Multi-photon decays of the Higgs boson at the LHC

Samuel D. Lane

w/ Hye-Sung Lee & Ian M. Lewis

arXiv: 2305.00013

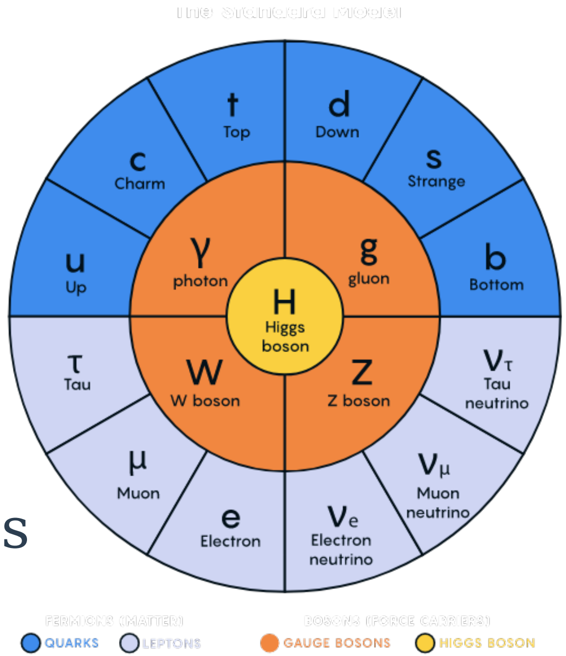
PPC 2023

Outline

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

Introduction

- **We know the SM well**
- **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



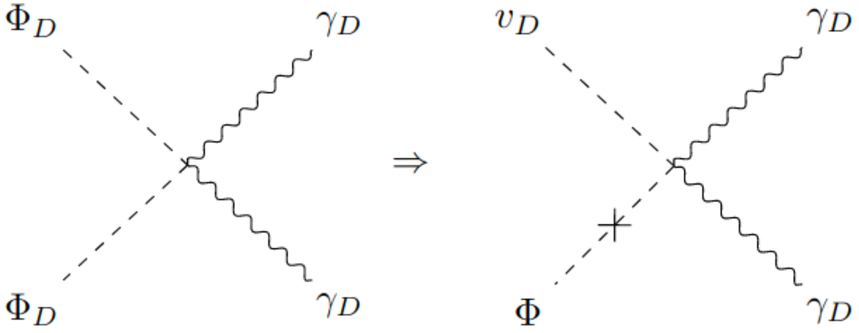
K. Kaneta, H.-S. Lee, and S. Yun. 1611.01466

Field	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_{\text{Dark}}$	$U(1)_{PQ}$
ψ	3	1	Q_ψ	D_ψ	PQ_ψ
ψ^c	$\bar{3}$	1	$-Q_\psi$	$-D_\psi$	PQ_{ψ^c}
Φ_{PQ}	1	1	0	0	PQ_Φ
Φ_D	1	1	0	D_Φ	0

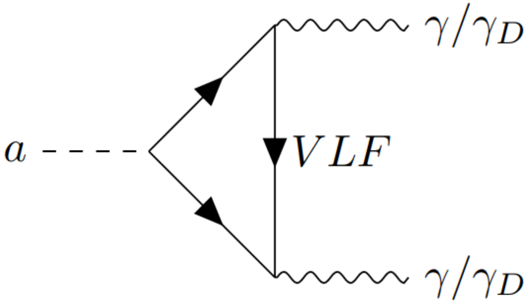
- **Axion comes from a Peccei Quinn mechanism**
- **DP gets mass from dark Higgs mechanism**
- **Will work in the small kinetic mixing limit**

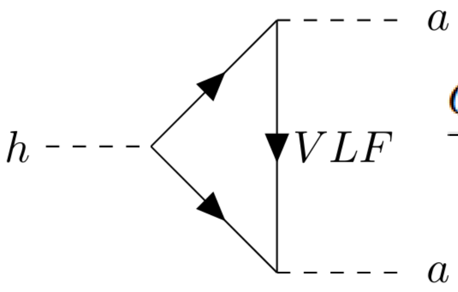
Model

- **Important Couplings**
  - Higgs Dark Photon coupling
  - Higgs axion couplings
  - ALP-photon-photon
  - ALP-photon-dark photon



$$\frac{\lambda_{h\gamma_D\gamma_D}}{2} h \gamma_D^{\mu} \gamma_{D\mu}$$

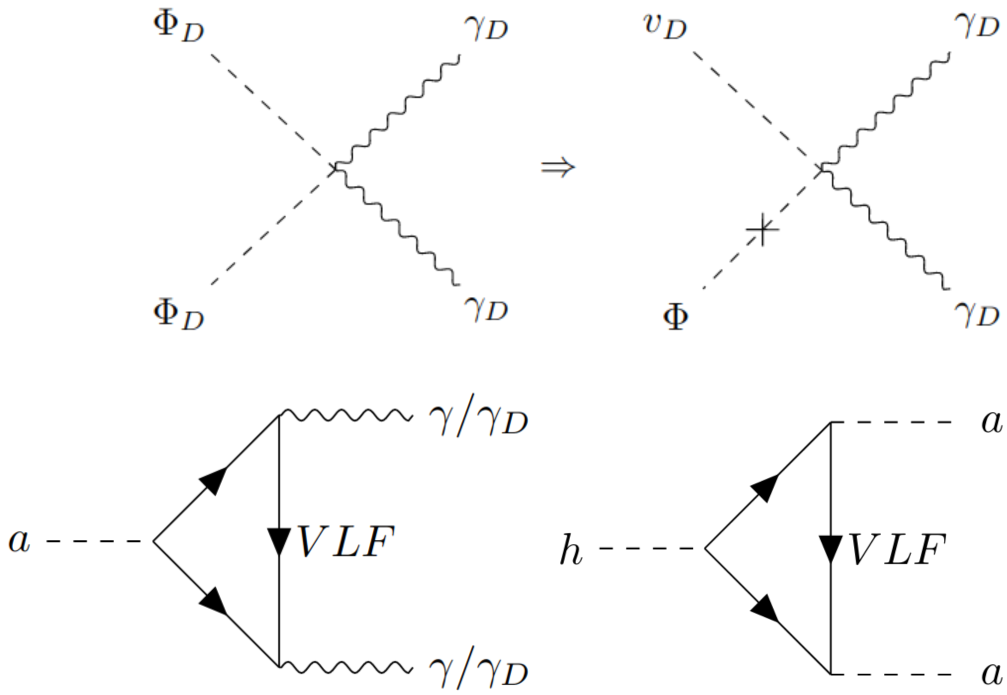




$$\frac{G_{a\gamma\gamma}}{4} a F^{\mu\nu} \tilde{F}_{\mu\nu} + \frac{G_{a\gamma\gamma_D}}{2} a F_D^{\mu\nu} \tilde{F}_{\mu\nu} + \frac{G_{a\gamma_D\gamma_D}}{4} a F_D^{\mu\nu} \tilde{F}_{D\mu\nu}$$

