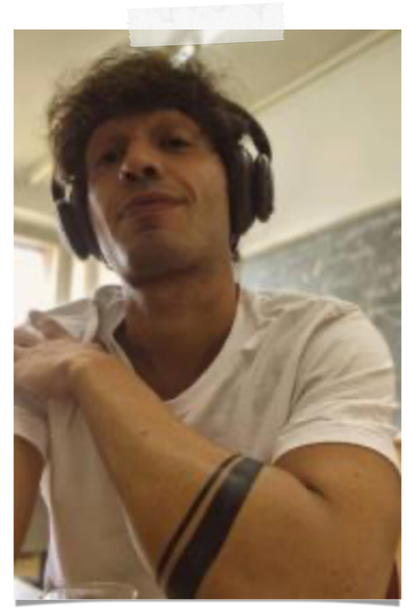
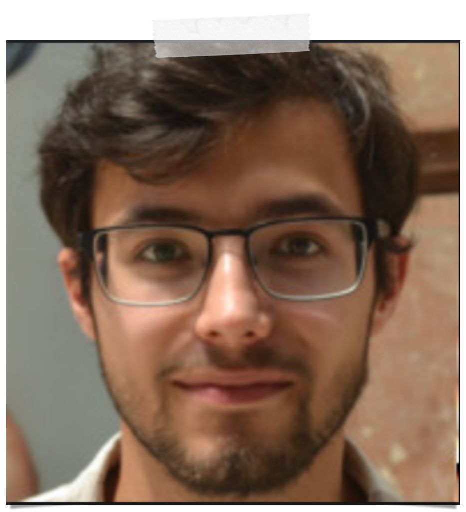
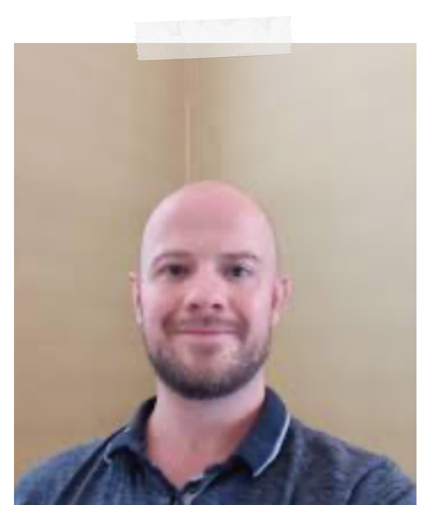
Dark dipole operators

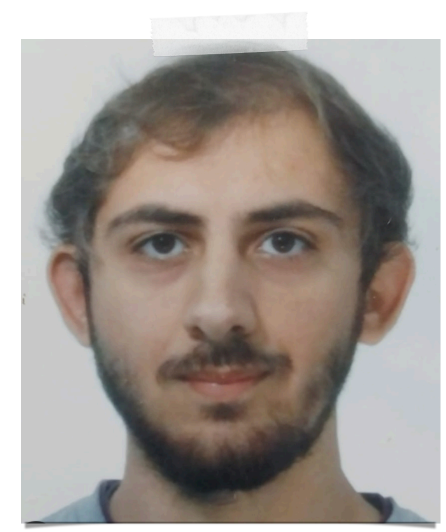
Daniele Barducci

Neutrinos and Flavour: a stairway to New Physics
3rd April 2025

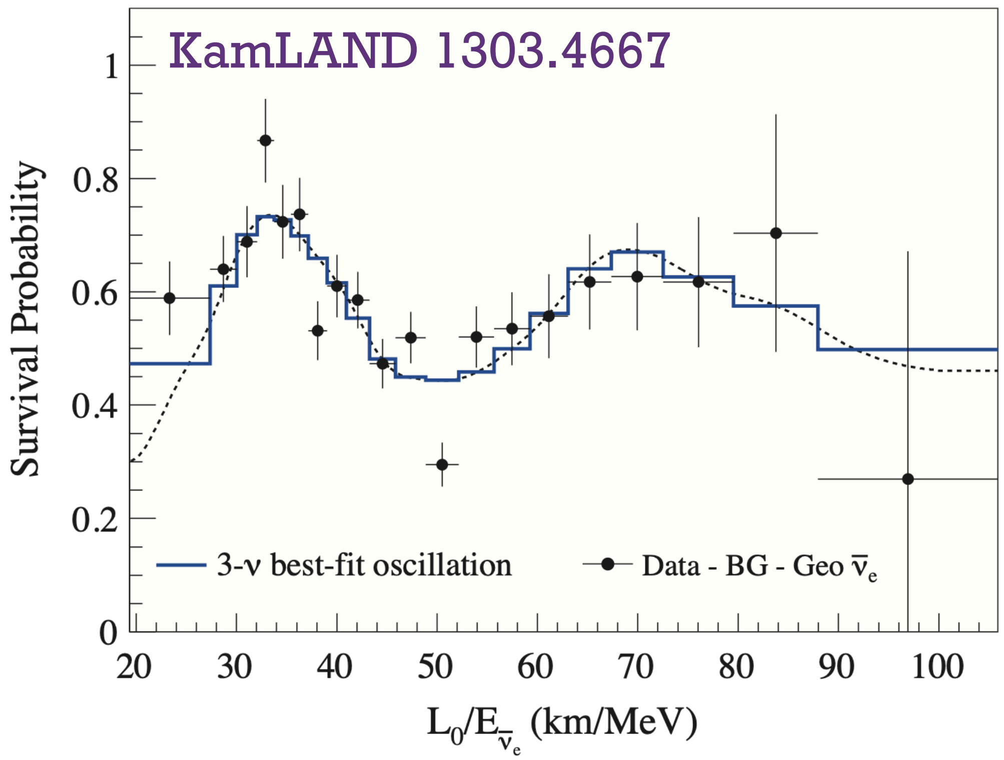




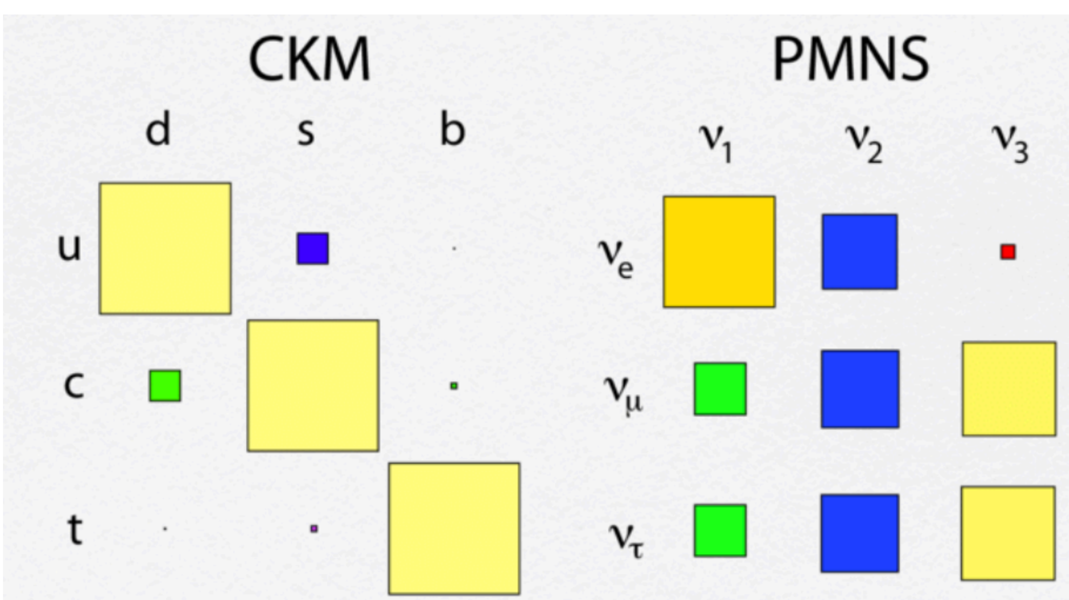


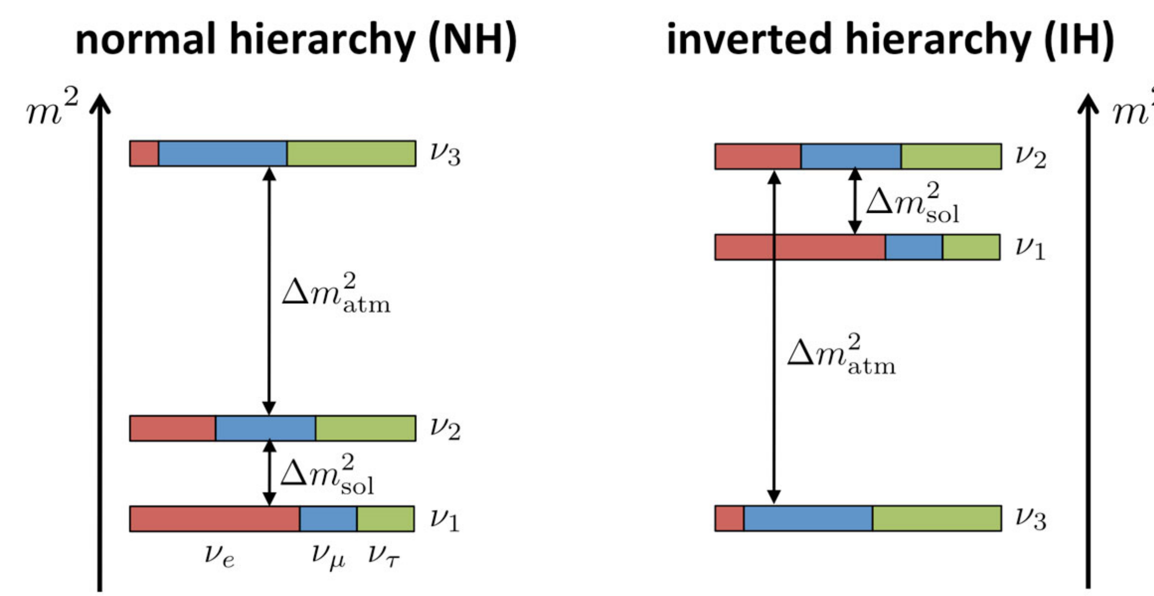


- Neutrino masses and mixings are determined with more and more precisions



NO	Ref. [188] w/o SK-ATM		Ref. [188] w SK-ATM	
	Best Fit Ordering		Best Fit Ordering	
Param	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\frac{\sin^2\theta_{12}}{10^{-1}}$	$3.10^{+0.13}_{-0.12}$	$2.75 \to 3.50$	$3.10^{+0.13}_{-0.12}$	$2.75 \to 3.50$
$\theta_{12}/^\circ$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$
$\frac{\sin^2\theta_{23}}{10^{-1}}$	$5.58^{+0.20}_{-0.33}$	$4.27 \to 6.09$	$5.63^{+0.18}_{-0.24}$	$4.33 \to 6.09$
$\theta_{23}/^\circ$	$48.3^{+1.2}_{-1.9}$	$40.8 \to 51.3$	$48.6^{+1.0}_{-1.4}$	$41.1 \to 51.3$
$\frac{\sin^2\theta_{13}}{10^{-2}}$	$2.241^{+0.066}_{-0.065}$	$2.046 \to 2.440$	$2.237^{+0.066}_{-0.065}$	$2.044 \to 2.435$
$\theta_{13}/^\circ$	$8.61^{+0.13}_{-0.13}$	$8.22 \to 8.99$	$8.60^{+0.13}_{-0.13}$	$8.22 \to 8.98$
$\delta_{CP}/^\circ$	222^{+38}_{-28}	$141 \to 370$	221^{+39}_{-28}	$144 \to 357$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$
$\frac{\Delta m^2_{32}}{10^{-3}\ \text{eV}^2}$	$2.449^{+0.032}_{-0.030}$	$2.358 \to 2.544$	$2.454^{+0.029}_{-0.031}$	$2.362 \to 2.544$



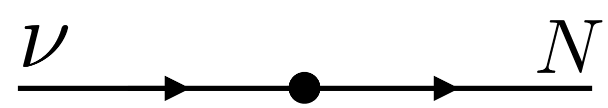


- Physics beyond the Standard Model is required to explain these patterns

- Minimal possibility is to mimic the SM quark sector

$$\mathcal{L} = \mathcal{L}_{\rm SM} - Y_\nu \bar{L} \tilde{H} N_R + h.c.$$

Dirac mass

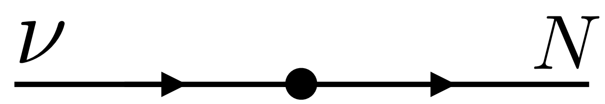


$$Y_\nu \sim \frac{m_\nu}{v} \ll 1$$

- Minimal possibility is to mimic the SM quark sector

$$\mathcal{L} = \mathcal{L}_{\rm SM} - Y_\nu \bar{L} \tilde{H} N_R + h.c.$$

Dirac mass

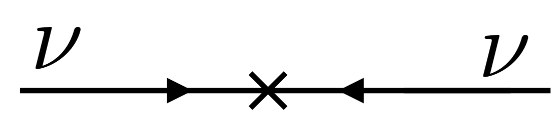


$$Y_\nu \sim \frac{m_\nu}{v} \ll 1$$

- But neutrinos transform under a real irrepr. of the SM unbroken group

$$m_\nu \bar{\nu}_L^c \nu_L$$

Majorana mass



- In the EW unbroken phase parametrized by a $d = 5$ operator

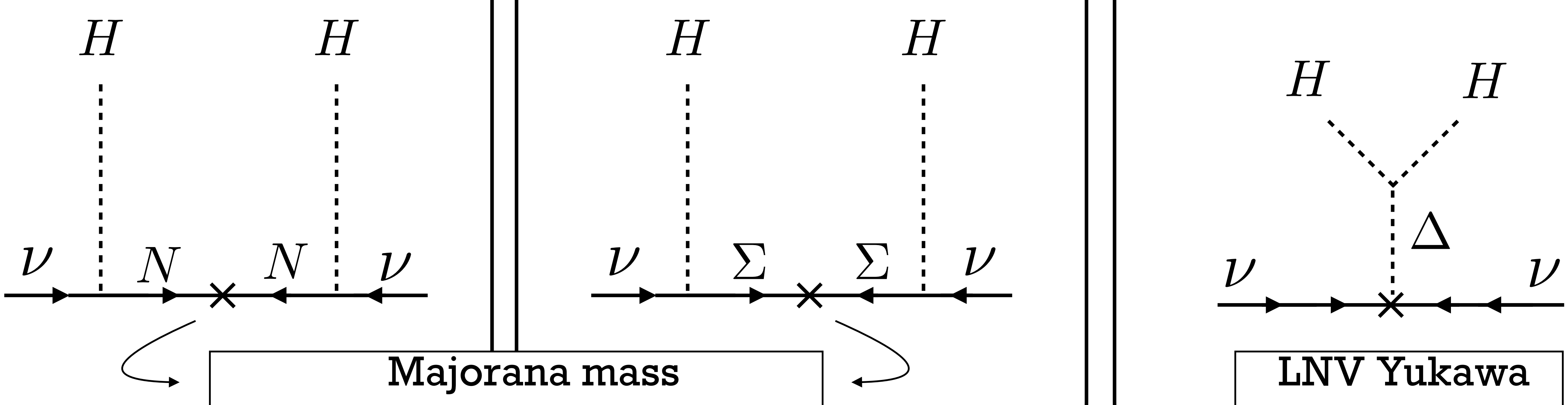
$$\mathcal{O} = \frac{1}{\Lambda} (\bar{L}^c \tilde{H}^*)(\tilde{H}^\dagger L) \qquad m_\nu \simeq \frac{v^2}{\Lambda}$$

- At tree-level only three possible SM extensions

Singlet fermion
$N \in (\mathbf{1},\mathbf{1})_0$

Triplet fermion
$\Sigma \in (\mathbf{1},\mathbf{3})_0$

Triplet scalar
$\Delta \in (\mathbf{1},\mathbf{3})_{-1}$



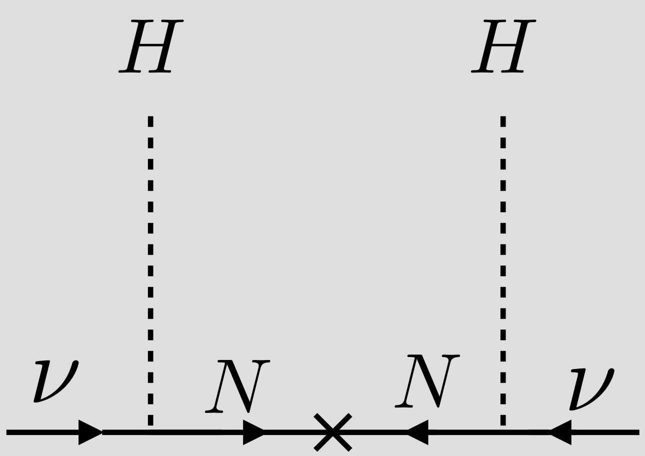
$$m_\nu \simeq \frac{v^2}{m_{N,\Sigma}}$$

$$m_\nu \simeq \mu_\Delta \frac{v^2}{m_\Delta^2}$$

- At tree-level only three possible SM extensions

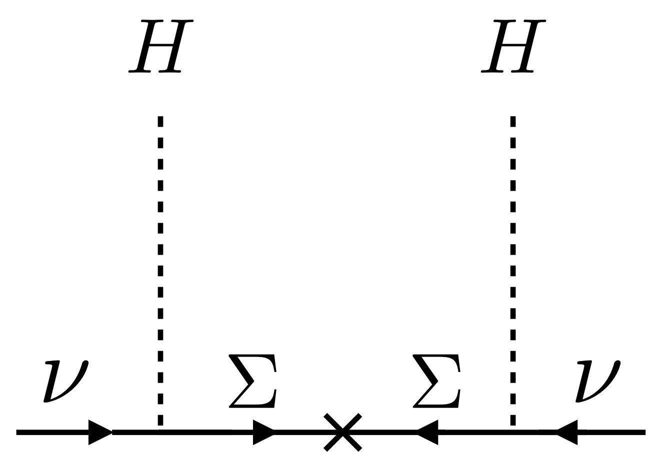
Singlet fermion

$N \in (\mathbf{1}, \mathbf{1})_0$



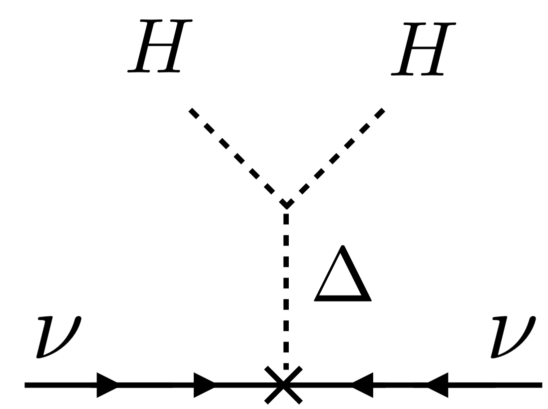
Triplet fermion

$\Sigma \in (\mathbf{1}, \mathbf{3})_0$



Triplet scalar

$\Delta \in (\mathbf{1}, \mathbf{3})_{-1}$



Majorana mass

LNV Yukawa

$$m_\nu \simeq \frac{v^2}{m_{N,\Sigma}}$$

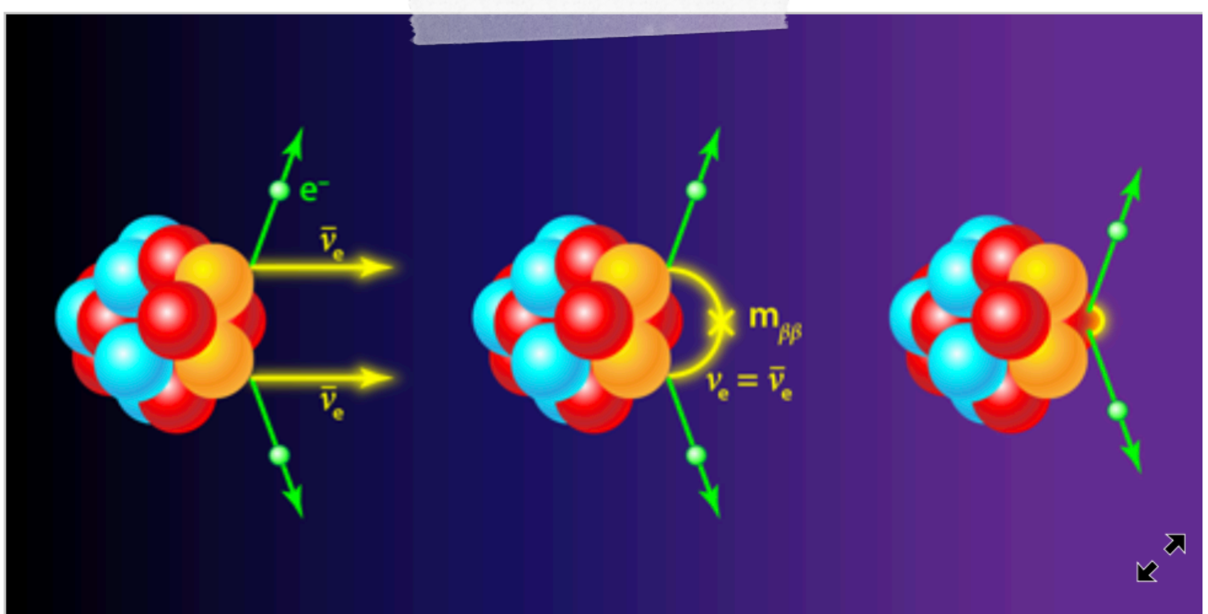
$$m_\nu \simeq \mu_\Delta \frac{v^2}{m_\Delta^2}$$

