Placing Bounds on New Physics with Displaced Photons

Joel Jones-Pérez
Pontificia Universidad Católica del Perú (PUCP)

Based on the following work:
F. Delgado, L. Duarte, JJP, C. Manrique-Chavil, S. Peña (2205.13550)
L. Duarte, JJP, C. Manrique-Chavil (2311.17989)
B. Díaz, L. Duarte, JJP, W. Rodriguez, D. Zegarra (25xx.xxxxx)

Why don’t we find physics beyond the Standard Model?

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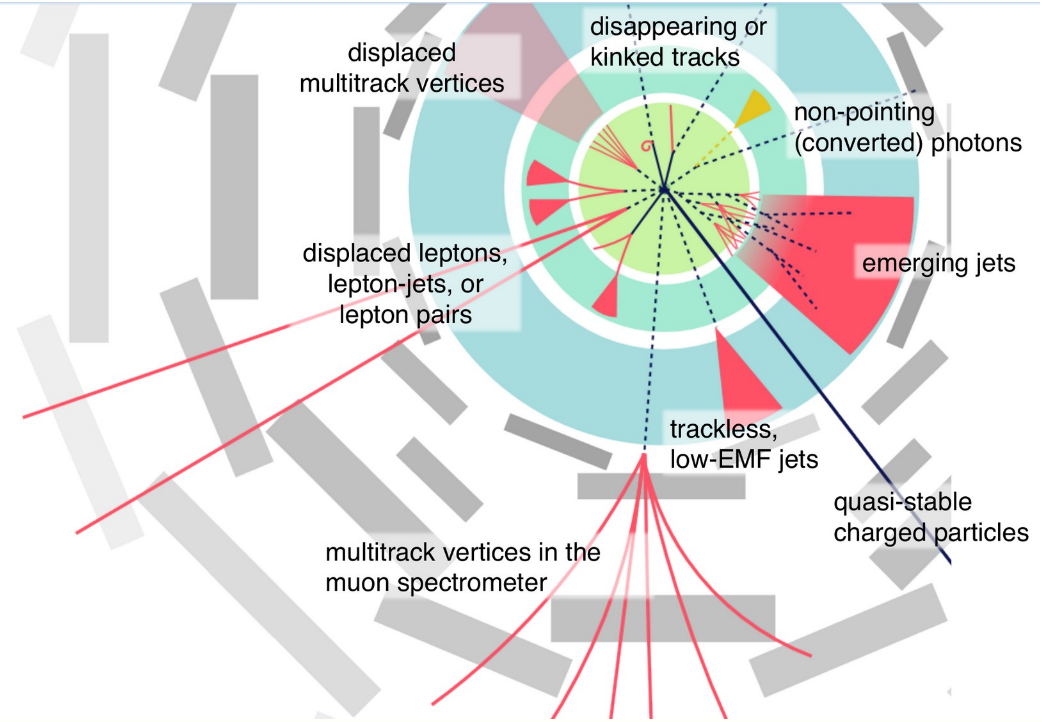
Maybe the new physics sector implies signals we did not expect when the LHC was first designed!

Focus on long-lived particles (LLPs).

A large lifetime implies a macroscopic decay length:

Non-standard signals!



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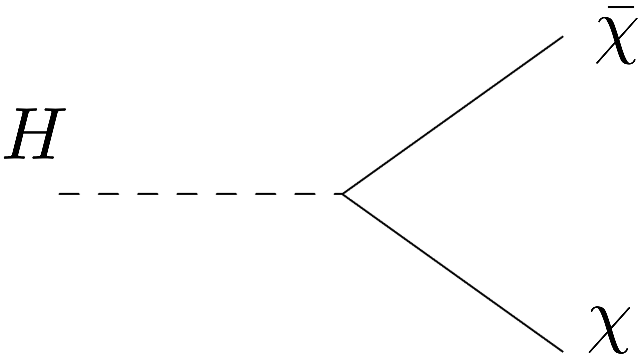
In this work, we are interested in looking for neutral LLPs, assuming production via Higgs decays



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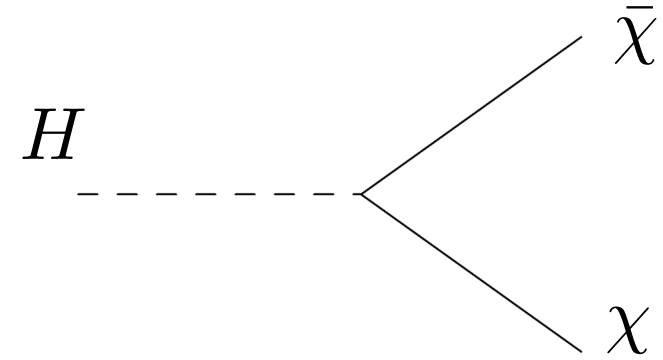
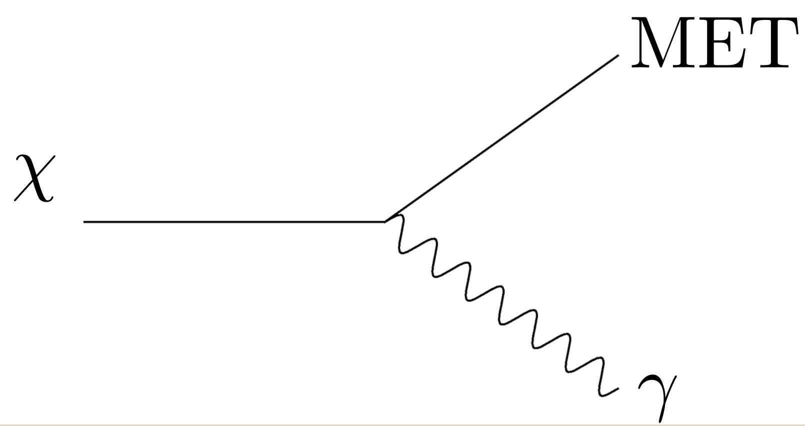


We are also interested in models where the LLP decays into a photon and an invisible state: displaced photon!



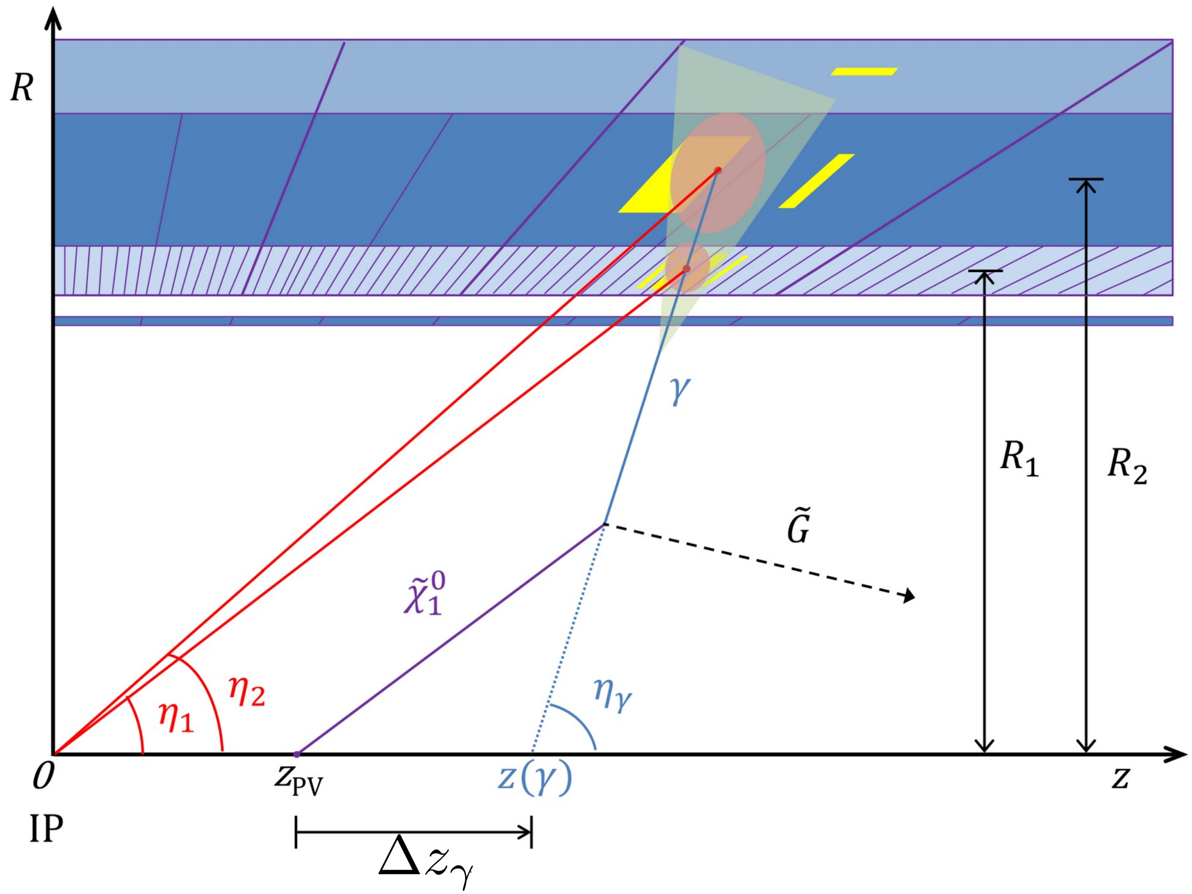
The search for displaced photons

How do you distinguish displaced photons?

Photons coming from long-lived particles take longer to reach the ECAL, and do not point towards the primary vertex.

Important variables:

t_γ $|\Delta z_\gamma|$



D. Mahon (PhD Thesis)

Displaced photon search

- Trigger: isolated lepton with p_T > 27 GeV.

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ATLAS (2209.01029 [hep-ex])

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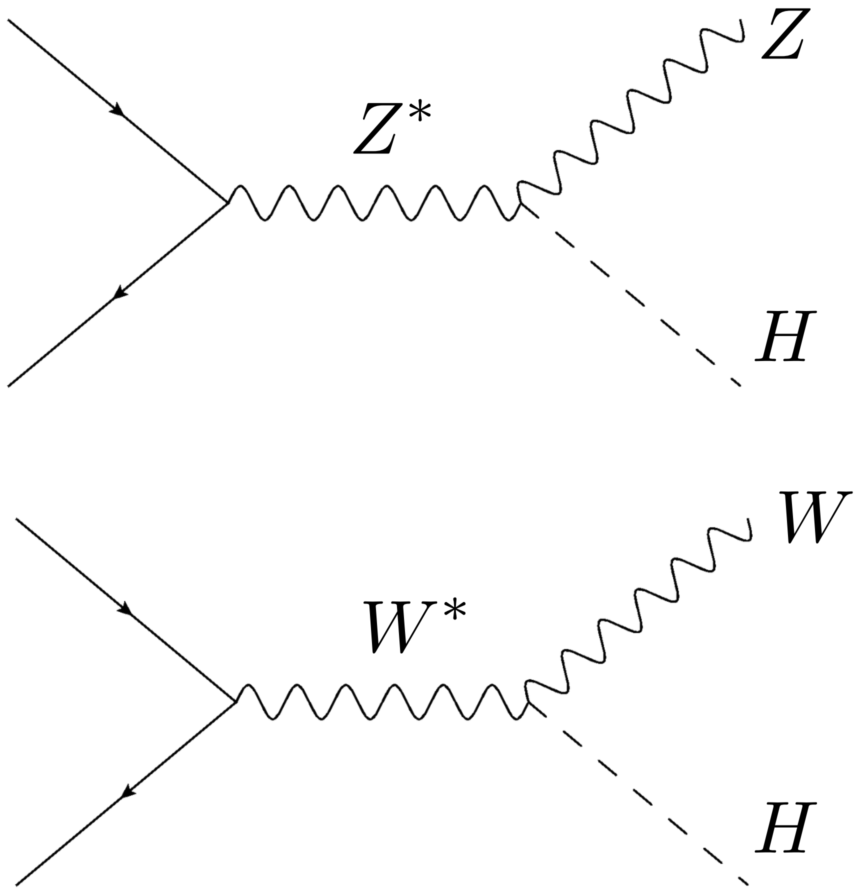
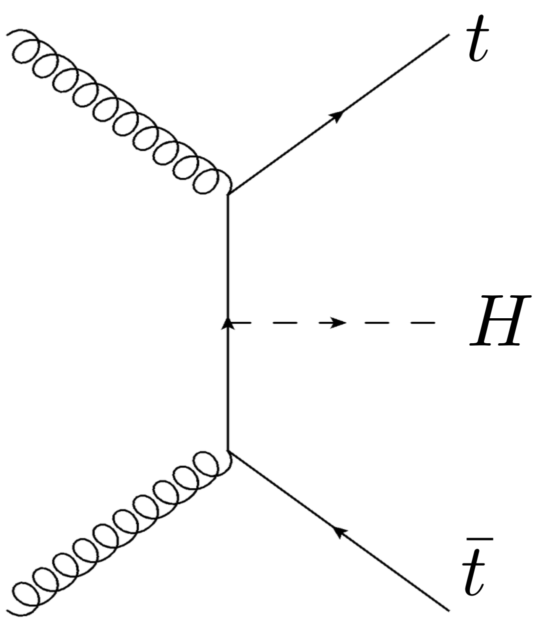


Idea:

LLPs come from Higgs decay.

Trigger on leptons from Z, W or t.



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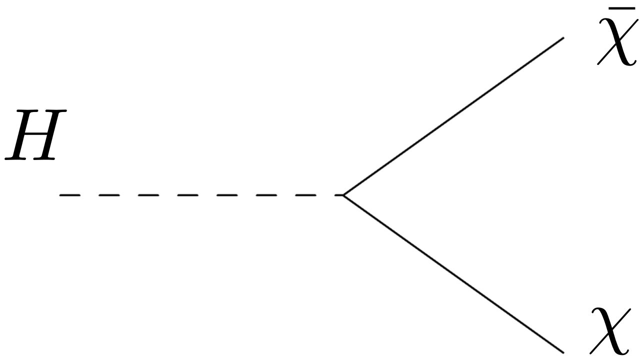

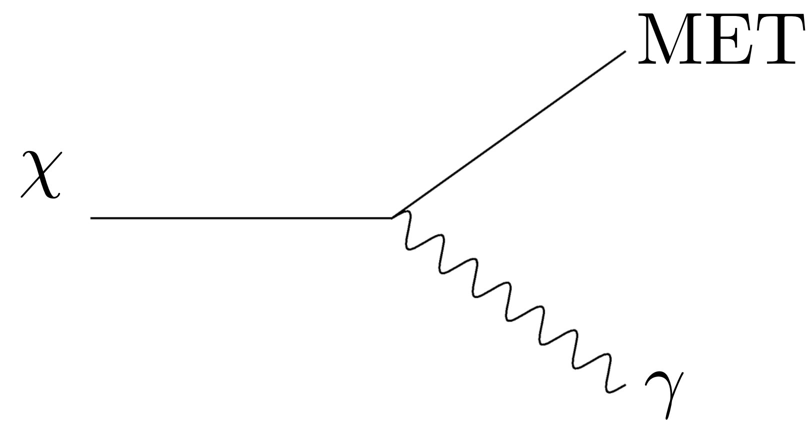

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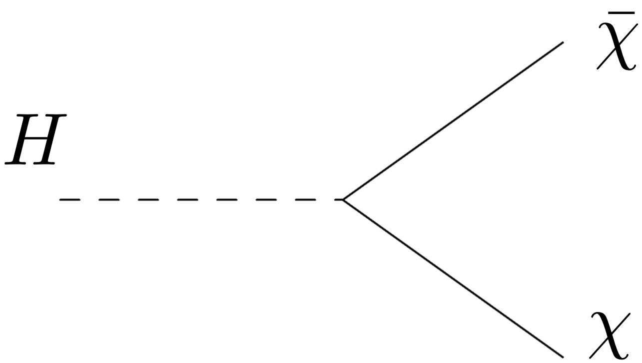

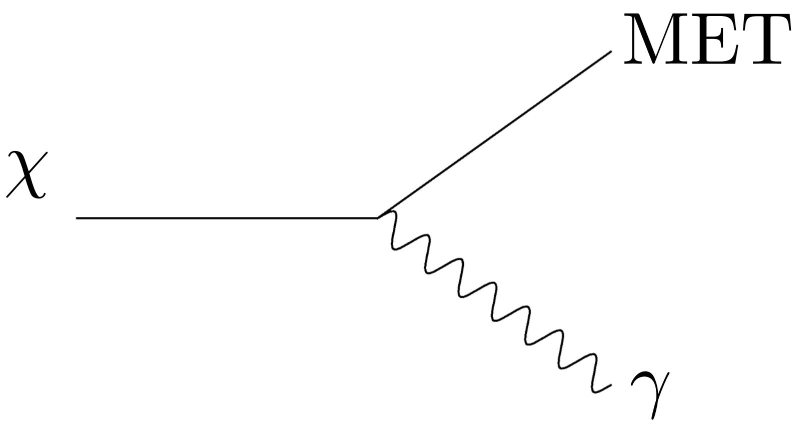

Issue:

Final state photons are somewhat soft!

Probably not much MET

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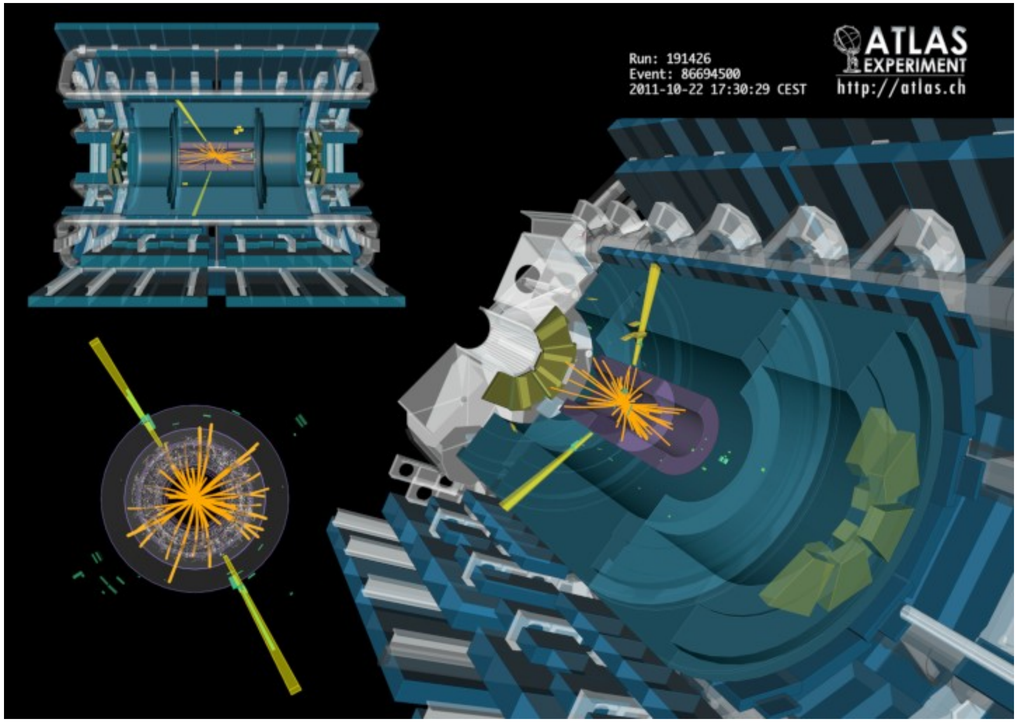
Displaced photon search

- Trigger: isolated lepton with p_T > 27 GeV.
- At least one “loose” photon with energy larger than 10 GeV.
- Isolation criteria: no deposits larger than 5% - 6.5% of energy within $\Delta R = 0.2$.



