Impact of Non-Pointing Photon Searches at ATLAS for Dark Matter Models

Walter Rodríguez
walter.rodriguez@pucp.edu.pe

QUANTUM UNIVERSE
ATTRACT. WORKSHOP

PUCP

Based on the following work:
P. Arias, B. Díaz, L. Duarte, J. Jones-Perez, WR, D. Zegarra (2507.15930)

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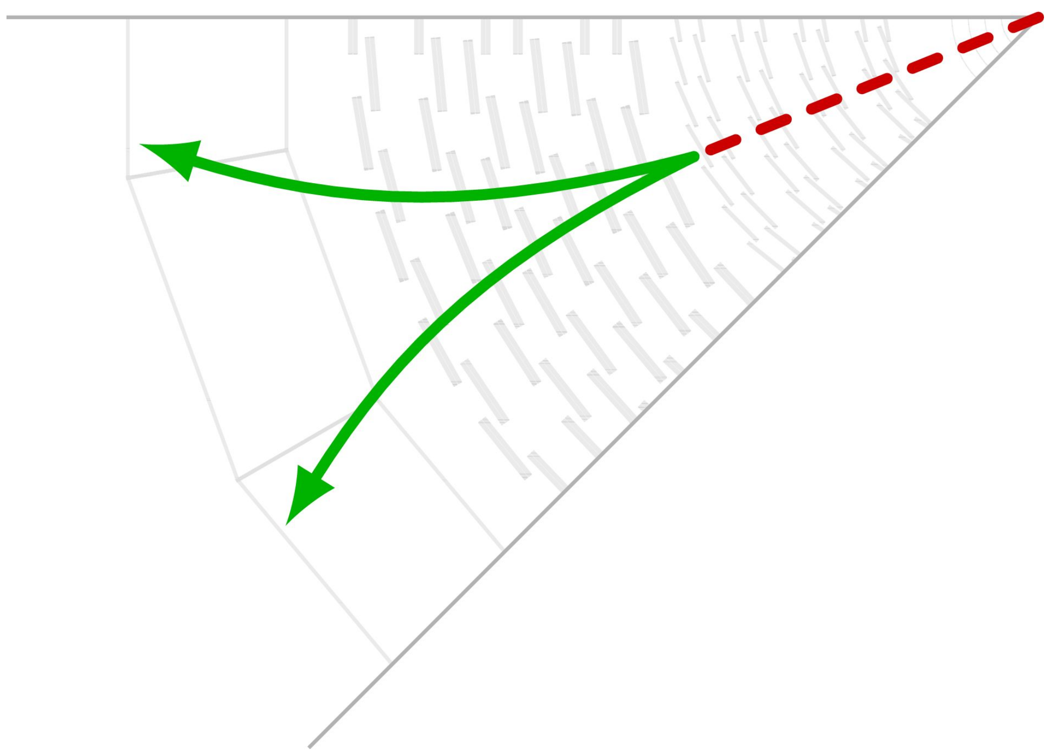

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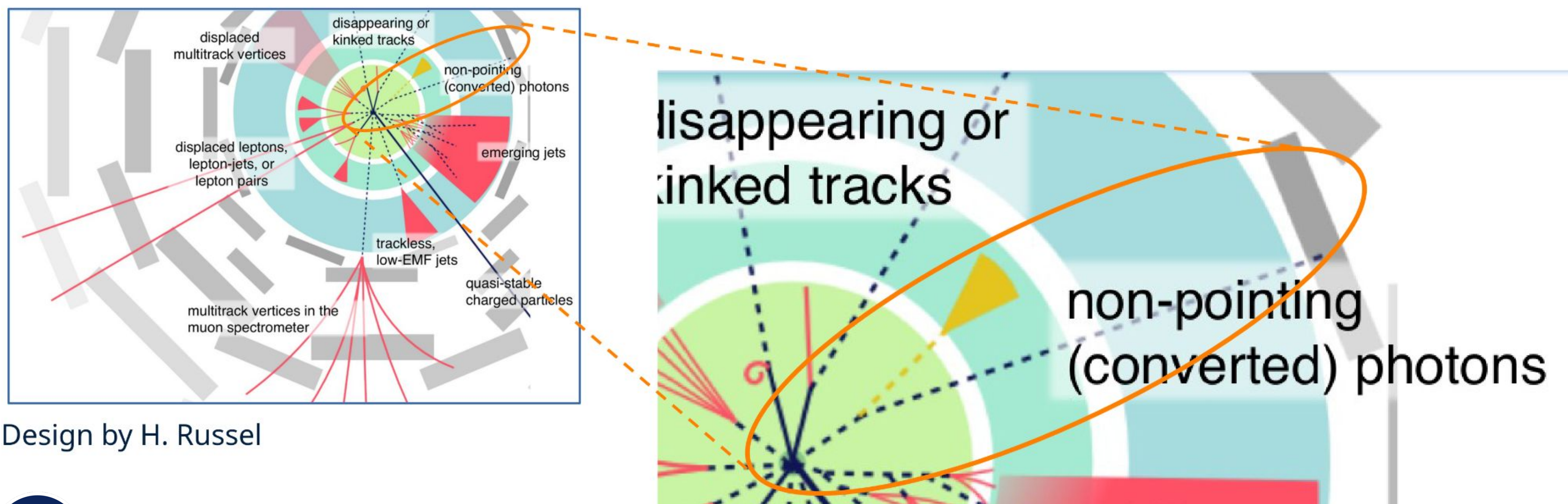

Design by H. Russel

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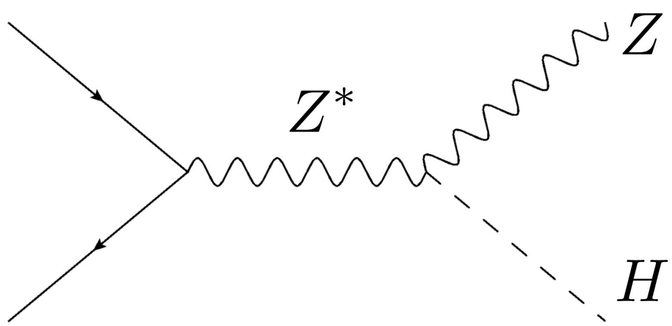
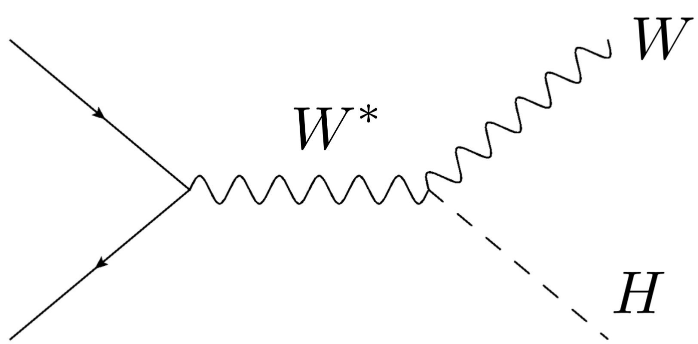
- Many models predict long-lived particles (LLPs), including in Higgs decays.
- LLPs can give displaced photons, a clean and striking LHC signature.
- This work recasts ATLAS displaced-photon searches to probe these scenarios using refined collider searches.

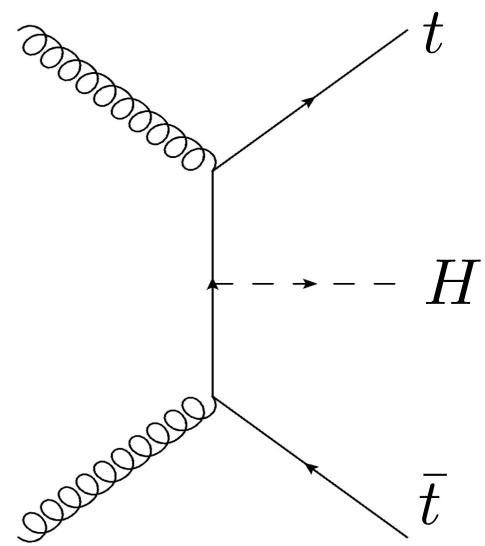
ATLAS (2209.01029)

Recasting

- Trigger: isolated lepton with p_T > 27 GeV.







