Rays of light through the dark window

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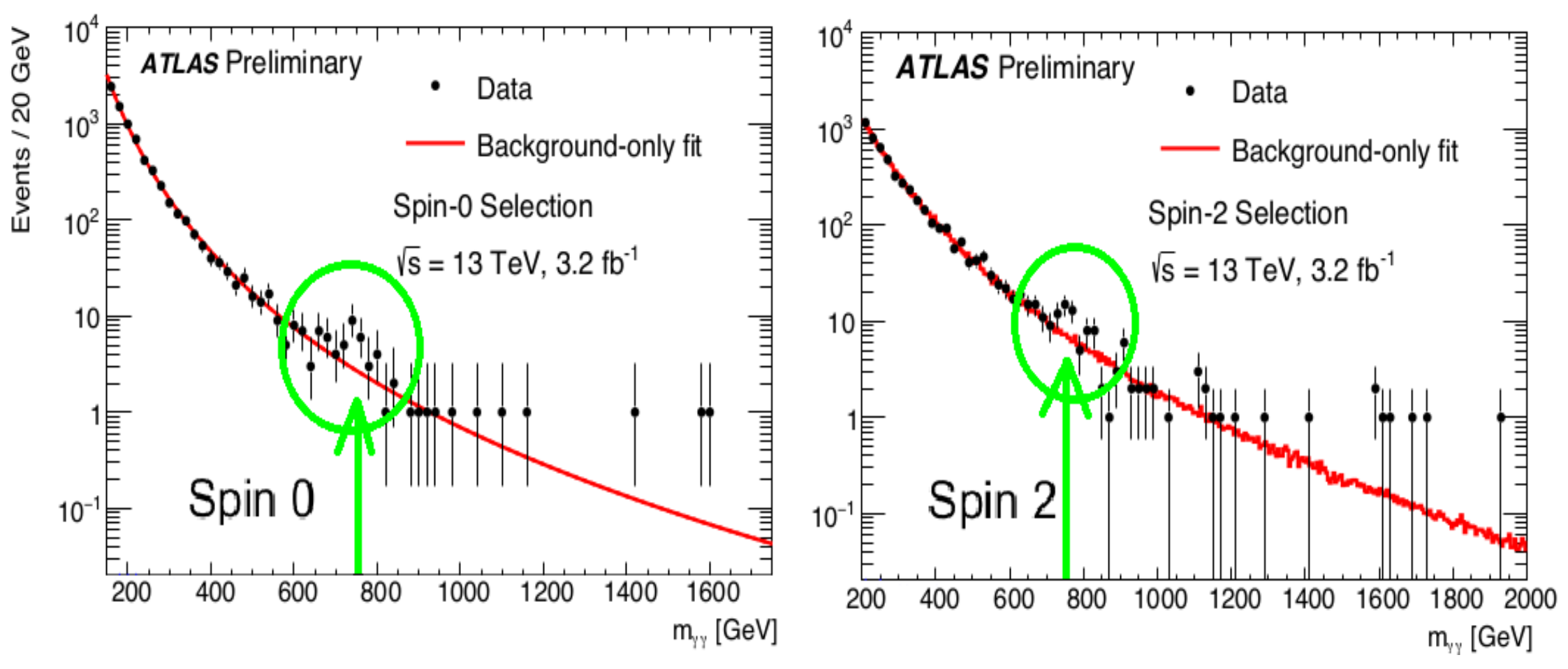
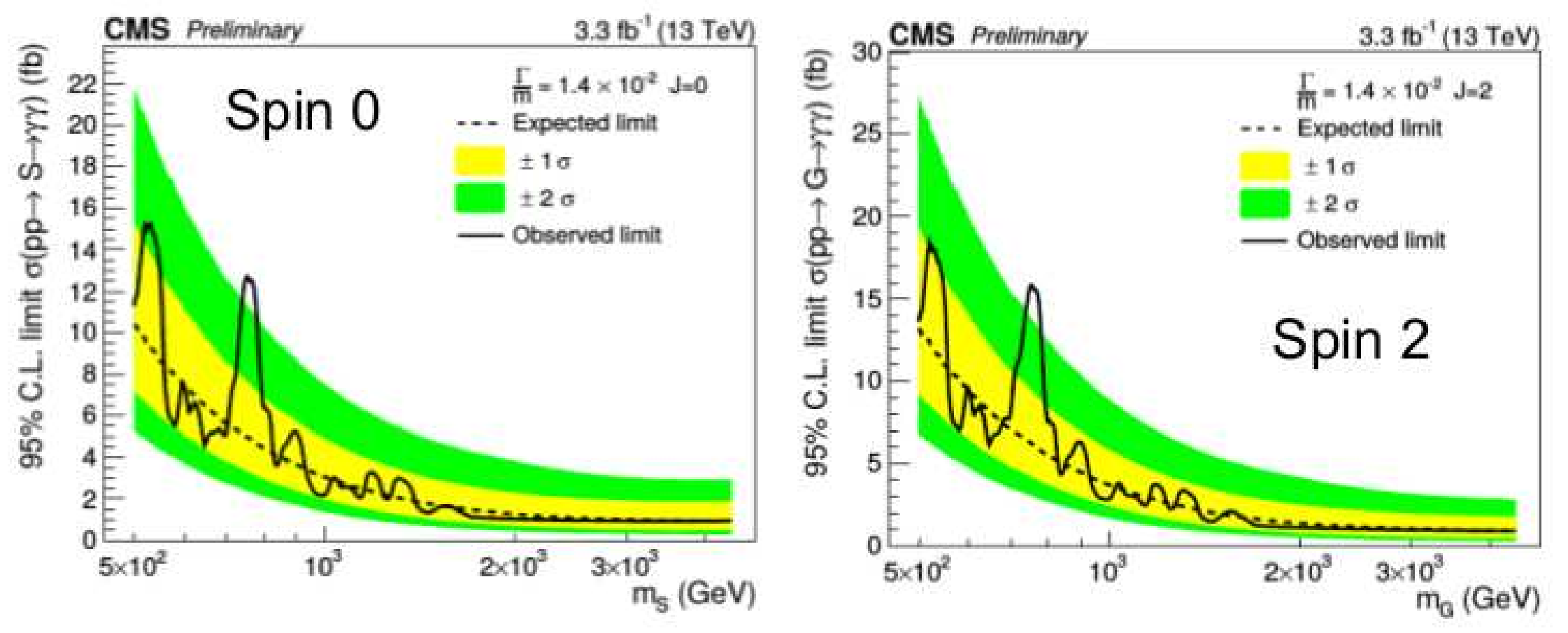
Latest from the LHC...