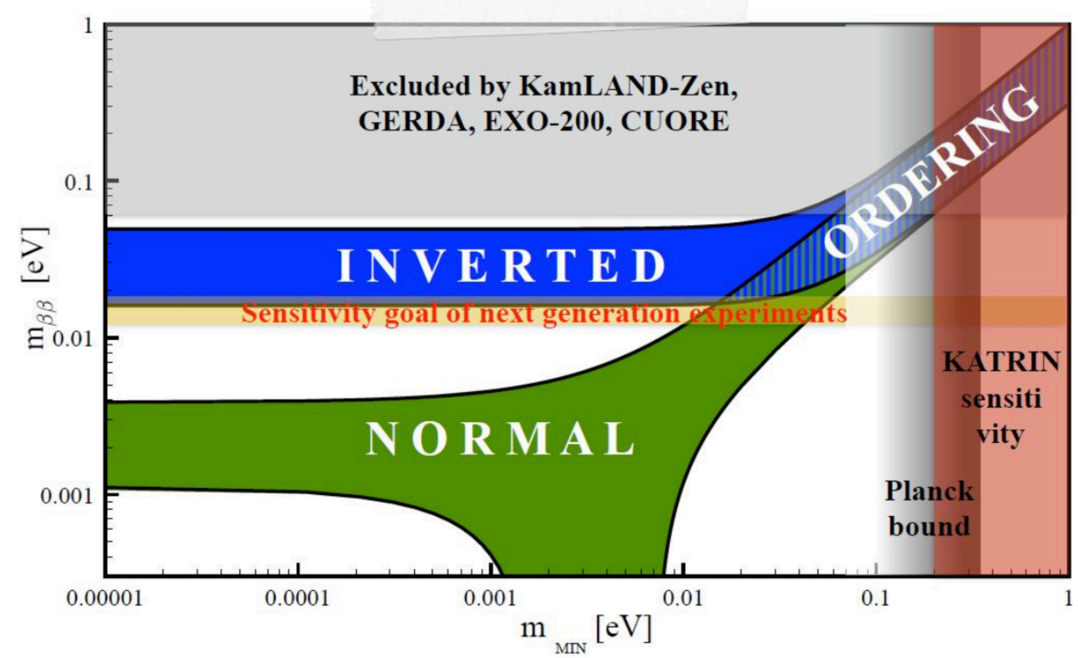
- Singlet fermion most economical possibility

$$\mathcal{L} = \mathcal{L}_{\rm SM} + Y_\nu \bar{L} \tilde{H} N_R + \frac{1}{2} M_N \bar{N}_R^c N_R + h.c.$$

$$-\mathcal{L}_{\rm mass} = \frac{1}{2} \begin{pmatrix} \bar{\nu}_L^c \\ N_R \end{pmatrix} \begin{pmatrix} 0 & Y_\nu v \\ Y_\nu^T v & M_N \end{pmatrix} \begin{pmatrix} \nu_L \\ N_R^c \end{pmatrix} + h.c.$$

- Light and heavy neutrinos are Majorana particles and mix among themselves
- Majorana mass $\longleftrightarrow$ $\Delta L = 2$ process





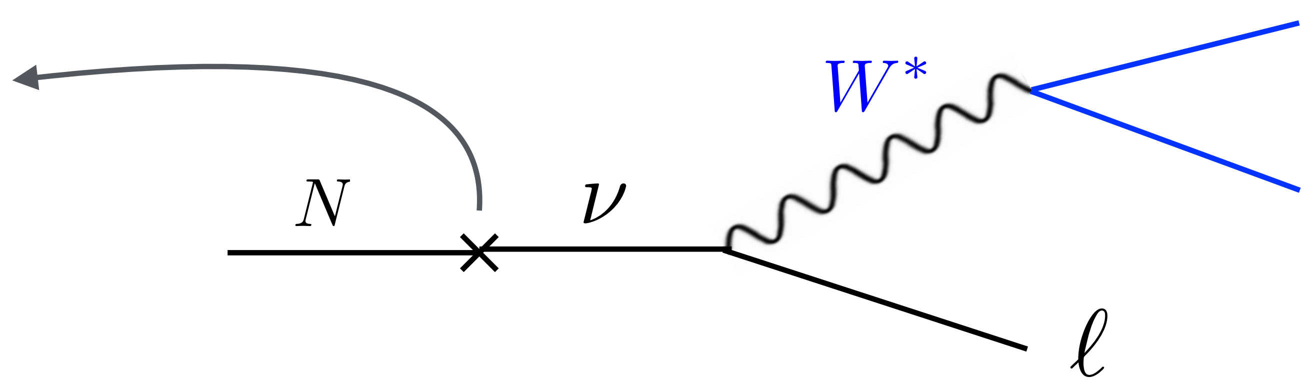
- RHN masses can span several orders of magnitudes

- Generate matter asymmetry via neutrino oscillations
- Potentially relevant for (surviving) flavour anomalies
- Can be searched in terrestrial based experiments!

How do we test this theory?

- Heavy-light mixing induces production and decay modes for N

$$\theta \simeq \frac{Y_\nu v}{M_N}$$

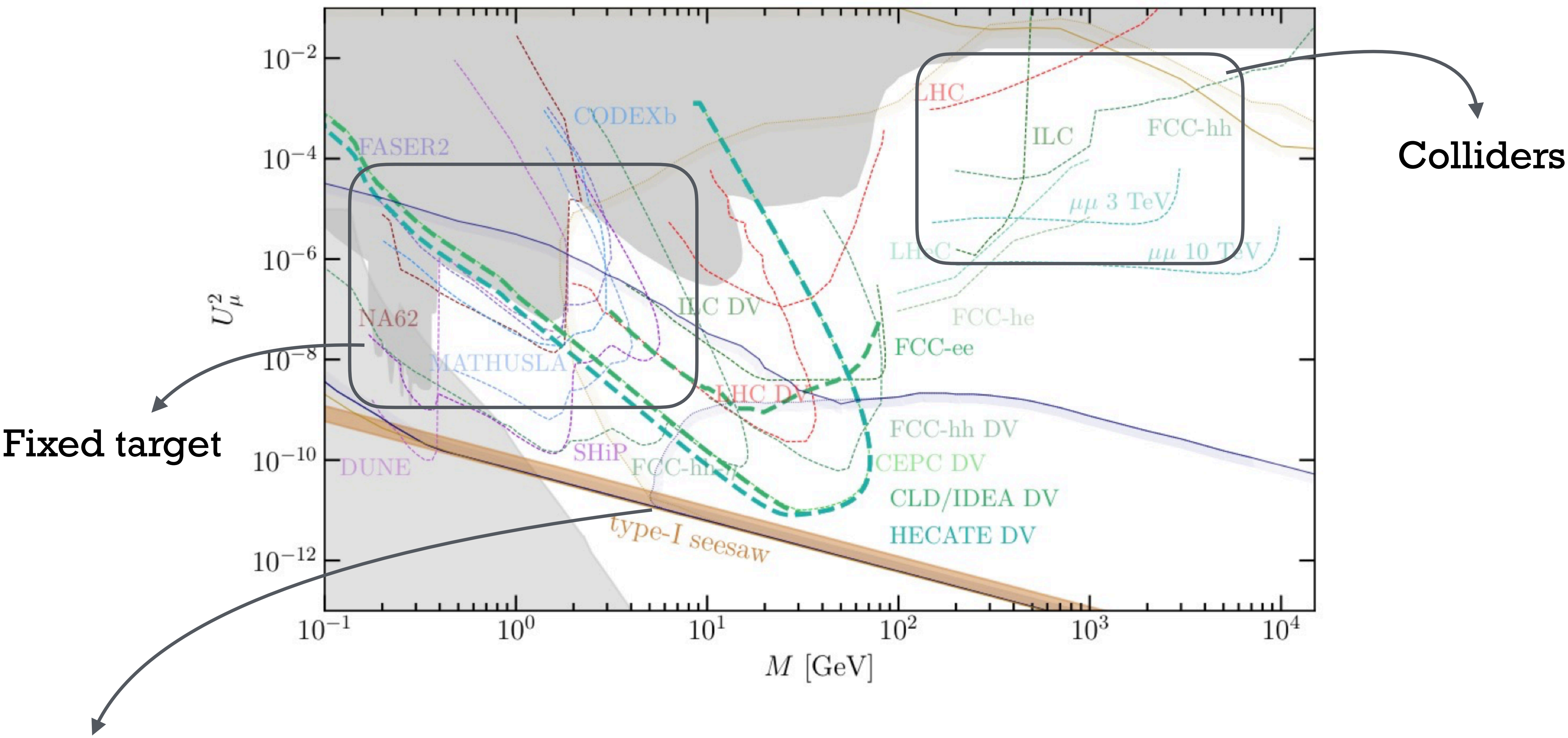


$$\Gamma \sim \frac{1}{192\pi^3}\theta^2\frac{m_N^5}{m_W^4}$$

$$L_{\rm lab} \sim 5\ {\rm m}\left(\frac{\rm GeV}{m_N}\right)^6\left(\frac{10^{-2}}{\theta}\right)^2\frac{E_N}{10\ {\rm GeV}}$$

The sterile neutrino parameter space

- High-energy and high-intensity experiments test different masses and mixings



- Naive see-saw limit hard to reach, but the naive scaling is altered with $\mathcal{N} > 1$ RHN
- Can assume m_N and θ to be independent parameters

The minimal see-saw might not be the whole story…

$$\mathcal{L} = \mathcal{L}_{\rm SM} - Y_\nu \bar{L}\tilde{H} N_R - \frac{1}{2} M_N \bar{N}_R^c N_R + h.c.$$

Extra particles/interactions

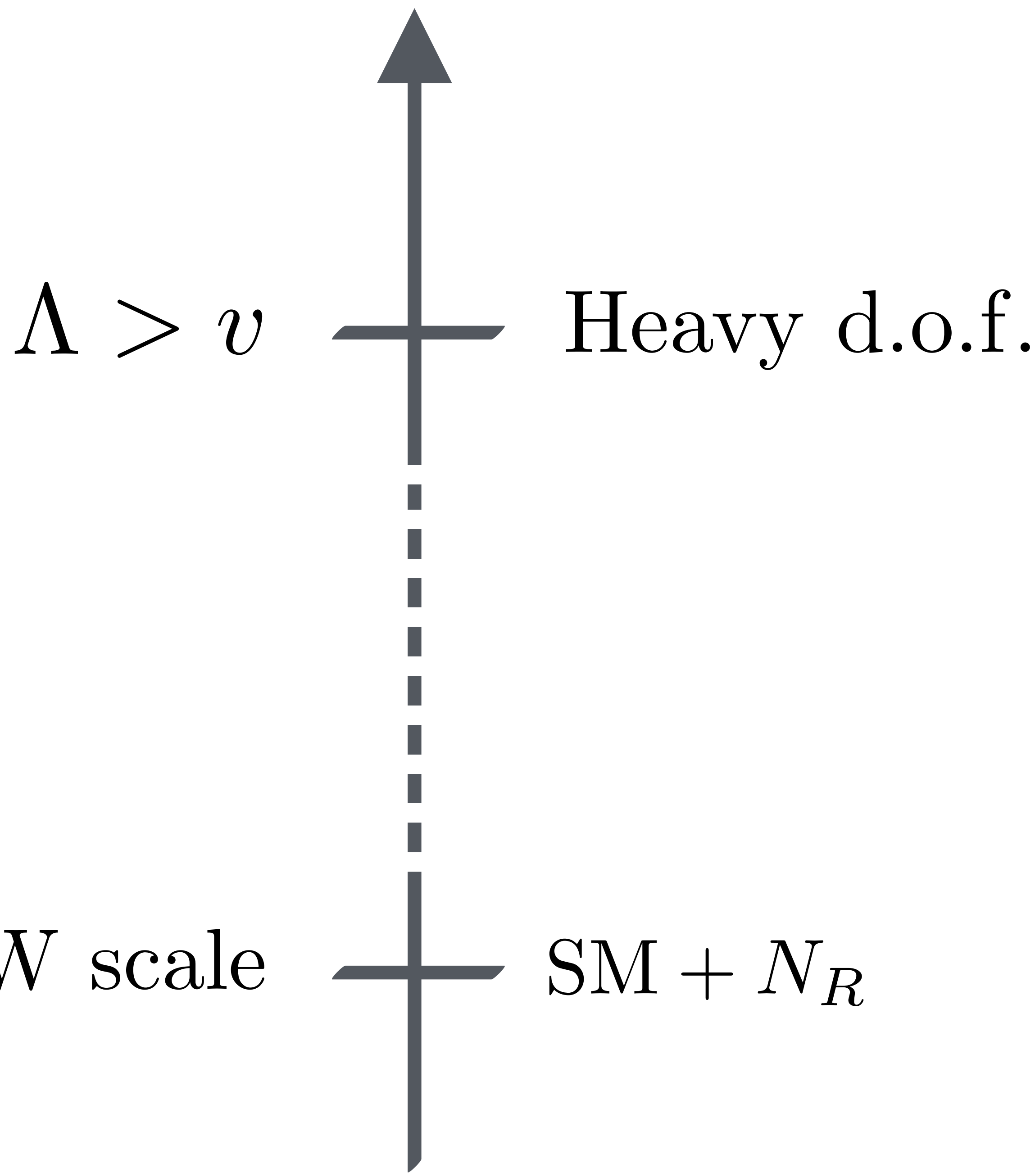
Why ?

- Theory motivated models, *e.g.* LR symmetric with $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$
  - Additional W' and Z' heavy gauge bosons

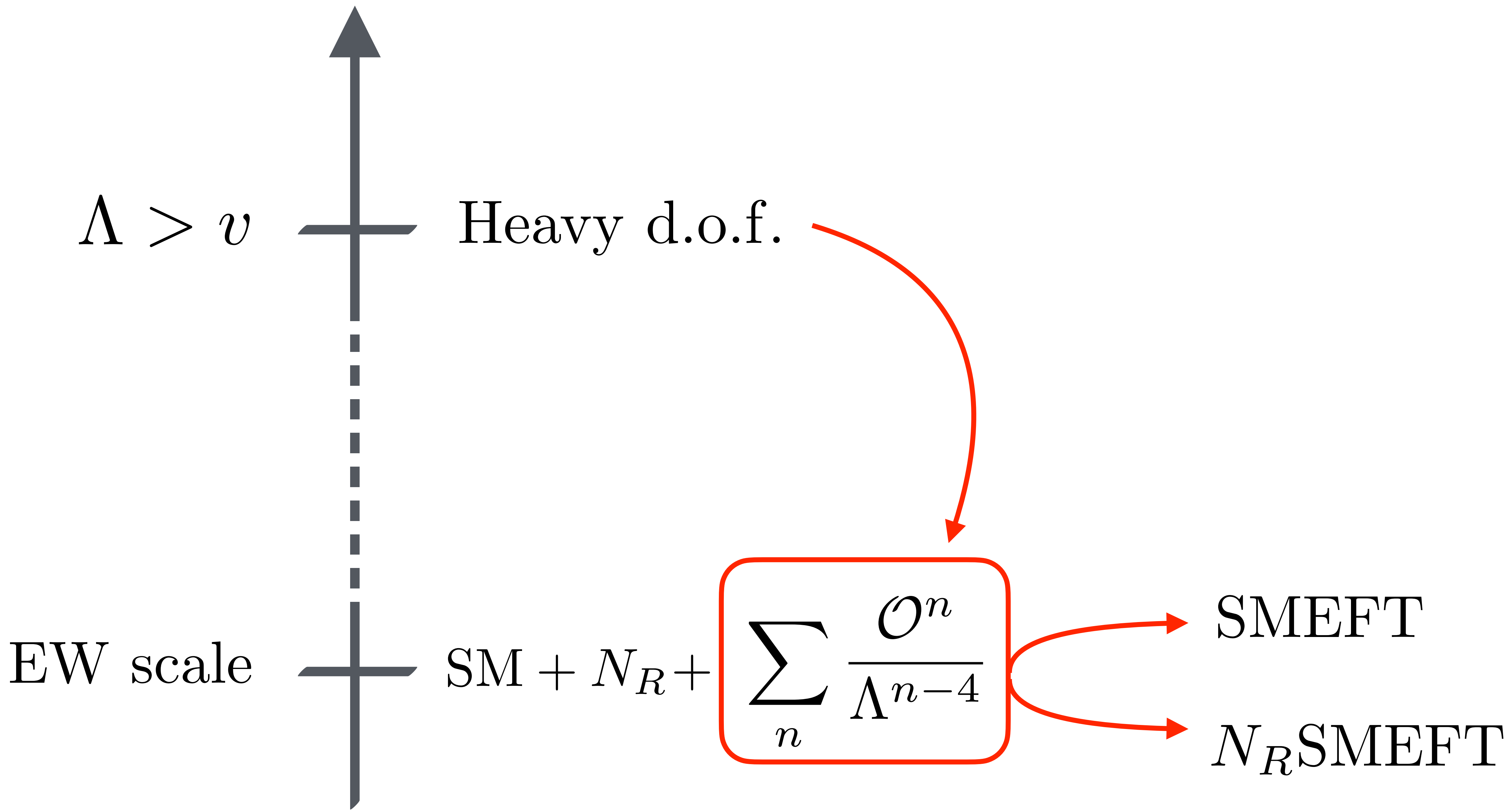
- Pheno motivated models, *e.g.* leptoquark models with RH neutrinos to explain $R_{D^{(*)}}$ and $R_{K^{(*)}}$ anomalies [DB+ '18 , Asadi+ '18, Greljo+ '18]
  or extended sectors to explain the MiniBooNe anomaly through RH neutrino decay [Gninenko+ '09, Bertuzzo+ '18]

