Placing Limits on the Dimension-5 Seesaw Portal with Non-pointing Photons

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Based on the following work:
F. Delgado, L. Duarte, JJP, C. Manrique-Chavil, S. Peña (2205.13550)
L. Duarte, JJP, C. Manrique-Chavil (231x.xxxx)

Type-I Seesaw

Type I Seesaw is probably most popular mechanism for neutrino masses

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

If you have more than one heavy neutrino, the mixing does not have to be vanishingly small. This is shown in the Casas-Ibarra parametrization.

$$U_{a4} = \pm Z_a^{\rm NH} \sqrt{\frac{m_3}{M_4}} \cosh\gamma_{45} \, e^{\mp i\theta_{45}} \qquad U_{a5} = i \, Z_a^{\rm NH} \sqrt{\frac{m_3}{M_5}} \cosh\gamma_{45} \, e^{\mp i\theta_{45}}$$

"Active-heavy" mixing

Casas, Ibarra (hep-ph/0103065)

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.

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

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

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

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The dipole operator will play a central role in our research. Notice that to have a non-vanishing dipole coefficient, one needs at least two ν_R states!

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Modifications to Heavy Neutrino Width

The new dipole coupling adds a new decay channel, dominating the decay:

$$\Gamma(N_h \to \nu\,\gamma) = \frac{2}{\pi}\, c_W^2\, M_h^3 \sum_\ell \left| U_{s\ell}\, \frac{(\alpha_{NB})_{ss'}}{\Lambda}\, U_{s'h} \right|^2$$

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We also find modifications to three-body decays that used to involve the *Z* boson. They now also have a virtual photon. However, small impact.

For example, lifetime changes in less than 10%.

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

Outline

- Re-evaluation of LEP constraints
- Searches for Non-Pointing Photons by ATLAS
- Recast of Non-Pointing Photon Search

Re-evaluation of LEP Constraints

Craiyon: “an electron-positron collider”

Constraints from LEP

For GeV scale heavy neutrinos, most constraints from astrophysics and light neutrino dipole moments vanish.

LEP searches, on the other hand, are sensitive to:

$$e^+e^- \to N_h \, \nu_\ell \qquad\qquad N_h \to \nu_\ell \, \gamma$$

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If one assumes an infinite detector, with no cuts, it is possible to write a simple expression for the cross-section:

$$\sigma_{N\nu} = \frac{(M_h^2 - m_Z^2)^2}{2\pi m_Z^2 \Gamma_Z^2}(c_V^2 + c_A^2)\left\{ \left|\frac{(\alpha'_{NB})_{\ell h}}{\Lambda}\right|^2 \frac{e^2(2M_h^2 + m_Z^2)}{3c_W^2 m_Z^2}\left(1 + \frac{4c_W^2\Gamma_Z^2}{(c_V^2 + c_A^2)m_Z^2}\right)\right.$$

$$\left. + \frac{1}{6}|C_{\ell h}|^2 G_F^2 (M_h^2 + 2m_Z^2)\, c_W^2 - \sqrt{2}\,\Re e\left[\frac{(\alpha'_{NB})_{\ell h}}{\Lambda} C_{\ell h}\right] e\,G_F\,M_h \right\}$$

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Constraints from LEP

$$\sigma_{N\nu}^{\text{cuts}} = \frac{(\hbar c)^2}{32\pi\, m_Z^2}\left(1 - \frac{M_h^2}{m_Z^2}\right)\left(\frac{1}{4\pi\,\tau_N^{\text{lab}}}\right)\text{BR}(N_h \to \nu\,\gamma)$$

$$\int d(\cos\theta_\gamma)\, d\phi_\gamma\, d(\cos\theta_N)\, dt_N \exp\left[-\frac{t_N}{\tau_N^{\text{lab}}}\right]$$

$$\frac{d\sigma_{N\nu}}{d\cos\theta_N}\Theta_H\left(\sqrt{x_\gamma^2 + y_\gamma^2} - z_{\text{det}}\tan\theta_{\text{veto}}\right)$$

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Amplitude + phase space integration

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Amplitude + phase space integration

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Branching ratio

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Branching ratio

Angular cut

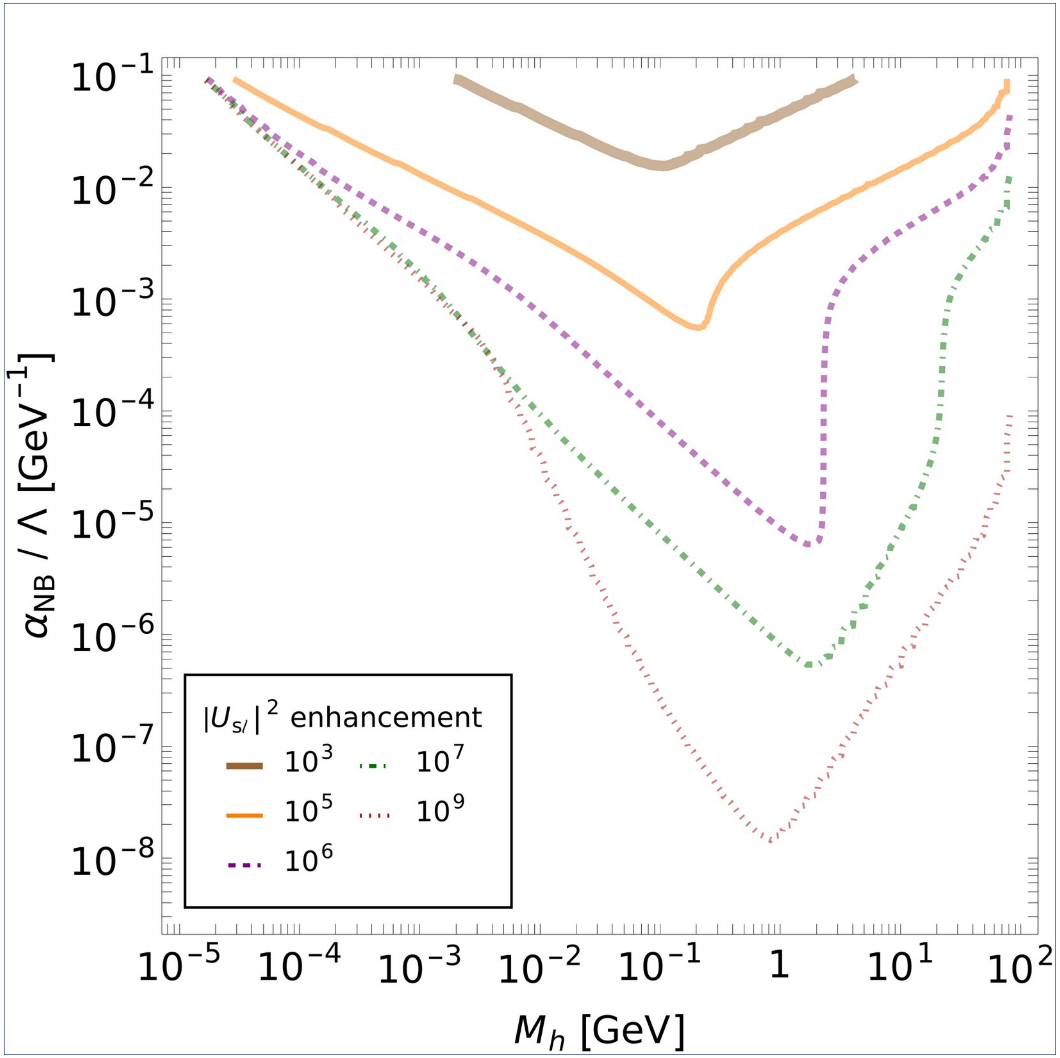
Constraints from LEP

$$\sigma_{N\nu}^{\exp} < 0.1 \text{ pb}$$

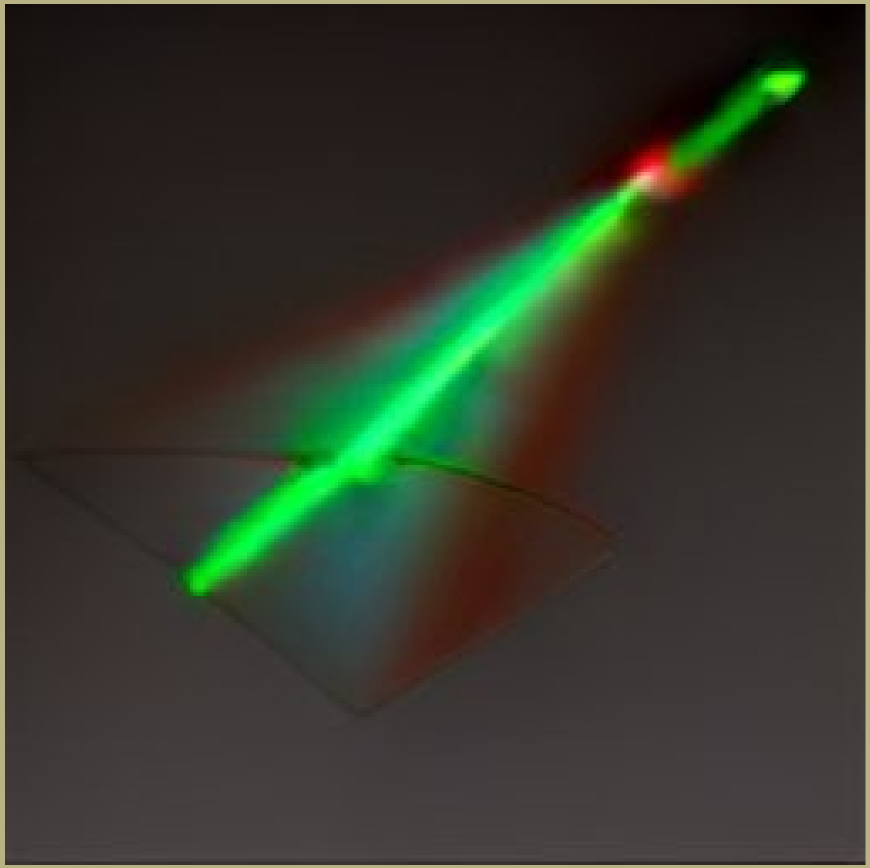
Bound depends on enhancement of light-sterile mixing.

For no enhancement, there is no bound.

Enhancement reaches unitarity limit around 10^9, where dipole coupling can be constrained down to order 10^{-8} GeV^{-1}.



