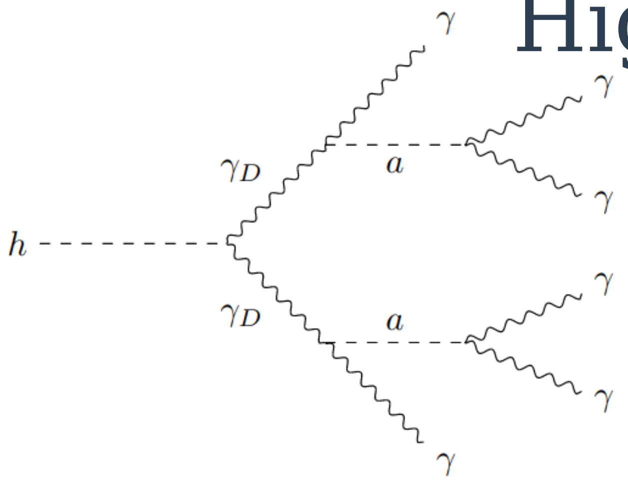
Multi-photon decays of the Higgs boson at the LHC



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w/ Hye-Sung Lee (KAIST) & Ian M. Lewis (Univ. Kansas)

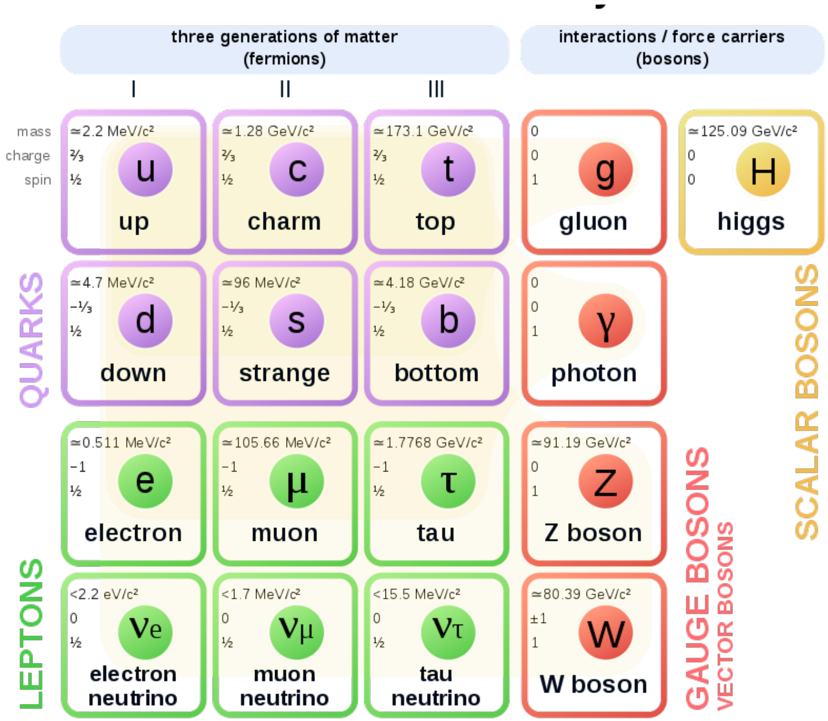
arXiv: 2305.00013

Outline

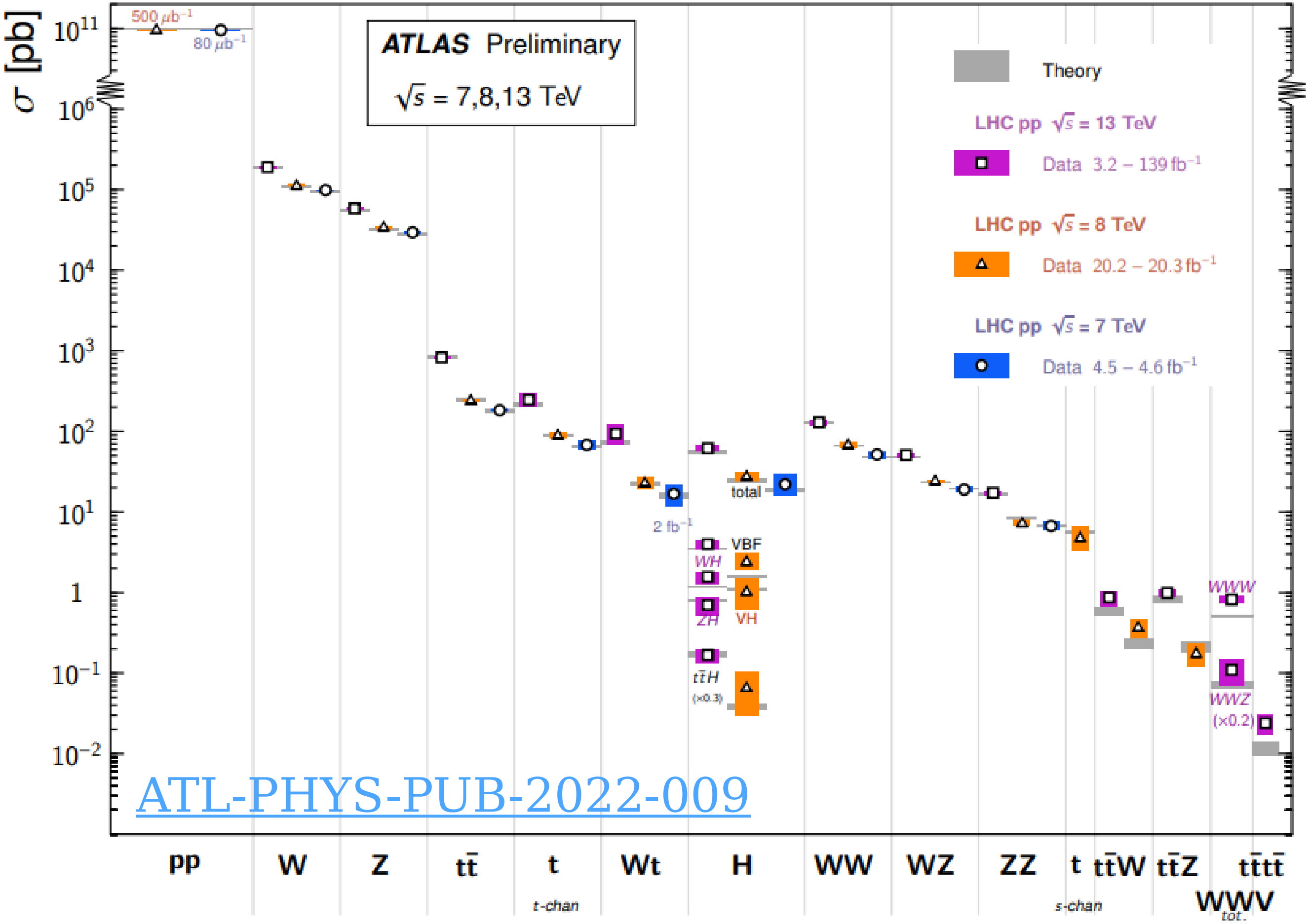
- **Introduction and Motivation**
- **Model Overview**
  - Particle content, key ideas, constraints, assumptions
- **Multi-photon objects & Signal Categories**
  - Photon jets, isolated photons, simulation
- **Results**
- **Conclusion**

The Standard Model

- **The SM works incredibly well**
- **The Higgs mechanism provides masses for all particles in the SM**
- **Nearly every measurement agrees with SM prediction**



The Standard Model



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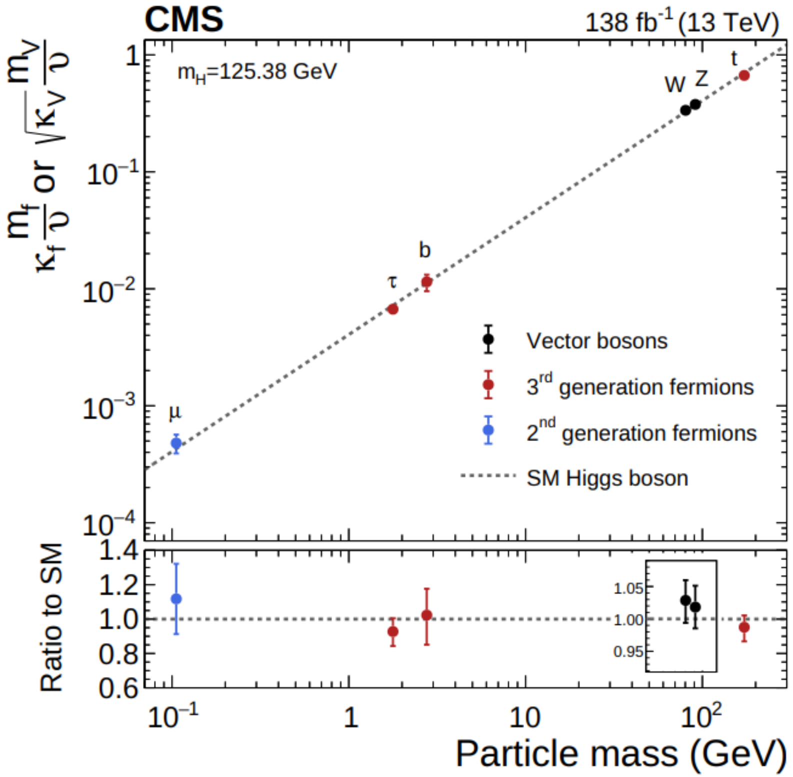
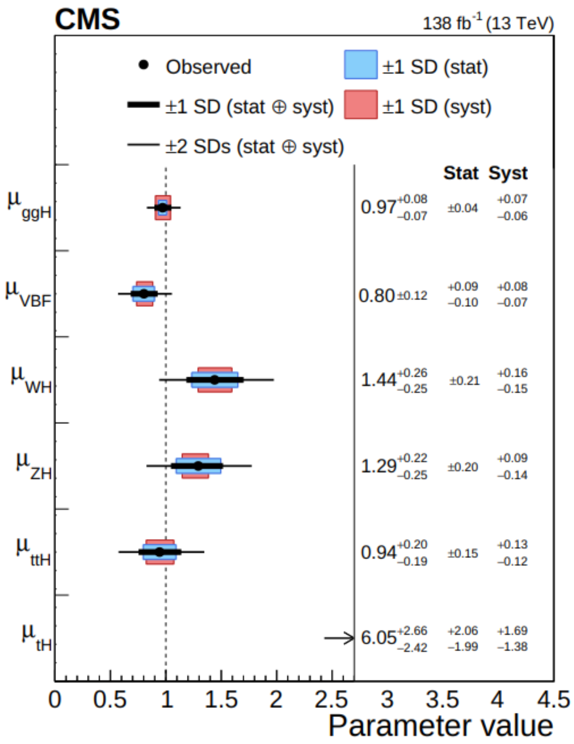
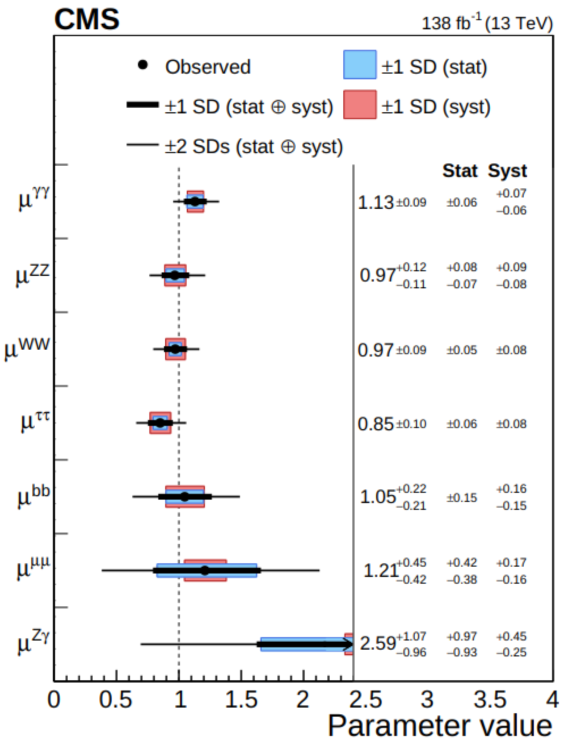
The Standard Model

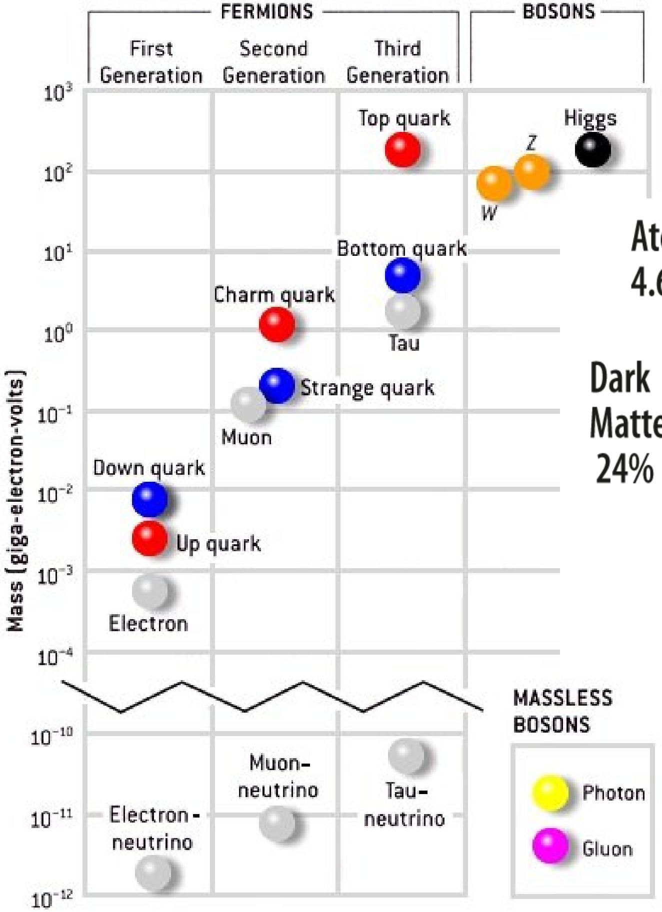


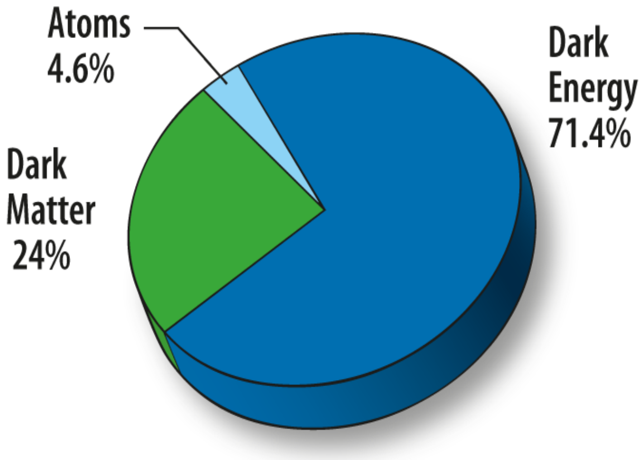




[Nature 607 (2022) 7917, 60-68, arXiv:2103.04956.](#)

