Probing Lepton Number Violation at Same-Sign Lepton Colliders

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Lepton Number in the Standard Model

Lepton number (L) tracks the *number of leptons in a system*

Leptons: $L = +1$

ν_e	ν_μ	ν_τ
e^-	μ^-	τ^-

Anti-leptons: $L = -1$

$\bar{\nu}_e$	$\bar{\nu}_\mu$	$\bar{\nu}_\tau$
e^+	μ^+	τ^+

Can also define *lepton family numbers* for each generation L_e, L_μ, L_τ so that total lepton number is $L = L_e + L_\mu + L_\tau$

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Can also define *lepton family numbers* for each generation L_e, L_μ, L_τ so that total lepton number is $L = L_e + L_\mu + L_\tau$

Lepton number is observed to be conserved — *accidental symmetry of the SM*

β-decay: $\overset{0}{n} \to \overset{0}{p}\ \overset{+1}{e^-}\ \overset{-1}{\bar{\nu}_e}$

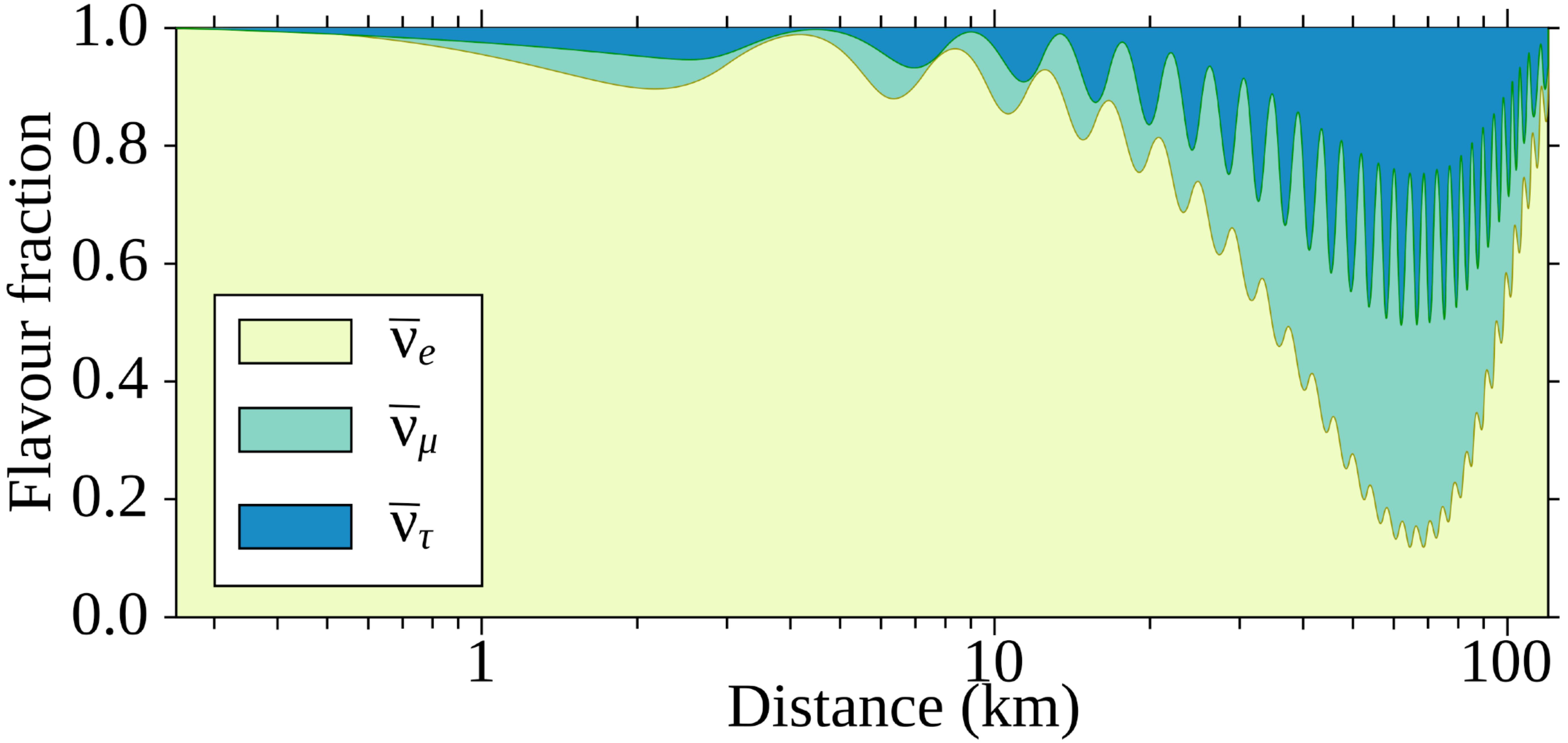
Pion decay: $\overset{0}{\pi^+} \to \overset{-1}{\mu^+}\ \overset{+1}{\nu_\mu}$

Muon decay: $\underset{+1}{\overset{+1}{\mu^-}} \to \underset{+1}{\overset{+1}{e^-}}\ \underset{-1}{\overset{-1}{\bar{\nu}_e}}\ \underset{+1}{\overset{+1}{\nu_\mu}}$

Strong bounds on LNV processes. See PDG — Tests of Conservation Laws

However, there are fundamental reasons for lepton number violation in our universe.

Neutrino Oscillations



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

Neutrino oscillations only possible if *neutrinos have mass!*

Some open questions:

1) Neutrino oscillations violate lepton flavor. Does this imply that lepton number is not conserved?
2) How do neutrinos get mass? Neutrinos are massless in the SM.

Neutrino Masses: The Seesaw Mechanism

- Introduce right-handed neutrinos/sterile neutrinos/heavy neutral leptons N_R that are:
  1) SM singlets — no electric charge, but have lepton number $L = 1$
  2) Majorana fermions — their own anti-particles

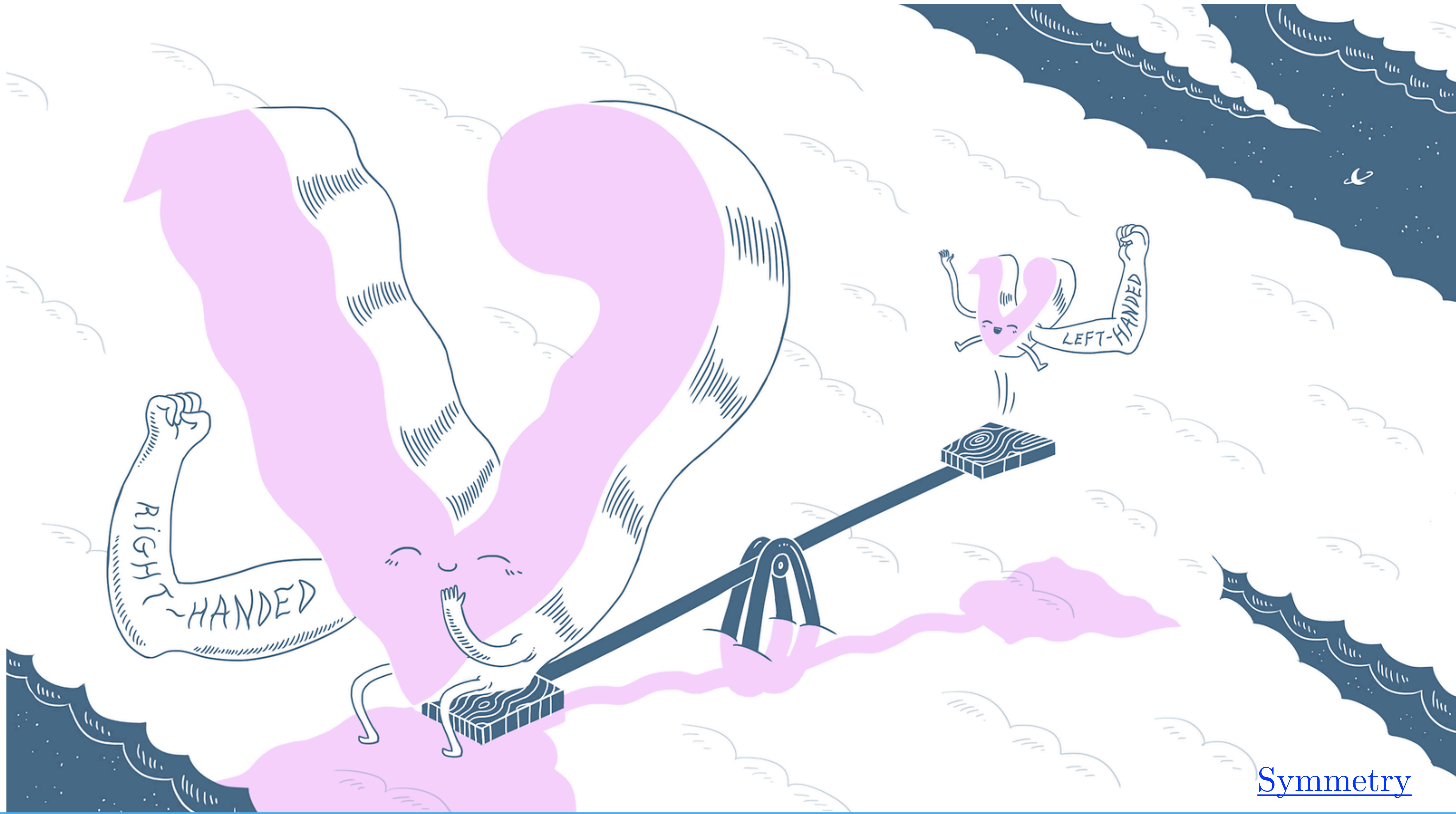
Dirac Mass   Marjorana Mass

$$\mathcal{L} \supset Y \bar{L} \tilde{H} N_R + \frac{1}{2} M_N \bar{N}_R N_R \xrightarrow{\text{EWSB}} m_D \bar{\nu}_L N_R + M_N \bar{N}_R N_R$$

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

Neutrino masses *inversely proportional to Majorana mass*

$$m_\nu \sim 0.1 \text{ eV}, \; Y \sim 1 \implies M_N \sim 10^{14} \text{ GeV}$$



Symmetry

HNLs and Lepton Number Violation

Marjorana Mass

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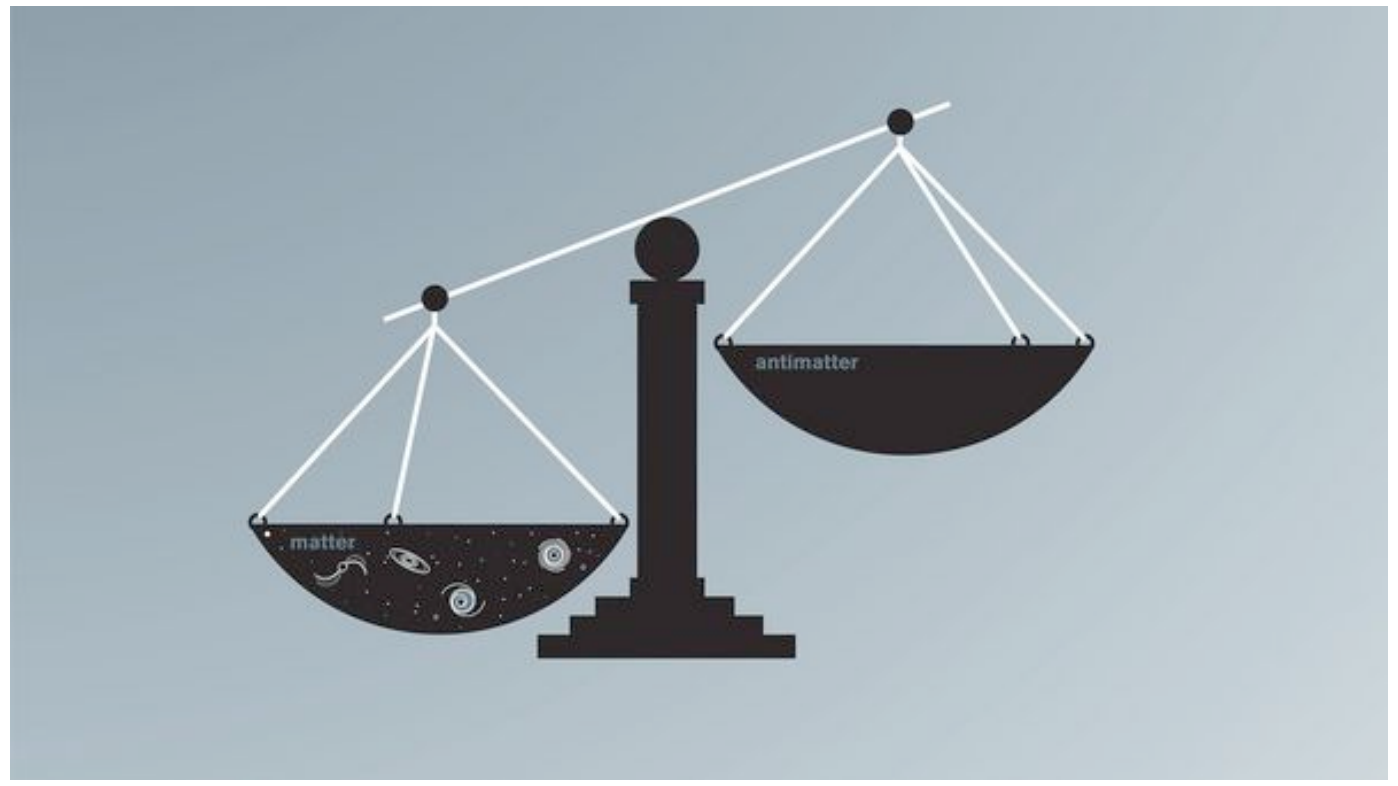
Violates Lepton Number!

