SHANGHAI JIAO TONG UNIVERSITY 上海交通大学

The dipole portal to heavy neutrinos at future colliders (experiments)

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Outline

Background

Current constraints/sensitivities from cosmological, astrophysical and laboratory observations

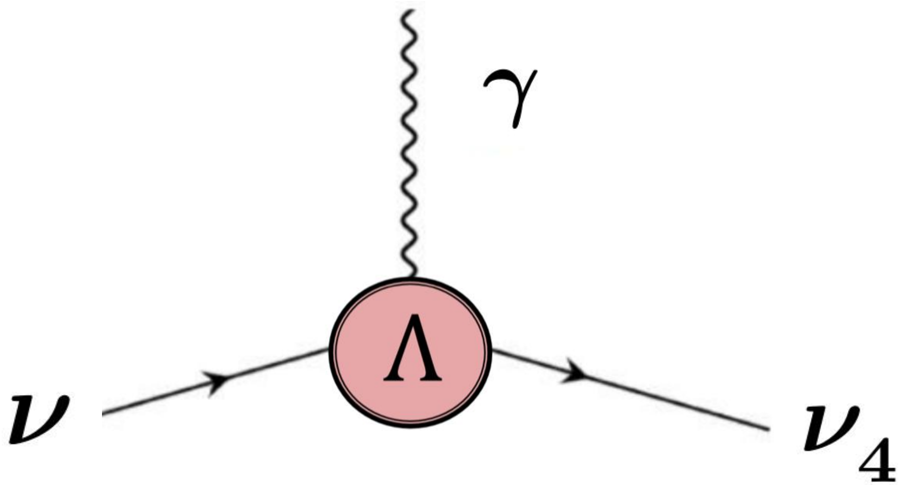
Sensitivities at future FCC/high-luminosity LHC

Summary and outlook

Motivations:

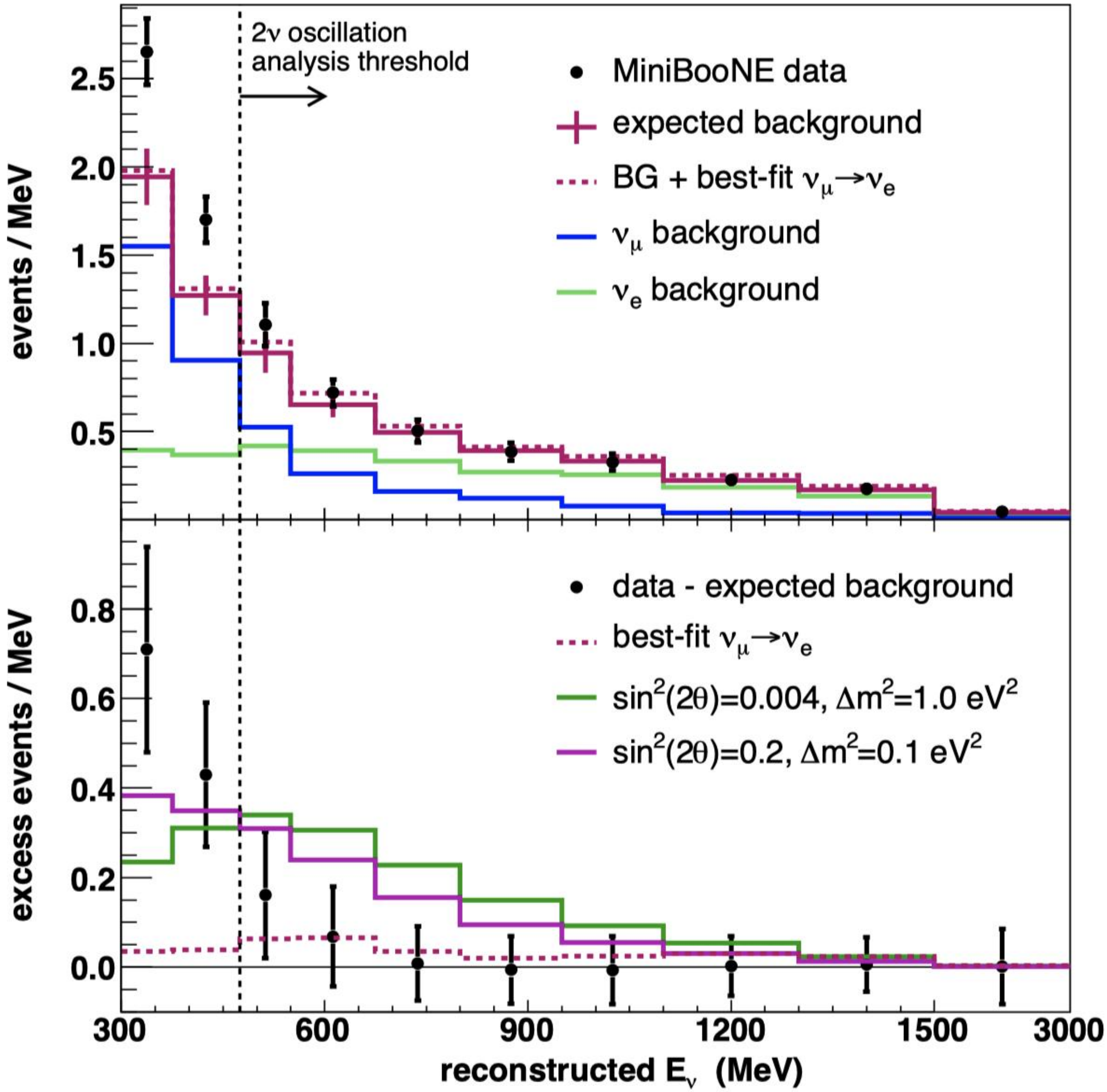
The neutrino portal to heavy neutrinos (active-sterile neutrino transition magnetic moments):

$$\mathcal{L} = d_\alpha \overline{\nu}_{\alpha L} \sigma^{\mu\nu} \nu_4 F_{\mu\nu} + \mathrm{h.c.}$$



- This Lagrangian is technically only valid at energies below the EW scale;
- Above the EW scale, we need construct UV-completion theory (Model dependent) ;
- Agnostic about the UV origin of this operator and study its phenomenological implications at energies below EW scale in most experiments.
- Model-building discussion

