北京師範大學
BEIJING NORMAL UNIVERSITY

Distinguishing Dirac/Majorana Heavy Neutrino at Future Lepton Colliders

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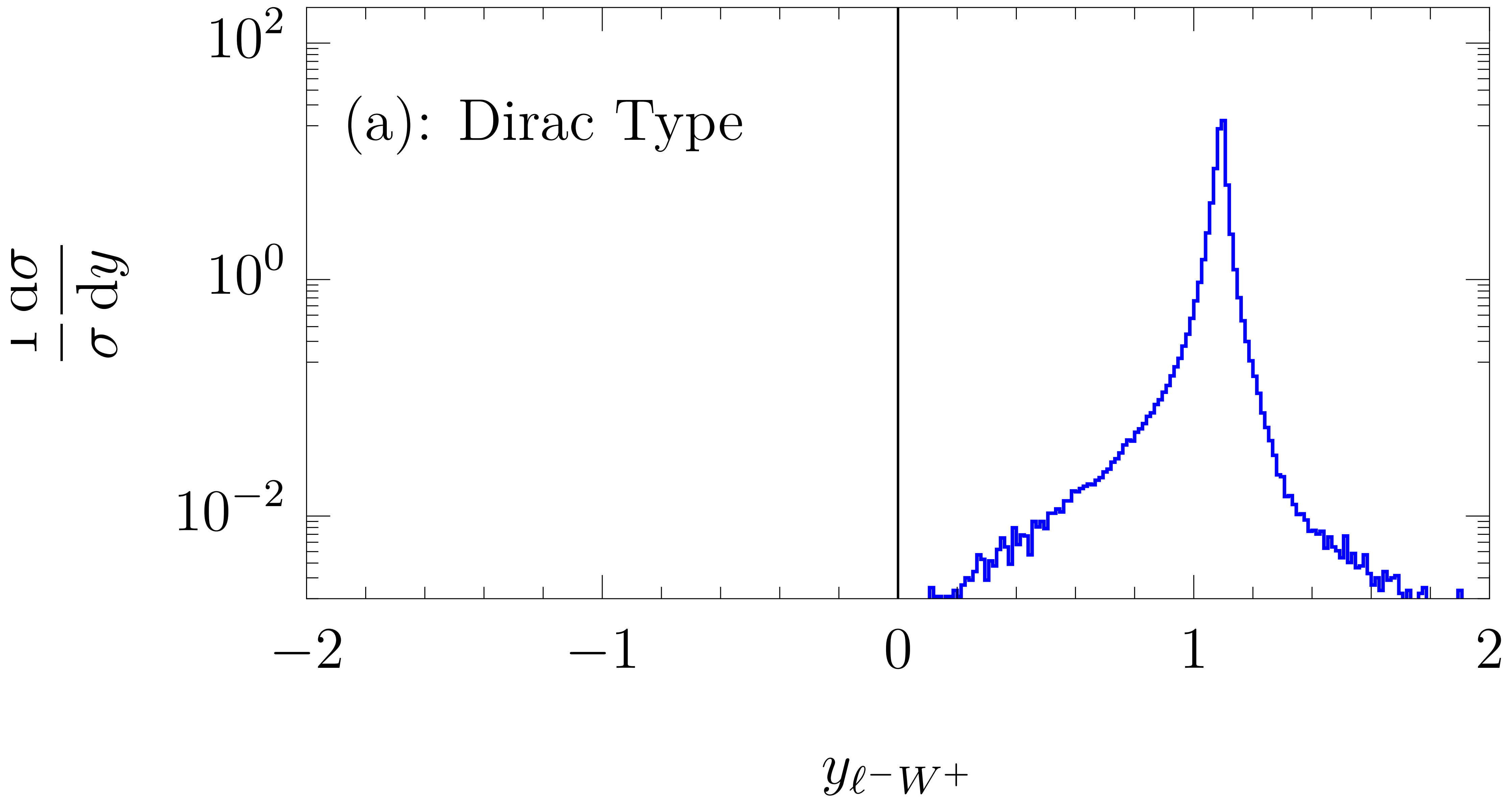
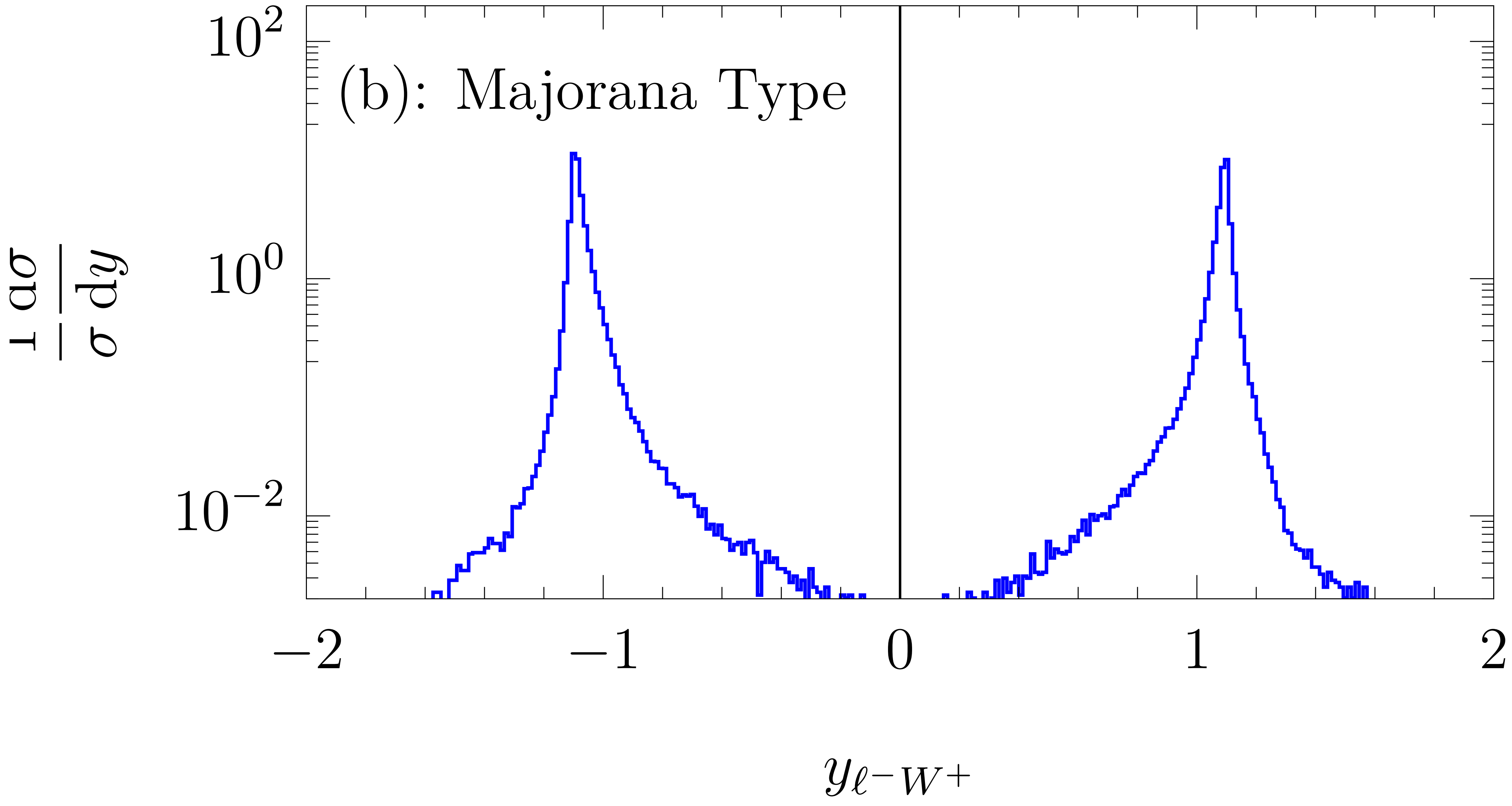
Collaboration with Qing-Hong Cao and Kun Cheng

2024.7.14

Motivation

How to identify the nature of a fermion (heavy neutral lepton)? Is it Dirac or Majorana?





Proposal of Majorana Fermion:1937

Ettore Majorana

Majorana in the 1930s

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

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

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

3. Complex two-component

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

Particle≡Anti-Particle

$$\psi \equiv \psi^c$$

Whether the Majorana fermion (mode) exists?

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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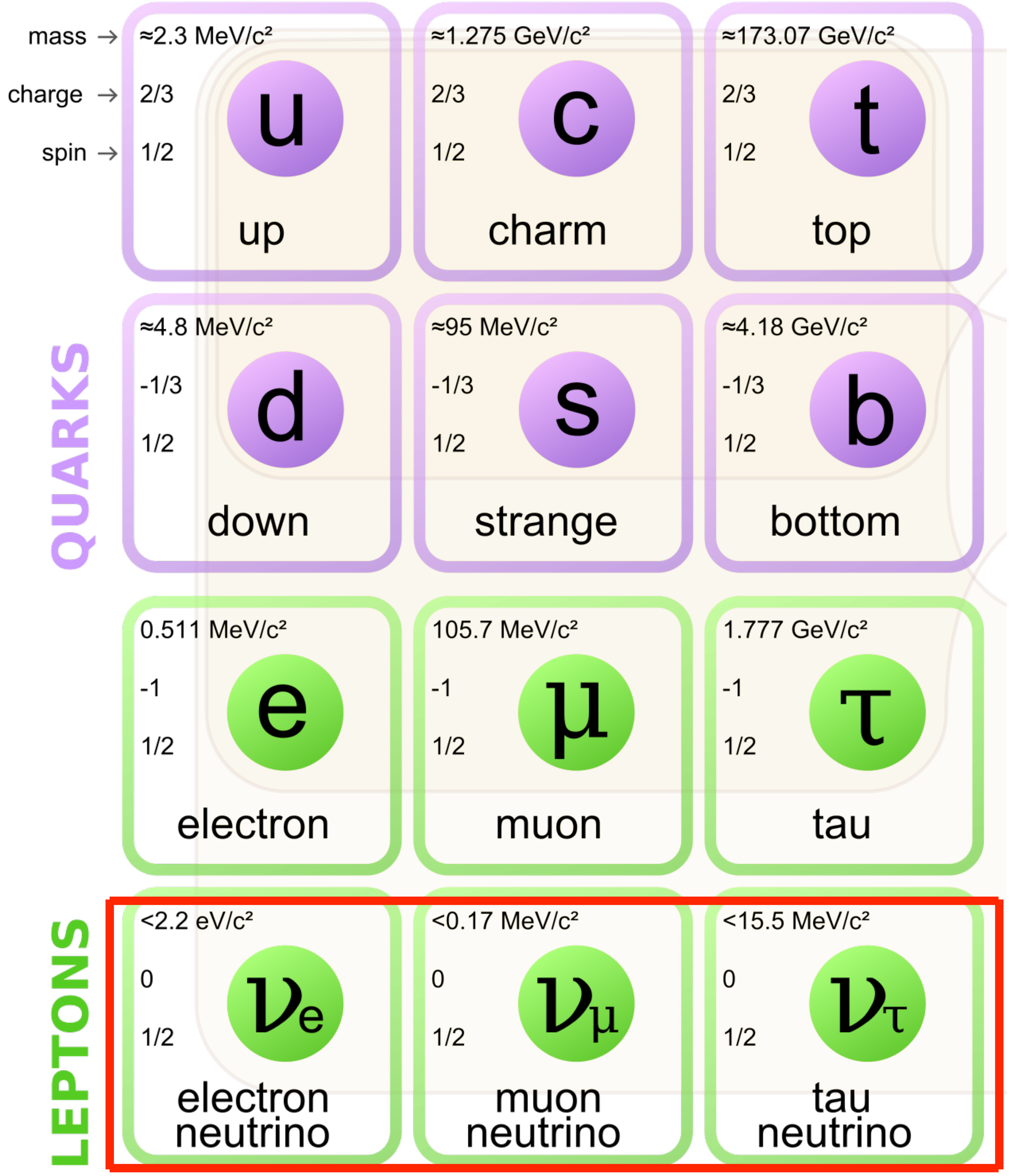
Whether the Majorana fermion exists in SM?



