Probing Heavy Neutrino Magnetic Moments at the LHC Using Non-Pointing Photon Signatures

Jožef Stefan Institute

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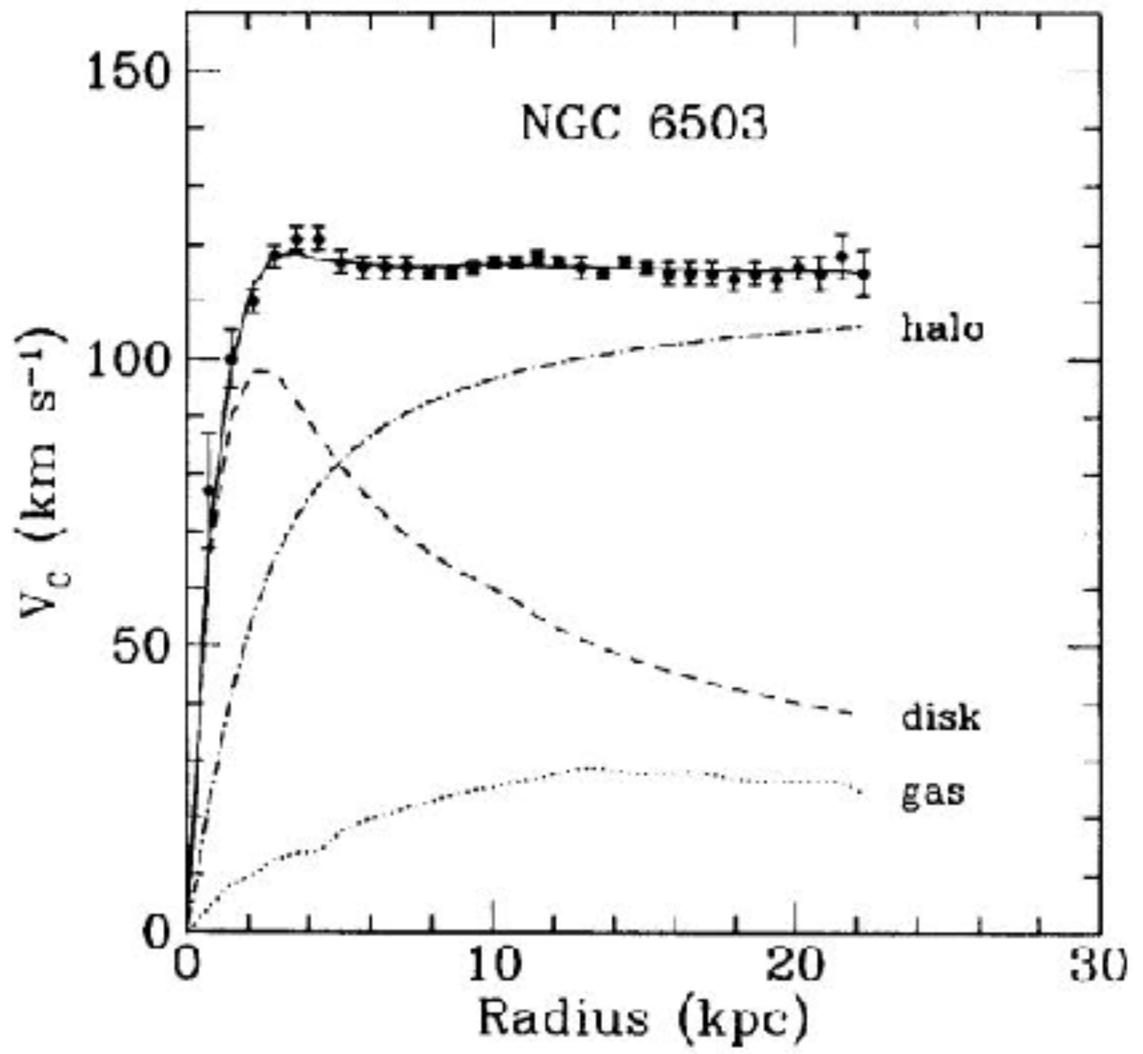
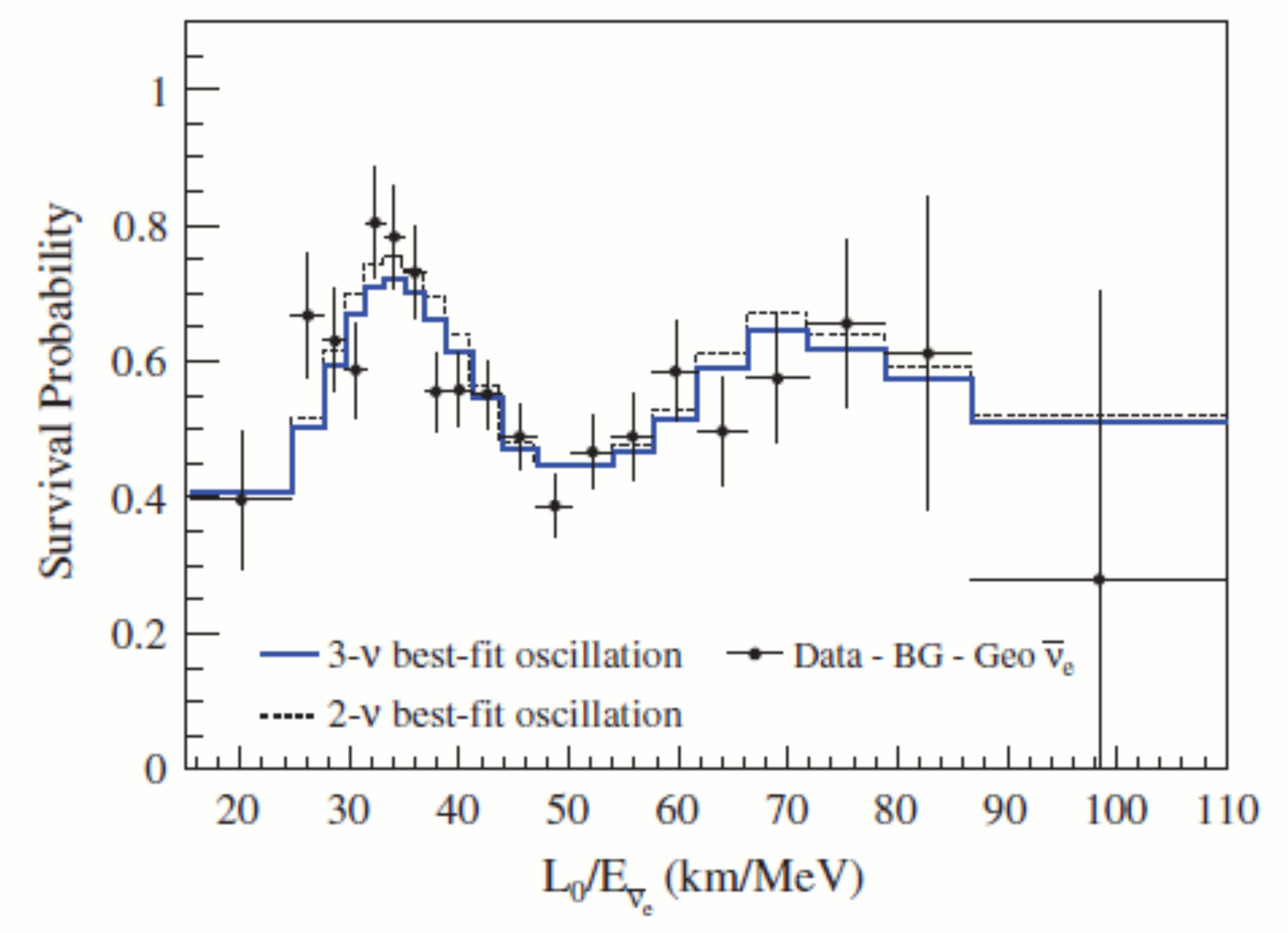
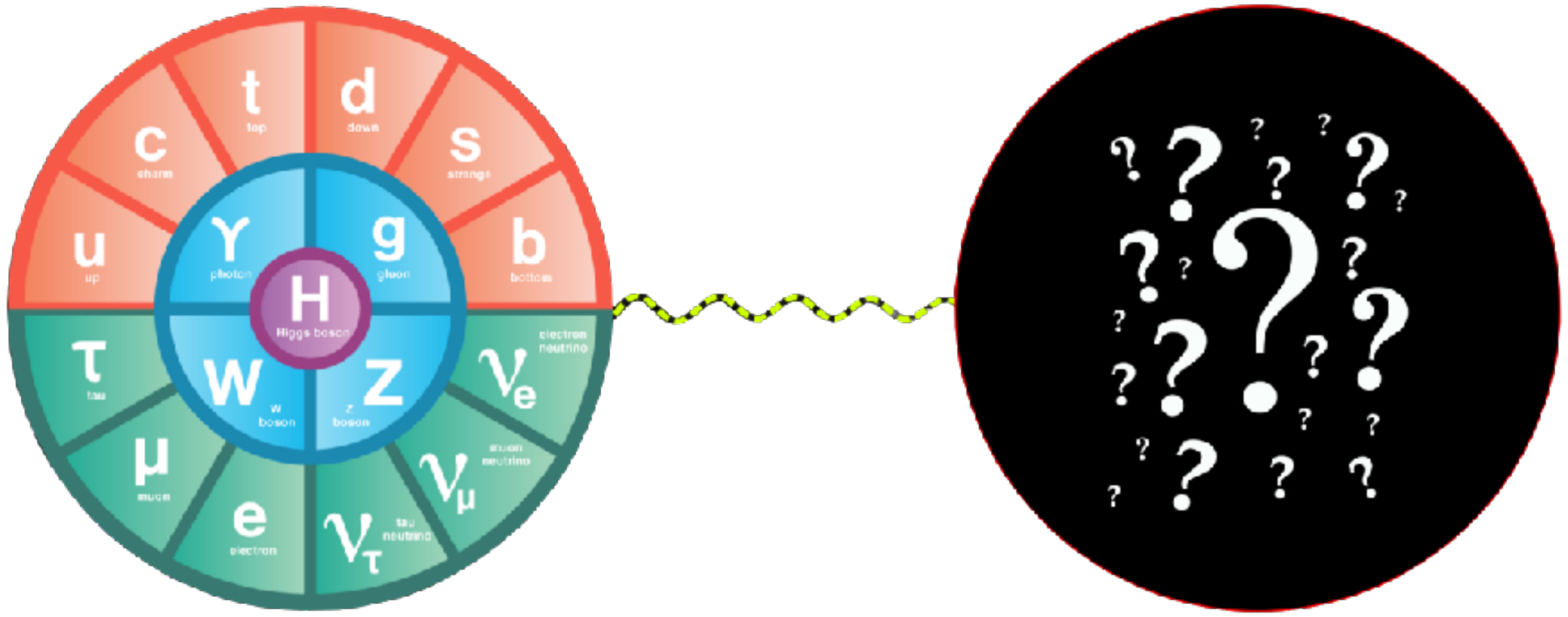
See: arXiv:2405.08877

Heavy Neutral Leptons - where and why?

Unsolved Problems







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Dark Matter

Neutrino Masses

Baryon Asymmetry

?

=

Hidden sector

[Graphic: Youngst@rs MITP Workshop]

Right-Handed Neutrinos

Consider N_R (SM gauge singlet), only $U(1)_L$ forbids a mass term:

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

Extended neutrino mass matrix:

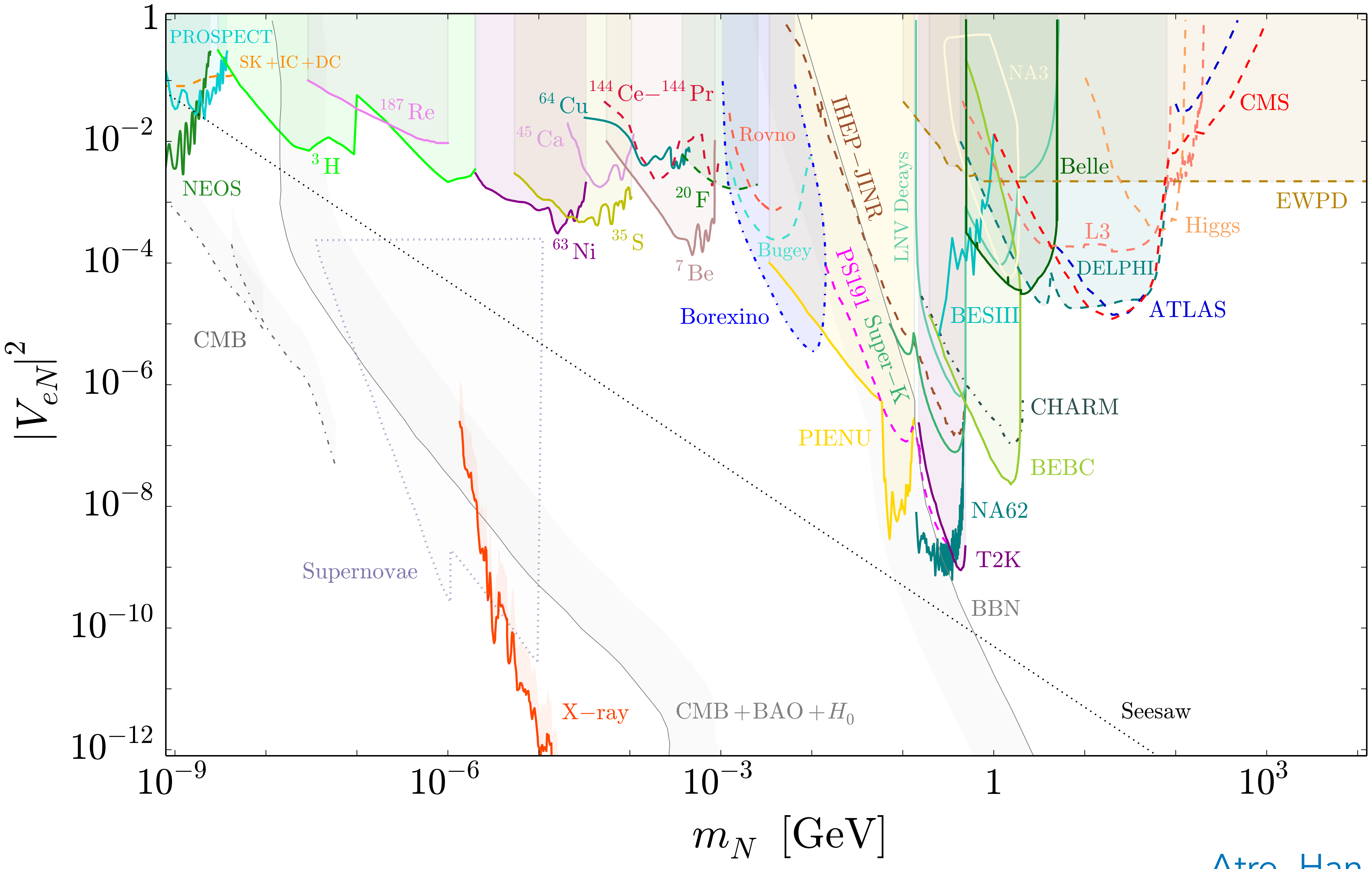
$$-\frac{1}{2}\begin{pmatrix}\bar{\nu}_L & \bar{N}_R^c\end{pmatrix}\begin{pmatrix}0 & M_D \\ M_D^T & M_R\end{pmatrix}\begin{pmatrix}\nu_L^c \\ N_R\end{pmatrix} + \mathrm{h.c.}\,, \quad M_D = \frac{v}{\sqrt{2}} Y_\nu$$

Diagonalise: 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 seesaw) or pseudo-Dirac (inverse seesaw) fermions

Active-Sterile Mixing Phenomenology



$$\mathcal{L} \supset \left[-\frac{g}{\sqrt{2}} V_{\alpha N_i} \bar{\ell}_\alpha \slashed{W} P_L N_i + \text{h.c.}\right] - \frac{g}{2c_W}\left[V_{\alpha N_i} \bar{\nu}_\alpha \slashed{Z} P_L N_i + V^*_{\alpha N_i} V_{\alpha N_j} \bar{N}_i \slashed{Z} P_L N_j\right]$$

Atre, Han, Pascoli, Zhang, 0901.3589

Bondarenko et al., 1805.08567

PDB, Deppisch, Dev, 1912.03058

Coloma et al., 2007.03701

Beyond the Renormalisable: SMEFT + N_R

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

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

Λ

$E \ll \Lambda$

$SU(3)_c \times SU(2)_L \times U(1)_Y$ with N_R (N_RSMEFT)

$v = 246$ GeV

N_R can only couple to invariant combinations of SM fields

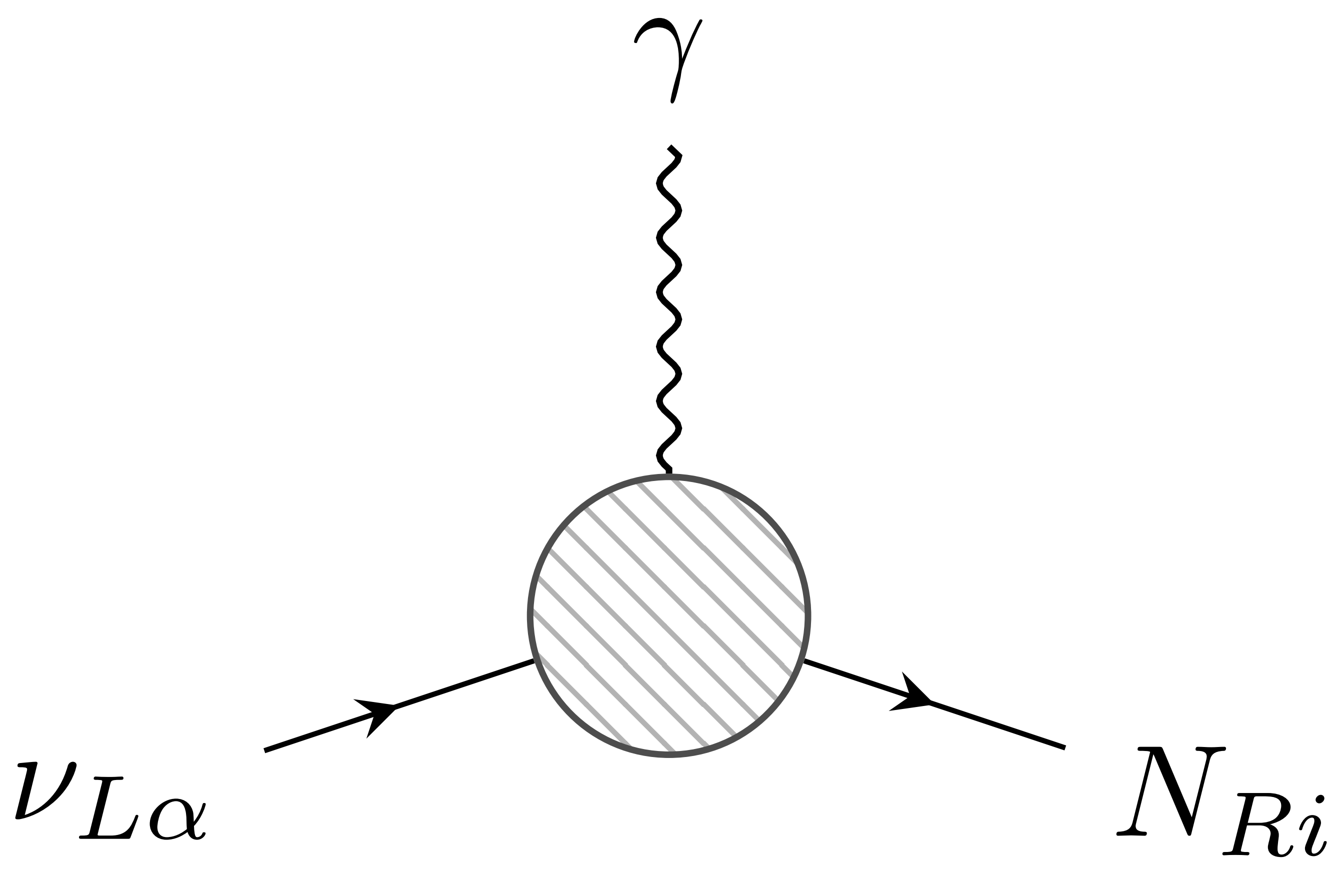
$E \ll m_W, m_Z, m_h, m_t$

$SU(3)_c \times U(1)_Q$ with N_R (N_RLEFT)

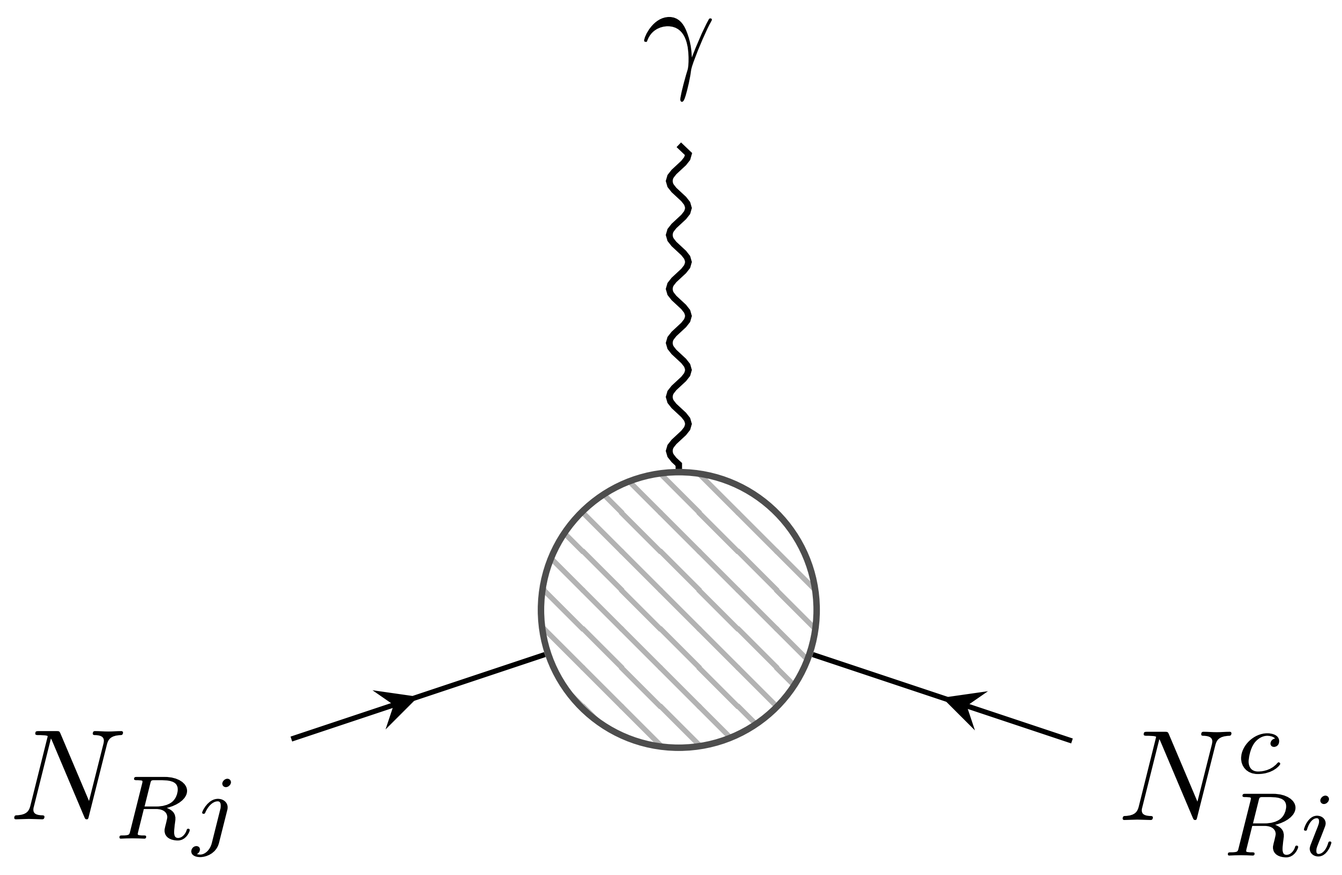
Active-to-Sterile and Sterile-to-Sterile Neutrino Magnetic Moments

In the N_RLEFT, magnetic moments of RH fields are described by the operators:

$$\mathcal{O}_{\nu N\gamma} = (\bar{\nu}_L \sigma_{\mu\nu} N_R) F^{\mu\nu}$$



$$\mathcal{O}_{NN\gamma} = (\bar{N_R^c} \sigma_{\mu\nu} N_R) F^{\mu\nu}$$



Phenomenology:

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

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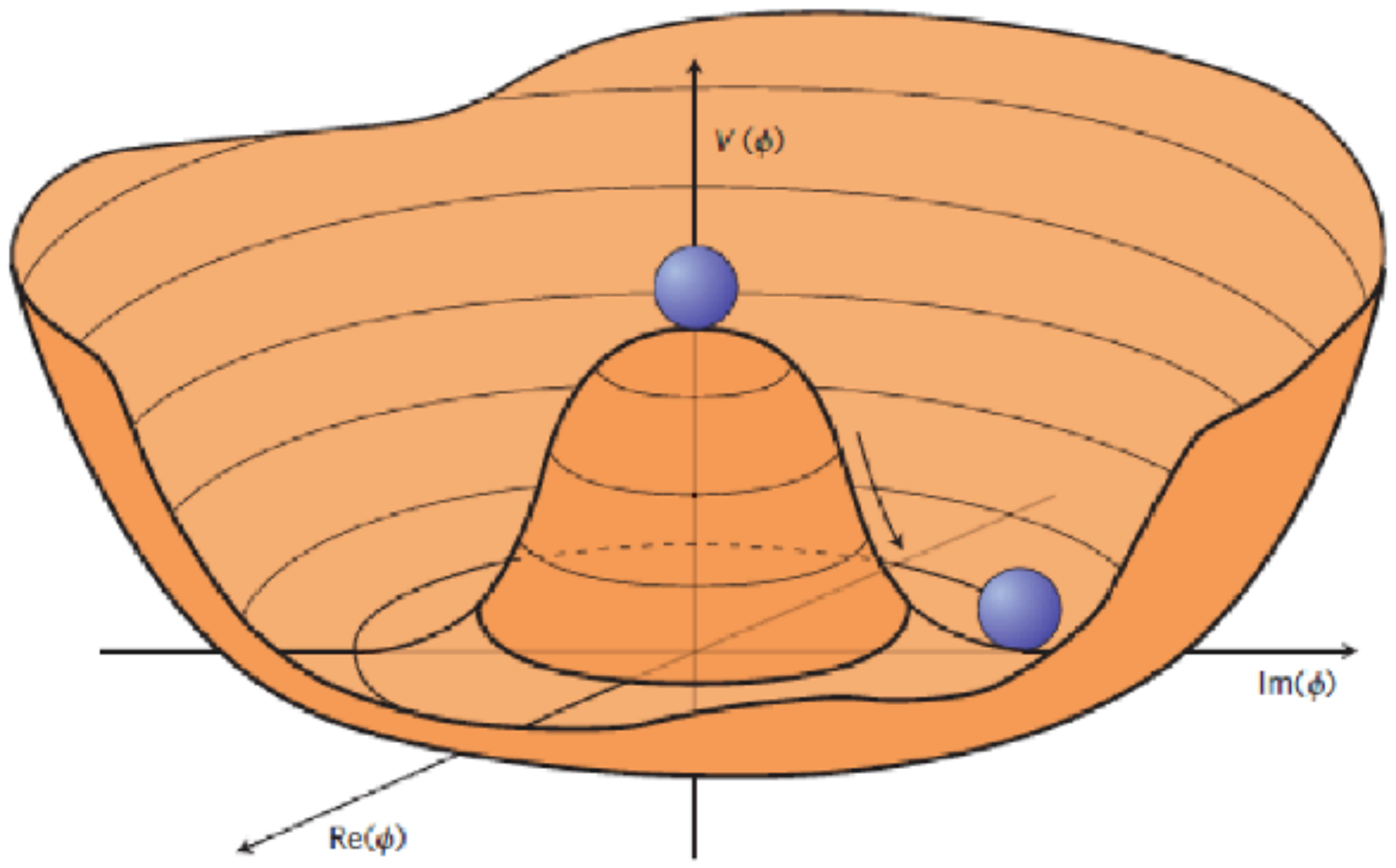
From the SMEFT

These are induced by the N_RSMEFT operators:

$$\mathcal{O}^{(5)}_{NNB} = (\bar{N}^c_R \sigma_{\mu\nu} N_R) B^{\mu\nu}$$

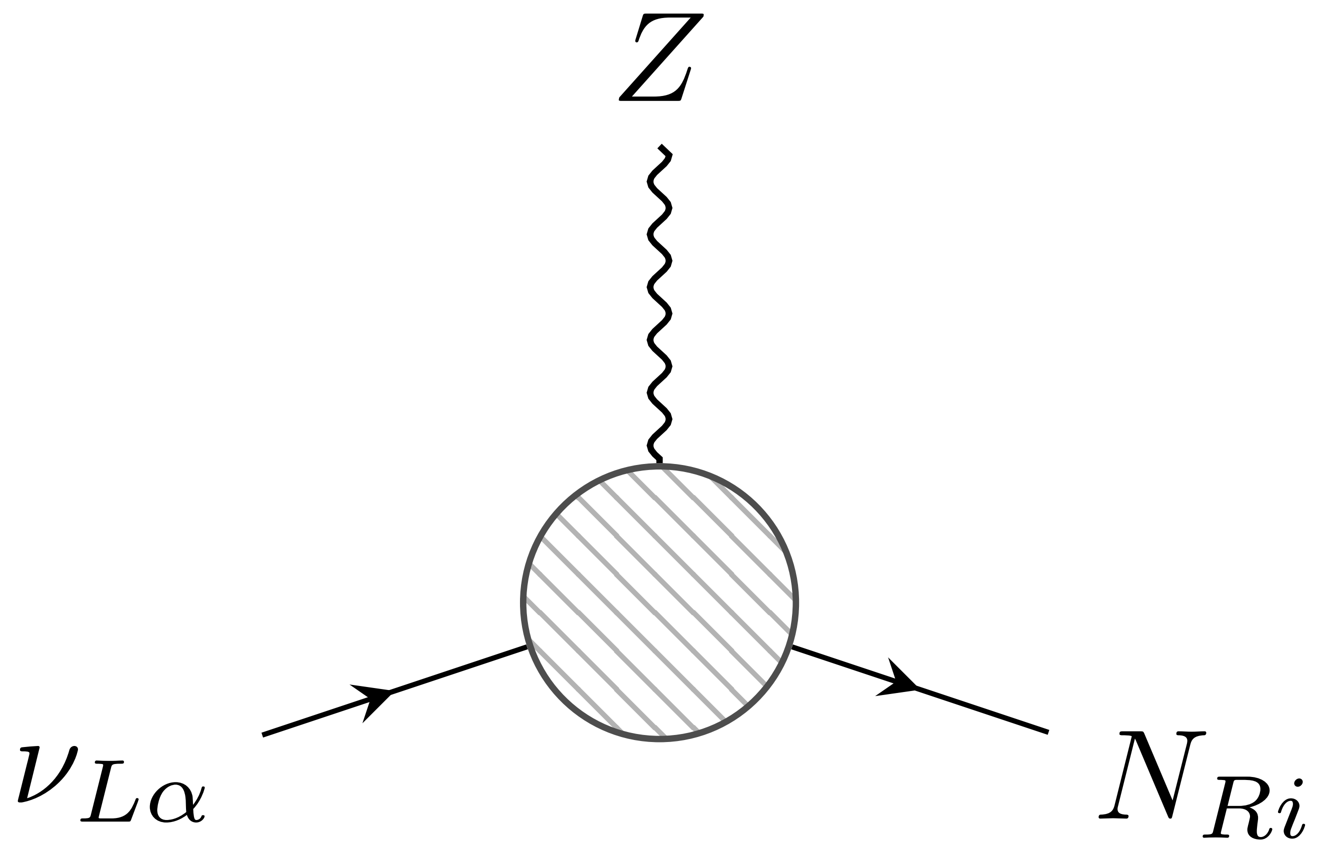
$$\mathcal{O}^{(6)}_{NB} = (\bar{L}\sigma_{\mu\nu} N_R)\tilde{H} B^{\mu\nu} \qquad \mathcal{O}^{(6)}_{NW} = (\bar{L}\sigma_{\mu\nu} N_R)\tau^I \tilde{H} W^{I\mu\nu}$$



