# Distinguishing Dirac/Majorana Fermion at future lepton colliders

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Based on Phys. Rev. Lett. 134 (2025) 2, 021801, Collaboration with Qing-Hong Cao and Kun Cheng

# The 1937 Proposal of the Majorana Fermion



**Ettore Majorana**

Majorana in the 1930s

| | |
|---|---|
| **Born** | 5 August 1906<br>Catania, Italy |
| **Died** | Missing since 1938, likely still alive in 1959[1]<br>unknown |

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

A symmetric theory of electrons and positrons

Majorana Equation:

1. Purely Hermitian Dirac Operator

$$(-i\frac{\partial}{\partial t} - i\hat{\alpha}\cdot\nabla + \beta m)\psi = 0$$

2. Charge-Conjugate Four-Component Form

$$i\partial\!\!\!/\psi - m\psi^c = 0$$

3. Two-Component Weyl Form

$$i\bar{\sigma}^\mu\partial_\mu\psi_L + \eta m\omega\psi_L^* = 0$$

Neutrino!!!

# Majorana Fermion Candidates

- Standard model neutrinos
- 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)
- Loop-level seesaw mechanism: $Z_2$ symmetry

  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
- Supersymmetric Models: neutralinos

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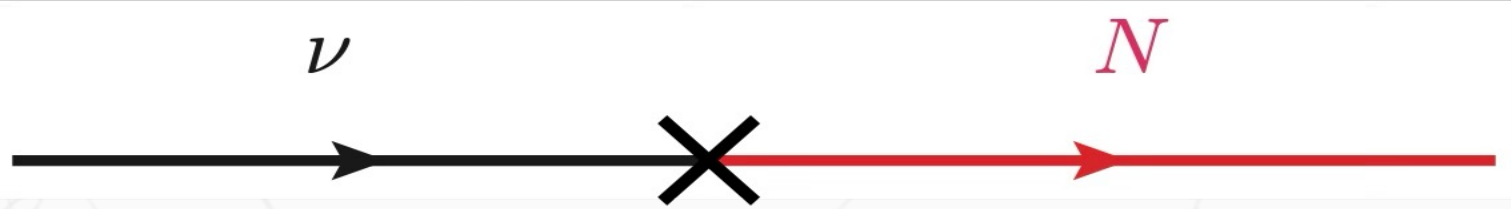
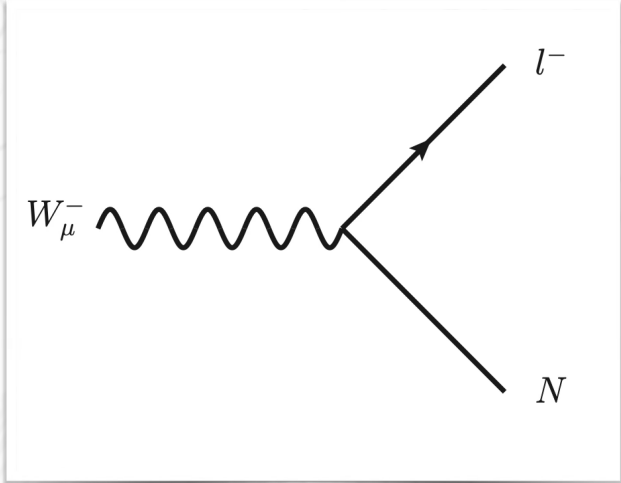
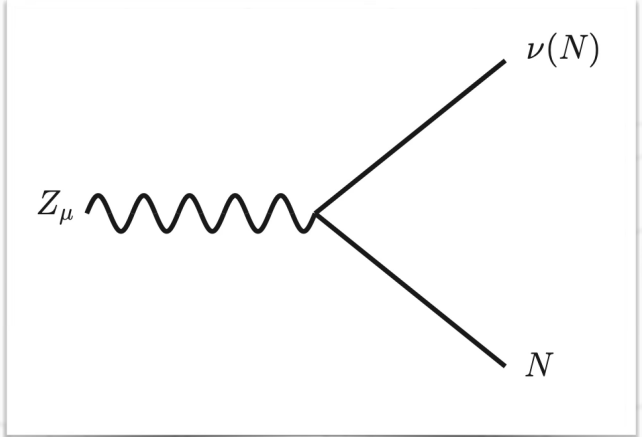
# Heavy Neutral Leptons (HNLs)




