Enhanced Production of Sterile Neutrinos at Accelerator Experiments

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with M. Pospelov and B. Shuve; 1604.06099 + to appear

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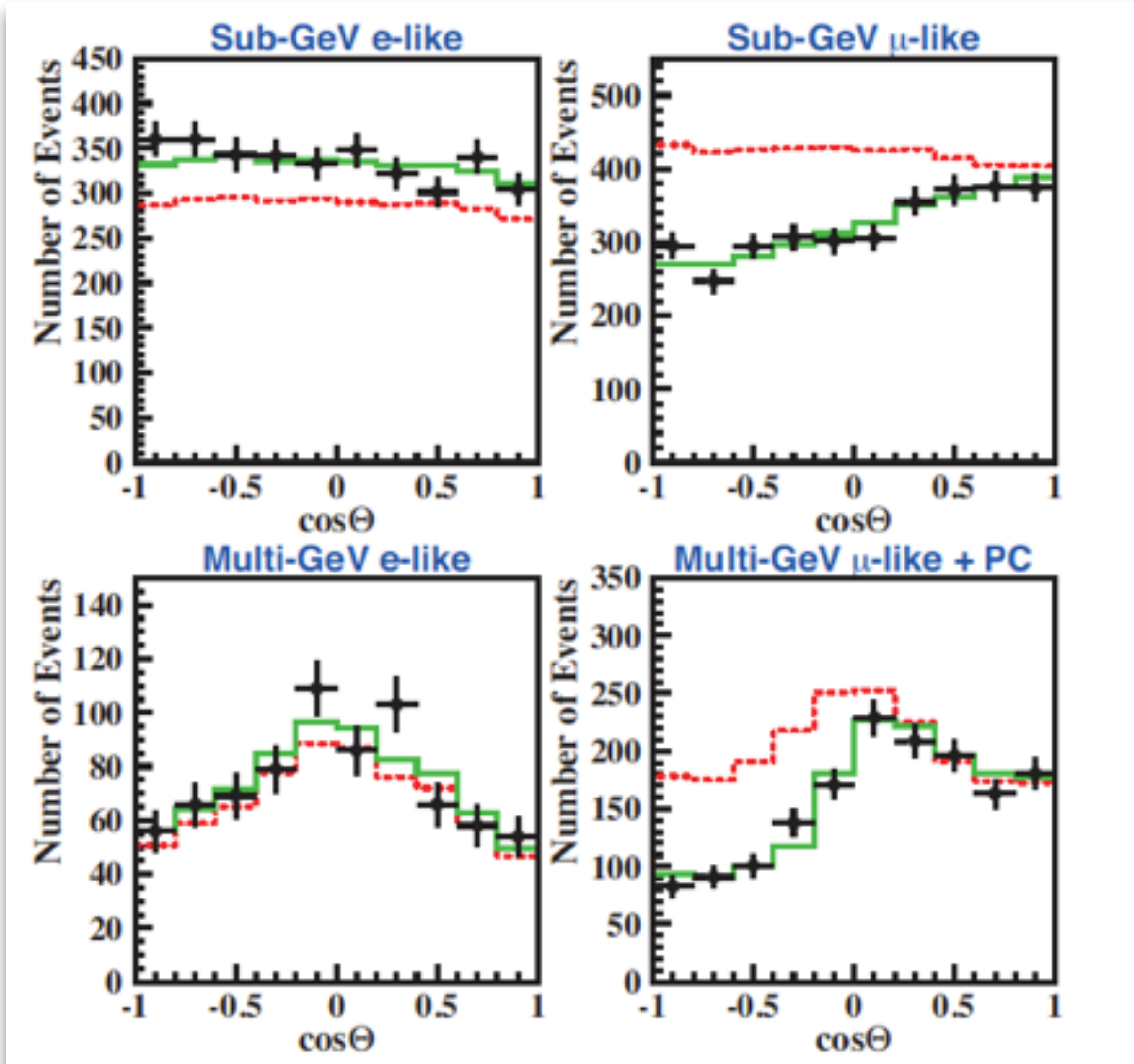
Neutrino Oscillations and Neutrino Mass

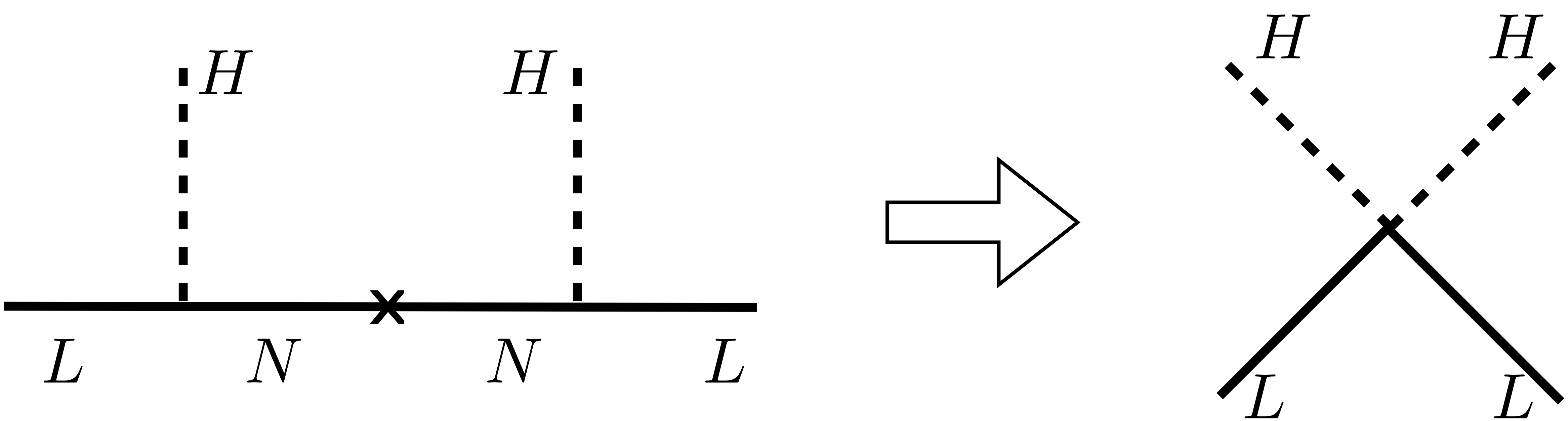


Takaaki Kajita and Arthur McDonald
2015 Nobel Prize in Physics

- Firm empirical evidence of new physics
- New dynamics potentially accessible in laboratory experiments

Type I Seesaw

$$yLHN + \frac{1}{2}MN^2 + \text{h.c.}$$



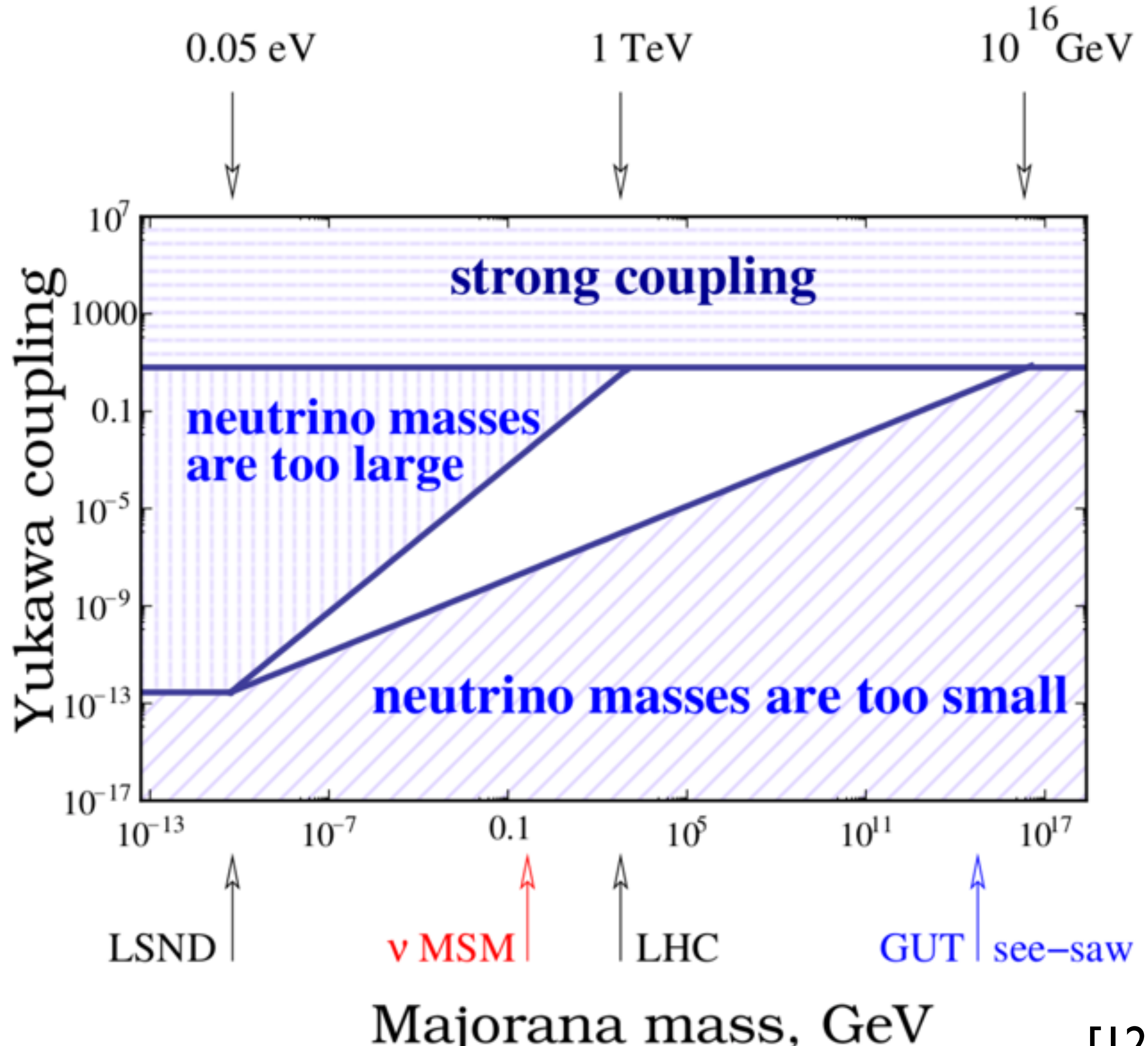
$$\mathcal{M}_\nu = \begin{pmatrix} 0 & yv \\ yv & M \end{pmatrix} \quad \Rightarrow \quad m_\nu \sim \frac{y^2v^2}{M}$$

What is the mass of *N*?