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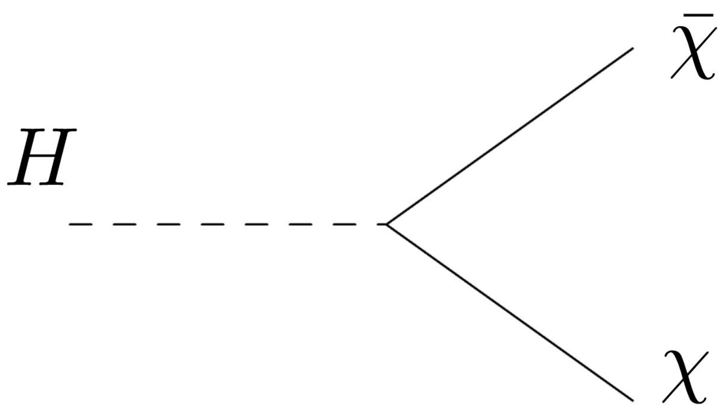

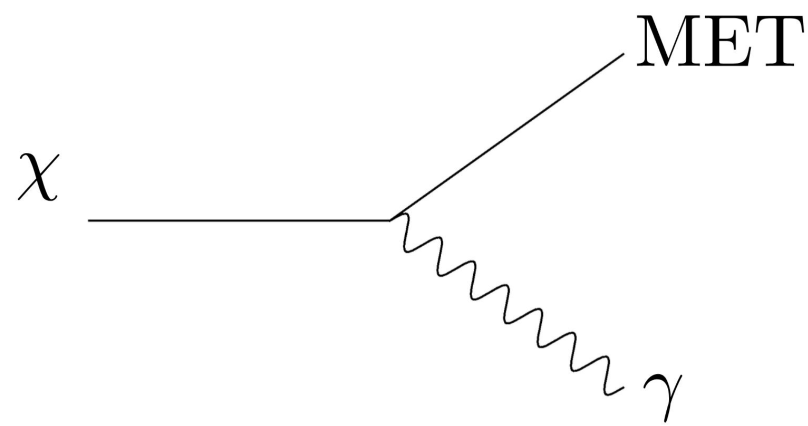

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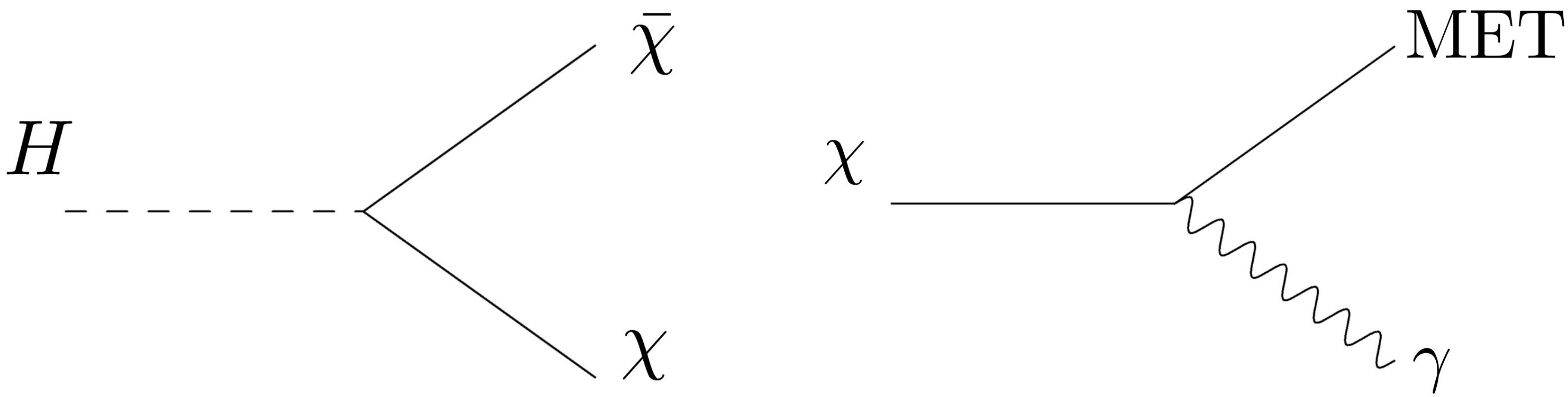

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- Place cuts on t_γ and $|\Delta z_\gamma|$. Distinguish single and multi-photon samples.

$$(1) \quad 1.5\,\text{ns} < t_\gamma < 12\,\text{ns} \qquad\qquad 1\,\text{ns} < t_\gamma < 12\,\text{ns} \quad (2+)$$

$$|\Delta z_\gamma| > 300\,\text{mm}$$

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- Define signal region depending on MET > 50 GeV.
- Place cuts on t_γ and $|\Delta z_\gamma|$. Distinguish single and multi-photon samples.
- Results obtained for SUSY:

	1	2+	1+
Expected	3.8 ± 1.6	0.28 ± 0.04	4.1 ± 1.7
Observed	4	0	4

ATLAS (2209.01029)

Theoretical Model

Dark Sector includes

- A new real pseudo-scalar field ϕ

Y. Farzan, A. R. Akbarieh (1207.4272 [hep-ph])
P. Arias, A. Arza, J. Jaeckel, D. Vargas-Arancibia (2007.12585 [hep-ph])
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  - Dark fields A'_μ and ϕ are odd under $\mathbb{Z}_2$
  - Standard Model (SM) fields are even under $\mathbb{Z}_2$

$$\mathcal{L} \supset -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m_{\gamma'}^2 A'^2_\mu + \frac{1}{2}(\partial_\mu\phi)^2 - \frac{1}{2}\tilde{m}_\phi^2\,\phi^2 - \lambda_\phi\,\phi^4 - \lambda_{HS}\,\phi^2|H|^2$$

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  - Standard Model (SM) fields are even under $\mathbb{Z}_2$
- A 5-dimension EFT operator involving A'_μ and preserving $\mathbb{Z}_2$ and $U'(1)$ symmetries is used to include the decoupled sector.

$$\mathcal{L}_5 = \frac{g_D}{2}\phi\, F'_{\mu\nu}\tilde{B}^{\mu\nu}$$

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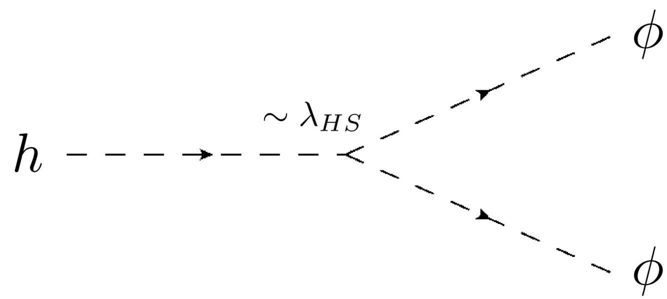

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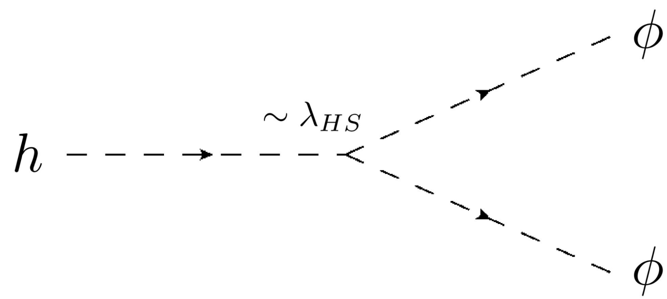
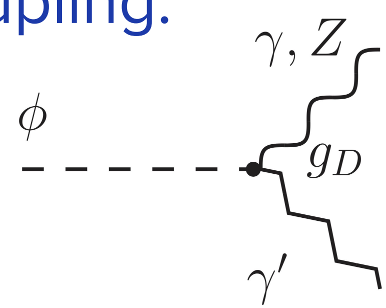


- Meanwhile, the displaced photon and the MET will be generated via the effective coupling.

$$\mathcal{L}_5 = \frac{g_D}{2}\phi\, F'_{\mu\nu}\tilde{B}^{\mu\nu}$$



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- Sensitivity requires 1 *cm* < $c\tau_\phi$ < 100 *cm* to make it decay in the Inner Detector.

$$\Gamma_\phi(\phi \to \gamma\gamma') = \frac{g_D^2\, c_W^2}{32\pi} m_\phi^3 \left(1 - \frac{m_{\gamma'}^2}{m_\phi^2}\right)^3$$

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- We focus on light DM candidates γ' ($m_{\gamma'} \lesssim$ 5 GeV).

