Heavy Neutral Lepton on Future Muon Collider

Kunfeng Lyu
University of Minnesota

2301.07117, *JHEP* **03 (2023) 231**

In Collaboration with Peiran Li and Zhen Liu

Muon Collider Study Group, Nov 9, 2023

Outline

- Neutrino Mass
- Heavy Neutral Leptons
- Search at Future Muon Collider
  - Muon flavor
- 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. $U_l = \sin\theta_l$

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

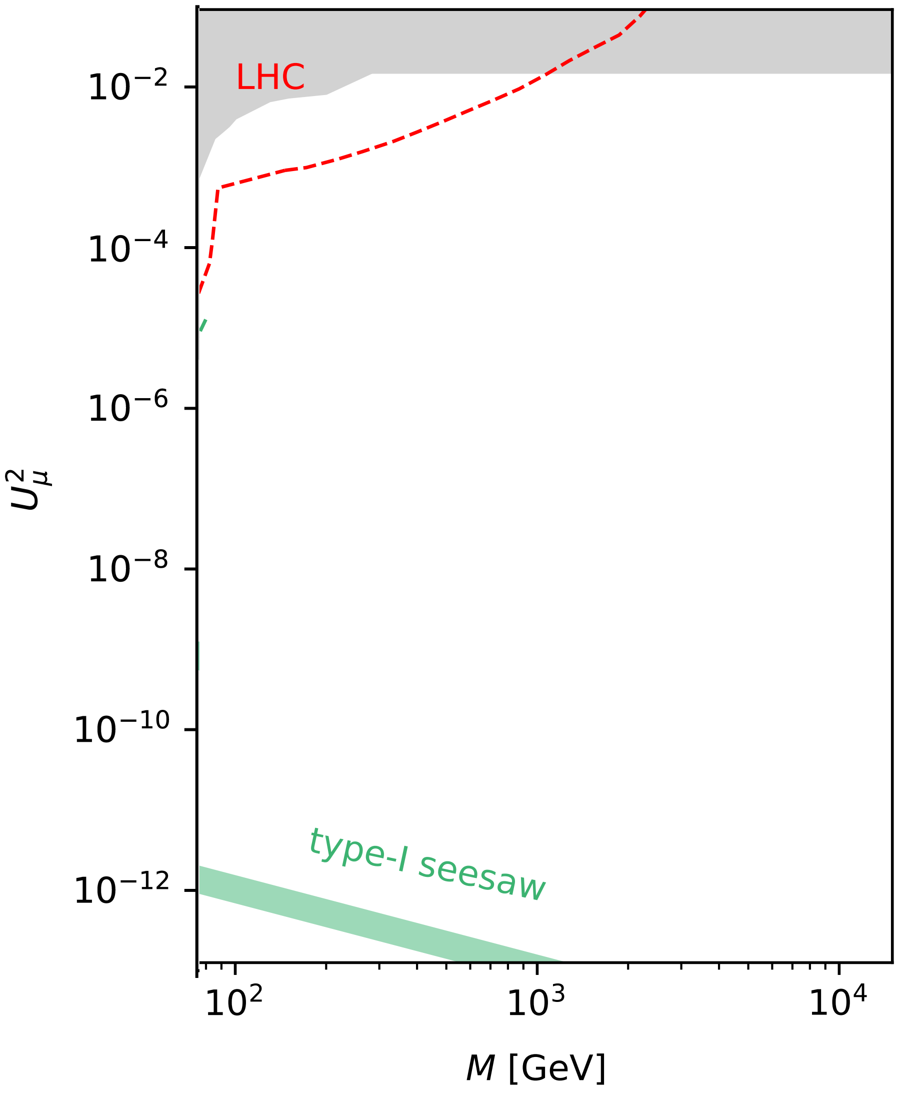
$$\mathcal{L}_W = \frac{gU_l}{\sqrt{2}}\left(W_\mu \bar{l}_L \gamma^\mu N + h.c.\right)$$

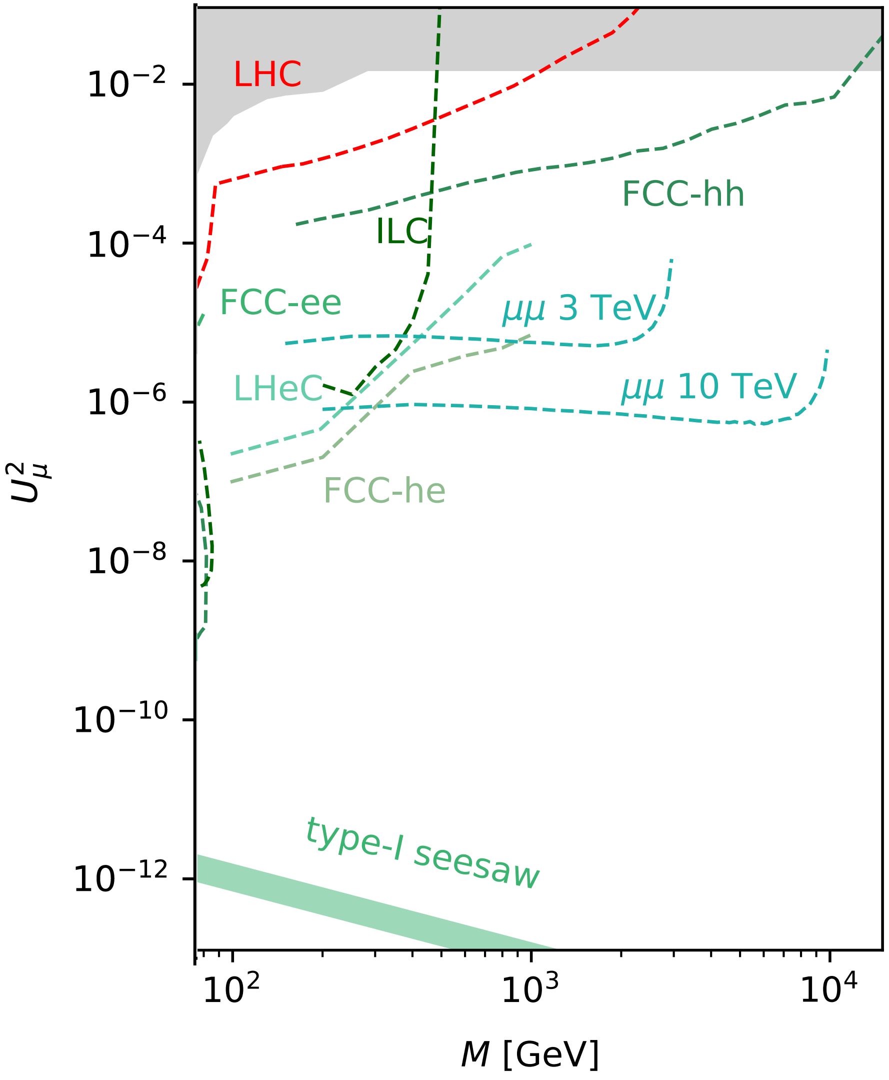
$$\mathcal{L}_Z = -\frac{gU_l}{2\cos\theta_w} Z_\mu \left(\bar{\nu}_L \gamma^\mu N + \bar{N}\gamma^\mu \bar{\nu}_L\right)$$

