Heavy Neutral Lepton on Future Muon Collider and Beamdump Experiment

Kunfeng Lyu

University of Minnesota

2301.07117, *JHEP* **03 (2023) 231** Peiran Li, Zhen Liu, **KFL**

2306.07315, *JHEP* **08 (2023) 169**

Yohei Ema, Zhen Liu, **KFL**,Maxim Pospelov

CETUP* 2024 Jul 10, 2024

Outline

- Neutrino Mass
- Heavy Neutral Leptons
- HNL at Muon Collider
- HNL at LSND and Future PIP2-BD
- Conclusion

Origin of Neutrino Mass

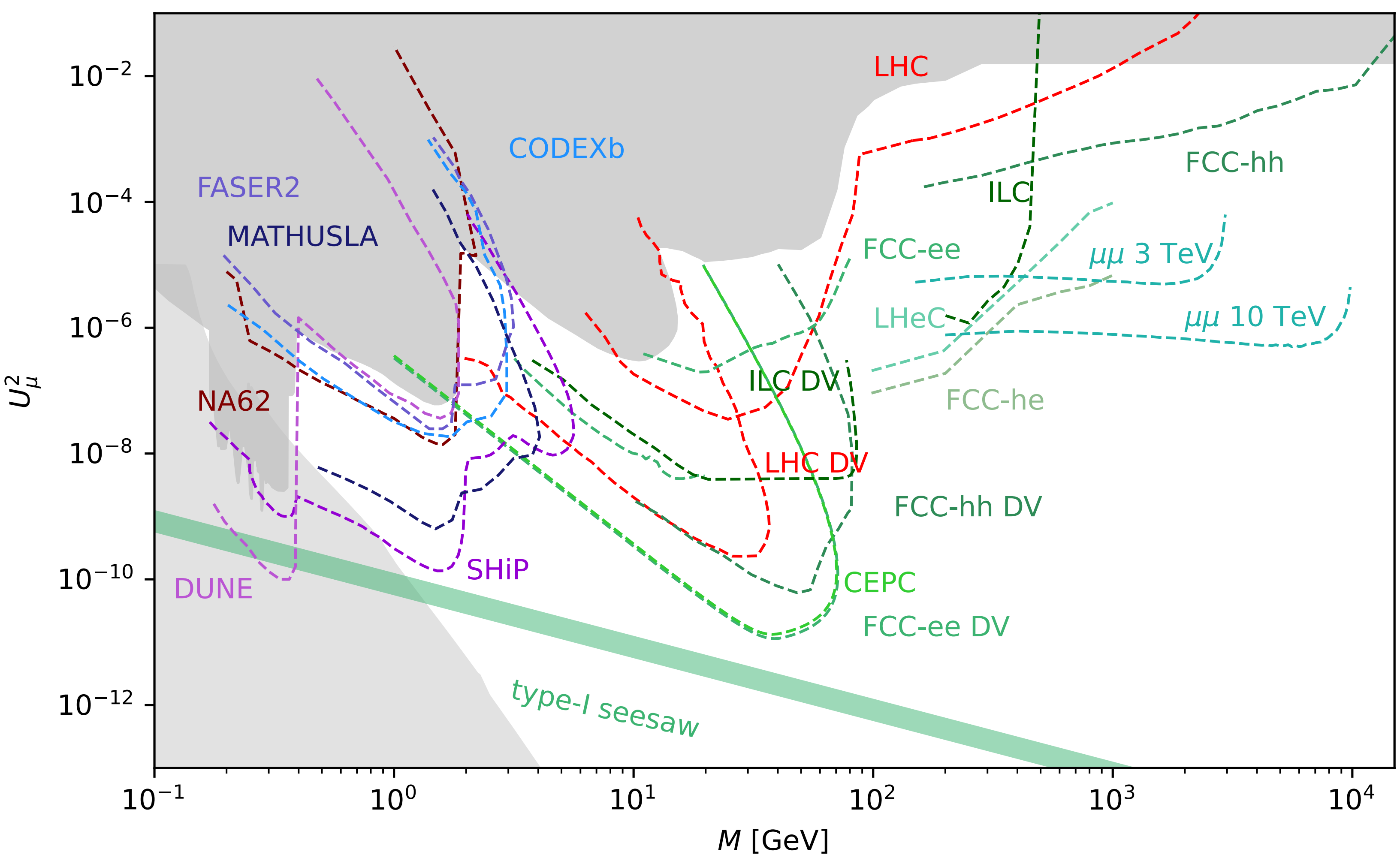
- In SM, neutrino is massless. While the experiments have confirmed its tiny mass smaller than O(0.1) eV.
- Effective Operator: Weinberg Operator $\frac{LLHH}{\Lambda}$
- Seesaw mechanism
  - Simple Type I
  - Inverse seesaw model
  - Linear seesaw model
- We choose to work in a simple scenario. Suppose there is heavy neutral lepton. We can parametrize its mass m_N
  mixing angle with SM neutrino. $U_l = \sin\theta_l$

$$\mathcal{L} = \mathcal{L}_W + \mathcal{L}_Z + \mathcal{L}_H$$

$$\mathcal{L}_W = \frac{gU_l}{\sqrt{2}} \left(W_\mu \bar{l}_L \gamma^\mu N + h.c.\right)$$

$$\mathcal{L}_Z = -\frac{gU_l}{2\cos\theta_w} Z_\mu \left(\bar{\nu}_L \gamma^\mu N + \bar{N}\gamma^\mu \bar{\nu}_L\right)$$

$$\mathcal{L}_H = -\frac{U_l m_N}{v} h \left(\bar{\nu}_L N + \bar{N}\nu_L\right)$$


LHC
CODEXb
FASER2
MATHUSLA
ILC
FCC-hh
FCC-ee
$\mu\mu$ 3 TeV
LHeC
$\mu\mu$ 10 TeV
ILC DV
NA62
FCC-he
LHC DV
FCC-hh DV
SHiP
DUNE
CEPC
FCC-ee DV
type-I seesaw
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
U_μ^2
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
M [GeV]

Short Review of Various Probes

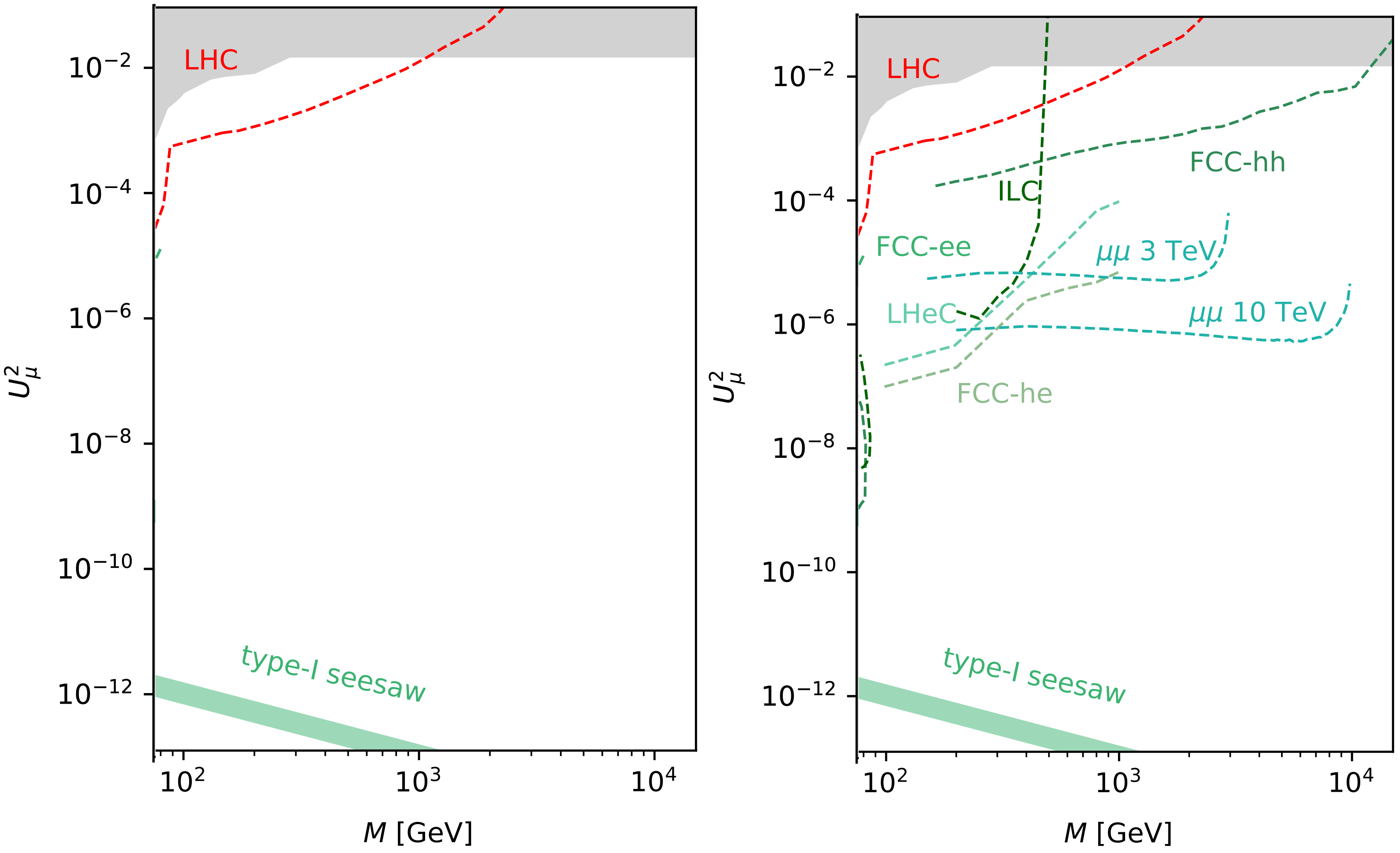
- People have tried to constrain in the $U_\ell^2 - m_N$ plane via various channels and different machines.
- Cosmo and astrophysical probe: BBN, CMB, etc
- Indirect constraints: branching ratio of SM particles decays, etc
- Direct constraints
  - Production
    - Meson decay, heavy lepton decay
    - (On-shell/Off-shell) Gauge/higgs boson decay
  - Decay
    - Short-lived
    - Long-lived