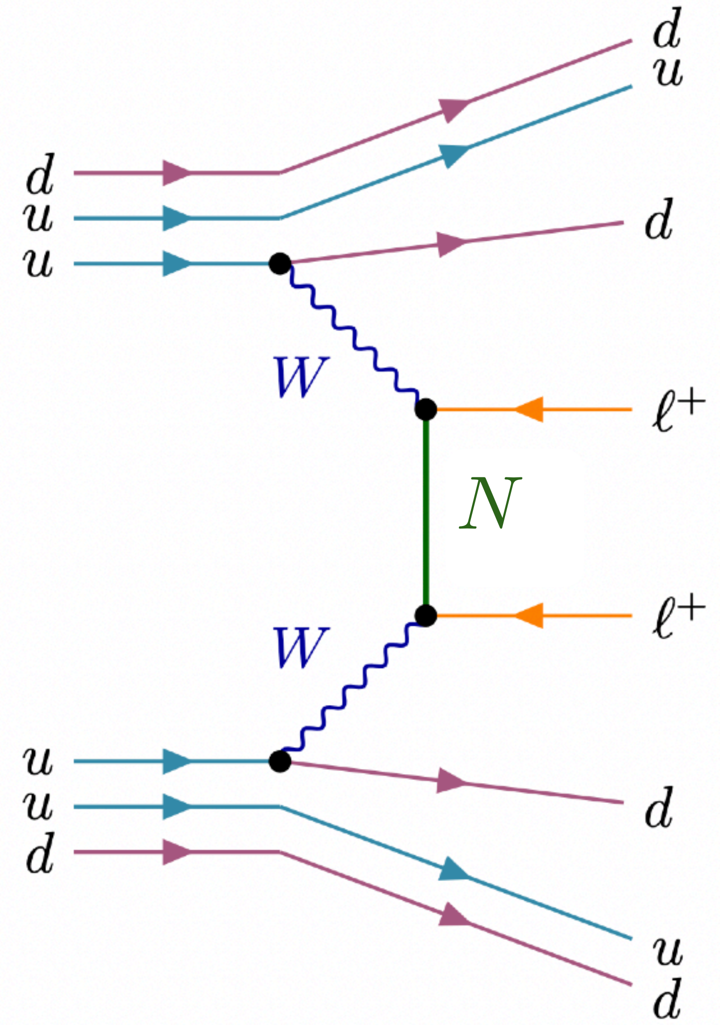
Implications of LNV by heavy neutral leptons:

1) Matter-Antimatter Asymmetry

$$\Gamma(N \to \ell) \neq \Gamma(N \to \bar{\ell})$$



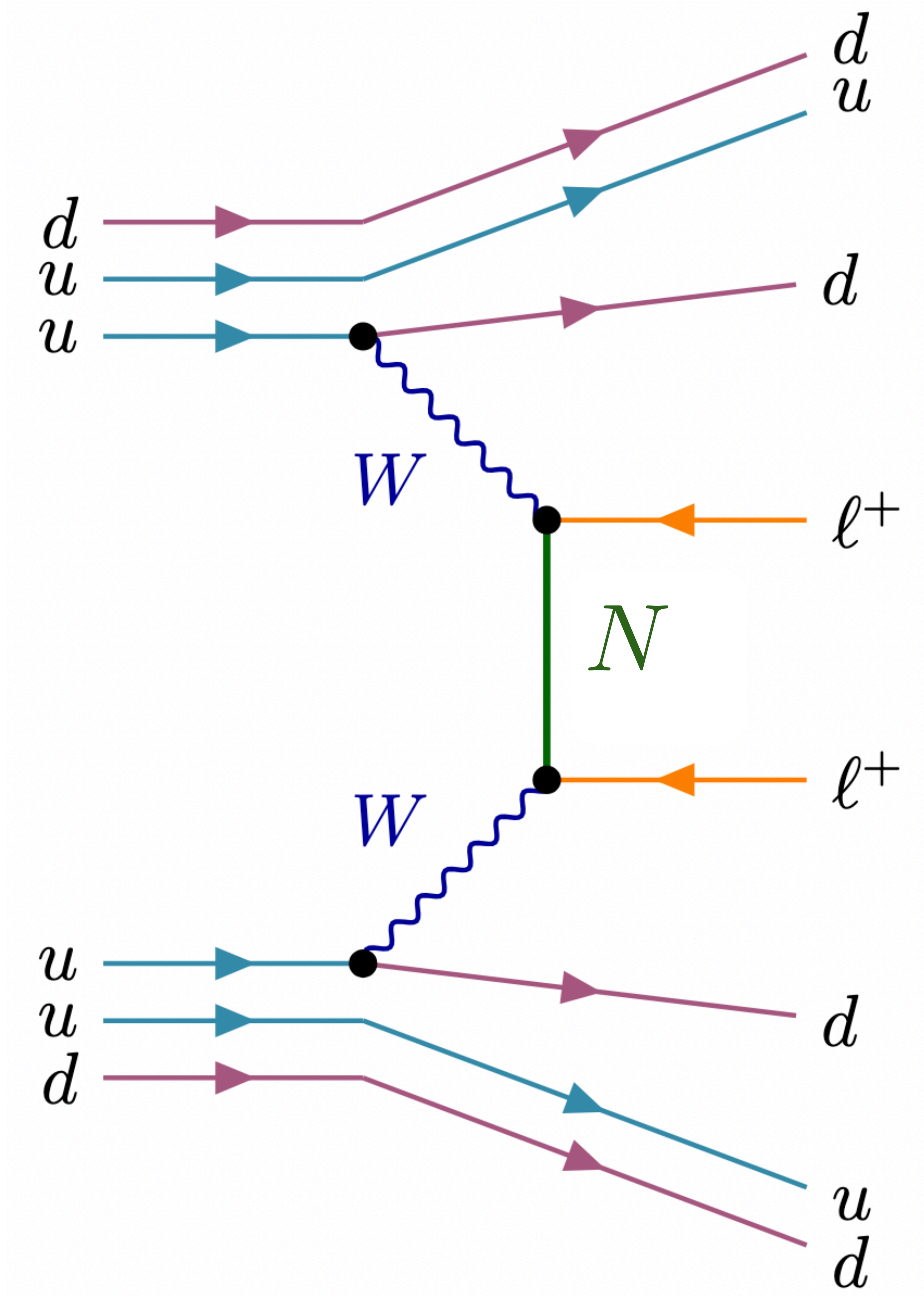
2) Neutrinoless Double Beta Decay



Connected to the question of whether neutrinos are Dirac or Majorana fermions

Neutrinoless Double Beta Decay

- **Observation of $0\nu\beta\beta$ would be clear evidence of LNV and physics beyond-the-SM!**
- Receives contributions from Majorana HNLs



$$\left(T^{0\nu}_{1/2}\right)^{-1} \sim \underbrace{G_{0\nu} g_A^4 m_p^2 |\mathcal{M}_N^{0\nu}|^2}_{\text{Nuclear physics stuff}} \left| \sum_{i=1}^{3} \underbrace{\frac{U_{ei}^2 m_i}{\langle \mathbf{p^2} \rangle}}_{\text{SM neutrino}} + \underbrace{\frac{V_{eN}^2}{M_N}}_{\text{HNL}} \right|^2$$

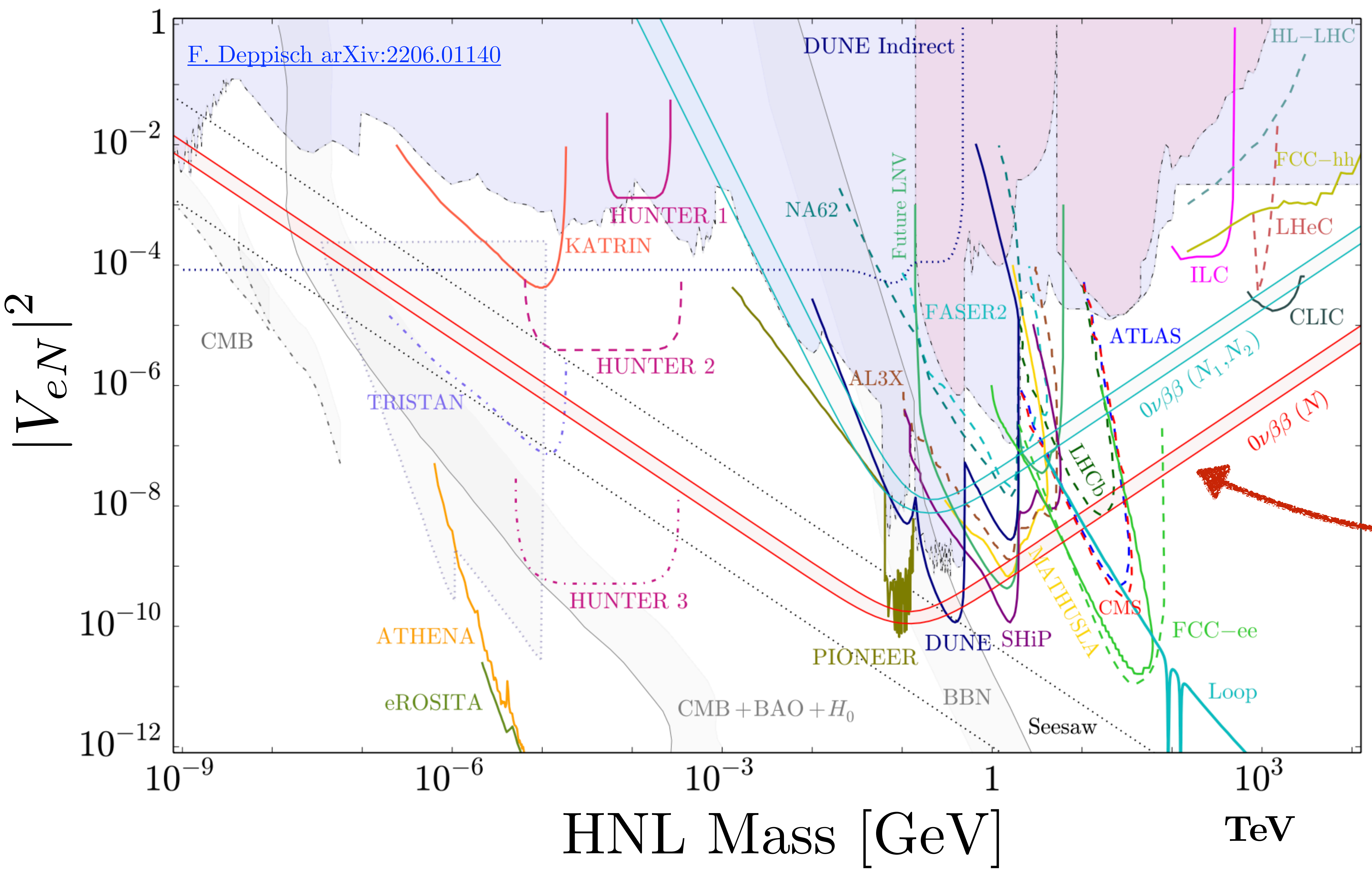
Existing Bounds on $0\nu\beta\beta$

Experiment	Isotope	$T^{0\nu}_{1/2}/10^{25}$yr (90%C.L.)
GERDA	^{76}Ge	18.0
MAJORANA	^{76}Ge	8.30
CUORE	^{130}Te	2.61
KamLAND-Zen	^{136}Xe	22.86
EXO-200	^{136}Xe	3.50

arXiv:2404.12316

Neutrinoless Double Beta Decay

Electron-Mixed HNL

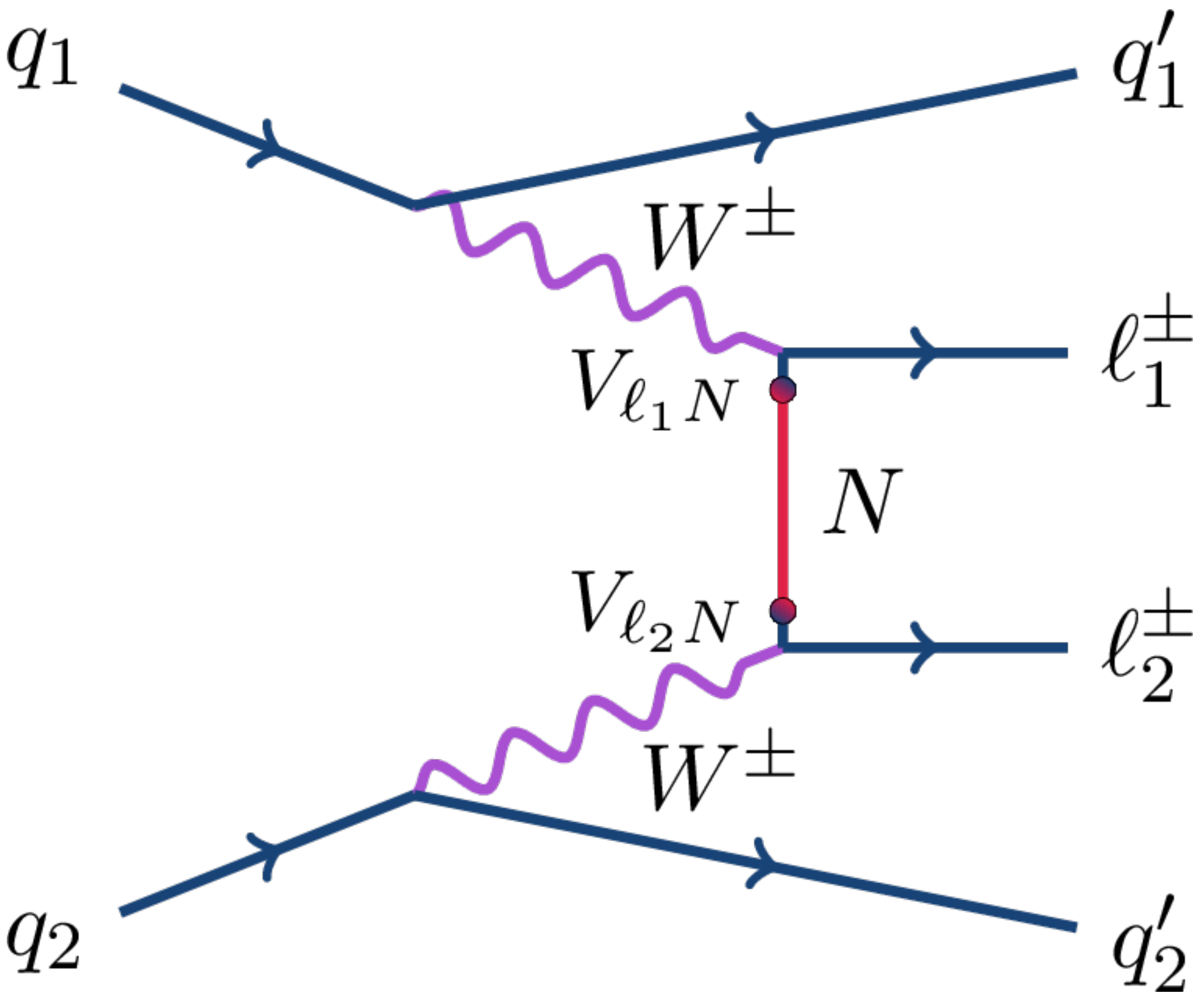


Probe of electron-mixed HNLs beyond the TeV-scale!

