LLP2024 Workshop
Tokyo, 1-5 July 2024

Probing sterile **neutrino magnetic moments** with **non-pointing photon searches** @ LHC

based on **arXiv:2405.08877** with P. Bolton, F. Deppisch, C. Hati, M. Hirsch

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Motivation

Neutrino mass models often predict the existence of RH or **sterile neutrinos**.

Seesaw Type-I: $m_N, V_{\ell N} = f(m_\nu, m_N)$

Minimal scenario. Sterile neutrinos interact only through neutrino mixing:

$$\mathcal{L}_{\text{SM}+N_R} \supset \mathcal{L}_{N_R}^{\text{mass}} - \frac{g}{\sqrt{2}} V_{\ell N} \left(\bar{\ell}\gamma^\mu N_R^c\right) W_\mu - \frac{g}{2\cos\theta_W} U_{\ell i} V_{\ell N}^* \left(\overline{N_R^c}\gamma^\mu \nu_{iL}\right) Z_\mu + \text{h.c.}$$

Independent parameters: $m_N, V_{\ell N}$

LLP searches @LHC have looked for sterile neutrinos in the minimal scenario.

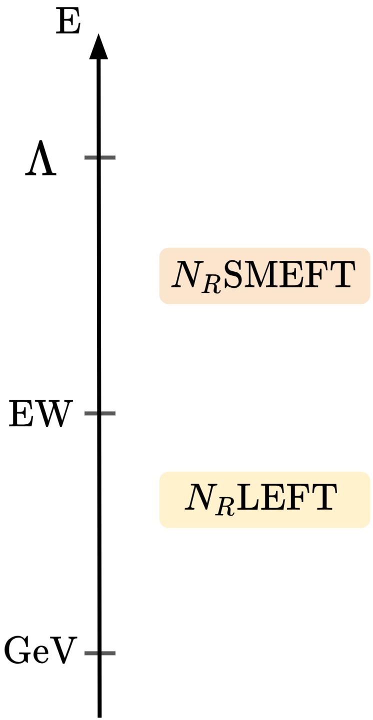
Beyond the minimal scenario

If sterile neutrinos couple to heavy new physics at $\boldsymbol{\Lambda}$

$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{SM}+N_R} + \sum_{d>4} C_i^{(d)} \mathcal{O}_i^{(d)} \qquad C_i^{(d)} \propto \Lambda^{4-d}$$

Much more phenomenology to explore if we consider **new interactions** beyond the minimal scenario.

