10-100 GeV ALPs in diphoton

mostly based on **Mariotti Redigolo** FS **Tobioka** 1710.01743 + in progress

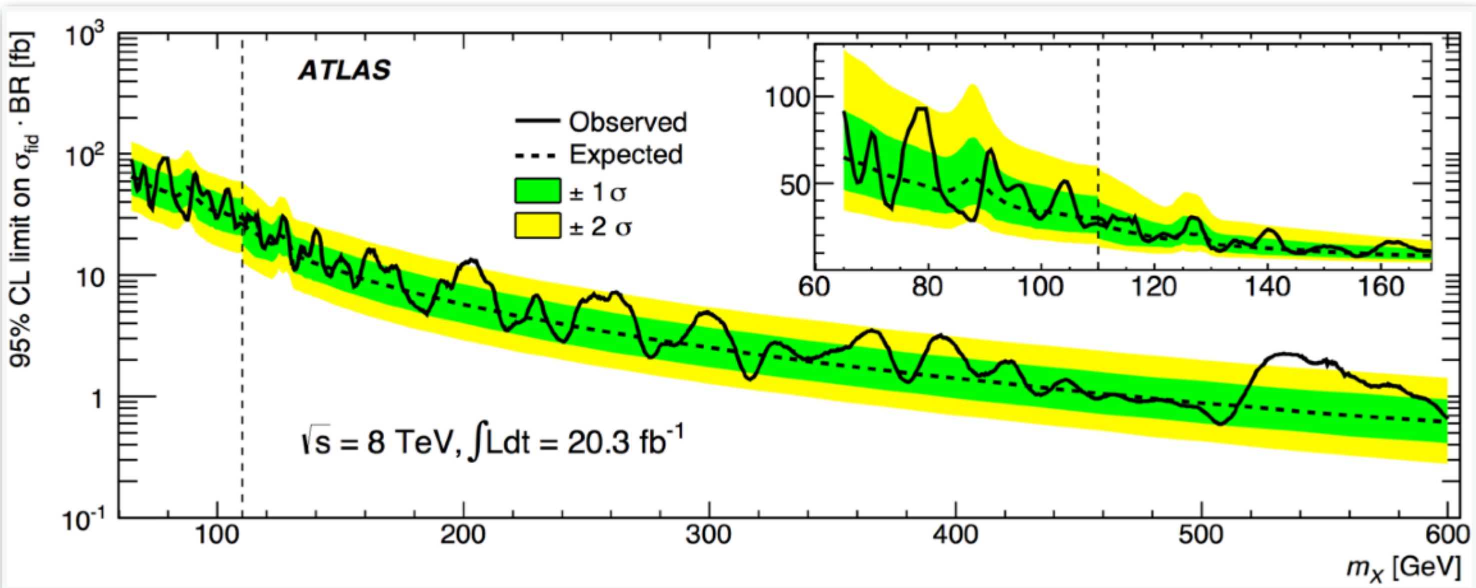
Filippo Sala

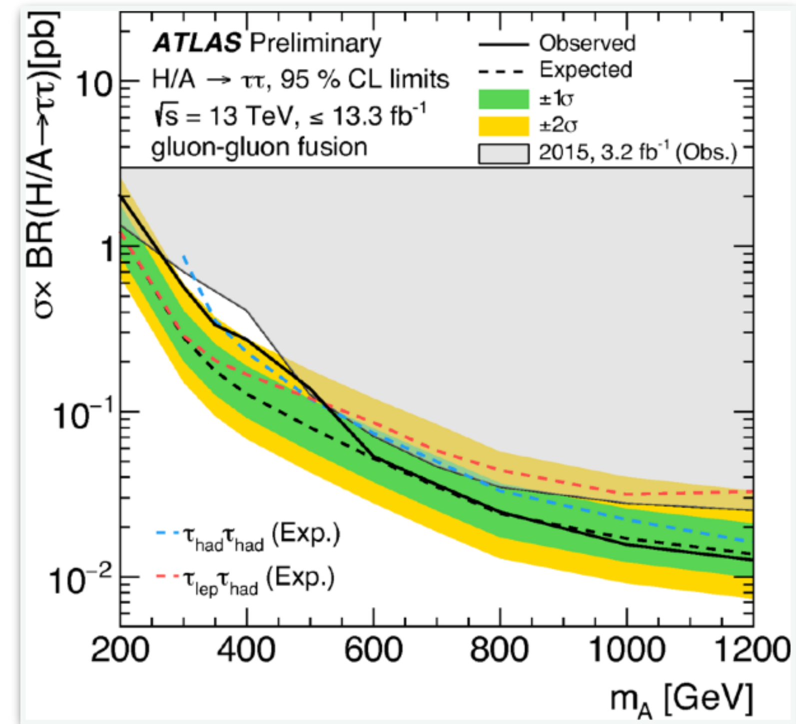
DESY Hamburg

2nd FCC physics workshop, CERN, Wed 17 Jan 2018

BSM resonances: where to look?

Looking for peaks in invariant mass distributions is **solid discovery method** at colliders





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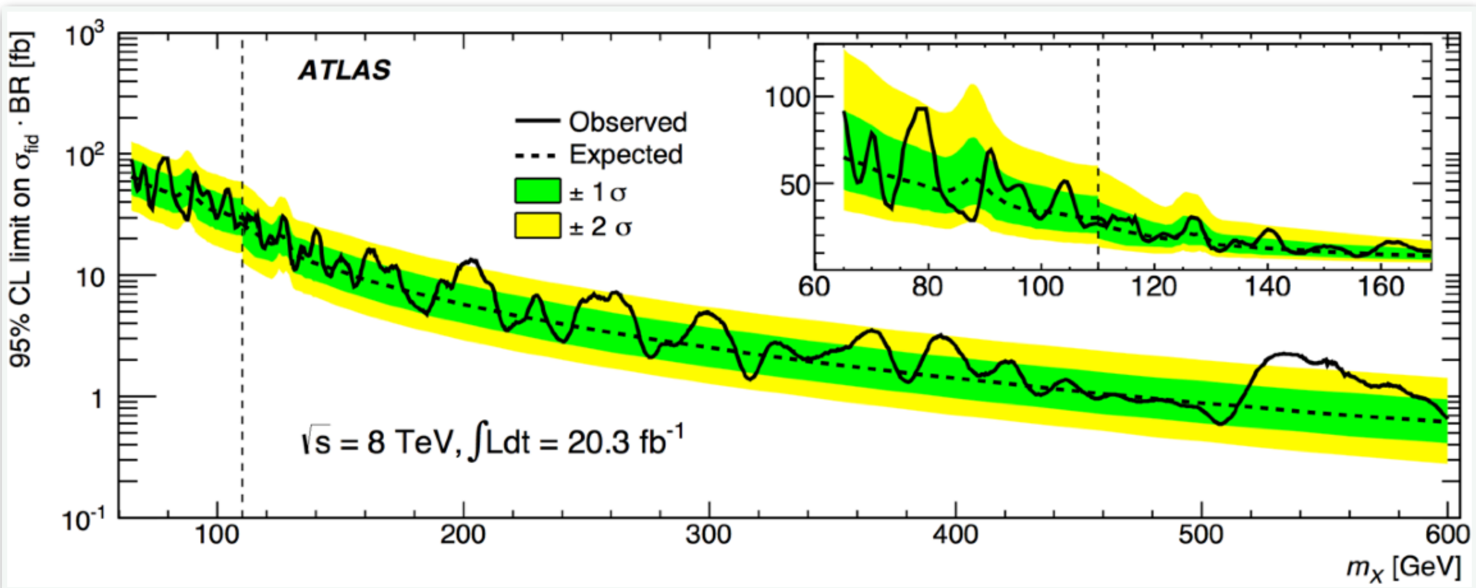

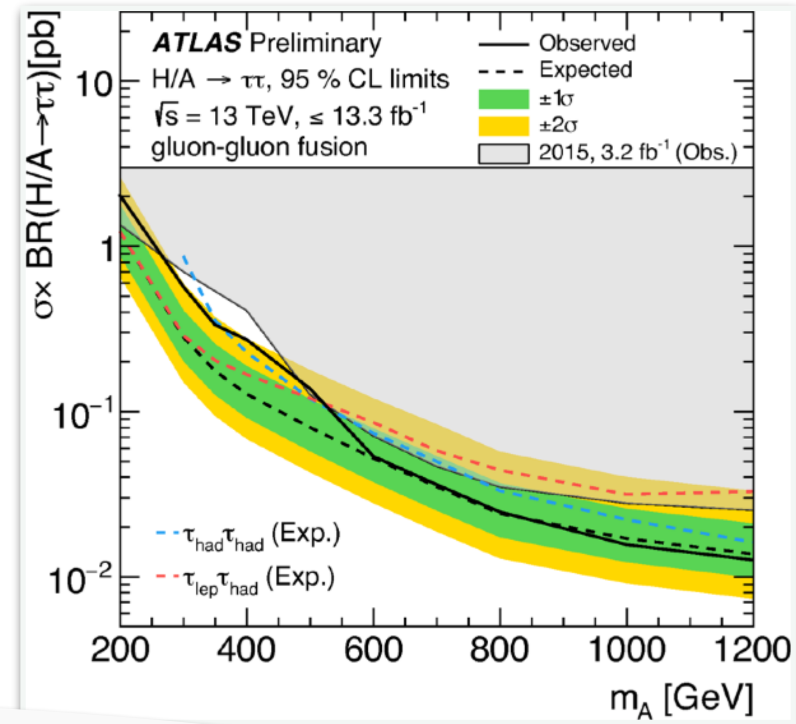

Why not $M_X < O(100)$ GeV ?

1. Theory bias towards high masses
2. "Low-mass already constrained by previous colliders (LEP,…)"
3. "It is very difficult!" Minimal pT cuts, …

This seminar: demystify 1. 2. and 3., and prospects at LHC and FCC see Martin's talk for more on this

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ALPs from strong sectors

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[add gauge group that confines at $\gtrsim$TeV, w/new fermions, vector-like to satisfy EW precision tests]

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Natural strong sector: composite Higgs models

Example: SO(6)/SO(5) has 5 PGB, the Higgs and a singlet η see e.g. Gripaios+ 0902.1483 Redi Tesi 1205.0232

No tuning in η potential $\Rightarrow \quad m_\eta \sim m_h \times \frac{f}{v} \sim 600 \text{ GeV} \times \sqrt{\frac{0.05}{(v/f)^2}}$

see Giacomo's talk for more on this

with dependence on top representation

e.g. if only bottom contributes: $m_\eta \sim 10 \text{ GeV} \times \sqrt{\frac{0.05}{(v/f)^2}}$

Larger coset structures have more PGBs

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Less natural composite Higgs models:

give up on little hierarchy and focus on

- DM & GUT — Bernard+ 1409.7391
- QCD axion — Redi Strumia 1208.6013
- generate EW & DM scales — Antipin+1410.1817

ALPs from SUSY: the R-axion

Nelson-Seiberg NPB416 (1994)

i) SUSY broken in global minimum

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

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

$U(1)_R$ needs to be broken because of

gaugino masses

$\mathcal{L} \supset m_\lambda \, \lambda\lambda \quad [r_\lambda = 1]$

EW symmetry breaking
& Higgsino masses

$\mathcal{L} \supset B_\mu \, H_u H_d + \text{c.c.}$ & $W \supset \mu \, H_u H_d$

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Massless Goldstone in the spectrum R-axion a

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Bagger+ hep-ph/9405345

→ Metastable vacuum Intriligator Seiberg Shih 2007

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light SUSY particle by symmetry

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Could be first sign of SUSY at colliders!

Bellazzini Mariotti Redigolo FS Serra 1702.02152

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gaugino mass... $\mathcal{L} \supset$ ...

EW symmetry breaking & Higgsino masses

... c.c. & $W \supset \mu H_u H_d$

NB. coupling to gluons $\sim aG\tilde{G}$
very often neglected in pheno studies
but **natural in CHM** (e.g. loops of tops, ...)
as well as **in SUSY**! (e.g. loops of tops, gluinos, ...)

... the spectrum R-axion a

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$m_a^2 \sim (10\ \mathrm{MeV})$ ... $\frac{\ \ ^{3/2}}{\mathrm{eV}}$ Bagger+ hep-ph/9405345

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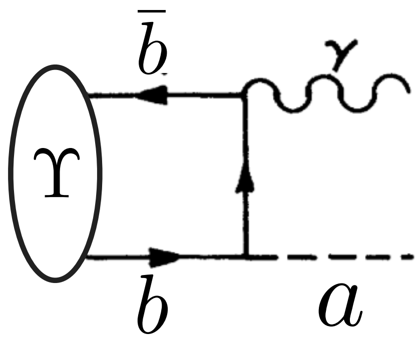
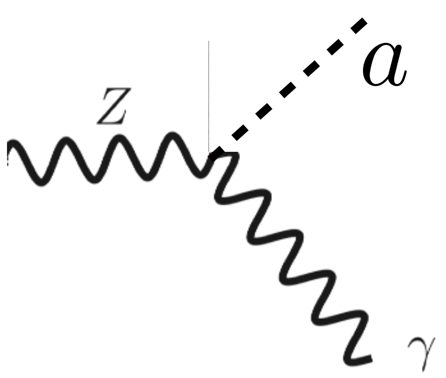
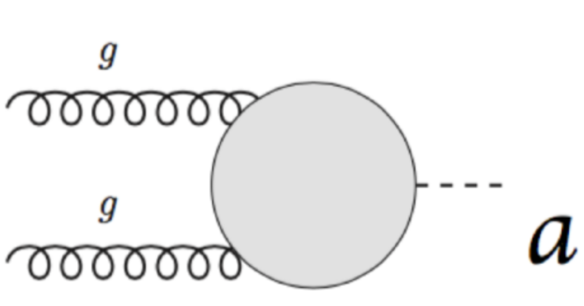
Present ALP mass coverage

$$\mathcal{L}_{\rm int} = \frac{a}{4\pi f_a}\left[\alpha_s c_3 G\tilde{G} + \alpha_2 c_2 W\tilde{W} + \alpha_1 c_1 B\tilde{B}\right] + iC_f m_f \frac{a}{f_a}\bar{f}\gamma_5 f + C_h v \left(\frac{\partial_\mu a}{f_a}\right)^2 h + \cdots$$







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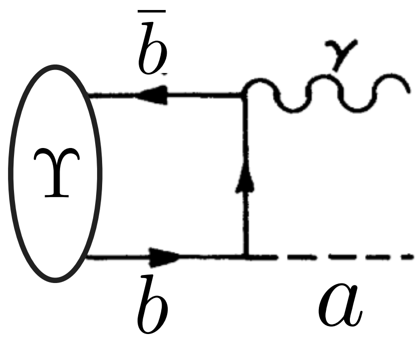

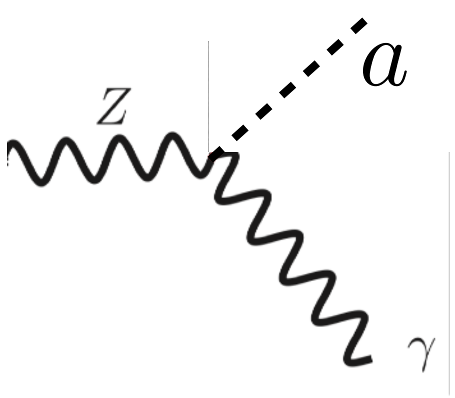

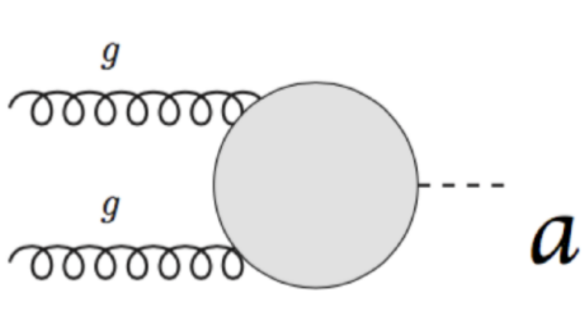

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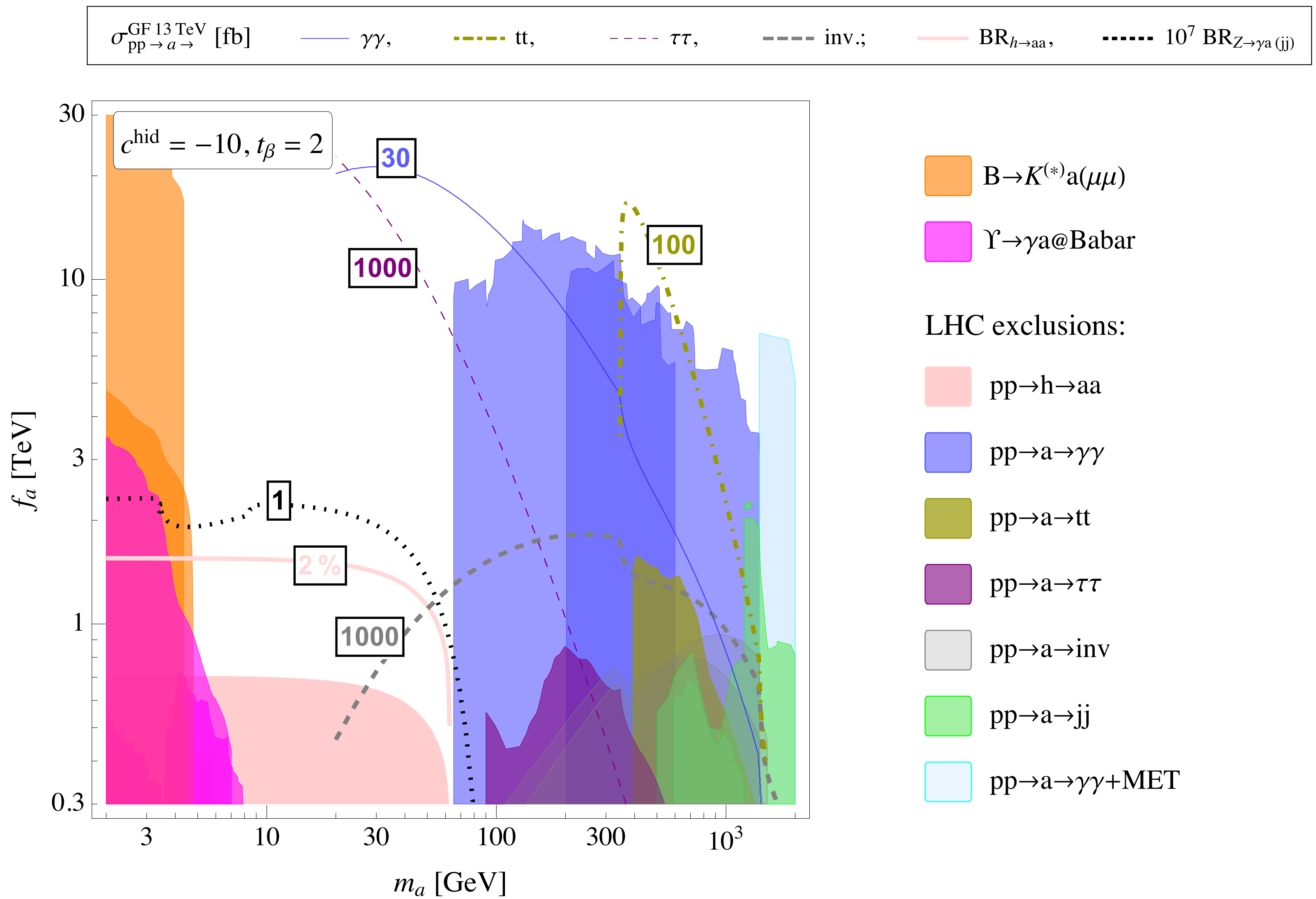