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

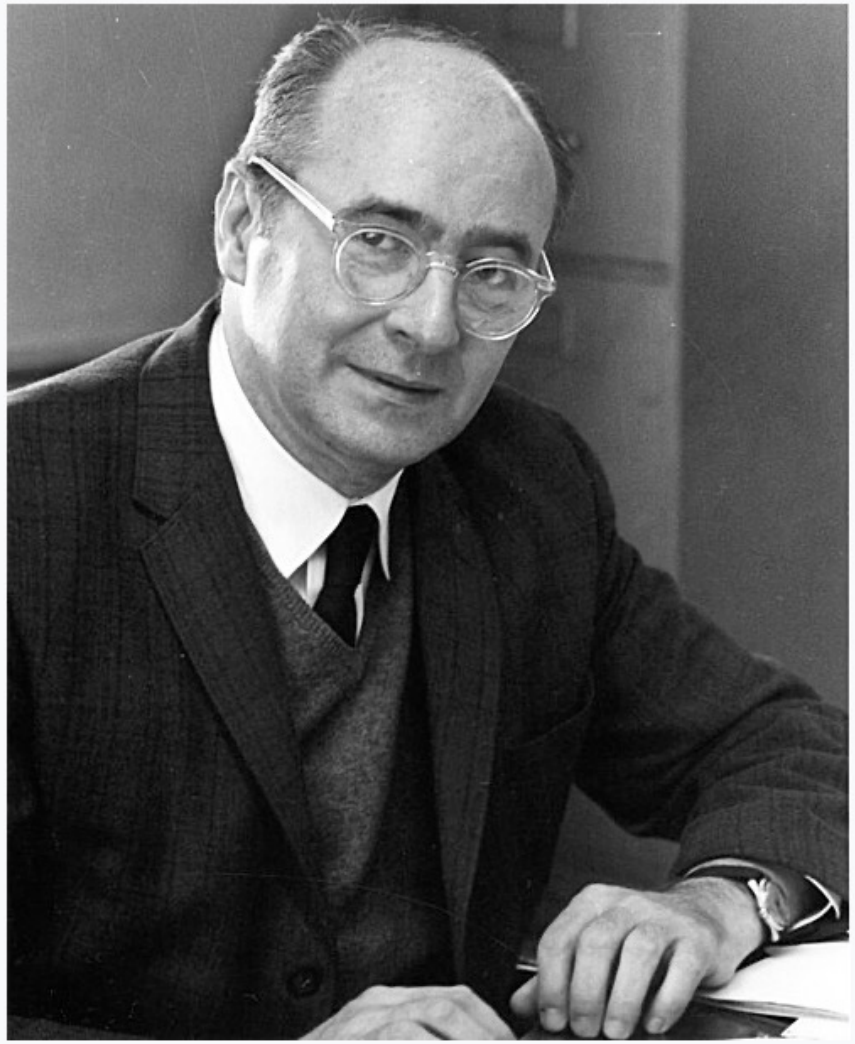


# neutrinoless double beta decay



**Wendell H. Furry**



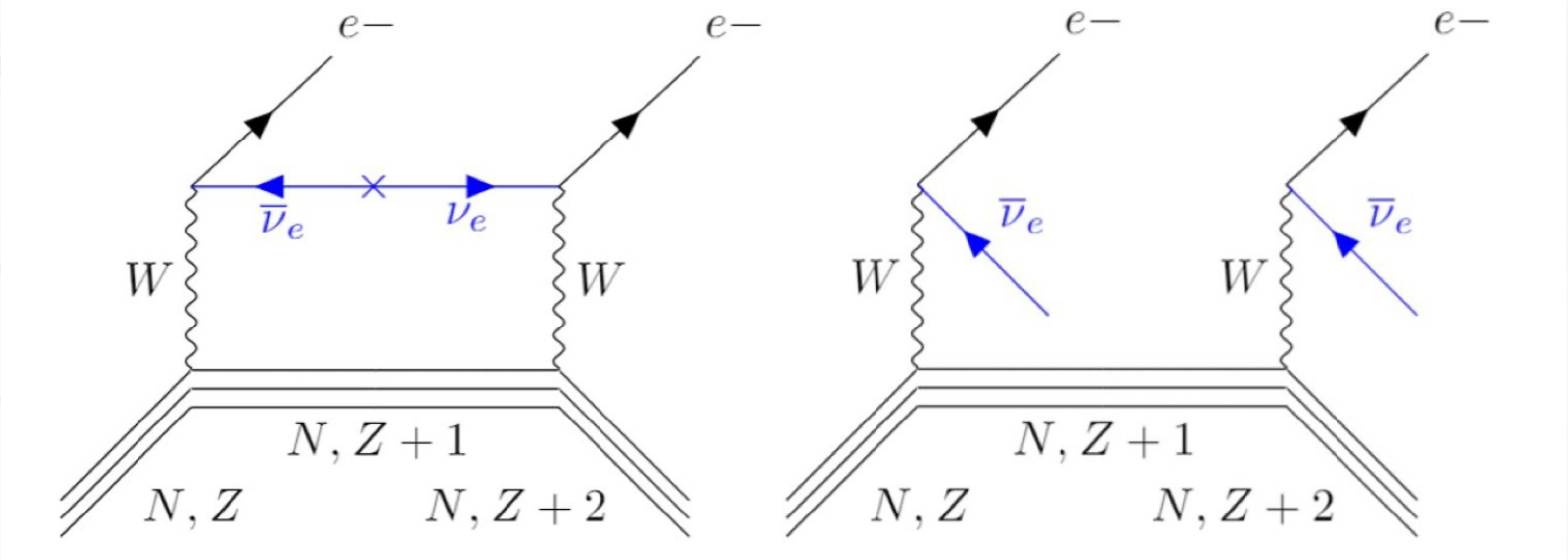
DECEMBER 15, 1939 PHYSICAL REVIEW VOLUME 56

**On Transition Probabilities in Double Beta-Disintegration**

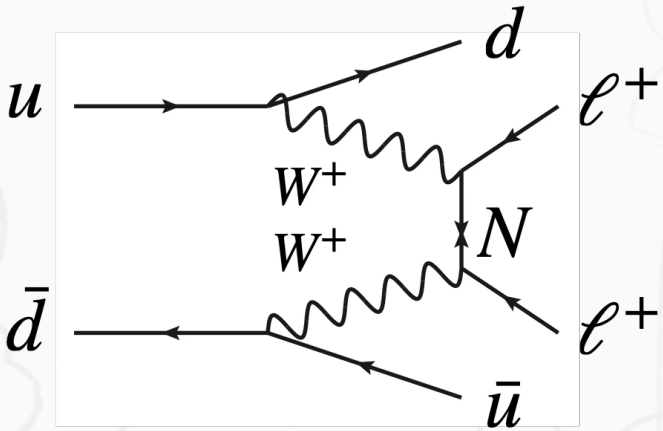
W. H. Furry
*Physics Research Laboratory, Harvard University, Cambridge, Massachusetts*