Electron effective Majorana Mass:

$$m_{ee} < 61 - 165 \text{ meV}$$

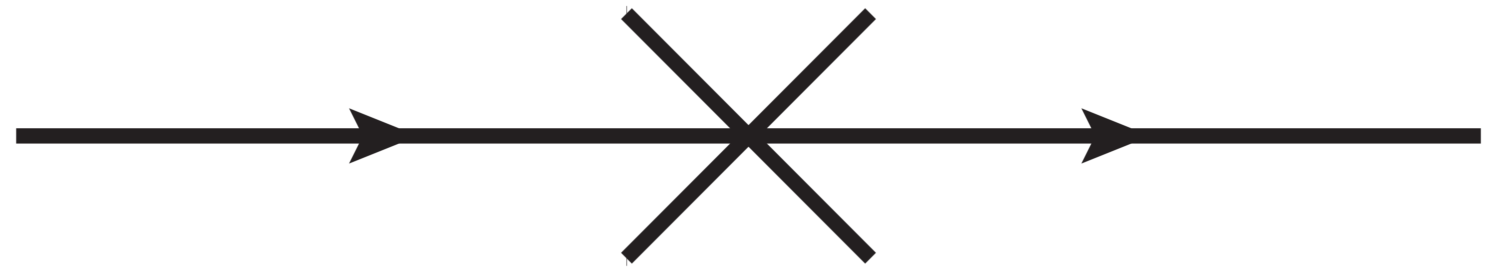
Search for Majorana Neutrinos near the Inverted Mass Hierarchy Region with KamLAND-Zen

A. Gando,[1] Y. Gando,[1] T. Hachiya,[1] A. Hayashi,[1] S. Hayashida,[1] H. Ikeda,[1] K. Inoue,[1,2] K. Ishidoshiro,[1] Y. Karino,[1] M. Koga,[1,2] S. Matsuda,[1] T. Mitsui,[1] K. Nakamura,[1,2] S. Obara,[1] T. Oura,[1] H. Ozaki,[1] I. Shimizu,[1] Y. Shirahata,[1] J. Shirai,[1] A. Suzuki,[1] T. Takai,[1] K. Tamae,[1] Y. Teraoka,[1] K. Ueshima,[1] H. Watanabe,[1] A. Kozlov,[2] Y. Takemoto,[2] S. Yoshida,[3] K. Fushimi,[4] T.I. Banks,[5] B.E. Berger,[2,5] B.K. Fujikawa,[2,5] T. O'Donnell,[5] L.A. Winslow,[6] Y. Efremenko,[2,7] H.J. Karwowski,[8] D.M. Markoff,[8] W. Tornow,[2,8] J.A. Detwiler,[2,9] S. Enomoto,[2,9] and M.P. Decowski[2,10]
(KamLAND-Zen Collaboration)

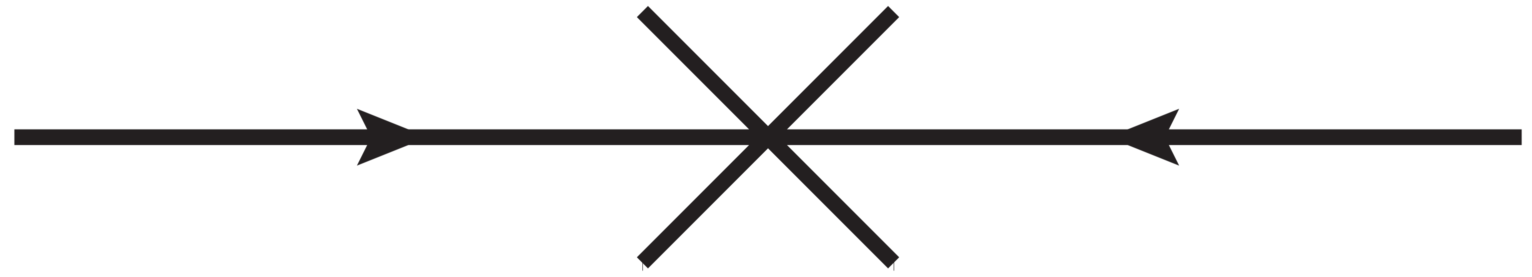
Interactions of neutrinos

	Dirac	Majorana
Charged Current Interaction	$e_L^\dagger \bar{\sigma}^\mu \nu_L W_\mu^- + h.c.$	$e_L^\dagger \bar{\sigma}^\mu \nu_L W_\mu^- + h.c.$
Nuetral Current Interaction	$\nu_L^\dagger \bar{\sigma}^\mu \nu_L Z_\mu$	$\nu_L^\dagger \bar{\sigma}^\mu \nu_L Z_\mu$
Mass term	$\nu_L \nu_R + h.c.$	$\nu_L \nu_L + h.c.$

Dirac Mass



Majorana Mass



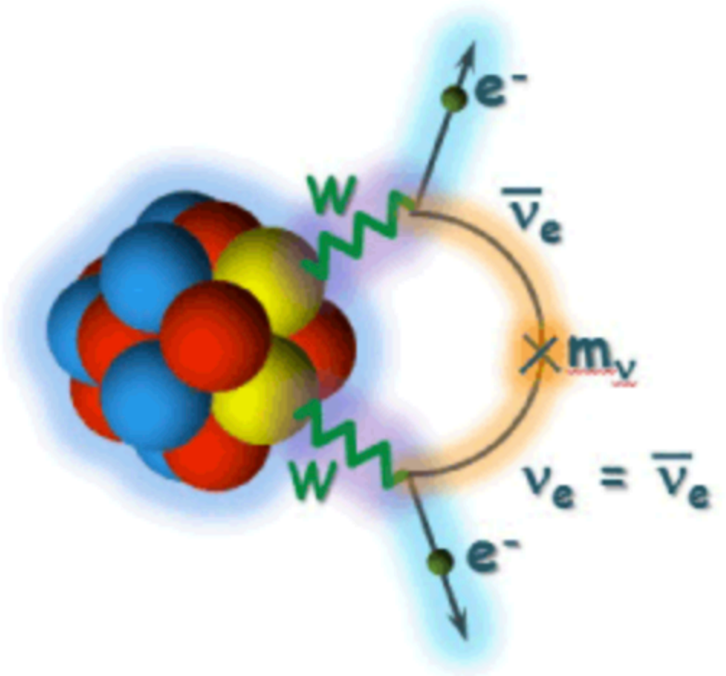
fermion (lepton) number violation

Discriminating power: $\frac{m_\nu}{\mu}$

Signal: lepton number violation

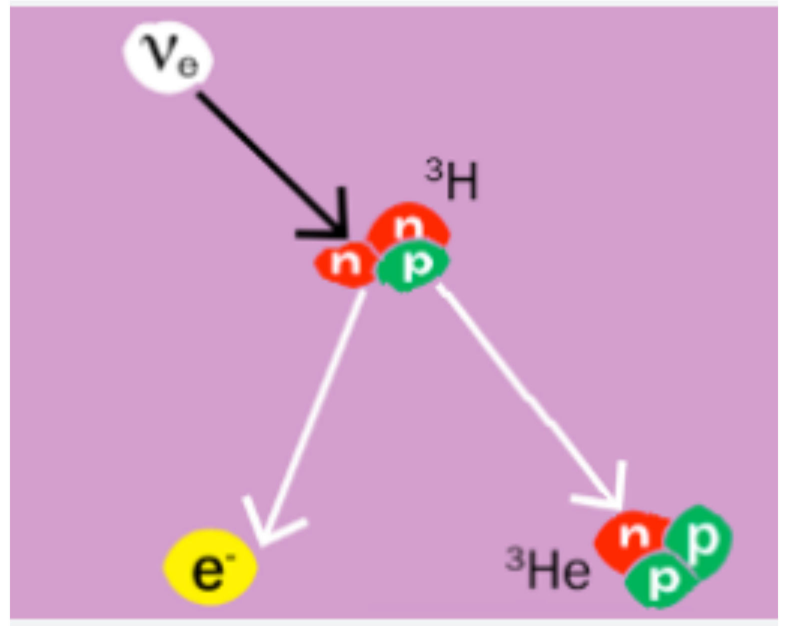
Experiments to explore the neutrino Majorana mass

- The neutrinoless double beta decay experiments



Lepton number violation $m_{ee} < 61 - 165$ meV

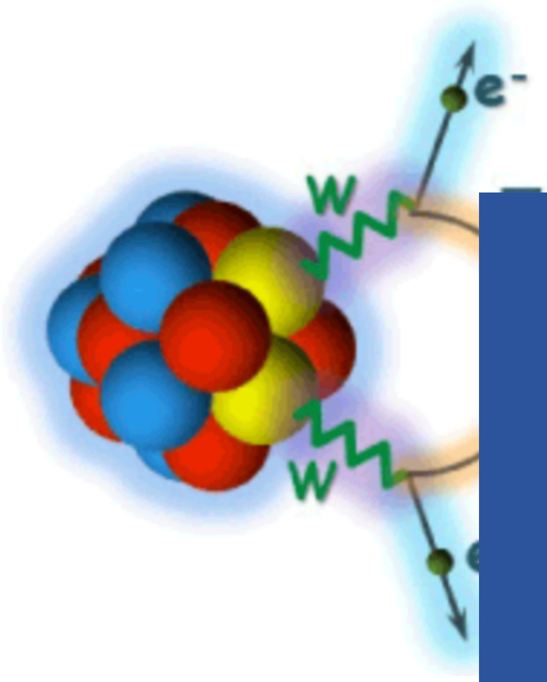
- The PTOLEMY experiment: cosmic neutrinos (non-relativistic neutrinos)



$$\Gamma_M = 2\Gamma_D \simeq 8/y$$

Experiments to explore the neutrino Majorana mass

- The neutrinoless double beta decay experiments

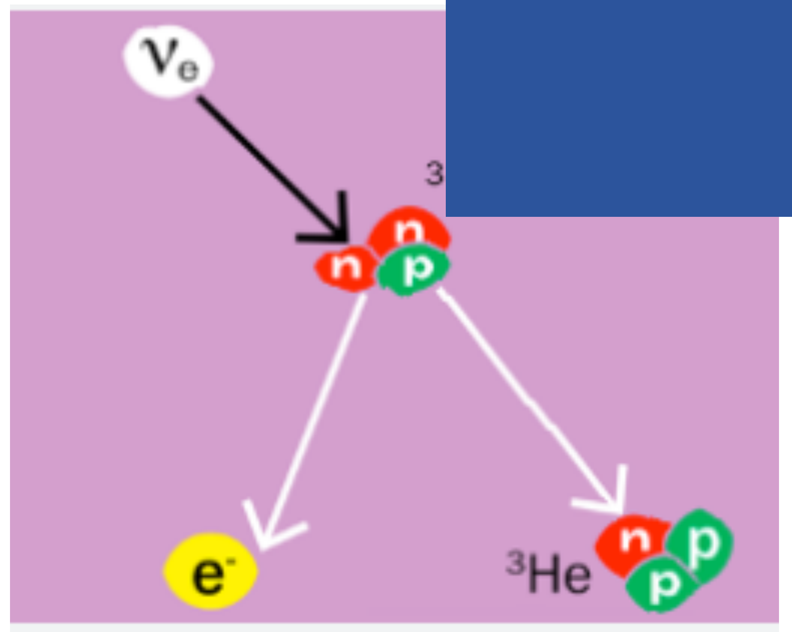


eV

Colliders power $\propto \frac{m_\nu}{\sqrt{s}}$

Impossible to answer the question at collider?

- The PTOL tic neutrinos)



$$\Gamma_M = 2\Gamma_D$$

Massive neutrinos: new physics beyond the SM

1. Yukawa interaction: right-handed neutrino (spectator)

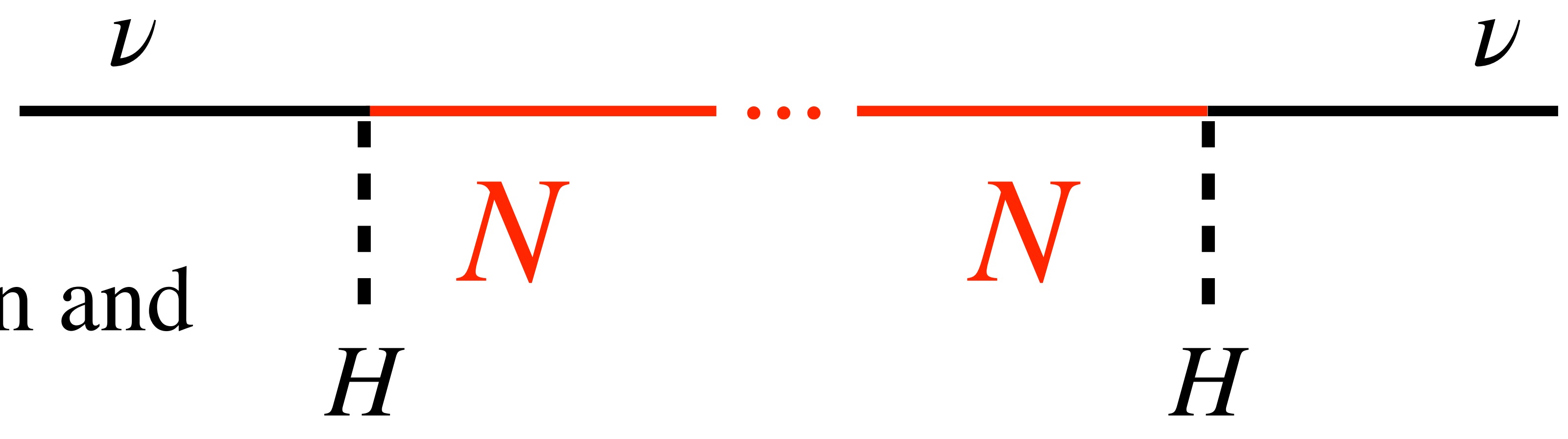
   J. Zhang, S. Zhou, *Nucl.Phys.B* 903 (2016) 211-225

2. Loop-level seesaw mechanism: Z_2 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

3. 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)



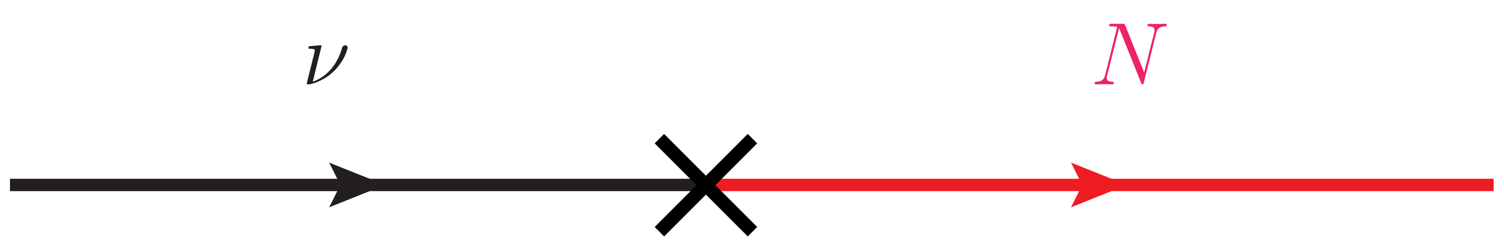
4. String theory or extra dimension models