↳ Neutrino magnetic moments



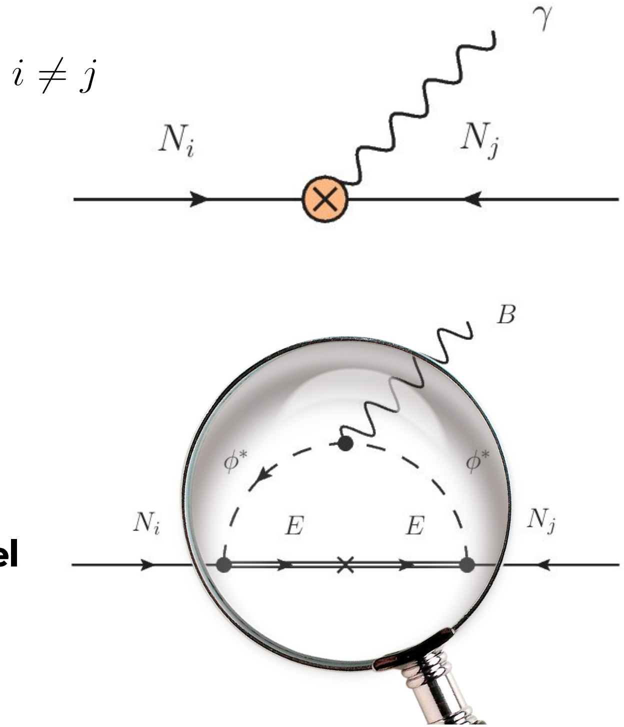
Sterile neutrino magnetic moments

Sterile neutrino magnetic moments

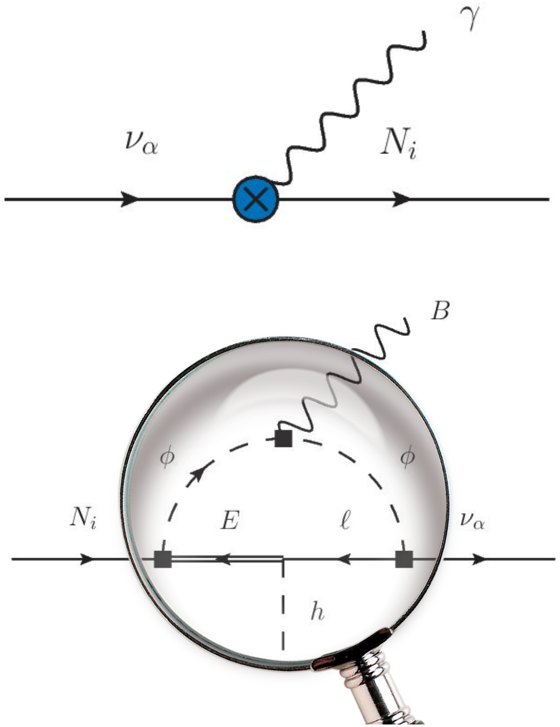
EFT description

Specific UV model

Sterile-to-sterile

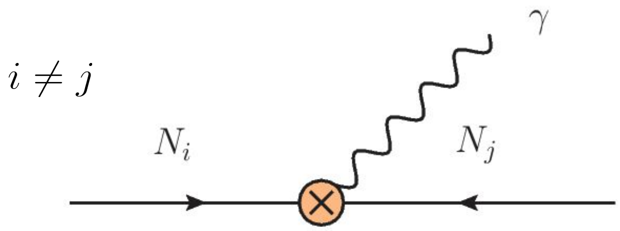


Active-to-sterile

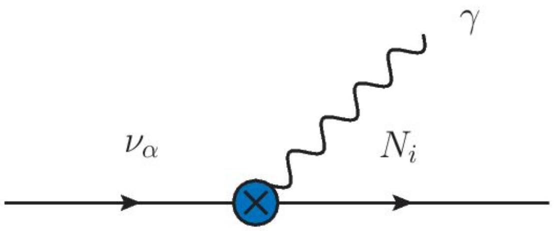


Effective description

Sterile-to-sterile

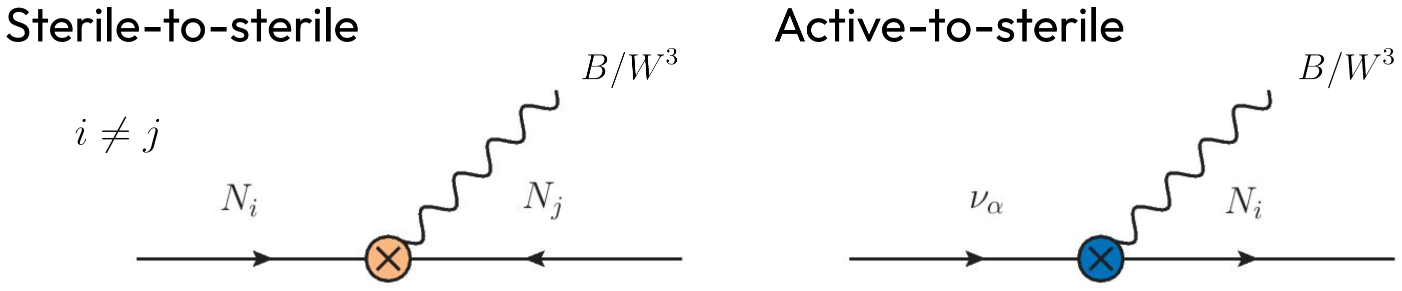


Active-to-sterile



$$\mathcal{L}_{\rm NLEFT} \supset d_{NN\gamma}^{ij} \left(\overline{N_{Ri}^c} \sigma^{\mu\nu} N_{Rj}\right) F_{\mu\nu} + d_{\nu N\gamma}^{\alpha i} \left(\overline{\nu_{L\alpha}} \sigma^{\mu\nu} N_{Ri}\right) F_{\mu\nu} + \text{h.c.}$$

Effective description



$$\mathcal{L}_{\text{NLEFT}} \supset d^{ij}_{NN\gamma} \left(\overline{N^c_{Ri}} \sigma^{\mu\nu} N_{Rj}\right) F_{\mu\nu} + d^{\alpha i}_{\nu N\gamma} \left(\overline{\nu_{L\alpha}} \sigma^{\mu\nu} N_{Ri}\right) F_{\mu\nu} + \text{h.c.}$$

Above EW scale ⇓

$$\mathcal{L}_{\text{NSMEFT}} \supset C^{(5)ij}_{NNB} \left(\overline{N^c_{Ri}} \sigma^{\mu\nu} N_{Rj}\right) B_{\mu\nu} + \text{h.c.}$$

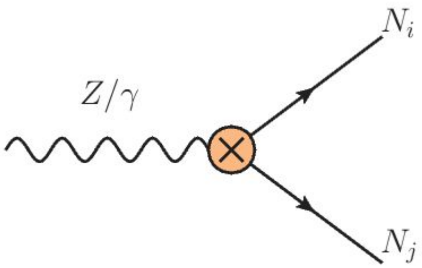
$$+ C^{(6)\alpha i}_{NB} \left(\overline{L_\alpha} \sigma^{\mu\nu} N_{Ri}\right) \tilde{H} B_{\mu\nu} + C^{(6)\alpha i}_{NW} \left(\overline{L_\alpha} \sigma^{\mu\nu} N_{Ri}\right) \tau^I \tilde{H} W^I_{\mu\nu} + \text{h.c.}$$

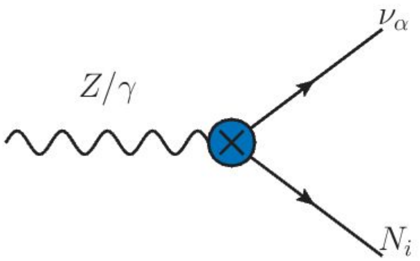
Electroweak dipole moments

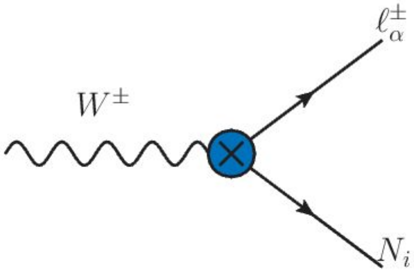
In *N*SMEFT, it is convenient to use rotated basis with electroweak gauge boson operators:

$$\mathcal{O}_{NN\gamma} = \left(\overline{N^c_R}\sigma_{\mu\nu}N_R\right) F^{\mu\nu} \qquad \mathcal{O}_{\nu N\gamma} = \left(\overline{\nu_L}\sigma_{\mu\nu}N_R\right) F^{\mu\nu}$$

$$\mathcal{O}_{NNZ} = \left(\overline{N^c_R}\sigma_{\mu\nu}N_R\right) Z^{\mu\nu} \qquad \mathcal{O}_{\nu NZ} = \left(\overline{\nu_L}\sigma_{\mu\nu}N_R\right) Z^{\mu\nu} \qquad \mathcal{O}_{\ell NW} = \left(\overline{\ell_L}\sigma_{\mu\nu}N_R\right) W^{\mu\nu}$$







$$C^{(5)}_{NNB} \Leftrightarrow d_{NN\gamma}, d_{NNZ}$$

$$C^{(6)}_{NB}, C^{(6)}_{NW} \Leftrightarrow d_{\nu N\gamma}, d_{\nu NZ}, d_{\ell NW}$$

Dictionary

$$C^{(5)}_{NNB} \Leftrightarrow d_{NN\gamma}, d_{NNZ}$$

$$C^{(6)}_{NB}, C^{(6)}_{NW} \Leftrightarrow d_{\nu N\gamma}, d_{\nu NZ}, d_{\ell NW}$$

