Testing Neutrino Dipole Portal by LLP Detectors at the LHC

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Arxiv: 2302.02081

Work in collaboration with **Yu Zhang**

thirteenth workshop of the LLP Community

Neutrino Mass

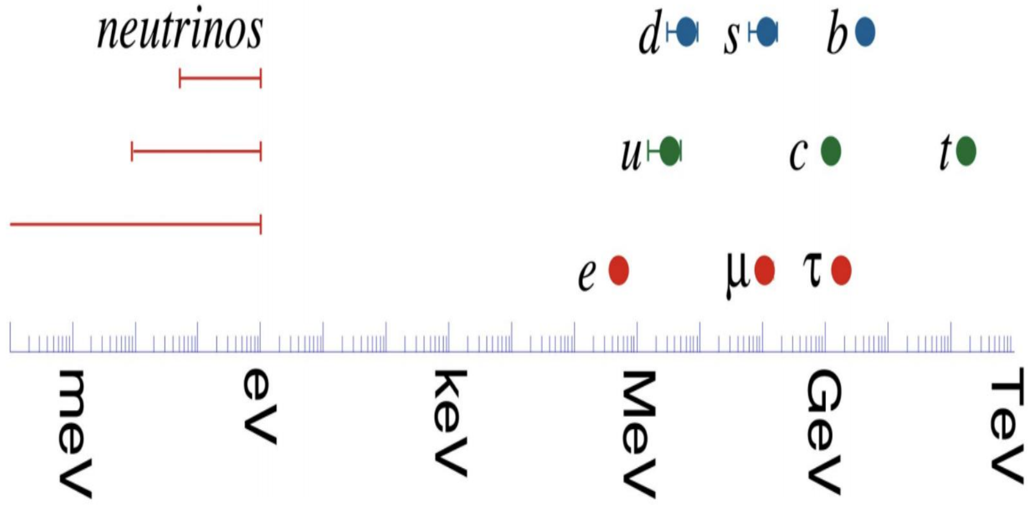
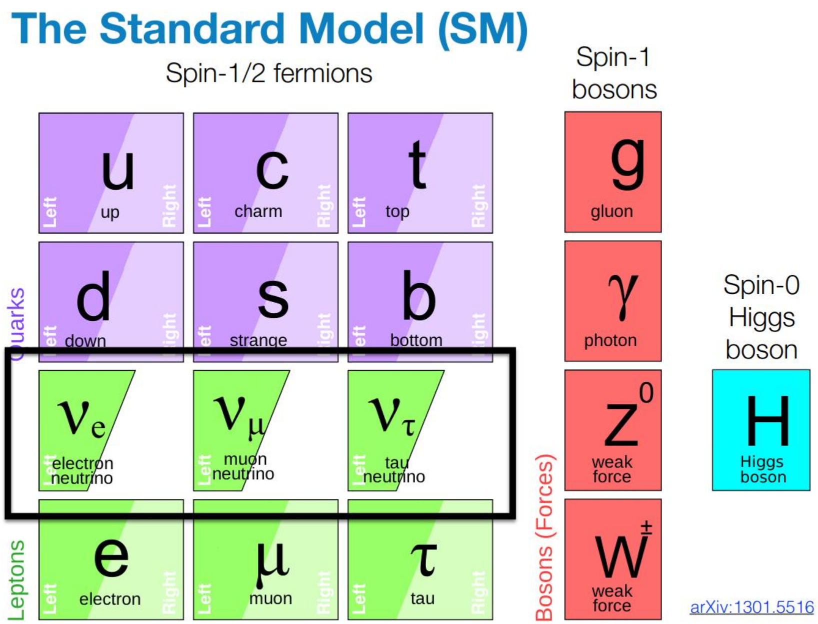
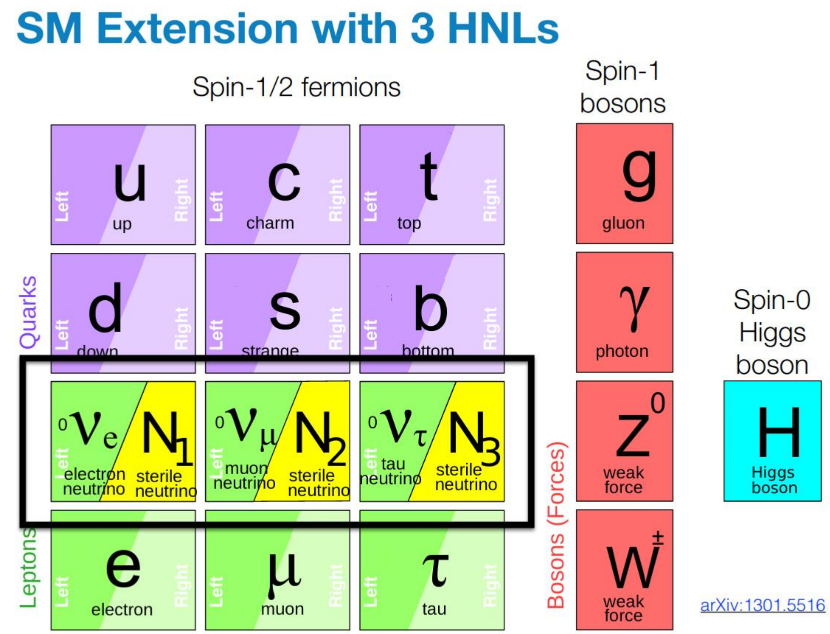


