New Searches Beyond the SM

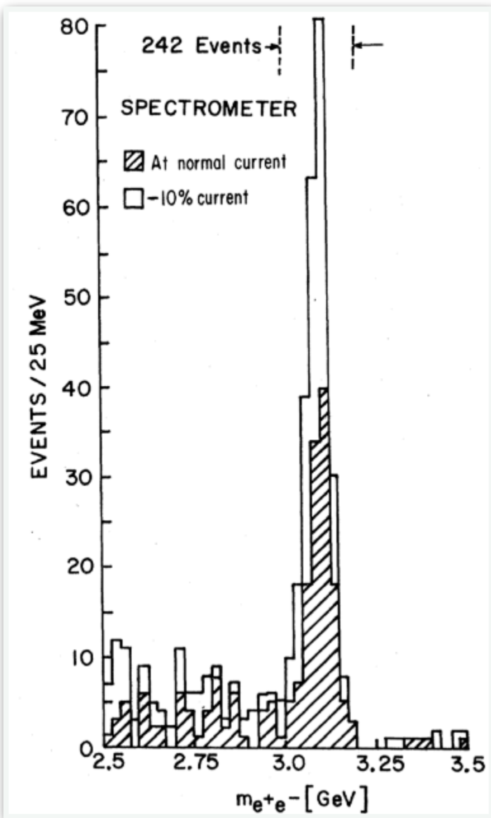
Light Resonances @ the LHC

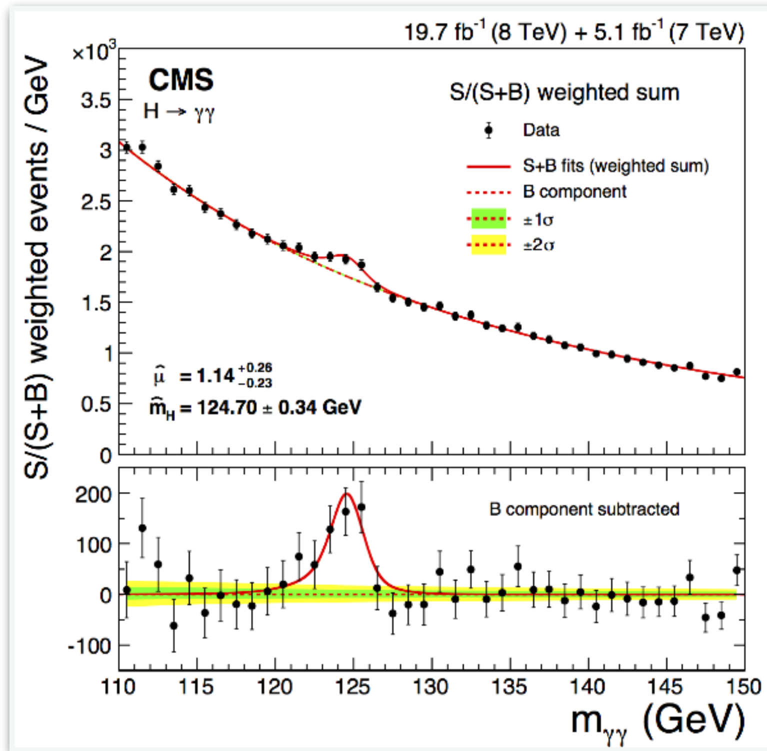
Filippo Sala

DESY Hamburg

Joint Rome Seminar 21 Dec 2017 University Rome1 La sapienza

Searching for Resonances





Searches for resonances decaying 2-body are **solid discovery** method at colliders

Famous examples:

$$J/\psi,\ \Upsilon,\ Z,\ h$$

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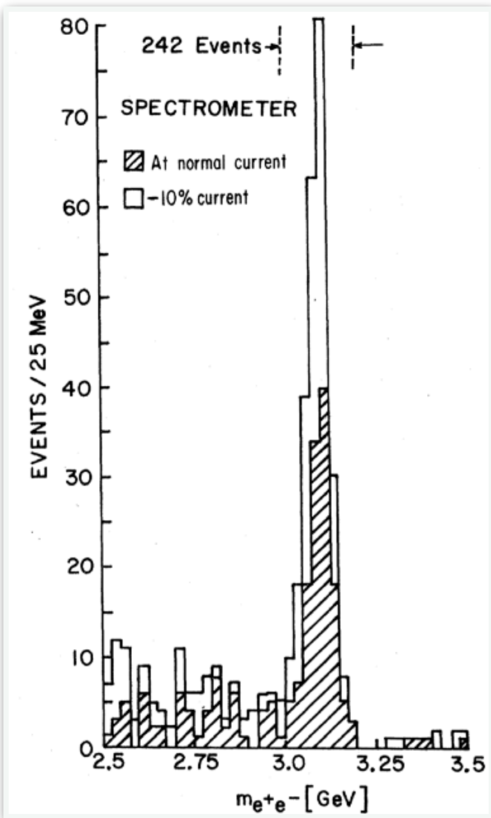

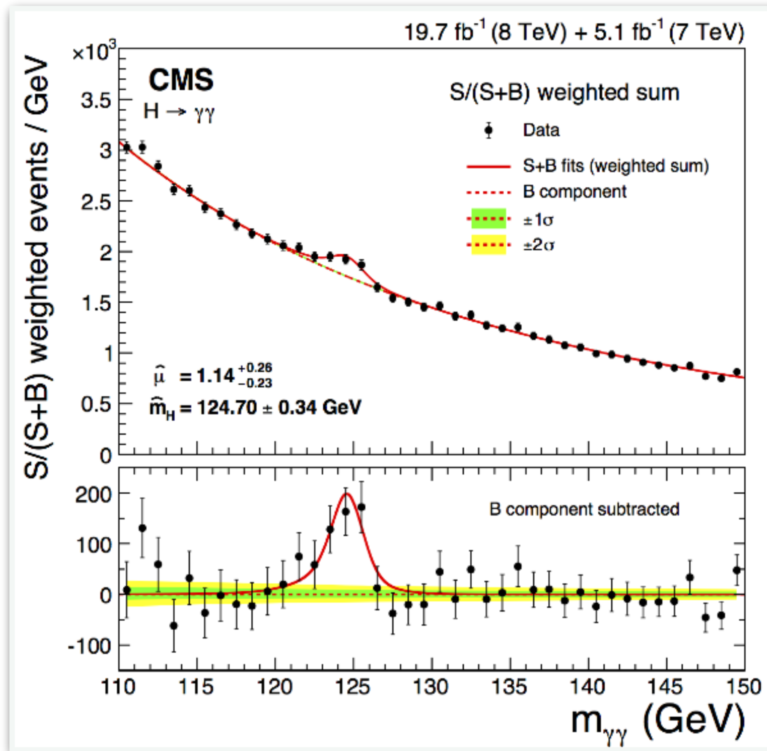

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Beyond the Standard Model (**BSM**)

Extensive coverage of "peaks" at the LHC:

Diphotons **Dijets** **Dibosons (W,Z)**

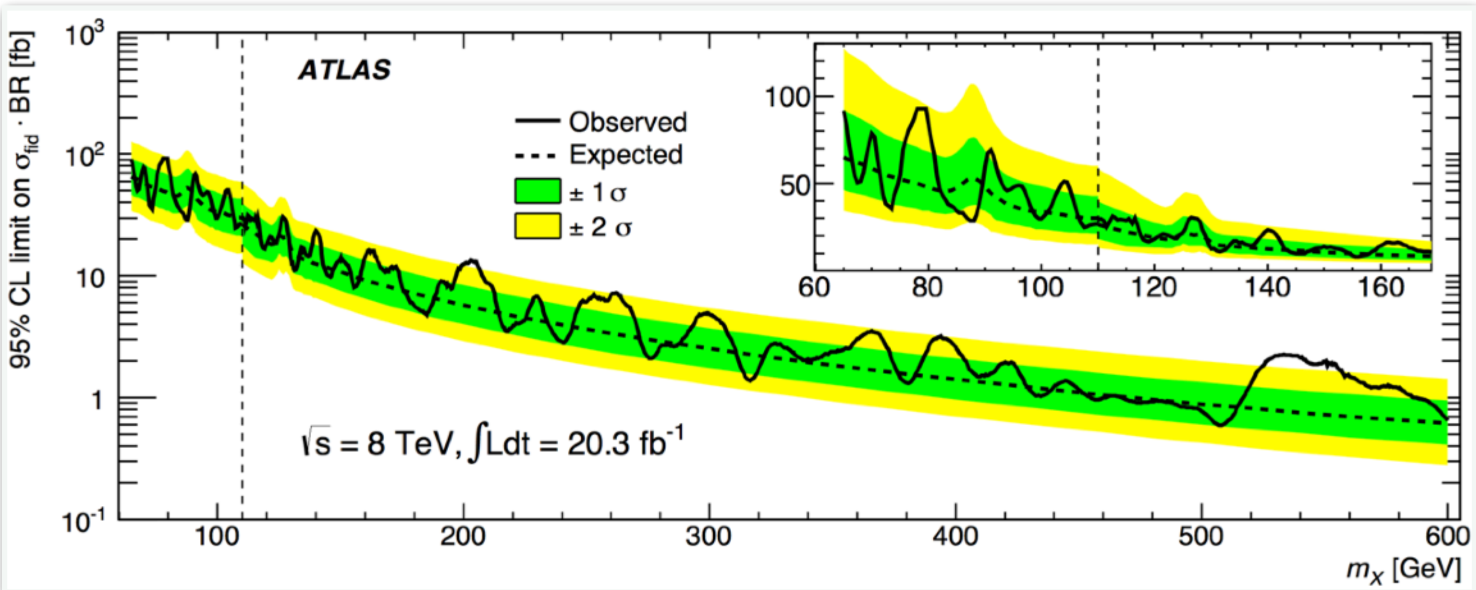
Dileptons **Ditop** **DiHiggs**

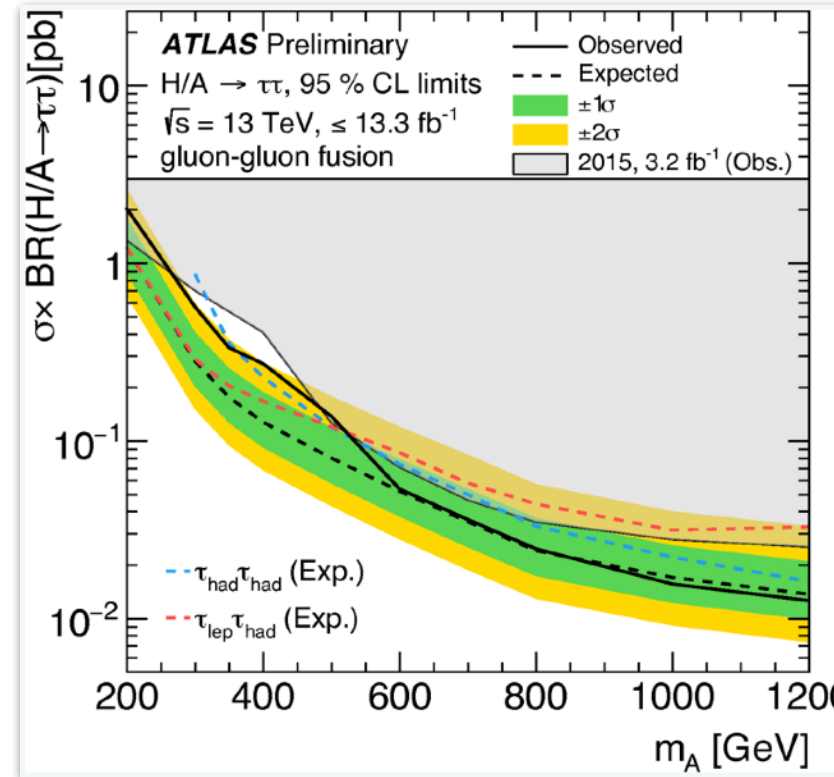
"Vojamo vede' er piccone"

A. Wulzer

BSM resonances: where to look?

Present searches: $M_{\gamma\gamma,\tau\tau,\ldots} > O(100)\ \mathrm{GeV}$





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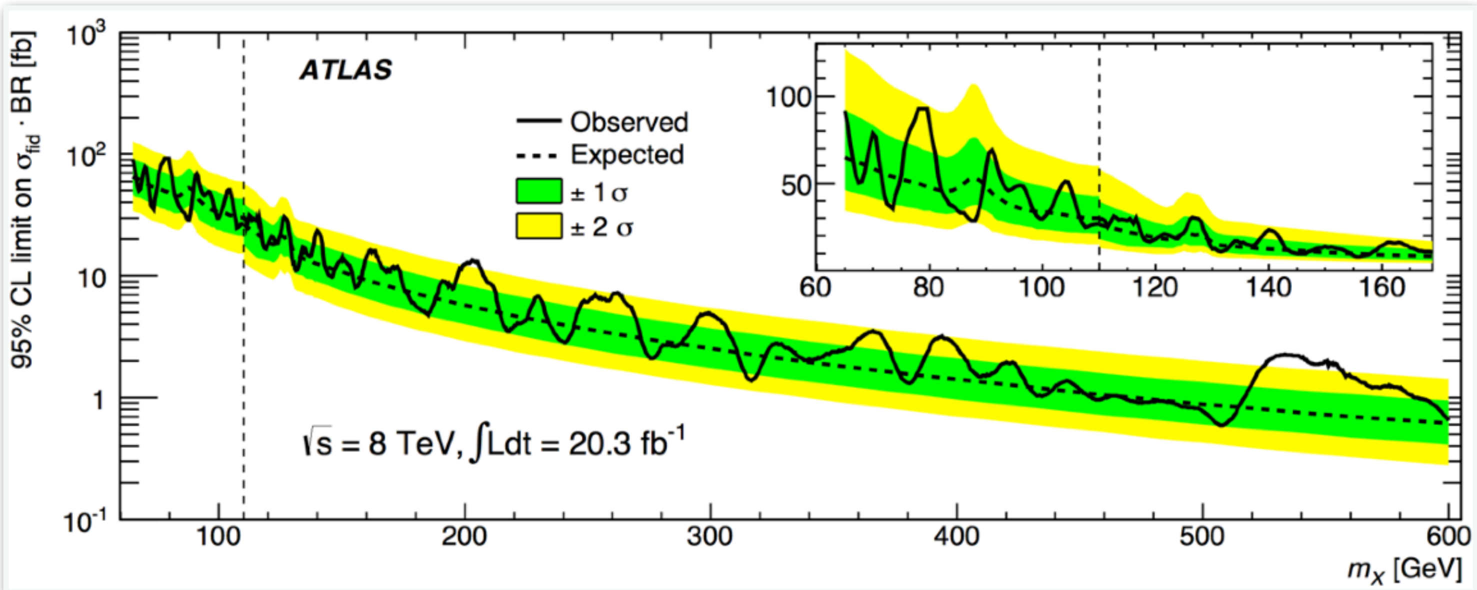

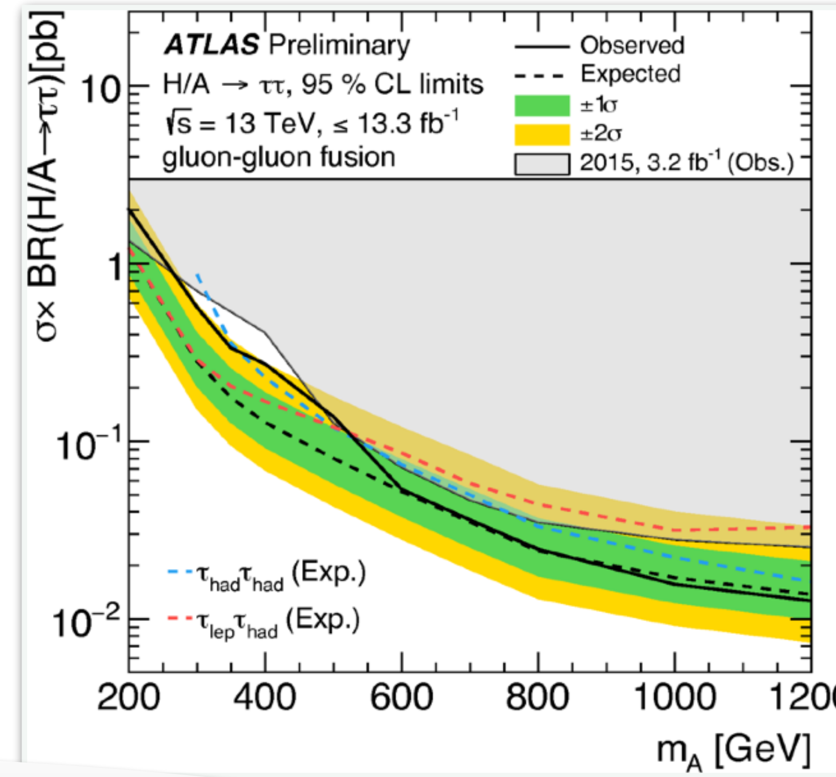

Why not below?

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

This seminar: demystify 1. 2. and 3., and extend scope of LHC!

