Multi-Photon Decay of the Higgs Boson at the LHC

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Hye-Sung Lee, Samuel D. Lane, **IML**, arXiv:2305.00013

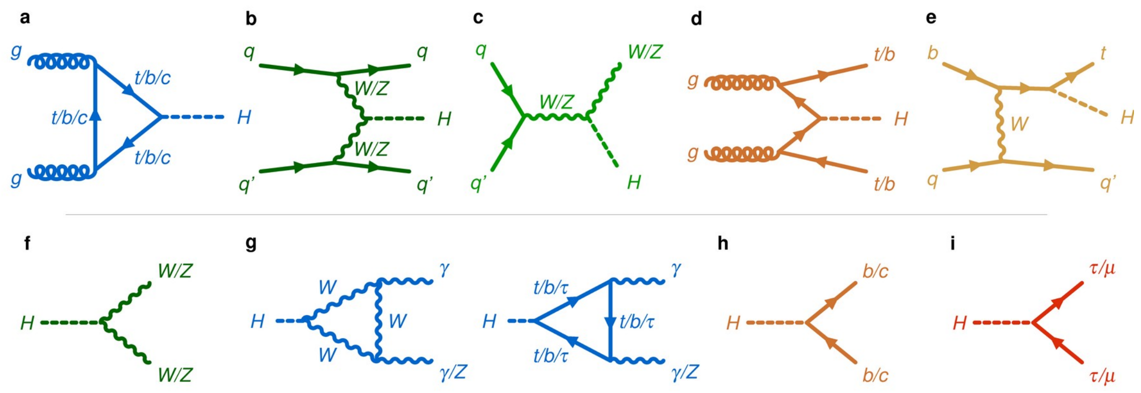
Outline

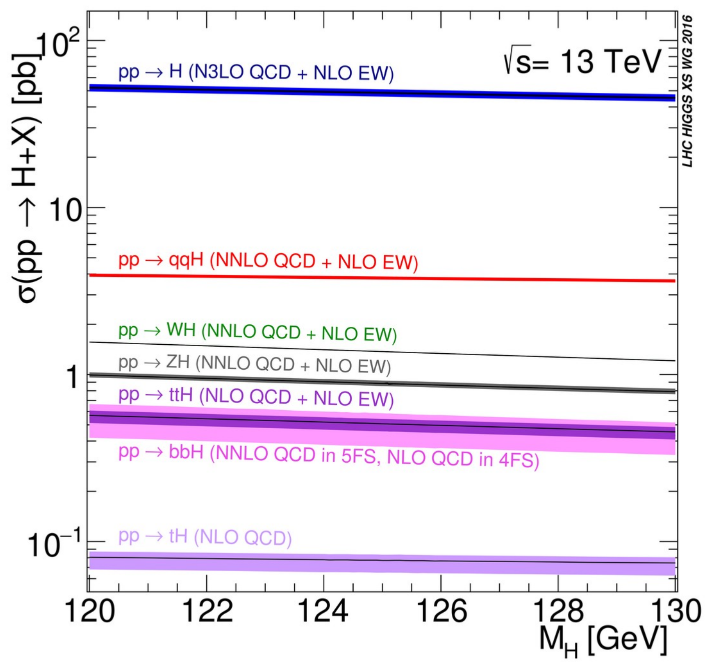
- Motivation.
- Introduction to dark axion model
  - Higgs to six photon decay.
- Classification of signals:
  - Events appearing as 2 photon, 4 photon, 6 photon, and non-isolated photon resonances.
- Detector efficiencies.
- Discussion of different signals and current constraints.
  - 4 photon signal: apparent Landau-Yang theorem violation.
- Conclude

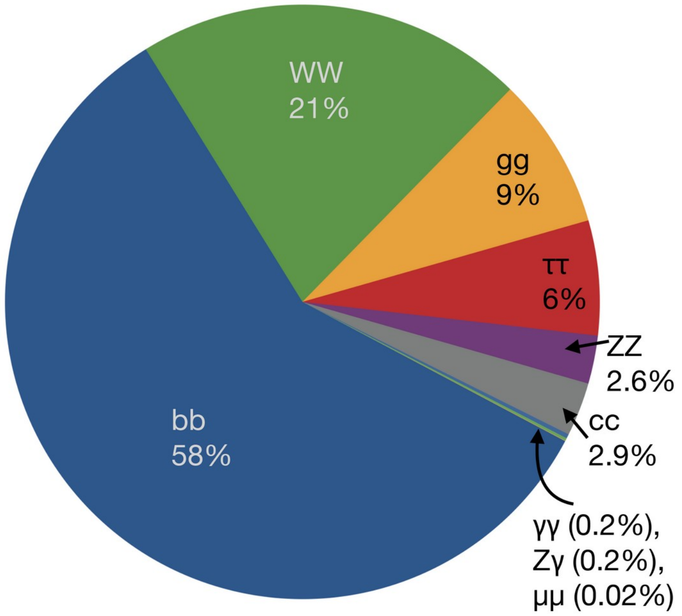
Feynman Diagrams from ATLAS, Nature, arXiv:2207.00092

Completely Predictive

- Once we know Higgs mass, can calculate production and decay rates to high precision.



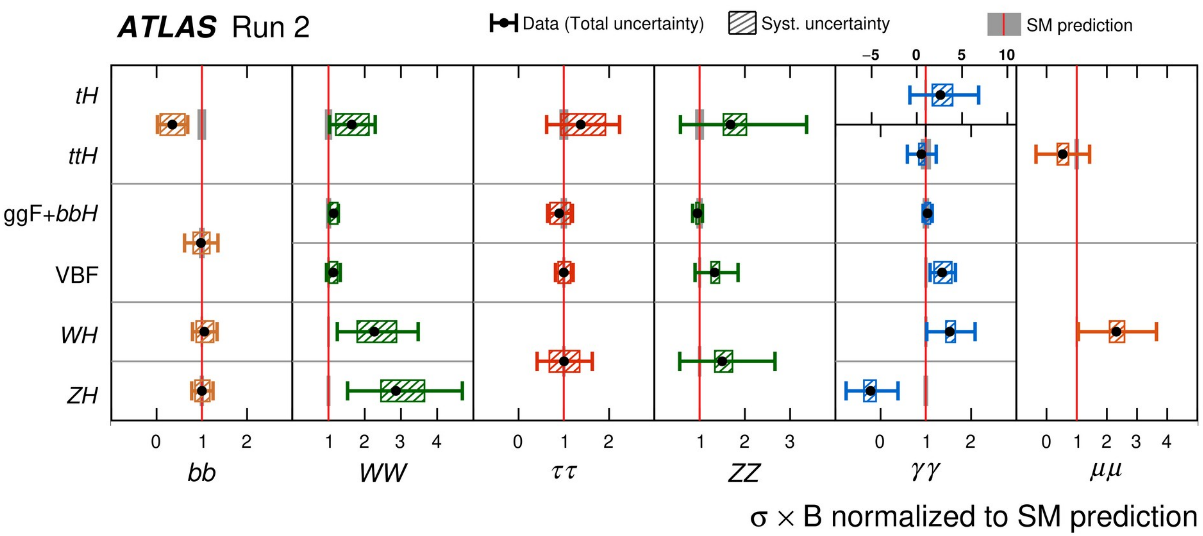


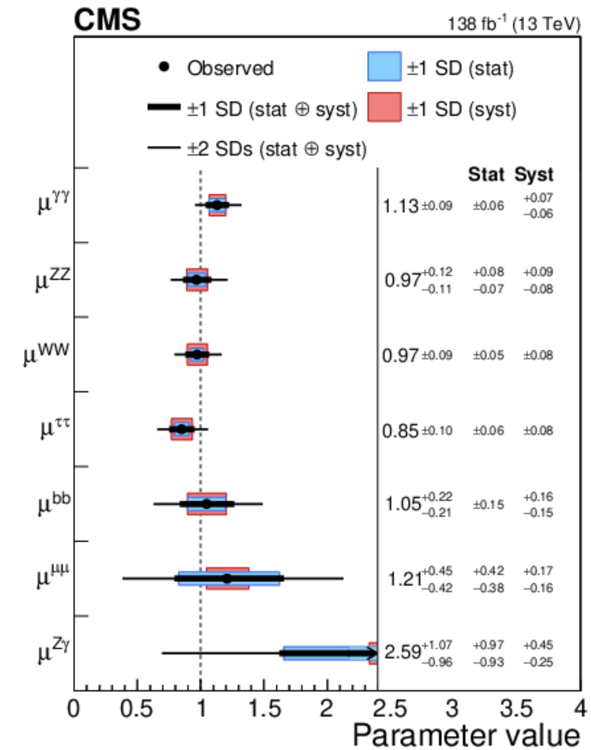


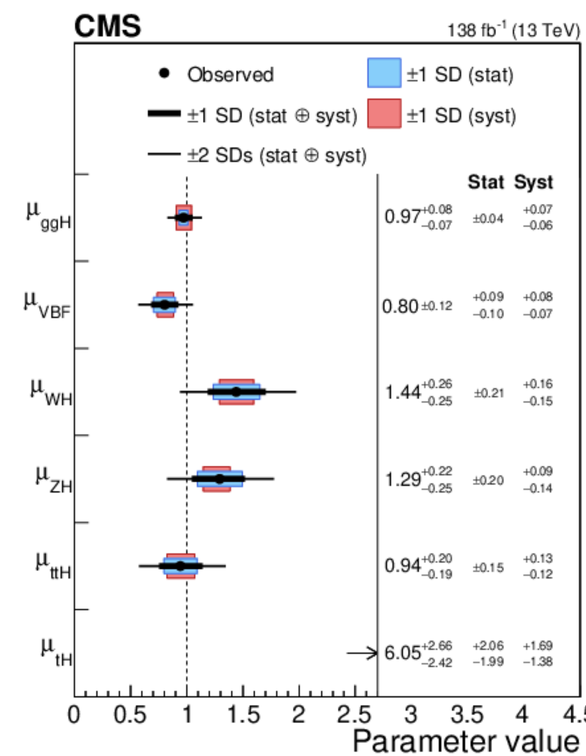
CMS, Nature, arXiv:2207.00043

ATLAS, Nature, arXiv:2207.00092

Where We're At







- Higgs precision shown in terms of signal strengths.

