Multi-photon decays of the Higgs boson at the LHC

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w/ Hye-Sung Lee & Ian M. Lewis

arXiv: 2305.00013

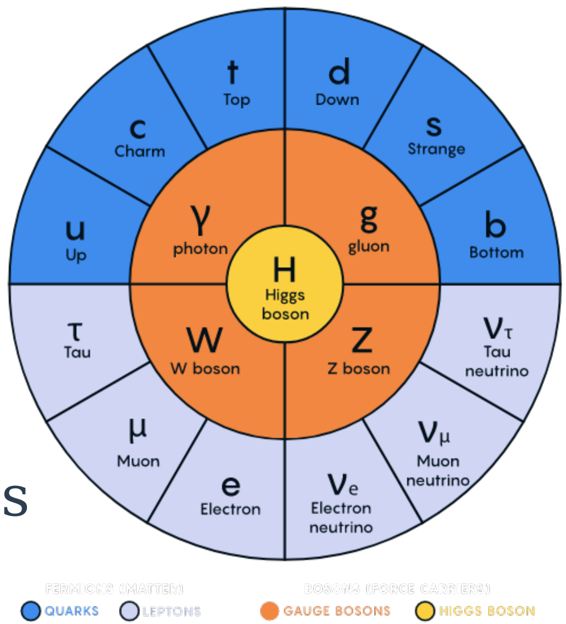
Pheno 2023

Outline

- Introduction and Motivation
- Model
- Multi-photon objects
- Results
- Summary & Conclusion

Introduction

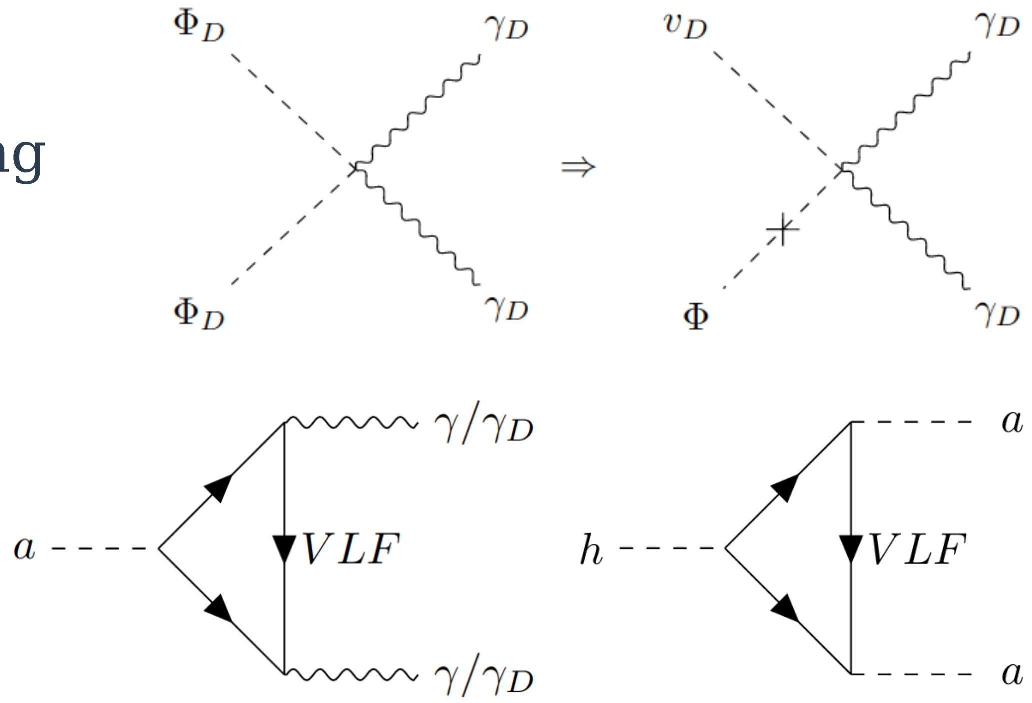
- **SM is ''complete''**
- **SM cannot explain dark matter, matter-antimatter asymmetry,…**
- **Dark Photons**
- **ALPS**
- **Dark axion portal**
  - Connect ALP and dark photon
  - Dark higgs, Dark photon, ALP, VLFs



K. Kaneta, H.-S. Lee, and S. Yun. 1611.01466

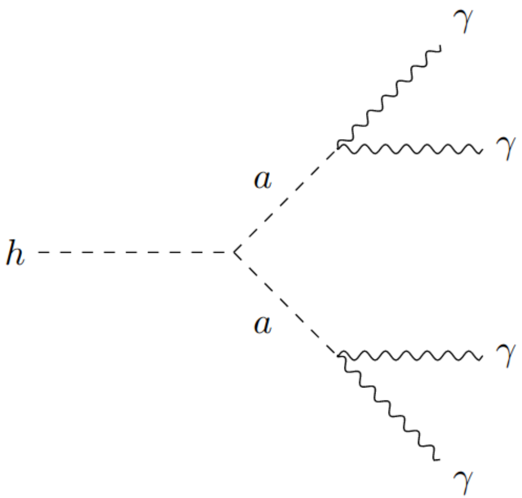
Model

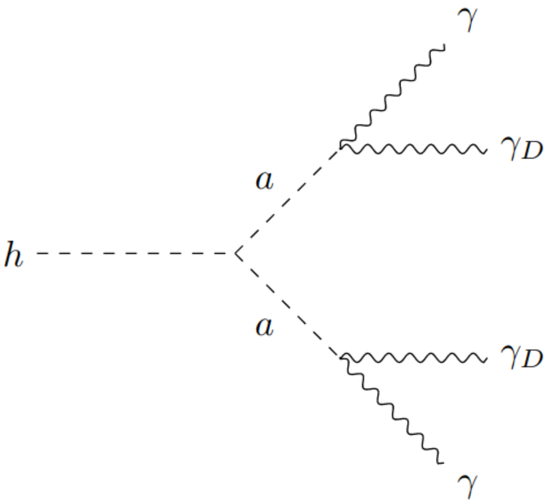
- **Couplings**
  - Higgs Dark Photon coupling
  - Higgs axion couplings
  - ALP-photon-photon
  - ALP-photon-dark photon
- **Photons are ‘clean’**
- **Go look for additional photon signals at LHC**