- Others…

Consider a scenario with light RH neutrino and additional heavy fields



Consider a scenario with light RH neutrino and additional heavy fields



- Non redundant basis built up to $d = 7$ [Liao, Ma 1612.04527]
- At $d = 5$ only 1+2 operators exist

Weinberg operator	Higgs operator	Dipole operator
$(\bar{L}^c \tilde{H}^*)(\tilde{H}^\dagger L)$	$\|H\|^2 \bar{N}_R^c N_R$	$\bar{N}_R^c \sigma^{\mu\nu} N_R B_{\mu\nu}$
[Weinberg '79]	[Graesser 0704.0438]	[Aparici+ 0904.3244]

- At $d = 6$ many more operators appear

Higgs operators & dipoles

$$(\bar{L}\tilde{H} N_R)(H^\dagger H) + h.c.$$
$$(\bar{L}\sigma^{\mu\nu} N_R) B_{\mu\nu} \tilde{H} + h.c.$$
$$(\bar{L}\sigma^{\mu\nu} N_R)\sigma^a W^a_{\mu\nu} \tilde{H} + h.c.$$
$$(\bar{N}_R \gamma^\mu N_R)(H^\dagger i \overleftrightarrow{D}_\mu H)$$
$$(\bar{N}_R \gamma^\mu e_R)(\tilde{H}^\dagger i \overleftrightarrow{D}_\mu H) + h.c.$$

Four-fermi operators

$$(\bar{N}_R^c N_R)(\bar{N}_R^c N_R) + h.c.$$
$$(\bar{N}_R L)(\bar{q}_L u_R) + h.c$$
$$(\bar{N}_R \gamma^\mu N_R)(\bar{e}_R \gamma_\mu e_R)$$
$$(\bar{u}_R^c d_R \bar{d}_R^c) N_R + h.c.$$

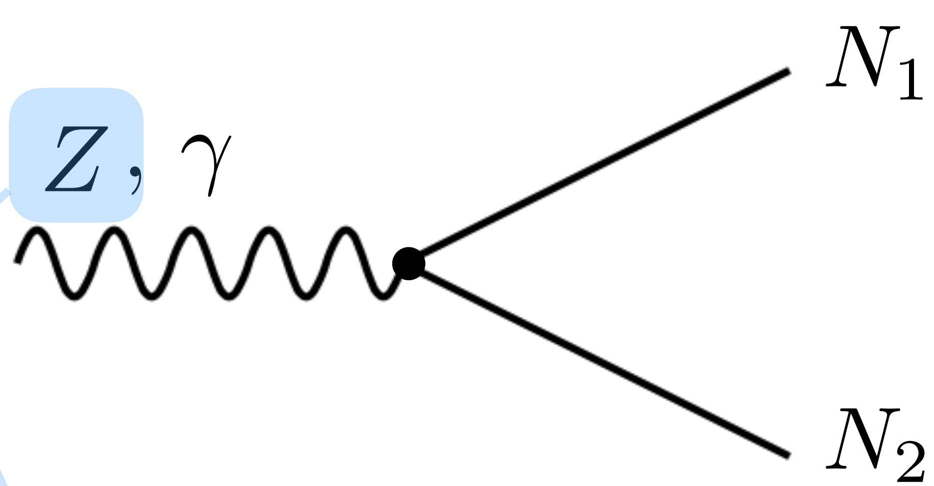
… and many other

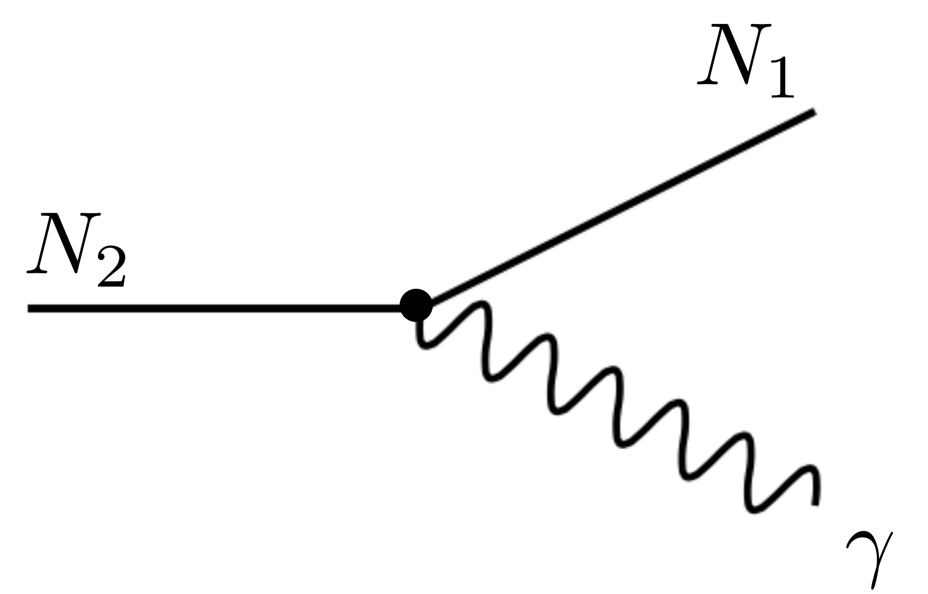
- Focus on $d = 5$ and $d = 6$ dipole operators

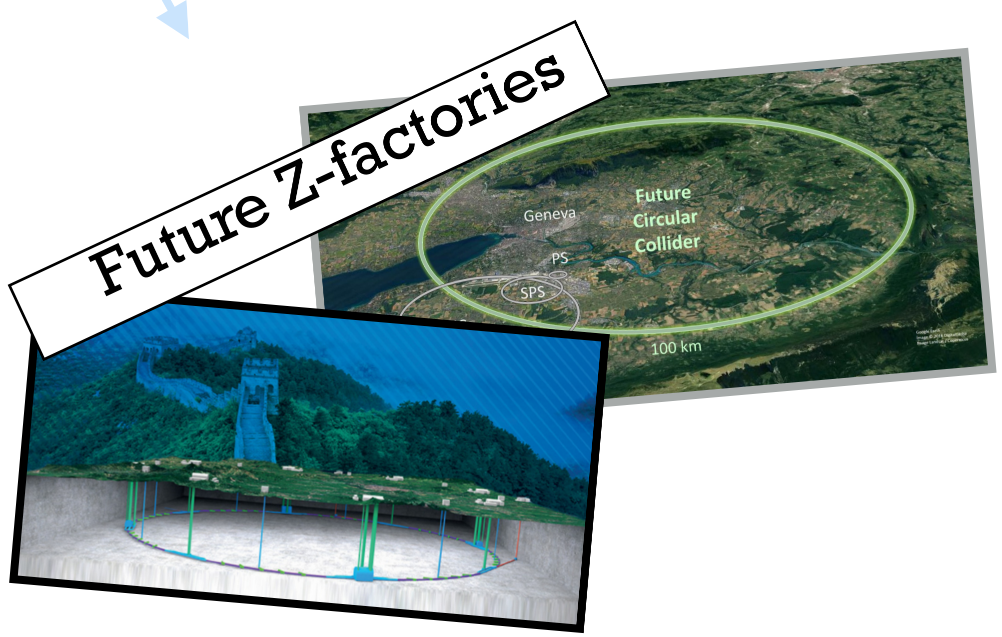
$d = 5$ Dipole operator

$$\frac{\alpha_{NB}}{\Lambda} \bar{N}_R^c \sigma^{\mu\nu} N_R B_{\mu\nu} \xrightarrow{\text{EWSB}} \frac{\alpha_{NB}}{\Lambda} \bar{N}_R^c \sigma^{\mu\nu} N_R \left(\cos\omega A_{\mu\nu} + \sin\omega Z_{\mu\nu}\right)$$

- Antisymmetric in the flavor structure, dipole with a single RH neutrino vanishes
- Provide new production and decay channels for RH neutrinos

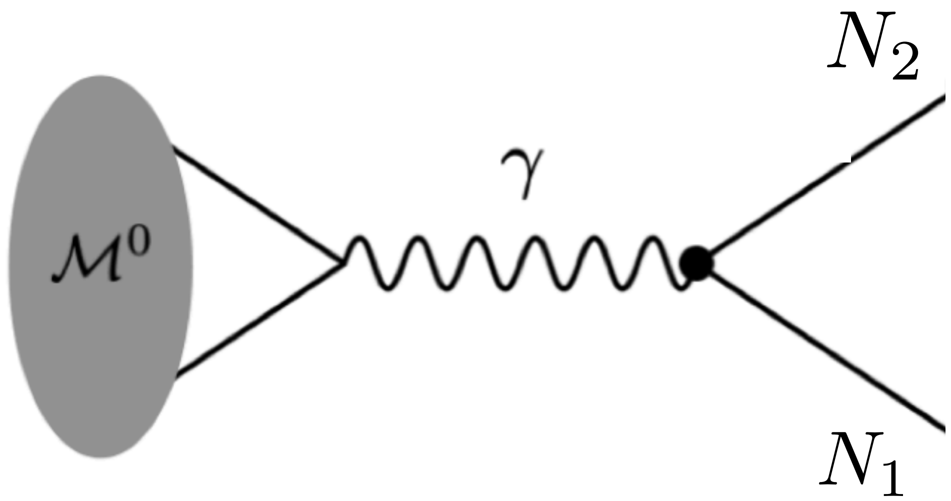




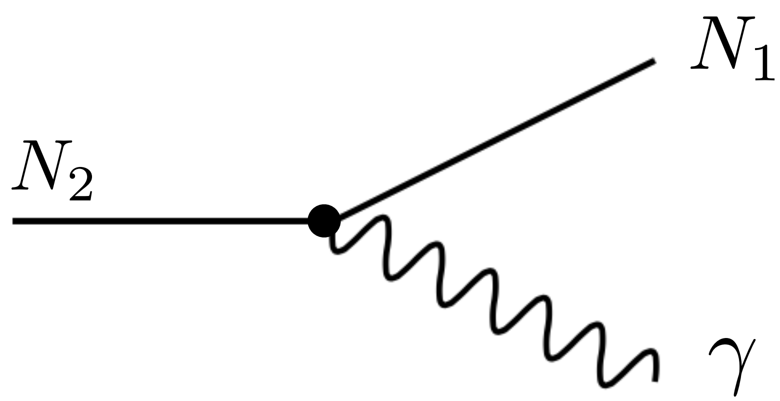


- Improve LEP limits by a factor ~ 100 on Λ in clean LNV same-sign lepton final state
[DB+ 2011.04725]

- Photon dipole more relevant for lighter masses and high-intensity experiments

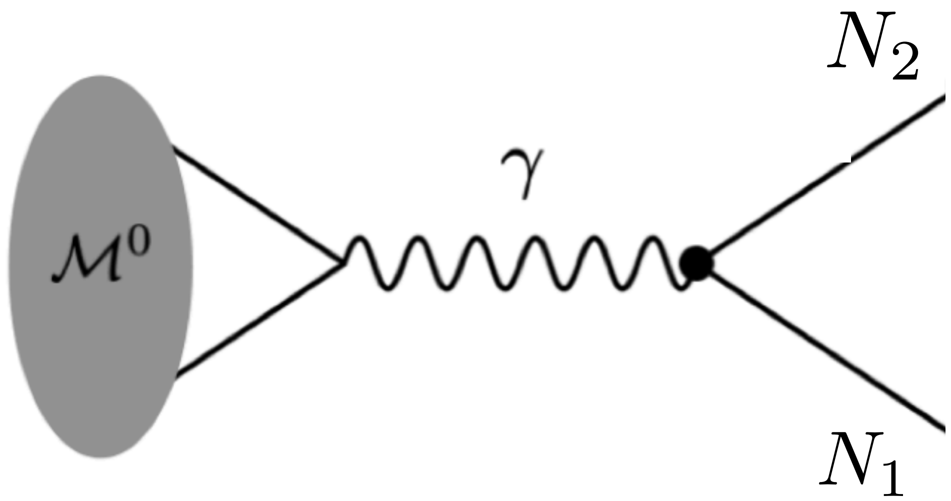


Production via rare neutral meson decay



Dominant decay mode for small enough mixing

- Photon dipole more relevant for lighter masses and high-intensity experiments



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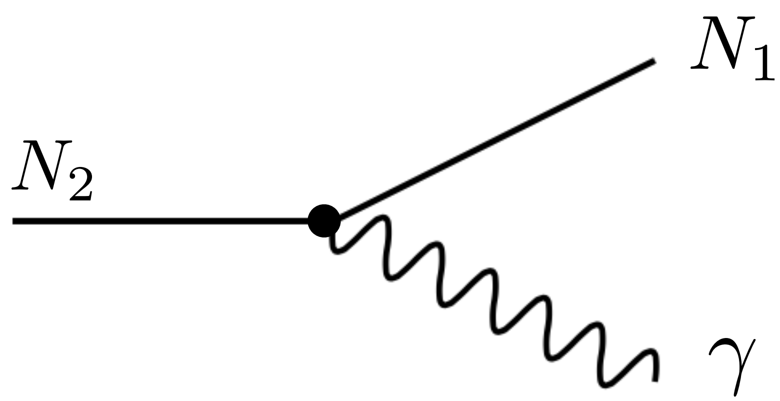


Dominant decay mode for small enough mixing

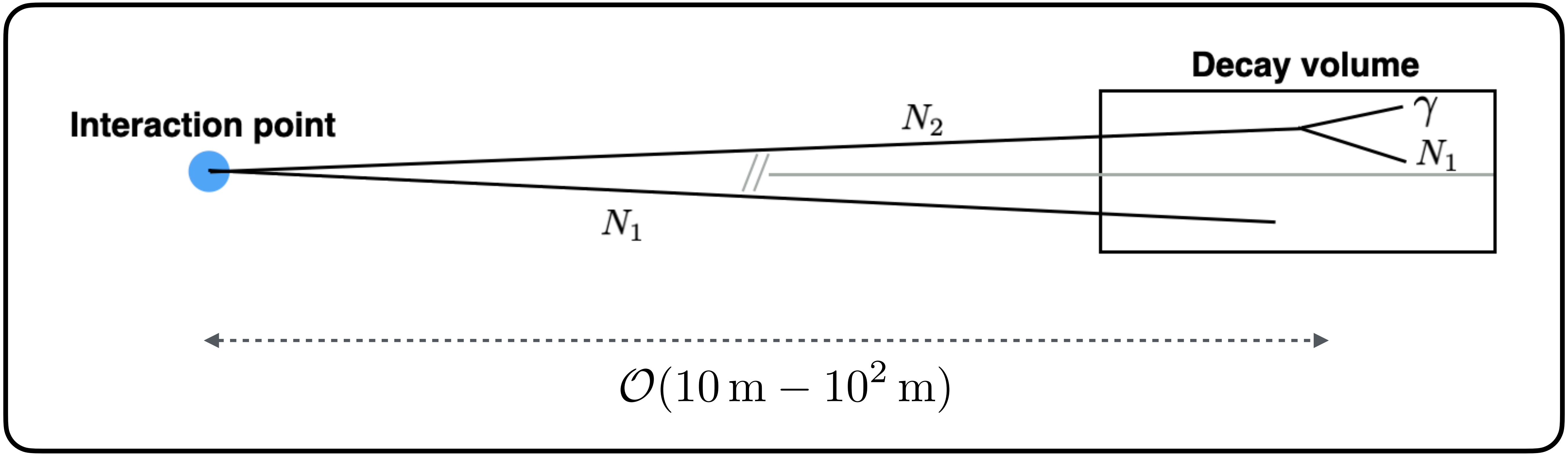
- Decay rate depend on the relative mass splitting between the two sterile states

$$\Gamma(N_2 \to N_1 \gamma) = \frac{1}{\Lambda^2} \frac{M_{N_1}^3}{2\pi} \frac{\delta^3 (2+\delta)^3}{(1+\delta)^3} = \frac{1}{\tau_{N_2}} \qquad \delta = \frac{M_{N_2} - M_{N_1}}{M_{N_1}}$$

$$\frac{\Gamma_{d=5}}{\Gamma_{\rm mix}} \simeq 10^4 \left(\frac{1\ \text{GeV}}{m_N}\right)^2 \left(\frac{10^{-6}}{\theta^2}\right)^2 \left(\frac{10\ \text{TeV}}{\Lambda}\right)^2 \left(\frac{\delta}{0.1}\right)^3$$

- Small mass splitting implies large $\beta\gamma c\tau_{N_2} \gg \text{m}$

- Many high-intensity experiments can be sensitive to long-long-lived states



- Clean decay volume allows to detect a **single photon signal**… with enough En…
- In the N_2 rest frame the photon energy is function of the masses

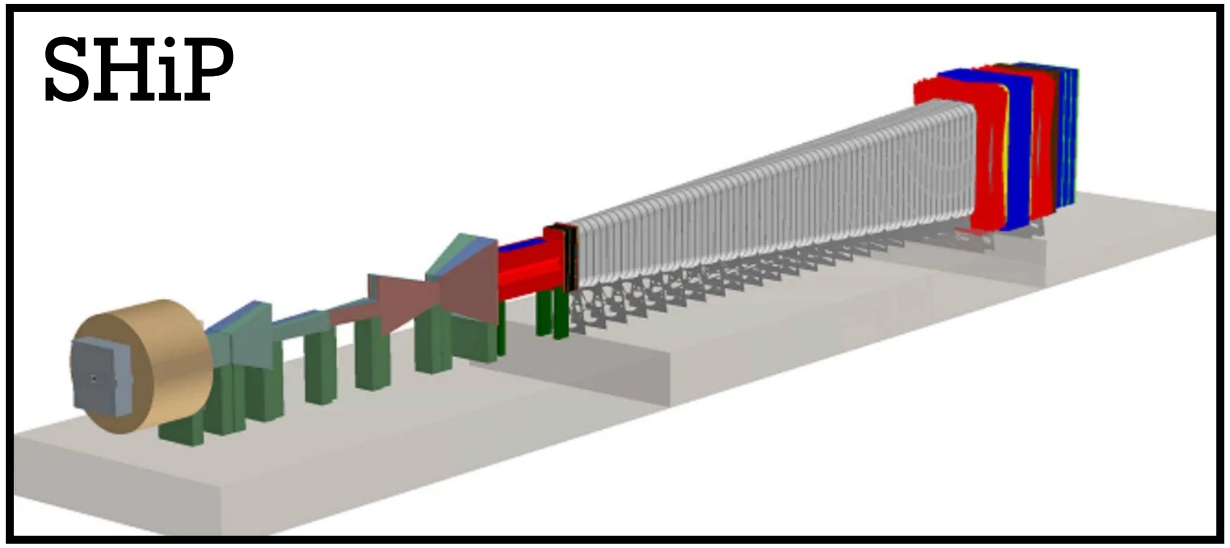
$$E_\gamma = m_{N_2} \frac{\delta}{2} \frac{2+\delta}{(1+\delta)^2}$$