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Axion-like particles (ALPs)

$M_{\rm BSM} \approx g_* f_a$

m_a

aka Pseudo Goldstone Bosons (**PGB**s)

associated to spontaneous breaking of global symmetry $a \to a + \theta f_a$

with a small explicit breaking that controls $m_a \neq 0$

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m_a — **Mass** of the ALP naturally lighter than any BSM scale $M_{\rm BSM}$ (*technically natural*, unlike Higgs mass)

f_a — decay constant controls **Couplings** of the ALP

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

Axion-like particles (ALPs)

$M_{\rm BSM} \approx g_* f_a \gtrsim \rm TeV$ ~ from LHC exclusions

$m_a \sim 1 - 100 \ \rm GeV$ ~ an unexplored range

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

Bosons (**PGB**s)

to spontaneous breaking of global symmetry $a \to a + \theta f_a$

with a small explicit breaking that controls $m_a \neq 0$

an any BSM scale $M_{\rm BSM}$

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They already exist: pions from QCD

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"**Just because**" strong sector: vector-like confinement see e.g. Kilic Okui Sundrum 0906.0577

[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 $\Rightarrow$ $m_\eta \sim m_h \times \frac{f}{v} \sim 600 \text{ GeV} \times \sqrt{\frac{0.05}{(v/f)^2}}$

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

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

PGB 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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→ Tune CC to zero: explicit breaking of $U(1)_R$

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

Bagger+ hep-ph/9405345

→ Metastable vacuum Intriligator Seiberg Shih 2007

....

R-axion gets a mass

$$m_a \ll M_{\text{SUSY}}$$

light SUSY particle by symmetry
rather than e.g. by naturalness!

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...try breaking
...gino masses

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

... $(1)_R$ spontaneously

Massless Goldstone in the spectrum R-axion a

Only mass range studied
before Bellazzini Mariotti Redigolo FS Serra PRL119 (2017)

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

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

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

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

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

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

R-axion summary

Spontaneously broken R-symmetry is quite generic

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

ALP aficionado: R-axion is an Axion-like particle, with a reason for its couplings

Bellazzini Mariotti Redigolo FS Serra 1702.02152

SUSY aficionado: could be the first sign of SUSY at colliders!

following part of the talk

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ALP pheno: setting the stage

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

just for definiteness

otherwise ~ not a pseudo Goldstone

R-axion specific: Could it be the first sign of SUSY at the LHC?

All other SUSY particles "decoupled" i.e. beyond reach of LHC14

Benchmark in plots of next page: $m_{\tilde{B}} \simeq 500\ \mathrm{GeV}$ $m_{\tilde{W}} \simeq 1\ \mathrm{TeV}$ $m_{\tilde{g}} \simeq 2.5\ \mathrm{TeV}$

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

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

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

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

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

i.e. an anomaly

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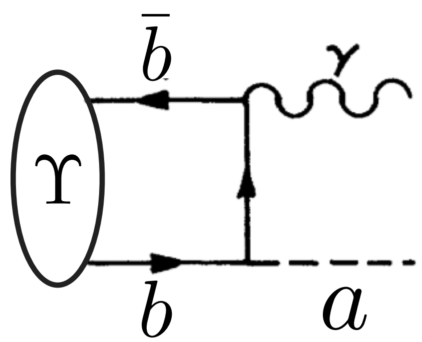
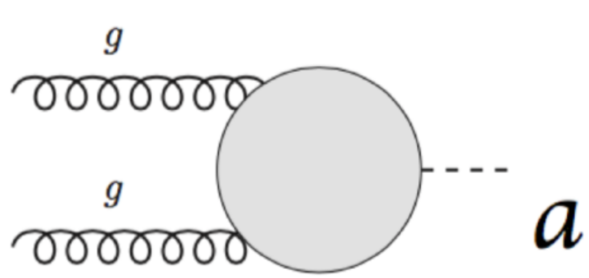
Present ALP mass coverage





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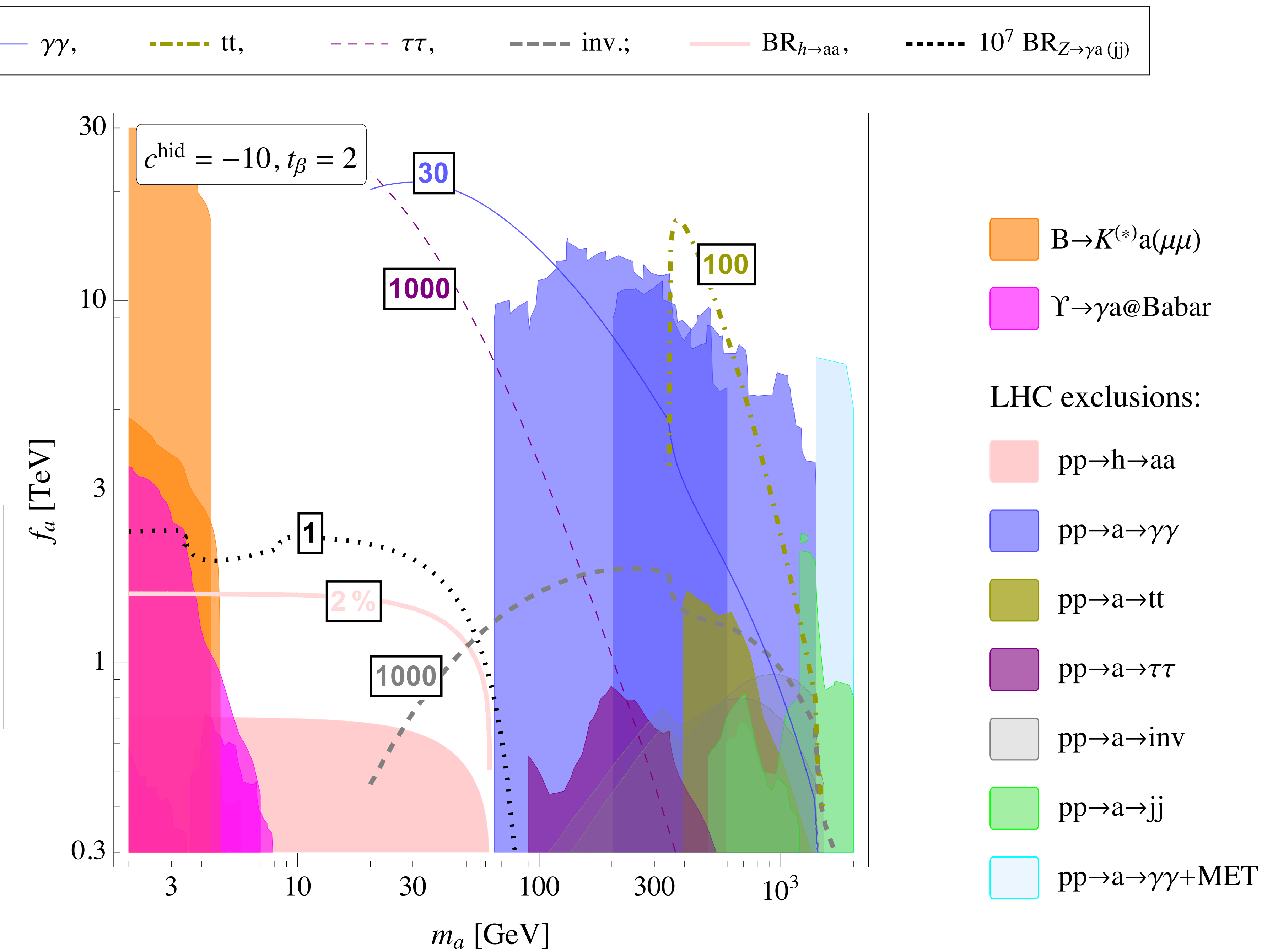

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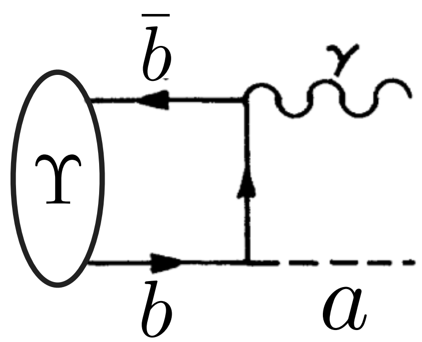

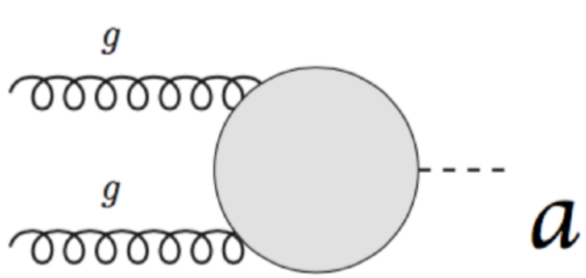

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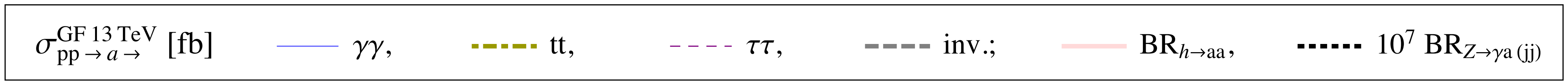
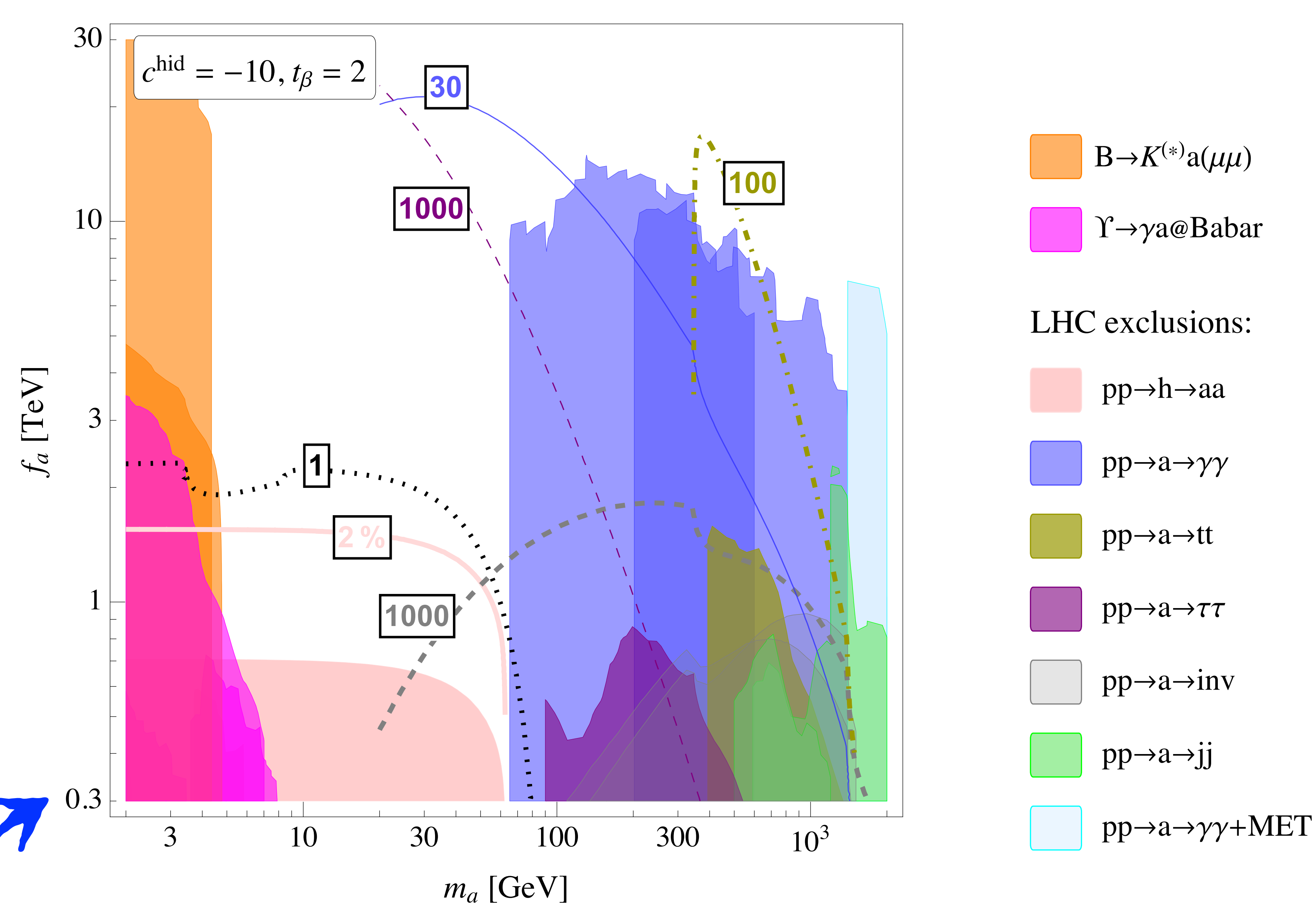
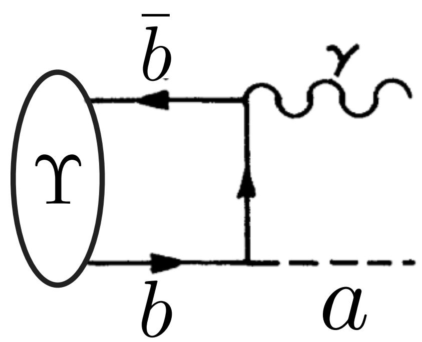
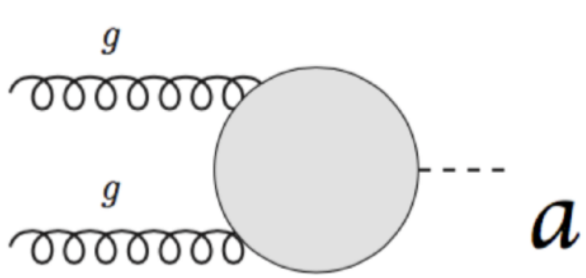




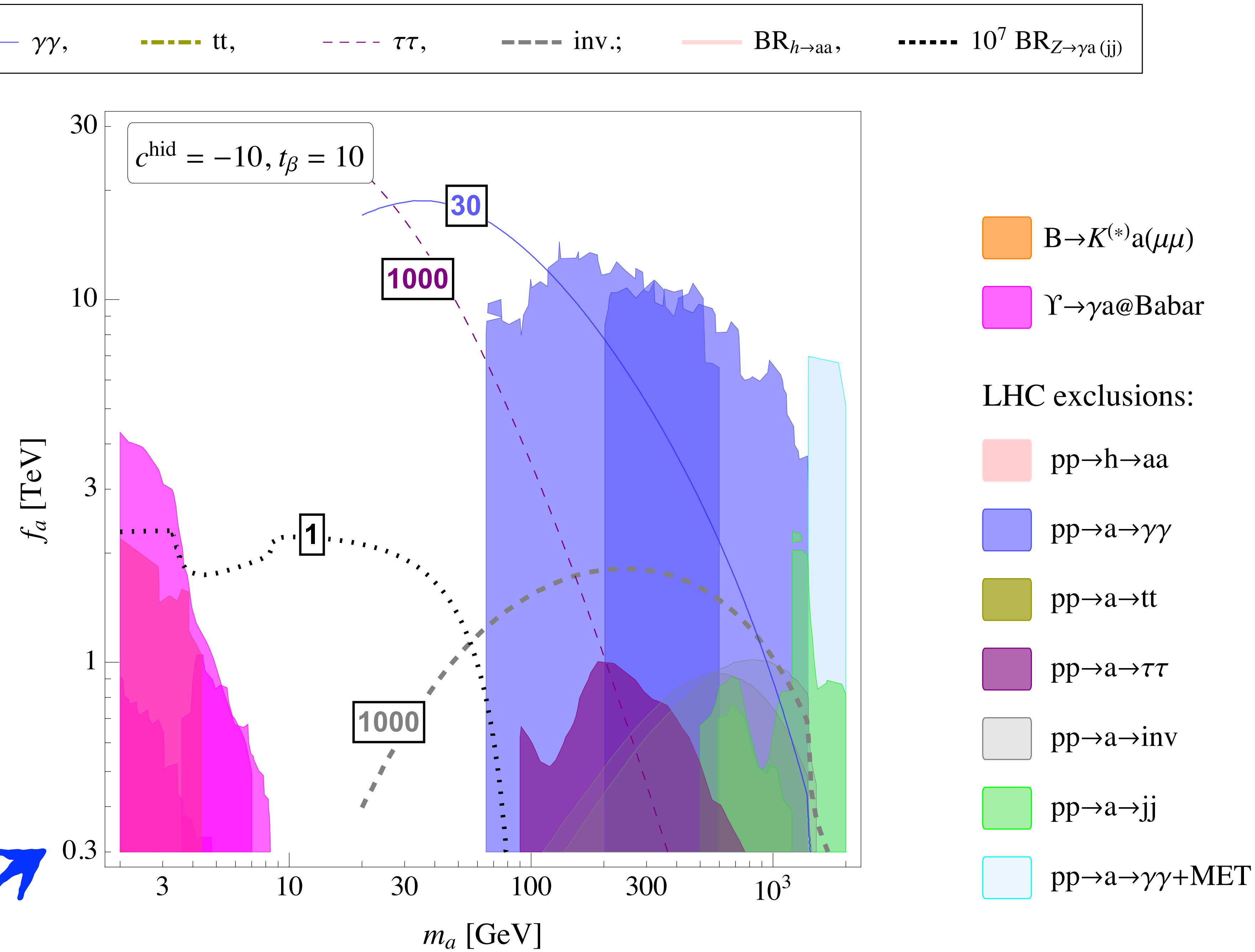
LEP only constrains smaller values of f_a

Present ALP mass coverage



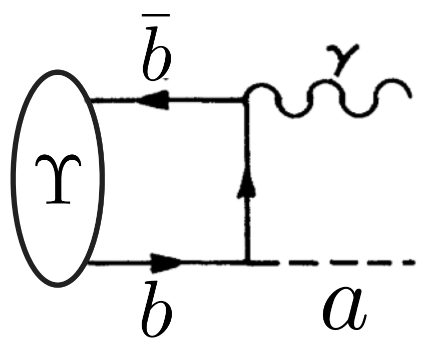


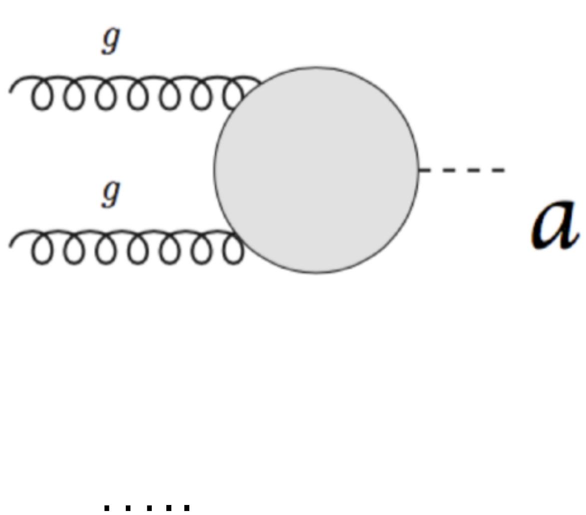
.....

