HNL at Muon Colliders

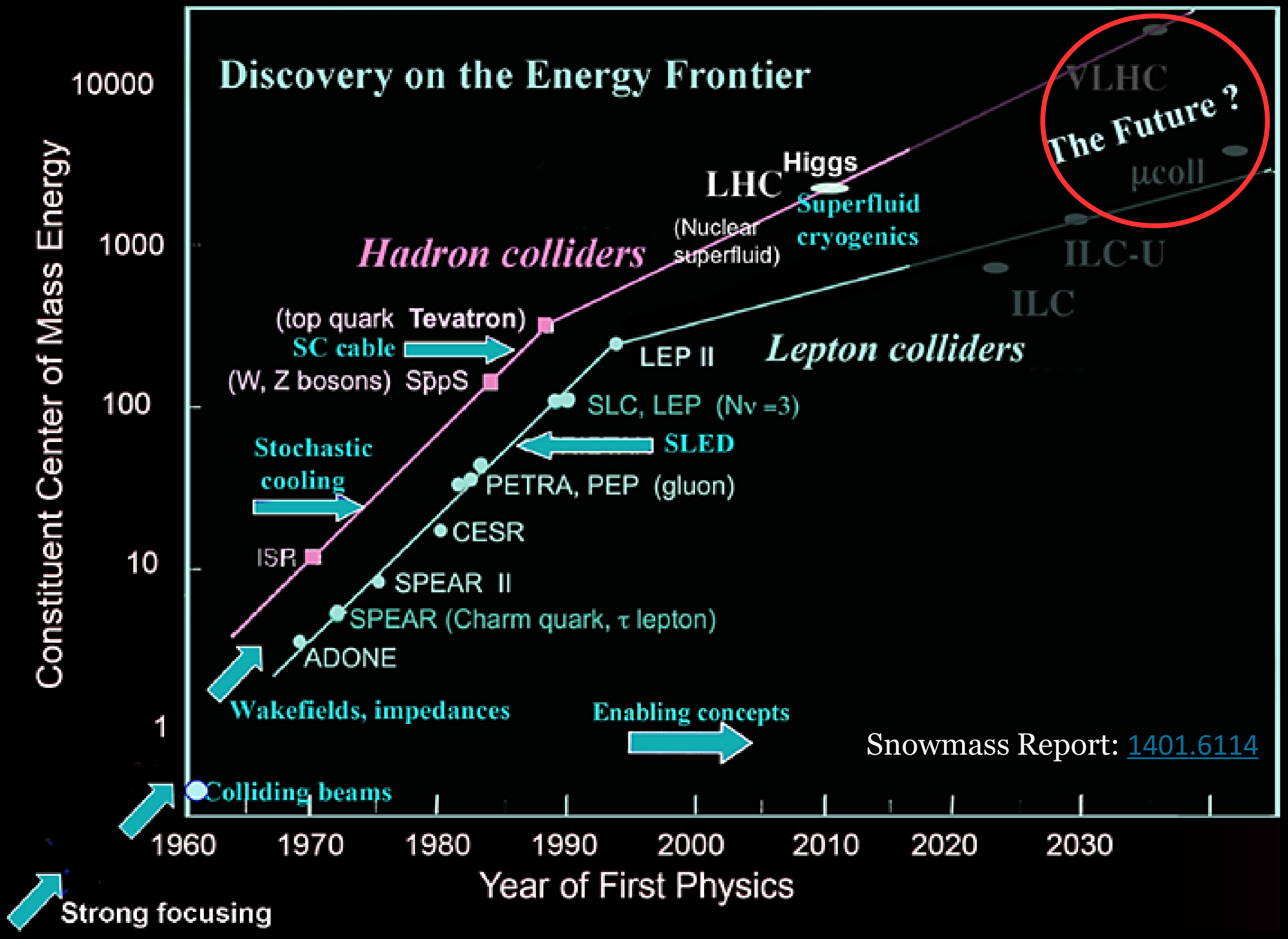
Zhen Liu
University of Minnesota
05/17/2023

HNL at Muon Colliders

Zhen Liu
University of Minnesota
05/17/2023

Mainly based upon Peiran Li, ZL, Kun-Feng Lyu, 2301.07117,

High Energy Rules

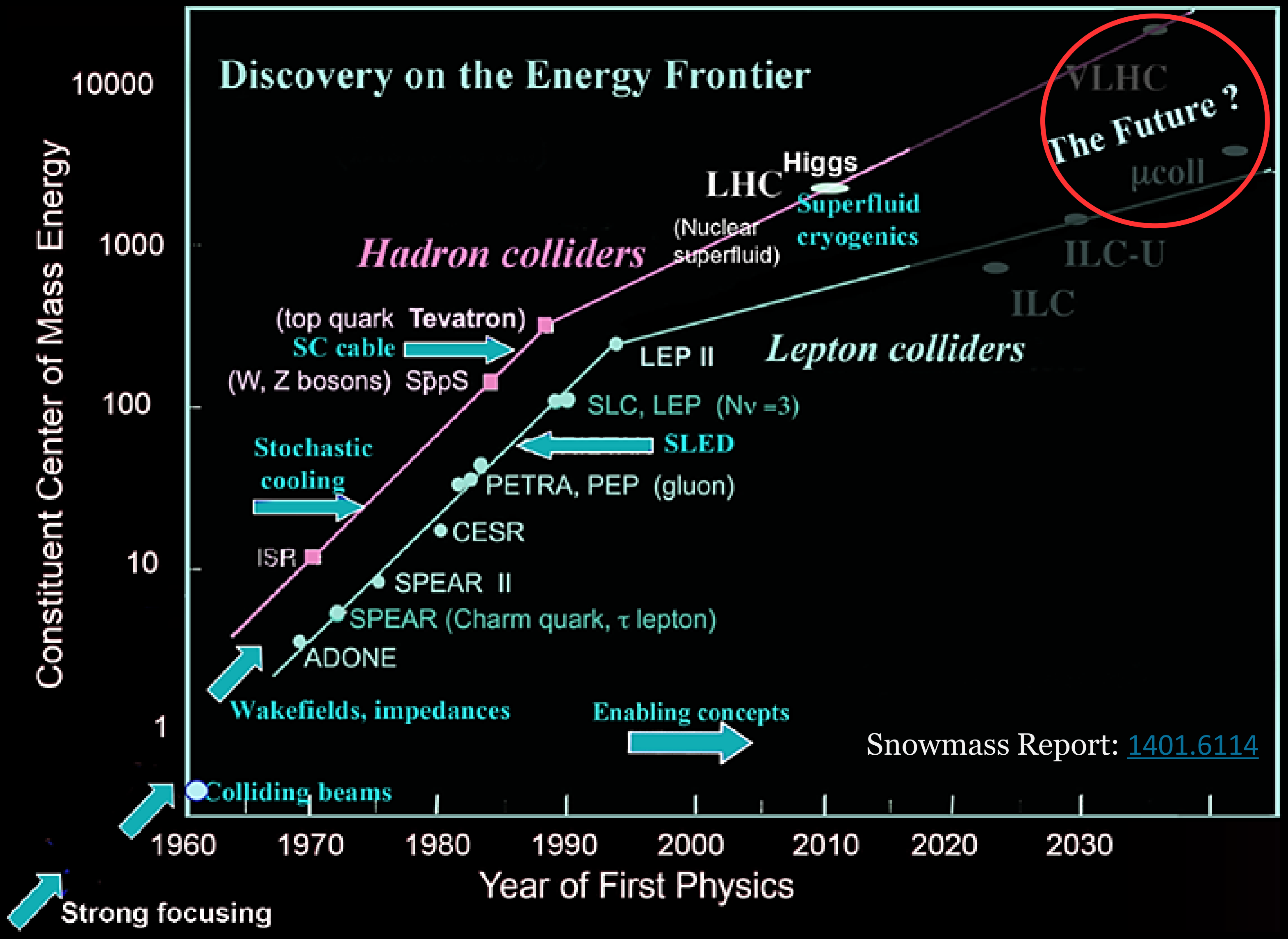


Snowmass Report: [1401.6114]

The forefront of tech & ambitions leads to discoveries.

The dream for high energy machines persists in our field

High Energy Rules



Snowmass Report: 1401.6114

The forefront of tech & ambitions leads to discoveries.

The dream for high energy machines persists in our field

People's perspectives change over time, now:

- there are excitement/call for future high energy muon collider from theory, accelerator and experimental community.
- Interesting aspects of physics to be examined.

Neutrino is a puzzling sector

- In SM, neutrino is massless. While the experiments have confirmed its tiny mass <0.1 eV.
- Seesaw mechanism
  - Simple Type I
  - Inverse seesaw model
  - Linear seesaw model
- We choose to work in a simple scenario. Suppose there is a heavy neutral lepton. We can parametrize its mass m_N and mixing angle with SM neutrino $U_\ell = sin\theta_\ell$.

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

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

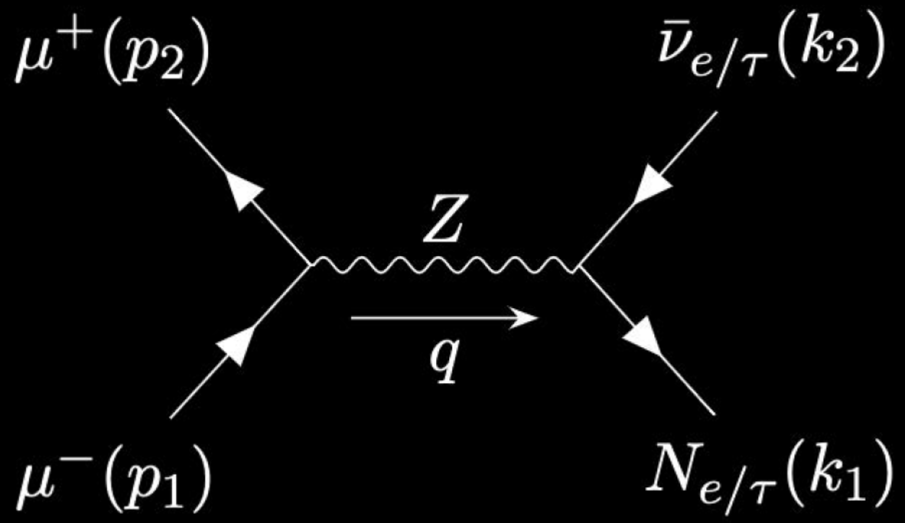
$$\mathcal{L}_Z = -\frac{gU_l}{2\cos\theta_w} Z_\mu \left(\bar{\nu}_L \gamma^\mu N + \bar{N}\gamma^\mu \bar{\nu}_L\right)$$

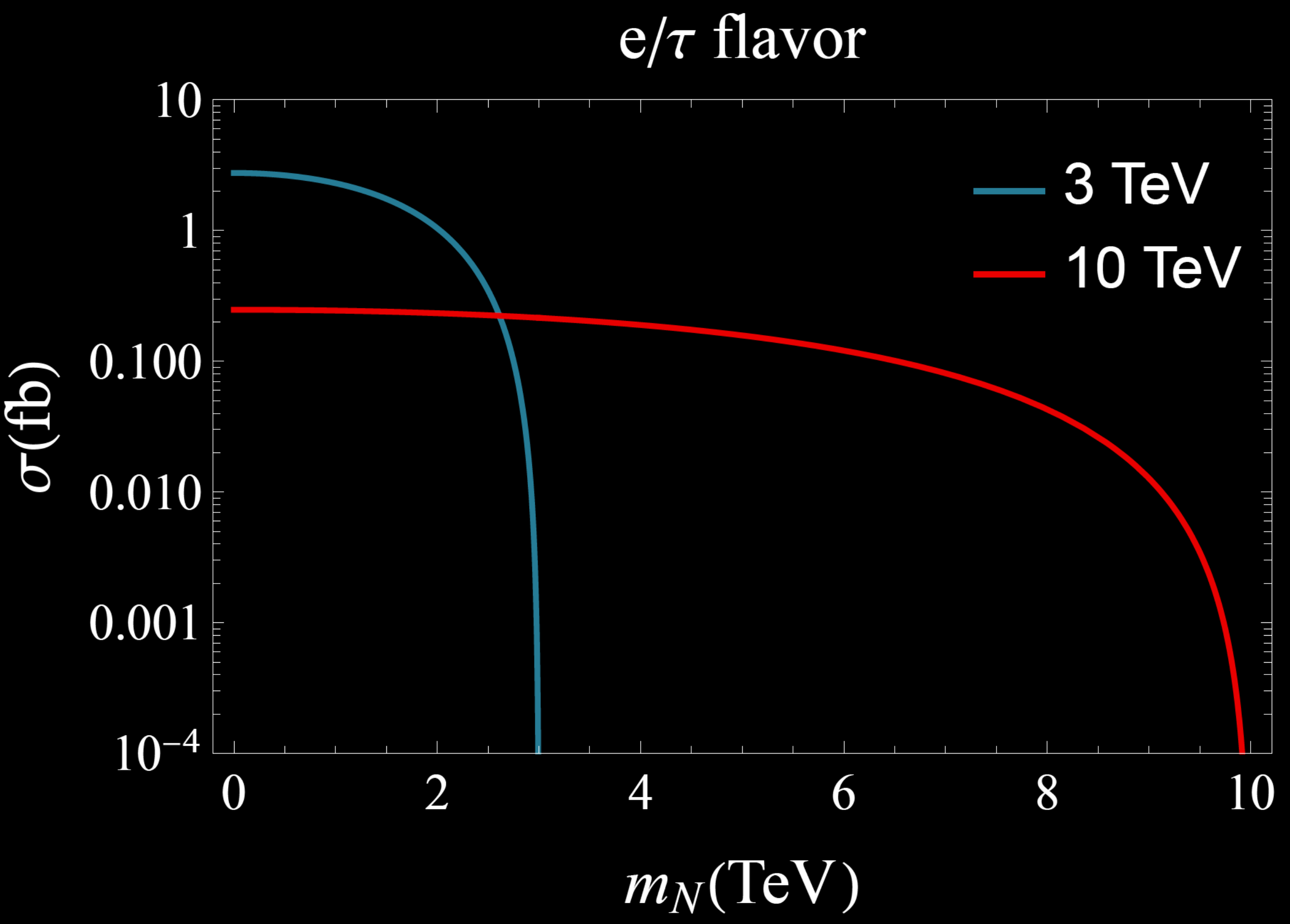
$$\mathcal{L}_H = -\frac{U_l m_N}{v} h \left(\bar{\nu}_L N + \bar{N}\nu_L\right)$$