- Boosting in the laboratory frame

$$E_\gamma^{\rm lab} = \left(P_{N_2} + \sqrt{m_{N_2}^2 + P_{N_2}^2}\right) \frac{\delta}{2} \frac{2+\delta}{(1+\delta)^2} \simeq 2 P_{N_2} \delta$$

Production mode dependent

High-intensity experiment landscape



MATHUSLA

CODEX-b

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MAPP

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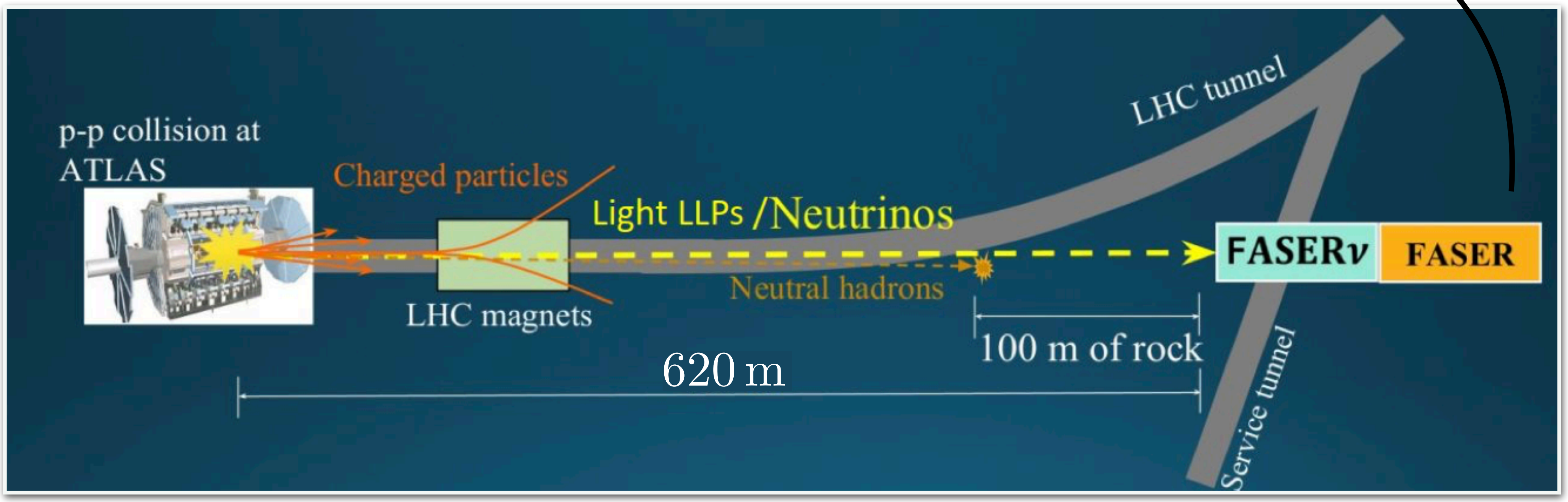
FACET

...

FASER

- Exploits the enormous flux of forward particles produced by the LHC
- Cylindrical detector of radius 1m and length 10m + 10m

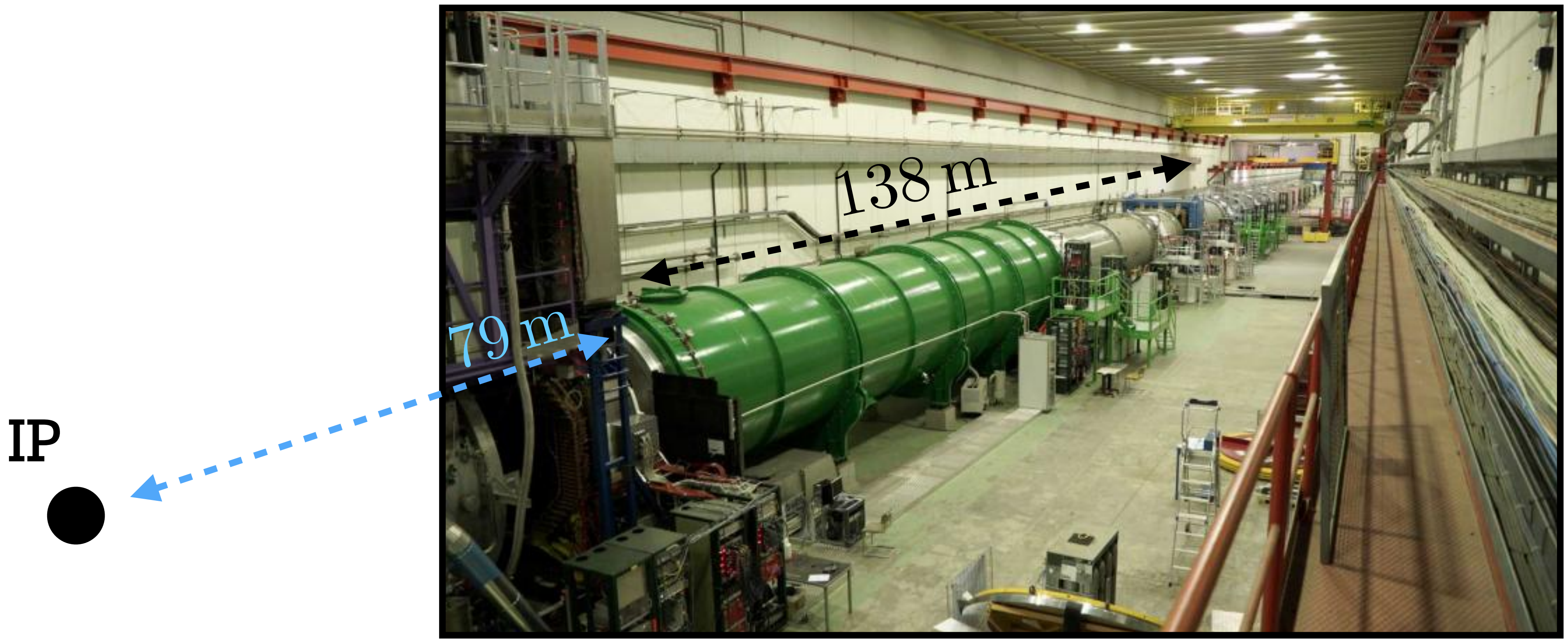


IMPORTANT - FASER IS TAKING DATA NOW!!!

- Around $40\ \mathrm{fb}^{-1}$ of data collected at 13.6 TeV during 2022 running
- First analysis with limits on dark photons out in summer 2023 [FASER 2308.05587]
- Equipped with an eCAL, capable of detecting a single photon signal

NA62 - beam dump

- 400 GeV proton beam from SPS dumped on a copper target
- Cylindrical decay volum of 1m radius
- Integrated dataset $N_{\rm POT} = 10^{18}$ running until LS3 in 2026
  - HIKE, upgrade with $N_{\rm POT} = 5 \times 10^{19}$ cancelled, in favor of SHiP



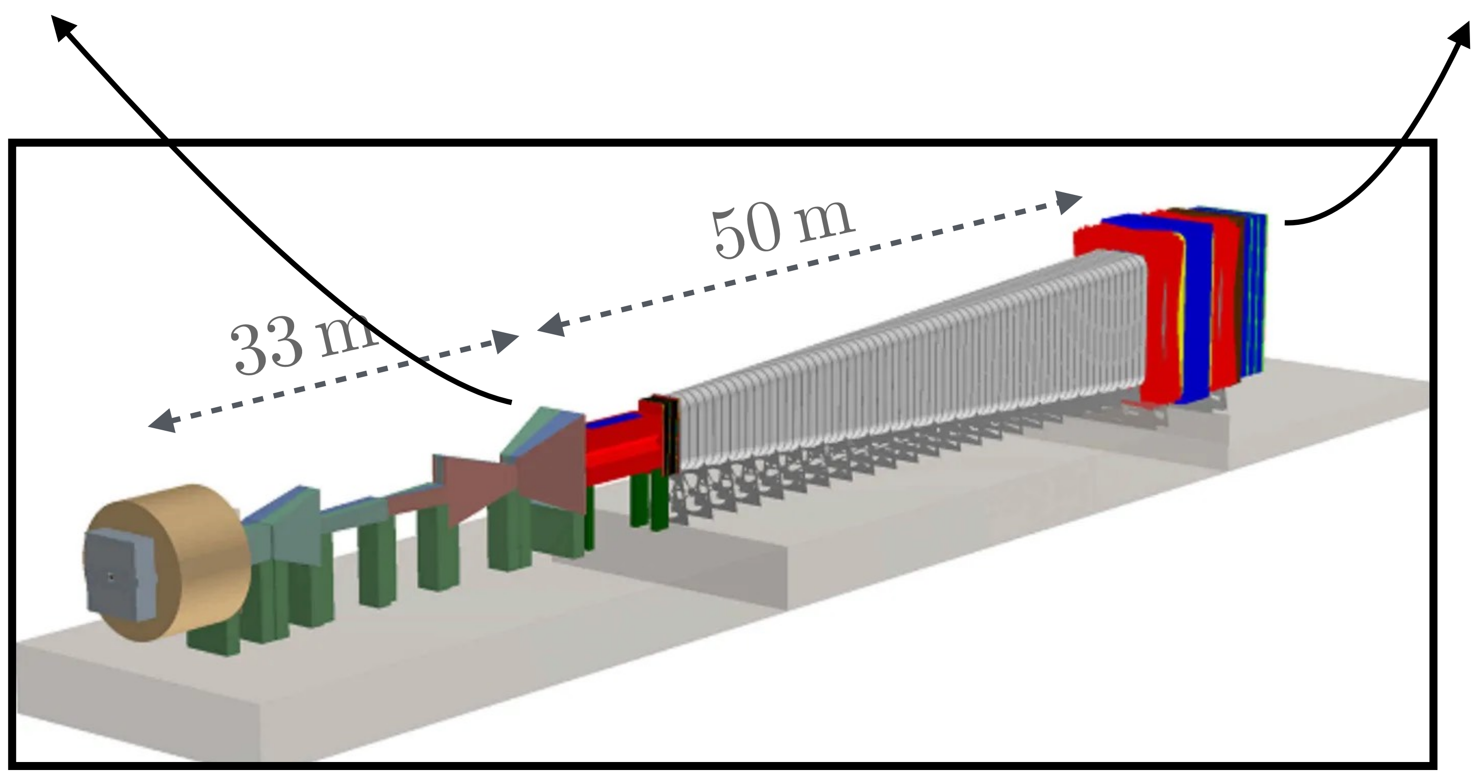
- NA62 is designed as a *K* factory to search for the rare $K^+ \to \pi^+ \nu \bar{\nu}$ decay
  - Excellent photon rejection to suppress $\pi^0 \to \gamma\gamma$ from $K^+ \to \pi^+ \pi^0$

Can it be used for this search as for the $a \to \gamma\gamma$ search?

SHiP

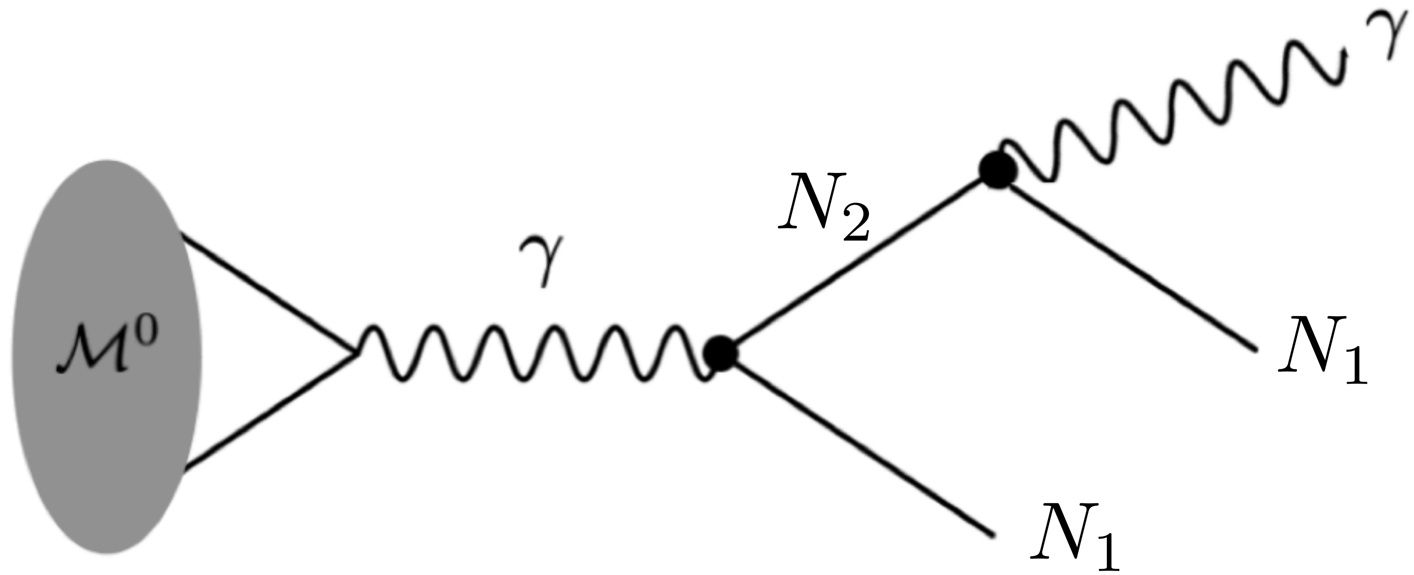
- High intensity beam-dump experiment
- 400 GeV proton beam dumped on a molybdenum/tungsten target
- Decay volume is a square based pyramidal shape

$A_{\rm in} = 1.0 \times 2.7\,{\rm m}^2$ $A_{\rm out} = 4.0 \times 6.0\,{\rm m}^2$



- Planned collected dataset $N_{\rm POT} = 6 \times 10^{20}$

Production mode via meson decay



- Event yield given by

$$N_{\rm evts} = \sum_{\mathcal{M}} N_{\mathcal{M}} \times {\rm BR}_{\mathcal{M}} \times f_{\rm dec} \times \epsilon_{\rm sel}$$

Selection efficiency, function of geometry, E_γ threshold

Decay probability

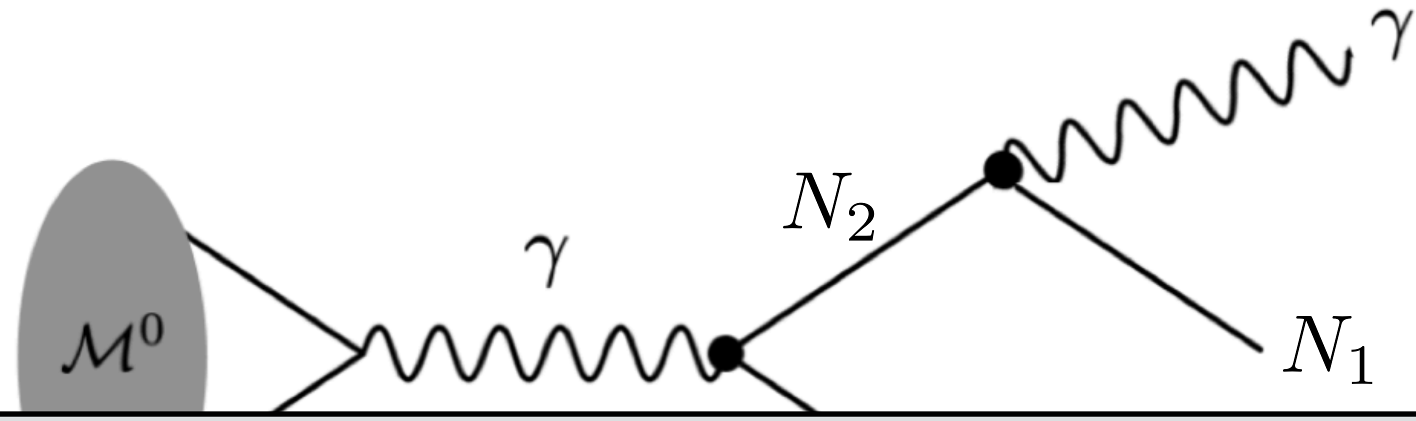
$$e^{-\frac{x_i}{\beta\gamma c\tau}} - e^{-\frac{x_f}{\beta\gamma c\tau}}$$

Number of mesons

$$N_{\mathcal{M}} = \begin{cases} N_{\rm POT} \times f_{\mathcal{M}}, & \textbf{SHiP, NA62} \\ \sigma_{\rm inel} \times \mathcal{L} \times f_{\mathcal{M}} & \textbf{FASER} \quad \sigma_{\rm inel} = 79.5 \text{ mb} \end{cases}$$

$f_{\mathcal{M}}$ average number of meson per interaction

Production mode via meson decay



- For FASER momentum and energy distribution of different mesons taken from **FORESEE** [Trojanowsky+ 2105.07077] cross-checked with **EPOS-LHC** [Pierog+ 1306.0121]
- For NA62 & SHiP fixed target experiments used **PYTHIA8** cross-check with SHiP simulation notes

- Event yie

Fixed-target meson multiplicities

f_{π^0}	f_η	$f_{\eta'}$	f_ρ	f_ω	f_ϕ	$f_{J/\Psi}$	f_Υ	$f_{D^\pm}$	f_{D_s}	$f_{B^\pm}$
4.3	0.49	0.055	0.58	0.57	0.021	4.7×10^{-6}	2.2×10^{-9}	4.3×10^{-4}	1.8×10^{-4}	6.0×10^{-8}

Numbe

$$N_{\mathcal{M}} = \begin{cases} N_{\rm POT}\times f_{\mathcal{M}}, & \textbf{SHiP, NA62} \\ \sigma_{\rm inel}\times\mathcal{L}\times f_{\mathcal{M}} & \textbf{FASER} \quad \sigma_{\rm inel} = 79.5 \text{ mb} \end{cases}$$

$f_{\mathcal{M}}$ average number of meson per interaction

- Require LLP decay in the decay volume and its trajectory to intersect the eCAL
- Photon threshold $E_\gamma > 1\,\mathrm{GeV}$
- Assume negligible background, N=3 contour events