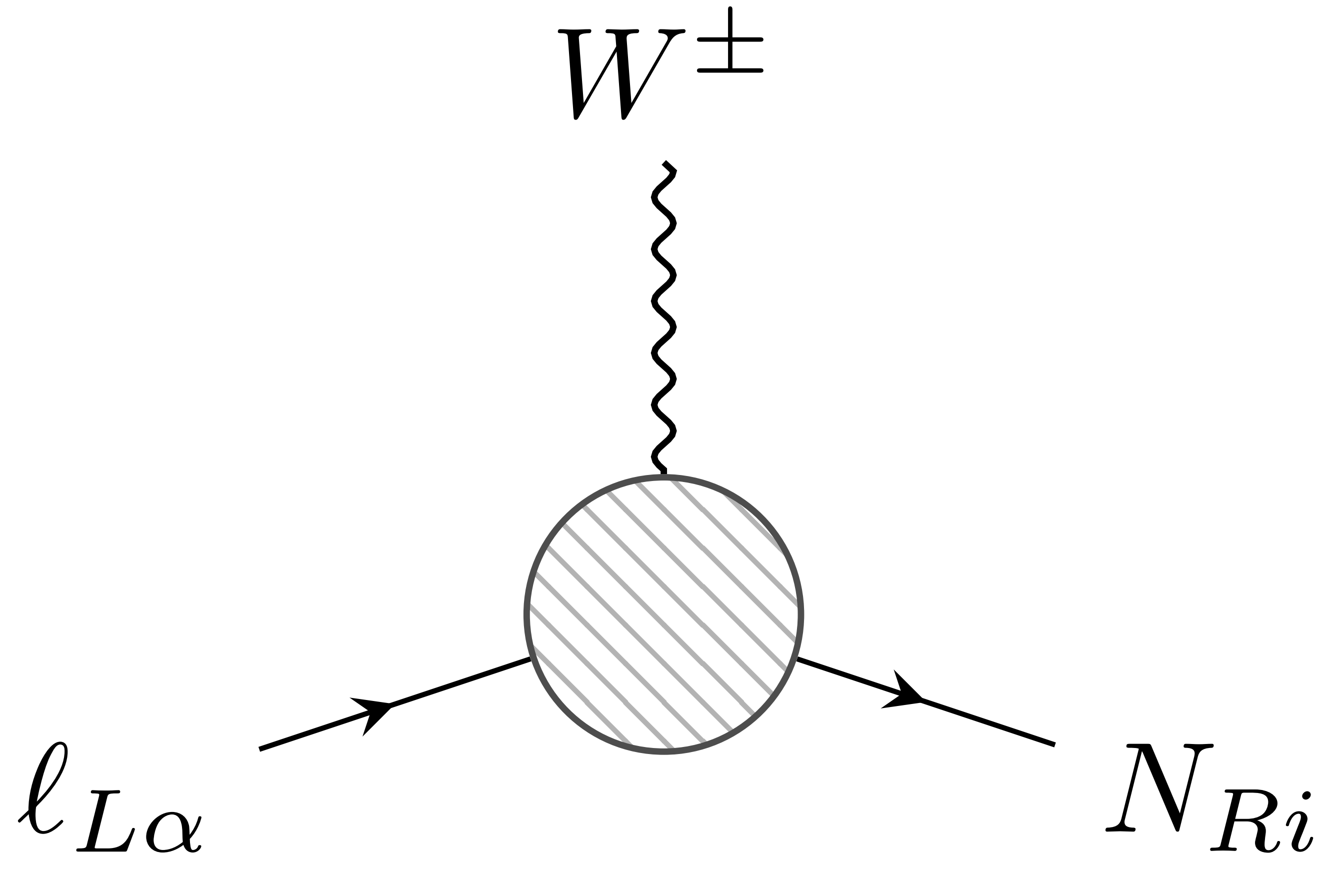
$$H = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v+h \end{pmatrix} \longrightarrow \quad d^{ij}_{NN\gamma} = c_w C^{(5)ij}_{NNB} \quad d^{\alpha i}_{\nu N\gamma} = \frac{v}{\sqrt{2}}\left(c_w C^{(6)\alpha i}_{NB} + \frac{s_w}{2} C^{(6)\alpha i}_{NW}\right)$$

Electroweak Dipole Moments

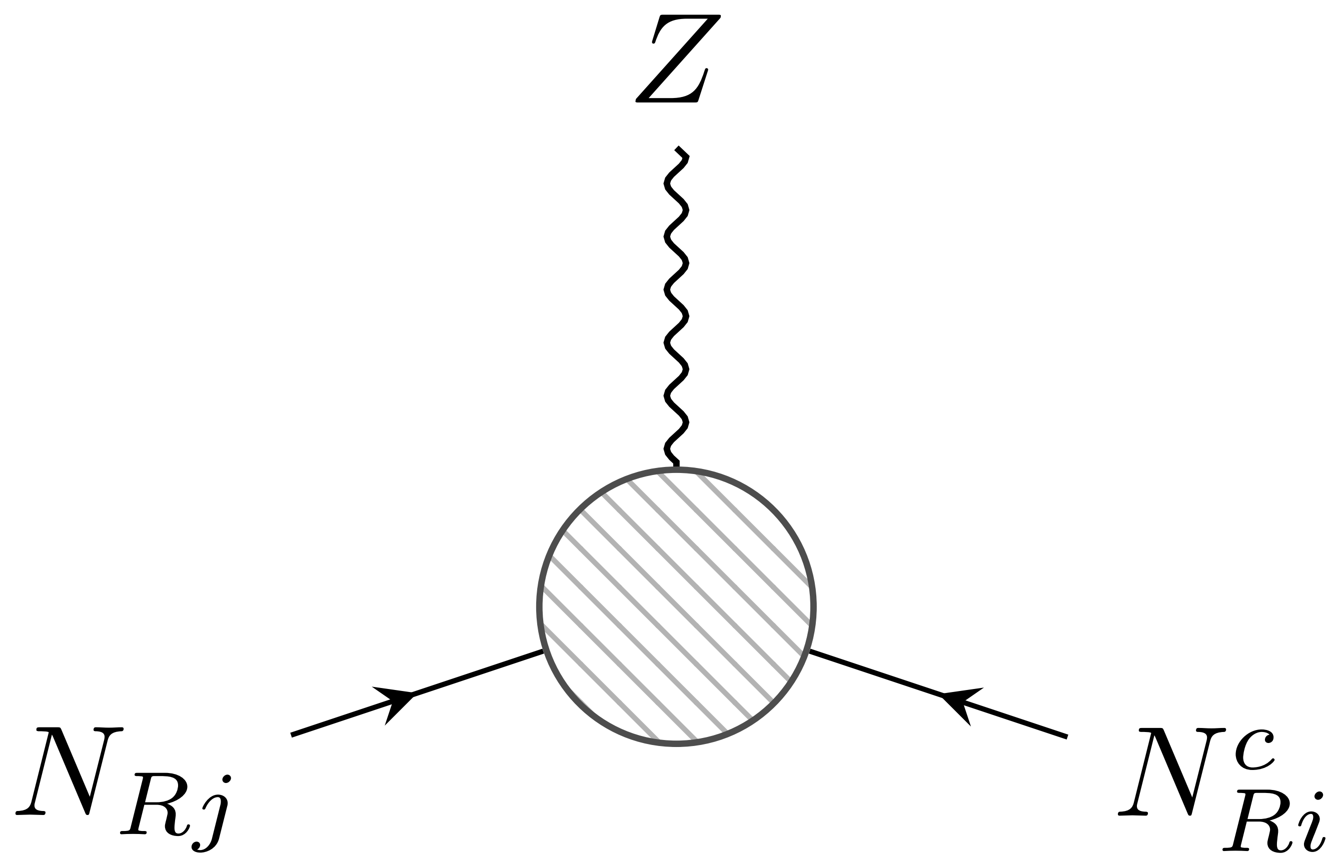
For high-energy collider processes, also relevant are



$$\mathcal{O}_{\nu N Z} = (\bar{\nu}_L \sigma_{\mu\nu} N_R) Z^{\mu\nu}$$



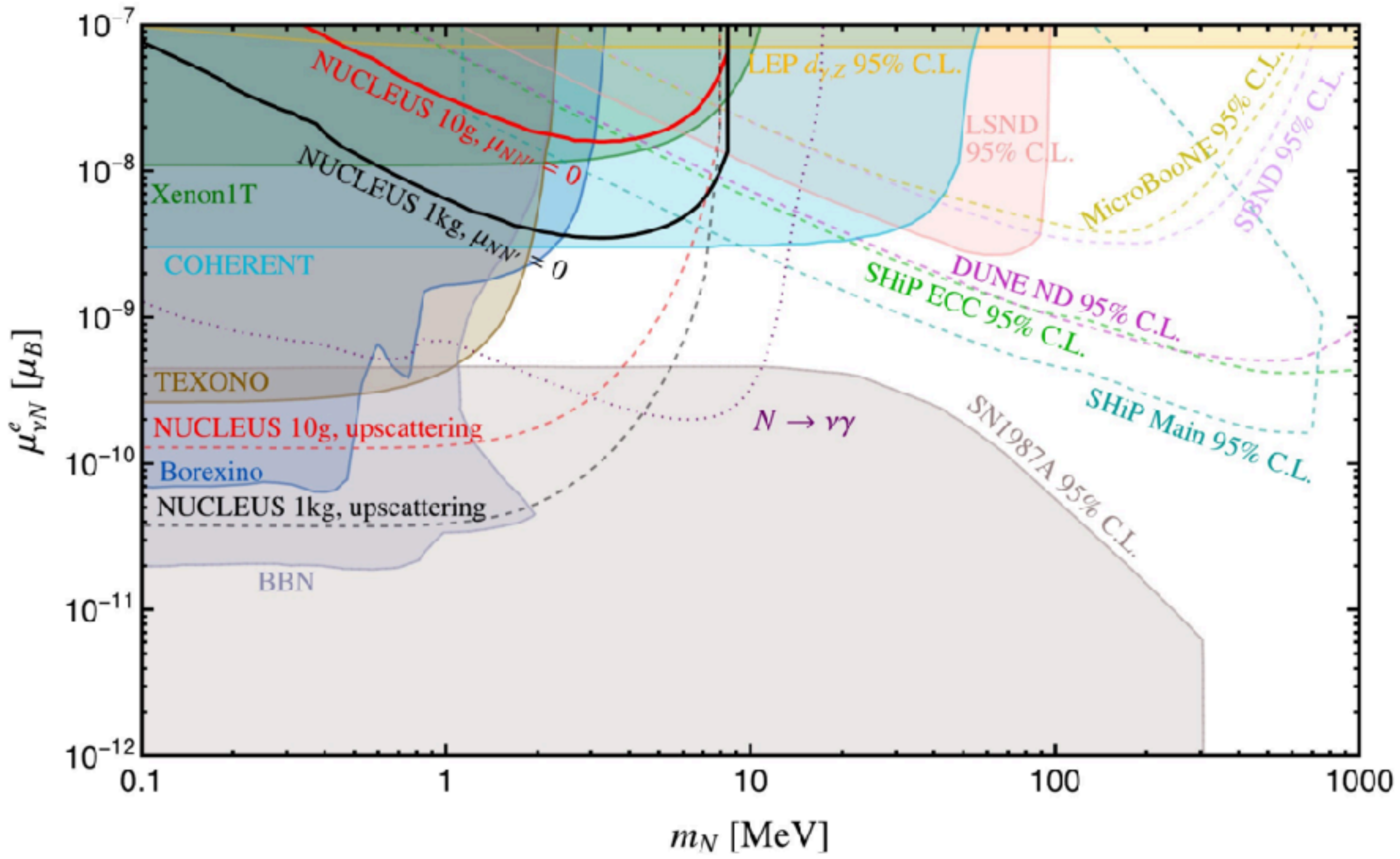
$$\mathcal{O}_{\ell N W} = (\bar{\ell}_L \sigma_{\mu\nu} N_R) W^{\mu\nu}$$



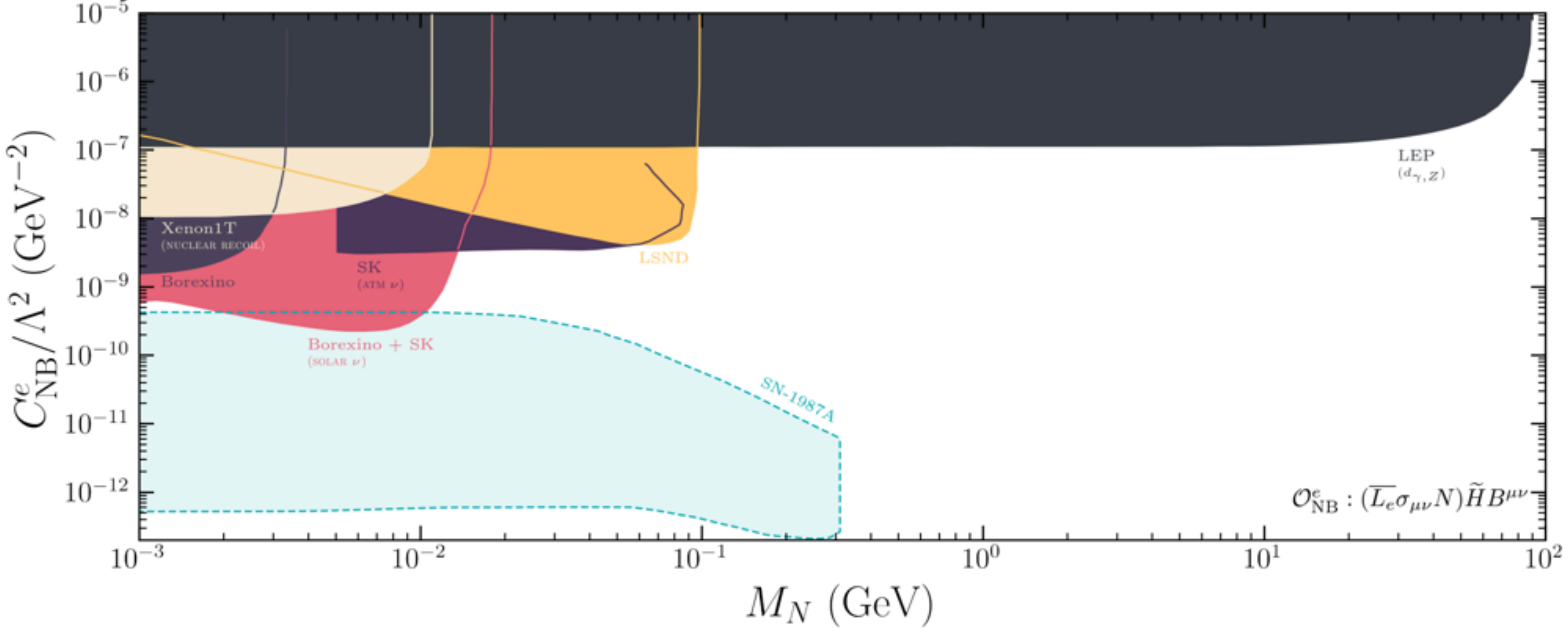
$$\mathcal{O}_{N N Z} = (\bar{N}^c_R \sigma_{\mu\nu} N_R) Z^{\mu\nu}$$

Current Bounds: Active-Sterile Dipole Moments

PDB, Deppisch, Fridell, Harz, Hati, Kulkarni, 2110.02233



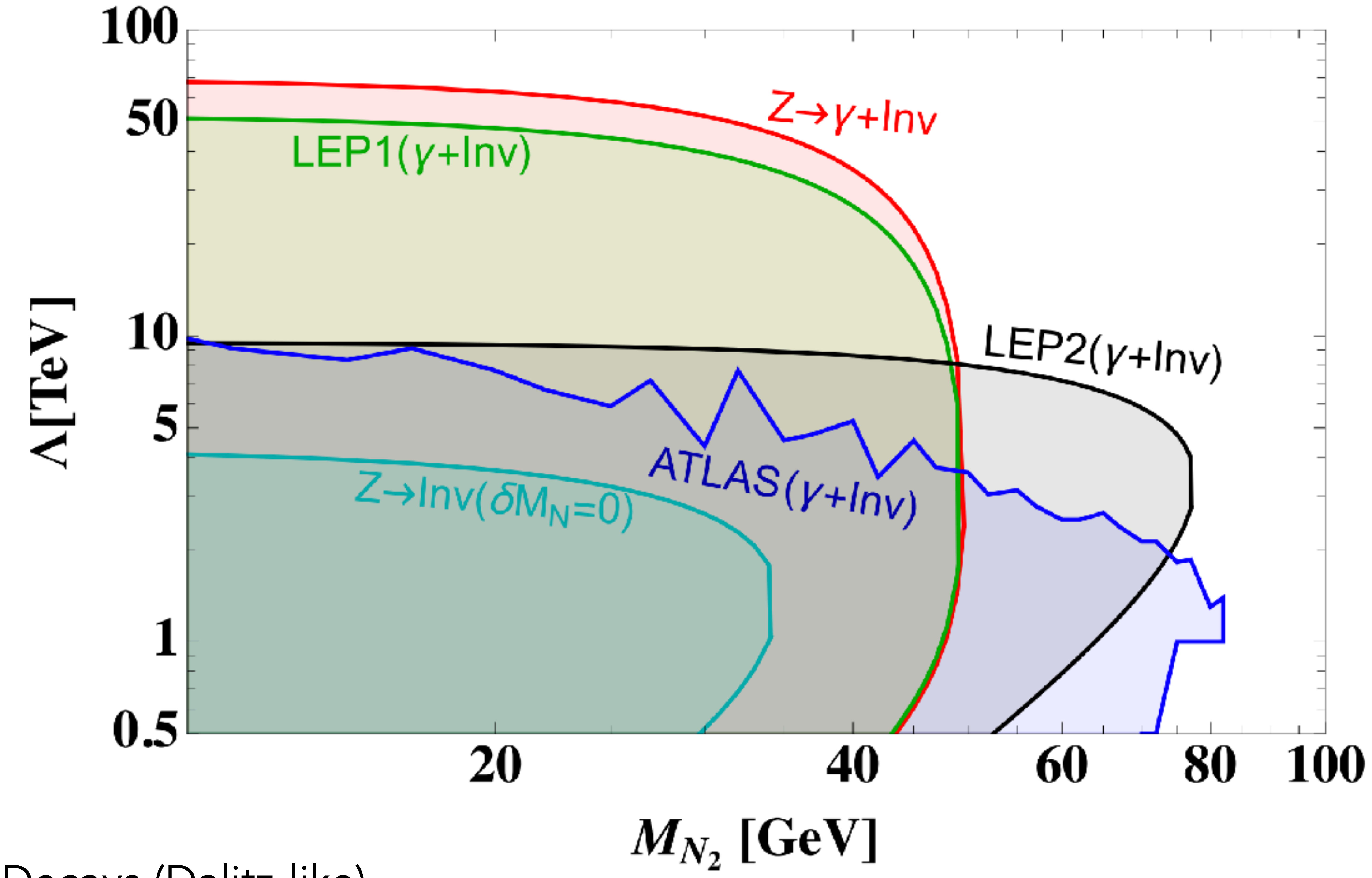
Fernández-Martínez et al., 2304.06772



- 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

Current Bounds: Sterile-Sterile Dipole Moments



$$C^{(5)}_{NNB} = \frac{1}{\Lambda}$$

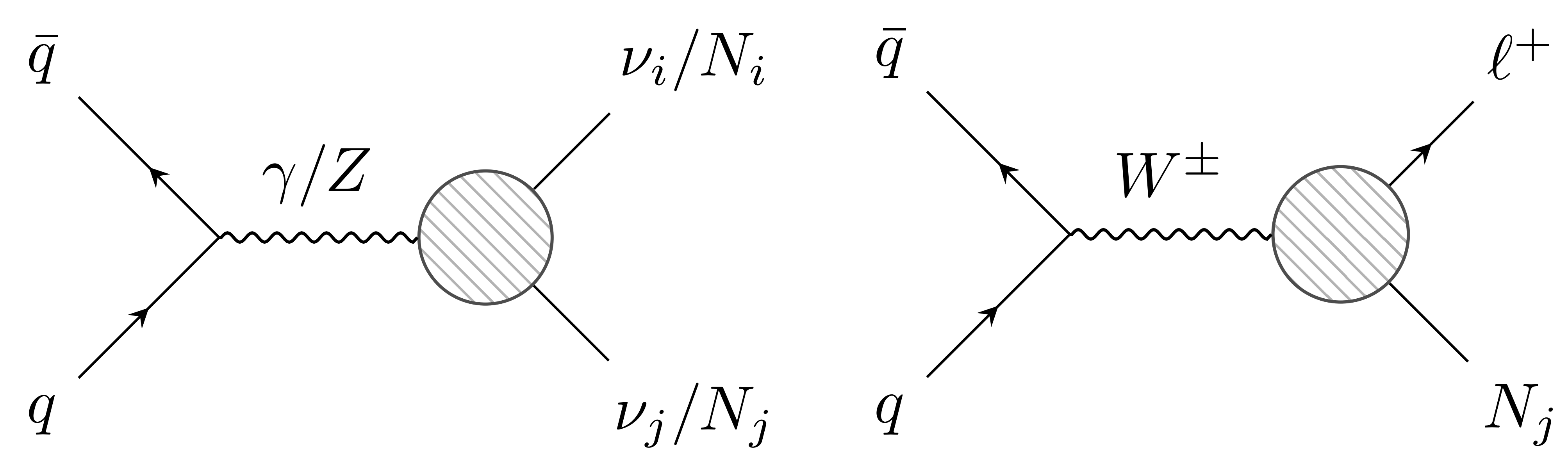
Bounds depend on $m_{N_2} - m_{N_1}$

- Meson Decays (Dalitz-like)
- Supernova cooling (SN1987A)
- Monophoton + E_T^{miss}, Γ_Z^{inv}, at LEP, LHC

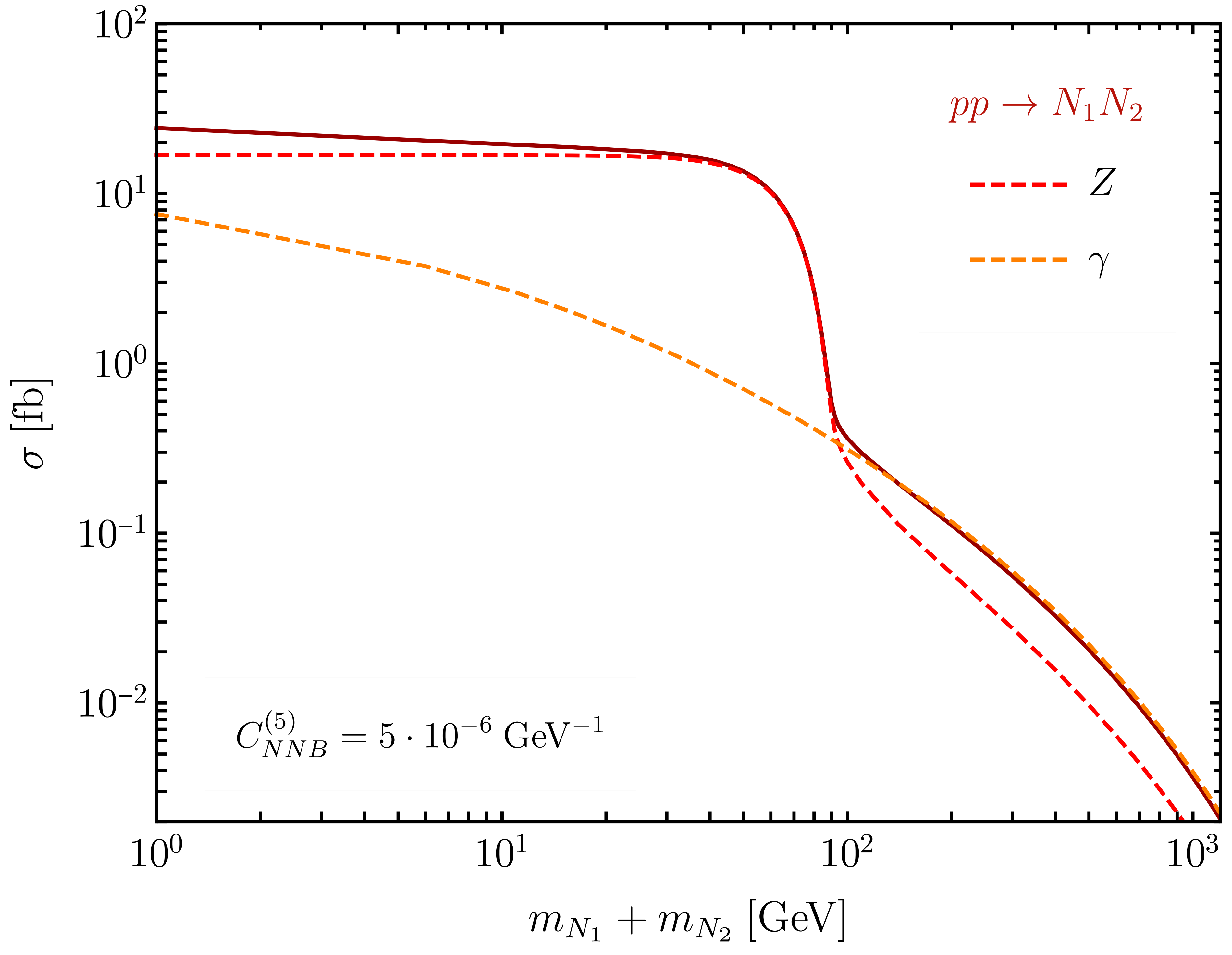
Delgado, Duarte, Jones-Pérez, Manrique-Chavil, Pēna, 2205.13550
Barducci, Bertuzzo, Taoso, Toni, 2209.13469
Chun, Mandal, Padhan, 2401.05174

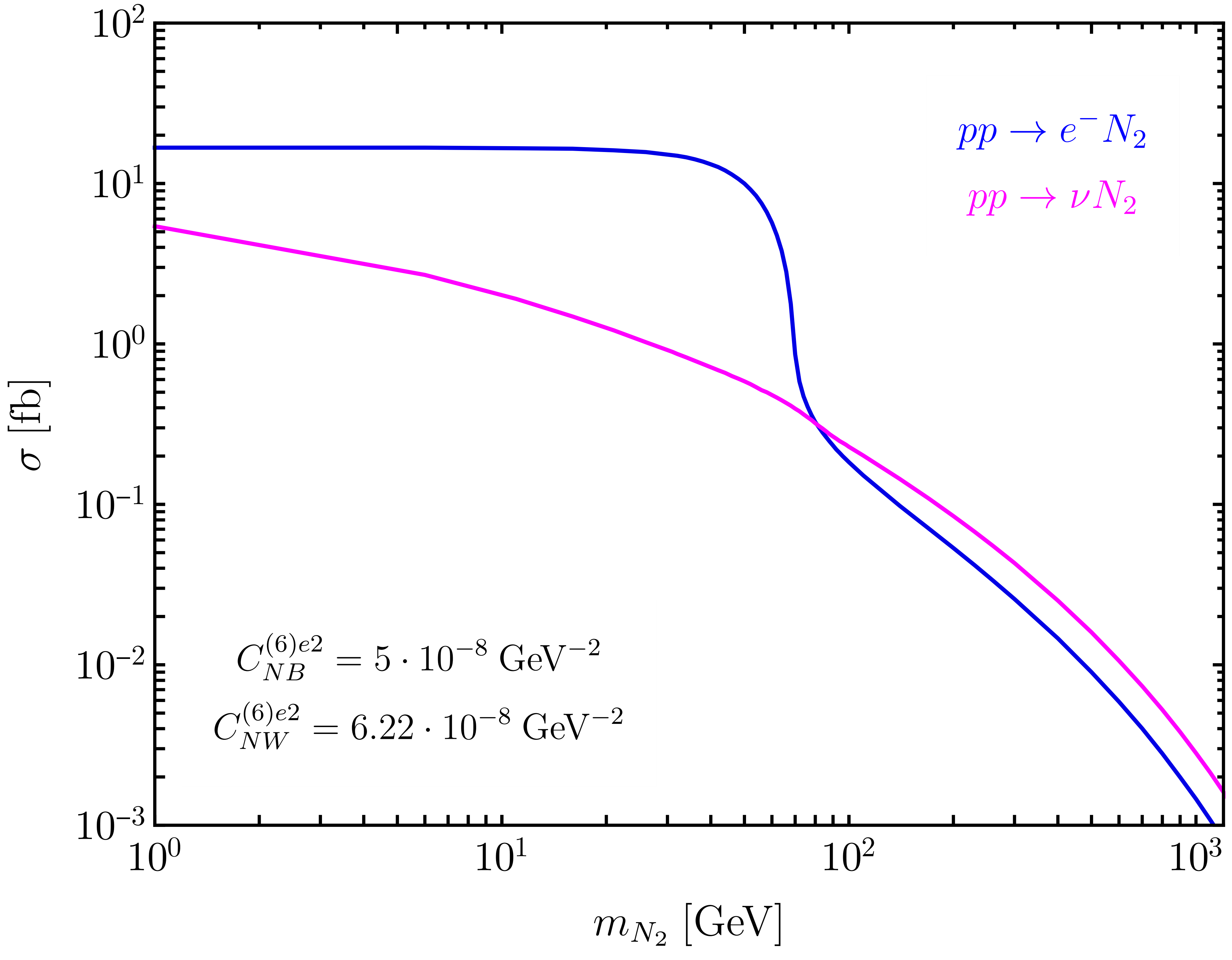
Displaced Vertex Searches with Non-Pointing Photons at LHC

