Heavy Neutrino Magnetic Moments and **L**ong **L**ived **P**article Searches

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based on *JHEP* 07 (2024) 153 (2405.08877)

with Rebeca Beltrán, Patrick Bolton, Frank Deppisch and Martin Hirsch

applying this cycle

Gen—T

Right-Handed Neutrinos / HNL / Sterile neutrinos

$$\mathcal{L}_{\mathrm{SM}+N_R} \supset \mathcal{L}_{\mathrm{SM}} + i\bar{N}_R \partial\!\!\!/ N_R - \left[\bar{L} Y_\nu N_R \tilde{H} + \frac{1}{2} \bar{N}_R^c M_R N_R + \mathrm{h.c.} \right]$$

$$-\frac{1}{2} \begin{pmatrix} \bar{\nu}_L & \bar{N}_R^c \end{pmatrix} \begin{pmatrix} 0 & M_D \\ M_D^T & M_R \end{pmatrix} \begin{pmatrix} \nu_L^c \\ N_R \end{pmatrix} + \mathrm{h.c.}\,, \quad M_D = \frac{v}{\sqrt{2}} Y_\nu$$

Diagonalise: Naturally generate the light neutrino masses if $M_D \ll M_R$ or $U(1)_L$ is approximately conserved

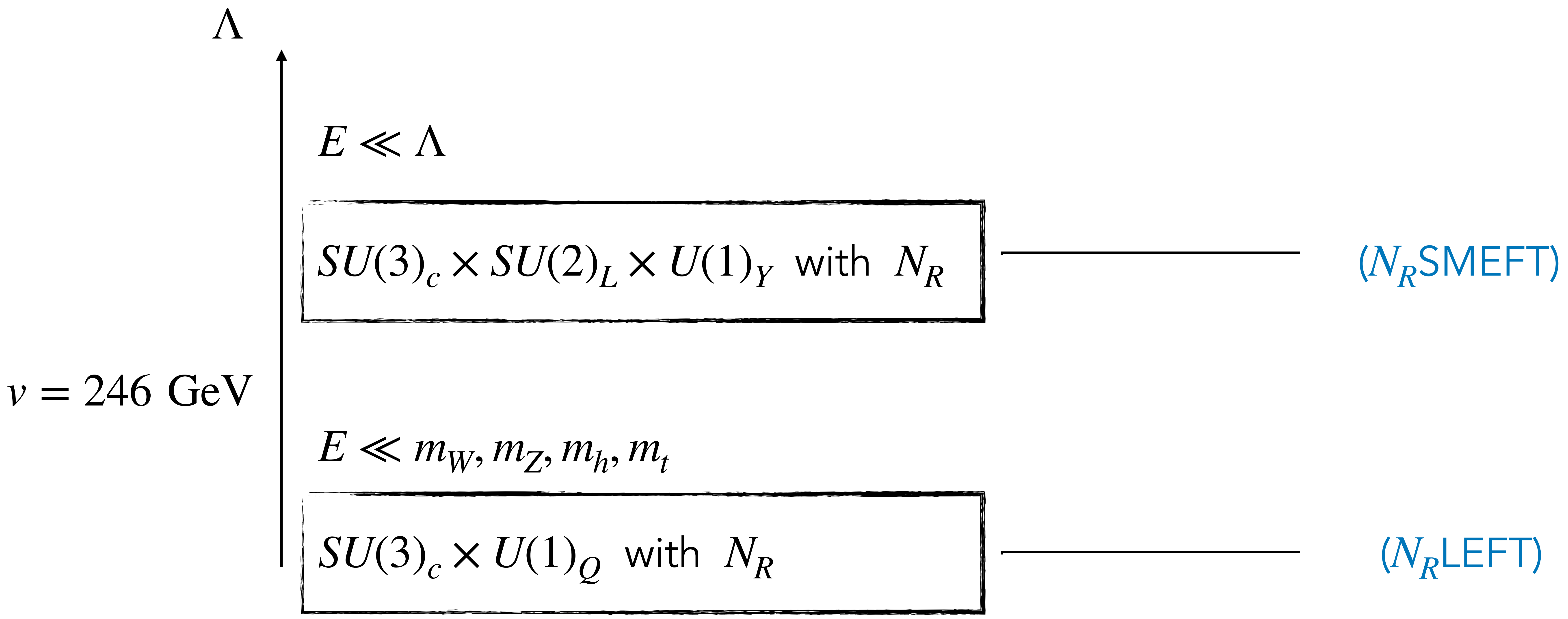
$$[M_\nu]_{\alpha\beta} = U_{\alpha i} U_{\beta i} m_i \approx -[M_D M_R^{-1} M_D^T]_{\alpha\beta} \qquad V_{\alpha N_i} = i U_{\alpha j} \mathcal{R}_{ji} \sqrt{\frac{m_j}{m_{N_i}}}$$

Resulting heavy states: Majorana (Type-I) or pseudo-Dirac (inverse)

Beyond the Renormalisable

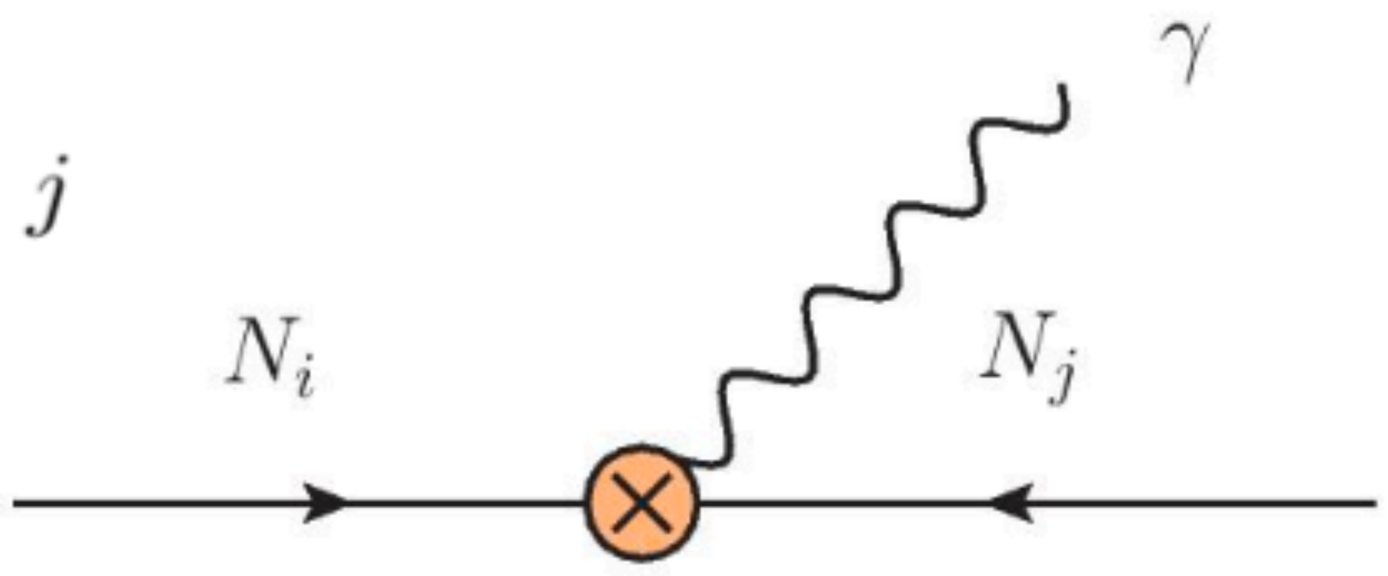
If N_R is coupled to some heavy new physics at Λ:

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}+N_R} + \sum_i C_i^{(d)} \mathcal{O}_i^{(d)} \qquad C_i^{(d)} \propto \Lambda^{4-d}$$

