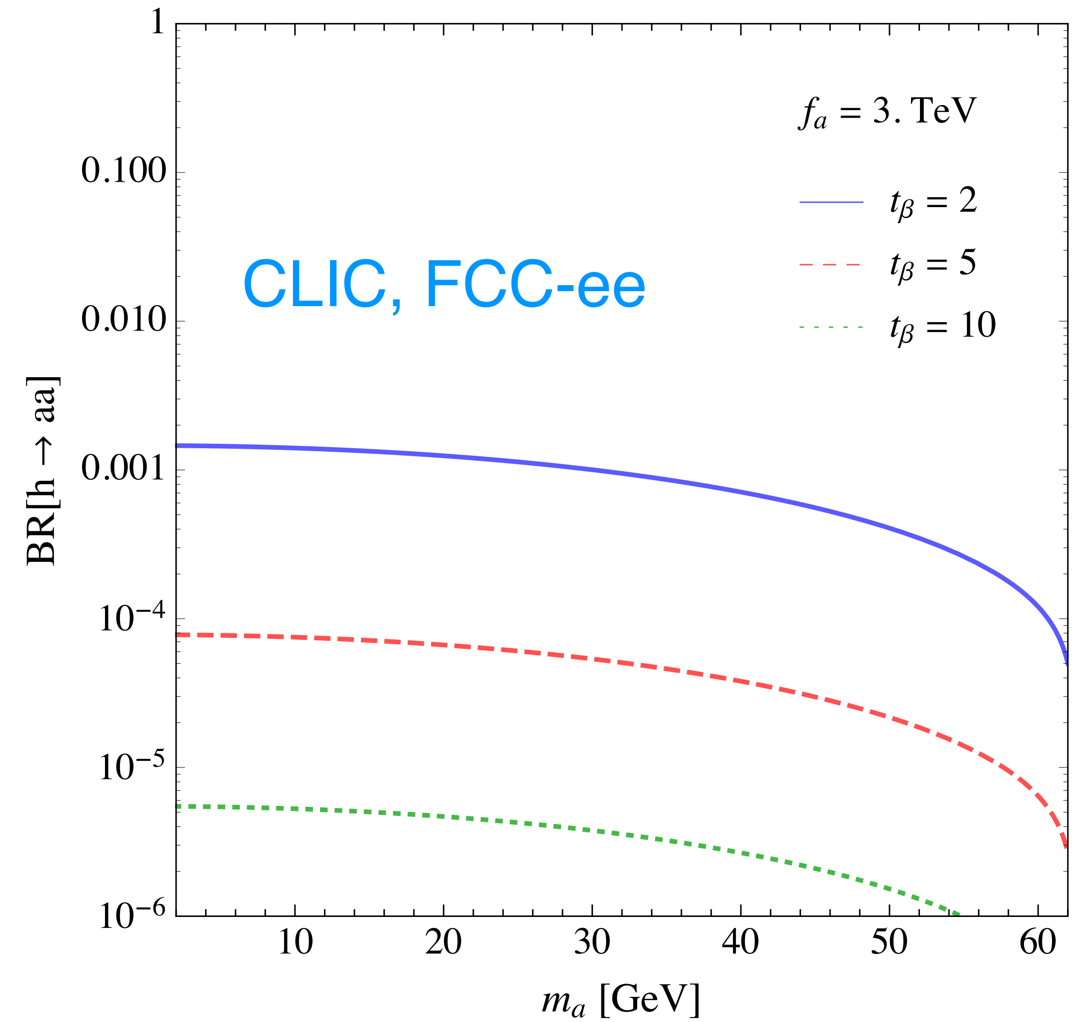

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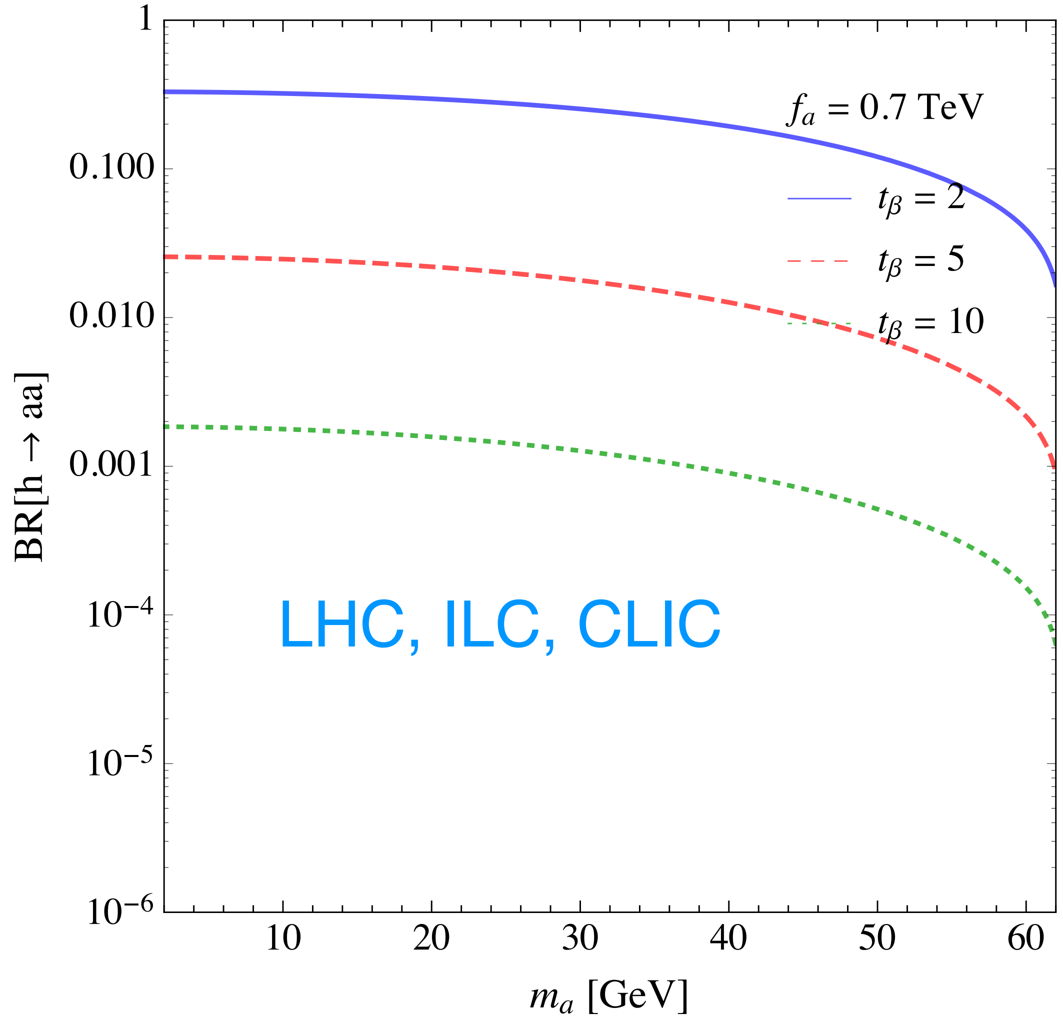

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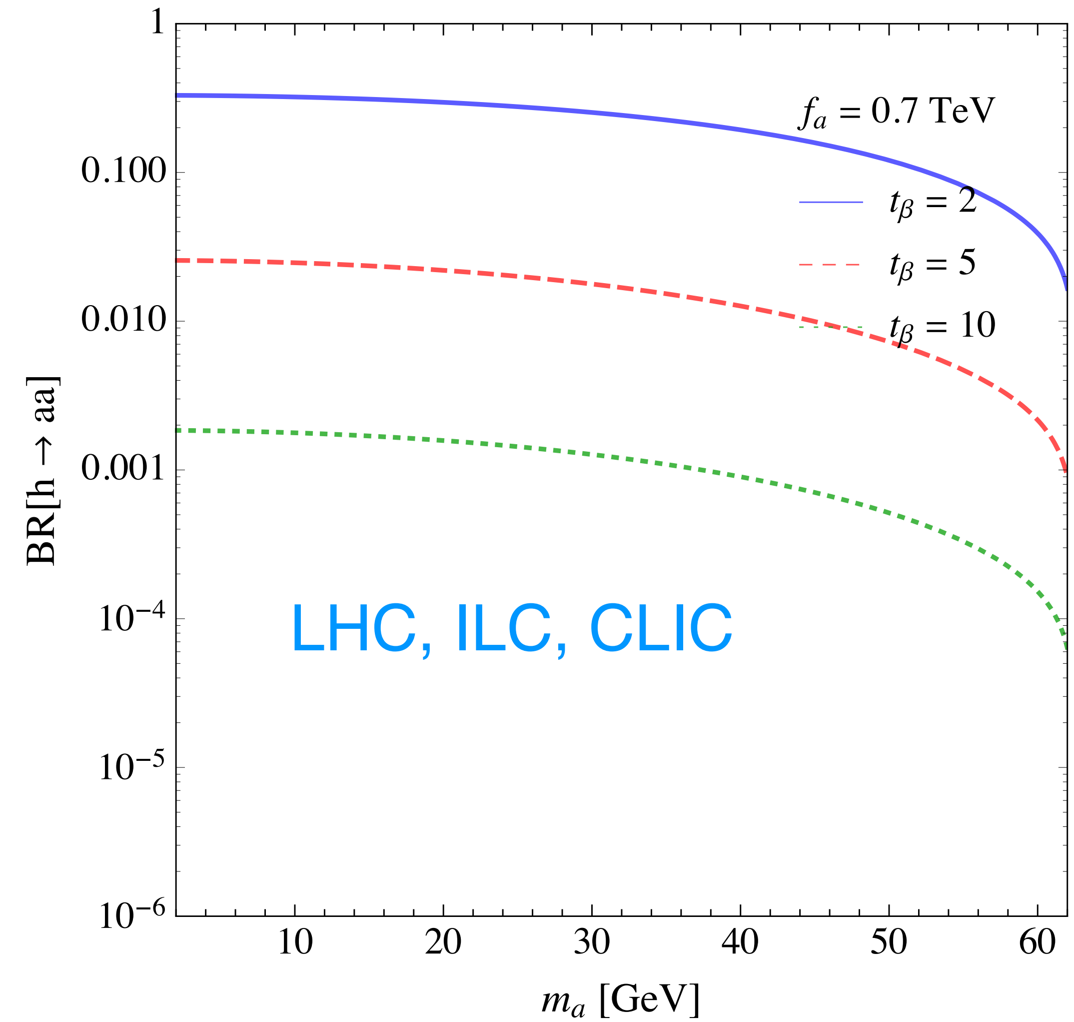