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L. Duarte, J. Jones-Pérez and C. Manrique-Chavil (2311.17989)

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- Sensitivity requires $1\ cm < c\tau_\phi < 100\ cm$ to make it decay in the Inner Detector.
- We focus on light DM candidates γ' ($m_{\gamma'} \lesssim 5$ GeV).
- We require a sufficient number of scalars produced from the Higgs.

$$\Gamma(h \to \phi\phi) = \frac{\lambda_{HS}^2\, v^2}{8\pi\, m_h}\sqrt{1 - 4\frac{m_\phi^2}{m_h^2}}$$

this calls for $\mathcal{O}(10^{-5}) \lesssim \lambda_{HS} \lesssim \mathcal{O}(1)$

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Parameter Space

- We end up with the following parameter space:

$$m_{\gamma'} \sim 1 \text{ GeV} \ll m_\phi \lesssim m_h/2$$

$$10^{-11} \text{ GeV}^{-1} \leq g_D \leq 10^{-9} \text{ GeV}^{-1}$$

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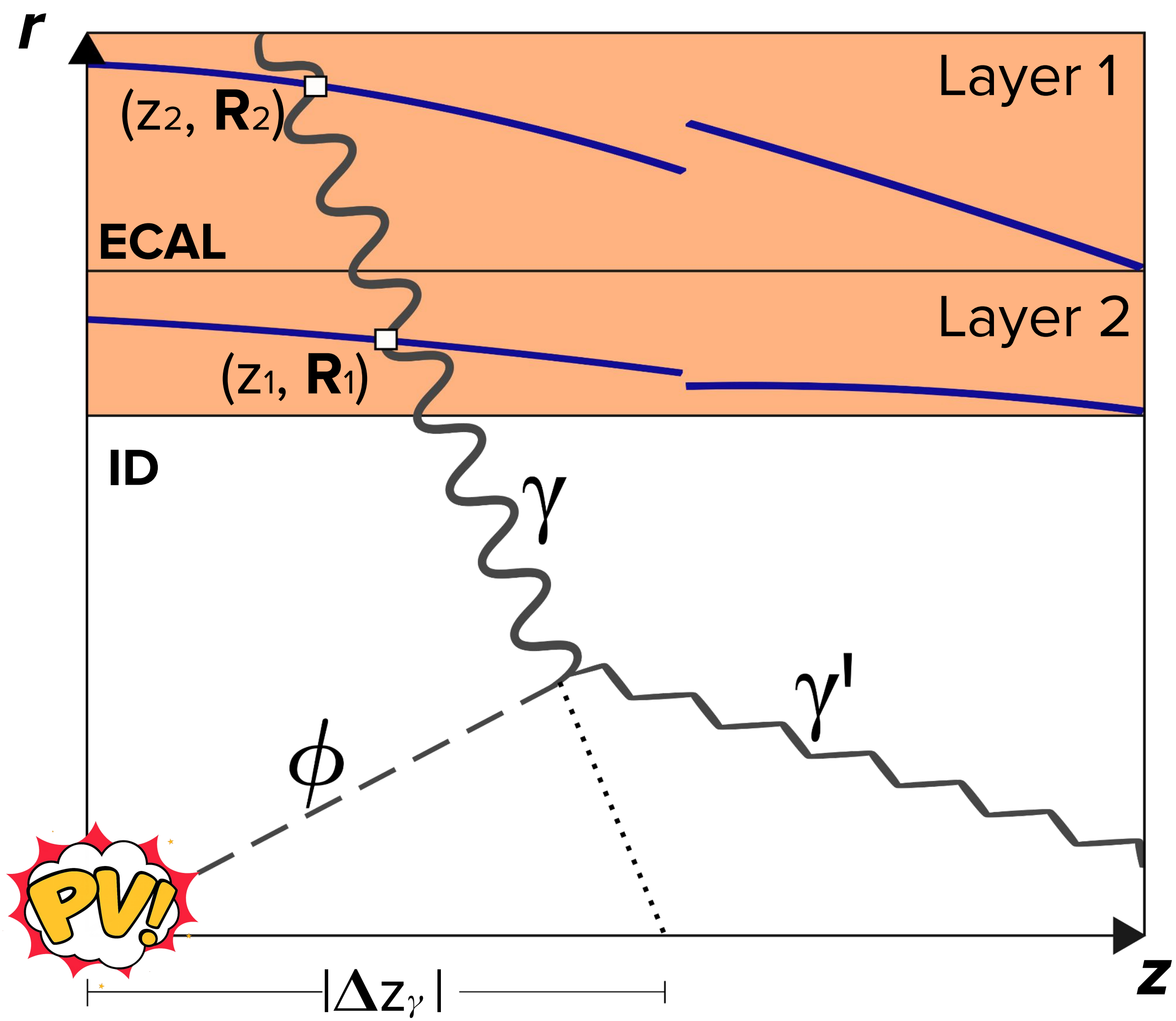
- This dark matter scenario also reproduces the correct DM relic abundance and satisfies cosmological constraints.

Non Pointing Variable: ATLAS



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D. Mahon (PhD Thesis)

Non Pointing Variables: Δz_γ

- With this, at first instance, one would use the following expression to find the non pointing parameter:

$$\Delta z_\gamma = \frac{z_1 R_2 - z_2 R_1}{R_2 - R_1}$$

Non Pointing Variable: $\Delta z\gamma$

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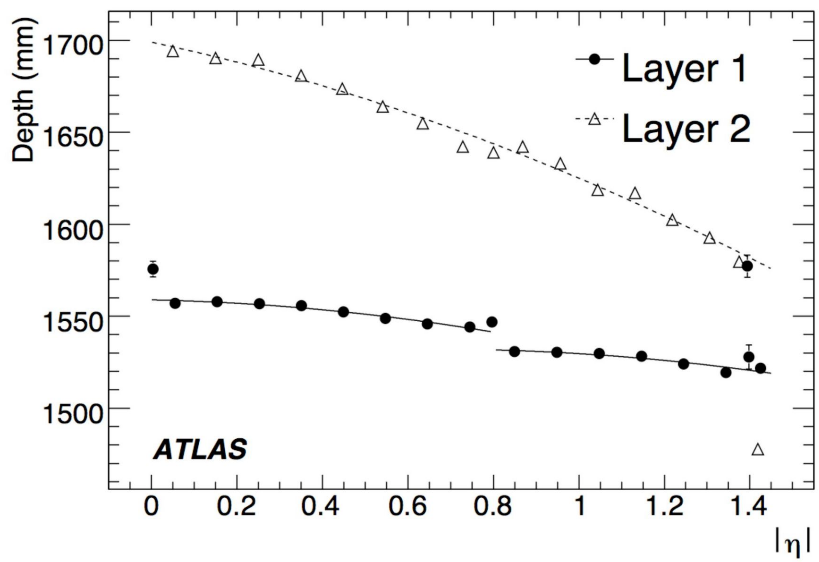
- ATLAS neglects the information on the azimuthal angle. R_i, however are functions on pseudorapidity: γ trace needs to be reconstructed and its η has to be determined when it enters the ECAL layers.



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ATLAS (0901.0512 [hep-ex])

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$$\Delta z_\gamma = r_{\phi z} - \frac{p_{\gamma z}}{p_{\gamma T}^2}(r_{\phi x}\, p_{\gamma x} + r_{\phi y}\, p_{\gamma y})$$
$$+ \frac{p_{\gamma z}}{p_{\gamma T}}\left(\frac{R_1 R_2}{R_2 - R_1}\right)\left\{\left(1 - \frac{d_0^2}{R_1^2}\right)^{1/2} - \left(1 - \frac{d_0^2}{R_2^2}\right)^{1/2}\right\}$$

with d_0: photon impact parameter

$$d_0 = (r_{\phi x}\, p_{\gamma y} - r_{\phi y}\, p_{\gamma x})/p_{\gamma T}$$

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Non Pointing Variable: t_γ

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- Note that for these calculations, the truth level of Pythia is used.

