Theory perspective on NP searches with photons

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INFN Trieste

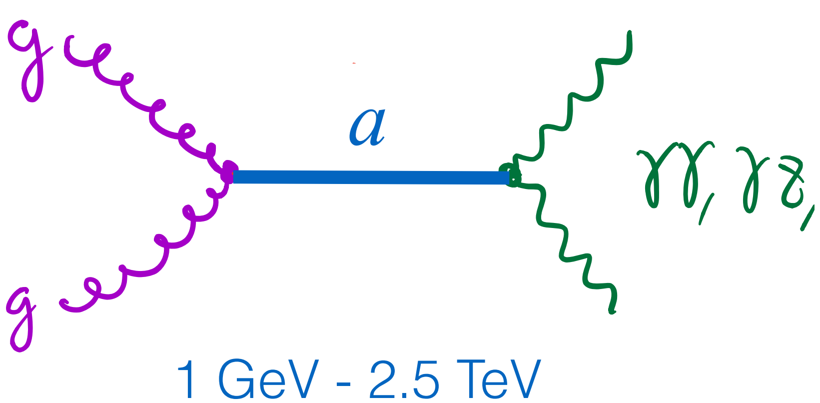
Workshop on Photon Physics and Simulation at Hadron Colliders
LNF, Frascati, 07/06/2019

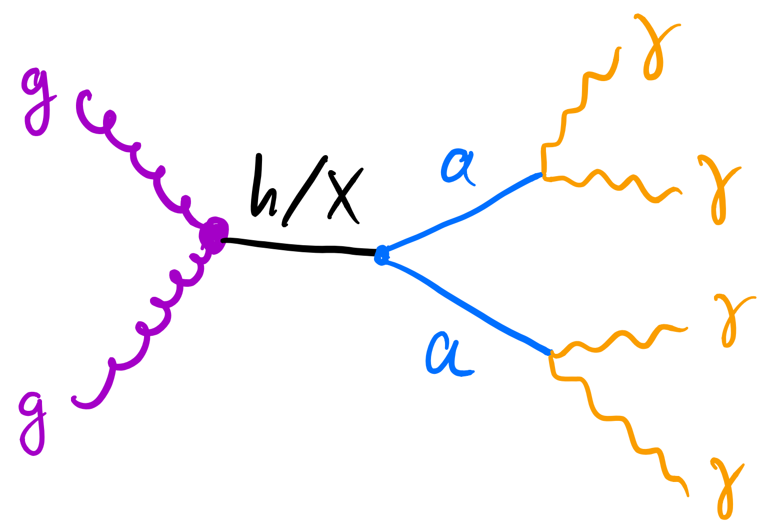
Disclaimer: The number of possible topics to discuss is very large, each of which could fill dedicated workshops (EFT & TGC/QGC, Higgs, HH, SUSY, ALPs, resonances,…).
In the limited time of one talk, I chose to focus on searches connected to one particular topic only: searches for scalar singlets / ALPs.

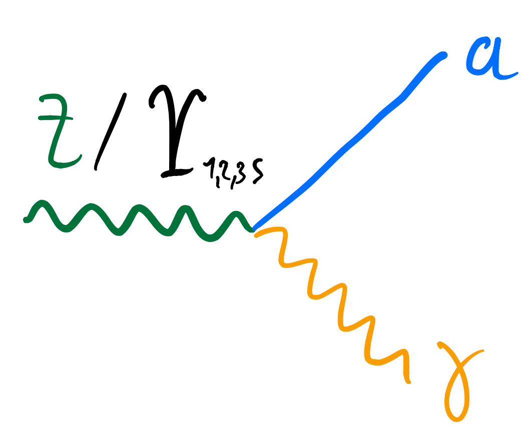
Outline

- Introduction

- Scalar singlets and ALPs







- Application to a UV solution to the B-anomalies

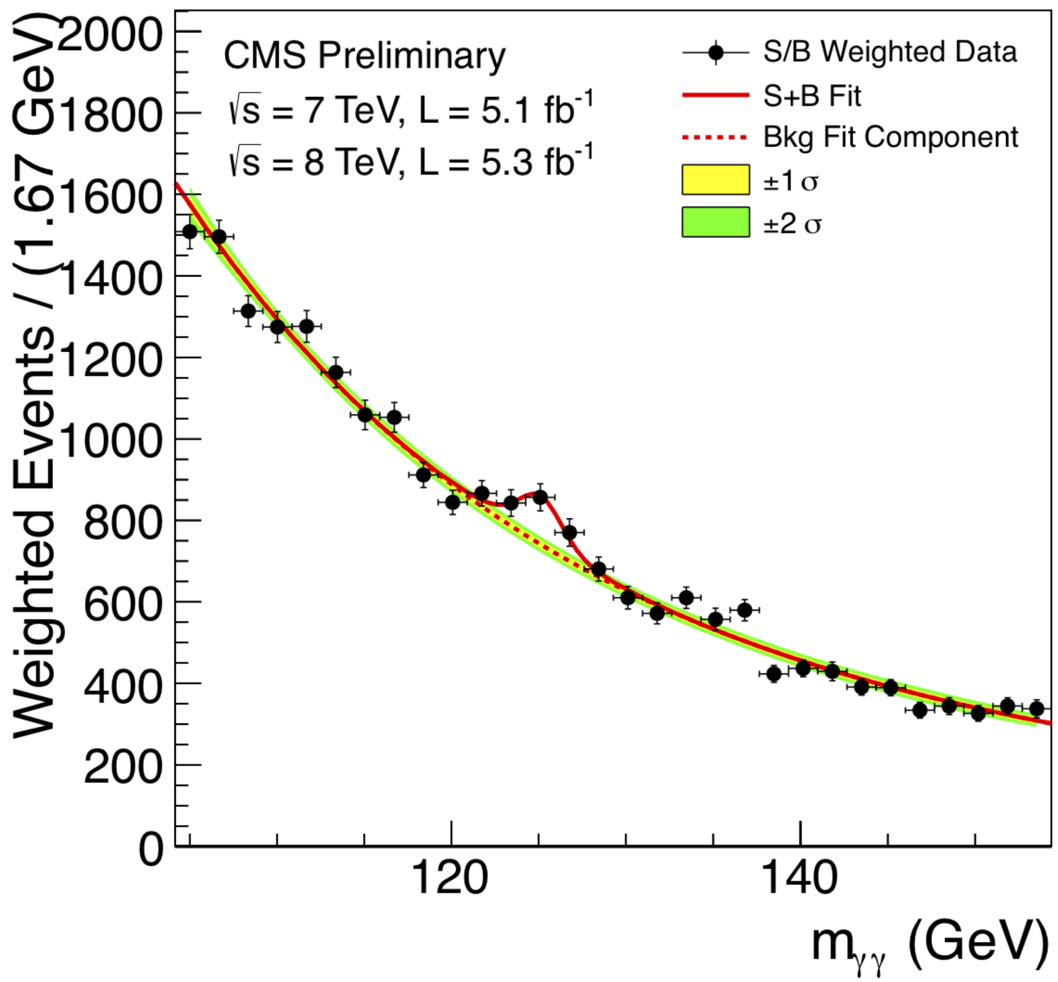
- Conclusions

$\gamma\gamma$ - a discovery channel

One of the most significant scientific discoveries in the last 20+ years, the Higgs discovery was an impressive achievement of LHC, ATLAS, and CMS.

$$m_h = 125 \text{ GeV}$$

The diphoton channel, together with the 4-lepton one, was instrumental to reach this goal.



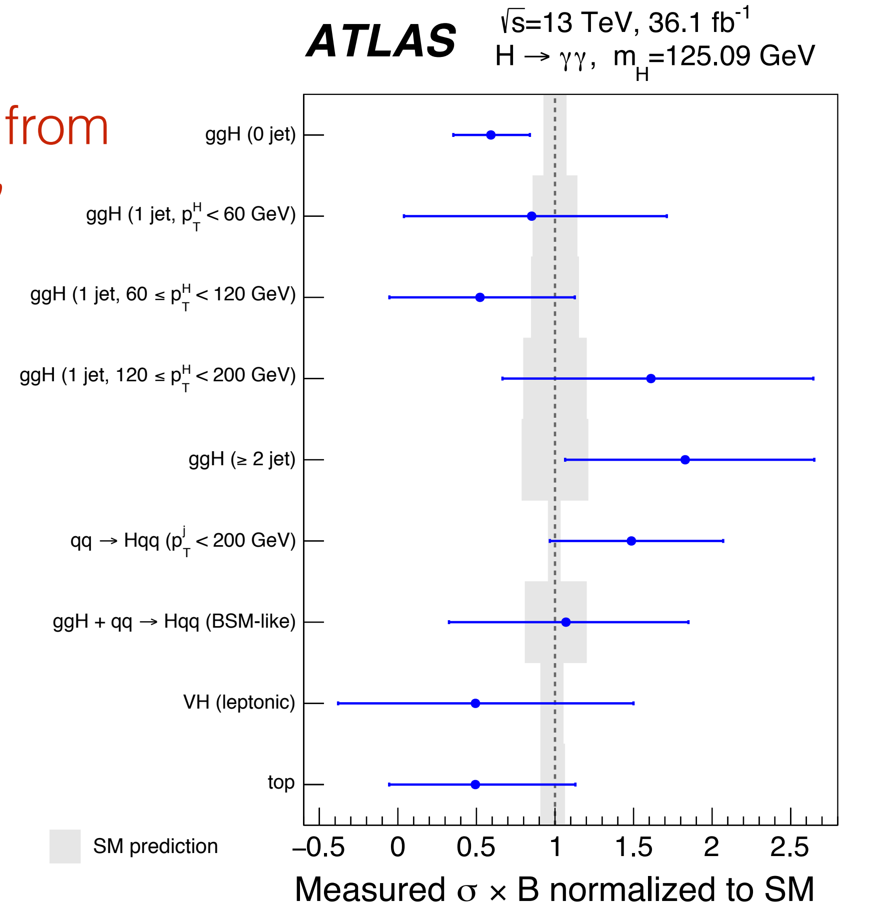
We now have

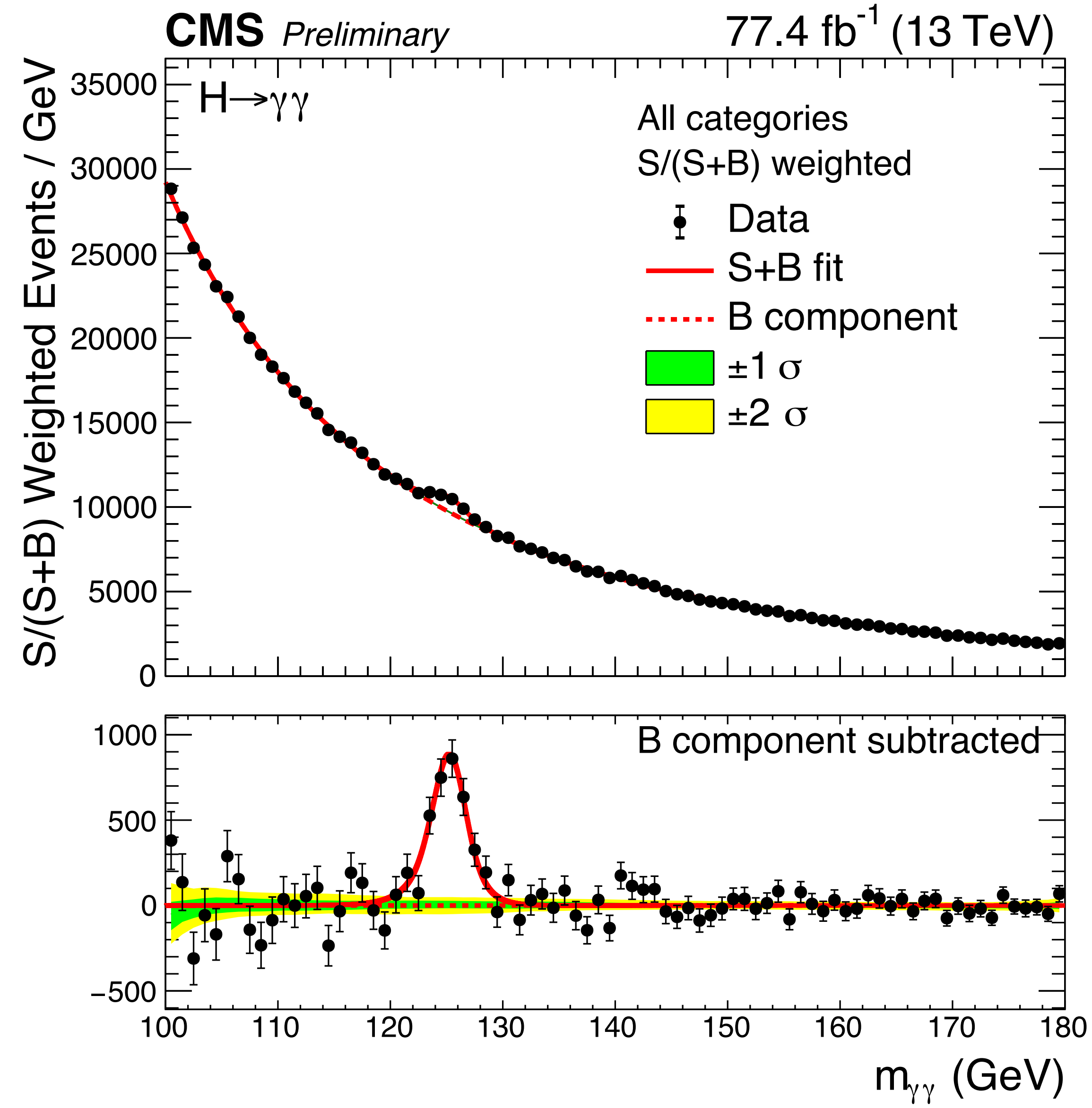
consistent theory of elementary particles and their interactions

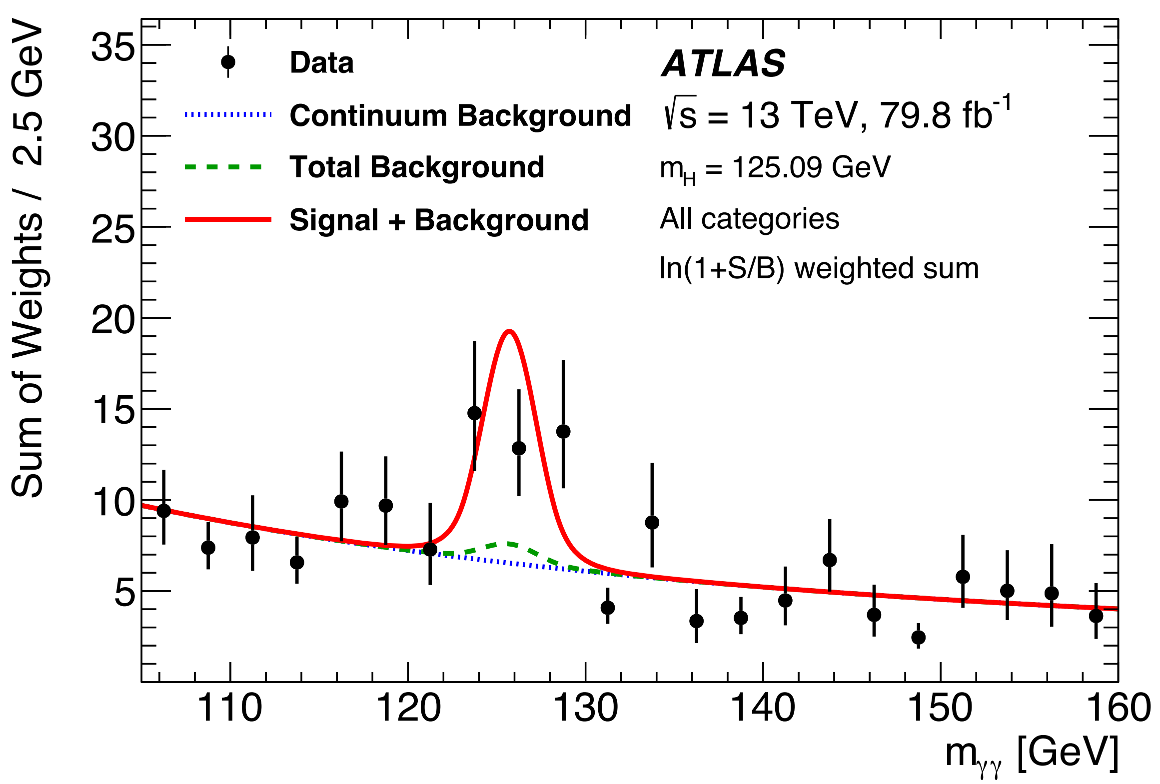
at the electroweak scale.

$\gamma\gamma$ - a precision channel!

STXS from $h\rightarrow\gamma\gamma$







$h\rightarrow\gamma\gamma$ also crucial for the observation of tth production.

What next?

Deep issues still remain open:

- What stabilises the EW scale from shot-distance dynamics?
- What is the origin of the observed fermion masses and mixing?
- What is the nature of dark matter?
- What is the mechanism generating matter/antimatter asymm.?
- Why is $\overline{\theta}_{QCD}$ so small?
- Grand Unification of forces?
- Dark Energy? Inflation? Quantum gravity?

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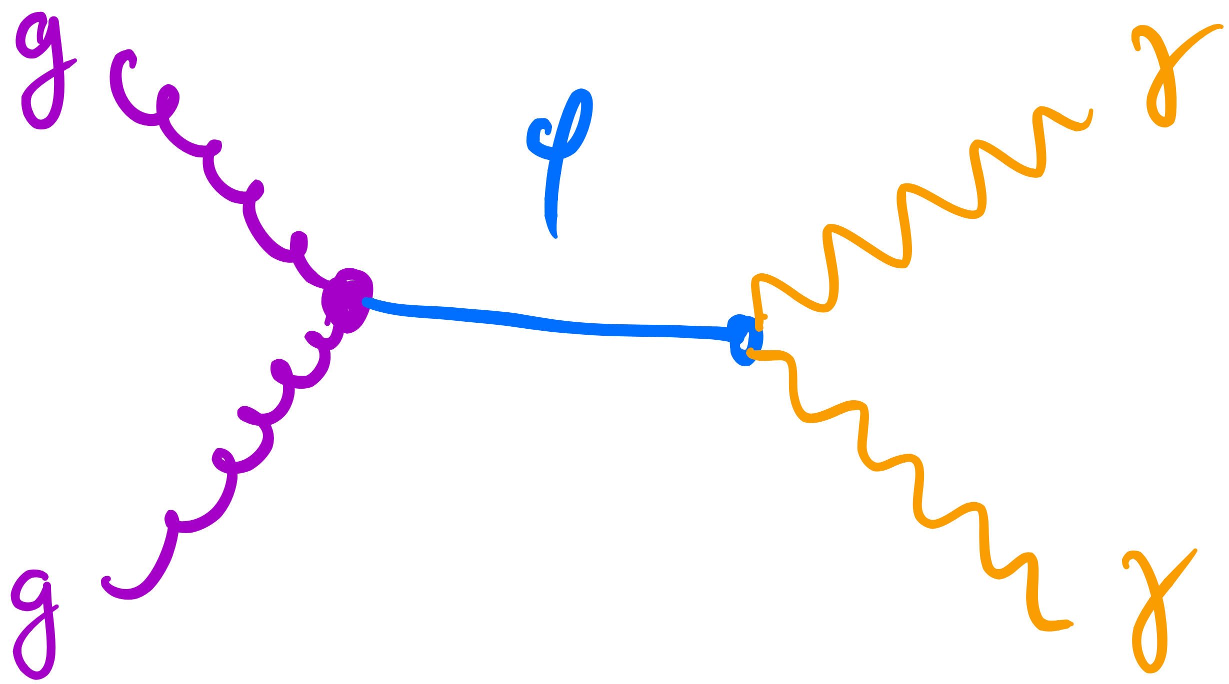
Some hints for possible New Physics at the TeV scale have been building up in B-meson physics.
Final states with photons might still have something important to reveal.