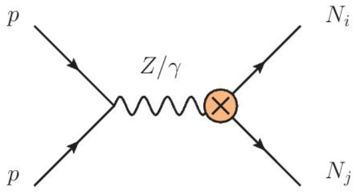
$$d^{ij}_{NN\gamma} = c_w C^{(5)ij}_{NNB}, \qquad d^{ij}_{NNZ} = -s_w C^{(5)ij}_{NNB},$$

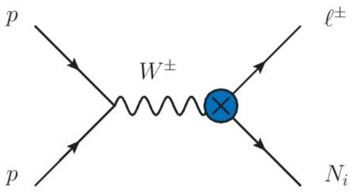
$$d^{\alpha i}_{\nu N\gamma} = \frac{v}{\sqrt{2}}\left(c_w C^{(6)\alpha i}_{NB} + \frac{s_w}{2} C^{(6)\alpha i}_{NW}\right), \qquad d^{\alpha i}_{\nu NZ} = \frac{v}{\sqrt{2}}\left(-s_w C^{(6)\alpha i}_{NB} + \frac{c_w}{2} C^{(6)\alpha i}_{NW}\right)$$

$$d^{\alpha i}_{\ell NW} = \frac{v}{2} C^{(6)\alpha i}_{NW}$$

Phenomenology @ LHC

Sterile neutrino production

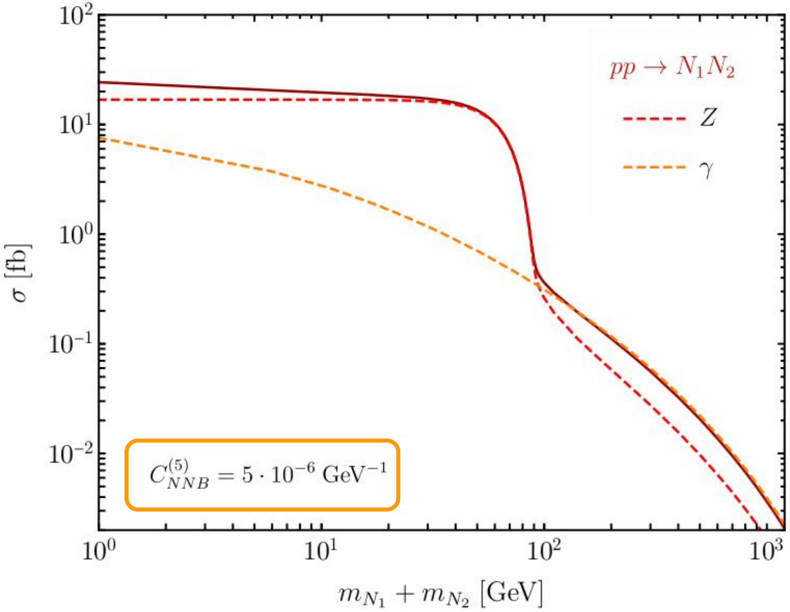


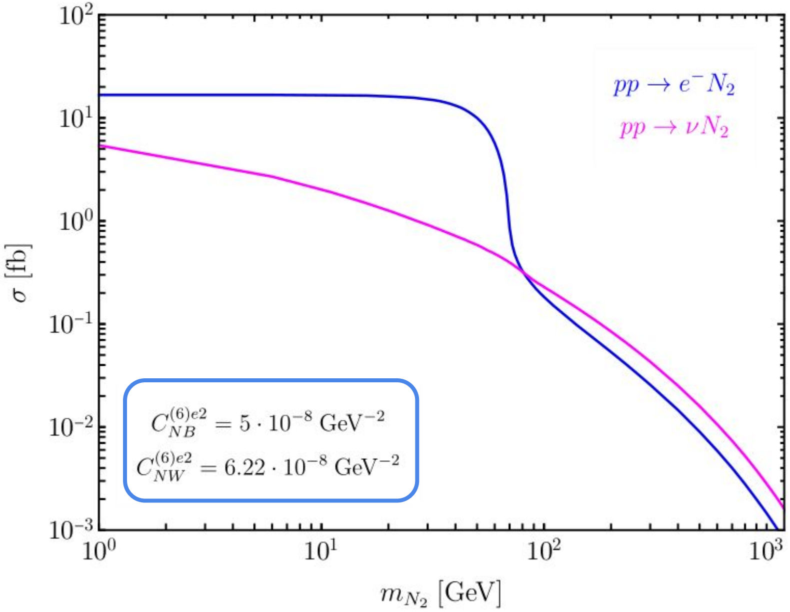


$$\sigma(pp \to N_1 N_2) \propto |C^{(5)}_{NNB}|^2$$

$$\sigma(pp \to \ell N_i) \propto |C^{(6)}_{NW}|^2$$

$\sqrt{s} = 14$ TeV

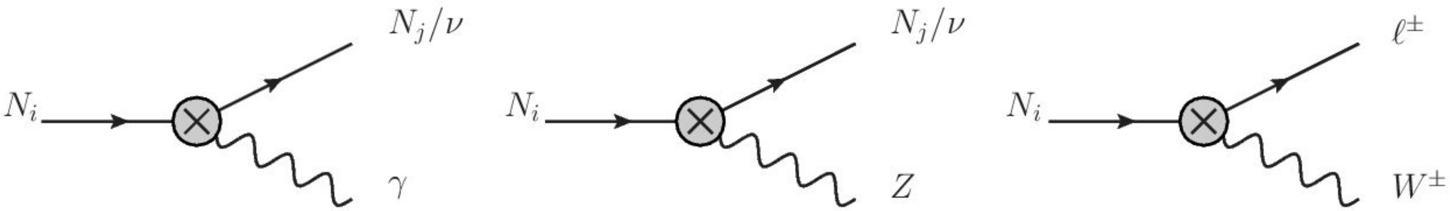




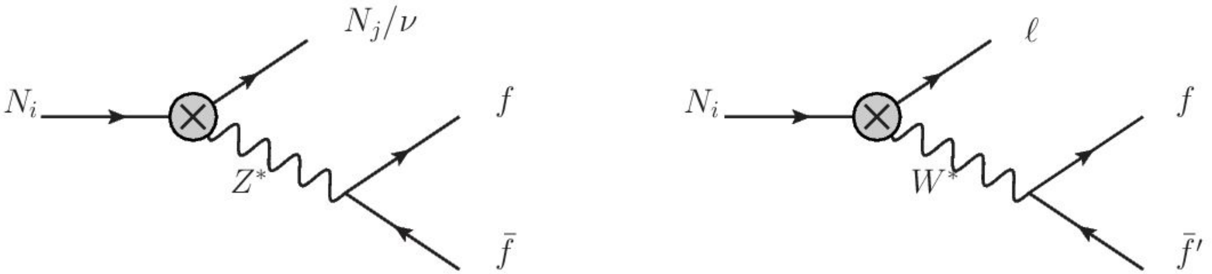
Sterile neutrino decay

Sterile neutrinos can undergo 2-body or 3-body decays, depending on available phase space

