The 750 GeV Diphoton Excess and Its Possible Connection to Dark Matter

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Based on Bi, Xiang, Yin, ZHY, arXiv:1512.06787

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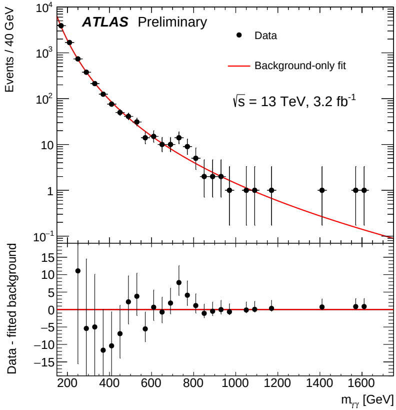
750 GeV Diphoton Excess at the 13 TeV LHC

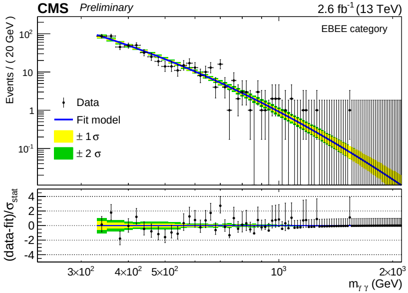
Local (global) significance: ATLAS 3.9σ (2.3σ), CMS 2.6σ (1.2σ)

Signal cross section: $\sigma_{\gamma\gamma} \sim 10$ fb

ATLAS data favor a resonance ϕ with $m_\phi \sim 750$ GeV and $\Gamma_\phi \sim 45$ GeV



[ATLAS-CONF-2015-081]



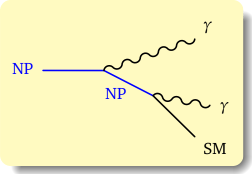
[CMS-PAS-EXO-15-004]

Decay topologies

From a resonance?

[Knapen *et al.*, 1512.04928]

Decay topologies



↑ No

From a resonance?

NP for New Physics. SM for Standard Model. [Knapen *et al.*, 1512.04928]

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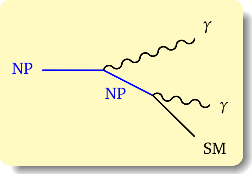

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From a resonance? $\xrightarrow{\text{Yes}}$ **Cascade decay?**

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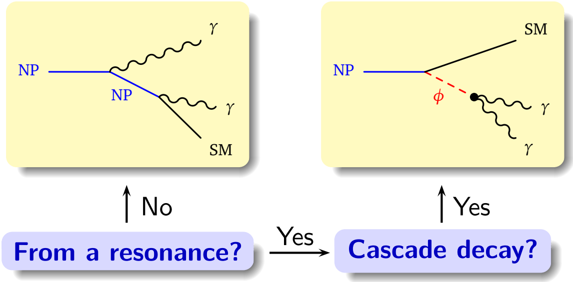

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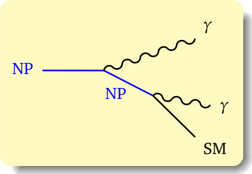

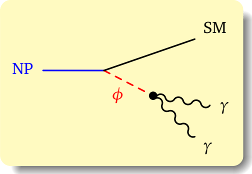

No ↑ **From a resonance?** — Yes → **Cascade decay?** (Yes ↑) — No → **Collimated photons?**

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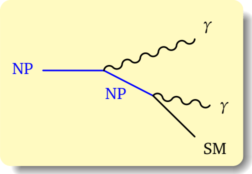