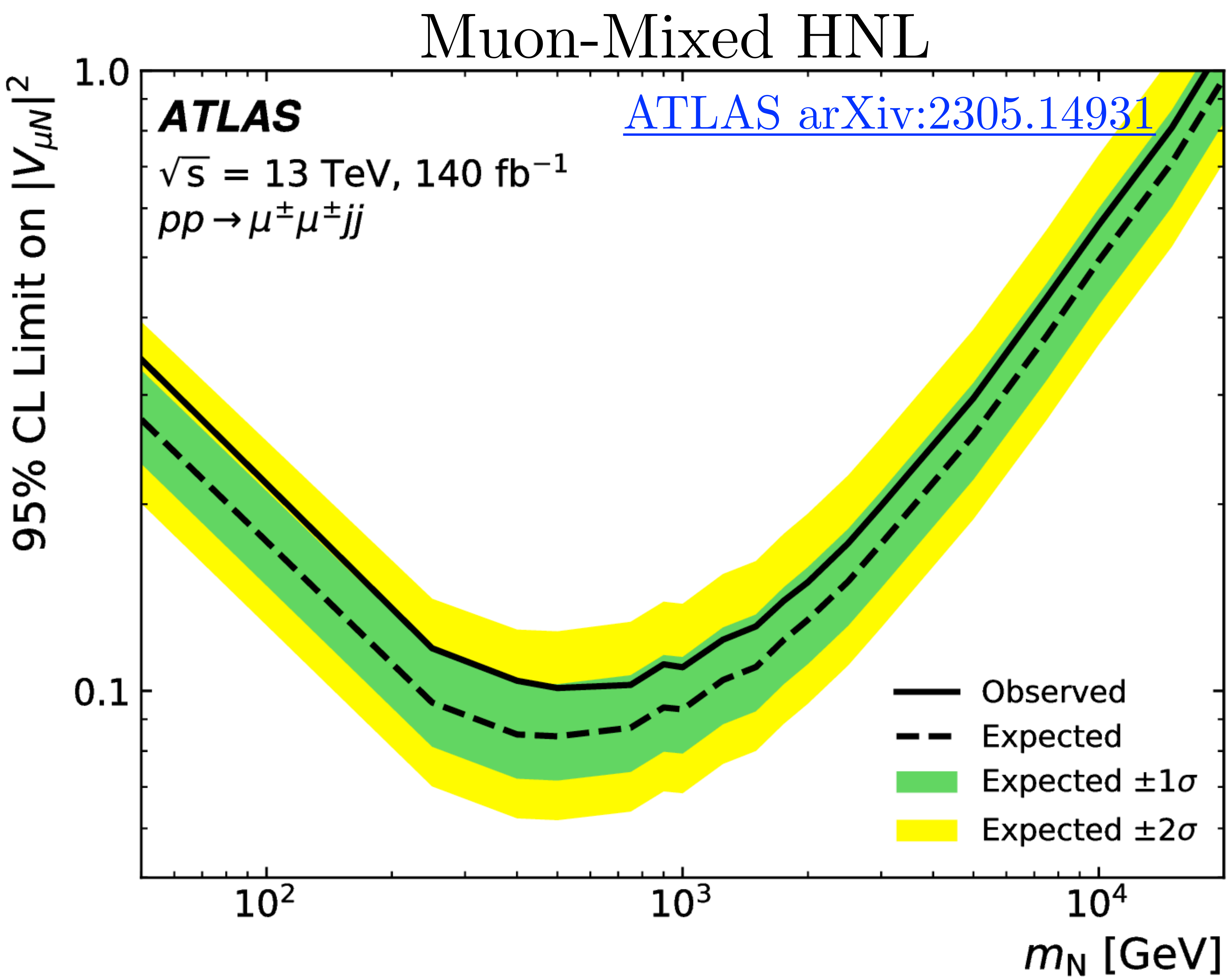
Only for electron-mixing. *What about muon- or tau-mixed HNLs?*

Same-Sign Leptons at the LHC

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

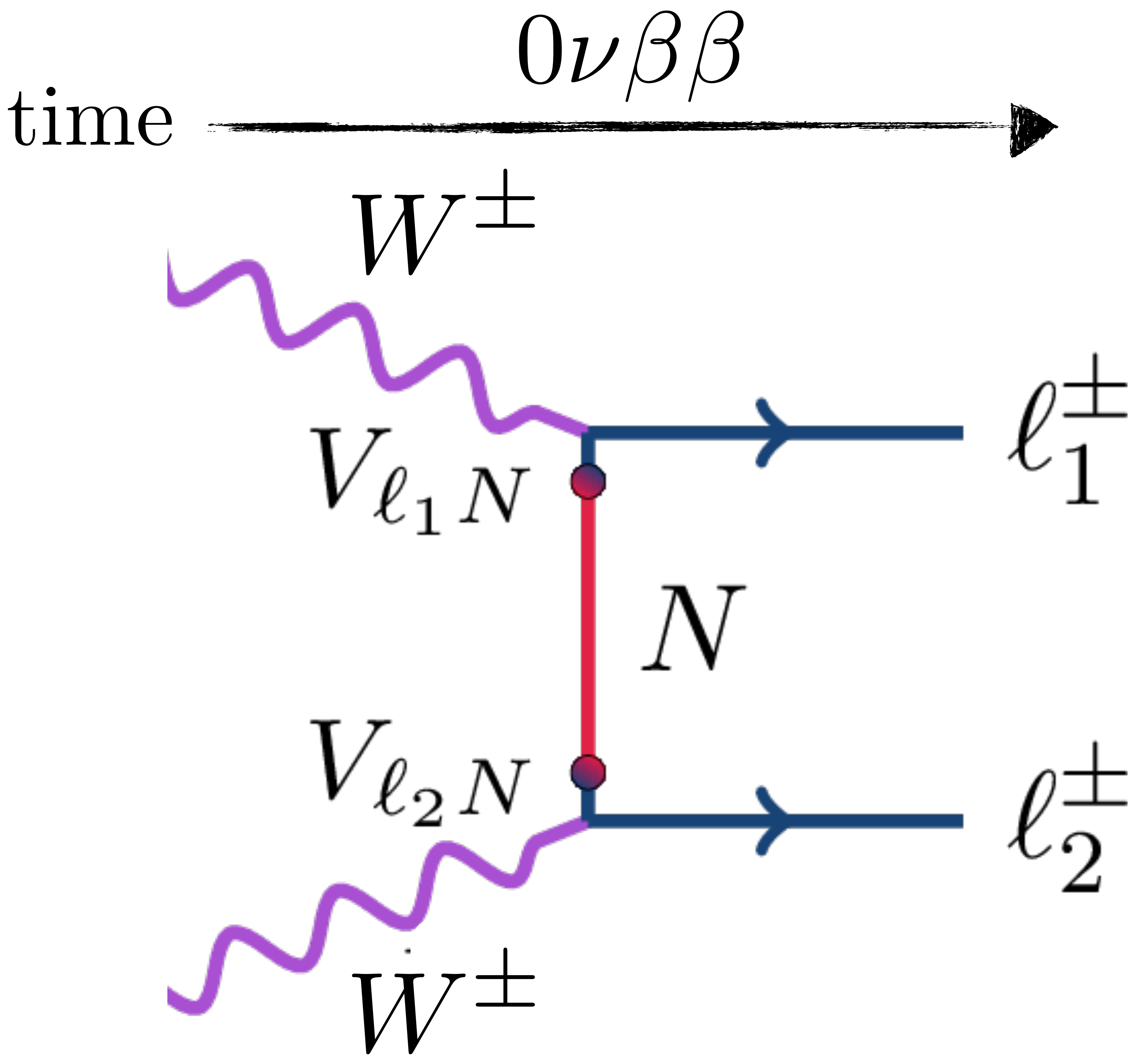


CMS arXiv:2206.08956



Not as sensitive as $0\nu\beta\beta$

HNLs at Same-Sign Lepton Colliders



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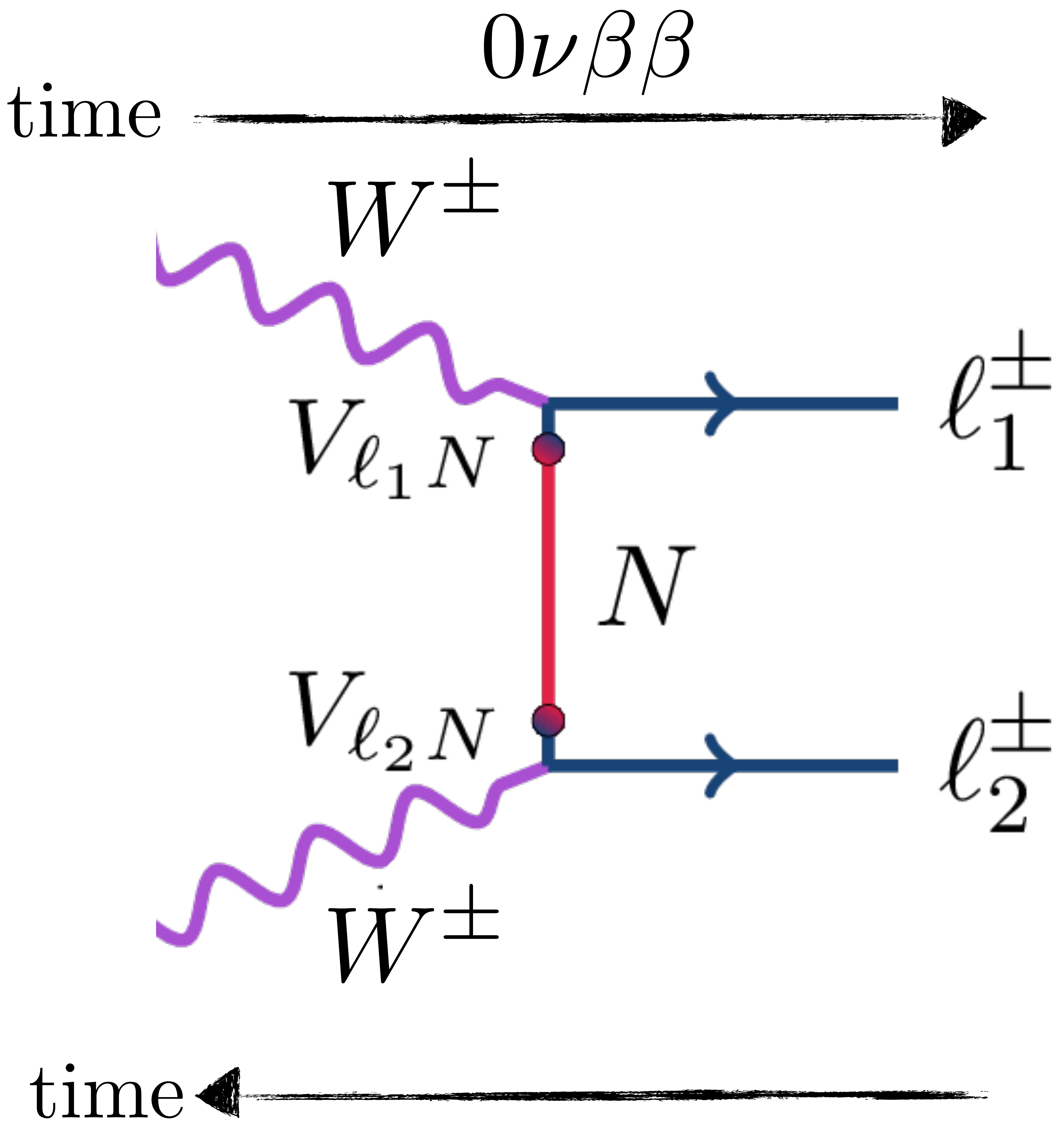

