What could the di-photon "signal" be?



"Vanilla scenario"

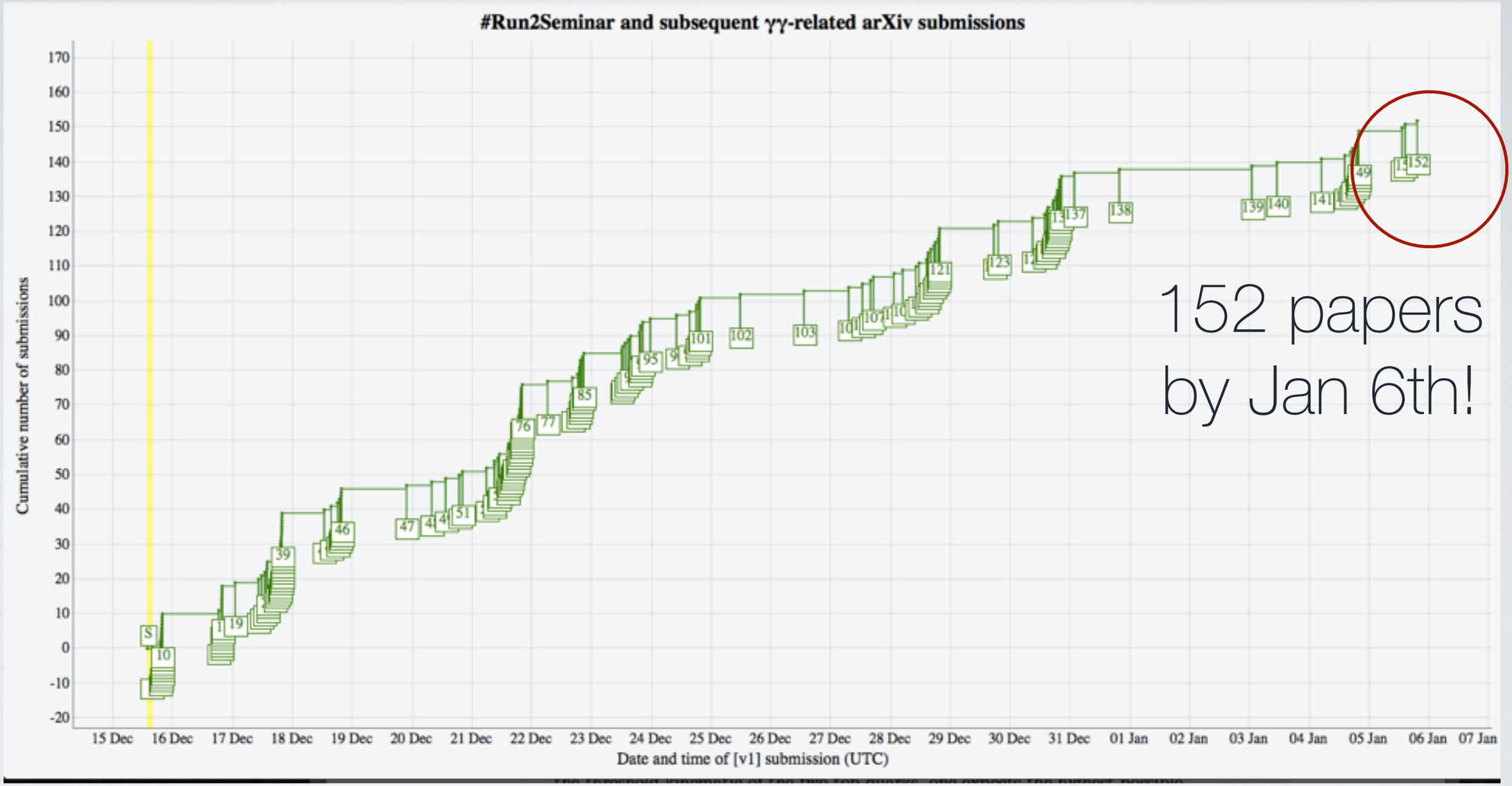
(Mihailo)



"Tropical fruit scenario"

(Alberto)

Enormous amount of theory papers!



Skimming through, about 50% of the papers are “serious”

0.04 seconds per paper in this talk.

Vanilla scenario

(Nothing here is set in stone… because there is not stone)

"The di-photon signal is a **new resonance!**"

Landau-Yang theorem suggests it's a **scalar**

(** spin-2 unlikely due to universal couplings to matter)

Large production rate suggests it's **gluon initiated**

The minimal interaction Lagrangian you need is:

$$\mathcal{L} \sim \frac{g_{BB}}{\Lambda}\phi B^{\mu\nu}B_{\mu\nu} + \frac{g_{WW}}{\Lambda}\phi W^{\mu\nu}W_{\mu\nu} + \frac{g_{GG}}{\Lambda}\phi G^{\mu\nu}G_{\mu\nu}$$

The immediate implication is that the vanilla scenario predicts **new vector-like fermions!**

Vanilla scenario

(Nothing here is set in stone… because there is not stone)

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Landau-Yang theorem suggests it's a **scalar**

(** spin-2 unlikely due to

Large production rate suggests it's **gluon initiated**

Most of this works for pseudo-scalars as well but this is a mundane detail

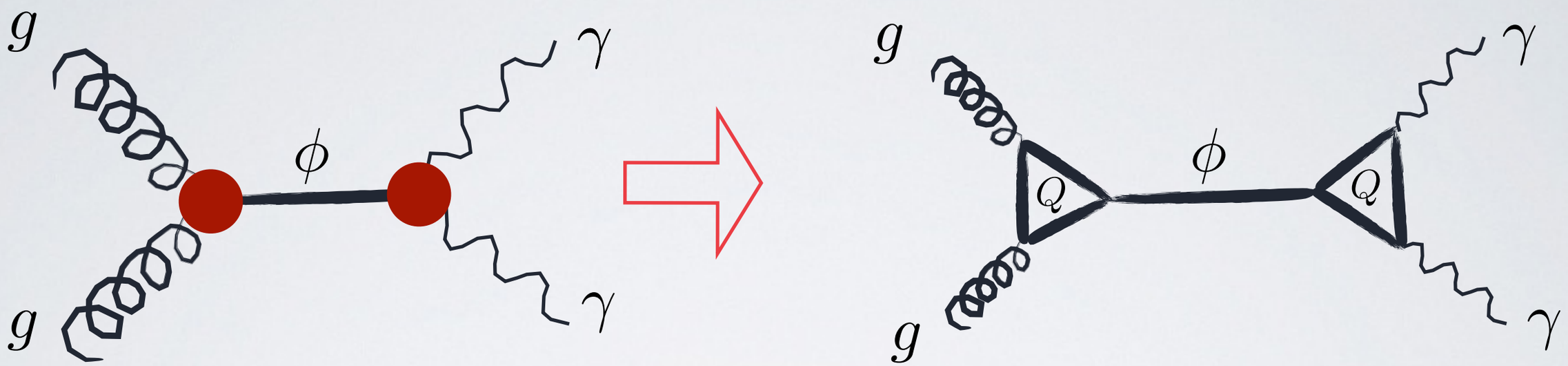
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The immediate implication is that the vanilla scenario predicts **new vector-like fermions!**

New Vectorlike fermions

The effective coupling to gluons and photons should be fairly large (O(1)) to accommodate $\sigma_{\gamma\gamma} \sim 1 - 10\,\mathrm{fb}$



- Loop-supressed
- How many vector-like generations do you need to fit the excess?
- What kind of couplings do you need?

Issue of the total width

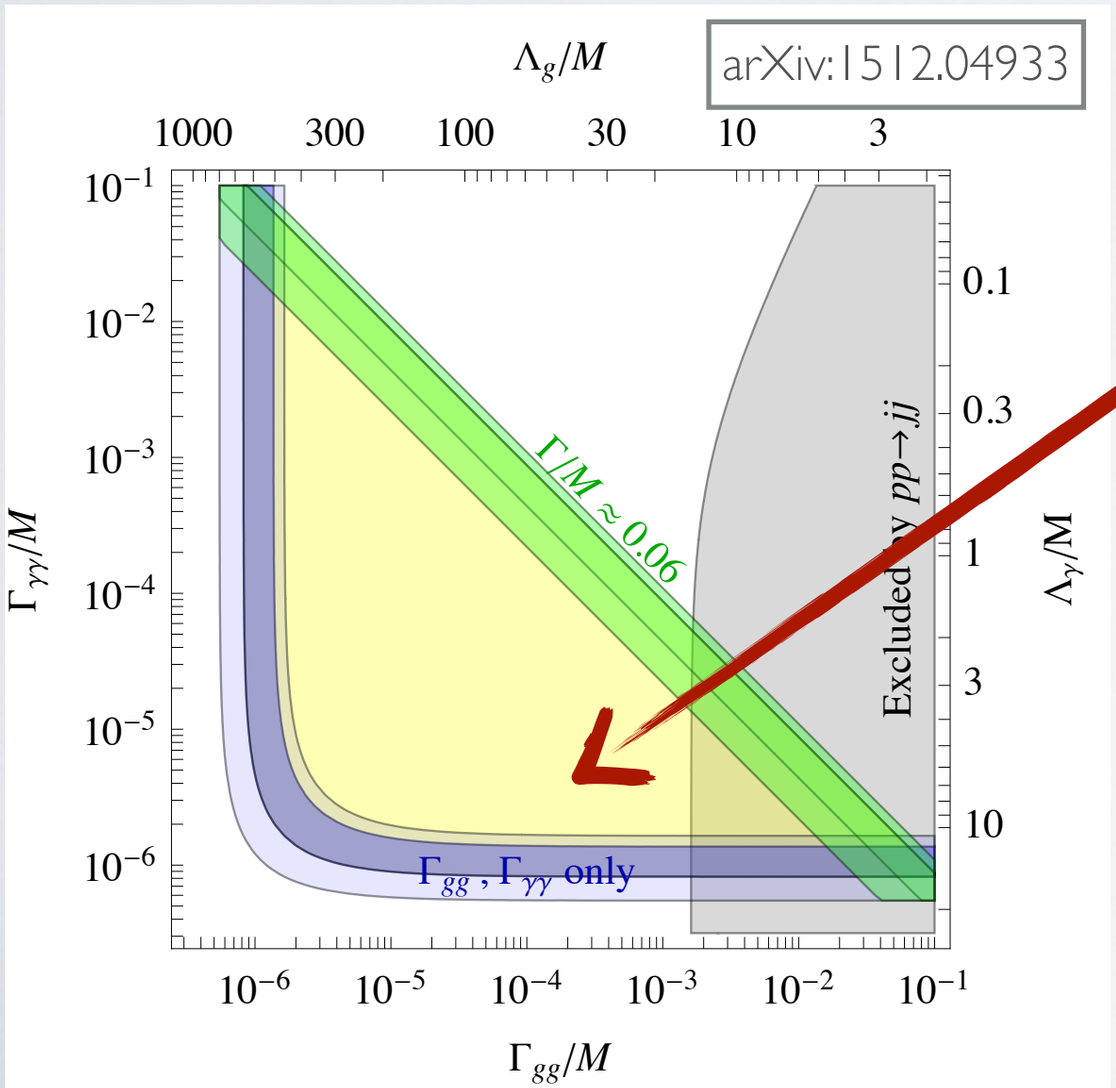
$$\Gamma[\phi \to gg] = \frac{2g_{GG}^2}{\Lambda^2}\frac{m_\phi^3}{\pi}$$

similar exp. for photons

$$g_{GG} \sim \alpha_s/4\pi \times O(1)$$

Generically difficult to boost up the couplings. **Big problem with all models.**

Narrow width (< O(1) GeV)?