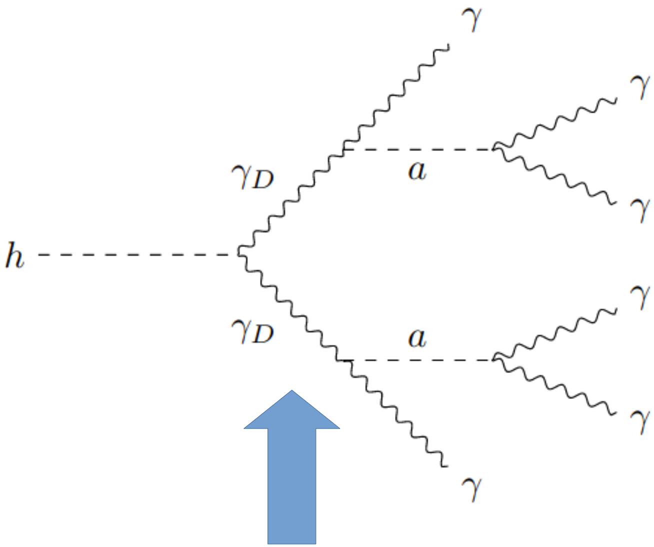


Some Signals

- **Some candidate signals in the dark axion portal**





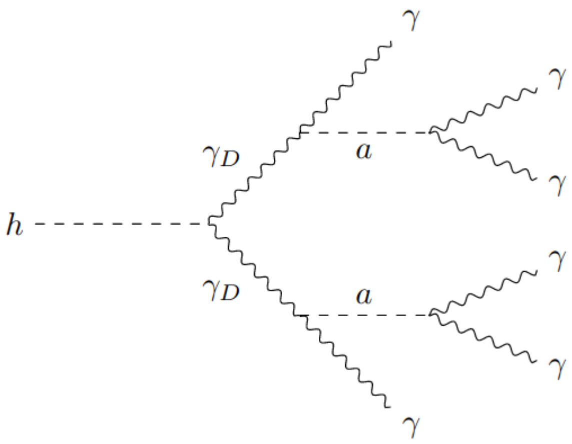


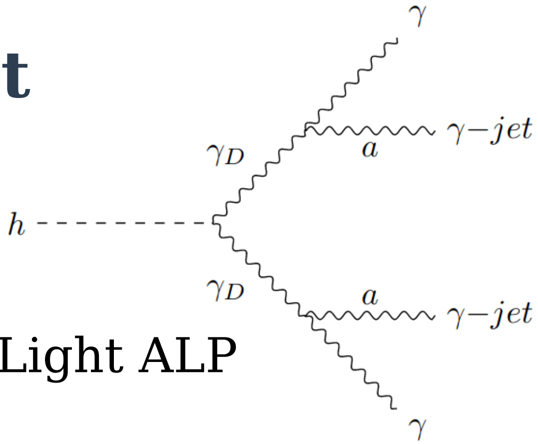
This Talk/Work

P. Draper and D. McKeen 1204.1061,
A. Chakraborty et al. 1707.07084,
B. Sheff et al. 2008.10568 ,
G. Cacciapaglia et al. 2210.01826,
and many many more

Photon Jets

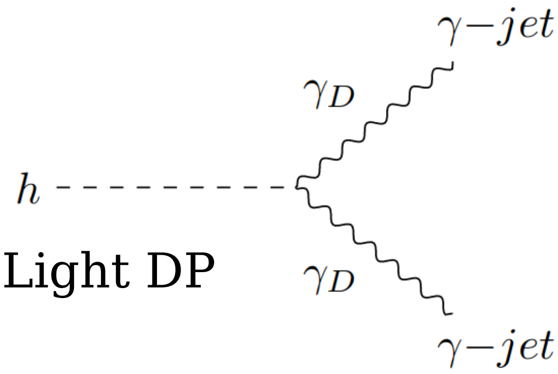
- **Light particles get large boost**
- **Decay products become collimated**





Apparent Landau-Yang Violation

Light ALP



Light DP

Multi-Photon Objects

$$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$$

$$\eta = \frac{1}{2}\ln\frac{E+pz}{E-pz}$$

Well collimated photons end up in same detector location

Appear as a single photon

$$\Delta R < 0.04$$

Photon Jets

Sets of photons or photon-jets that have intermediate separation

$$0.04 < \Delta R < 0.4$$

ξ Jets

Use Isolated Photons to reduce QCD backgrounds

$$\Delta R > 0.4$$

Isolated Photons

B. Sheff et al. 2008.10568

Results

$$\mathrm{BR}(h \to \gamma_d\gamma_d \to a\gamma a\gamma \to 6\gamma \to n\gamma_{iso} + m\xi)$$