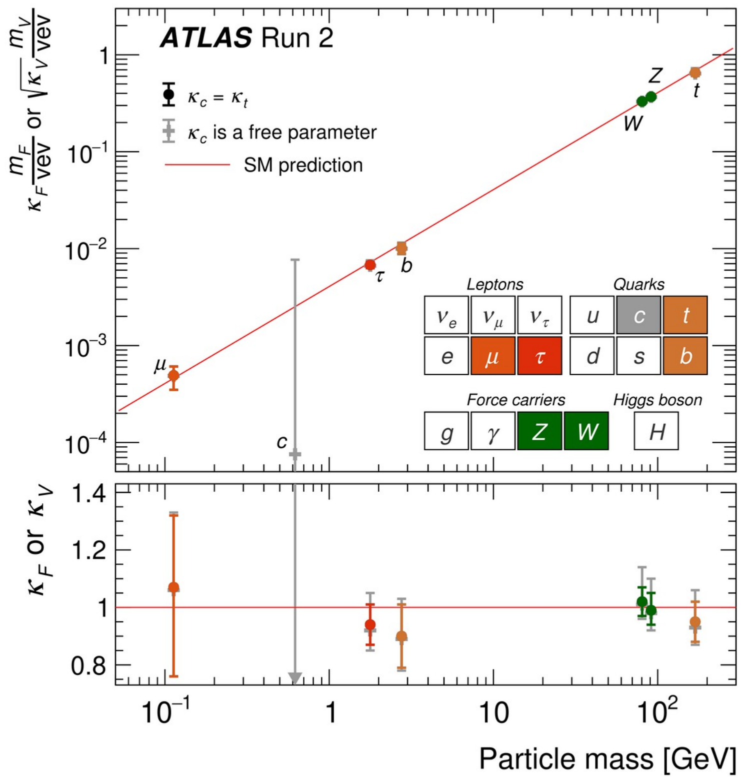
$$\mu_i^f = \frac{\sigma_{\rm exp}\left(i \to h \to f\right)}{\sigma_{SM}\left(i \to h \to f\right)}$$

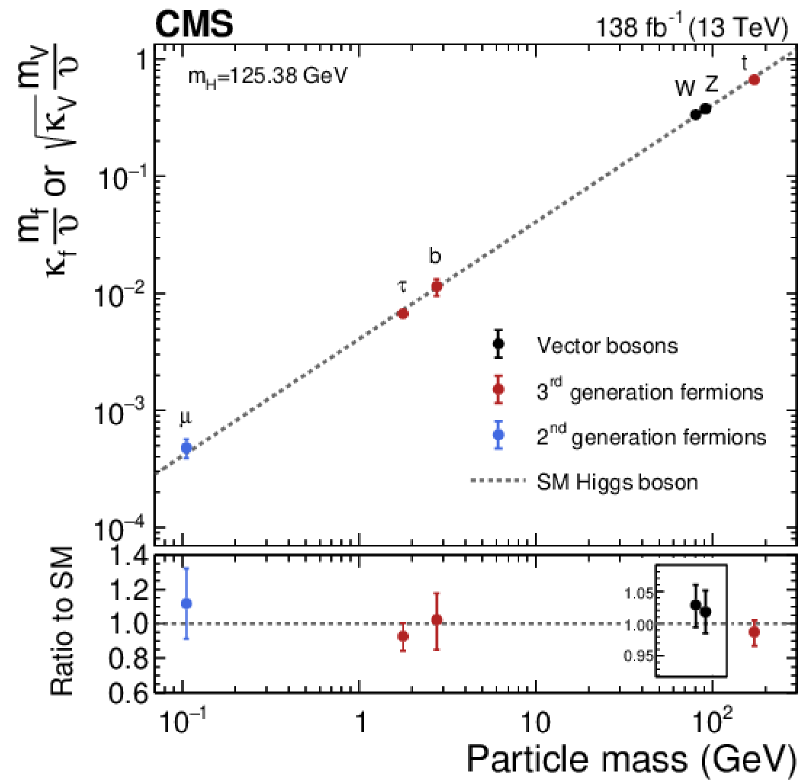
- Most measurements agree well with the SM.
- Already measuring many rates to order 10% accuracy.

Where We're At

CMS, Nature, arXiv:2207.00043

ATLAS, Nature, arXiv:2207.00092





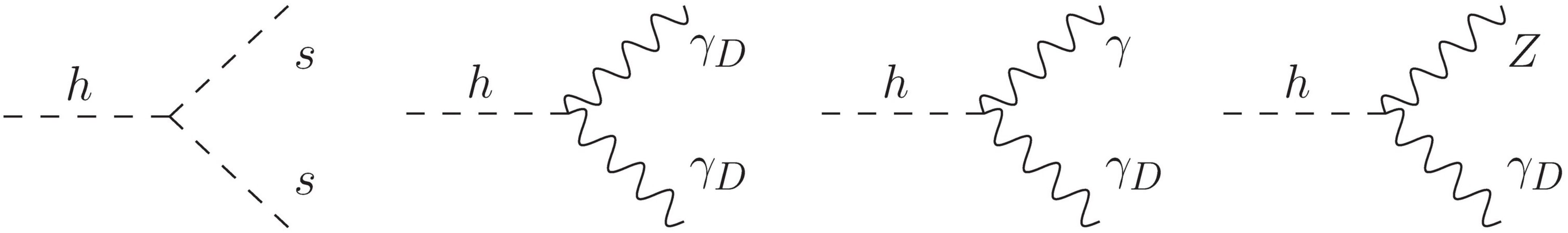
- Higgs boson associated with the source of EW symmetry breaking.
  - Higgs couplings should be proportional to masses (or squared masses)
  - Have verified that over many orders of magnitude in coupllings and mass.

Where From Here?

- May still hope for deviations from SM physics.
- The Higgs width is very small: $\Gamma = 4.1\, MeV$
  - Generic partial width (ignoring longitudinal enhancements):

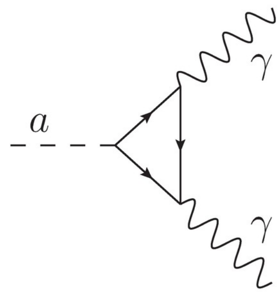
$$\Gamma \sim \frac{g^2}{8\pi} m_h \sim g^2 (5\, GeV)$$

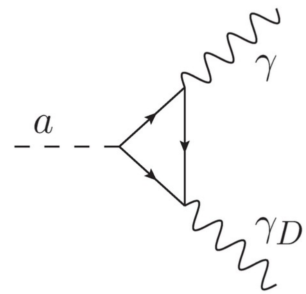
  - Decays of Higgs into exotic states can be sensitive to small couplings.
- Many different types of portals (non-exhaustive list):
  - Scalar portal: $h\, s\, s$
  - Dark photon from scalar mixing: $h\, \gamma_D\, \gamma_D$
  - Dark photon vector boson mass mixing: $h\, Z\, \gamma_D$
  - Dark photon from loops: $h\, F_{D,\mu\nu} F_D^{\mu\nu}$ $\quad h\, F_{D,\mu\nu} F^{\mu\nu}$
- Can give many different interesting Higgs decays:



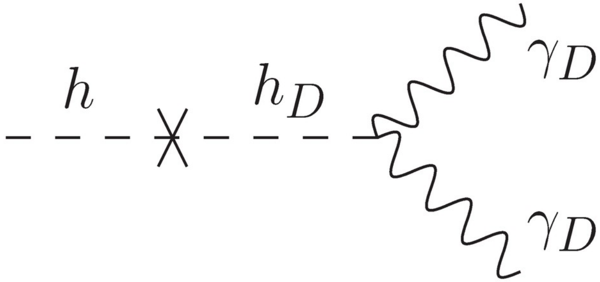
Dark Axion Portal

- Interested in exploring dark axion portal Kaneta, Lee, Yun PRL118 (2017)
  - Assume some heavy new physics that is charged under the SM electroweak gauge group and some new $U(1)_d$.
  - Introduce an axion like particle: a.
  - Can get interesting couplings between ALPs, photons, and dark photon:





  - Assume new $U(1)_d$ is Higgsed, and SM Higgs can couple to dark photons via mixing?

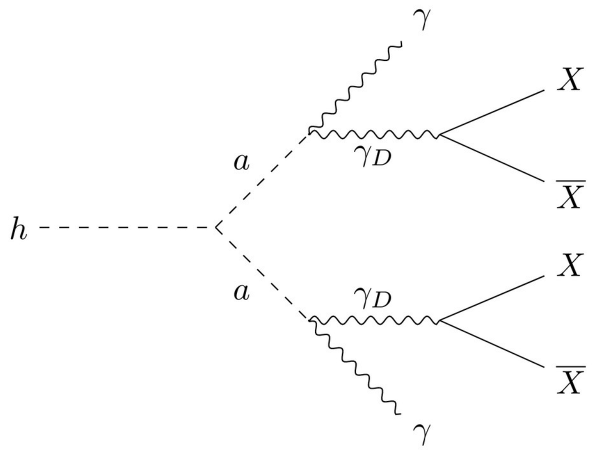


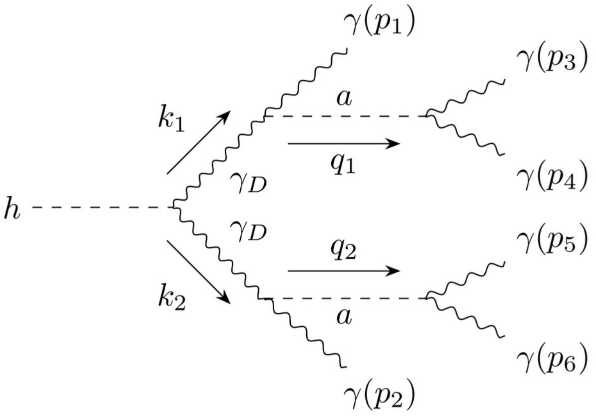
- Parameterize couplings as (and promptly forget about any UV completion):

$$L_{portal}=\frac{1}{4}G_{a\gamma\gamma}aF^{\mu\nu}\widetilde{F}_{\mu\nu}+\frac{1}{2}G_{a\gamma\gamma_D}aF^{\mu\nu}\widetilde{F}_{D\mu\nu}+\frac{1}{4}G_{a\gamma_D\gamma_D}aF_D^{\mu\nu}\widetilde{F}_{D\mu\nu}+\frac{1}{2}\lambda_{h\gamma_D\gamma_D}h\gamma_D^{\mu}\gamma_{D\mu}$$