   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)

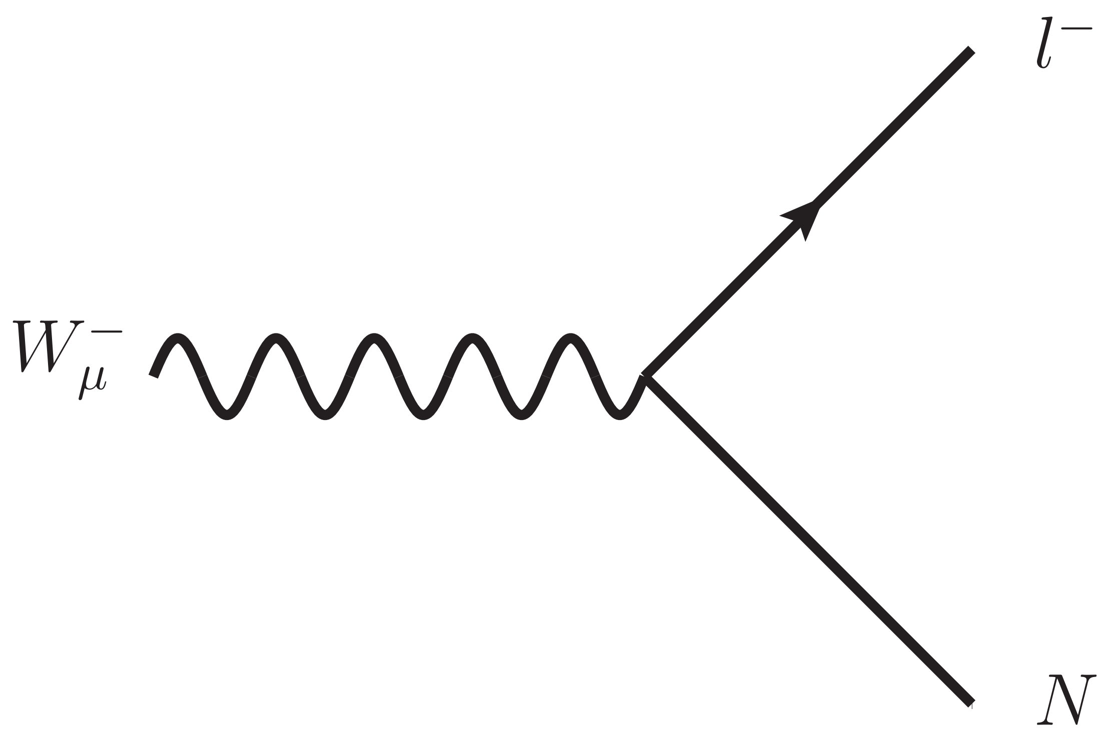
Heavy Neutral Lepton (HNL)

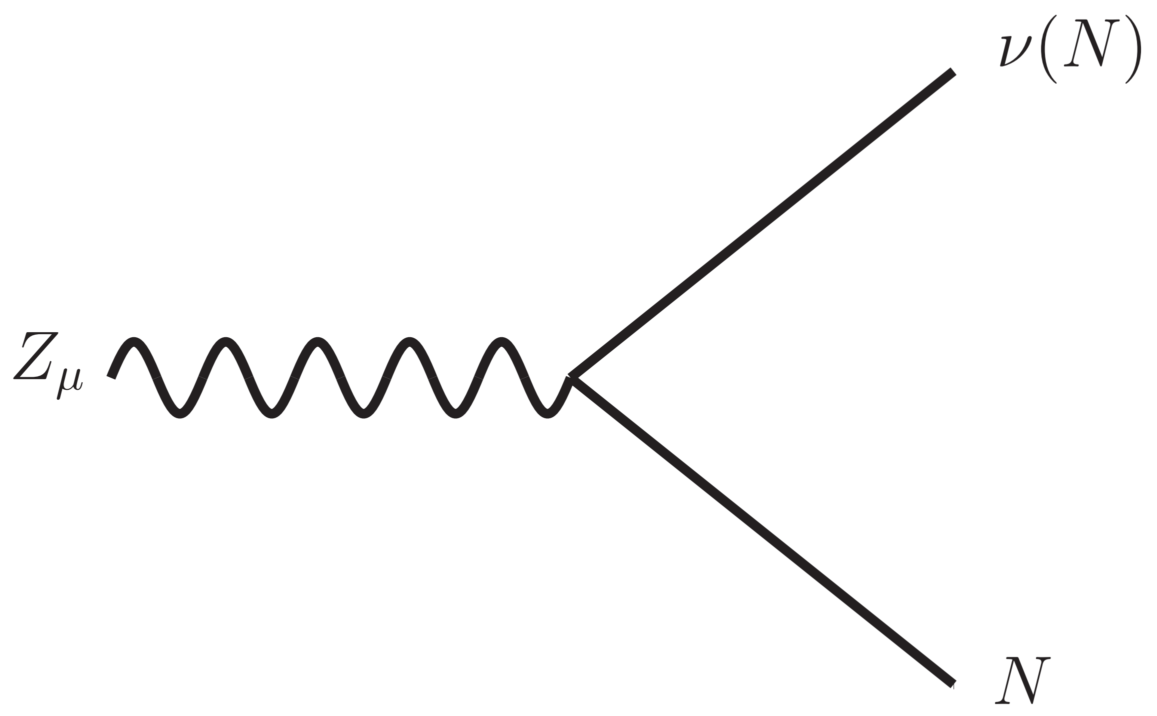
tree-level seesaw mechanism or string theory or extra dimension models

Heavy neutral lepton: Dirac or Majorana N



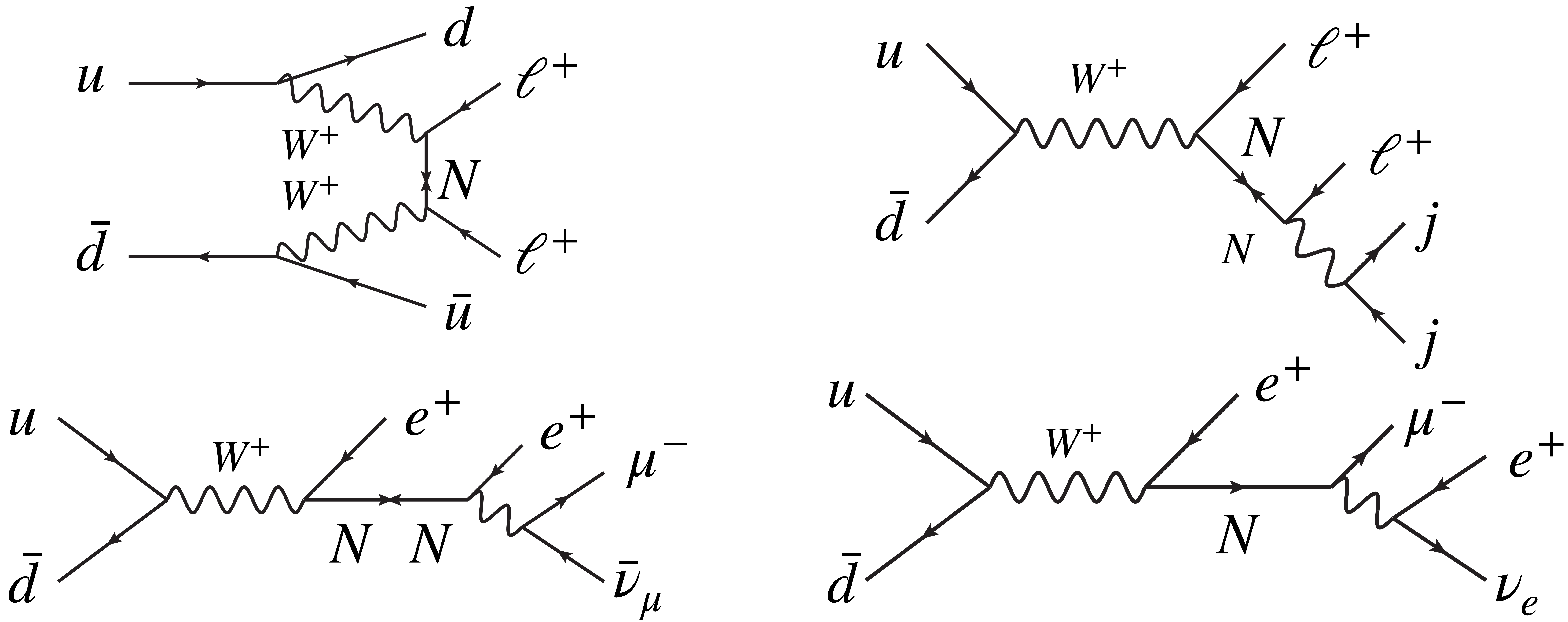
$$\sum_{i=e,\mu,\tau} \frac{g}{\sqrt{2}} U_i W_\sigma^- \bar{\ell}_{iL} \gamma^\sigma N + h.c. - \sum_{i=e,\mu,\tau} \frac{g}{2\cos\theta_W} U_i Z_\sigma (\bar{\nu}_{iL} \gamma^\sigma N + \bar{N} \gamma^\sigma \nu_{iL})$$