2b:

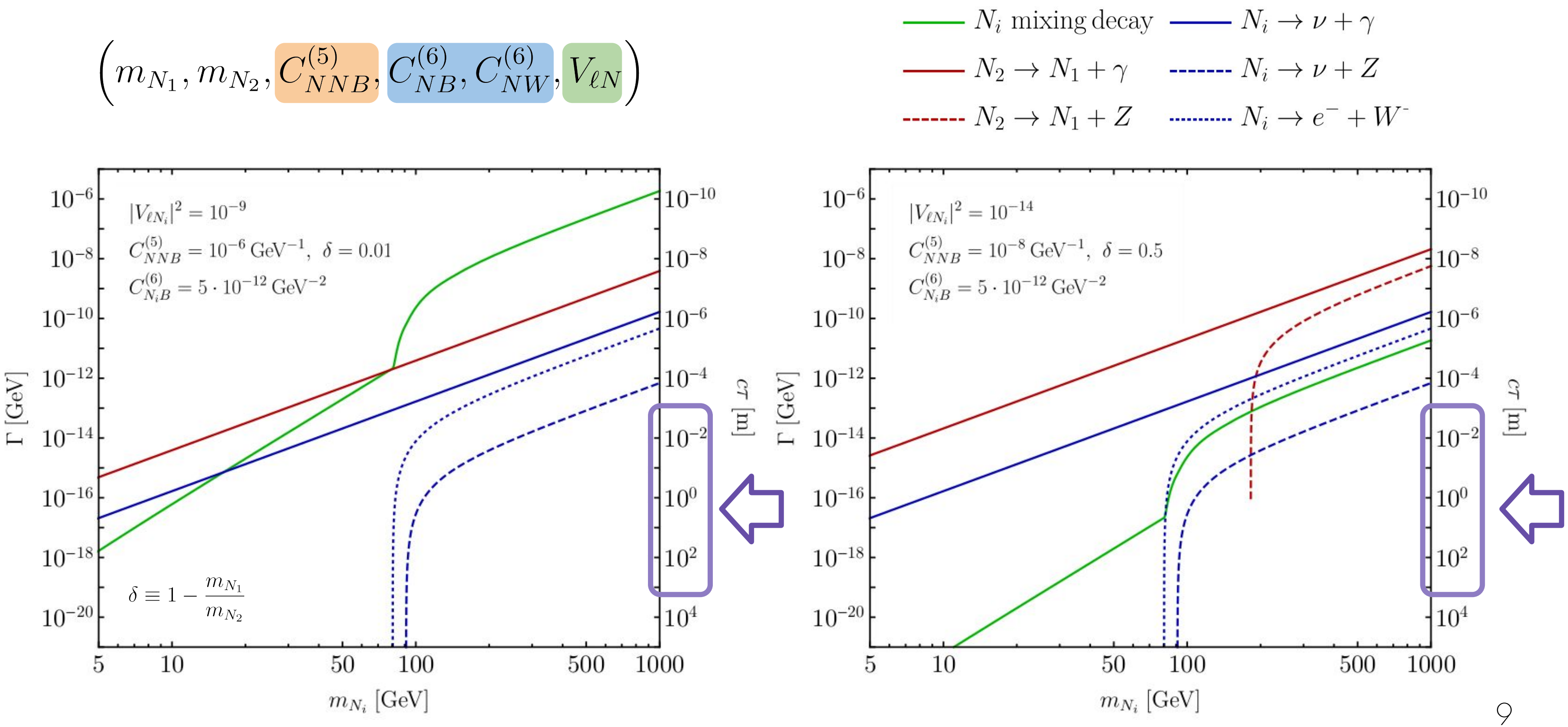


3b:



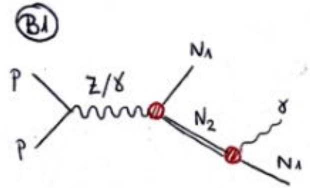
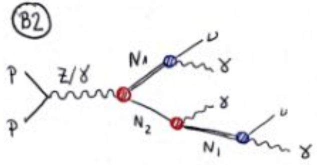
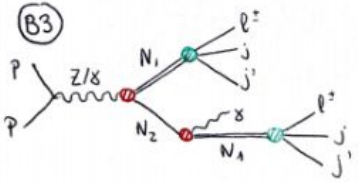
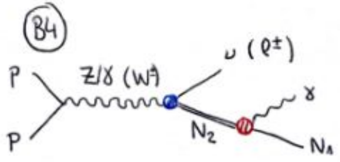
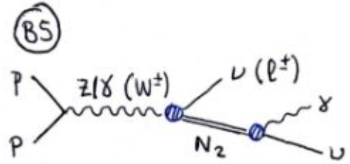
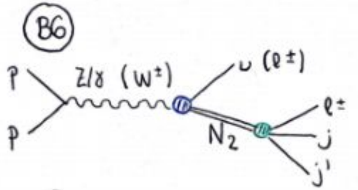
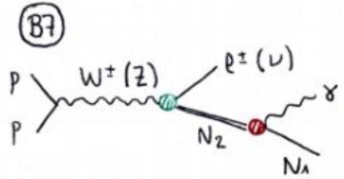
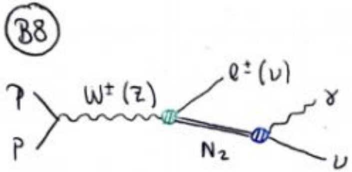
Sterile neutrino decay

$$\left(m_{N_1}, m_{N_2}, C^{(5)}_{NNB}, C^{(6)}_{NB}, C^{(6)}_{NW}, V_{\ell N}\right)$$