Searches for Non-Pointing Photons (ATLAS)



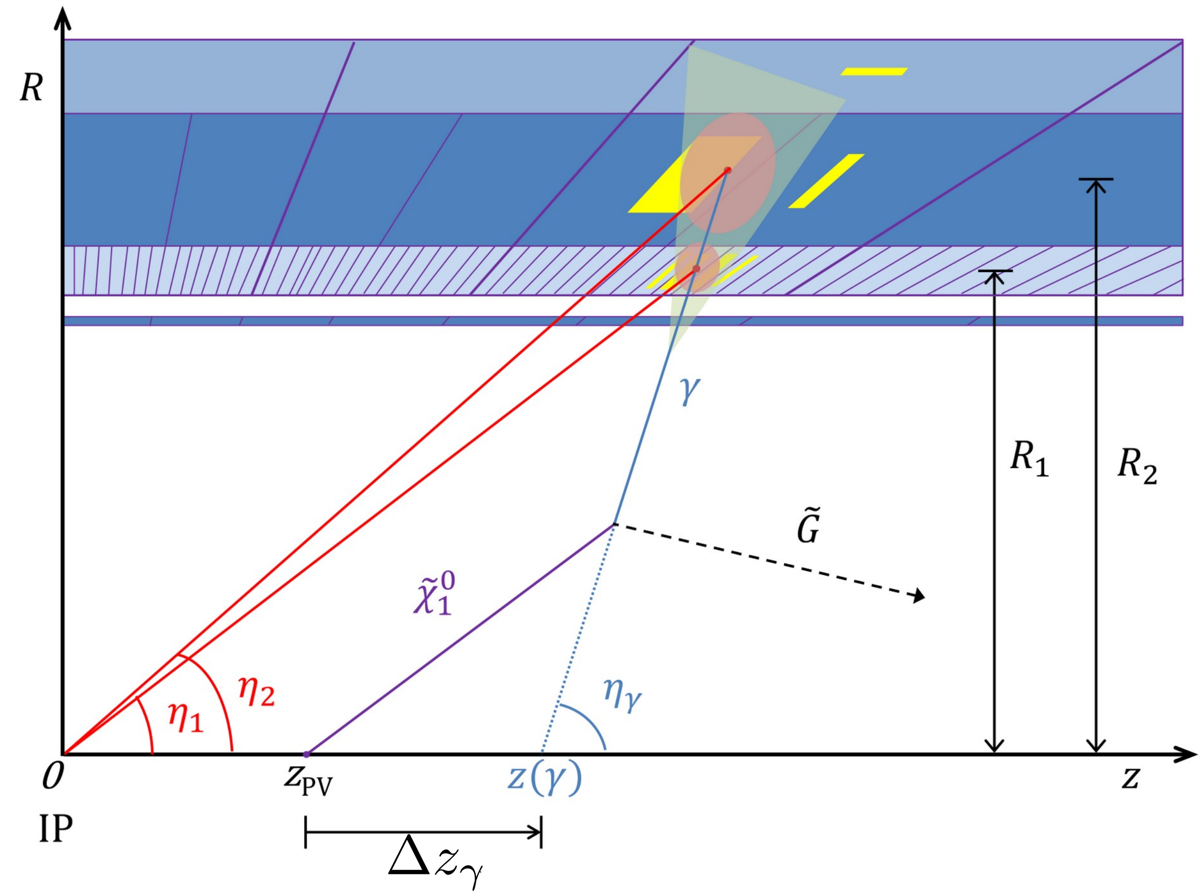
Craiyon: “a photon not pointing in the expected direction”

What are non-pointing photons?

Photons coming from long-lived particles do not point towards primary vertex. And ATLAS can notice!

Important variables:

t_γ $|\Delta z_\gamma|$



D. Mahon (PhD Thesis)

Heavy Neutrino Production at the LHC

Enhancing the mixing reduces the lifetime. Thus, in this analysis we do not use enhancements. However, standard production modes become irrelevant!

Produce the heavy neutrinos via exotic Higgs decays, mediated by the 2ν - 2h effective operator:

$$\Gamma(H \to N_h\, N_{h'}) = S_{hh'}\,\frac{v^2}{2\pi}\,\frac{\sqrt{\lambda(m_H^2,\, M_h^2,\, M_{h'}^2)}}{m_H^3}$$

$$\left|\frac{(\alpha_{N\phi})_{hh'}}{\Lambda}\right|^2 \left(m_H^2 - M_h^2 - M_{h'}^2 - 2M_h\, M_{h'}\cos 2\delta_{hh'}\right)$$

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(Not dipole!)

13 TeV Search!

- Trigger: isolated lepton with $p_T > 27$ GeV.
- At least one “loose” photon with energy larger than 10 GeV.
- Require E_{cell} larger than 10 GeV.
- One of the photons must be in barrel region.
- Isolation criteria: no deposits larger than 6.5% of energy within $\Delta R = 0.2$.
- If more than one photon in barrel region, use the one with largest energy.
- Define background, control and signal region depending on MET.
- Use bin-based analysis considering t_γ and $|\Delta z_\gamma|$. Distinguish single and multi-photon samples.

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ATLAS (ATLAS-CONF-2022-017)
ATLAS (2209.01029 [hep-ex])

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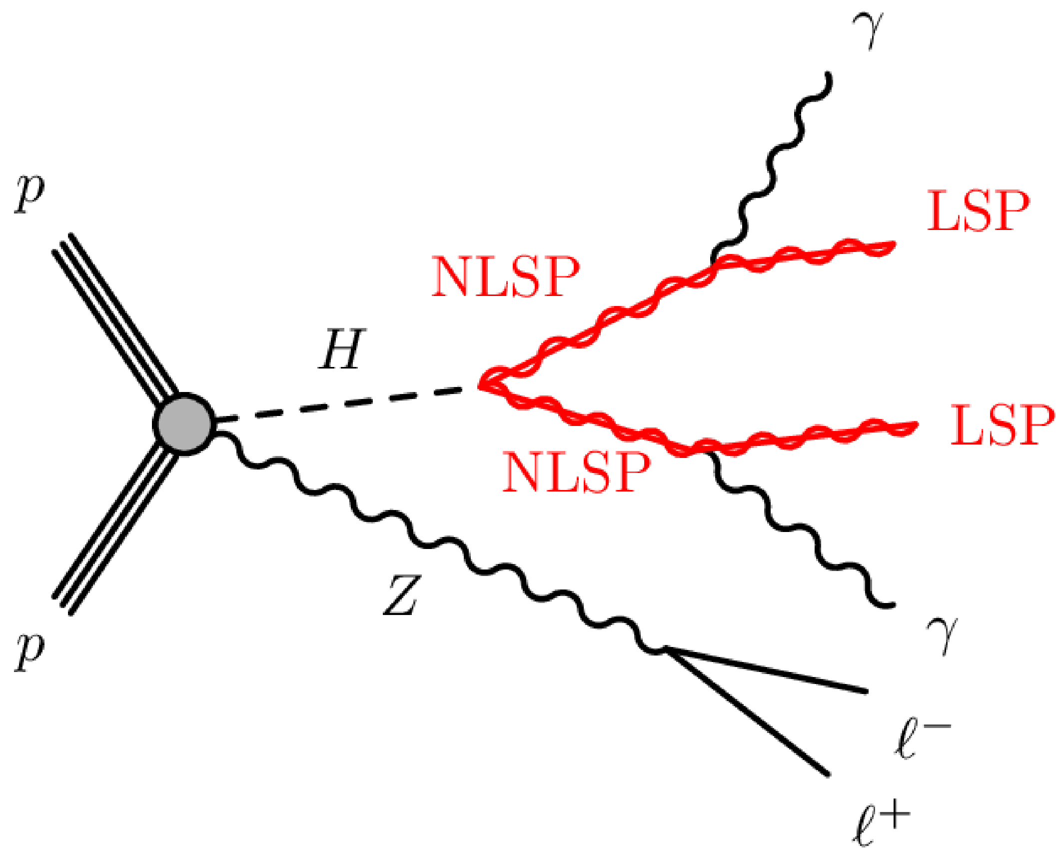
Recast of Non-Pointing Photon Search

Craiyon: “a lepton produced associated to a Higgs boson”

Production Modes

- Following search, we consider ZH, WH and ttH modes.



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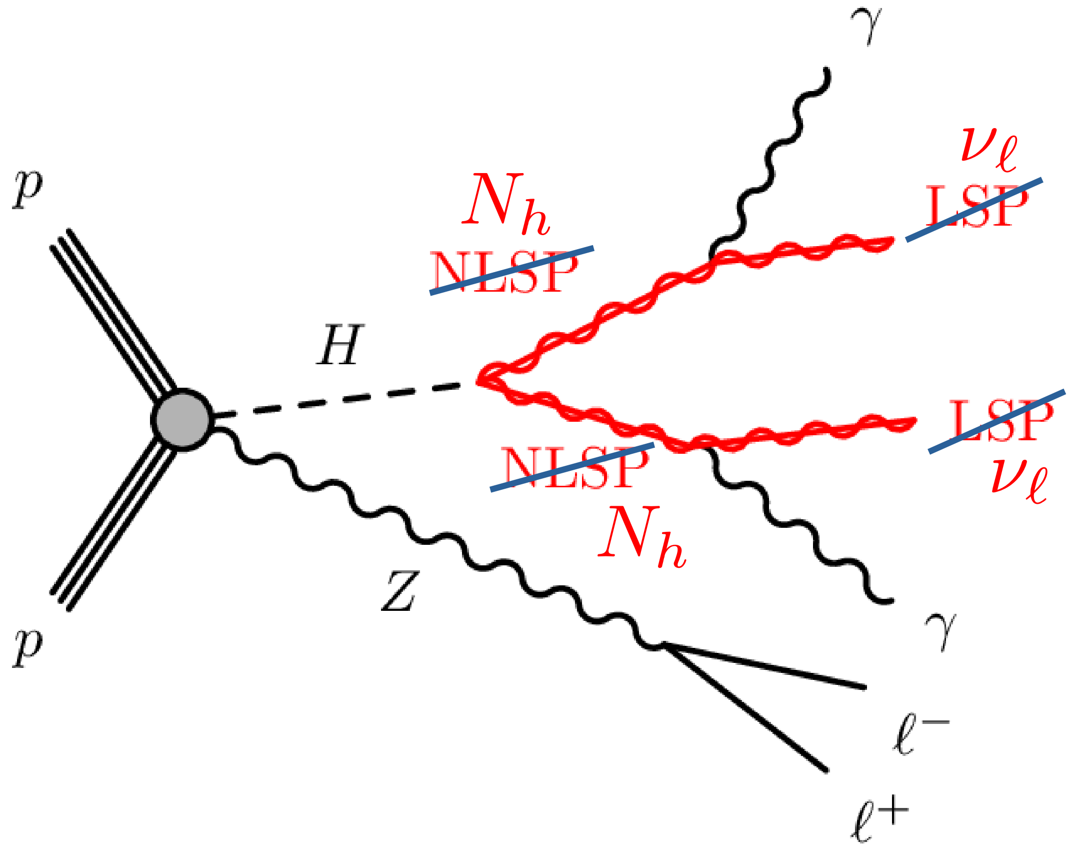

Model implemented in FeynRules, events were generated by MadGraph.