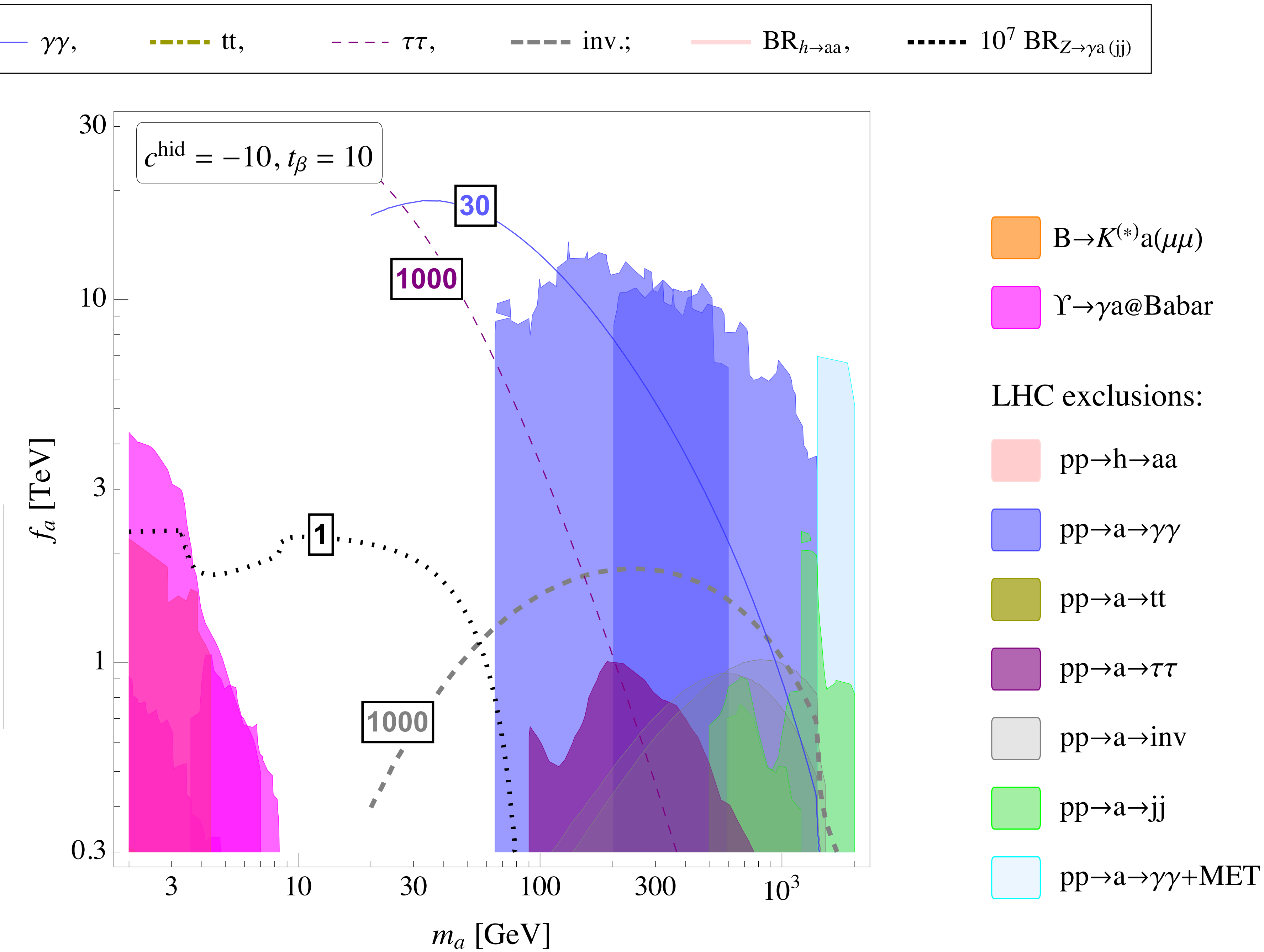


LEP only constrains smaller values of f_a

Present ALP mass coverage



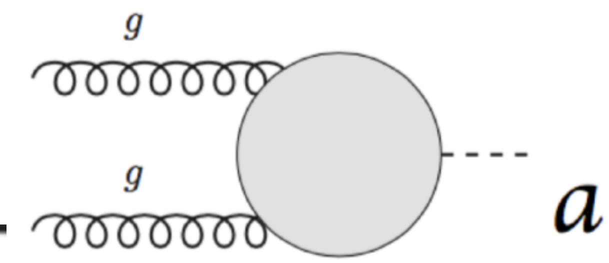


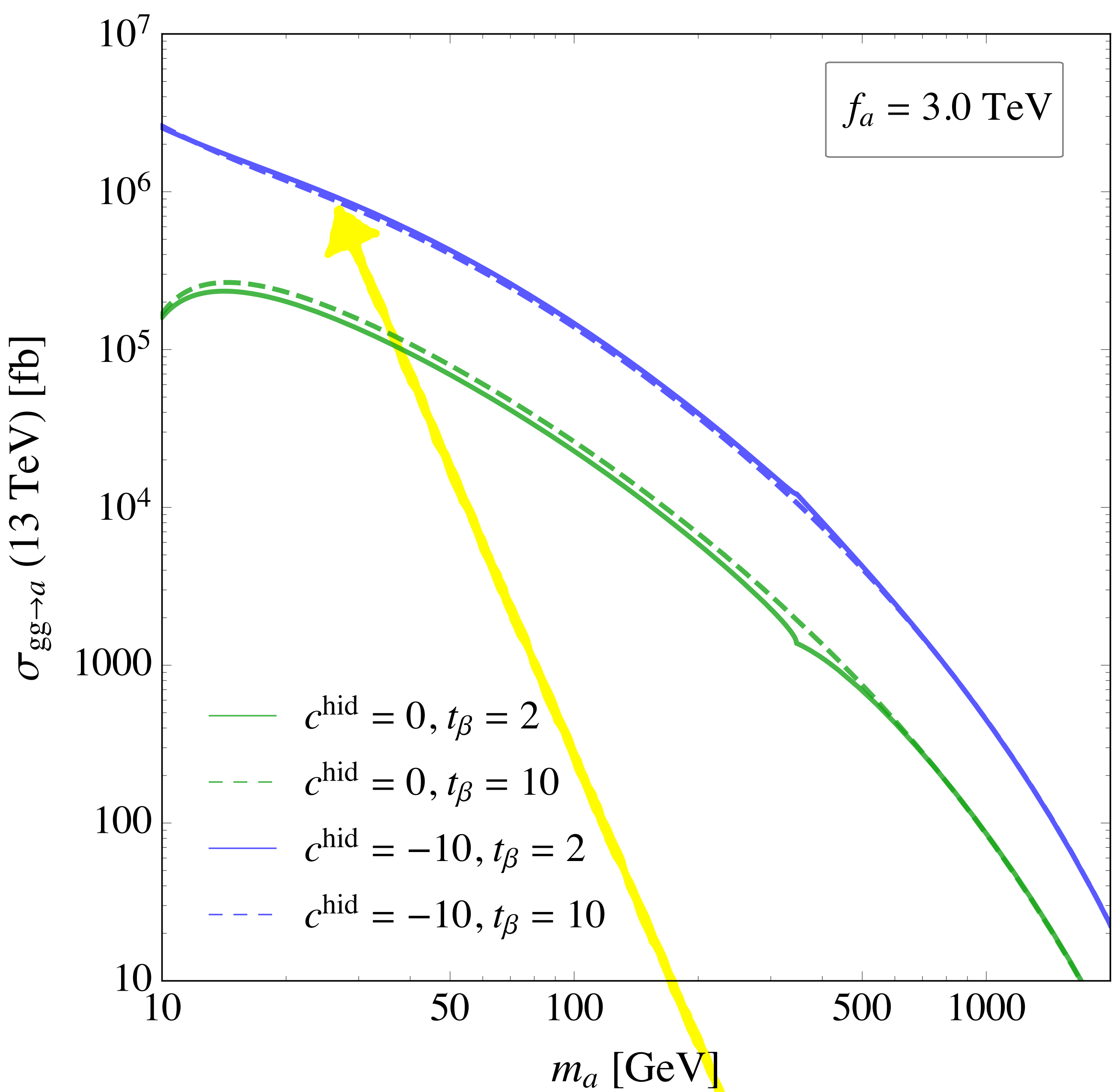


Flavor ← ? → LHC(diphoton, dijet…)

~1GeV — m_a — 50GeV

ALP production at the LHC





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

BSM resonances: where to look?

Present searches: $M_{\gamma\gamma,\tau\tau,\ldots} > O(100)\ \mathrm{GeV}$

Why not below?

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

BSM resonances: where to look?

Present searches: $M_{\gamma\gamma,\tau\tau,...} > O(100)\ \mathrm{GeV}$

Why not below?

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

Why difficult to go below ~ 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

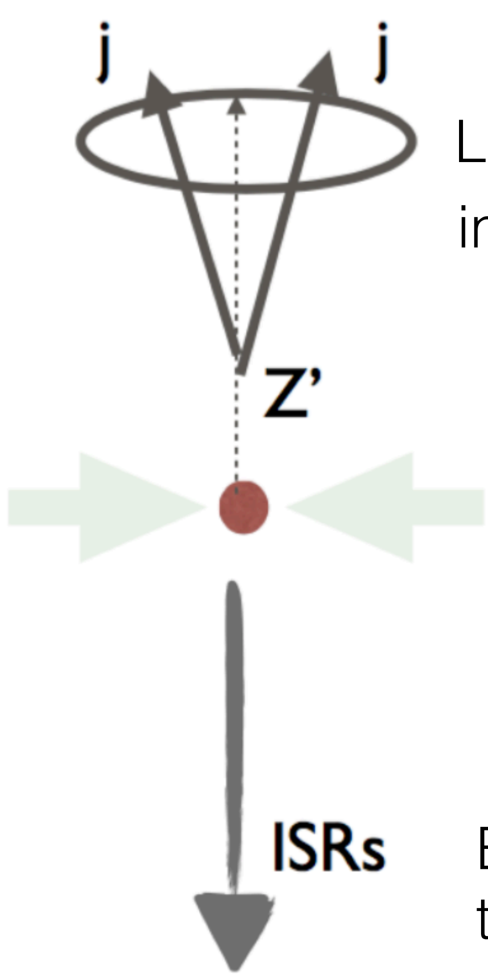
Two ways to lower $M_{\gamma\gamma}$

- Lower ΔR
- Lower $p_T^{\min}$

Lower ΔR

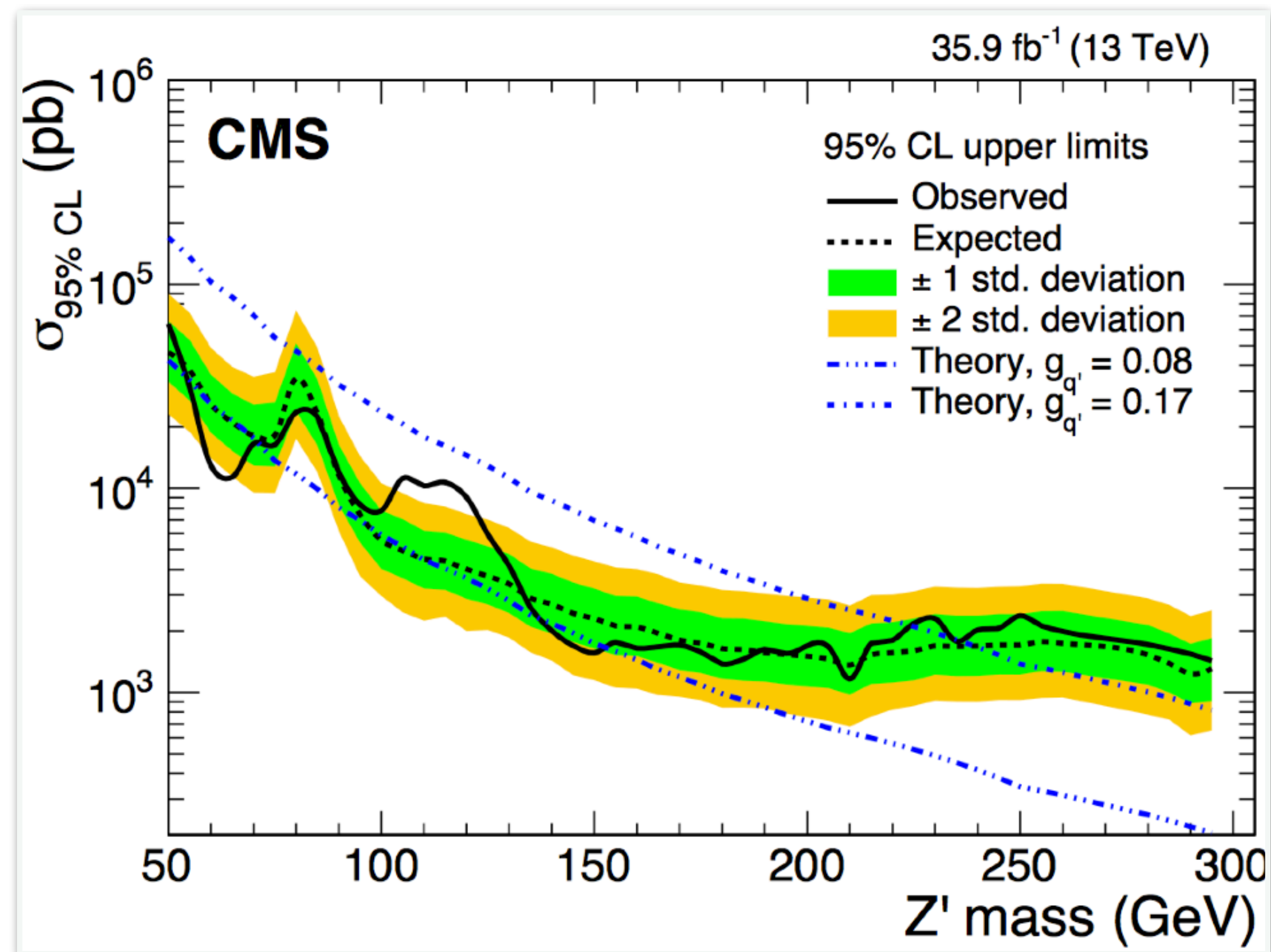
CMS	$pp \to a \to jj$	18.8 fb^{-1}	8 TeV	500 GeV	[38]
ATLAS	$pp \to a \to jj$	20.3 fb^{-1}	8 TeV	350 GeV	[39]
CMS	$pp \to a \to jj$	12.9 fb^{-1}	13 TeV	600 GeV	[40]
ATLAS	$pp \to a \to jj$	3.4 fb^{-1}	13 TeV	450 GeV	[41]
CMS	$pp \to ja \to jjj$	35.9 fb^{-1}	13 TeV	50 GeV	[42]