Figure from Hitoshi Murayama

- Existence of the neutrino masses, is beyond the SM!

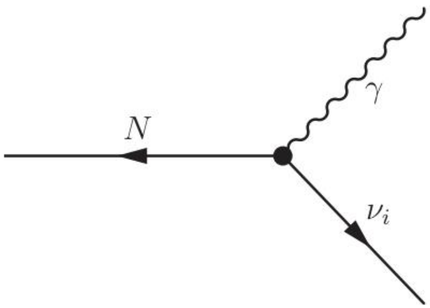
Heavy Neutral Lepton



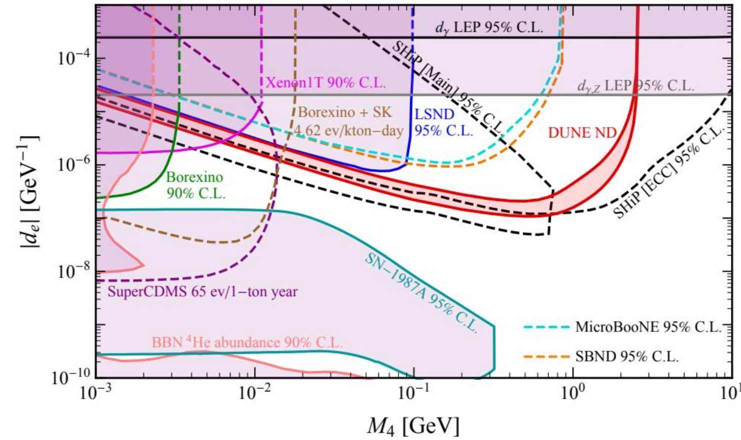


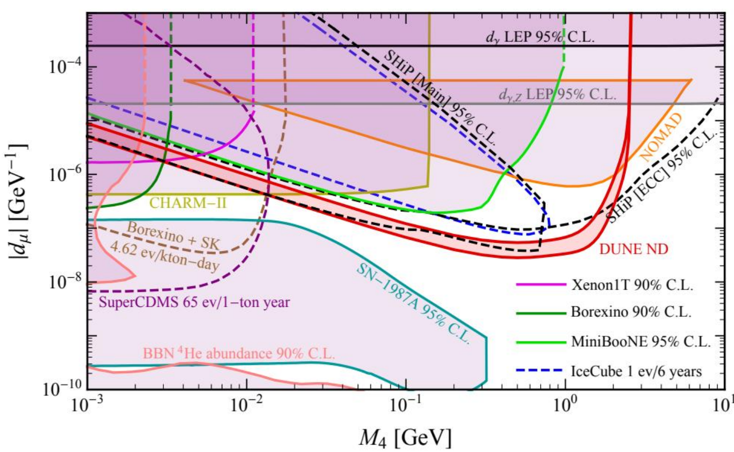
- Introduce right-handed heavy neutrinos (HNL) to explain the neutrino masses
- Various models

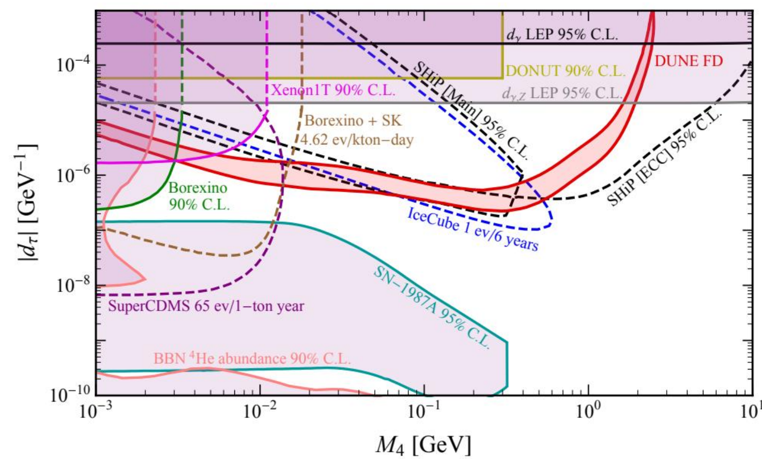
A EFT Model: Dipole portal



$$\mathcal{L} \supset d_k \bar{\nu}_L^k \sigma_{\mu\nu} F^{\mu\nu} N + \text{H.c.},$$







arXiv: 2105.09699

- Collider, beam dump, neutrino scattering, Astrophysical...

