

# New LHC Searches for Resonances of 1 to 100 GeV

Filippo Sala

DESY Hamburg



# THANK YOU!



# BSM at the LHC?

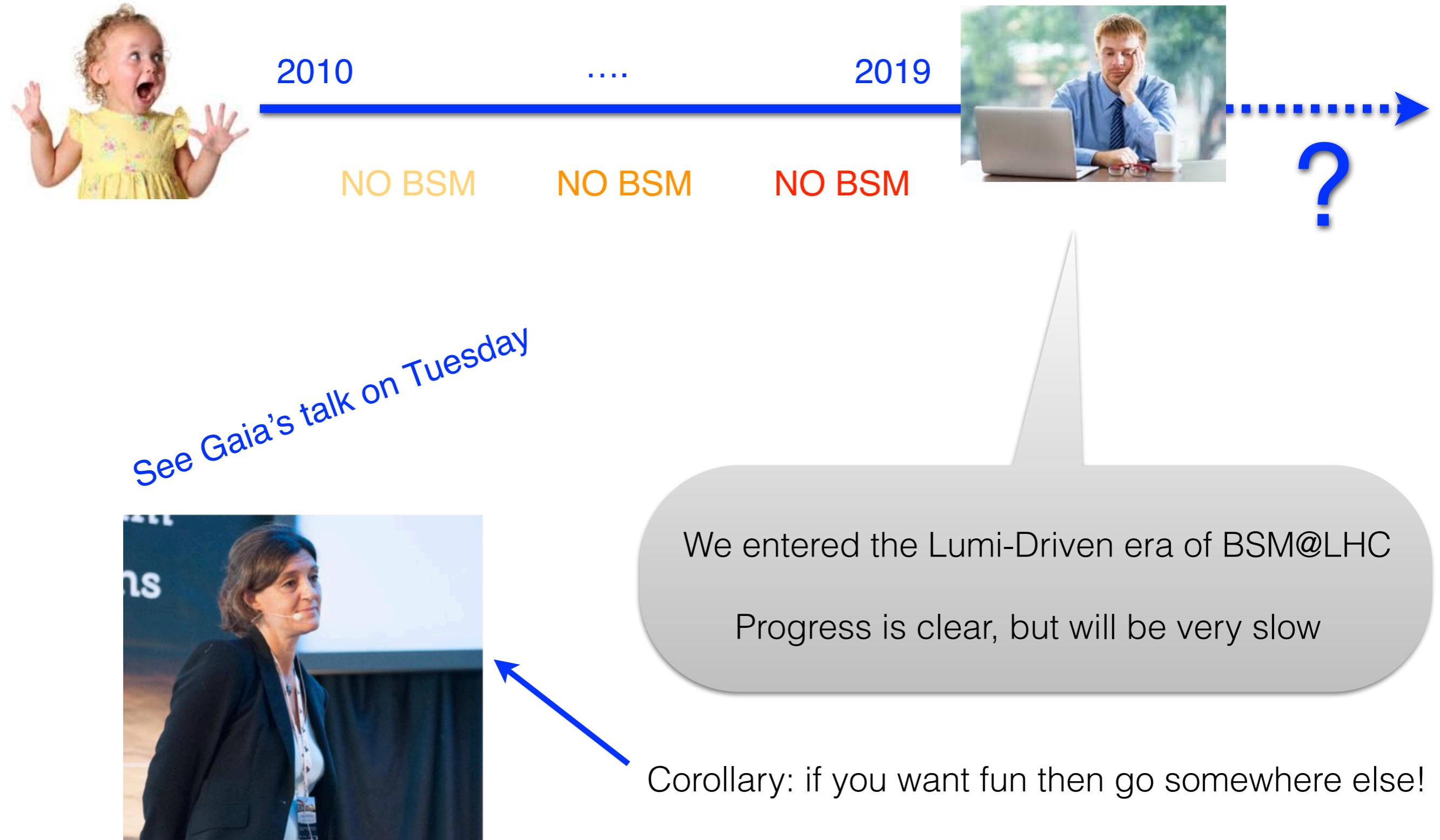


We entered the Lumi-Driven era of BSM@LHC

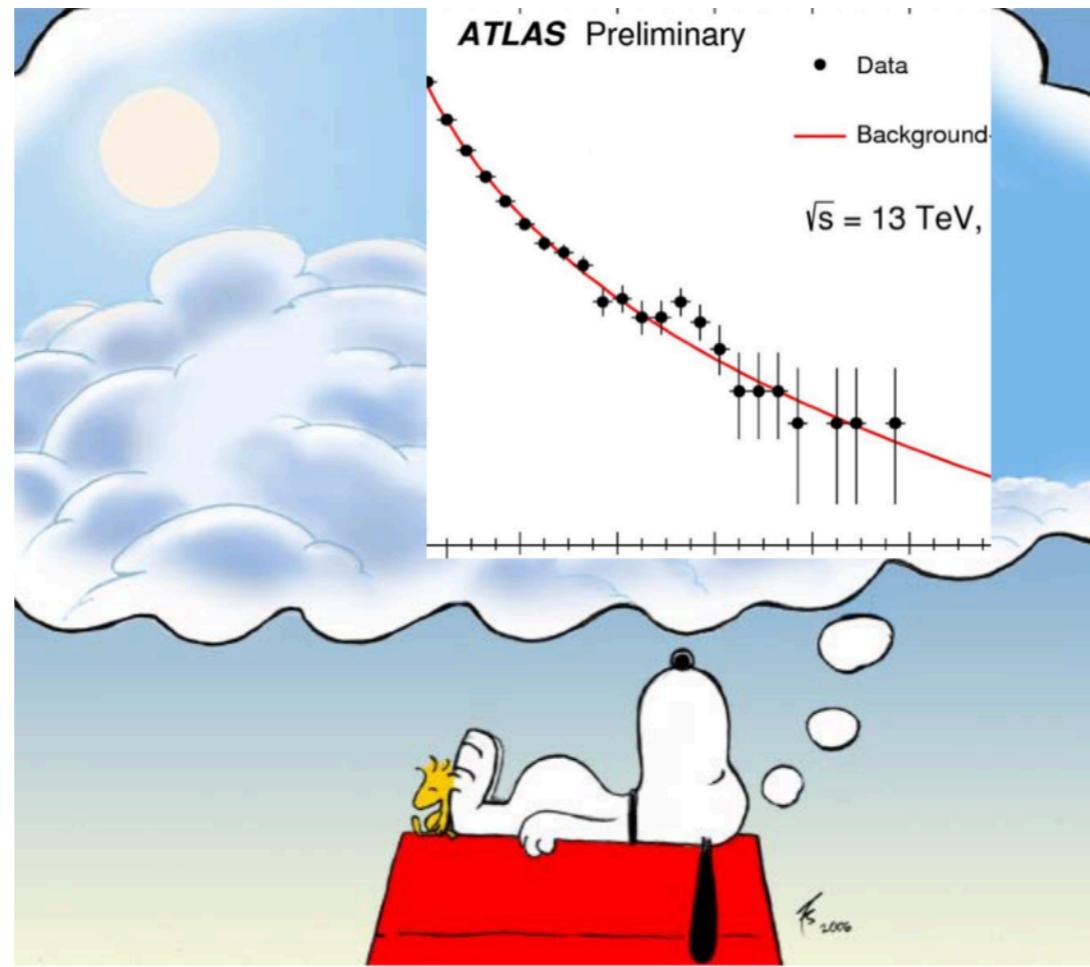
Progress is clear, but will be very slow

Corollary: if you want fun then go somewhere else!

# BSM at the LHC?



# An LHC Dream



(Most?) **Solid discovery method** at colliders: Look for peaks in invariant mass distributions

Diphotons

Dijets

Dibosons ( $W,Z$ )

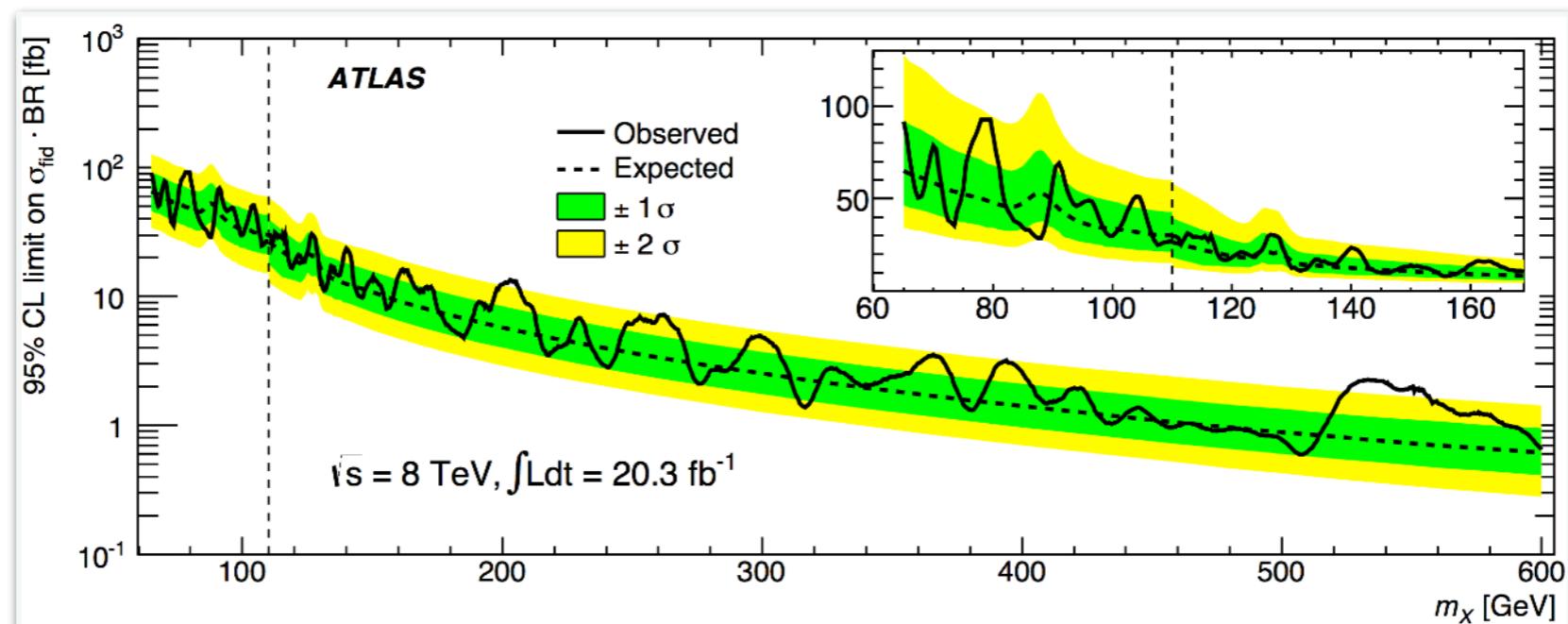
Dileptons

Ditop

DiHiggs

# BSM resonances: where are we looking?

→  $M_{\gamma\gamma, \tau\tau, \dots} > O(100) \text{ GeV}$



→ Or from other particle's decays

$$h \rightarrow aa \rightarrow 2\mu 2b, 2\gamma 2j, \dots$$

Verena's talk on Monday



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$h \rightarrow a\gamma, \gamma\gamma, \gamma Z, Z^0 \nu\bar{\nu}, 2\mu 2b, 2\gamma 2j, \dots$

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# Novel Light Particle Searches

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Why?

Today

Tomorrow (?)

# Novel Light Particle Searches

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## Why?

# Why low-mass resonances?

LHC is pushing **solutions to SM problems** (hierarchy, flavour, ...) to  $M_{\text{BSM}} \gg \text{TeV}$

Richer sectors could exist there

**How to test them?**

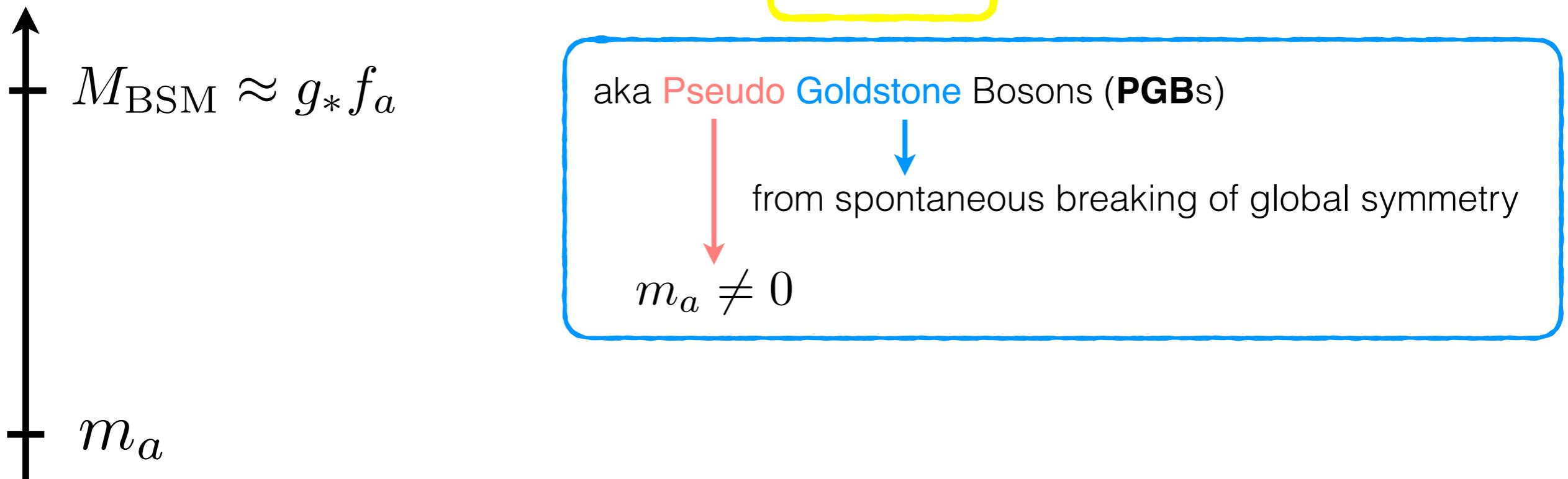
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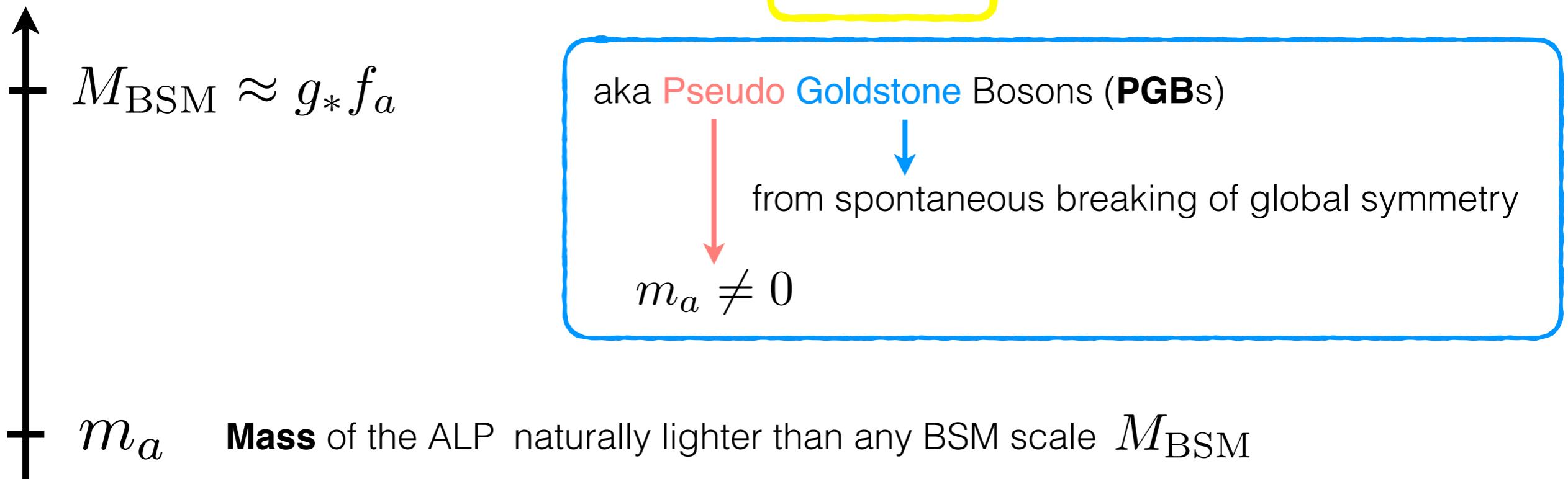
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$f_a$  decay constant controls ALP **Couplings**

$$\text{e.g. } \mathcal{L}_{\text{int}} = \frac{a}{4\pi f_a} [\alpha_s c_3 G \tilde{G} + \alpha_2 c_2 W \tilde{W} + \alpha_1 c_1 B \tilde{B}]$$

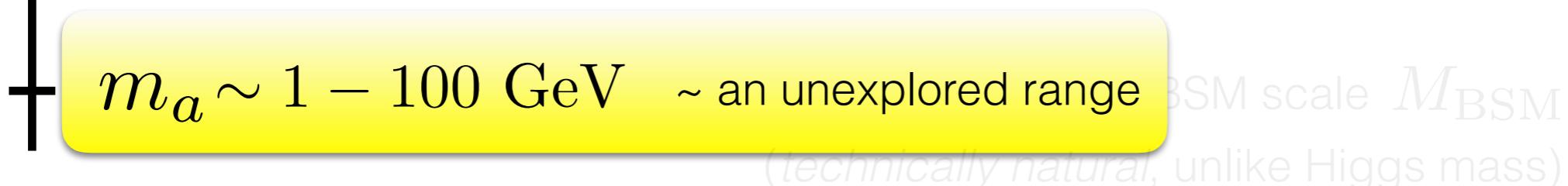
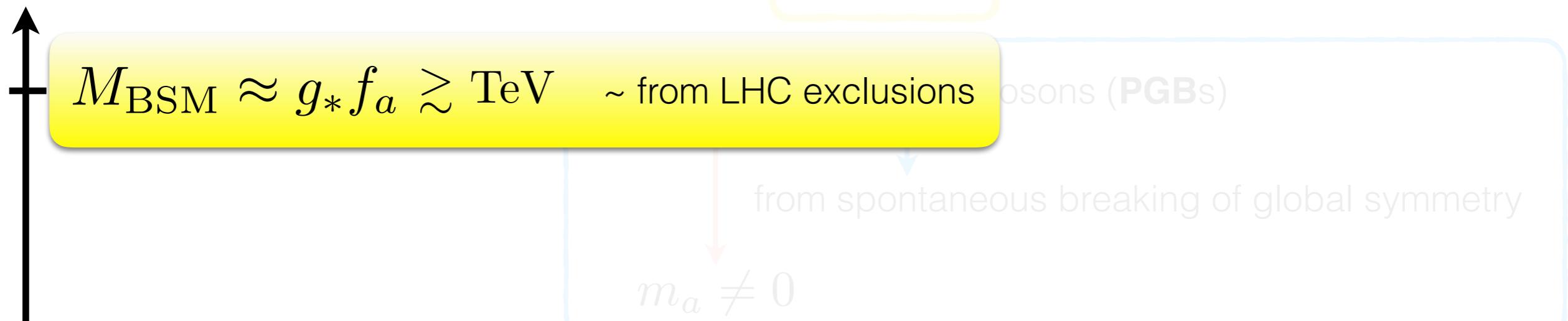
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$f_a \sim 0.1 - 100 \text{ TeV}$  of interest for colliders (see rest of talk)

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Example: SO(6)/SO(5) has 5 PGB, the Higgs and a singlet

$$m_\eta \sim c \times m_h \times \frac{f}{v} \sim 5 - 500 \text{ GeV} \times \sqrt{\frac{0.05}{(v/f)^2}}$$

model-dependent, see e.g. Gripaios+ 0902.1483, Redi Tesi 1205.0232

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## FROM SUPERSYMMETRY

Nelson Seiberg 1994, Colliders  $\rightarrow$  Spontaneously broken  $U(1)_R \rightarrow$  R-axion  $a$

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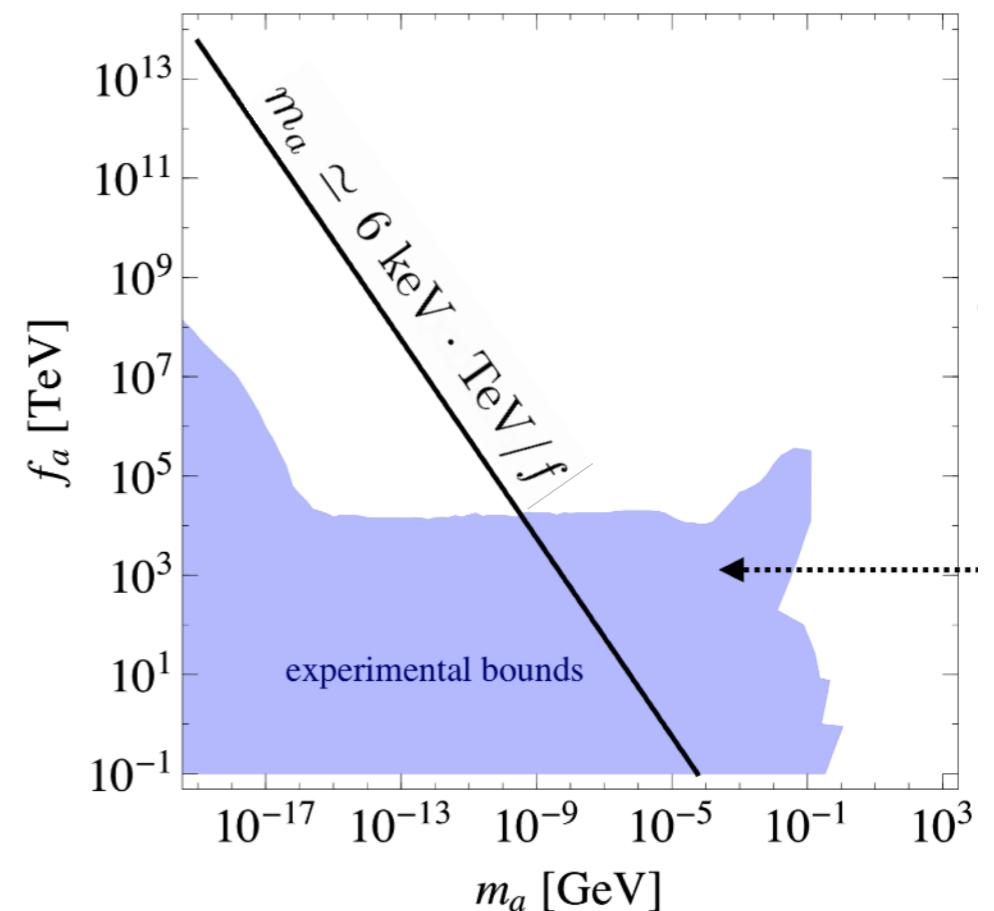
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Bellazzini Mariotti Redigolo FS Serra 2017  $\rightarrow$  **Could be first sign of SUSY at colliders!**

# Heavy QCD axion

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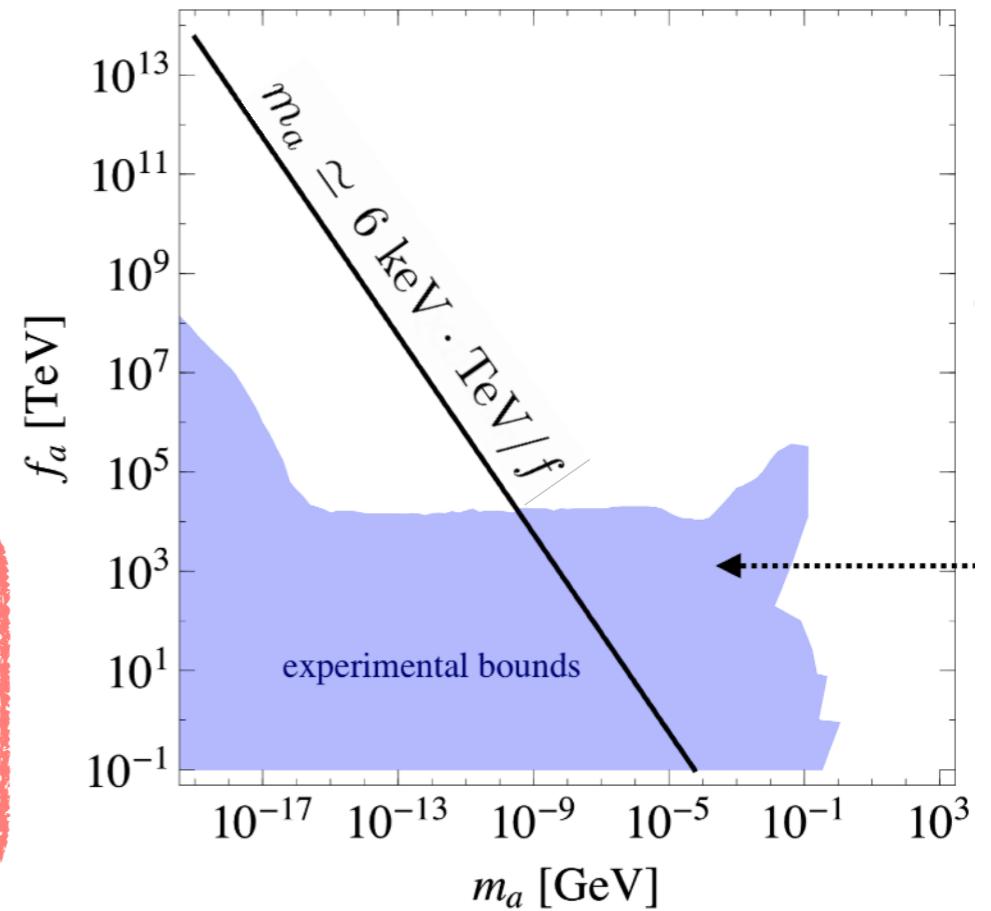
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but: “**Axion Quality**” problem spoils solution to strong CP

$$\Delta V_{\text{PQ}} = \lambda_\Delta \frac{\Phi^\Delta}{\Lambda_{\text{UV}}^{\Delta-4}} + \text{h.c.} \quad \Phi = \frac{f_a}{\sqrt{2}} e^{ia/f_a}$$

Kamionkowski March-Russel hep-th/9202003, ...