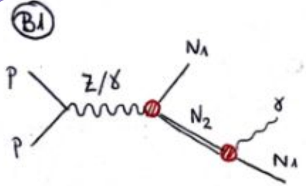
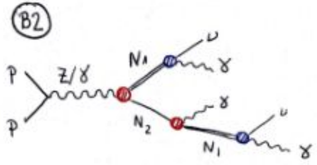
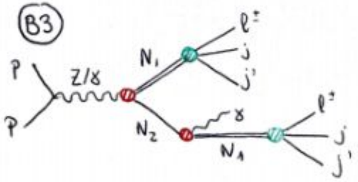
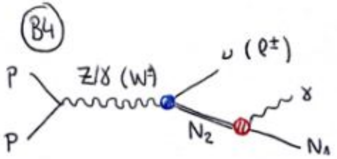
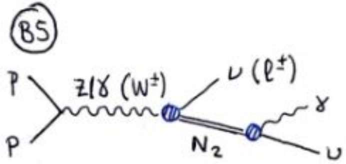
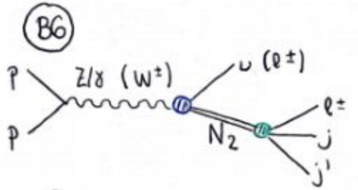
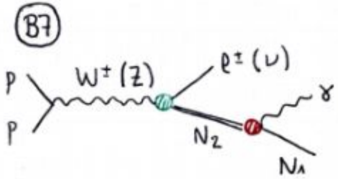
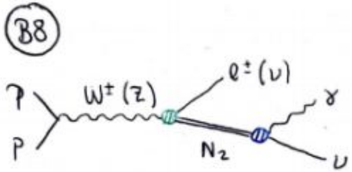
Possible scenarios

Each coupling can dominate production and decay (9 benchmarks)

Prod. \ Dec.	$C^{(5)}_{NNB}$	$C^{(6)}_{NB}, C^{(6)}_{NW}$	$V_{\ell N}$
$C^{(5)}_{NNB}$			
$C^{(6)}_{NB}, C^{(6)}_{NW}$			
$V_{\ell N}$			Minimal scenario

Possible scenarios

Each coupling can dominate production and decay (9 benchmarks)

Prod. \ Dec.	$C_{NNB}^{(5)}$	$C_{NB}^{(6)}, C_{NW}^{(6)}$	$V_{\ell N}$
$C_{NNB}^{(5)}$			
$C_{NB}^{(6)}, C_{NW}^{(6)}$			
$V_{\ell N}$			Minimal scenario

Non-pointing photon search

LLP signature: non-pointing photons

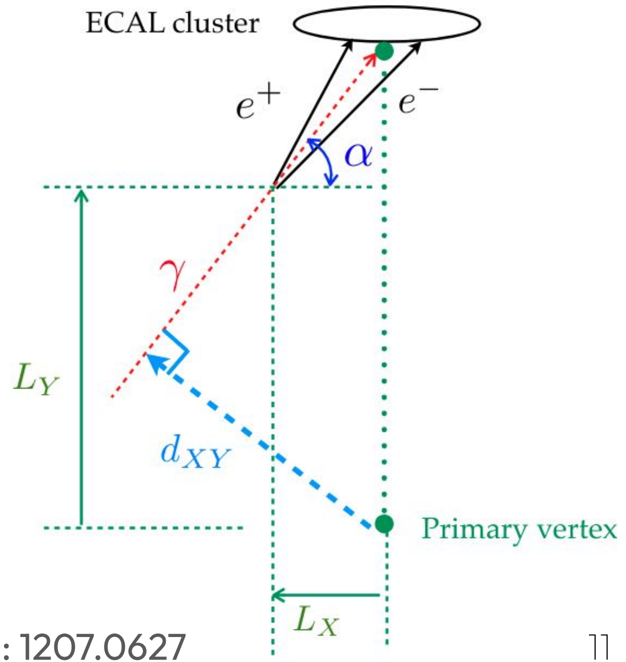
Non-pointing photons are emitted in the decay of LLPs:

- occur at a secondary vertex, displaced from PV
- leave a signal at ECAL
- displacement characterized by **Impact Parameter**

Minimal distance from photon trajectory to PV

$$d_{XY} = -L_X \cdot \sin\alpha + L_Y \cdot \cos\alpha$$
$$d_Z = L_Z - \frac{L_X \cdot p_X + L_Y \cdot p_Y}{p_T} \cdot \frac{p_Z}{p_T}.$$

❗ requires knowing precisely PV location



CMS: 1207.0627

Simulation process

We perform numerical study to estimate ATLAS sensitivity reach:

1. Model implemented in `FeynRules`
2. pp collisions at $\sqrt{s} = 14\ \text{TeV}$ in `MadGraph5`, 100k events at each grid point $\rightarrow (m_{\text{LLP}}, c_{\text{decay}})$
3. Particle decays handled in `MadSpin`
4. Detection efficiencies obtained with `Pythia8`

Scenario	Model parameters		Simulated decay
	Scan	Fixed	
B1	m_{N_2}, $C^{(5)}_{NNB}$	δ	$N_2 \to N_1\gamma$
B2	m_{N_1}, $C^{(6)}_{N_1X}$	m_{N_2}, $C^{(5)}_{NNB}$	$N_2 \to N_1\gamma$ $N_1 \to \nu\gamma$
B3	m_{N_1}, $\lvert V_{eN_1}\rvert^2$	m_{N_2}, $C^{(5)}_{NNB}$	$N_2 \to N_1\gamma$ $N_1 \to ejj$

Efficiencies: selection cuts

Scenario	Signature	Selection cuts
B1	Non-pointing γ	$\|p_T^\gamma\| > 10$ GeV , $\|\eta^\gamma\| < 2.47$ $r_{\rm DV} < 1450$ mm , $\|z_{\rm DV}\| < 3450$ mm $\|d_{XY}^\gamma\| > 6$ mm *
B2	Non-pointing γ ($\times 2$) (+ prompt γ)	
B3	Displaced Vertex ($\times 2$) (+ prompt γ)	$\|p_T^e\| > 120$ GeV, $\|\eta^e\| < 2.47$ 4 mm $< r_{\rm DV} < 300$ mm, $\|z_{\rm DV}\| < 300$ mm 4 tracks with $\|d_0\| > 2$ mm $m_{\rm DV} > 5$ GeV