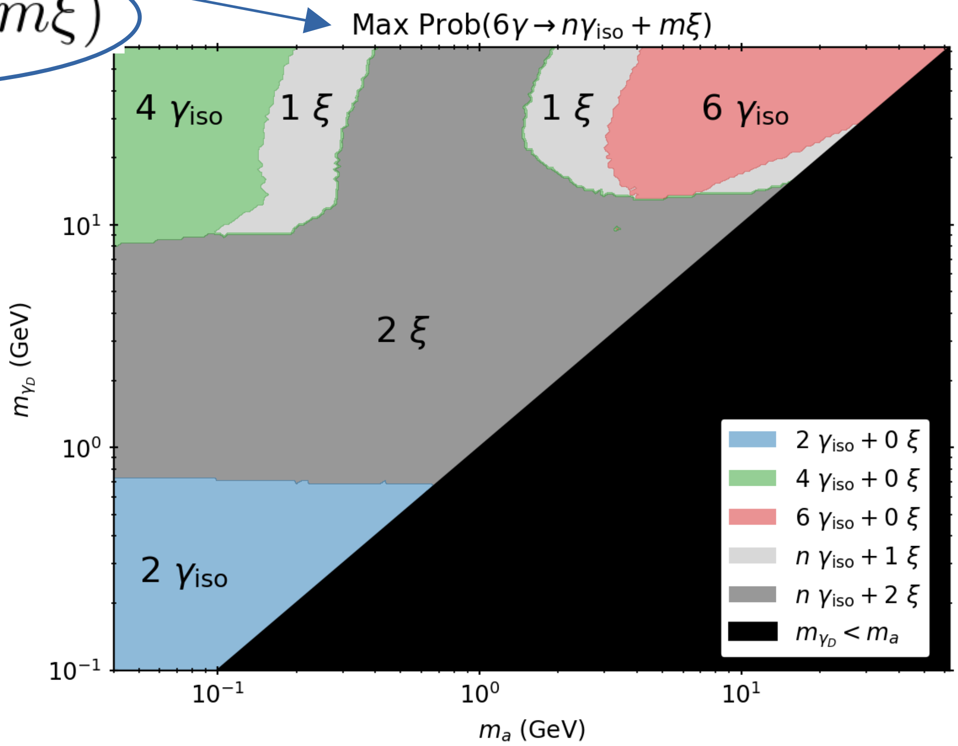
1. Truth level events {γ}

Merge γ-Jets $\Delta R < 0.04$

2. Observable Photons $\{\gamma_{obs}\}$

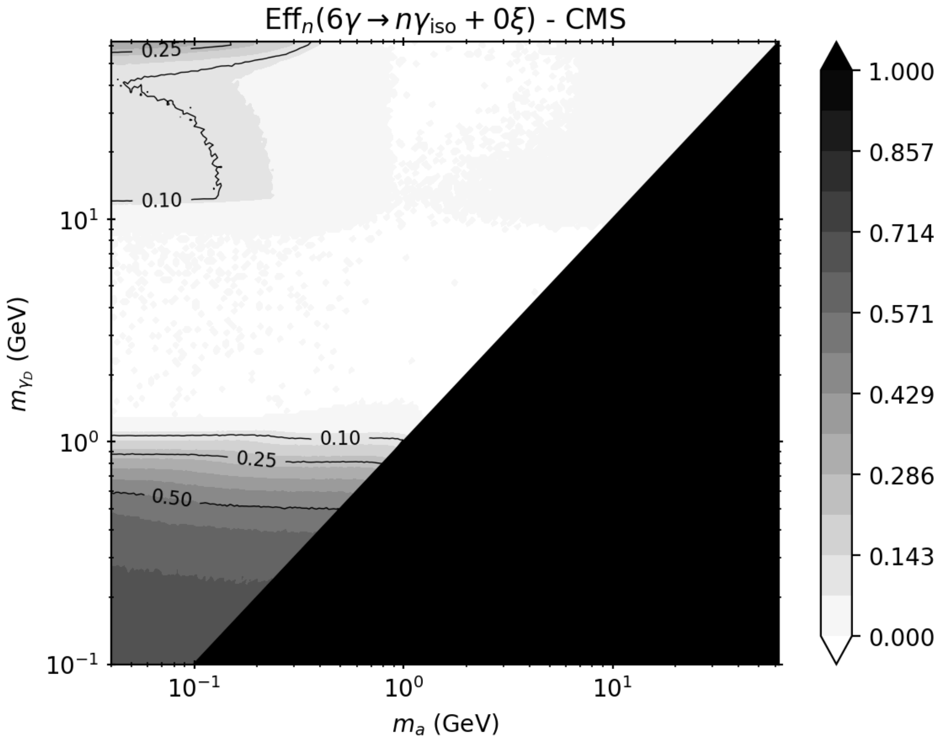
Isolate γ $\Delta R > 0.4$

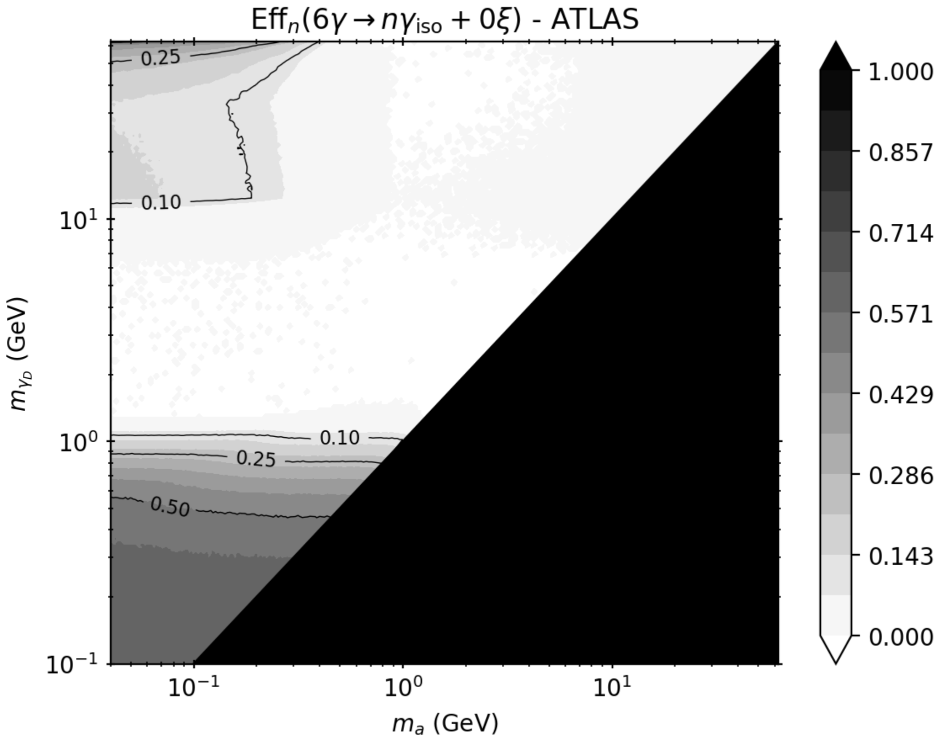
3. Isolated Photons $\{\gamma_{iso}, \xi\}$



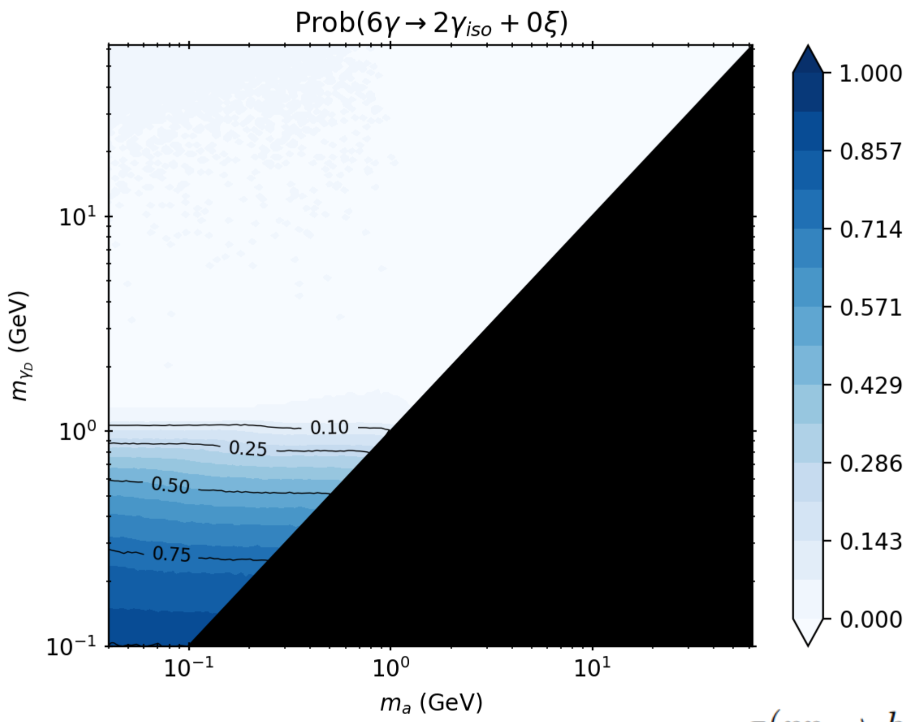
$$\mathrm{Prob}(6\gamma \to n\gamma_{iso} + m\xi) = \frac{\mathrm{BR}(h \to \gamma_D\gamma_D \to a\gamma a\gamma \to 6\gamma \to n\gamma_{iso} + m\xi)}{\mathrm{BR}(h \to \gamma_D\gamma_D)\mathrm{BR}^2(\gamma_D \to a\gamma)\mathrm{BR}^2(a \to \gamma\gamma)}$$