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Simulation Refinement

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Higgs Decay to Invisible & Undetected

- Invisible decays: Long-lived scalars ϕ that decay outside detector contribute to the Higgs invisible BR, limited by ATLAS $\boldsymbol{B_{inv} < 0.107}$

$$B_{\rm inv} = {\rm BR}(h \to \phi\phi)\,\exp\left[-\frac{2L_{\rm det}}{\gamma_{\rm rel}\,\beta_{\rm rel}\,c\,\tau_\phi}\right] < 0.107$$

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ATLAS (2301.10731 [hep-ex])
CMS (2303.01214 [hep-ex])

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- Assuming a **spherical detector** of $L_{det} = 1.97\ m$ radius, the probability of ϕ decaying beyond the detector is known

$$P(L_{\rm det},\,\infty) = \exp\left[-\frac{L_{\rm det}}{\gamma_{\rm rel}\,\beta_{\rm rel}\,c\,\tau_\phi}\right]$$

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- Assuming a spherical detector of $L_{det} = 1.97\ m$ radius, the probability of ϕ decaying beyond the detector is known.
- Undetected signals: Global fits to Higgs data (ATLAS/CMS) constrain additional exotic decays not covered by direct searches, yielding $\mathbf{B_{und} < 0.12}$

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ATLAS (2207.00092 [hep-ex])
CMS (1809.10733 [hep-ex])

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- Events also require MET > 50 GeV
- No excess observed → bounds on BR($h \to \phi\phi$) and LLP parameter space.

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Search Bounds & Cutflow

- Efficiency (in %) for m_ϕ = 60 GeV, $m_{\gamma'}$ = 1 GeV. We combine the three production processes. Results shown for gD = 5.7 × 10^(−10) and 1.6 × 10^(−10) GeV^−1, which respectively imply decay lengths $c\tau_\phi$ = 0.69 and 4.4 m.

Cut	$c\tau_\phi = 0.69$ m		$c\tau_\phi = 4.4$ m	
Trigger, $p_{\gamma T} > 10$ GeV, Acceptance	71		44	
Isolation, Efficiencies, Z-veto	39		18	
	Channel			
	1	2+	1	2+
$E_{\text{cell}} > 10$ GeV	15	20	11	3.2
MET > 50 GeV	6.2	8.3	5.4	1.3
$\lvert\Delta z_\gamma\rvert > 300$ mm	2.2	1.8	2.6	0.46
$t_\gamma > 1\,(1.5)$ ns	0.20	0.45	0.89	0.27

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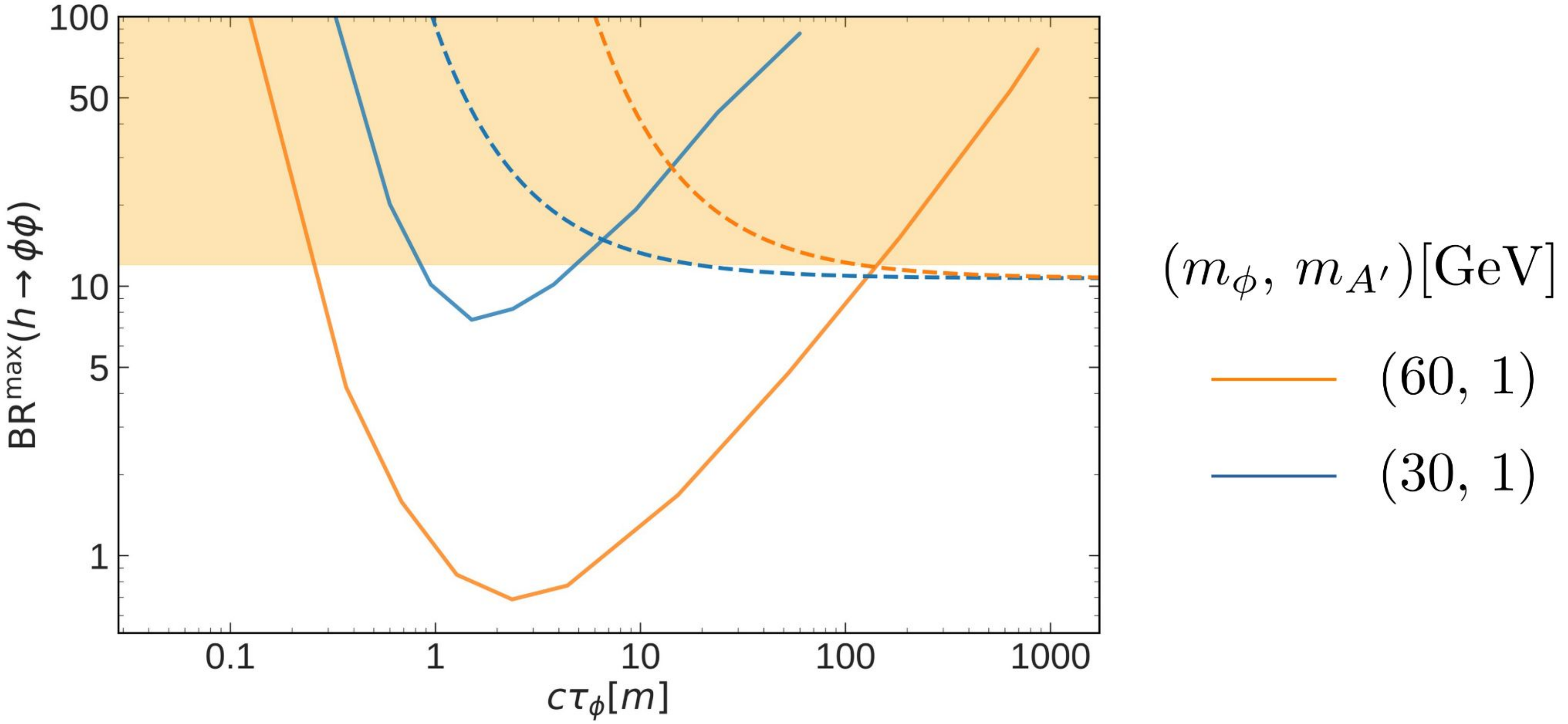
Results



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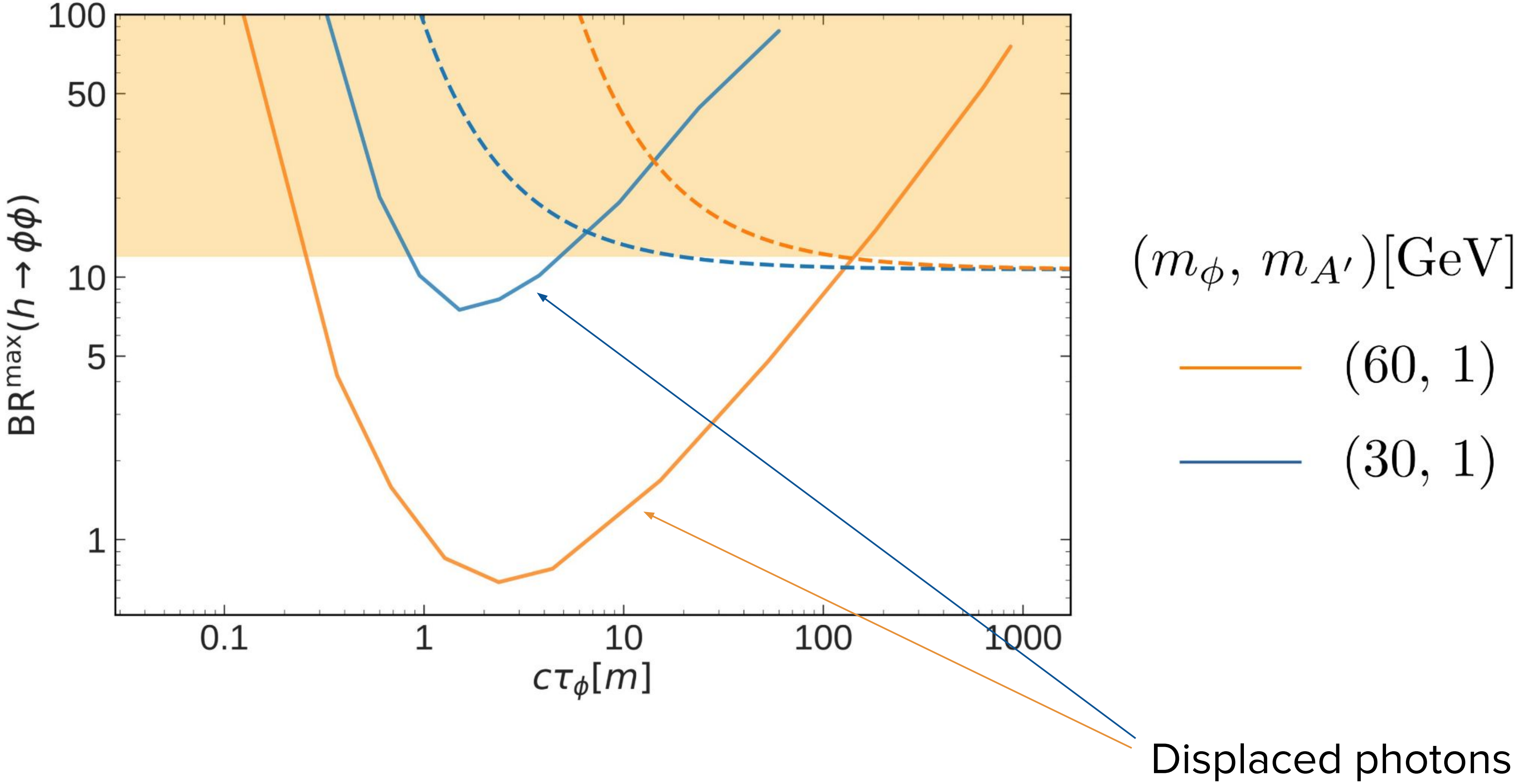