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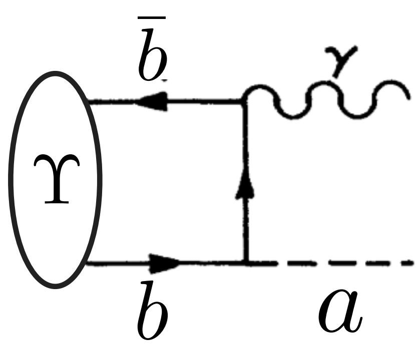

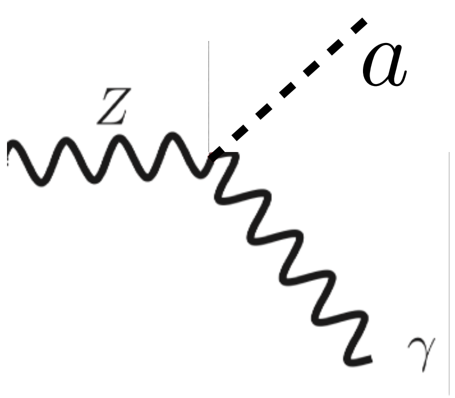

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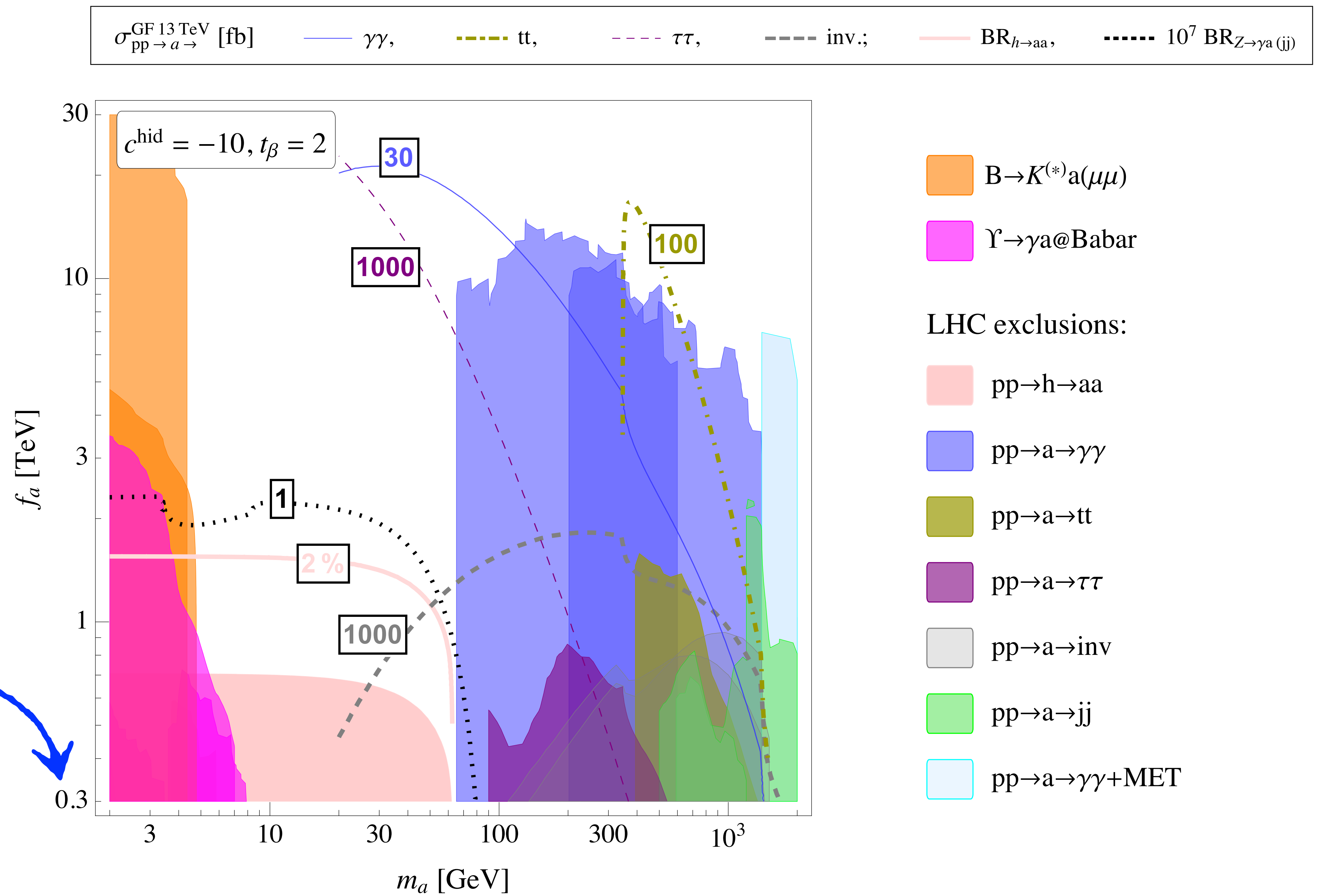

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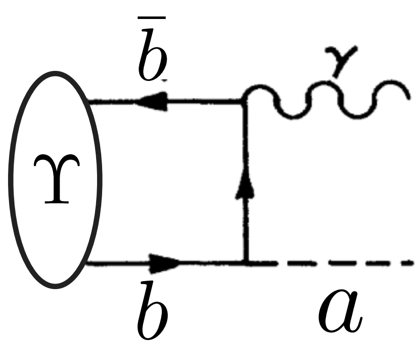

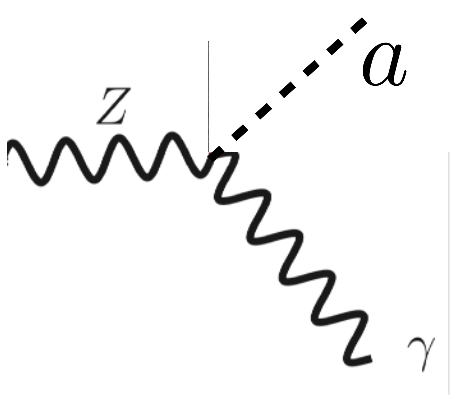

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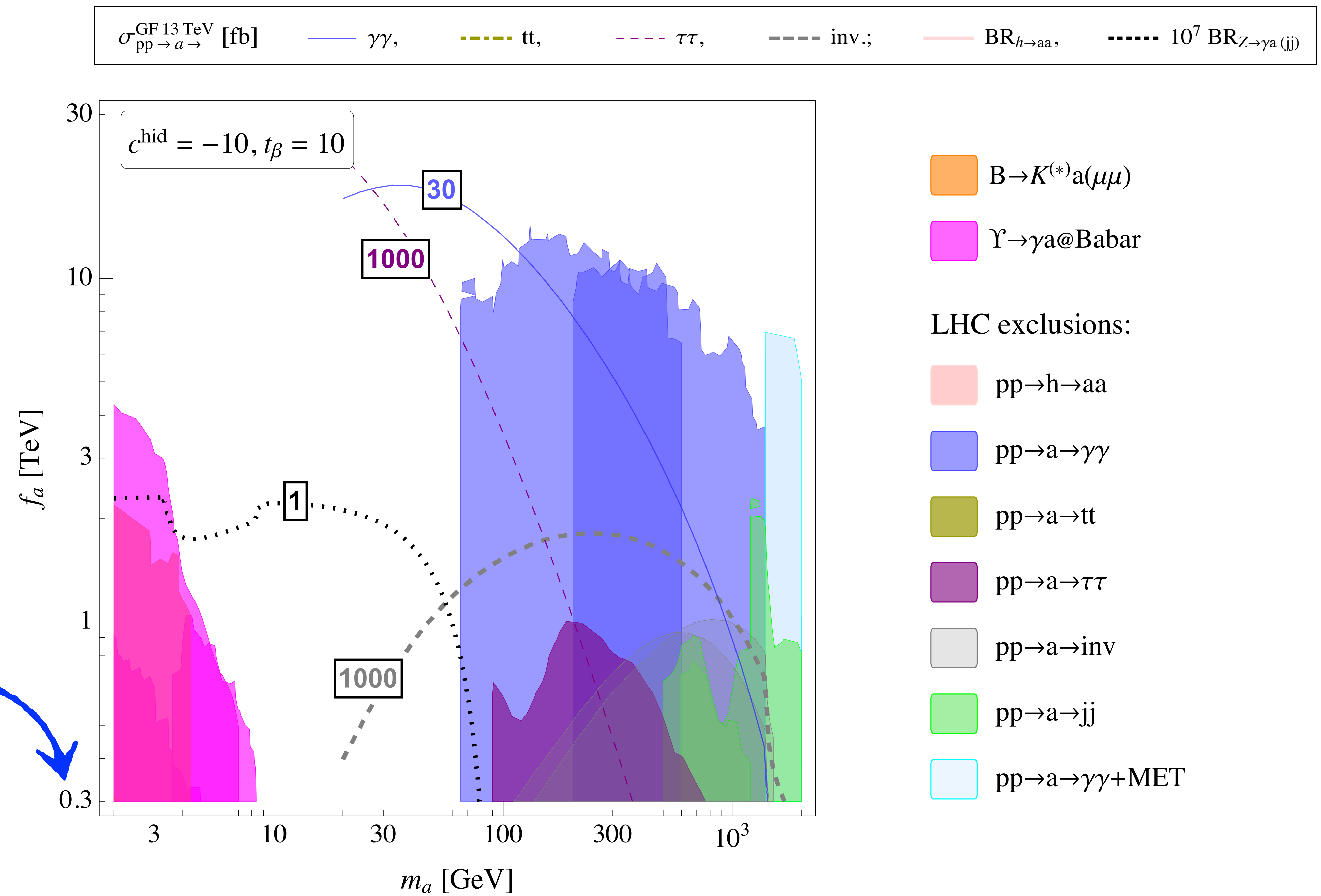

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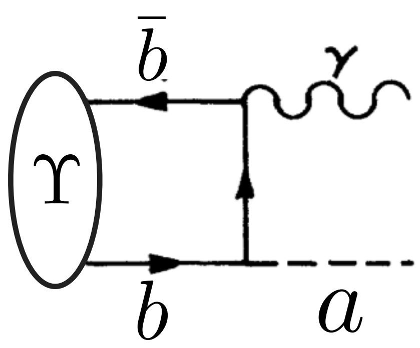

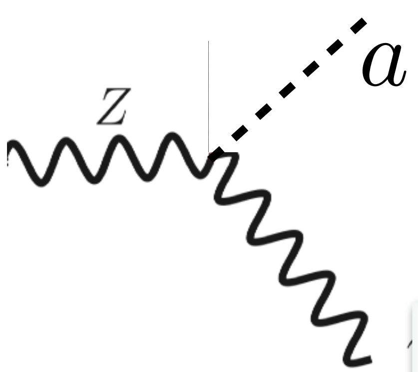

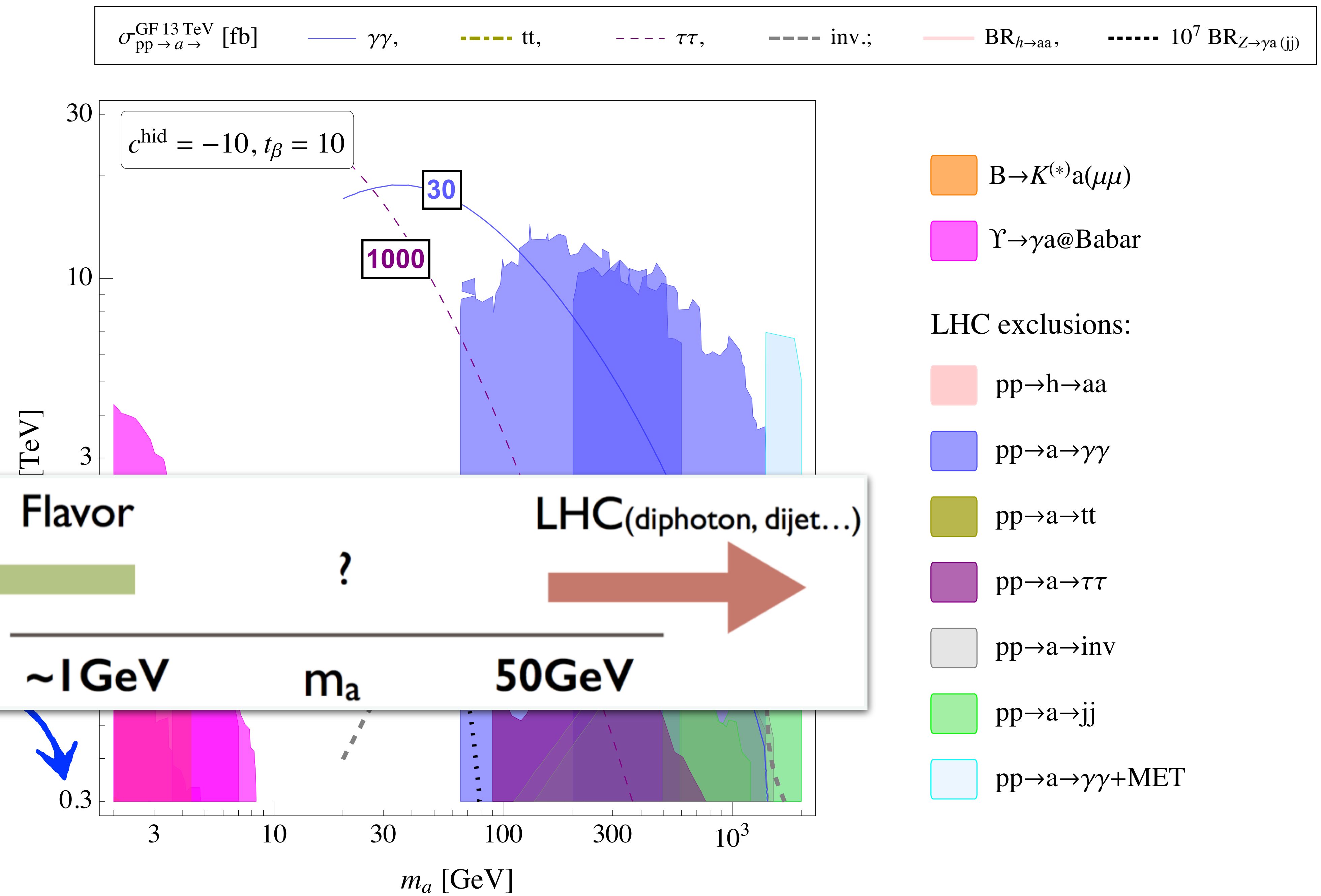

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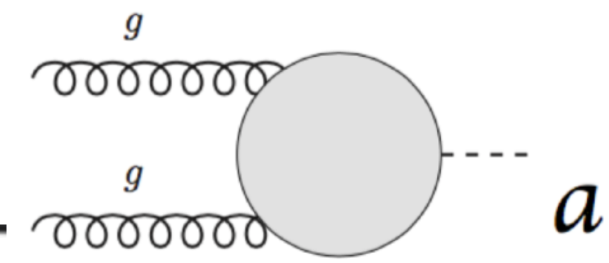
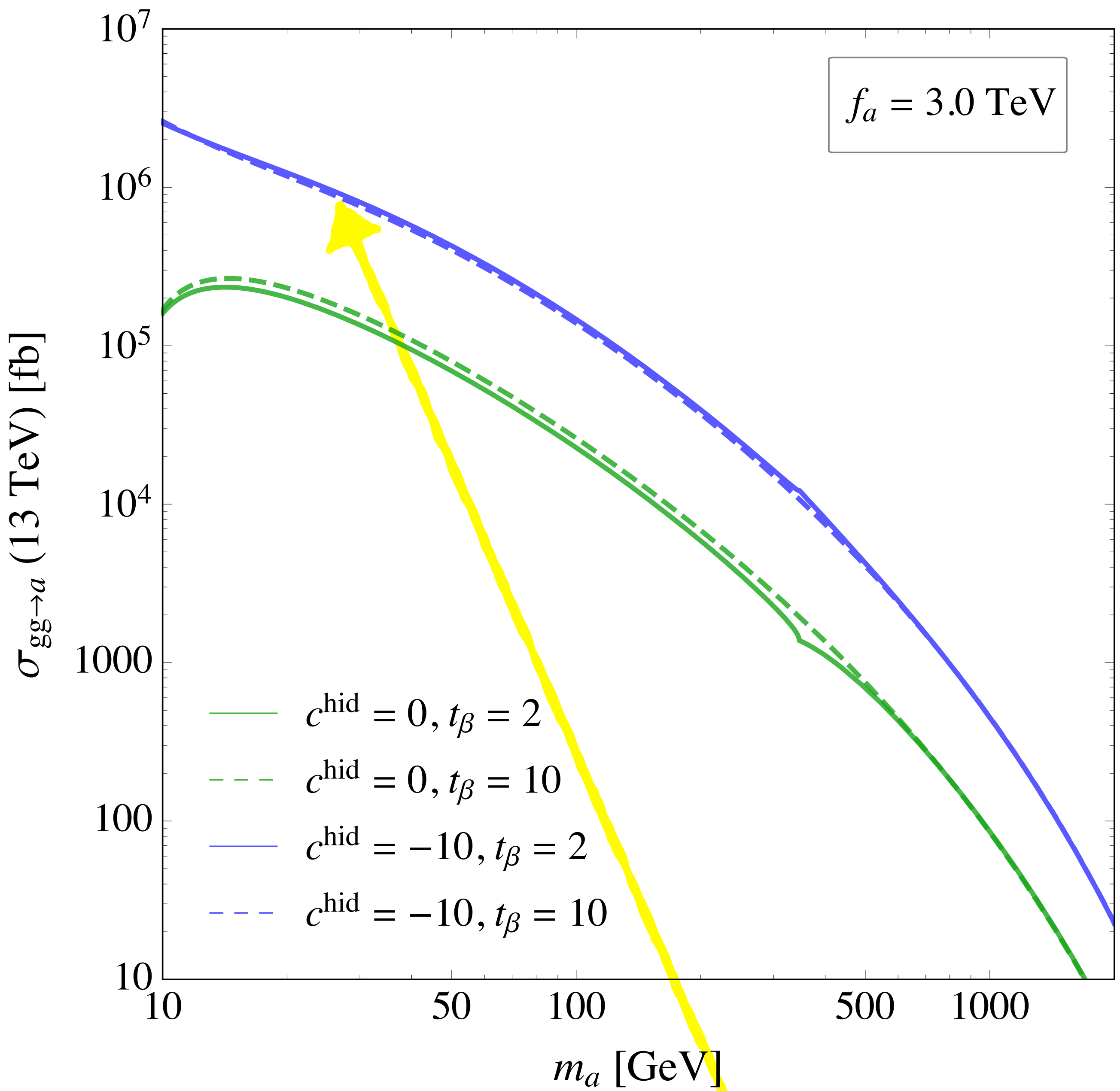
ALP production at the LHC





