The Di-photon excitement at the LHC: TH

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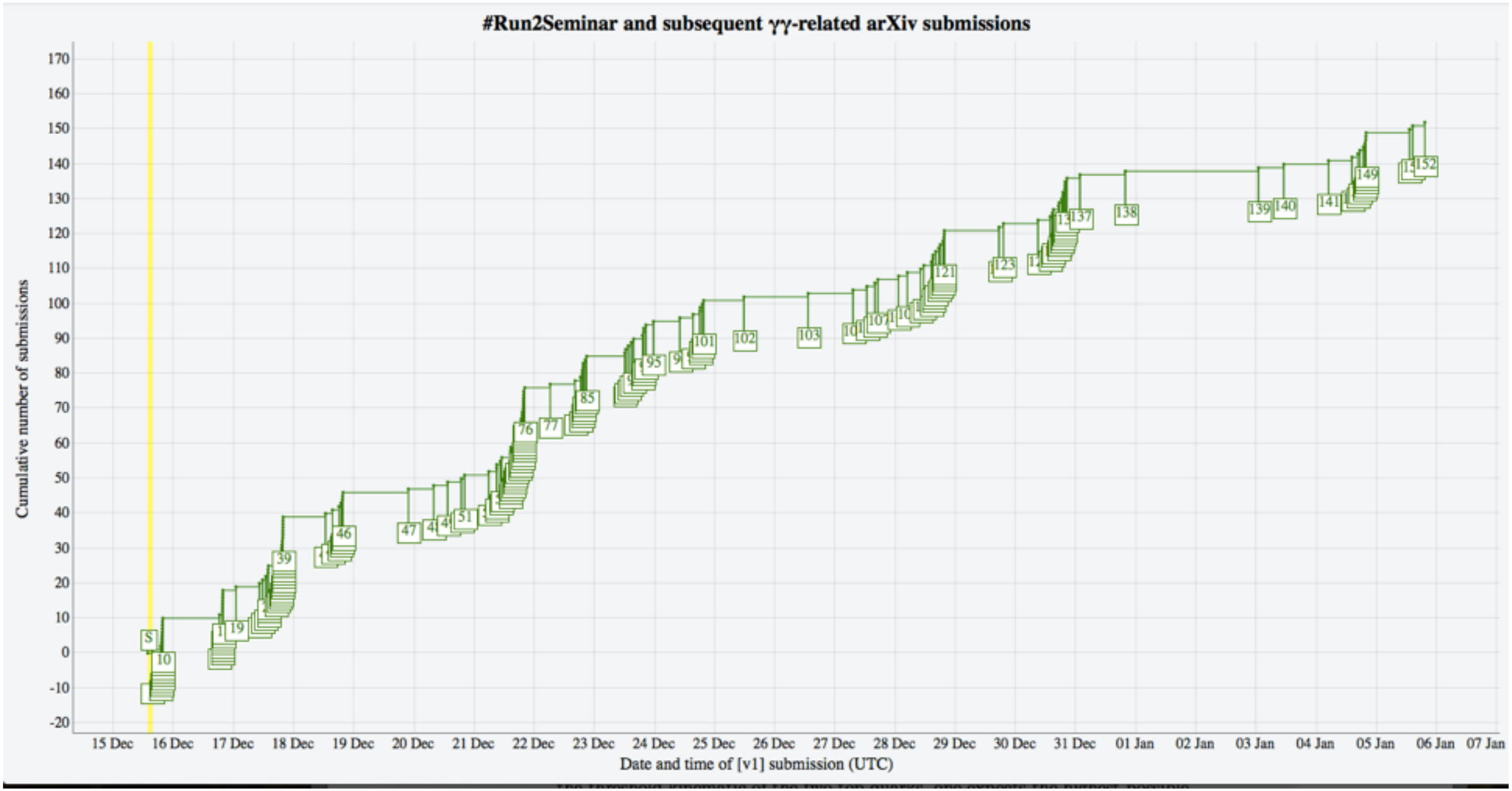
What happened at 15-12-2015 ?

Two Bumps!!!

Need more data to be conclusive but very promising !!!

The DiPhoton Frenzy

Enormous amount of theory papers already in the first two weeks!



Now we have reached around 400 papers

Compatible with prediction of arXiv:1603.01204

How to explain the excess?

Basic features of the excess
Peak at 750 GeV

$\sigma(pp \to \gamma\gamma)$	$\sqrt{s} = 8\,\text{TeV}$		$\sqrt{s} = 13\,\text{TeV}$	
	narrow	broad	narrow	broad
CMS	$0.63 \pm 0.31\,\text{fb}$	$0.99 \pm 1.05\,\text{fb}$	$4.8 \pm 2.1\,\text{fb}$	$7.7 \pm 4.8\,\text{fb}$
ATLAS	$0.21 \pm 0.22\,\text{fb}$	$0.88 \pm 0.46\,\text{fb}$	$5.5 \pm 1.5\,\text{fb}$	$7.6 \pm 1.9\,\text{fb}$

***WIDTH**: inconclusive but ATLAS favours large* $\dfrac{\Gamma}{m_S} \sim 6\%$

Simpler interpretation: new resonance at 750 GeV

Open questions?

Is it really a resonance at 750 GeV in diphotons?

Spin-0 or Spin-2 ?

If a scalar: does it mix with the SM scalar?

What is the production mode at the LHC?

What are expected correlated signature?

Is well motivated in UV completions of the SM?

Is it a portal to a dark sector?

Elementary of composite?

How would explain a large width?

Plan of today

Characterisation of the excess

- **Production Modes at the LHC**
- **Spin 0 or Spin 2**
- **Elementary or not …**
- **Not a resonance in diphotons …**

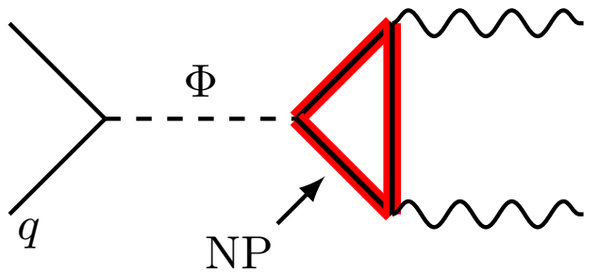
My personal choice over 400 papers
Apologize if I miss something …

Model building aspects

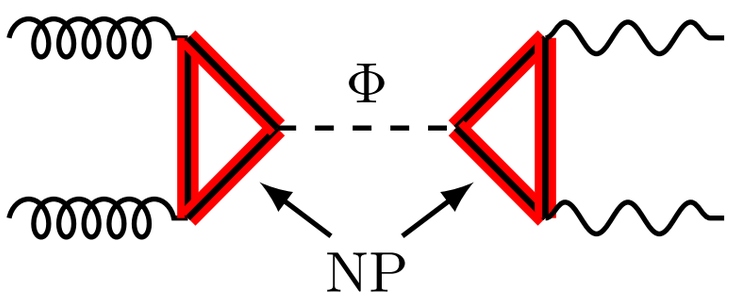
- **Hierarchy problem …**
- **SUSY**
- **PNGB … composite models**
- **Dark matter portal**

Production Mechanism

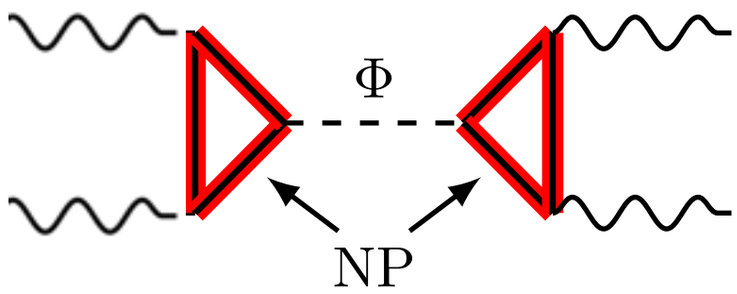
QUARKS



GLUONS



PHOTONS



$$\sigma(pp \to \Phi \to \gamma\gamma) = \frac{2J+1}{M\Gamma_\Phi s}\left[\sum_{\mathcal{P}} C_{\mathcal{P}\bar{\mathcal{P}}}\Gamma(\Phi \to \mathcal{P}\bar{\mathcal{P}})\right]\Gamma(\Phi \to \gamma\gamma)$$

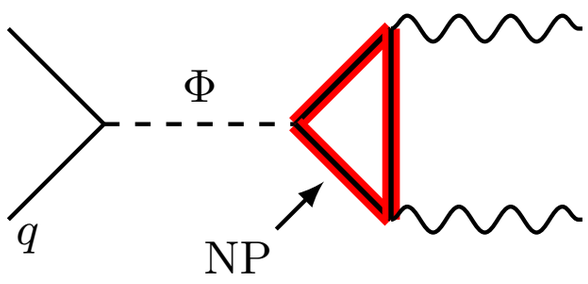
- ***To fit the excess we need*** $\sigma^{\gamma\gamma}_{13\mathrm{TeV}} \simeq 6\ \mathrm{fb}$
- ***How about compatibility with 8TeV constraints?*** $\sigma^{\gamma\gamma}_{8\mathrm{TeV}} \leq 1.5\ \mathrm{fb}$

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

Production Mechanism

The production mode should be compatible with 8TeV (<1.5 fb)

QUARKS



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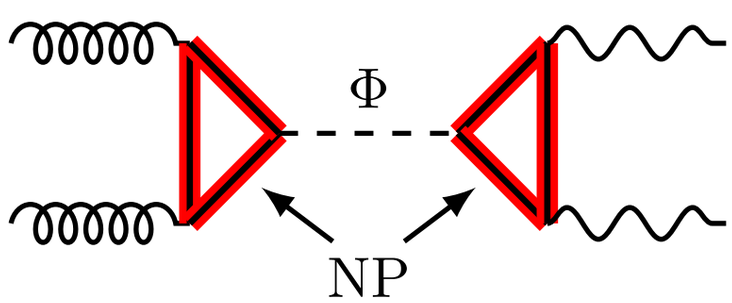

