Distinguishing Dirac/Majorana Fermions at Future Lepton Colliders

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Based on Phys. Rev. Lett. 134 (2025) 2, 021801

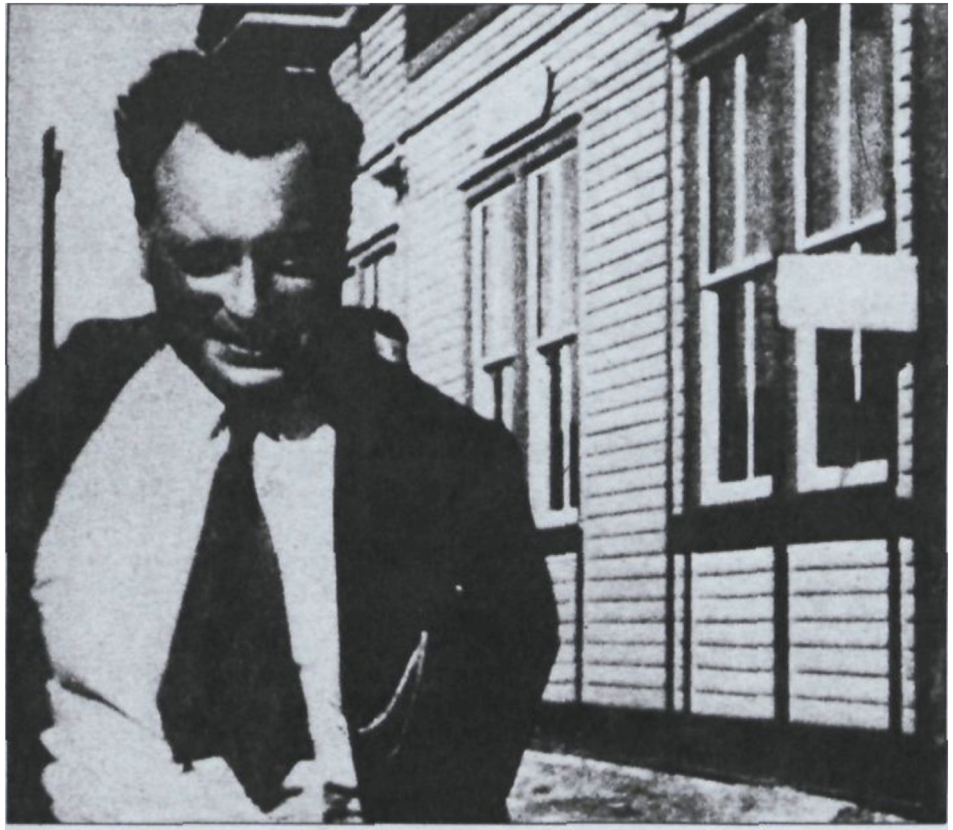
In collaboration with **Qing-Hong Cao** and **Kun Cheng**

The 1937 Proposal of the Majorana Fermion

Pauli's neutrino idea and Majorana's symmetric theory laid the foundation of the Majorana fermion concept

The Neutrino Hypothesis (Pauli, 1930)

To avoid anomalies of spin and statistics Pauli suggested in 1930 that a neutral particle of small mass might accompany the electron in nuclear beta decay, calling it (until Chadwick's discovery) the *neutron*.



PAULI ON THE WAY TO PASADENA, 1931

Majorana's Symmetric Theory (1937)

Home > Il Nuovo Cimento (1924–1942) > Article

Teoria simmetrica dell'elettrone e del positrone

Published: 21 September 2008

Volume 14, pages 171–184, (1937) Cite this article

Ettore Majorana

Majorana in the 1930s

Born	5 August 1906 Catania, Italy
Died	Missing since 1938, likely still alive in 1959[1] unknown

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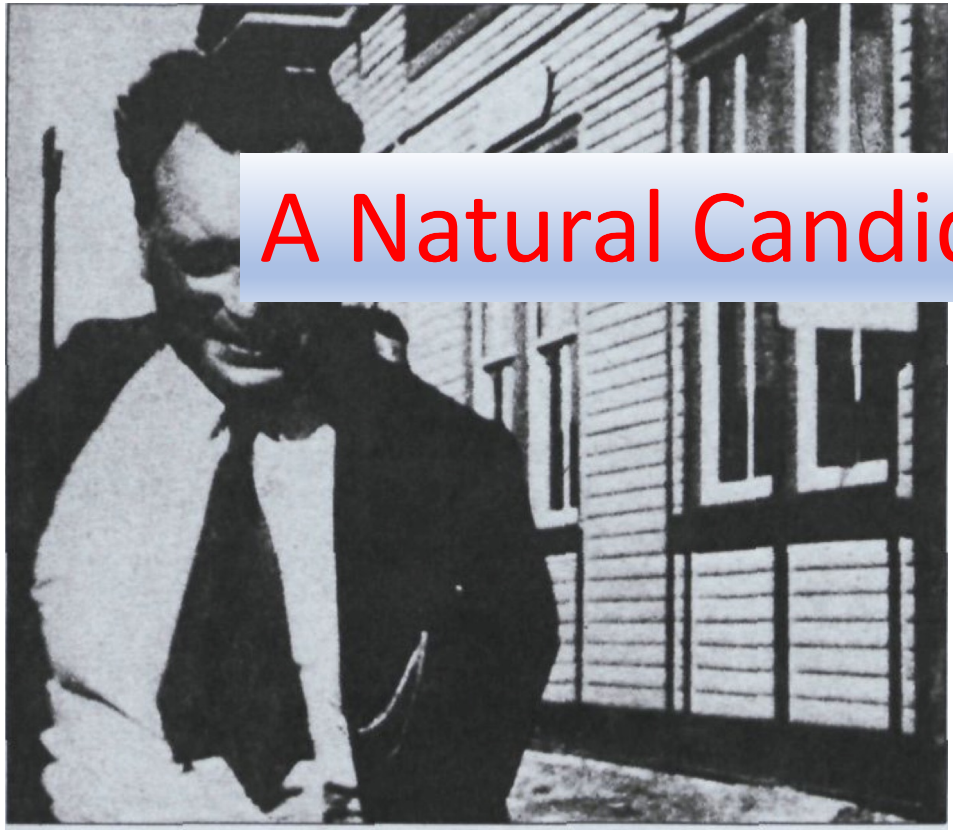

PAULI ON THE WAY TO PASADENA, 1931

A Natural Candidate: the SM Neutrino

Majorana's Symmetric Theory (1937)

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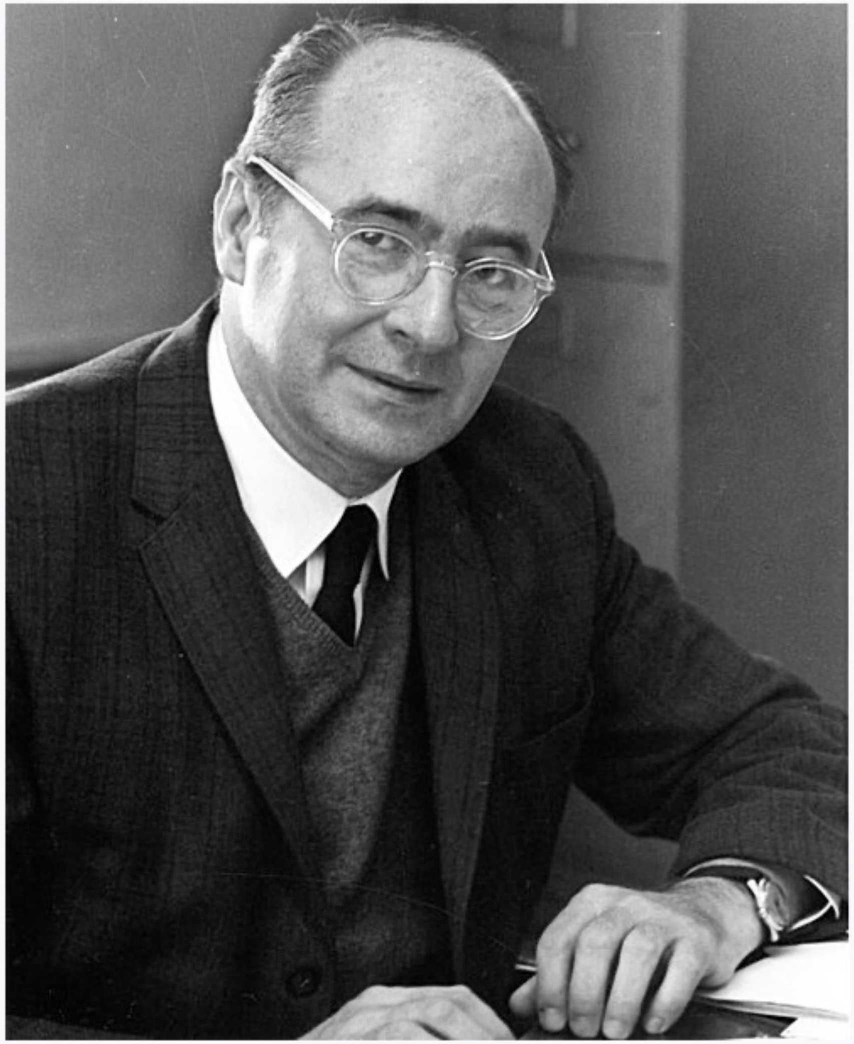
Are Standard Model Neutrinos Dirac or Majorana?

