Assessment of the Dimension-5 Seesaw Portal and Impact of Exotic Higgs Decays on Non-Pointing Photon Searches

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)

Type-I Seesaw

Type I Seesaw is probably most popular mechanism for neutrino masses

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

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.

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

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

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

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

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

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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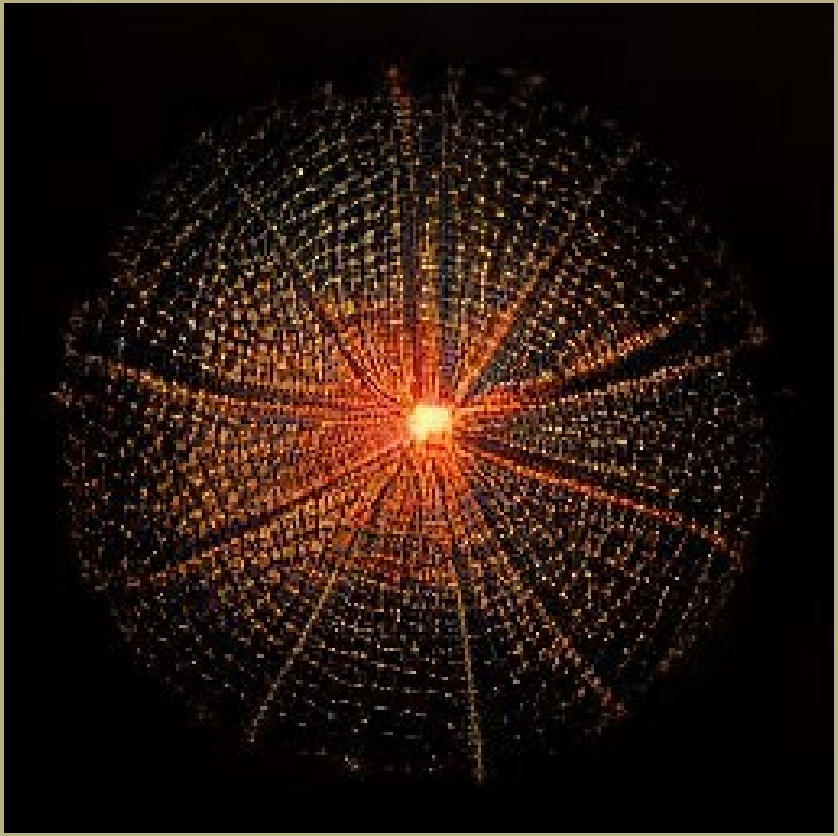
Outline

- Re-calculation of the Heavy Neutrino Width
- Re-evaluation of LEP constraints
- Recast of Non-Pointing Photon Search

Recalculating the Heavy Neutrino Width



Craiyon: “a heavy neutrino particle”

Modifications to Heavy Neutrino Width

The new dipole coupling adds a new decay channel:

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

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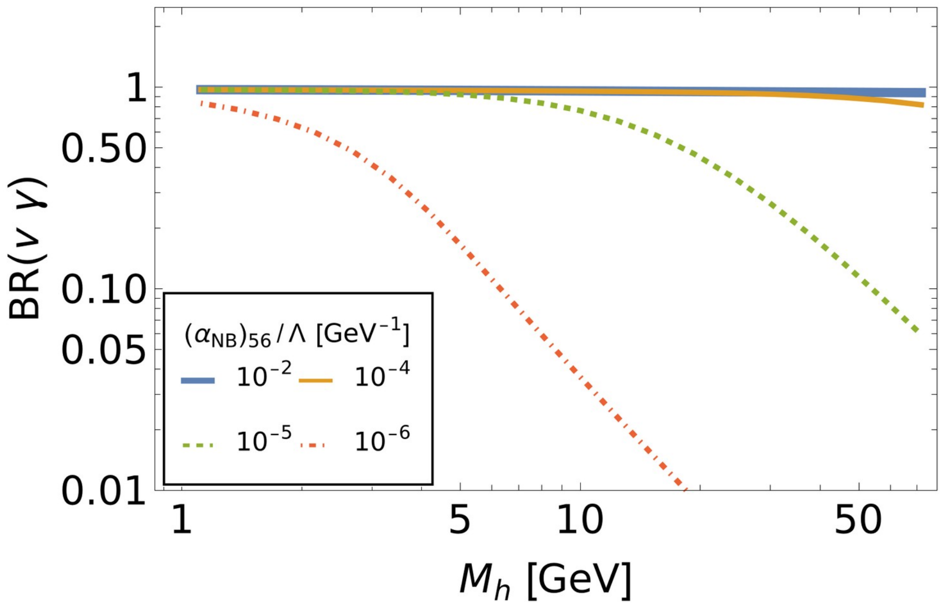
We also find modifications to three-body decays that used to involve the *Z* boson. They now also have a virtual photon:

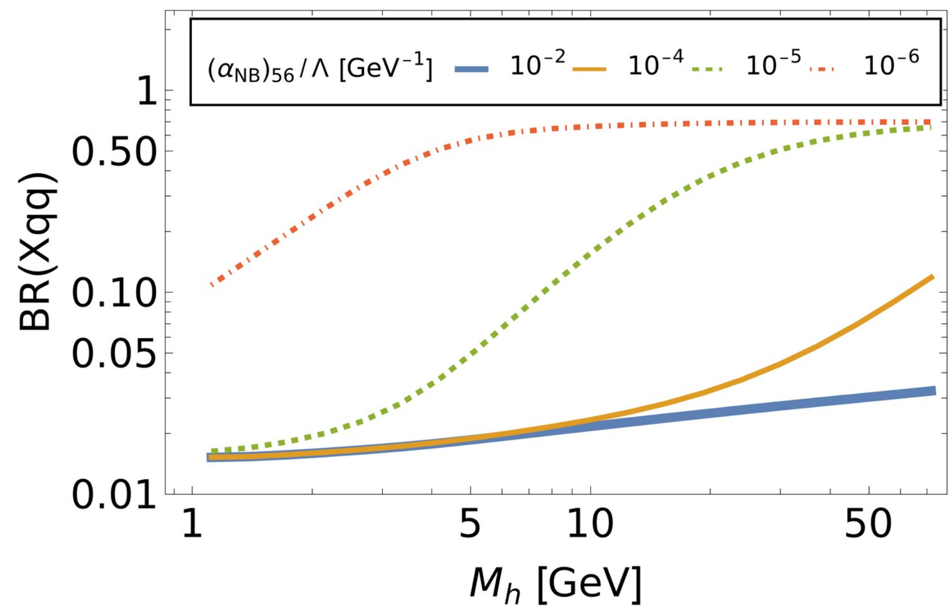
$$\Gamma(N_h \to \nu\,f\,\bar{f}) \approx N_c\,(1+\Delta_{\rm QCD})\,\frac{\alpha_{\rm em}\,Q_f^2}{24\pi^2}\,\Phi(x_f)\;c_W^2\,M_h^3 \sum_\ell \left| U_{s\ell}\,\frac{(\alpha_{NB})_{ss'}}{\Lambda}\,U_{s'h} \right|^2$$

