BEIJING NORMAL UNIVERSITY

Physics Opportunities at Muon Colliders

Yandong Liu

Based on Phys.Rev.D 109 (2024) 7, 073005,
Phys.Rev.Lett. 134 (2025) 2, 021801

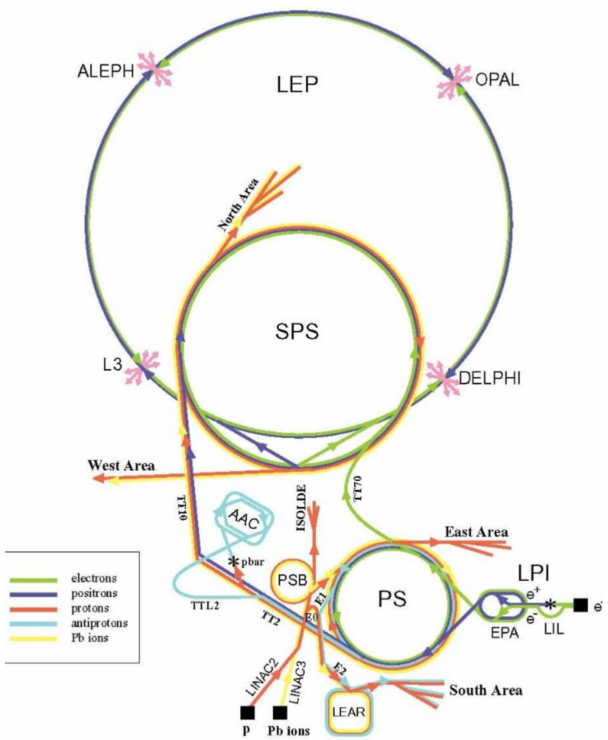
In Collaboration with Qing-Hong Cao, Kun Cheng and Xiao-Rui Wang

Outline

- Physics progress at muon colliders
- Precision Measurements within the Standard Model
  - Measurement of Quartic Higgs–Gauge Boson Couplings
- Searches for New Physics
  - Discriminating Dirac vs. Majorana Heavy Neutral Leptons
- Conclusion

Motivation for a Muon Collider

Lepton Colliders: precision machines

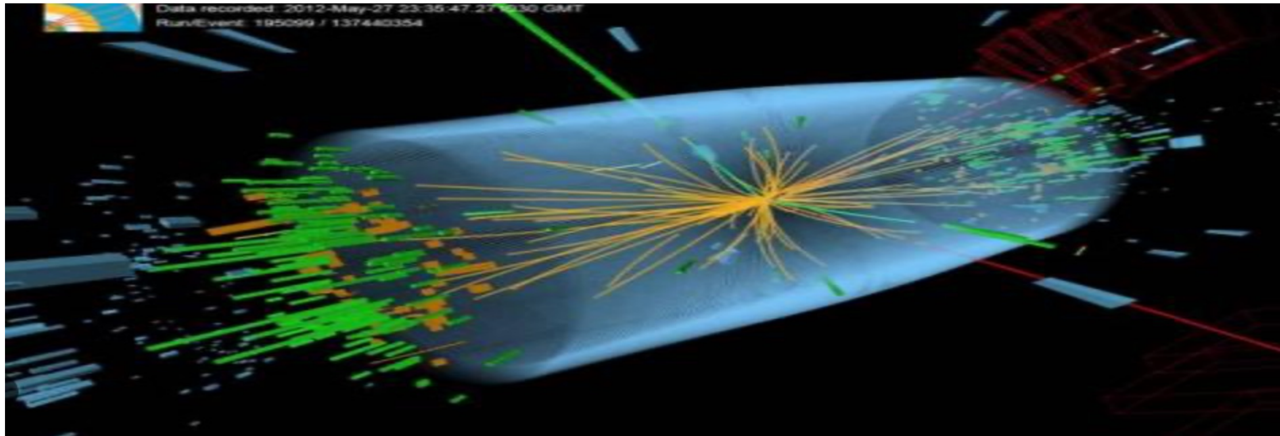


- ❖ Well-difined initial states
- ❖ Clean final states
- ❖ Indirect sensitivity to new physics

Muon Colliders

- Broad energy reach
- Sensitive to new heavy resonances
- Messy environment

Hadron Colliders: discovery machines



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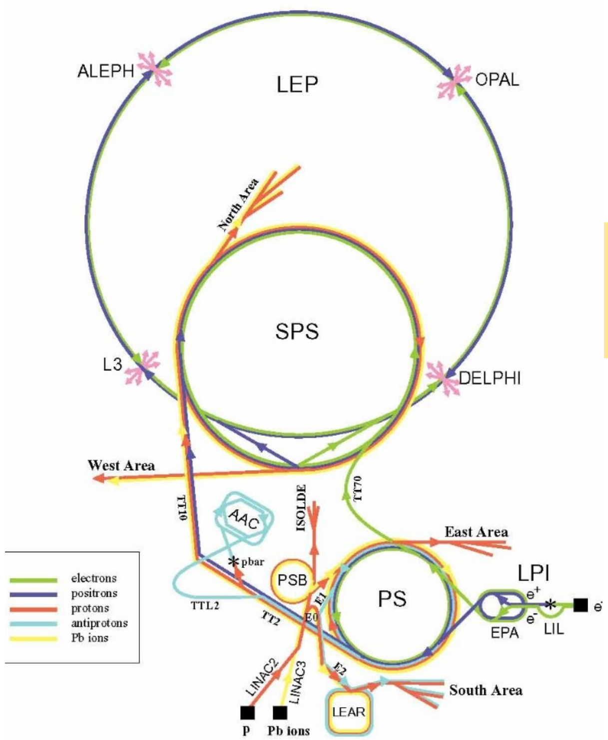

- ❖ Well-difined initial states
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Muon Colliders

Precision & Discovery Machine

- Broad energy reach
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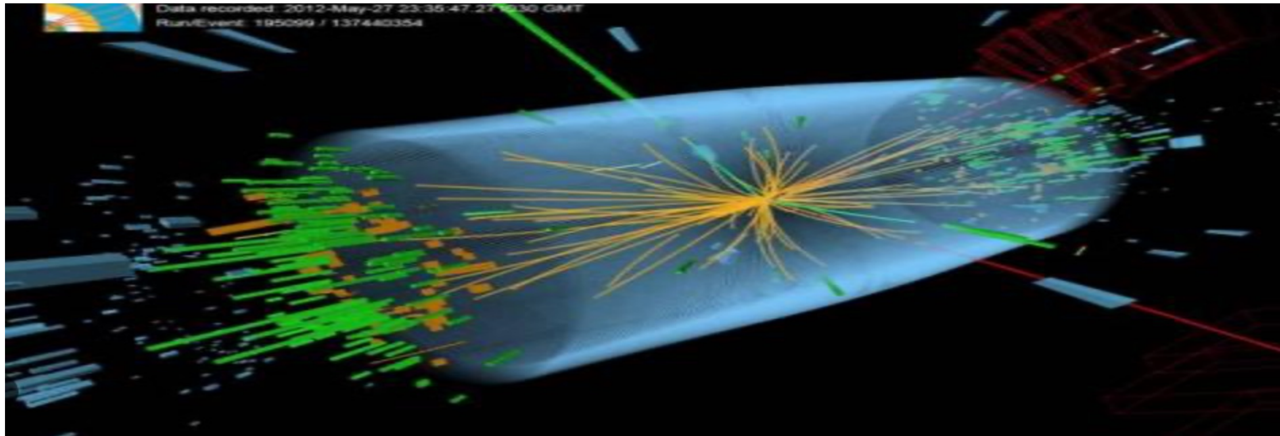
Hadron Colliders: discovery machines

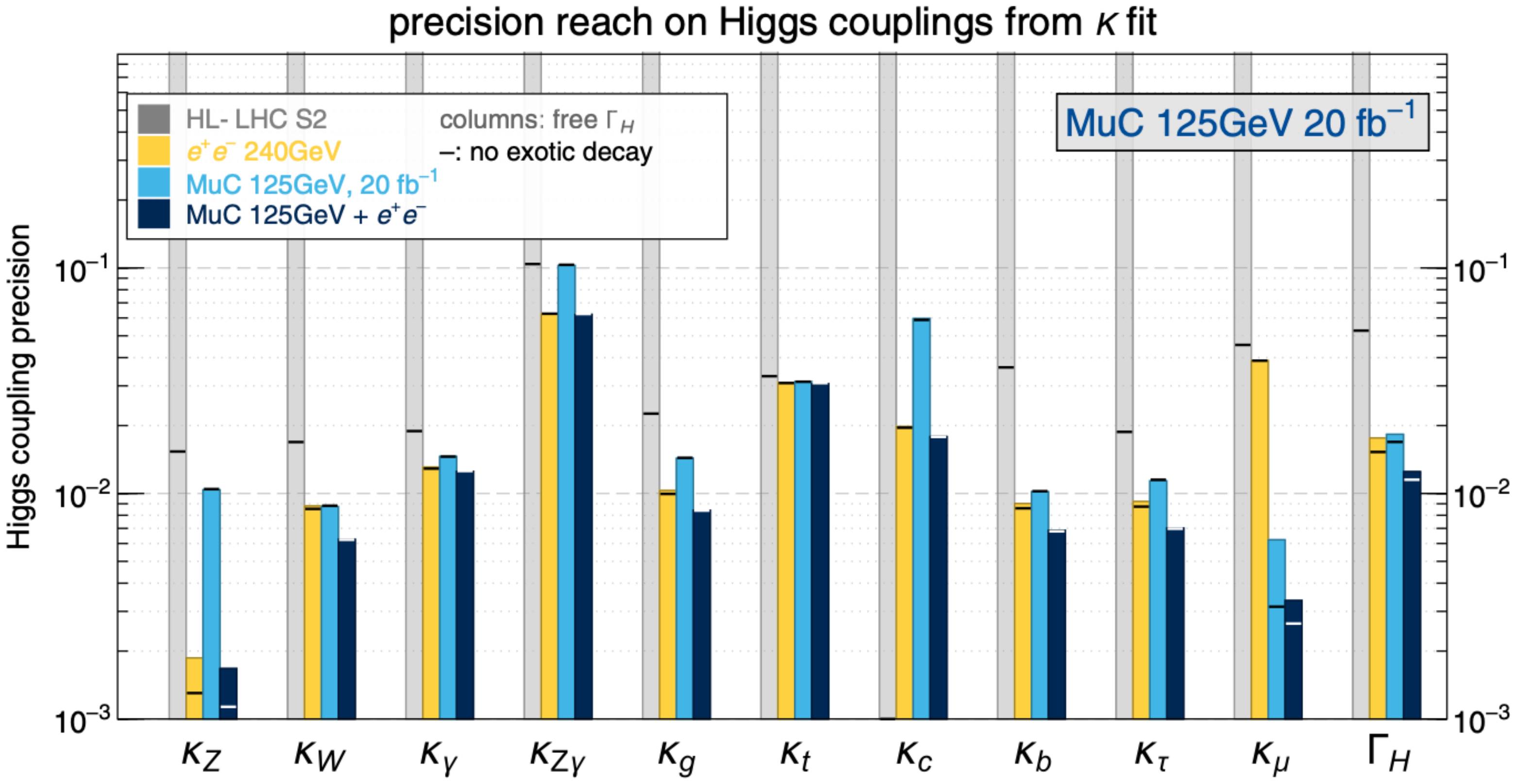


Precison Measurements at Muon Colliders

➢ Low energy muon collider: Higgs factory

J. Blas, J. Gu and Z. Liu; PHYSICAL REVIEW D 106, 073007 (2022)

Higgs boson mass, width, $h\bar{\mu}\mu$ coupling etc.