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

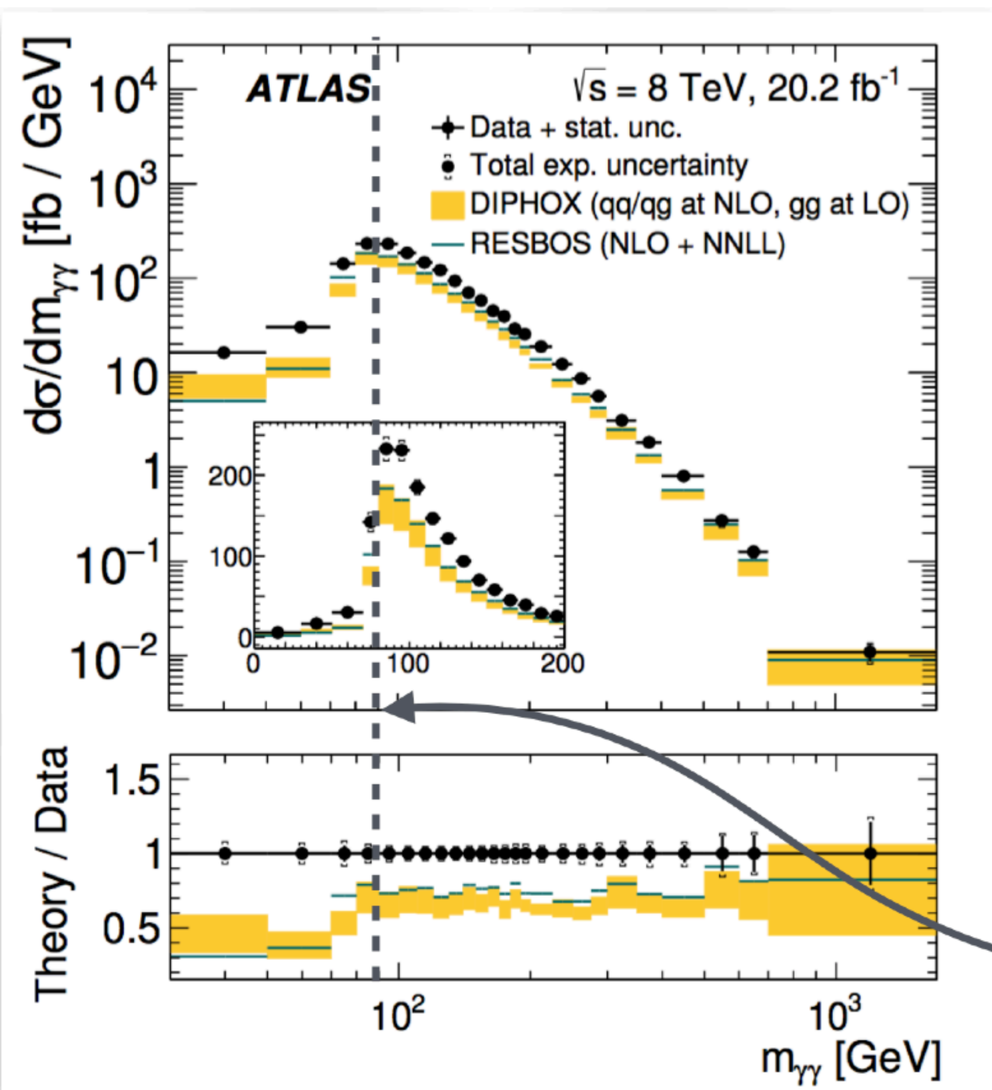


Lower $p_T^{\min}$

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	[35]
CDF ($\sigma_{\gamma\gamma}$)	$p\bar{p} \to a \to \gamma\gamma$	5.36 fb^{-1}	1.96 TeV	$p_{T_1}, _{T_2} > 17\,, 15$ GeV	[36]
ATLAS	$pp \to a \to \gamma\gamma$	4.9 fb^{-1}	7 TeV	$p_{T_1}, _{T_2} > 25\,, 22$ GeV	[8]
ATLAS	$pp \to a \to \gamma\gamma$	20.2 fb^{-1}	8 TeV	$p_{T_1}, _{T_2} > 40\,, 30$ GeV	[9]
CMS	$pp \to a \to \gamma\gamma$	5.0 fb^{-1}	7 TeV	$p_{T_1}, _{T_2} > 40\,, 25$ GeV	[10]

LHC pT cuts in diphoton cross section measurements

background shape



effect of pT cuts

$$p_{T_1}^{\min} = 40\ \text{GeV}$$
$$p_{T_2}^{\min} = 30\ \text{GeV}$$

Lower $p_T^{\min}$

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	[35]
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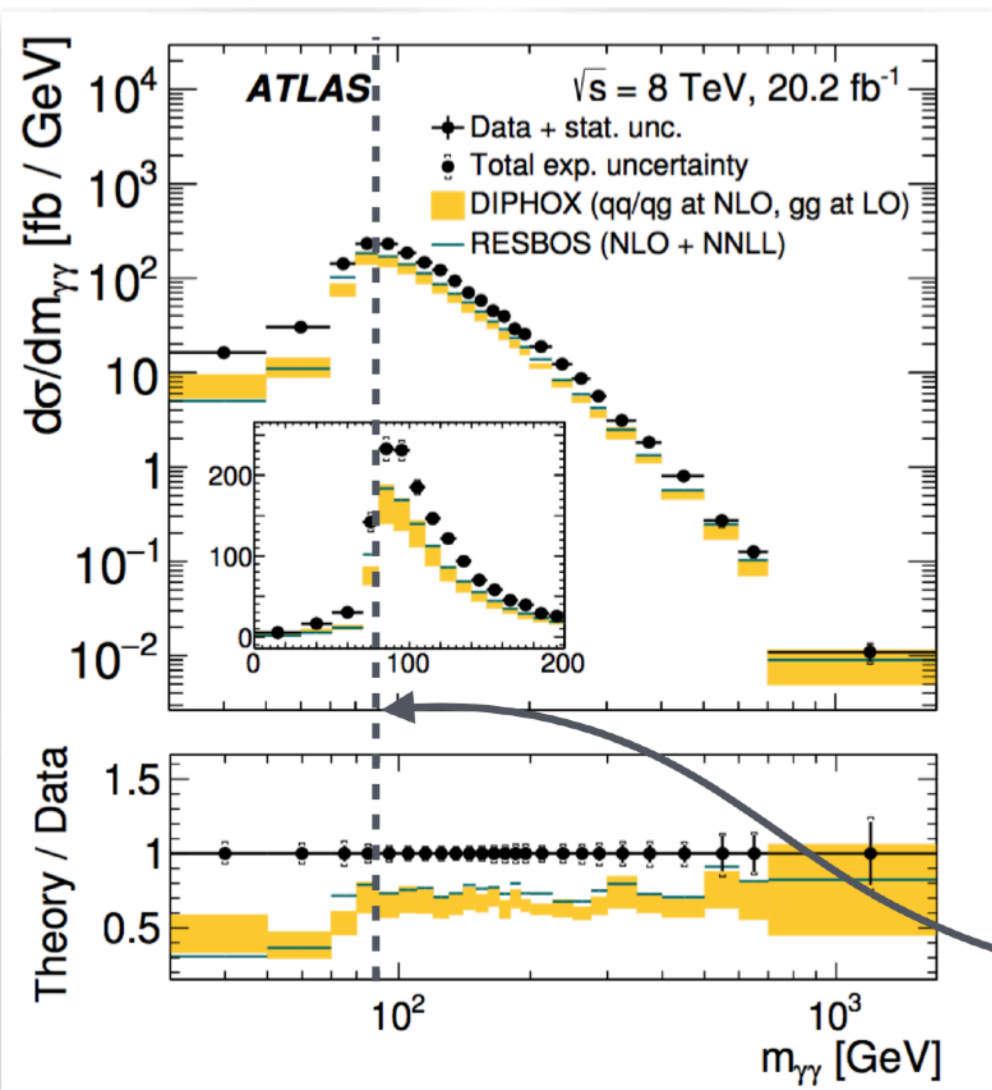
LHC pT cuts in diphoton **cross section measurements**

background shape



standard
ISOLATION requirement

$$\Delta R > 0.4$$

low mass reach
9.4 GeV
13.9 GeV
14.2 GeV

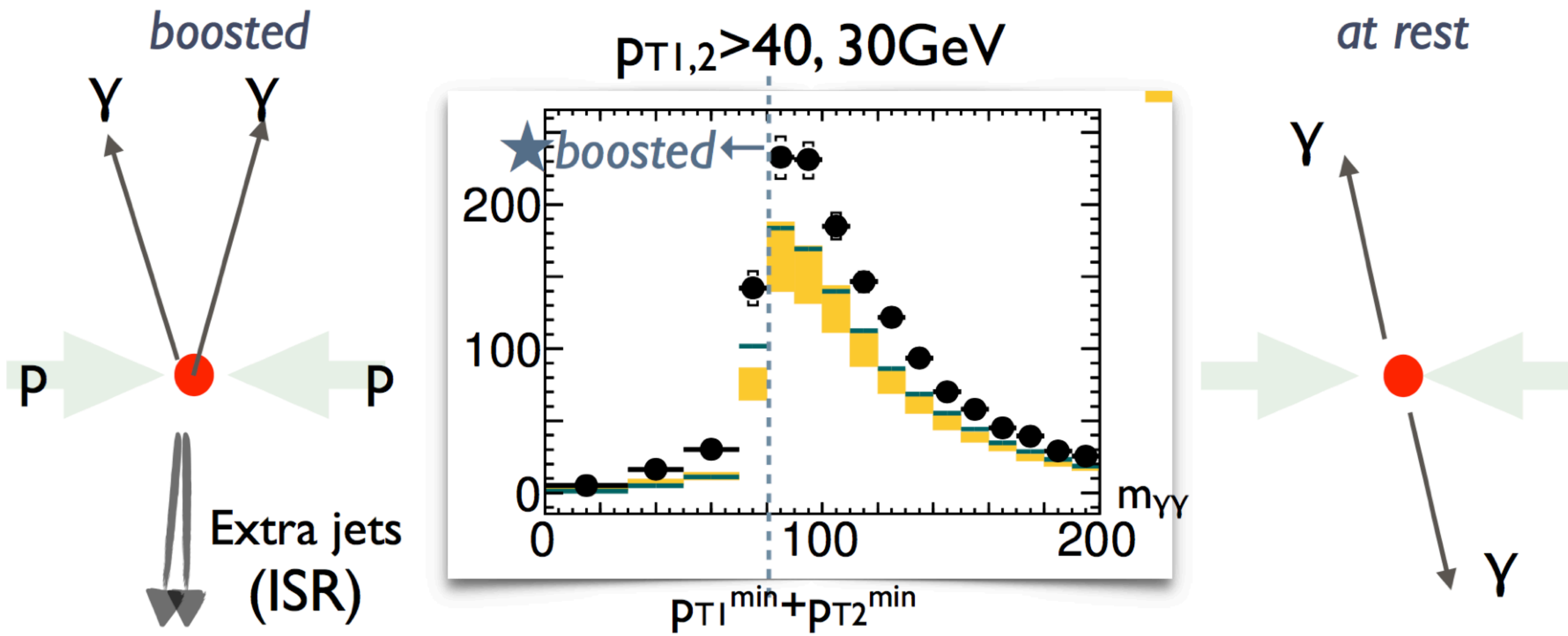
but LHC **diphoton searches** do not reach at all such low masses

Reason is bkg shape!

effect of pT cuts

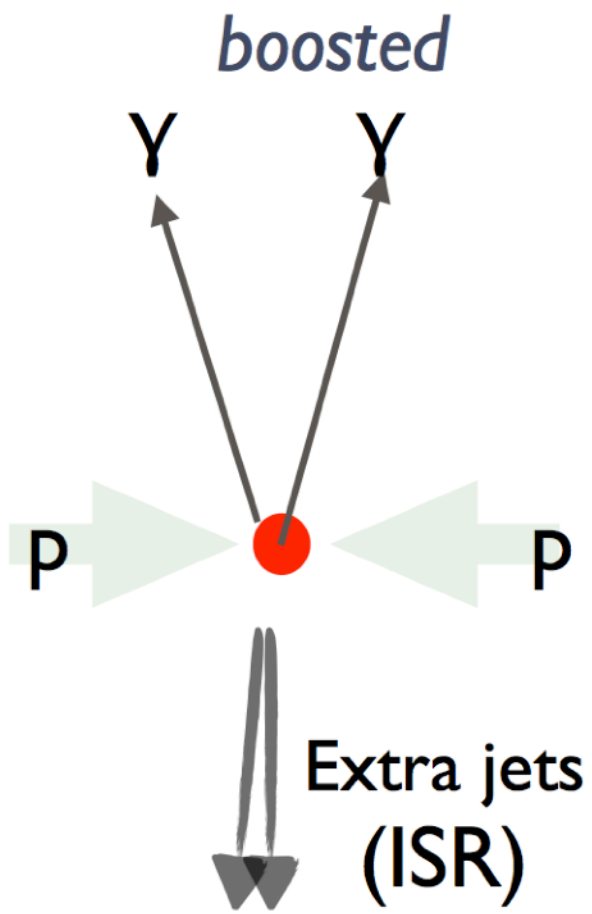
$$p_{T_1}^{\min} = 40 \text{ GeV}$$
$$p_{T_2}^{\min} = 30 \text{ GeV}$$

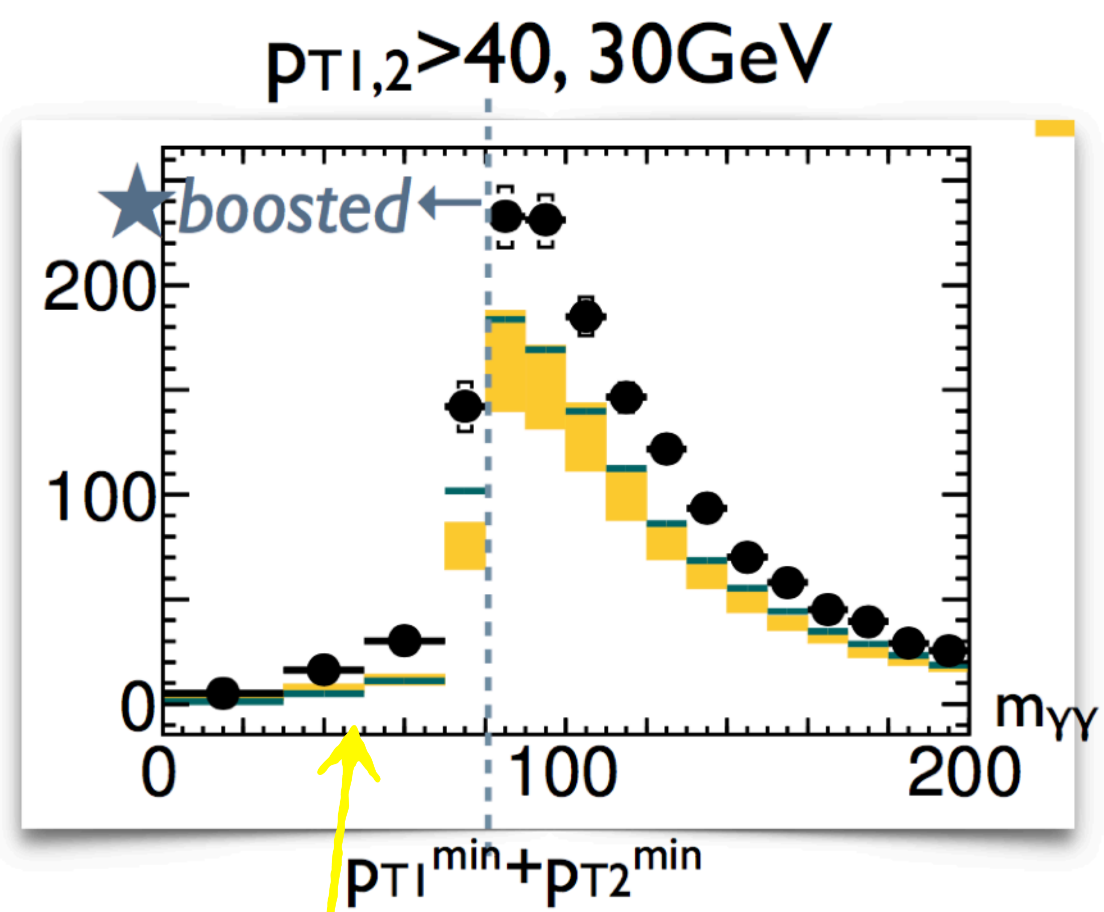
Shape of Inclusive Diphoton

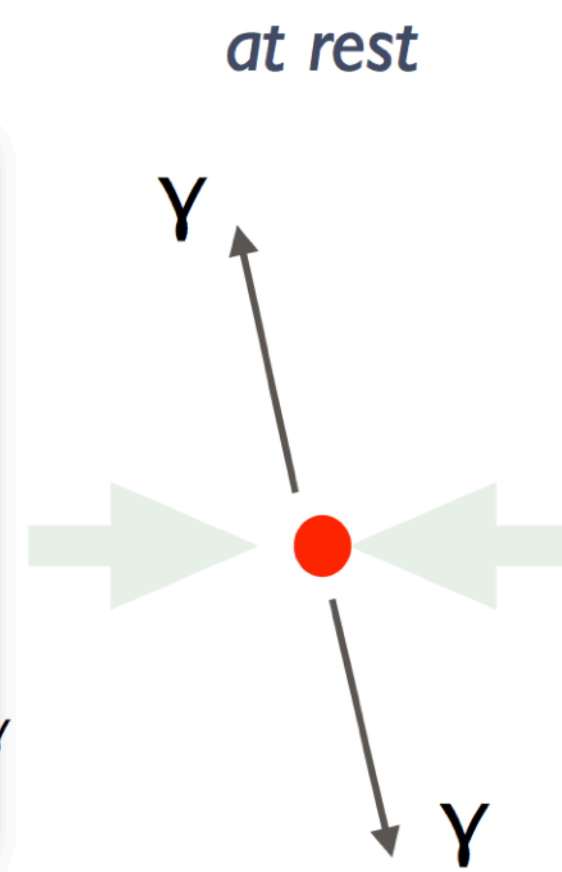


Measurements are inclusive: you get events with extra jets even w/o tagging on them

Shape of Inclusive Diphoton







Measurements are inclusive: you get events with extra jets even w/o tagging on them

Below pT cuts:

Background has a structure, so data-driven estimates are difficult

Signal is still non-zero!