HNL at Muon Collider

$$m_N > O(100)\mathrm{GeV}$$

$$\Gamma_N \sim G_F m_N^3 |U_\ell|^2$$

Prompt decay



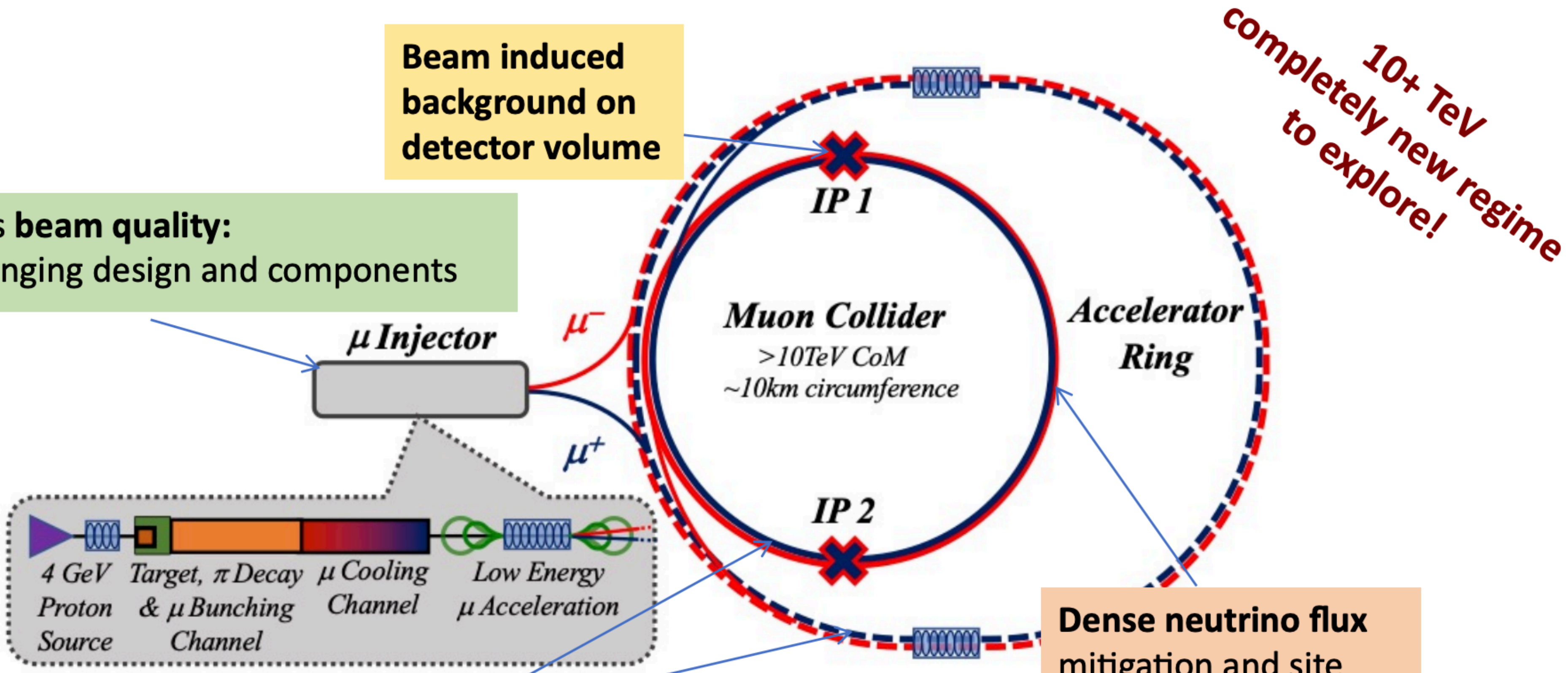
The muon collider can open and probe new region space in the parameter space. even compared to other future colliders!

Snowmass Energy Frontier Report: 2211.11084

Muon Collider

Beam induced background on detector volume

Drives **beam quality:** challenging design and components



Dense neutrino flux mitigation and site

Cost and **power** consumption drivers, limit energy reach
e.g. 30 km accelerator for 10/14 TeV, 10/14 km collider ring

arxiv: 2209.01318

Search at Muon Collider

- The future muon collider includes 3 TeV and 10 TeV scenarios.
- Clean background, fixed cms energy, excellent environment for the muon flavor HNL
- Here we show the muon-flavor Dirac HNL as benchmark.

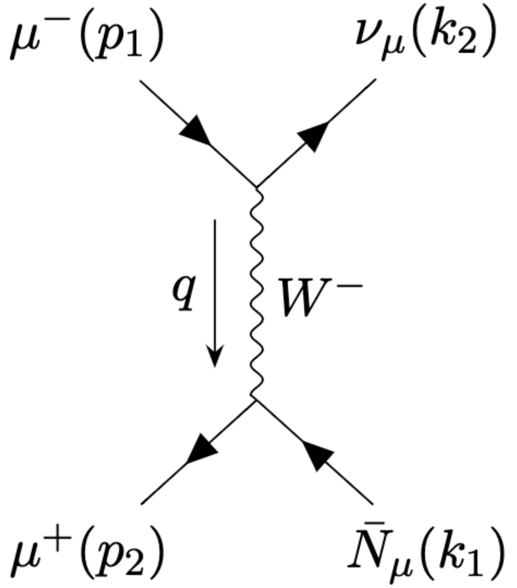
- Tools:

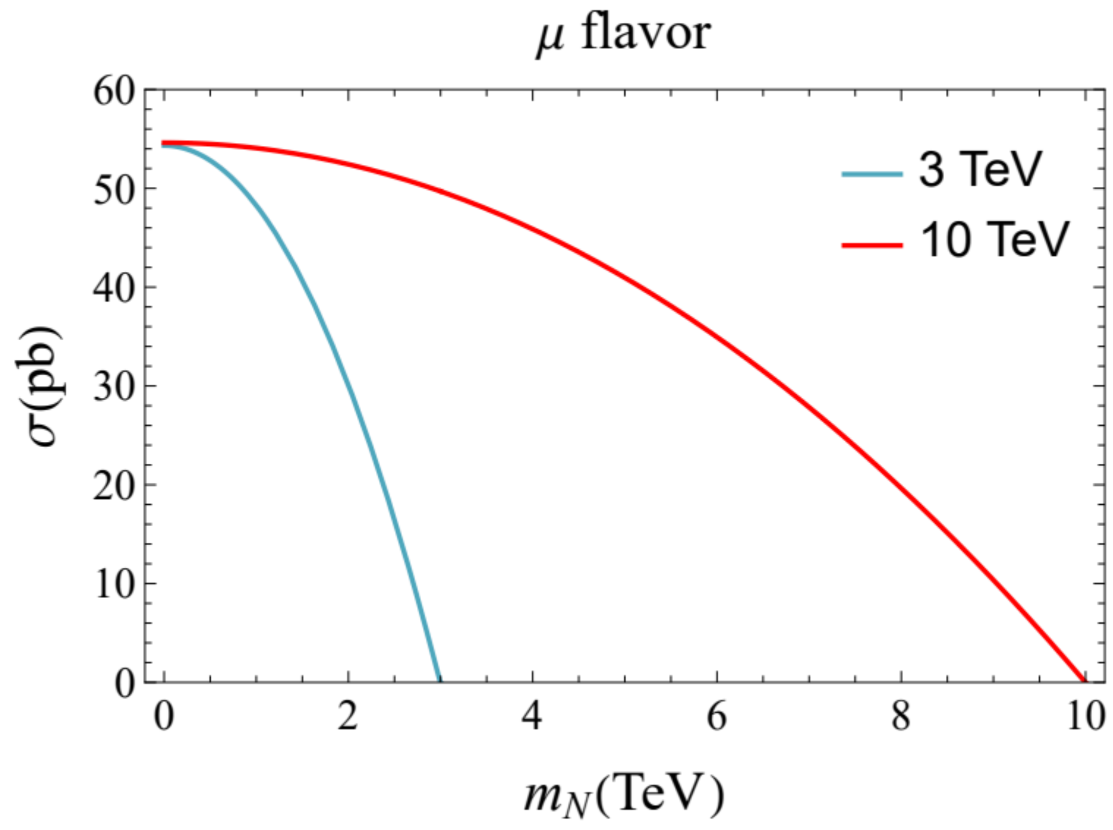
  Using MadGraph 3.4 to simulate and then make analysis
- Effective Vector-Boson Approximation (EVA) or gauge boson PDF has been implemented

Muon Flavor

- Signal: Production of N_μ
  Dominated by the t-channel

$$\mu^+ + \mu^- \to N_\mu + \bar{\nu}_\mu$$





Type	Signal process	$\sigma/\lvert U_\mu\rvert^2$ (w. conj. channel) $m_N = 1$ TeV
t-channel	$\mu^+\mu^- \longrightarrow N_\mu\bar{\nu}_\mu$	20.28 pb
VBF	$\mu^+\mu^- \longrightarrow \mu^+\mu^- N_\mu\bar{\nu}_\mu$	~ 1 pb
VBF	$\mu^+\mu^- \longrightarrow \bar{\nu}_\mu\nu_\mu N_\mu\bar{\nu}_\mu$	~ 0.1 pb

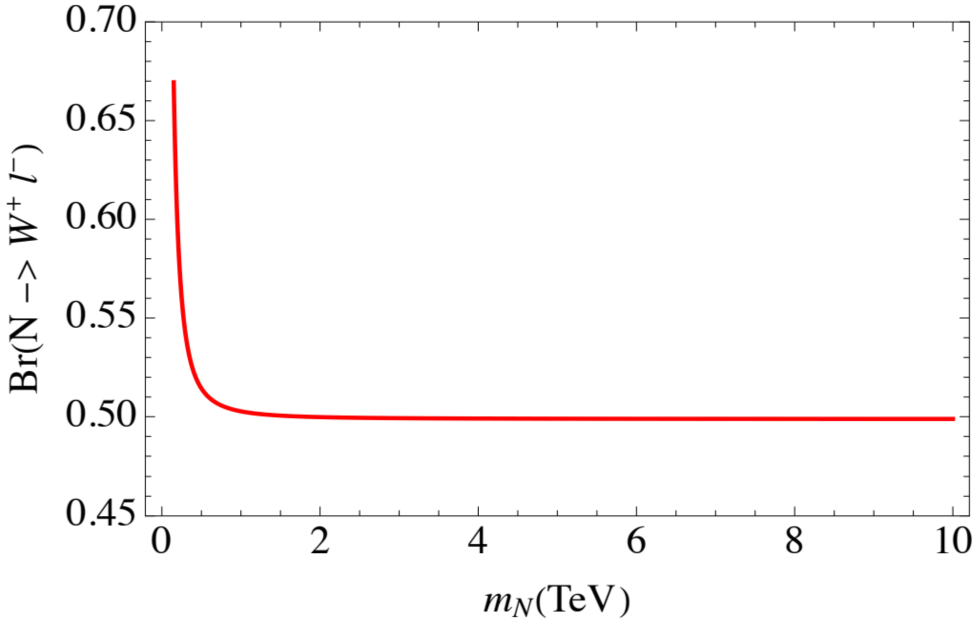
Decay of N_μ

HNL can promptly decay via neutral current or charged current or to the higgs. Here we select its decay channel to W boson.