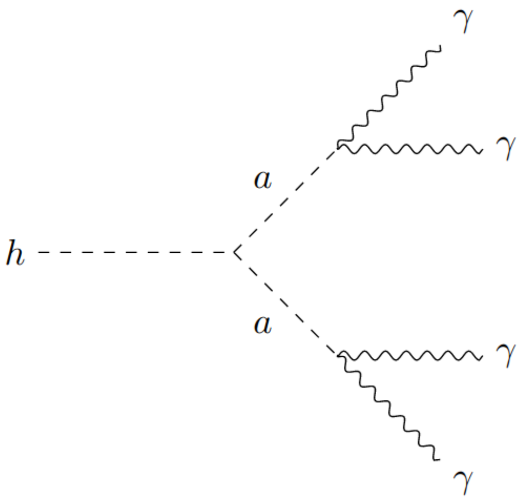
Model

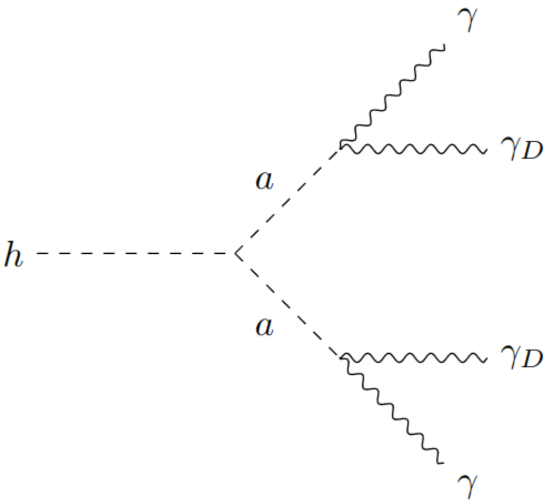
- **Axion to diphoton is well known**
- **Higgs to diphoton is also well known**
- **Photons are “clean” at colliders**
- **Go look for additional signals at LHC that contain photons**

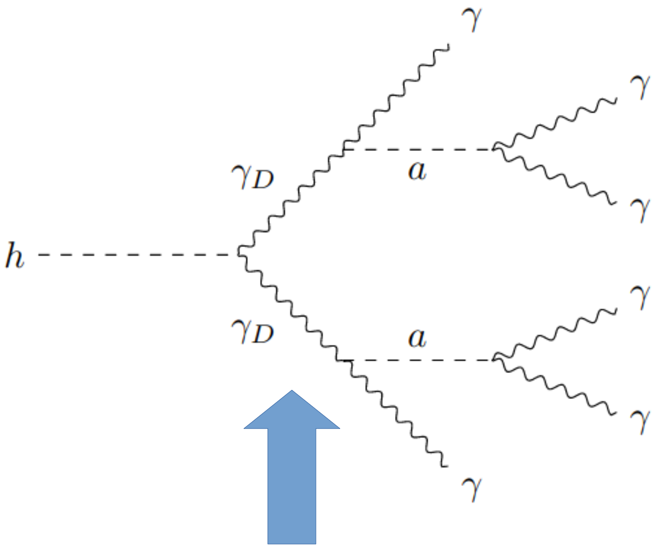


Some Signals

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





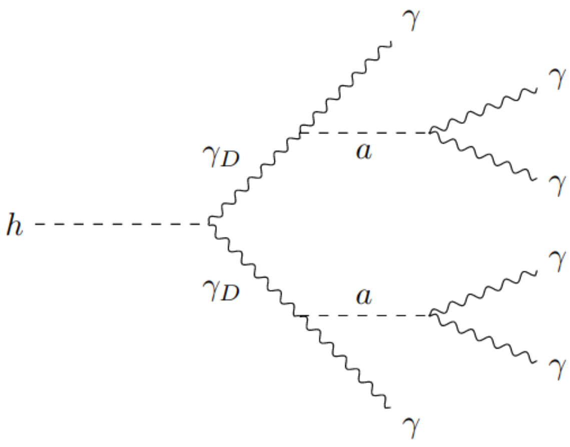


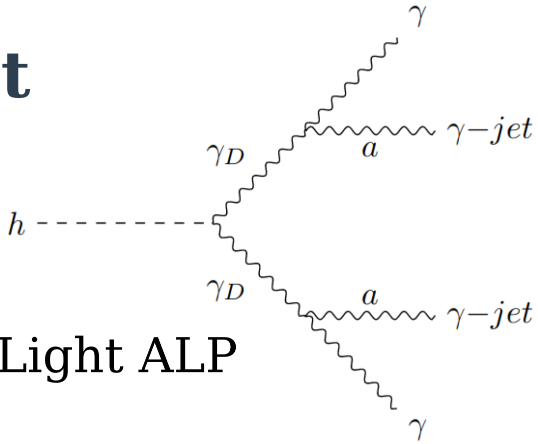
This Talk/Work

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

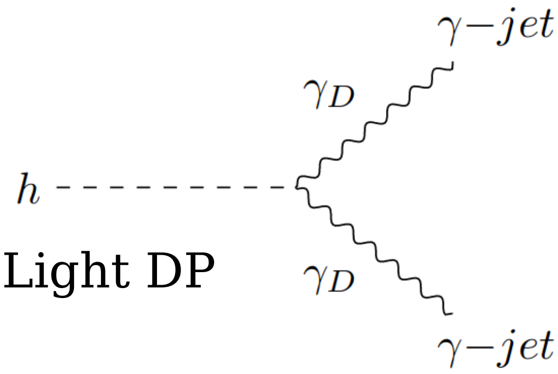
- **Light particles get large boost**
- **Decay products become collimated**