- **A promising way to test the existence of sterile neutrinos**
- **Anomalies(XENON1T, ANITA, MiniBooNE, muon g-2 anomalies)**
- **A possible way to answer the questions: are neutrinos Dirac or Majorana particles?**

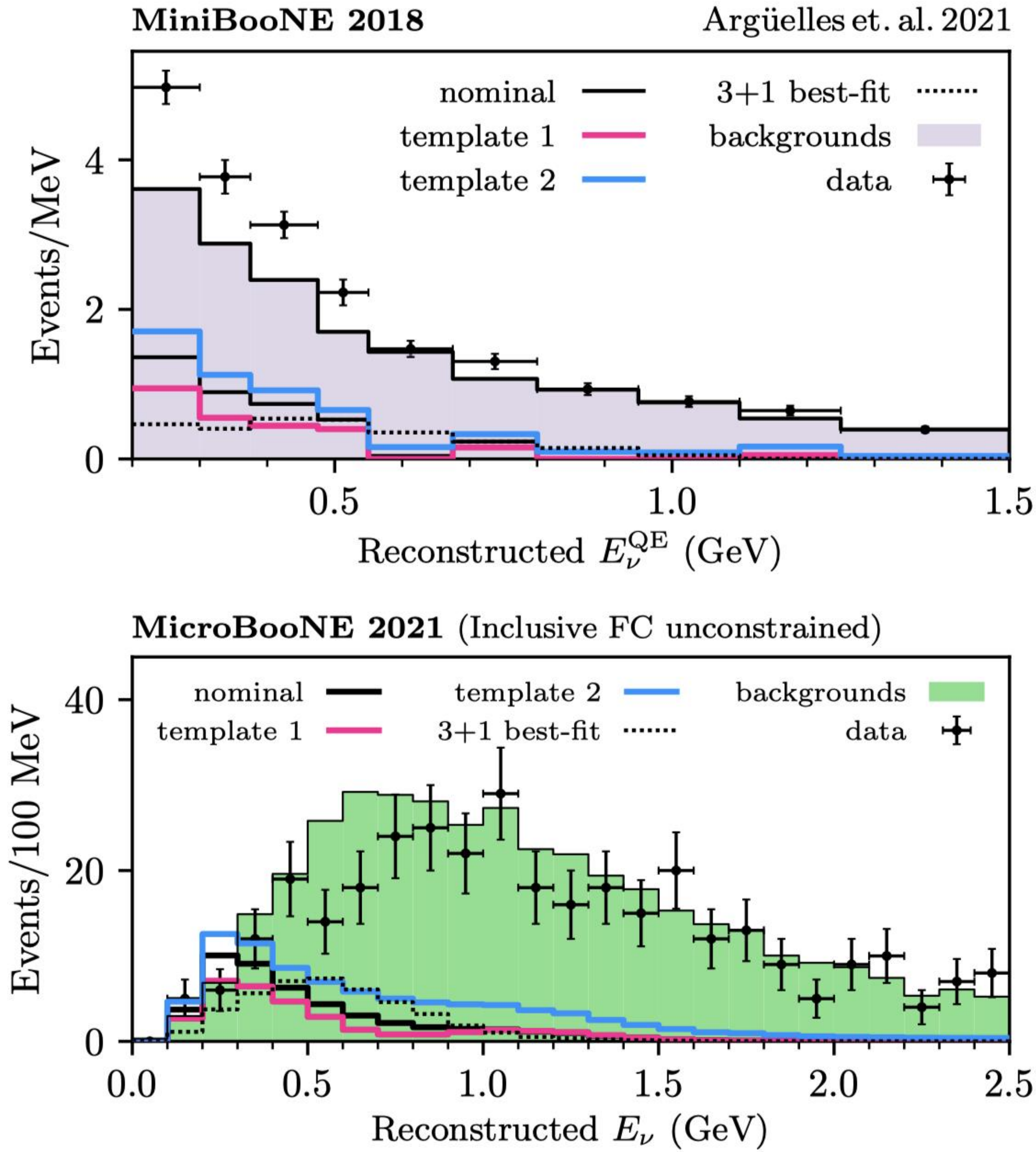


Low energy electron-like excess

LSND, PRD2001

MiniBoonNE 0704.1500 and update later

First trial using the dipole portal to solve this: Gninenko PRL 2009, PRD2010



Low energy electron-like excess

MicroBooNE
Kopp et. al. PRL2021

Anomaly still exists

Current constraints or sensitives:

The bounds on d_α (α=e, μ, τ) come from various laboratory, astrophysical and cosmological observations, for example the ones derived from