--Neutrinoless Double Beta Decay ($0\nu\beta\beta$)

Wendell H. Furry

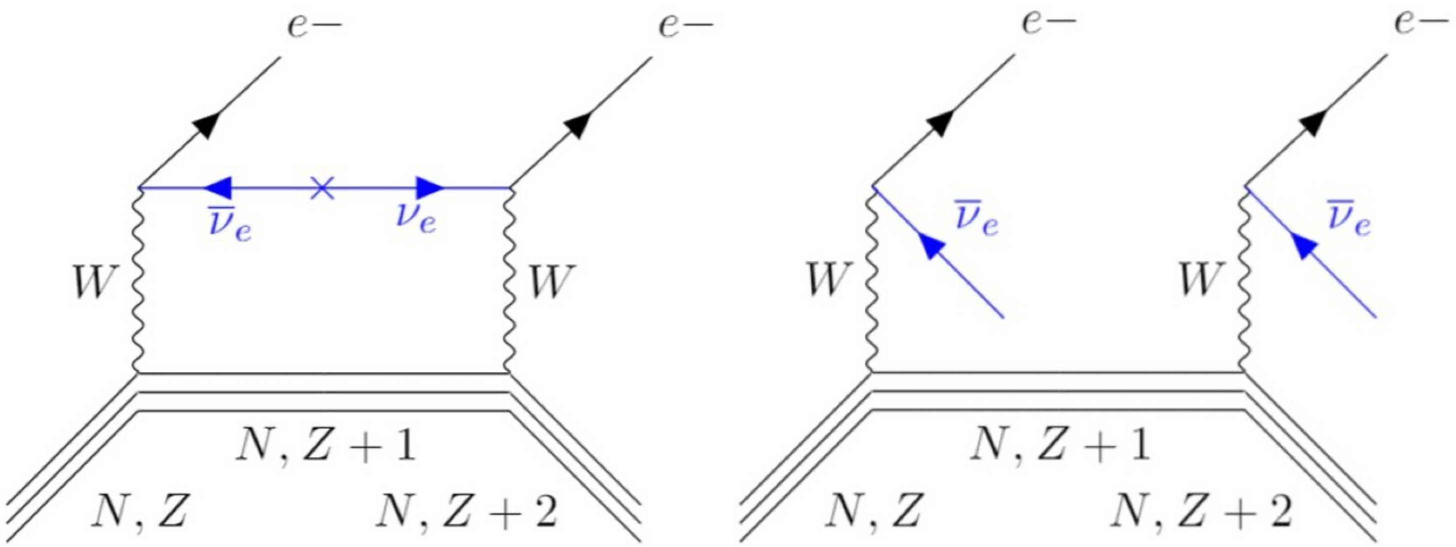


DECEMBER 15, 1939 PHYSICAL REVIEW VOLUME 56

On Transition Probabilities in Double Beta-Disintegration

W. H. Furry
Physics Research Laboratory, Harvard University, Cambridge, Massachusetts
(Received October 16, 1939)

Furry (1939)



The existence of $0\nu\beta\beta$ is a smoking-gun signature of Majorana neutrinos

Are Standard Model Neutrinos Dirac or Majorana? (Challenges)

--Neutrinoless Double Beta Decay

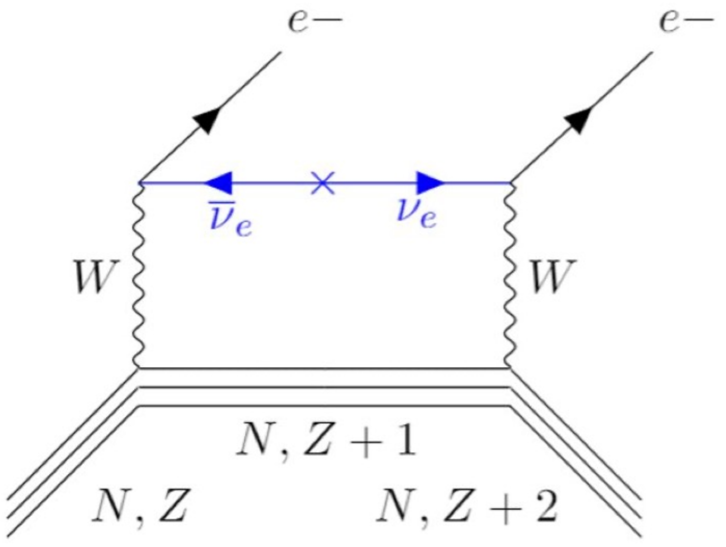
- Dirac Majorana confusion theorem $\propto \frac{m_\nu}{E}$

Majorana neutrinos and their electromagnetic properties

Boris Kayser

Division of Physics, National Science Foundation, Washington, D. C. 20550

(Received 29 January 1982)



- $0\nu\beta\beta$ without Majorana neutrinos with NP

P. Gu, Physics Letters B 820 (2021) 136553

Do Majorana Fermions or Majorana Modes Exist in Nature?

Condensed-matter Majorana modes are emergent quasiparticles, not fundamental Majorana fermions like neutrinos

Paired states of fermions in two dimensions with breaking of parity and time-reversal symmetries and the fractional quantum Hall effect
N Read, D Green
Physical Review B, 2000 · APS

Abstract
We analyze pairing of fermions in two dimensions for fully gapped cases with broken parity (P) and time reversal (T), especially cases in which the gap function is an orbital angular momentum (l) eigenstate, in particular l=− 1 (p wave, spinless, or spin triplet) and l=− 2 (d wave, spin singlet). For l≠ 0, these fall into two phases, weak and strong pairing, which may be distinguished topologically. In the cases with conserved spin, we derive explicitly the Hall conductivity for spin as the corresponding topological invariant. For the

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Unpaired Majorana fermions in quantum wires
AY Kitaev
Physics-uspekhi, 2001 · iopscience.iop.org

Abstract
Certain one-dimensional Fermi systems have an energy gap in the bulk spectrum while boundary states are described by one Majorana operator per boundary point. A finite system of length L possesses two ground states with an energy difference proportional to exp ÀLal0 and different fermionic parities. Such systems can be used as qubits since they are intrinsically immune to decoherence. The property of a system to have boundary Majorana fermions is expressed as a condition on the bulk electron spectrum. The

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New directions in the pursuit of Majorana fermions in solid state systems
J Alicea
Reports on progress in physics, 2012 · iopscience.iop.org

Abstract
The 1937 theoretical discovery of Majorana fermions—whose defining property is that they are their own anti-particles—has since impacted diverse problems ranging from neutrino physics and dark matter searches to the fractional quantum Hall effect and superconductivity. Despite this long history the unambiguous observation of Majorana fermions nevertheless remains an outstanding goal. This review paper highlights recent advances in the condensed matter search for Majorana that have led many in the field to

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American Physical Society
https://link.aps.org › doi › PhysRevLett.86.268

Non-Abelian Statistics of Half-Quantum Vortices in $\mathit{p}

by DA Ivanov · 2001 · Cited by 2217 — Excitation spectrum of a **half-quantum vortex** in a p-**wave superconductor** contains a zero-energy Majorana fermion.

