Sterile Neutrino Portals

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CERN-EPFL-Korea TH Institute - "New Physics at the Intensity Frontier"
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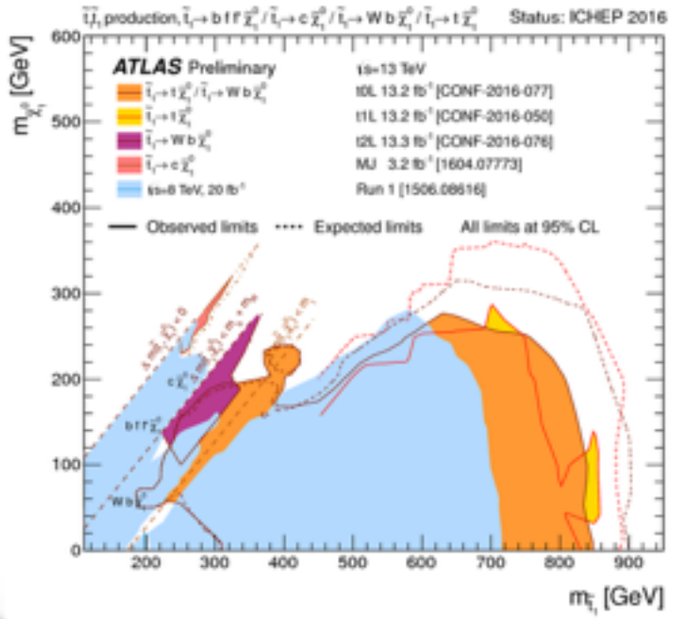
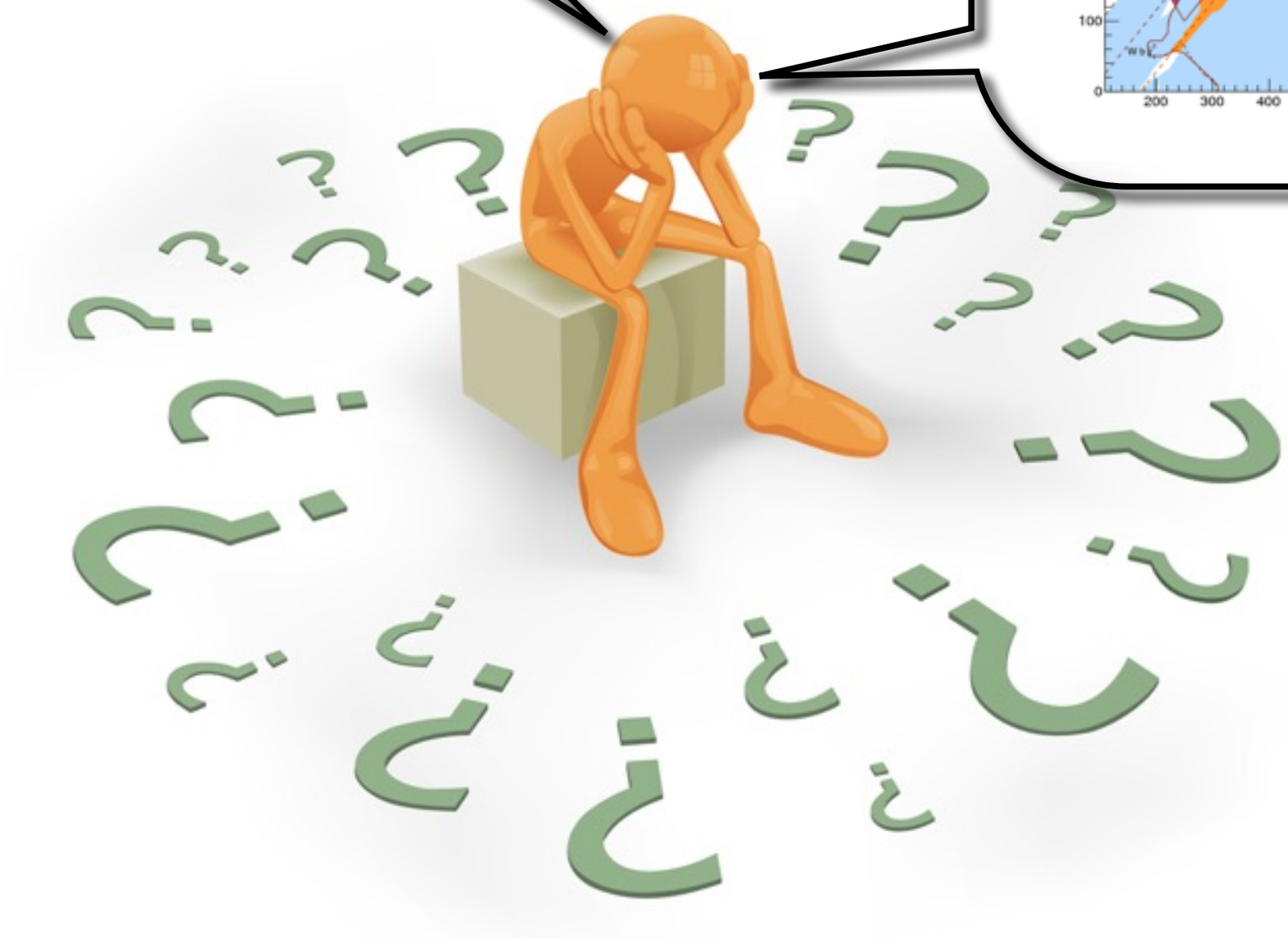
Naturalness? Baryon Asymmetry?
Strong CP? Neutrino Mass?
Flavor Puzzle? Dark Matter?
Unification? Inflation?
Quantum Gravity? ...

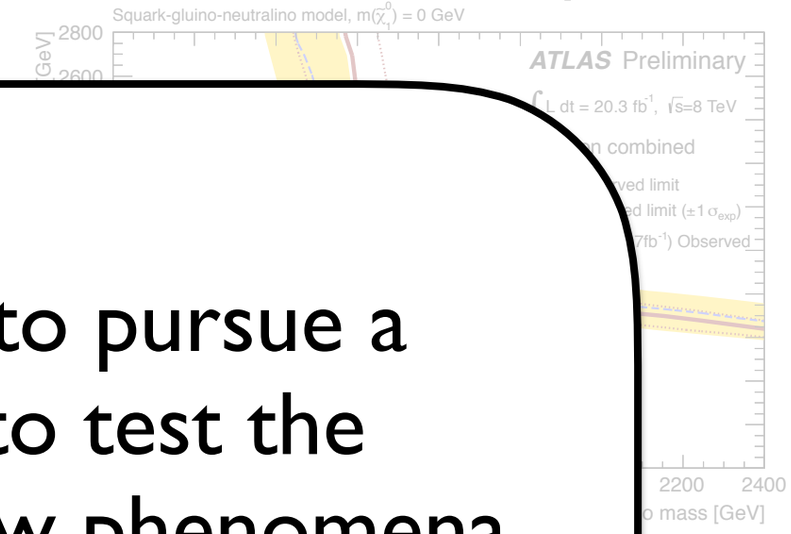
Where is the New Physics?



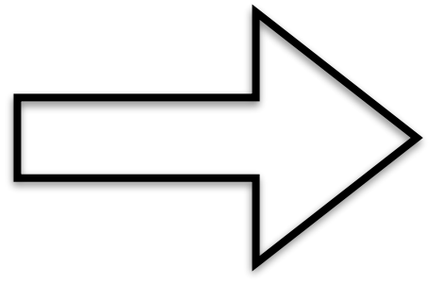


Naturalness? Baryon Asymmetry?
Strong CP? Neutrino Mass?
Flav

Where is New Physics?



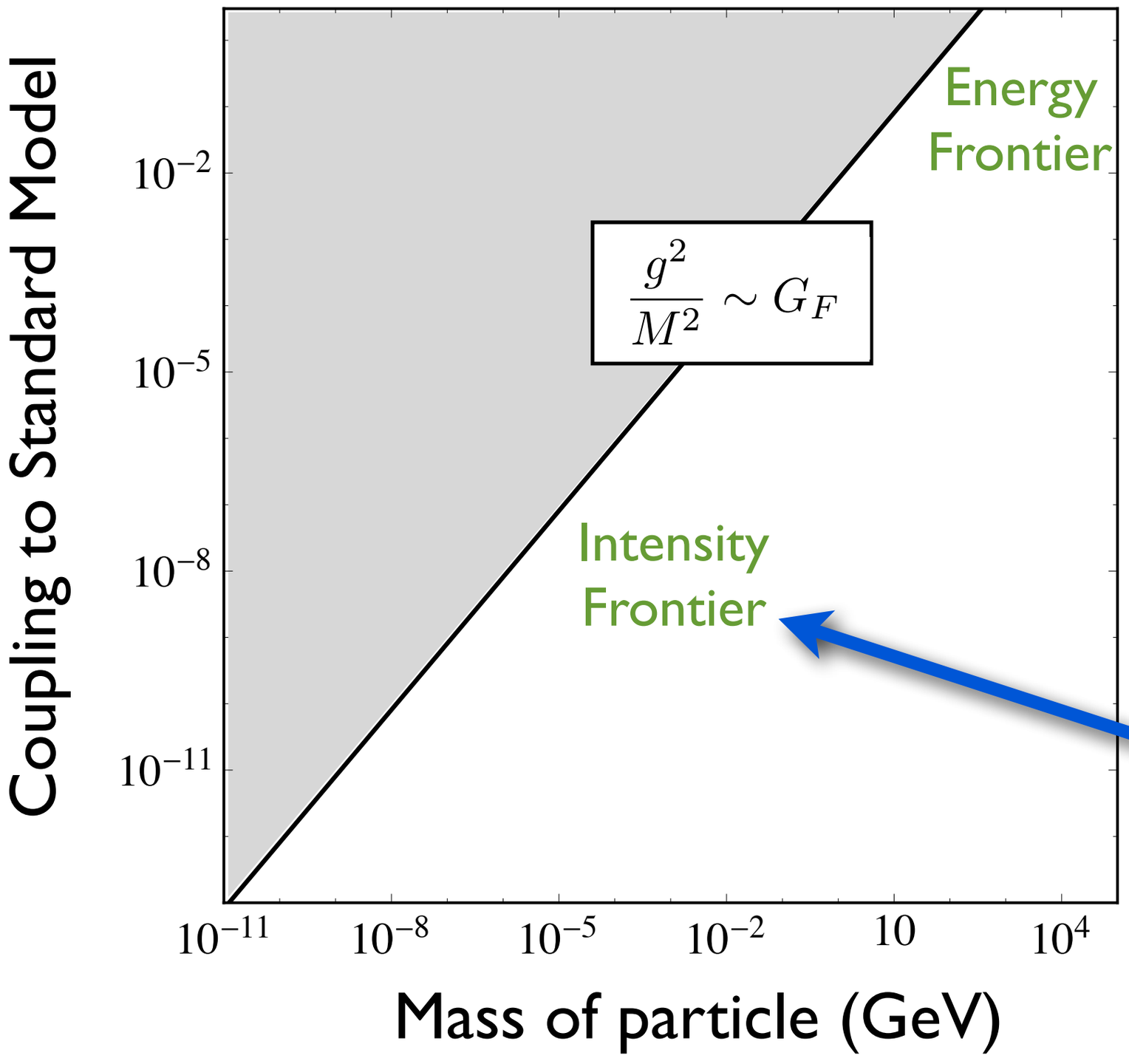
In this situation it is important to pursue a broad experimental program to test the Standard Model and search for new phenomena



CERN

Physics Beyond Colliders

Where is the New Physics?



- Higgs Naturalness
- WIMPs
- EW Baryogenesis

- Neutrino Mass
- Leptogenesis
- Dark Sector
- Strong CP
- …

Portals

$$(AS + \lambda S^2) H^\dagger H$$ Higgs Portal

$$y L H N$$ Neutrino portal

$$-\frac{\kappa}{2} B_{\mu\nu} V^{\mu\nu}$$ Vector Portal

- Only three *renormalizable* portals in the Standard Model
- May play a role in addressing a variety of outstanding questions:
  - Naturalness, dark matter, baryogenesis, neutrino mass, …

Neutrino Mass

$$LHN$$

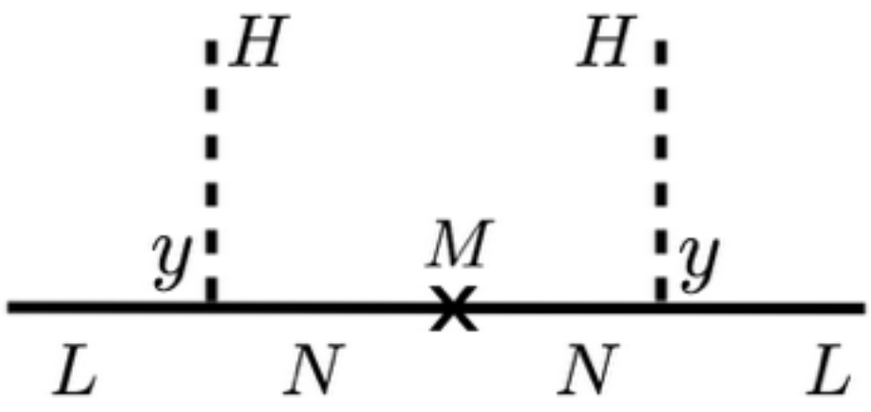
Neutrino portal

- Right handed neutrinos, N, are Standard Model gauge singlet fermions
- Deep connection to the SM structure in the UV ... e.g. SO(10) GUT?
- Or, alternatively, neutral fermions from a dark sector?
- May have deep connection to mysteries in cosmology
- Strong hint that that this "portal" operates in nature via ν - oscillations

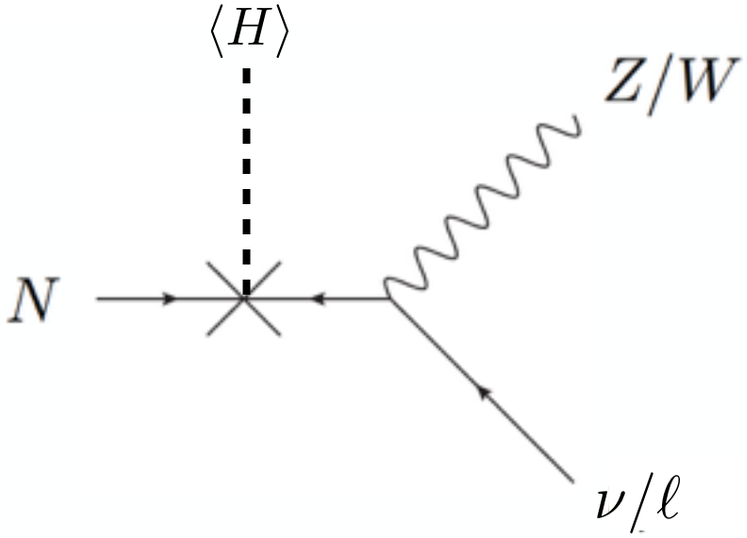
Seesaw

Minkowski; Yanagida; Mohapatra, Senjanovic;
Gell-Mann, Ramond, Slansky; Schechter, Valle