Production cross sections of ~ 10^5 pb are still allowed! $[f_a \approx 300$ GeV$]$

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3. "It is very difficult!" Minimal pT cuts, …

Why difficult to go below ~ 100 GeV?

$$M_{\gamma\gamma,jj,\ldots} > \Delta R \sqrt{p_{T_1}^{\min} p_{T_2}^{\min}}$$

Isolation of photon/jet/... $\Delta R \equiv \sqrt{\Delta\eta^2 + \Delta\phi^2}$

Minimal cuts on transverse momenta

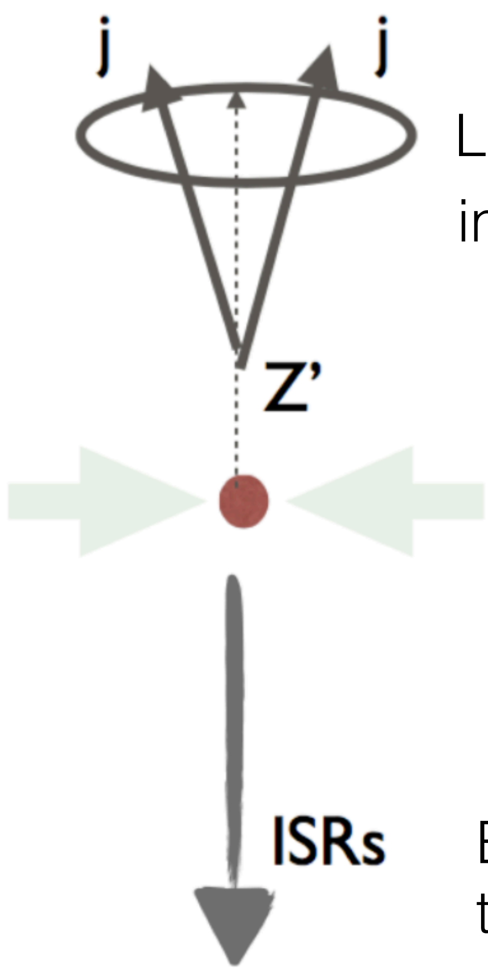
Two ways to lower $M_{\gamma\gamma}$

- Lower ΔR
- Lower $p_T^{\min}$

Lower ΔR

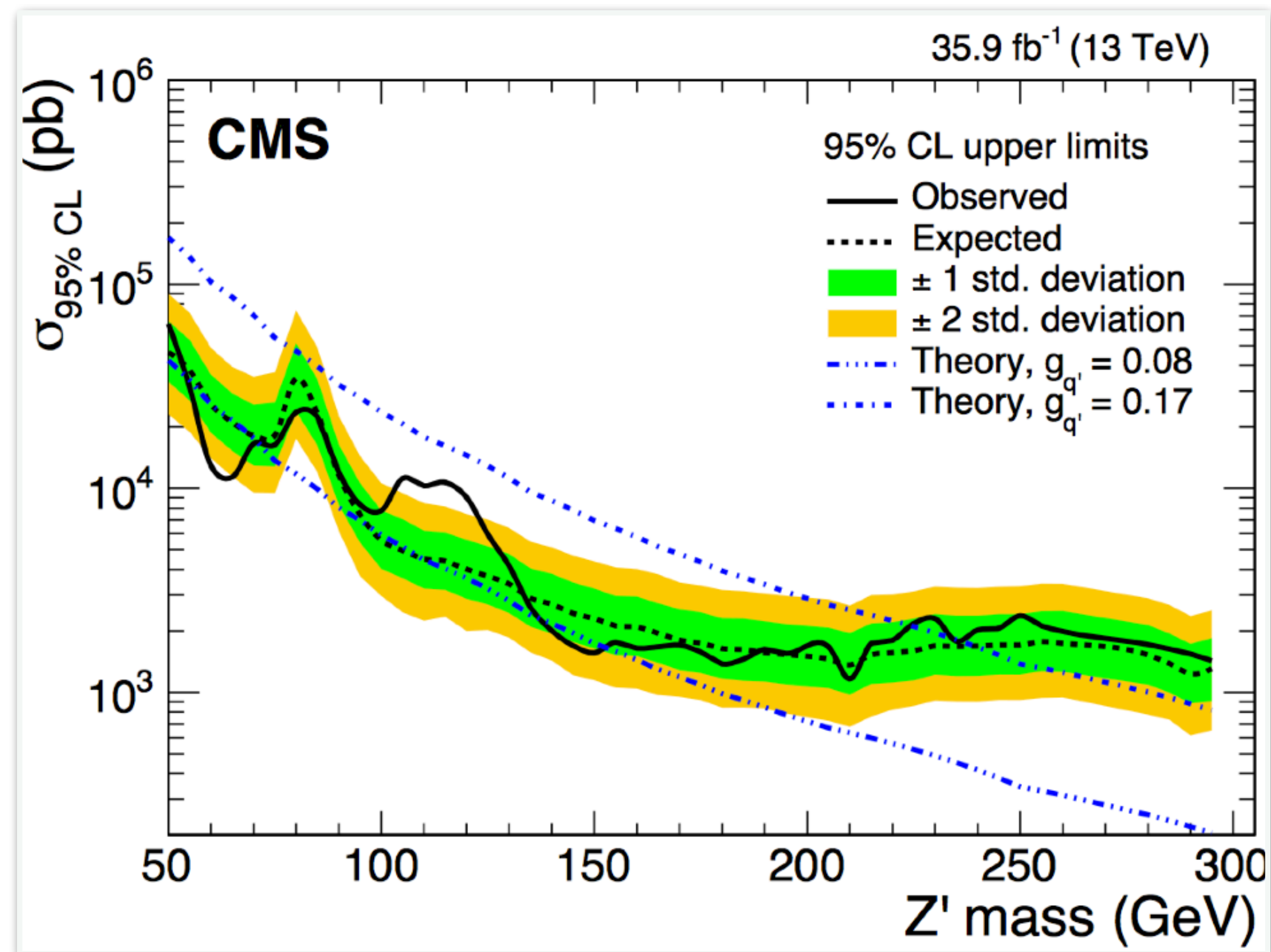
				$m_{jj}^{\rm MIN}$	
CMS	$pp \to a \to jj$	18.8 fb^{-1}	8 TeV	500 GeV	[38]
ATLAS	$pp \to a \to jj$	20.3 fb^{-1}	8 TeV	350 GeV	[39]
CMS	$pp \to a \to jj$	12.9 fb^{-1}	13 TeV	600 GeV	[40]
ATLAS	$pp \to a \to jj$	3.4 fb^{-1}	13 TeV	450 GeV	[41]
CMS	$pp \to ja \to jjj$	35.9 fb^{-1}	13 TeV	$\boxed{\text{50 GeV}}$	[42]

Done recently by CMS in dijet, tremendous improvement in mass reach! CMS 1710.00159



Look for boosted resonance in jet substructure

Extra hard object to pass the trigger



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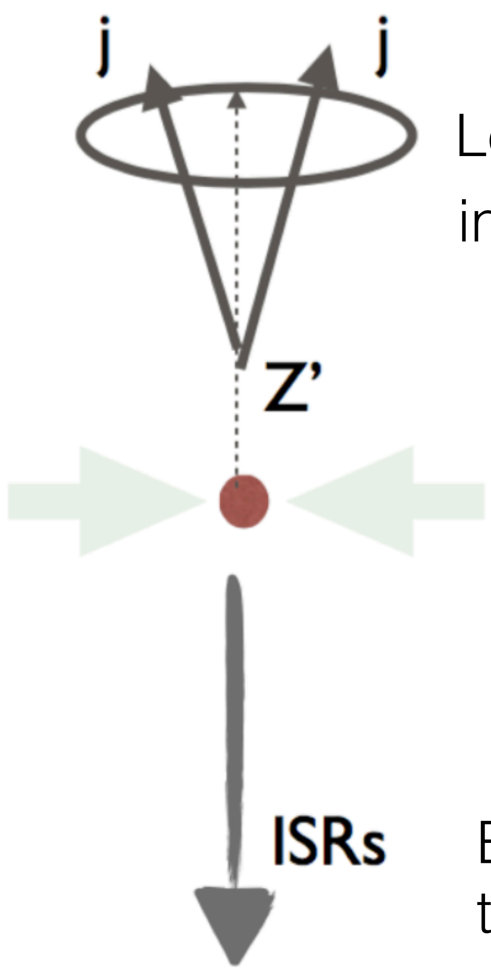

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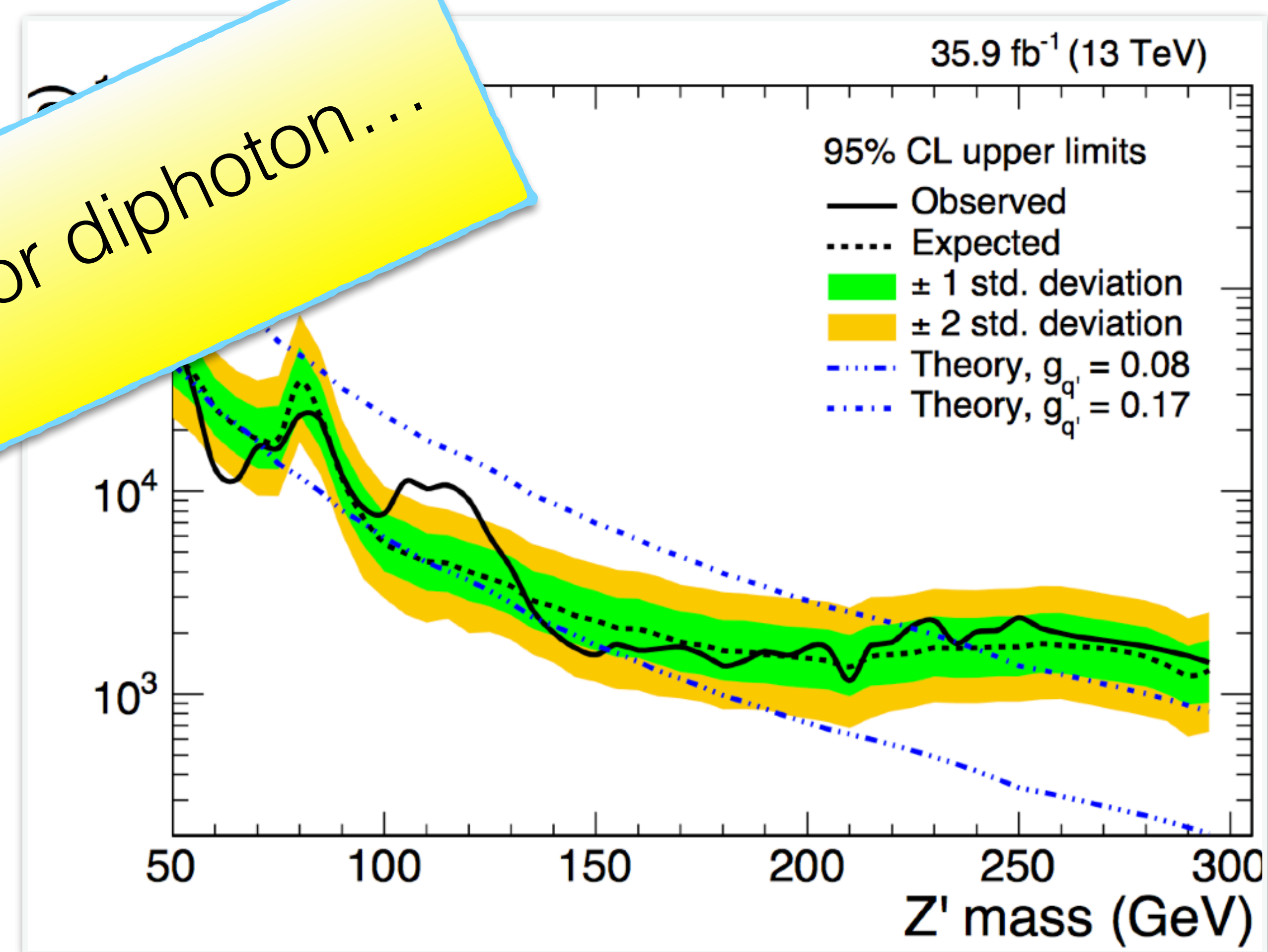
...In progress for diphoton...



Lower $p_T^{\rm min}$?

$$\Delta R \gtrsim 0.4$$

D0 ($\sigma_{\gamma\gamma}$)	$p\bar{p} \to a \to \gamma\gamma$	4.2 fb^{-1}	1.96 TeV	$p_{T_1}, {}_{T_2} > 21\,, 20$ GeV	[illegible]	
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LHC pT cuts in diphoton cross section measurements

but LHC diphoton searches do not reach such low masses

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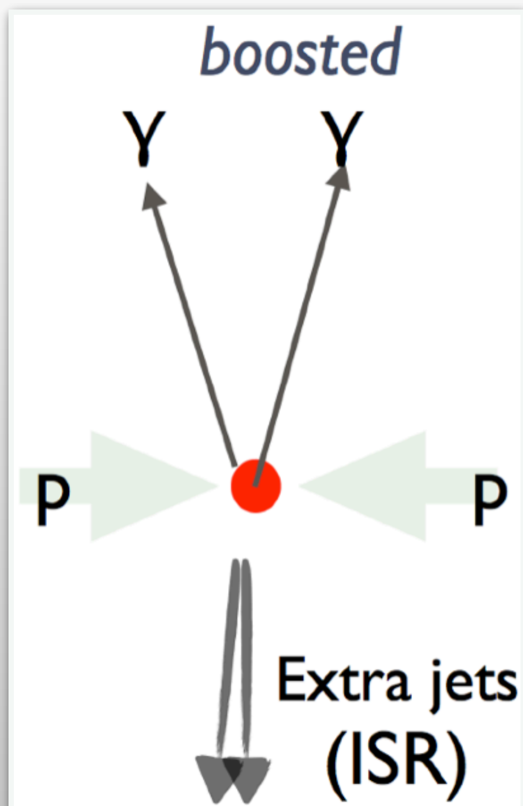
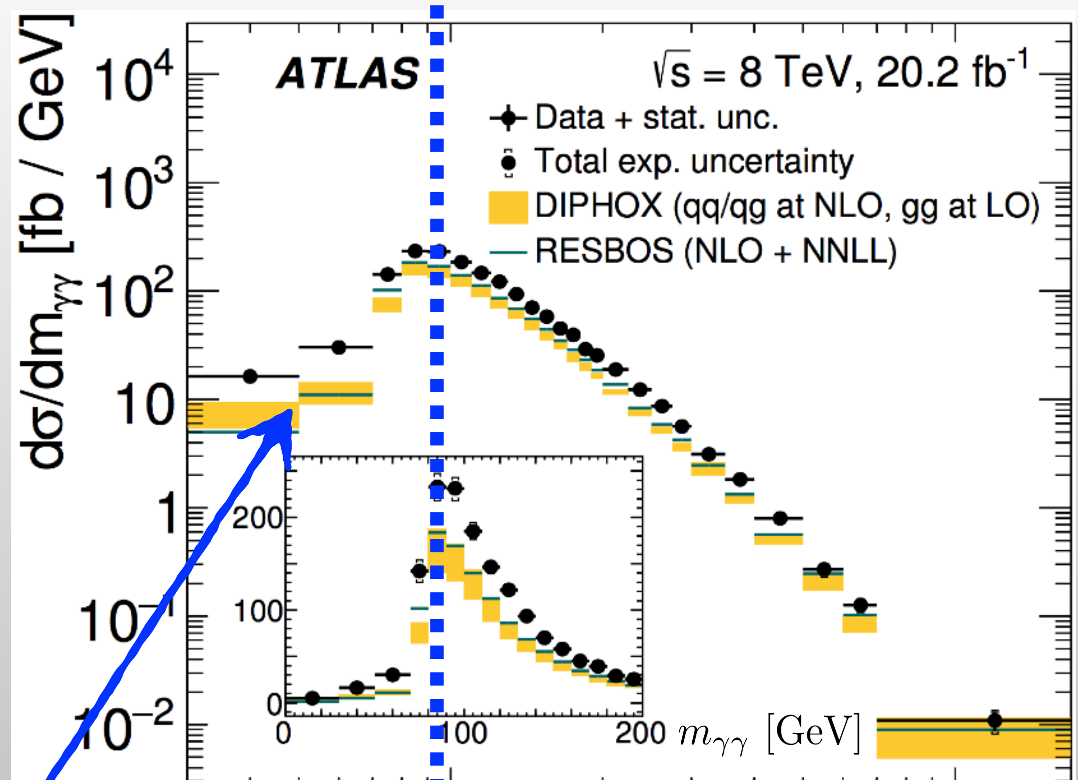
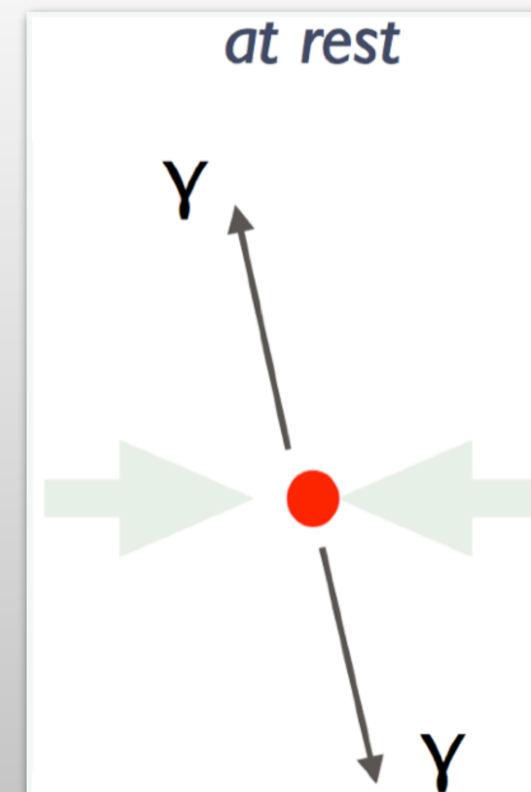
Why? **Background Shape**







$$m_{\gamma\gamma} \simeq p_{T_1}^{\min} + p_{T_2}^{\min}$$

Below pT cuts: Background has a structure, so **data-driven estimates are difficult**