Goldstone-Boson Equivalence Theorem

$$N_\mu \to W^+ + \mu^-$$
$$N_\mu \to Z + \nu_\mu$$
$$N_\mu \to H + \nu_\mu$$

$$\Gamma_N \sim G_F m_N^3 |U_\ell|^2$$



$$N_\mu \to W^+ + \mu^-, W^+ \to jj$$

We assume the W boson can be well reconstructed from the two jets.

We focus on the final states W^+ and μ^- and reconstruct its invariant mass distribution.

10TeV Background

Dijets can be from either W or Z boson.

Type	Background process	σ (w. conj. channel)	Pre-selection cut (PSC)	Included
t-channel	$\mu^+\mu^- \longrightarrow W^+\mu^-\bar{\nu}_\mu$	0.214 pb	PSC	Yes
t-channel	$\mu^+\mu^- \longrightarrow Z\mu^+\mu^-$	0.464 pb	PSC & missing μ^+	Yes
VBF	$\mu^+\mu^- \longrightarrow \mu^+\mu^-W^+\mu^-\bar{\nu}_\mu$	0.401 pb	PSC & missing $\mu^+\mu^-$	Yes
VBF	$\mu^+\mu^- \longrightarrow \bar{\nu}_\mu\nu_\mu W^+\mu^-\bar{\nu}_\mu$	0.0686 pb	PSC	No

Table 4. N_μ background at 10 TeV. The cross section includes the charge conjugate process.

Using EVA in MadGraph, especially photon PDF
VBF processes dominates at 10 TeV

Default cut:
For muon:
PT > 20GeV,
Eta < 2.5

Using EVA will lead to t-channel singularity.
So we just generate 2 -> 5 processes directly in MadGraph.

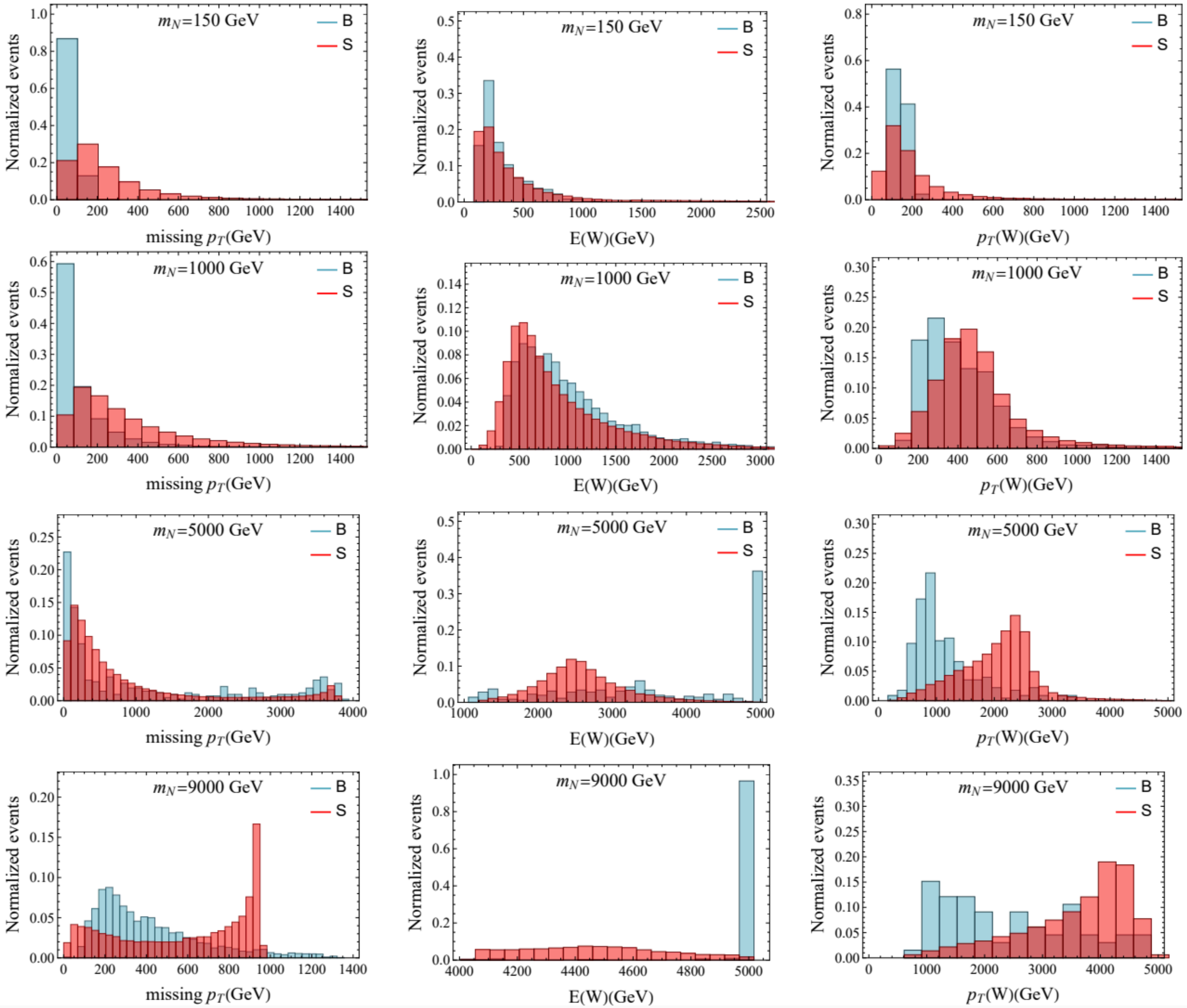
Cutflow Analysis

- Pre-selection: require single visible charged lepton
  - $|\eta(\mu)| < 2.5$ and $p_T(\mu) > 20\ \mathrm{GeV}$

- Central hadronic W selection: require visible on-shell W boson
  - $|\eta(W)| < 2.5$ and $p_T(W) > 20\ \mathrm{GeV}$

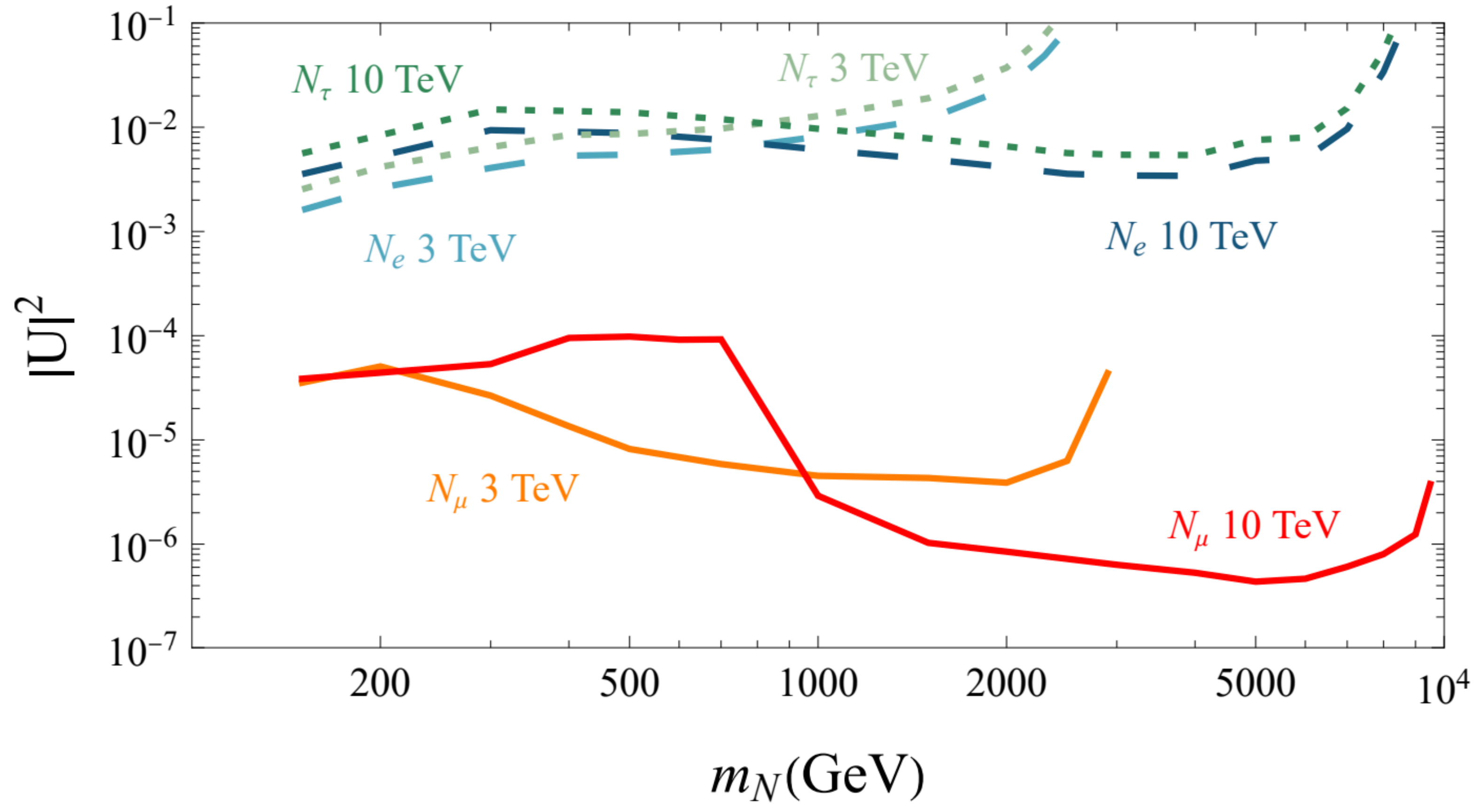
- Mass window: reconstructed mass $m_{W\mu}$ within $m_N \pm 5\% m_N$

- Optimization cuts:
  - Customized cut on missing p_T, $E(W)$, $p_T(W)$ for each m_N benchmark


m_N=150 GeV
m_N=1000 GeV
m_N=5000 GeV
m_N=9000 GeV
B
S
Normalized events
missing p_T(GeV)
E(W)(GeV)
p_T(W)(GeV)

