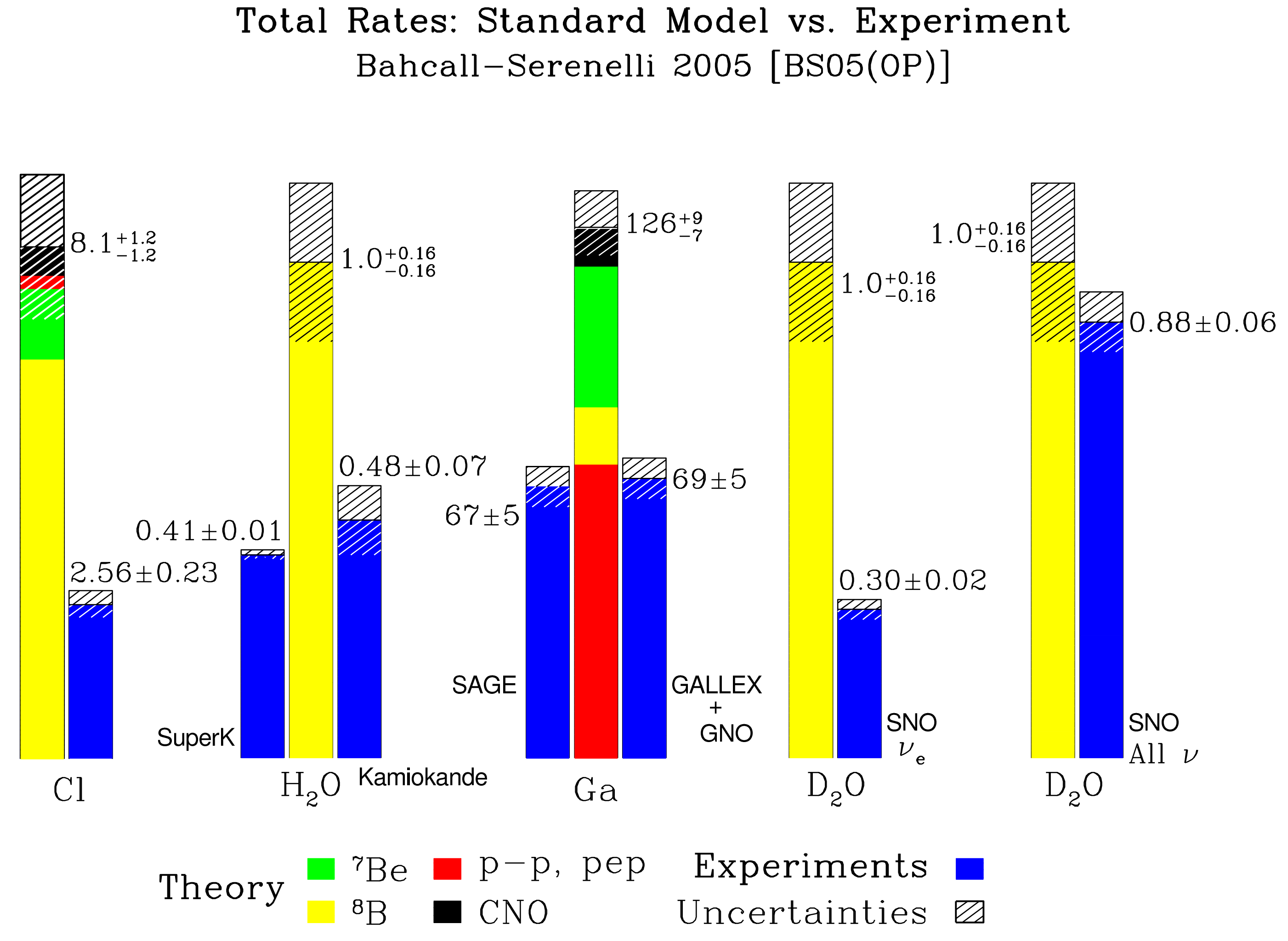
(Biased) Overview of Heavy Neutral Leptons

Douglas Tuckler
TRIUMF & Simon Fraser University
dtuckler@triumf.ca

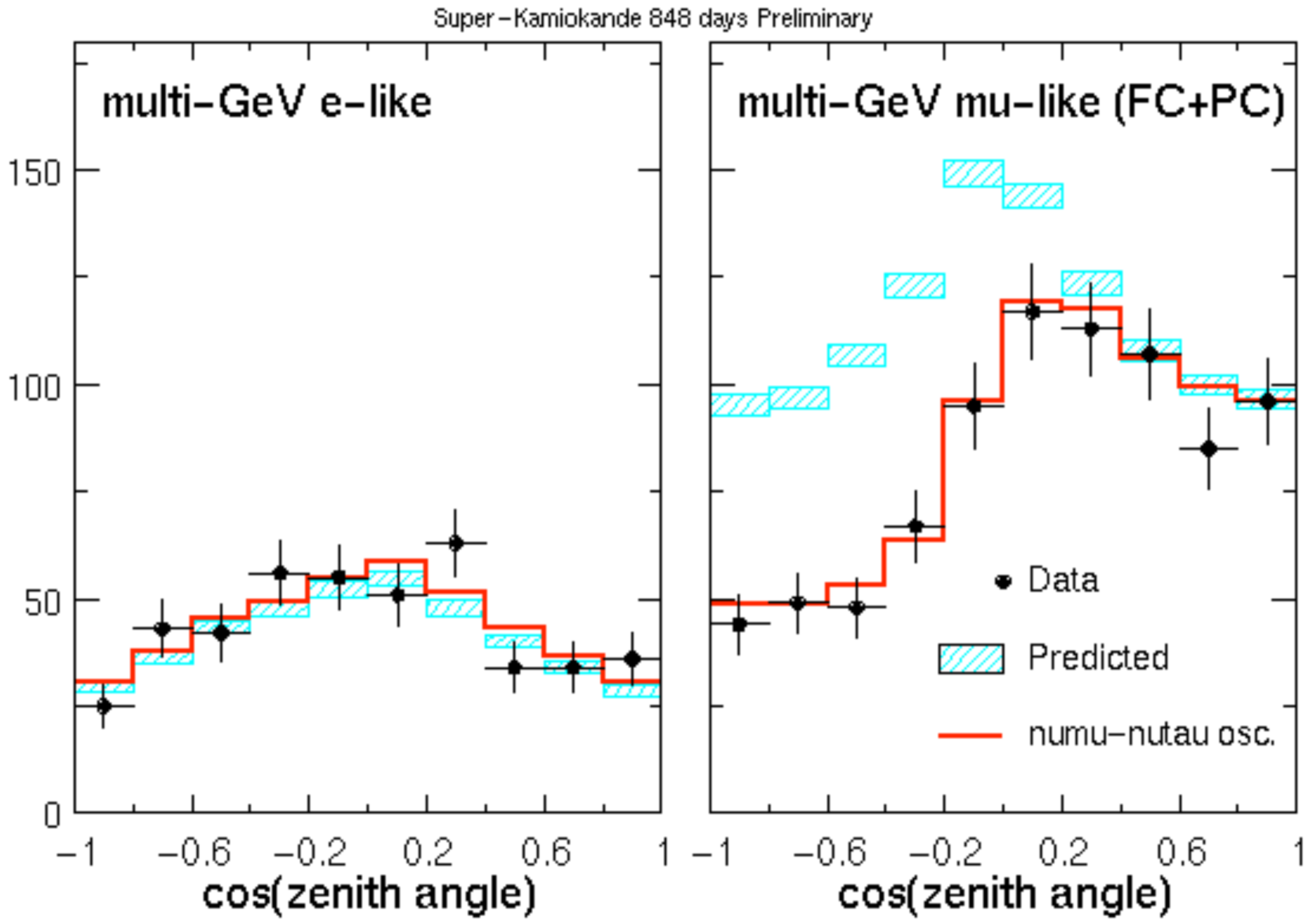
Dark Interactions 2024
Oct. 17, 2024

Neutrino Oscillations

Solar Neutrinos



Atmospheric Neutrinos



Neutrino oscillations only possible if *neutrinos have mass!*

$$P(\nu_\alpha \to \nu_\beta) \simeq |U_\alpha|^2 |U_\beta|^2 \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

NuFit-6.0 arXiv:2410.05380

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 6.1$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.49^{+0.19}_{-0.19}$	$6.92 \to 8.05$	$7.49^{+0.19}_{-0.19}$	$6.92 \to 8.05$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.513^{+0.021}_{-0.019}$	$+2.451 \to +2.578$	$-2.484^{+0.020}_{-0.020}$	$-2.547 \to -2.421$

Neutrino Mass Generation

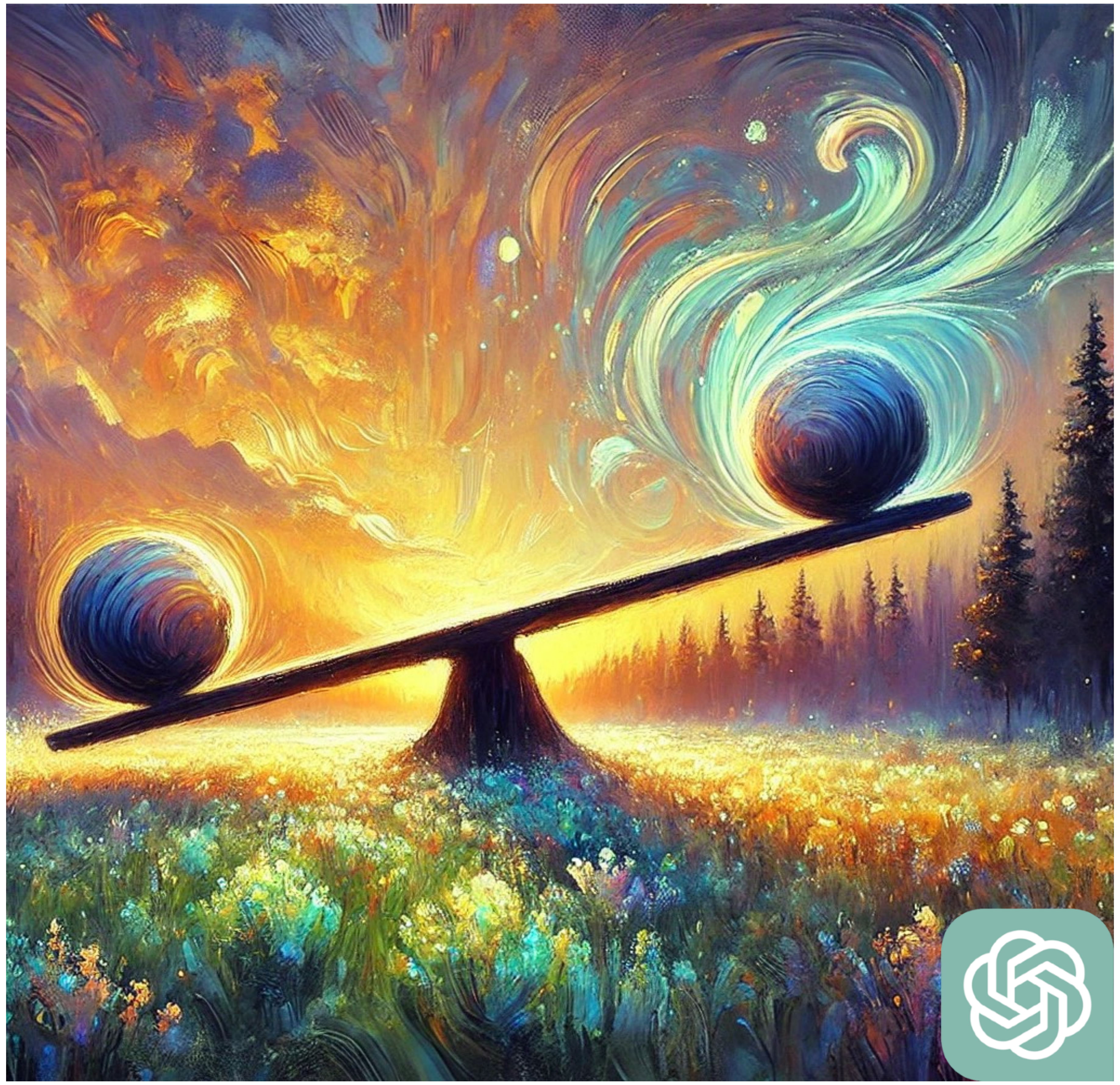
Seesaw Mechanism

$$\mathcal{L} \supset Y \bar{L} \tilde{H} N_R + \frac{1}{2} M_N \bar{N}_R N_R$$

$$\xrightarrow{\text{EWSB}} m_D \bar{\nu}_L N_R + M_N \bar{N}_R N_R$$

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & m_D \\ m_D & M_N \end{pmatrix} \rightarrow m_\nu \simeq \frac{Y^2 v^2}{M_N}$$

Neutrino masses *inversely proportional to Majorana mass*



"Here is an impressionist version of the seesaw mechanism with an abstract seesaw. The contrast between the heavy and light sides is represented through expressive brushstrokes and vibrant colors, capturing the essence of the mechanism in a serene, dreamlike setting."

Neutrino Mass Generation

Seesaw Mechanism

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Neutrino masses *inversely proportional to Majorana mass*

Inverse Seesaw Mechanism

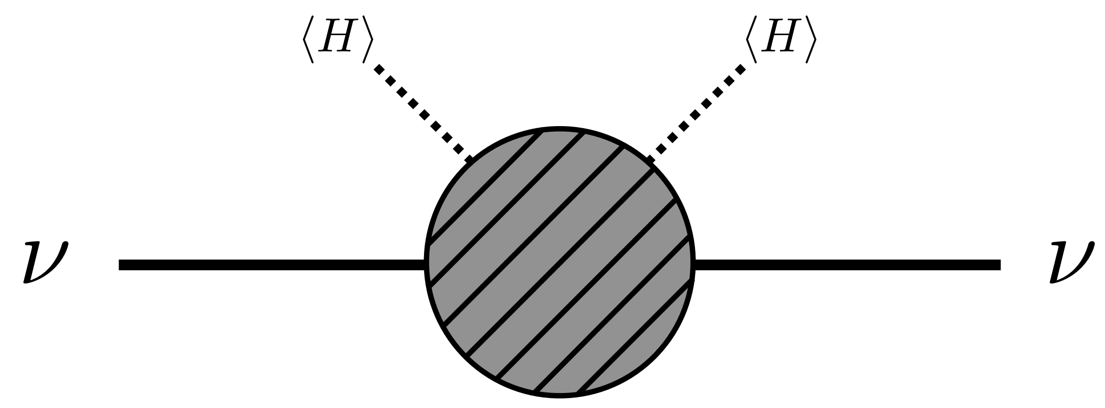
$$\mathcal{L} \; \supset \; Y\bar{L}\tilde{D}N + M_D\bar{N}N'^c + \mu\bar{N}N^c$$

$$m_\nu \sim \mathcal{O}\left(\frac{Y^2\mu v^2}{M_D^2}\right)$$

Neutrino masses *proportional to Majorana mass*

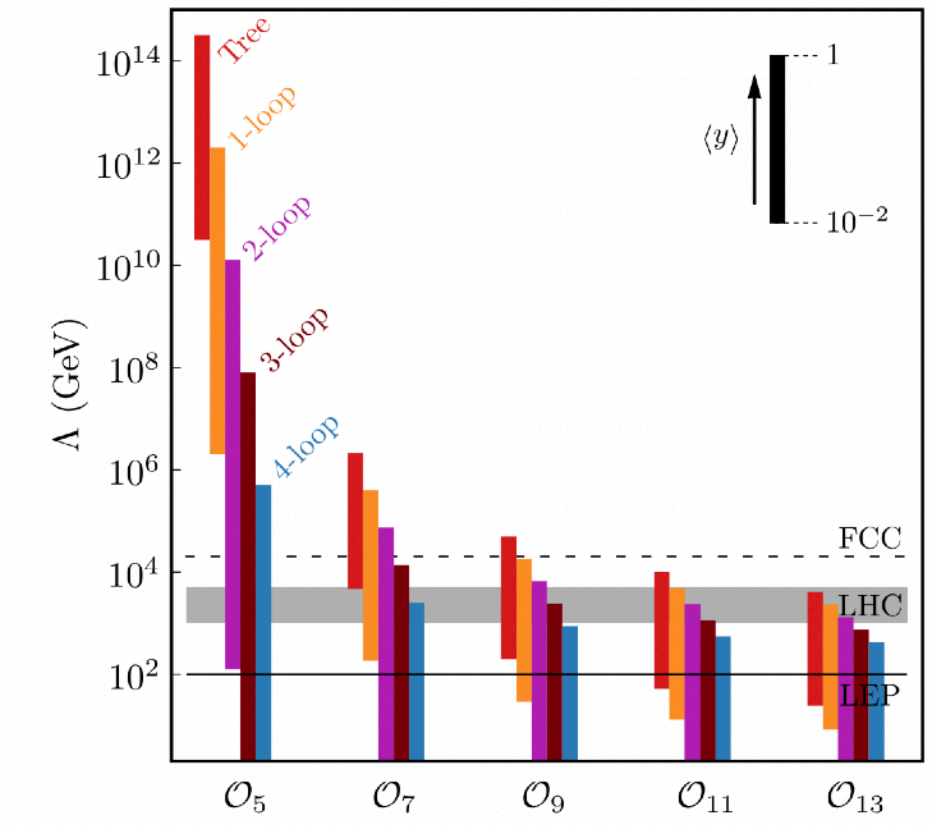
Detectable, weak scale RH neutrinos $\to Y \sim 1$, $M_D \sim$ GeV - TeV

Loop Mechanism



$(1/16\pi^2)^n$ suppression

arXiv:1806.07264



Neutrino Mass Generation

Seesaw Mechanism

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Neutrino masses *inversely proportional to Majorana mass*

Weak interactions induced my mixing with active neutrinos

$$\mathcal{L} \supset \frac{g_2}{\sqrt{2}} U_\alpha W_\mu^- \ell_\alpha^\dagger \bar{\sigma}^\mu N$$

Charged Current

$$+ \frac{g_2}{2\cos\theta_W} U_\alpha Z_\mu \nu_\alpha^\dagger \bar{\sigma}^\mu N$$

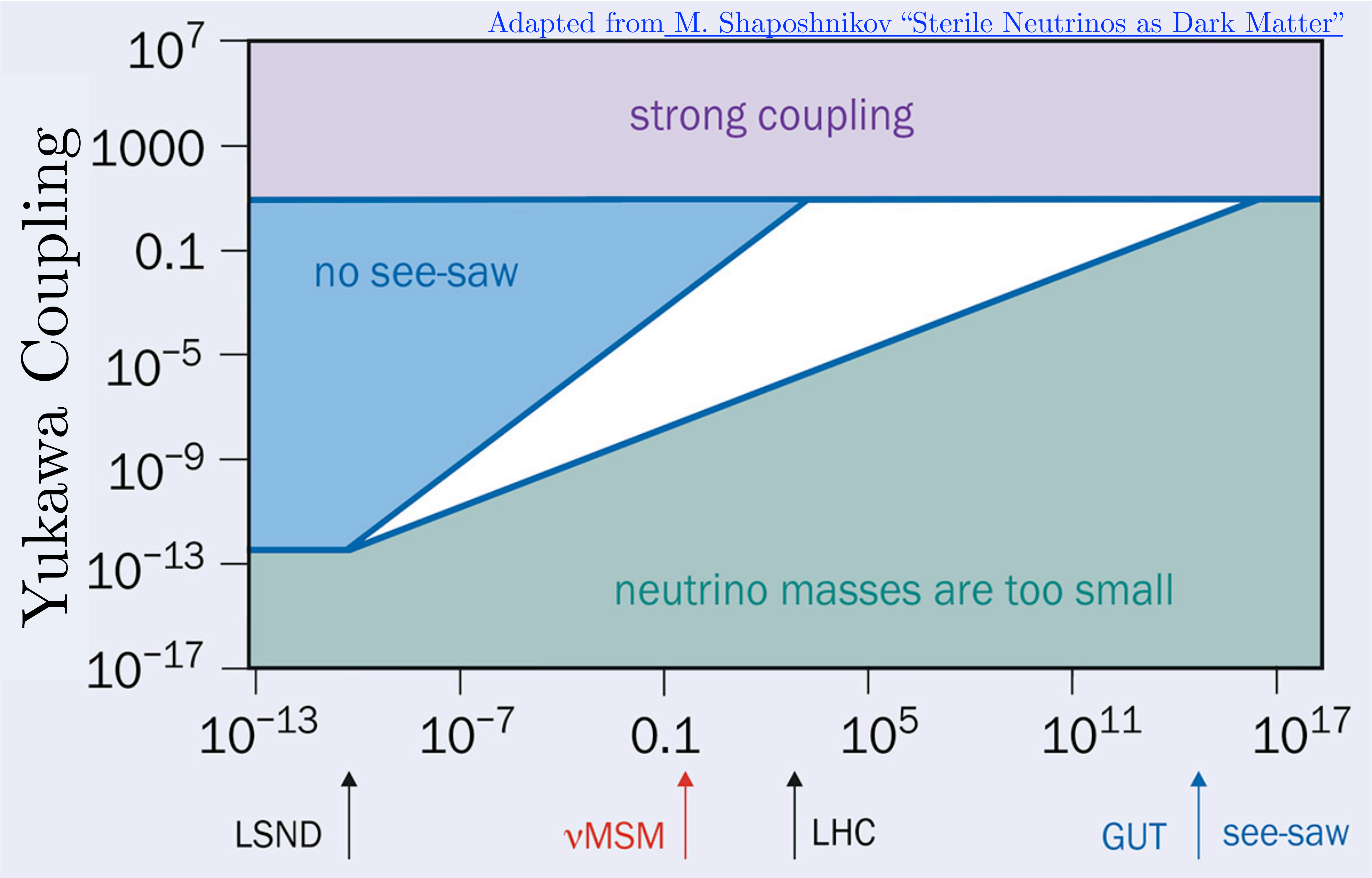
Neutral Current

N_R is produced in any process where a SM neutrino is produced

Heavy Neutral Lepton Landscape

- We don't know the scale of neutrino mass mechanism

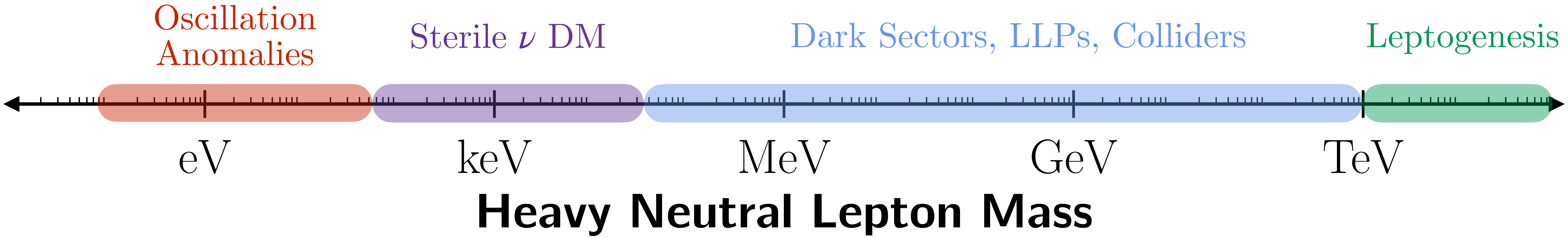
$$m_\nu \simeq \frac{Y^2 v^2}{M_N}$$



HNL Mass [GeV]

Heavy Neutral Lepton Landscape

- We don't know the scale of neutrino mass mechanism
- But we know the testable range of HNL masses



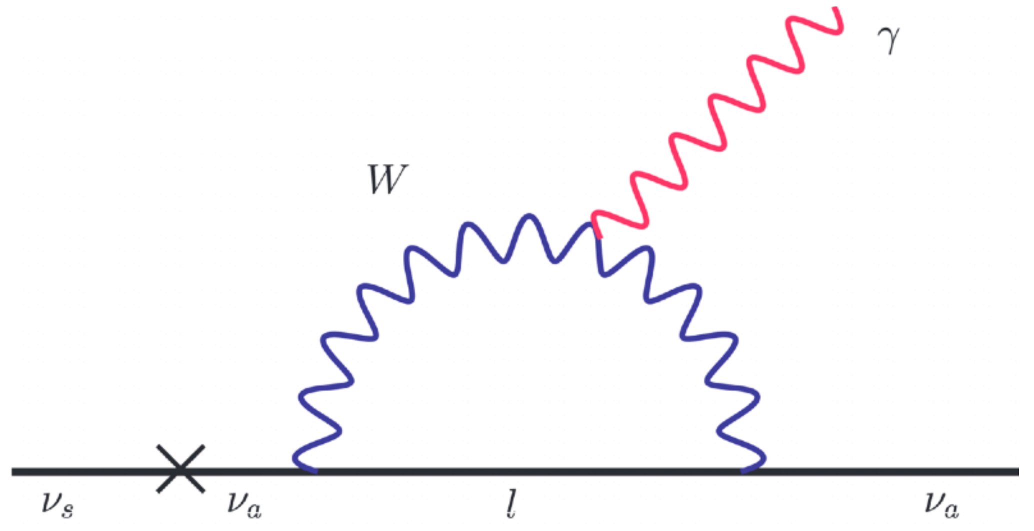
Focus of this talk: keV - TeV range

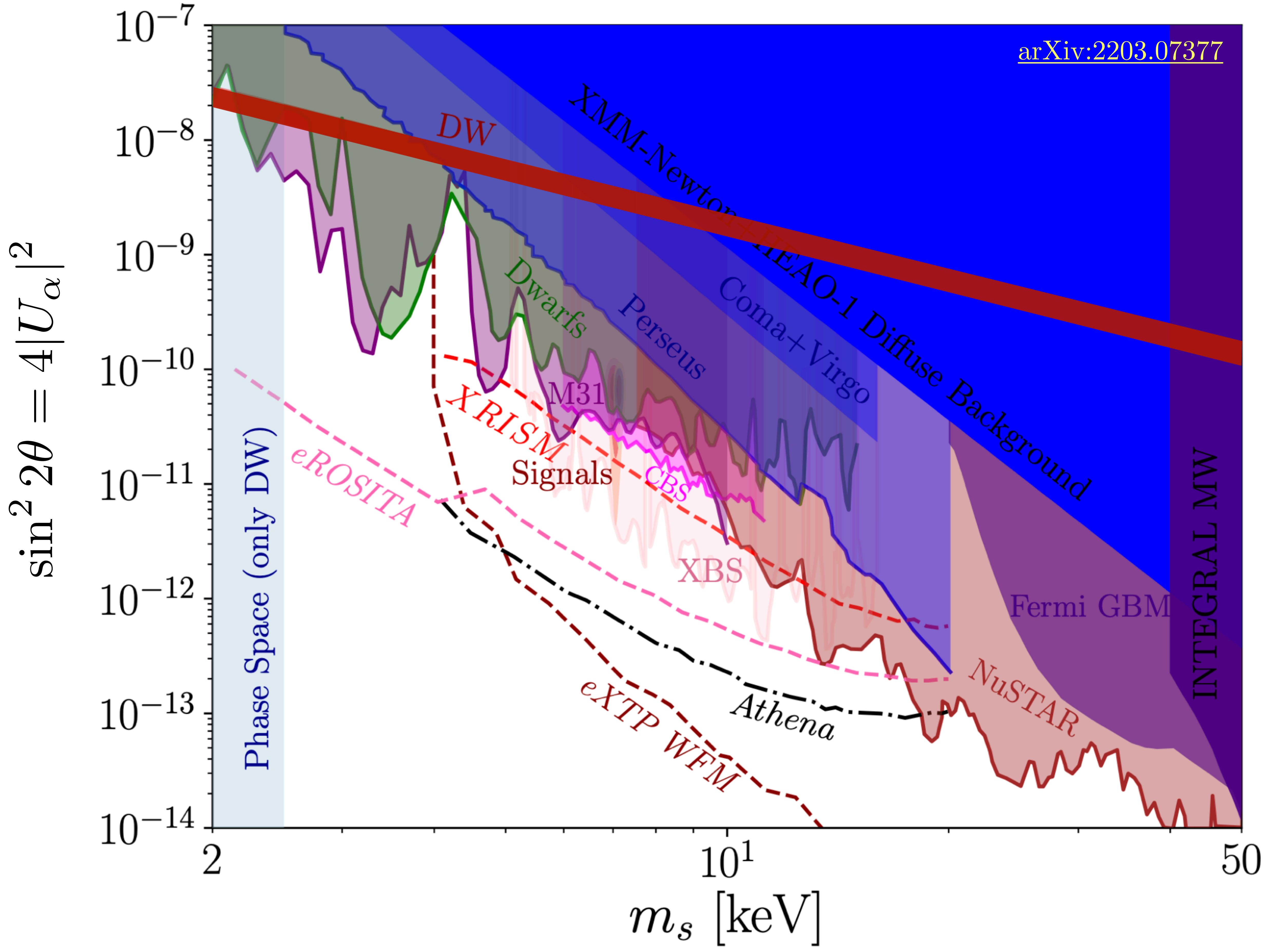
keV-scale Heavy Neutral Leptons

- Also called sterile neutrinos. Can potentially make up all of the ***dark matter***
- 4th neutrino eigenstate

$$\nu_4 = v_a \sin\theta + \nu_s \cos\theta$$

- Relic abundance via Dodelson-Widrow Mechanism
- Decay to monochromatic X-ray photons





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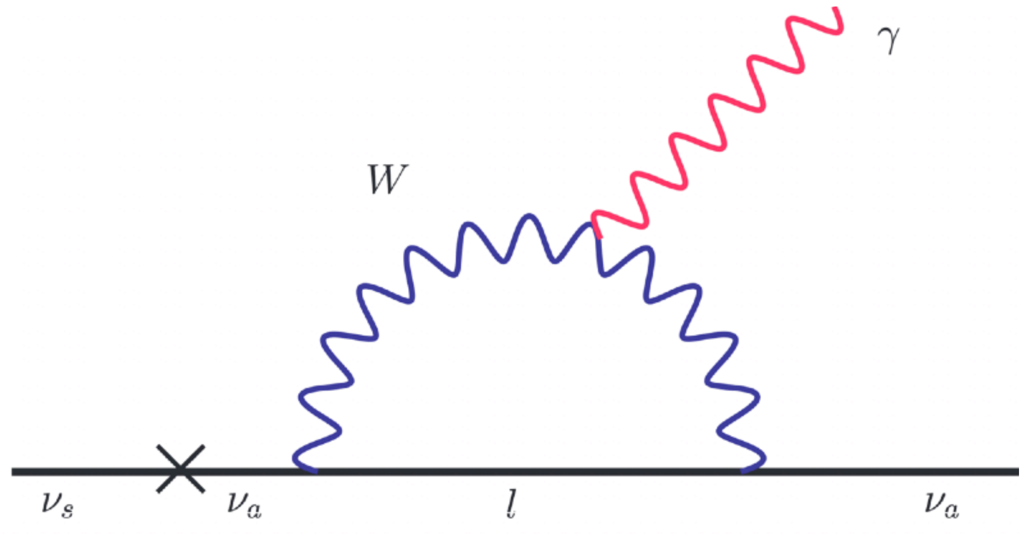