HNL Production

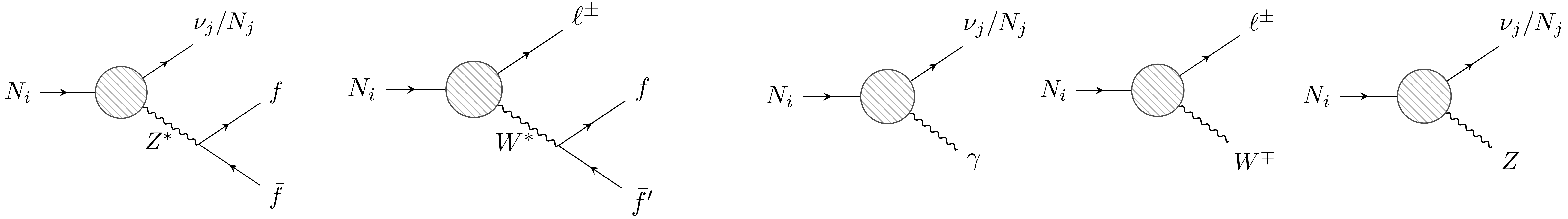


$$d\sigma(pp \to N_i N_j X) = \sum_q \int_0^1 dx_1 \int_0^1 dx_2 \left(f_q(x_1, \hat{s}) f_{\bar{q}}(x_2, \hat{s}) + q \leftrightarrow \bar{q}\right) d\hat{\sigma}(q\bar{q} \to N_1 N_2)$$

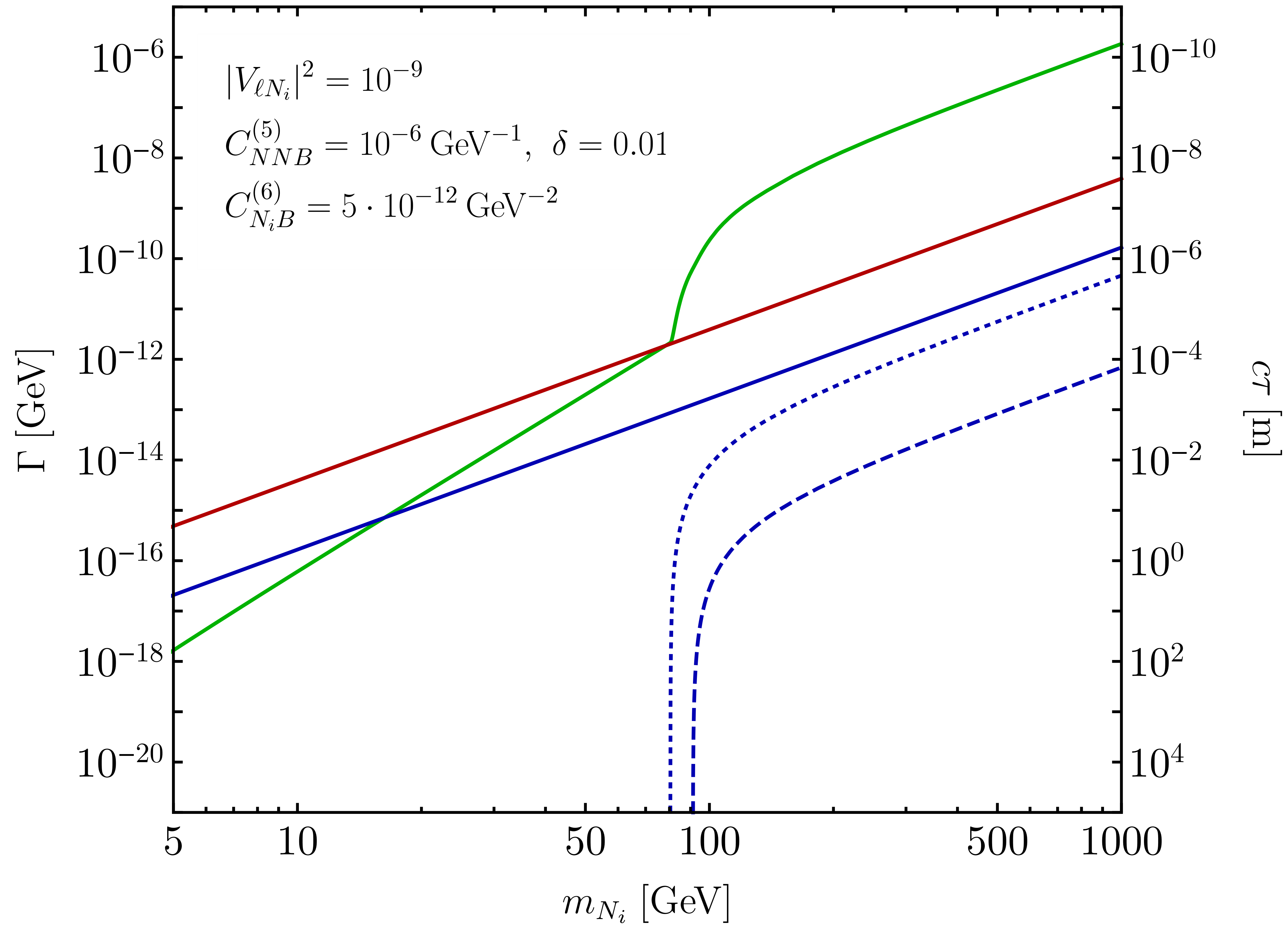




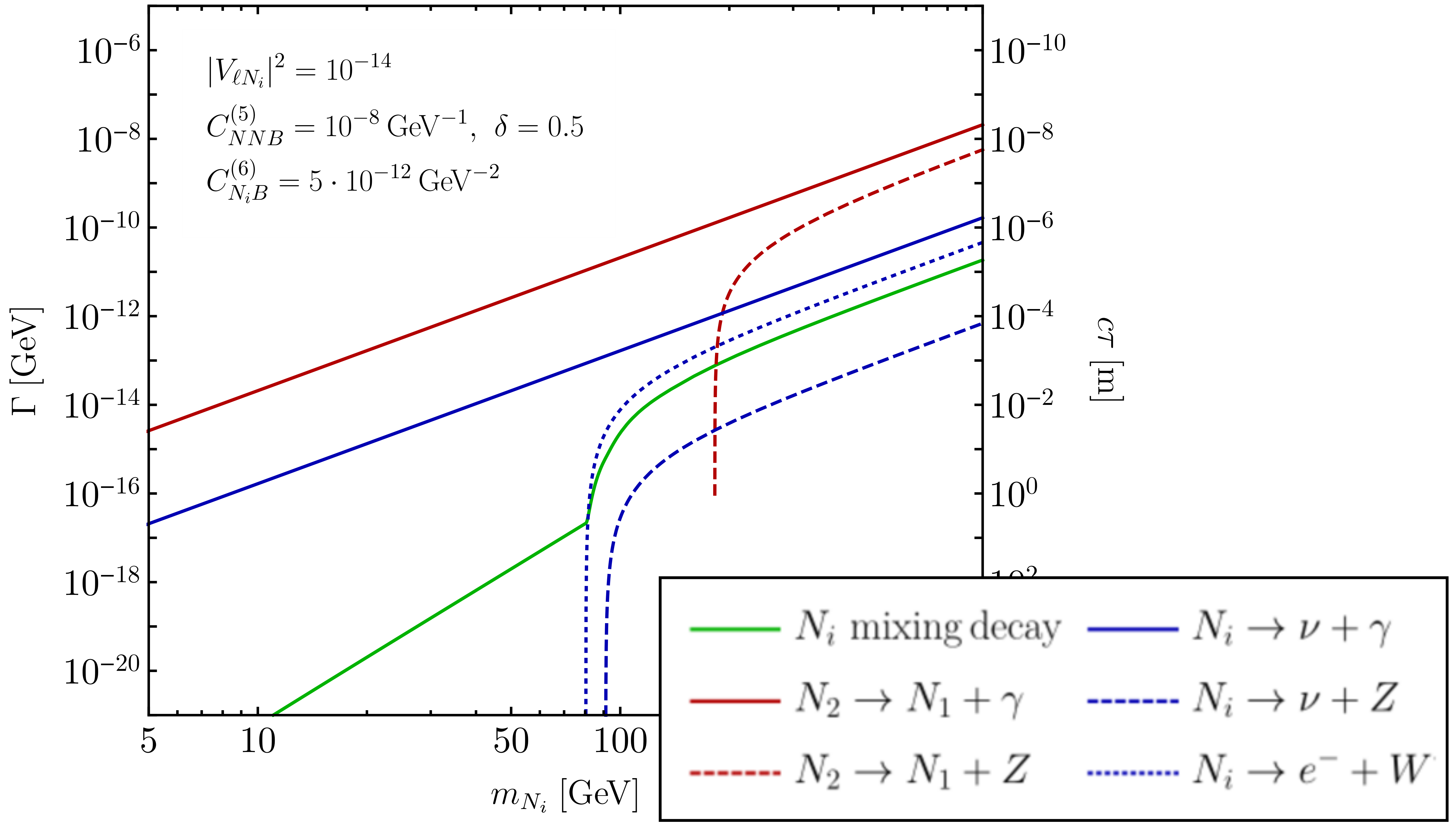
HNL Decays



N_i
ν_j/N_j
Z^*
f
$\bar{f}$
N_i
$\ell^\pm$
W^*
f
$\bar{f}'$
N_i
ν_j/N_j
γ
N_i
$\ell^\pm$
$W^\mp$
N_i
ν_j/N_j
Z



$|V_{\ell N_i}|^2 = 10^{-9}$
$C^{(5)}_{NNB} = 10^{-6}\,\mathrm{GeV}^{-1},\ \delta = 0.01$
$C^{(6)}_{N_iB} = 5 \cdot 10^{-12}\,\mathrm{GeV}^{-2}$
Γ [GeV]
$c\tau$ [m]
m_{N_i} [GeV]

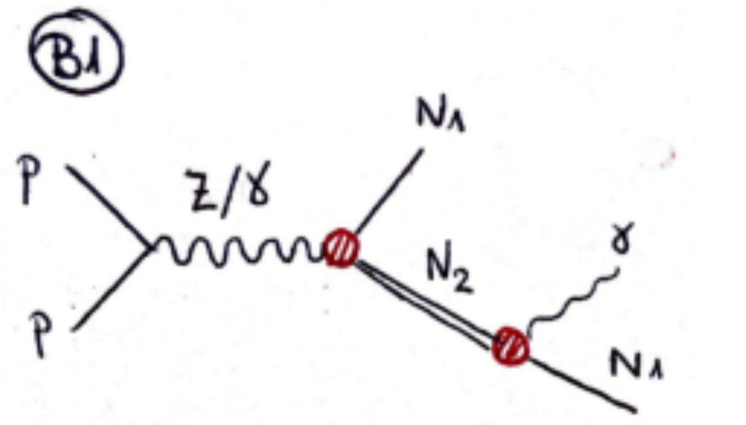
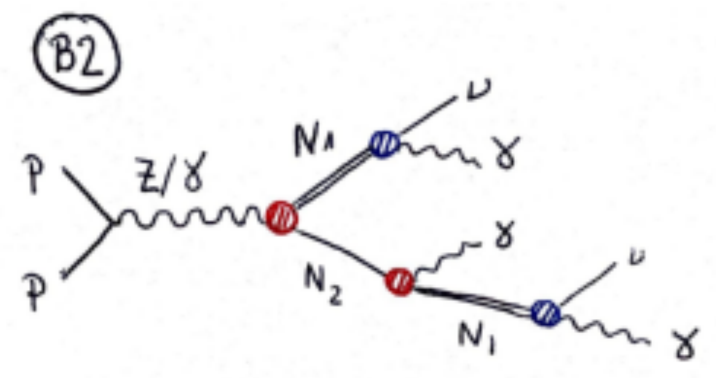
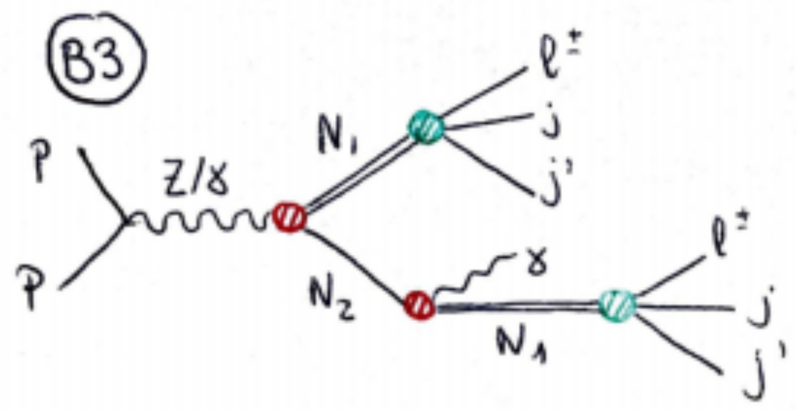
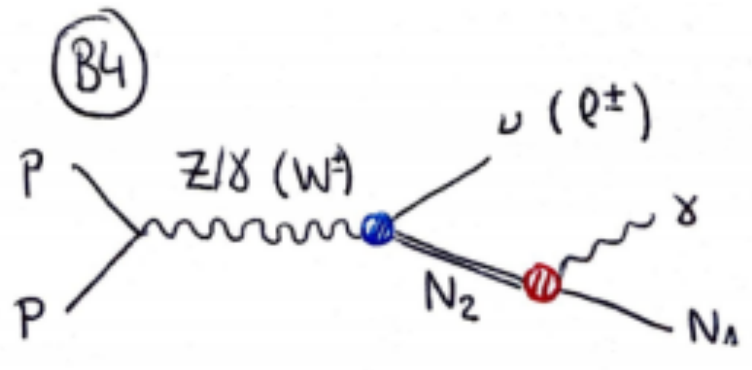
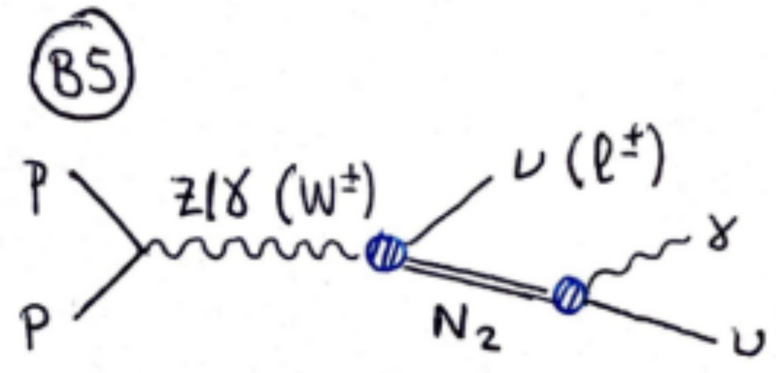
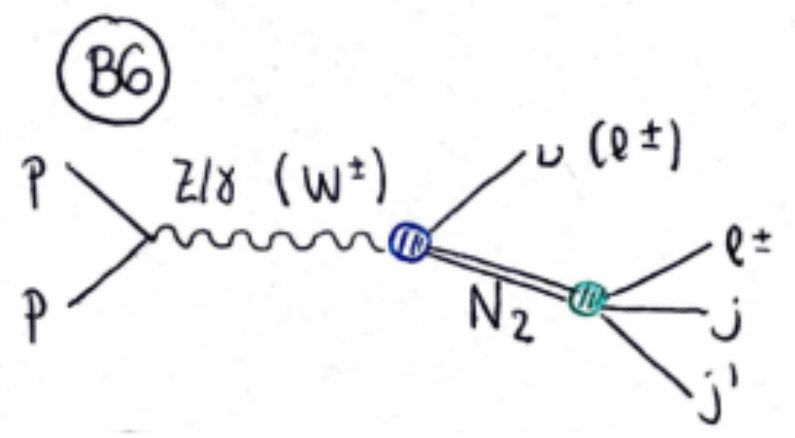
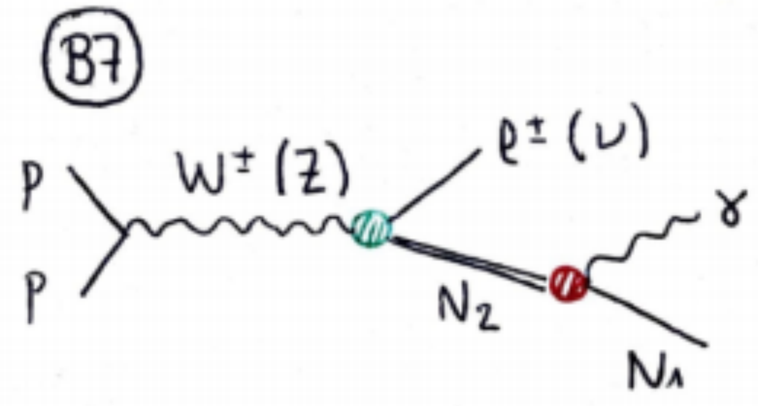
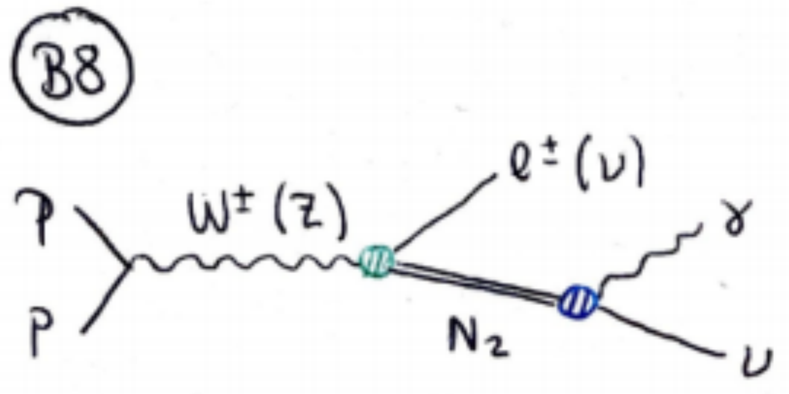


$|V_{\ell N_i}|^2 = 10^{-14}$
$C^{(5)}_{NNB} = 10^{-8}\,\mathrm{GeV}^{-1},\ \delta = 0.5$
$C^{(6)}_{N_iB} = 5 \cdot 10^{-12}\,\mathrm{GeV}^{-2}$
Γ [GeV]
$c\tau$ [m]
m_{N_i} [GeV]
N_i mixing decay
$N_i \to \nu + \gamma$
$N_2 \to N_1 + \gamma$
$N_i \to \nu + Z$
$N_2 \to N_1 + Z$

Possible Scenarios

With active-sterile mixing ($V_{\alpha N}$), active-to-sterile dipole moments ($C^{(6)}_{NB}$) and sterile-to-sterile moments ($C^{(5)}_{NNB}$)

↳ Each coupling can dominate production and decay (limiting cases are taken as 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

Production and decay via mixing $V_{\alpha N}$

Displaced Vertex Signatures: Non-Pointing Photons

Non-pointing photons can be emitted in the decay of LLP N

↳ Occur at secondary vertex, displaced from primary vertex (PV)

↳ Motivation: Significantly reduce SM backgrounds

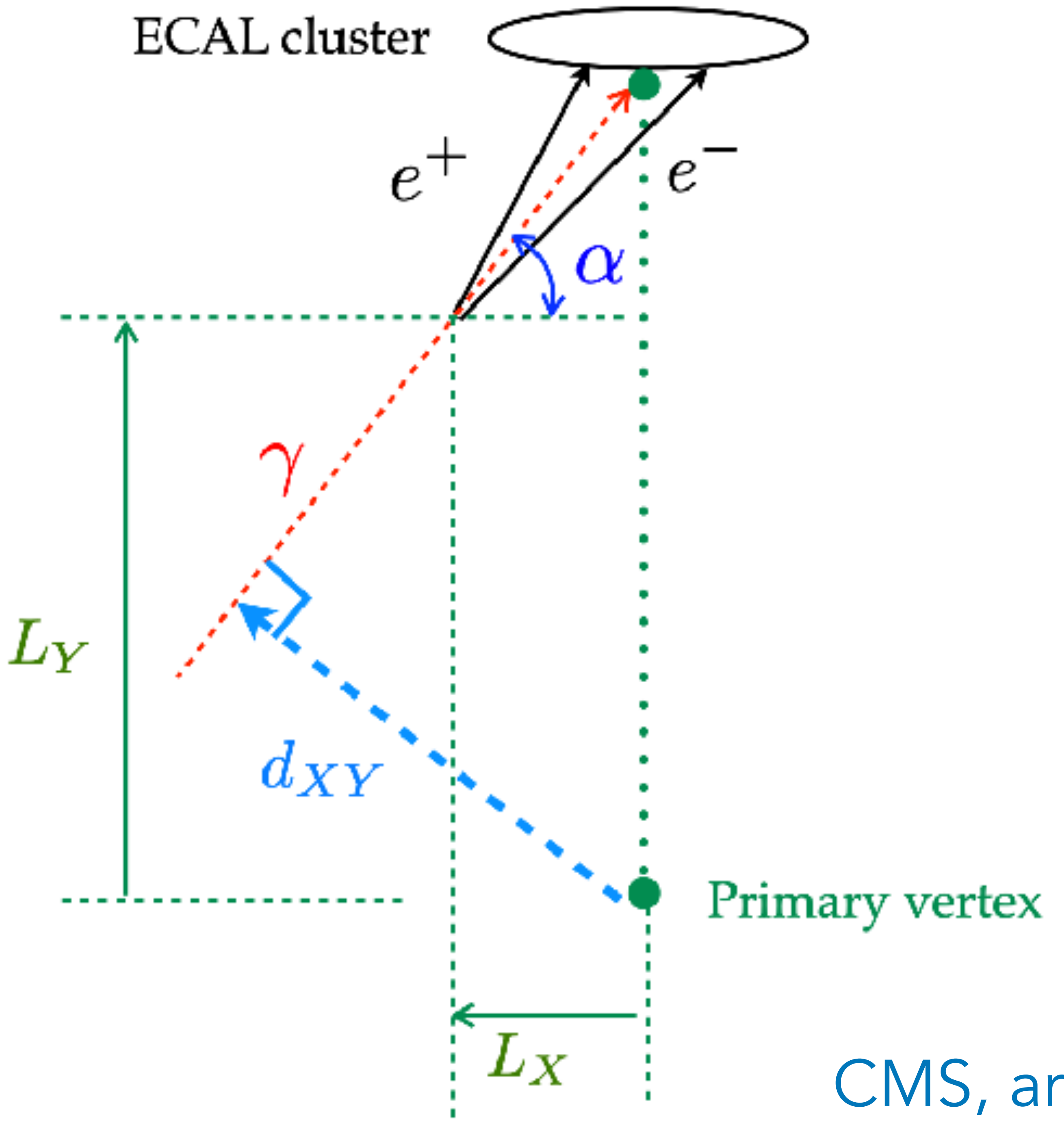
ATLAS and CMS ECals reconstruct trajectory of photons ⟶ Displacement via impact parameter (IP)

$$d_{XY} = x_{LLP}\frac{p_Y}{p_T} - y_{LLP}\frac{p_X}{p_T} \qquad d_Z = \frac{z_{LLP} - (\vec{r}\cdot\vec{p})p_Z/|\vec{p}|^2}{1 - p_Z^2/|\vec{p}|^2}$$

$$\vec{r} = \{x_{LLP}, y_{LLP}, z_{LLP}\}$$

Impact parameter: Minimal distance from from γ to PV

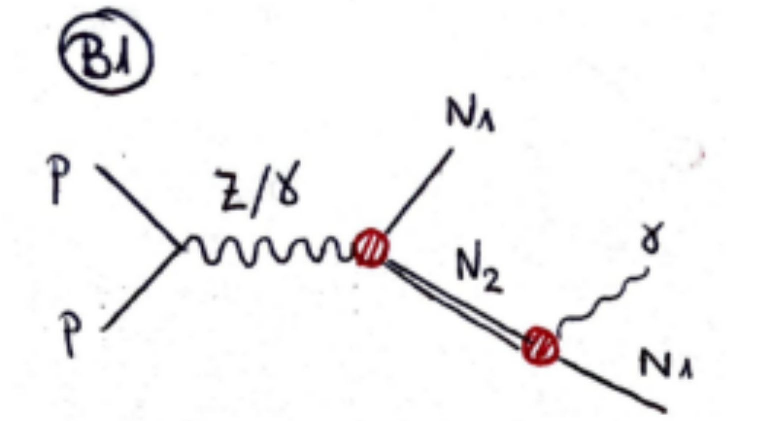
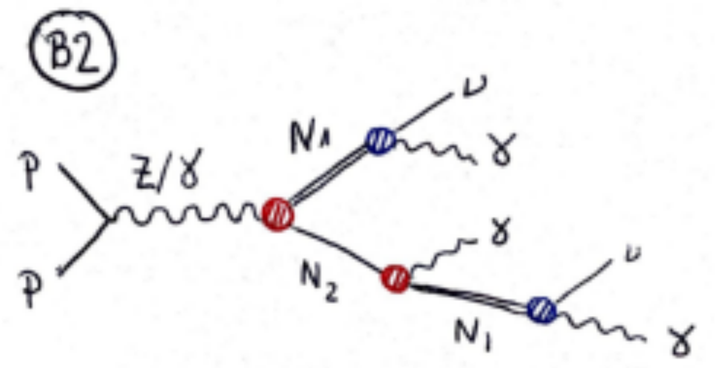
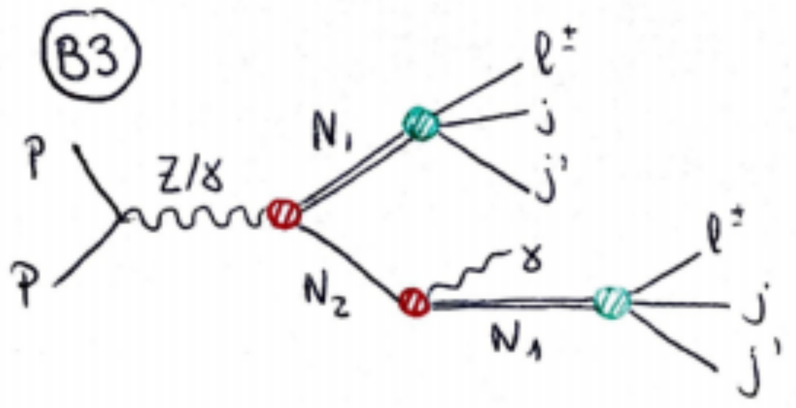
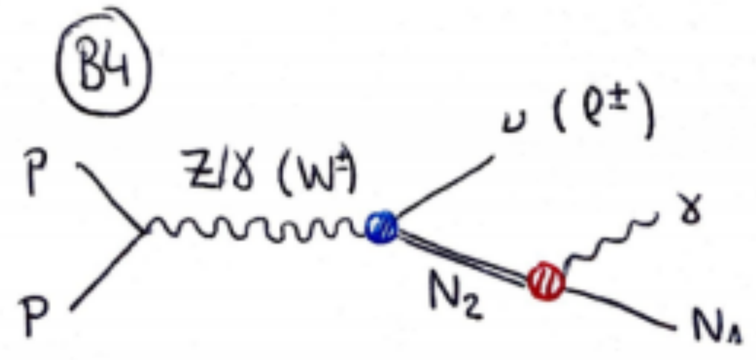
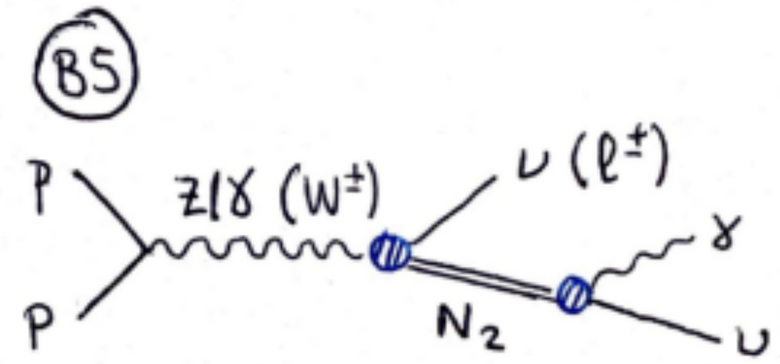
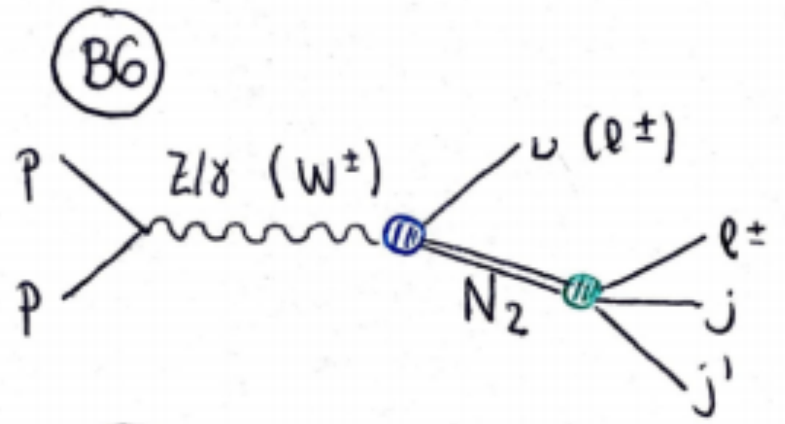
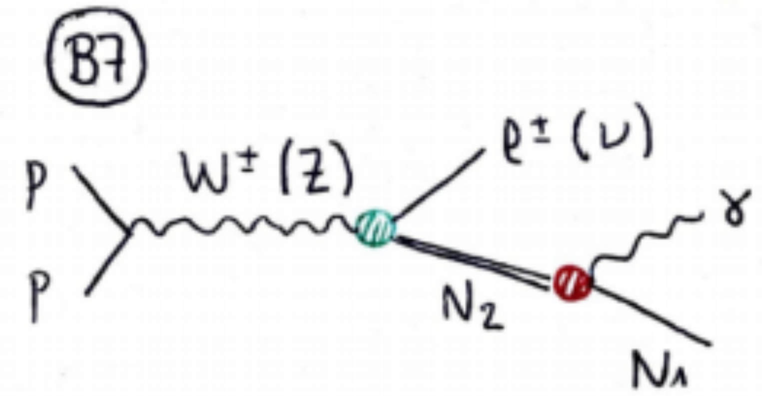
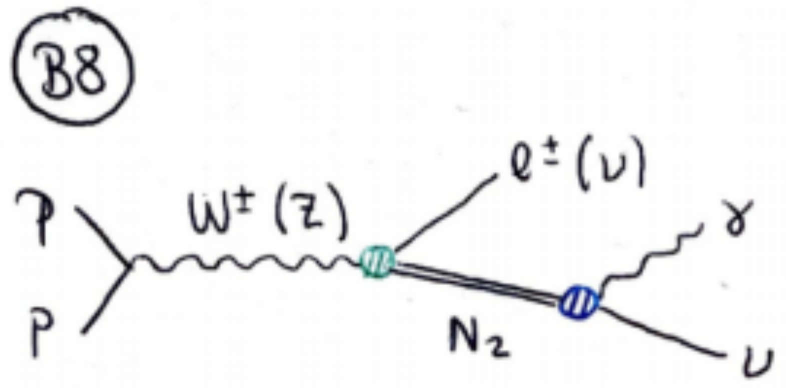
In practice: Measuring d_Z difficult (several PVs, no $\ell^\pm$). Use only d_{XY}