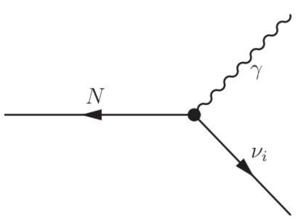
A EFT Model: Dipole portal

$$\mathcal{L} \supset \bar{L}(d_{\mathcal{W}} \mathcal{W}^a_{\mu\nu} \tau^a + d_B B_{\mu\nu}) \tilde{H} \sigma_{\mu\nu} N_D + \text{H.c.}$$

S
S
B

$$\mathcal{L} \supset d_W (\bar{\ell}_L W^-_{\mu\nu} \sigma^{\mu\nu} N_D) + \bar{\nu}_L [d_\gamma F_{\mu\nu} - d_Z Z_{\mu\nu}] \sigma^{\mu\nu} N_D + \text{H.c.}$$

$\sim$ **1 GeV**



$$\mathcal{L} \supset d_k \bar{\nu}^k_L \sigma_{\mu\nu} F^{\mu\nu} N + \text{H.c.},$$

$$d_\gamma = \frac{v}{\sqrt{2}} \left(d_B \cos\theta_w + \frac{d_{\mathcal{W}}}{2} \sin\theta_w \right)$$
$$d_Z = \frac{v}{\sqrt{2}} \left(\frac{d_{\mathcal{W}}}{2} \cos\theta_w - d_B \sin\theta_w \right)$$
$$d_W = \frac{v}{\sqrt{2}} \frac{d_{\mathcal{W}}}{2} \sqrt{2}.$$

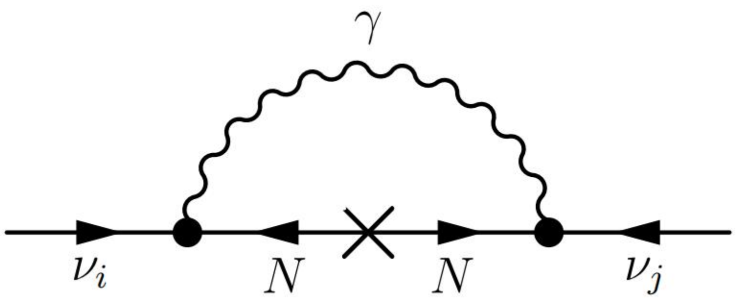
$$\{m_N, d_{\mathcal{W}}, d_B\}$$

$$d_{\mathcal{W}} = a \times d_B$$
$$d_Z = \frac{d_\gamma (a\cos\theta_w - 2\sin\theta_w)}{2\cos\theta_w + a\sin\theta_w}$$
$$d_W = \frac{\sqrt{2} a d_\gamma}{2\cos\theta_w + a\sin\theta_w}.$$

$$\{m_N, d_\gamma, a\}$$

- Dipole portal via Effective Field Theory

Origin of Neutrino Mass



Assumption I

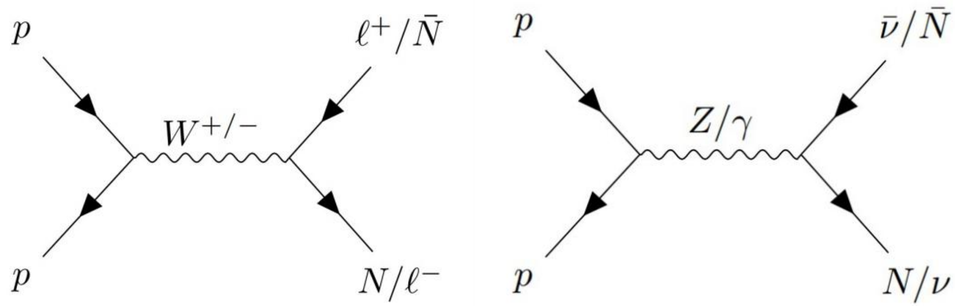
- The HNLs should be Dirac,
  othwise the Dipole is suppressed by the neutrino mass