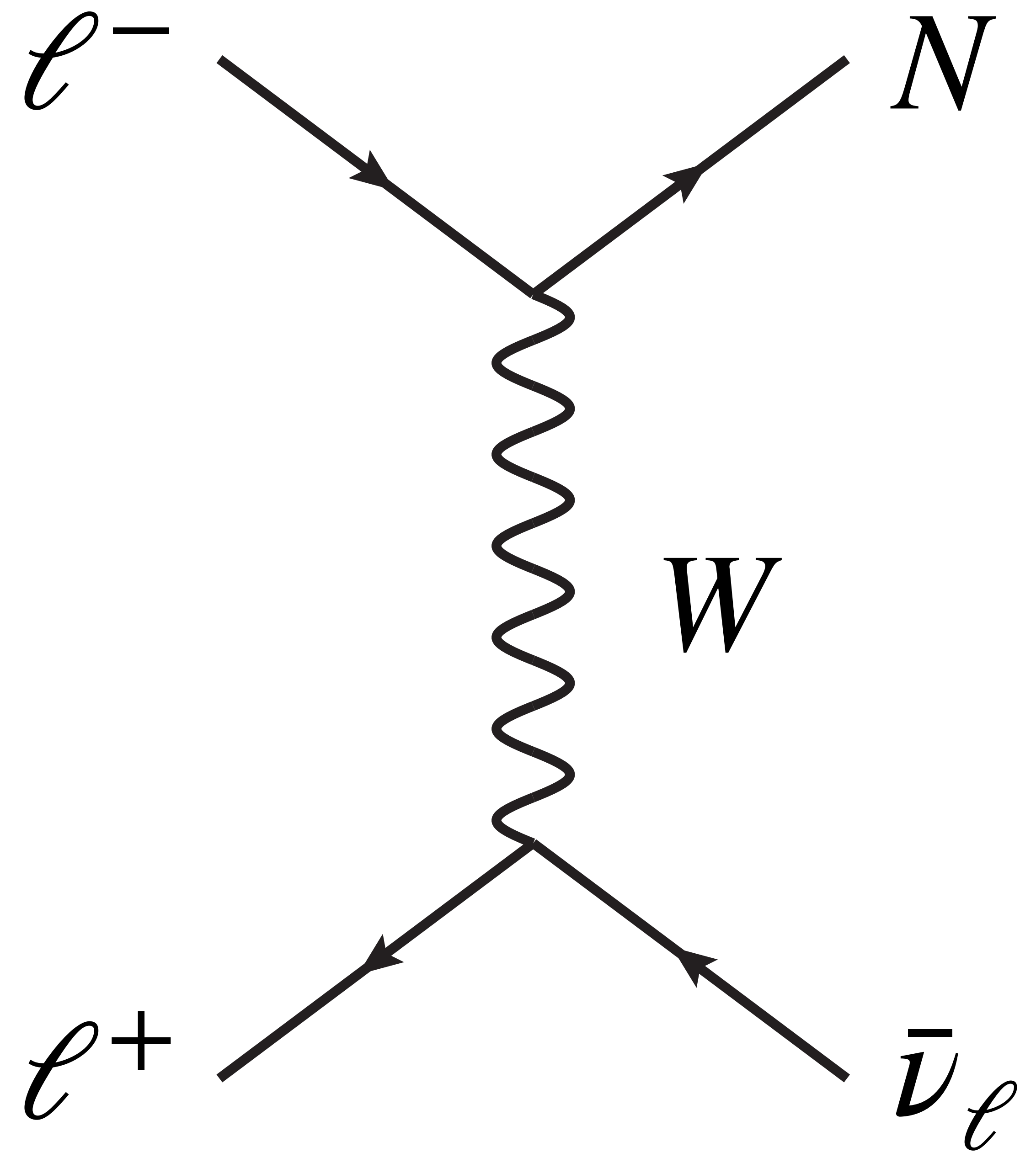
HNL@Hadron Colliders

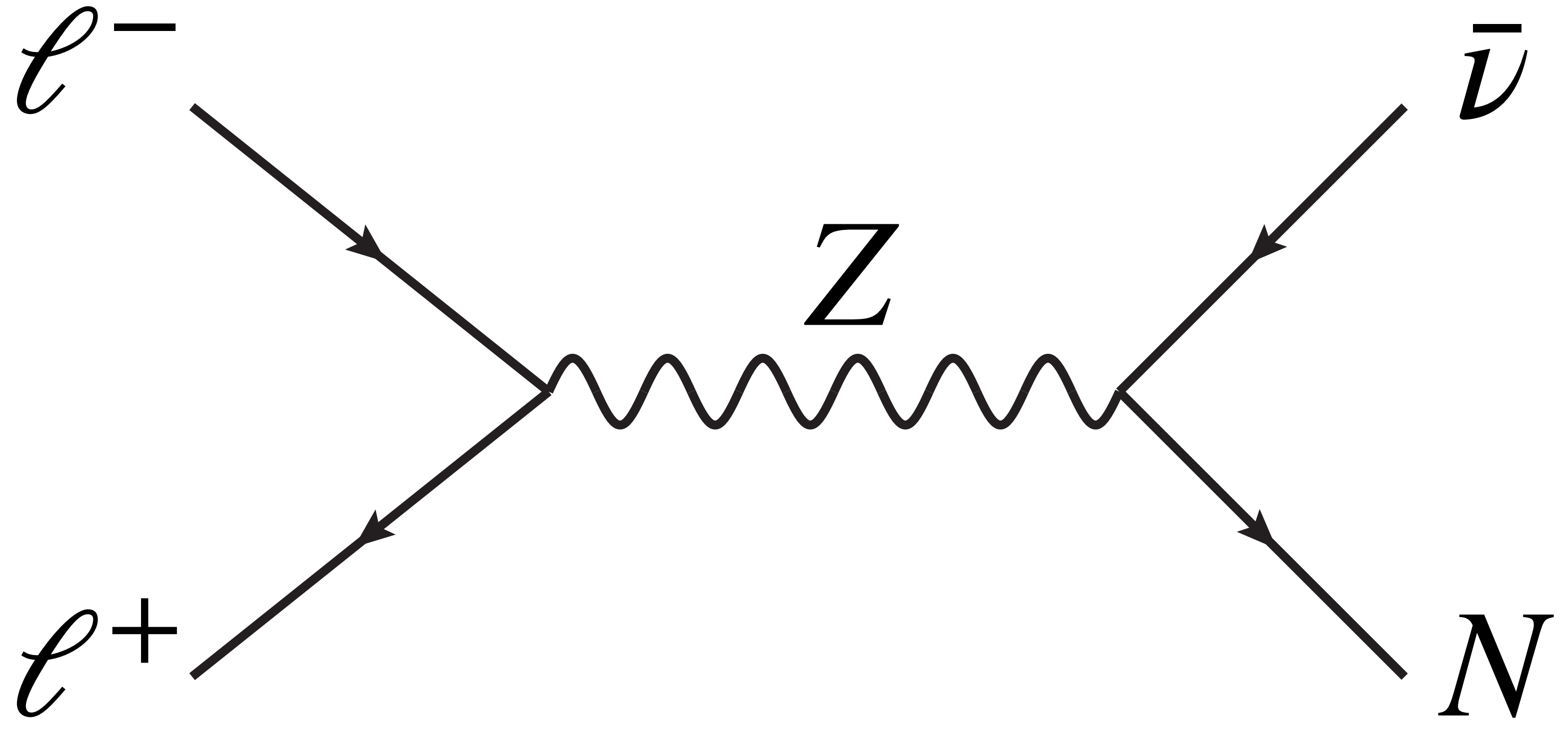
T. Han and B. Zhang, Phys. Rev. Lett. 97, 171804 (2006);A. Atre, T. Han, S. Pascoli, and B. Zhang, JHEP 05, 030 (2009);A. Atre, T. Han, S. Pascoli, and B. Zhang, JHEP 05, 030 (2009); A. Das and N. Okada, Phys. Rev. D 88, 113001 (2013); P. S. B. Dev, A. Pilaftsis, and U.-k. Yang, Phys. Rev. Lett. 112, 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)