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



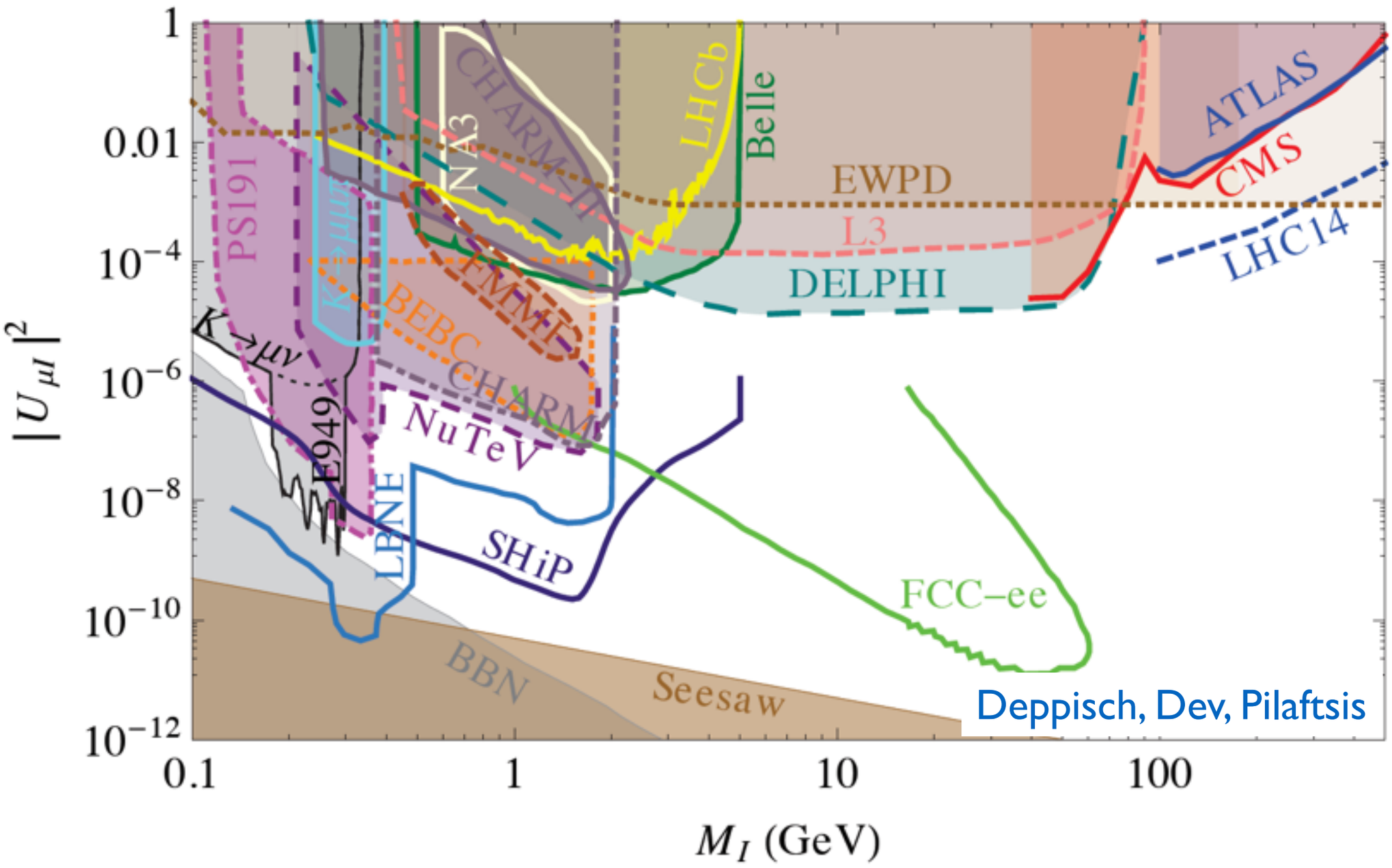
$$\Rightarrow \quad m_\nu \sim \frac{y^2 v^2}{M}$$



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

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

Experimental Landscape

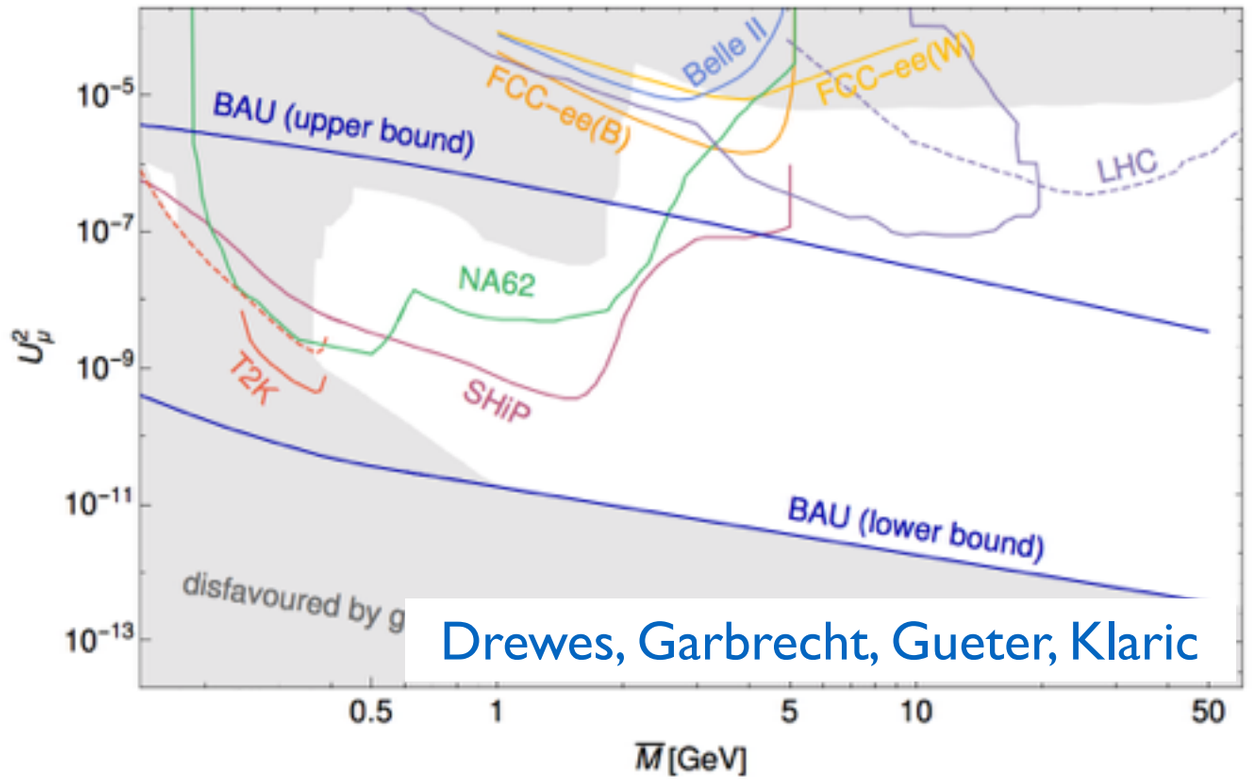


Probing seesaw is challenging

Caveat: Yukawas, mixing angles can be larger

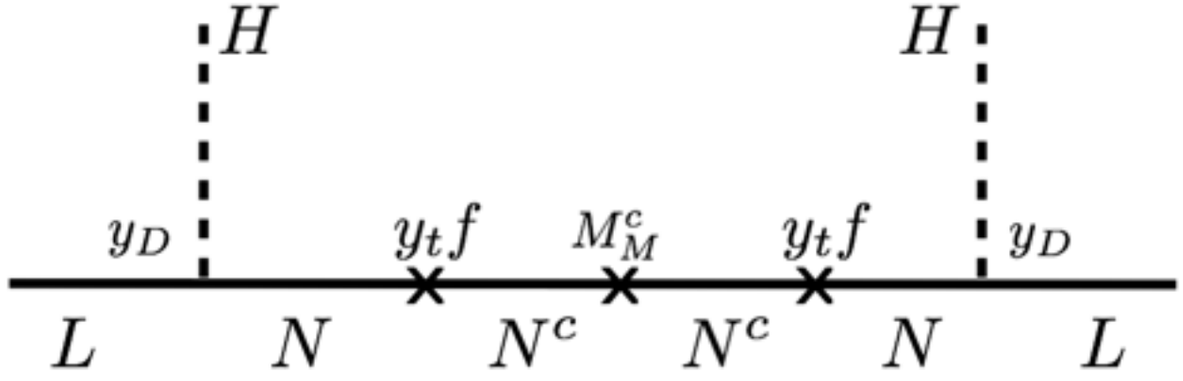
- In the νMSM , leptogenesis, sterile neutrino dark matter considerations may allow larger couplings

  Asaka, Blanchet, Shaposhnikov



- The seesaw structure may be more intricate, and/or have additional approximate symmetries (e.g. inverse seesaw)

  Mohapatra, Valle



Sterile Neutrino Portals

It is possible that sterile neutrinos have additional exotic interactions beyond seesaw

- Vector portals: $B - L, L_\mu - L_\tau, ...$
- Scalar portal: $(AS + \lambda S^2)|H|^2 + (\lambda_N S N^2 + \text{h.c.})$
- Neutrino portal to dark matter: $yLHN + \lambda N \chi \phi + \text{h.c.}$

These portals can lead to novel phenomenology and potentially allow us to probe the seesaw motivated parameter space

Local $B - L$ symmetry

[BB, Pospelov, Shuve '16]

Mohapatra, Marshak, …

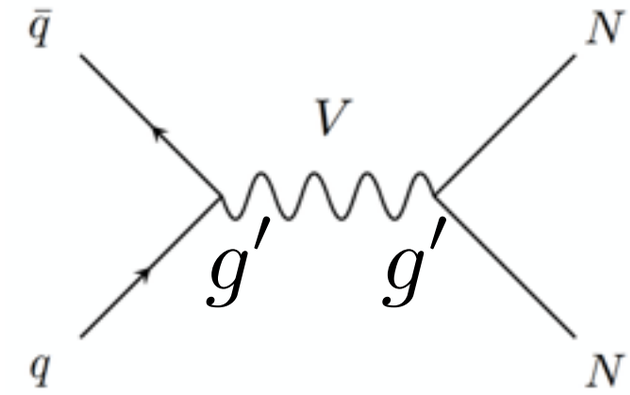
- Simple, well-motivated gauge extension of SM
- Three sterile neutrinos required for anomaly cancellation
- Majorana mass arises from $B - L$ symmetry breaking
- Simplified model:

$$\begin{aligned}\mathcal{L} \supset\ & \frac{1}{2}M_V^2 V_\mu^2 - \frac{1}{2}M_N(N^2 + \text{h.c.}) \\ & + g' V_\mu \left(\sum_{\text{SM}} Q_{B-L}\psi^\dagger \bar{\sigma}^\mu \psi + N^\dagger \bar{\sigma}^\mu N\right) + \ U\ \frac{g}{\sqrt{2}}\left(\mu_L^\dagger \bar{\sigma}^\mu W_\mu^- N + \text{h.c.}\right) + \ldots\end{aligned}$$

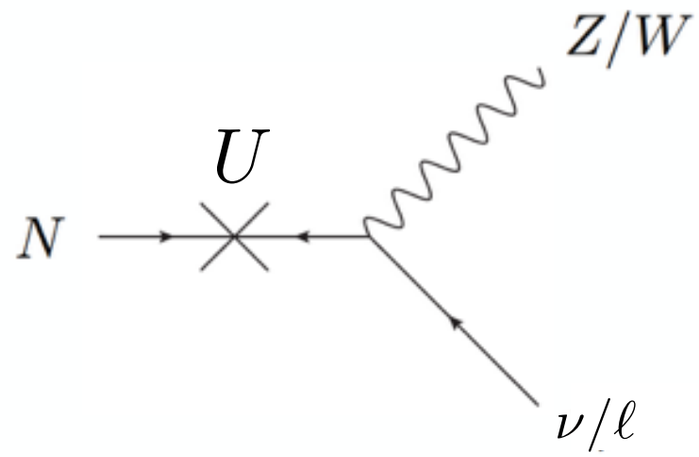
- Four parameters govern the physics: M_N, U, M_V, g'

