Searching for Heavy Neutral Leptons at A Future Muon Collider

Ariel Rock with Tsz Hong Kwok, Lingfeng Li, and Tao Liu

Based on 2301.05177

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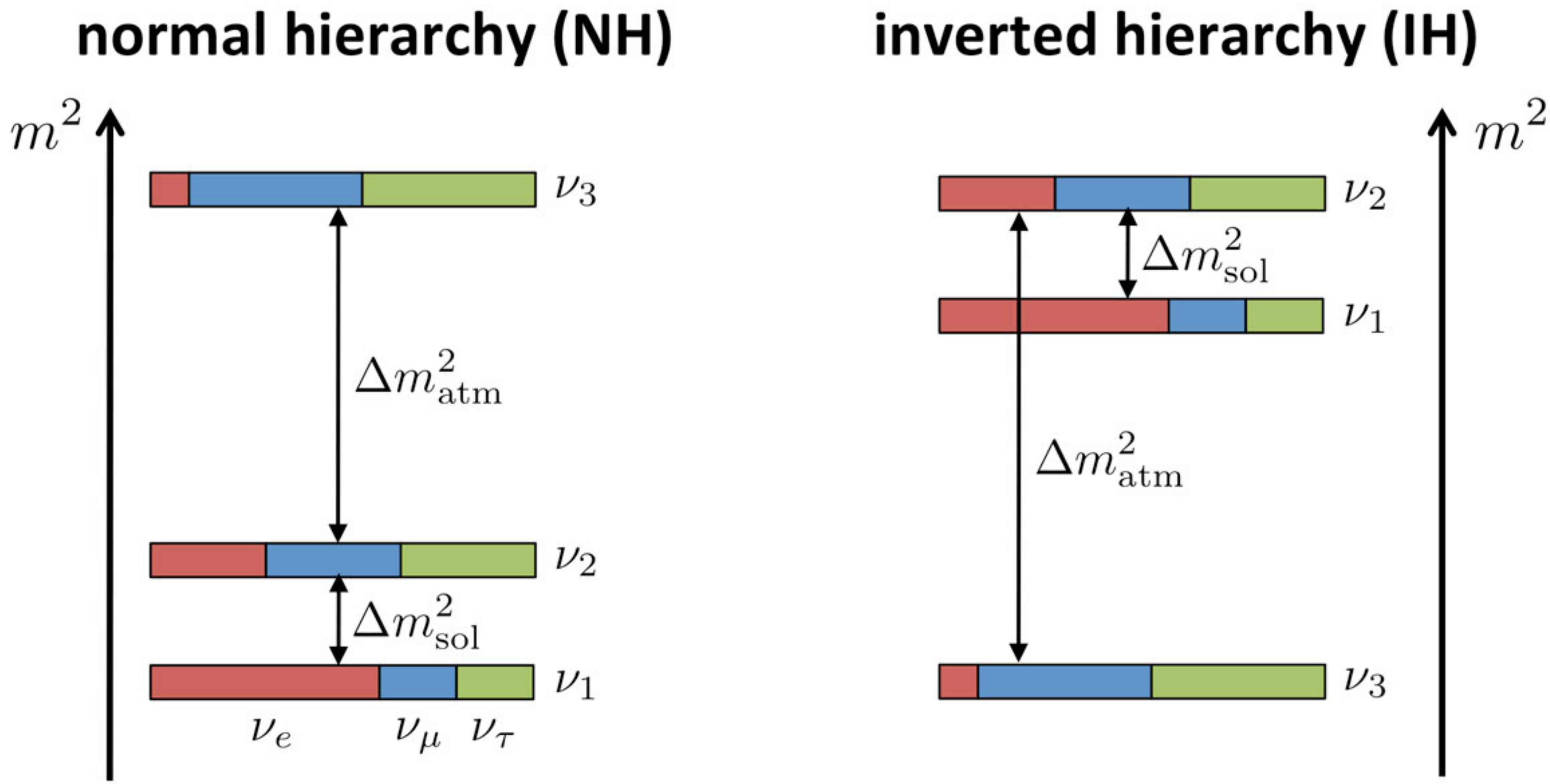
THE HONG KONG UNIVERSITY OF SCIENCE AND TECHNOLOGY

IAS HKUST JOCKEY CLUB INSTITUTE FOR ADVANCED STUDY

Heavy Neutral Leptons

JUNO Collaboration / JGU-Mainz



Decades of evidence of neutrino oscillations and masses

Homestake, SuperK, SNO, KamLAND, Daya Bay, RENO, Double Chooz, MINOS, T2K, NOvA, IceCube ...