Nonabelions in the fractional quantum Hall effect
G Moore, N Read
Nuclear Physics B, 1991 · Elsevier

Abstract
Applications of conformal field theory to the theory of fractional quantum Hall systems are discussed. In particular, Laughlin's wave function and its cousins are interpreted as conformal blocks in certain rational conformal field theories. Using this point of view a hamiltonian is constructed for electrons for which the ground state is known exactly and whose quasihole excitations have nonabelian statistics; we term these objects "nonabelions". It is argued that universality classes of fractional quantum Hall systems can

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Signatures of Majorana fermions in hybrid superconductor-semiconductor nanowire devices
V Mourik, K Zuo, SM Frolov, SR Plissard… - Science, 2012 - science.org
Majorana fermions are particles identical to their own antiparticles. They have been theoretically predicted to exist in topological superconductors. Here, we report electrical measurements on indium antimonide nanowires contacted with one normal (gold) and one superconducting (niobium titanium nitride) electrode. Gate voltages vary electron density and define a tunnel barrier between normal and superconducting contacts. In the presence of magnetic fields on the order of 100 millitesla, we observe bound, midgap states at zero …
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Search **for** Majorana fermions in superconductors
CWJ Beenakker - Annu. **Rev**. Condens. Matter **Phys**., **2013** - annualreviews.org
… In **condensed matter** we can build on what nature offers, by constructing quasiparticle excitations with exotic … This transforms a thermal insulator into a thermal metal (**113**, 114). …
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Majorana Fermions in Particle Physics: Theoretical Candidates

- Yukawa interaction: right-handed neutrino (spectator)

  J. Zhang, S. Zhou, *Nucl.Phys.B* 903 (2016) 211-225

- Loop-level seesaw mechanism: symmetry (dark sector)

  E. Ma, Phys. Rev. Lett. 81, 1171 (1998); E. Ma, Phys. Rev. D73, 077301 (2006); R. Barbieri, L. J. Hall, and V. S. Rychkov, Phys. Rev.D74, 015007 (2006); Q.-H. Cao, E. Ma, and G. Rajasekaran, Phys. Rev. D76,095011 (2007); Q.-H. Cao, S.-L. Chen, E. Ma, B. Yan, D.-M. Zhang, *Phys.Lett.B* 779 (2018) 430-435

- Tree-level seesaw mechanism

  P. Minkowski, Phys. Lett. B 67, 421 (1977);R. N. Mohapatra and G. Senjanovic, Phys. Rev. Lett. 44, 912 (1980); T. Yanagida, Conf. Proc. C 7902131, 95 (1979); M. Gell-Mann, P. Ramond, and R. Slansky, Conf. Proc. C 790927, 315 (1979); J. Schechter and J. W. F. Valle, Phys. Rev. D 22, 2227 (1980); M. Magg and C. Wetterich, Phys. Lett. B 94, 61 (1980);T. P. Cheng and L.-F. Li, Phys. Rev. D 22, 2860 (1980);R. N. Mohapatra, Phys. Rev. Lett. 56, 561 (1986);R. N. Mohapatra and J. W. F. Valle, Phys. Rev. D 34, 1642 (1986)

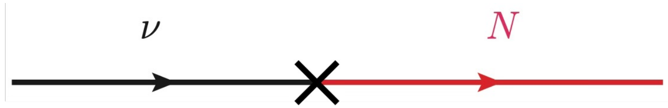
- String theory or extra dimension models

  A. Lukas and A. Romanino, (2000), arXiv:hep- ph/0004130; Y. Grossman and M. Neubert, Phys. Lett. B 474, 361 (2000) ;A. De Gouvea, G. F. Giudice, A. Strumia, and K. Tobe, Nucl. Phys. B 623, 395 (2002) W. Rodejohann and H. Zhang, Phys. Lett. B 737, 81 (2014)

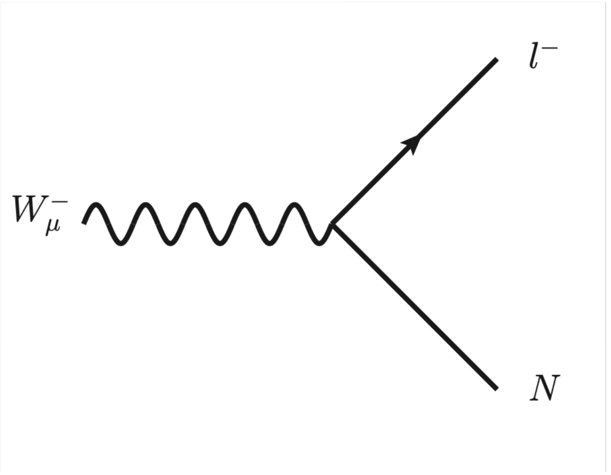
Heavy Neutral Leptons

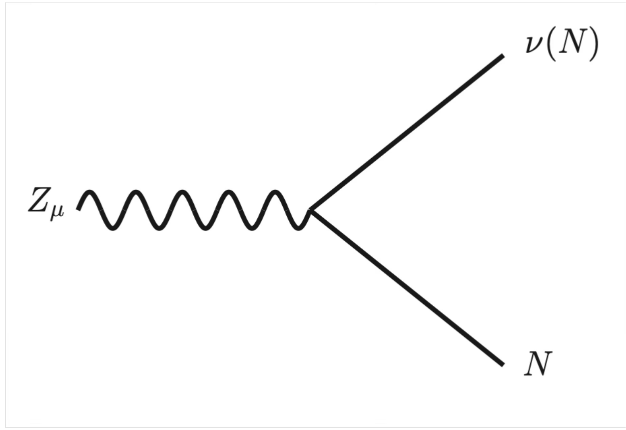
HNLs provide a realistic and testable Majorana fermion candidate

Heavy neutral lepton: Dirac or Majorana N

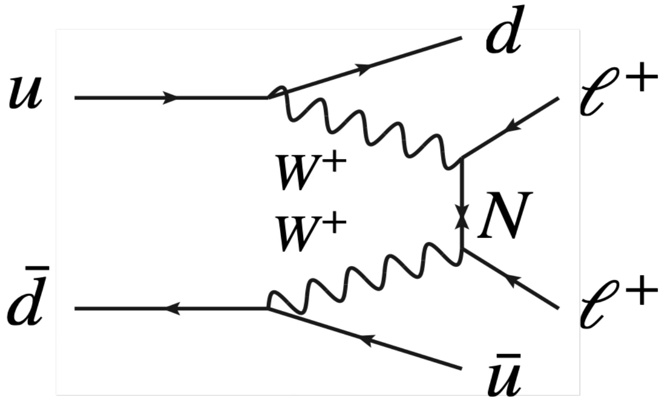


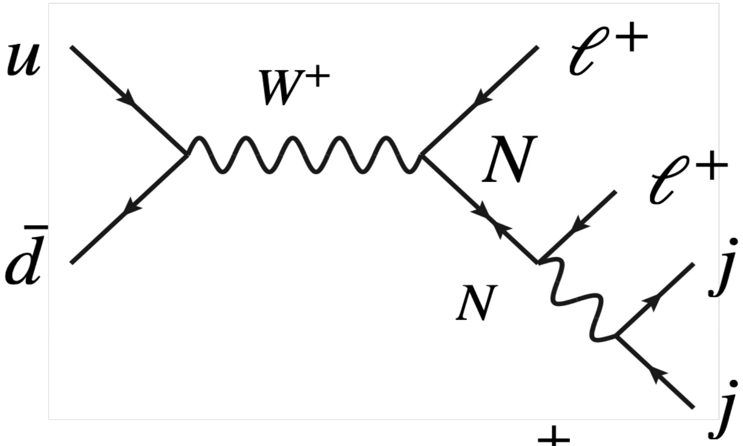
$$\sum_{i=e,\mu,\tau} \frac{g}{\sqrt{2}} U_i W_\sigma^- \bar{\ell}_{iL} \gamma^\sigma N + h.c. - \sum_{i=e,\mu,\tau} \frac{g}{2\cos\theta_W} U_i Z_\sigma (\bar{\nu}_{iL} \gamma^\sigma N + \bar{N} \gamma^\sigma \nu_{iL})$$