- High Scale, 10^9 - 10^{14} GeV
  - GUTs, "natural" Yukawa couplings, leptogenesis
- Weak Scale, 10^2 - 10^3 GeV
  - Hierarchy problem
- keV Scale
  - Sterile neutrino dark matter
- eV Scale
  - Short baseline, reactor, gallium anomalies

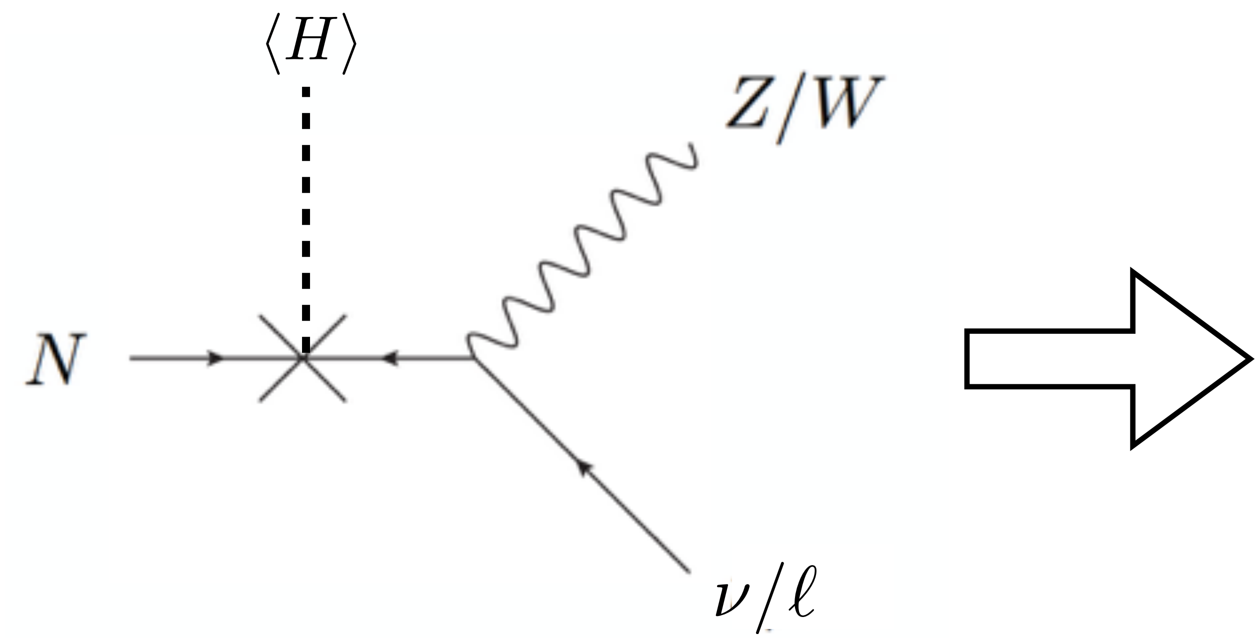
No clear empirical preference for a particular scale

We must search for *N* in as broad a manner as possible and at all accessible scales!


0.05 eV
1 TeV
10 16 GeV
strong coupling
neutrino masses
are too large
neutrino masses are too small
Yukawa coupling
10^7
1000
0.1
10^-5
10^-9
10^-13
10^-17
10^-13
10^-7
0.1
10^5
10^11
10^17
LSND
ν MSM
LHC
GUT
see-saw
Majorana mass, GeV

[1204.5379]

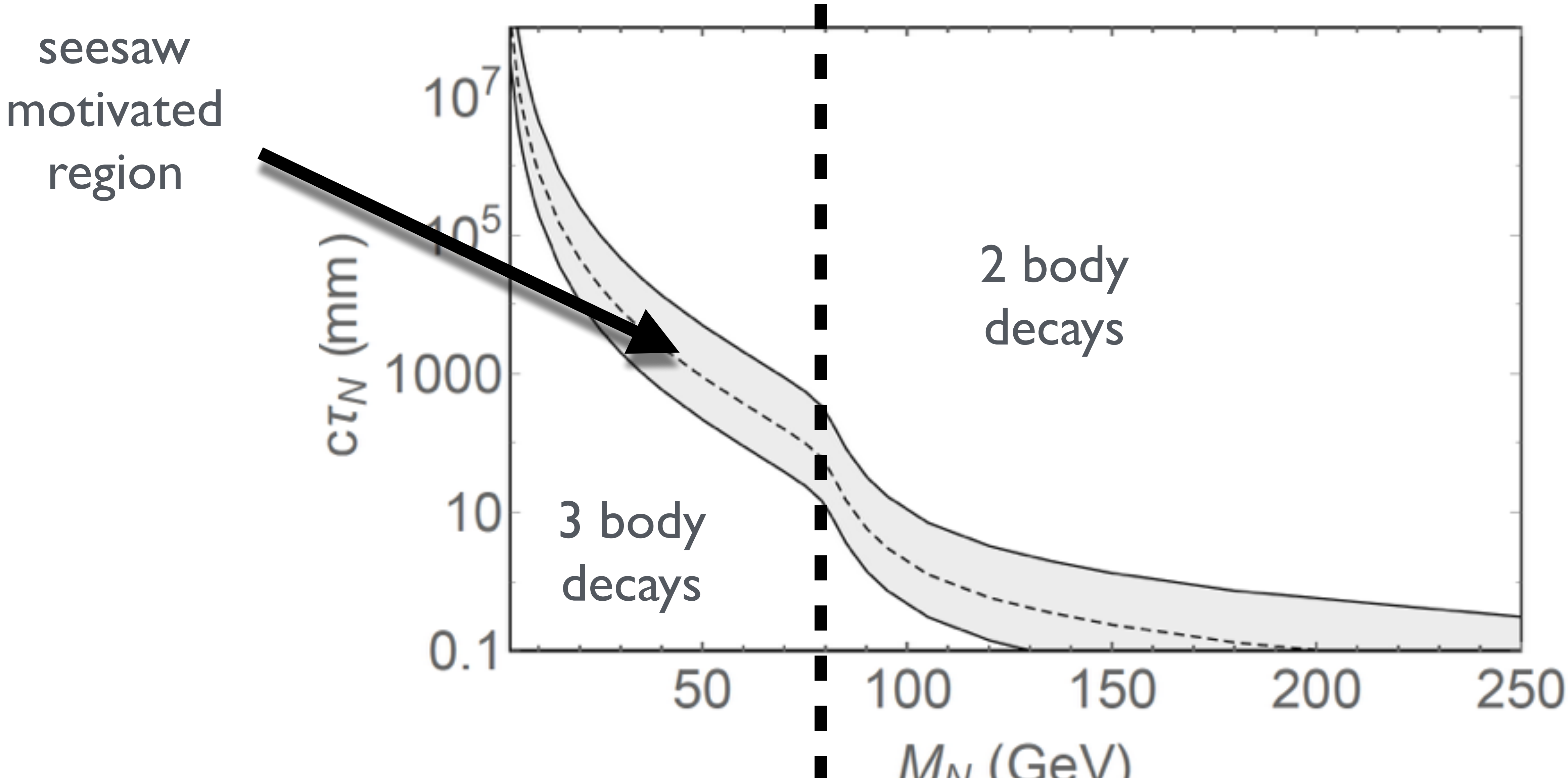
Weak interactions of *N*



$$\theta \frac{g}{\sqrt{2}} W_\mu^- \ell^\dagger \bar{\sigma}^\mu N + \text{h.c.} + \ldots$$

$$\theta \sim \frac{yv}{M} \sim \sqrt{\frac{m_\nu}{M}} \sim 10^{-5} \times \left(\frac{m_\nu}{0.05\ \text{eV}}\right)^{1/2} \left(\frac{\text{GeV}}{M}\right)^{1/2}$$