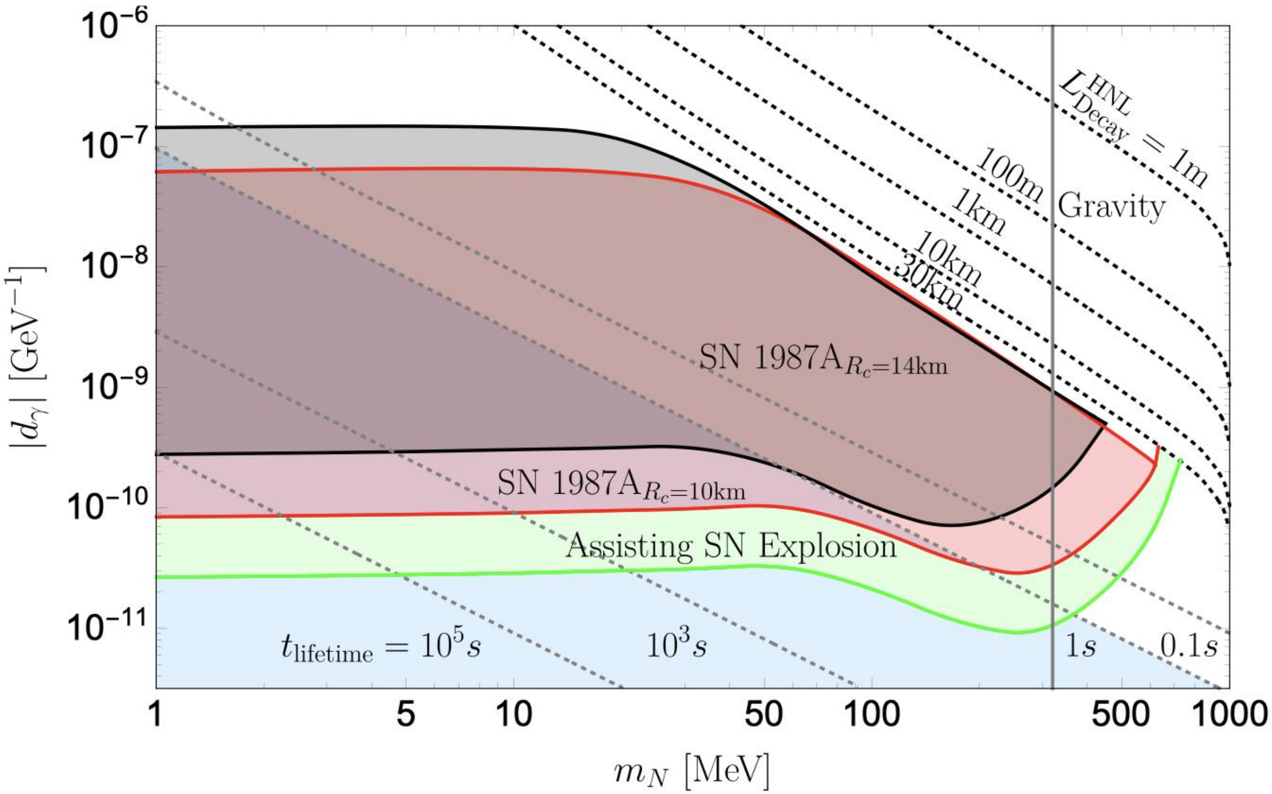
- neutrino oscillation experiments (solar, atmospheric, reactor),
- dark matter experiments,
- the observation of high-energy neutrinos

by studying

- coherent elastic neutrino-nucleus scattering (CEvNS),
- elastic neutrino-electron scattering,
- deep inelastic interactions

etc.

Supernova neutrinos

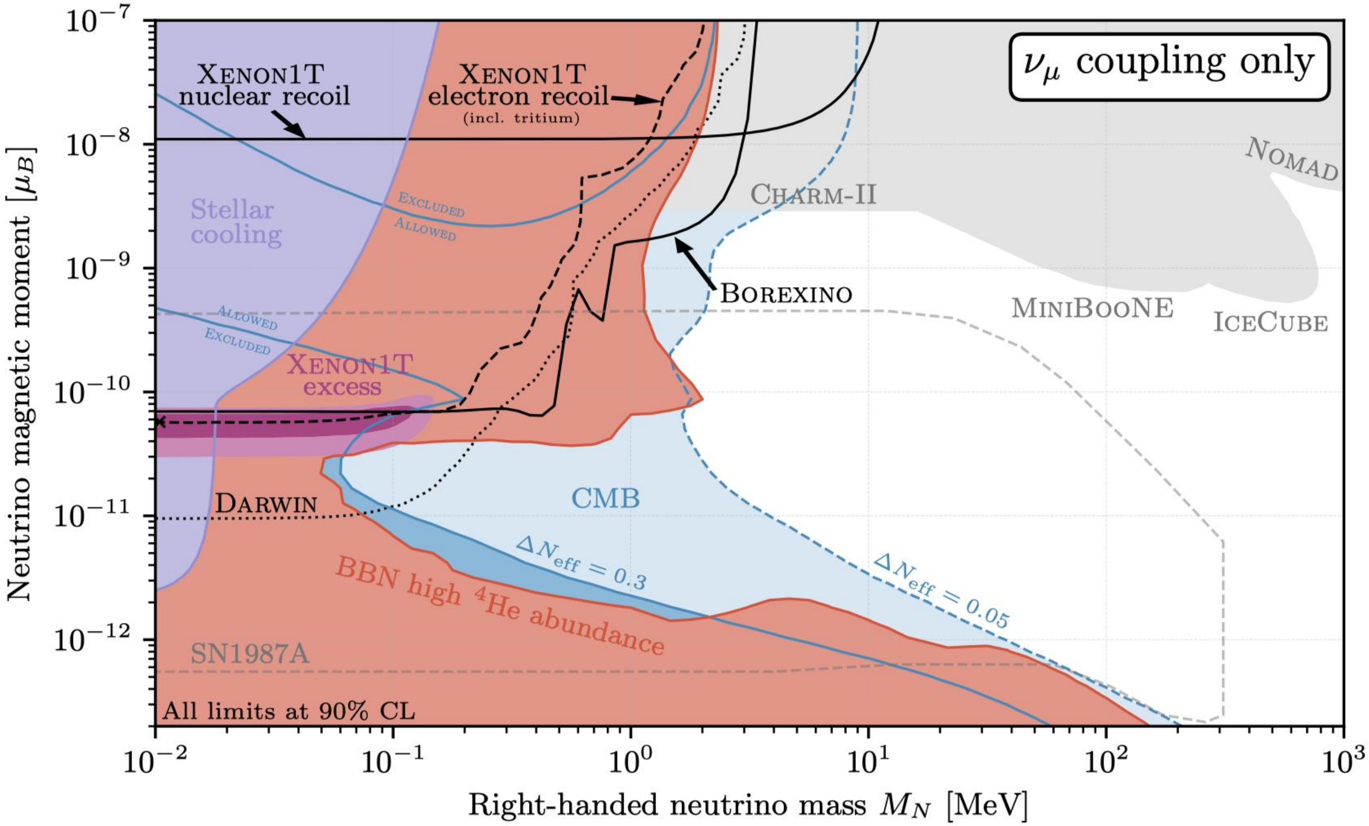


[Magill, Plestid, Pospelov, Tsai, PRD2018]

Up to 300 MeV

- Below the curve, the induced cooling effect is too weak
- Above the interaction becomes strong enough so that steriles cannot escape the collapsing core
- If the sterile is too heavy, the gravitational pull will also prevent it from leaving the supernova, leading to the vertical cut-off of the exclusion curve