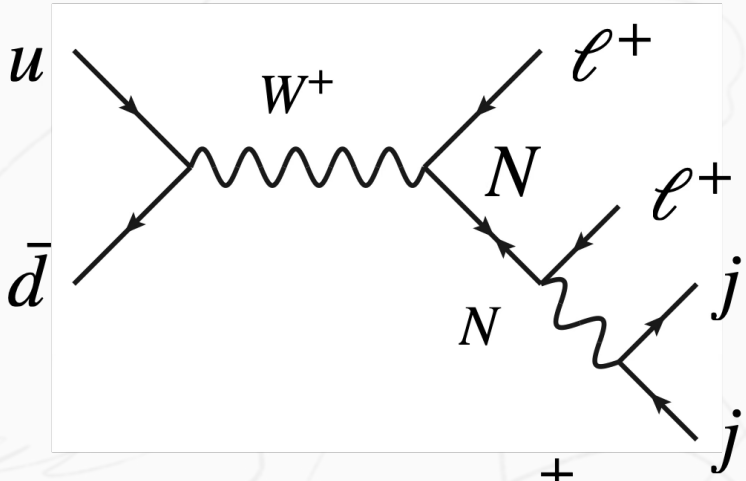
(Received October 16, 1939)

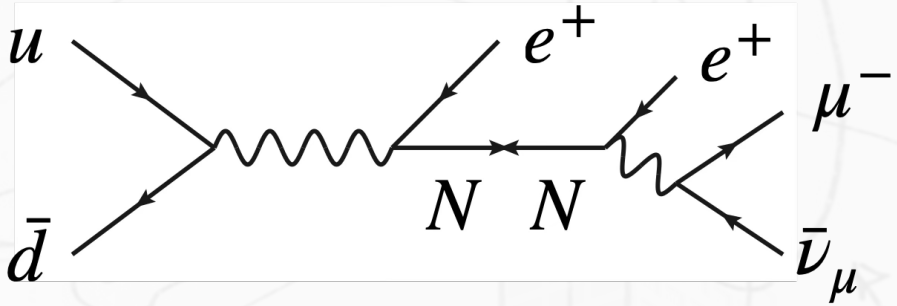
1939.10

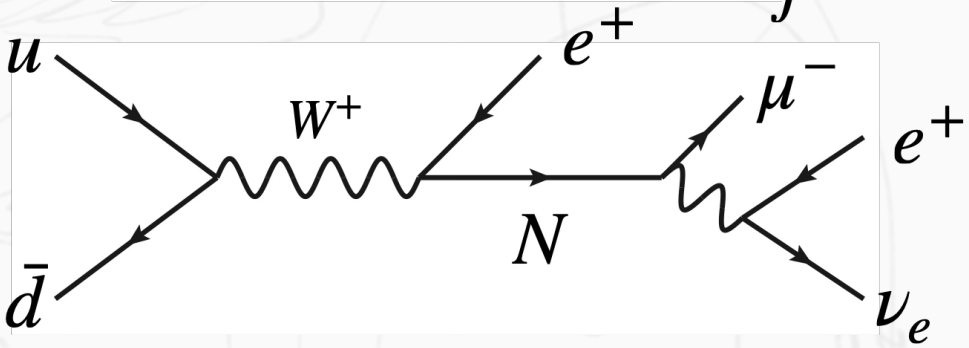


# “neutrinoless double beta decay” at the LHC




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)

# Distinguishing Dirac vs. Majorana by Distributions



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

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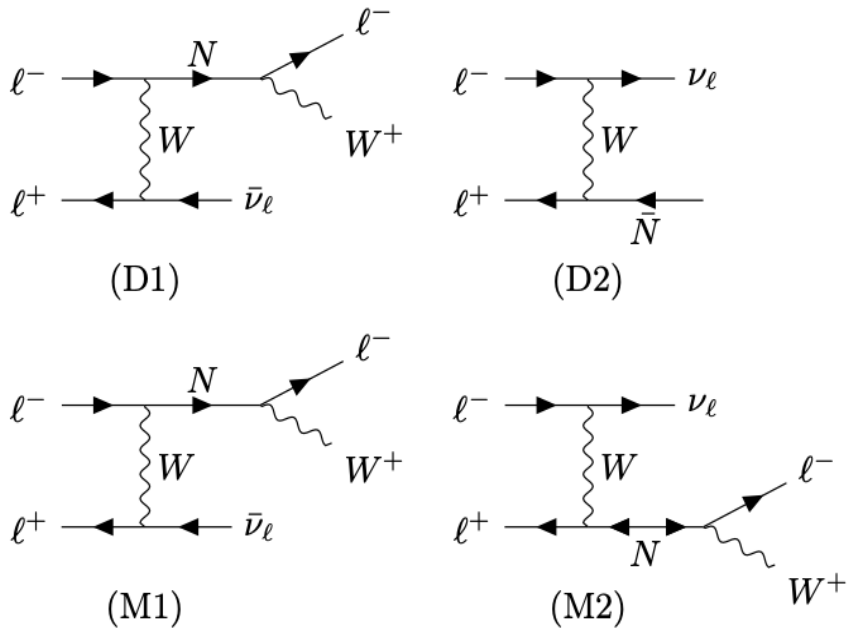
*Institute of Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Boulevard Lenin 72, Sofia 1184, Bulgaria and Fermi National Accelerator Laboratory, Batavia, IL 60510, USA*