Same-Sign Lepton Colliders

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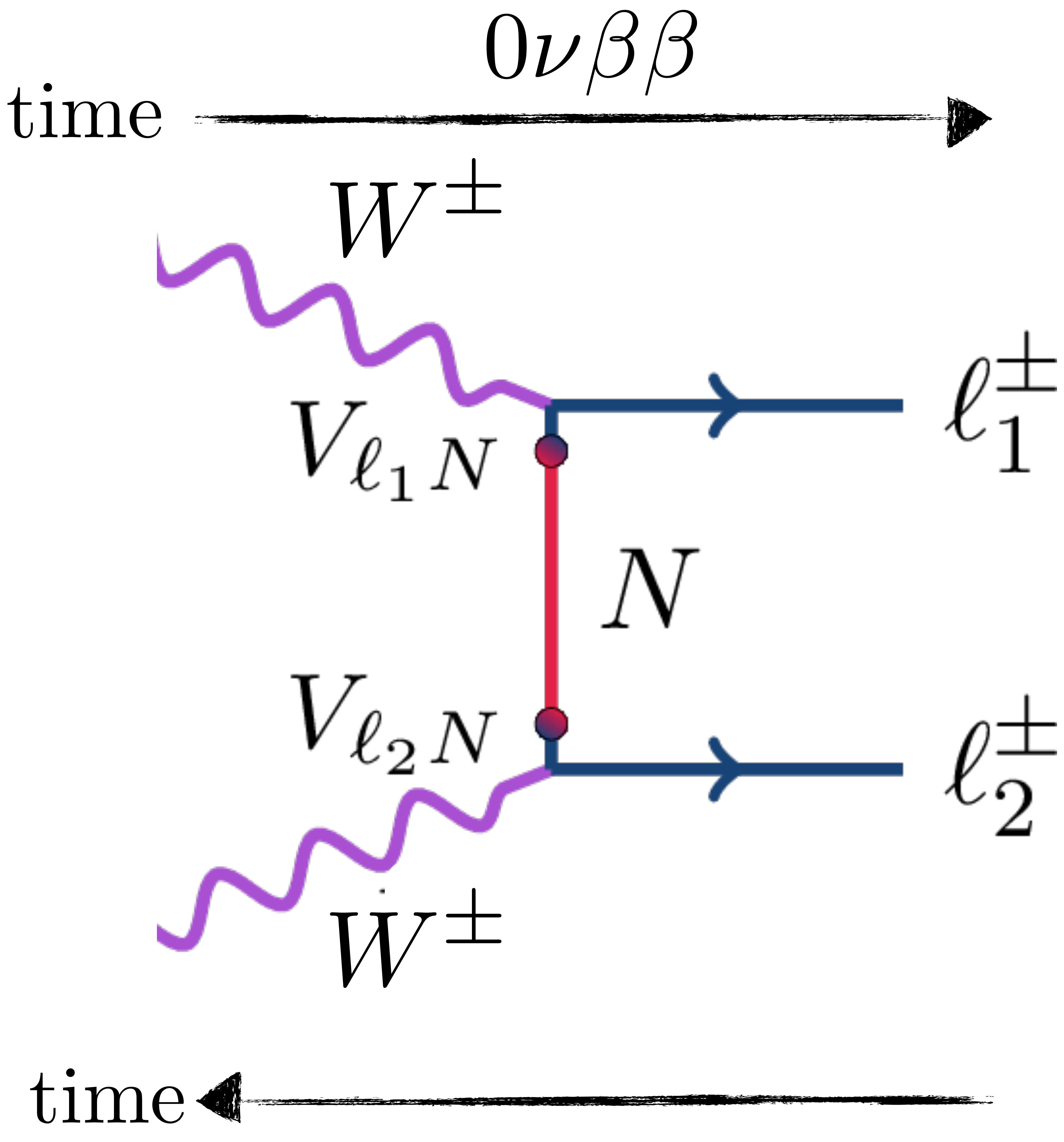


Same-Sign Lepton Colliders

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

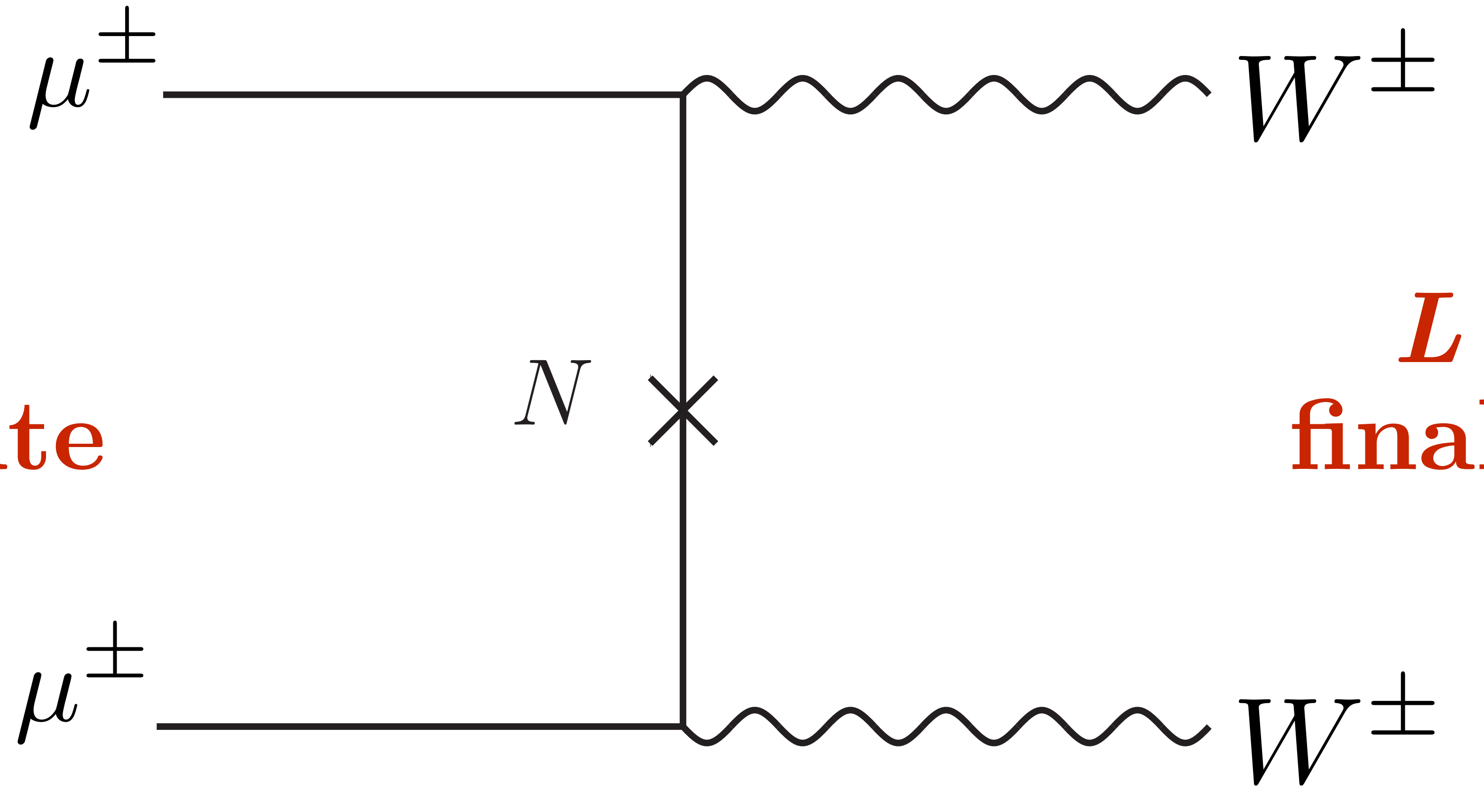
Linear e^+e^- colliders have the potential to also be used to realise e^-e^- collisions. Some preliminary thoughts about the realisation of this at CLIC are presented. Luminosity and some background estimates are also given.

CLIC Note 512 (2002)