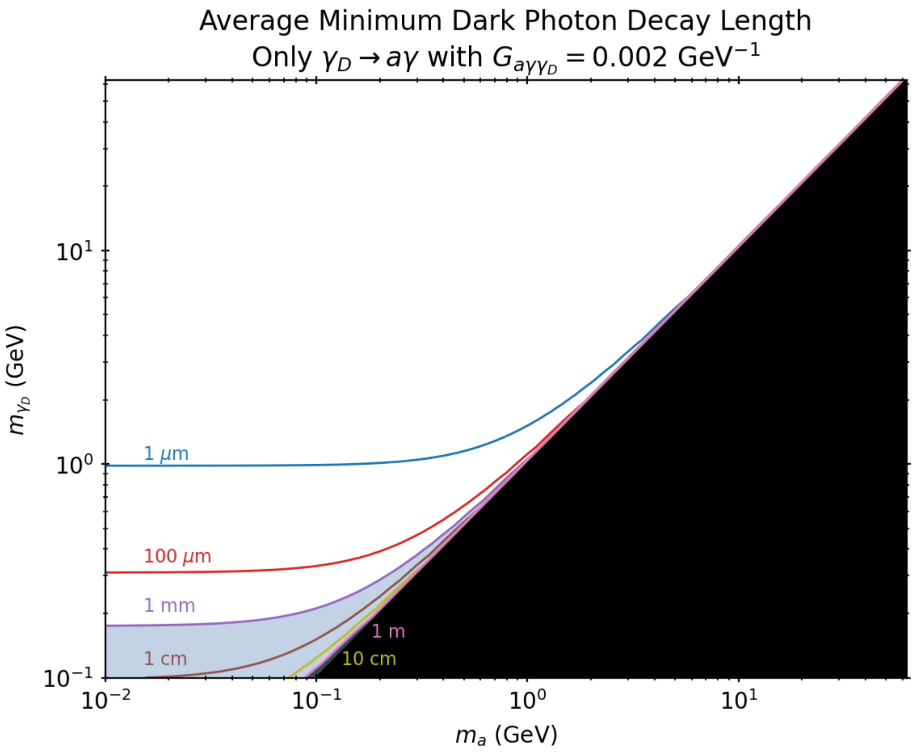
Apparent Landau-Yang Violation

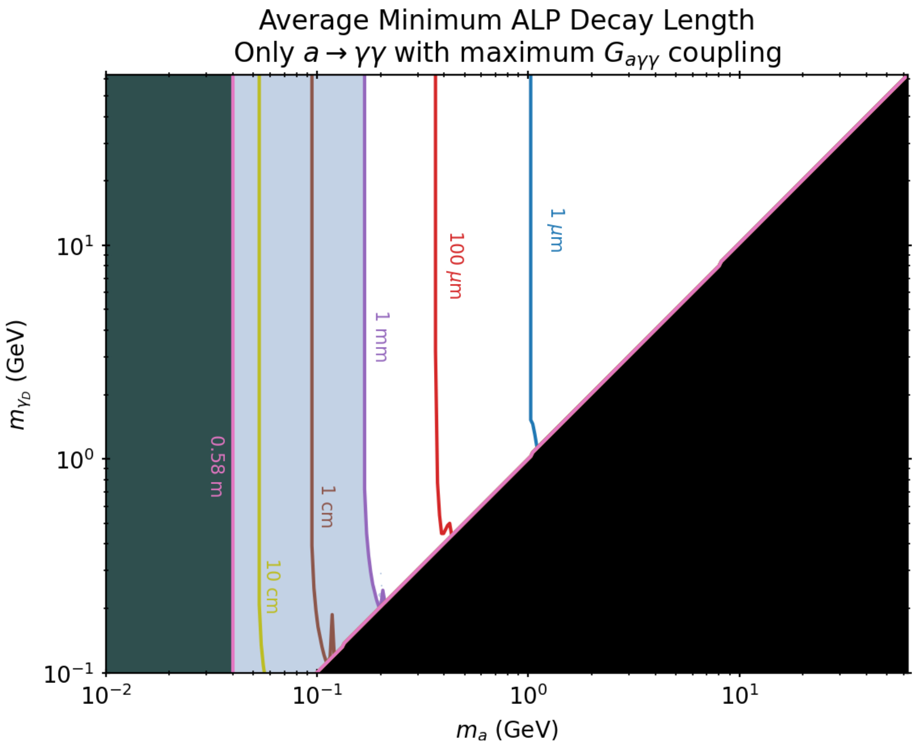
Light ALP



Light DP

Average Decay Lengths





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

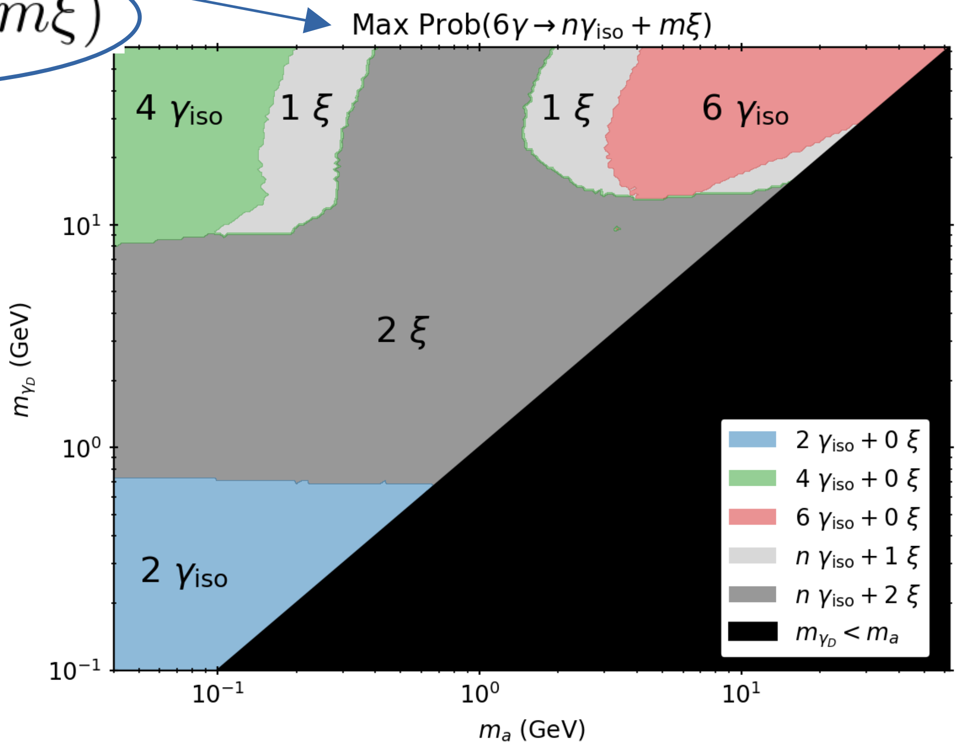
$$\Delta R > 0.4$$

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 {γ_{obs}}

Isolate γ $\Delta R > 0.4$

3. Isolated Photons {γ_{iso}, ξ}

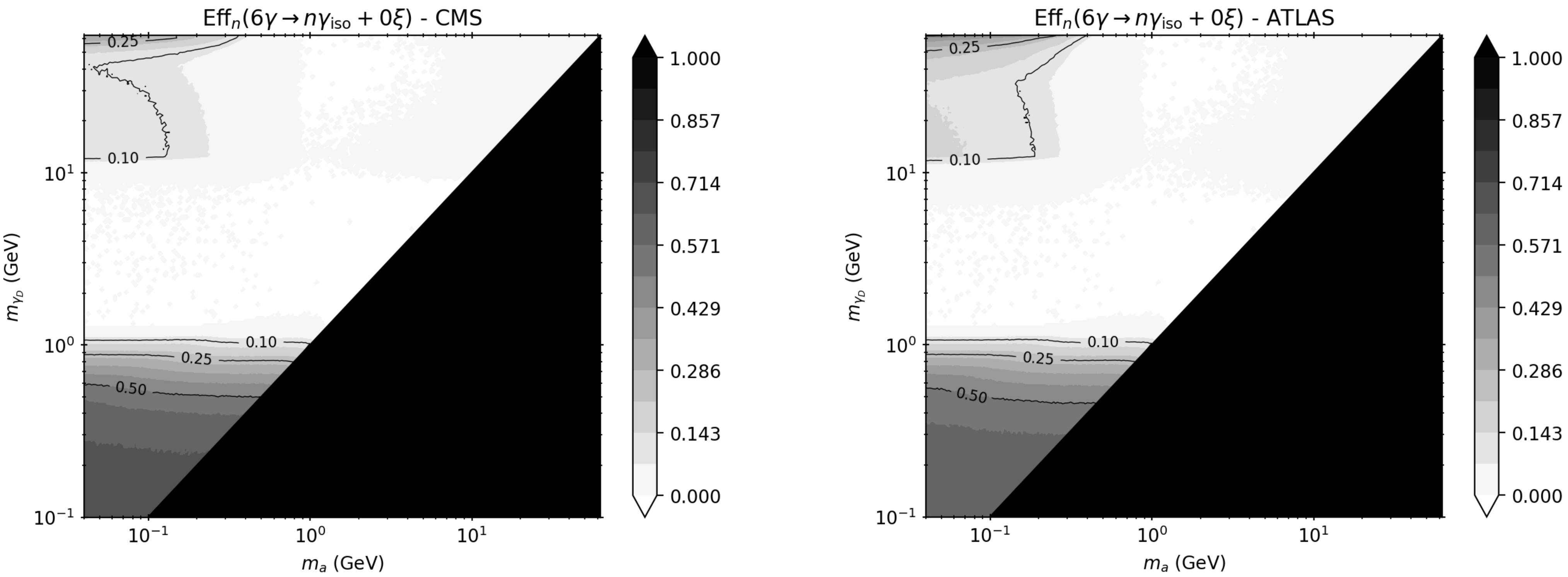
$$\mathrm{Prob}(6\gamma \to n\gamma_{iso} + m\xi) = \frac{\mathrm{BR}(h \to \gamma_D \gamma_D \to a\gamma a\gamma \to 6\gamma \to n\gamma_{iso} + m\xi)}{\mathrm{BR}(h \to \gamma_D \gamma_D)\mathrm{BR}^2(\gamma_D \to a\gamma)\mathrm{BR}^2(a \to \gamma\gamma)}$$