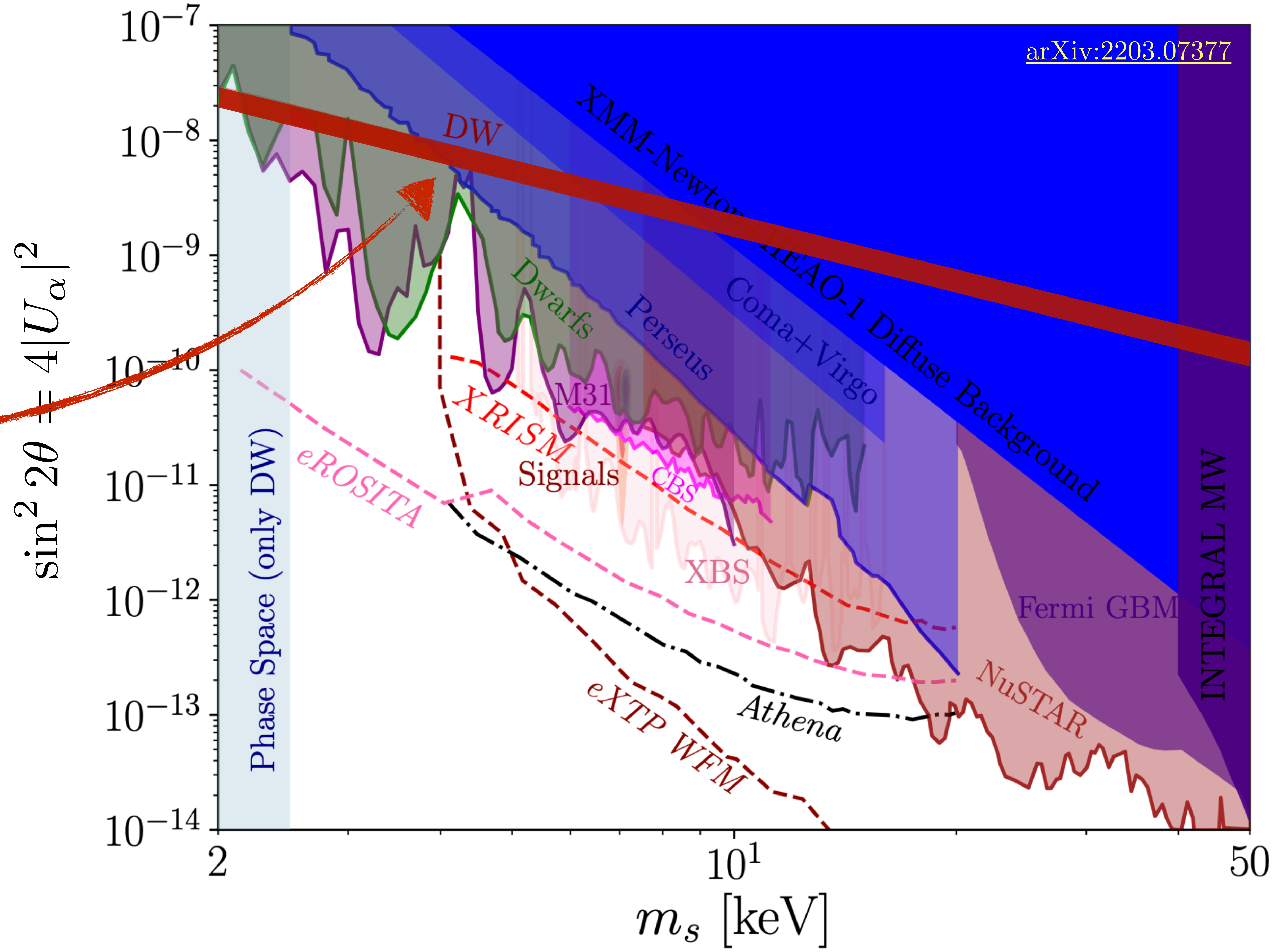

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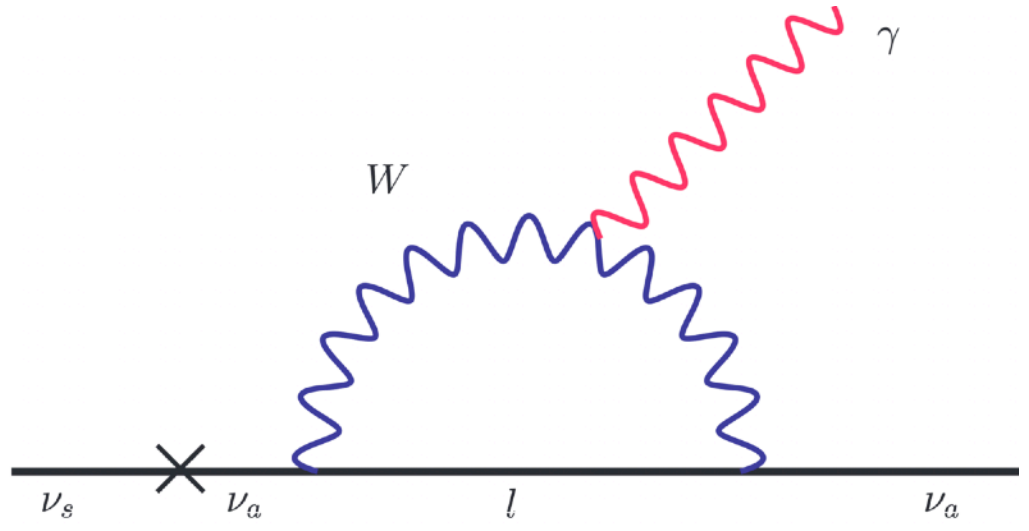

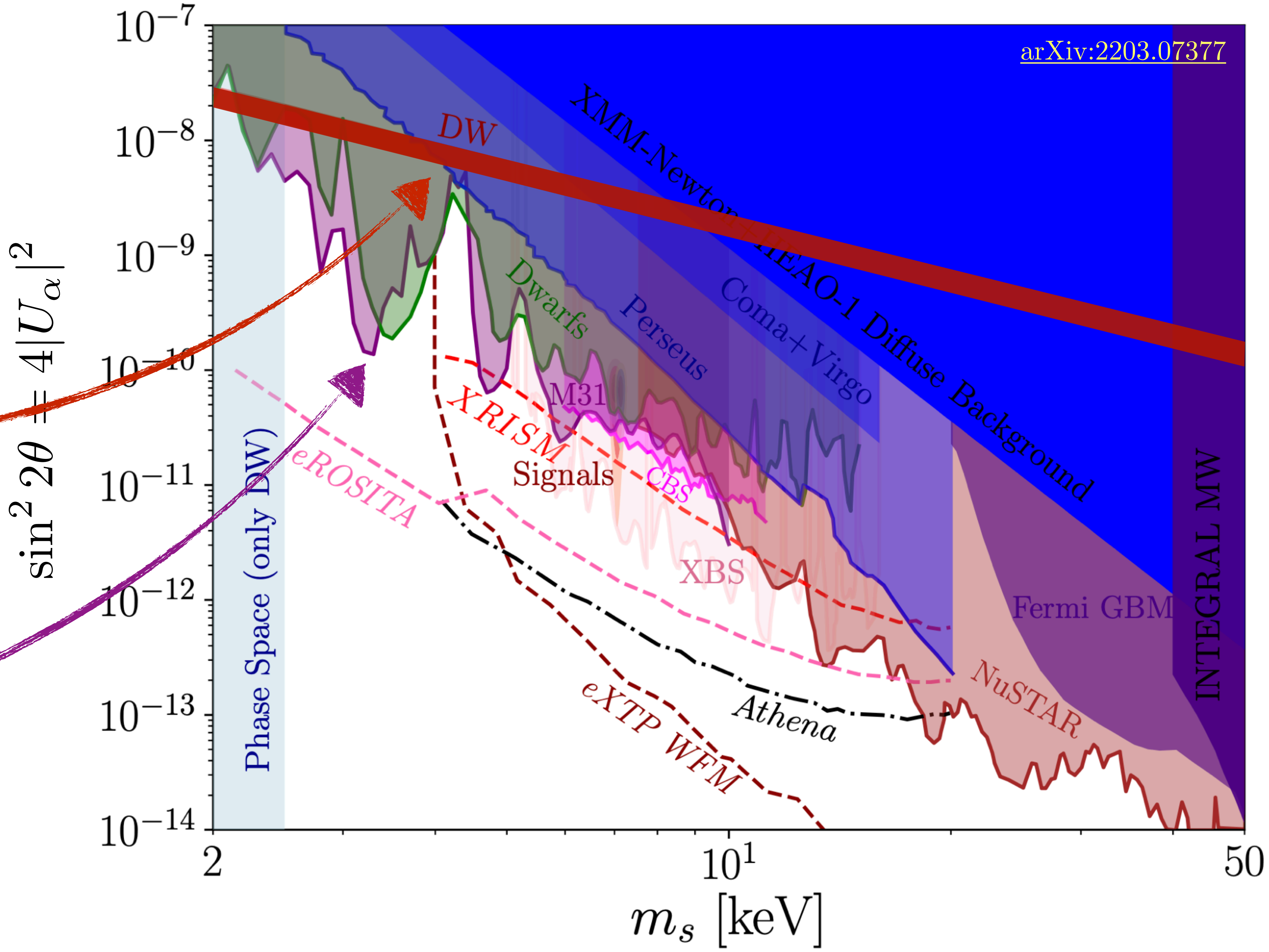

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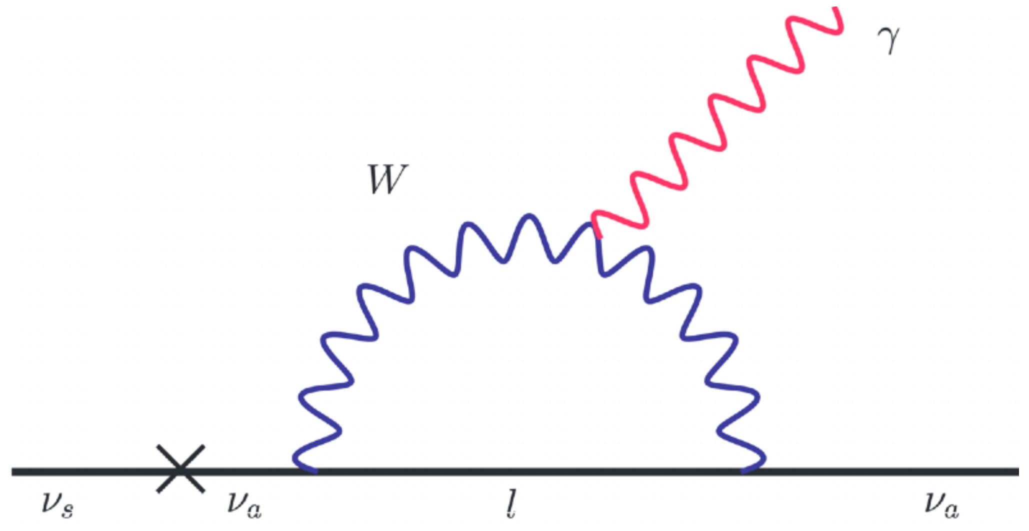
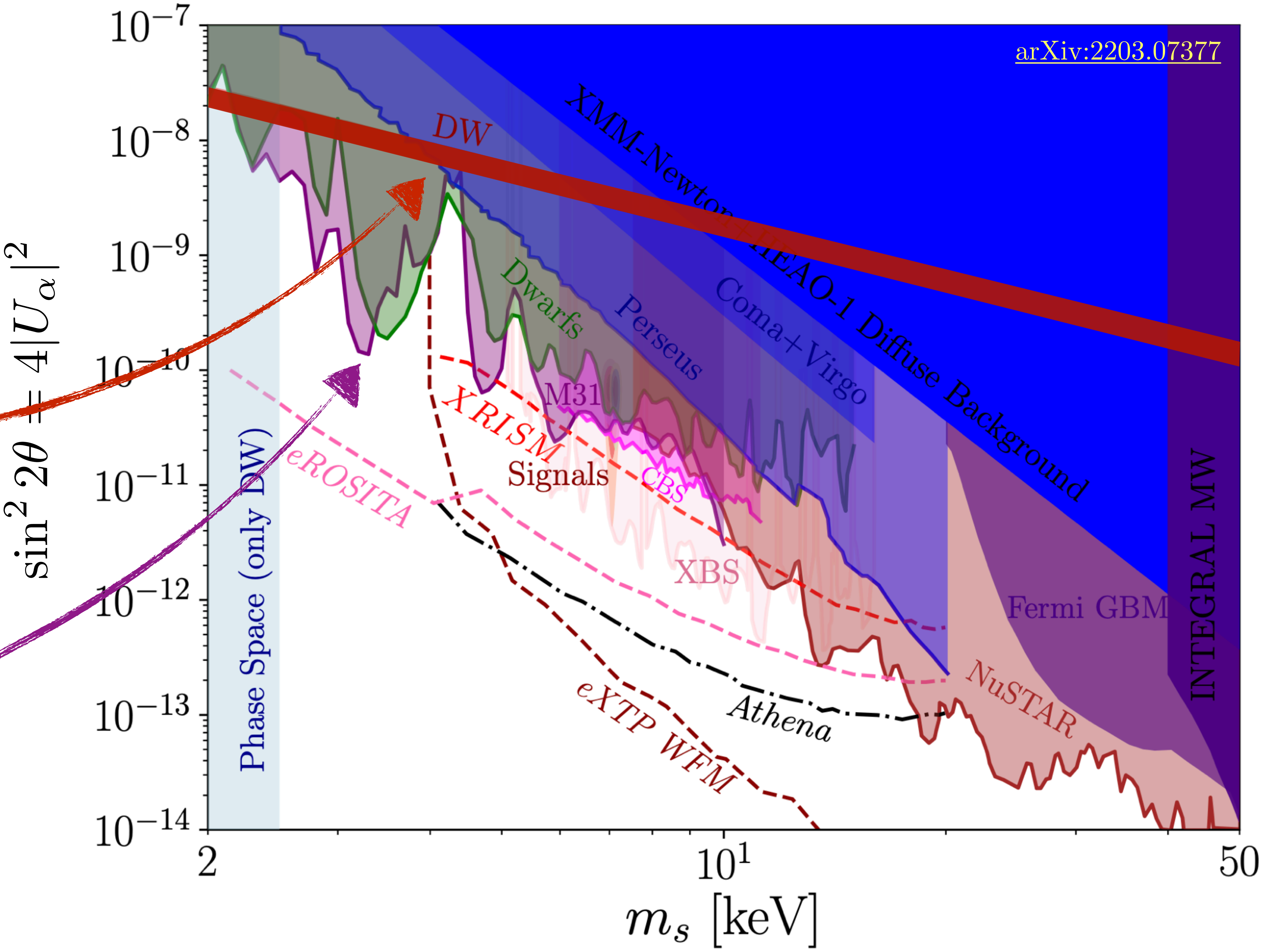




Can we save Dodelson-Widrow?

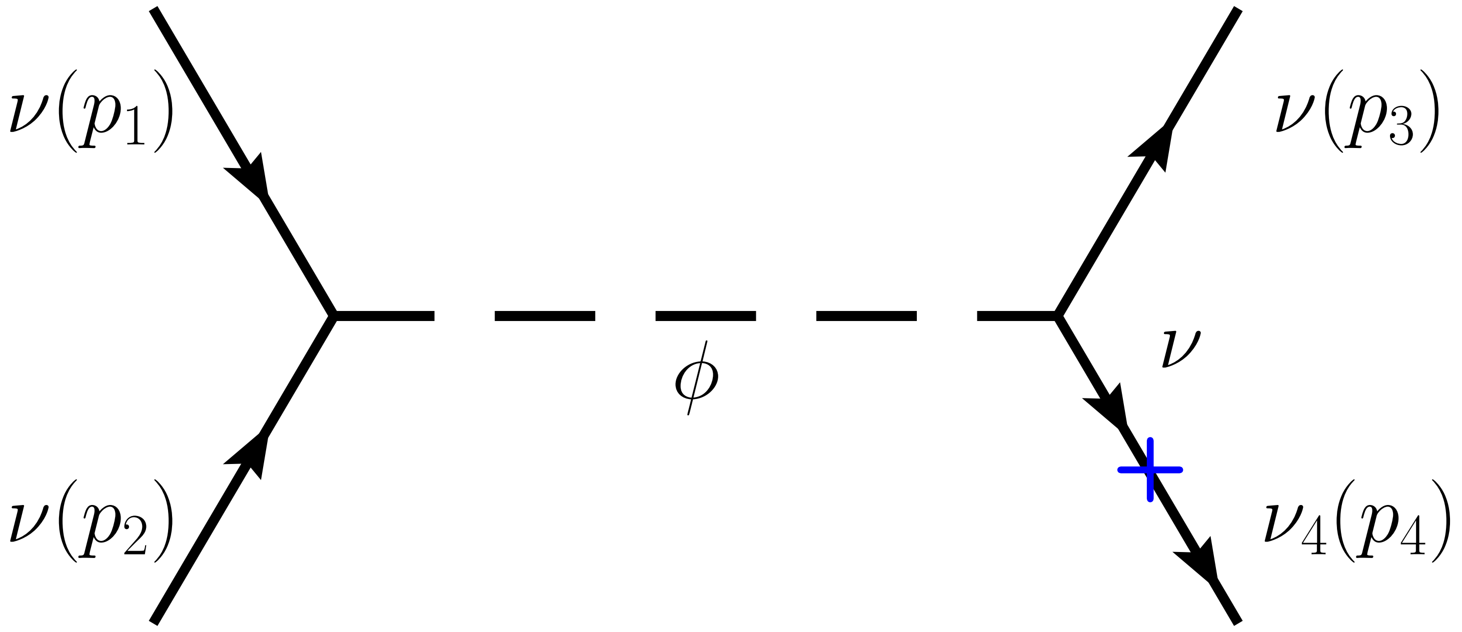
Neutrino Self Interactions

- Schematically, the sterile neutrino relic abundance is

$$\Omega \sim \Gamma \times \sin^2(2\theta)$$

- $\Gamma = \Gamma_W \rightarrow$ large angle is required $\rightarrow$ X-ray constraints.
- Smaller mixing angle by increasing the interaction rate? Yes! Introduce a scalar field ϕ of mass m_ϕ that mediates *new self interactions among SM neutrinos.*

$$\mathcal{L} \supset \frac{1}{2}\lambda_{\alpha\beta}\nu_\alpha\nu_\beta\phi + \text{ h.c.}$$



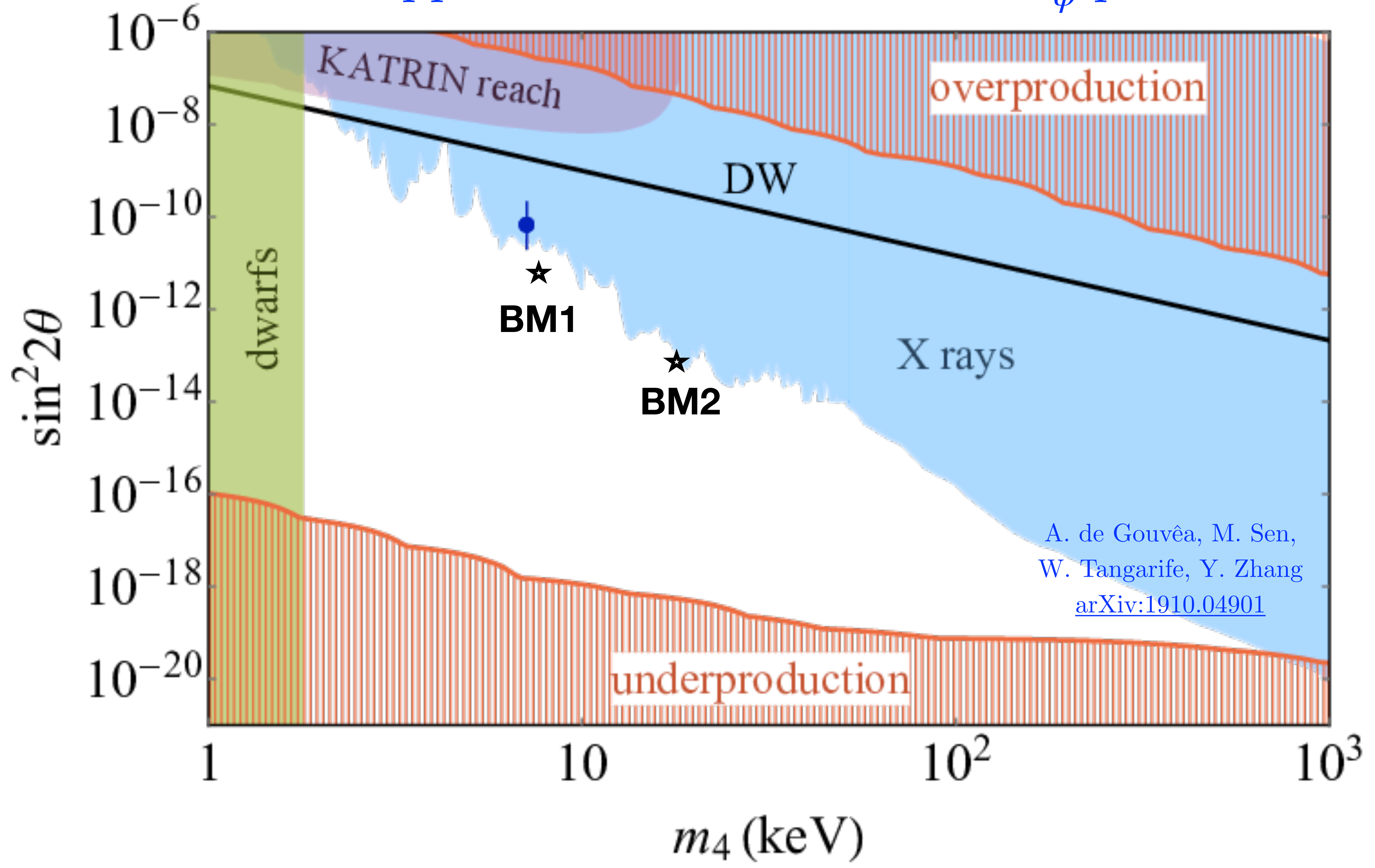
A. de Gouvêa, M. Sen, W. Tangarife, Y. Zhang arXiv:1910.04901

Larger rate than the weak interactions keeps SM neutrinos in contact for a longer period of time to build up the DM abundance!

Neutrinophilic Scalar

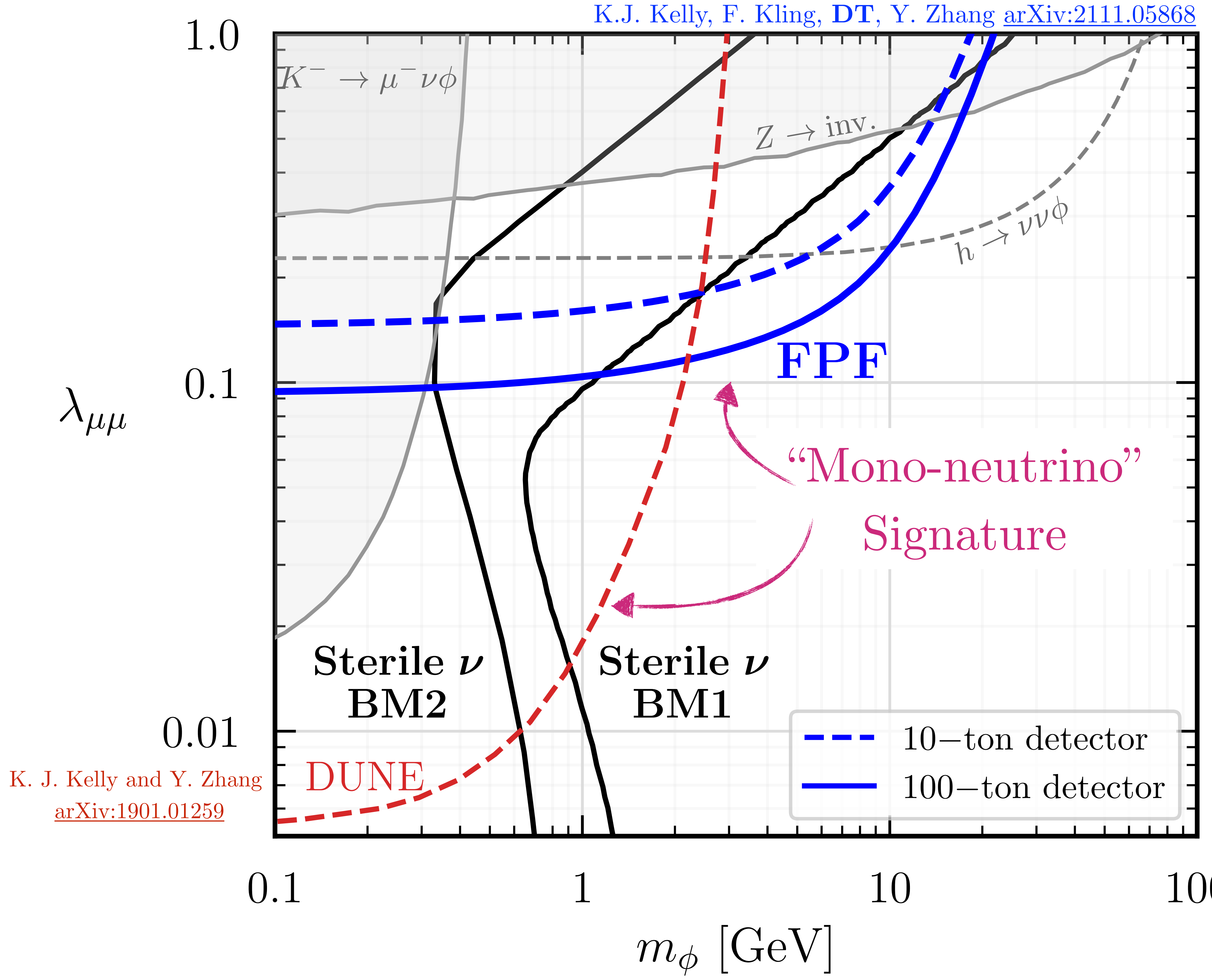
- New production mode → don't have to live on DW line!

Any point in this parameter space can be mapped to a curve in the λ vs m_ϕ plane



BM1 : $m_4 = 7$ keV, $\sin^2(2\theta) = 7 \times 10^{-11}$

BM2 : $m_4 = 21$ keV, $\sin^2(2\theta) = 1.4 \times 10^{-13}$



Sterile ν DM still alive! Testable at neutrino facilities

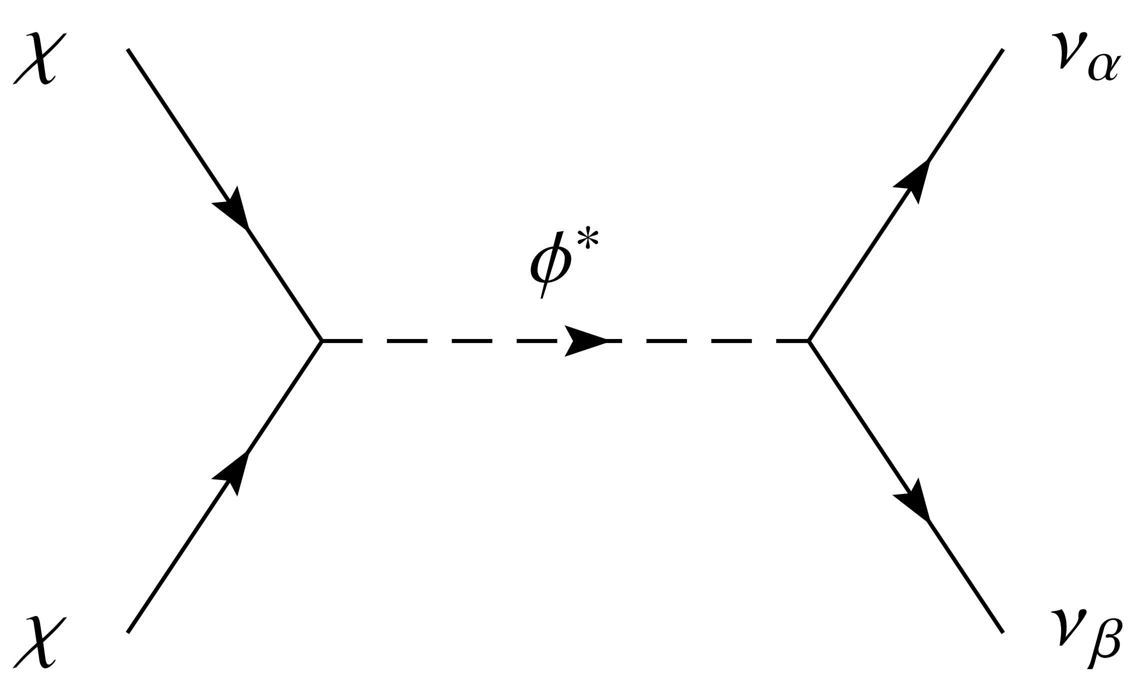
See Vera's talk however.

Thermal Dark Matter

- The neutrinophilic scalar can also be a mediator to thermal DM

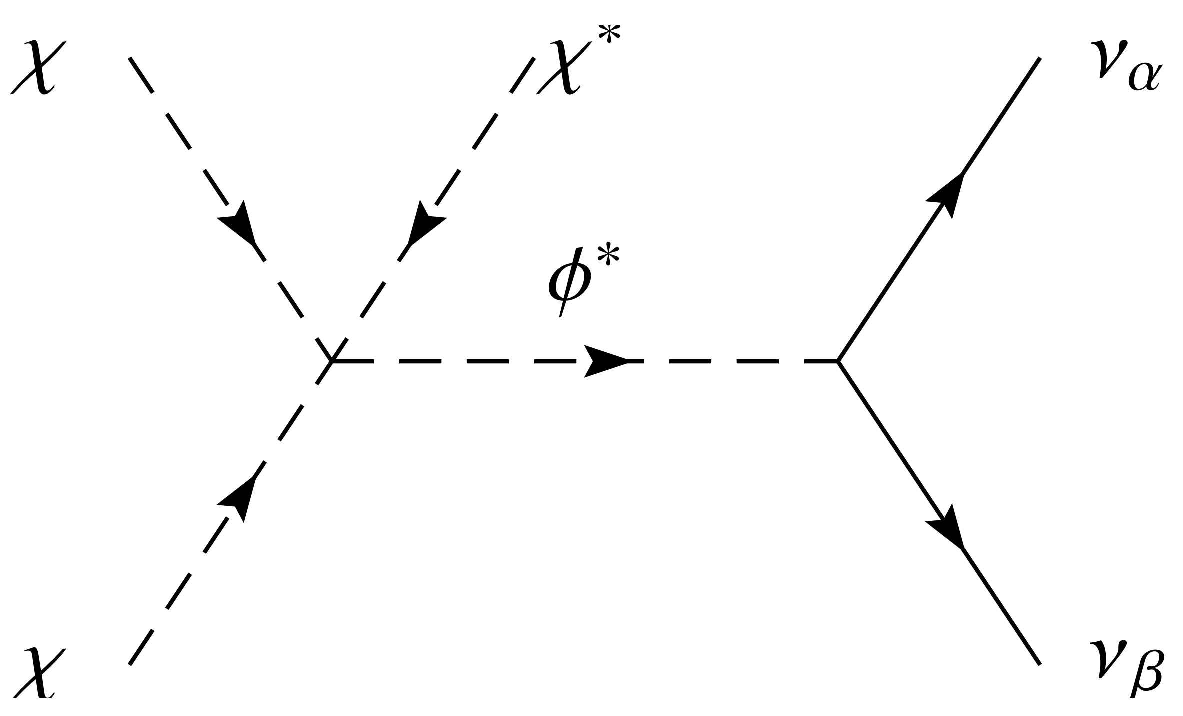
Fermion DM

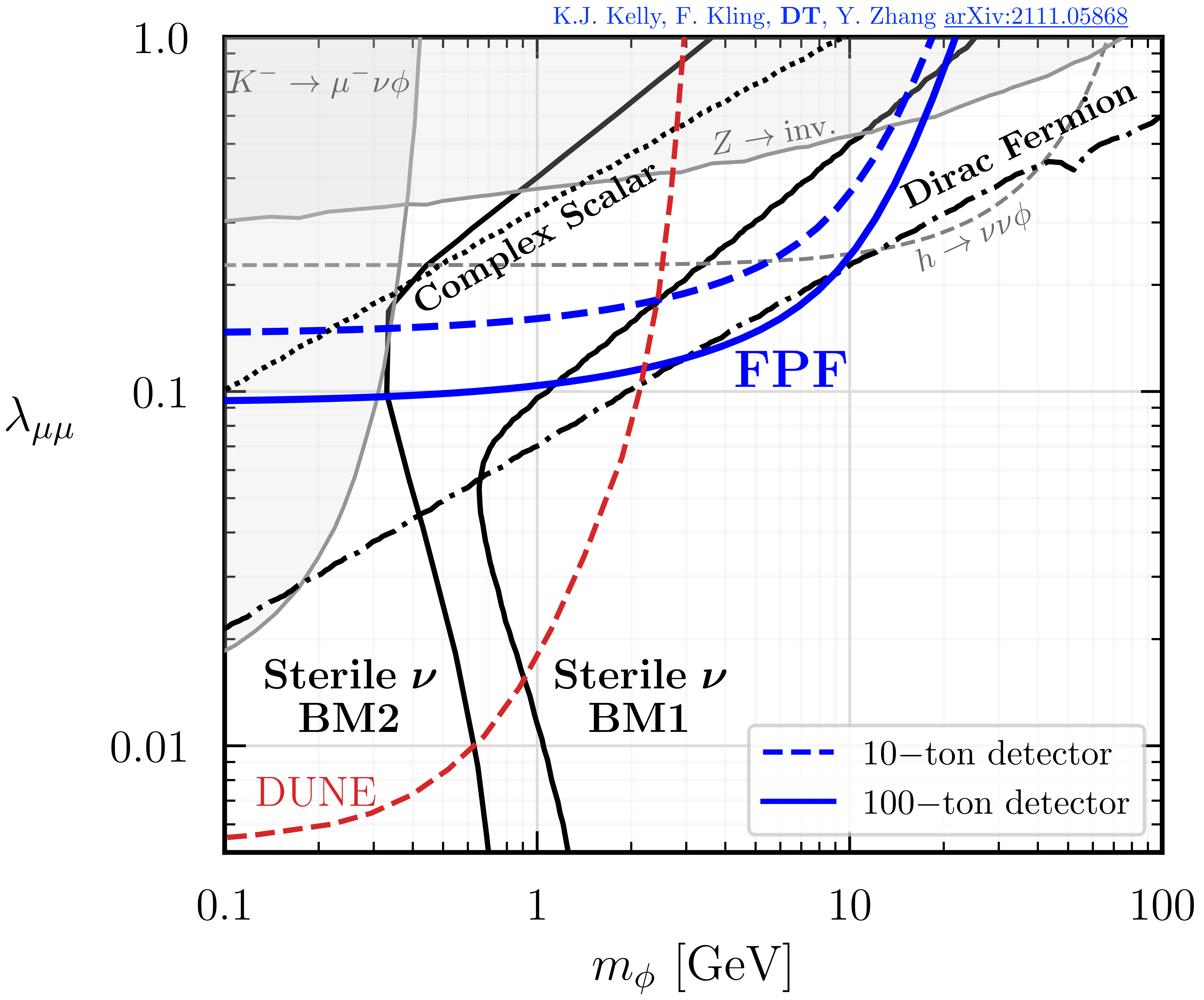
$$\mathcal{L} = \frac{1}{2} y_\chi \bar{\chi}\chi\phi + \text{ h.c.}$$