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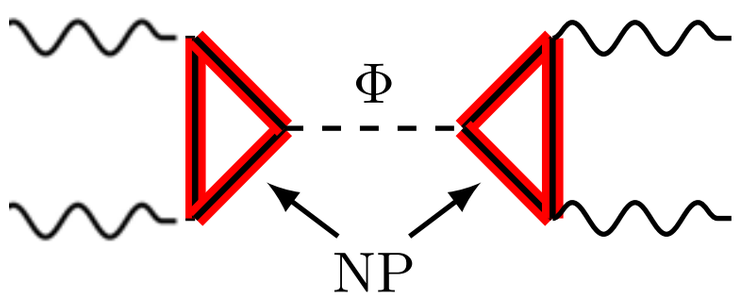


channel	$u\bar{u}$	$d\bar{d}$	$s\bar{s}$	$c\bar{c}$	$b\bar{b}$	$\gamma\gamma$	gg
$\frac{\sigma_{13\mathrm{TeV}}}{\sigma_{8\mathrm{TeV}}}$	2.5	2.7	4.3	5.1	5.4	2.9	4.7

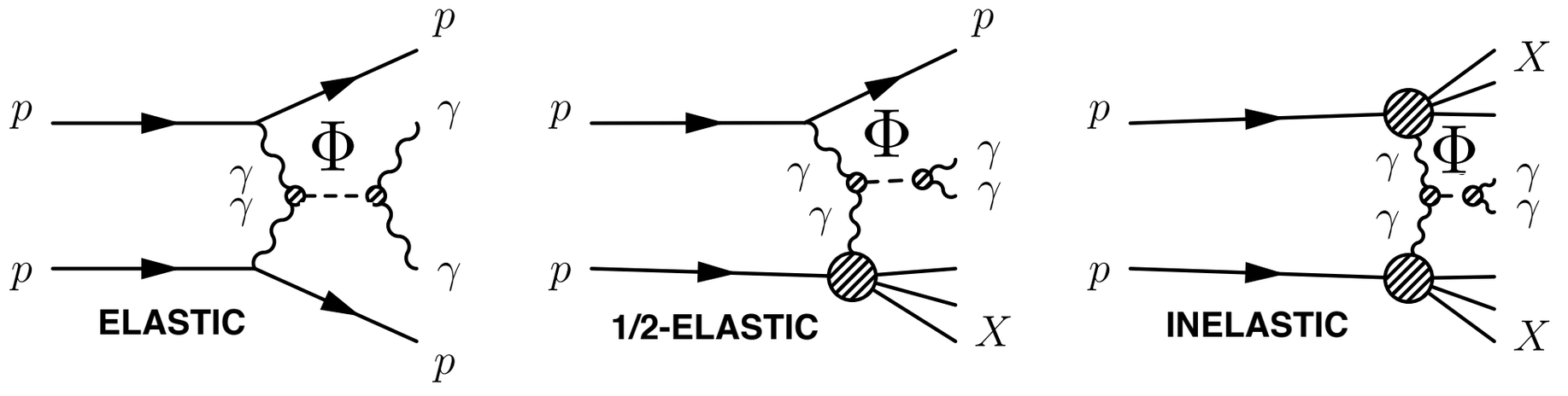
Rescaling 8-TeV bound

$\sigma^{\gamma\gamma}_{13\mathrm{TeV}} \leq 3.75$ fb

$\sigma^{\gamma\gamma}_{13\mathrm{TeV}} \leq 8.1$ fb

$\sigma^{\gamma\gamma}_{13\mathrm{TeV}} \leq 7.05$ fb

Photon production



Dominant is inelastic scattering

Large uncertainties in photon PDF

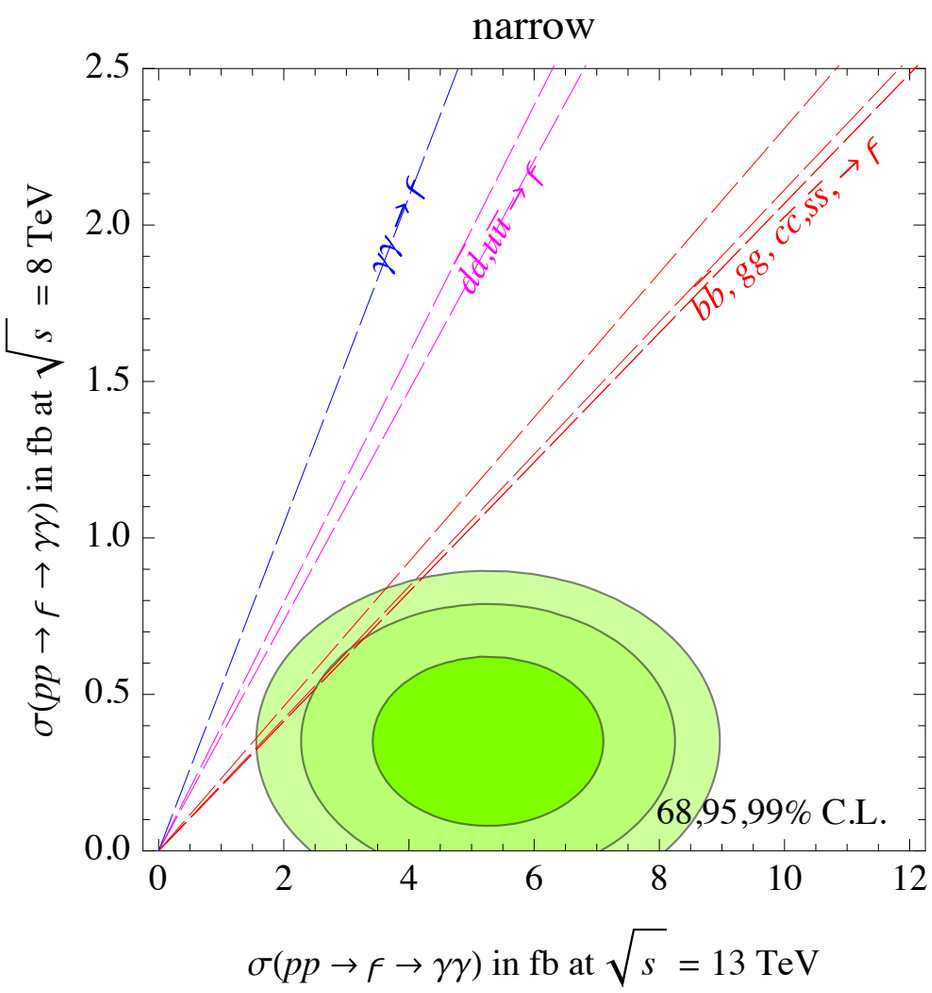
Latest result → $\frac{\sigma^{\gamma\gamma}_{13\mathrm{TeV}}}{\sigma^{\gamma\gamma}_{8TeV}} = 2.9$

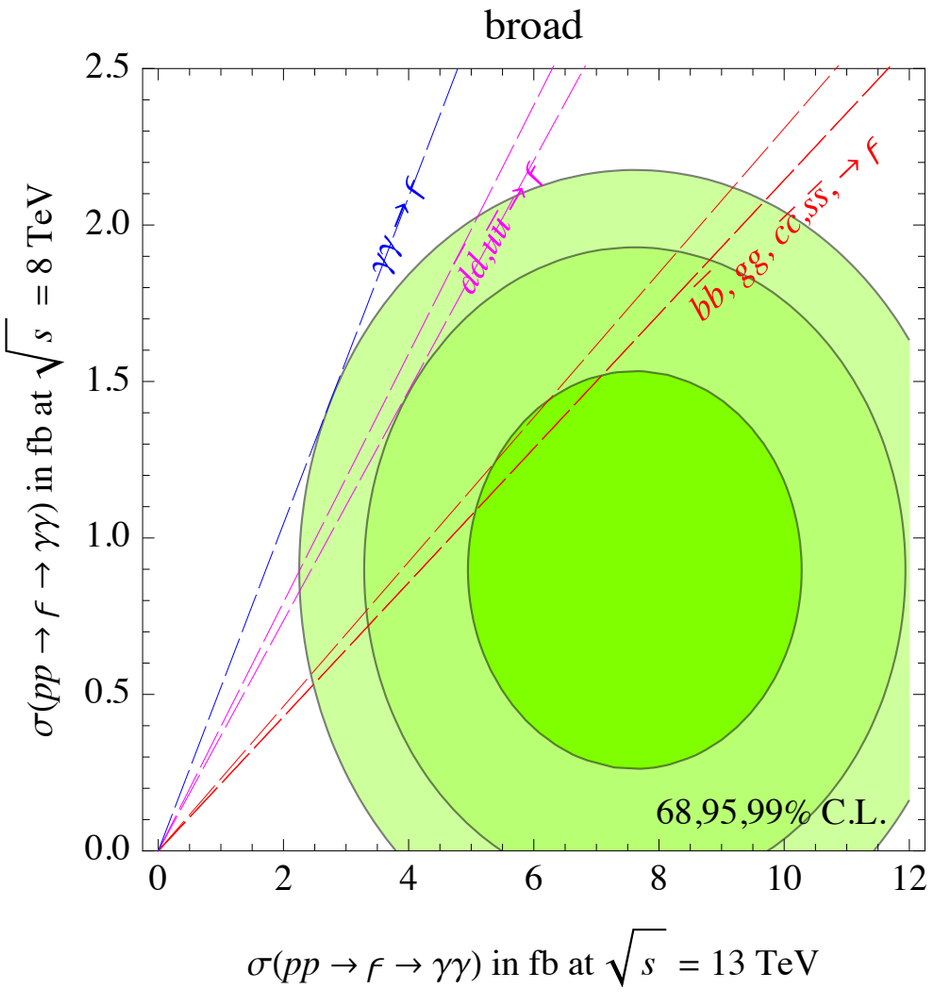
arXiv:1601.07187

Still not optimal for compatibility with 8TeV but it could be …

!Could be particularly promising if no other objects in final state!

Summary on production modes





arXiv:1605.09401

Gluon fusion and heavy quarks are more promising ones

“Vanilla” Model for spin 0

Minimal Lagrangian to achieve gluon-fusion:

—Majority of papers based on this effective theory—

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

Implies new physics to generate dimension 5 operators

Implies correlated signals in di-bosons

CHANNELS	$\gamma\gamma$	ZZ	$Z\gamma$	WW	jj
coupling	$g_{BB}c_w^2 + g_{WW}s_w^2$	$g_{BB}s_w^2 + g_{WW}c_w^2$	$s_{2w}(g_{BB} - g_{WW})$	g_{WW}	g_{GG}
8 TeV bounds	<2 fb	<12 fb	<4 fb	<40 fb	<2.5 pb

Can accommodate the signal and be compatible with 8TeV !