Dark Axion Portal

- Depending on mass ordering, can have many different interesting exotic decays:

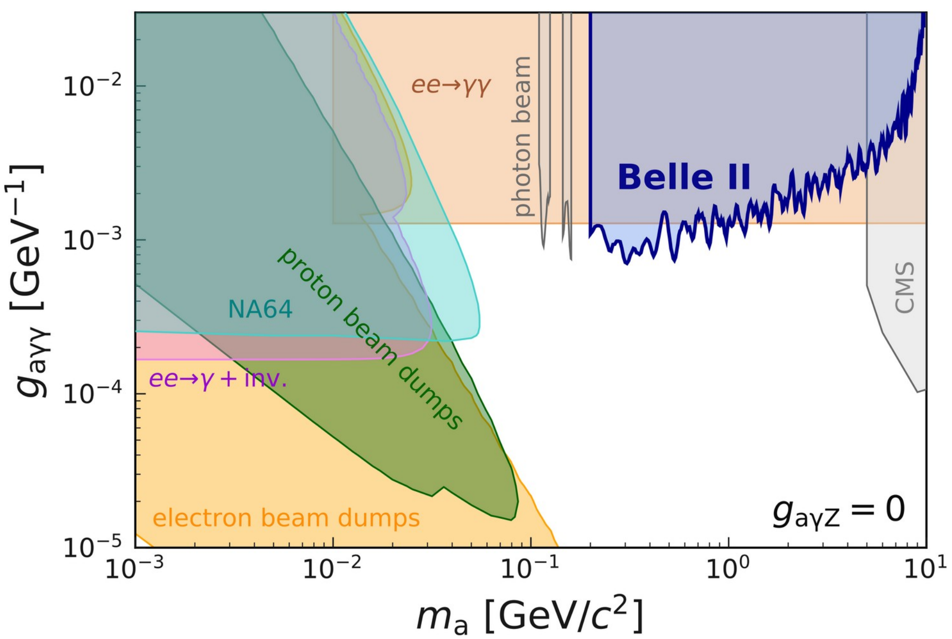




- We will focus on six photon decay.
  - Will assume the dominant decays: $\gamma_D \rightarrow a\,\gamma \qquad a \rightarrow \gamma\,\gamma$
- Depending on mass hierarchies, dark photon and ALP can be very boosted .
  - Many different combinations of collimated photons.
  - Will classify signals according to:
    - Photon-jets: when two photons would hit the same electromagnetic calorimeter cell.
      Draper, McKeen PRD85 (2012); Ellis, Roy, Scholtz PRD87 (2013), etc.
    - Non-isolated photons: ξ -jets
      Chakraborty, Iyer, Roy, NPB932 (2018), Sheff, Steinberg, Wells PRD104 (2021), etc.

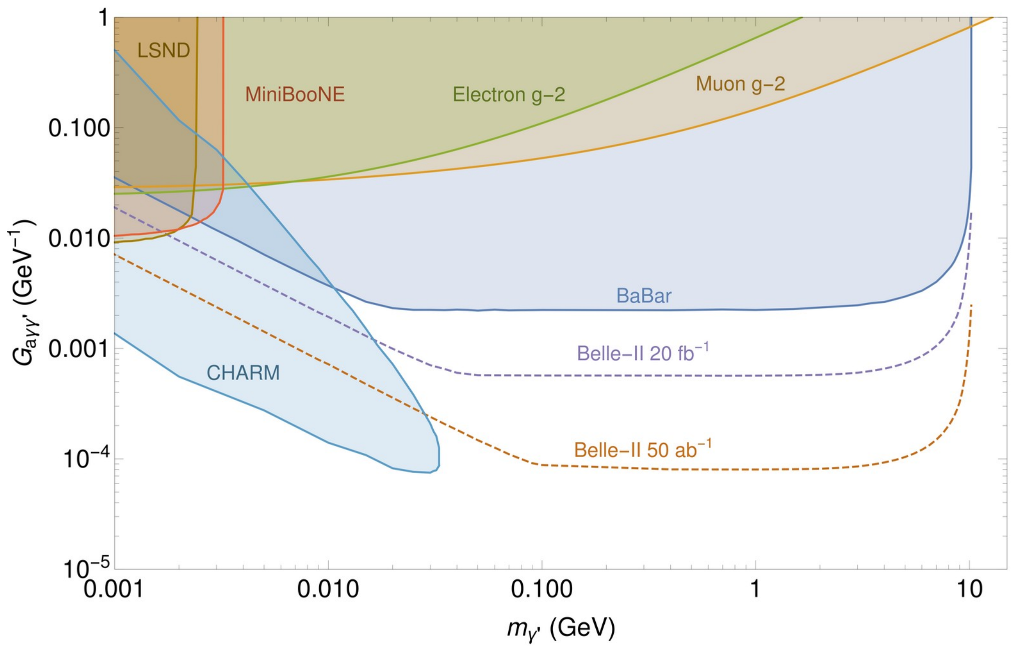
Constraints

ALP Constraints



Belle-II PRL125 (2020)

Dark ALP Constraints



DeNiverville, Lee, Seo, PRD98 (2018);
Deniverville, Lee, Lee PRD103 (2021

- Very small couplings, can make dark photon or ALP long lived….

Decay Lengths for $h \to 2\gamma_D \to 2a2\gamma \to 6\gamma$

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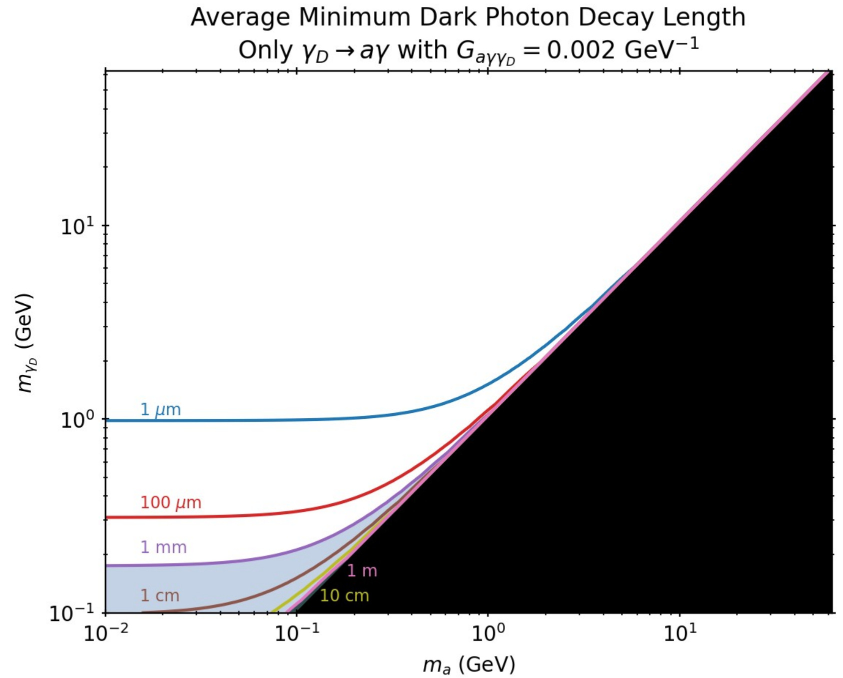

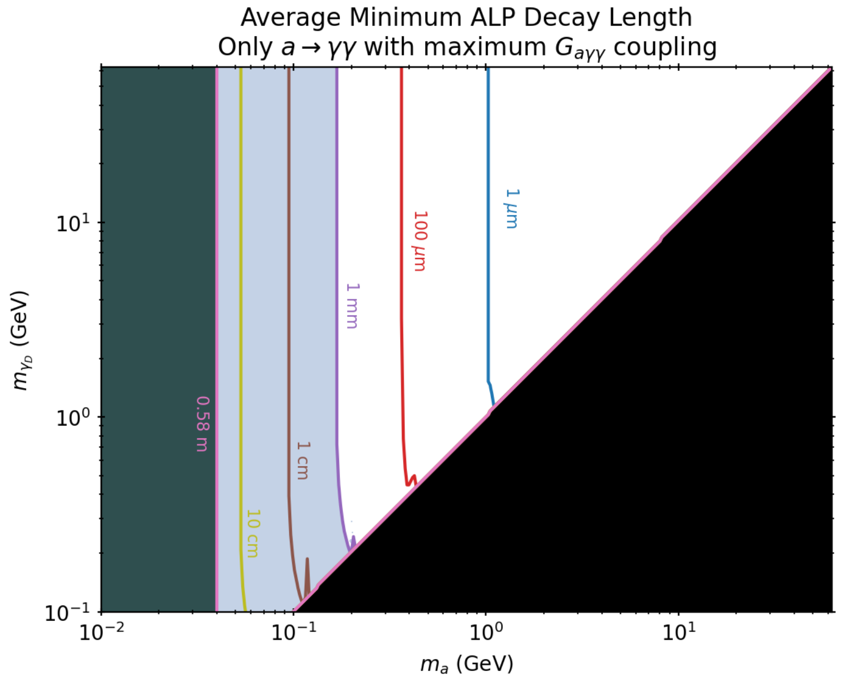

- Average decay lengths of dark photon and ALP in Higgs rest frame.
  - Set couplings to the maximum allowed by current constraints.
  - Assume 100% branching ratios for: $\gamma_D \to a\gamma$ $\quad a \to \gamma\gamma$
- For ALP masses below 40 MeV:
  - Beam dump/astrophysical/cosmological constraints make ALP long lived on LHC time scales.
- Will only consider ALPs with mass above 40 MeV.
  - Even then many ALPs/dark photons still decay within the tracker.
    - However decay products are photons, which don't leave tracks in the tracker.
    - Will not consider then as displaced vertices (there are subtleties about photon conversions…)
    - For a proposal to use photon conversions in the tracker to tag displaced ALP vertices see Alonso-Alvarez, Jaeckel, Lopes 2302.12262