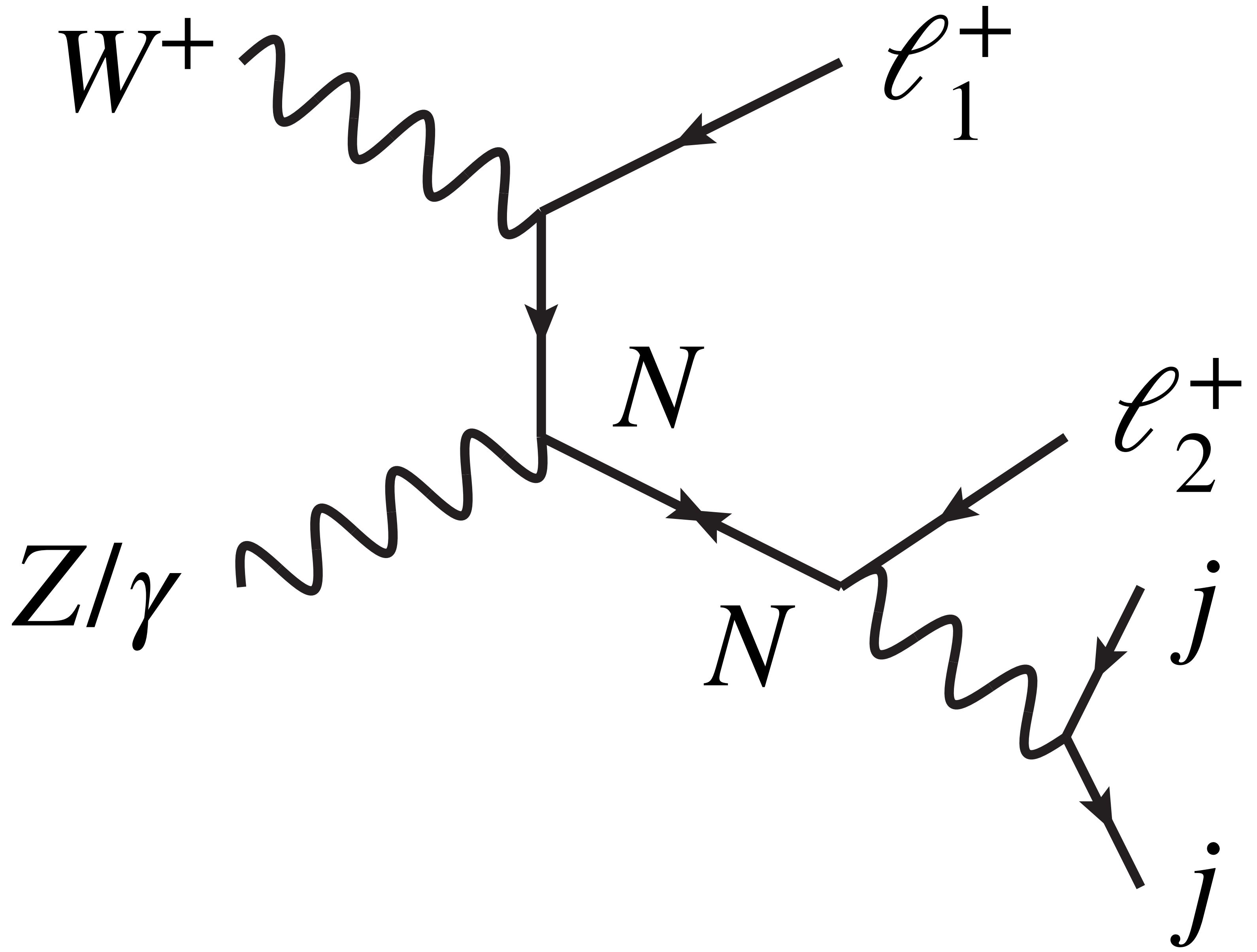


HNL@ high energy lepton colliders

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



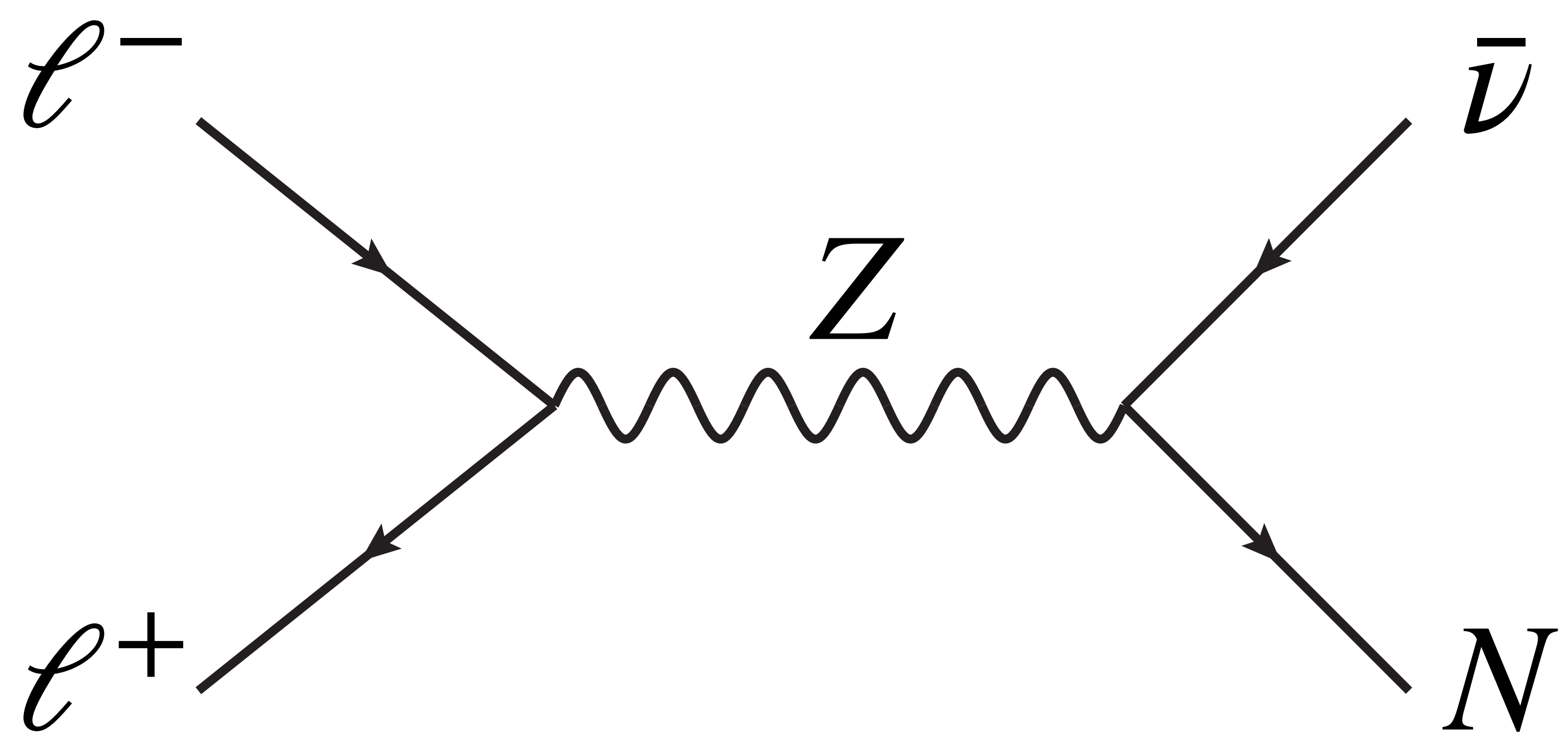




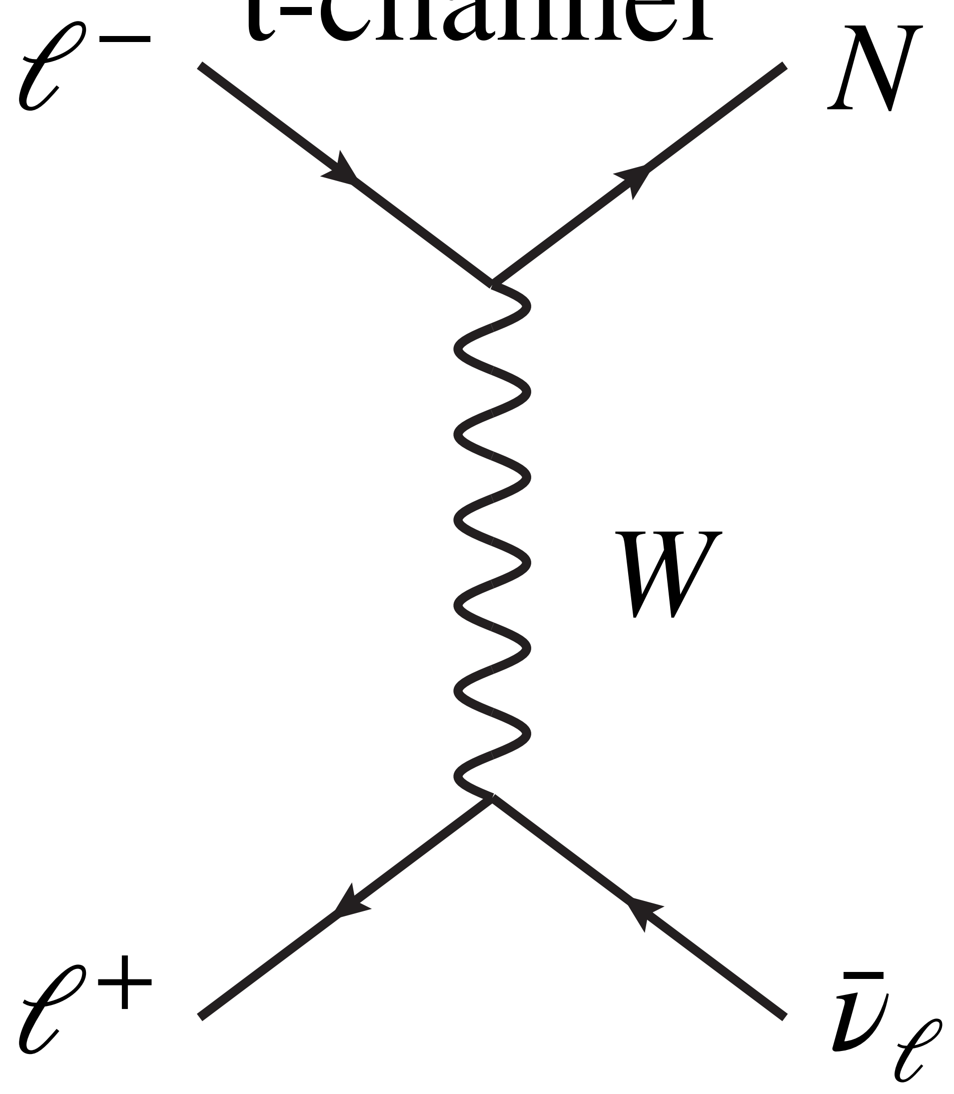
HNL@ high energy lepton colliders

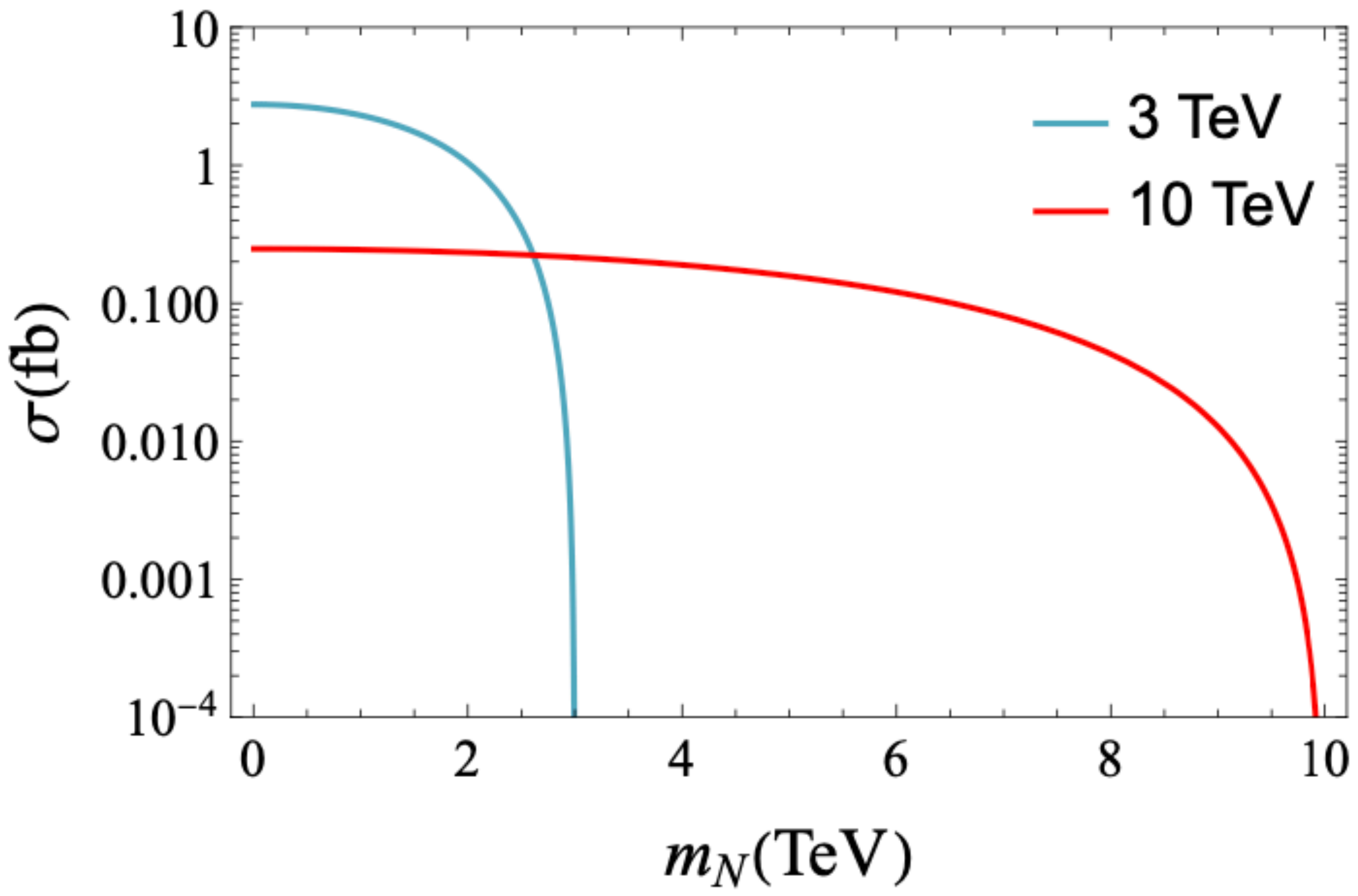
P. Li, Z. Liu, and K.-F. Lyu, JHEP 03, 231 (2023)