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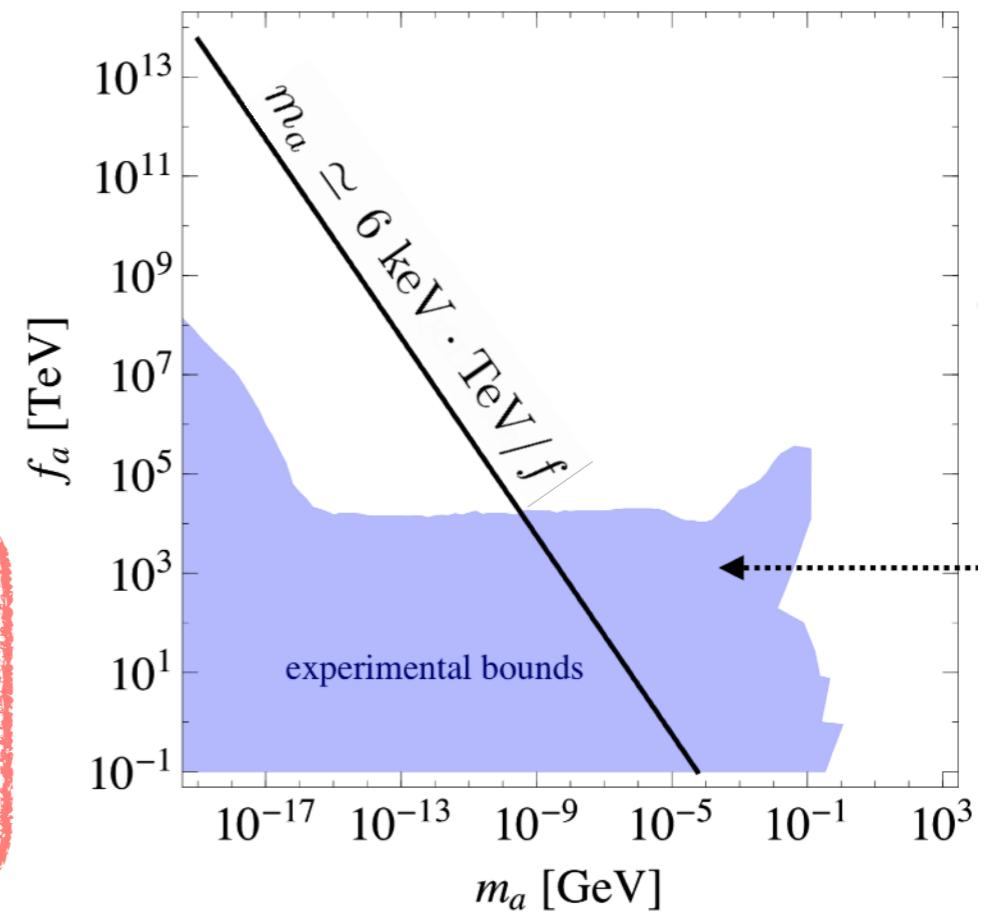
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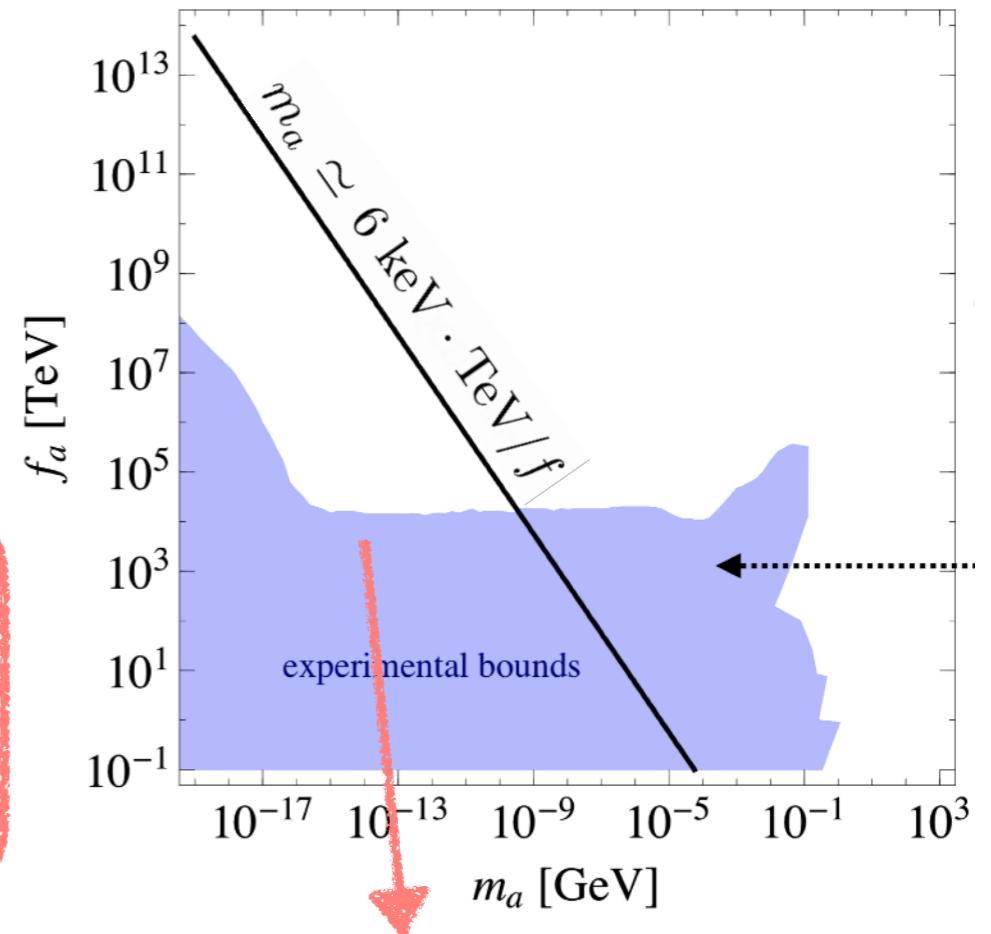
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1. Push  $\Delta$  to much larger values  
... Redi Sato 1602.05427  
Duerr+ 1712.01841
2. Model building for smaller  $f_a$   
and larger  $m_a$

Rubakov hep-ph/9703409 .....  
M.K Gaillard+ 1805.06465

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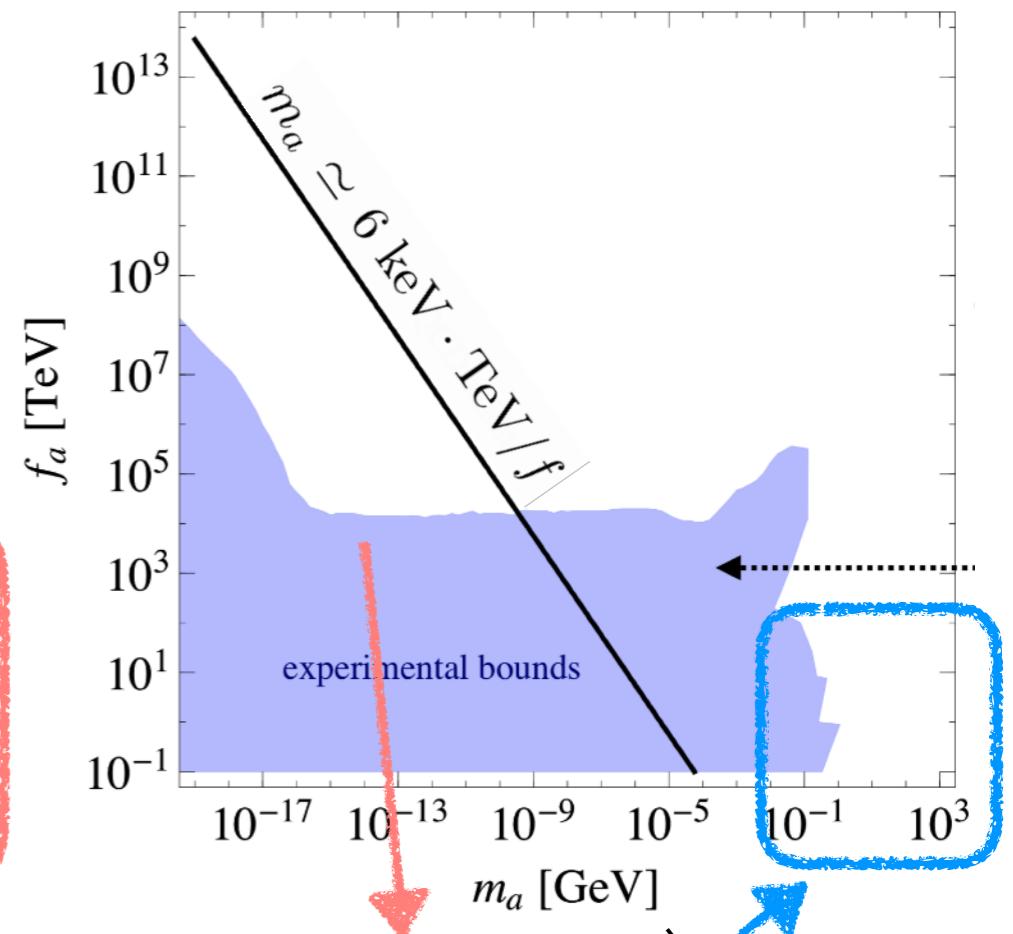
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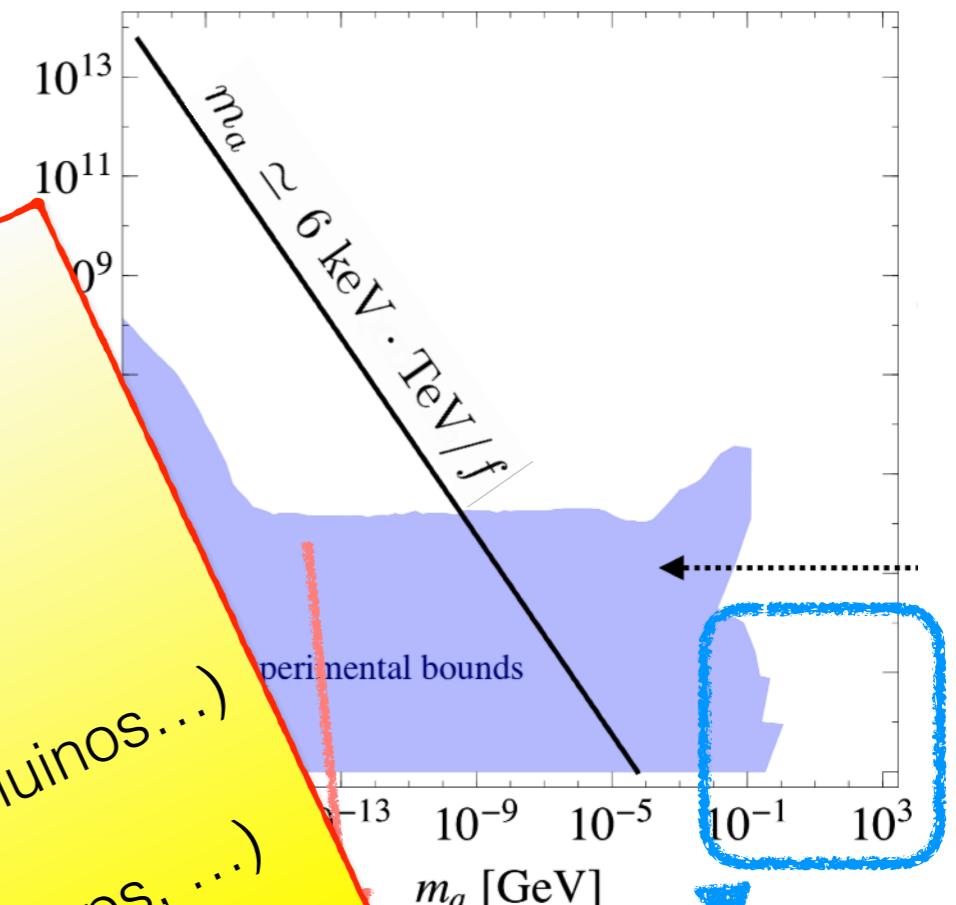
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but: “**Axion Quality**” problem

$$\Delta V_{\text{PQ}} = \lambda_\Delta \frac{\Phi^\Delta}{\Lambda}$$

N.B. coupling to gluons  
**mandatory in QCD axion**  
**natural in SUSY** (e.g. loops of tops, gluinos...)  
could be there **in CHM** (e.g. loops of tops, ...)



strong CP solved here!

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# Dark Matter via the ALP portal

$$\mathcal{L}_{\text{int}} = \frac{a}{4\pi f_a} \alpha_s c_3 G \tilde{G} + g_* \Phi \psi \tilde{\psi}$$

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Observed relic abundance for

$$m_\psi \simeq 4.6 \text{ TeV} \frac{c_3}{10} \left( \frac{g_*}{3} \right)^2 \Rightarrow f \simeq 1.9 \text{ TeV} \frac{3}{g_*}$$

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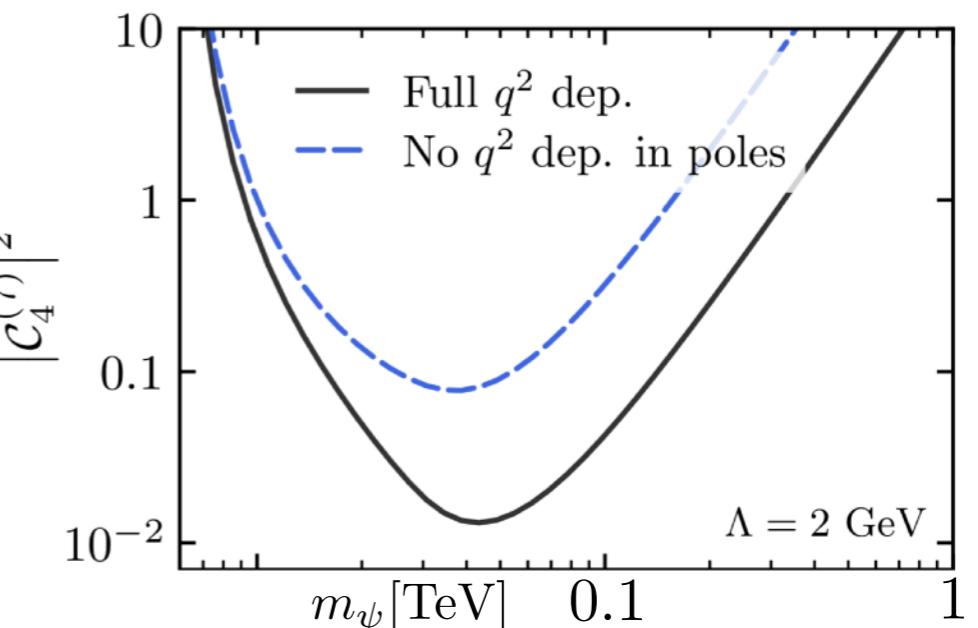
**Direct Detection** completely irrelevant

**Indirect Detection** not yet competitive  
(caveat: should compute Sommerfeld)

**Colliders** are needed to test this scenario!

$$\mathcal{Q}_4^{(7)} = \frac{\alpha_s}{8\pi} (\bar{\chi} i \gamma_5 \chi) G^{a\mu\nu} \tilde{G}_{\mu\nu}^a$$

Bishara+ 1707.06998



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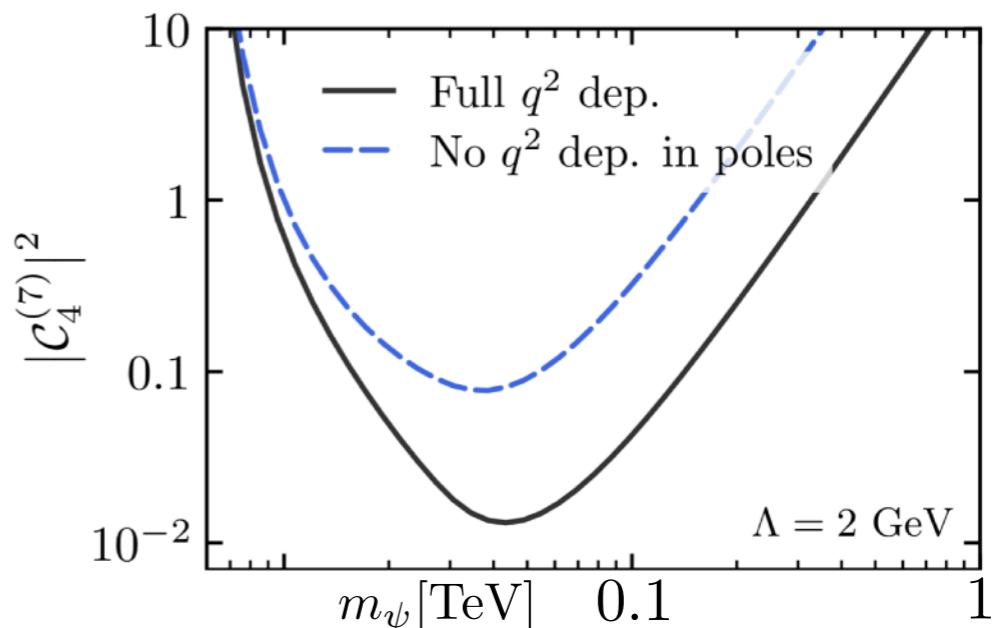
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Bishara+ 1707.06998



**Low energy SUSY breaking in gauge mediation**

Gravitino cannot be DM

DM candidates in messenger/breaking sectors  
Dimopoulos Giudice Pomarol hep-ph/9607225

R-axion as natural mediator!  
Mardon Nomura Thaler 0905.3749

# Novel Light Particle Searches

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Why?

Today

Tomorrow (?)

# Novel Light Particle Searches

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Today

# ALPs with Fermion & Higgs Couplings

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**Higher Dimension!**

Some pre-2017 refs:

Jaeckel Jankowiak Spannowsky 1212.3620

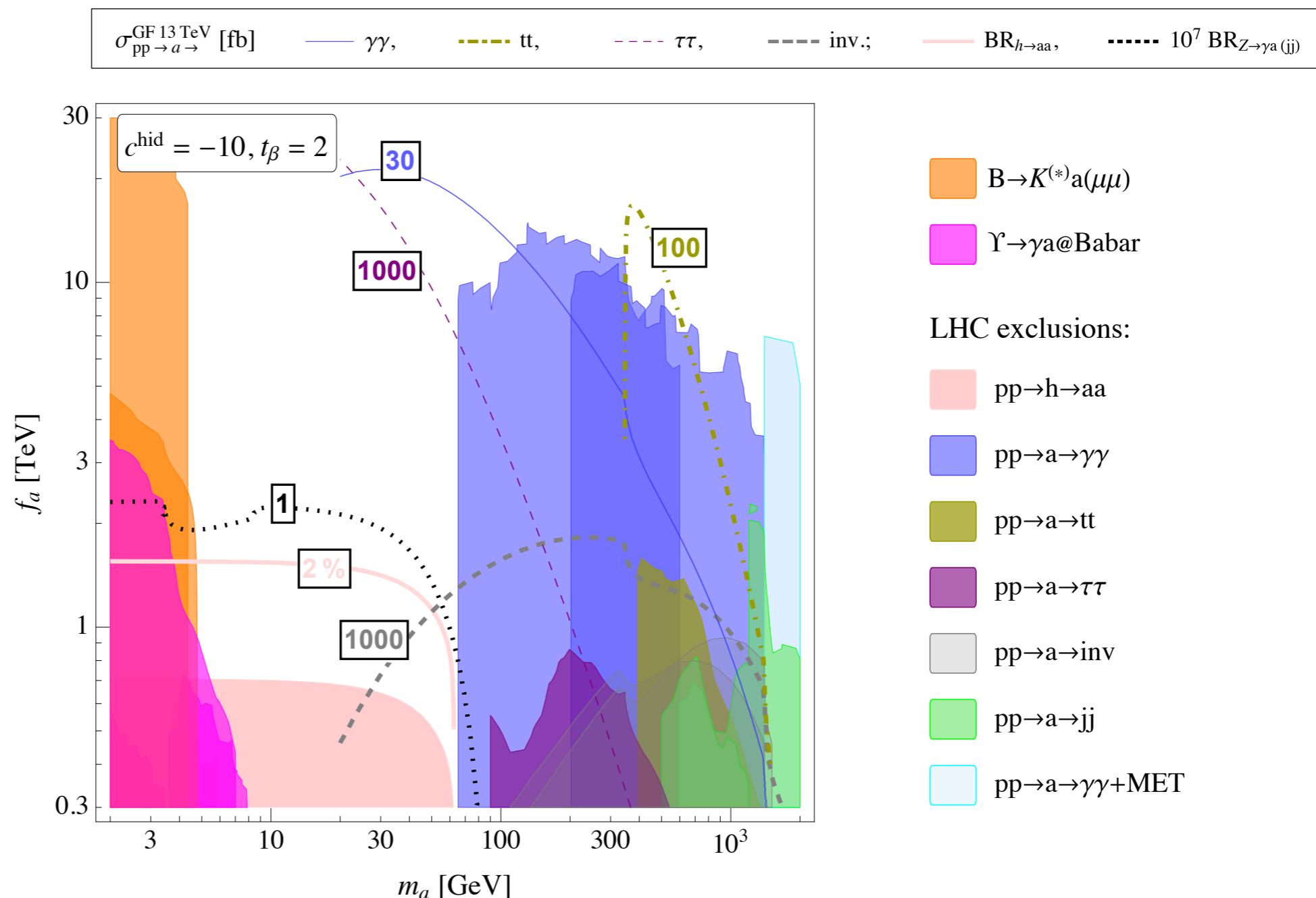
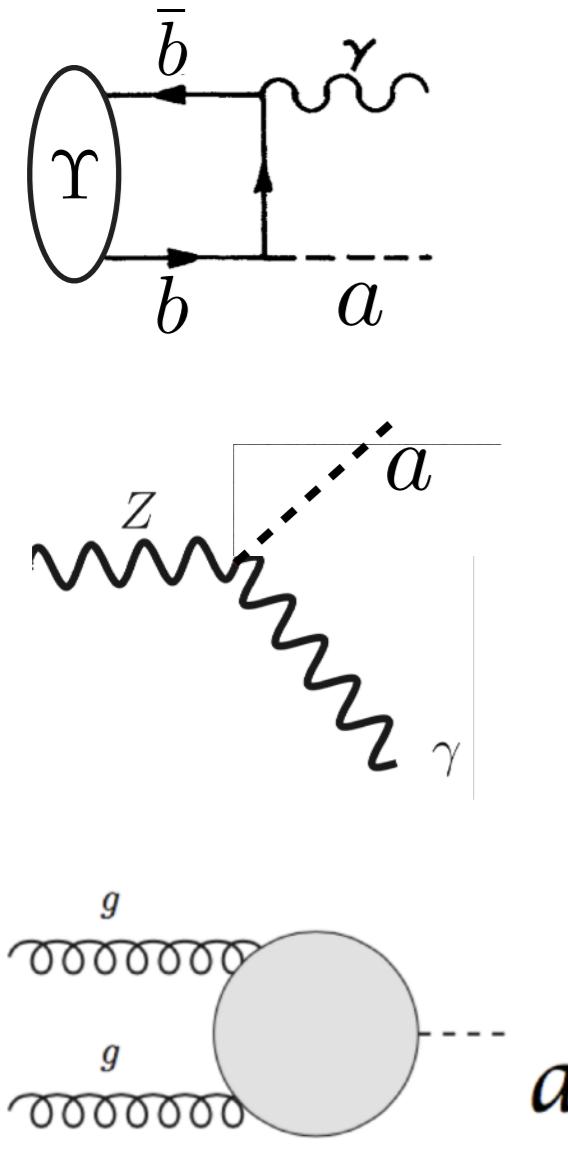
Mimasu Sanz 1409.4792

Bauer Neubert Thamm 1708.00443

...

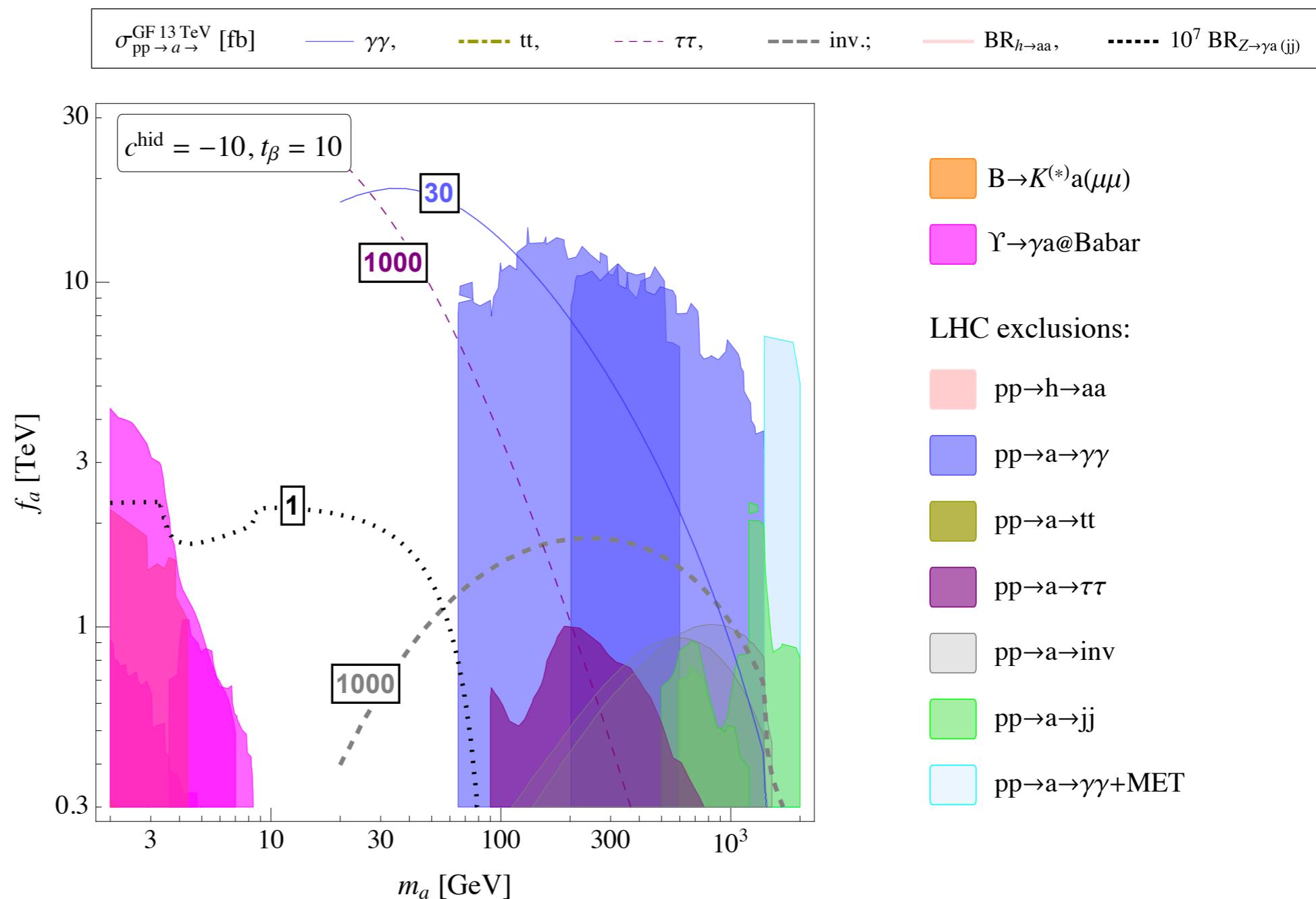
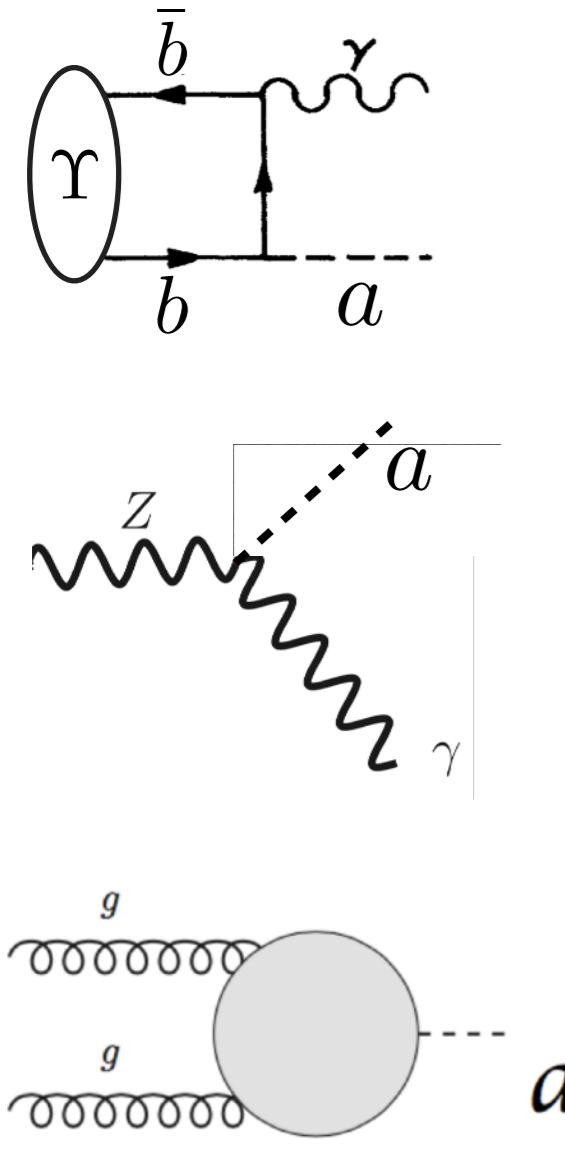
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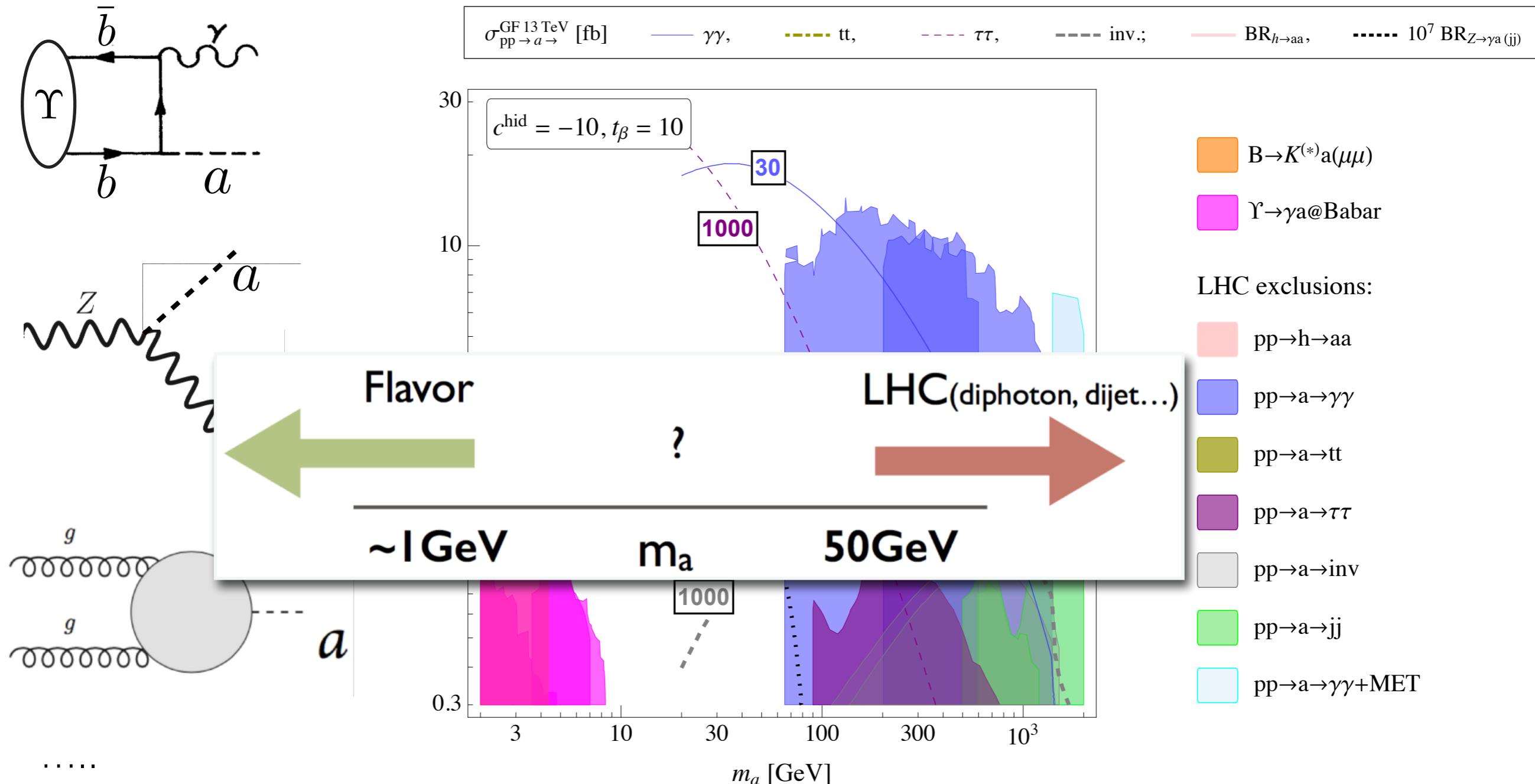
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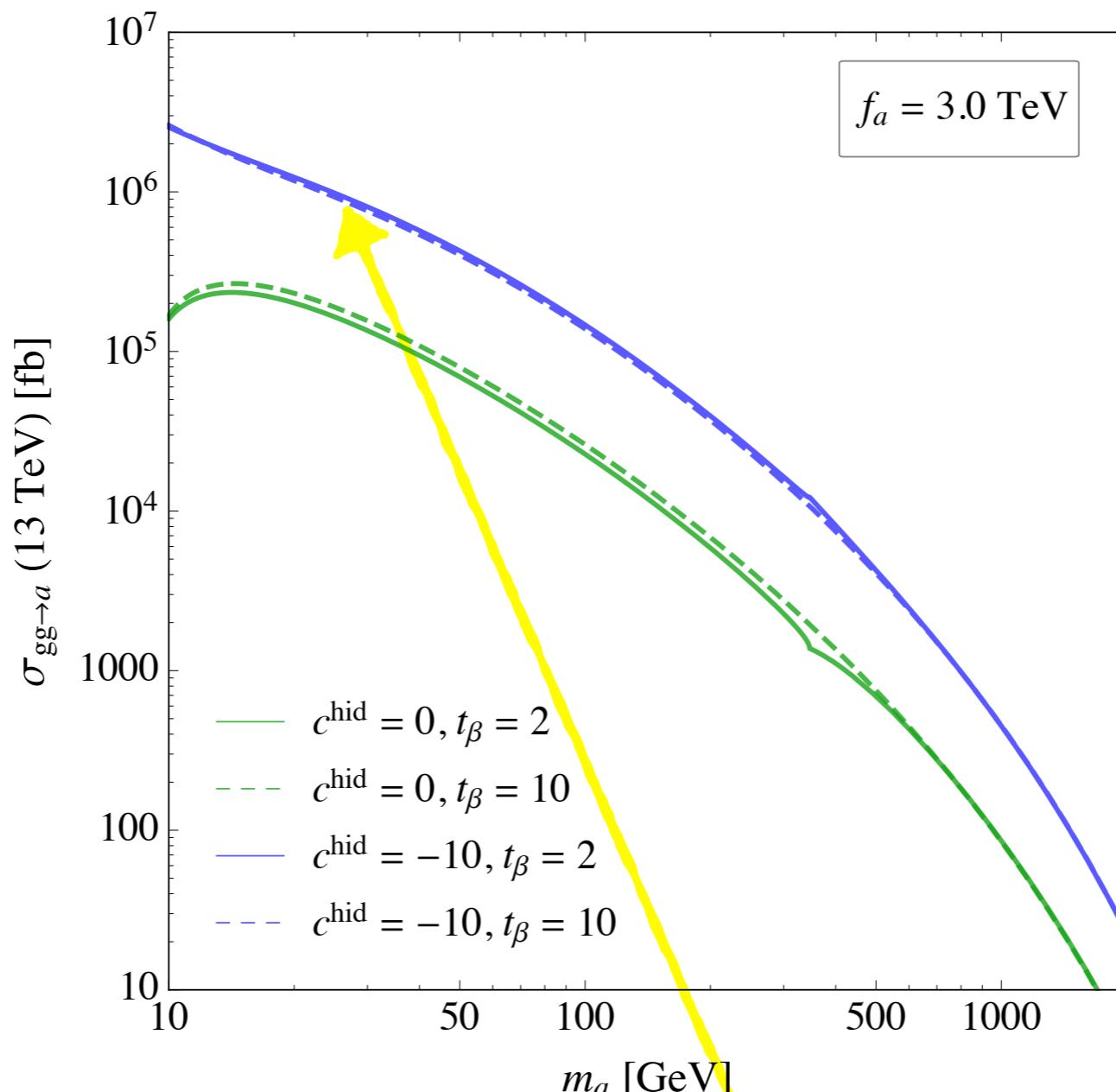
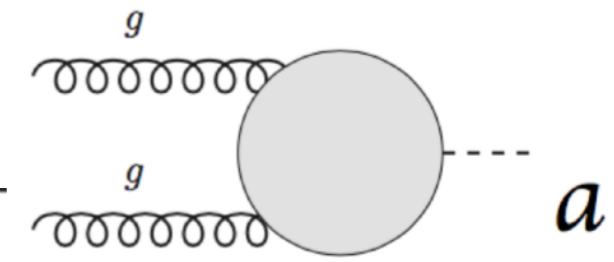