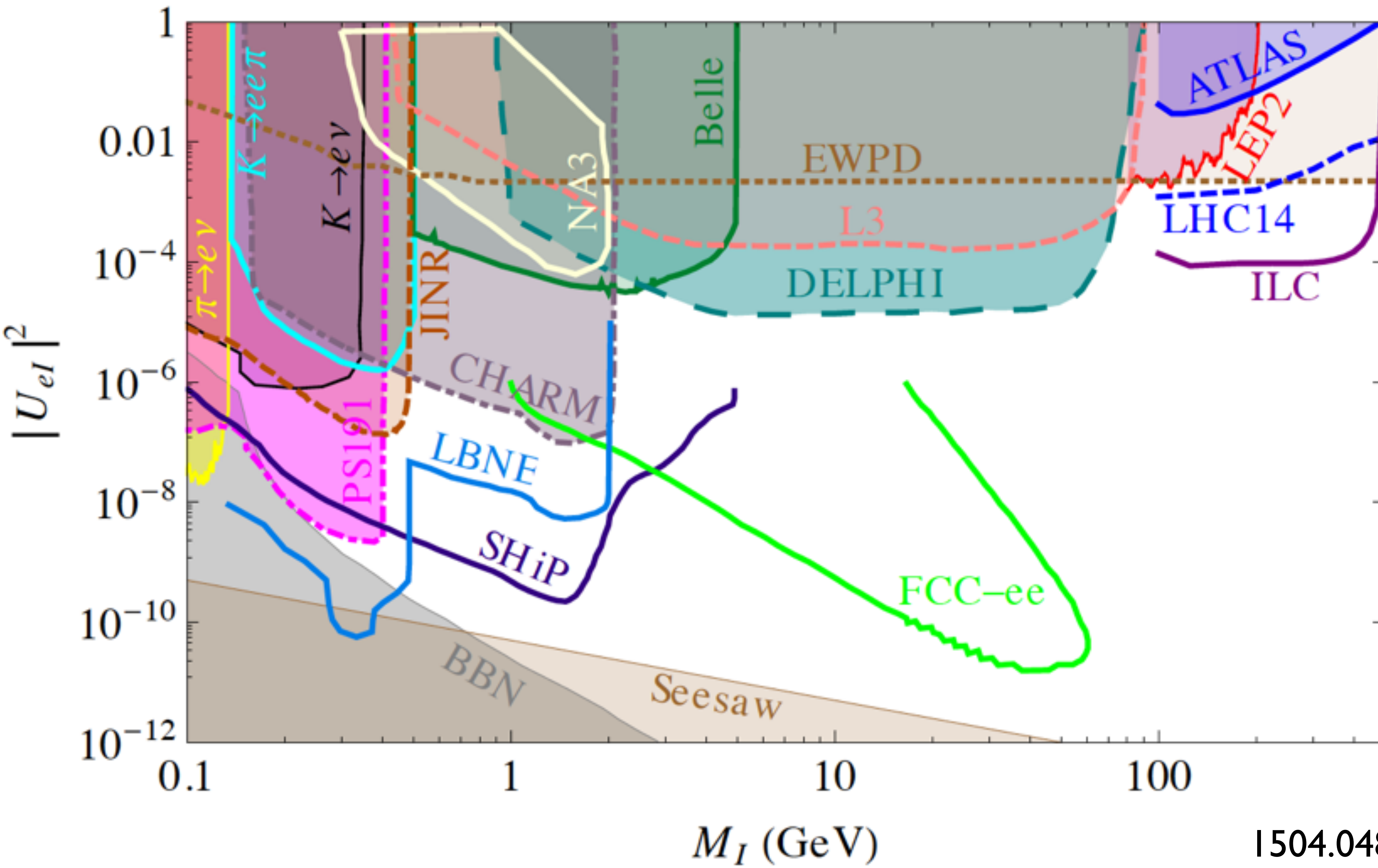
N Lifetime



For *N* lighter than *W*, the decays of *N* are macroscopic

Accelerator tests of *N*

$(\text{note} : U = \theta)$



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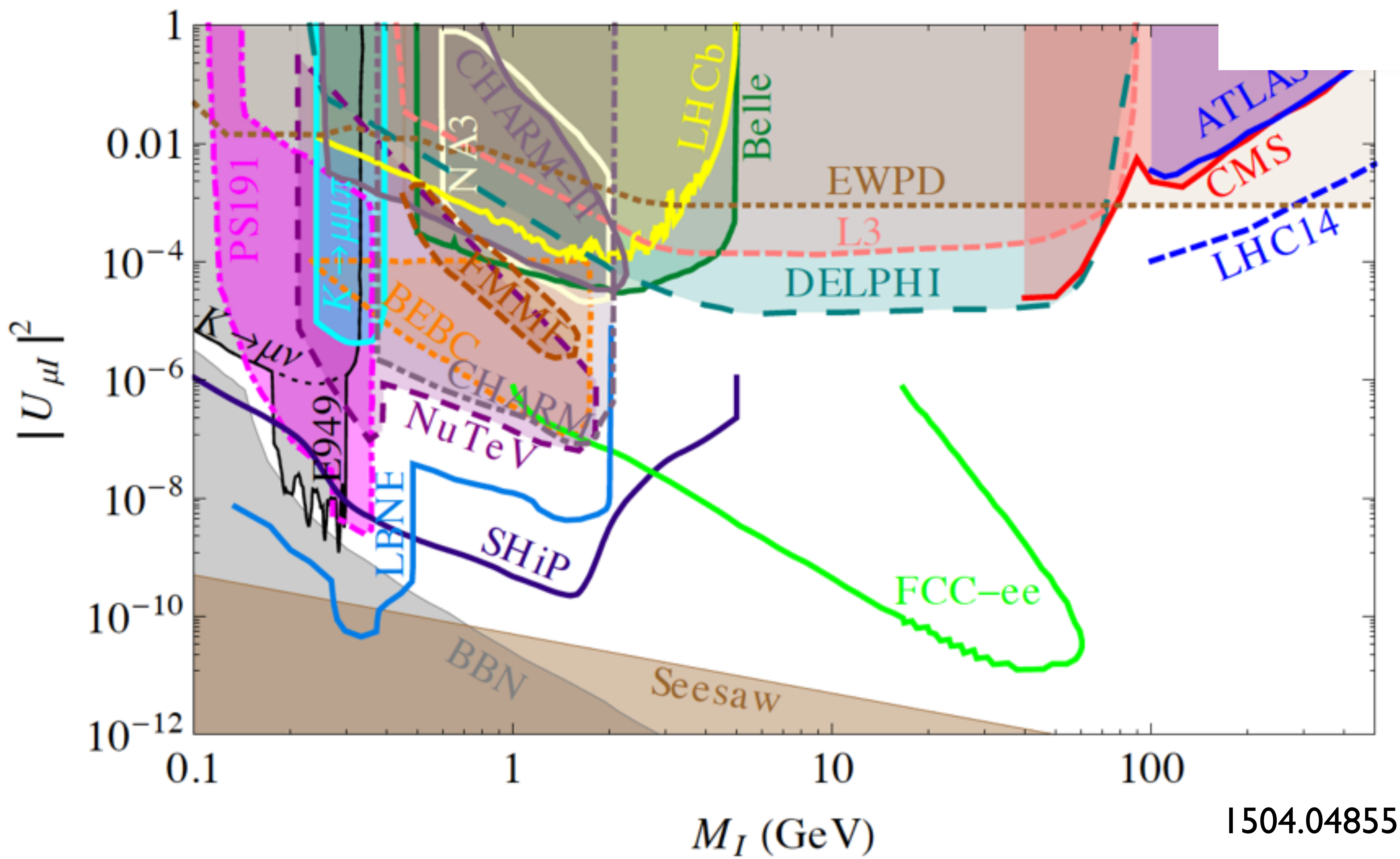
Accelerator tests of *N*

$(\text{note}: U = \theta)$



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Accelerator tests of *N*

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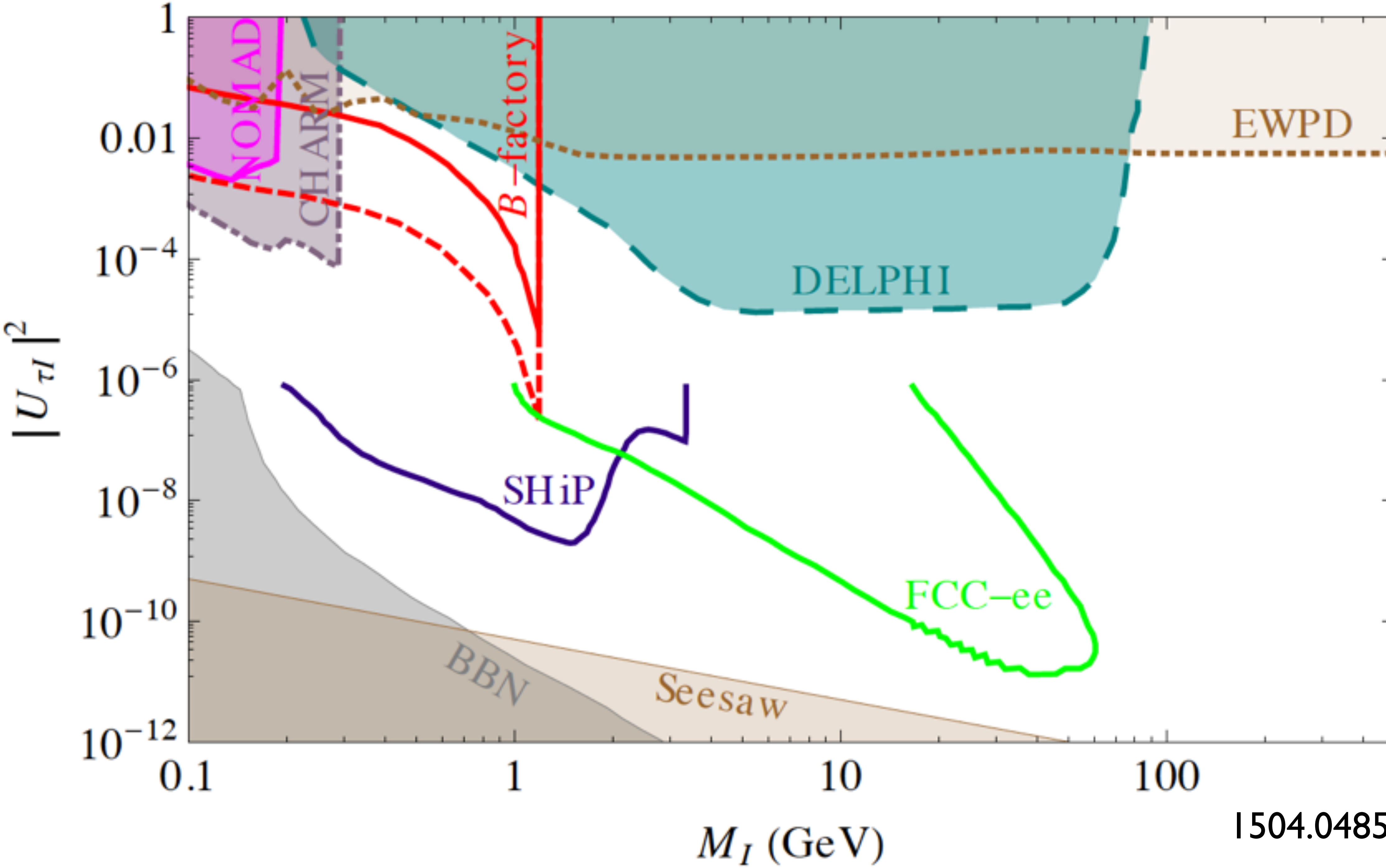

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Accelerator tests of *N*

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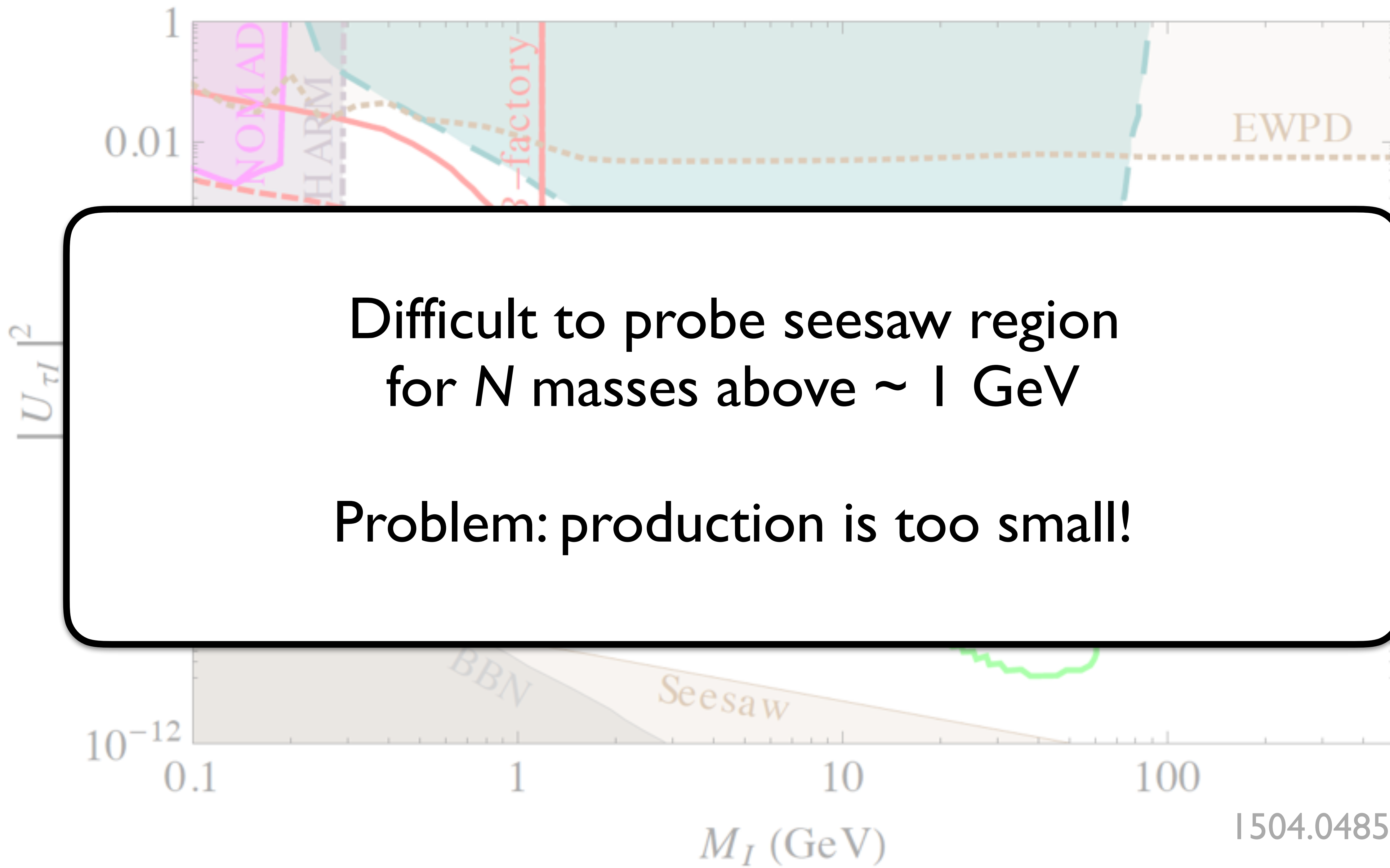

Difficult to probe seesaw region
for *N* masses above ~ 1 GeV

Problem: production is too small!