Scalar DM

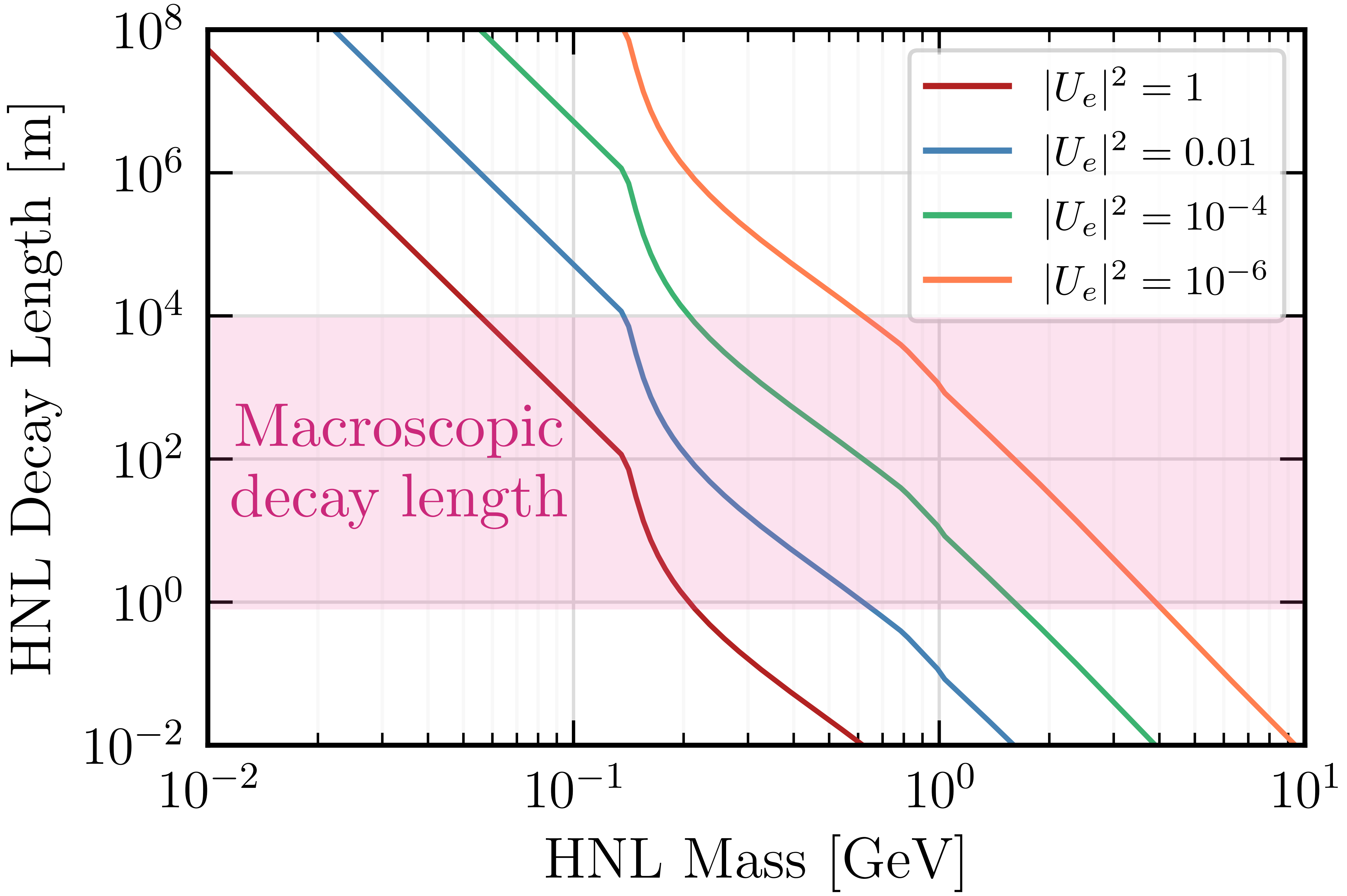
$$\mathcal{L} = \frac{1}{6} y_\chi \chi^3\phi + \text{ h.c.}$$





GeV-Scale Heavy Neutral Leptons

- MeV - GeV scale HNLs are *long-lived.*



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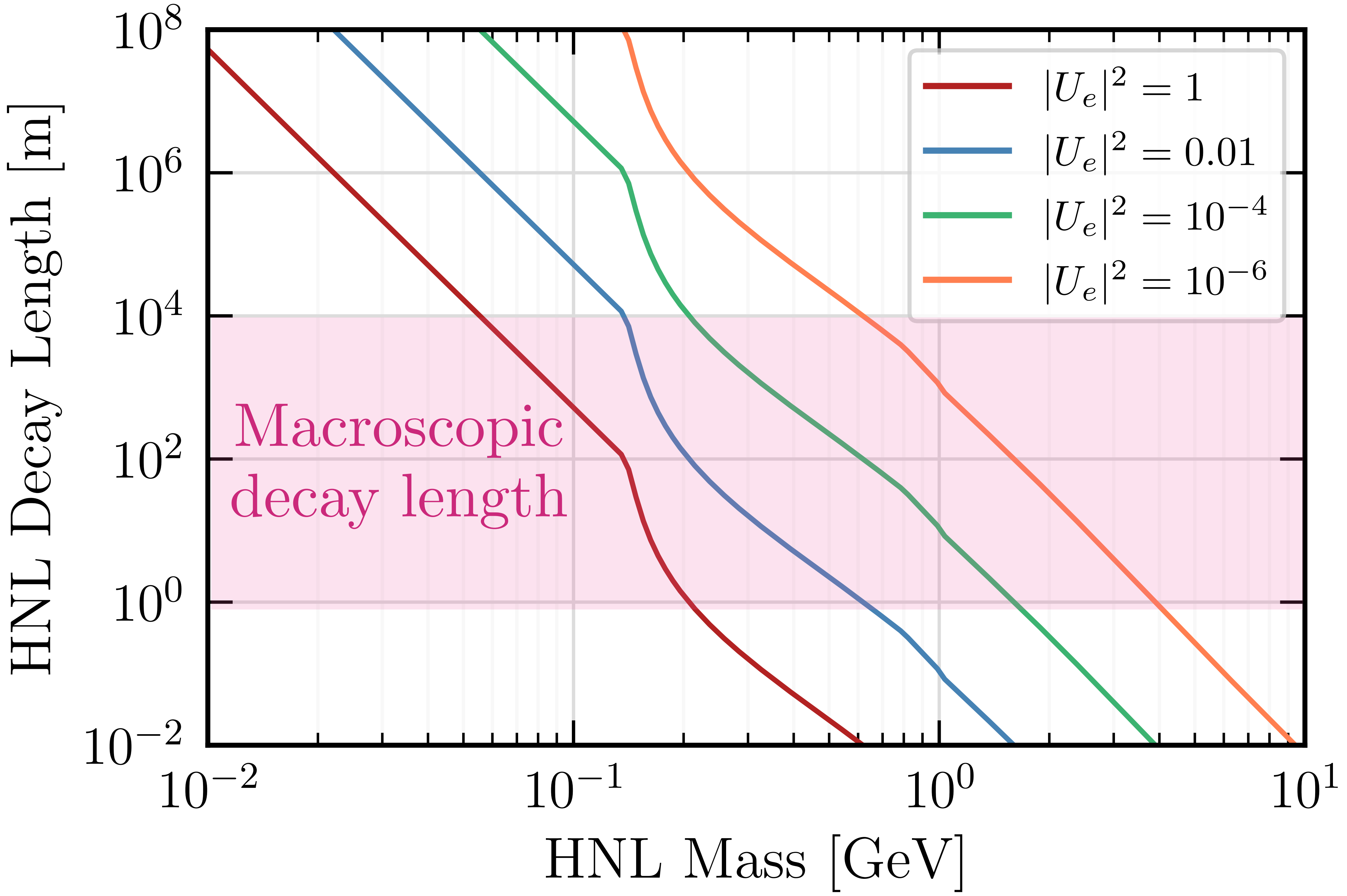
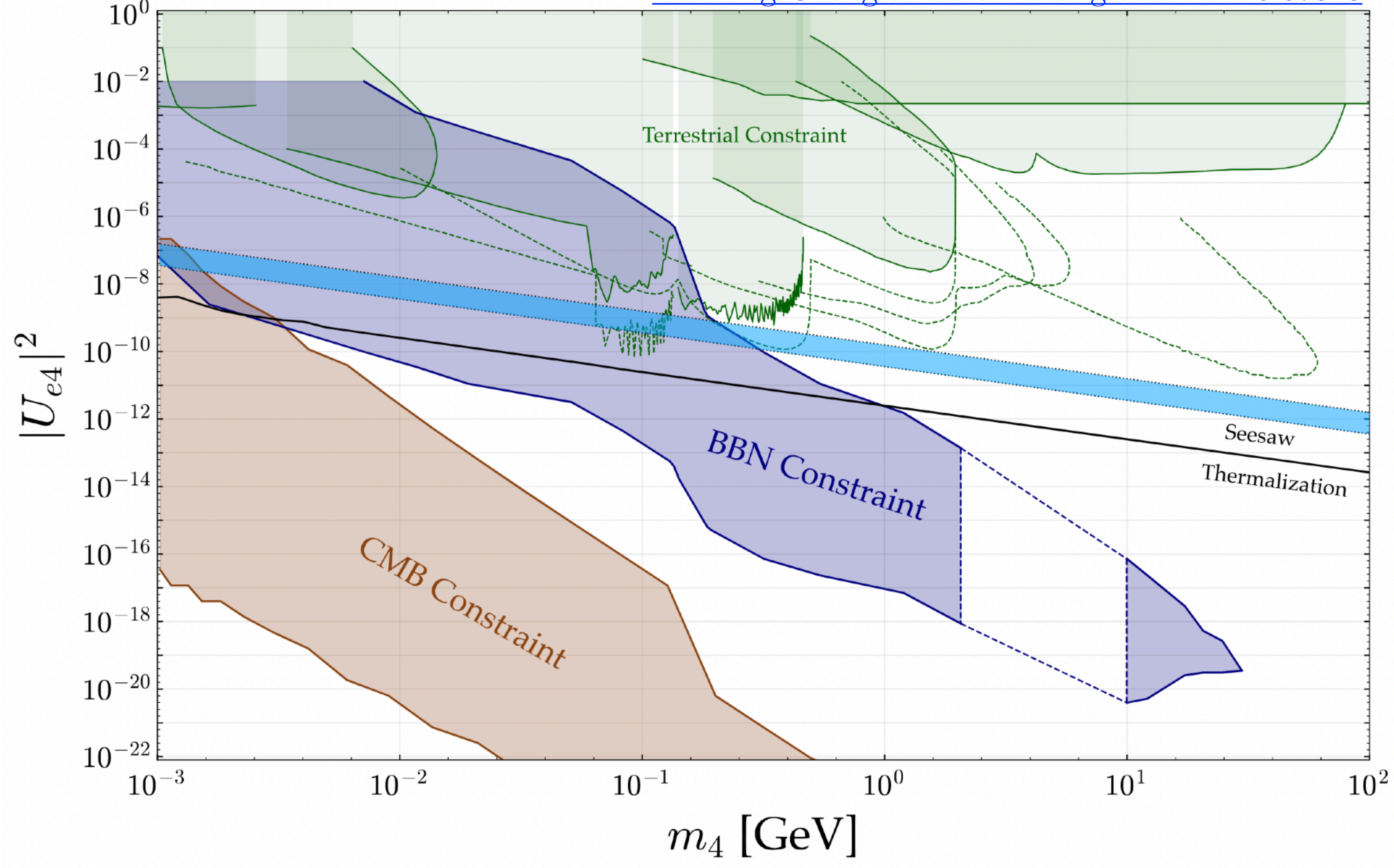


Yu-Ming Cheng and Yue Zhang arXiv:2410.07343

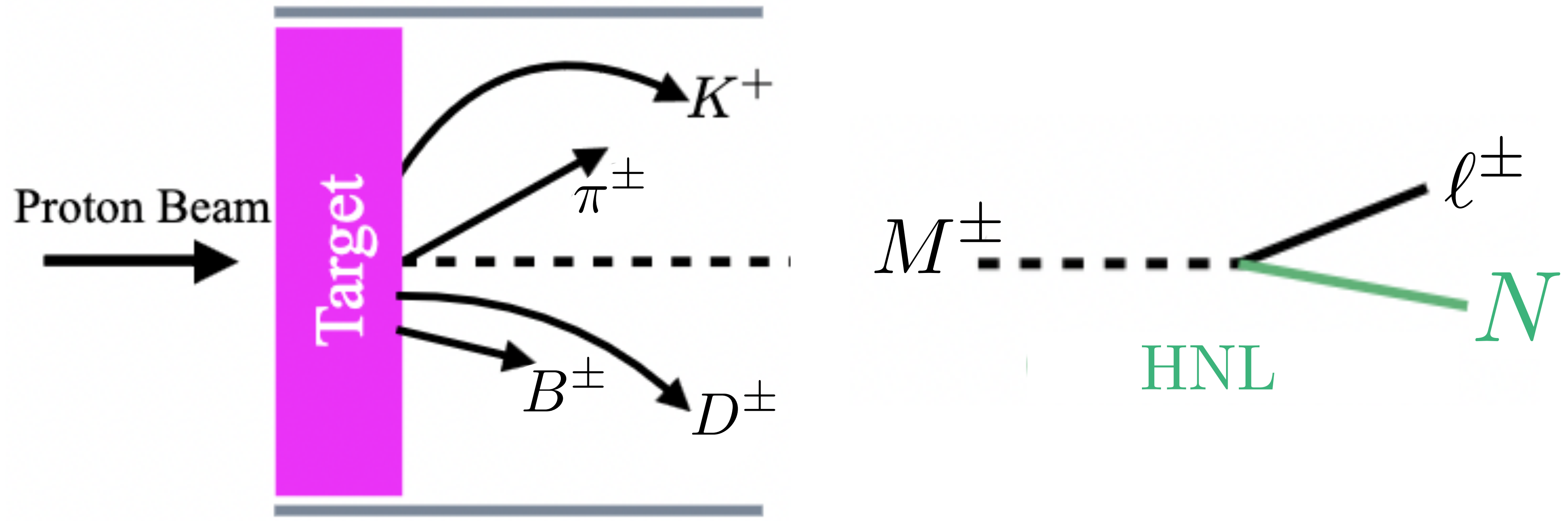


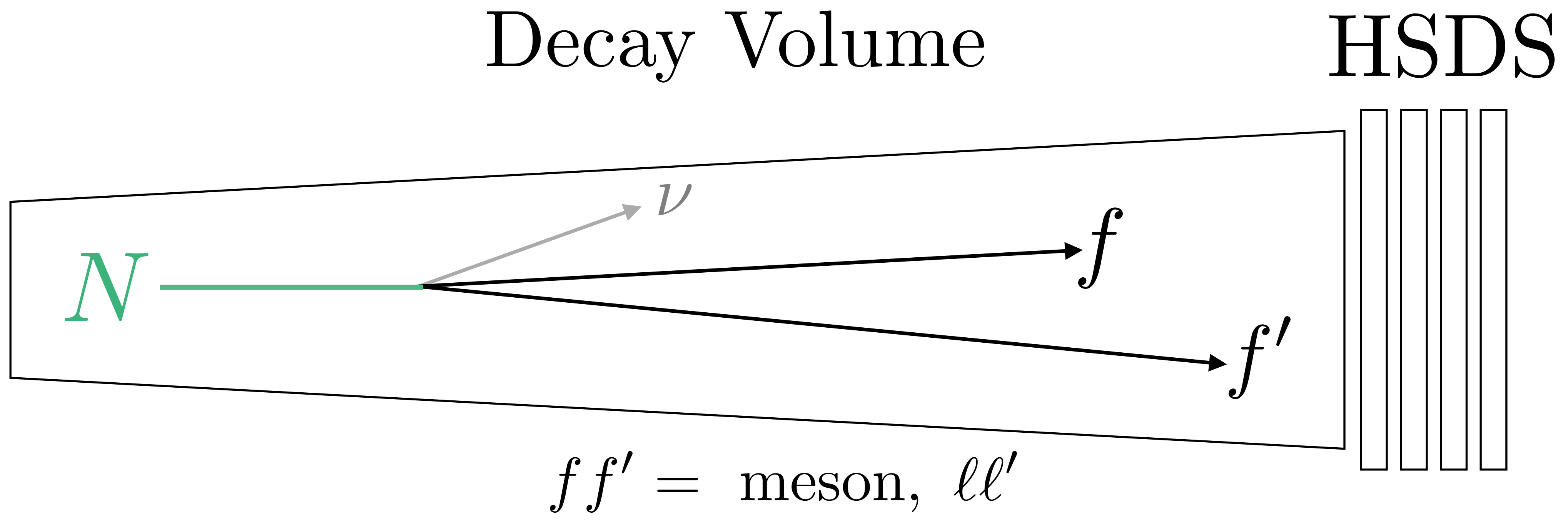
Constraints from BBN force minimal GeV-scale HNLs to be above ~100 MeV if they thermalize in the early universe

HNLs @ Intensity Frontier

- Long-lived particles → *high-intensity experiments*
  - Beam dump experiments (e.g SHiP, DarkQuest); far forward or transverse detectors (e.g FASER, MATHUSLA)
  - Large number protons-on-target → high flux of BSM particles
  - Long decay volumes → small couplings

Shamelessly stolen and adapted from K. J. Kelly et al. arXiv:2304.11189

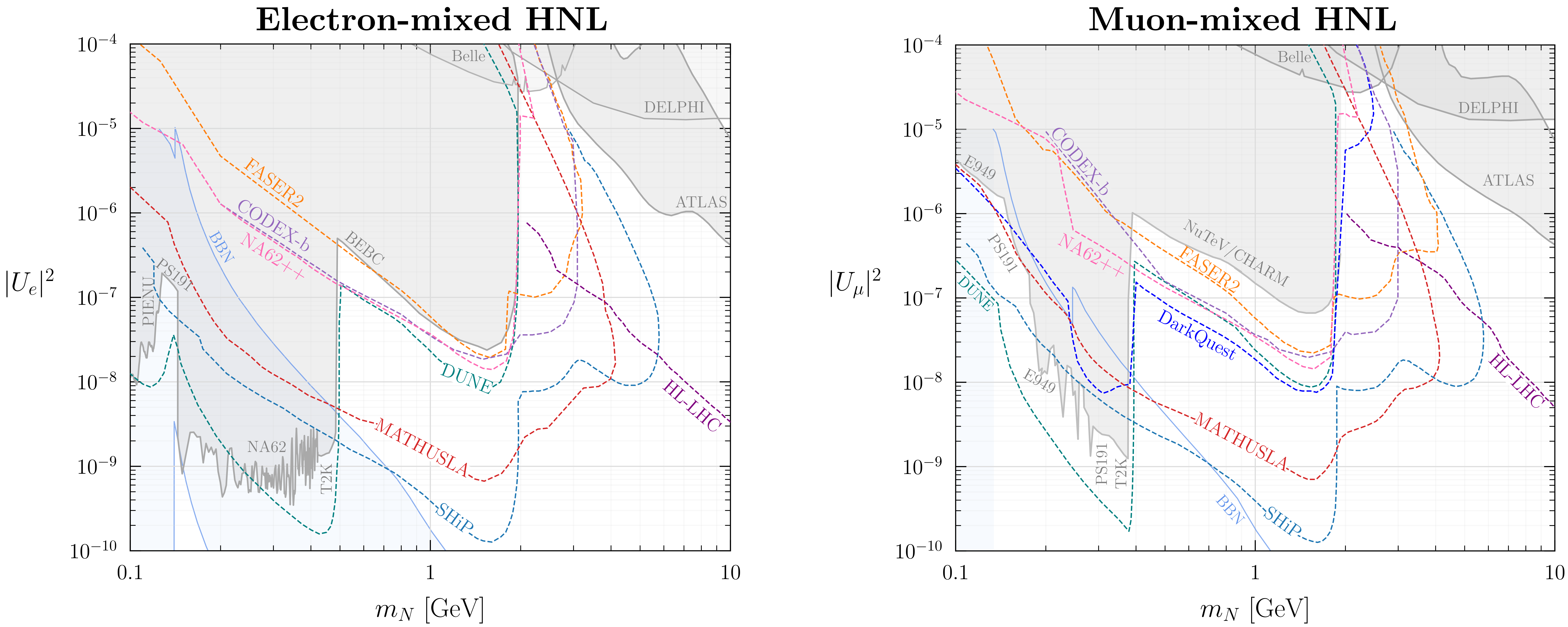




HNL production mainly from meson decays in proton beam experiments

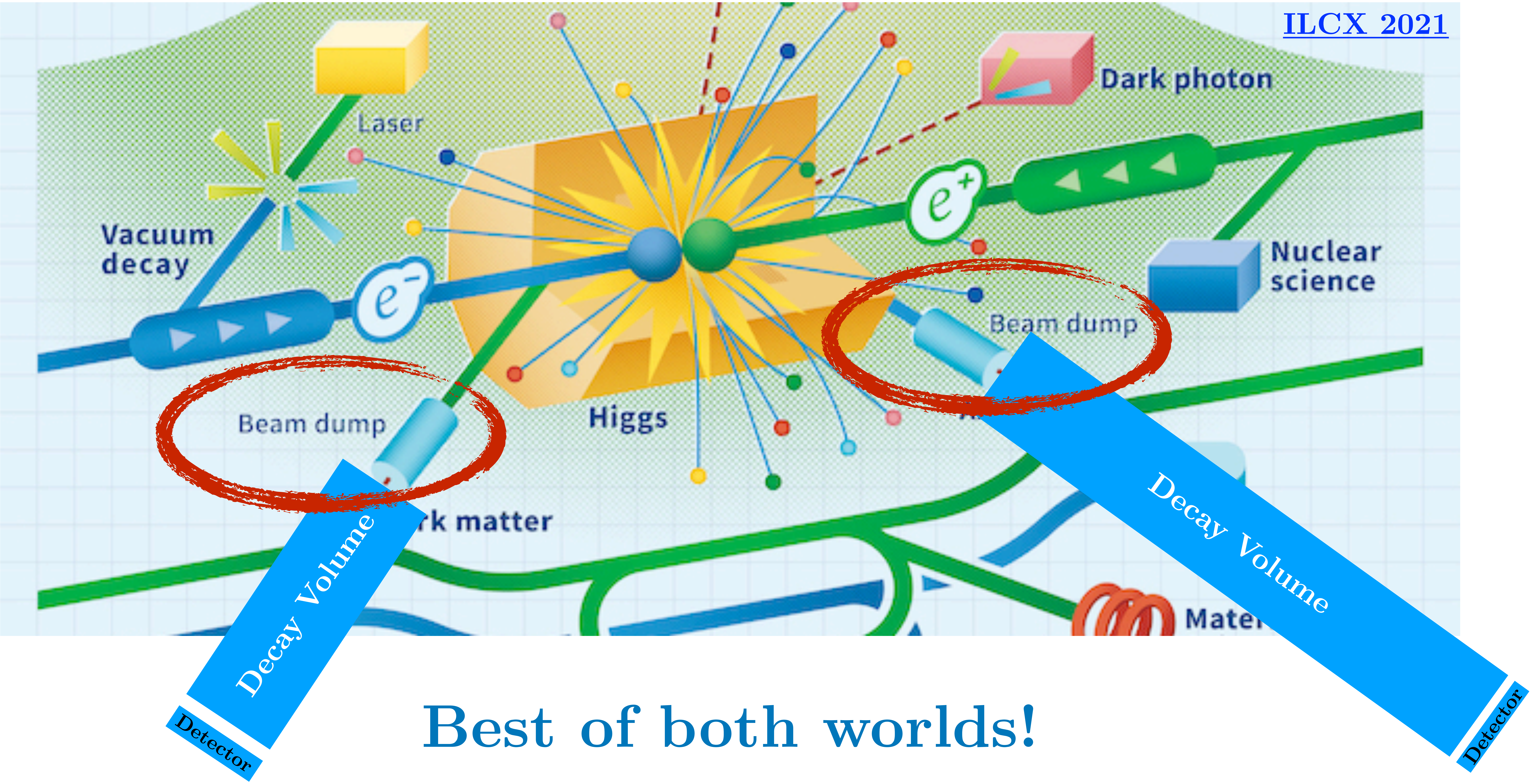
Existing bounds from: M. Hostert - Heavy Neutrino Limits

P. Bolton - Sterile Neutrino Constraints



Good coverage by SHiP, MATHUSLA, and LHC

Future Linear Colliders



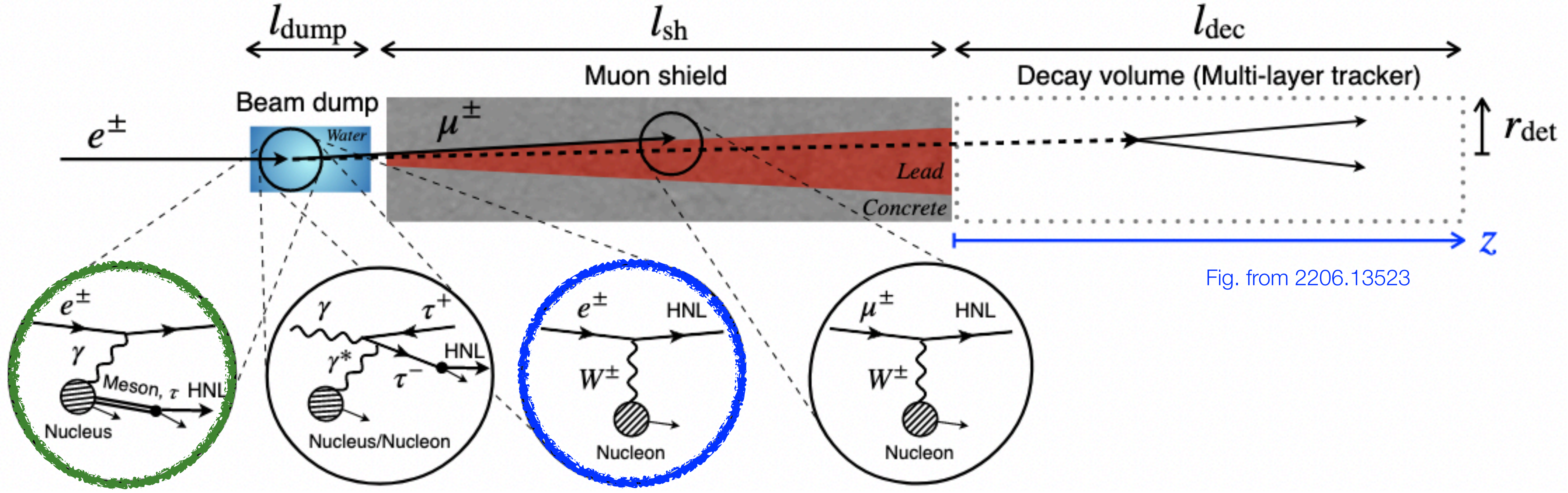
Best of both worlds!