$$\mathrm{BR}_{\Upsilon\to\gamma\, a} \simeq 3-5\times 10^{-5}\left(\frac{\mathrm{TeV}}{f_a}\right)^2$$

since Wilczek PRL39 (1977)

experiments: BABAR

Belle-II

$$\mathrm{BR}_{B\to K a,\, K^* a} \simeq 3-5\times 10^{-4}\left(\frac{\mathrm{TeV}}{f_a}\right)^2$$

LHCb

Belle, Belle-II

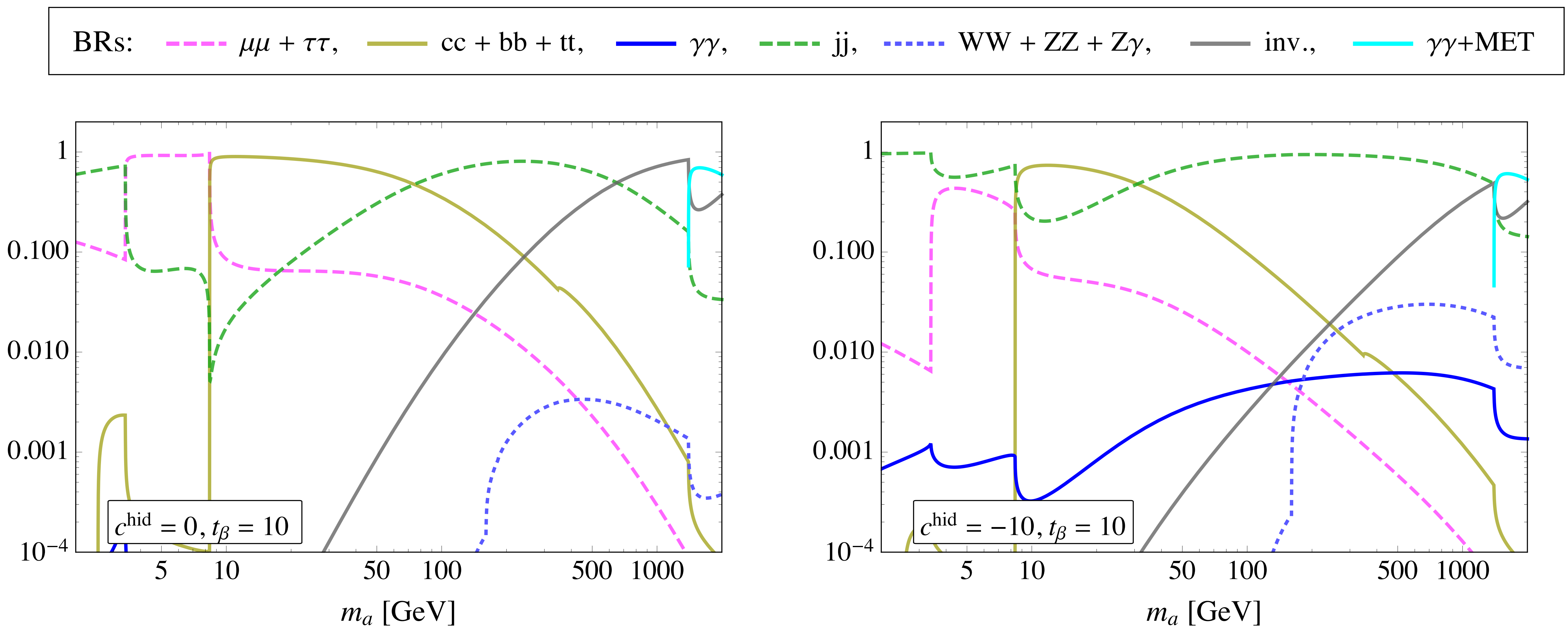
see Hall Wise 1981, Freytsis Ligeti Thaler 0911.5355