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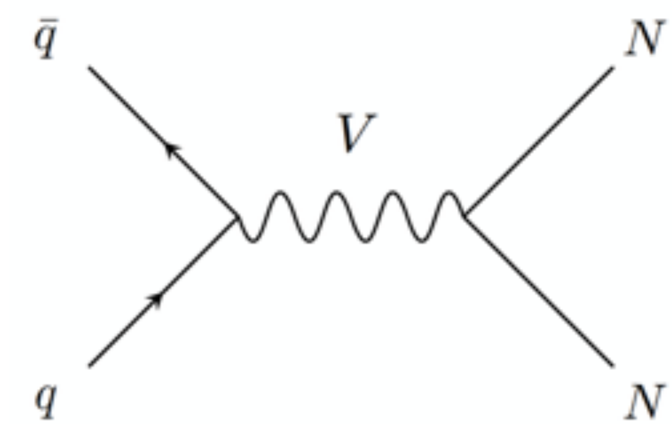
Enhanced production of Sterile Neutrinos

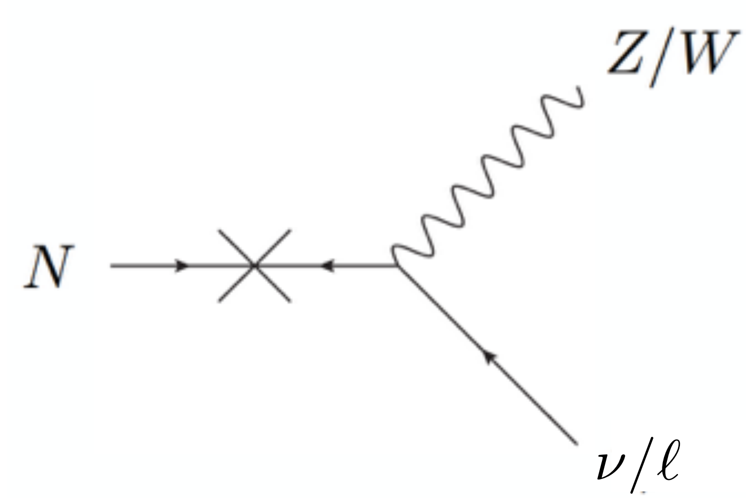
Basic idea:

Decouple the production and decay of *N* with new interactions

Production via new force carrier



Decay via weak interactions



Two Scenarios:

1. *B* - *L* gauge symmetry

[See also talk by K. Kaneta]

- *N* required by anomaly cancellation
- *N* Majorana mass generated by *B* - *L* Higgs field, *N* mass tied to lightness of gauge boson
- Other gauge symmetries also possible

2. Higgs portal coupling

- New scalar field may spontaneously break lepton number, generate Majorana mass
- Scalar could be Higgs of some gauge symmetry (e.g. *B* - *L*)

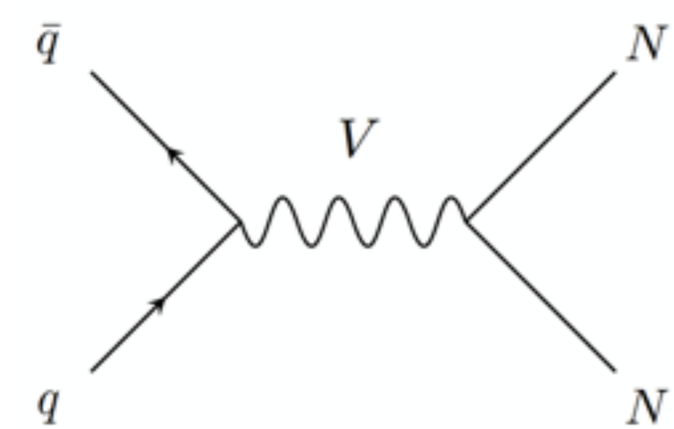
Gauged *B* - *L* Model

[BB, Pospelov, Shuve ‘ 16]

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4}V_{\mu\nu}^2 - \frac{1}{2}M_V^2 V_\mu^2 + iN^\dagger\bar{\sigma}^\mu\partial_\mu N$$
$$-\frac{M_N}{2}(N^2 + {\rm h.c.}) + g' V_\mu \left(\sum_{\rm SM} Q_{B-L}\psi^\dagger\bar{\sigma}^\mu\psi + N^\dagger\bar{\sigma}^\mu N\right)$$
$$+\theta_{\mu N}\ \frac{g_W}{\sqrt{2}}\left(\mu_L^\dagger\bar{\sigma}^\mu W_\mu^- N + {\rm h.c.}\right) + \ldots$$

- 4 parameters: $m_V\,, g'\,, M_N\,, \theta_{\mu N}$

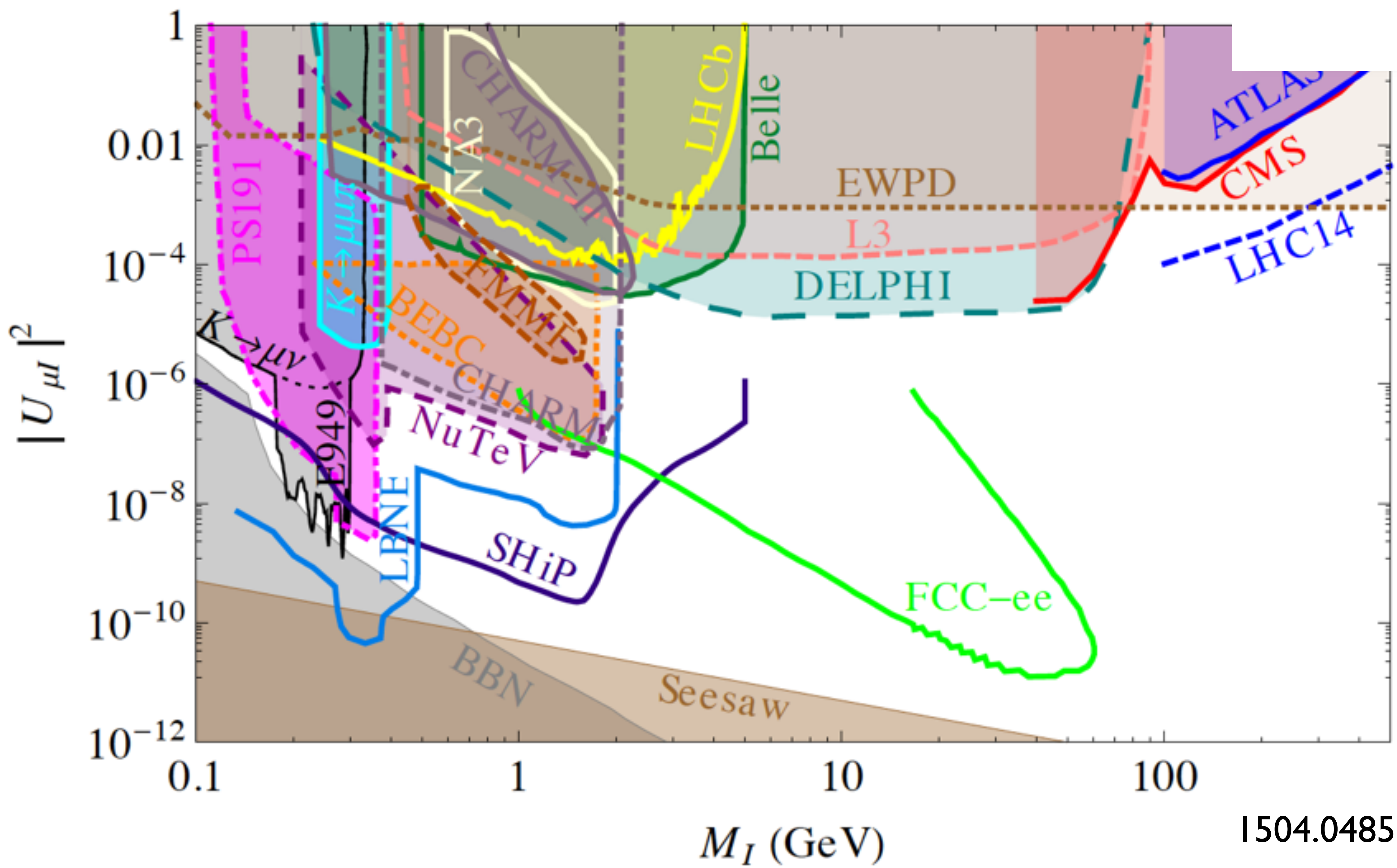
- Production of *N* enhanced due to new gauge interaction



- Decay of N via weak interaction

Can we probe seesaw?

$(\text{note}: U = \theta)$



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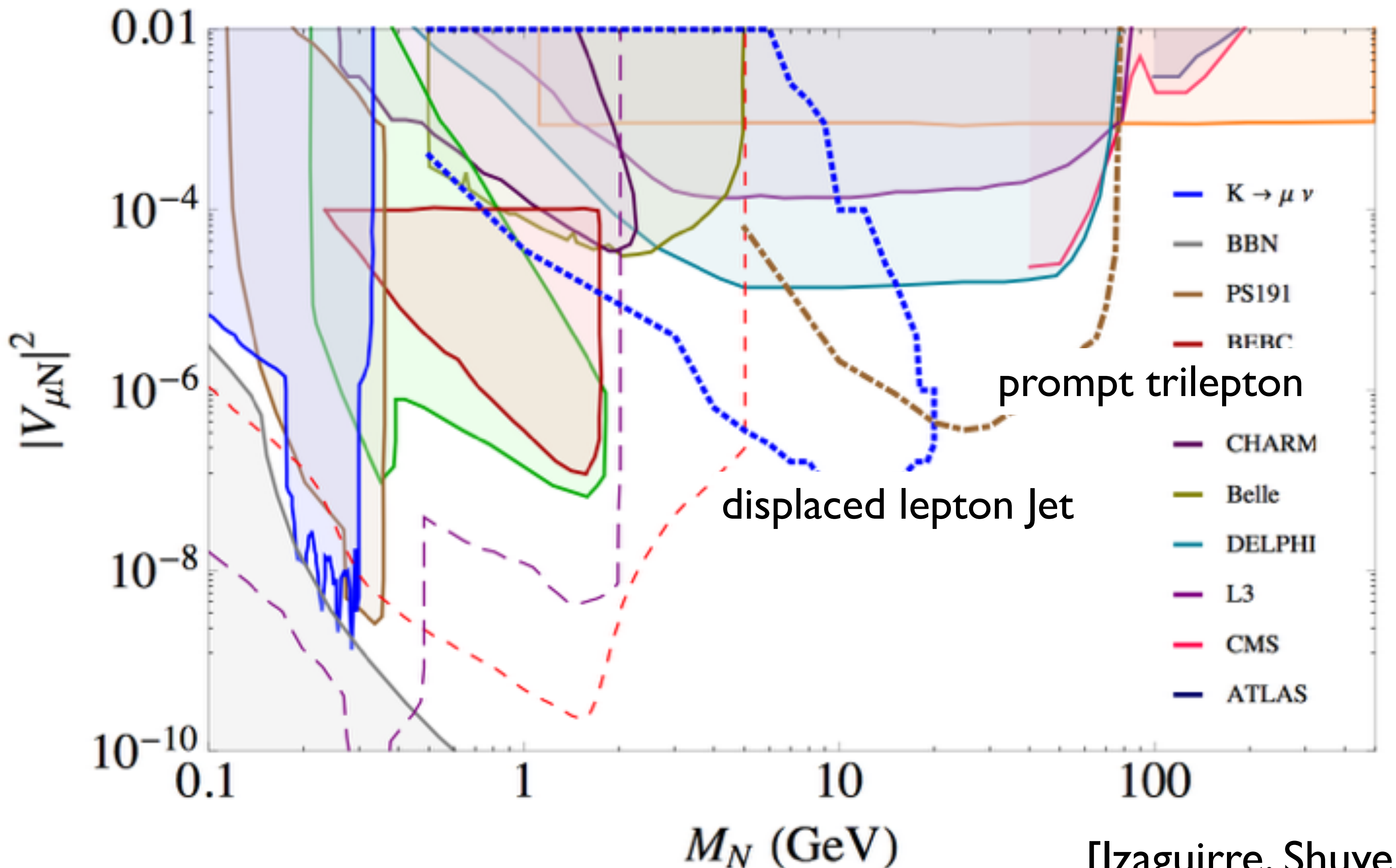
LHC