Estimating Trigger/Detector Efficiency

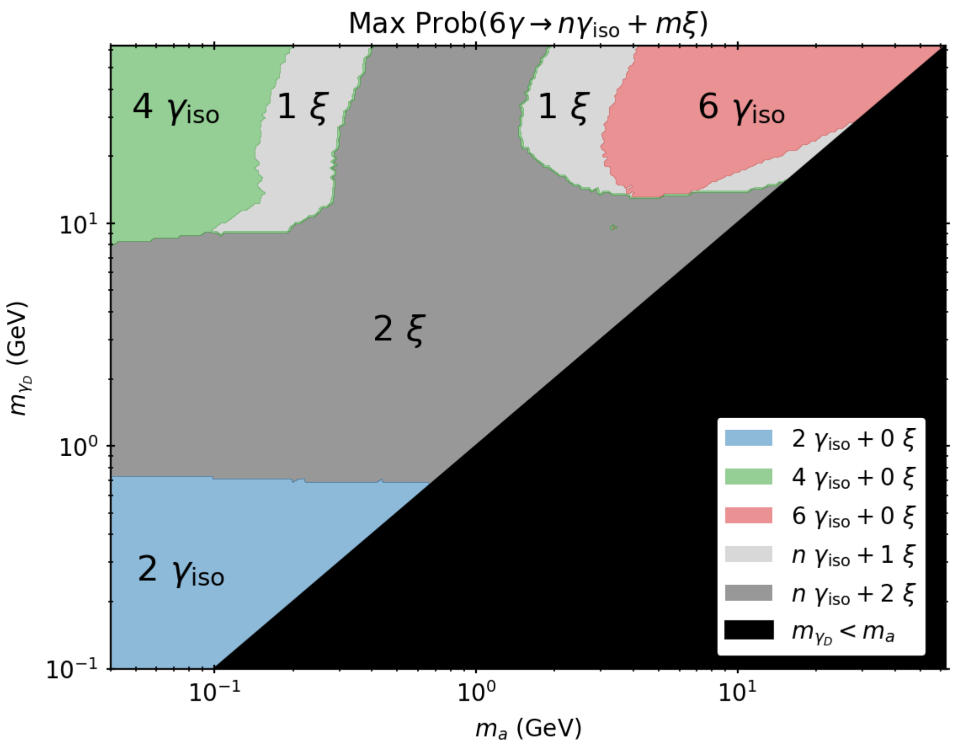
- **Impose some transverse momentum cuts**
- **Impose some rapidity cuts**

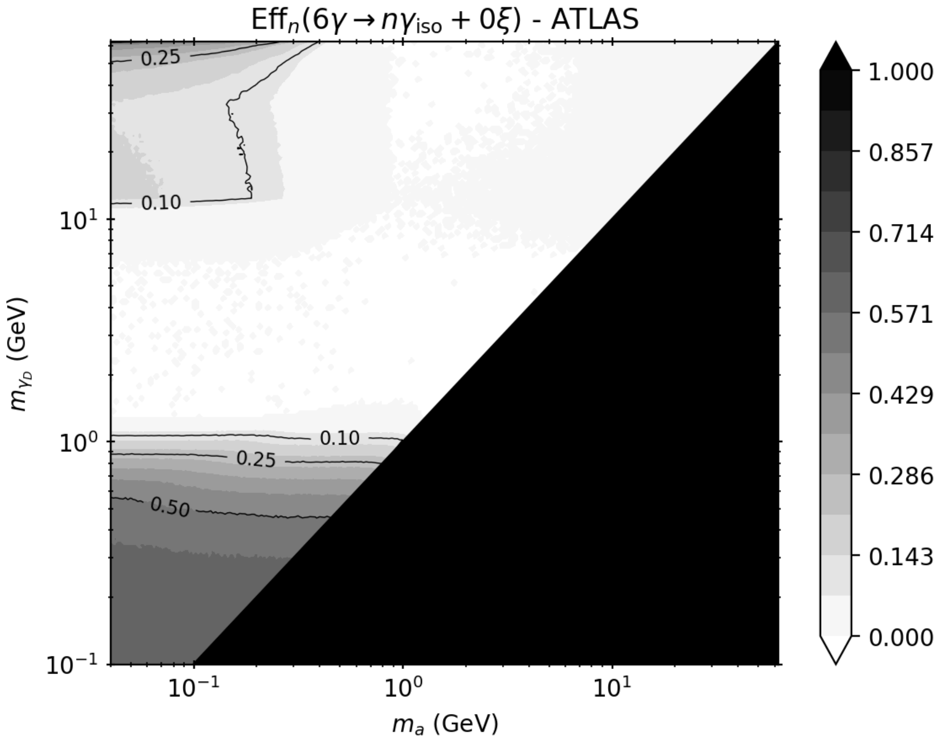
Channel	CMS p_T Requirements
1γ	$p_{1,T} > 145$ GeV [98]
2γ	$p_{1,T} > 30$ GeV and $p_{2,T} > 18$ GeV [30]
3γ	$p_{1,T} > 15$ GeV, $p_{2,T} > 15$ GeV, and $p_{3,T} > 15$ GeV [95]
4γ	$p_{1,T} > 30$ GeV, $p_{2,T} > 18$ GeV, $p_{3,T} > 15$ GeV, and $p_{4,T} > 15$ GeV [27]
5γ	$p_{i,T} > 15$ GeV $(i = 1, 2,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