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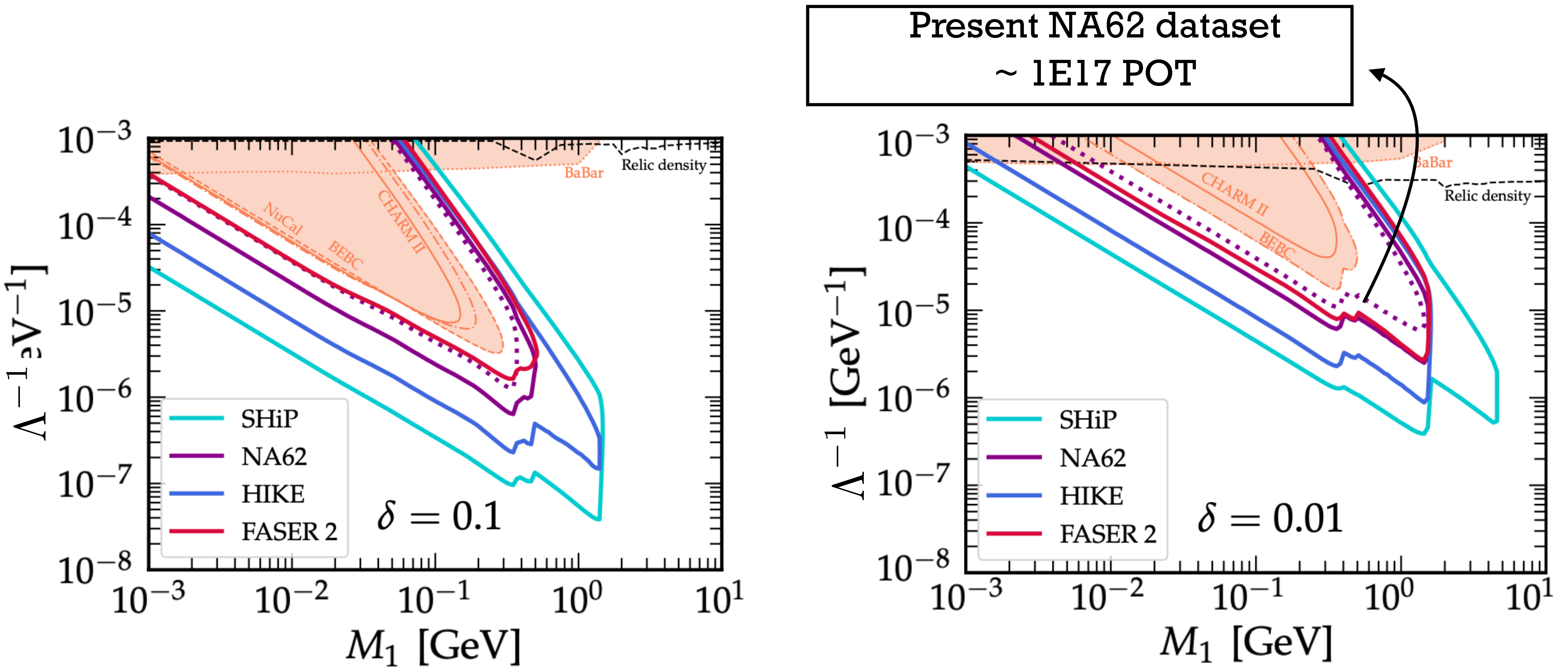
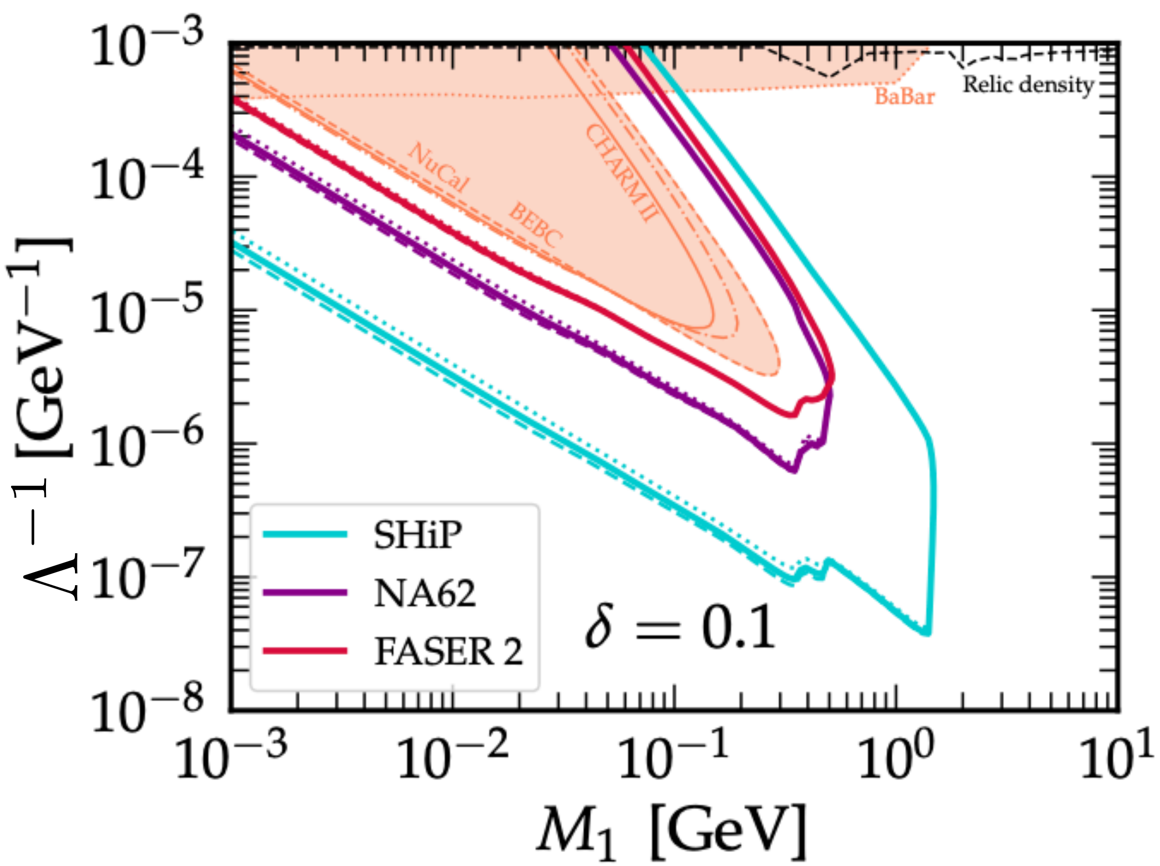


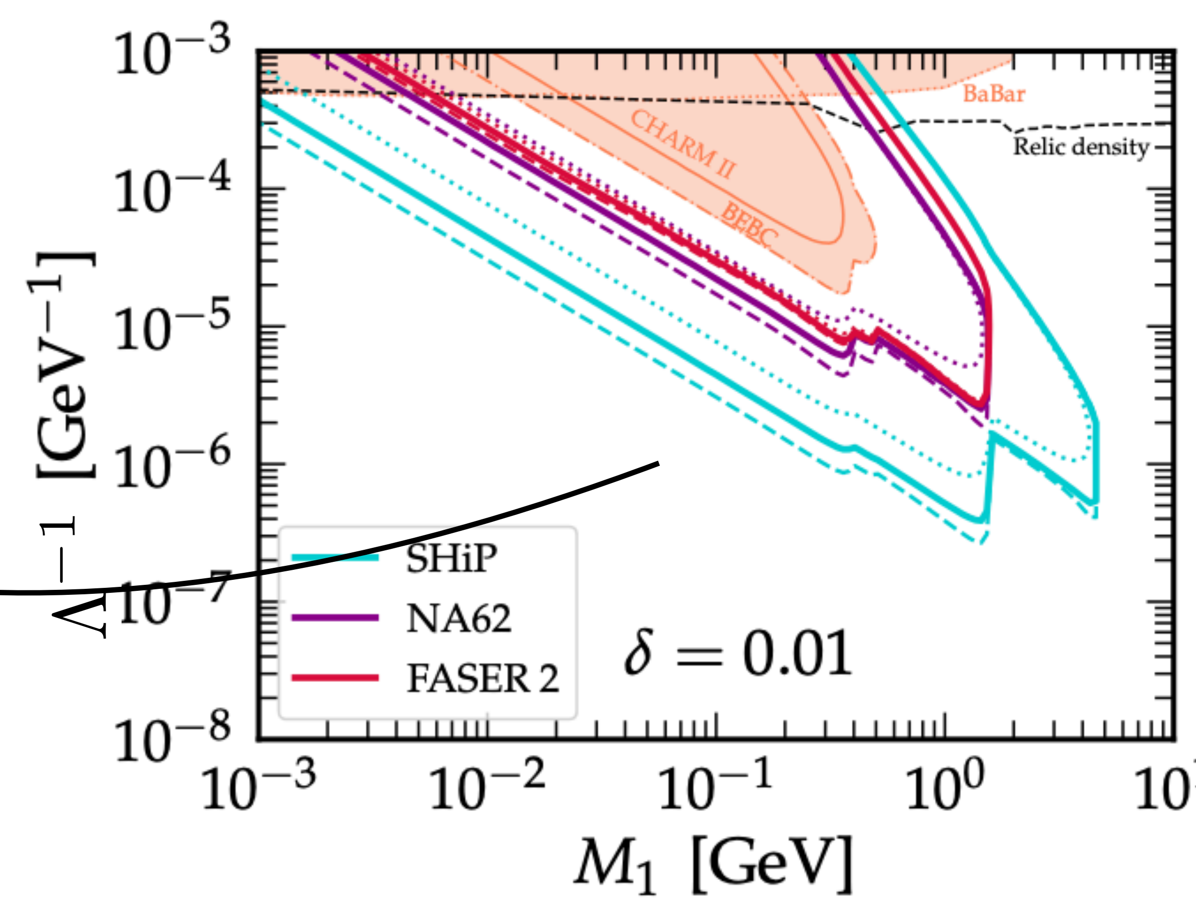
- Smaller mass splitting, softer photons: more likely not to pass the E_γ threshold
- Limits apply also to inelastic dipole dark matter

$$\mathcal{L} \sim \frac{1}{\Lambda}\bar{\chi}_2\sigma^{\mu\nu}\chi_1 B_{\mu\nu}$$

- Sensitivity to the photon energy threshold: vary $E_\gamma > 0.5, 1, 2\,\mathrm{GeV}$



More important for smaller mass splittings



$d = 6$ Dipole operators

$$\mathcal{O}^6_{\mathcal{W}} = d_{\mathcal{W}} \bar{L} W_{\mu\nu} \tilde{H} \sigma^{\mu\nu} N_R \qquad \mathcal{O}^6_{\mathcal{B}} = d_{\mathcal{B}} \bar{L} B_{\mu\nu} \tilde{H} \sigma^{\mu\nu} N_R$$

$$\longrightarrow \; d_\gamma \; \bar{\nu}_L \sigma^{\mu\nu} N_R F_{\mu\nu} \; \longleftarrow$$

- Similar strategy can be applied at FASER, NA62 & SHiP
  [See also Pospelov+ 1803.03262, Greljo+2007.15563, Ismail+ 2109.05032…]

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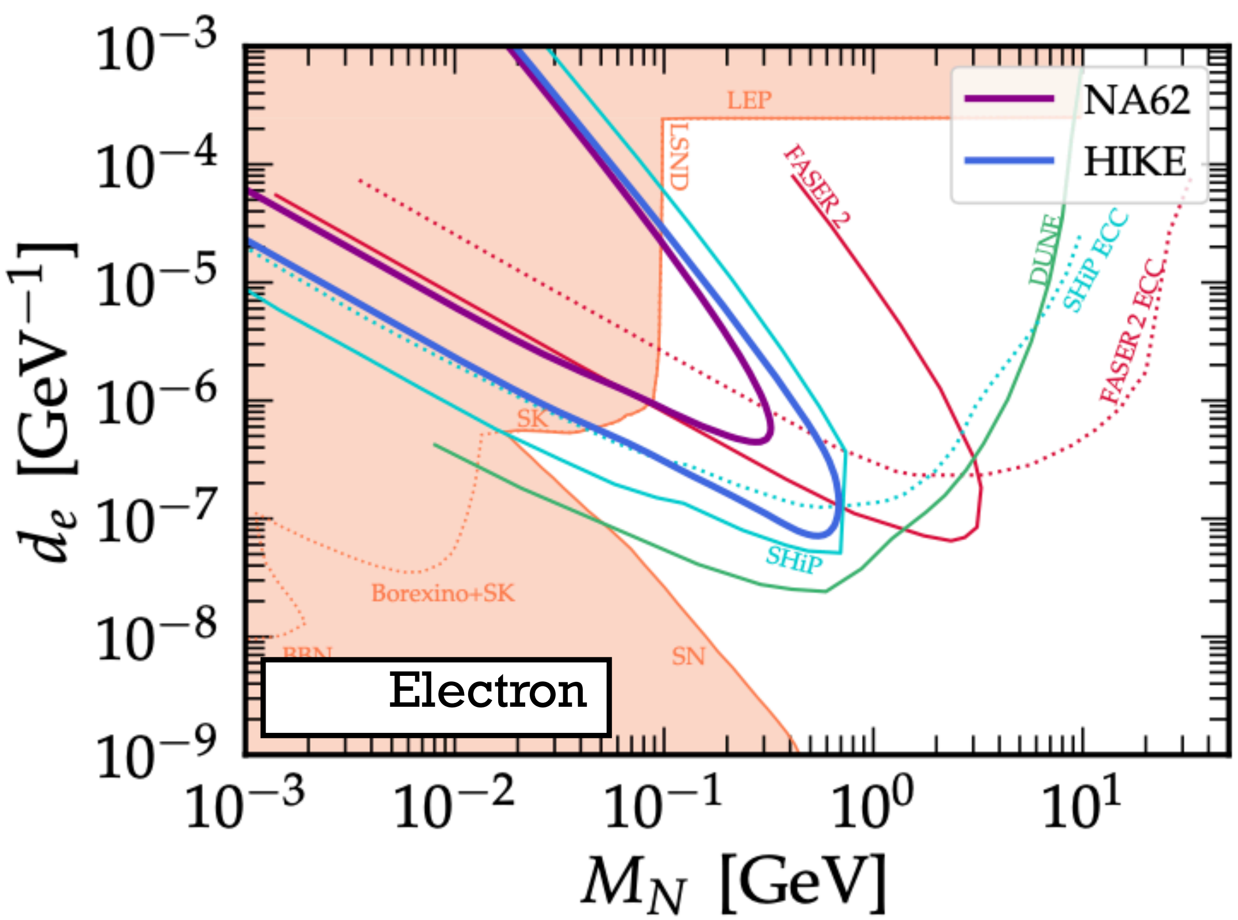
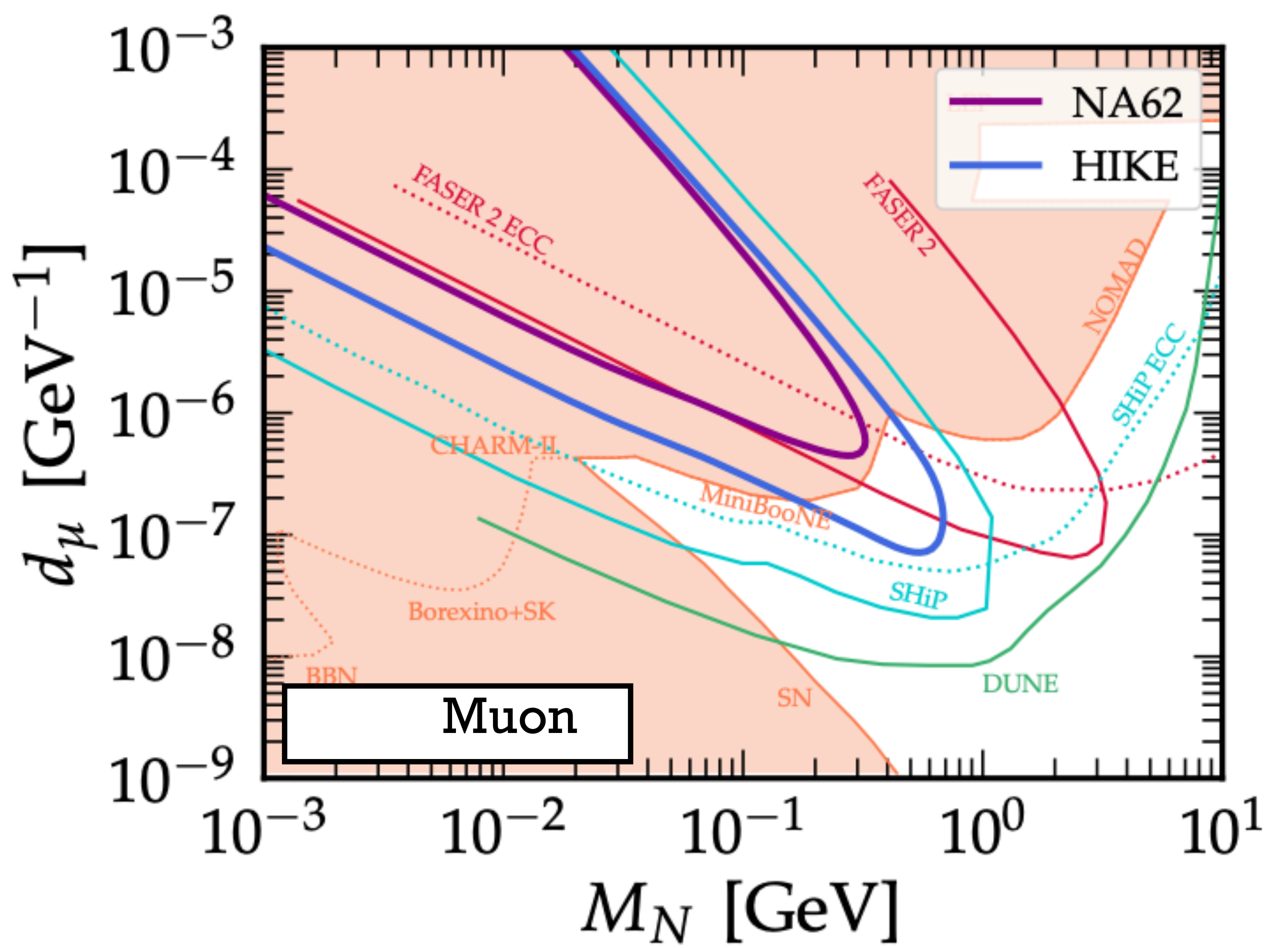
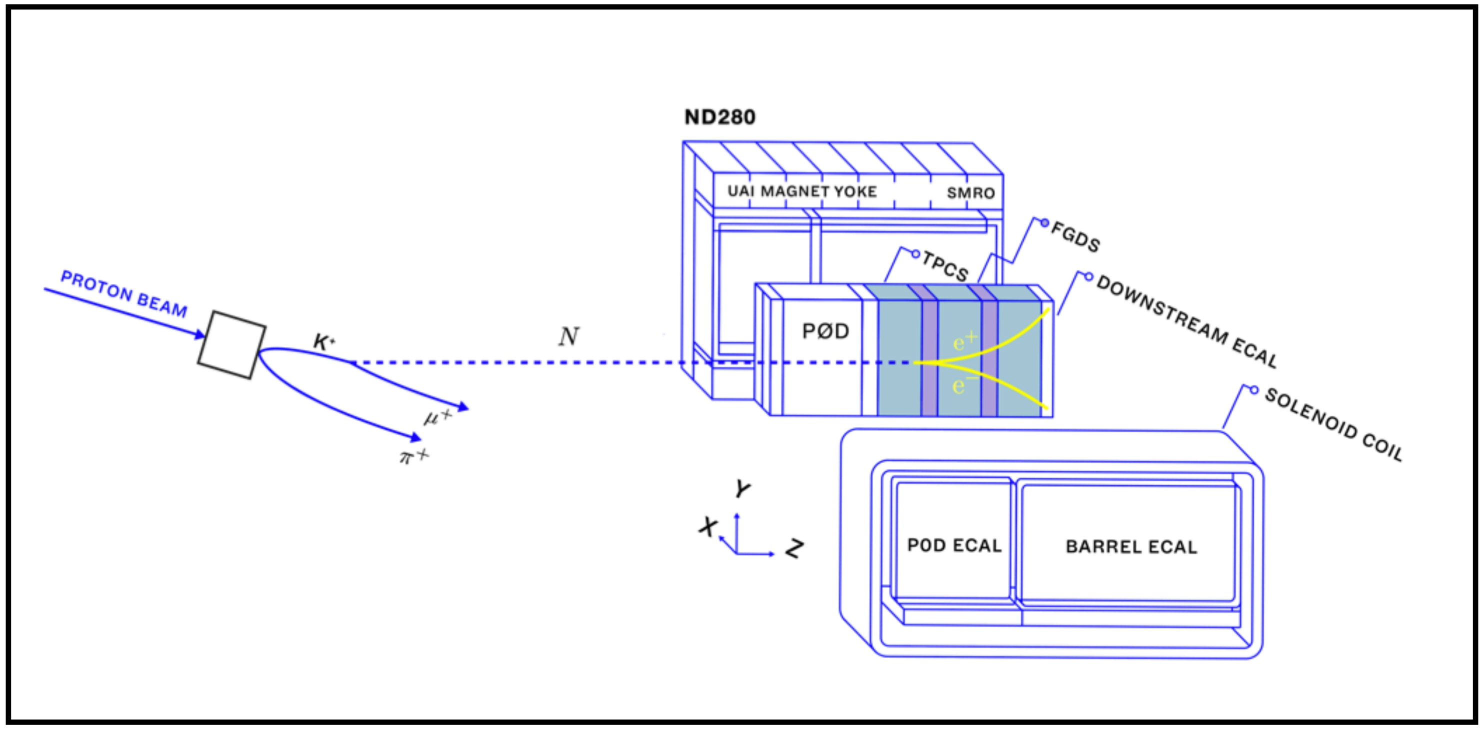




Can T2K play a role?