CMS, arXiv:1207.0627

Possible Scenarios

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

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

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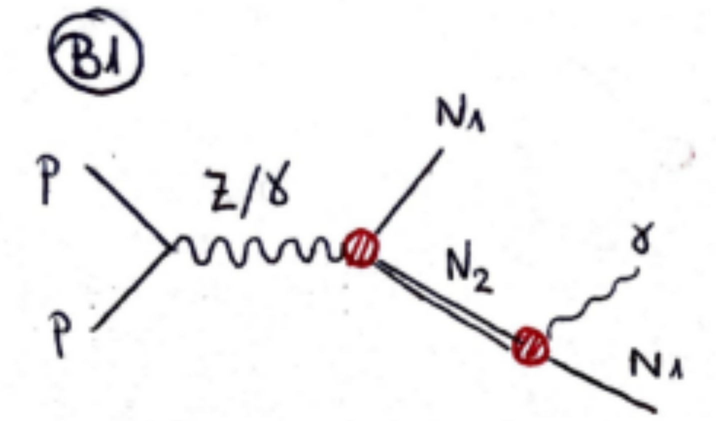
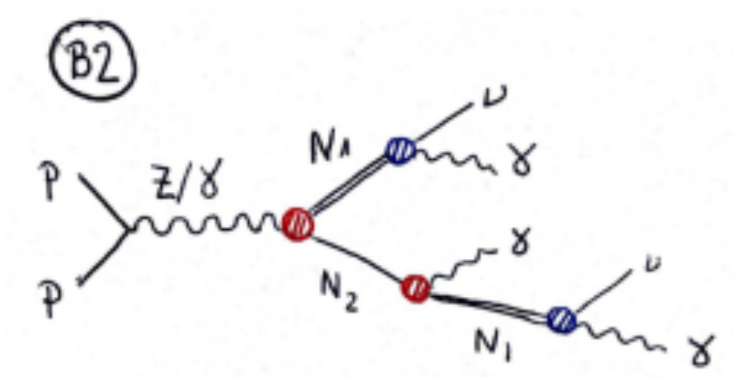
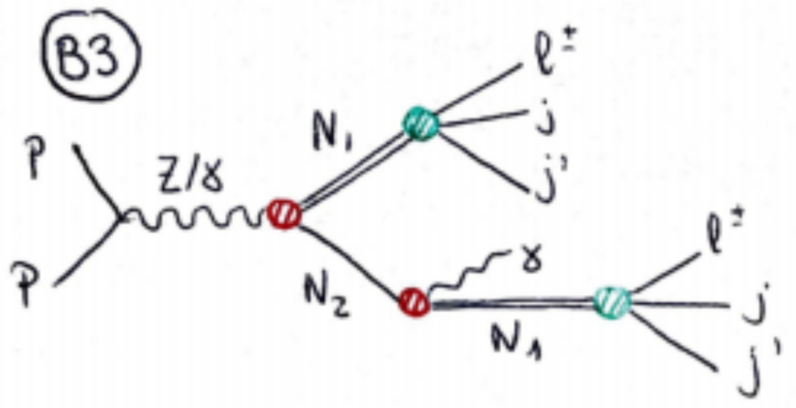
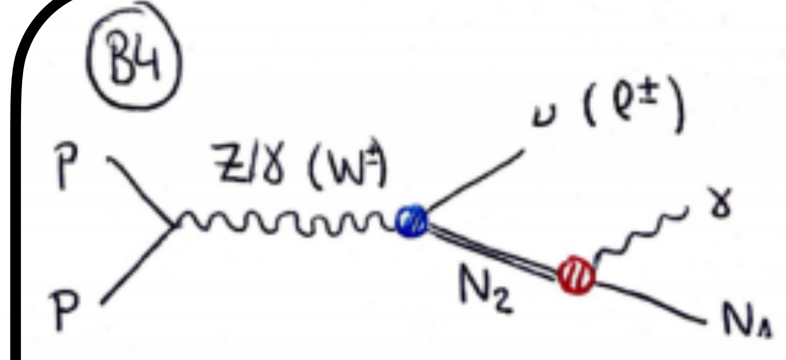
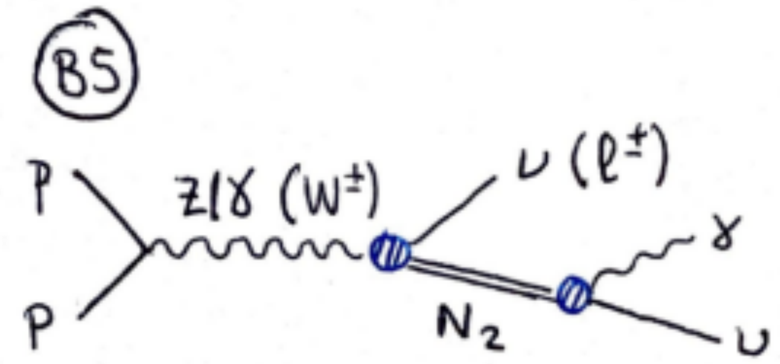
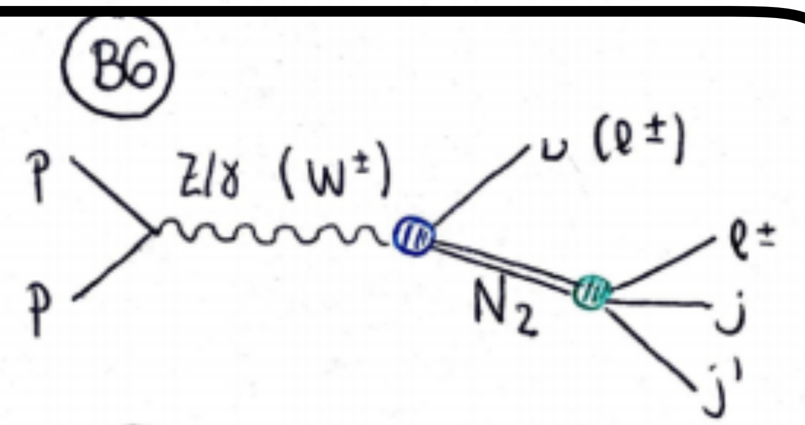
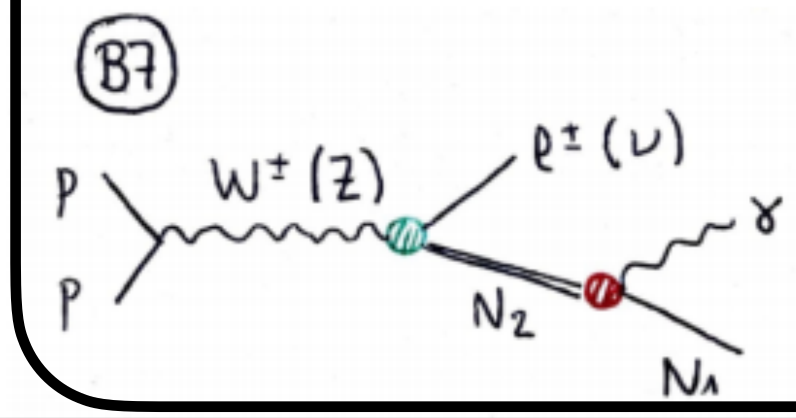
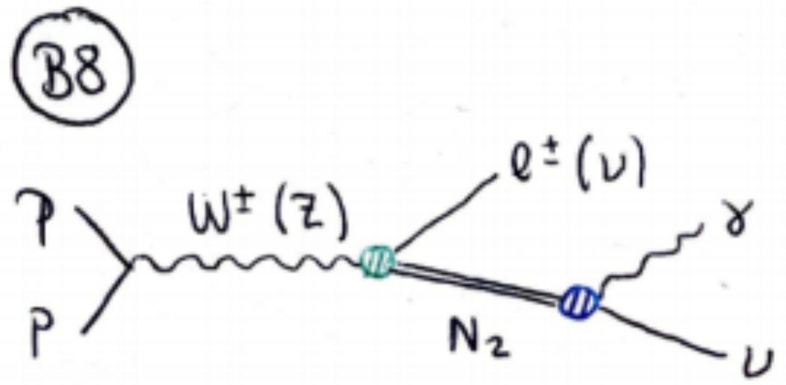
$C^{(5)}_{NNB}$			
$C^{(6)}_{NB}$, $C^{(6)}_{NW}$			
$V_{\ell N}$			Minimal scenario

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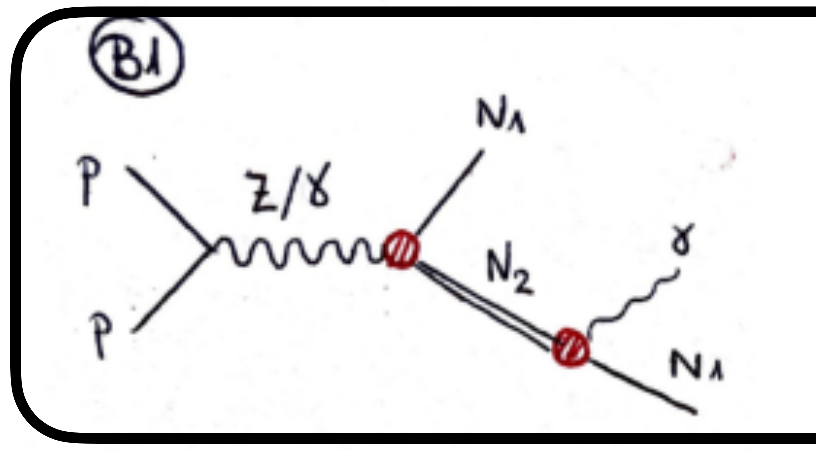
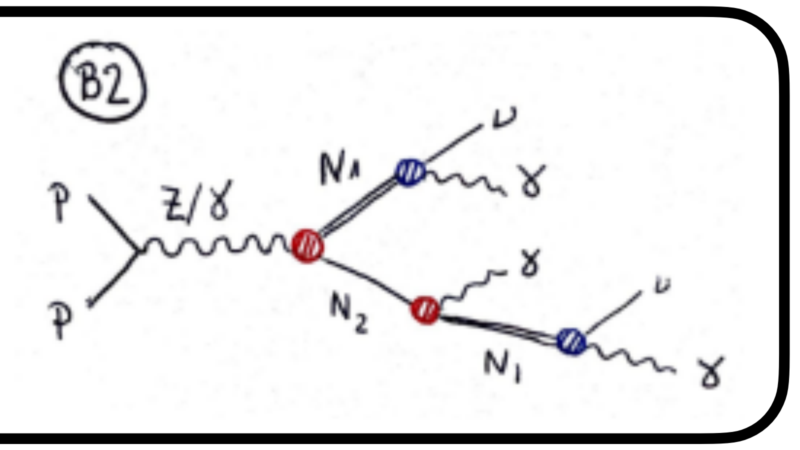
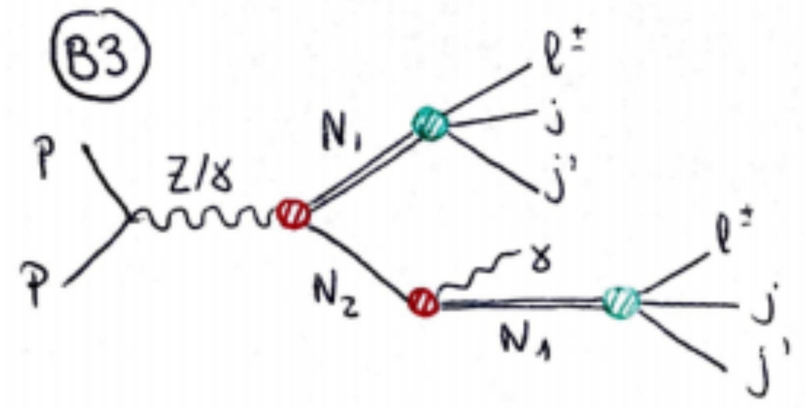
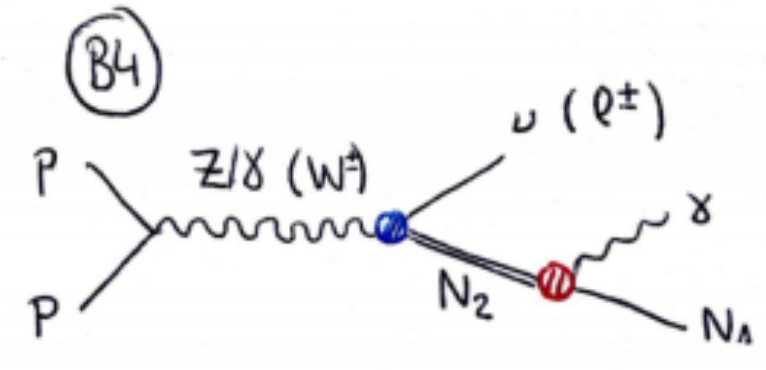
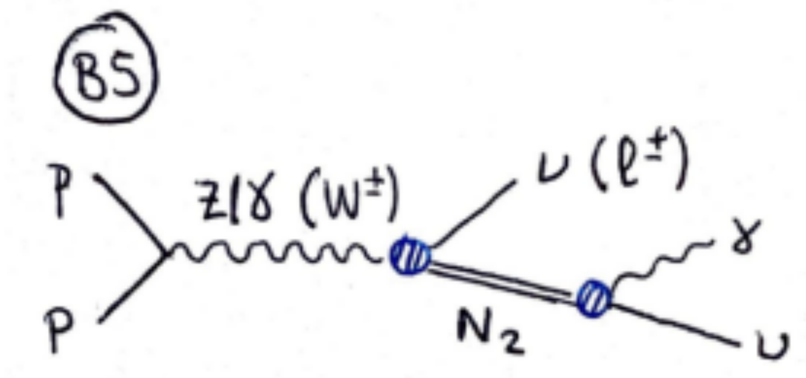
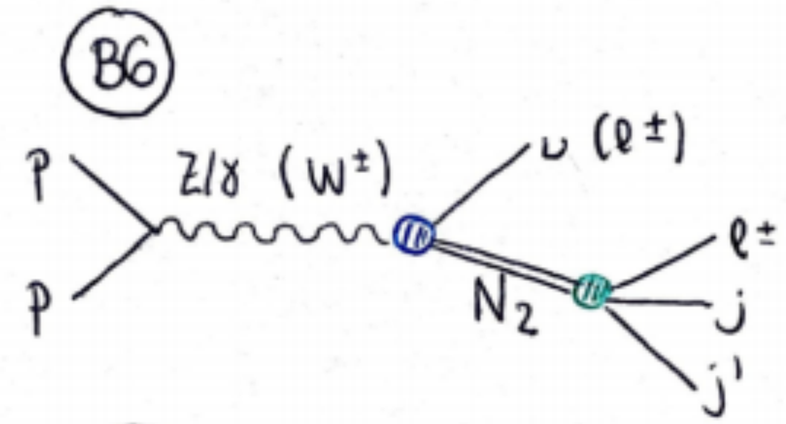
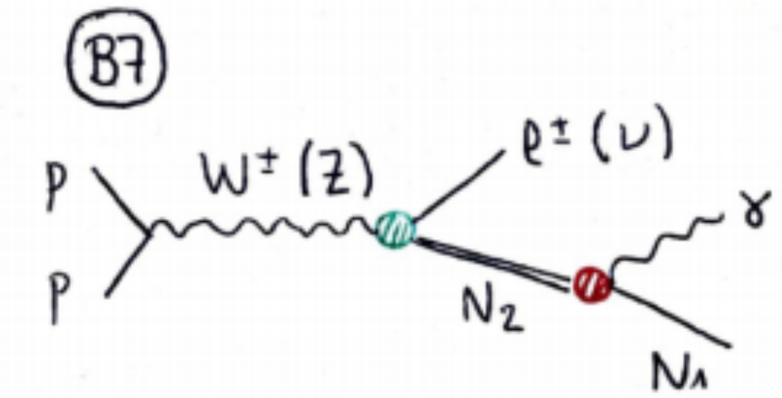
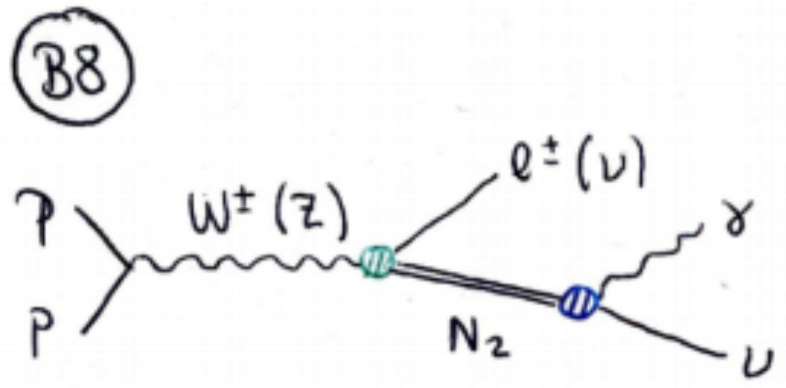
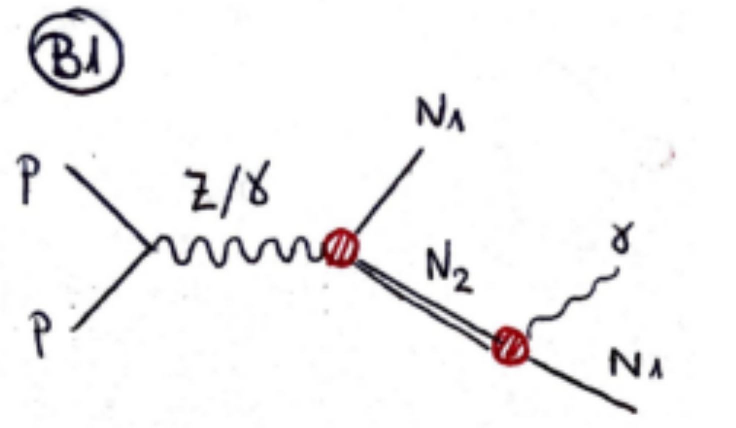
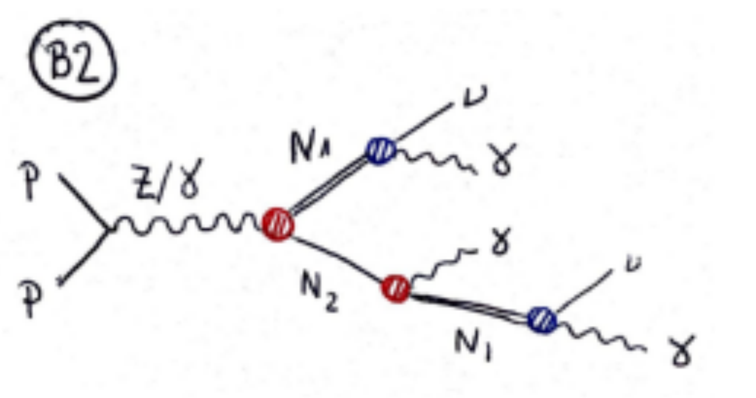
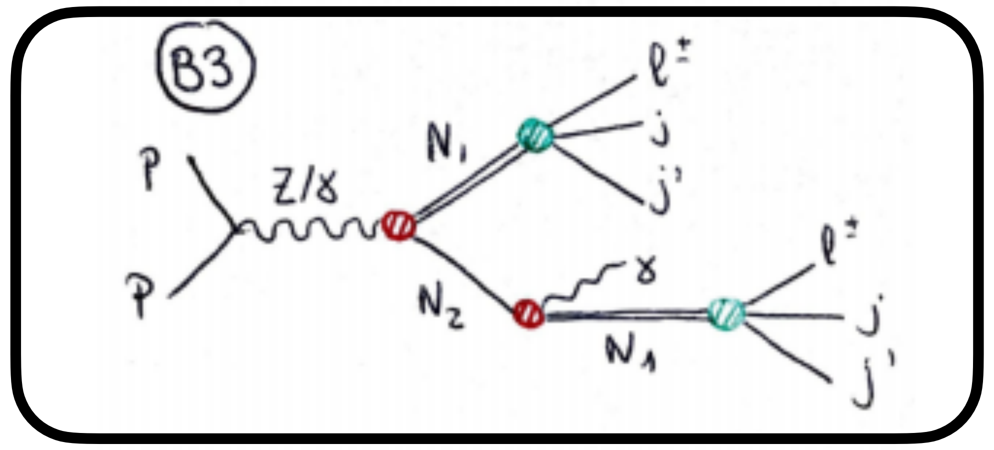
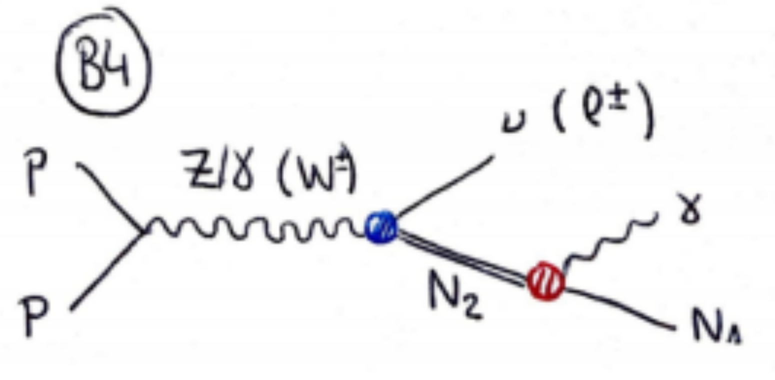
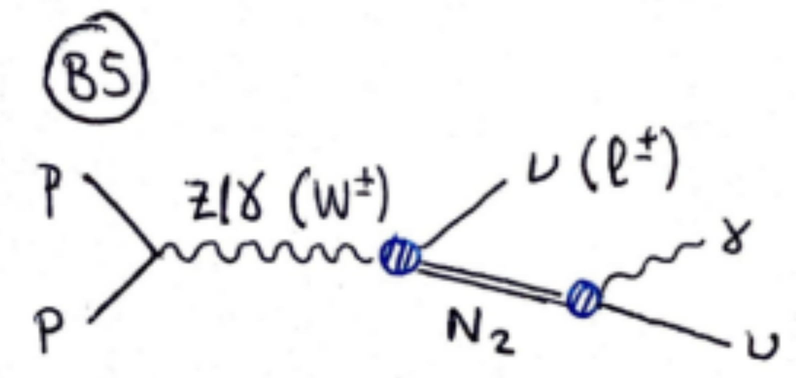
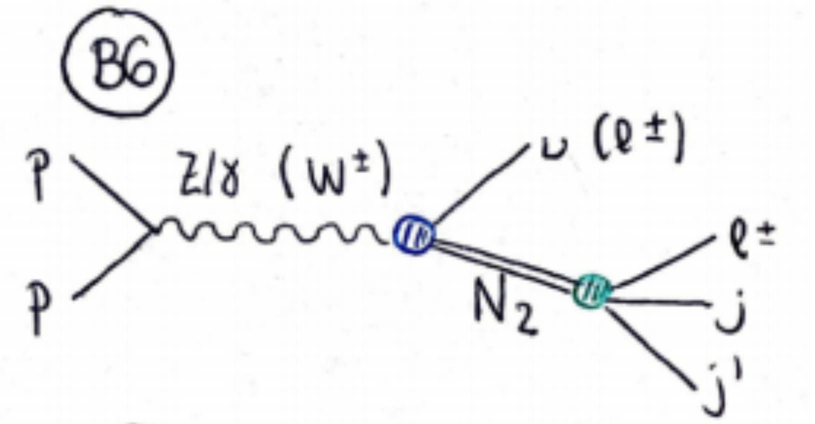
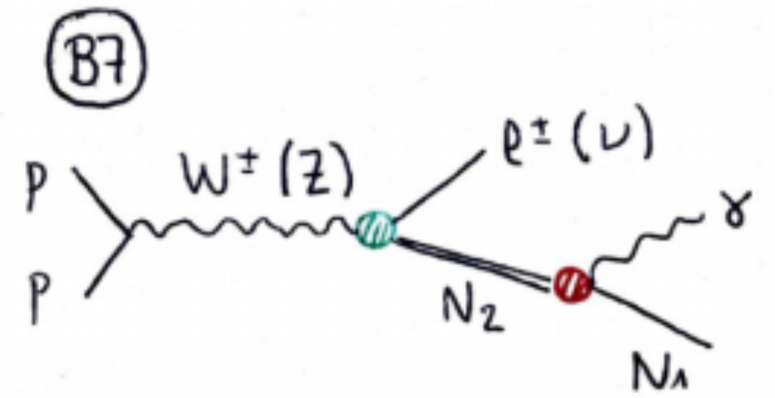
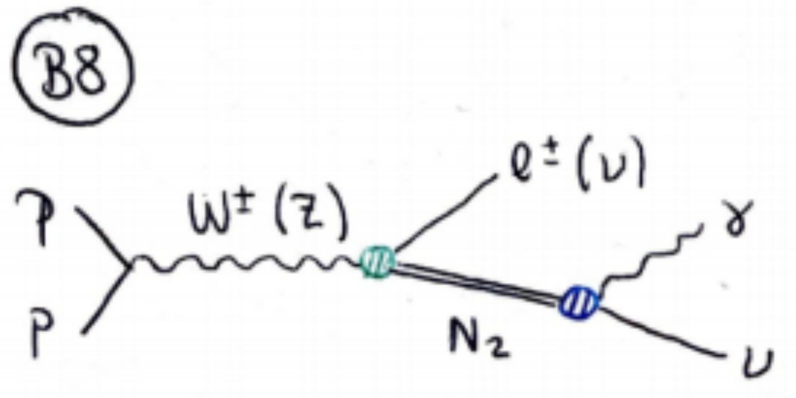
Prod. \ Dec.	$C^{(5)}_{NNB}$	$C^{(6)}_{NB}$, $C^{(6)}_{NW}$	$V_{\ell N}$
$C^{(5)}_{NNB}$			
$C^{(6)}_{NB}$, $C^{(6)}_{NW}$			
$V_{\ell N}$			Minimal scenario

B1-B2: (> 1) non-pointing photons from N_1 and N_2 decays

Possible Scenarios

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

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

B3: No non-pointing photons but DVs (j) + prompt photon still possible

Simulation

To determine the sensitivity reach of ATLAS, performed numerical study:

- Dipole operators up to $d = 6$ implements in $\texttt{FeynRules}$, UFO output
- For each benchmark, 10^5 events in $\texttt{MadGraph5}$ at $\sqrt{s} = 14$ TeV covering the parameter space $(m_{LLP}, c_{\text{decay}})$
- Remaining parameter(s) fixed
- Decays handled by $\texttt{MadSpin}$, $\texttt{Pythia8}$ showering ⇒ estimate efficiencies

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}, $C^{(6)}_{N_1 X}$	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}, $C^{(5)}_{NNB}$	$N_2 \to N_1\gamma$ $N_1 \to ejj$

Selection Cuts and Events

Trigger: $|p_T^\gamma|$ and $|\eta^\gamma|$ (B1 and B2)
$|p_T^e|$ and $|\eta^e|$ (B3)

B1 and **B2**: LLP in ECal (cut on d_{XY}^γ)
B3: LLP in inner detector (cut on d_0, $m_{\rm DV}$)

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

CMS, 1207.0627
ATLAS, 2209.01029

Number of non-pointing photon events:

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

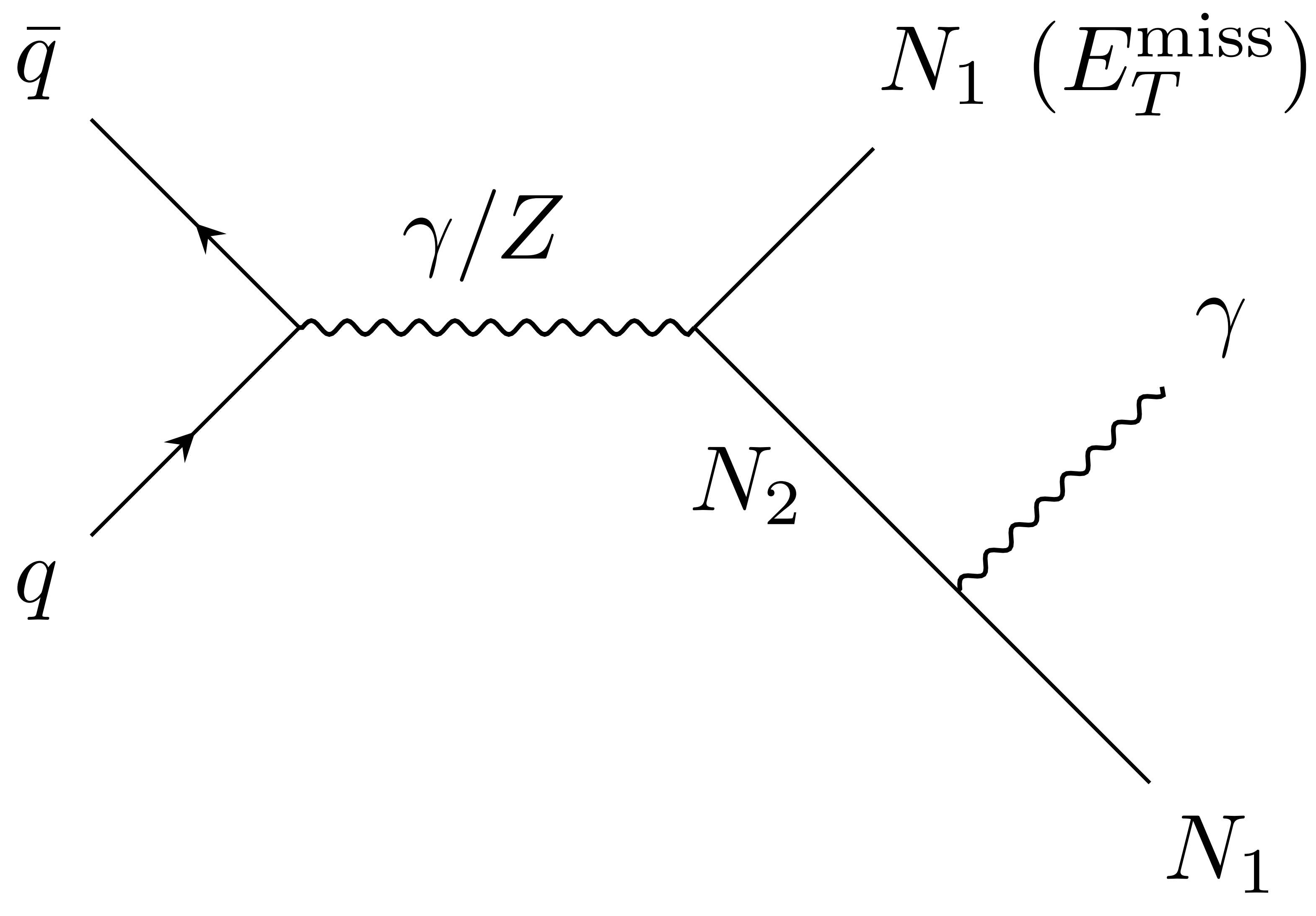
$$N_{\rm sig.}^{\rm B2} = \sigma \cdot \mathcal{L} \cdot \mathcal{B}\,(N_2 \to N_1\gamma) \cdot 2 \cdot \mathcal{B}\,(N_1 \to \nu\gamma) \cdot \epsilon_{\rm sel}^{\rm B2}$$