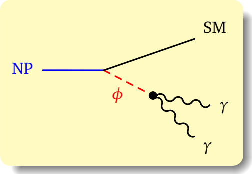

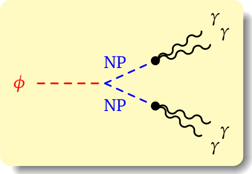

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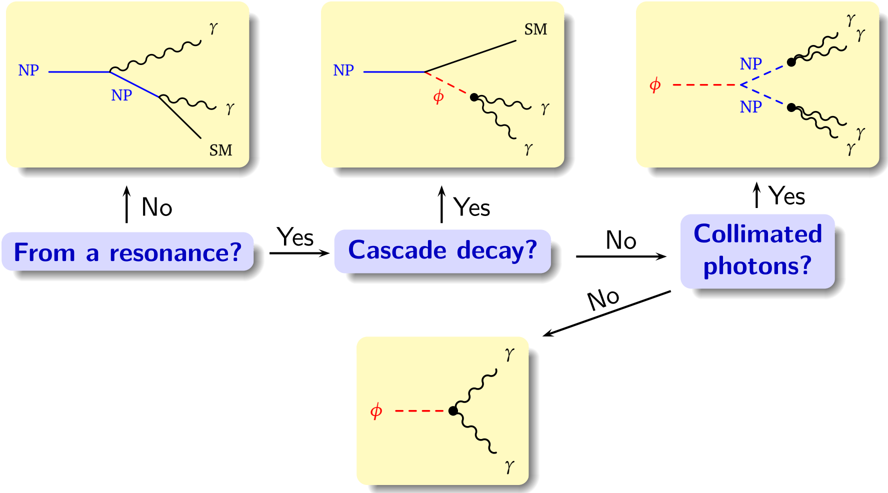

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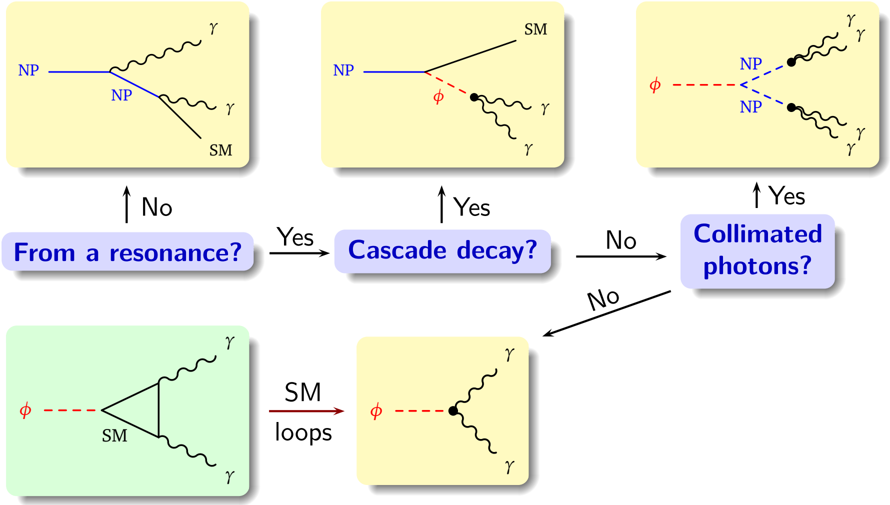

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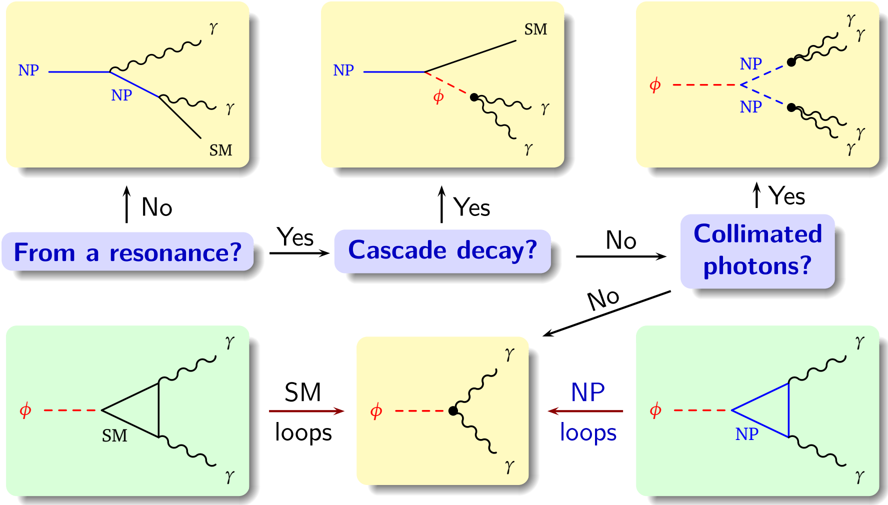