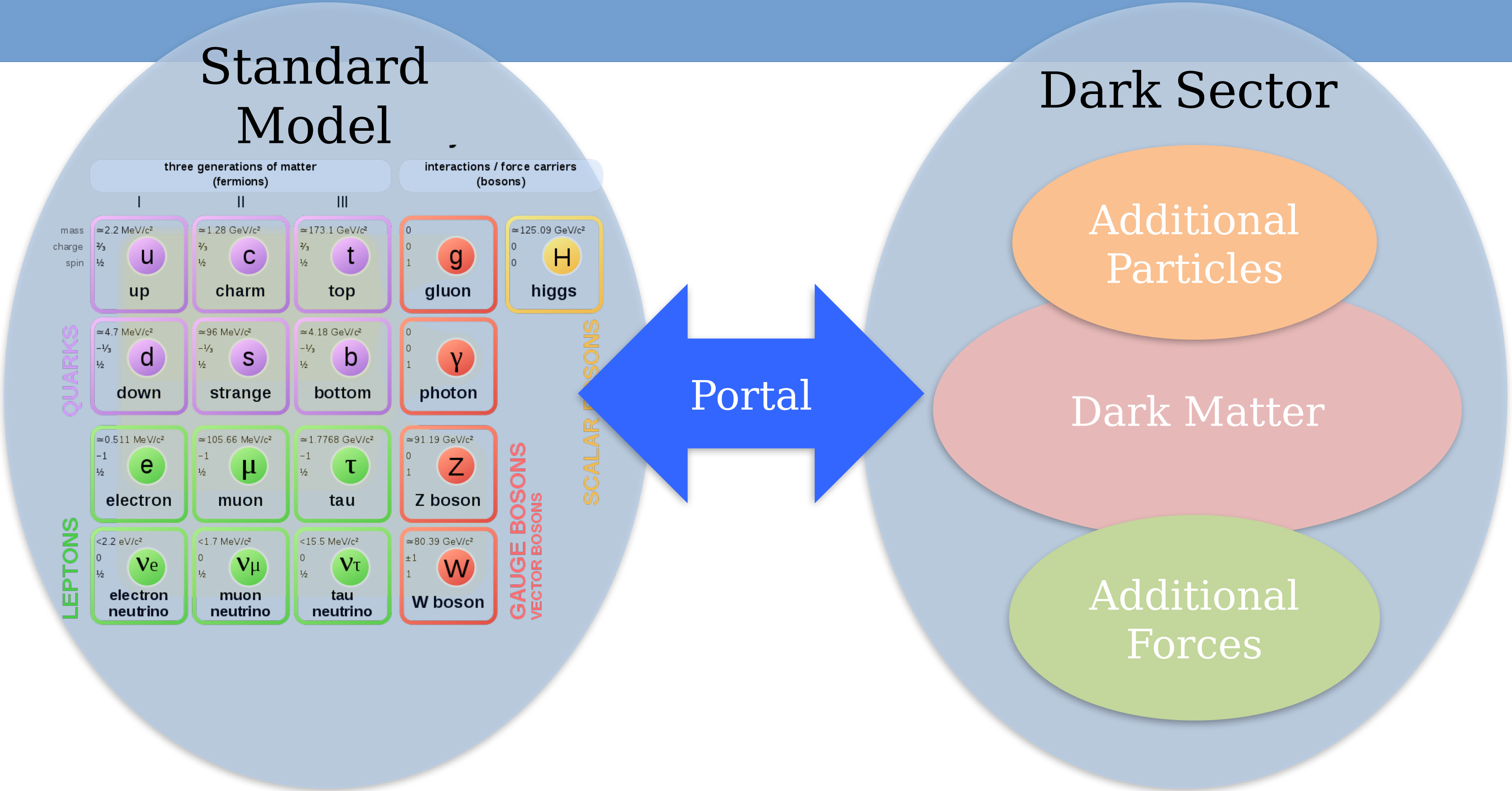
What is the SM missing?





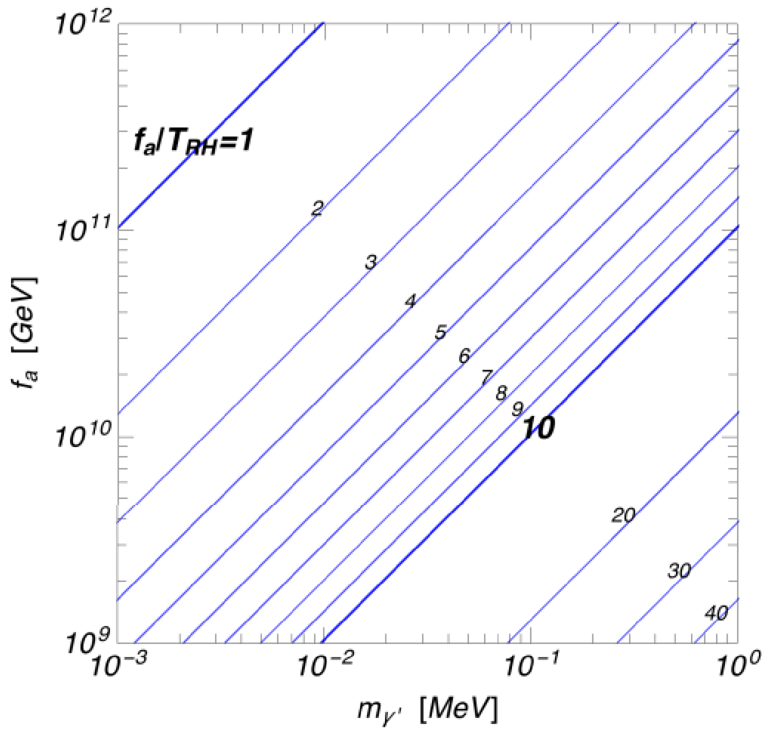
- **Dark Matter**
- **Dark Energy**
- **Matter-antimatter asymmetry**
- **Scale differences in the model (hierarchy, naturalness, etc.)**
- **…**

Portals & Dark Sector



Dark Axion Portal

- **Connect ALP and dark photon**
- **Dark higgs, Dark photon, ALP, VLFs**
- **ALPs/DP could give the right relic density for dark matter**
- **Does not solve strong CP problem**



K. Kaneta, H.-S. Lee, and S. Yun, arXiv: [1611.01466]

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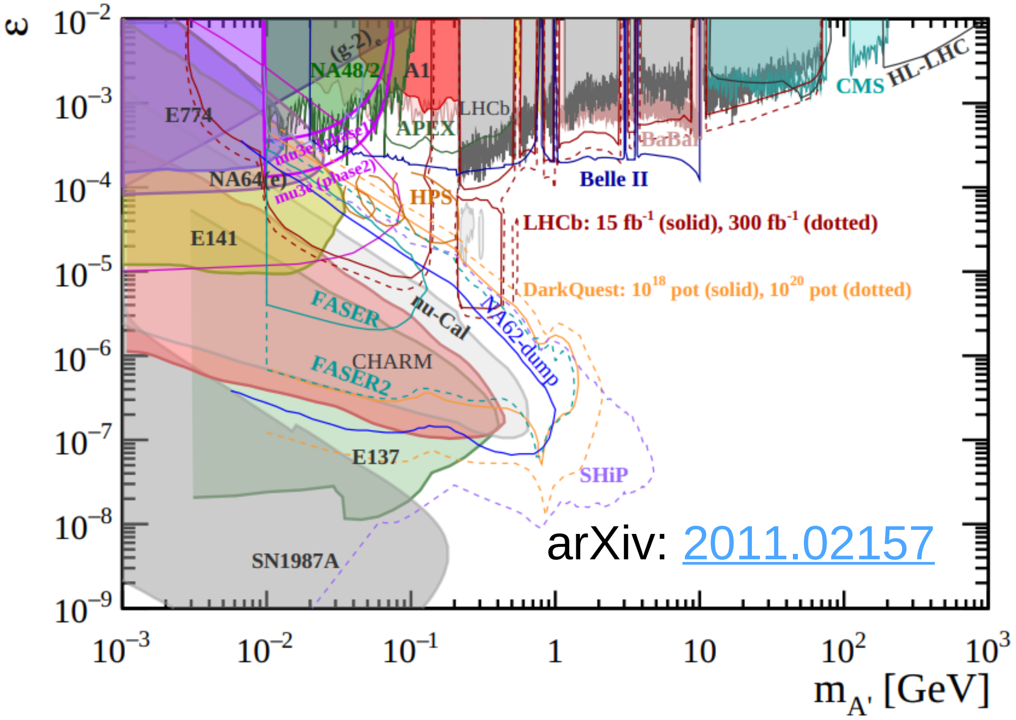
Particle Content

	$SU(3)$	$SU(2)_L$	Y	Y_D	Y_{PQ}
ψ_L	$\mathbf{1}$	$\mathbf{1}$	Q_L	D_L	PQ_L
ψ_R	$\mathbf{1}$	$\mathbf{1}$	Q_R	D_R	PQ_R
H_{PQ}	$\mathbf{1}$	$\mathbf{1}$	0	0	PQ_H
H_D	$\mathbf{1}$	$\mathbf{1}$	0	D_H	0

- **Global PQ symmetry, gauged dark symmetry**
- **SM particles have no PQ or dark charge**
- **BSM Charges chosen to cancel anomalies**

Kinetic Mixing

$$\mathcal{L}_{U(1)} = -\frac{1}{4}\left(F_Y^{\mu\nu}F_{Y\mu\nu} - 2\epsilon F_Y^{\mu\nu}F_{D\mu\nu} + F_D^{\mu\nu}F_{D\mu\nu}\right)$$



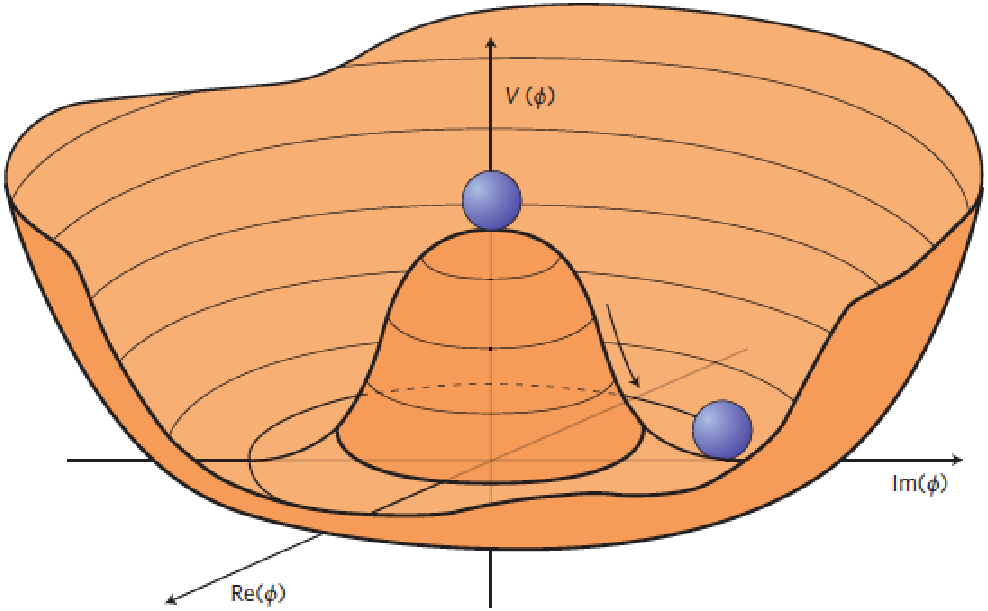
arXiv: [2011.02157](https://arxiv.org/abs/2011.02157)

- **Experimental limits are important**
- **The VLFs induce kinetic mixing**
- **For O(1) dark gauge couplings expect O(0.1) kinetic mixing**
- **We will assume zero kinetic mixing**

Tracking the Goldstone modes

- **Normal SM Higgs mechanism**
  - SM Higgs goldstones become the longitudinal modes of W and Z
- **Dark Higgs mechanism**
  - H_D goldstone becomes longitudinal modes of dark photon
- **PQ mechanism at some scale f_a**
  - H_{PQ} goldstone becomes the ALP

SM Higgs Mechanism



$$V(\varphi) = -\mu^2(\varphi^\dagger\varphi) + \lambda(\varphi^\dagger\varphi)^2.$$

$$\frac{\partial \mathcal{V}}{\partial|\varphi|^2} = \mu^2 - 2\lambda\varphi_0^\dagger\varphi_0 = 0$$

$$\varphi_0^\dagger\varphi_0 = v^2 = \frac{\mu^2}{2\lambda}$$

$$\varphi = \frac{1}{\sqrt{2}}\begin{pmatrix} \sqrt{2}G^+ \\ h + v + iG_0 \end{pmatrix}$$

Scalar Sector Summary

- Potential depends on all scalars
- Should in principle write down the most general renormalizable potential
- Each scalar acquires a vev
- Scalar kinetic terms give masses to vetor bosons
- There could be some scalar mixing between the CP even neutral states

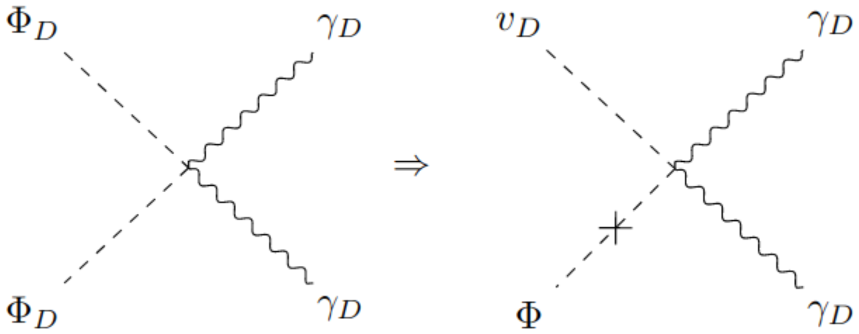
$$\mathcal{V}(\Phi, H_D, H_{\mathrm{PQ}})$$

$$|D_\mu \Phi|^2 + |D_\mu H_D|^2$$

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \hat{R}(\theta_S) \begin{pmatrix} h \\ h_d \end{pmatrix}$$