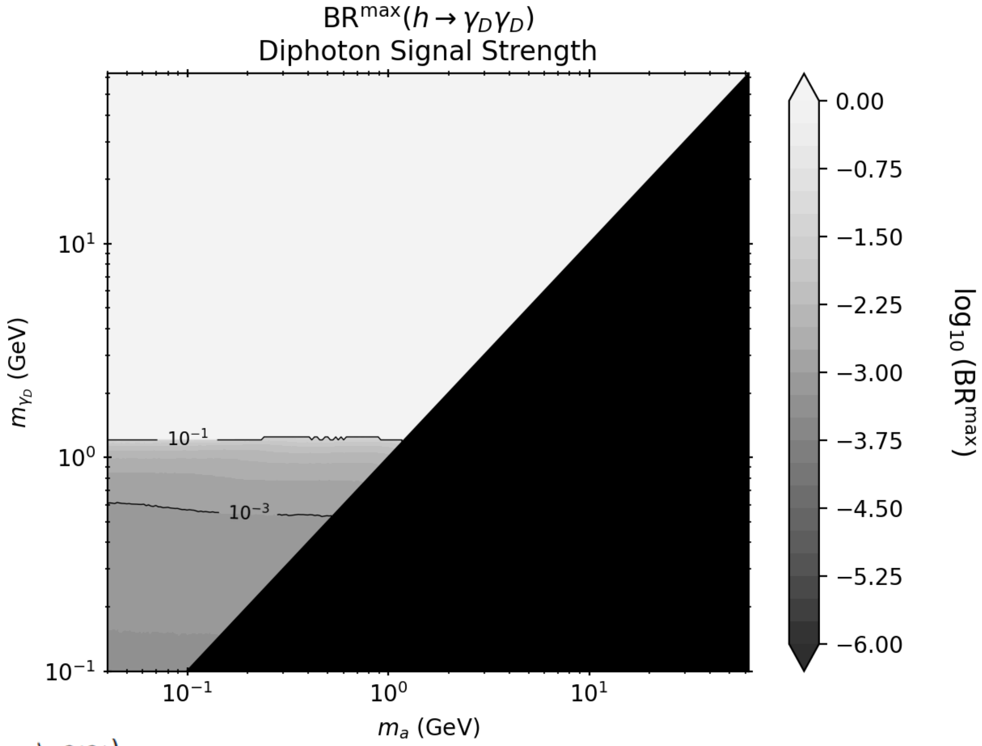
Estimated Trigger Efficiencies





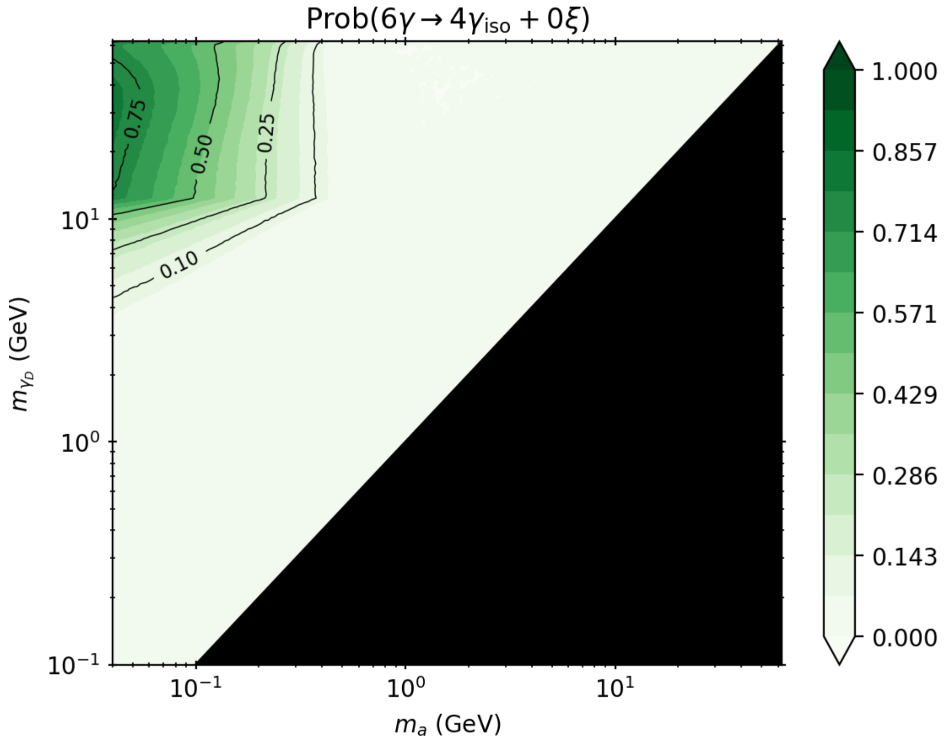
Results Diphoton

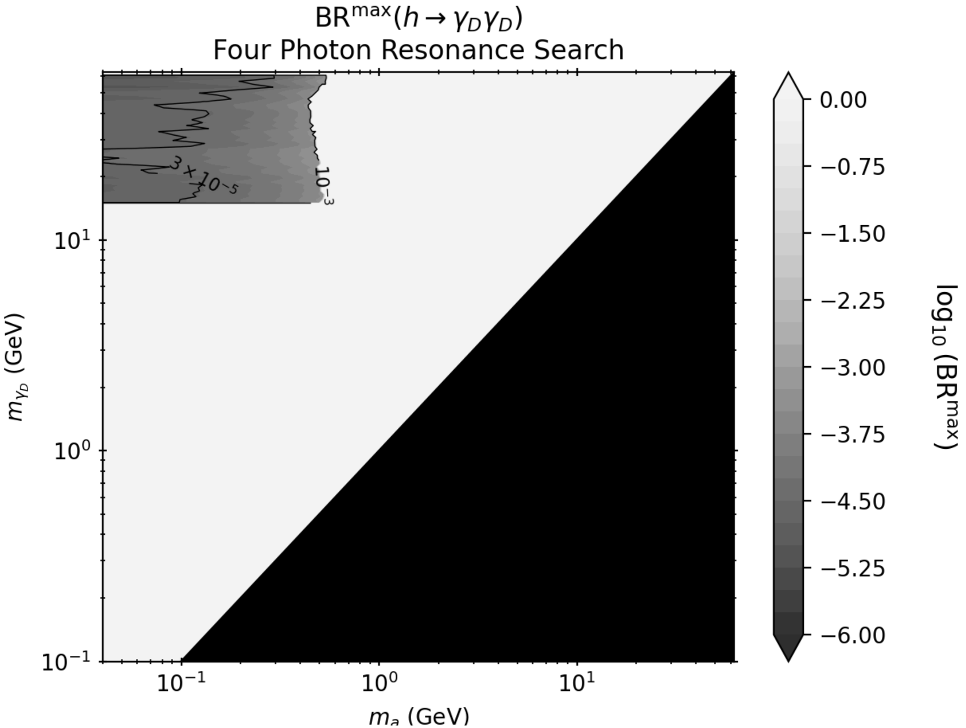




$$\mu = \frac{\sigma(pp \to h)}{\sigma_{\mathrm{SM}}(pp \to h)} \frac{\mathrm{BR}(h \to \gamma\gamma)}{\mathrm{BR}_{\mathrm{SM}}(h \to \gamma\gamma)}$$