Cosmology

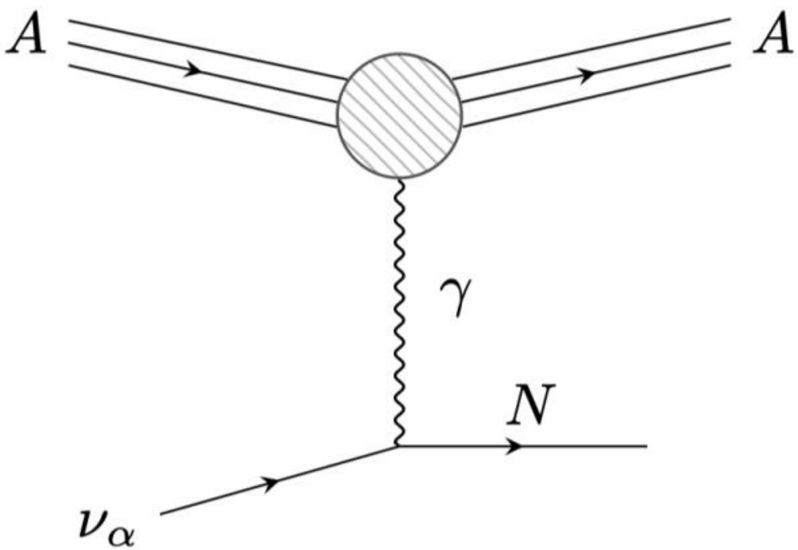


The dipole interaction alters the expansion and cooling rates of the universe, leading to a corrected neutron-to-proton ratio and baryon-to-photon ratio. The final ^{4}He abundance depends on M_N and neutrino magnetic moment (up to 200 MeV).

[Badar, Greljo, Kopp, Opferkuch, JCAP2021]

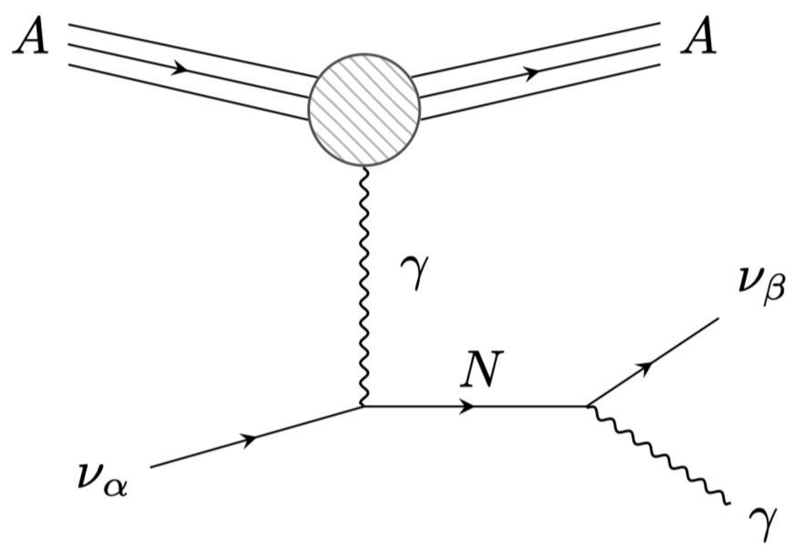
Coherent neutrino-nucleus elastic sctttering (CEvNS)

$$\frac{d\sigma_{\nu_\alpha A \to NA}}{dE_R} \approx (\mu^{\alpha}_{\nu N})^2 \alpha Z^2 \left[\frac{1}{E_R} - \frac{m_N^2}{4E_R E_\nu^2}\right]$$



Primakoff Upscattering
Signal: recoil energy
Not sensitive to Dirac vs. Majorana nature of *N*

$$\left.\frac{d\sigma^{\mathrm{D(M)}}_{\nu_\alpha A \to \nu_\beta A \gamma}}{dE_R}\right|_{\mathrm{NWA}} = \frac{d\sigma^{\mathrm{D(M)}}_{\nu_\alpha A \to N A}}{dE_R} \frac{\Gamma^{\mathrm{D(M)}}_{N \to \nu_\beta \gamma}}{\Gamma_N}$$