Process	Central W	Mass window 150/1000/5000/9000 GeV	Optimization
Background	34.19%	1.2/0.63/0.023/0.134%	0.16/0.22/0.011/0.0032%
$m_N = 150$ GeV	83.84%	83.84%	66.63%
$m_N = 1000$ GeV	93.67%	93.67%	80.55%
$m_N = 5000$ GeV	99.01%	99.01%	89.69%
$m_N = 9000$ GeV	99.48%	99.48%	87.53%

Projected sensitivity



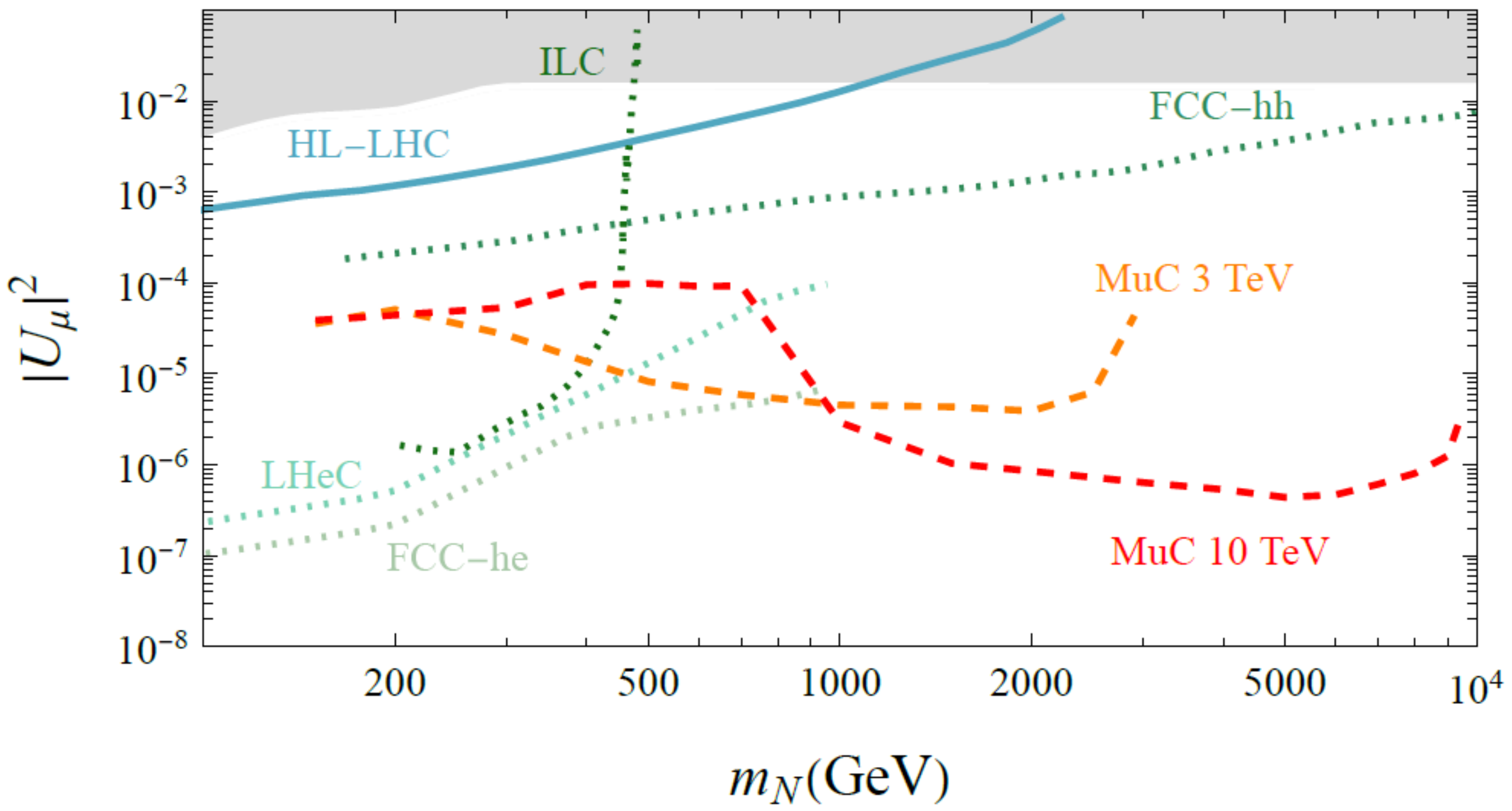
The 95% projected sensitivity of $|U_e|^2, |U_\mu|^2$ and $|U_\tau|^2$ as a function of HNL mass mN at 3 and 10 TeV muon collider.

Sensitivity to e and τ flavor is moderate

Muon Collider features the strong direct probe of the μ flavored HNL

10 TeV muon collider can probe the $|U_\mu|^2$ to a few 10^{-7} for TeV scale HNLs.

The VBF background increases for high energy muon colliders and renders the 3 TeV muon collider competitive in sub TeV scale.



Heavy neutral leptons at muon colliders
PL, Z. Liu, K. Lyu, arXiv:2301.07117

T.H. Kwok, L. Li, T. Liu and A. Rock, arXiv:2301.05177
K. Mekała, J. Reuter and A.F. Zarnecki, arXiv:2301.02602

HNL at LSND and Future PIP2-BD

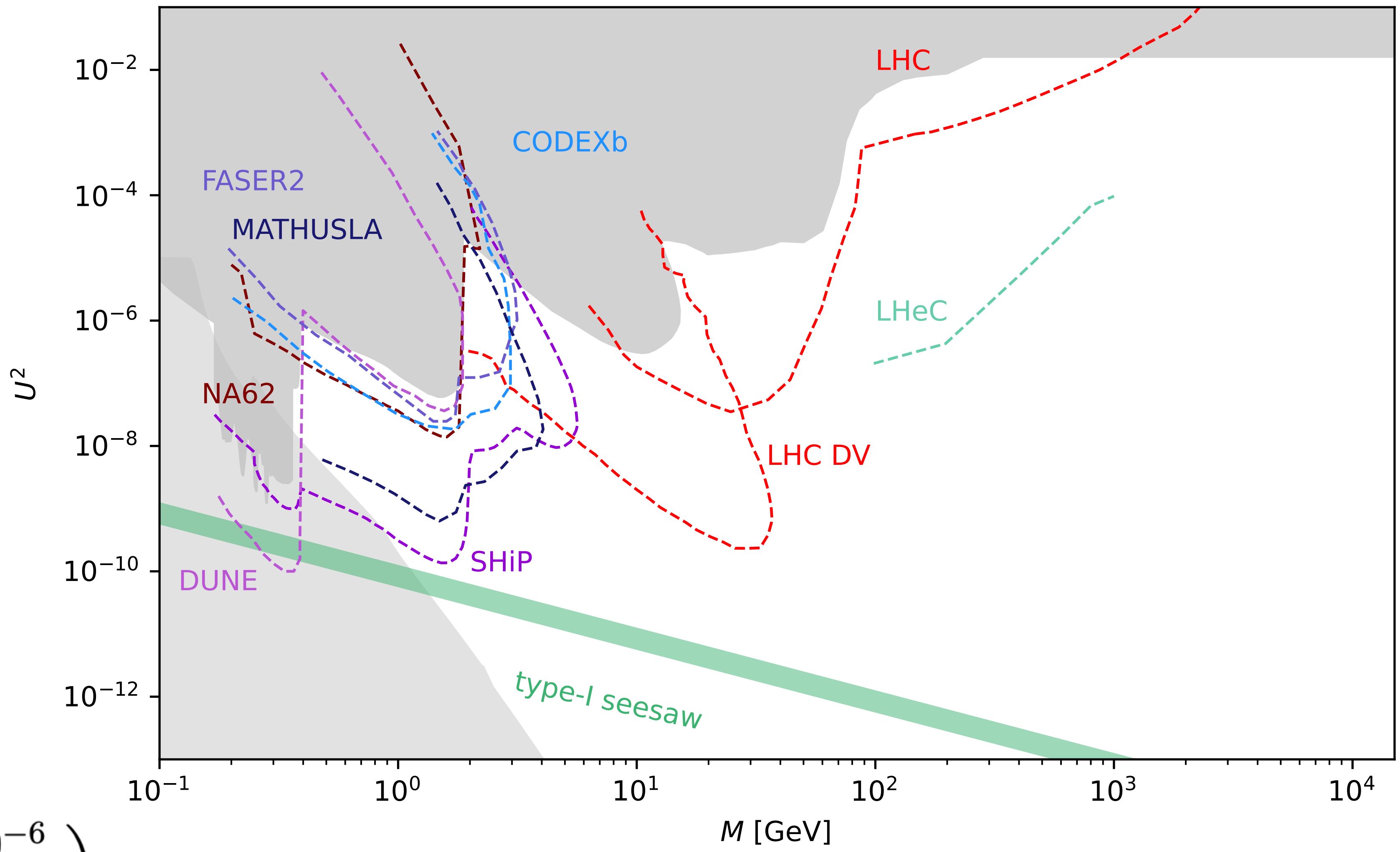
Various Bounds

Some future proposed beam-dump experiments or far detector to probe the long-lived HNL

Low mass region, three body decay

$$\Gamma_N \sim G_F^2 m_N^5 |U_\ell|^2$$

$$c\tau_N \sim 10^8\,\mathrm{m} \times \left(\frac{m_\mu}{m_N}\right)^5 \left(\frac{10^{-6}}{|U_{lN}|^2}\right)$$