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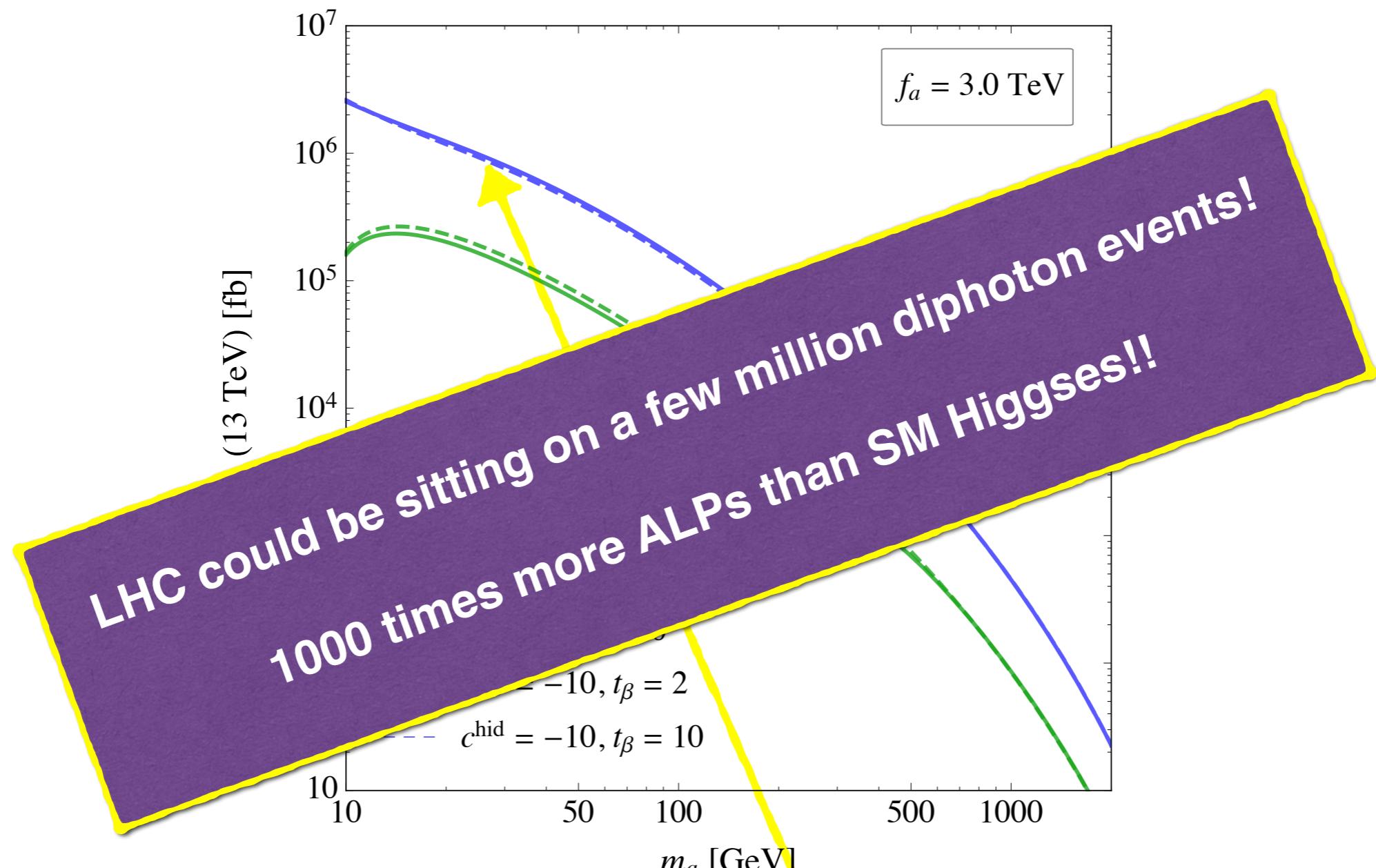
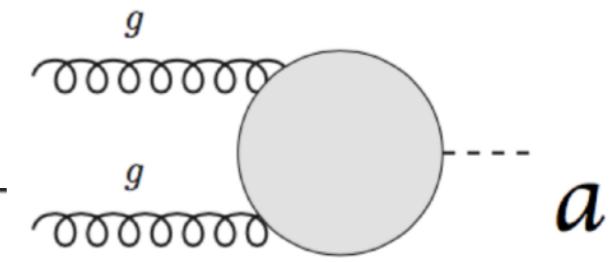


# ALP production at the LHC



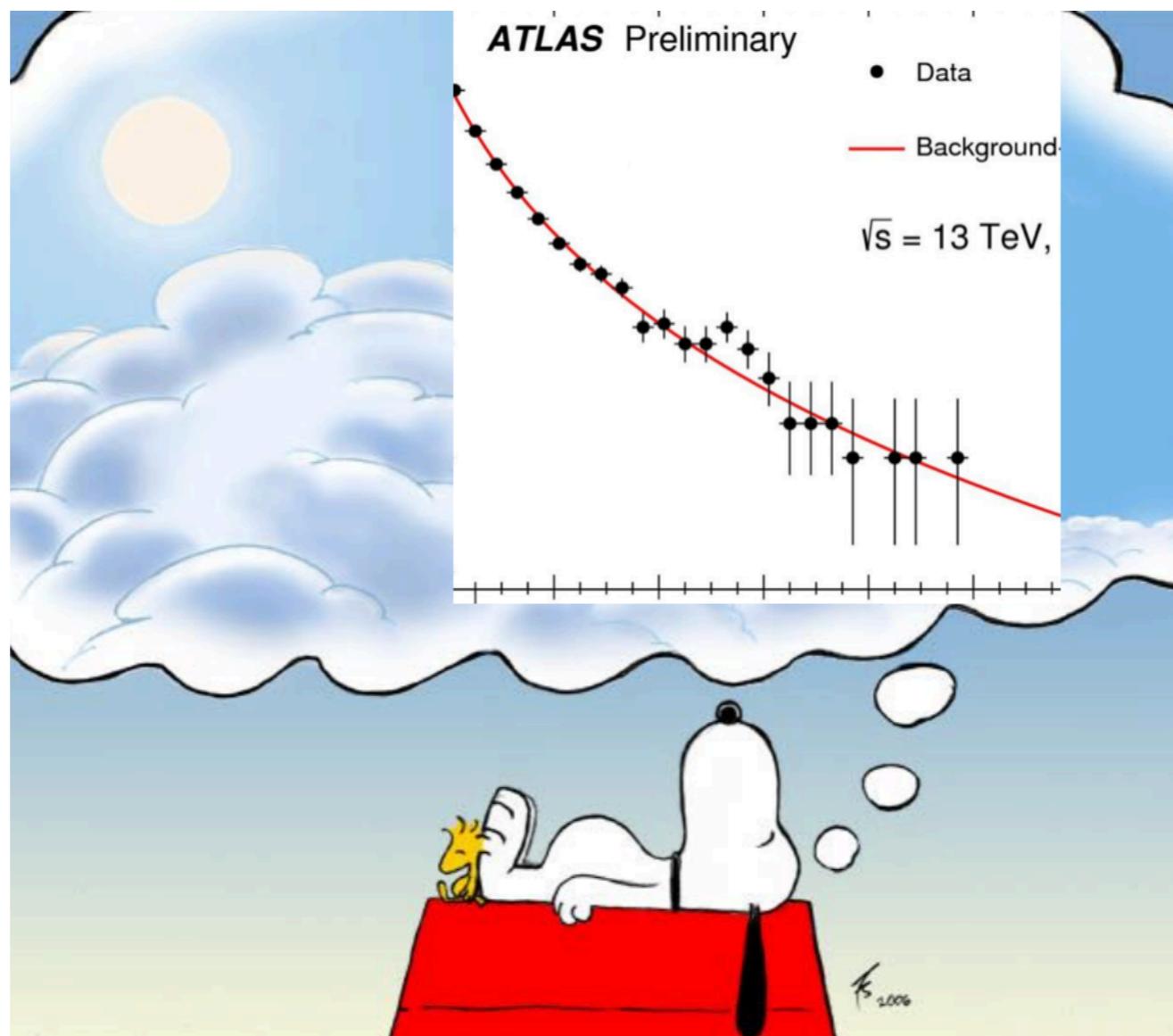
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Production cross sections of  $\sim 10^5 \text{ pb}$  are still allowed!  $[f_a \approx 300 \text{ GeV}]$

# May our dreams come true?



# Why difficult to go below $\sim 100$ GeV?

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

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  $\Delta R$

■ Lower  $p_T^{\min}$



# Lower $p_T^{\min}$ ?

							$\Delta R \gtrsim 0.4$	
D0 ( $\sigma_{\gamma\gamma}$ )	$p\bar{p} \rightarrow a \rightarrow \gamma\gamma$	$4.2 \text{ fb}^{-1}$	$1.96 \text{ TeV}$	$p_{T_1, T_2} > 21, 20 \text{ GeV}$	[7]			
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LHC pT cuts in diphoton cross section measurements

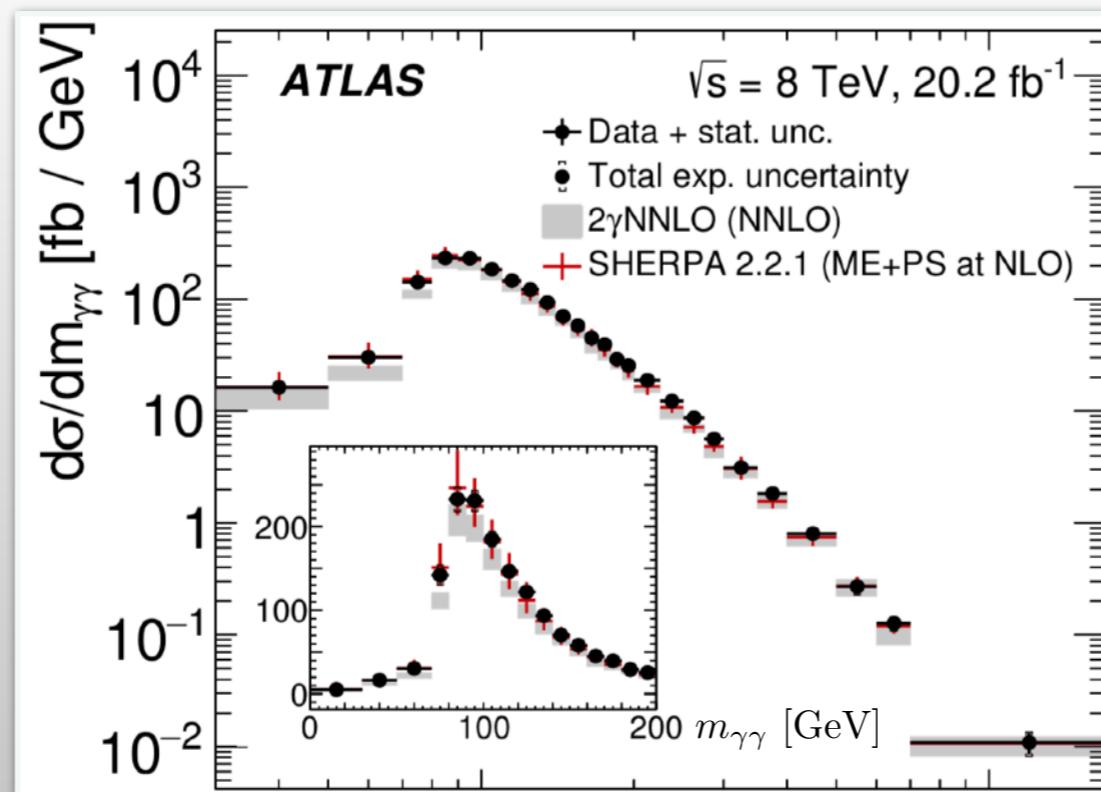
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## Why? Background Shape

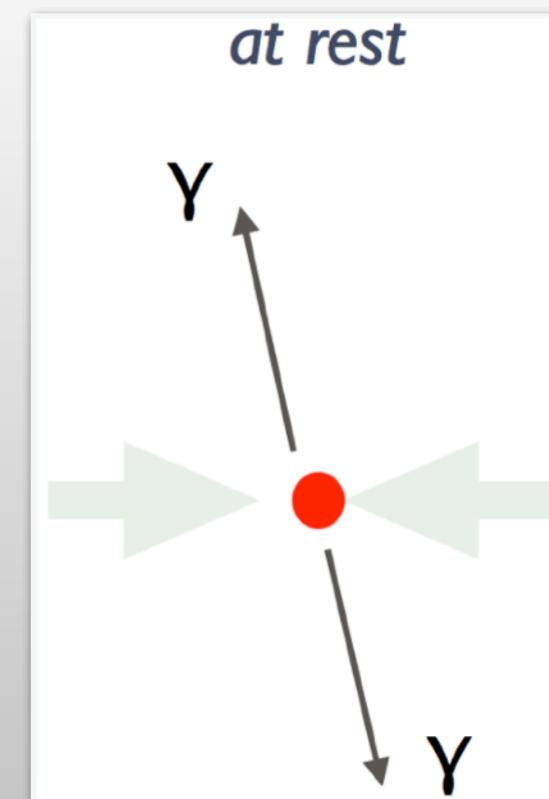
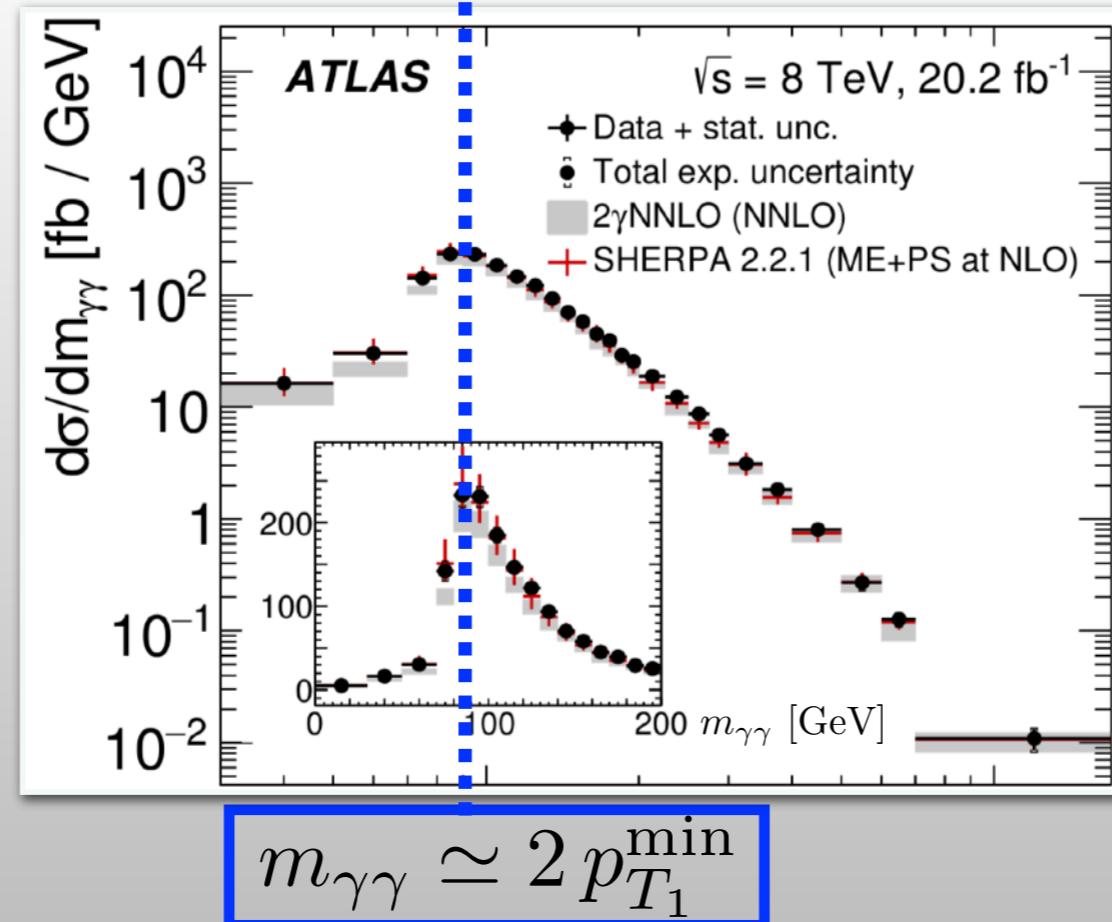
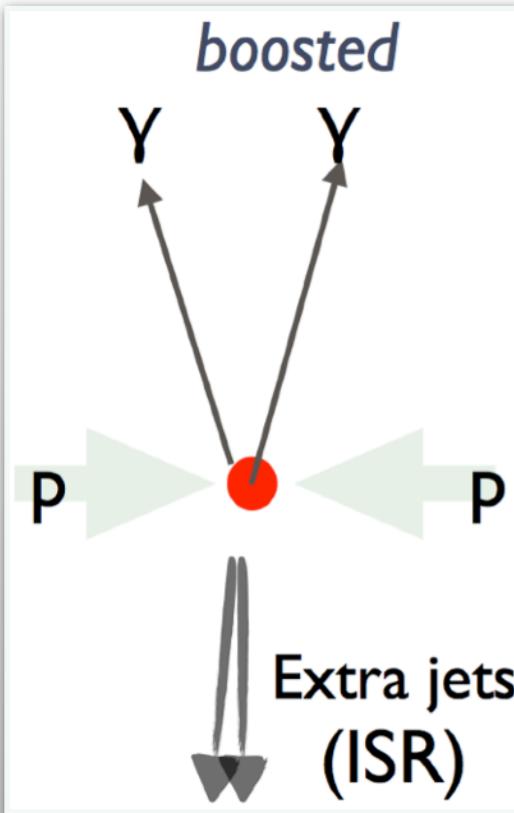


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	$p\bar{p} \rightarrow a \rightarrow \gamma\gamma$	$4.2 \text{ fb}^{-1}$	$1.96 \text{ TeV}$	$p_{T_1, T_2} > 21, 20 \text{ GeV}$	$\Delta R \gtrsim 0.4$
D0 ( $\sigma_{\gamma\gamma}$ )	$p\bar{p} \rightarrow a \rightarrow \gamma\gamma$	$5.36 \text{ fb}^{-1}$	$1.96 \text{ TeV}$	$p_{T_1, T_2} > 17, 15 \text{ GeV}$	[7]
CDF ( $\sigma_{\gamma\gamma}$ )	$p\bar{p} \rightarrow a \rightarrow \gamma\gamma$	$4.9 \text{ fb}^{-1}$	$7 \text{ TeV}$	$p_{T_1, T_2} > 25, 22 \text{ GeV}$	[8]
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CMS	$p\bar{p} \rightarrow a \rightarrow \gamma\gamma$				$9.4 \text{ GeV}$
					$13.9 \text{ GeV}$
					$14.2 \text{ GeV}$

LHC pT cuts in diphoton cross section measurements  
but LHC diphoton searches do not reach such low masses

## Why? Background Shape

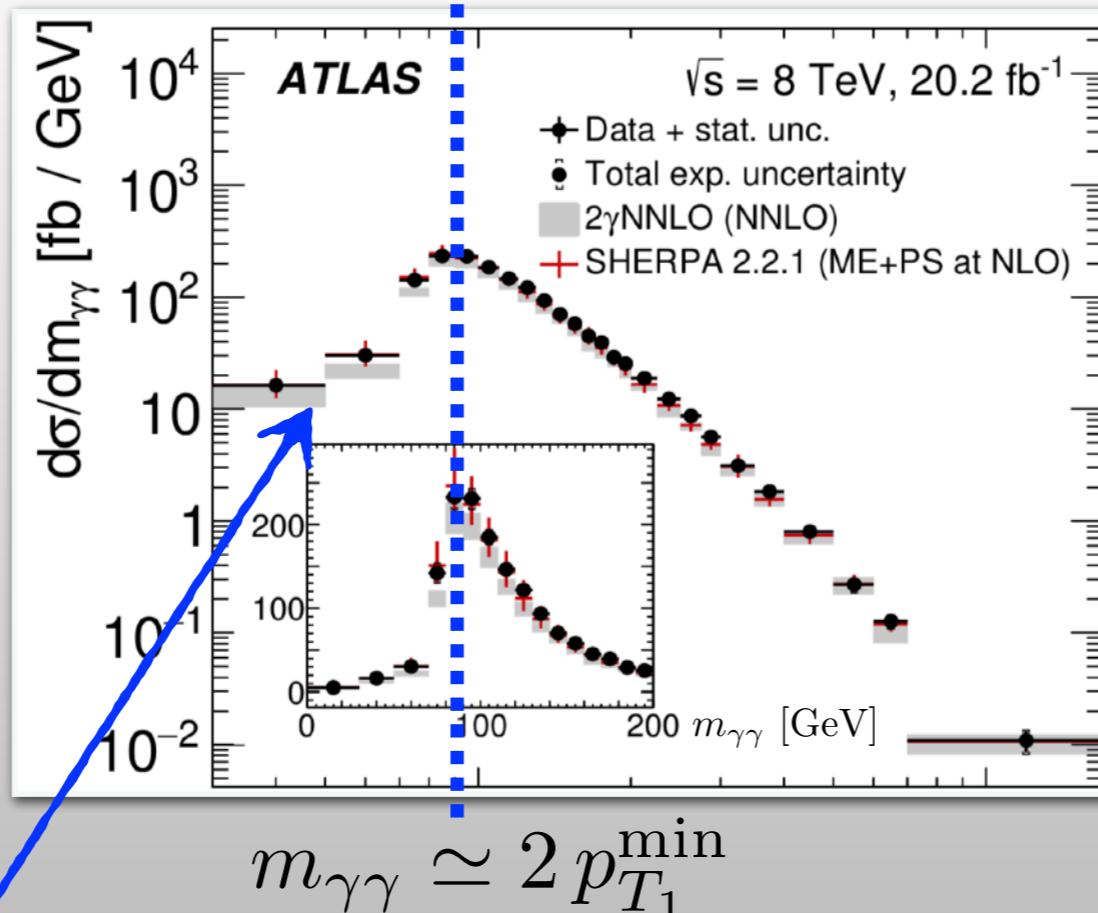


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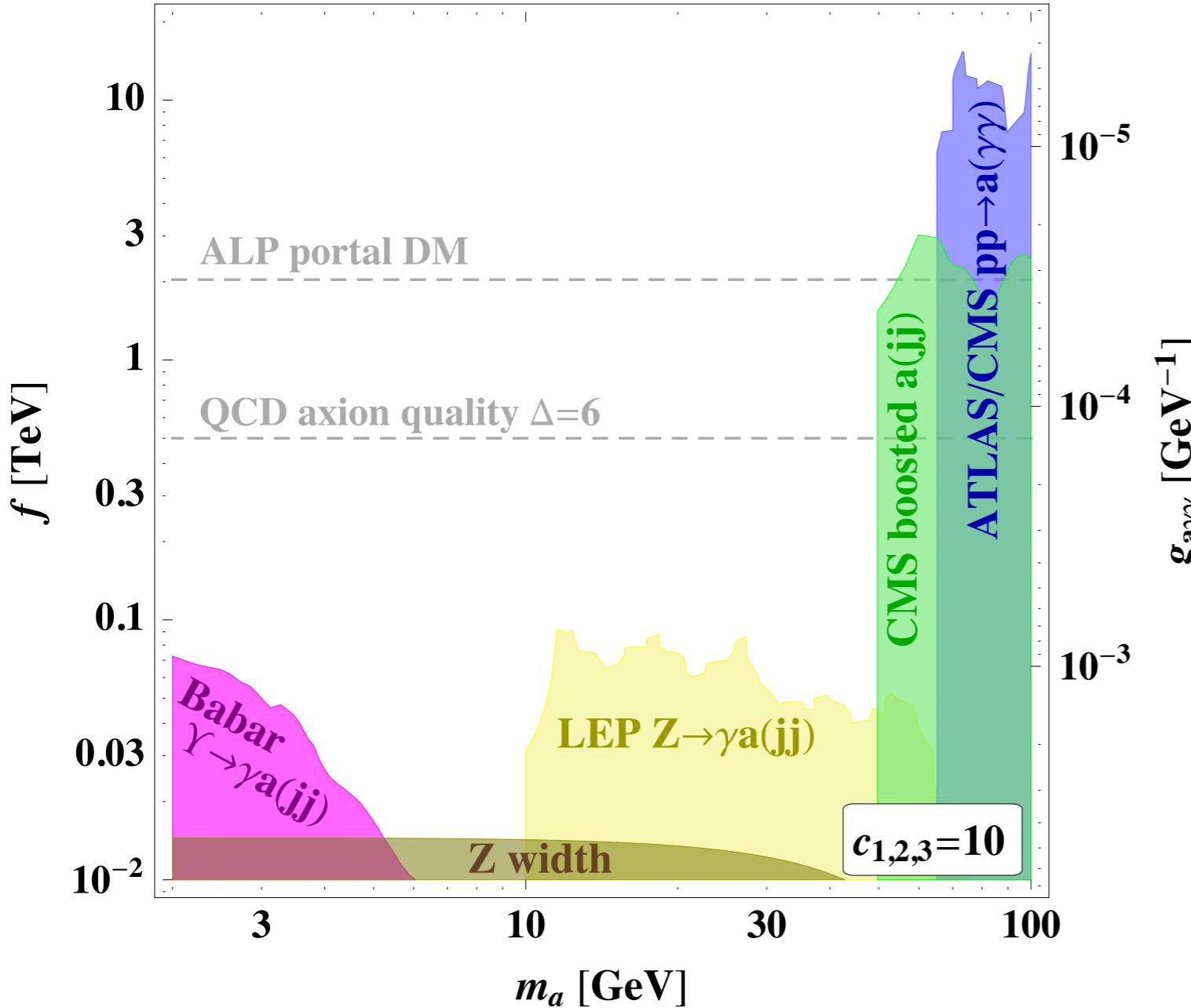