Discovering a new heavy Higgs using photons?



Scalar Singlets with Higgs portal

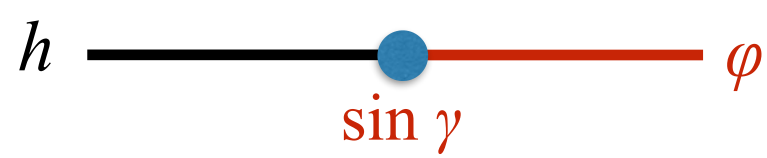
SM + singlet scalar S

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}(\partial S)^2 - \mu_S^2 S^2 - a_{HS}|H|^2 S - \lambda_{HS}|H|^2 S^2 - a_S S^3 - \lambda_S S^4$$

e.g. [Buttazzo, Sala, Tesi 1505.05488, also 1812.07831]

The scalar singlet couples to SM states only via a mixing with the SM Higgs:

Mixing angle γ



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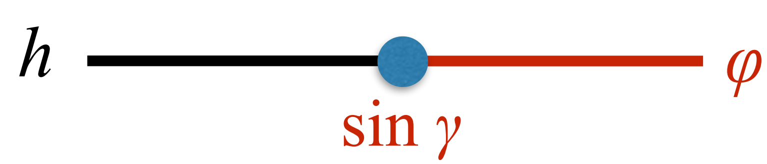

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Higgs couplings rescaled by overall factor $\cos^2\gamma$. $\mu_h = c_\gamma^2\, \mu_{\rm SM}$

From 8TeV ATLAS+CMS

$$s_\gamma^2 \lesssim 0.12$$

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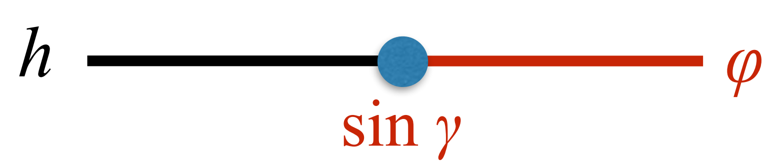

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S couplings to SM particles only depend on γ:

$$\mu_{\phi\to VV,ff} = s_\gamma^2\, \mu_{\rm SM}(m_\phi)\cdot(1-\mathcal{B}(\phi\to hh)), \quad \mu_{\phi\to hh} = s_\gamma^2\, \sigma_{\rm SM}(m_\phi)\cdot\mathcal{B}(\phi\to hh)$$

Equivalence theorem:

$$\mathcal{B}(\phi\to hh) = \mathcal{B}(\phi\to ZZ) = 25\% \text{ for } m_\phi \gg m_h$$

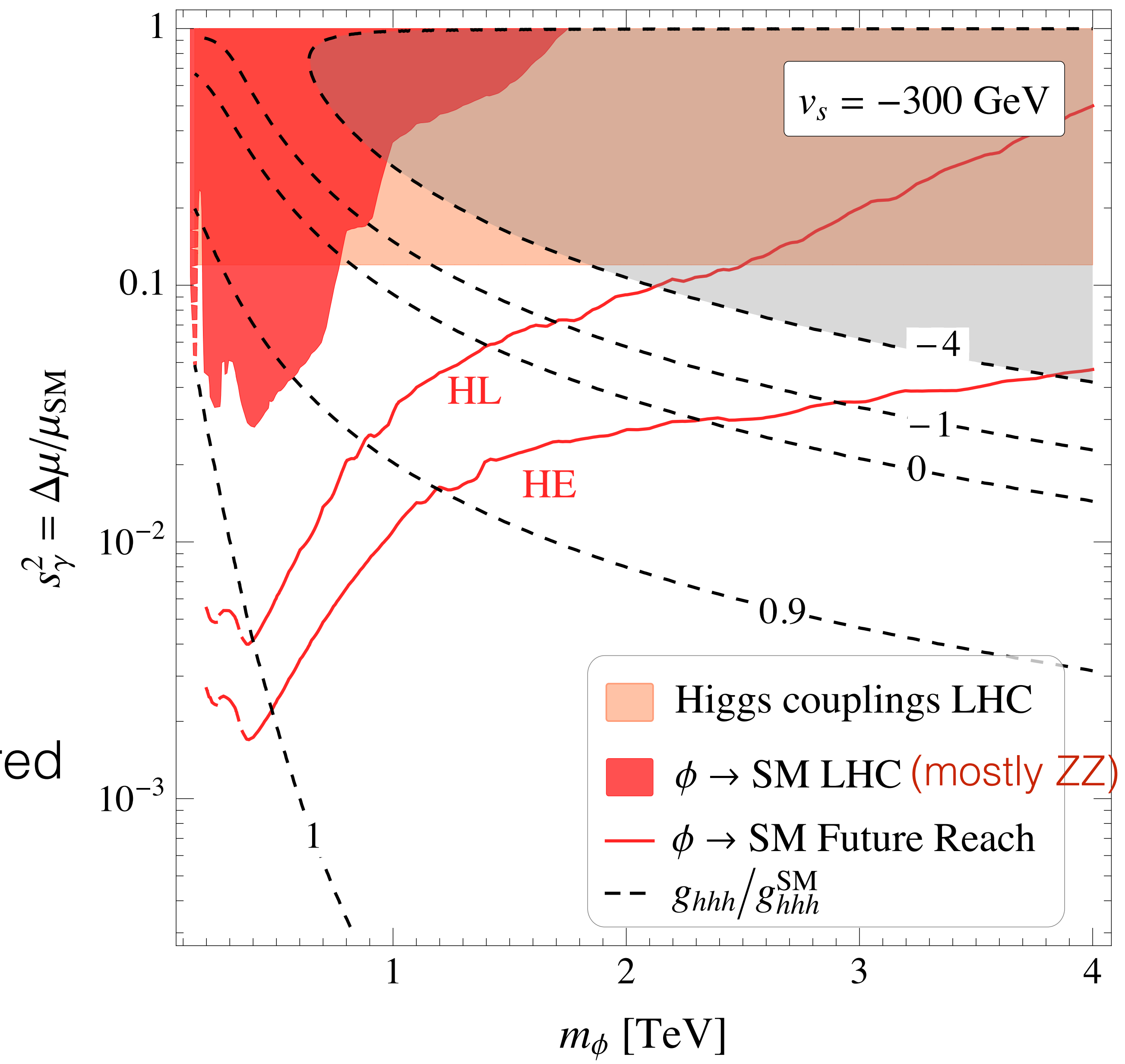
Scalar Singlets with Higgs portal

At large masses $m_\varphi \gg m_W$,
decays into WW, ZZ, hh dominate.

$\gamma\gamma$ and γZ decays are very suppressed in this setup.

To have a **sizeable Br$_{\gamma\gamma}$**, extra states are required to enhance the $\varphi\gamma\gamma$ coupling at 1-loop, e.g. with **vector-like fermions**.

1812.07831 Sec.6.1.4



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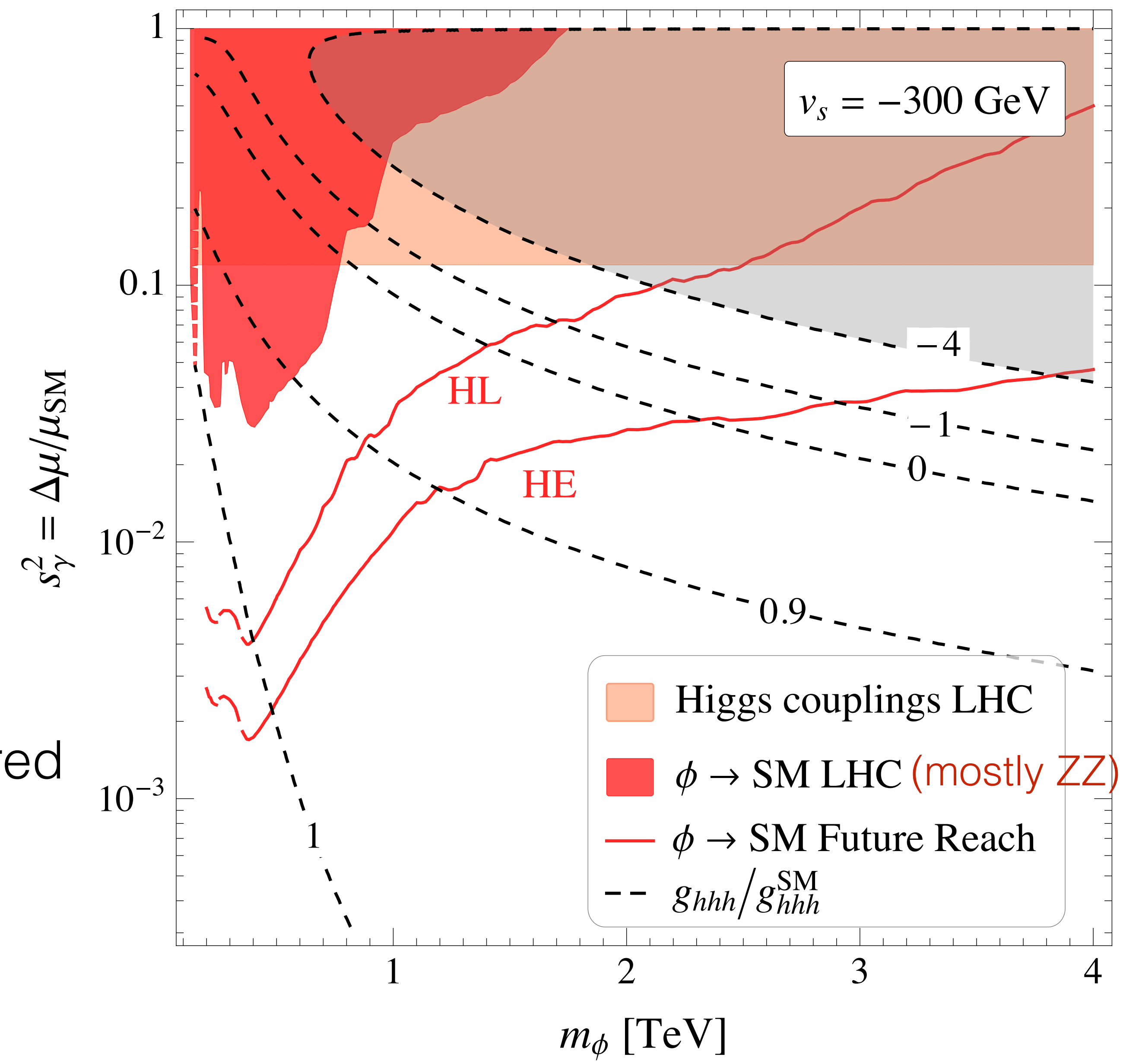

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To have a **sizeable Br$_{\gamma\gamma}$**, extra states are required to enhance the $\varphi\gamma\gamma$ coupling at 1-loop, e.g. with **vector-like fermions**.

Doing this, one can obtain larger Br$_{\gamma\gamma}$ while having a scalar with sizeable total width.
→ 90% of all models for the old 750 GeV diphoton excess

Somewhat similar conclusions apply for the neutral component of a second Higgs doublet.

Scalar pNGB - ALPs

Consider a spontaneously broken global U(1) at a scale f_a

(or a bigger group containing a U(1) factor which commutes with the SM)

The Goldstone theorem implies the presence of a massless scalar Nambu-Goldstone boson (NGB) a

If the symmetry is approximate → naturally small mass $m_a \ll f_a$

(all global symmetries are expected to be approximate)

pseudo-NGB ≡ ALP

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The leading operators in the low-energy Effective theory of pNGB are:

$$\mathcal{L}_{\text{eff}} = \frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2}m_a^2 a^2 + \frac{a}{f}\sum_{i=1}^{3} c_i \frac{\alpha_i}{4\pi} F_{i,\mu\nu}\tilde{F}_i^{\mu\nu}$$

Axial coupling to SM gauge bosons given by the ABJ anomalies of the global U(1) with SM gauge group.

New colored and EW-charged states expected below $\Lambda \sim 4\pi f_a$.
→ f_a cannot be too small.

Scalar pNGB - ALPs

Real-life example:

π^0 is one of the pNGBs of chiral symmetry breaking, and the U(1)$_A$ axial anomaly generates a $\pi^0\gamma\gamma$ coupling: its main decay mode.

Some motivated BSM examples:

- Singlet pNGB in Composite Higgs models, $f_a \sim 1$ TeV $m_a \sim$ 10GeV - 1TeV
- ALP-mediated dark matter $f_a \sim$ TeV $m_a \sim$ 10GeV - 1TeV
- pNGBs from SUSY - *R*-axion [e.g. 1702.02152] $f_a \sim 1$ TeV - ?? $m_a \sim$ MeV - TeV (?)
- QCD axions (but expected much larger f_a), $f_a = 10^{\sim 13}$ GeV $m_a \sim$ μeV
- String axions (but expected much larger f_a), $f_a \sim M_{pl}$ $m_a \ll$ μeV

Scalar pNGB - ALPs

See e.g. 1812.07831 sec. 6.1.7

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

$$\Gamma_{gg} = \frac{K_g \alpha_s^2 c_3^2}{8\pi^3}\frac{m_a^3}{f_a^2}, \qquad \Gamma_{\gamma\gamma} = \frac{\alpha_{\rm em}^2 c_\gamma^2}{64\pi^3}\frac{m_a^3}{f_a^2}$$

$$c_\gamma = c_2 + 5c_1/3$$

Total width is typically small.
Leading decay channel in gluons,
unless large hierarchy in anomaly coefficients.

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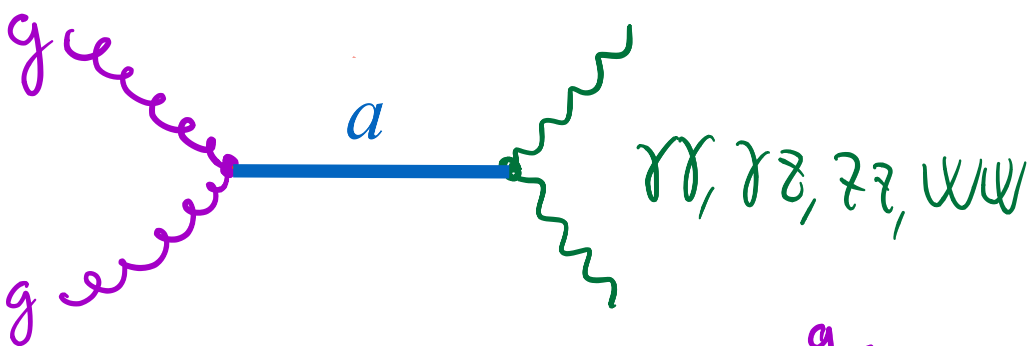
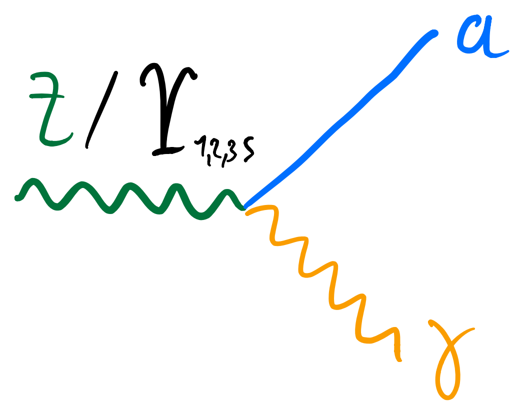
ALP searches with photons in final state

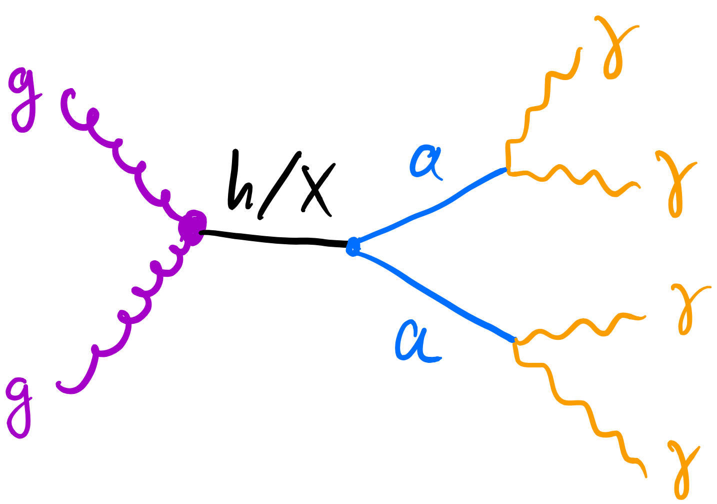
Signals at LHC in diboson resonant searches:



Decay of massive vectors:

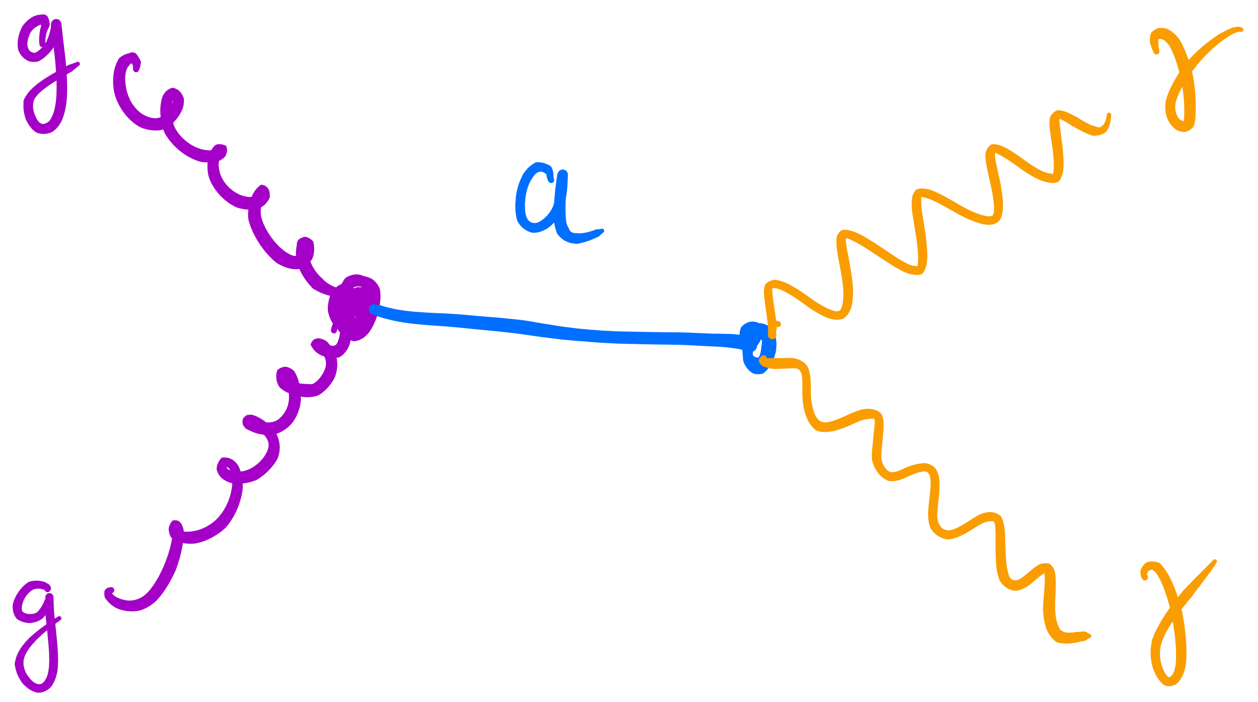


ALP pair production
via res. s-channel mediator,
decay to photons or gluons:

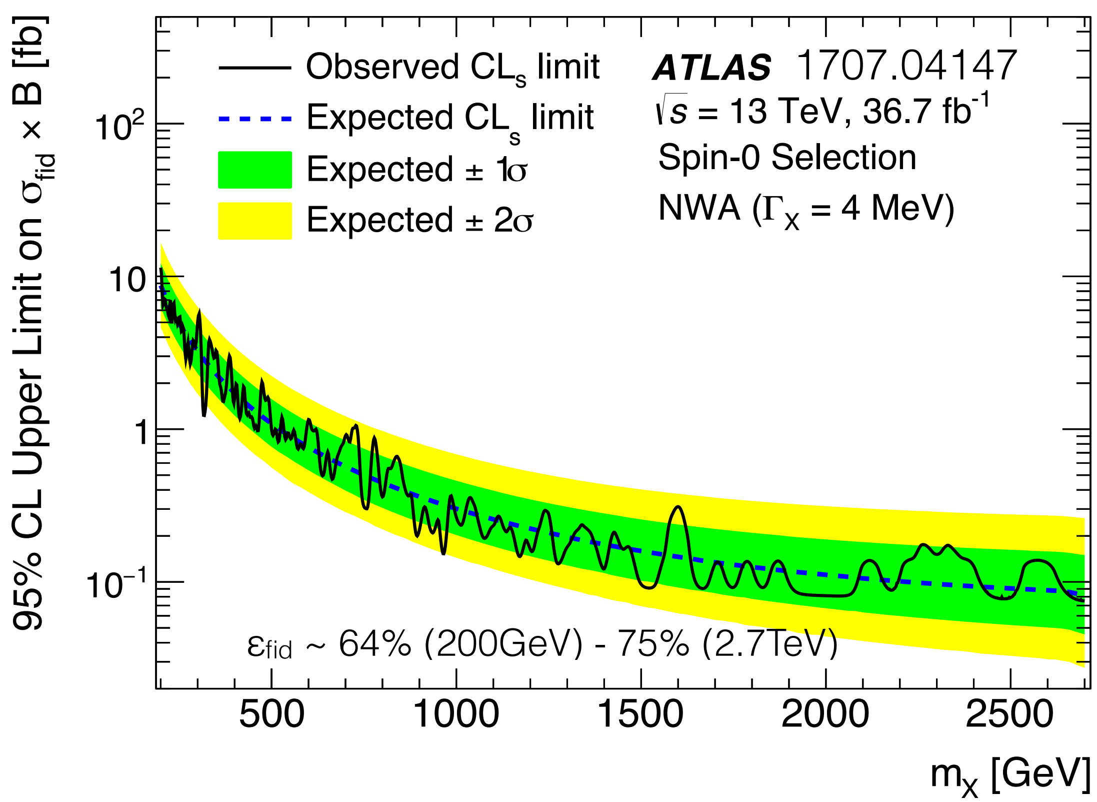


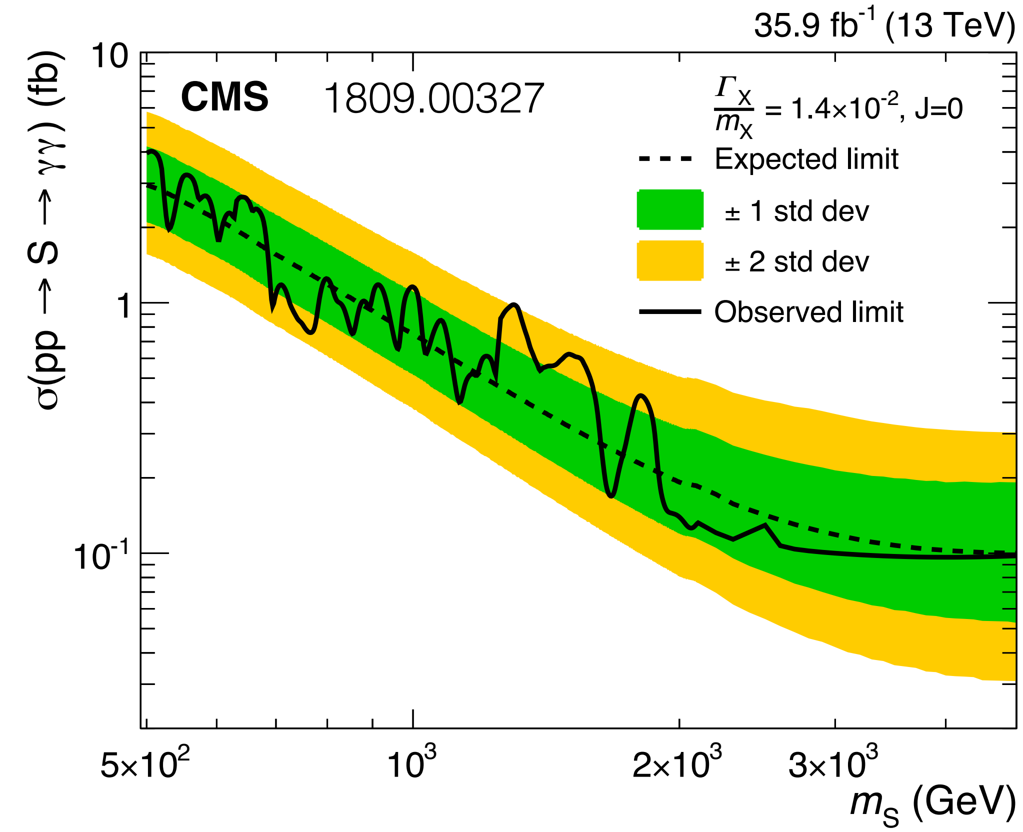
LHC can be relevant for
$f_a \lesssim 100$ TeV.
$m_a \sim 10$ GeV - few TeV.

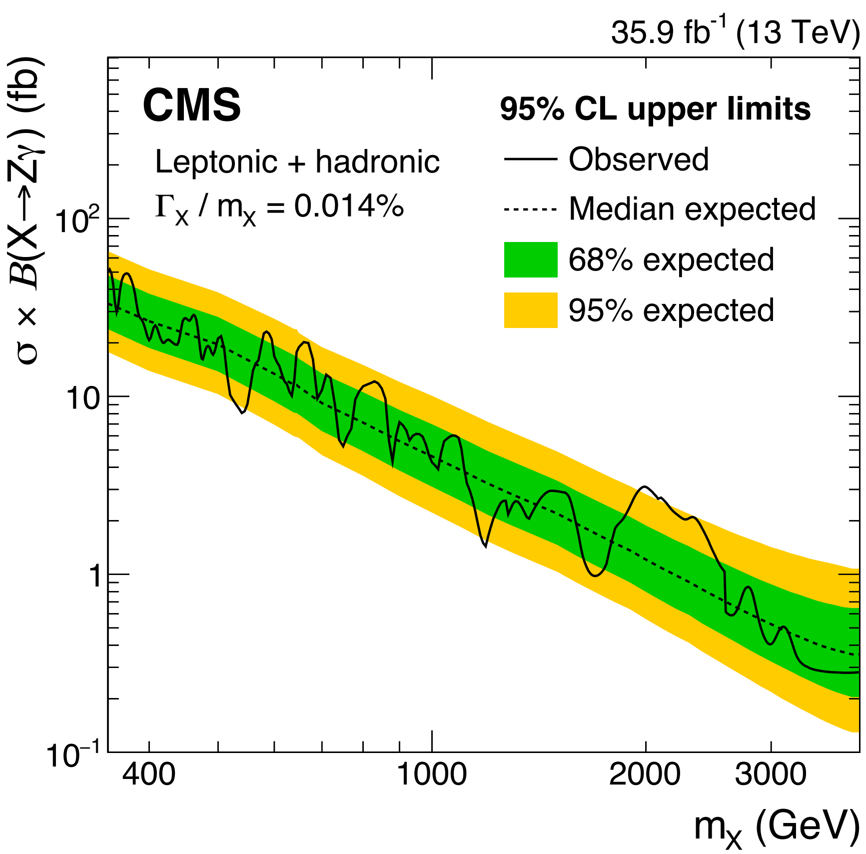
ALP to $\gamma\gamma$ / $Z\gamma$



$\gamma\gamma$ and $Z\gamma$ channels - $m_a \gg m_h$



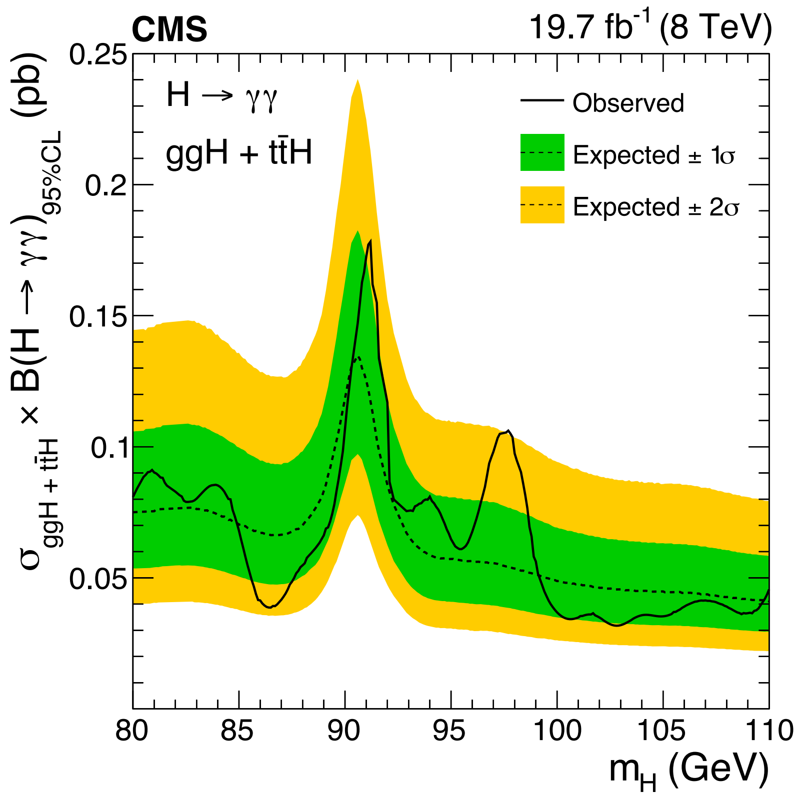


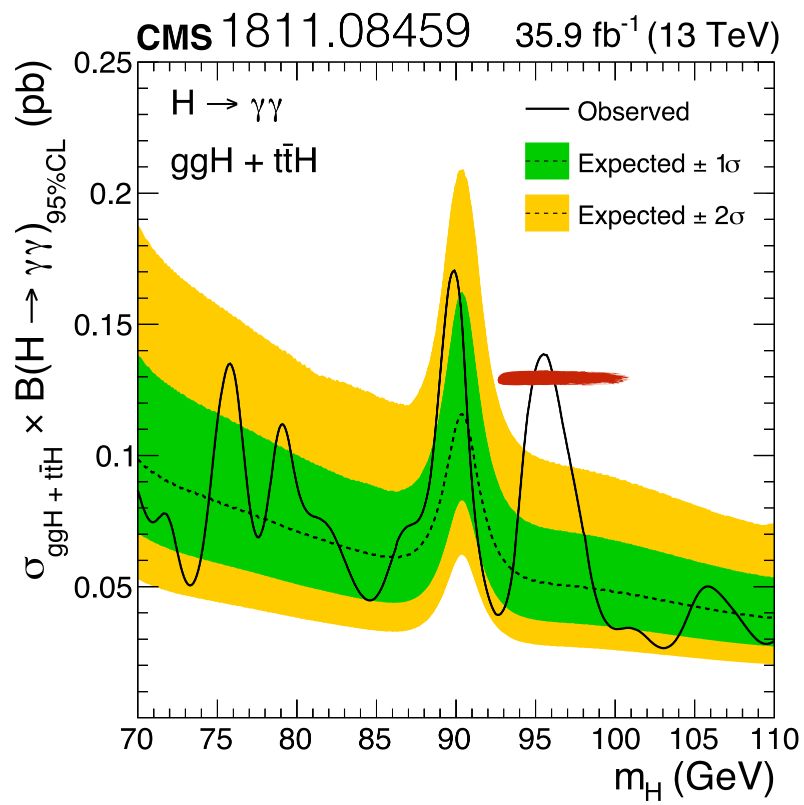


$$\sigma(pp \to a\ (1\text{TeV}) \to \gamma\gamma) \lesssim 0.8\text{fb}$$

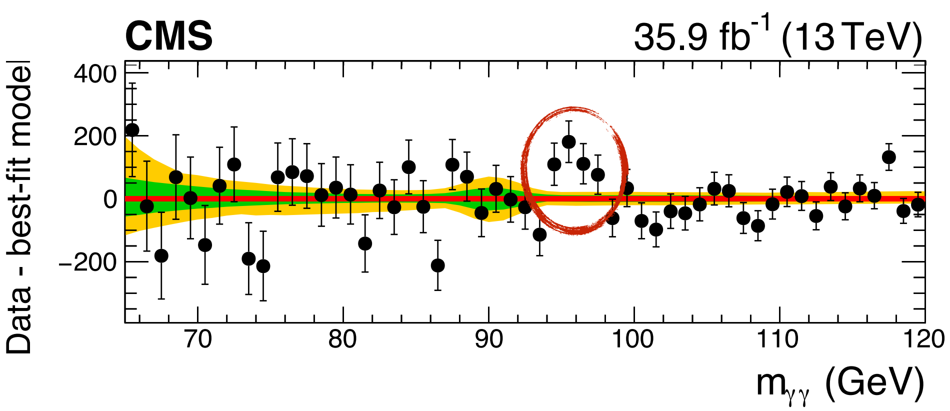
$$\sigma(pp \to a\ (1\text{TeV}) \to Z\gamma) \lesssim 4\text{fb}$$

$\gamma\gamma$ channel - 65-110GeV





The excess at **~ 95GeV** has a combined significance of 2.8σ local (1.3σ global)



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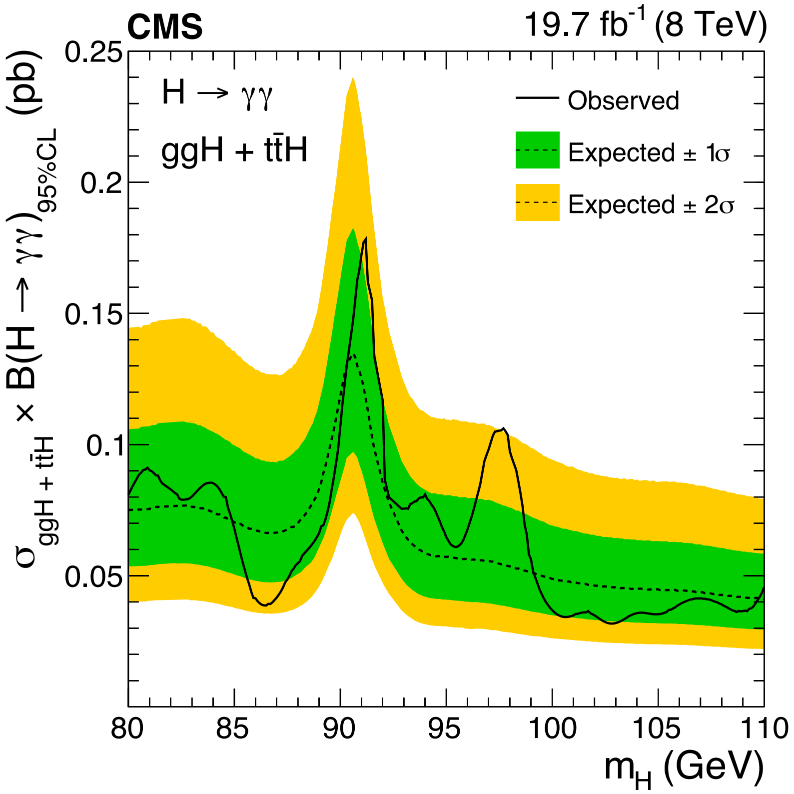

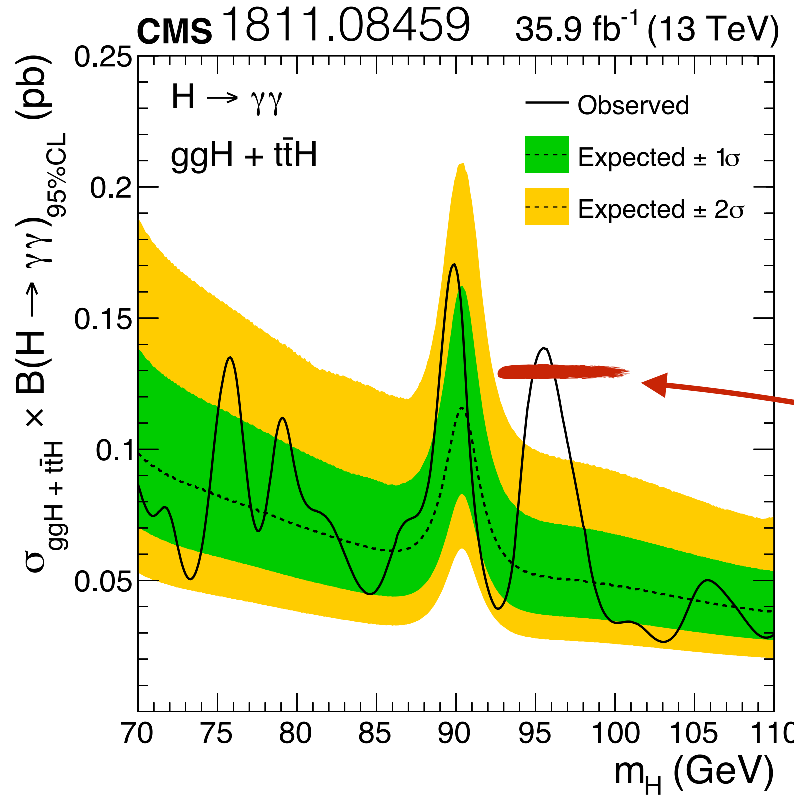

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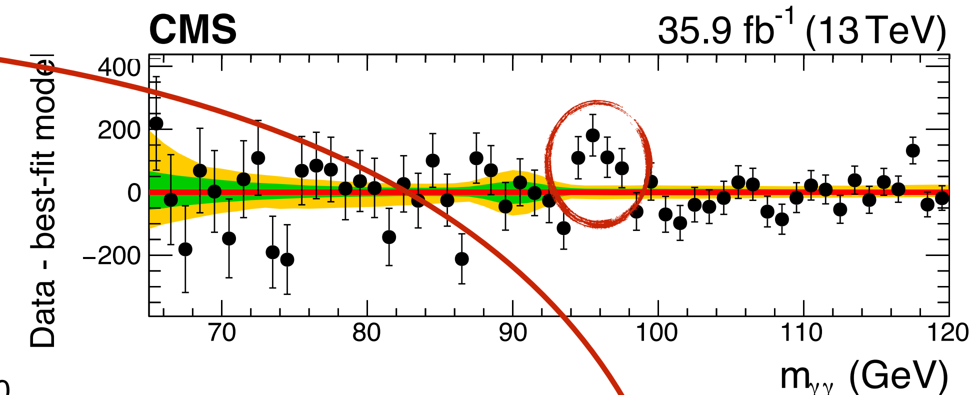