- T2K is already sensitive to RHN of the minimal see-saw interacting via mixing
- Sterile neutrino from *K* decay, decaying in ND280 time projection chamber



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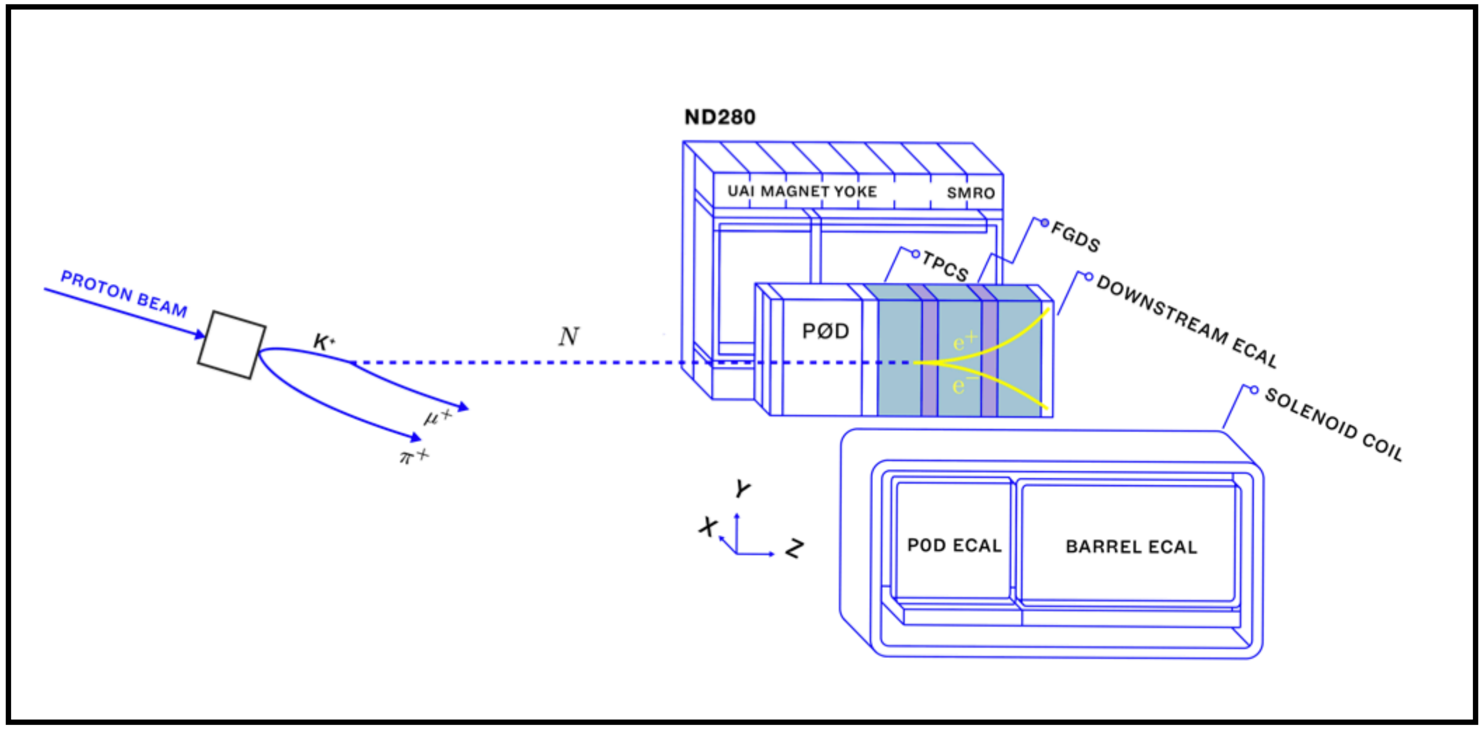
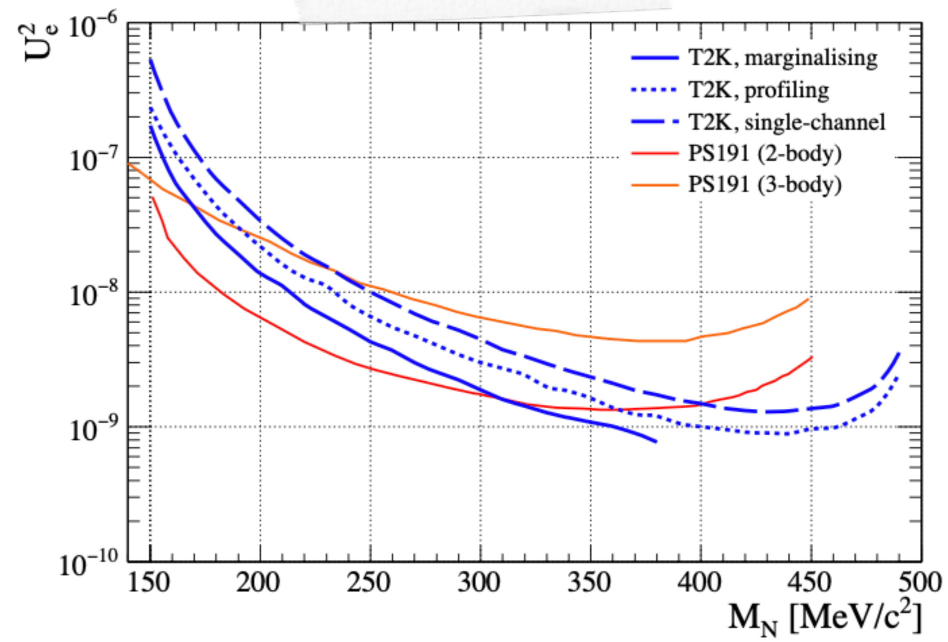
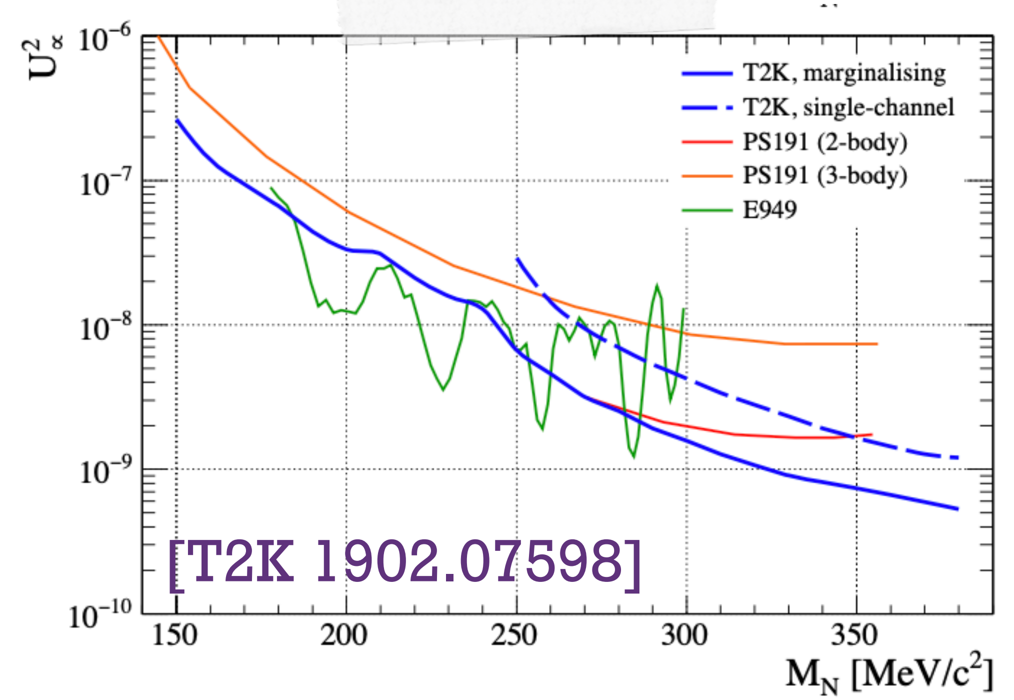


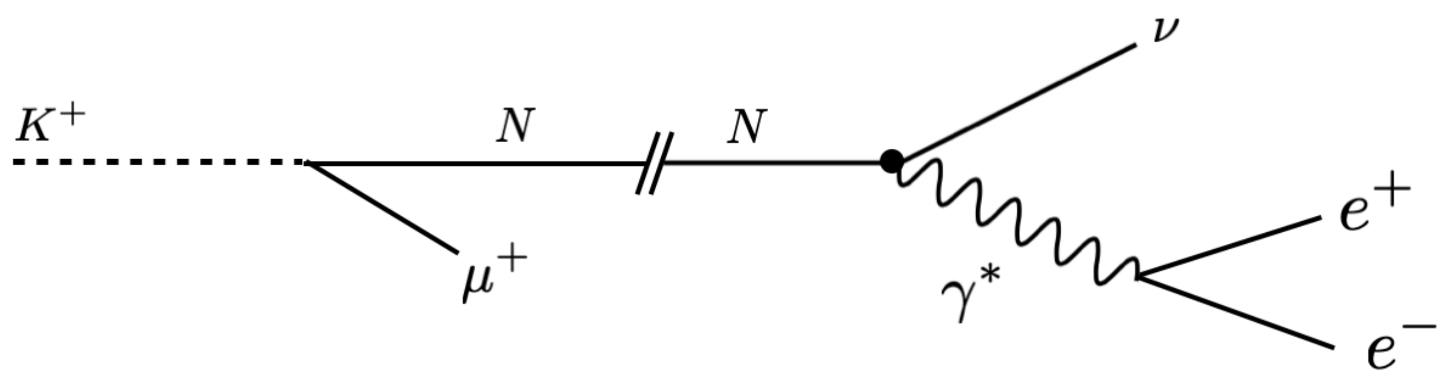


Mode	Ch.	Expected background	Mode	Ch.	Expected background
neutrino	$\mu^{\pm}\pi^{\mp}$	1.543	anti-neutrino	$\mu^{\pm}\pi^{\mp}$	0.384
	$e^-\pi^+$	0.376		$e^-\pi^+$	0.018
	$e^+\pi^-$	0.328		$e^+\pi^-$	0.219
	$\mu^+\mu^-$	0.216		$\mu^+\mu^-$	0.038
	e^+e^-	0.563		e^+e^-	0.015

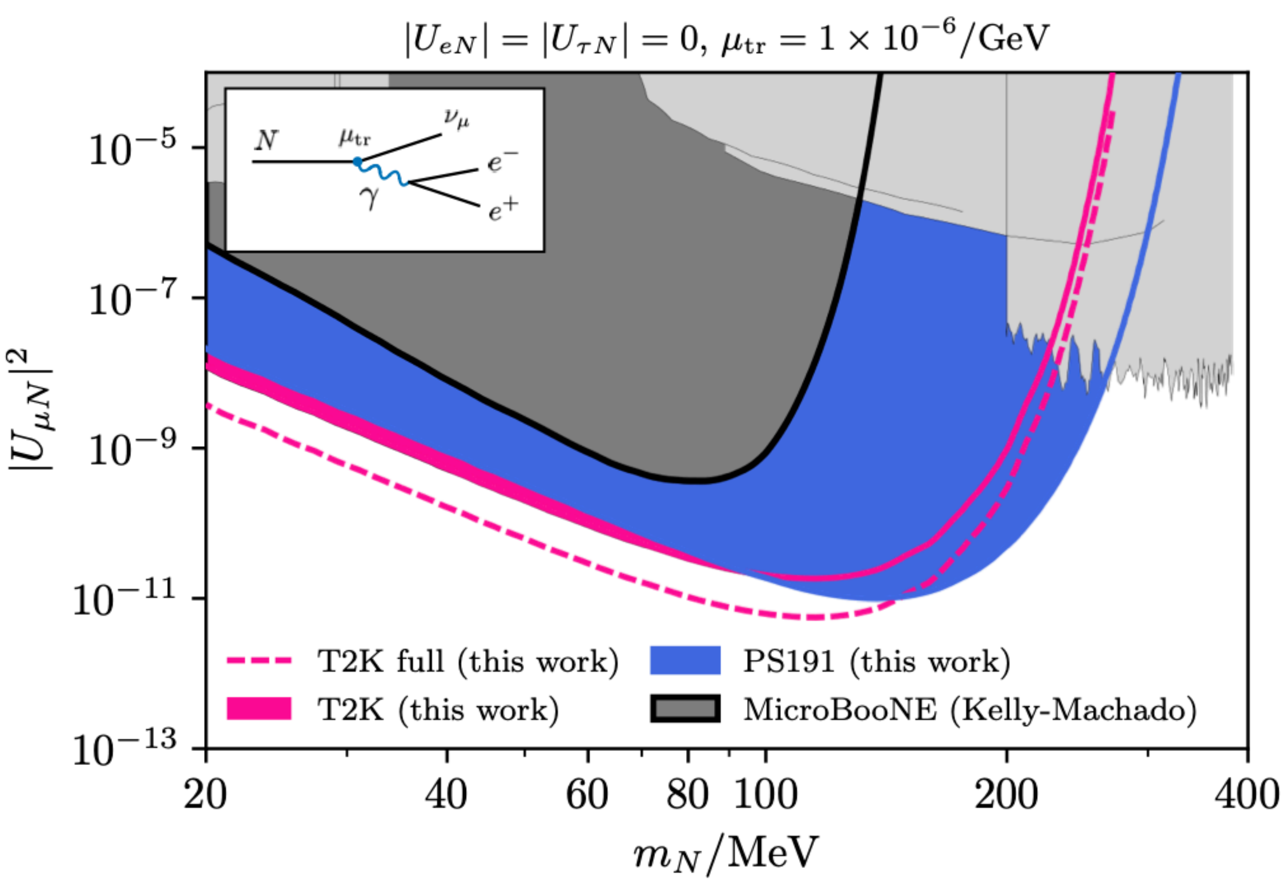


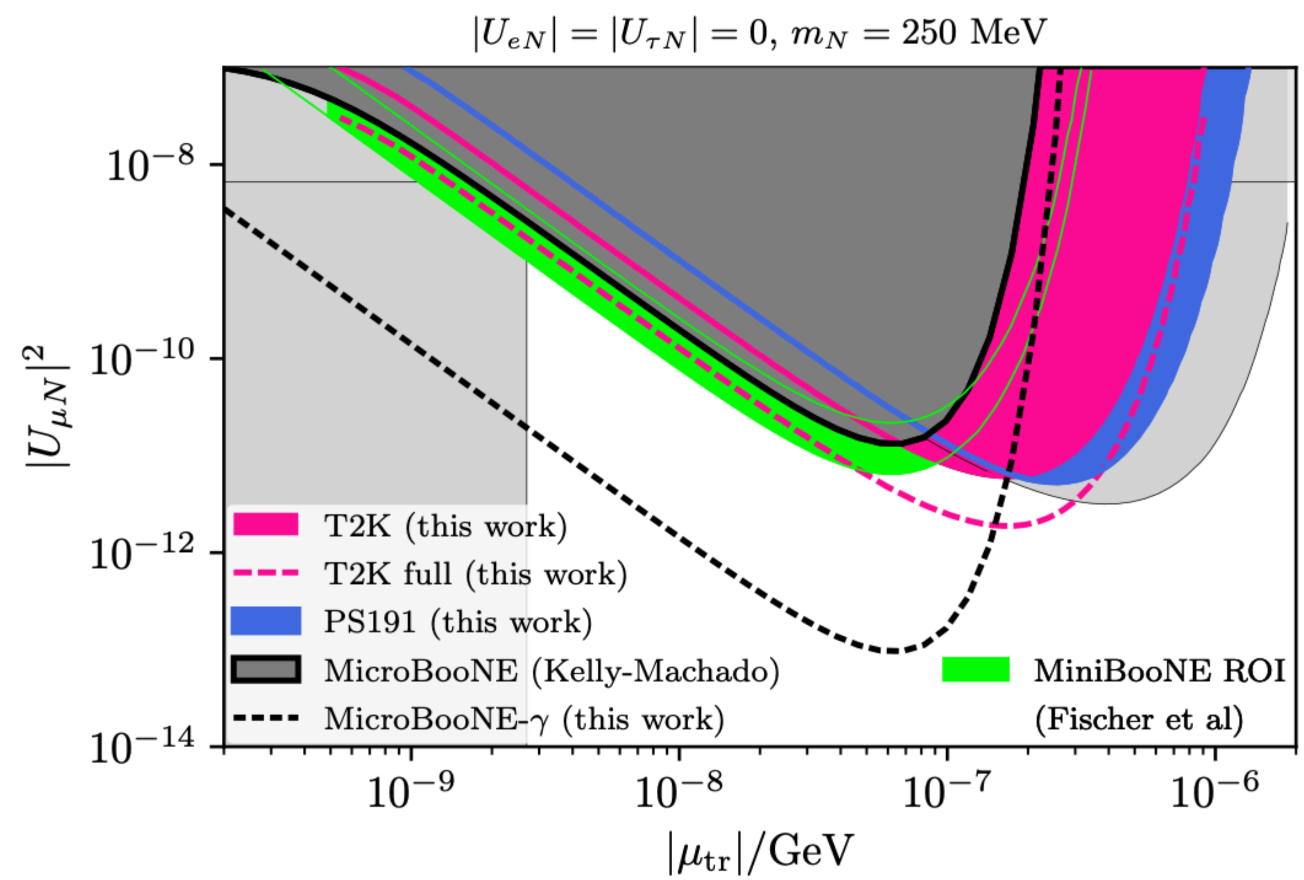
[T2K 1902.07598]

- T2K can have sensitivity also to dipole portal interactions [Arguelles+ 2109.03831]
- Instead than the direct $N \to \nu\gamma$ decay they instead considered the process