Below pT cuts: Background has a structure, so **data-driven estimates are difficult**

# New $\gamma\gamma$ Bound & Sensitivities

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

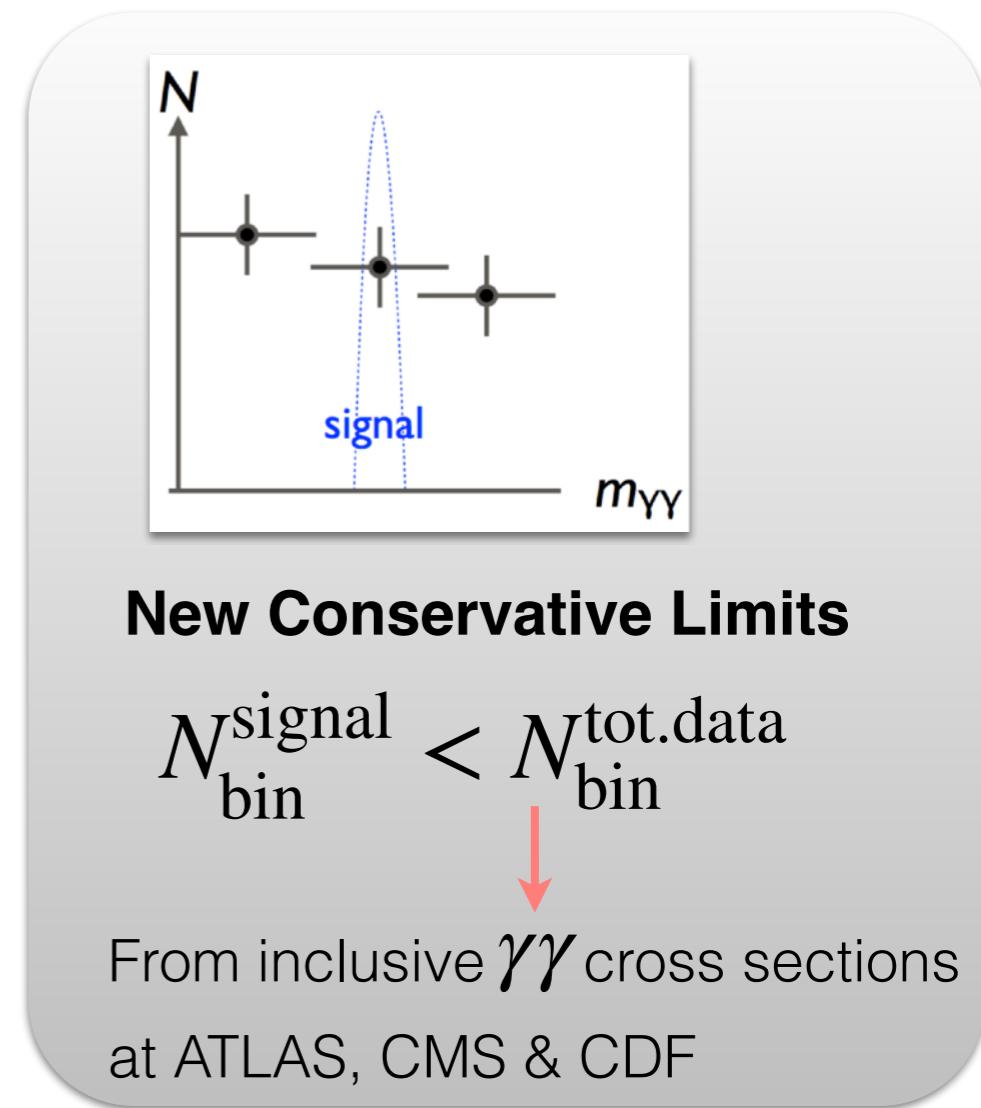
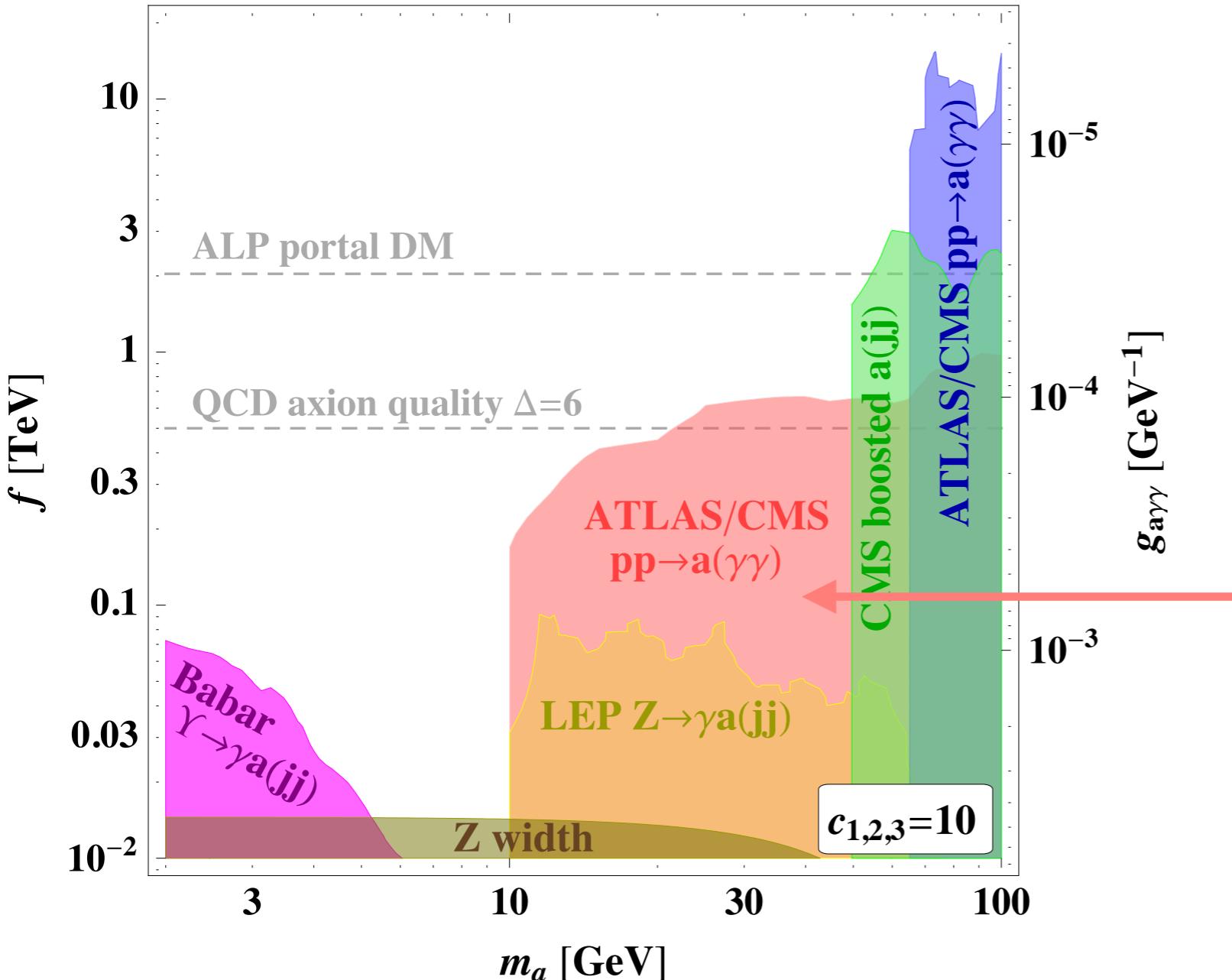
$$\alpha_1 = \frac{5}{3} \alpha_y$$



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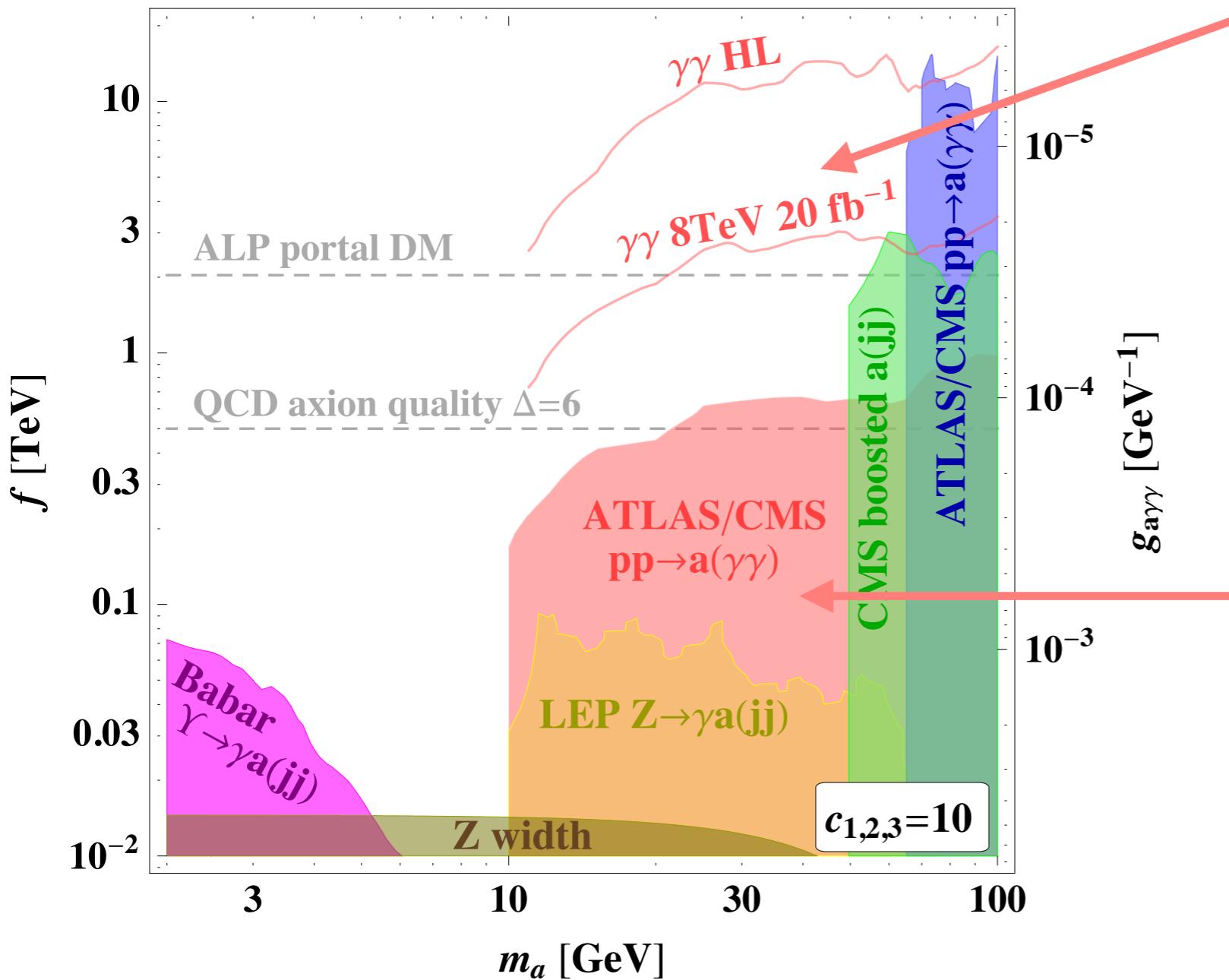
$\alpha_1 = \frac{5}{3} \alpha_y$



# New $\gamma\gamma$ Bound & Sensitivities

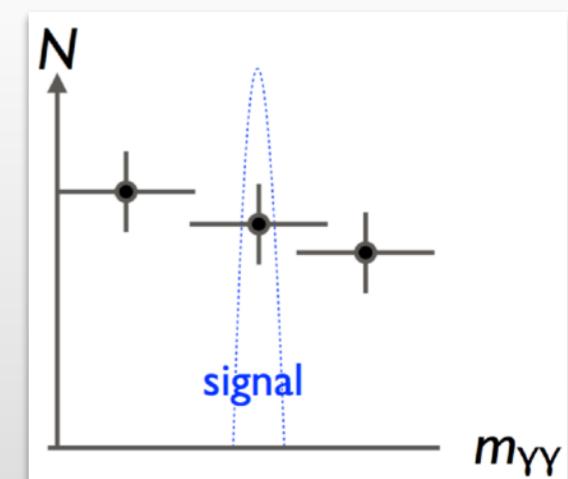
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$\alpha_1 = \frac{5}{3} \alpha_y$



From Boosted Diphoton Searches

Already in current data!



**New Conservative Limits**

$$N_{\text{bin}}^{\text{signal}} < N_{\text{bin}}^{\text{tot.data}}$$

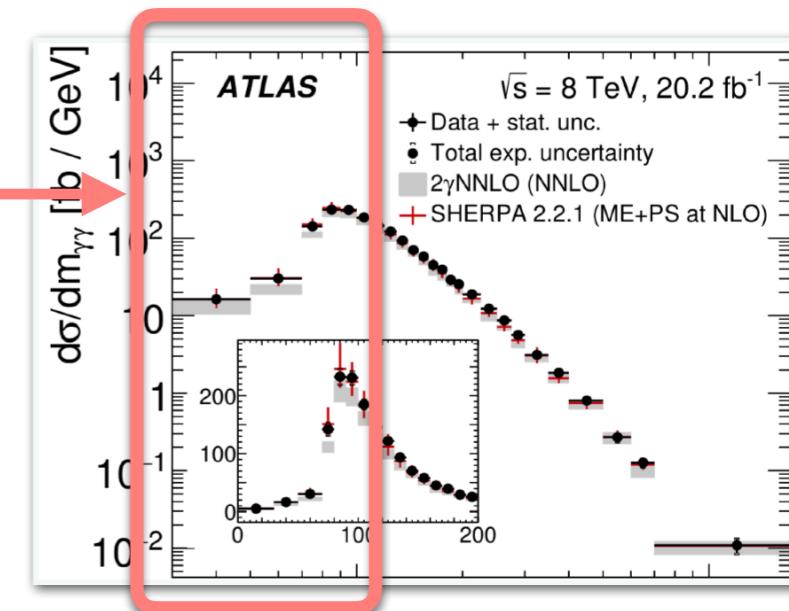
From inclusive  $\gamma\gamma$  cross sections  
at ATLAS, CMS & CDF

# So, what should ATLAS & CMS do?

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## 1. Hunt bumps on steep data

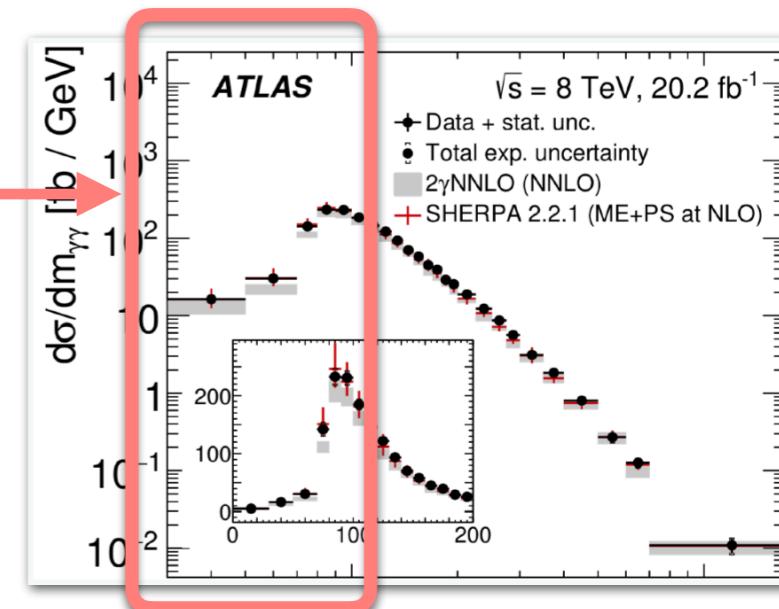
Using small bins would be enough to start



# So, what should ATLAS & CMS do?

## 1. Hunt bumps on steep data

Using small bins would be enough to start



## 2. Perform Boosted Searches!

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

- Lower  $\Delta R$  and look for resonances recoiling against a jet (or any ISR)

**Background is smooth** and bump hunt is easy!



**Good News**

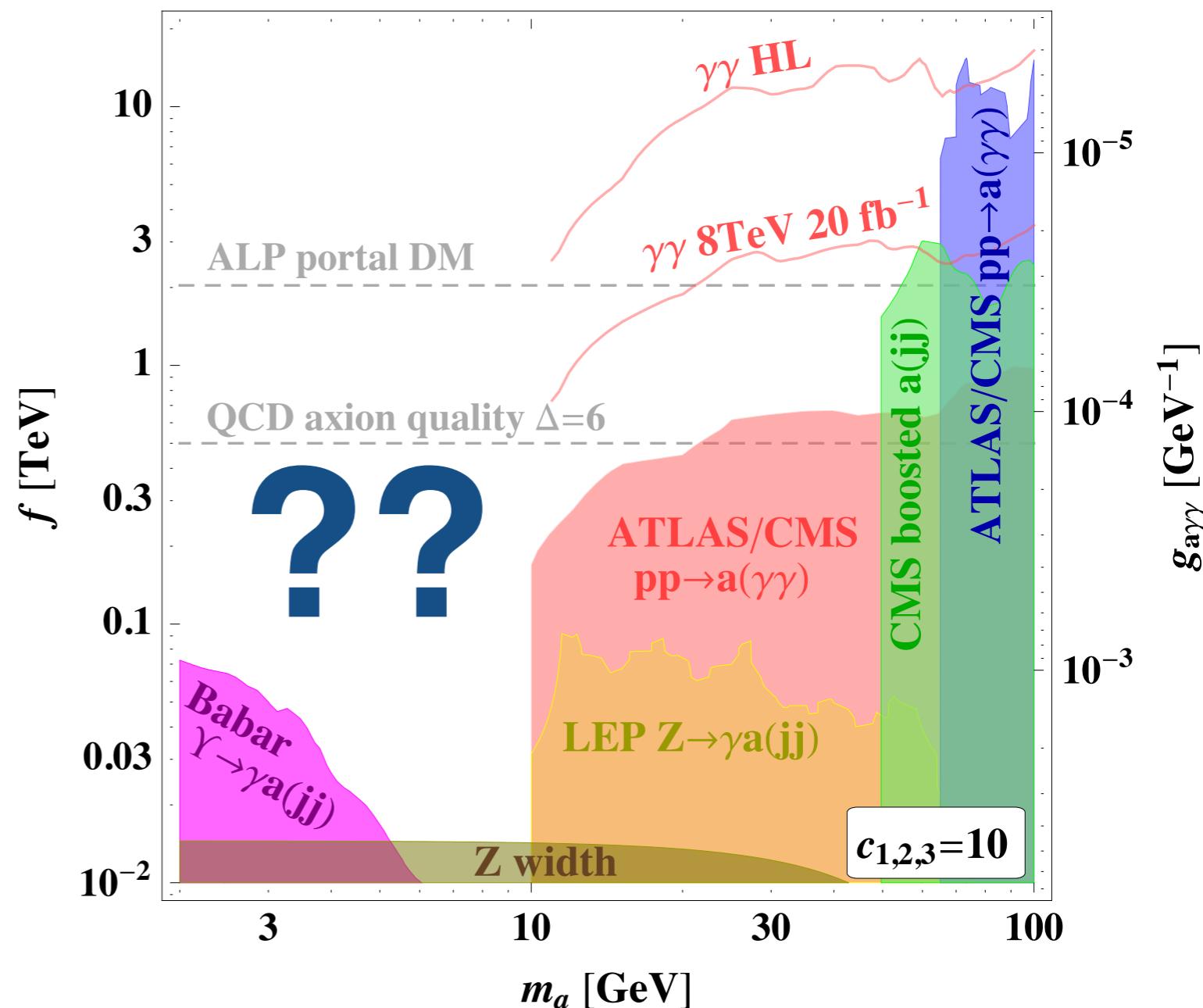
LHC already managed for Dijet Resonances

CMS 1710.00159

ATLAS already achieved  $\Delta R_{\gamma\gamma} \simeq 0.15$  in  $Z \rightarrow \gamma a(\gamma\gamma)$

1509.05051

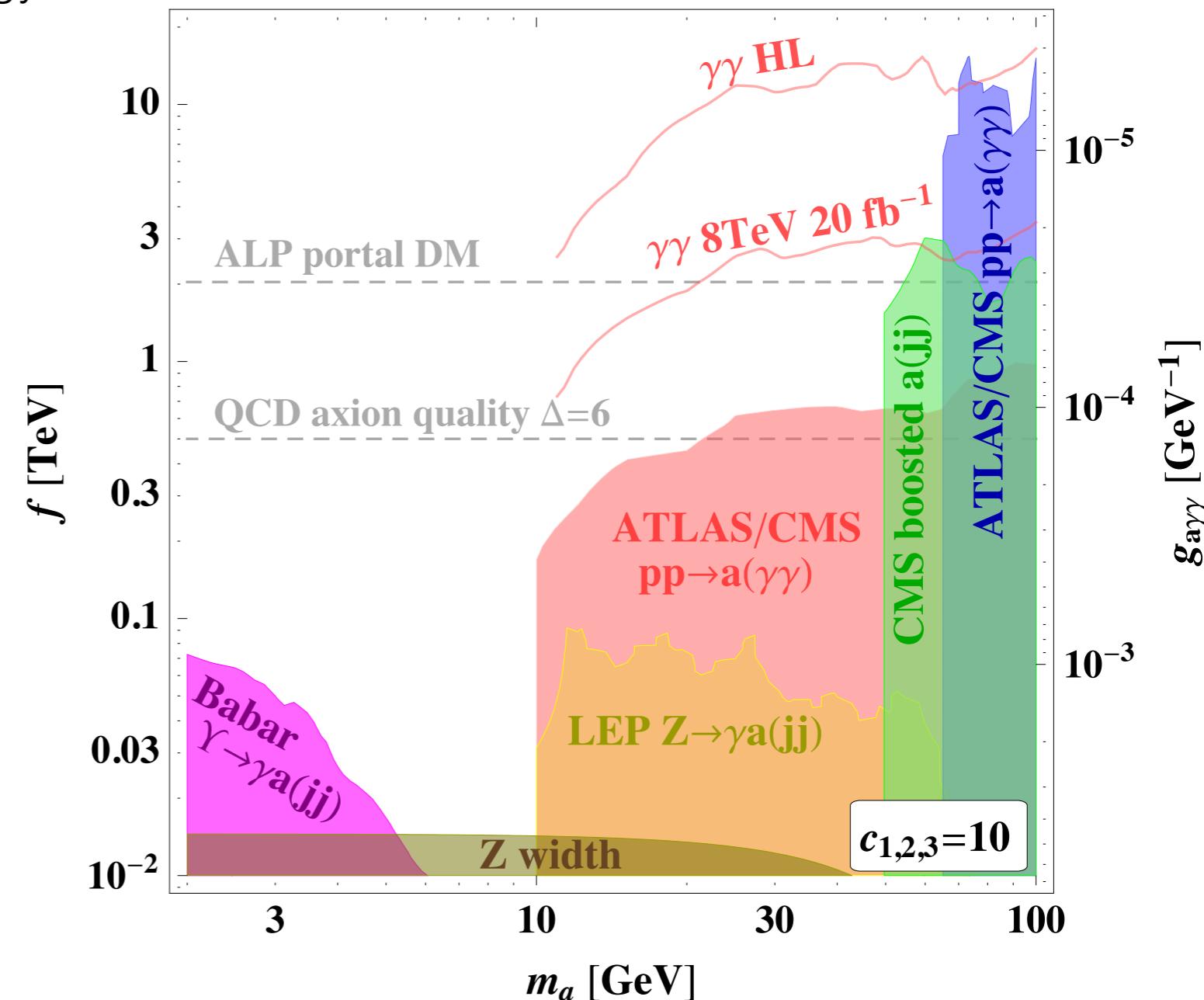
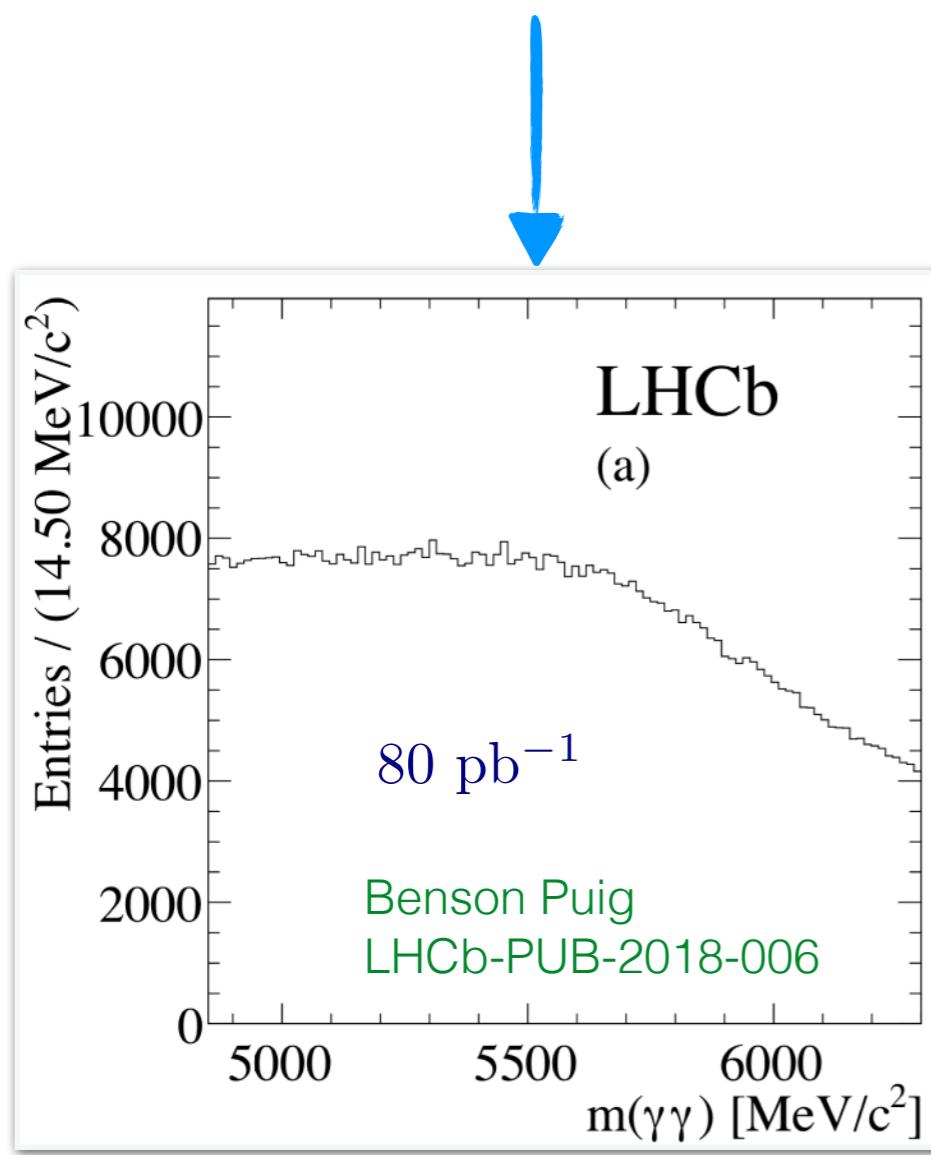
# Even smaller masses?