The physics is rich

- Direct Particle Probes:
  - Production
    - Meson decay, heavy lepton decay
    - (On-shell/Off-shell) Gauge/Higgs boson decay
  - Decay
    - Short-lived
    - Long-lived
- Cosmo and astrophysical probe: BBN, CMB, etc (see in B. Dev's talk.)
- Indirect constraints: branching ratio of SM particles decays, oscillations, etc.

S-channel production (e/ μ /τ flavored)



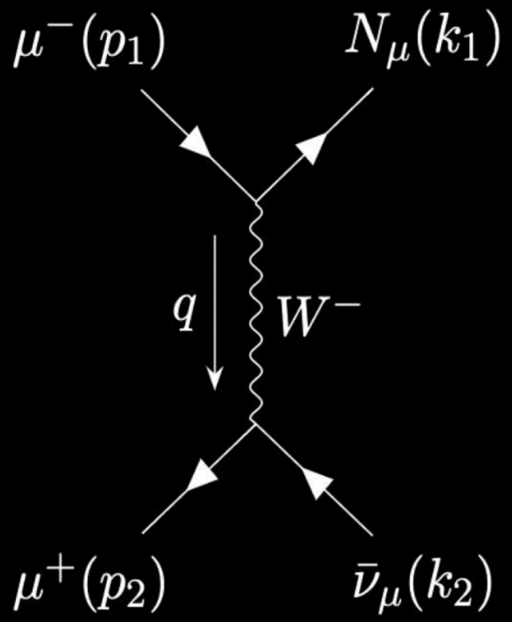


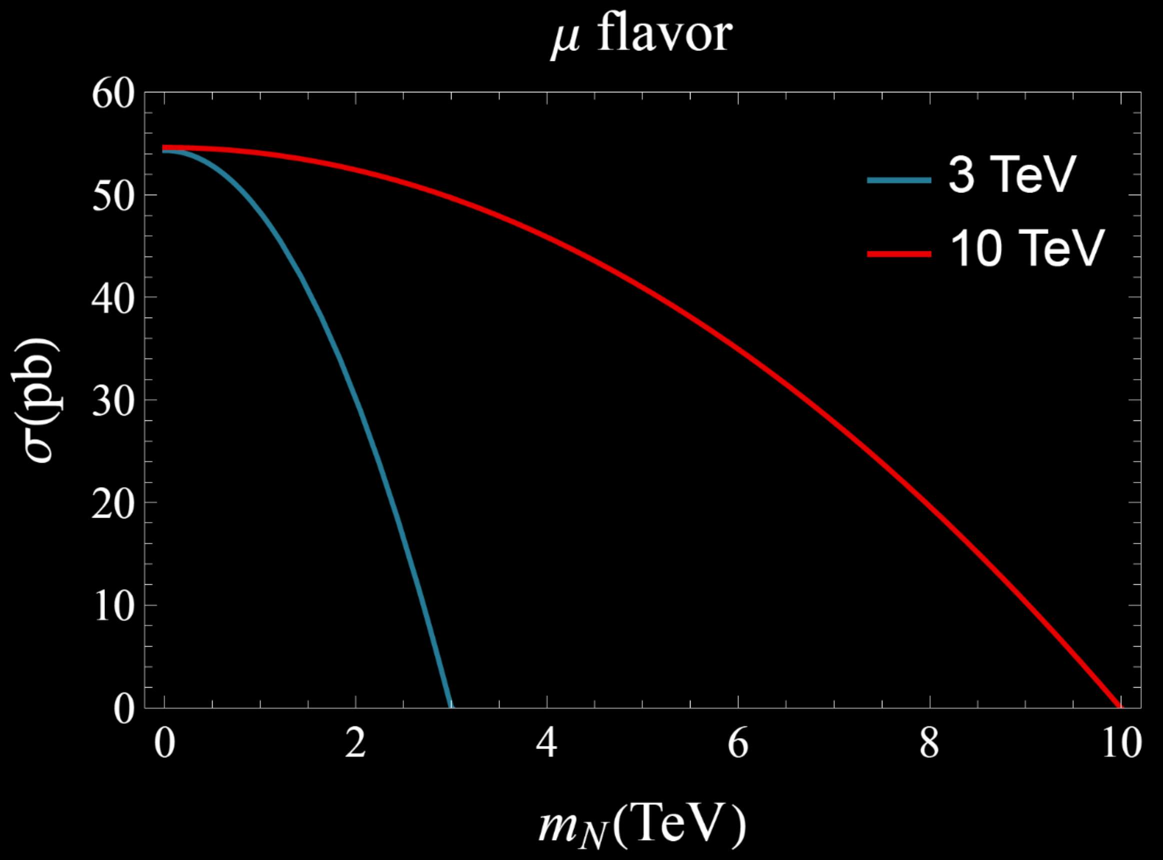
- 1/s suppressed;
- Flat rate until near the threshold s/2
- $O(fb)$ cross section;

Muon Flavor

Production dominated by t-channel

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





Type	Signal process	$\sigma/\|U_\mu\|^2$ (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 selection $m_N > O(100)$ GeV

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

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

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

The dijets almost come from onshell W/Z boson.

We focus on the final states of W and μ and reconstruct its invariant mass distribution.

Including the charge conjugation process

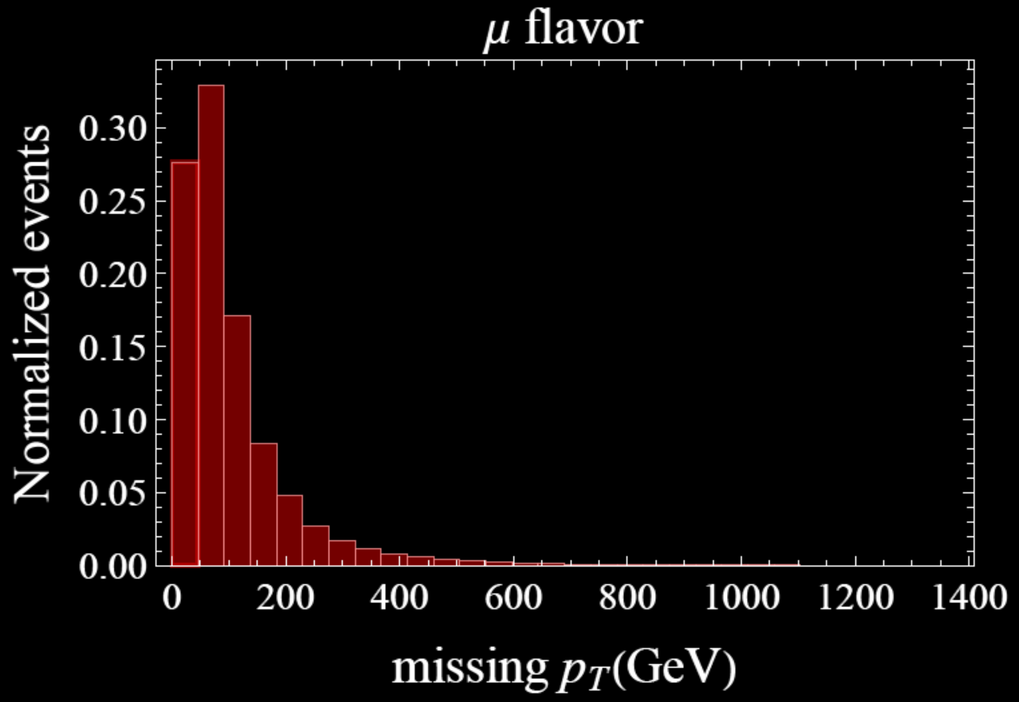
10TeV Background

Type	Background process	σ (w. conj. channel)	Pre-selection cut (PSC)
t-channel	$\mu^+\mu^- \longrightarrow W^+\mu^-\bar{\nu}_\mu$	0.214 pb	PSC
t-channel	$\mu^+\mu^- \longrightarrow Z\mu^+\mu^-$	0.464 pb	PSC & missing μ^+
VBF	$\mu^+\mu^- \longrightarrow \mu^+\mu^-W^+\mu^-\bar{\nu}_\mu$	0.401 pb	PSC & missing $\mu^+\mu^-$
VBF	$\mu^+\mu^- \longrightarrow \bar{\nu}_\mu\nu_\mu W^+\mu^-\bar{\nu}_\mu$	0.0686 pb	PSC

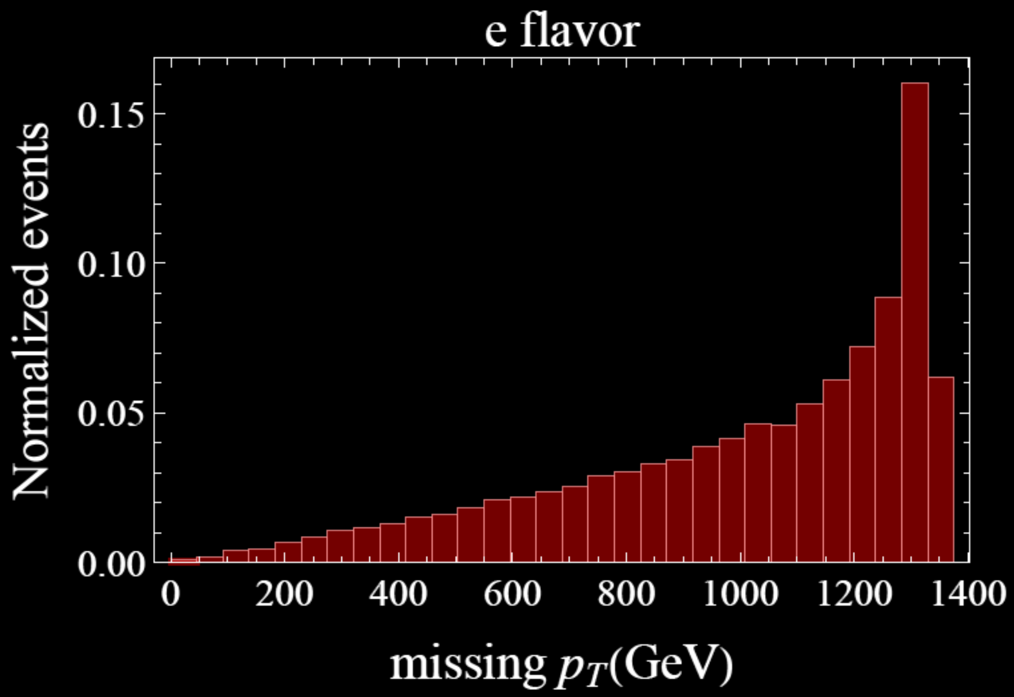
- Using EVA in MadGraph, especially photon PDF (EVA: Effective Vector-Boson Approximation)

- Including Z boson: Dijets can come from either W or Z boson.