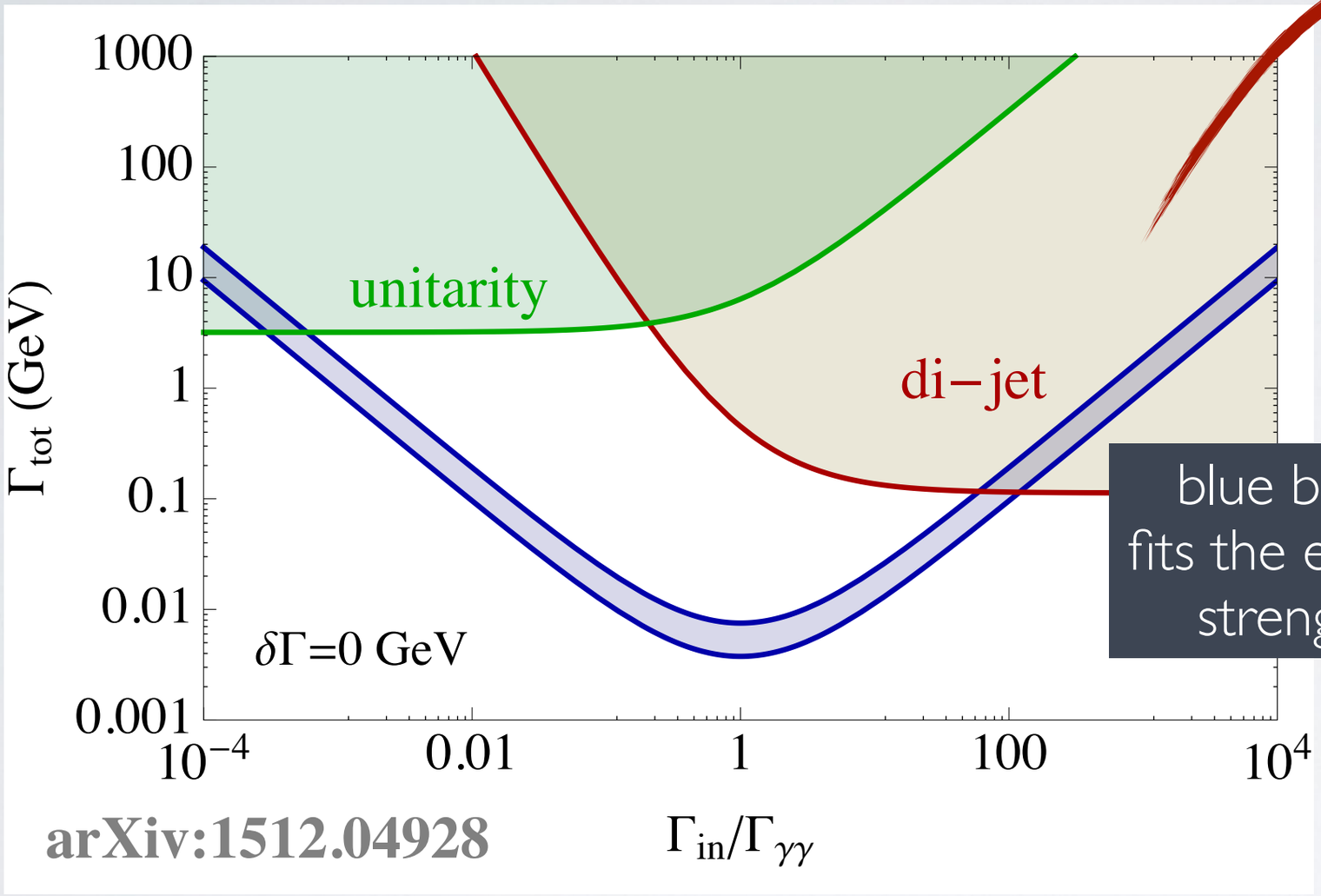
arXiv:1512.04933

- Yellow region can fit the signal strength.
- Dark blue band can fit the signal strength assuming **only decays to photons and gluons.**

No real problems!
photons and gluons alone are sufficient
if the width is small!

Issue of the total width

Large width (> O (1) GeV)?



You can not get a width of O(10) GeV that is not ruled out and fits the signal with photons and gluons only.

blue band fits the excess strength

The resonance must decay to states other than photons and gluons!

Issue of the total width

Large width (> O (1) GeV)?

What else could the new resonance decay to?

We haven't observed any charged states with mass of O(100) GeV…

Invisible particles?

Dark Matter?
Hidden Valleys?

Degenerate states?

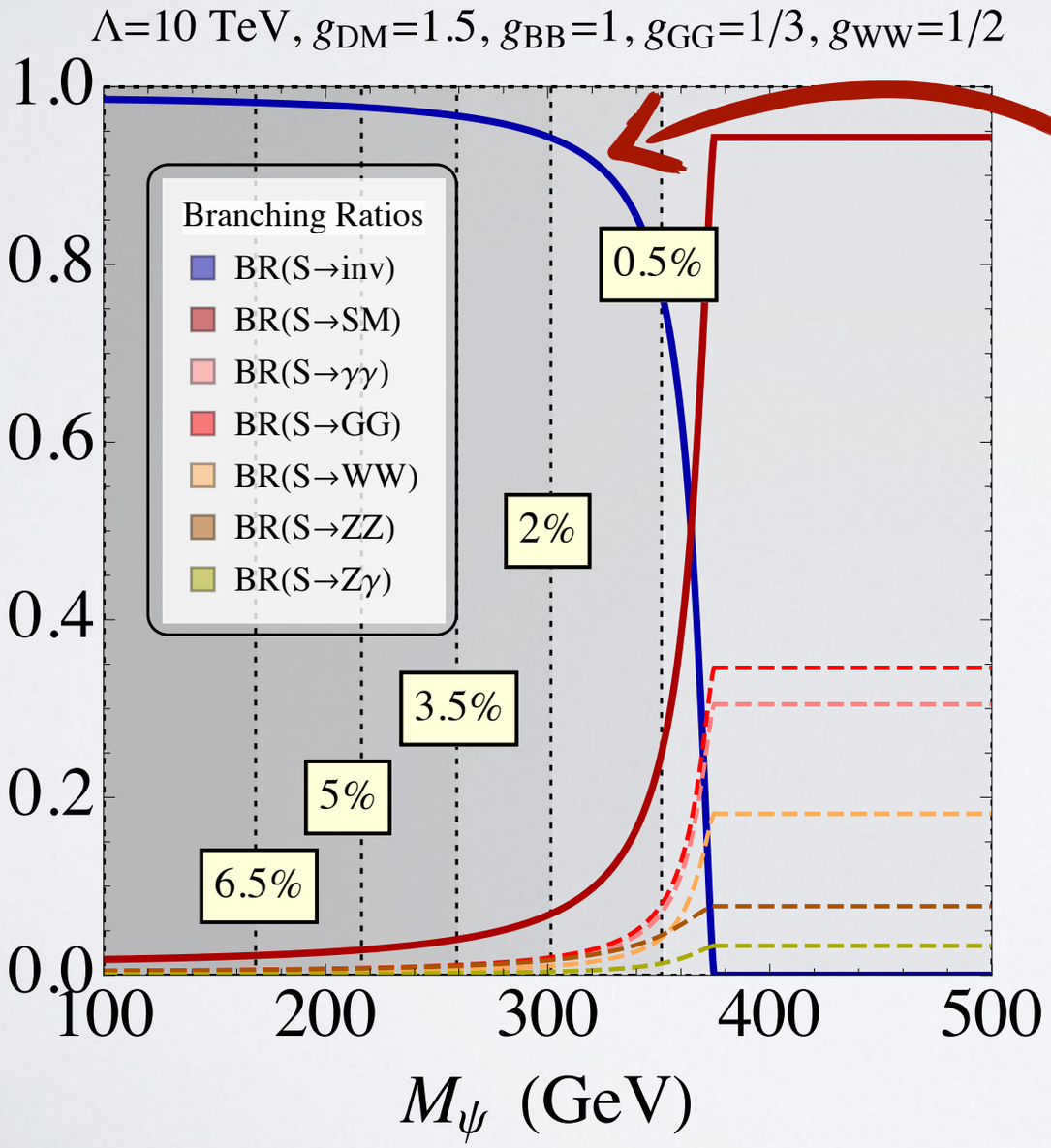
Large width and DM

$$\mathcal{L}^{+}_{NP} = \frac{1}{2}(\partial S)^2 + \frac{m_S^2}{2}S^2 + \bar{\psi}\partial\!\!\!/\psi + (g_{DM}S + M_\psi)\bar{\psi}\psi + \frac{g_{GG}}{\Lambda}SG^{\mu\nu}G_{\mu\nu} + \frac{g_{WW}}{\Lambda}SW^{\mu\nu}W_{\mu\nu} + \frac{g_{BB}}{\Lambda}SB^{\mu\nu}B_{\mu\nu}$$