R axion branching ratios

Both plots: $t_\beta = 10$

No anomaly

Large anomalies

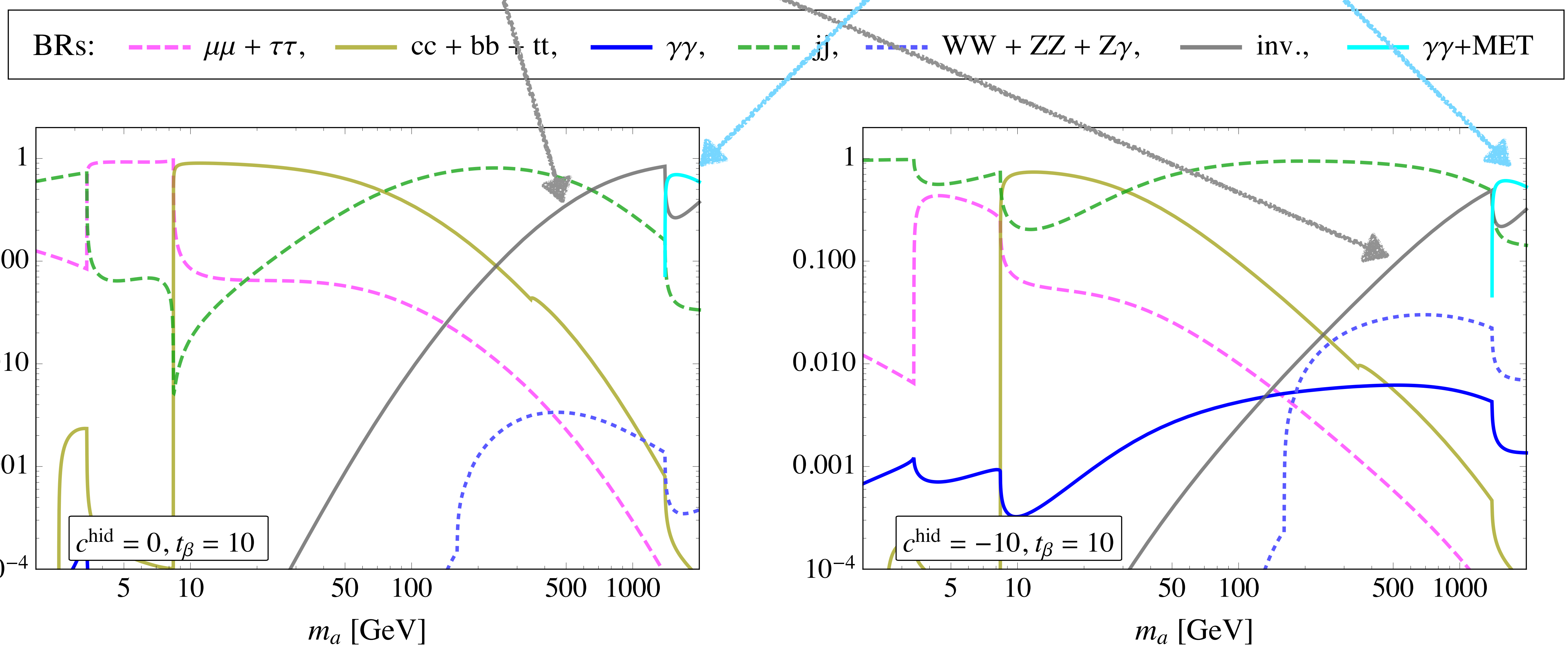


R axion branching ratios

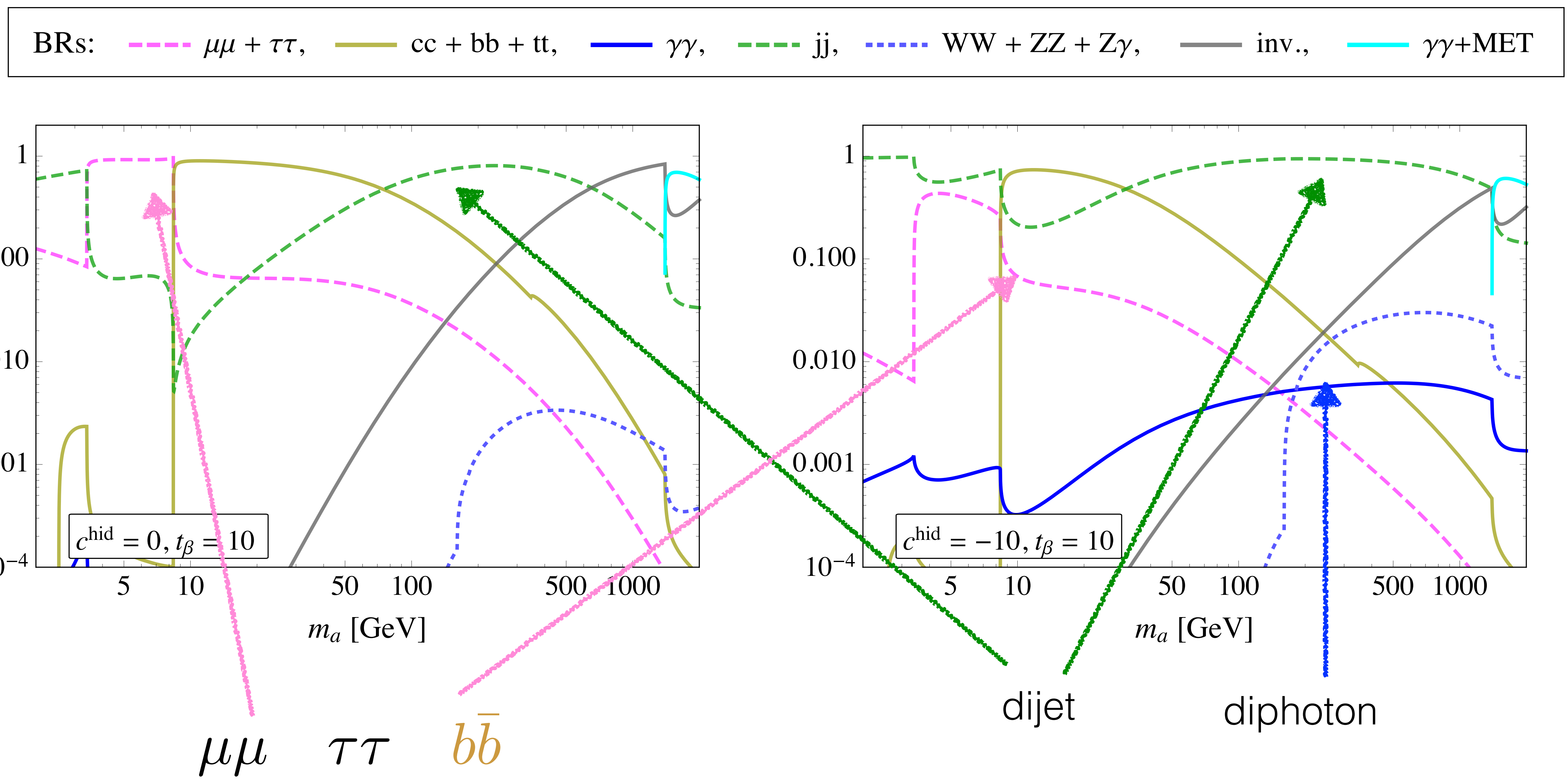
more model dependent

MET from decays into gravitinos

$$a \to \tilde{B}\tilde{B} \to \gamma\gamma + \text{MET}$$



R axion branching ratios

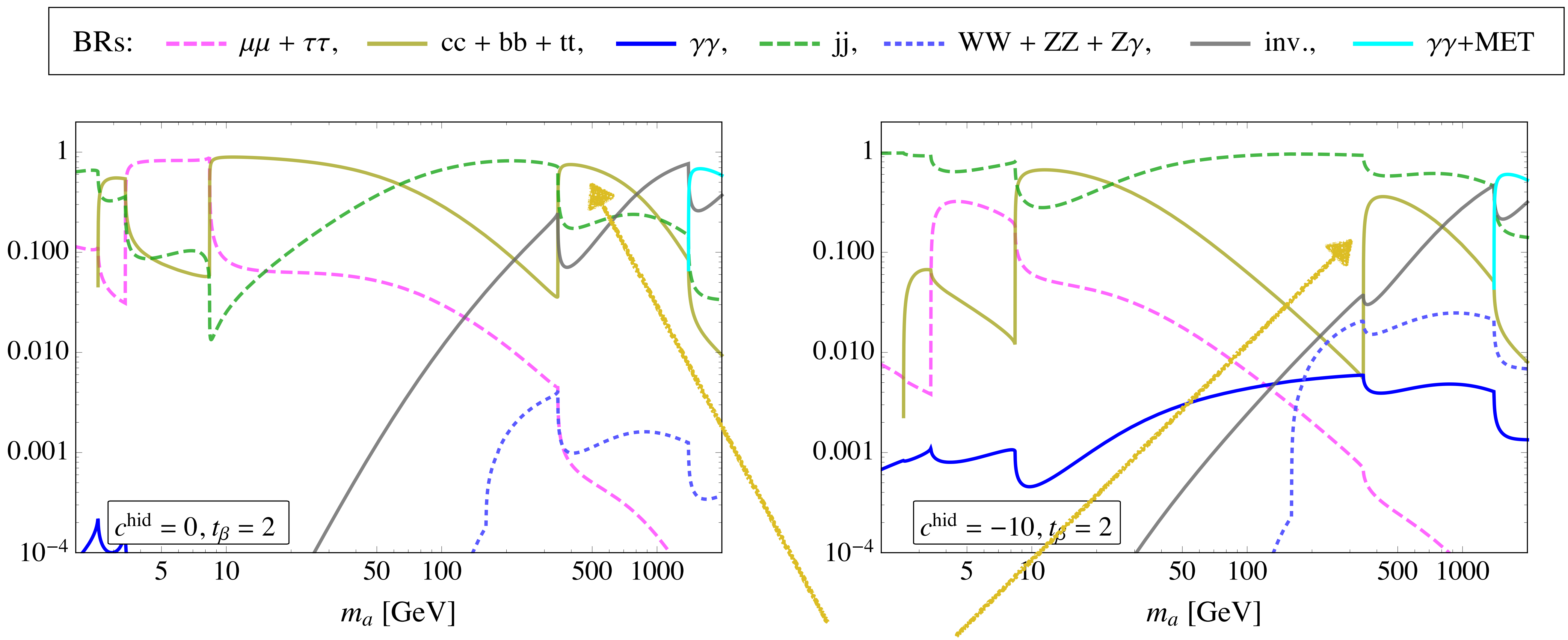


R axion branching ratios

Both plots: $t_\beta = 2$