Higgs Couplings

- **Higgs dark photon coupling**

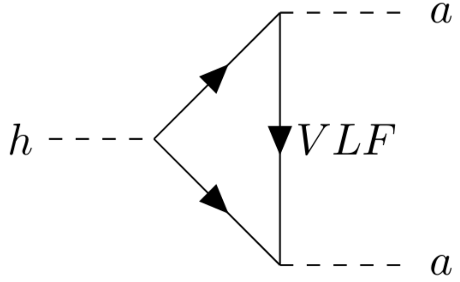


$$|D_\mu H_D|^2 \longrightarrow \frac{\lambda_{h\gamma_D\gamma_D}}{2} h\gamma_D^\mu \gamma_{D\mu}$$

$$H_D = \frac{1}{\sqrt{2}}(h_D + v_D)$$

$$\lambda_{h\gamma_D\gamma_D} \sim \sin\theta \frac{m_{\gamma_D}^2}{v_D}.$$

- **In principle there is a Higgs ALP coupling**



ALP Couplings

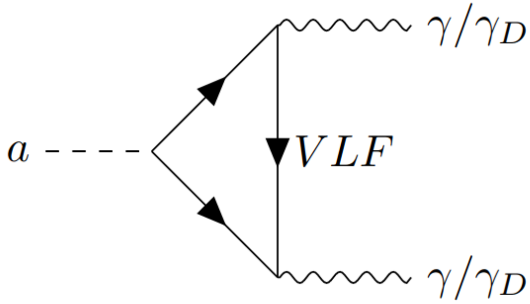
$$\frac{G_{a\gamma\gamma}}{4} a F^{\mu\nu} \tilde{F}_{\mu\nu} + \frac{G_{a\gamma\gamma_D}}{2} a F_D^{\mu\nu} \tilde{F}_{\mu\nu} + \frac{G_{a\gamma_D\gamma_D}}{4} a F_D^{\mu\nu} \tilde{F}_{D\mu\nu}$$

- **ALP-photon-photon**
- **ALP-photon-dark photon**
- **ALP-dark photon-dark photon**

$$G_{a\gamma\gamma} = \frac{e^2}{8\pi^2}\frac{PQ_\Phi}{f_a}\left[2N_C Q_\psi^2 - \frac{2}{3}\frac{4+z}{1+z}\right],$$

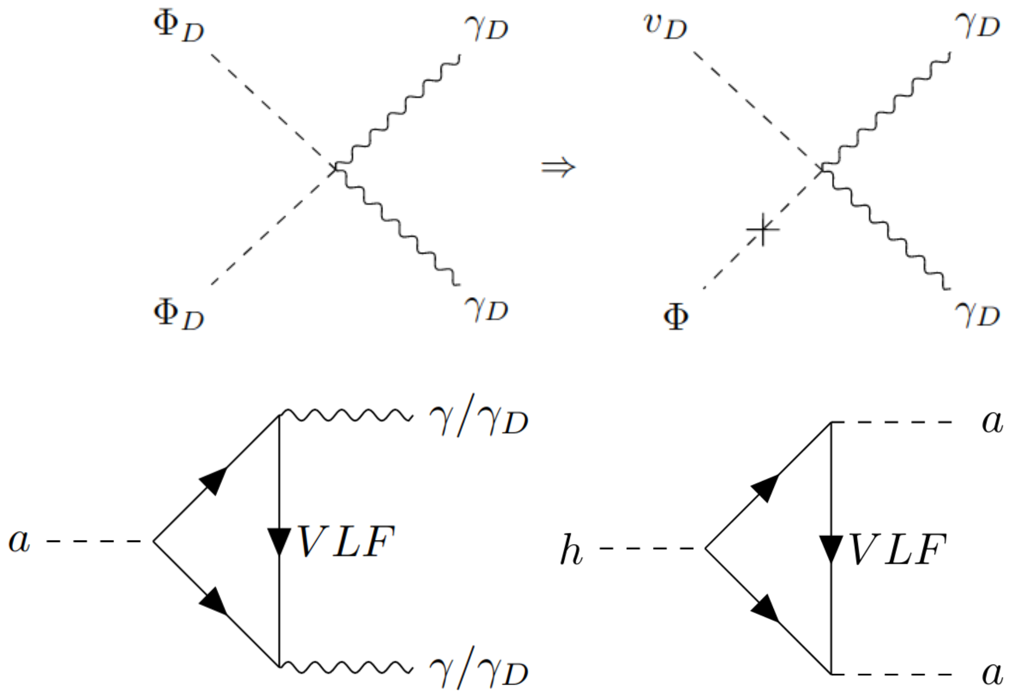
$$G_{a\gamma\gamma'} \simeq \frac{ee'}{8\pi^2}\frac{PQ_\Phi}{f_a}\left[2N_C D_\psi Q_\psi\right] + \varepsilon G_{a\gamma\gamma},$$

$$G_{a\gamma'\gamma'} \simeq \frac{e'^2}{8\pi^2}\frac{PQ_\Phi}{f_a}\left[2N_C D_\psi^2\right] + 2\varepsilon G_{a\gamma\gamma'}.$$



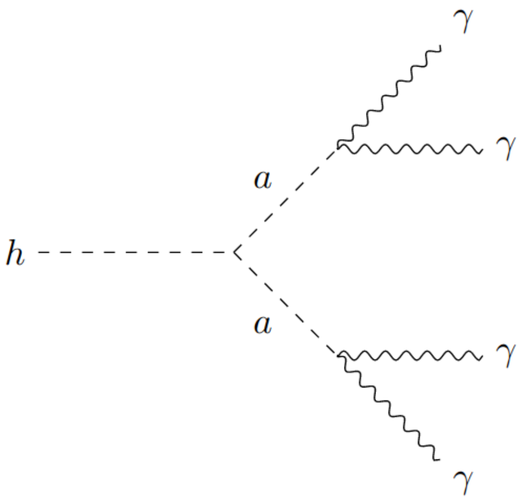
Why photons?

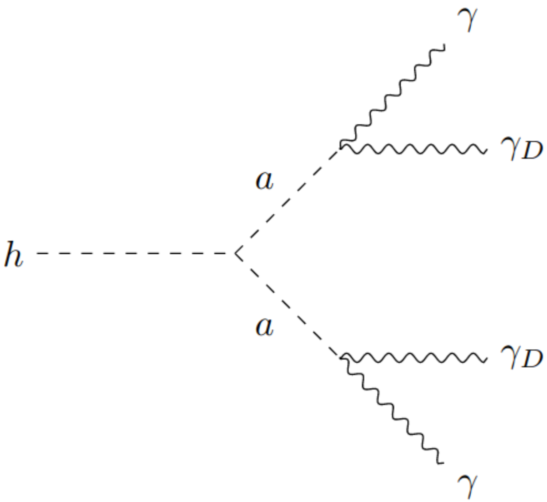
- Axion to diphoton is well known
- Higgs to diphoton is also well known
- Photons are “clean” at colliders
- Go look for additional signals at LHC that contain photons

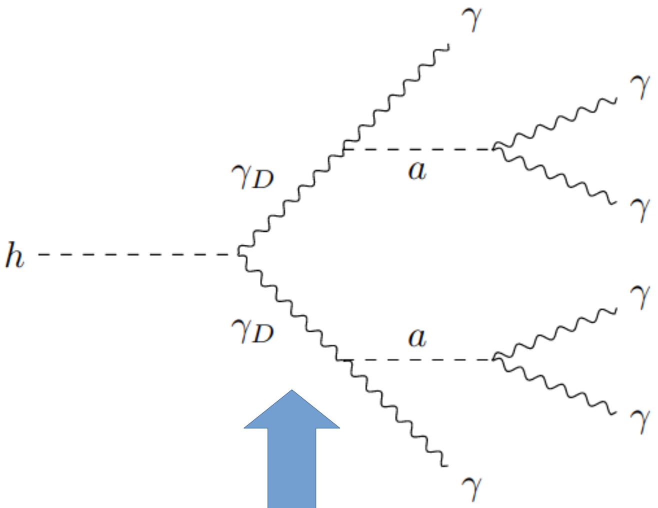


Some Signals With Photons

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







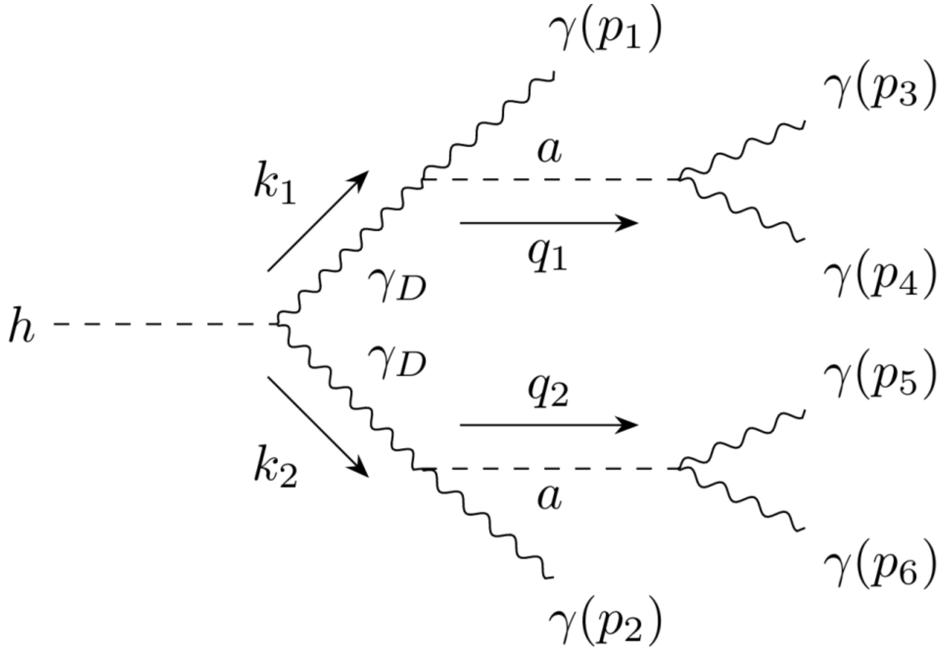
This Talk/Work

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

Higgs to six photons

$$\sigma(pp \to h \to \gamma_D\gamma_D \to 6\gamma) \approx \sigma(pp \to h)\mathrm{BR}\left(h \to \gamma_D\gamma_D\right)\mathrm{BR}^2\left(\gamma_D \to a\gamma\right)\mathrm{BR}^2\left(a \to \gamma\gamma\right)$$

- **Assume Shell decays**
- **Use narrow width approximation**
- **Take the spin averaged matrix element**

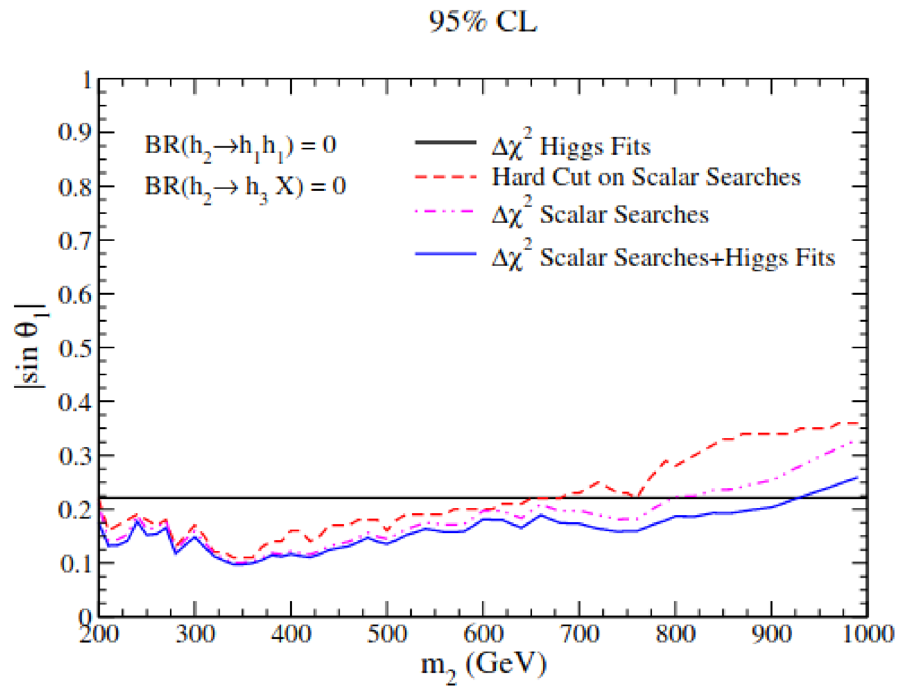


Full Branching Ratio

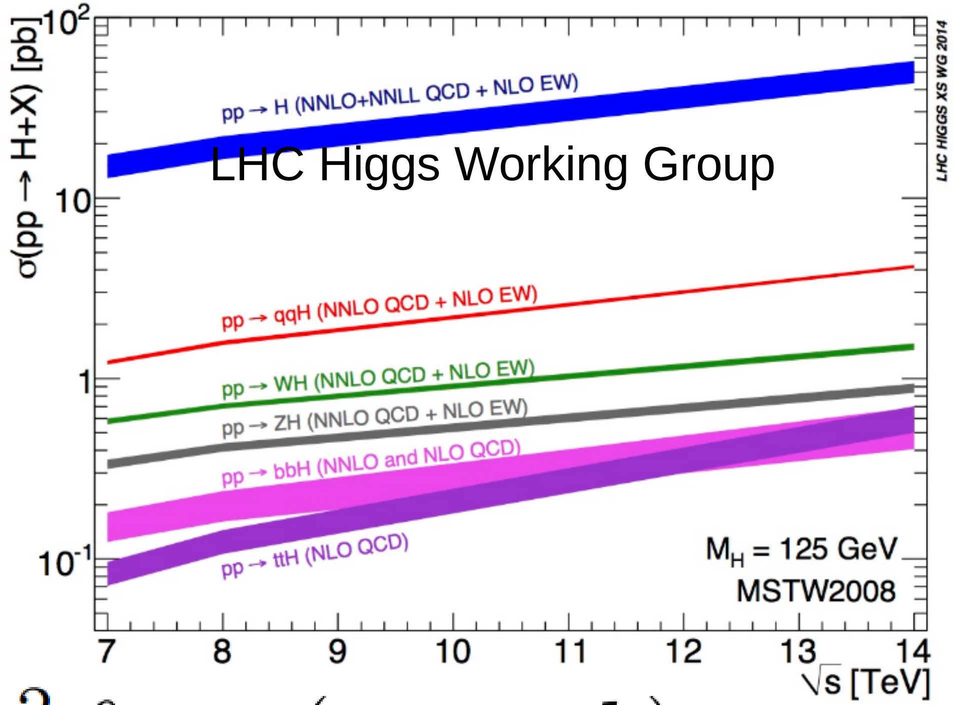
$$\begin{aligned}
&\mathrm{BR}\big(h \to \gamma_D(k_1)\gamma_D(k_2) \to \gamma(p_1)a(q_1)\gamma(p_2)\gamma(q_2) \to \gamma(p_1)\gamma(p_3)\gamma(p_4)\gamma(p_2)\gamma(p_5)\gamma(p_6)\big) \\
&\quad = \mathrm{BR}(h \to \gamma_D\gamma_D)\ \mathrm{BR}(\gamma_D \to a\gamma)^2\ \mathrm{BR}(a \to \gamma\gamma)^2 \frac{9\int d\Omega_h d\Omega_{\gamma_D(k_1)} d\Omega_{\gamma_D(k_2)} f(p_1,k_1,p_2,k_2)}{(2\pi)^3 \left(12 - 4\frac{m_h^2}{m_{\gamma_D}^2} + \frac{m_h^4}{m_{\gamma_D}^4}\right)(m_{\gamma_D}^2 - m_a^2)^4}
\end{aligned}$$

$$\begin{aligned}
f(p_1,k_1,p_2,k_2) = {} & (p_2\cdot k_2)(k_1\cdot k_2)(p_1\cdot p_2)(p_1\cdot k_1) + (p_2\cdot k_1)(p_2\cdot k_2)(p_1\cdot k_2)(p_1\cdot k_1) \\
& - (p_2\cdot k_1)(p_1\cdot p_2)(p_1\cdot k_1)k_2^2 - (p_2\cdot k_2)(p_1\cdot k_2)(p_1\cdot p_2)k_1^2 \\
& + \frac{1}{2}(p_1\cdot p_2)^2 k_1^2 k_2^2.
\end{aligned}$$