Add a **Dirac Fermion Dark Matter** to the minimal Lagrangian

S = new resonance

arXiv:1512.04917



Most of the width generically comes from invisible decays

Large width and DM

Signal strength

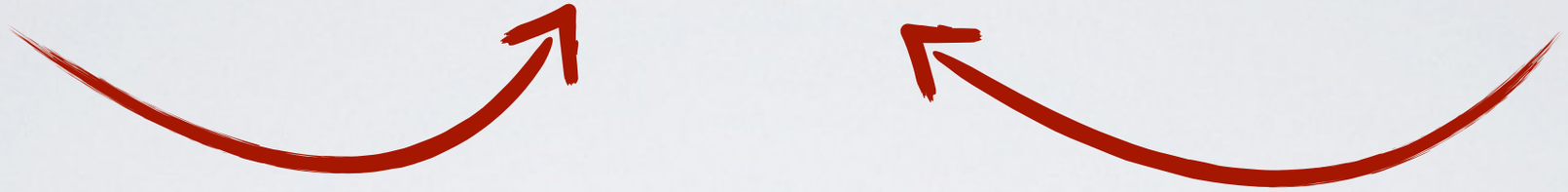
$g_{BB} \times g_{GG}$

Relic density

$g_{BB}, g_{GG}, M_\psi, g_{DM}$

Total width

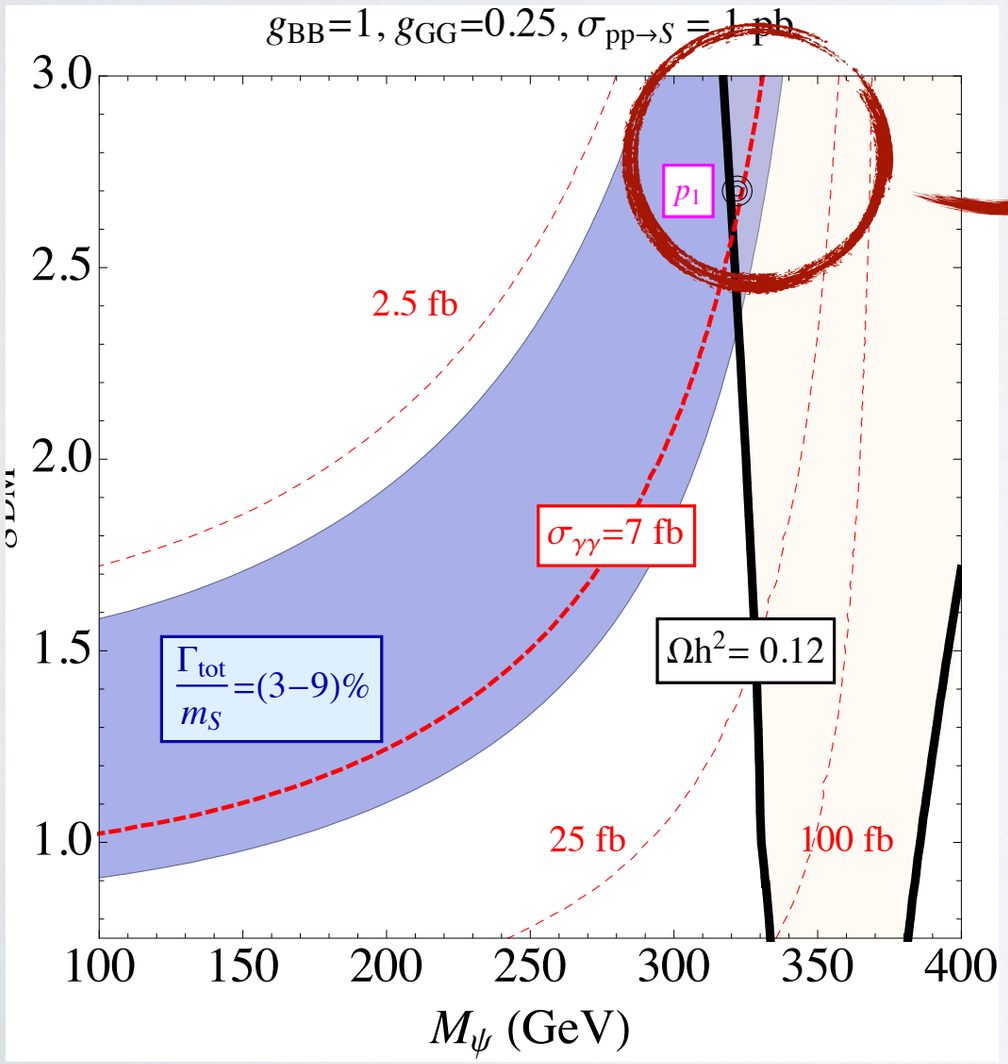
M_ψ, g_{DM}



Large width and DM

Signal strength	Relic density	Total width
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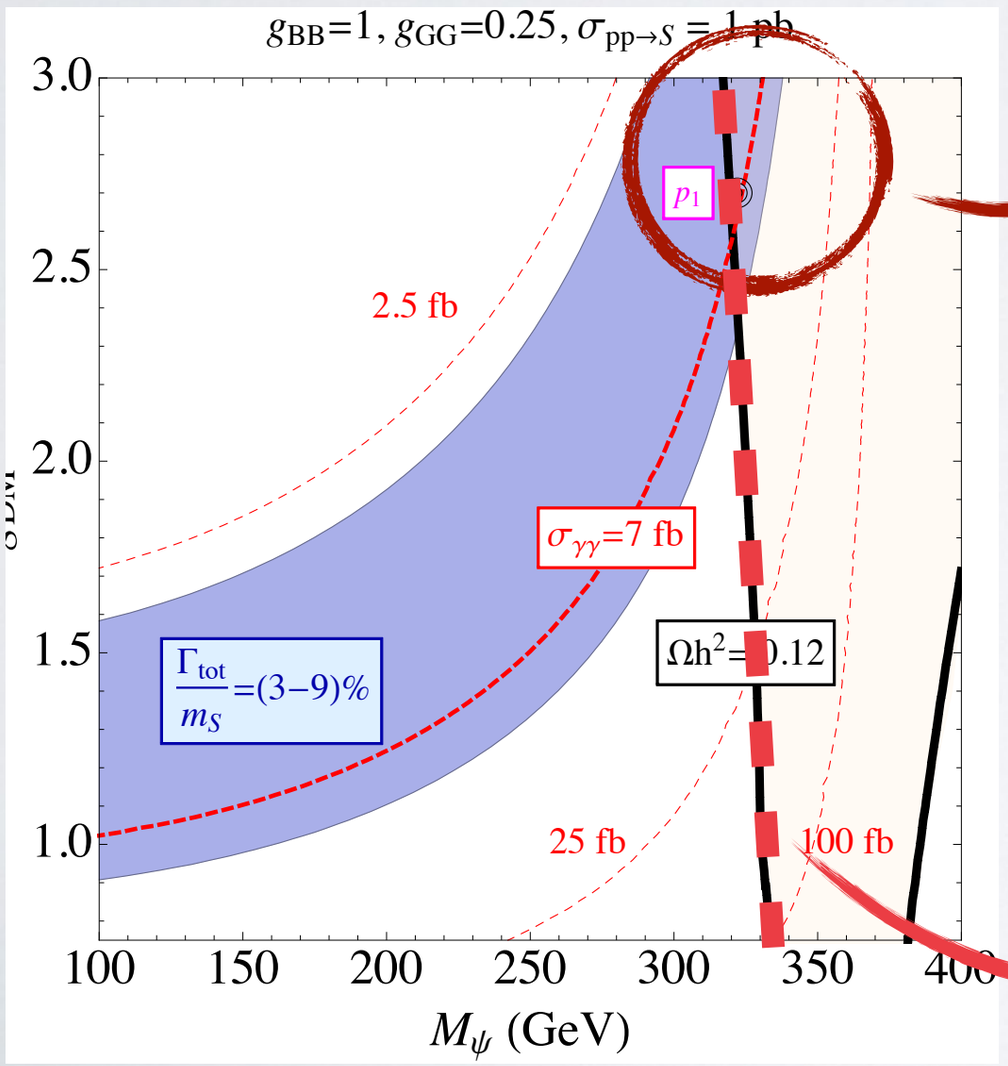
In fact, requiring $\Omega h^2 \sim 0.1$ and the width **essentially fixes the DM parameters!**



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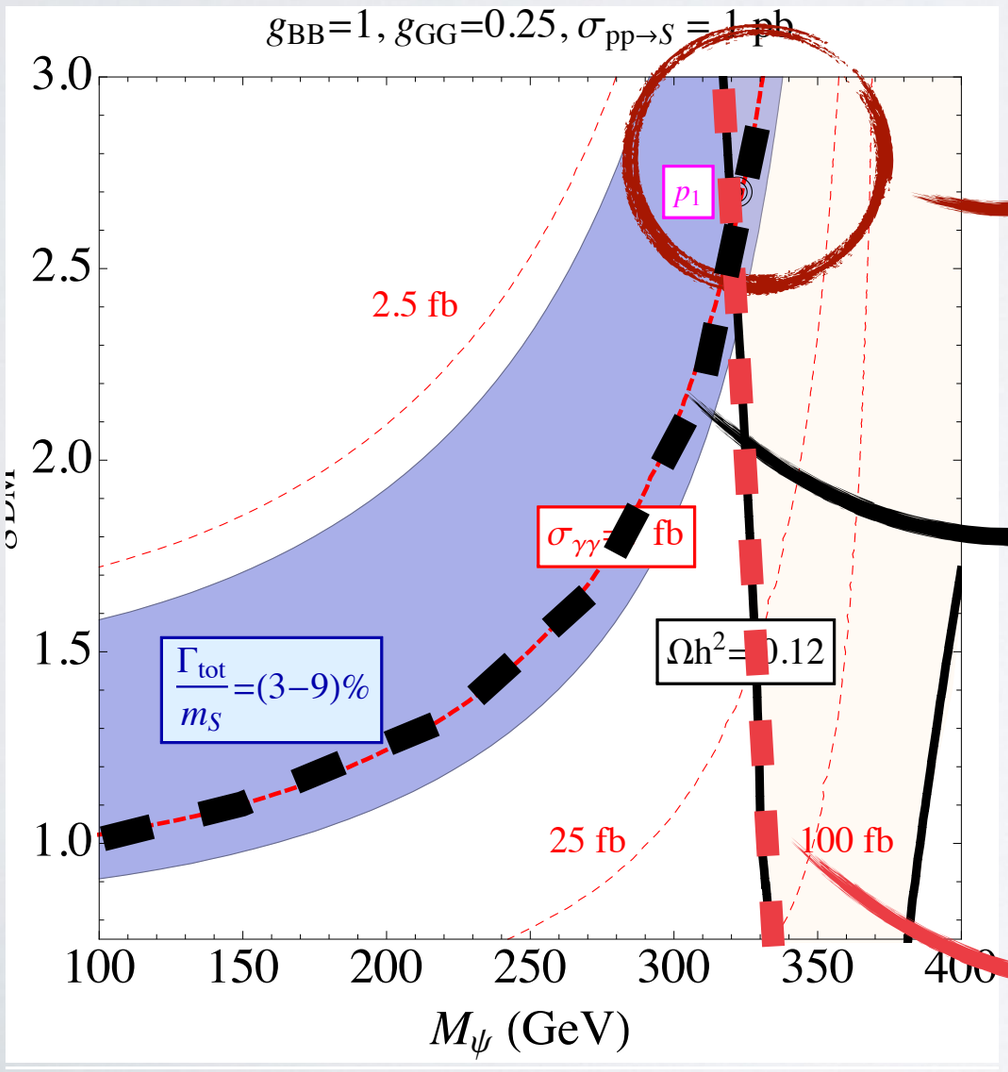


Correct relic density

Large width and DM

Signal strength	Relic density	Total width
$g_{BB} \times g_{GG}$	$g_{BB}, g_{GG}, M_\psi, g_{DM}$	M_ψ, g_{DM}