Enhanced production of sterile neutrinos

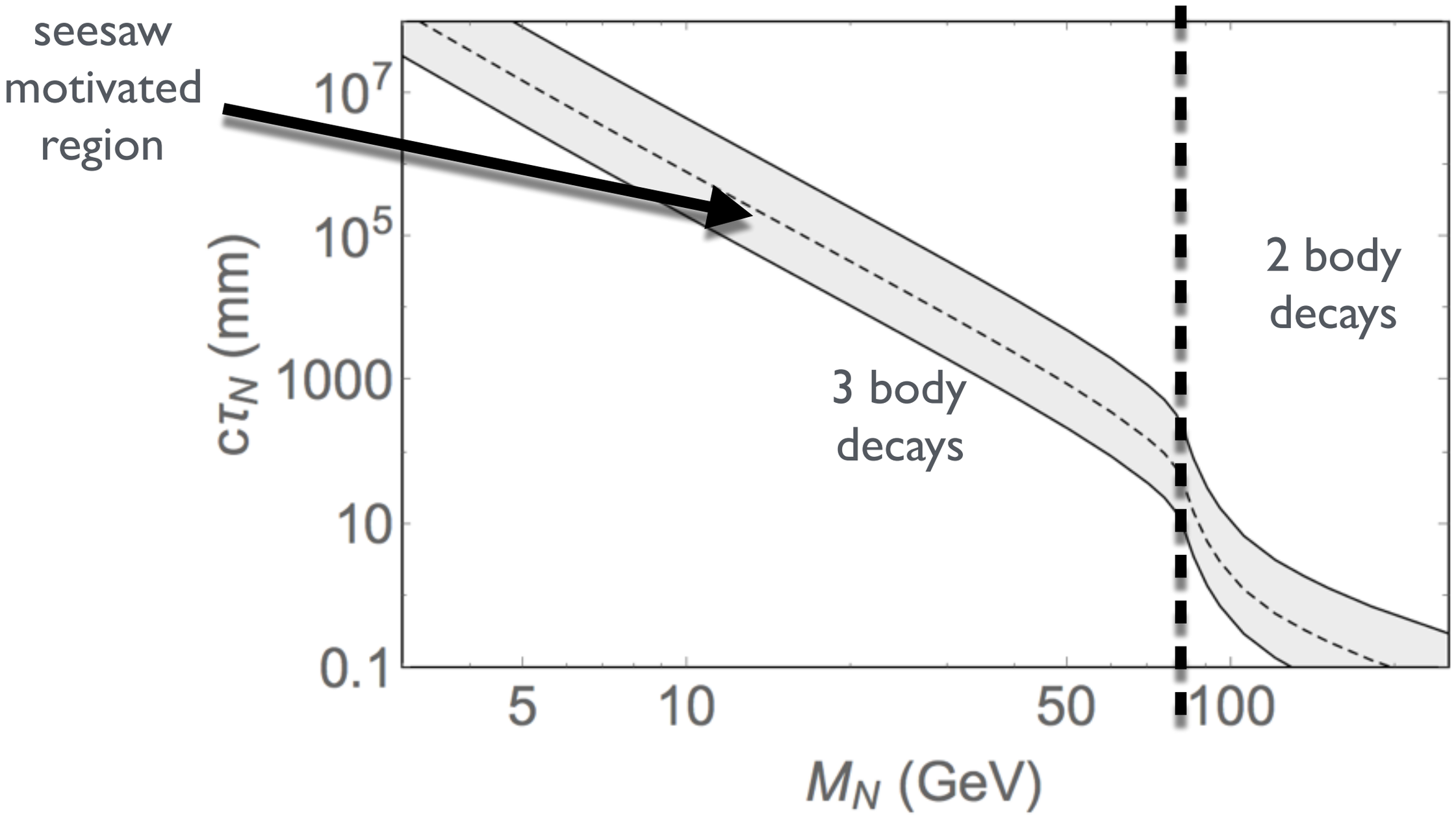
Production via new vector boson



Decay via weak interactions

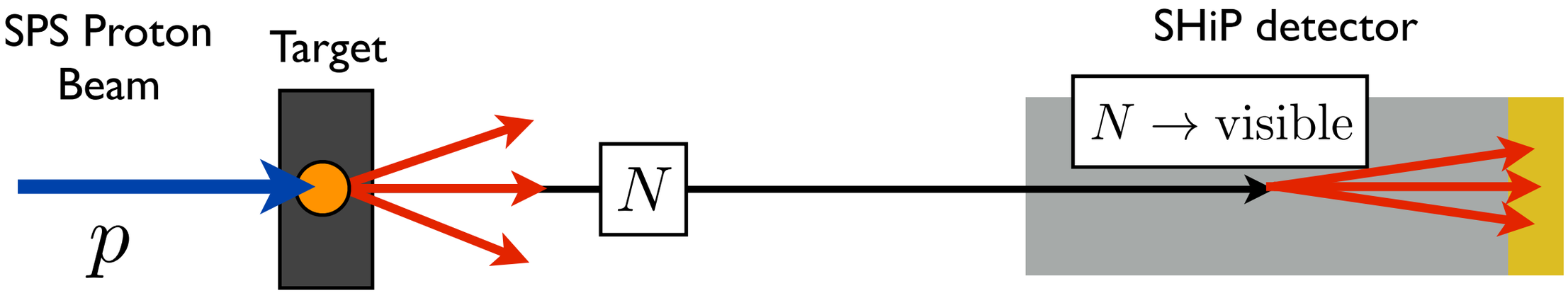


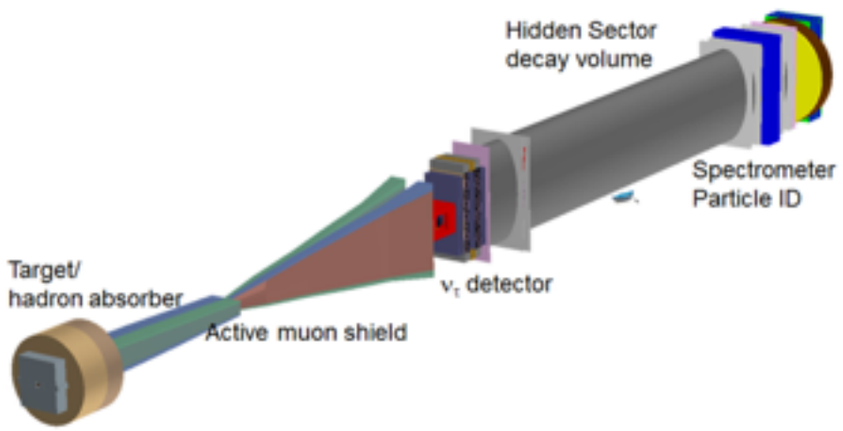
Sterile Neutrino Lifetime



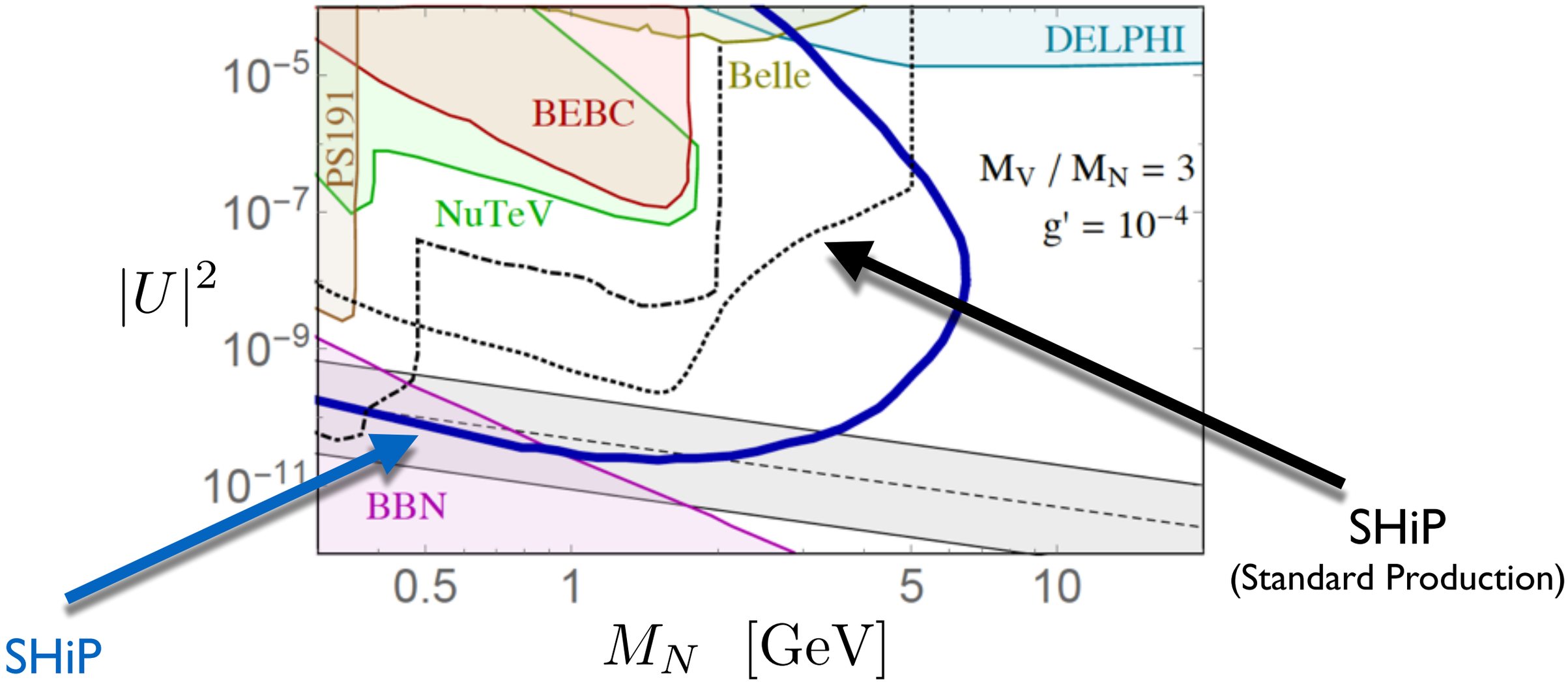
For N lighter than W the decays of N are macroscopic

SHiP


SPS Proton Beam
Target
SHiP detector
$N \to$ visible
p
N

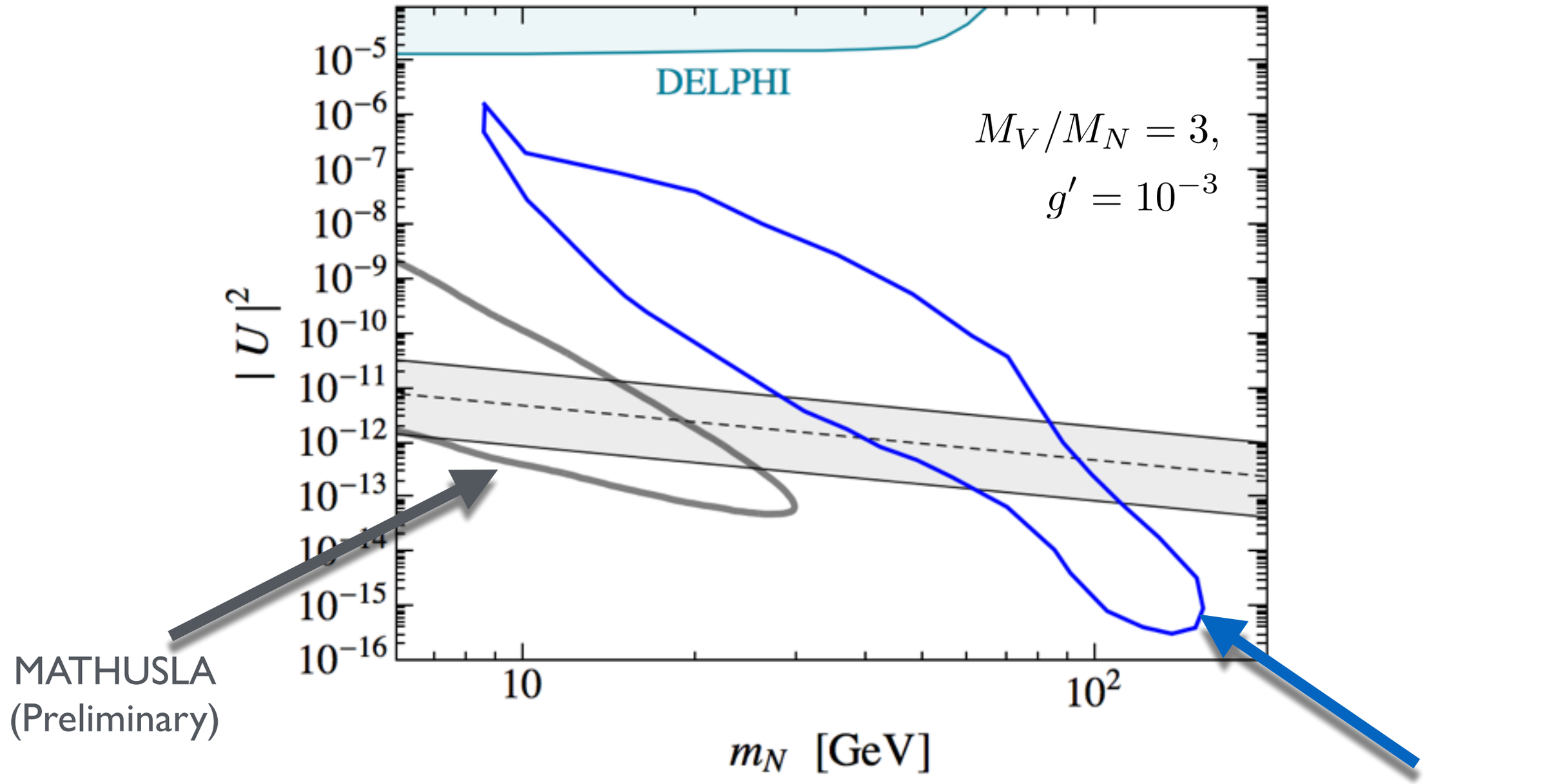

Hidden Sector decay volume
Spectrometer Particle ID
Target/ hadron absorber
Active muon shield
ν_τ detector