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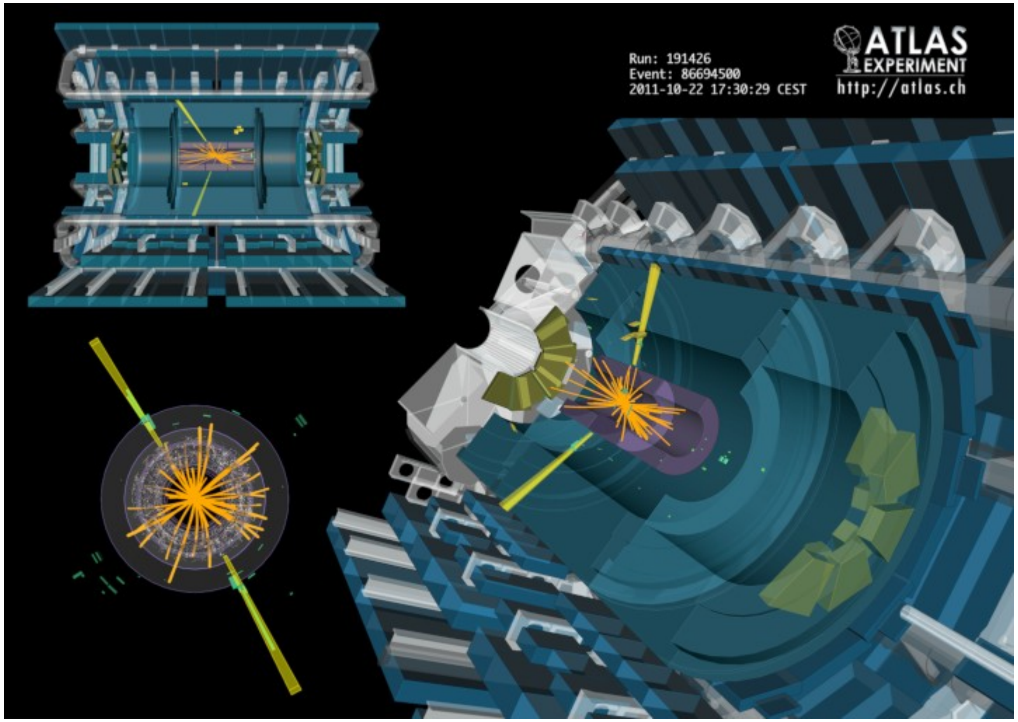

Issue:

Backgrounds are huge! Need to cut using timing, displacement, and MET.

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- One of the photons must be in barrel region (used for analysis).
- If more than one photon in barrel region, use the one with largest energy.
- Require E_{cell} larger than 10 GeV.

E_{cell}:

Maximum energy deposit in a middle-layer ECAL cell (about 0.2 – 0.5 of total energy)

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- If more than one photon in barrel region, use the one with largest energy.
- Require E_{cell} larger than 10 GeV.
- Define signal region depending on MET > 50 GeV.
- Place cuts on t_γ and $|\Delta z_\gamma|$. Distinguish single and multi-photon samples.

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

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

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ATLAS (2209.01029 [hep-ex])

What did the search find?

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

Let us put bounds on models… recast the search!

Dimension Five Seesaw Portal

F. Delgado, L. Duarte, JJP, C. Manrique-Chavil, S. Peña (2205.13550)
L. Duarte, JJP, C. Manrique-Chavil (2311.17989)

Dimension-5 Type-I Seesaw Portal

We are interested in an extension of Type-I Seesaw model with *d=5* operators, involving the sterile neutrino states and neutral SM bosons.

We again add only two sterile neutrinos.

$$\mathcal{L} = \mathcal{L}_{\rm SM} + Y_\nu \left(\bar{L}\cdot\tilde{\phi}\,\nu_R\right) + \frac{1}{2} M_R\left(\bar{\nu}_R\,\nu_R^c\right) + \text{h.c.}$$

$$+ \left(\frac{(\alpha_{N\phi})_{ss'}}{\Lambda}(\phi^\dagger\phi)\,\bar{\nu}_{Rs}\,\nu^c_{Rs'} + \frac{(\alpha_{NB})_{ss'}}{\Lambda}\bar{\nu}_{Rs}\,\sigma^{\mu\nu}\,\nu^c_{Rs'}\,B_{\mu\nu} + h.c.\right)$$

Light neutrinos interact via these operators through "sterile-light" mixing.

Graesser (0704.0438 [hep-ph])
Aparici, Kim, Santamaria, Wudka (0904.3244 [hep-ph])

Decay chain

The new couplings allow:

$$pp \to H \underset{(\alpha_{N\phi})_{45}}{\longrightarrow} N_4\, N_5$$

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$$pp \to H \xrightarrow[(\alpha_{N\phi})_{45}]{} N_4 \, N_5$$

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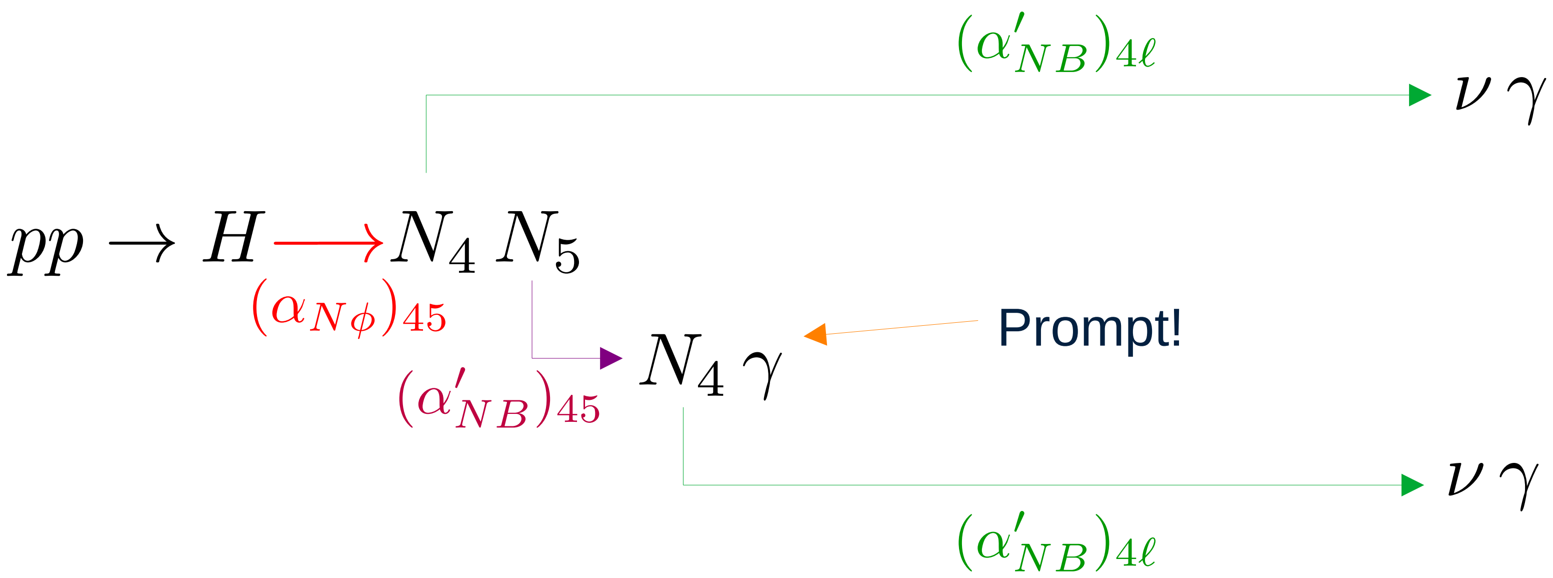

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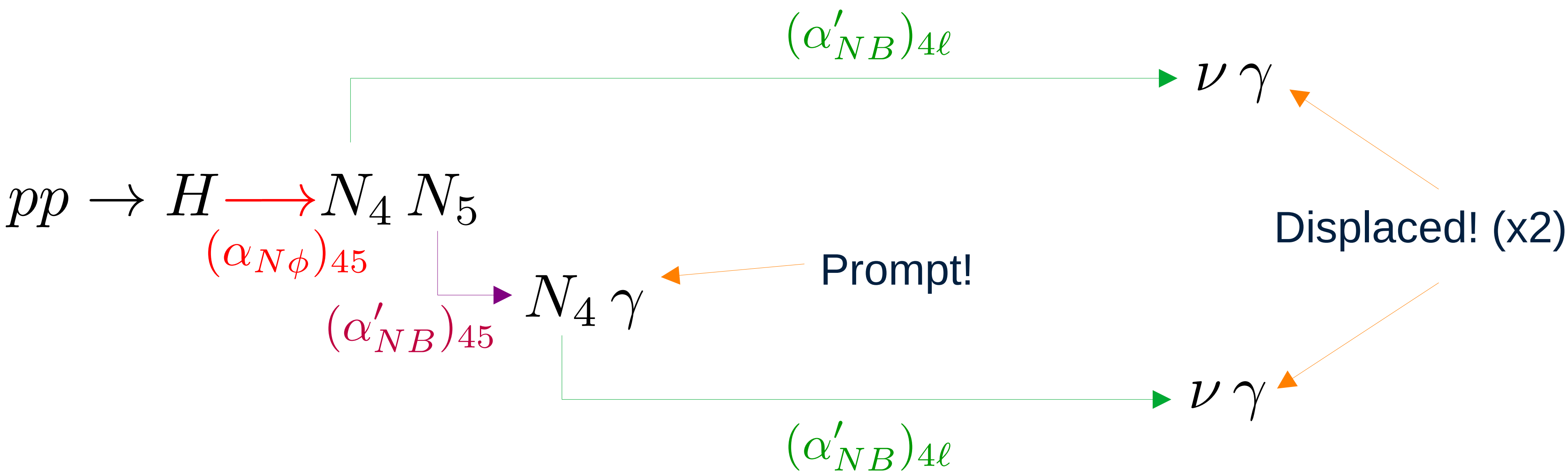

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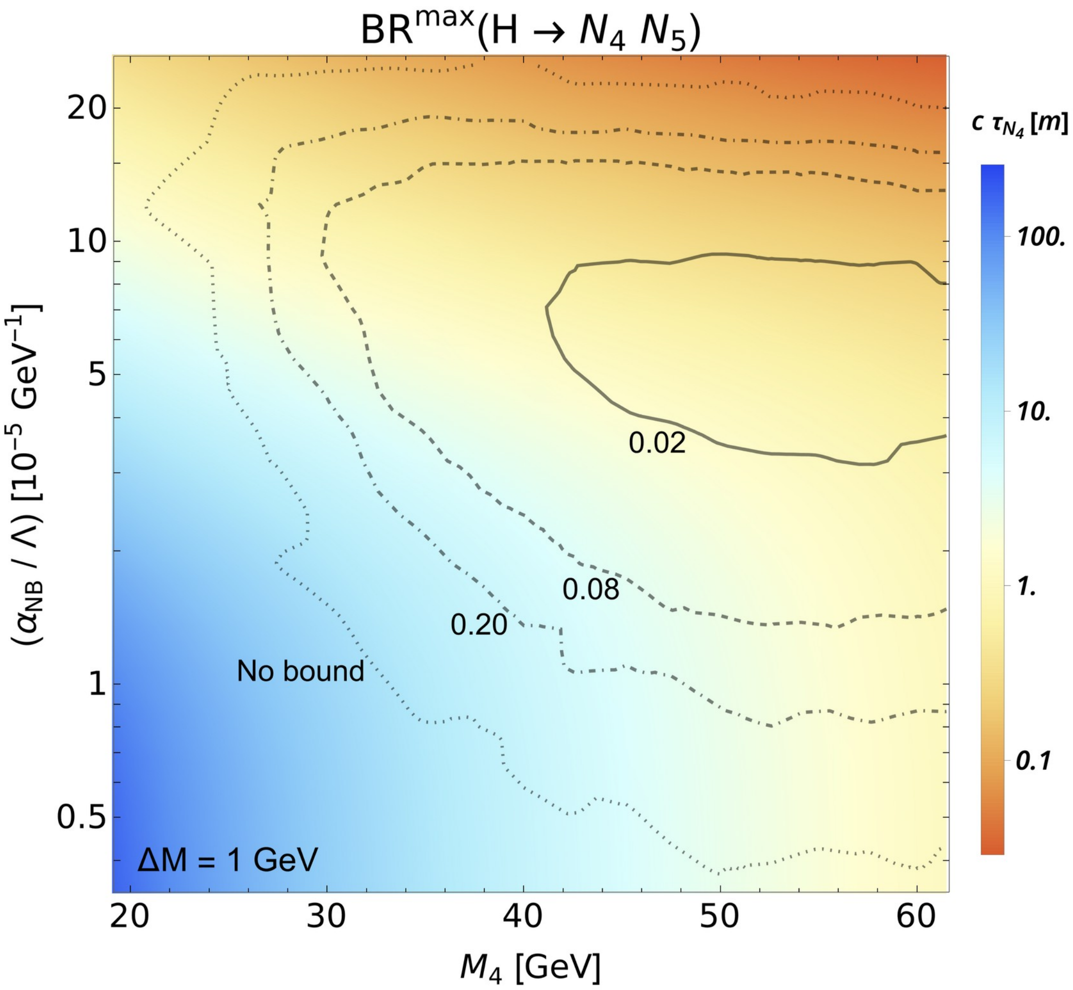
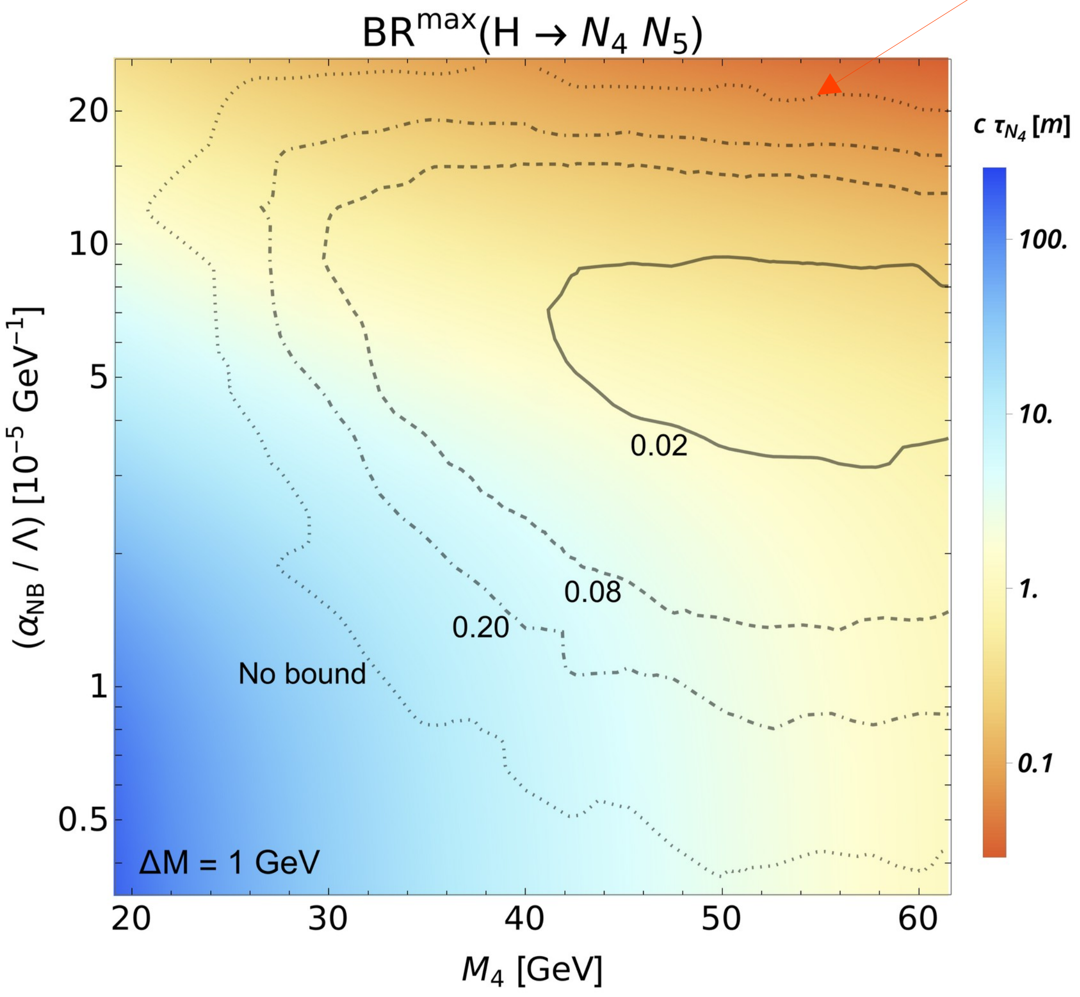
Bounds on BR($H \to N_4 N_5$) !



Bounds on BR(H → N_4 N_5) !

Large coupling implies that N_4 decay is prompt.