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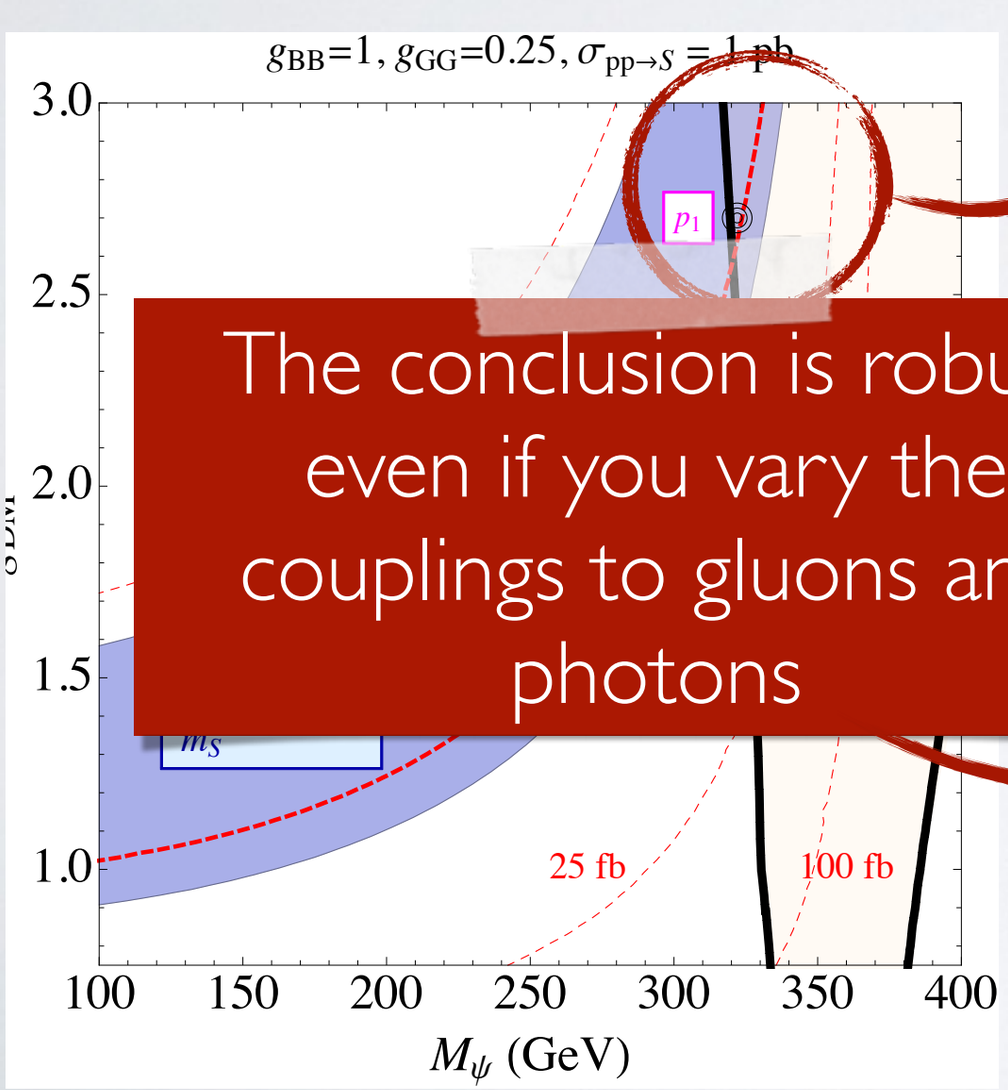
Width = 30 GeV

Correct relic density

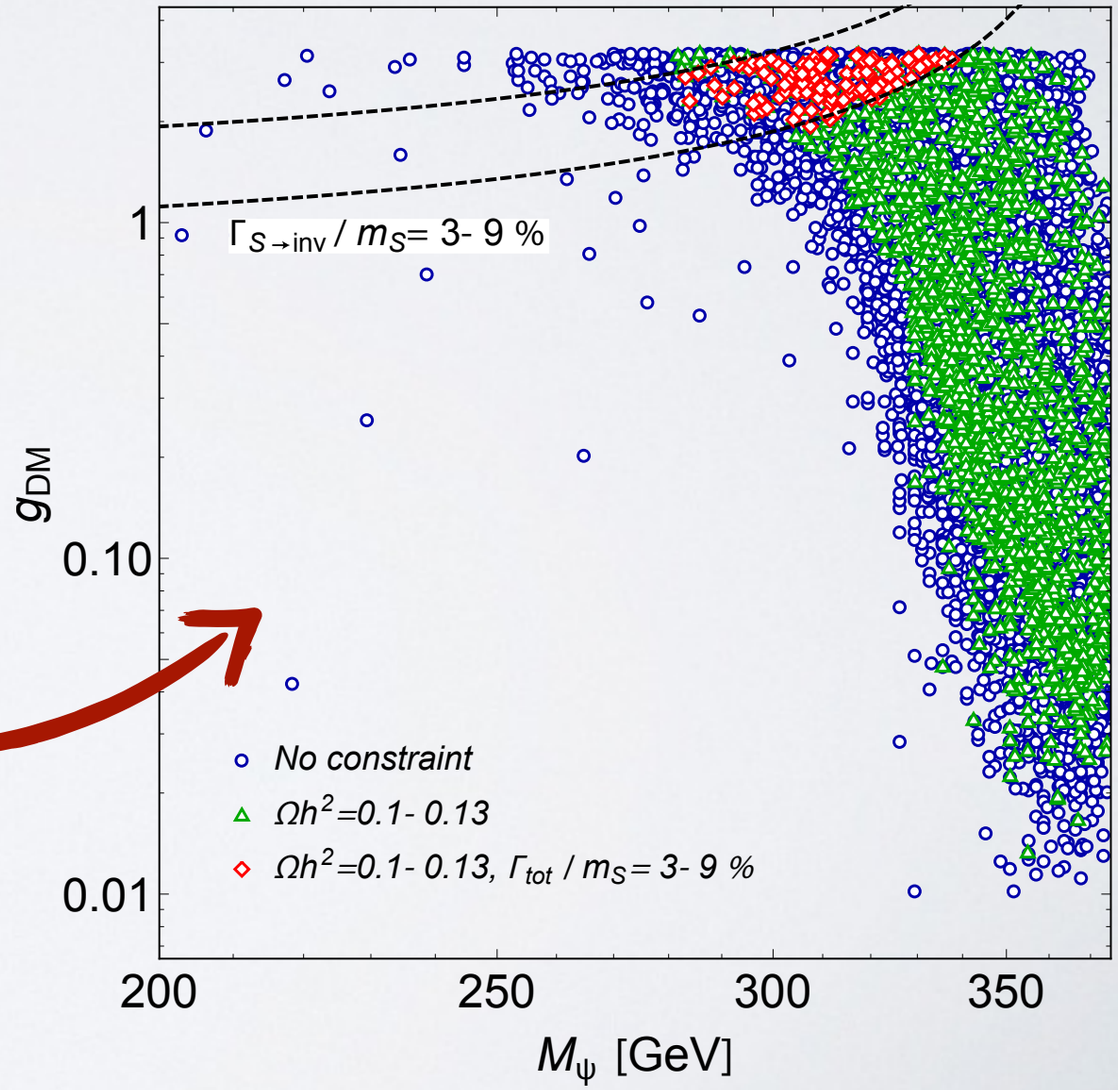
Large width and DM

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In fact, requiring $\Omega h^2 \sim 0.1$ and the width **essentially fixes the DM parameters!**



The conclusion is robust even if you vary the couplings to gluons and photons



If the di-photon signal is indeed real…

… and the large width is explained by DM …

… a signal consistent with a 750 GeV DM mediator
and 300 GeV DM with O(1) couplings
should appear in the MET+j channel

… and a signal consistent with ~300 GeV DM
particle should appear in direct detection

Is the prediction reasonable?

example points which give
the right resonance features and
correct relic density

Predictions

benchmark	(g_{GG}, g_{BB})	g_{DM}	M_ψ (GeV)	Γ_{tot}(GeV)	$\sigma_{\gamma\gamma}$(fb) at 13TeV	Ωh^2
p_1	(0.25,1)	2.7	322	30	6.2	0.10
p_2	(0.25,2)	2.2	307	29	25	0.12
p_3	(0.14,1)	2.7	323	29	2.1	0.12
p_4	(0.14,2)	2.3	308	31	7.8	0.12

Constraints

Benchmark	$\sigma_{\gamma Z}$	$\sigma_{\text{MET}+j}$	$\sigma_{\gamma\gamma}$	σ_{jj}	$\langle\sigma v\rangle_{\gamma\gamma}$	σ_{SI}
	< 3.5 fb	< 6 fb	< 2 fb	$< 10^3$ fb	$< 10^{-28}\frac{\text{cm}^3}{\text{s}}$	$< 4 \times 10^{-45}\text{cm}^2$
p_1	0.86	3.7	1.4	1.3	$3.9 \cdot 10^{-32}$	$6.9 \cdot 10^{-46}$
p_2	3.6	3.5	6.0	1.4	$5.5 \cdot 10^{-32}$	$4.6 \cdot 10^{-46}$
p_3	0.3	1.2	0.48	0.14	$4.1 \cdot 10^{-32}$	$2.3 \cdot 10^{-46}$
p_4	1.1	1.2	1.8	0.13	$6.2 \cdot 10^{-32}$	$1.6 \cdot 10^{-46}$

except for ***p2***, example points **consistent**
with existing exp. constraints

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example points which give
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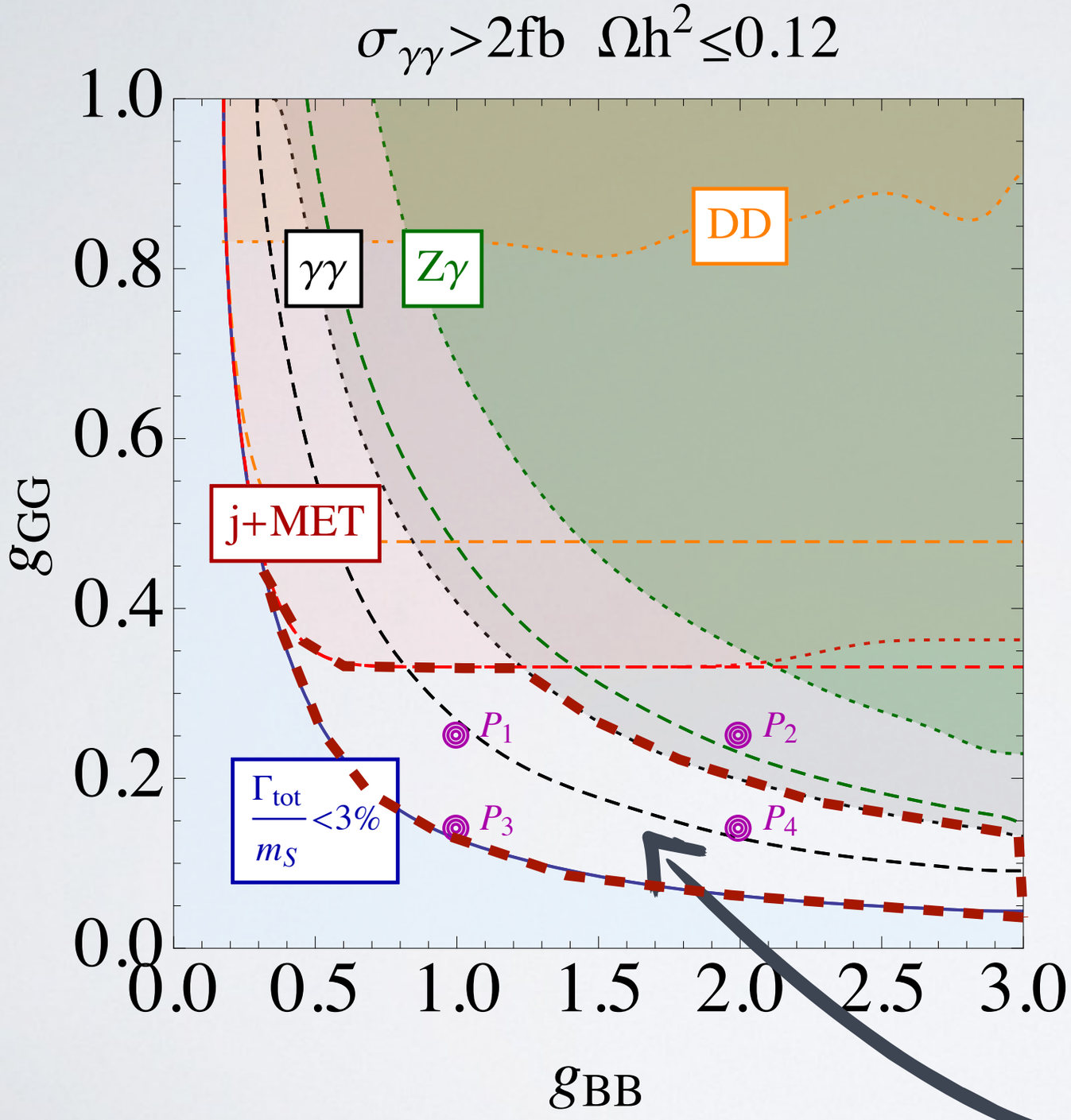
Constraints

Indirect detection favors
pure scalars because of
p-wave suppression

Benchmark					$\langle\sigma v\rangle_{\gamma\gamma}$	σ_{SI}
				b	$< 10^{-28}\,\frac{\mathrm{cm}^3}{\mathrm{s}}$	$< 4 \times 10^{-45}\mathrm{cm}^2$
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except for ***p*2**, example points **consistent**
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Is the prediction reasonable?