No anomaly

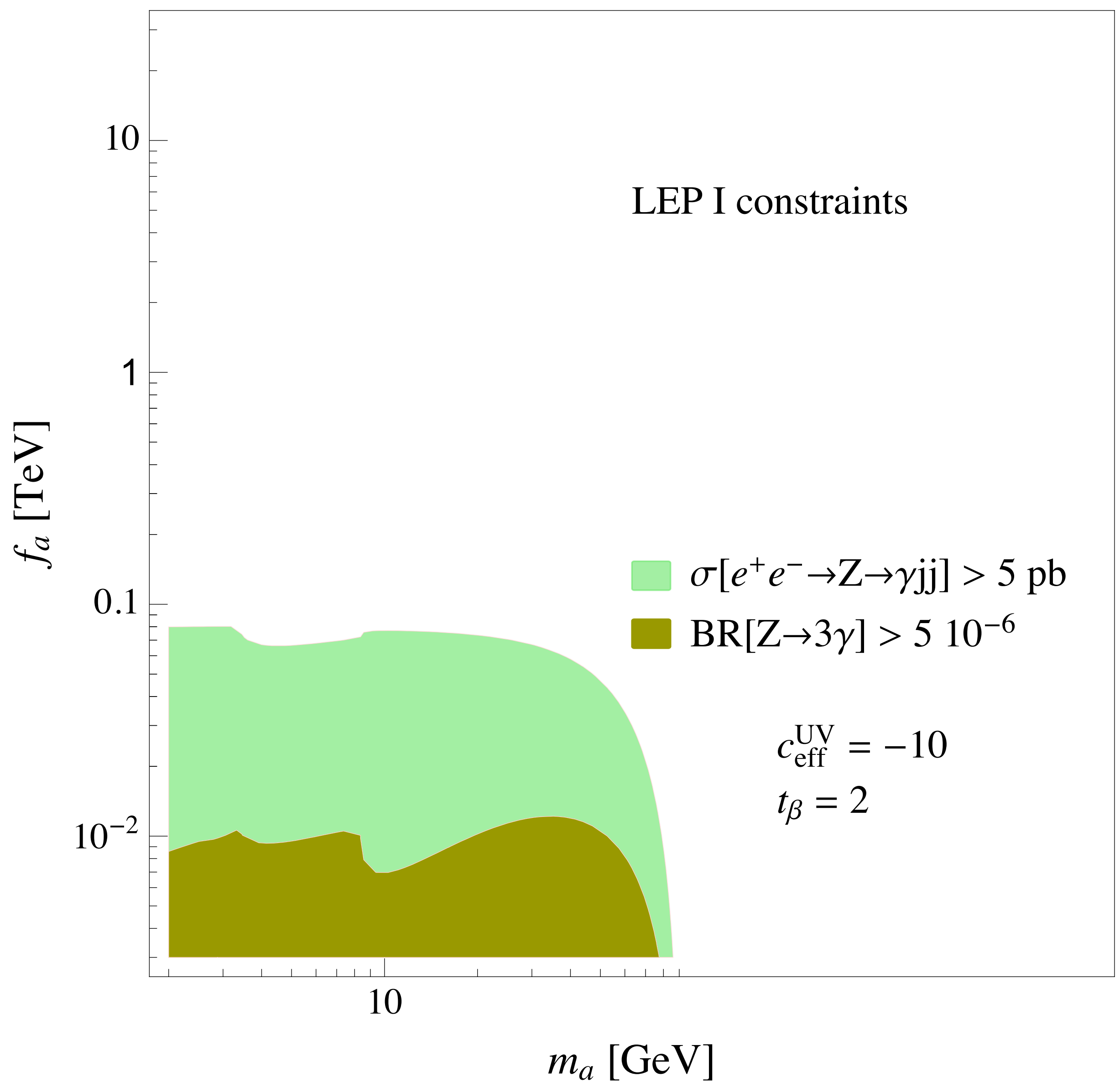
Large anomalies

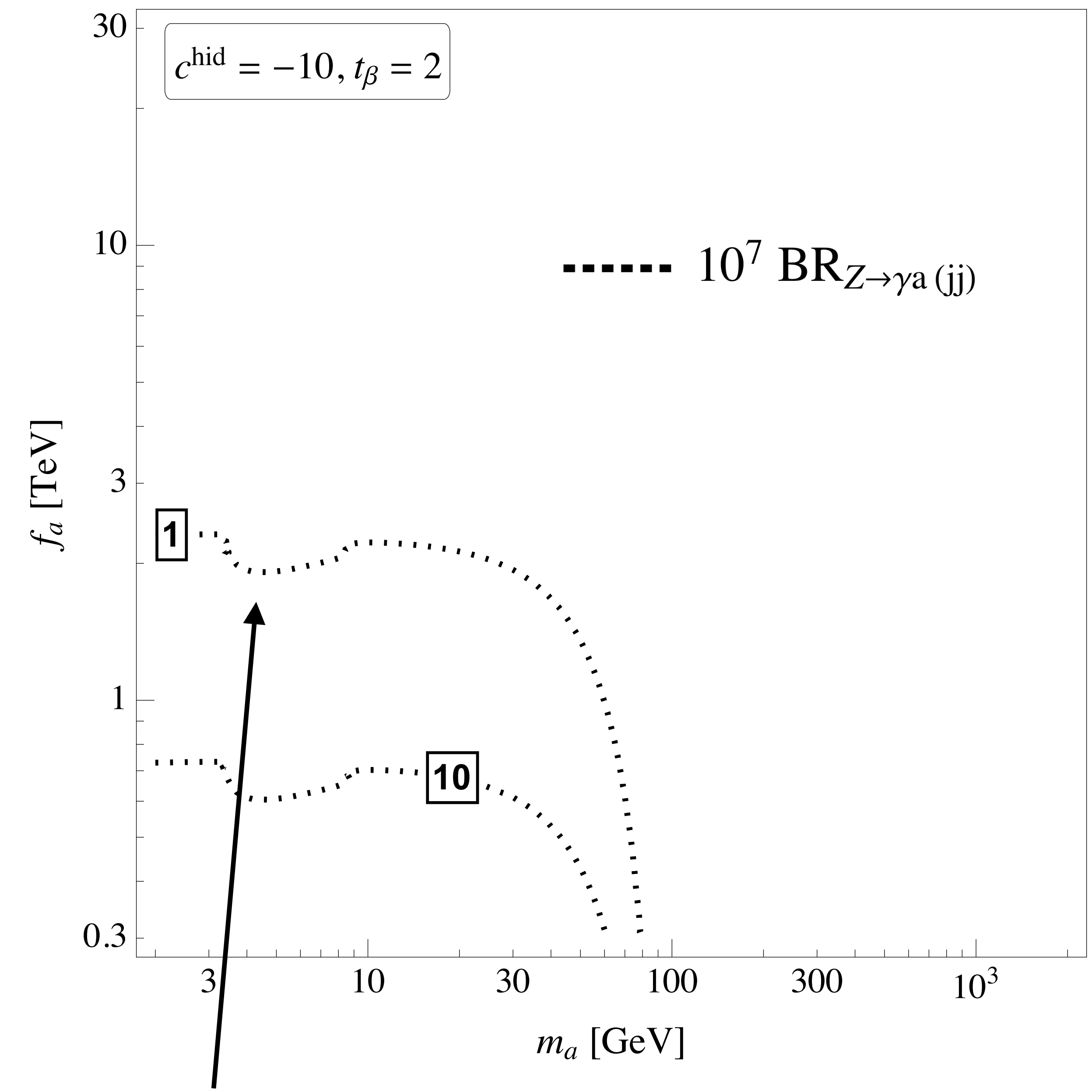


$t\bar{t}$ becomes more important!

LEP & future lepton colliders

$$\mathcal{L}_{aZ\gamma} = \frac{\alpha_w}{2\pi}\, c_{Z\gamma}\, \frac{a}{f_a}\, Z_{\mu\nu}\widetilde{F}^{\mu\nu}$$





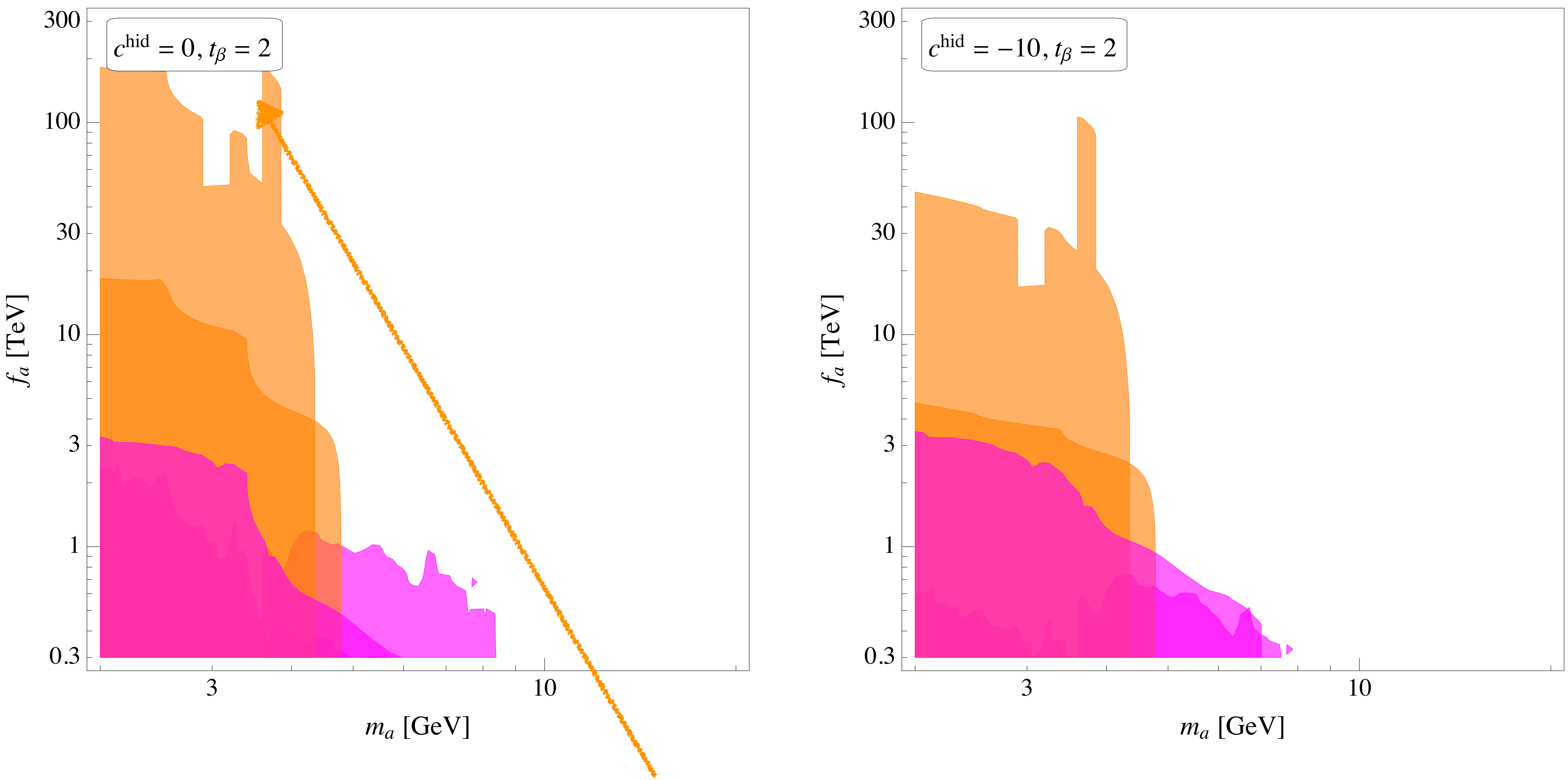
LEP: not really relevant

Reach of FCC-ee ?
(from naive luminosity rescaling of LEPI search)