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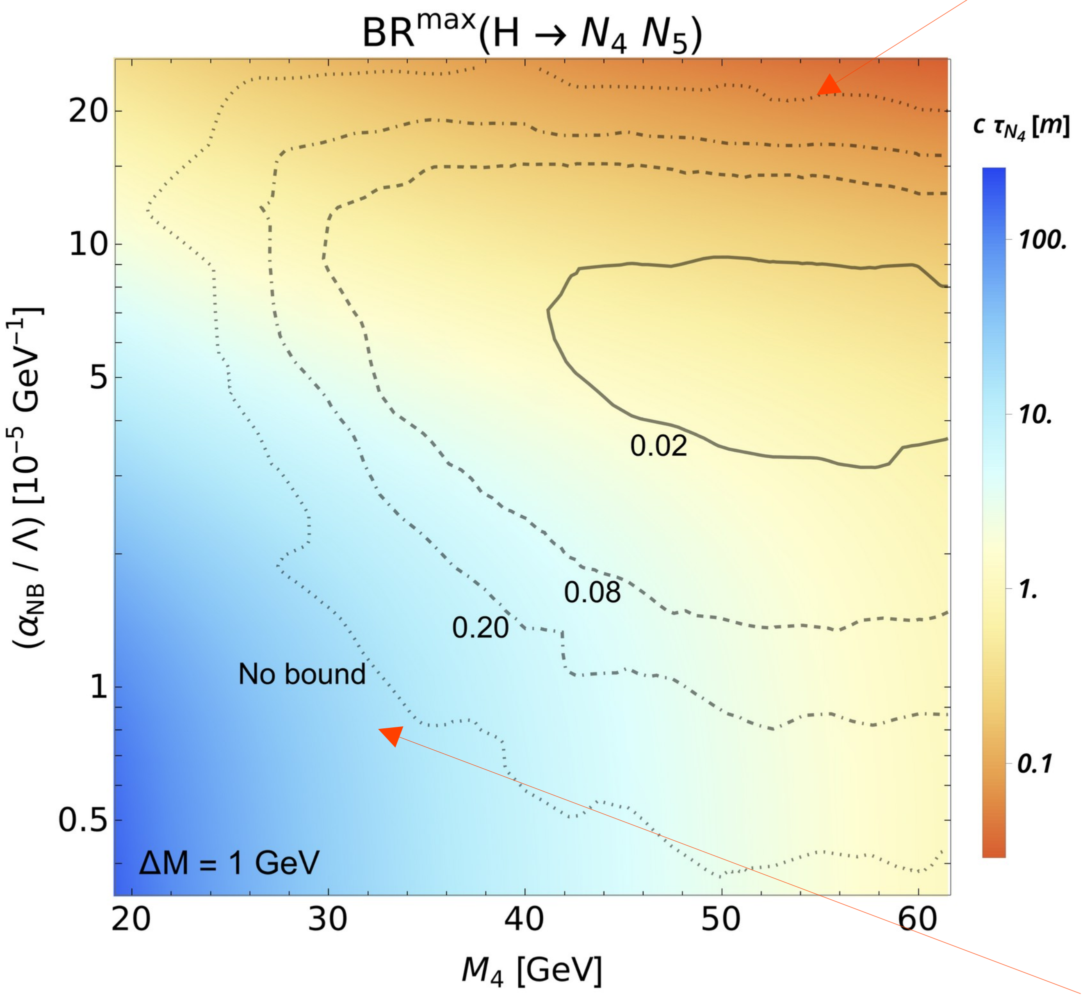

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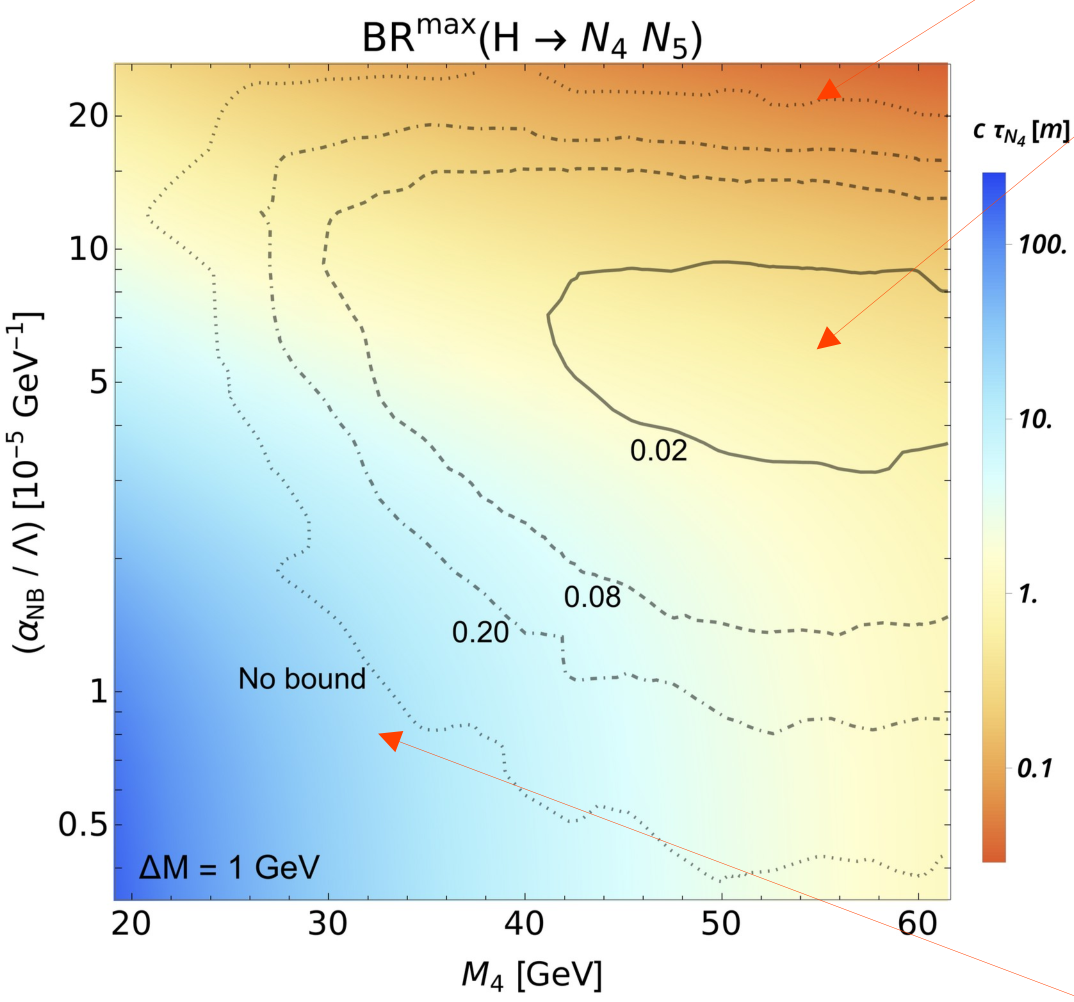

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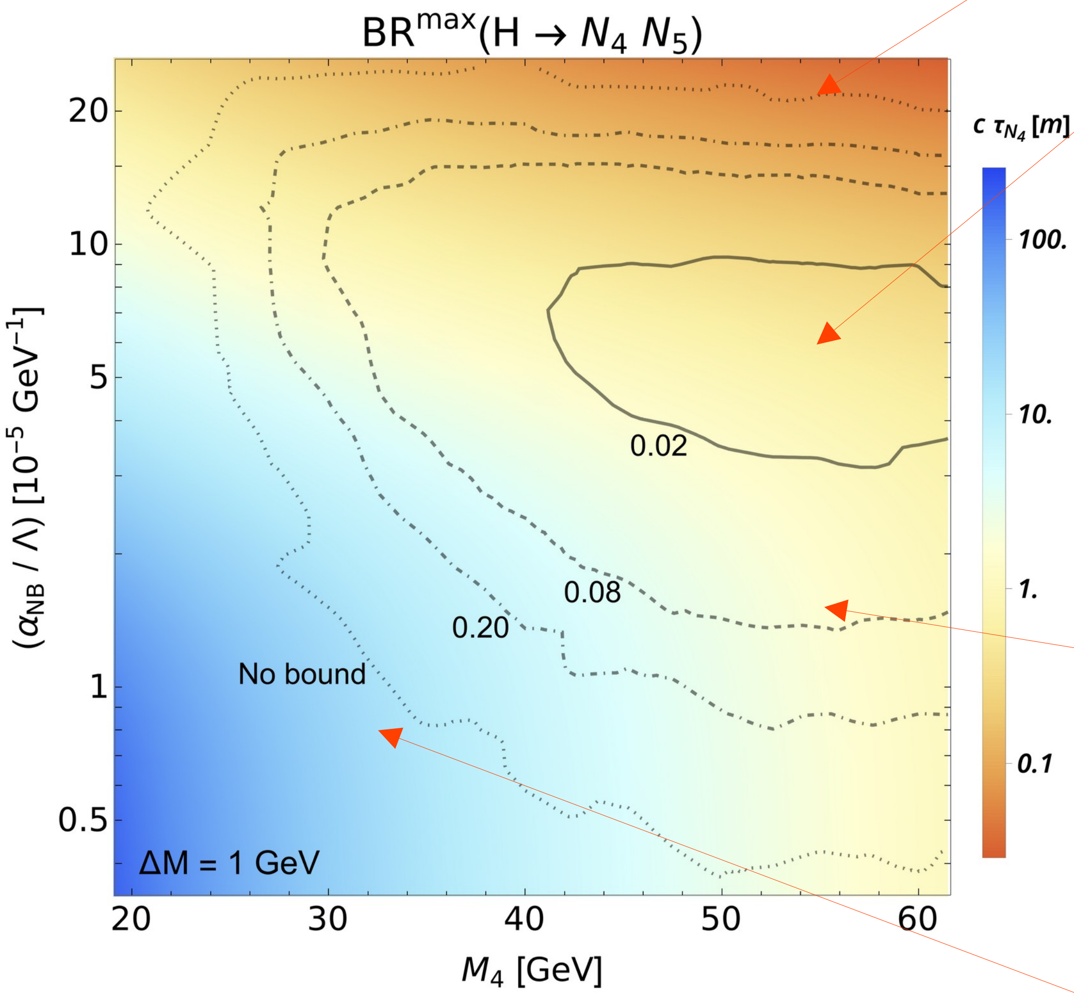

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Standard seesaw decays start to dominate, so lifetime does not depend on α_{NB}.

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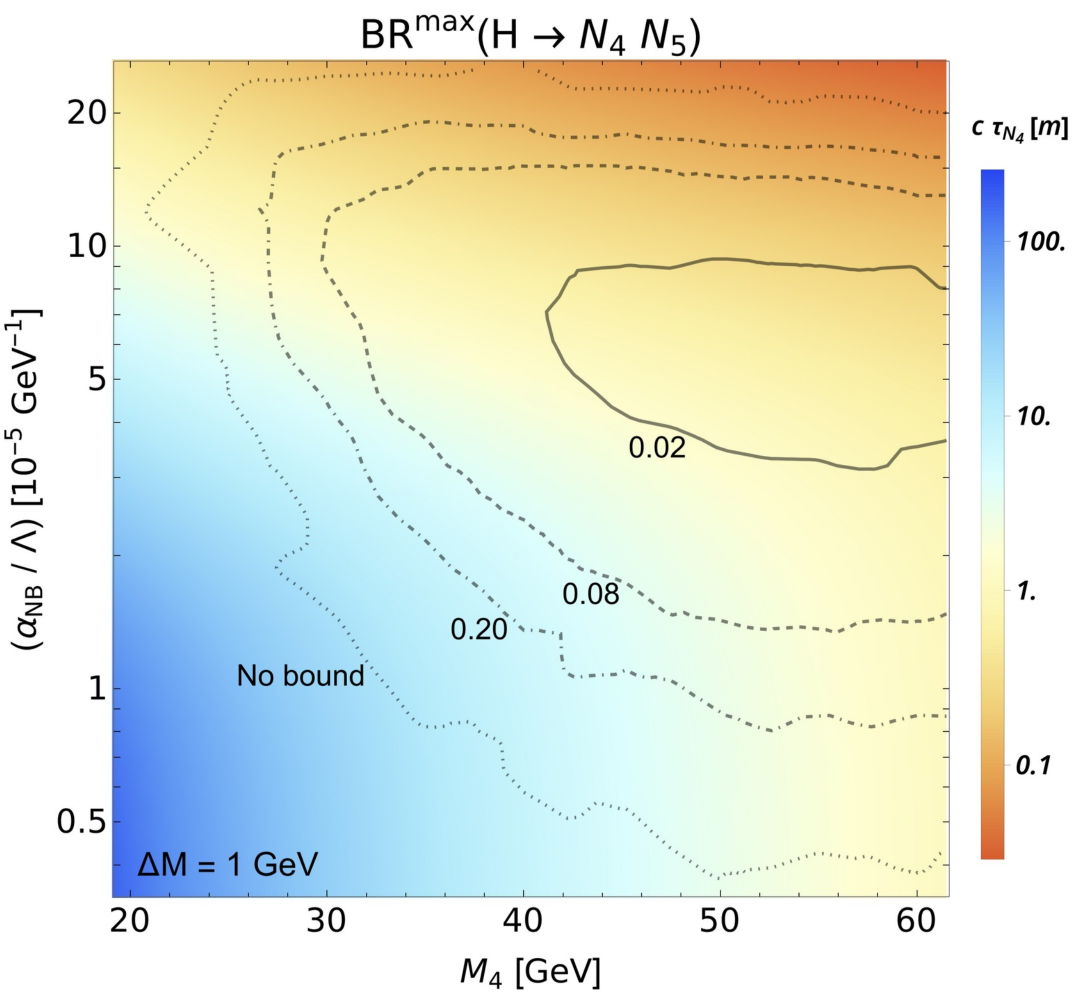
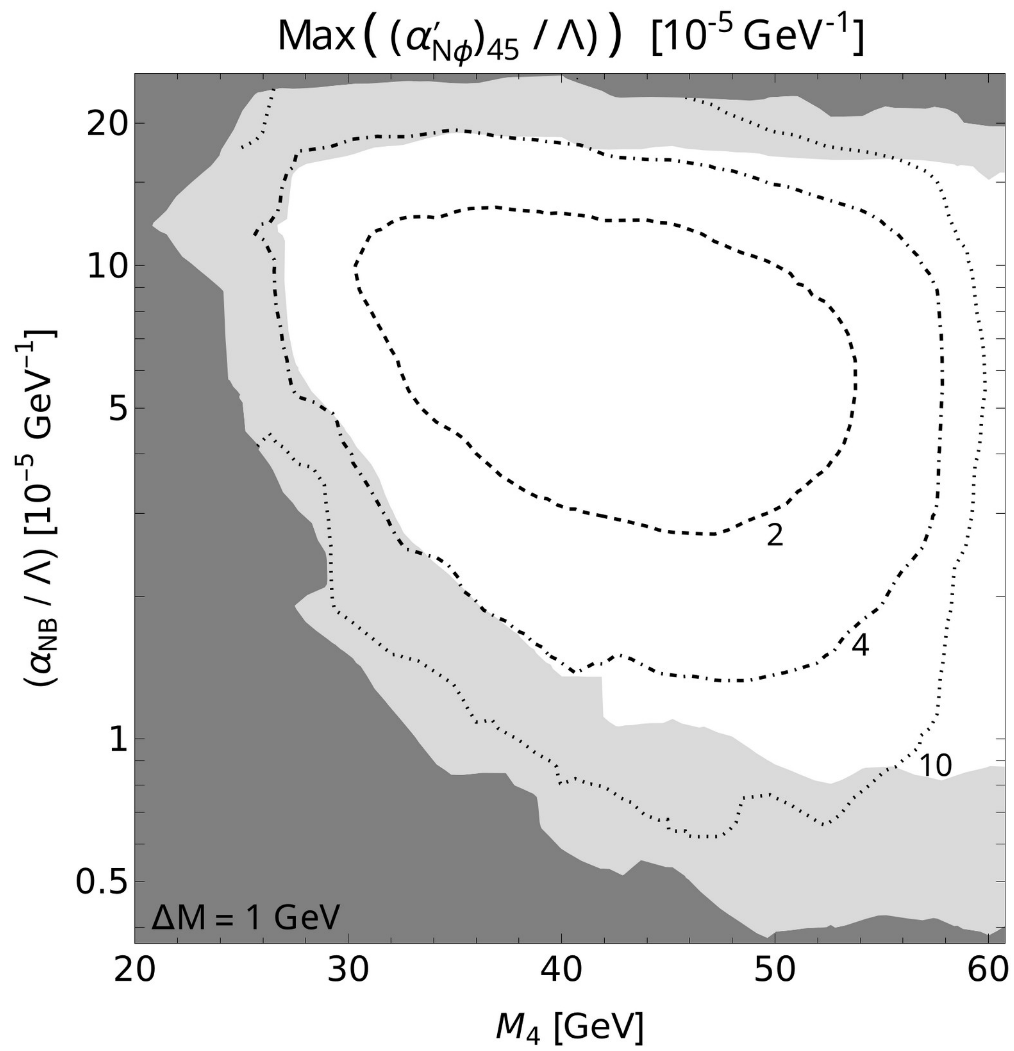
Bounds on $\alpha_{N\phi}$!





Dark Photon Model

B. Díaz, L. Duarte, JJP, W. Rodriguez, D. Zegarra (25xx.xxxxx)

Dark photons

- Can we think of any other model that could leave a displaced photon signal?

- Inspiration: dark axion models!

$$\mathcal{L}_{\text{d.a.}} = \frac{G_1}{4}\phi\, F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{G_2}{4}\phi\, F'_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{G_3}{4}\phi\, F'_{\mu\nu}\tilde{F}'^{\mu\nu}$$

Kaneta, Lee, Yun (1611.01466 [hep-ph])
Kaneta, Lee, Yun (1704.07542 [hep-ph])

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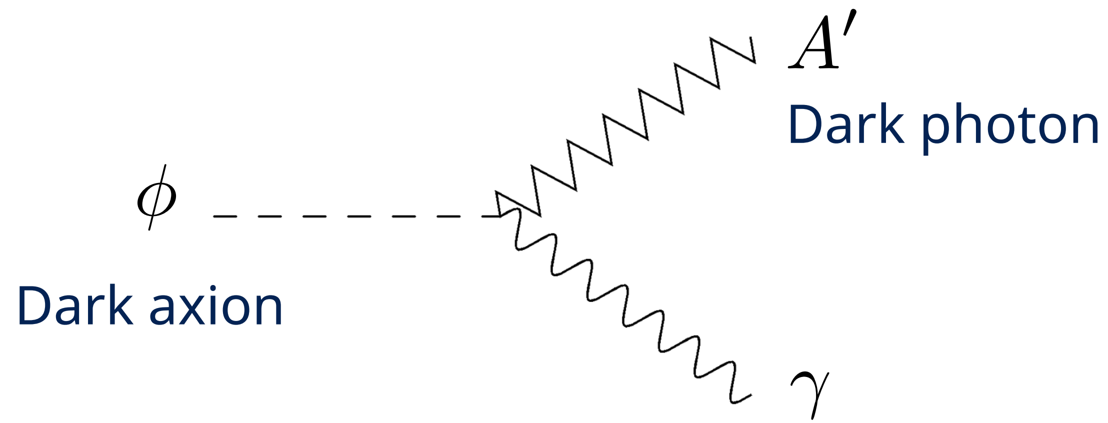

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PUCP

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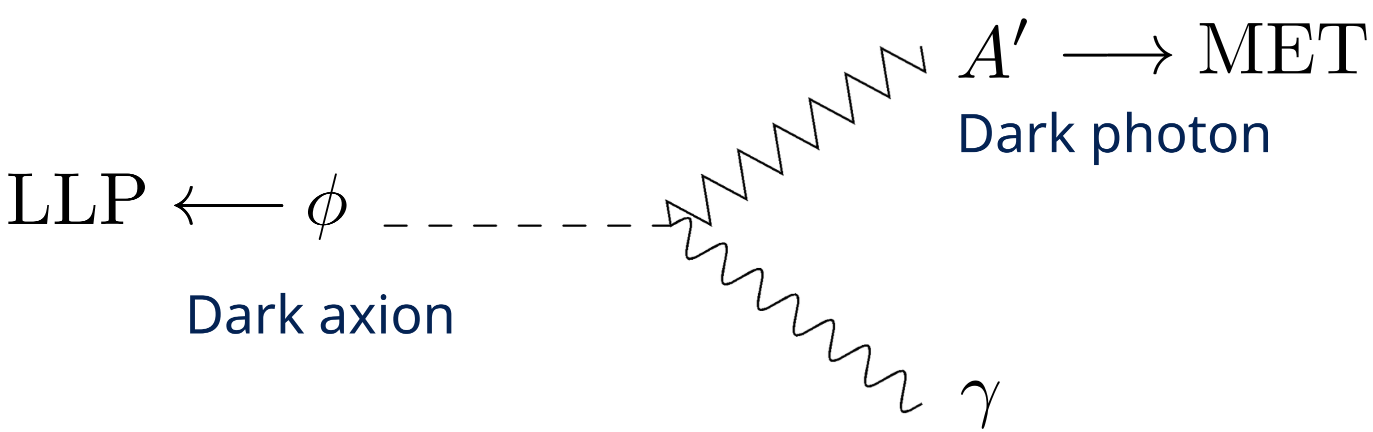

Kaneta, Lee, Yun (1611.01466 [hep-ph])
Kaneta, Lee, Yun (1704.07542 [hep-ph])

Dark photons

- Need to keep A' stable. Or at least very long lived!