Parton shower and hadronization was carried out by Pythia, returning a HepMC output.

Long-lived parameters

- Photon non-pointing variable

$$|\Delta z_\gamma| = \left| \frac{r_z - p_z(\vec{p}\cdot\vec{r})/|\vec{p}|^2}{1 - p_z^2/|\vec{p}|^2} - z_{\rm PV} \right|$$

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- Arrival time:

Simulated prompt heavy neutrinos, and calculated arrival time in this case (as a function of pseudorapidity). Subtract this from long-lived case.

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- Calculated for all photons (pT > 10 GeV) in HepMC output from MadGraph + Pythia. Rewrite HepMC and feed into Delphes.

Delphes

- Adapted to read new HepMC with displacement information.
- Modified electron and photon isolation modules → isolation from tracks, as in search.

$$\Delta R_{\gamma,\,e} = 0.2$$

$$\sum_{\substack{\text{tracks} \\ p_T > 1\ \text{GeV}}} |\vec{p}_T| < 0.05\, |\vec{p}_T^{\,\gamma}| \qquad \sum_{\substack{\text{tracks} \\ p_T > 1\ \text{GeV}}} |\vec{p}_T| < 0.15\, |\vec{p}_T^{\,e}|$$

Delphes

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- Modified electron and photon isolation modules → isolation from tracks, as in search.
- Added new electron and photon isolation modules → isolation from other calorimeter deposits, as in search.

$$\Delta R_{\gamma,\,e} = 0.2$$

$$\sum_{\substack{\text{calo}\\\text{deposits}}} |\vec{p}_T| < 0.065\,|\vec{p}_T^{\,\gamma}| \qquad \sum_{\substack{\text{calo}\\\text{deposits}}} |\vec{p}_T| < 0.20\,|\vec{p}_T^{\,e}|$$

Delphes

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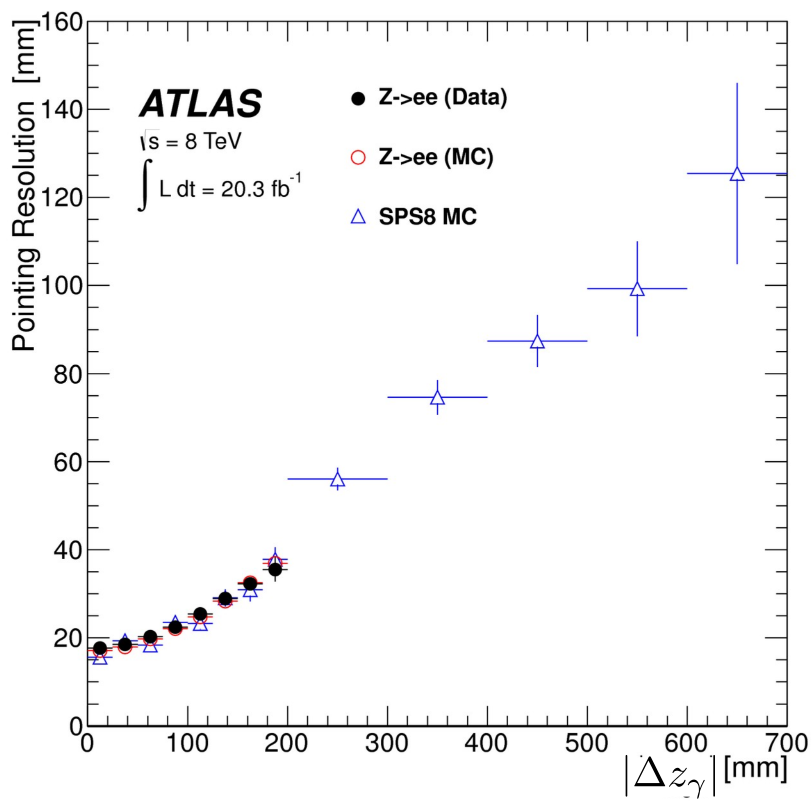
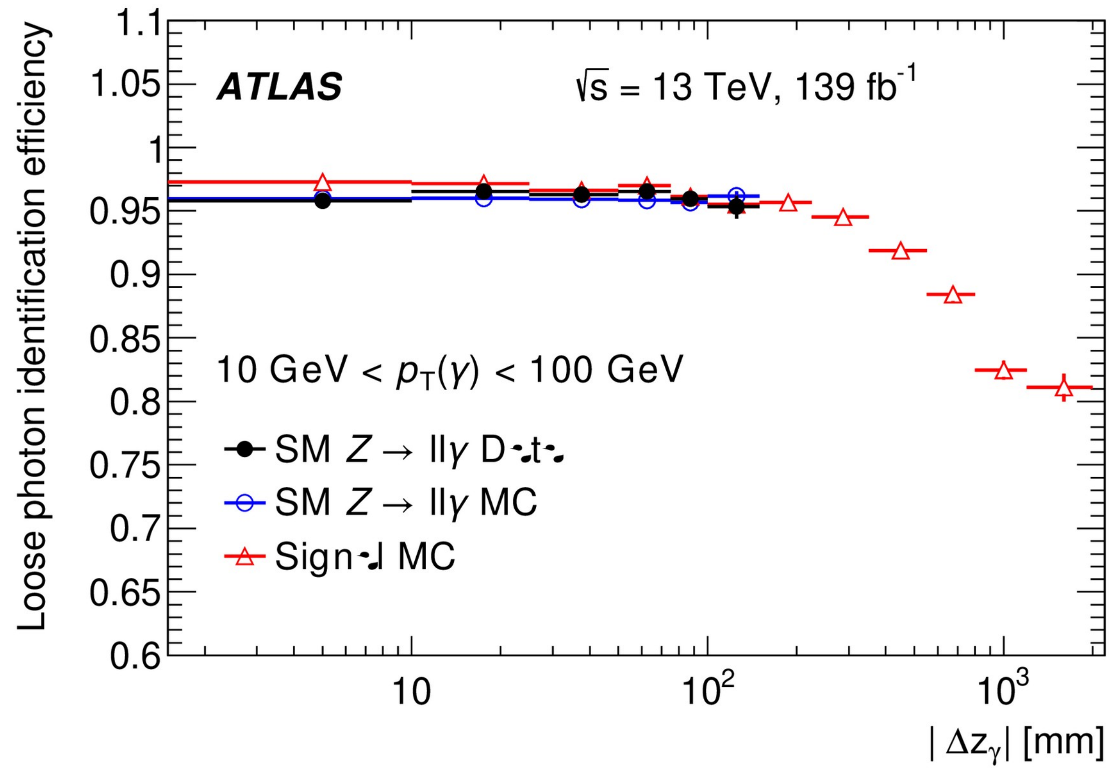
- Added new electron and photon isolation modules → isolation from other calorimeter deposits, as in search.

- Photon and electron efficiencies applied outside Delphes.
- Muon isolation applied outside Delphes (efficiency)
- Jets mostly untouched, with *R* parameter 0.4

Post-Delphes Cuts

- Applied gaussian smear on $|\Delta z_\gamma|$, use this for ID efficiency.





ATLAS (1409.5542 [hep-ex])
ATLAS (2209.01029 [hep-ex])

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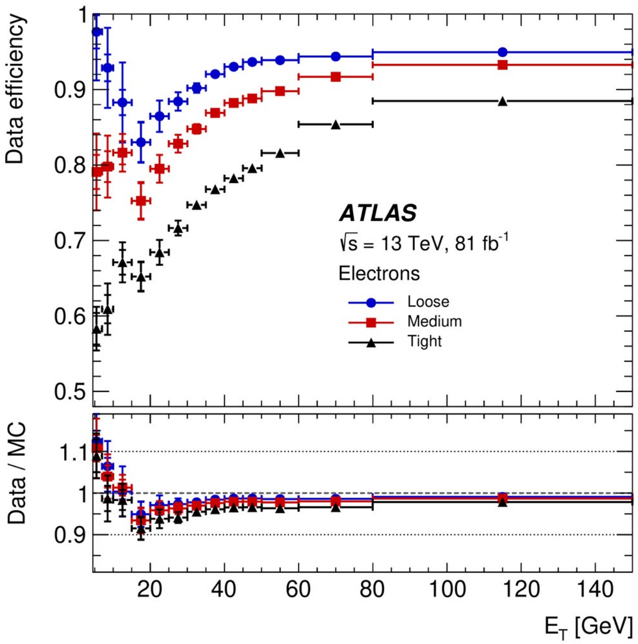

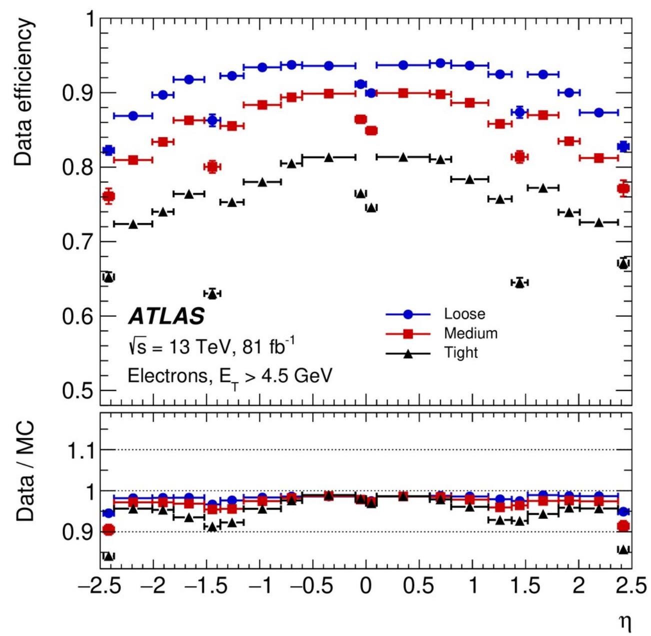

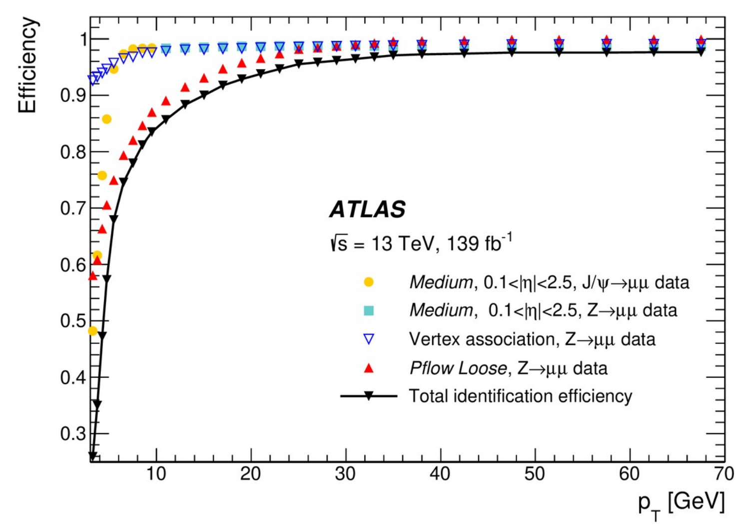

ATLAS (1908.00005 [hep-ex])
ATLAS (2012.00578 [hep-ex])