→ LLP decay before escaping ECAL

*original cut from CMS: 1207.0627 to reduce background

Number of signal events for each scenario:

$$N_{\rm sig.}^{\rm B1} = \sigma \cdot \mathcal{L} \cdot \mathcal{B}\left(N_2 \to N_1\gamma\right) \cdot \epsilon_{\rm sel}^{\rm B1}$$

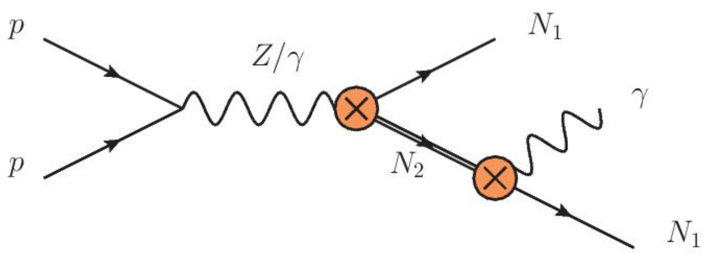
$$N_{\rm sig.}^{\rm B2} = \sigma \cdot \mathcal{L} \cdot \mathcal{B}\left(N_2 \to N_1\gamma\right) \cdot 2 \cdot \mathcal{B}\left(N_1 \to \nu\gamma\right) \cdot \epsilon_{\rm sel}^{\rm B2}$$

$$N_{\rm sig.}^{\rm B3} = \sigma \cdot \mathcal{L} \cdot \mathcal{B}\left(N_2 \to N_1\gamma\right) \cdot 2 \cdot \mathcal{B}\left(N_1 \to ejj\right) \cdot \epsilon_{\rm sel}^{\rm B3}$$

Sensitivity prospects: B1

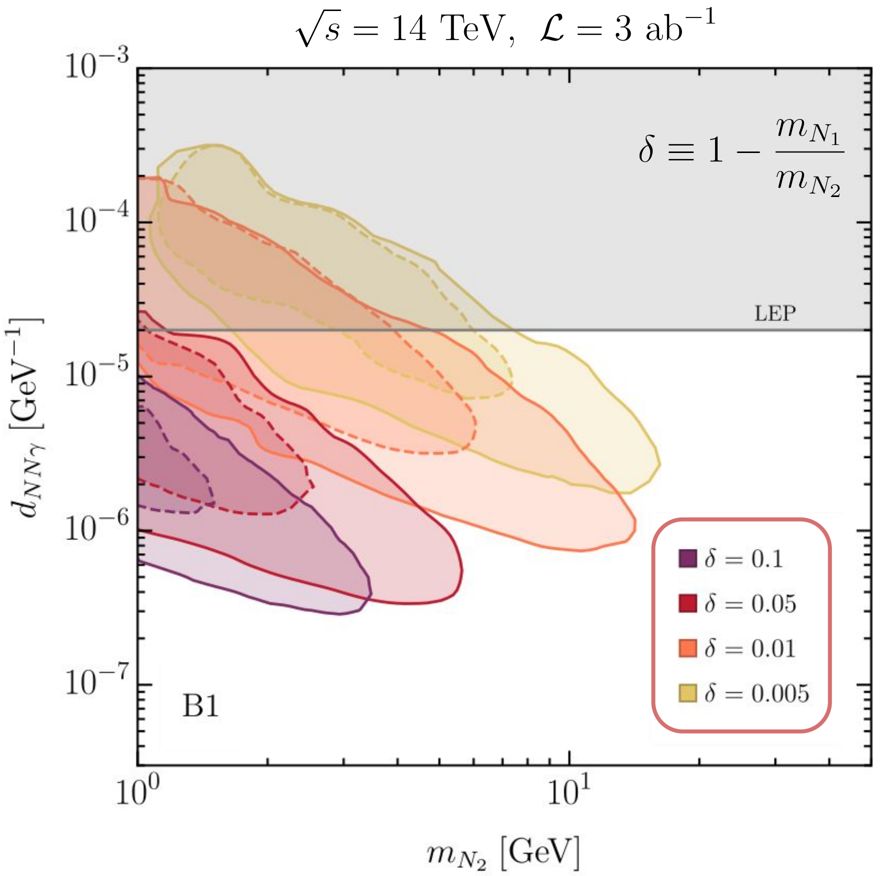
$pp \to N_1 N_2 : (d_{NN\gamma}, d_{NNZ})$

$N_2 \to (N_1\gamma)^{\text{LLP}} : (d_{NN\gamma}, \delta)$



$$N_{\text{sig.}}^{\text{B1}} = \sigma \cdot \mathcal{L} \cdot \mathcal{B}(N_2 \to N_1\gamma) \cdot \epsilon_{\text{sel}}^{\text{B1}}$$