Decays of B and Upsilon

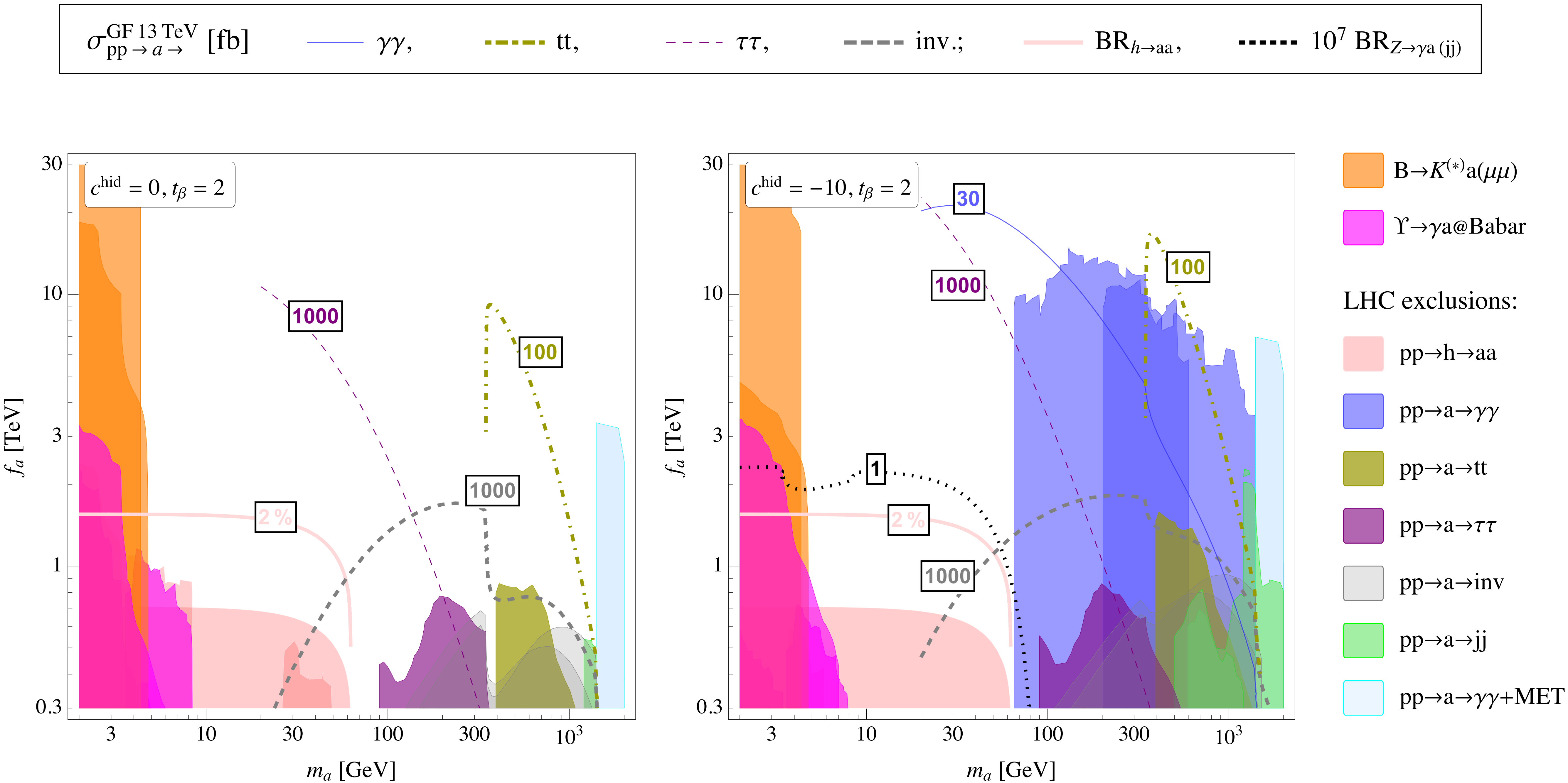
$B \to K^{(*)} a(\mu\mu)$ LHCb 1508.04094 (+ Belle)

$\Upsilon \to \gamma a$@Babar BABAR 1210.0287 (muons), 1210.5669 (taus), 1108.3549 (hadrons)



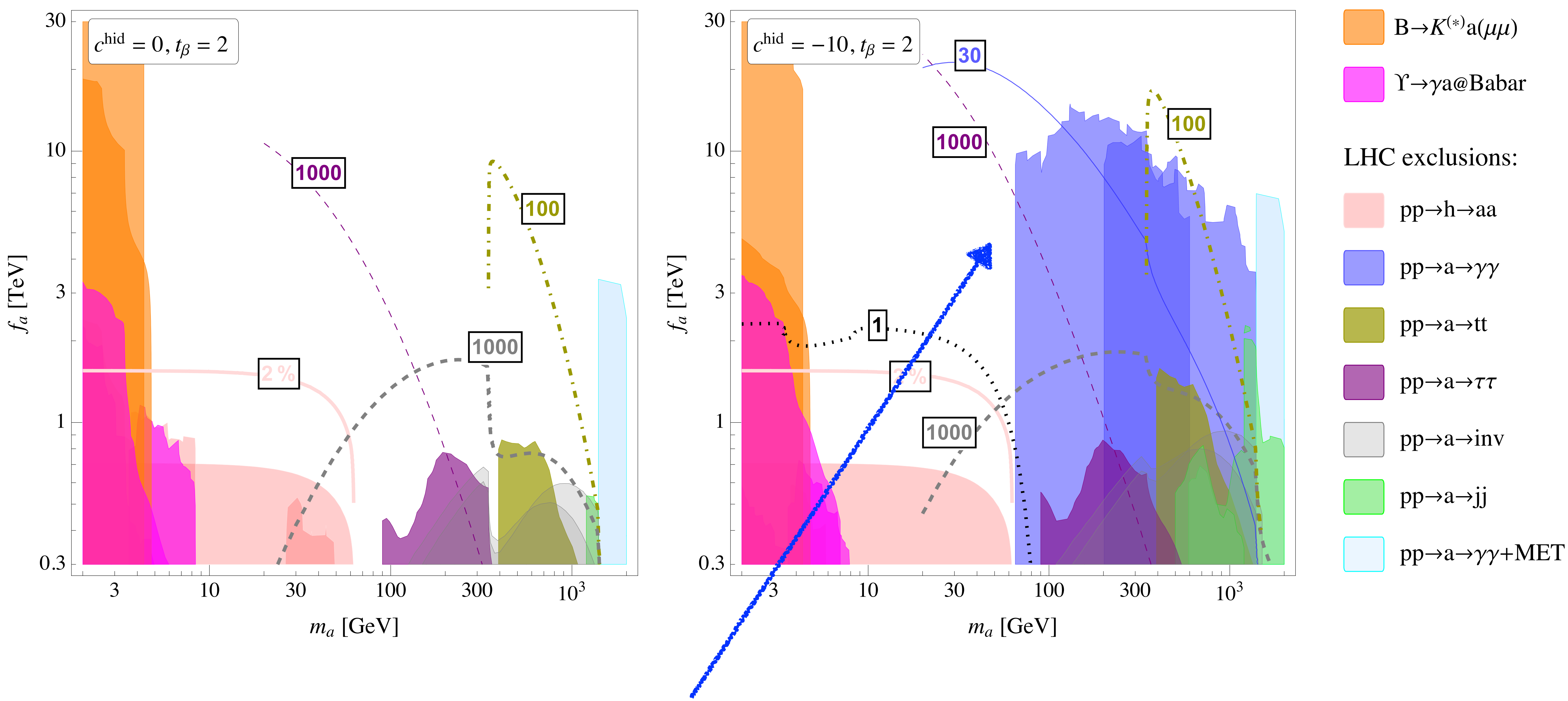
LHCb sensitive to beyond-100-TeV flavour-preserving SUSY!!