Assumption II

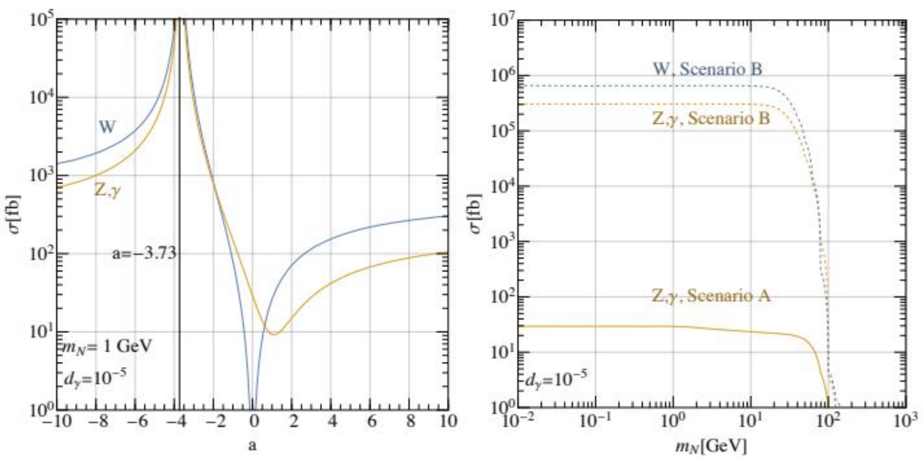
- We assume the NLH coupling is small, thus dipole portal is dominant

- The neutrino masses can still be explained by the inverse seesaw, whatever the NLH coupling is

Production at the LHC



- We focus mainly via the on-shell decays of W/Z,
- the EFT should be valid with $\Lambda > M_{W,Z}$



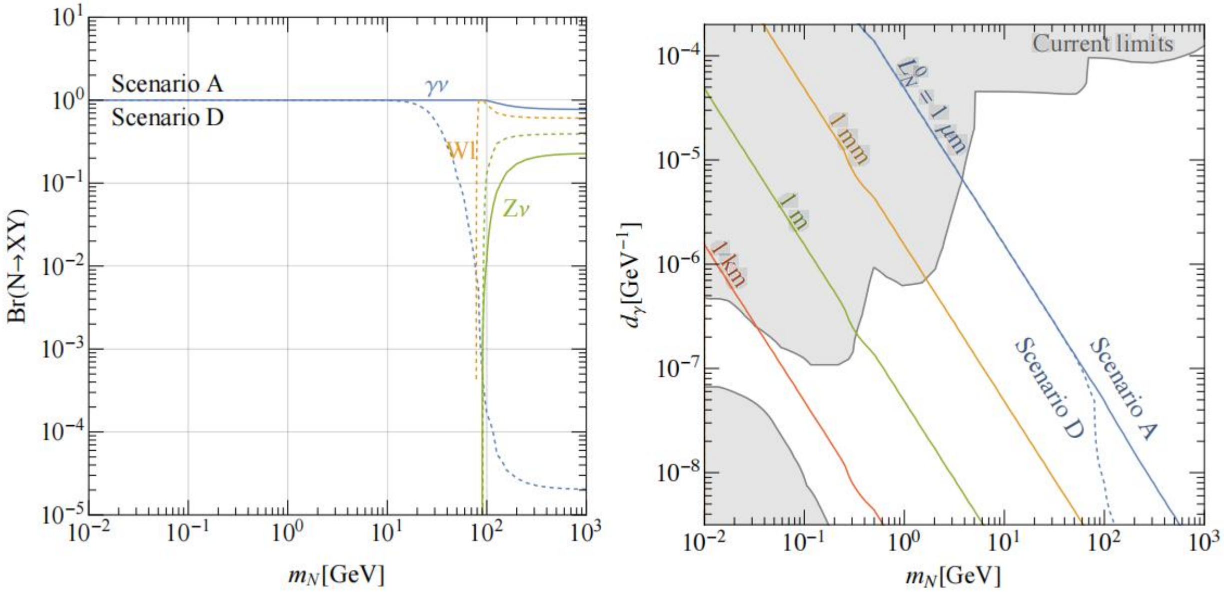
- The cross section can be high, and depend on $a = d_B/d_{\mathcal{W}}$

Scenarios

Scenario	Assumptions	Relations
A	$d_{\mathcal{W}} = 0$	$d_Z = -d_\gamma \tan\theta_w$; $d_W = 0$
B	$d_{\mathcal{W}} = 2\tan\theta_w \times d_B$	$d_Z = 0$, $d_W = \sqrt{2} d_\gamma \sin\theta_w$
C	$d_{\mathcal{W}} = -3 \times d_B$	$d_Z \approx 11.250 \times d_\gamma$, $d_W \approx 13.258 \times d_\gamma$
D	$d_{\mathcal{W}} = -3.73 \times d_B$	$d_Z \approx 139.55 \times d_\gamma$; $d_W \approx 173.52 \times d_\gamma$