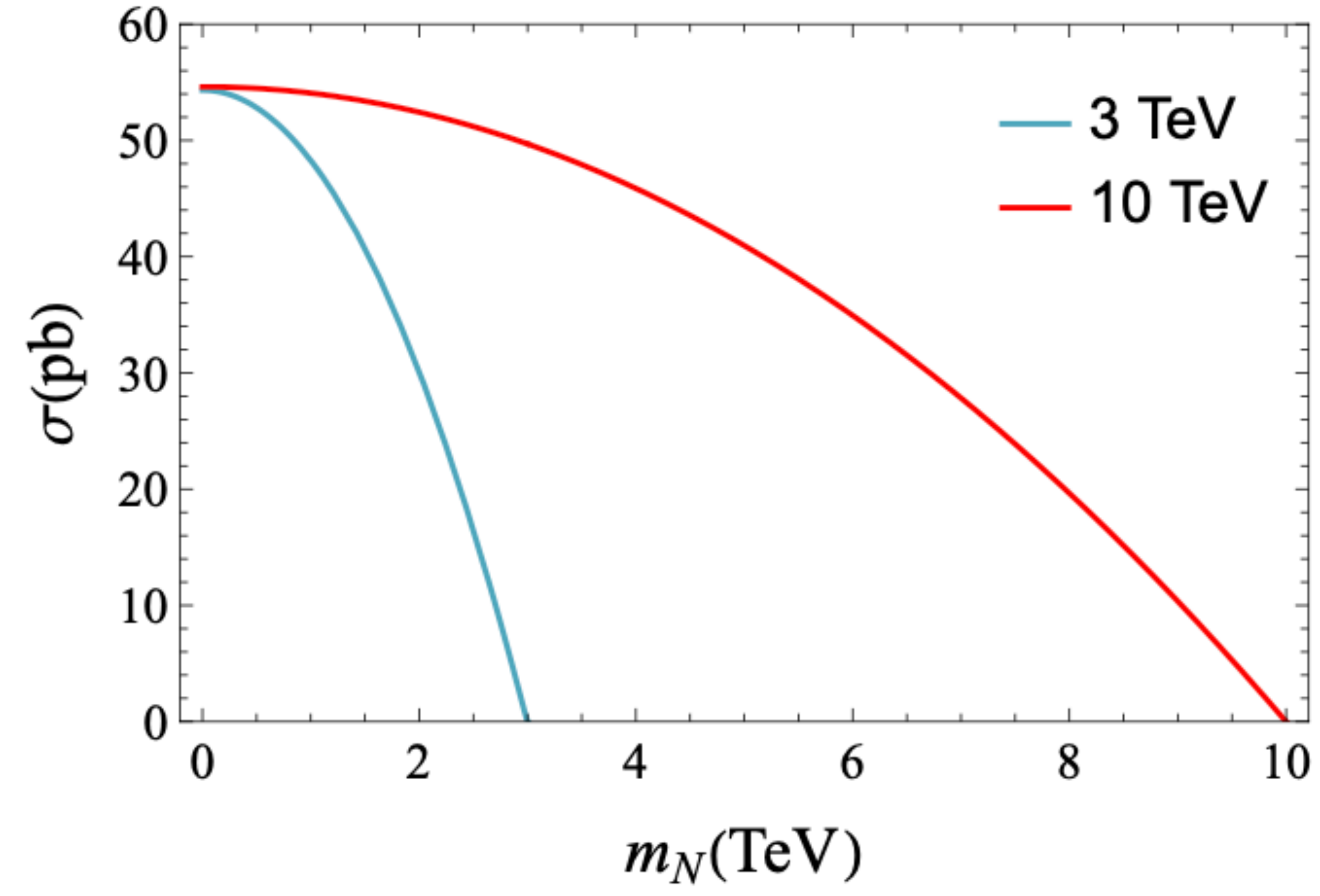
s-channel



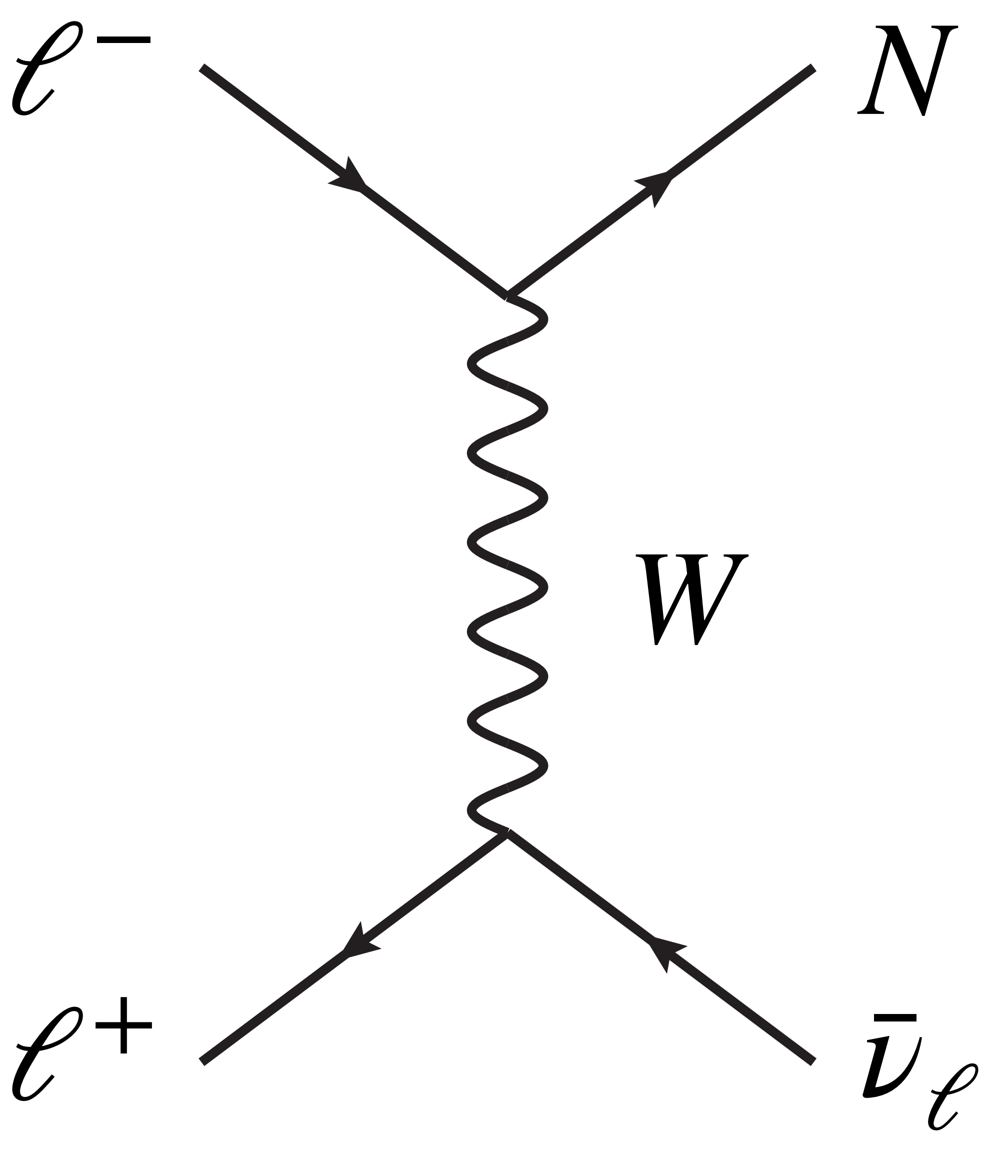
t-channel







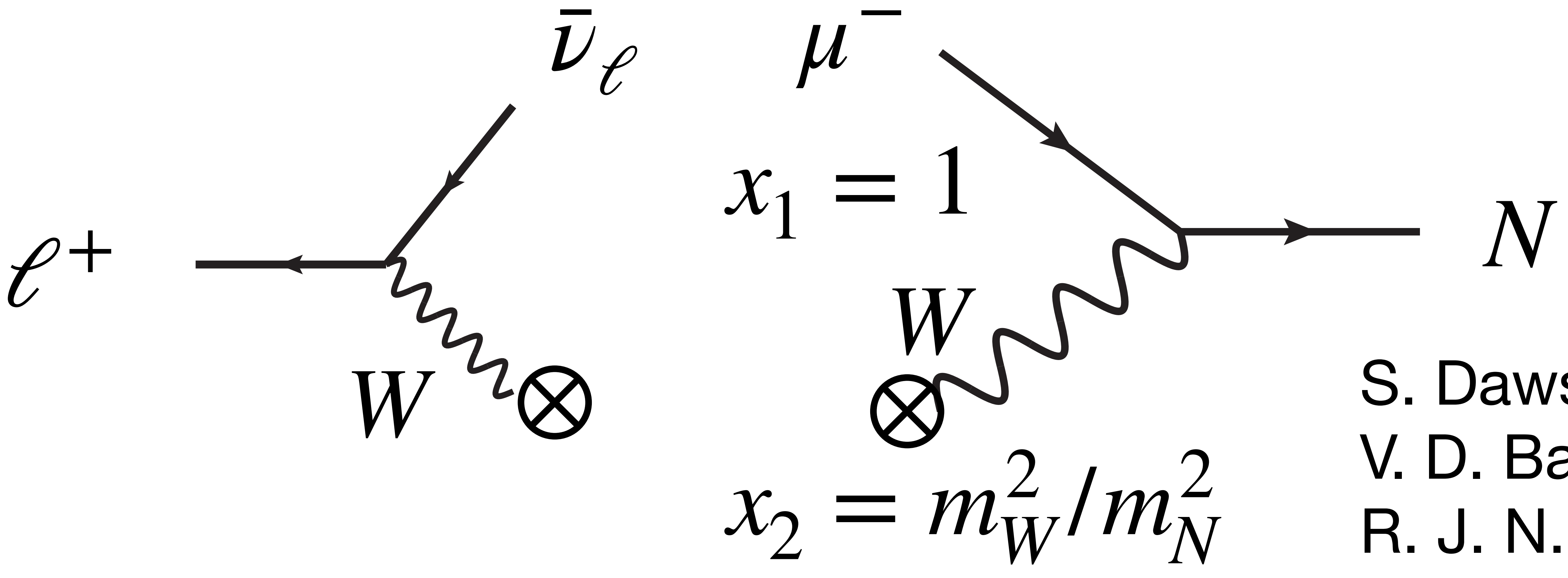
HNL@ high energy lepton colliders



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

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

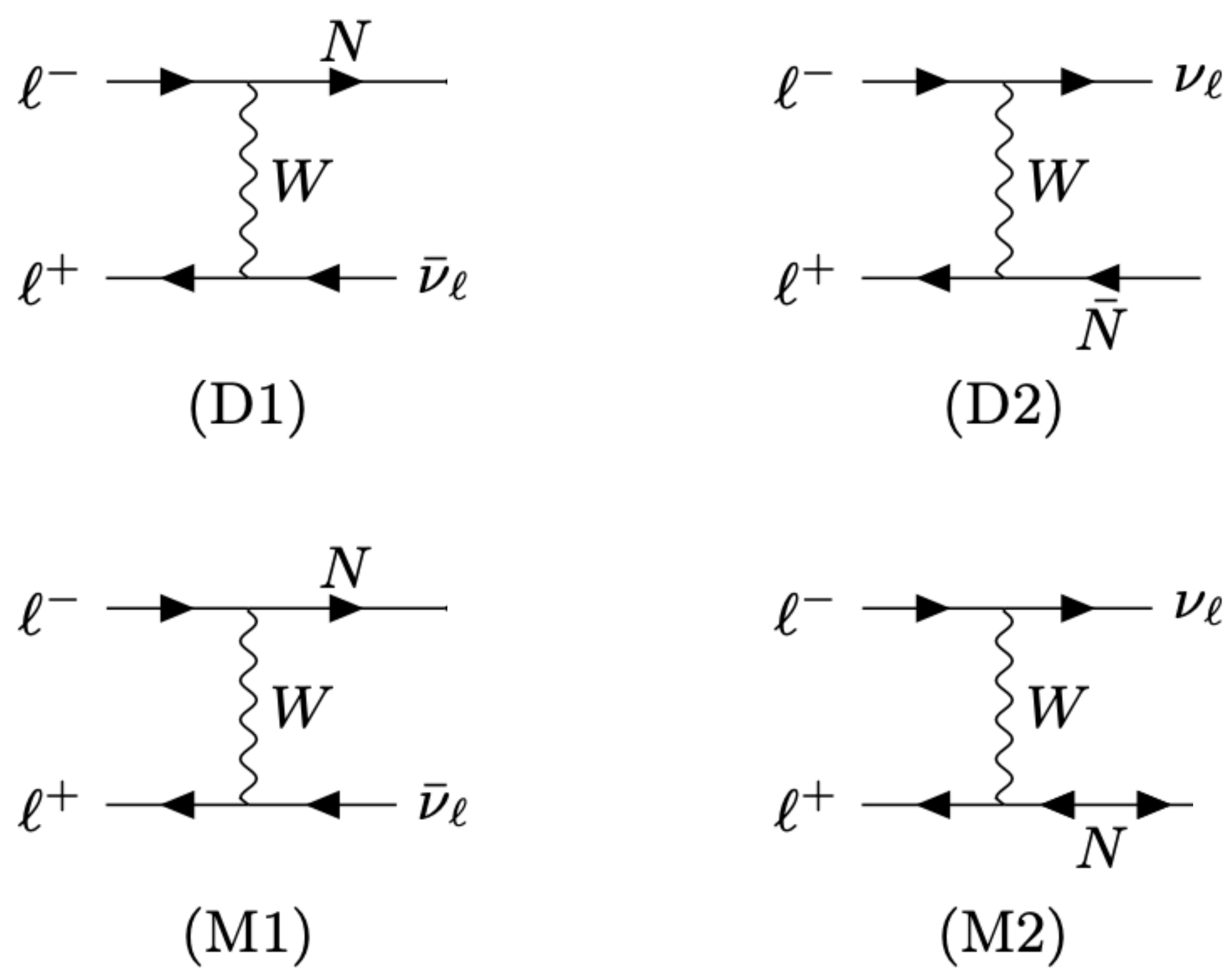
$$y_N \sim \frac{1}{2}\log(s + m_W^2)/(m_N^2 - m_W^2) \text{ for } m_N > m_W$$

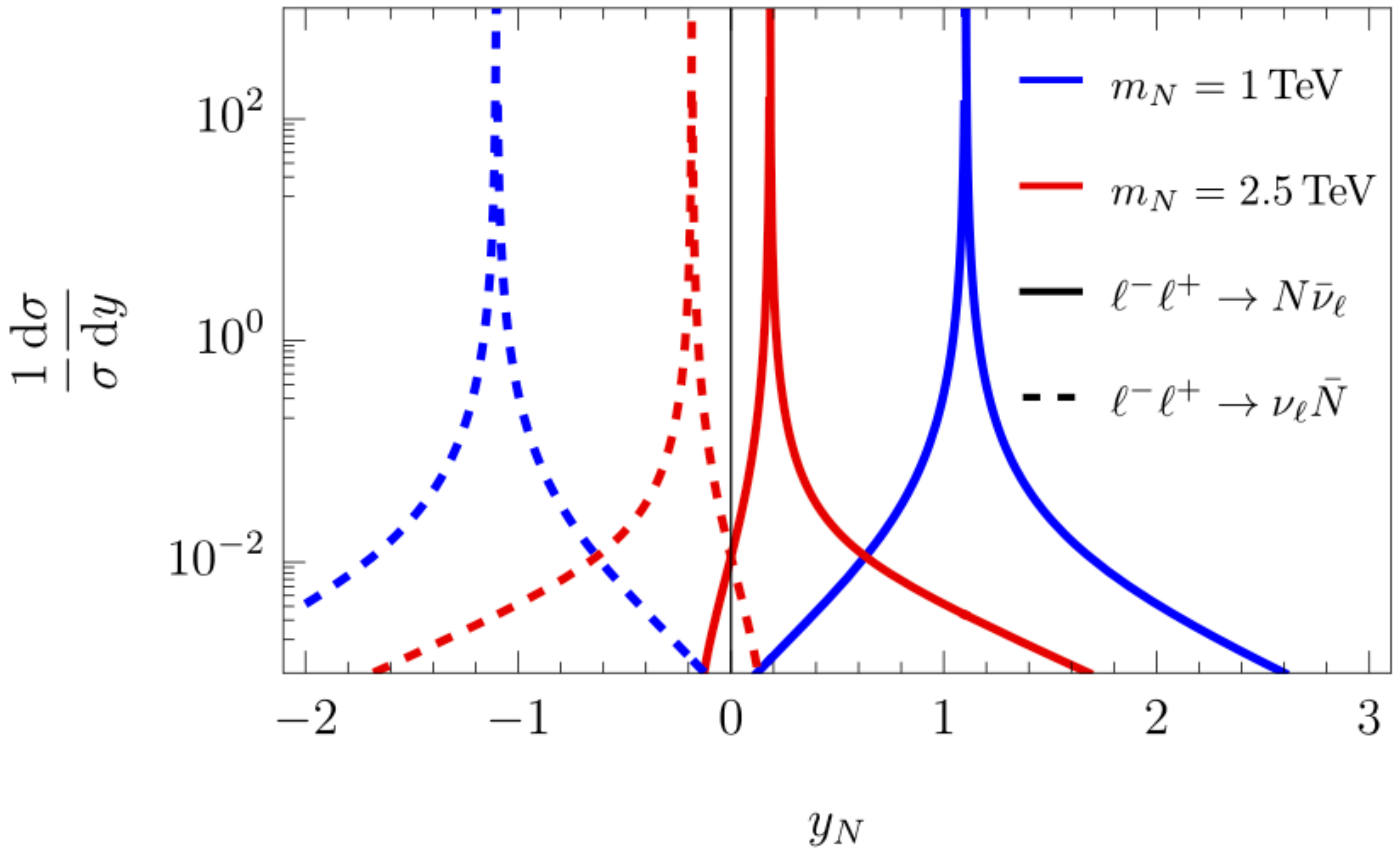


$$y_N = \frac{1}{2}\log(x_1/x_2) = \frac{1}{2}\log(s/m_N^2)$$

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)