Generating Neutrino Masses

- How to introduce neutrino masses?

- Lowest order using only SM fields, introduce d=5 Weinberg operator

$$-\frac{Y}{\Lambda}\left(\overline{L}\tilde{H}L^{c}H\right),$$

Weinberg 1979

Minkowski 1977, Gell-Mann et al. 1979, Yanagida 1979, Mohapatra et al. 1980

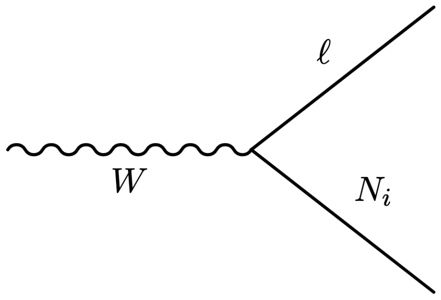
- Type I Seesaw — Weinberg operator descended from integrating out heavy sterile Majorana Neutrinos, $\Lambda = m_N$

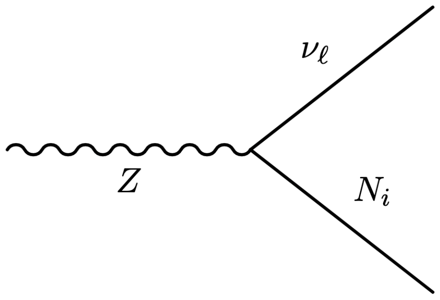
- Effective Lagrangian

$$-\mathcal{L}_{\text{int,EW}} = \frac{g}{\sqrt{2}} W^{\mu+} \sum_{\ell=e}^{\tau} \left(\sum_{m=1}^{3} U^{*}_{\ell m} \bar{\nu}_m \gamma^{\mu} P_L \ell + \sum_{m=1}^{3} V^{*}_{\ell m} \bar{N}^{c}_{m} \gamma^{\mu} P_L \ell \right)$$
$$+ \frac{g}{2\cos\theta_W} Z^{\mu} \sum_{\ell=e}^{\tau} \left(\sum_{m=1}^{3} U^{*}_{\ell m} \bar{\nu}_m \gamma^{\mu} P_L \nu_\ell + \sum_{m=1}^{3} V^{*}_{\ell m} \bar{N}^{c}_{m} \gamma^{\mu} P_L \nu_\ell \right) + h.c.$$