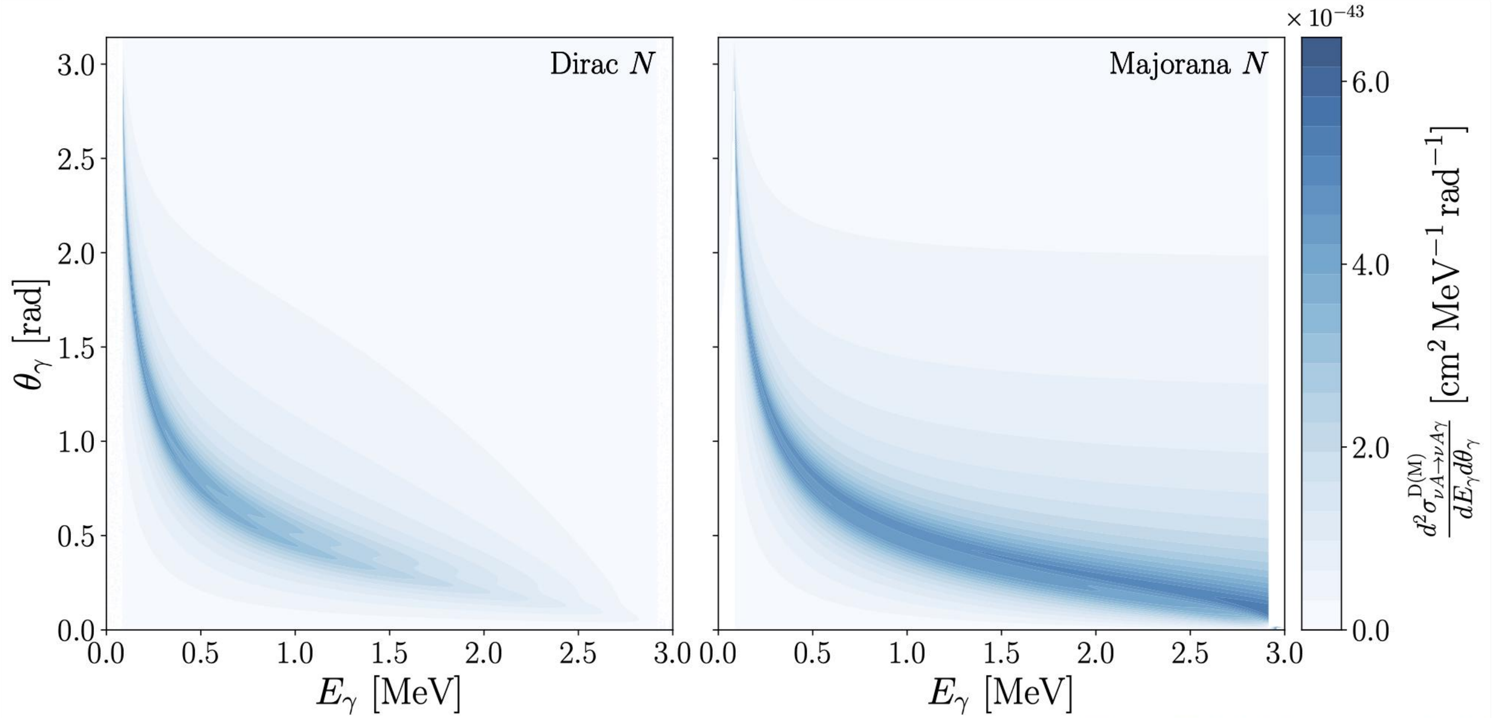


Radiative Upscattering
Signal: recoil energy plus photon
Sensitive to Dirac vs. Majorana nature of *N*

[Bolton, Deppisch, Fridell, Harz, Hati, Kulkarni, 2022PRD]

Dirac or Majorana?

$$\Gamma^{\rm M}_{N\to\nu_\beta\gamma} = 2\Gamma^{\rm D}_{N\to\nu_\beta\gamma} = \frac{(\mu^\beta_{\nu N})^2 m_N^3}{4\pi}$$



$E_\nu = 3$ MeV, $m_N = 1$ MeV

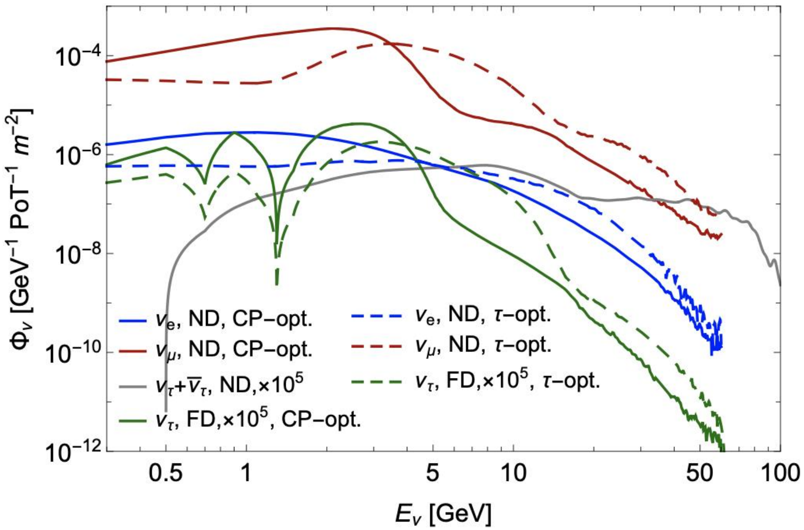
More forward emissions of high energy γ in Majorana vs. Dirac case

Clear distrinction for $E_\gamma > E_\nu/2$

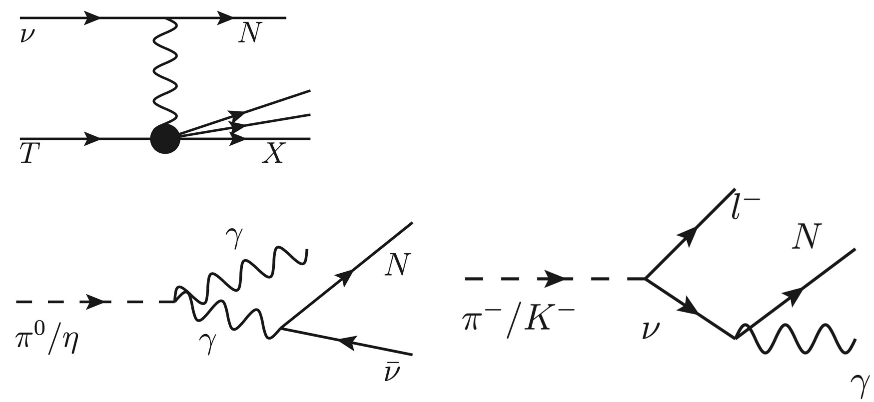
[Bolton, Invisible22] the outgoing photon energy E_γ and angle θ_γ

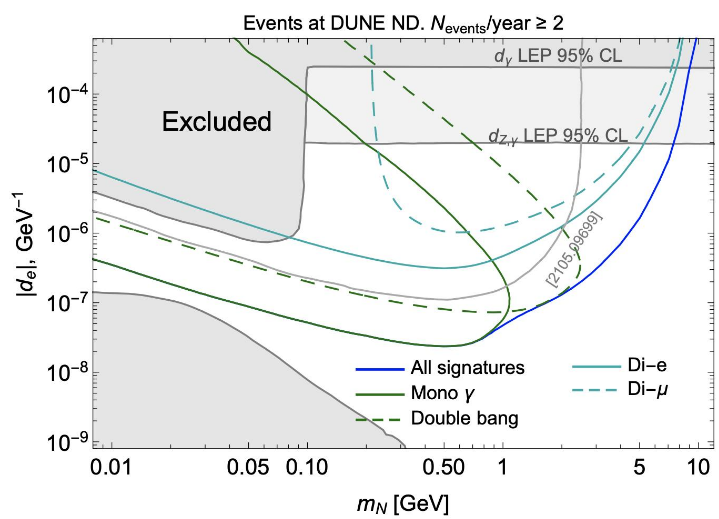
[Ovchynnikov, Schwetz, Zhu, PRD2023]