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- Evaluate if trigger is fired.
- Apply gaussian smear on t_γ.

$$\sigma_t(E_{\text{cell}}) = \frac{p_0}{E_{\text{cell}}} \oplus p_1$$

$$p_0 = 1962\,\text{ps}/\text{GeV}$$
$$p_0 = 262\,\text{ps}$$

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Post-Delphes Cuts

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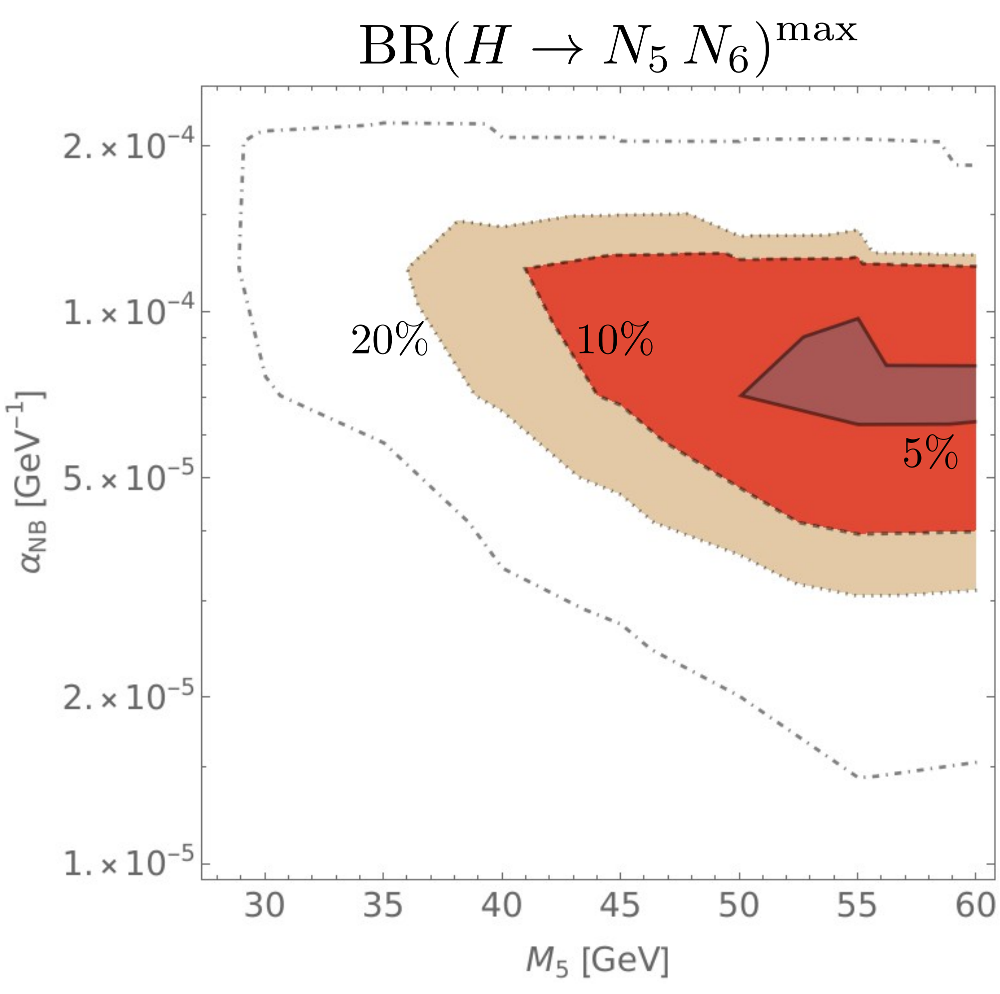
- Apply p_T and η cuts on electrons, muons, jets.
- Implement overlap removal: photons > electrons > jets > muons.
- Evaluate if trigger is fired.
- Apply gaussian smear on t_γ.
- Assign to signal region if MET > 50 GeV.

Bounds on $\alpha_{N\phi}$! (Preliminary)



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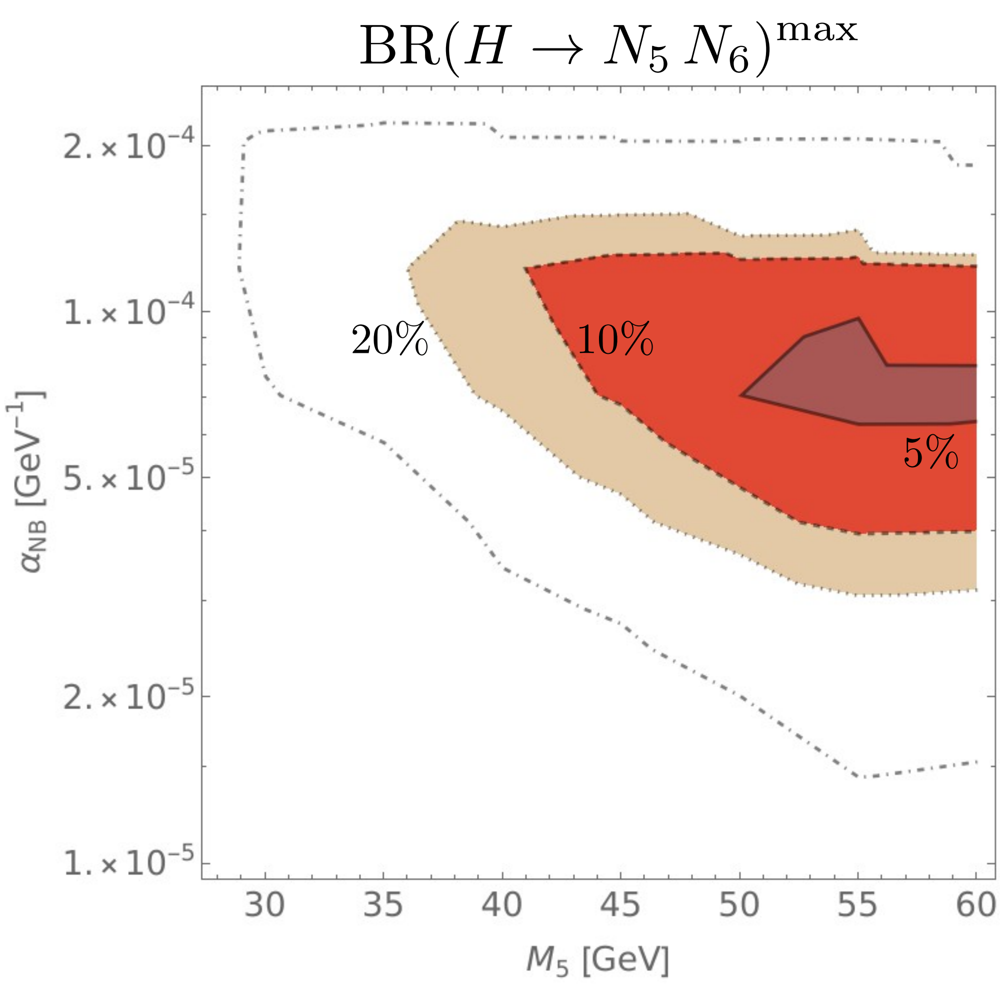
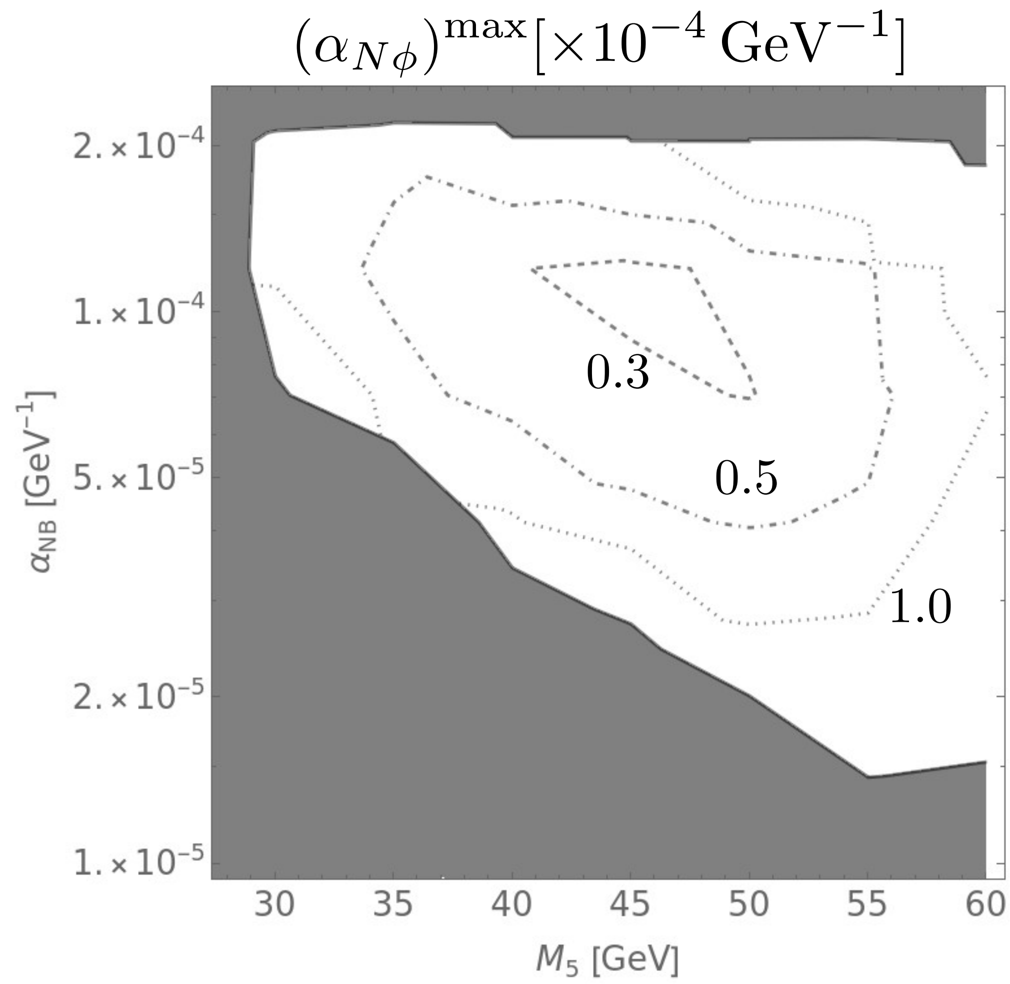




Conclusions

- The *d=5* Type-I Seesaw portal features new interactions featuring the sterile states. Light neutrinos access these interactions through mixing.