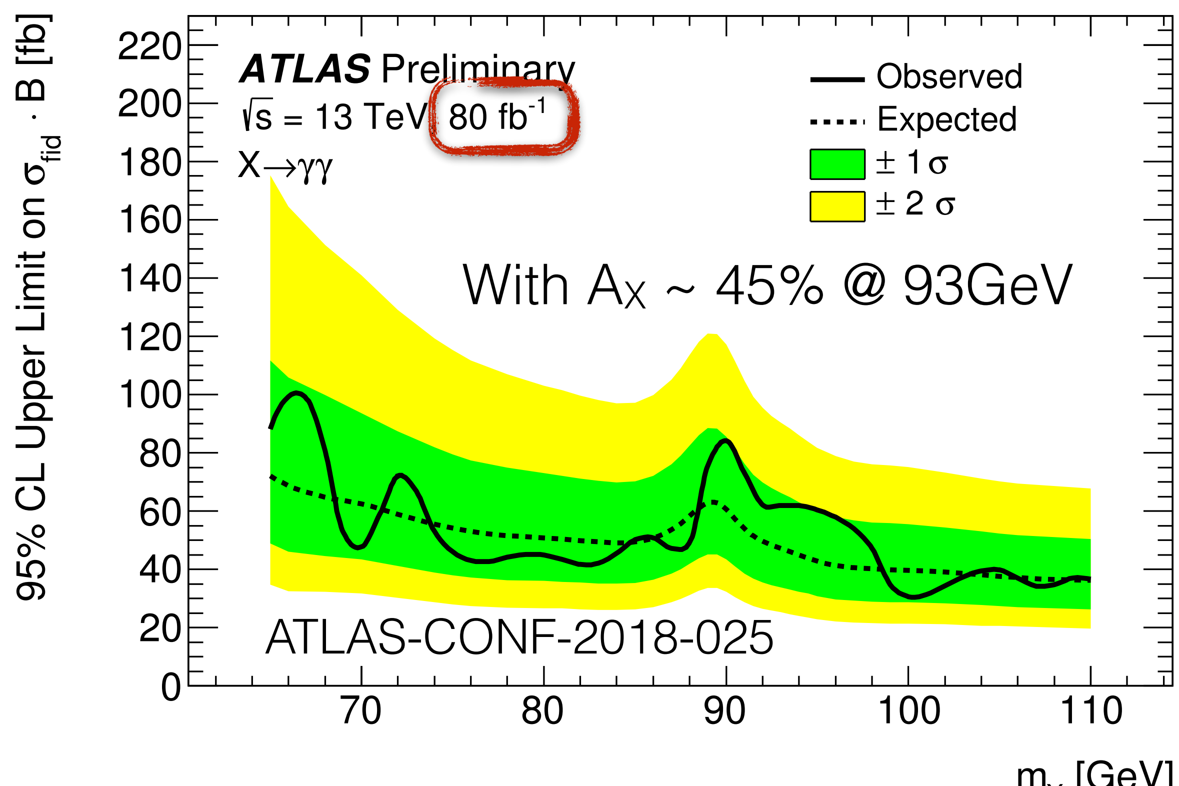

The ATLAS limit, taking into account the acceptance in the fiducial volume, is:

$$\sigma_{13\mathrm{TeV}}(pp \to a\ (93\mathrm{TeV}) \to \gamma\gamma) \lesssim 0.13\ \mathrm{pb}$$

Inconclusive

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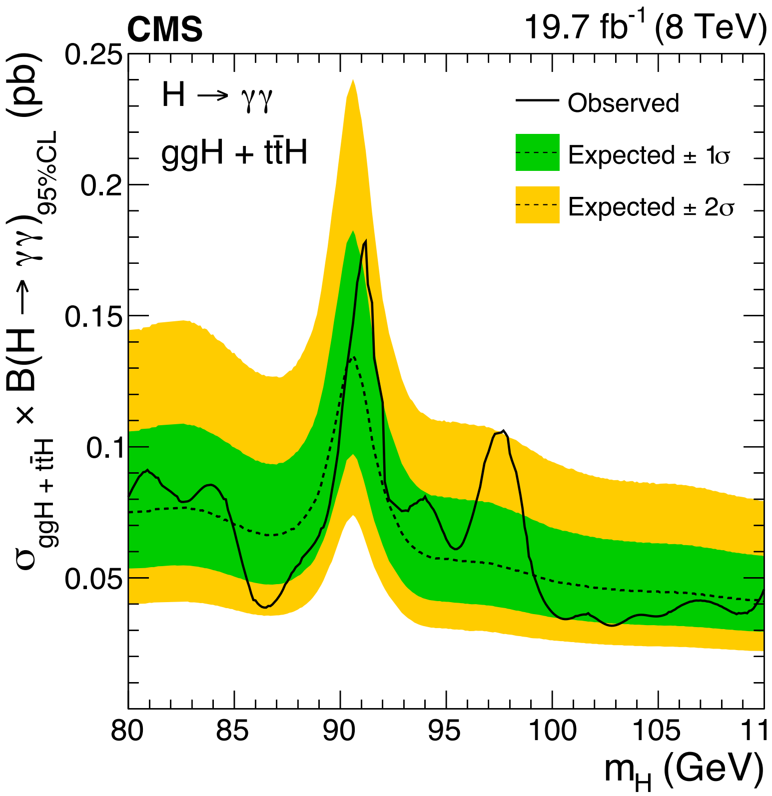

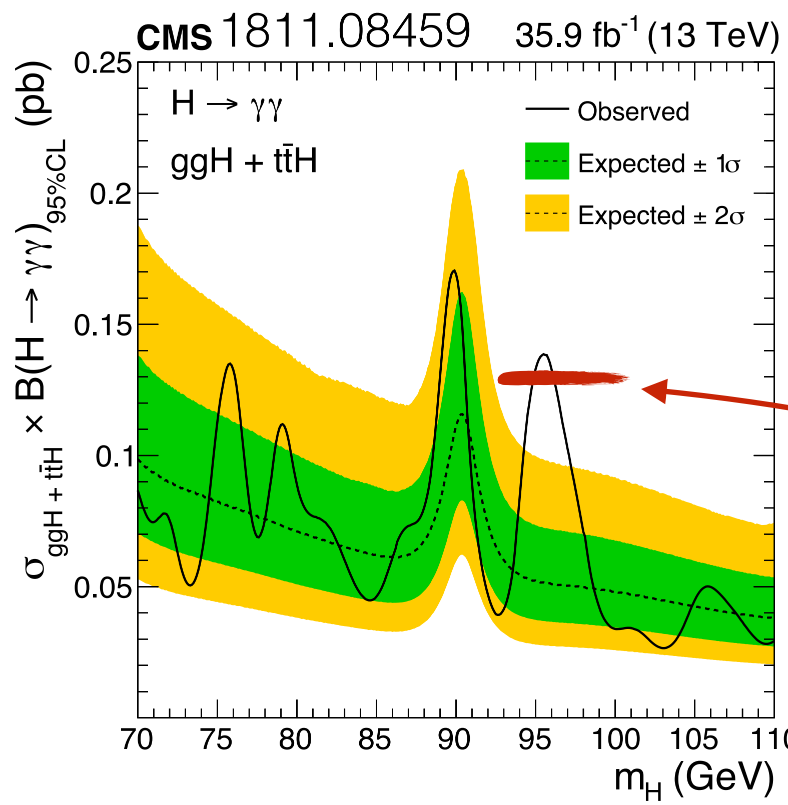

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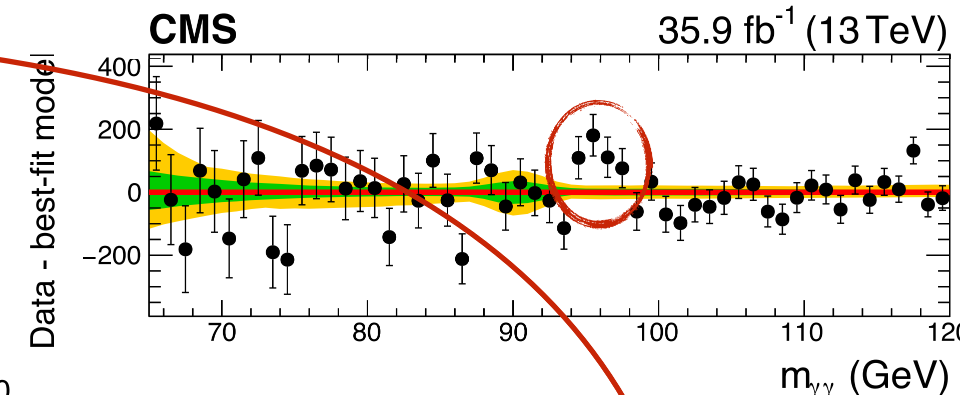

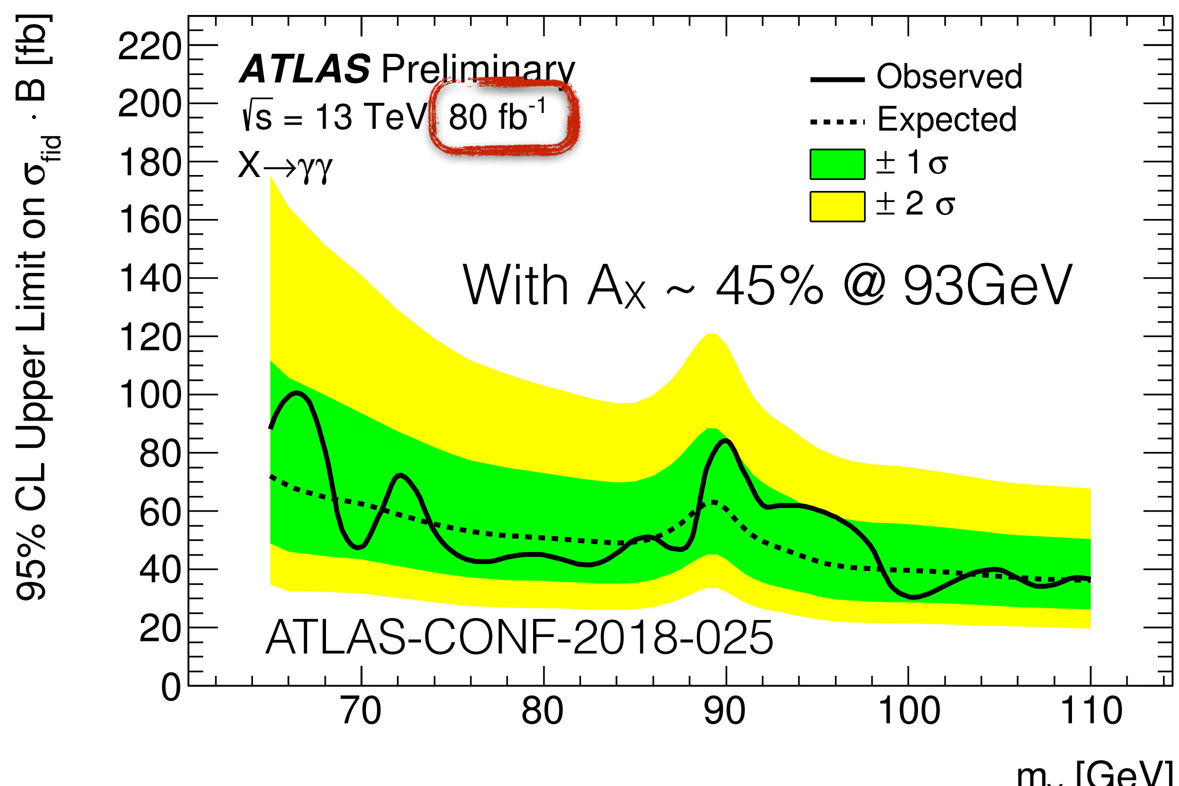

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Could be interpreted as: Mariotti et al. 1710.01743

$$\frac{f_a}{c_\gamma} \simeq 470\ \text{GeV}\sqrt{\frac{50\ \text{fb}}{\sigma_{\gamma\gamma}^{\text{sign}}}}, \qquad c_3 \lesssim 2 \cdot c_\gamma$$

Very reasonable values, worth keeping an eye on.

$\gamma\gamma$ channel - 10-65 GeV

The low-mass resonance regime is challenging for ATLAS and CMS due to p_T cuts.

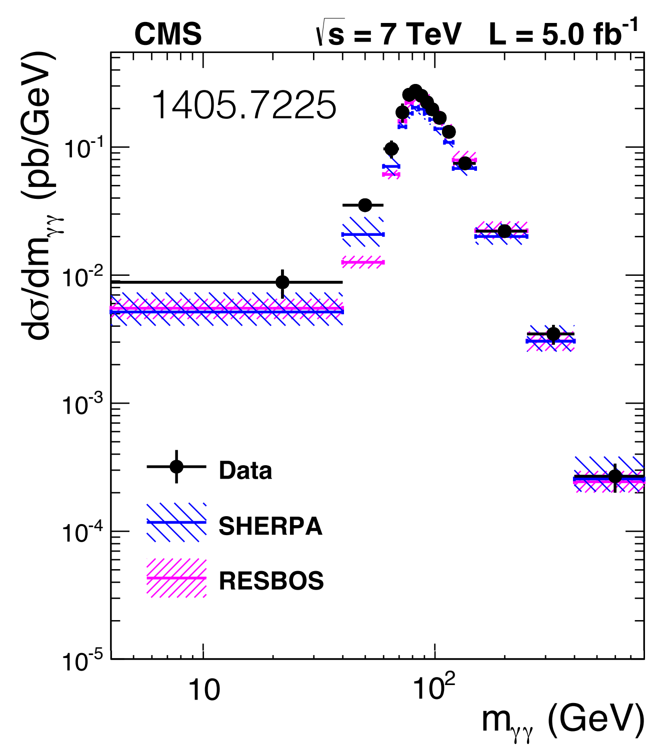
A limit in this mass range can be obtained by using published inclusive differential diphoton cross sections and imposing this very conservative bound:

$$N_{NP} < N_{data}\,(1+ 2\,\Delta)$$

Mariotti, Redigolo, Sala, Tobioka 1710.01743, 1812.07831

Lower bound on accessible $m_{\gamma\gamma}$ from kinematics:

$$m_{\gamma\gamma} > \Delta R \cdot \sqrt{p_{T1}^{\min} p_{T2}^{\min}}$$



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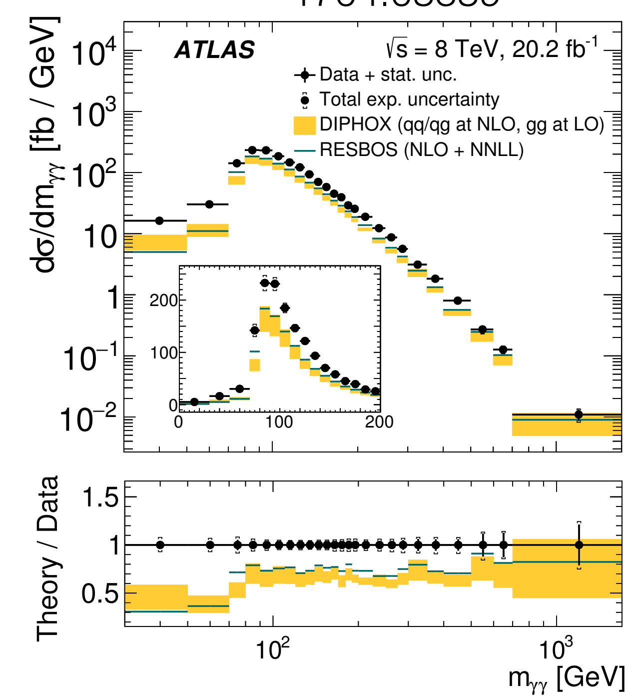

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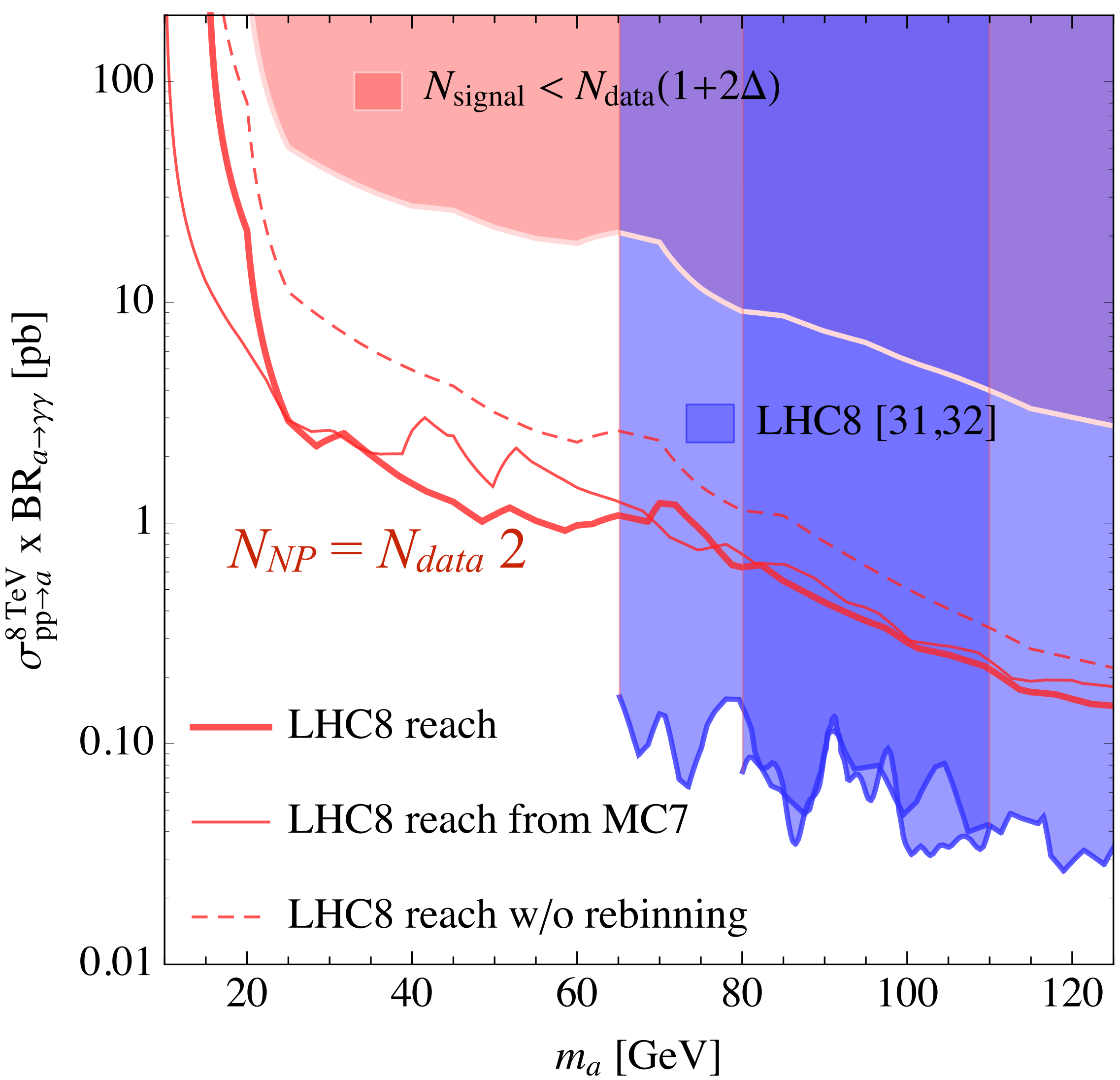