4-dimensional par. space projected onto g_{GG} and g_{BB}

Dashed/dotted curves represent the **strongest/weakest** bounds (depending on the values of DM mass and coupling)

Allowed parameter space

Tropical fruit scenarios



- ***Mixing with the Higgs***
- ***Production mechanism at LHC***
- ***Alternative to 750 GeV resonance***
- ***Model building aspects***

Issue of the mixing

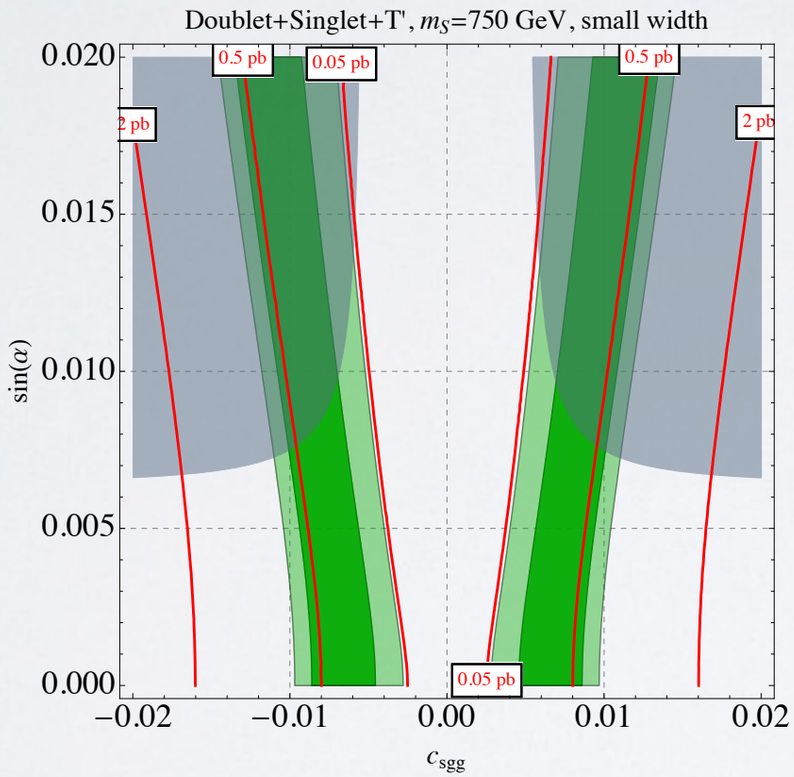
arXiv:1512.05777

Assume new resonance mixes with the Higgs

$$h \to h\cos\alpha + S\sin\alpha\,, \qquad S \to -h\sin\alpha + S\cos\alpha\,,$$

Couplings with EW bosons and fermions are induced

$$\mathcal{L} \supset \frac{1}{v}\left(h\cos\alpha + S\sin\alpha\right)\left[2m_W^2 W_\mu^+ W_\mu^- + m_Z^2 Z_\mu Z_\mu - \sum_f m_f \bar{f} f\right]$$



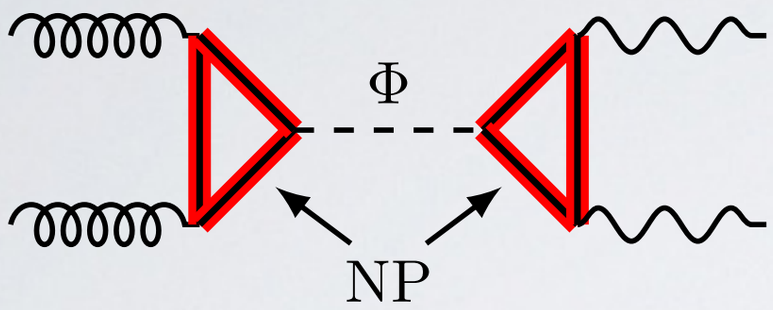
Bound on Mixing angle from di-boson signal at LHC8

Mixing will also induce extra Higgs coupling to gluons and photons
! Generic tension with Higgs coupling measurement for large mixing angle !

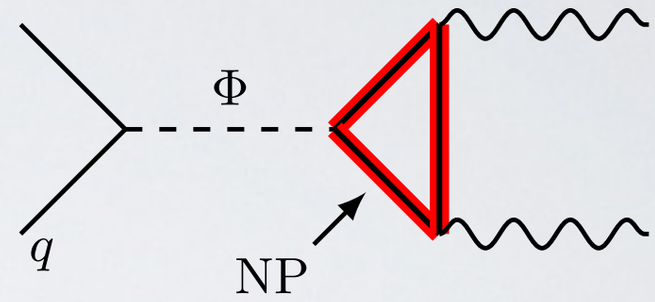
Production modes

arXiv:1512.04933
arXiv:1512.04928

Gluons



Quarks



$$\sigma(pp \to S \to \gamma\gamma) = \frac{1}{sM_S}\left(C_{gg}\Gamma_{gg} + \sum_q C_{q\bar{q}}\Gamma_{q\bar{q}}\right)\frac{\Gamma_{\gamma\gamma}}{\Gamma_{tot}}$$

To fit the excess we need $\sigma^{\gamma\gamma}_{13\mathrm{TeV}} \simeq 10 \pm 3 \text{ fb}$

How about compatibility with 8TeV constraints?

Difference from 8 and 13 TeV xsec is set by $\frac{C_{ii}}{s}$

Production modes

arXiv:1512.04933

To fit the excess we need $\sigma^{\gamma\gamma}_{13\mathrm{TeV}} \simeq 10 \pm 3$ fb

8-TeV limit $\sigma^{\gamma\gamma}_{8\mathrm{TeV}} \leq 2.4$ fb

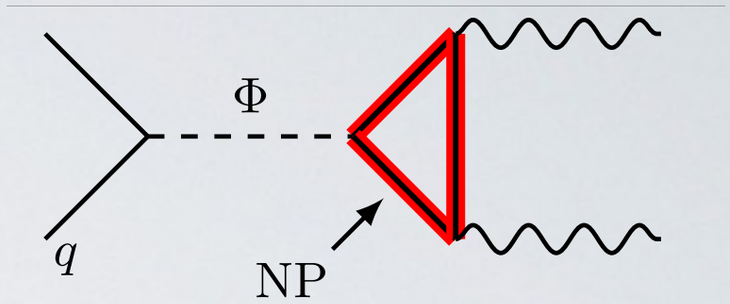
Gain Factors in production mechanisms $r = \dfrac{\sigma^{\gamma\gamma}_{13\mathrm{TeV}}}{\sigma^{\gamma\gamma}_{8\mathrm{TeV}}}$ $(\mu = 750\ \mathrm{GeV})$

$r_{b\bar{b}}$	$r_{c\bar{c}}$	$r_{s\bar{s}}$	$r_{d\bar{d}}$	$r_{u\bar{u}}$	r_{gg}
5.4	5.1	4.3	2.7	2.5	4.7

Rescale 8-TeV bound

gg	$\longleftrightarrow$	$\sigma^{\gamma\gamma}_{13\mathrm{TeV}} \leq 11$ fb	***Compatible***
$u\bar{u}$	$\longleftrightarrow$	$\sigma^{\gamma\gamma}_{13\mathrm{TeV}} \leq 6$ fb	***Some Tension***
$b\bar{b}$	$\longleftrightarrow$	$\sigma^{\gamma\gamma}_{13\mathrm{TeV}} \leq 13$ fb	***Compatible***

Quark production



$\mathcal{L} \supset y_b \bar{b} b S$ Need very large y_b to give sizeable signal rate

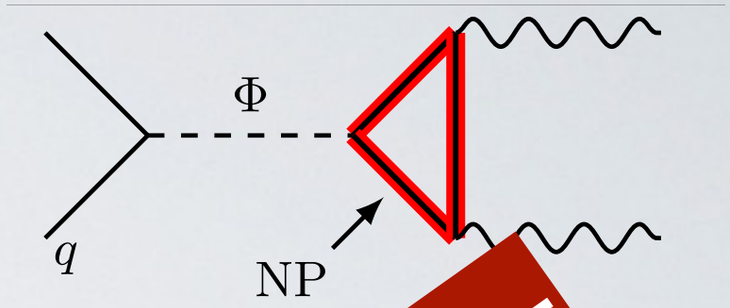
$\mathcal{L} \supset y_u \bar{u} u S$ Can work but partial tension with 8TeV constraints

- ***Cross section contours for gamma gamma signal at 13 TeV***
- ***Here photon coupling induced by vector like fermions***
- ***Total width anyway bounded from di-jet constraints***

$$\mathrm{Max}(\Gamma_{\bar{q}q}) \simeq 1 \text{ GeV}$$

arXiv:1512.04928

Quark production



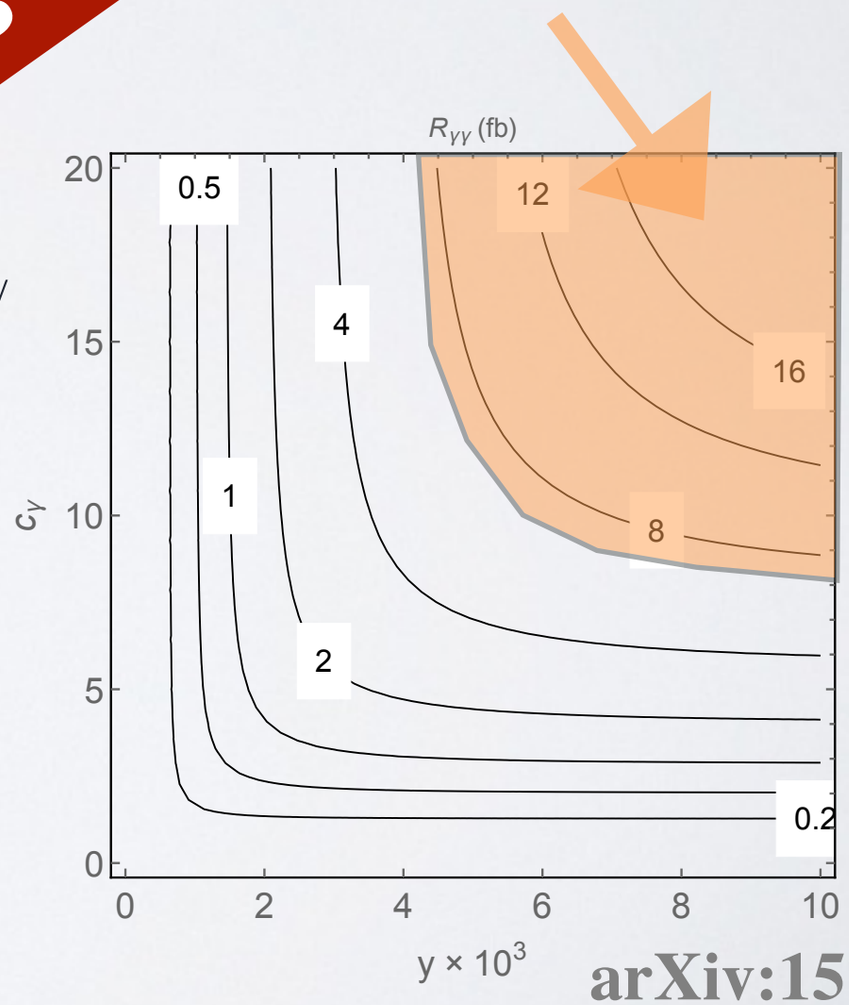
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- Cross section contours for gam… signal at 13 TeV
- Here photon coupling i… ctor like fermions
- Total width any… from di-jet constraints