Higgs Production

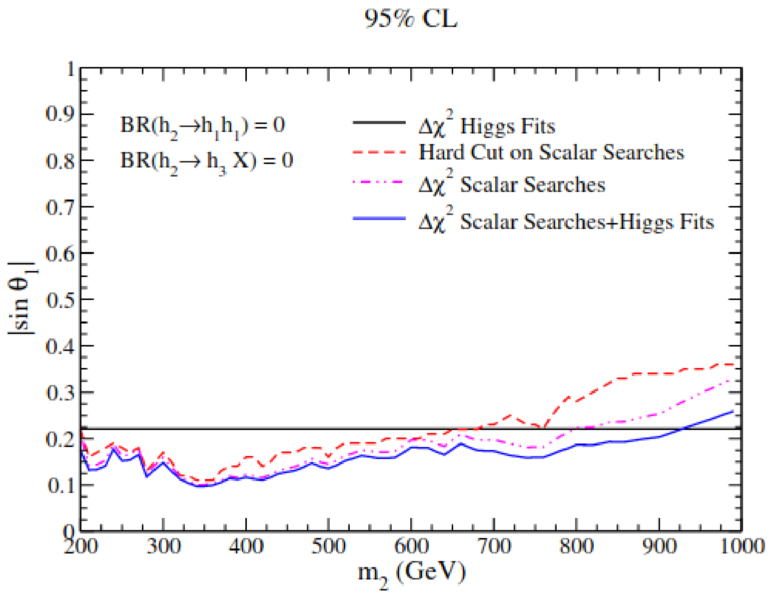


S. Adhikari, SDL, I.M. Lewis, M. Sullivan arXiv: [2203.07455]

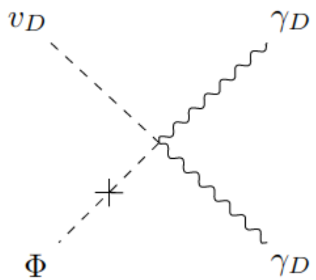


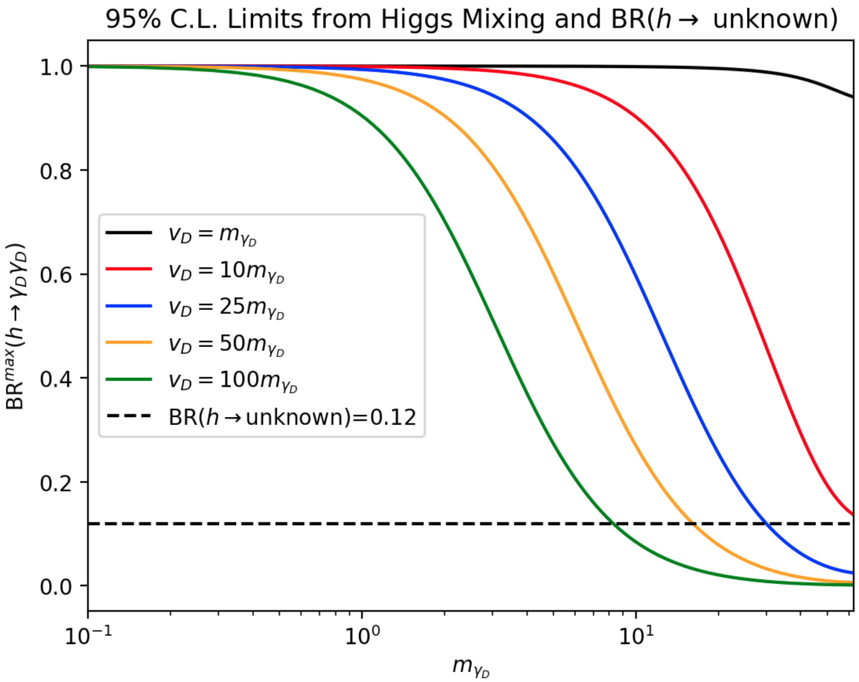
$$\sigma(pp \to h) = \cos^2\theta\,\sigma_{\rm SM}(pp \to h)$$

Higgs Constraints



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

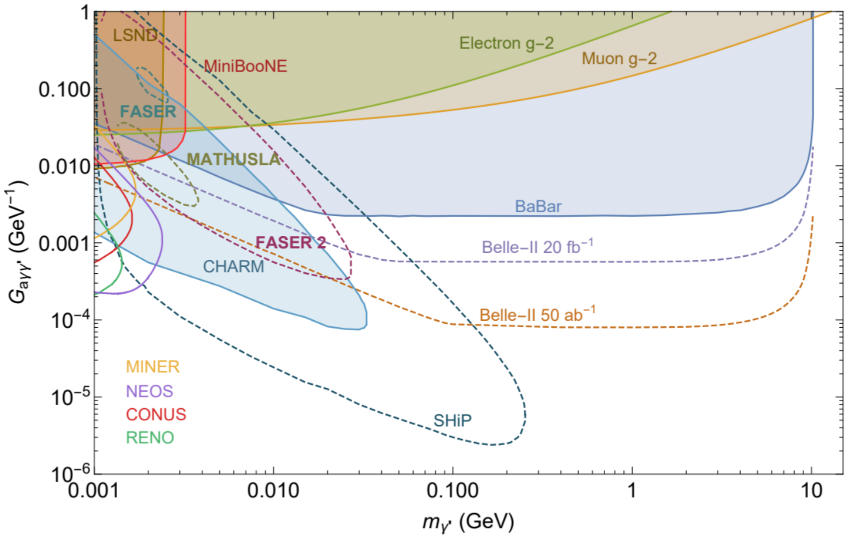




$$|\lambda^{\max}_{h\gamma_D\gamma_D}| \sim |\sin\theta_{\max}|\frac{m^2_{\gamma_D}}{v_D} \approx 0.1 m^2_{\gamma_D}/v_D$$

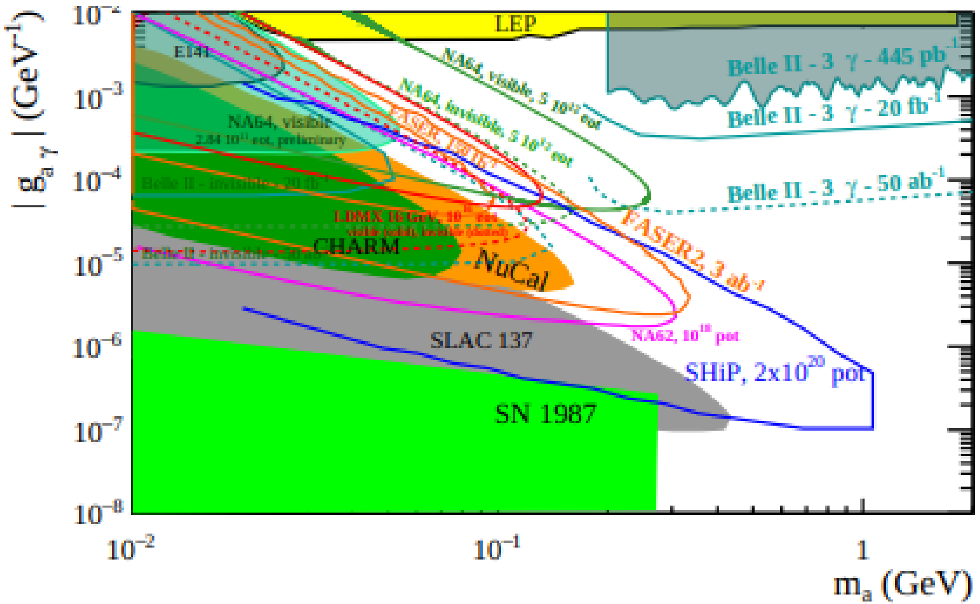
Axion Constraints

ALP-photon-dark photon



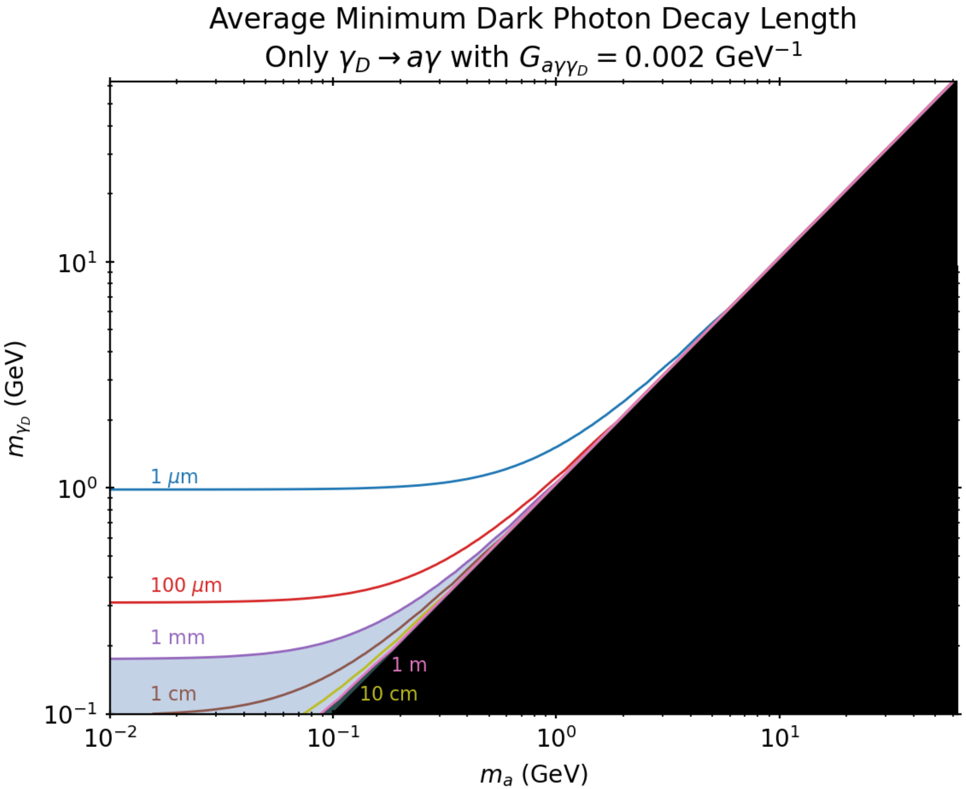
J.Phys.G 50 (2023) 3, 030501

ALP-photon-photon



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

Average Decay Lengths



$$\Gamma(\gamma_D \to \gamma a) = \frac{|G_{a\gamma\gamma_D}|^2 m_{\gamma_D}^3}{96\pi}\left(1 - \frac{m_a^2}{m_{\gamma_D}^2}\right)^3$$

$$G_{a\gamma\gamma_D} \approx 2 \times 10^{-3}\ \mathrm{GeV}^{-1}$$

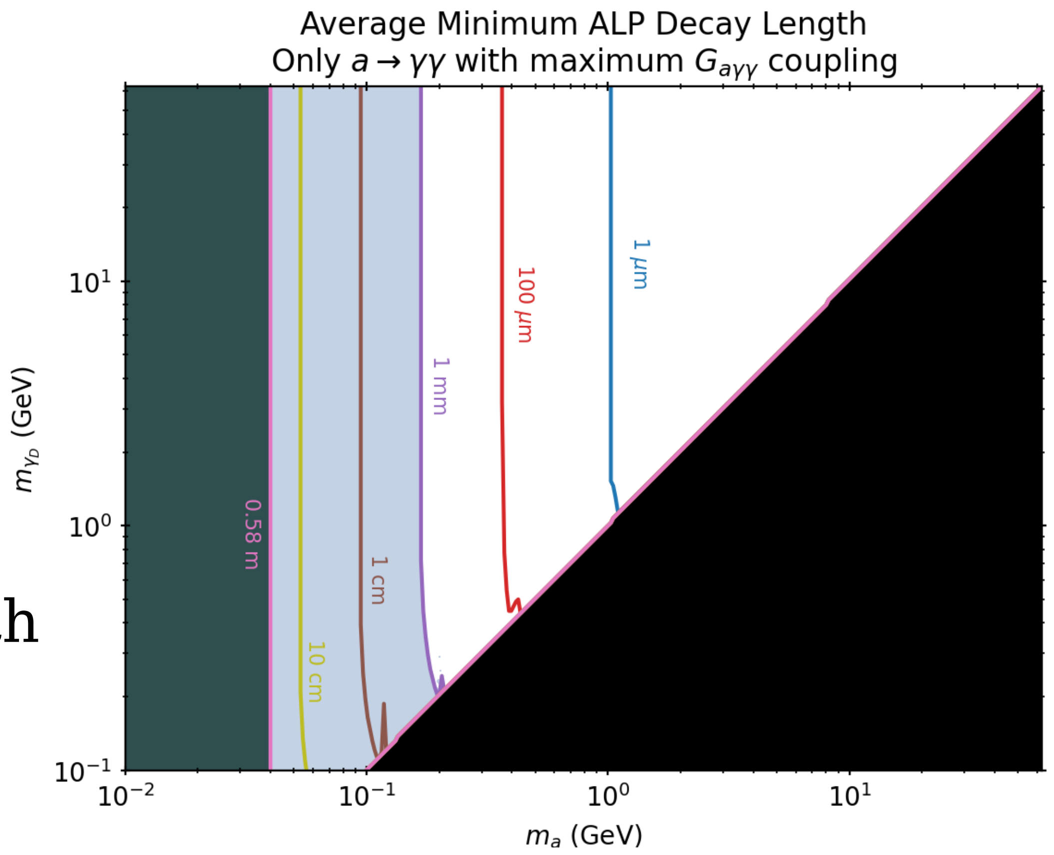
Mostly prompt decays with some displaced vertices