Run-II of the LHC has come up with a new surprise (December, 2015): An excess in the di-photon invariant mass distribution around 750 GeV. The excess is compatible with a spin-0 or a spin-2 resonance and can not be explained within the Standard Model (SM) framework.





☞ What we know about this resonance [1, 2]:

Information	ATLAS	CMS
E_{CM}, $\mathcal{L}$ (TeV, fb^{-1})	$13,\ 3.2$	$13,\ 3.3$
$\sigma(gg \to S/G \to \gamma\gamma)$ (fb)	10 ± 3	6 ± 3
Local significance	3.9σ	$2.8\sigma - 2.9\sigma$
Global significance	2.0σ	$< 1\sigma$
Largest significance for mass (GeV)	750	760
Largest significance for width/mass (%)	6.0	1.4
Estimated width (GeV)	45	10.64

♦ An insignificant hint was also observed during run-I with 8 TeV centre-of-mass energy.

☞ What we would like to know about this resonance:

♣ Why a stand-alone excess in $\gamma\gamma$ without any accompanying partners... e.g., excess in di-jets or in ZZ, $Z\gamma$ etc.

♣ What is the spin of this resonance: an answer is well envisaged with more data-set.

♣ What is the width of this resonance: The CMS run-II data prefers a moderate width ~ 10.6 GeV while run-I+II data-set hints a narrow width ~ 0.1 GeV.
ATLAS, on the other hand, votes for a width as large as 45 GeV.

♣ What can we expect from this excess, e.g., a zoo of new particles beyond the SM awaiting to be detected ?

♣ What is the *complete* underlying theory to explain this excess ?

Explaining the excess ....not quite complete

The ready-to-use *minimal effective* Lagrangian for a scalar resonance, s:

$$\underbrace{\frac{c_{BB}}{\Lambda} s B^{\mu\nu} B_{\mu\nu} + \frac{c_{GG}}{\Lambda} s G^{\mu\nu}_{\alpha} G^{\alpha}_{\mu\nu},}_{\text{effective couplings between the resonance and the SM gauge fields}}$$

☞ Information about the new physics, e.g., new scalars/fermions beyond the SM that can generate this excess through higher order effects, are encapsulated within c_{BB}, c_{GG} couplings.

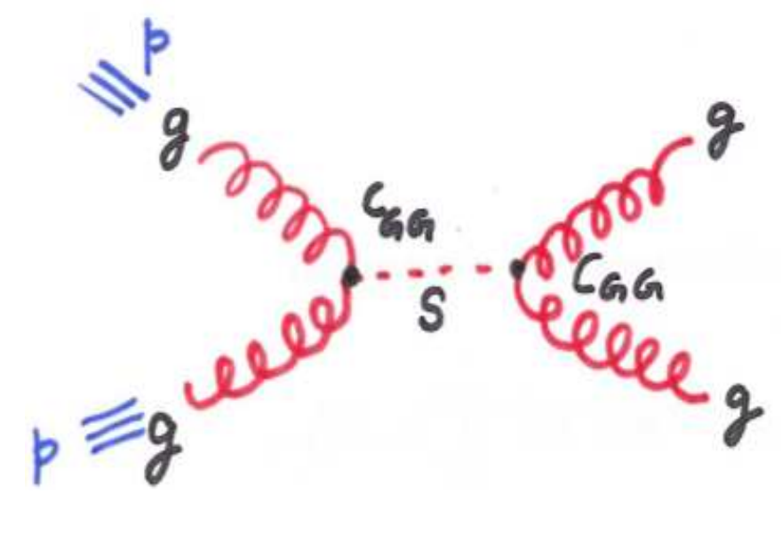
The trivial success:.....

♦ This effective Lagrangian can explain the excess, e.g., the observed $\sigma(pp \to s \to \gamma\gamma)$ and the width Γ_s with free parameters c_{BB}, c_{GG} and a suitable new physics scale Λ.

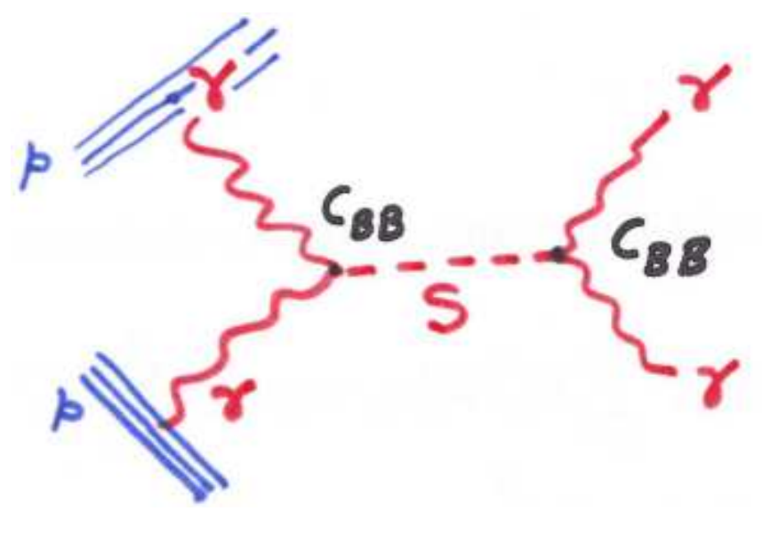
♦ Certain specific choices of c_{BB}, c_{GG} values can justify the observed production cross-section, $\sigma(pp(gg) \to s \to \gamma\gamma)$ and possibly the large decay width, $\Gamma_s \sim 45$ GeV.