Mariotti Redigolo FS Tobioka 1710.01743

m_a in GeV	10	20	30	40	50	60	70	80	90	100	110	120
ϵ_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

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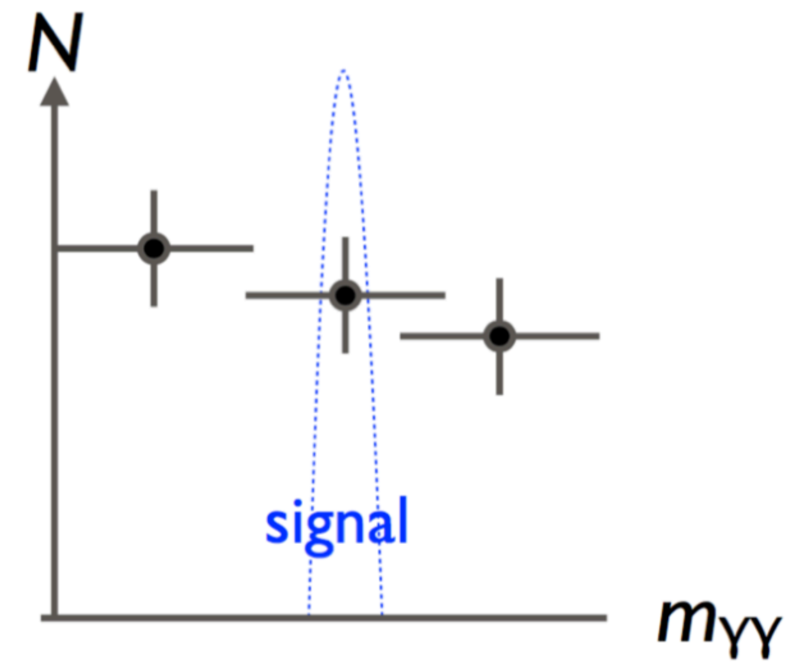
New $\gamma\gamma$ Bounds & Sensitivities

1. New Bound

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

(we assume zero knowledge of bkg)

experimental rel. uncertainty



2. Reach

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

(we assume data = SM prediction)

3. Reach with smarter bins

(we reduce ~ 10 GeV bins to mass resolution of ~ 3 GeV)

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

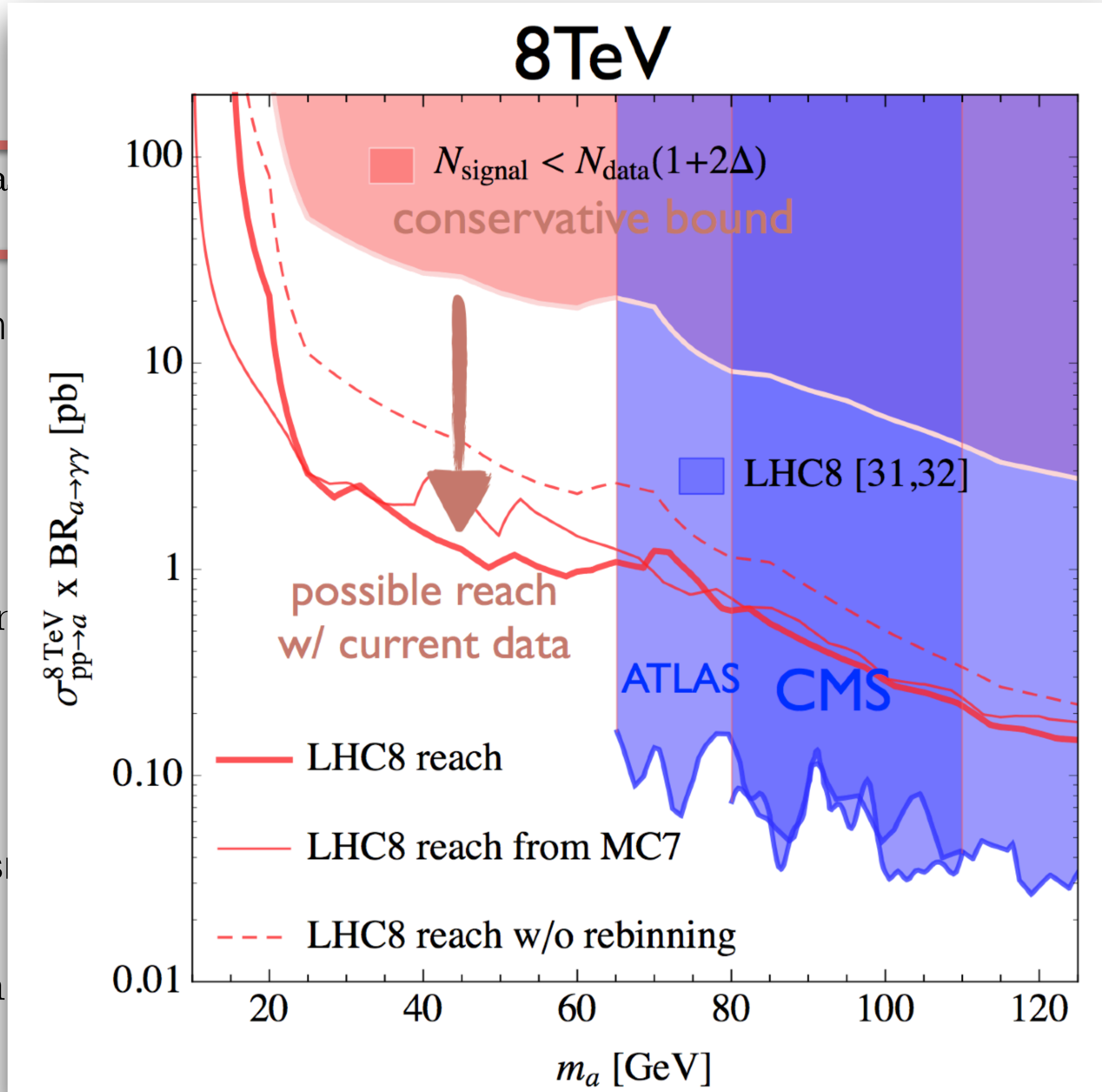
Signal efficiencies etc w/Madgraph+Pythia+Delphes [see back-up for more details, validations of our tools,…]

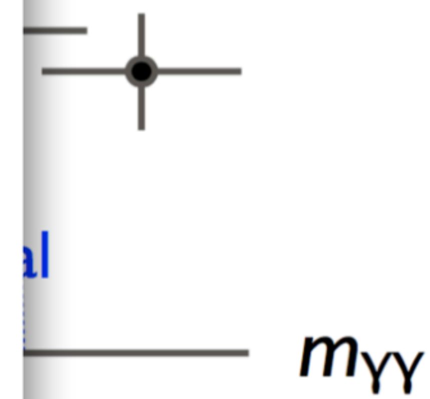
New $\gamma\gamma$ Bounds & Sensitivities

1. New Bound

$N^{\text{signa}}_{\text{bin}}$

(we assum





2. Reach

$N^{\text{sign}}_{\text{bin}}$

ediction)

3. Reach with s

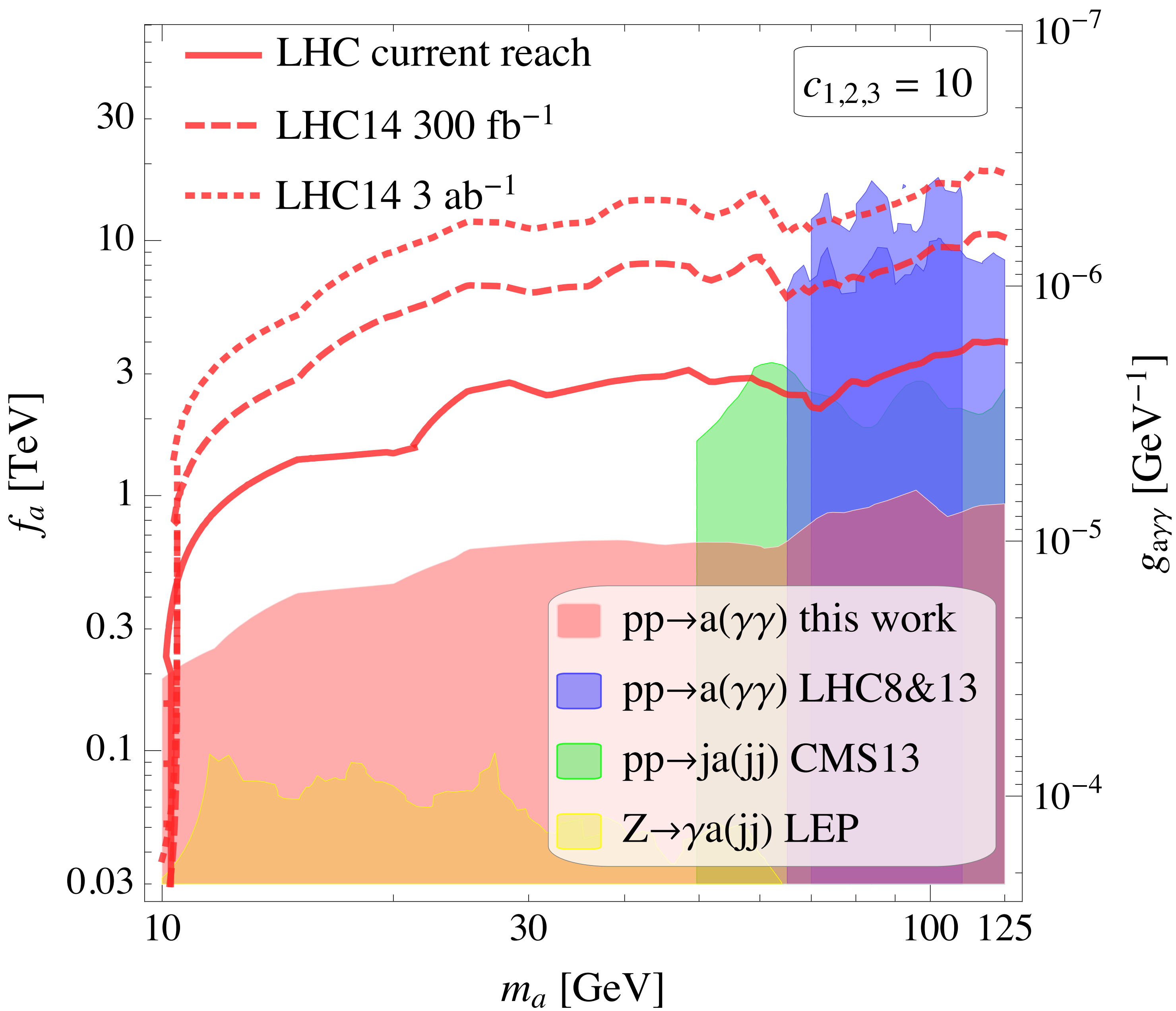
on of ~ 3 GeV)

$N^{\text{sign}}_{\text{res.}}$

Signal efficiencies etc w/Madgraph+Pythia+Delphes [see back-up for more details, validations of our tools,…]

Impact on ALP parameter space

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



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

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

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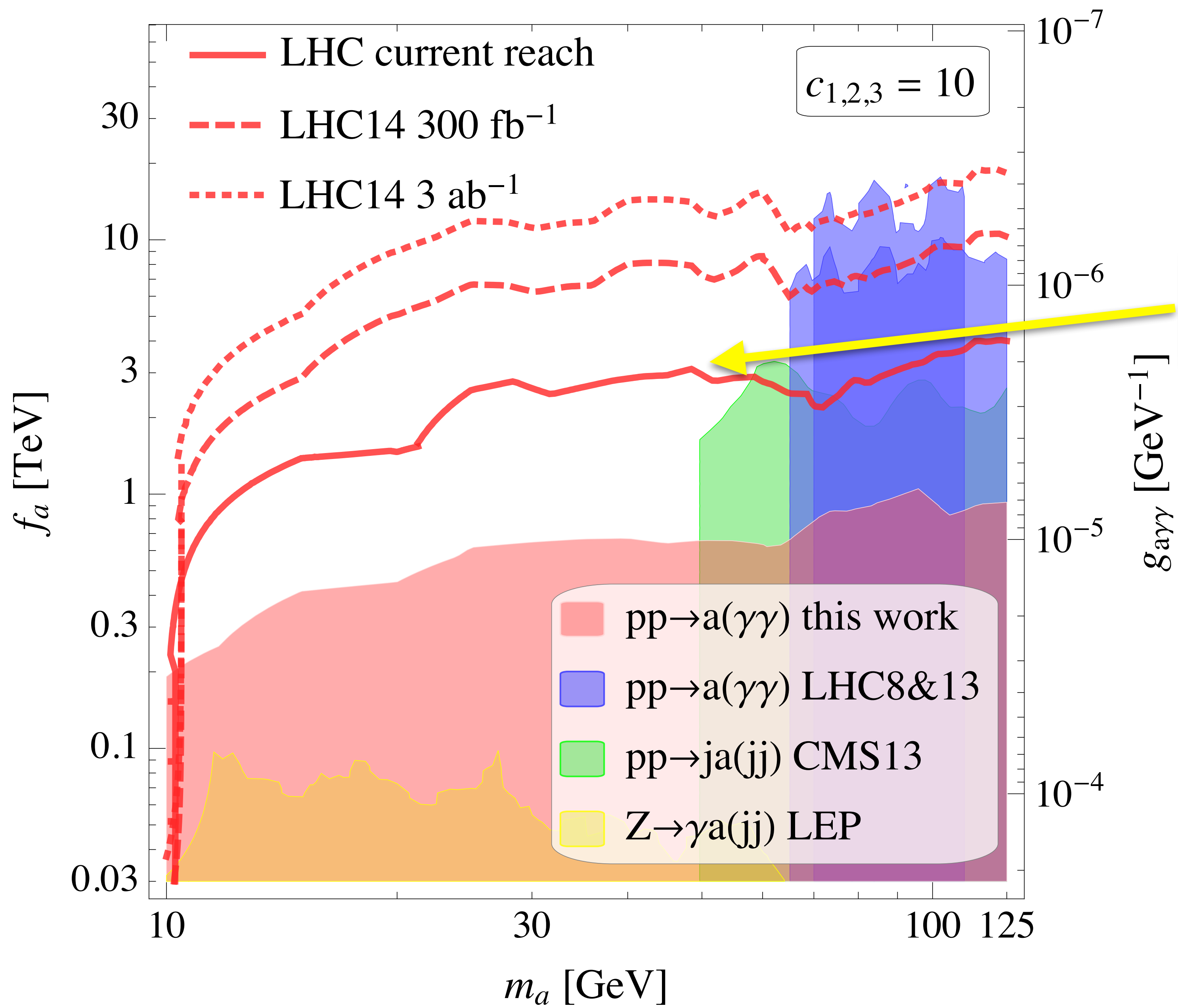

ATLAS&CMS could do much better already with current data!