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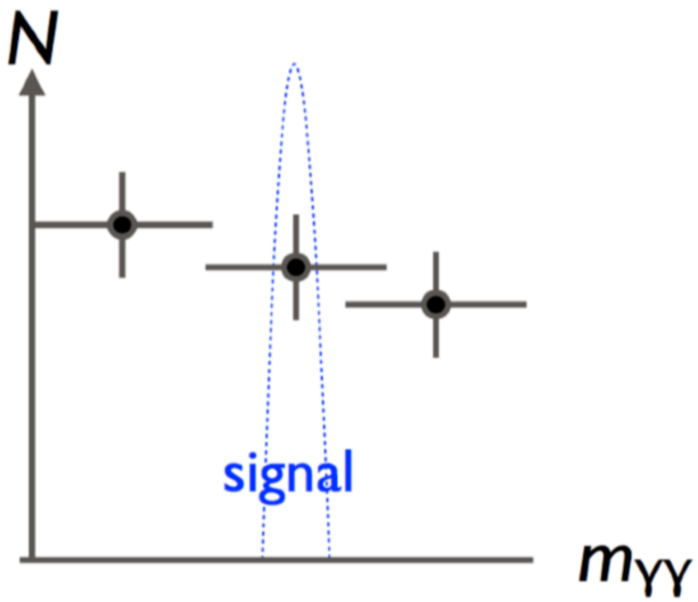
New $\gamma\gamma$ Bound & Sensitivities

Starting point: inclusive **diphoton cross section measurements** @ ATLAS7,8 and CMS7



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$$\boxed{N_{\rm bin}^{\rm signal} < N_{\rm bin}^{\rm meas.}(1 + 2\,\Delta_{\rm bin})}$$

experimental rel. uncertainty

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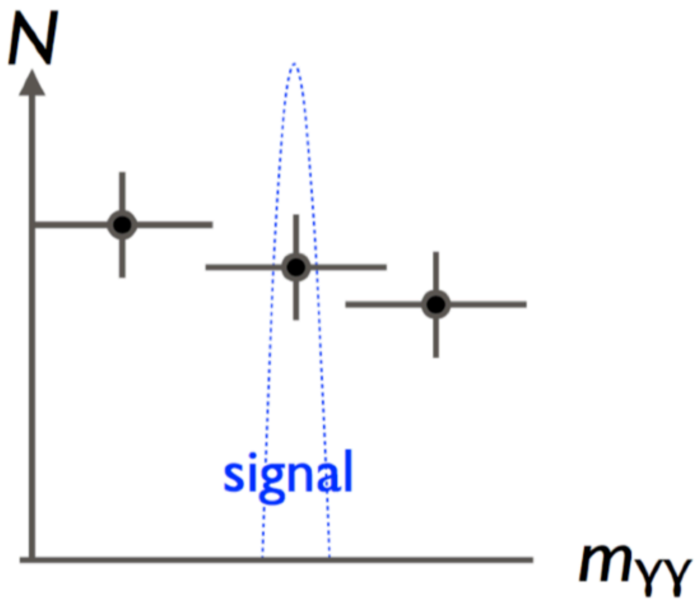

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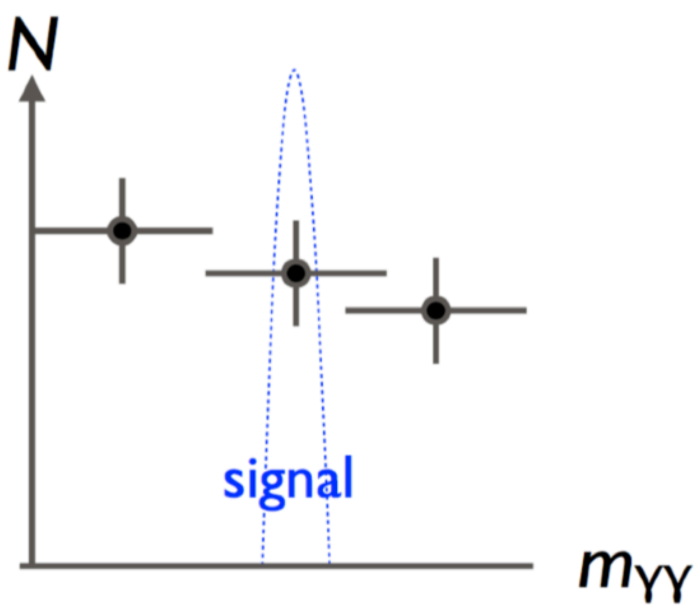
experimental rel. uncertainty

2. **Reach** we assume data = SM prediction $\boxed{N_{\rm bin}^{\rm signal} < N_{\rm bin}^{\rm meas.} \times 2\,\Delta_{\rm bin}}$

3. **Reach** with smarter bins (= 2., where we reduce ~ 10 GeV bins to mass resolution of ~ 3 GeV)

New $\gamma\gamma$ Bound & Sensitivities

Starting point: inclusive **diphoton cross section measurements** @ ATLAS7,8 and CMS7



1. **New Bound** we assume zero knowledge of bkg

$$\boxed{N_{\rm bin}^{\rm signal} < N_{\rm bin}^{\rm meas.}(1+2\,\Delta_{\rm bin})}$$

experimental rel. uncertainty

2. **Reach** we assume data = SM prediction

$$\boxed{N_{\rm bin}^{\rm signal} < N_{\rm bin}^{\rm meas.} \times 2\,\Delta_{\rm bin}}$$

3. **Reach** with smarter bins (= **2.**, where we reduce ~ 10 GeV bins to mass resolution of ~ 3 GeV)

4. **Reach** we simulate bkg with <u>same cuts</u> at <u>different energies</u> [Madgraph+Pythia+Delphes]

$$\boxed{N_{\rm bin}^{\rm signal}(E_{\rm high}) < N_{\rm bin}^{\rm signal}(E_{\rm low}) \cdot \sqrt{\frac{L_{\rm low}}{L_{\rm high}} \cdot \frac{\sigma_{\rm high}^{\rm MC}}{\sigma_{\rm low}^{\rm MC}} \cdot \frac{\epsilon_S^{\rm low}}{\epsilon_S^{\rm high}}}}$$

Reach of **3.** Simulated bkg cross sections Simulated signal efficiencies

New $\gamma\gamma$ Bound & Sensitivities

Starting point: inc ... and CMS7

N

si

... ge of bkg

$\Delta_{\rm bin})$

... l rel. uncertainty

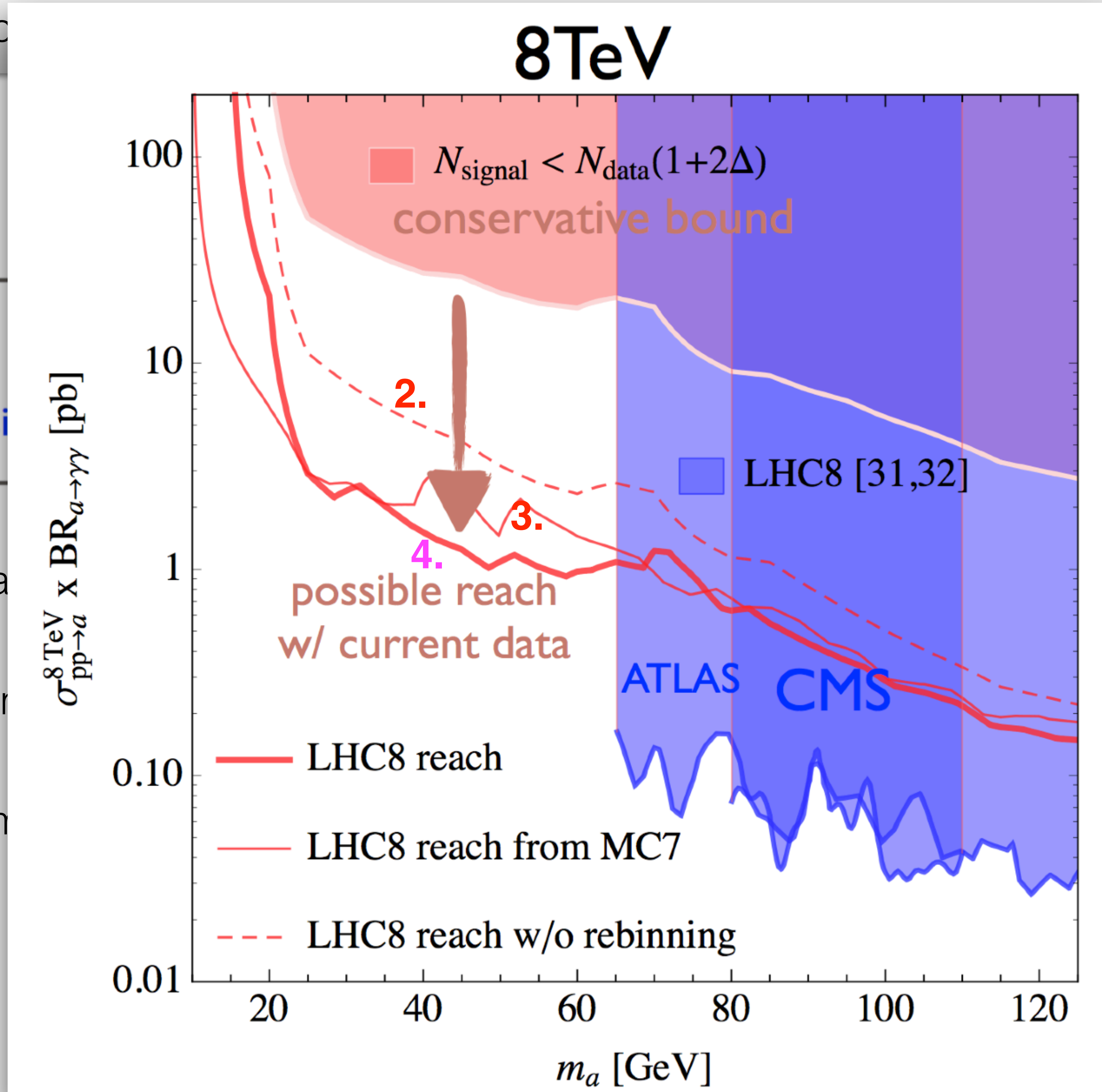
2. Reach we a ... bin

3. Reach with sr ... esolution of ~ 3 GeV)

4. Reach we sin ... Pythia+Delphes]

$\epsilon_S^{\rm low}$ / $\epsilon_S^{\rm high}$

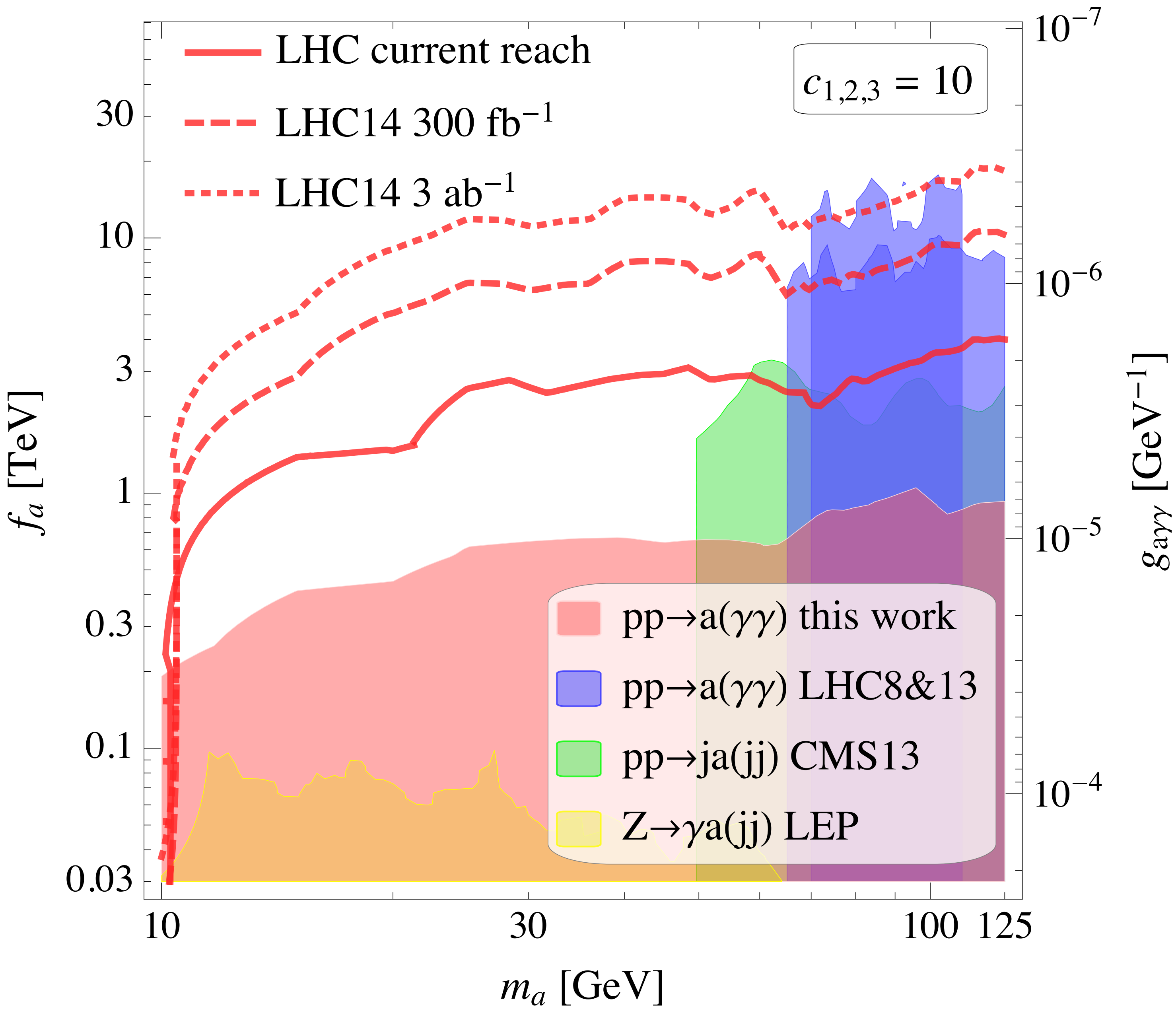
... d signal efficiencies



Mariotti Redigolo FS Tobioka 1710.01743

Impact on ALP parameter space

Allowed cross sections were so large, that our simple bound is by far the strongest one



LHC current from data [reach **3.**]

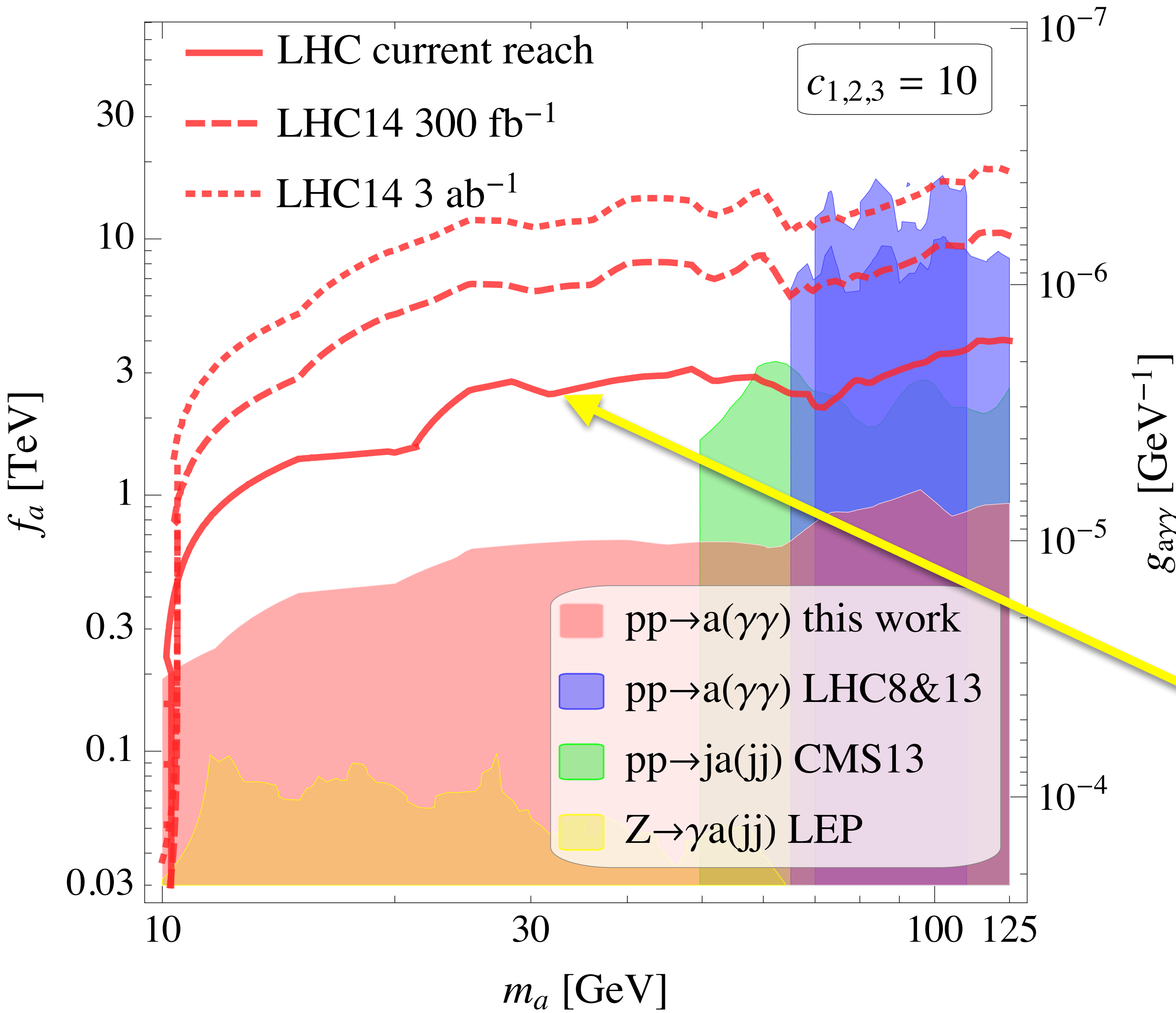
LHC14 from MC simulations [reach **4.**]

$$\mathcal{L}_{\rm int} = \frac{a}{4\pi f_a}\left[\alpha_s c_3 G\tilde{G} + \alpha_2 c_2 W\tilde{W} + \alpha_1 c_1 B\tilde{B}\right]$$

$$\alpha_1 = \tfrac{5}{3}\alpha_y$$

Impact on ALP parameter space

Allowed cross sections were so large, that our simple bound is by far the strongest one