Including high-energy tail of DUNE



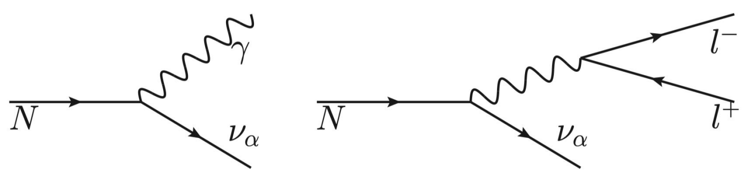
Production





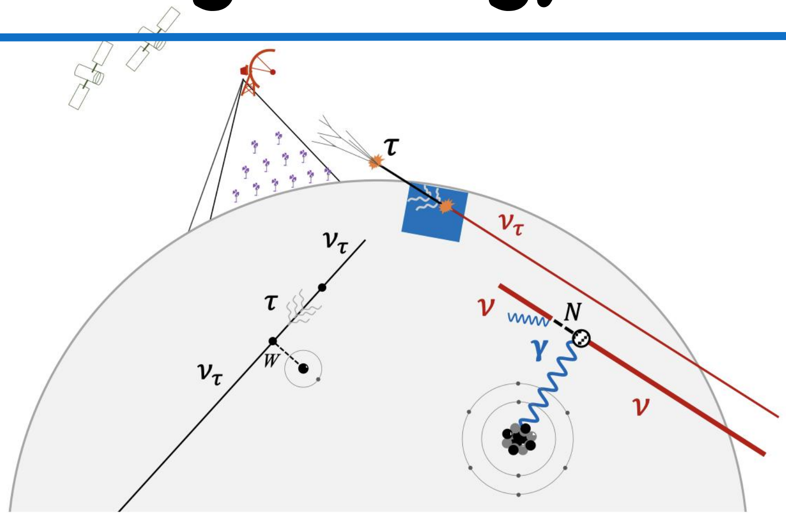
DUNE may probe masses up to O(10 GeV)

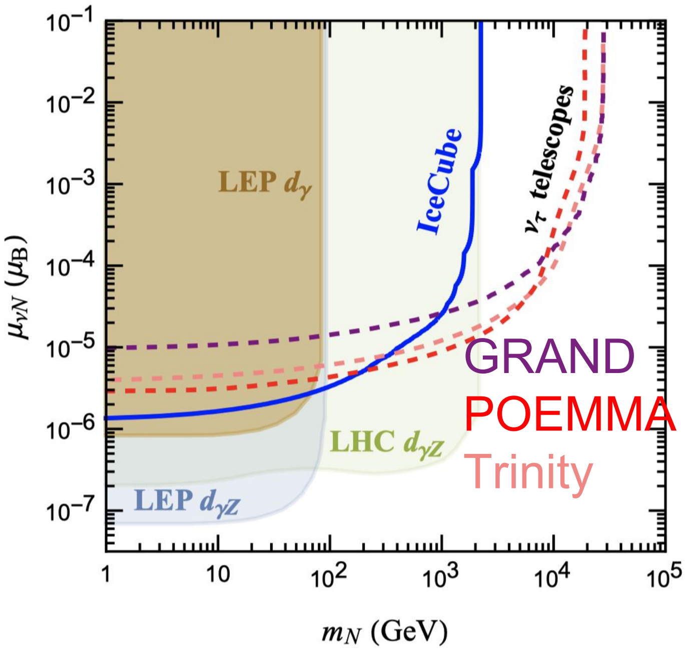
Decay



(a) Single photon
(b) Double bang
(c) Prompt di-lepton

Ultrahigh energy neutrino telescopes





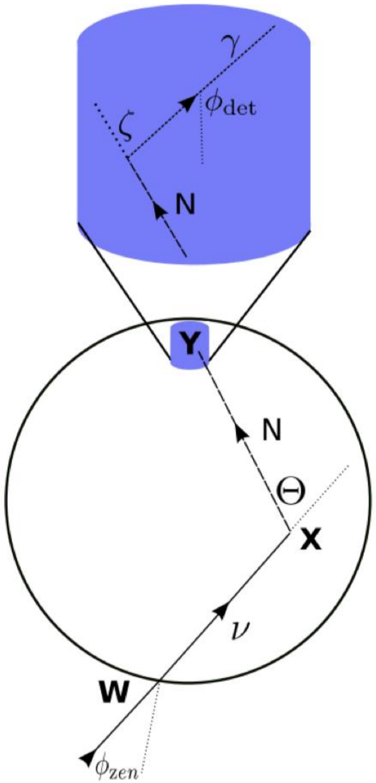
- The incoming neutrino flux can be severely affected by the conversion process before reaching the neutrino detector
- The UHE neutrinos are then detected by an in-ice volume (for all neutrino flavors), and an atmospheric radio or imaging telescope (for tau neutrinos)

1. Much heavier neutrino masses can be detected (up t0 30 TeV)

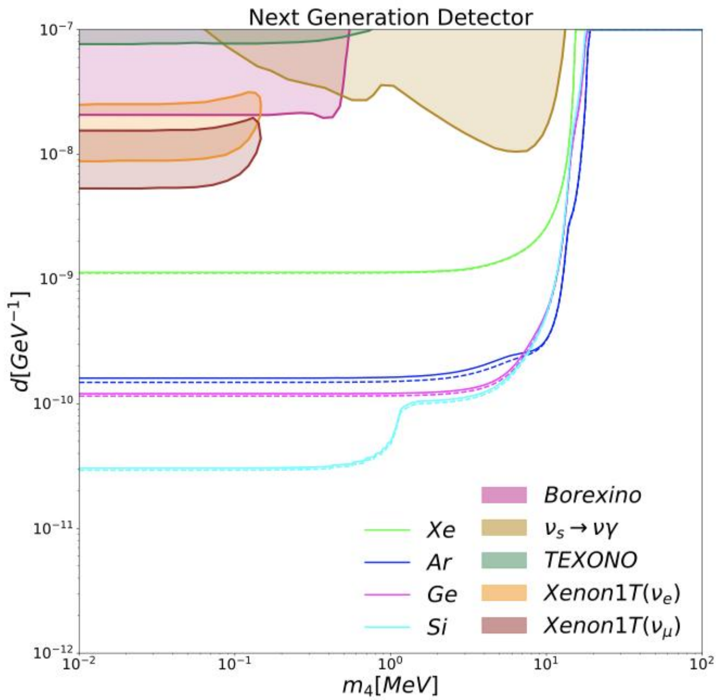
2. Depend on rare high-energy neutrino events from the universe

[Huang, Jana, Lindner, Rodejohann, PLB2023]

More...