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Classification of Signatures

- Photon jets:
  - Two photons would hit the same electromagnetic calorimeter cell.
  - Defined as photons with angular separation:

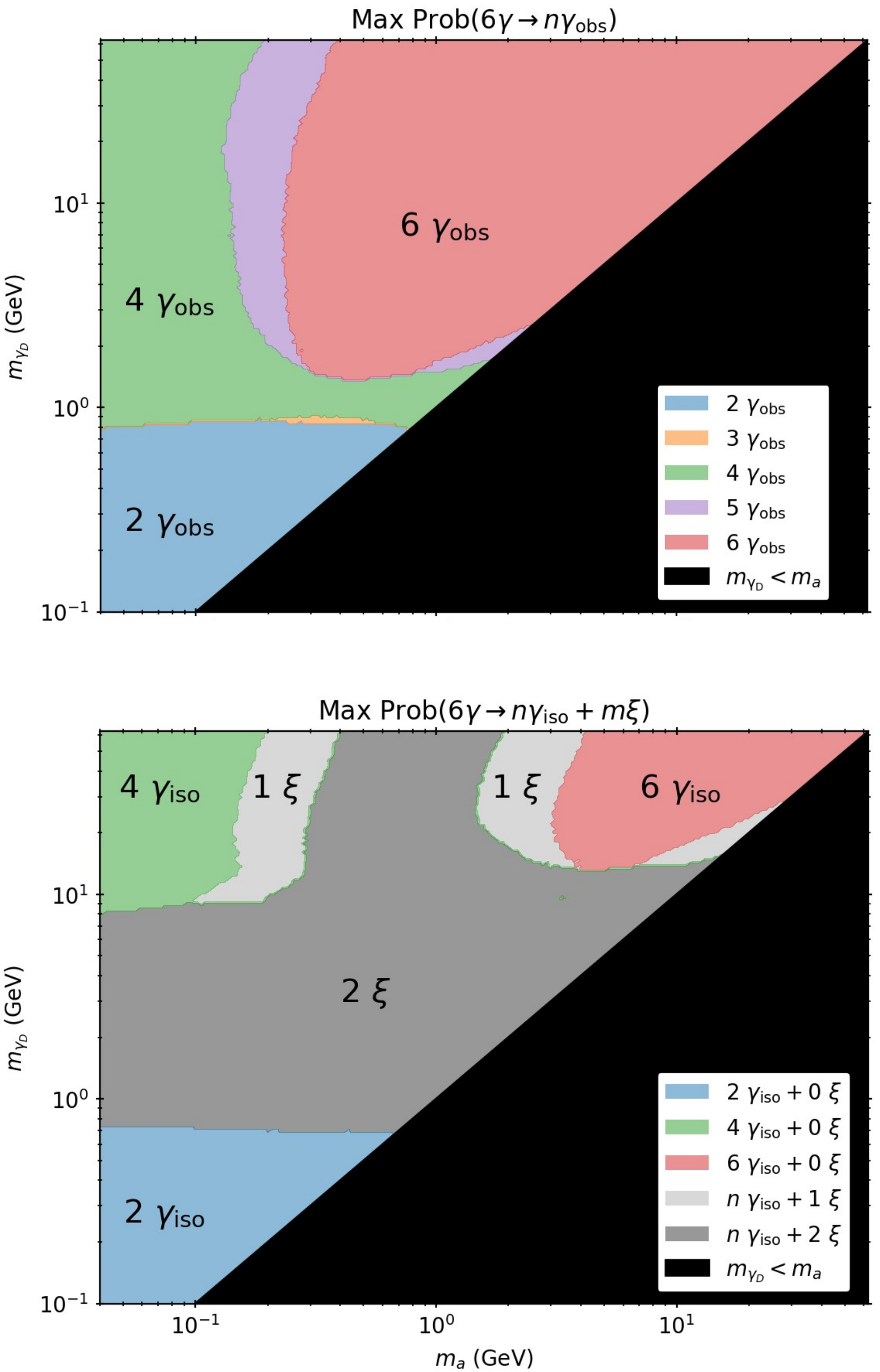
    $$\Delta R \leq 0.04$$

  - After forming photon jets:
    - Collectively call remaining photons and photon jets as “observed photons”
- Intermediately separated photons:
  - Will label as ξ -jets.
  - Define ξ -jets as observed photons with angular separation:

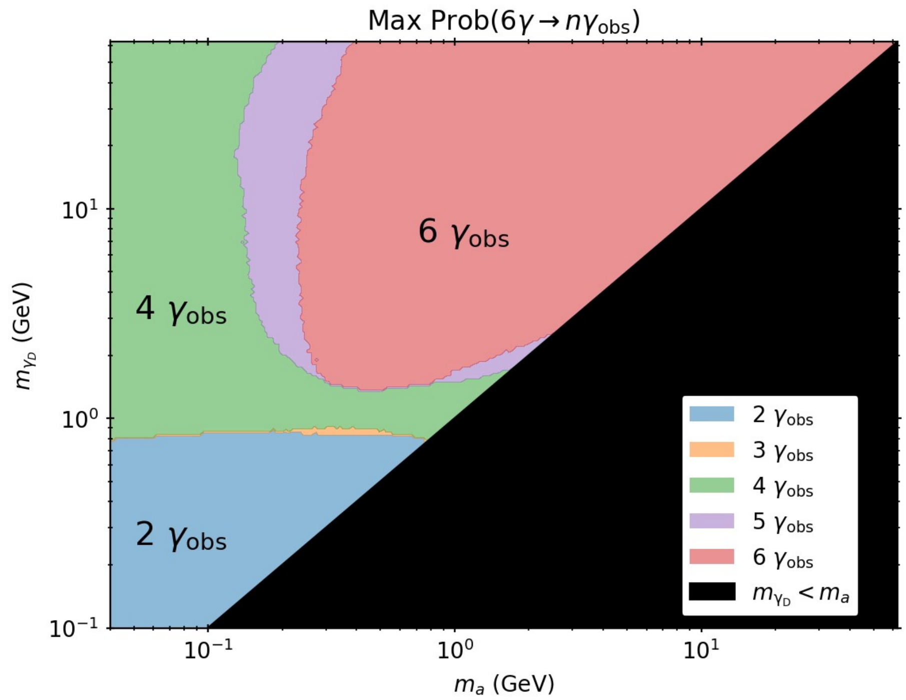
    $$0.04 \leq \Delta R \leq 0.4$$

- After forming ξ-jets, any remaining photons or photon-jets are called “isolated photons”
- Angular separation defined as:

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



- Between 6 and 4-photons:
  - $m_a \ll m_{\gamma_D} \approx m_h/2$
    - Dark photon at rest, ALP essentially massless, so approximate:
      $$E_a \approx m_h/4$$
    - Calculate angular separation of ALP decay products:
      $$\Delta R_{\gamma\gamma} \approx 2\frac{m_{\gamma_a}}{E_a} \approx 8\frac{m_a}{m_h} \leq 0.04$$
    - Gives constraint:
      $$m_a \lesssim \frac{m_h}{200} \approx 0.625 \text{ GeV}$$
  - $m_a \approx m_{\gamma_D}$
    - ALP at rest in dark photon rest frame, photon from dark photon decay very soft.
    - Boosting to Higgs rest frame, ALP (roughly) inherits dark photon energy:
      $$E_a \approx m_h/2.$$
    - Angular separation about axion decay products:
      $$\Delta R_{\gamma\gamma} \approx 4\frac{m_a}{m_h} \leq 0.04$$
    - Gives constraint: $m_{\gamma_D} \approx m_a \lesssim \frac{m_h}{100} \approx 1.25 \text{ GeV}.$



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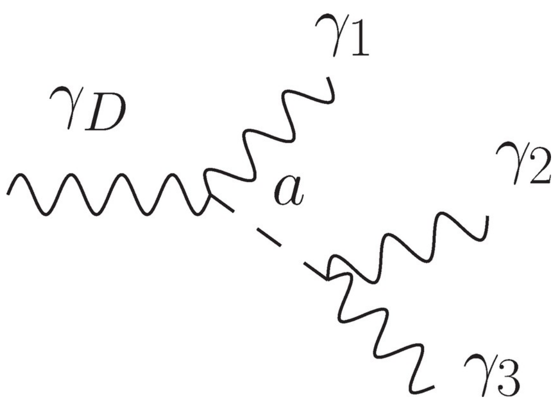
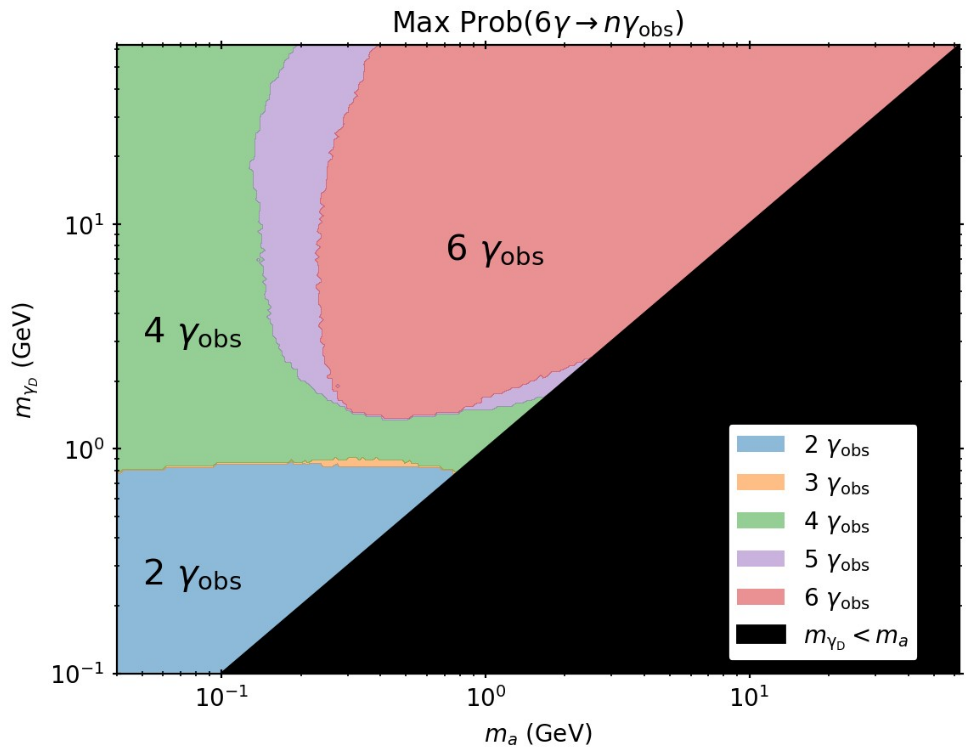
- Between 4 and 2-photons:
  - Need to calculate angular separation between photons from dark photon decay.
  - Configuration where photons are most widely separated is when dark photon and ALP decay planes coincide:





  - Assume $\Delta R_{\gamma_2\gamma_3} \leq 0.04$
  - To obtain $\Delta R_{\gamma_1\gamma_3} \leq 0.04$ need angular separation between photon from dark photon and ALP:

$$\Delta R_{\gamma_1 a} \approx \frac{2\, m_{\gamma_D}}{E_{\gamma_D}} \lesssim 0.02$$

  - Gives a constraint on the dark photon mass: $m_{\gamma_D} \lesssim \frac{m_h}{200} \approx 0.625 \text{ GeV}$

Do the Signatures Survive in the Detector?

- Ensure photons land in barrel or endcap:
  - ATLAS: $|\eta| < 1.37 \quad \text{or} \quad 1.52 < |\eta| < 2.5$
  - CMS: $|\eta| < 1.44 \quad \text{or} \quad 1.57 < |\eta| < 2.5$
- Require some minimum transverse momentum on photons:

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

- No 6-photon triggers, so we estimated them choosing pTs such that photon identification is at 50-75%

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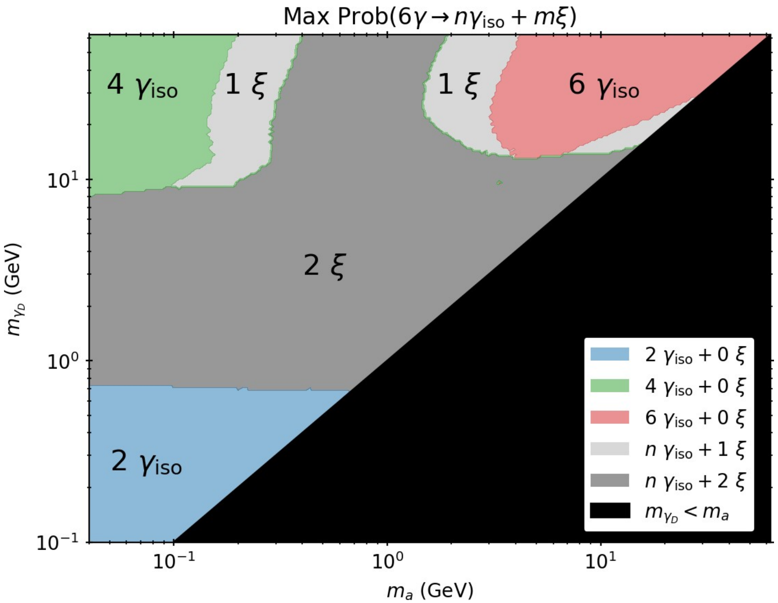
Detector Efficiencies

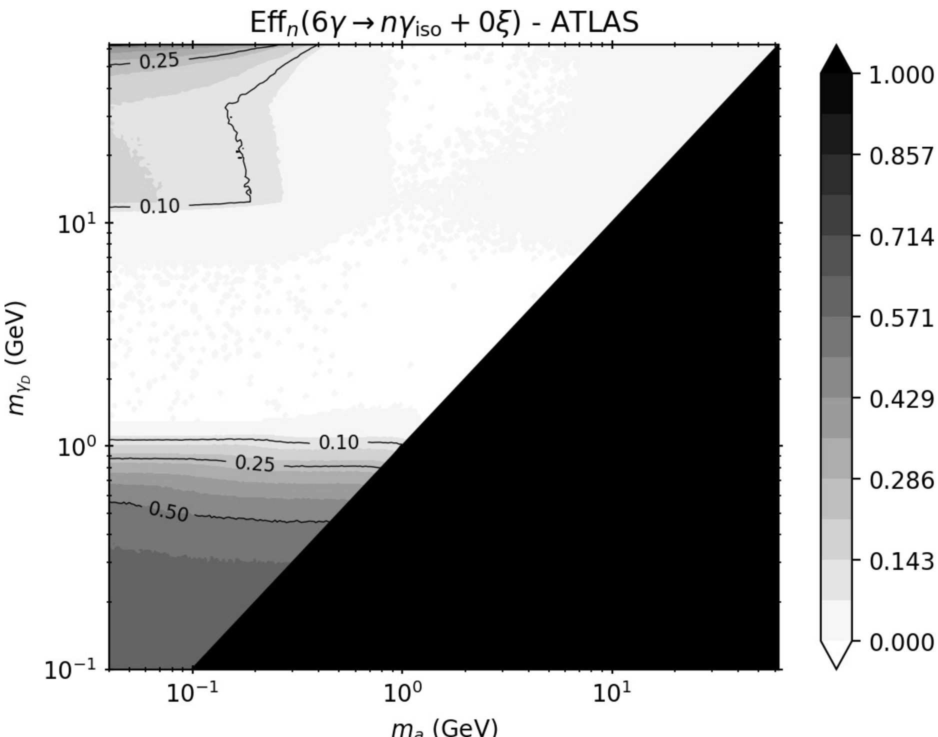
- Define a detector efficiency as percentage of signal events with n-isolated photons and m ξ -jets that pass a k-photon trigger:

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

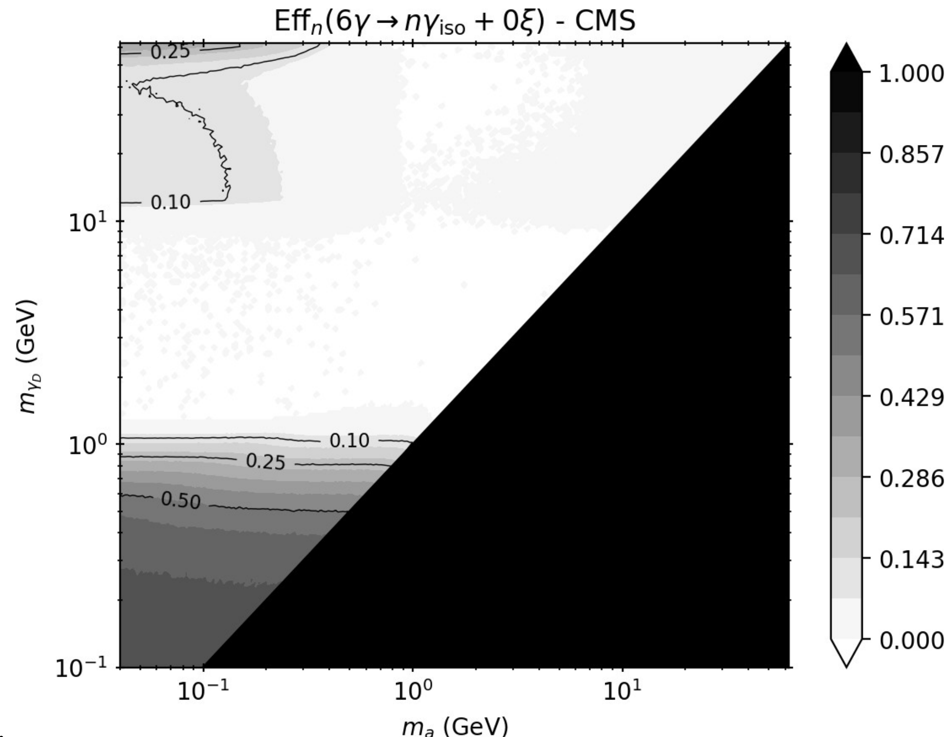
- n-isolated photon with no ξ-jet events passing n-photon triggers