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

Bounds from Displaced Vertex Searches at LHC

Scenario B1

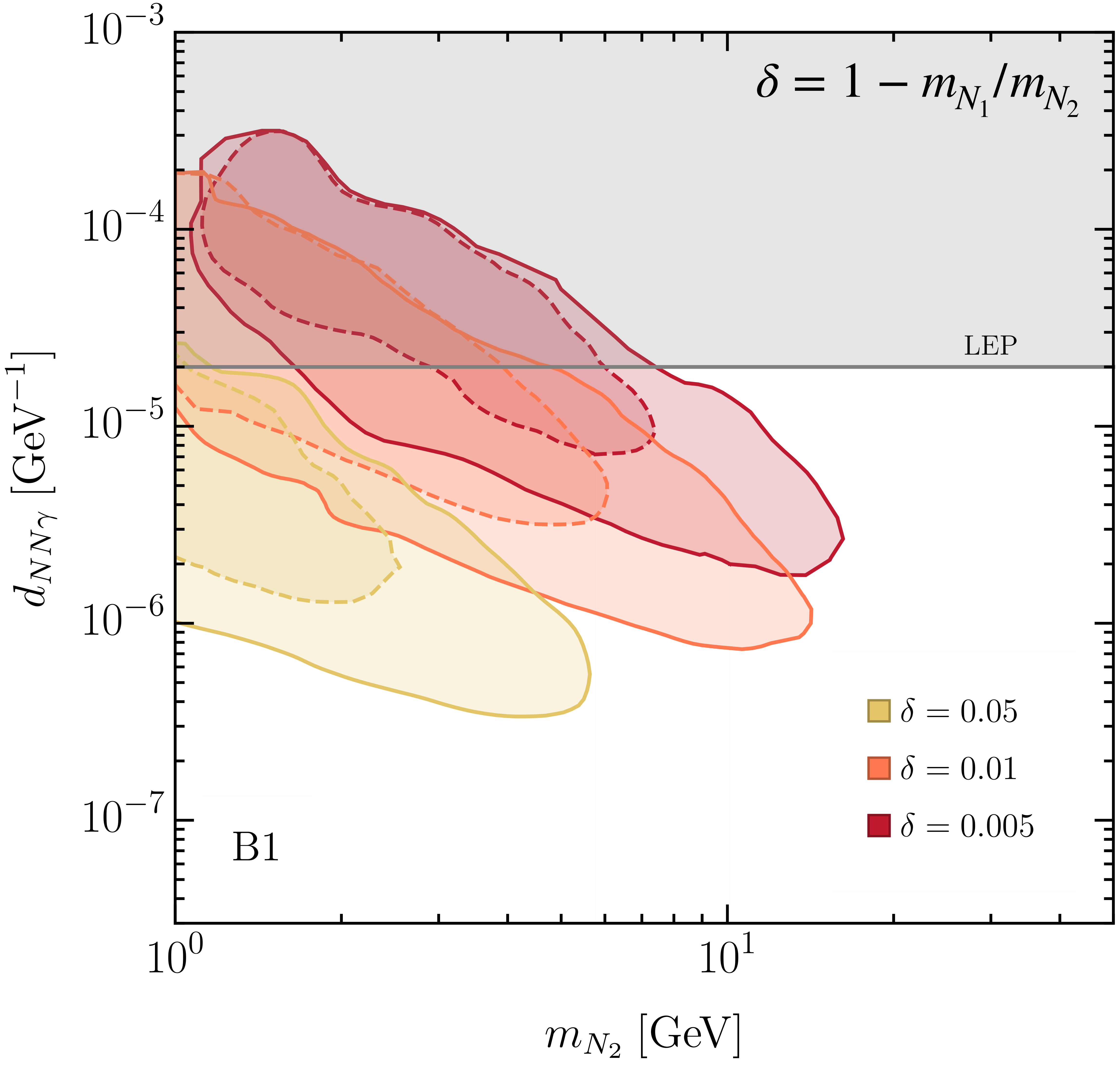
$pp \to N_1 N_2 \ (d_{NN\gamma})$
$N_1 \ (E_T^{\text{miss}})$
$N_2 \to (N_1\gamma)^{\text{LLP}} \ (d_{NN\gamma})$



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

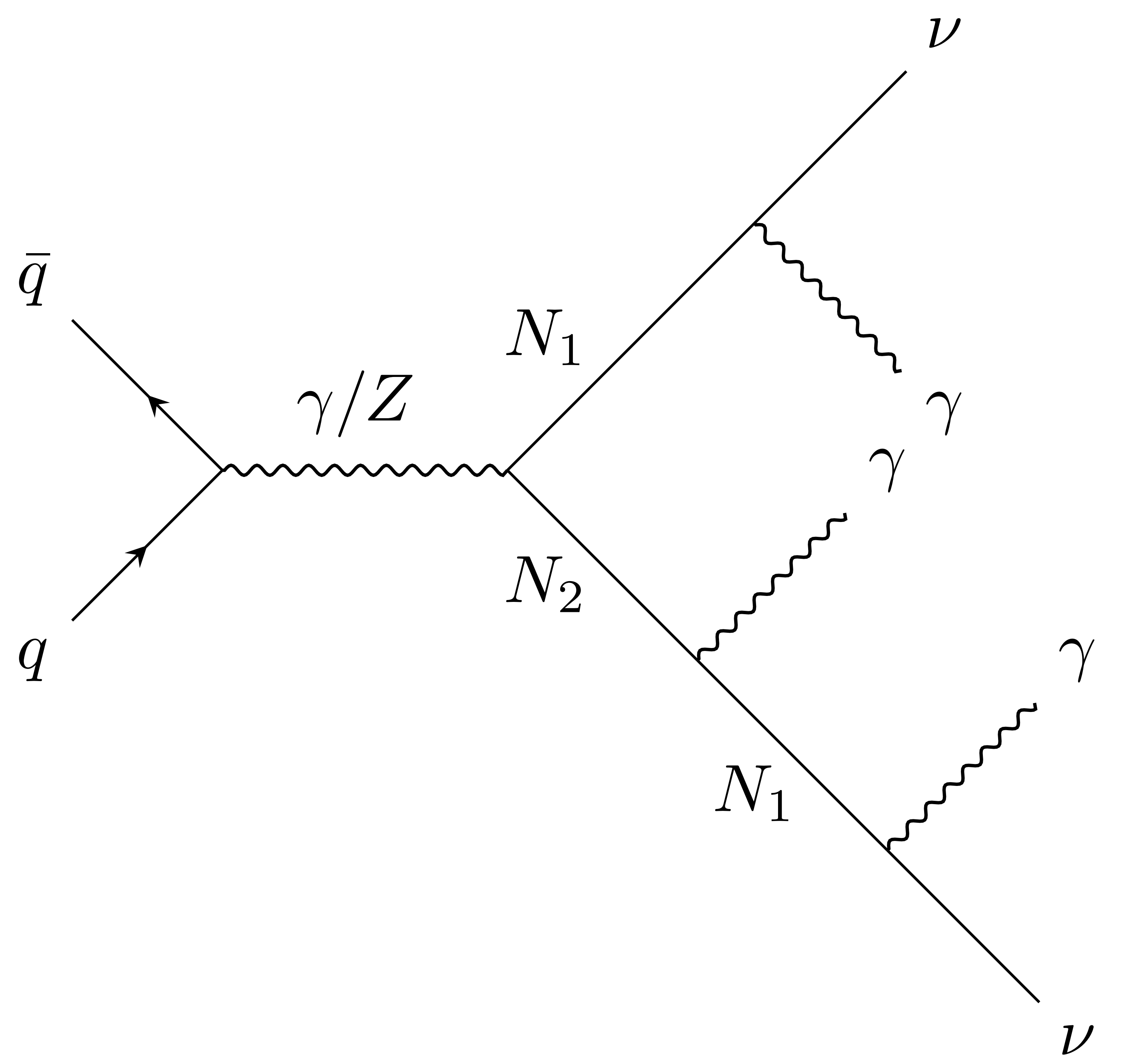
Solid: 3 events (95% C.L.)
Dashed: 30 events

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



Scenario B2

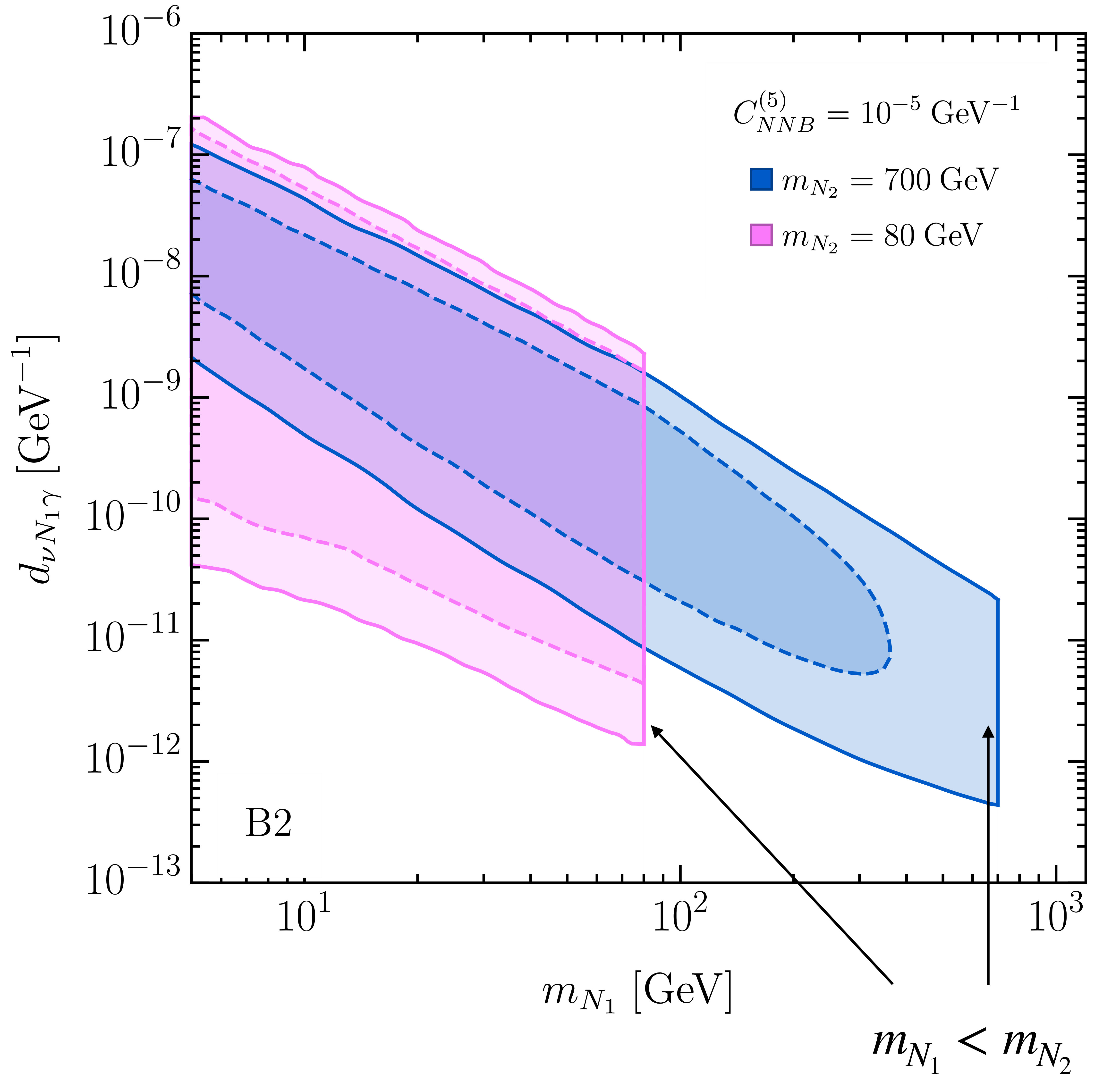
$pp \to N_1 N_2 \ (d_{NN\gamma})$
$N_1 \to (\nu\gamma)^{\mathrm{LLP}} \ (d_{\nu N\gamma})$
$N_2 \to N_1\gamma \to (\nu\gamma)^{\mathrm{LLP}}\gamma \ (d_{\nu N\gamma}, d_{NN\gamma})$



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

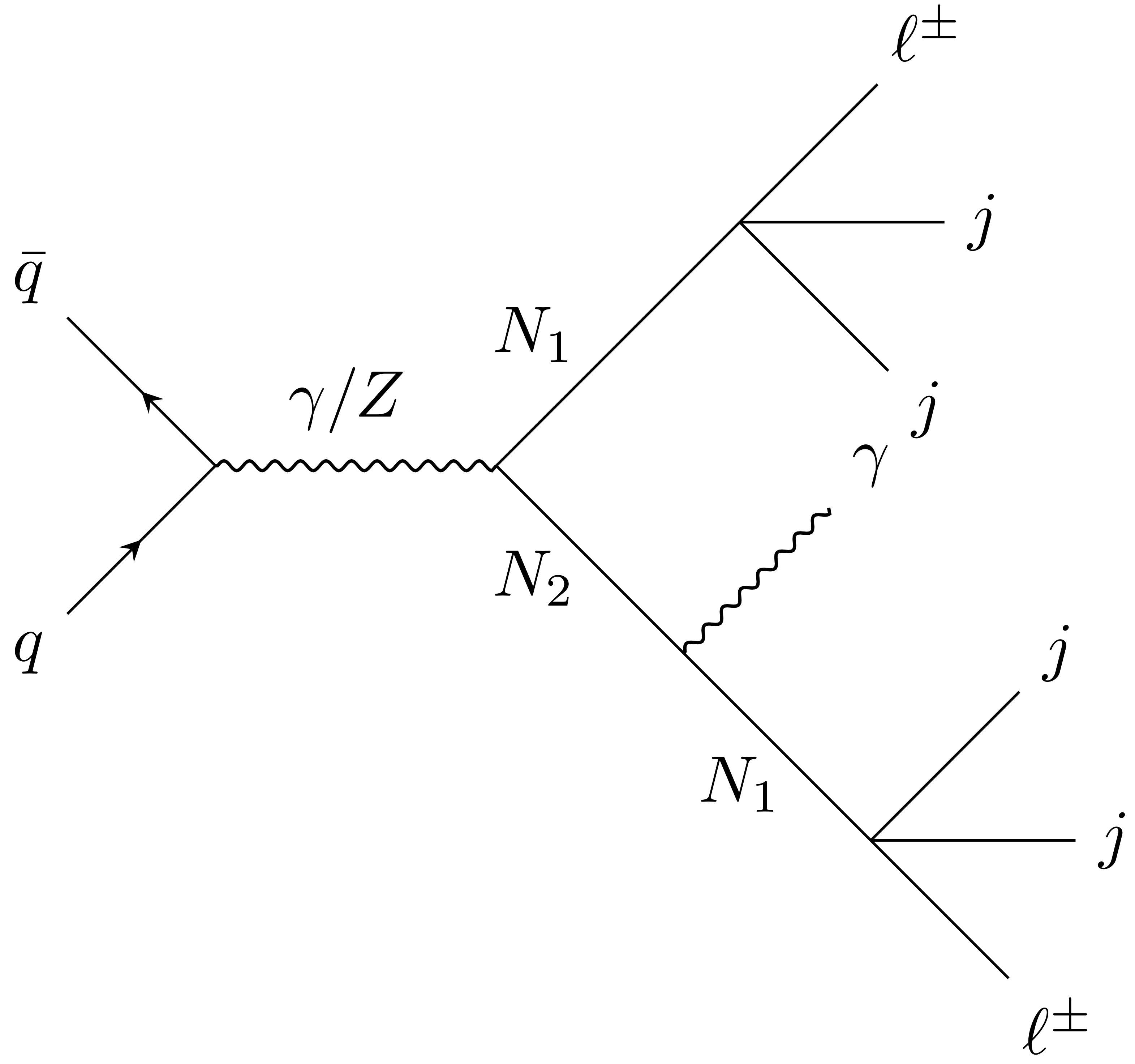
Solid: 3 events (95% C.L.)
Dashed: 30 events

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



Scenario B3

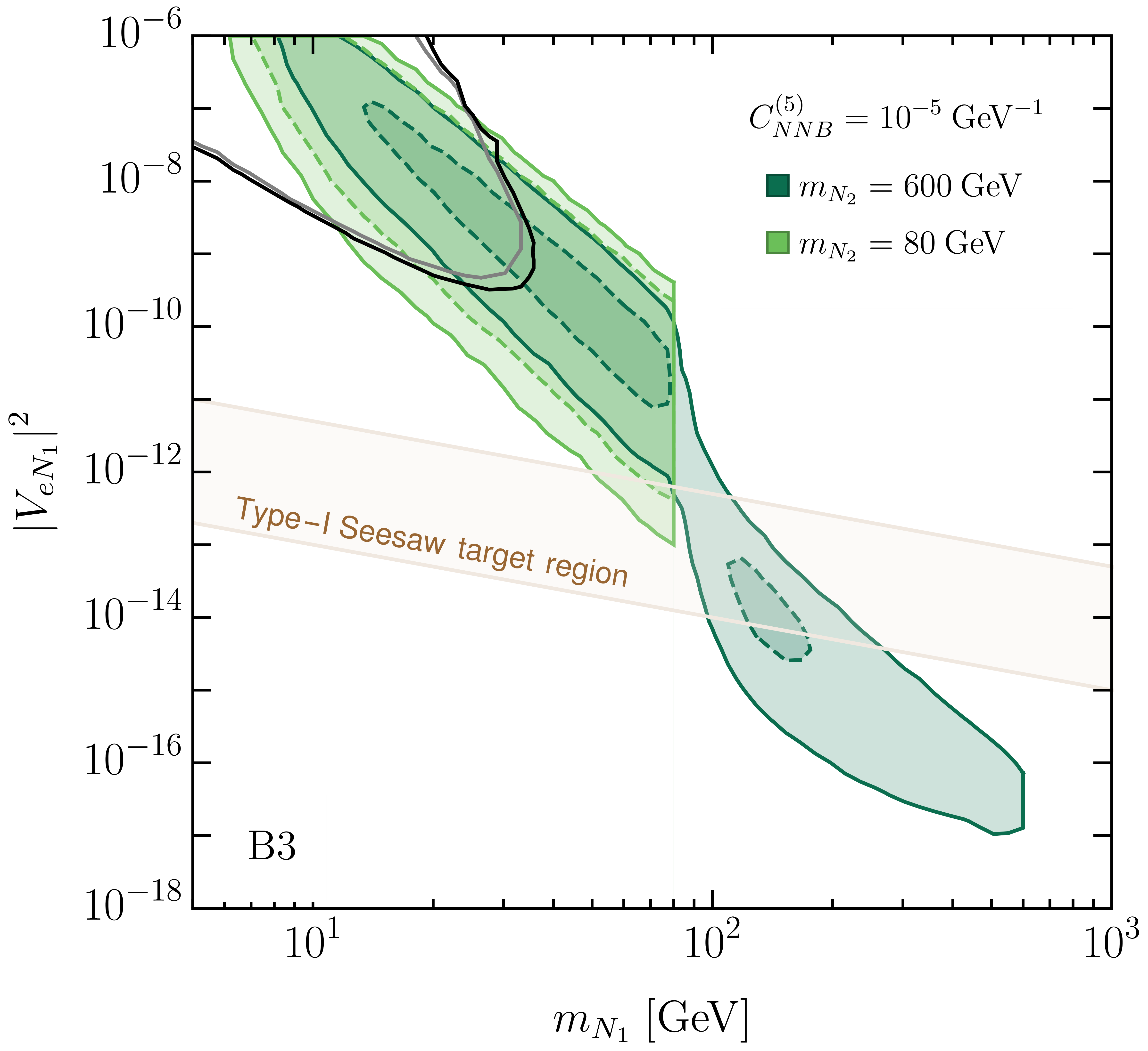
$pp \to N_1 N_2 \; (d_{NN\gamma})$,
$N_1 \to (ejj)^{\text{LLP}} \; (V_{eN})$
$N_2 \to N_1\gamma \to (ejj)^{\text{LLP}}\gamma \; (d_{NN\gamma}, V_{eN})$



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

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

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



Solid black: DV + prompt ℓ

Cottin et al., 2105.13851

Constraints on Specific UV Model

UV Model for Neutrino Magnetic Moments

To generate active (sterile)-to-sterile magnetic moments for N_R, we introduce two additional fields:

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

Introducing the vector-like lepton $E = E_L + E_R$:

$$\mathcal{L} \supset \bar{E}\left(i\not{D} - m_E\right)E - \left[\bar{L}Y_E H E_R + \text{h.c.}\right] \qquad Y_E = \begin{pmatrix} Y_E^e \\ Y_E^\mu \\ Y_E^\tau \end{pmatrix}$$

Introducing the scalar ϕ:

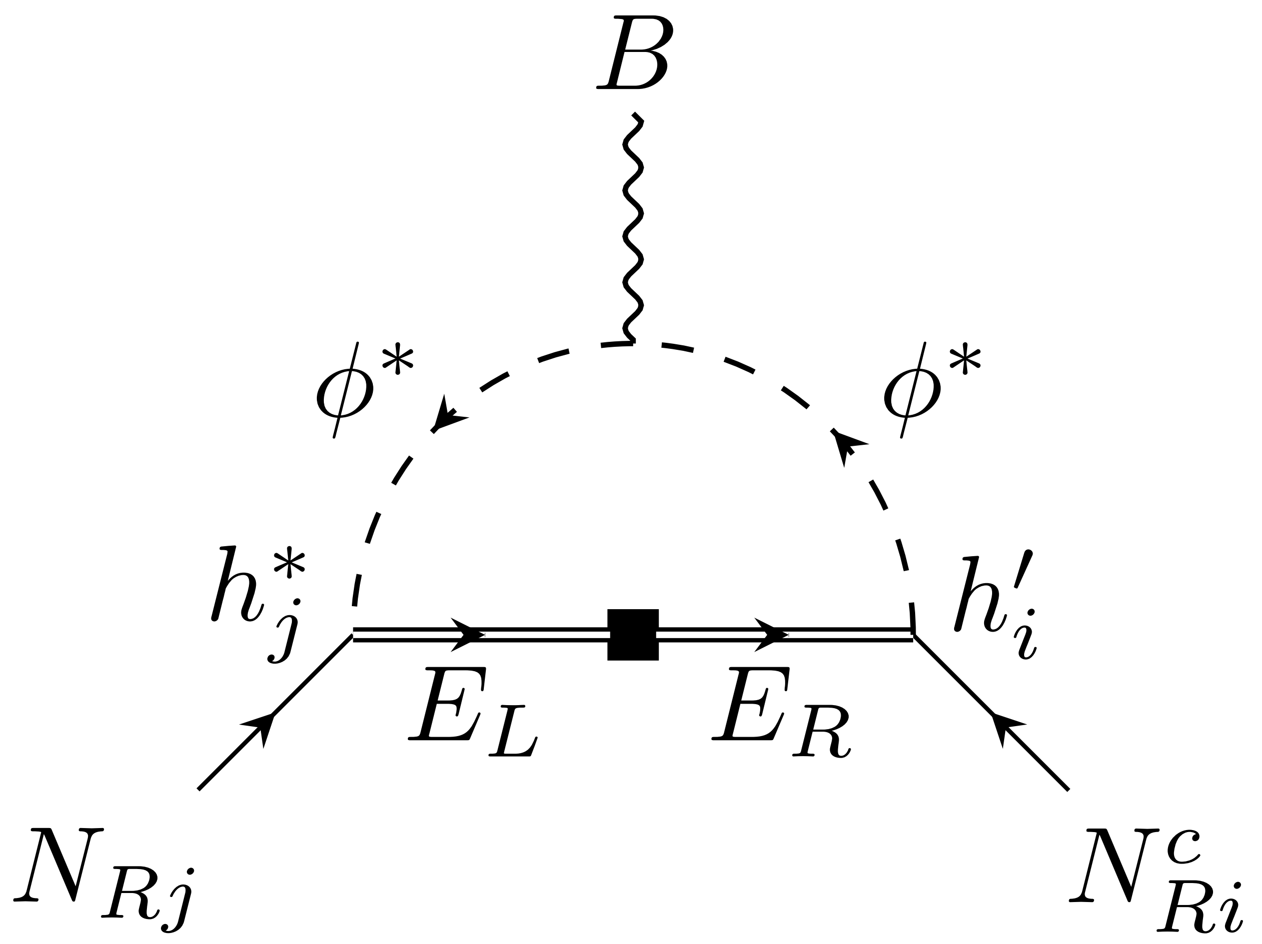
$$\mathcal{L} \supset (D_\mu\phi)^*(D^\mu\phi) - V(\phi) - \left[\bar{L}f\tilde{L}\phi + \bar{N}_R^c f'\ell_R\phi^* + \text{h.c.}\right] \qquad f = \begin{pmatrix} 0 & f_{e\mu} & f_{e\tau} \\ -f_{e\mu} & 0 & f_{\mu\tau} \\ -f_{e\tau} & -f_{\mu\tau} & 0 \end{pmatrix}$$

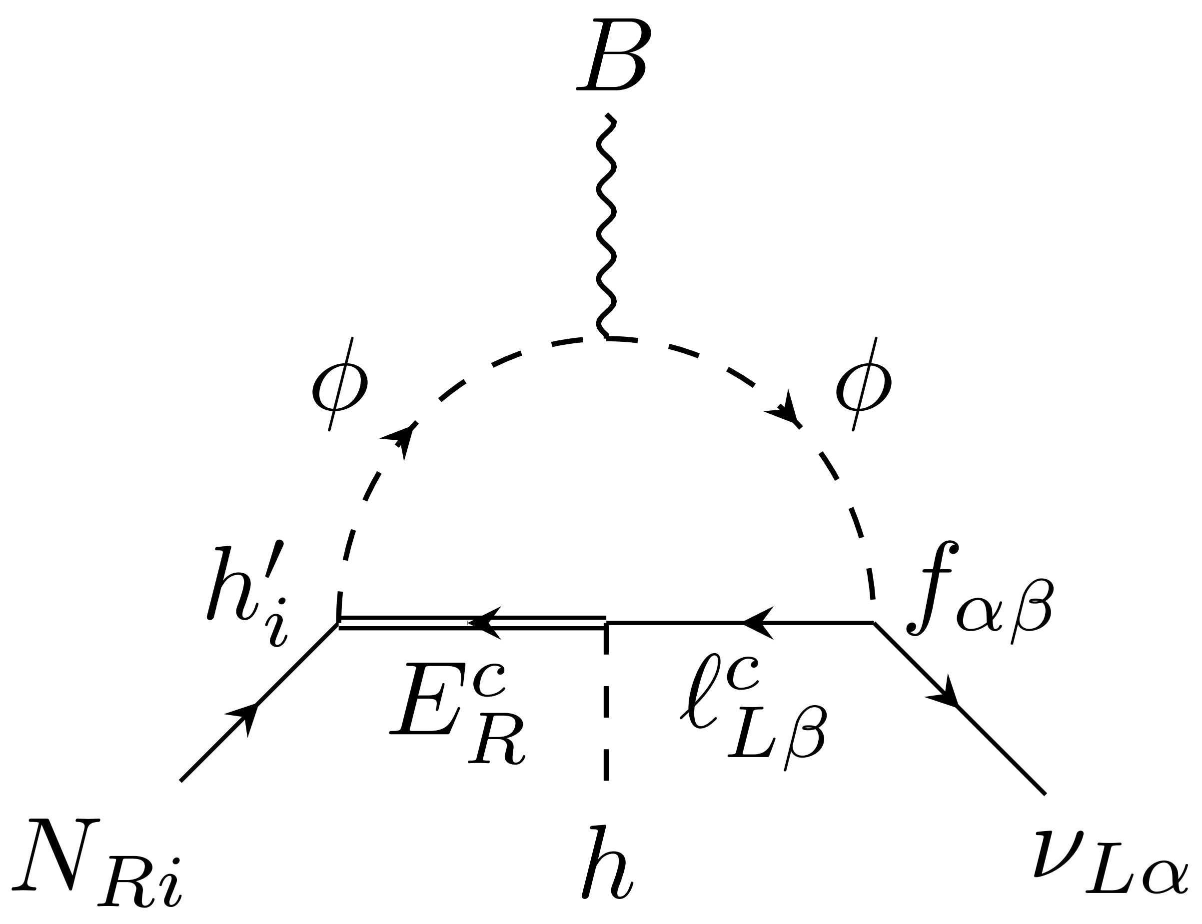
When both E and ϕ are Present

When both the vector-like lepton and singly-charged scalar are present, we can write

$$\mathcal{L} \supset \bar{N}_R h E_L \phi^* + \bar{N}_R^c h' E_R \phi^* + \text{h.c.}\,,$$