Upscattering of atmospheric neutrinos in the interior of the Earth
[Gustafson,Plestid,Shoemaker,2205.02234]



Solar neutrinos
[Li, Xia, 2203.16525]

...
2007.05513
2010.04193
2105.09357
2108.12998
2109.05032
2109.09545
2110.02233
etc.

Sensitivities at future FCC/high-luminosity LHC

$$\mathcal{L}_{\text{dipole}} = \bar{L}(d_{\mathcal{W}} \mathcal{W}^a_{\mu\nu} \tau_a + d_B B_{\mu\nu}) \tilde{H} \sigma^{\mu\nu} N + \text{h.c.}$$

$$\mathcal{L}^{\text{eff}}_{\text{dipole}} = \bar{\nu}_{\alpha L}(d_\alpha F_{\mu\nu} - d_Z Z_{\mu\nu}) \sigma^{\mu\nu} N + d_W \bar{l}_L W_{\mu\nu} \sigma^{\mu\nu} N + \text{h.c.}$$

$$|d_Z/d_\alpha| \in (0, \cot\theta_W), \quad |d_W/d_\alpha| \in \left(0, \frac{\sqrt{2}}{\sin\theta_W}\right)$$

Experiment	N_W	N_Z
HL-LHC	$6 \cdot 10^{11}$	$1.5 \cdot 10^{11}$
FCC-hh	$1.2 \cdot 10^{13}$	$9 \cdot 10^{12}$
FCC-ee	$5 \cdot 10^{8}$	$5 \cdot 10^{12}$

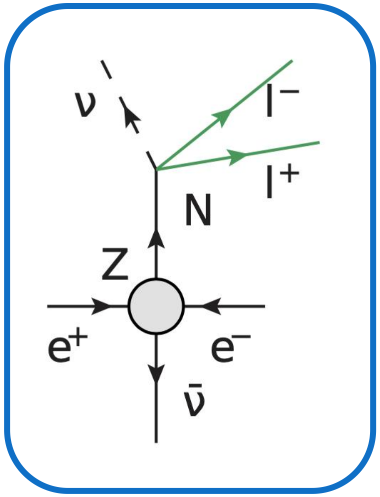
The searches at colliders prefer observing a displaced decay vertex (Single photon signal can not work well).

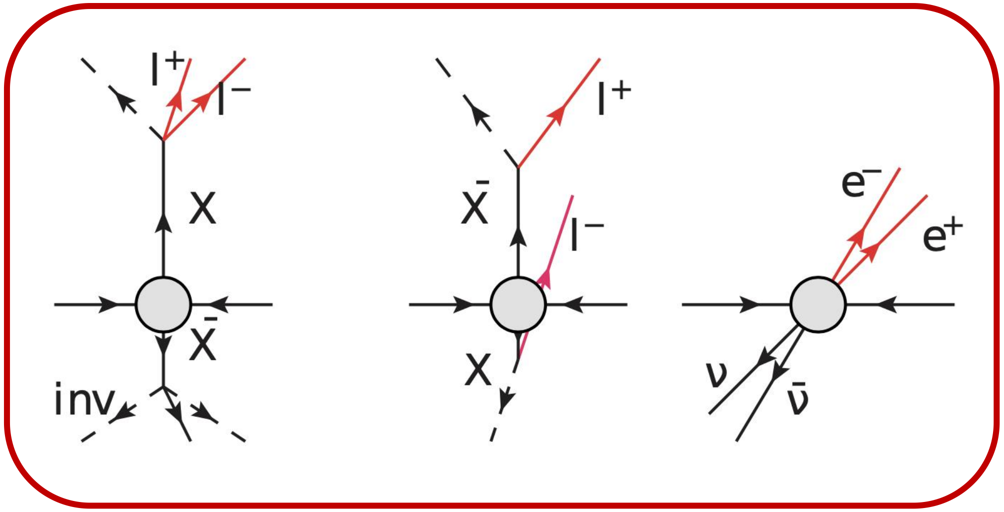
[Ovchynnikov, Zhu, JHEP2023]

Production and decay (Using displaced vertex techniques)

Lepton collider

$$e^+ + e^- \to Z, \quad Z \to N + \nu, \quad N \to l^+ + l^- + \nu$$





Hadron collider

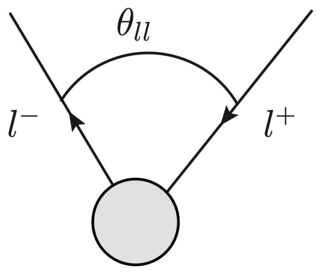
$$p + p \to W + X, \quad W \to N + l, \quad N \to l'^+ + l''^- + \nu$$