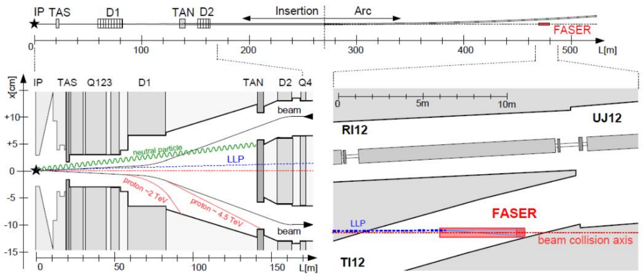
- We select four scenarios according to different $a = d_B/d_{\mathcal{W}}$
- The production cross section is different for each scenarios

Decay of the HNLs

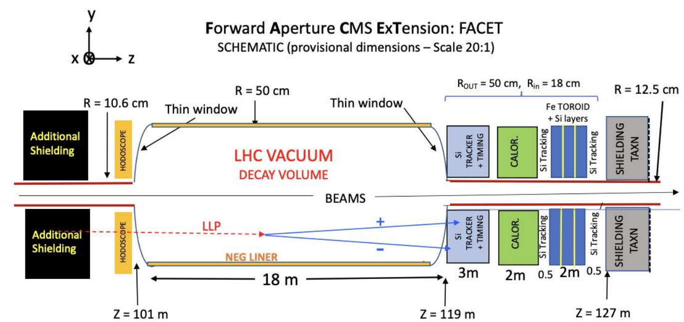


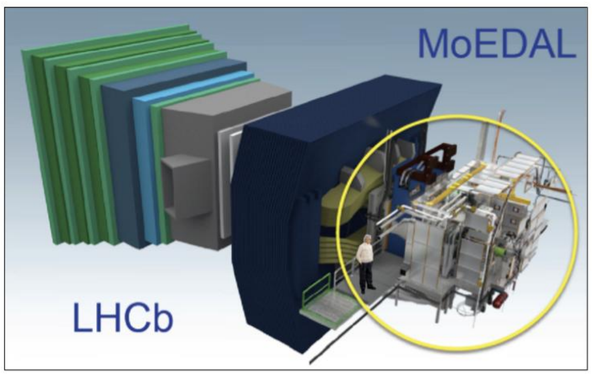
- The RHNs dominantly decay into $N \to \gamma\nu$, mono photon plus MET
- The current limits has already pointed towards HNLs as LLPs.

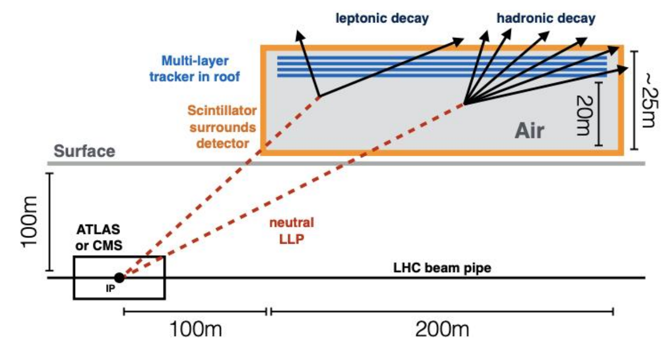
LLP detection at the LHC



Approved experiment







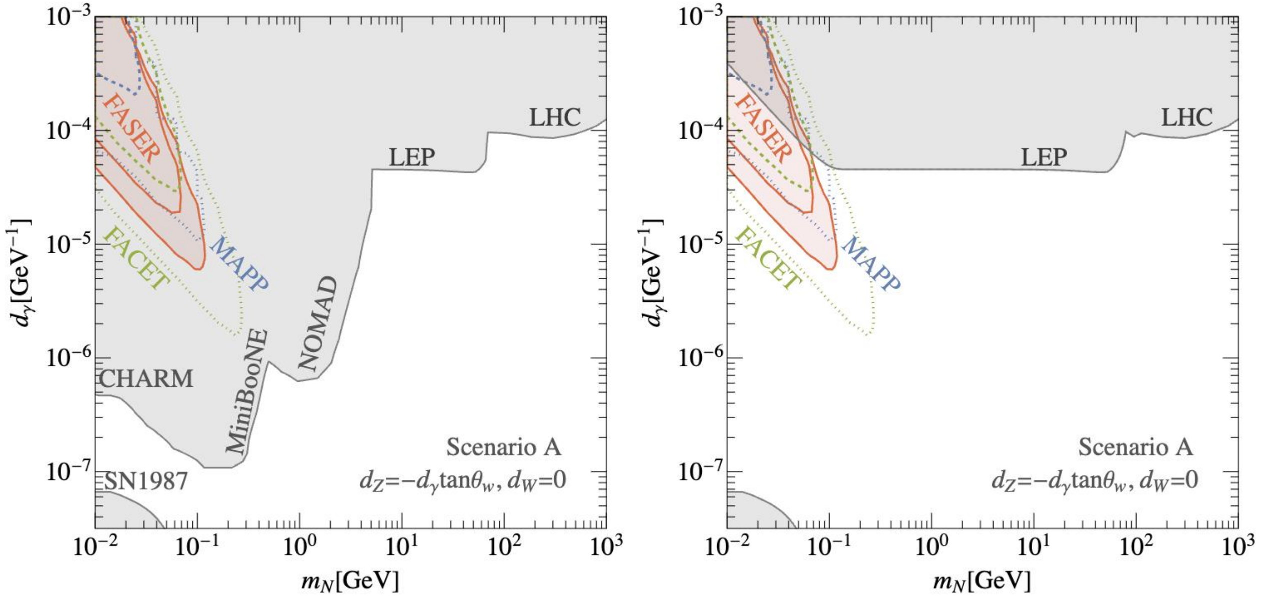
- mono photon signal **can not be** detected at MATHUSLA
- **Can** be detected at the FASER, if the photon is energetic
- FACET should be similar
- MoEDAL-MAPP **can** detect photon, but lacks literature