Advantages of Future Electron Colliders

- Large beam energies compared to past/current experiments
  - $E_e \sim 100$ GeV - few TeV
  - *Staged energy approach*. No need to build a new facility for higher energy beams!
- High intensity - $\sim 10^{21}$ electrons-on-target/year
- New production modes:
  - e^- beam $\rightarrow$ charged current scattering production of heavy neutral leptons
  - e^+ beam $\rightarrow$ pair annihilation production of dark photons/ALPs

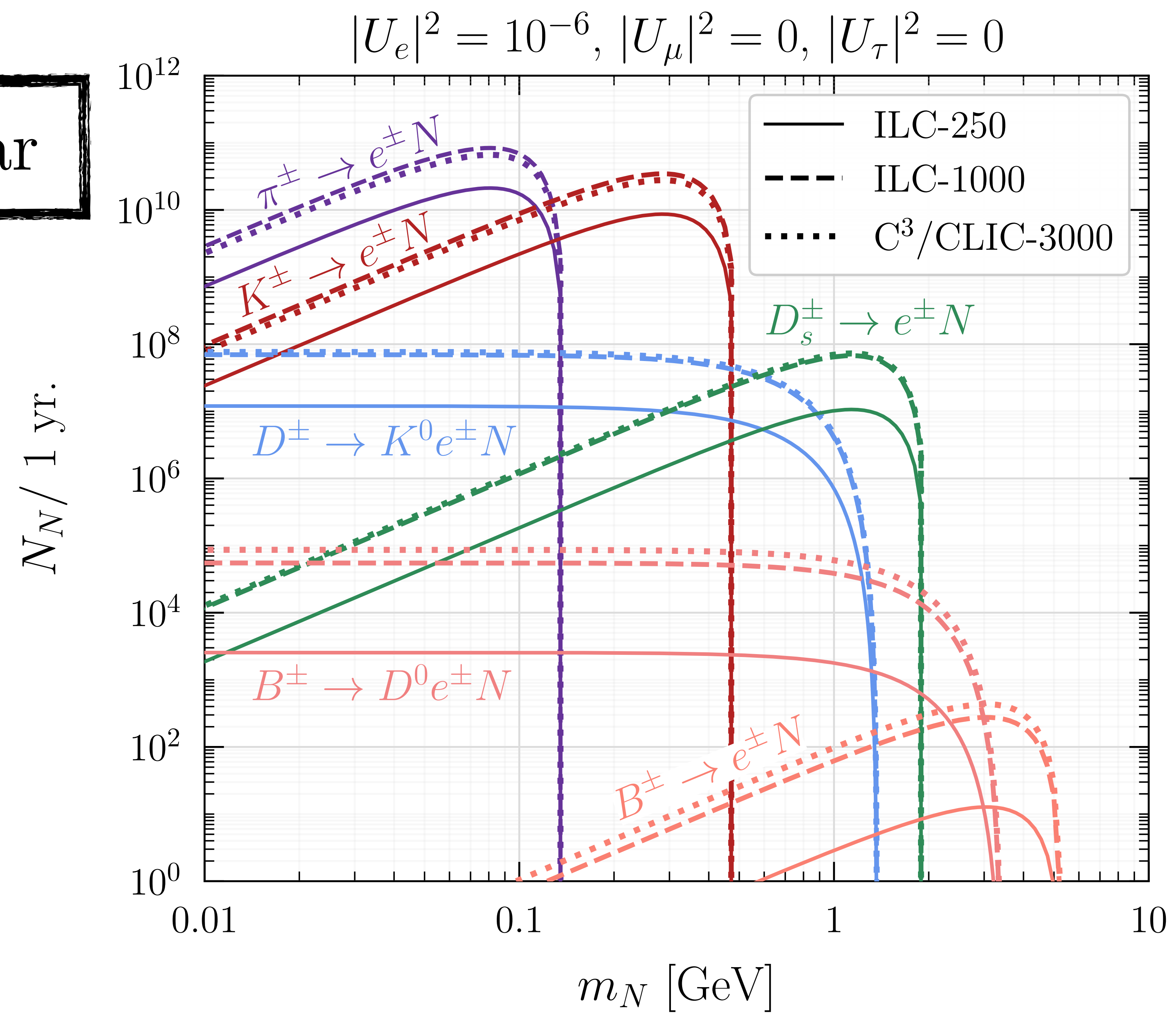
Collider-$\sqrt{s}$ [GeV]	EOT/year
ILC-250/1000	4.1×10^{21}
C^3-250	3.1×10^{21}
C^3-3000	1.8×10^{21}
CLIC-3000	1.8×10^{21}

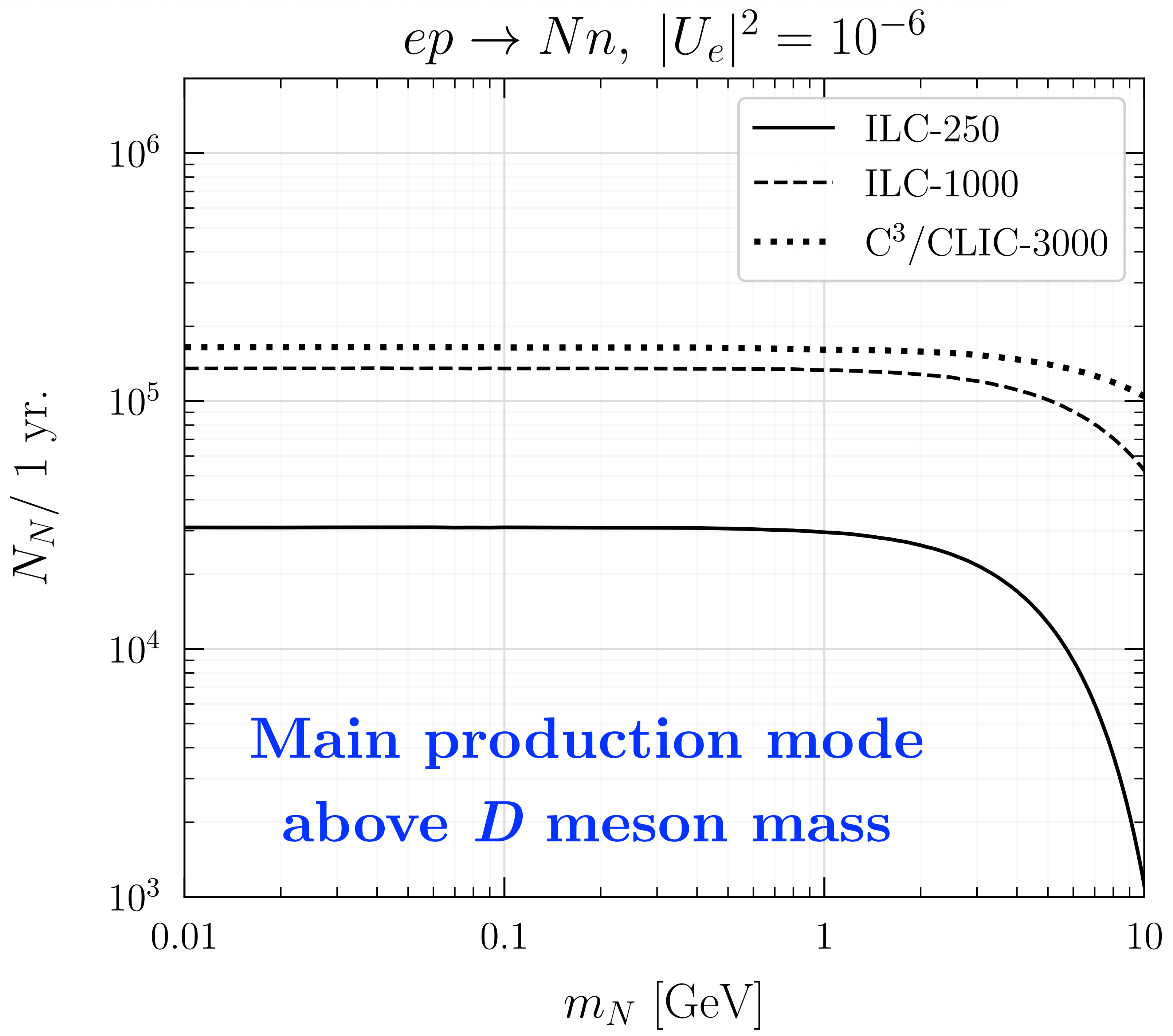
Recall: SHiP $\sim 10^{19}$ POT/year



$N_{\text{EOT}} \simeq 10^{21}$year

Meson Decays

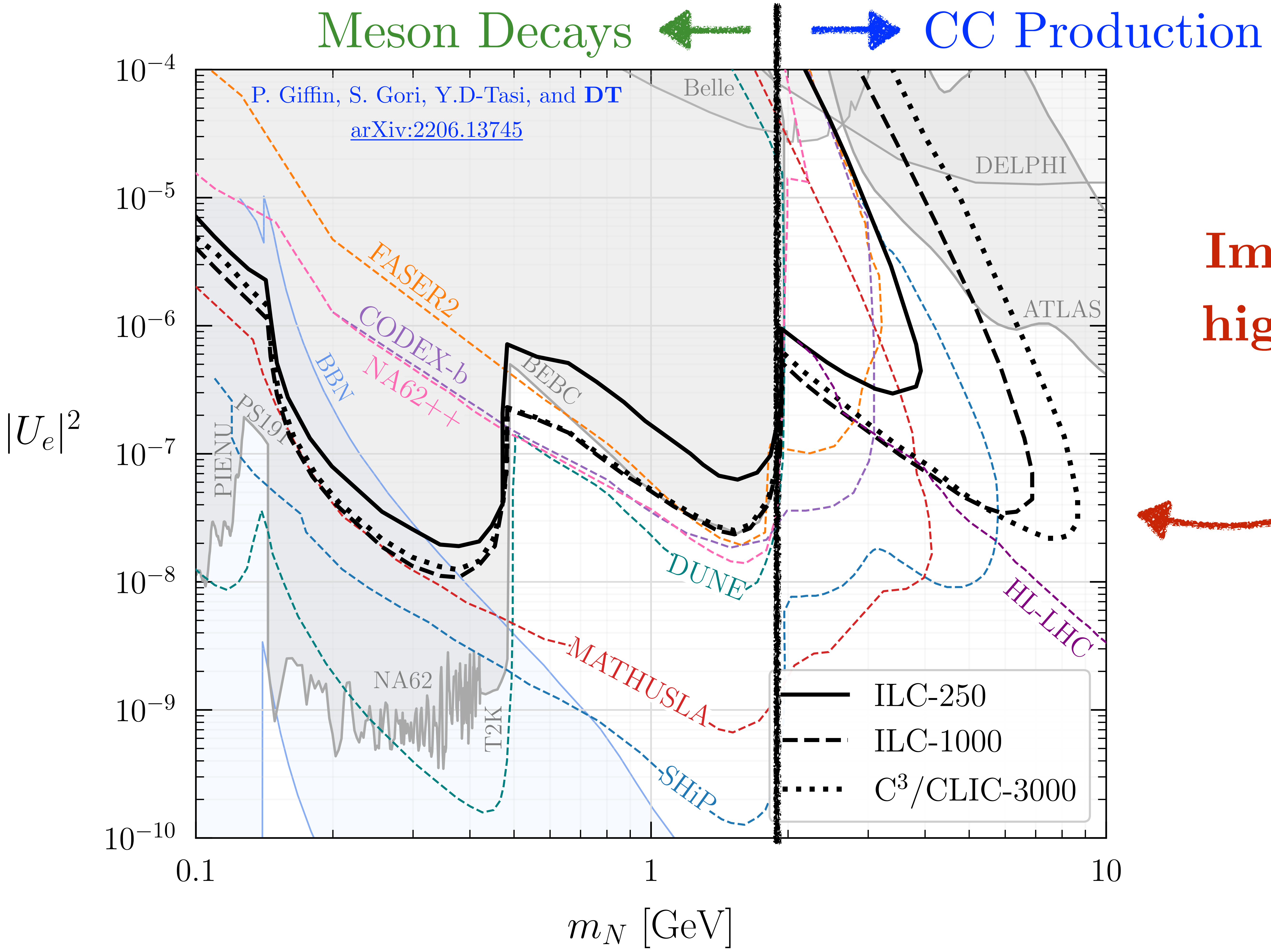




Main production mode above D meson mass

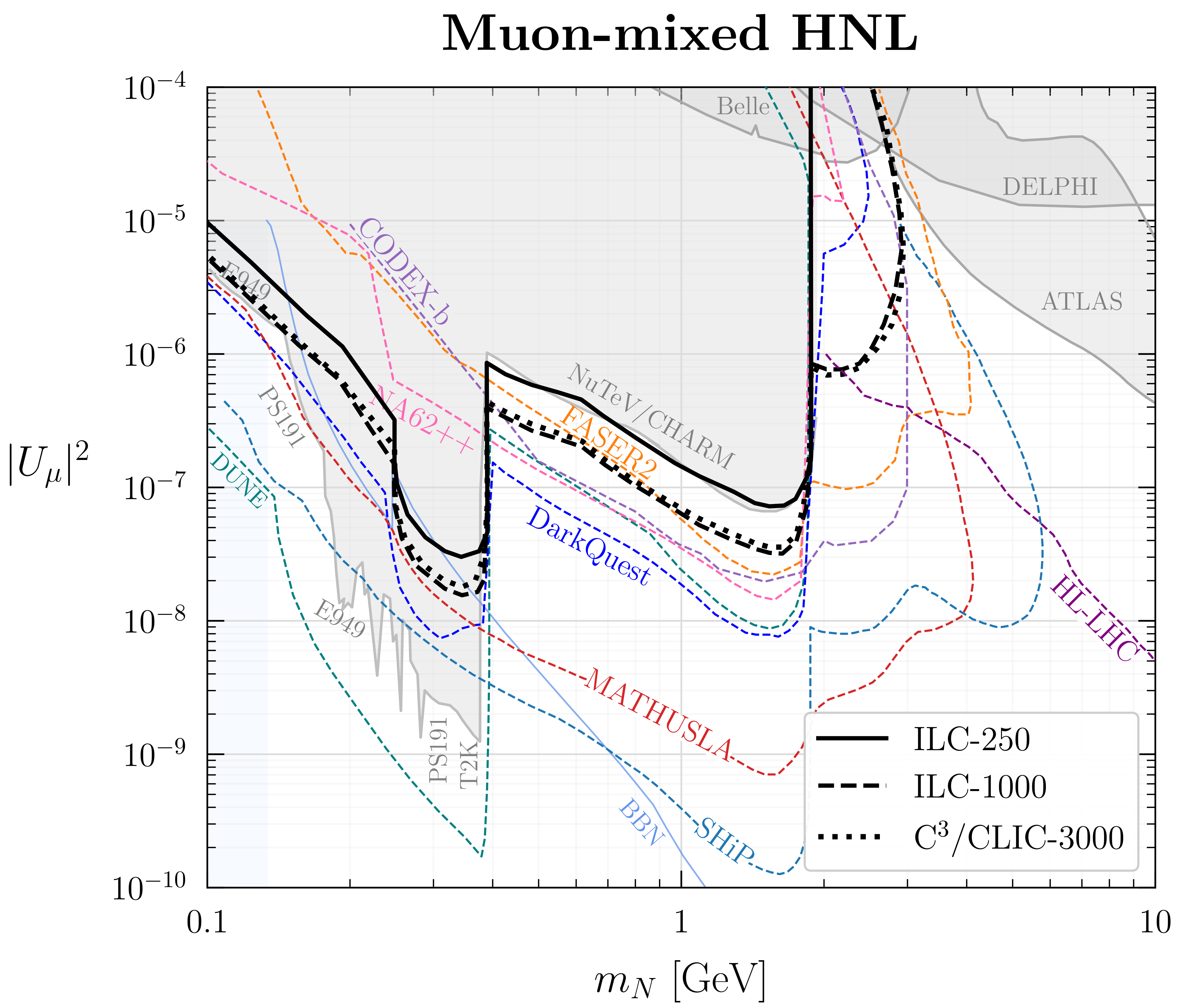
Direct CC Production

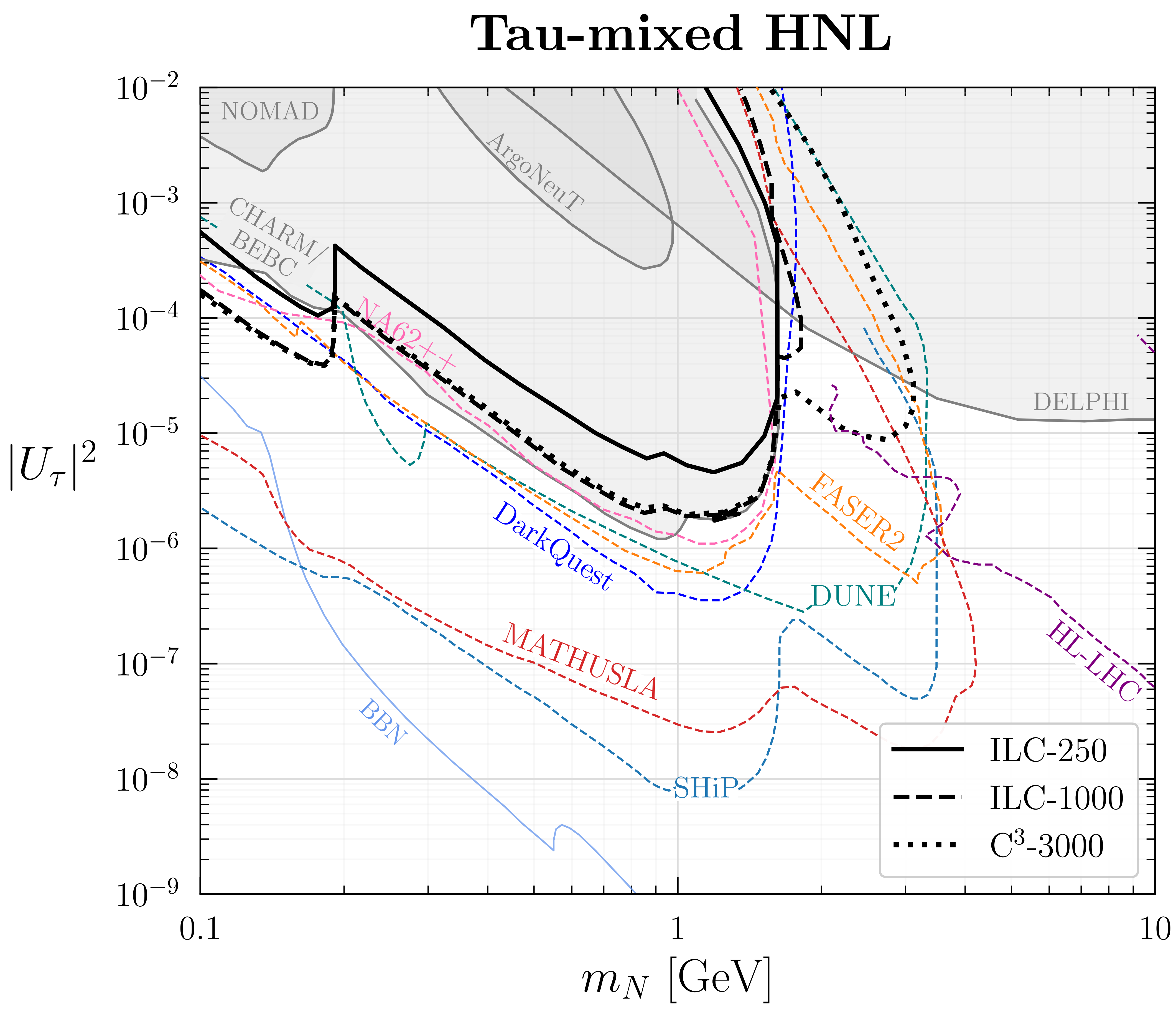
Sensitivity: Electron-Mixed HNL



Importance of higher energy!

Sensitivity: Muon and Tau Mixed HNLs





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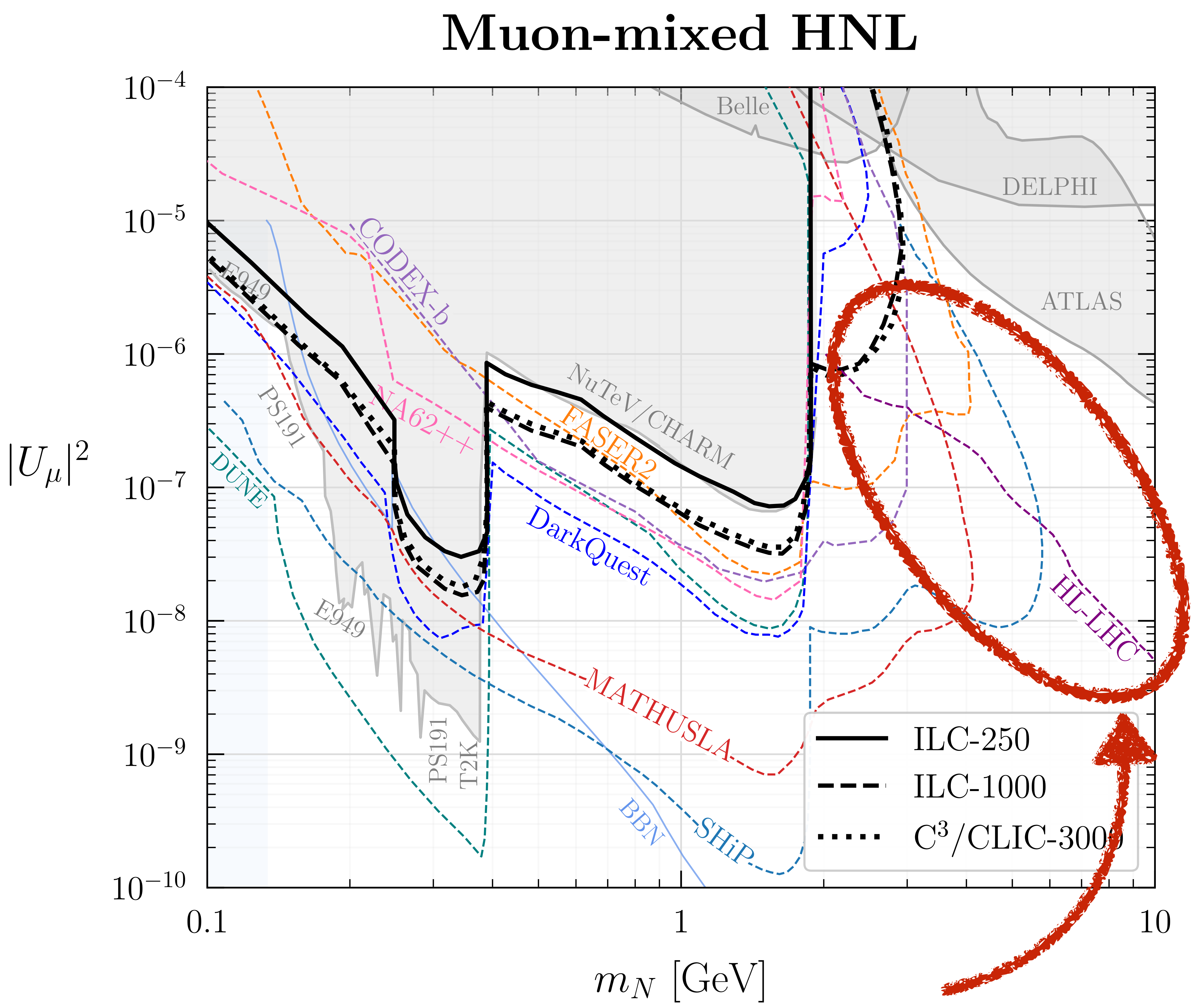
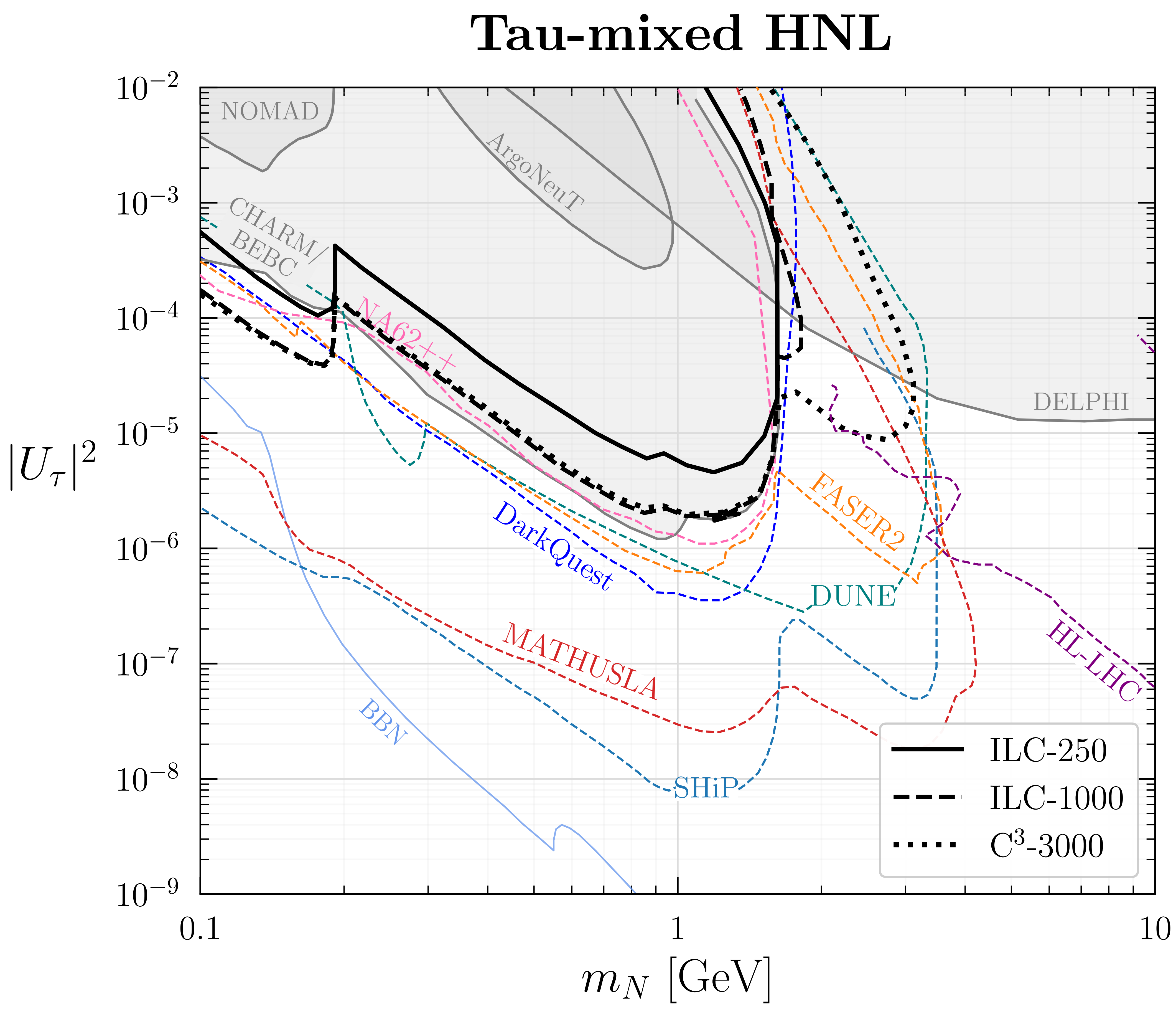
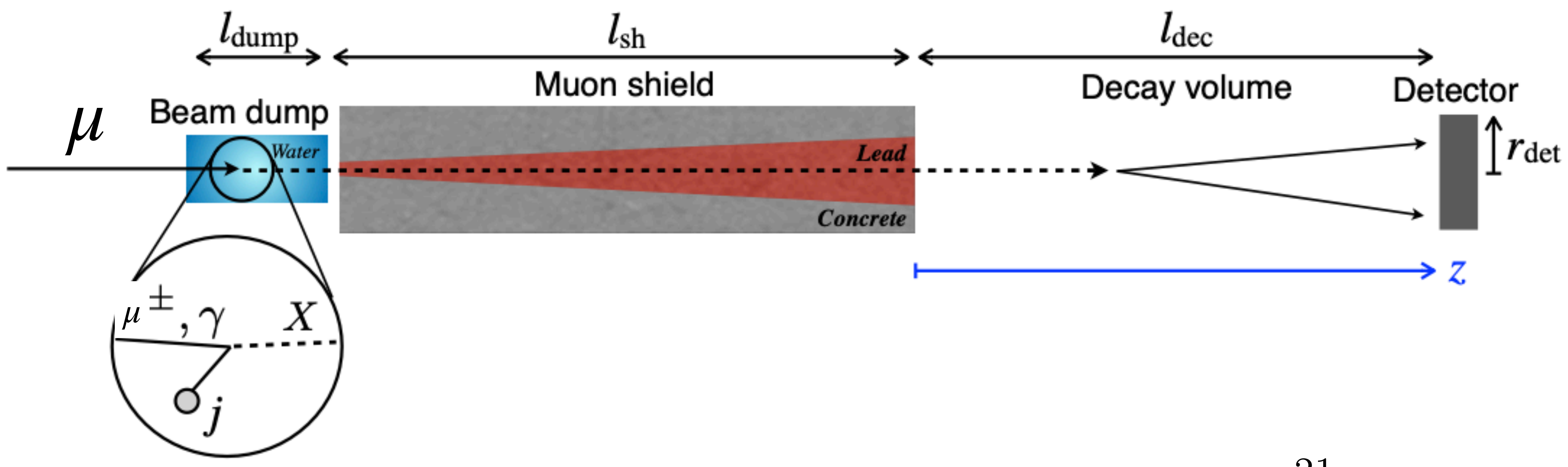




Far, far future: CC production @ TeV muon beam dump exp??

HNLs @ Muon Beam Dump

- Direct production of muon-mixed HNL via charged-current scattering is now available!

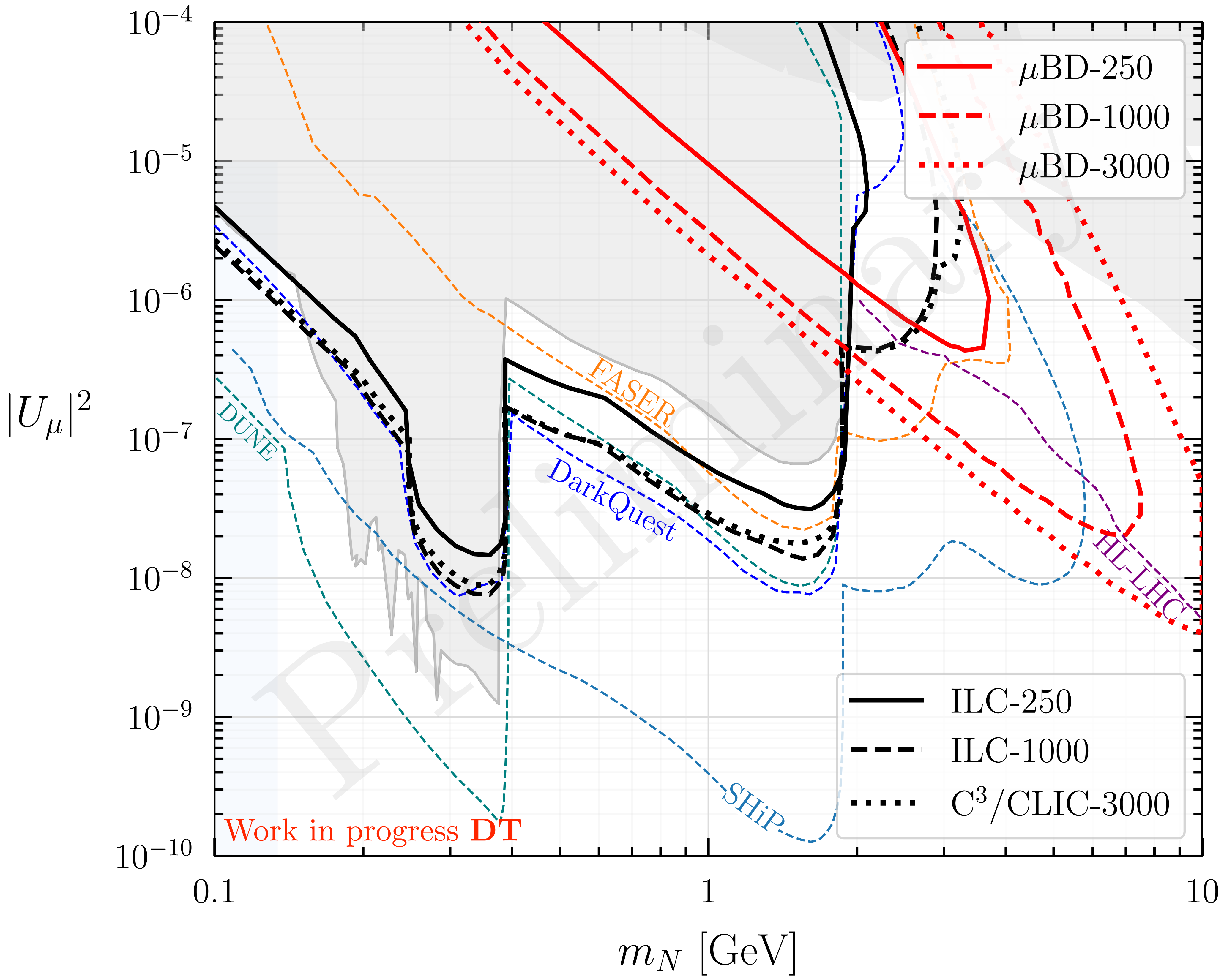


$E_\mu = 125,\ 500,\ 1500$ GeV, $N_\mu = 4.1 \times 10^{21}$

$\ell_{dump} = 10\text{m},\ \ell_{sh} = 70\text{m}$

$\ell_{dec} = 50\text{m},\ r_{det} = 2\text{m}$

Might be too optimistic but we want a direct comparison with ILC beam dump



Reach beyond HL-LHC projections!