Estimated Trigger Efficiencies

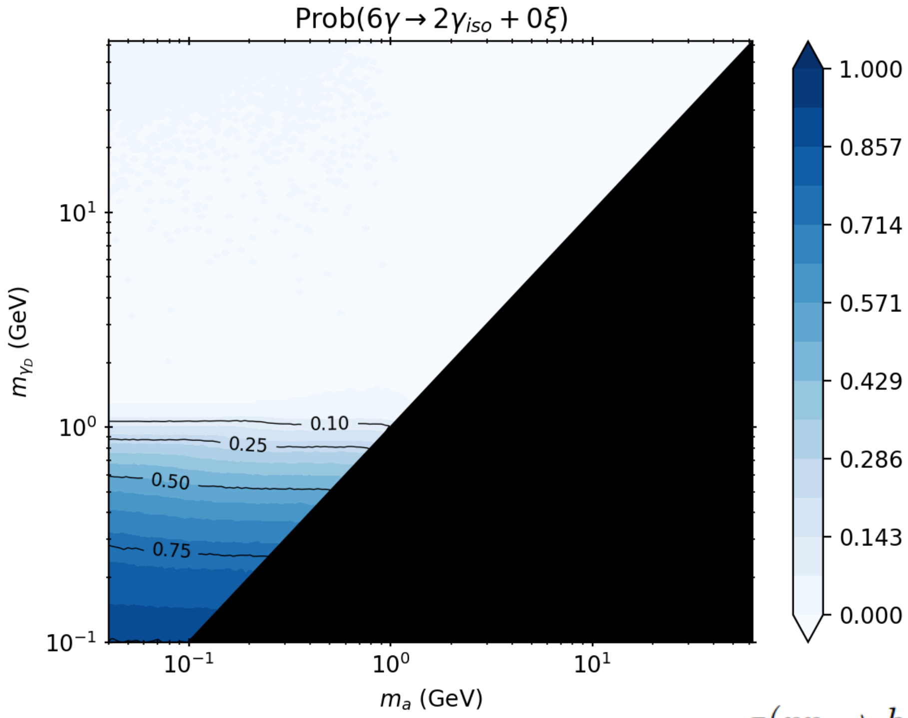


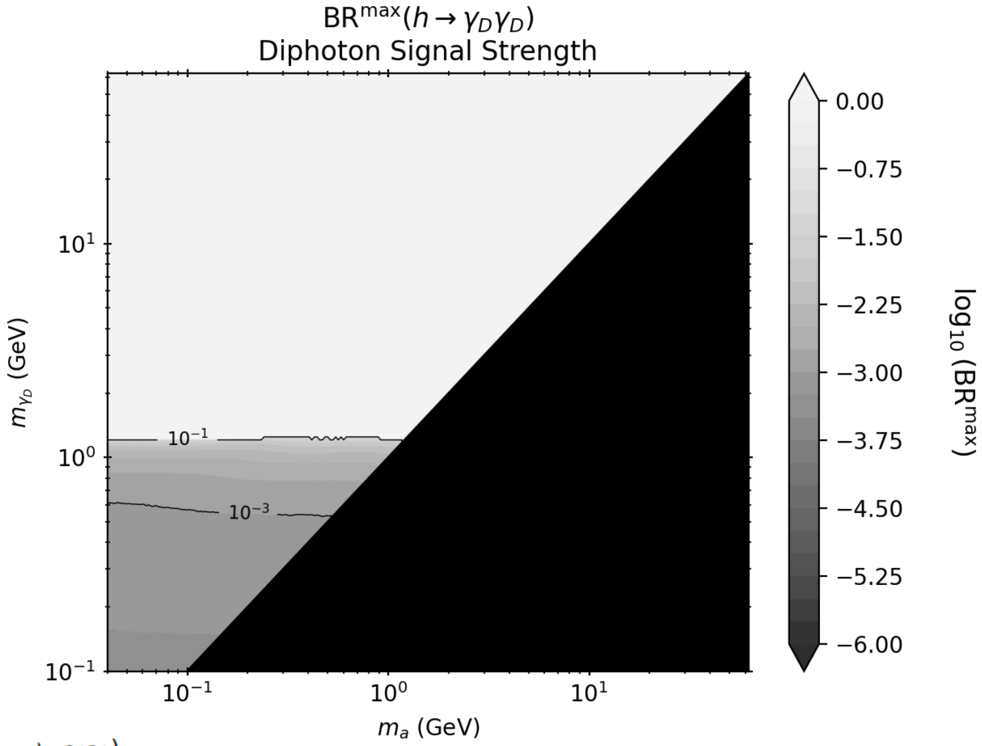
Estimated Trigger Efficiencies





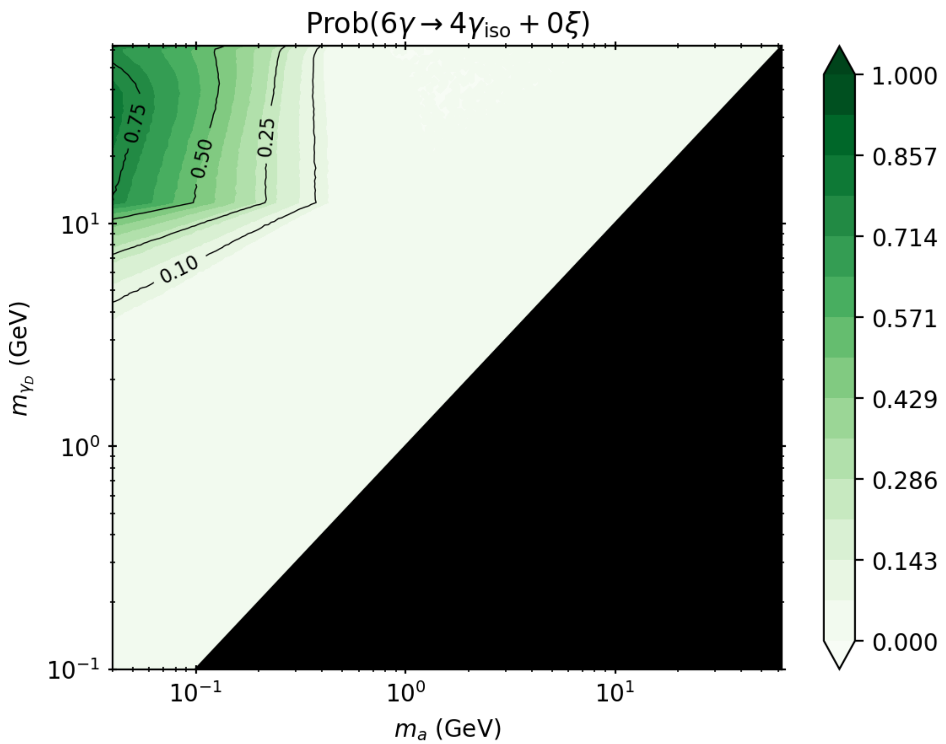
Two Photon Signals

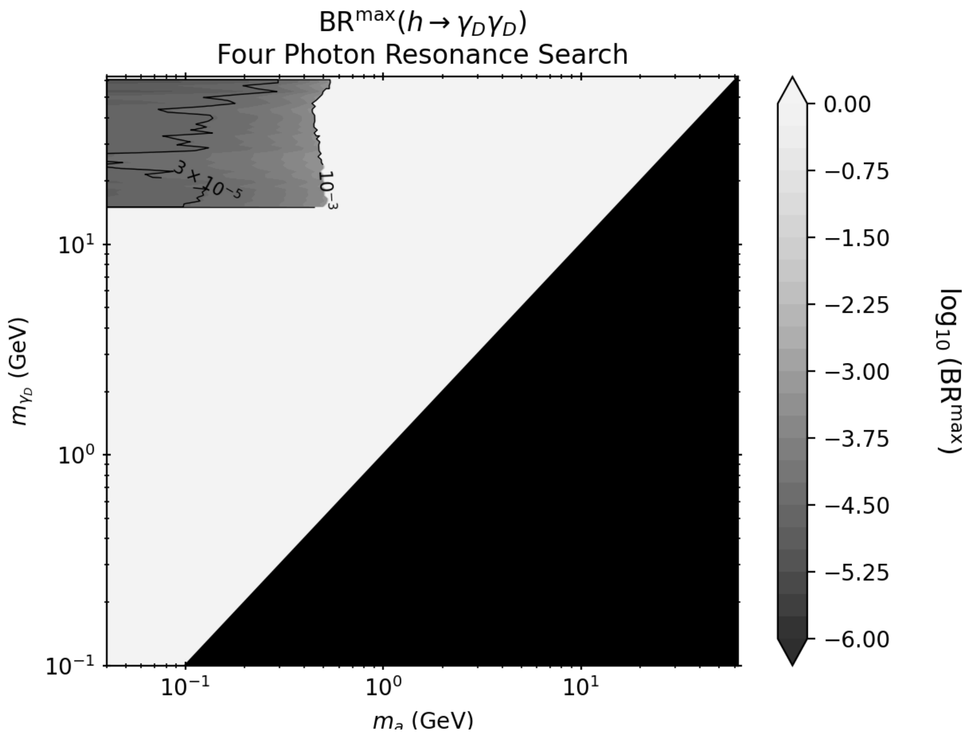




$$\mu = \frac{\sigma(pp \to h)}{\sigma_{\rm SM}(pp \to h)} \frac{\mathrm{BR}(h \to \gamma\gamma)}{\mathrm{BR}_{\rm SM}(h \to \gamma\gamma)}$$