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

Modifications to Heavy Neutrino Width

New branching ratios:

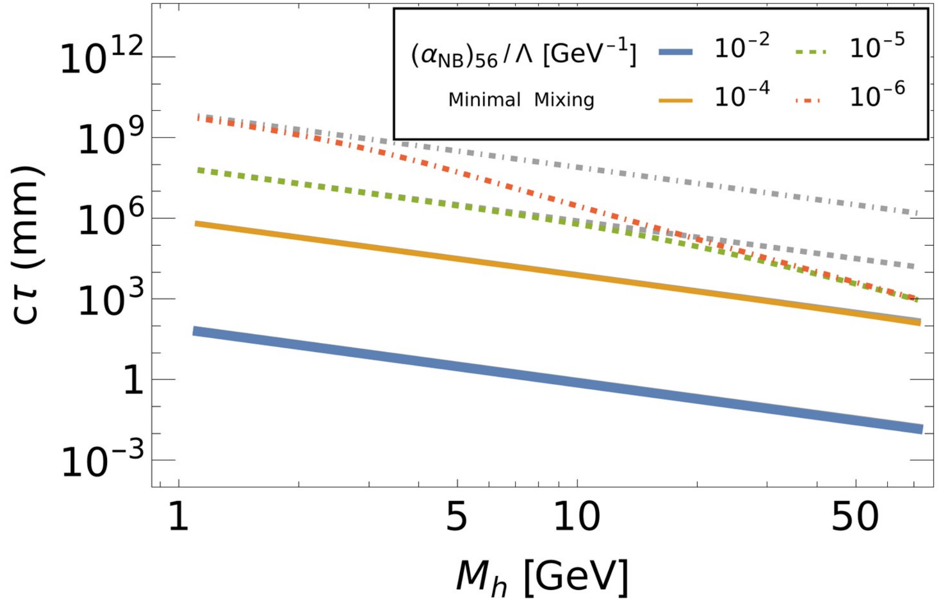


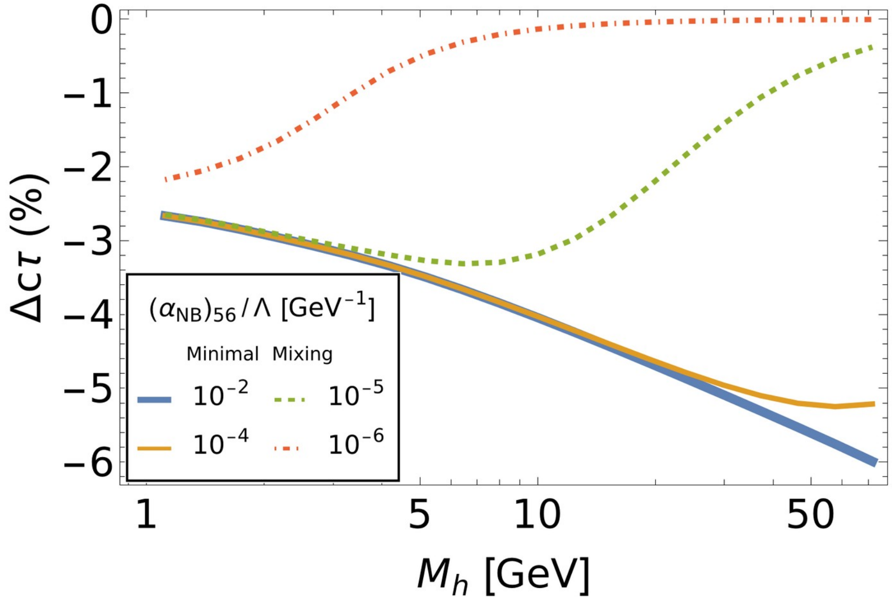


Photon + ν final state will usually dominate over small masses, but on the GeV regime the other decays are also relevant.

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.

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:

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

Magill, Plestid, Pospelov, Tsai (1803.03262 [hep-ph])

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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

$$C_{\ell h} = \sum_a U^*_{a\ell} U_{a h}$$

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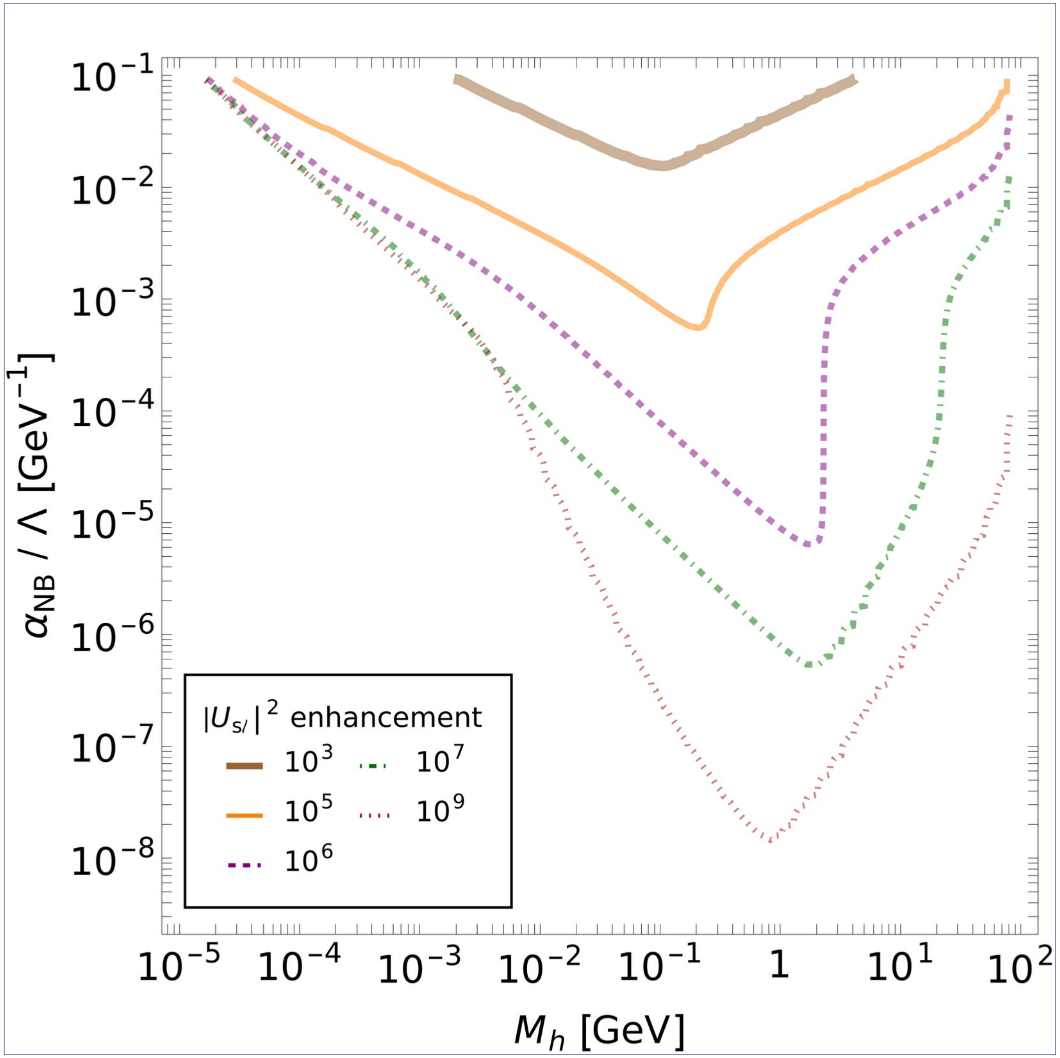
Constraints from LEP