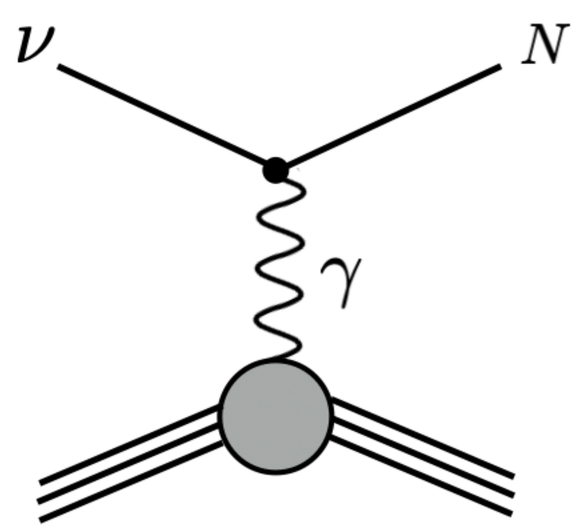
with a rate $\mathcal{B}(N \to \nu\gamma^* \to \nu e^+ e^-) \simeq 0.6\%$ detectable in low density detectors as GArTPC. Recasted the T2K HNL search



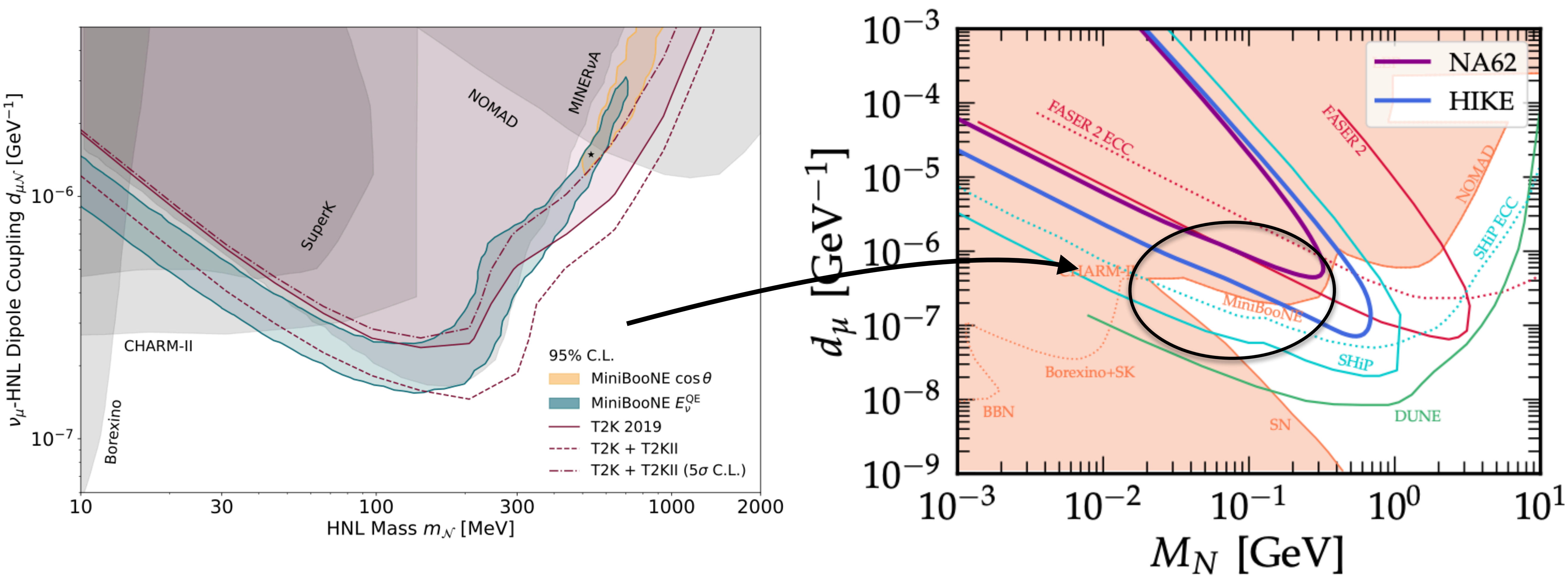


- Similar strategy can be applied to the dark dipole, with mass splitting dependence and four-fermi operators

- The RH neutrino production can also occur through the dipole operator via up-scattering in the ND280 detector & the upstream bedrock **[Liu+ 2412.15051]**



- Production and decay controlled by one parameter
- Again considered the $N \to \nu\gamma^* \to \nu e^+ e^-$ in the GArTPC
- NA280 P0D detector can detect single photon but, but background is substantial



Backup slides

A closer look at the see-saw model

- For $\mathcal{N} > 1$ right-handed neutrinos Y_ν and M_N are matrices in flavor space

$$-\mathcal{L}_{\rm mass} = \frac{1}{2}\begin{pmatrix}\bar{\nu}_L^c \\ N_R\end{pmatrix}\begin{pmatrix}0 & Y_\nu v \\ Y_\nu^T v & M_N\end{pmatrix}\begin{pmatrix}\nu_L \\ N_R^c\end{pmatrix} + h.c.$$

- The neutrino mass relation changes

$$m_\nu = \frac{y_\nu^2 v^2}{M_N} \longrightarrow m_\nu = v^2 Y_\nu \frac{1}{M_N} Y_\nu^T = U^* m_\nu^{(d)} U^\dagger$$

- One can write $Y_\nu = \frac{1}{v} U^* \sqrt{\mu}\sqrt{M_N}$ with $\sqrt{\mu}\sqrt{\mu}^T = m_\nu^{(d)}$

$\sqrt{\mu}$ → $3 \times \mathcal{N}$ matrix

- Then decompose $\sqrt{\mu} = \sqrt{m}\mathcal{R}$

$$\begin{cases} \sqrt{m} \text{ is a } 3 \times \mathcal{N} \text{ matrix containing the physical neutrino masses} \\ \mathcal{R} \text{ is a } \mathcal{N} \times \mathcal{N} \text{ complex orthogonal matrix} \end{cases}$$

Take now the scenario $\mathcal{N} = 2$ so that $m_{\nu_1} = 0$

Normal hierarchy

$m_{\nu_1} = 0$ $\qquad m_{\nu_3} > m_{\nu_2}$

$$\sqrt{m_{NH}} = \begin{pmatrix} 0 & 0 \\ 0 & \sqrt{m_2} \\ \sqrt{m_3} & 0 \end{pmatrix}$$

$$m_{\nu_2} = |\Delta m_{\rm sol}|\,,\; m_{\nu_3} = |\Delta m_{\rm atm}|$$

Inverted hierarchy

$m_{\nu_3} = 0$ $\qquad m_{\nu_2} > m_{\nu_1}$

$$\sqrt{m_{IH}} = \begin{pmatrix} 0 & \sqrt{m_1} \\ \sqrt{m_2} & 0 \\ 0 & 0 \end{pmatrix}$$

$$m_{\nu_2} \simeq m_{\nu_1} \simeq |\Delta m_{\rm atm}|$$

- For both cases $\mathcal{R} = \begin{pmatrix} \cos z & \pm \sin z \\ -\sin z & \pm \cos z \end{pmatrix}$ with $z = \beta + i\gamma$ [Casas, Ibarra 0103065]

- The mass relation becomes

$$Y_\nu = \frac{1}{v} U^* \sqrt{m} \mathcal{R} \sqrt{M_N}$$

- And the active-sterile mixing is

$$\theta = -U^* \sqrt{m} \mathcal{R} \frac{1}{\sqrt{M_N}}$$

- **For real** $z \simeq 1$ **one has** $\theta \simeq \left(\frac{m_\nu}{M_N}\right)^{\frac{1}{2}} \simeq 7 \times 10^{-6} \left(\frac{1\,\mathrm{GeV}}{M_N}\right)^{\frac{1}{2}}$

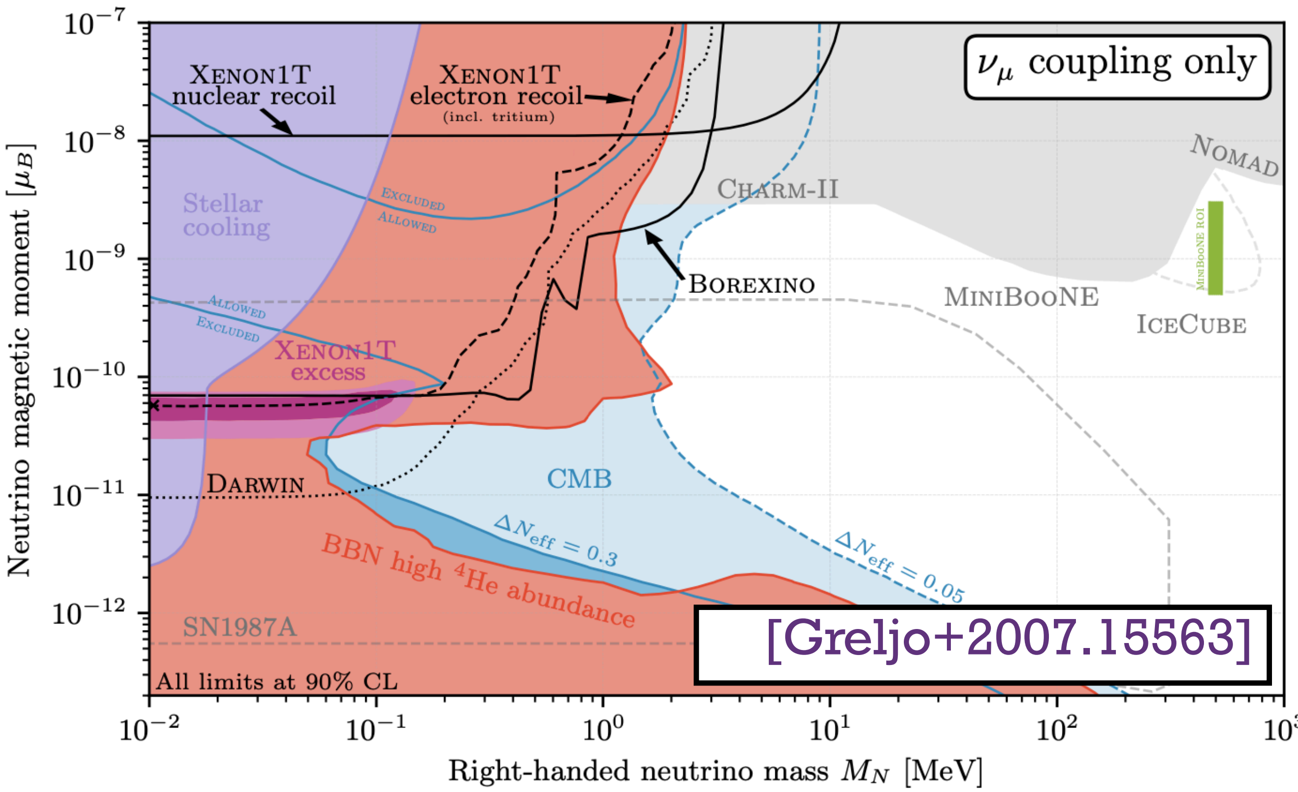
- **For complex** z **and** $\gamma \gg 1$ **get** $\mathcal{R} \simeq \frac{e^{\gamma - i\beta}}{2} \begin{pmatrix} 1 & \pm i \\ -i & \pm 1 \end{pmatrix}$

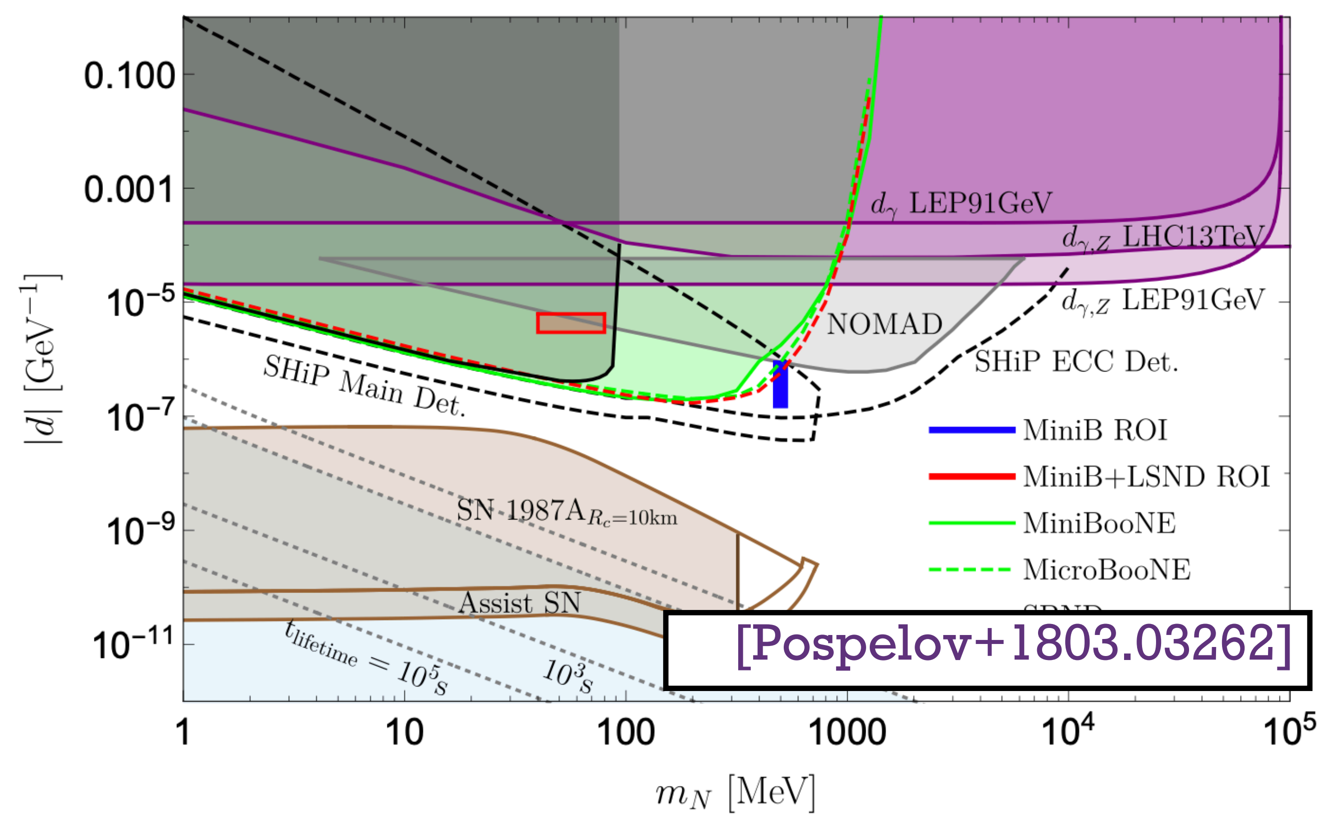
$$\theta \simeq 7 \times 10^{-6} e^{\gamma - i\beta} \left(\frac{1\,\mathrm{GeV}}{M_N}\right)^{\frac{1}{2}}$$

Dipole at high-intensity experiments

- High-intensity experiments can give an additional handle to test dipole interactions
- Active-sterile dipole $d_\gamma \, \bar{\nu}_L \sigma^{\mu\nu} N_R F_{\mu\nu}$ thoroughly studied

[Pospelov+ 1803.03262, Greljo+2007.15563, Ismail+ 2109.05032…]





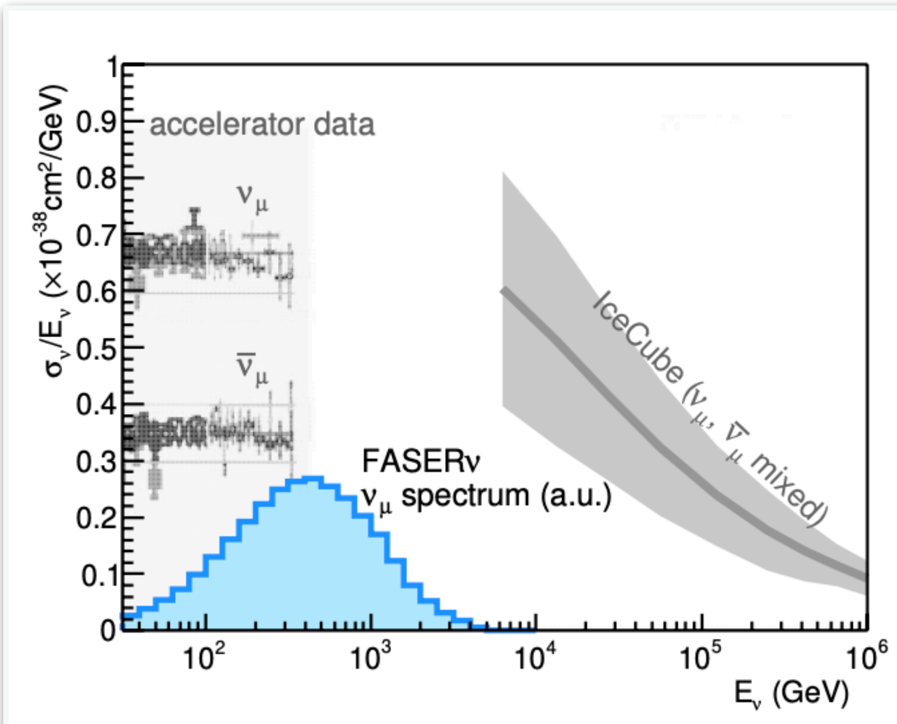
- Above the EW scale arises from $SU(2)_L \times U(1)_Y$ invariant $d = 6$ operators

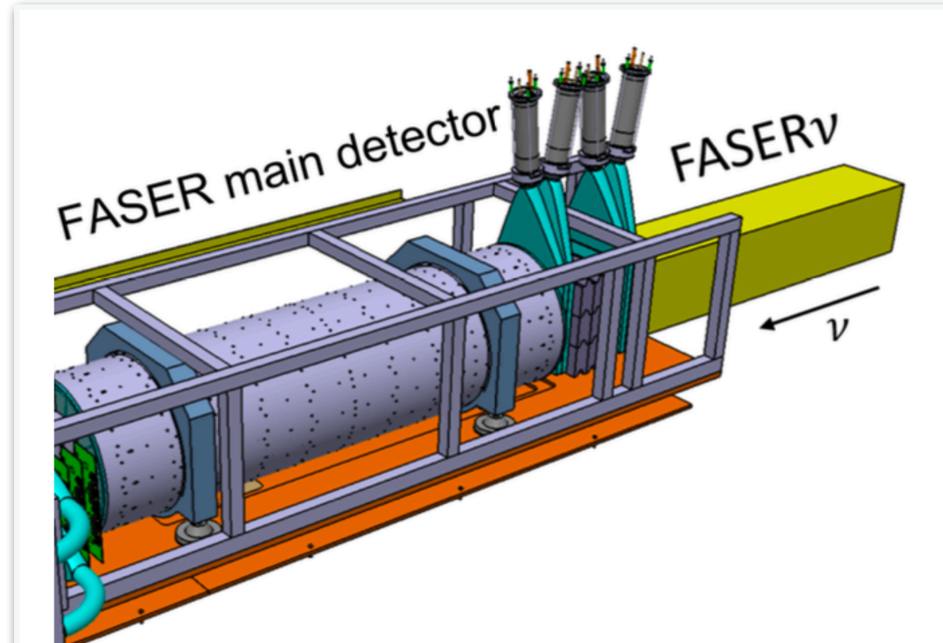
$$\mathcal{O}^6_{\mathcal{W}} = d_{\mathcal{W}} \bar{L} W_{\mu\nu} \tilde{H} \sigma^{\mu\nu} N_R \qquad \mathcal{O}^6_{\mathcal{B}} = d_{\mathcal{B}} \bar{L} B_{\mu\nu} \tilde{H} \sigma^{\mu\nu} N_R$$