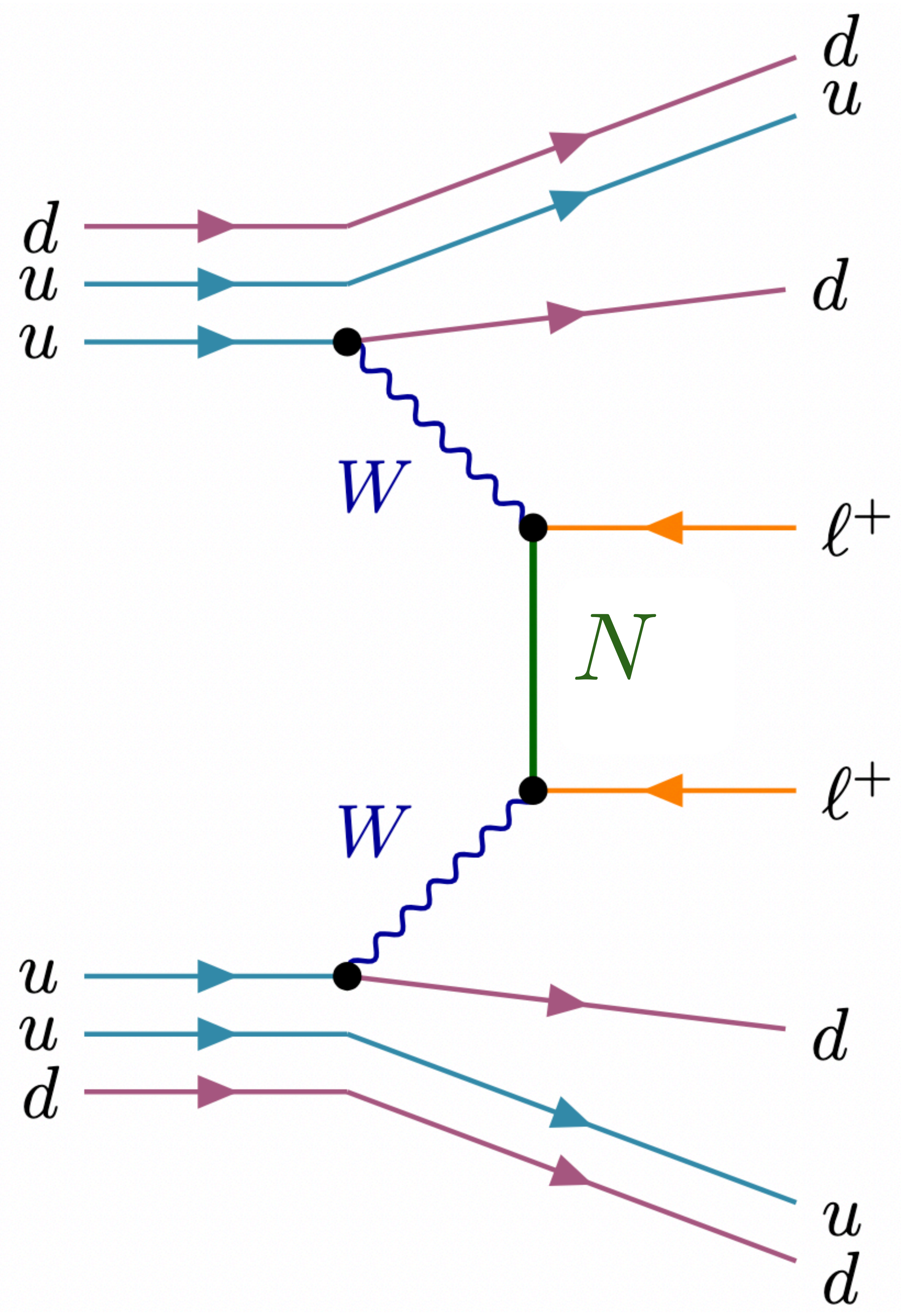
HNLs and Lepton Number Violation

Are neutrinos Dirac or Majorana? Lepton number is an approximate symmetry of the SM. Violated by Majorana mass terms.

$$\mathcal{L} \supset Y\bar{L}\tilde{H}N_R + \frac{1}{2}M_N\bar{N}_R N_R$$

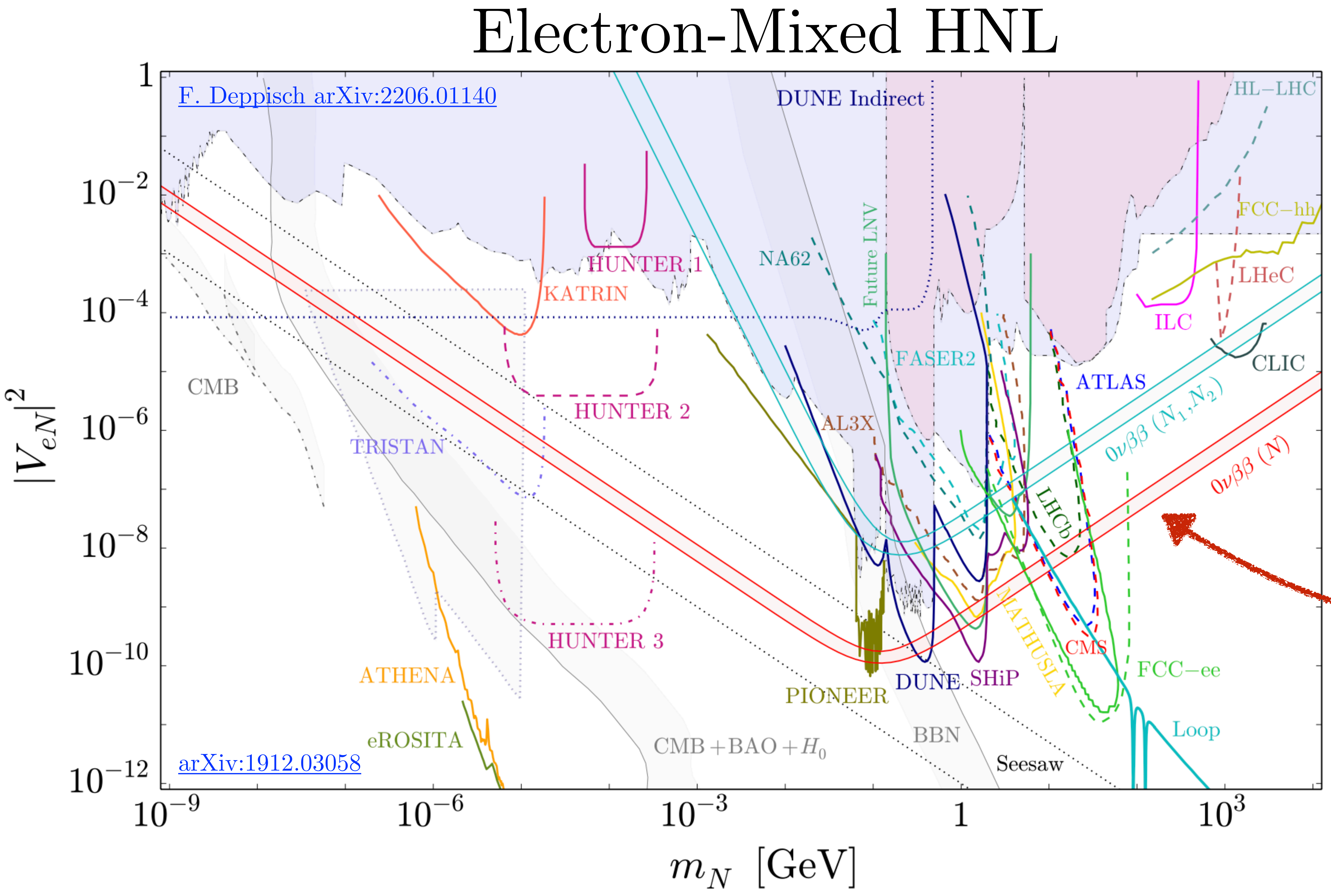
$$\xrightarrow{\text{EWSB}} m_D\bar{\nu}_L N_R + M_N\bar{N}_R N_R$$

Violates Lepton Number!



Neutrinoless Double Beta Decay is a smoking gun signature of Majorana HNLs

Neutrinoless Double Beta Decay

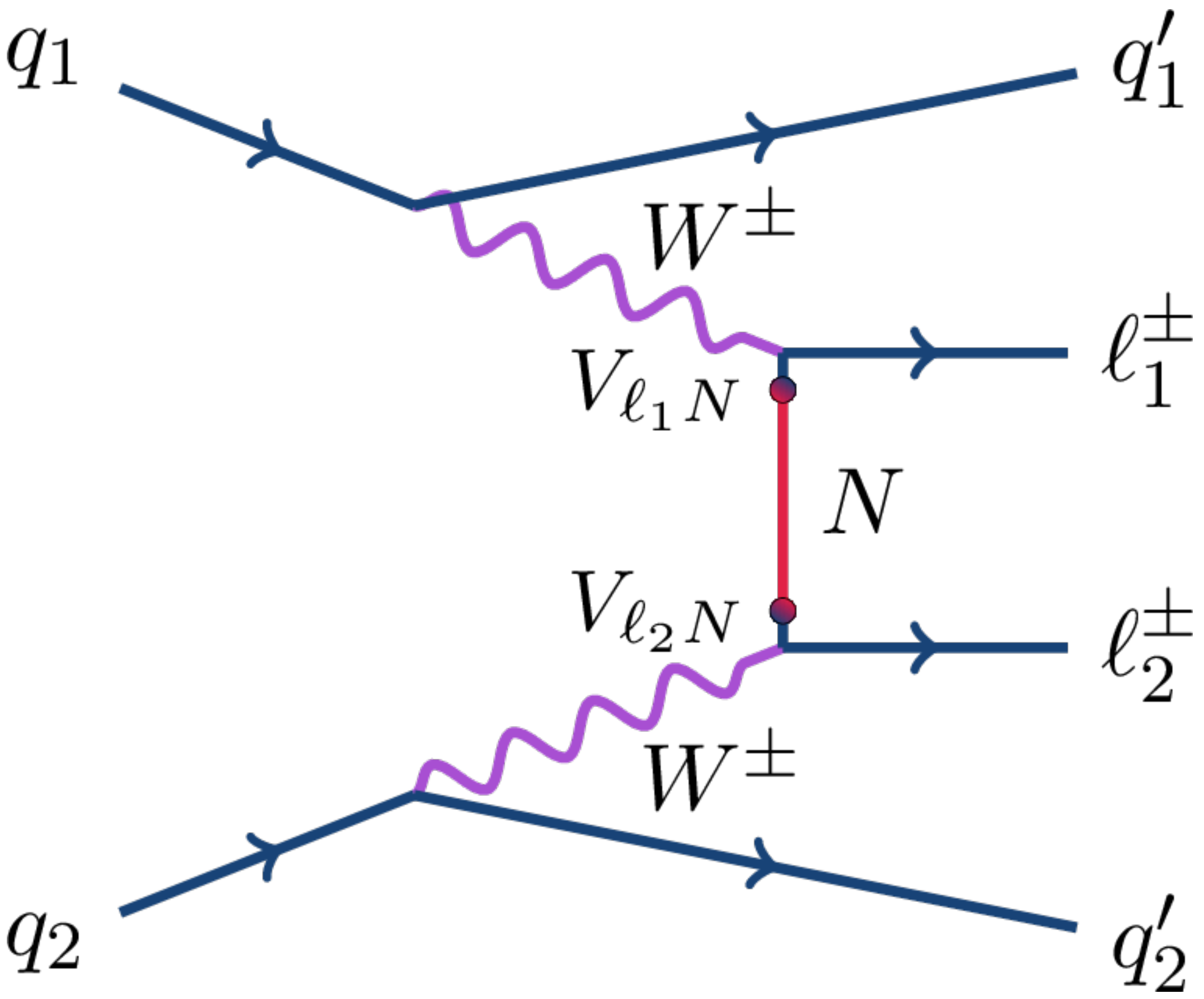


Probe of electron-mixed HNLs beyond the TeV-scale!

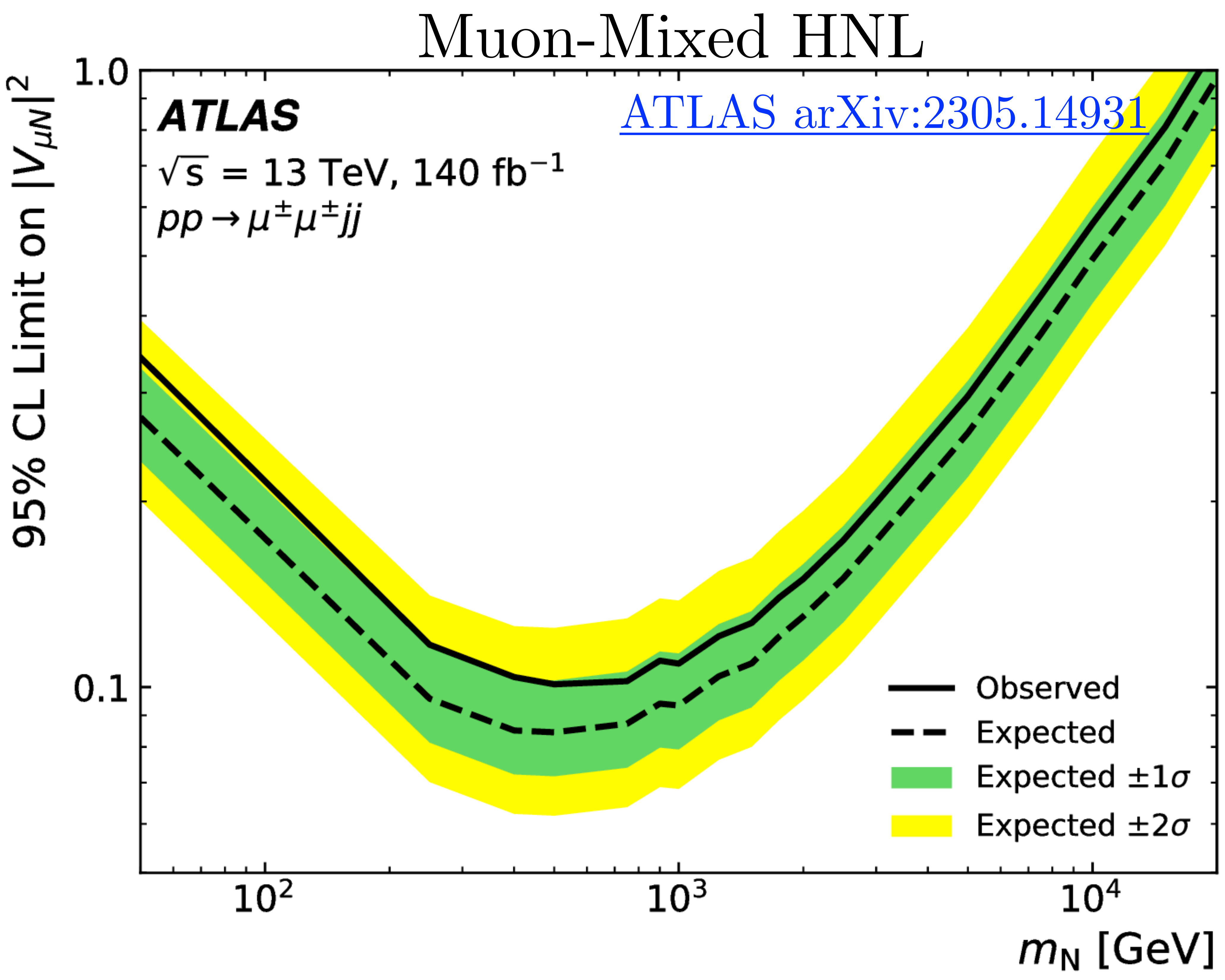
Only for electron-mixing. What about muon- or tau-mixed HNLs?

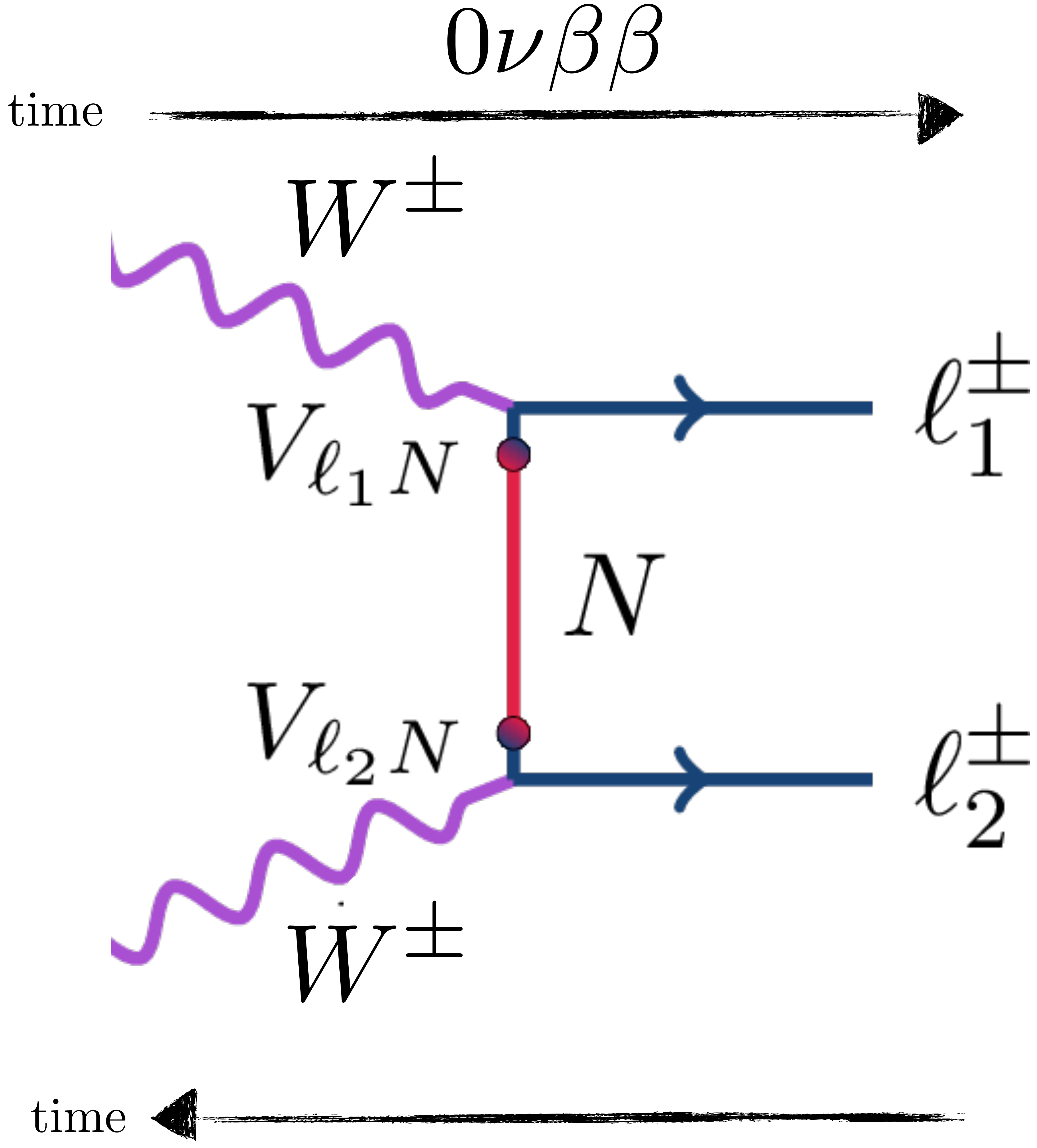
Same-Sign Leptons @ LHC

Same-sign final state leptons probe Majorana HNLs at the LHC



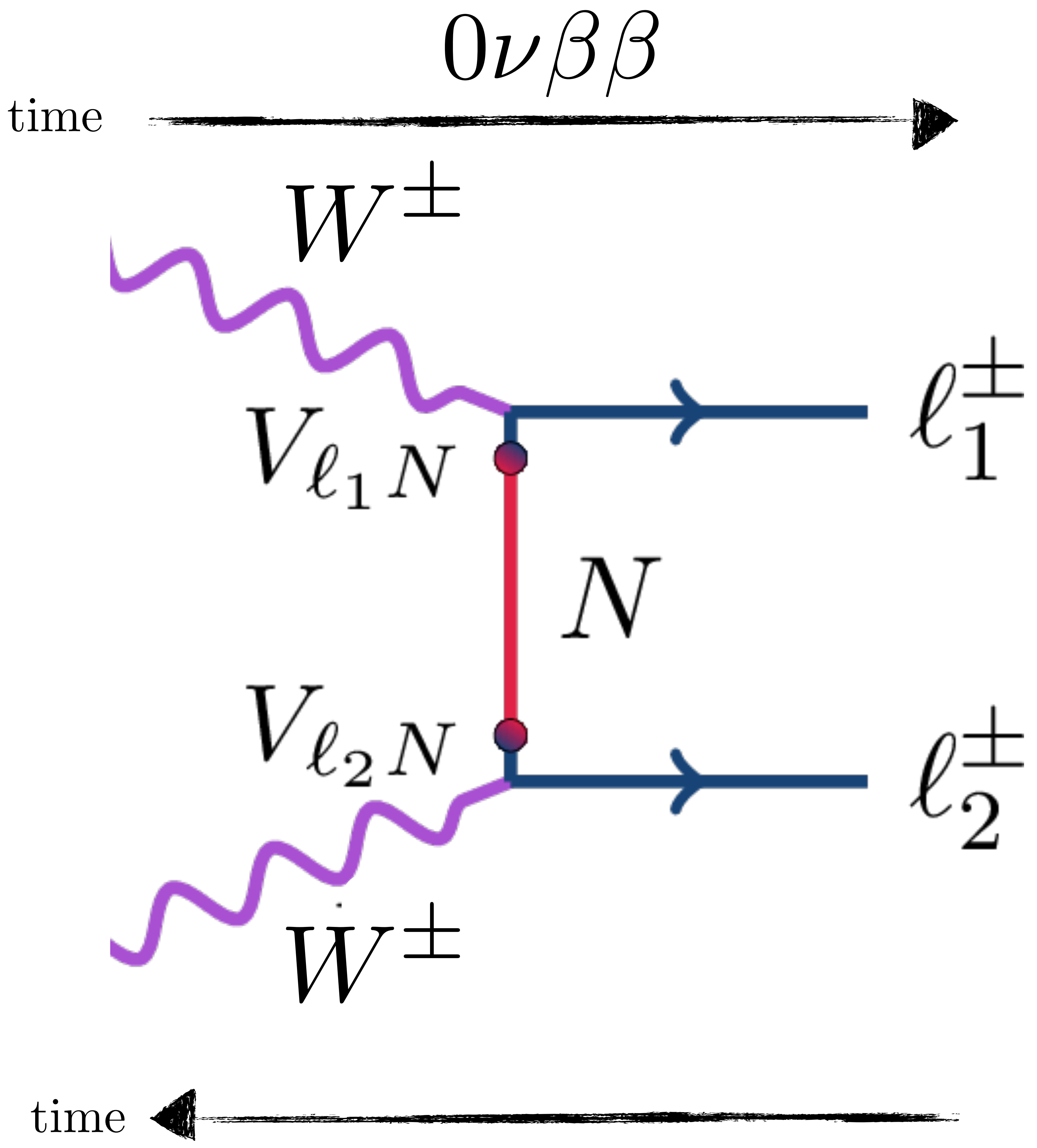
CMS arXiv:2206.08956





Same-Sign Lepton Colliders

Same-Sign Lepton Colliders



Same-Sign Lepton Colliders

μTRISTAN

arXiv:2201.06664

arXiv > hep-ph > arXiv:2201.06664

High Energy Physics – Phenomenology

[Submitted on 17 Jan 2022 (v1), last revised 21 Apr 2022 (this version, v2)]

µTRISTAN

Yu Hamada, Ryuichiro Kitano, Ryutaro Matsudo, Hiromasa Takaura, Mitsuhiro Yoshida

Compact Linear Collider

SOME THOUGHTS ON E⁻E⁻ COLLISIONS IN CLIC

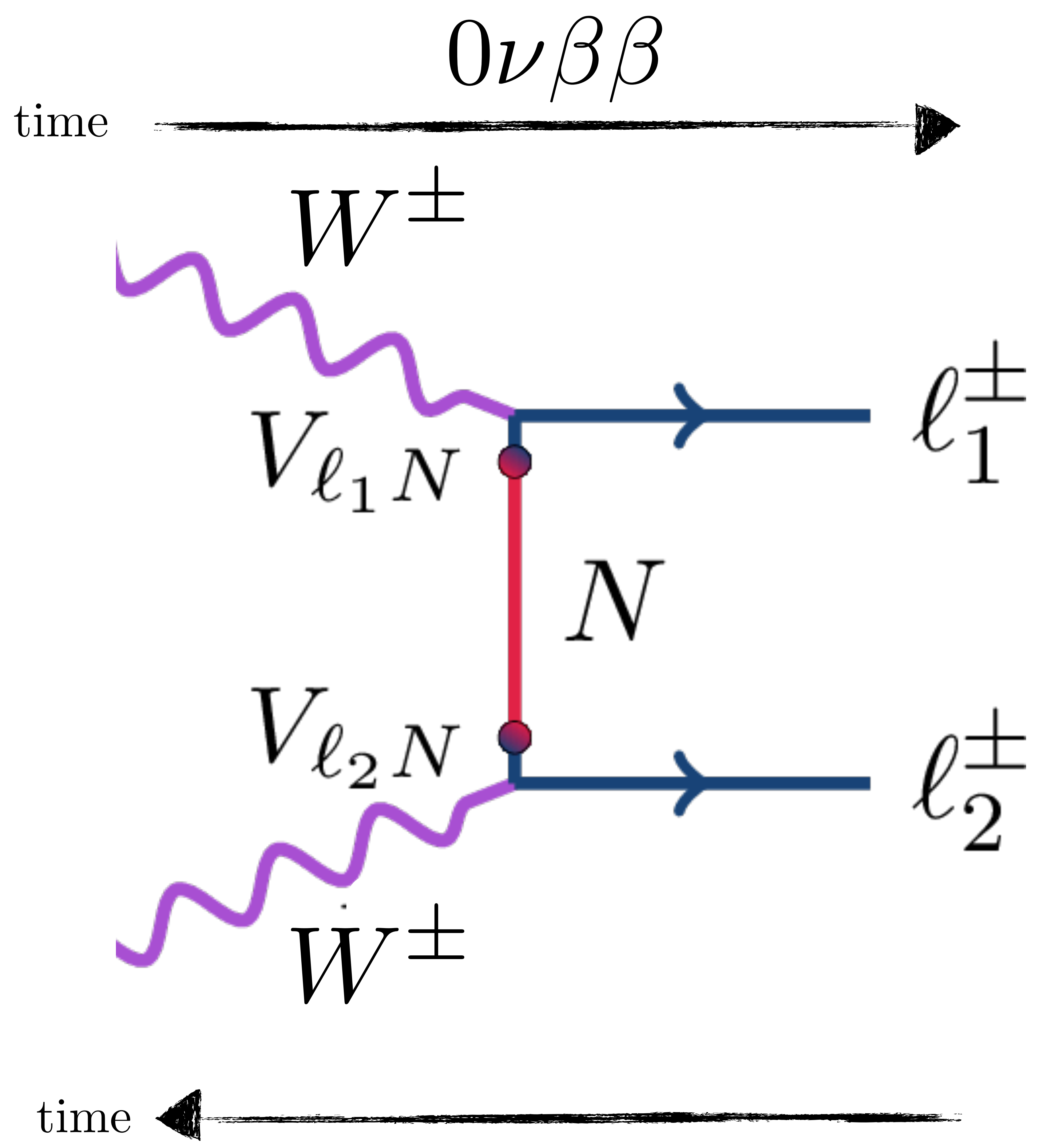
D. SCHULTE

CERN, Geneva, Switzerland

Linear e^+e^- colliders have the potential to also be used to realise e^-e^- collisions. Some preliminary thoughts about the realisation of this at CLIC are presented. Luminosity and some background estimates are also given.

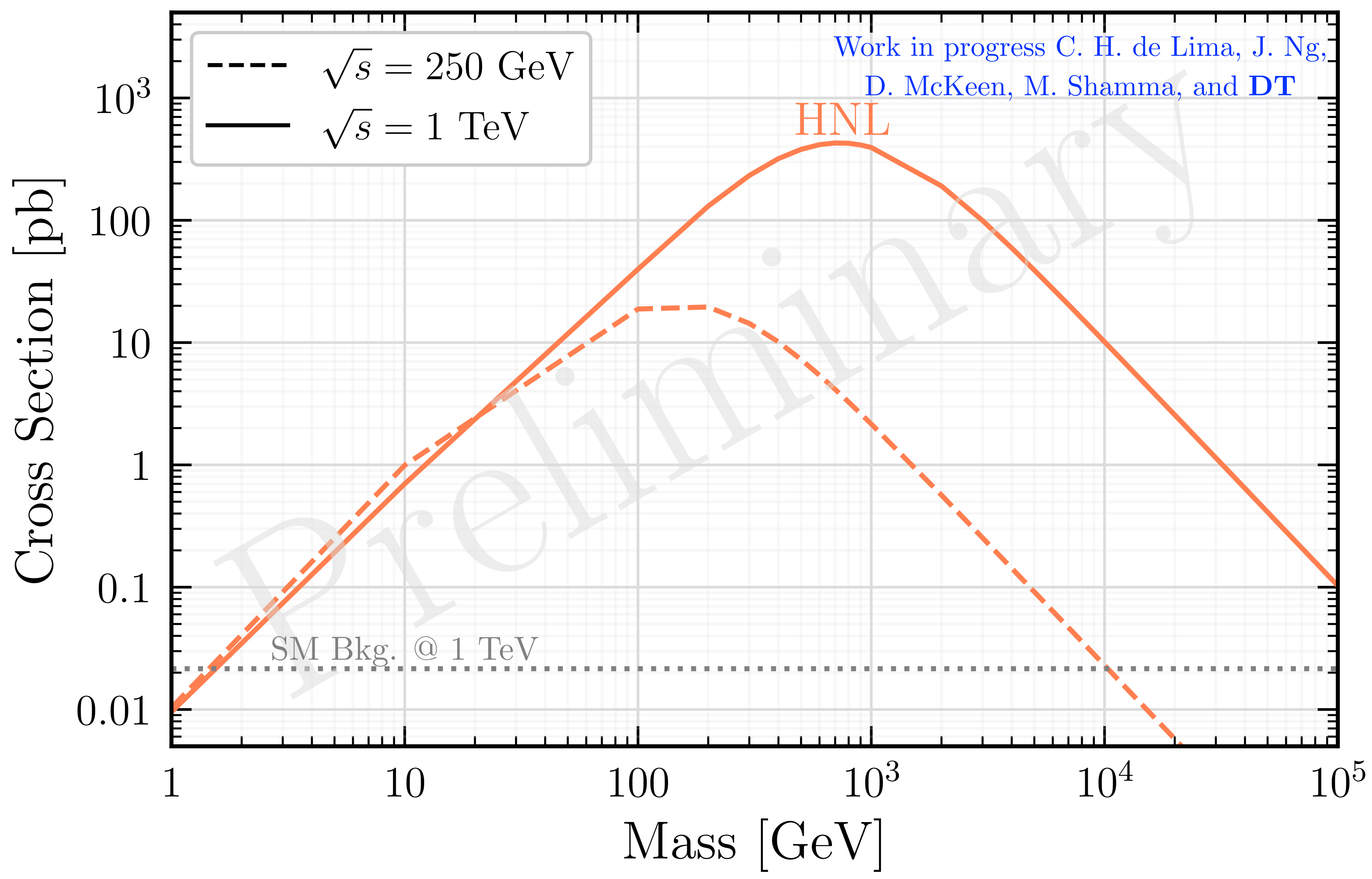
CLIC Note 512 (2002)

Same-Sign Lepton Colliders



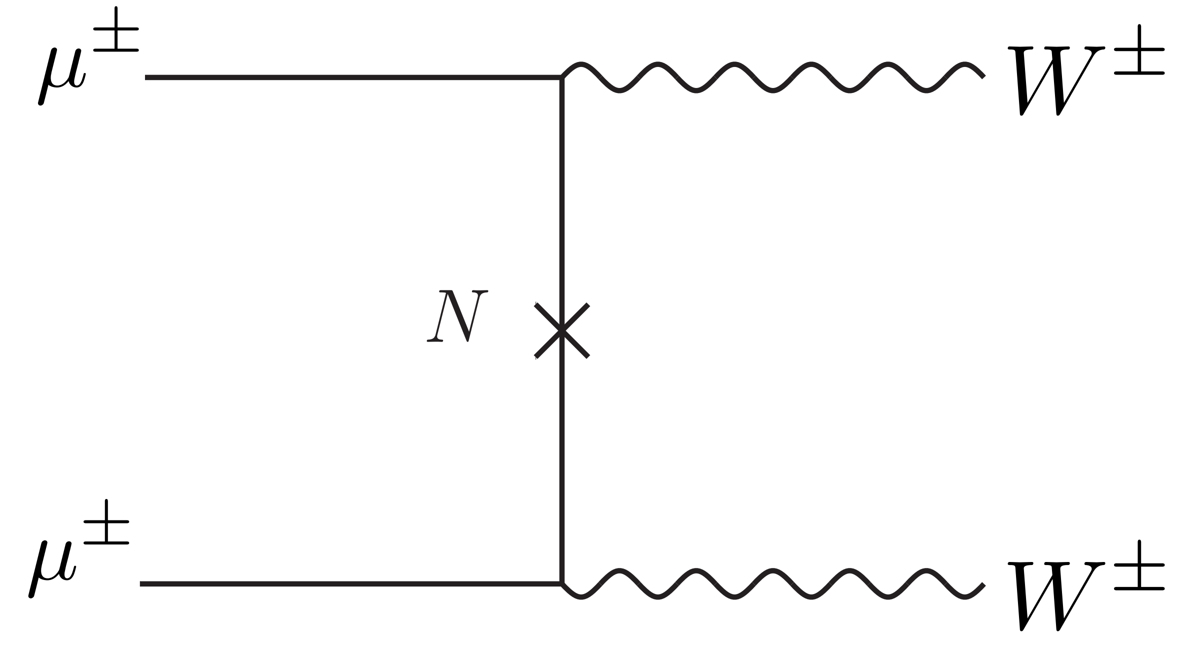
Same-Sign Lepton Colliders

$$\sigma \simeq \begin{cases} 42\ \text{pb}\,|U_\ell|^4 \left(\frac{m_N}{100\ \text{GeV}}\right)^2, & m_N \ll \sqrt{s} \\ 11\ \text{pb}\,|U_\ell|^4 \left(\frac{\sqrt{s}}{1\ \text{TeV}}\right)^4 \left(\frac{10\ \text{TeV}}{m_N}\right)^2, & m_N \gg \sqrt{s}\,. \end{cases}$$