- LEP can place important bounds on the dipole operator, but only in the presence of enhanced mixing.

- New analyses tailored for softer non-pointing photons are promising, and bounds on $\alpha_{N\phi}$ will be placed.

- Stay tuned for upcoming paper!

Thanks!

Funded by:

Contrato 123-2020-FONDECYT

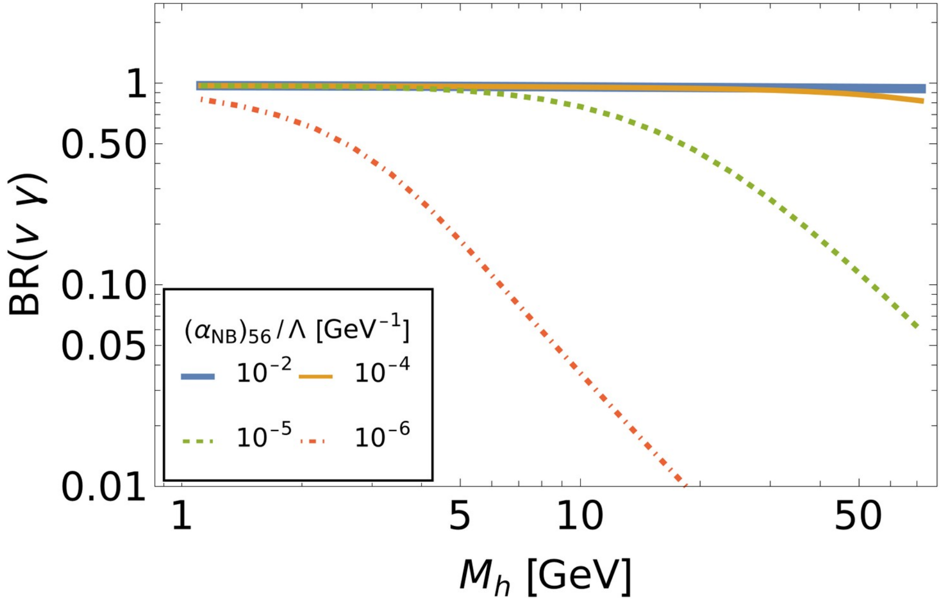
Backup

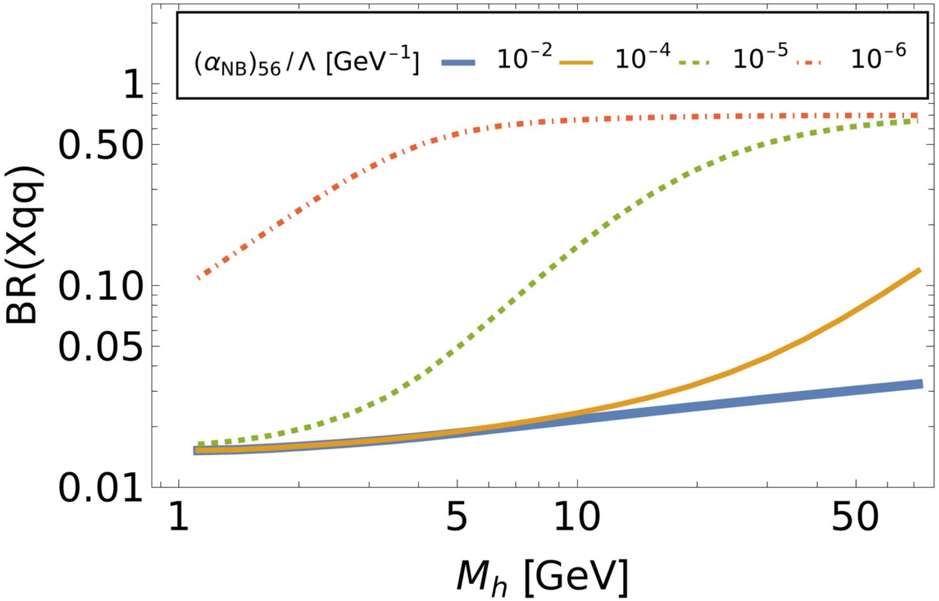
Couplings

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

Modifications to Heavy Neutrino Width

New branching ratios:

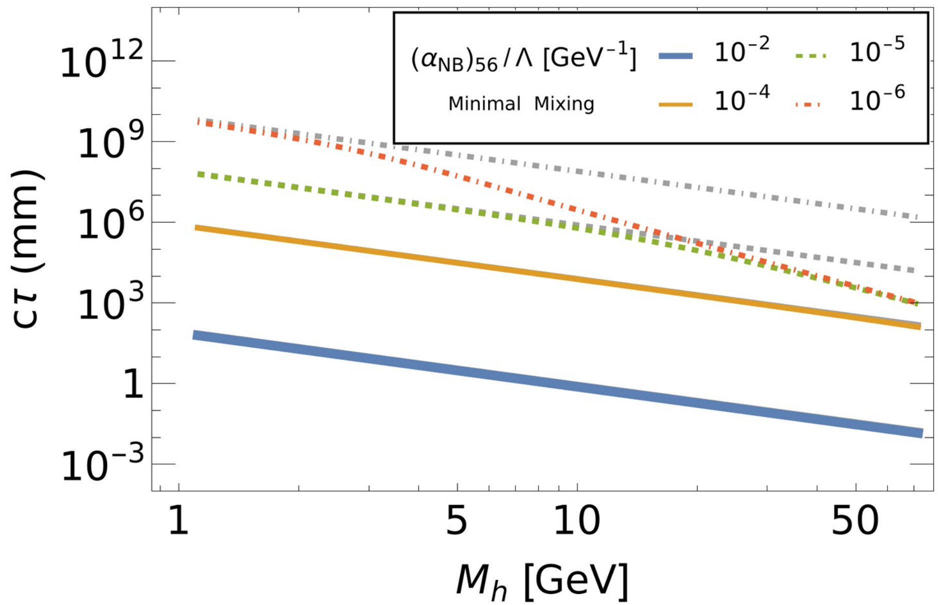


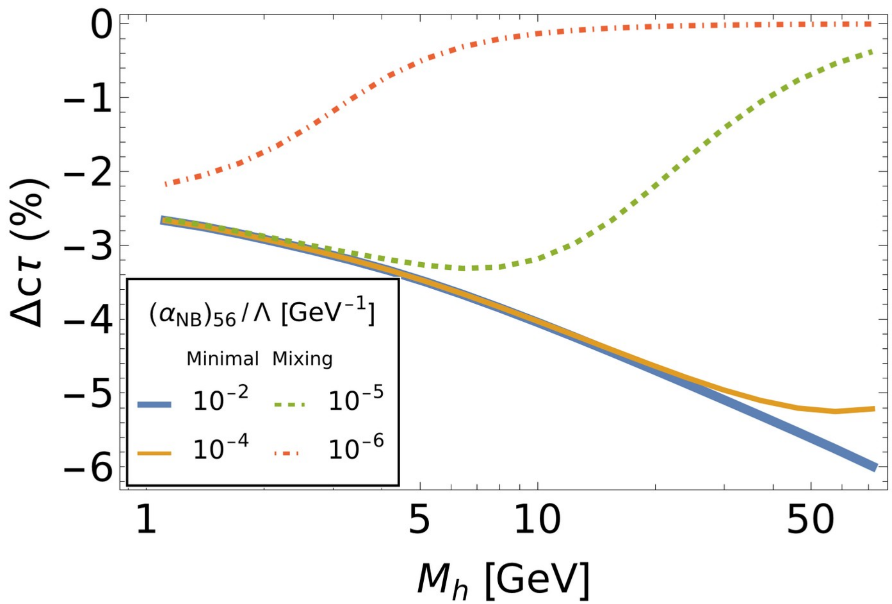


Photon + ν final state will usually dominate over small masses, but on the GeV regime the other decays are also relevant.

Modifications to Heavy Neutrino Width

New lifetimes:





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

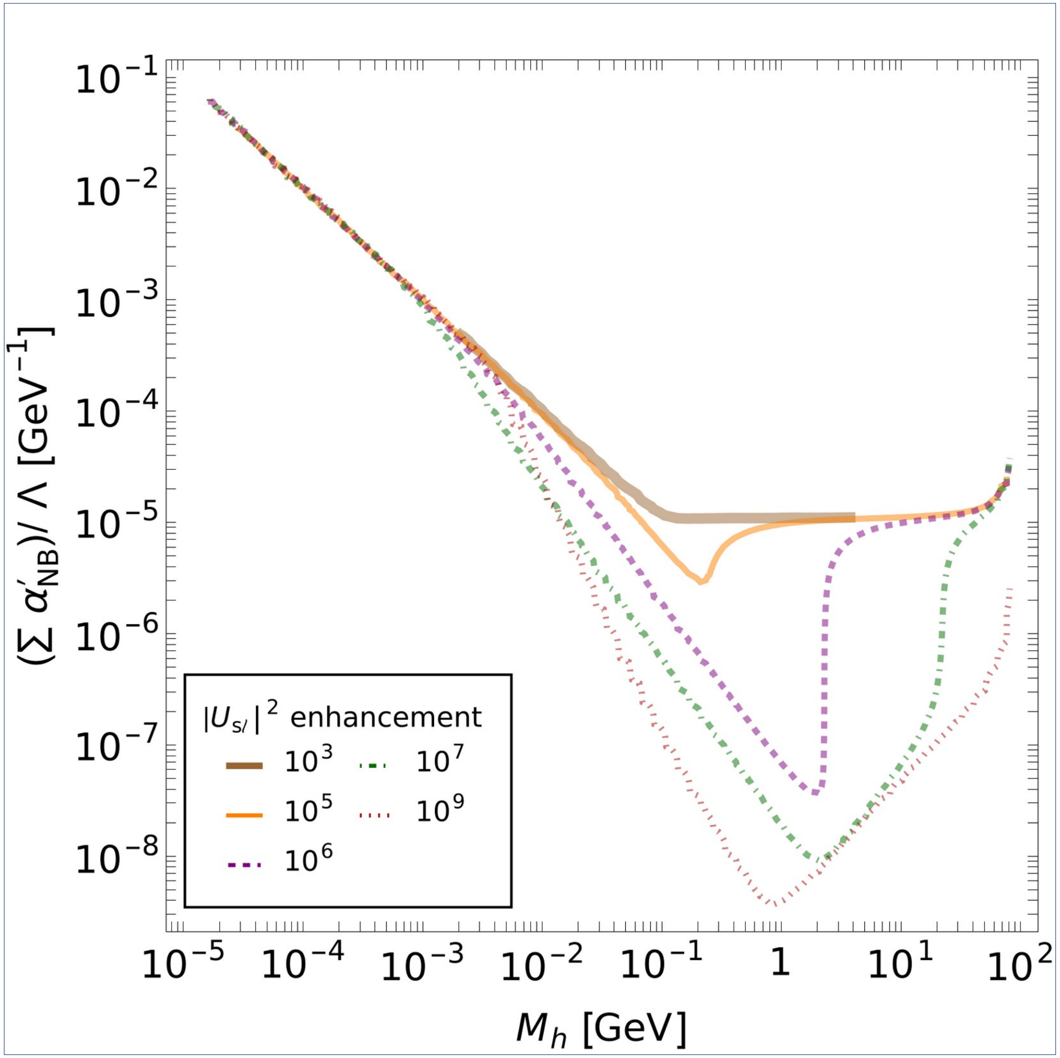
Modifications to three-body widths have small impact, might be relevant after a putative discovery.