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EQUIVALENT ONE WITH CP ODD SCALAR CAN BE ALSO CONSIDERED

Can accommodate the signal and be compatible with 8TeV !

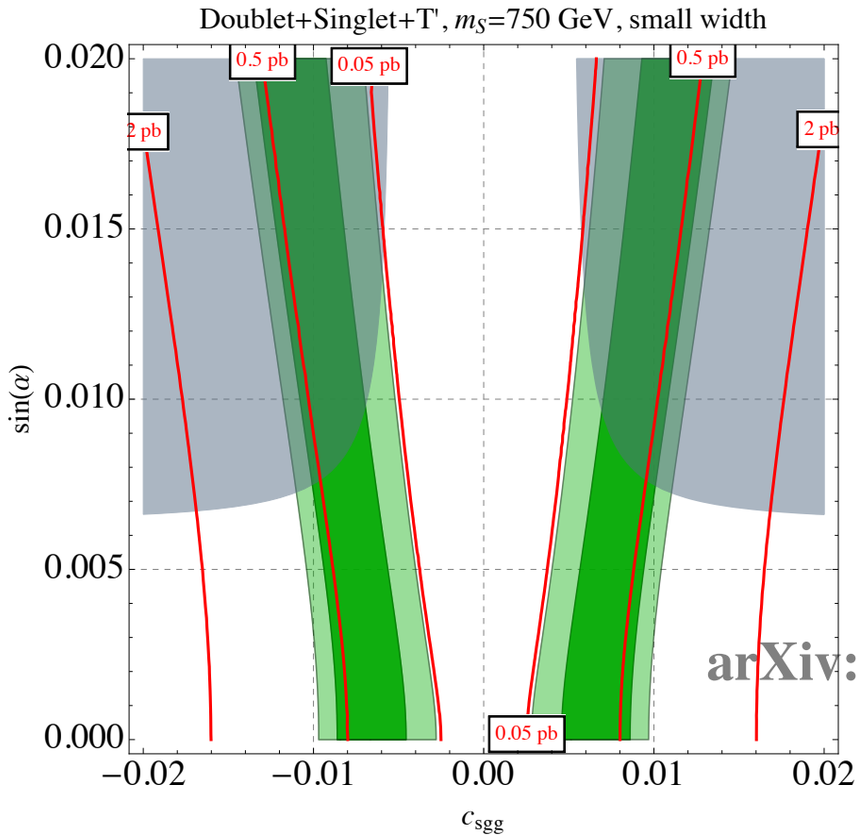
What about the mixing?

Assume new resonance mixes with the SM scalar

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

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

arXiv:1512.05777

Mixing will also induce extra BEH coupling to gluons and photons

! Generic tension with BEH coupling measurement for large mixing angle !

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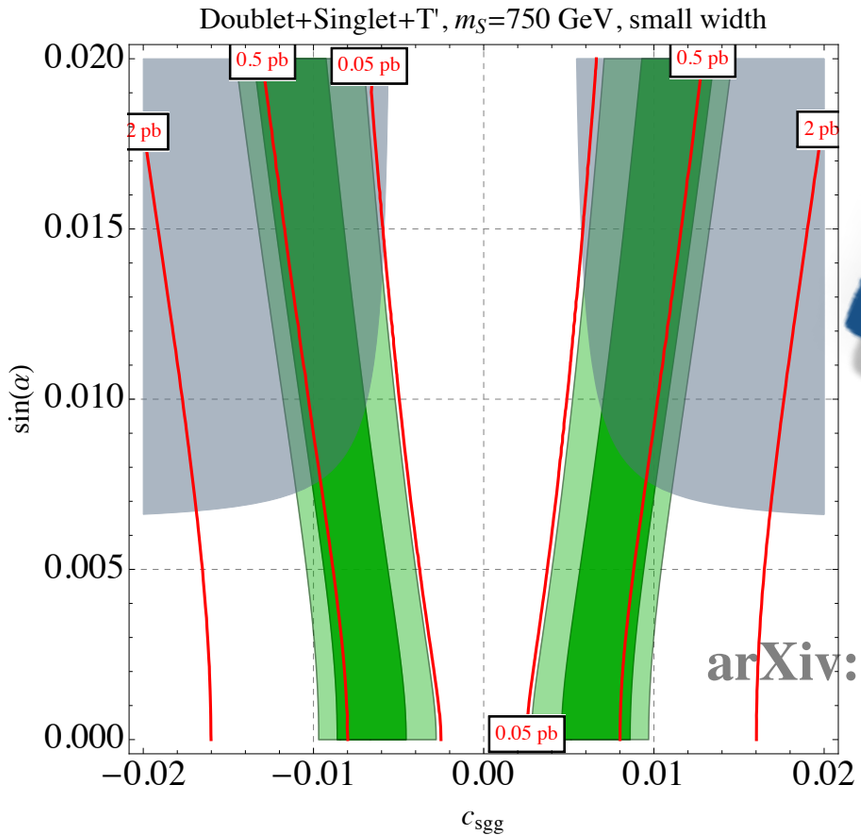


Bound on Mixing angle from di-boson ... at LHC8

The mixing issue favors a CP-odd scalar

arXiv:1512.05777

Mixing will also induce extra BEH coupling to gluons and photons

! Generic tension with BEH coupling measurement for large mixing angle !

The width of the resonance ?