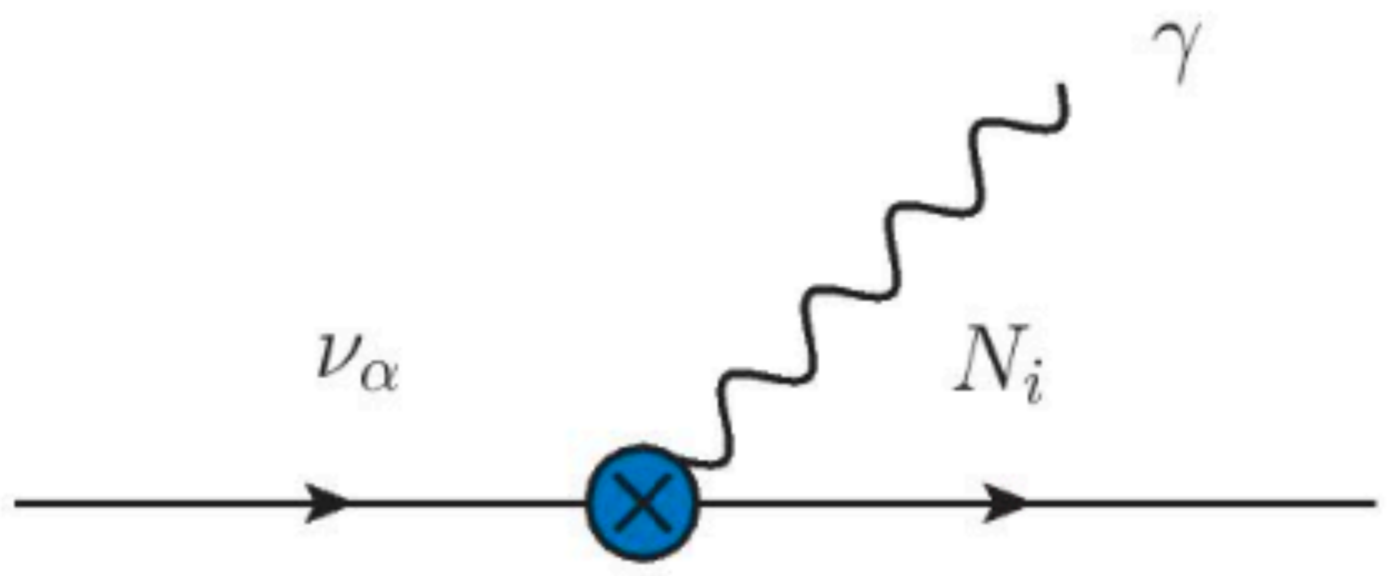


Active-to-Sterile and Sterile-to-Sterile Neutrino Magnetic Moments

Sterile-to-sterile



Active-to-sterile



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

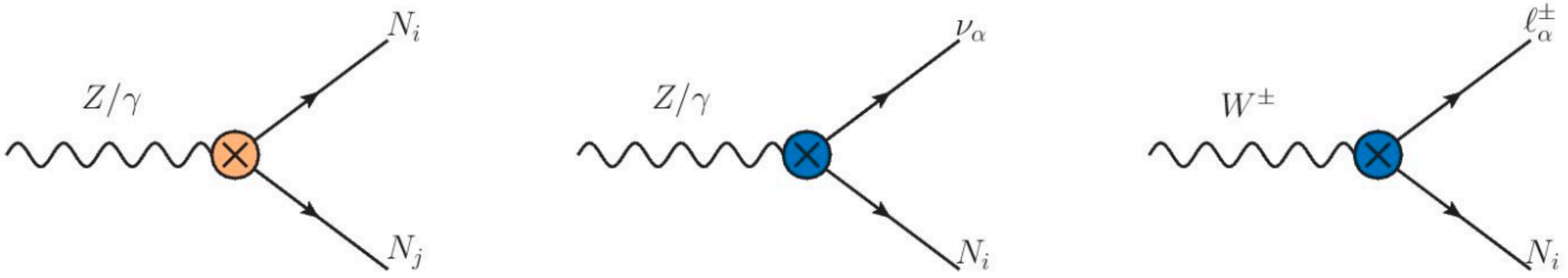
Above EW scale ⇓

$$\mathcal{L}_{\mathrm{NSMEFT}} \supset C^{(5)ij}_{NNB} \left(\overline{N^c_{Ri}} \sigma^{\mu\nu} N_{Rj}\right) B_{\mu\nu} + \mathrm{h.c.}$$
$$+ C^{(6)\alpha i}_{NB} \left(\overline{L_\alpha} \sigma^{\mu\nu} N_{Ri}\right) \tilde{H} B_{\mu\nu} + C^{(6)\alpha i}_{NW} \left(\overline{L_\alpha} \sigma^{\mu\nu} N_{Ri}\right) \tau^I \tilde{H} W^I_{\mu\nu} + \mathrm{h.c.}$$ (N_RSMEFT)

Good choice for LHC studies!

To make life easier: rotated N_RSMEFT

$$\mathcal{L}_{\text{NSMEFT}} \supset C^{(5)ij}_{NNB} \left(\overline{N^c_{Ri}} \sigma^{\mu\nu} N_{Rj}\right) B_{\mu\nu} + \text{h.c.}$$
$$+ C^{(6)\alpha i}_{NB} \left(\overline{L_\alpha} \sigma^{\mu\nu} N_{Ri}\right) \tilde{H} B_{\mu\nu} + C^{(6)\alpha i}_{NW} \left(\overline{L_\alpha} \sigma^{\mu\nu} N_{Ri}\right) \tau^I \tilde{H} W^I_{\mu\nu} + \text{h.c.}$$



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

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

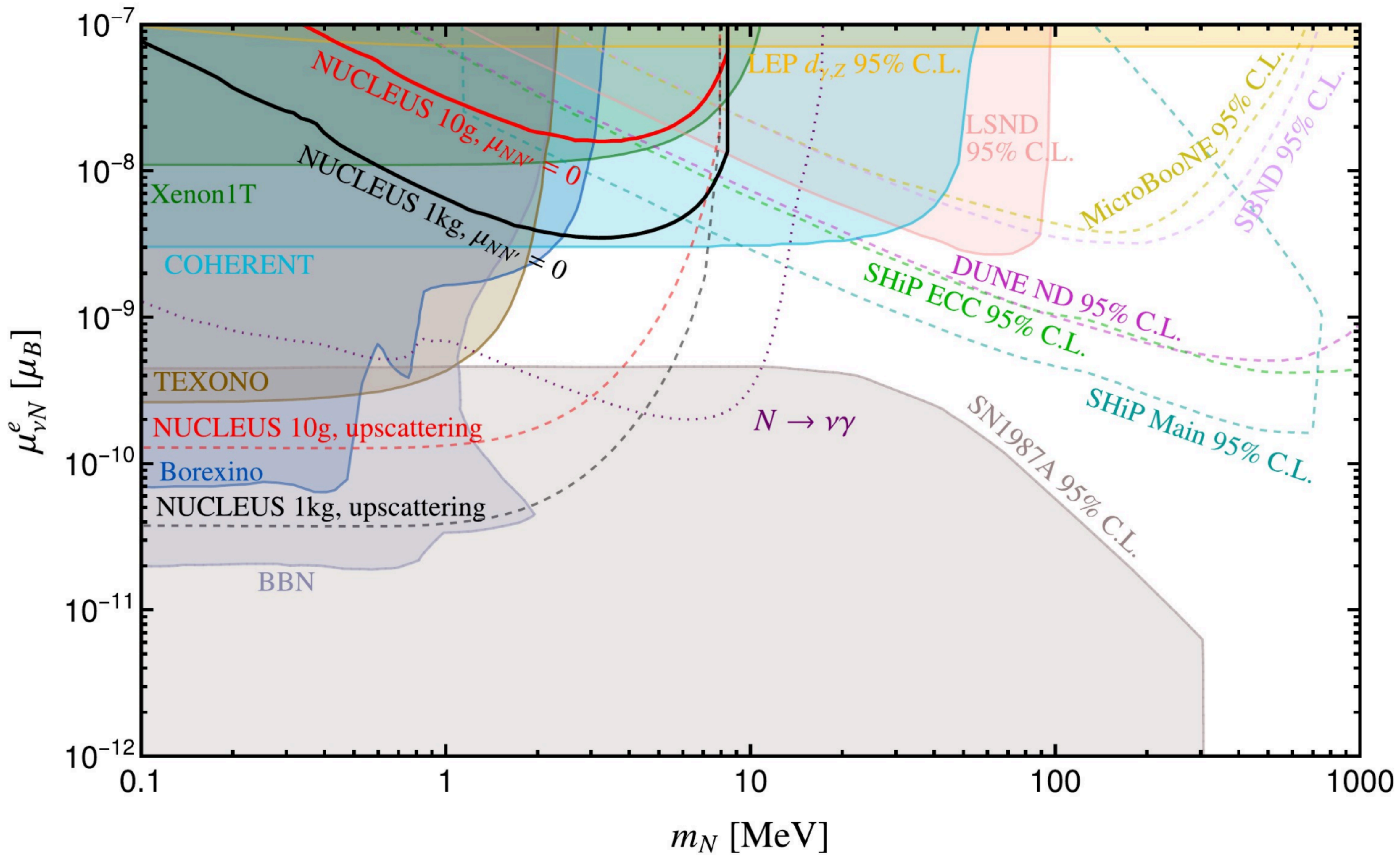
$$d^{ij}_{NN\gamma} = c_w C^{(5)ij}_{NNB}, \quad d^{ij}_{NNZ} = -s_w C^{(5)ij}_{NNB},$$

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

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

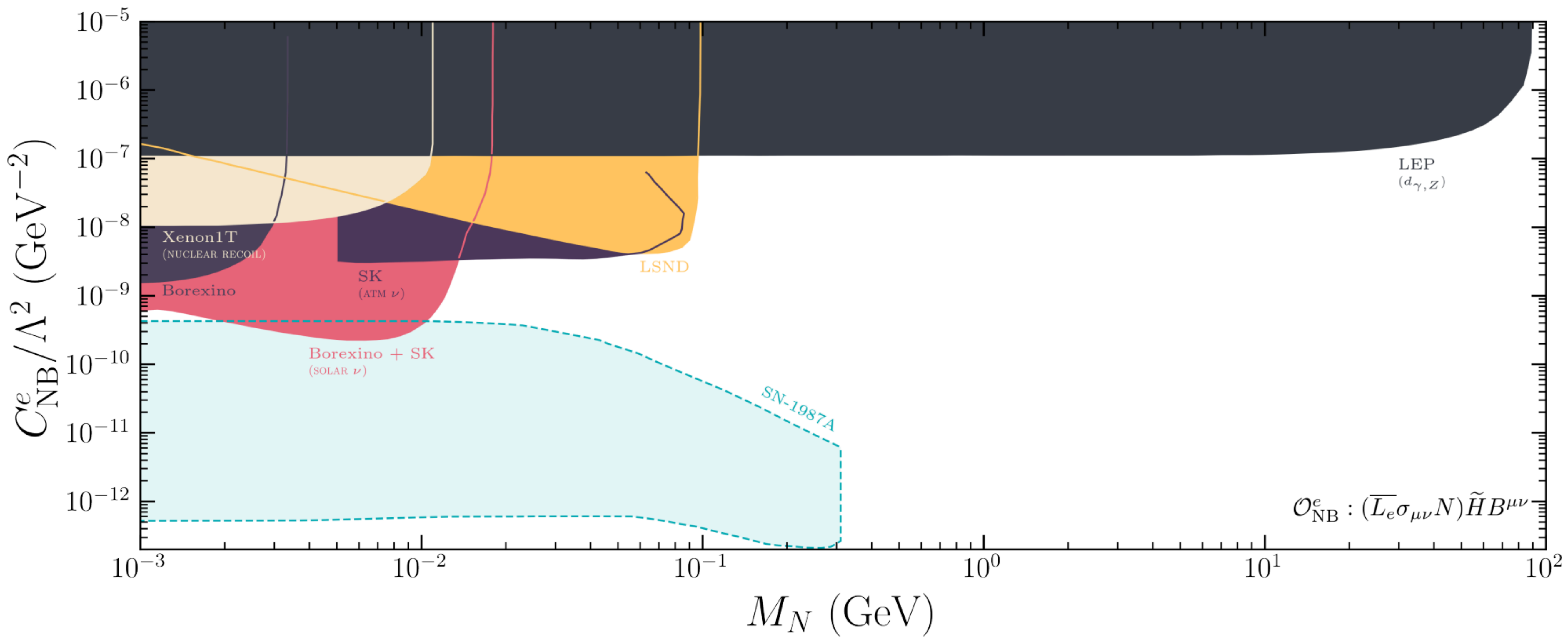
Current Bounds: Active-Sterile Dipole Moments

Bolton, Deppisch, Fridell, Harz, C.H. , Kulkarni, 2110.02233



$$\mu_B \sim \frac{e}{2m_e} \sim 3 \times 10^2 \ \textbf{GeV}^{-1}$$

Fernández-Martínez et al., 2304.06772



- Neutrino upscattering (solar ν, CEνNS)
- Meson Decays (Dalitz-like)
- Supernova cooling (SN1987A)
- Monophoton + $E_T^{\rm miss}$, $\Gamma_Z^{\rm inv}$ at LEP, LHC