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

Our current focus

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





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

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:

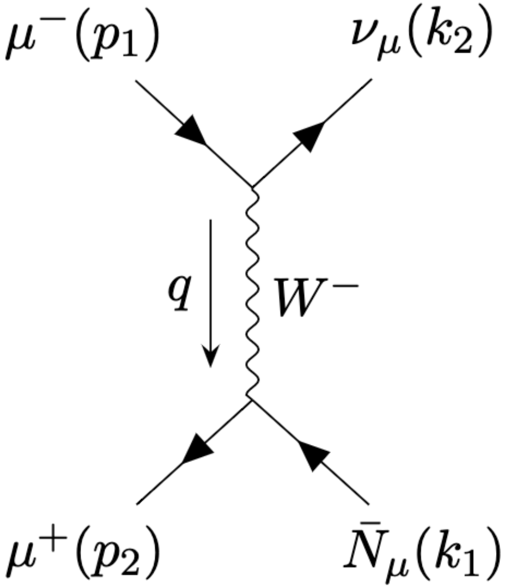
  Using MadGraph 3.4 to simulate and then make analysis
- Effective Vector-Boson Approximation (EVA) or gauge boson PDF has been implemented

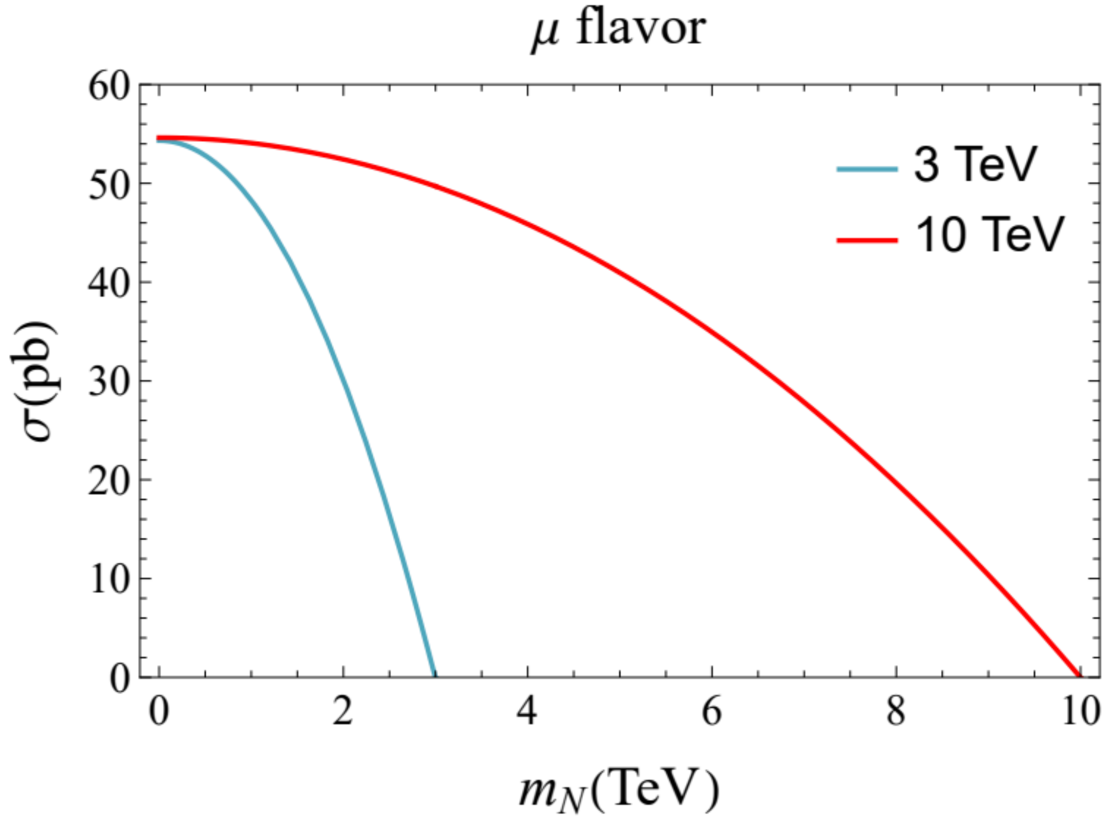
Muon Flavor

- Signal: Production of N_μ

  Dominated by the t-channel

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





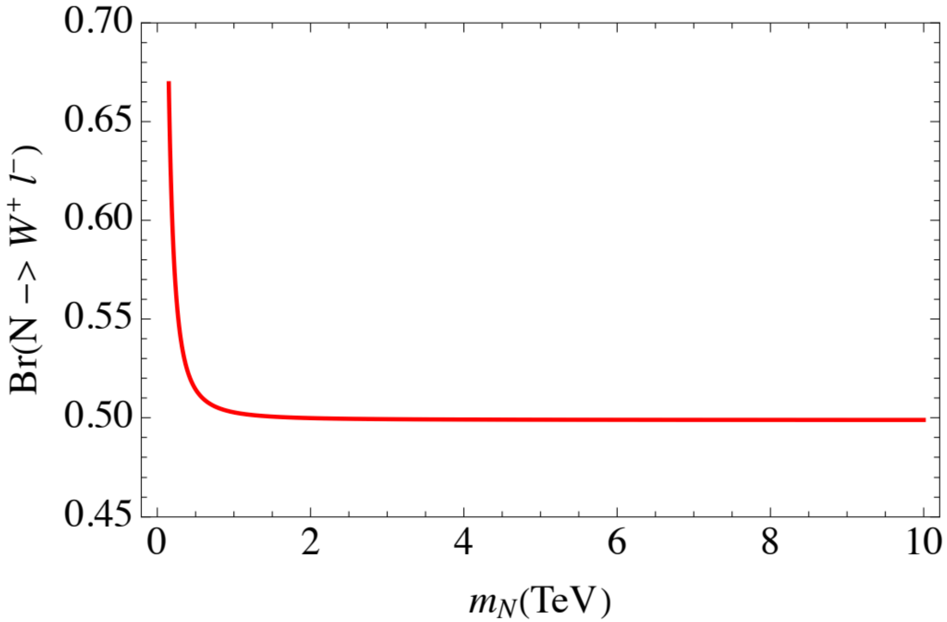
Type	Signal process	$\sigma/\lvert U_\mu\rvert^2$ (w. conj. channel) $m_N = 1$ TeV
t-channel	$\mu^+\mu^- \longrightarrow N_\mu\bar{\nu}_\mu$	20.28 pb
VBF	$\mu^+\mu^- \longrightarrow \mu^+\mu^- N_\mu\bar{\nu}_\mu$	~ 1 pb
VBF	$\mu^+\mu^- \longrightarrow \bar{\nu}_\mu\nu_\mu N_\mu\bar{\nu}_\mu$	~ 0.1 pb

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.