LHC current from data [reach **3.**]

LHC14 from MC simulations [reach **4.**]

ATLAS&CMS could do much better already with current data!

$$\mathcal{L}_{\rm int} = \frac{a}{4\pi f_a}\left[\alpha_s c_3 G\tilde{G} + \alpha_2 c_2 W\tilde{W} + \alpha_1 c_1 B\tilde{B}\right]$$

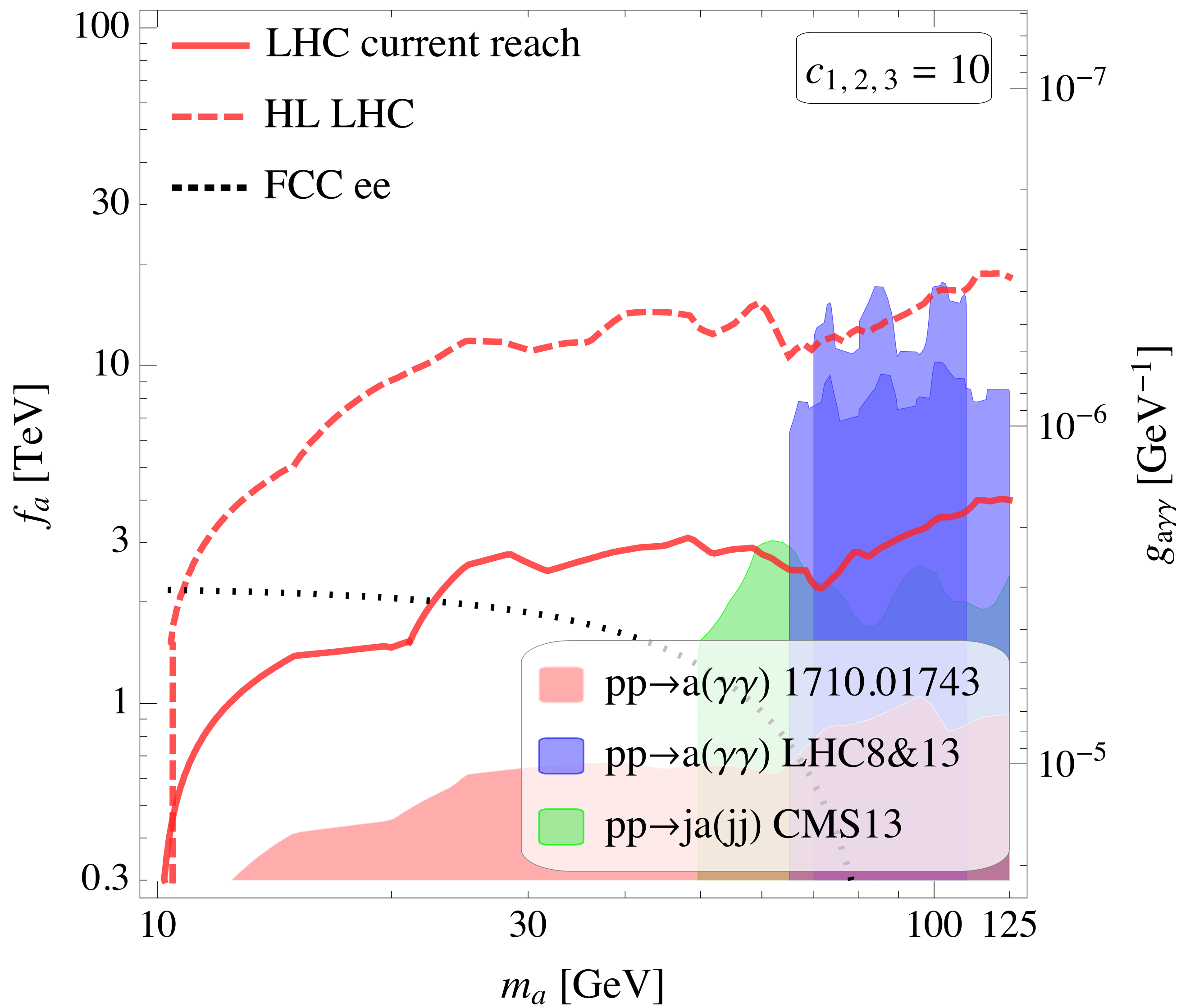
$$\alpha_1 = \tfrac{5}{3}\alpha_y$$

FCC

Mariotti Redigolo FS Tobioka in progress

FCC ee reach computed rescaling
LEP limits on $\mathrm{BR}[Z \to \gamma a(jj)]$
and assuming 10^{12} Z bosons

If $aG\tilde{G}$ switched on
HL-LHC wins over FCC ee



FCC

Mariotti Redigolo FS Tobioka in progress

FCC ee reach computed rescaling

LEP limits on $\mathrm{BR}[Z \to \gamma a(jj)]$

and assuming 10^{12} Z bosons

If $aG\tilde{G}$ switched on

HL-LHC wins over FCC ee

FCC hh reach computed like LHC14 one

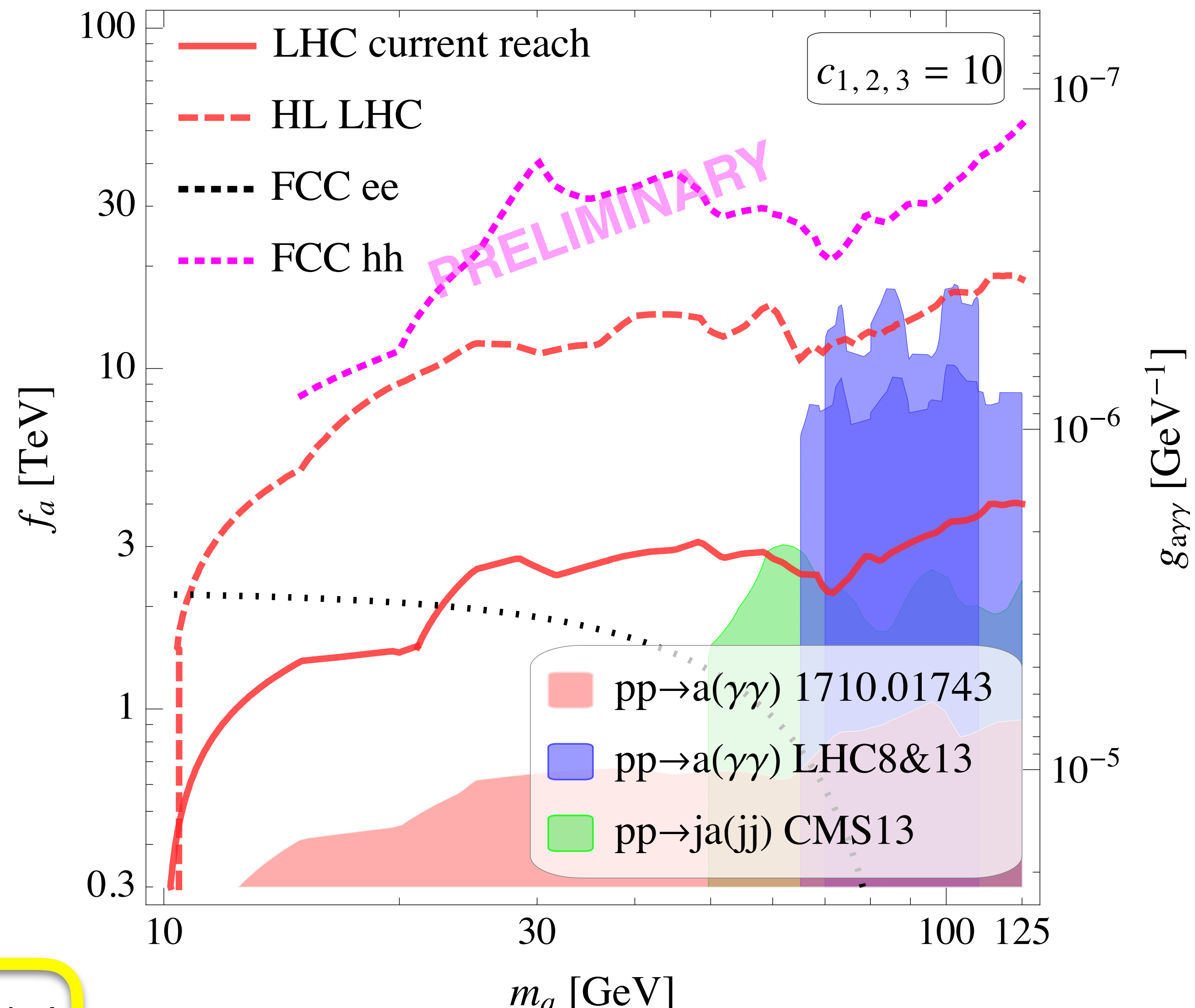
[4., from simulations, Lumi= $3\ \mathrm{ab}^{-1}$]

NB. pT cuts as in ATLAS8 (30, 40 GeV)

Still, speculative even for FCC standards!

this search has not even been performed at 8 TeV

at 100 TeV game could be very different (larger boosts,…)



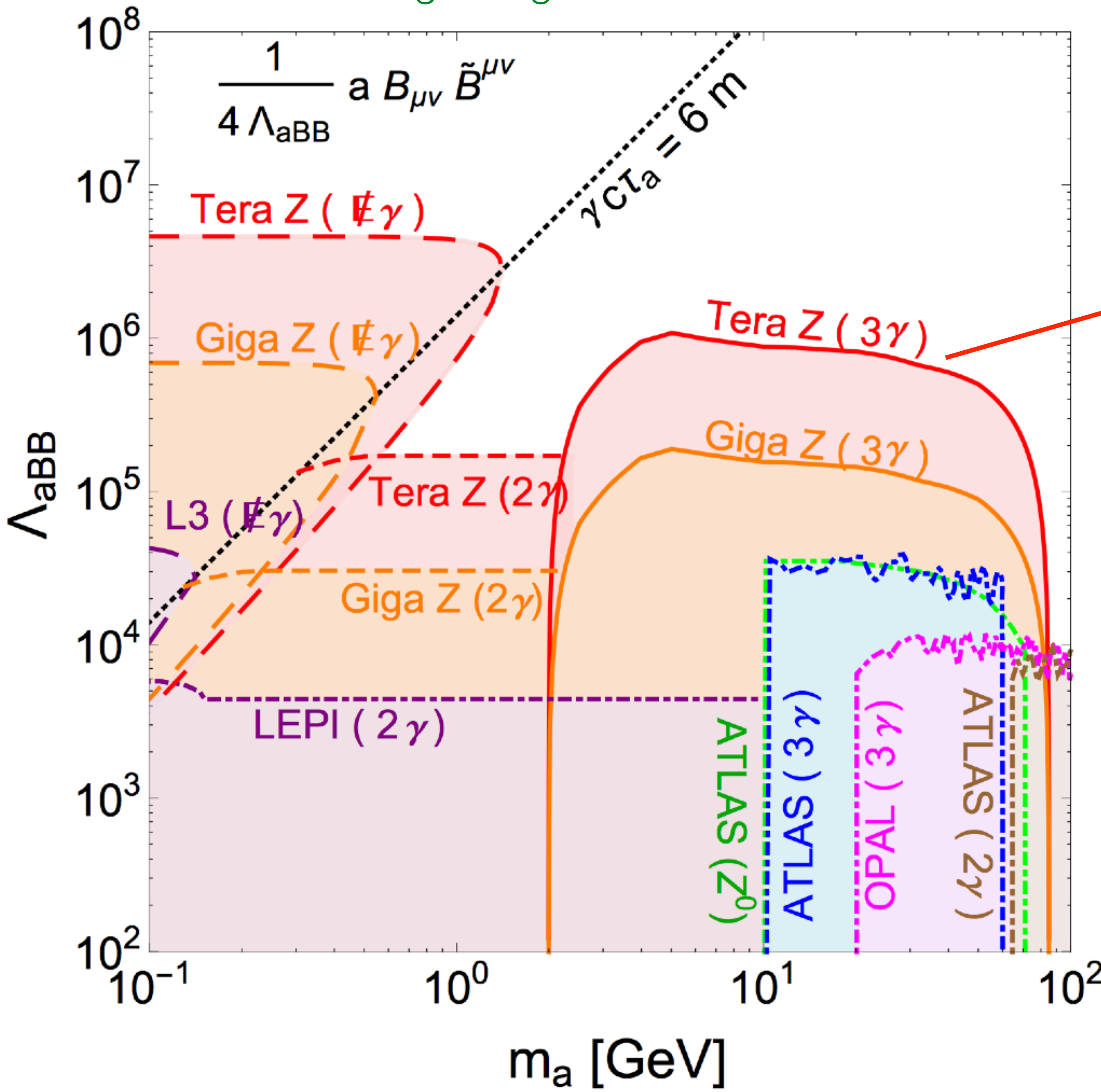
Thoughts in progress…

FCC-ee with no gluon coupling

$$\mathcal{L}_{\rm int} = \frac{a}{4\pi f_a}\left[\cancel{\alpha_s c_3 G\tilde{G}} + \alpha_2 c_2 W\tilde{W} + \alpha_1 c_1 B\tilde{B}\right]$$

$$\alpha_1 = \tfrac{5}{3}\alpha_y$$

Liu Wang Wang Xue 1712.07237



To compare with previous slides:

$$\Lambda_{\rm aBB} = \frac{\pi}{c_1\,\alpha_1} f_a \simeq 20\, f_a\, \frac{10}{c_1}$$

For Tera Z $\mathrm{BR}[Z\to\gamma a(\gamma\gamma)] \lesssim 3\times 10^{-9}$

[current LEP limit $\lesssim 5\times 10^{-6}$]

FCC ee could reach $f_a \lesssim 100$ TeV

FCC hh VBF ?

Associated production ?

Photon fusion ?

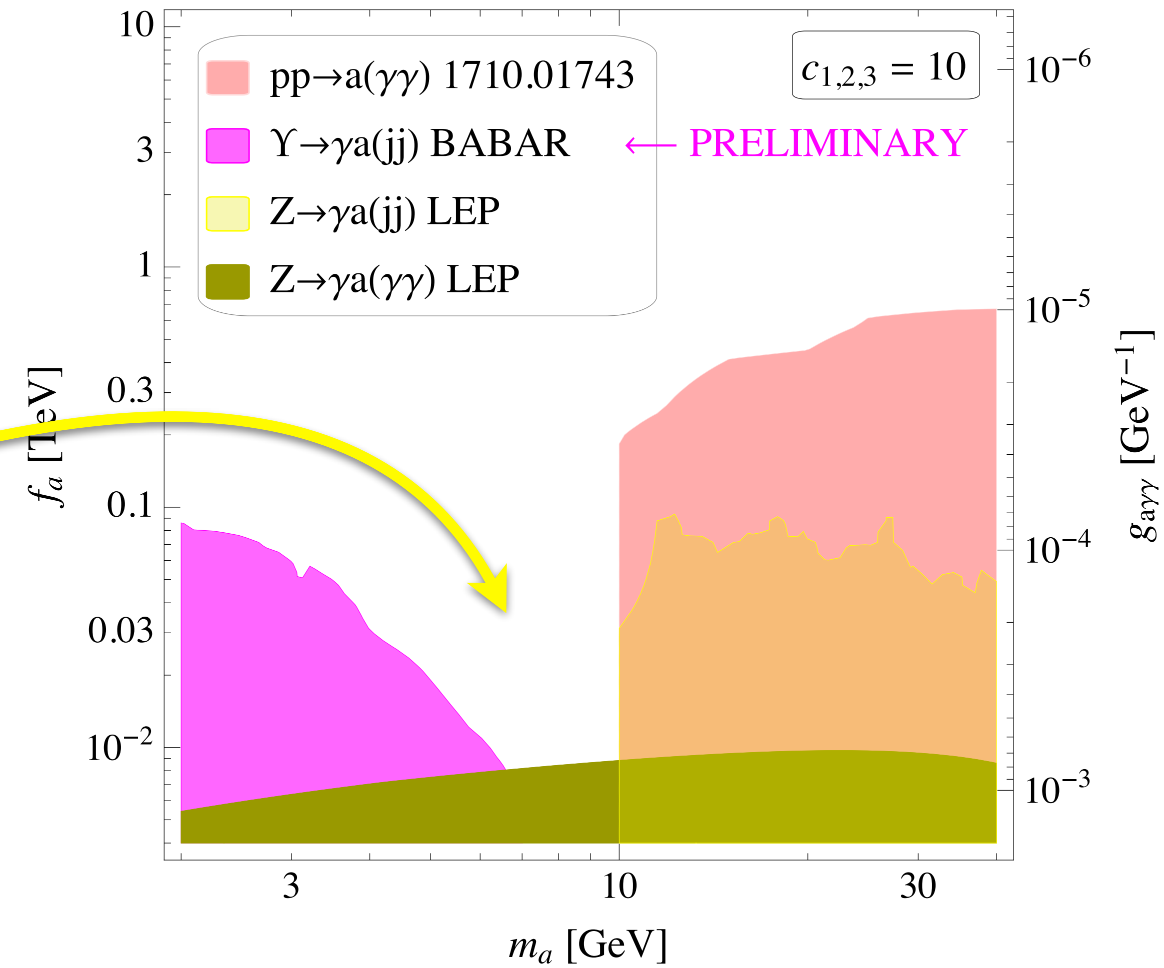
???

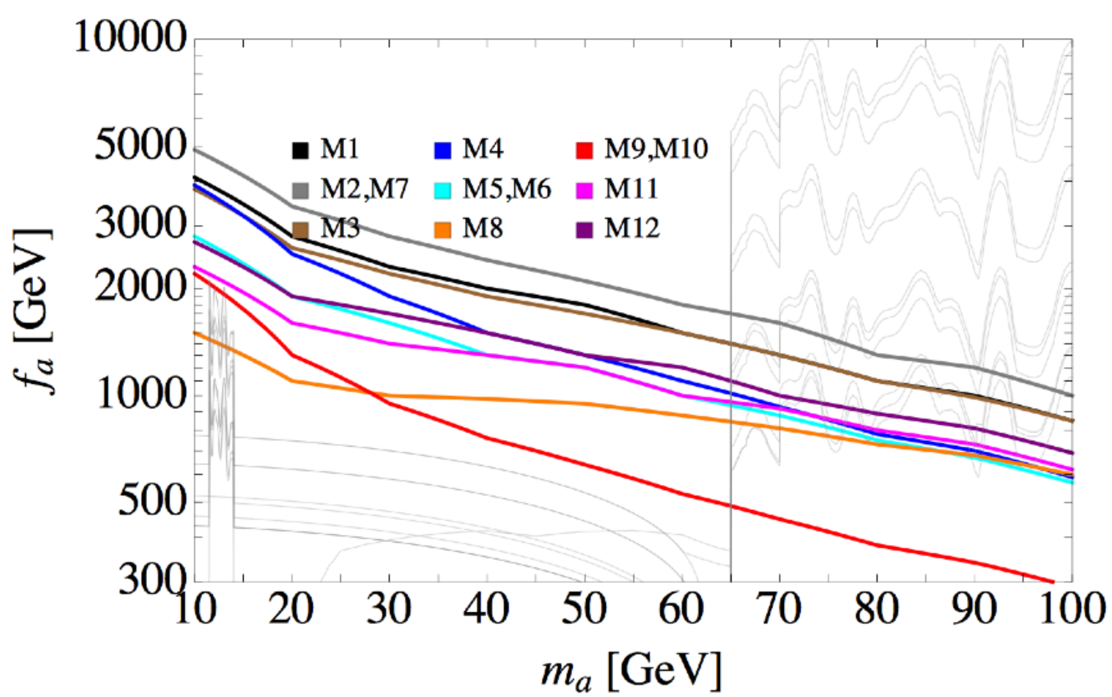
Other ways to low-mass resonances?