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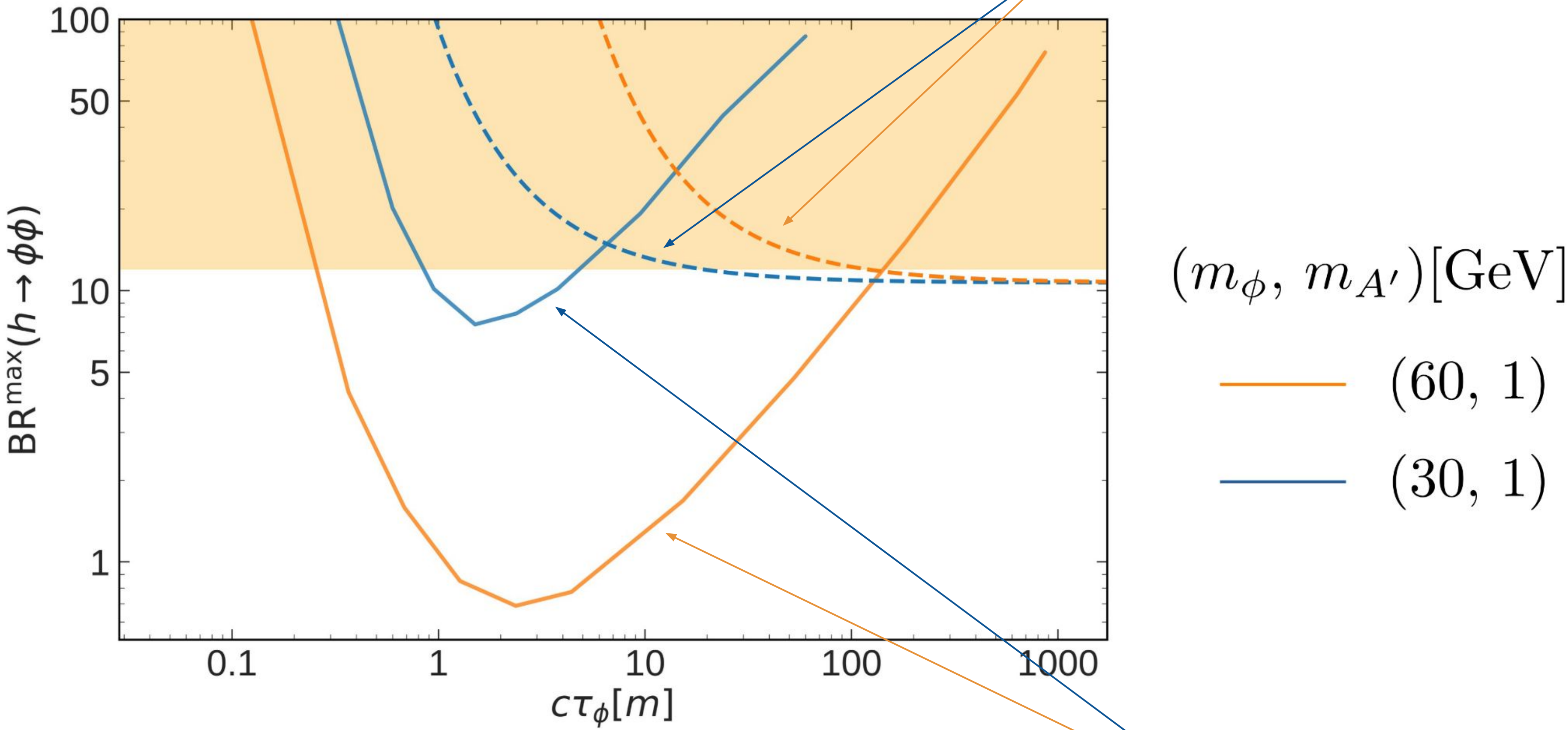
Results

Higgs → Invisible

ATLAS (2301.10731 [hep-ex])



Displaced photons

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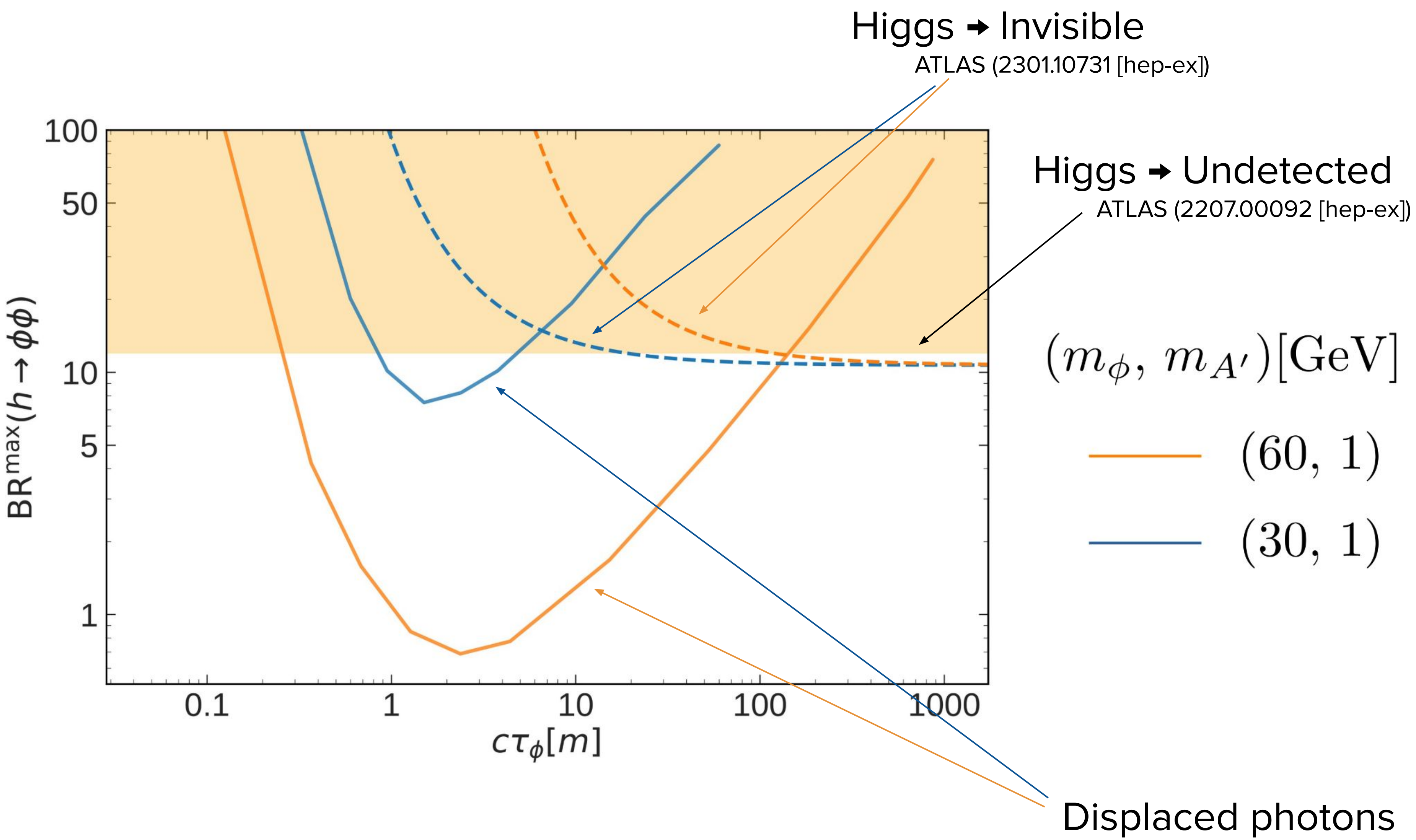
Results