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

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



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.

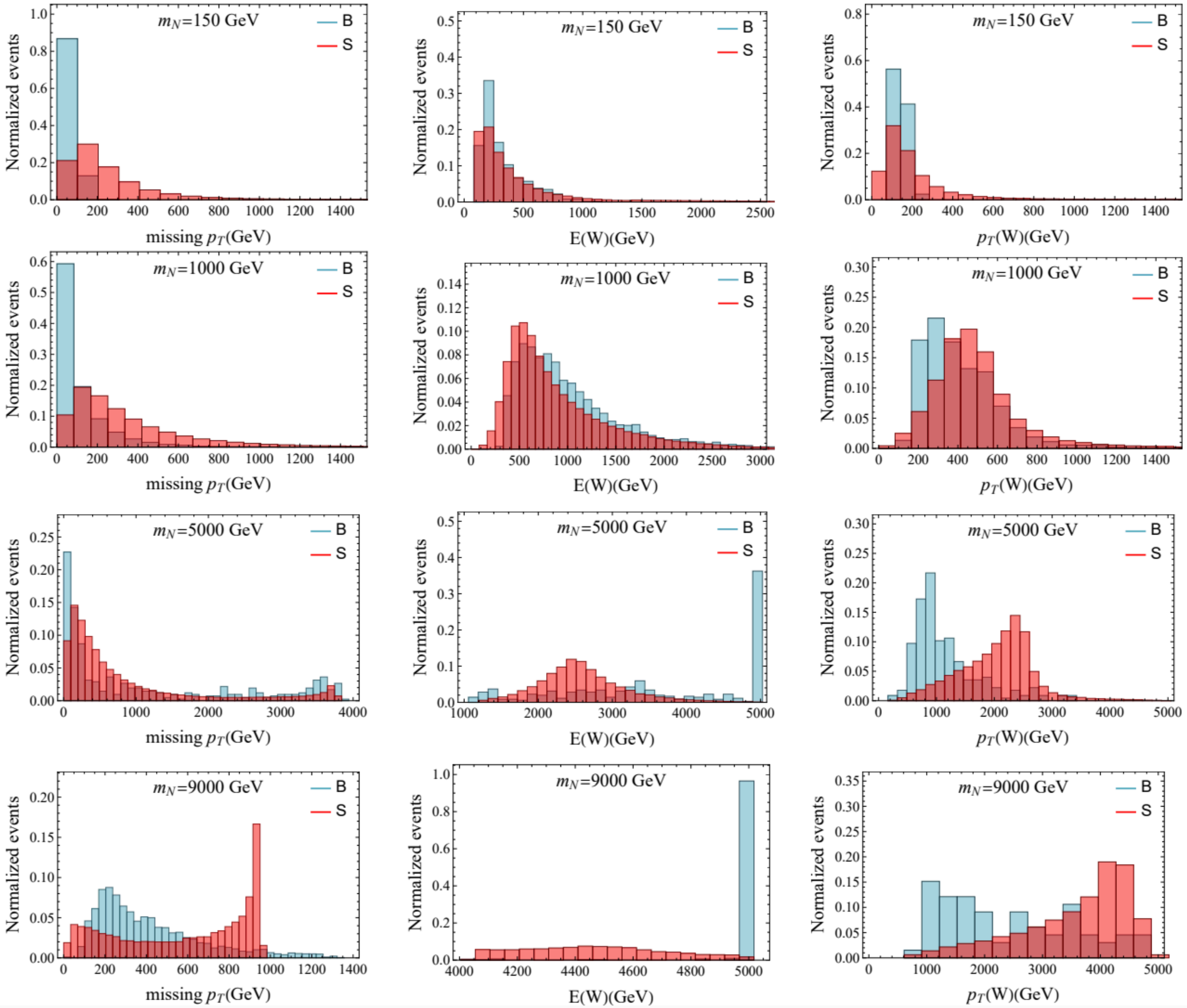
Cutflow Analysis

- 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 $m_N \pm 5\% m_N$

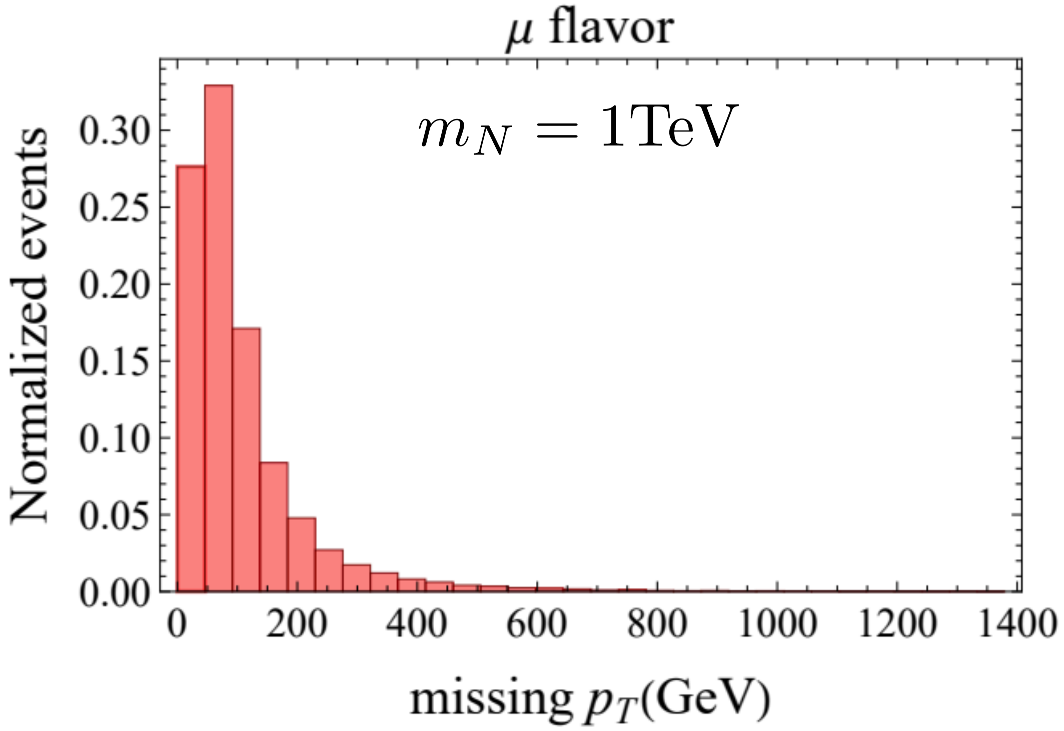
- Optimization cuts:
  - Customized cut on missing p_T, $E(W)$, $p_T(W)$ for each m_N benchmark