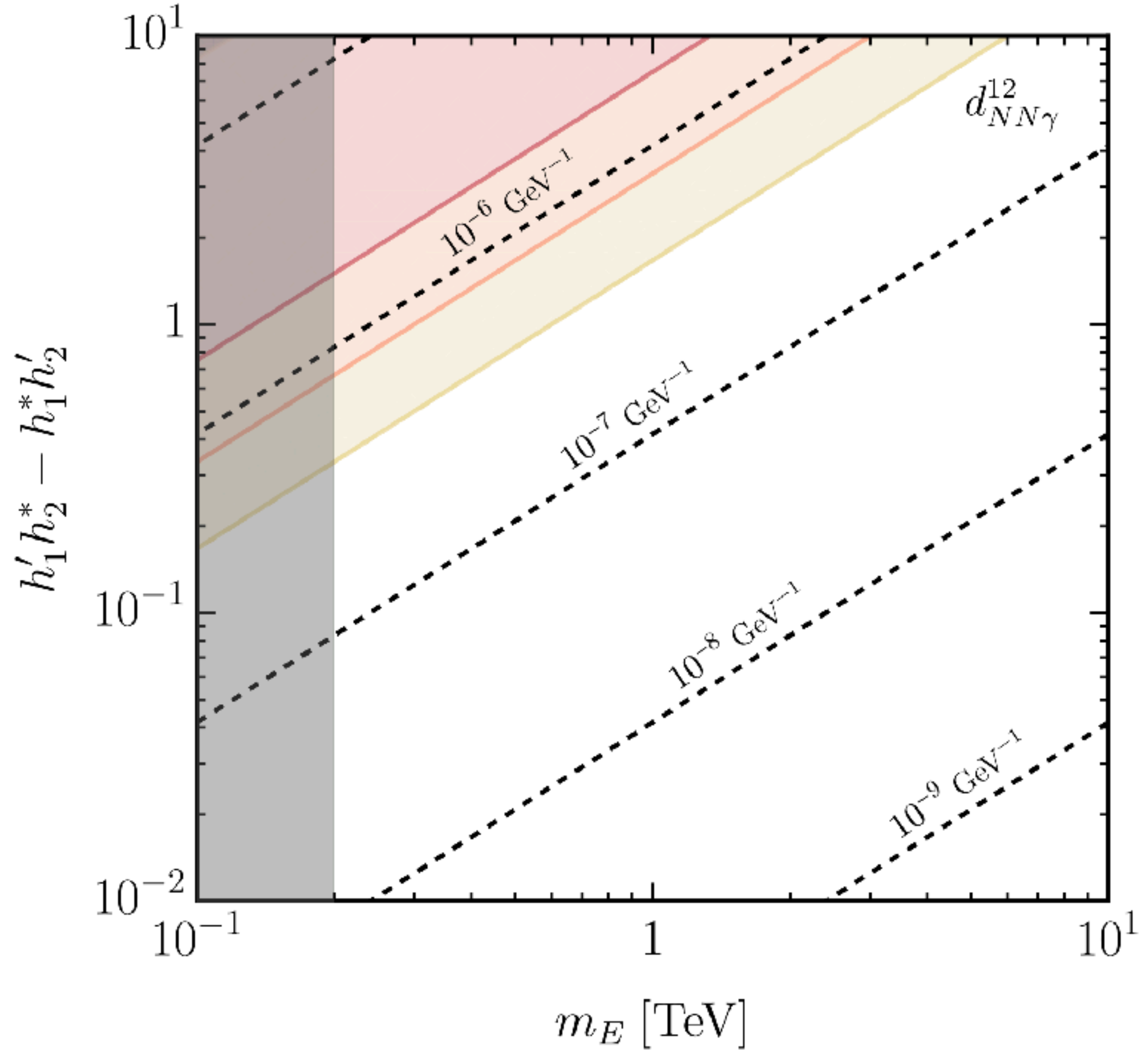
If $E \to -E$ and $\phi \to -\phi$ under Z_2, these are the only possible new interactions

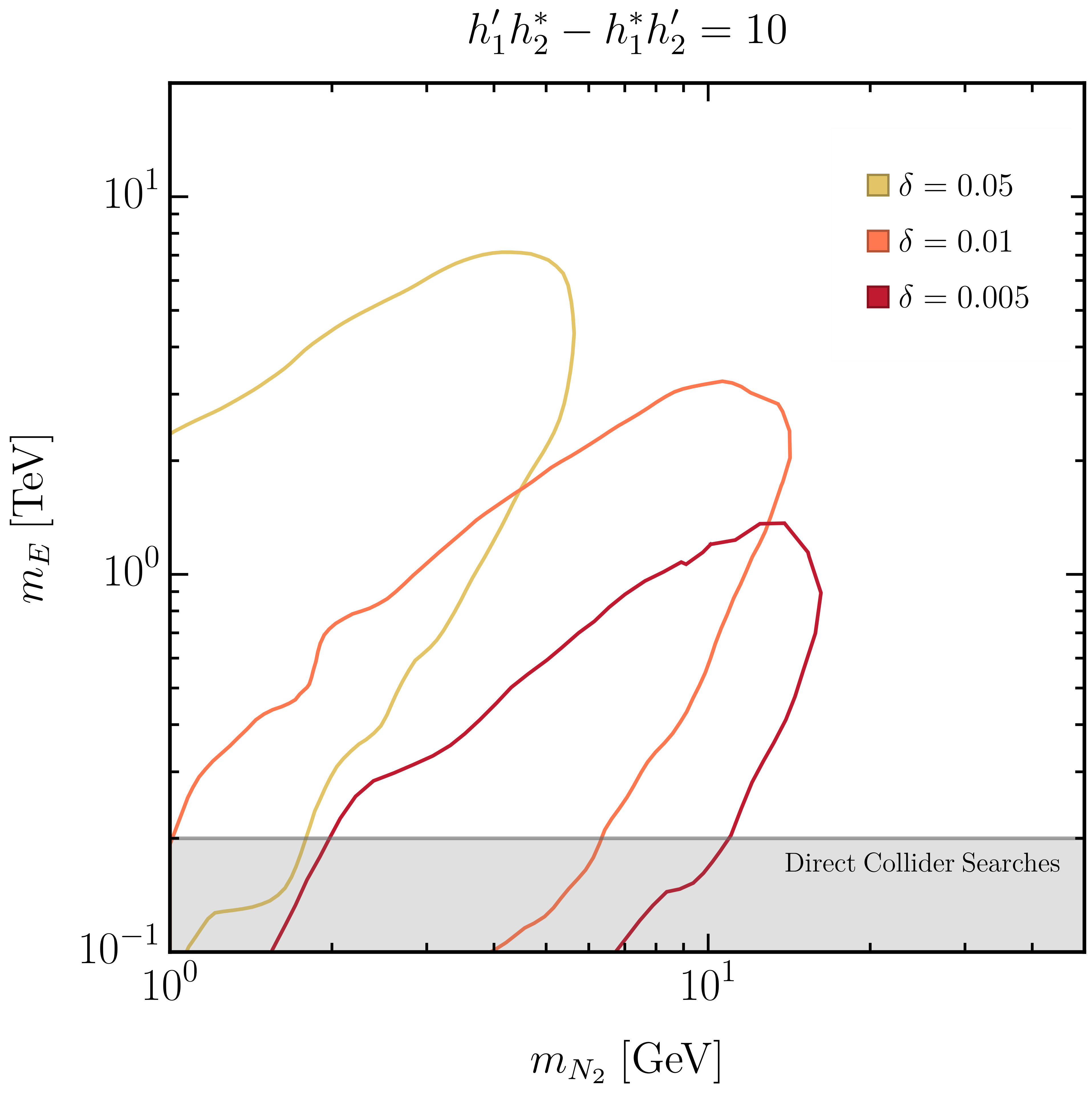




UV Model Bounds from Benchmark 1

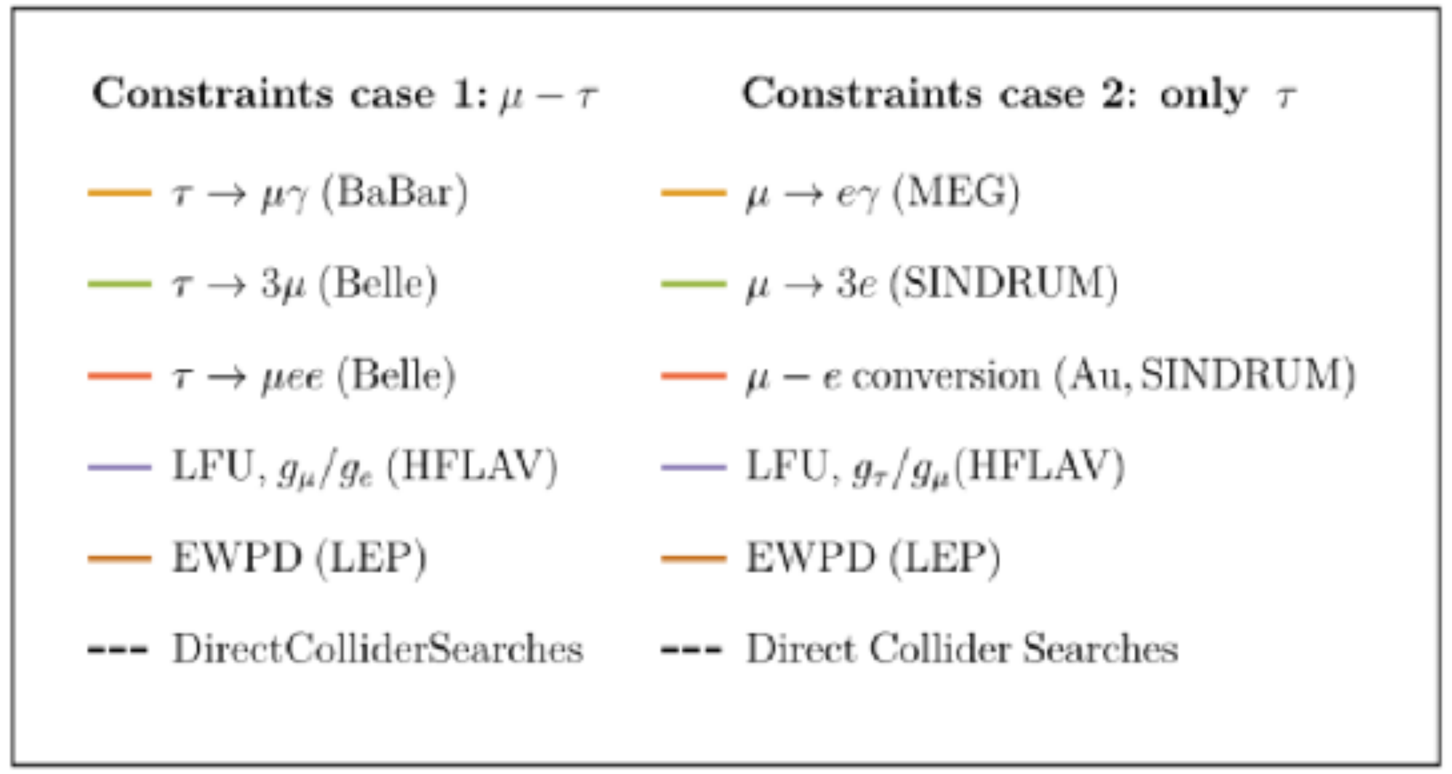
$$d_{NN\gamma}^{ij} = c_w C_{NNB}^{(5)ij} \qquad C_{NNB}^{(5)ij} = \frac{1}{16\pi^2}\frac{g'(h_i' h_j^* - h_i^* h_j')}{4m_E} f(r)$$



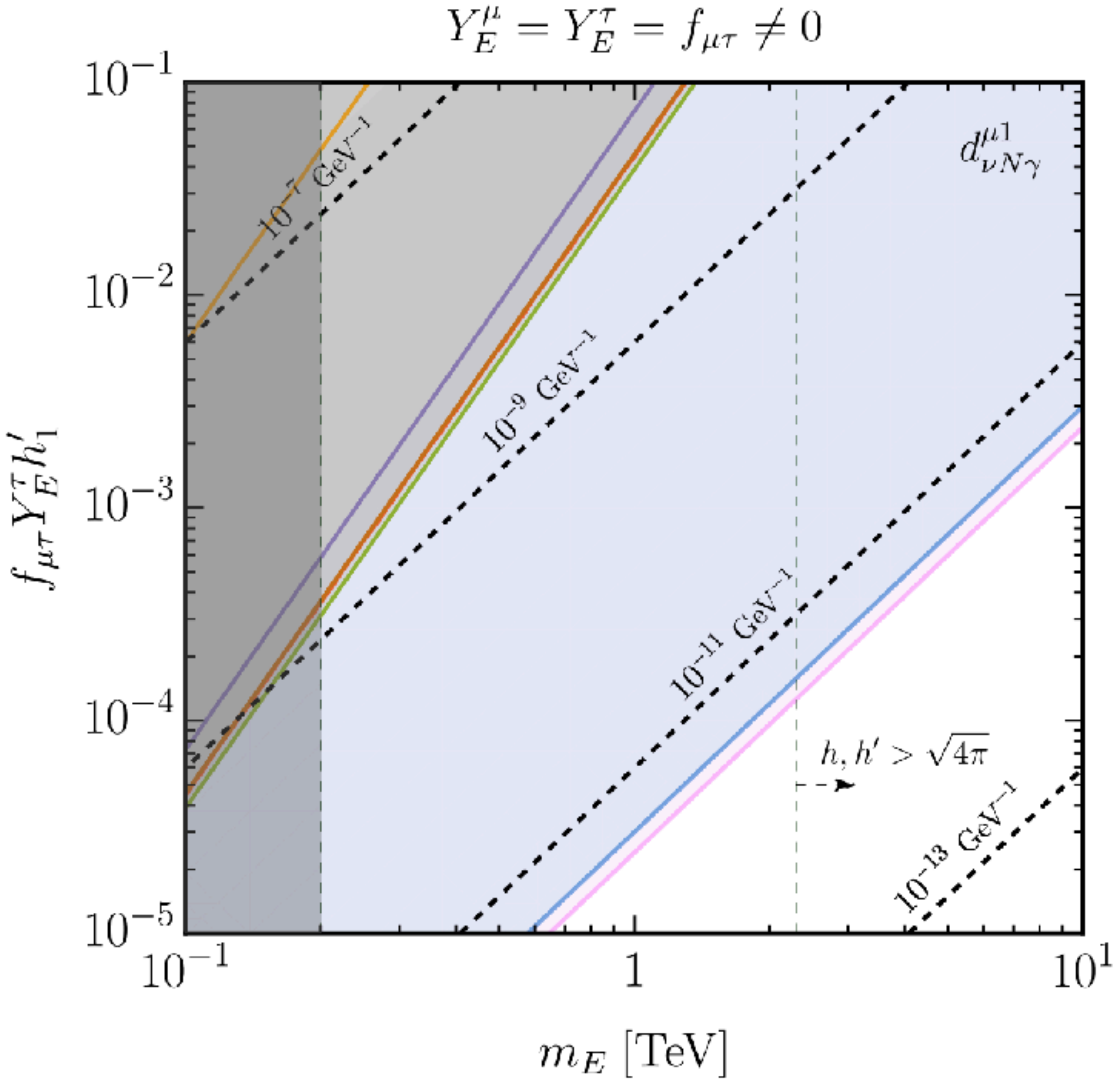


Active-to-Sterile Bounds

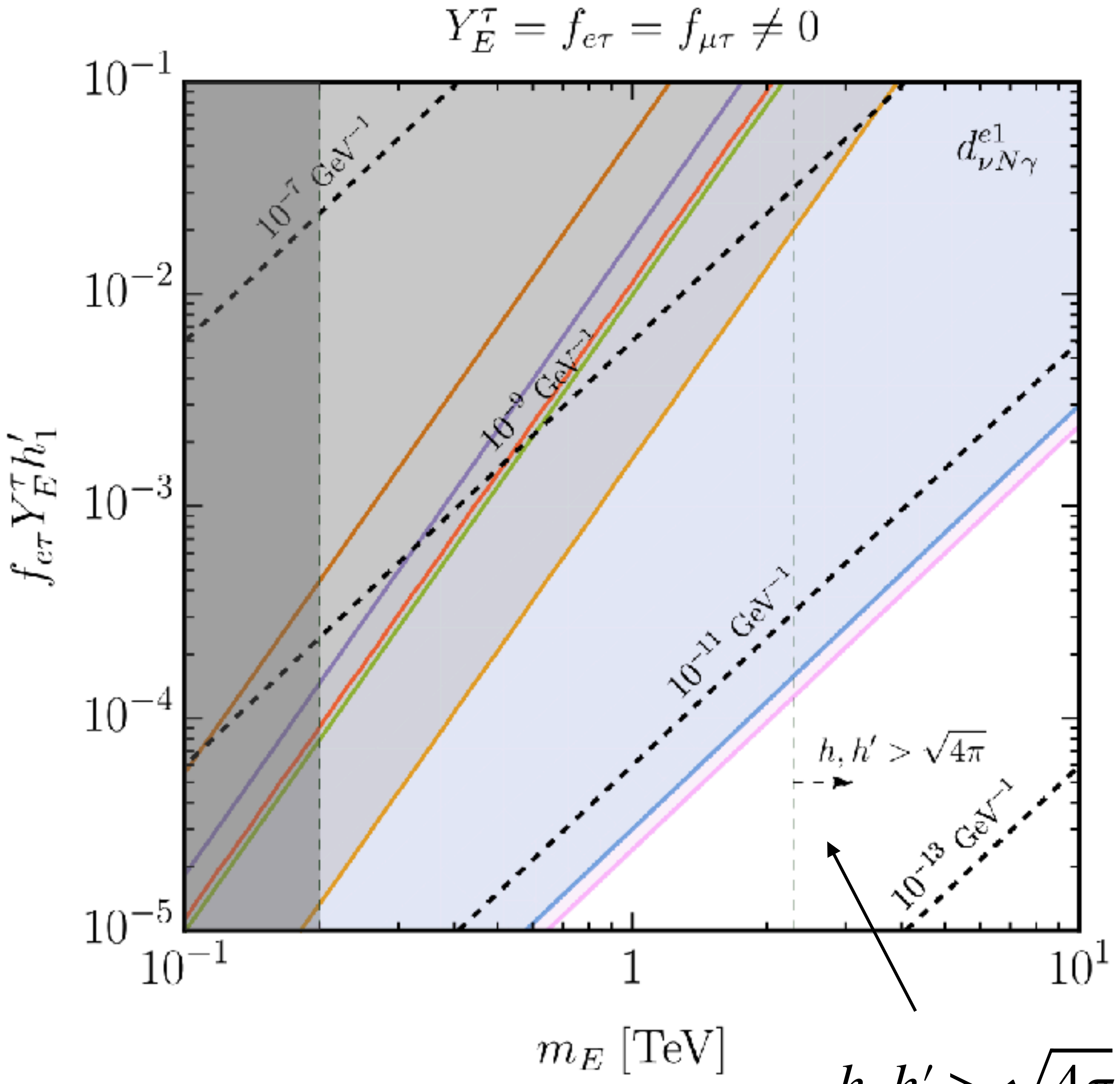
$$C_{NB}^{(6)\alpha i} = \frac{1}{16\pi^2}\frac{3g'_{\alpha\beta}Y_E^{\beta *}h'_i}{4m_E^2}f(r)$$



‘No e’ couplings



‘τ only’ couplings



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

Summary and Conclusions

Study: Phenomenology of heavy sterile neutrinos with magnetic moments at the LHC

EFT analysis with the N_RSMEFT operators $\mathcal{O}^{(5)}_{NNB}$, $\mathcal{O}^{(6)}_{NB}$ and $\mathcal{O}^{(6)}_{NW}$:

- Examined future sensitivity of LHC experiments using displaced **non-pointing photons**
- Excluded regions in 3 of 9 limiting benchmark cases

Toy UV model to generate $C^{(5)}_{NNB}$, $C^{(6)}_{NB}$ and $C^{(6)}_{NW}$ at one-loop

- Single vector-like lepton E and singly-charged scalar ϕ
- Additional constraints from EWPT, cLFV and LFU violating observables

Conclusions:

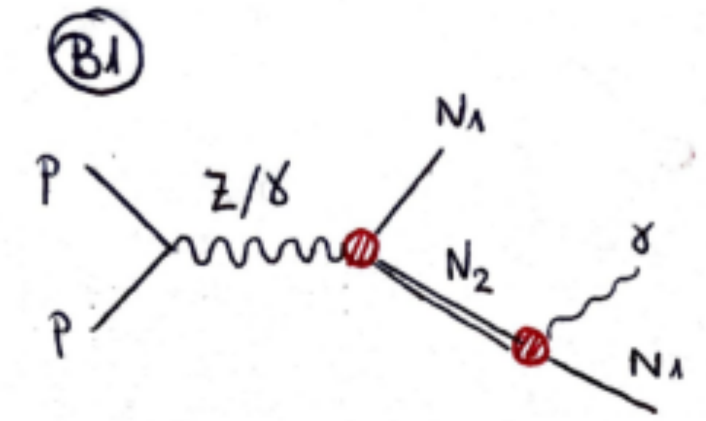
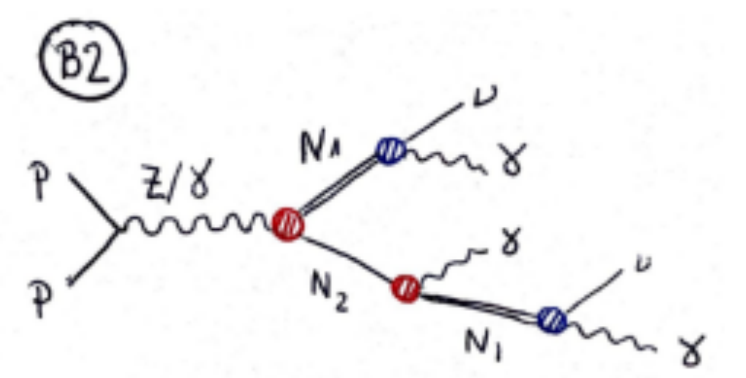
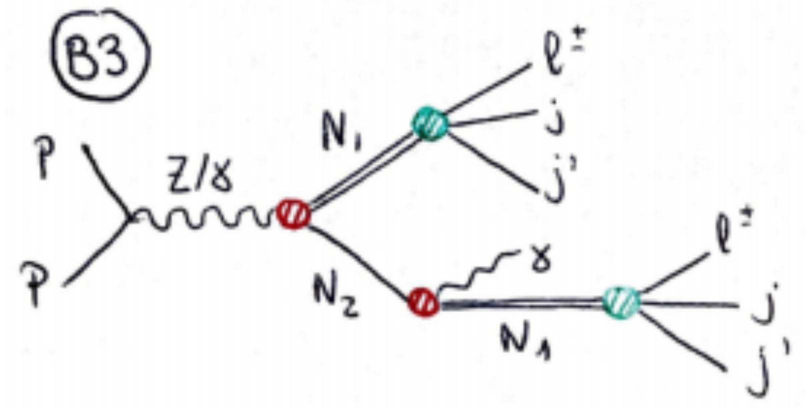
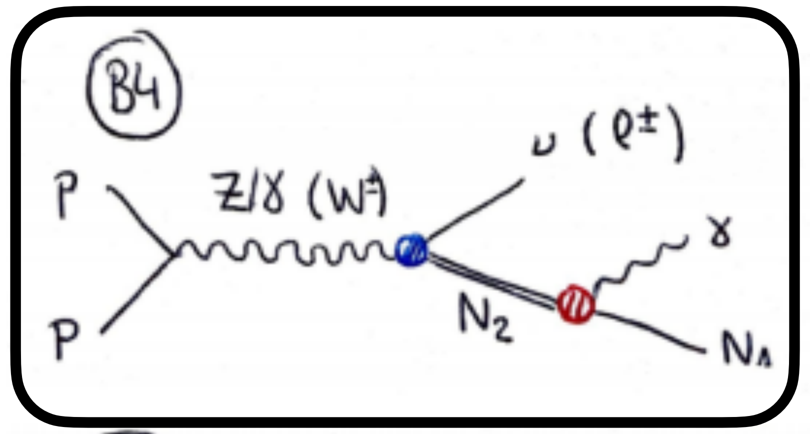
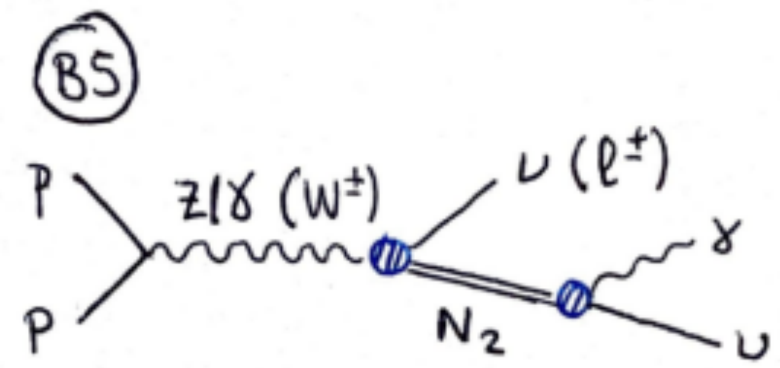
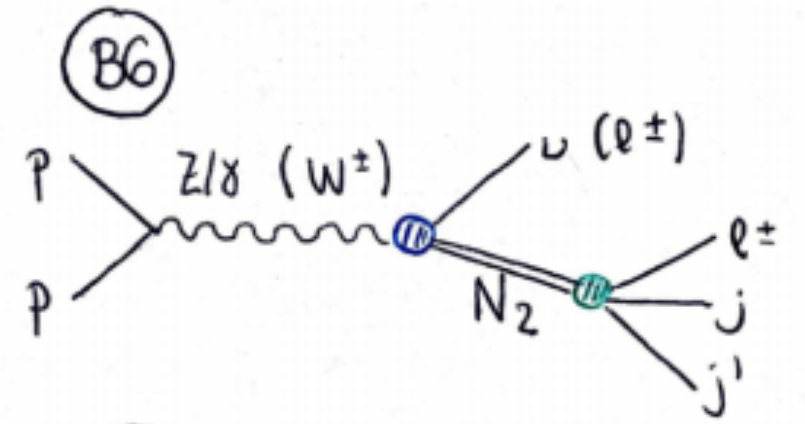
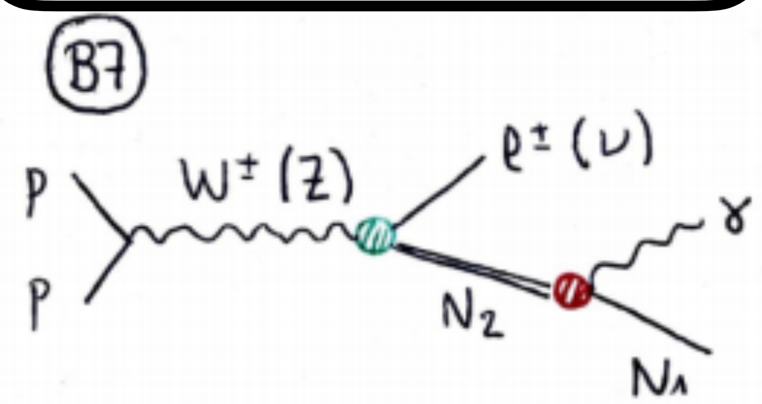
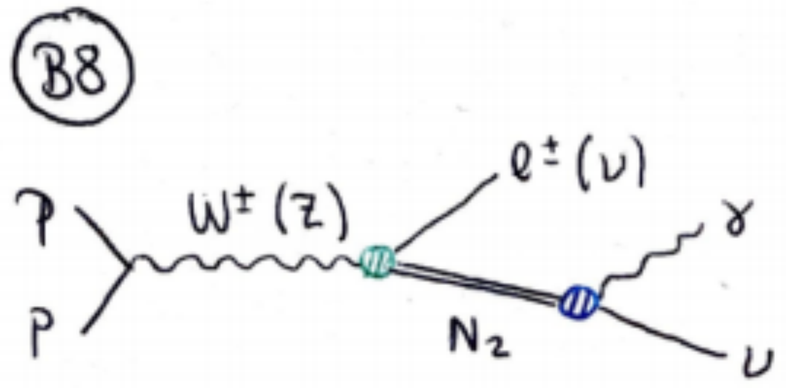
- Non-pointing photons can explore new regions of EFT parameter space for $d_{NN\gamma}$, $d_{\nu N\gamma}$ and $V_{\alpha N}$
- In specific model, complementarity with EWPT, cLFV

Thank you for your attention!