JHEP 07 (2022) 081

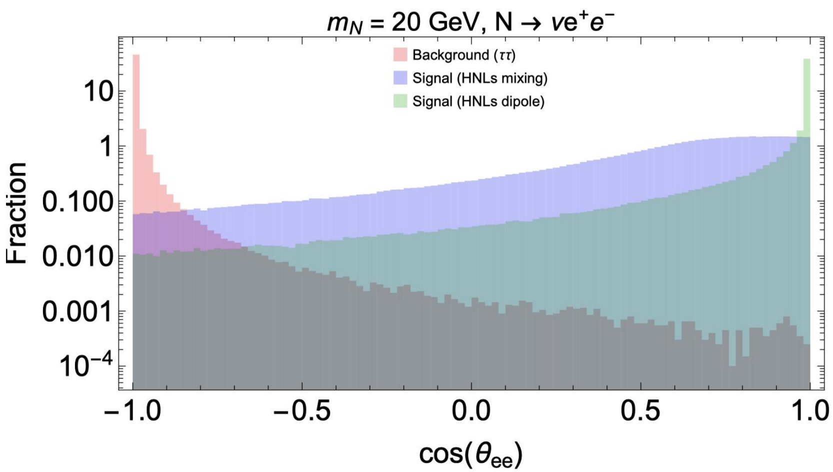
New selection rules at FCC-ee

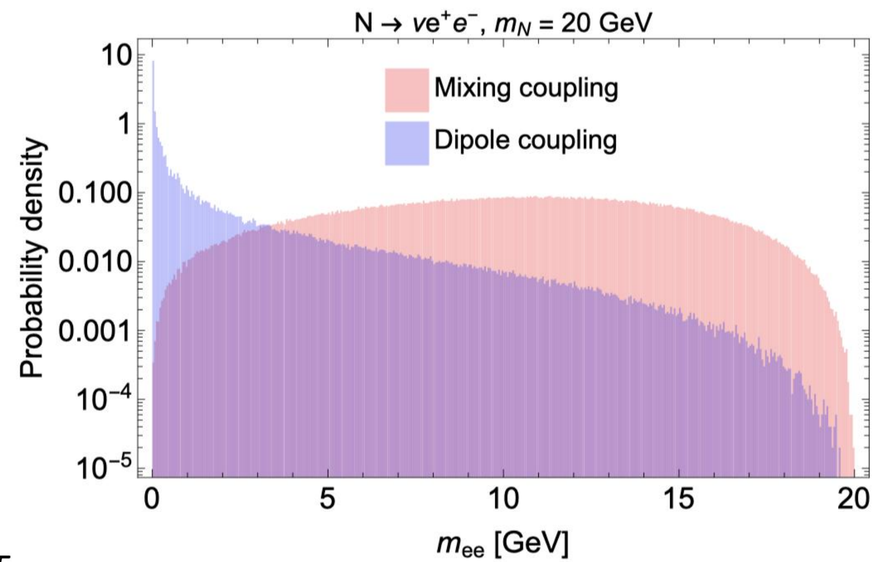
Front. in Phys. 10 (2022) 967881

$$Z \to \tau + \bar{\tau} \to e^+ + e^- + \text{inv}$$



$$\cos(\theta_{ee}) > -0.5, \quad E_{e^+} > 2\ \text{GeV}, \quad E_{e^-} > 2\ \text{GeV}$$

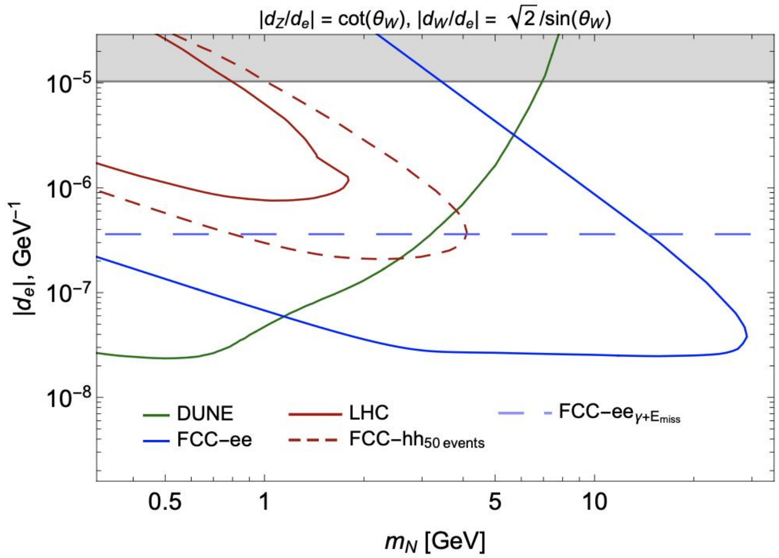


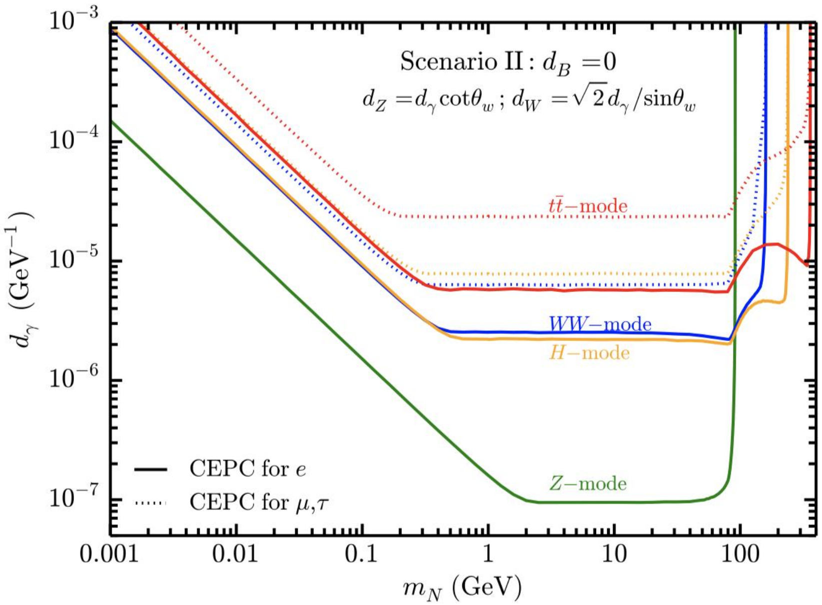


$$5 \cdot 10^9 \text{ decays } Z \to \tau\bar{\tau} \to e^+ e^- \nu_e \bar{\nu}_e \nu_\tau \bar{\nu}_\tau$$

$$m_{ee} = \sqrt{(p_{e^+} + p_{e^-})^2}$$

Results at FCC/LHC





[Zhang, Liu, PRD2023]

- Probe masses up to 30 GeV and two orders lower than current constraints
- LHC and FCC complement each other

Comparable sensitivities with FCC-ee in the case of CEPC

Yu Zhang's talk later at 18th

Summary and outlook

- Various ways to constrain/search for the dipole portal signals
- Big new parameter space which can be probed through future experiments
- For heavier neutrinos will be complementally detected at colliders and neutrino telescopes
- Next step and more general: Dipole + mixing

Thank you for your attention!