ATLAS preliminary analysis favours large width

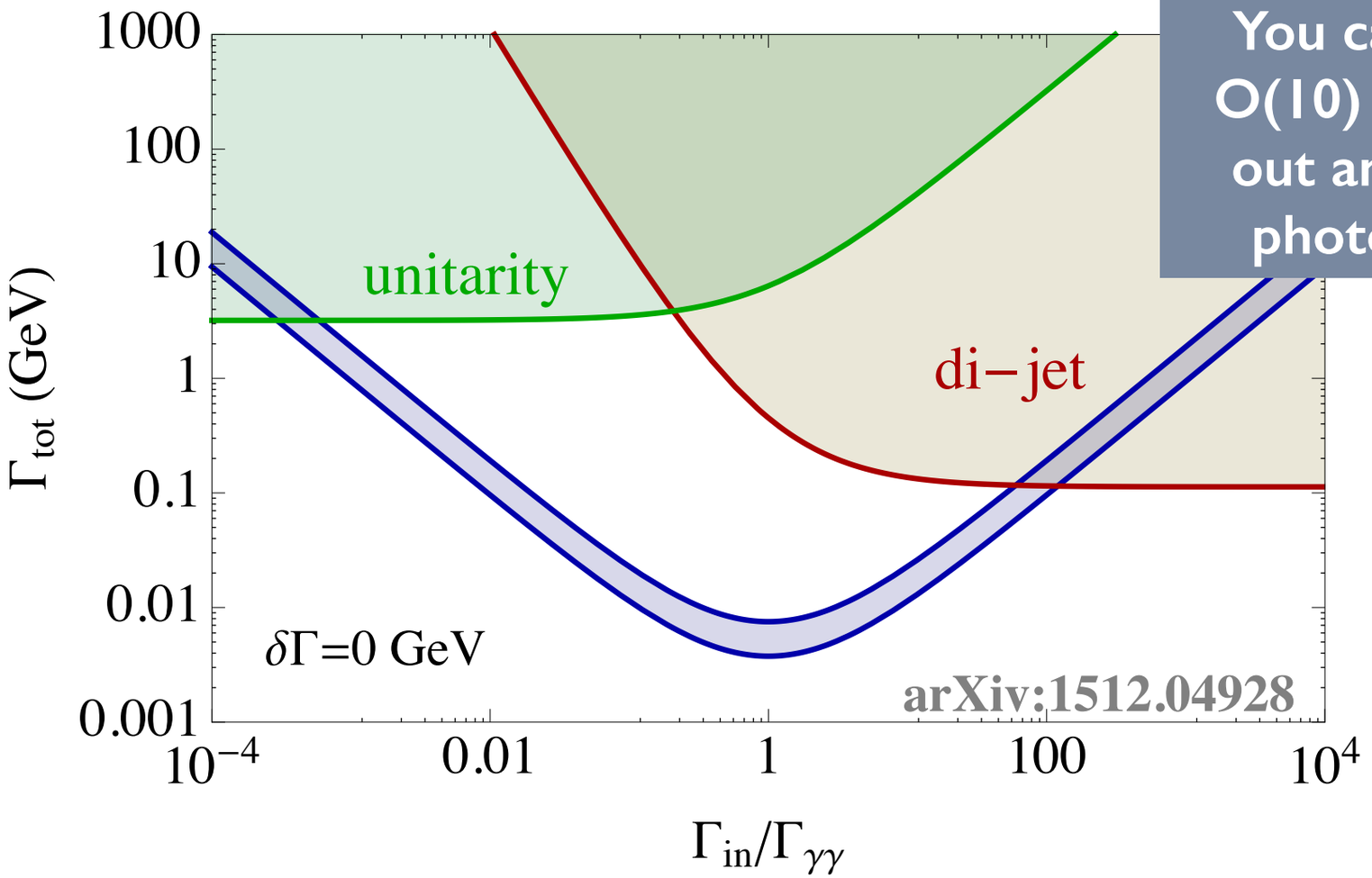
$$\frac{\Gamma}{m_\phi} \sim 6\%$$

Large width cannot be achieved in Vanilla Model

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

similar exp. for photons

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

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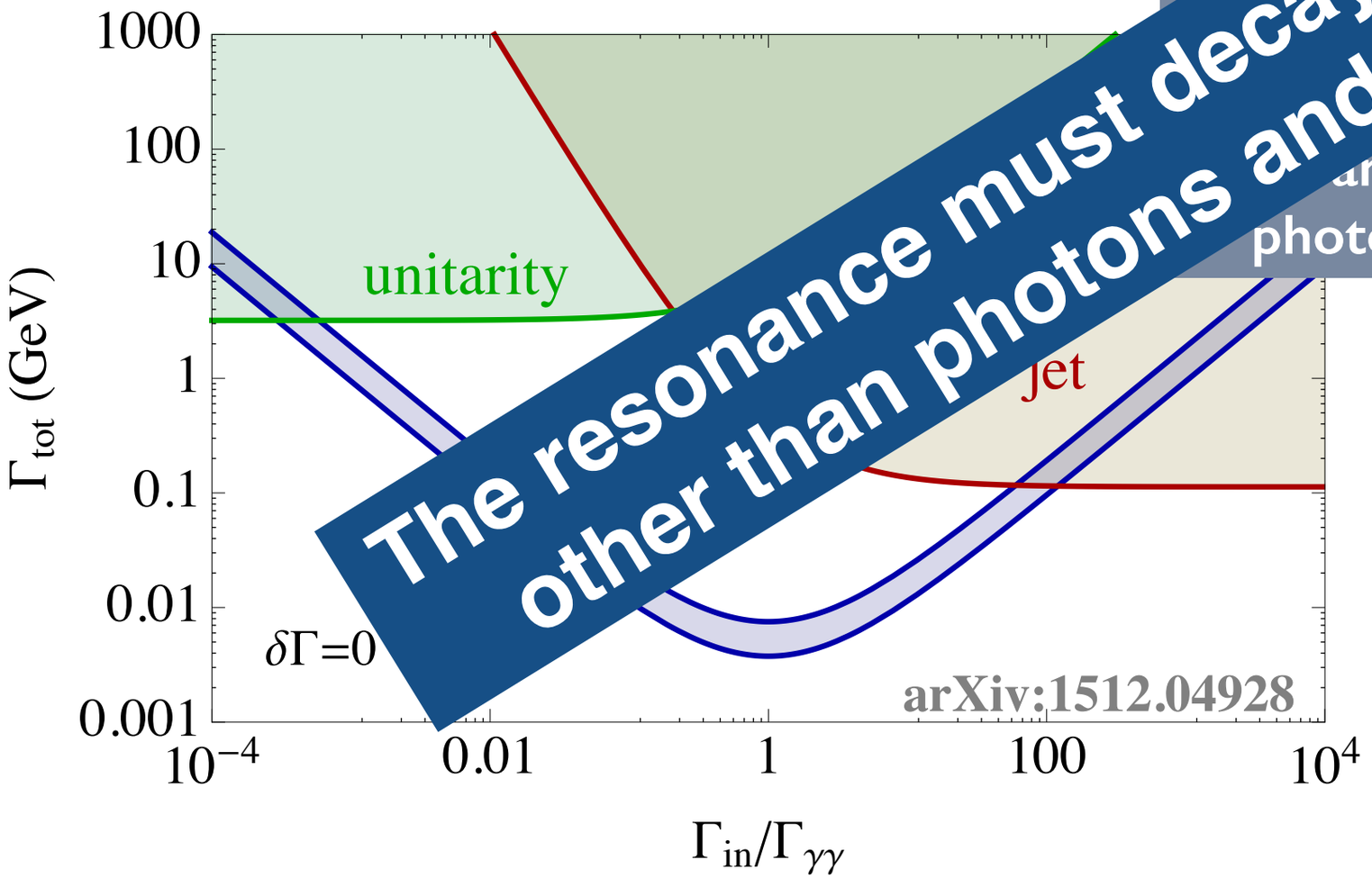
simil otons

get a width of V that is not ruled and fits the signal with photons and gluons only.

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



blue band fits the excess strength

What if spin 2 ?

Spin 2 particle interacting with the SM via the Energy momentum tensor

$$\mathcal{L}^{Y_2}_{\mathrm{V,f}} = -\frac{\kappa_{V,f}}{\Lambda} T^{V,f}_{\mu\nu} Y_2^{\mu\nu}$$

In tension with di-lepton searches

Graviton would have universal coupling to fermions and bosons

Need non universal couplings

Non universal couplings can lead to unitarity problems in amplitudes

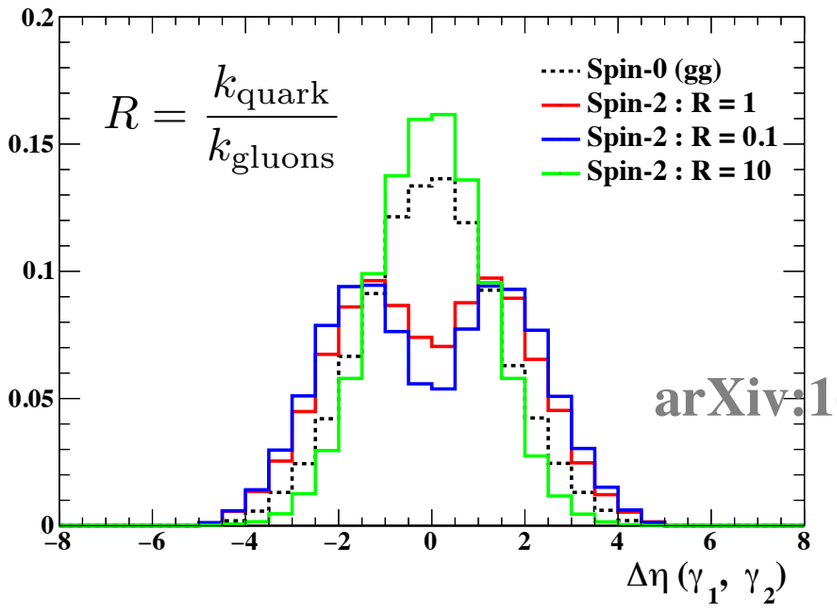
arXiv:1306.6464 arXiv:1605.09359

Non universal couplings need UV completions (e.g. warped scenario in RS)

arXiv:1603.06980

@ the LHC

We could distinguish spin-2 from spin-0 using angular distributions

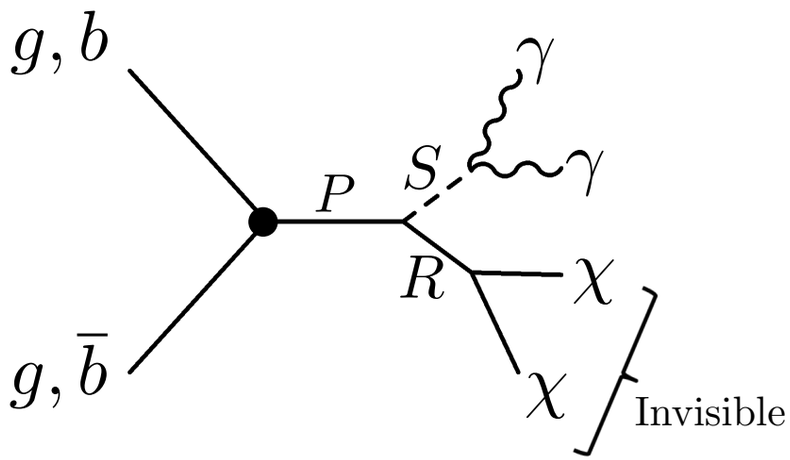


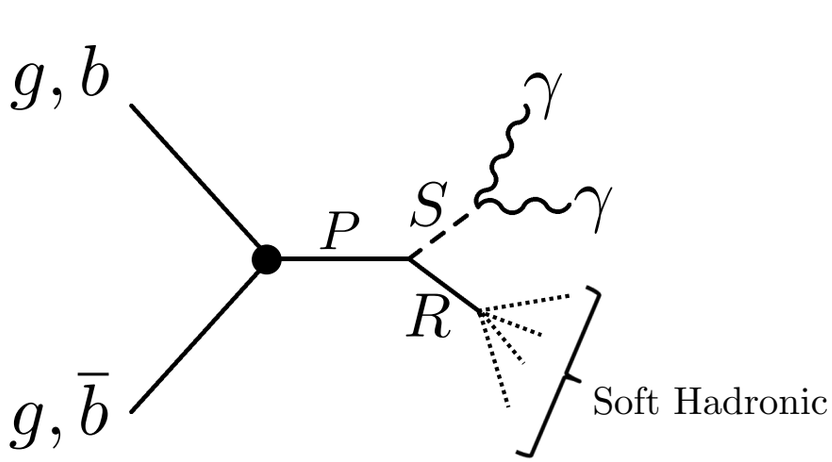
arXiv:1603.03421

Surely a resonance?

Parent resonance decaying into 750 GeV particle plus other stuff

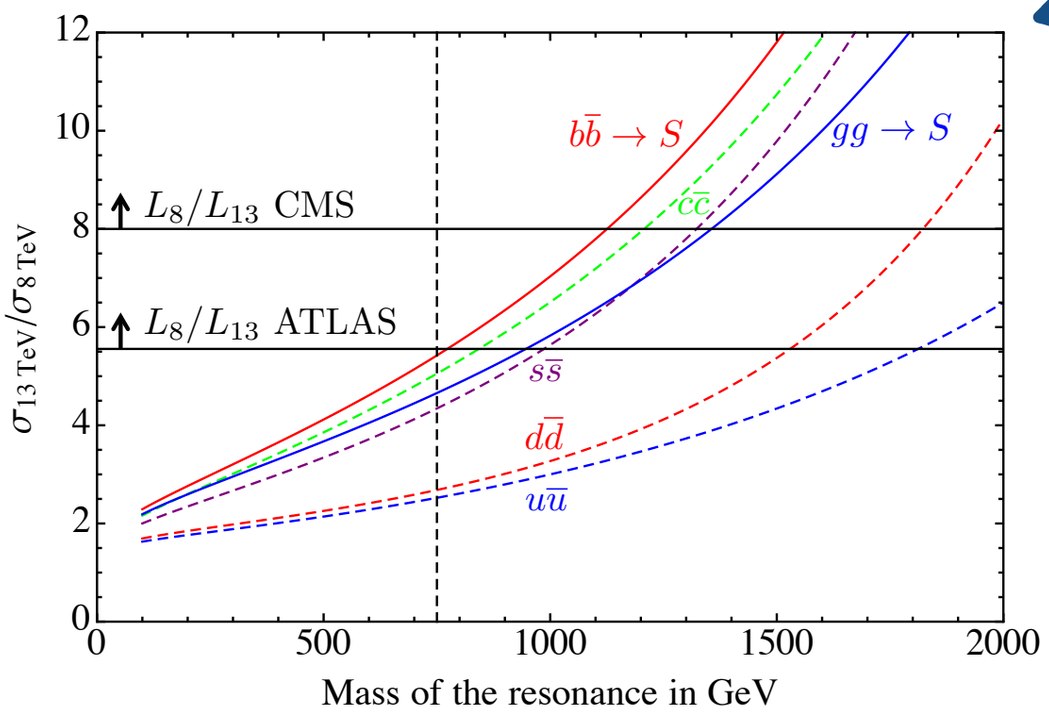
arXiv:1512.04933





This typically implies other objects in final state

Small mass splitting to hide other products



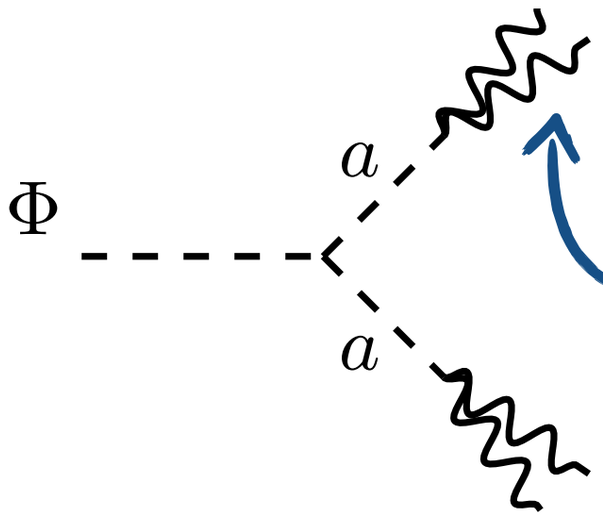
Stronger enhancement in signal rate from 8 to 13 TeV