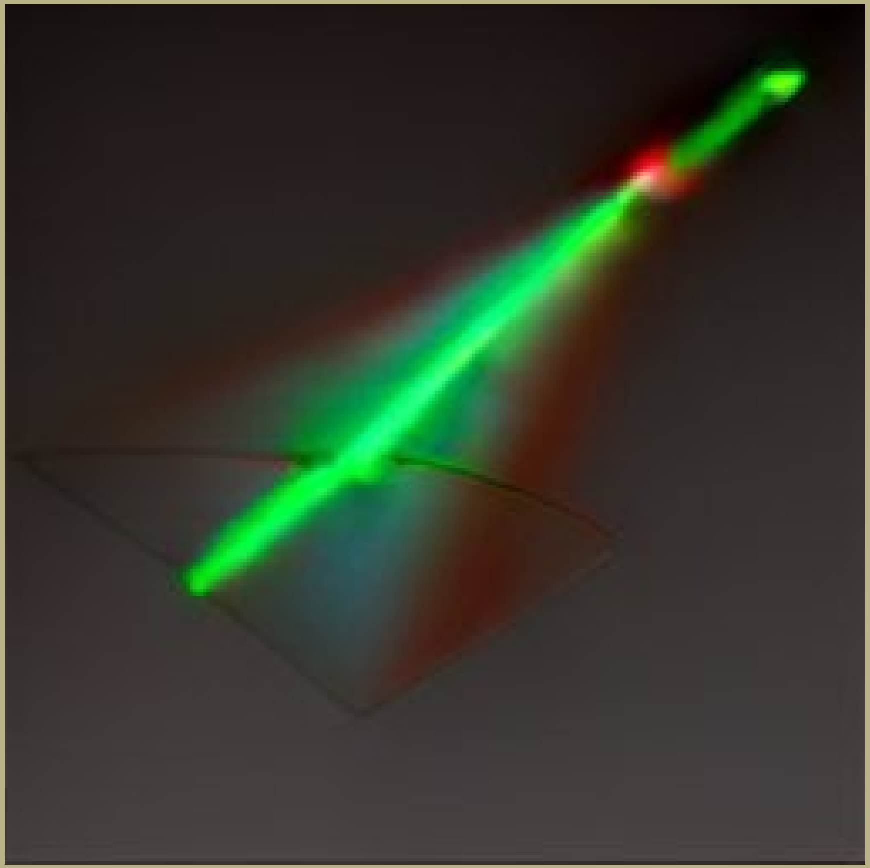
Bound depends on enhancement of light-sterile mixing.

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}.



Recast of Non-Pointing Photon Search (ATLAS)



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

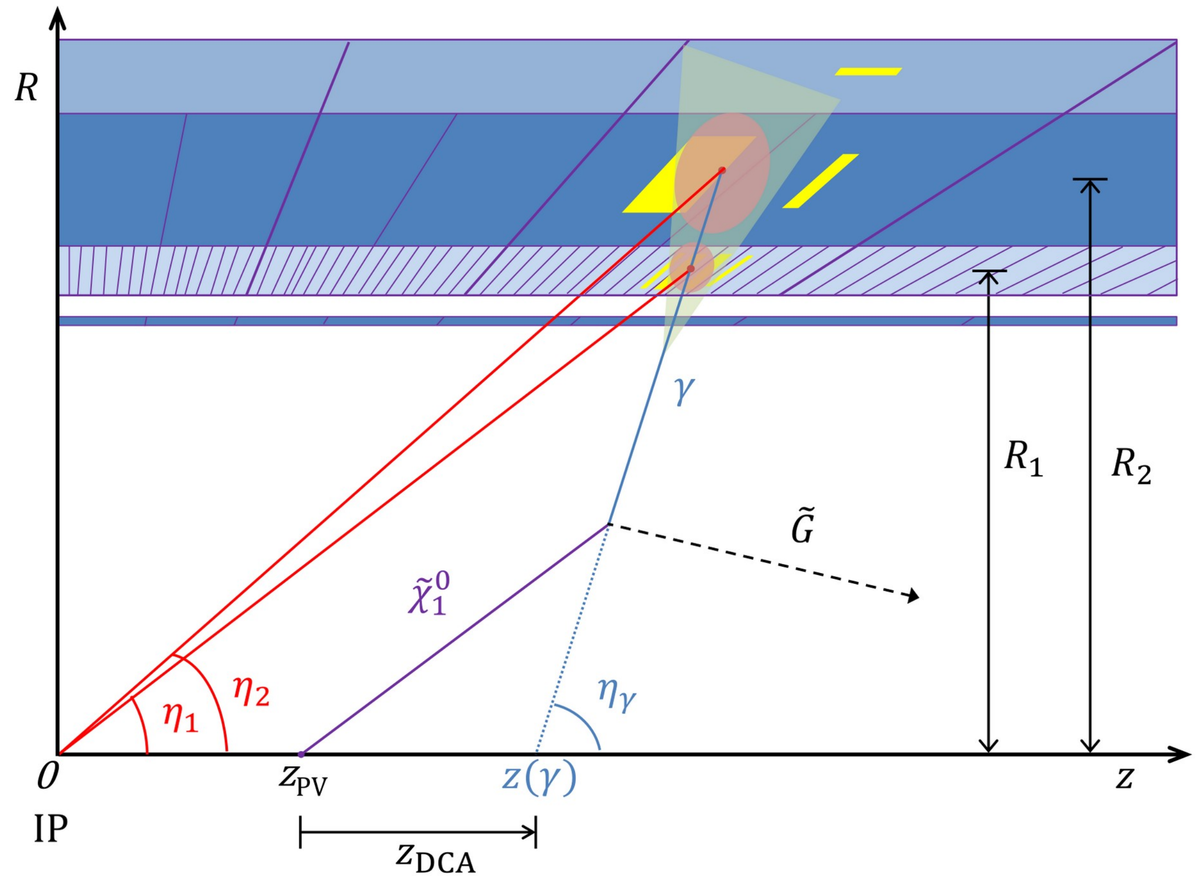
Joel Jones-Pérez

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 $|\Delta z_\gamma|$



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:

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

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

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

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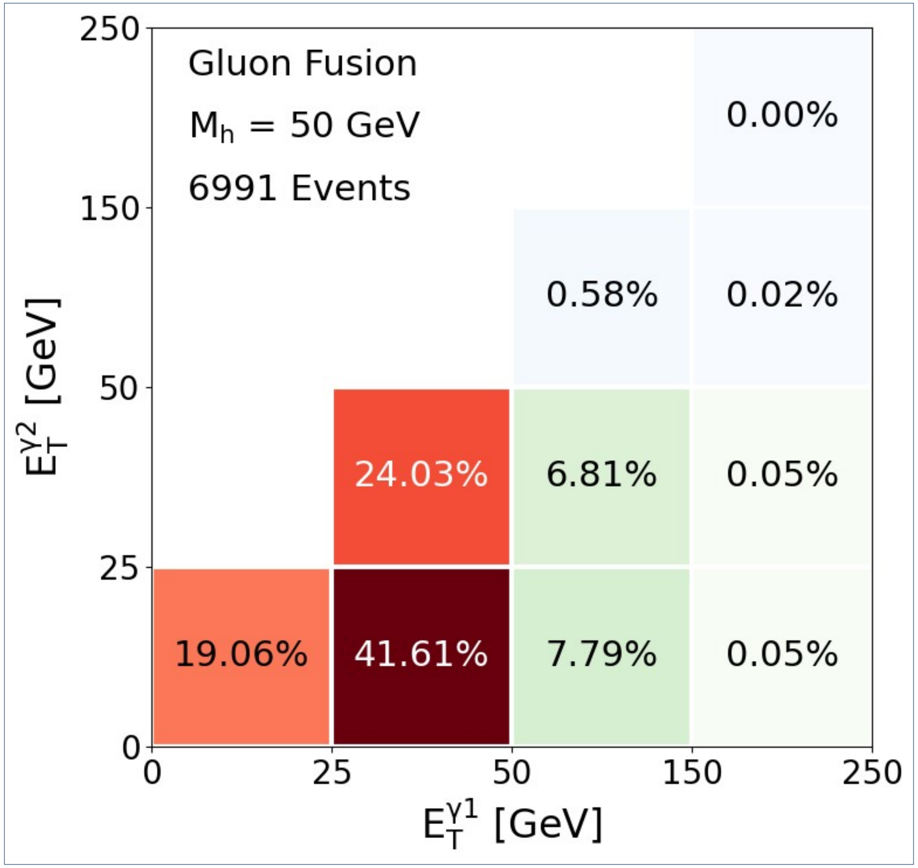
(Not dipole!)

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

8 TeV Search

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

- Triggered using high pT photons.

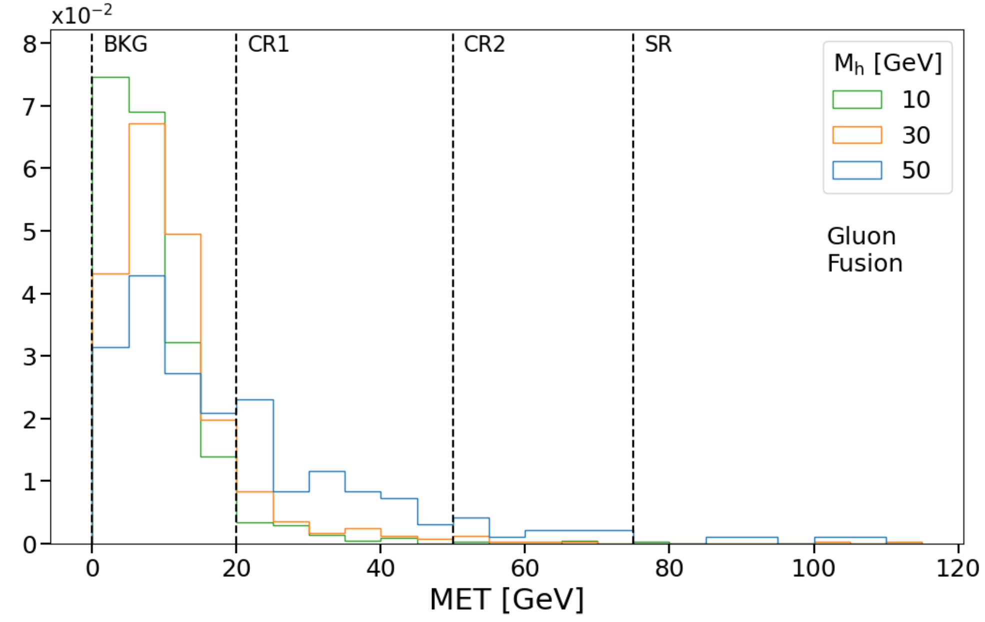


ATLAS (1409.5542 [hep-ex])

8 TeV Search

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

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



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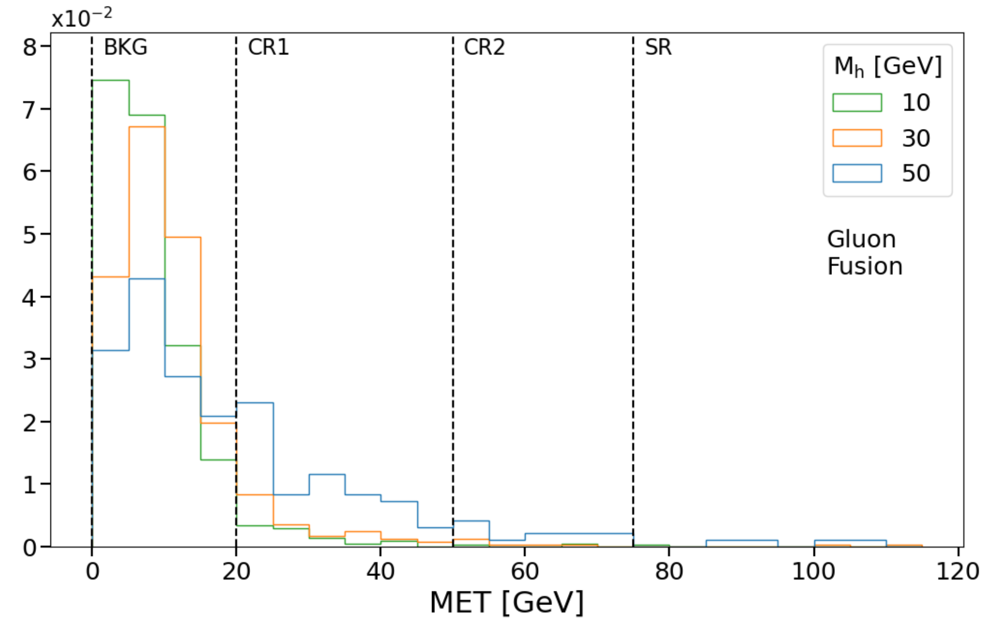
Even if a photon pair from long-lived N_h passed the energy cuts, and even if they also had large t_γ and $|\Delta z_\gamma|$, they are likely to be assigned to the background or control region. Thus, this strongly suggests the 8 TeV search is not optimal for studying our model.