ATLAS



CMS



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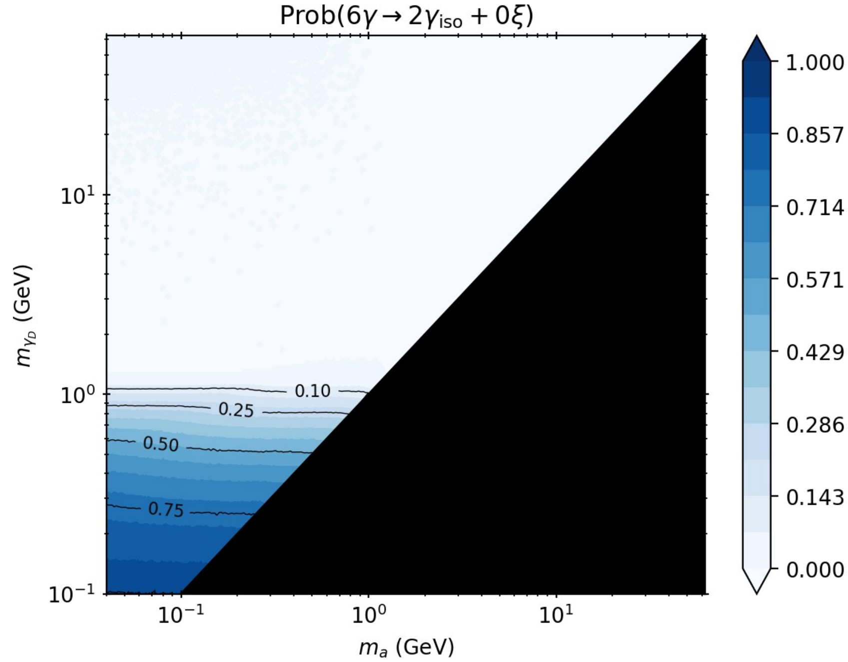
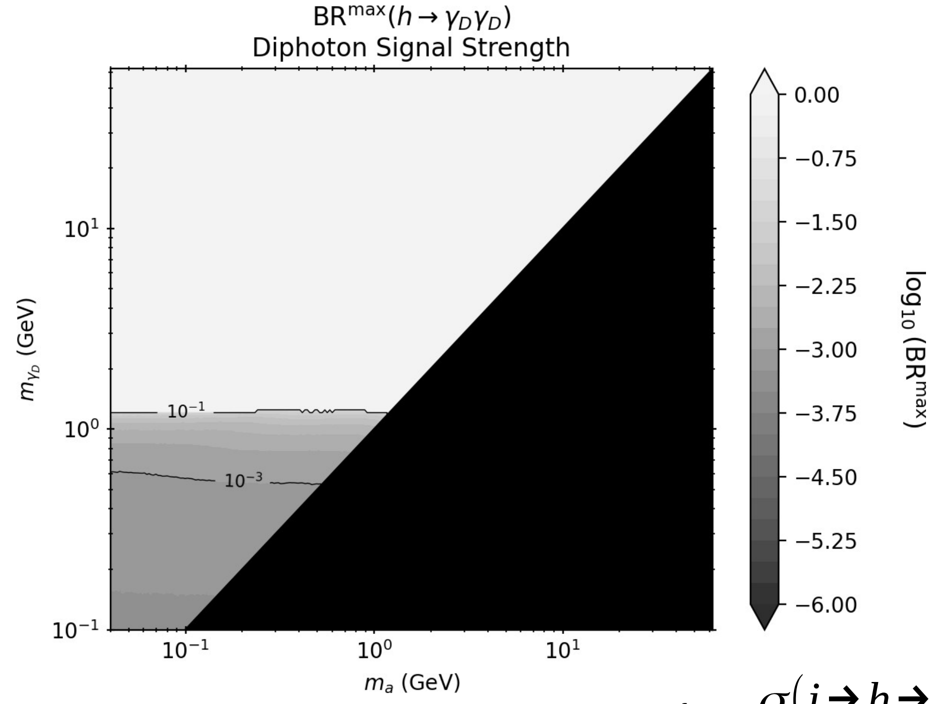
Di-photon signal





$$\mu_i^f = \frac{\sigma(i \to h \to f)}{\sigma_{SM}(i \to h \to f)}$$

- Largest probability for di-photon signal at low dark photon masses.
- Signal strength measurements for ATLAS (CMS): ATLAS 2207.00348, CMS JHEP07 (2021)

$$\mu = 1.04 \pm^{0.10}_{0.09} \; (1.12 \pm^{0.09}_{0.09})$$

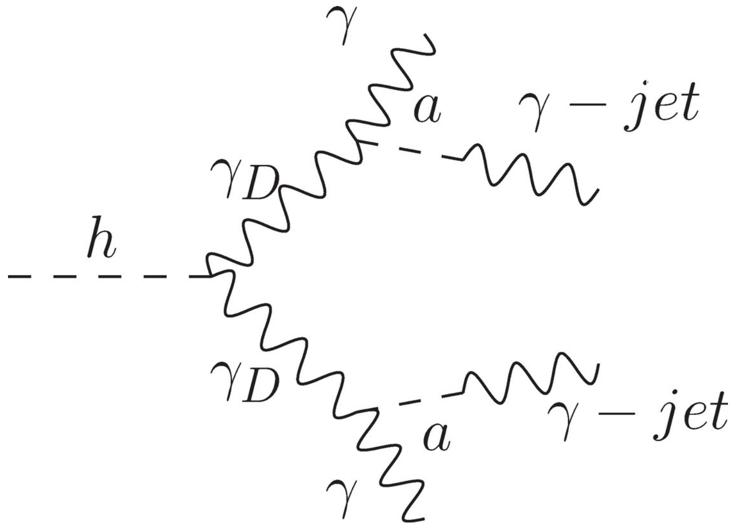
- BR into di-photons changed as:

$$\mu = \frac{1}{\mathrm{BR_{SM}}(h \to \gamma\gamma)} \frac{\Gamma_{\mathrm{SM}}(h \to \gamma\gamma) + \Gamma(h \to \gamma_D\gamma_D)\mathrm{BR}^2(\gamma_D \to a\gamma)\mathrm{BR}^2(a \to \gamma\gamma)\mathrm{Prob}(6\gamma \to 2\gamma_{\mathrm{iso}} + 0\xi)}{\Gamma_{\mathrm{SM}}(h) + \Gamma(h \to \gamma_D\gamma_D)}$$

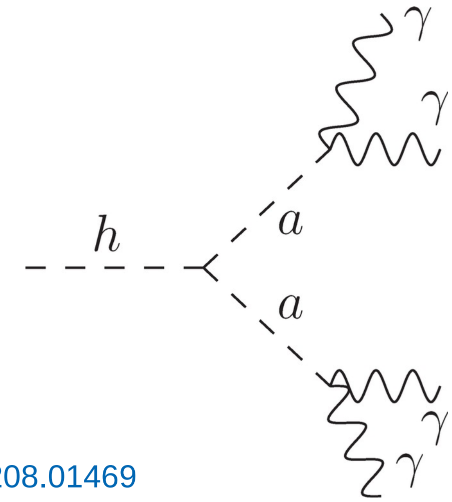
- Assume ALP and dark photon branching ratios as: $\mathrm{BR}(\gamma_D \to a\gamma) = \mathrm{BR}(a \to \gamma\gamma) = 1$
- From now on place limits on $\mathrm{BR}(h \to \gamma_D\gamma_D)$

Four photon signal

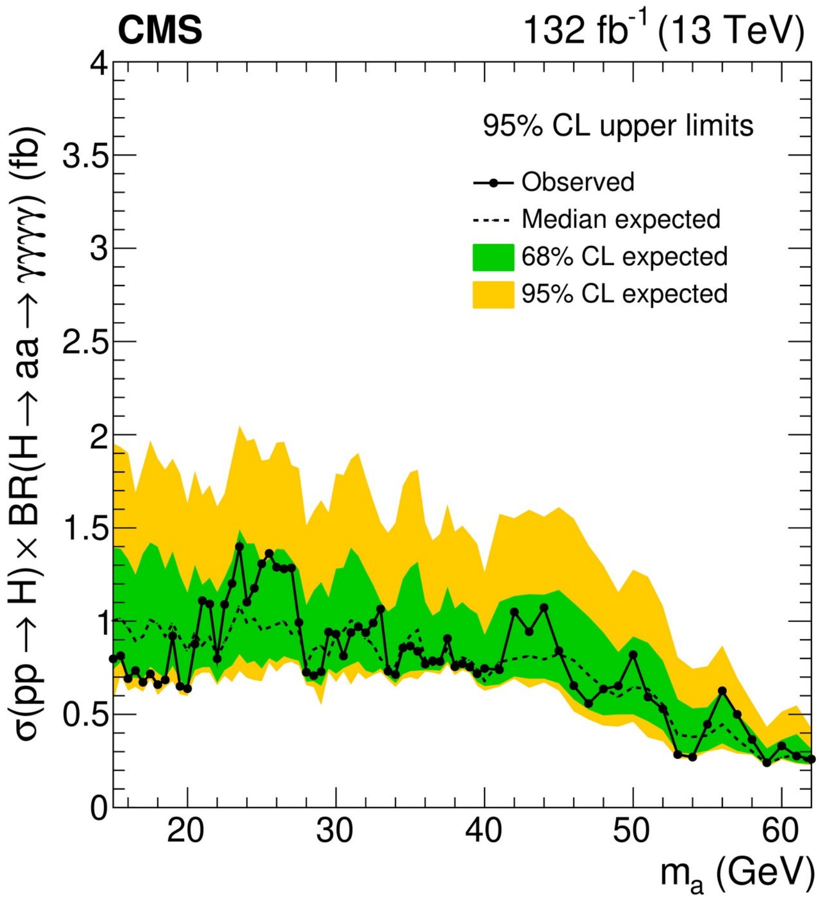
- Higgs to four photon has long been proposed Draper, McKeen, PRD85 (2012), Curtin, et al PRD90 (2014), etc.
- Unlike the typical scenario, our four isolated photons originate from a spin-1 particle:



  - An apparent violation of Landau-Yang theorem.
  - Similar signals:
    - $Z \to \gamma a \to \gamma + \gamma - jet$ Toro, Yavin PRD86 (2012)
    - $Z' \to \gamma a \to \gamma + \gamma - jet$ Chala, et al PLB755 (2016)
- Detector resolutions are finite.