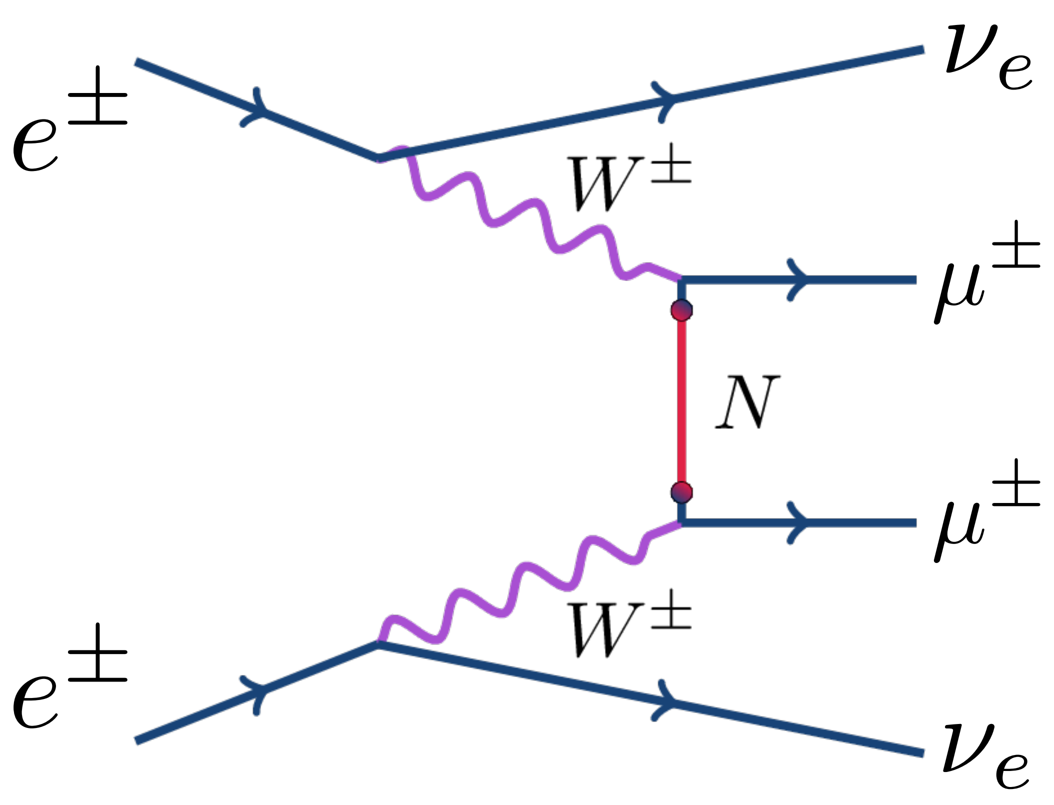


Same-Sign Lepton Colliders

$W^\pm$ Direct Production

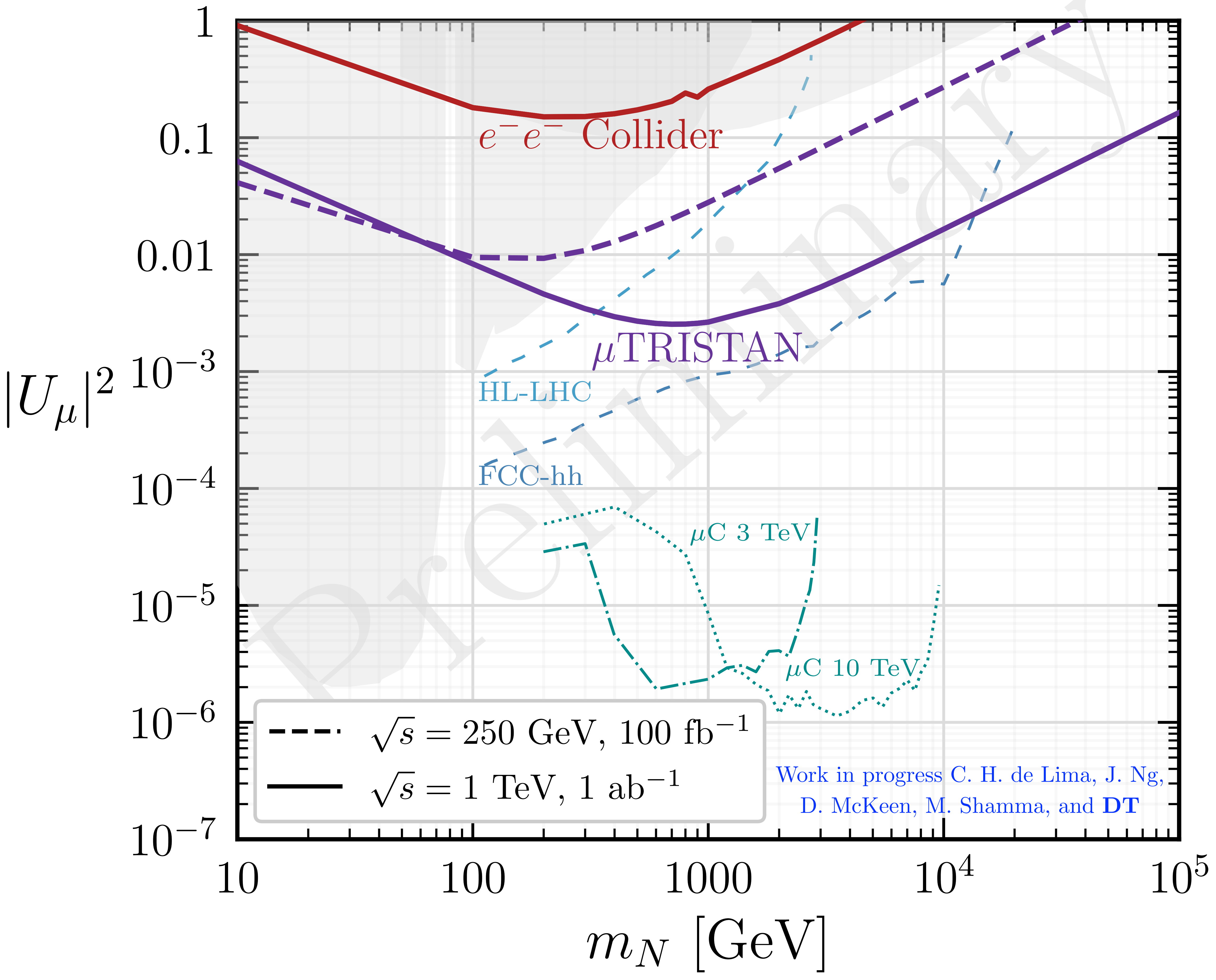


$W^\pm$ Boson Scattering



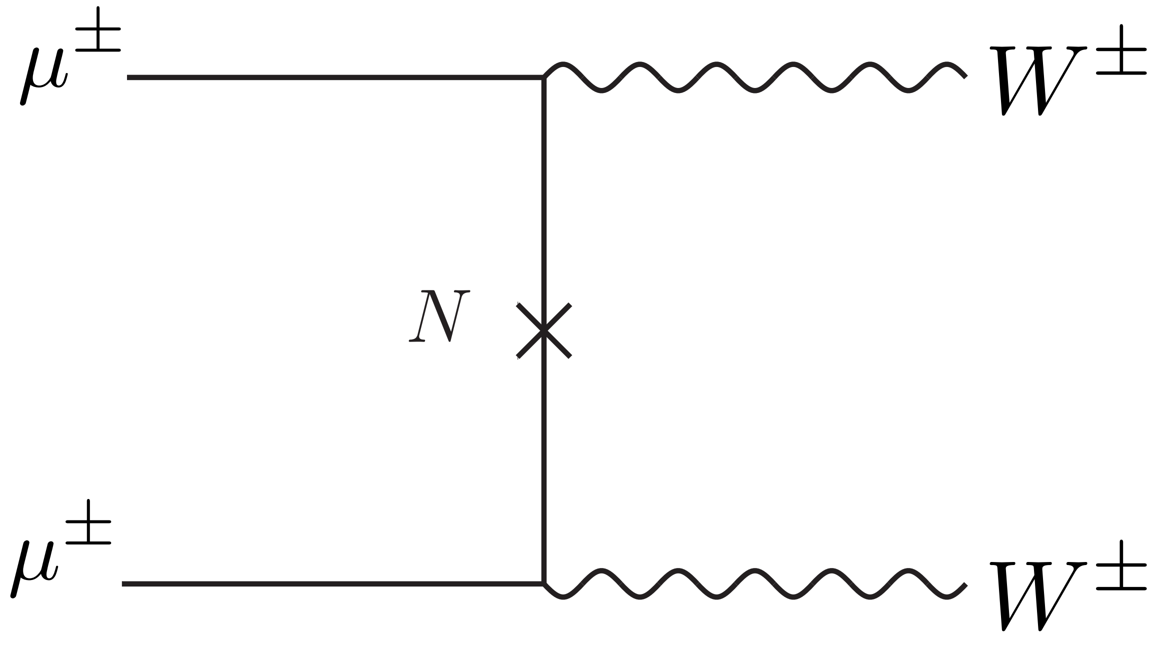
Probe HNLs with a different flavor initial state lepton!

Muon-Mixed HNL

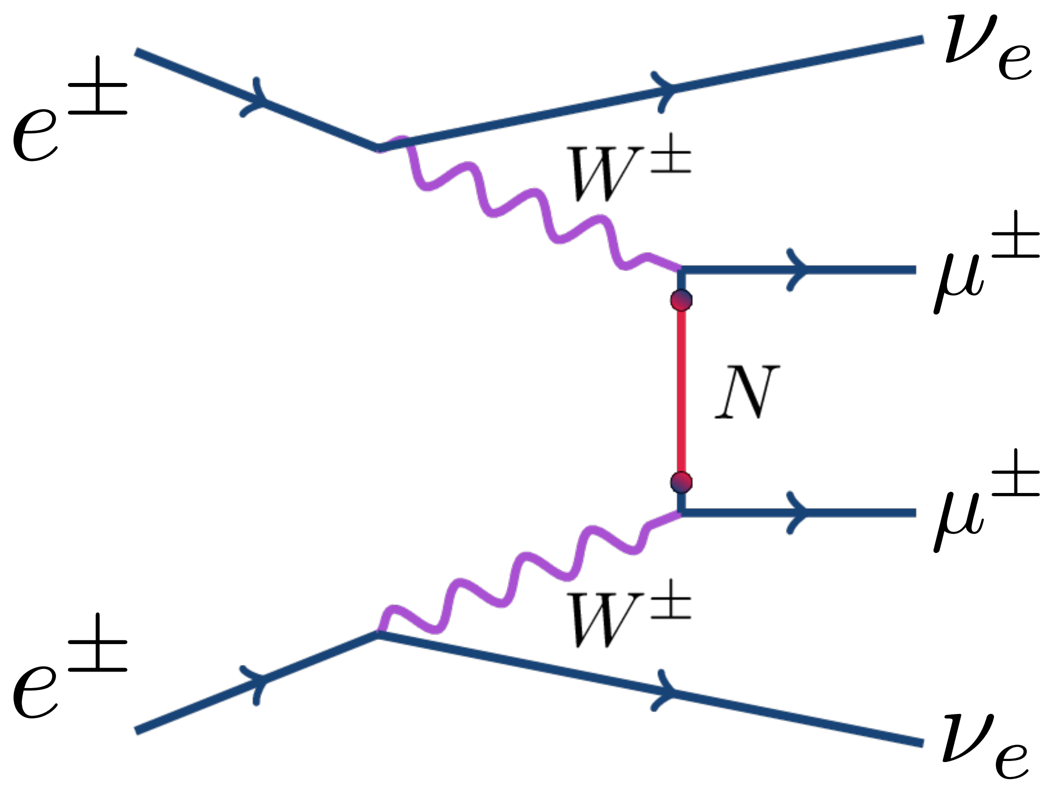


Same-Sign Lepton Colliders

$W^\pm$ *Direct Production*



$W^\pm$ *Boson Scattering*



Probe HNLs with a different flavor initial state lepton!

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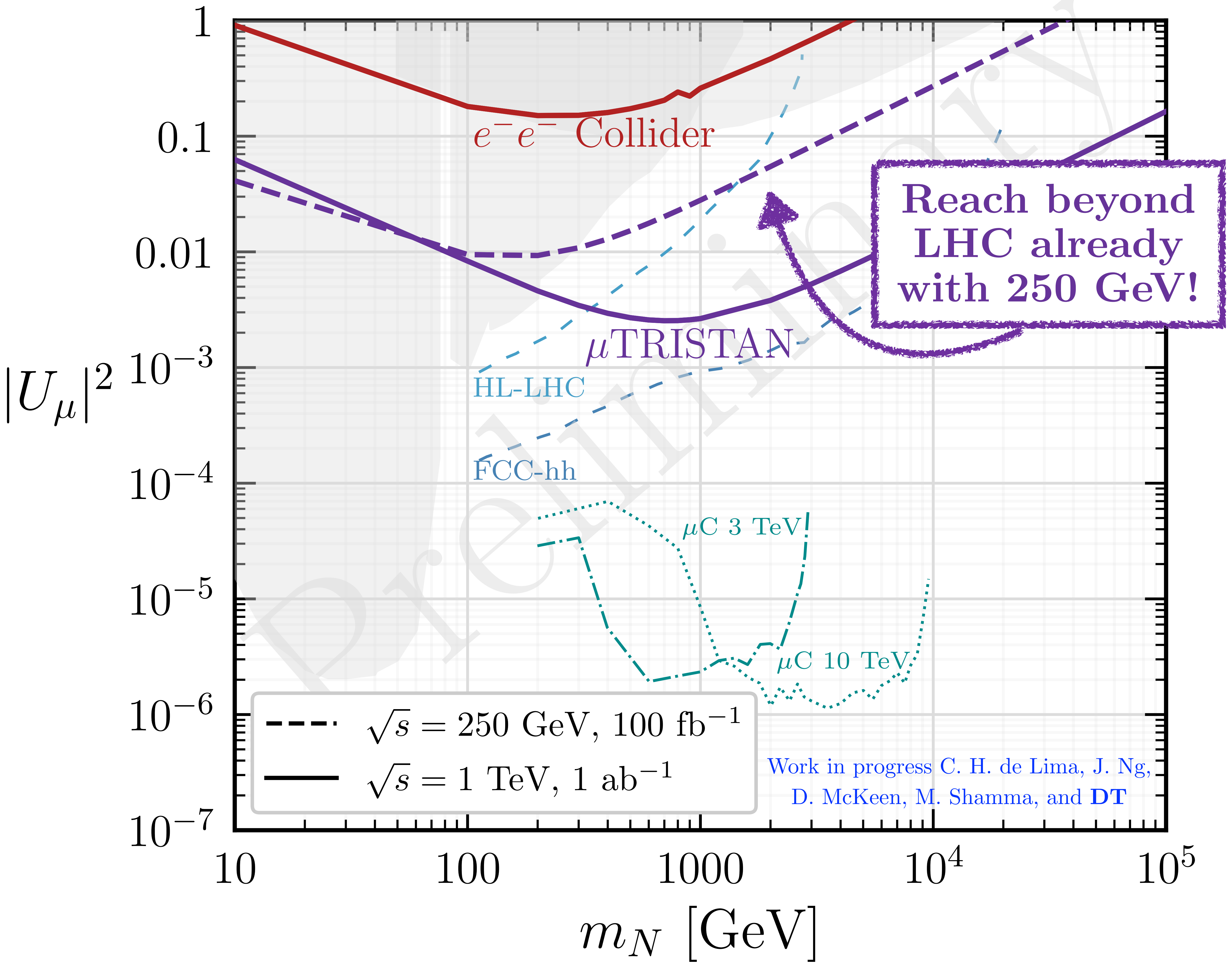
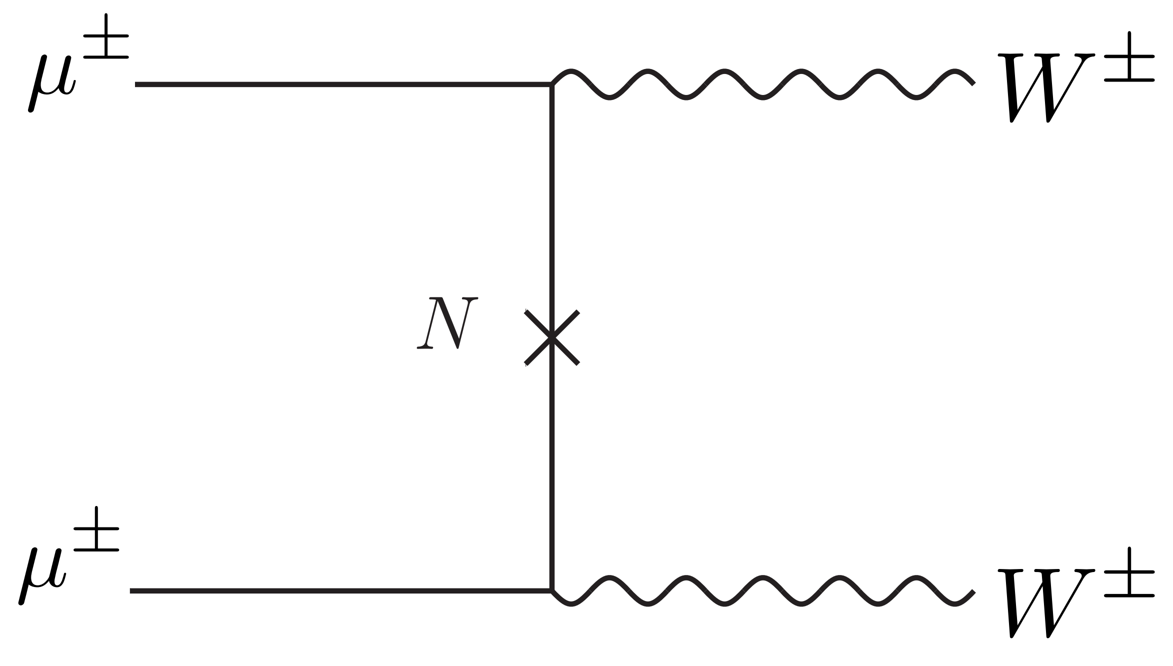
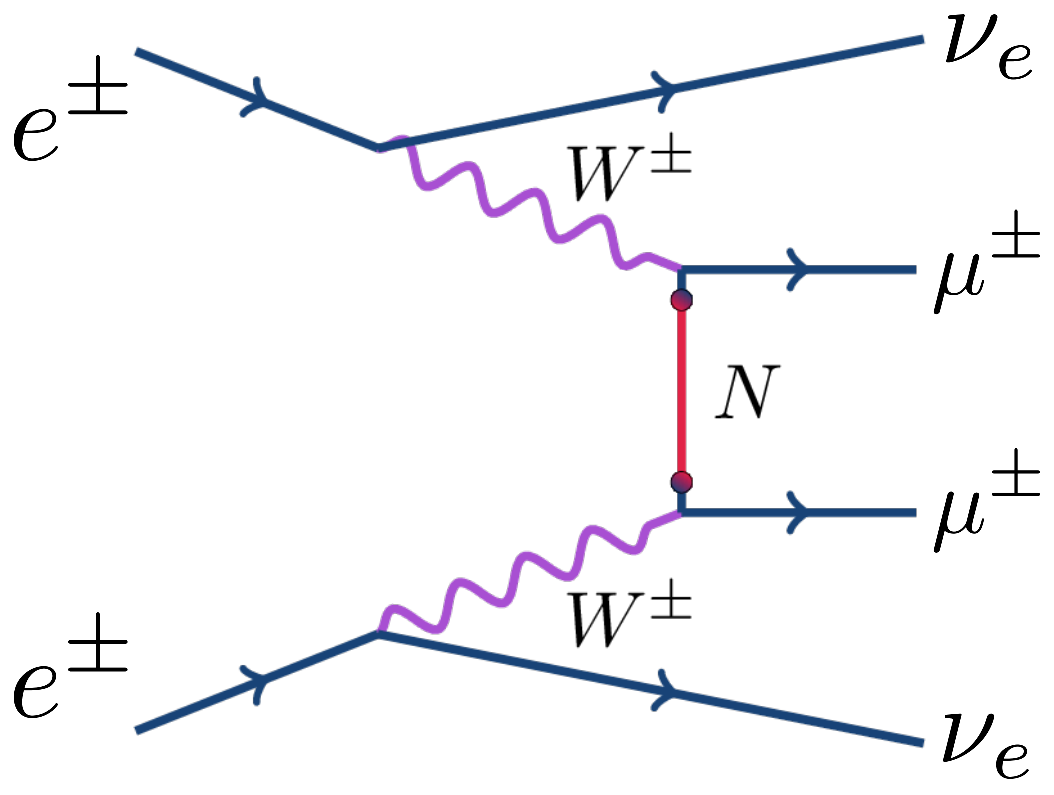


Same-Sign Lepton Colliders

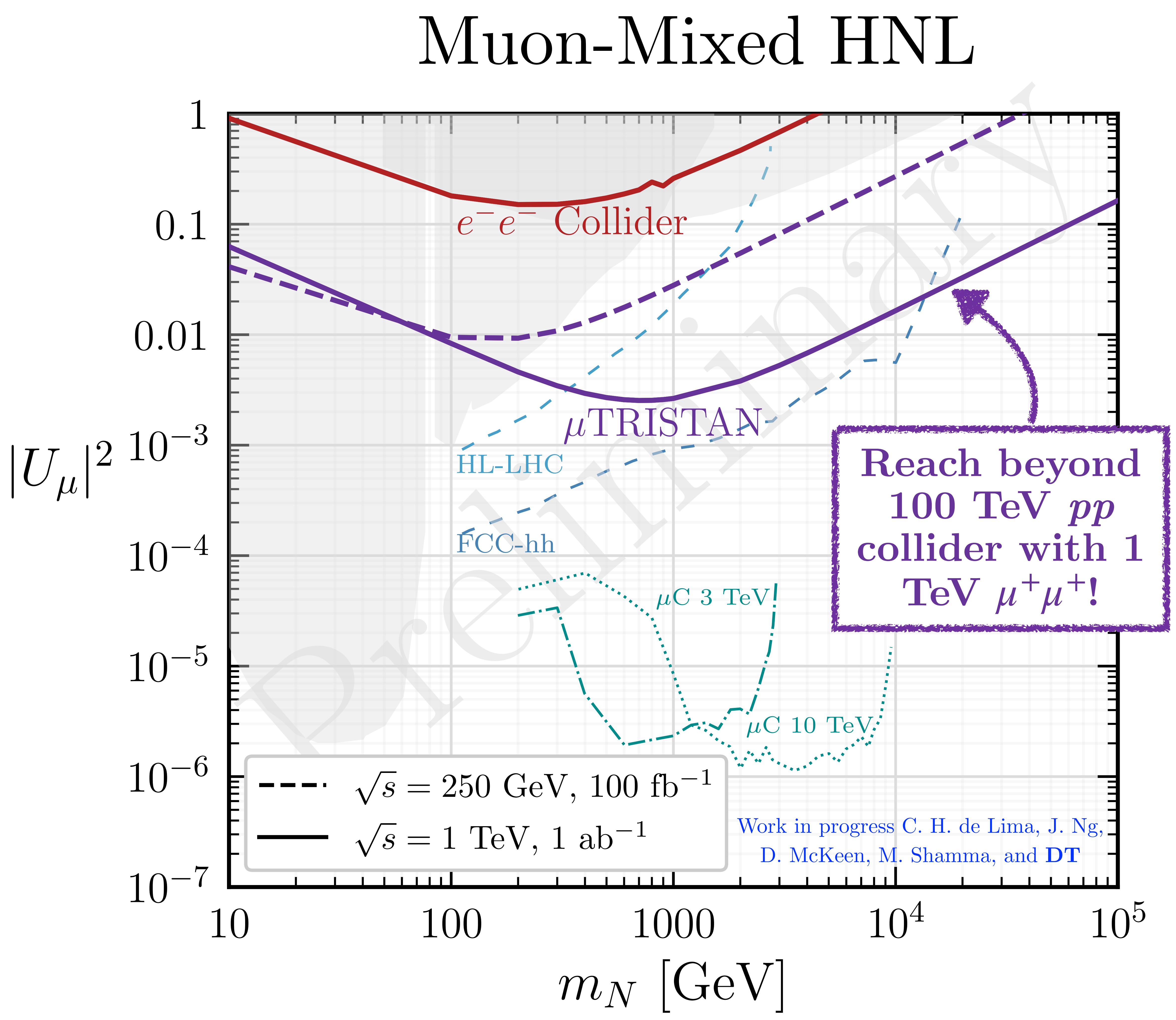
$W^\pm$ Direct Production



$W^\pm$ Boson Scattering

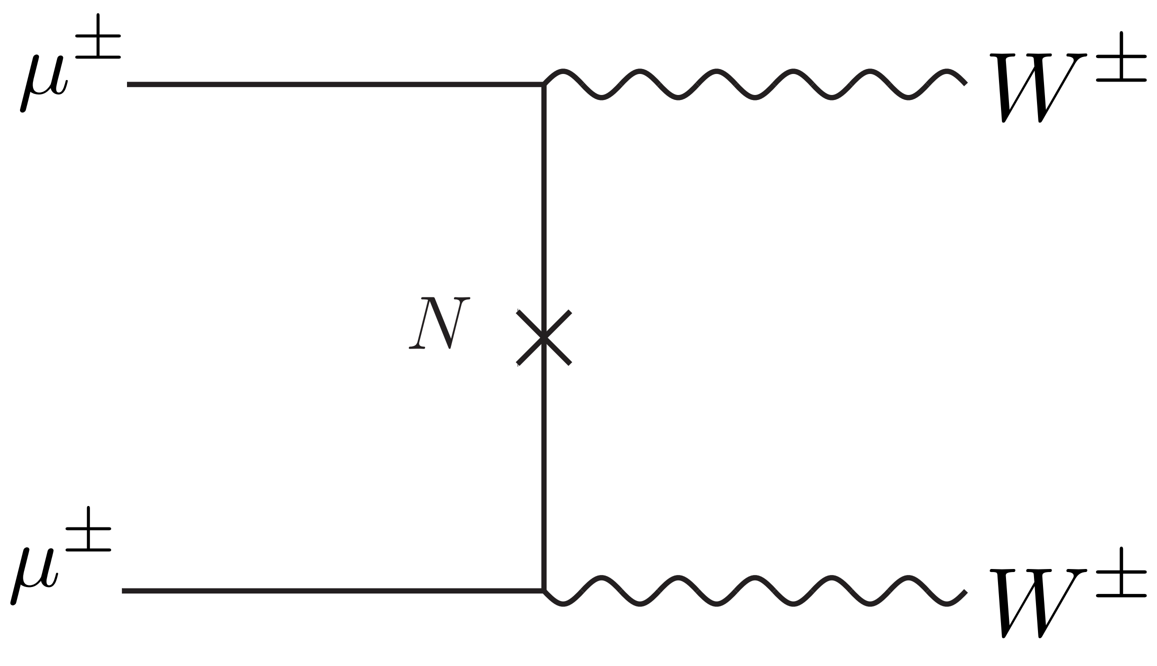


Probe HNLs with a different flavor initial state lepton!