Magill, Plestid, Pospelov, Tsai, 1803.03262

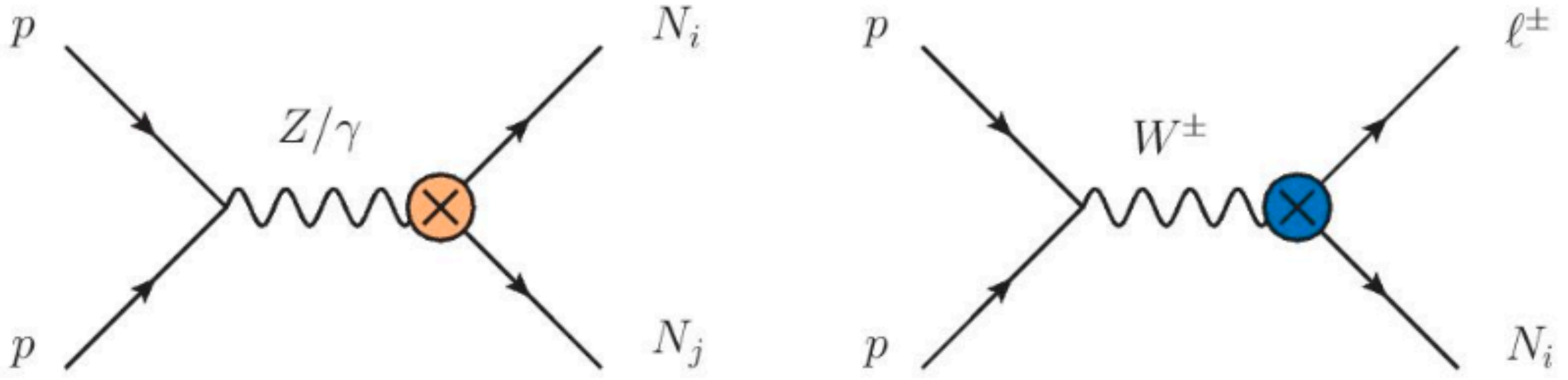
Brdar, Greljo, Kopp, Opferkuch, 2007.15563