- Neutrino Mixing

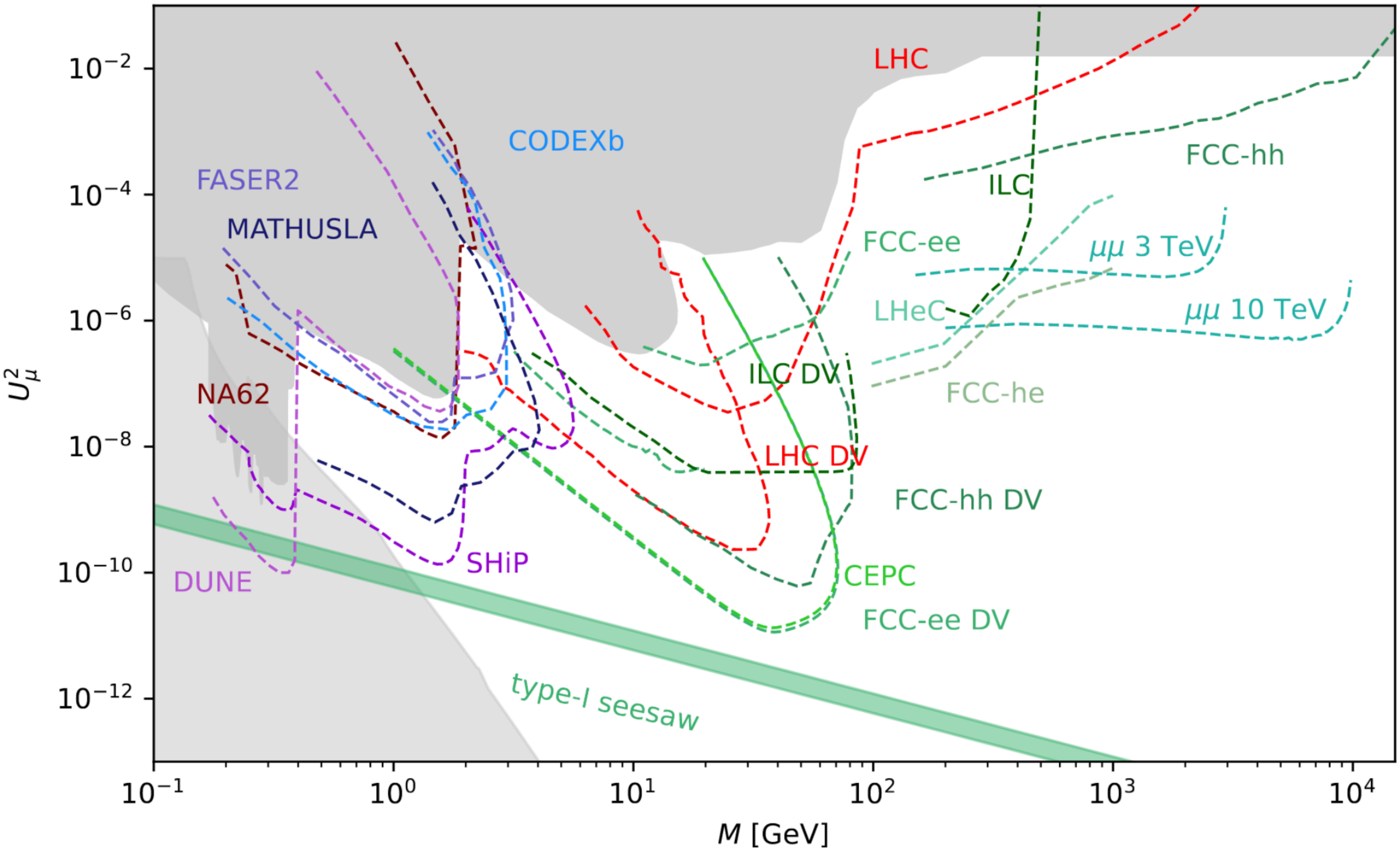
$$\nu_{\ell L} = \sum_{m=1}^{3} U_{\ell m} \nu_{mL} + \sum_{m'=1}^{3} V_{\ell m'} N^{c}_{m' L}$$