PHYSICAL REVIEW D 106, 073007 (2022)

Precison Measurements at Muon Colliders

- Multi-TeV muon colliders
  - $h\bar{\mu}\mu$ coupling: Higgs boson associated gauge bosons T. Han et al. JHEP12(2021)162
  - Higgs boson couplings and width: percent level

    M. Forlund et al. JHEP 08 (2022) 185, JHEP 01 (2024) 182;
    P. Li et al. Phys.Rev.D 109 (2024) 7, 073009;
  - Higgs potential: Higgs self-coupling and quartic Higgs coupling

    J. Chen et al. Phys. Rev. D 105, 053009; J. Chen JHEP 10 (2021) 099
  - Weak boson collider A. Belloni 2209.08078
    - The Nature of Electroweak Symmetry

      T. Yang Phys. Rev. D 104, 093003; A. Belloni 2209.08078; B. Abbott Phys. Rev. D 108, 093009 (2023)
    - Top quark Yukawa coupling y_t 1.5%

      M. Chen et al. PHYSICAL REVIEW D 109, 075020 (2024);
      Z. Liu PHYSICAL REVIEW D 109, 035021 (2024)

New Physics Search at the Muon Colliders

➢ Direct Production Reach for Heavy Particles

C. Aime et al. 2203.07256; H. Ali 2103. 14043

- Supersymmetry: spaerticle up to ~ 5 TeV at the 10 TeV μ collider
- Composite Higgs models: Fermionic top-partner quarks T, B
- New gauge boson W', Z' S. Chen et al. JHEP 05 (2022) 180
- Leptoquarks S. Parashar et al. PoS LHCP2023 (2024) 240
- Long-Lived particles T. Han et al. Phys. Rev. D 103, 075004 (2021)

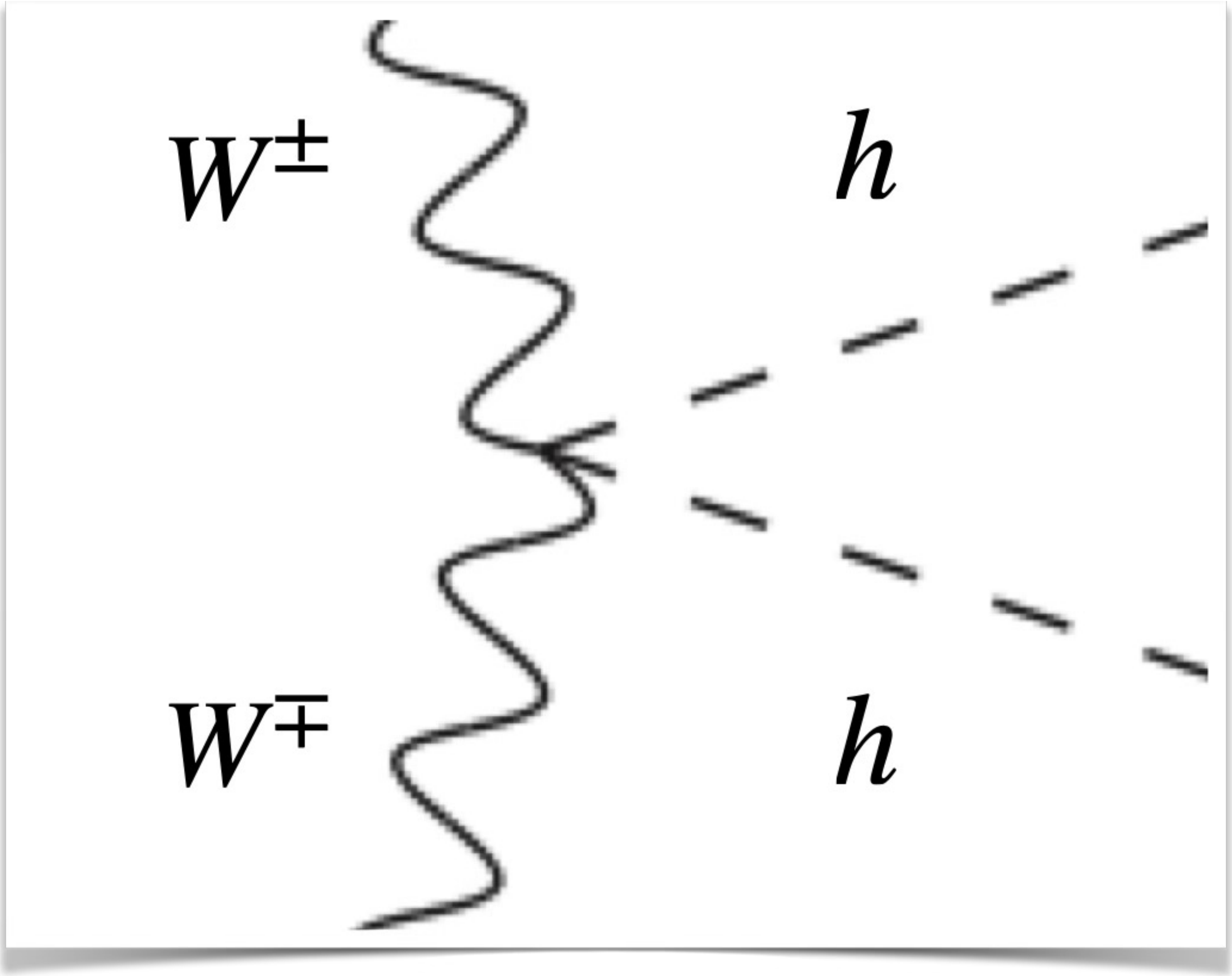
➢ Muon-Specific Physics: Flavor Anomalies and Lepton Universality

J. Blas et al. 2203.07261

- Muon $g-2$ Anomaly No-Lose Theorem R. Capdevilla et al. Phys. Rev. D 105, 015028
- B-meson Decay Anomalies

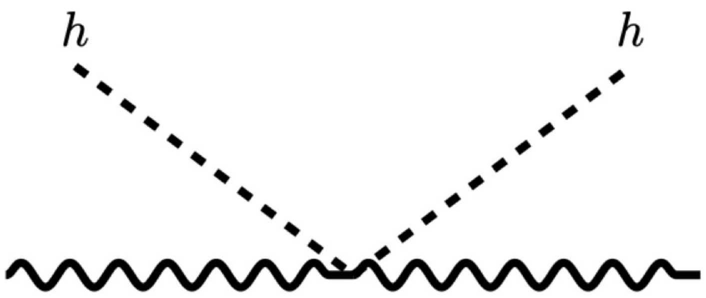
G. Huang et al. Phys. Rev. D 103, 095005 (2021); G. Huang et al. Phys. Rev. D 105, 015013
P. Asadi et al. JHEP 10 (2021) 182

Measurement of Quartic Higgs–Gauge Boson Couplings

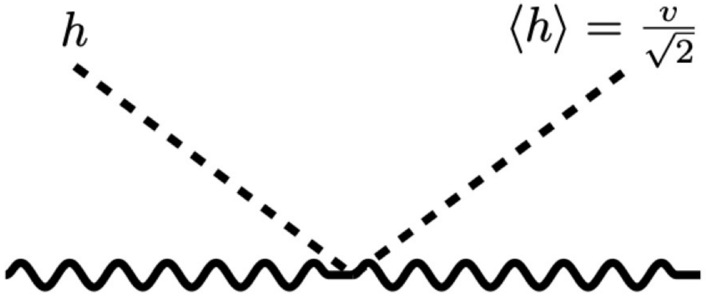


Measurement of Quartic Higgs–Gauge Boson Couplings

➢Comparison of $hhVV$ and hVV couplings in the Standard Model



$$\frac{g_{hhVV}}{g_{hhVV}^{SM}} = \kappa_{hhVV}$$



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➢Comparison of $hhVV$ and hVV couplings in the New Physics models

- Extensions of the Higgs boson sector: Triplet Higgs boson model
- Extensions of the gauge group: 3-3-1 model
- Composite Higgs boson scenarios: $\kappa_{hVV} = \sqrt{1 - v^2/f^2}$, $\kappa_{hhVV} = 1 - 2v^2/f^2$

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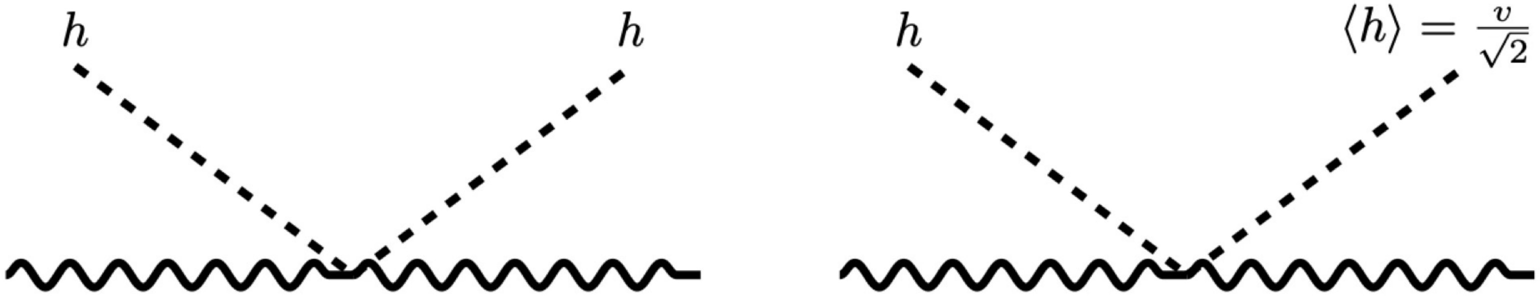

Precision measurement of the SM electroweak breaking mechanism
Searching for /Ditinguishing the NP beyond the SM