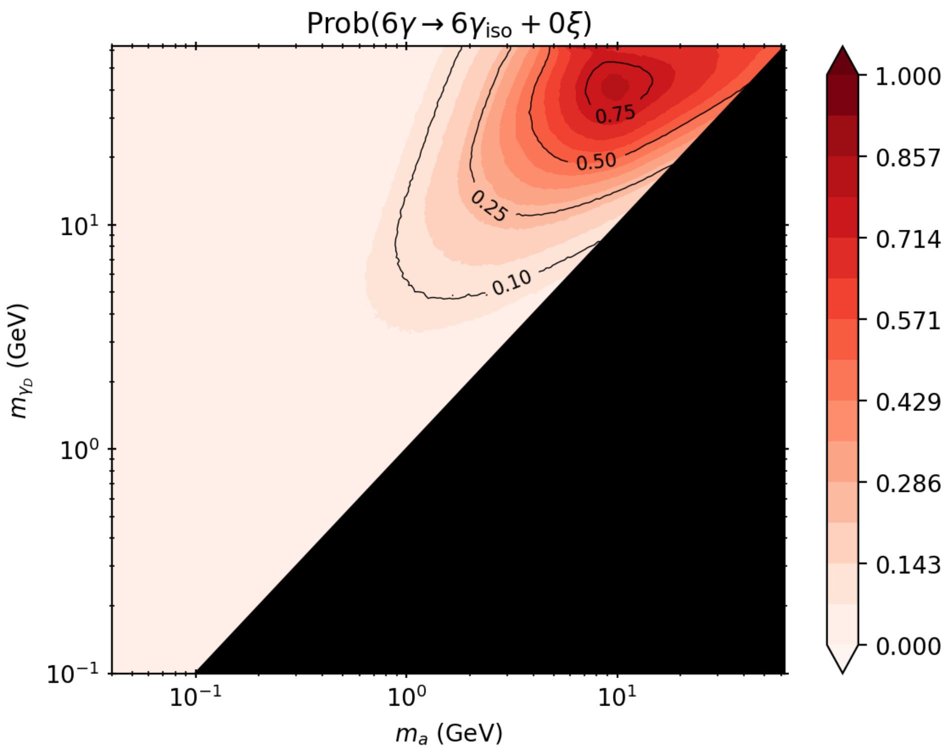
Six Photon Signals

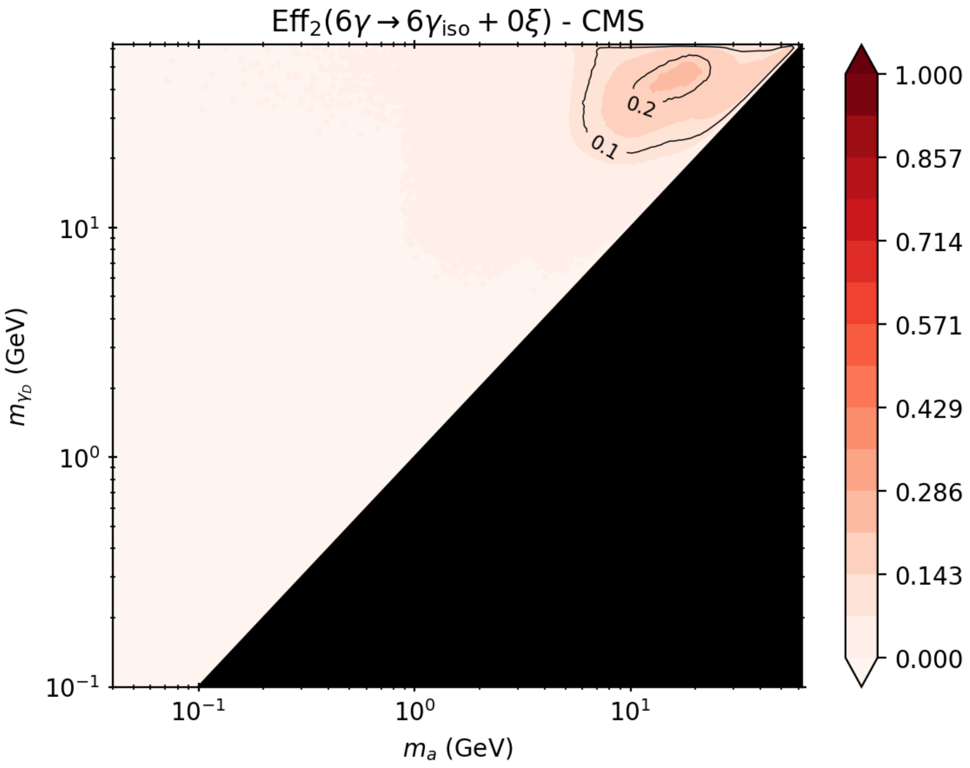




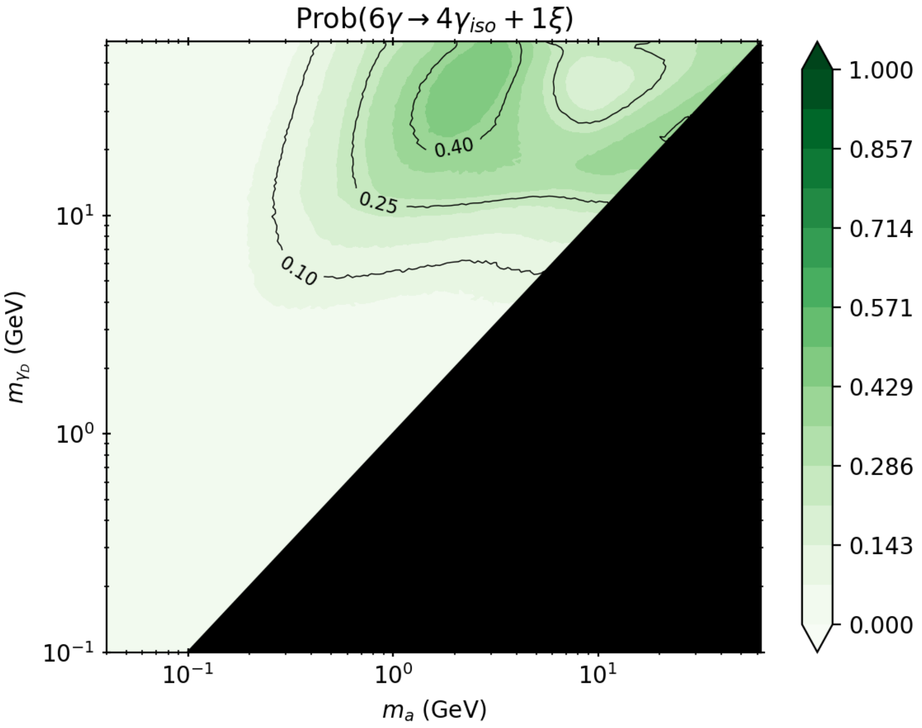
$$\mathrm{BR}(h \to 4\gamma) = \mathrm{BR}(h \to \gamma_D\gamma_D)\mathrm{Prob}(6\gamma \to 4\gamma_{iso})$$