The trivial and not-so trivial issues:.....

▼ Large $c_{GG} \gtrsim 0.1$ values are constrained from di-jet searches, $gg \to s \to gg$. Similarly, $c_{BB} \gtrsim 0.1$ values are constrained from photon fusion process, $\gamma\gamma \to s \to \gamma\gamma$.



Di-jet production

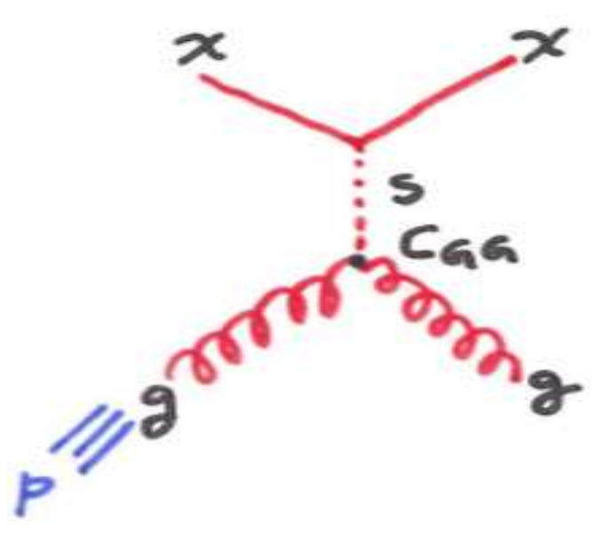


Di-photon from photon fusion

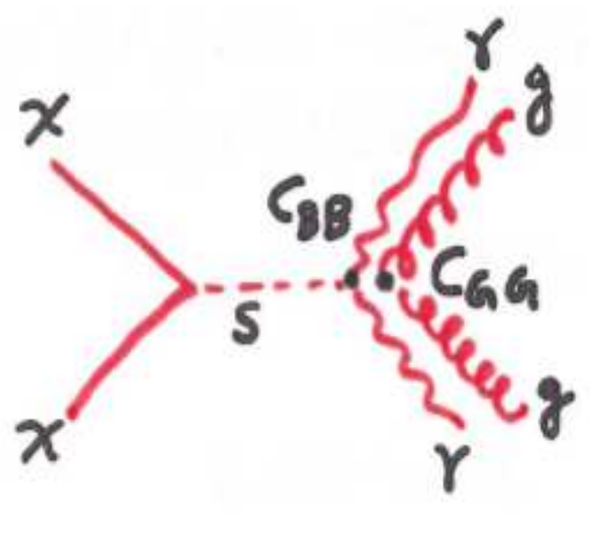
▲ An apparent solution is to use small c_{GG}, c_{BB} to efface the constraints of di-jet searches and photon fusion process, yet to reproduce the observed $\sigma(pp(gg) \to s \to \gamma\gamma)$.

▲ The price of using small c_{GG}, c_{BB} values, i.e., a small Γ_s, can be compensated by adding extra, e.g., invisible decay mode for the resonance.

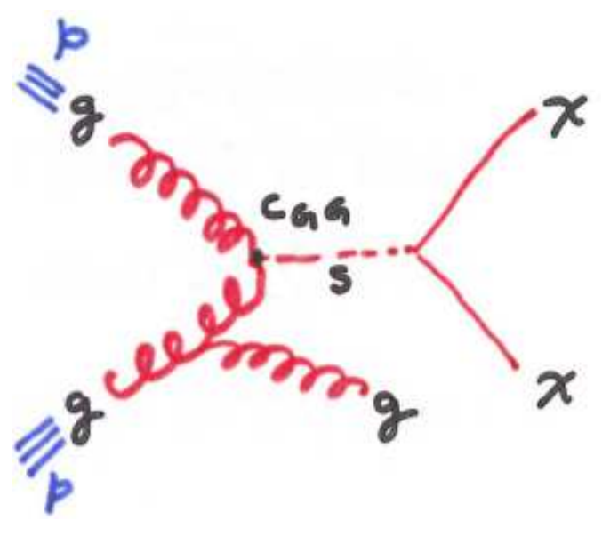
▼ Unfortunately, a large invisible decay width would indicate sizable couplings between the resonance and the invisible particles, e.g., dark matter which are constrained from different dark matter searches:



Direct



Indirect



Collider

▼ Dark matter mass $m_\chi \lesssim 375$ GeV, with sizable $s\chi\chi$ coupling, is excluded in the absence of $pp \to s \to \chi\chi \to$ large missing transverse energy signal.

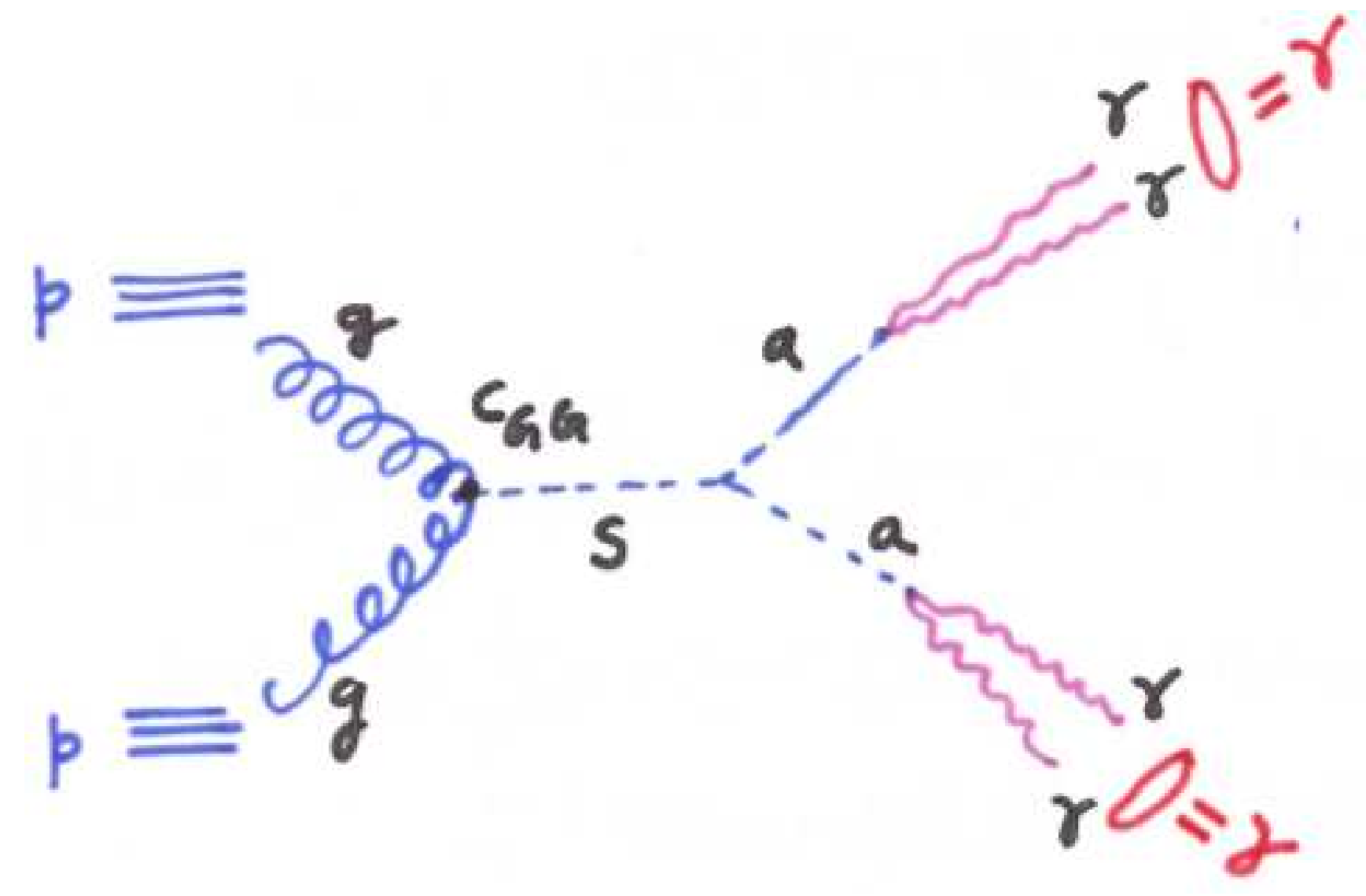
▼ $375\ \mathrm{GeV} \lesssim m_\chi \lesssim 1$ TeV is in tension with dark matter searches.