$m_{\gamma\gamma} < 10~\text{GeV}$ at the LHCb?

work in progress…

Big hole for $4~\text{GeV} \lesssim m_a \lesssim 10~\text{GeV}$





Difermions, e.g. ditaus?

Cacciapaglia Ferretti Flacke Serodio 1710.11142

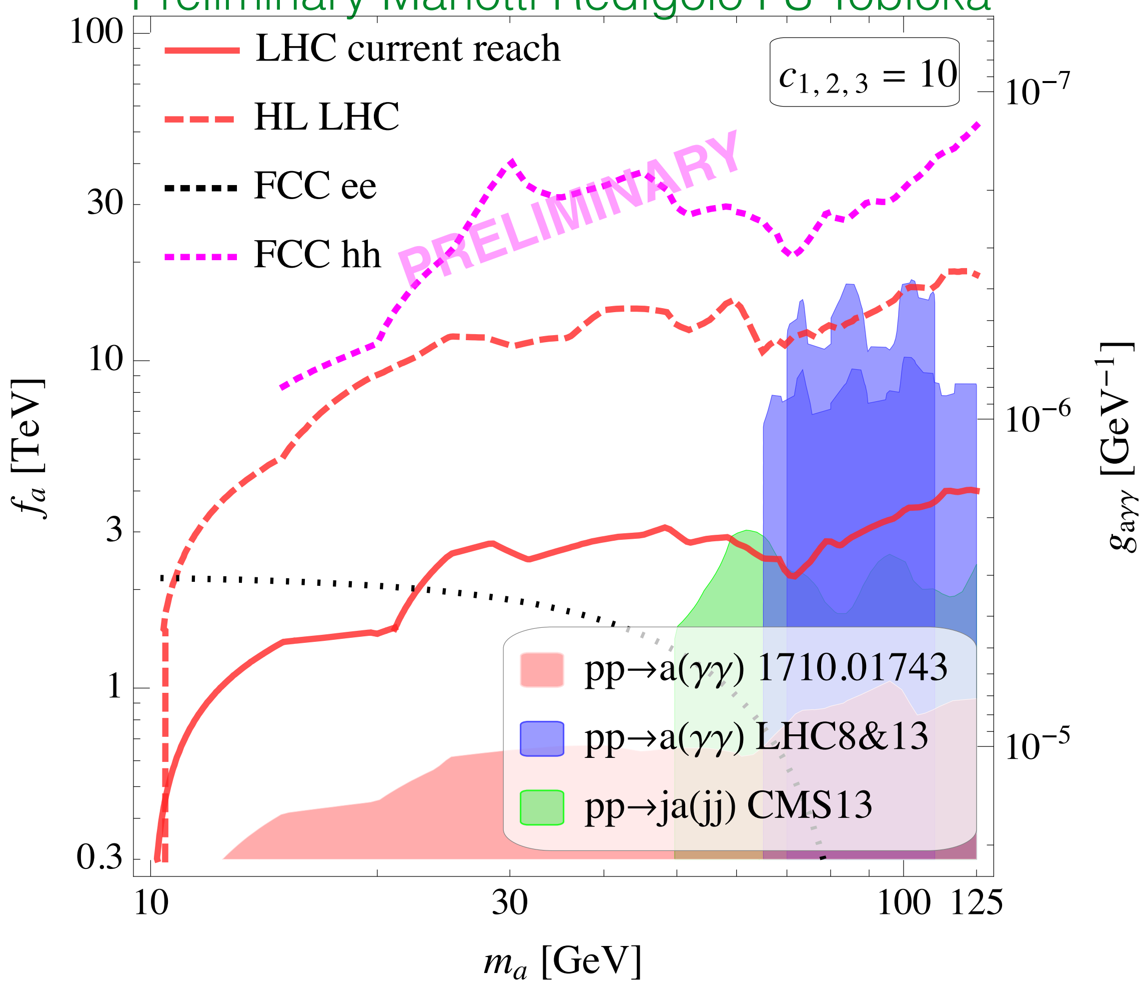
NB. sensitivities not based on data

definitely worth investigating

Summary & Outlook

- Existing resonance searches do not go below 50-70 GeV
- But they could! We set **strongest bound on ALPs** from $\gamma\gamma$ Mariotti Redigolo FS Tobioka 1710.01743
- **NEXT**: LHCb, difermions, actual searches by LHC collaborations

Preliminary Mariotti Redigolo FS Tobioka



- **FCC-ee** excellent if no coupling $aG\tilde{G}$

  otherwise HL LHC will be better

- **FCC-hh** appears promising, but

  more work needed, already with current run

  qualitative novelties still to be explored

Back up

More on R-axion

PGB from SUSY: R-symmetry

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

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

needs a strongly coupled sector

m_*

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

$$m_a \approx \sqrt{\epsilon_{\not R}}\, m_*$$

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

so that $m_{\lambda^i} \sim \dfrac{g_i^2}{g_*^2} m_*$ 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

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

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: $r_X = 2 \quad r_{\mathcal{R}} = 1$

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

Absent for any other axion

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

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

R-axion decays to missing energy

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

Dine Festuccia Komargodski 0910.2527
see also Bellazzini 1605.06111

R-axion pheno overview

Tool: constrained superfield formalism

Komargodski Seiberg 0907.2441

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

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

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

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

$r_\mathcal{R} = 1 \quad r_X = 2 \quad r_\mathcal{W} = 1$

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

$$\frac{g_i^2 c_i^\text{hid}}{16\pi^2}\frac{a}{f_a}F^i\tilde{F}^i$$

$$g_i^2\frac{c_i^\text{eff}}{16\pi^2}\frac{\partial_\mu a}{f_a}\bar{\lambda}_i\gamma_\mu\gamma_5\lambda_i - i\frac{m_{\lambda_i}}{f_a}a\,\bar{\lambda}_i\gamma_5\lambda_i$$

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

$$\mathcal{L}_\text{Higgs} \supset \int d^4\theta \left(\frac{\mu}{F}X^\dagger H_u H_d \mathcal{R}^{2-R_H} - \frac{B_\mu}{F^2}X^\dagger X H_u H_d \mathcal{R}^{-R_H} + \text{c.c}\right)$$

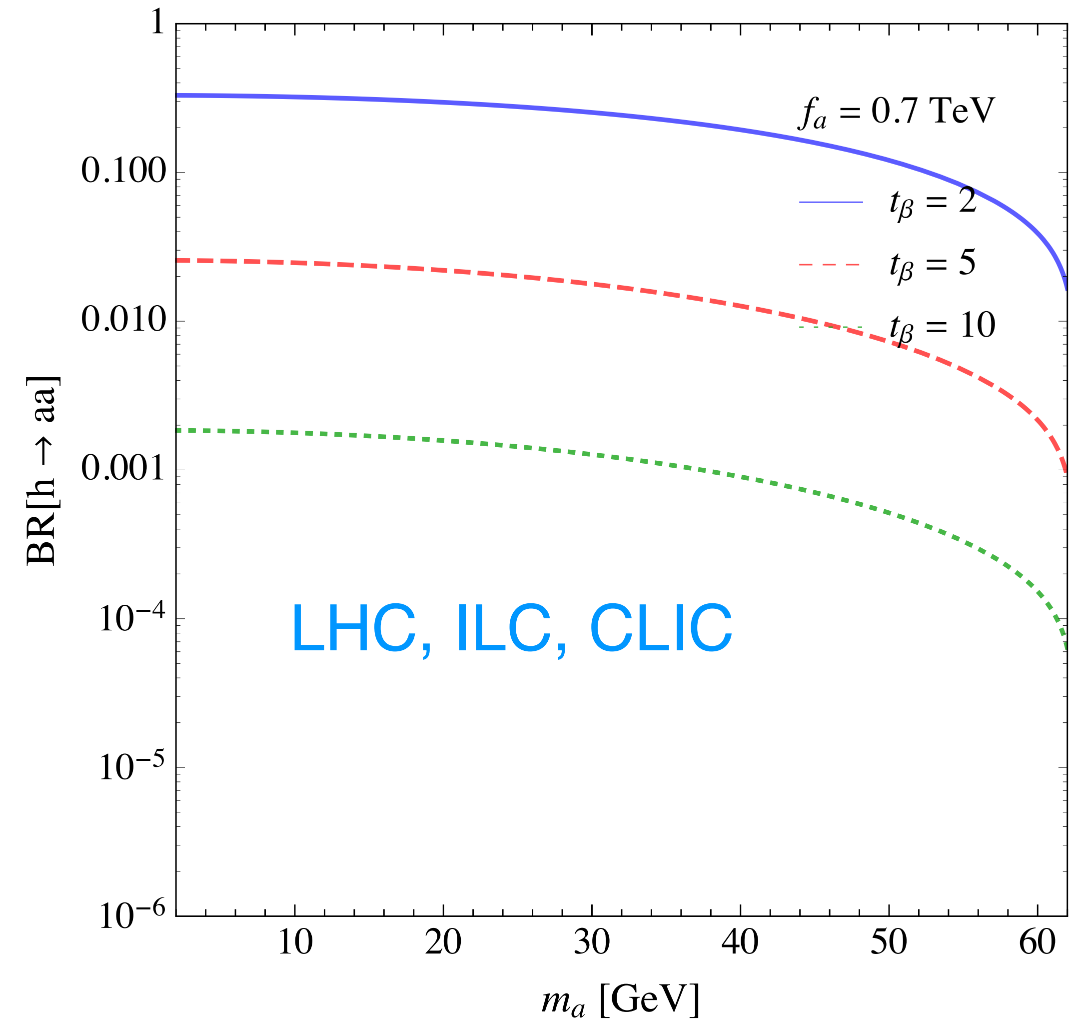
$$-i\,a\,R_H\left(c_\beta^2\frac{m_u}{f_a}\bar{u}\gamma_5 u + s_\beta^2\frac{m_d}{f_a}\bar{d}\gamma_5 d + s_\beta^2\frac{m_\ell}{f_a}\bar{\ell}\gamma_5\ell\right)$$

$$\frac{\delta^2}{v}(\partial_\mu a)^2 h \qquad \delta = R_H\frac{v}{f_a}\frac{s_{2\beta}}{2}$$

a from decays of h, Υ and B

$$\mathcal{L}_{ha^2} = \frac{\delta^2}{v}(\partial_\mu a)^2 h$$

$$\delta = R_H \frac{v}{f_a}\frac{s_{2\beta}}{2}$$



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

since Wilczek PRL39 (1977)