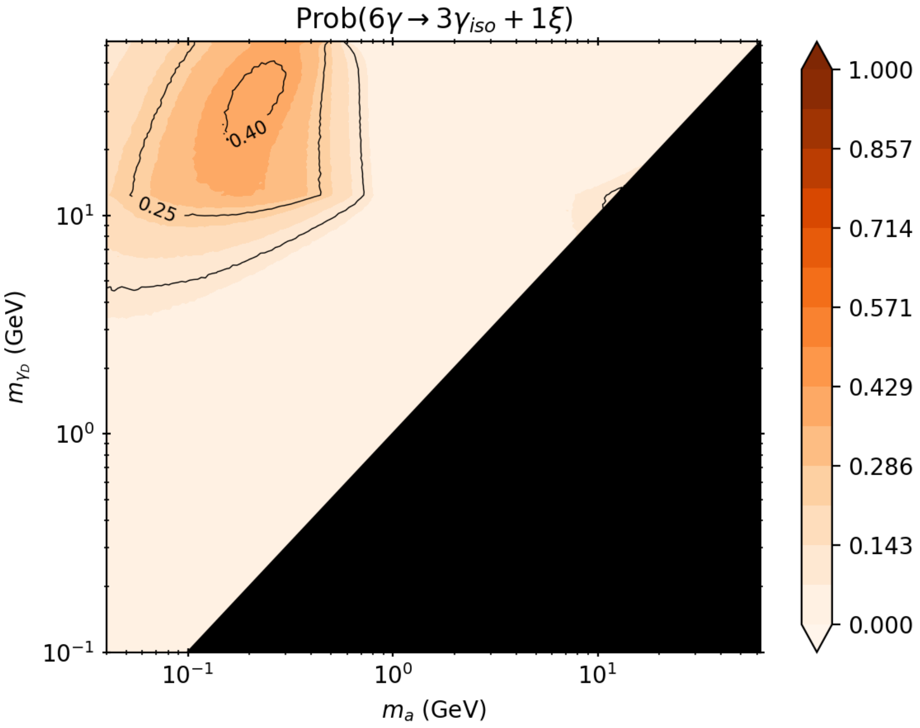
Six Photon Signals



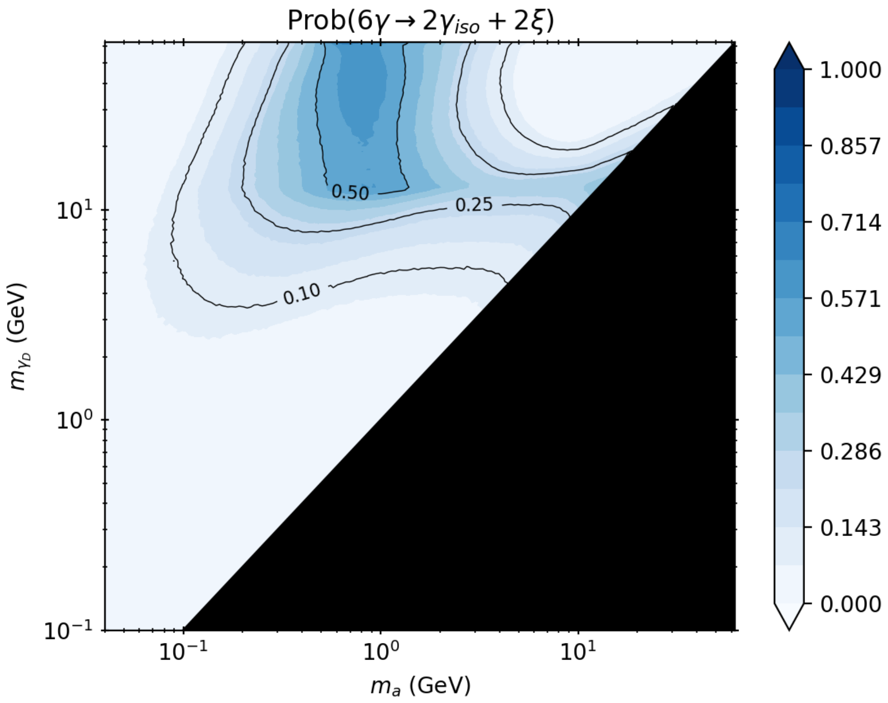


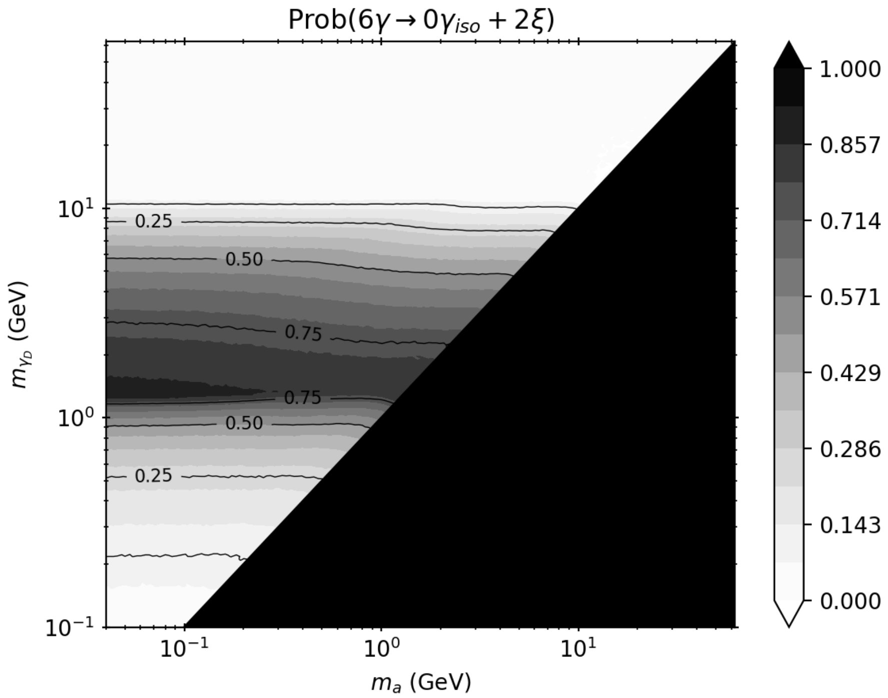
Some Other Signals





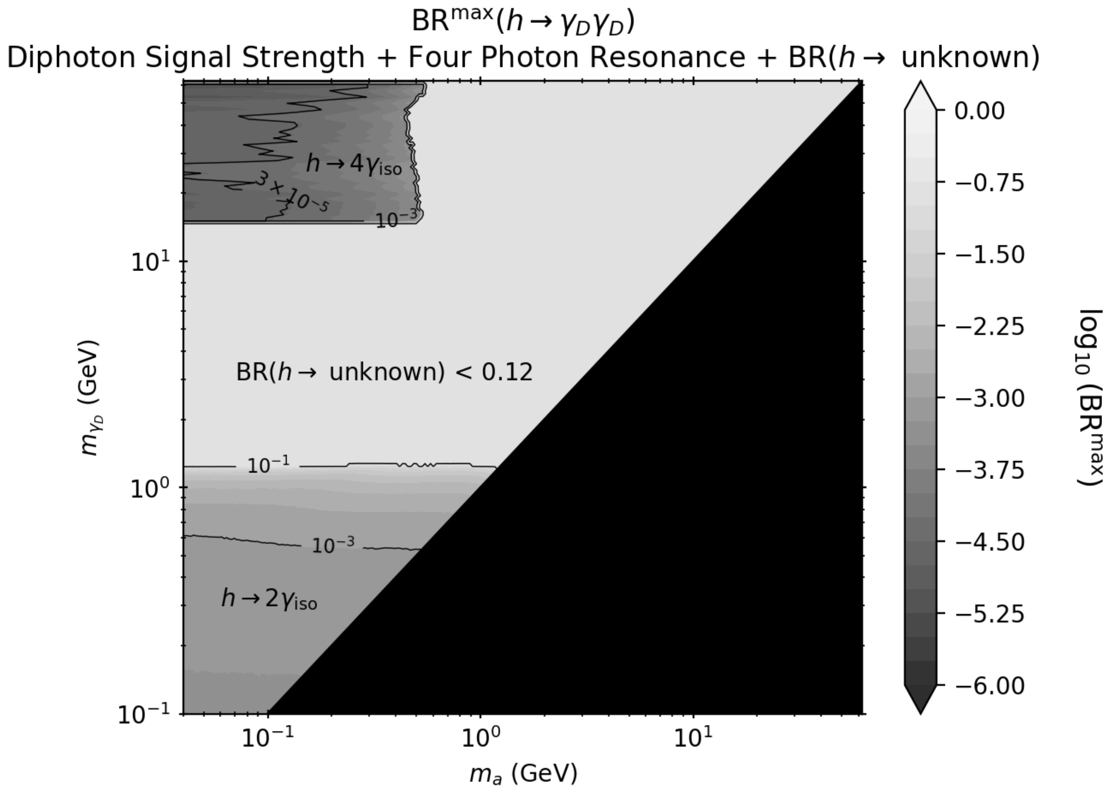
Some Other Signals





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 good chance to be seen



Questions?