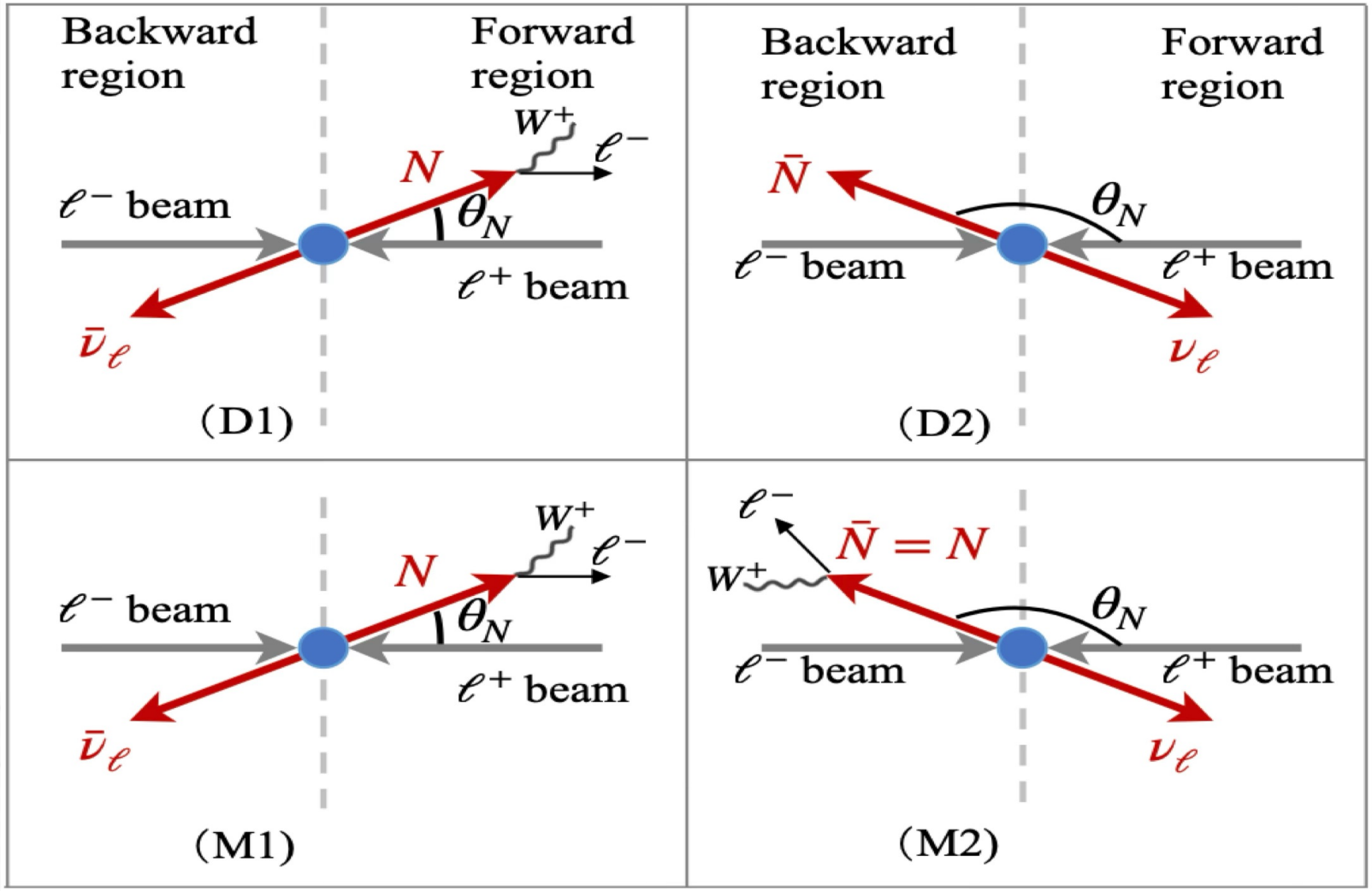
Received 4 January 1984

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

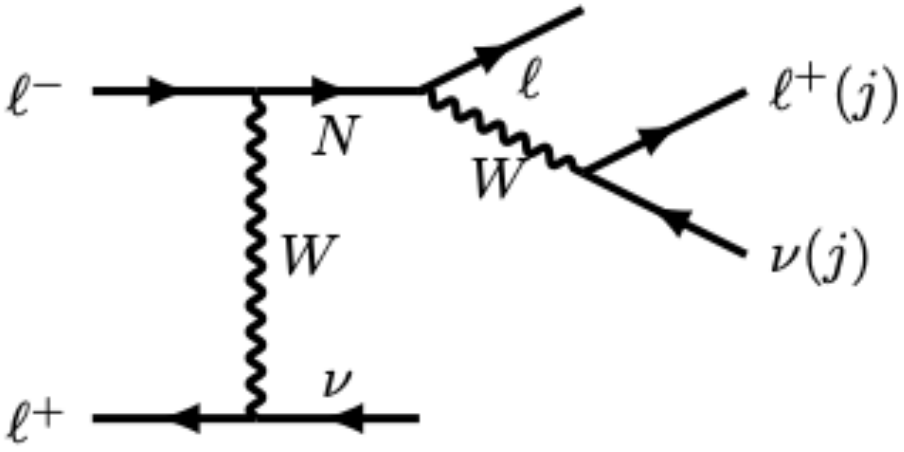
It is shown that the forward–backward asymmetry in the production of Majorana particles in $e^+$–$e^-$ and p–$\bar{p}$ collisions is identically equal to zero if the couplings generating the process conserve the *CP*-parity, and that the asymmetry vanishes to leading order in perturbation theory if the production mechanism is perturbative and the *S*-matrix is *CPT*-invariant. In the case of p–$\bar{p}$ 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–$\bar{p}$ collisions at high energies.