experiments: BABAR

Belle-II

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

see Hall Wise 1981, Freytsis Ligeti Thaler 0911.5355

LHCb

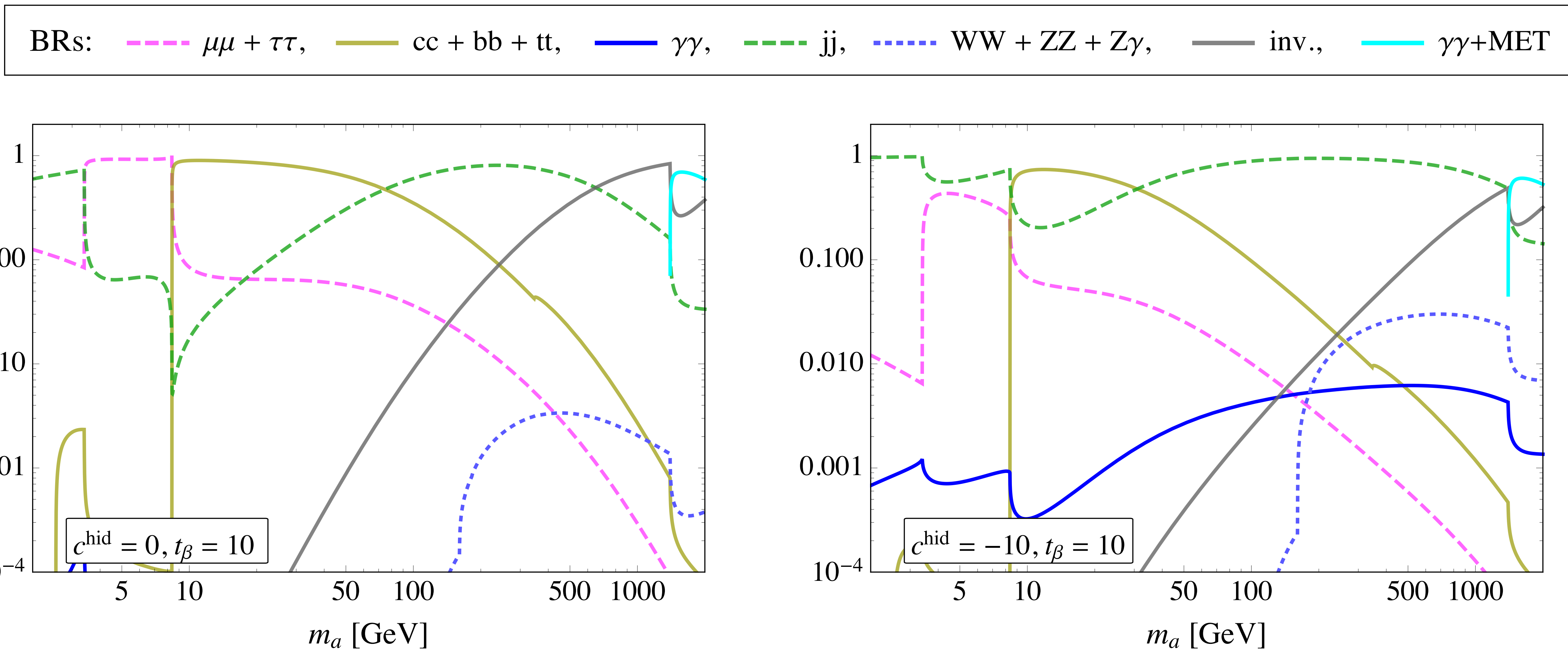
Belle, Belle-II

R axion branching ratios

Both plots: $t_\beta = 10$

No anomaly

Large anomalies

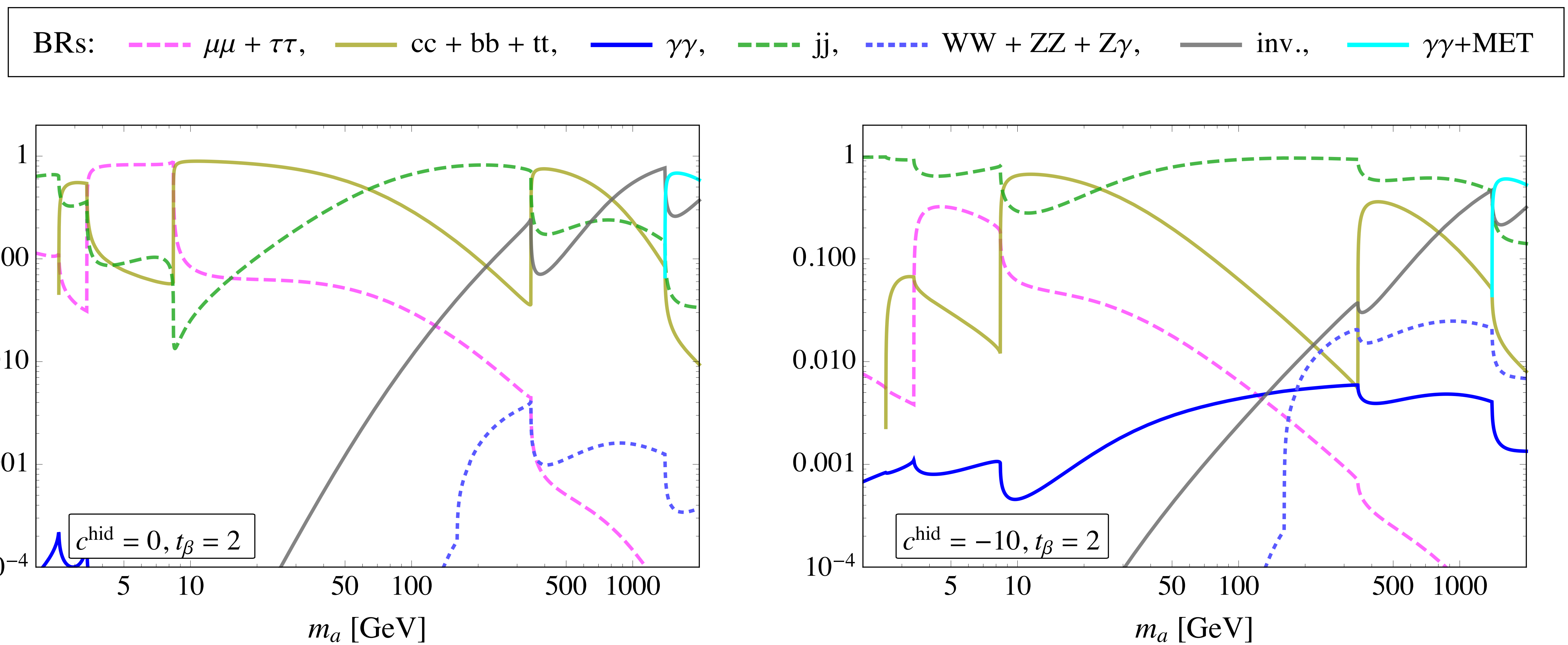


R axion branching ratios

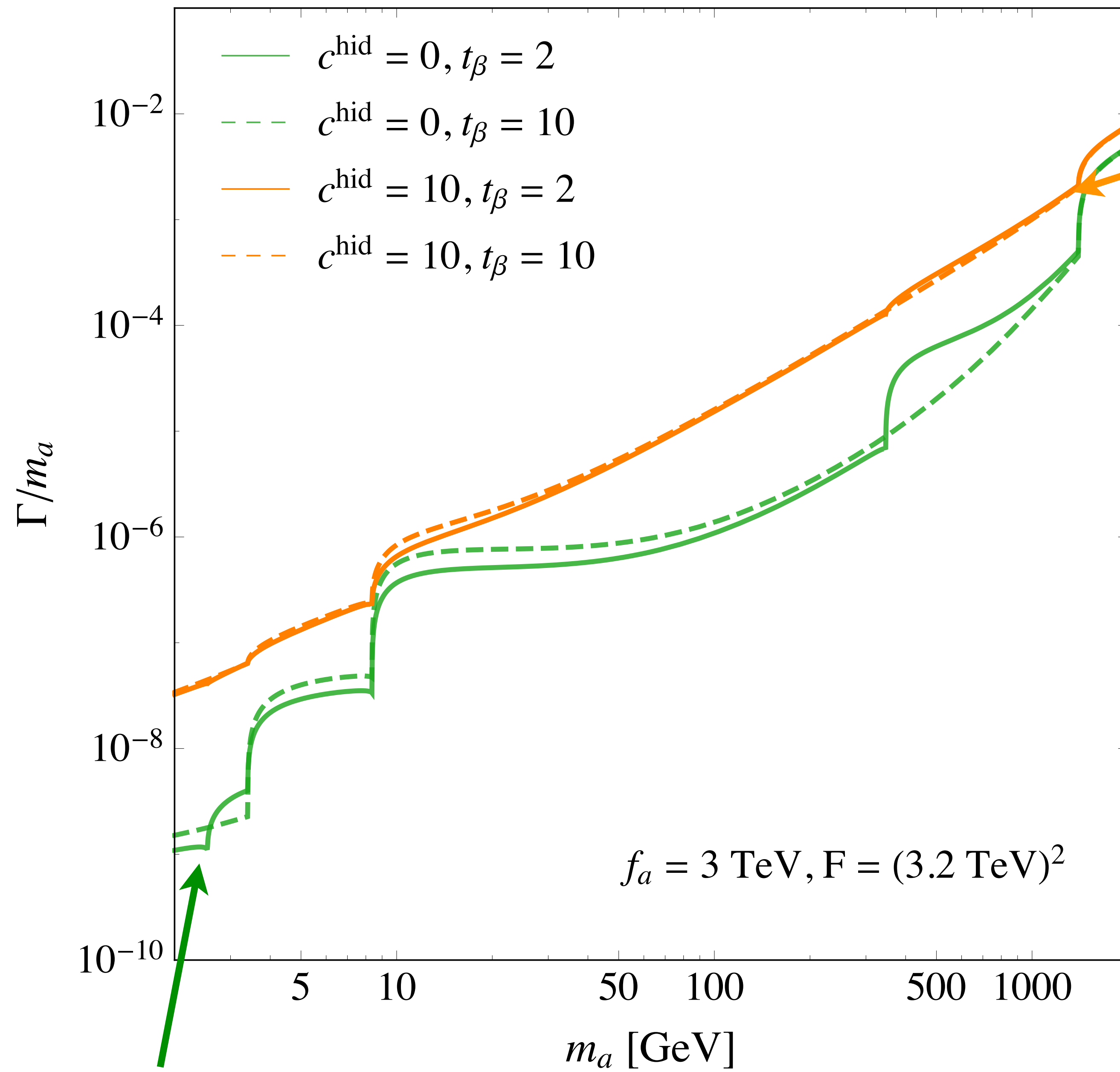
Both plots: $t_\beta = 2$

No anomaly

Large anomalies



R axion total width



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

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)

$c\tau \approx \mu m$

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

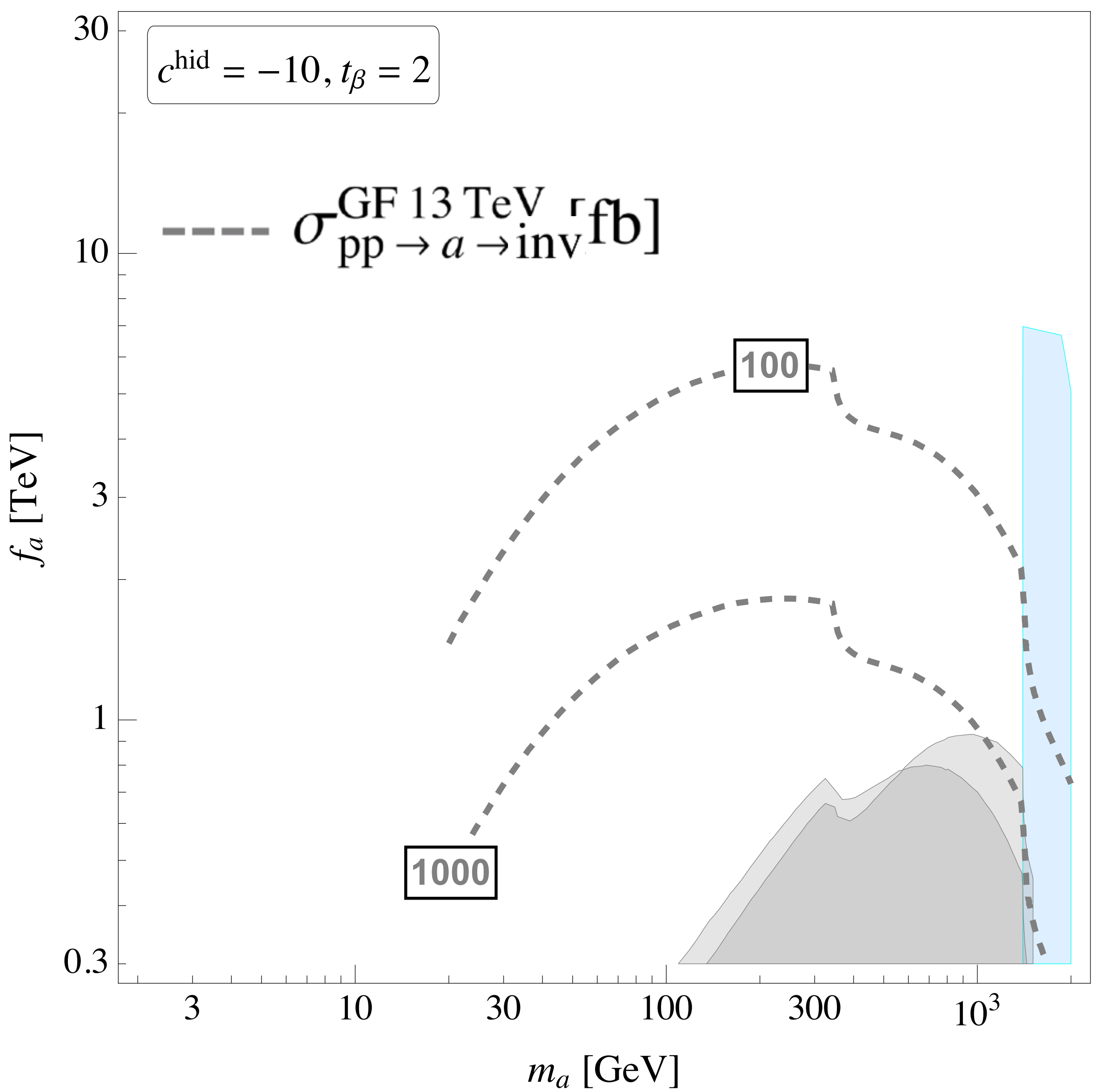
LHC: MET + monojet, MET + diphoton

	$p_T > 250$	$p_T > 500$	$p_T > 700$
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 $\sigma_{pp \to a \to GG}$



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

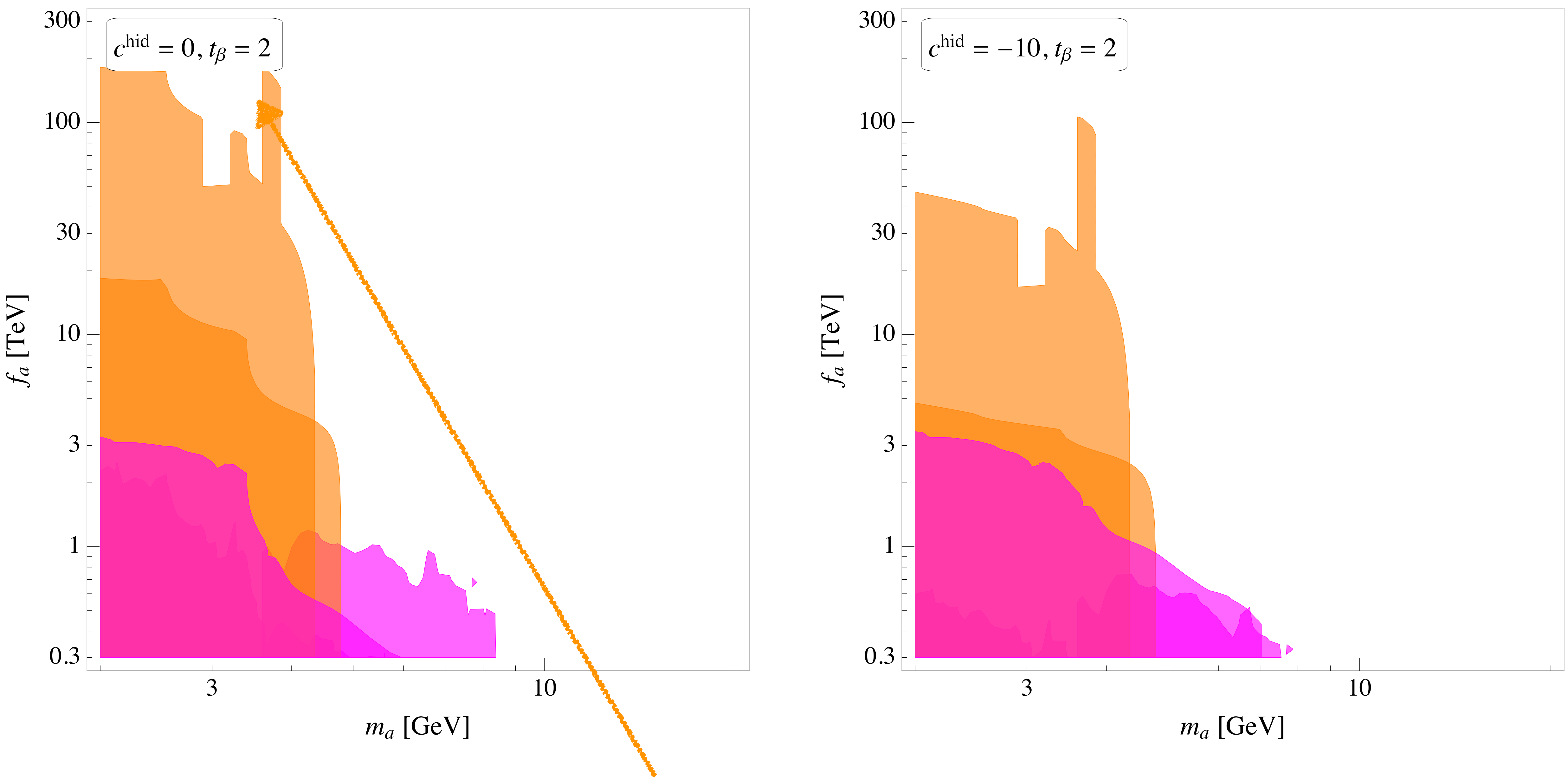
excludes signals down to **0.3 fb** @LHC8

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

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!!

Decays of B and Upsilon

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

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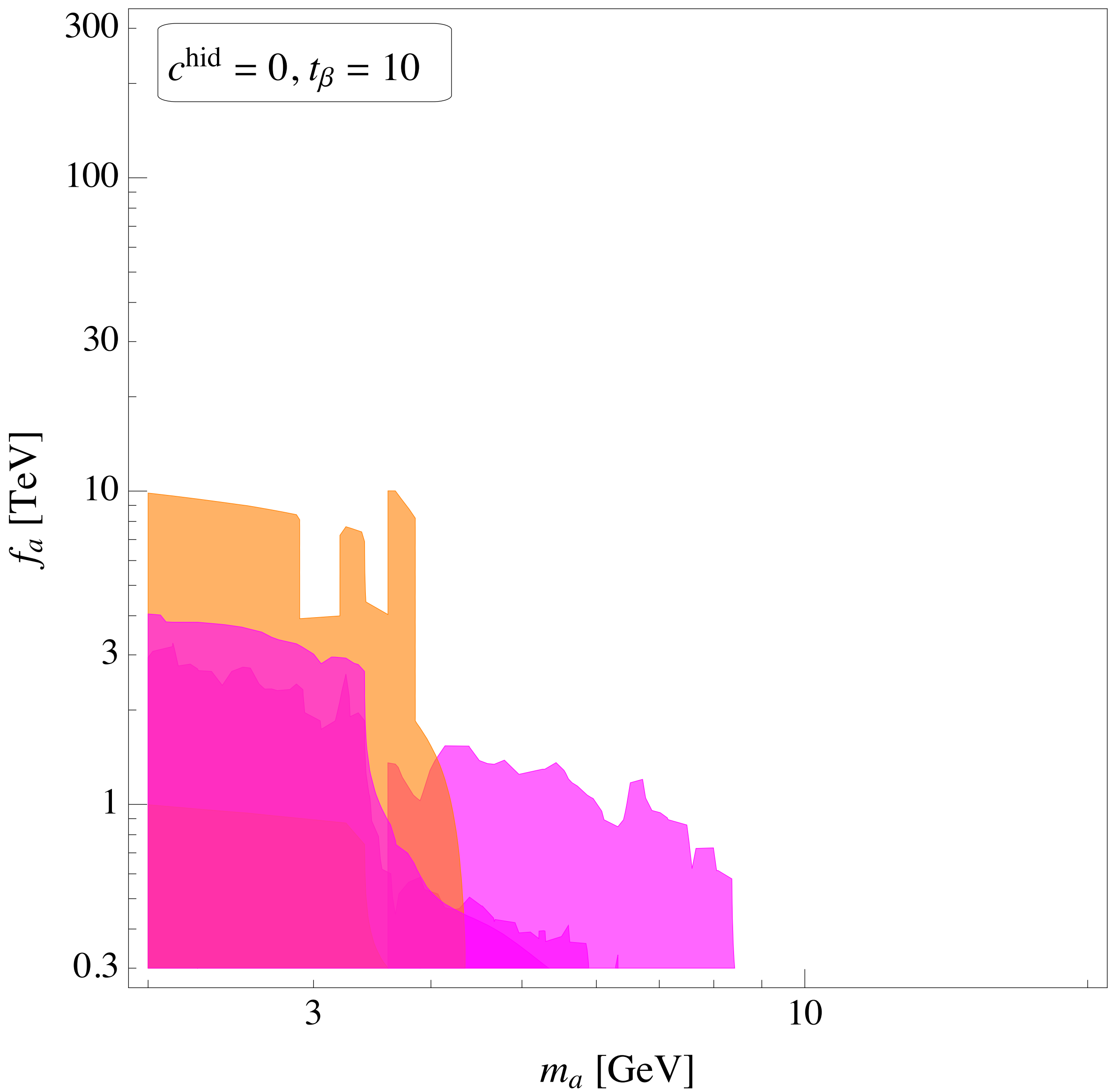
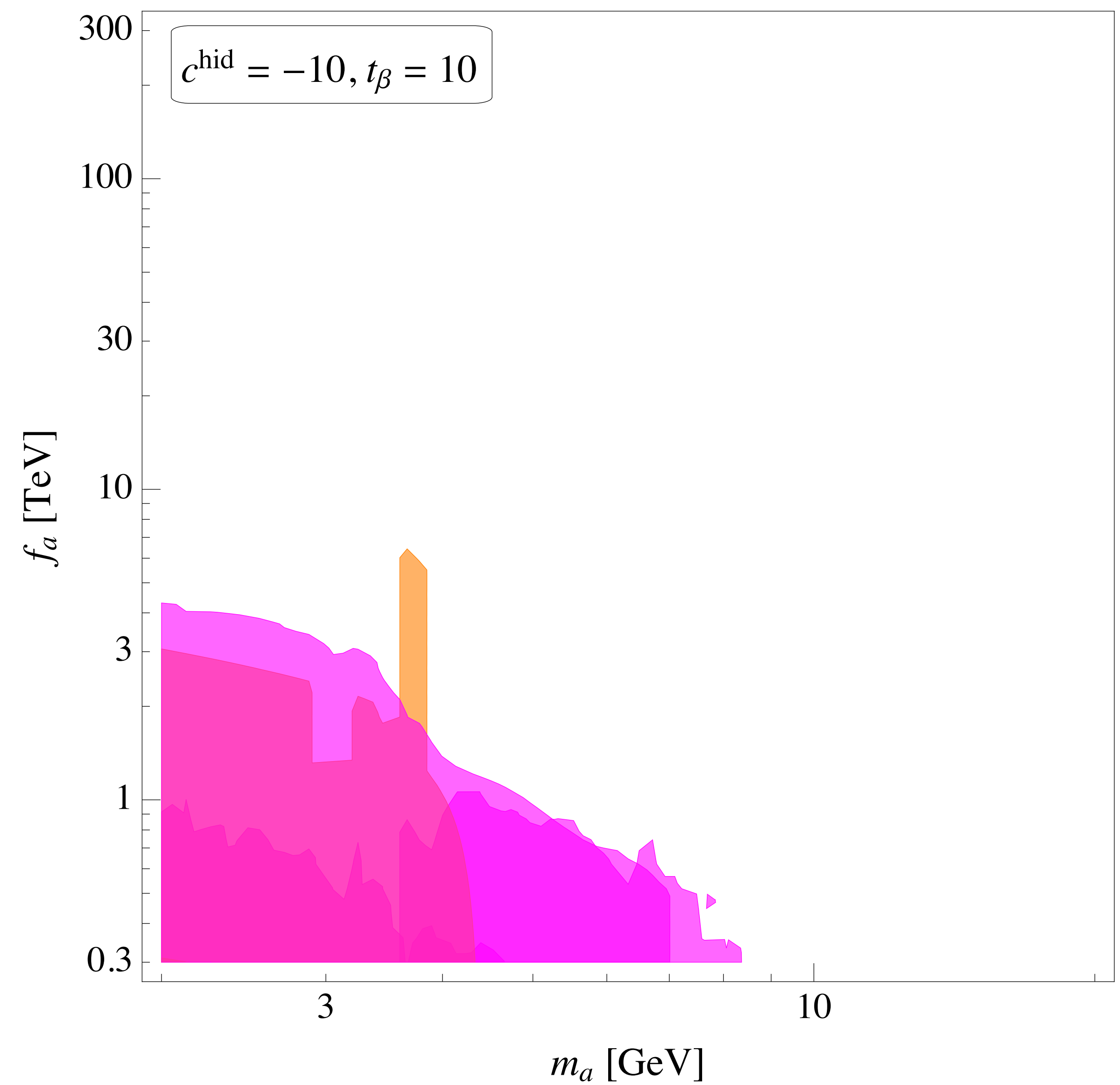