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.



Constraints from LEP

- Energy cut:

$$E_\gamma^{\rm cut} = 0.7 \text{ GeV}$$

$$\Rightarrow \cos\theta_\gamma > \frac{1}{\beta_{\rm rel}}\left(\frac{2E_\gamma^{\rm cut}}{\gamma_{\rm rel} M_h} - 1\right)$$

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$$\Rightarrow \cos\theta_\gamma > \frac{1}{\beta_{\rm rel}}\left(\frac{2E_\gamma^{\rm cut}}{\gamma_{\rm rel} M_h} - 1\right)$$

- To be contained, there is a maximum time of flight:

$$t_N^{\rm max} = d_N^{\rm max} E_N / (|\vec{p}_N| c) \qquad d_N^{\rm max} = 2 \text{ m}$$

Constraints from LEP

- To pass through the ECal, photon angle with respect to beamline must satisfy:

$$\cos\theta_{\rm veto} > 0.7$$

- This implies constraints on (*x*, *y*) coordinates of photon by the time it reaches endcap:

$$\sqrt{x_\gamma^2 + y_\gamma^2} > z_{\rm det}\tan\theta_{\rm veto}$$

Effective Couplings for Non-Pointing Photon Searches

M_h [GeV]	10	30	50
$(\alpha_{N\phi})_{56}/\Lambda$ [GeV^{-1}]	3.0×10^{-5}	3.6×10^{-5}	6.4×10^{-5}
$(\alpha_{NB})_{56}/\Lambda$ [GeV^{-1}] (2014)	6.5×10^{-4}	1.4×10^{-4}	4.8×10^{-5}
$(\alpha_{NB})_{56}/\Lambda$ [GeV^{-1}] (2021)	7.9×10^{-4}	1.5×10^{-4}	6.3×10^{-5}

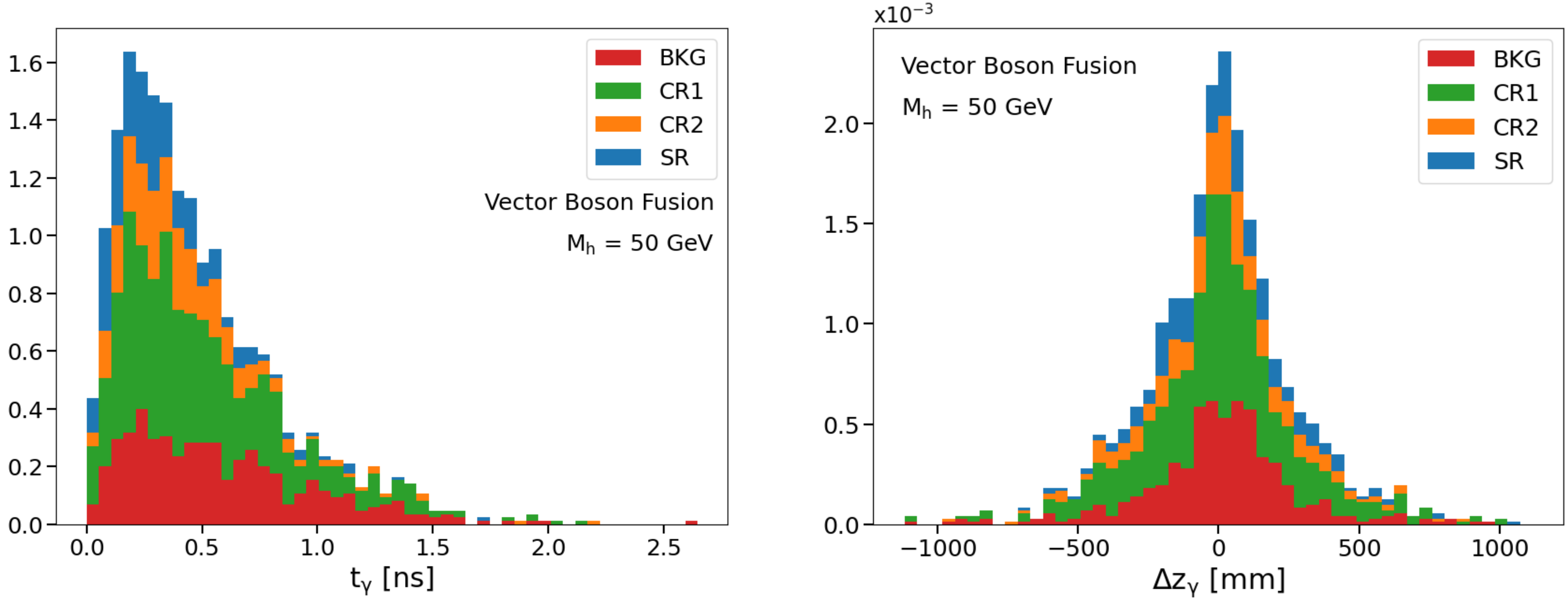
Table 1: Benchmarks used in our analysis. In the second row we show the effective heavy neutrino coupling to the Higgs $\alpha_{N\phi}/\Lambda$ giving a $H \to N_5 N_6$ branching ratio of 21%. The third and fourth rows give the value of the dipole couplings α_{NB}/Λ optimal for the searches.

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])

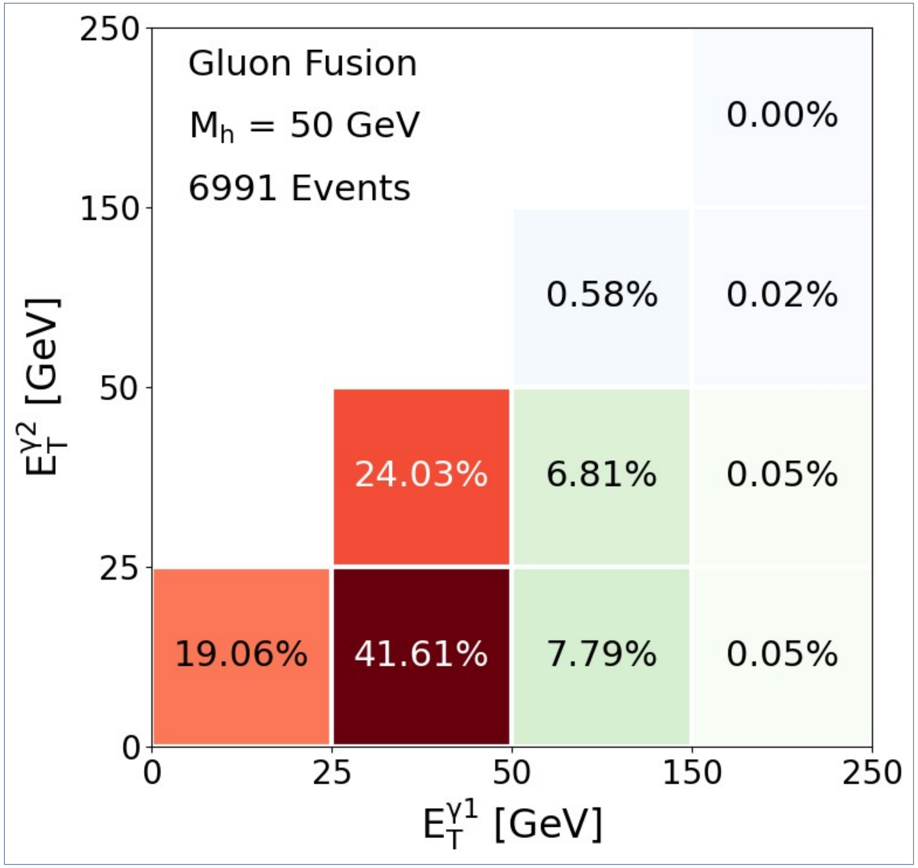
8 TeV Search, for 20.3 fb^{-1}



8 TeV Search

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

- Triggered using high pT photons.



ATLAS (1409.5542 [hep-ex])

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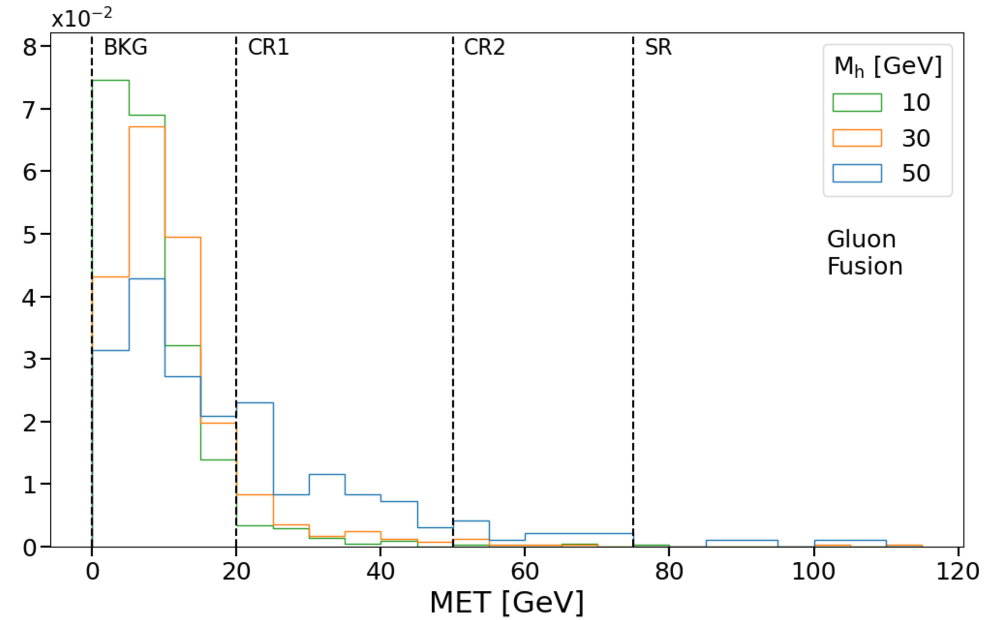