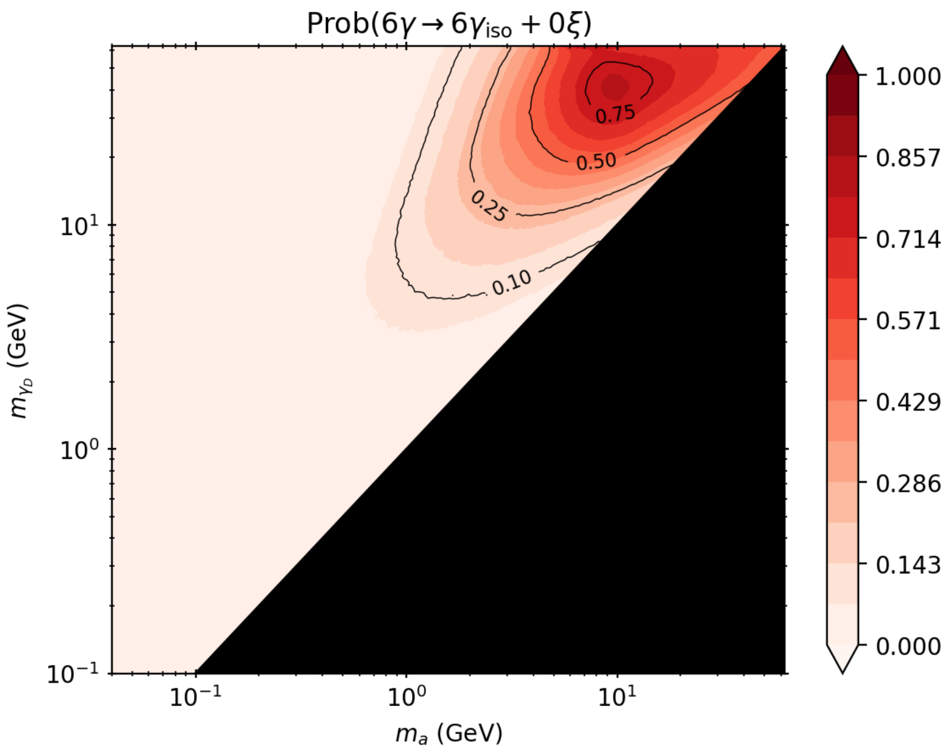
Results Four Photon

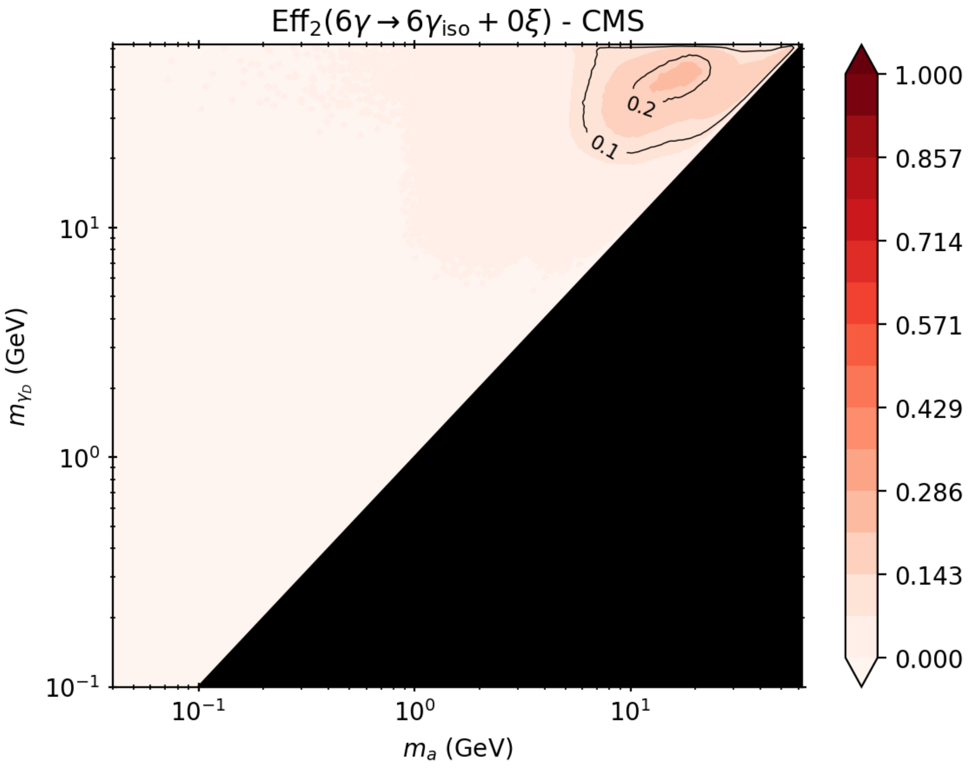




$$\text{BR}(h \to 4\gamma) = \text{BR}(h \to \gamma_D \gamma_D)\text{Prob}(6\gamma \to 4\gamma_{iso})$$