Average Decay Lengths

$$\Gamma(a \to \gamma\gamma) = \frac{|G_{a\gamma\gamma}|^2 m_a^3}{64\pi}$$

Maximal $G_{a\gamma\gamma}$

Mostly prompt decays, with some displaced vertices, and some missing energy



Model Assumptions

- **Want on-shell decays**
- **Zero kinetic mixing**
- **Dark photon only decays to ALP and photon**
- **ALP only decays to photon pairs**

$$m_h > m_{\gamma_D} > m_a$$

$$\varepsilon \to 0$$

$$\mathrm{BR}(\gamma_D \to a\gamma) = 1$$

$$\mathrm{BR}(a \to \gamma\gamma) = 1$$

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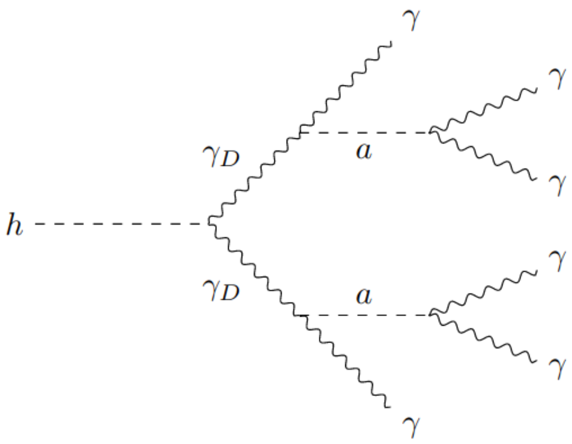
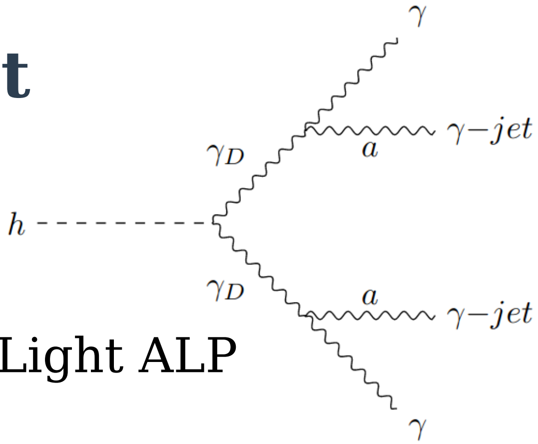
Photon Jets

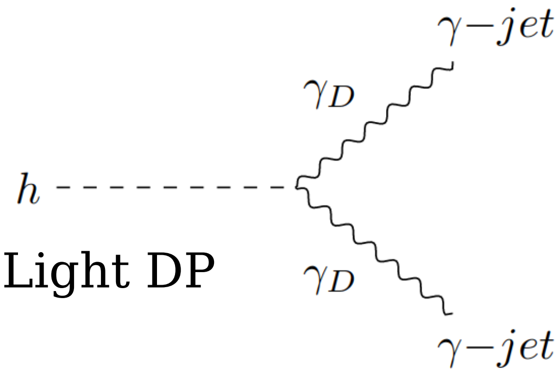
- **Light particles get large boost**
- **Decay products become collimated**





Light ALP

Apparent Landau-Yang Violation



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

Generate Truth Level Events

$$h \to \gamma_d \gamma_d \to a\gamma a\gamma \to 6\gamma$$

1. Truth level events {γ}

$$\tau = m_h^2/S,\ \sqrt{S} = 13\ \text{TeV}$$

- Parton Luminoisty
- Spin-correlations
- Uniformly sample phase space
- Uniformly sample higgs rapidity

$$\mathcal{L}(\tau) = \int_{\ln\sqrt{\tau}}^{-\ln\sqrt{\tau}} dy_h g(\sqrt{\tau}e^{y_h}, \mu_F) g(\sqrt{\tau}e^{-y_h}, \mu_F),$$

$$\frac{9\int d\Omega_h d\Omega_{\gamma_D(k_1)} d\Omega_{\gamma_D(k_2)} f(p_1, k_1, p_2, k_2)}{(2\pi)^3 \left(12 - 4\frac{m_h^2}{m_{\gamma_D}^2} + \frac{m_h^4}{m_{\gamma_D}^4}\right)(m_{\gamma_D}^2 - m_a^2)^4}$$

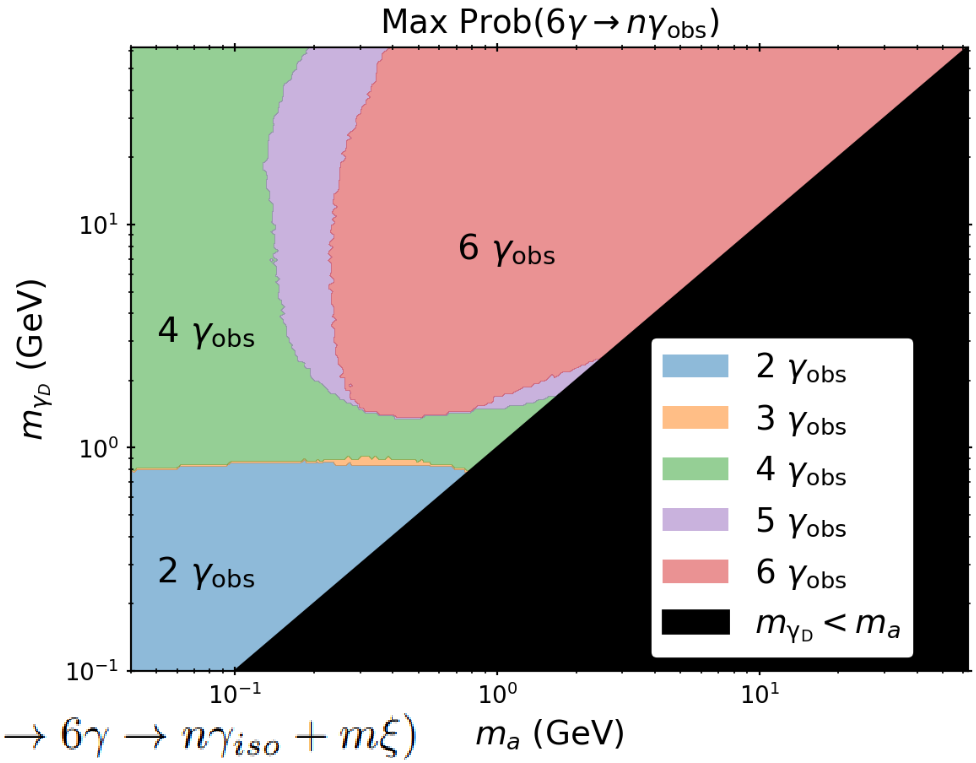
Merge Photon Jets

$$h \to \gamma_d \gamma_d \to a\gamma a\gamma \to 6\gamma \to n\gamma$$

1. Truth level events {γ}

Merge γ-Jets $\Delta R < 0.04$

2. Observable Photons {γ_{obs}}



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

Signals after Merging

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

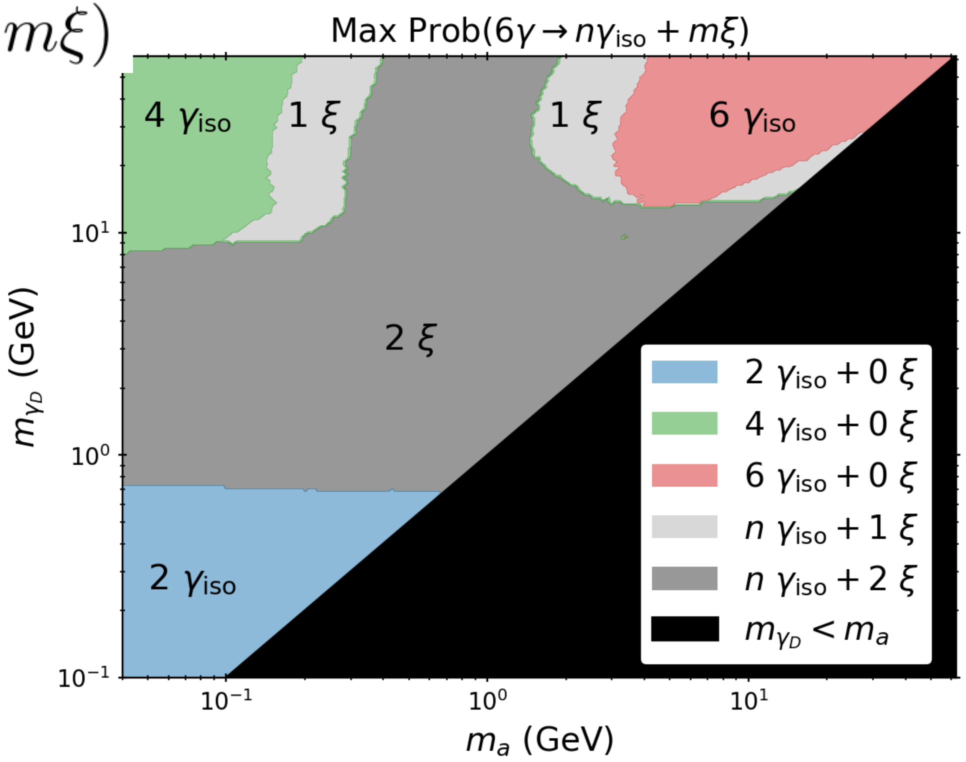
1. Truth level events {γ}

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

- Use simple cut and count
- Impose some transverse momentum cuts on k photons
- Impose some rapidity cuts on all photons
- Try to match existing searches when possible

$$\mathrm{Eff}_k(h \to n\gamma_{\mathrm{iso}} + m\xi)$$

CMS Cuts

$$|\eta| < 1.44 \quad \text{or} \quad 1.57 < |\eta| < 2.5.$$

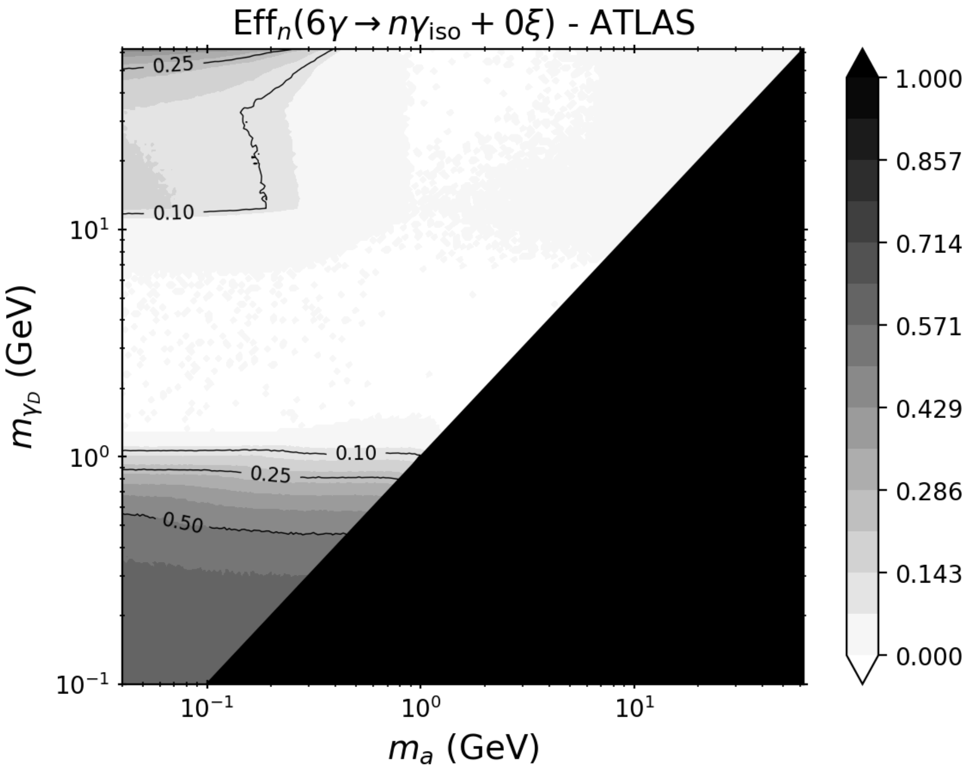
Channel	CMS p_T Requirements
1γ	$p_{1,T} > 145$ GeV [98]
2γ	$p_{1,T} > 30$ GeV and $p_{2,T} > 18$ GeV [30]
3γ	$p_{1,T} > 15$ GeV, $p_{2,T} > 15$ GeV, and $p_{3,T} > 15$ GeV [95]
4γ	$p_{1,T} > 30$ GeV, $p_{2,T} > 18$ GeV, $p_{3,T} > 15$ GeV, and $p_{4,T} > 15$ GeV [27]
5γ	$p_{i,T} > 15$ GeV $(i = 1, 2,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