➢Comparison of $hhVV$ and hVV couplings in the New Physics models

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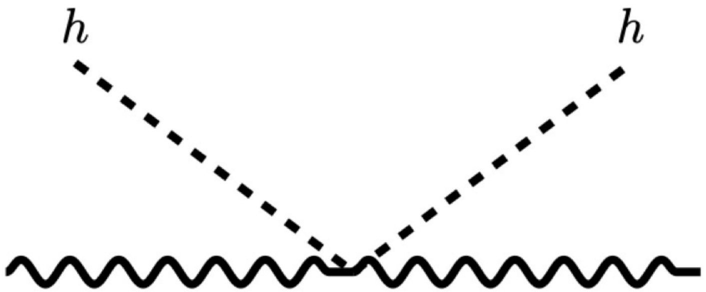
$hh\,VV$ Coupling at the LHC

- κ_{hhVV} lies in the range [0, 2.1]; κ_{hVV} lies in the rangle [0.97, 1.13]

G. Aad et al. Phys. Rev. D 101, 012002 (2020); G. Aad et al. Phys. Rev. D 108 (2023) 052003

- κ_{hhVV} can be measured with a precision of 40% at the HL-LHC using GNNs



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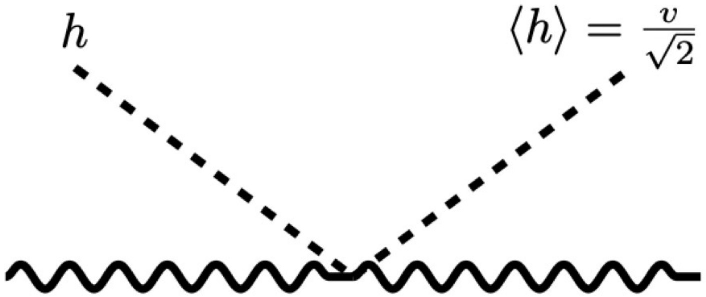

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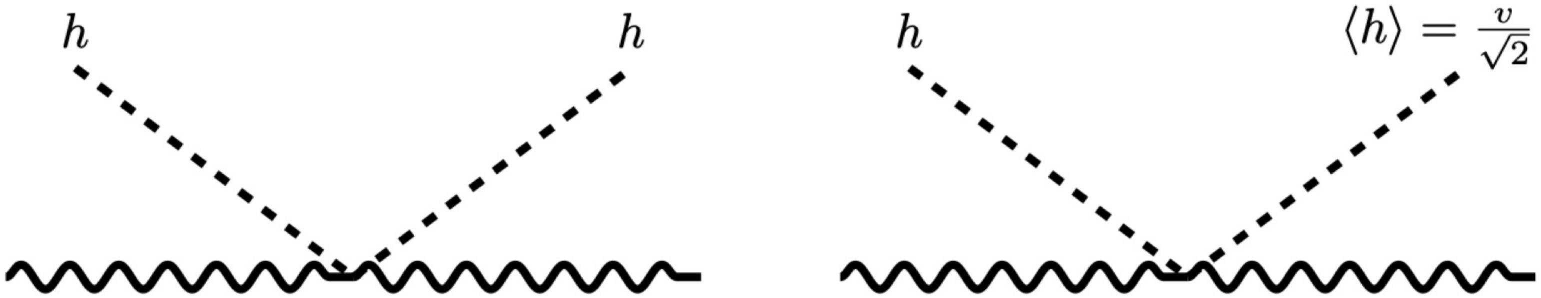
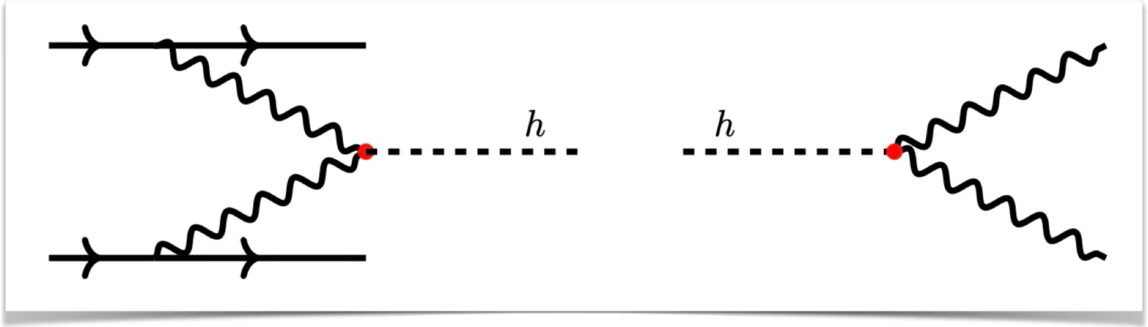


$$\frac{g_{hhVV}}{g_{hhVV}^{SM}} = \kappa_{hhVV} \qquad \frac{g_{hVV}}{g_{hVV}^{SM}} = \kappa_{hVV}$$

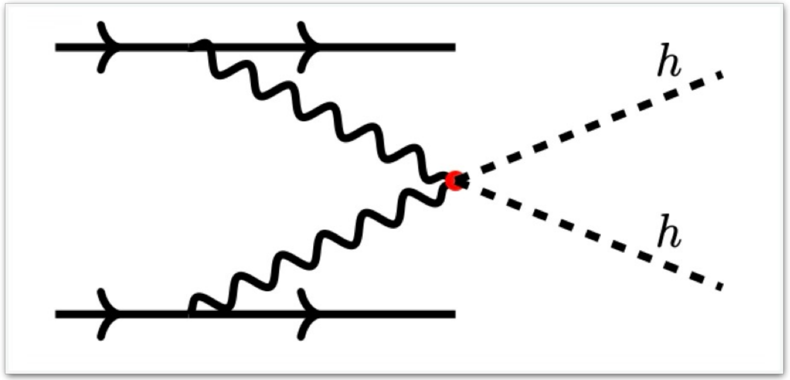
Why?

Comparison of $hhVV$ and hVV Couplings at the LHC

- κ_{hVV} can be measured through single Higgs boson production and decay processes