Bonus Slides

Possible Scenarios

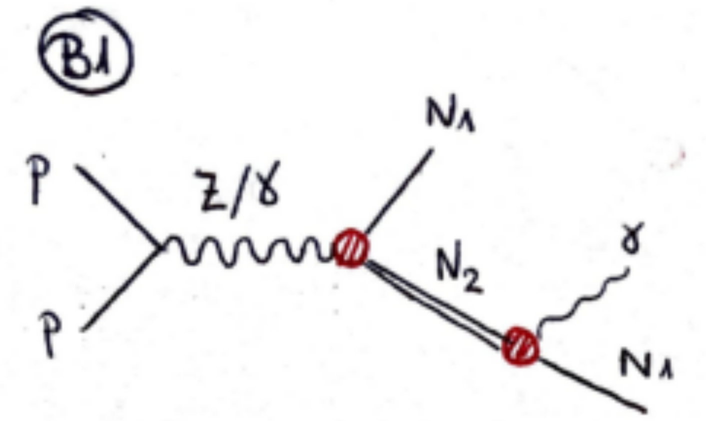
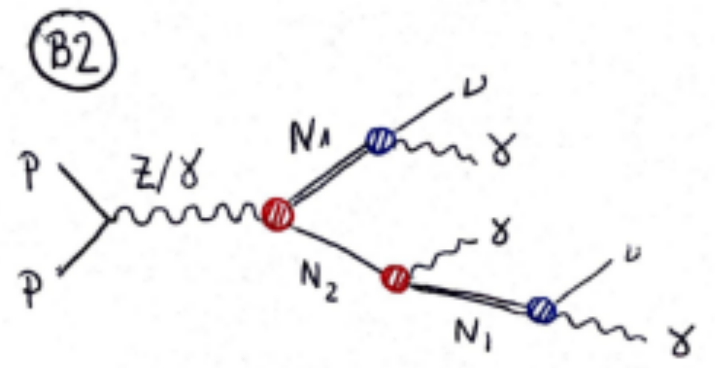
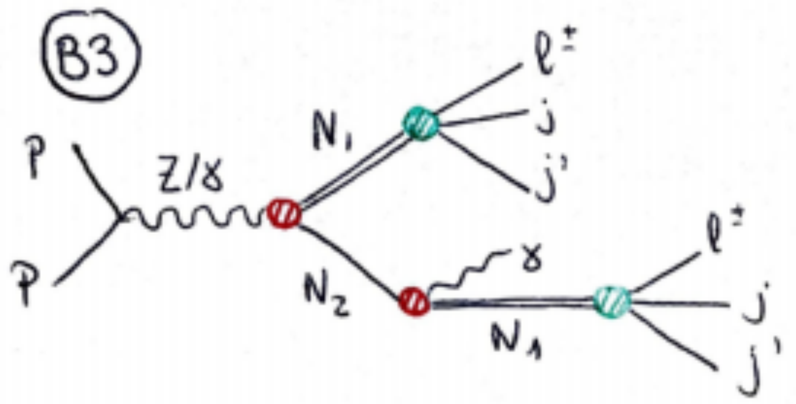
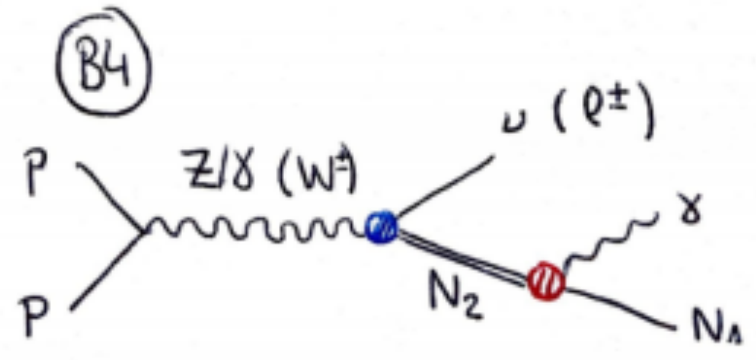
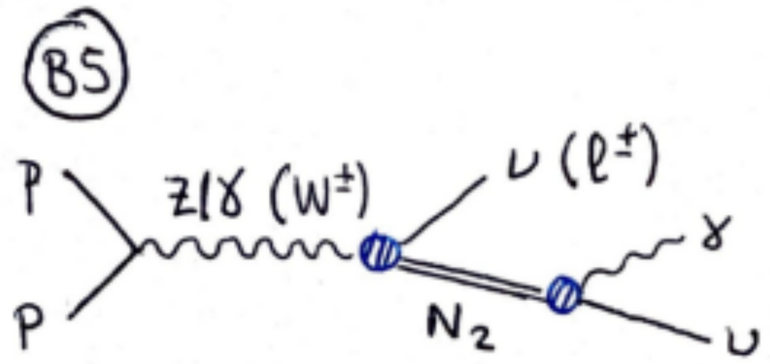
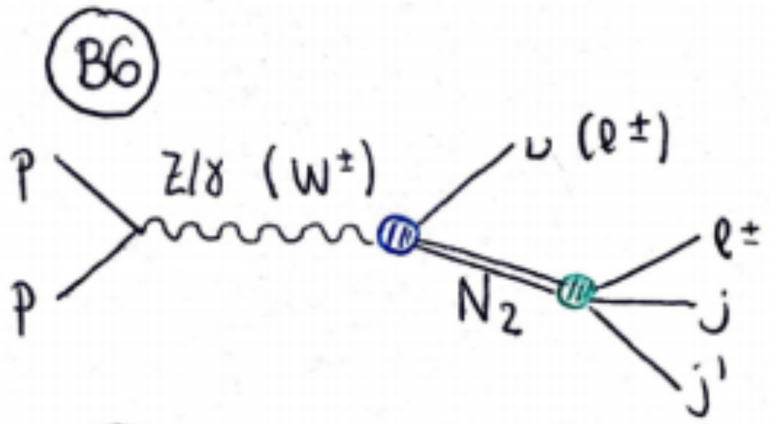
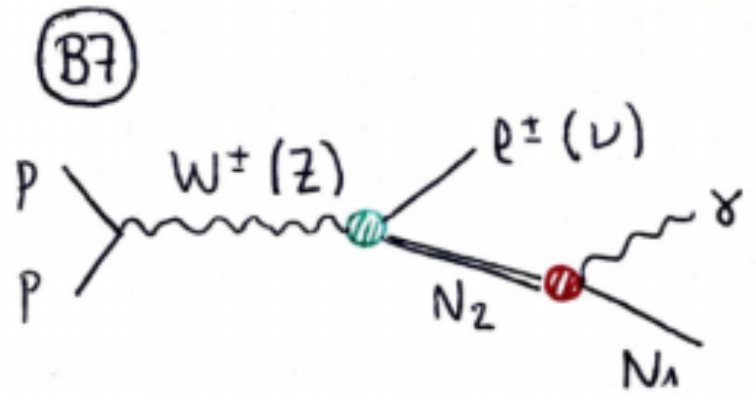
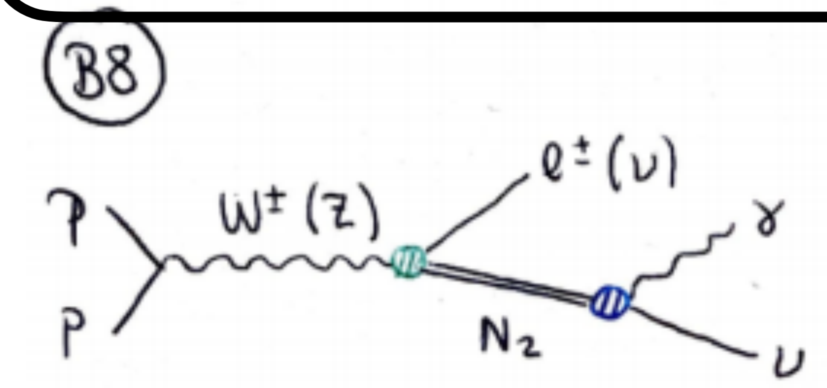
9 Scenarios: Where is the non-pointing photon signature viable?

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

B4: $C^{(5)}_{NNB}$ large enough to dominate the decay of N_2 would also dominate $\sigma(pp \to X)$

Possible Scenarios

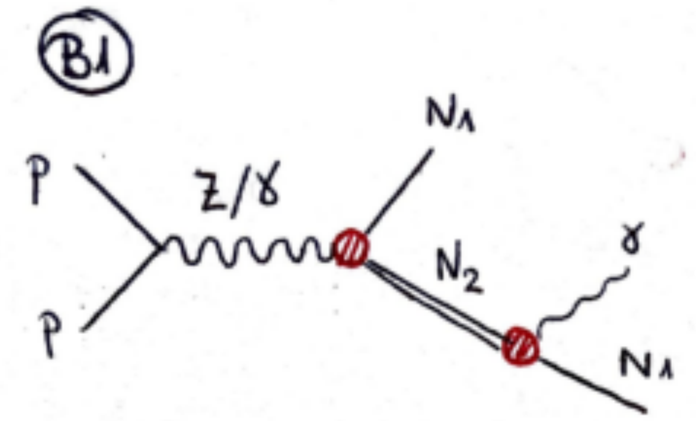
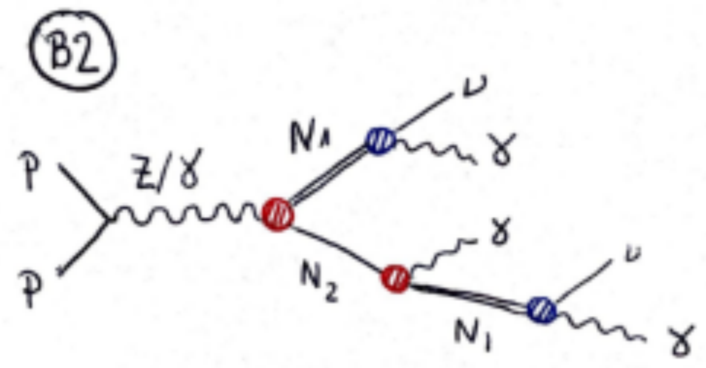
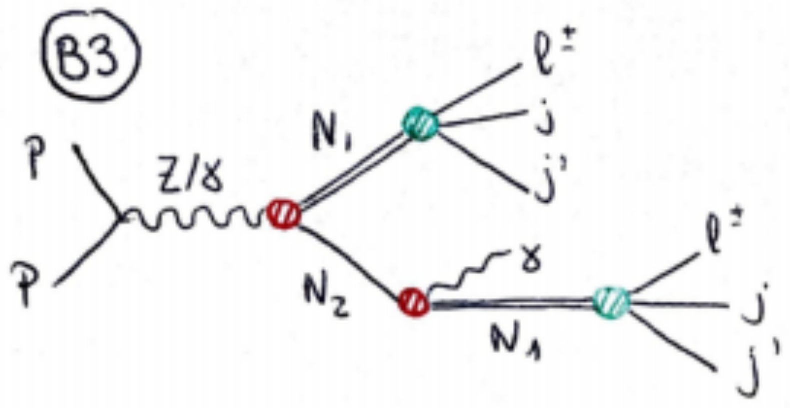
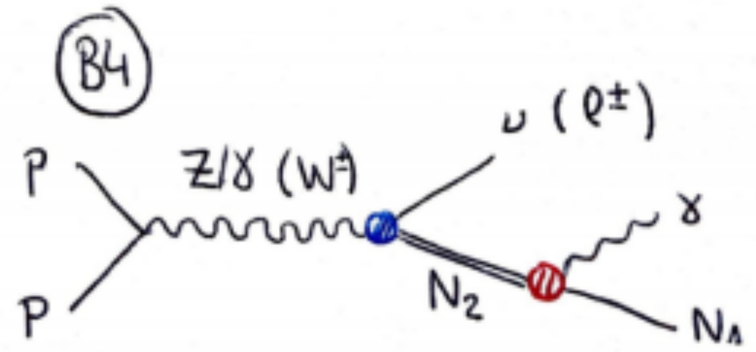
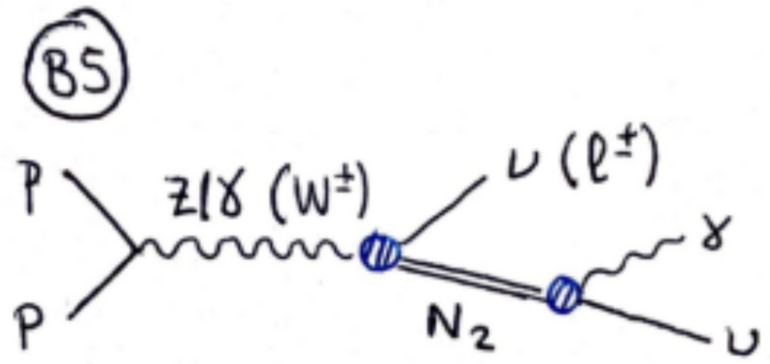
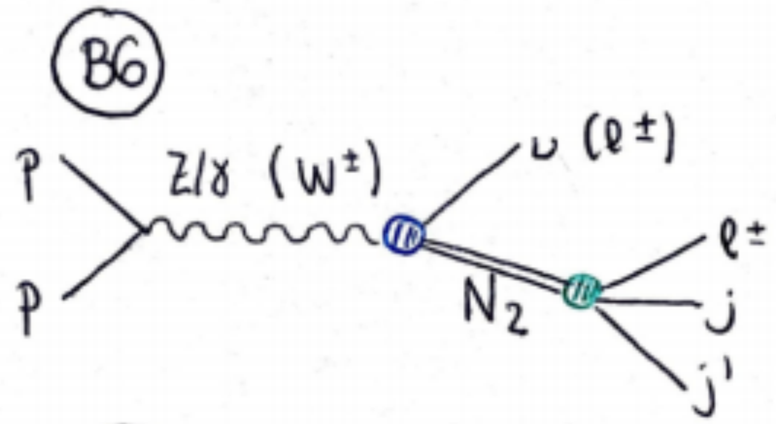
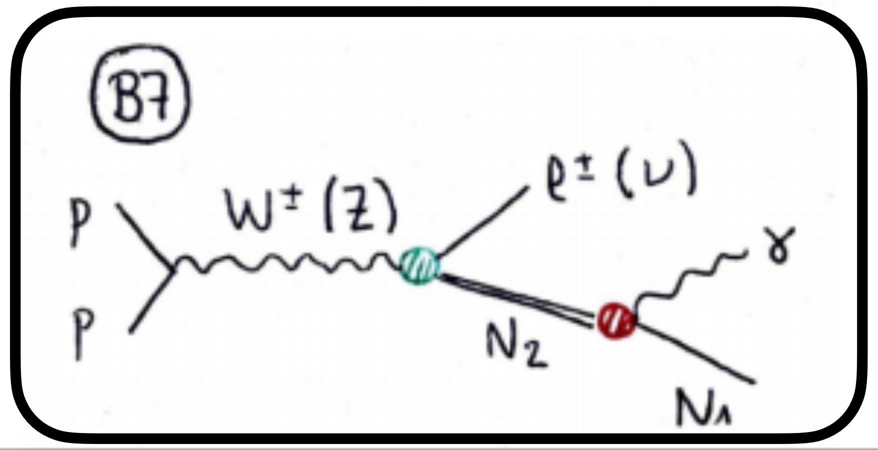
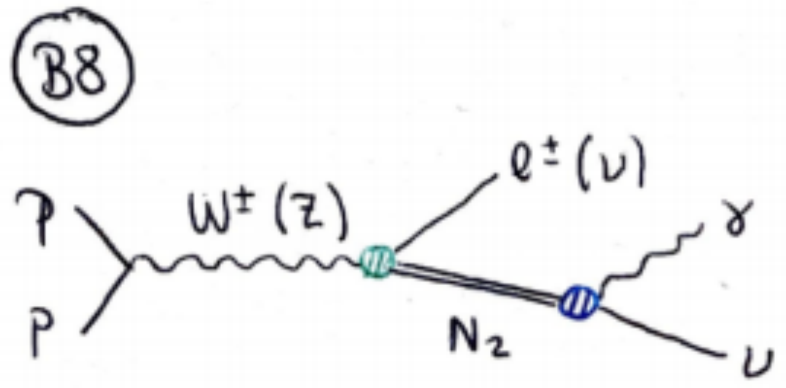
9 Scenarios: Where is the non-pointing photon signature viable?

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

B5 and **B6**: Difficult to realise displaced vertex (decay prompt if $C^{(6)}_{NB}$ dominates σ)

Possible Scenarios

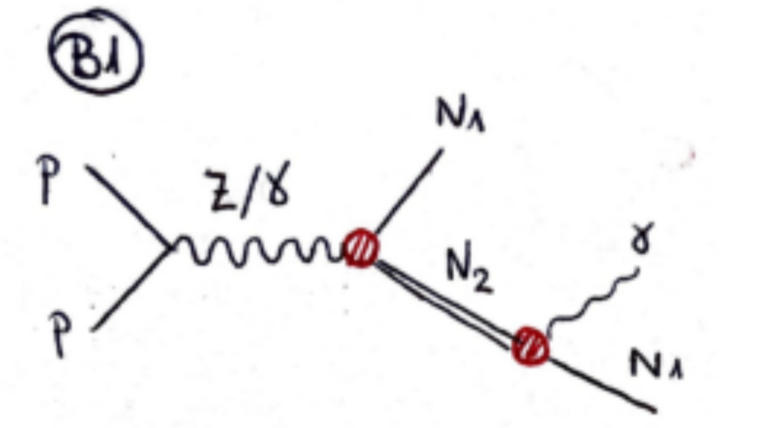
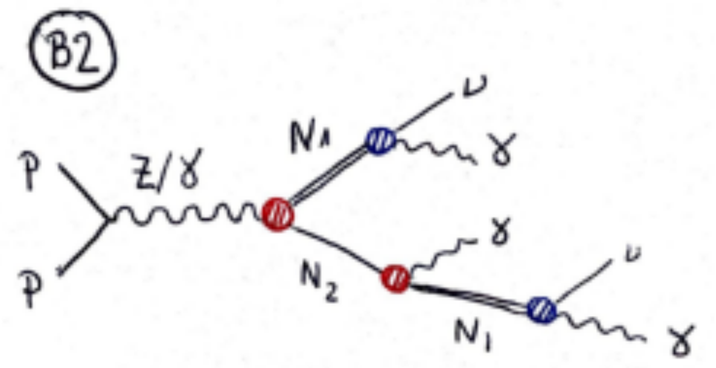
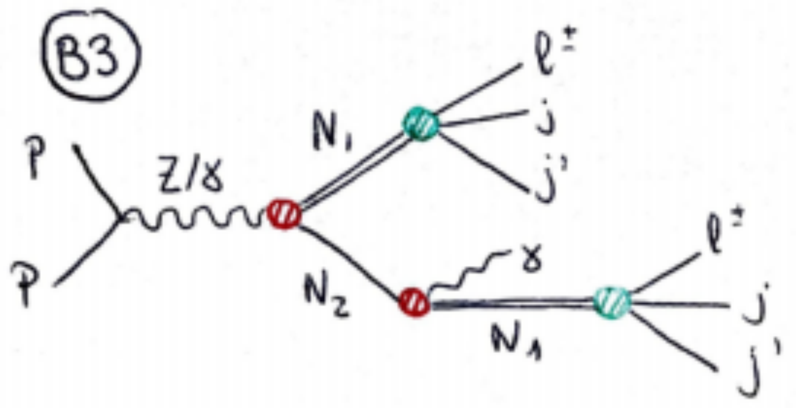
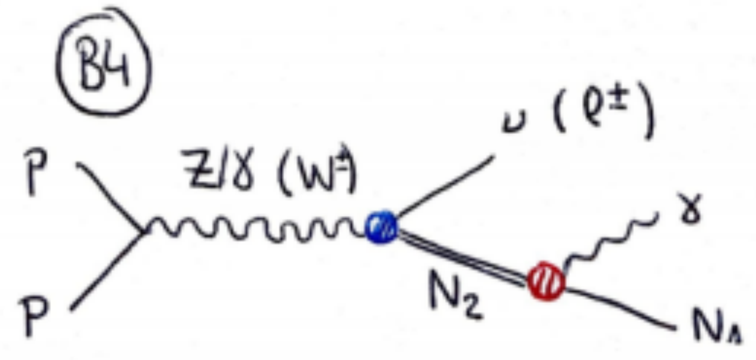
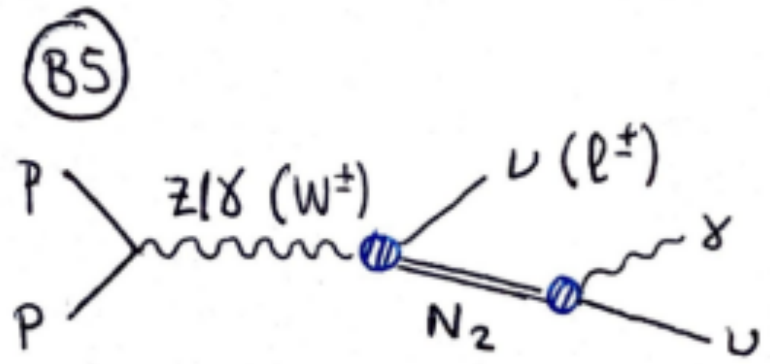
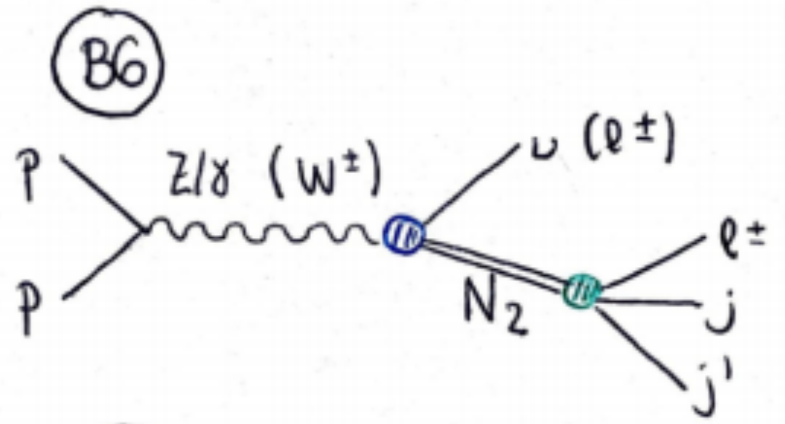
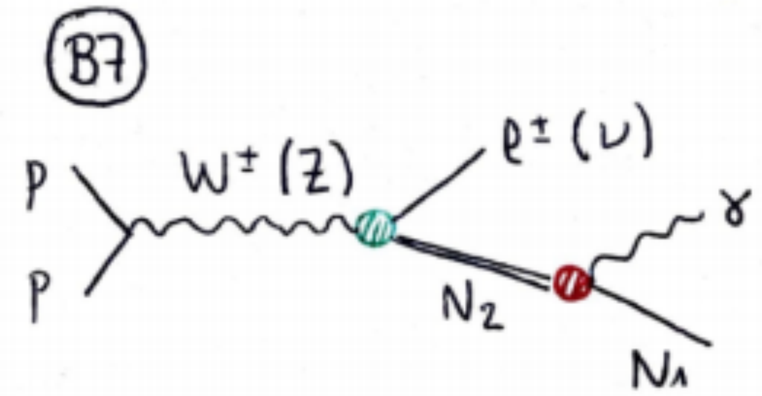
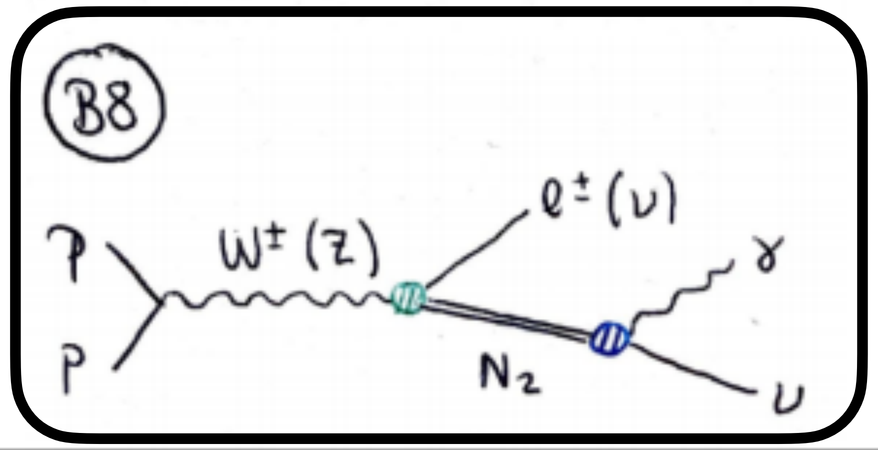
9 Scenarios: Where is the non-pointing photon signature viable?

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

B7: Can only be realised in a narrow region of parameter space

Possible Scenarios

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

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

B8: Prompt $\ell^{\pm}$ plus photon (prompt or displaced depending on $C^{(6)}_{NB}$)

UV Model for Neutrino Magnetic Moments

Vector-Like Lepton

Extended charged lepton mass term including vector-like lepton

$$\mathcal{L} \supset -\left(\bar{\ell}_L \; \bar{E}_L\right) \mathcal{M}_E \begin{pmatrix} \ell_R \\ E_R \end{pmatrix} + \text{h.c.}\,; \quad \mathcal{M}_E = \begin{pmatrix} \frac{vY_e}{\sqrt{2}} & \frac{vY_E}{\sqrt{2}} \\ 0 & m_E \end{pmatrix}$$

Diagonalise:

$$\begin{pmatrix} \ell_{L\alpha} \\ E_L \end{pmatrix} = \begin{pmatrix} V^L_{\alpha\beta} & V^L_{\alpha E} \\ V^L_{E\beta} & V^L_{EE} \end{pmatrix} P_L \begin{pmatrix} \ell'_\beta \\ E' \end{pmatrix}, \quad \begin{pmatrix} \ell_{R\alpha} \\ E_R \end{pmatrix} = \begin{pmatrix} V^R_{\alpha\beta} & V^R_{\alpha E} \\ V^R_{E\beta} & V^R_{EE} \end{pmatrix} P_R \begin{pmatrix} \ell'_\beta \\ E' \end{pmatrix},$$

In the limit $m_\ell \ll m_E$, seesaw-like mixing

$$V^L_{\alpha E} = -V^{L*}_{E\alpha} \approx \frac{vY^\alpha_E}{\sqrt{2}m_E}, \quad V^R_{\alpha E} = -V^{R*}_{E\alpha} \approx \frac{v^2[Y_e]^*_{\alpha\gamma}Y^\gamma_E}{2m_E^2}$$

$\Rightarrow V^{L,R}$ enters SM charged and neutral currents

Vector-Like Lepton

Equivalently, for $m_\ell \ll m_E$, the vector-like lepton can be integrated out. At tree-level:

$$\mathcal{O}_{Hl}^{(1)} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{L}\gamma^\mu L) \qquad \mathcal{O}_{Hl}^{(3)} = (H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{L}\tau^I\gamma^\mu L) \qquad \mathcal{O}_{eH} = (H^\dagger H)\bar{L}H\ell_R$$

With matching conditions:

$$C_{Hl}^{(1)\alpha\beta} = C_{Hl}^{(3)\alpha\beta} = -\frac{Y_E^\alpha Y_E^{\beta *}}{4m_E^2} \qquad C_{eH}^{\alpha\beta} = \frac{Y_E^\alpha Y_E^{\gamma *}[Y_e]_{\gamma\beta}}{2m_E^2}$$

del Aguila, de Blas, Perez-Victoria, arXiv:0803.4008

Give off-diagonal Z, Higgs couplings or flavour-changing neutral currents (FCNCs)

↳ Bounds from electroweak precision tests (EWPT) and charged-lepton flavour violation (cLFV)

Singly-Charged Scalar

For the singly-charged scalar, we can write

$$\mathcal{L} \supset -\left(\bar{\nu}_L \;\bar{\ell}_L\right) f \begin{pmatrix} \ell_L^c \\ -\nu_L^c \end{pmatrix} \phi + \text{h.c.} = -2\bar{\nu}_L f \ell_L^c \phi + \text{h.c.}\,,$$

Similarly, for $m_\ell \ll m_\phi$, we obtain from f and f' couplings:

$$\mathcal{O}_{ll} = (\bar{L}\gamma_\mu L)(\bar{L}\gamma^\mu L) \qquad \mathcal{O}_{lNle} = (\bar{L}N_R)\epsilon(\bar{L}\ell_R) \qquad \mathcal{O}_{eN} = (\bar{\ell}_R\gamma_\mu \ell_R)(\bar{N}_R\gamma^\mu N_R)$$

With tree-level matching conditions:

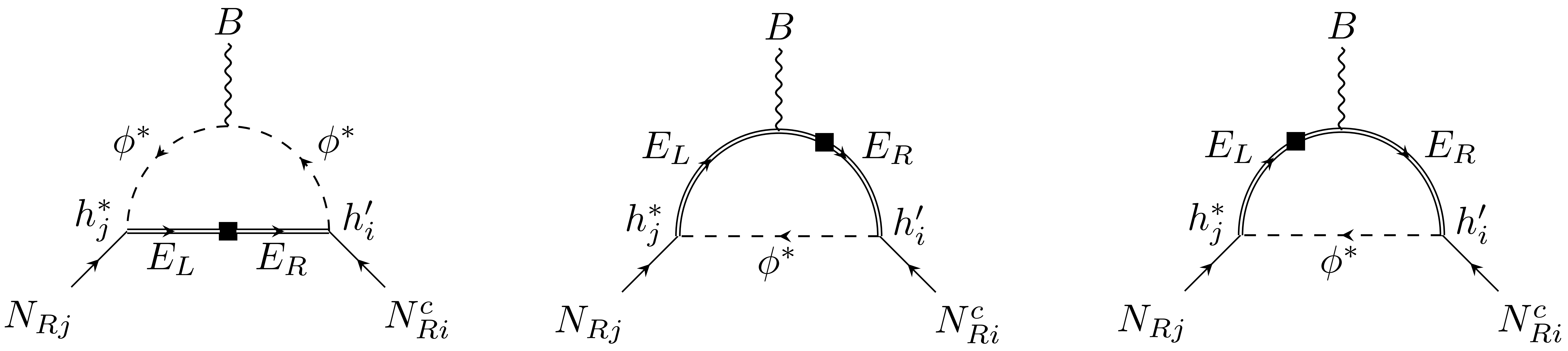
$$C_{ll}^{\alpha\beta\gamma\delta} = \frac{f_{\alpha\gamma} f_{\delta\beta}^*}{m_\phi^2} \qquad C_{lNle}^{\alpha i\beta\gamma} = \frac{2 f_{\alpha\beta} f'_{i\gamma}}{m_\phi^2} \qquad C_{eN}^{\alpha\beta ij} = \frac{f'^*_{i\alpha} f'_{j\beta}}{2m_\phi^2}$$

Exotic lepton interactions

↳ Bounds from lepton flavour universality (LFU) and charged lepton flavour violating probes

Sterile-to-Sterile Neutrino Magnetic Moments

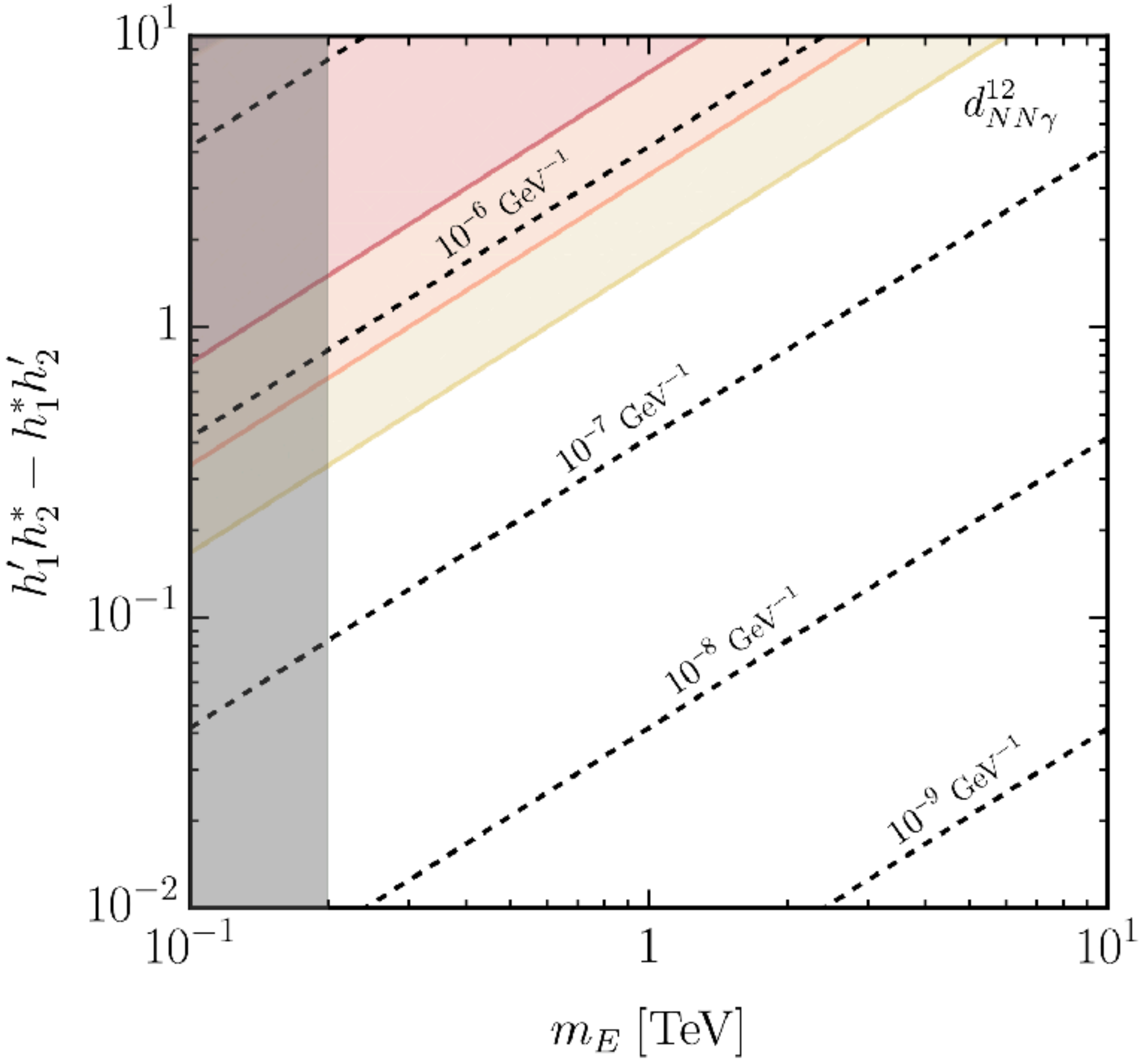
At one-loop in the UV model:



One-loop matching:

$$C_{NNB}^{(5)ij} = \frac{1}{16\pi^2} \frac{g'(h_i' h_j^* - h_i^* h_j')}{4m_E} f(r) \qquad f(r) = \frac{1}{1-r} + \frac{r \log r}{(1-r)^2}$$

Sterile-to-Sterile Neutrino Magnetic Moments

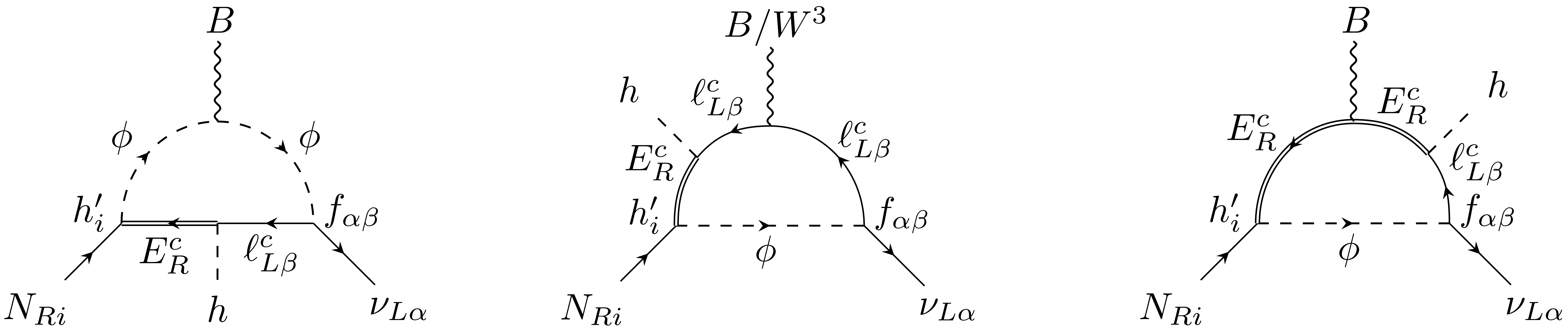


$$d^{ij}_{NN\gamma} = c_w C^{(5)ij}_{NNB} \approx 2.4 \times 10^{-6}\ \text{GeV}^{-1} \left(\frac{h'_i h^*_j - h^*_i h'_j}{10}\right)\left(\frac{1\ \text{TeV}}{m_E}\right)$$

$$h_i, h'_i < \sqrt{4\pi}$$

Active-to-Sterile Neutrino Magnetic Moments

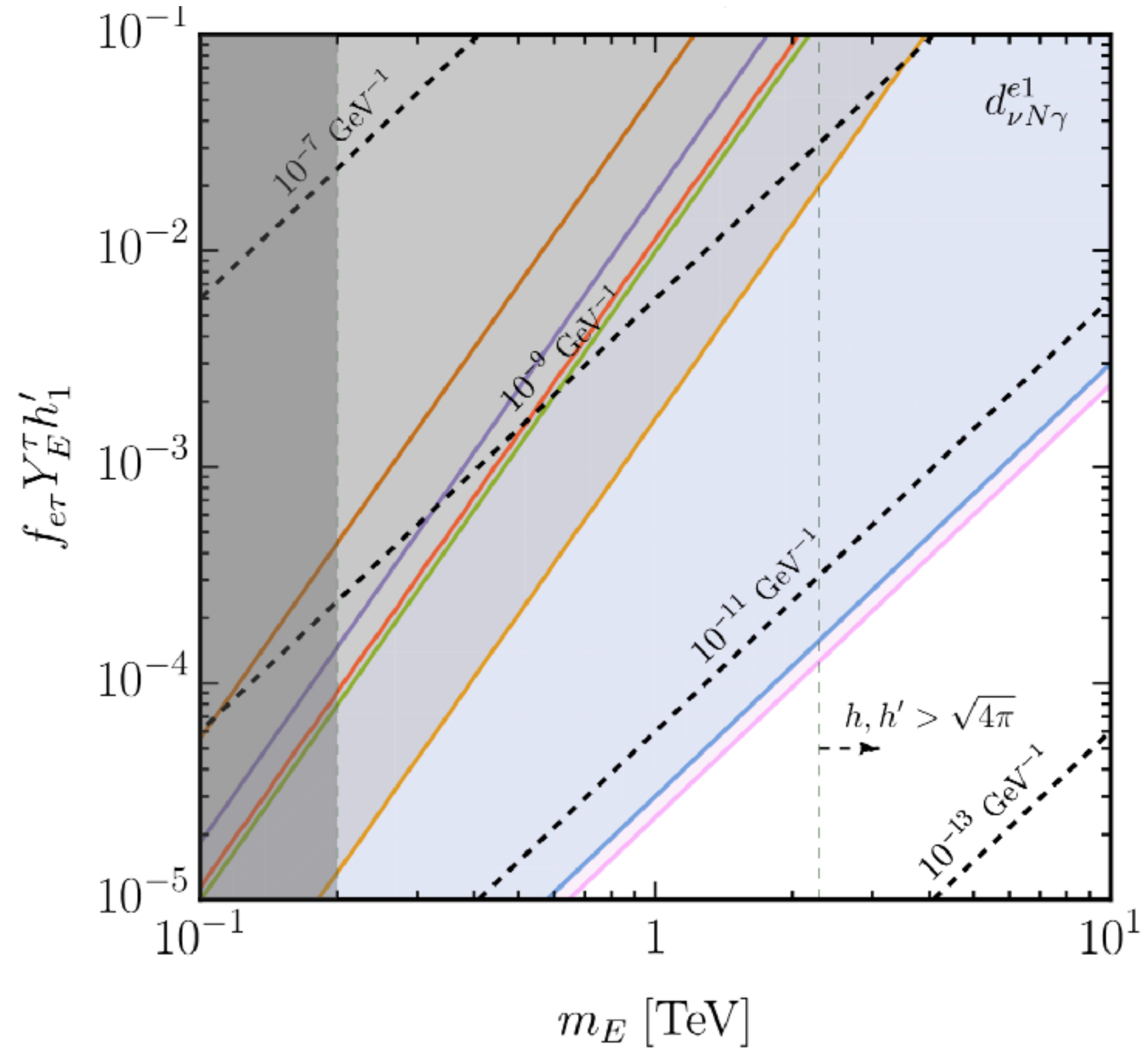
Without Z_2, at one-loop in the UV model:



Matching: $$C_{NB}^{(6)\alpha i} = \frac{1}{16\pi^2}\frac{3g'_{\alpha\beta}Y_E^{\beta *}h'_i}{4m_E^2}f(r) \qquad C_{NW}^{(6)\alpha i} = \frac{1}{16\pi^2}\frac{gf_{\alpha\beta}Y_E^{\beta *}h'_i}{2m_E^2}f(r)\,.$$

The UV model therefore predicts $a = \frac{g'}{g}\frac{C_{NW}^{(6)\alpha i}}{C_{NB}^{(6)\alpha i}} = \frac{2}{3}$ which narrows down the phenomenology

Active-to-Sterile Neutrino Magnetic Moments



$$d^{\alpha i}_{\nu N\gamma} = \frac{4 v c_w}{3\sqrt{2}} C^{(6)\alpha i}_{NB} \approx 1.7 \times 10^{-9}\ \mathrm{GeV}^{-1} \left(\frac{f_{\alpha\beta} Y^{\beta *}_{E} h'_i}{10^{-2}}\right)\left(\frac{1\ \mathrm{TeV}}{m_E}\right)^2$$

Other Constraints on UV Scenario

Charged Lepton Flavour Violation Bounds

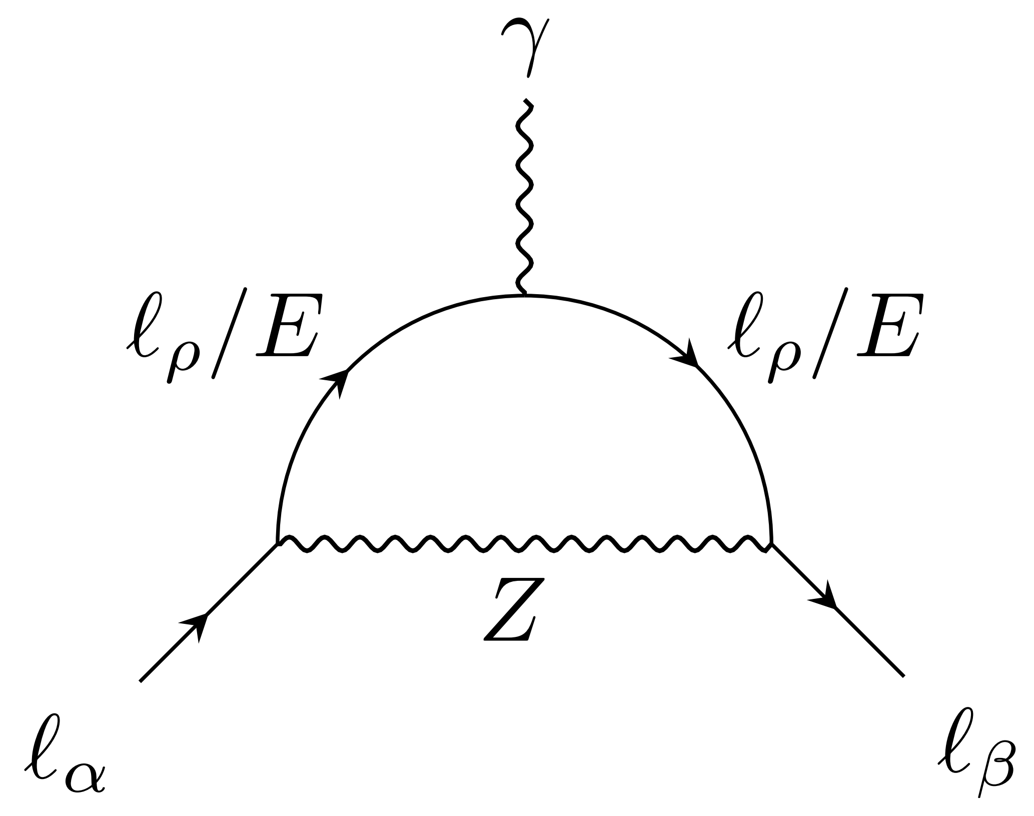
cLFV processes via the general couplings Y_E^{α} and $f_{\alpha\beta}$ can also be used to constrain the model:

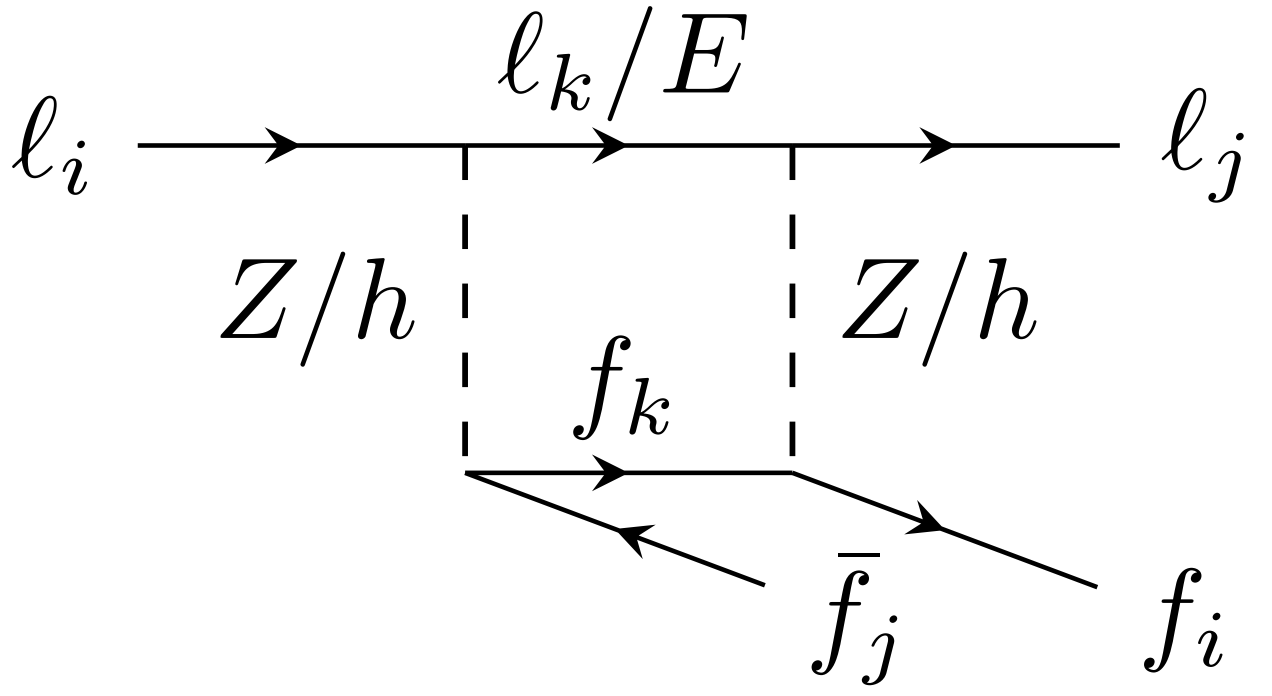
Tree-level

- $\mu \to 3e$, $\tau \to 3e$, $\tau \to 3\mu$ (SINDRUM, Belle)
- $\mu \to e$ conversion in nuclei (SINDRUM)
- LFU violation in charged-currents
- Flavour-violating Z and Higgs decays (ATLAS, CMS)

One-loop

- $\mu \to e\gamma$, $\tau \to e\gamma$, $\tau \to \mu\gamma$ (MEG, BaBar)

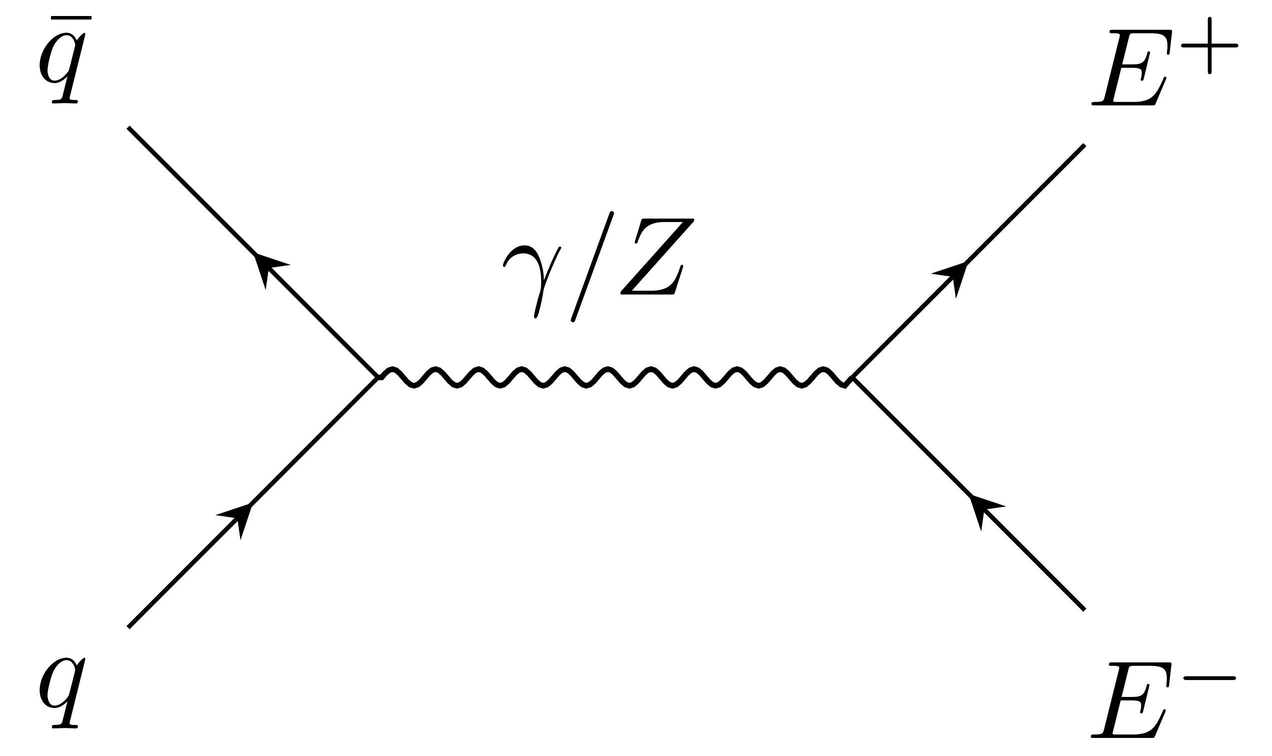




Direct Production Bounds

The vector-like lepton E and singly-charged scalar ϕ can also be produced directly at the LHC

- Drell-Yan production: $pp \to \gamma/Z \to E^+E^-,\ pp \to \gamma/Z \to \phi^+\phi^-$
- Decays: $\phi^\pm \to \ell^\pm\nu,\ E^\pm(\to N\phi^\pm) \to \ell^\pm\nu N$



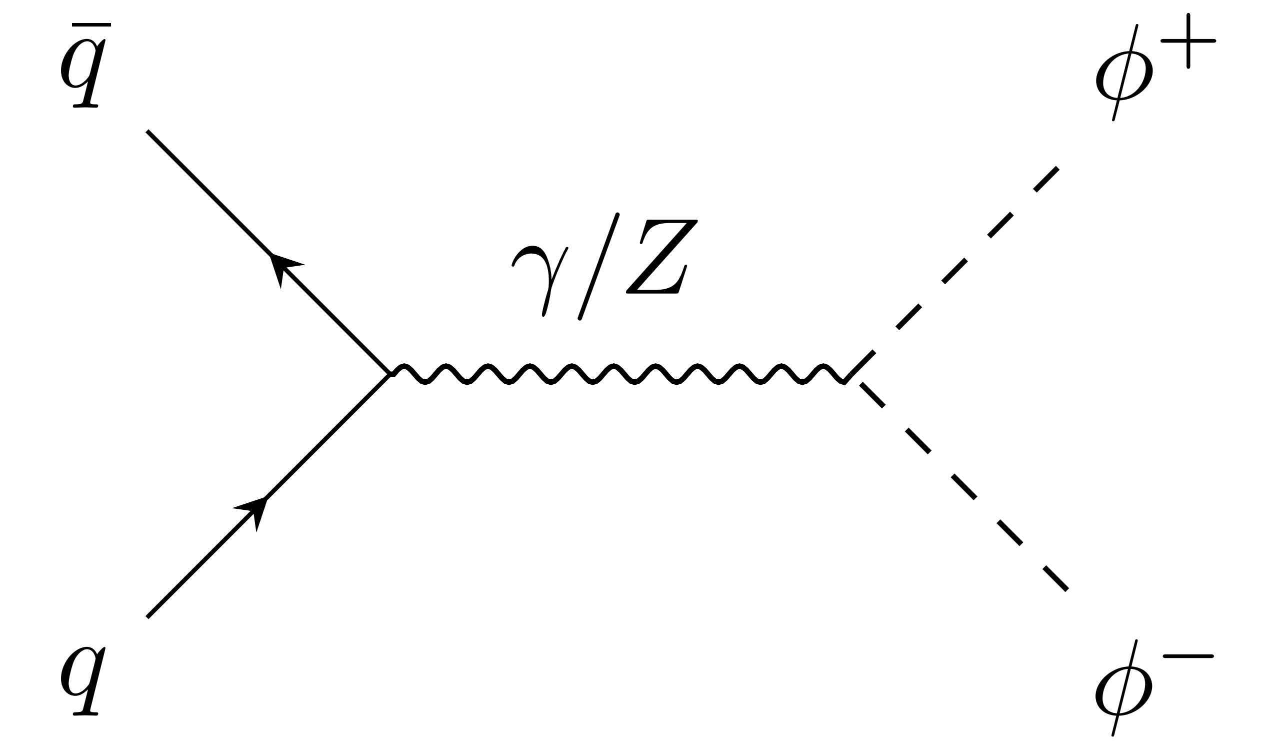
Recast:

- Slepton ATLAS search using oppositely-charged e and μ pairs

$$m_E, m_\phi \gtrsim 200\ \text{GeV}$$

- Dark matter LEP monophoton bounds

$$m_\phi/|f_{e\mu}|^2 \gtrsim 350\ \text{GeV}$$



Benchmark Flavour Scenarios

1) Flavour universal couplings: $Y_E^e = Y_E^\mu = Y_E^\tau = f_{e\mu} = f_{e\tau} = f_{\mu\tau}$

↳ Strongest bounds from $\mu \to 3e$ and $\mu \to e$ conversion (tree-level)

2) 'Tau-only' couplings: $Y_E^e = Y_E^\mu = f_{e\mu} = 0\,,\;\; Y_E^\tau = f_{e\tau} = f_{\mu\tau} \neq 0$

↳ Strongest bounds from $\mu \to e\gamma$ and $\mu \to 3e$ (one-loop)

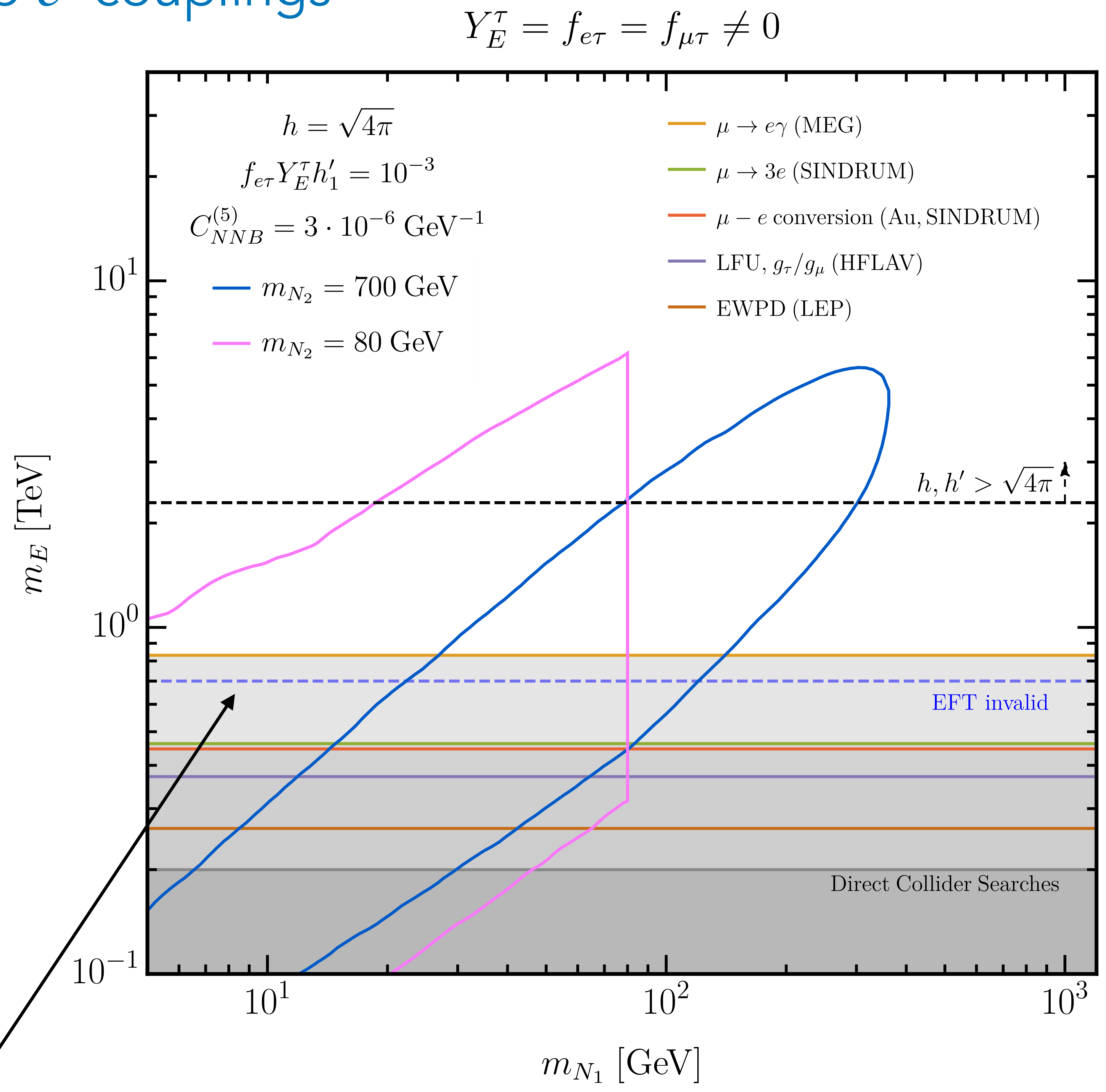
3) 'No electron' or $\mu - \tau$ couplings: $Y_E^e = f_{e\mu} = f_{e\tau} = 0\,,\;\; Y_E^\mu = Y_E^\tau = f_{\mu\tau} \neq 0$

↳ Strongest bounds from $\tau \to 3\mu$ and $\tau \to \mu ee$ (tree-level)

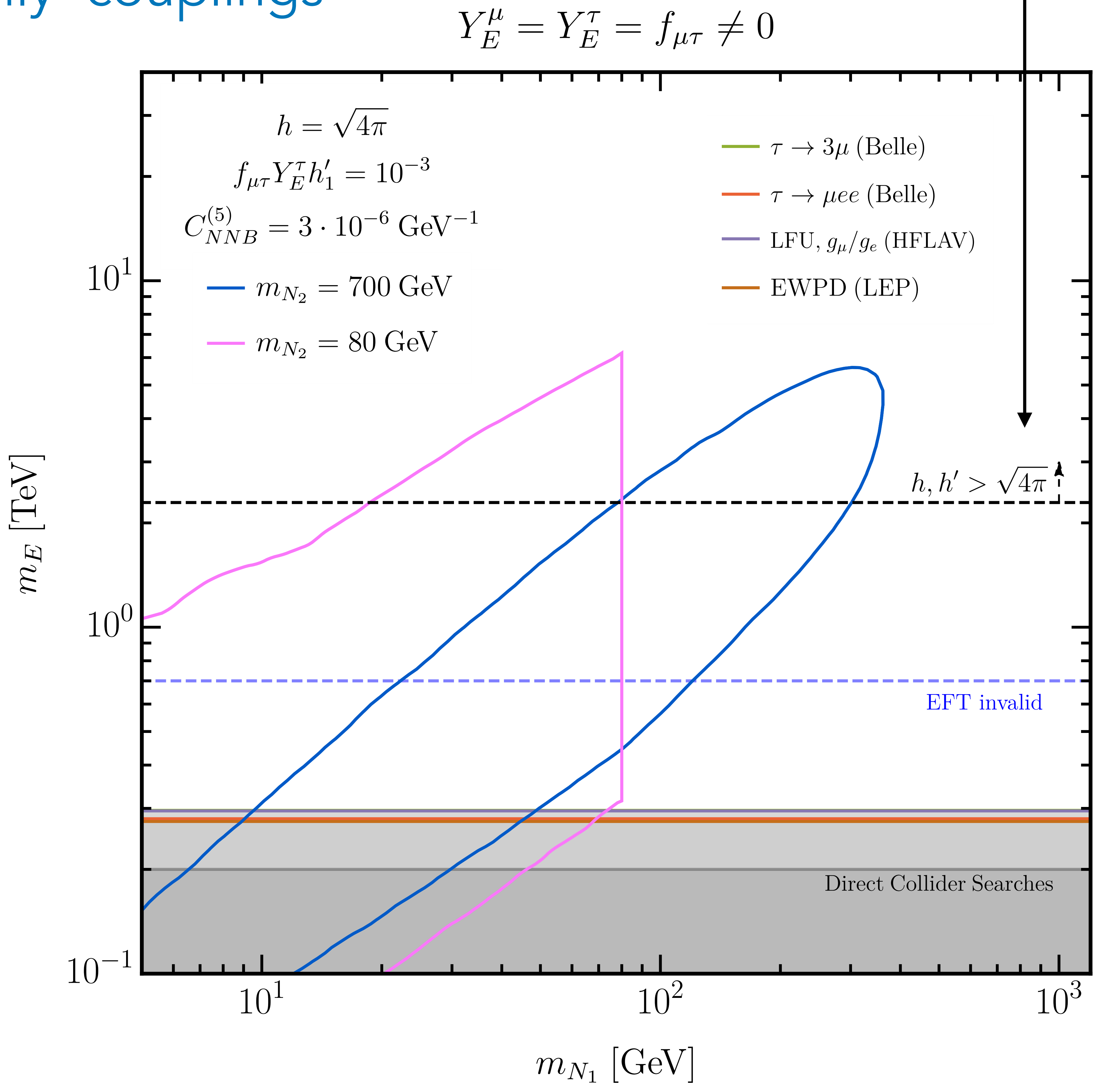
Active-to-Sterile Bounds

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

'No e' couplings



'τ only' couplings



EFT invalid for $m_E < m_{N_2} = 700$ GeV