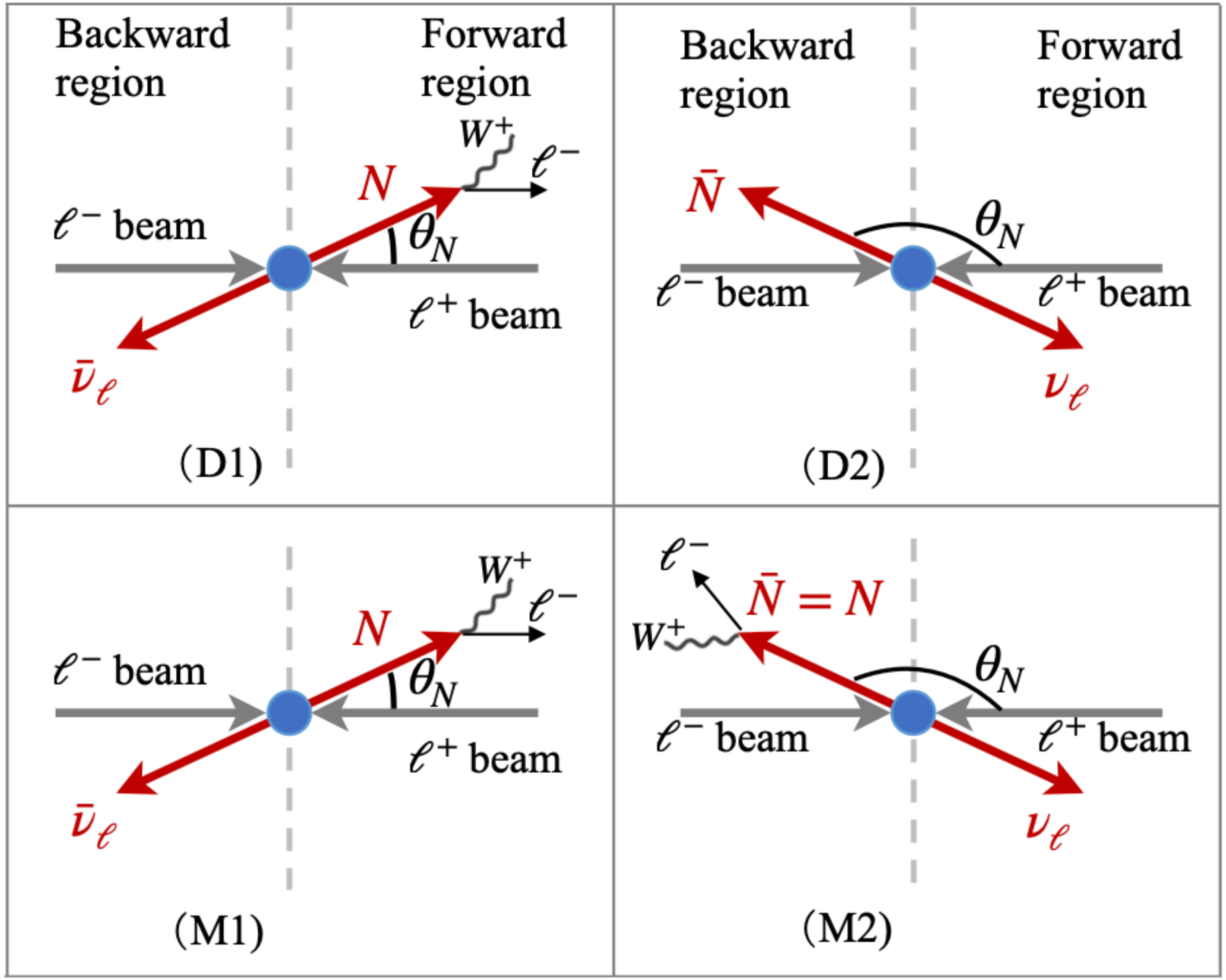
HNL@ high energy lepton colliders



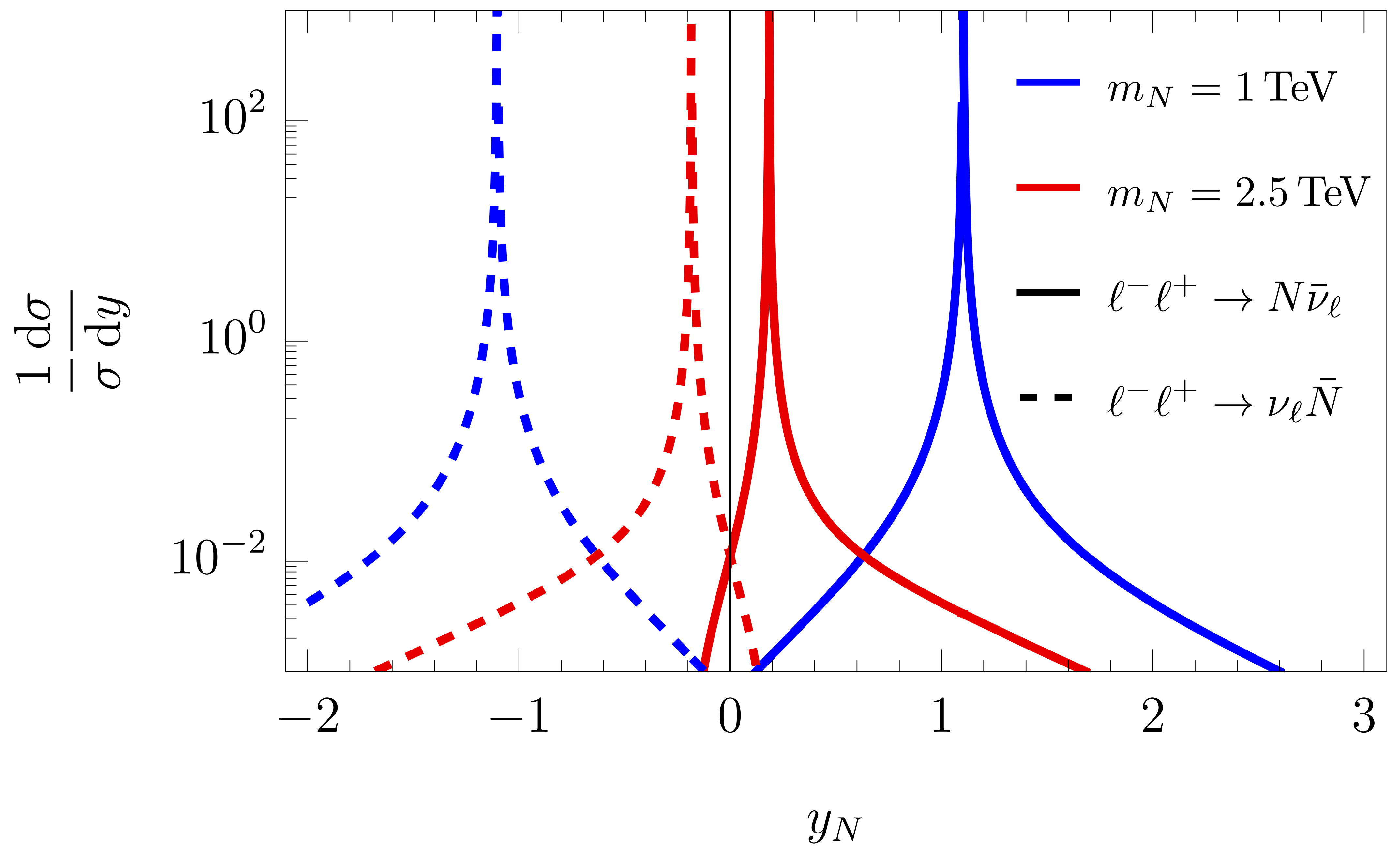


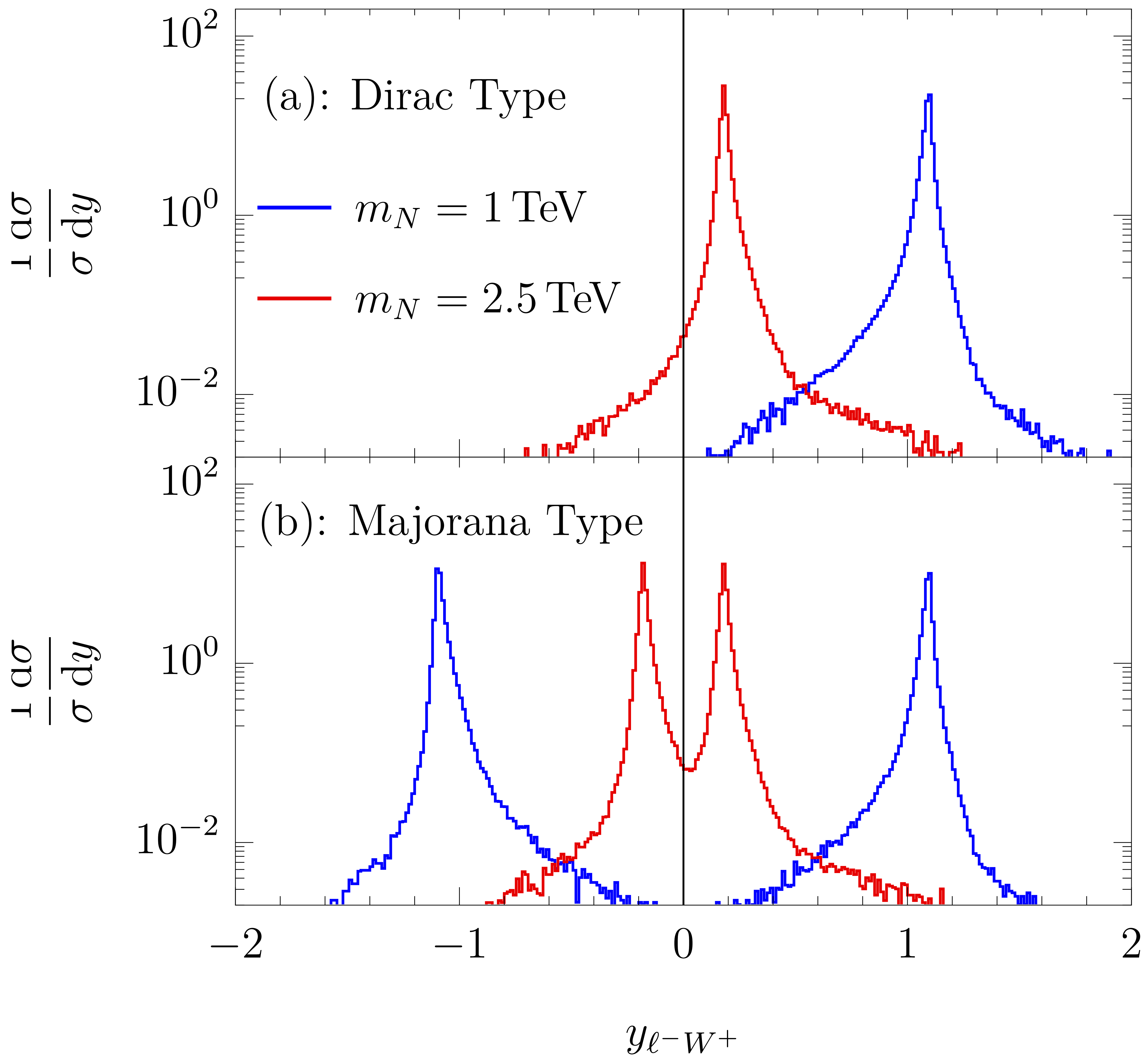
Dirac: $N \neq \bar{N}$
Majorana: $N = \bar{N}$

HNL@ high energy lepton colliders



Simulation @ the high energy muon collider





Discrimination at the 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)

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

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

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

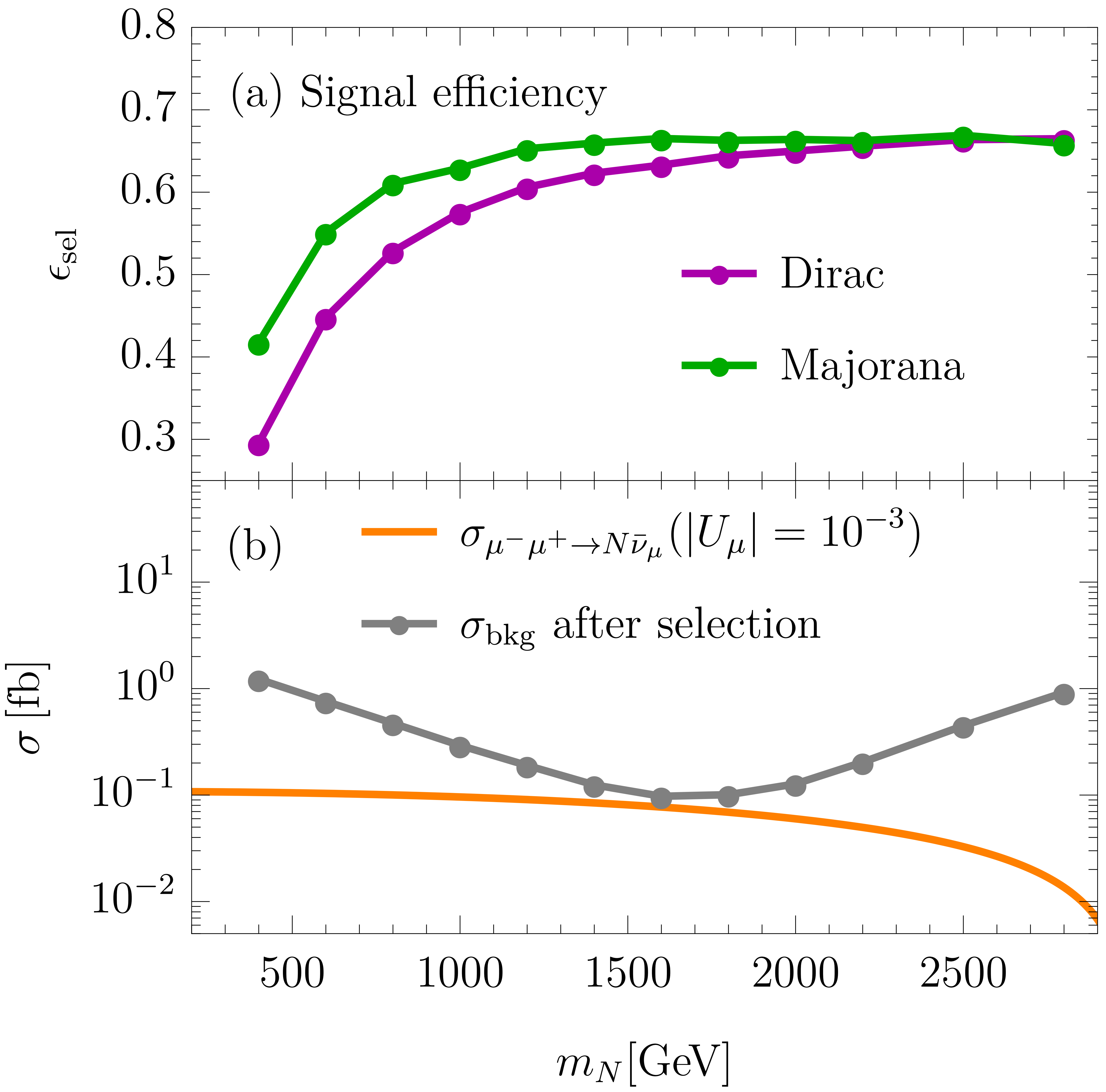
Cut efficiency at the 3 TeV muon collider

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

W resonance:

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

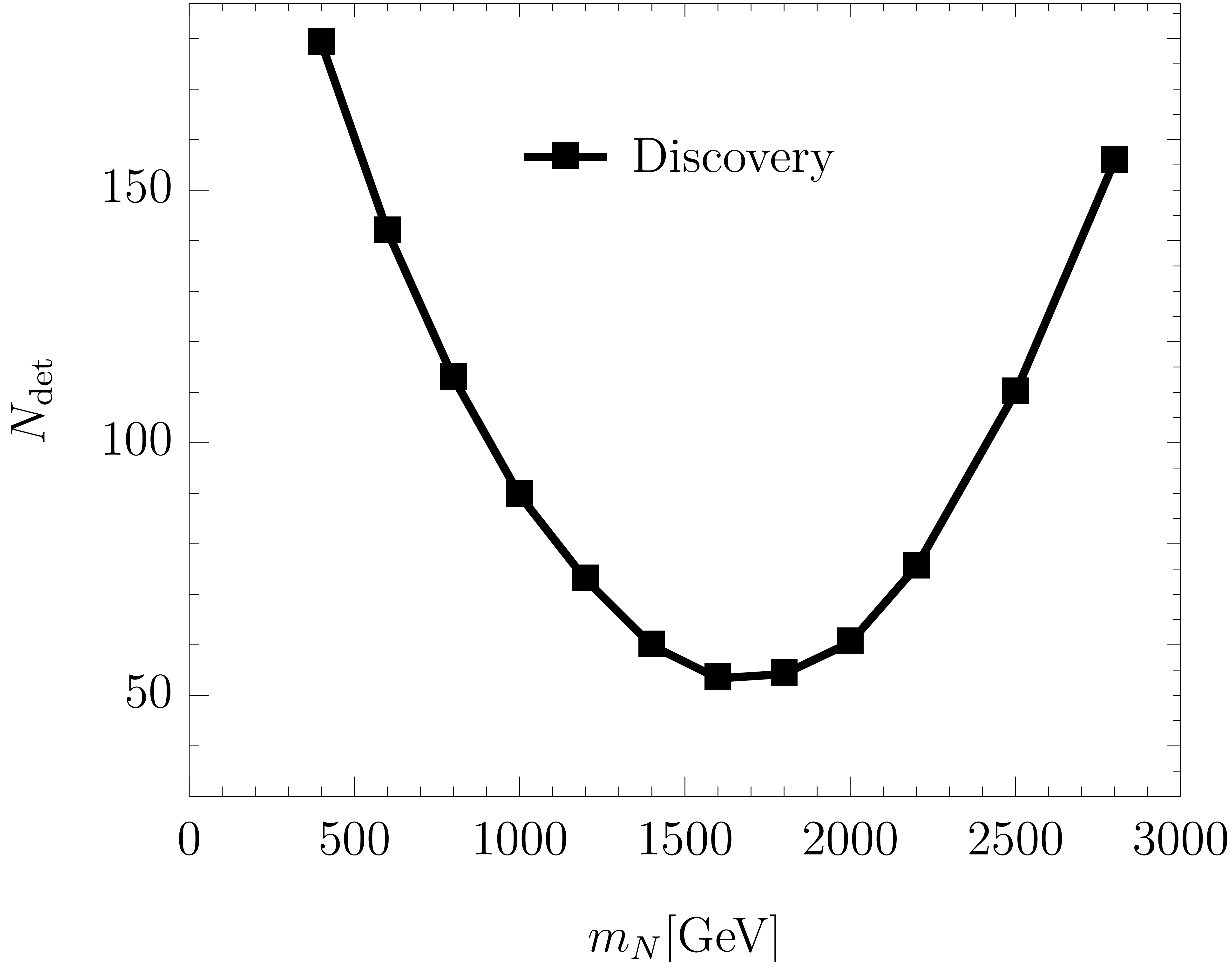
N resonance: $m_{\ell-W} \subset m_N \pm 5\,\%\, m_N$