- Add Z_2 symmetry:

$$\phi \to -\phi \qquad\qquad A'_\mu \to -A'_\mu$$

$$\Rightarrow \mathcal{L}_{\rm d.a.} = \frac{g_D}{\Lambda}\phi\, F'_{\mu\nu}\tilde{B}^{\mu\nu}$$

- This is the only interaction term of dark photon, with no kinetic mixing!
- The field ϕ does not transform under *U(1)* symmetry of dark photon.

Farzan, Akbarieh (1207.4272 [hep-ph])
Arias, Arza, Jaeckel, Vargas-Arancibia (2007.12585 [hep-ph])

Dark photons

- Next: add an interaction term for ϕ with the Higgs:

$$V = -\frac{\mu_H^2}{2}|H|^2 + \frac{\lambda_H}{4}(H^\dagger H)^2 + \frac{\mu_\phi}{2}\phi^2 + \frac{\lambda_\phi}{4}\phi^4 + \lambda_{h\phi}|H|^2\phi^2$$

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Should be large-ish…
Not really an axion?

REBRANDING:

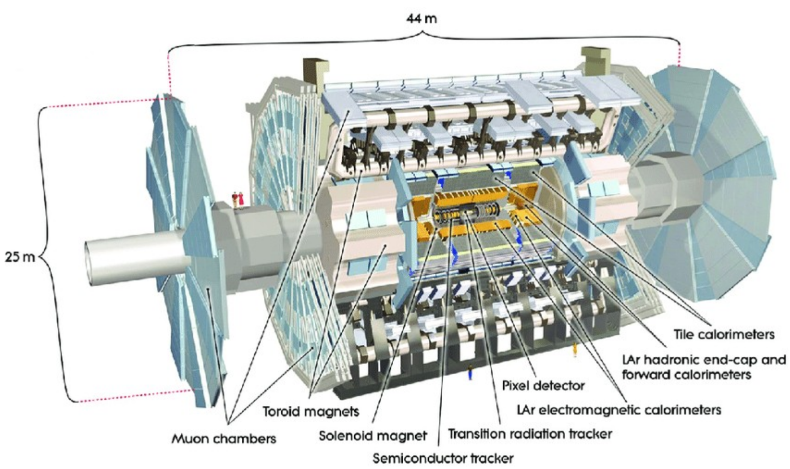
Dark photon with a scalar portal!

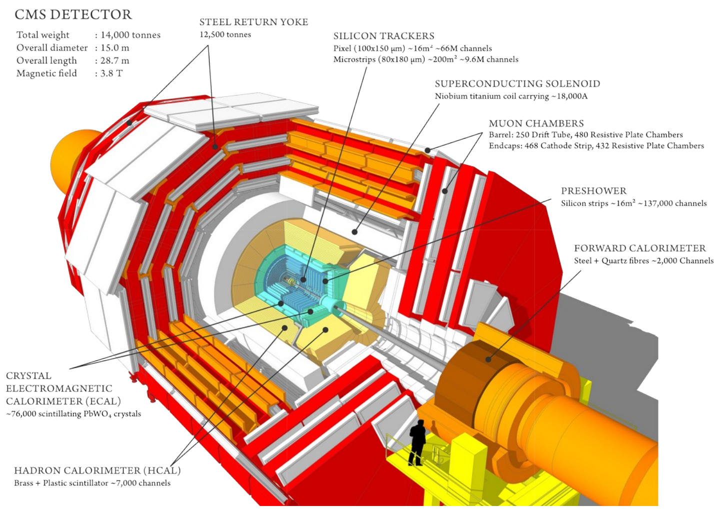
OBJECTIVE:

- Bound the model with displaced photons
- Check if good DM candidate

Additional constraint: Higgs invisible decays

- If the lifetime of the LLP is very long, the particle could escape the detector before it decays.
- In this case, one can constrain models with searches for Higgs invisible decays.



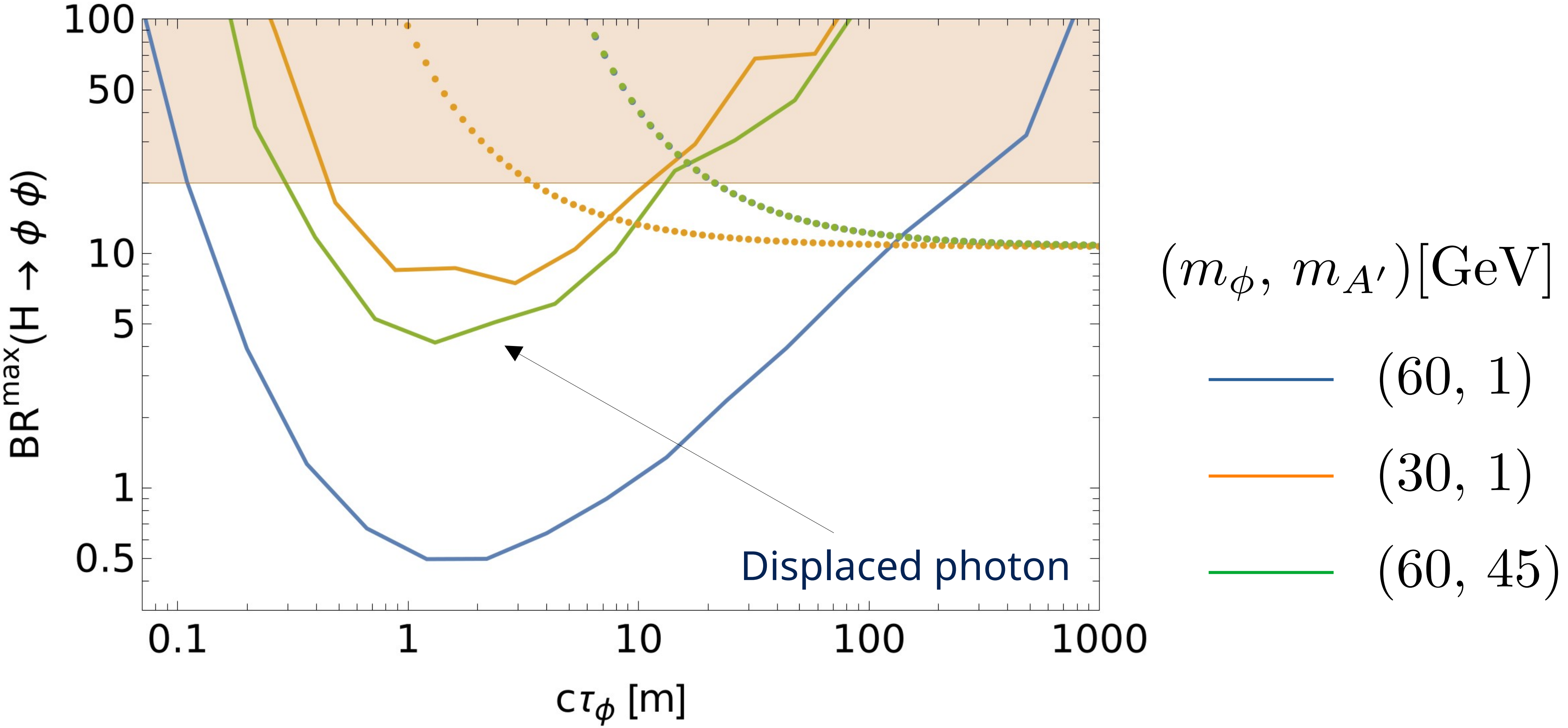


$$\mathrm{BR}(H \to \mathrm{inv}) < 10.7\%$$

$$\mathrm{BR}(H \to \mathrm{inv}) < 15\%$$

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

Preliminary results



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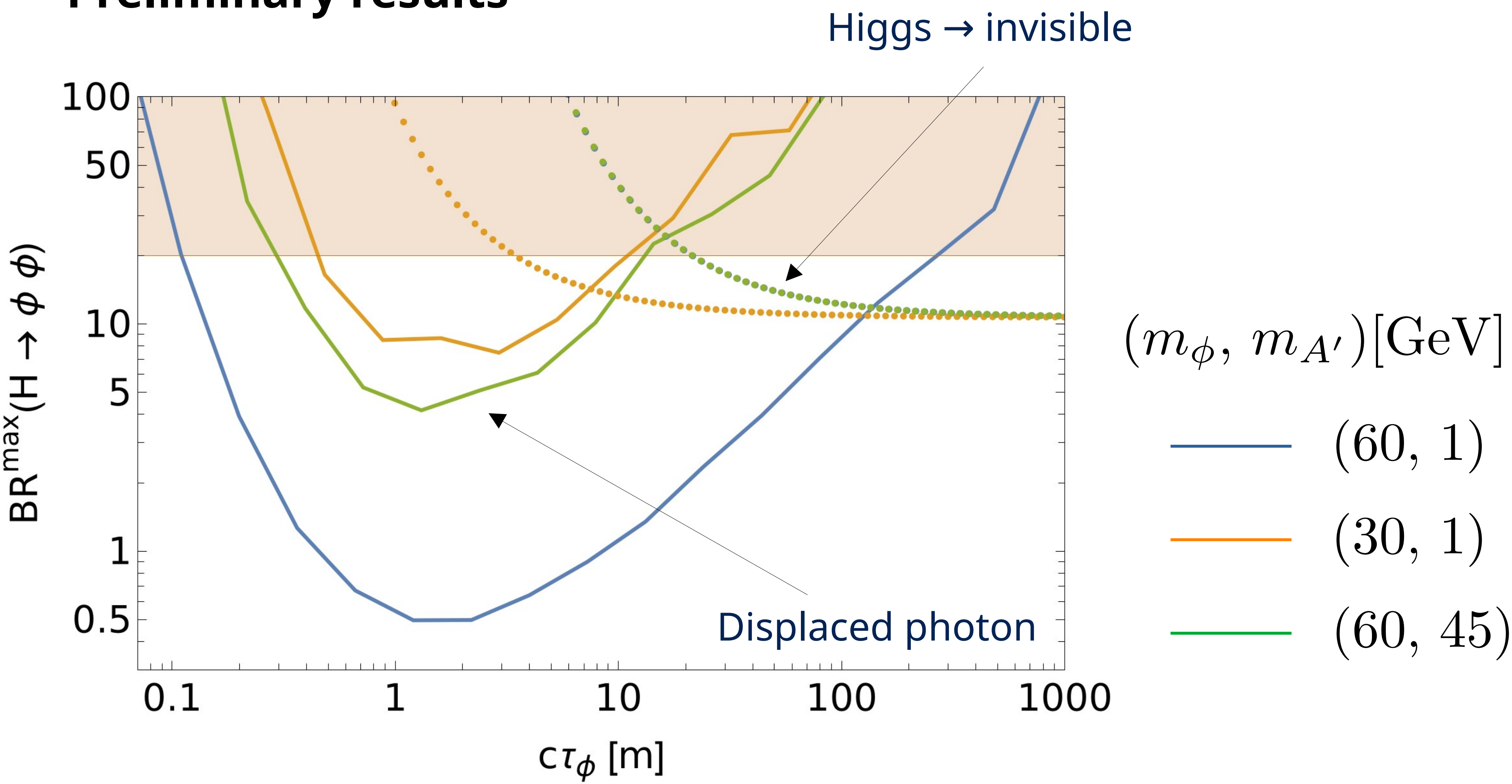

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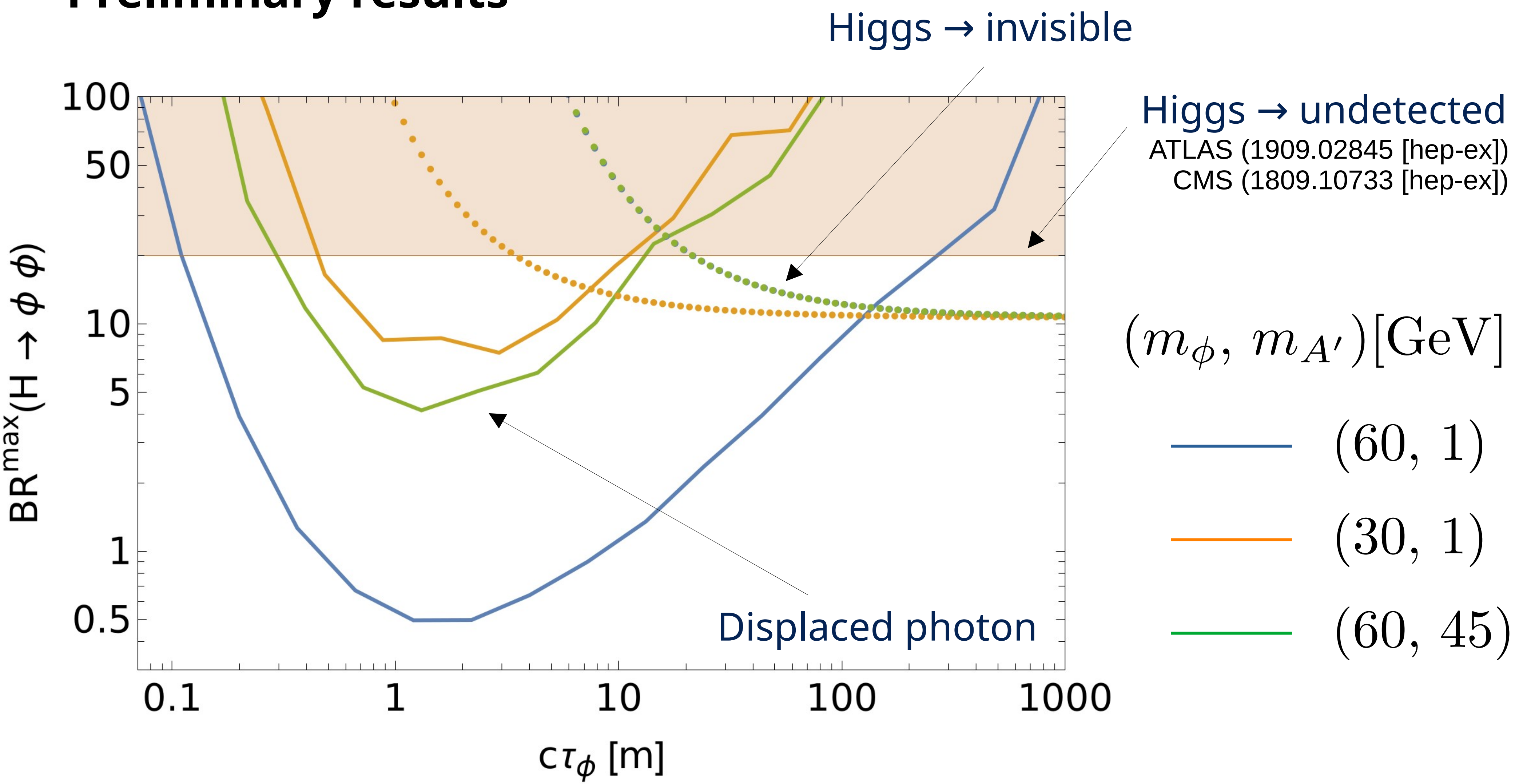

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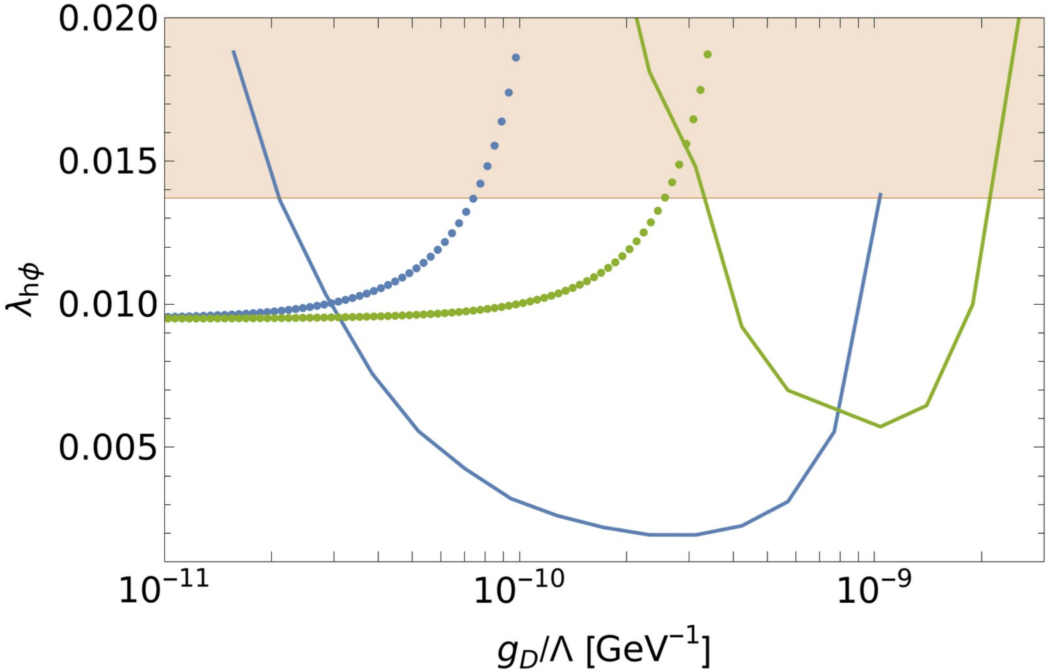
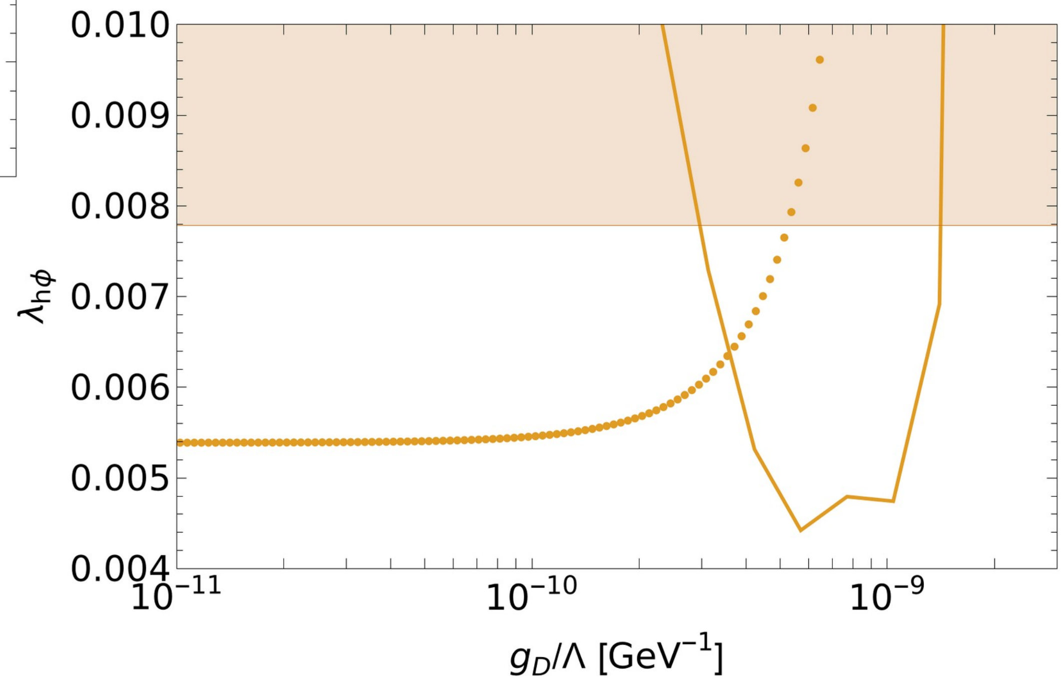


$(m_\phi,\ m_{A'})[\mathrm{GeV}]$

(30, 1)

(60, 1)

(60, 45)



Implications for Dark Photon dark matter

To be continued! Some musings on the topic:

- The dark photon is a **FIMP**, as g_D is very small.
- The scalar should be **thermal**, depends on $\lambda_{h\phi}$.