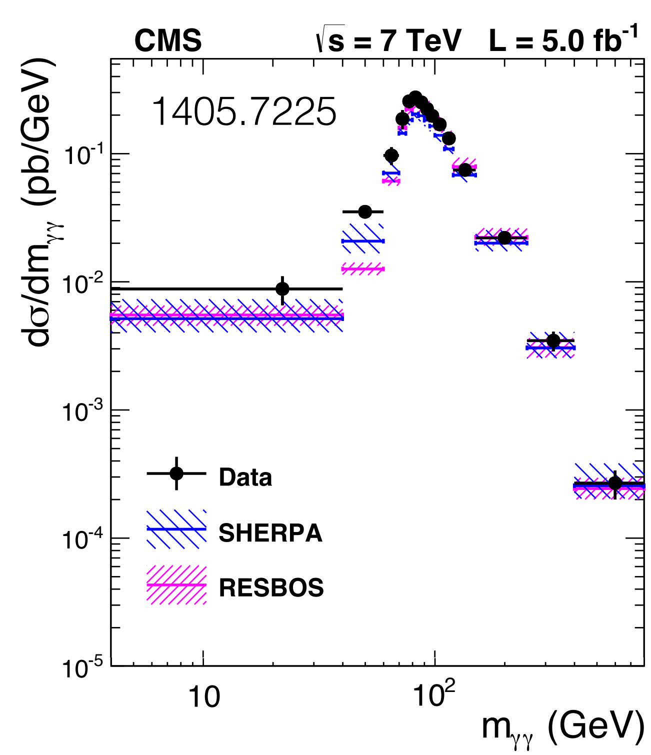

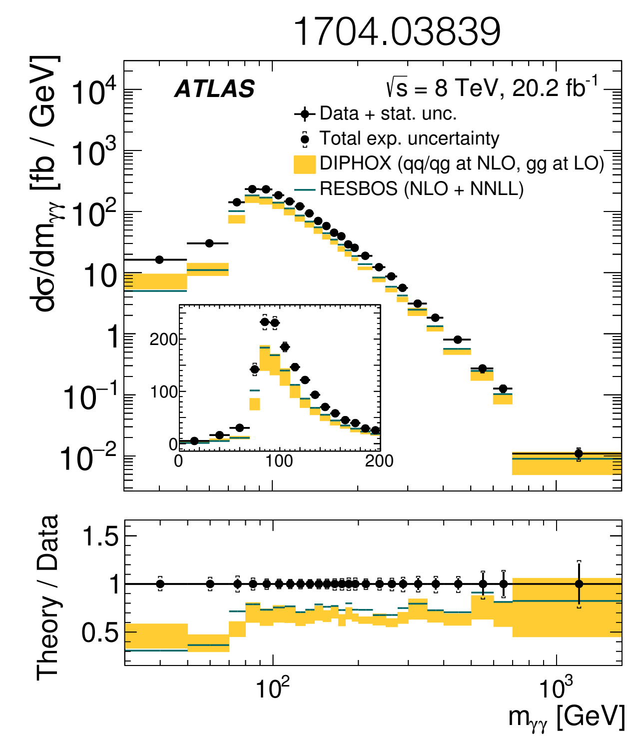

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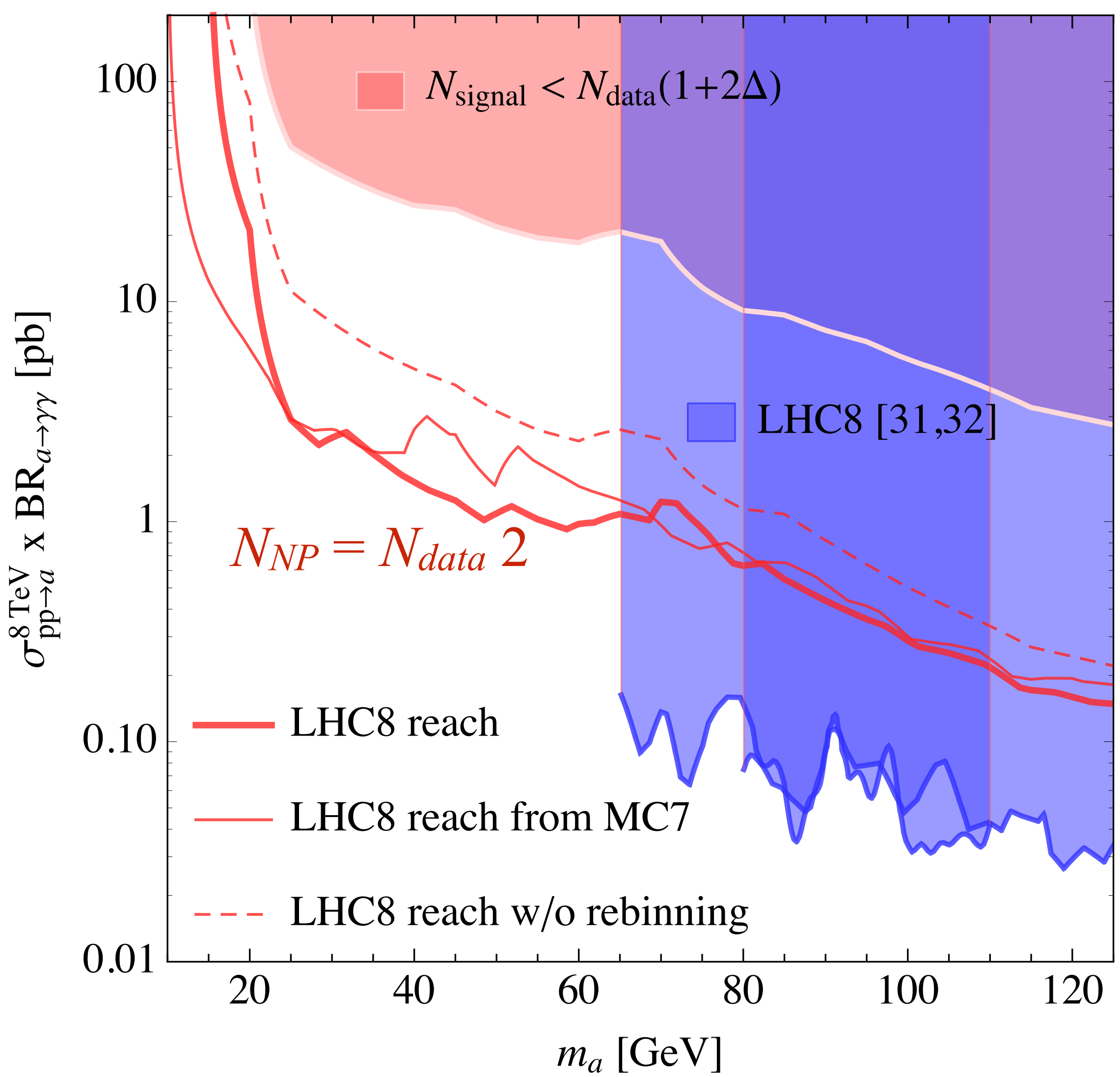
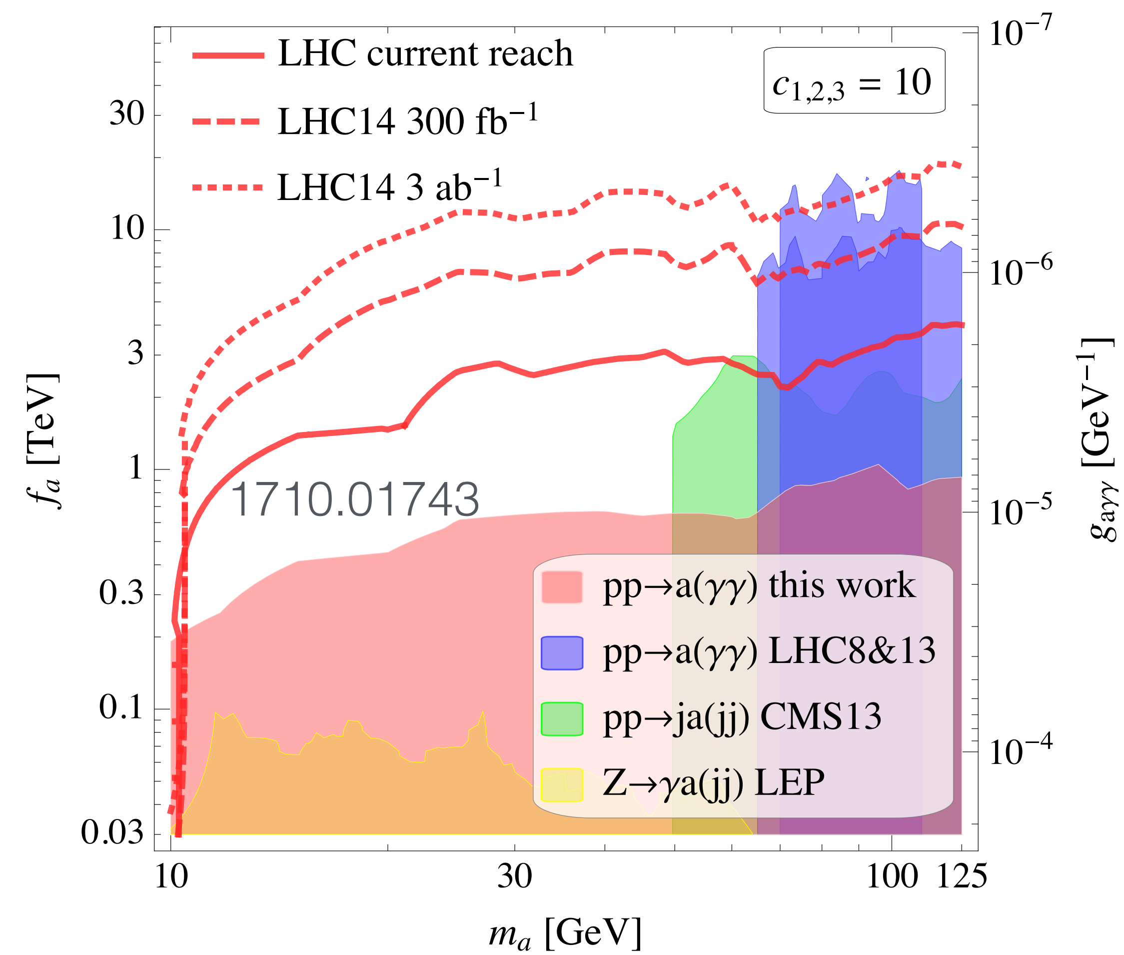


Exclusion potential:

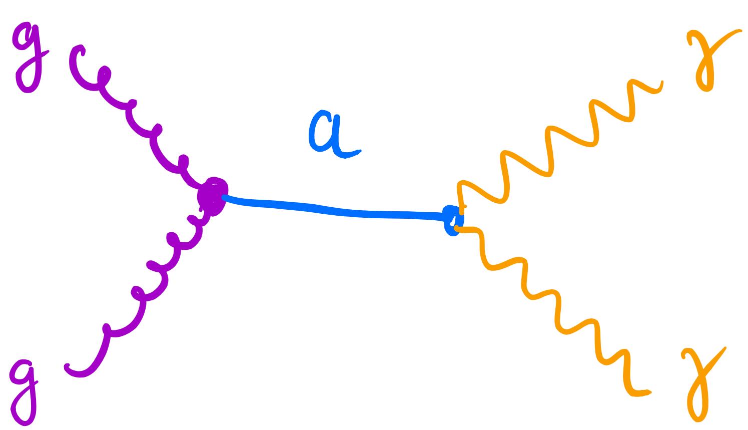
$$\mathcal{L}_{\text{int}} = \frac{a}{4\pi f_a}\left[\alpha_s c_3 G\tilde{G} + \alpha_2 c_2 W\tilde{W} + \alpha_1 c_1 B\tilde{B}\right]$$



$\gamma\gamma$ channel - 2-10 GeV

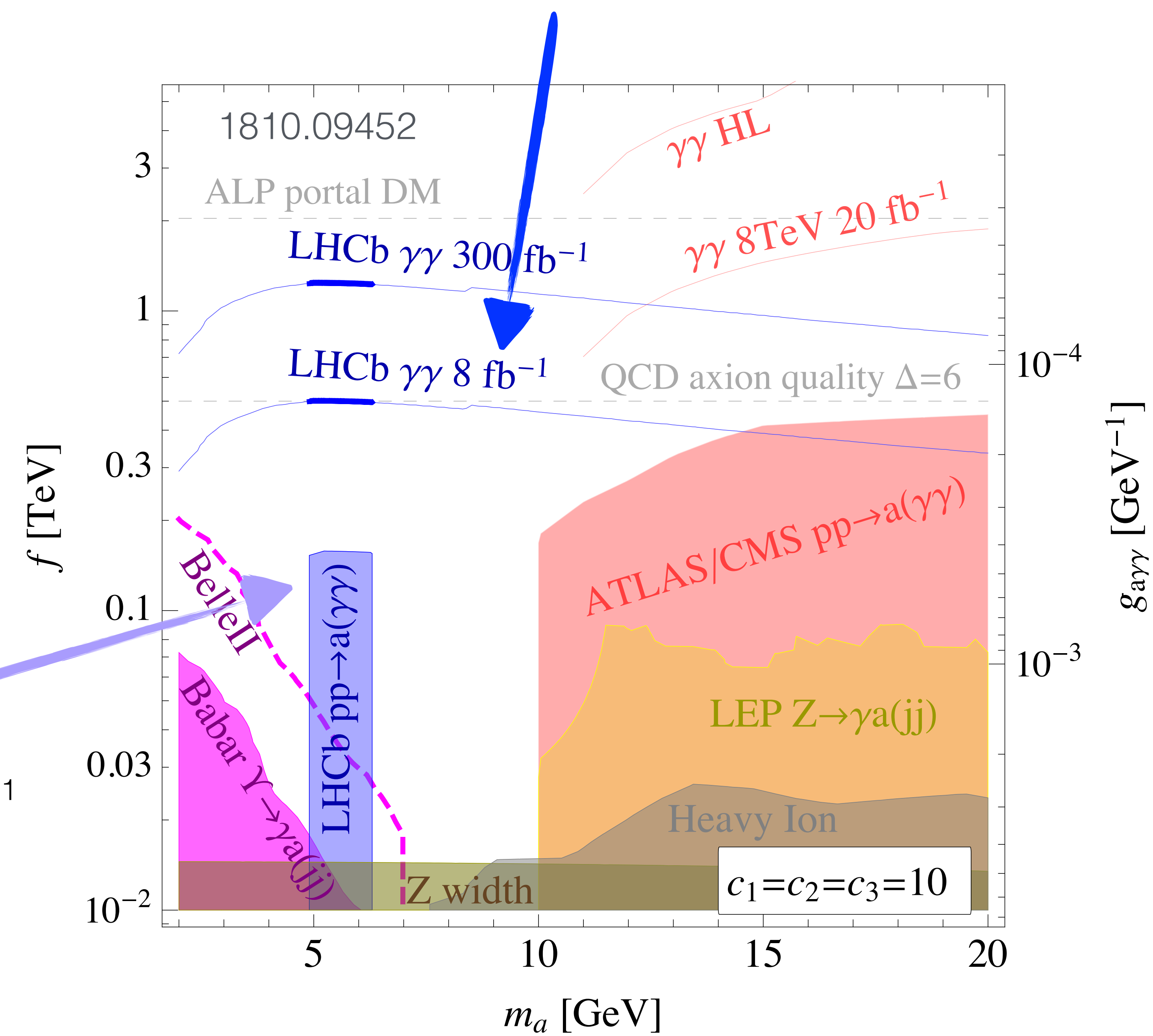
Vidal, Mariotti, Redigolo, Sala, Tobioka 1810.09452

LHCb potentially strong sensitivity to small ALP mass, thanks to low-mass diphoton trigger, necessary for $B_s \to \gamma\gamma$.

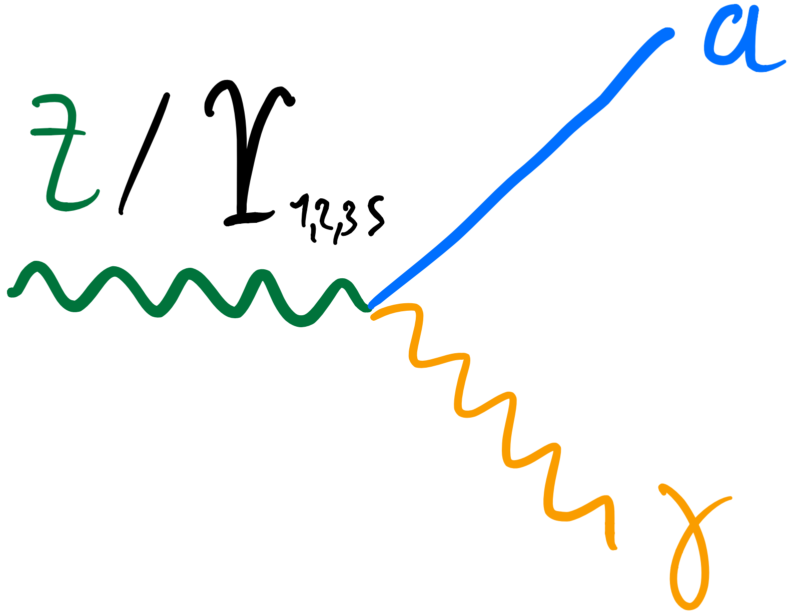


From recast around B_s mass with 80pb^{-1}

Sensitivity estimate of a dedicated LHCb search



Vector decays into ALP + γ

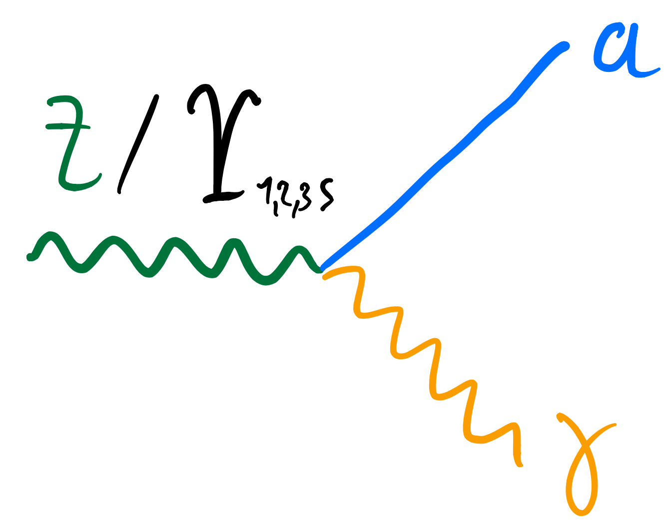


Vector decays into ALP + γ

See e.g. Vidal et al. 1810.09452, 1812.07831 sec. 6.1.7

For $m_a < m_V$

Bound from total Z width,
$Z \to \gamma a(gg/\gamma\gamma)$ search (LEP,ATLAS),
$\Upsilon \to \gamma a(gg)$ (Babar)



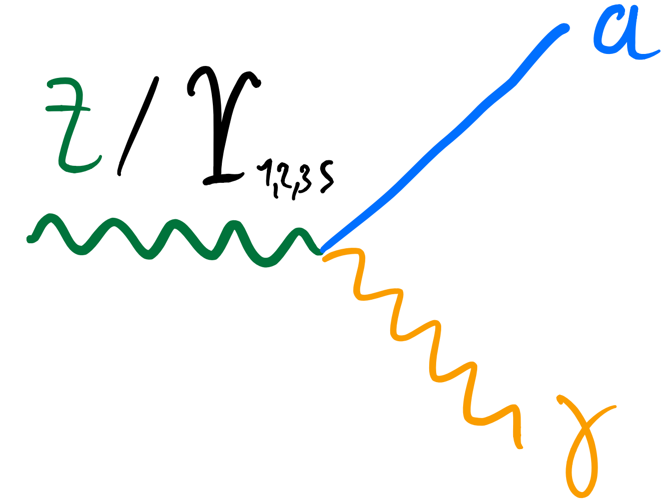
$$\Gamma(Z \to \gamma a) = \frac{\alpha_{\rm em}^2 c_{Z\gamma}^2}{96\pi^2 t_w^2} \frac{m_Z^3}{f_a^2} \left(1 - \frac{m_a^2}{m_Z^2}\right)^3 ,$$

$$\Gamma(\Upsilon_X \to \gamma a) = \frac{\alpha_{\rm em} c_{\gamma\gamma}^2}{\pi} \left(\frac{m_{\Upsilon_X}}{4\pi f_a}\right)^2 \left(1 - \frac{m_a^2}{m_{\Upsilon_X}^2}\right)^3 \Gamma(\Upsilon_X \to ll)$$

Via Υ mixing with the photon.