# Even smaller masses? LHCb

LHCb aims at competitive search for  $B_s \rightarrow \gamma\gamma$

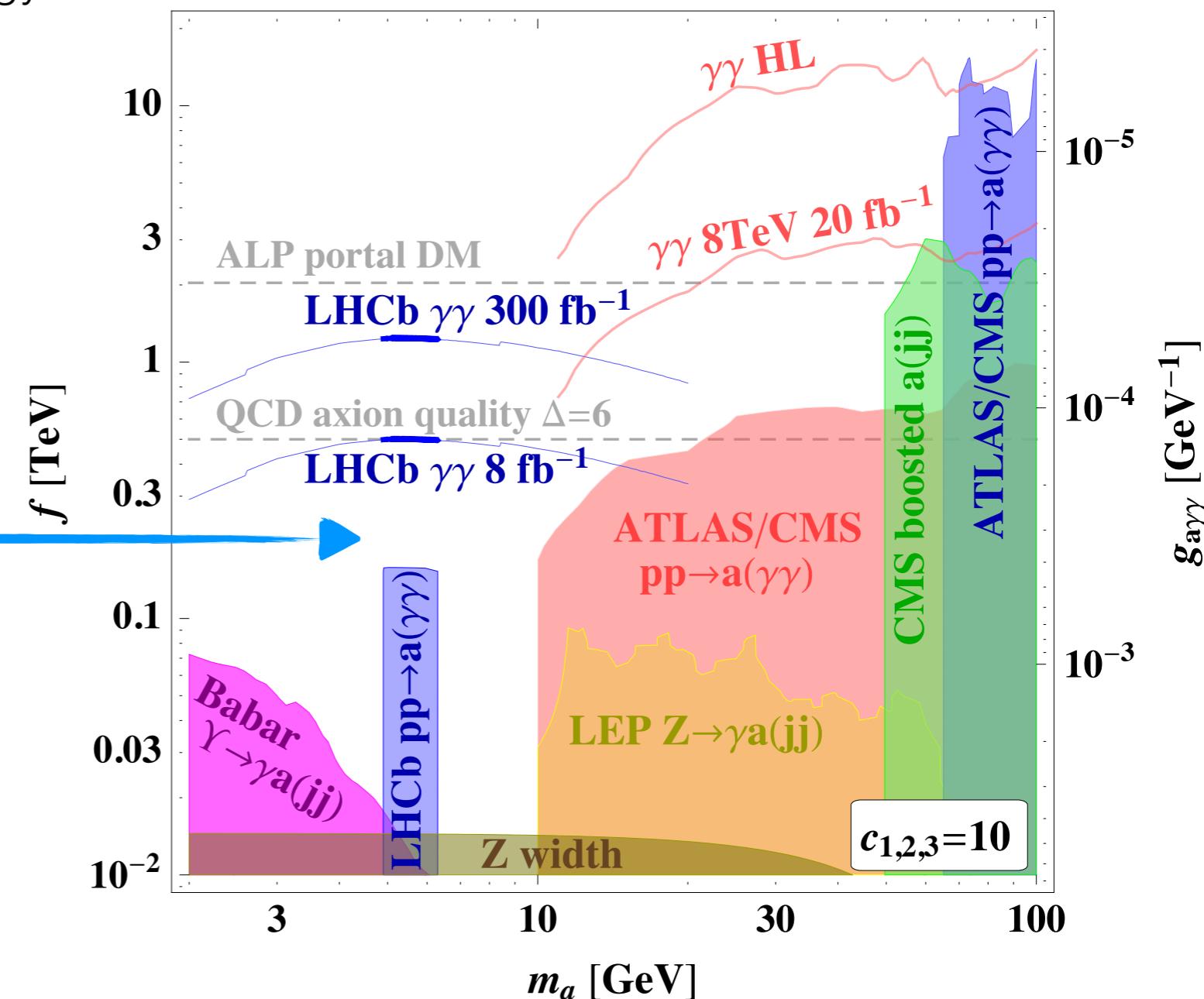
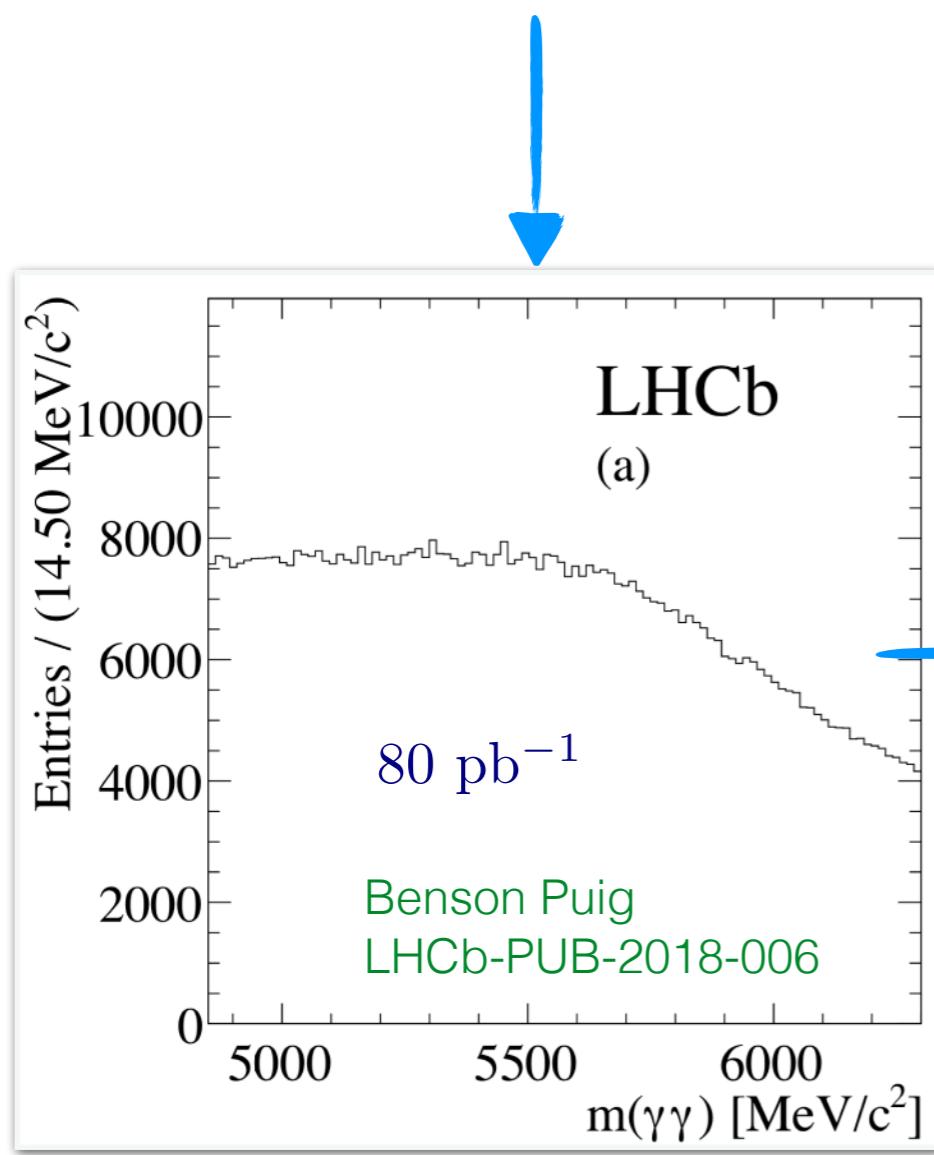
They published note with search strategy



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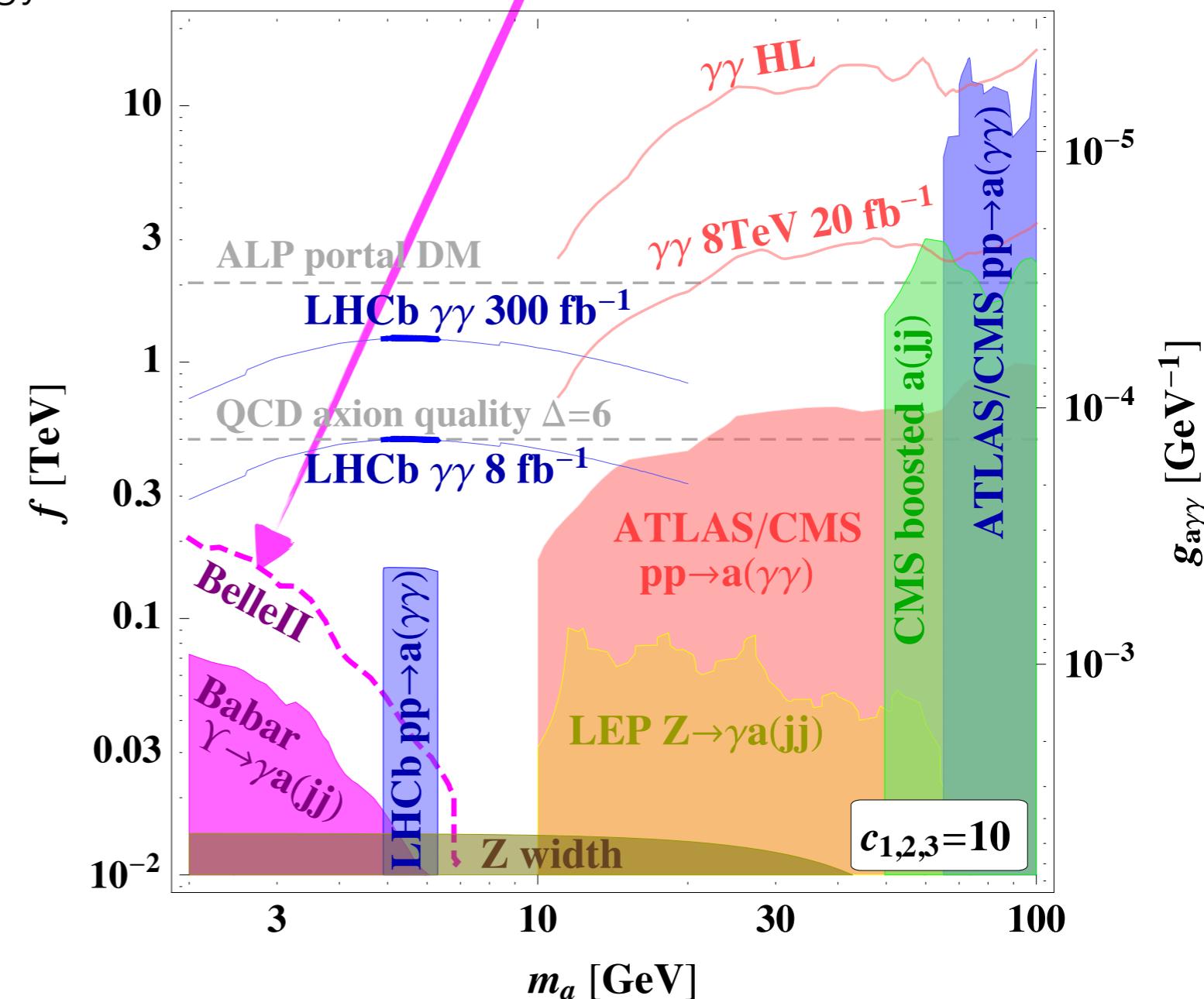
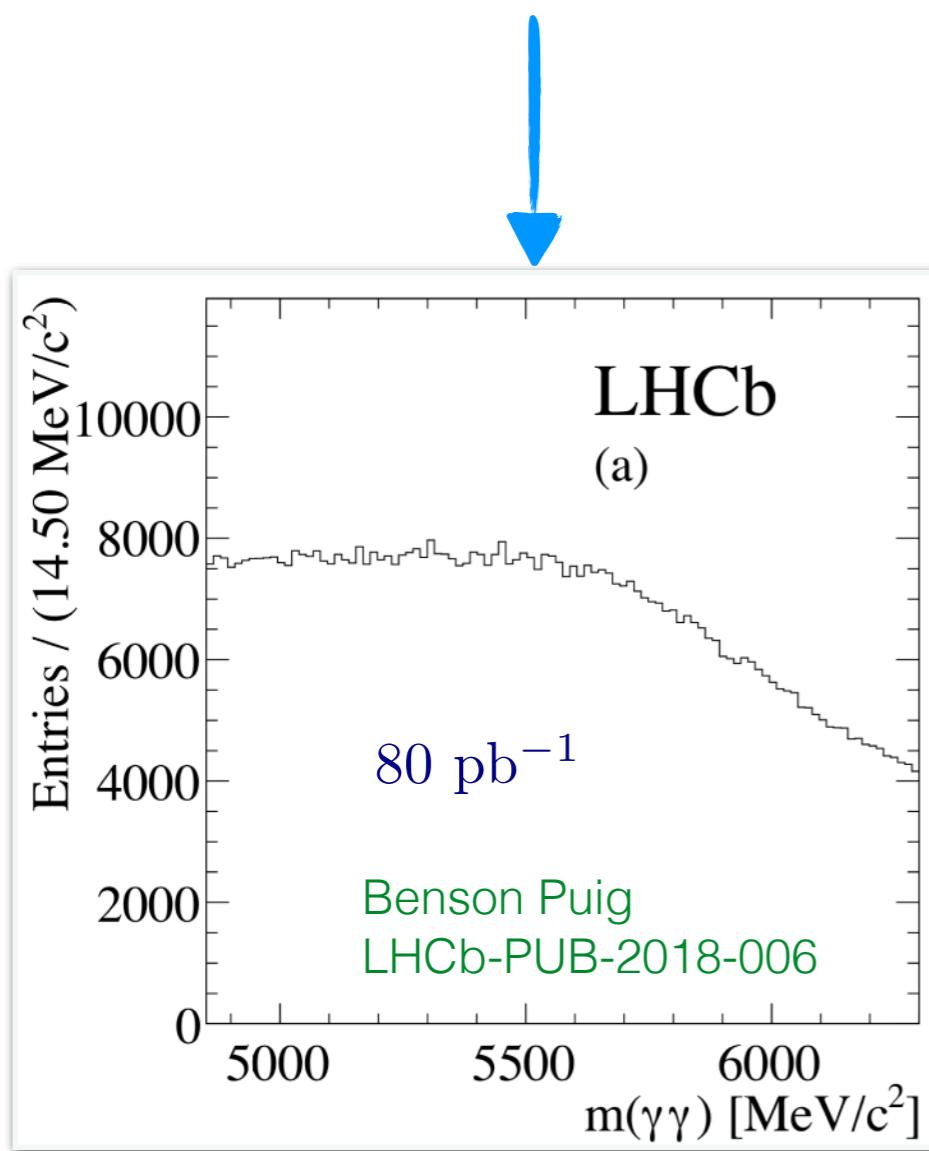


# Even smaller masses? Belle2

LHCb aims at competitive search for  $B_s \rightarrow \gamma\gamma$

Rescale current BABAR search

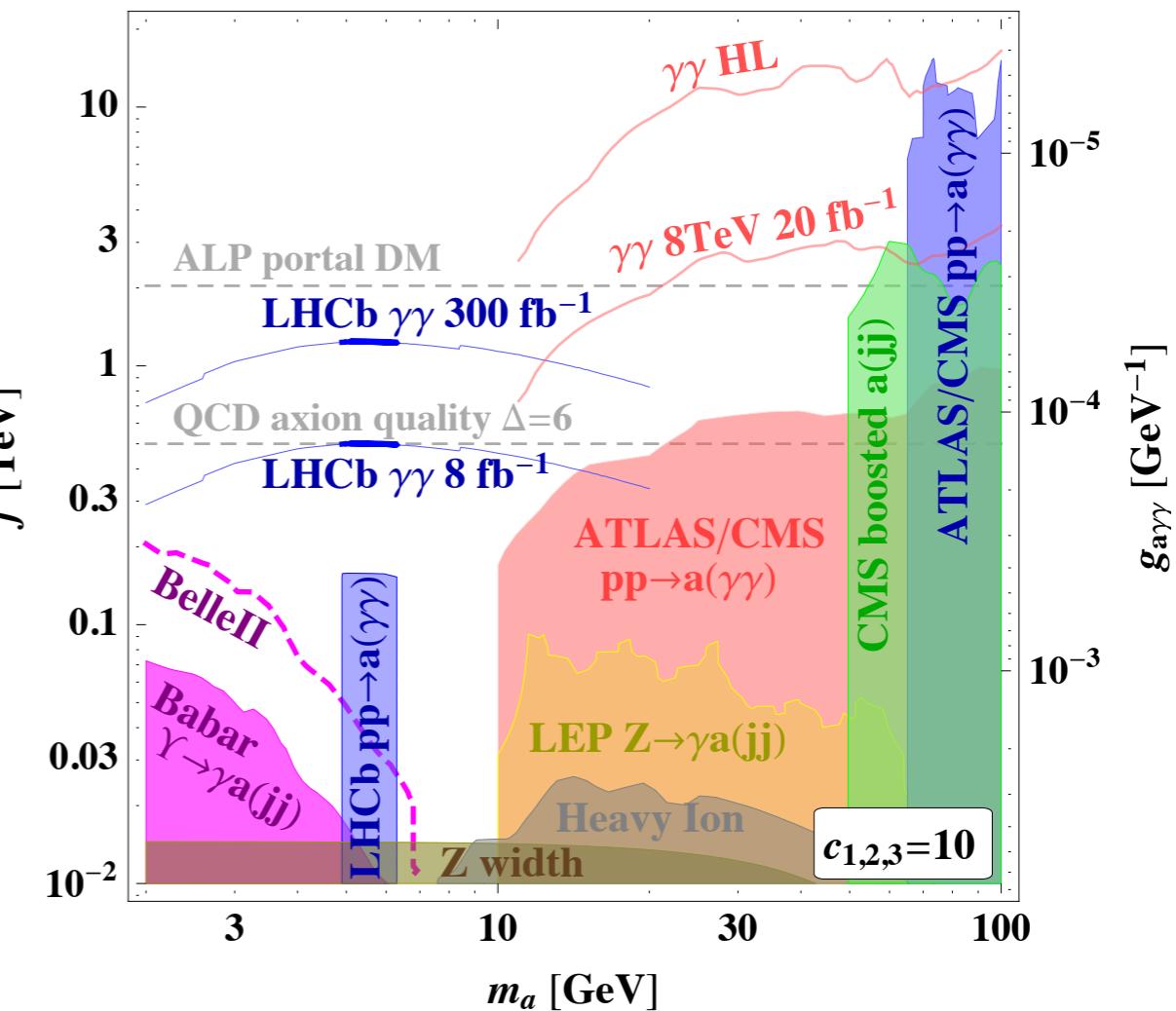
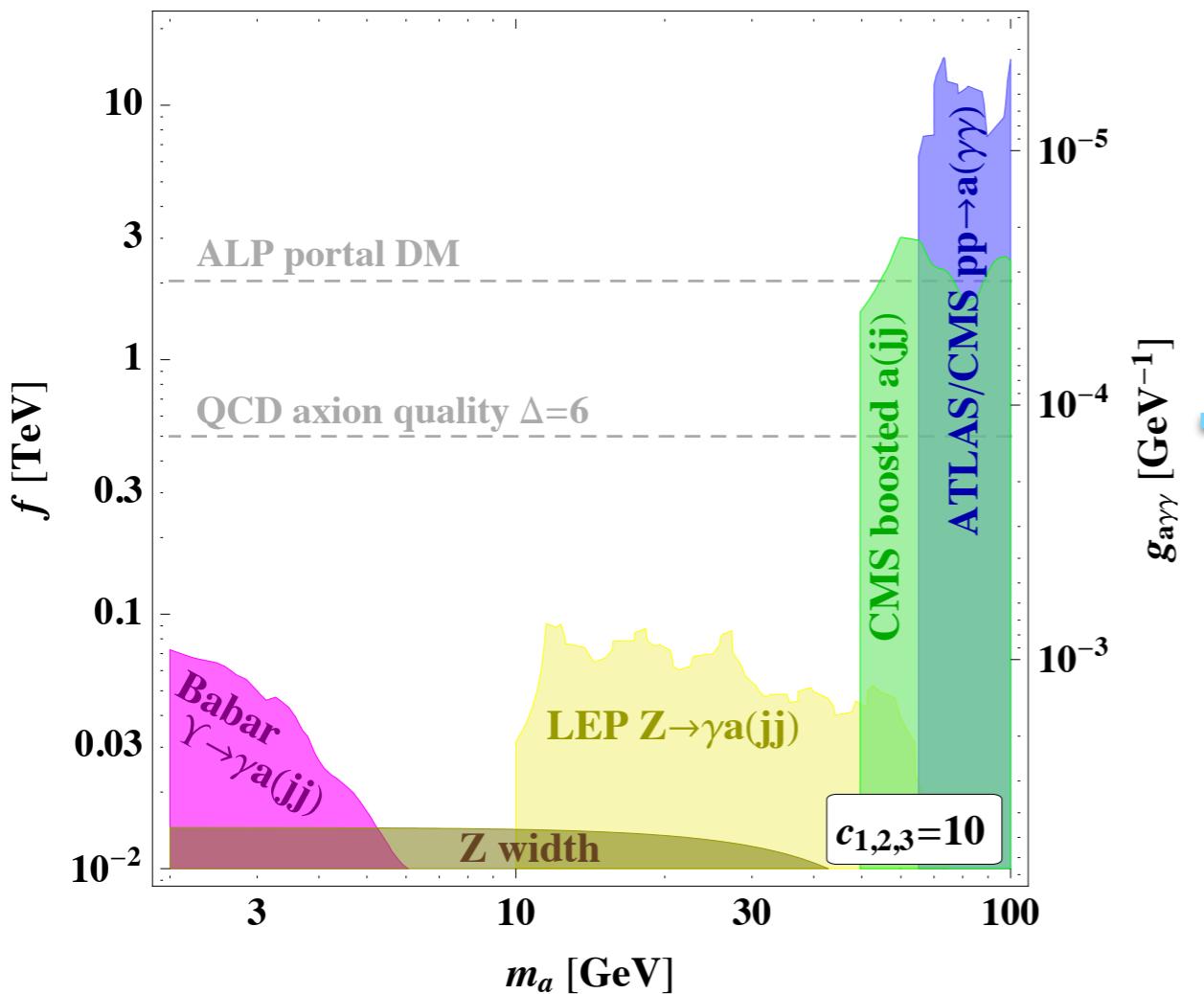
They published note with search strategy



# Summary

Mariotti Redigolo FS Tobioka 1710.01743 + Cid Vidal 1810.09452

- ALPs at LHC are well motivated  
(heavy **QCD axion**, **SUSY** R-axion, **Strong Sectors**)
- We should look for them!



# Summary

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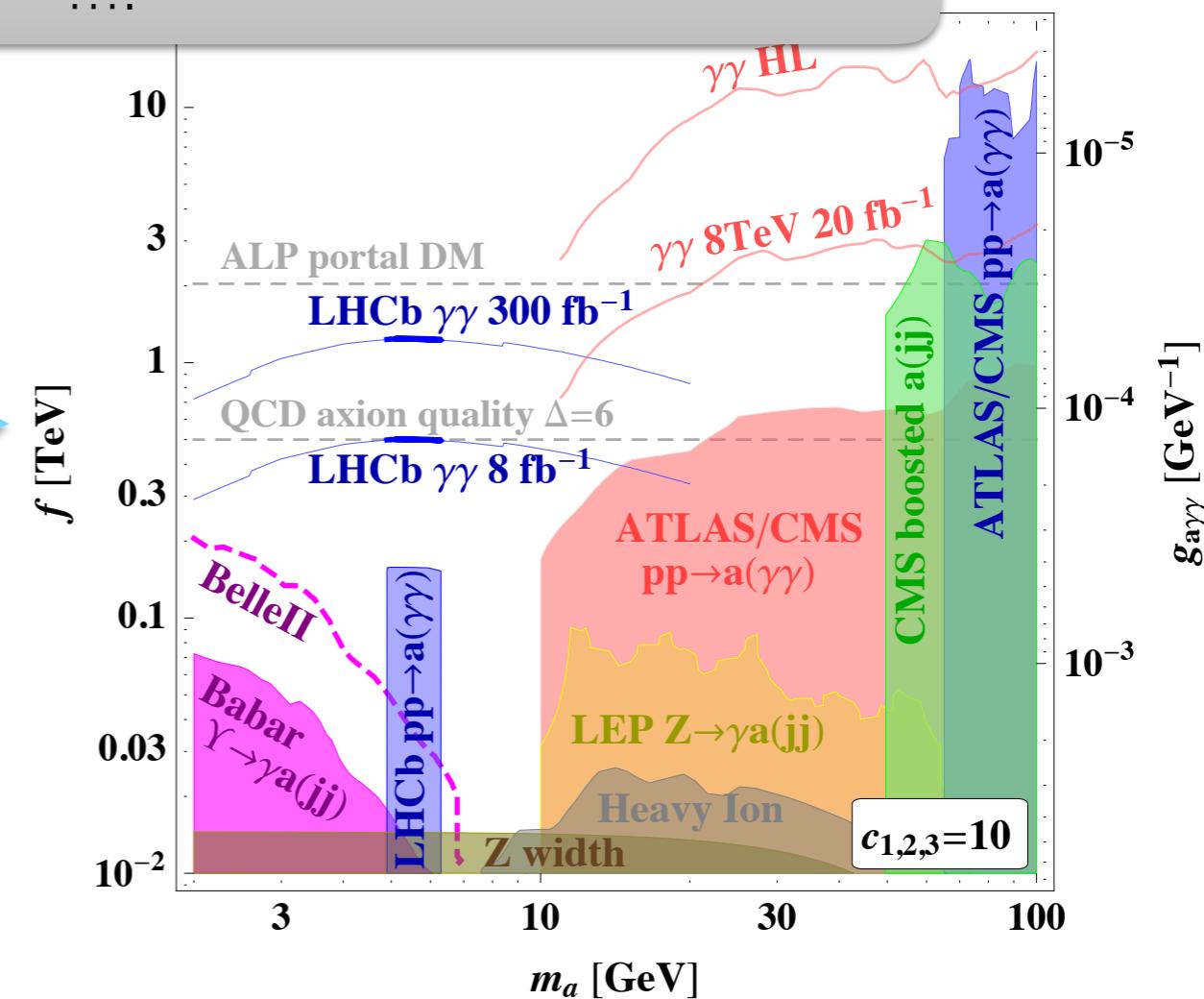
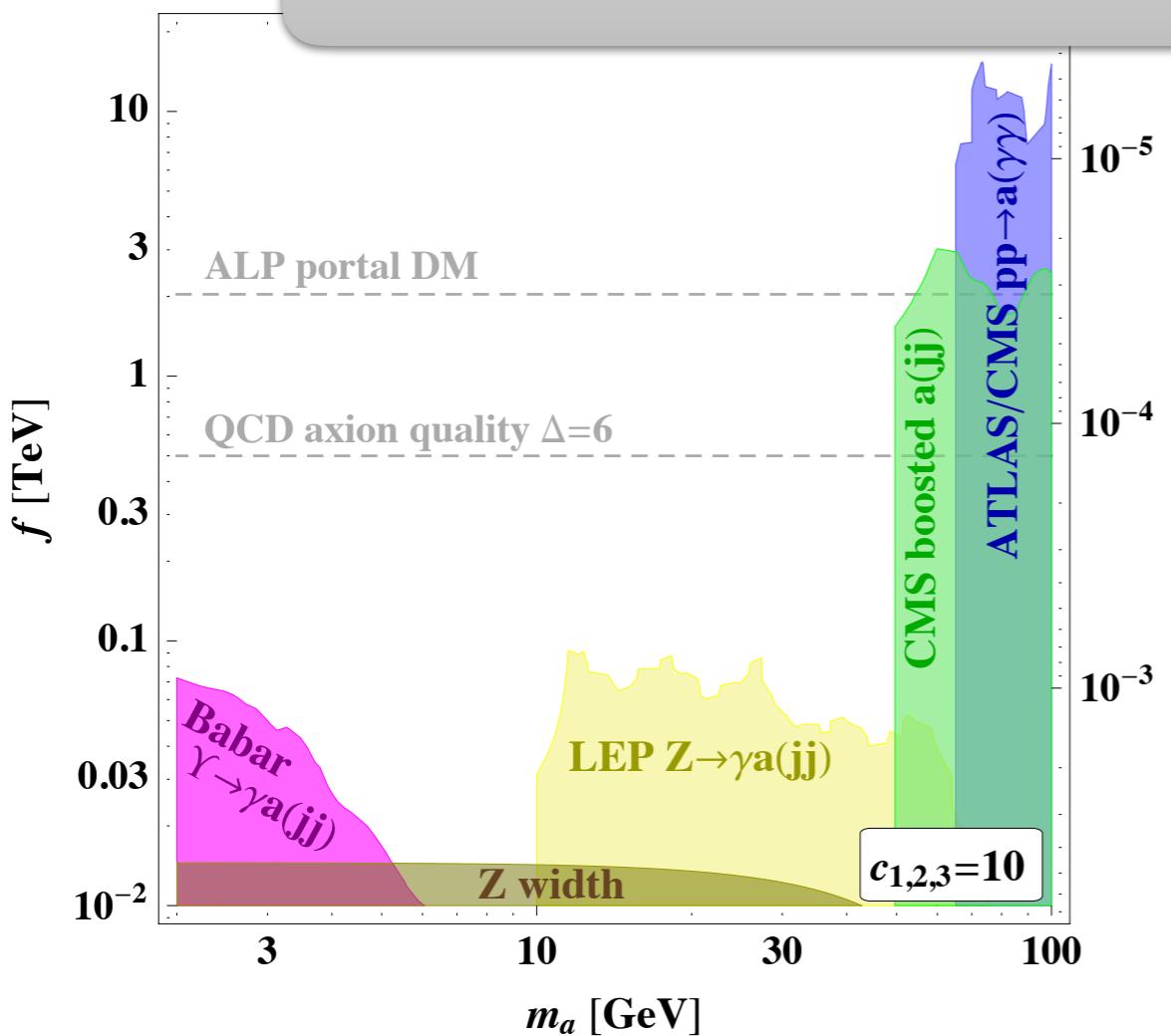
- ALPs at LHC are well motivated

(heavy **QCD axion**, **SUSY** R-axion, **Strong Sectors**)

- We Could be useful to **non-ALP scenarios!**

Light Z' (e.g. as DM mediators)

Extra Higgses Delgado+ 1603.00962



# Back up

# More on R-axion

# PGB from SUSY: R-symmetry

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

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

R-charge assignments:

$$\begin{aligned} \Phi &= \phi + \sqrt{2}\theta \psi + \theta^2 F & r_\phi &= r_\Phi \\ && r_\psi &= r_\Phi - 1 \\ && r_F &= r_\Phi - 2 \end{aligned}$$

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

Lagrangian  $\mathcal{L}$  R-symmetric  $\Rightarrow R(W) = 2$   $\mathcal{L} \supset \int d^2\theta W + \text{c.c.}$   
( $\Leftarrow$  if Kahler canonical)  $W$  superpotential

# R-axion- as Dark Matter mediator

Spectrum à la gauge mediation

**Gravitino DM**

$$m_{3/2} = F/(\sqrt{3}M_{\text{Pl}}) \simeq 11 \text{ meV} \cdot (g_*/3) \cdot (f/4 \text{ TeV})^2$$



Cannot make observed DM for these values of parameter

(motivated by naturalness of Fermi scale)