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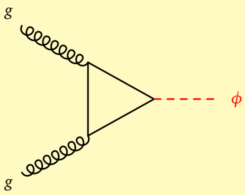
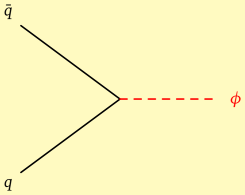
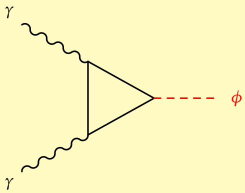
Resonance production at the LHC



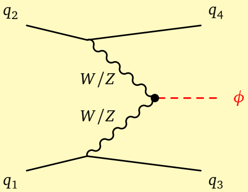
Gluon-gluon fusion



$q\bar{q}$ annihilation



Photon-photon fusion



Vector boson fusion

Effective interactions

According to the **Landau-Yang theorem**, a diphoton resonance should be either a spin-0 or spin-2 particle

Effective interactions between **a spin-0 resonance ϕ** and SM gauge bosons:

- **CP-even ϕ**

$$\mathcal{L}_{0^+} = \frac{1}{\Lambda}\phi(k_1 B_{\mu\nu}B^{\mu\nu} + k_2 W^a_{\mu\nu}W^{a\mu\nu} + k_3 G^a_{\mu\nu}G^{a\mu\nu})$$

- **CP-odd ϕ**

$$\mathcal{L}_{0^-} = \frac{1}{\Lambda}\phi(k_1 B_{\mu\nu}\tilde{B}^{\mu\nu} + k_2 W^a_{\mu\nu}\tilde{W}^{a\mu\nu} + k_3 G^a_{\mu\nu}\tilde{G}^{a\mu\nu})$$

In terms of physical states,

$$\mathcal{L}_{0^+} \supset \frac{1}{\Lambda}\phi(k_{\mathrm{AA}} A_{\mu\nu}A^{\mu\nu} + k_{\mathrm{AZ}} A_{\mu\nu}Z^{\mu\nu} + k_{\mathrm{ZZ}} Z_{\mu\nu}Z^{\mu\nu})$$

$$\mathcal{L}_{0^-} \supset \frac{1}{\Lambda}\phi(k_{\mathrm{AA}} A_{\mu\nu}\tilde{A}^{\mu\nu} + k_{\mathrm{AZ}} A_{\mu\nu}\tilde{Z}^{\mu\nu} + k_{\mathrm{ZZ}} Z_{\mu\nu}\tilde{Z}^{\mu\nu})$$

with $k_{\mathrm{AA}} \equiv k_1 c_W^2 + k_2 s_W^2$, $k_{\mathrm{AZ}} \equiv 2 s_W c_W (k_2 - k_1)$, $k_{\mathrm{ZZ}} \equiv k_1 s_W^2 + k_2 c_W^2$

Decay widths:

$$\Gamma(\phi \to \gamma\gamma) = \frac{k_{\rm AA}^2 m_\phi^3}{4\pi\Lambda^2} = 3.4\ \text{MeV}\left(\frac{k_{\rm AA}}{0.01}\right)^2 \left(\frac{\Lambda}{1\ \text{TeV}}\right)^{-2} \left(\frac{m_\phi}{750\ \text{GeV}}\right)^3$$

$$\Gamma(\phi \to gg) = \frac{2k_3^2 m_\phi^3}{\pi\Lambda^2} = 27\ \text{MeV}\left(\frac{k_3}{0.01}\right)^2 \left(\frac{\Lambda}{1\ \text{TeV}}\right)^{-2} \left(\frac{m_\phi}{750\ \text{GeV}}\right)^3$$