Kinematics



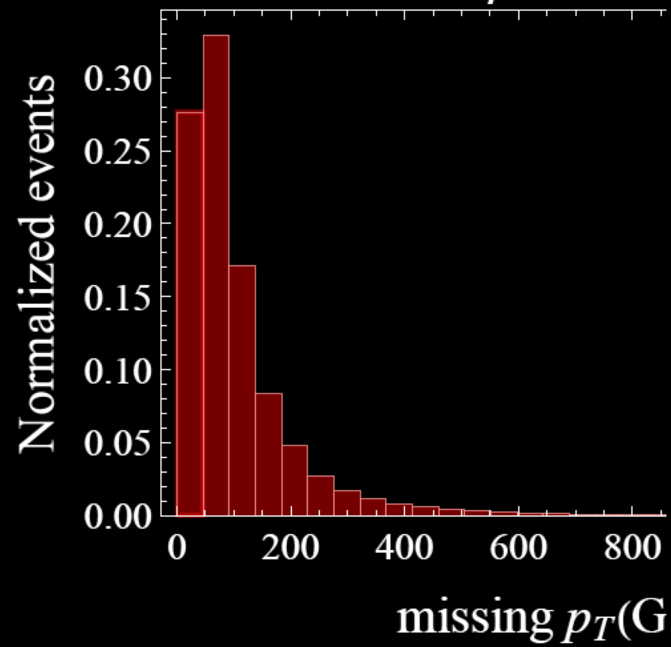
μ flavor
Normalized events
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
200
400
600
800
1000
1200
1400
missing p_T(GeV)

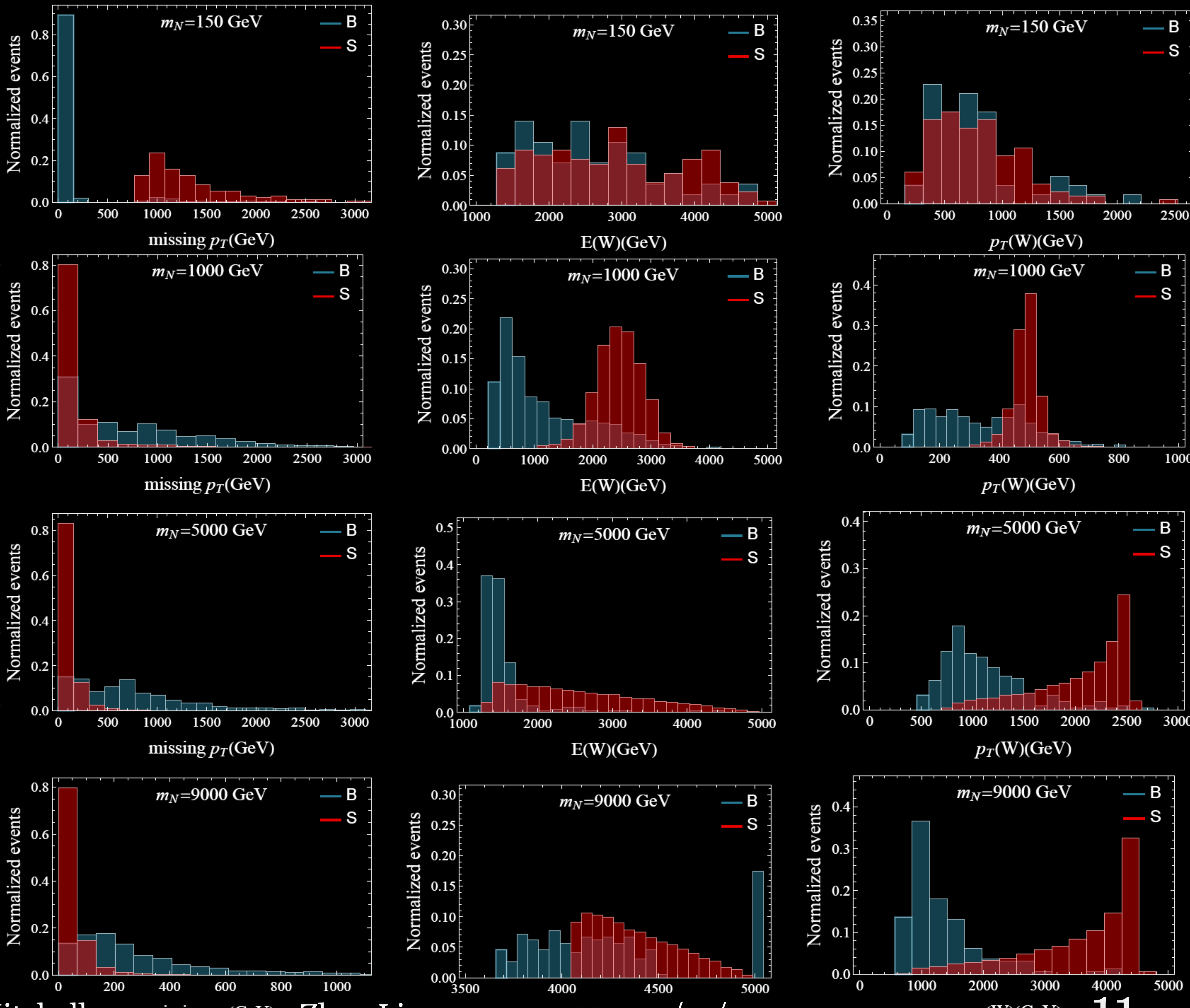


e flavor
Normalized events
0.15
0.10
0.05
0.00
0
200
400
600
800
1000
1200
1400
missing p_T(GeV)

Kinematics

μ flavor





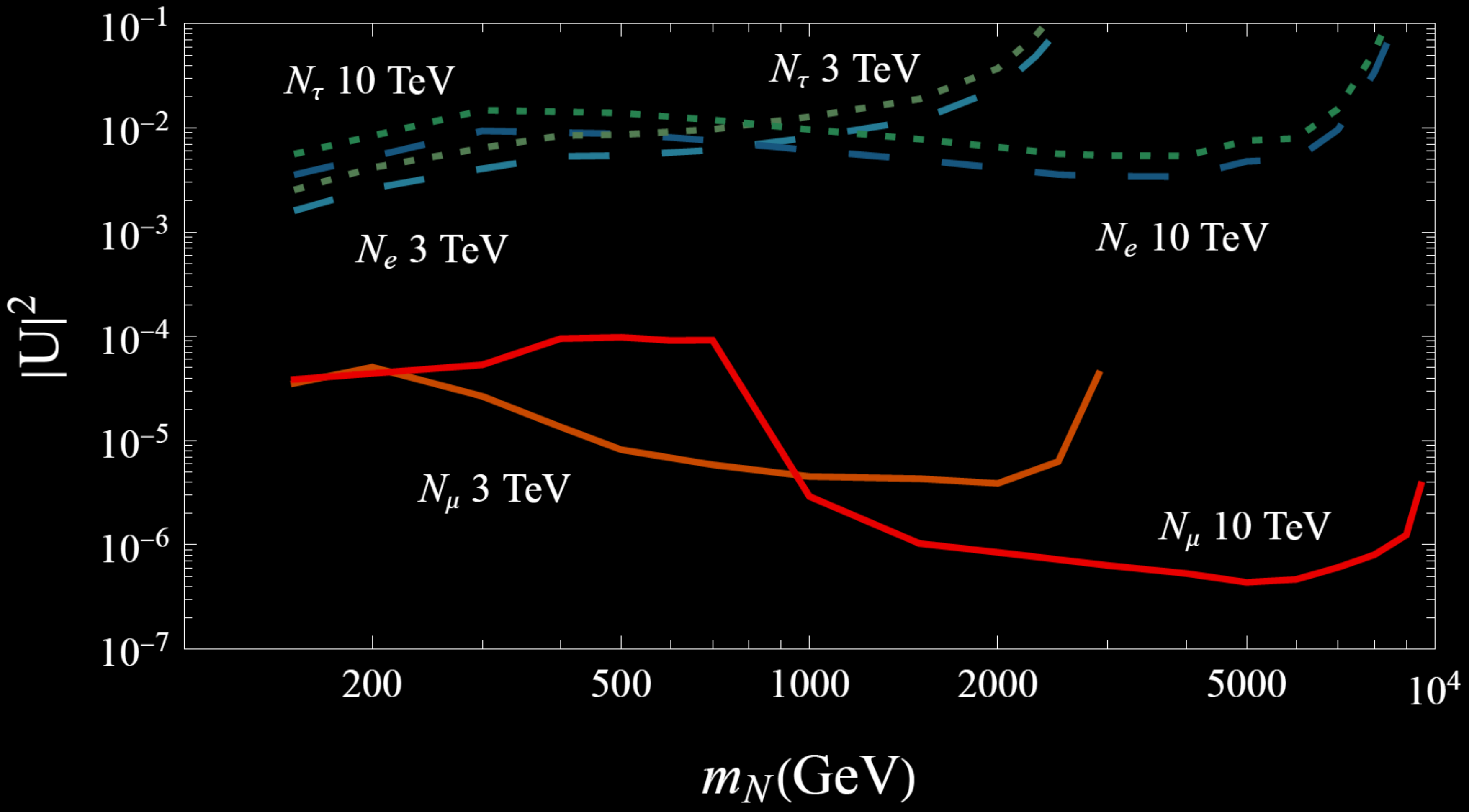
Cutflow Analysis

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

- Pre-selection: require single visible charged lepton
  - $|\eta(\mu)| < 2.5$ and $p_T(\mu) > 20$ GeV
- Central hadronic W selection: require visible on-shell W boson
  - $|\eta(W)| < 2.5$ and $p_T(W) > 20$ 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

Background process	Central W	Mass window 150/1000/5000/9000 GeV	Optimization
$\mu^+\mu^- \longrightarrow W^+\mu^-\bar{\nu}_\mu$	89.14%	0.28/2.4/3.2/1.6%	0.28/0.42/1.1/0.80%
$\mu^+\mu^- \longrightarrow Z\mu^+\mu^-$	1.60%	0/0.085/0.039/0.016%	0/0.051/0/0%
$\mu^+\mu^- \longrightarrow \mu^+\mu^-W^+\mu^-\bar{\nu}_\mu$	43.39%	1.6/0.75/0.011/0%	0/0.73/0.0083/0%
$\mu^+\mu^- \longrightarrow N_\mu\bar{\nu}_\mu$	Central W	Mass window	Optimization
$m_N = 150$ GeV	55.04%	55.04%	55.04%
$m_N = 1000$ GeV	54.75%	54.75%	51.63%
$m_N = 5000$ GeV	99.93%	99.93%	97.46%
$m_N = 9000$ GeV	99.99%	99.99%	98.27%

Projected sensitivity



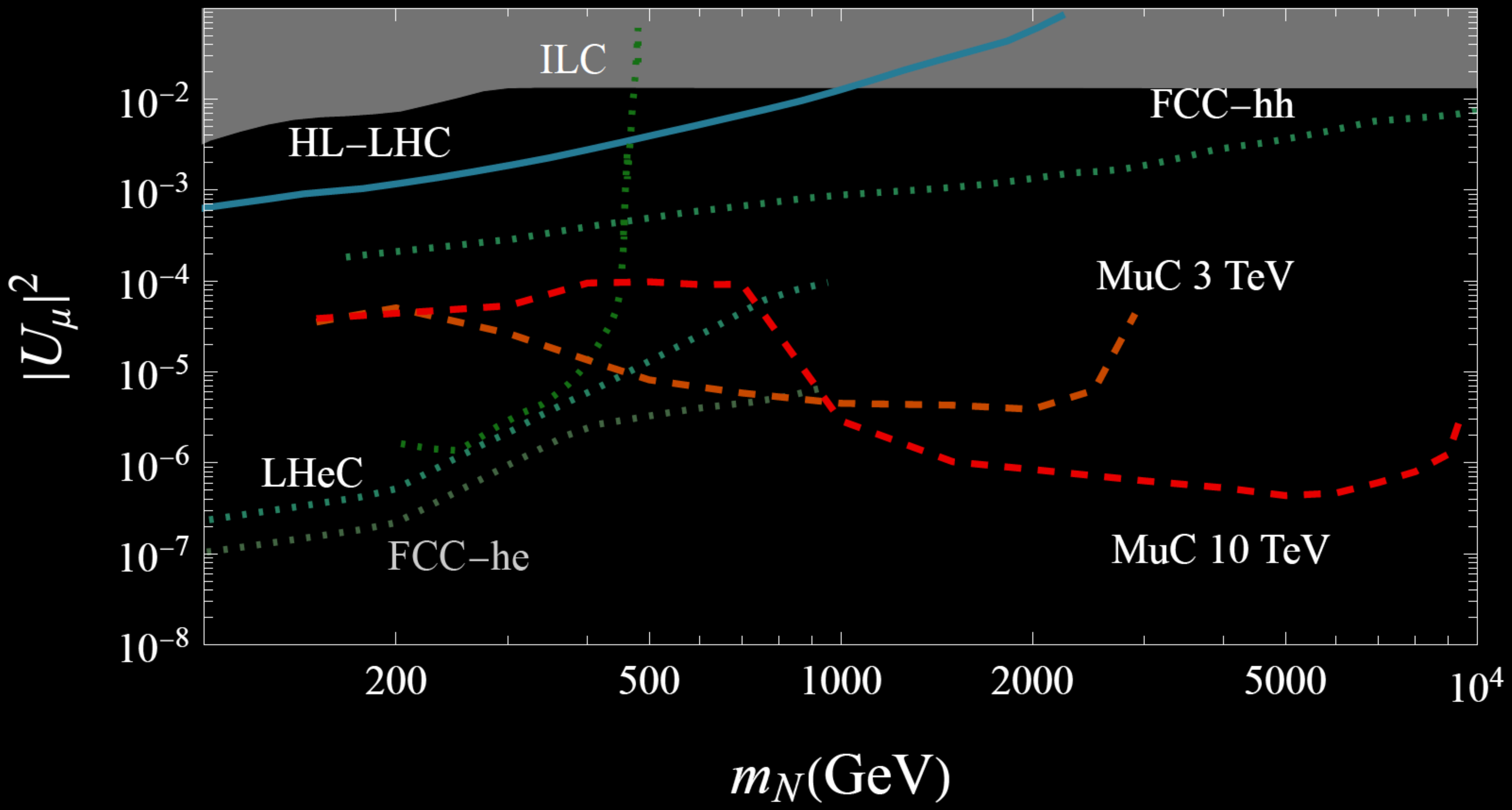
Sensitivity to e and τ flavor is moderate

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.