■ Di-photon excess is incompatible with dark matter ?

An elegant proposal: Illuminating the darkness with collimated photon pairs

☞ Waking up with an idea [3]...

★ How about producing two pairs of collimated photons from a pair of *light* pseudoscalars, a, produced from $s \to aa$ process.



Di-photon excess through collimated photons

Relevant part of the *chosen* Lagrangian:

$$\overbrace{\mu_\Phi^2 |\Phi|^2 - \lambda_\Phi |\Phi|^4 - g_\chi \Phi \bar{\chi}\chi}^{U(1)\ \text{invariant}}$$

$$\underbrace{+\frac{\epsilon_\Phi^2}{2}\Phi^2 - \sum_{X=B,G^a} \frac{c_{XX}}{\Lambda} \Phi X^{\mu\nu}(X_{\mu\nu} + i\widetilde{X}_{\mu\nu})}_{\text{explicitly breaks U(1)}} + \text{ h.c.}$$

☞ What do we learn from this Lagrangian...

● The Lagrangian contains both $U(1)$ preserving and $U(1)$ violating terms. The latter is needed to promote a to a pseudo-Goldstone boson after spontaneous breaking of the associated $U(1)$.

● After spontaneous breaking of the $U(1)$ symmetry, one gets $\Phi = (v_\Phi + s + ia)/\sqrt{2}$ and hence, mass of the scalar resonance $m_s = \sqrt{2\lambda_\Phi} v_\Phi$, mass of the pseudo-Goldstone $m_a = \sqrt{2}\epsilon_\Phi$, dark matter mass $m_\chi = \sqrt{2} g_\chi v_\Phi$. We consider $\Lambda = v_\Phi$ in this study.

● The chosen Lagrangian contains five independent free *relevant* parameters, c_{BB}, c_{GG}, λ_Φ, m_a, m_χ.

● Using the information of measured Γ_s, m_s and $\sigma(pp \to s \to \gamma\gamma) \Longrightarrow$ *only two* free parameters left.

☞ What do we need ?

★ A light pseudo-Goldstone a such that the separation between the pair of *boosted and collimated* daughter photons, $\Delta\Phi \sim 4m_a/m_s < 1.15°$, resolution of the LHC detector.

★ The pseudo-Goldstone a decaying before the electromagnetic calorimeter (ECAL), i.e., decay length $\lesssim 1$ m.

★ Need $m_a \lesssim 2$ GeV with $m_a|_{min} \gtrsim 200$ MeV, estimated from other constraints.

☞ The sparkling advantages....

★ Di-photon signal primarily through $s \to aa \to 4\gamma$, independent of c_{BB} for $m_a \lesssim 500$ MeV, needed for experimentally viable collimated photon pairs.

★ Main decay mode of the resonance s, i.e., $s \to aa$ is sensitive to λ_Φ and independent of c_{GG}. Thus, with large λ_Φ, large Γ_s appears naturally without violating di-jet bound.

★ Sizable production cross-section with branching ratio $s \to aa \sim 1$, independent of c_{GG}.