$$\Gamma(\phi \to ZZ) \simeq \frac{k_{\rm ZZ}^2 m_\phi^3}{4\pi\Lambda^2}, \quad \Gamma(\phi \to \gamma Z) \simeq \frac{k_{\rm AZ}^2 m_\phi^3}{8\pi\Lambda^2}, \quad \Gamma(\phi \to W^+W^-) \simeq \frac{k_2^2 m_\phi^3}{2\pi\Lambda^2}$$

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95% CL upper limits from 8 TeV LHC resonance searches

$$\sigma_{pp\to\phi} \text{Br}(\phi \to \gamma\gamma) < \begin{cases} 1.5\ \text{fb for } \Gamma_\phi = 0.1\ \text{GeV} \\ 2.4\ \text{fb for } \Gamma_\phi = 75\ \text{GeV} \end{cases}$$

$$\sigma_{pp\to\phi} \text{Br}(\phi \to \gamma Z) < 4\ \text{fb}, \quad \sigma_{pp\to\phi} \text{Br}(\phi \to ZZ) < 12\ \text{fb}$$

$$\sigma_{pp\to\phi} \text{Br}(\phi \to W^+W^-) < 40\ \text{fb}, \quad \sigma_{pp\to\phi} \text{Br}(\phi \to jj) < 2.5\ \text{pb}$$

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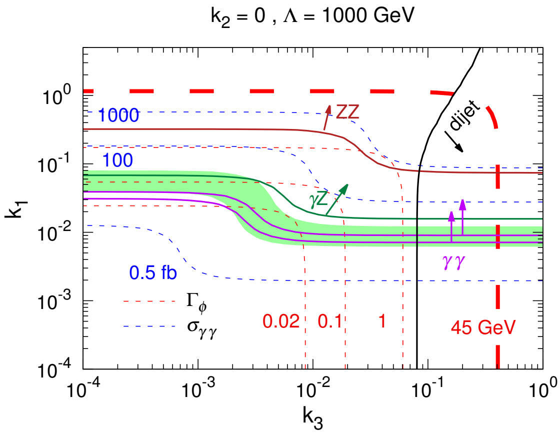
Production cross section $\sigma_{pp\to\phi}$ via gg **fusion** and $\gamma\gamma$ **fusion** can be calculated by `MadGraph` using `NNPDF2.3` **with QED corrections**

$\sigma_{\gamma\gamma} \equiv \sigma_{pp\to\phi} \mathrm{Br}(\phi \to \gamma\gamma)$ and Γ_ϕ (assuming $k_2 = 0$)

Only consider ϕ decays into SM gauge bosons

Green band corresponds to favored $\sigma_{\gamma\gamma} = 5 - 20$ fb at $\sqrt{s} = 13$ TeV

Solid lines denote the bounds from LHC resonance searches at $\sqrt{s} = 8$ TeV



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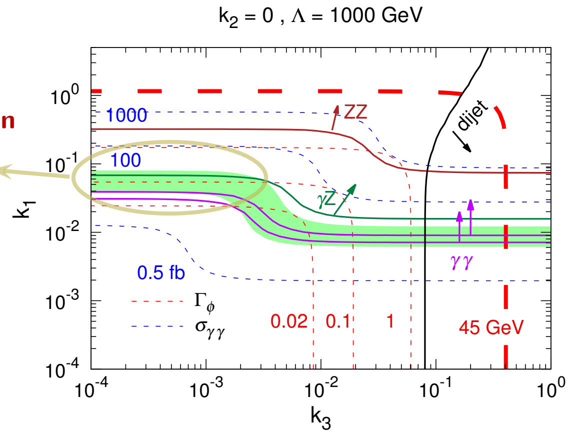
$\gamma\gamma$ fusion dominated