Pheno Summary



Pheno Summary

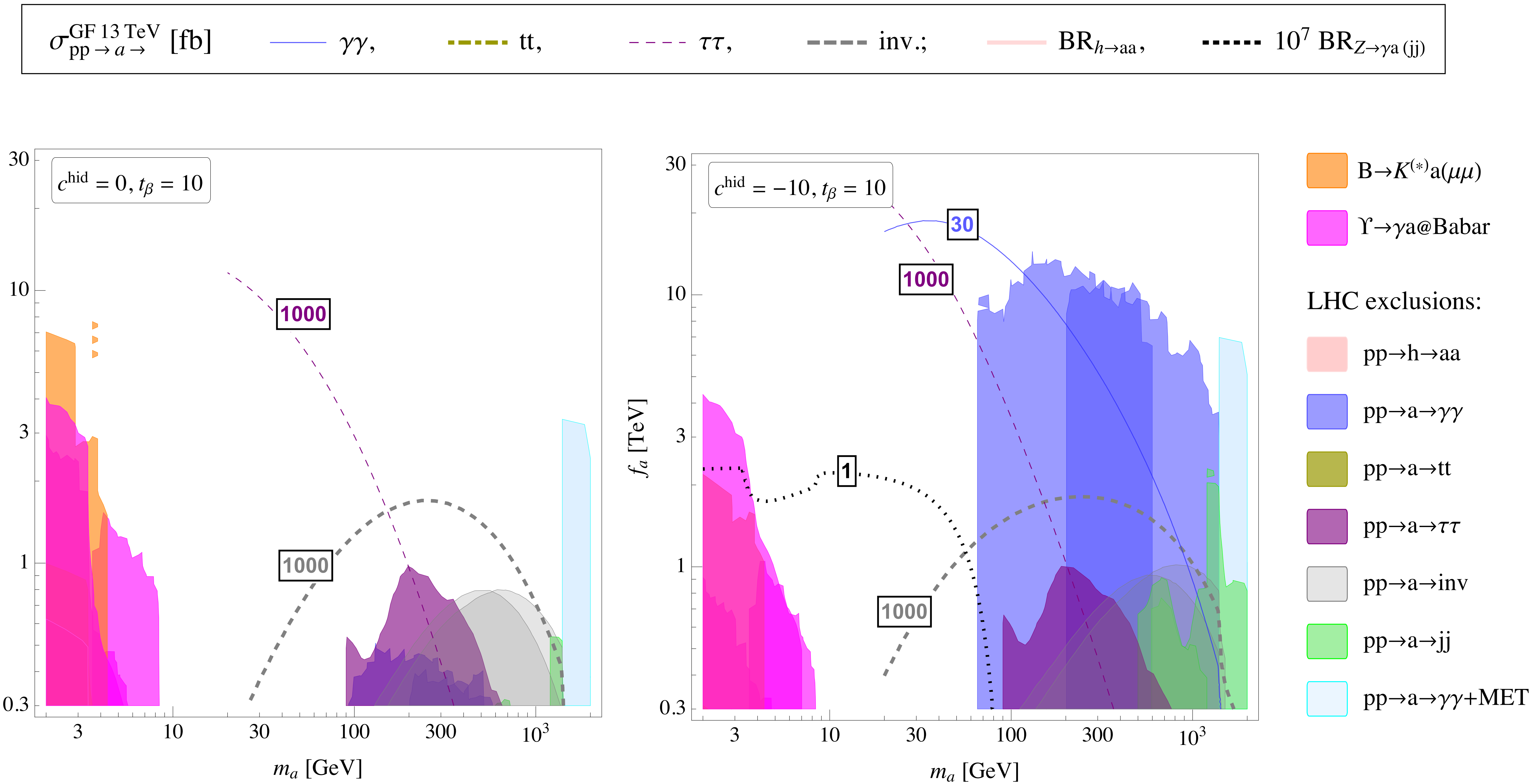
$\sigma^{\text{GF 13 TeV}}_{pp\to a\to}$ [fb] $\gamma\gamma$,   tt, $\tau\tau$,   inv.; $\text{BR}_{h\to aa}$, $10^7\ \text{BR}_{Z\to\gamma a\,(jj)}$



Why not diphoton below 65 GeV?

Pheno Summary

$t_\beta = 10$



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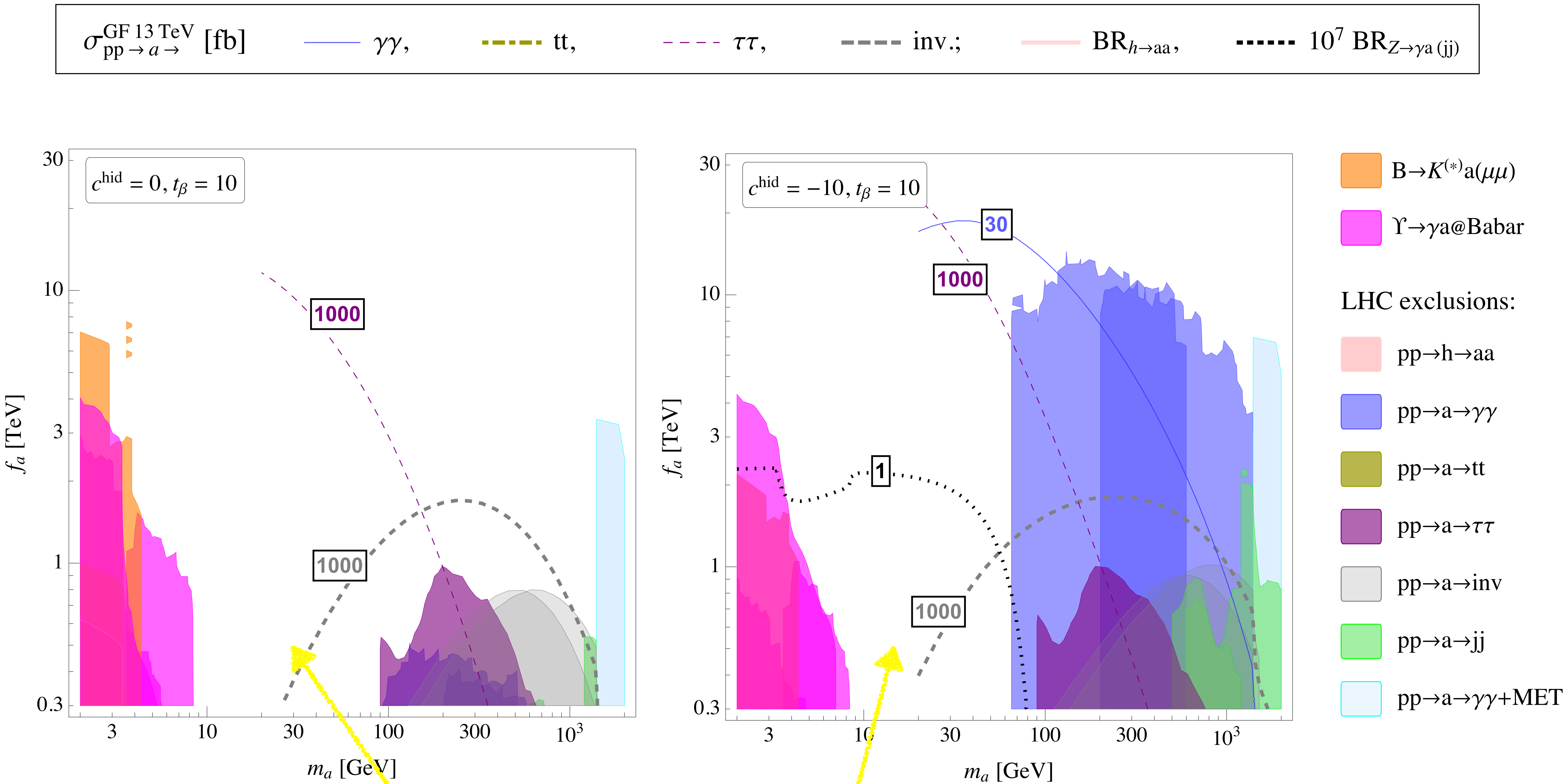


How to explore $10\ \text{GeV} \lesssim m_a \lesssim 60\ \text{GeV}$?

Crucial for any ALP that couples dominantly to gauge bosons!

Take-home messages

Any other sign of SUSY to be looked for at colliders?

beyond gluino, stop, EWinos, extra Higgses,…

Spontaneously broken R-symmetry is quite generic

provides a naturally light state, the "R-axion" (whose pheno had been overlooked)

Bellazzini Mariotti Redigolo FS Serra, 1702.02152

could be the first sign of SUSY at colliders

gives access to properties of the SUSY-breaking sector

opens new pheno & model-building avenues

Conclusions and outlook

How to know it is R-axion and not another scalar?