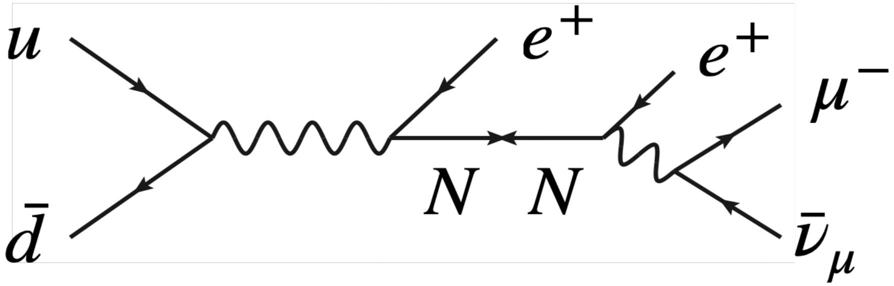


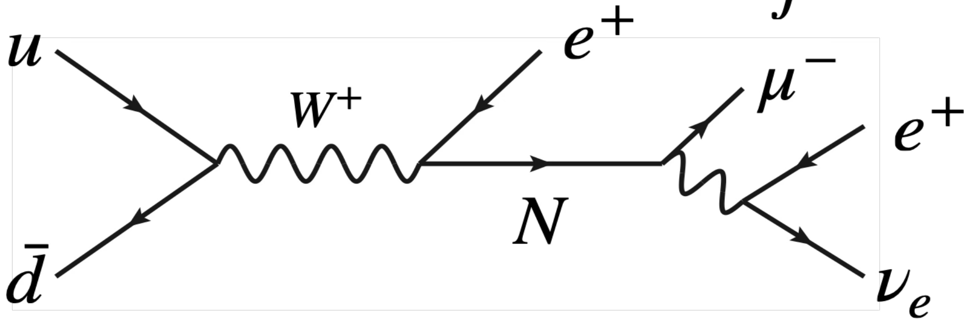


“Neutrinoless Double Beta Decay” at the LHC



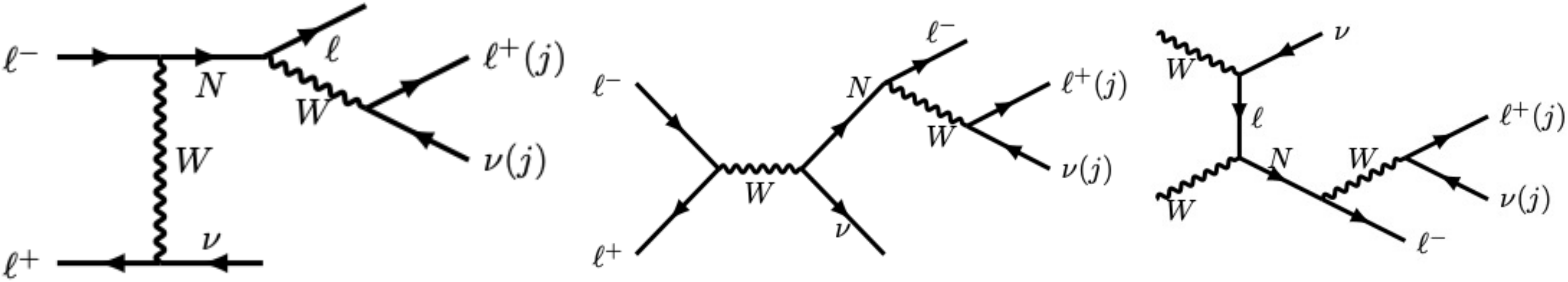






T. Han and B. Zhang, Phys. Rev. Lett. 97, 171804 (2006);A. Atre, T. Han, S. Pascoli, and B. Zhang, JHEP 05, 030 (2009); A. Atre, T. Han, S. Pascoli, and B. Zhang, JHEP 05, 030 (2009); A. Das and N. Okada, Phys. Rev. D 88, 113001 (2013); P. S. B. Dev, A. Pilaftsis, and U.-k. Yang, Phys. Rev. Lett. 112, 081801 (2014); E. Arganda, M. J. Herrero, X. Marcano, and C. Weiland, Phys. Lett. B 752, 46 (2016); C. O. Dib, C. S. Kim, K. Wang, and J. Zhang, Phys. Rev. D 94, 013005 (2016); A. Das, P. Konar, and A. Thalapillil, JHEP 02, 083 (2018)

HNLs at High-Energy Lepton Colliders



I. Chakraborty, H. Roy, and T. Srivastava, (2022), 10.1140/ep jc/s10052-023-11406-0; T. Li, C.-Y. Yao, and M. Yuan, JHEP 09, 131 (2023); T. H. Kwok, L. Li, T. Liu, and A. Rock, (2023), arXiv:2301.05177; P. Li, Z. Liu, and K.-F. Lyu, JHEP 03, 231 (2023), arXiv:2301.07117; R.-Y. He, J.-Q. Huang, J.-Y. Xu, F.-X. Yang, Z.-L. Han, and F.-L. Shao, (2024), arXiv:2401.14687

Distinguishing Dirac vs. Majorana by Distributions

POSSIBLE SIGNATURE FOR PRODUCTION OF MAJORANA PARTICLES IN e^+–e^- AND p–$\bar{\text{p}}$ COLLISIONS

S.T. PETCOV

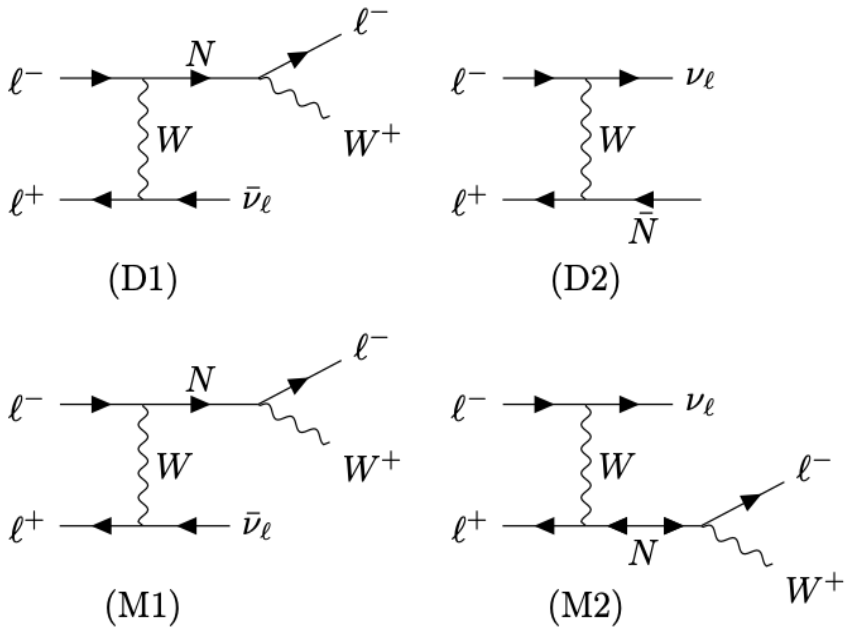
Institute of Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Boulevard Lenin 72, Sofia 1184, Bulgaria and Fermi National Accelerator Laboratory, Batavia, IL 60510, USA

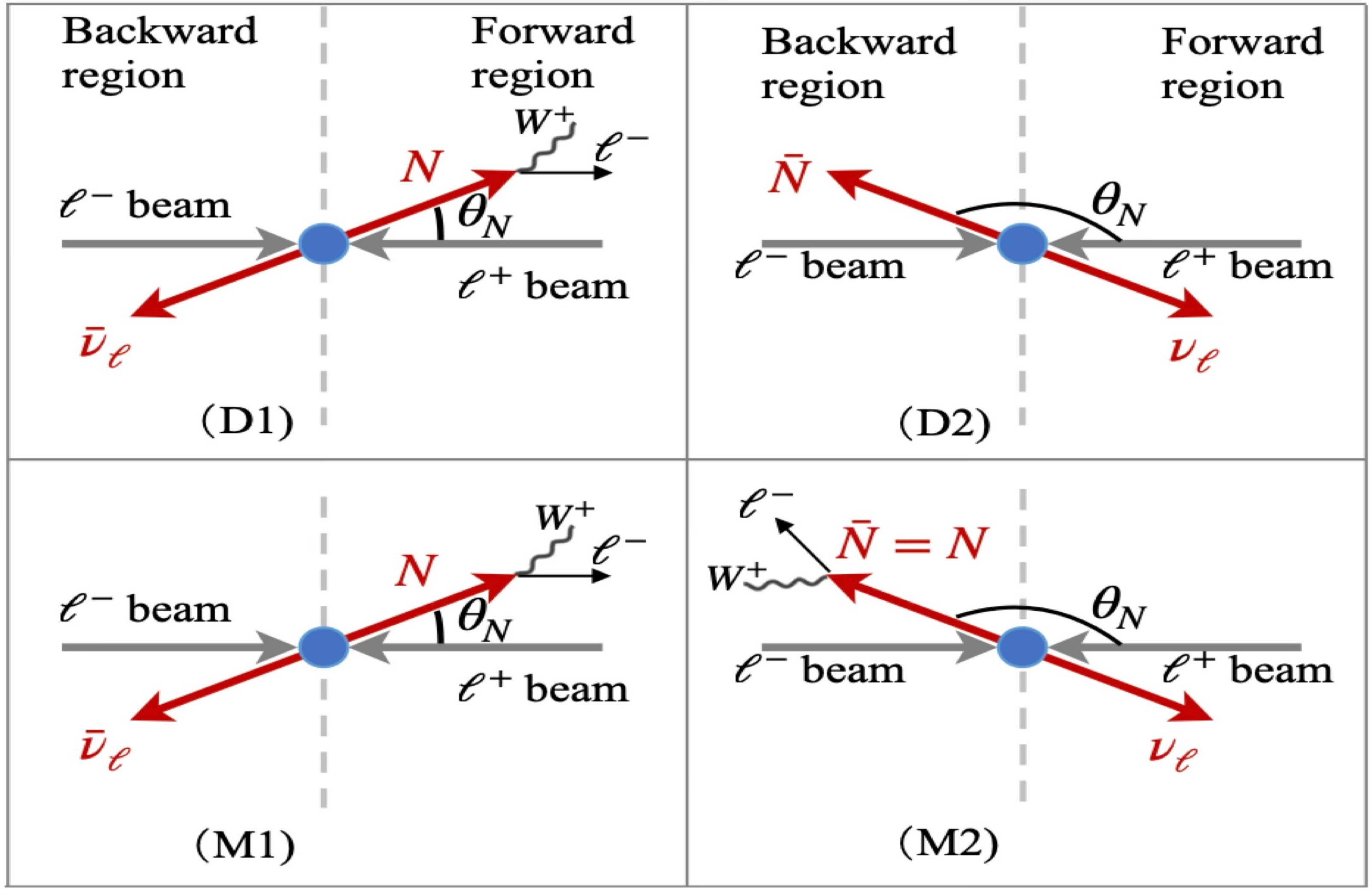
Received 4 January 1984

“The absence of forward–backward asymmetry is one possible signature for the production of Majorana particles…”

It is shown that the forward–backward asymmetry in the production of Majorana particles in e^+–e^- and p–$\bar{\text{p}}$ collisions is identically equal to zero if the couplings generating the process conserve the *CP*-parity, and that the asymmetry vanishes to leading order in perturbation theory if the production mechanism is perturbative and the *S*-matrix is *CPT*-invariant. In the case of p–$\bar{\text{p}}$ interactions the second statement is proved assuming that the strong interactions are described by QCD and that the relevant subprocesses involve in the leading approximation two particles (quarks, gluons or a quark and a gluon) in the initial state. The absence of forward–backward asymmetry is one possible signature for production of Majorana particles (other than light neutrinos) in e^+–e^- and p–$\bar{\text{p}}$ collisions at high energies.