Respects all bounds from cosmology and collider



**R-axion** is natural portal! Mardon Nomura Thaler 0905.3749  
Fan Thaler Wang 1004.0008

Motivated realisation of ALP-portal Dark Matter

# 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

$m_*$

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

$$m_a \approx \sqrt{\epsilon_R} m_*$$

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

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

SUSY Naive Dimensional Analysis

$$M_{\text{SUSY}} \sim m_* \sim g_* f \quad f_a \sim f$$

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

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

$a \rightarrow GG$  saturates the upper bound

# The R-axion pheno Lagrangian-I

Komargodski Seiberg 0907.2441

Tool: constrained superfield formalism

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

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

satisfy the constraints

~ analogous to  
ordinary Goldstones

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

$$U^\dagger U = 1 \quad U = e^{i\pi}$$

Most general effective Lagrangian:

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

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

Absent for any other axion

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

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

R-axion decays to missing energy

$$w_R < \frac{1}{2} f_a F$$

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

Dine Festuccia Komargodski 0910.2527  
see also Bellazzini 1605.06111

# R-axion pheno overview

Tool: constrained superfield formalism

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

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

Komargodski Seiberg 0907.2441

satisfy the constraints

~ analogous to  
ordinary Goldstones

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

$$U^\dagger U = 1 \quad U = e^{i\pi}$$

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

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

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

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

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

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

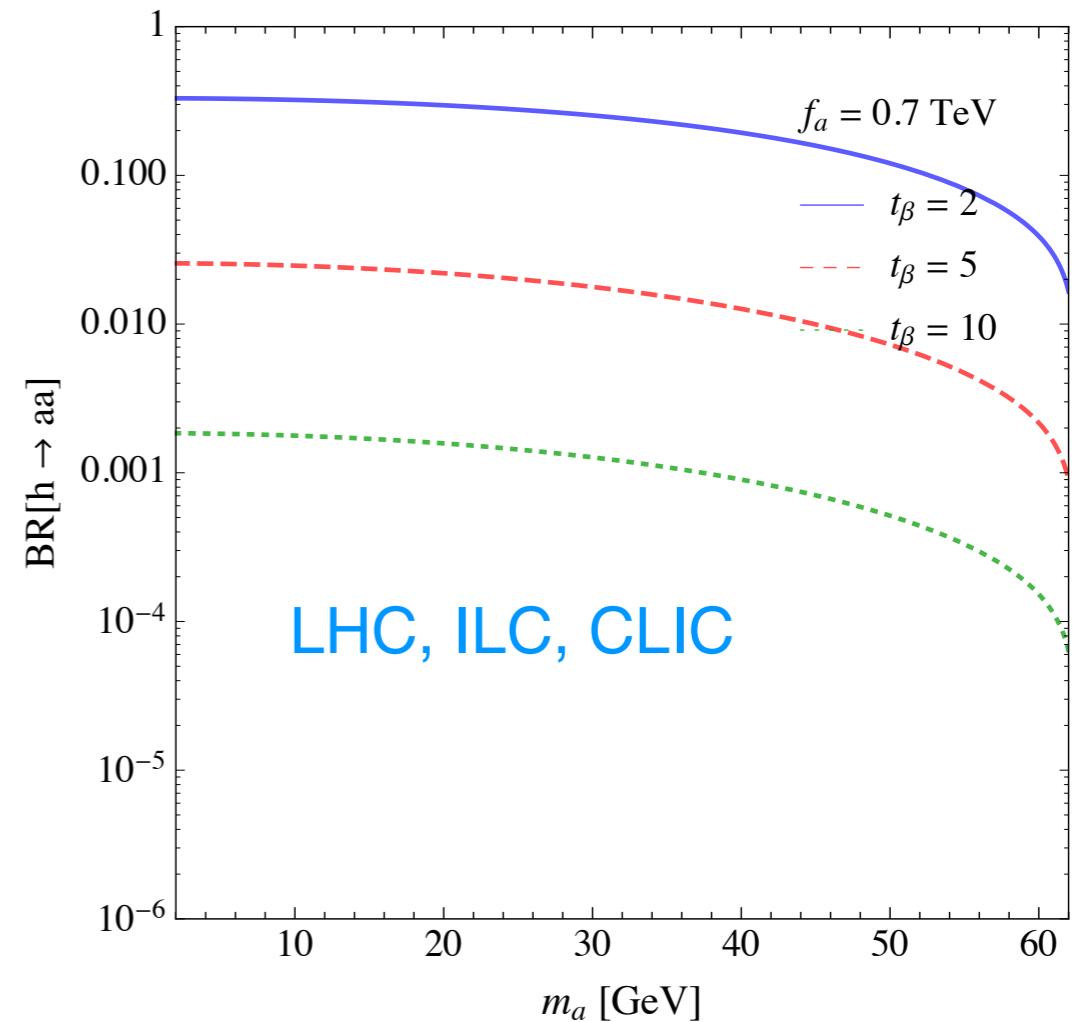
$$-i a R_H \left( c_\beta^2 \frac{m_u}{f_a} \bar{u} \gamma_5 u + s_\beta^2 \frac{m_d}{f_a} \bar{d} \gamma_5 d + s_\beta^2 \frac{m_\ell}{f_a} \bar{\ell} \gamma_5 \ell \right)$$

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

# $a$ from decays of $h$ , $\gamma$ and $B$

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

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



$$\text{BR}_{\gamma \rightarrow \gamma a} \simeq 3 - 5 \times 10^{-5} \left( \frac{\text{TeV}}{f_a} \right)^2$$

since Wilczek PRL39 (1977)

experiments: **BABAR**  
**Belle-II**

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

**LHCb**  
**Belle, Belle-II**

see Hall Wise 1981, Freytsis Ligeti Thaler 0911.5355

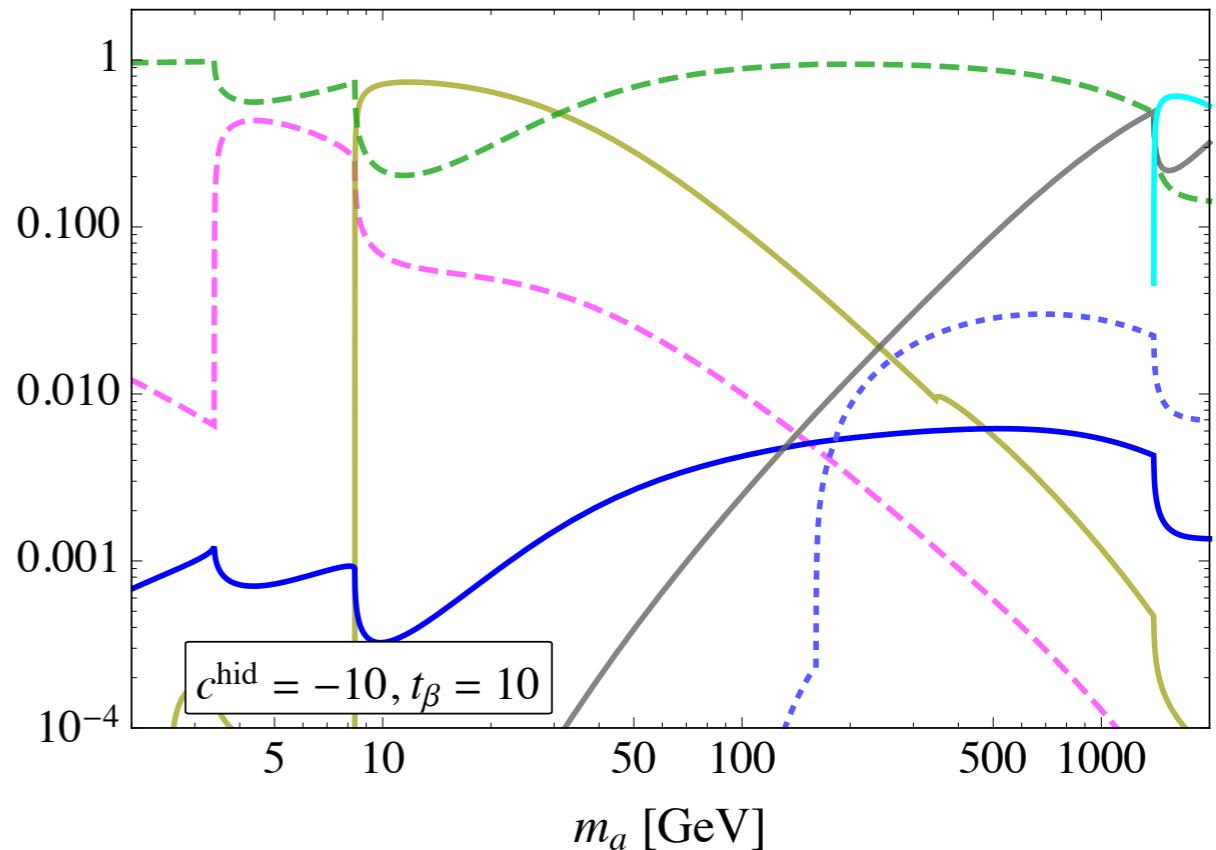
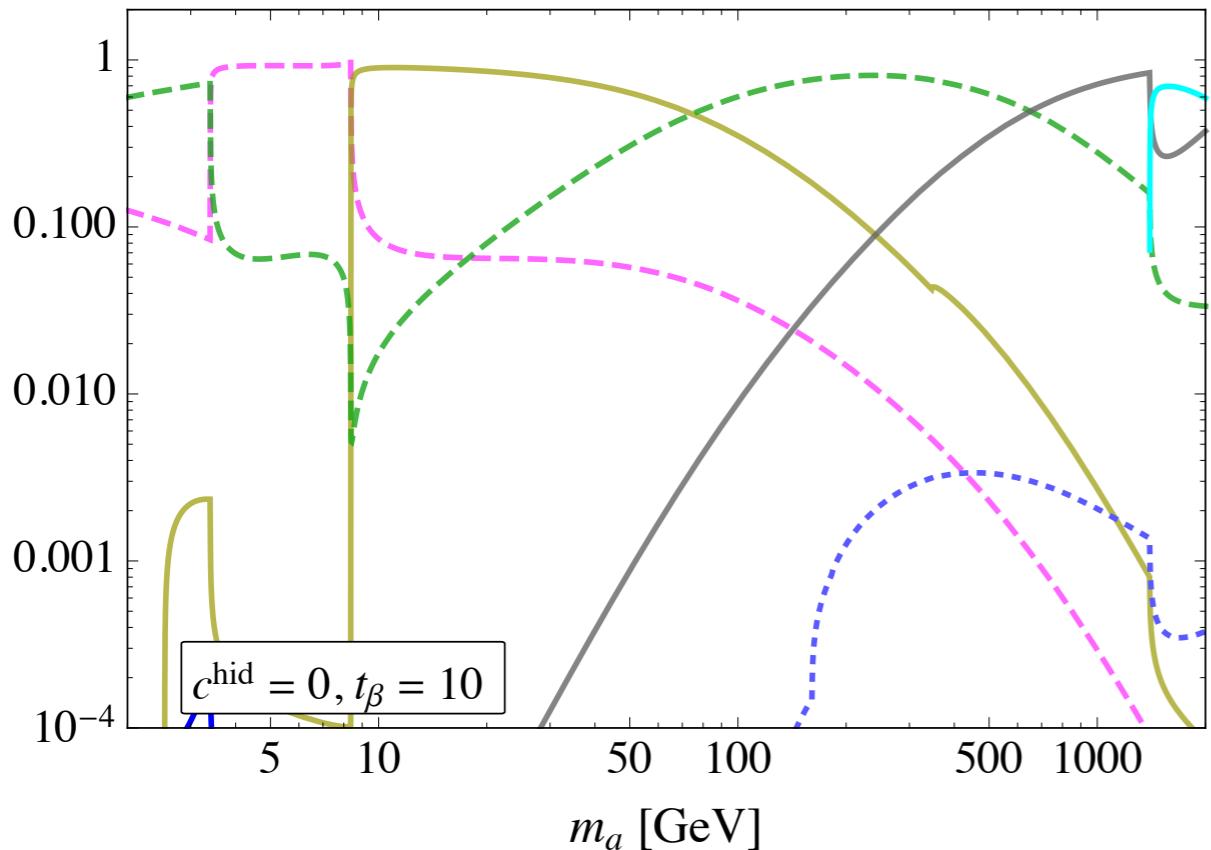
# R axion branching ratios

Both plots:  $t_\beta = 10$

No anomaly

Large anomalies

BRs:  $\mu\mu + \tau\tau$ ,  $cc + bb + tt$ ,  $\gamma\gamma$ ,  $jj$ ,  $WW + ZZ + Z\gamma$ , inv.,  $\gamma\gamma + MET$

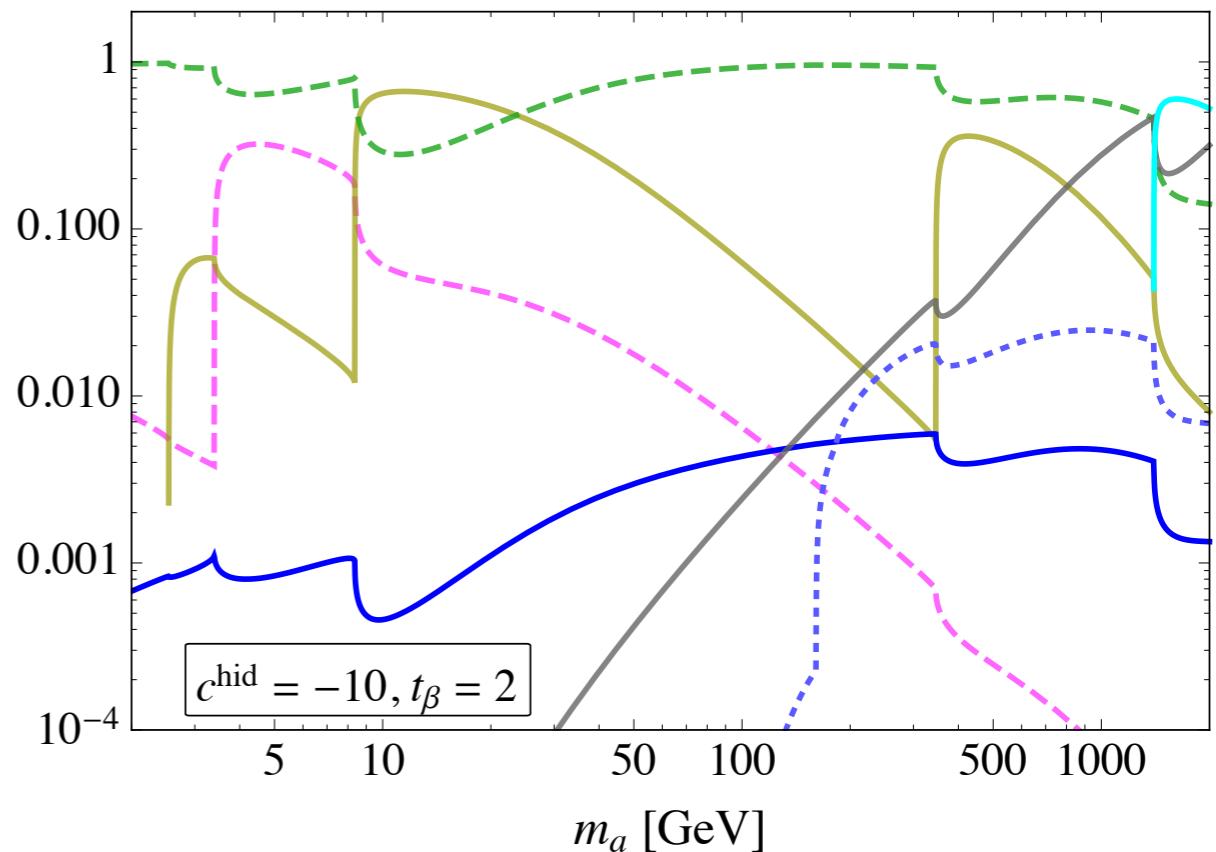
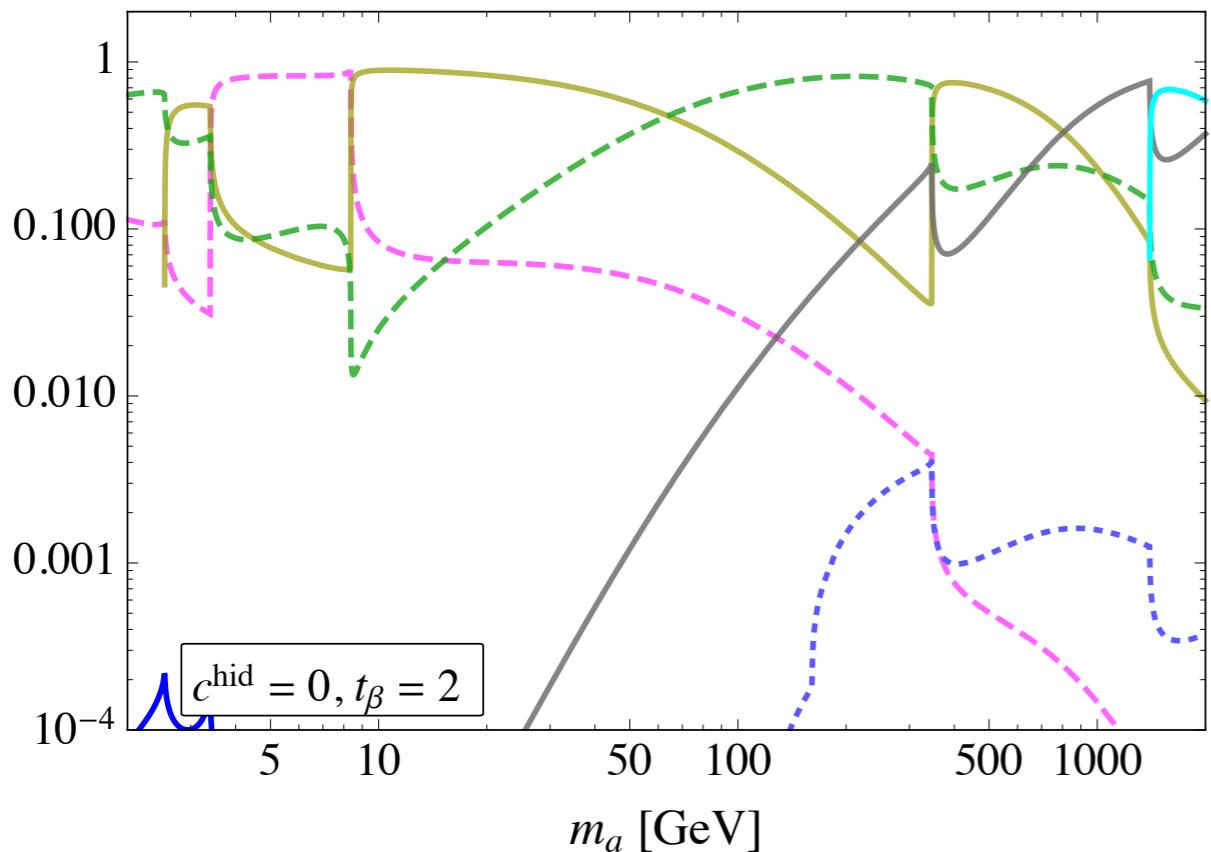
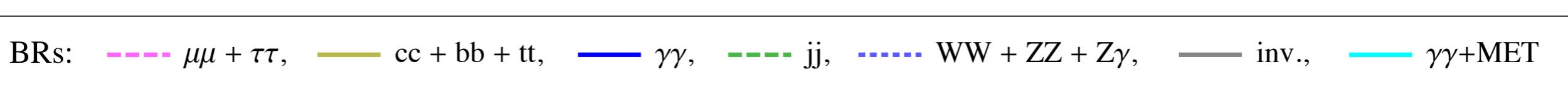


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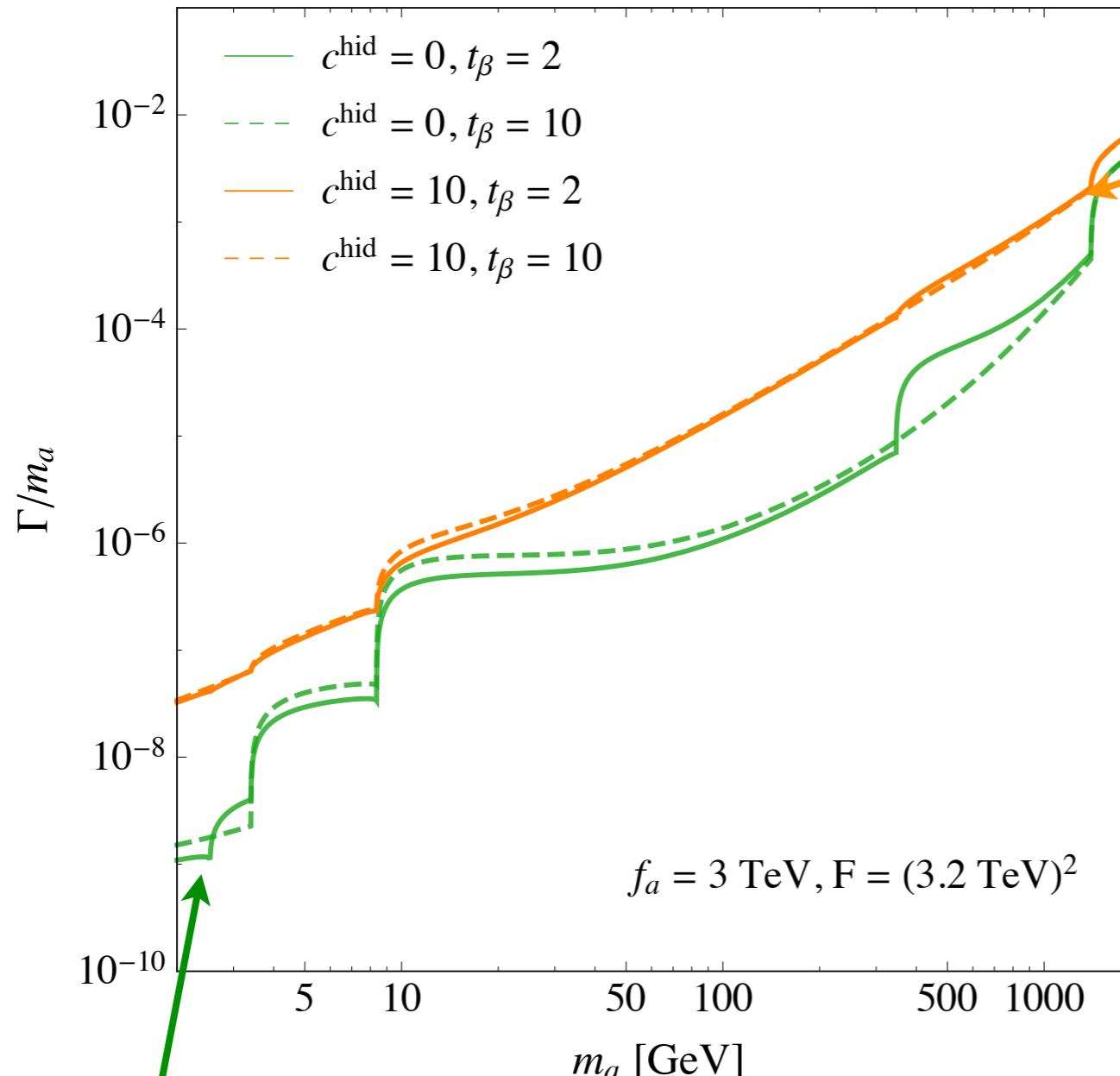
Both plots:  $t_\beta = 2$

No anomaly

Large anomalies



# 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)

$$m_a < \Lambda_{\text{QCD}}$$

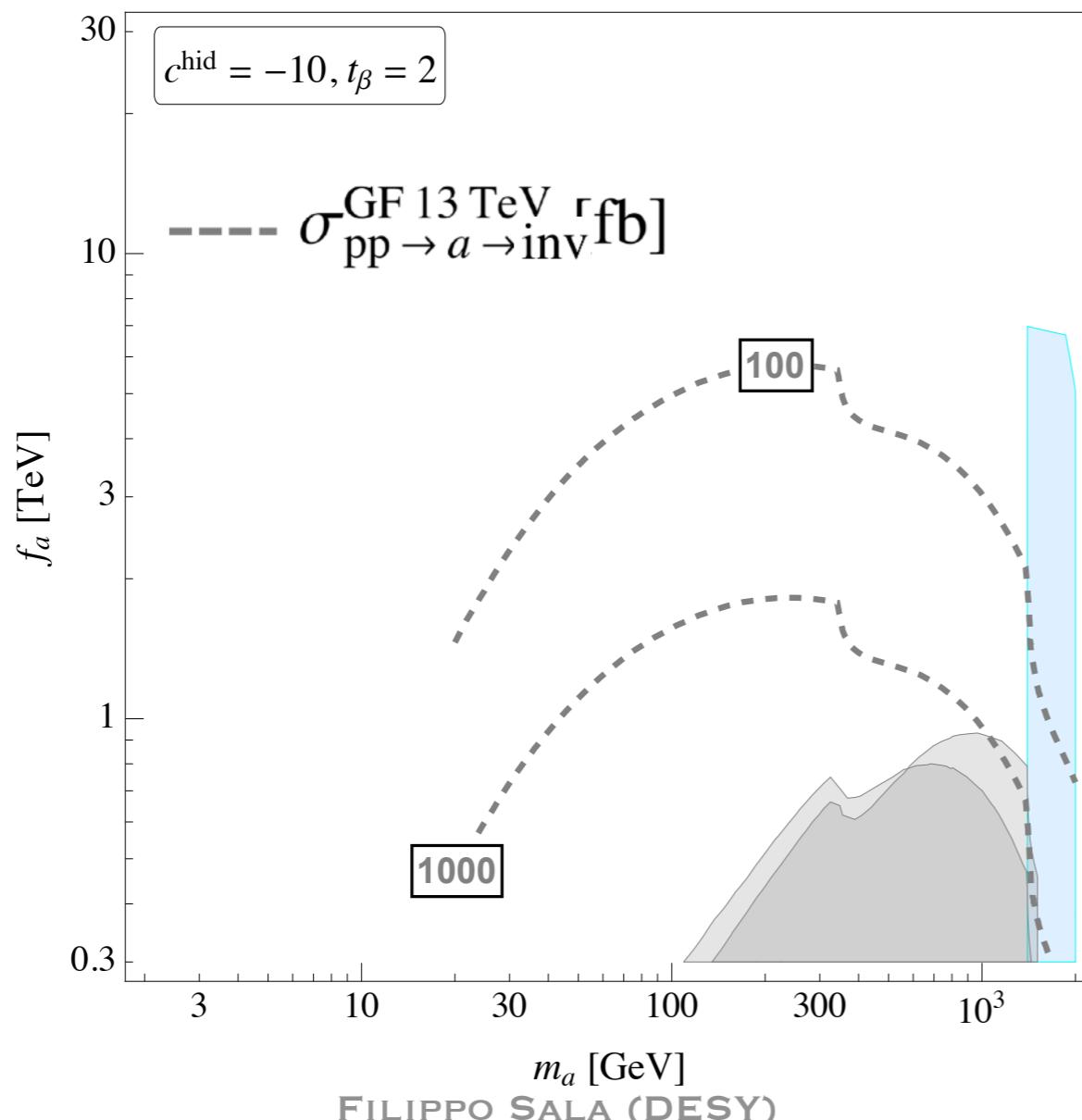
Displaced vertices  
Long lived

Other collider searches  
Beam dump, ...