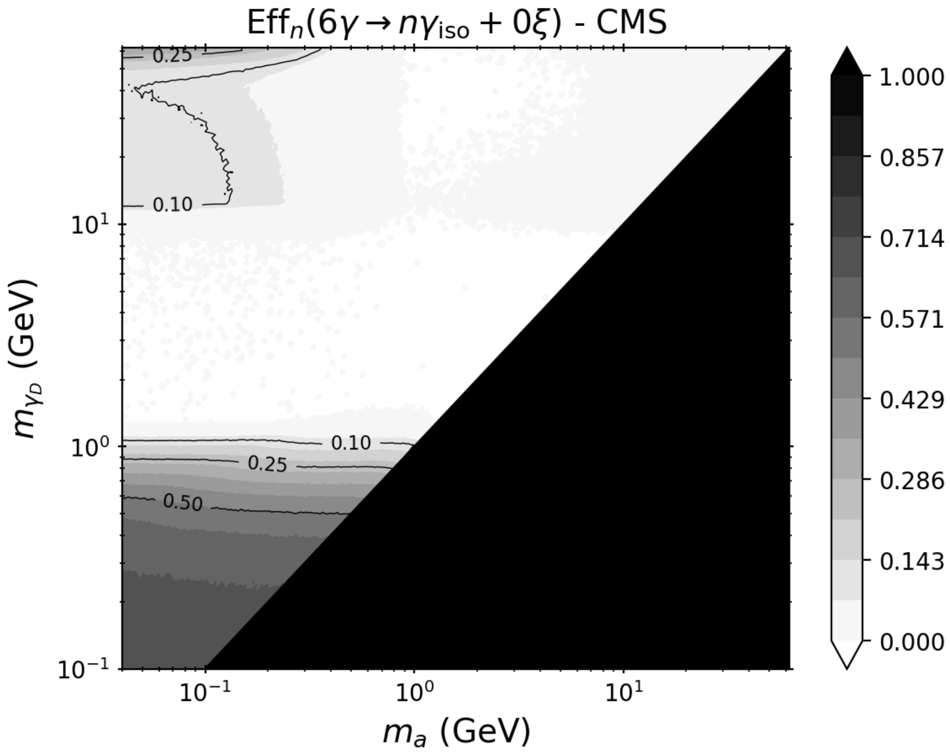
ATLAS Cuts

$$|\eta| < 1.37 \quad \text{or} \quad 1.52 < |\eta| < 2.5,$$

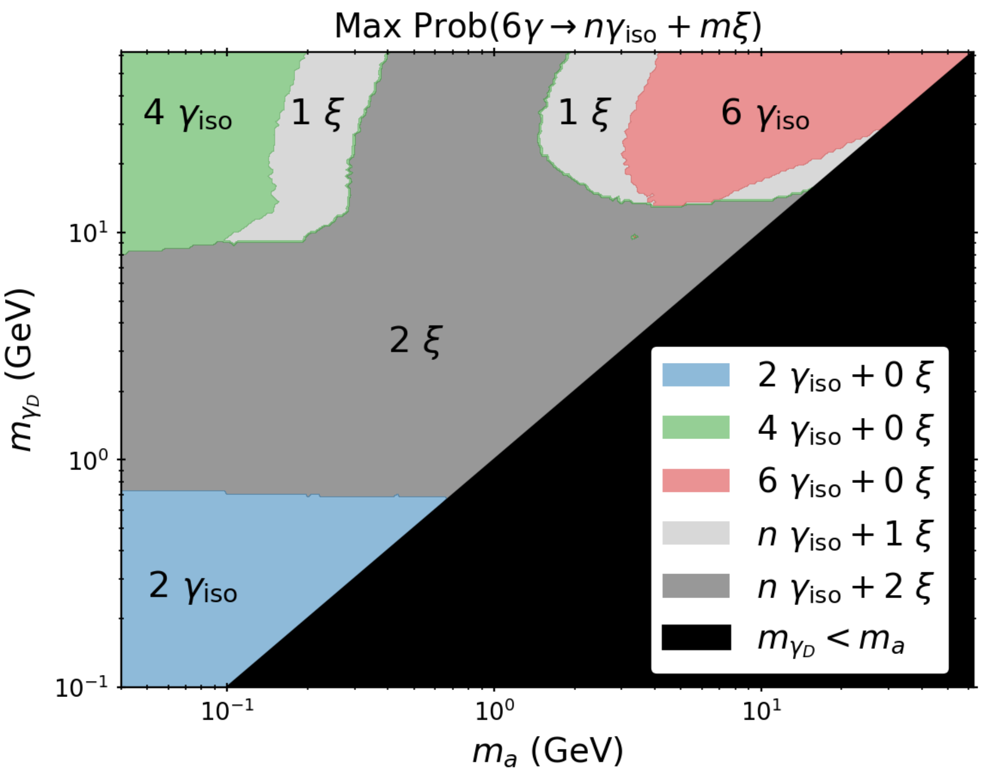
Channel	ATLAS p_T Requirements
1γ	$p_{1,T} > 150$ GeV [94]
2γ	$p_{1,T} > 35$ GeV and $p_{2,T} > 25$ GeV [24]
3γ	$p_{1,T} > 15$ GeV, $p_{2,T} > 15$GeV, and $p_{3,T} > 15$ GeV [95]
4γ	$p_{1,T} > 30$ GeV, $p_{2,T} > 18$ GeV, $p_{3,T} > 15$ GeV, and $p_{4,T} > 15$ GeV [95]
5γ	$p_{i,T} > 15$ GeV $(i = 1,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

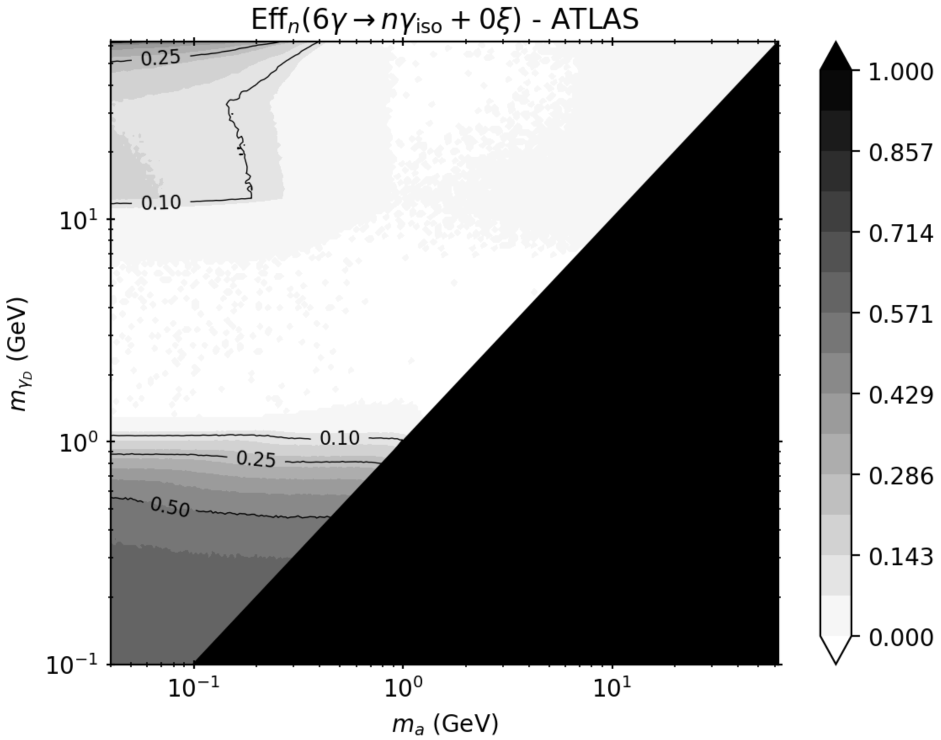
Estimated Trigger Efficiencies





Estimated Trigger Efficiencies





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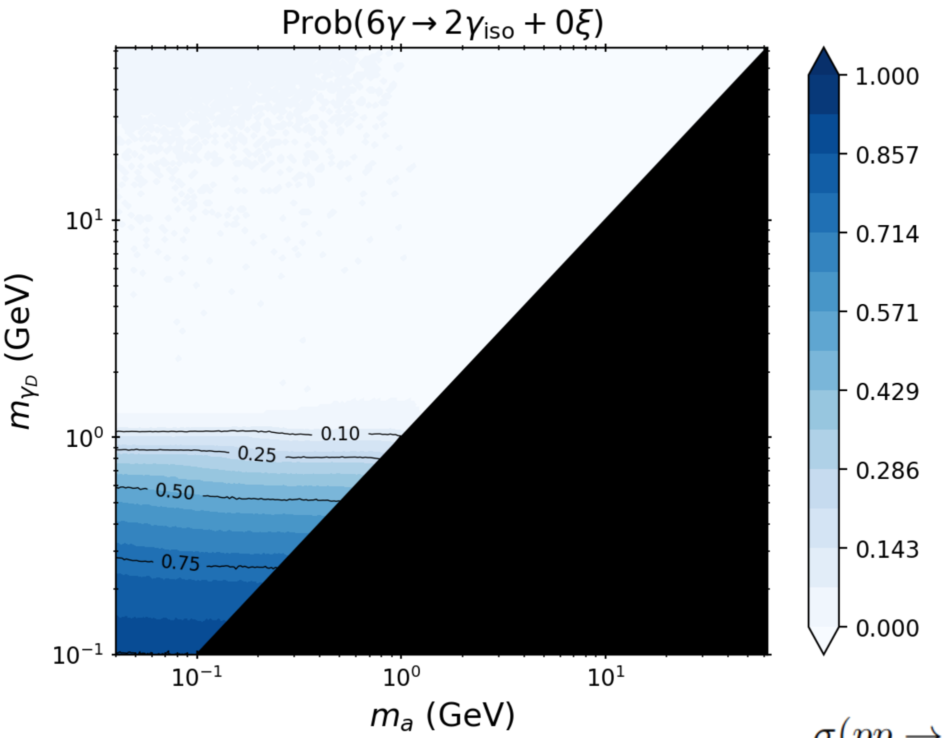
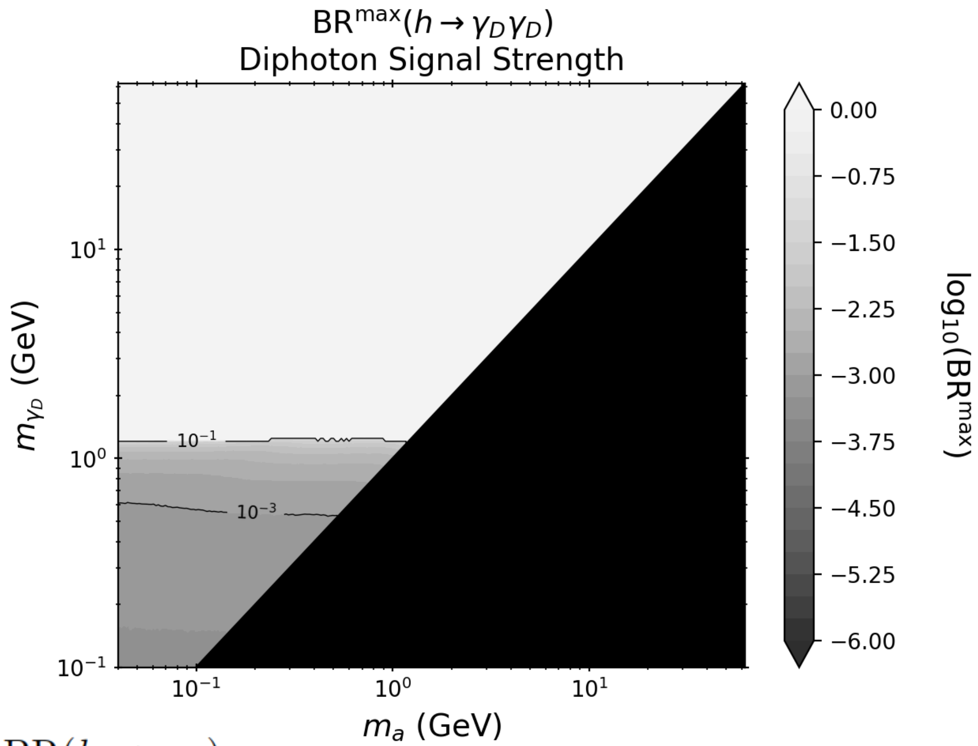
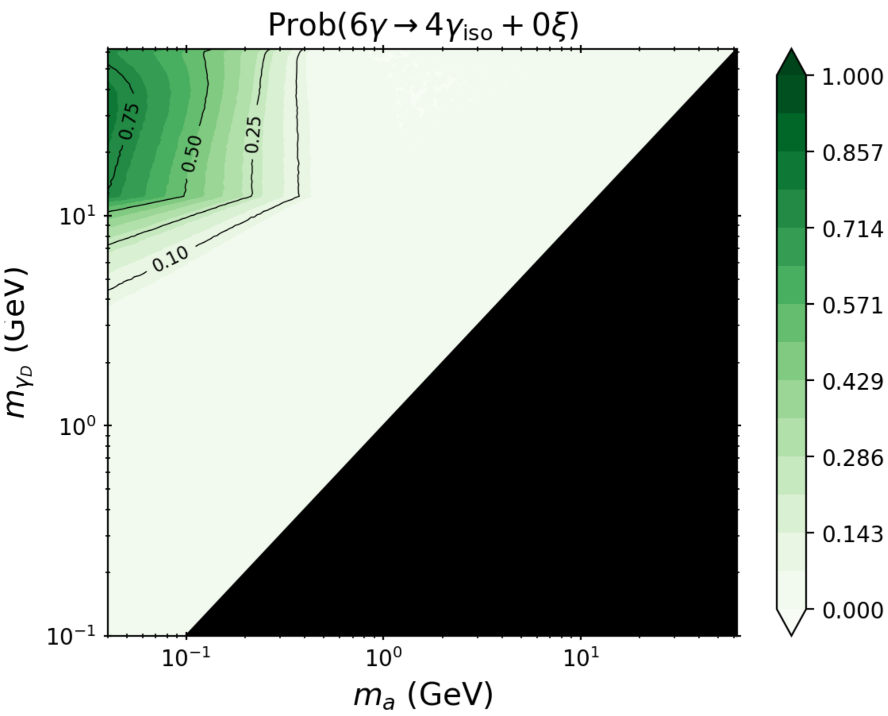
Two Photon Signals

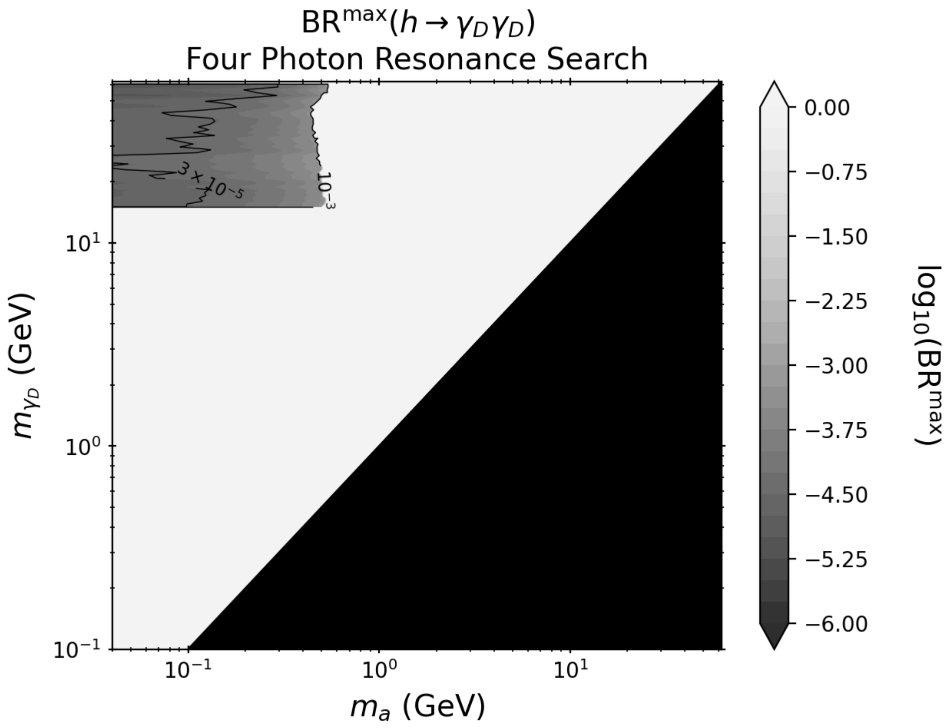




$$\mu = \frac{\sigma(pp \to h)}{\sigma_{\mathrm{SM}}(pp \to h)} \frac{\mathrm{BR}(h \to \gamma\gamma)}{\mathrm{BR}_{\mathrm{SM}}(h \to \gamma\gamma)}$$