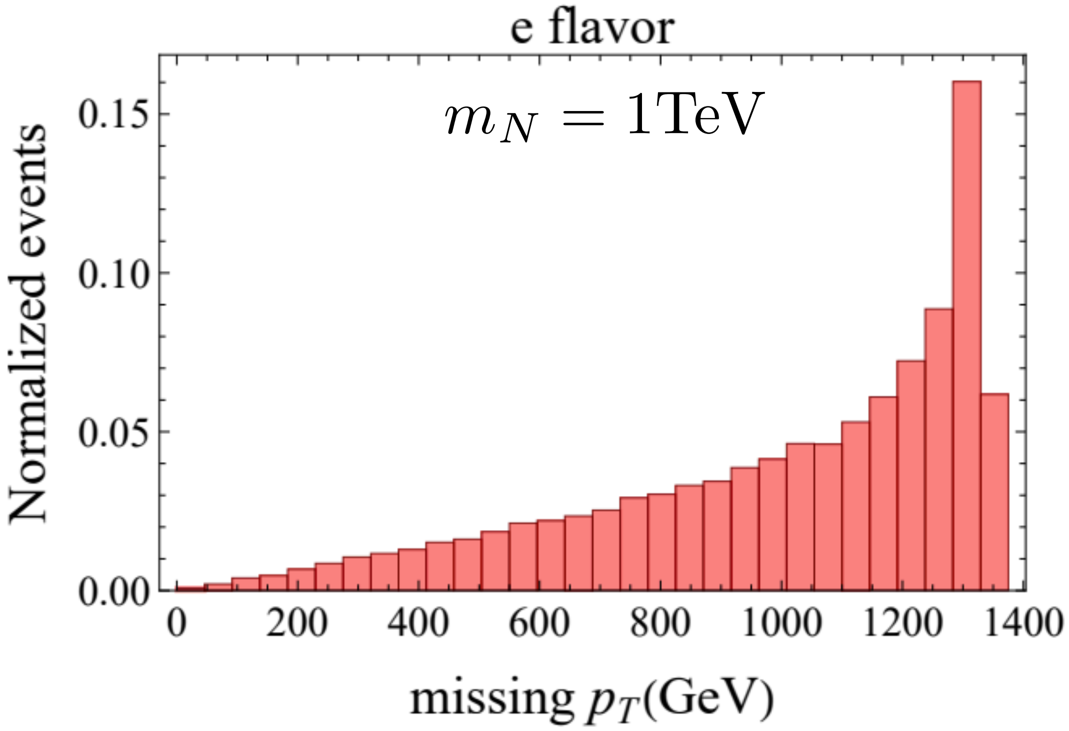


m_N=150 GeV
B
S
Normalized events
missing p_T(GeV)
m_N=150 GeV
B
S
Normalized events
E(W)(GeV)
m_N=150 GeV
B
S
Normalized events
p_T(W)(GeV)
m_N=1000 GeV
B
S
Normalized events
missing p_T(GeV)
m_N=1000 GeV
B
S
Normalized events
E(W)(GeV)
m_N=1000 GeV
B
S
Normalized events
p_T(W)(GeV)
m_N=5000 GeV
B
S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

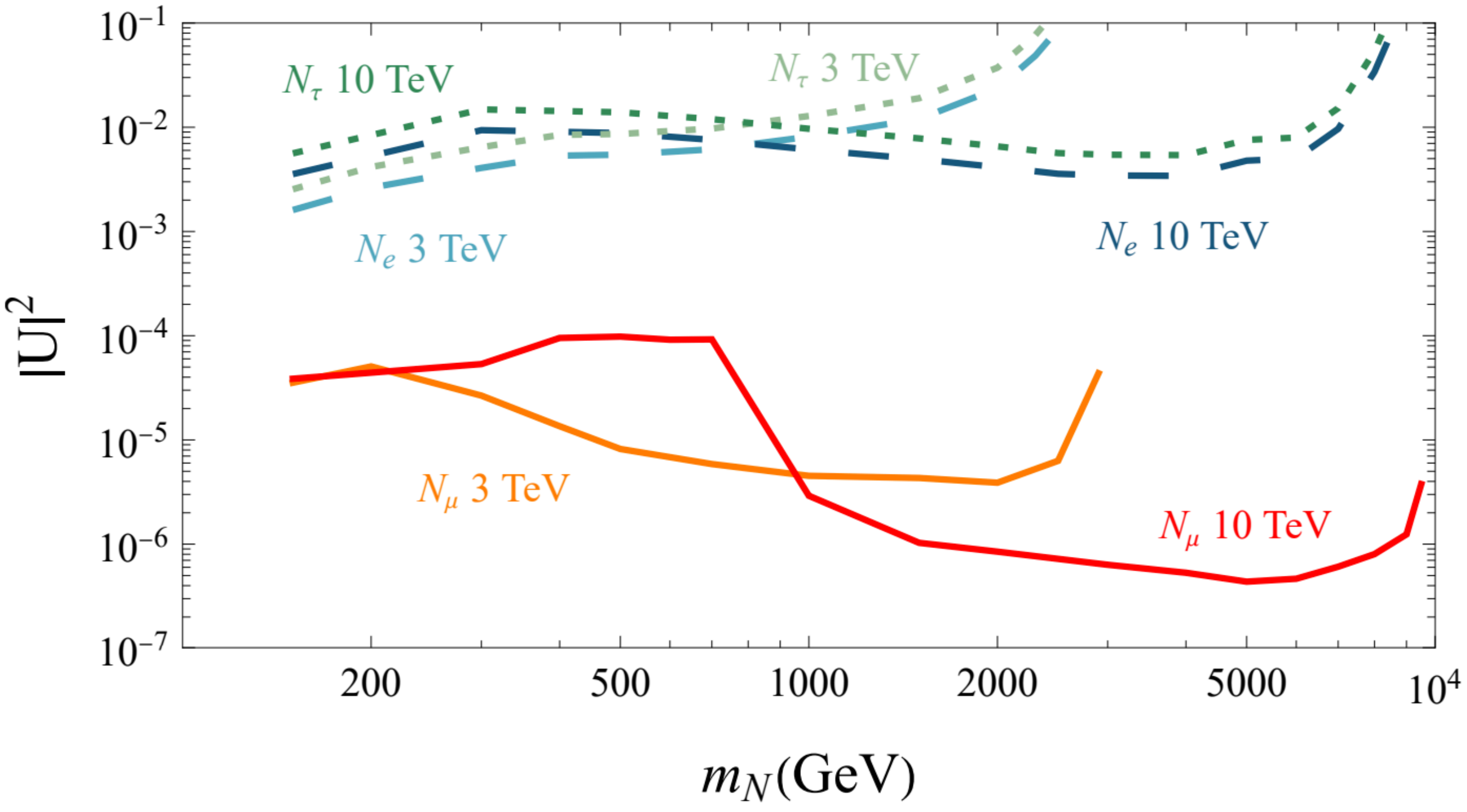
Process	Central W	Mass window 150/1000/5000/9000 GeV	Optimization
Background	34.19%	1.2/0.63/0.023/0.134%	0.16/0.22/0.011/0.0032%
$m_N = 150$ GeV	83.84%	83.84%	66.63%
$m_N = 1000$ GeV	93.67%	93.67%	80.55%
$m_N = 5000$ GeV	99.01%	99.01%	89.69%
$m_N = 9000$ GeV	99.48%	99.48%	87.53%