SHiP sensitivity to $B - L$ seesaw



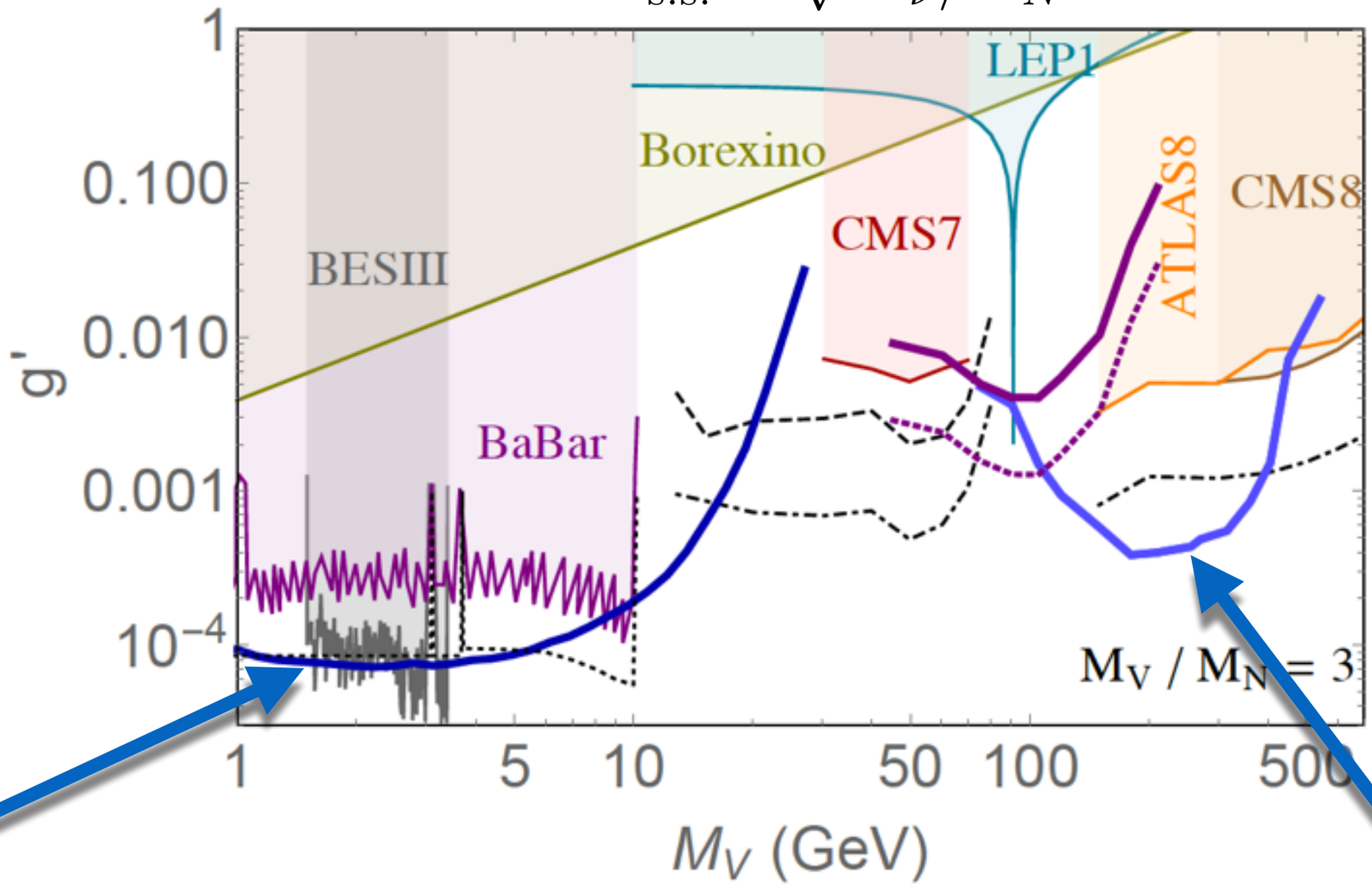
Can probe seesaw region

LHC complementarity



SHiP sensitivity to $B - L$ seesaw

$$U = U_{\text{s.s.}} = \sqrt{M_\nu / M_N}$$



SHiP

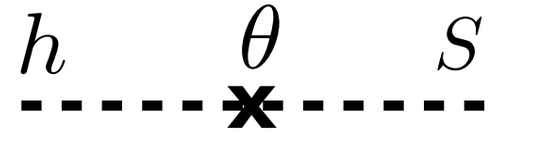
HL-LHC inner detector displaced vertex search

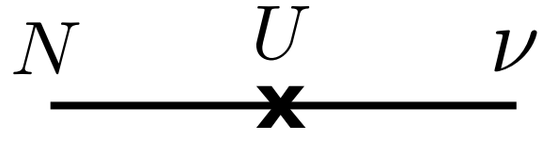
Higgs + Neutrino Portal

[BB, Pospelov, Shuve, in progress]

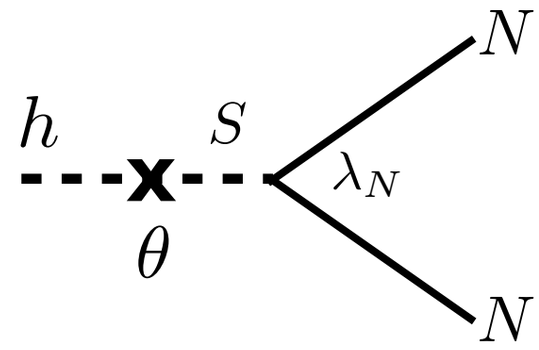
$$-\mathcal{L} \supset (AS + \lambda S^2)|H|^2 + \left(\lambda_N S N^2 + \text{h.c.}\right) + \dots$$

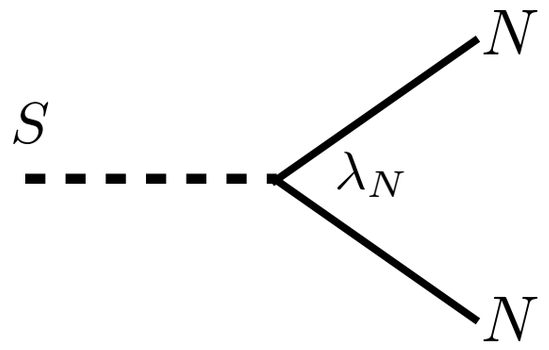
- Simple model, few parameters: $M_N, U, M_S, \theta, \lambda_N$
- Mixing