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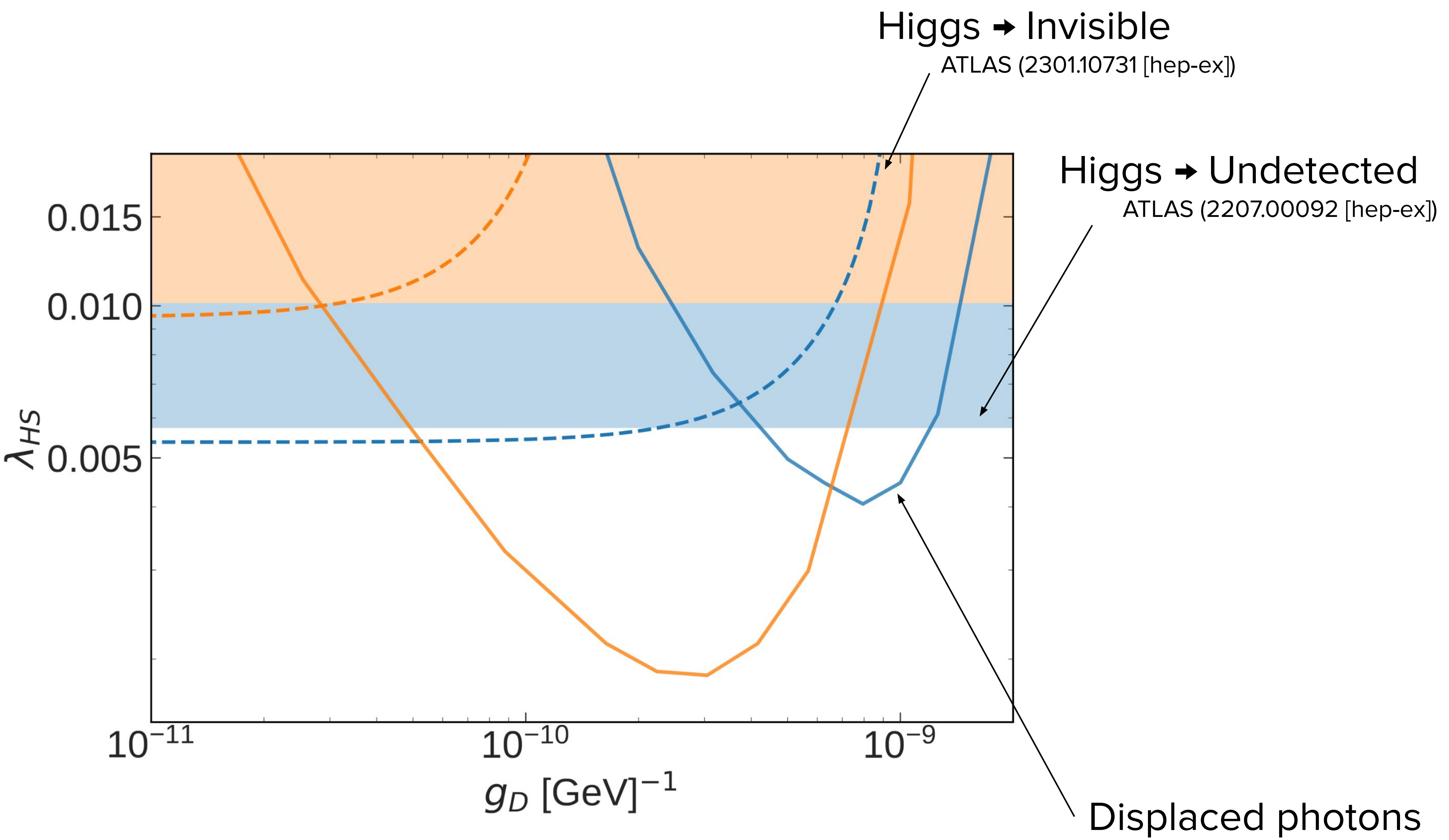

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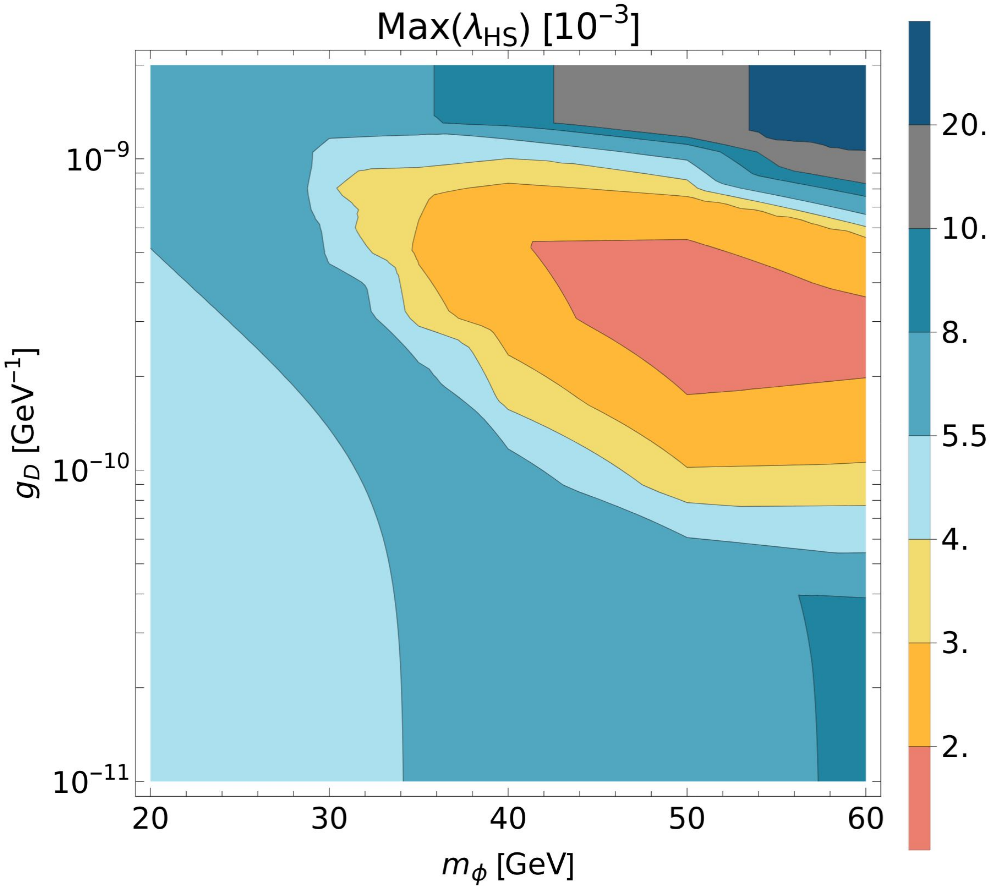
Results: Combined bounds



- Large coupling implies ϕ decays promptly.
- Heavier masses for ϕ are favoured: ϕ moves slowly so t$_\gamma$ is larger.
- For large gD, constraints from fit are strongest. For small gD, constraints from invisible decays are strongest.
- Small couplings implies ϕ decays outside detector.