Kinematics


μ flavor
$m_N = 1\text{TeV}$
Normalized events
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0
200
400
600
800
1000
1200
1400
missing p_T(GeV)


e flavor
$m_N = 1\text{TeV}$
Normalized events
0.00
0.05
0.10
0.15
0
200
400
600
800
1000
1200
1400
missing p_T(GeV)

Projected sensitivity



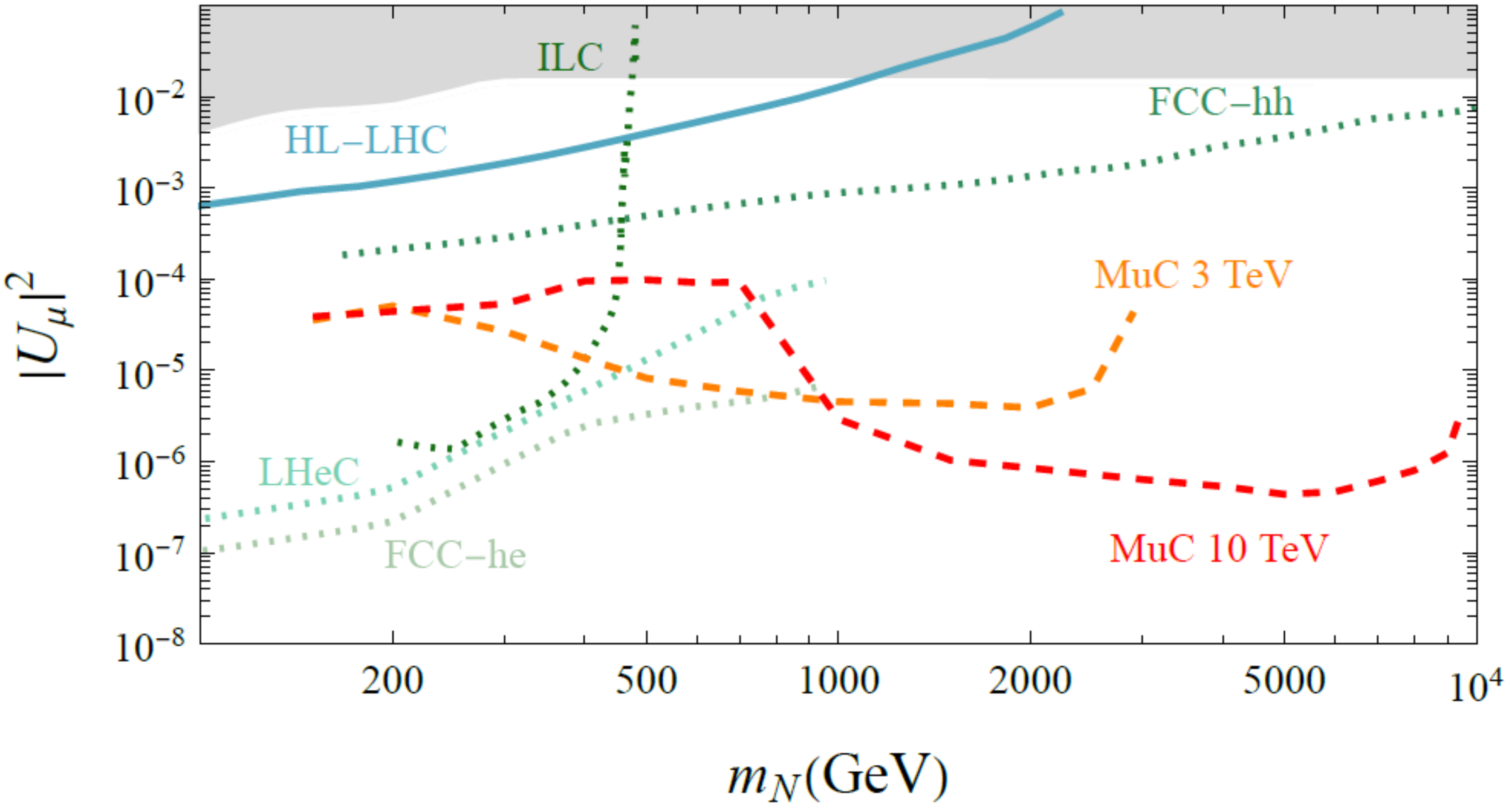
The 95% projected sensitivity of $|U_e|^2, |U_\mu|^2$ and $|U_\tau|^2$ as a function of HNL mass mN at 3 and 10 TeV muon collider.

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.