- κ_{hhVV} can only be measured through di-Higgs boson production



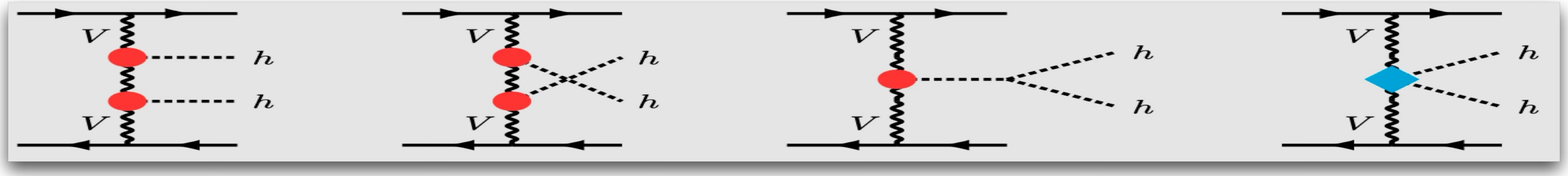
$\sigma(jjh) \sim 3$ pb

$\sigma(jjhh) \sim 1.5$ fb

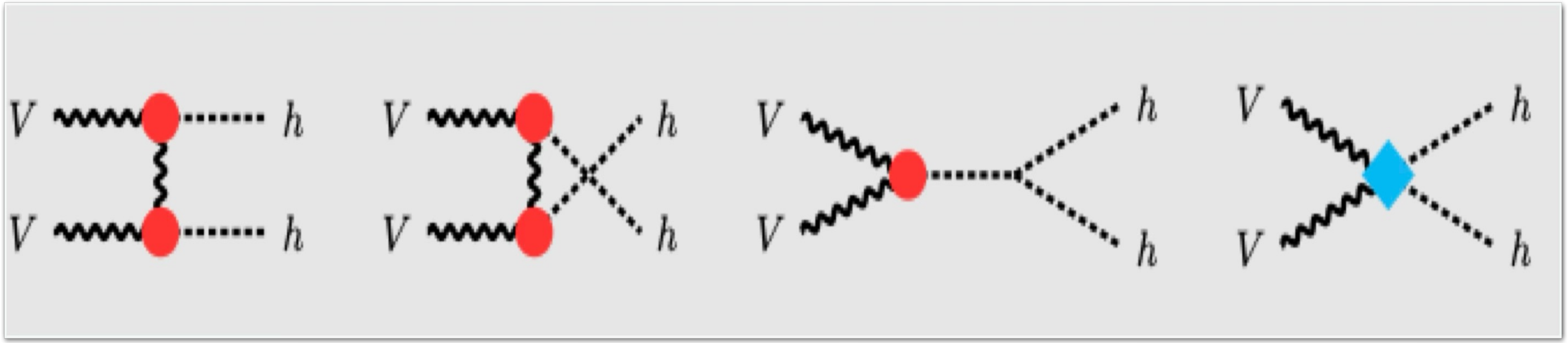
@13 TeV LHC

- Gluon fusion dominates di-Higgs boson production at the LHC

Di-Higgs boson production at a high energy muon collider



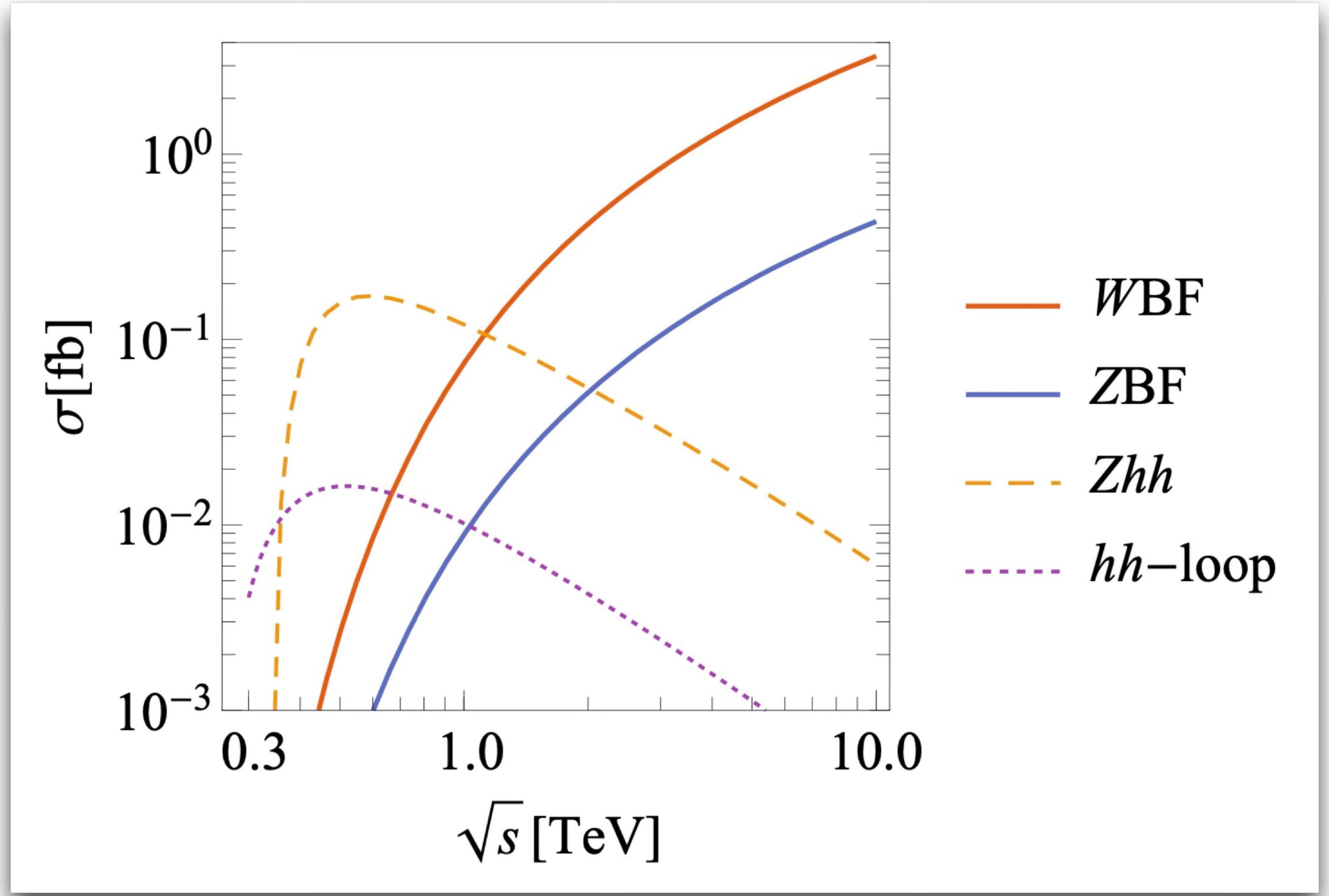
Nucl. Phys. B 249, 42 (1985), J. High Energ. Phys. 2020, 80 (2020), JHEP 2022, 114 (2022)

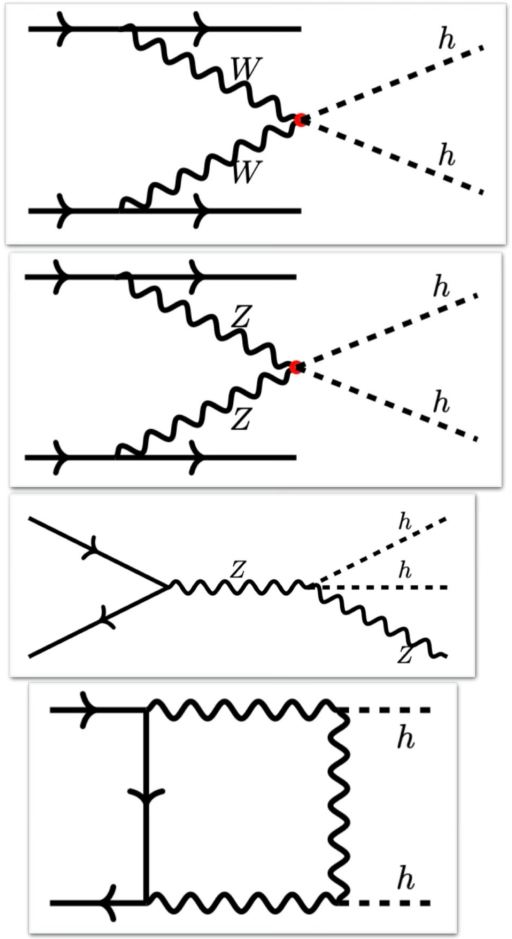


- The subprocess $VV \to hh$ amplitude is sensitive to the κ_{hhVV} and κ_{hVV} couplings

$$M_{LL} = \frac{\hat{s}}{v^2}\left(\kappa_{hhWW} - \kappa_{hWW}^2\right) + \mathcal{O}(\hat{s}^0)$$

Di-Higgs Boson Production at Muon Colliders





$$\log \frac{\hat{s}}{v^2}$$

Collider Simulation at a 10 TeV Muon Collider

$$\mu^+\mu^- \to \nu\bar{\nu}hh$$

- Production rate

$$\sigma^{hh} = 177.2\kappa_{hhWW}^2 + 206.1\kappa_{hWW}^4 + 0.88\kappa_{hWW}^2 - 378.1\kappa_{hhWW}\kappa_{hWW}^2 - 12.11\kappa_{hWW}^3 + 9.08\kappa_{hhWW}\kappa_{hWW}$$

- Signature $\mu^+\mu^- \to \nu\bar{\nu}h(\to \bar{b}b)h(\to \bar{b}b) \Rightarrow$ 4b-jet+$\not{E}$

- Backgrounds: $\mu^+\mu^- \to \nu\bar{\nu}h(\to \bar{b}b)Z(\to \bar{b}b)$, $\mu^+\mu^- \to \nu\bar{\nu}Z(\to \bar{b}b)Z(\to \bar{b}b)$

$\mu^\pm\gamma \to \nu(\bar{\nu})h(\to \bar{b}b)W^\pm(\to jj)$, $\mu^\pm\gamma \to \nu(\bar{\nu})Z(\to \bar{b}b)W^\pm(\to jj)$

$\mu^+\mu^- \to Z(\to \bar{b}b)Z(\to \bar{b}b)$, $\mu^+\mu^- \to Z(\to \bar{b}b)h(\to \bar{b}b)$

$$P_{b\to b} = 0.9, \qquad P_{c\to b} = 0.3, \qquad P_{j\to b} = 0.05$$

Cuts Flow at the 10 TeV Muon Collider

- Pre-selection cuts:
  $n^{\ell}(p_T > 10\ \text{GeV}) = 0,\ \not{E} > 10\text{GeV},$
  $p_T^{jet} > 15\ \text{GeV},\ -4.0 < \eta^{jet} < 4.0,\ \Delta R^{mn} > 0.5$

- Higgs Boson mass window:
  $100\ \text{GeV} < m_{bb} < 150\ \text{GeV}$

- Di-Higgs Boson Selection:
  $$\chi^2(m_1, m_2) \equiv \min_{i,j,k,l} \left[(m_{b_i b_j} - m_1)^2 + (m_{b_k b_l} - m_2)^2\right],$$
  $$\chi^2(m_h, m_h) < \chi^2(m_Z, m_Z), \quad \chi^2(m_h, m_h) < \chi^2(m_h, m_Z)$$

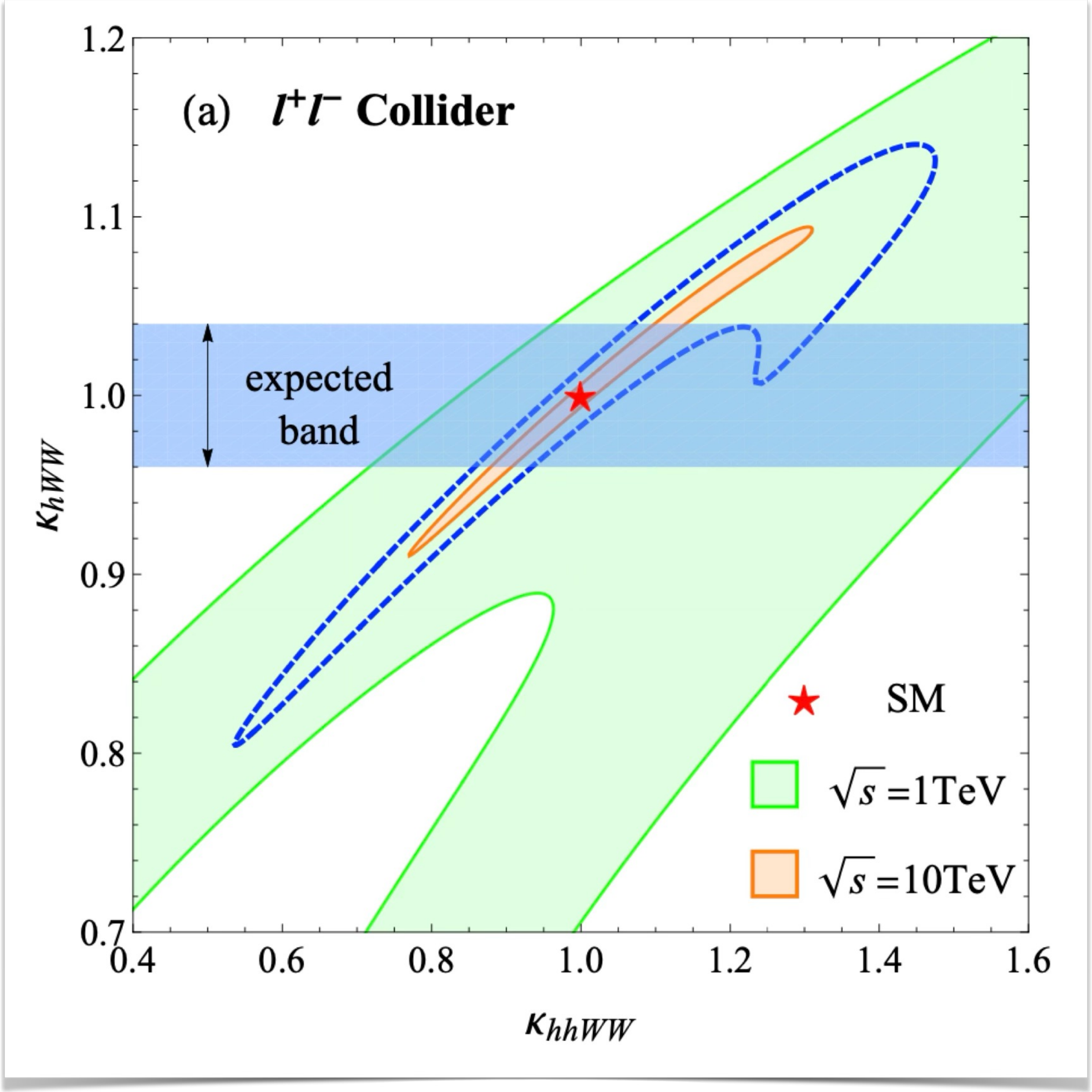
- Missing energy cut:
  $$M_{\text{recoil}} \equiv \sqrt{(p_1 + p_2 - p_{h_1} - p_{h_2})^2}\ M_{\text{recoil}} \geq 200\ \text{GeV}$$

$\mathscr{L} = 3\ \text{ab}^{-1}$

σ [ab]	pre-cuts	m_{bb} cut	HHCUT	M_{recoil} cut
Sig.	484.4	261.5	226.5	226.3
$\nu\nu hZ$	1163.1	168.6	97.8	97.6
$\nu\nu ZZ$	1557.9	121.2	36.7	36.6
$\nu W^{\pm}h$	560.7	26.2	17.2	17.2
$\nu W^{\pm}Z$	492.3	12.3	9.3	9.3
Bkg.	-	-	-	160.7

$\kappa_{hhWW} = \kappa_{hWW} = 1$

Discovery and Exclusion Potential on κ_{hhWW}



$0.96 < \kappa_{hWW} < 1.04$ arXiv:2207.03862

- 5σ discovery region

  $\kappa_{hhWW} < 0.86$ or $\kappa_{hhWW} > 1.32$

- 2σ exclusion region

  $\kappa_{hhWW} < 0.88$ or $\kappa_{hhWW} > 1.14$

Search for New Physics: Do Majorana Fermions Exist?