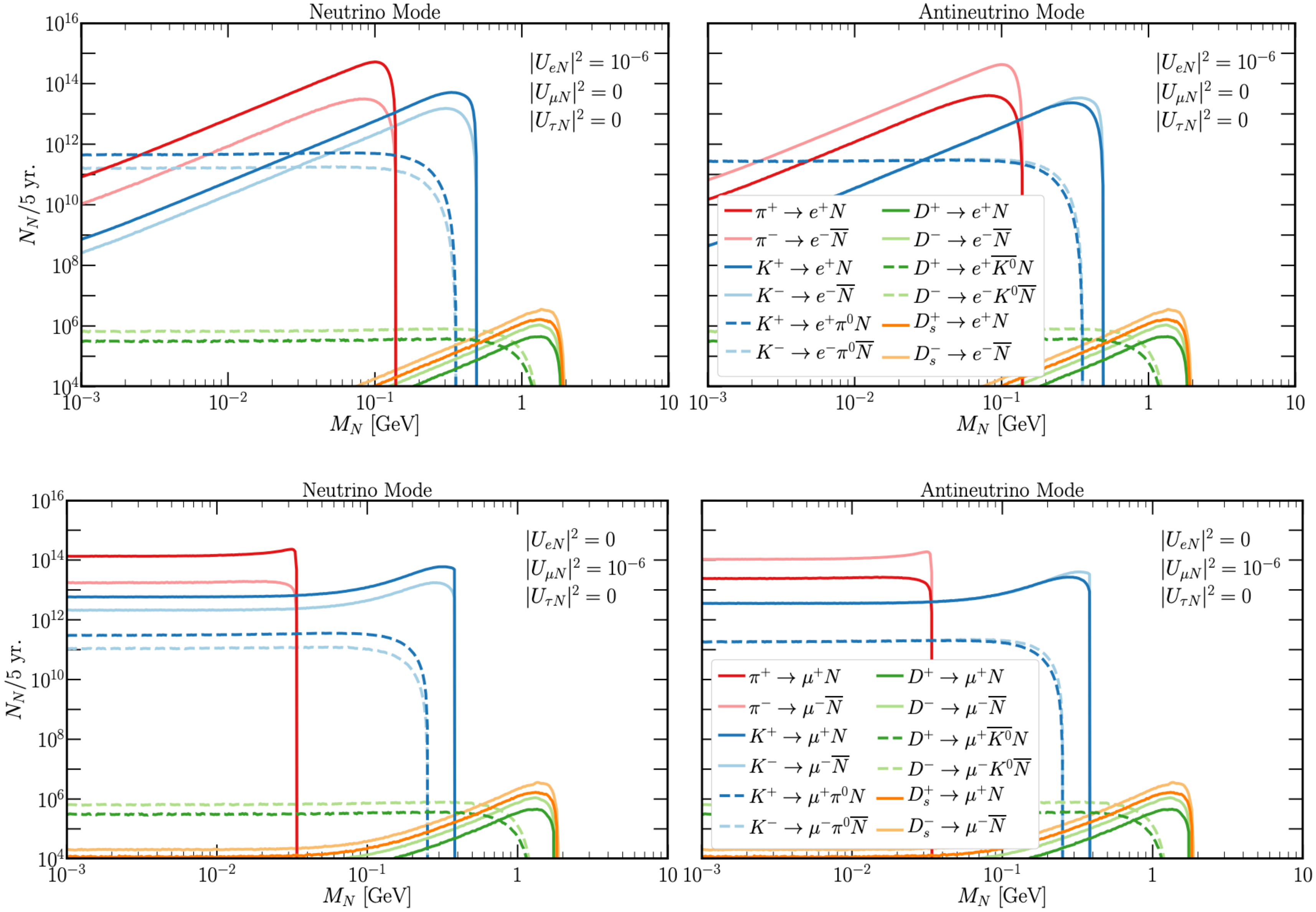


Fixed-Target: LSND

- Fixed-target experiment provides a good platform to search for feebly interacting GeV-scale particles.
- Light HNL with tiny mixing angle can be long-lived.
- It can travel for long distance before decaying. Thus it can leave imprints at the far detector.
- We are interested in the case $m_N < m_\pi$ and recast on the old LSND as well as future PIP2-BD experiment.
- First let me review the HNL search at DUNE.

Probing HNL at Dune

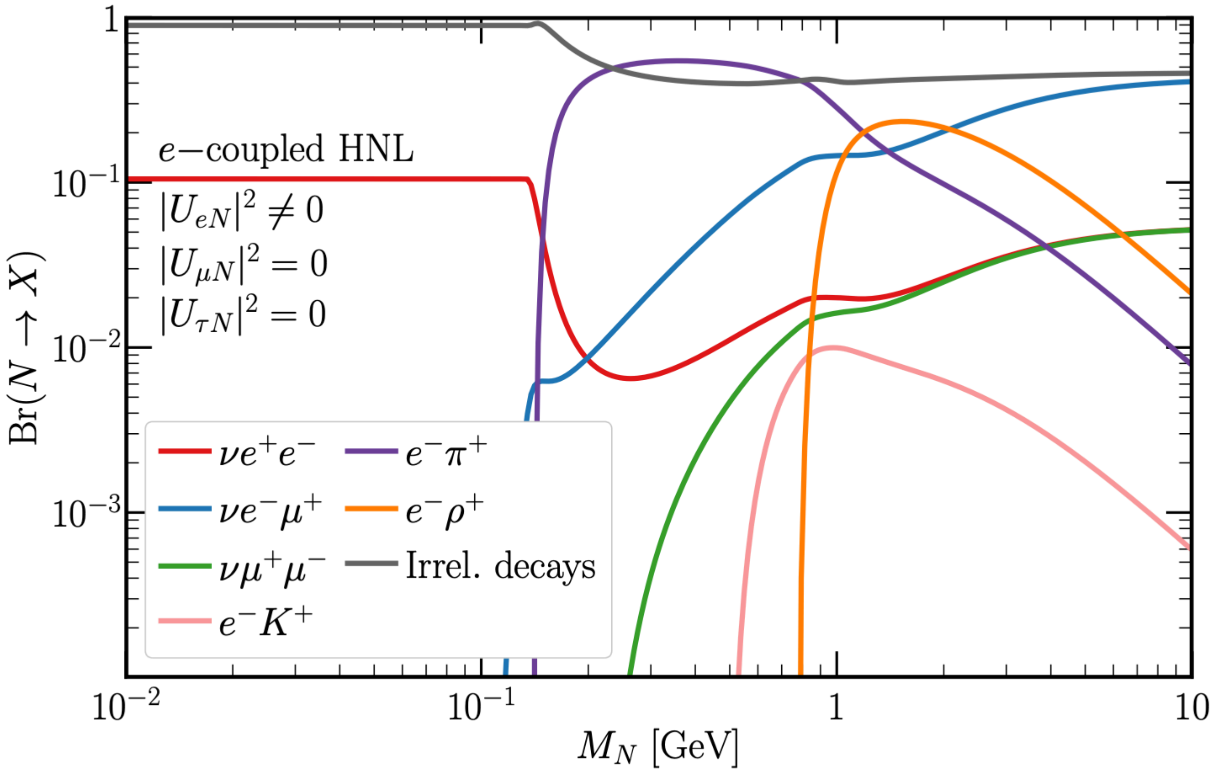
Production modes for the e flavor traveling toward the DUNE MPD