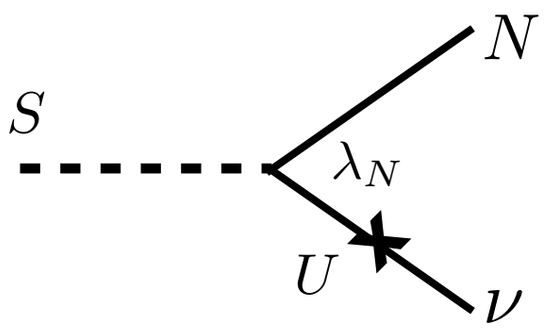


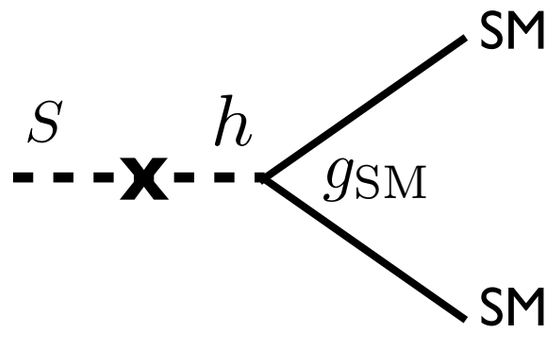


- Interactions

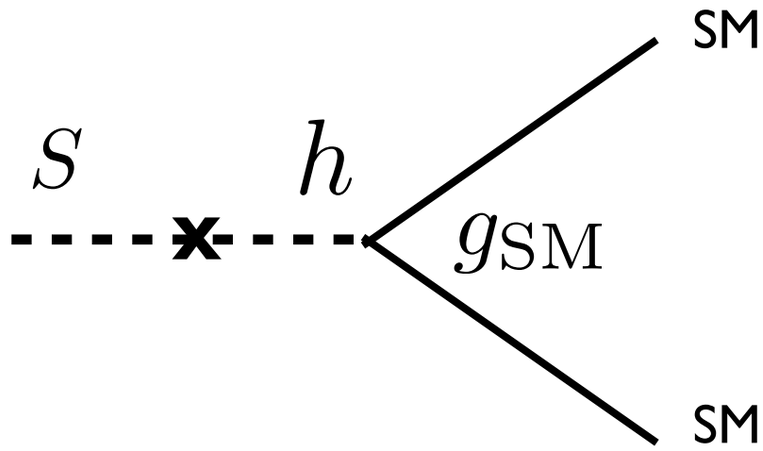


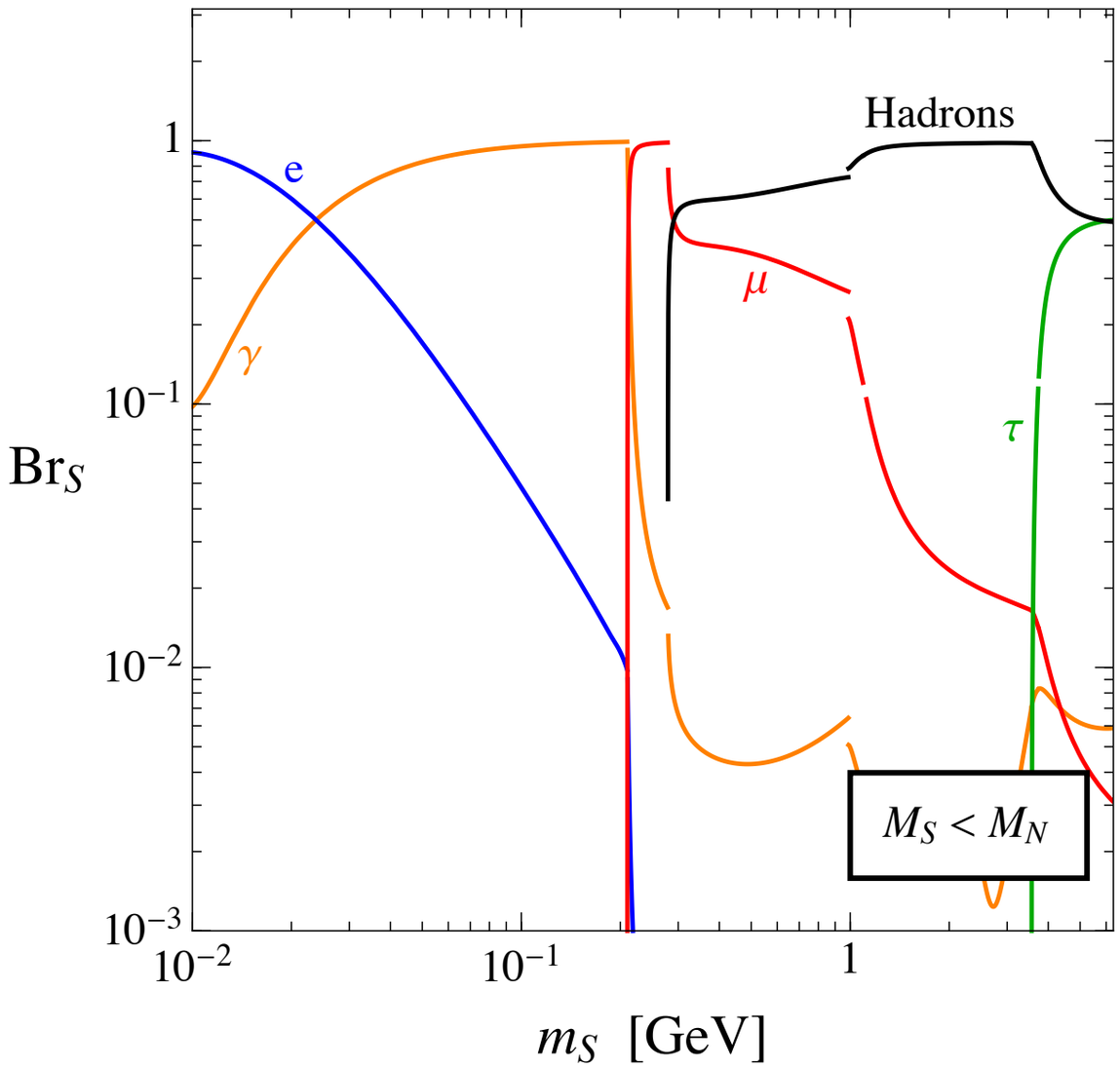


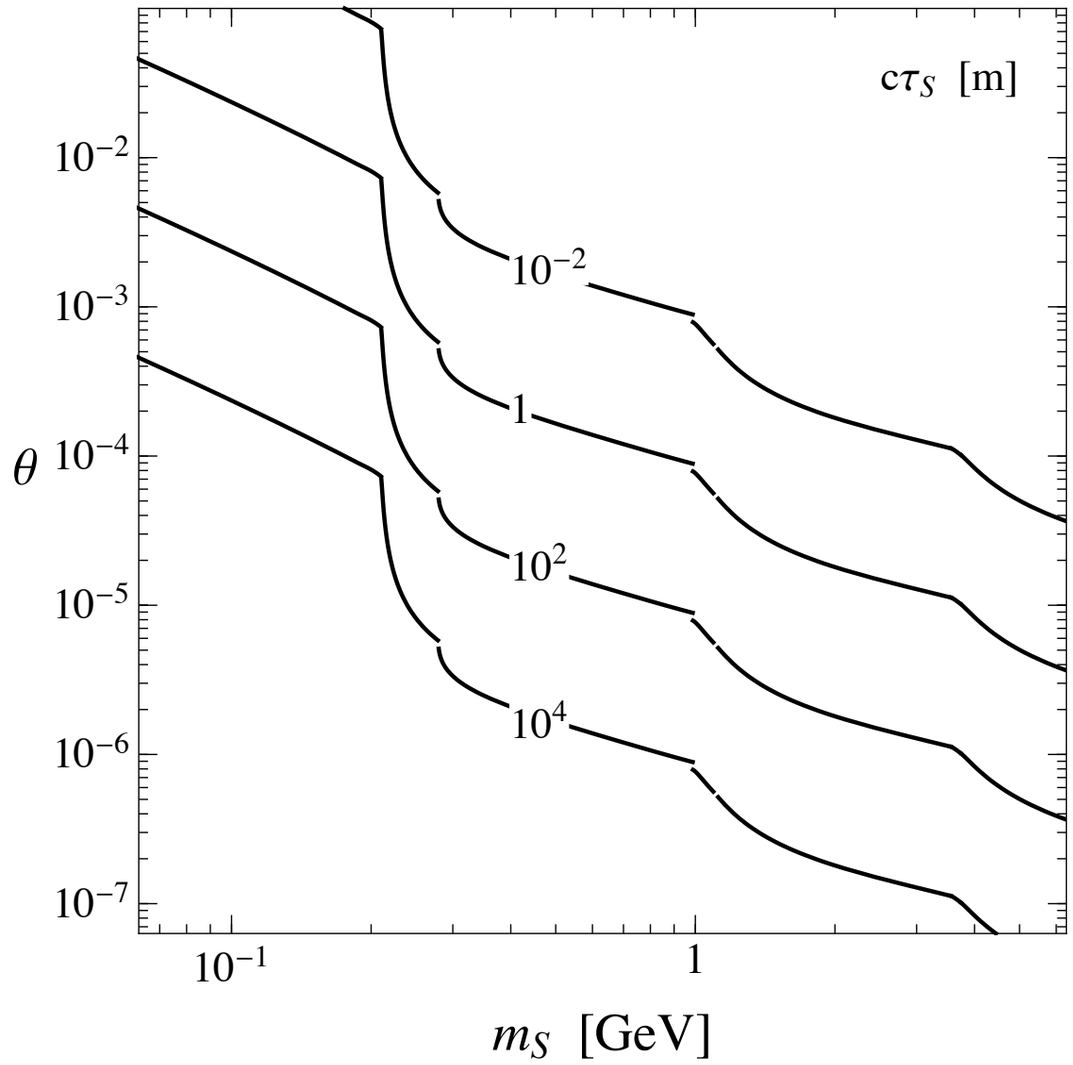




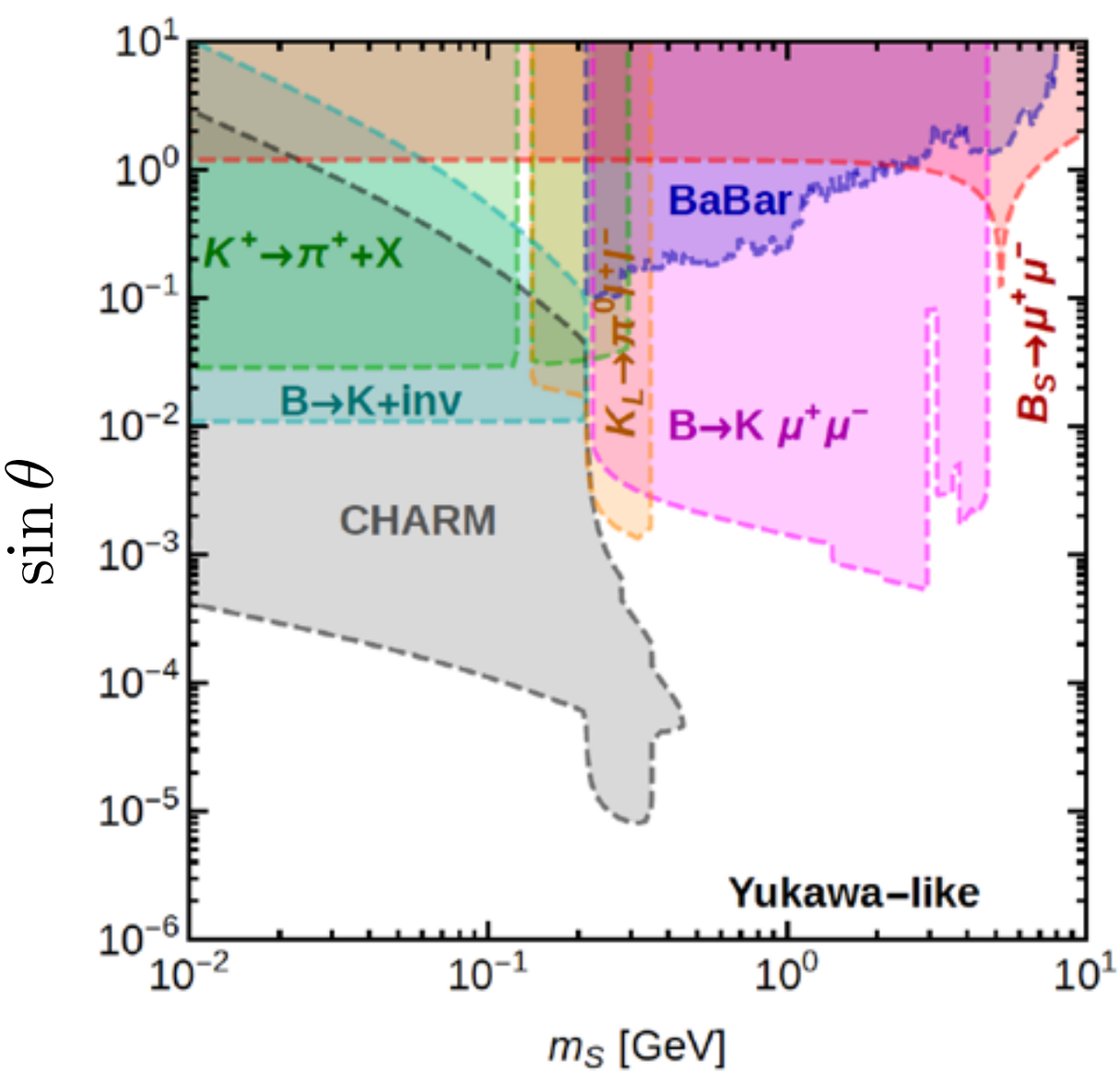
Singlet scalar decays and lifetime

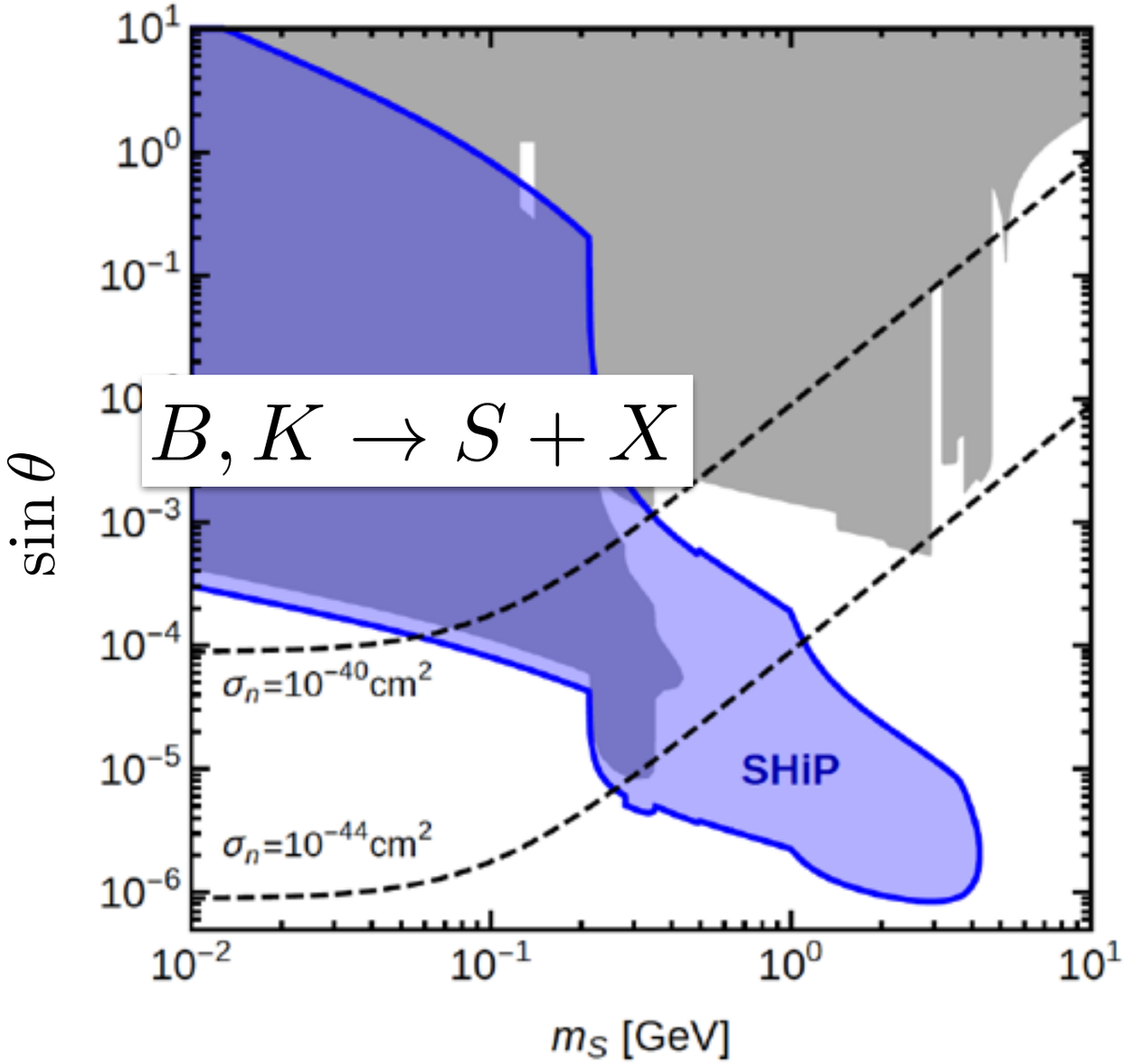






Scalar portal parameter space

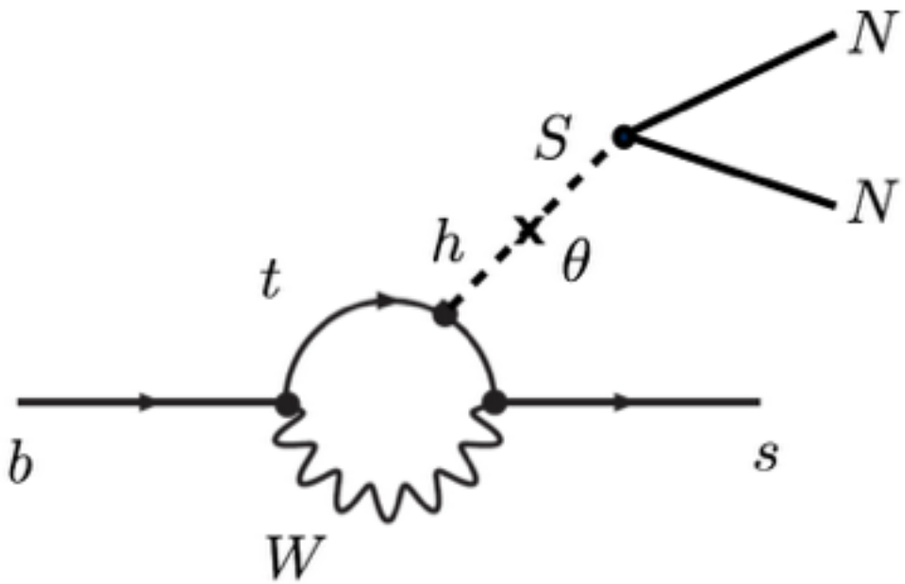




Limits can change if N couples to S

Production chain for $M_S > M_N$