LLP Selection at the LHC

Detectors	L_x [m]	L_y [m]	L_{xy} [m]	L_z [m]	Luminosity [fb^{-1}]
FASER-2	–	–	$[0,1]$	$[475,480]$	3000
MAPP-2	$[3,6]$	$[-2,1]$	–	$[48,61]$	300
FACET	-	-	$[0.18,\ 0.5]$	$[101,119]$	3000

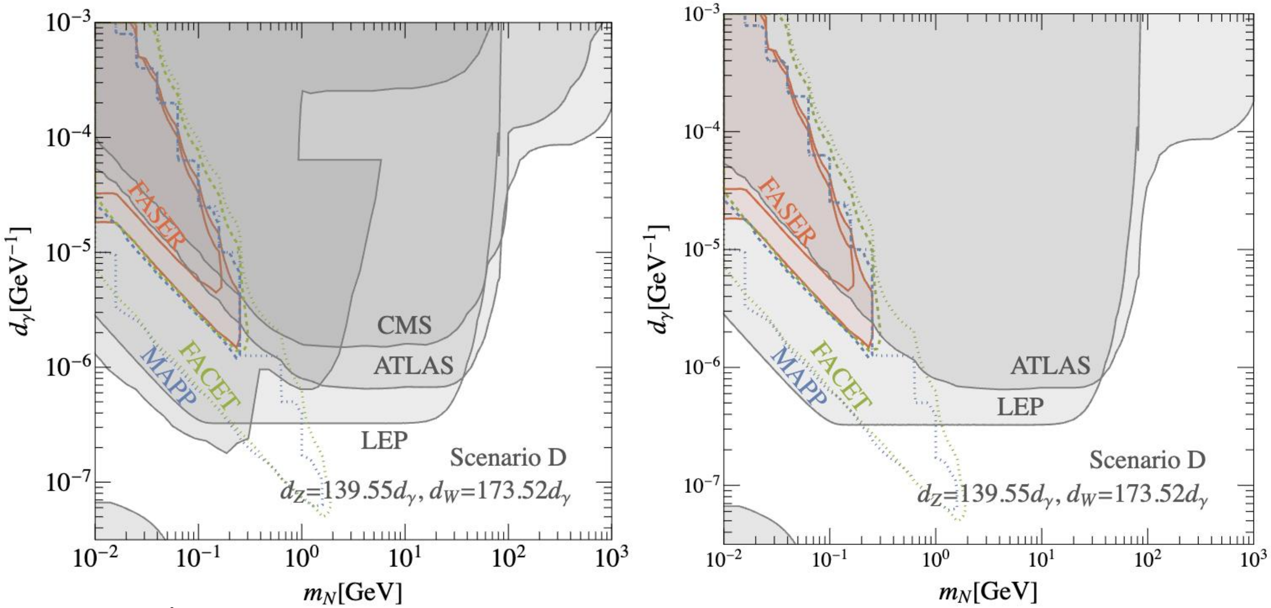
- The direction, solid angle coverage, length, distance are important
- FASER are at the very forward direction
- FACET is closer to the transerve direction
- MAPP-2 is similar to the LHCb

Results



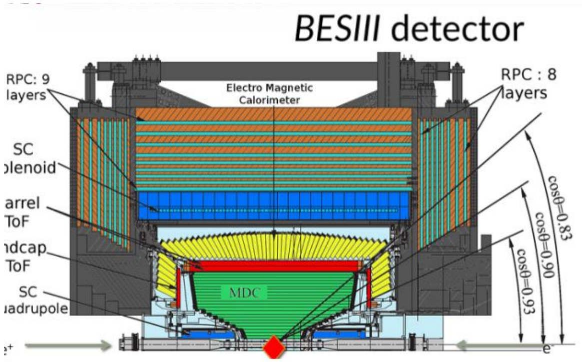
- Scenario A
- Left is the flavor universal coupling case, right for d_τ dominance
- The current limits from neutrino scattering are strong for e, μ flavor
- Less τ limits, since **hard to get ν_τ source**
- **Better sensitivity for d_τ** with LLP searches!
- The background of FACET and MAPP is not modelled very well
- We show N_S=3, 10 for FASER-2
- N_S=3, 1000 for FACET and MAPP