solid: 3 events (95% C.L.)
dashed: 30 events

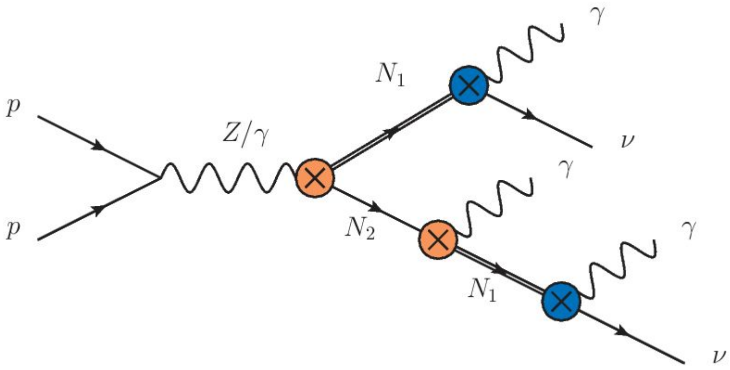


Sensitivity prospects: B2

$pp \to N_1 N_2 : (d_{NN\gamma}, d_{NNZ})$

$N_1 \to (\nu\gamma)^{\rm LLP} : (d_{\nu N\gamma})$

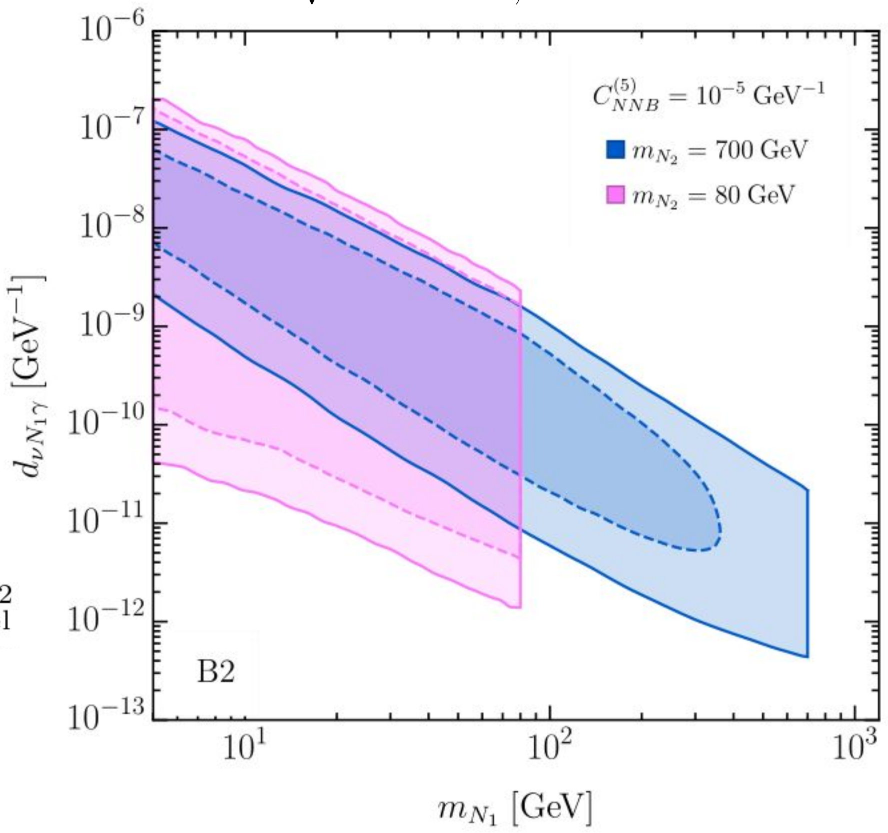
$N_2 \to (N_1\gamma) \to (\nu\gamma)^{\rm LLP}\gamma : (d_{\nu N\gamma})$



$$N_{\rm sig.}^{\rm B2} = \sigma \cdot \mathcal{L} \cdot \mathcal{B}(N_2 \to N_1\gamma) \cdot 2 \cdot \mathcal{B}(N_1 \to \nu\gamma) \cdot \epsilon_{\rm sel}^{\rm B2}$$

solid: 3 events (95% C.L.)
dashed: 30 events

$\sqrt{s} = 14$ TeV, $\mathcal{L} = 3$ ab^{-1}



Conclusions

Rich phenomenology of heavy sterile neutrinos with **magnetic moments** @ LHC

↳ displaced vertices + non-pointing/delayed photons

LHC experiments can use these signatures to probe new sterile neutrino interactions (beyond minimal neutrino mixing)

↳ **Non-pointing photon searches** could be sensitive to new parts of parameter space for $d_{NN\gamma}, d_{\nu N\gamma}$

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Tokyo, 1-5 July 2024

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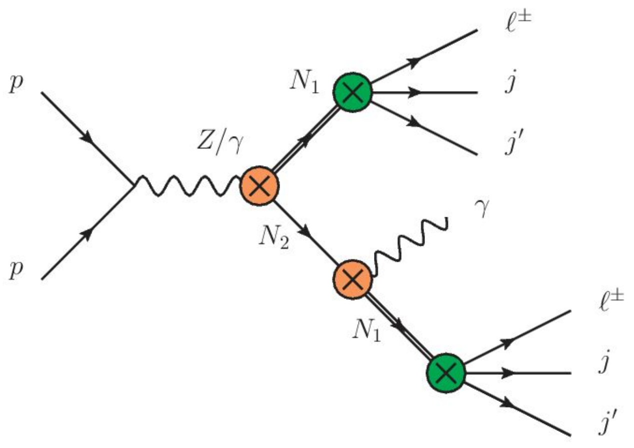
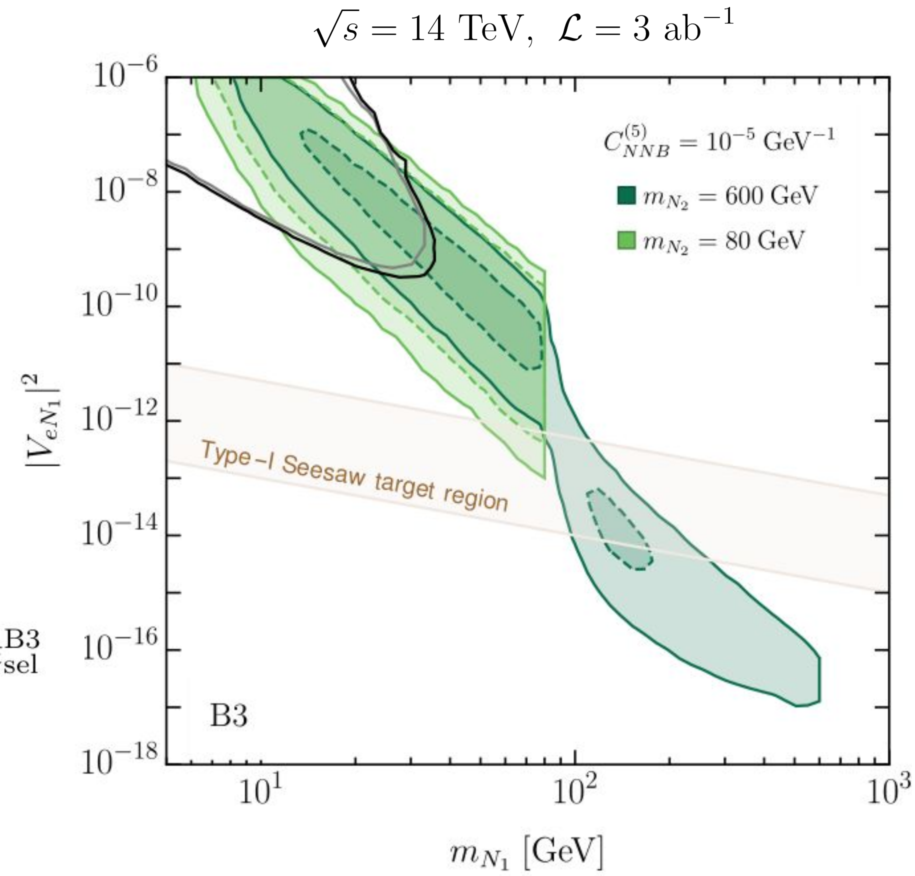
Sensitivity prospects: B3