Advantages of Same-Sign Lepton Collider

HNL Signal

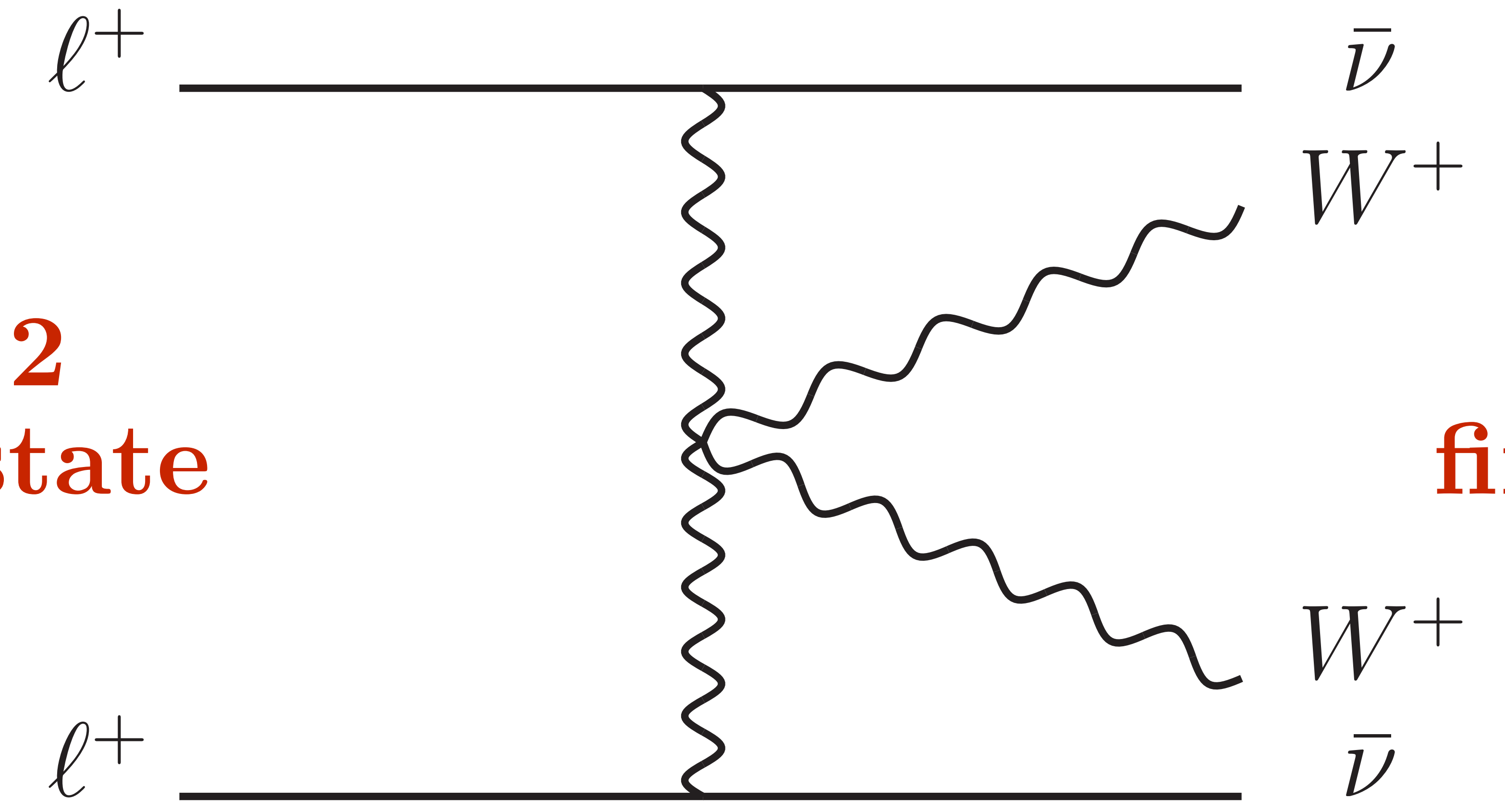
$L = 2$
initial state



$L = 0$
final state

SM Background

$L = 2$
initial state

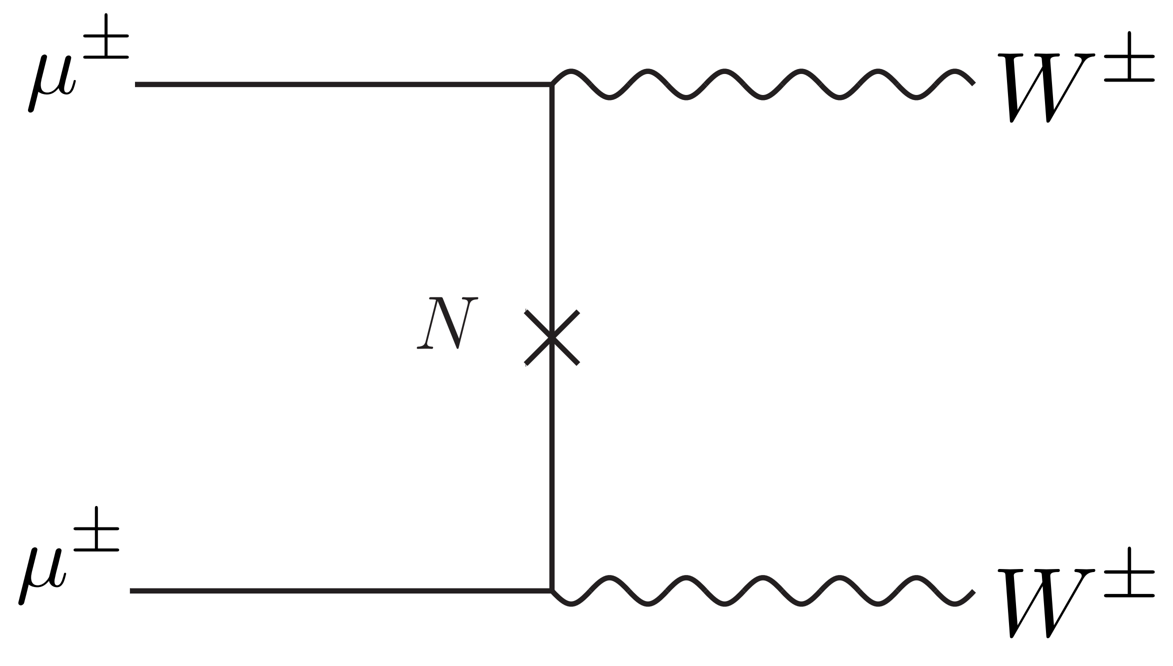


$L = 2$
final state

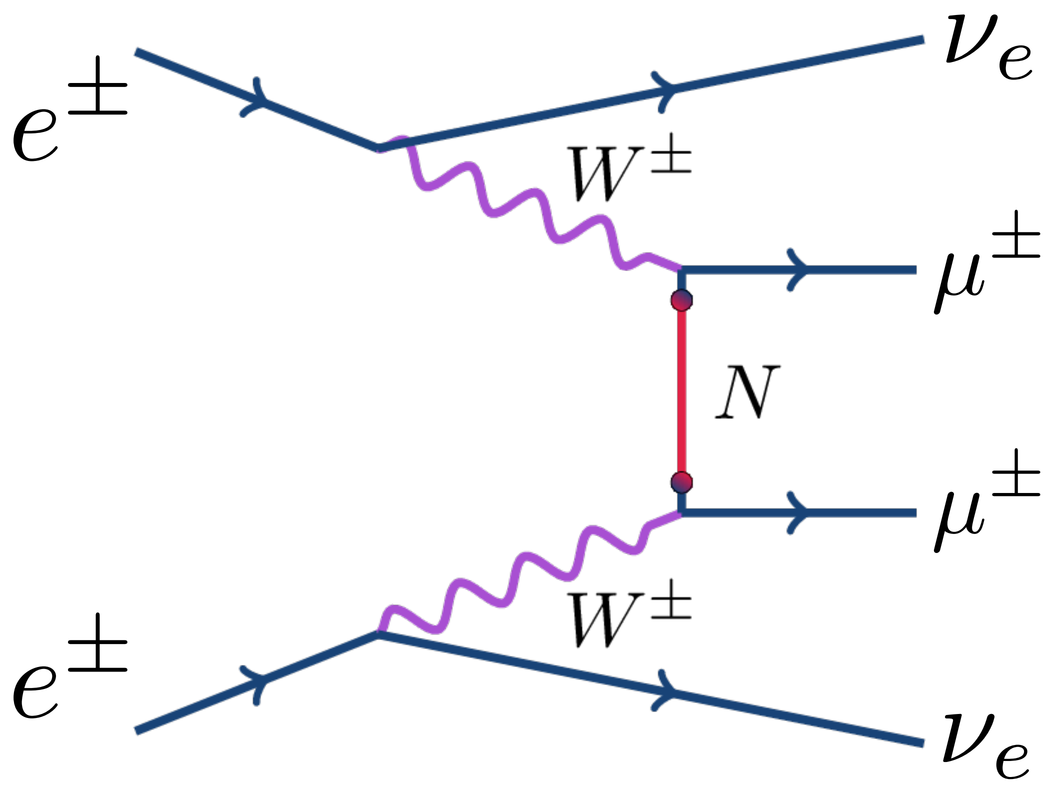
$\Delta L = 2$ *transition is not allowed in the SM.* Background processes are required to have additional neutrinos in the final state and are highly suppressed. This essentially a zero background search!

HNLs at Same-Sign Lepton Colliders

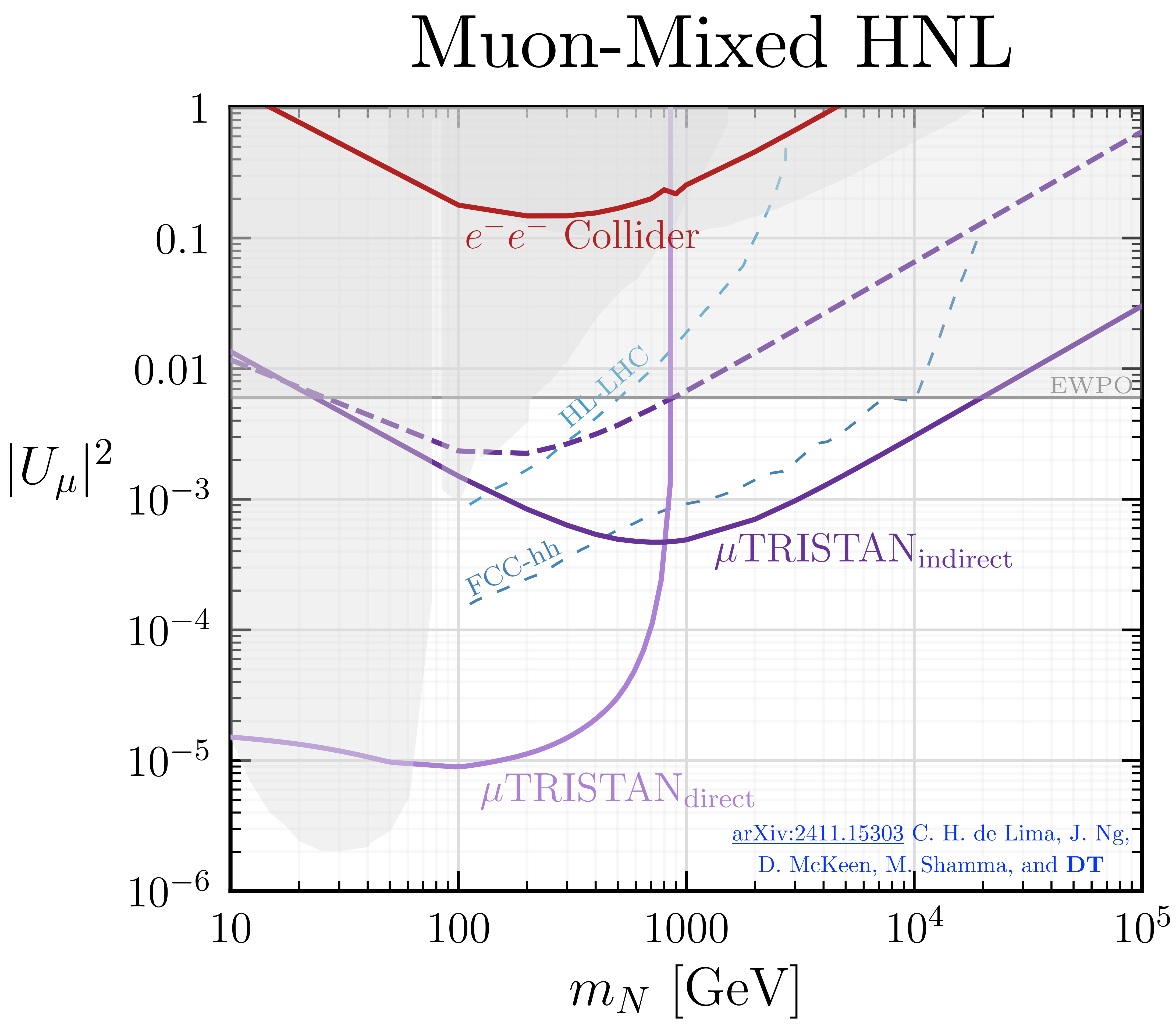
$W^\pm$ Pair Production



$W^\pm$ Boson Scattering



Probe HNLs with a different flavor initial state lepton!



Dashed: $\sqrt{s} = 250$ GeV, Solid: $\sqrt{s} = 1$ TeV

HNLs at Same-Sign Lepton Colliders

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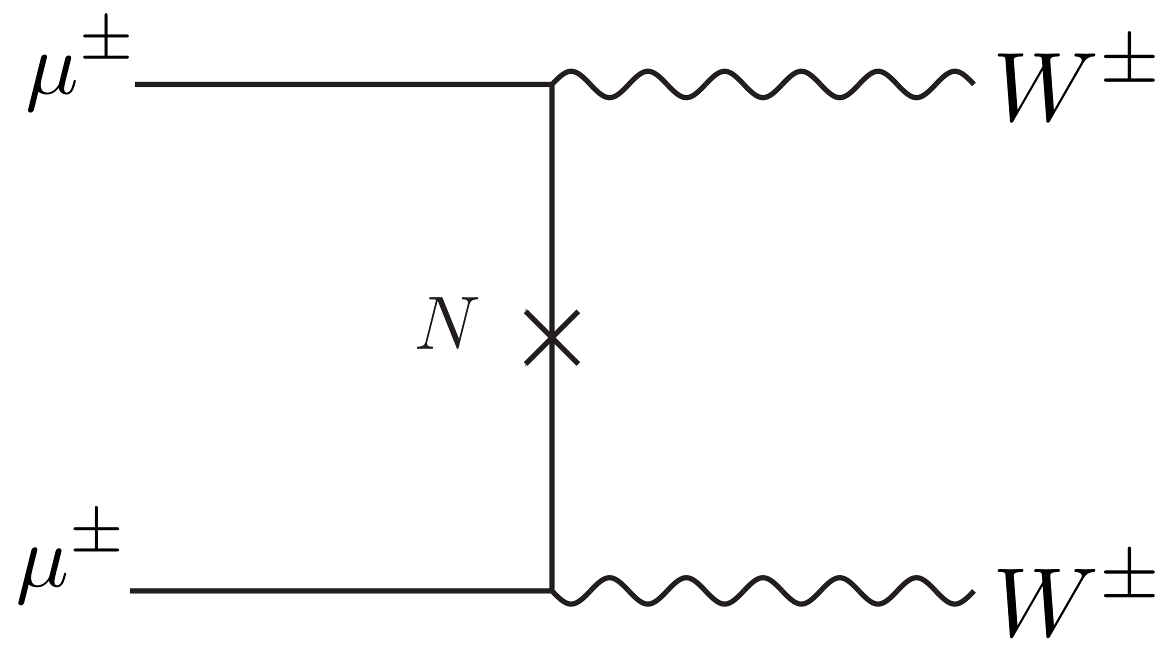

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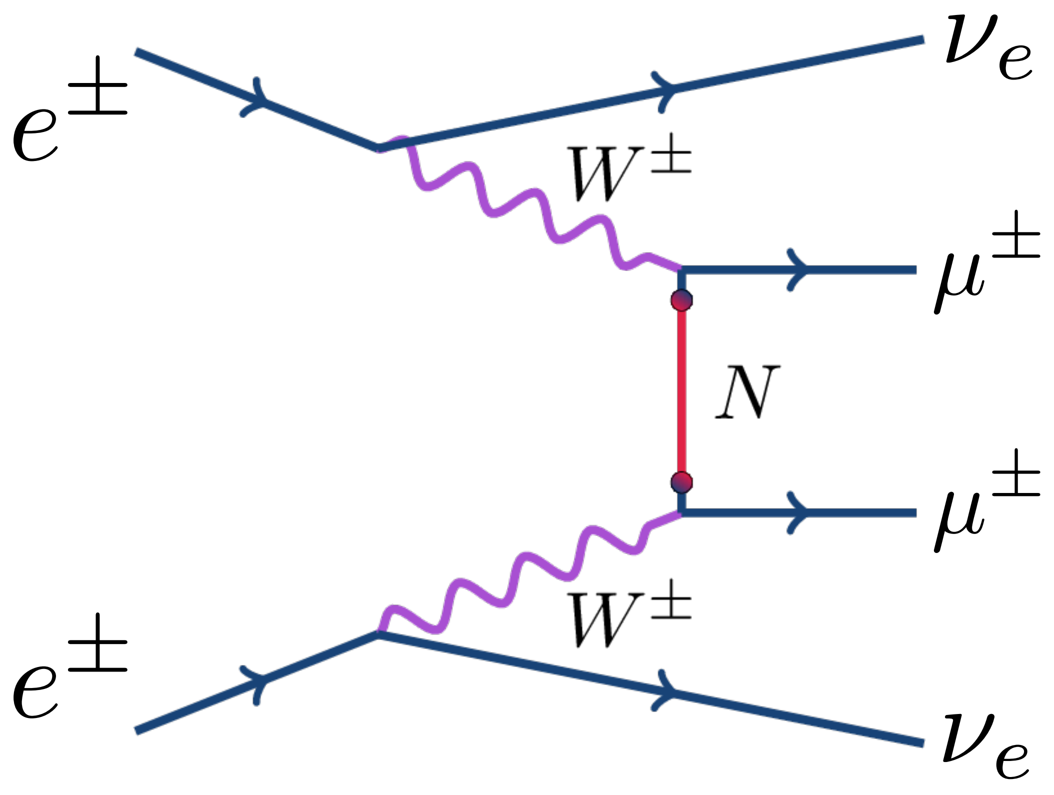