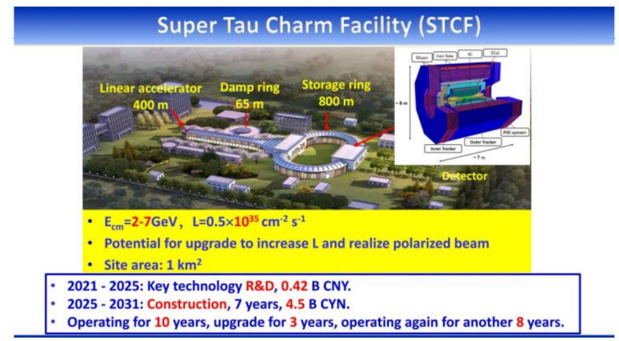
Results

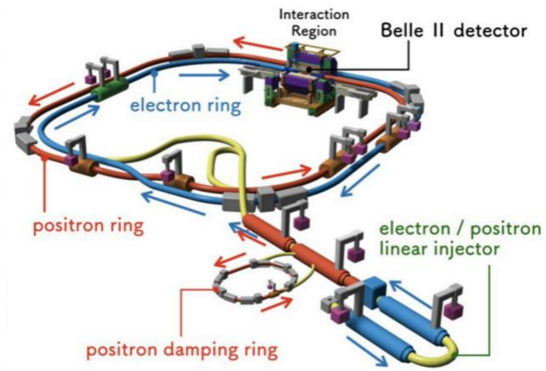


- Scenario D
- Left is the flavor universal coupling case, right for d_τ dominance
- The production is enhanced by large d_W and d_Z
- FACET and MAPP are better, closer to the **transverse direction**
- The existing limits are scaled
- The LLP searches can reach 10^{-7}