Projections w. others

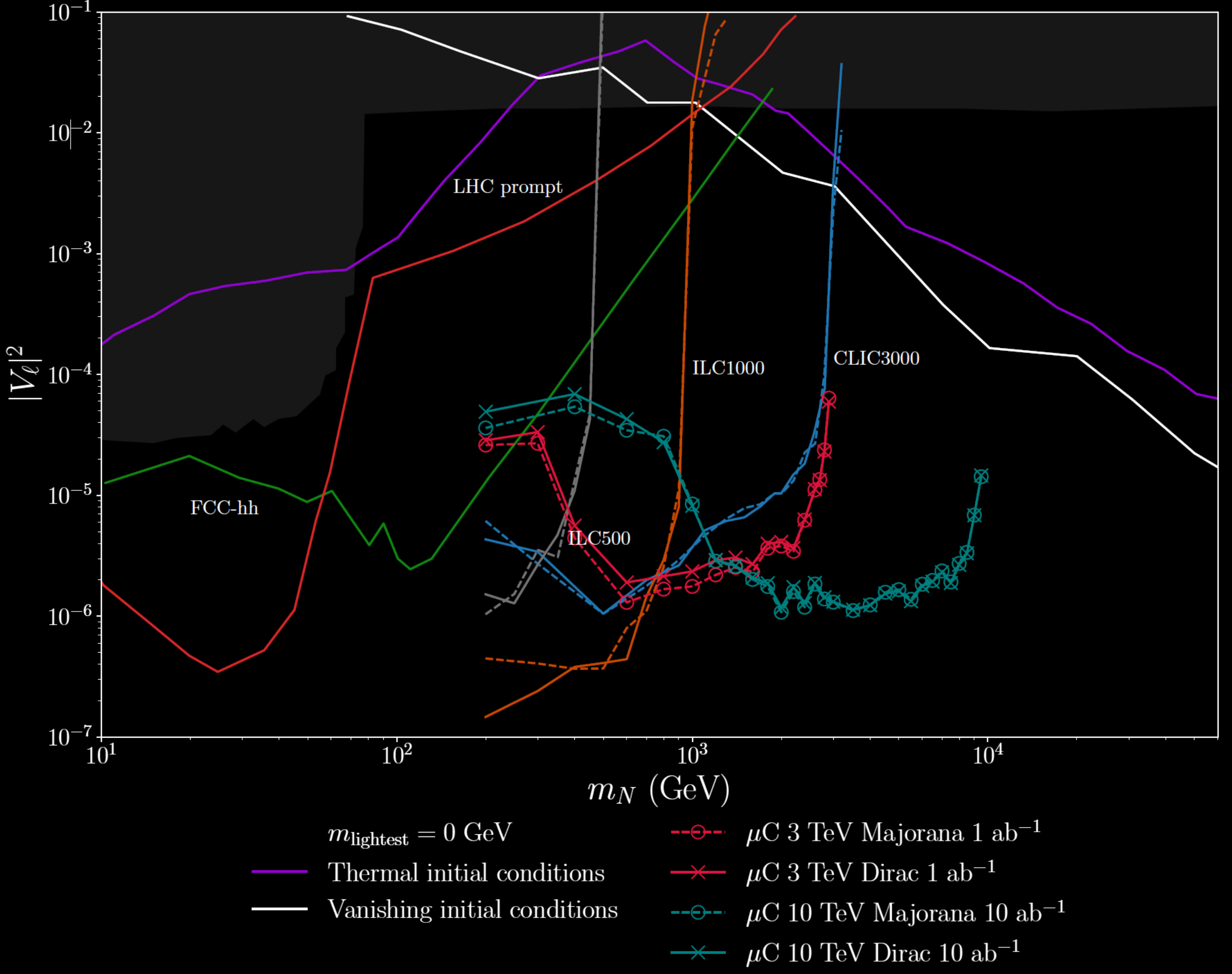


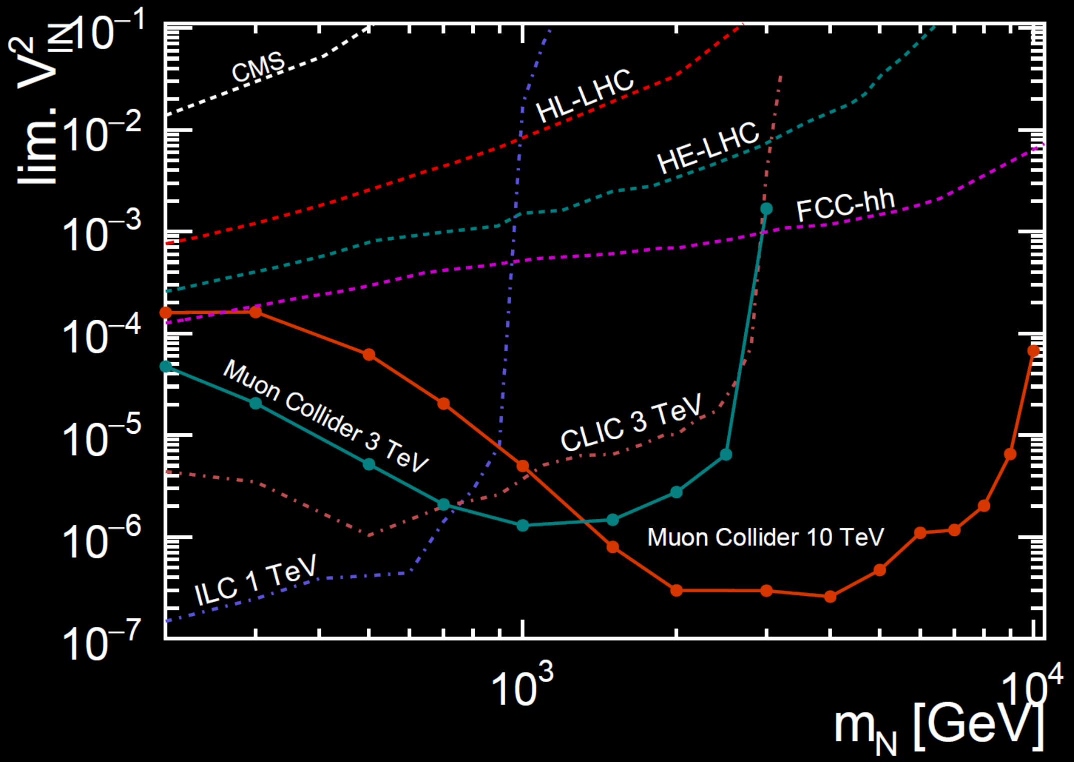
Focusing on the muon-flavored case:

LHC and EWPD probe $O(10^{-3})$

Muon Collider has unique roles in probing the parameter space (thanks to the t-channel enhancement).