How can we determine the nature of a heavy neutral lepton? Is it a Dirac or Majorana particle?

Heavy Neutral Lepton Candidates

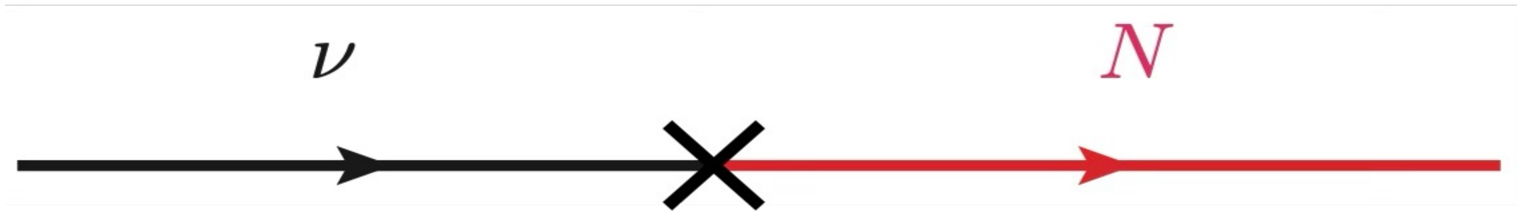
➢Tree-level seesaw mechanism

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)

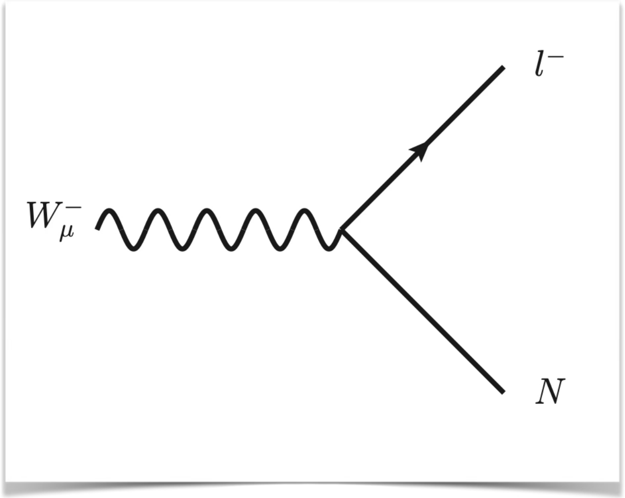
➢String theory or extra dimension models

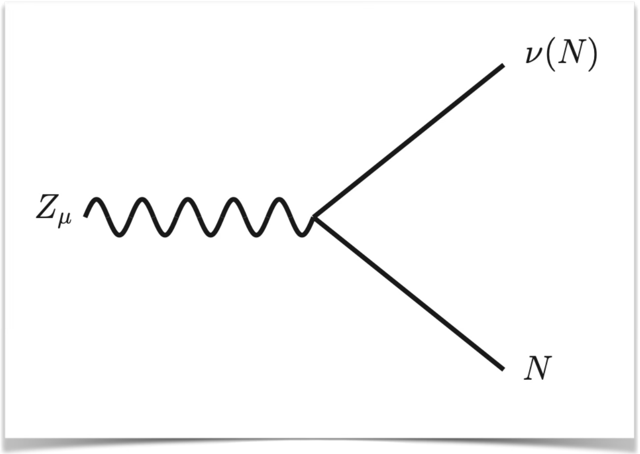
A. Lukas and A. Romanino, (2000), arXiv:hep- ph/0004130; Y. Grossman and M. Neubert, Phys. Lett. B 474, 361 (2000) ;A. De Gouvea, G. F. Giudice, A. Strumia, and K. Tobe, Nucl. Phys. B 623, 395 (2002)
W. Rodejohann and H. Zhang, Phys. Lett. B 737, 81 (2014)

Heavy Neutral Leptons (HNLs)

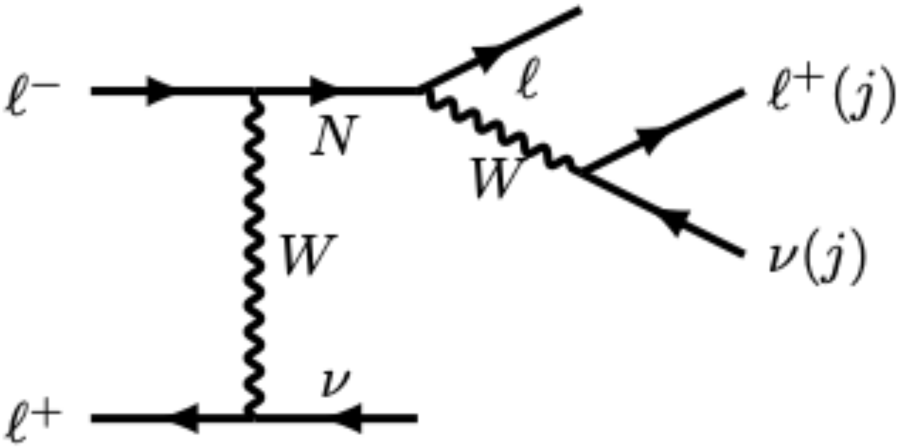


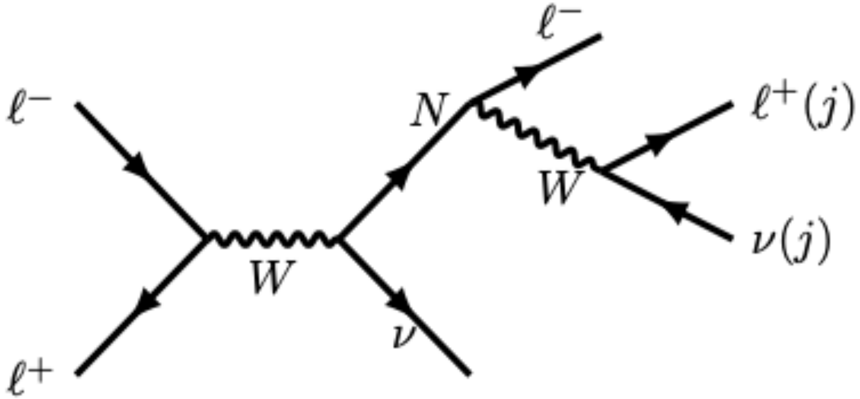
$$\sum_{i=e,\mu,\tau} \frac{g}{\sqrt{2}} U_i W_\sigma^- \bar{\ell}_{iL} \gamma^\sigma N + h.c. - \sum_{i=e,\mu,\tau} \frac{g}{2\cos\theta_W} U_i Z_\sigma (\bar{\nu}_{iL} \gamma^\sigma N + \bar{N} \gamma^\sigma \nu_{iL})$$