Schematic Example: Symmetric vs. Asymmetric Distributions

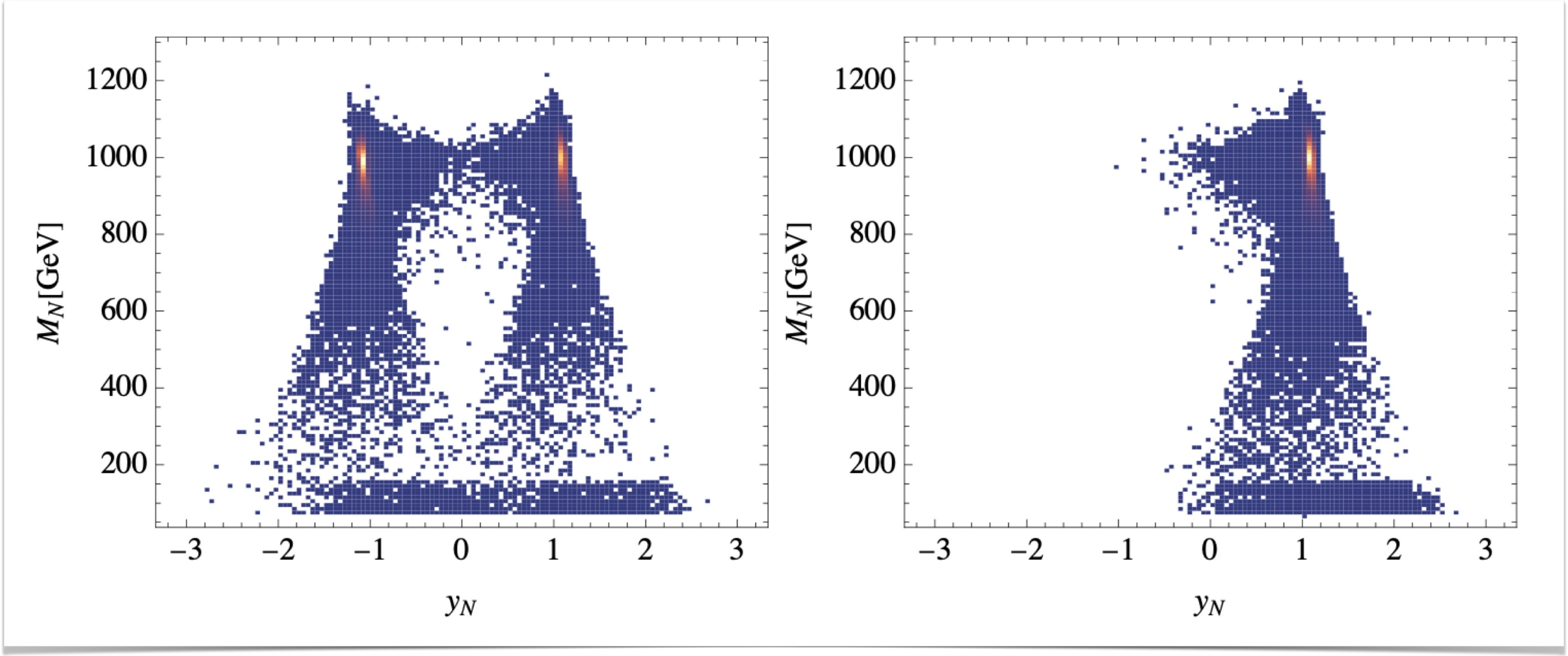




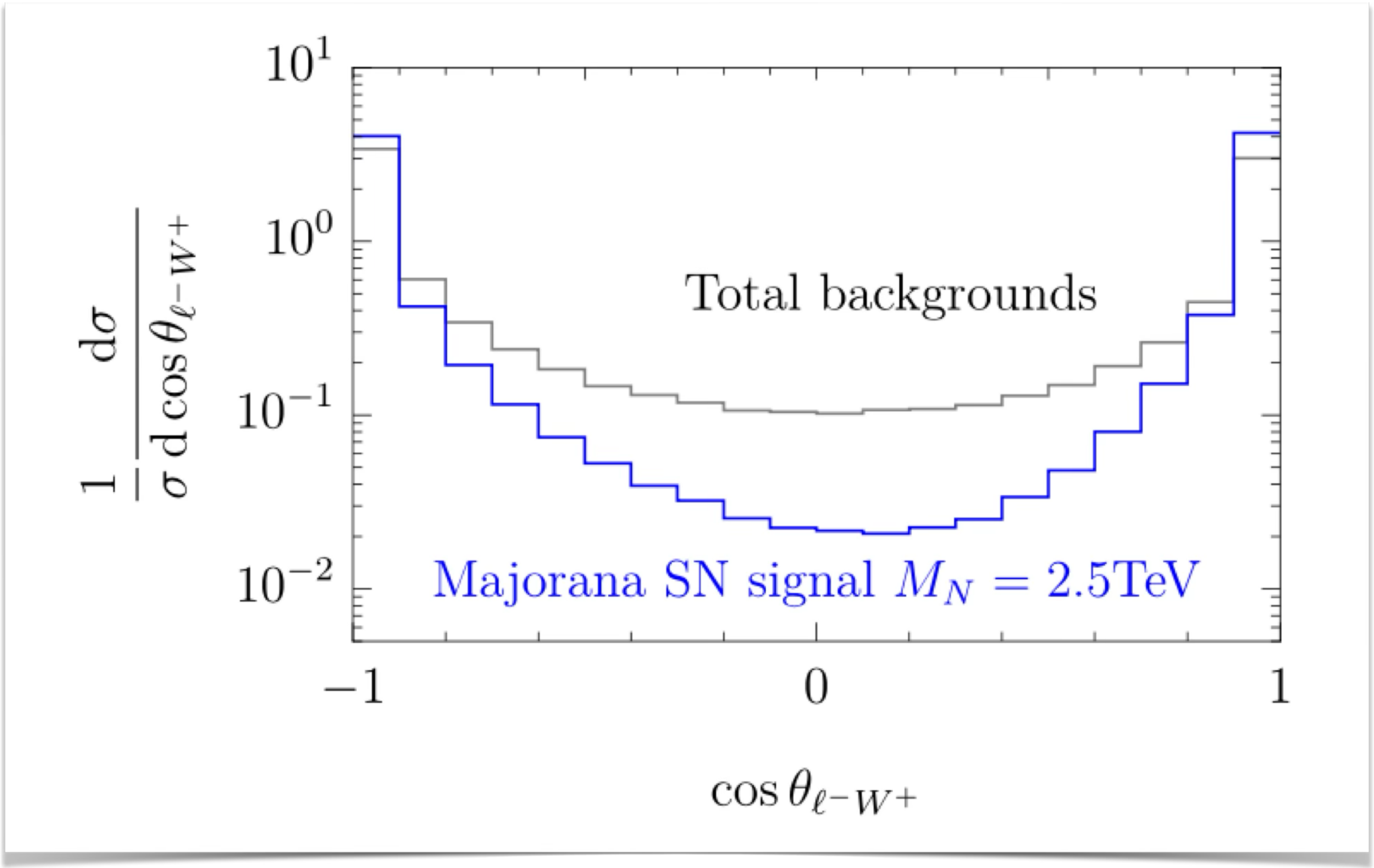
Rapidity and Its Correlation with HNL Mass