Improve compatibility with 8 TeV data

Collimated photons

Resonance decay into light scalars, decaying into collimated photons

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



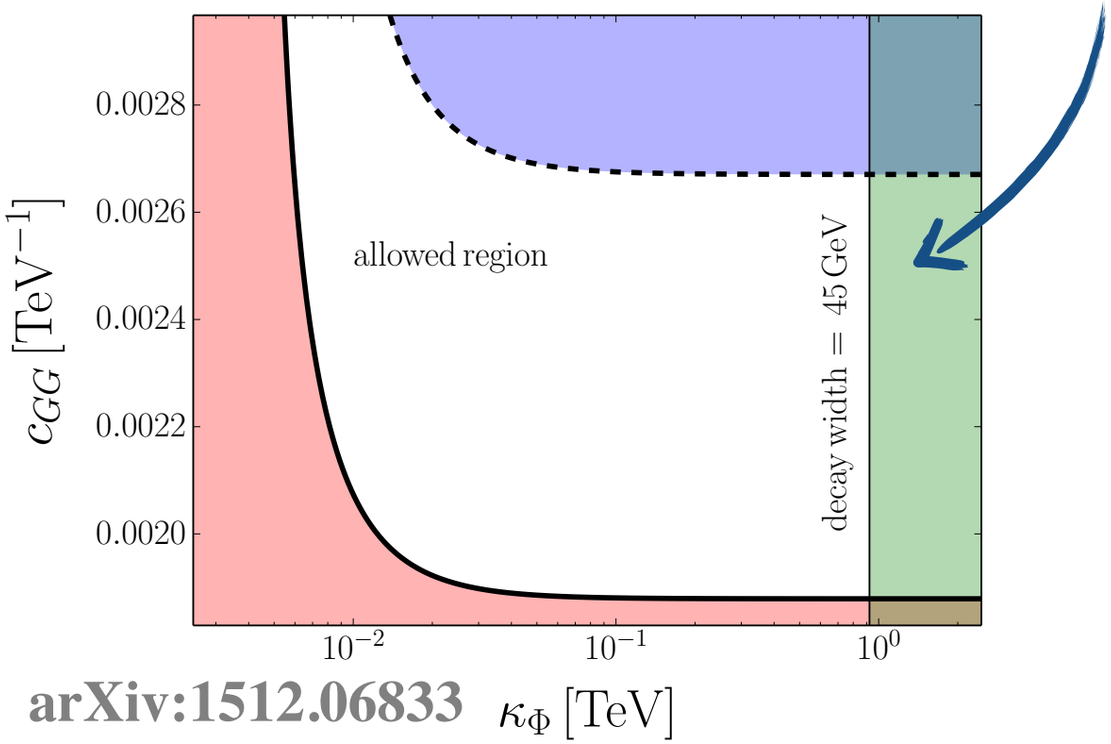
Collimated photons reconstructed as a single photon

a ***should be very light and boosted***

$m_a \lesssim 1GeV$

Tree level decay to light scalar

Width of resonance can be large



Decay of a can be displaced

arXiv:1512.06833

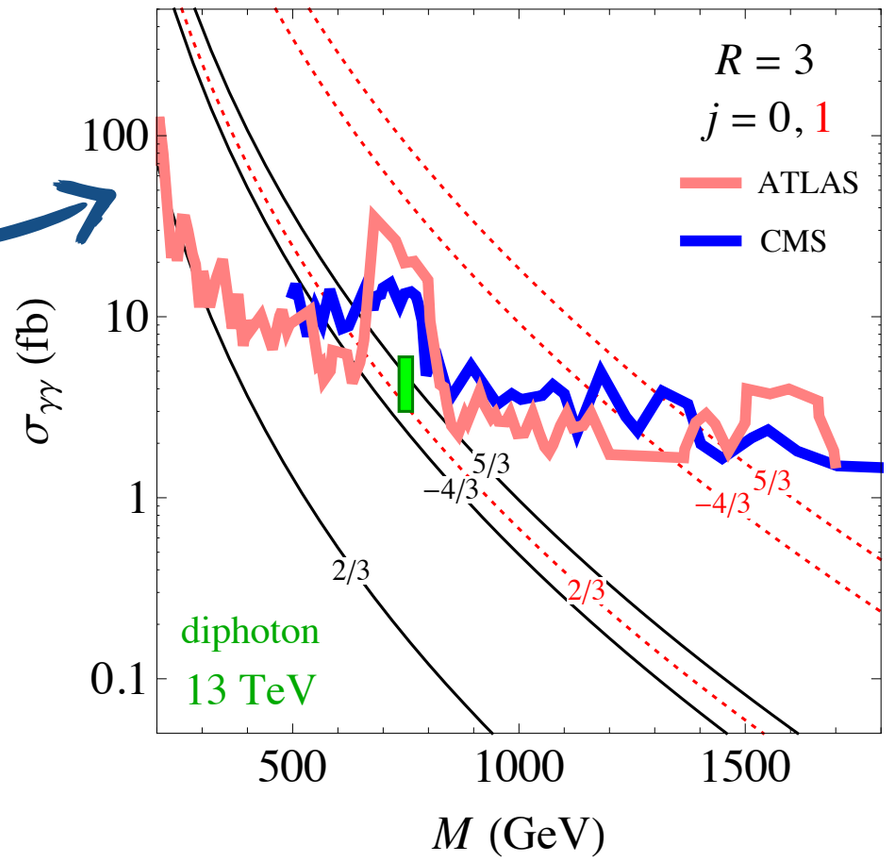
Elementary or not?

Could be a QCD bound state of new particles!

arXiv:1602.08819

E.g.: new scalar X of charge 2/3, 4/3, or 5/3

$$m_X \sim 375 \text{ GeV}$$



Simple case could fit the excess

$$j = 0\,, \quad R = \mathbf{3}\,, \quad Q = -\frac{4}{3}$$

LHC direct bounds on X can be easily escaped by introducing small decay into quarks

$$\mathcal{L} = -\frac{c_{ij}}{2}\,\epsilon_{\alpha\beta\gamma}\,X^{*\alpha}\,\overline{u}_i^{\beta}\,\overline{u}_j^{\gamma} + \text{h.c.},$$

Coupling should be small

Similar to stop in supersymmetry with RPV couplings

Break …

? What are the implications for BSM paradigms?

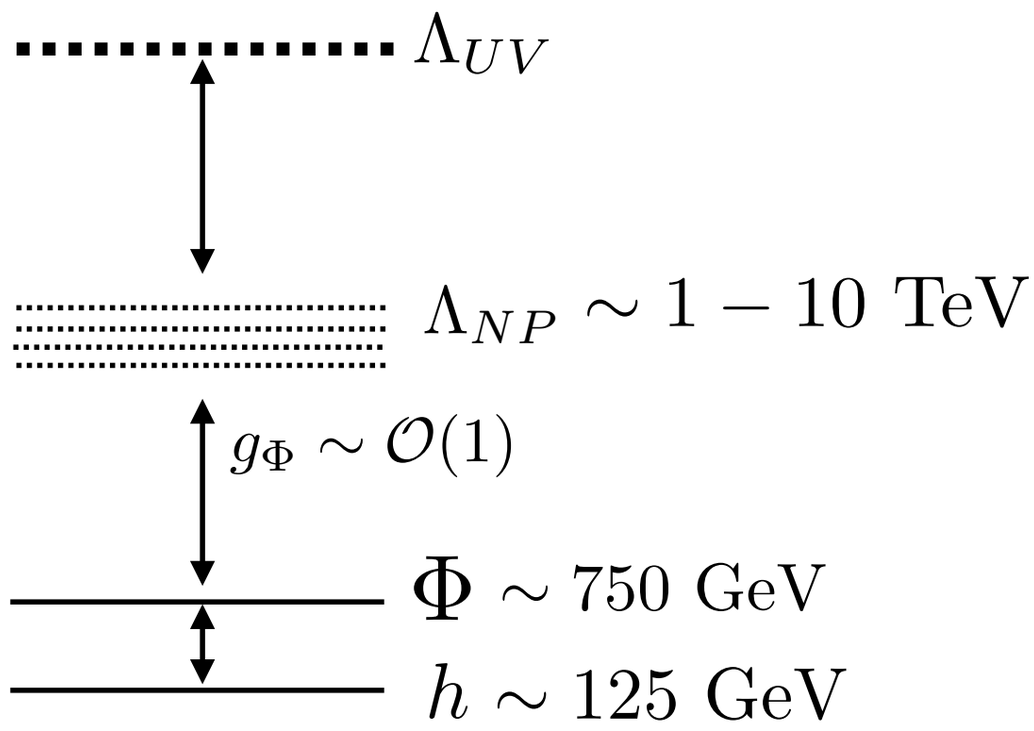
Another hierarchy problem?

Assume it is another fundamental scalar particle …

Why its mass is at 750 GeV ?

How its mass is stable under quantum corrections?

… it has couplings of order one with NP states to get sizable gauge boson couplings …



Little hierarchy problem

$$m_\Phi \sim \Lambda_{NP}$$

Hierarchy problem

$$m_\Phi \sim \Lambda_{UV}$$

The existence of another fundamental scalar makes even more challenging the hierarchy problems…

Another hierarchy problem?