Schwetz, Zhou, Zhu, 2105.09699

Barducci, Liu, Titov, Wang, Zhang, 2308.16608

LLPs @ LHC

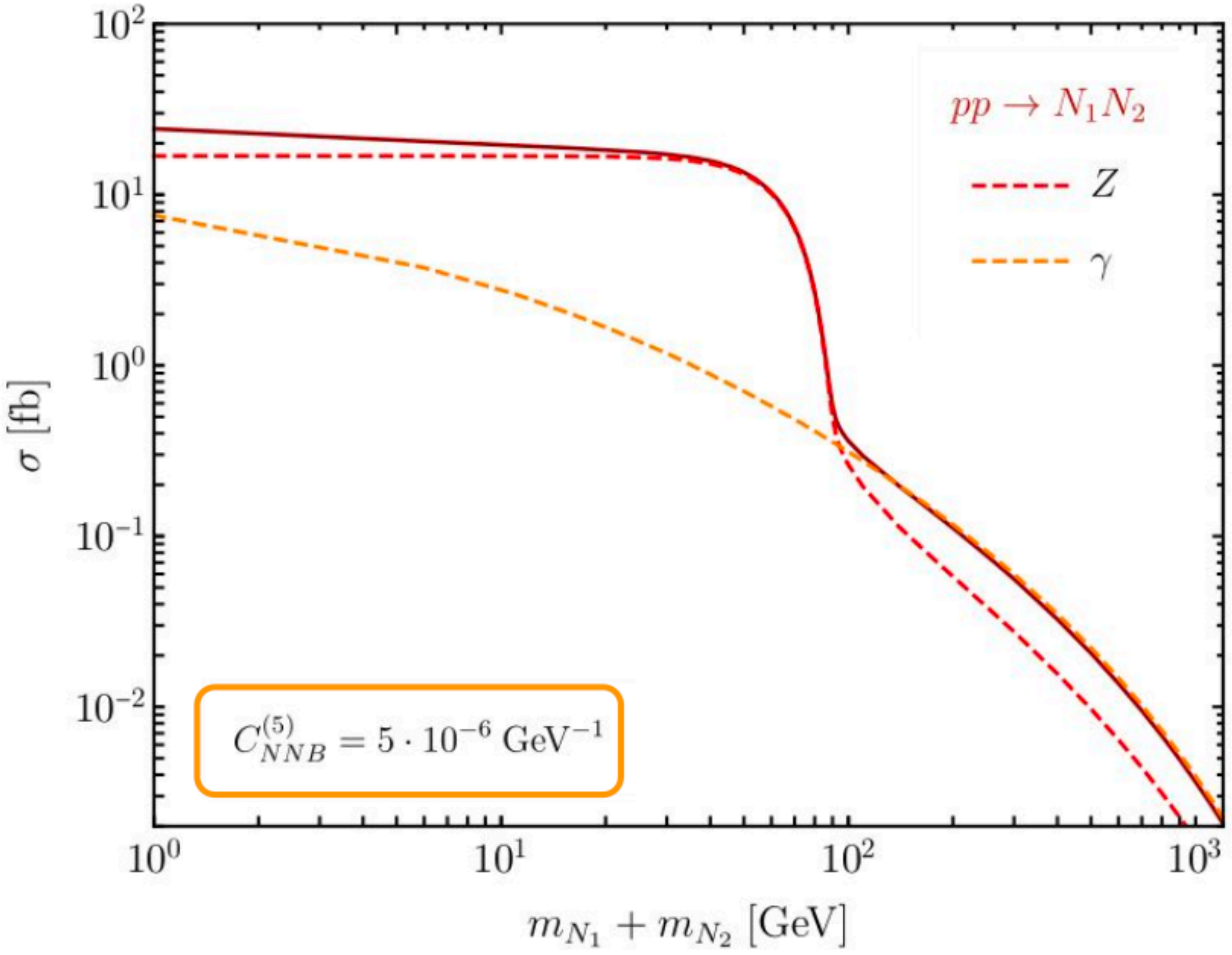
HNL Production

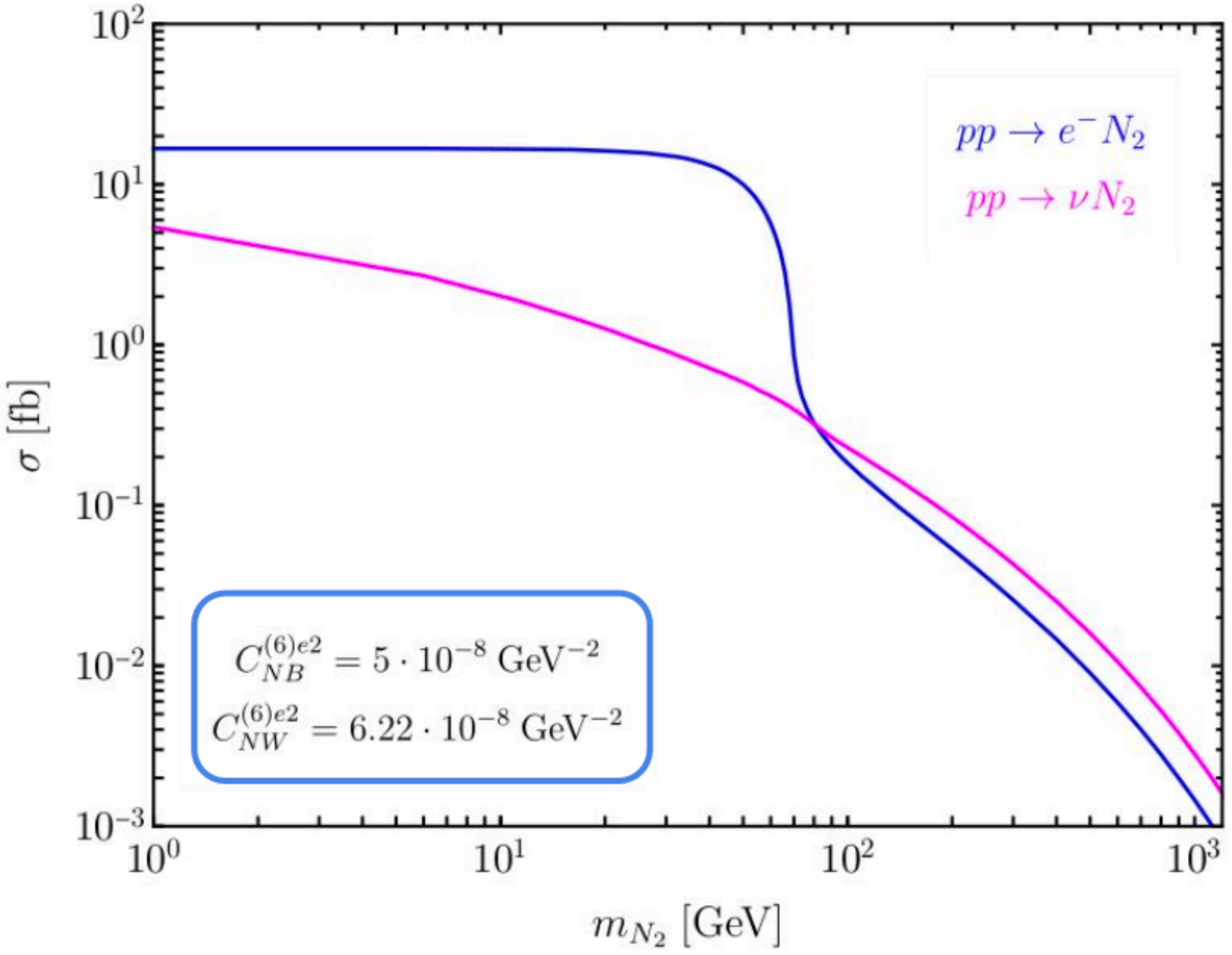


$$\sigma(pp \to N_1 N_2) \propto |C^{(5)}_{NNB}|^2$$

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

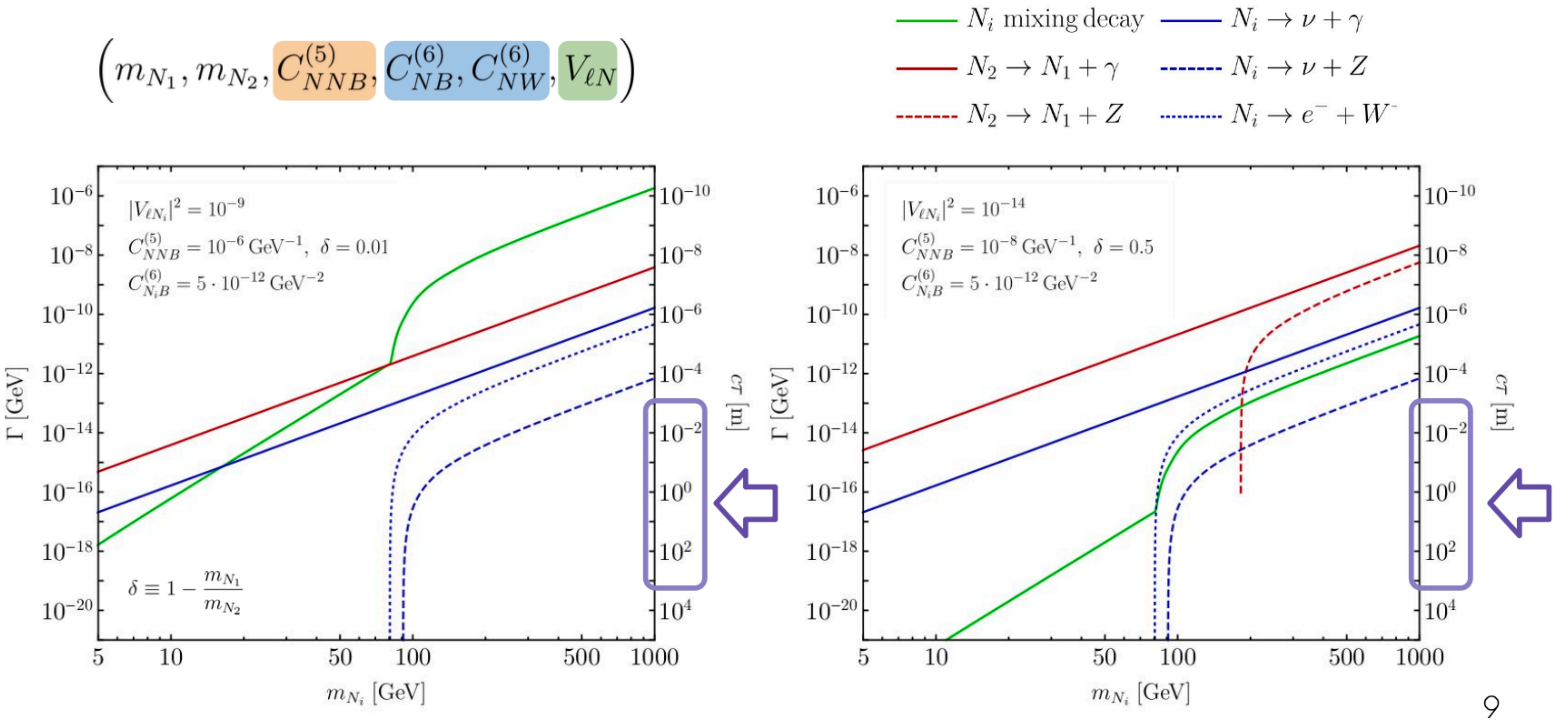
$\sqrt{s} = 14$ TeV





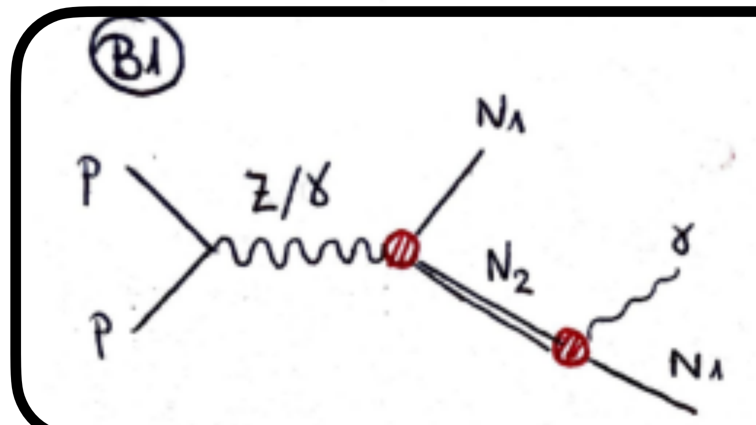
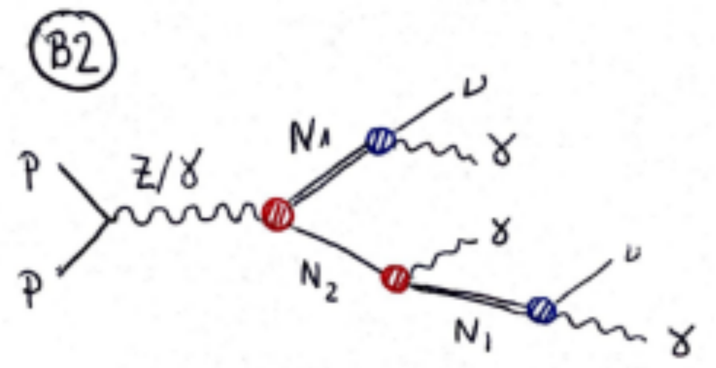
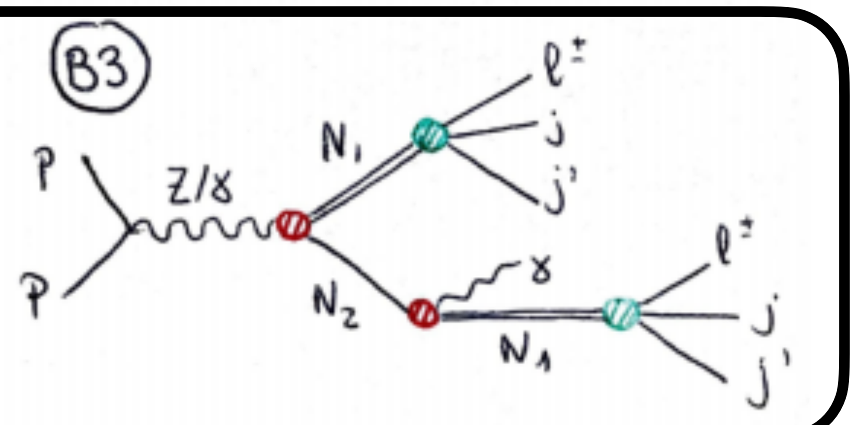
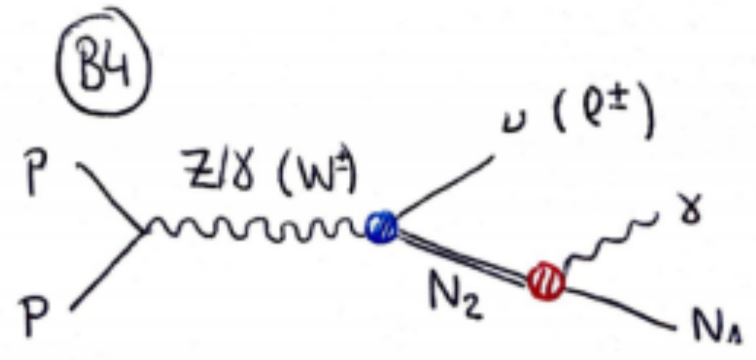
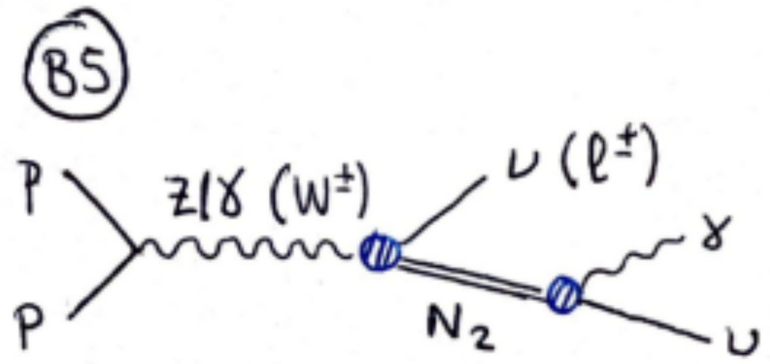
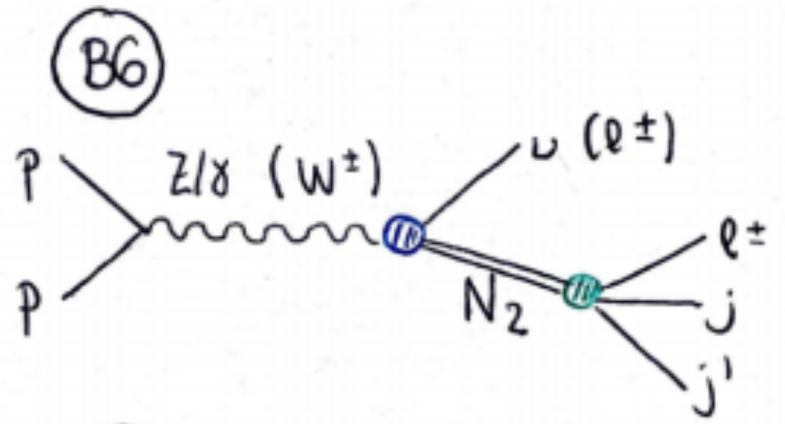
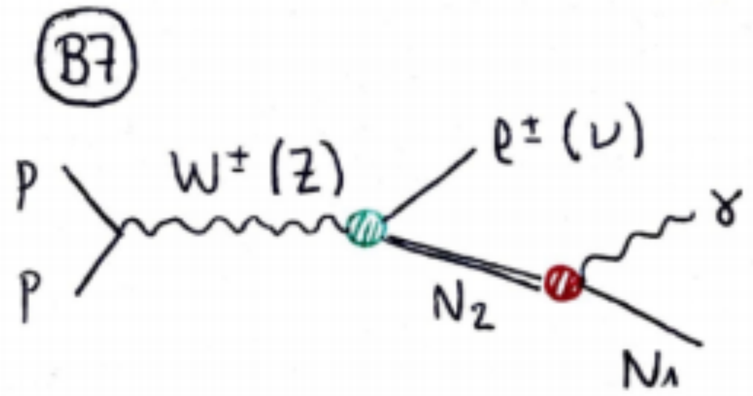
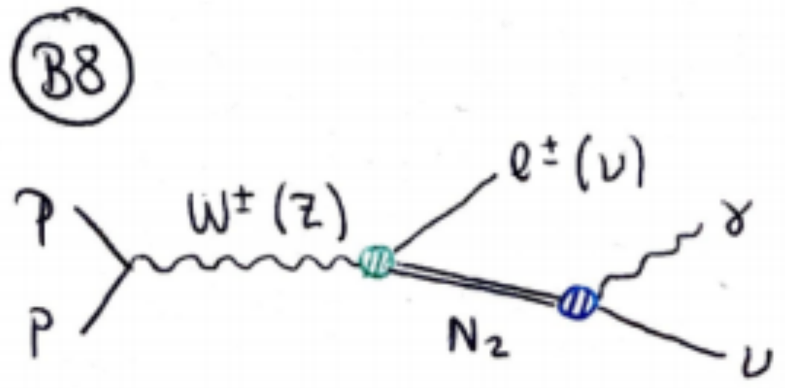
HNL Decays