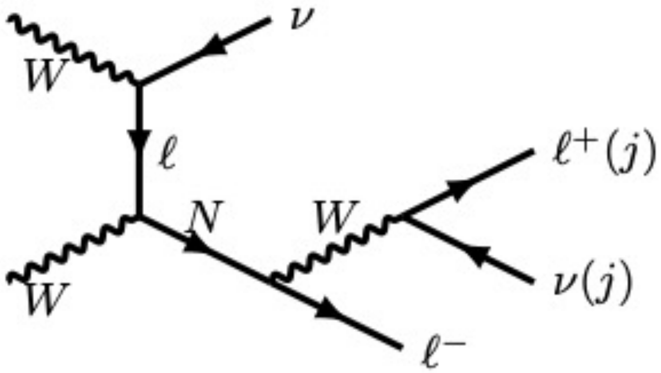




HNLs at Muon Colliders

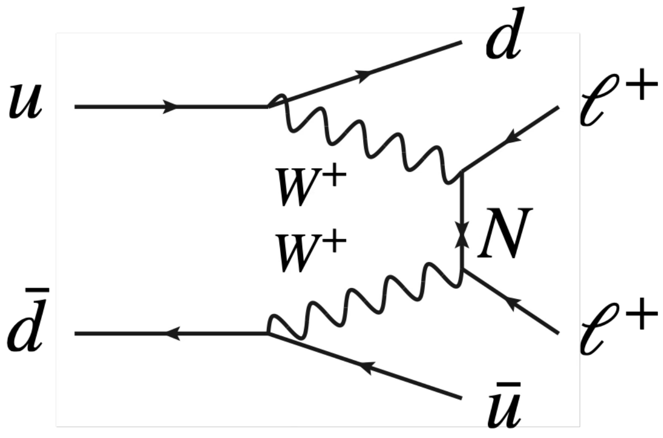


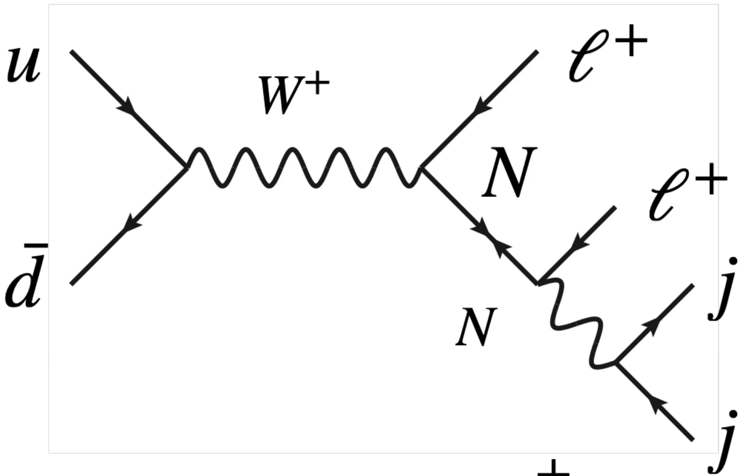


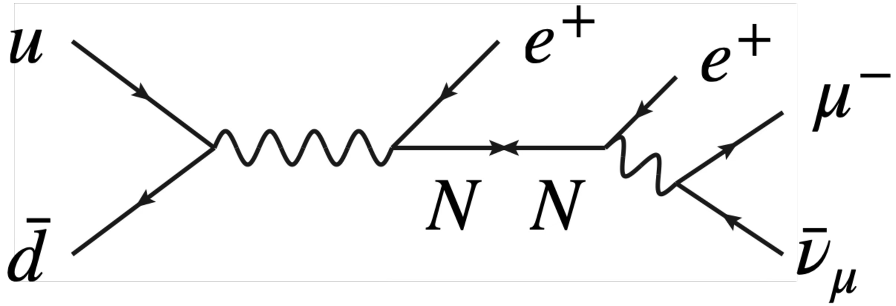


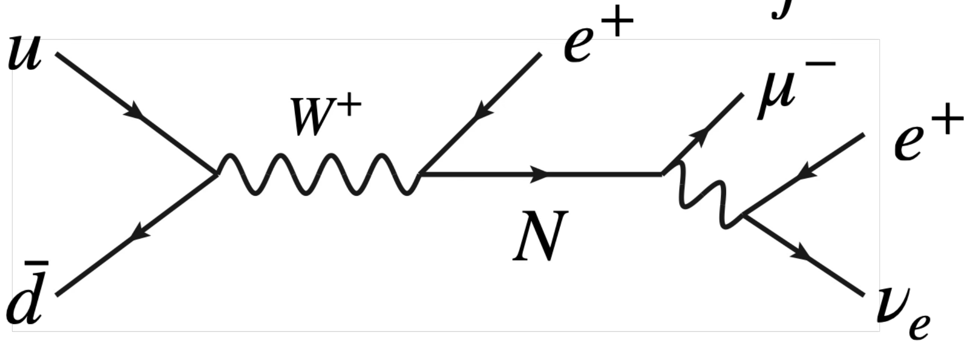
I. Chakraborty, H. Roy, and T. Srivastava, (2022), 10.1140/ep jc/s10052-023-11406-0; T. Li, C.-Y. Yao, and M. Yuan, JHEP 09, 131 (2023); T. H. Kwok, L. Li, T. Liu, and A. Rock, (2023), arXiv:2301.05177; P. Li, Z. Liu, and K.-F. Lyu, JHEP 03, 231 (2023), arXiv:2301.07117; R.-Y. He, J.-Q. Huang, J.-Y.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

“neutrinoless double beta decay”









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

S.T. PETCOV

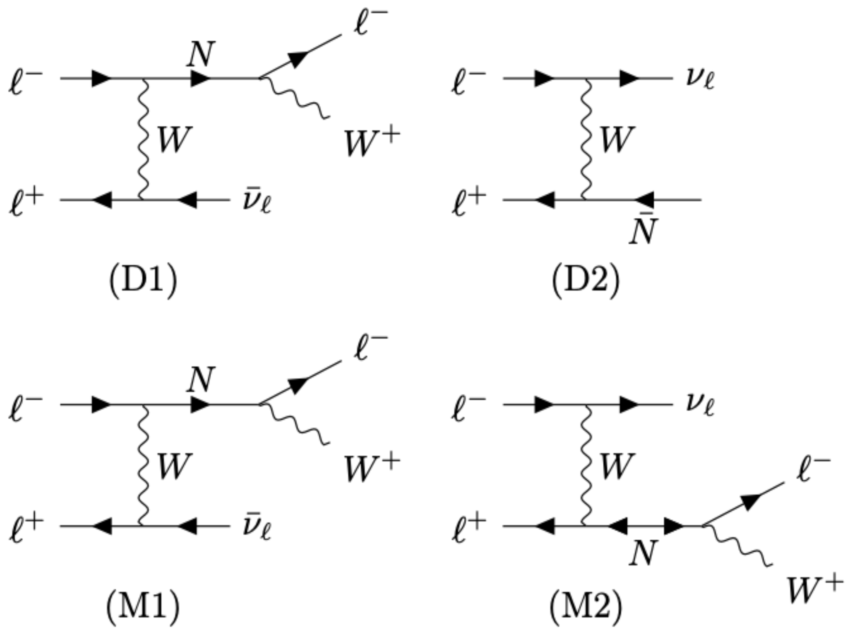
Institute of Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Boulevard Lenin 72, Sofia 1184, Bulgaria and Fermi National Accelerator Laboratory, Batavia, IL 60510, USA

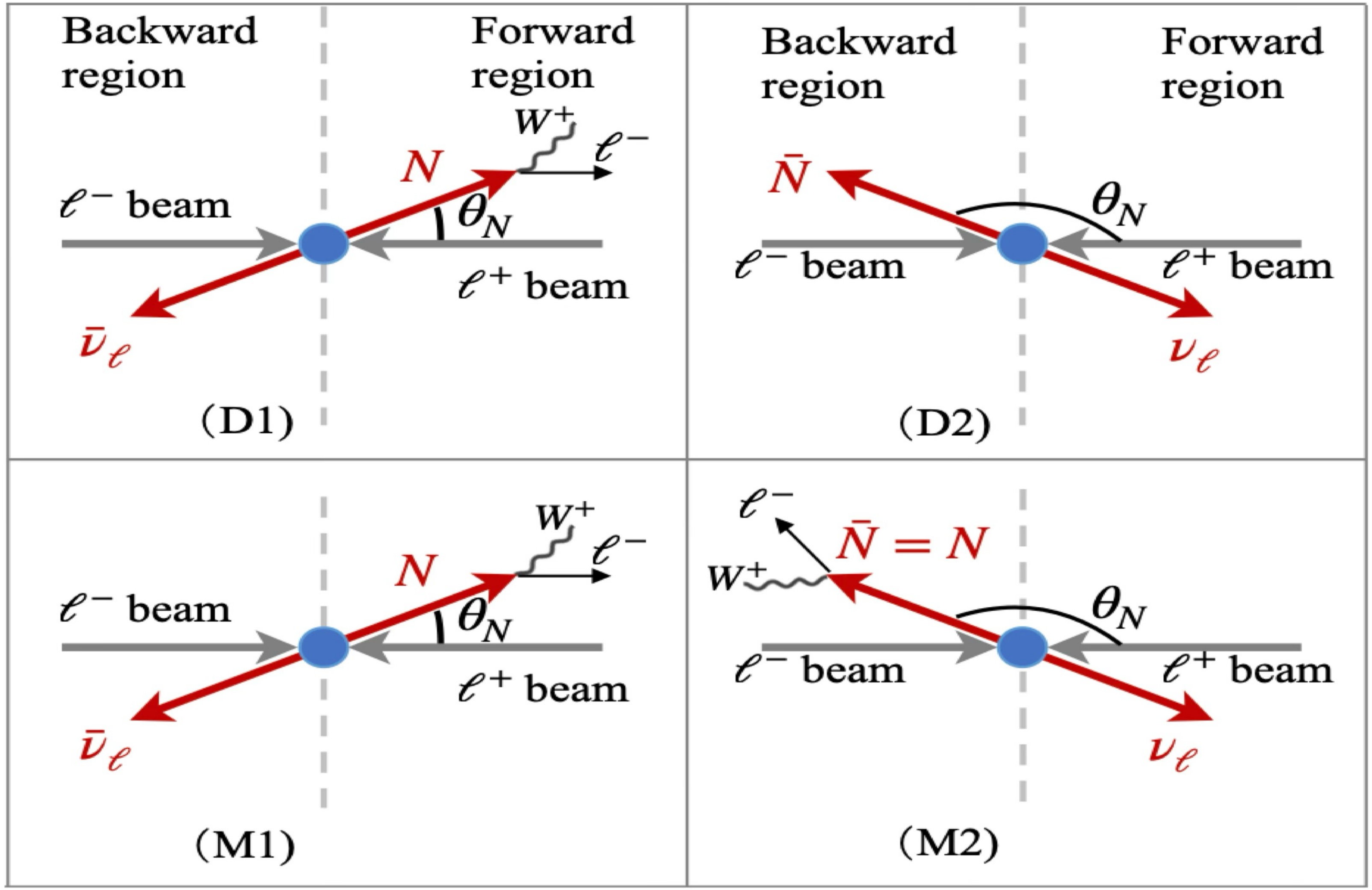
Received 4 January 1984

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

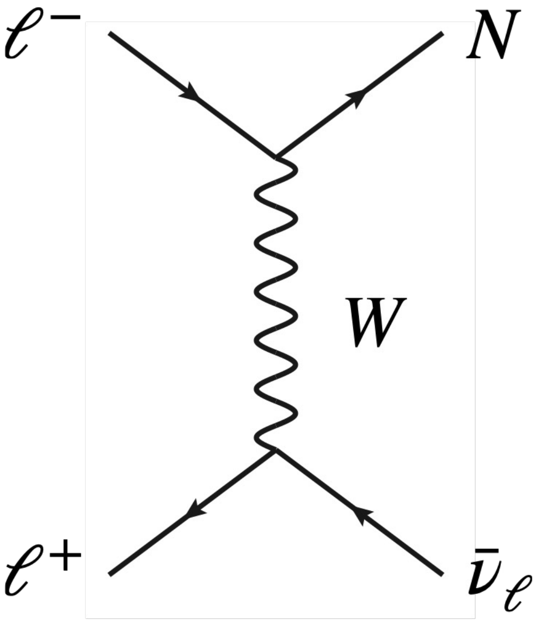
It is shown that the forward–backward asymmetry in the production of Majorana particles in e^+–e^- and p–$\bar{p}$ collisions is identically equal to zero if the couplings generating the process conserve the *CP*-parity, and that the asymmetry vanishes to leading order in perturbation theory if the production 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