Current and Future Bounds

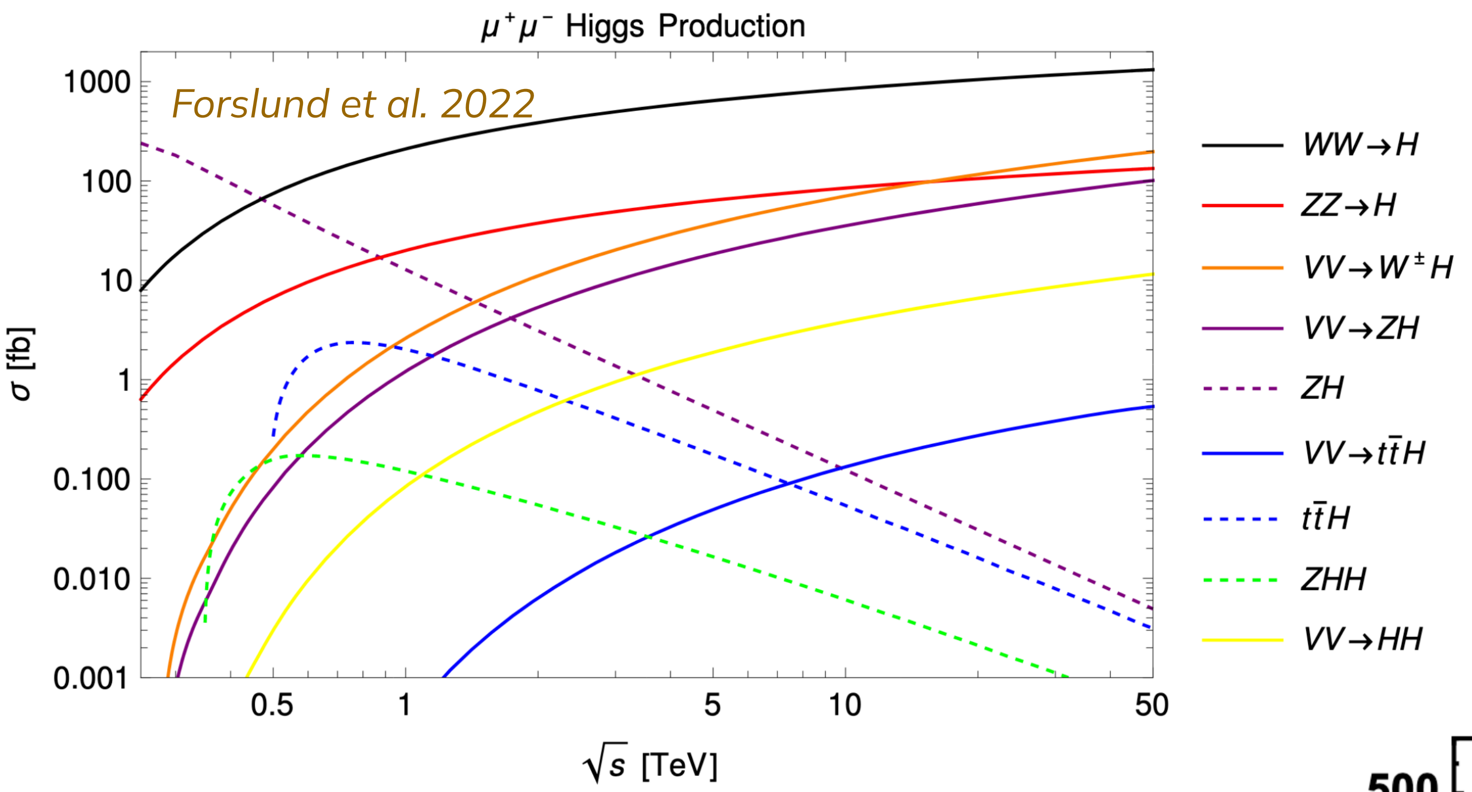
Snowmass Energy Frontier: 2211.11084



Why Muon Collider?