# LHC: MET + monojet, MET + diphoton

	$p_T > 250$	$p_T > 500$	$p_T > 700$	
$\sigma_{95}$ 8 TeV	90 fb	7.2 fb	3.4 fb	ATLAS 1502.01518
$\sigma_{95}$ 13 TeV [3.2 fb $^{-1}$ ]	553 fb	61 fb	19 fb	ATLAS 1604.07773

Rough procedure: gluon gluon resonance w/ and w/o extra jet simulated with Madgraph  
ratio used to rescale  $\sigma_{pp \rightarrow a \rightarrow GG}$



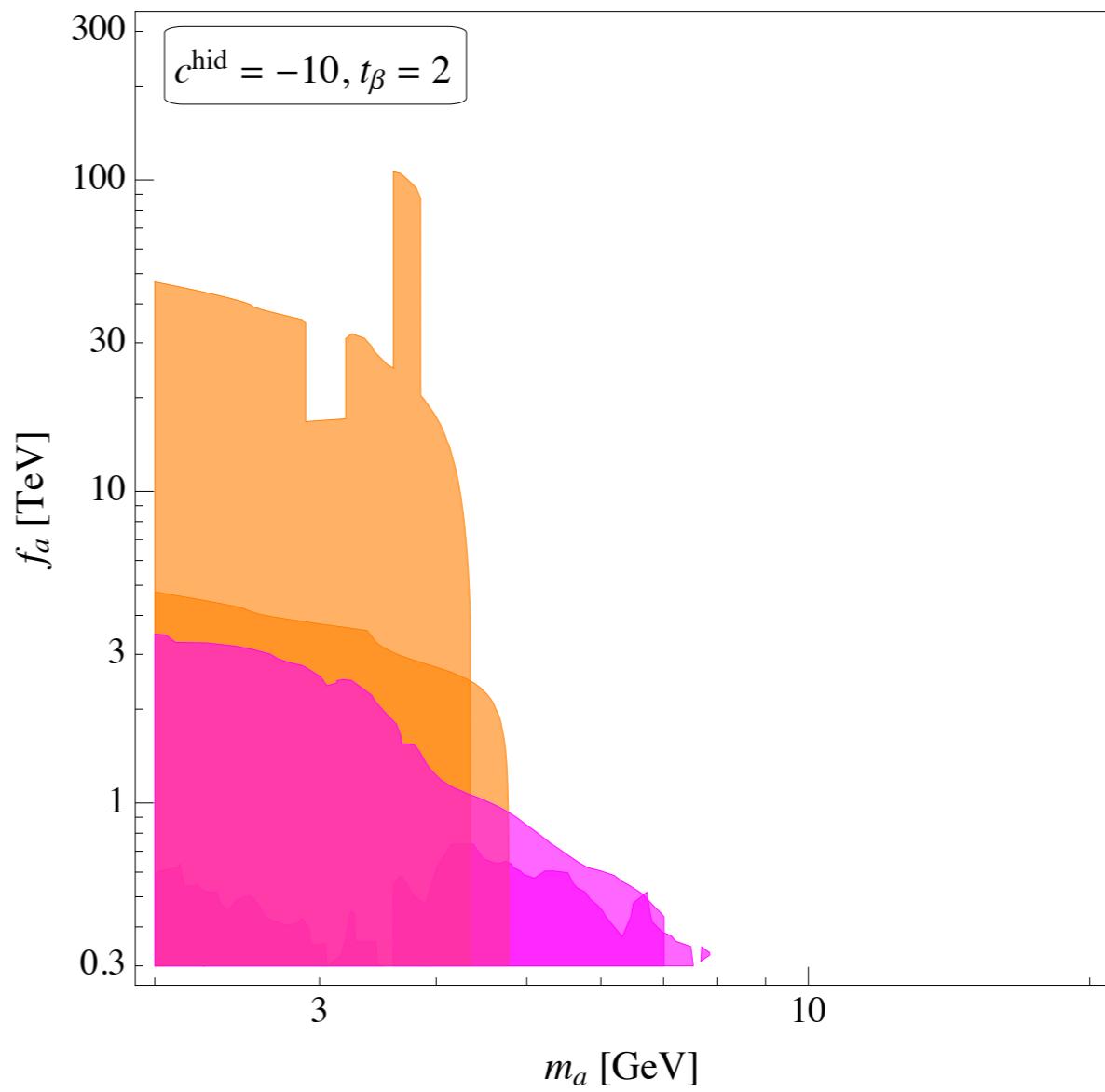
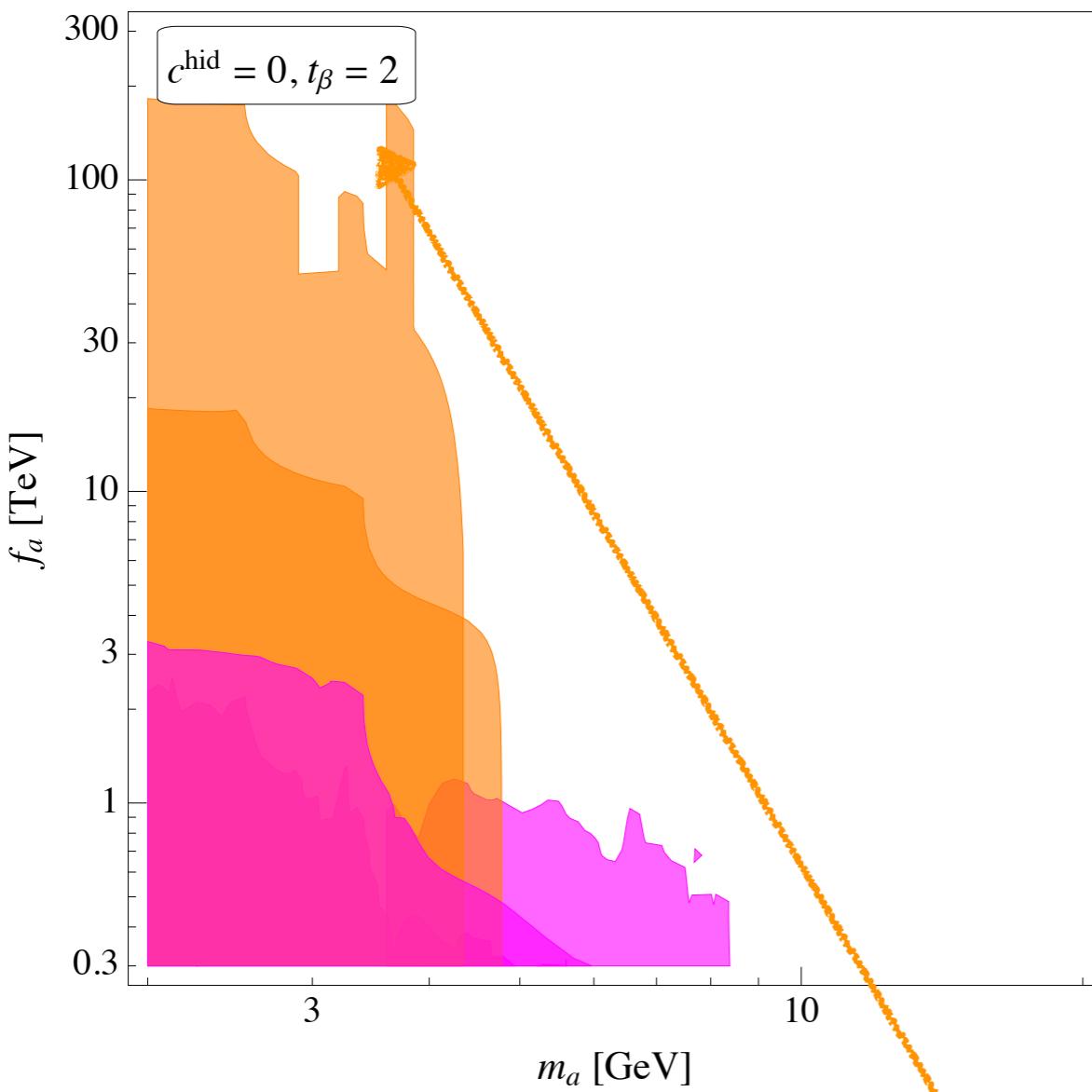
$a \rightarrow \tilde{B}\tilde{B} \rightarrow \gamma\gamma + \text{MET}$   
excludes signals  
down to **0.3 fb** @LHC8

These signals have little dependence on anomalies, and in particular on  $t_\beta$ ,  $r_H$

# Decays of B and Upsilon

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

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

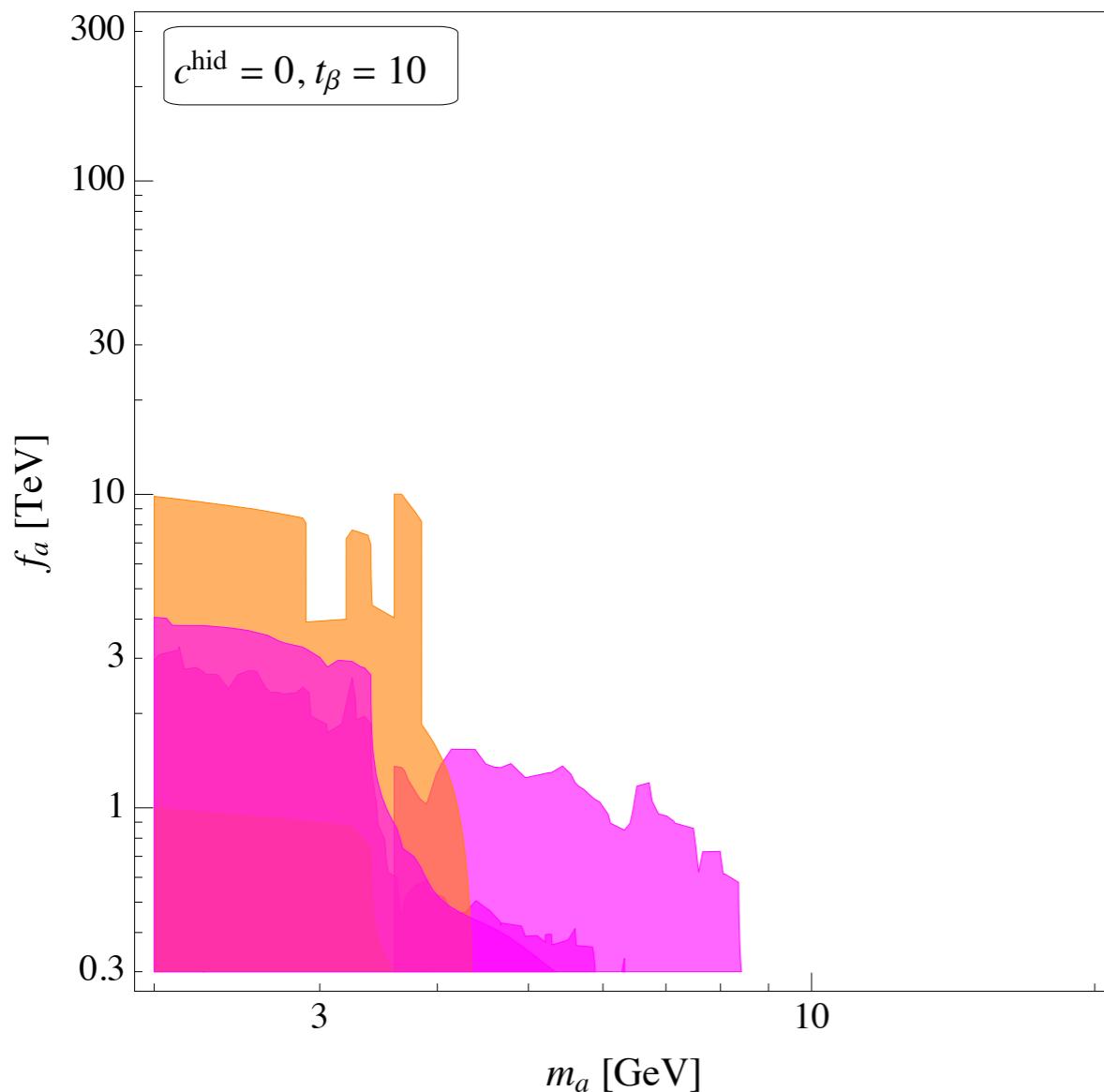


LHCb sensitive to beyond-100-TeV flavour-preserving SUSY!!

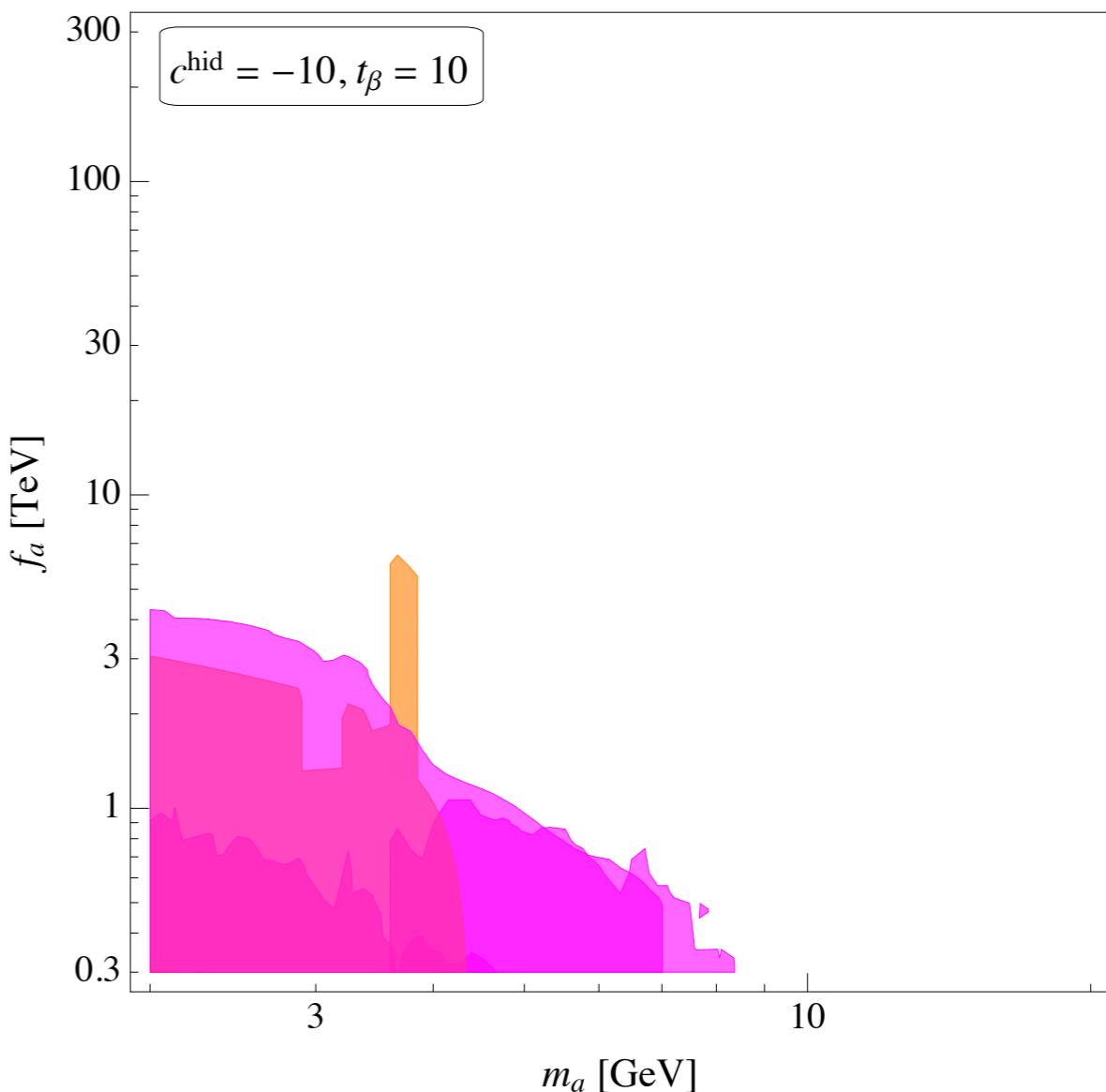
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$B \rightarrow K^{(*)} a(\mu\mu) \sim$  sensitive to value of  $t_\beta$



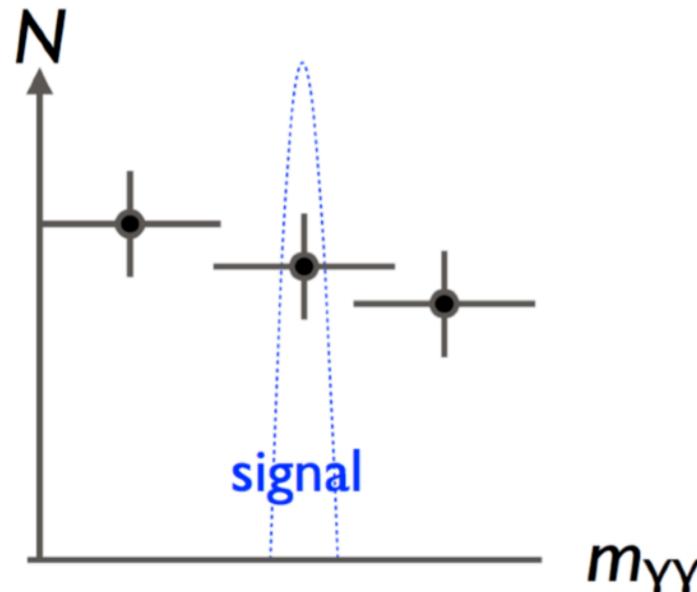
Both disappear for  $r_H = 0$

maybe not, work in progress...

# More on low-mass $\gamma\gamma$

# New $\gamma\gamma$ Bound & Sensitivities

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



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

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

experimental rel. uncertainty

**Current LHC reach?**

If bump-hunt on steep slope or if Monte Carlos improve:

$$N_{\text{bin}}^{\text{signal}} < N_{\text{bin}}^{\text{meas.}} \times 2 \Delta_{\text{bin}}$$

(we take data = SM prediction, and optimise binning)

**Future LHC Reach** we rescale by simulation of bkg with same cuts at different energies  
[Madgraph+Pythia+Delphes]

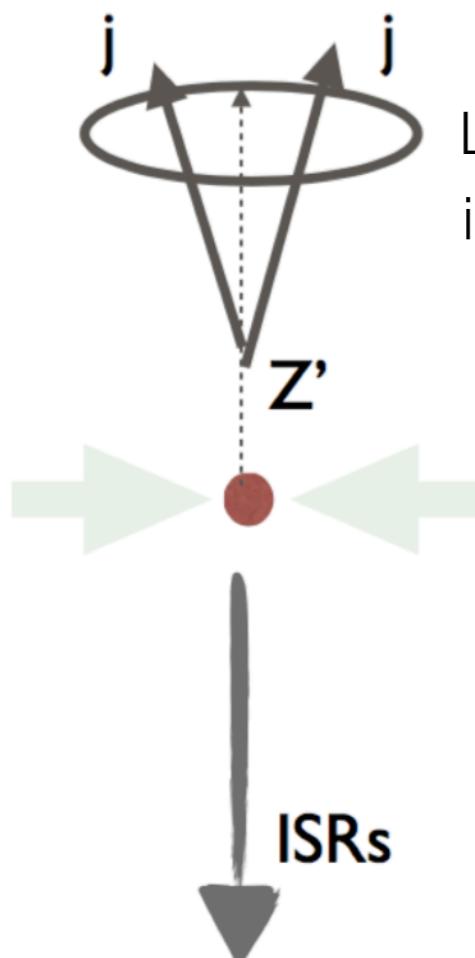
# Good News: they are already doing it!

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

Done recently in **dijet**, tremendous improvement in mass reach!

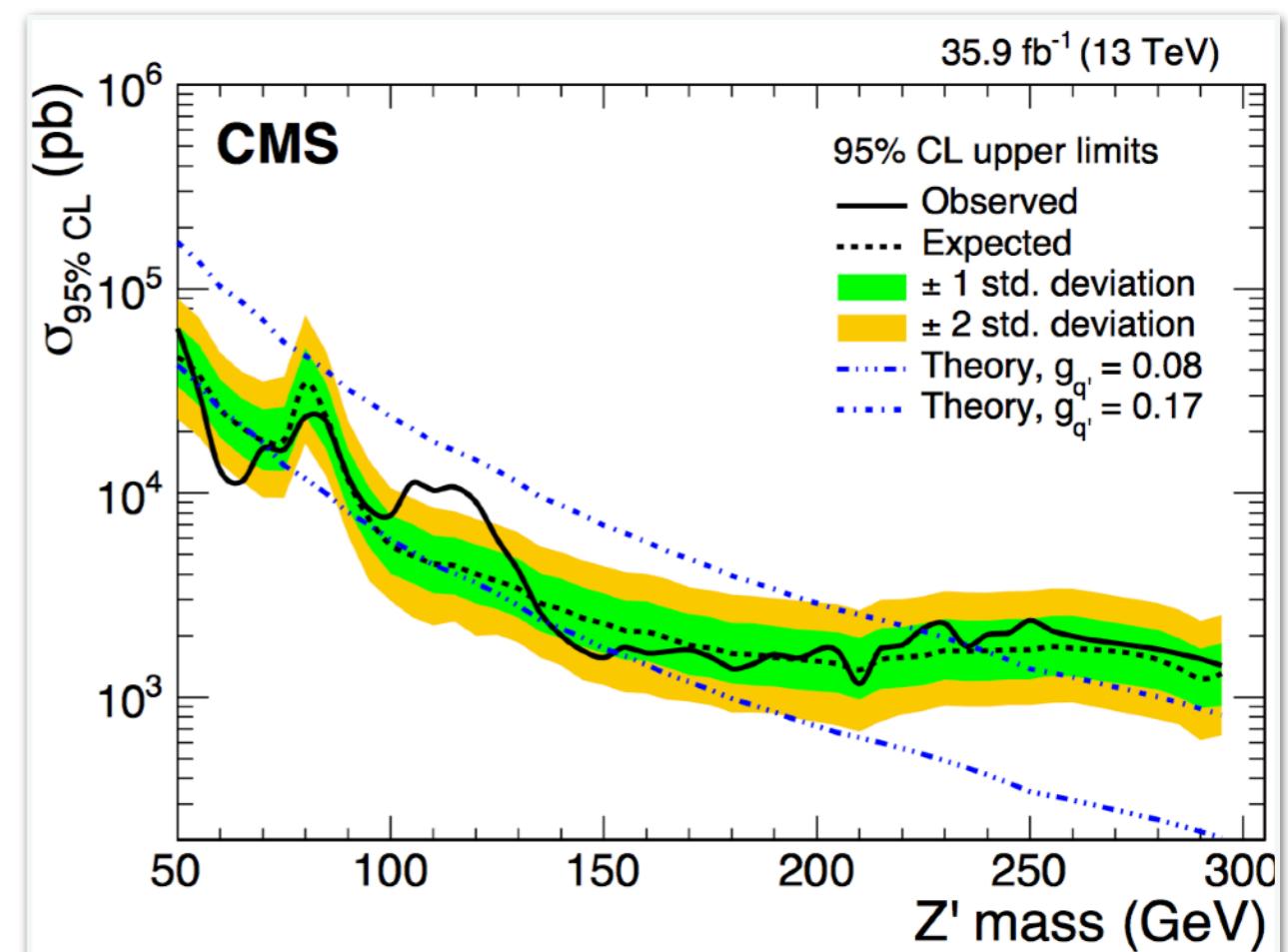
CMS 1710.00159

ATLAS 1801.08769



Look for **boosted** resonance  
in jet substructure

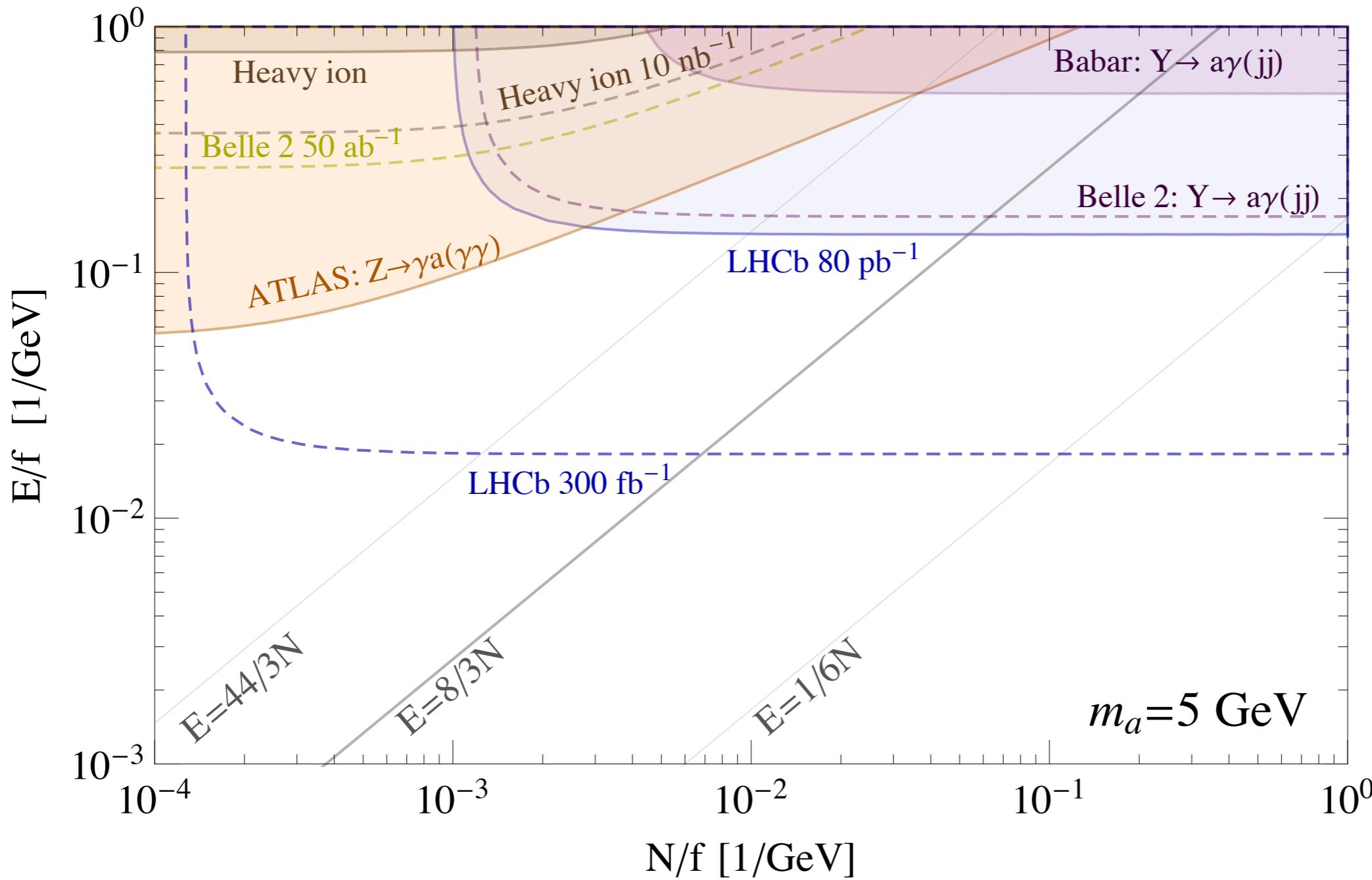
Extra hard object  
to pass the trigger



# What if different couplings?

$$\mathcal{L}_{\text{eff}} \supset \frac{N\alpha_3}{4\pi} \frac{a}{f} G_{\mu\nu} \tilde{G}^{\mu\nu} + \frac{E\alpha_{\text{em}}}{4\pi} \frac{a}{f} F_{\mu\nu} \tilde{F}^{\mu\nu}$$

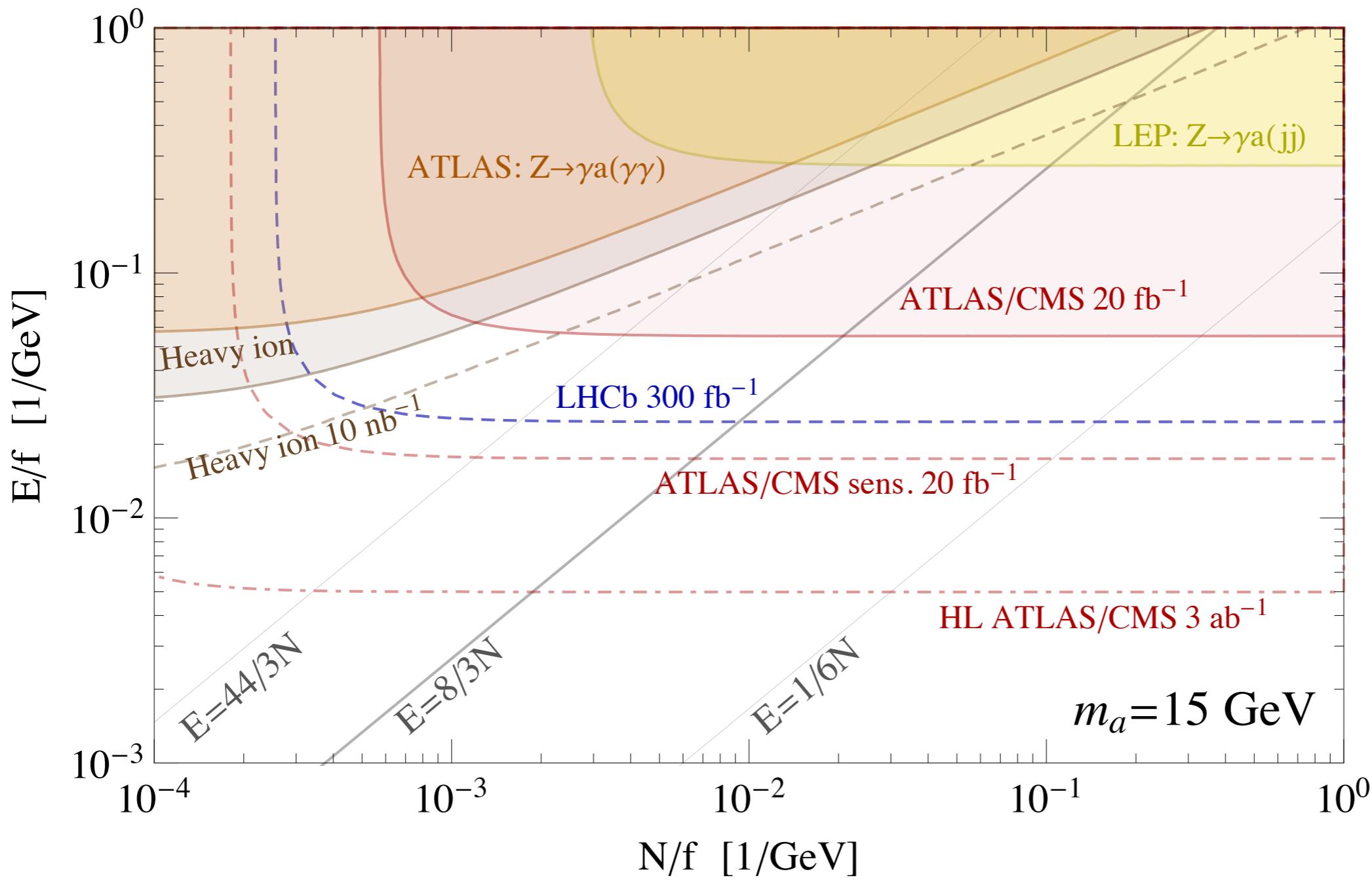
Cid-Vidal Mariotti Redigolo FS Tobioka 1810.xxxxx



# What if different couplings?

$$\mathcal{L}_{\text{eff}} \supset \frac{N\alpha_3}{4\pi} \frac{a}{f} G_{\mu\nu} \tilde{G}^{\mu\nu} + \frac{E\alpha_{\text{em}}}{4\pi} \frac{a}{f} F_{\mu\nu} \tilde{F}^{\mu\nu}$$