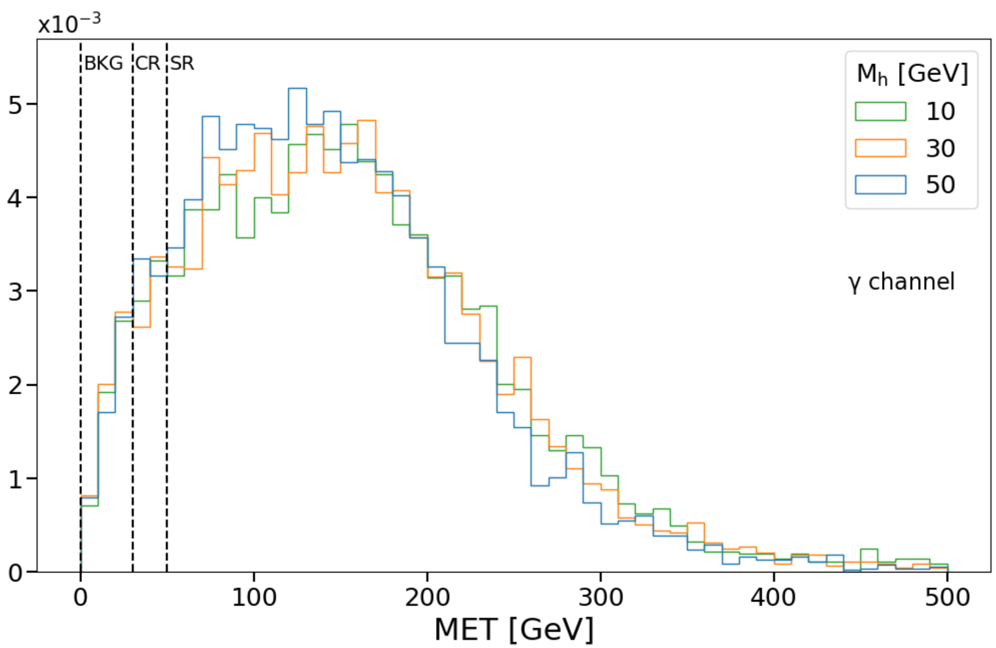
ATLAS (1409.5542 [hep-ex])

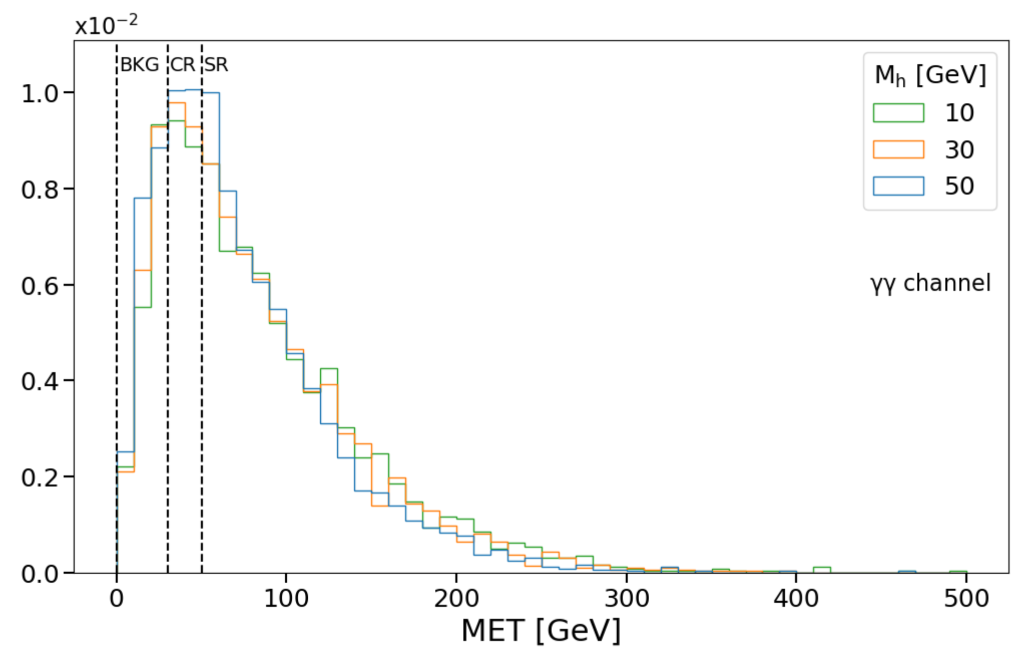
13 TeV Search!

Based on PhD thesis by D. Mahon (Recent conference notes and paper too)

Features analysis with soft photons, triggering Higgs production with an associated lepton.

We trigger with VBF. Currently implementing associated lepton.





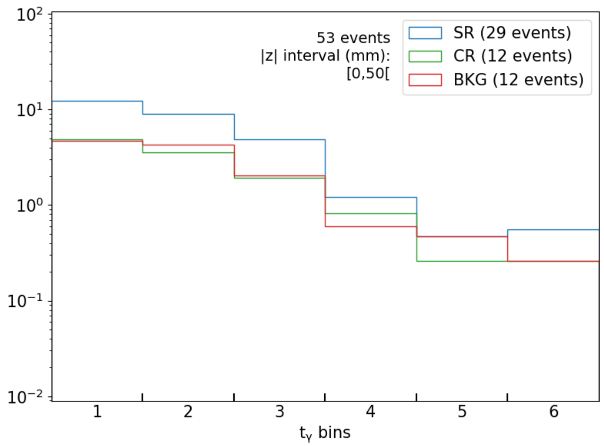
Mahon (PhD Thesis)
ATLAS (ATLAS-CONF-2022-017)
ATLAS (2209.01029 [hep-ex])

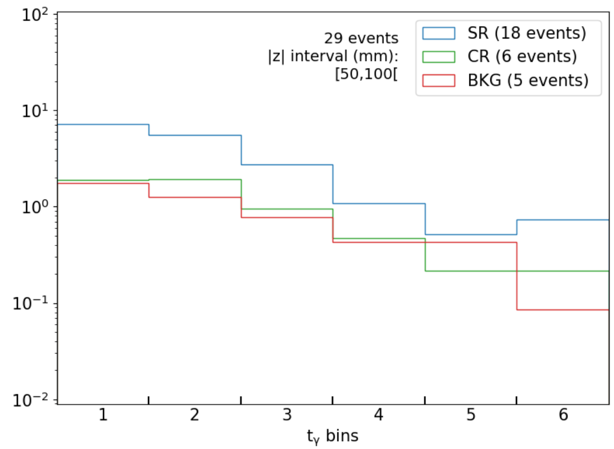
13 TeV Search!