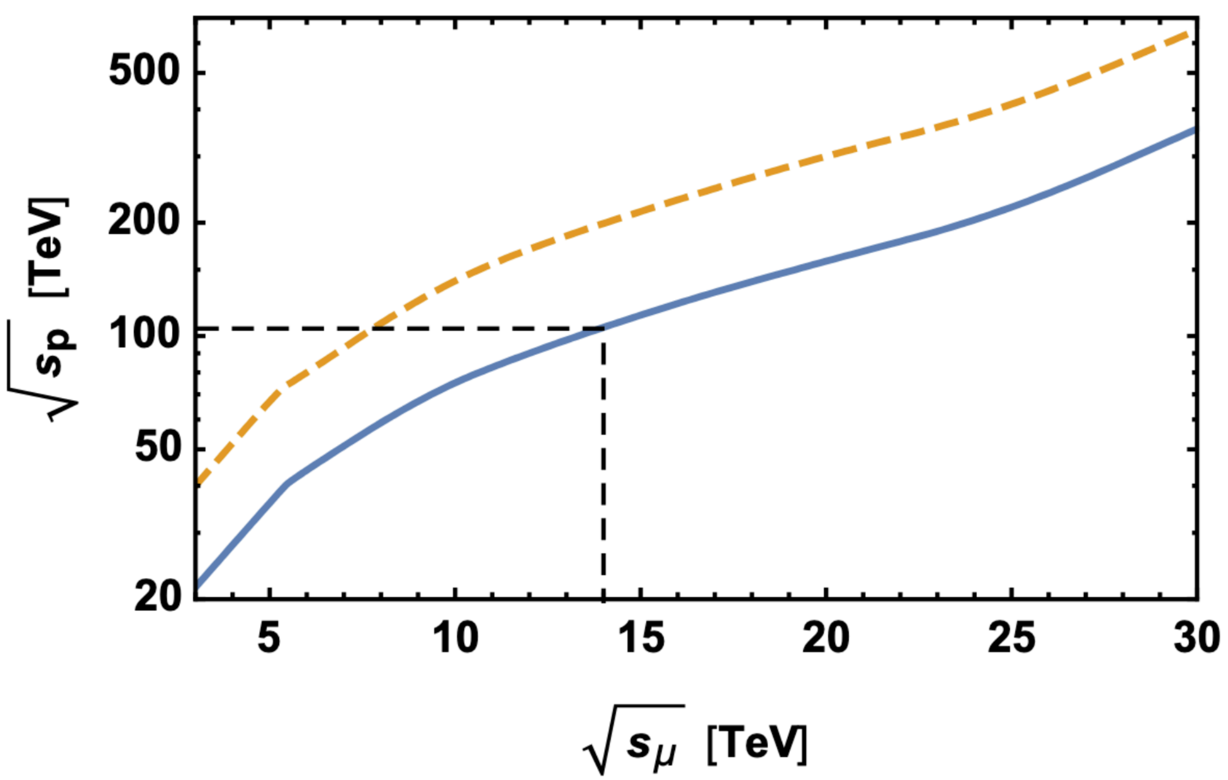
Reduced Synchrotron Radiation

$(m_e/m_\mu)^4 \approx (207)^{-4}$



Muon Colliders are Gauge Boson Colliders

Higher Equivalent COM Energy than Hadron Colliders



Event Generation

- Events generated using WHIZARD 3 *Kilian et al. 0708.4233, Moretti et al. hep-ph/0102195*
  - Includes Initial State Radiation (ISR)
    - New to WHIZARD 3 — p_T recoil from ISR
  - Using the FeynRules *HeavyN* models *Degrande et al. 1108.2040, Alloul et al. 1310.1921, Alva et al. 1411.7305, Degrande et al. 1602.06957, Atre et al. 0901.3589, Pascoli et al. 1812.08750*
- Generated using $|V_\ell| = 0.002$
- HNLs decayed on-shell, using Narrow Width Approximation
- Consider two collider benchmarks $\sqrt{s} = 3\ (10)$ TeV with $L = 1\ (10)$ ab^{-1}

Detector Simulation

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Bierlich et al. 2203.11601

- After PYTHIA 8 showering, detector response simulated using DELPHES 3 *DELPHES 3 Collaboration 1307.6346*