- Production controlled by Higgs-scalar mixing

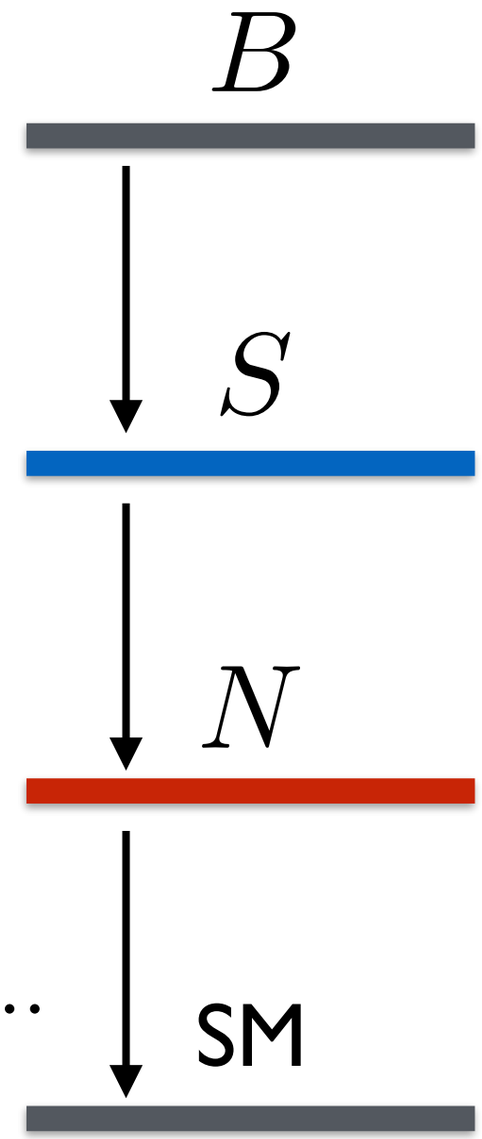


$B \to KS$

$S \to NN$

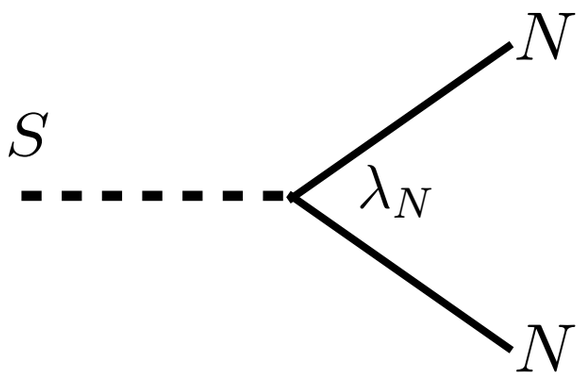
$S \to N\nu$

$N \to W^*\ell, \ldots$

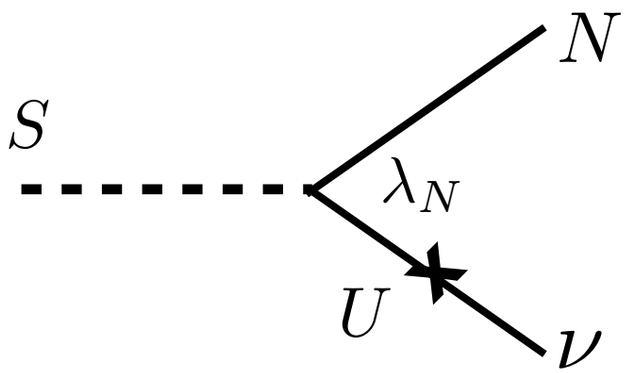


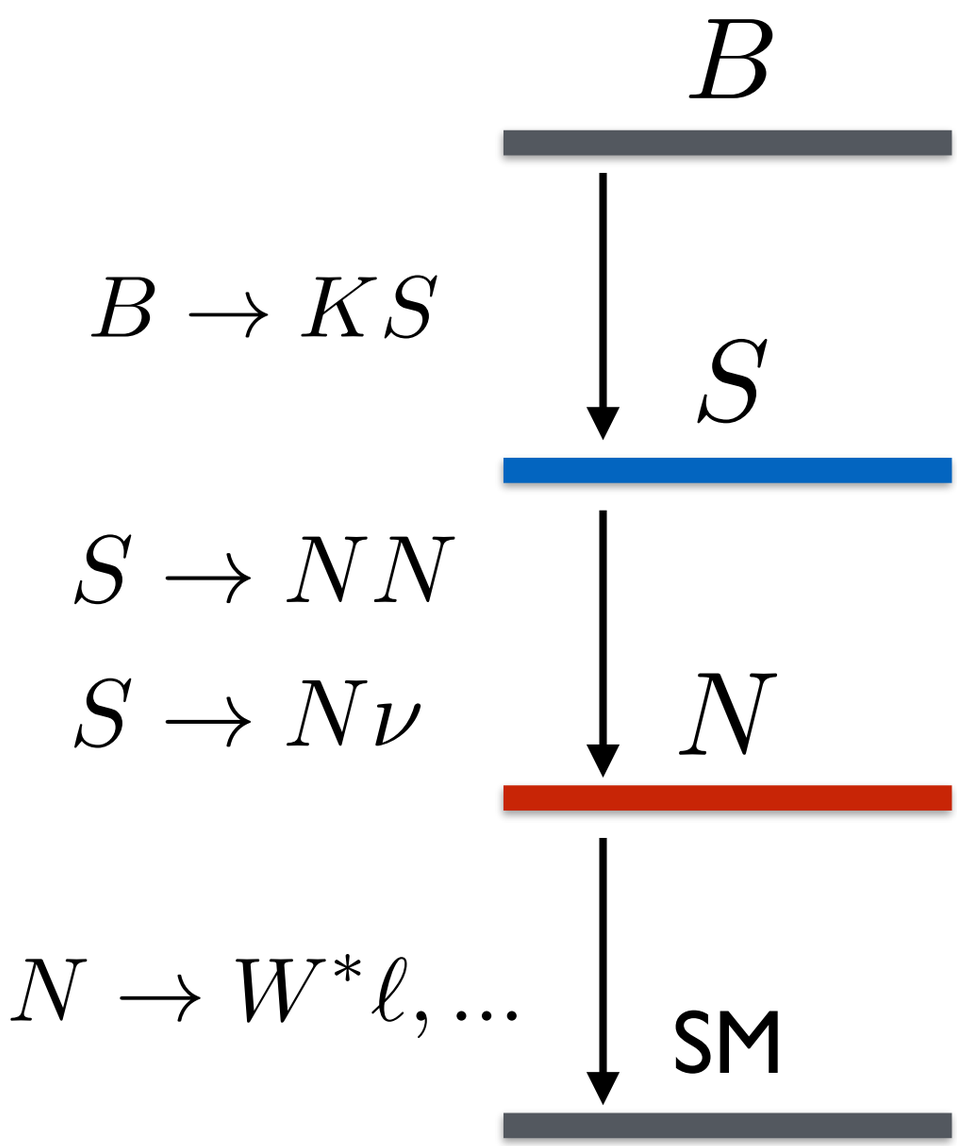
Production chain for $M_S > M_N$

- For $M_S > 2M_N$, the decay $S \to NN$ is unsuppressed and dominates

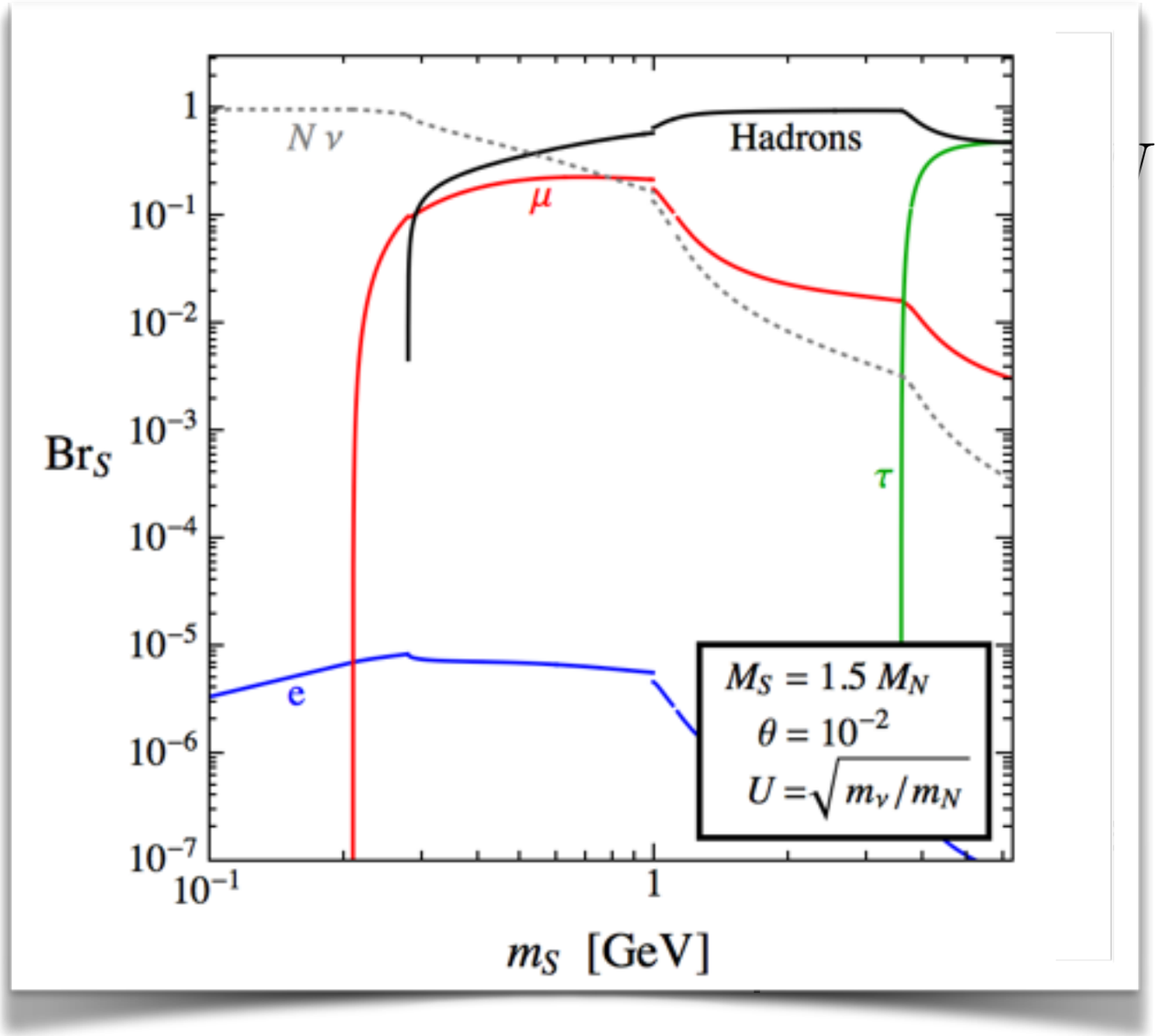


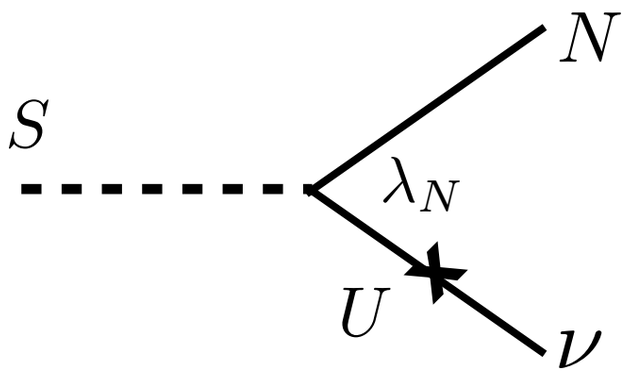
- For $M_N < M_S < 2M_N$, the channel $S \to N\nu$ can be competitive