- It seems ϕ **decays** dominate freeze-in production of A' . Then, as long as g_D is small, the value of $\lambda_{h\phi}$ is crucial for prediction. Maybe also **SuperWIMP**?
- Region of parameter space seems to **overproduce** dark matter, assuming **Standard Cosmology**.
- This works seems to point in the direction of displaced photon searches bounding **Non-Standard Cosmology** scenarios.

Take-home messages

- 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 larger lifetimes, Higgs → invisible searches present better bounds.
- Recast of search in the context of d=5 Seesaw Portal place strong bounds on coefficients of effective operators $\sim \mathcal{O}(10^{-5}\,\mathrm{GeV}^{-1})$
- Recast of search in the context of dark photon with scalar portal places bounds $\lambda_{h\phi} \sim \mathcal{O}(10^{-3})$
- Possibility of dark photon generating the relic density in this region of parameter space still under consideration. Stay tuned!

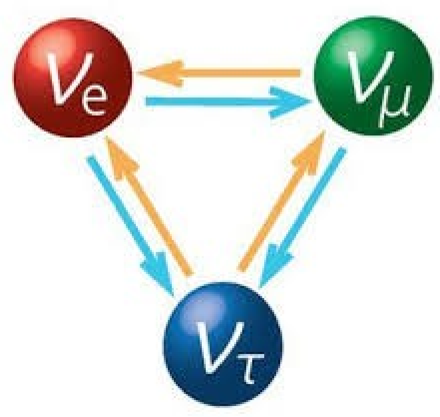
¡Gracias!

Funded by:

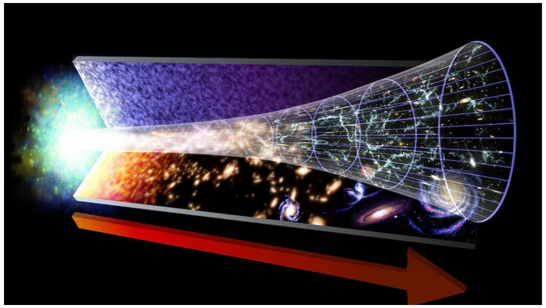
Backup

Why expand the Standard Model?

- No mechanism for neutrino masses
- No dark matter candidate
- No explanation for baryon – antibaryon asymmetry
- The Higgs is theoretically uncomfortable (naturalness, vacuum stability)

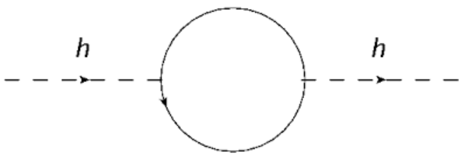


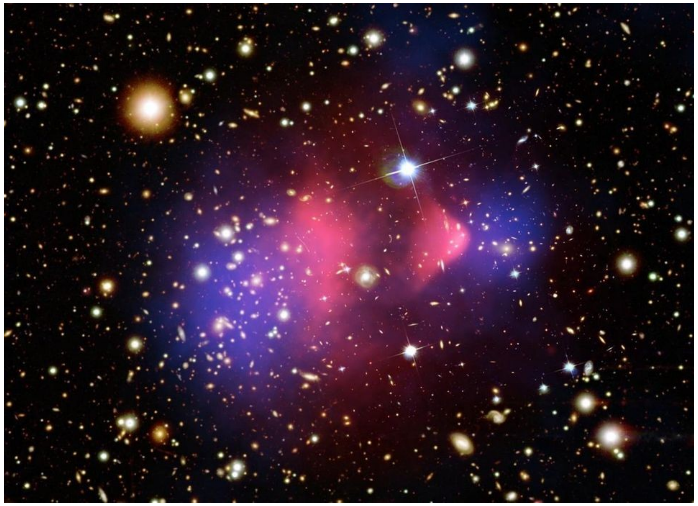
Neutrino oscillations



Where did antimatter go?

Loop corrections to Higgs mass

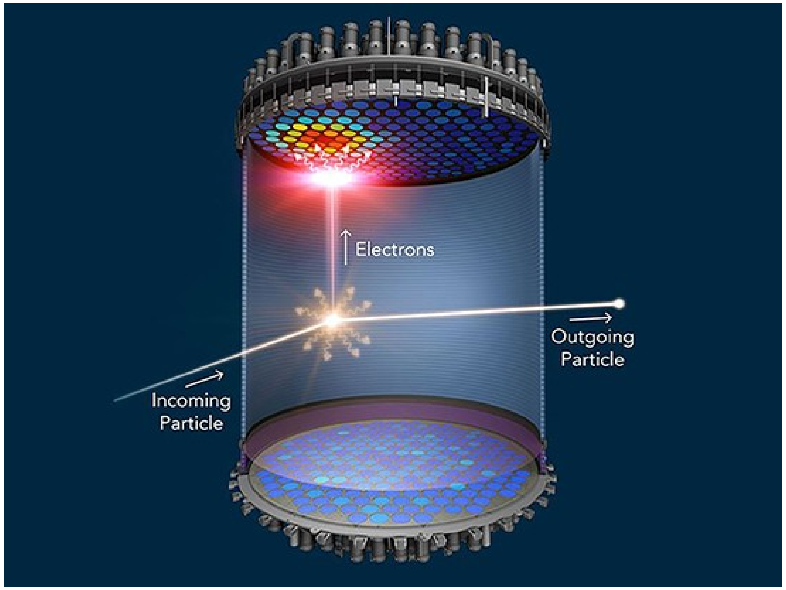




Mass and gas in *Bullet cluster*

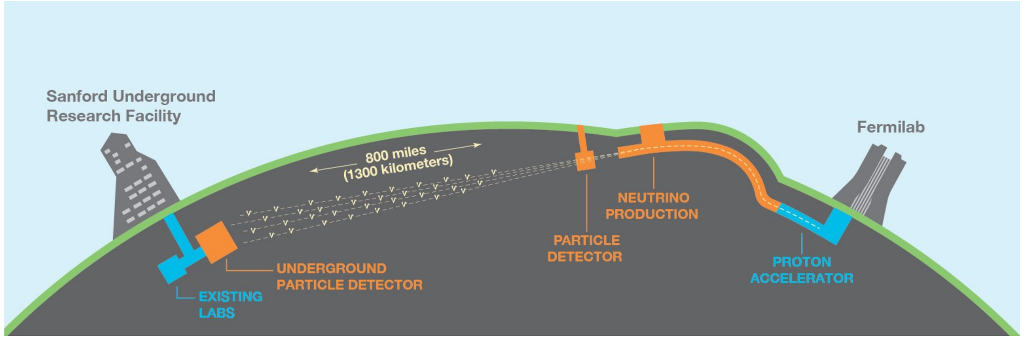
Where are we looking for New Physics?

- Colliders
- Neutrino oscillation experiments
- Dark matter experiments
- So many others!



XENON1T Experiment

Large Hadron Collider



DUNE experiment

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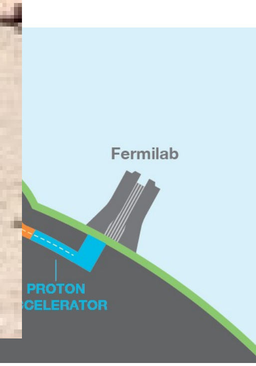
- Dark ma
- So many



DUNE experiment

Recasting the Displaced Photon search

- Events are generated in MadGraph, with parton shower and hadronization by Pythia.

- Need to calculate t_γ and $|\Delta z_\gamma|$ from truth-level information. Must include this info in HepMC files, and pass on to Delphes for detector simulation.

- Arrival time t_γ:
  Simulated ``prompt LLPs”, and calculated arrival time as a function of pseudorapidity. Subtract this from long-lived case.

Recasting the Displaced Photon search

- Photon non-pointing variable: separation between primary vertex and projected origin of photon, along the beamline.

$$|\Delta z_\gamma| = r_{\gamma_z^0} - \frac{p_{\gamma_z}}{p_{\gamma_T}^2}\left(r_{\gamma_x^0}\, p_{\gamma_x} + r_{\gamma_y^0}\, p_{\gamma_y}\right)$$

- Not exactly what ATLAS does. Measurement actually relies on information of first two layers of ECAL, disregards information on ϕ. Differences are fortunately small!

Post-Delphes Cuts

- Apply proper isolation criteria, based on tracks and energy deposits.
- Applied gaussian smear on $|\Delta z_\gamma|$, use this for efficiency.
- Apply p_T and η cuts on photons, separate into 1 or multi-photon channels.
- Apply ID efficency on electrons, and ID efficency + isolation on muons.
- Apply p_T and η cuts on electrons, muons, jets.
- Implement overlap removal: photons > electrons > jets > muons.
- Evaluate if trigger is fired.
- Apply gaussian smear on t_γ.
- Assign to signal region if MET > 50 GeV.
- Separate in different $|\Delta z_\gamma|$ categories, with a binning based on t_γ.
- Apply statistical analysis on largest t_γ bin, on largest $|\Delta z_\gamma|$ category.

Type-I Seesaw

Type I Seesaw is probably most popular mechanism for neutrino masses

$$\mathcal{L} = \mathcal{L}_{\rm SM} + Y_\nu \left(\bar{L} \cdot \tilde{\phi}\, \nu_R\right) + \frac{1}{2} M_R \left(\bar{\nu}_R\, \nu_R^c\right) + \text{h.c.}$$

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Mass matrix:

$$M_\nu = \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix} \qquad m_D = \frac{1}{\sqrt{2}} v \, Y_\nu^*$$

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Light neutrino mass matrix:

$$m_\nu \sim m_D\, M_R^{-1}\, m_D^T$$

Couplings

$$
\begin{aligned}
\mathcal{L}_W &= \frac{g}{\sqrt{2}} W^-_\mu \bar{\ell}_a \gamma^\mu \, U_{ai} \, P_L \, n_i + h.c. \\
\mathcal{L}_Z &= \frac{g}{4c_W} Z_\mu \bar{n}_i \gamma^\mu \left(C_{ij} \, P_L - C^*_{ij} \, P_R \right) n_j \\
& \quad - \frac{s_W}{\Lambda} (\partial_\mu Z_\nu - \partial_\nu Z_\mu) \, \bar{n}_i \, \sigma^{\mu\nu} \left[(\alpha'_{NB})_{ij} P_L - (\alpha'^*_{NB})_{ij} P_R \right] n_j \\
\mathcal{L}_\gamma &= \frac{c_W}{\Lambda} (\partial_\mu A_\nu - \partial_\nu A_\mu) \, \bar{n}_i \, \sigma^{\mu\nu} \left[(\alpha'_{NB})_{ij} P_L - (\alpha'^*_{NB})_{ij} P_R \right] n_j \\
\mathcal{L}_h &= -\frac{1}{v} h \, \bar{n}_i \left[\frac{1}{2} \left(C_{ij} \, m_{n_j} + C^*_{ij} \, m_{n_i} \right) - \frac{v^2}{\Lambda} (\alpha'^*_{N\phi})_{ij} \right] P_R \, n_j \\
& \quad - \frac{1}{v} h \, \bar{n}_i \left[\frac{1}{2} \left(C_{ij} \, m_{n_i} + C^*_{ij} \, m_{n_j} \right) - \frac{v^2}{\Lambda} (\alpha'_{N\phi})_{ij} \right] P_L \, n_j \\
\mathcal{L}_{hh} &= \frac{1}{2\Lambda} h^2 \, \bar{n}_i \left[(\alpha'_{N\phi})_{ij} P_L + (\alpha'^*_{N\phi})_{ij} P_R \right] n_j
\end{aligned}
$$

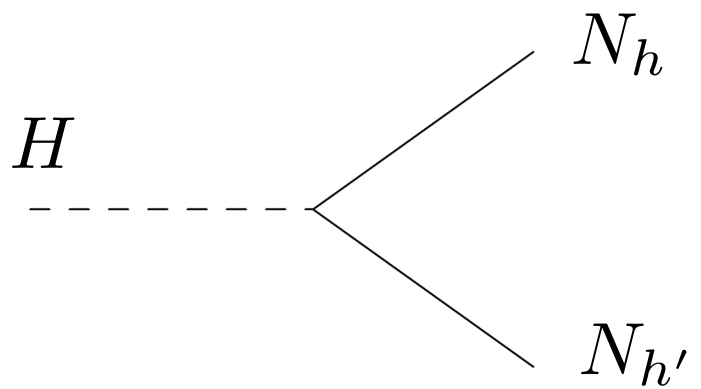
Dimension-5 Type-I Seesaw Portal

New interactions:

$$\mathcal{L}_{hNN} = \frac{v}{\Lambda} H \, \bar{N}_h \left[(\alpha'^{*}_{N\phi})_{hh'} P_R + (\alpha'_{N\phi})_{hh'} P_L \right] \, N_{h'}$$

$$(\alpha'_{N\phi})_{hh'} = U_{sh} \, (\alpha_{N\phi})_{ss'} \, U_{s'h'}$$

Allows the decay of the Higgs into two heavy neutrinos (tremendously suppressed in standard Seesaw)



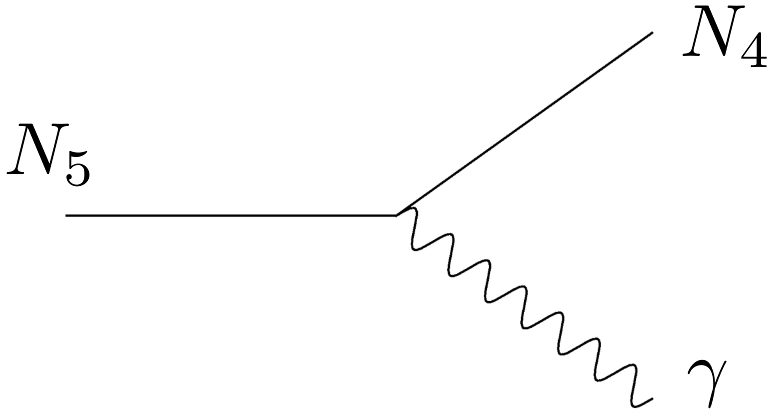
Dimension-5 Type-I Seesaw Portal

New interactions:

$$\mathcal{L}_{\gamma NN} = \frac{c_W}{\Lambda} F_{\mu\nu}\, \bar{N}_4\, \sigma^{\mu\nu} \left[(\alpha'_{NB})_{45} P_L - (\alpha'^{*}_{NB})_{45} P_R \right] N_5 + h.c.$$

$$(\alpha'_{NB})_{45} = U_{s4}\, (\alpha_{NB})_{ss'}\, U_{s'5}$$

Allows the decay of one heavy neutrino into another heavy neutrino and a photon. Usually dominates decay width.