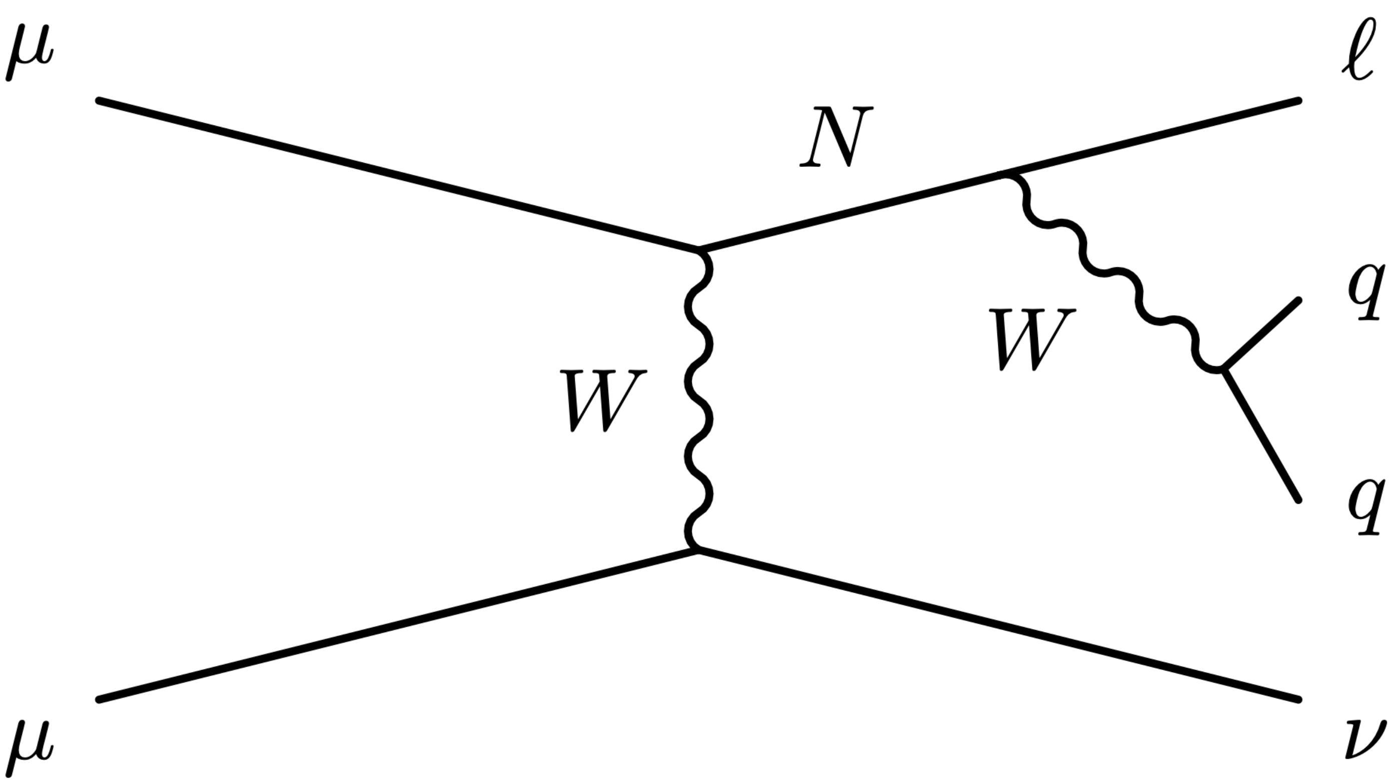
- Fast, modular simulation build on “cards”