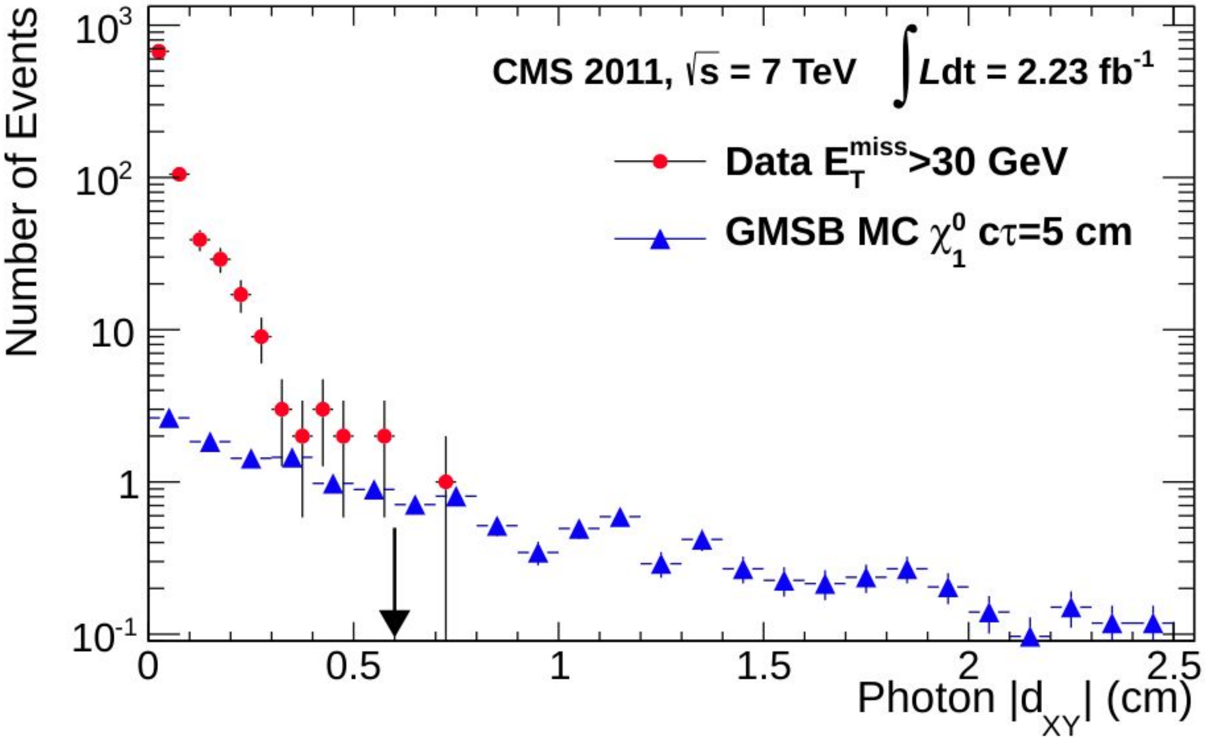


$$N_{\mathrm{sig.}}^{\mathrm{B3}} = \sigma \cdot \mathcal{L} \cdot \mathcal{B}\left(N_2 \to N_1 \gamma\right) \cdot 2 \cdot \mathcal{B}\left(N_1 \to ejj\right) \cdot \epsilon_{\mathrm{sel}}^{\mathrm{B3}}$$

solid: 3 events (95% C.L.)
dashed: 10 events

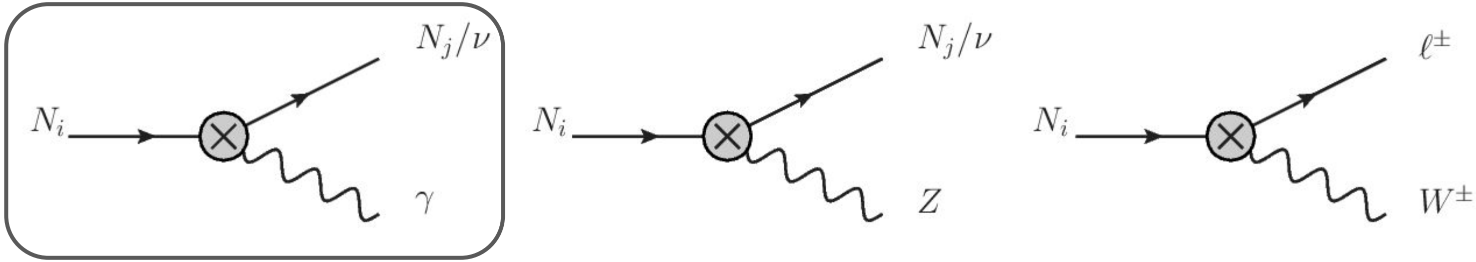


Non-pointing photon backgrounds



CMS: 1207.0627

Sterile neutrino decay



$$\Gamma(N_2 \to N_1\gamma) = \frac{2|d^{12}_{NN\gamma}|^2}{\pi} m^3_{N_2}(2-\delta)^3\delta^3 \qquad \delta \equiv 1 - \frac{m_{N_1}}{m_{N_2}}$$

$$\Gamma(N_i \to \nu\gamma) = \frac{|d_{\nu N_i\gamma}|^2}{2\pi} m^3_{N_i}$$