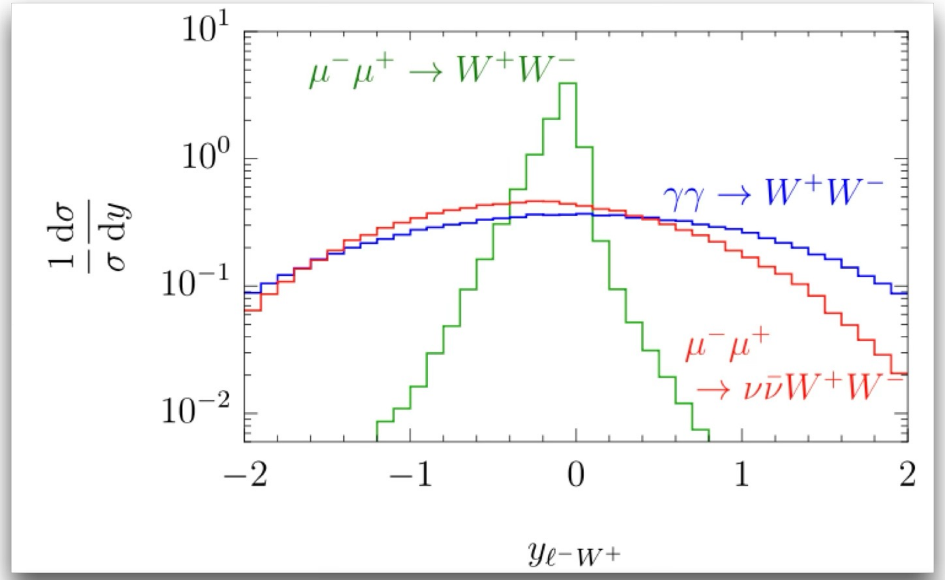
$$y_N = \frac{1}{2}\log\frac{E + p_N\ \cos\theta_N}{E - p_N\ \cos\theta_N}$$

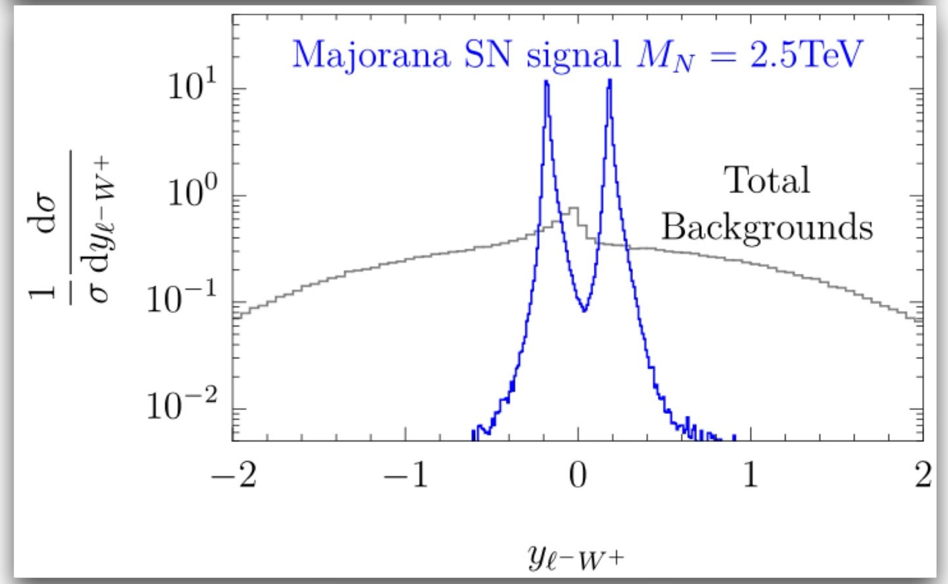
$$\mathrm{v}_N^Z = tanh\, y_N$$



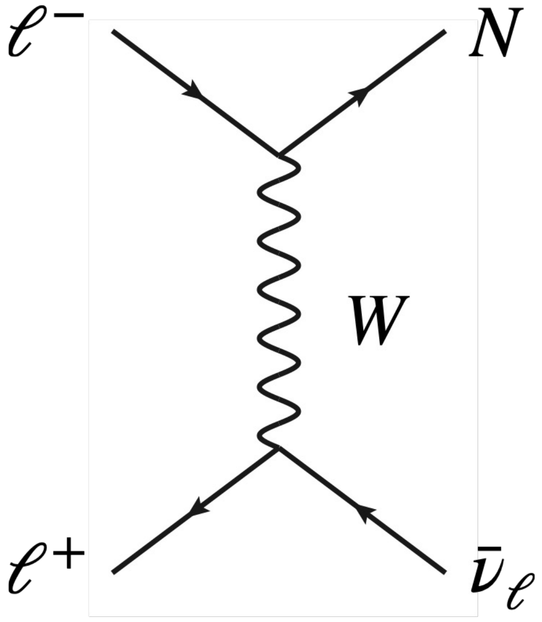
Advance of Rapidity: Signal Discrimination





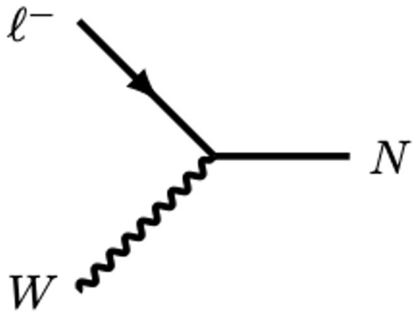


Rapidity of HNLs at Muon Colliders



$$\frac{\mathrm{d}\sigma}{\mathrm{d}y_N} \propto \frac{e^{4y_N}(se^{2y_N} - m_N^2)}{(e^{2y_N}+1)^2(s+m_W^2-e^{2y_N}(m_N^2-m_W^2))^2}$$