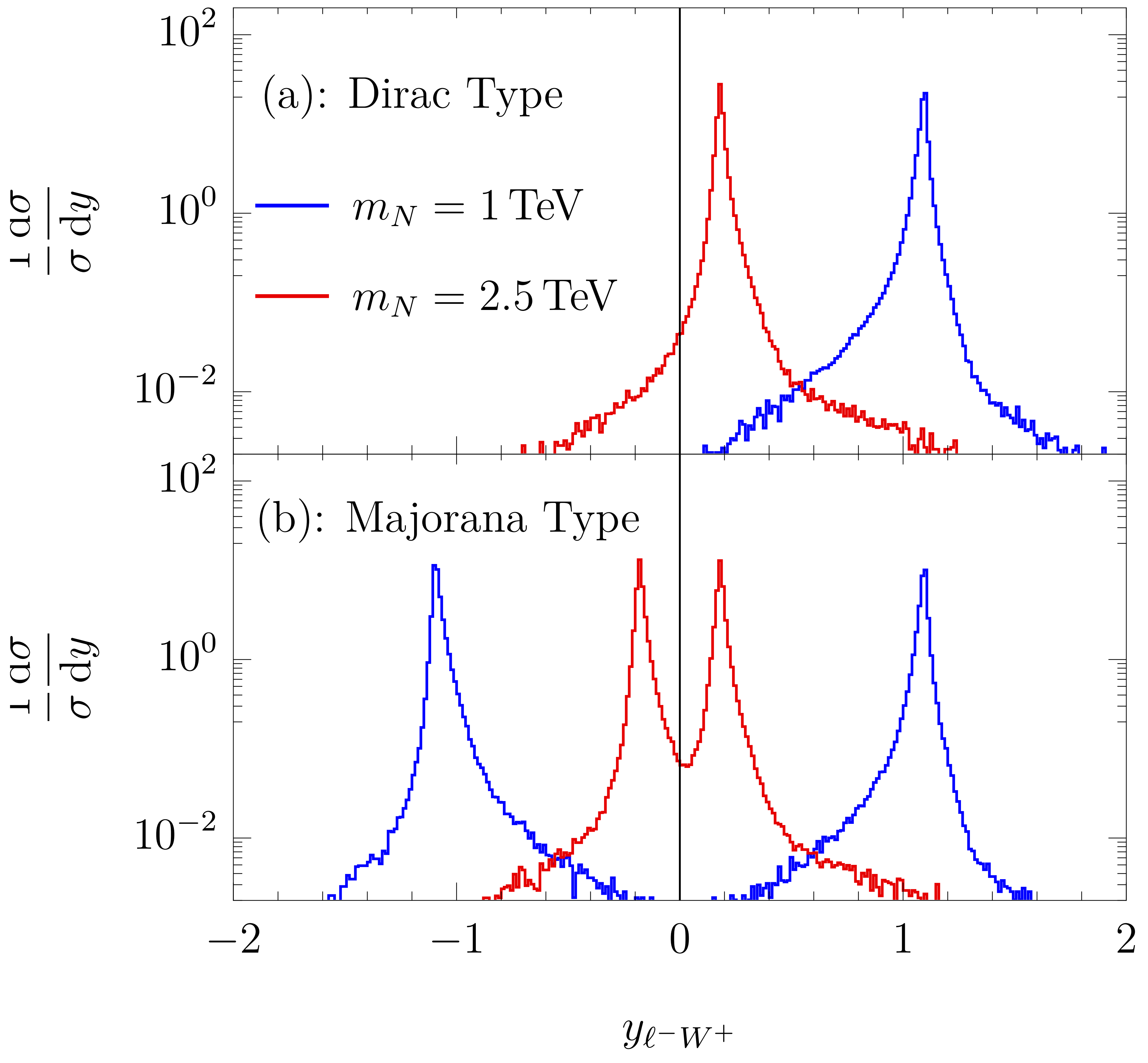
Discovery at the 3 TeV muon collider

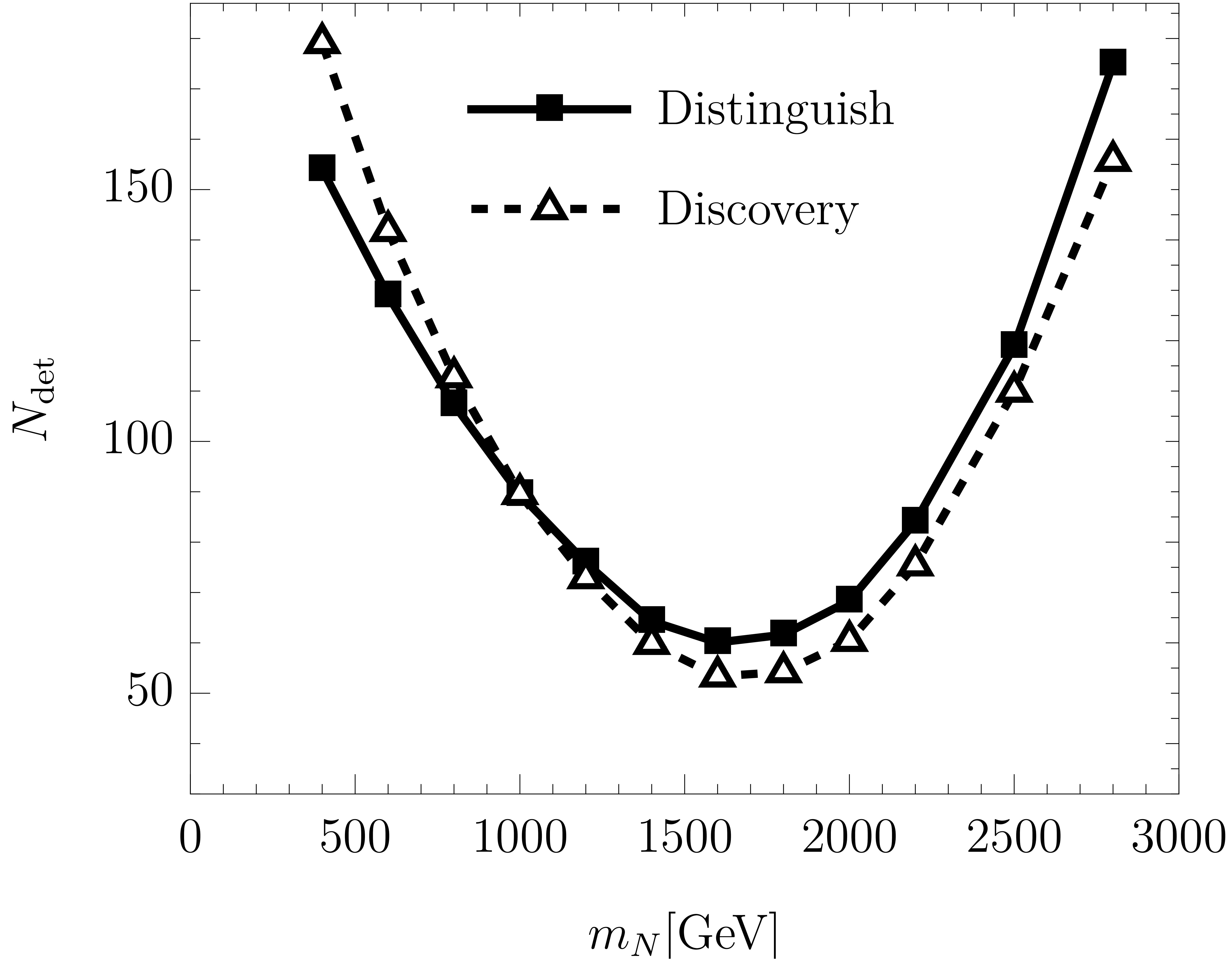
P. Li, Z. Liu, and K.-F. Lyu, JHEP 03, 231 (2023)

$\mathscr{L} = 1\ \mathrm{ab}^{-1}$

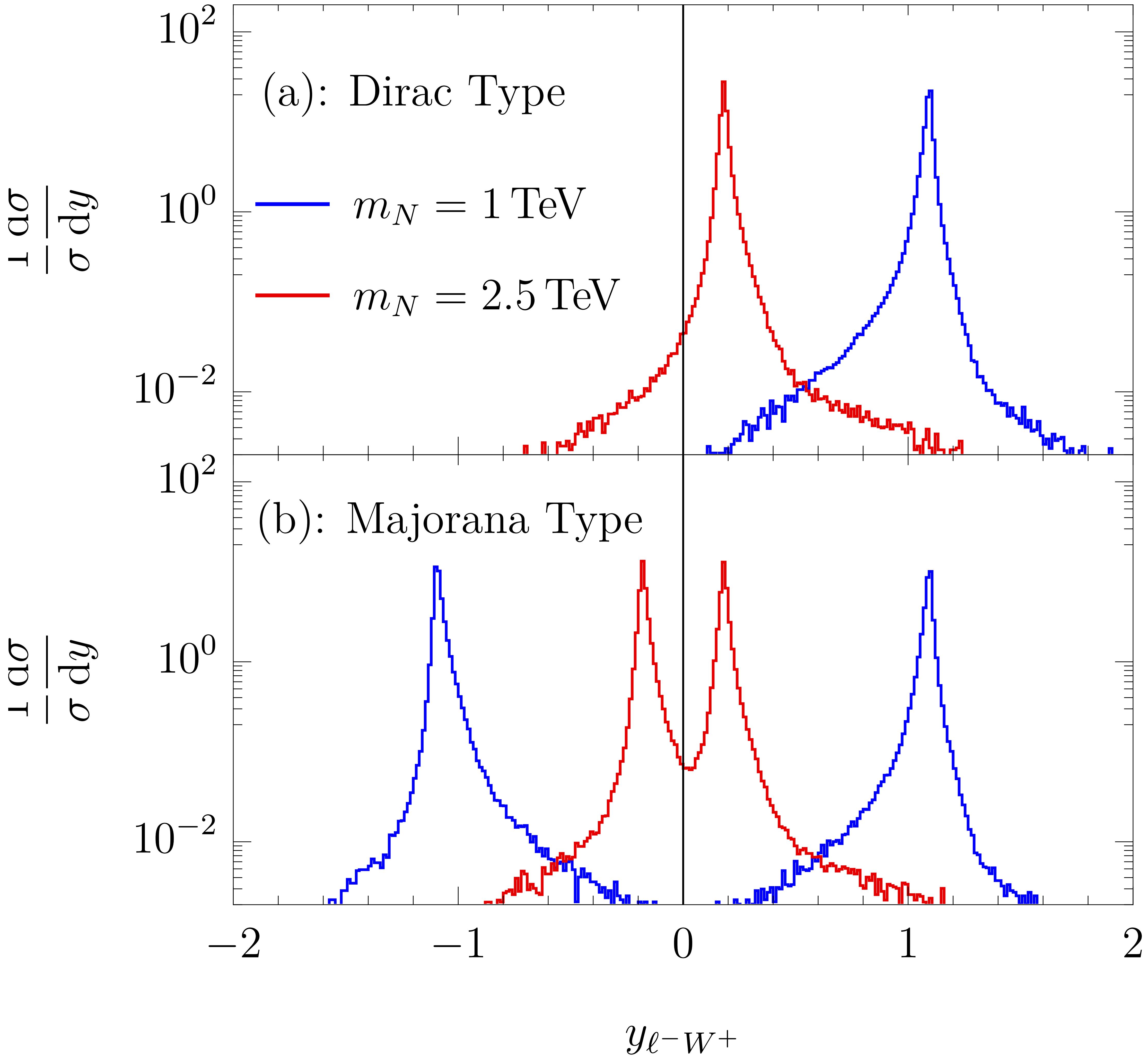


Discrimination at the 3 TeV muon collider





Mass and rapidity correlation



$$y_p = \frac{1}{2}\log(s + m_W^2)/(m_N^2 - m_W^2)$$

$$m_N = e^{y_p}\sqrt{s + e^{2y_p}m_W^2 + m_W^2}$$

Conclusion

- We propose to use the rapidity of reconstructed N to identify its nature, namely discriminate whether it is Dirac or Majorana fermion;

  One peak: Dirac fermion
  Two peaks: Majorana fermion

- We found the nature of N can be deciphered once it is confirmed.

Thanks!