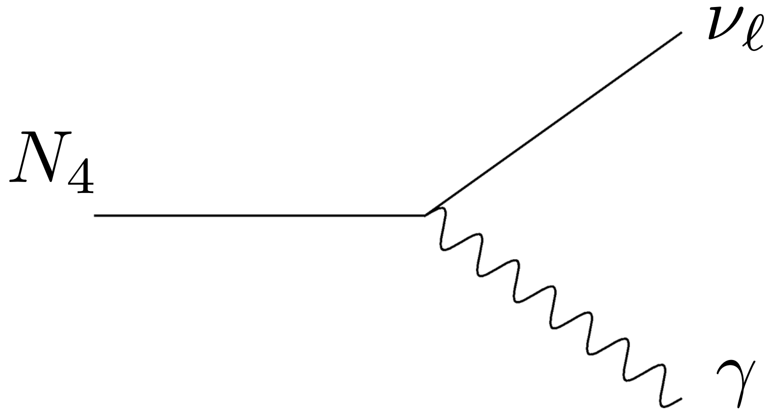
Dimension-5 Type-I Seesaw Portal

New interactions:

$$\mathcal{L}_{\gamma N\nu} = \frac{c_W}{\Lambda} F_{\mu\nu}\,\bar{\nu}_\ell\,\sigma^{\mu\nu}\left[(\alpha'_{NB})_{\ell 4} P_L - (\alpha'^{*}_{NB})_{\ell 4} P_R\right] N_4 + h.c.$$

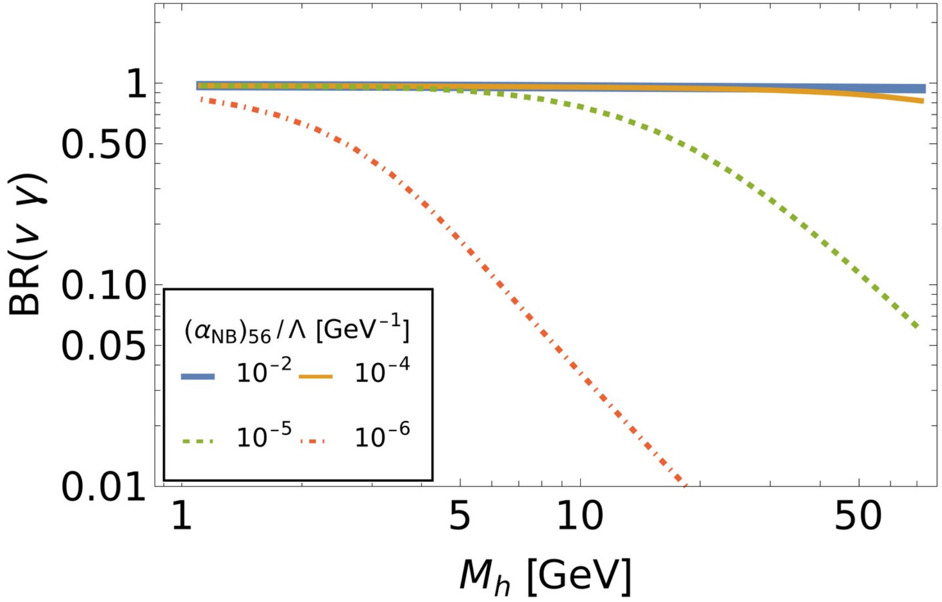
$$(\alpha'_{NB})_{\ell 4} = U_{s\ell}\,(\alpha_{NB})_{ss'}\,U_{s'4}$$

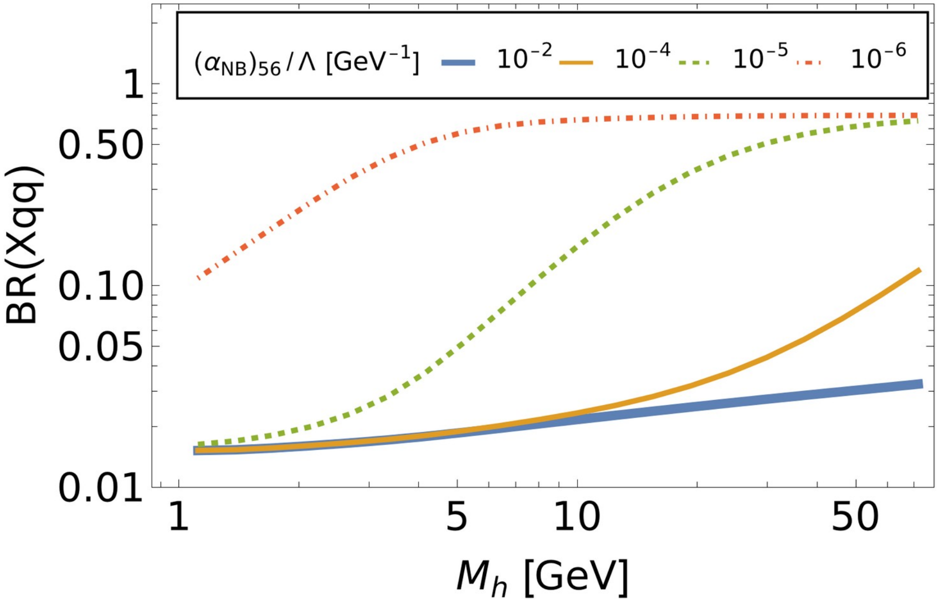
Allows the decay of a heavy neutrino into light neutrino and a photon.
Depends on “sterile-light” mixing.



Modifications to Heavy Neutrino Width

New branching ratios:



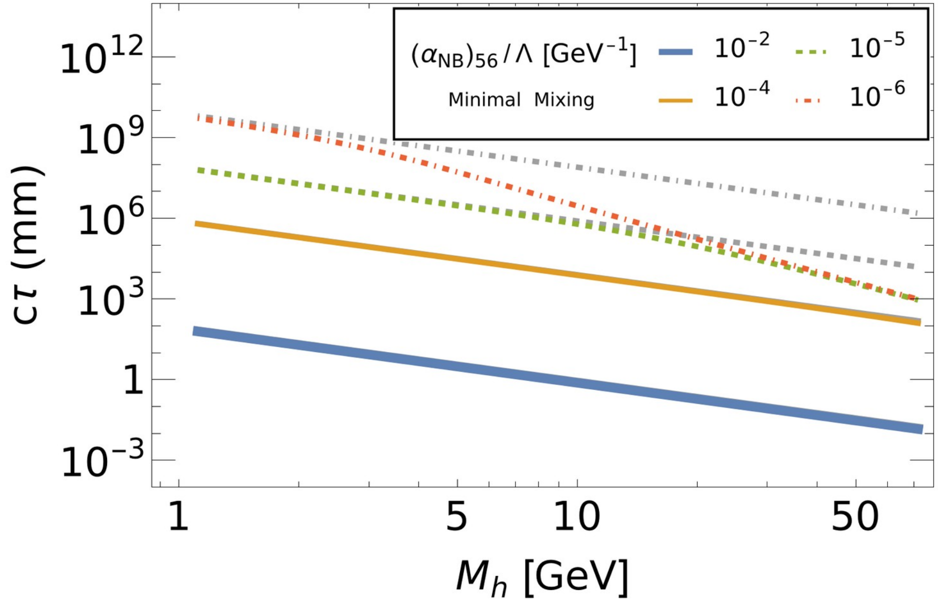


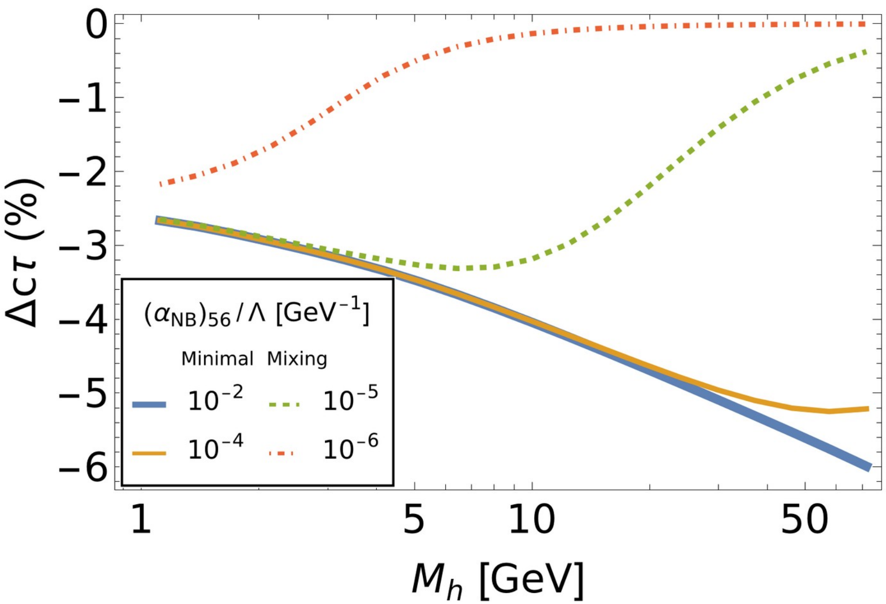
Photon + ν final state will usually dominate over small masses, but on the GeV regime the other decays are also relevant.

S. Peña (Thesis)

Modifications to Heavy Neutrino Width

New lifetimes:





It is important to include at least standard Seesaw three body decays!!

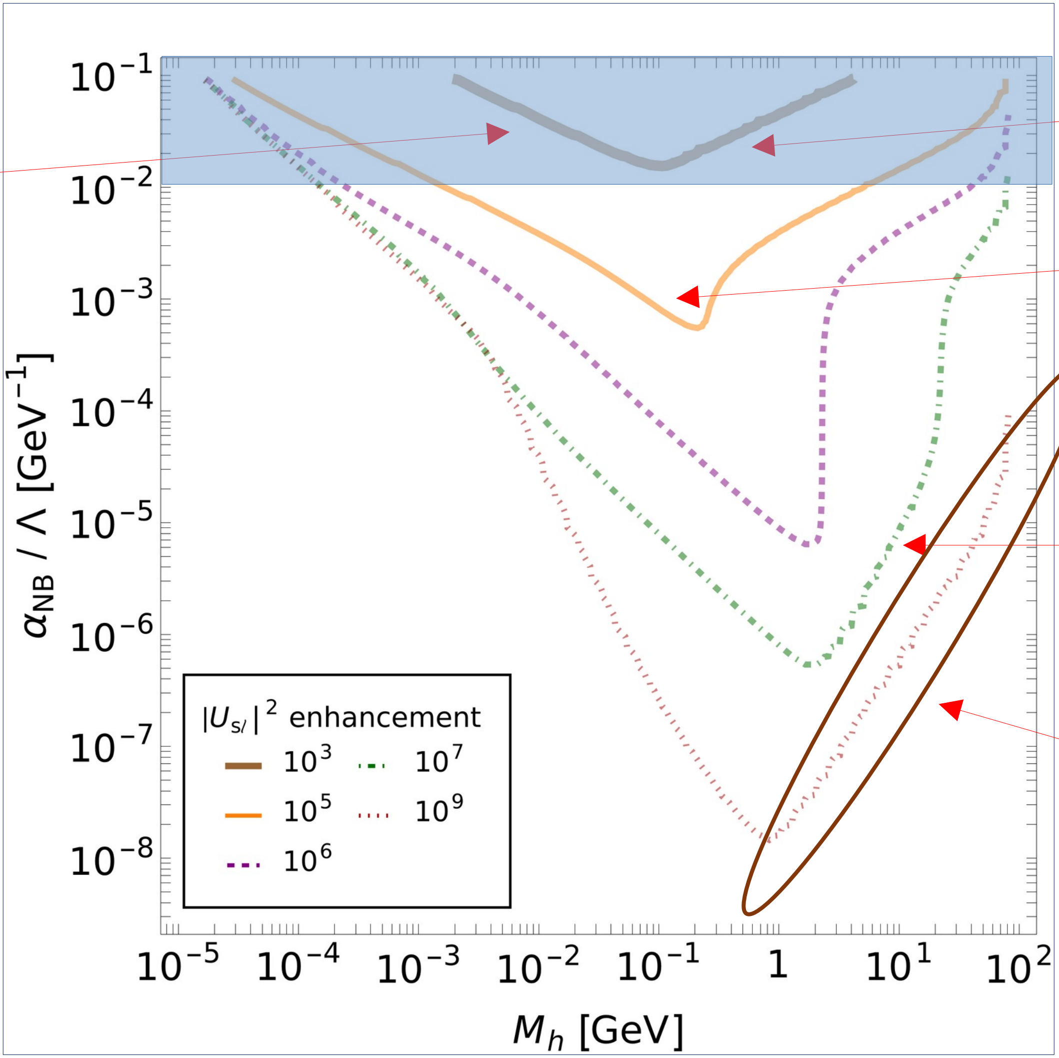
Modifications to three-body widths have small impact, might be relevant after a putative discovery.