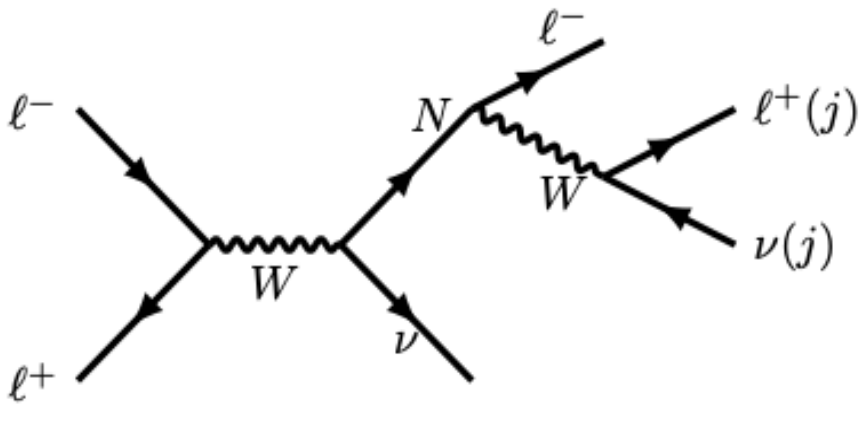
# Distinguishing Dirac vs. Majorana HNLs at Muon Colliders

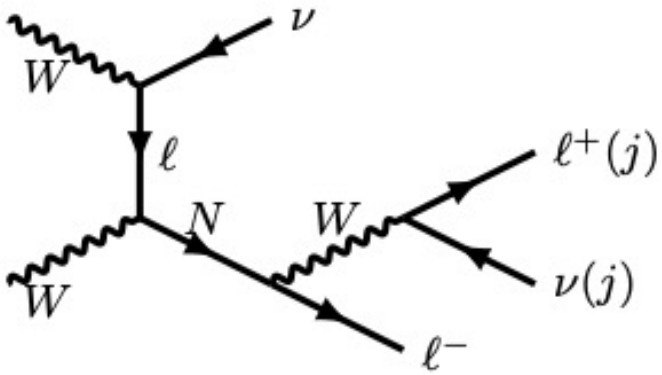


# HNLs at Muon Colliders

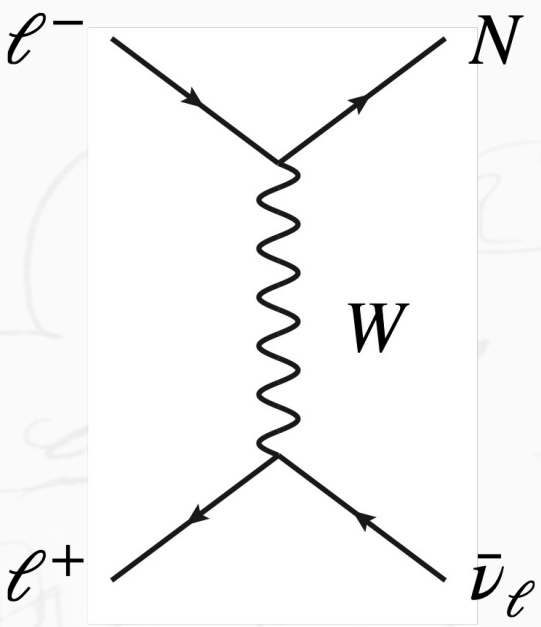


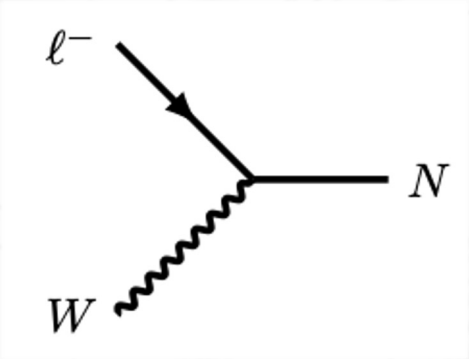

I. Chakraborty, H. Roy, and T. Srivastava, (2022), 10.1140/ep jc/s10052-023-11406-0; T. Li, C.-Y. Yao, and M. Yuan, JHEP 09, 131 (2023); T. H. Kwok, L. Li, T. Liu, and A. Rock, (2023), arXiv:2301.05177; P. Li, Z. Liu, and K.-F. Lyu, JHEP 03, 231 (2023), arXiv:2301.07117; R.-Y. He, J.-Q. Huang, J.-Y.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