Backup

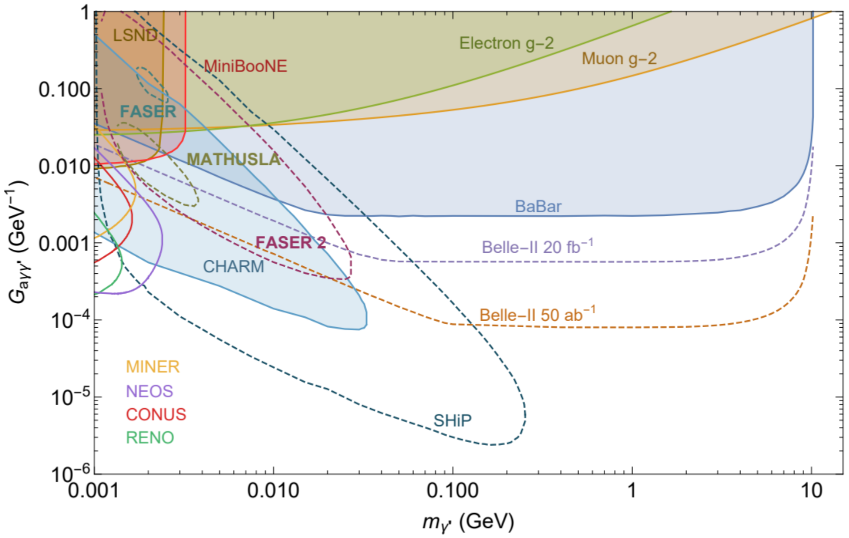
Transverse Momentum Cuts

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 $(i = 1, 2, 3, 4, 5, 6)$

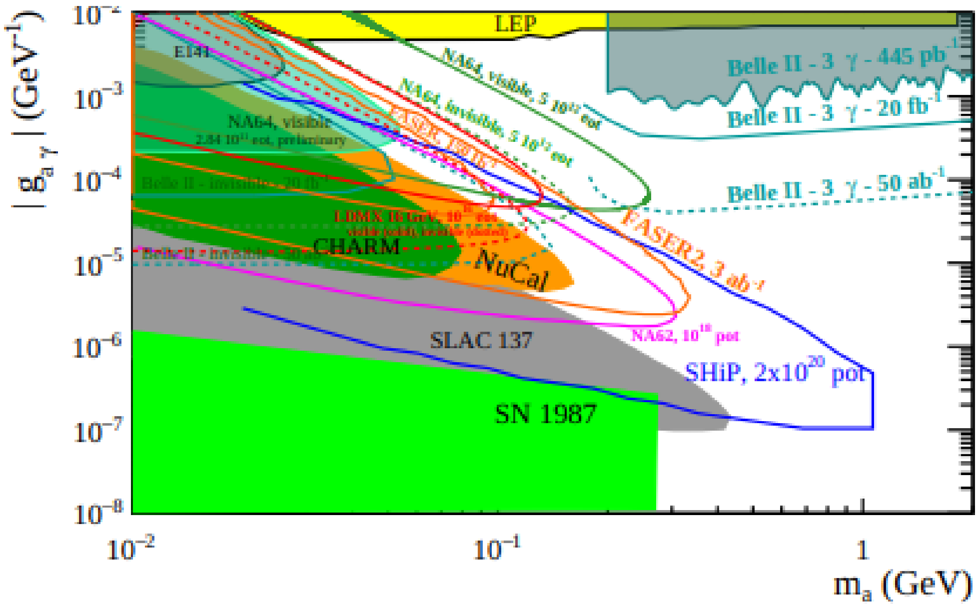
Axion Constraints

ALP-photon-dark photon



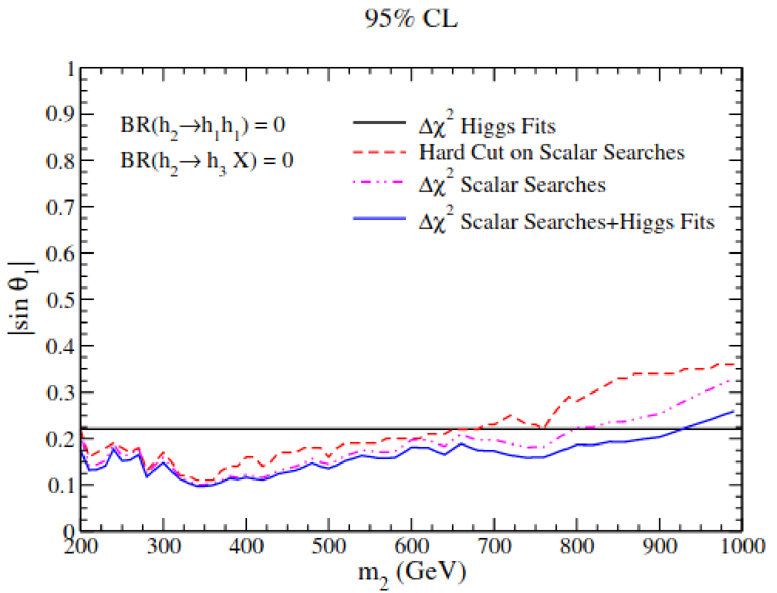
J.Phys.G 50 (2023) 3, 030501

ALP-photon-photon

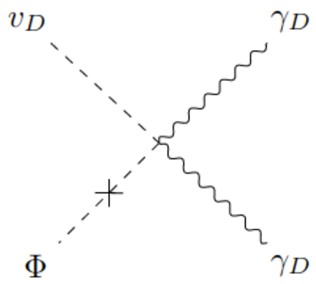


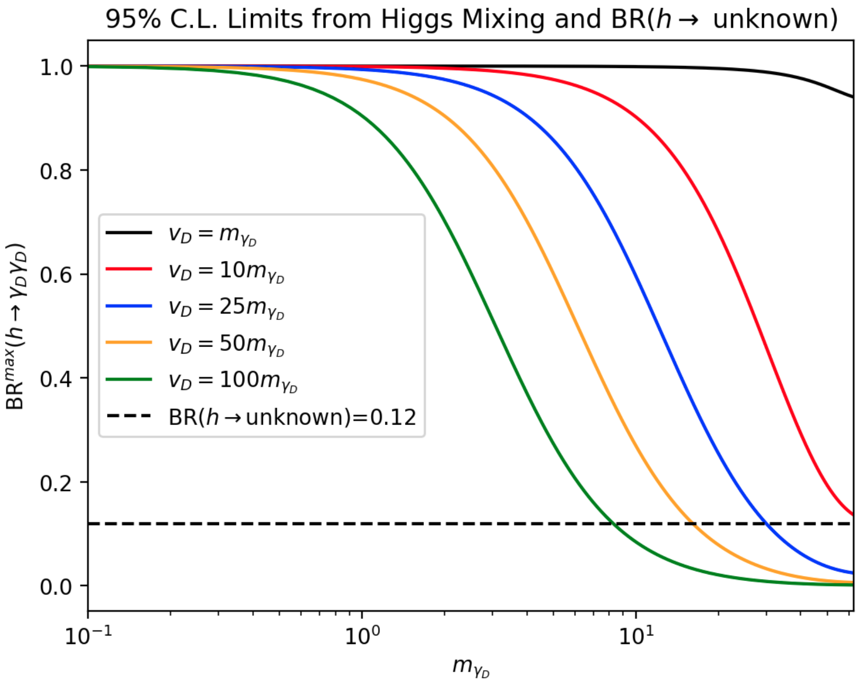
Ann.Rev.Nucl.Part.Sci. 71 (2021) 279-313

Higgs Constraints



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





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