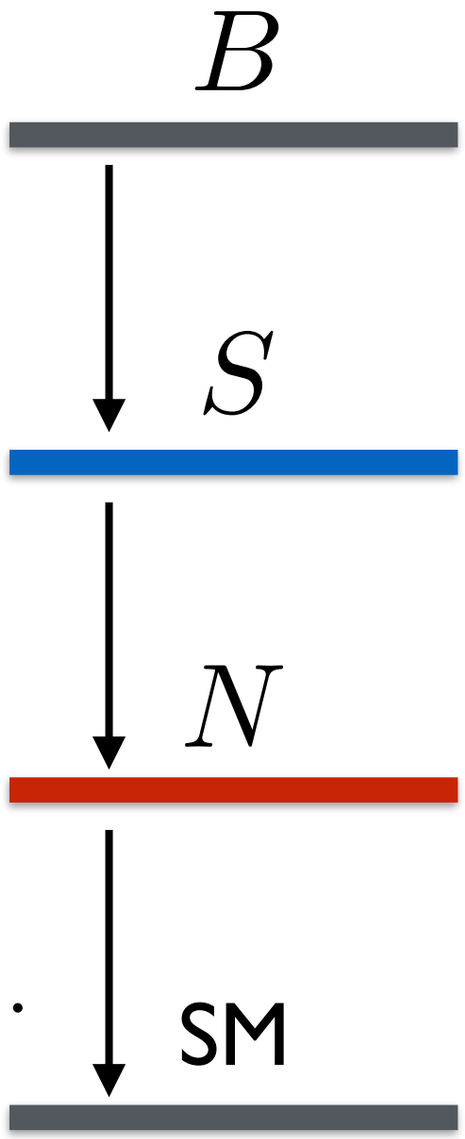


Production chain for $M_S > M_N$





$B \to KS$



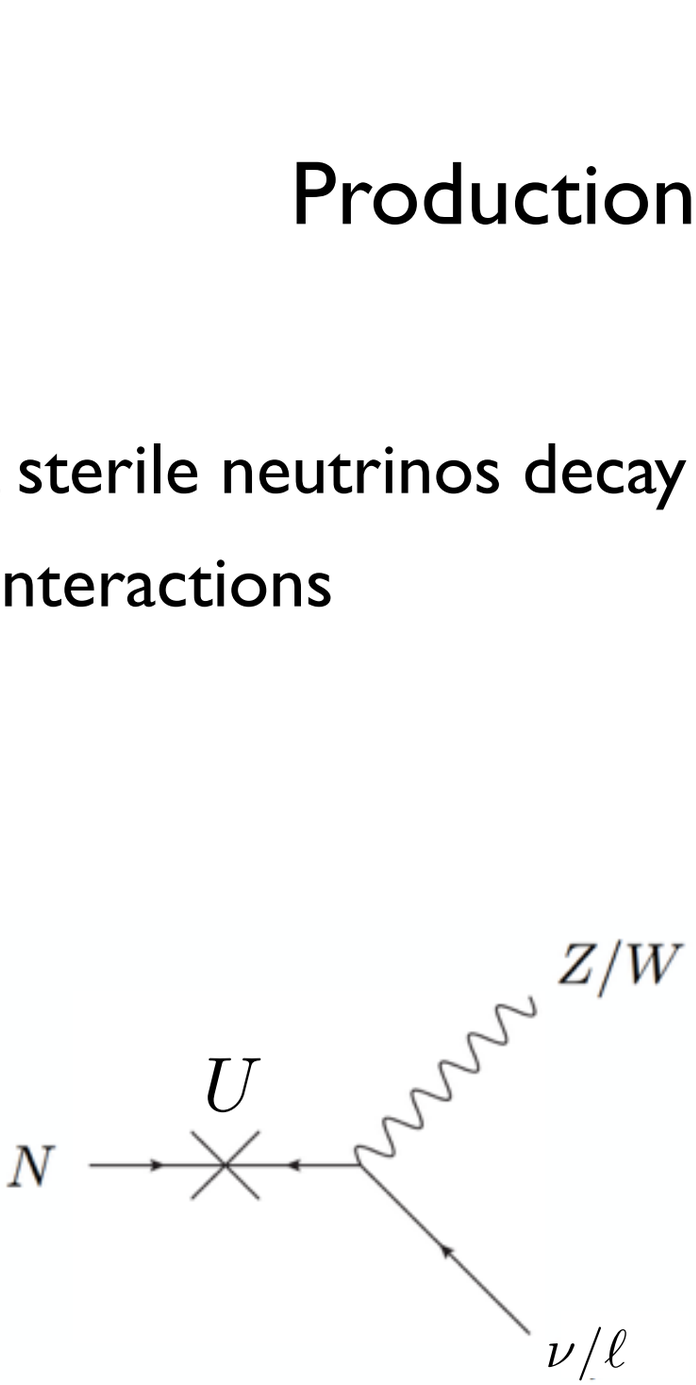
$S \to NN$

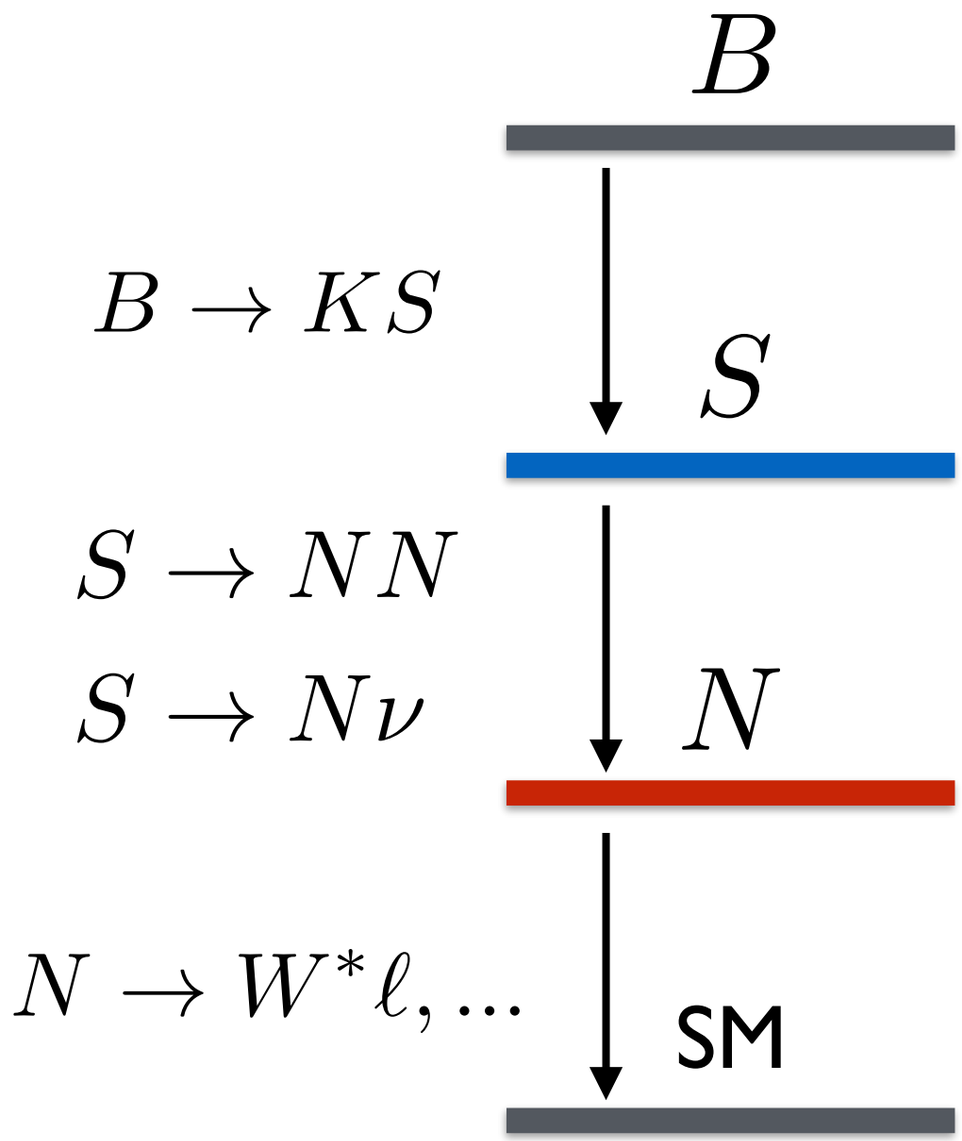
$S \to N\nu$

$N \to W^* \ell, \ldots$

Production chain for $M_S > M_N$

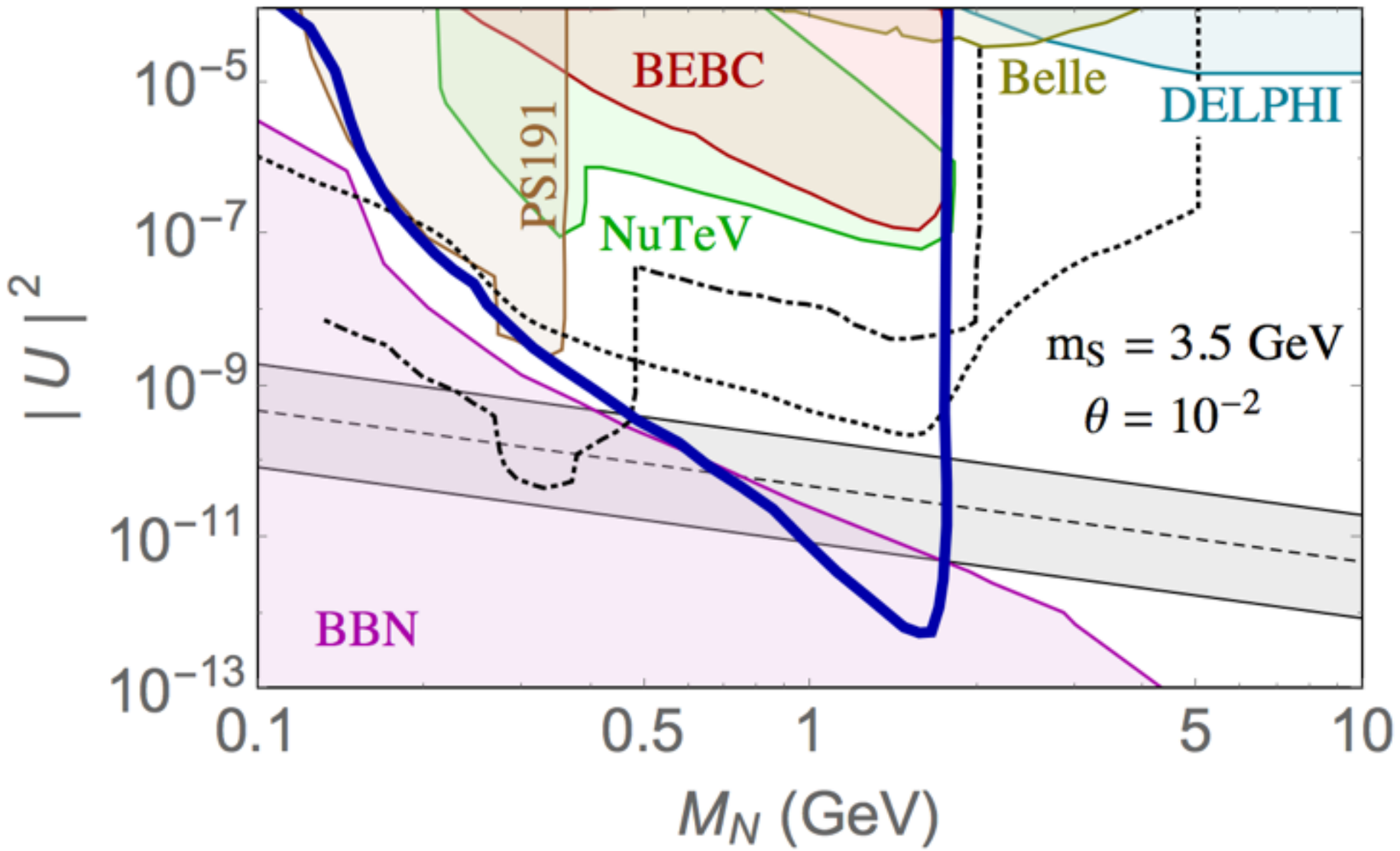
- Finally, sterile neutrinos decay via weak interactions





SHiP sensitivity (preliminary)

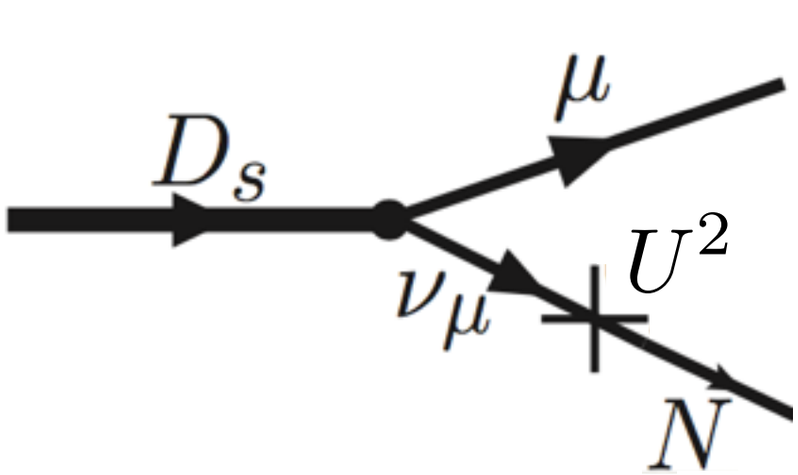
$$B \to KS,\ S \to NN,\ N \to \text{visible}$$



Can probe seesaw region

Production chain for $M_S < M_N$

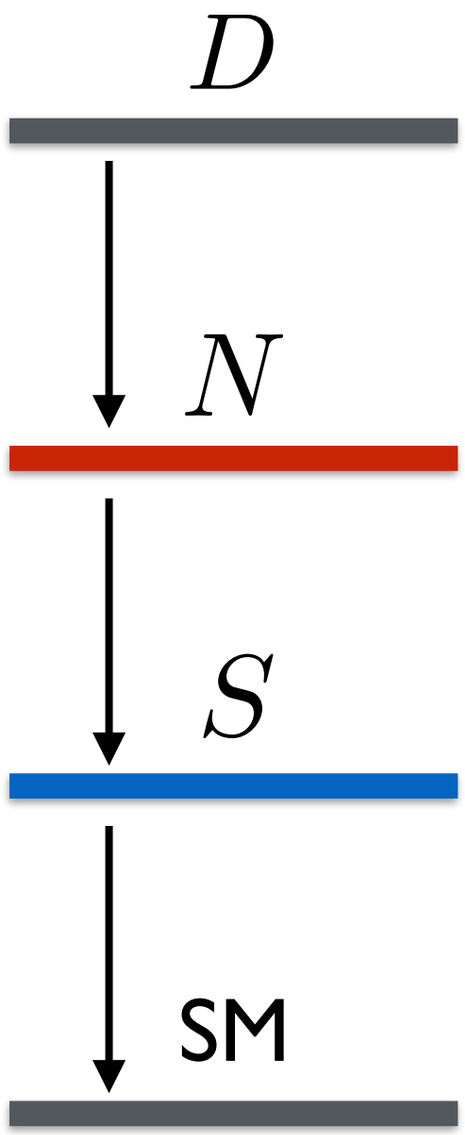
- Production of N controlled by active-sterile mixing angle



$D \to N + X$

$N \to S\nu$

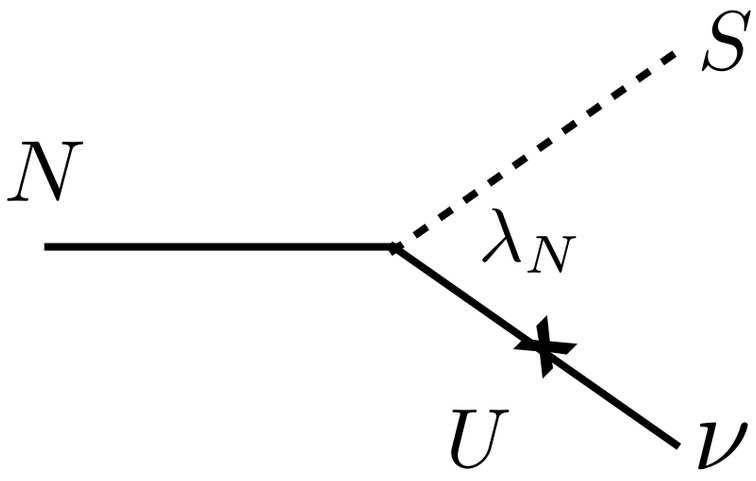
$S \to \mathrm{SM}\,\mathrm{SM}$



Production chain for $M_S < M_N$

- $N \to S\nu$ dominates over weak decays

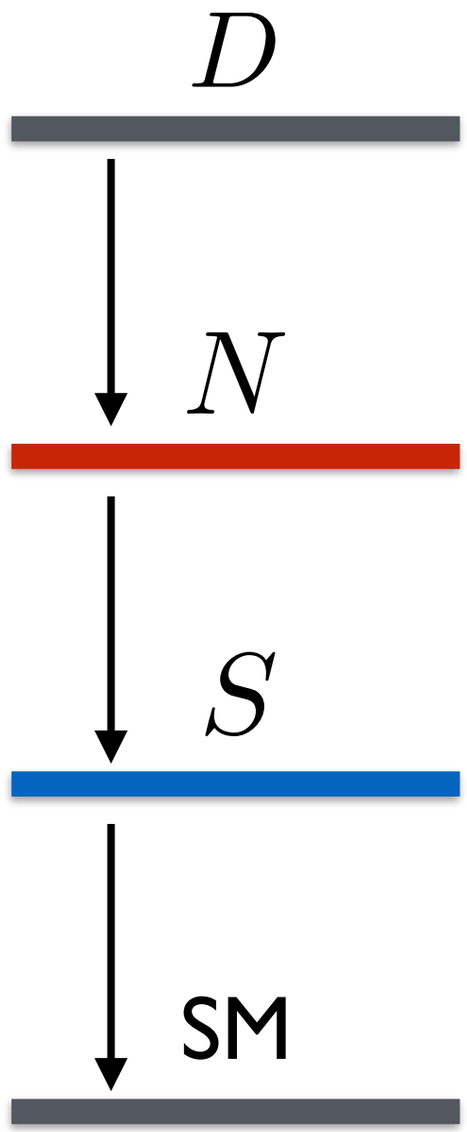
  (2-body vs. 3-body)