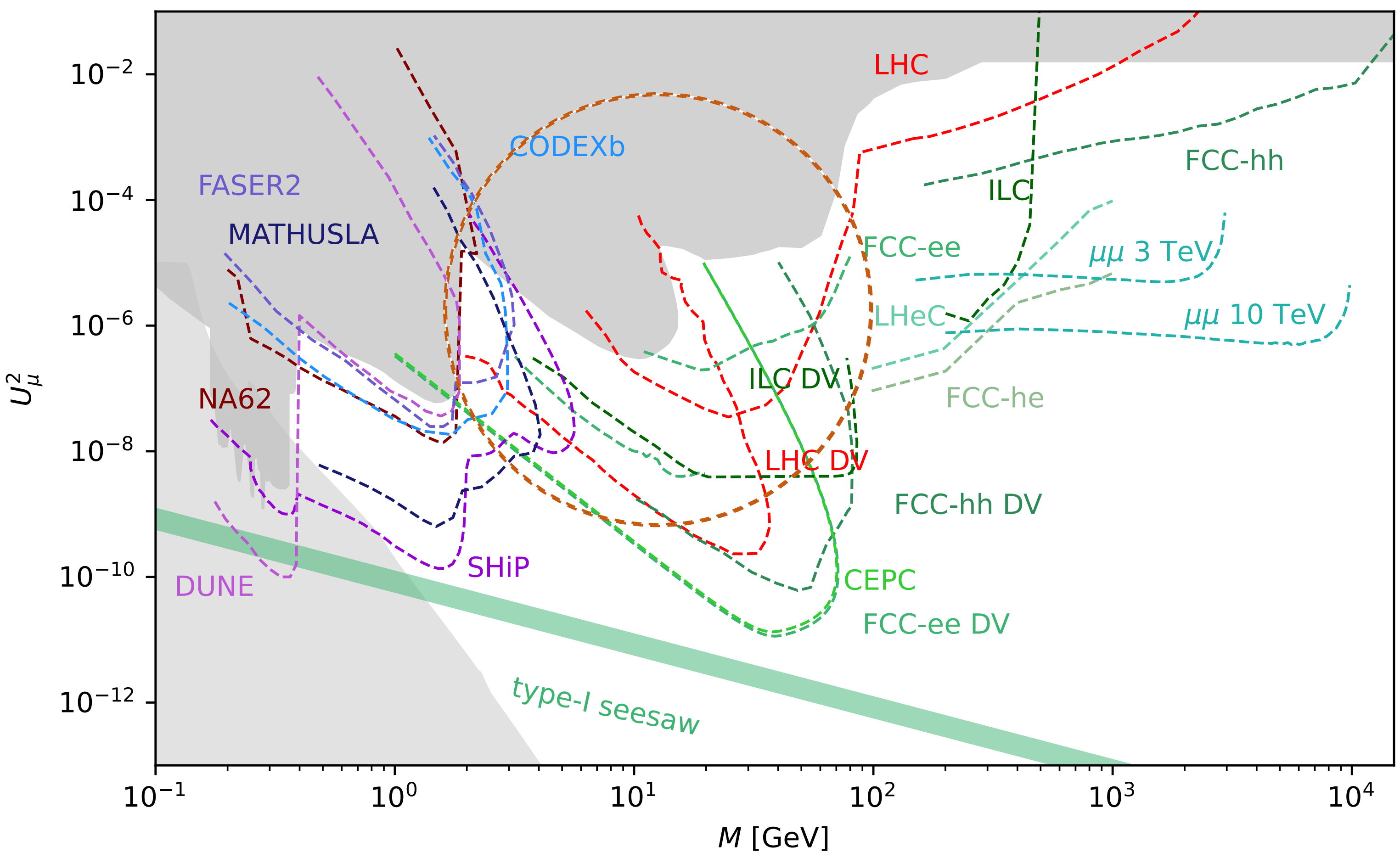


Heavy neutral leptons at muon colliders
PL, Z. Liu, K. Lyu, arXiv:2301.07117

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

Various Bounds

Next step



Conclusion

- 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 10^{-7}.
- There are t-channel singularity cases one should be careful to deal with.
- Many more interesting pheno in the HNL sector.