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

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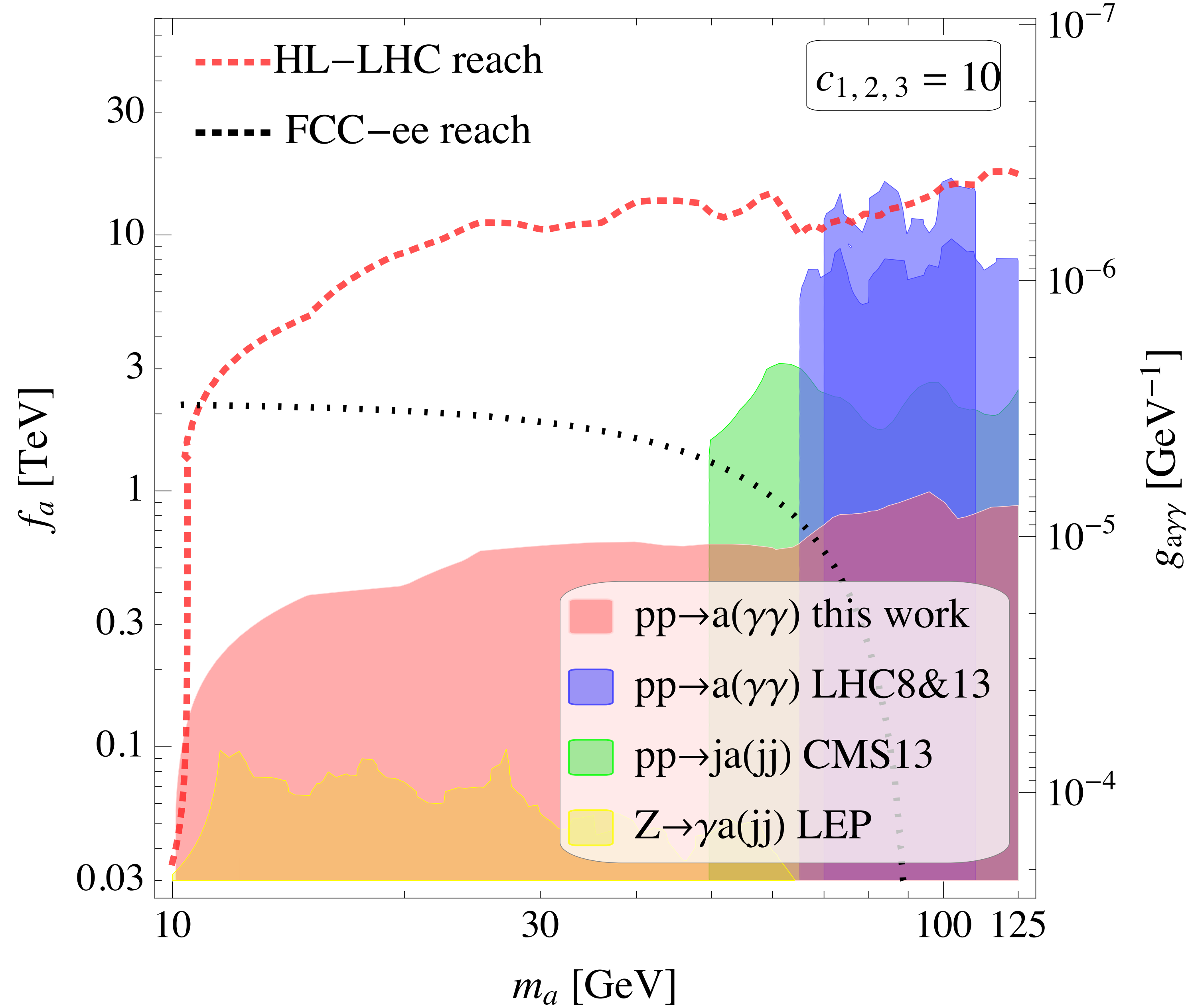
Impact on ALP parameter space

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

The HL-LHC reach is beyond what FCC-ee could probe

with $\mathrm{BR}[Z \to \gamma a(jj)]$

and 10^{12} Z bosons



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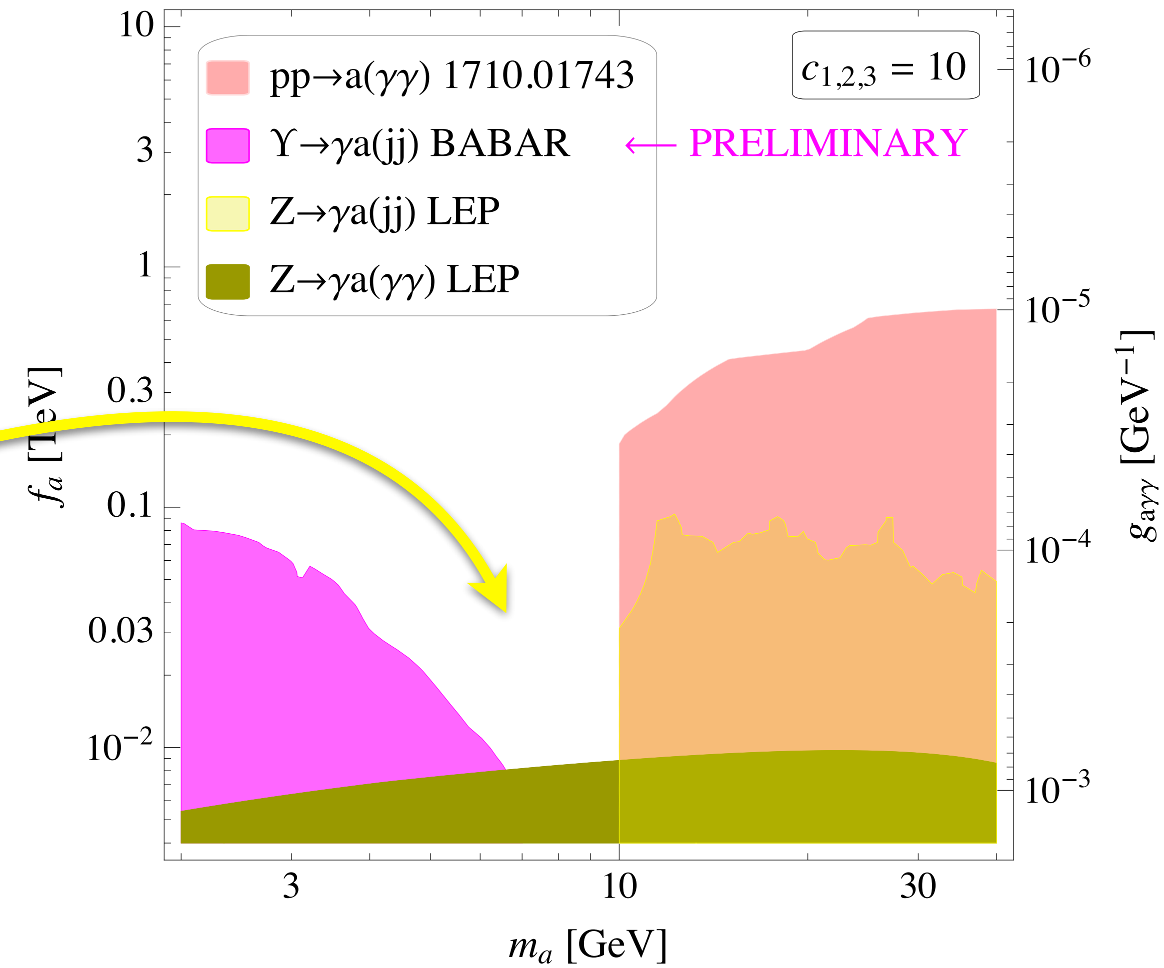
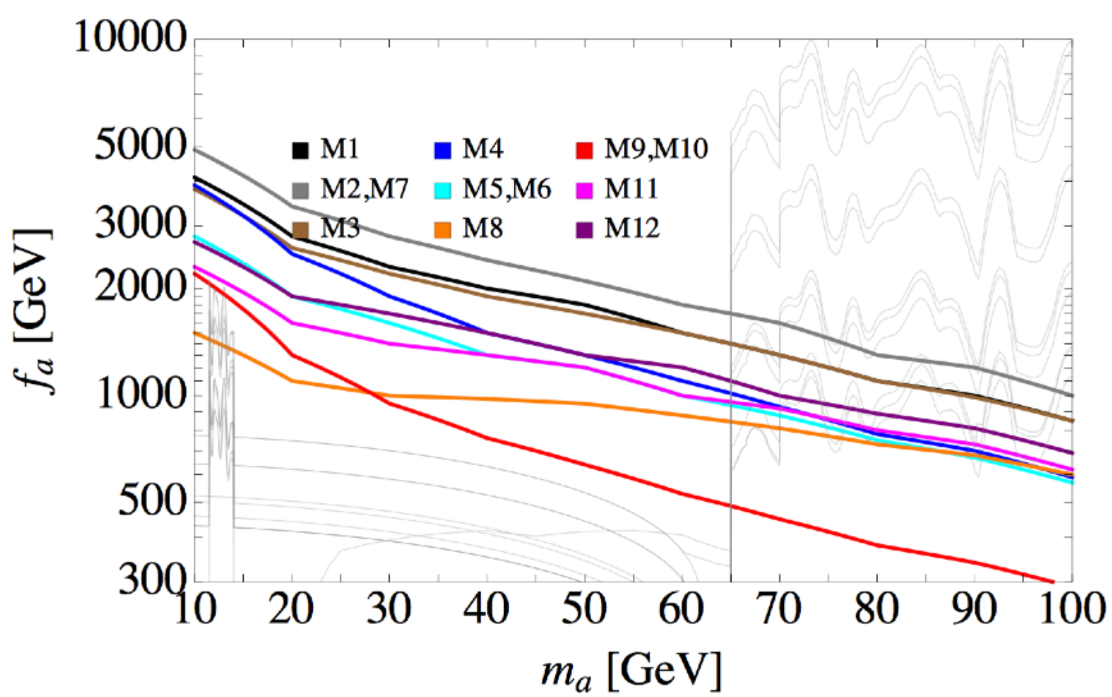
Other ways to low-mass resonances?

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

work in progress…

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





Difermions, e.g. ditaus?

Cacciapaglia Ferretti Flacke Serodio 1710.11142

NB. only sensitivities, not based on data

still worth investigating…

Take-Home

- Looking for peaks in invariant mass

  is most solid way to **discover BSM**

- Low-mass Resonances very well theoretically motivated

  notably **ALPs** w/ relevant pheno predicted in composite models

Bellazzini Mariotti Redigolo FS Serra 1702.02152

- Similar ALPs are general prediction also of Supersymmetry, had been overlooked!

  R-axion, could be first sign of SUSY at colliders

Take-Home

"Vojamo vede' er piccone"

- Looking for <u>peaks in invariant mass</u>
  is most solid way to **discover BSM**

- Low-mass Resonances very well theoretically motivated
  notably **ALPs** w/ relevant pheno predicted in composite models

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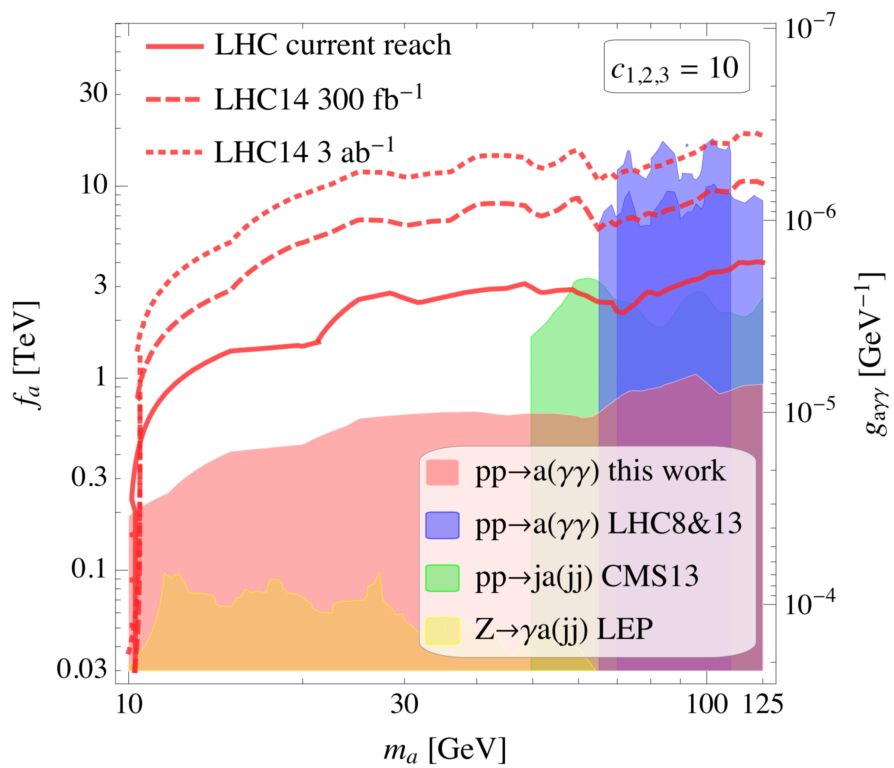


- Existing resonance searches do not go below 50-70 GeV

- But they could! We set **strongest bound on ALPs** from $\gamma\gamma$

Mariotti Redigolo FS Tobioka 1710.01743

- **NEXT**: LHCb, difermions, actual searches by experimentalists

Back up

More on R-axion

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 $m_{\lambda^i} \sim \frac{g_i^2}{g_*^2} m_*$ 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

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

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

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

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

~ 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

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

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

Dine Festuccia Komargodski 0910.2527
see also Bellazzini 1605.06111

R-axion pheno overview

Tool: constrained superfield formalism

Komargodski Seiberg 0907.2441

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

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

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

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

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

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

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

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

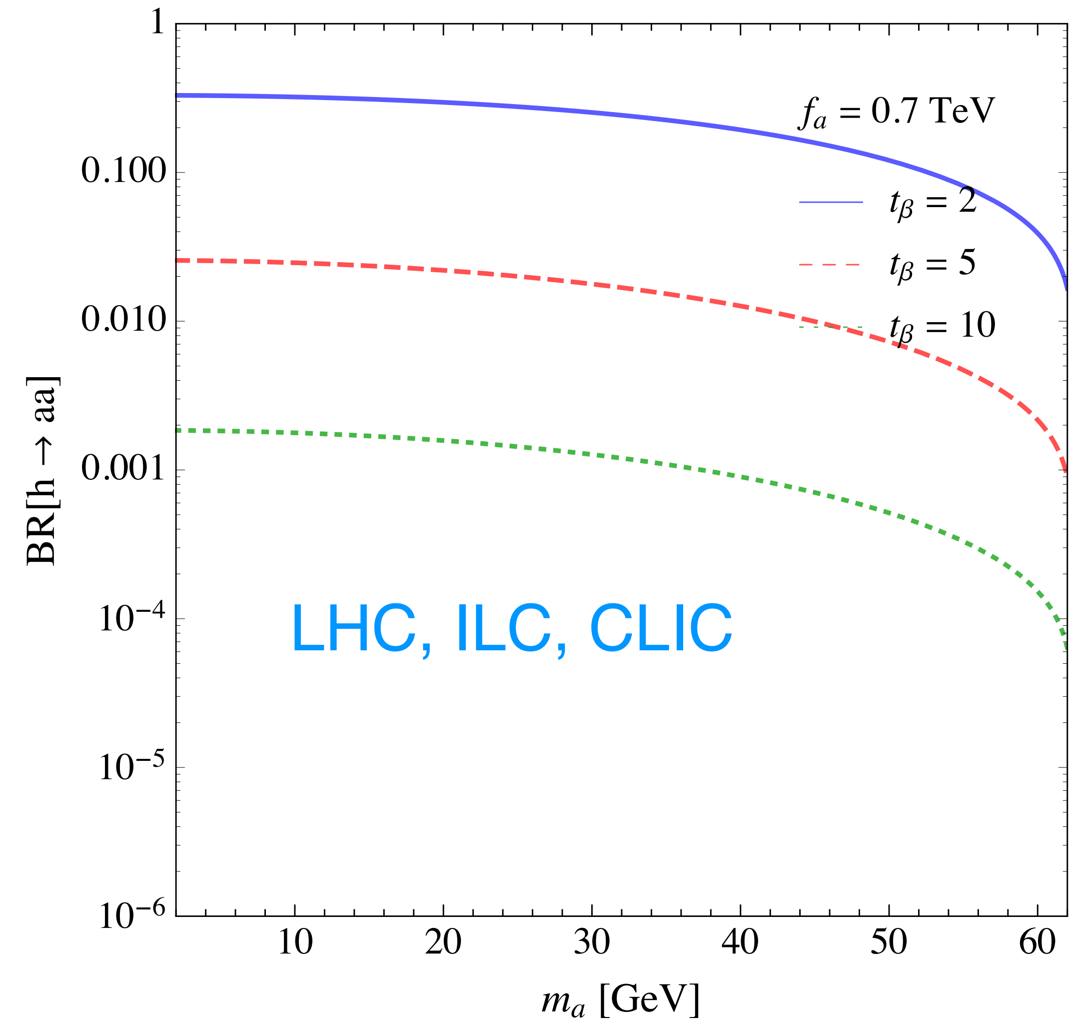
$$-i\,a\,R_H\left(c_\beta^2 \frac{m_u}{f_a}\bar{u}\gamma_5 u + s_\beta^2\frac{m_d}{f_a}\bar{d}\gamma_5 d + s_\beta^2 \frac{m_\ell}{f_a}\bar{\ell}\gamma_5\ell\right)$$