$$y_N \sim \frac{1}{2}\log(s+m_W^2)/(m_N^2-m_W^2) \text{ for } m_N > m_W$$



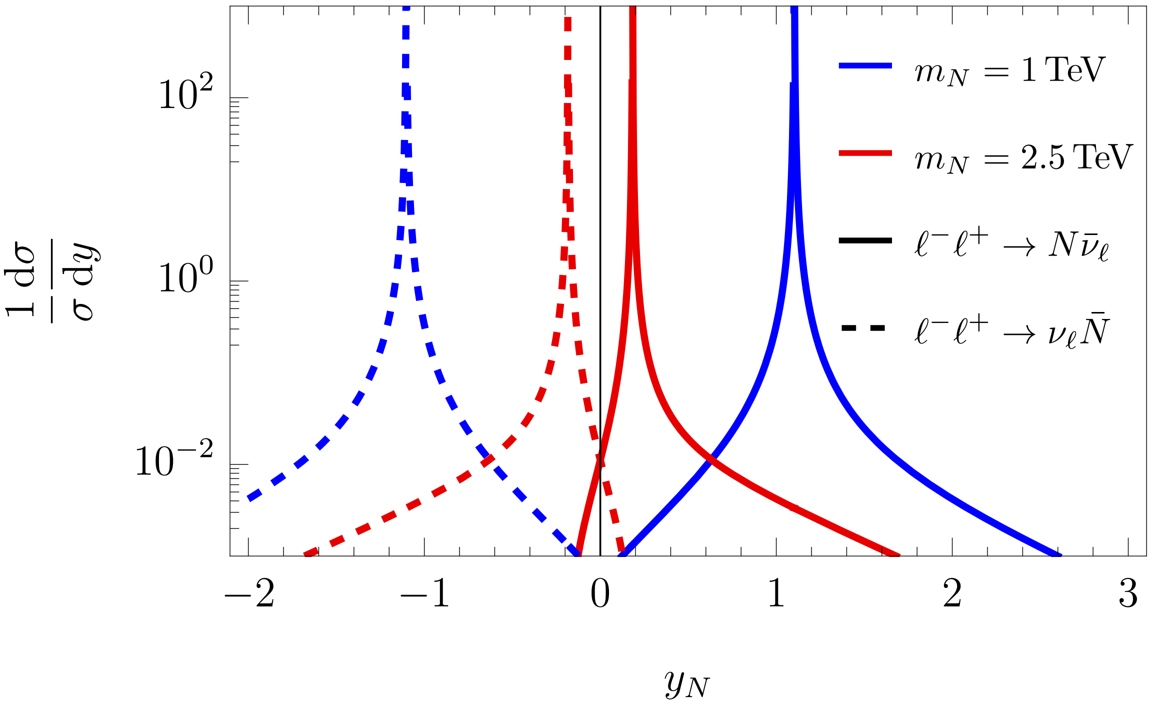
$$x_1 = 1$$

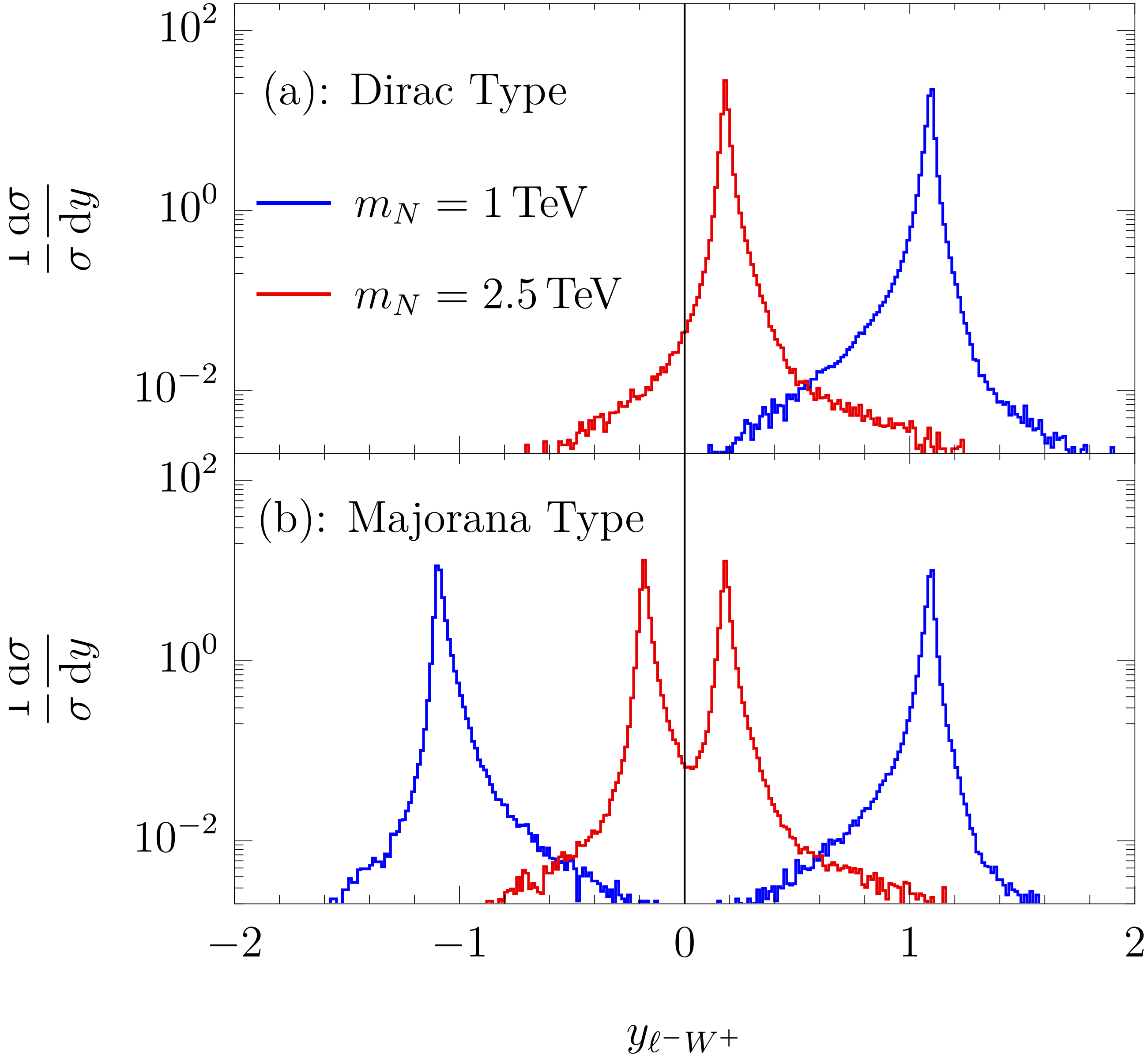
$$x_2 = \frac{m_W^2}{m_N^2}$$

$$y_N = \frac{1}{2}\log(x_1/x_2) = \frac{1}{2}\log(s/m_N^2)$$

S. Dawson, Nucl. Phys. B 249, 42 (1985); V. D. Barger, K.-m. Cheung, T. Han, and R. J. N. Phillips, Phys. Rev. D 42, 3052 (1990)

Rapidity of HNLs at Muon Colliders





Signal and Background Channels at a 3 TeV Muon Collider

$$\sum_{i=e,\mu,\tau} g U_i W_\sigma^- \bar{\ell}_{iL} \gamma^\sigma N + h.c. \qquad N \to \mu^- W^+ \text{ or } N \to e^- W^+$$

Signal: $\mu^-\mu^+ \to N\bar{\nu} \to \ell^- W^+ \bar{\nu} \to \ell^- jj\bar{\nu}$ for Dirac N

$\mu^-\mu^+ \to N\bar{\nu}(N\nu) \to \ell^- W^+ \bar{\nu}(\nu) \to \ell^- jj\bar{\nu}(\nu)$ for Majorana N

$\ell^- jj \not{E}_T$ or $\ell^- W_J \not{E}_T$

Backgrounds: $\mu^-\mu^+ \to W^+\ell^-\nu_\ell \to jj\ell^-\nu_\ell$ P. Li, Z. Liu, and K.-F. Lyu, JHEP 03, 231 (2023)

$\gamma^*\gamma^* \to W^+\ell^-\nu_\ell \to jj\ell^-\nu_\ell$

$\gamma^*\mu^+ \to \bar{\nu}_\mu W^+\ell^+\ell^- \to jj\ell^+\ell^-$

$\mu^-\mu^+ \to \nu_\mu\bar{\nu}_\mu W^+\ell^+\ell^- \to jj\ell^+\ell^-$

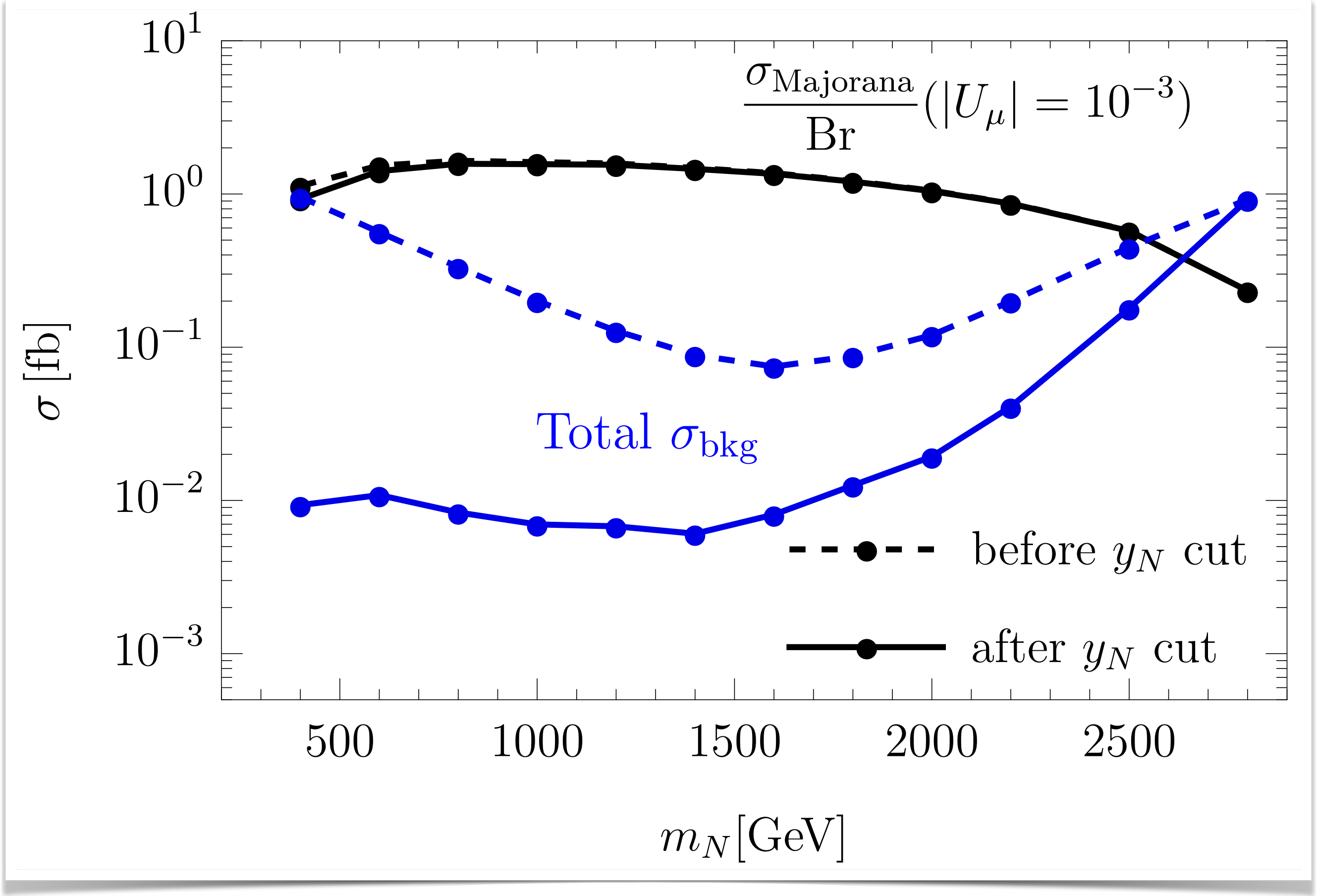
Cut efficiency at the 3 TeV muon collider