- We use the included Muon Collider Card

    - Hybrid of FCC-*hh* and CLIC detector cards

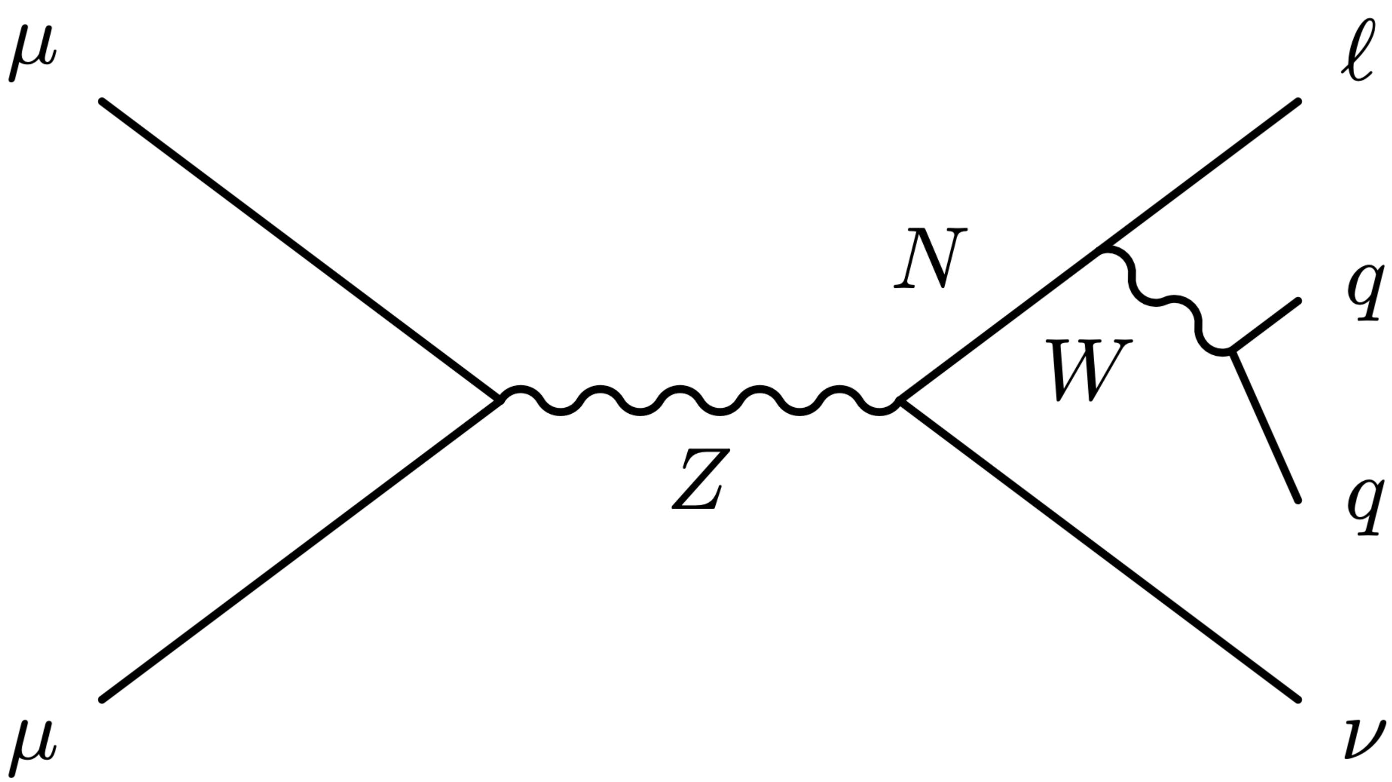
Selvaggi 2020 *Roloff et. al 2018*

Signal



Dominant above Z-pole

Signal: $\mu^+\mu^- \to N(qq\ell)\nu$



Assumptions

- Only one contributing HNL
- $|V_{1\tau}| = 0, |V_{1e}| = |V_{1\mu}| \equiv |V_\ell|$
- $\Gamma_N \ll m_N$
- Masses between 200 GeV and 9.5 TeV