- $m_{\gamma'} = 1$ GeV.

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Conclusions

- Searches for displaced photons can place bounds on models with LLPs decaying into photons and MET.
- These searches have largest sensitivity for $c\,\tau \sim \mathcal{O}(1\,\mathrm{m})$
- For lower (higher) lifetimes, Higgs → undetected (invisible) searches present better bounds.
- Recast of search in the context of dark photon with scalar portal places bounds $\lambda_{HS} \sim \mathcal{O}(10^{-3})$

Gracias

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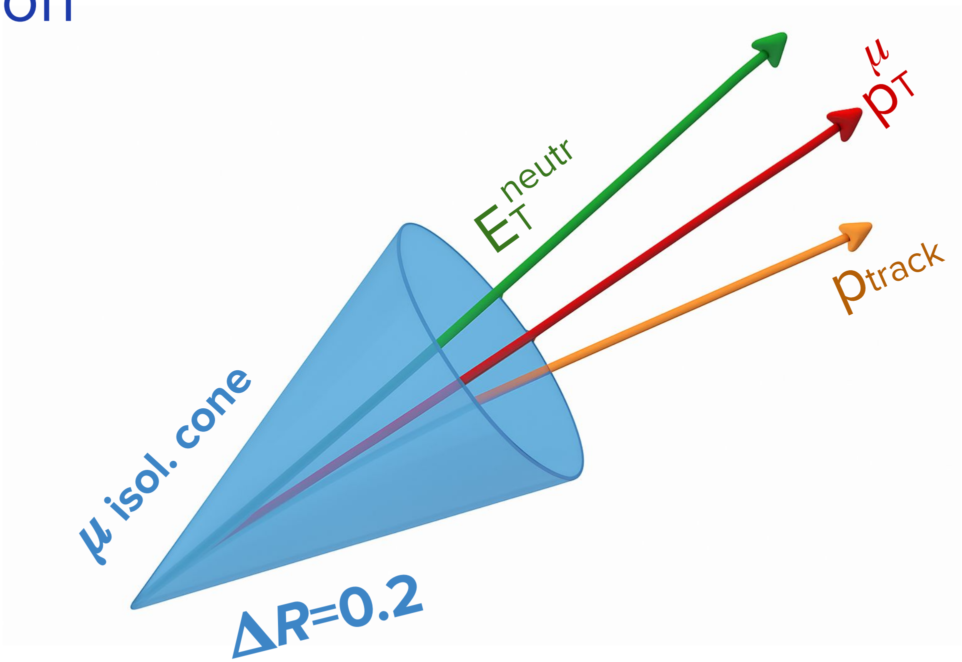
Backup Slides

Simulation Refinement

- ATLAS Delphes Card was modified to adapt them to match the performance more accurately.
- Muon Isolation



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

$$(p_{\mathrm{trk}} + 0.4 E_T^{\mathrm{neut}}) < 0.16\, p_T^{\mu}$$

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ATLAS (2012.00578 [hep-ex])

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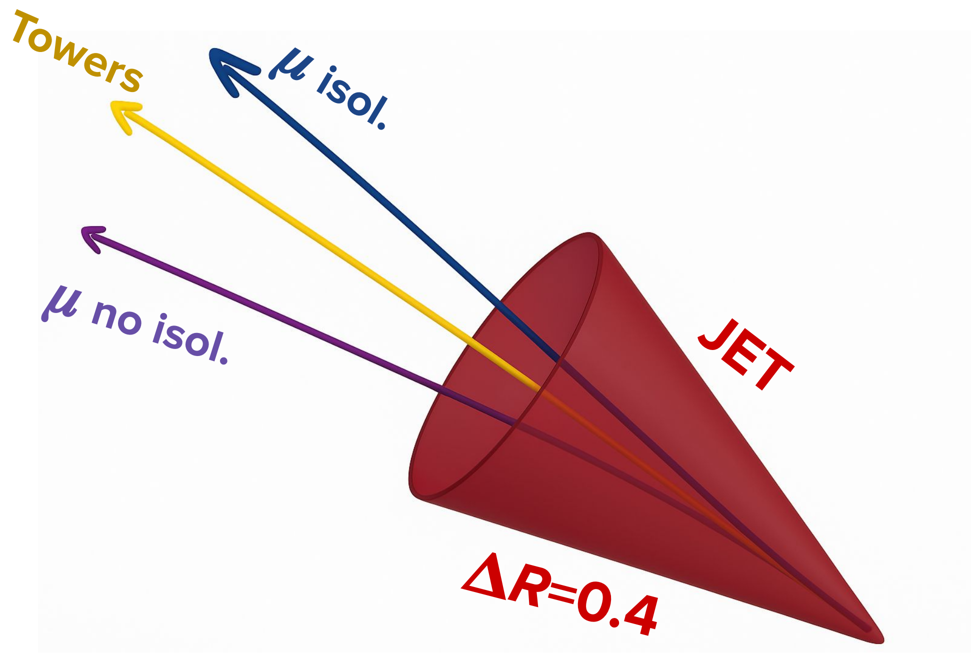

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ATLAS (2209.01029 [hep-ex])

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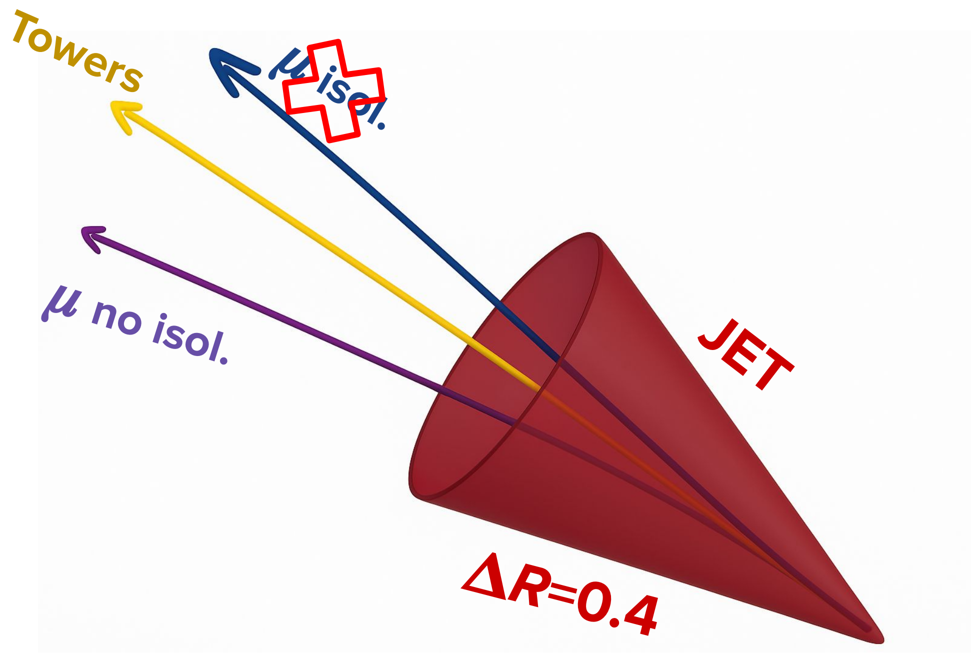