S. Peña (Thesis)

Constraints from LEP

Long-lived, escapes detector

$\Lambda < m_Z$



Suppression from mixing

Contribution of Seesaw to production

Branching ratio to ν γ is suppressed

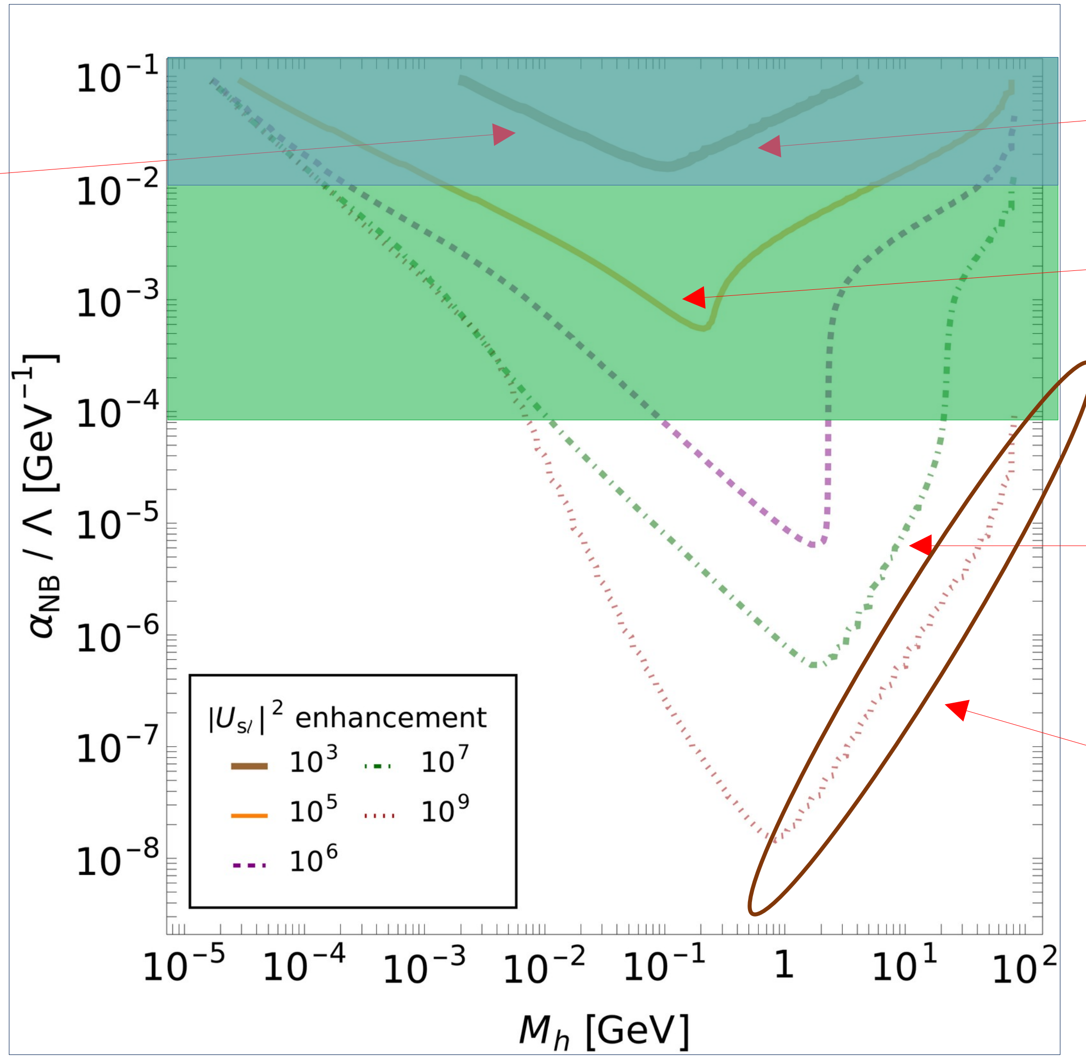
Ruled out by LFV

Constraints from LEP

Long-lived, escapes detector

$\Lambda < m_Z$

$\Lambda(\text{pert}) < m_Z$



Suppression from mixing

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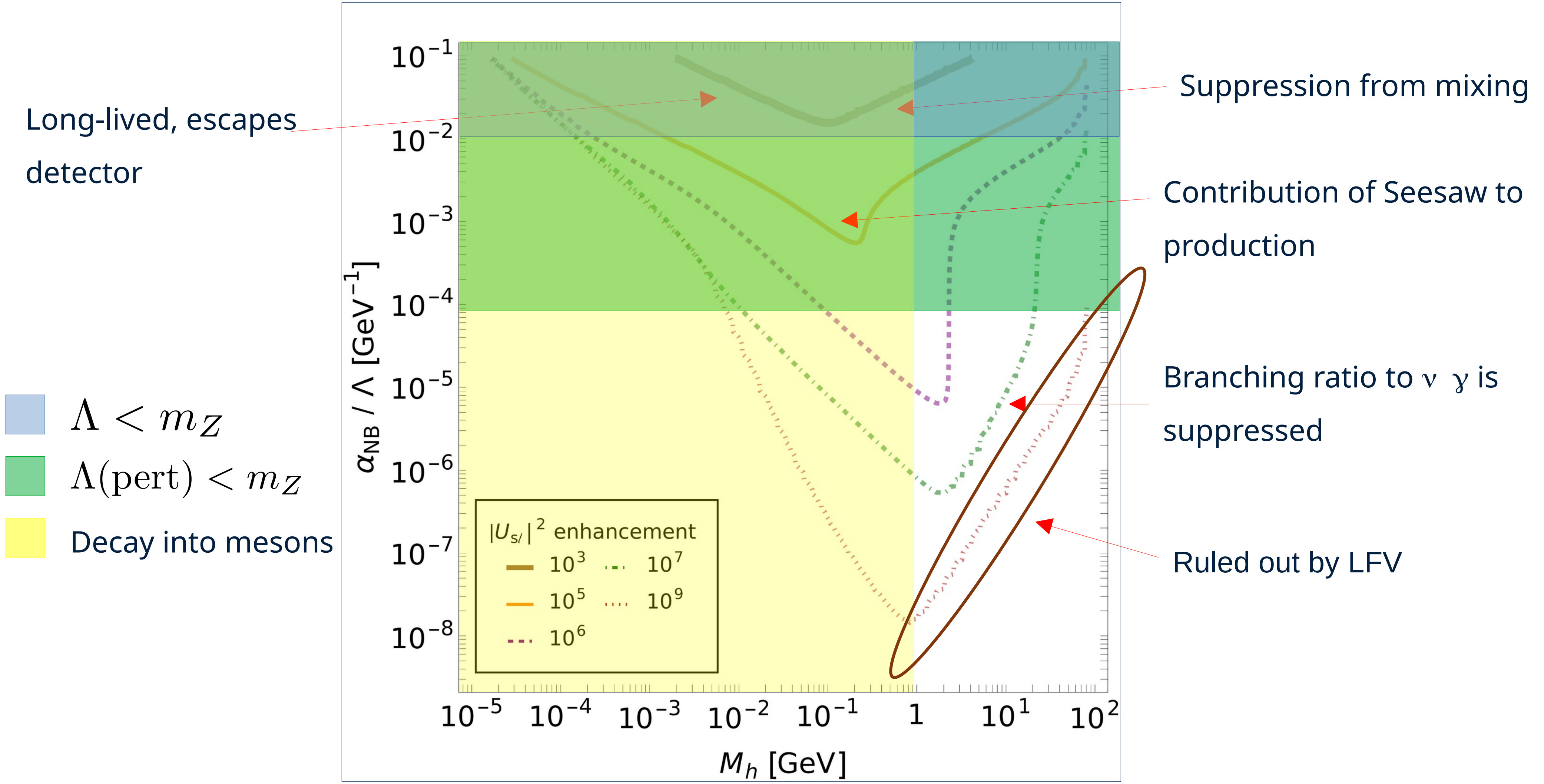
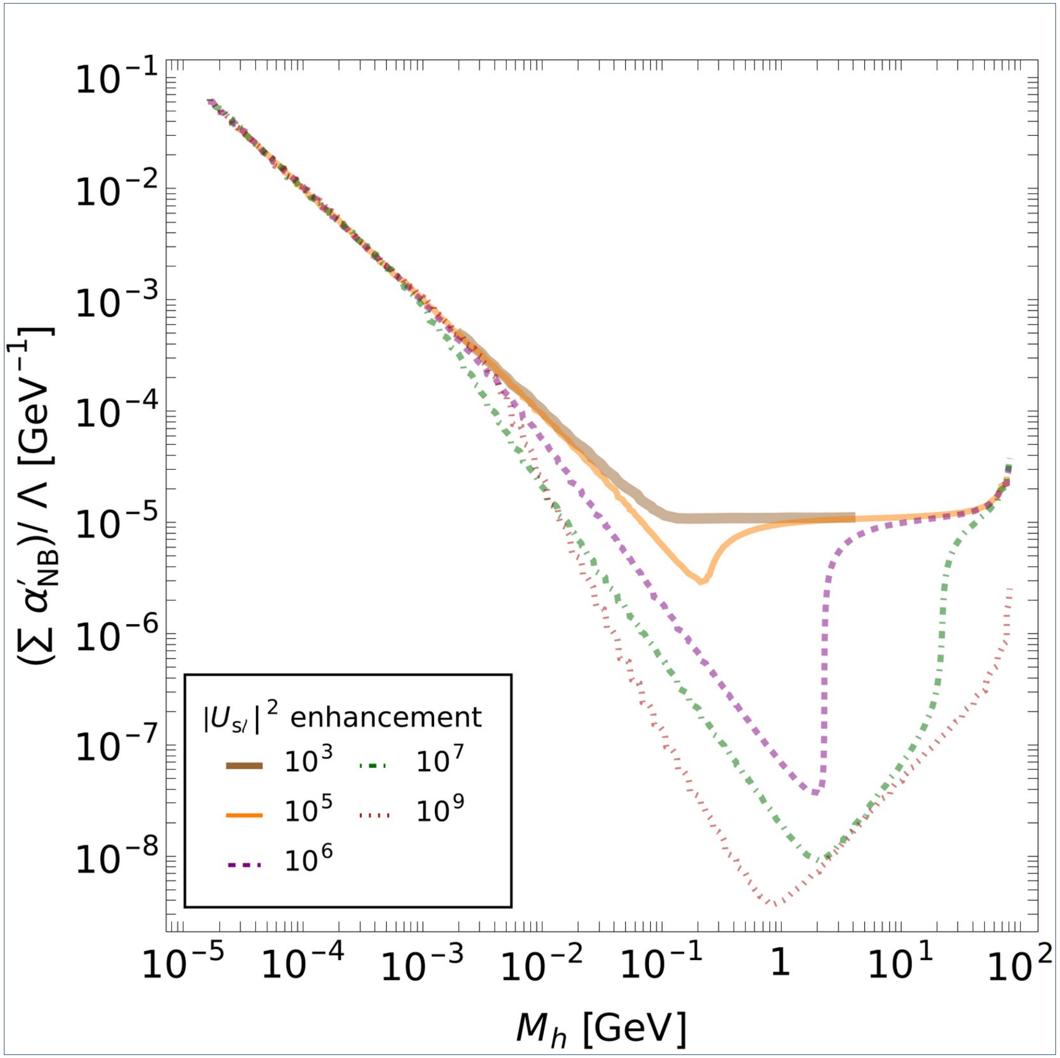


Constraints from LEP

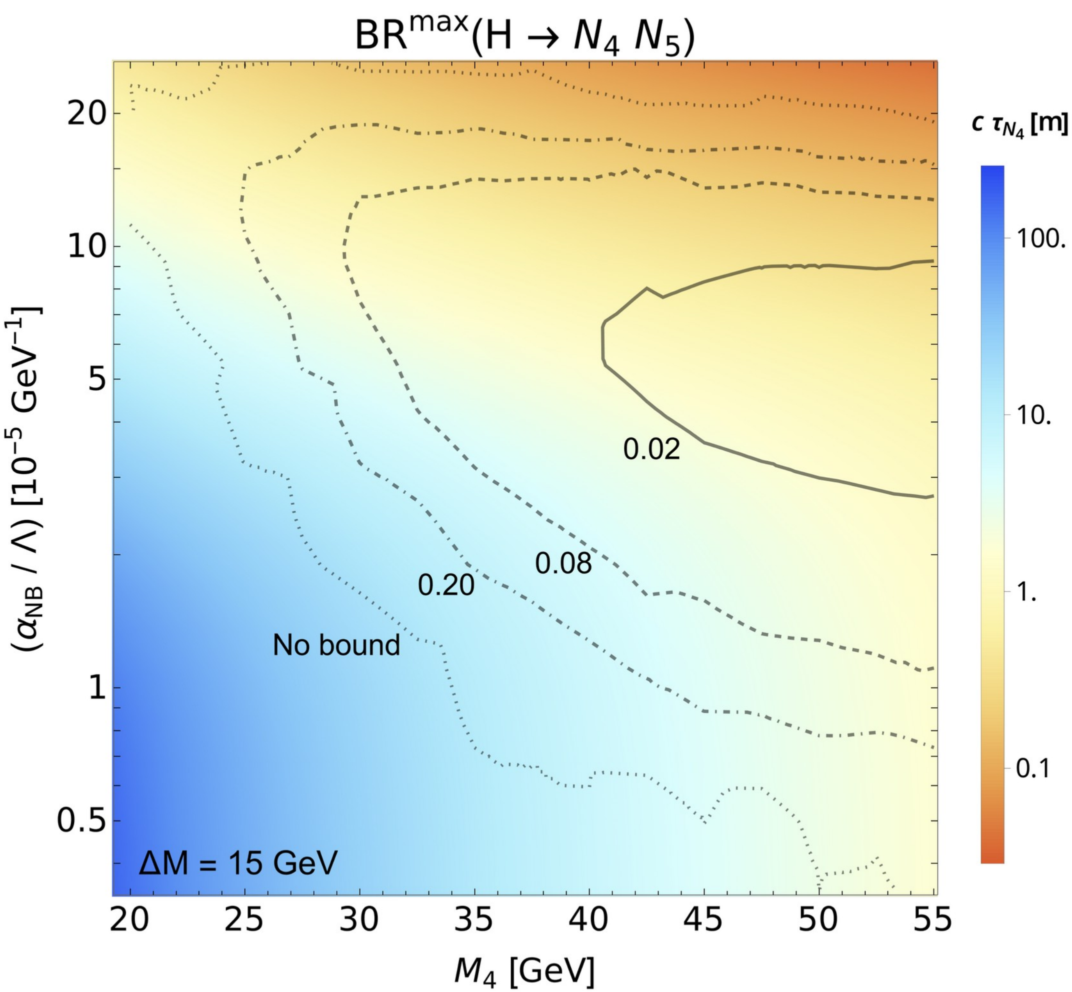
$$(\alpha'_{NB})_{\ell h} \equiv U_{s\ell}\,(\alpha_{NB})_{ss'}\,U_{s'h}$$

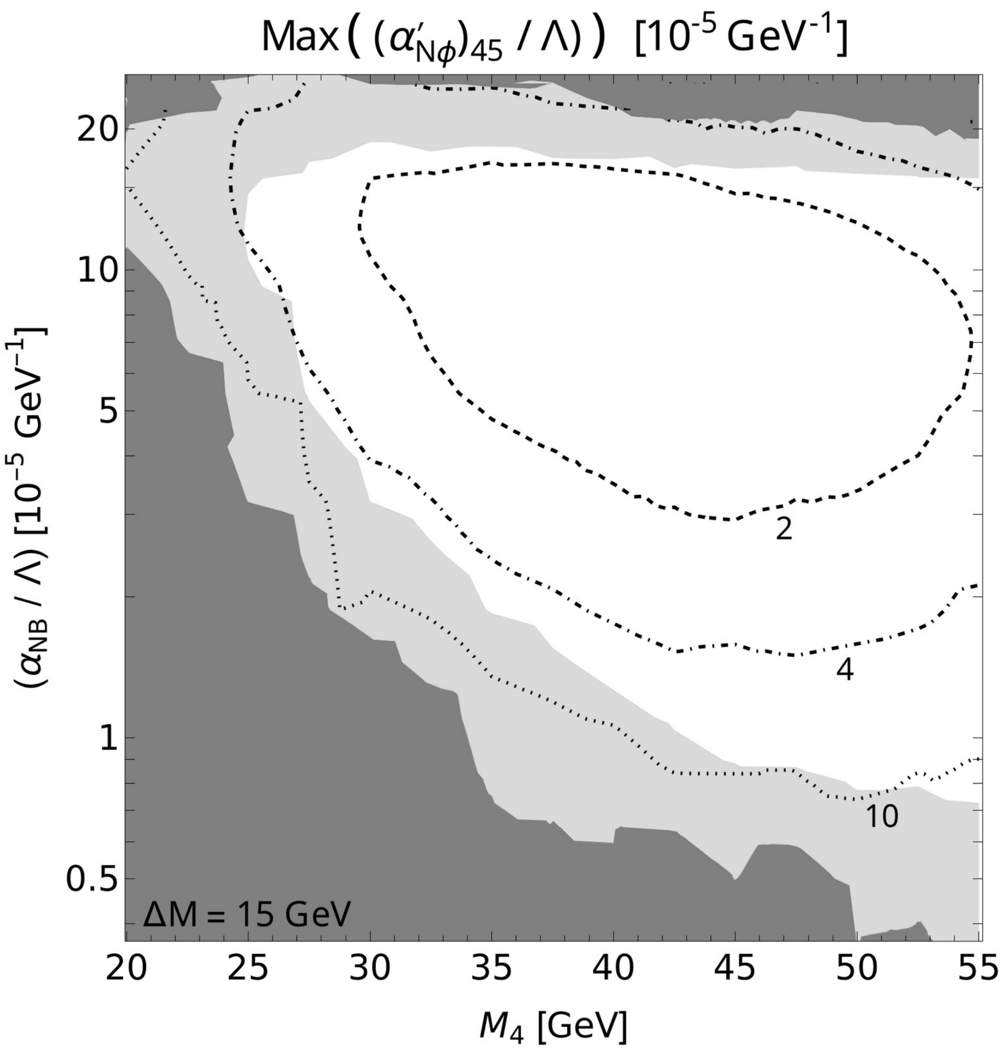
The bound can be written in terms of α'_{NB}, so can be applied to *d=6* operator.

This has been done before, but not in combination with Seesaw contribution.

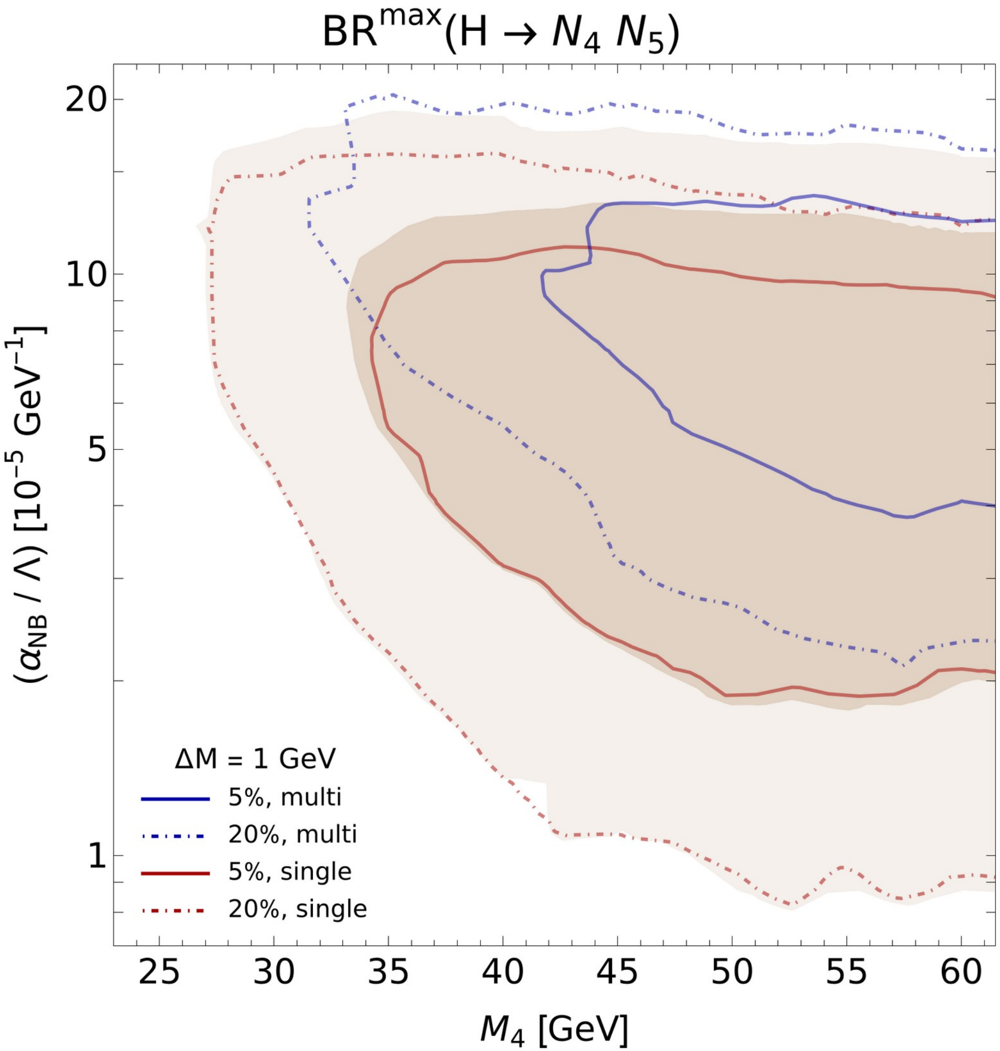


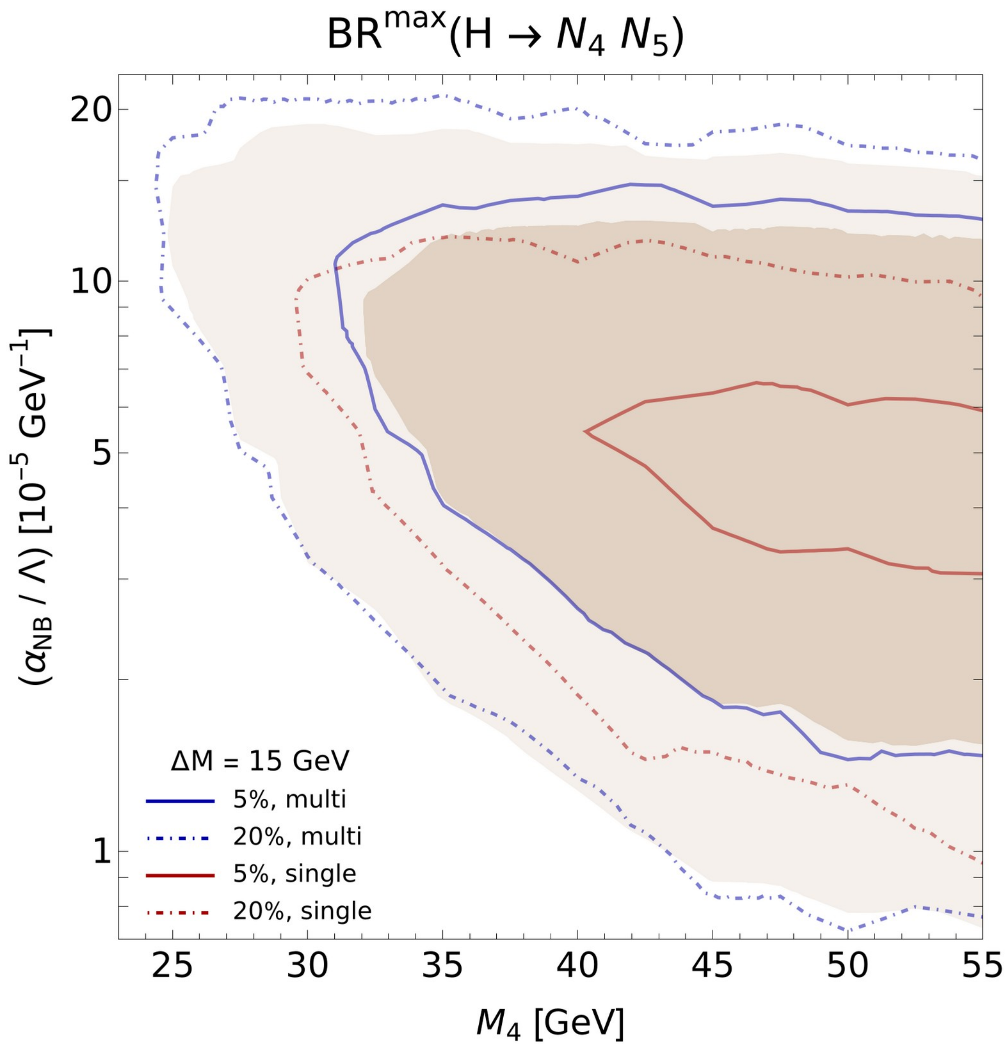
Bounds on $\alpha_{N\phi}$!





1+ channel is not always the most sensitive one!





Application of Higgs → invisible limit

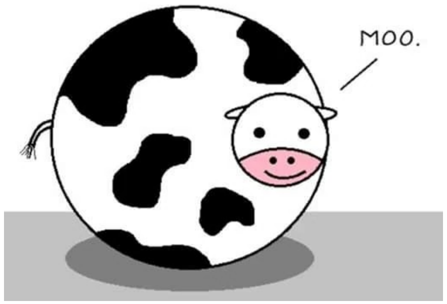
- One must take into account the probability of the LLP decaying outside the detector.

$$\mathrm{Prob}(x_1,\, x_2) = \exp\left[-\frac{x_1}{\gamma_{\rm rel}\,\beta_{\rm rel}\,c\,\tau_\chi}\right] - \exp\left[-\frac{x_2}{\gamma_{\rm rel}\,\beta_{\rm rel}\,c\,\tau_\chi}\right]$$

$$\gamma_{\rm rel} = E_\chi/m_\chi \qquad \beta_{\rm rel} = |\vec{p}_\chi|/E_\chi$$

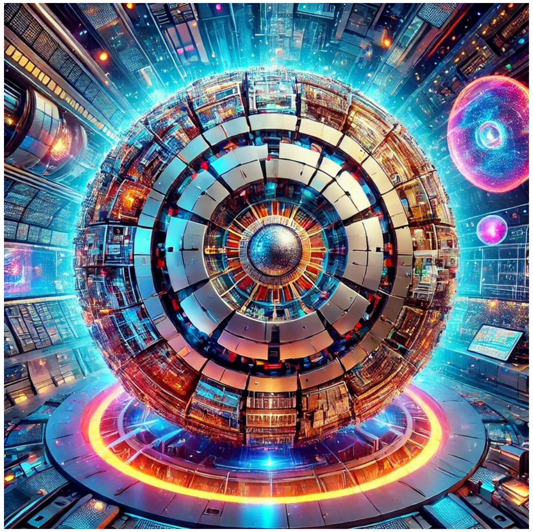
$\tau_\chi =$ Lifetime of χ in rest frame.