$B \to K^{(*)} a(\mu\mu)$ ~ sensitive to value of t_β

Both disappear for $r_H = 0$

maybe not, work in progress…

More on low-mass $\gamma\gamma$

Low-mass analyses we found

Experiment	Process	Lumi	$\sqrt{s}$	low mass reach	ref.
LEPI	$e^+e^- \to Z \to \gamma a \to \gamma jj$	12 pb^{-1}	Z-pole	10 GeV	[29]
LEPI	$e^+e^- \to Z \to \gamma a \to \gamma\gamma\gamma$	78 pb^{-1}	Z-pole	3 GeV	[30]
LEPII	$e^+e^- \to Z^*, \gamma^* \to \gamma a \to \gamma jj$	9.7,10.1,47.7 pb^{-1}	161,172,183 GeV	60 GeV	[31]
LEPII	$e^+e^- \to Z^*, \gamma^* \to \gamma a \to \gamma\gamma\gamma$	9.7,10.1,47.7 pb^{-1}	161,172,183 GeV	60 GeV	[31, 32]
LEPII	$e^+e^- \to Z^*, \gamma^* \to Z a \to jj\gamma\gamma$	9.7,10.1,47.7 pb^{-1}	161,172,183 GeV	60 GeV	[31]
D0/CDF	$p\bar{p} \to a \to \gamma\gamma$	7/8.2 fb^{-1}	1.96 TeV	100 GeV	[33]
ATLAS	$pp \to a \to \gamma\gamma$	20.3 fb^{-1}	8 TeV	65 GeV	[34]
CMS	$pp \to a \to \gamma\gamma$	19.7 fb^{-1}	8 TeV	80 GeV	[35]
CMS	$pp \to a \to \gamma\gamma$	19.7 fb^{-1}	8 TeV	150 GeV	[36]
CMS	$pp \to a \to \gamma\gamma$	35.9 fb^{-1}	13 TeV	70 GeV	[37]
CMS	$pp \to a \to jj$	18.8 fb^{-1}	8 TeV	500 GeV	[38]
ATLAS	$pp \to a \to jj$	20.3 fb^{-1}	8 TeV	350 GeV	[39]
CMS	$pp \to a \to jj$	12.9 fb^{-1}	13 TeV	600 GeV	[40]
ATLAS	$pp \to a \to jj$	3.4 fb^{-1}	13 TeV	450 GeV	[41]
CMS	$pp \to ja \to jjj$	35.9 fb^{-1}	13 TeV	50 GeV	[42]
UA2	$p\bar{p} \to a \to \gamma\gamma$	13.2 pb^{-1}	0.63 TeV	17.9 GeV	[43]
D0	$p\bar{p} \to a \to \gamma\gamma$	4.2 fb^{-1}	1.96 TeV	8.2 GeV	[44]
CDF	$p\bar{p} \to a \to \gamma\gamma$	5.36 fb^{-1}	1.96 TeV	6.4 GeV	[45, 46]
ATLAS	$pp \to a \to \gamma\gamma$	4.9 fb^{-1}	7 TeV	9.4 GeV	[8]
CMS	$pp \to a \to \gamma\gamma$	5.0 fb^{-1}	7 TeV	14.2 GeV	[10]
ATLAS	$pp \to a \to \gamma\gamma$	20.2 fb^{-1}	8 TeV	13.9 GeV	[9]

Signal efficiencies and cross section

$$\epsilon_S(m_a) = \frac{\sigma_{\gamma\gamma}^{\rm MCcuts}(m_a,s)}{C_s\,\sigma_{\gamma\gamma}^{\rm LO}(m_a,s)}$$

$\sigma_{\gamma\gamma}^{\rm MCcuts}$ Simulated w/Madgraph+Pythia+Delphes matched up to 2 extra jets

$\sigma_{\gamma\gamma}^{\rm LO}$ reproduces up to a constant factor C_s the shape of $\sigma_{\gamma\gamma}^{\rm MCtot}$ for $m_{\gamma\gamma} \gtrsim 60$ GeV (i.e. sufficiently far from the sum of the minimal detector p_T cuts on the photons). A constant factor $C_s \equiv \sigma_{\gamma\gamma}^{\rm MCtot}(s)/\sigma_{\gamma\gamma}^{\rm LO}(s)$ is hence included in Eq. (5) and we obtain $C_{7\,\rm TeV} \simeq C_{8\,\rm TeV} \simeq 0.85$ while $C_{2\,\rm TeV} \simeq 1$ at the Tevatron center of mass energy. The

$$\sigma_{\gamma\gamma}^{\rm th}(m_a,s) = \frac{K_\sigma}{K_g}\cdot\sigma_{\gamma\gamma}^{\rm LO}(m_a,s)\,, \qquad \text{(A1)}$$

where we work in the approximation $\Gamma_{\rm tot} \simeq \Gamma_{gg}$ (which is excellent in the parameter space that we have studied), and where

$$\sigma_{\gamma\gamma}^{\rm LO}(m_a,s) = \frac{1}{m_a s} C_{gg}(m_a^2/s)\cdot\Gamma_{\gamma\gamma}\,, \qquad \text{(A2)}$$

$$C_{gg} = \frac{\pi^2}{8}\int_{m_a^2/s}^1 \frac{dx}{x} f_g(x) f_g\left(\frac{m_a^2}{sx}\right)\,, \qquad \text{(A3)}$$

where $f_g(x)$ is the gluon PDF from the `MSTW2008nnlo68` set [58], where we fix the pdf scale $q = m_a$. We work with

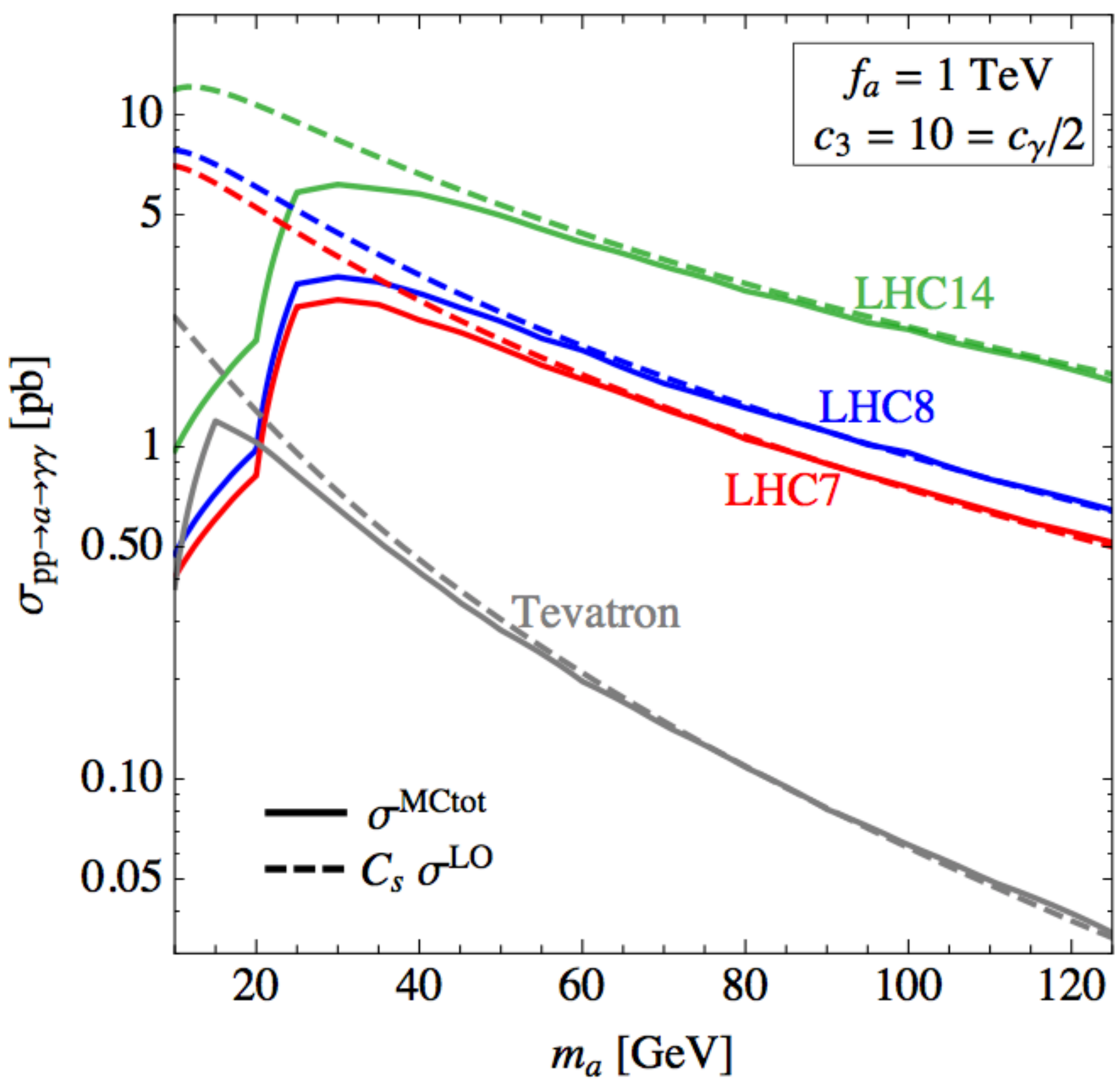
$K_\sigma = 3.7$ from ggHiggs v3.5

Bonvini et al. 2013-2016

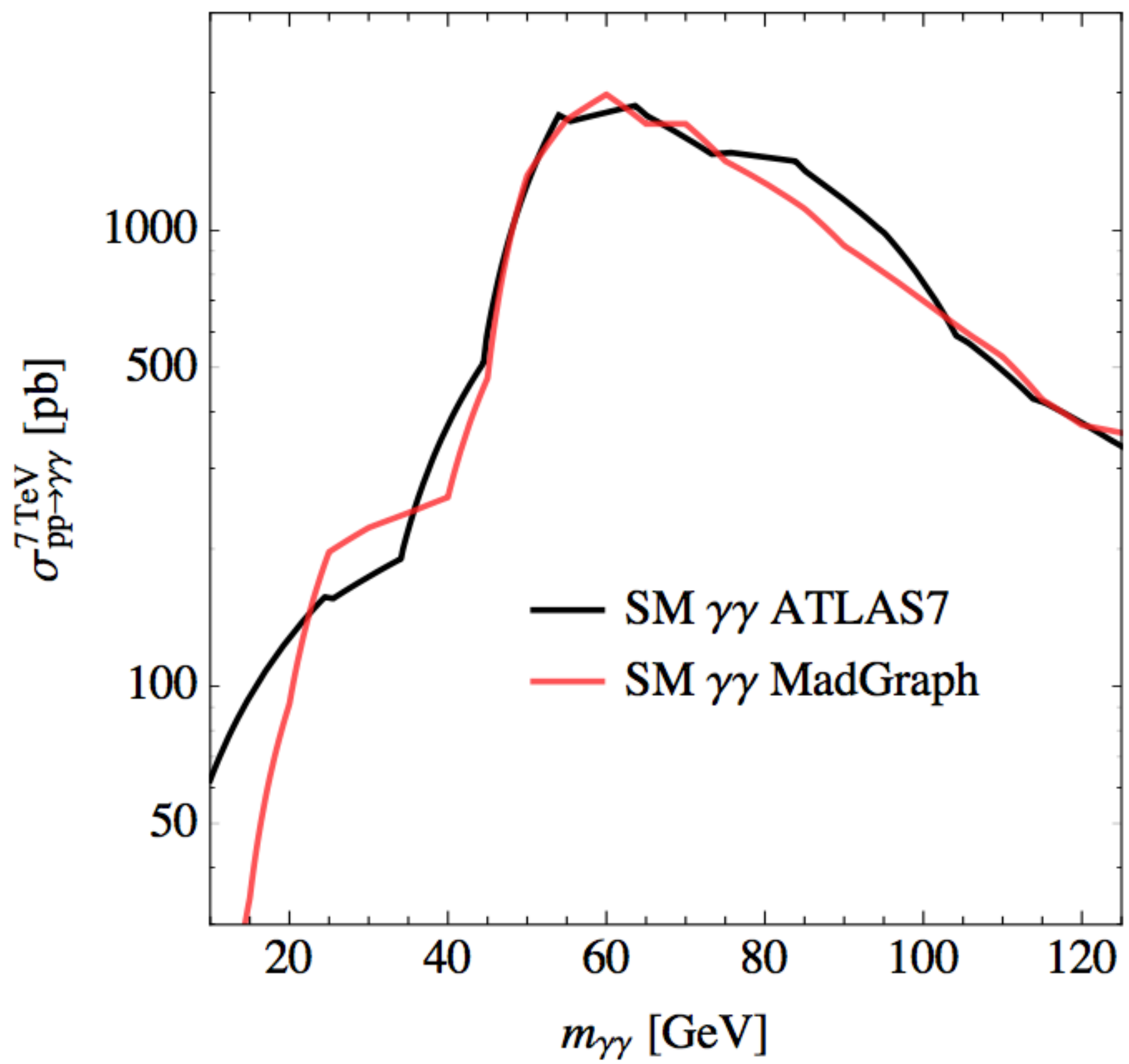
$K_g = 2.1$

m_a in GeV	10	20	30	40	50	60	70	80	90	100	110	120
ϵ_S for $\sigma_{7\rm TeV}$ ATLAS [8]	0	0.008	0.022	0.040	0.137	0.293	0.409	0.465	0.486	0.533	0.619	0.637
ϵ_S for $\sigma_{7\rm TeV}$ CMS [10]	0	0.002	0.010	0.020	0.030	0.058	0.156	0.319	0.424	0.499	0.532	0.570
ϵ_S for $\sigma_{8\rm TeV}$ ATLAS [9]	0	0.0007	0.008	0.014	0.024	0.037	0.071	0.233	0.347	0.419	0.452	0.484
ϵ_S for $\sigma_{2\rm TeV}$ CDF [45, 46]	0.001	0.007	0.026	0.143	0.212	0.241	0.276	0.275	0.283	0.3	0.319	0.327
ϵ_S for $\sigma_{2\rm TeV}$ D0 [44]	0	0.002	0.008	0.018	0.114	0.169	0.208	0.21	0.217	0.234	0.244	0.252

Validation

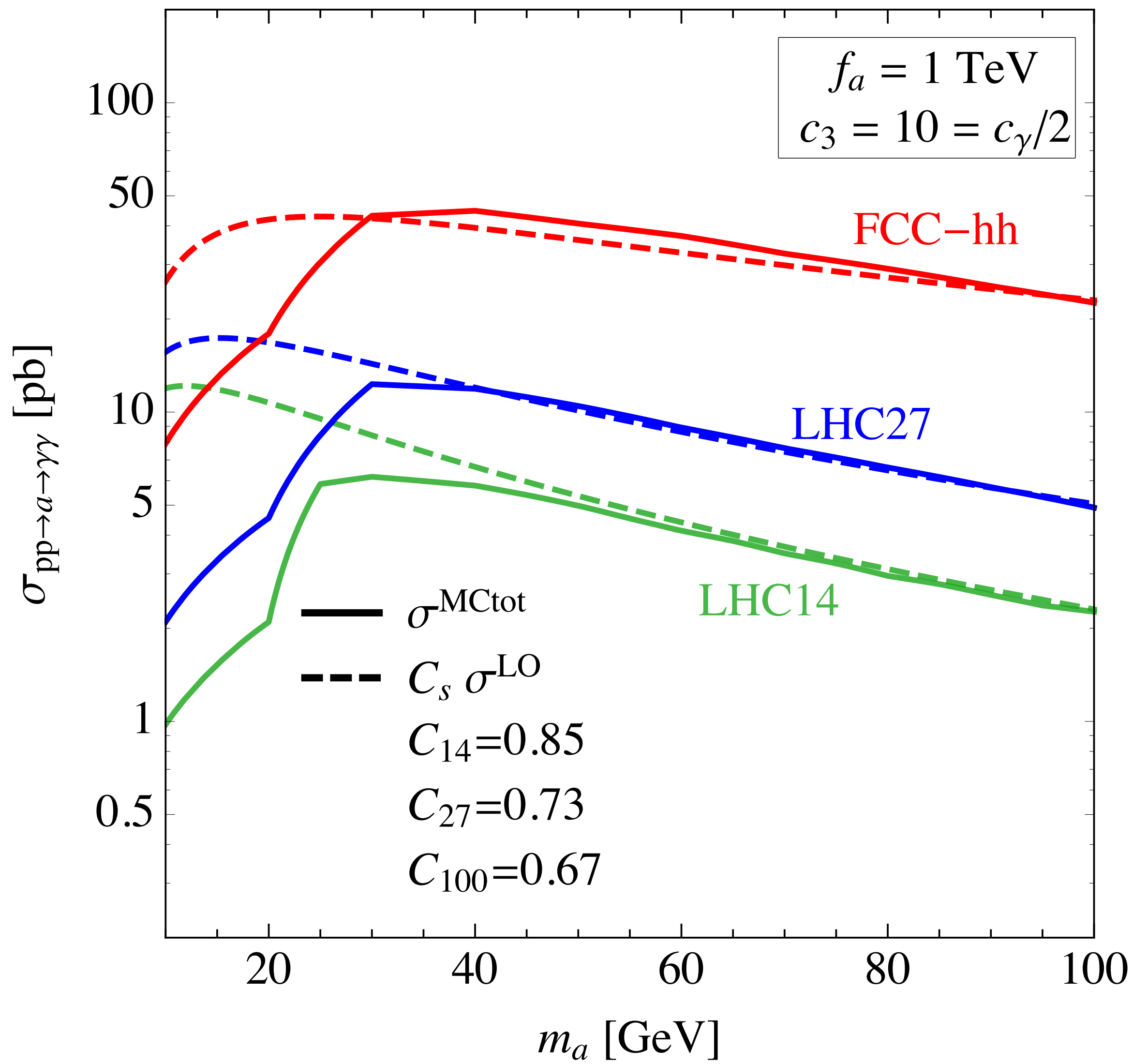


$f_a = 1$ TeV
$c_3 = 10 = c_\gamma/2$
LHC14
LHC8
LHC7
Tevatron
$\sigma^{\rm MCtot}$
$C_s\, \sigma^{\rm LO}$
$\sigma_{{\rm pp}\to a\to\gamma\gamma}$ [pb]
m_a [GeV]



SM $\gamma\gamma$ ATLAS7
SM $\gamma\gamma$ MadGraph
$\sigma^{7\,{\rm TeV}}_{{\rm pp}\to\gamma\gamma}$ [pb]
$m_{\gamma\gamma}$ [GeV]

Validation



f_a = 1 TeV
$c_3 = 10 = c_\gamma/2$
FCC−hh
LHC27
LHC14
$\sigma^{\rm MCtot}$
$C_s\ \sigma^{\rm LO}$
C_{14}=0.85
C_{27}=0.73
C_{100}=0.67
$\sigma_{pp\to a\to\gamma\gamma}$ [pb]
m_a [GeV]
100
50
10
5
1
0.5
20
40
60
80
100

Interplay of LHC and Tevatron