Assume it is another scalar particle …

The existence of another scalar makes even more hard the hierarchy problems…

What about SUSY ???

What about Composite Models ???

Is it a Pseudo-Goldstone Boson ?

The heavier A/H state of MSSM?

Consider decoupling limit $\frac{v}{M_S} \ll 1$

CP-Odd and CP-Even with small mass splitting and coupling mainly to fermions

$m^2_{H^0} - m^2_{A^0} \sim v^2$

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

$$(\sigma \mathrm{BR})(pp \to H \to \gamma\gamma) \lesssim (0.01/0.06/0.14)\,\mathrm{fb}$$
$$(\sigma \mathrm{BR})(pp \to A \to \gamma\gamma) \lesssim (0.01/0.07/0.18)\,\mathrm{fb}$$
$$\xi_t = \frac{y'_t}{y_t} = 1, 3, 5$$

arXiv:1512.07616

Constraints from ttbar and tautau searches

Way out

- ***Add heavy vector like states to enhance gluon/photon couplings***
- ***Enhance decay in $\gamma\gamma$ with threshold effects, e.g. $m_{\tilde{t}} \sim m_A/2$***

arXiv:1605.01040

Goldstone of a symmetry

Why it is light?

Goldstone of a global symmetry η

1) Goldstone boson of a composite model responsible for the EW scale

+ Many Composite Higgs models have extra singlets emerging from cosets

+ Would related EWSB scale and new resonance mass in a unified picture!

- Difficult to embed in consistent model with fermion representations

2) Goldstone boson emerging from strong sector not related to EWSB

+ Easier to realize but still interesting phenomenology, e.g. Dark Matter

3) Goldstone boson of global symmetry in SUSY (R-axion)

Work in progress

+ Arise naturally in models with spontaneous/dynamical supersymmetry breaking

Strongly coupled models

η and H are PNGB of strongly coupled model

- ***Strongly coupled sector with SU(N) gauge group***
- ***Global Symmetry breaking SO(6)/SO(5)***

→ ***H + Extra singlet*** η

→ Strong scale and strong coupling

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

Mass of PNGB

From external dynamics

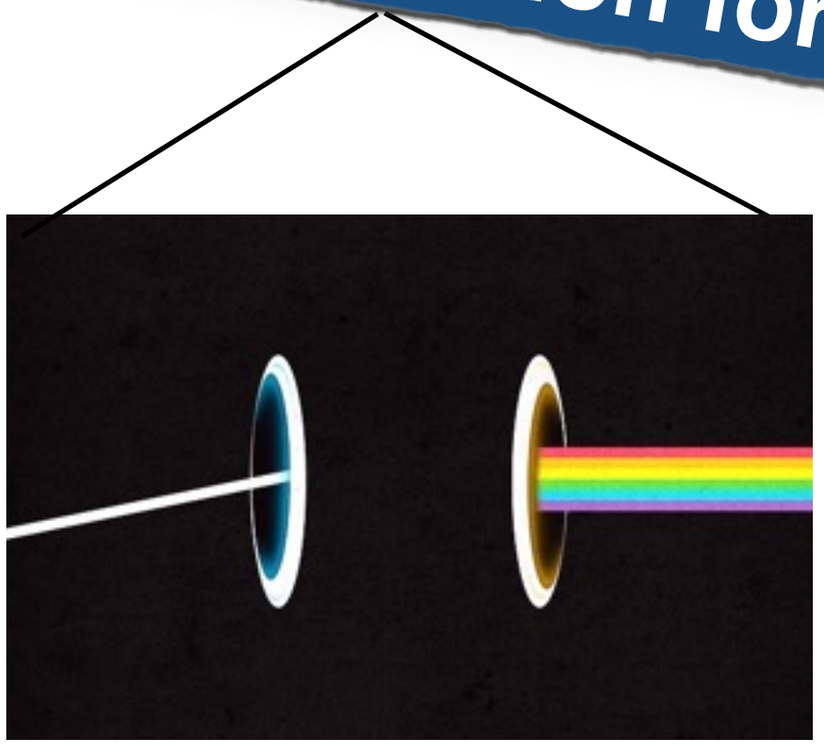
$$m_{PNGB} \sim m_h \times \frac{f}{v} \sim \frac{y_t}{4\pi} m_*$$

From internal dynamics

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

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

Maybe the 750 GeV resonance addresses another main motivation for BSM physics



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?

$t\bar{t}$

Degenerate states?

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??? Can it be a portal to Dark Matter ???

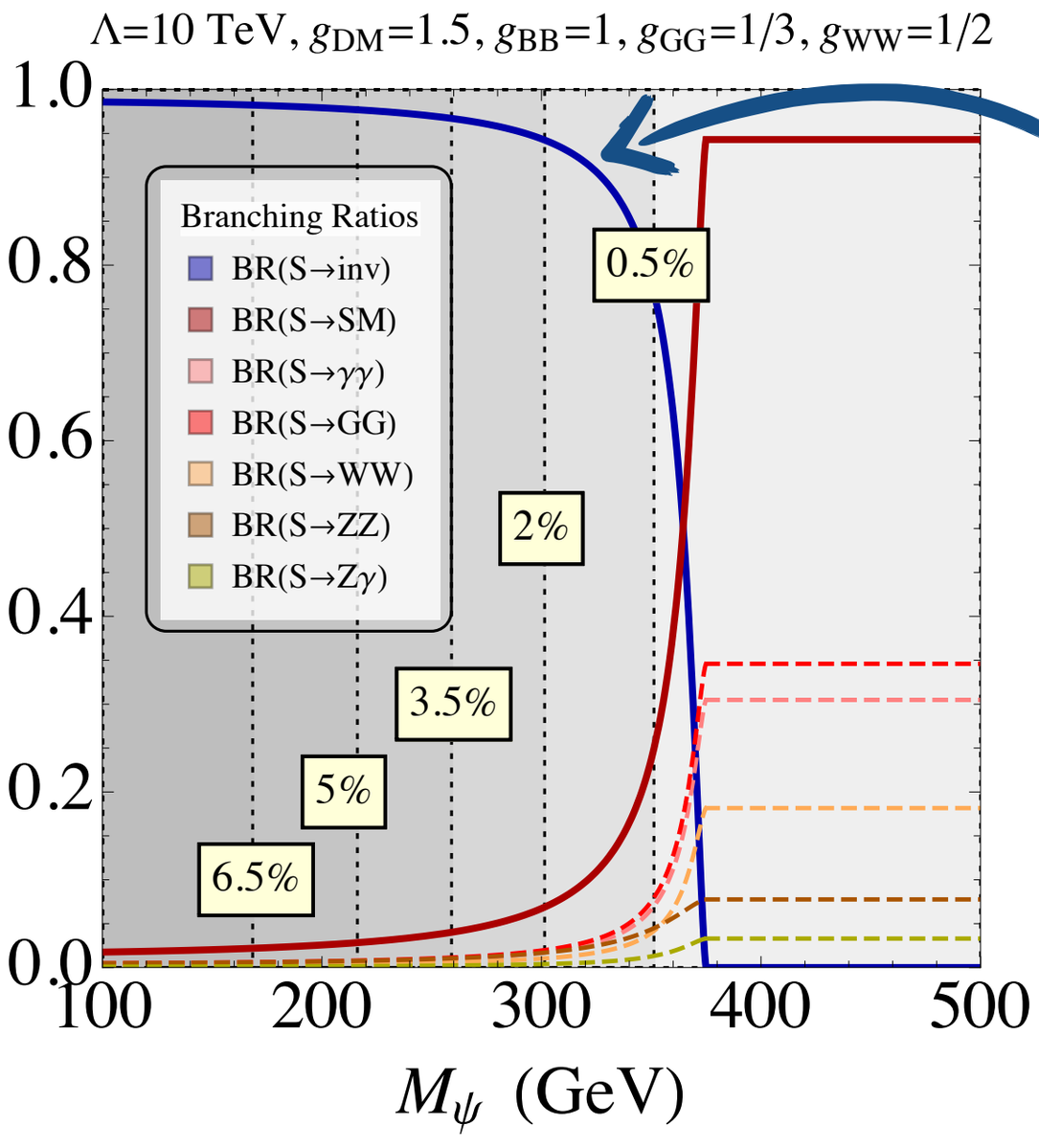
arXiv:1512.04917
M.Backovic, A.M., D.Redigolo