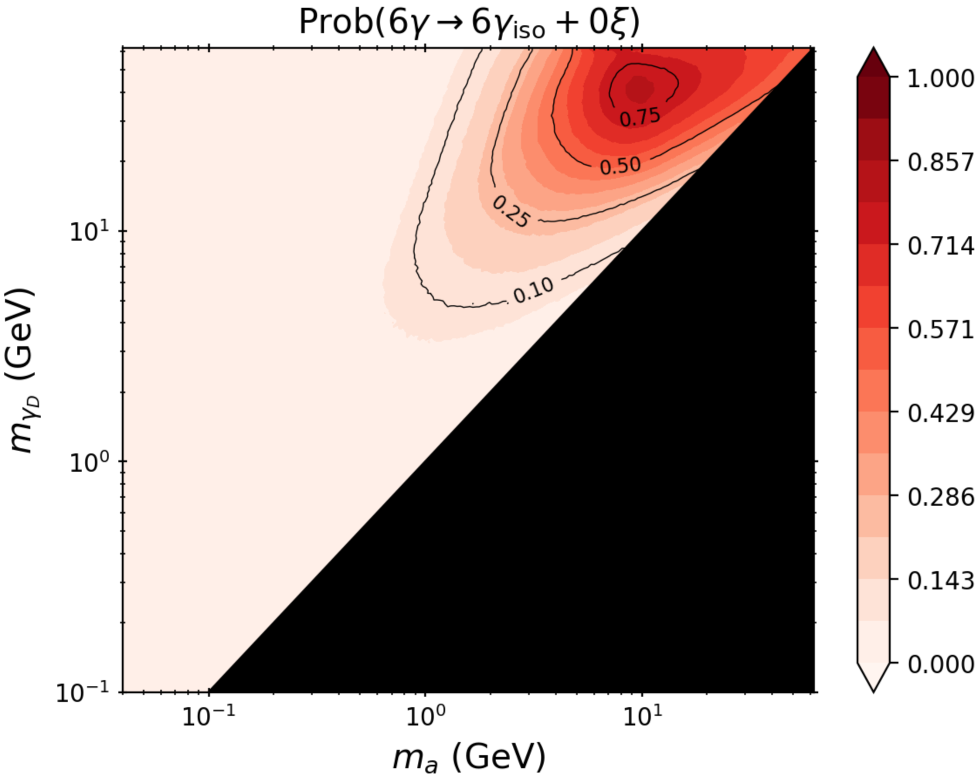
Four Photon Signals

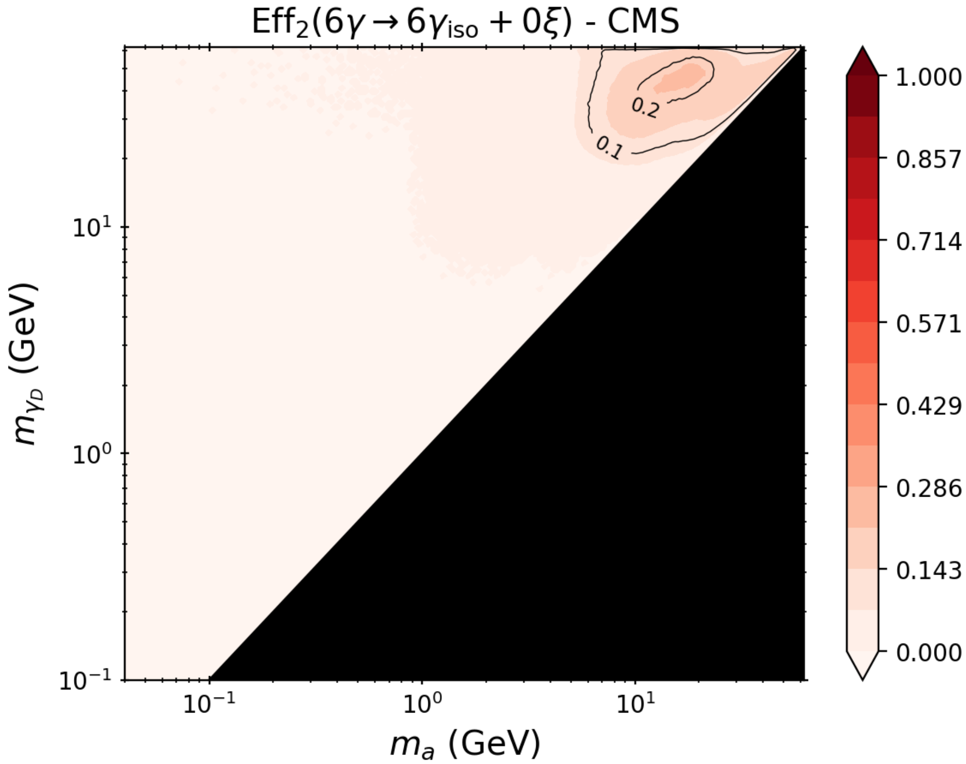




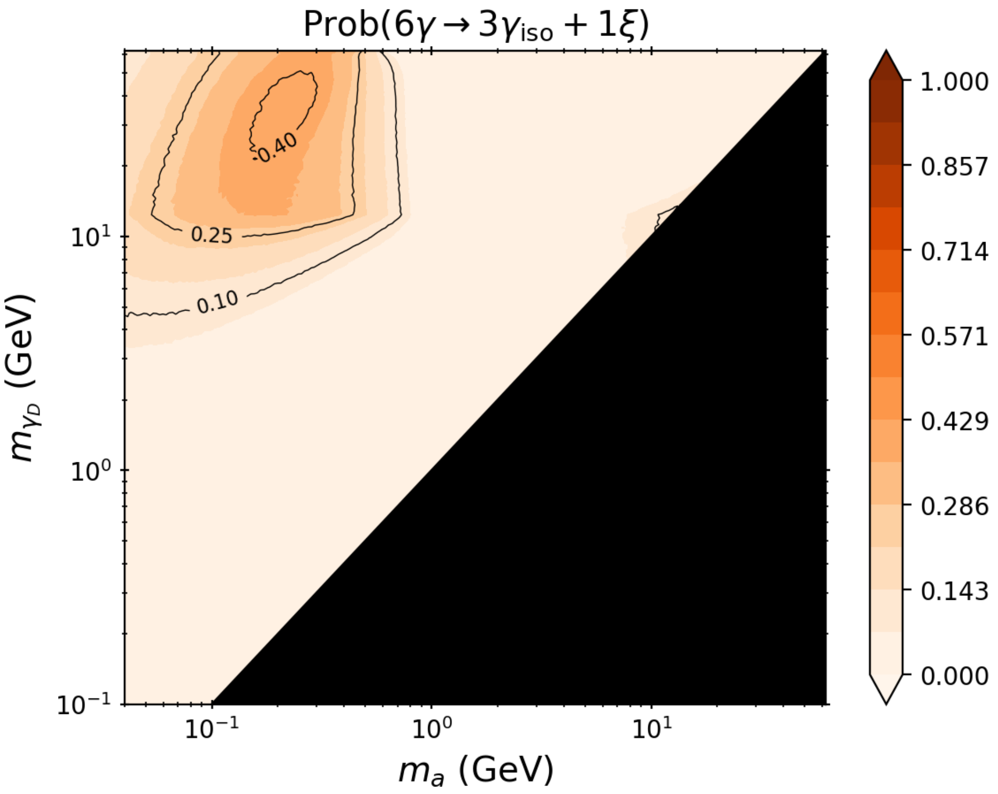
$$\mathrm{BR}(h \to 4\gamma) = \mathrm{BR}(h \to \gamma_D\gamma_D)\mathrm{BR}^2(\gamma_D \to a\,\gamma)\mathrm{BR}^2(a \to \gamma\gamma)\mathrm{Prob}(6\gamma \to 4\gamma_{\mathrm{iso}} + 0\xi)$$