# Rapidity of HNLs at Muon Colliders




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

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



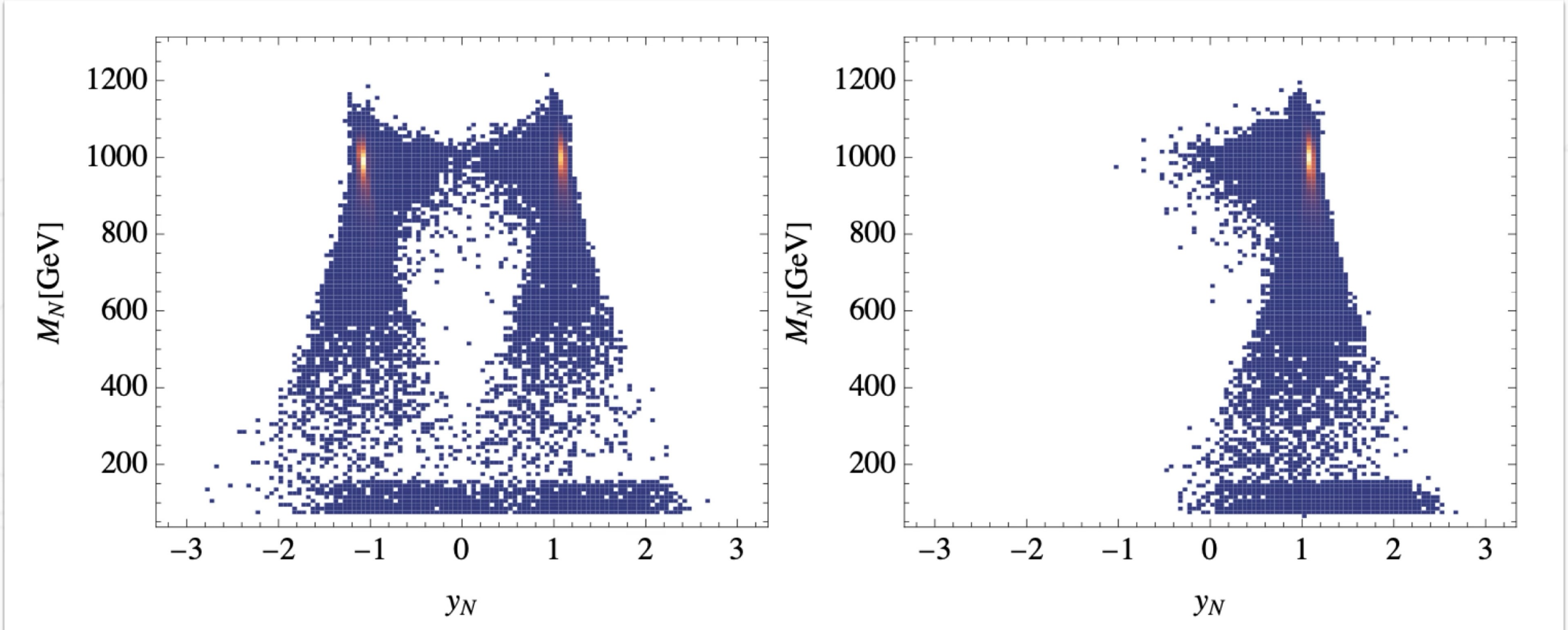

$x_1 = 1$

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

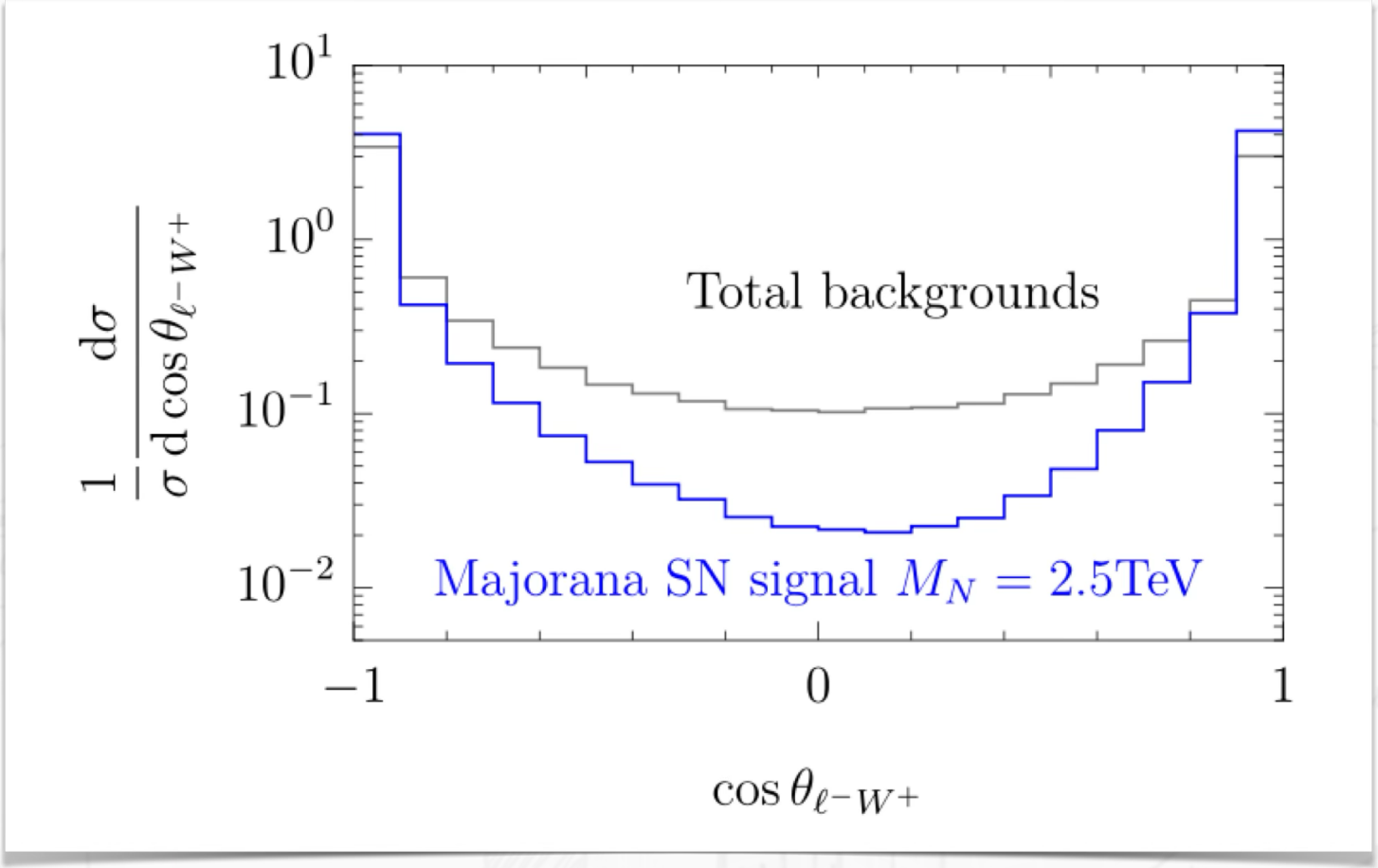
$$y_N = \frac{1}{2}\log(x_1/x_2) = \frac{1}{2}\log(s/m_N^2)$$