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



Possible Scenarios

9 Scenarios: Where is the non-pointing photon signature viable?

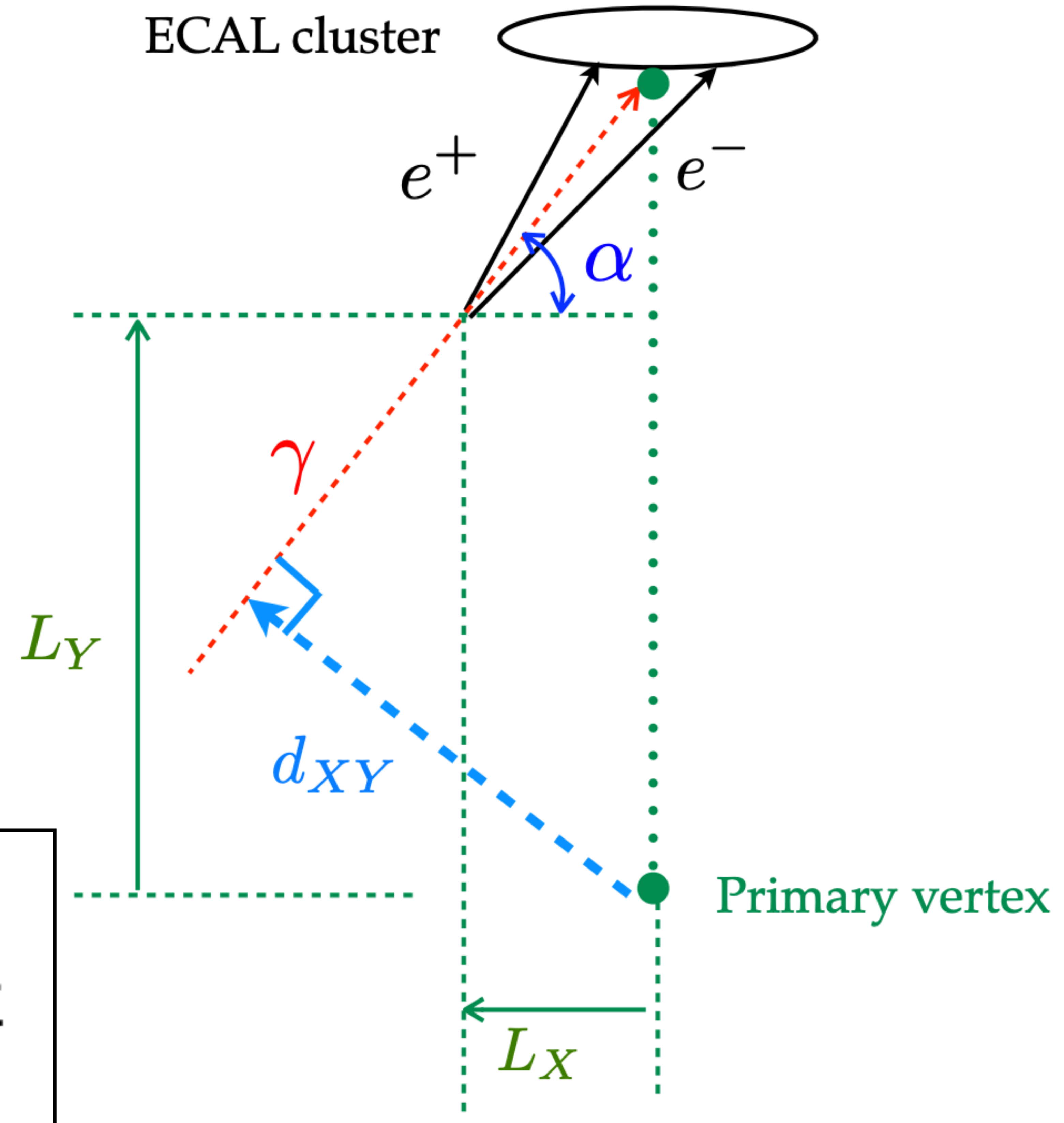
Dec. / Prod.	$C^{(5)}_{NNB}$	$C^{(6)}_{NB}$, $C^{(6)}_{NW}$	$V_{\ell N}$
$C^{(5)}_{NNB}$			
$C^{(6)}_{NB}$, $C^{(6)}_{NW}$			
$V_{\ell N}$			Minimal scenario

B1-B3: (> 1) non-pointing photons from N_1 and N_2 decays

Displaced Vertex Signatures: Non-Pointing Photons

Non-pointing photon signal from decaying HNL:
Characterized by impact parameter

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



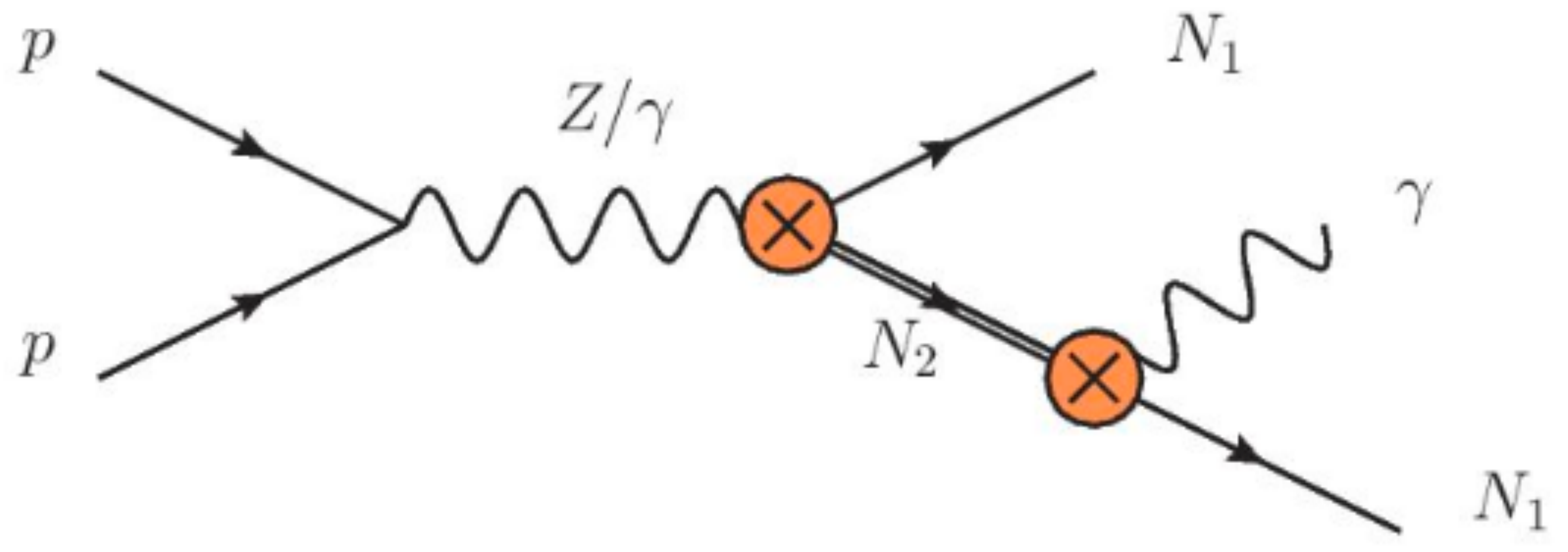
1. Model implemented in `FeynRules`
2. pp collisions at $\sqrt{s} = 14$ TeV in `MadGraph5`, 100k events at each grid point
3. Particle decays handled in `MadSpin`
4. Detection efficiencies obtained with `Pythia8`