Displaced vertex/long lived particle searches:

- *N* most often decays via charged current
    - displaced lepton + additional displaced leptons and/or tracks
- Very striking; little or no background;
    - potential for sensitivity to scale linearly with integrated luminosity!
- Care must be taken to keep trigger thresholds low
- Competitive probe comes from Drell-Yan searches

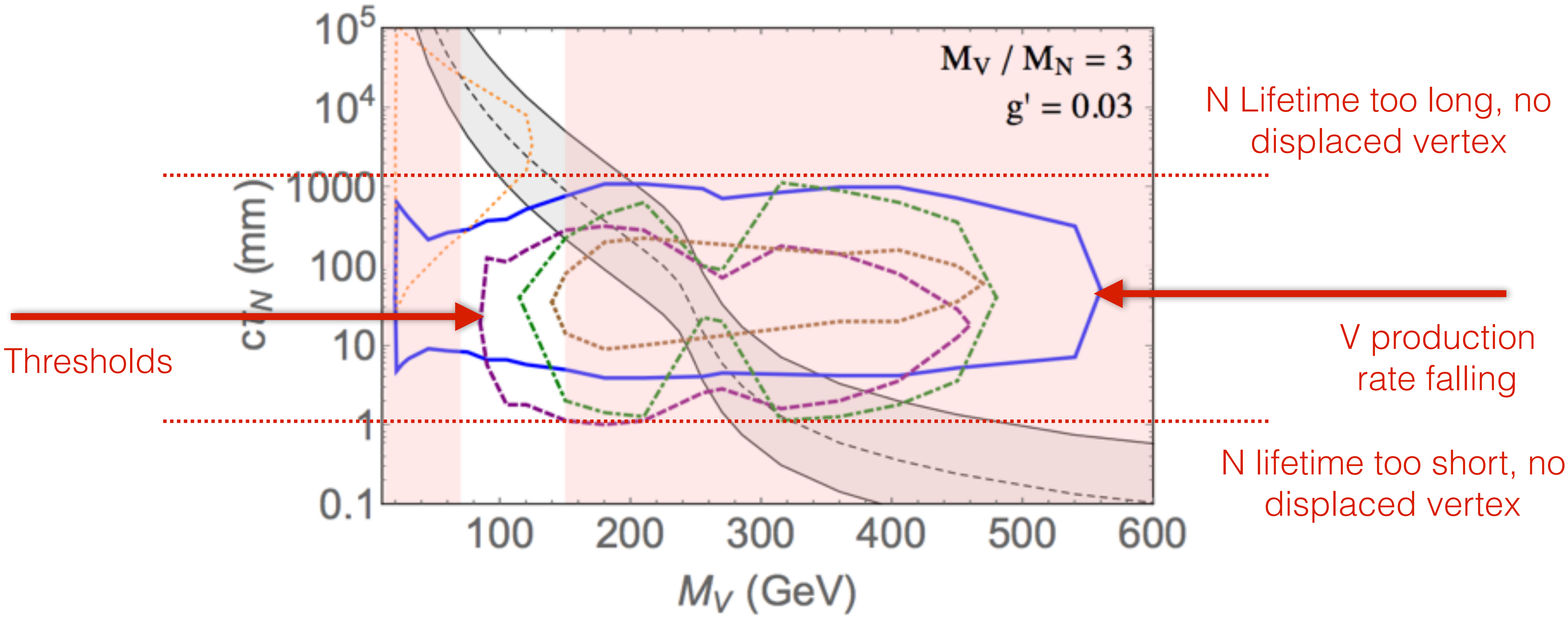
Production via weak interaction



[Izaguirre, Shuve '15]

Run I recasts of displaced searches for *B* - *L* model

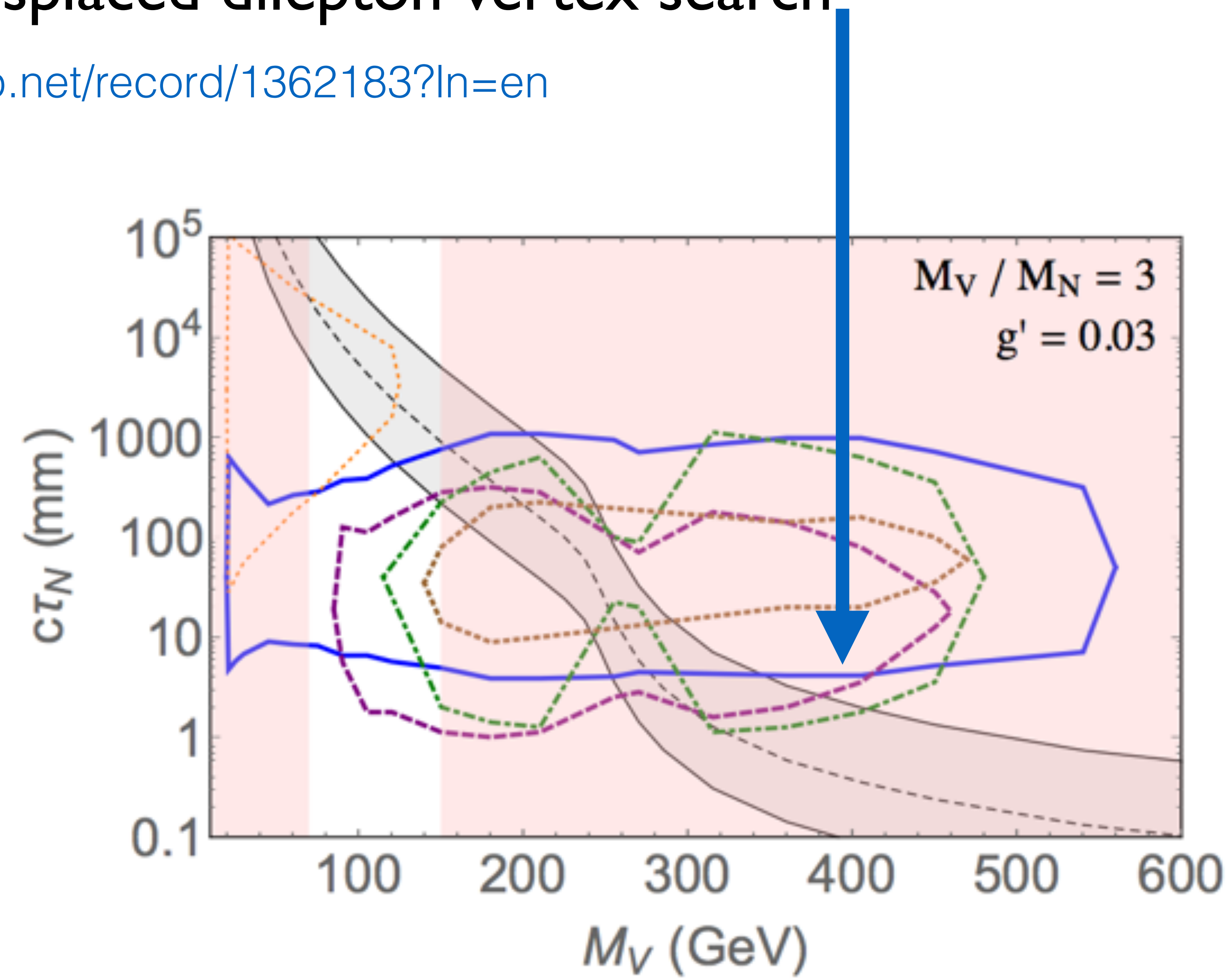
(CMS) displaced dilepton search, no vertex requirement [1409.4789]
(CMS) Displaced dilepton vertex search [1411.6977]
(ATLAS) Displaced lepton + hadrons vertex search [1504.05162]
(ATLAS) Displaced dilepton vertex search [1504.05162]
(ATLAS) Displaced vertices in muon spectrometer [1504.03634]



Example: ATLAS Displaced dilepton vertex search

http://inspirehep.net/record/1362183?ln=en

- Trigger:
  - muon p_T > 50 GeV,
  - or electron E_T > 120 GeV,
  - or 2 electrons with ET >40 GeV;
- leptons requirements
  - p_T > 10 GeV
  - $|d_0|$> 2mm;
- Invariant mass of all tracks at the vertex > 10 GeV
- Possible backgrounds
  - accidental crossing of unrelated leptons
  - tracks originating from primary vertex wrongly associated with displaced vertex
  - cosmic ray muons
  - heavy flavor, tau
- No events observed
- Expected background ~ 0.001