Incompatible with the **diphoton bound** from 8 TeV LHC data



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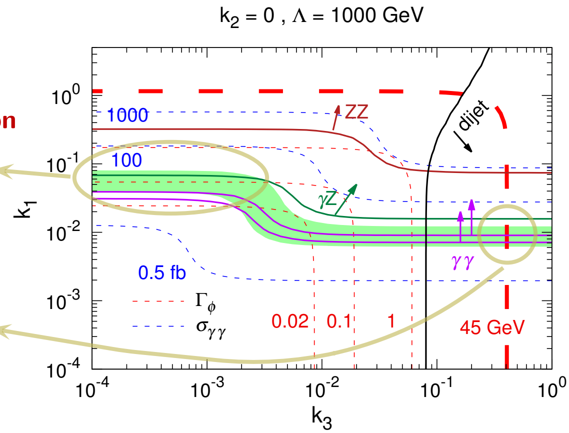
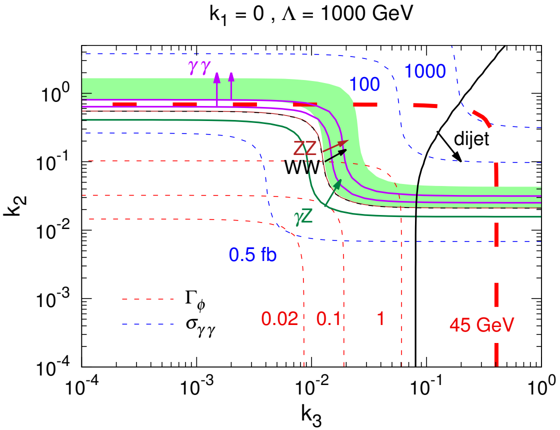
Favored $\sigma_{\gamma\gamma}$ and Γ_ϕ

Excluded by the **dijet bound** from 8 TeV LHC data



$\sigma_{\gamma\gamma} \equiv \sigma_{pp\to\phi} \mathrm{Br}(\phi \to \gamma\gamma)$ and Γ_ϕ (assuming $k_1 = 0$)



In the case of $k_1 = 0$, the $\phi\gamma\gamma$ coupling is relatively weak, because it solely comes from the coupling to the $SU(2)_L$ gauge fields

$\Rightarrow$ **The favored region is excluded by the 8 TeV bounds**

Invisible channel $\phi \to \chi\chi$

Invisible decay channel into dark matter $\phi \to \chi\chi \quad \Rightarrow \quad$ increase Γ_ϕ

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Constraint from **monojet $+ \not{E}_{\mathrm{T}}$ searches** at the 8 TeV LHC:

$$\sigma_{pp\to\phi}\mathrm{Br}(\phi \to \chi\chi) < 0.39\ \mathrm{pb}$$ [derived from ATLAS 1502.01518]

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$$\Gamma_\phi = \Gamma_{\text{visible}} + \Gamma(\phi \to \chi\chi)$$

$\Downarrow$

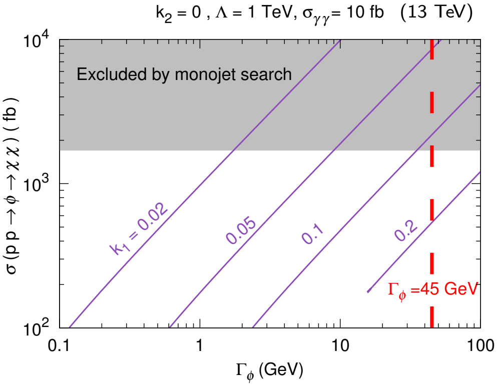
A broad resonance favors a large invisible width

$\Downarrow$

In the case of $k_2 = 0$, for fixed k_1 we adjust k_3 to make $\sigma_{\gamma\gamma} = 10$ fb at $\sqrt{s} = 13$ TeV

$\Downarrow$

$$k_1 \gtrsim 0.1 \text{ for } \Gamma_\phi = 45 \text{ GeV}$$



ϕ-portal dark matter simplified models

We assume the following simplified models for the interactions between ϕ and the dark matter (DM) particle χ