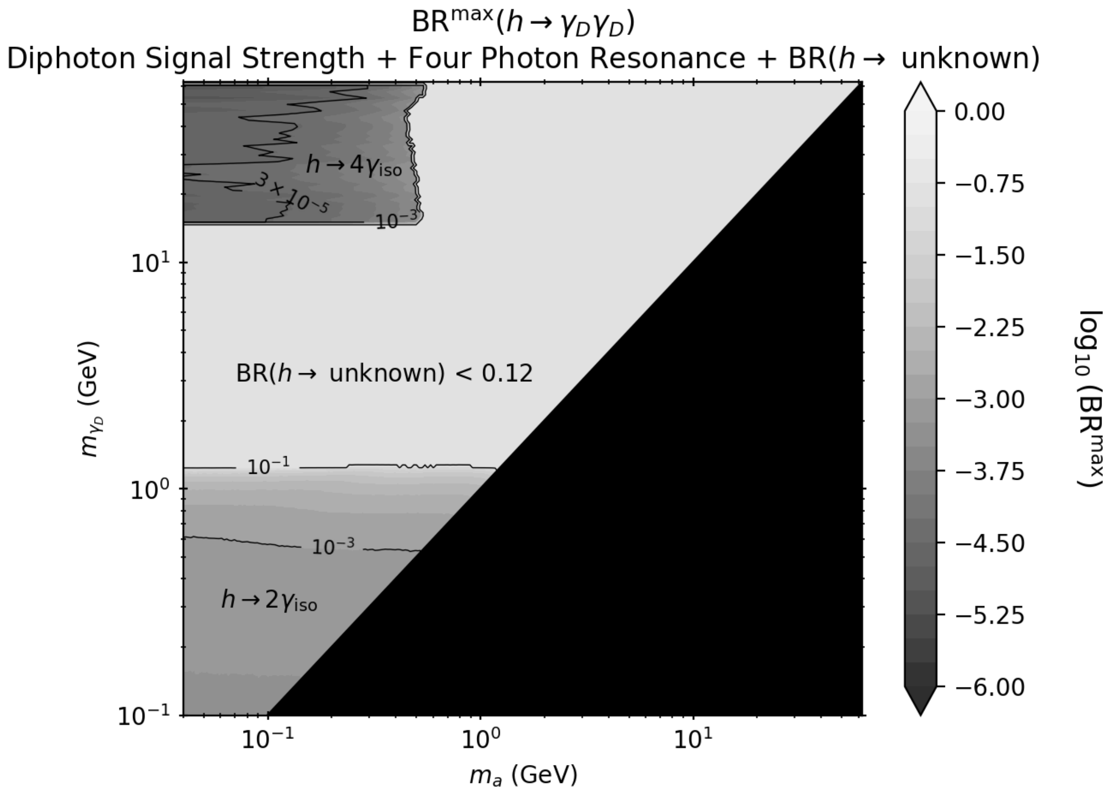
Results Continued





Summary & Conclusion

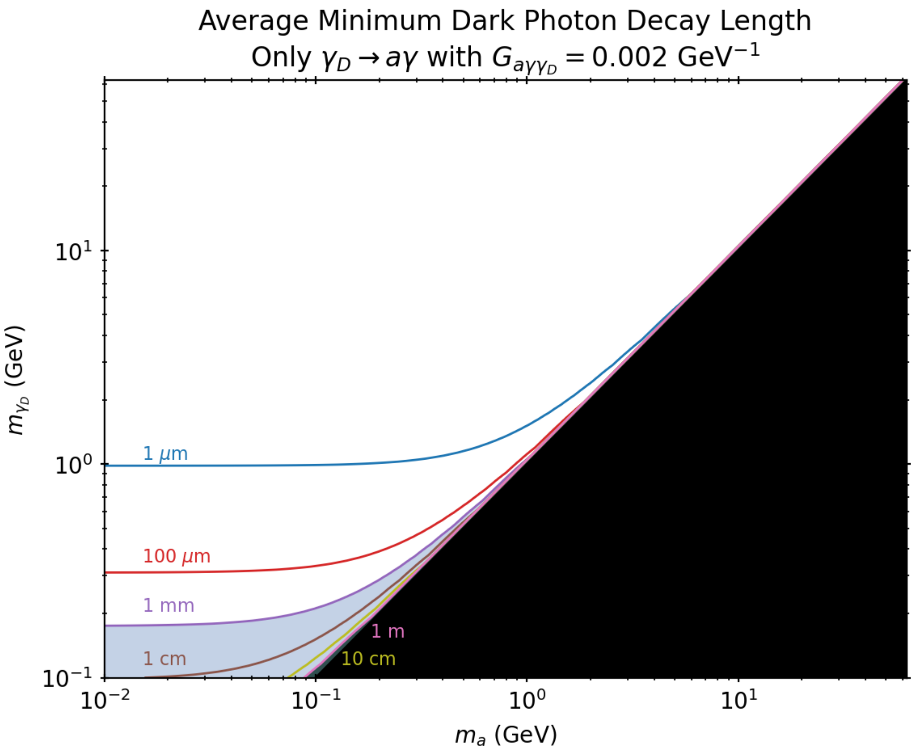
- **The DAP introduces a six photon Higgs resonance.**
- **We can place good constraints using the two and four photon categories.**
- **Could constrain other regions by doing appropriate searches**
- **The pure six photon signal has a chance to be seen**

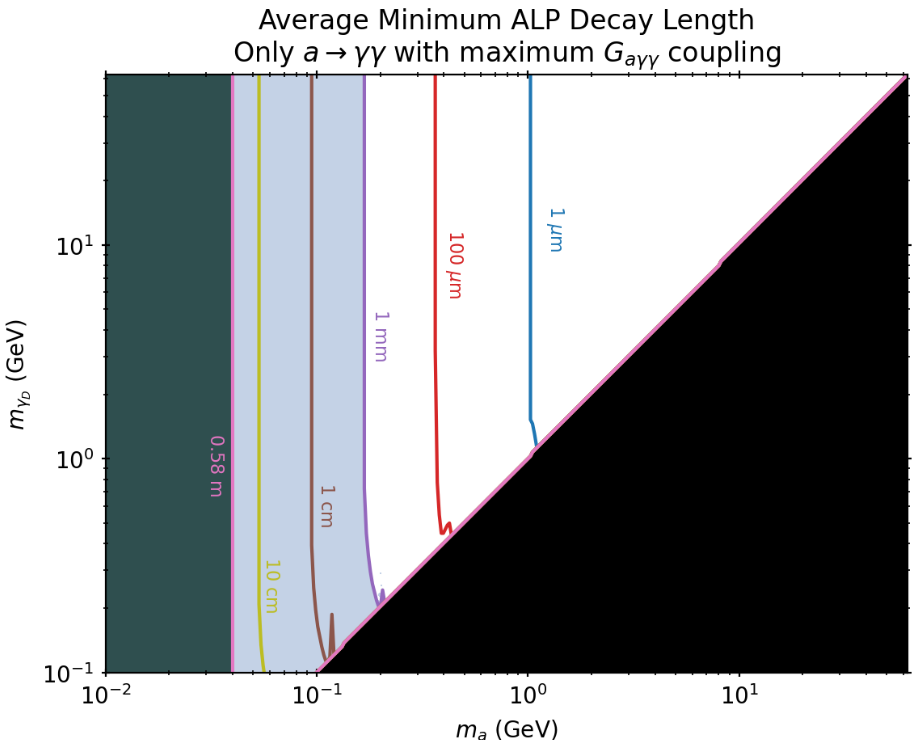


Questions?

Backup

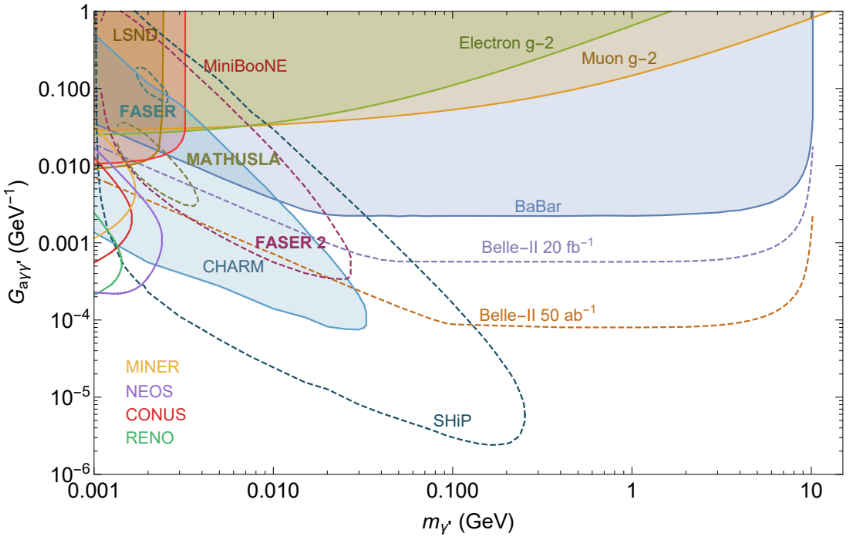
Decay Lengths





Axion Constraints

ALP-photon-dark photon



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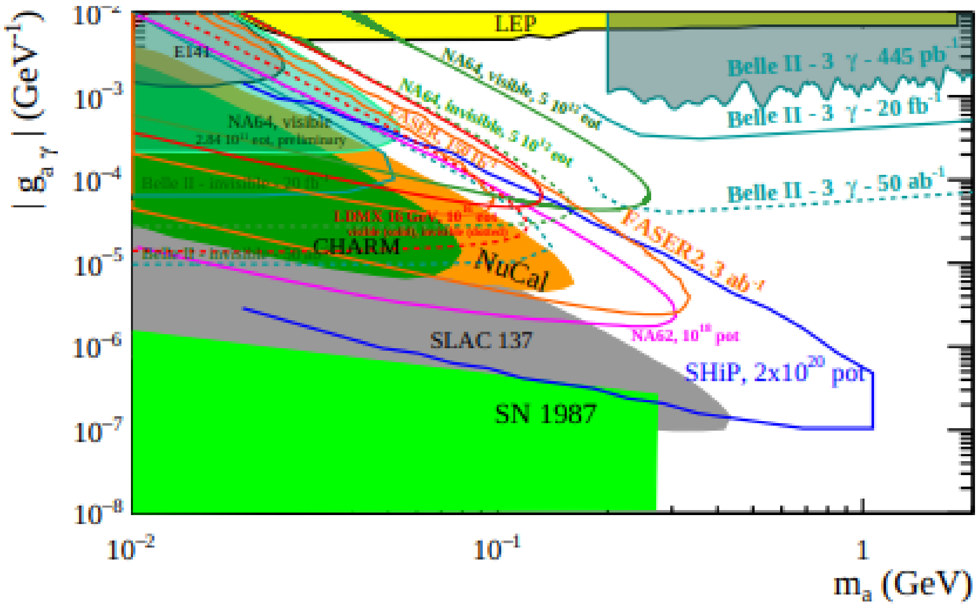
ALP-photon-photon