$(m_{\rm LLP}, c_{\rm decay})$

CMS, arXiv:1207.0627

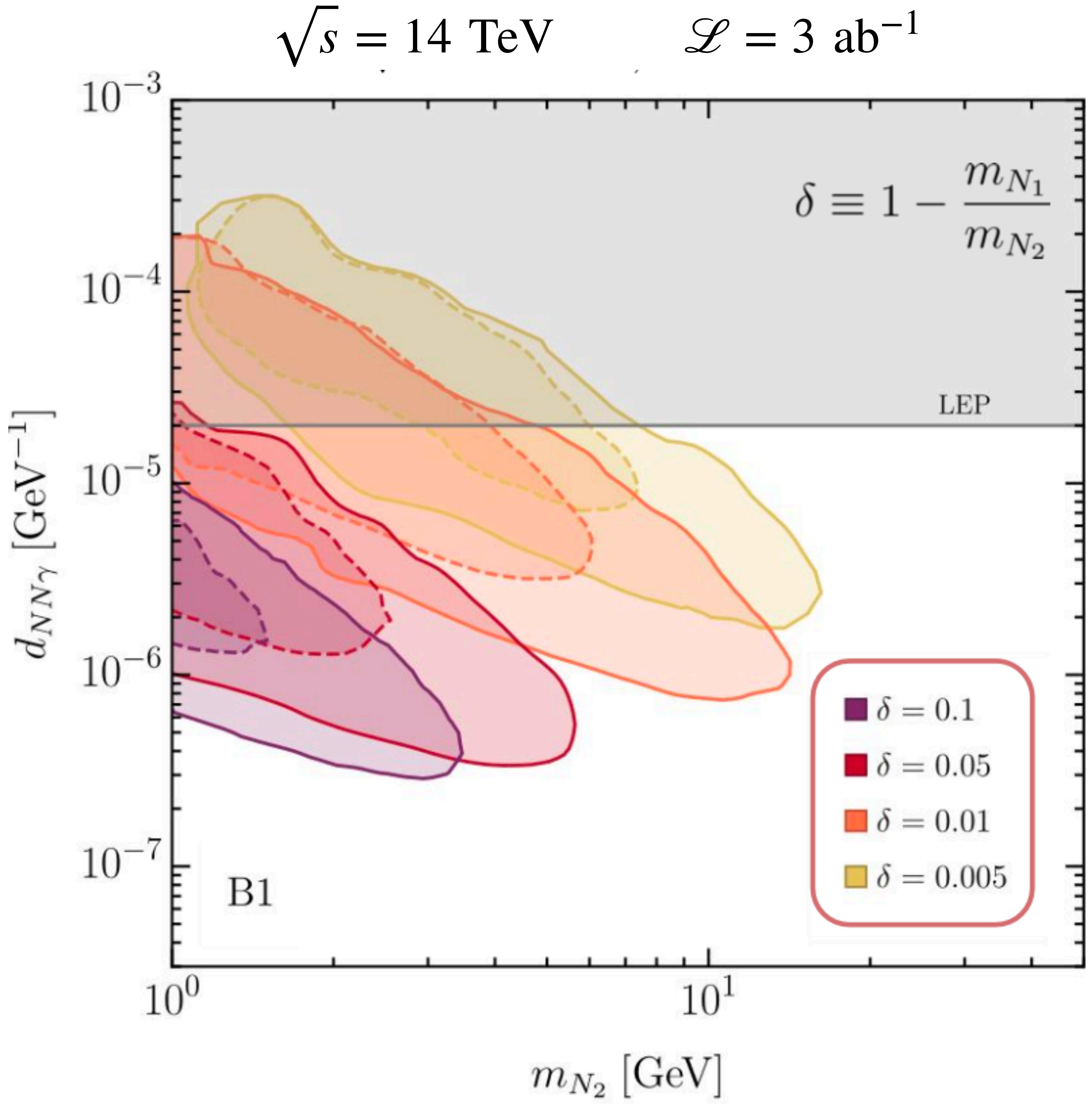
Scenario B1

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



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

Solid: 3 events (95% C.L.)
Dashed: 30 events

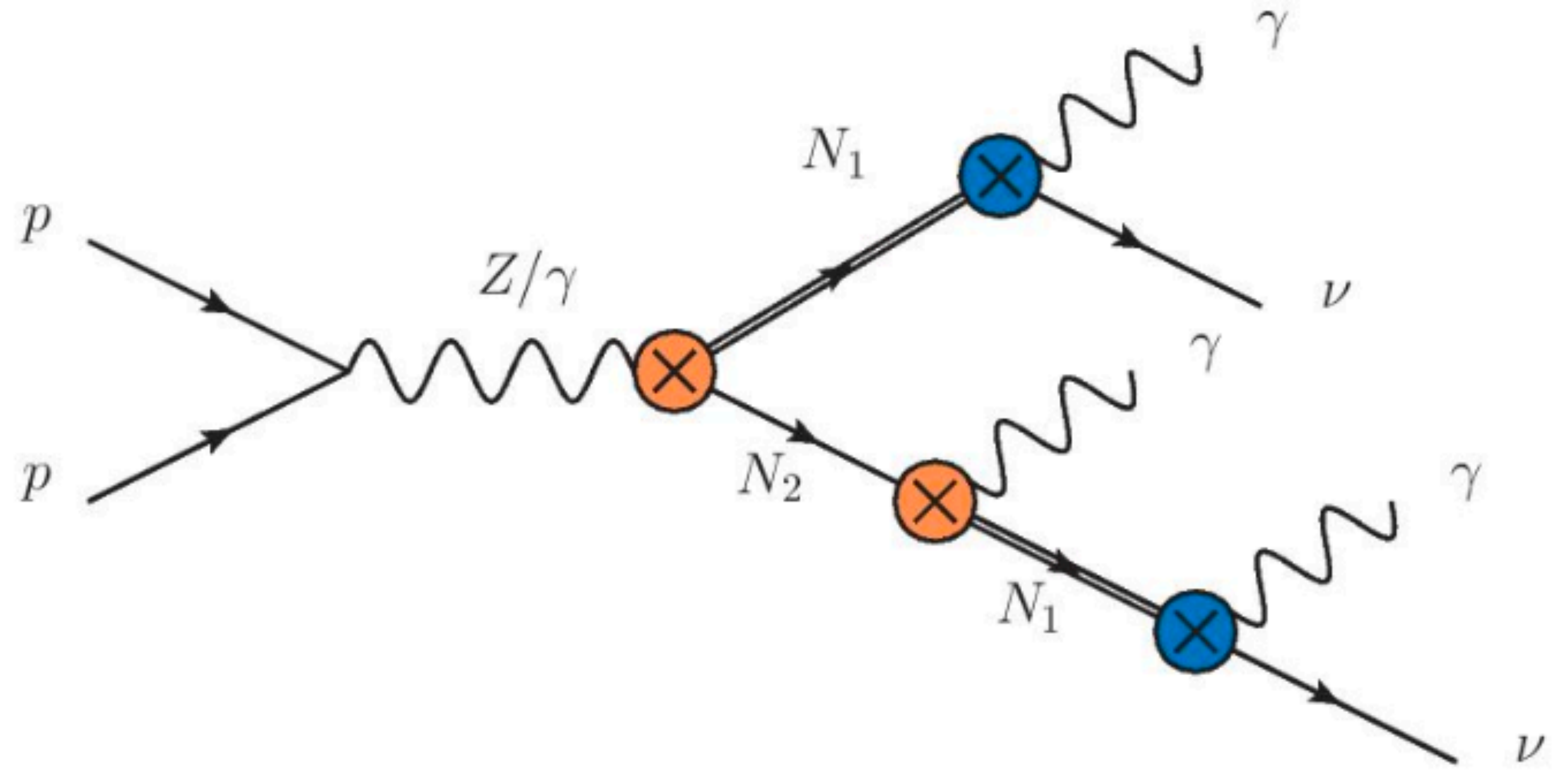


Scenario B2

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

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

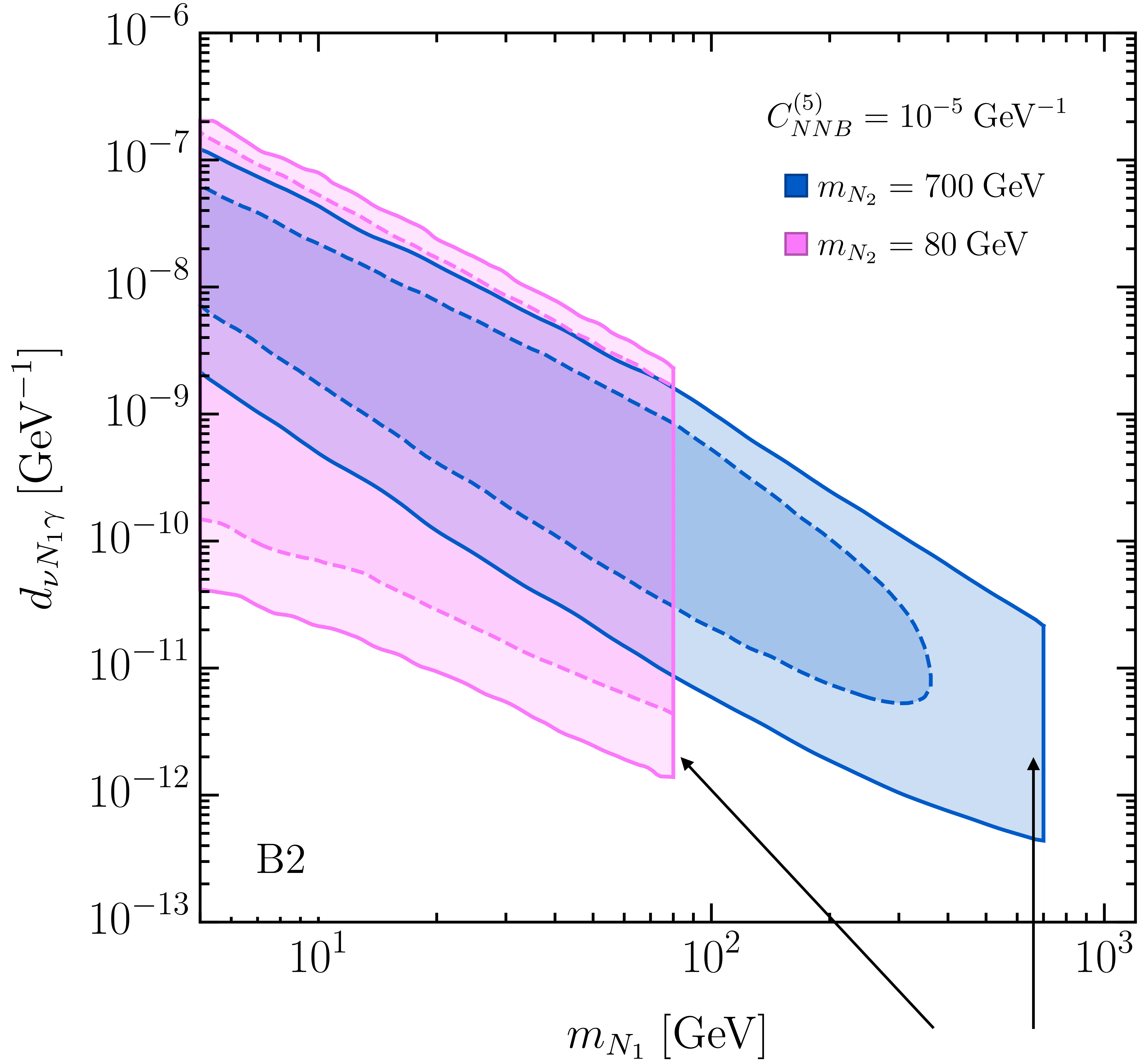
$N_2 \to N_1\gamma \to (\nu\gamma)^{\text{LLP}}\gamma : \ (d_{\nu N\gamma}, d_{NN\gamma})$