- **Model M1:** CP-even scalar ϕ, Majorana fermion χ

$$\mathcal{L}_{\mathrm{M1}} = \mathcal{L}_{0^+} + \frac{1}{2} m_\phi \phi^2 + \frac{1}{2} m_\chi \bar{\chi}\chi + \frac{1}{2} g_\chi \phi \bar{\chi}\chi$$

- **Model M2:** CP-odd scalar ϕ, Majorana fermion χ

$$\mathcal{L}_{\mathrm{M2}} = \mathcal{L}_{0^-} + \frac{1}{2} m_\phi \phi^2 + \frac{1}{2} m_\chi \bar{\chi}\chi + \frac{1}{2} g_\chi \phi \bar{\chi} i\gamma_5 \chi$$

- **Model S:** CP-even scalar ϕ, real scalar χ

$$\mathcal{L}_{\mathrm{S}} = \mathcal{L}_{0^+} + \frac{1}{2} m_\phi \phi^2 + \frac{1}{2} m_\chi \chi^2 + \frac{1}{2} g_\chi \phi \chi^2$$

- **Model V:** CP-even scalar ϕ, real vector χ

$$\mathcal{L}_{\mathrm{V}} = \mathcal{L}_{0^+} + \frac{1}{2} m_\phi \phi^2 + \frac{1}{2} m_\chi \chi^\mu \chi_\mu + \frac{1}{2} g_\chi \phi \chi^\mu \chi_\mu$$

Parameter scan

We fix $\Lambda = 1$ TeV and carry out a random parameter scan for every simplified model within the following ranges:

$0 < k_1 < 0.1, \quad -0.1 < k_2 < 0.1, \quad 0 < k_3 < 0.1, \quad 10\ \mathrm{GeV} < m_\chi < 10\ \mathrm{TeV}$

$0 < g_\chi < 10$ (Models M1 and M2), $\quad 10\ \mathrm{GeV} < g_\chi < 10\ \mathrm{TeV}$ (Models S and V)

Require $\sigma_{\gamma\gamma} = 5 - 20$ fb and $\Gamma_\phi < 75$ GeV

Impose 8 TeV LHC bounds

(γZ, ZZ, W^+W^-, dijet, and monojet)

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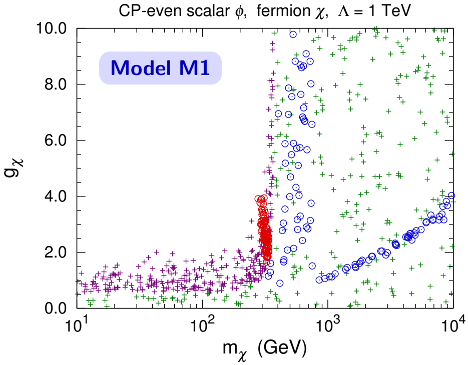

⊙ $\Omega_\chi h^2 \in (0.09, 0.13)$, $\Gamma_\phi \in (5, 75)$ GeV

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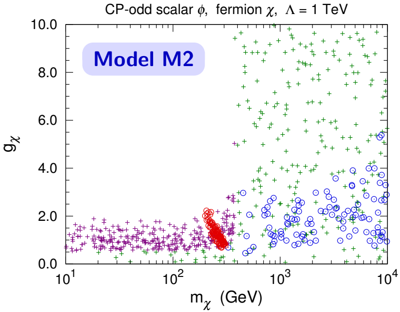
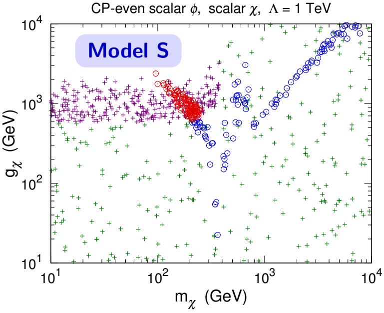
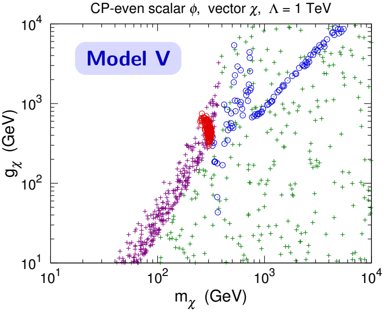