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

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

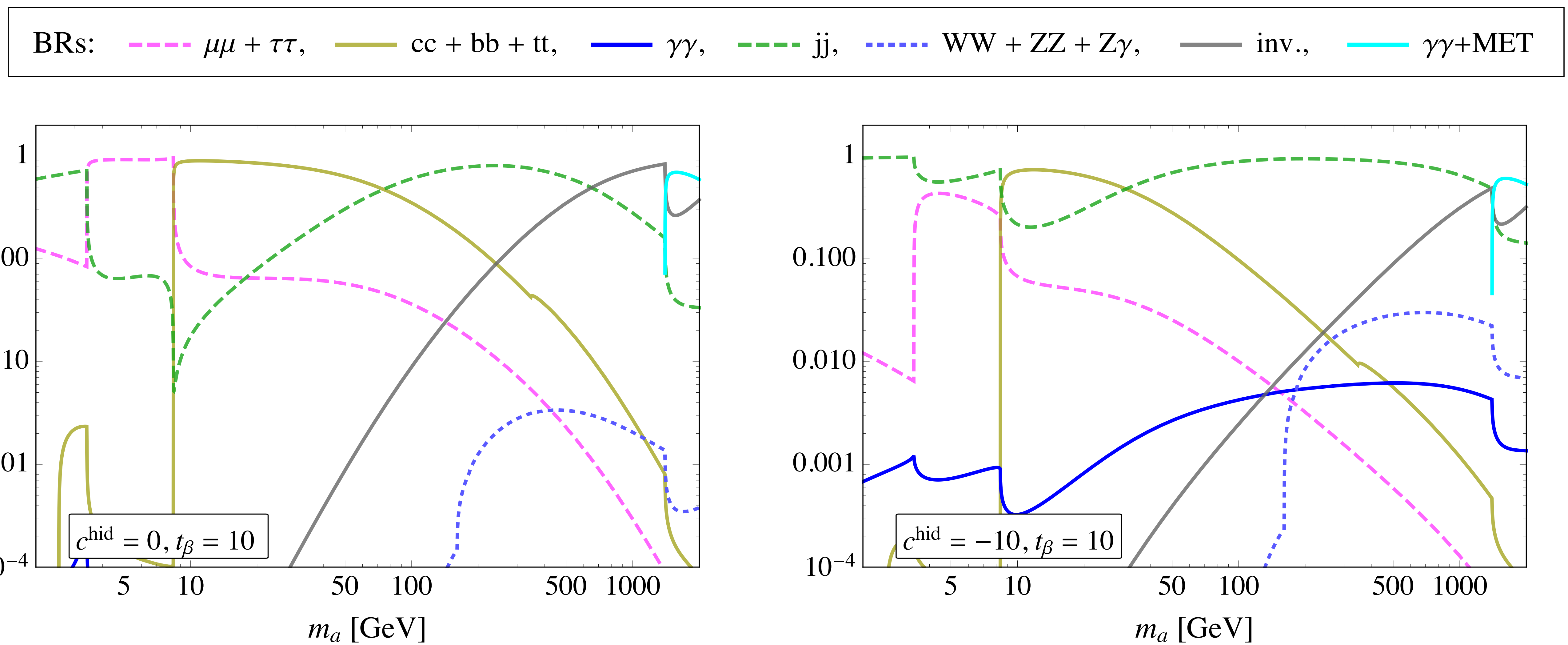
Belle, Belle-II

R axion branching ratios

Both plots: $t_\beta = 10$

No anomaly

Large anomalies

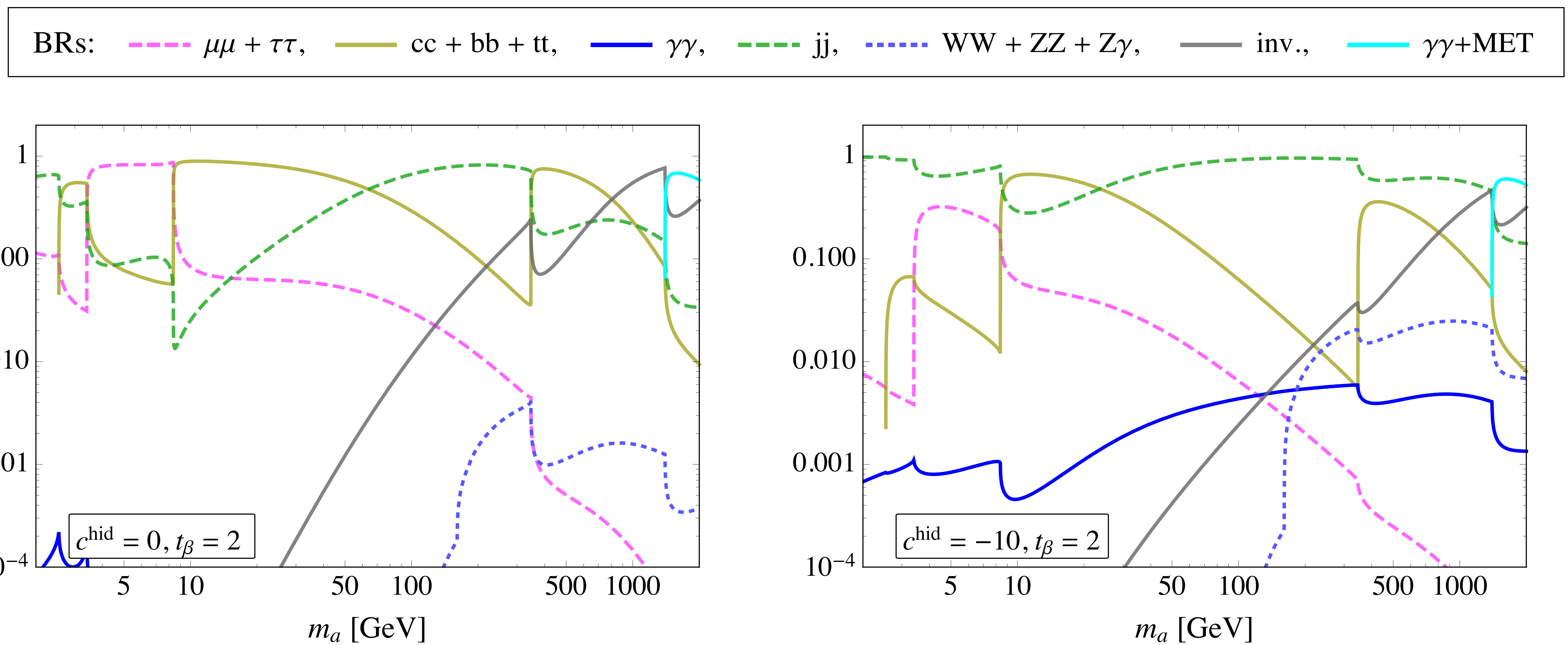


R axion branching ratios

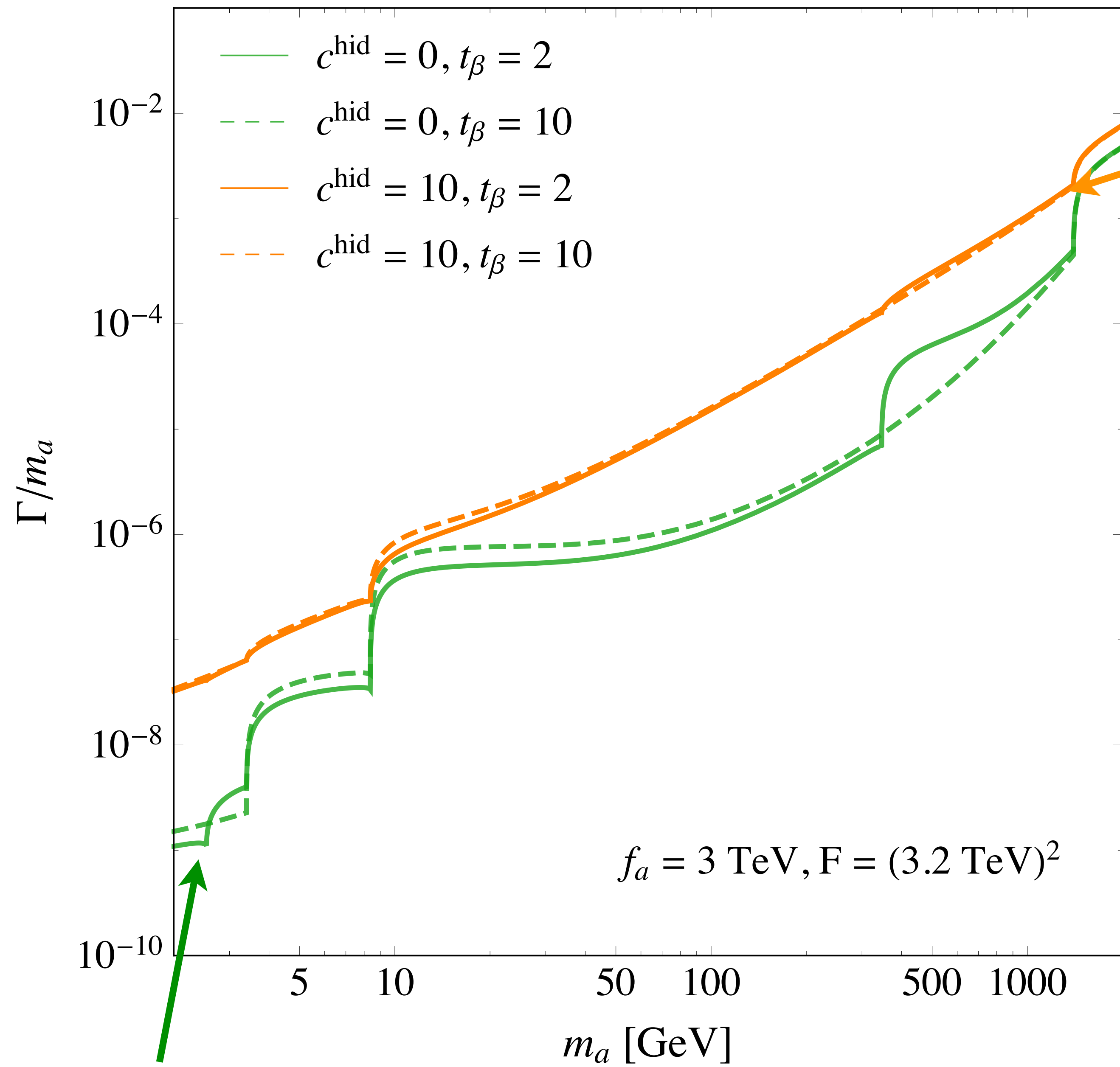
Both plots: $t_\beta = 2$

No anomaly

Large anomalies



R axion total width



$c\tau \approx \mu m$

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

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, …

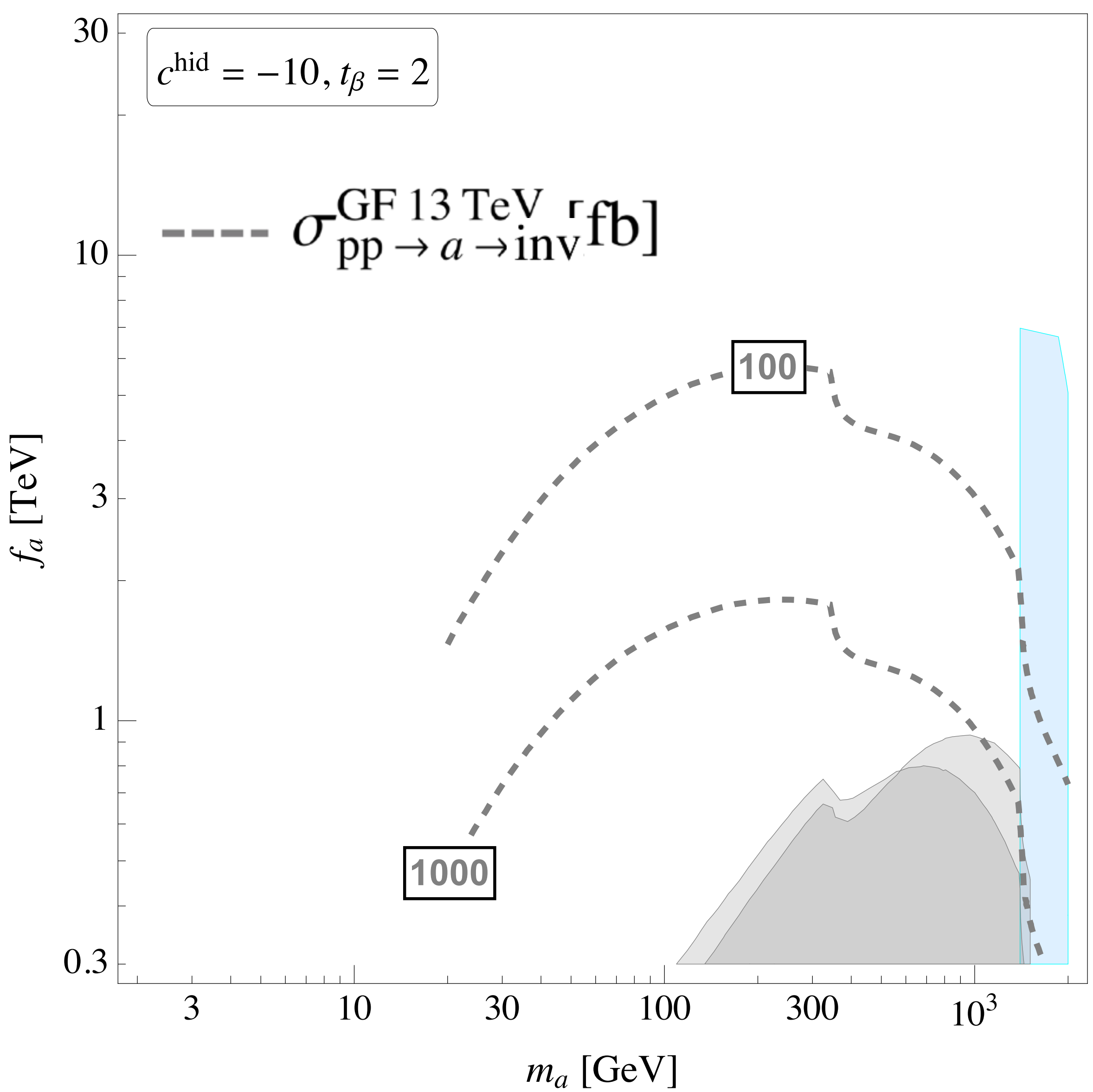
LHC: MET + monojet, MET + diphoton

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



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

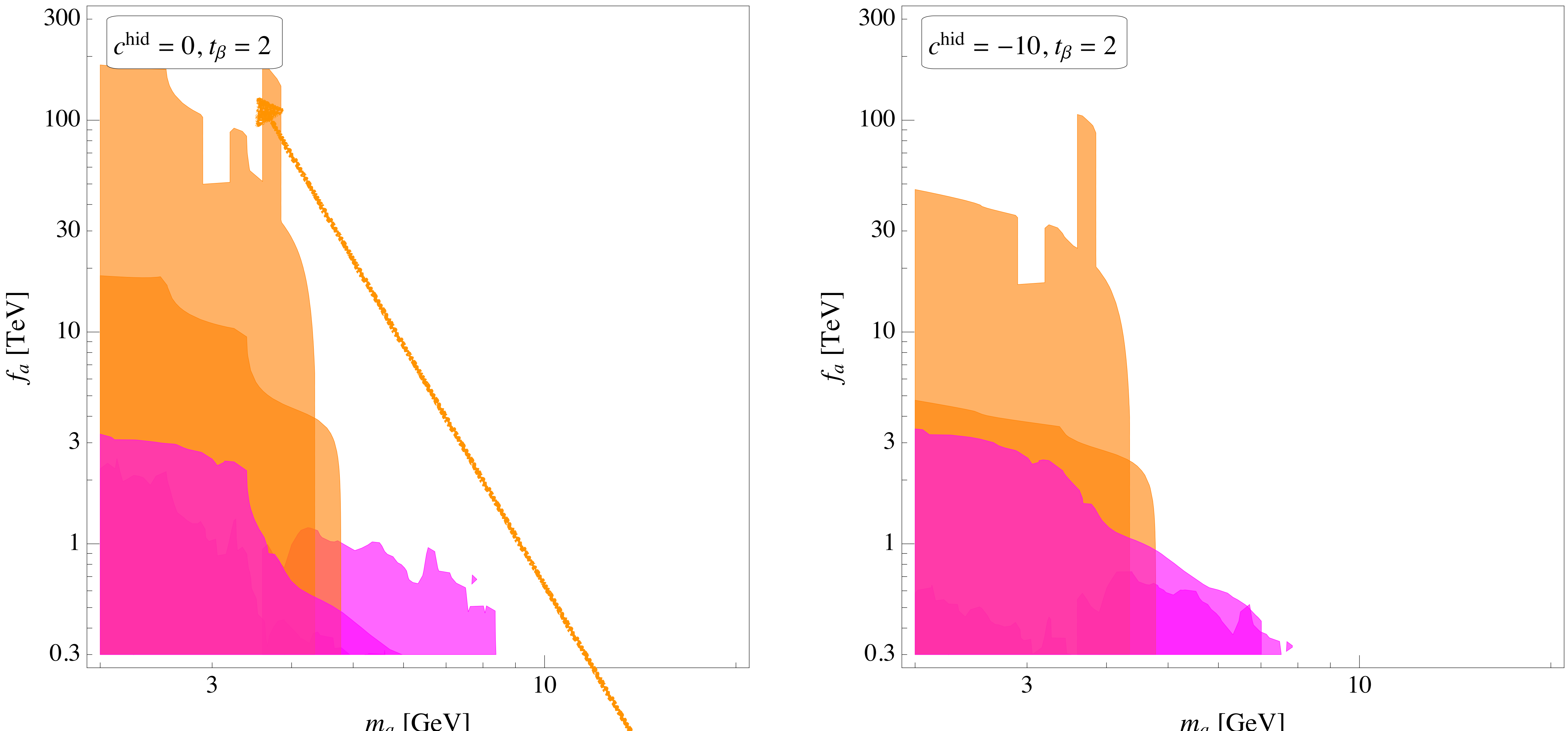
excludes signals
down to **0.3 fb** @LHC8