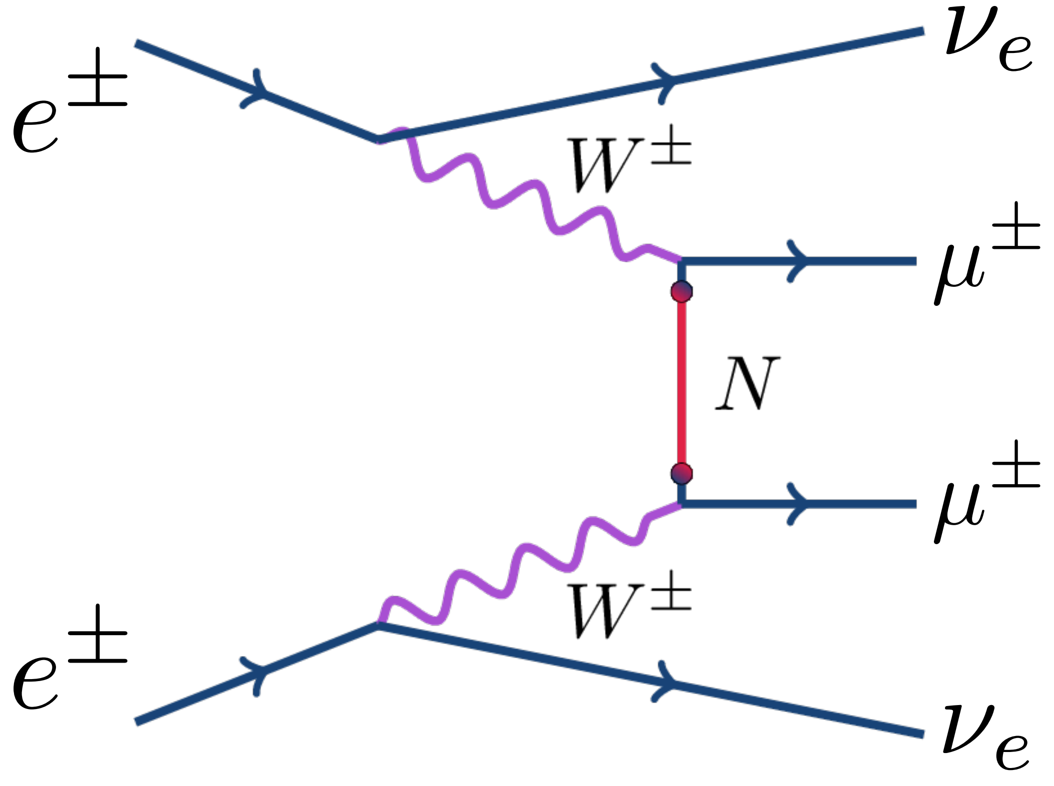


Same-Sign Lepton Colliders

$W^\pm$ *Direct Production*



$W^\pm$ *Boson Scattering*



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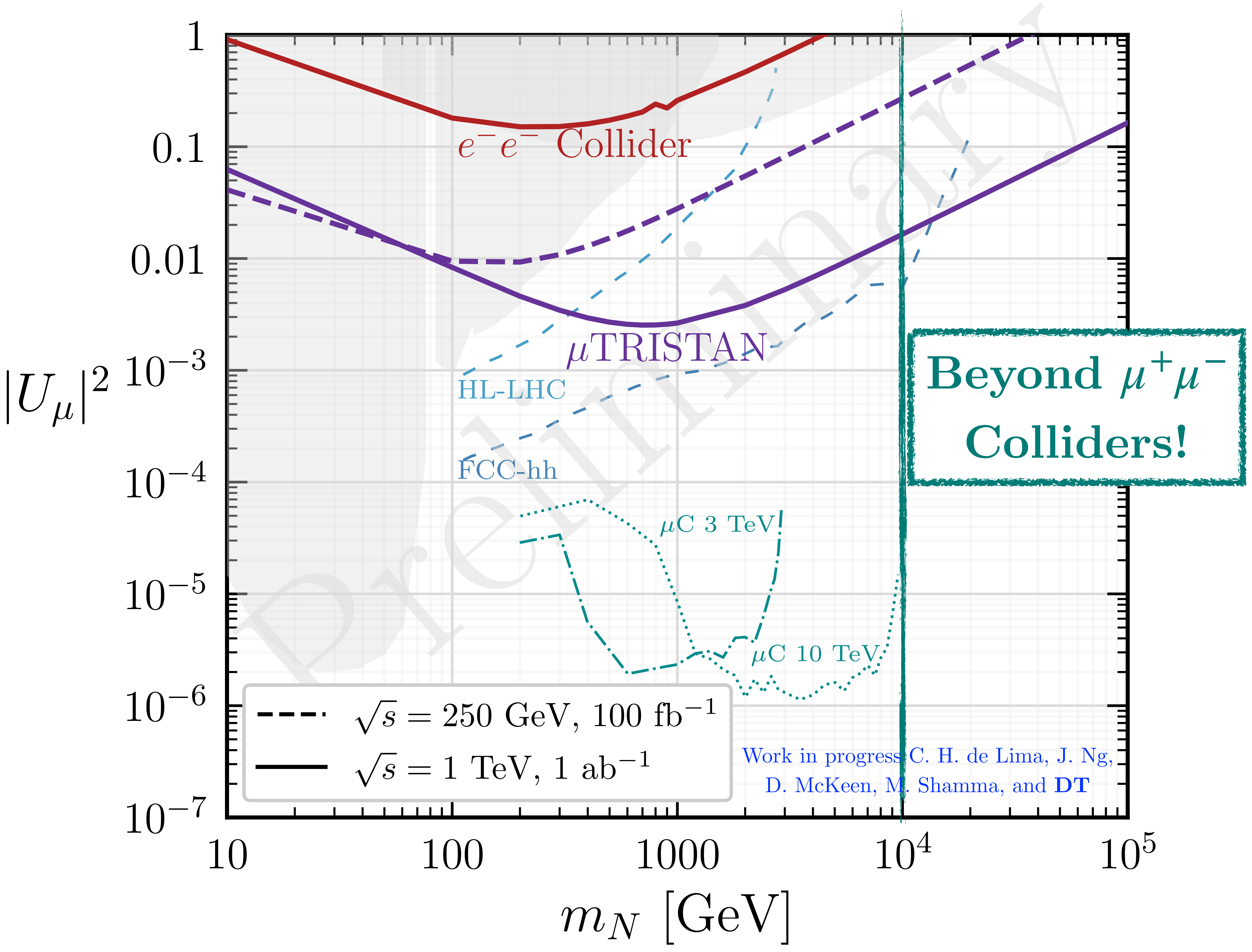
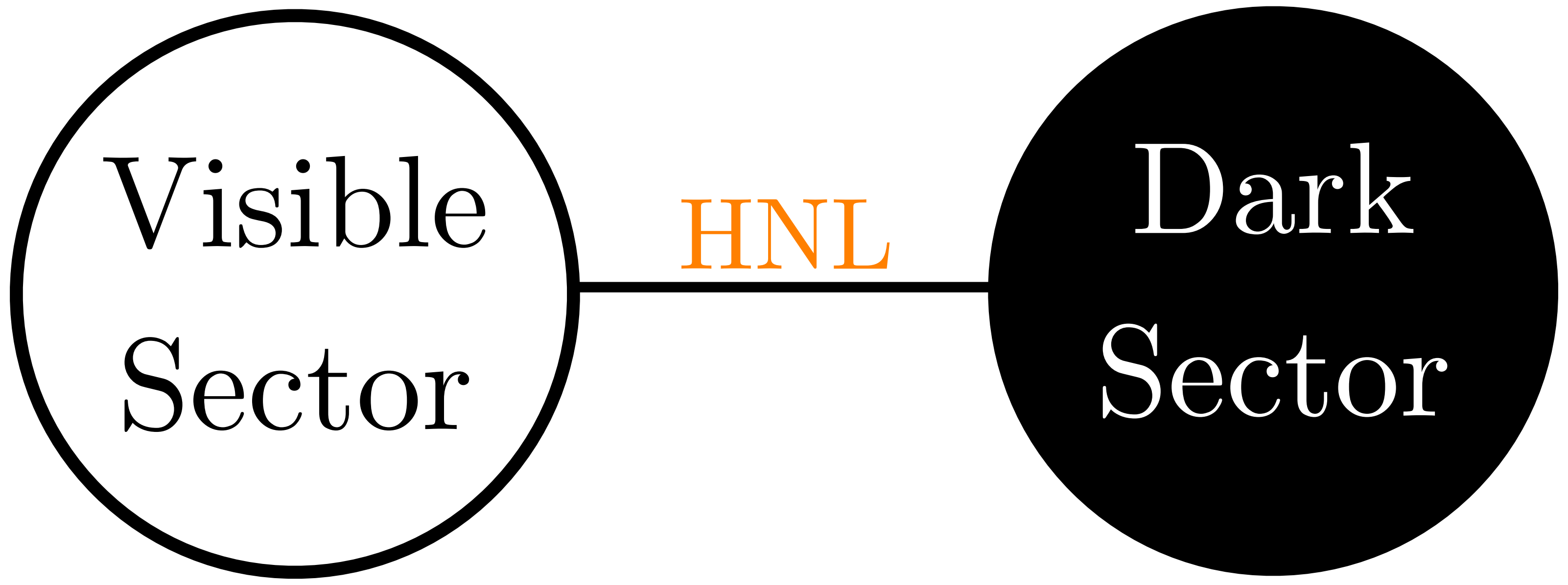
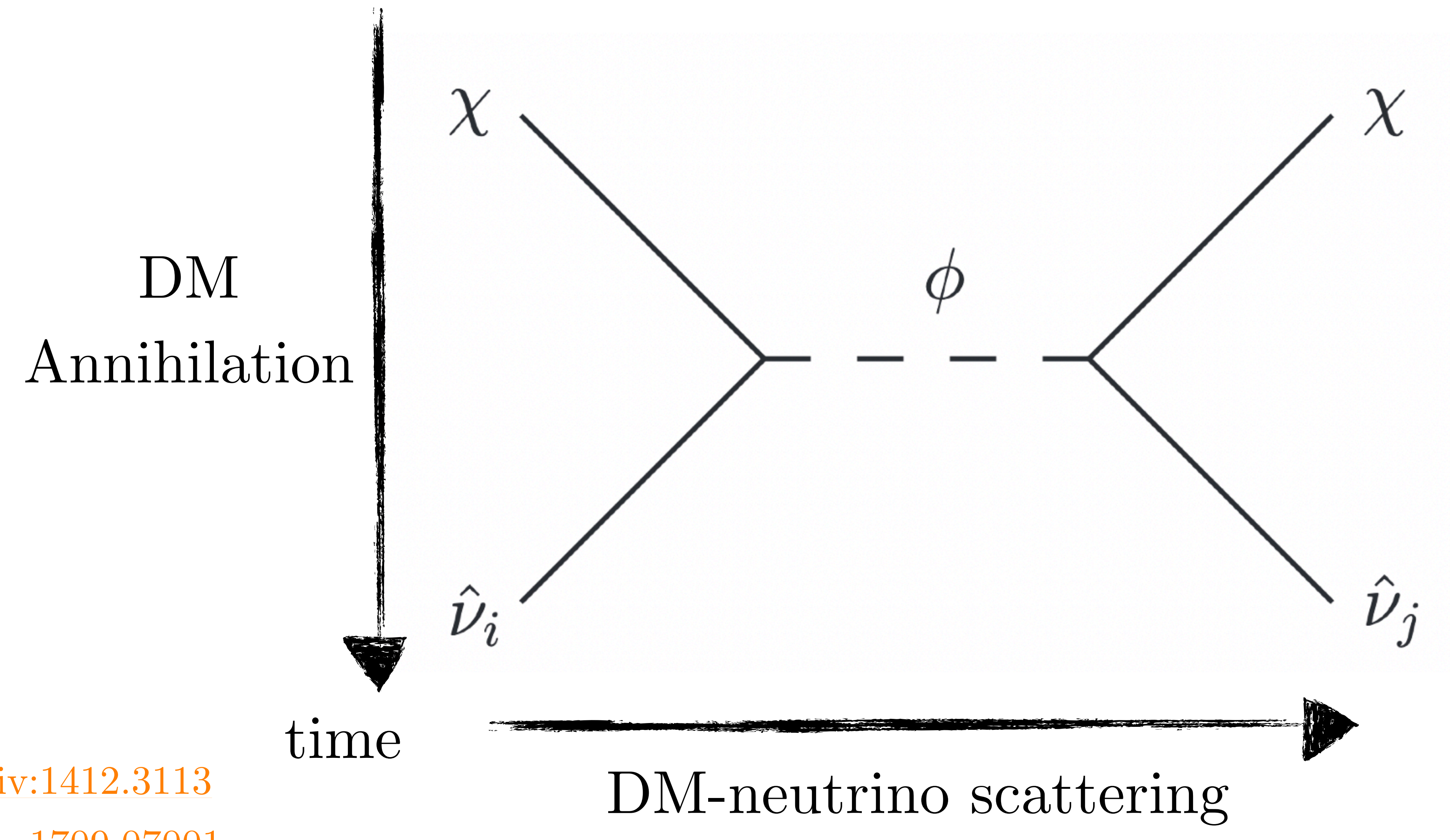


HNL Dark Sector Portal

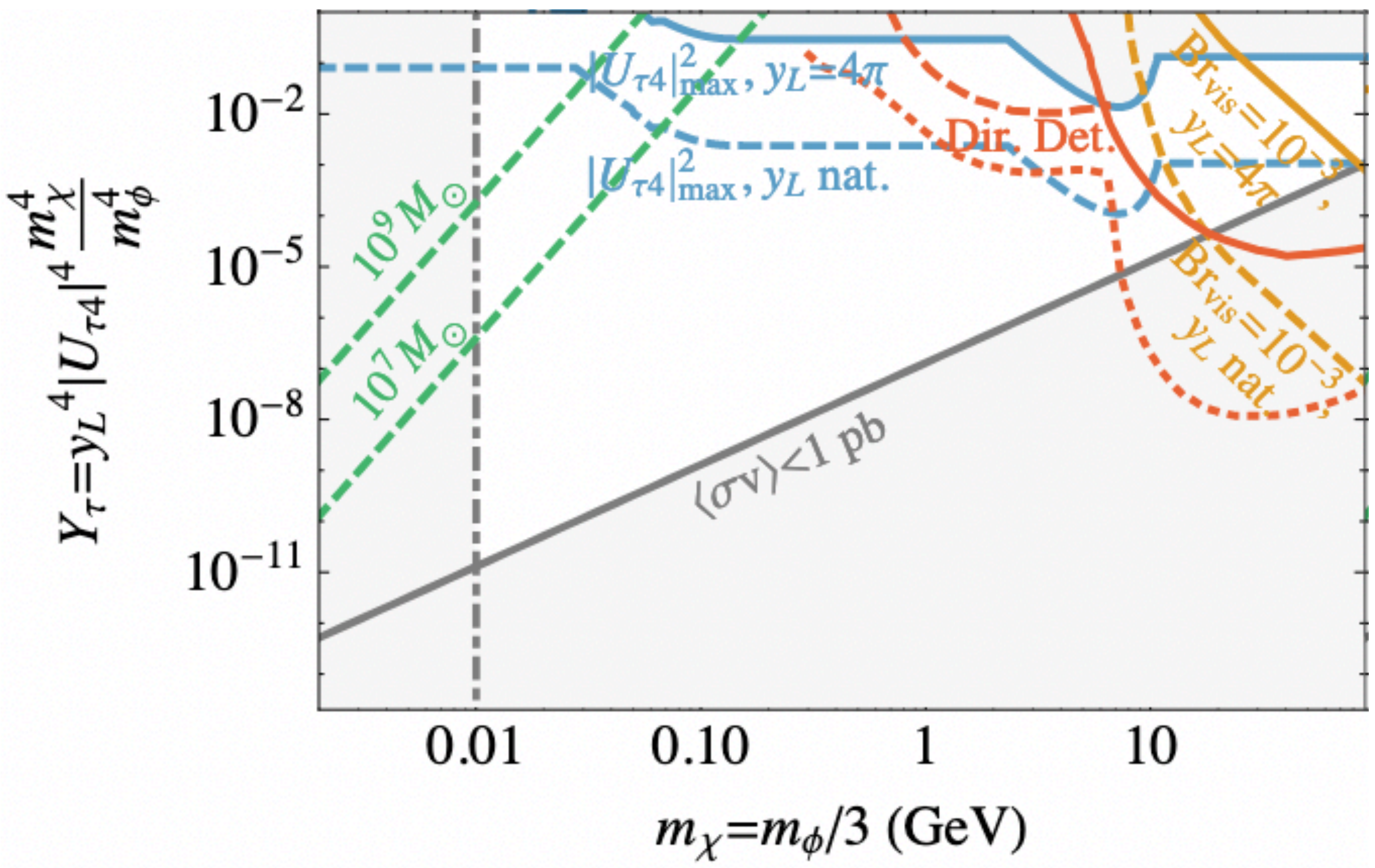


$$\mathcal{L} \supset \underbrace{m_\chi \bar{\chi}\chi}_{\text{DM}} + \lambda_\ell \bar{L}_\ell \tilde{H} N_R + \underbrace{y_\chi \phi \bar{\chi} N_R}_{\text{Portal}}$$



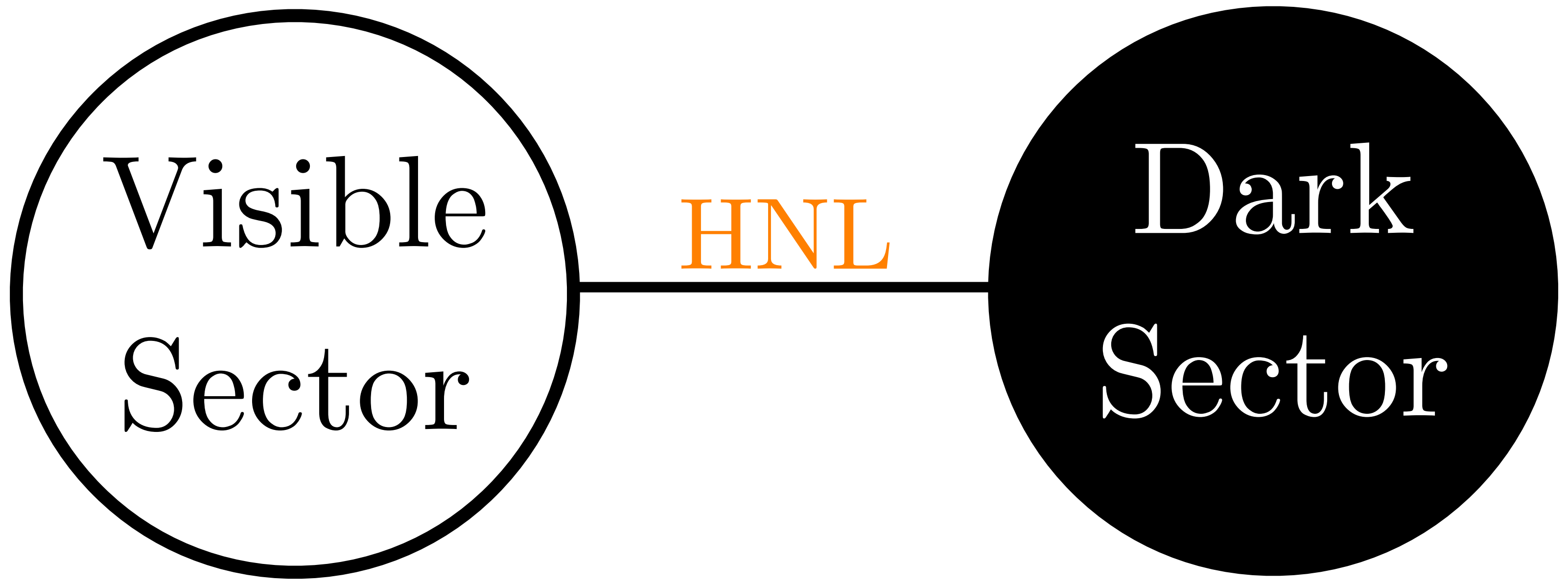
arXiv:1412.3113
arXiv:1709.07001

Tau-Mixed HNL

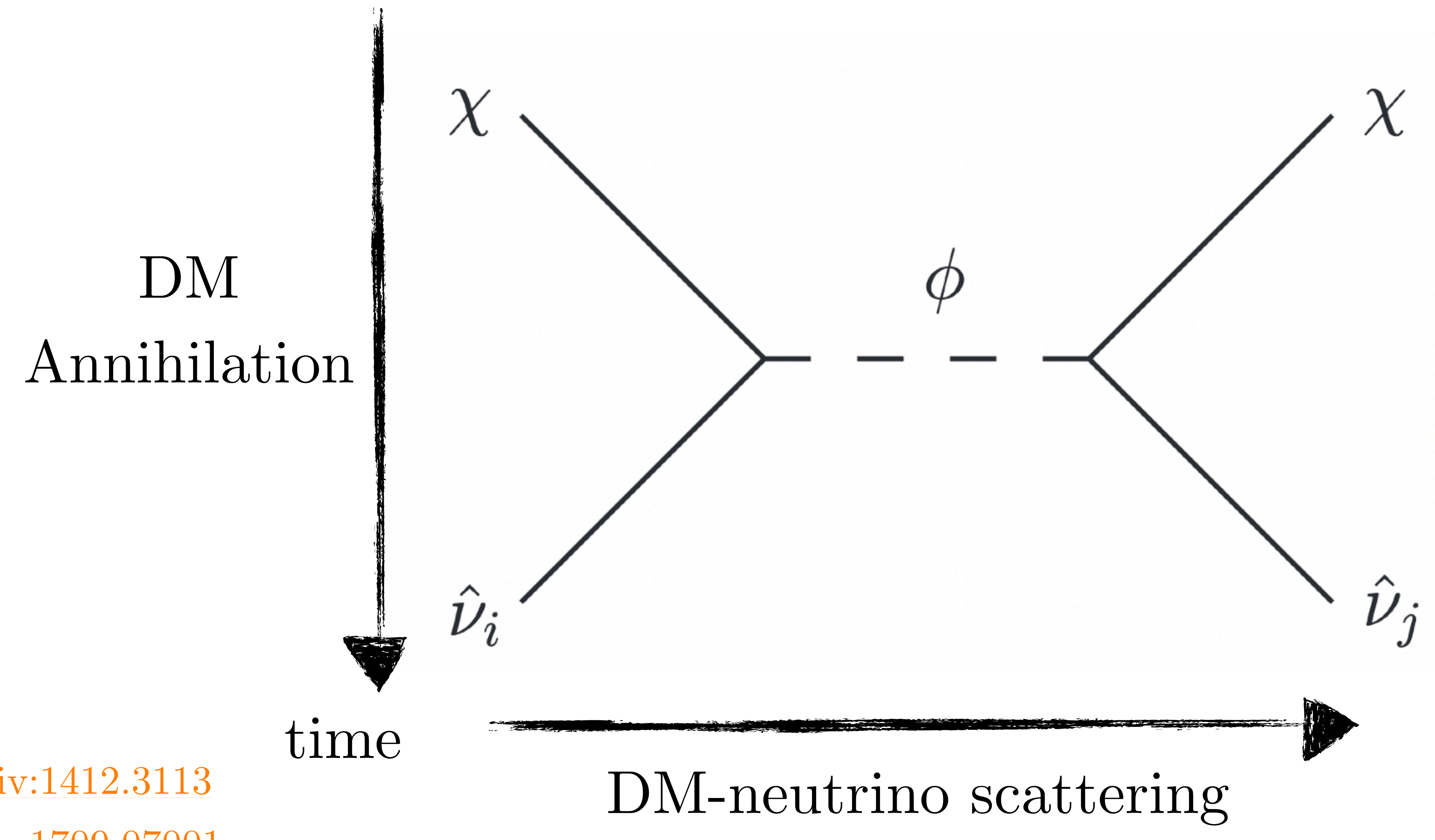


See B. Batell, T. Han, **Dave McKeen**, and B. S. Es Haghi arXiv:1709.07001 for more details
(Or ask Dave...)

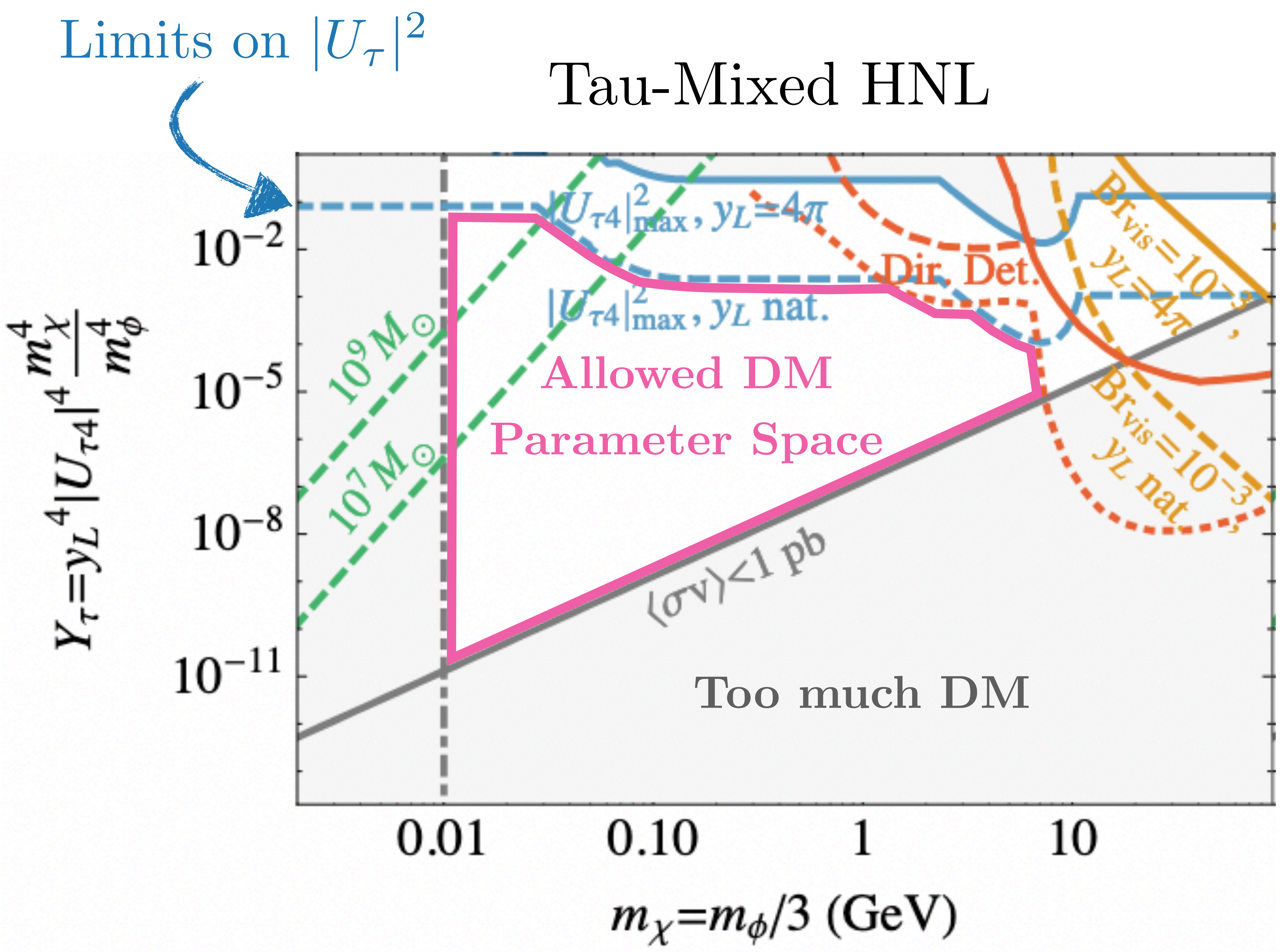
HNL Dark Sector Portal



$$\mathcal{L} \supset \underbrace{m_\chi \bar{\chi}\chi}_{\text{DM}} + \lambda_\ell \bar{L}_\ell \tilde{H} N_R + \underbrace{y_\chi \phi \bar{\chi} N_R}_{\text{Portal}}$$



arXiv:1412.3113
arXiv:1709.07001



See B. Batell, T. Han, **Dave McKeen**, and B. S. Es Haghi arXiv:1709.07001 for more details

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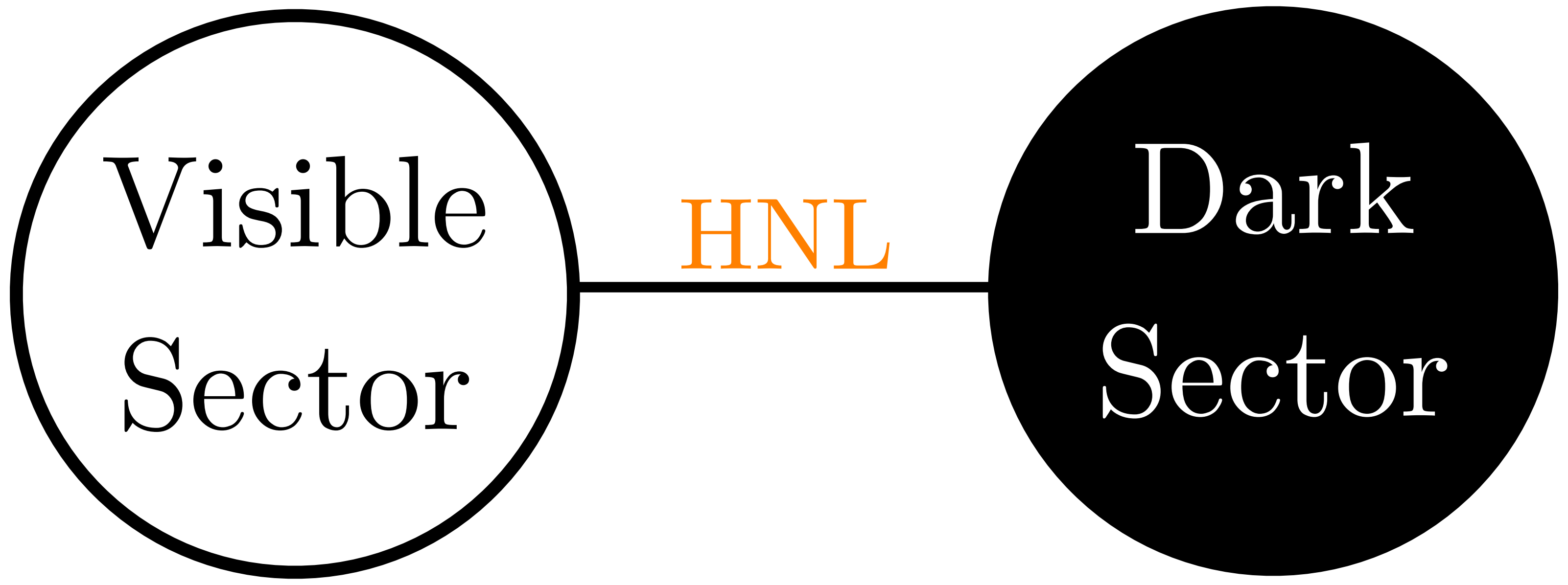
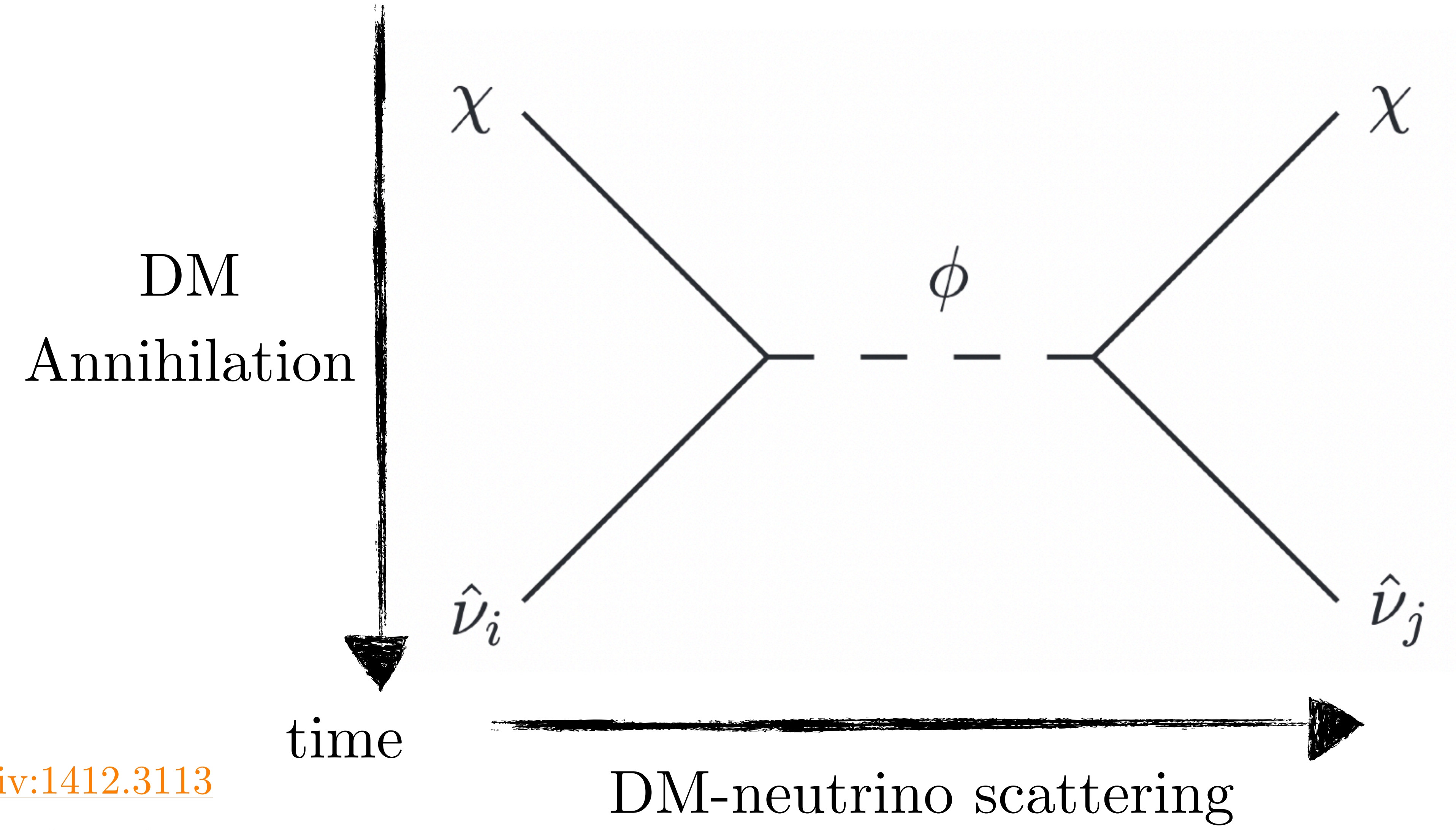
HNL Dark Sector Portal

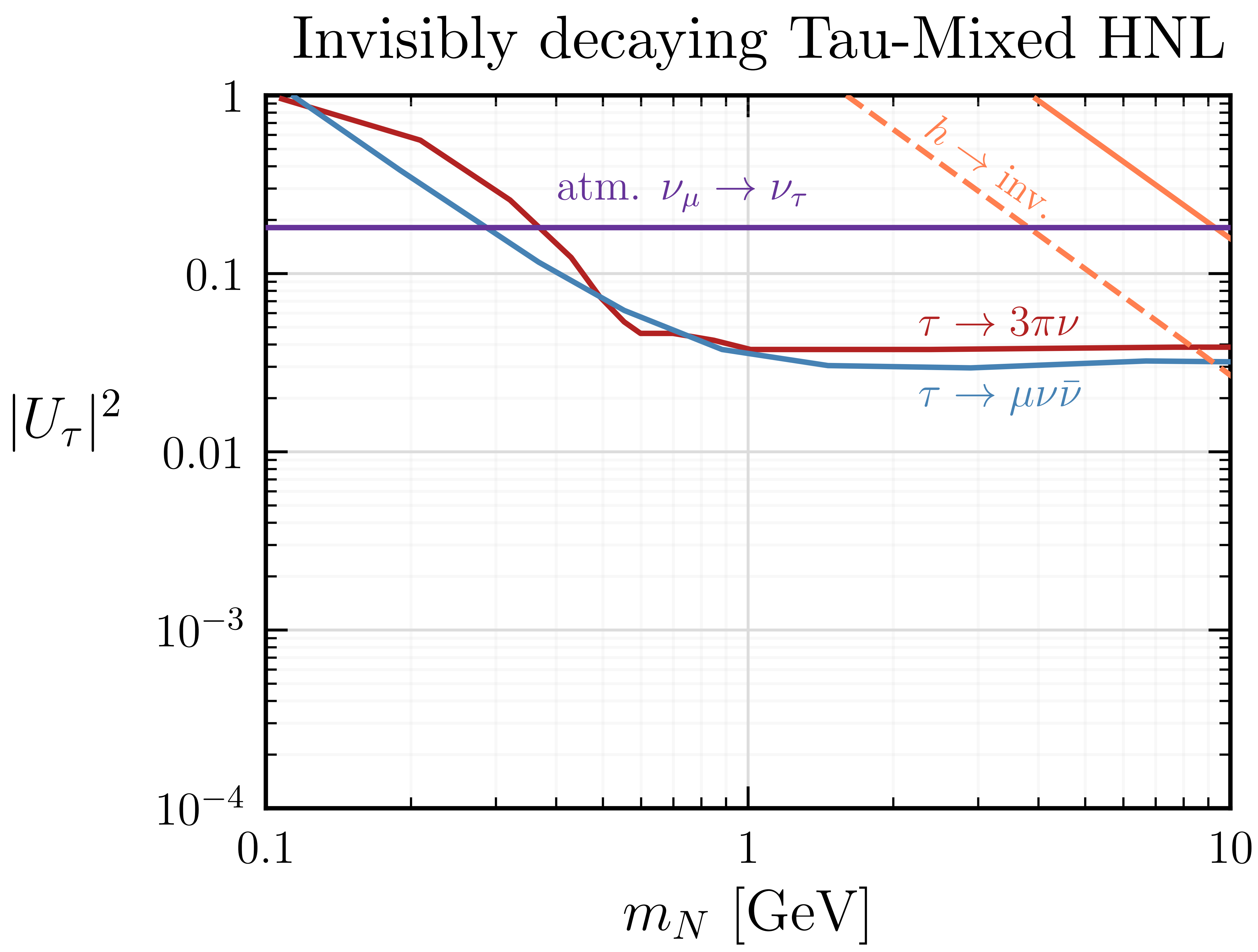


$$\mathcal{L} \supset m_\chi \bar{\chi}\chi + \lambda_\ell \bar{L}_\ell \tilde{H} N_R + y_\chi \phi \bar{\chi} N_R$$