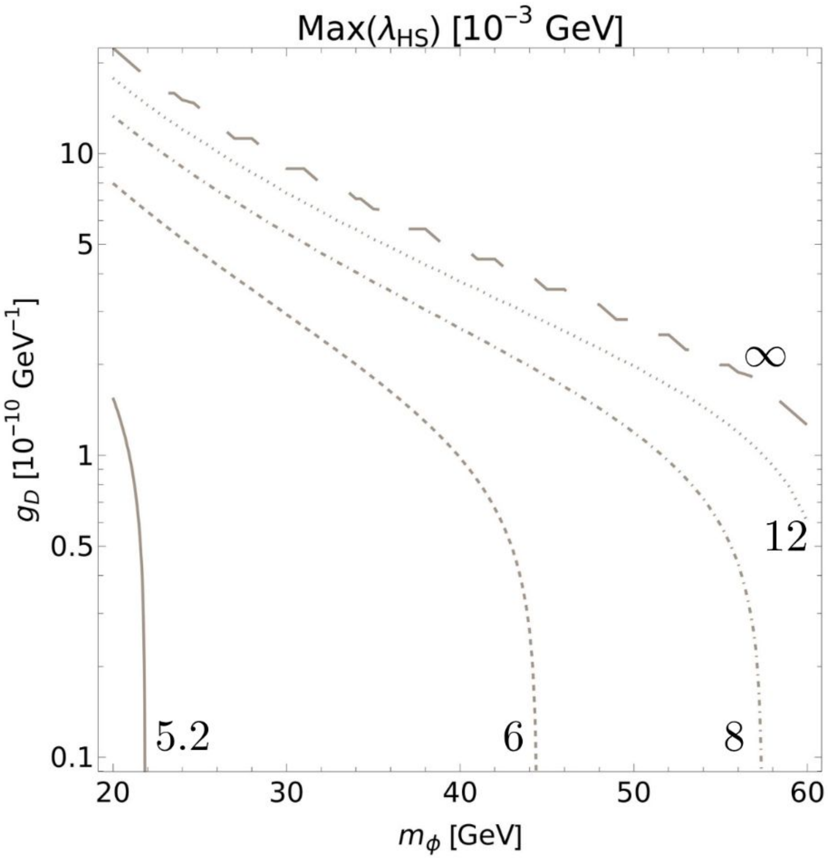
ATLAS (2209.01029 [hep-ex])

Delphes

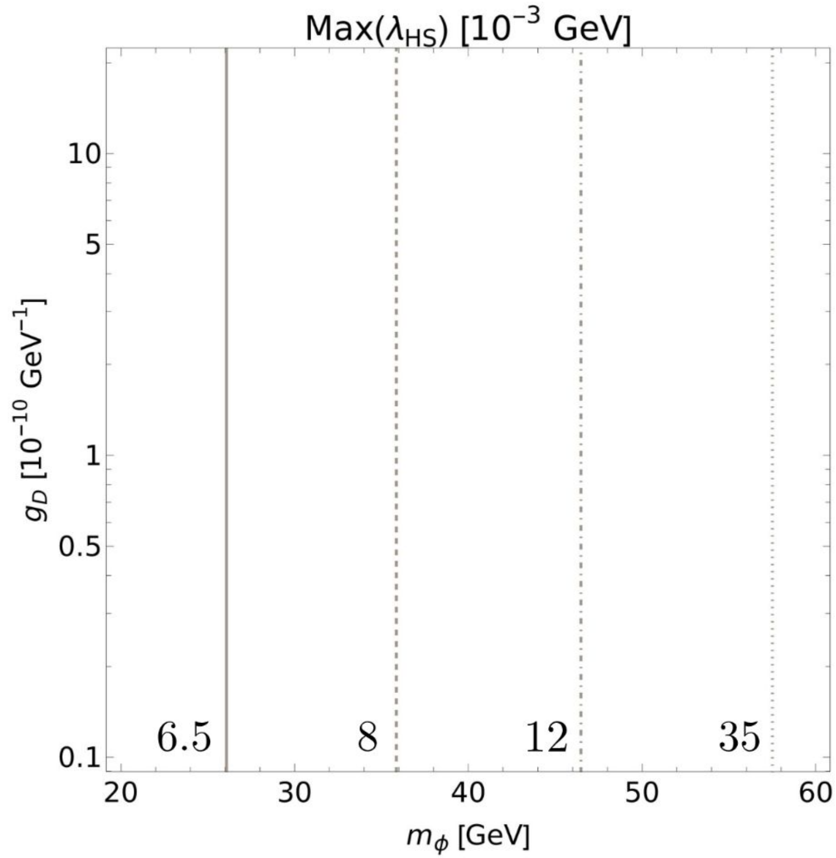
- Adapted to read HepMC with non-pointing Monte Carlo information.
- The photon and electron efficiencies are applied after Delphes.
- Muon isolation uses track and calorimeter information.
- Jets only include non-isolated muons, which later helps overlap removal to favour jets over muons.

Post-Delphes cuts

- Apply gaussian smear on delta Z (lster apply on t gamma)
- Apply momentum and eta cuts on photons and separate (later apply these on electrons, muons and jets)
- Apply electron efficiencies and ID
- Implement overlap removal for photons, electrons, jets and muons.
- Assign signal region if MET > 50 GeV



Higgs → invisible



Higgs → undetected

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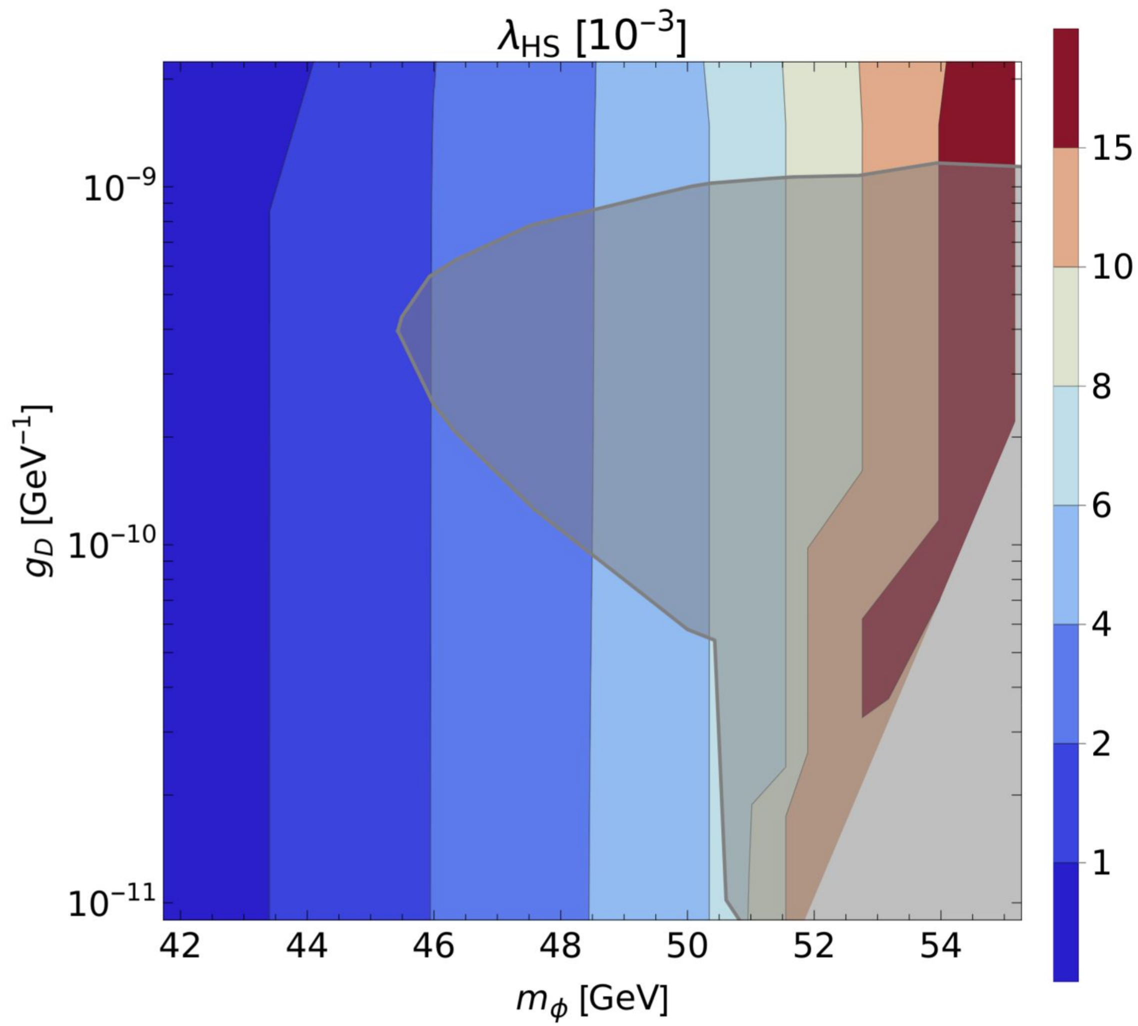

λ_{HS} [10^{-3}]
g_D [GeV^{-1}]
10^{-9}
10^{-10}
10^{-11}
42
44
46
48
50
52
54
m_ϕ [GeV]
15
10
8
6
4
2
1

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