$p_T^e > 20$ GeV $\quad |\eta^e| < 2.5$

W resonance:

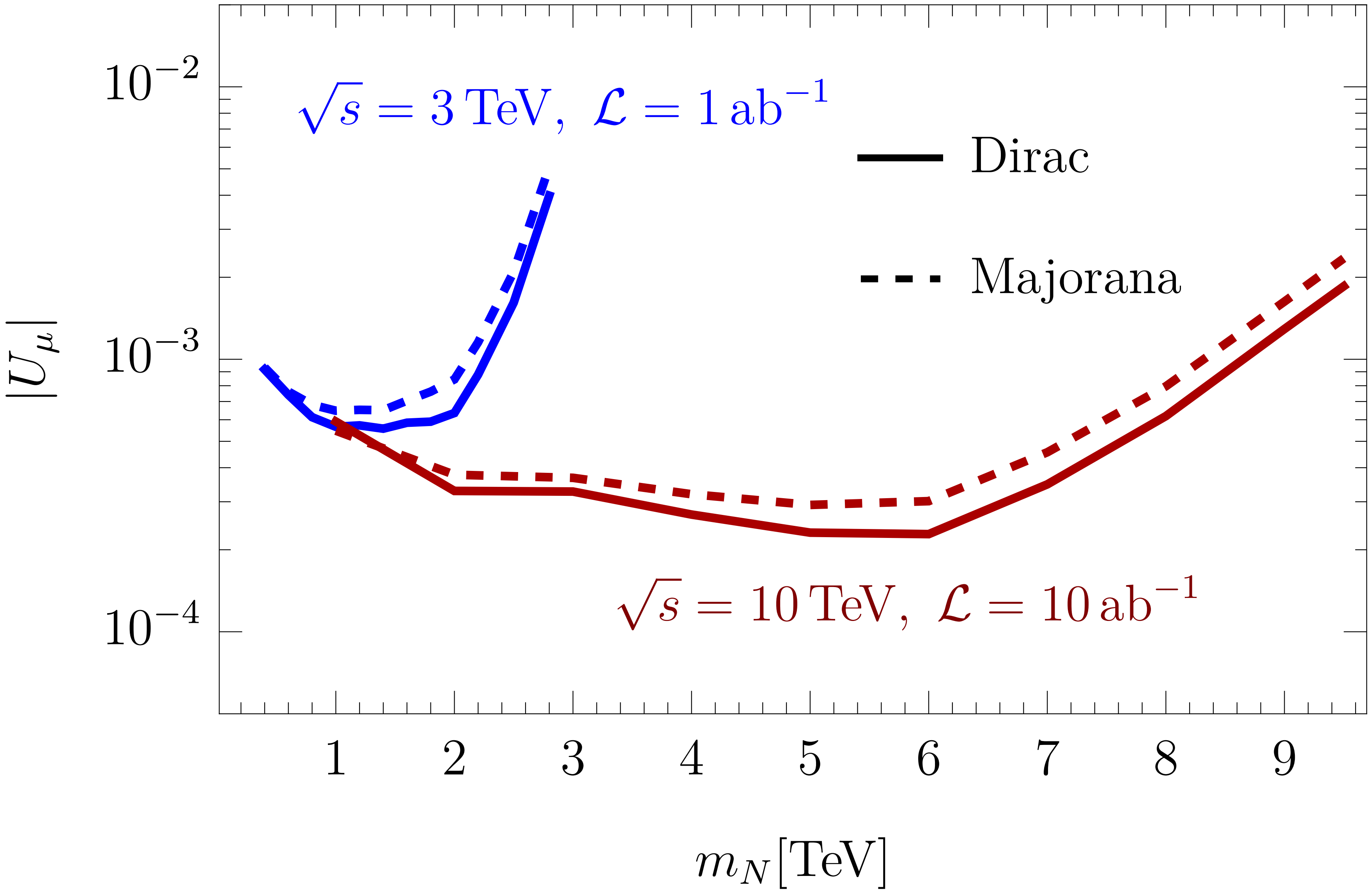
$$\begin{cases} 2\ jets \quad 50\ \text{GeV} < m_{j_1 j_2} < 100\ \text{GeV} \\ 1\ fat\ jet \quad 50\ \text{GeV} < m_J < 100\ \text{GeV} \end{cases}$$

N resonance: $m_{\ell\text{-}W} \subset m_N \pm 5\,\%\, m_N$

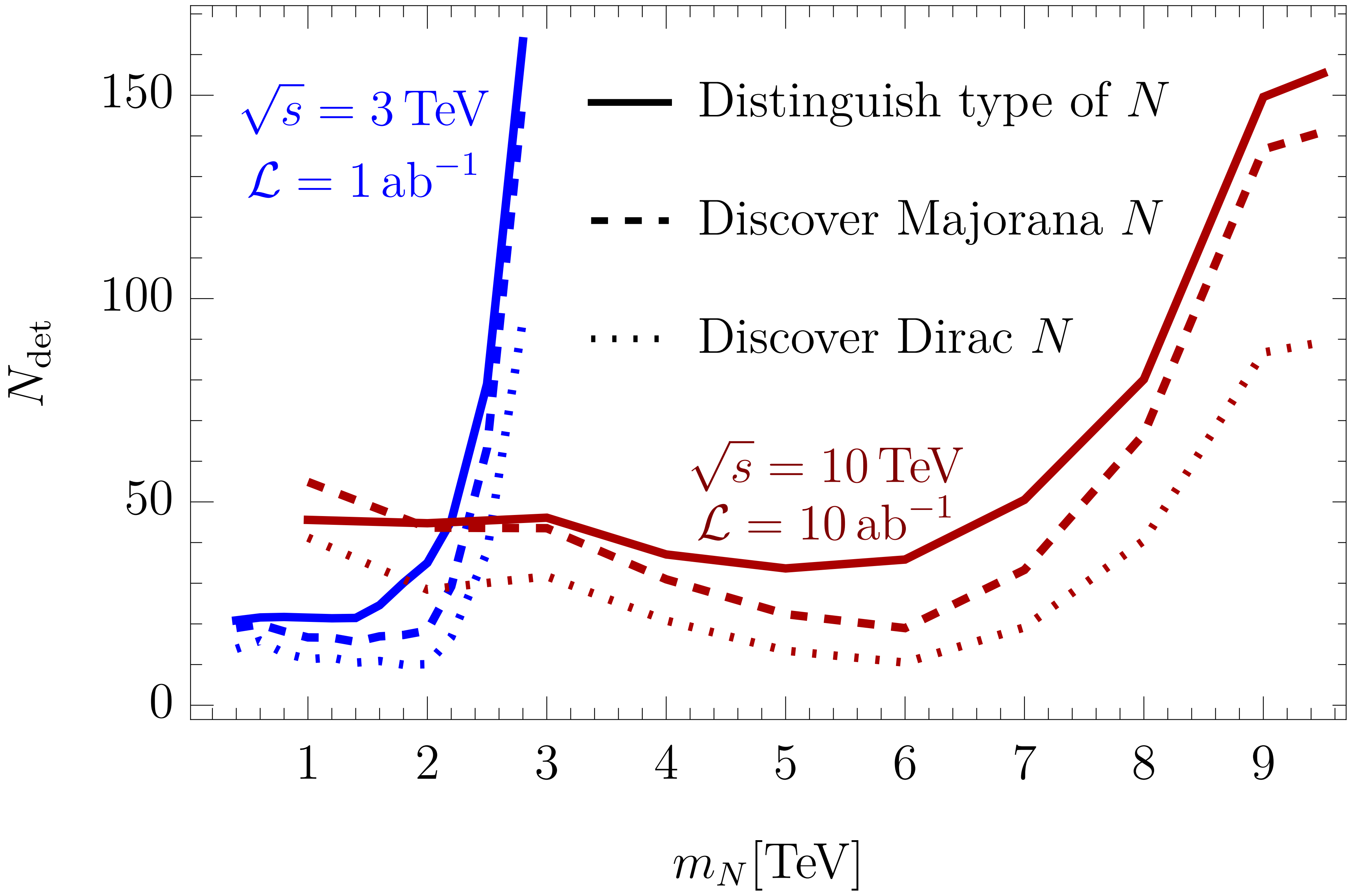


$$y_p - 0.1 < |y_{\ell\text{-}W}| < y_p + 0.1, \qquad y_p = \frac{1}{2}\log\frac{s}{m_N^2}$$

The 3 TeV Muon Collider Exclusion Potential on HNLs



Discovery and Discrimination Reach at the 3 TeV Muon Collider



Conclusion

- At the muon collider, the rapidity distribution of reconstructed N serves as a clear discriminator of its nature

  One peak: Dirac fermion Two peaks: Majorana fermion

- At the muon collider, Dirac/Majorana nature of can be efficiently determined once it is confirmed