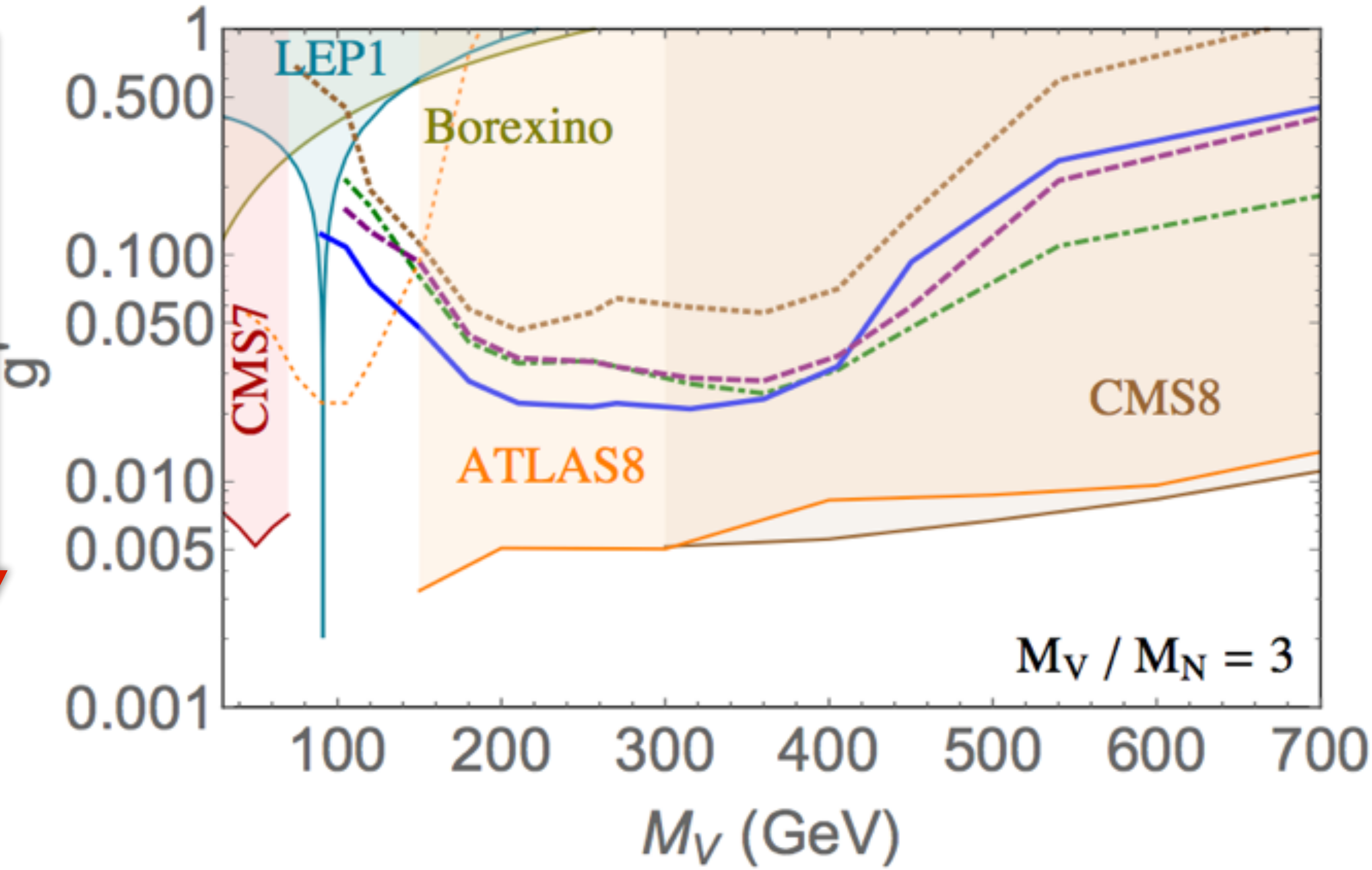


Need to reduce thresholds, without reintroducing signficant backgrounds, to probe low mass region

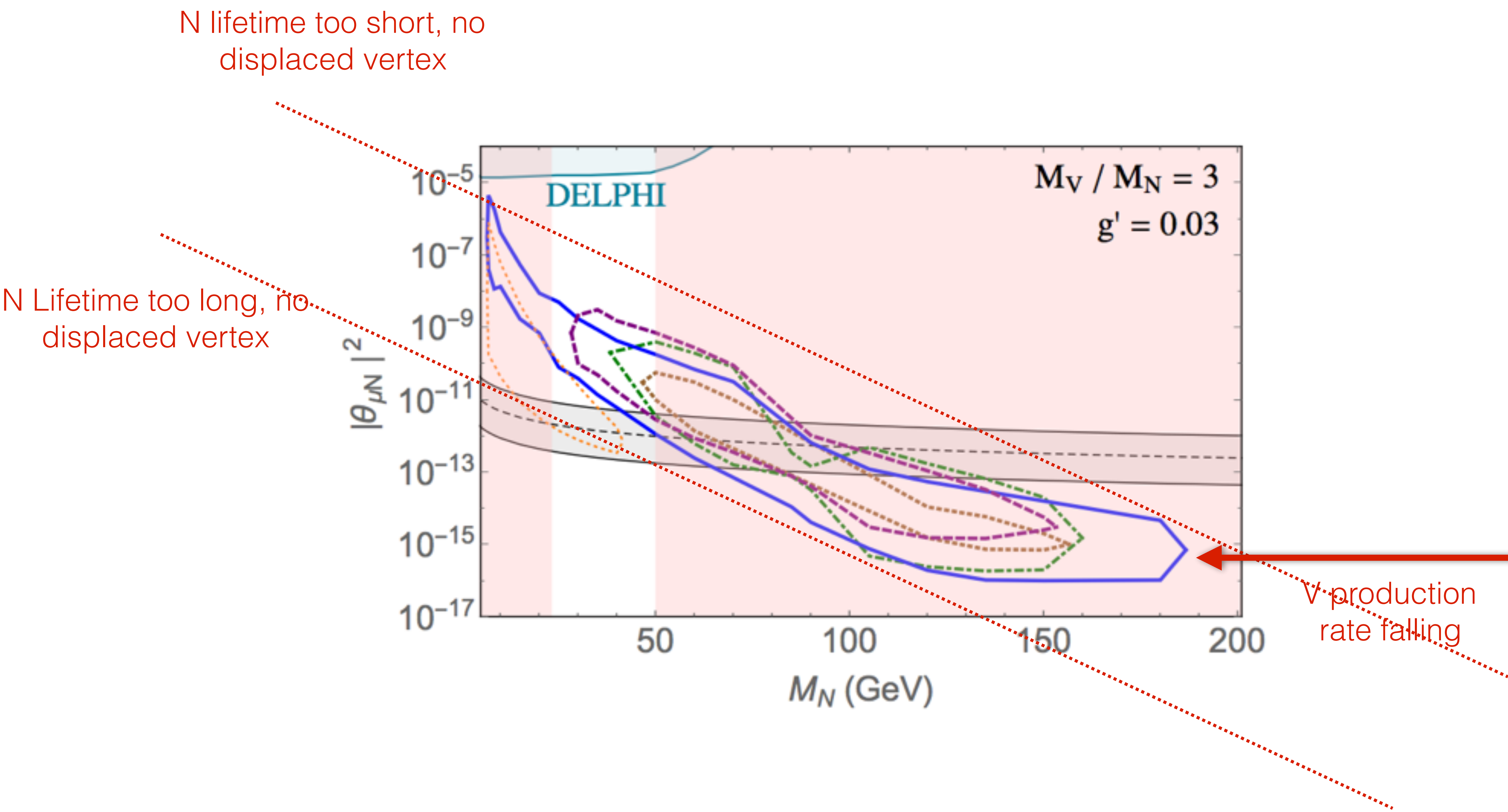
V production rate falling

lifetime also getting shorter

V production rate falling



$$\theta_{\mu I} = \theta_{\mathrm{s.s.}}$$



LHC already probing seesaw motivated parameter space!

Summary of Run I constraints:

- Displaced searches sensitive to *N* lifetimes in the range 1mm - 10m,
- Displaced searches are sensitive to seesaw mixing angles
- Drell-Yan searches are generally stronger than displaced searches, except in the region near *Z* mass which is usually excluded from the analyses; Displaced searches are stronger in this mass range.
- The existing displaced searches are not optimally configured to *N*, particularly with regard to the high thresholds

Prospects for High Luminosity LHC (3/ab at 14 TeV)

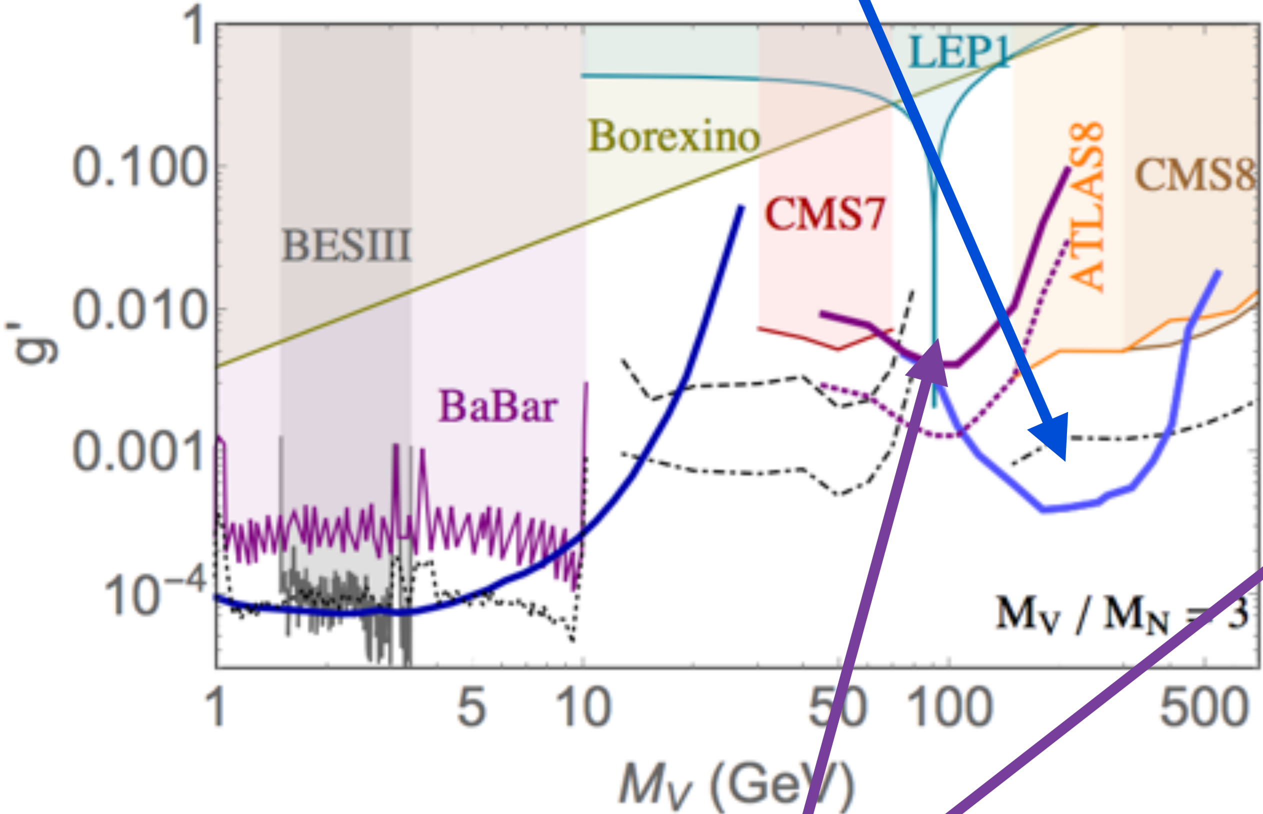
- Sensitivity in displaced searches can scale linearly with luminosity, making them very important for HL-LHC
- Can compete with Drell-Yan searches (scale as square root of luminosity)
- Difficult to estimate backgrounds; We extrapolate from Run 1 searches assuming background rates scale linearly with luminosity.
    - Order few events for inner detector searches,
    - Order 100-1000 events for MS DV search.
- Several factors will affect background determination
    - High pileup can degrade vertex reconstruction and lead to more accidental track crossings at high displacement.
    - Upgrades in ATLAS and CMS detectors
    - Improvements in vertex tagging, high impact parameter track reconstruction
- Two projections: 1) inner detector search and 2) muon spectrometer search