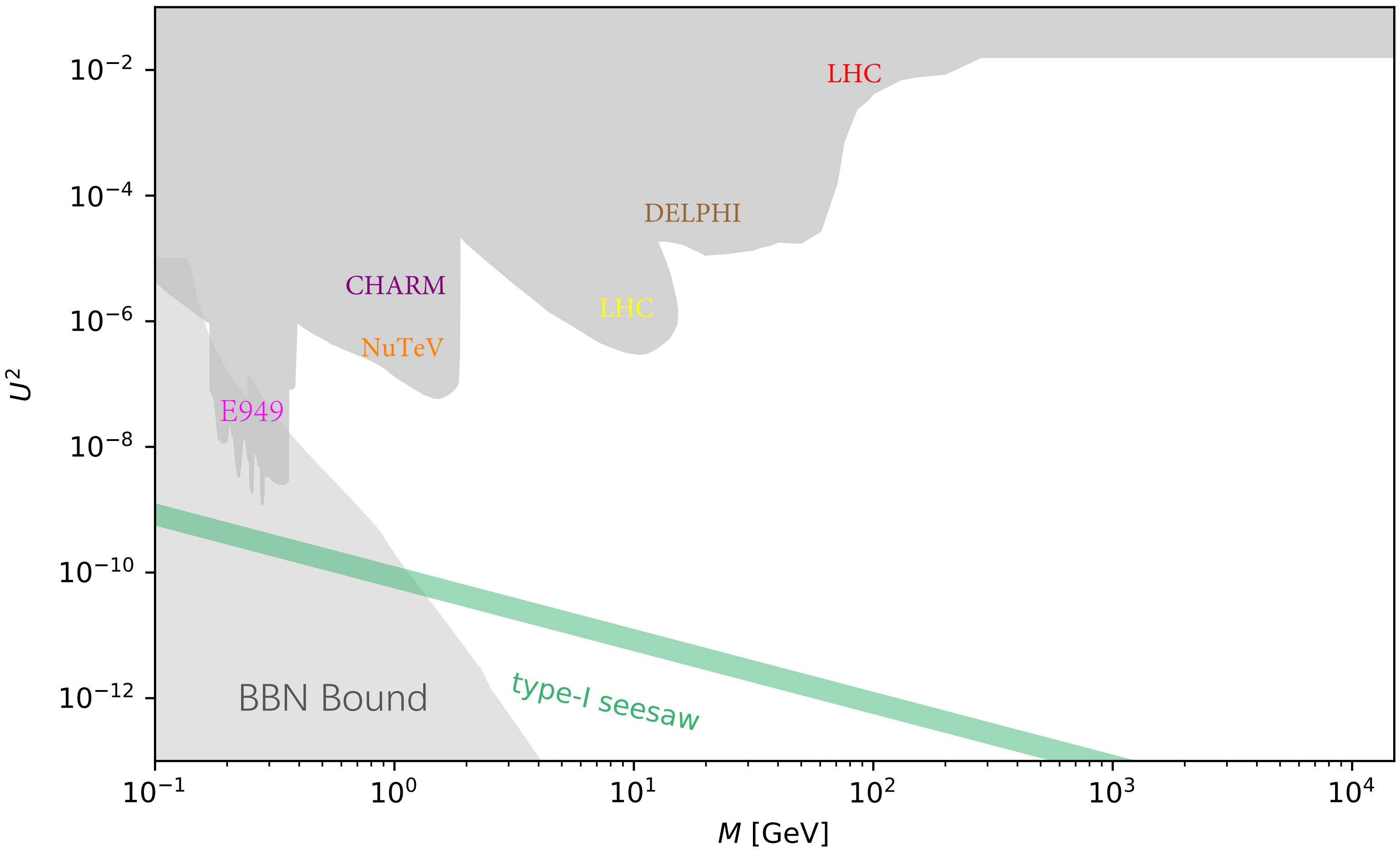
Short Review of Various Probes

- People have tried to constrain in the U^2-mN 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

Existing Bounds

Snowmass Energy Frontier Report: 2211.11084

From Past Experiments



NuTeV: Drell-Yan, NHL decay

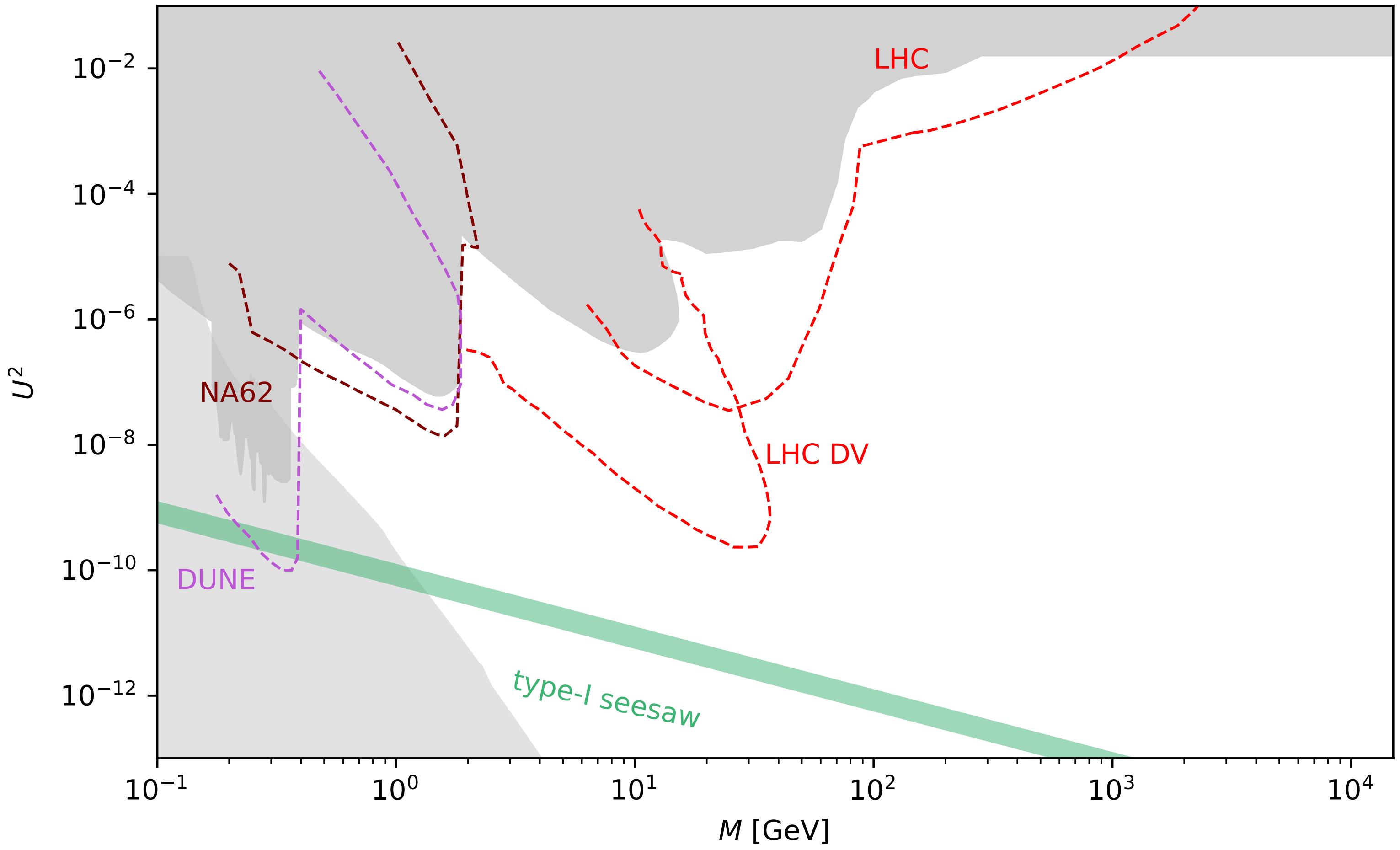
CHARM:
Beam-dump: D meson decay,
Wide-band: neutrino beam colliding with nucleus