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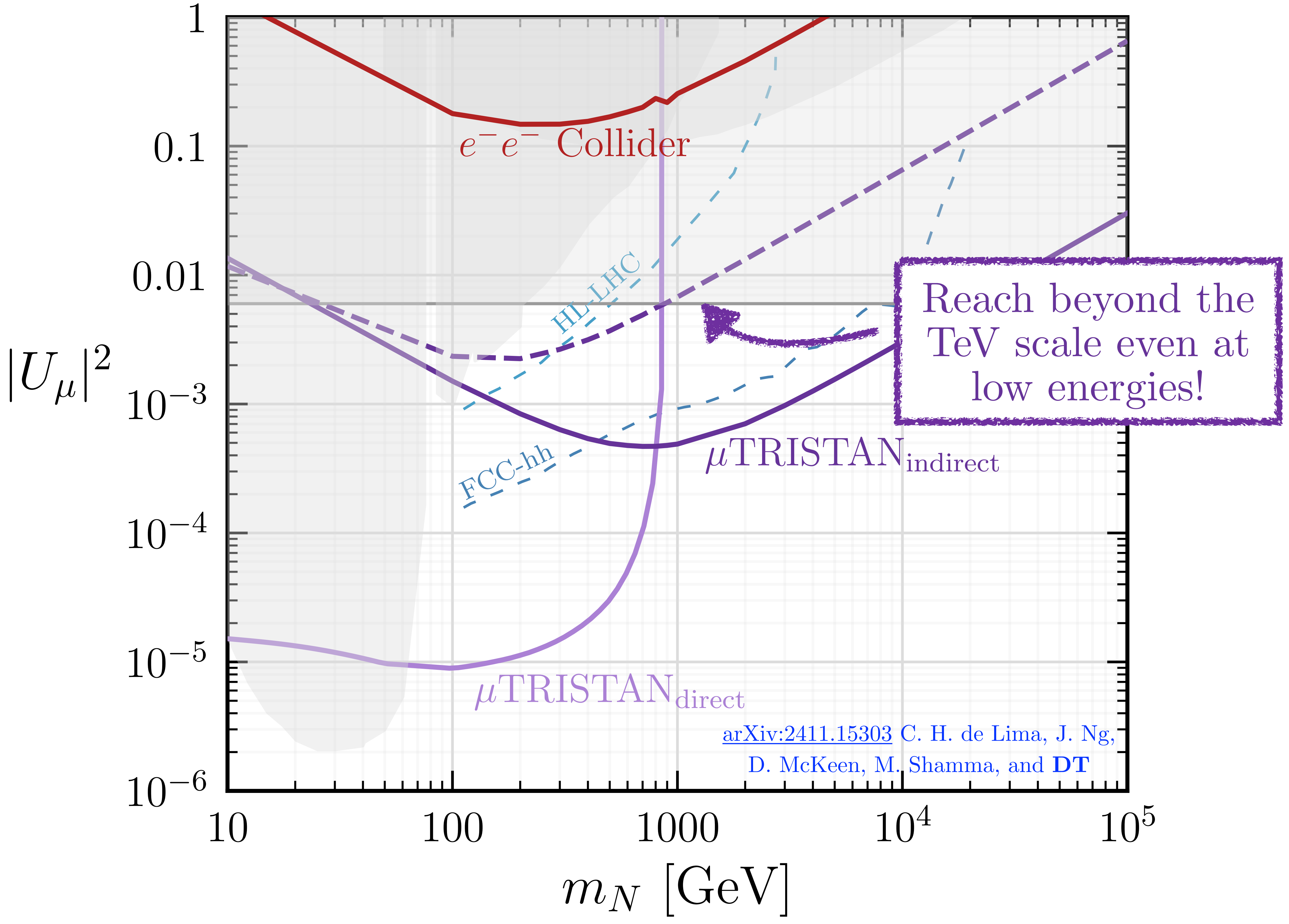
Muon-Mixed HNL



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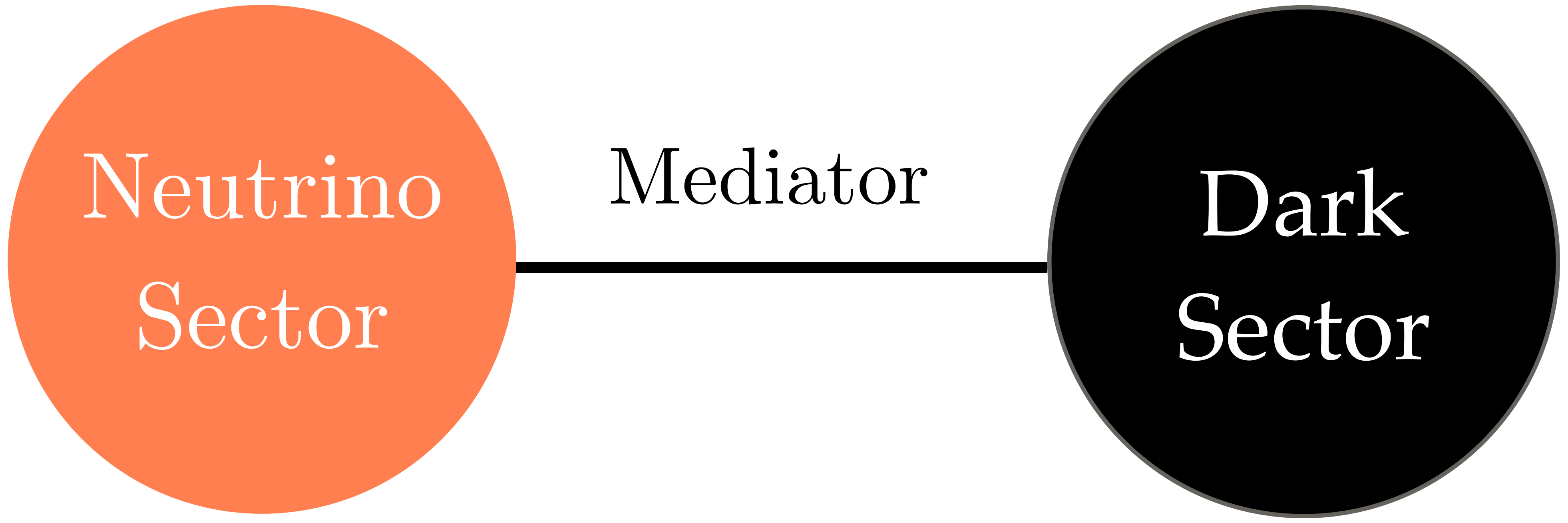
Lepton Number Violation and Dark Matter



Introduce a new scalar that

interacts only with the SM neutrinos

$$\mathcal{L} \supset \frac{1}{2}\lambda_{\alpha\beta}\, \boxed{\nu_\alpha \nu_\beta}\, \phi$$

Neutrino state has $L = 2$

$\Rightarrow \phi$ must have $L = -2$

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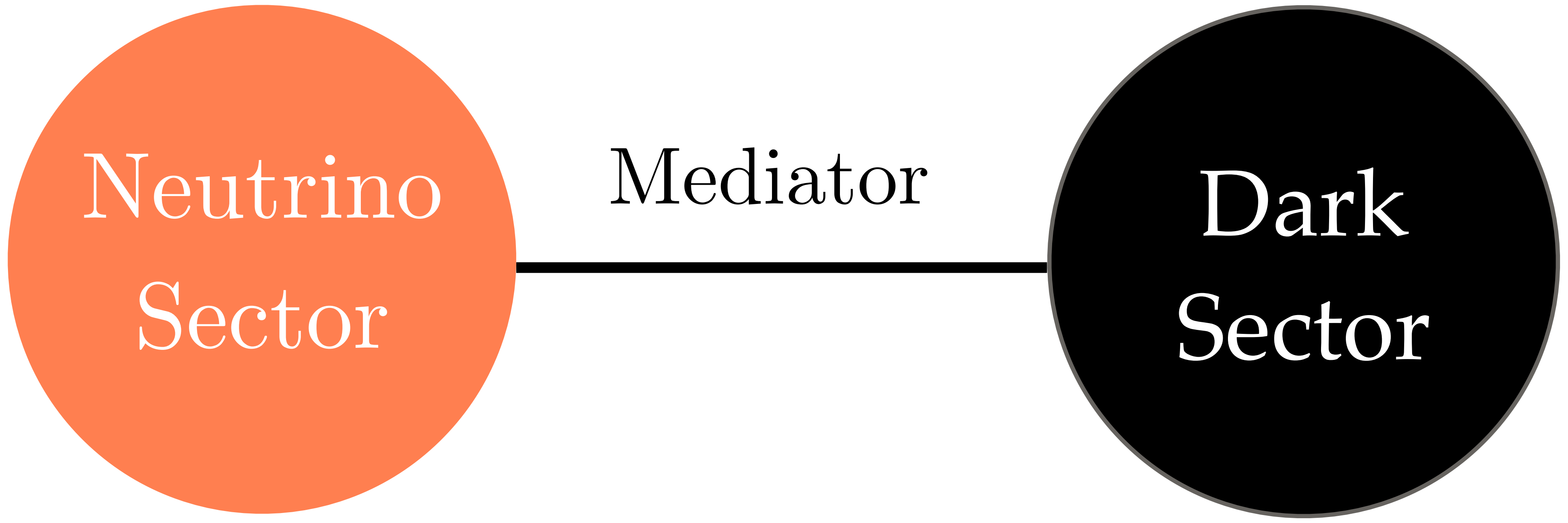

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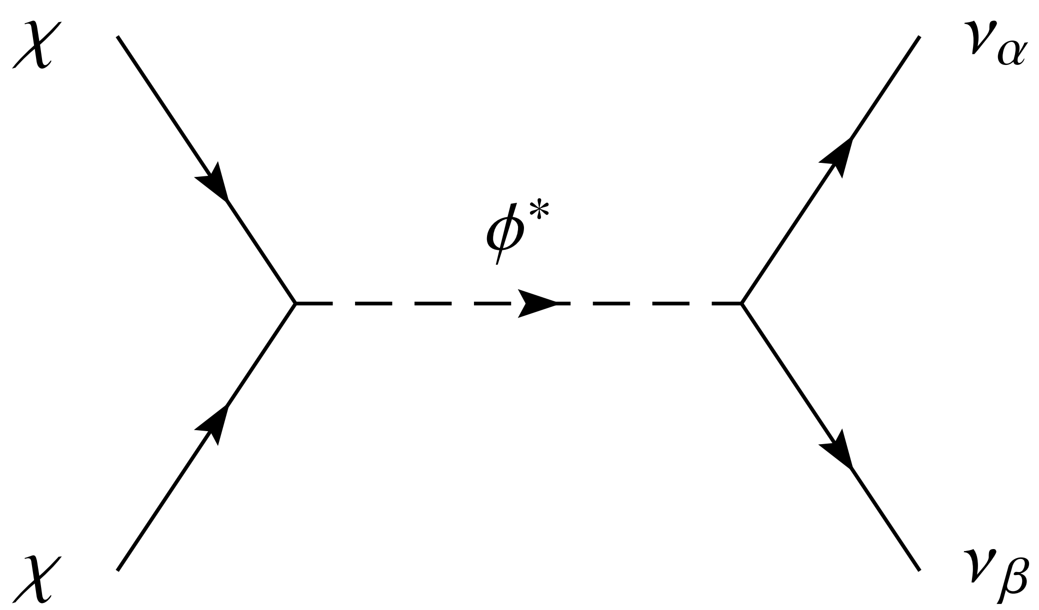
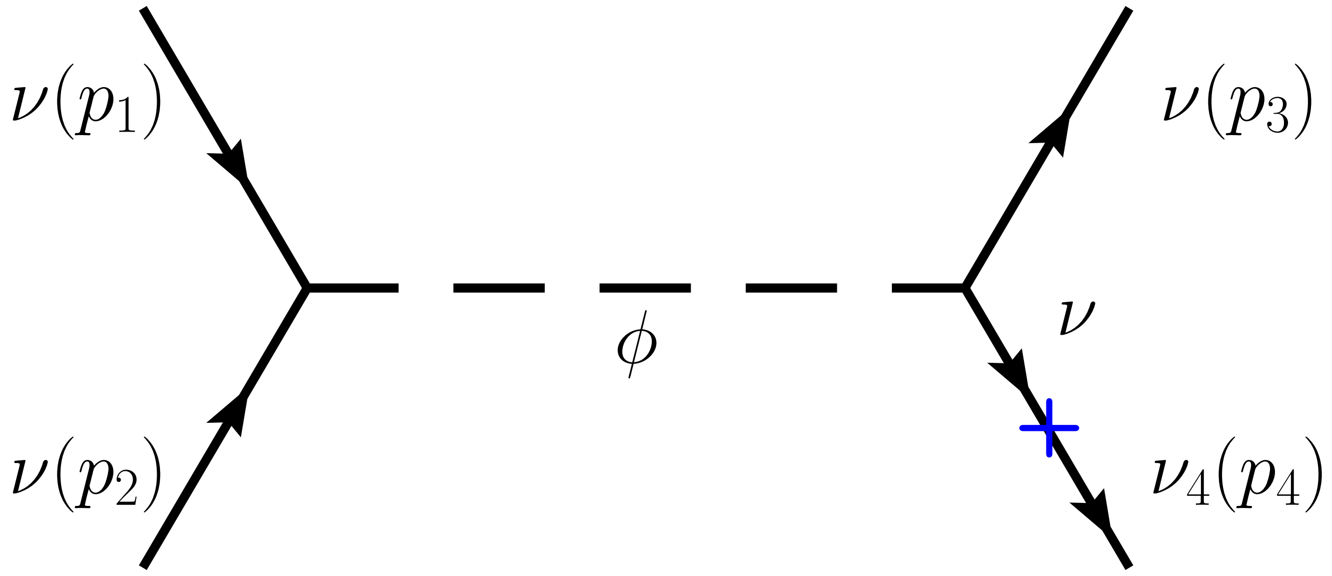
Thermal Dirac Fermion DM