Lepton Colliders

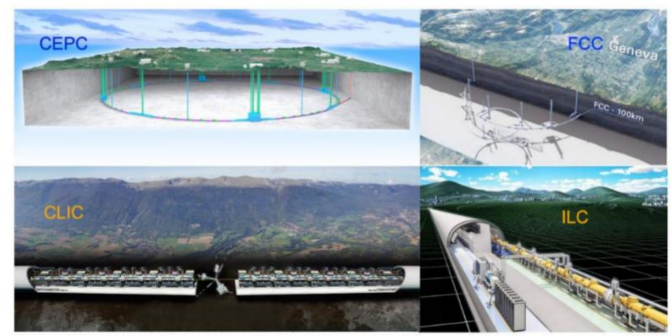






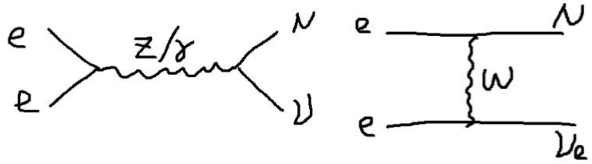
$\sqrt{s} \ll M_Z$

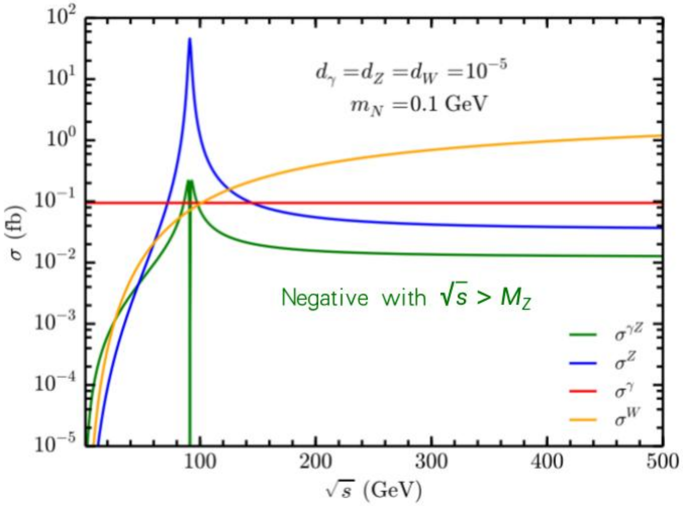
$\sqrt{s} \geq M_Z$

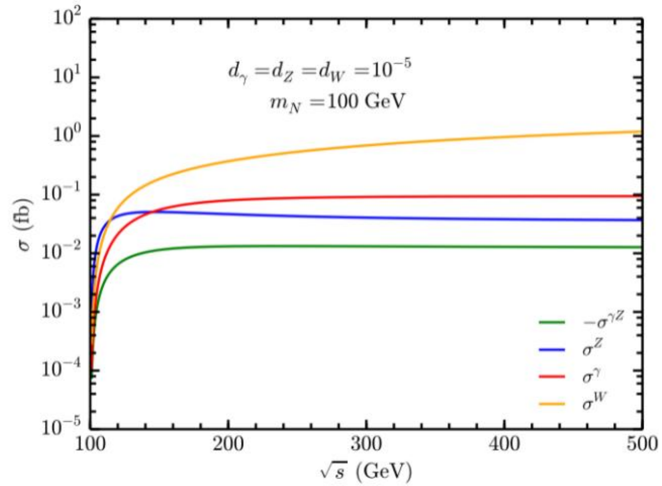


- There are several existing and proposal for lepton colliders
- BESIII, Belle II, STCF, CEPC...

Lepton Colliders

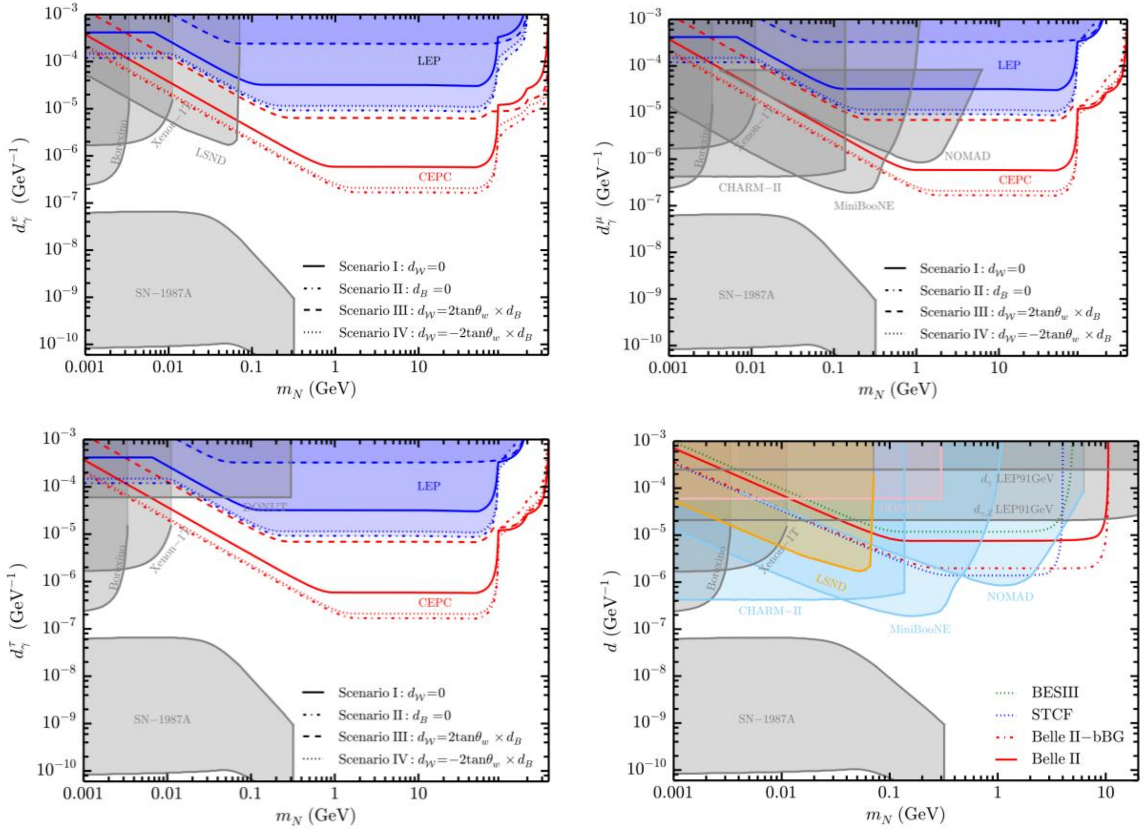






- The production cross section mainly from t channel W
- Z resonance for light HNL

Results



- Signals are **prompt mono photon**
- CEPC have 2 magnitude better sensitivity than the LEP
- BES-III, STCF and Belle-II are comparative to the neutrino scattering
- YZ, WL, Phys.Rev.D 107 (2023) 9, 095031

Conclusion

- The more general dipole couplings to HNL which respect the full gauge symmetries of the SM are considering.
- We present the constraints on various **electron colliders** and LHC by **Long-lived Particle Detectors**.
- The constraints on active-sterile neutrino transition magnetic moments dependent on the **scenarios** at high energy colliders.
- The current constraints basically do not dependent on the ratio a, since the typical scattering energies are **far less than the electroweak scale**.