$D \to N + X$

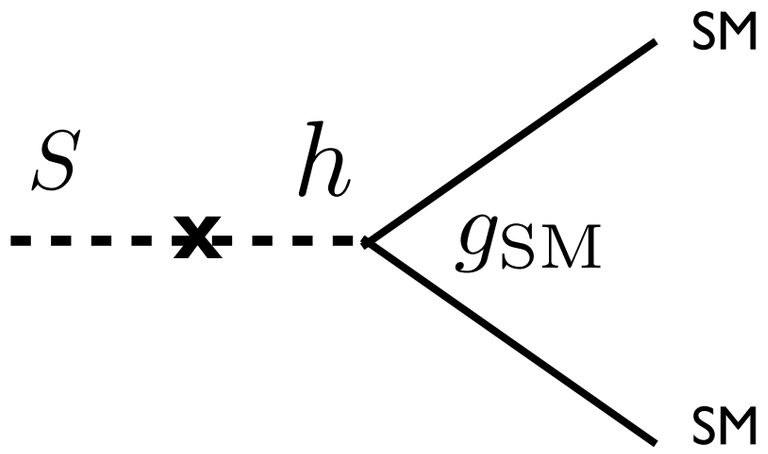
$N \to S\nu$

$S \to \mathrm{SM}\,\mathrm{SM}$



Production chain for $M_S < M_N$

- S decays in the "standard" way through Higgs mixing



$D \to N + X$

$N \to S\nu$

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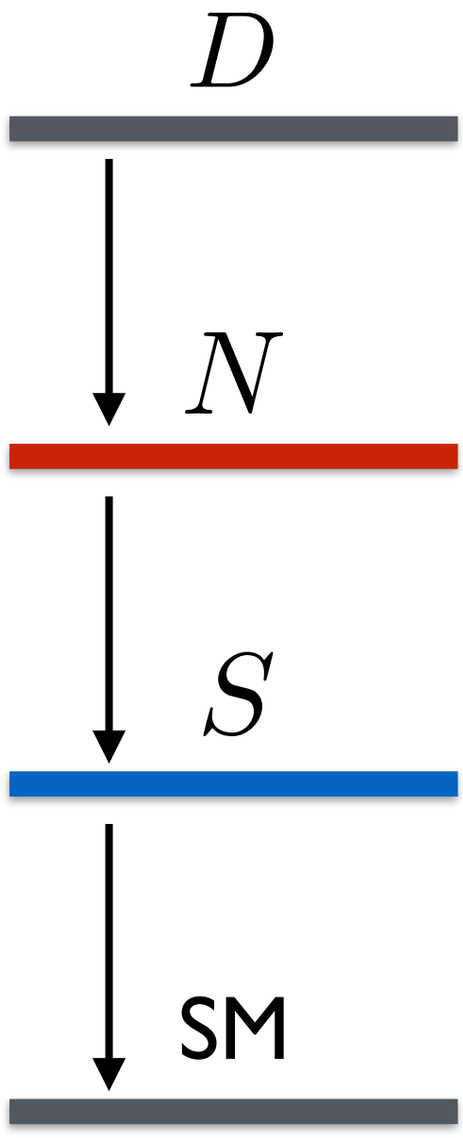
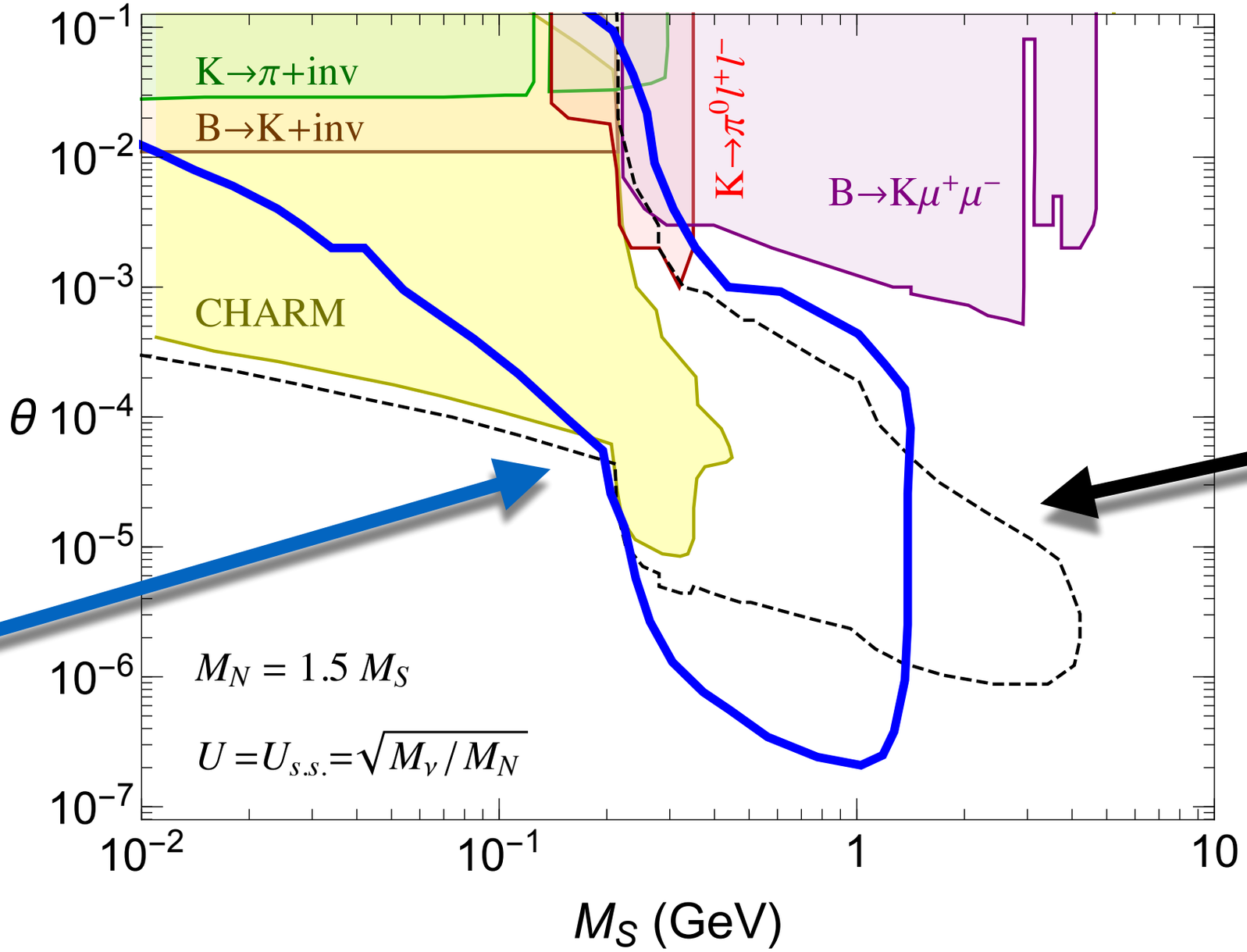


- There is a sweet-spot for lifetime controlled by the Higgs-scalar mixing angle

SHiP sensitivity (preliminary)

$$D \to N + X,\ N \to S\nu,\ S \to \text{visible}$$



SHiP

$D \to N + X,$

$N \to S\nu,$

$S \to$ visible

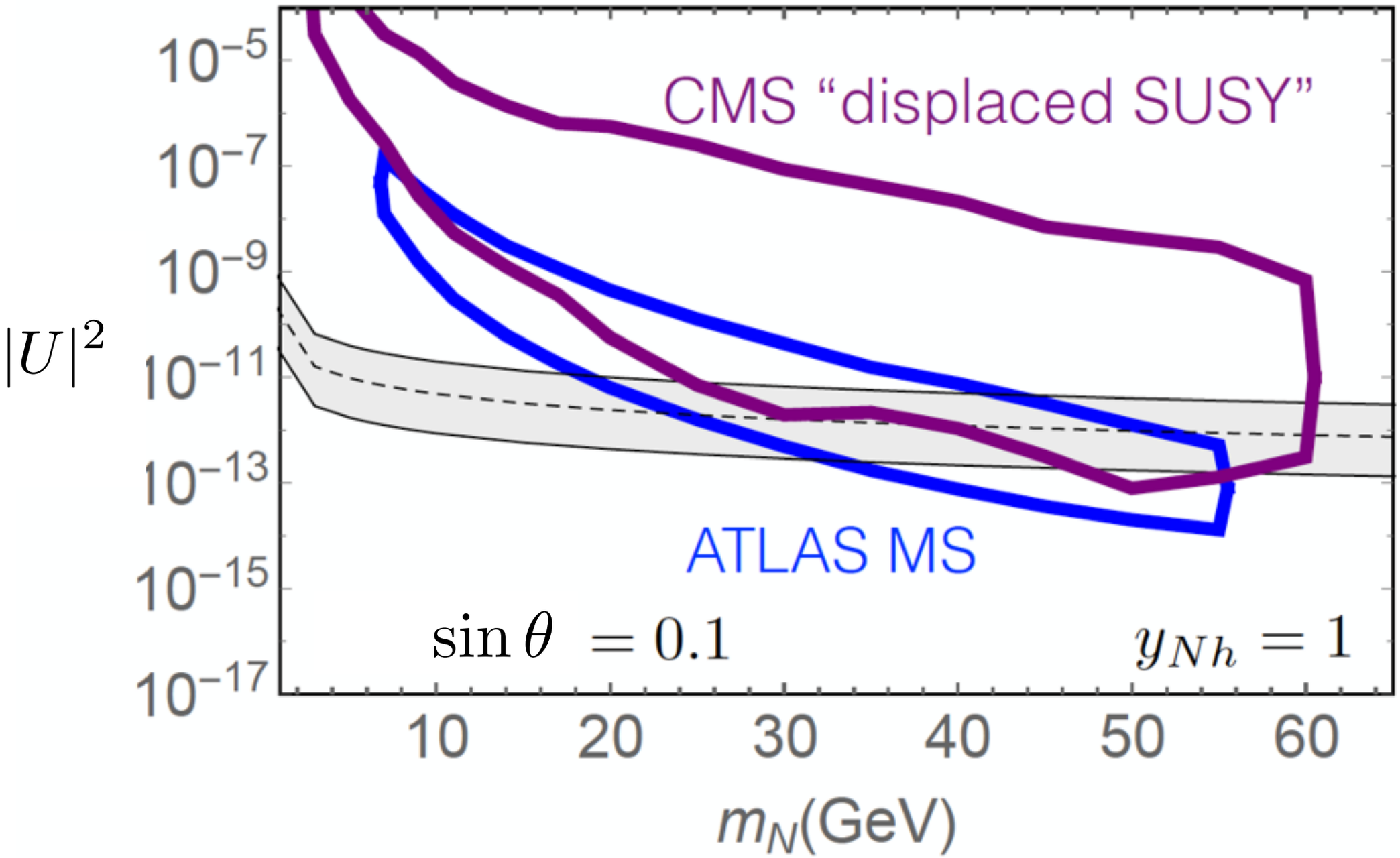
SHiP

$B \to KS,$

$S \to$ visible

Can probe seesaw region

LHC complementarity (preliminary)



Dedicated HL-LHC searches can probe seesaw with $\theta \sim 0.05$

Neutrino portal dark matter

[BB, Han, Shams Es Haghi, in progress]

- Basic idea - *N* mediates interactions between dark matter and the SM

$$yLHN + \lambda N \chi \phi + \text{h.c.}$$

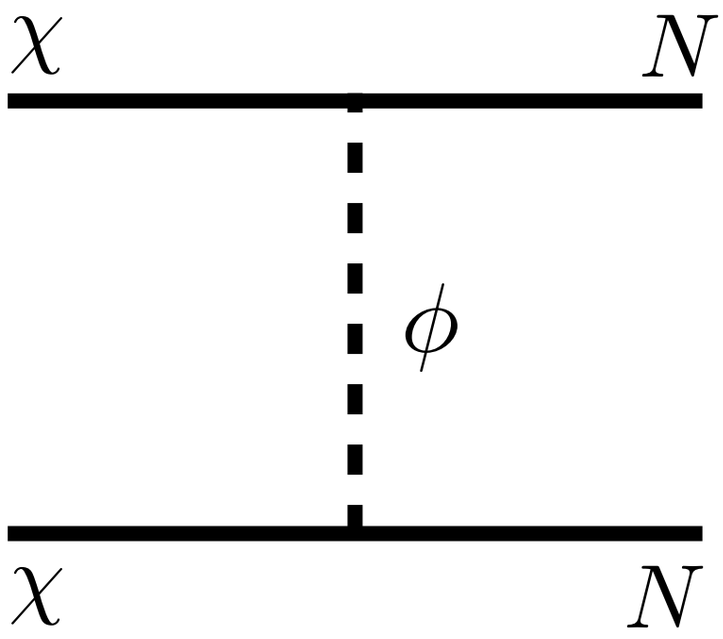
- Annihilation $\chi\chi \to NN$ is efficient - allows thermally produced DM
    - Example in the class of "Secluded" DM models

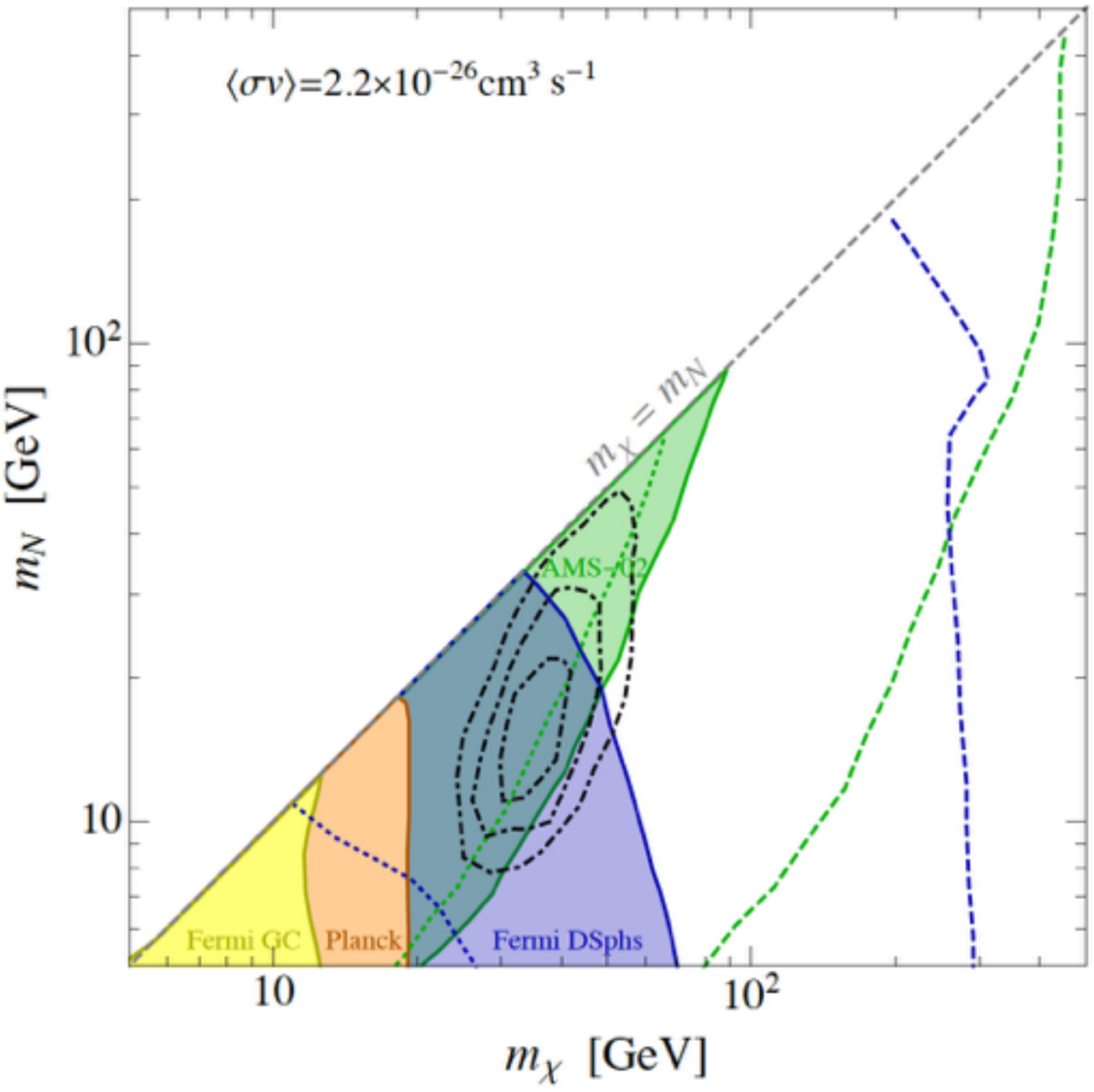
[Pospelov, Ritz, Voloshin]

- Most model independent signatures are in indirect detection
    - Gamma-rays, antiprotons, CMB, …

- Direct detection and accelerator probes are challenging, and more model dependent, but possible

Indirect Detection





Existing constraints probe masses below about 50 GeV

Accelerator probes

- If the dark sector is light, << 100 GeV, we can search for these particles in accelerator experiments
- Caution - annihilation should be in the *p*-wave — else there are stringent indirect constraints (see previous slide)
- LHC: exotic displaced Higgs decays (requires Higgs portal coupling)

$$h \to \phi\phi,\ \ \phi \to \chi N,\ \ N \to \text{visible}$$

- SHiP: Production through meson decays, cascade decay to SM

$$B \to \phi\phi,\ \ \phi \to \chi N,\ \ N \to \text{SM}$$

$$D, B \to N_2 + X, N_2 \to \chi\phi, \phi \to N_1\chi, N_1 \to \text{SM}$$

Work in progress…

Outlook

- Neutrino masses are elegantly explained by new sterile neutrinos + seesaw
- However, it is challenging to probe seesaw experimentally
- Sterile neutrinos themselves may have "portals"
  - E.g. New gauge forces, scalar portals, dark sector interactions, …
- Can probe seesaw region with new experiments + dedicated searches
- May mediate interactions with dark matter
- Provides additional motivation for long-lived particle searches at LHC and high intensity beam dump experiments like SHiP