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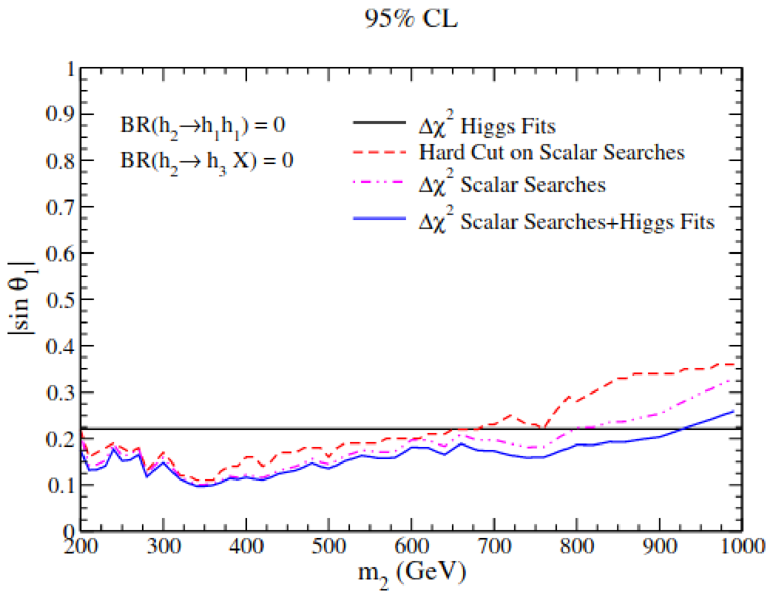
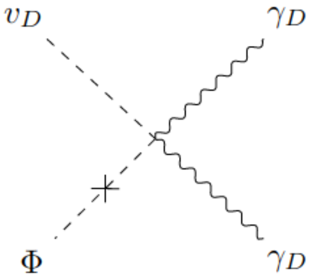
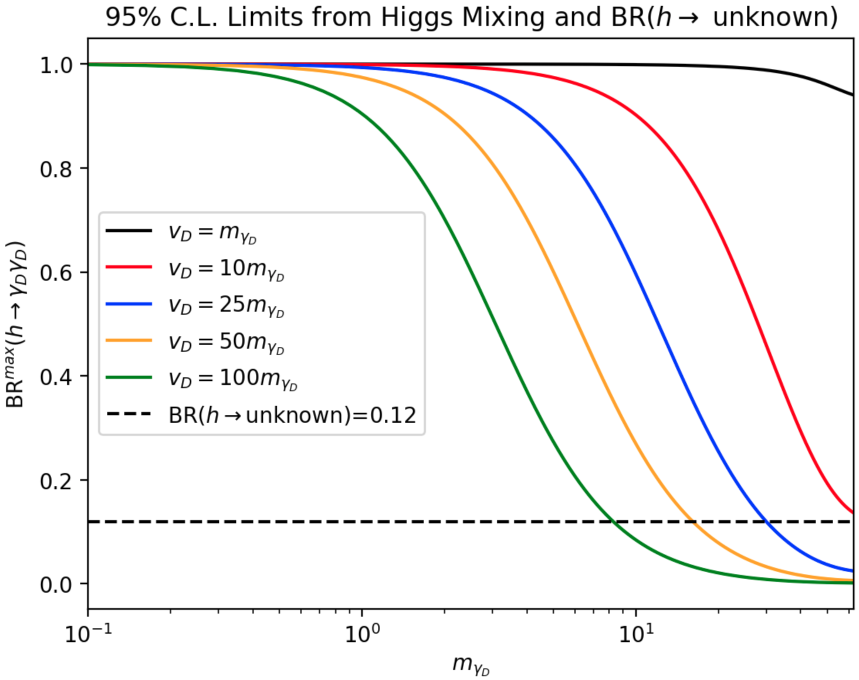
Higgs Constraints



S. Adhikari, SDL, I.M. Lewis, M. Sullivan 2203.07455





$$|\lambda^{\max}_{h\gamma_D\gamma_D}| \sim |\sin\theta_{\max}|\frac{m^2_{\gamma_D}}{v_D} \approx 0.1 m^2_{\gamma_D}/v_D$$

Lagrangian

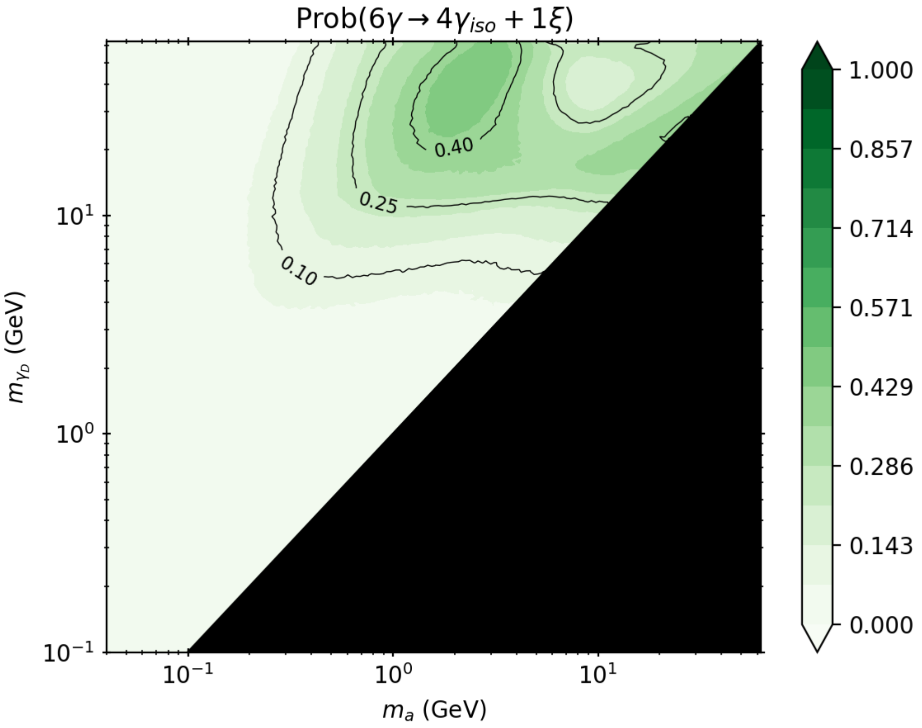
- **Relevant couplings**

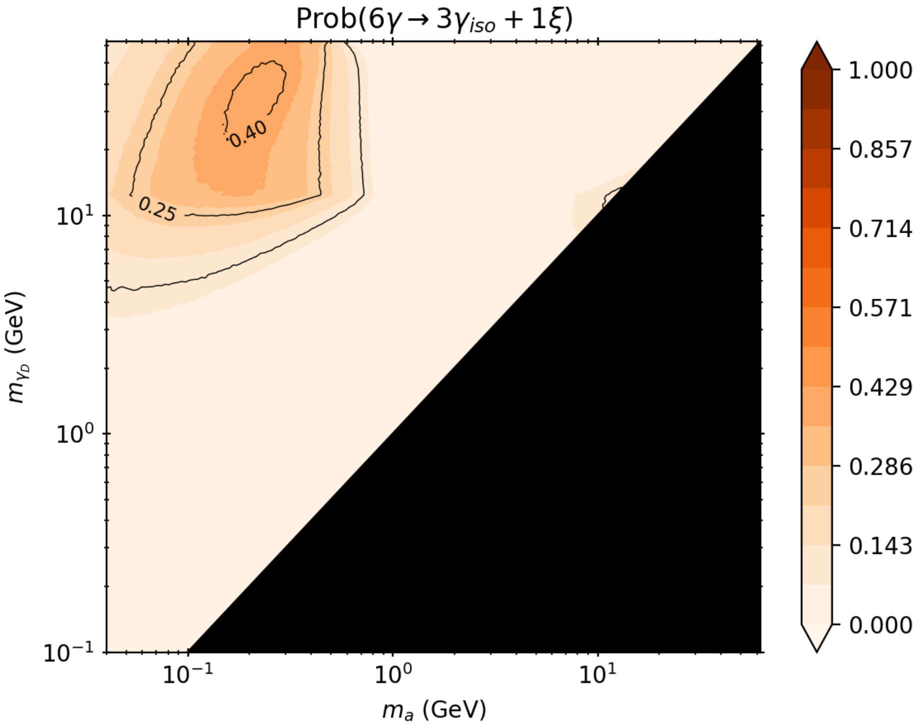
$$\mathcal{L}_{\text{kinetic+mass}} = -\frac{1}{4}F_D^{\mu\nu}F_{D\mu\nu} + \frac{1}{2}m_{\gamma_D}^2\gamma_D^{\mu}\gamma_{D\mu} + \frac{1}{2}\partial_\mu a\partial^\mu a - \frac{1}{2}m_a^2 a^2,$$