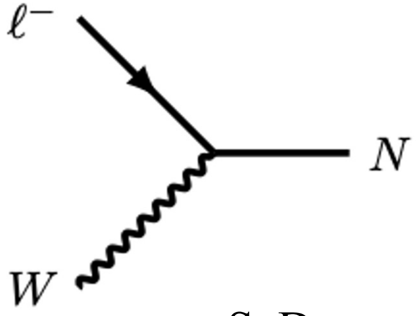


Rapidity of HNLs at Muon Colliders



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

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



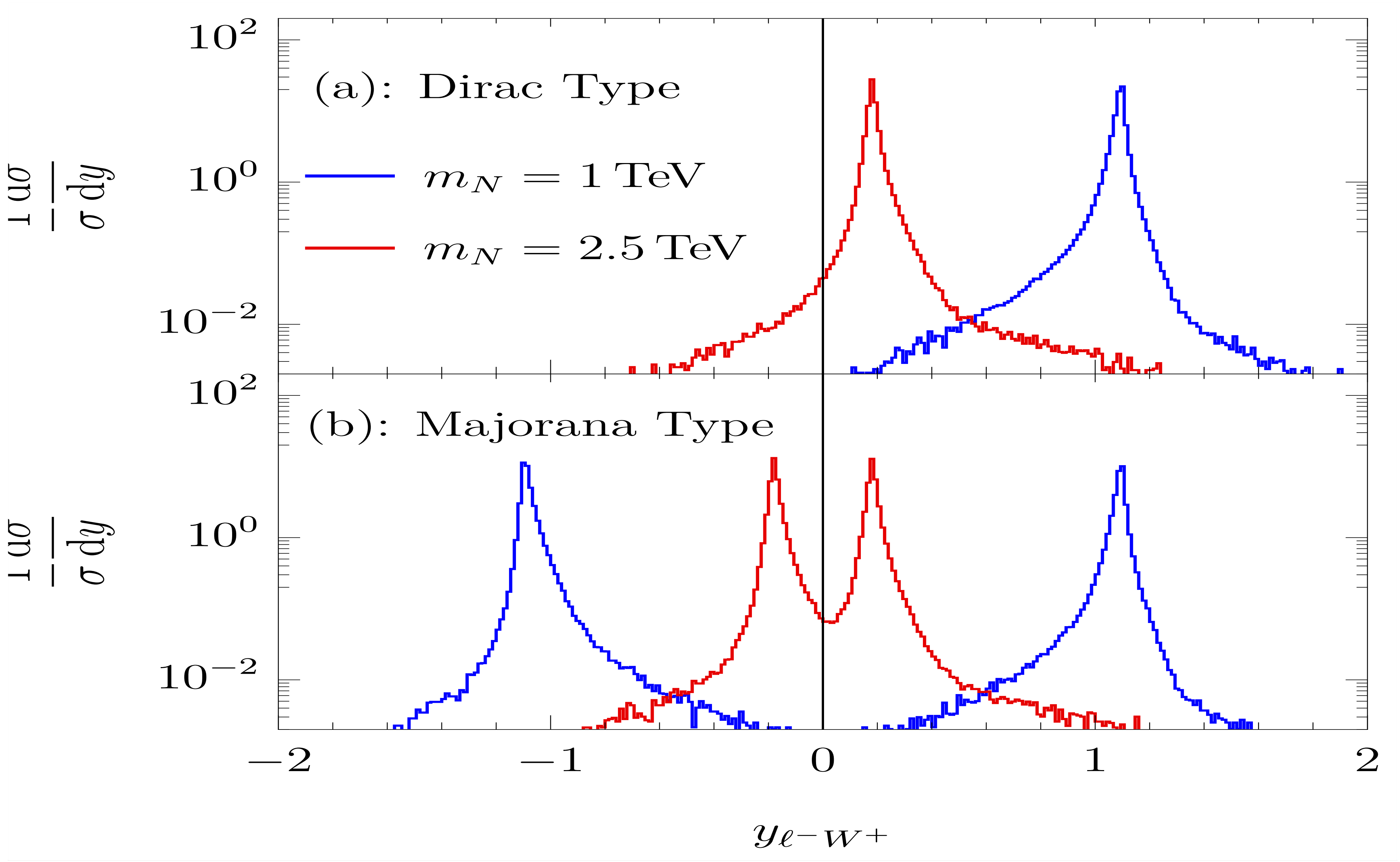
$$x_1 = 1$$

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

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

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)

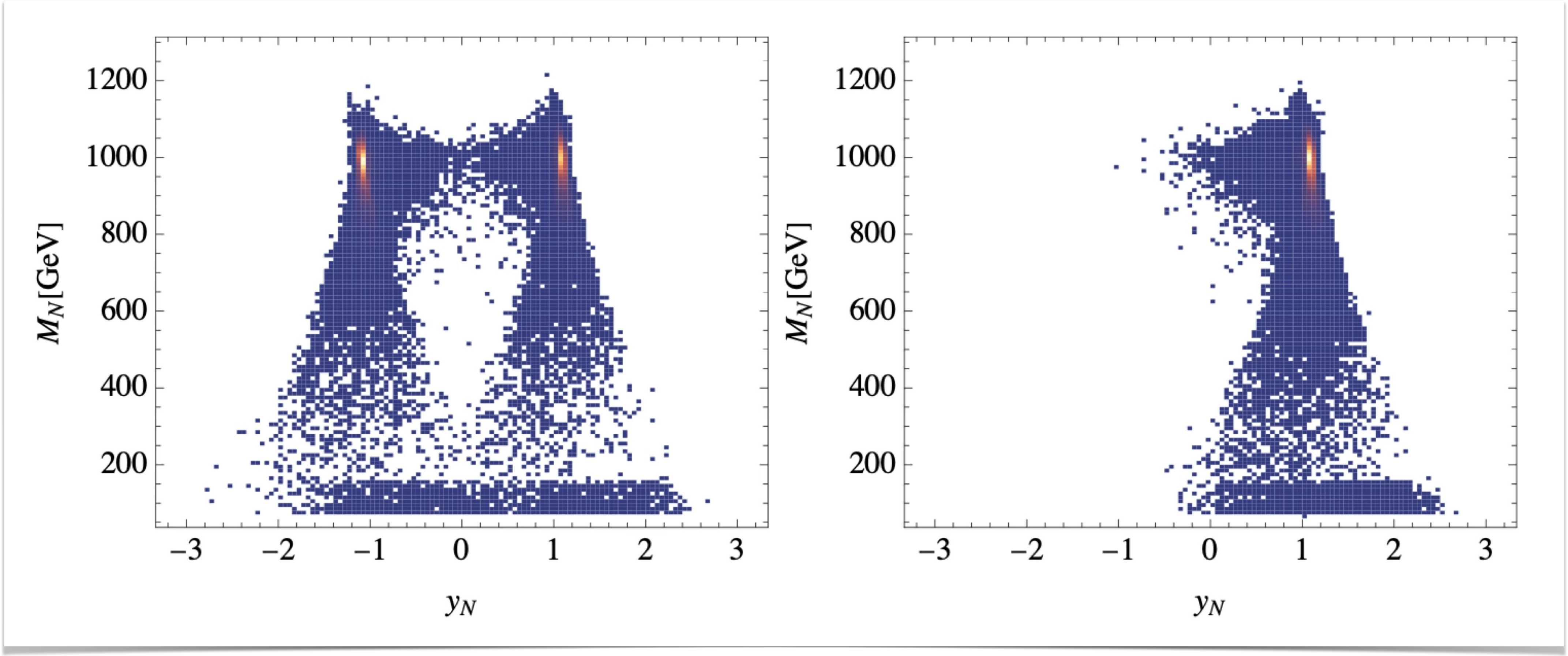
Rapidity of HNLs at Muon Colliders



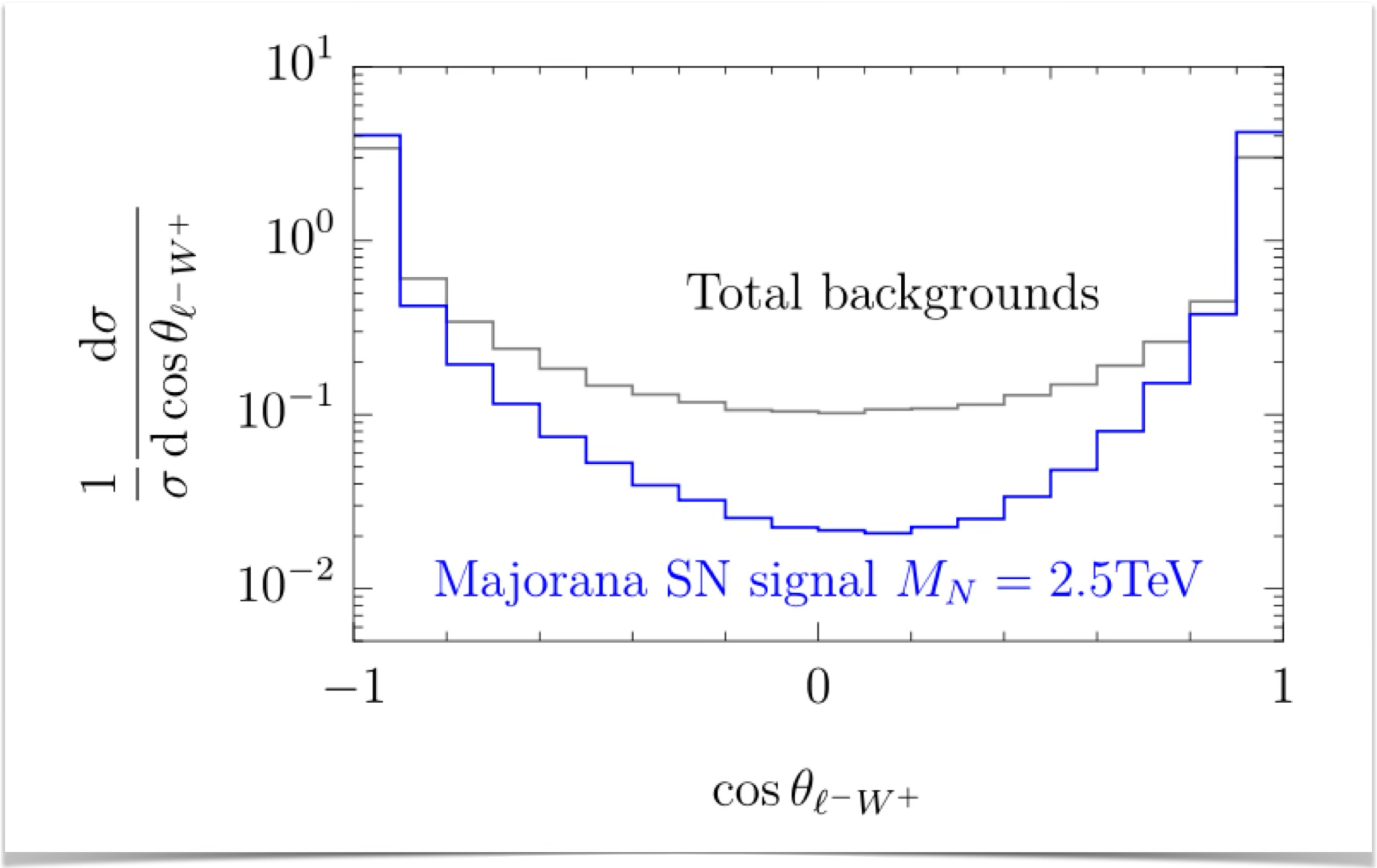
Advance of Rapidity: Correlation with Mass