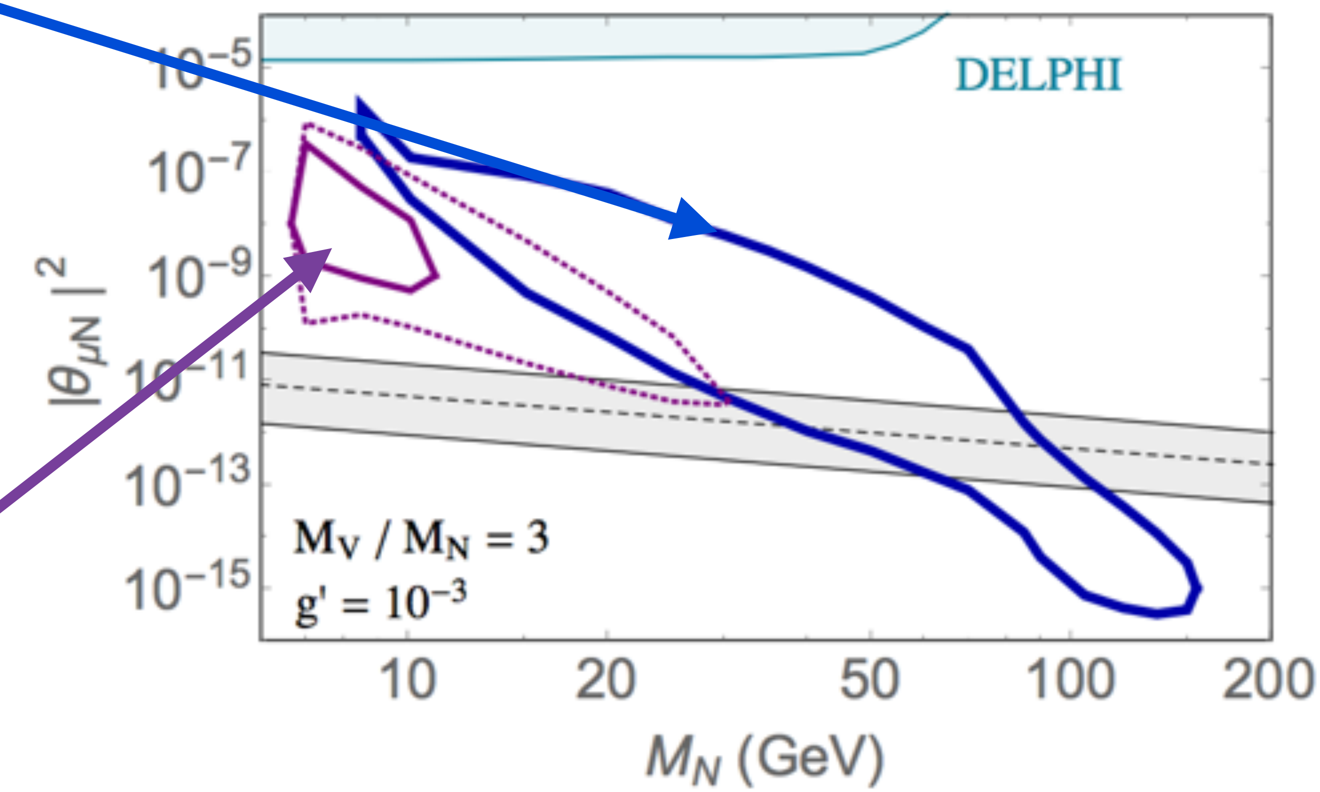
Inner Detector Search for HL-LHC

- Require two displaced vertices
  - should be background free even at HL-LHC with high pileup conditions, and allow to lower thresholds, relax vertex selection criteria, increasing signal efficiency
- Trigger:
  - single isolated lepton, $p_T > 25$ GeV,
  - or 2 isolated leptons each with $p_T > 15$ GeV,
  - or 3 muons each with $p_T > 6$ GeV;
- Event selection:
  - one *N* decays semileptonically, other *N* decays to at least one lepton;
  - $p_T > 5$ GeV (10 GeV) for muon, electron;
  - Displaced vertex with muon and four tracks;
  - invariant mass of tracks > 6 GeV to suppress heavy flavor backgrounds;
  - back-to-back muons are vetoed to suppress cosmic rays
  - displaced tracks have $1\text{mm} < |d_0| < 30$ cm;
  - apply $|d_0|$ dependent reconstruction efficiency for each track; tracks originate within 60cm of primary vertex in radial direction and 50cm in longitudinal direction;

LHC High Luminosity Run Projections

Inner detector search

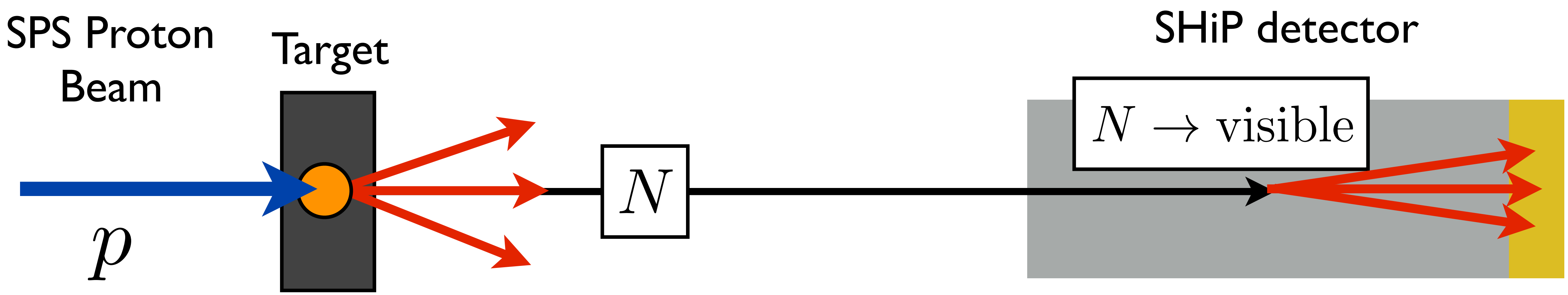


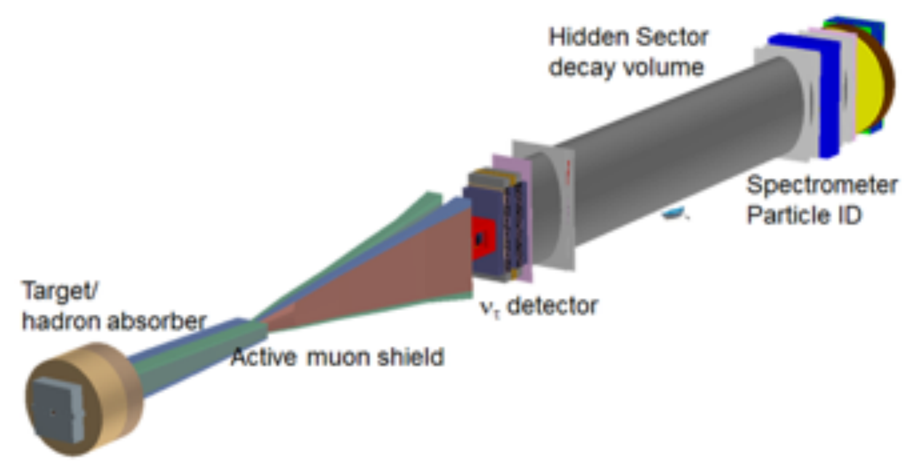


Muon spectrometer search

Can probe seesaw over a wide range of *N* masses

SHiP





- 400 GeV protons from CERN SPS
- 4 E 20 POT
- Large detector volume, close to the target
- Hadron absorber mitigates background from strongly interacting particles
- Active muon shielding to magnetically deflect muons away from SHiP detector
- Evacuated decay volume to minimize interaction of residual muons and neutrinos
- Goal is to achieve near zero background experiment

SHiP sensitivity

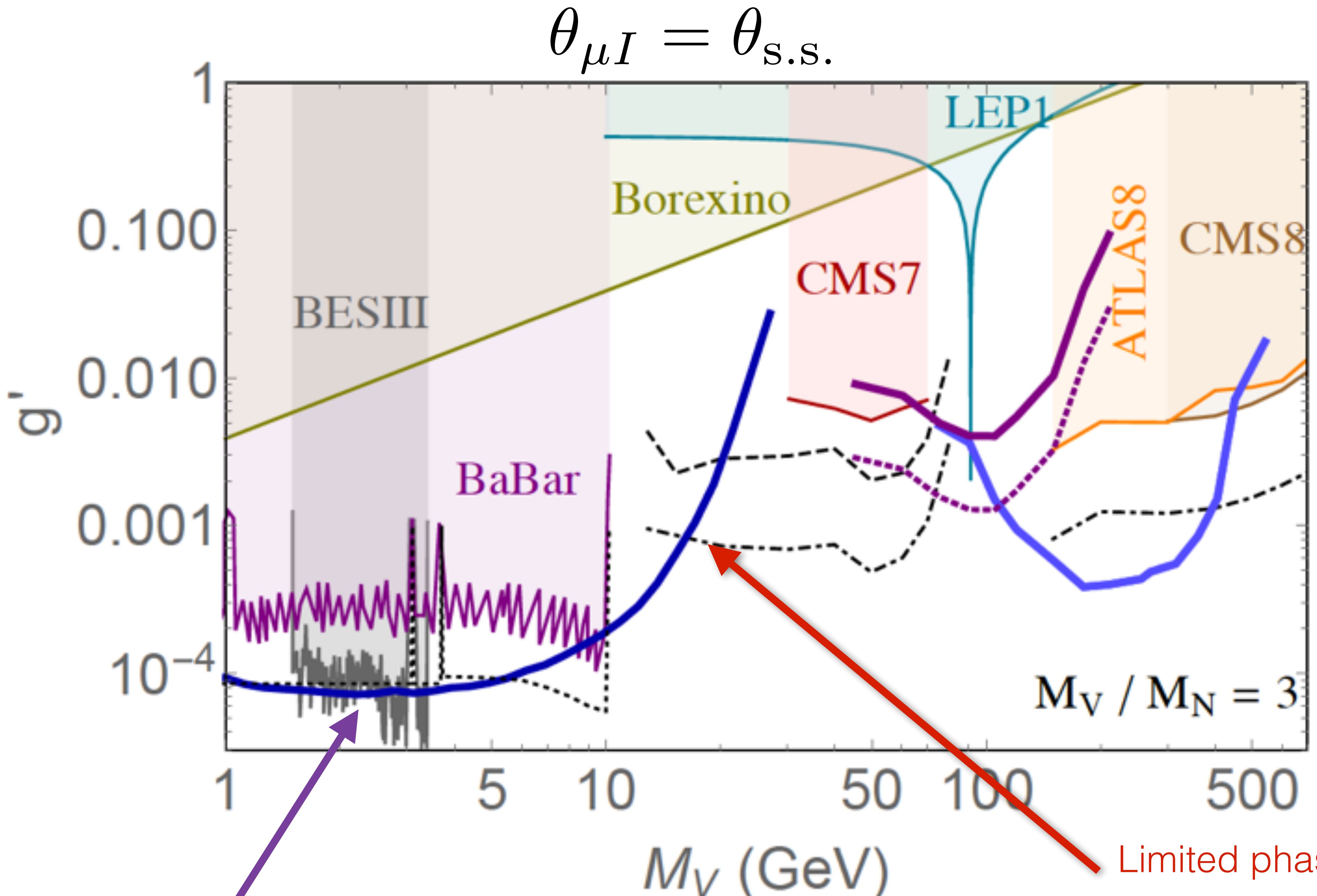
Production via partonic process $pp \to V \to NN$
Followed by decay of *N* in SHiP detector $N \to \text{visible}$