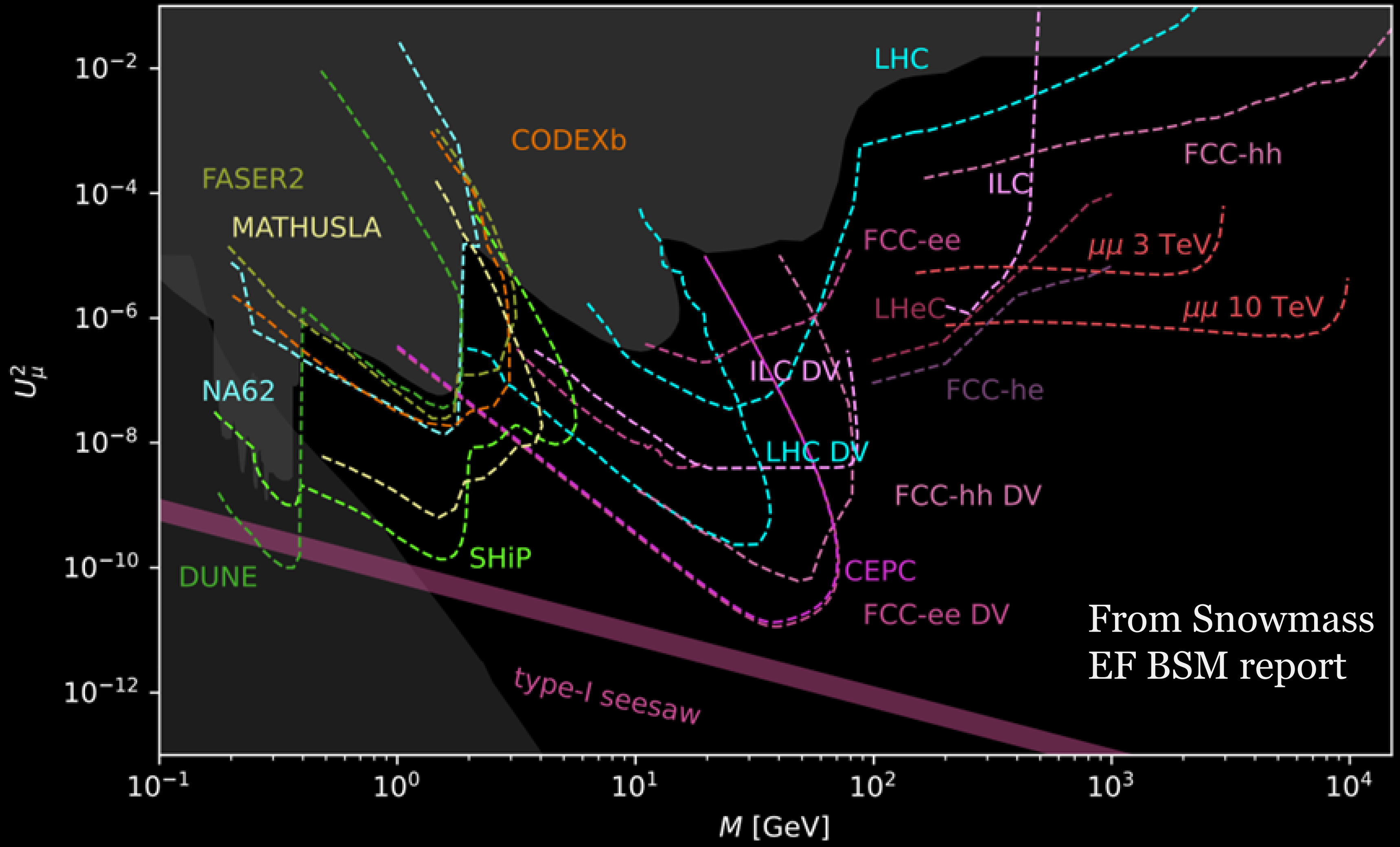
BDT-based projections



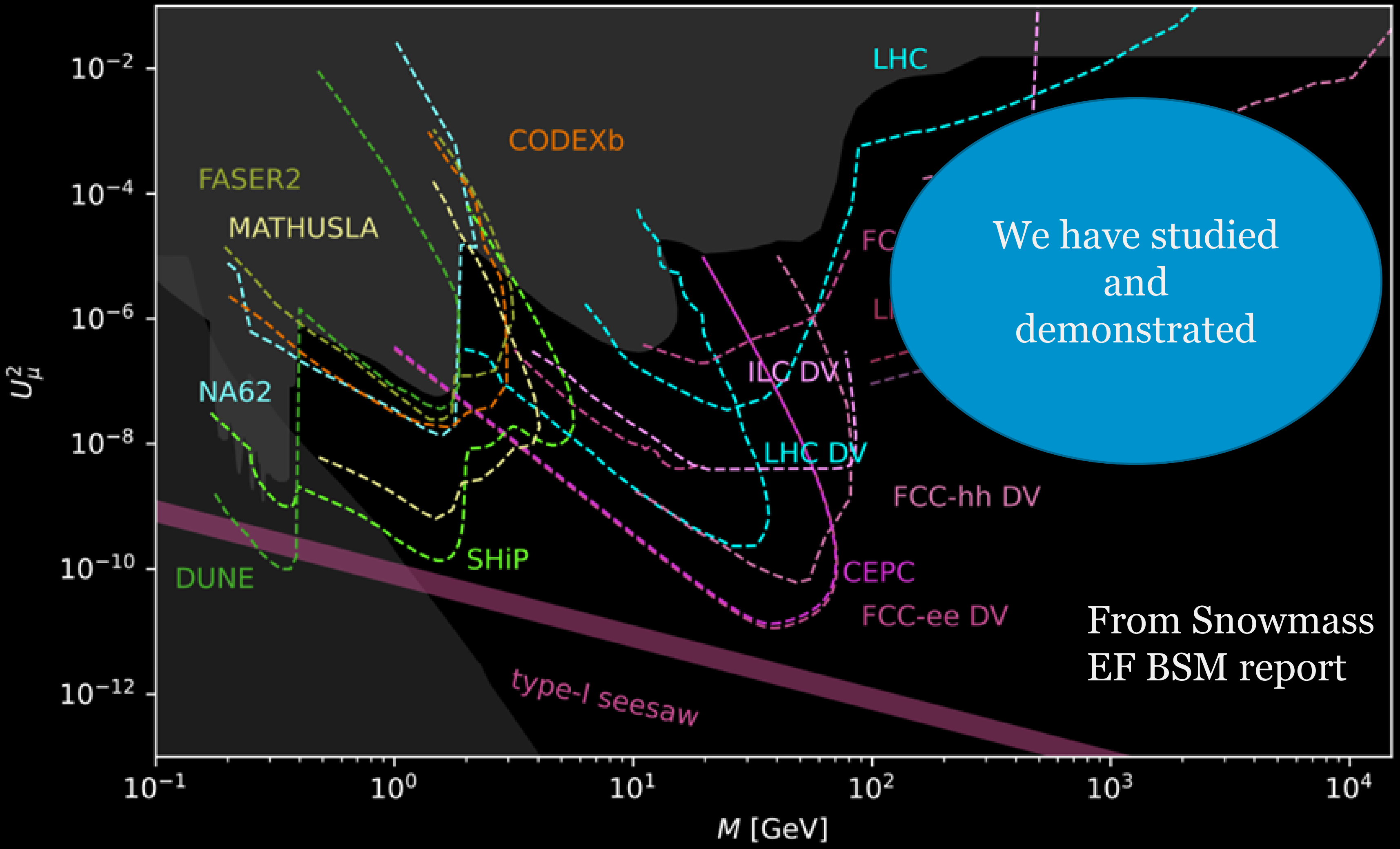


T.H. Kwok, L. Li, T. Liu and A. Rock, arXiv:2301.05177
K. Mekała, J. Reuter and A.F. Zarnecki, arXiv:2301.02602

New studies for other regions

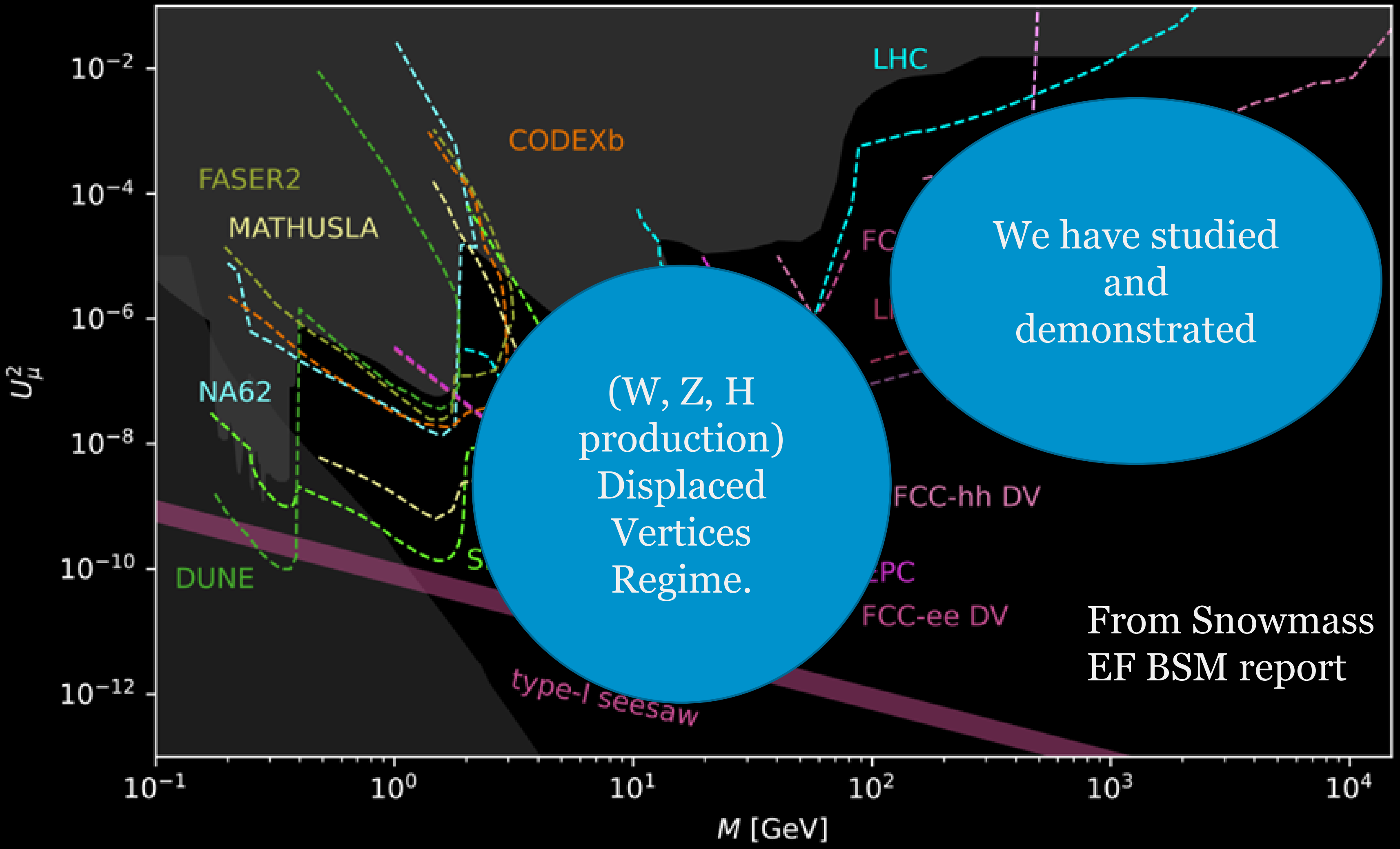


New studies for other regions



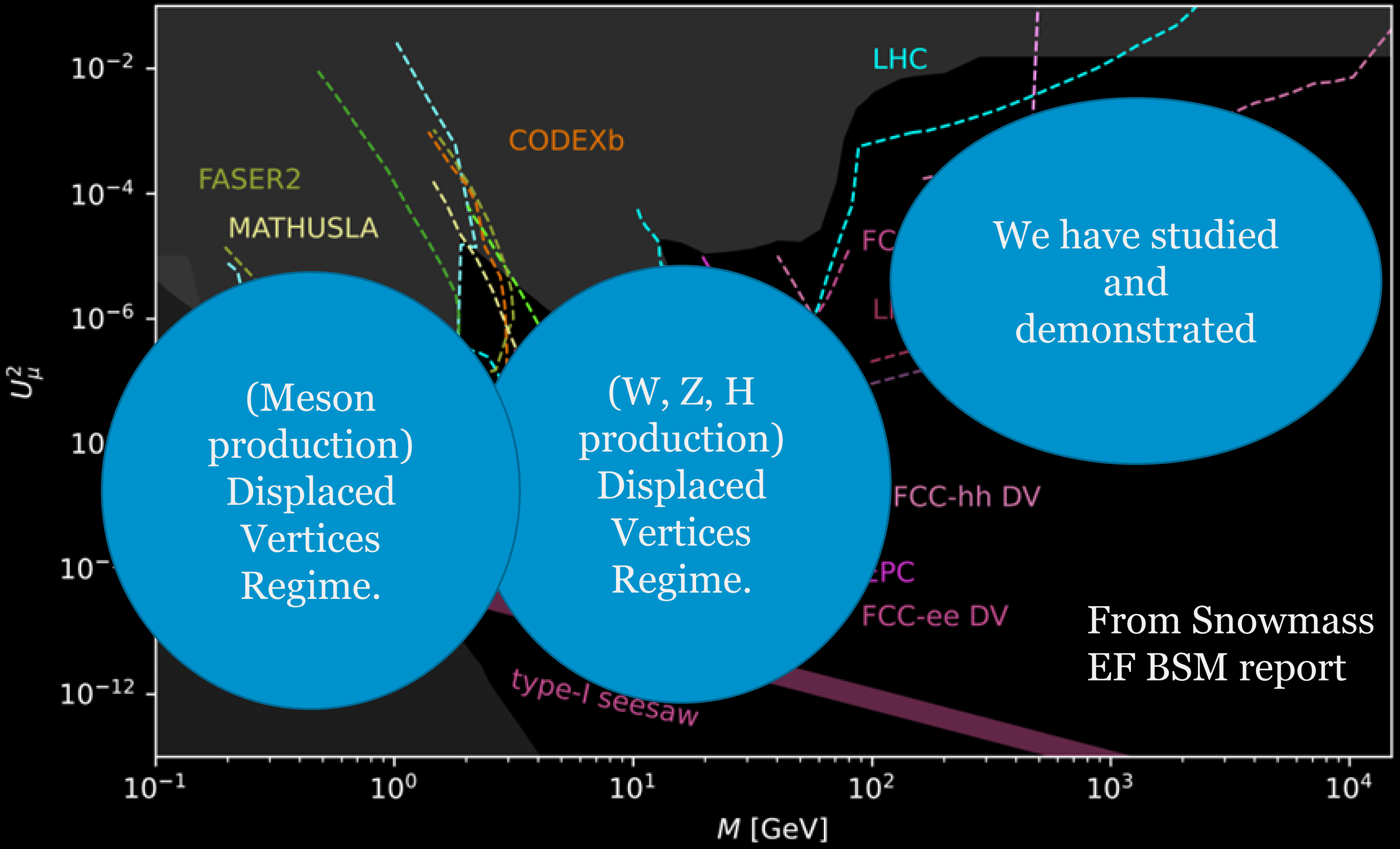
From Snowmass EF BSM report

New studies for other regions



From Snowmass EF BSM report

New studies for other regions



(Meson production) Displaced Vertices Regime.

(W, Z, H production) Displaced Vertices Regime.