$$\mathrm{Max}(\ldots q) \simeq 1 \text{ GeV}$$

Quark production is less promising



arXiv:1512.04928

Alternative to 750 GeV resonance

1. **Parent heavier resonance**

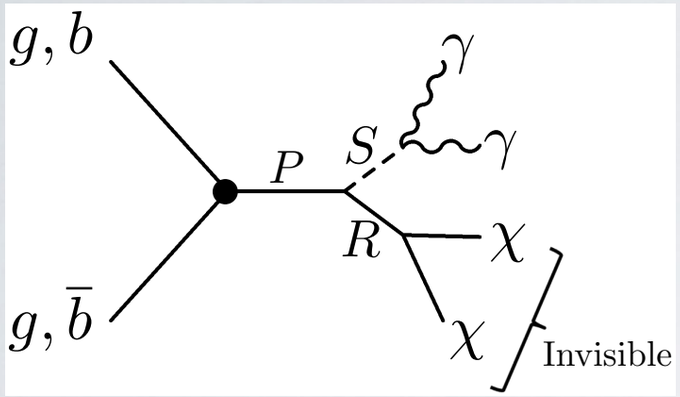
2. **Kinematic edge**

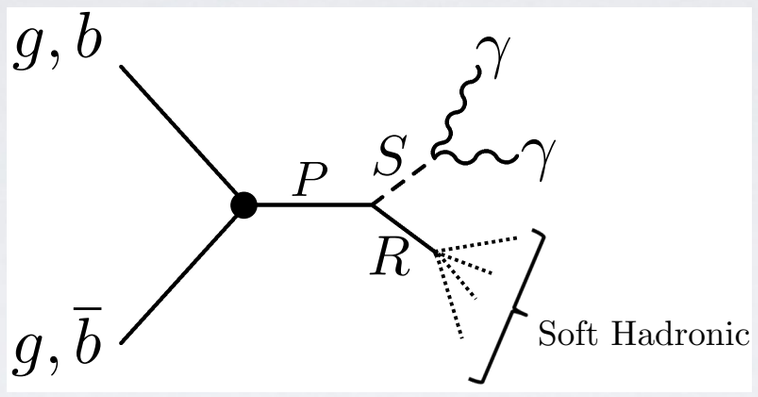
3. **Collimated photons**

Not a 750 resonance

Assume production of heavier parent resonance

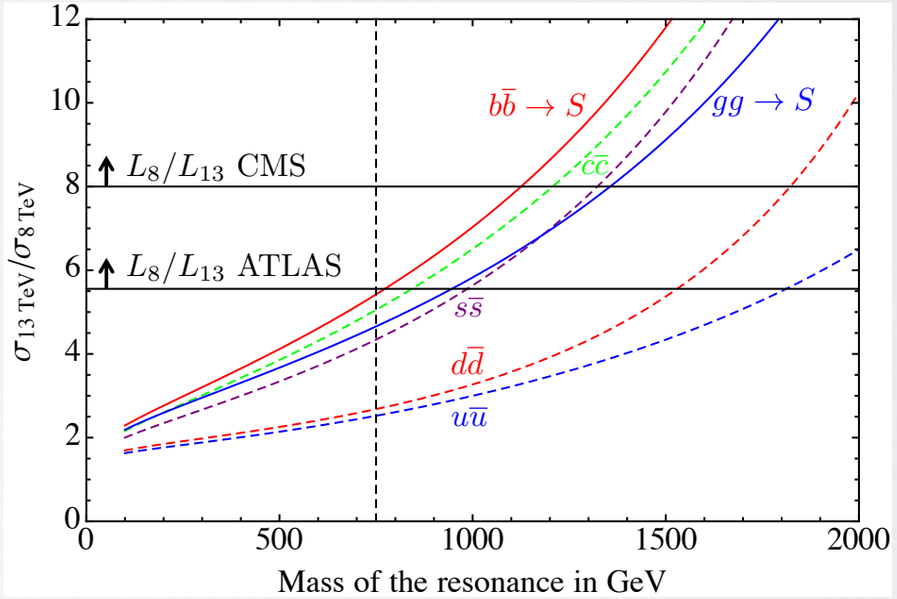
arXiv:1512.04933





Small mass splitting to hide other products

Stronger enhancement in signal rate from 8 to 13 TeV



Toy model

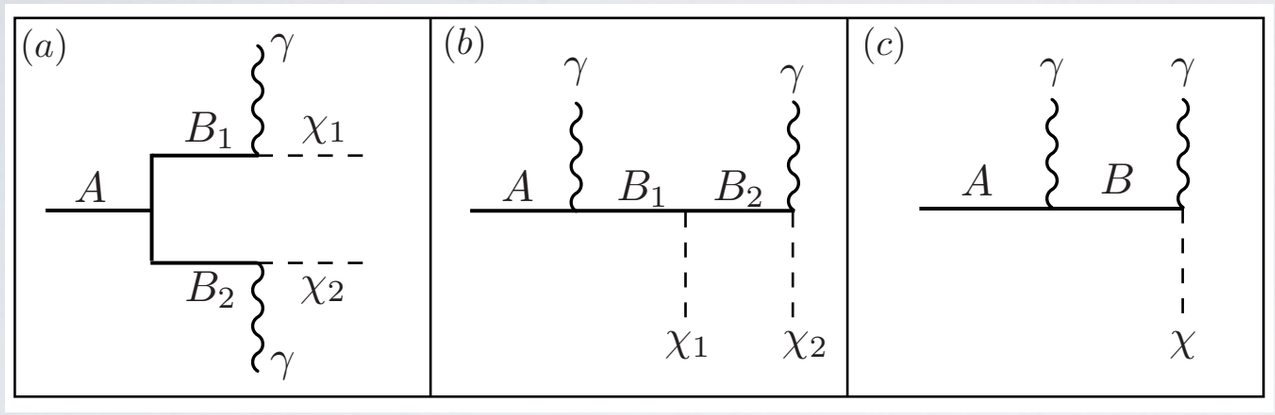
$V = \lambda m_P PSR$

$m_P = 1.2$ TeV $\quad m_S = 750$ GeV $\quad m_R = 440$ GeV $\quad \lambda \sim 1$

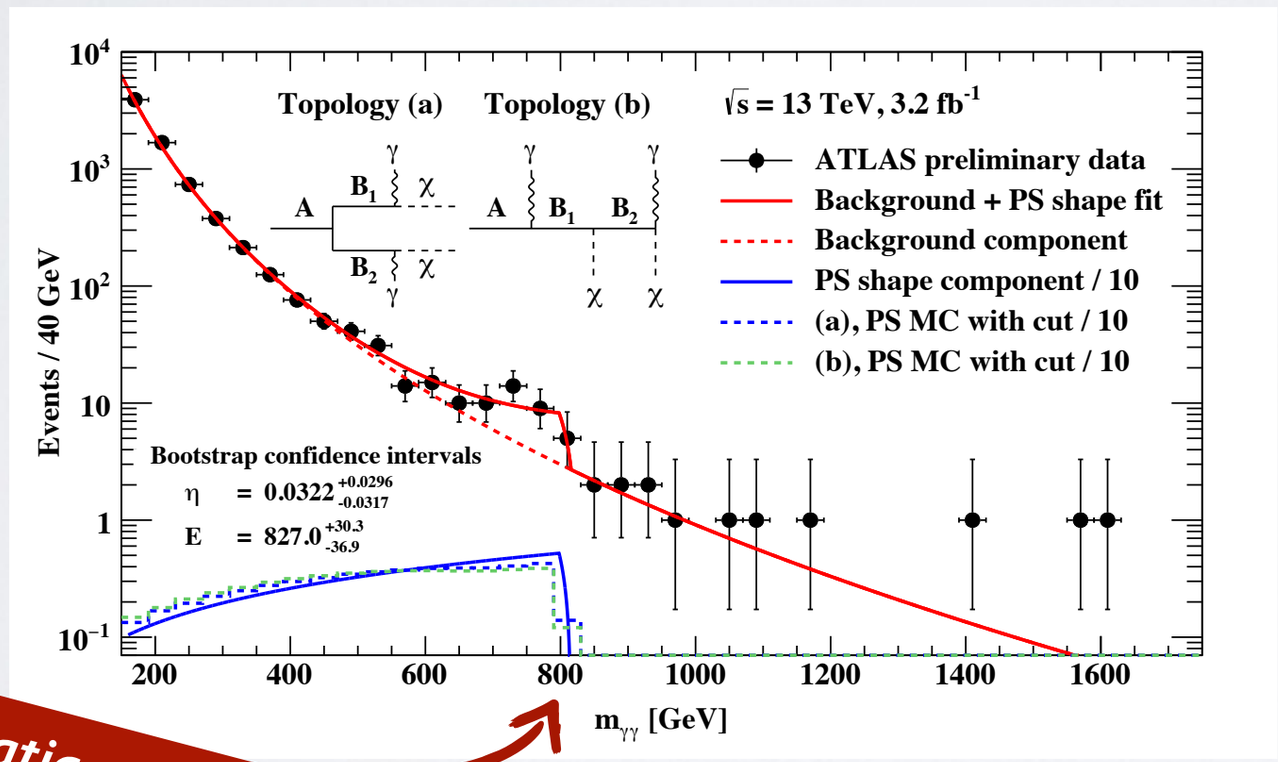
Kinematic edge

arXiv:1512.06824

Assume more complicated decay chain ending into invisible particles



Particle A generically heavier than 750 improving enhancement from 8 to 13



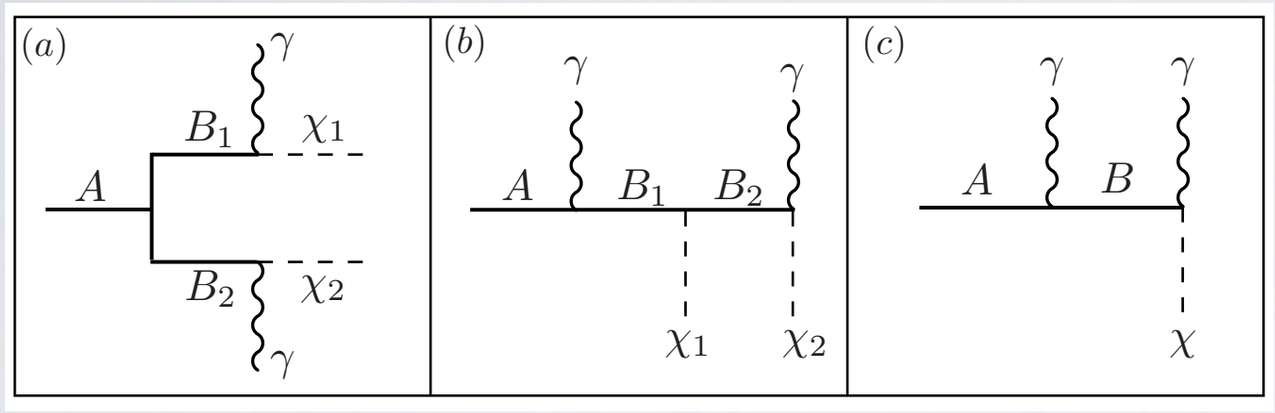
Kinematic edge depends on mass combination

Consistency with
observed signal ?