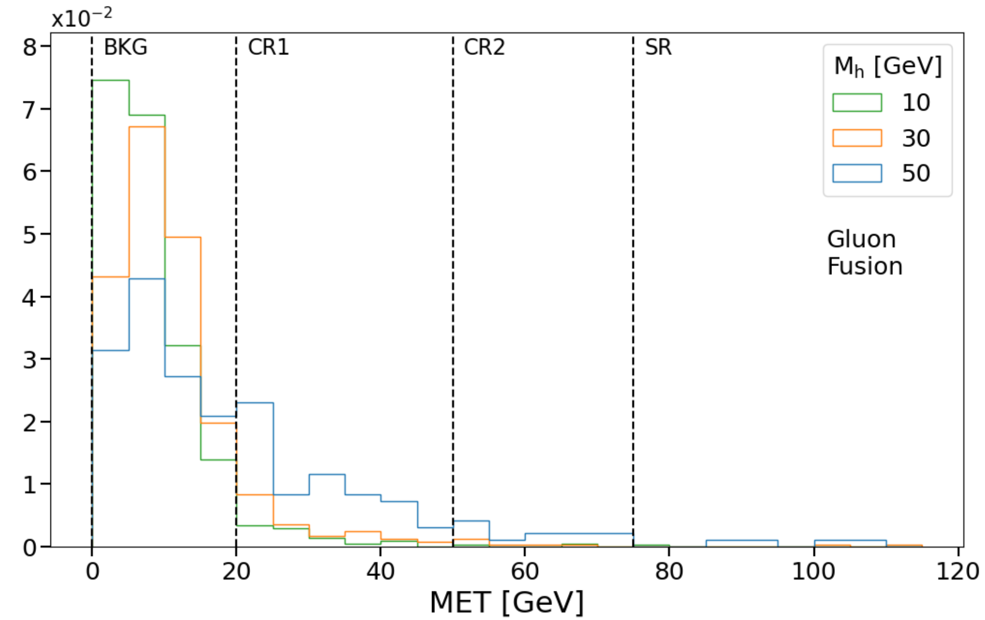
ATLAS (1409.5542 [hep-ex])

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])

Proposal of Non-Pointing Photon Search with VBF

Craiyon: “Higgs production via vector boson fusion”

Another possibility

One can try to trigger with VBF, as this is also independent of decay products.

$p_T(j_1)$	> 30 GeV	$\eta(j_1)\cdot\eta(j_2)$	< 0
$\lvert\,\eta(j_1)\,\rvert$	< 5.0	$\lvert\,\Delta\eta(j_1,j_2)\,\rvert$	> 4.2
$p_T(j_2)$	> 30 GeV	$m_{j_1 j_2}$	> 750 GeV
$\lvert\,\eta(j_2)\,\rvert$	< 5.0	$\sum_j p_T$	> 200 GeV

CMS (1506.01010 [hep-ph])
ATLAS (ATL-DAQ-PUB-2019-001 [hep-ph])

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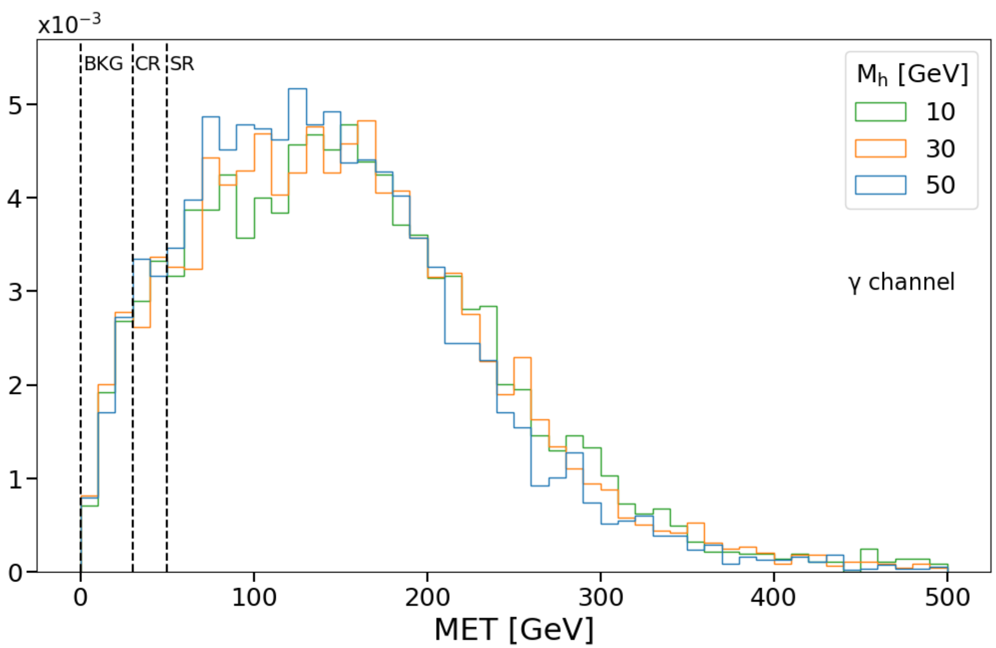
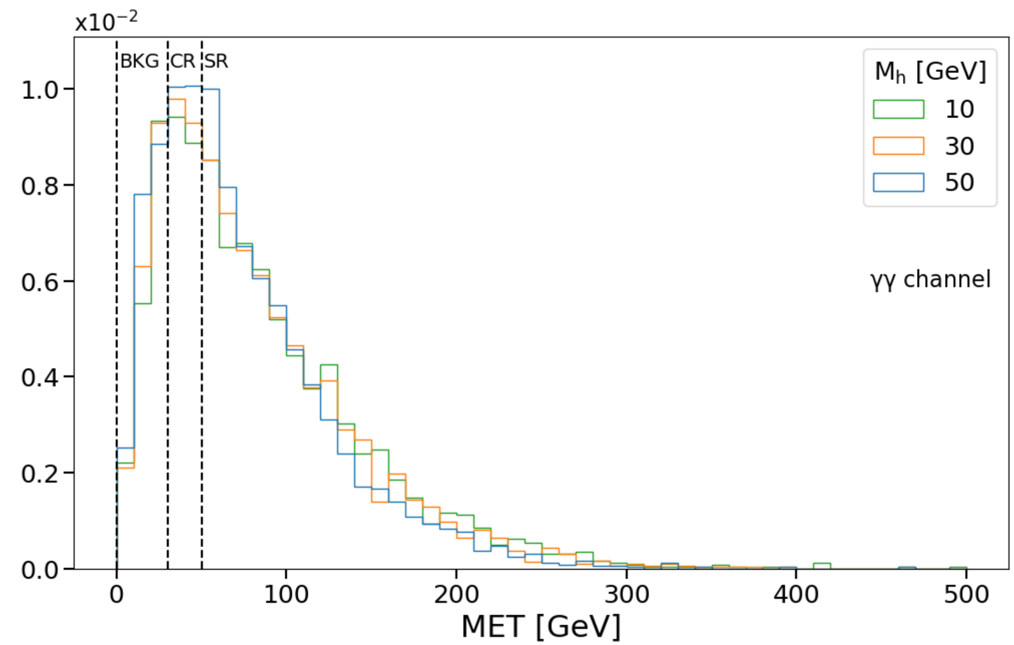
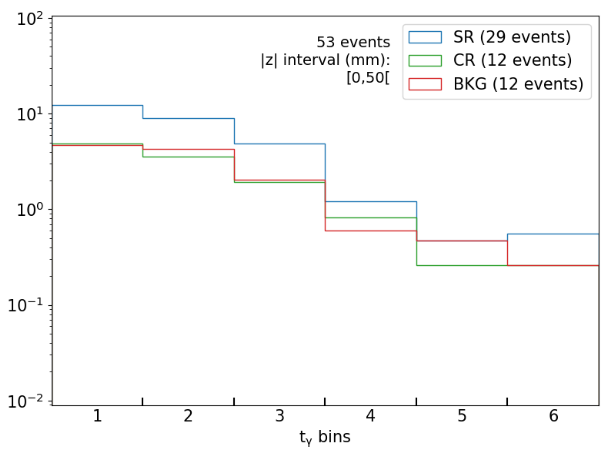


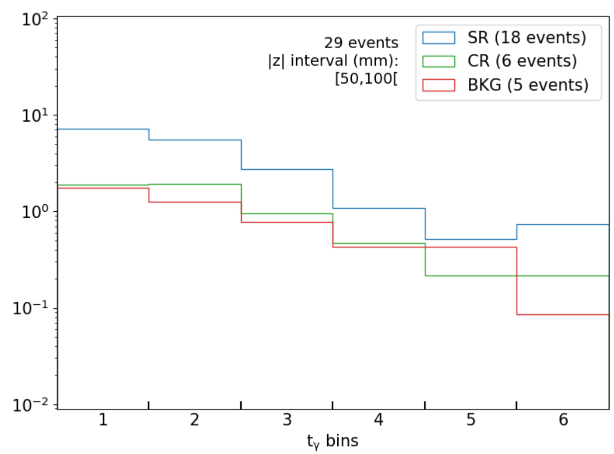


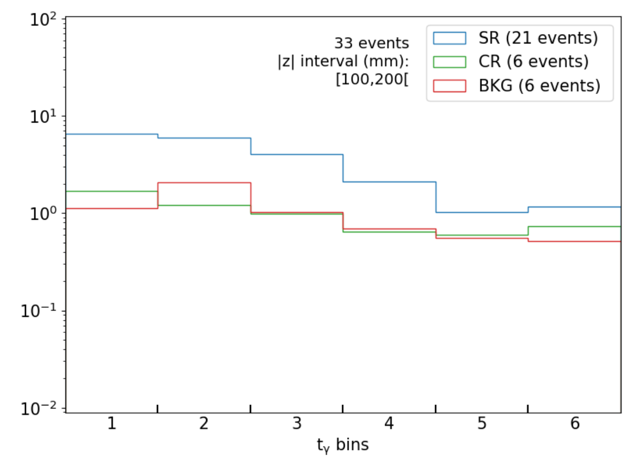
CMS (1506.01010 [hep-ph])
ATLAS (ATL-DAQ-PUB-2019-001 [hep-ph])