We have studied and demonstrated

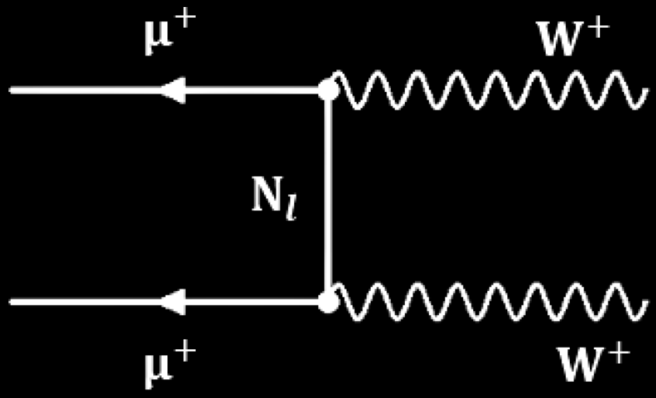
From Snowmass EF BSM report

A few other aspects

Same-sign muon collider

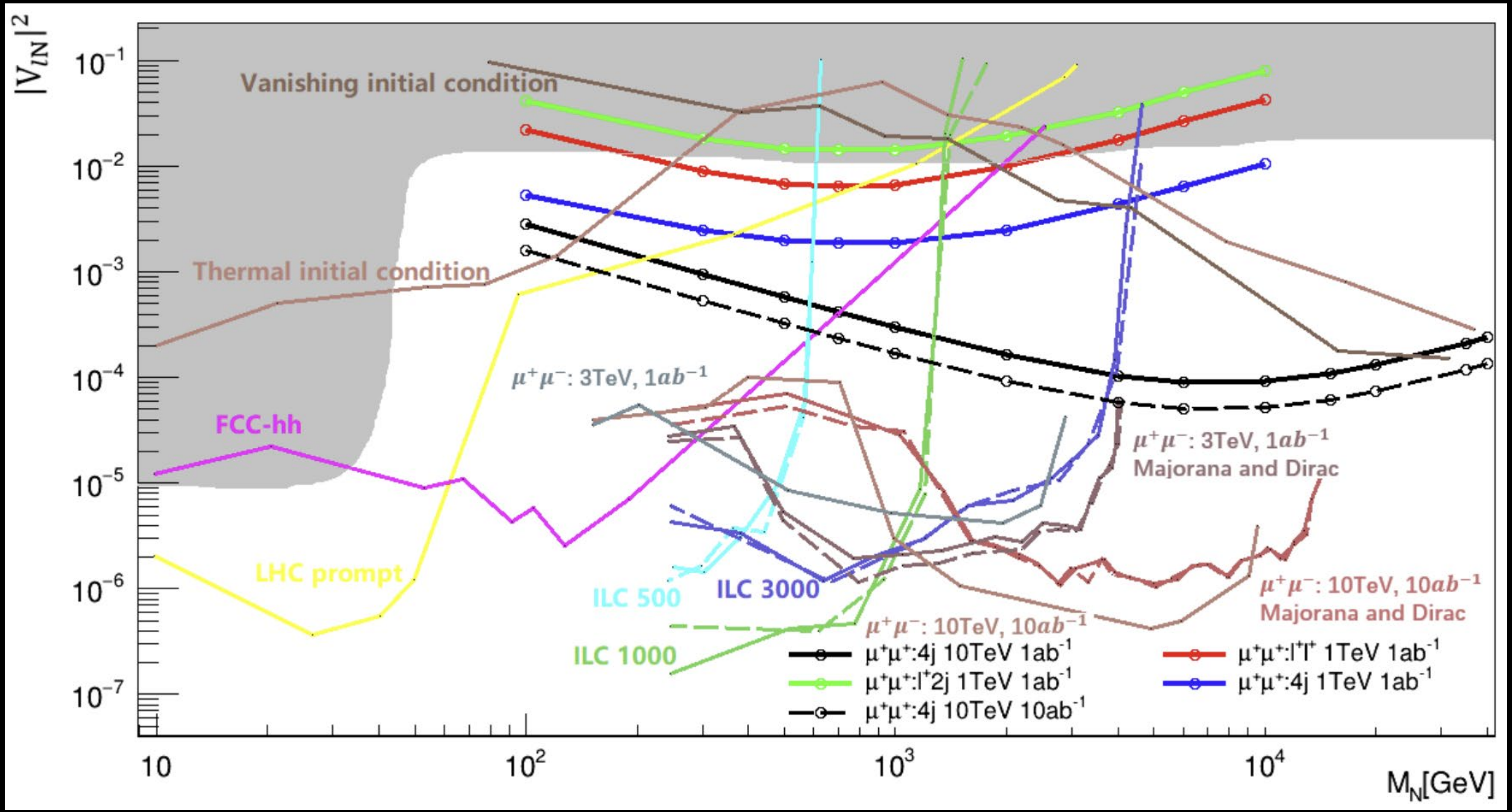
$\mu^+\mu^+$ collider, KEK muon program motivated, see, Kitano et al, 2304.14020, 2210.11083, 2201.06664

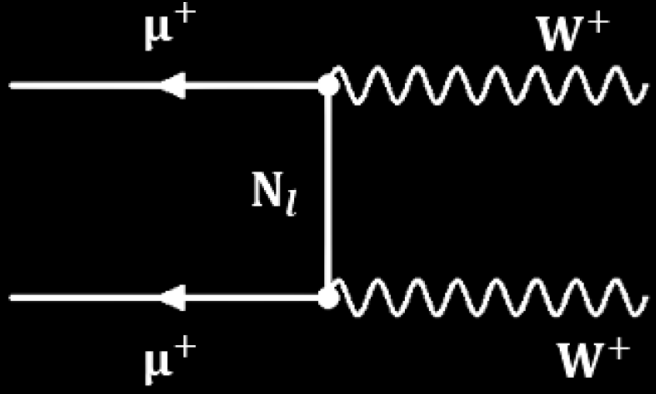
Same-sign muon collider



$\mu^+\mu^+$ collider, KEK muon program motivated, see, Kitano et al, 2304.14020, 2210.11083, 2201.06664

Same-sign muon collider

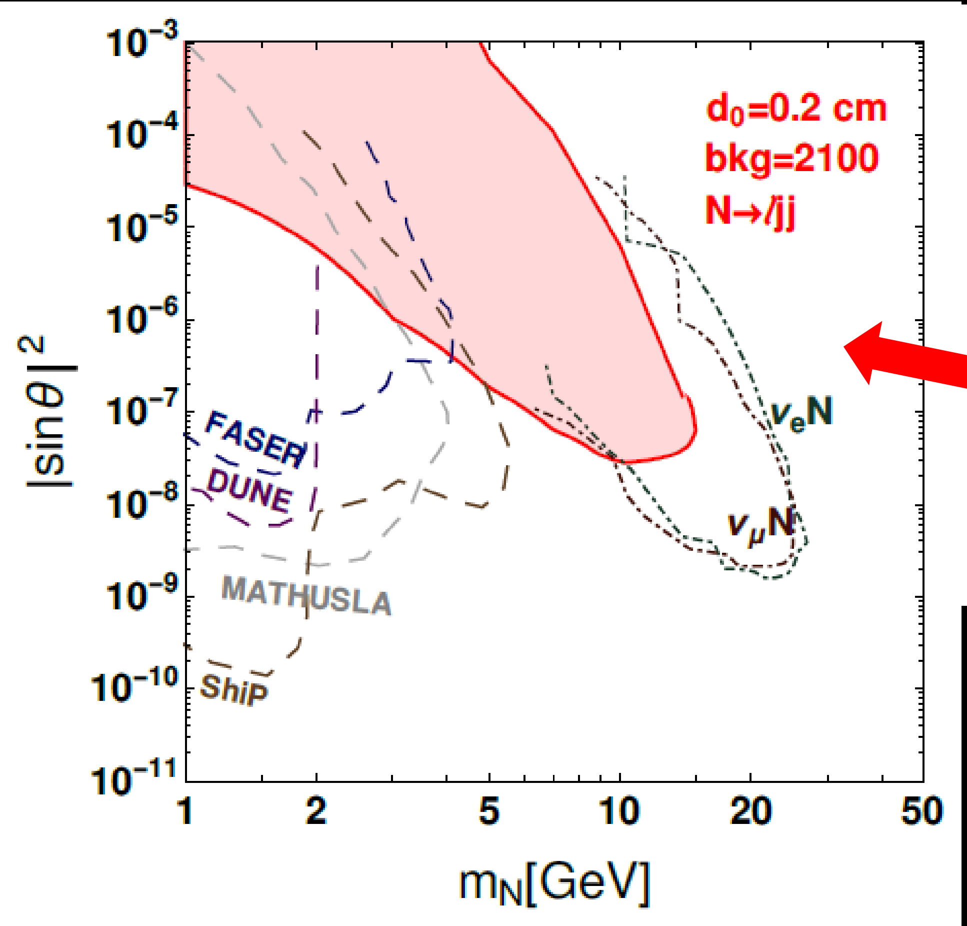


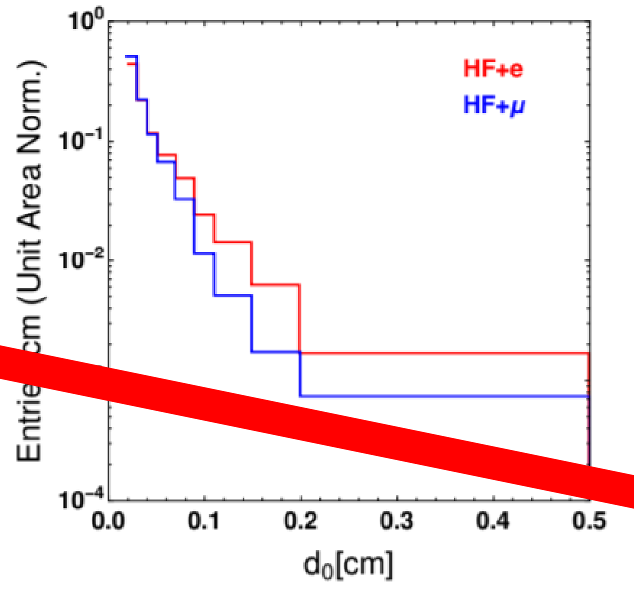


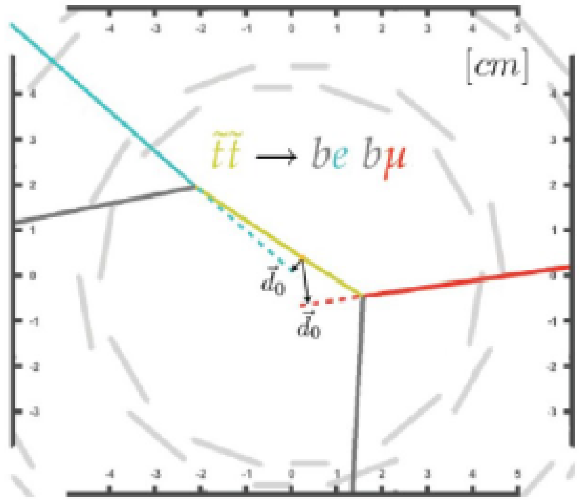
$\mu^+\mu^+$ collider, KEK muon program motivated, see, Kitano et al, 2304.14020, 2210.11083, 2201.06664