Cid-Vidal Mariotti Redigolo FS Tobioka 1810.xxxxx



# Low-mass analyses we found

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

# Signal efficiencies and cross section

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

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

$\sigma_{\gamma\gamma}^{\text{LO}}$  reproduces up to a constant factor  $C_s$  the shape of  $\sigma_{\gamma\gamma}^{\text{MCtot}}$  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  $C_s \equiv \sigma_{\gamma\gamma}^{\text{MCtot}}(s)/\sigma_{\gamma\gamma}^{\text{LO}}(s)$  is hence included in Eq. (5) and we obtain  $C_{7\text{ TeV}} \simeq C_{8\text{ TeV}} \simeq 0.85$  while  $C_{2\text{ TeV}} \simeq 1$  at the Tevatron center of mass energy. The

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

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

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

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

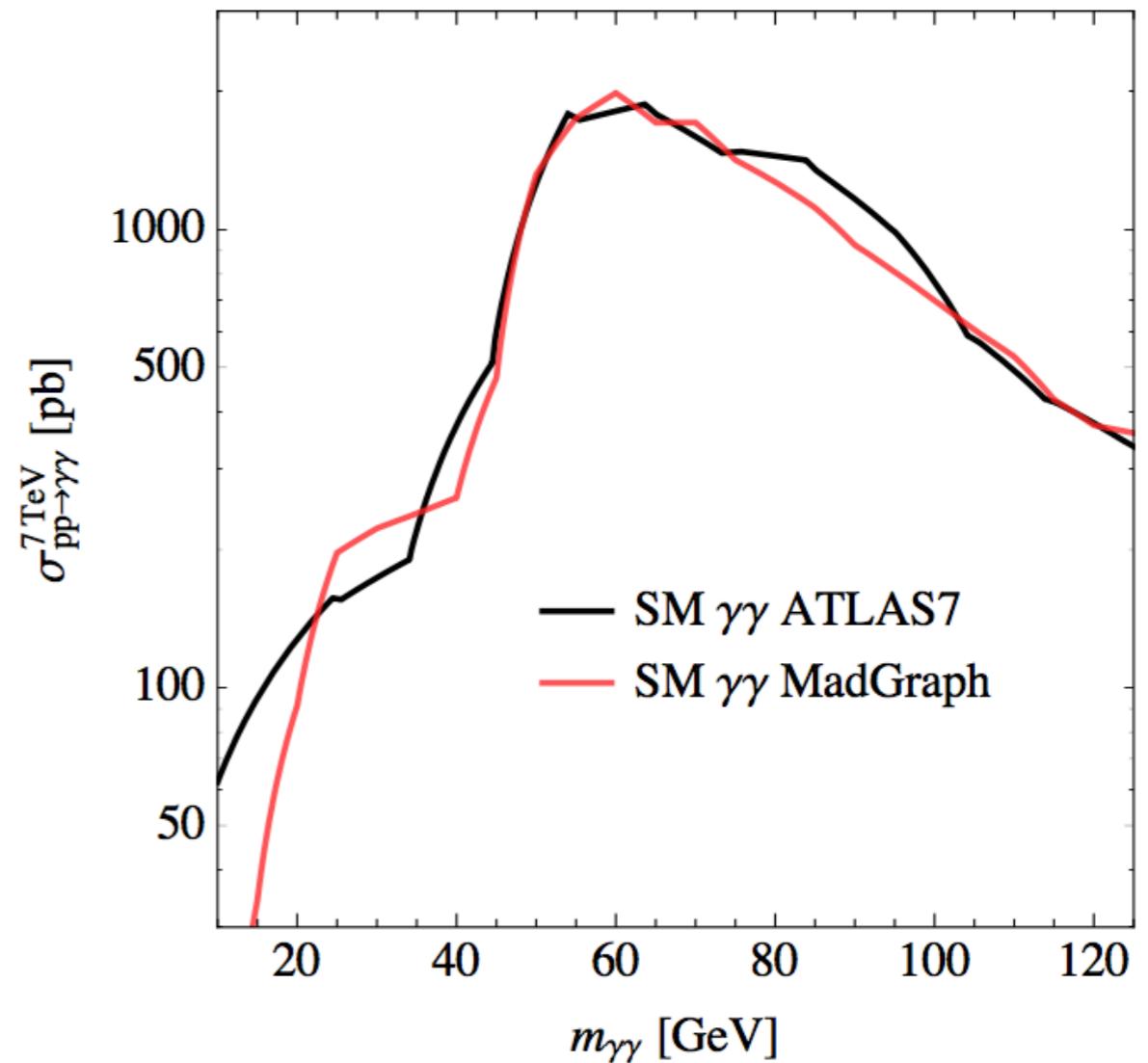
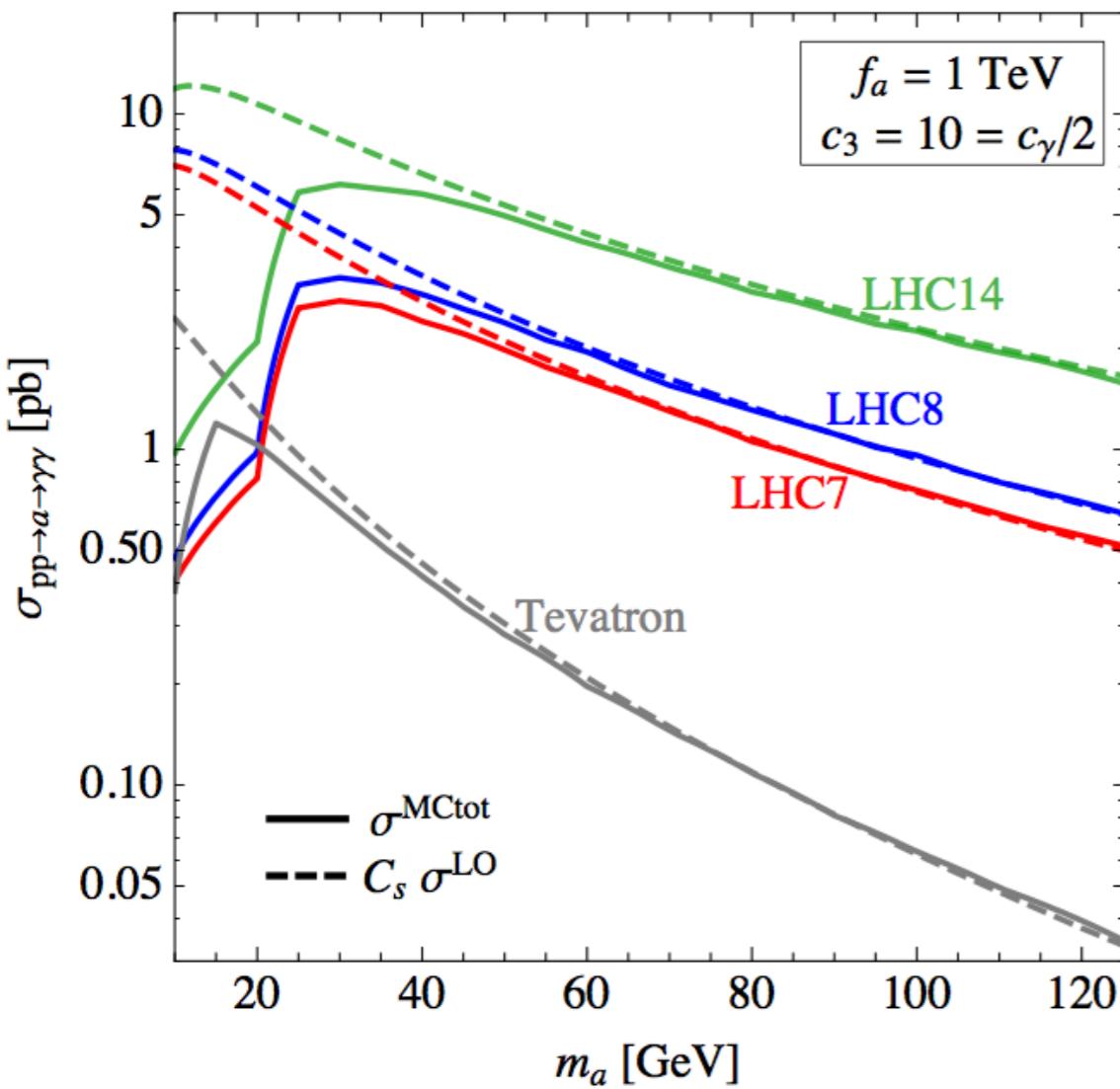
where  $f_g(x)$  is the gluon PDF from the **MSTW2008nnlo68** set [58], where we fix the pdf scale  $q = m_a$ . We work with

$$K_\sigma = 3.7 \quad \text{from ggHiggs v3.5} \\ \text{Bonvini et al. 2013-2016}$$

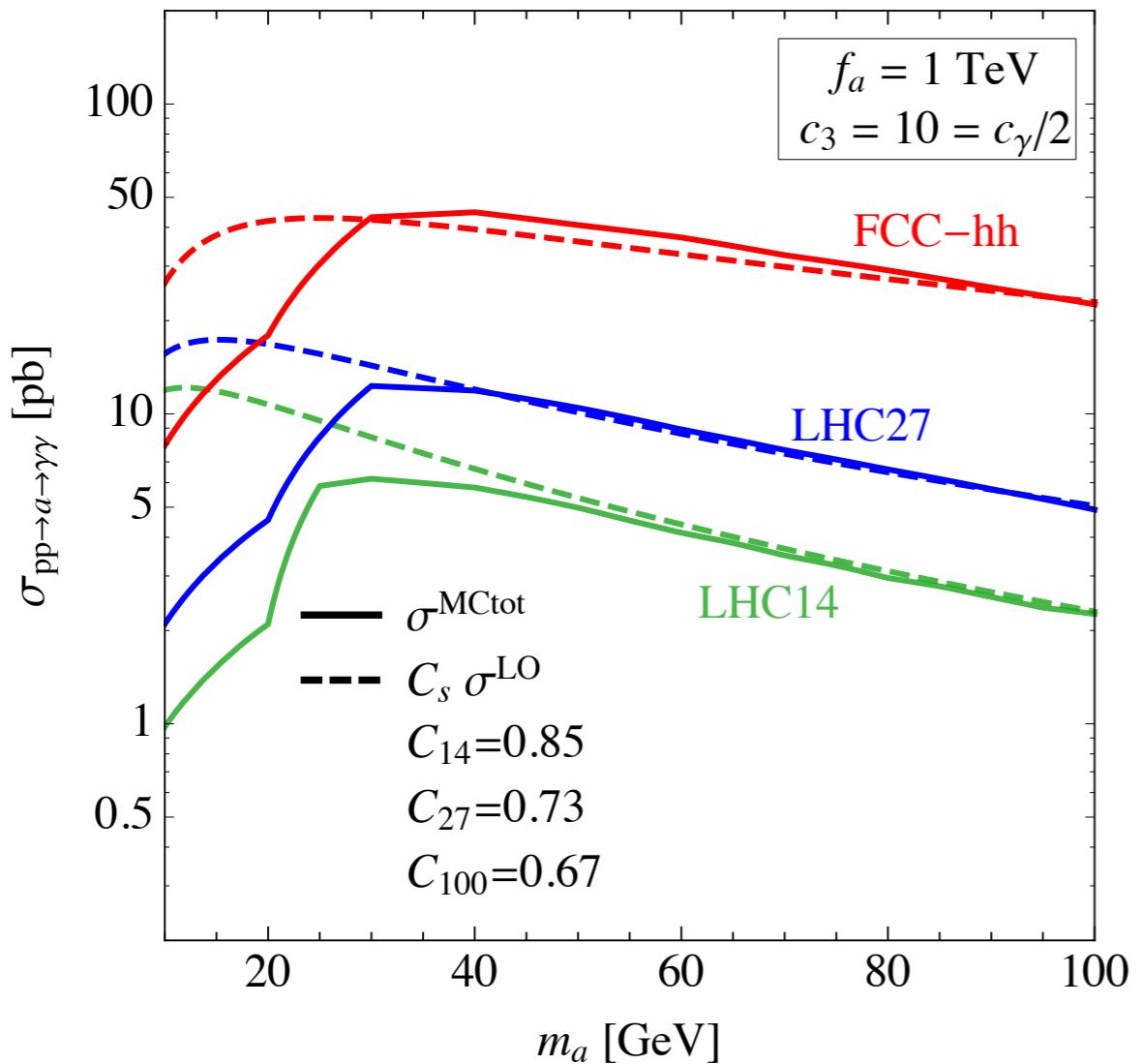
$$K_g = 2.1$$

$m_a$ in GeV	10	20	30	40	50	60	70	80	90	100	110	120
$\epsilon_S$ for $\sigma_{7\text{ TeV}}$ 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
$\epsilon_S$ for $\sigma_{7\text{ TeV}}$ 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
$\epsilon_S$ for $\sigma_{8\text{ TeV}}$ 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
$\epsilon_S$ for $\sigma_{2\text{ TeV}}$ 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
$\epsilon_S$ for $\sigma_{2\text{ TeV}}$ 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

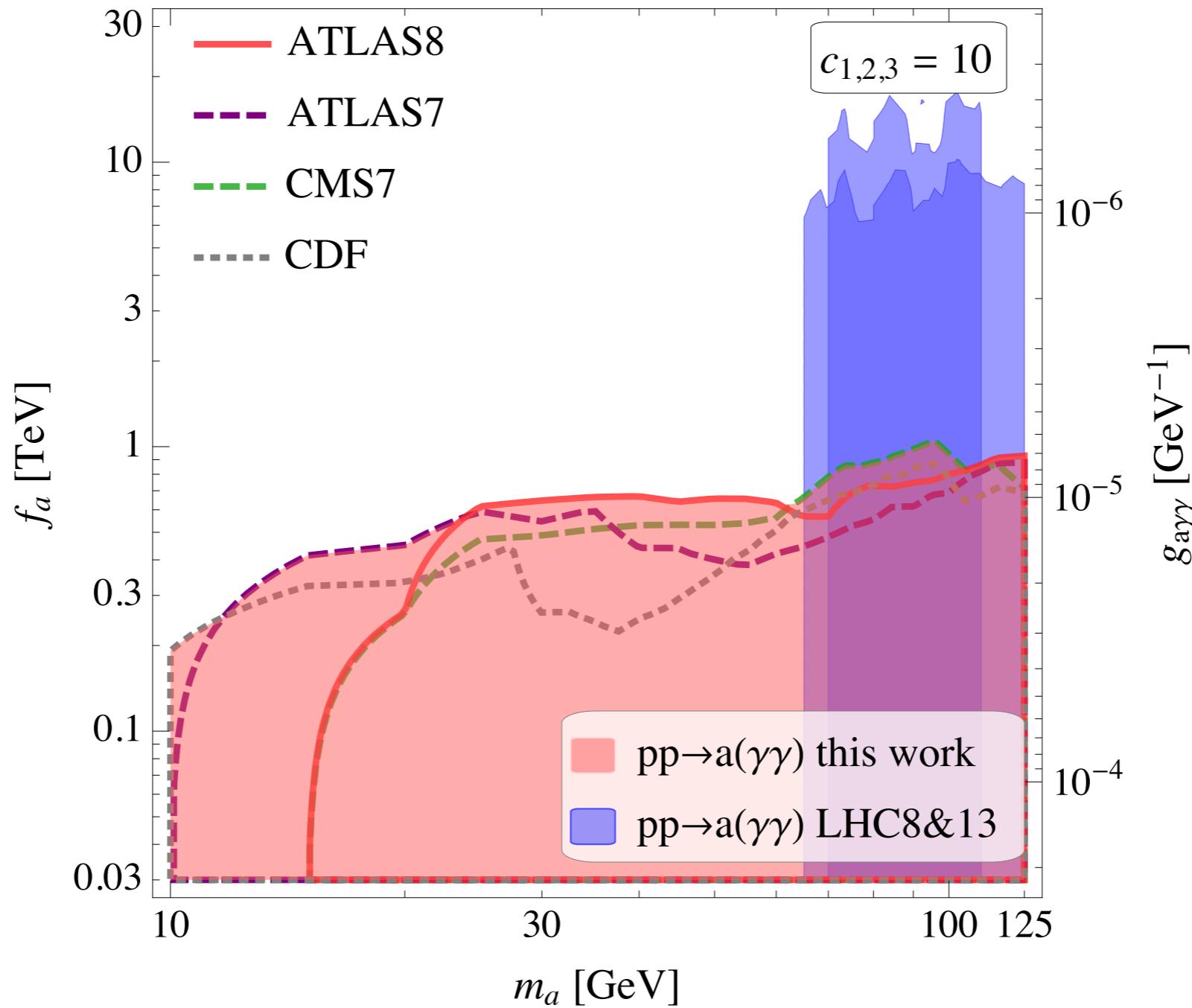
# Validation



# Validation



# Interplay of LHC and Tevatron

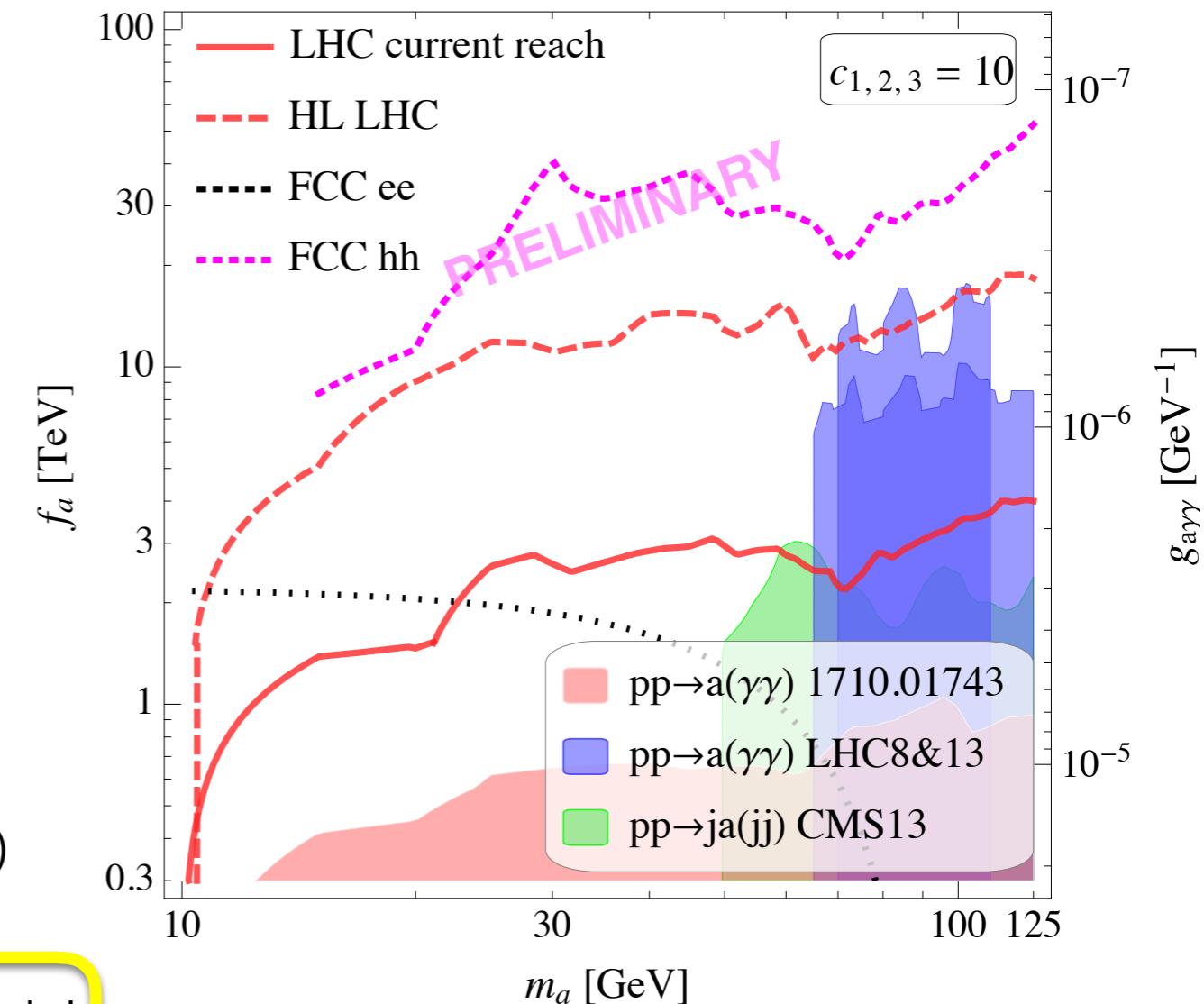


**FCC ee** reach computed rescaling  
LEP limits on  $\text{BR}[Z \rightarrow \gamma a(jj)]$   
and assuming  $10^{12}$   $Z$  bosons

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

**FCC hh** reach computed like LHC14 one  
[4., from simulations, Lumi=  $3 \text{ ab}^{-1}$ ]  
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

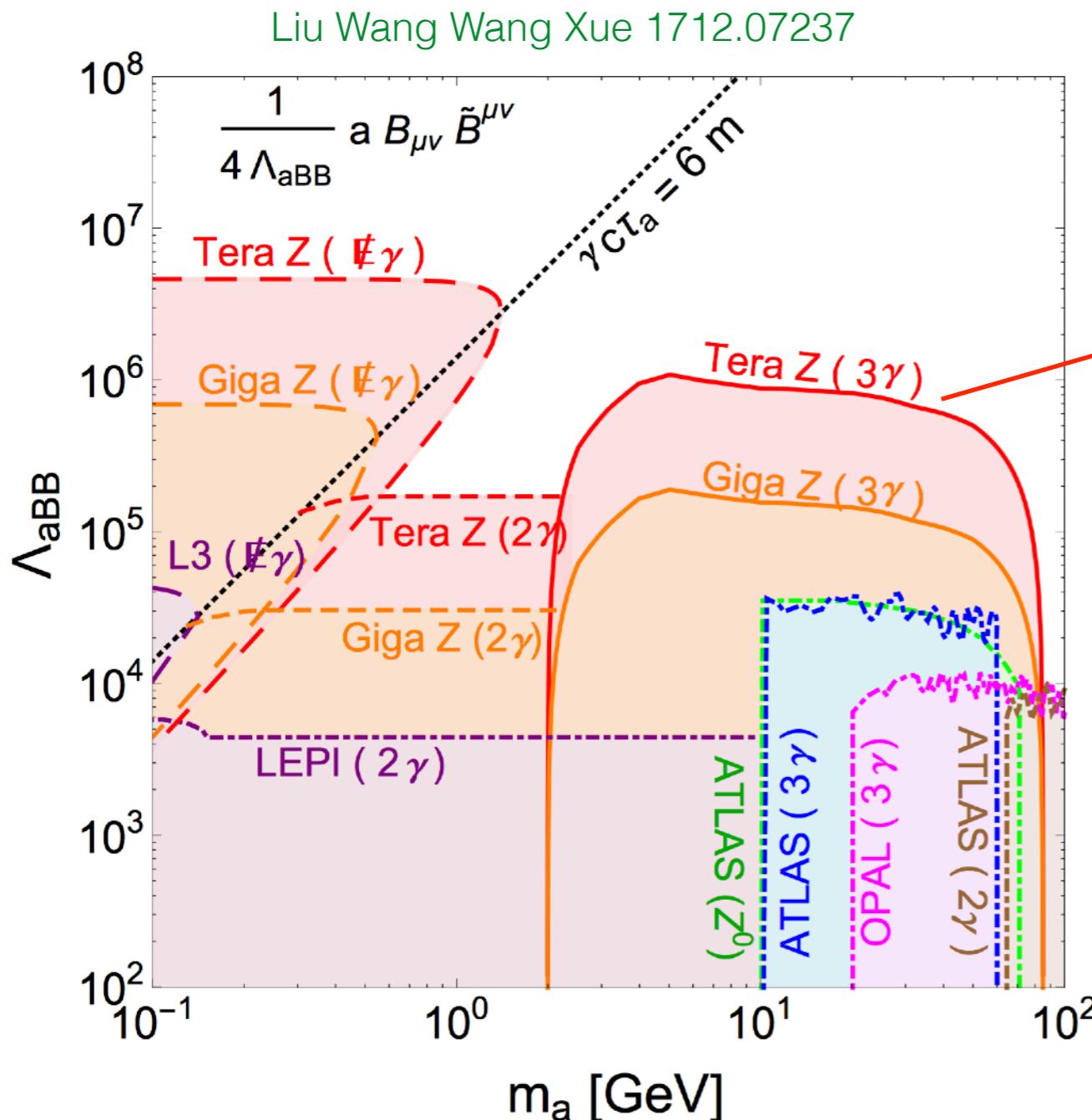
at 100 TeV game could be very different (larger boosts,...)

Thoughts in progress...

# FCC-ee with no gluon coupling

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

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



To compare with previous slides:

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

For Tera Z  $\text{BR}[Z \rightarrow \gamma a(\gamma\gamma)] \lesssim 3 \times 10^{-9}$   
[current LEP limit  $\lesssim 5 \times 10^{-6}$  ]

**FCC ee** could reach  $f_a \lesssim 100$  TeV

**FCC hh** VBF ?

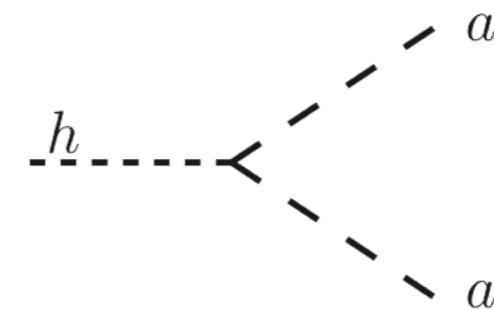
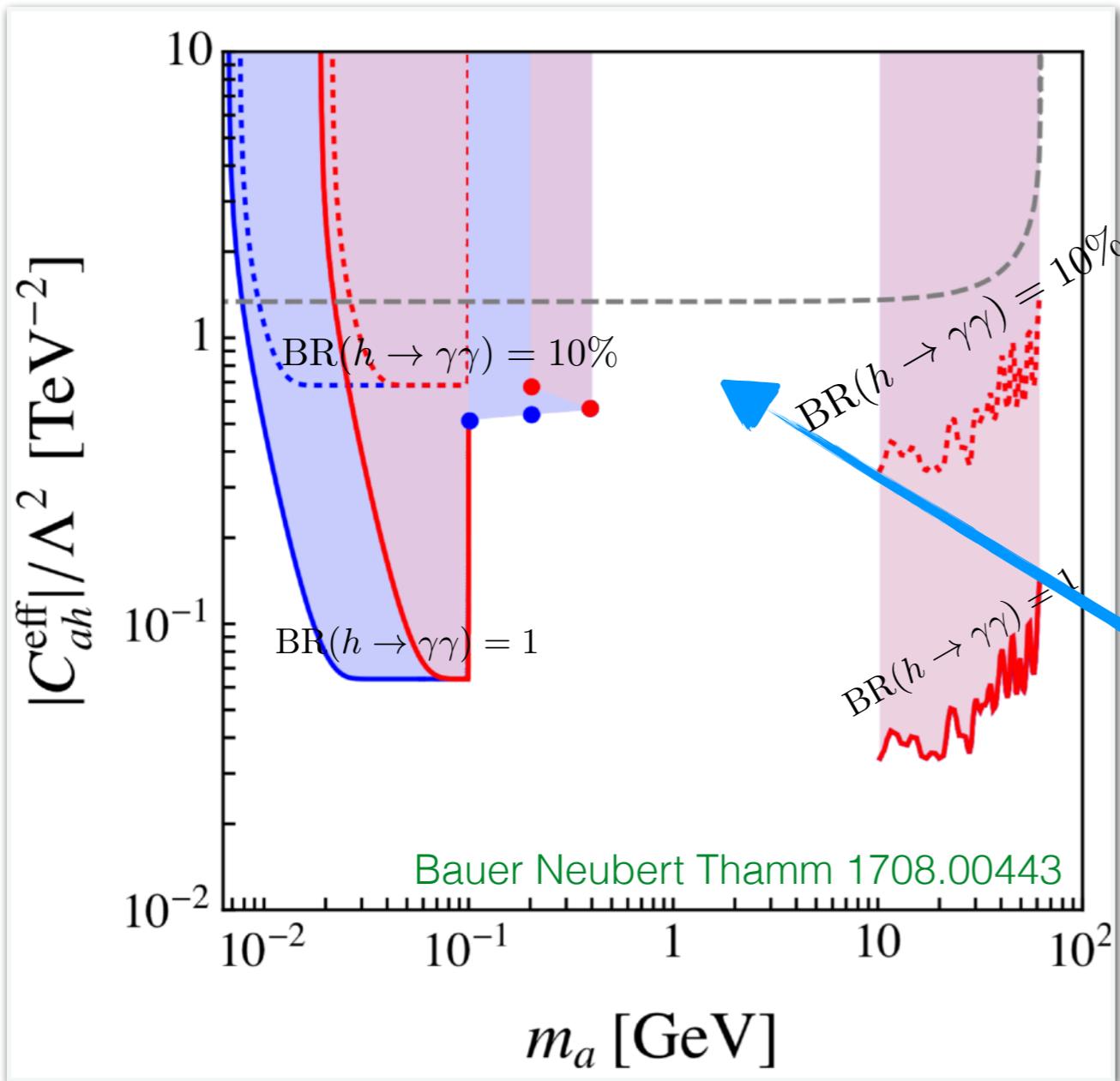
Associated production ?

Photon fusion ?

???

# LHC & other ALP couplings (no gluons)

A selected example: **Higgs decays** to 4 photons



$$\mathcal{L}_{\text{eff}}^{D \geq 6} = \frac{C_{ah}}{\Lambda^2} (\partial_\mu a)(\partial^\mu a) \phi^\dagger \phi$$

$$\mathcal{L}_{\text{eff}}^{D \leq 5} \ni e^2 C_{\gamma\gamma} \frac{a}{\Lambda} F_{\mu\nu} \tilde{F}^{\mu\nu}$$

Modified Diphoton Isolation  
could help fill this gap?

For more on ALP at colliders see e.g.

Mimasu Sanz 1409.4792, ...., Bauer+1808.10323