Vector decays into ALP + γ

See e.g. Vidal et al. 1810.09452, 1812.07831 sec. 6.1.7



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Via Υ mixing with the photon.

ATLAS 1509.05051

$$\mathrm{BR}(Z \to \gamma a(\gamma\gamma)) < 2.2 \cdot 10^{-6}$$

LEP ‘92

$$\mathrm{BR}(Z \to \gamma a(jj)) < 1 - 5 \times 10^{-4}$$

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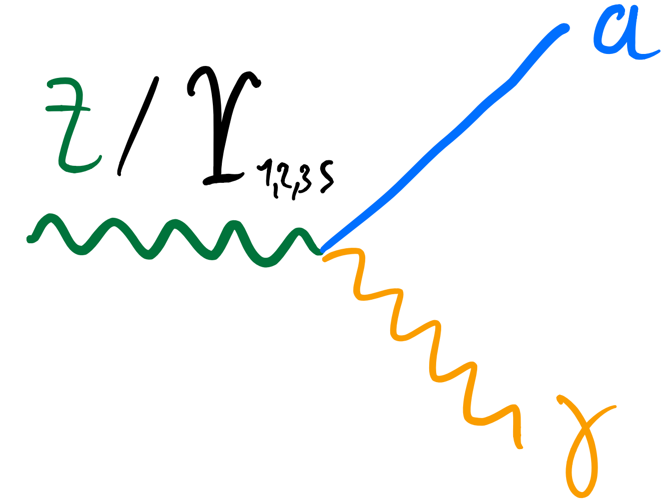

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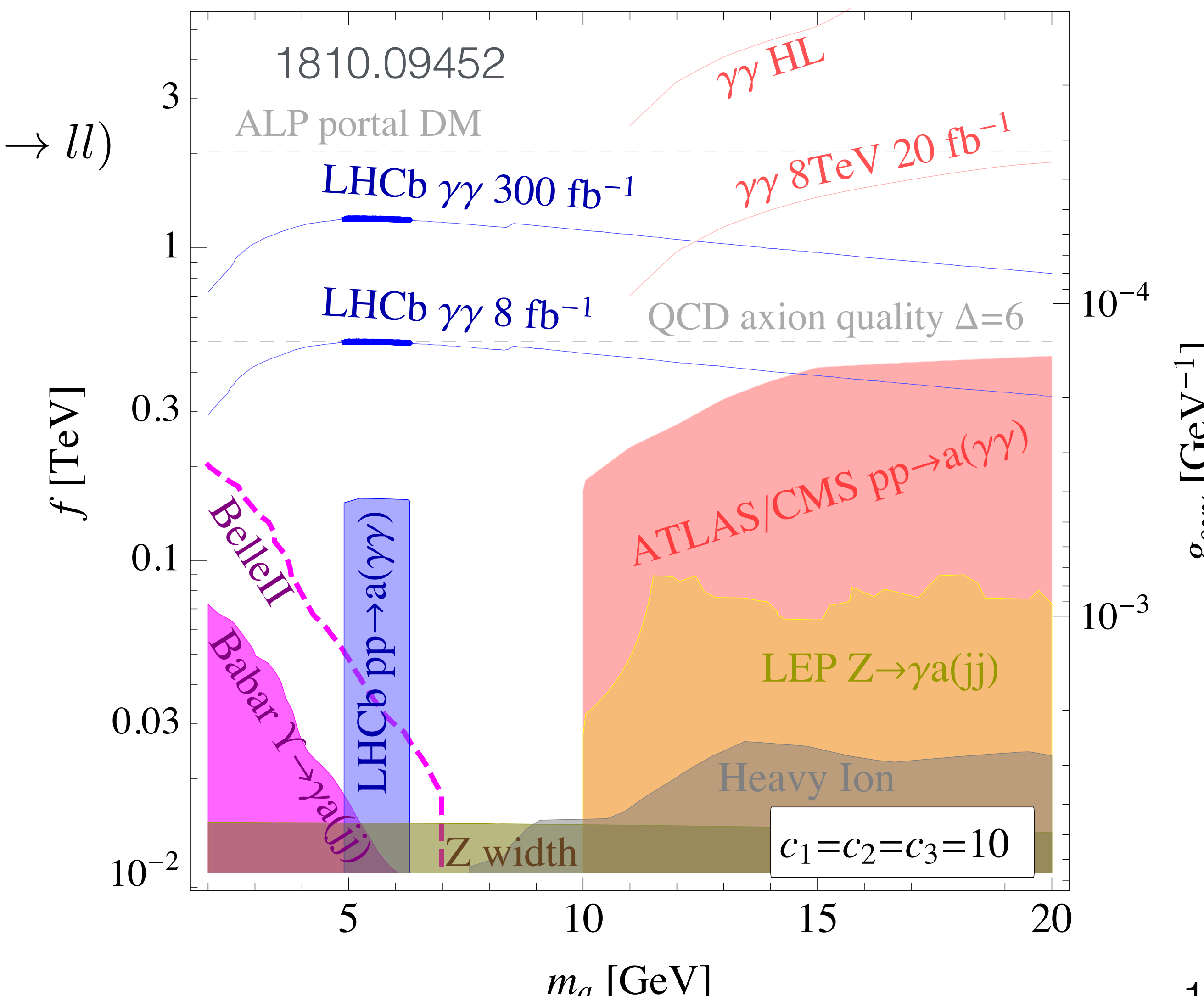
Via Υ mixing with the photon.



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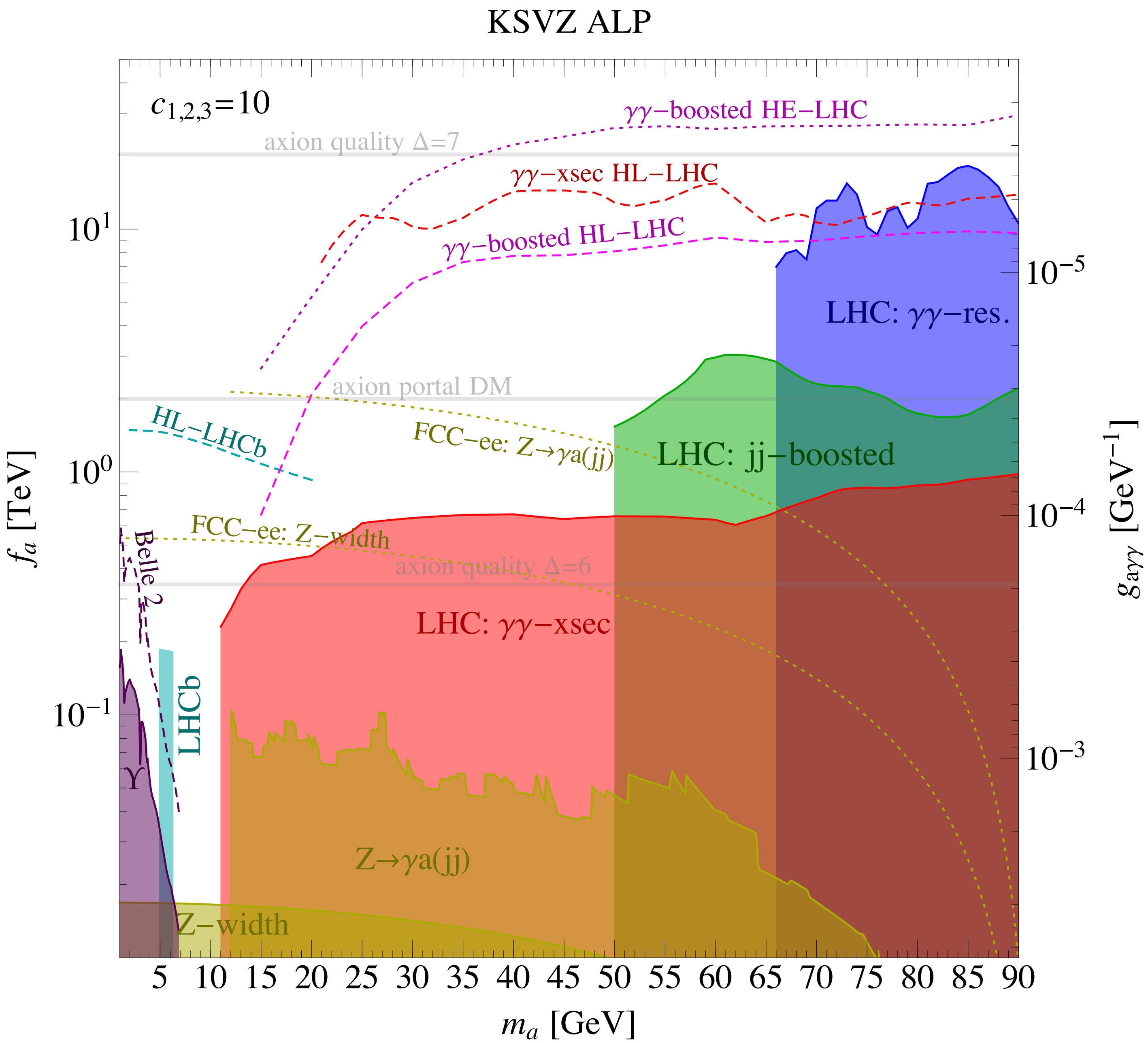
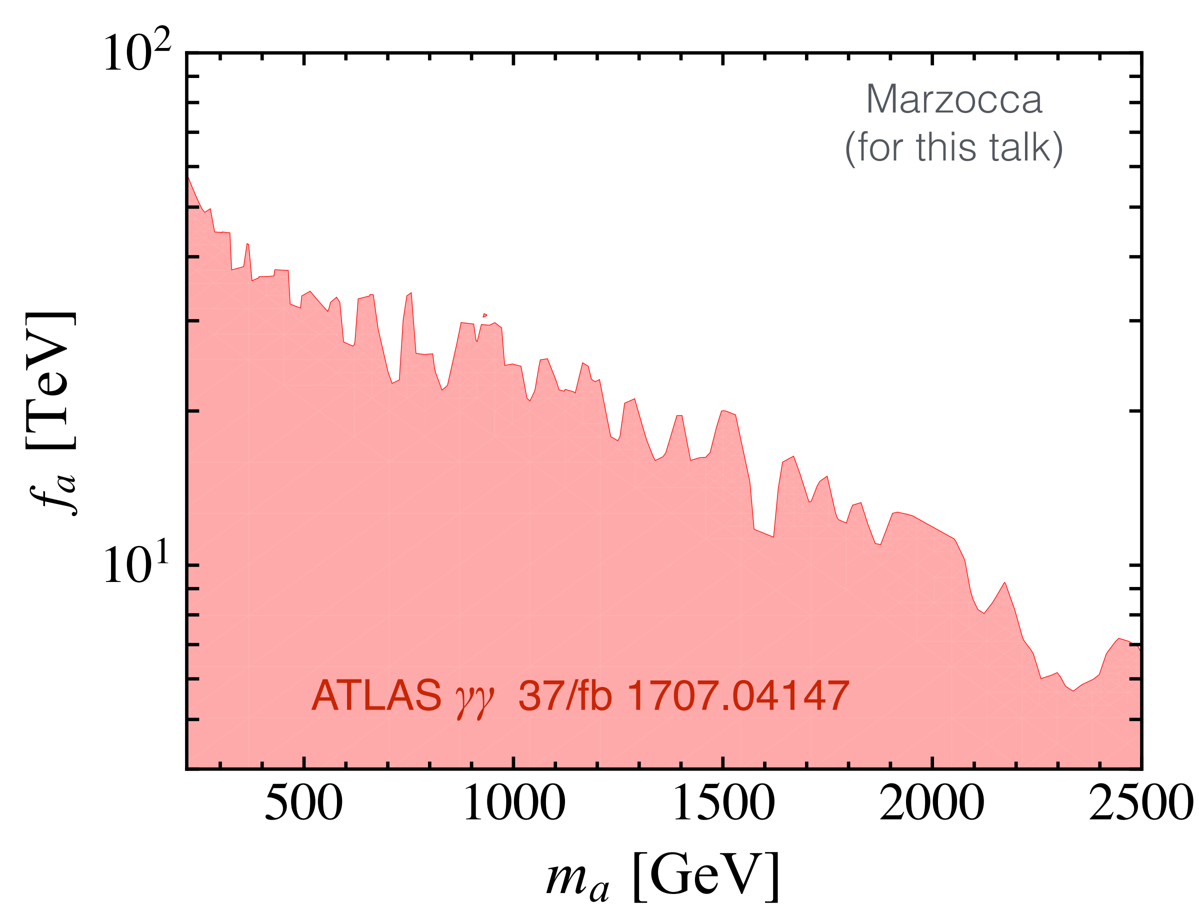
Summary on ALP constraints

1812.07831 sec. 6.1.7

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

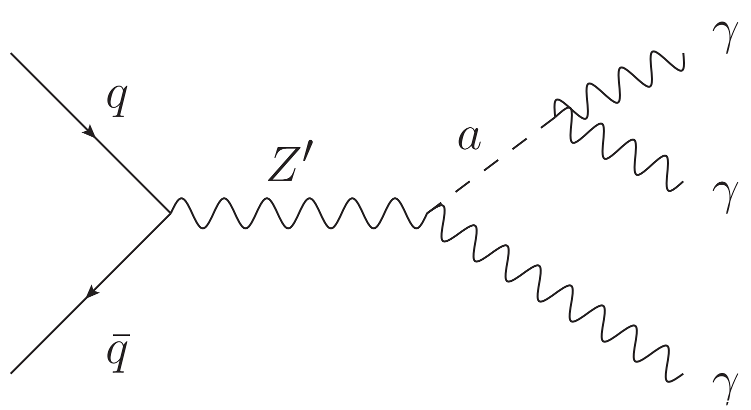
$$c_1 = c_2 = c_3 = 10$$





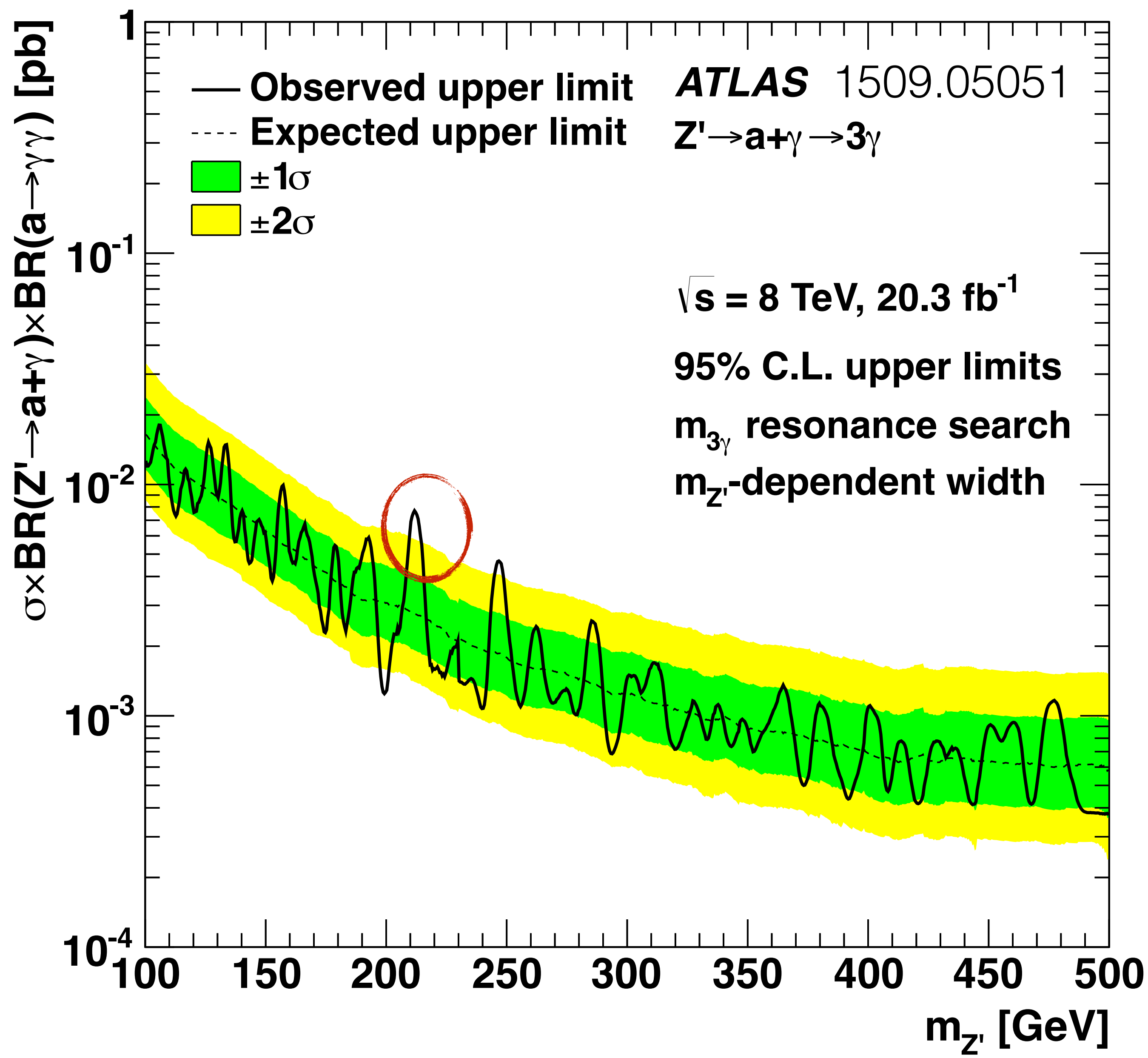
ALP($\gamma\gamma$) + γ production via Z' decay

Instead of the SM Z,
$a\gamma$ could be produced via a Z' decay.



m_a not much lighter than Z' in order to have isolated photons.