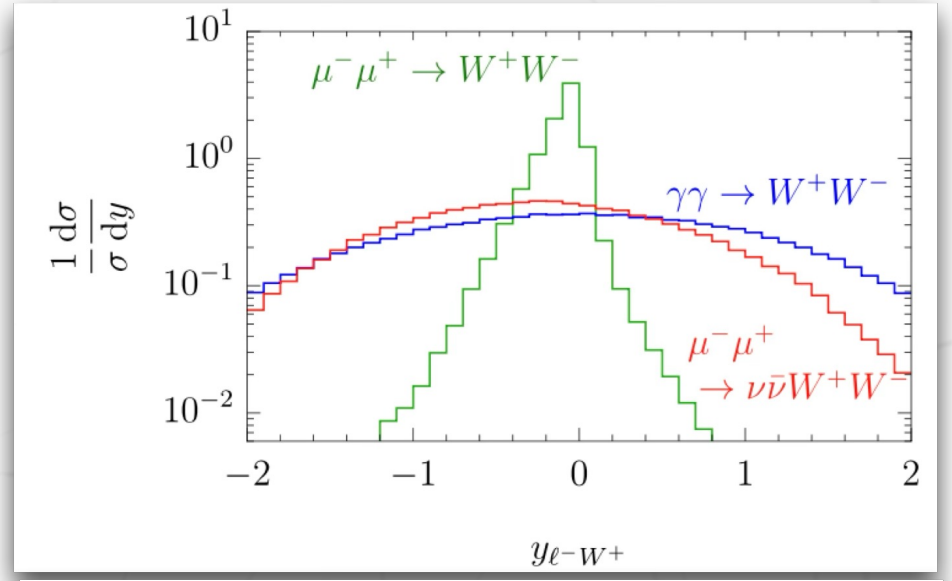
# Advance of Rapidity: Correlation with Mass

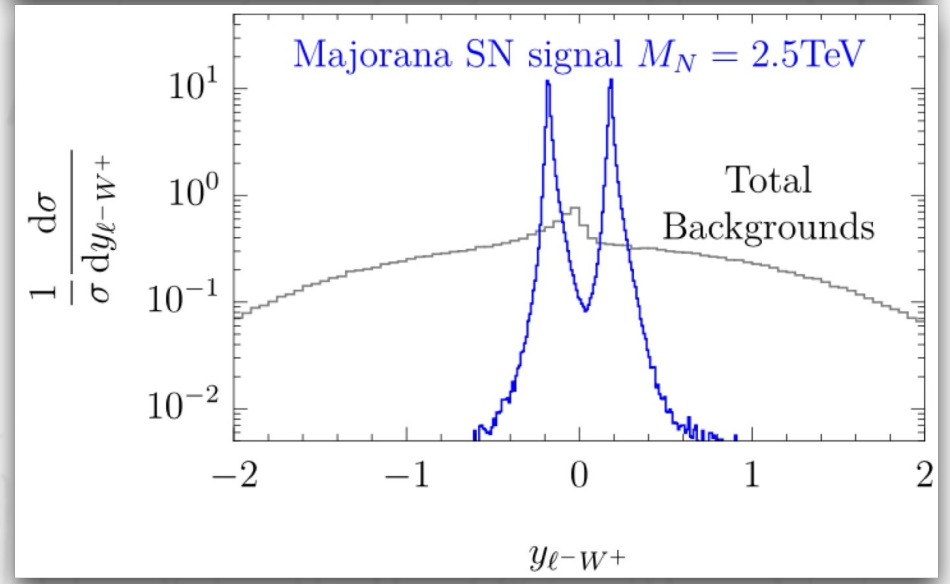
$$y_N = \frac{1}{2}\log\frac{E + p_N \cos\theta_N}{E - p_N \cos\theta_N} \qquad \mathrm{v}_N^Z = tanh\, y_N$$



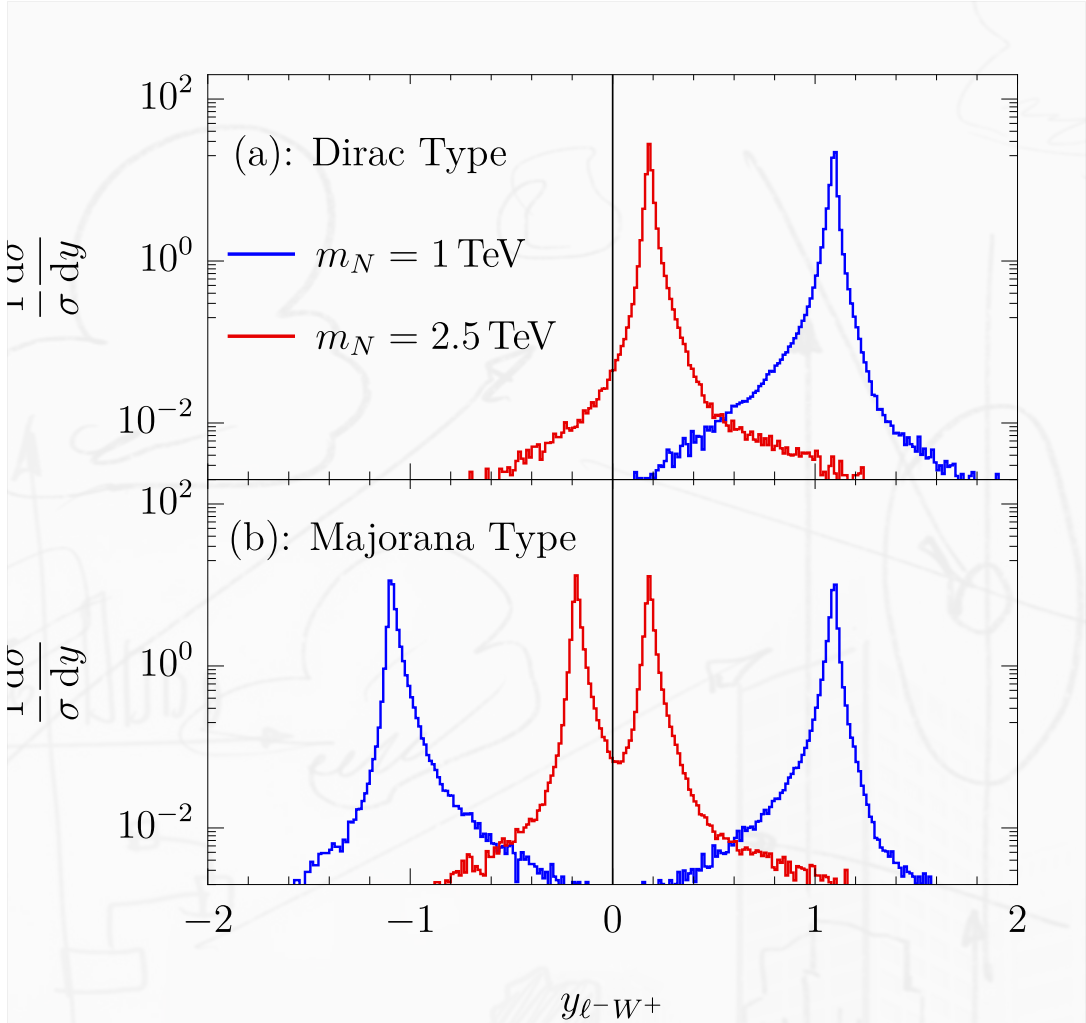
# Advance of Rapidity: Signal Discrimination