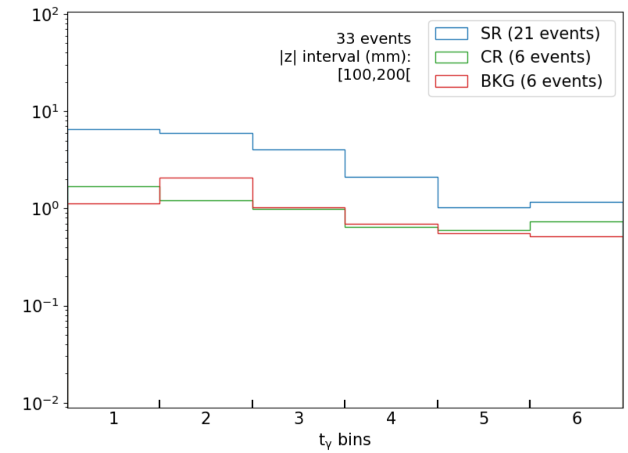
- Trigger: ~~isolated lepton with pT > 27 GeV~~. Vector boson fusion.
- At least one “loose” photon with energy larger than 10 GeV.
- Require E_{cell} larger than 10 GeV.
- One of the photons must be in barrel region.
- Isolation criteria: no deposits larger than 6.5% of energy within $\Delta R = 0.2$.
- 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.

Mahon (PhD Thesis)

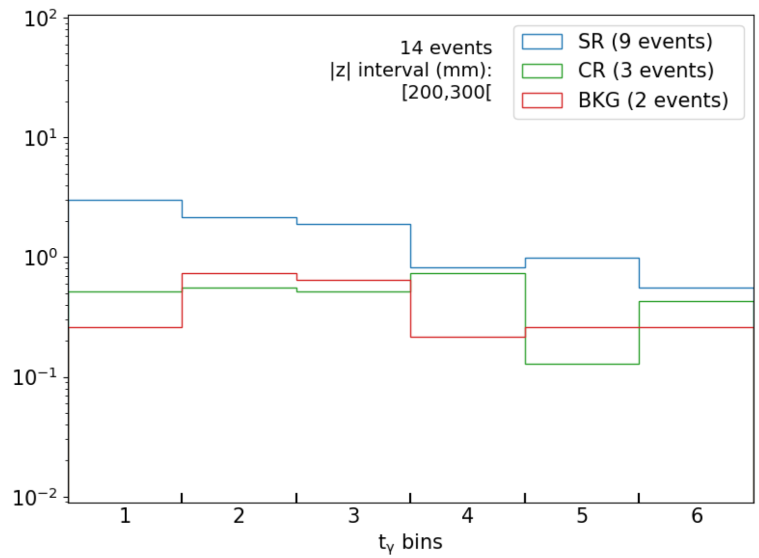
13 TeV Search!

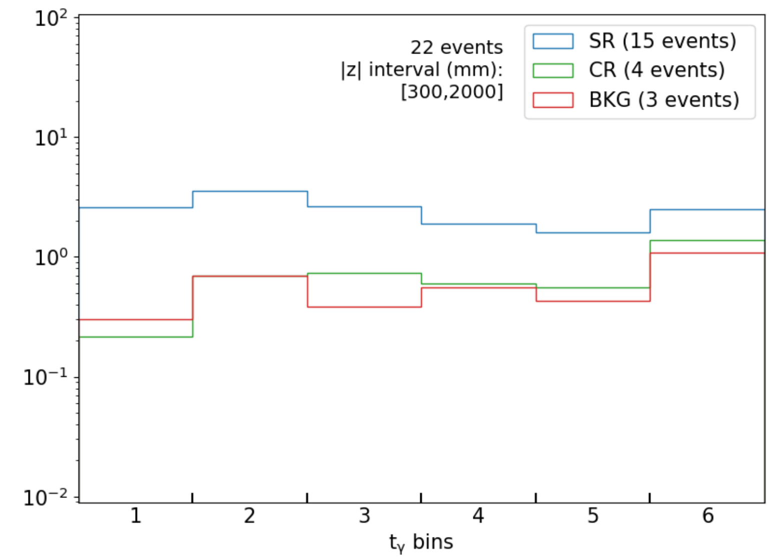






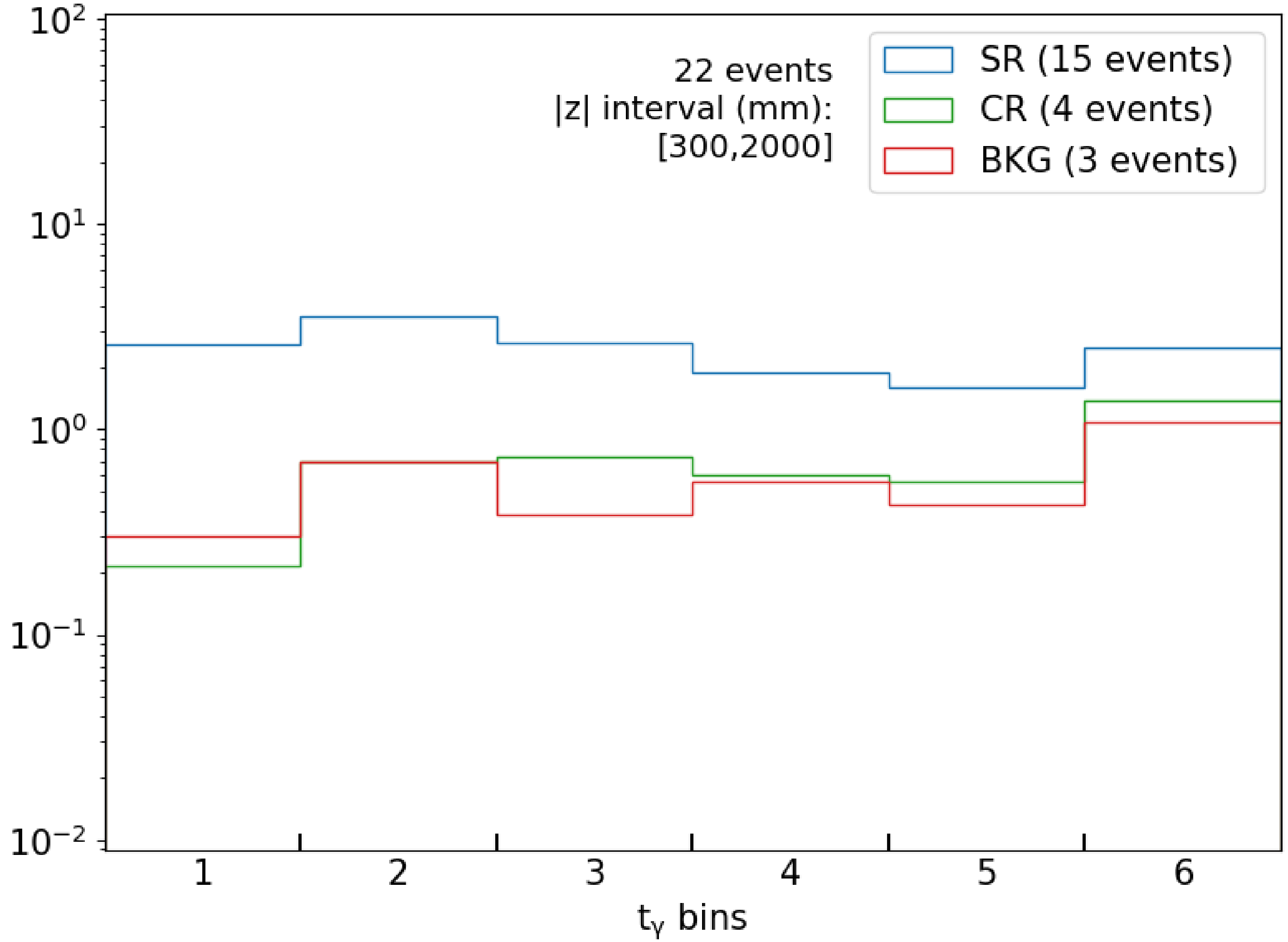
Numbers are comparable to those on thesis in high t_γ and $|\Delta z_\gamma|$ bins.