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

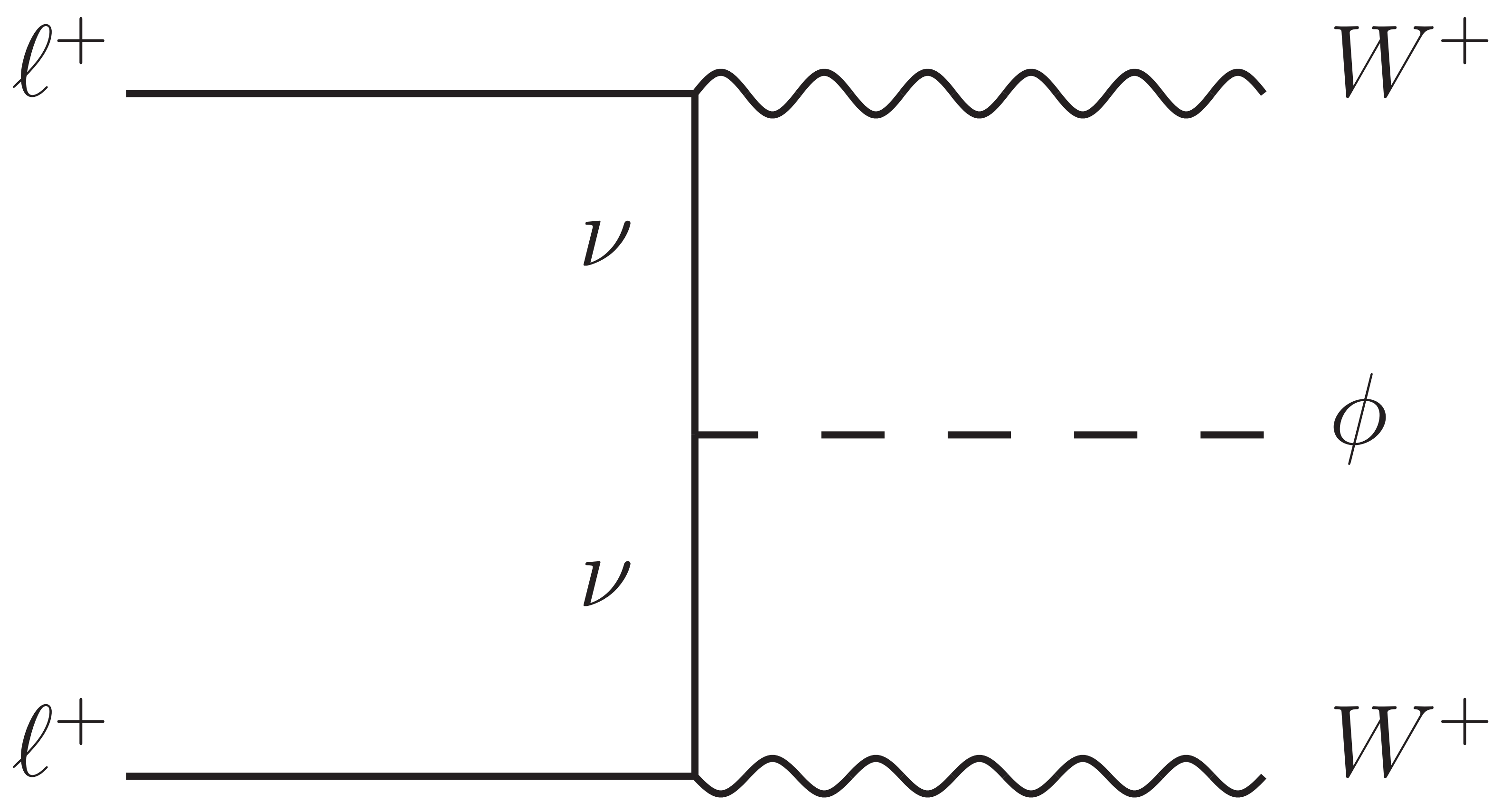


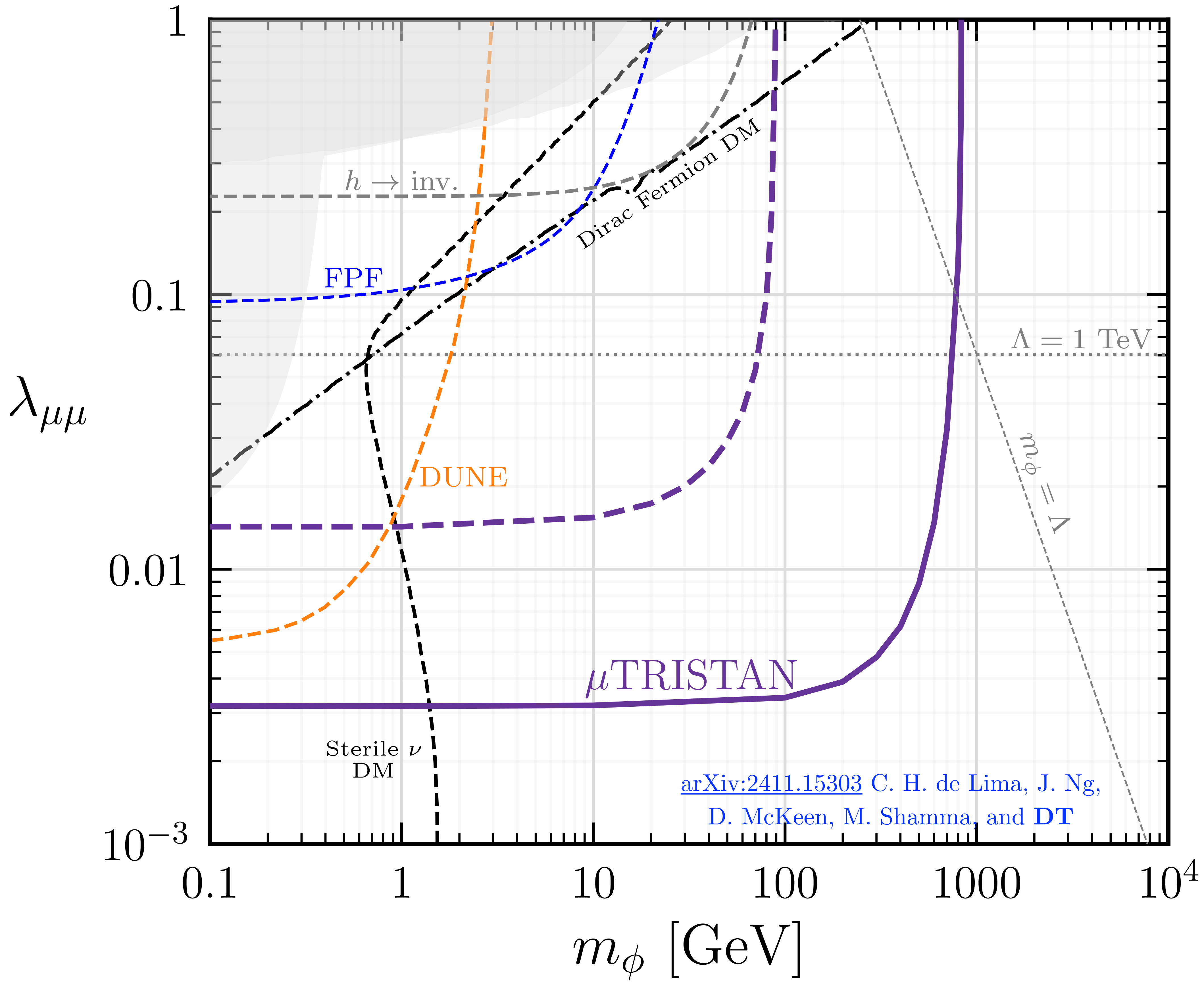
Sterile Neutrino DM

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



Neutrinophilic Scalars





Since the scalar has L = -2 but decays invisibly, this is an *apparent LNV* but lepton number is actually conserved

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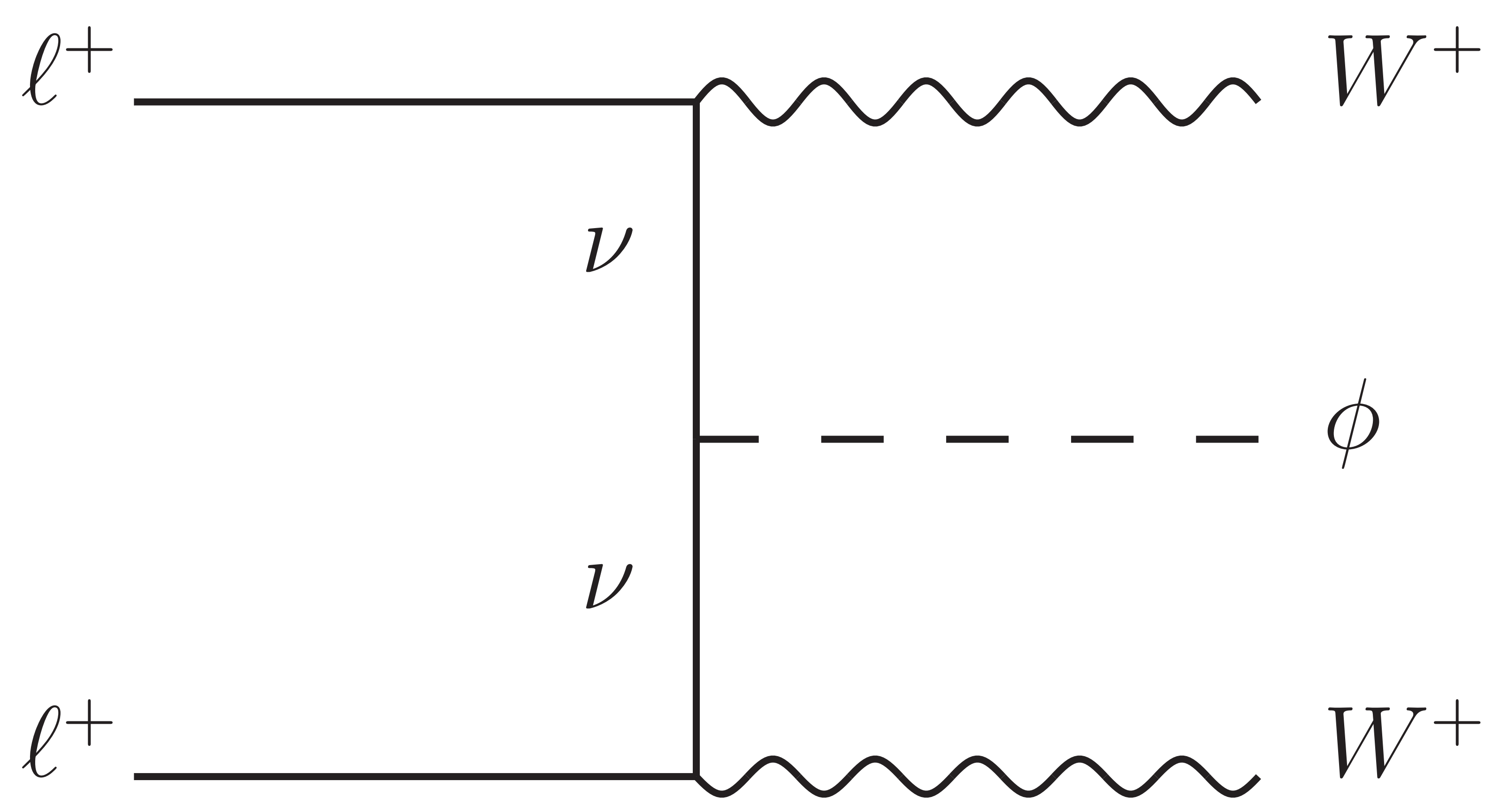