$$\mathcal{L}_{\text{portal}} = \frac{G_{a\gamma\gamma}}{4}aF^{\mu\nu}\tilde{F}_{\mu\nu} + \frac{G_{a\gamma\gamma_D}}{2}aF_D^{\mu\nu}\tilde{F}_{\mu\nu} + \frac{G_{a\gamma_D\gamma_D}}{4}aF_D^{\mu\nu}\tilde{F}_{D\mu\nu} + \frac{\lambda_{h\gamma_D\gamma_D}}{2}h\gamma_D^{\mu}\gamma_{D\mu}$$

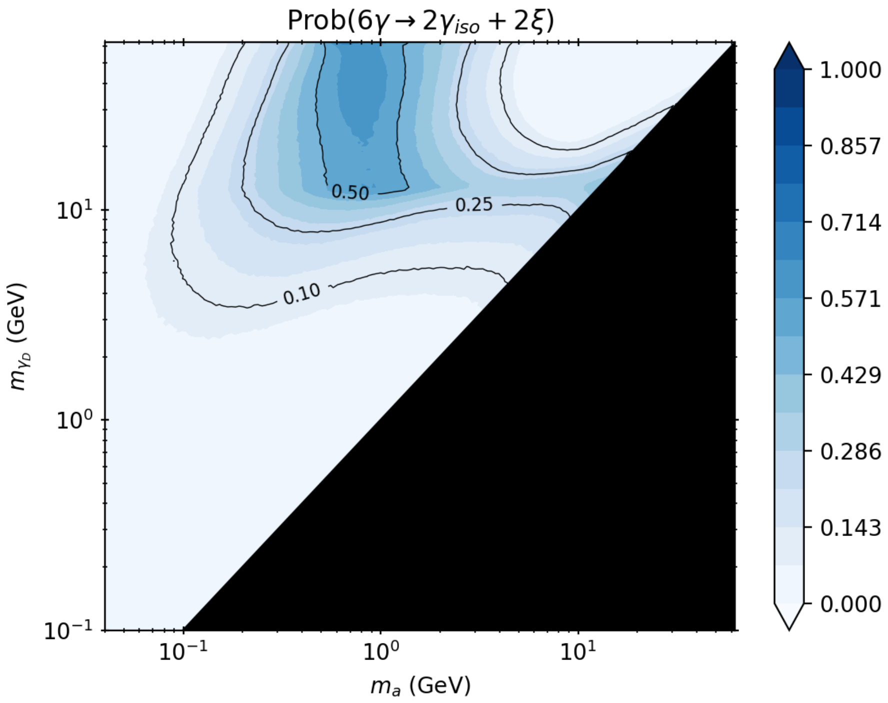
$$\mathcal{L}_{\text{total}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{kinetic+mass}} + \mathcal{L}_{\text{portal}}.$$

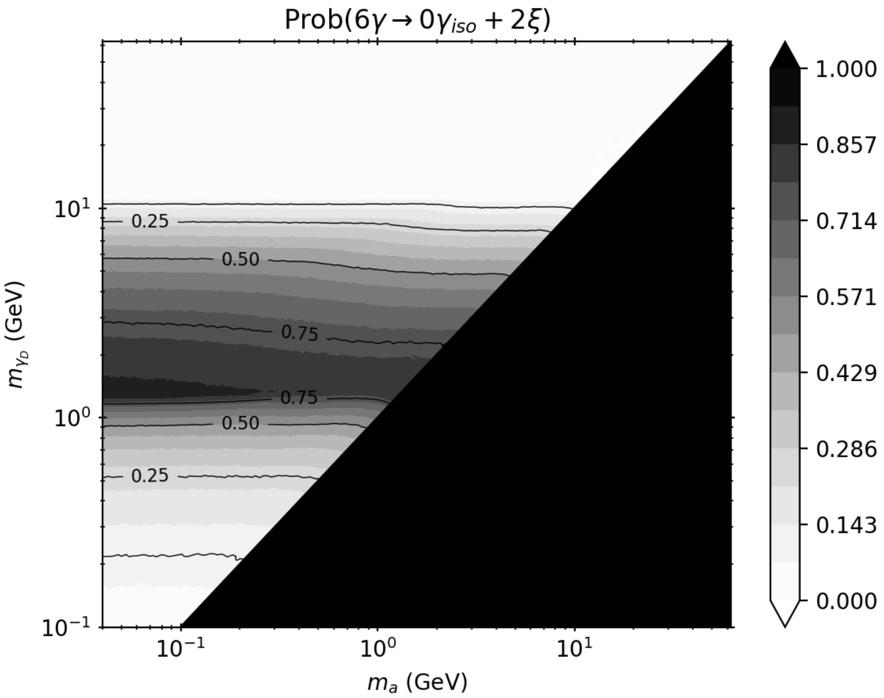
Some Other Signals





Some Other Signals





Transverse Momentum Cuts

Channel	ATLAS p_T Requirements
1γ	$p_{1,T} > 150$ GeV [94]
2γ	$p_{1,T} > 35$ GeV and $p_{2,T} > 25$ GeV [24]
3γ	$p_{1,T} > 15$ GeV, $p_{2,T} > 15$GeV, and $p_{3,T} > 15$ GeV [95]
4γ	$p_{1,T} > 30$ GeV, $p_{2,T} > 18$ GeV, $p_{3,T} > 15$ GeV, and $p_{4,T} > 15$ GeV [95]
5γ	$p_{i,T} > 15$ GeV $(i = 1, 2, 3, 4, 5)$
6γ	$p_{i,T} > 15$ GeV $(i = 1, 2, 3, 4, 5, 6)$

Channel	CMS p_T Requirements
1γ	$p_{1,T} > 145$ GeV [98]
2γ	$p_{1,T} > 30$ GeV and $p_{2,T} > 18$ GeV [30]
3γ	$p_{1,T} > 15$ GeV, $p_{2,T} > 15$ GeV, and $p_{3,T} > 15$ GeV [95]
4γ	$p_{1,T} > 30$ GeV, $p_{2,T} > 18$ GeV, $p_{3,T} > 15$ GeV, and $p_{4,T} > 15$ GeV [27]
5γ	$p_{i,T} > 15$ GeV $(i = 1, 2, 3, 4, 5)$
6γ	$p_{i,T} > 15$ GeV $(i = 1, 2, 3, 4, 5, 6)$