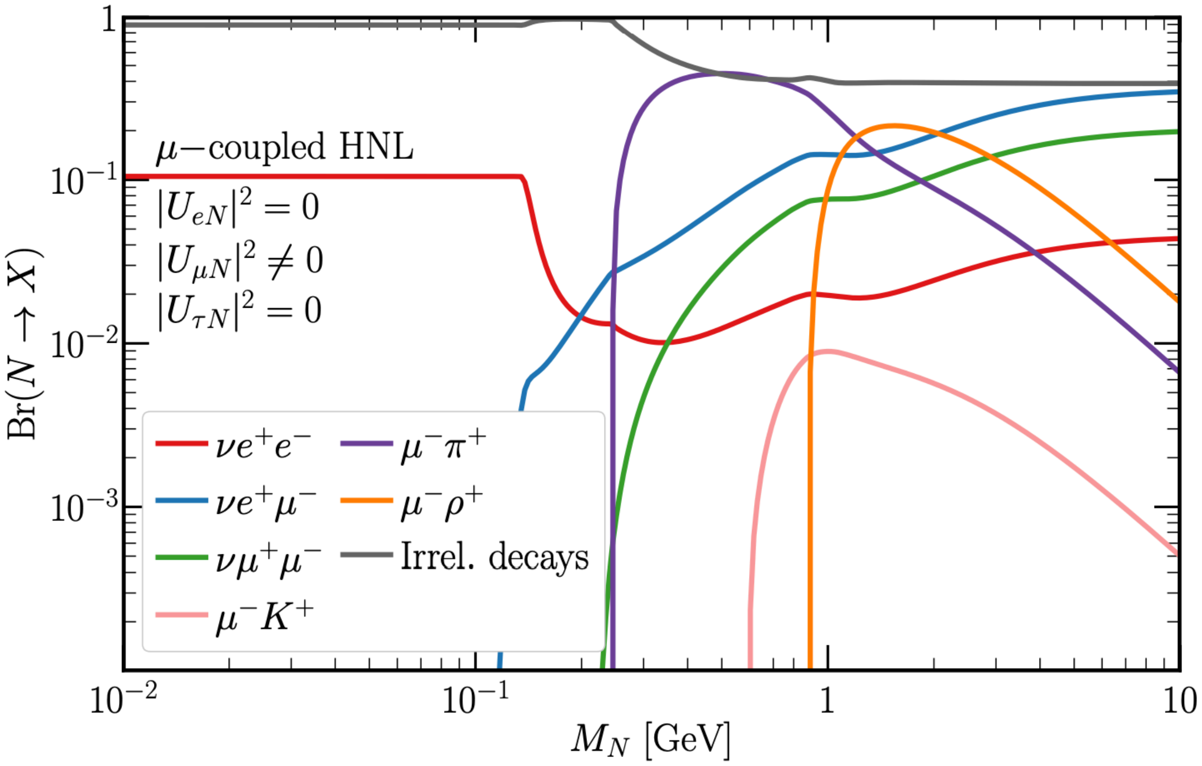
1912.07622 Berryman etc

Decay Mode

e flavor



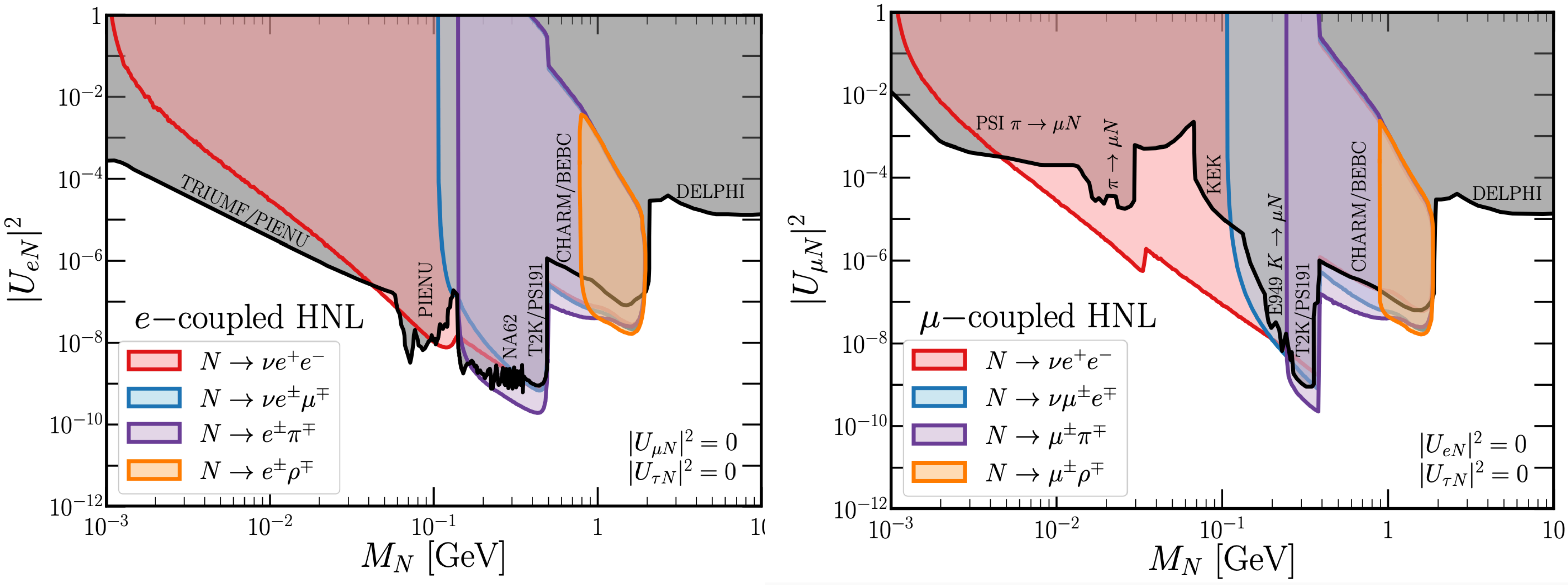
mu flavor



Irrel. Decays: background dominated

1912.07622 Berryman etc

Projected Sensitivity at DUNE

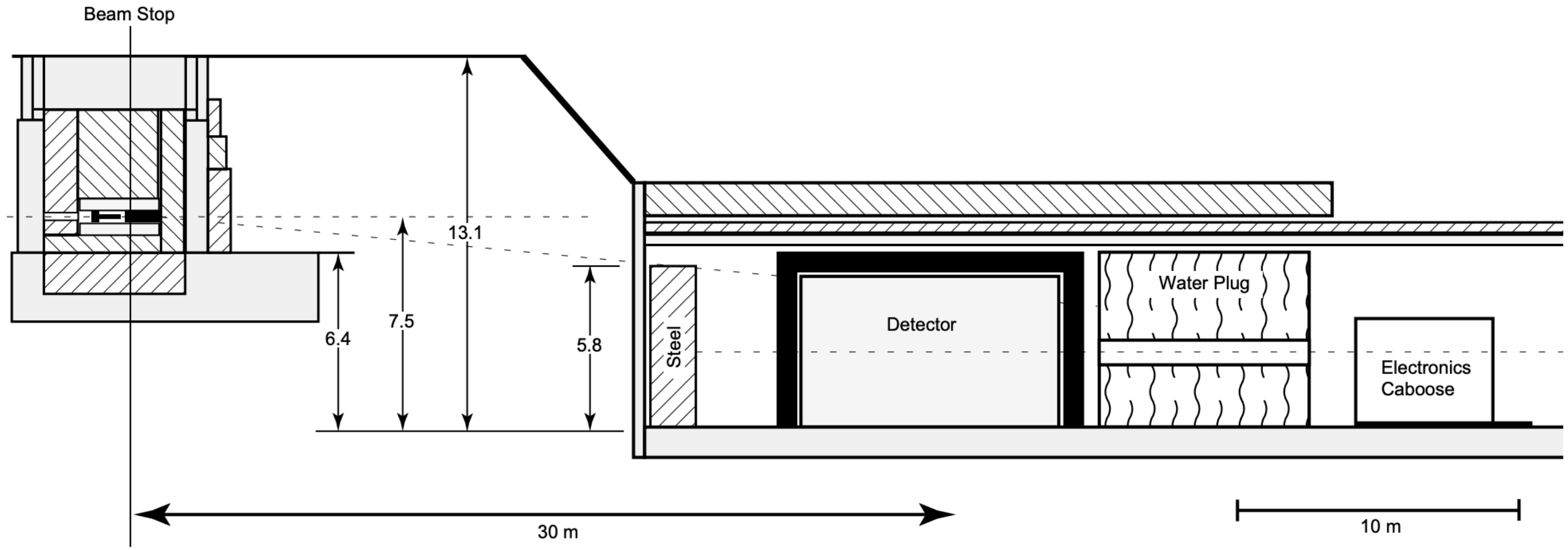


Liquid Scintillator Neutrino Detector (LSND) Experiment

HNL produced
at the target

Decay at flight

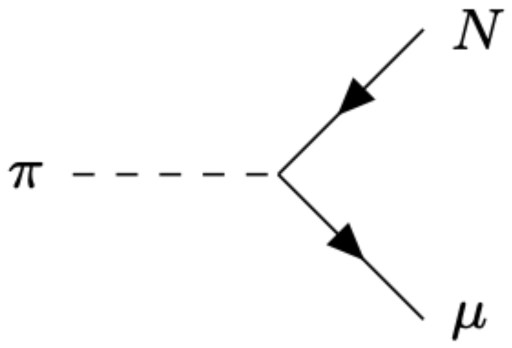
798 MeV proton beam

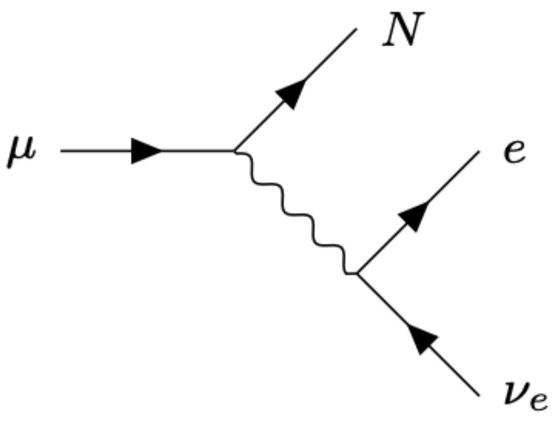


Leave imprints at detector

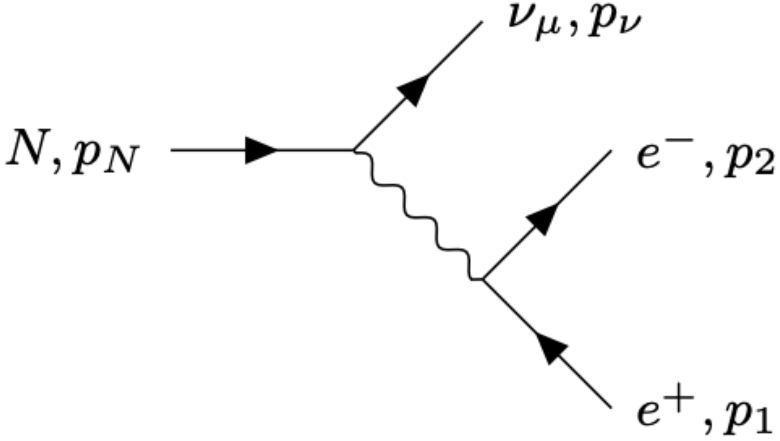
Production: Muon and Pion Decay at Rest

- At LSND, the neutrino arise from the decay at rest (DAR) of stopped π^+ and μ^+.





Decay of N_μ



Three body decay

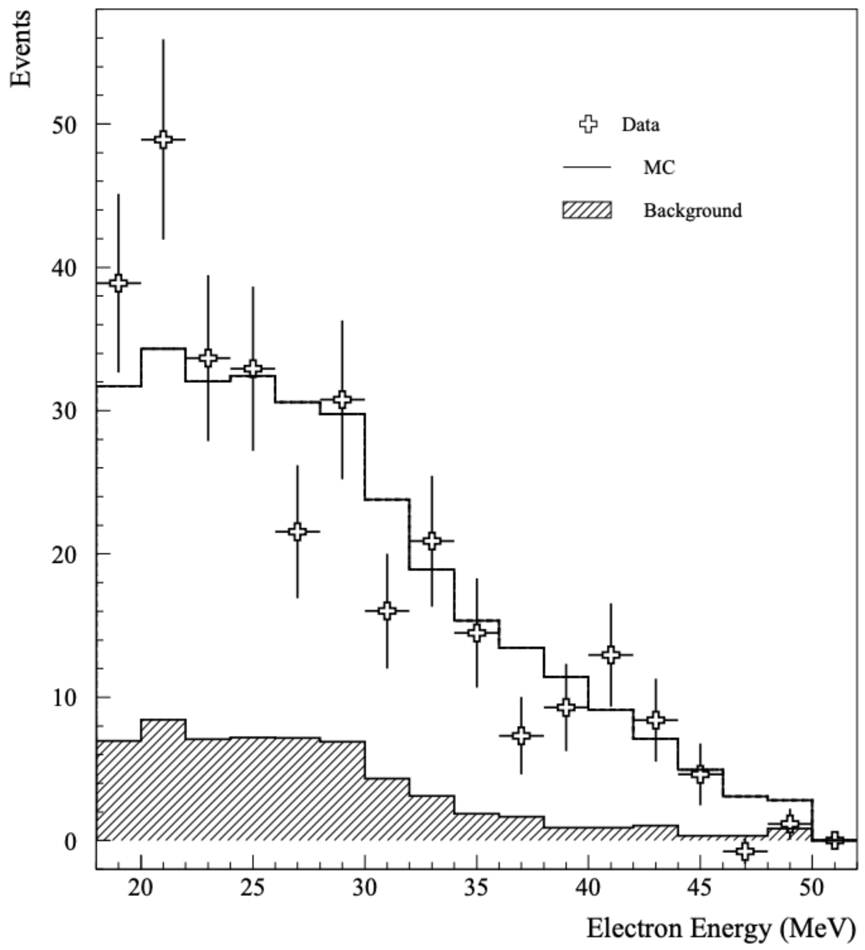
$$\Gamma_N \sim G_F^2 m_N^5 |U_\ell|^2$$

$$c\tau_N \sim 10^8\,\mathrm{m} \times \left(\frac{m_\mu}{m_N}\right)^5 \left(\frac{10^{-6}}{|U_{lN}|^2}\right)$$

$$\exp\left(-\frac{D}{\gamma c\tau}\right)\left[1 - \exp\left(-\frac{L_{\mathrm{det}}}{\gamma c\tau}\right)\right]$$

Signal at the detector: $e^+ \, e^-$ pair

$$N_{ee}^{(i)} = N_i \times \epsilon_{\mathrm{det}} \times \frac{1}{\Gamma_i} \int dE_N \frac{d\Gamma(i \to fN)}{dE_N} \times \frac{L_{\mathrm{det}}}{\gamma\beta c\tau_{N\to ee\nu}}$$



$$\text{cut 1}: \ 18\,\text{MeV} < E_{\pm} < 50\,\text{MeV}, \ E_{\mp} < E_{\rm th}, \ \cos\theta_{\pm} > 0.9, \ \cos\theta_{\mp} < 0.9,$$

$$\text{cut 2}: \ 18\,\text{MeV} < E_{+} + E_{-} < 50\,\text{MeV}, \ \cos\theta_{\pm} > 0.9.$$

The LSND experiment observed in total 242 single e events (including all the ν_e ν_μ and $\bar{\nu}_\mu$ initiated signals) while 229 events are expected within the SM.