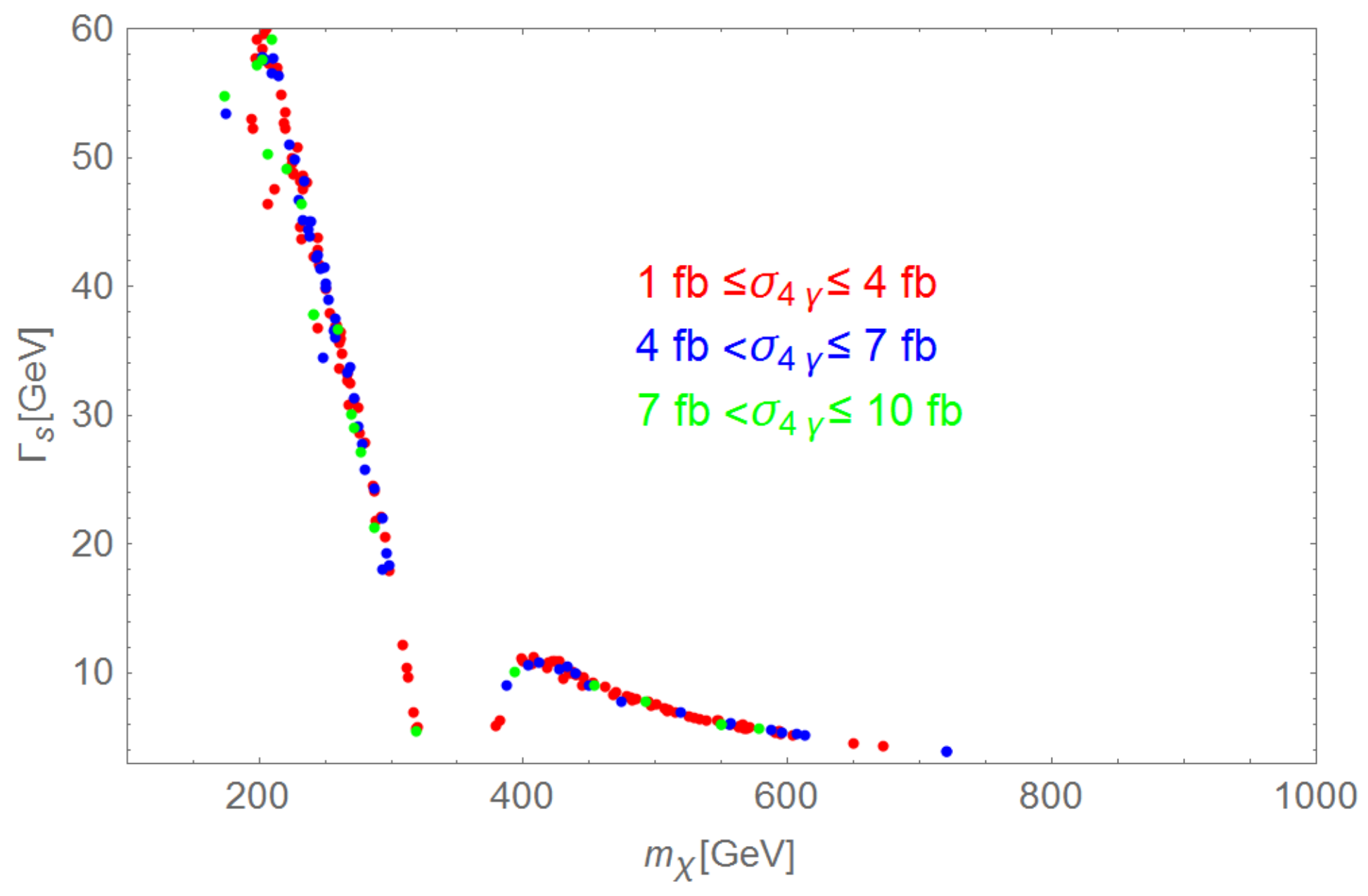
★ Smaller values of the associated c_{GG}, c_{BB} couplings also ameliorate constraints from dark matter searches.