DM Portal



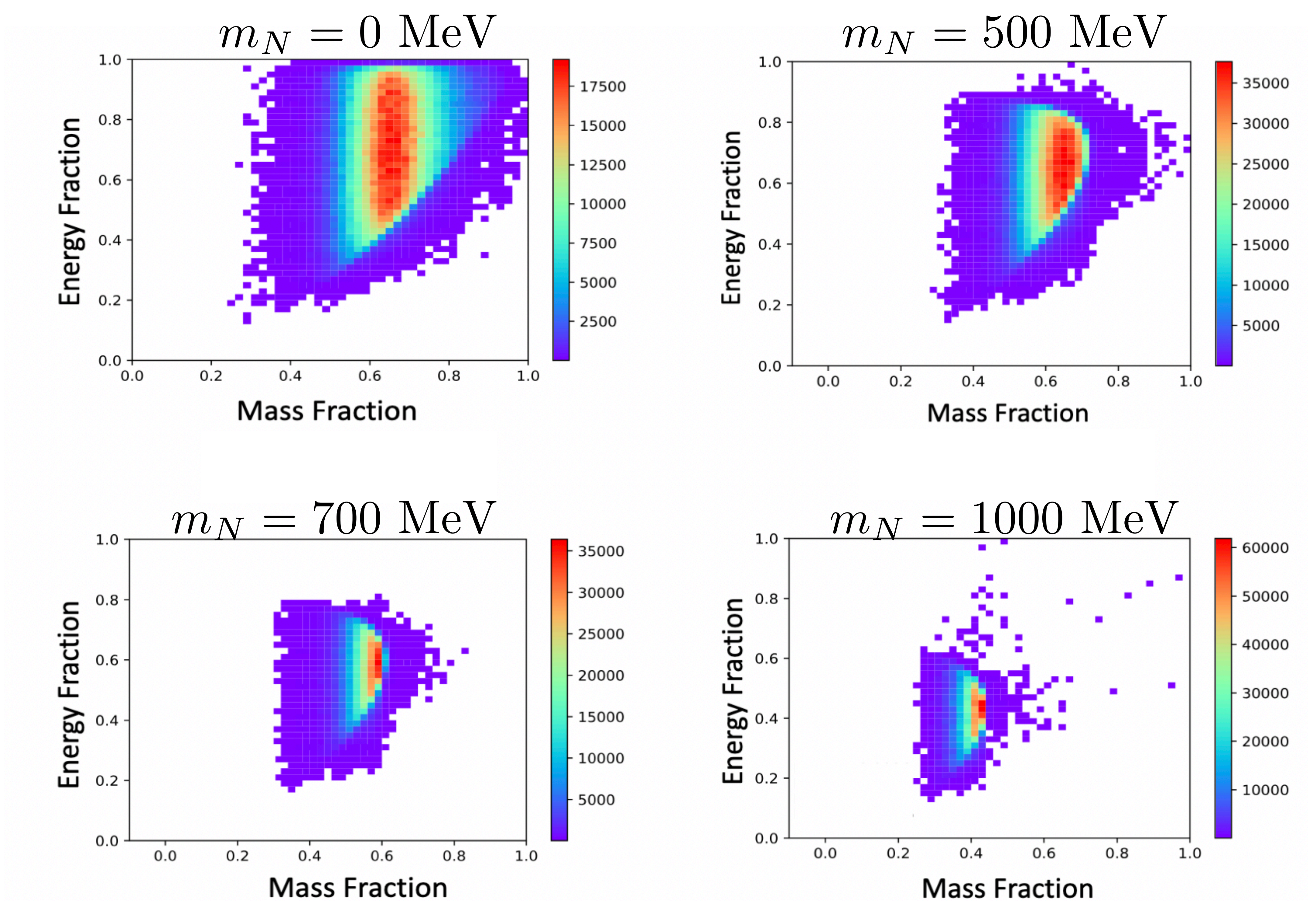
arXiv:1412.3113
arXiv:1709.07001



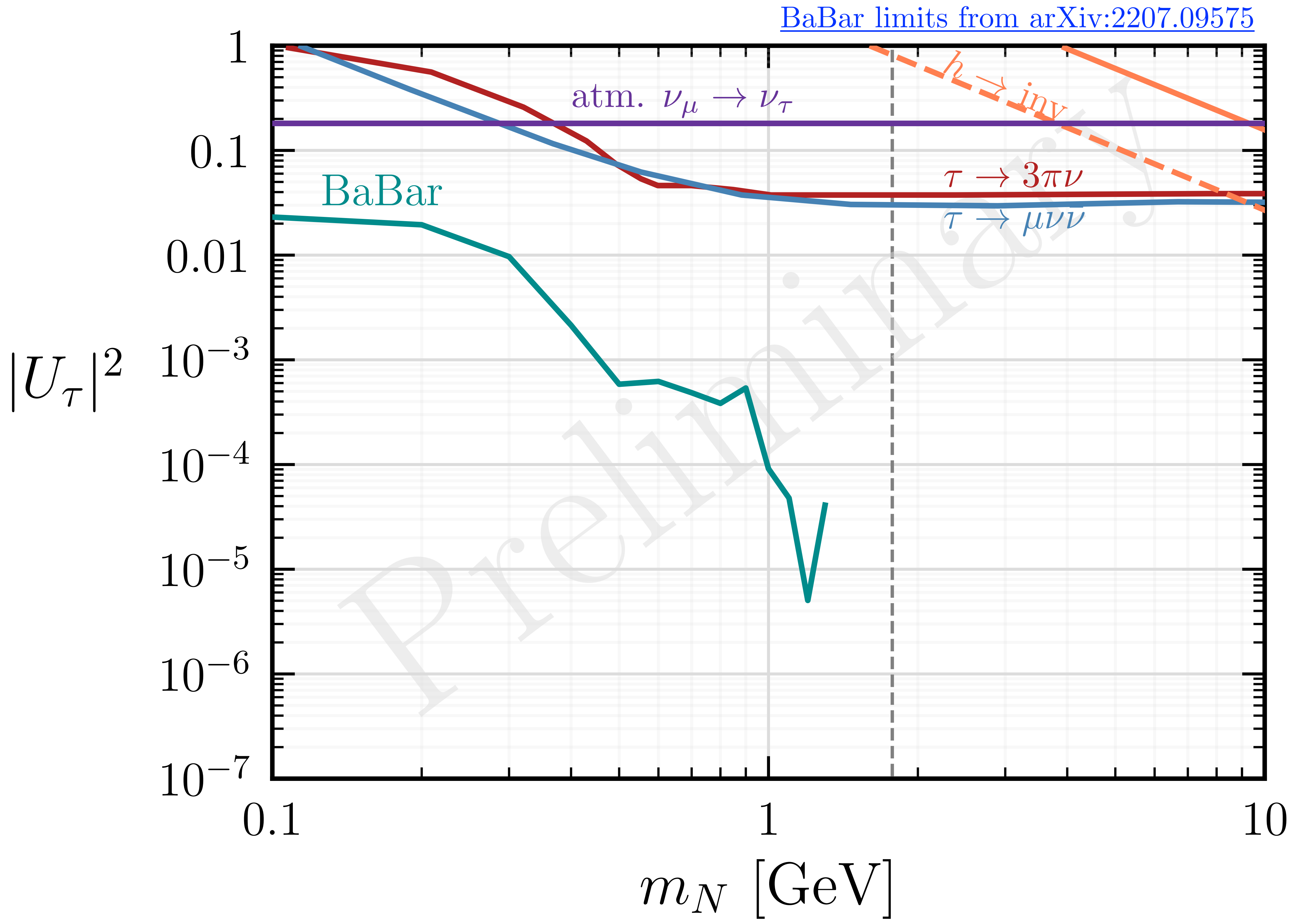
A lot of unexplored parameter space!

Invisible HNL@BaBar

BaBar search for invisible HNLs using *phase space strategy*



BaBar arXiv:2207.09575

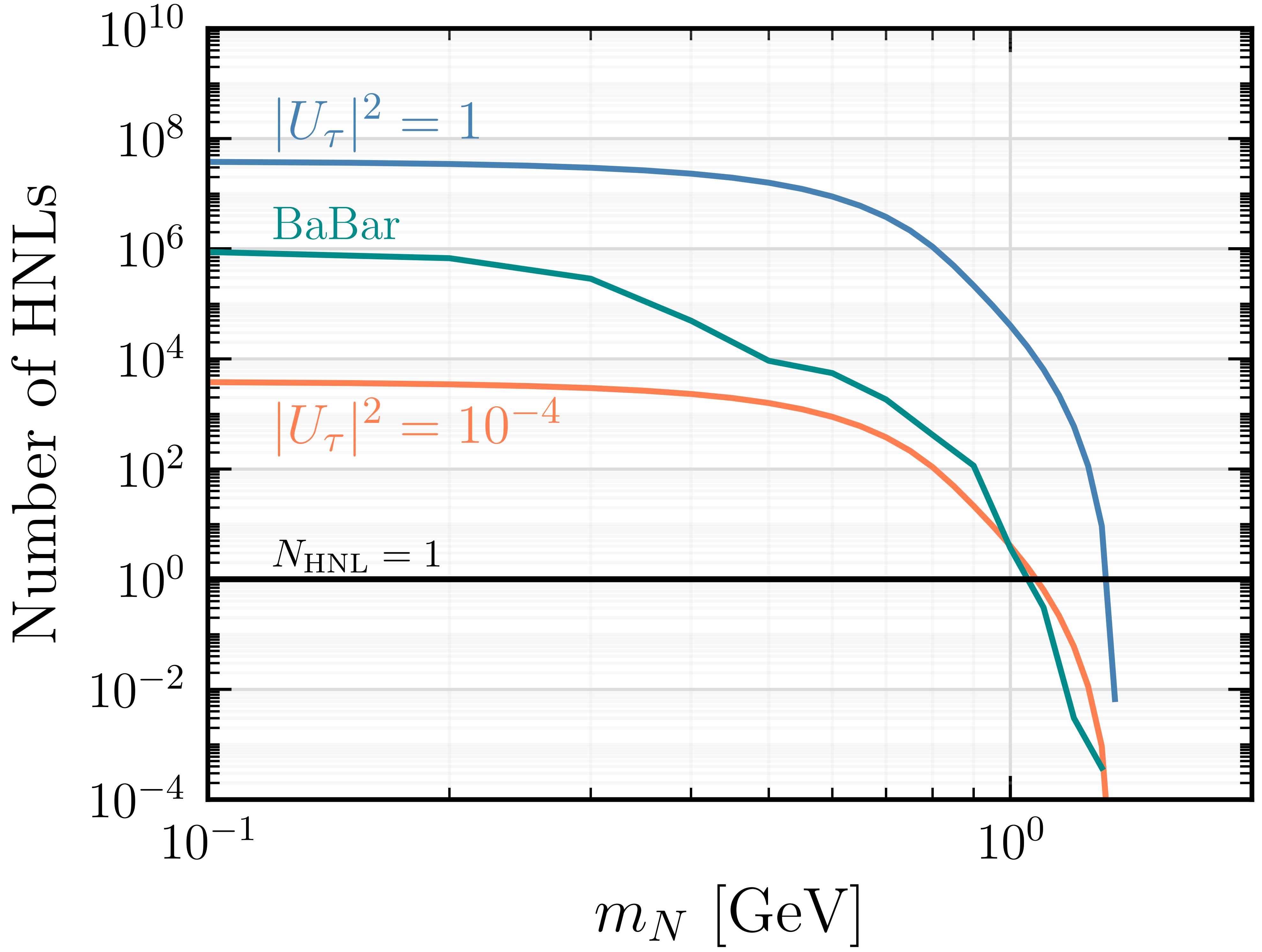


Really, really good bound....

Scrutinizing BaBar Bound

How many HNLs should you expect?

$$N_{\mathrm{HNL}} = N_{\tau\tau} \times \mathrm{BR}(\tau \to \ell\nu\bar{\nu}) \times \mathrm{BR}(\tau \to 3\pi N)$$

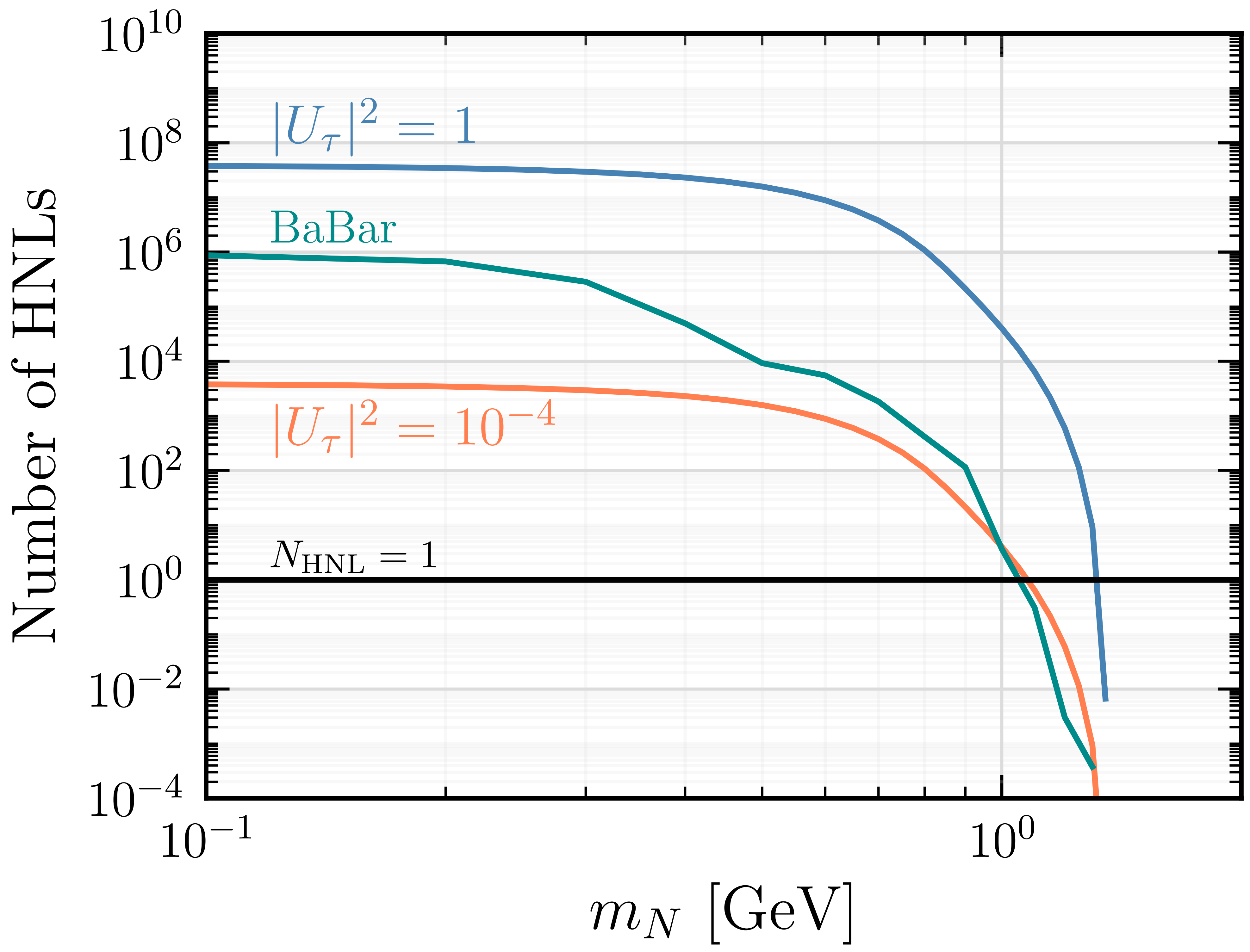


Less than 1 HNL above 1 GeV...?

Scrutinizing BaBar Bound

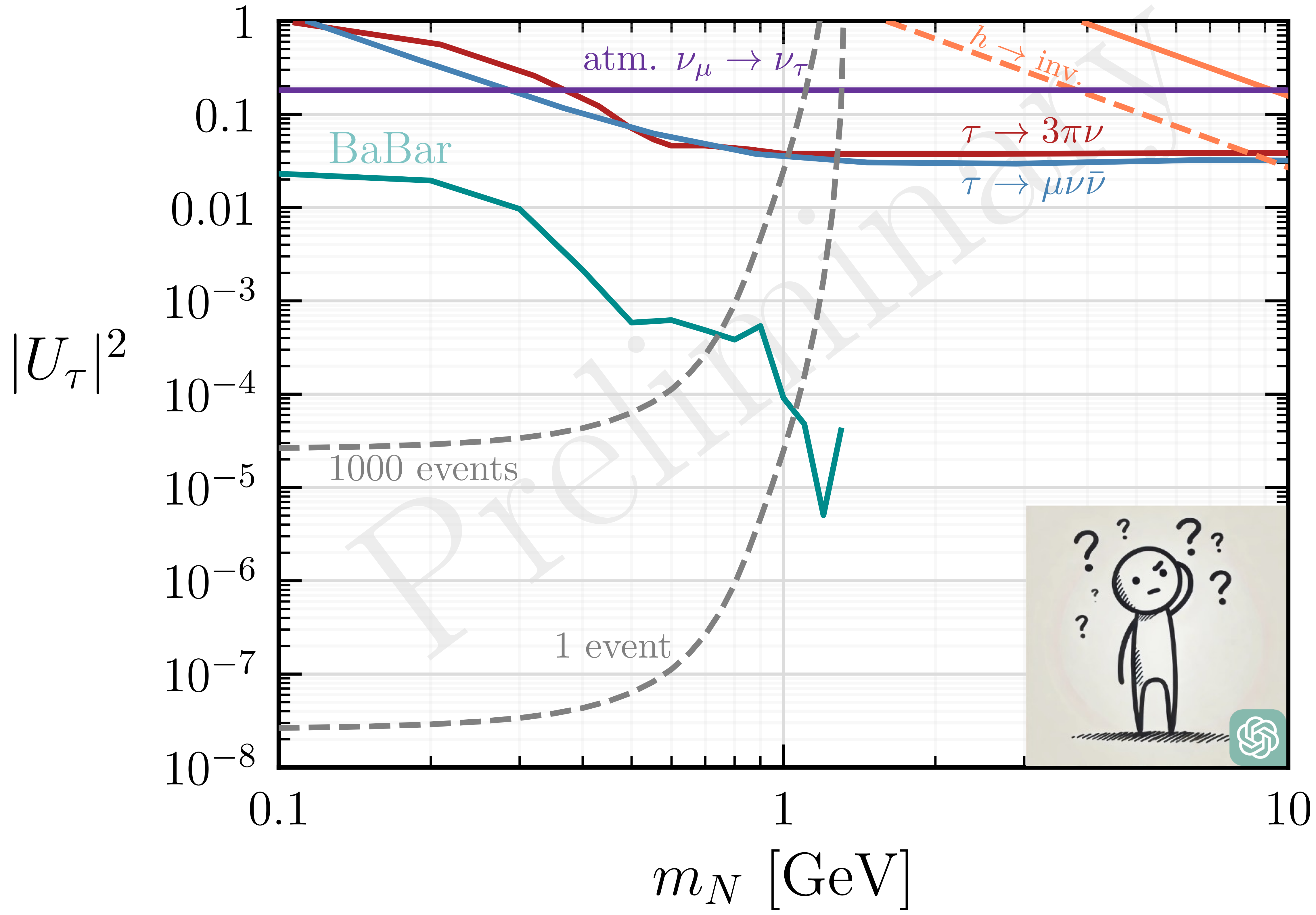
How many HNLs should you expect?

$$N_{\rm HNL} = N_{\tau\tau} \times {\rm BR}(\tau \to \ell\nu\bar{\nu}) \times {\rm BR}(\tau \to 3\pi N)$$



Less than 1 HNL above 1 GeV...?

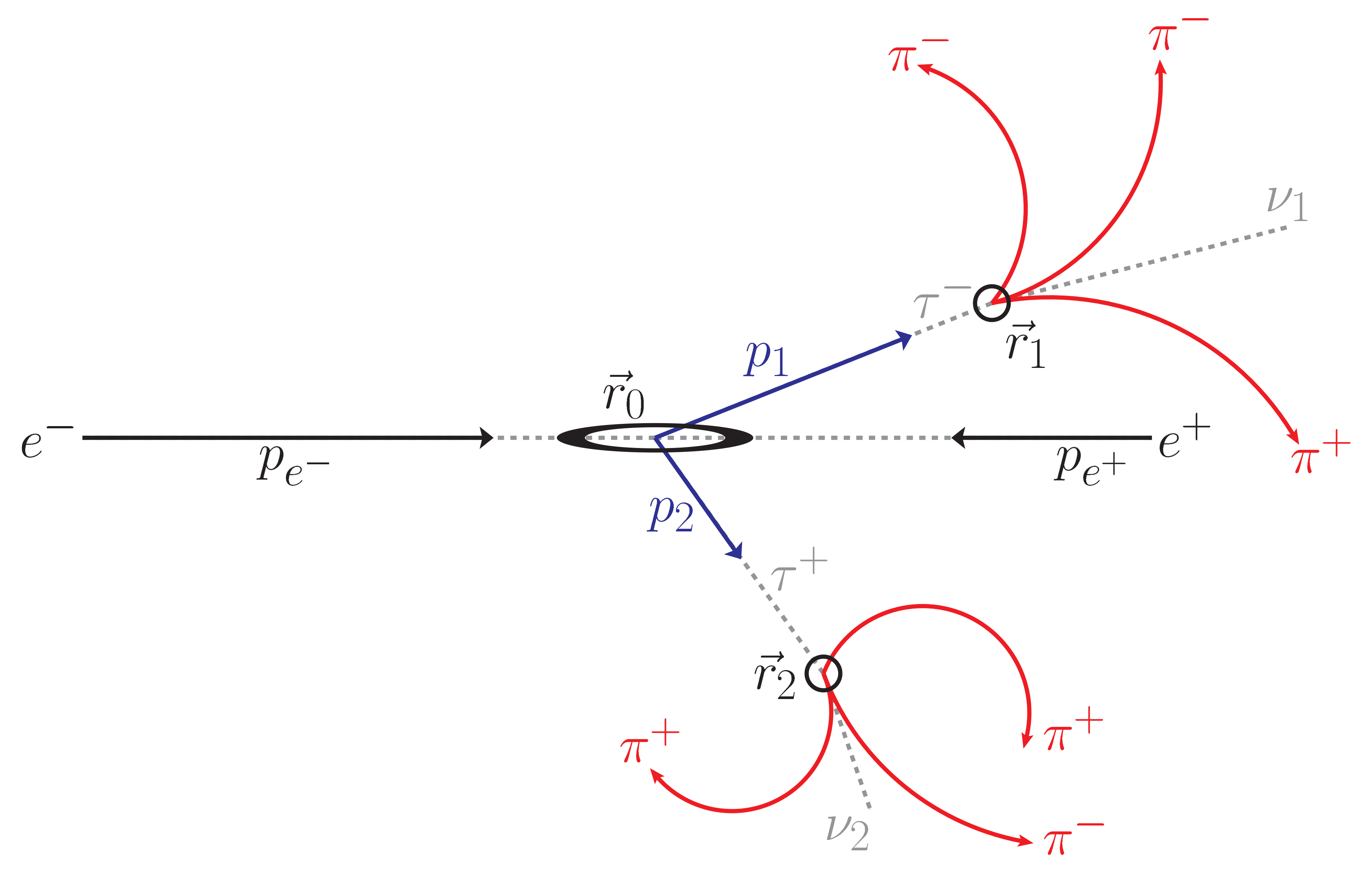
Contours of Number of Events



Can Belle II confirm the BaBar bound?

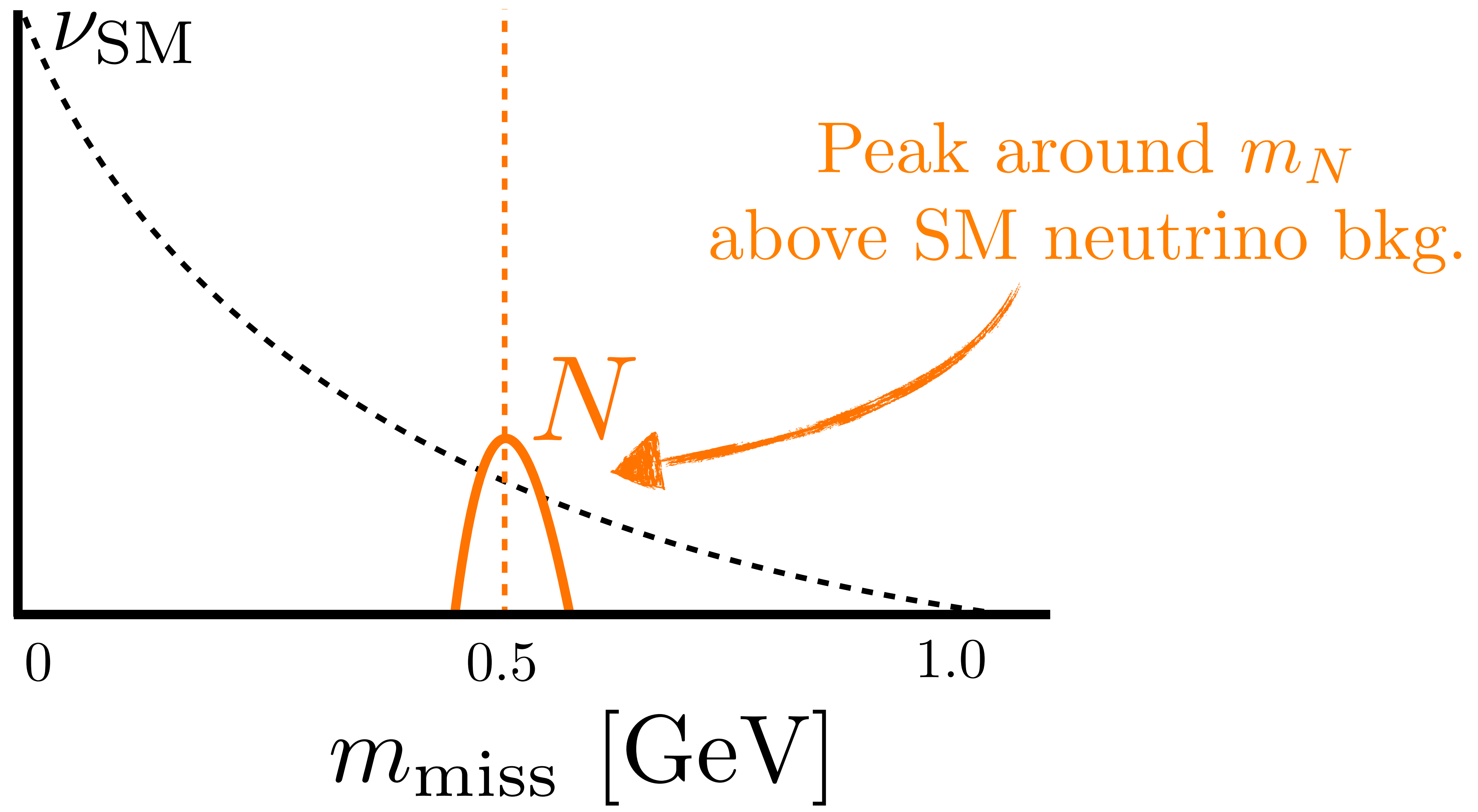
Belle II: Missing Mass Strategy

- N_R decays invisibly → *missing mass search B factories?*



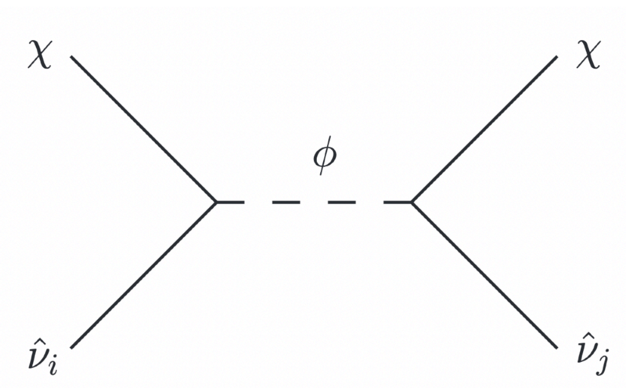
3-prong tau decays for reconstructing tau momentum

$\Longrightarrow$



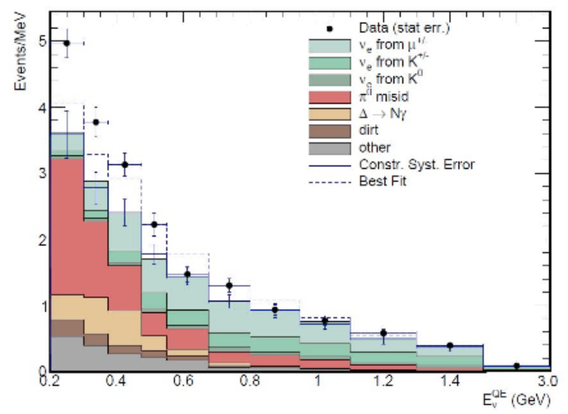
Work in progress W. Altmannshofer, A. Ghalsasi, D. McKeen, and **DT**

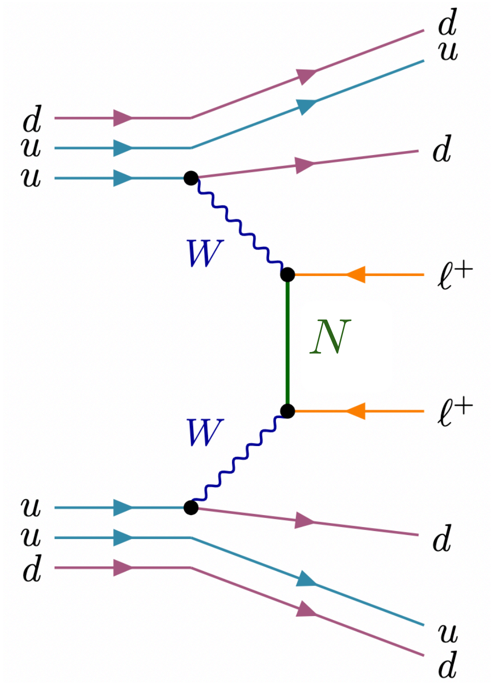
HNL Connections



Dark Matter

Experimental Anomalies

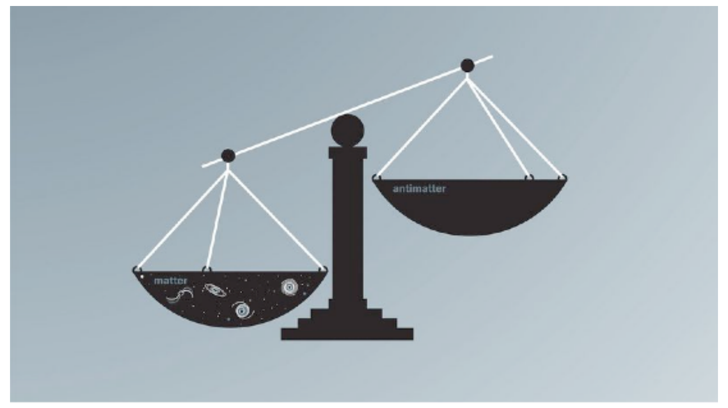




Dirac/Majorana Neutrinos

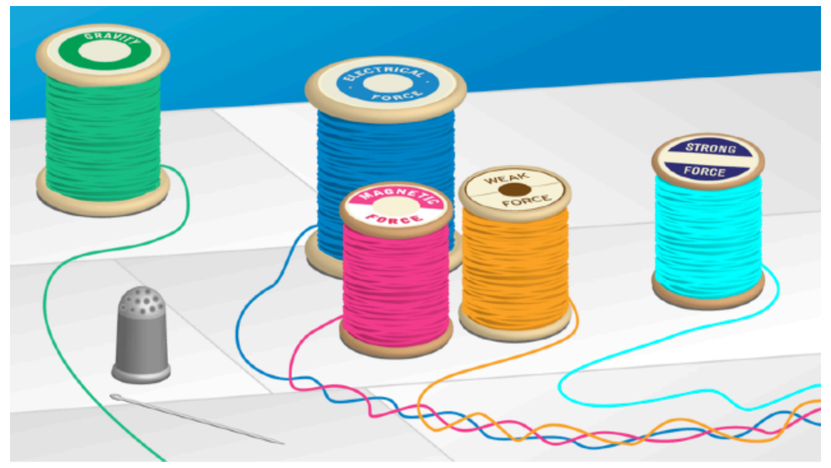
Heavy Neutral Leptons

Matter-Antimatter Asymmetry



Neutrino Masses

Unification of Fundamental Forces



Thanks! Questions?