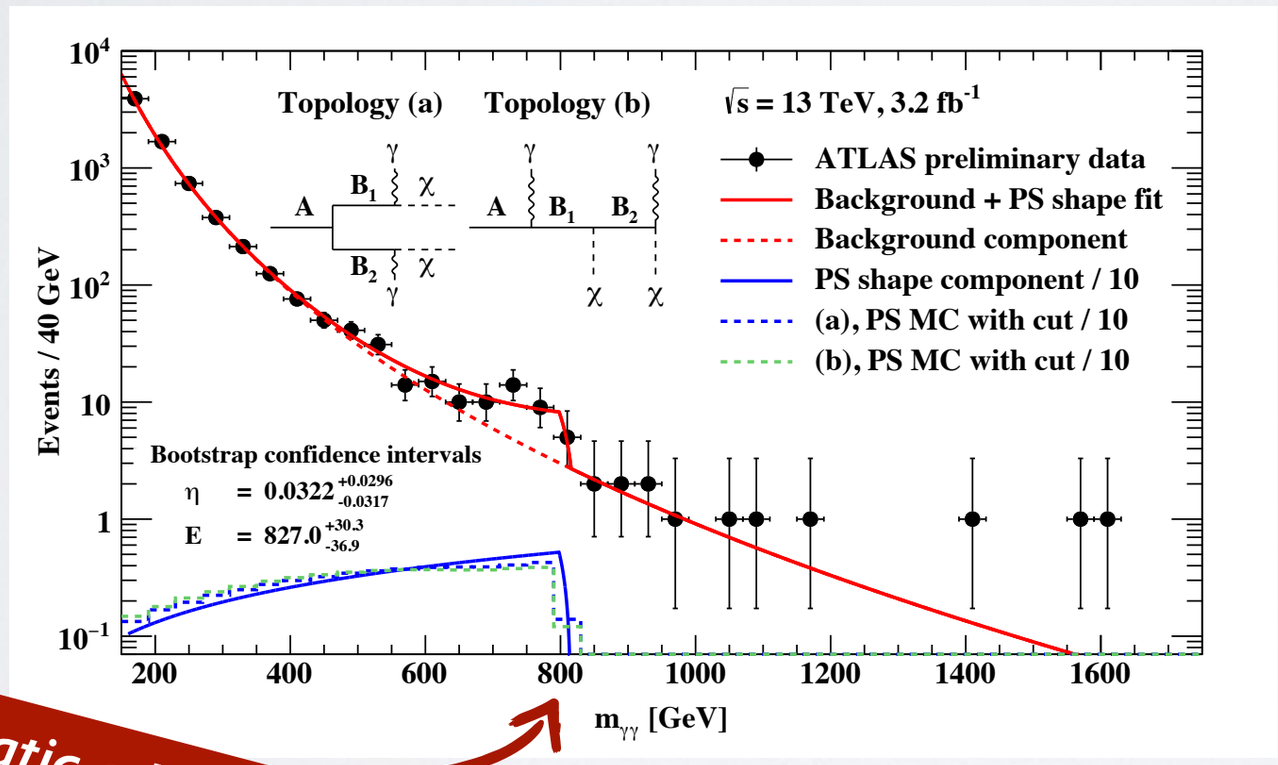
Kinematic edge

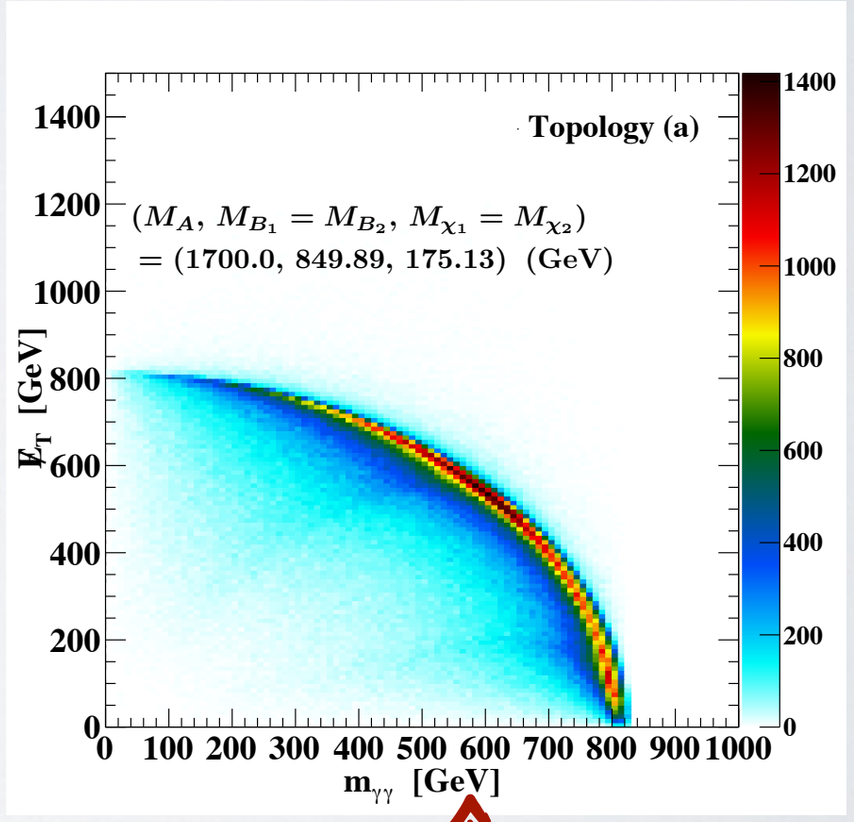
arXiv:1512.06824

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Kinematic edge depends on mass combination

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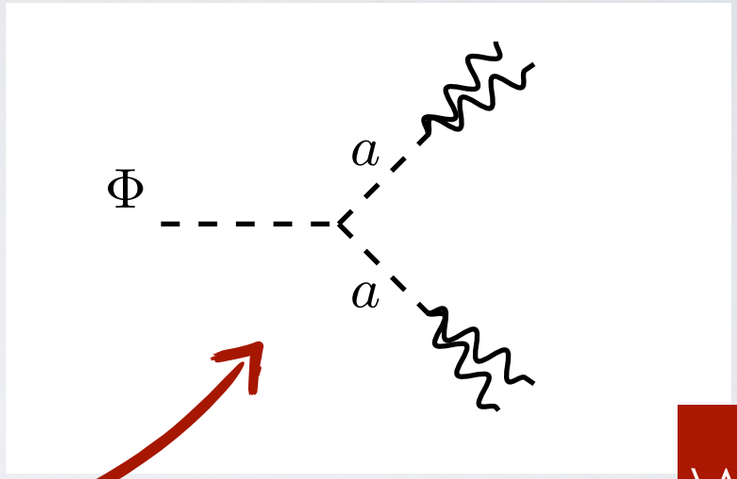
Small Missing energy in events with large $m_{\gamma\gamma}$

Collimated photons

arXiv:1512.04928
arXiv:1512.06833

Resonance decay at tree level to a pair of light scalars a

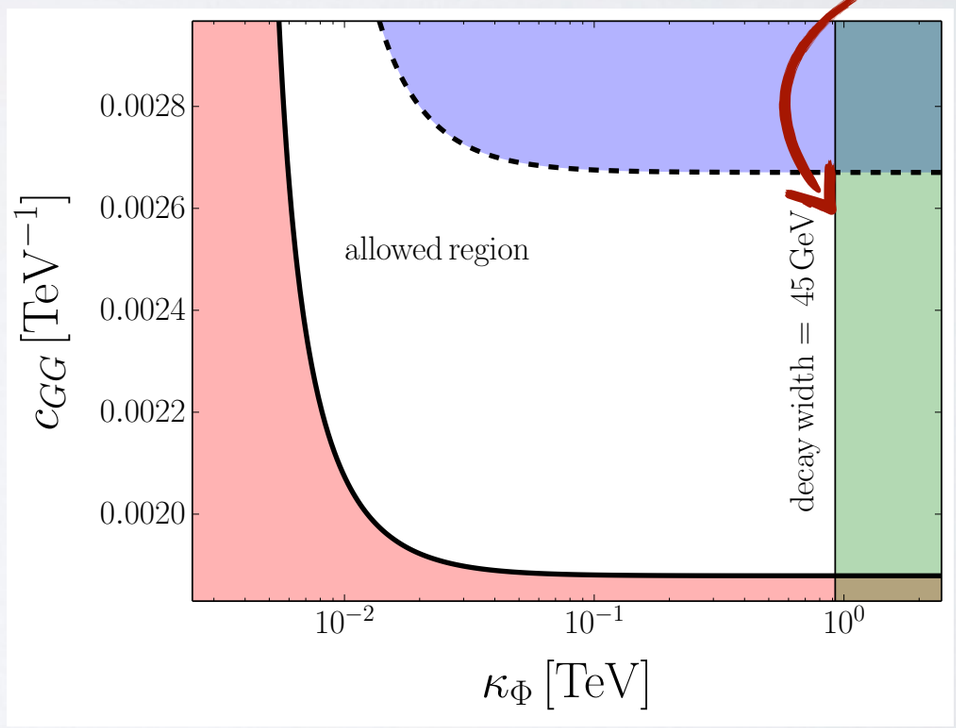
$$\mathcal{L} \supset c_{GG}\Phi G^a_{\mu\nu}G^{\mu\nu a} + \kappa_\Phi \Phi a^2$$