Hint: other peculiar decays like MET; pattern of signals

Observe other SUSY & correlate parameters

light diphoton resonances work in progress…

Rich pheno adds motivation to

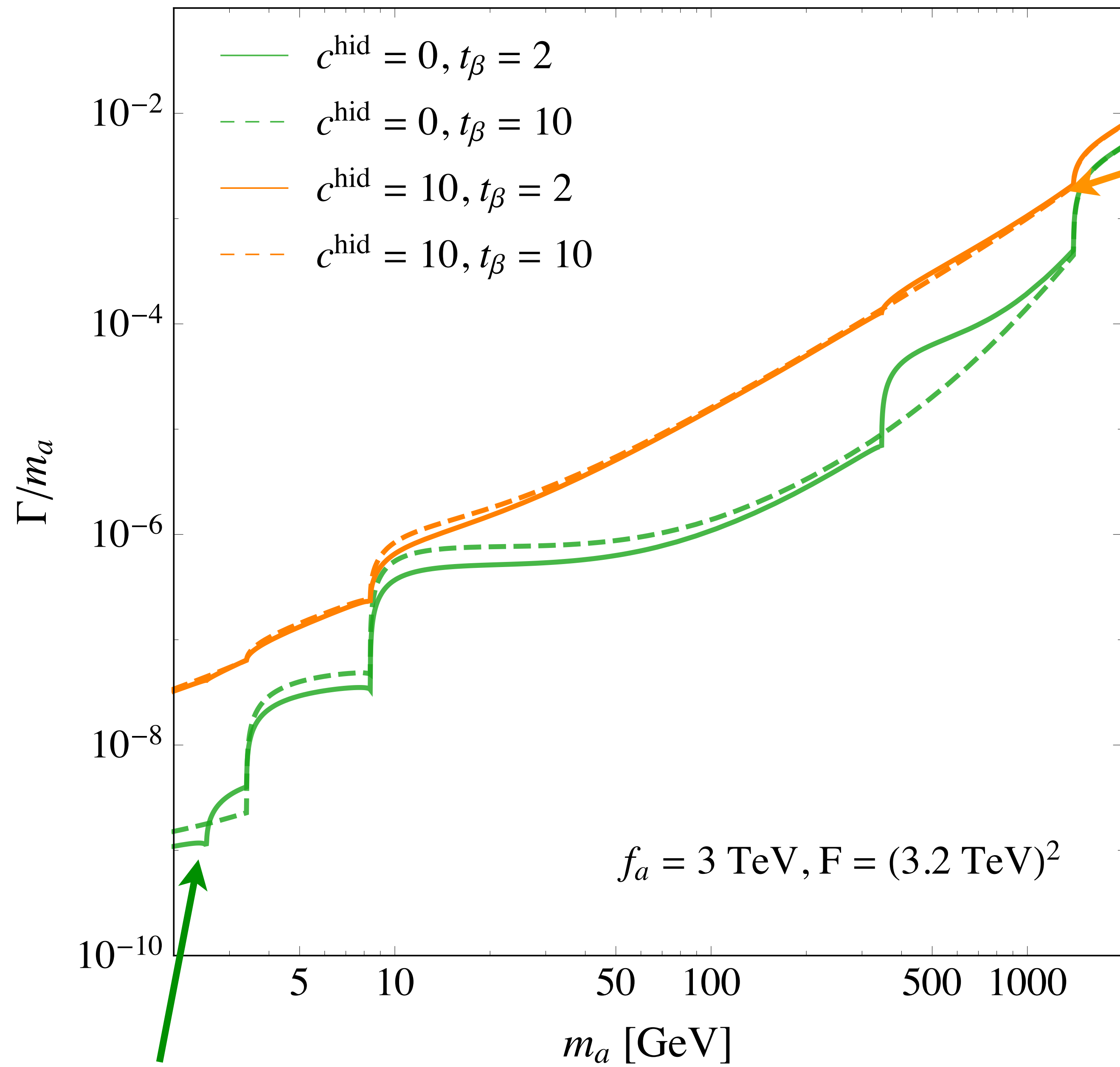
- LHC (heavy & light) scalar searches!
- flavour factories (e.g. look for bump in B decays)
- lepton colliders program

Future

- more model building (e.g. split SUSY? models for m_a?)
- pheno other than colliders (e.g. cosmo?)
- ….

Back-up

R axion total width



$c\tau \approx \mu m$

$$\Gamma_a/m_a < 10^{-3}$$

so interference with SM in $t\bar{t}$ should not give problems…

see e.g. Craig et al. 1504.04630

(unlike usual targets for $t\bar{t}$, like MSSM Higgses)

$m_a < \Lambda_{\rm QCD}$ → Displaced vertices, Long lived → Other collider searches, Beam dump, …

More on R-axion production

$$\sigma_{pp\to a} = \frac{K}{m_a\, s} C_{gg}\, \Gamma^{\text{tree}}_{a\to gg}$$

$K \simeq 2.4$ see e.g. Ahmed et al. 1606.00837

$$C_{gg} = \frac{\pi^2}{8}\int_{m_a^2/s}^{1} \frac{dx}{x} f_g(x)\, f_g\!\left(\frac{m_a^2}{s\,x}\right)$$

gluon pdfs f_g from mstw2008

$$\mathcal{L}_{aZ\gamma} = \frac{\alpha_w}{2\pi} c_{Z\gamma} \frac{a}{f_a} Z_{\mu\nu}\widetilde{F}^{\mu\nu}$$

too small far **LEP**, not for FCC-ee!

$$\text{BR}(Z\to a\gamma) \approx 3\cdot 10^{-7}\left(\frac{\text{TeV}}{f_a}\right)^2 \quad \text{for} \quad N_{\text{mess}} \approx 10$$

All single productions scale as $\sim 1/f_a^2$

double productions (here only $h \to aa$) as $\sim 1/f_a^4$

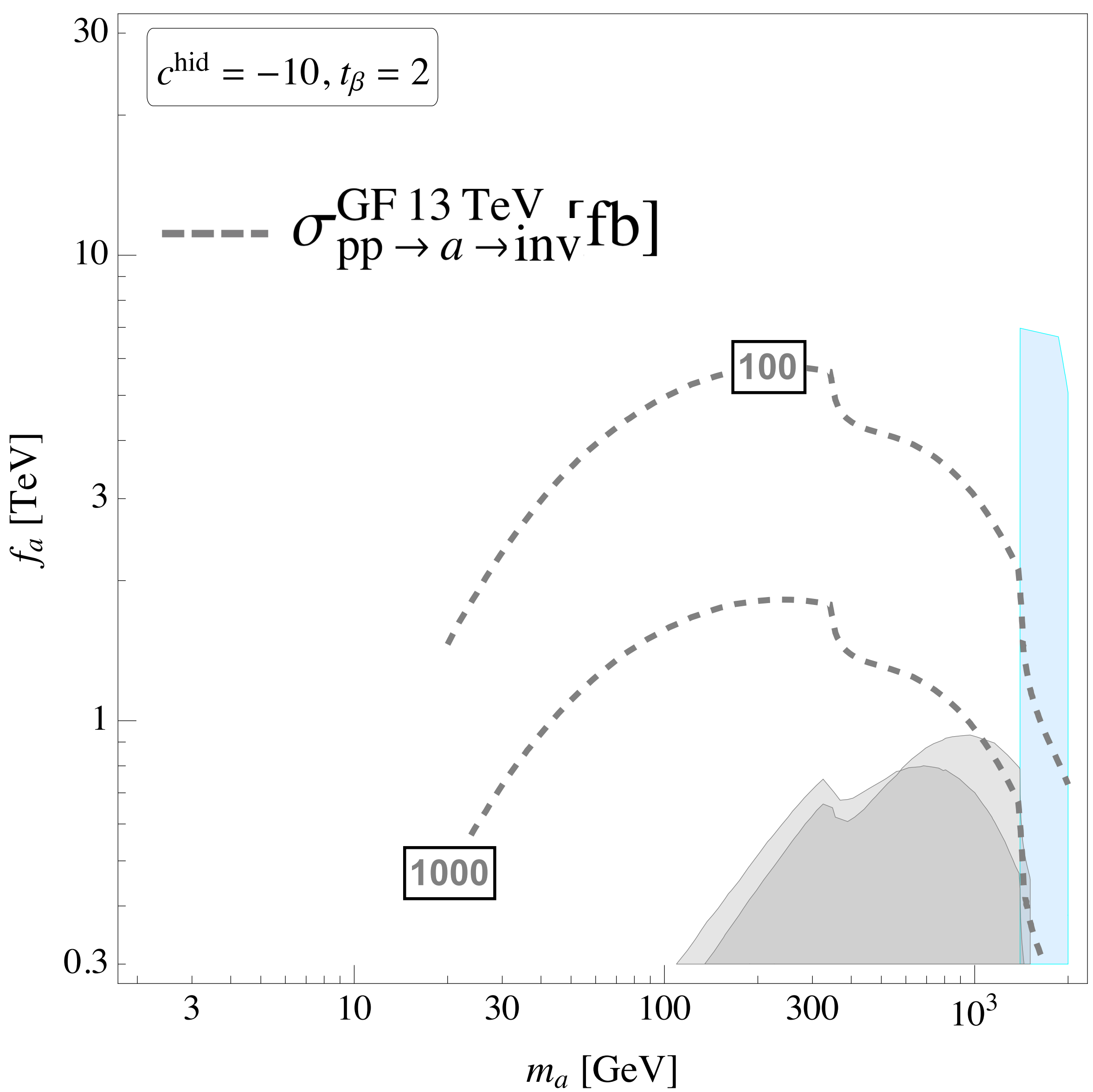
LHC: MET + monojet, MET + diphoton

	$p_T > 250$	$p_T > 500$	$p_T > 700$
σ_{95} 8 TeV	90 fb	7.2 fb	3.4 fb
σ_{95} 13 TeV [3.2 fb^{-1}]	553 fb	61 fb	19 fb