CMS 2208.01469



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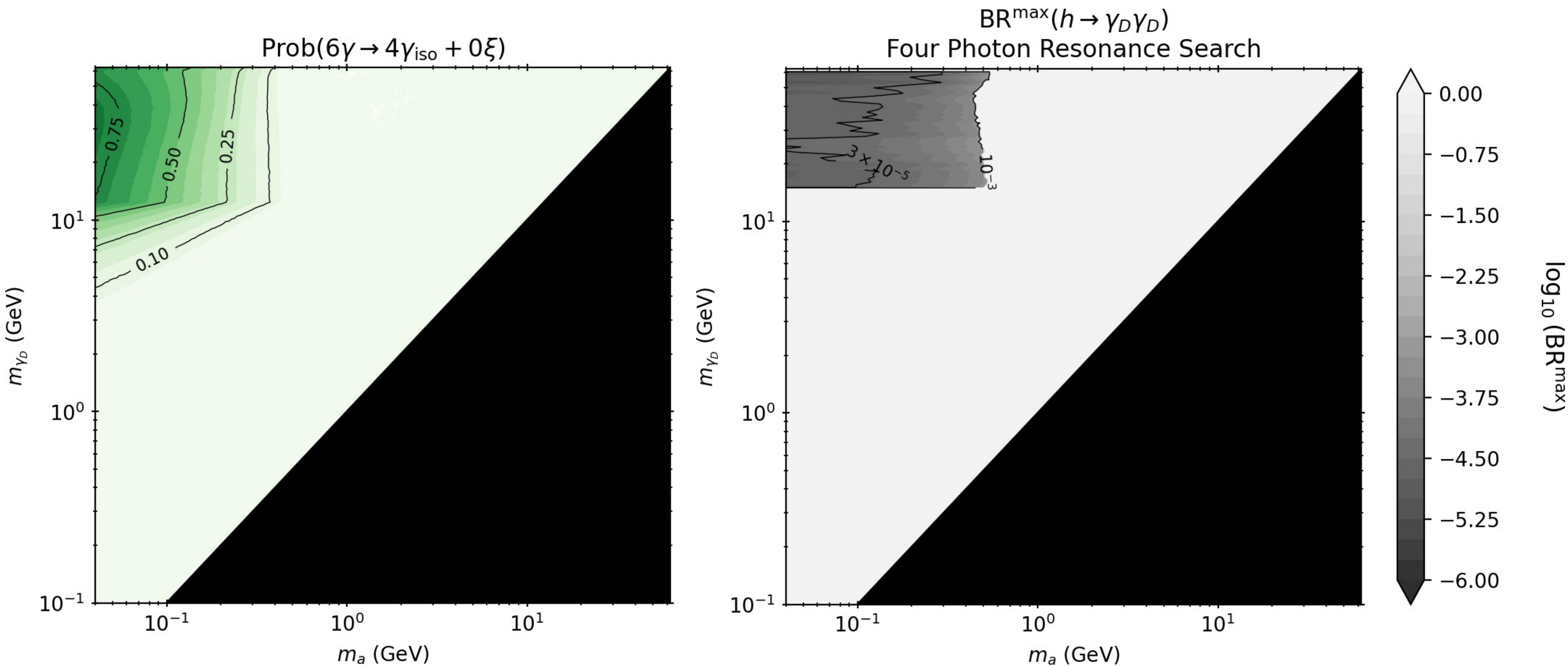
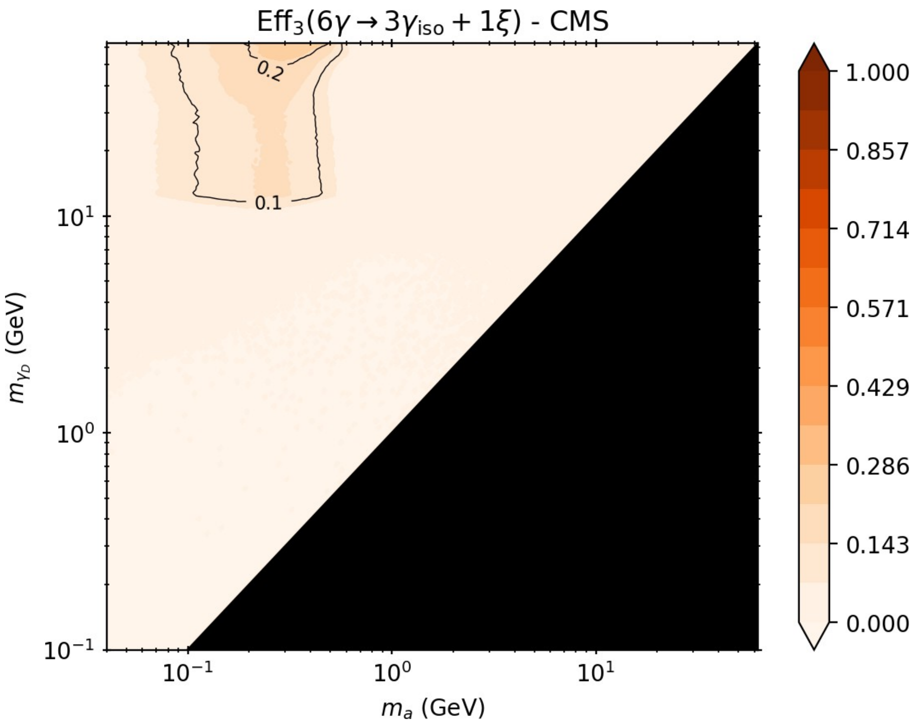
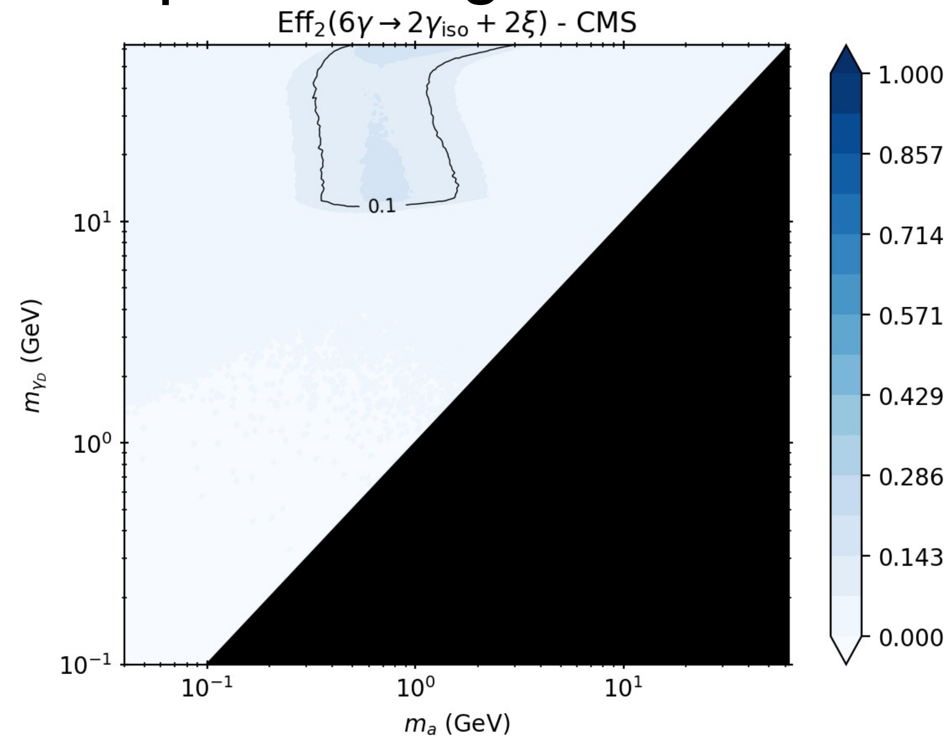
Four Photon Constraints



- Demand detector efficiencies greater than 1%
- Direct searches very constraining on this signal.
  - Limit branching ratio to less that 10^{-3} over relevant range.

Six photon and non-isolate photon signals





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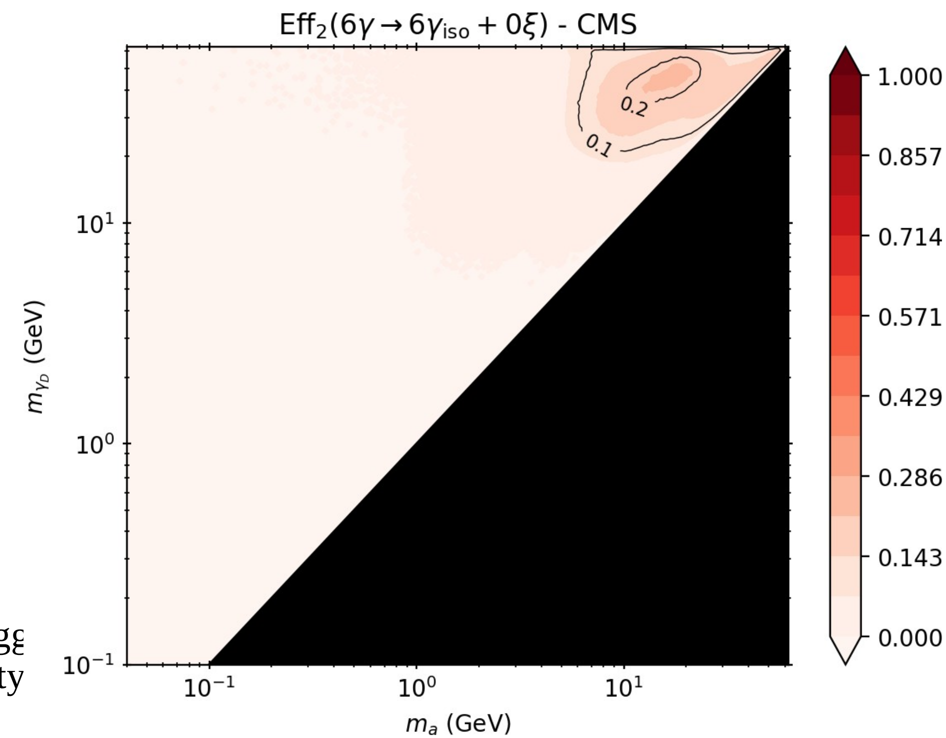
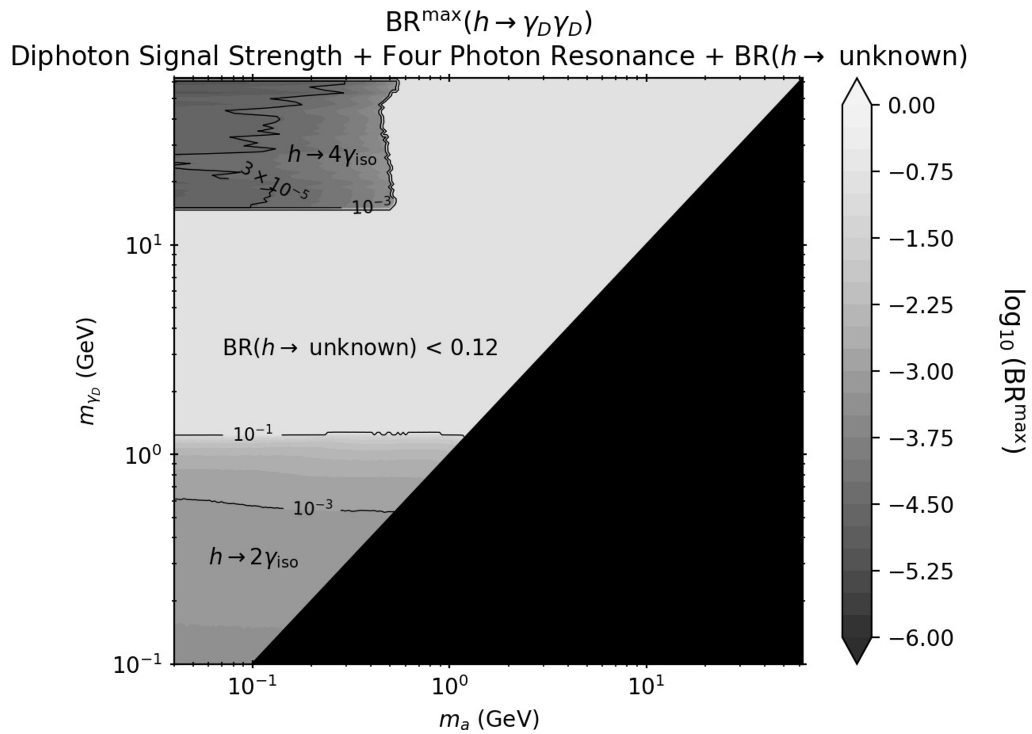
- 6-photon signal did not pass 6-photon triggers.
  - May be possible to lower trigger requirements.
- Showing the 2 and 3-photon triggers for 6-photon and ξ -jet signals
  - The photons that pass the trigger will not reconstruct the Higgs mass.
  - Would not survive a standard analysis.
  - However, the may be save to "tape" and a reanalysis may find these signals.