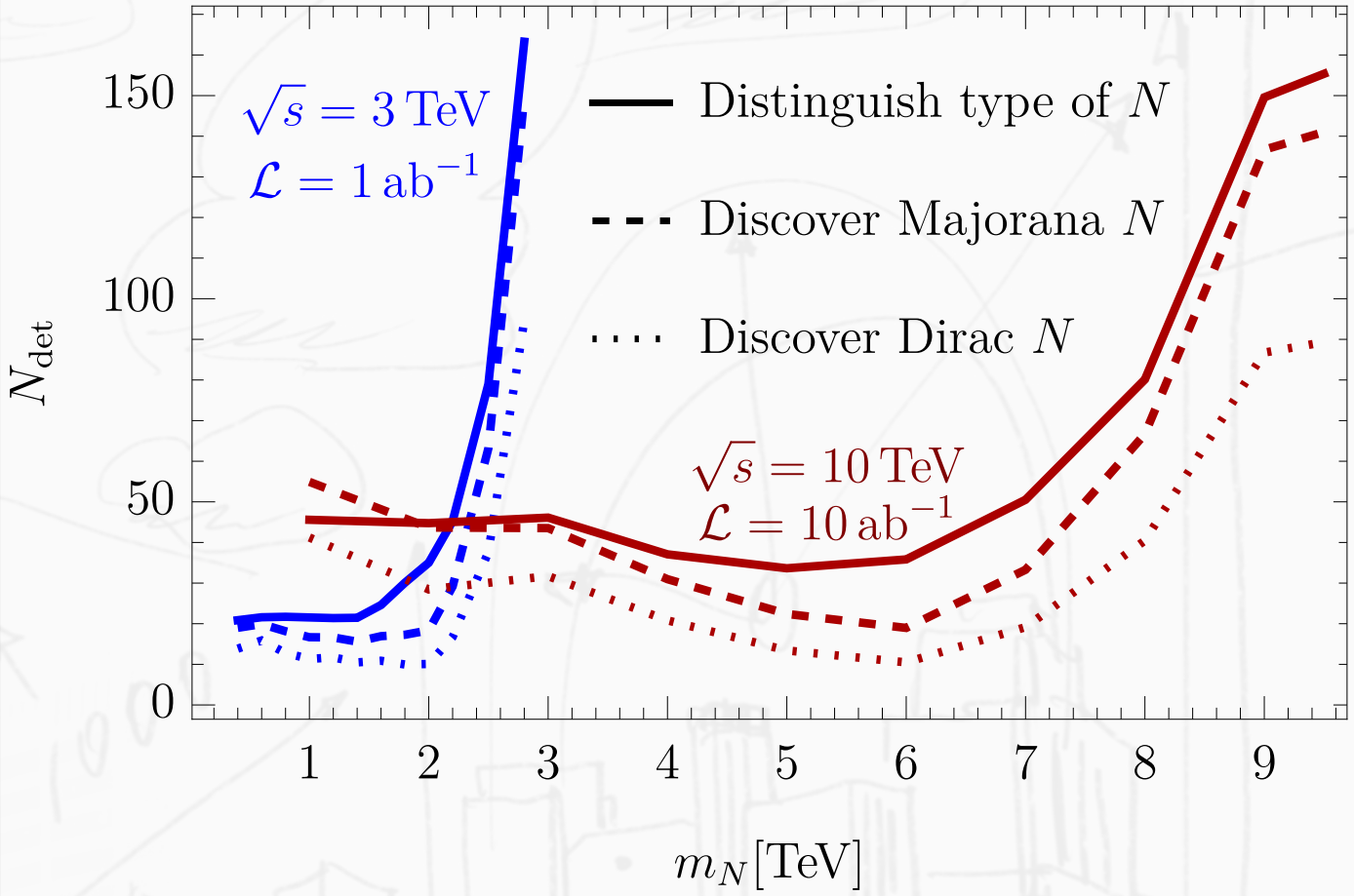


# Discovery and Discrimination Reach at Muon Colliders



# 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

# 谢谢！