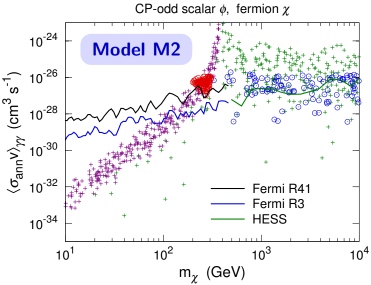


Indirect detection: γ-ray line spectrum searches

Fermionic DM annihilation mediated by a CP-even ϕ is velocity suppressed: **no indirect detection bound for Model M1**

Fermi-LAT bounds are based on 5.8-year observations of the regions **R41** and **R3** optimized for NFW profiles with $\gamma = 1$ and $\gamma = 1.3$, respectively [1506.00013]

HESS bound is based on 112-hour effective observation of the central Galactic halo region [1301.1173]



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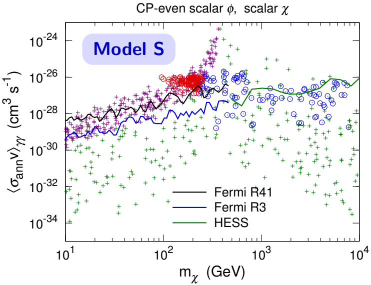
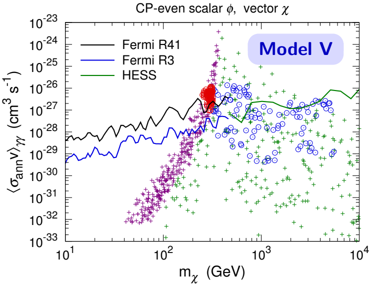




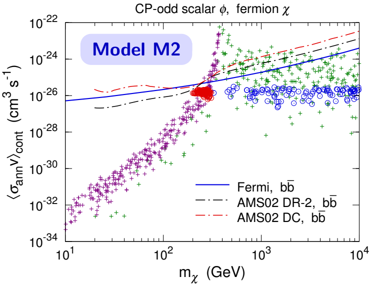
Indirect detection: γ-ray and cosmic-ray searches

Effective total cross section for the annihilation channels inducing **continuous spectrum γ-rays** and **cosmic-ray $\bar{p}$**:

$$\langle\sigma_{\rm ann}v\rangle_{\rm cont} = \langle\sigma_{\rm ann}v\rangle_{ZZ} + \langle\sigma_{\rm ann}v\rangle_{W^+W^-} + \frac{1}{2}\langle\sigma_{\rm ann}v\rangle_{Z\gamma} + \langle\sigma_{\rm ann}v\rangle_{gg} + 2\langle\sigma_{\rm ann}v\rangle_{\phi\phi}$$

Fermi-LAT bound is based on 6-year γ-ray observations of 15 dwarf galaxies [1503.02641]

AMS-02 bounds are derived from the cosmic-ray $\bar{p}/p$ measurement for 2 propagation models [1504.07230]



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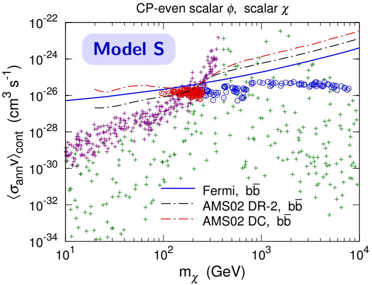
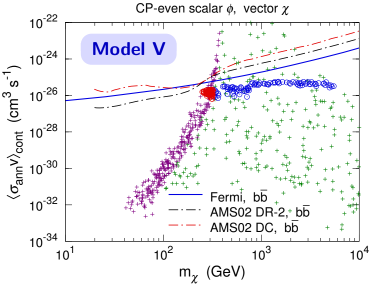
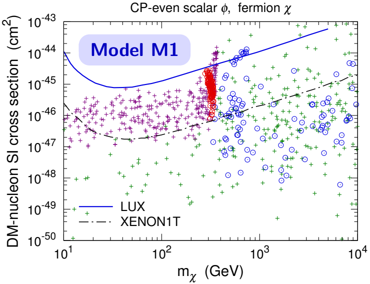