Jiang, Yang, Qian, Ban, Li, You, Li, 2304.04483

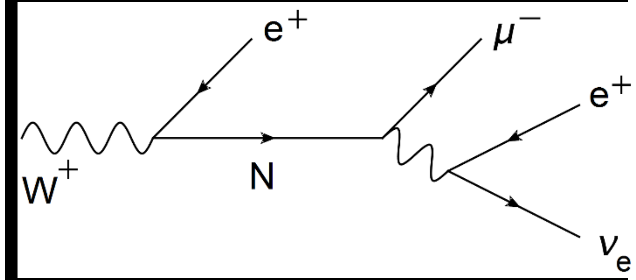
displaced lepton for HNL



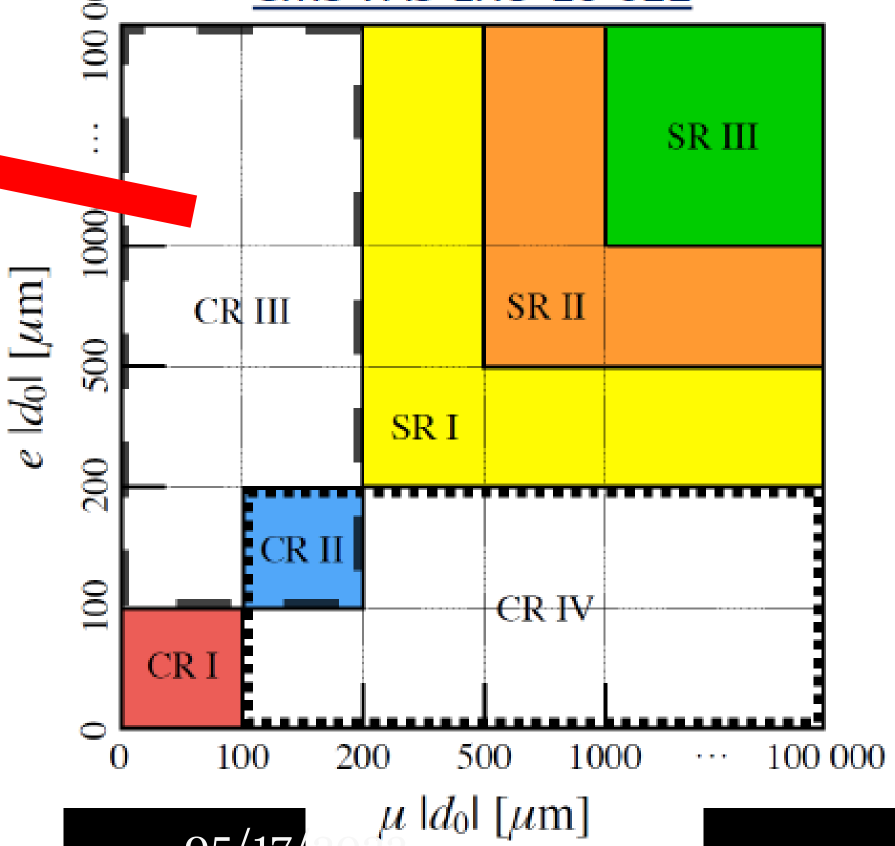




← Single displaced leptons not from the same vertex; focused on e-mu state



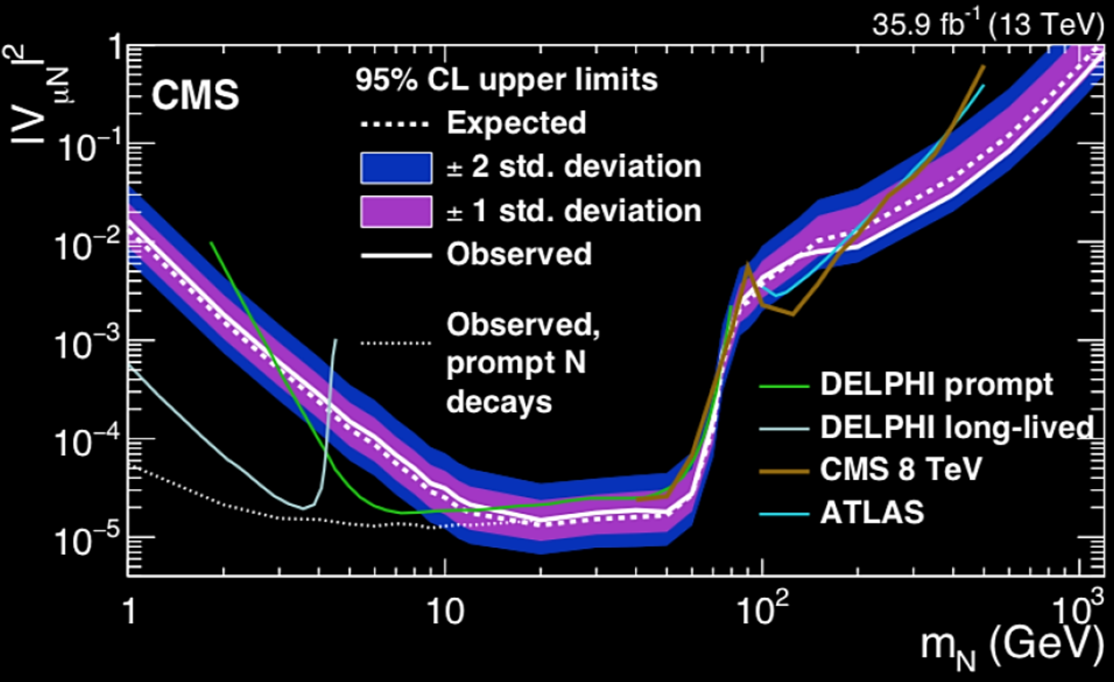
CMS-PAS-EXO-16-022

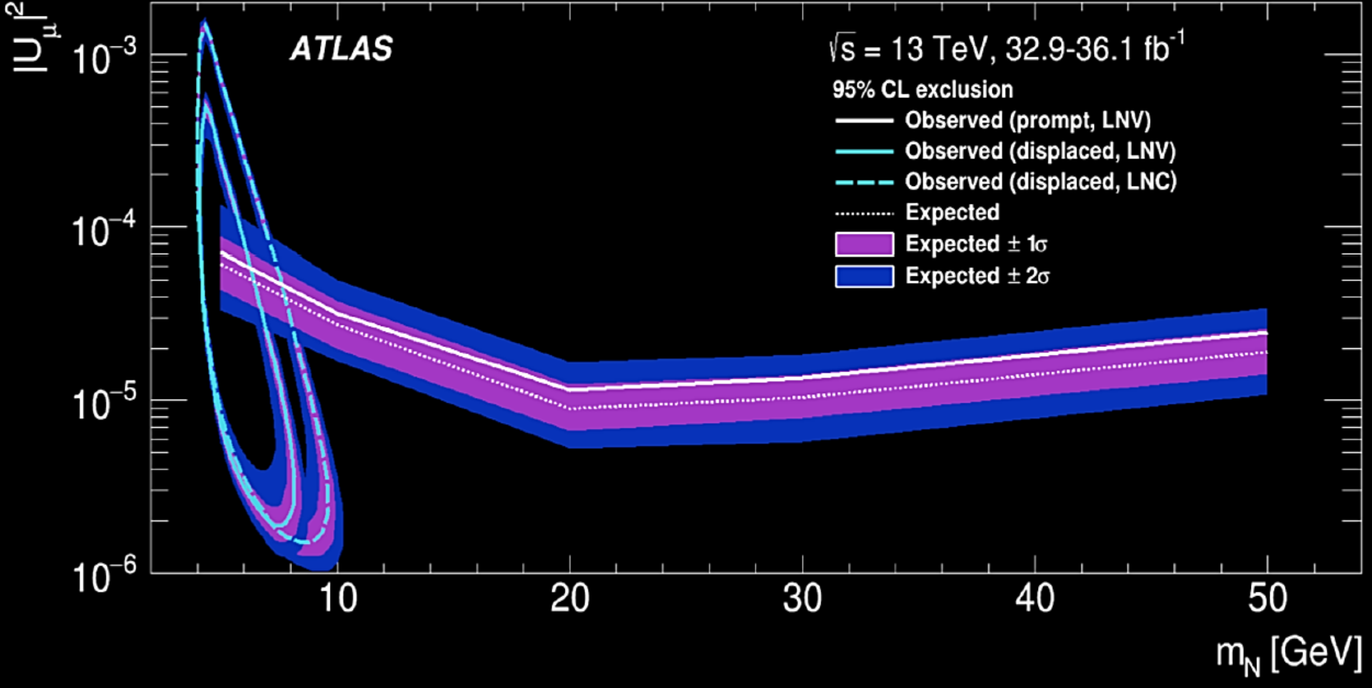


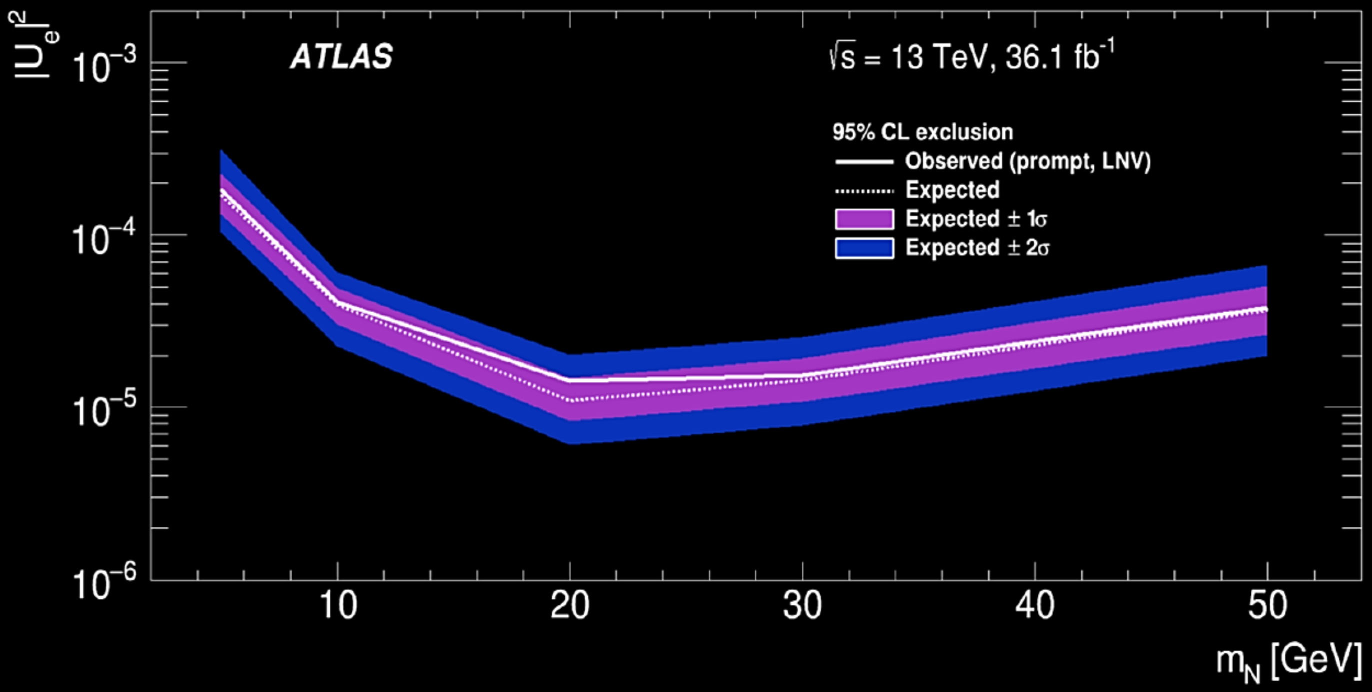
Digging hard and use the control region studies to propose new searches on sterile neutrinos.

ZL, J. Liu, L.-T. Wang, X. Wang, 1904.01020

Current LHC


35.9 fb^{-1} (13 TeV)
CMS
95% CL upper limits
Expected
± 2 std. deviation
± 1 std. deviation
Observed
Observed, prompt N decays
DELPHI prompt
DELPHI long-lived
CMS 8 TeV
ATLAS
$|V_{\mu N}|^2$
m_N (GeV)


ATLAS
$\sqrt{s}$ = 13 TeV, 32.9-36.1 fb^{-1}
95% CL exclusion
Observed (prompt, LNV)
Observed (displaced, LNV)
Observed (displaced, LNC)
Expected
Expected ± 1σ
Expected ± 2σ
$|U_\mu|^2$
m_N [GeV]

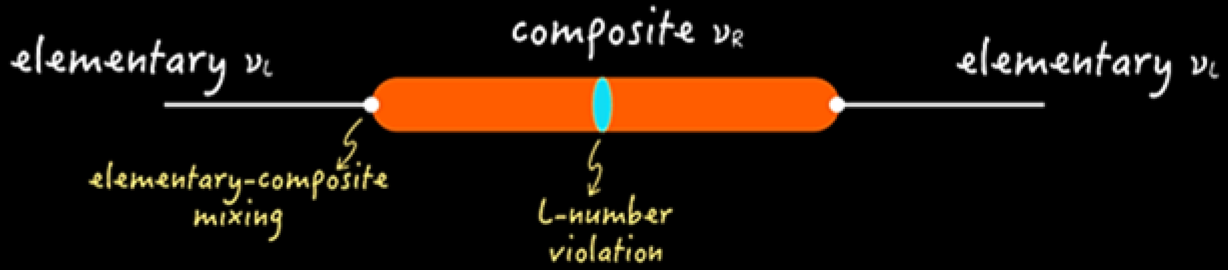

ATLAS
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
95% CL exclusion
Observed (prompt, LNV)
Expected
Expected ± 1σ
Expected ± 2σ
$|U_e|^2$
m_N [GeV]

Further motivating Inverse Seesaw

$$L_{IR} \ni -m_N \bar{N} N - (\lambda \bar{L} \tilde{H} N_R + \mu N_L^2 + h.c.)$$

$$m_\nu \approx \mu \left(\frac{\lambda v_{EW}}{M_N} \right)^2$$

Further motivating Inverse Seesaw



Chacko, Fox, ZL, Harnik, 2012.01443;

General CFT:

$$L_{UV} \supset L_{CFT} + \frac{\hat{\lambda}}{M^{\Delta-3/2}} \bar{L}\tilde{H} O_N + \frac{\hat{\mu}}{M^{\Delta_{2N}-4}} O_{2N}$$

CFT generates

CFT deformation generates

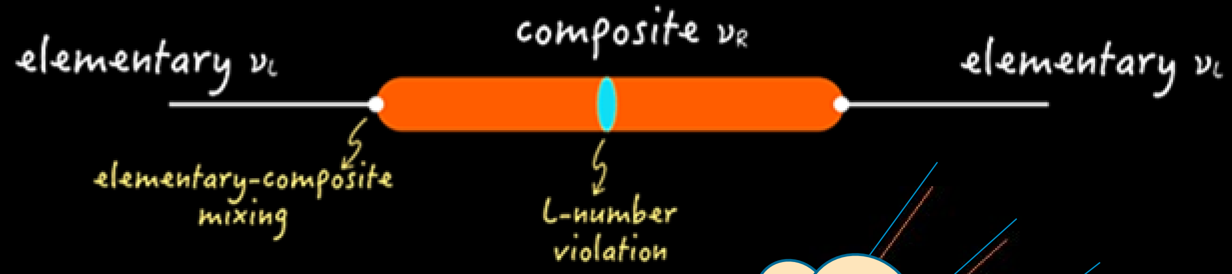
$$L_{IR} \ni -m_N \bar{N} N - (\lambda \bar{L} \tilde{H} N_R + \mu N_L^2 + h.c.)$$

$$\Lambda \quad C_\lambda \hat{\lambda} \left(\frac{\Lambda}{M}\right)^{\Delta-\frac{3}{2}} \quad C_\mu \hat{\mu} \left(\frac{\Lambda}{M}\right)^{\Delta_{2N}-4}$$