Large Width and DM

S new resonance

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

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



Most of the width generically comes from invisible decays

Large Width and DM

Signal strength

$$g_{GG}^2 g_{BB}^2$$

Relic density

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

Total width

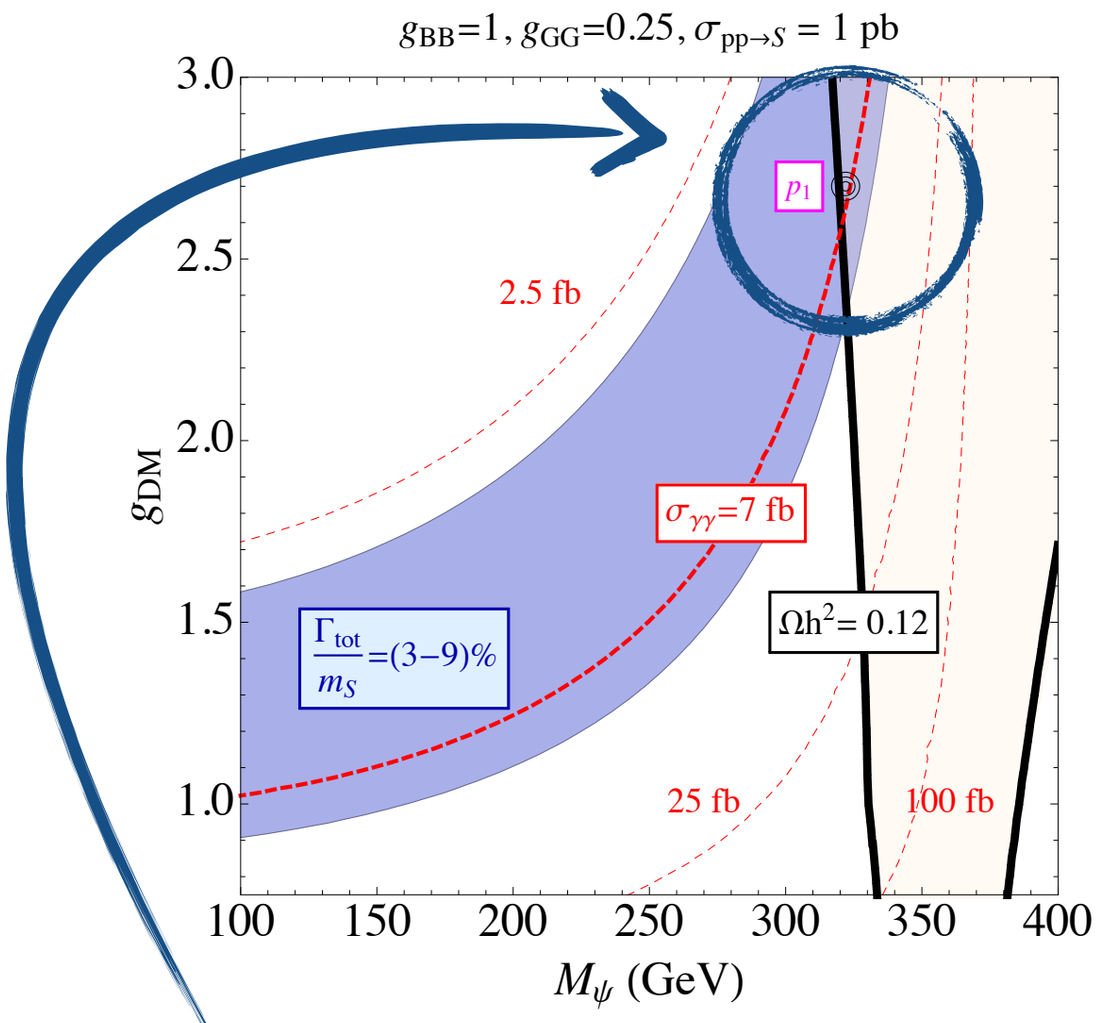
$$M_\psi, g_{DM}$$

Large Width and DM

Signal strength $g_{GG}^2 g_{BB}^2$

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

Total width M_ψ, g_{DM}



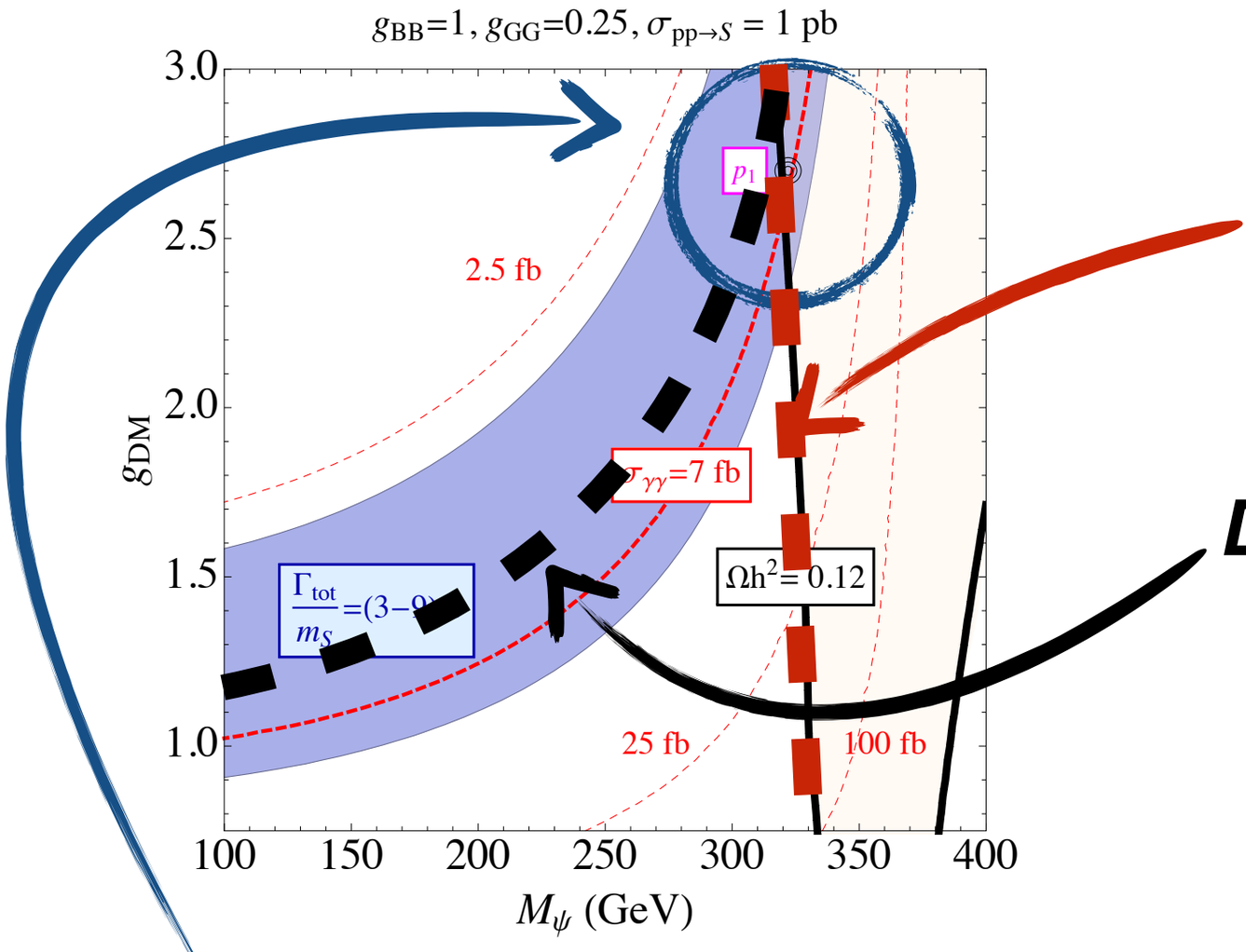
In fact, requiring $\Omega h^2 \sim 0.1$ and **the width essentially fixes the DM parameters!**