- Many pheno studies at present and future experiments

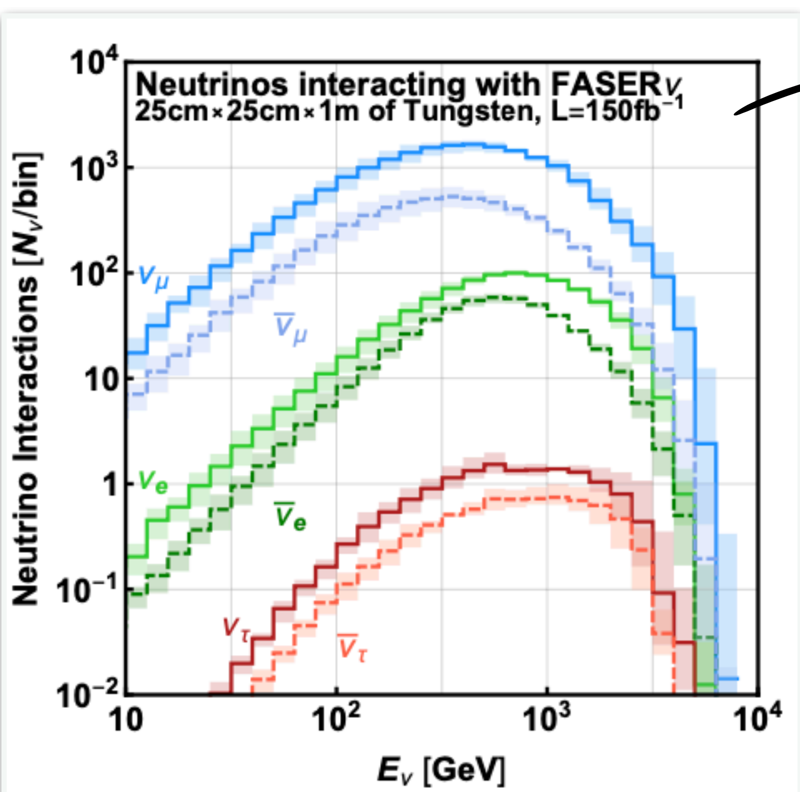
FASERν

- **FASER** is also sensitive to SM neutrinos produced at the LHC, through **FASERν**
- Huge number of high-energy forward neutrinos from hadron decay in *pp* collisions





25cm x 25 cm x 1.35 m tungsten



$\mathcal{O}(10^2, 10^4, 10)$ ν_e, ν_μ, ν_τ interactions

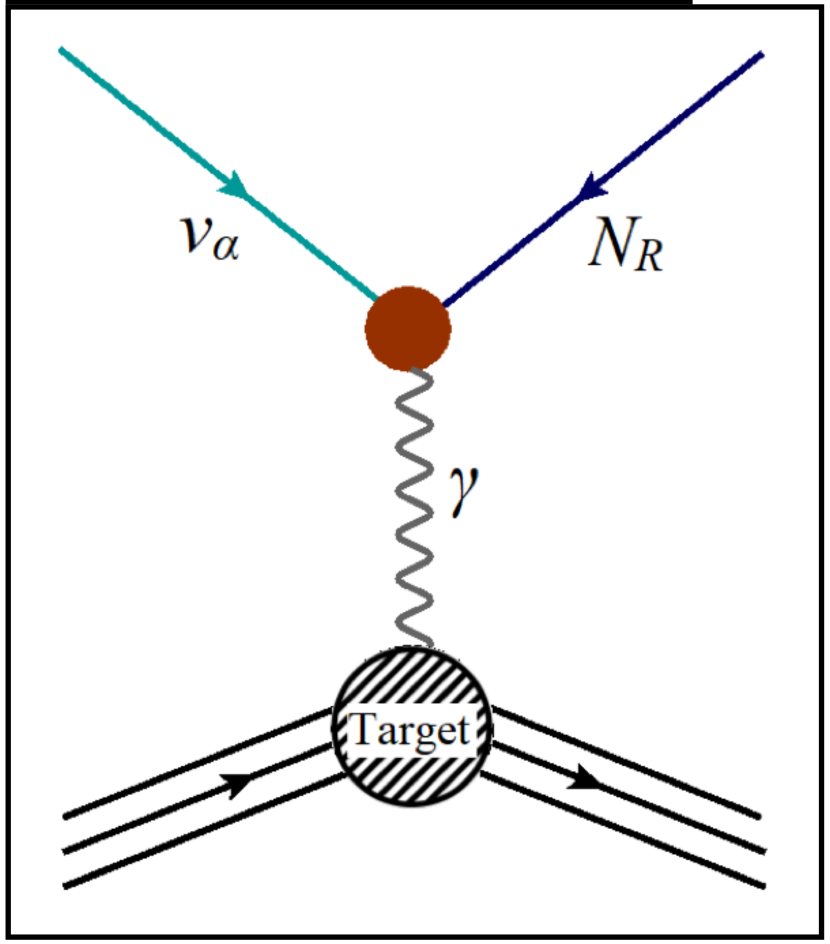
Directly test TeV neutrino properties

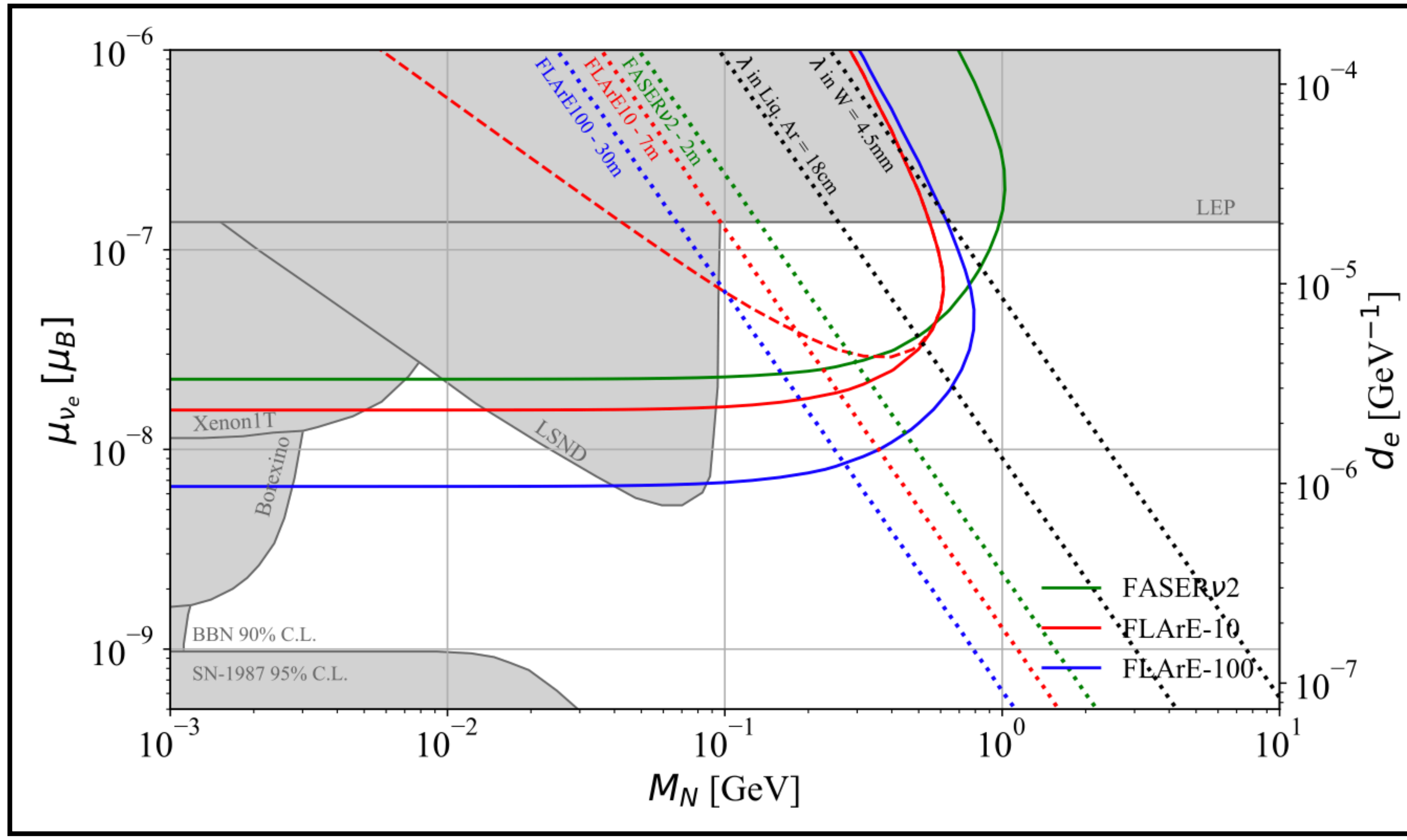
First Direct Observation of Collider Neutrinos with FASER at the LHC

FASER Collaboration [FASER 2303.14185]

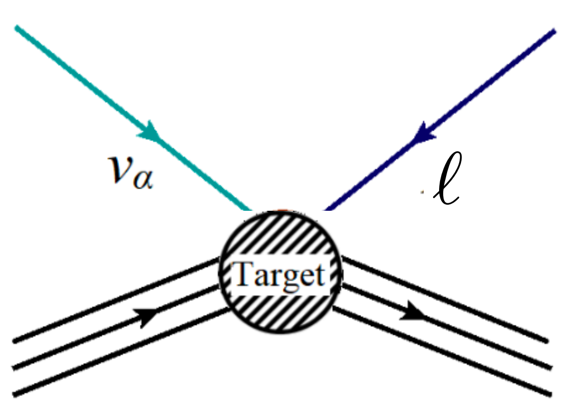
- Can also be used to test BSM neutrino up-scattering

[Ismail+ 2109.05032]

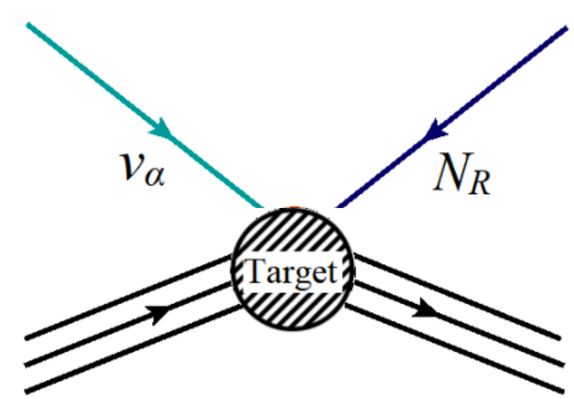




- Can also test four-fermi SMEFT operators [Falkowsky+ 2105.12136]



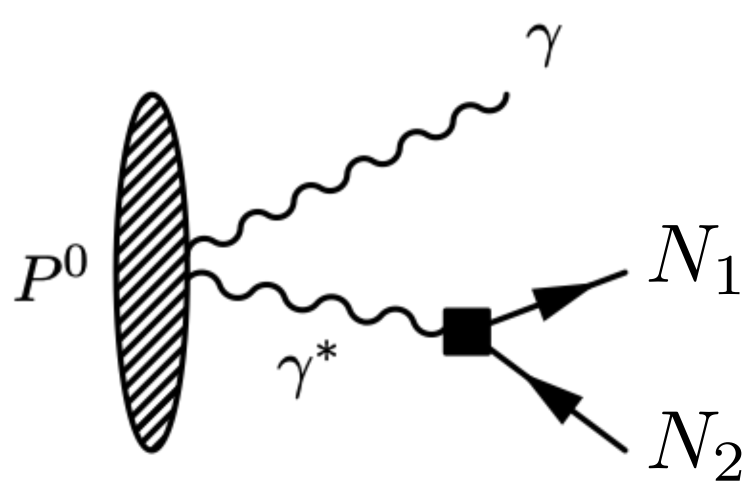
- And SMEFT operators



- Decay with of neutral pseudoscalar meson $\{\rho, \omega, J/\psi, \Upsilon, \phi\}$

$$\Gamma(V \to \chi_1 \chi_2) = \frac{e^2 Q_q^2 f_V^2 M_V}{6\pi\, \Lambda^2} \left(1 - \frac{(M_2 - M_1)^2}{M_V^2}\right)^{3/2} \left(1 + \frac{2(M_2 + M_1)^2}{M_V^2}\right) \left(1 - \frac{(M_2 + M_1)^2}{M_V^2}\right)^{1/2}$$

- Small contribution from decay of light pseudoscalar neutral mesons $\{\pi^0, \eta, \eta'\}$ via chiral anomaly and photon splitting



Ugly expression….

$$\Gamma = \frac{1}{(2\pi)^3\, 32 M_P^3} \int dm_{12}^2 dm_{23}^2 |\overline{\mathcal{M}}|^2$$

$$|\overline{\mathcal{M}}|^2 = \frac{d^2 e^4}{4\pi^4 F_P^2 m_{23}^4} \left[M_P^4 \left(m_{23}^2 (M_2^2 + 2M_1 M_2 - M_1^2) - (M_1^2 - M_2^2)^2\right) - m_{23}^4 (M_1^4 - 2M_1^2 m_{12}^2 - m_{23}^2 (M_1 + M_2)^2 + 2m_{12}^4 - 2m_{12}^2 M_2^2 + 2m_{12}^2 m_{23}^2 + M_2^4) - 2m_{23}^2 M_P^2 \left((M_1^2 - M_2^2)(M_2^2 - m_{12}^2) + M_2 m_{23}^2 (2M_1 + M_2) - m_{12}^2 m_{23}^2\right)\right],$$

$$p_{ij} = p_i + p_j\ , \quad m_{ij}^2 = p_{ij}^2$$

Meson spectra

- For FASER momentum and energy distribution of different mesons taken from the **FORESEE** package [Trojanowsky+ 2105.07077] cross-checked with **EPOS-LHC** [Pierog+ 1306.0121]

- For NA62 & SHiP fixed target experiments used **PYTHIA8** cross-check with SHiP simulation notes

Fixed-target meson multiplicities

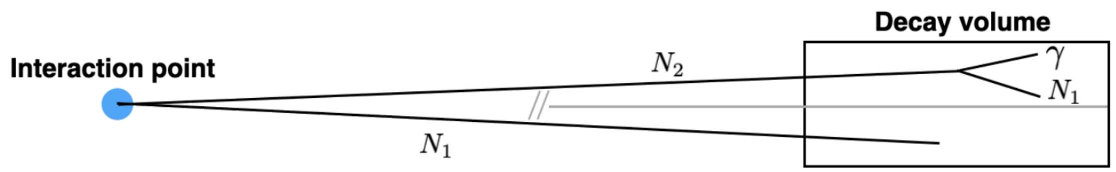
f_{π^0}	f_η	$f_{\eta'}$	f_ρ	f_ω	f_ϕ	$f_{J/\Psi}$	f_Υ	$f_{D^\pm}$	f_{D_s}	$f_{B^\pm}$
4.3	0.49	0.055	0.58	0.57	0.021	4.7×10^{-6}	2.2×10^{-9}	4.3×10^{-4}	1.8×10^{-4}	6.0×10^{-8}

Analysis selection

- Require the LLP particle to decay within the decay volume and its trajectory to intersect the eCAL of the related experiment - polar angle requirement on θ_{N_2}

- Require $E_\gamma > 1\,\mathrm{GeV}$ for a photon to be identified in the eCAL

- Assume background reduced to a negligible level, show $N_{\mathrm{ev}} = 3$ isocontours



UV model

- Same heavy physics that generates the active-sterile dipole will also contribute to Dirac neutrino masses
- Can one get a large active-sterile dipole without large contribution to Dirac mass?

Voloshin mechanims

- Postulate an $SU(2)_H$ symmetry under which $\psi = (\nu_L^c, N_R)$ is a doublet [Voloshin '88]
- Dipole is an $SU(2)_H$ singlet, while the mass term is a triplet

$$\mathcal{L}_{\rm dipole} = \frac{m}{2}\bar{\psi}^c \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} \psi + h.c. \qquad \mathcal{L}_{\rm mass} = \frac{m}{2}\bar{\psi}^c \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \psi + h.c.$$

- Dipole is an $SU(2)_H$ singlet, while the mass term is a, forbidden, triplet
- Explicit models can be built, see e.g. [Barbieri+ '89, Babu+ '90, Leurer+ 90…]

More dependence on threshold energy

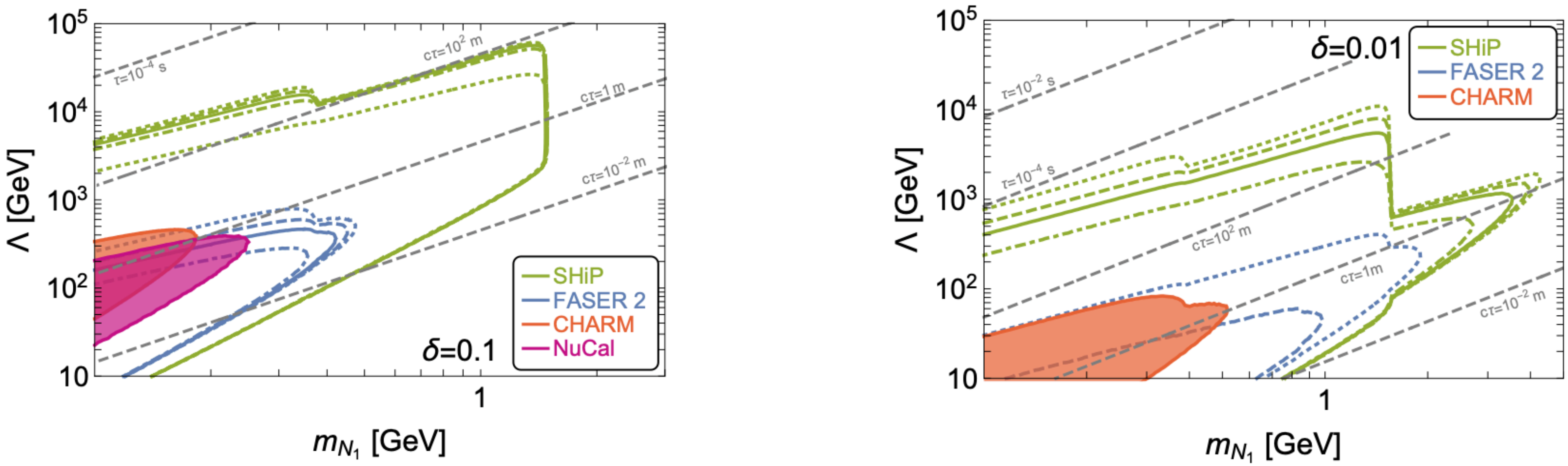


Figure 2. Isocontours of $N_{\rm signal} = 3$ for SHiP (green lines) and FASER 2 (blue lines). For SHiP dotted, dashed, solid, dot-dashed and dotted lines are for $E_{\rm cut} = 0.1, 0.5, 1, 2, 10$ GeV respectively while for FASER 2 dotted, dashed, solid and dot-dashed lines are for $E_{\rm cut} = 10, 50, 100, 200$ GeV respectively. The CHARM and NuCal regions and the gray lines are as in Fig. 1. We fix $\alpha = \pi/2$.