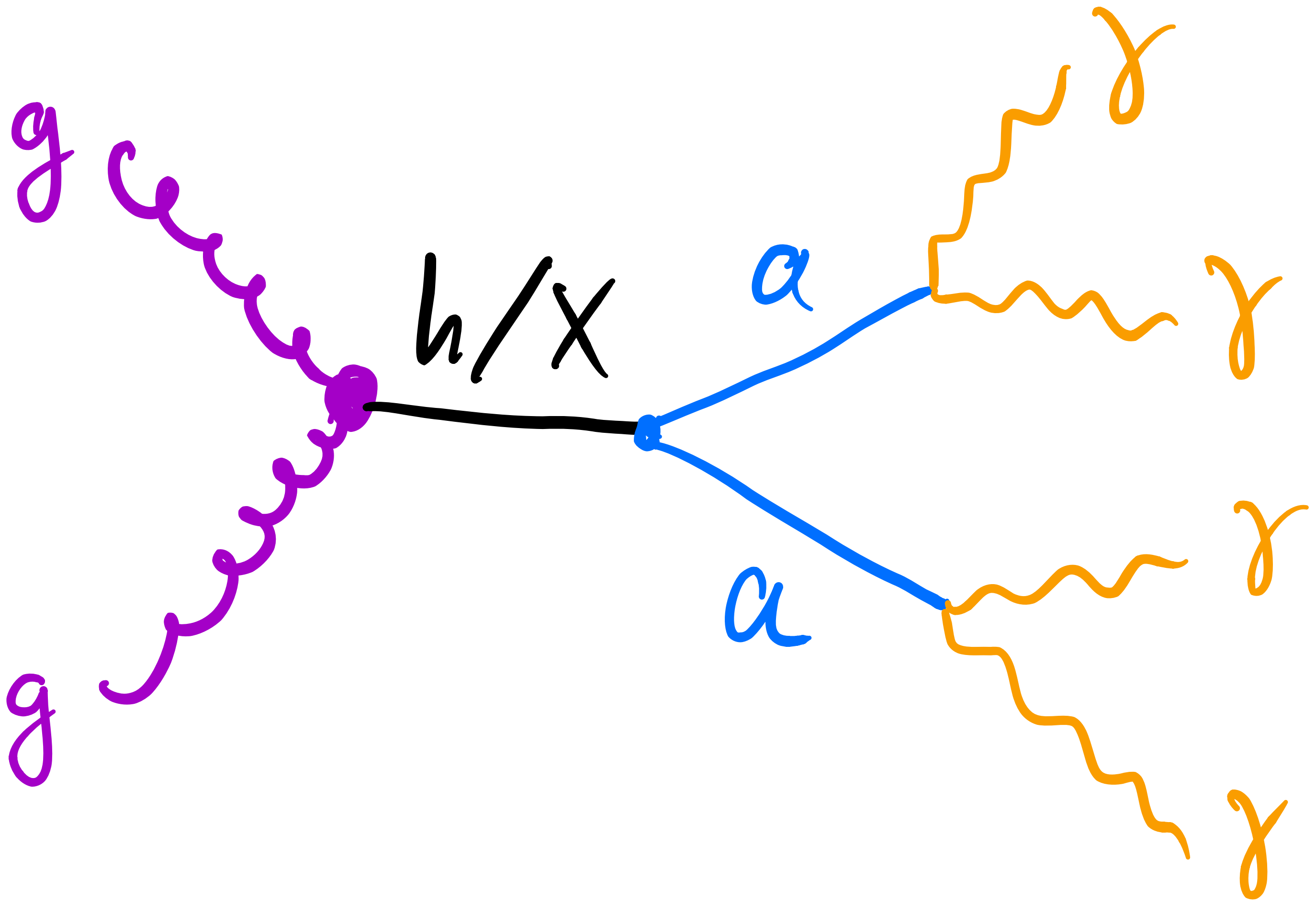
The excess at **$M_{Z'}$ = 212GeV** from the 8TeV search has a significance of **3.4σ local (1.4σ global)**

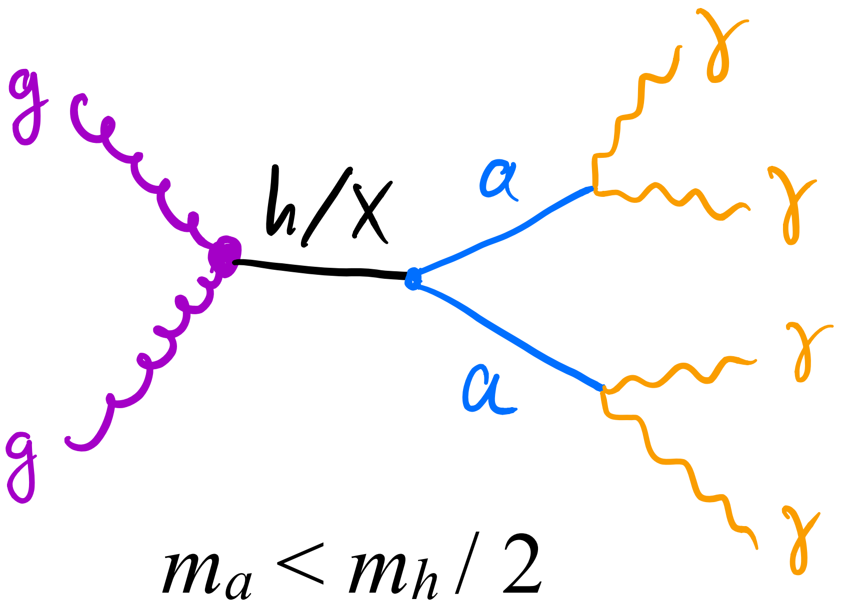


Connection with photon+ (jj / Zγ) channel?

Curious to see the 13TeV search result in the same channel.

Pair-produced ALP from resonant s-channel mediator





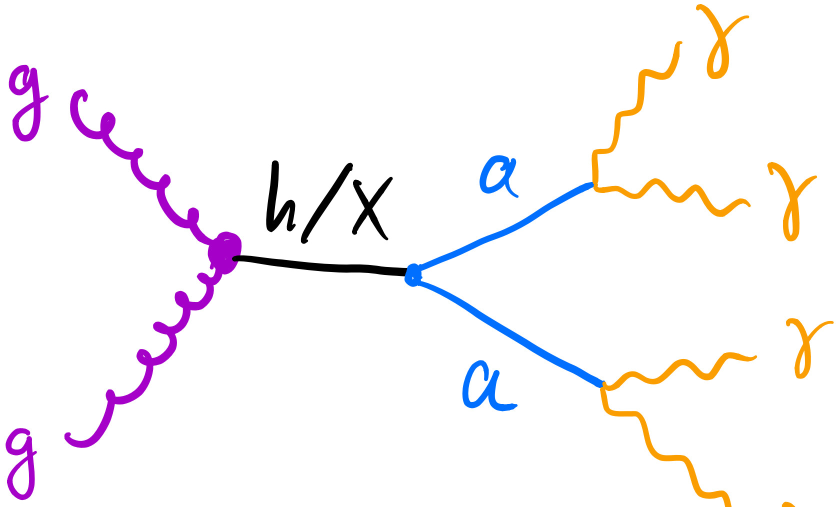
$m_a < m_h / 2$

$$h / X \to aa \to 4\gamma,\ 2g2\gamma$$

A coupling *haa* is very common, for example in models in which both h and a are pNGBs

$$\mathcal{L} \supset -\lambda_{aH} |H|^2 a^2$$

a decays to photons or gluons via the ABJ anomaly.



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$$\mathcal{L} \supset -\lambda_{aH} |H|^2 a^2$$

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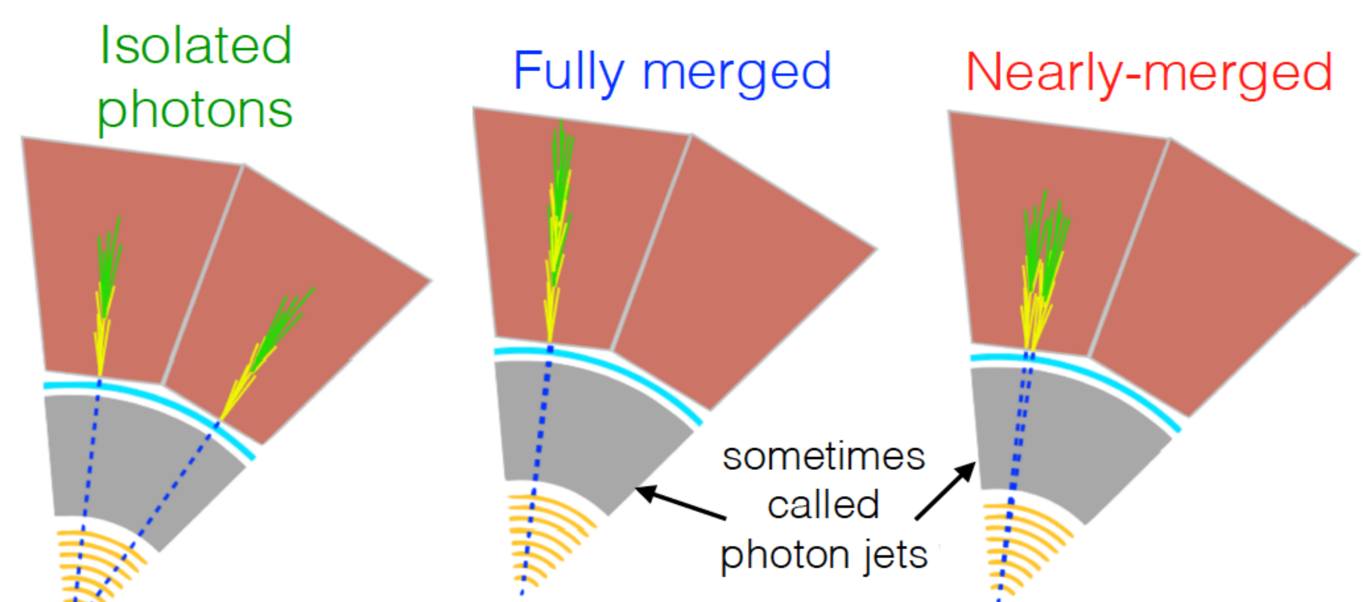
Isolated or collimated photons:

$$\Delta R_{\gamma\gamma}^{MAX} \sim \frac{4 m_a}{m_X}$$

$m_a \ll m_X / 2$ the two photons are merged in a "photon jet"



8 TeV

$10 \leq m_a \leq 60$ GeV, for $m_X = 125$ GeV

arXiv: 1509.05051

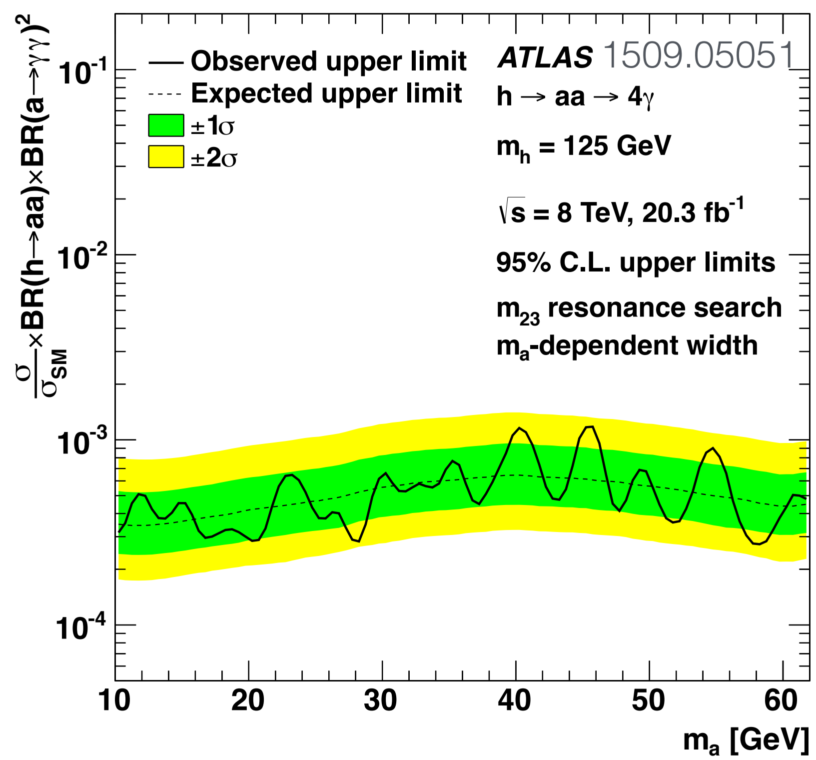
EPJC 76 (2016) 4, 210

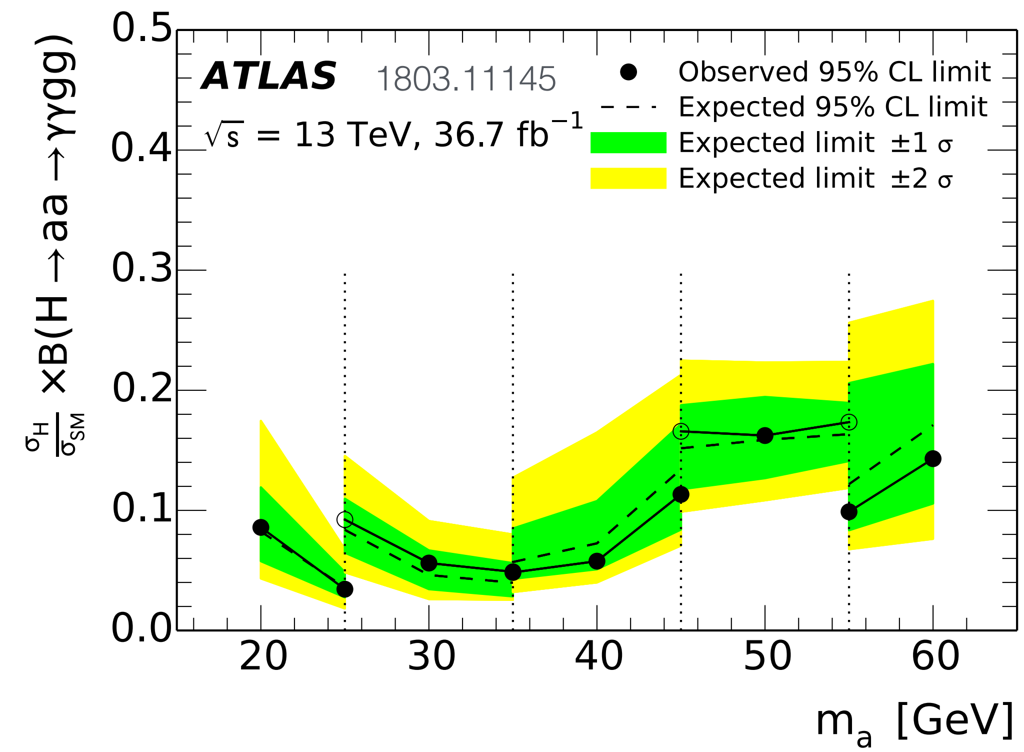
From A. Juste, NPKI forum 2019

Light scalars from Heavy state

$h \rightarrow aa \rightarrow 4\gamma$, 2g 2γ

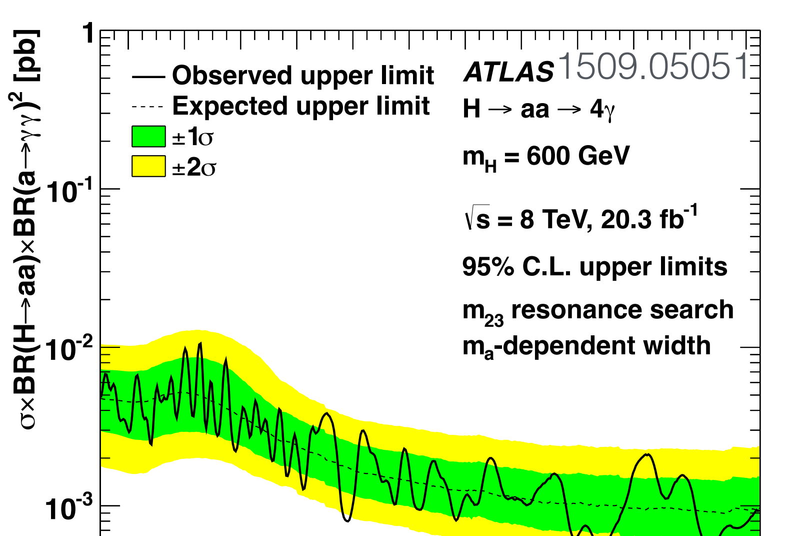
Isolated photons.



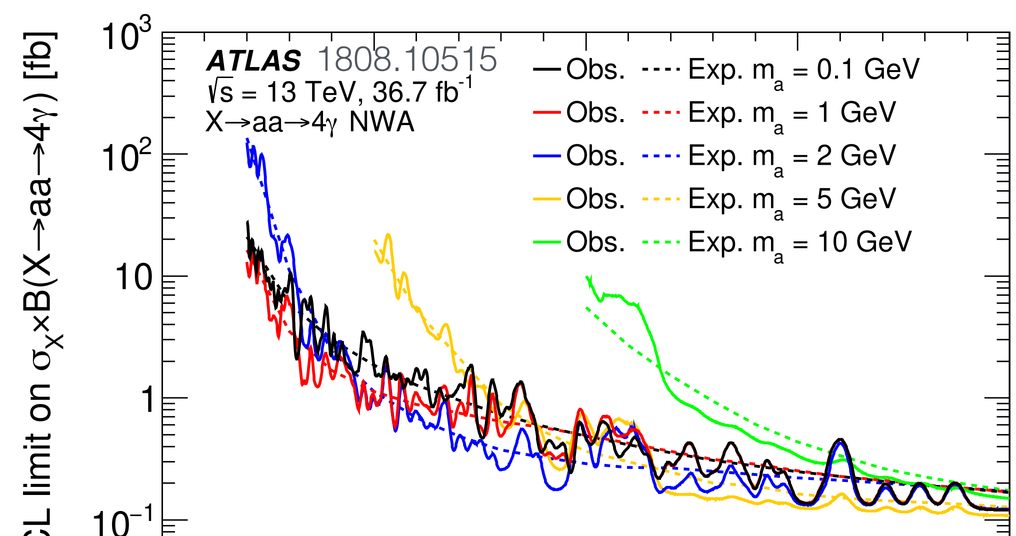


$X \rightarrow aa \rightarrow 4\gamma$

$m_X = 600$ GeV



Merged - isolated photons.



Photon jets

B-anomalies $\leftrightarrow$ $\gamma\gamma$ searches

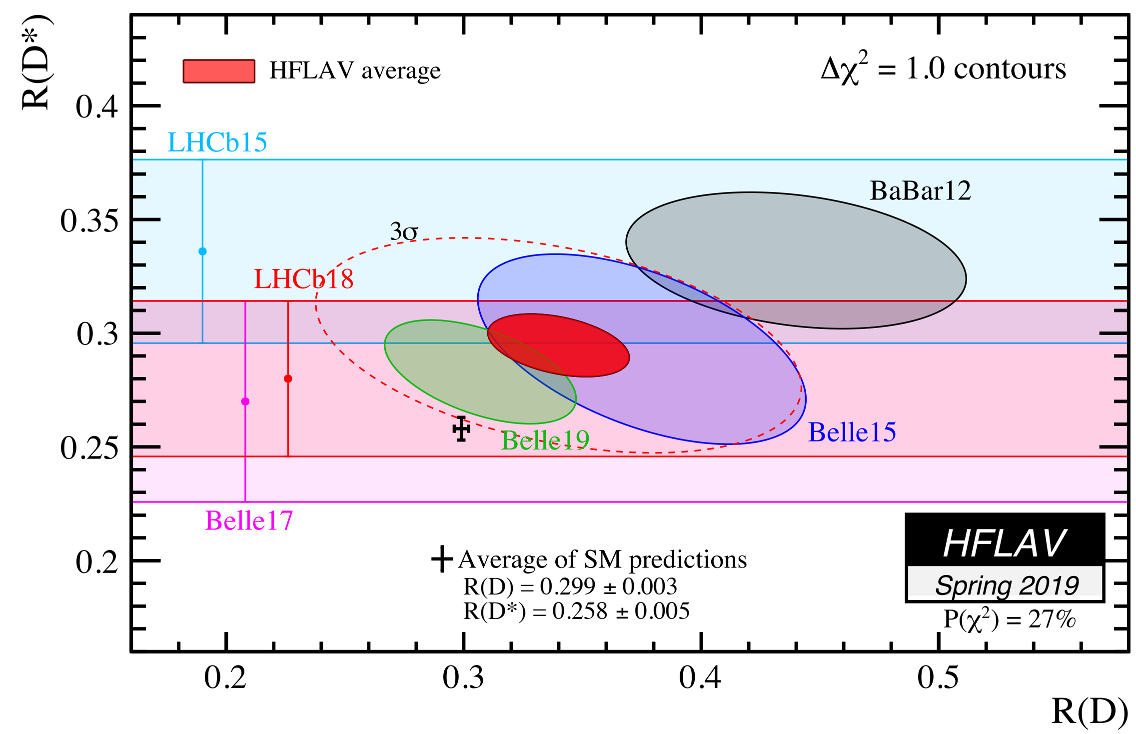
B-anomalies

$b \to c\,\tau\,\nu$ vs. $b \to c\,\ell\,\nu$

$$R(D^{(*)}) \equiv \frac{\mathcal{B}(B^0 \to D^{(*)+}\tau\nu)}{\mathcal{B}(B^0 \to D^{(*)+}\ell\nu)}, \quad \ell = \mu, e$$