a should be very light (and boosted) and decays to a pair of collimated photons

$m_a \lesssim 1GeV$

Width of resonance can be large

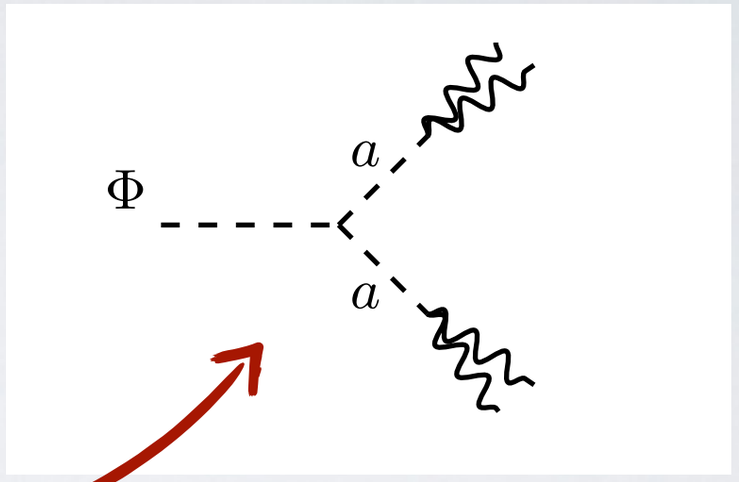


Collimated photons

arXiv:1512.04928
arXiv:1512.06833

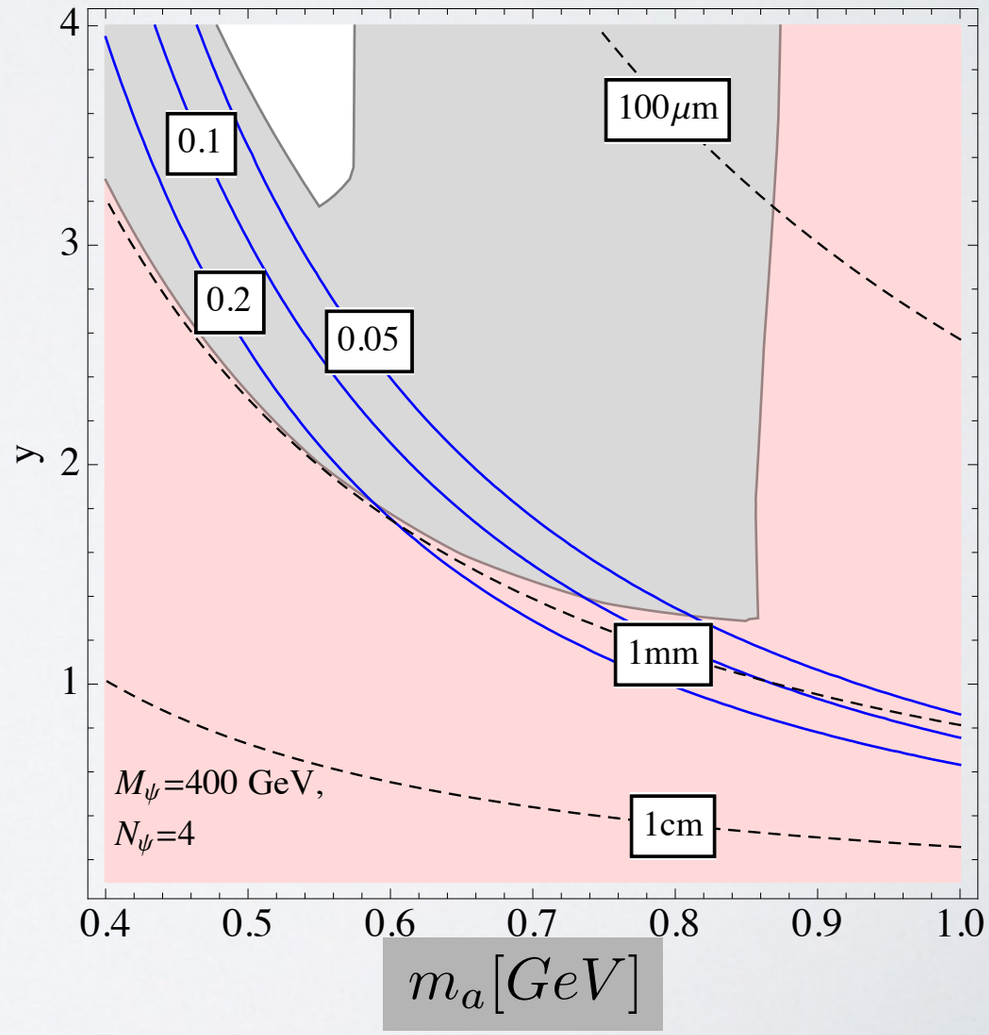
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$m_a \lesssim 1GeV$

a should be very light (and boosted) and decays to a pair of collimated photons



!! HOWEVER !!

Decay of a into photons typically displaced

arXiv:1512.04928

Model building aspects

1. **2 Higgs Doublet Model**
2. **Supersymmetry and the sgoldstino**
3. **Strongly coupled models**

2HDM

- Heavy Higgses in decoupling limit $\frac{v}{M_S} \ll 1$
- CP-Odd and CP-Even with small mass splitting $m^2_{H^0} - m^2_{A^0} \sim v^2$
- → Can mimic large width

Couplings to photons/gluons induced by coupling to SM quarks

$$\mathcal{L} \supset y'_f \bar{Q}_L (H^0 + iA^0) f_R$$

Same coupling induces tree level decay of heavy Higgses

→ **BR into gluons and photons will be suppressed**

Maximum possible signal rate arXiv:1512.07616

$$(\sigma \mathrm{BR})(pp \to H \to \gamma\gamma) \lesssim (0.01/0.06/0.14)\,\mathrm{fb}$$
$$(\sigma \mathrm{BR})(pp \to A \to \gamma\gamma) \lesssim (0.01/0.07/0.18)\,\mathrm{fb}$$

For three values of $\xi_t = \frac{y'_t}{y_t} = 1, 3, 5$

Need to add vector like fermion to enhance gluon/photon couplings

2HDM

- Heavy Higgses in decoupling limit $\frac{v}{M_S} \ll 1$
- CP-Odd and CP-Even with small mass splitting $m^2_{H^0} - m^2_{A^0} \sim$
- → Can mimic large width

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For three values of $\xi_t = \frac{y'_t}{y_t} = 1, 3, 5$

MSSM heavy Higgs also not promising

Need to add vector like fermion to enhance gluon/photon couplings

SUSY and sgoldstino

arXiv:1512.05330
arXiv:1512.05333

In low scale supersymmetric models we expect
complex scalar partner of the goldstino to be moderately light

Couplings to MSSM particles determined by soft terms

Vector couplings or CP-even component

$$\mathcal{L}_1 = -\frac{M_3}{2\sqrt{2}F}\, S\, \mathrm{tr}\, G_{\mu\nu}G^{\mu\nu} - \frac{M_{\gamma\gamma}}{2\sqrt{2}}\, S\, F_{\mu\nu}F^{\mu\nu}$$

$M_{\gamma\gamma} = M_1\, \cos^2\theta_W + M_2\, \sin^2\theta_W$

$M_{1,2,3}$ ***Gaugino soft masses***

Fermion couplings of CP-even component

$$\mathcal{L} = \frac{m_t A_t}{\sqrt{2}F} S\bar{t}t$$

A_t ***Fermion A-term***

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Can be large for large gaugino masses

$M_{\gamma\gamma} = M_1 \cos^2\theta_W + M_2 \sin^2\theta_W$

$M_{1,2,3}$ ***Gaugino soft masses***

Fermion couplings of CP-even component

$$\mathcal{L} = \frac{m_t A_t}{\sqrt{2}F} S\bar{t}t$$

Small for small A-terms

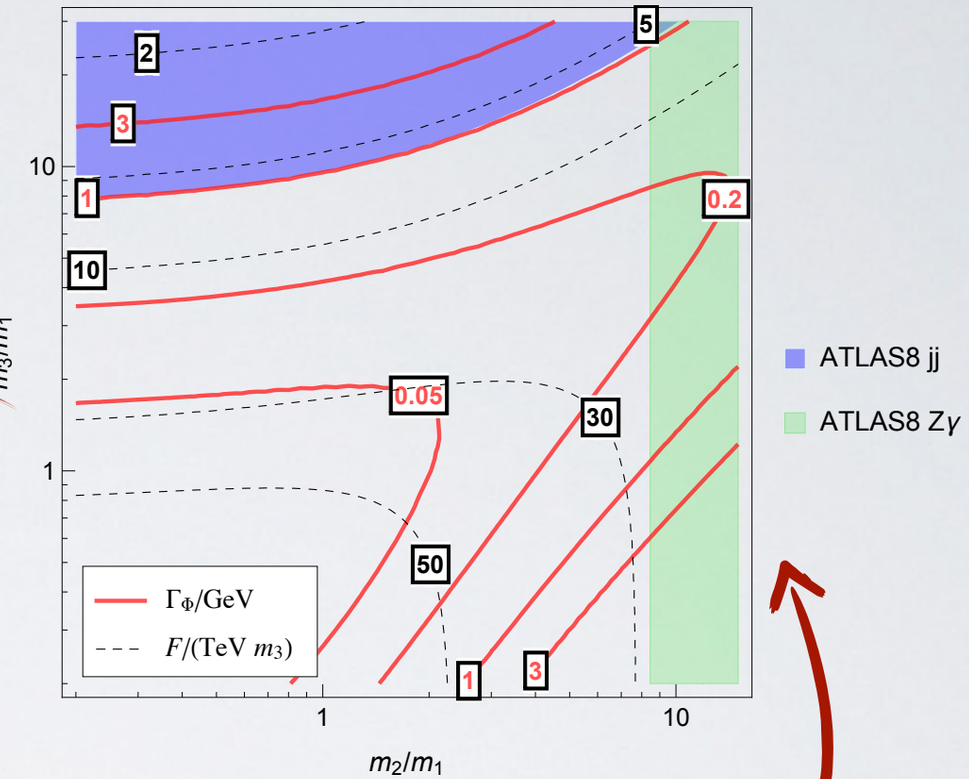
A_t ***Fermion A-term***

Simplified model Lagrangian discussed previously

SUSY and sgoldstino

arXiv:1512.05330
arXiv:1512.05333

- ***Consider only CP-even component***
- ***Fixed diphoton signal yield at 13TeV to 7 fb***



Width is always small

Similar results for CP-odd

Mimic Large Width with two sgoldstino components

Non trivial to control the mass splitting

Strongly coupled models

arXiv:1512.04933

Large width suggest strongly coupled models

Large number of composite states induce large photon coupling

Two Scenarios

1. **S is a PNGB of sector that produces Higgs**

2. **S is a PNGB of a sector not related to EWSB**

Strongly coupled models

arXiv:1512.04933

S is a PNGB of sector that produces Higgs

- ***Strongly coupled sector with SU(N) gauge group***
- ***Global Symmetry breaking SO(6)/SO(5)***
- ***Higgs + Extra singlet S***

Strong scale and strong coupling

$$m_* \simeq g_* f = 4\pi f/\sqrt{N}$$

Mass of PNGB

From external dynamics

$$m_{PNGB} \sim m_h \times \frac{f}{v} \sim \frac{y_t}{4\pi} m_*$$

From internal dynamics

$$m_{PNGB} \sim \frac{g_*}{4\pi} m_*$$

We can produce PNGB masses in the range $m_h \ll m_{PNGB} \ll m_\star$

Conclusions

DiPhoton excess stimulated a frenzied activity

Many proposals on the market

Vanilla scenario implies new resonance at 750 GeV
coupled to gluons and photon

Large Width difficult to achieve



Possibly related to Invisible Decay into DM
More data will probe the proposal

All scenarios include other NP accessible at LHC13