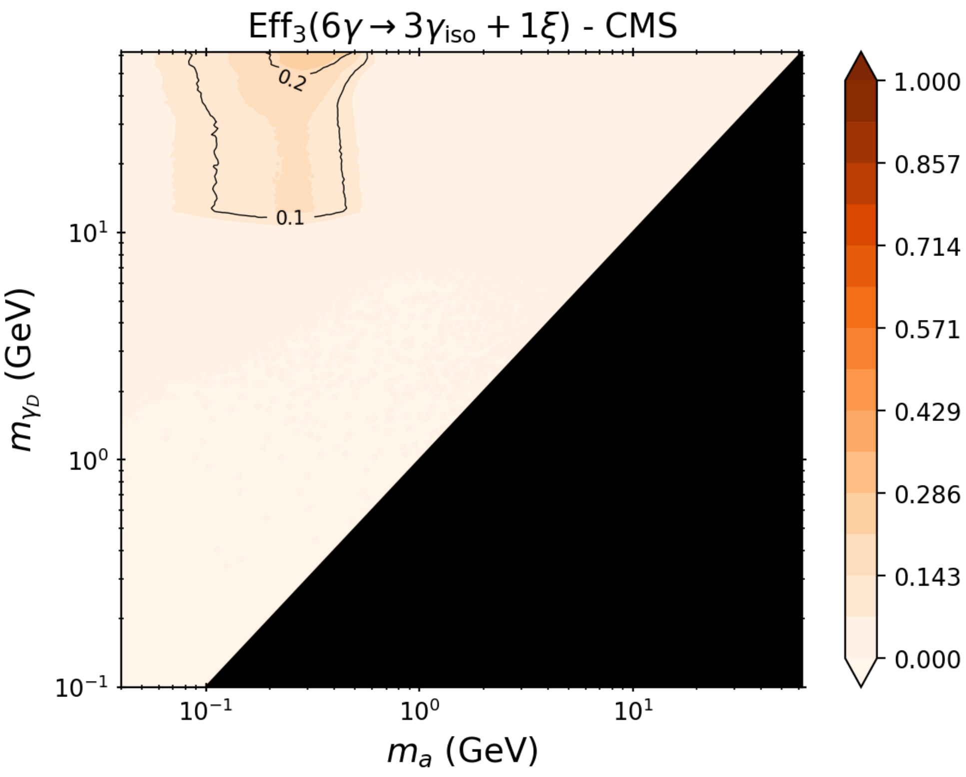
Six Photon Signals



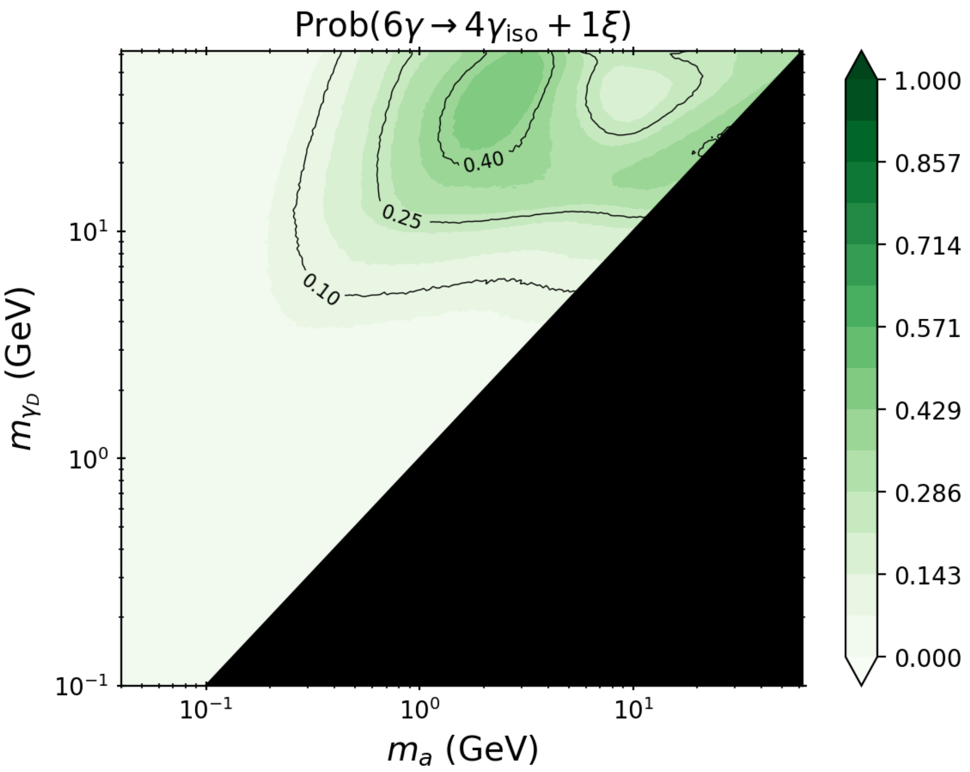


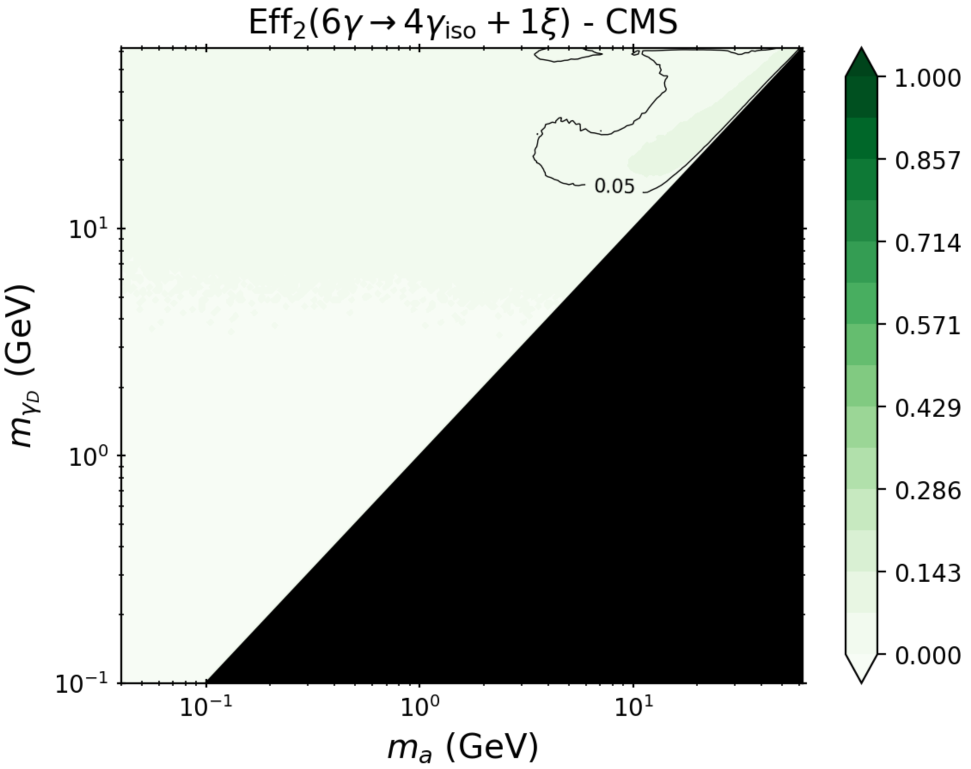
Some Other Signals



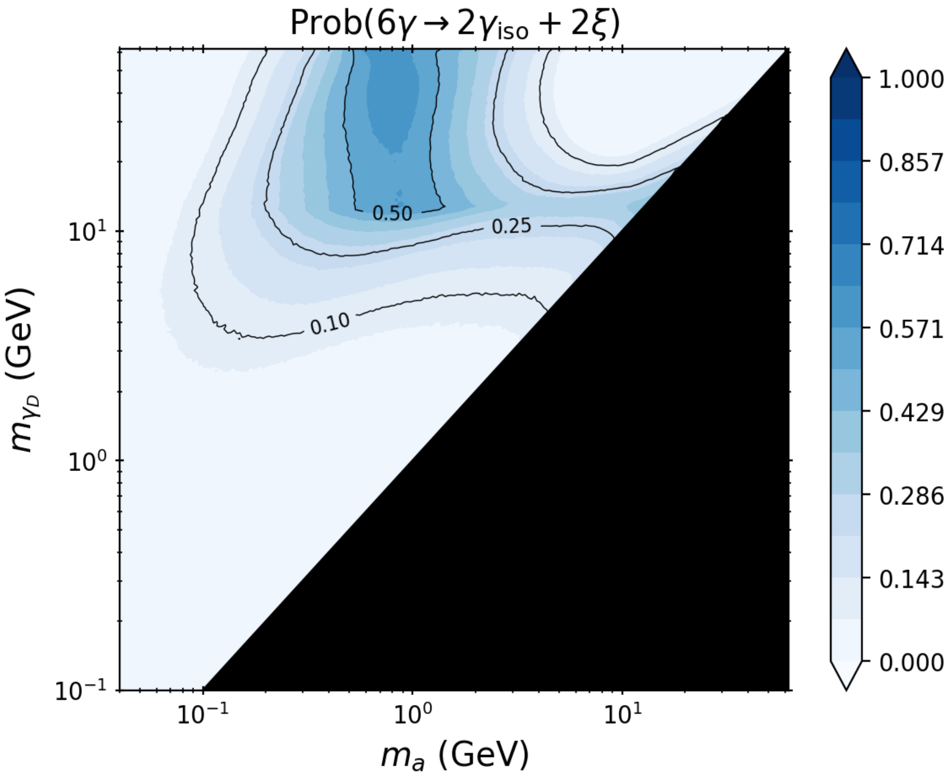


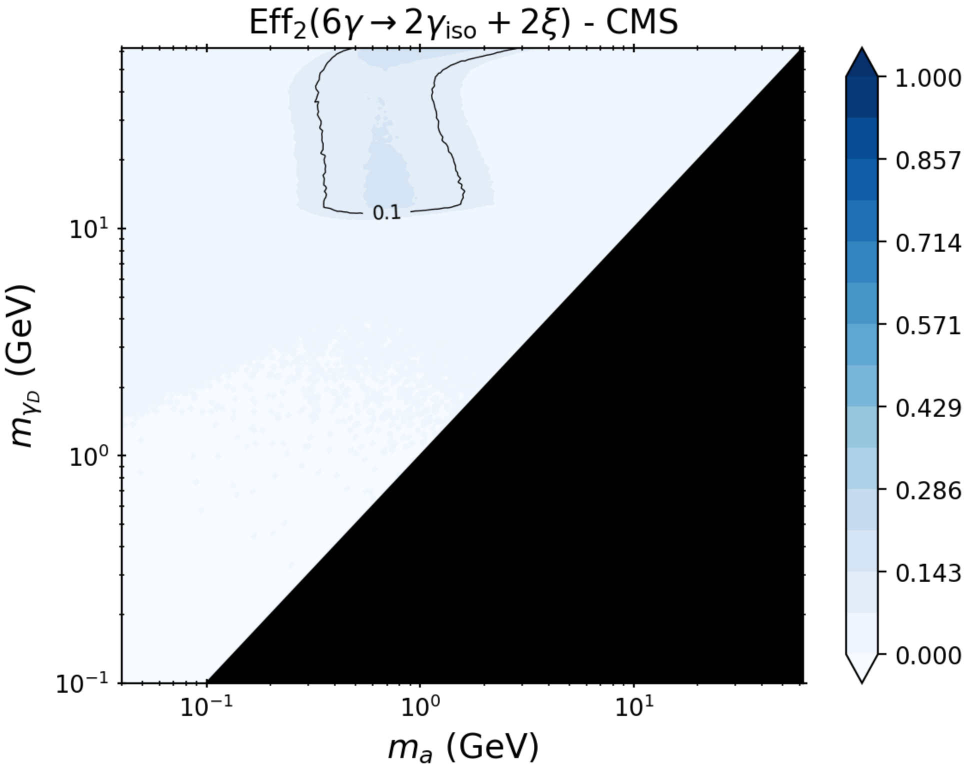
Some Other Signals



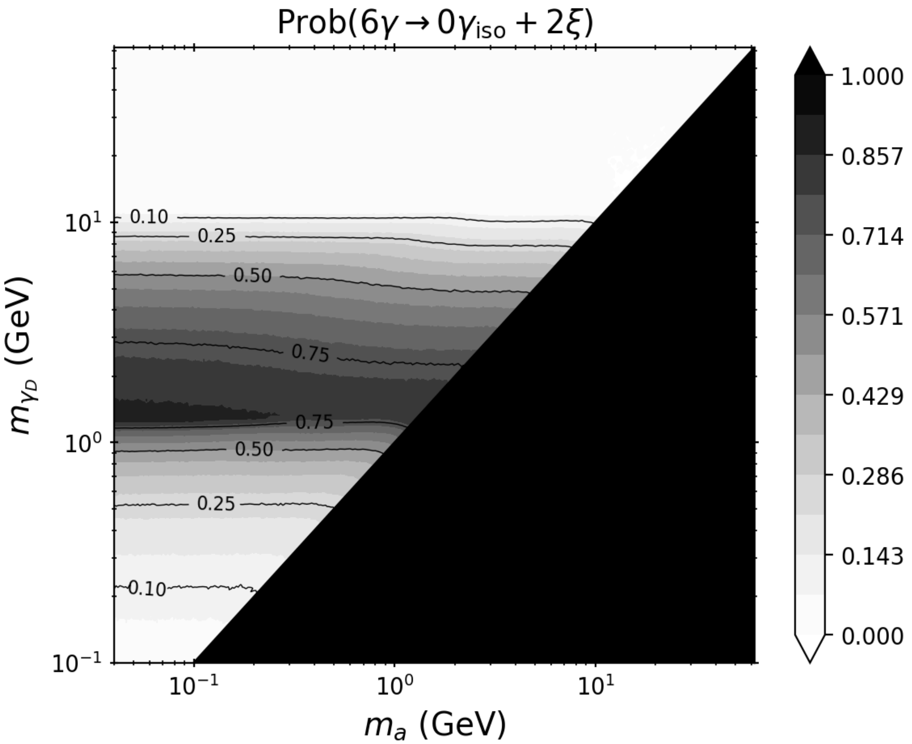


Some Other Signals

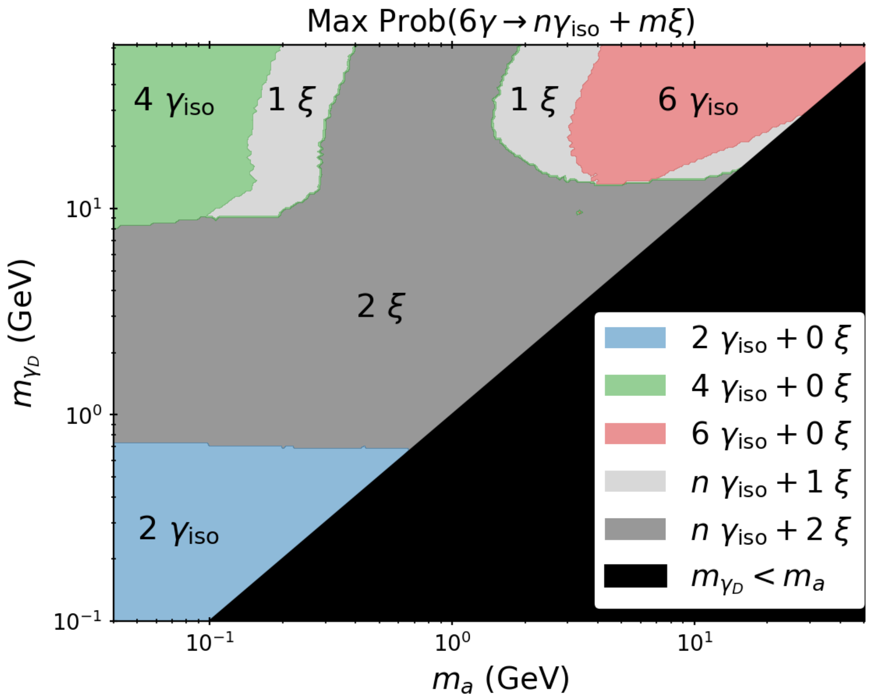


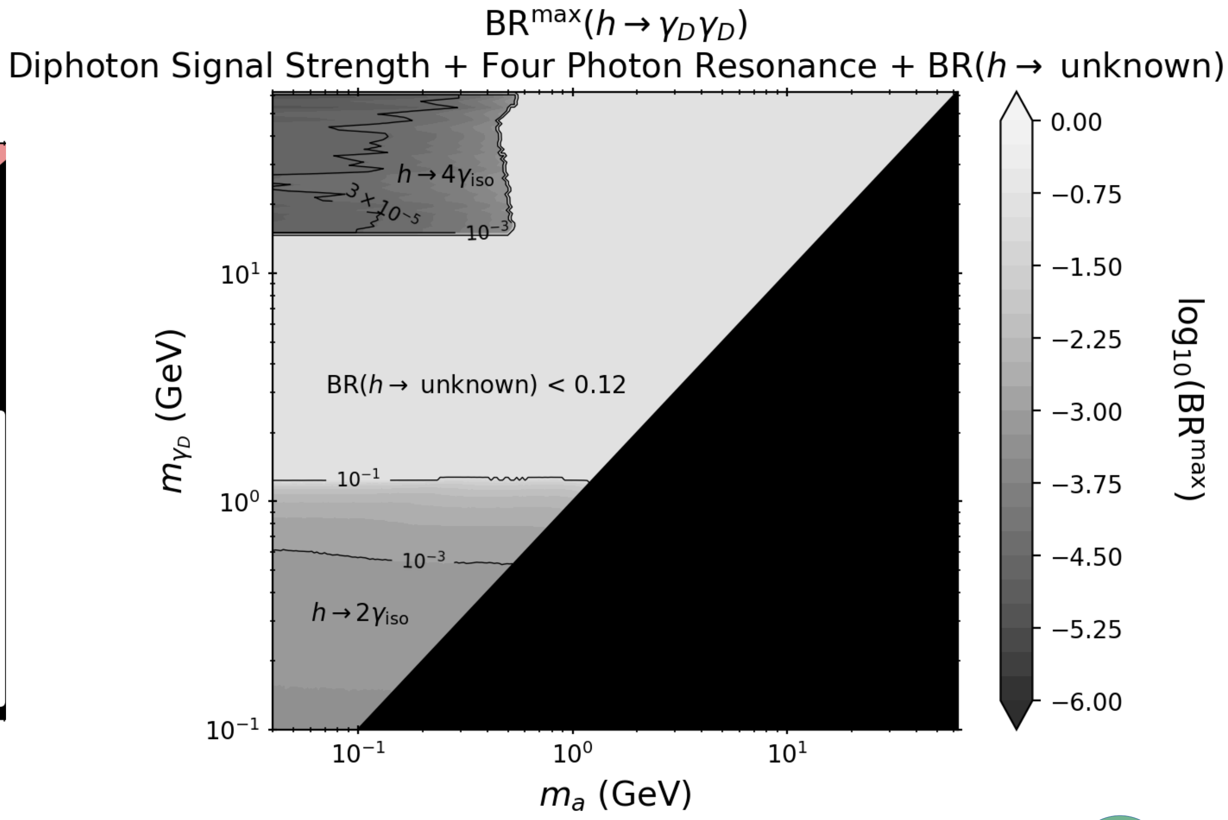


Some Other Signals



Combining Constraints





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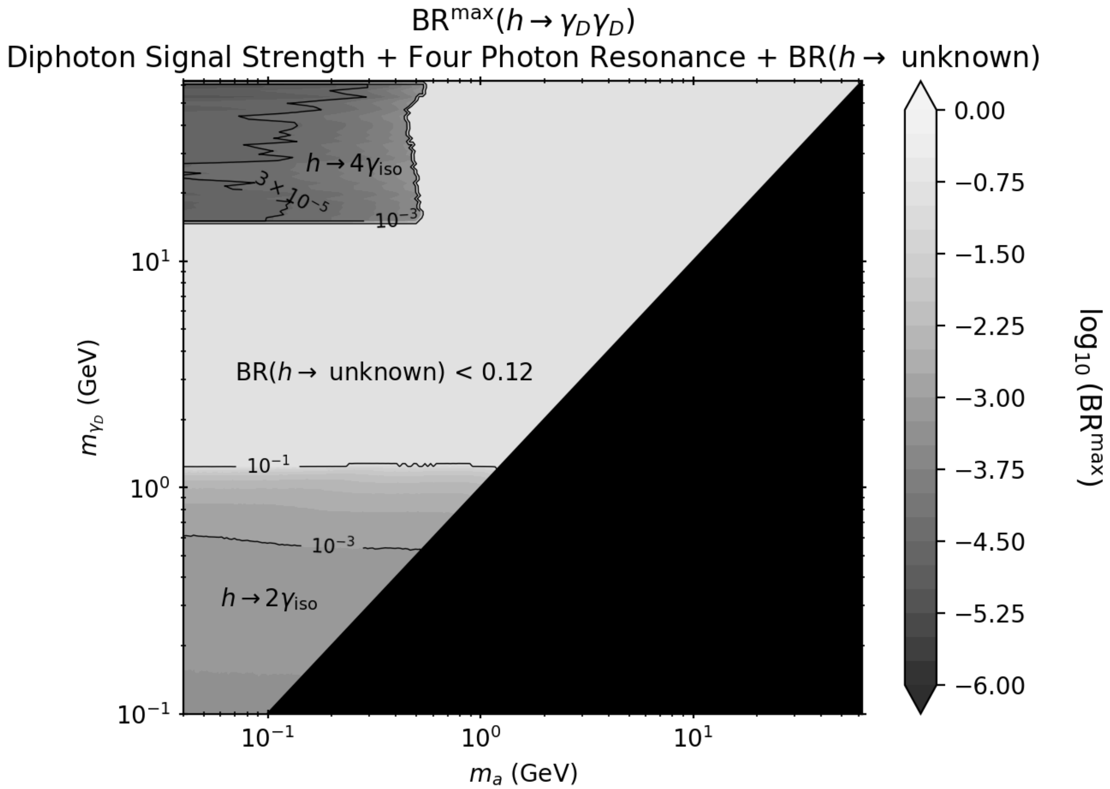
Summary & Conclusion

- **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**



Thanks for your attention!

Questions?