With the systematic error included, we impose at 90% C.L.

$N = N(\mu) \times \varepsilon(\mu) + N(\pi) \times \varepsilon(\pi) < 55.$

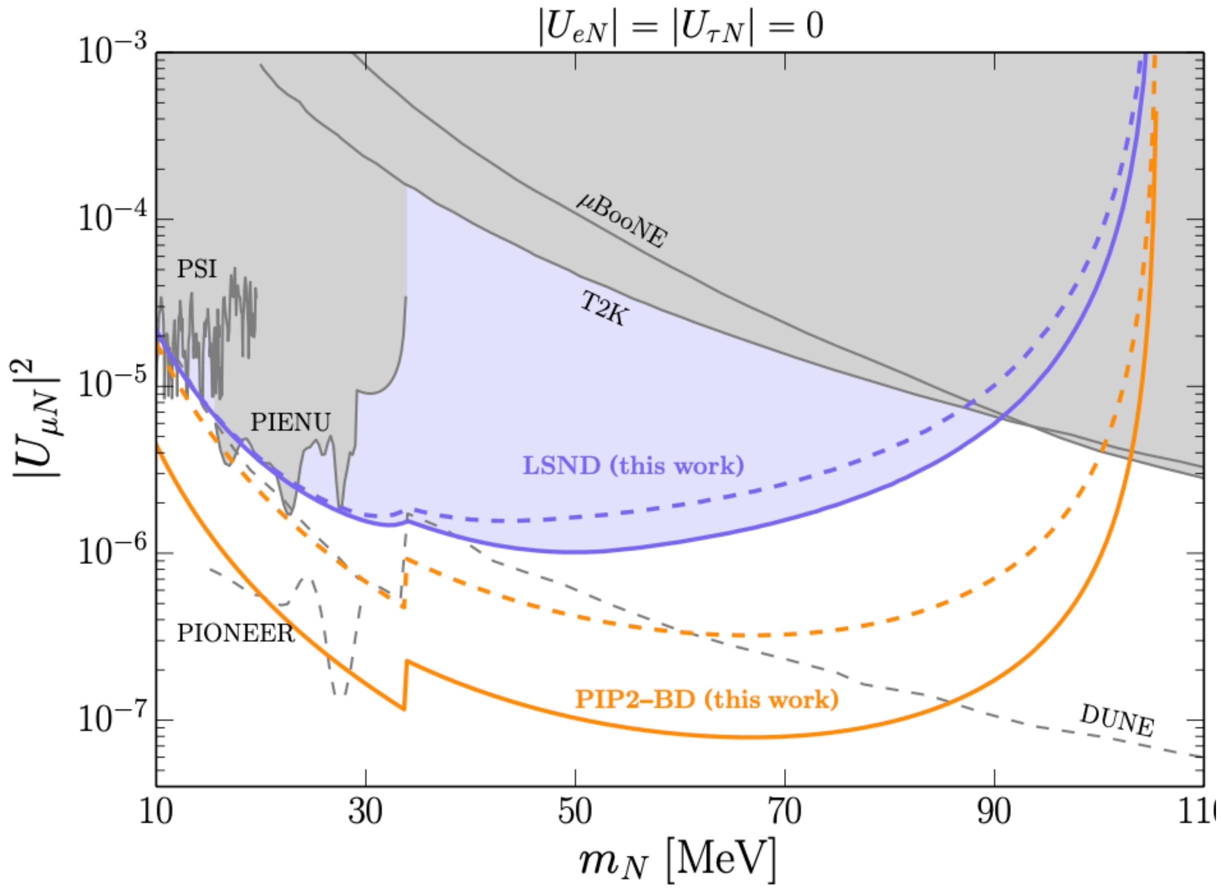
PIP2-BD

- Proton Improvement Project II (PIP-II) is a major upgrade of the accelerator complex at Fermilab to meet the requirement of hosting the Deep Underground Neutrino Experiment (DUNE).
- We may assume five years of physics run with the baseline PAR option, which results in an 800 MeV proton beam with $1.2\times\mathbf{10^{23}}$ POT. Considering the formation rate

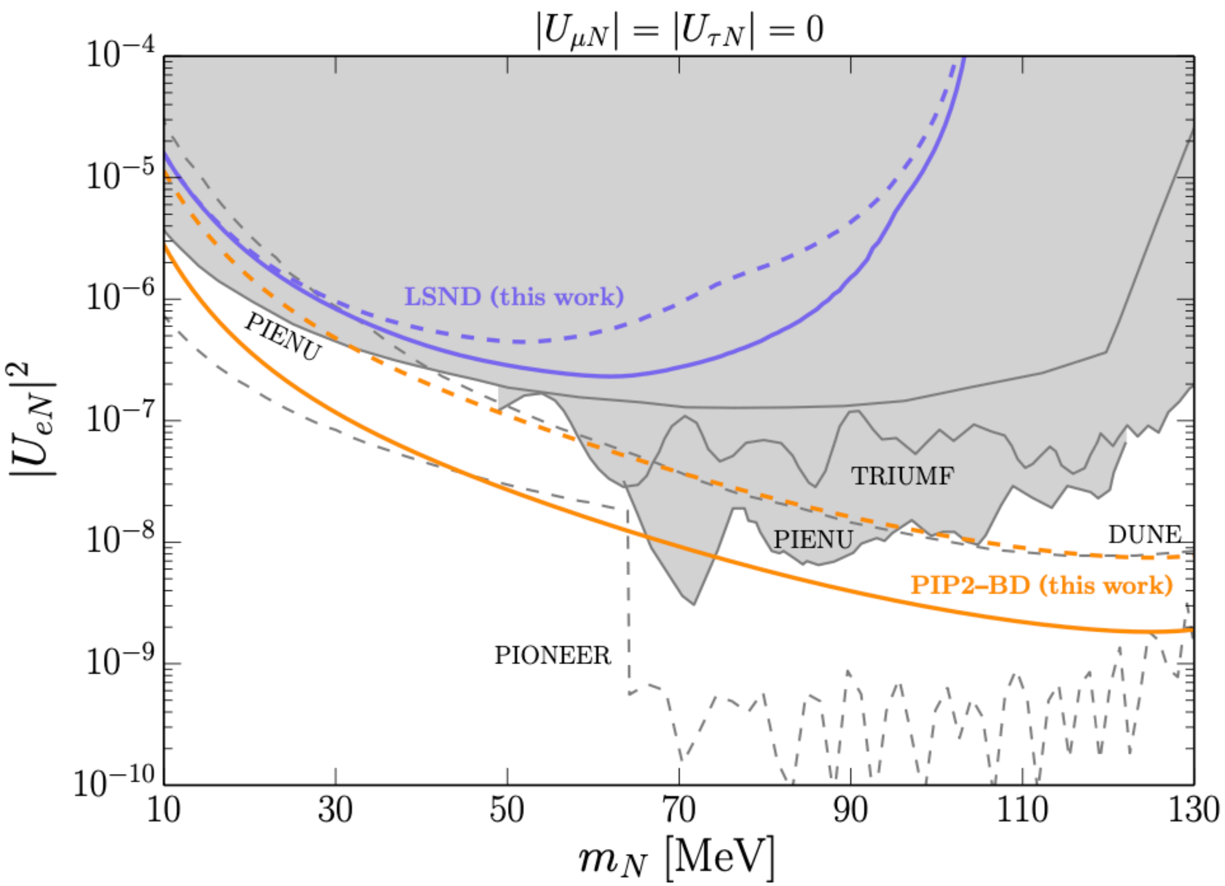
$$N_\pi = N_\mu = 1.2 \times 10^{22}$$

- Detector is in cylindrical in shape with 4.5m in height and 4.5m in diameter, located 18m away from the HNL production point.

mu flavor



e flavor



Conclusion

- We focus on two mass range for the HNL.
- Muon Collider is a good platform to probe the TeV scale HNL.