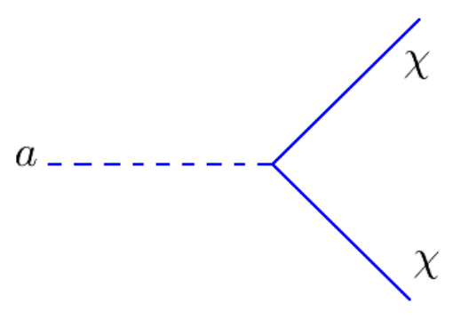
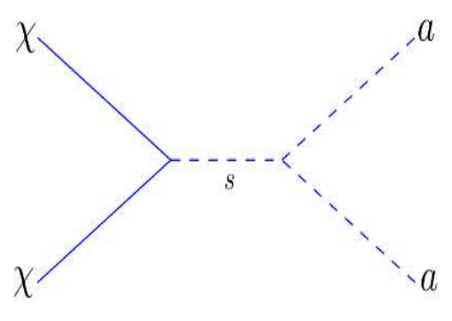
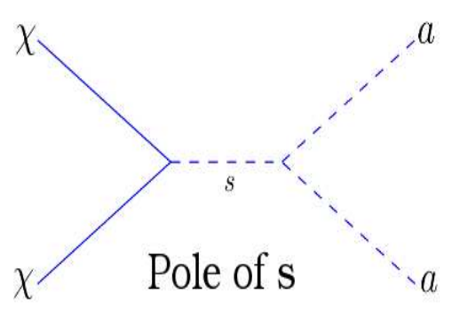
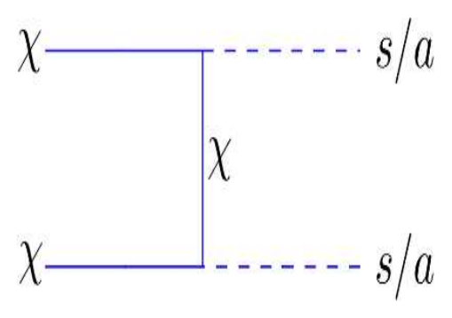
★ Dark matter mass in the span of 200 GeV to 1 TeV as well as keV dark matter can co-exist with the observed di-photon excess.

★ The width of the resonance can change depending on the scale of dark matter mass.

The results in a nutshell...

★ Summary plot representing points in the (m_χ, Γ_s) plane that simultaneously respect the LHC and cosmological constraints and correspond to different di-photon production cross-sections.



Dark Matter mass m_χ (GeV)	$\sigma(pp \to s \to \gamma\gamma)$ (fb) width Γ_s (GeV), $\Omega_\chi h^2$	Correct relic density via	How to produce χ
$\gtrsim 10^{-6}$	$1 - 10,\ \lesssim 7.5,\ 0.12$		Freeze-in
$200 - 300$	$1 - 10,$ $12 - 60,\ 0.12$		Freeze-out
$300 - 400$	$1 - 10,$ $4 - 12,\ 0.12$	 Pole of s	Freeze-out
> 400	$1 - 10,\ \lesssim 12,\ 0.12$		Freeze-out

Final words

★ The studied framework can accommodate the observed resonance with correct production cross-section and a width in the span of a few GeV to 50 GeV.

★ A correct relic density for the dark matter is also possible for 200 GeV $\lesssim m_\chi \lesssim 1$ TeV as well as $m_\chi \sim$ keV.

★ The required values of c_{BB}, c_{GG} couplings are consistent with the LHC constraints and dark matter searches.

★ $\chi\chi \to sa$ annihilation process gives a characteristic gamma-ray box signal that can be proved by the Cherenkov Telescope Array (CTA).

References

[1] **ATLAS-CONF-2015-081; ATLAS-CONF-2016-018**.

[2] **CMS-PAS-EXO-15-004; CMS-PAS-EXO-16-018**.

[3] **Re-opening dark matter windows compatible with a diphoton excess. arXiv:1603.05601 [hep-ph].**
Giorgio Arcadi, Pradipta Ghosh, Yann Mambrini, Mathias Pierre.