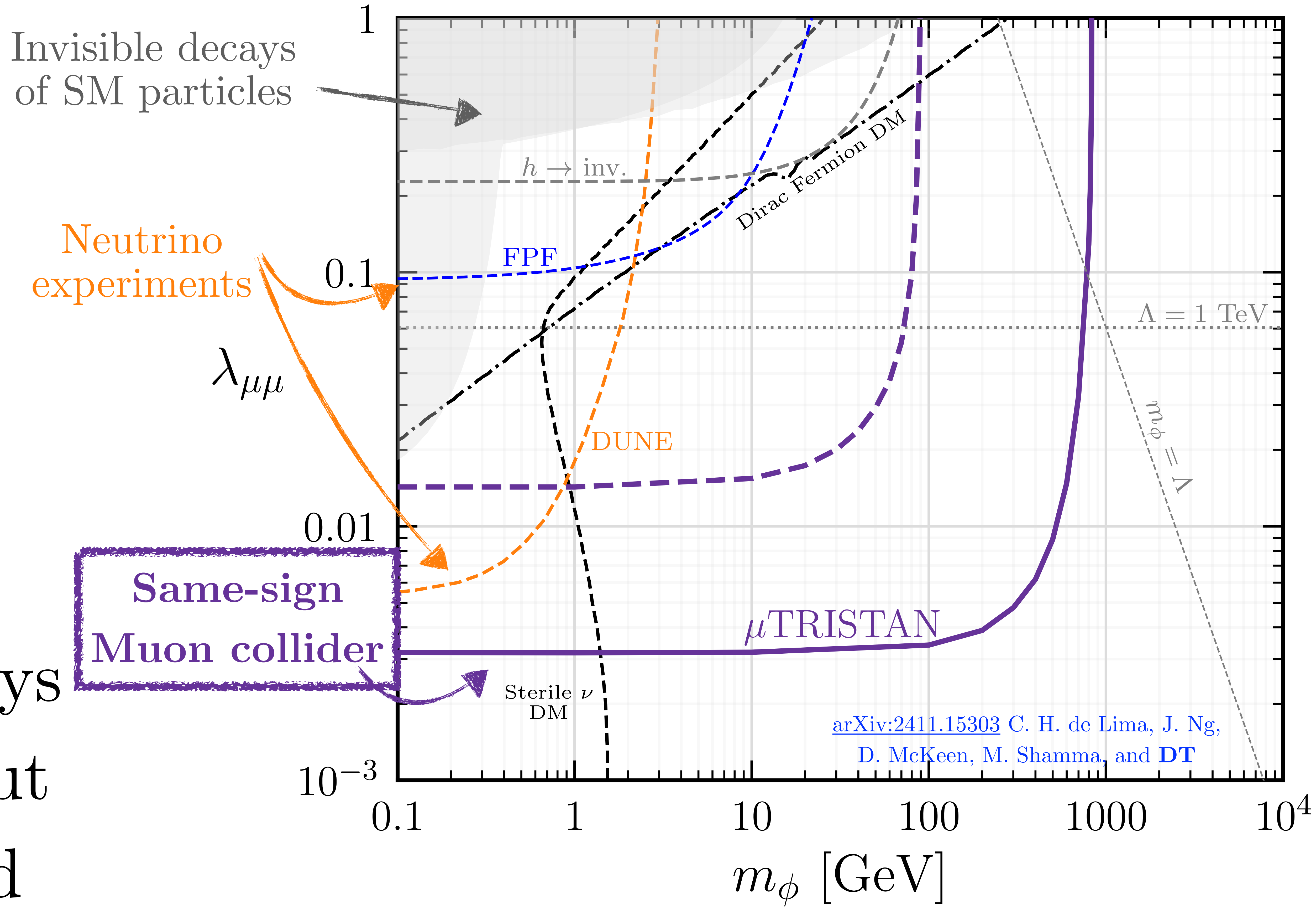

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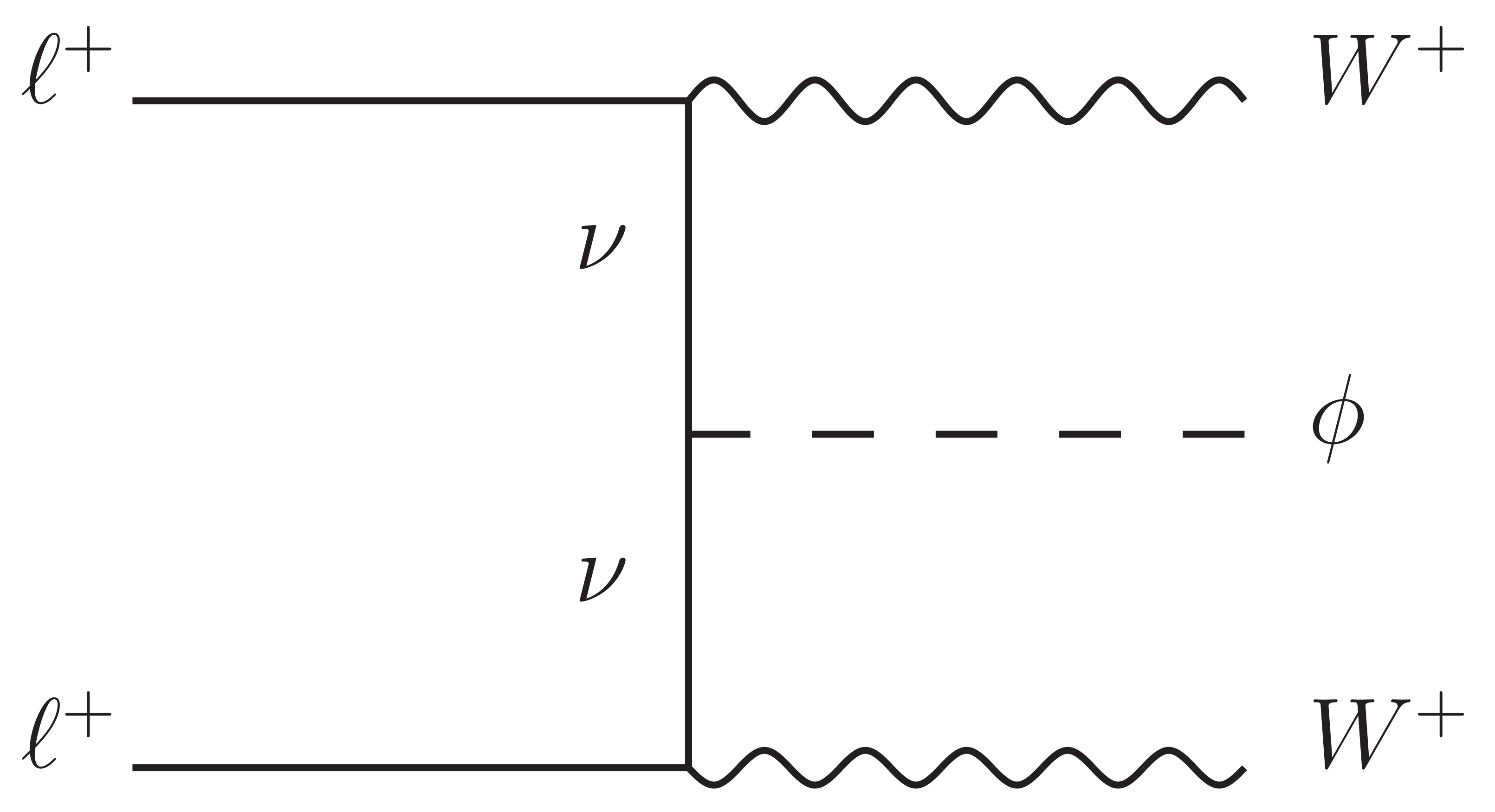

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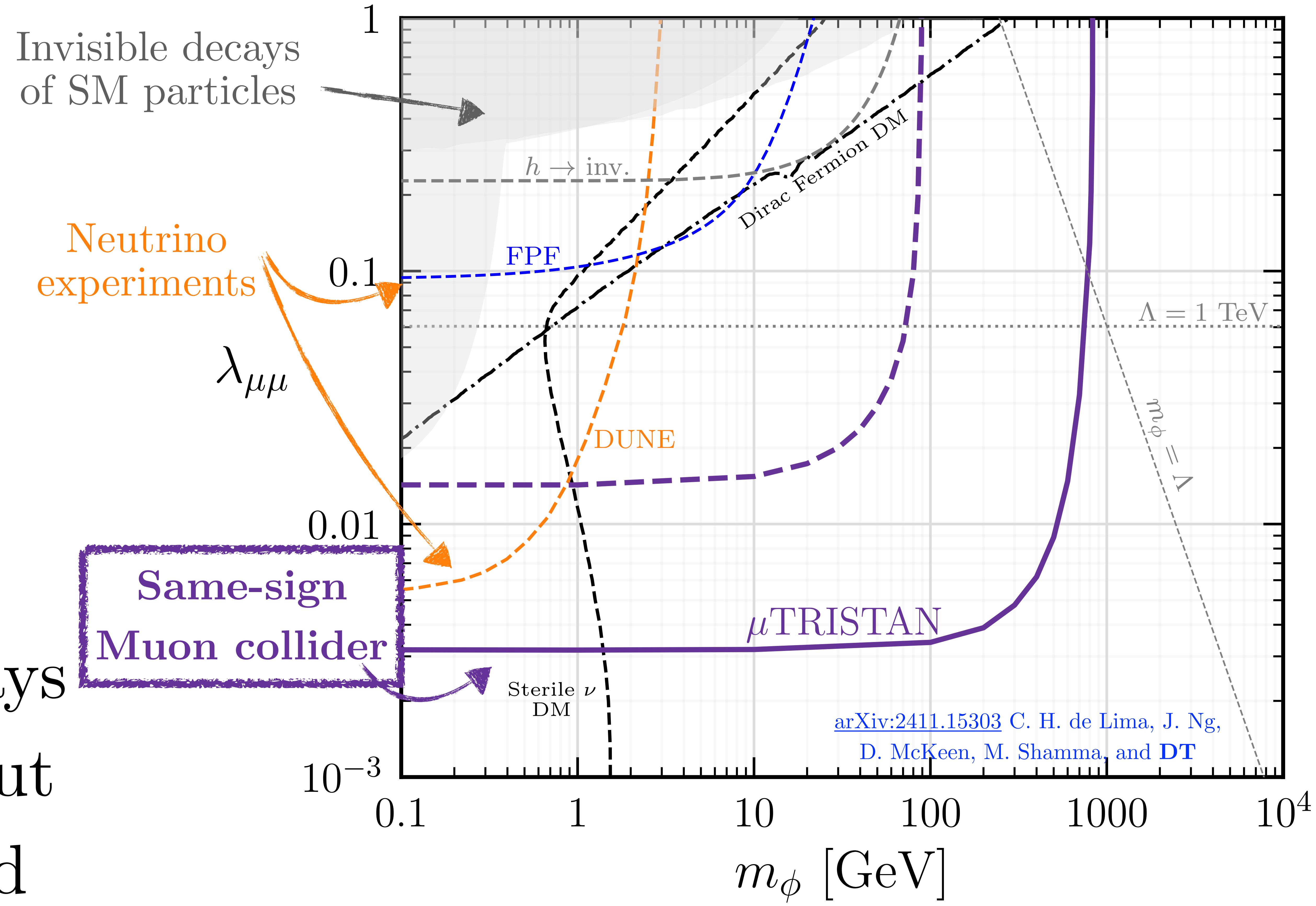
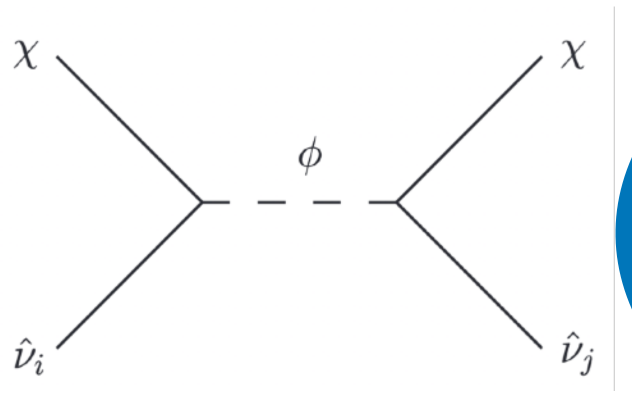


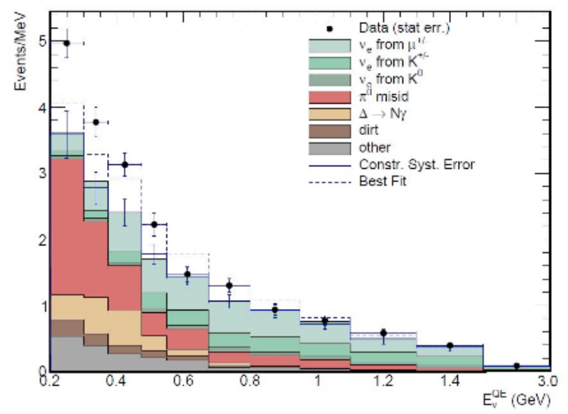
Same-sign muon collider can cover probe the full dark matter parameter space!

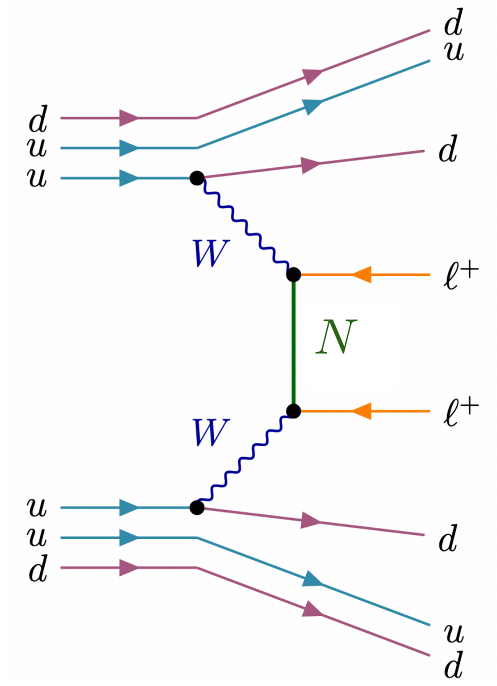
Summary



Dark Matter

Experimental Anomalies

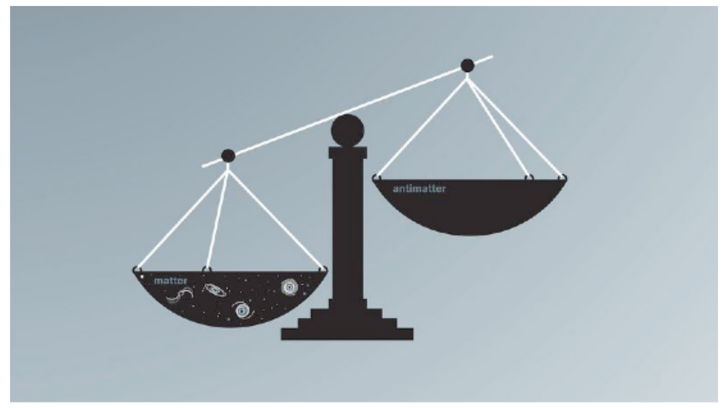




Dirac/Majorana Neutrinos

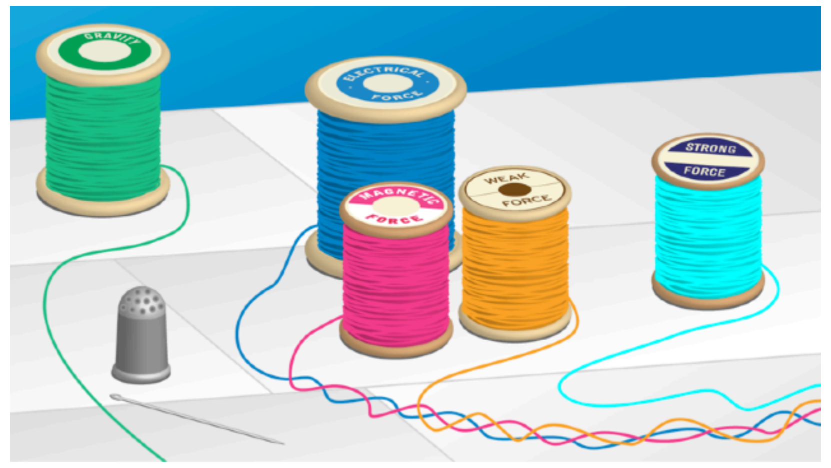
Lepton Number Violation

Matter-Antimatter Asymmetry



Neutrino Masses

Unification of Fundamental Forces



Thanks!

Questions?