Cumulative Result



- Six photon a ξ-jet signals will contribute to the total width of the Higgs.
  - In fits to Higgs precision measurements, assume there is some “undetermined” Higgs width into states not explicitly included in the fits.
  - Limit on the undetermined branching ratio ATLAS, Nature, arXiv:2207.00092

$$BR(h \to unknown) \leq 0.12$$

  - Not relevant for two photon signal.
    - Changes di-photon partial width in addition to total width.
  - Direct searches for four photons always better.

Conclusions

- In the past 11 years, Higgs physics has progressed greatly.
- May still have interesting signatures to search for.
  - May still expect deviations to SM predictions.
  - Due to small width, may still be sensitive decays through small couplings.
- Studied the dark axion model.
  - Have Higgs to six photon decay.
  - Can give rise to di-photon and four photon signatures.
    - Four-photon signature would be an apparent Landau-Yang theorem violation: dark photon decays into two photons.
  - More challenging signatures as well: six isolated photon and non-isolated photons.
    - Estimated a six photon trigger, however kills signal.
    - These events may have passed a two photon or three photon triggers.
    - Even if they pass the triggers, may not pass the standard analysis since the photons that pass the triggers would not reconstruct the Higgs mass.
    - However, these events may be save to “tape” and signal may be seen with a reanalysis.

Thank You

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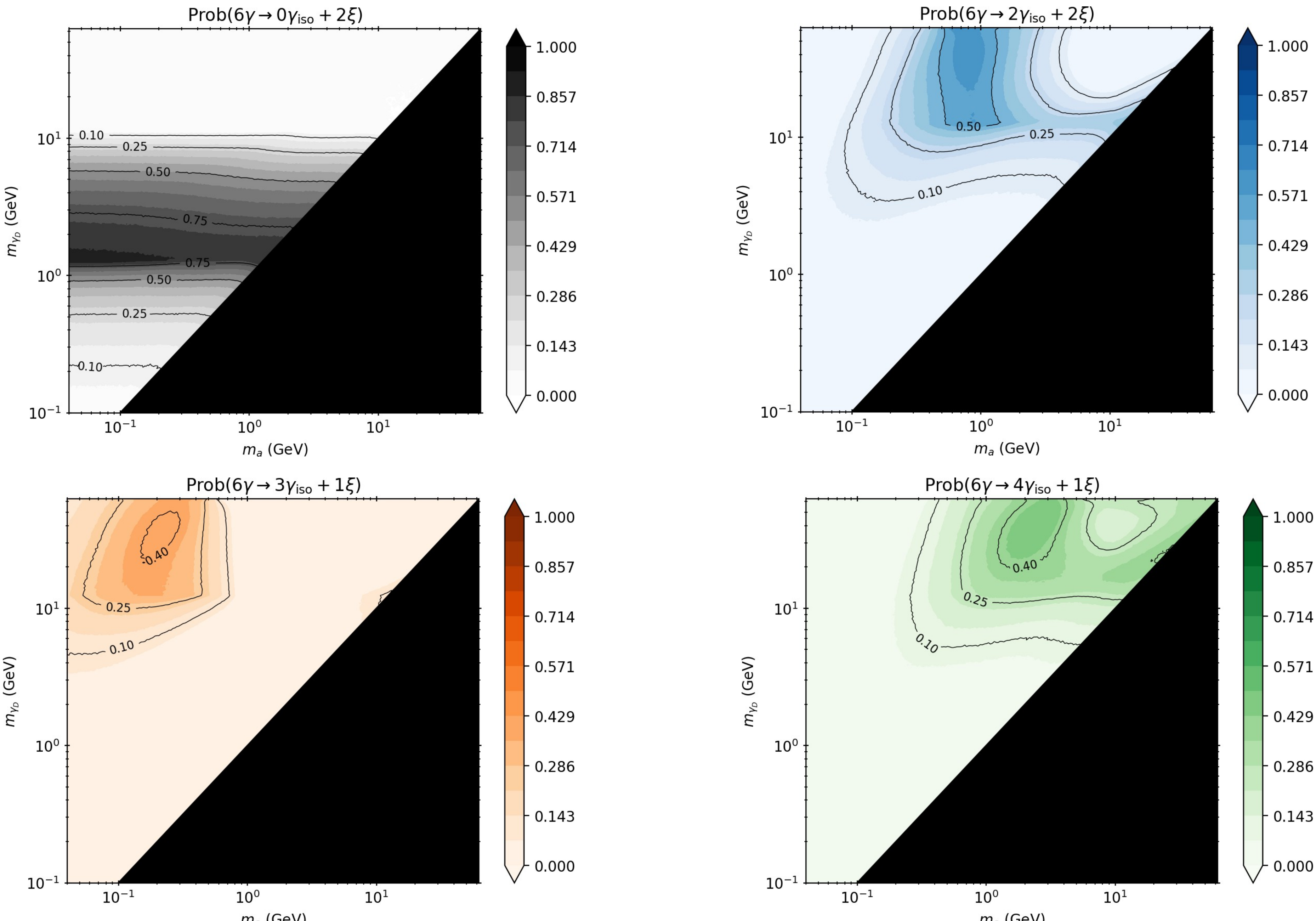
Non-Isolated Photon Signals



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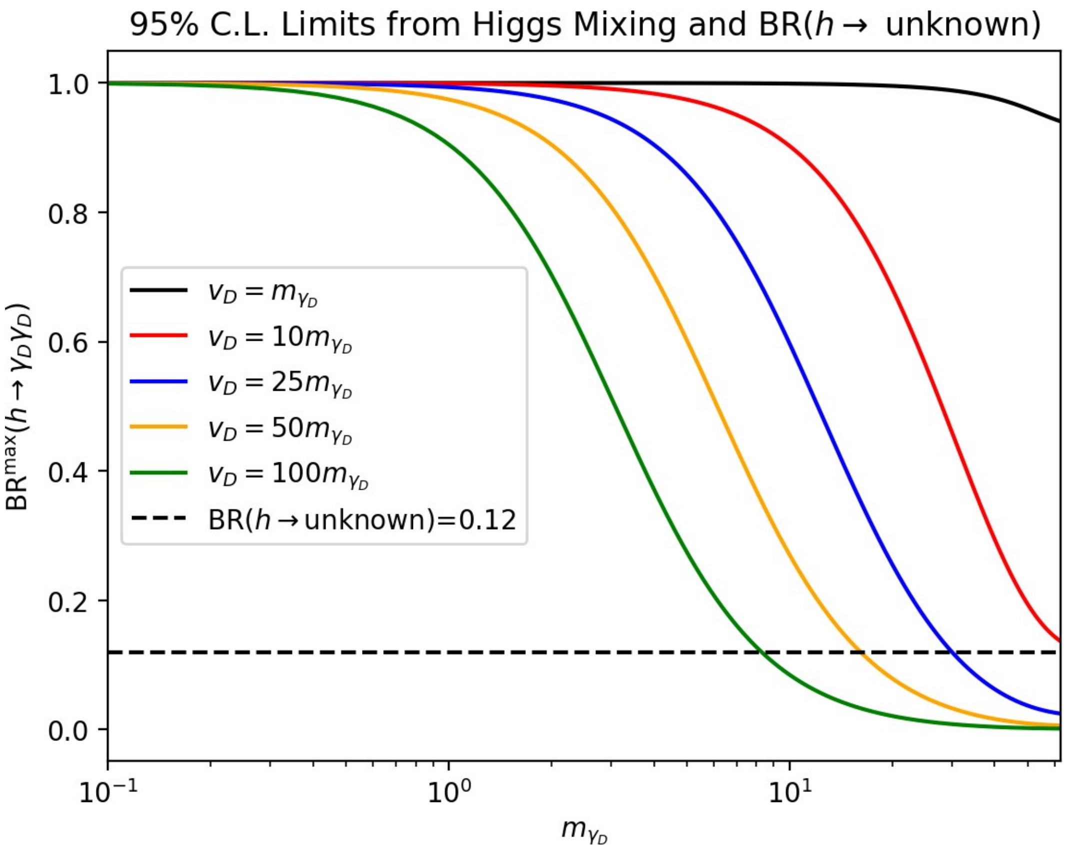
Higgs Mixing Constraints



- Higgs dark photon coupling from scalar mixing:

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