Simplifications

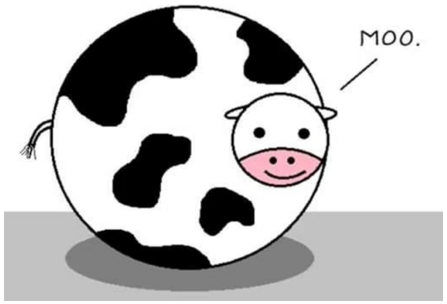


- Take a spherical detector.

$$\mathrm{BR}(H \to \chi\bar{\chi}) \times [\mathrm{Prob}(L_{\mathrm{det}}, \infty)]^2 < \mathrm{BR}_{\mathrm{limit}}$$



Simplifications

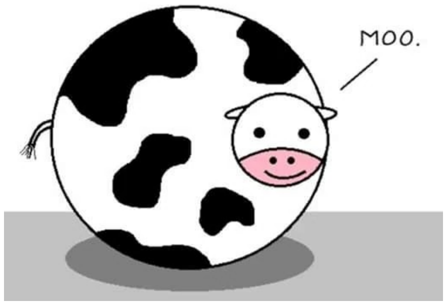


- Take a spherical detector.
- Assume the Higgs decays at rest.

$$E_\chi = m_H/2 \quad \Rightarrow \gamma_{\rm rel}\,\beta_{\rm rel} = \sqrt{\frac{m_H^2}{4m_\chi^2} - 1}$$

Simplifications

- Take a spherical detector.
- Assume the Higgs decays at rest.

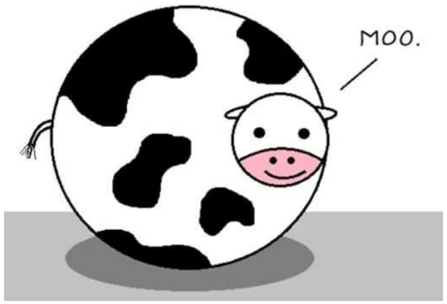


$$E_\chi = m_H/2 \quad \Rightarrow \gamma_{\rm rel}\,\beta_{\rm rel} = \sqrt{\frac{m_H^2}{4m_\chi^2} - 1}$$

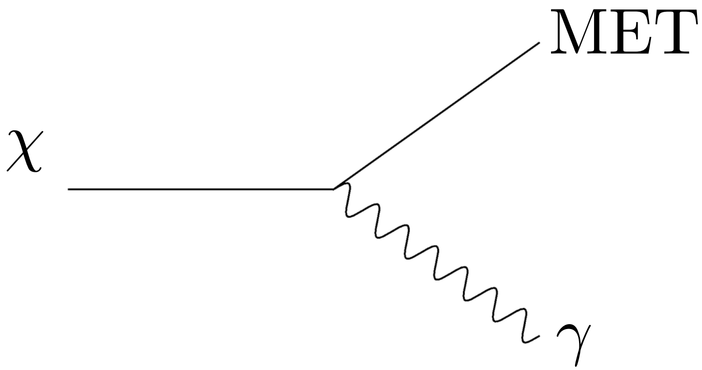
So far:

$$\mathrm{BR}(H \to \chi\bar{\chi}) \times \exp\left[-\frac{2L_{\rm det}}{\gamma_{\rm rel}\,\beta_{\rm rel}\,c\,\tau_\chi}\right] < \mathrm{BR}_{\rm limit}$$

Simplifications



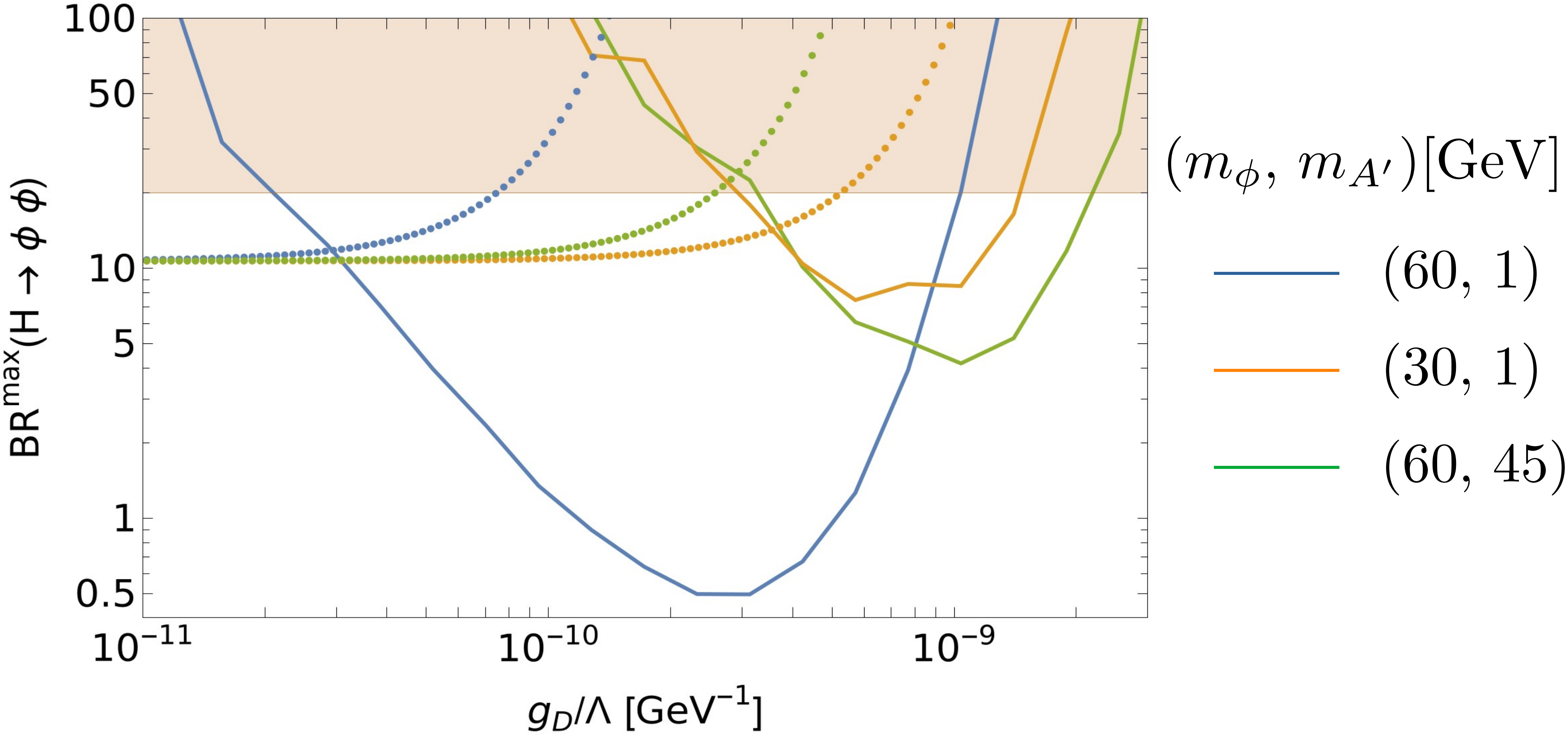
- Take a spherical detector.
- Assume the Higgs decays at rest.
- Assume the decay is invisible if the LLP decays after the ECAL.



$$\Rightarrow \qquad L_{\rm det} = 1.97\,{\rm m}$$

$$\mathrm{BR}(H \to \chi\bar{\chi}) \times \exp\left[-\frac{2L_{\rm det}}{\gamma_{\rm rel}\,\beta_{\rm rel}\,c\,\tau_\chi}\right] < \mathrm{BR}_{\rm limit}$$

Preliminary results

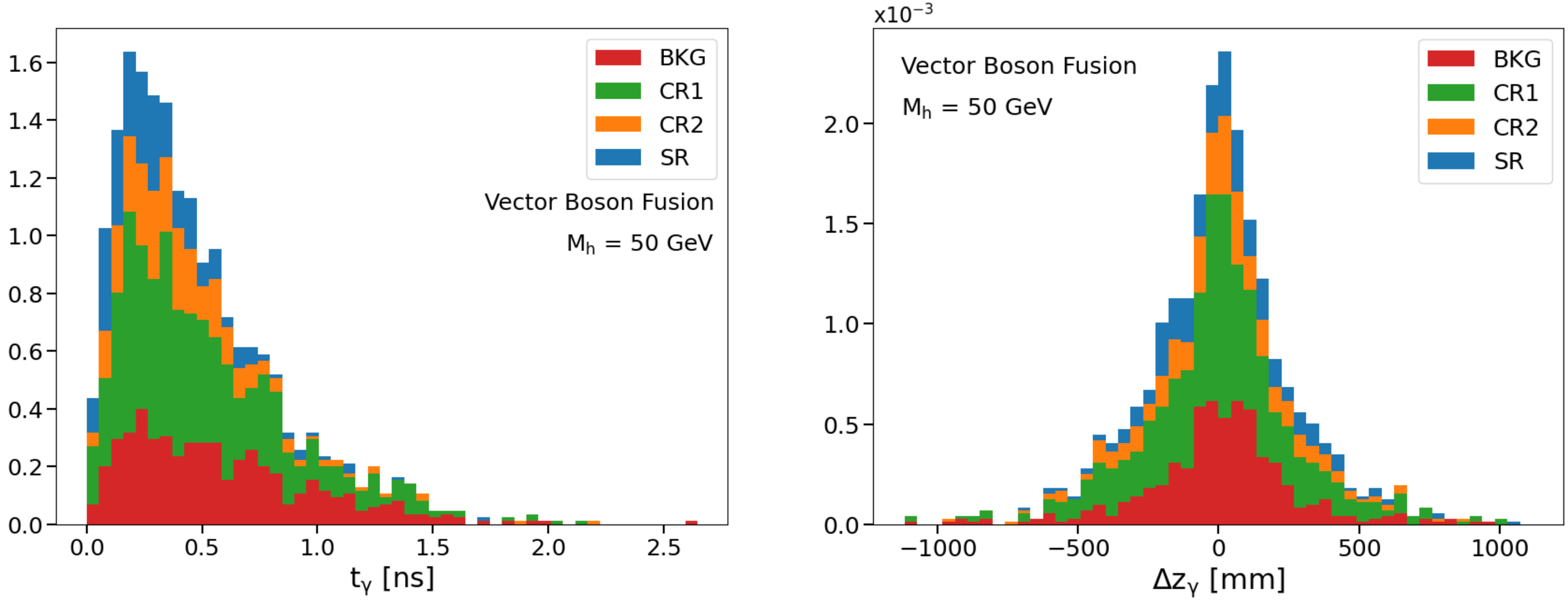


8 TeV Search, for 20.3 fb^{-1}

- Two “loose” photons with energy larger than 50 GeV.
- One of the photons must be in barrel region.
- Isolation criteria: no deposits larger than 4 GeV within $\Delta R = 0.4$.
- If more than one photon in barrel region, use the one with largest t_γ.
- Define background, control and signal region depending on MET.
- Use bin-based analysis considering t_γ and $|\Delta z_\gamma|$

ATLAS (1409.5542 [hep-ex])

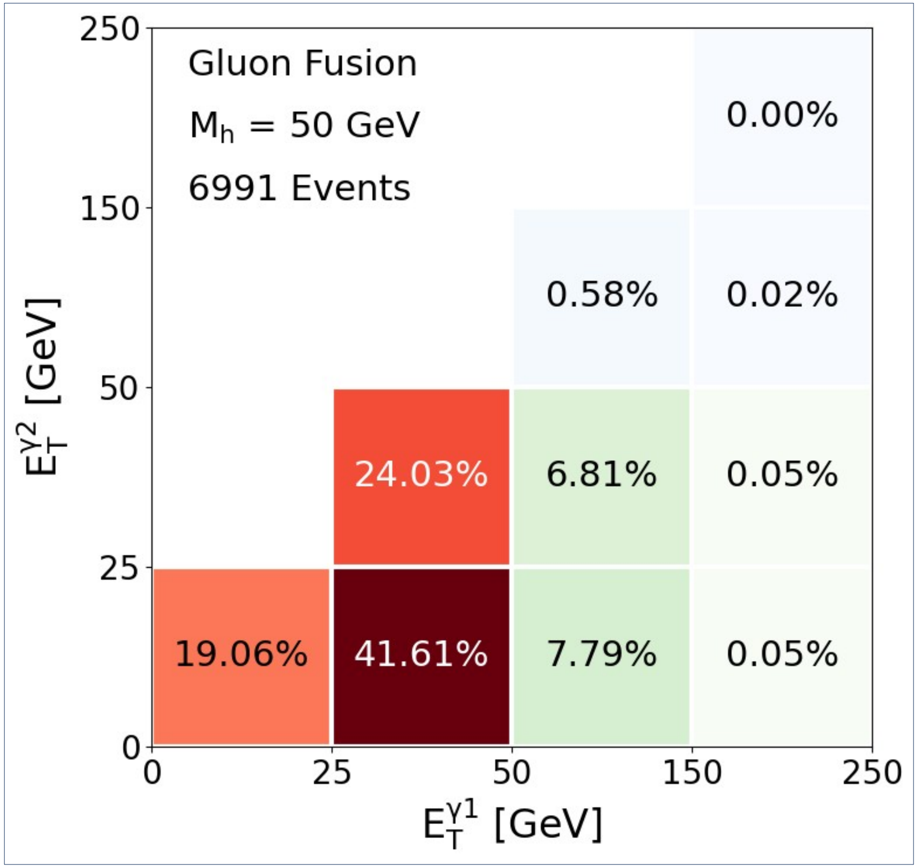
8 TeV Search, for 20.3 fb^{-1}



8 TeV Search

Old searches for non-pointing photons were designed for heavy particles.

- Triggered using high pT photons.



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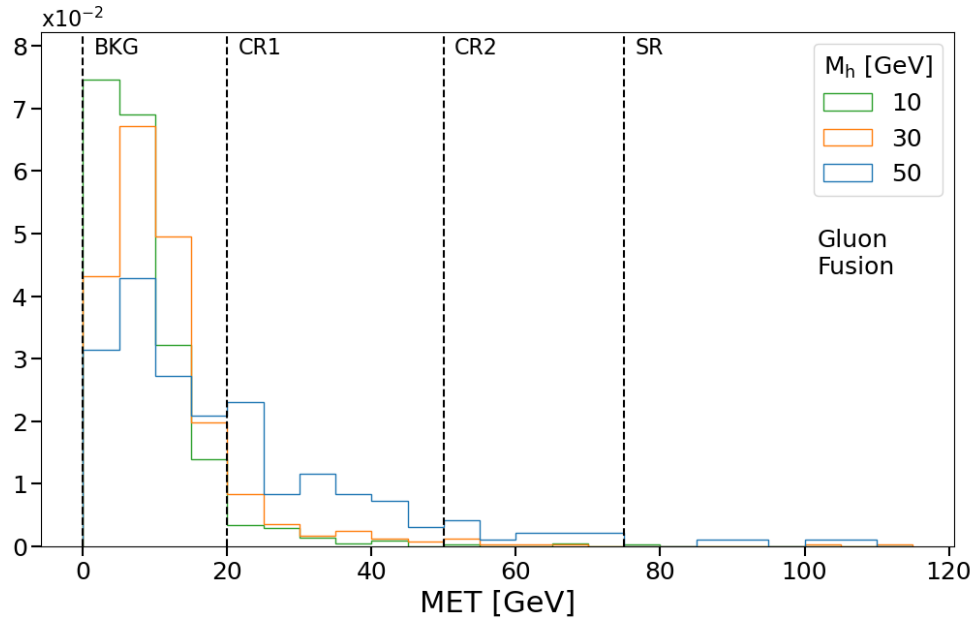
- Non optimal signal regions.



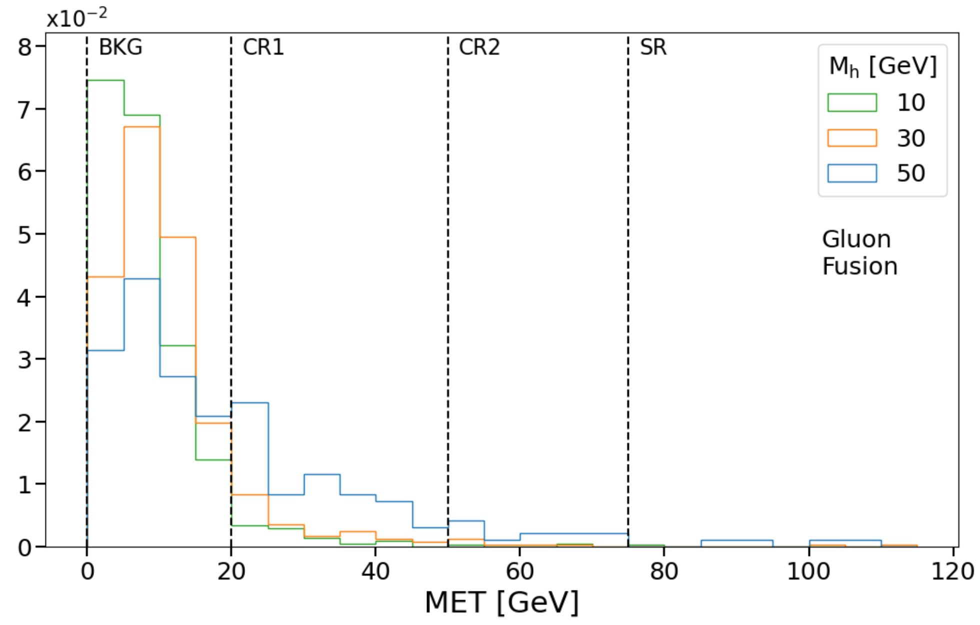
ATLAS (1409.5542 [hep-ex])

8 TeV Search

Old searches for non-pointing photons were designed for heavy particles.

- Triggered using high pT photons.
- Non optimal signal regions.

Even if a photon pair from long-lived N_h passed the energy cuts, and even if they also had large t_γ and $|\Delta z_\gamma|$, they are likely to be assigned to the background or control region. Thus, this strongly suggests the 8 TeV search is not optimal for studying our model.



ATLAS (1409.5542 [hep-ex])