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)

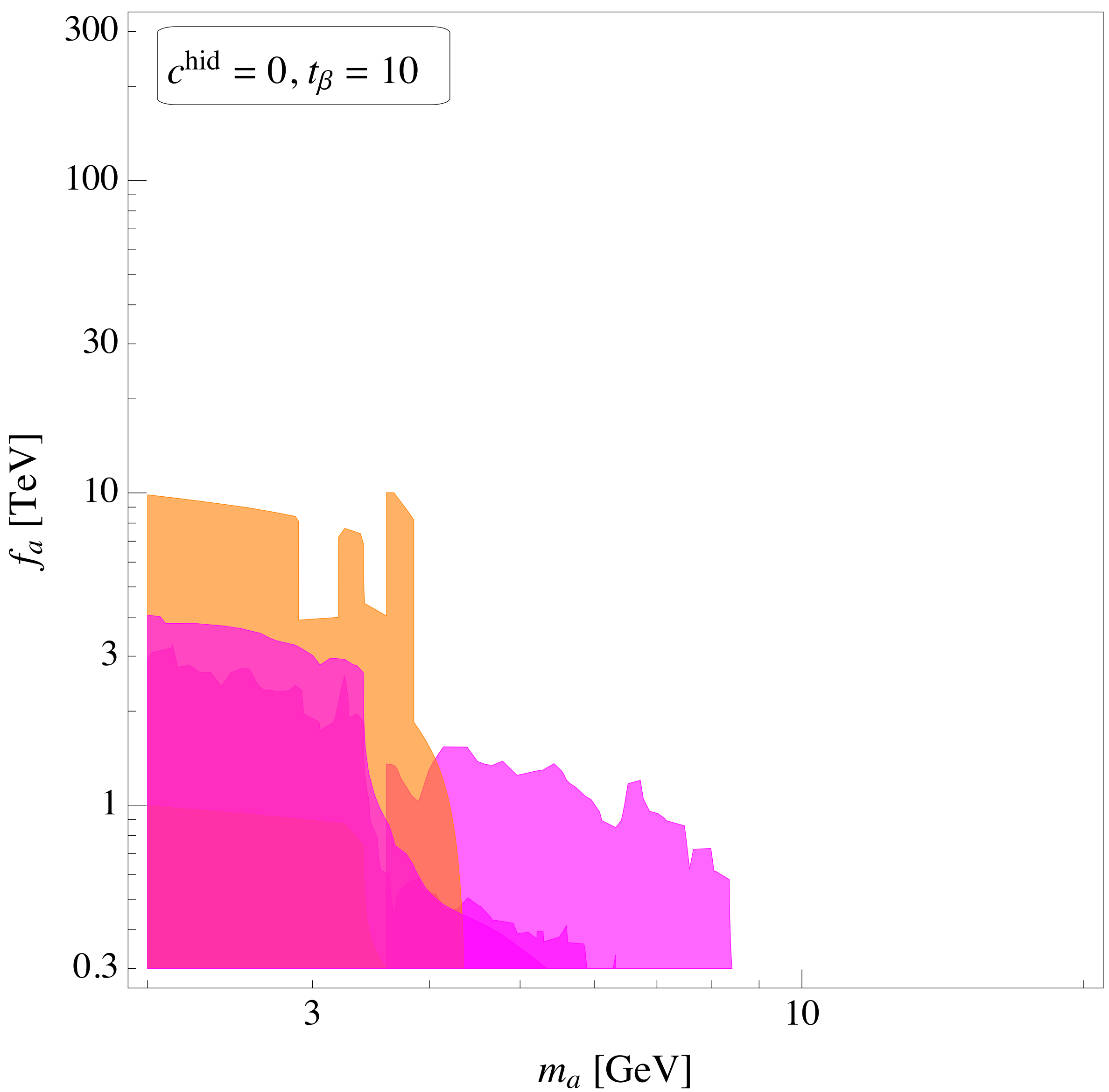


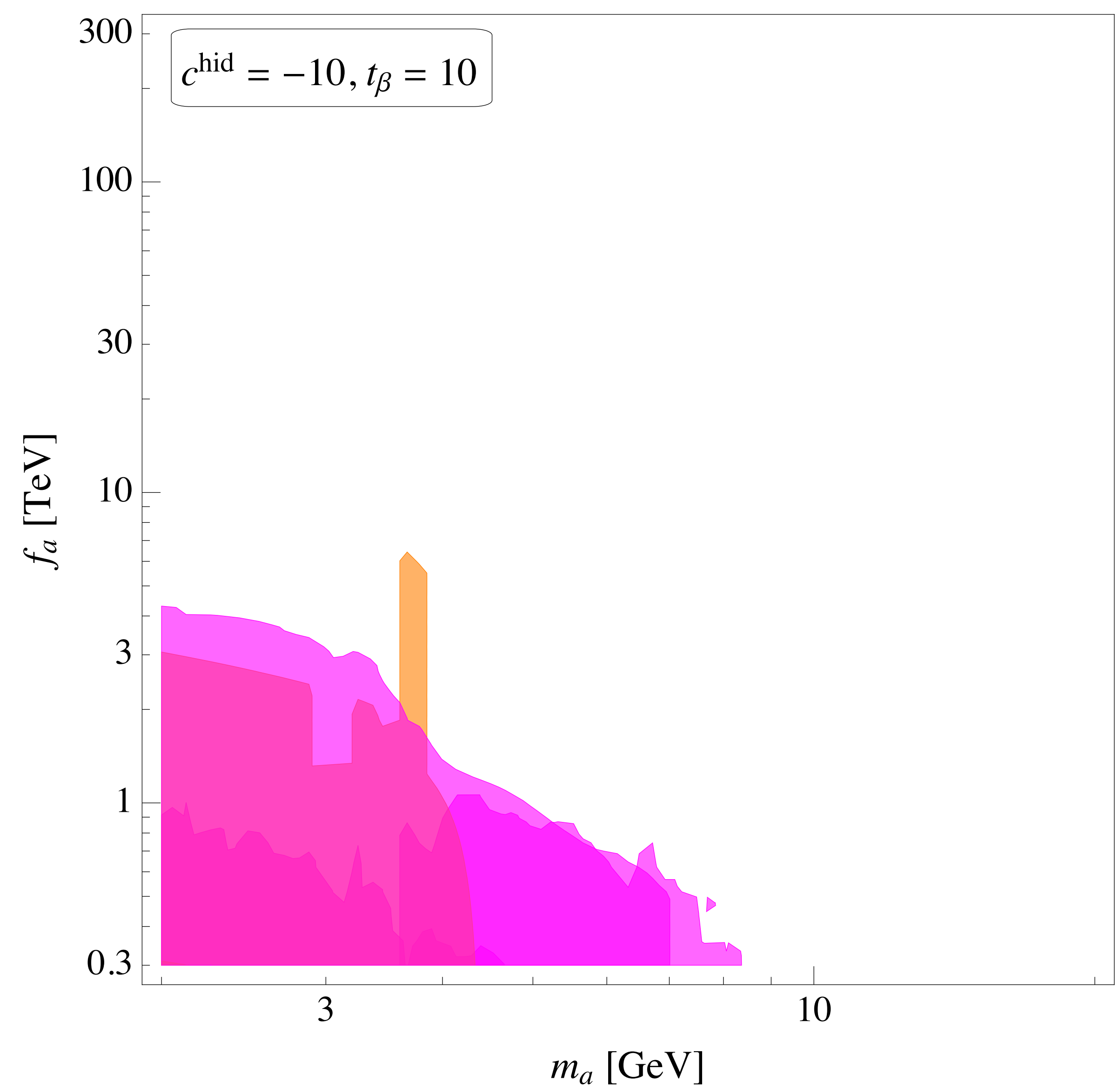
LHCb sensitive to beyond-100-TeV flavour-preserving SUSY!!

Decays of B and Upsilon

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

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





$B \to K^{(*)} a(\mu\mu)$ ~ 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	$e^+e^- \to Z^*, \gamma^* \to Za \to jj\gamma\gamma$	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

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

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

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

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

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

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

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

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

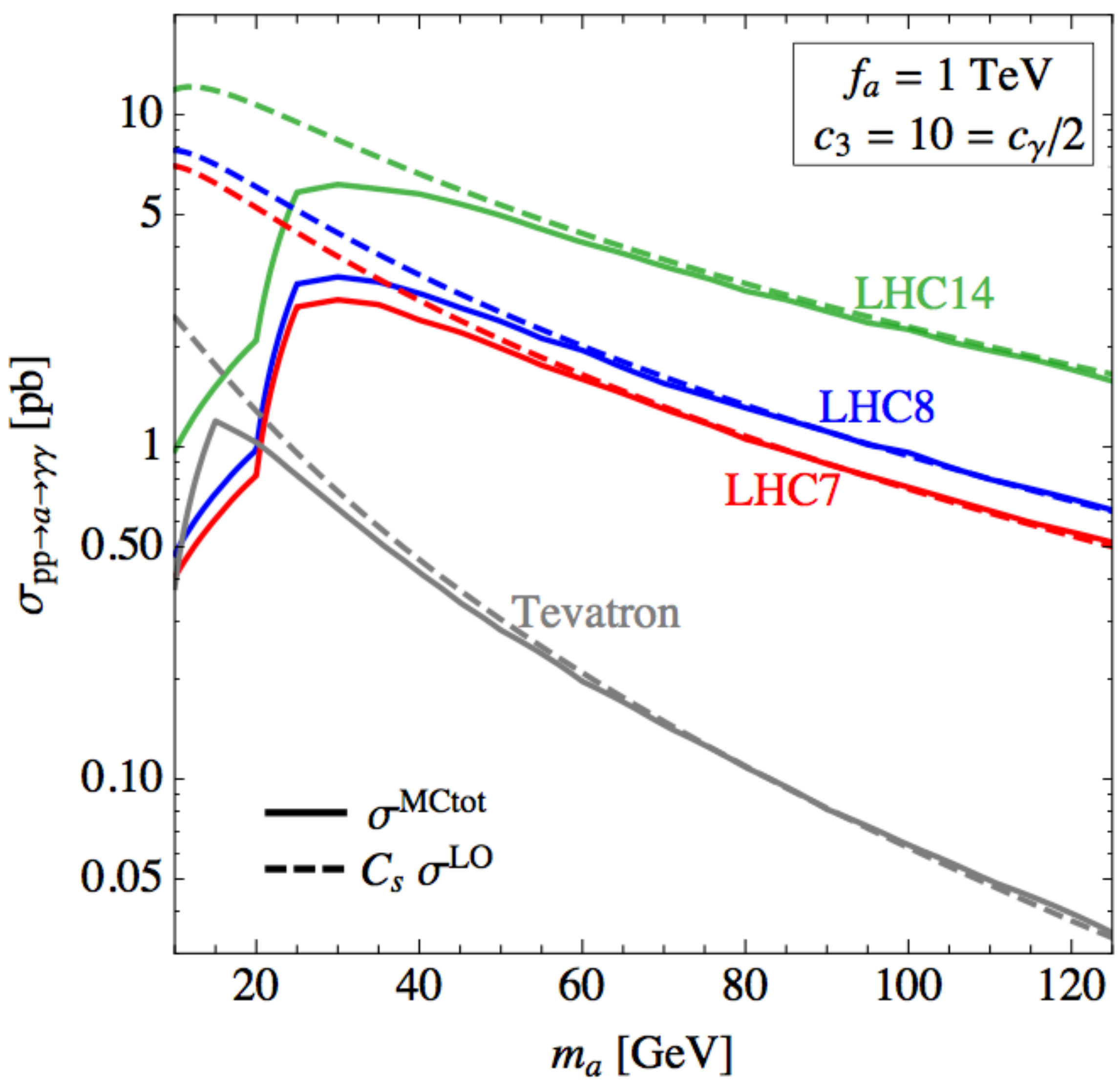
$K_\sigma = 3.7$ from ggHiggs v3.5

Bonvini et al. 2013-2016

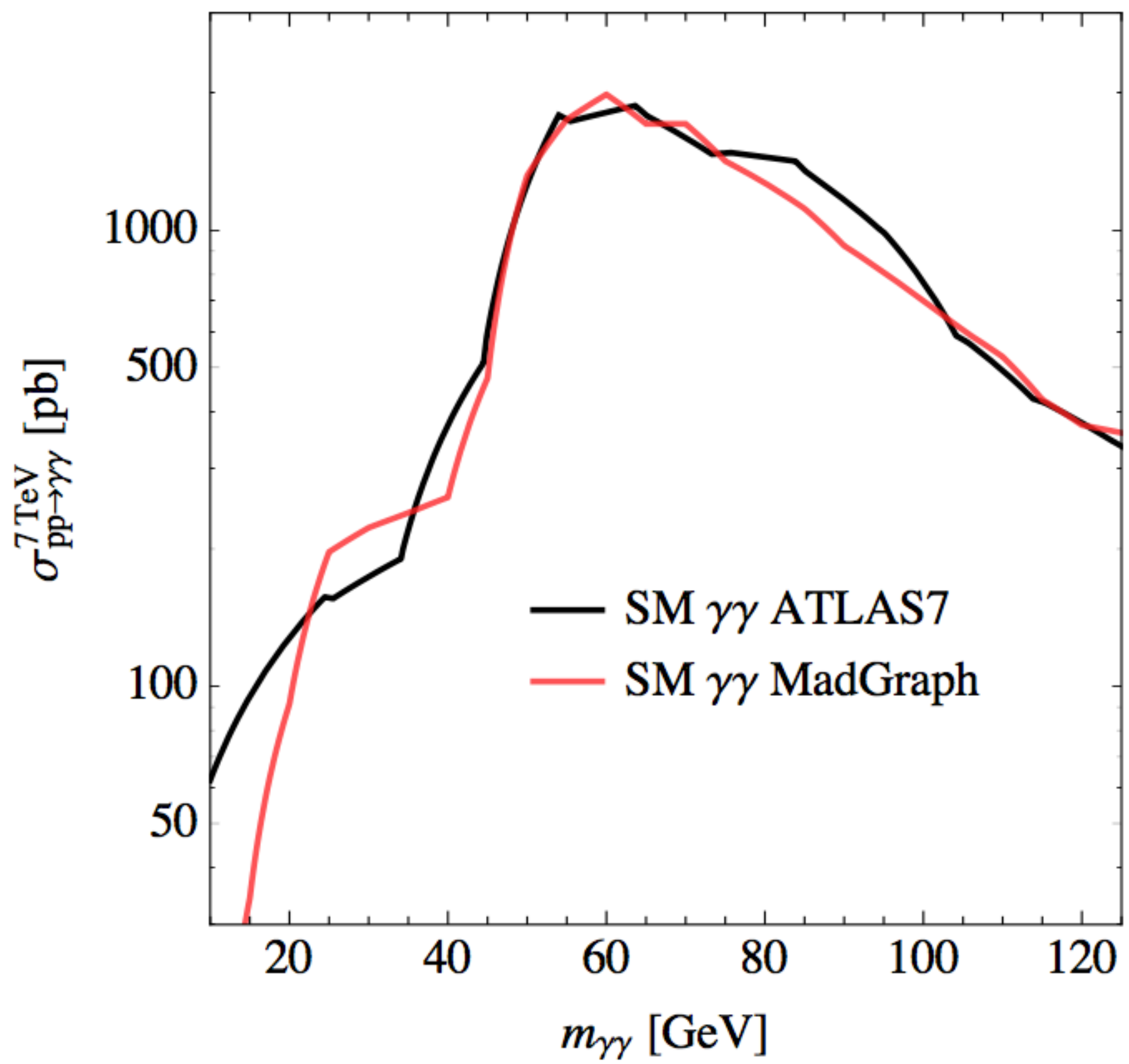
$K_g = 2.1$

m_a in GeV	10	20	30	40	50	60	70	80	90	100	110	120
ϵ_S for $\sigma_{7\mathrm{TeV}}$ 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 $\sigma_{7\mathrm{TeV}}$ 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 $\sigma_{8\mathrm{TeV}}$ 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 $\sigma_{2\mathrm{TeV}}$ 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 $\sigma_{2\mathrm{TeV}}$ 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
σ^{MCtot}
$C_s\, \sigma^{\text{LO}}$
$\sigma_{\text{pp}\to a\to\gamma\gamma}$ [pb]
m_a [GeV]



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

Interplay of LHC and Tevatron