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

Solid: 3 events (95% C.L.)
Dashed: 30 events

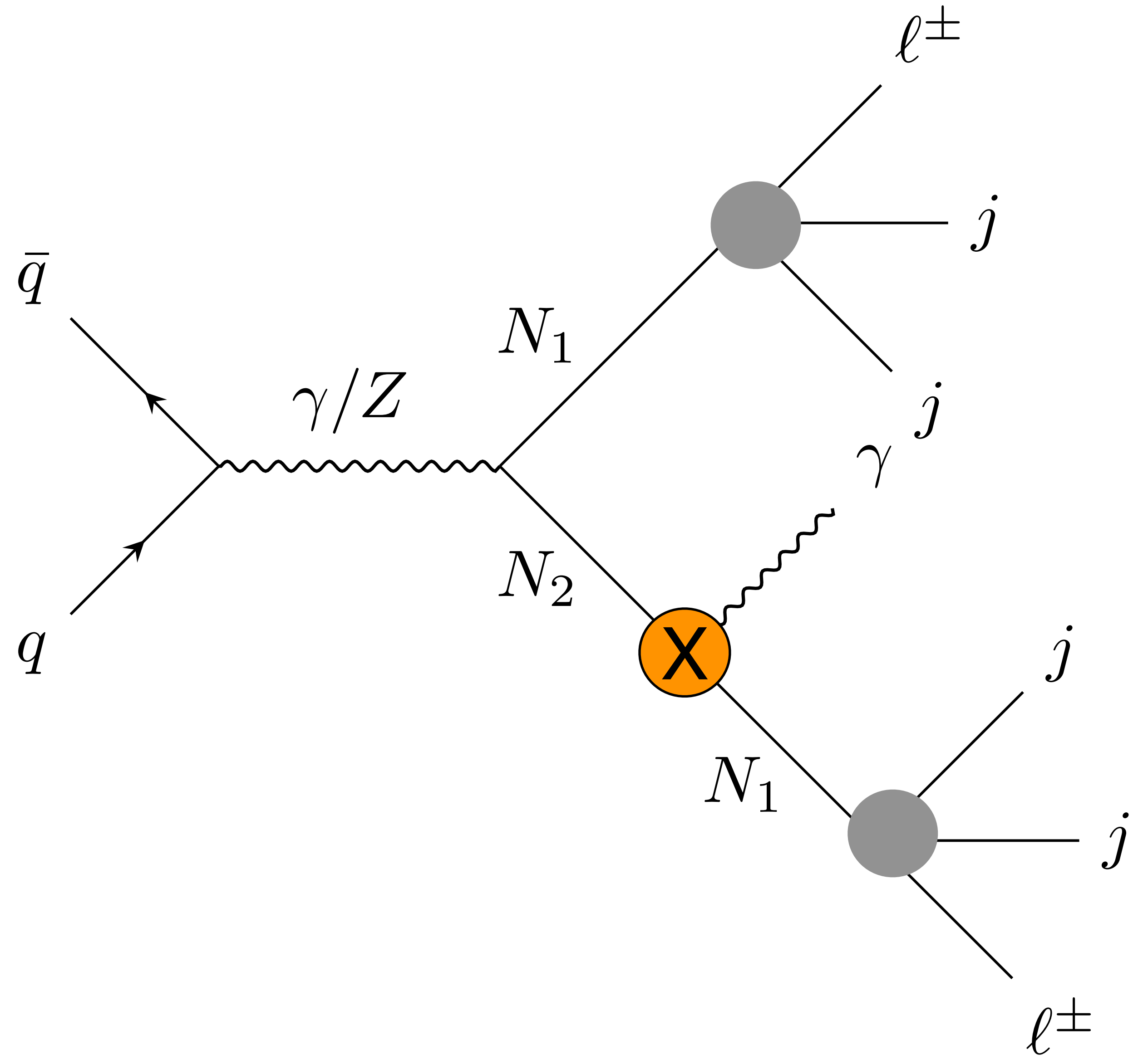
$\sqrt{s} = 14$ TeV $\quad \mathscr{L} = 3\ \text{ab}^{-1}$



$m_{N_1} < m_{N_2}$

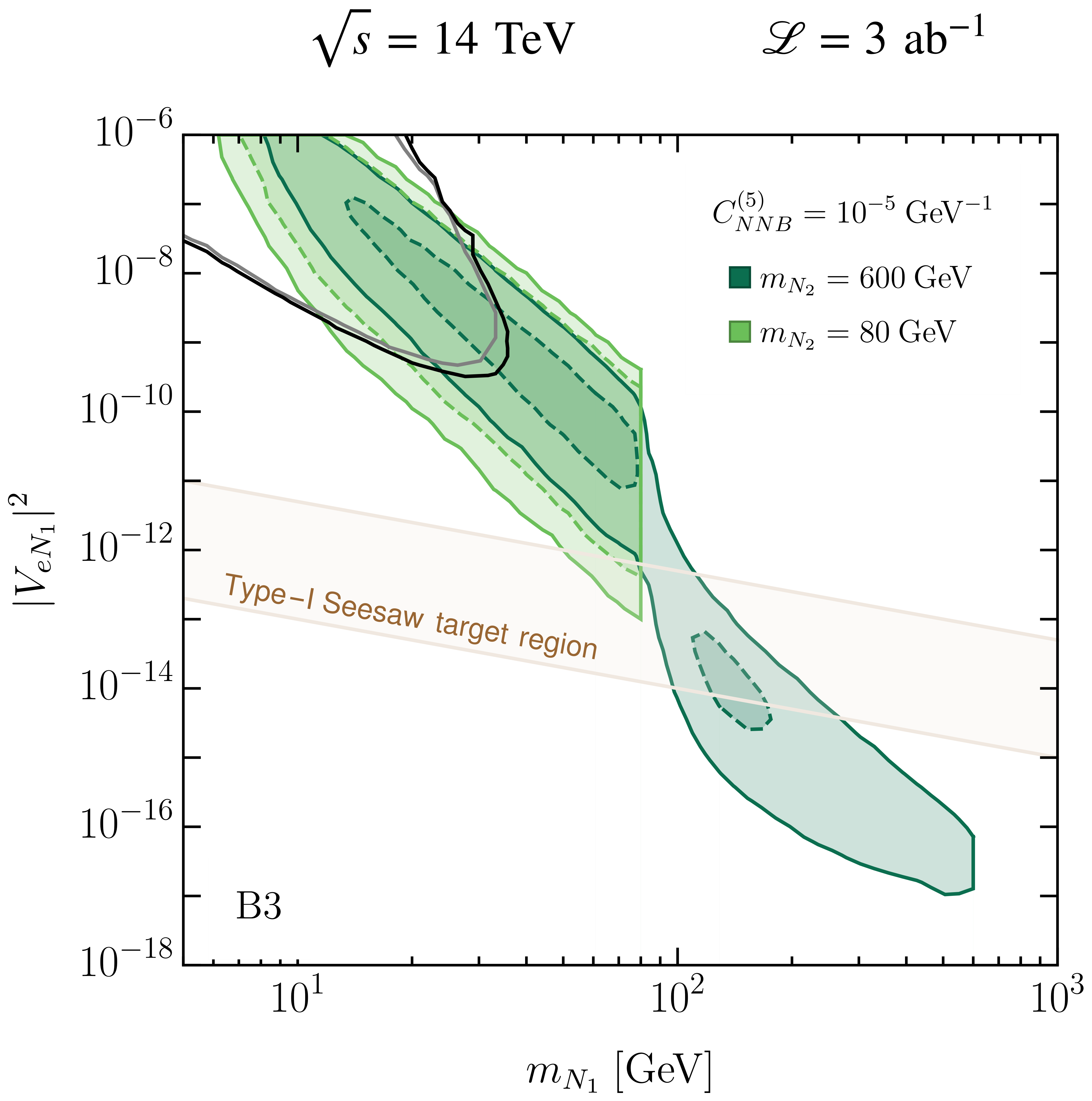
Scenario B3

$pp \to N_1 N_2 : \ (d_{NN\gamma}, d_{NNZ}),$
$N_1 \to (ejj)^{\mathrm{LLP}} : \ (V_{eN})$
$N_2 \to N_1\gamma \to (ejj)^{\mathrm{LLP}}\gamma : \ (d_{NN\gamma}, V_{eN})$



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

Solid: 3 events (95% C.L.)
Dashed: 10 events



Solid black: DV + prompt ℓ Cottin et al., 2105.13851

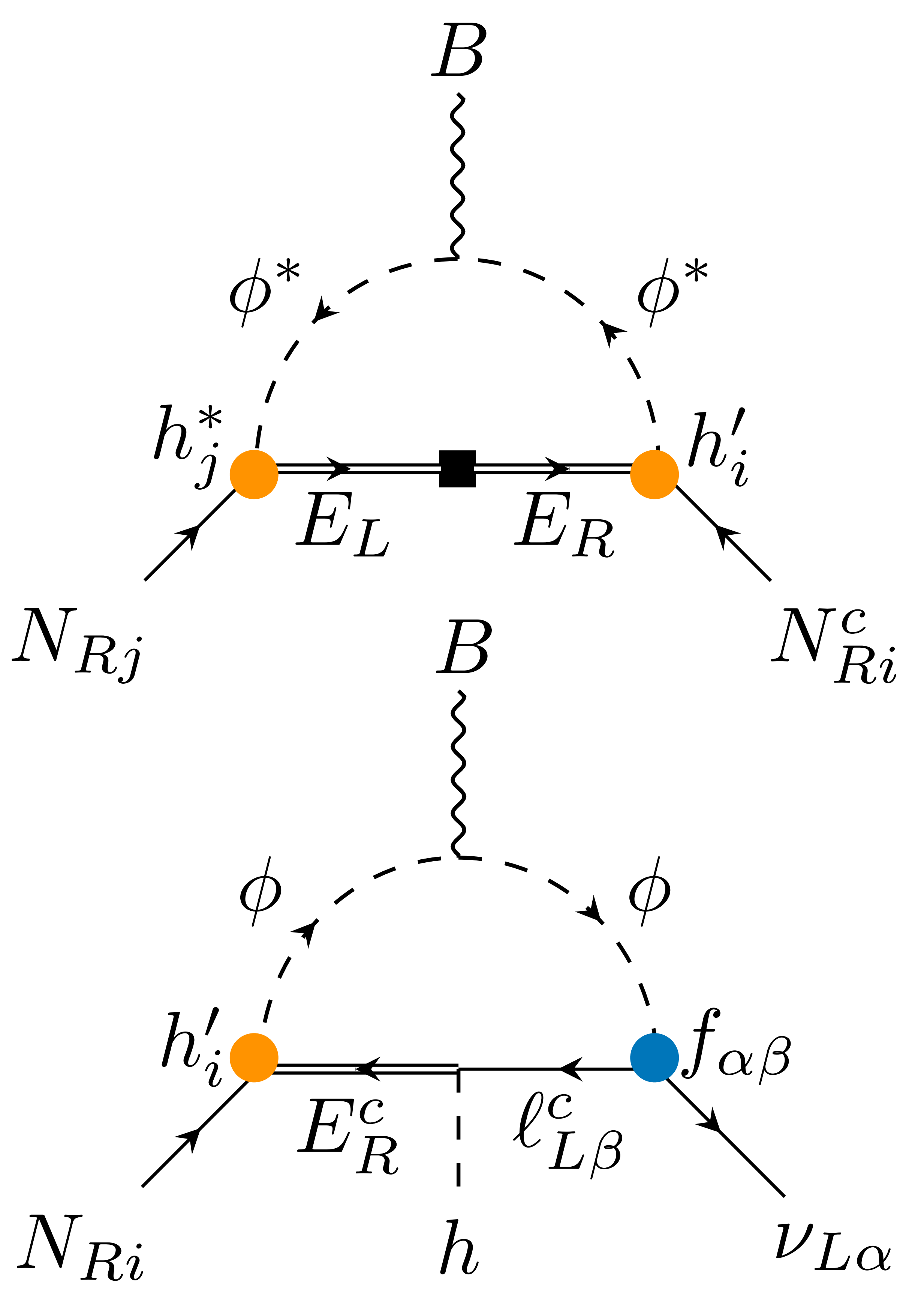
A Model Example:

Field(s)	Irrep	Couplings
N_R	$(\mathbf{1},\mathbf{1})_0$	Y_ν
E	$(\mathbf{1},\mathbf{1})_{-1}$	Y_E
ϕ	$(\mathbf{1},\mathbf{1})_{-1}$	$f,\ \lambda_{\phi H}$