ATLAS 1502.01518
ATLAS 1604.07773

Rough procedure: gluon gluon resonance w/ and w/o extra jet simulated with Madgraph

ratio used to rescale $\sigma_{pp\to a\to GG}$



$$a \to \tilde{B}\tilde{B} \to \gamma\gamma + \text{MET}$$

excludes signals down to **0.3 fb** @LHC8

These signals have little dependence on anomalies, and in particular on t_β, r_H

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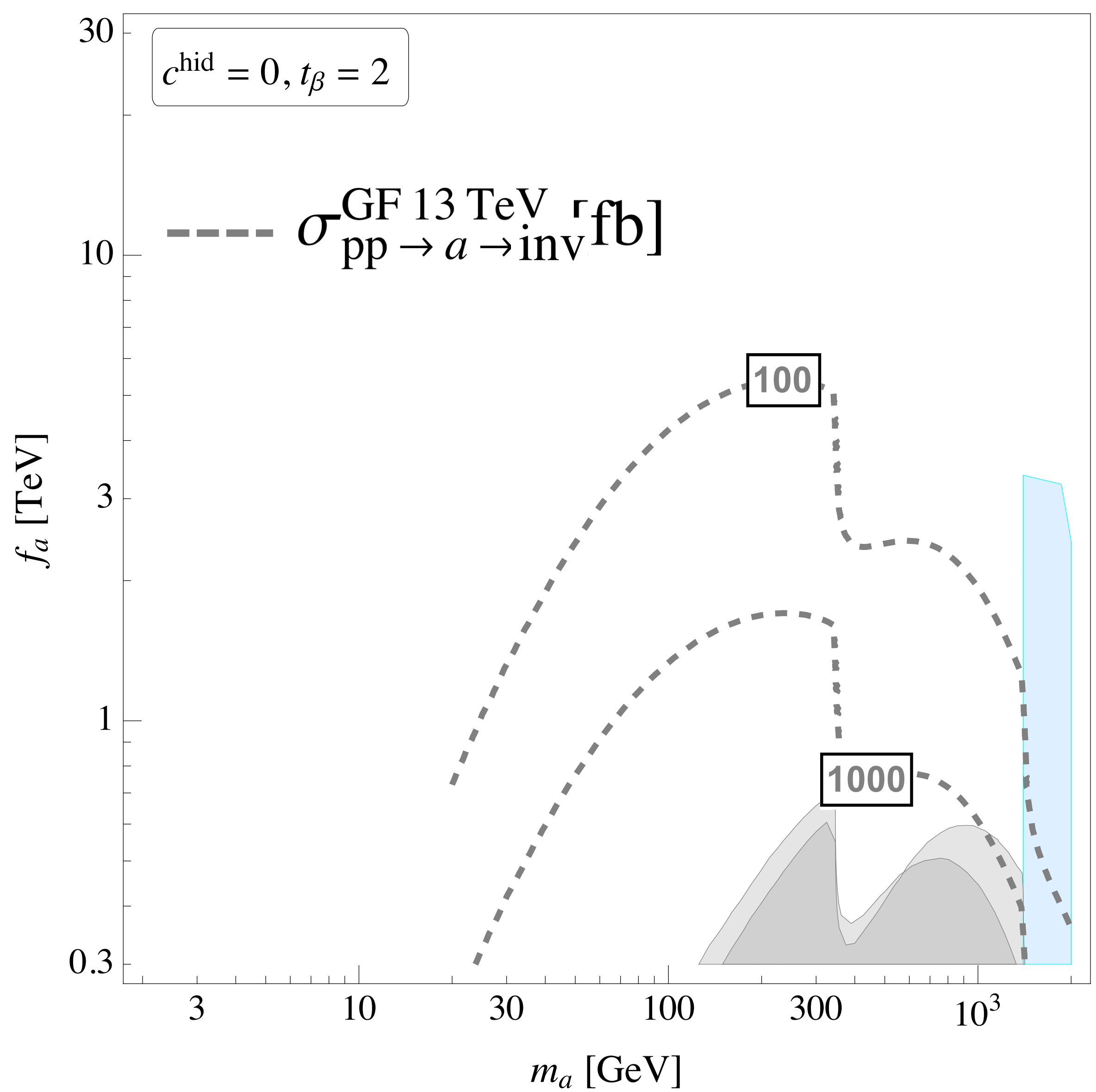

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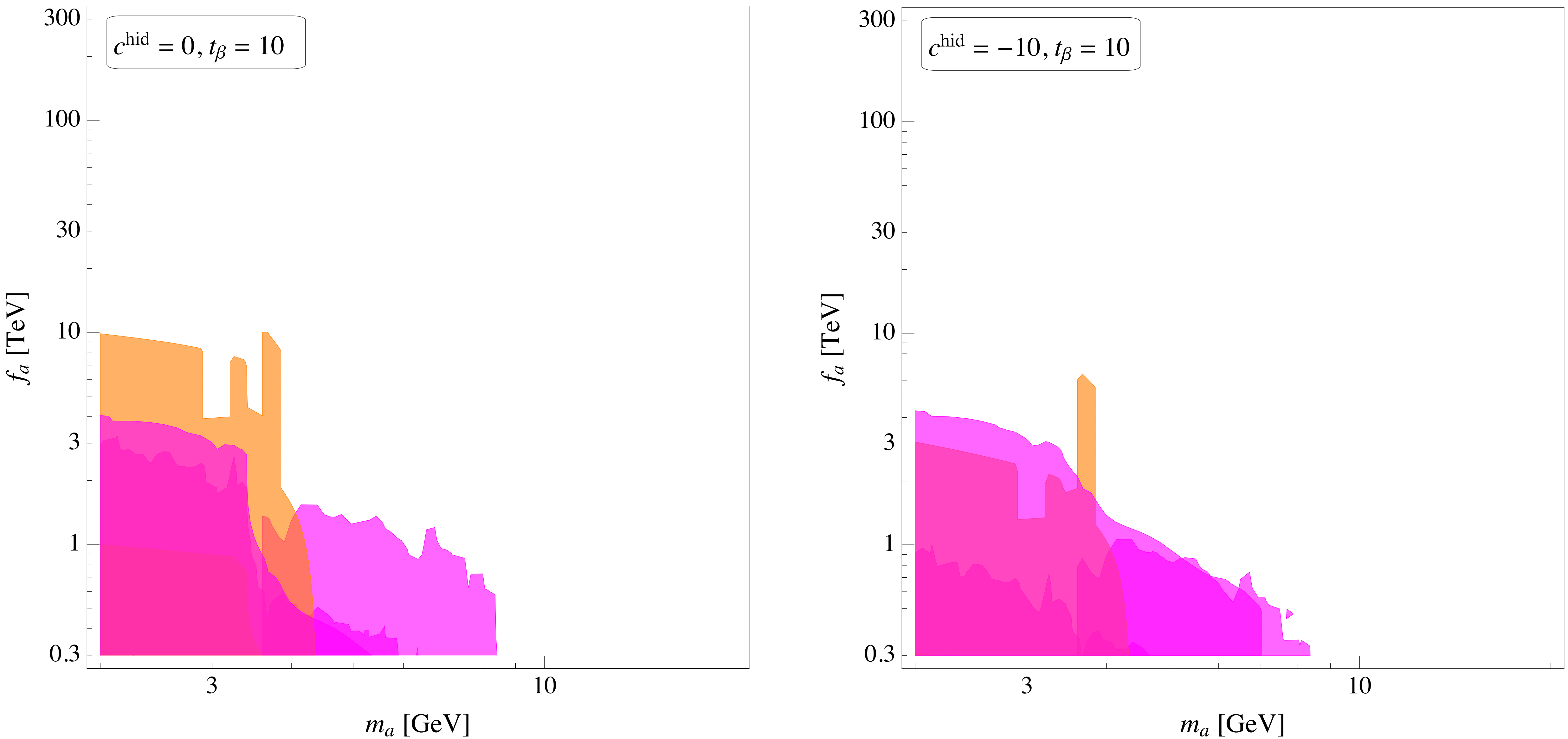

$B \to K^{(*)} a(\mu\mu)$ ~ sensitive to value of t_β

Both disappear for $r_H = 0$

maybe not, work in progress…

R-axion from decays of MSSM Higgses

very preliminary