Events for VBF Production

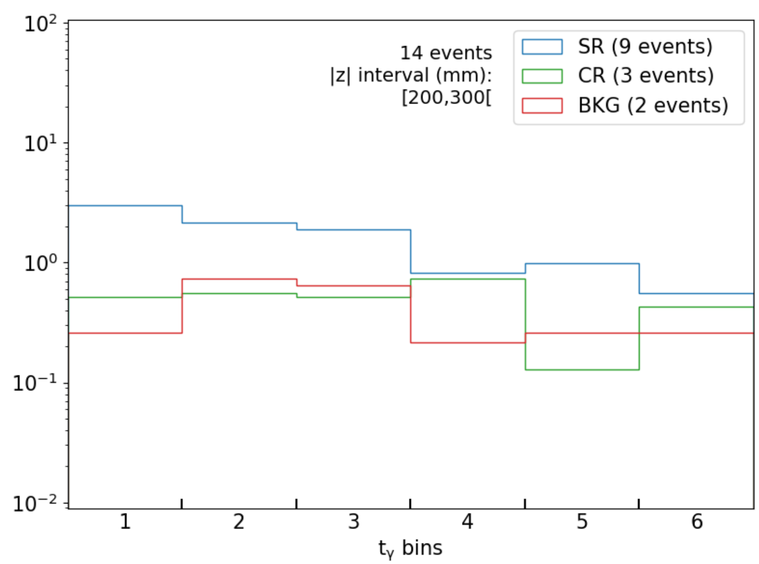
(We saturate ATLAS and CMS bounds on Higgs → undetected)

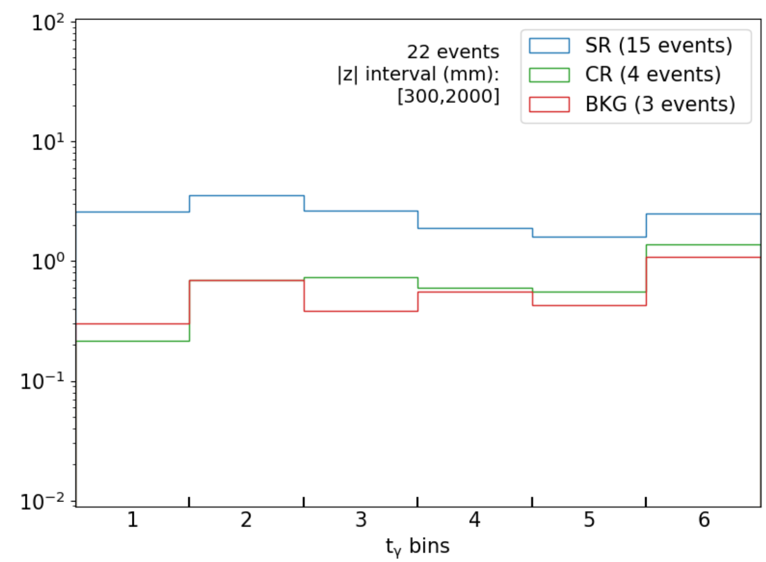






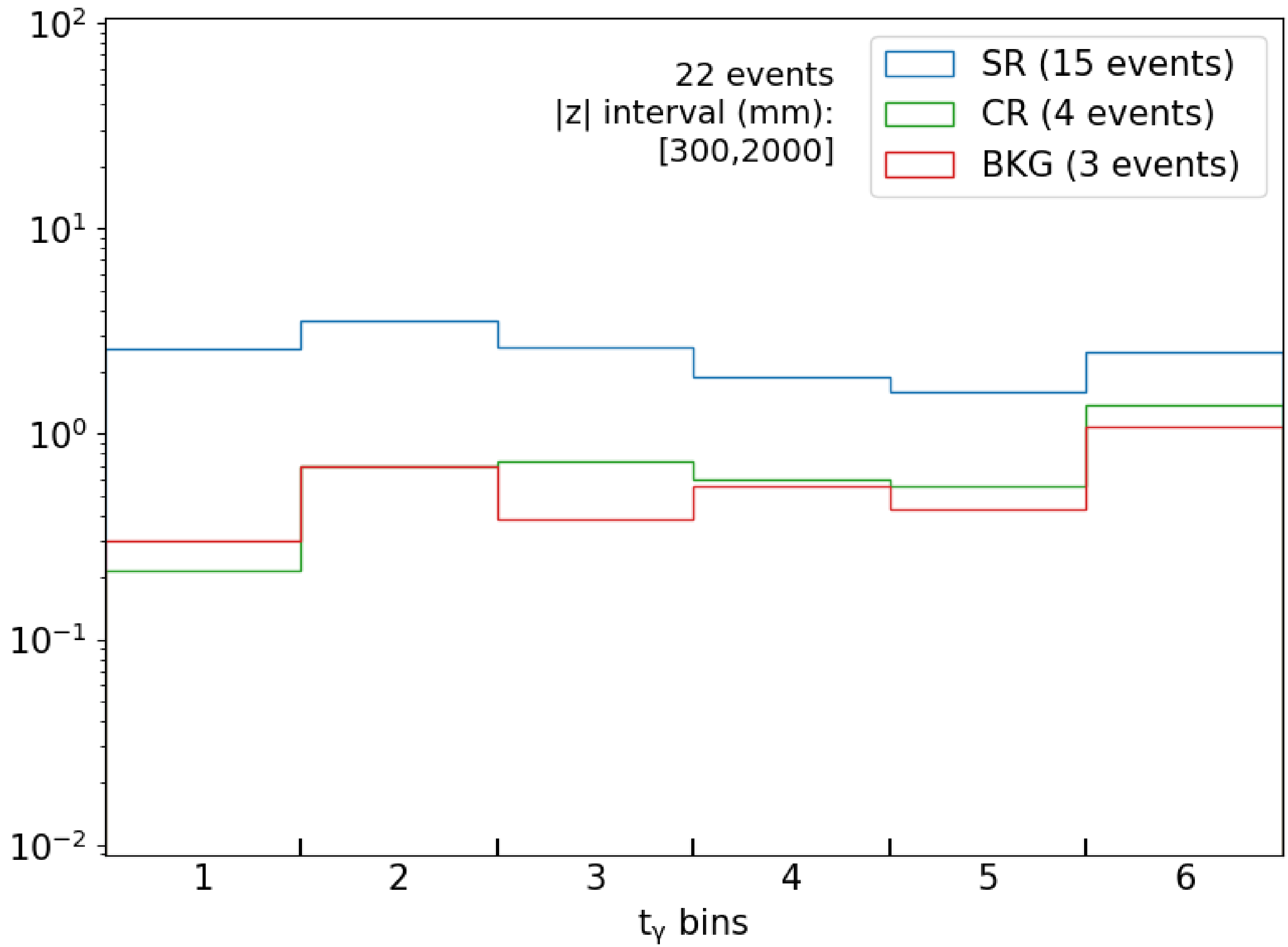
Numbers are comparable to those on thesis in high t_γ and $|\Delta z_\gamma|$ bins.





Constraints from VBF Production?

Largest $|\Delta z_\gamma|$ interval.



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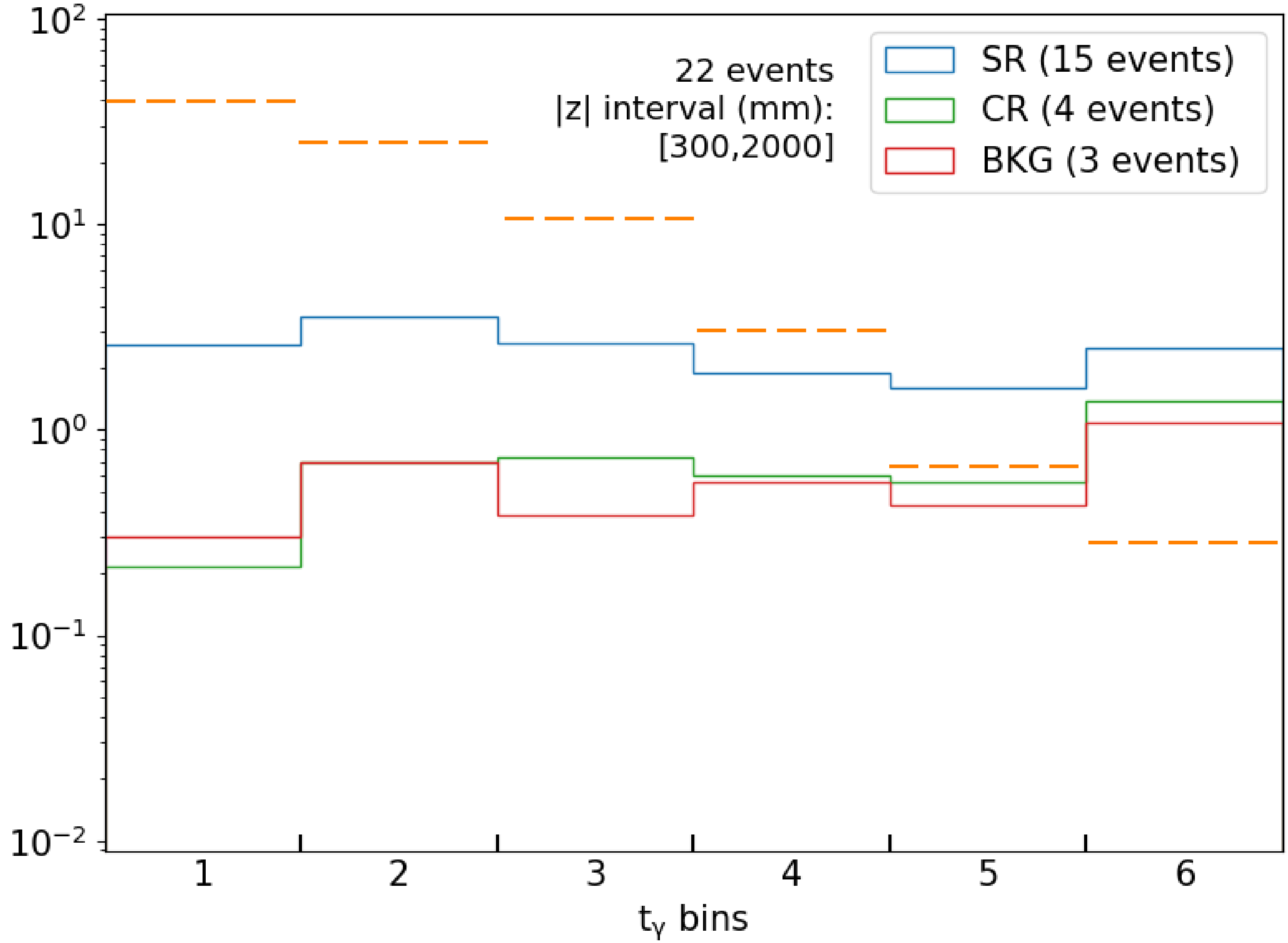
Background, from 2209.01029: – – – – –



Constraints from VBF Production?

Largest $|\Delta z_{\gamma}|$ interval.

Background, from 2209.01029: – – – – –

"Model independent" analysis from ATLAS-CONF-2022-017: Z = 2.8