DELPHI: Z boson decay

E949: Kaon decay

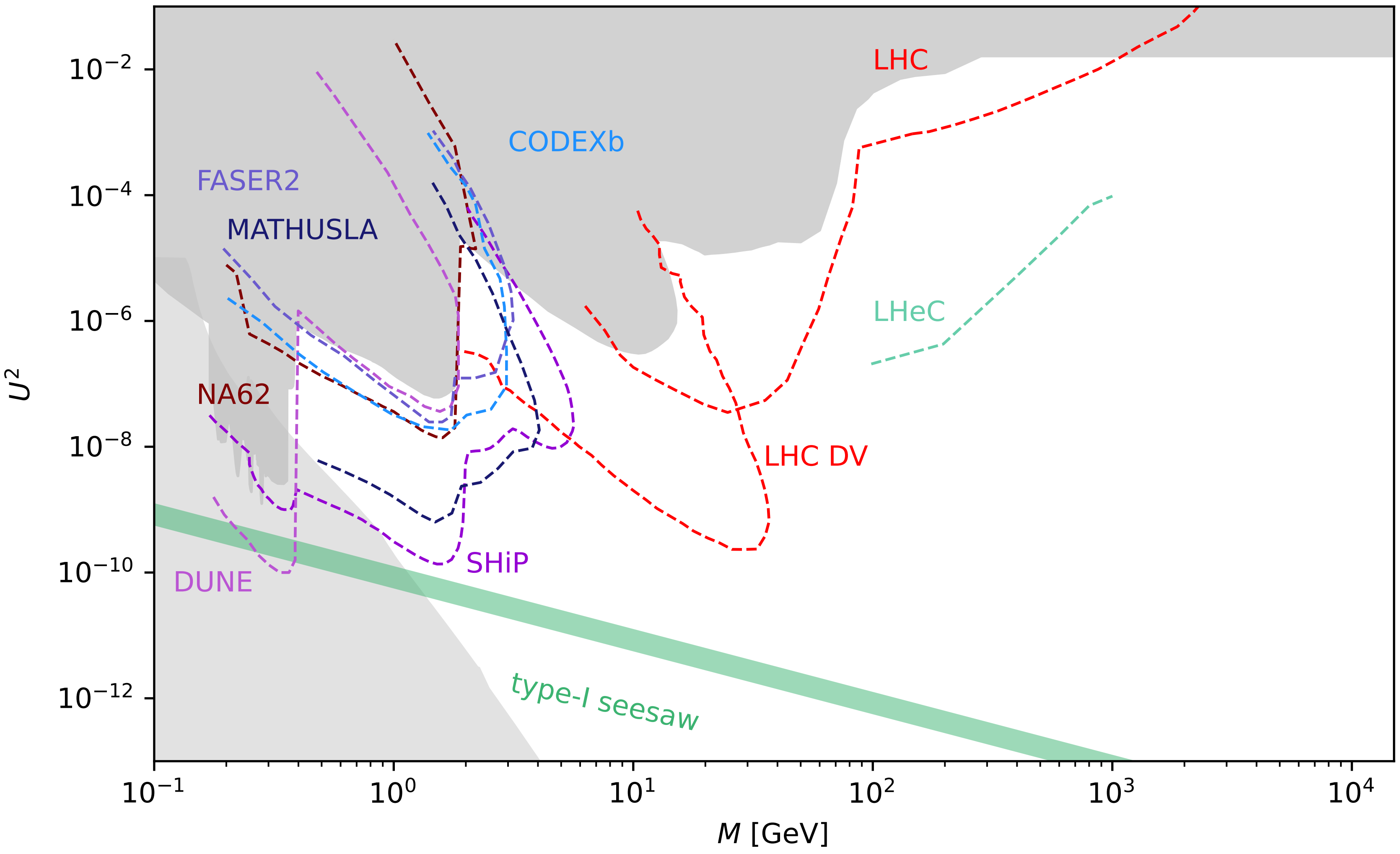
LHC: Off-shell W/Z decay

Upgraded Bounds



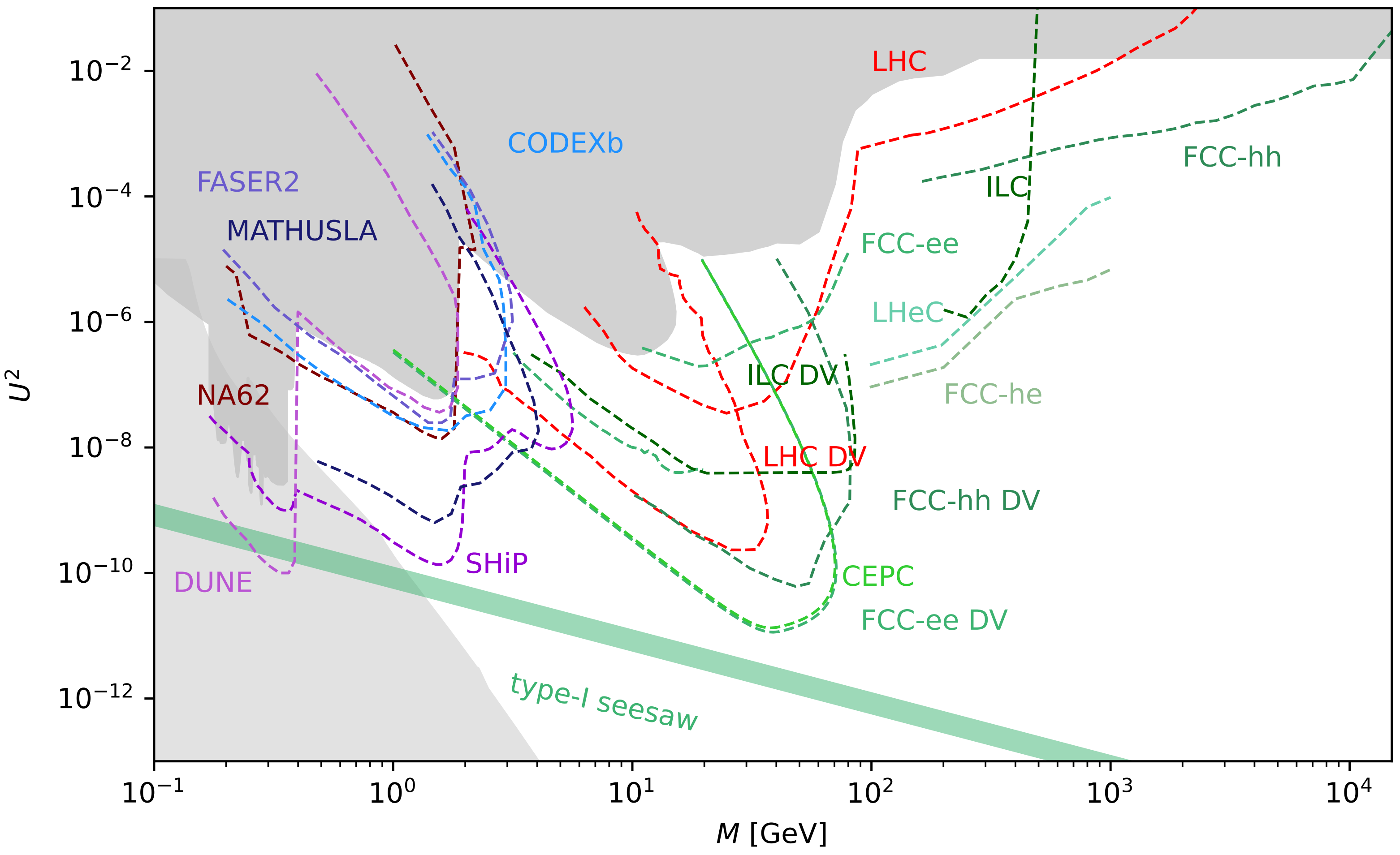
Future Upgraded Projection on LHC, NA62 and DUNE

Various Bounds



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

Various Bounds



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