Signal rate estimate

$$N_{\text{events}} = 2 \times X_{NN} \times N_{\text{POT}} \times \text{Br}_{\text{vis}} \times \epsilon_{\text{det}}$$

where

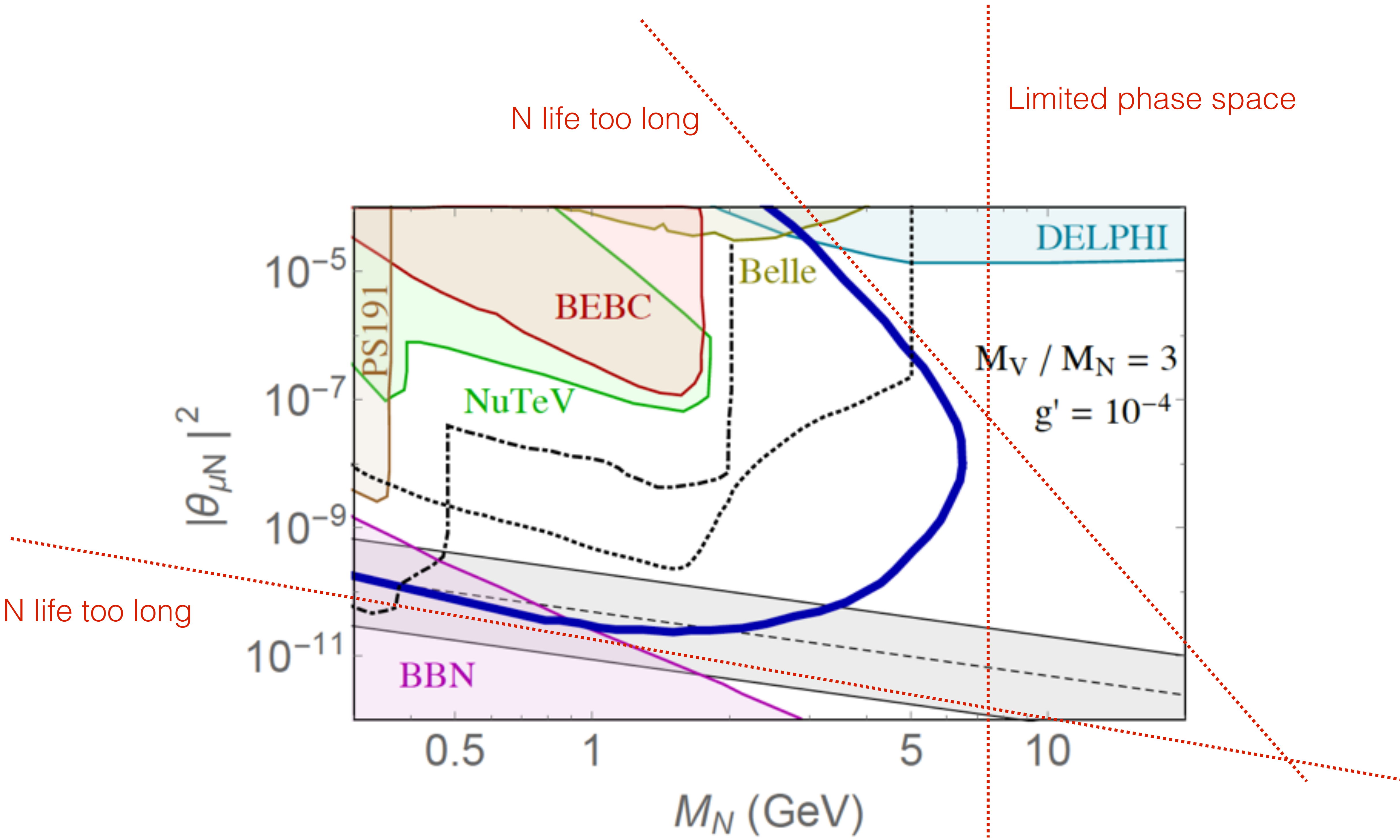
$X_{NN} = \frac{\sigma(pp \to V \to NN)}{\sigma_{\text{tot}}}$	Production cross section of *N* normalized to total cross section
$N_{\text{POT}} = 4.5 \times 10^{20}$	Number of protons on target
ϵ_{det}	Probability for *N* to decay in SHiP detector (via Monte Carlo)
Br_{vis}	Branching of N to visible particles



V production falling

Limited phase space

Note competitive constraints from BaBar, BesIII below 10 GeV



Can probe seesaw for *N* masses below few GeV!

Higgs + Neutrino Portal

[BB, Pospelov, Shuve, to appear]

$$\mathcal{L} \supset -\frac{y}{2} S N^2 + (AS + \lambda S^2)|H|^2 + \ldots$$

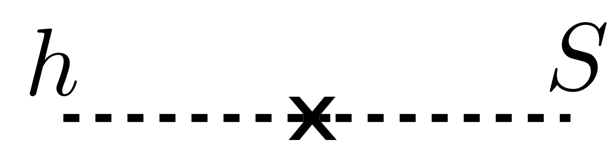
Enhancement of *N* production via *S*:

- Higgs-scalar mixing

$$h \to NN$$

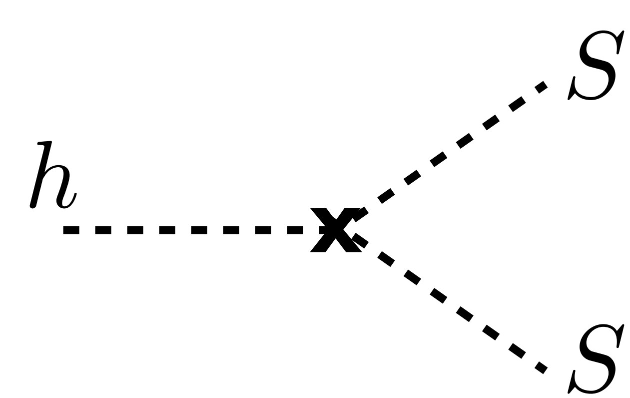
$$pp \to S \to NN$$

$$B \to K^{(*)} S, S \to NN$$

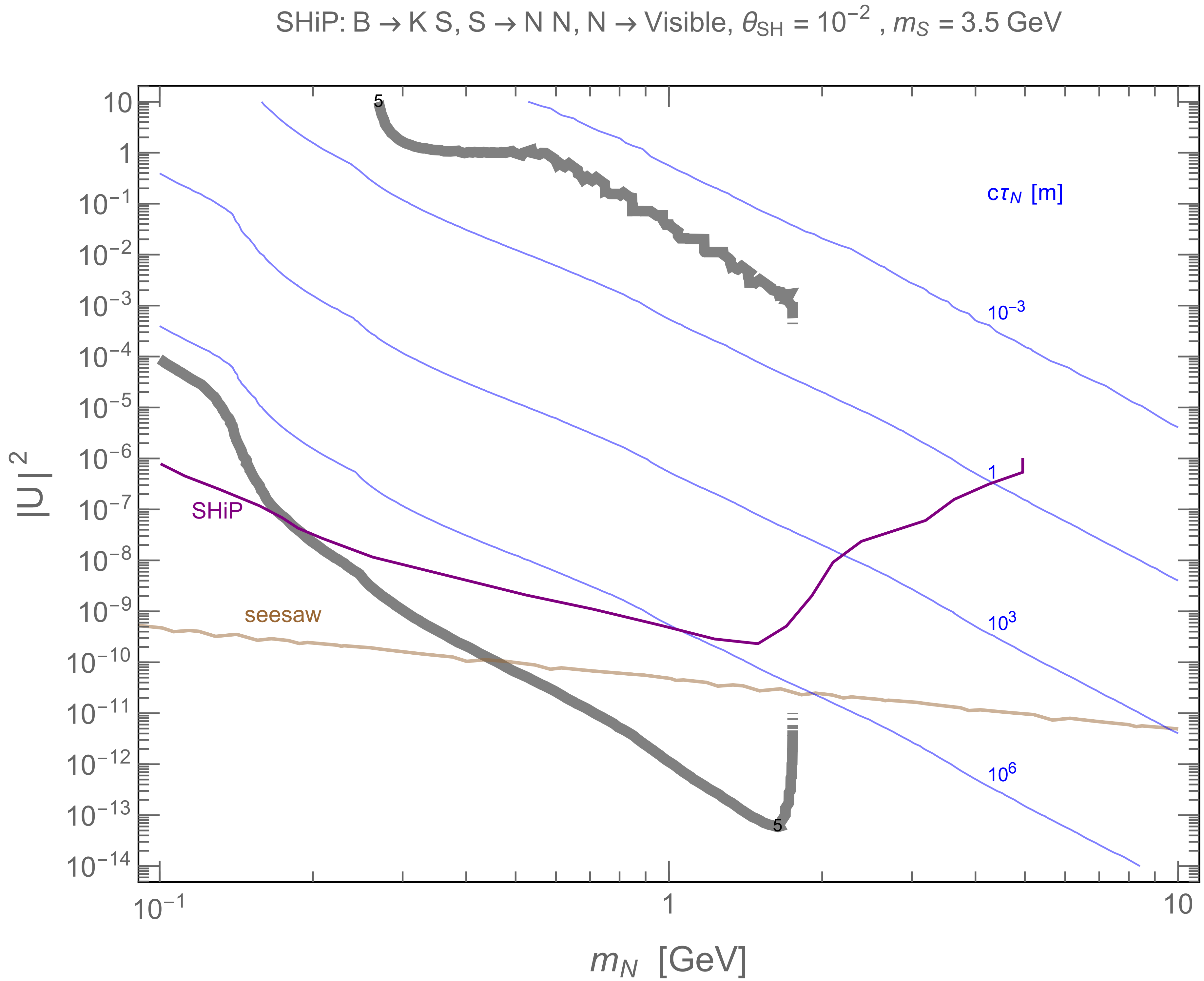


- Higgs decays to scalars

$$h \to SS \to 4N$$



SHiP (preliminary)



Can probe seesaw region with Higgs portal!

Outlook

- Neutrino masses require new physics
- No conclusive empirical guidance on seesaw scale (look everywhere!)
- Difficult to probe seesaw parameter space for *N* masses above ~ GeV
- Simple, motivated extensions, including gauged *B* - *L* or Higgs portal can lead to a dramatic enhancement of *N* production
- Can potentially probe seesaw region with dedicated searches + experiments
- Provides additional motivation for long-lived particle searches at LHC and high intensity beam dump experiments like SHiP