13 TeV Search!

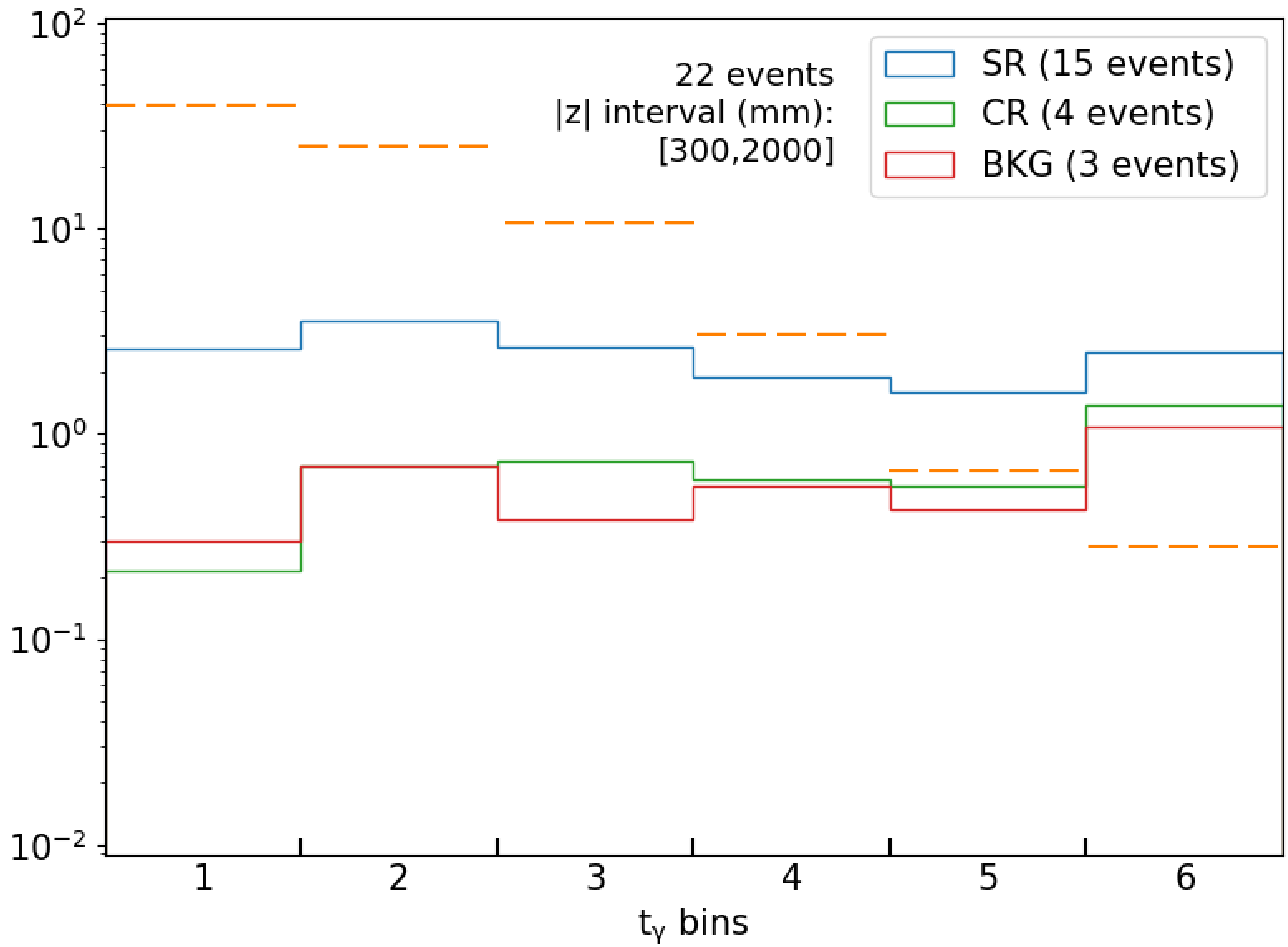
Largest $|\Delta z_\gamma|$ interval.