Direct detection

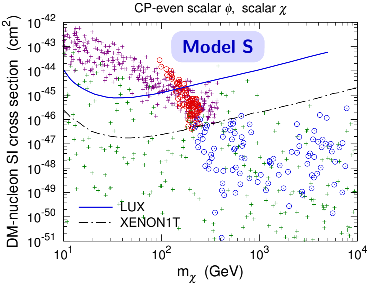


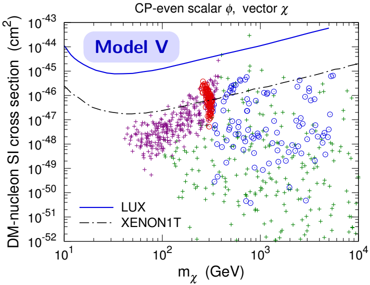
For **Model M2**, DM-nucleus scattering is momentum suppressed: **no direct detection bound**

For Models M1, S, and V, DM-nucleus scattering is spin independent, induced by the $\chi\chi gg$ **coupling** due to the ϕgg **coupling**

LUX: 118 kg · 85.3 day exposure [1310.8214]

XENON1T: 2 t · year exposure expected [1512.07501]





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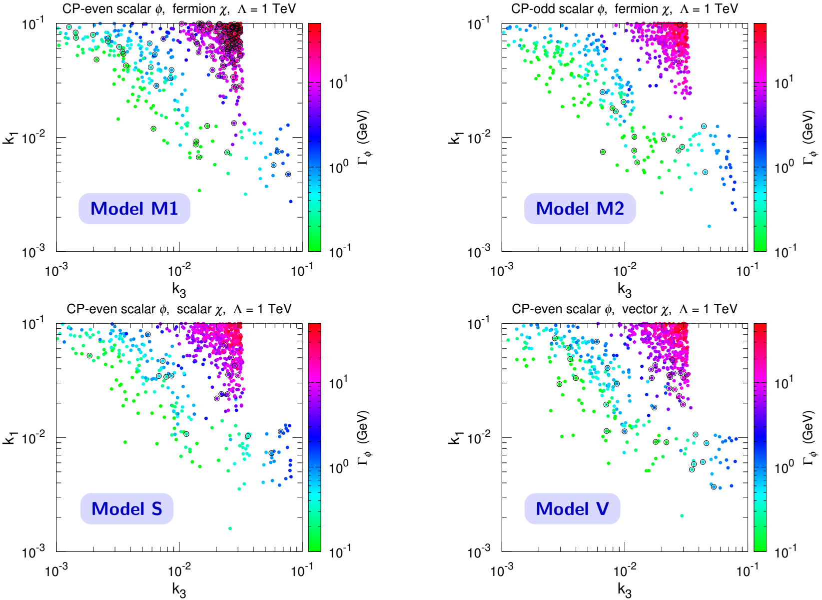

⊙ satisfy the observed relic abundance & pass current DM detection bounds

Summary

1. We interpret the diphoton excess as a spin-0 resonance particle ϕ and find that **an invisible decay channel** is favored by the broad width.
2. Regarding ϕ as **a dark matter portal** to the Standard Model, we study the possible connection to DM phenomenology with four simplified models.
3. Current **line spectrum γ-ray searches** have set very strong constraints on the ϕ-portal DM models, except for **Model M1**, which will be well explored by the XENON1T experiment.

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Thanks for your attention!