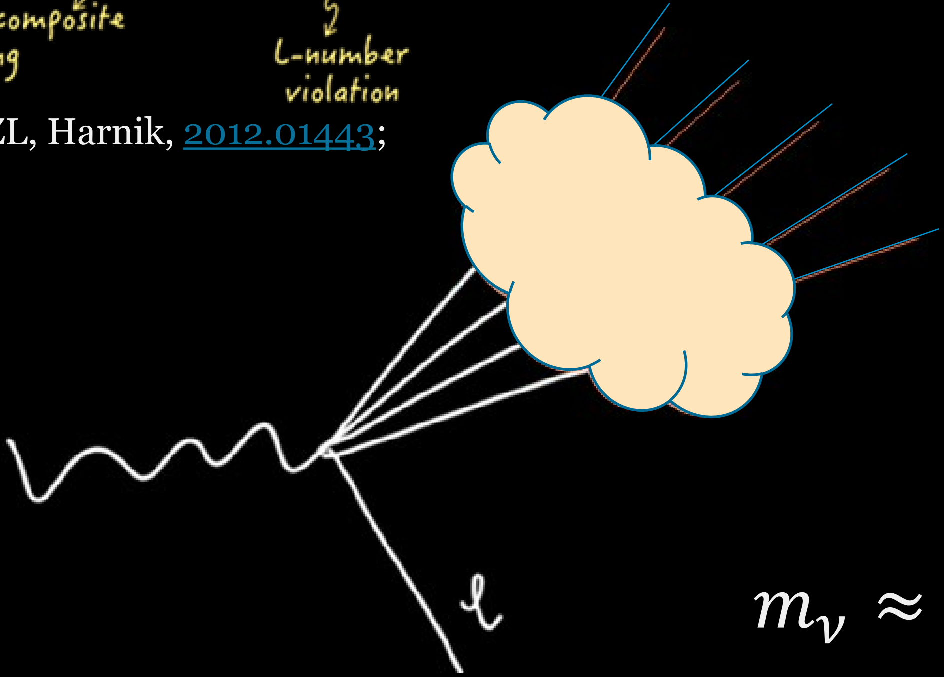
$$m_\nu \approx \mu \left(\frac{\lambda v_{EW}}{M_N}\right)^2$$

Arkani-Hamed, Grossman, hep-ph/9806223, Okui, hep-ph/0405083, Grossman, Tsai, 0811.0871, Grossman, Robinson, 1009.2781, McDonald, 1010.2659, Robinson, Tsai, 1205.0569, 1404.7118...

Further motivating Inverse Seesaw



Chacko, Fox, ZL, Harnik, 2012.01443;



A shower of Sterile Neutrinos…
Chacko, Dev, ZL, Sanket, in progress;

General CFT:

$$L_{UV} \supset L_{CFT} + \frac{\hat{\lambda}}{M^{\Delta-3/2}} \bar{L}\tilde{H} O_N + \frac{\hat{\mu}}{M^{\Delta_{2N}-4}} O_{2N}$$

CFT generates

CFT deformation generates

$$L_{IR} \ni -m_N \bar{N} N - (\lambda \bar{L}\tilde{H} N_R + \mu N_L^2 + h.c.)$$

$$\Lambda \quad C_\lambda \hat{\lambda} \left(\frac{\Lambda}{M}\right)^{\Delta-\frac{3}{2}} \quad C_\mu \hat{\mu} \left(\frac{\Lambda}{M}\right)^{\Delta_{2N}-4}$$

$$m_\nu \approx \mu \left(\frac{\lambda v_{EW}}{M_N}\right)^2$$

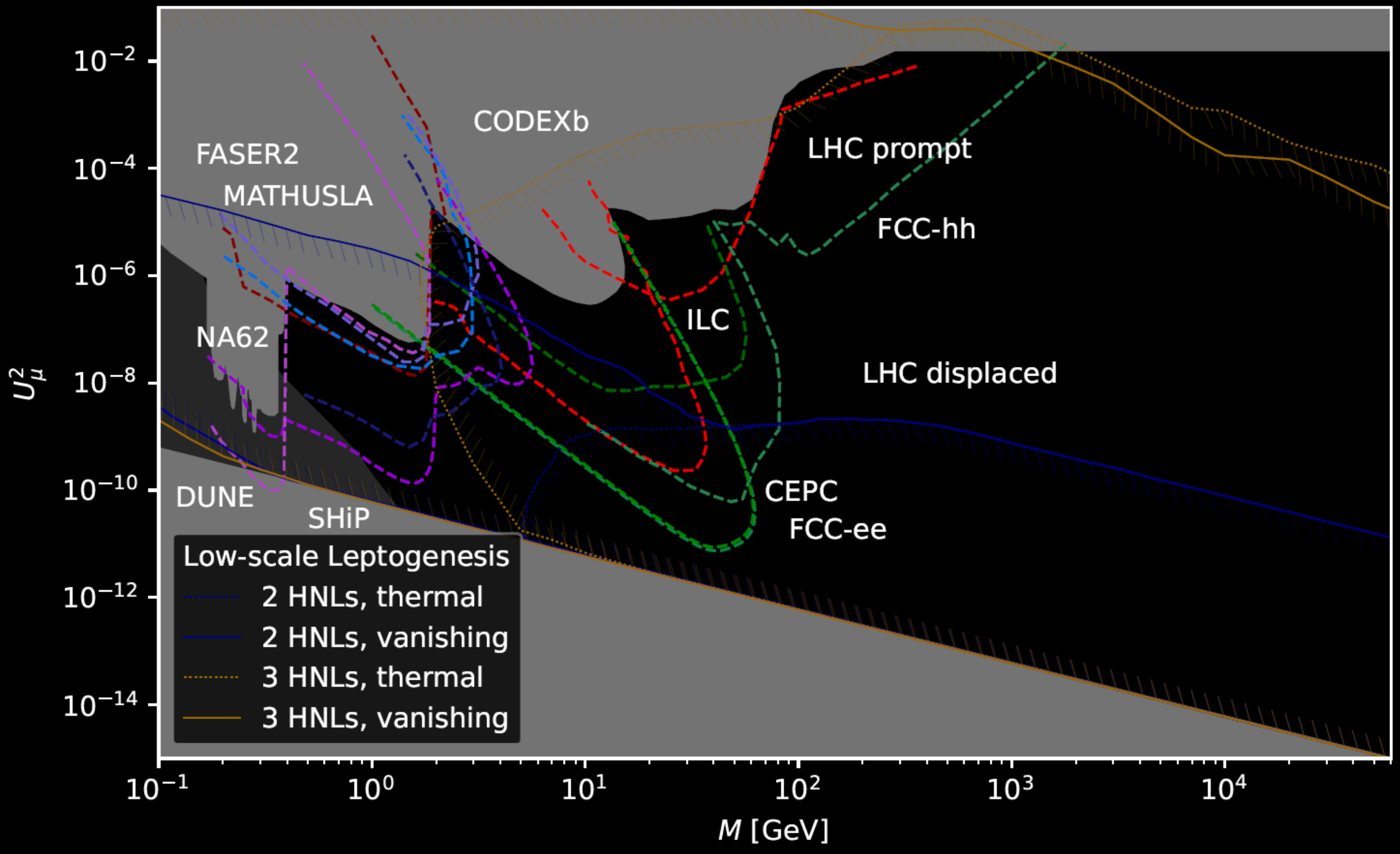
Arkani-Hamed, Grossman, hep-ph/9806223, Okui, hep-ph/0405083, Grossman, Tsai, 0811.0871, Grossman, Robinson, 1009.2781, McDonald, 1010.2659, Robinson, Tsai, 1205.0569, 1404.7118…

Conclusion

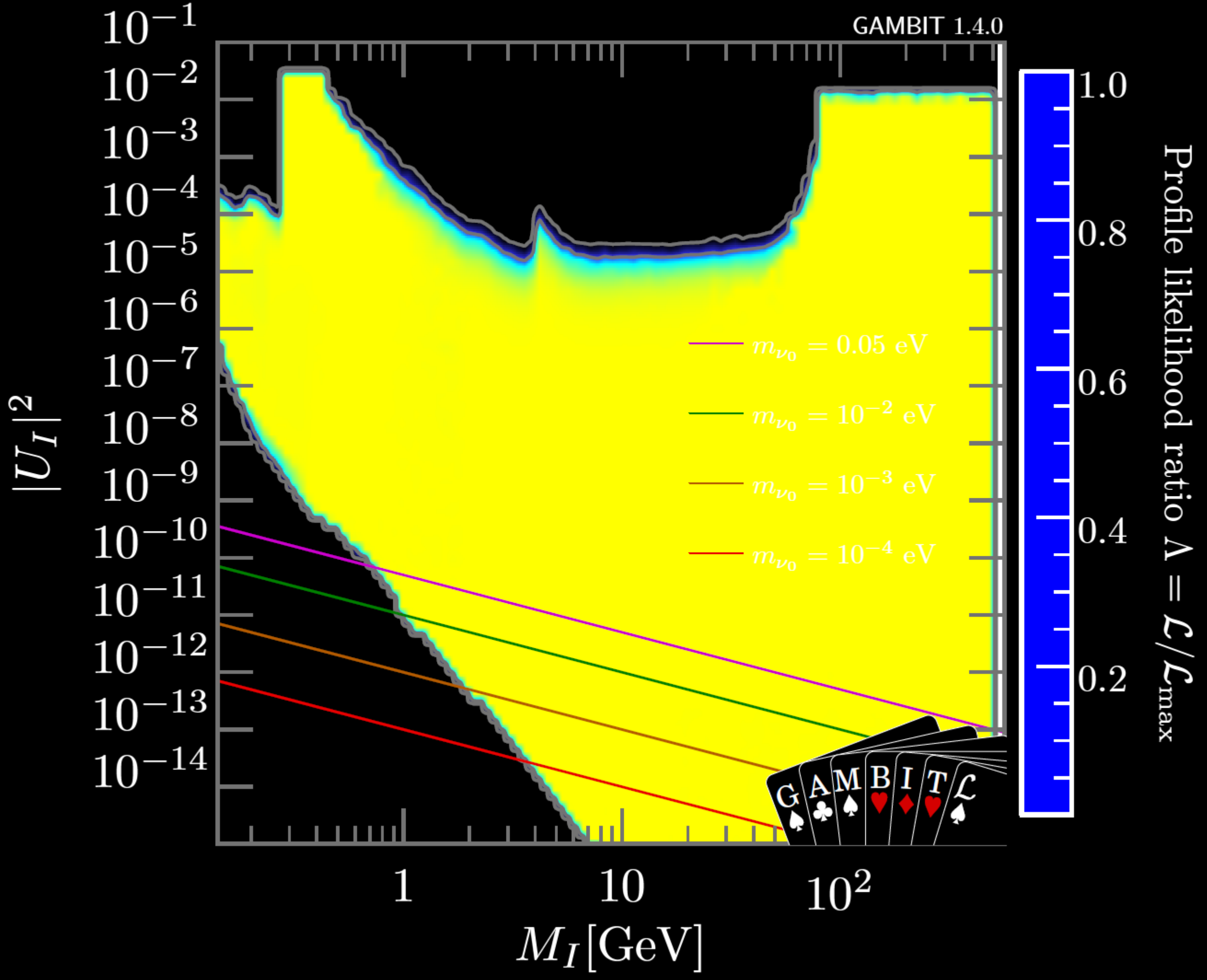
- Muon Collider is a good platform to probe the TeV scale HNL.

  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.



CODEXb
FASER2
MATHUSLA
LHC prompt
FCC-hh
ILC
NA62
LHC displaced
CEPC
FCC-ee
DUNE
SHiP
Low-scale Leptogenesis
2 HNLs, thermal
2 HNLs, vanishing
3 HNLs, thermal
3 HNLs, vanishing
U_μ^2
M [GeV]
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}



GAMBIT 1.4.0
$m_{\nu_0} = 0.05$ eV
$m_{\nu_0} = 10^{-2}$ eV
$m_{\nu_0} = 10^{-3}$ eV
$m_{\nu_0} = 10^{-4}$ eV
$|U_I|^2$
M_I[GeV]
Profile likelihood ratio $\Lambda = \mathcal{L}/\mathcal{L}_{\max}$