13 TeV Search!

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

Background, from 2209.01029: - - - - -

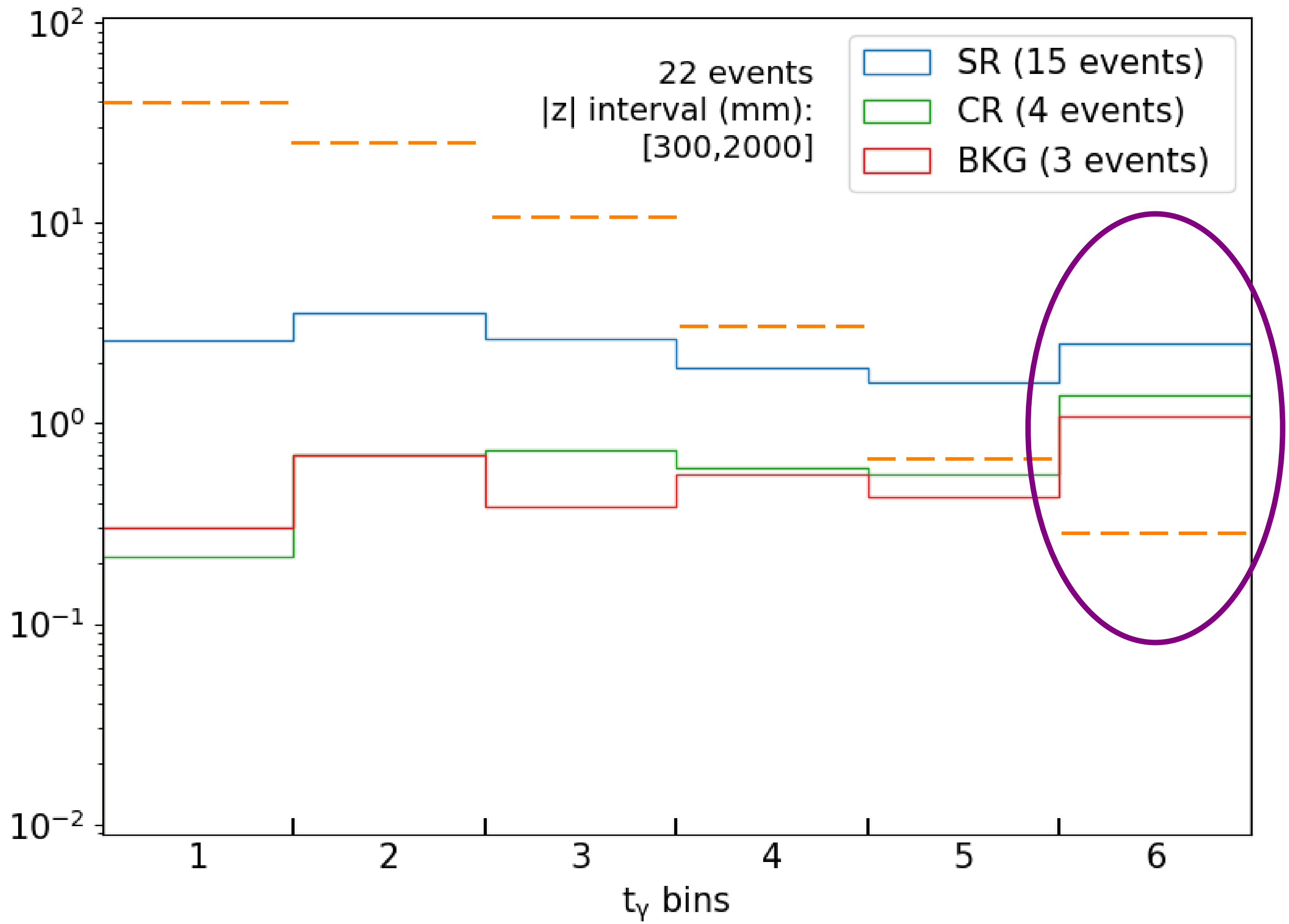


13 TeV Search!

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

Background, from 2209.01029: – – – – –

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



Conclusions

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

- New interactions modify heavy neutrino branching ratios and lifetimes. It is important not to neglect three-body decays!

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

Conclusions

- If the heavy neutrino is long-lived, old searches using non-pointing photons are not sensitive to our signal.

- New analyses tailored for softer photons are promising. We consider our findings to be very encouraging, and recommend the experimental community to take into account VBF triggers for these searches in the future.

- Stay tuned for our recast featuring the associated lepton trigger!

Thanks!

Funded by:

Backup

Couplings

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

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.

Long-lived parameters

- Photon non-pointing variable

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

- Arrival time:

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

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])

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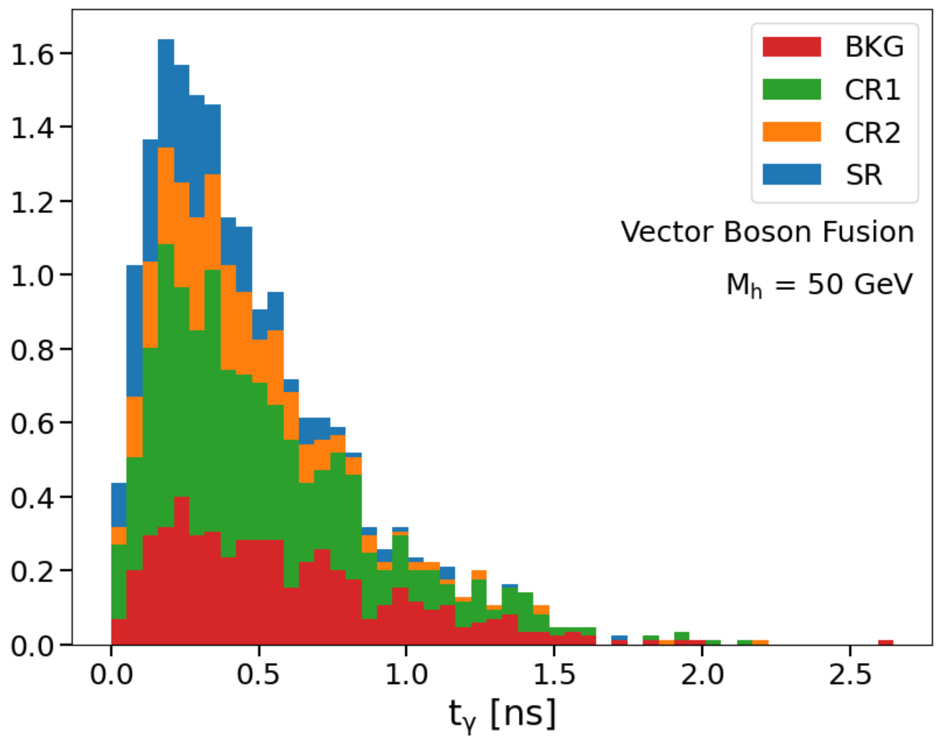

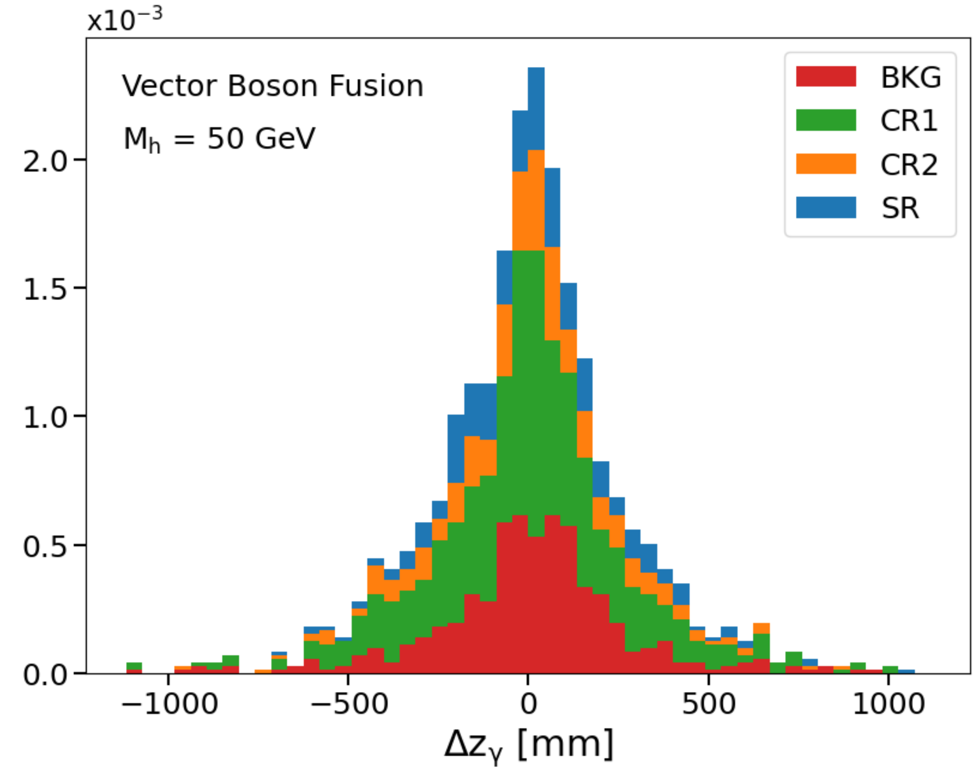

Vector Boson Fusion: Triggering independent of decay products

$p_T(j_1)$	> 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])

Placing bounds at LEP

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

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

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

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

Placing bounds at LEP

- Energy cut:

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

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

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

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

$$d_N^{\text{max}} = 2 \text{ m}$$

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.