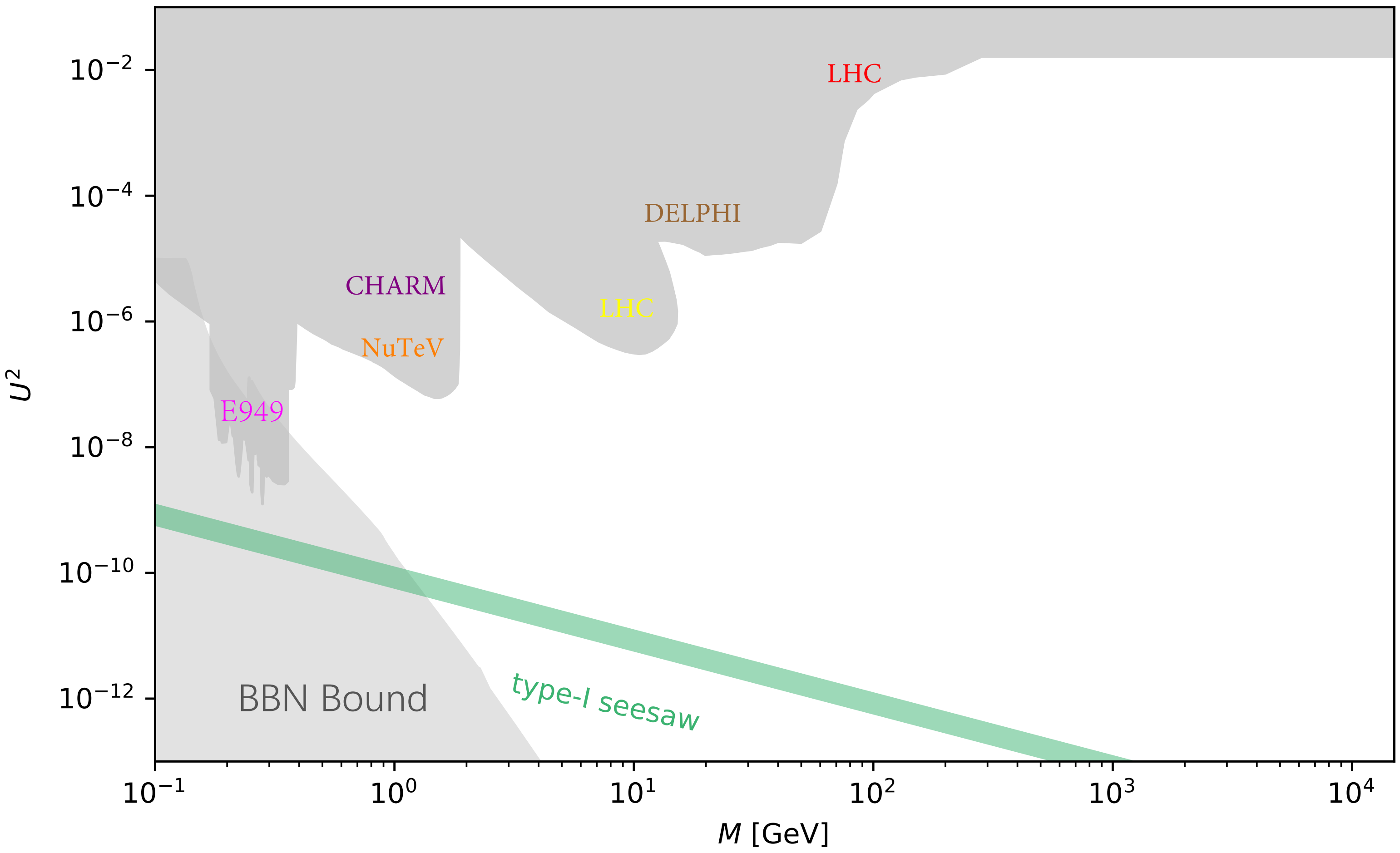
  We can open a new region in the parameter space.

  For the muon flavor case, we can probe the $|U_{\mu}|^2$ down to $\mathbf{10^{-7}}$.
- For the lighter HNL, we revisit LSND and make projections on future PIP2-BD. The sensitivity can be improved a lot.
- There are more interesting phenomena in the HNL sector.

Existing Bounds

Snowmass Energy Frontier Report: 2211.11084

From Past Experiments



NuTeV: Drell-Yan, HNL decay

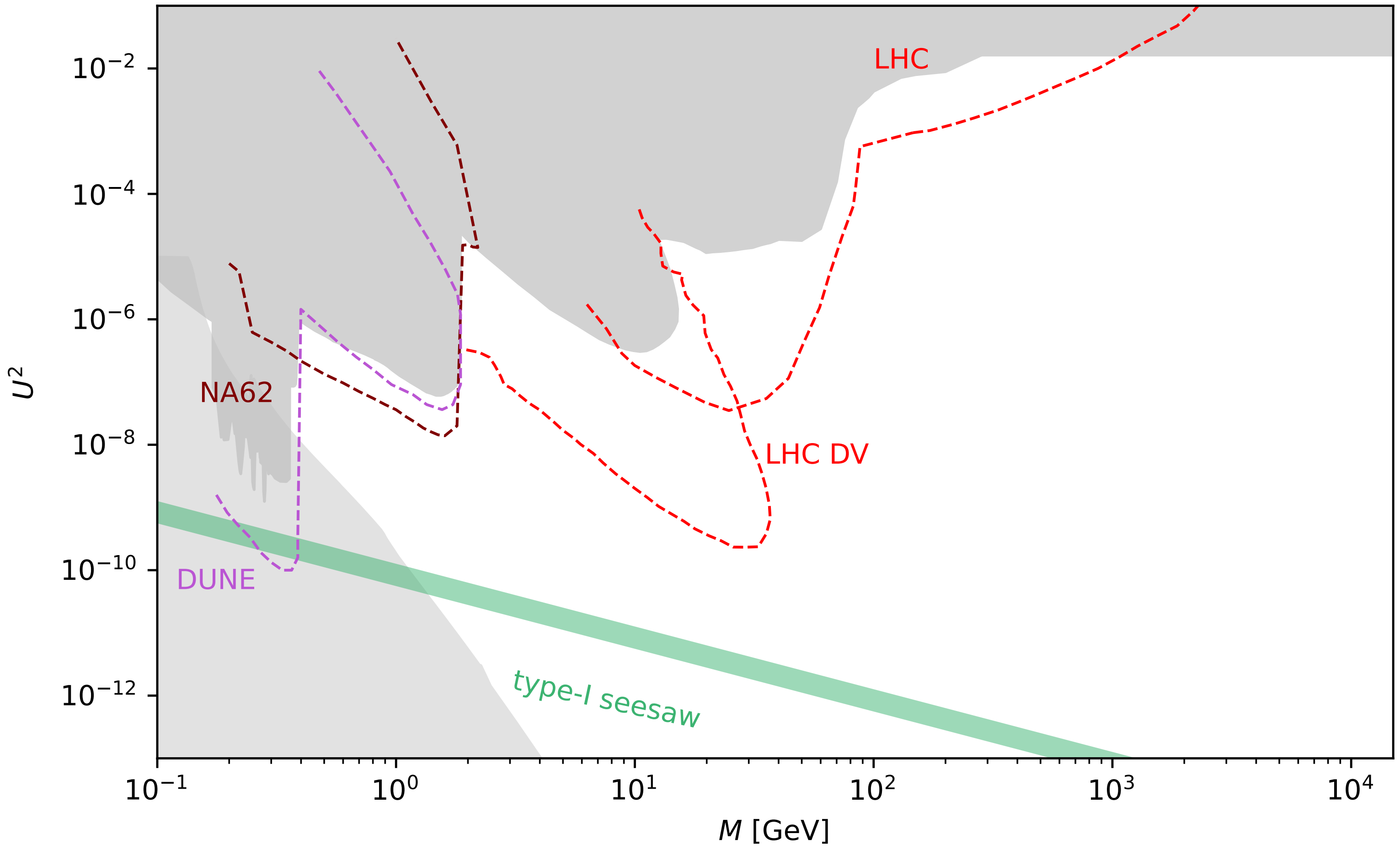
CHARM:
Beam-dump: D meson decay,
Wide-band: neutrino beam colliding with nucleus

DELPHI: Z boson decay

E949: Kaon decay

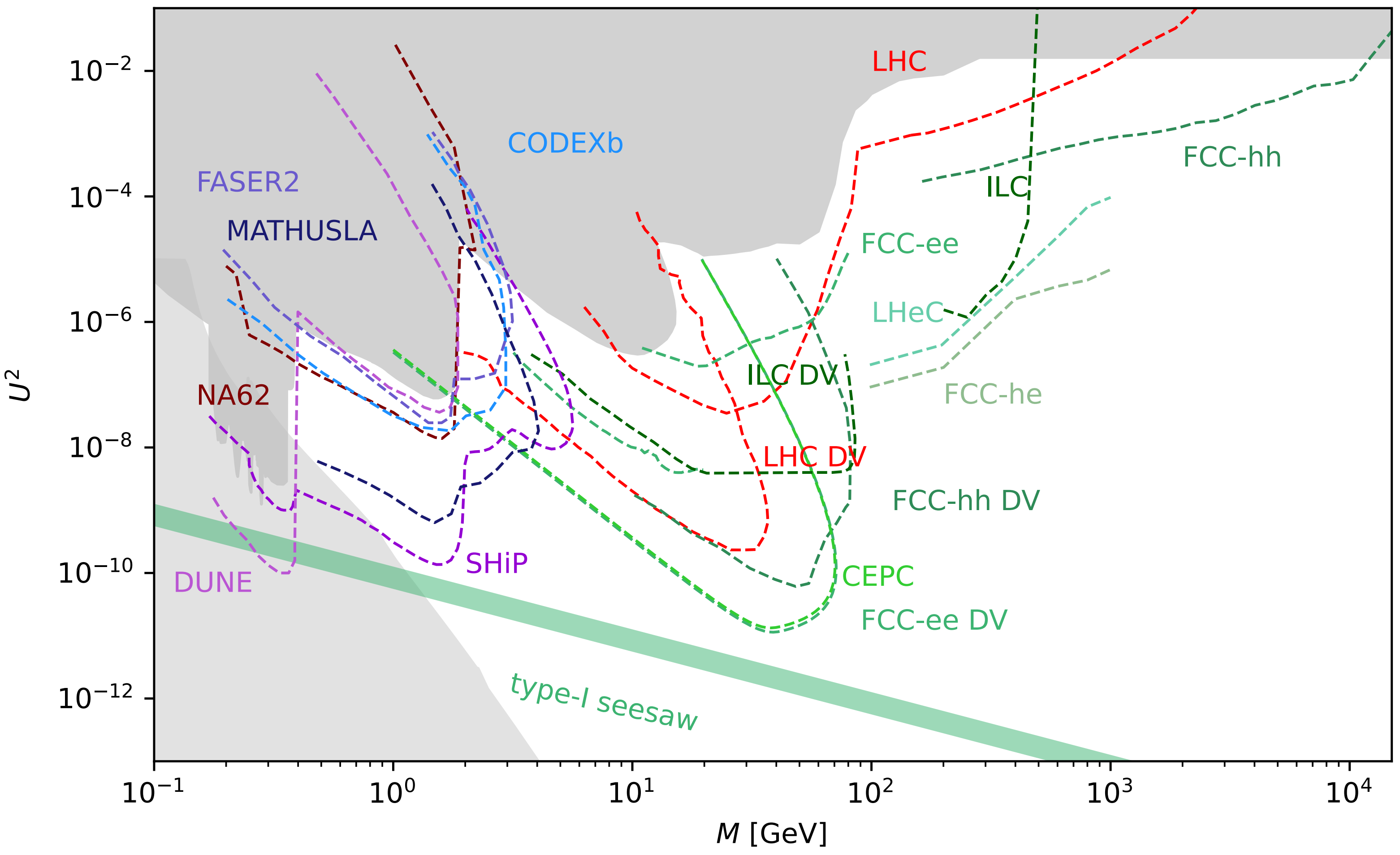
LHC: Off-shell W/Z decay

Upgraded Bounds



Future Upgraded Projection on LHC, NA62 and DUNE

Various Bounds



Bounds from the proposed future collider: FCC, CEPC, ILC, LHeC