Aparici, Kim, Santamaria, Wudka, 0904.3244

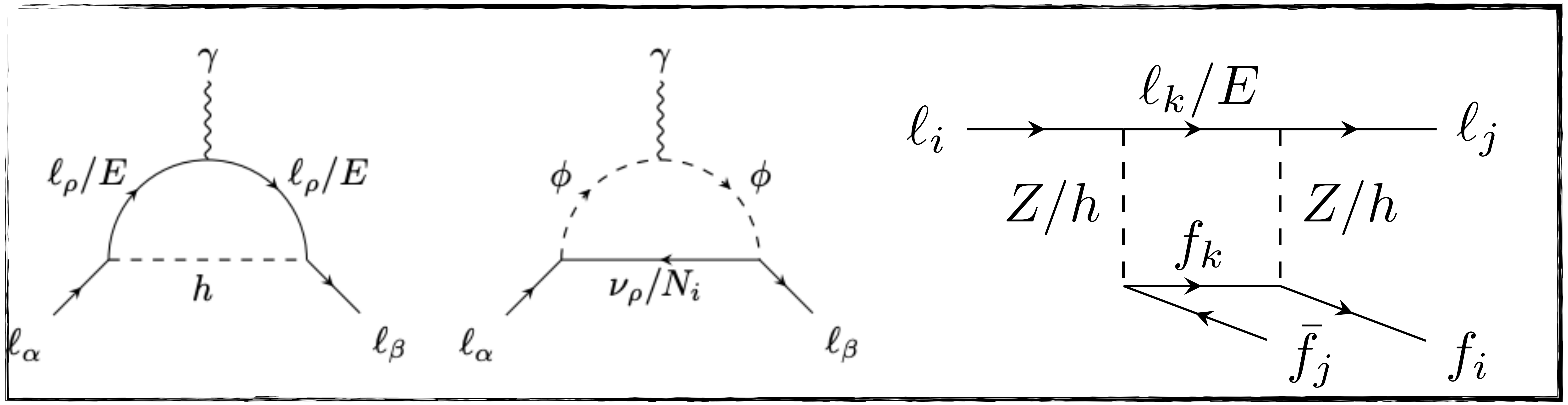
Aparici , Santamaria , Wudka, 0911.4103

“ $-Z_2$ ”



$$-\left[\bar{N}_R h E_L \phi^* + \bar{N}_R^c h' E_R \phi^* + \bar{L} Y_E H E_R + \bar{E}_L m_{eE} \ell_R + \bar{L} f \tilde{L} \phi + \bar{N}_R^c f' \ell_R \phi^* + \text{h.c.}\right]$$

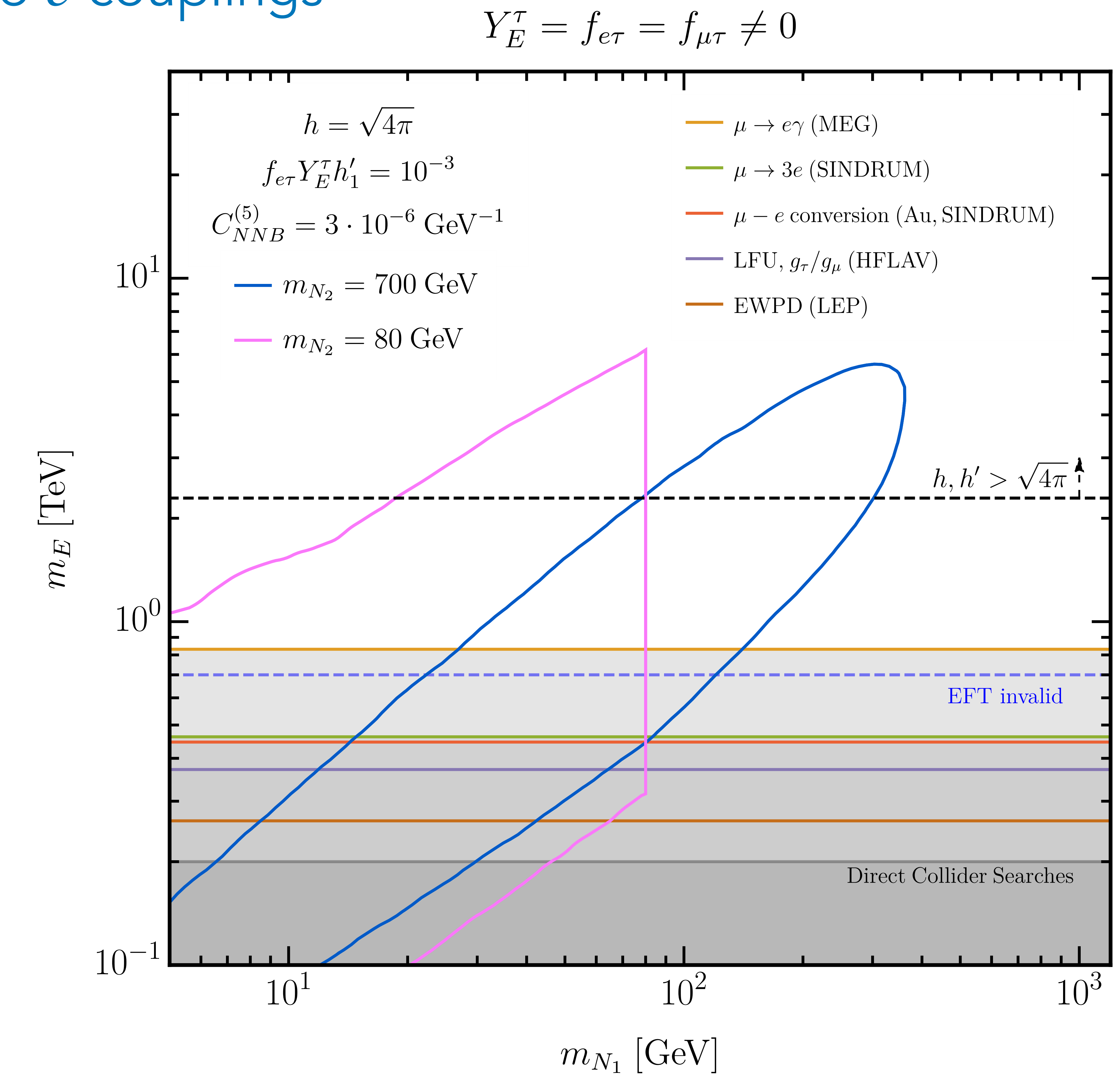
Charged Lepton Flavour Violation:



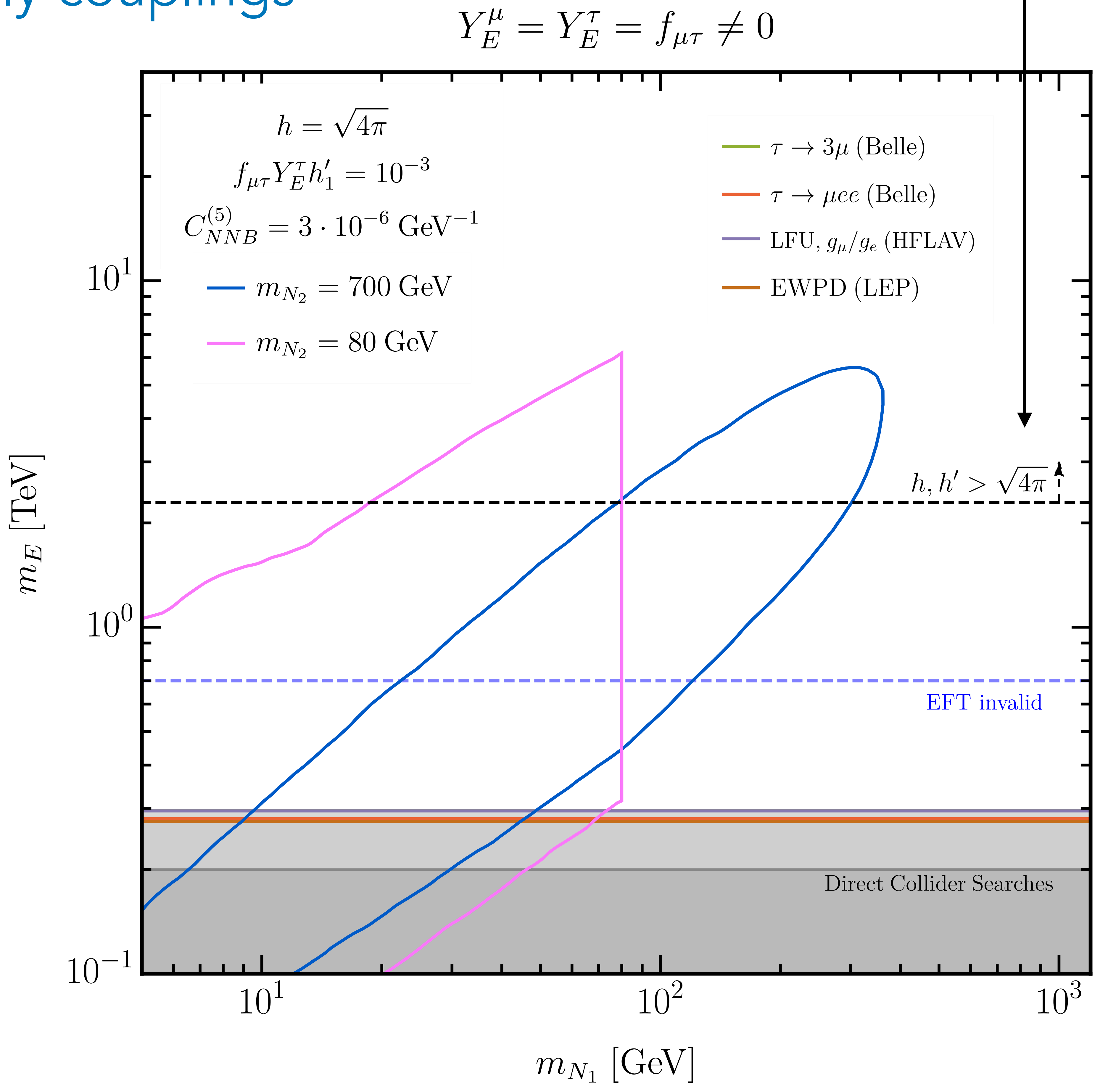
A case example of Active-to-Sterile moment

$h, h' > \sqrt{4\pi}$ to obtain $C^{(5)}_{NNB}$

No e couplings



τ only couplings



cLFV shows excellent complementary to LLP searches @ LHC

Take home:

- Non-pointing photons can explore new regions of parameter space for $d_{NN\gamma}$, $d_{\nu N\gamma}$ and $V_{\alpha N}$ @ LHC
- In realistic models complementarity with cLFV

Thank you for your attention!

Short url: https://indico.cern.ch/e/LLP_June_2025