Large Width and DM

Signal strength $g_{GG}^2 g_{BB}^2$

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

Total width M_ψ, g_{DM}



Relic density Line

Decay Width of 6%

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

Large Width and DM

Signal strength

$$g_{GG}^2 g_{BB}^2$$

Relic density

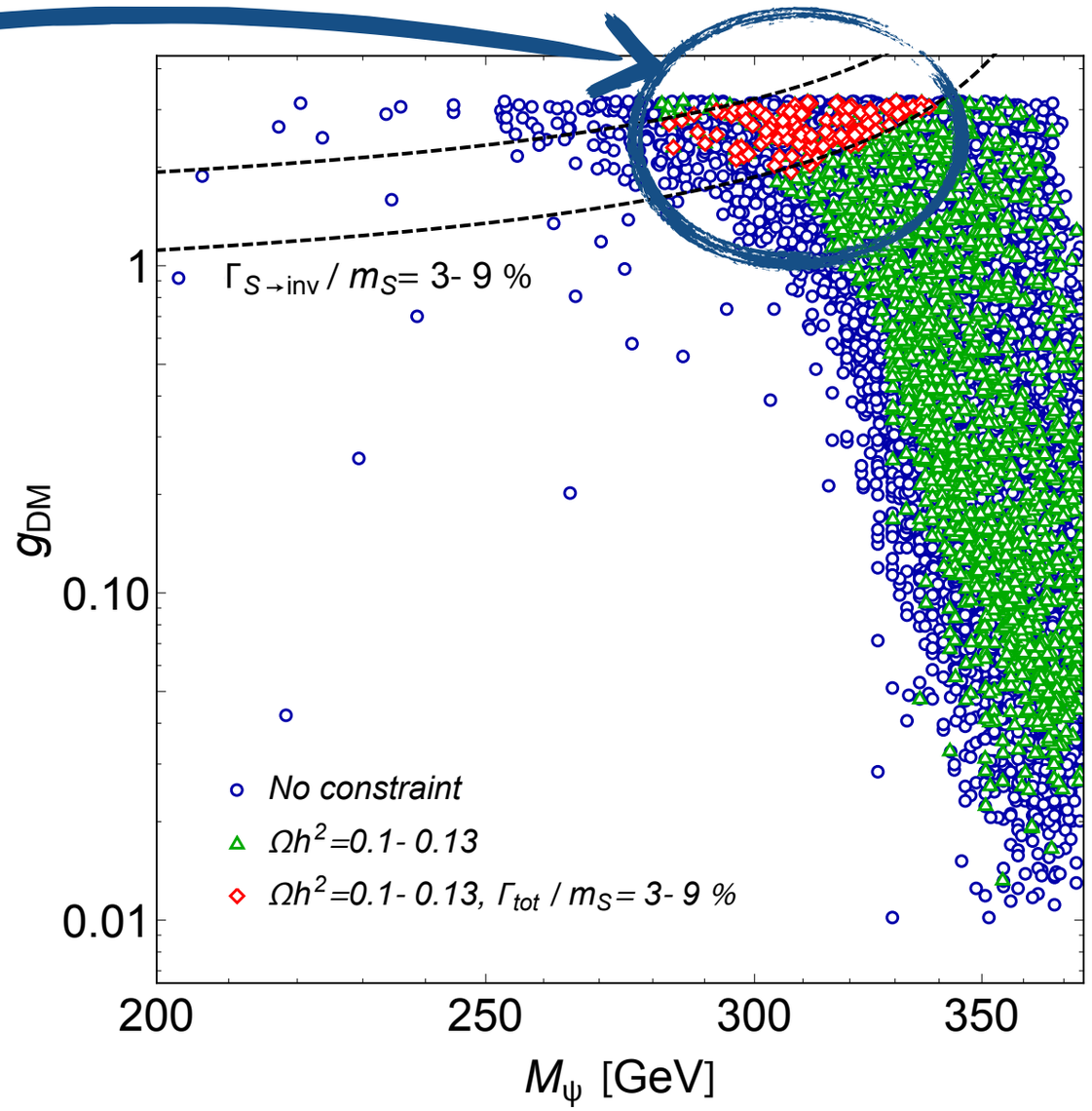
$$g_{BB}, g_{GG}, M_\psi, g_{DM}$$

Total width

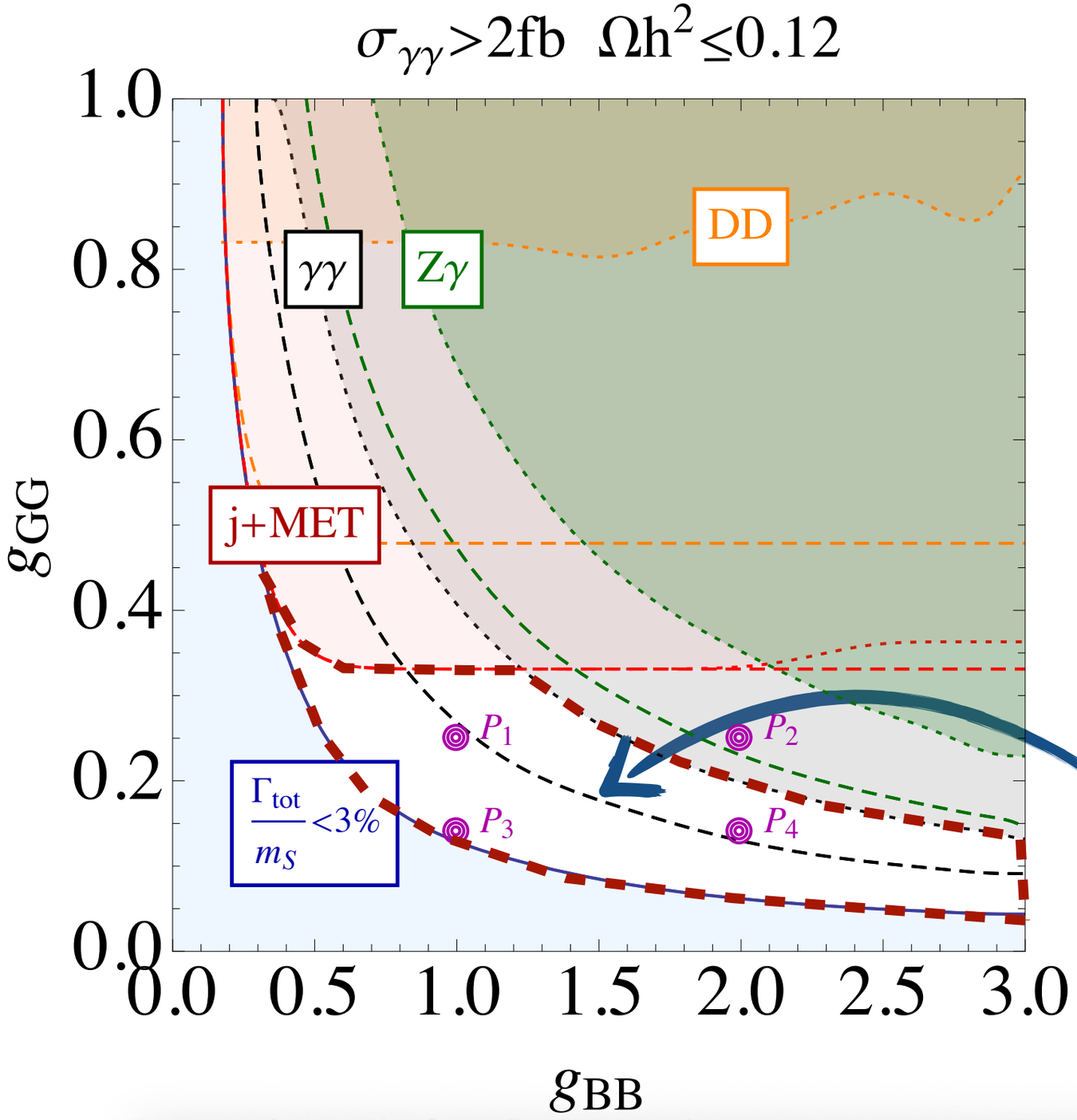
$$M_\psi, g_{DM}$$

$$g_{DM} \sim O(2)\,,\, m_{DM} \sim O(300)\mathrm{GeV}$$

Result is robust even changing couplings to gluons and photons



Compatibility with exp constraints



4-dimensional par. space projected onto ***gGG*** and ***gBB***

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

Allowed parameter space

We can fit the di-photon signal and feature a large width!

Large Width and DM

If the di-photon signal is indeed real…

… and the large width is confirmed …

… a possible consistent interpretation is a scalar mediator to dark matter with ~300 GeV DM mass and O(1) couplings …

This scenario is compatible with existing experimental constraints

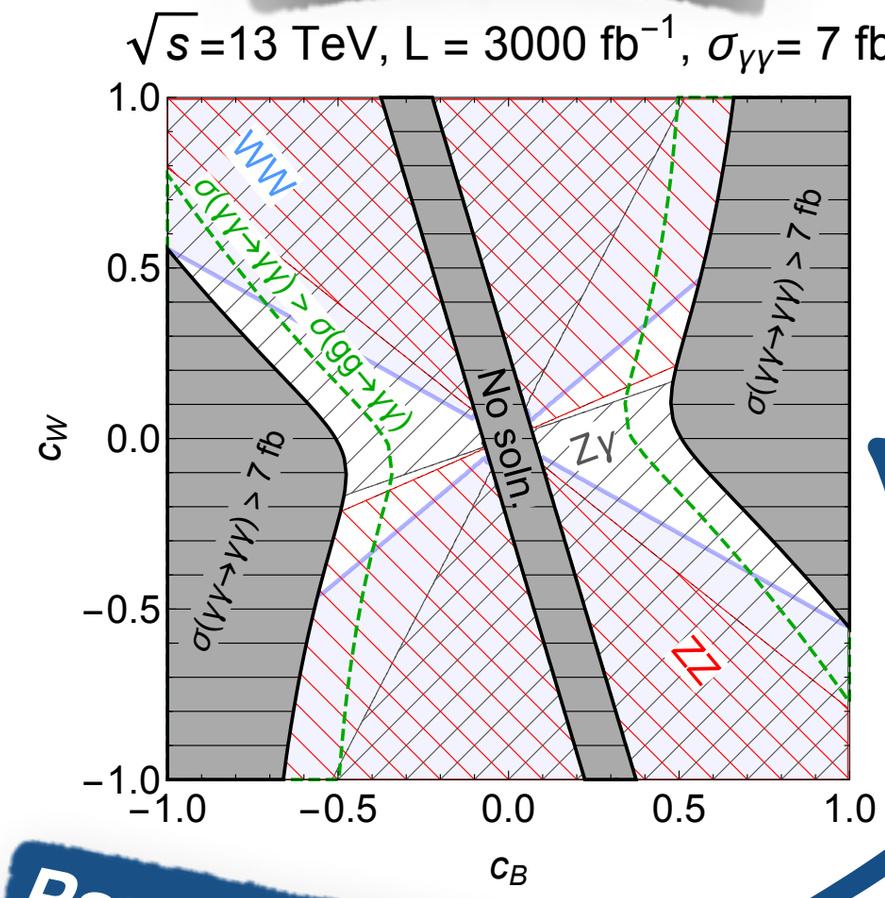
… signals correlated with such interpretation should appear in MET+j channel at LHC and in direct detection experiments …

Prospects for LHC13

arXiv:1605.07962

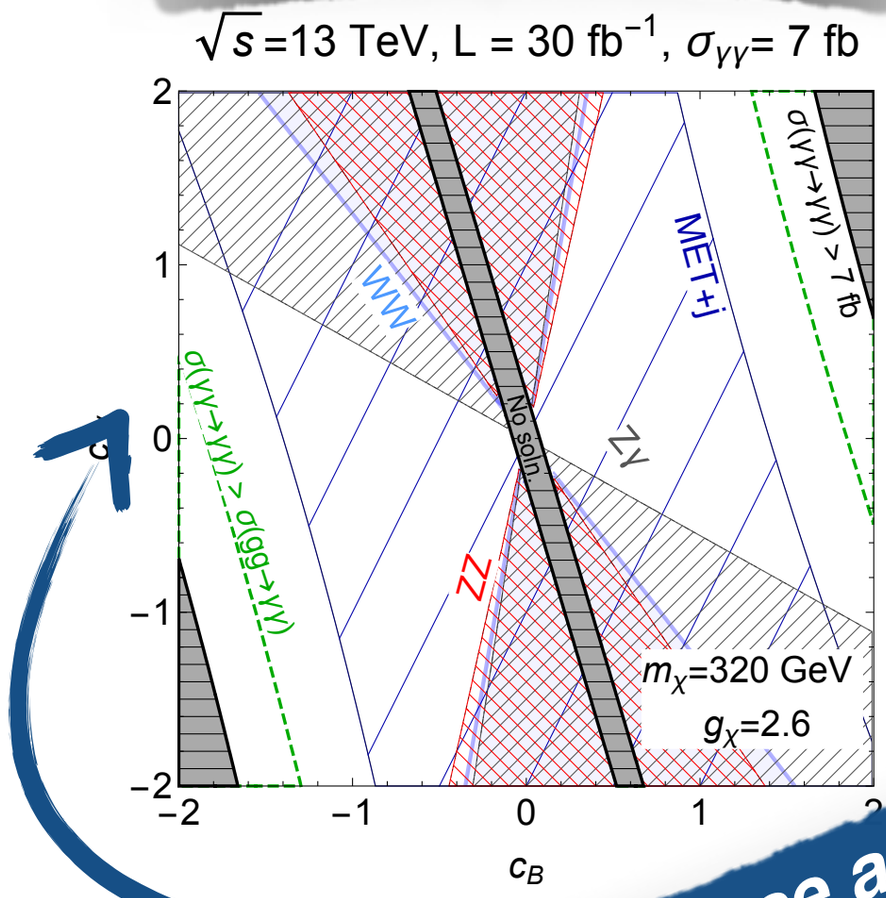
- ***Extrapolate existing bounds from LHC8 to LHC13***
- ***Explore parameter space imposing diphoton signal at 13 TeV***

Vanilla model



Parameter space covered with 3000 inverse fb

Dark matter model



Parameter space almost covered with 30 inverse fb

The End

- Di-Photon excess triggered a lot of activity (and hope …)
- Most explanations predict other NP around the corner
- Correlated signatures in EW gauge bosons
- Production mechanism could suggest vector like matter

@LHC

- Large width could be explained by invisible decay into DM

Dir.Det

Jet+MET

- If it is confirmed, and it's a scalar, we will have again

hierarchy problem to solve …

The End

Thanks for your attention!

… let's see what the new data will tell us …