~ 14% enhancement from the SM

~ 3σ significance



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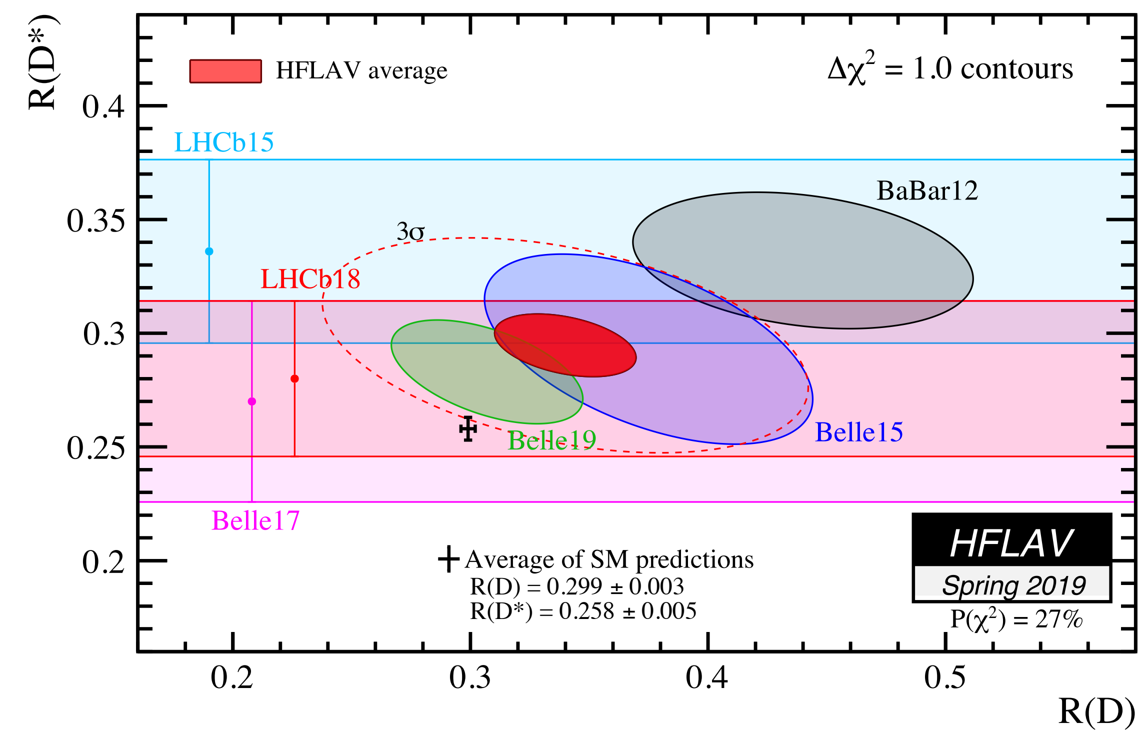
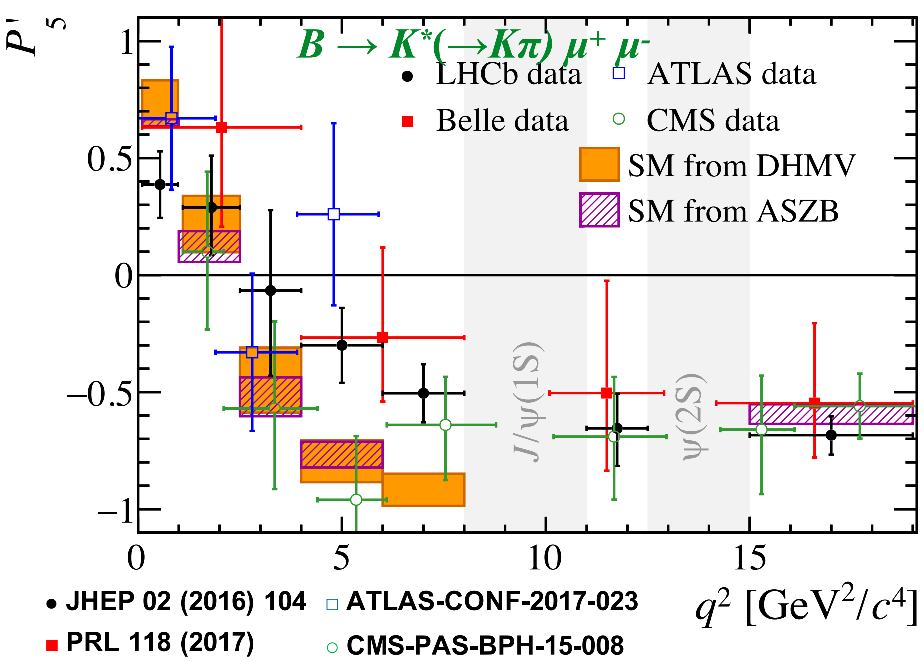
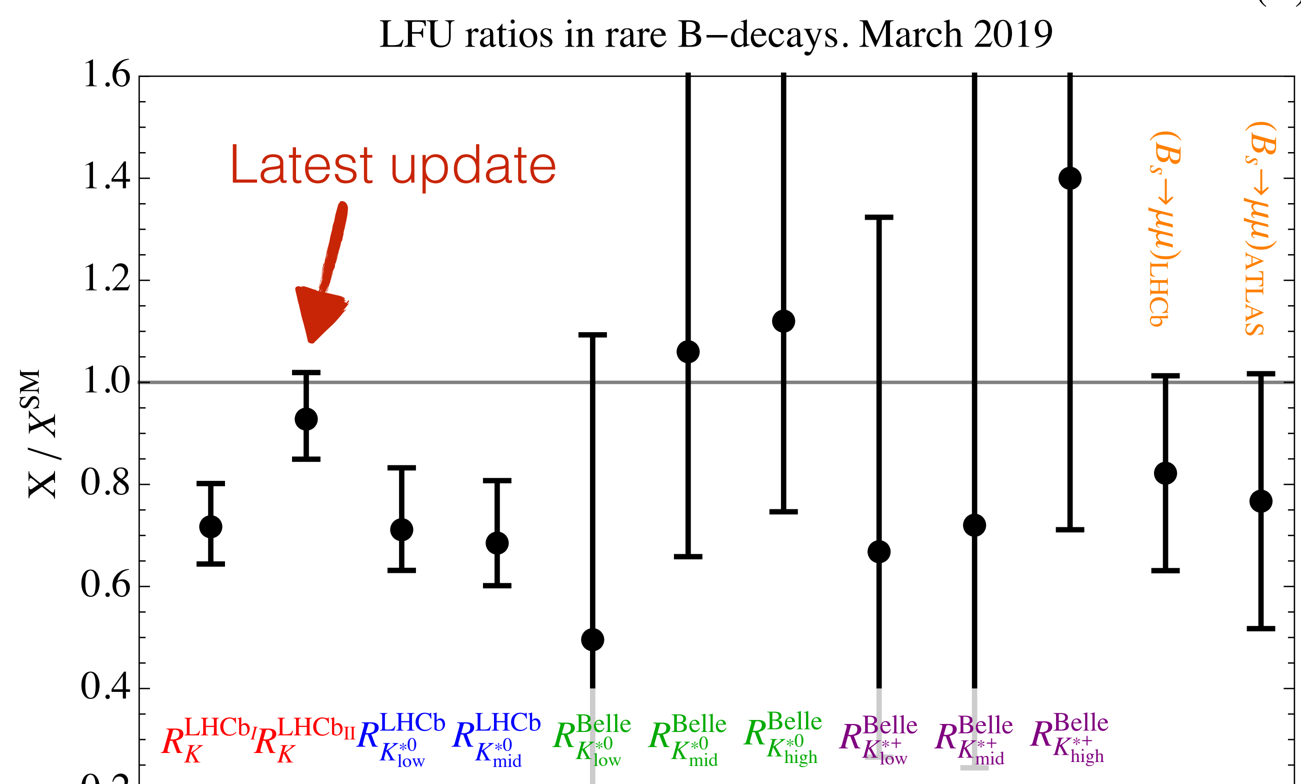


$b \to s\,\mu^+\,\mu^-$





~ 4-5σ global significance

$$R(K^{(*)}) = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)}$$

A UV model for B-anomalies

Buttazzo, Greljo, Isidori, D.M. 1706.07808, D.M. 1803.10972

This pair of **scalar leptoquarks** can provide a **good fit of both anomalies**, while passing all other flavor, LEP, and high-pT constraints.

$S_1 = (\bar{\mathbf{3}}, \mathbf{1}, 1/3)$,
$S_3 = (\bar{\mathbf{3}}, \mathbf{3}, 1/3)$

$\boldsymbol{M_S \gtrsim 1.5}$ **TeV**

$B_c \to \tau\nu$
$B \to K^*\nu\nu$
B_s mixing
$Z \to \tau\tau$
$Z \to \nu\nu$
τ LFU
Direct searches

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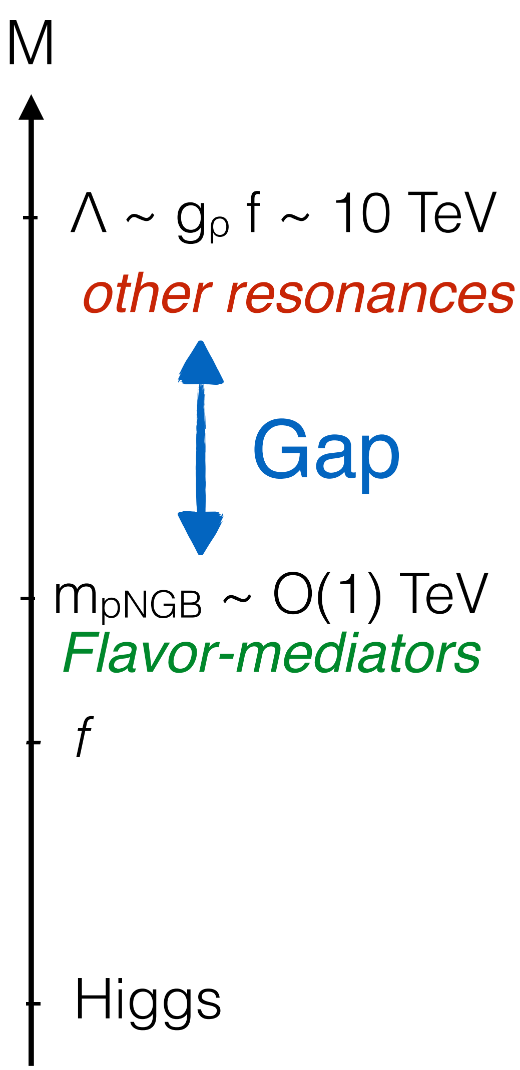

M_{LQ} ~ TeV & **$M_{\text{BSM-Higgs hierarchy problem}}$ ~ TeV**

Is it an accident or is there a connection?

They could be pseudo-NGB, partners of the Higgs, in a non-minimal Composite Higgs model.

[Gripaios 0910.1789, Gripaios, Nardecchia, Renner 1412.1791]

1) Automatic hierarchy between LQ and other resonances.
2) Singlet pNGB are a prediction of such models. **ALPs**!

An explicit model

D.M. 1803.10972

New ***"HyperColor"*** gauge group

$\mathrm{SU}(N_{\mathrm{HC}})$

confines at $\Lambda_{\mathrm{HC}} \sim 10$ TeV

New fermions

	$\mathrm{SU}(N_{HC})$	$\mathrm{SU}(3)_c$	$\mathrm{SU}(2)_w$	$\mathrm{U}(1)_Y$
Ψ_L	$\mathbf{N_{HC}}$	$\mathbf{1}$	$\mathbf{2}$	Y_L
Ψ_N	$\mathbf{N_{HC}}$	$\mathbf{1}$	$\mathbf{1}$	$Y_L + 1/2$
Ψ_E	$\mathbf{N_{HC}}$	$\mathbf{1}$	$\mathbf{1}$	$Y_L - 1/2$
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Chiral symmetry breaking (as in QCD)

$$G = SU(10)_L \times SU(10)_R \times U(1)_V \xrightarrow{f \sim 1\text{TeV}} H = SU(10)_V \times U(1)_V$$

pNGBs include:

Two Higgs doublets: $H_{1,2} \sim (\mathbf{1},\mathbf{2})_{1/2}$

Singlet and Triplet LQ: $S_1 \sim (\mathbf{3},\mathbf{1})_{-1/3} \quad + \quad S_3 \sim (\mathbf{3},\mathbf{3})_{-1/3}$

Three singlets: $\eta_{1,2,3} \sim (\mathbf{1},\mathbf{1})_0$

An explicit model

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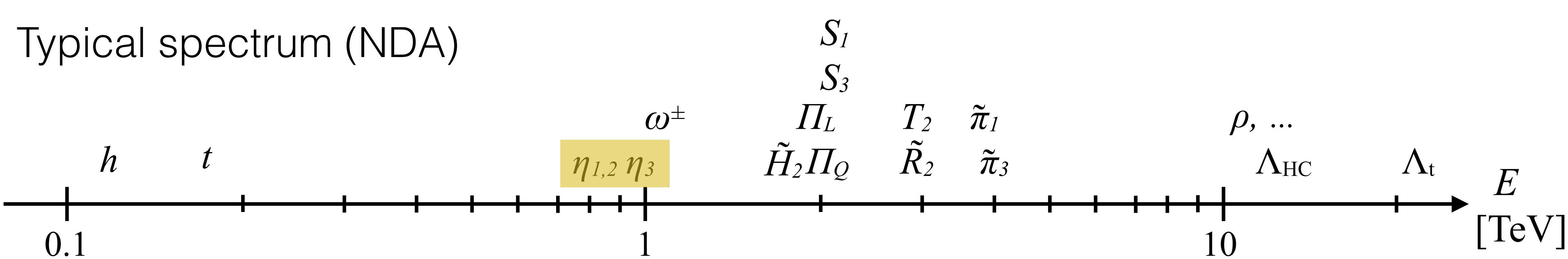
Typical spectrum (NDA)



Singlets are expected to be the lightest states (no gauge contributions to their mass)

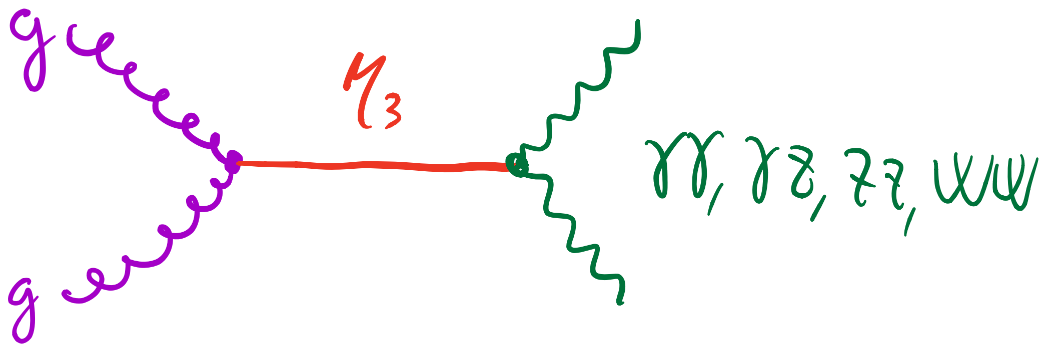
Limits on the singlets from $\gamma\gamma$

$$\mathcal{L}_{\rm WZW} \supset -\frac{g_\beta g_\gamma}{16\pi^2}\frac{\phi^\alpha}{f} 2N_{HC} A^{\phi^\alpha}_{\beta\gamma} F^\beta_{\mu\nu}\widetilde{F}^{\gamma\mu\nu}$$

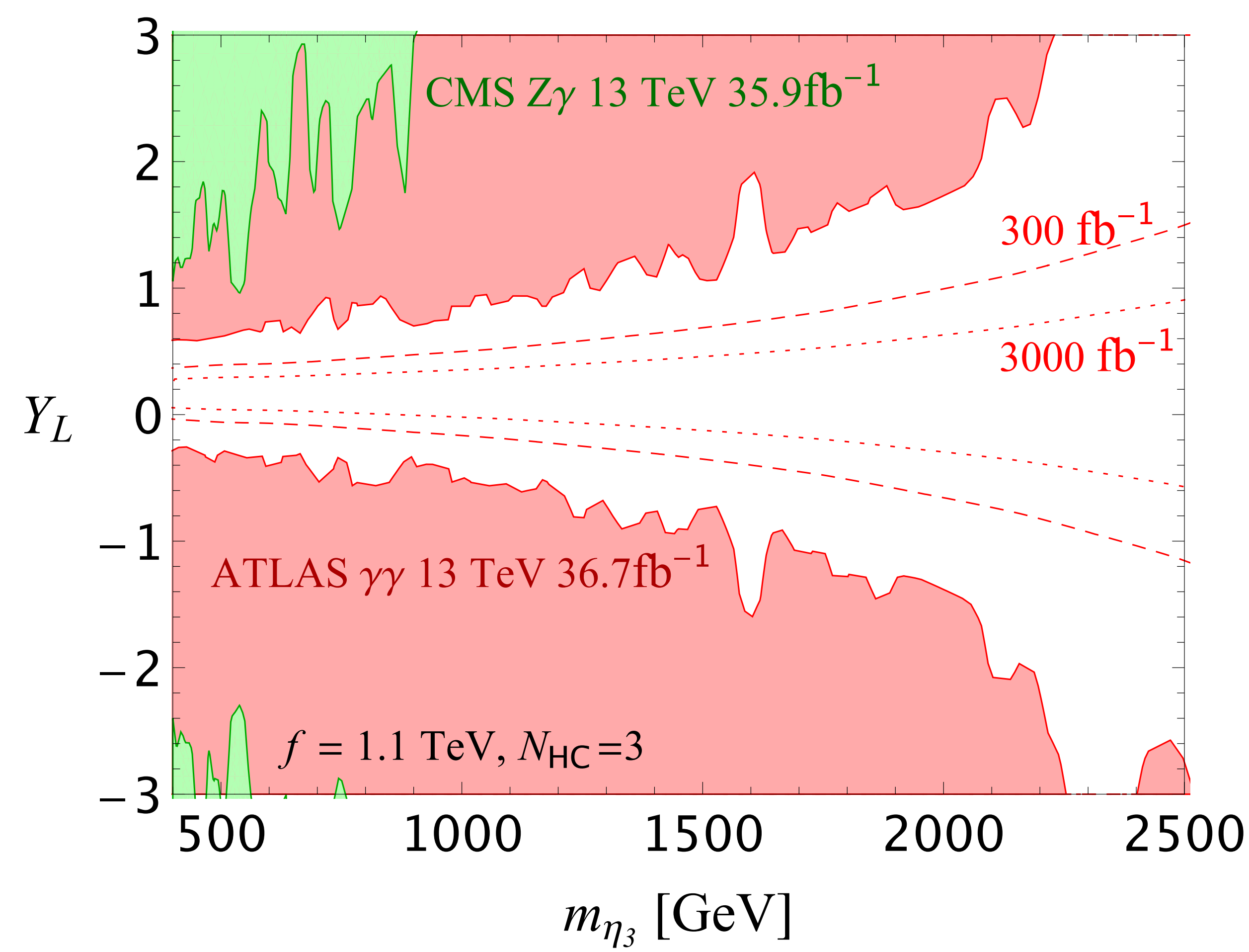
Anomaly coefficients:

$A^{\phi^\alpha}_{\beta\gamma}$	g_1^2	g_2^2	g_3^2
η_3	$\frac{1+48Y_L}{12\sqrt{30}}$	$-\frac{\sqrt{3}}{4\sqrt{10}}$	$-\frac{1}{\sqrt{30}}$

η_3 Couples to gluons and EW gauge bosons via the chiral anomaly (like $\pi^0 \to \gamma\gamma$).
Possible signal in diphoton, ZZ,Zγ searches.



The present limit already excludes some portions of parameter space.



Conclusions

The diphoton channel was crucial for the Higgs discovery.

While LHC did not discover any New Physics up to this point, the deep questions left open by the SM are still not addressed. NP signals might still be waiting for us to dig them out with more data.

Final states with photons remain crucial to test a wide class of well-motivated models.

Thank you!