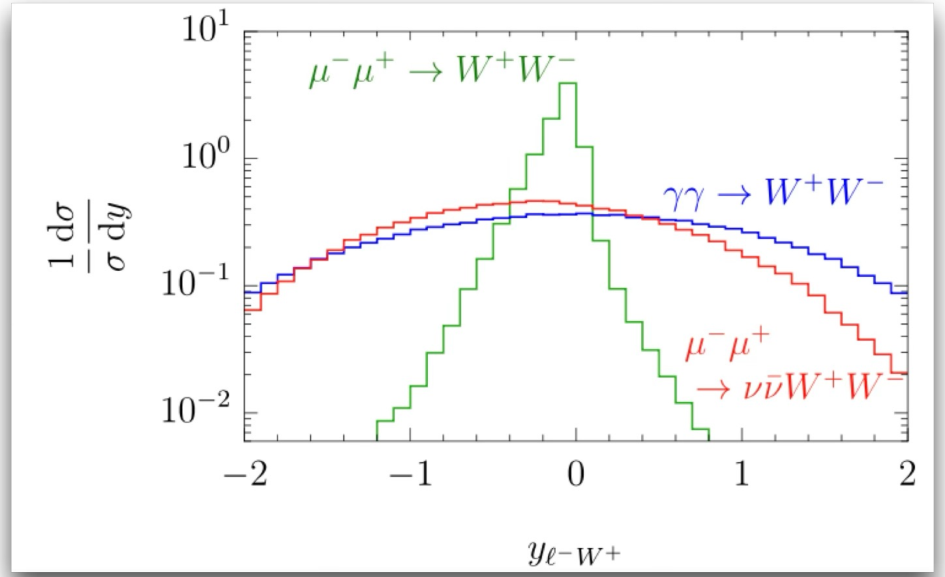
$$y_N = \frac{1}{2}\log\frac{E + p_N \cos\theta_N}{E - p_N \cos\theta_N}$$

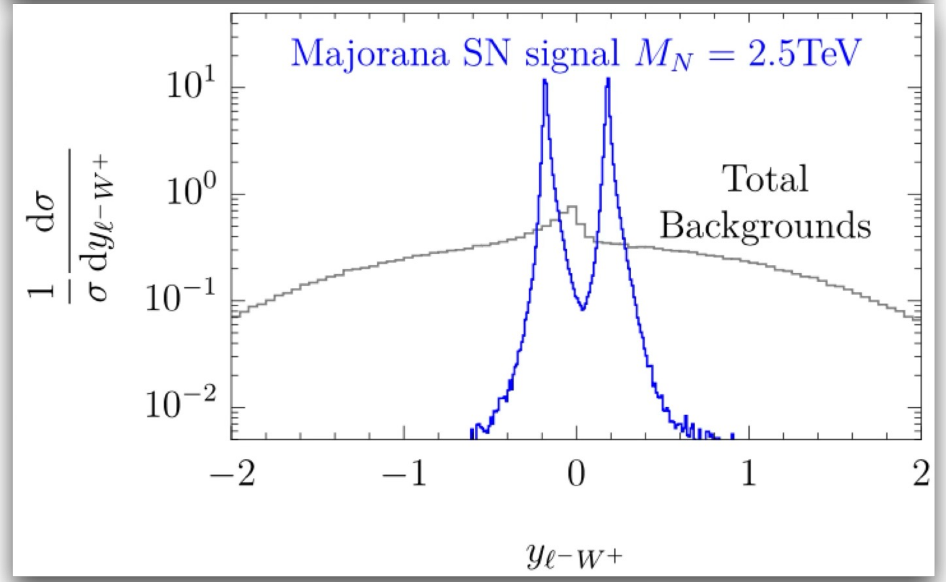
$$v_N^Z = tanh\, y_N$$



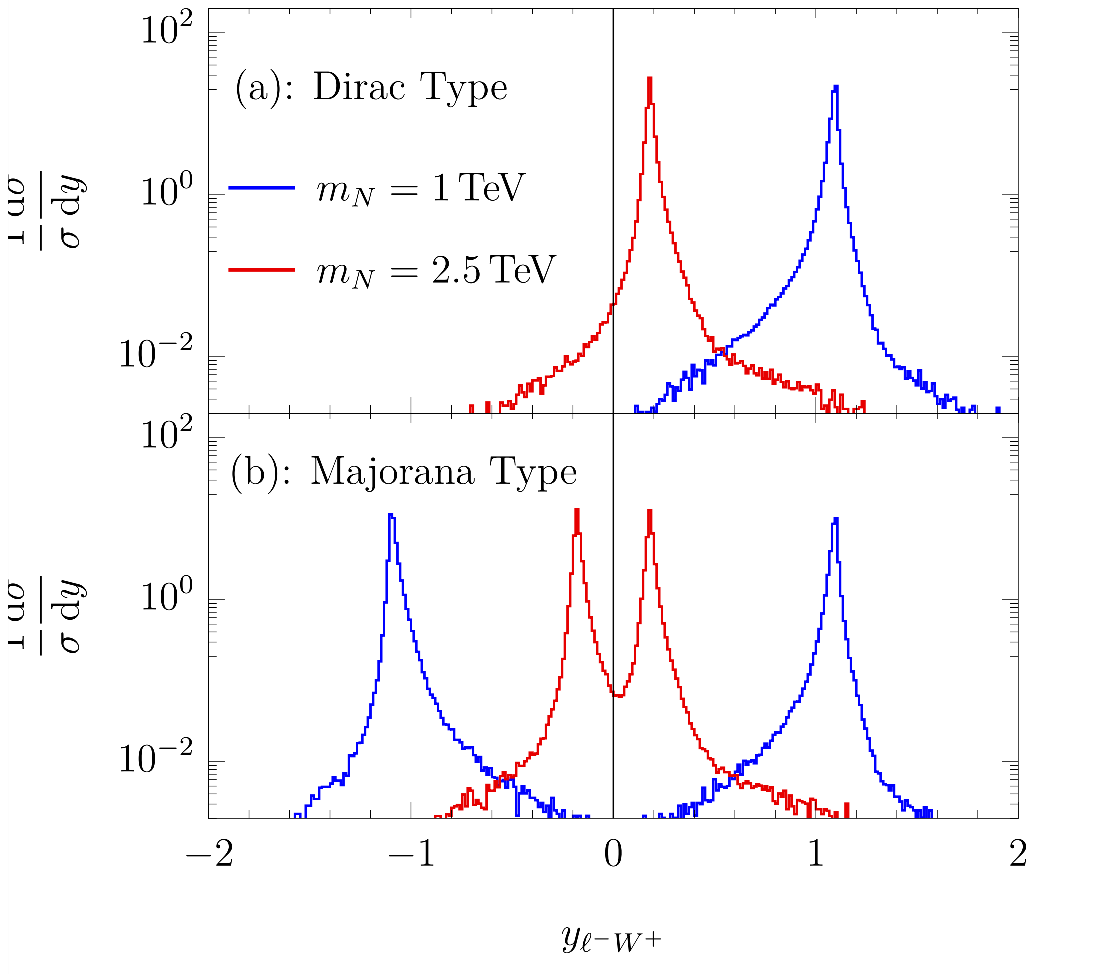
Advance of Rapidity: Signal Discrimination

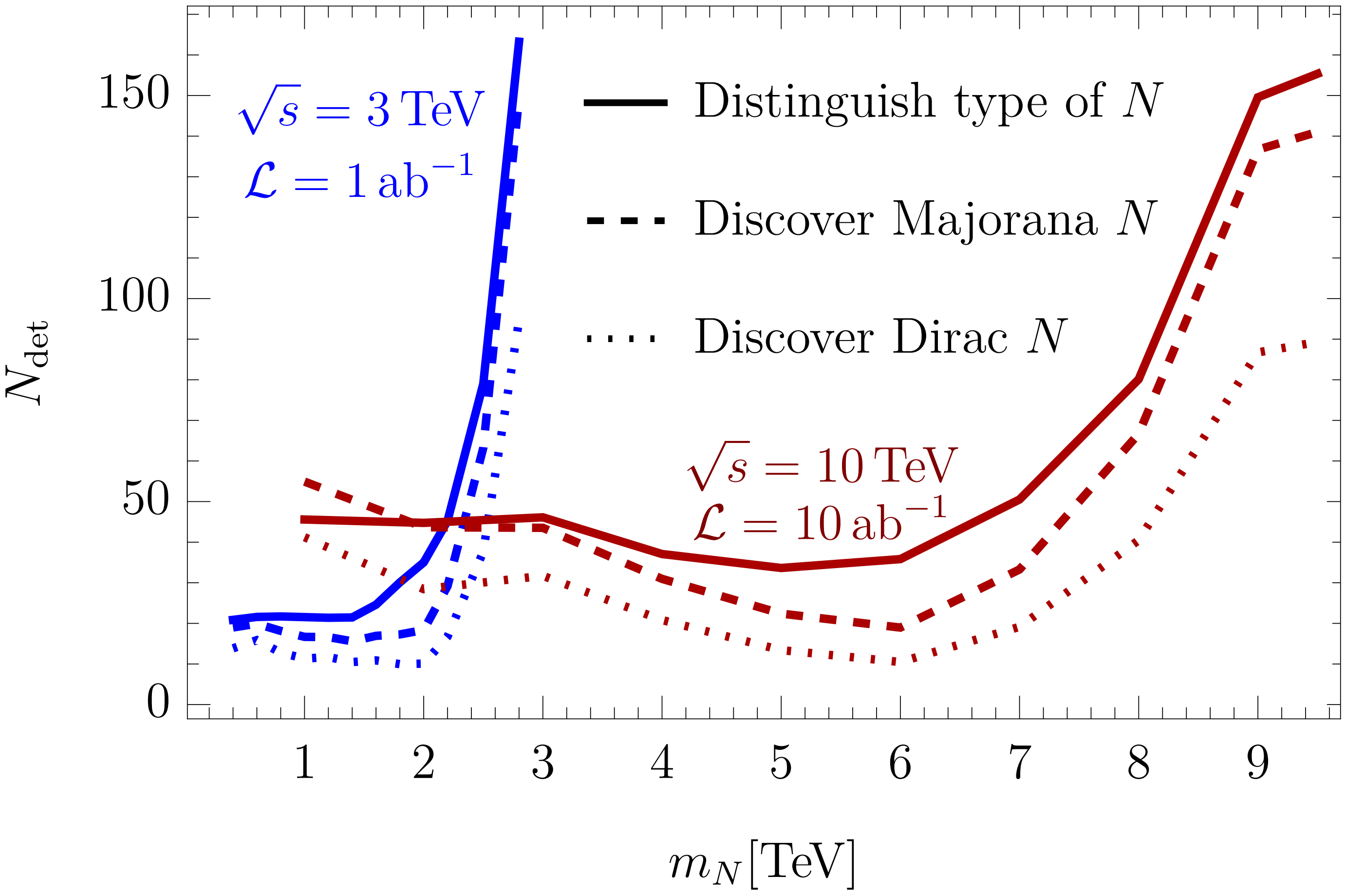






Discovery and Discrimination Reach at Muon Colliders





Conclusion

- At the muon collider, the quartic Higgs-gauge coupling can be measured about 10% precision

- 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

  Dirac/Majorana nature of N can be efficiently determined once it is confirmed

Thanks!