Cross Section

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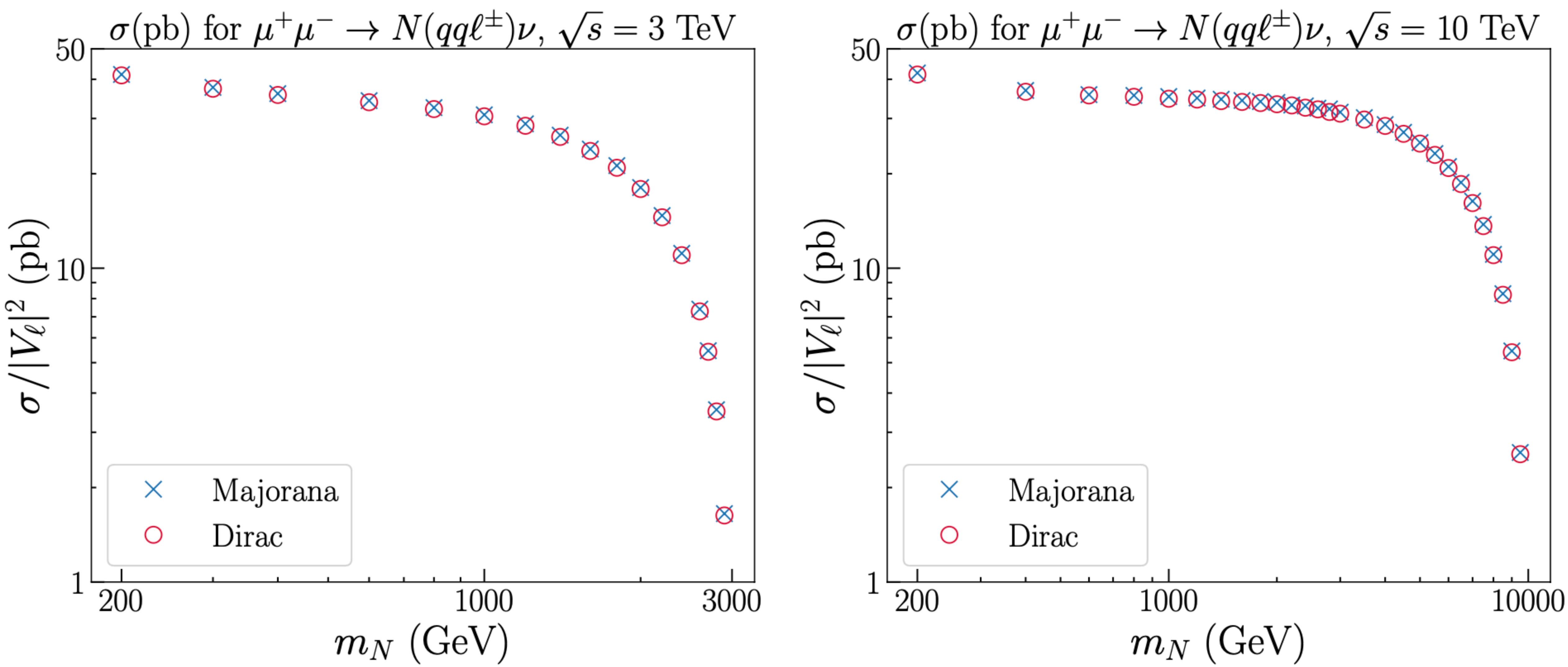
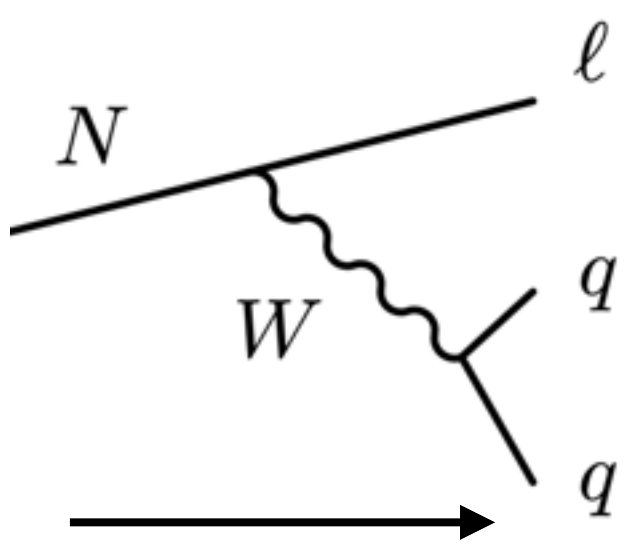


Total Process Cross Section (Production + Decay to $qq\ell$)

Reconstruction

- At least 1 isolated $\ell = e, \mu$ candidate
  - $p_{T,\ell} > 0.5$ GeV
  - $\sum_{\neq \ell} p_T / p_{T,\ell} < 0.2$ within cone of $\Delta R = 0.1$
- If $> 1\ \ell$, choose largest $p_{T,\ell}$
- Reconstruct jet system J using VLC algorithm *Boronat et al. 1404.4294*
  - Single fat jet, $J = J_{\text{fat}}$, with $R = 1.2, \beta = \gamma = 1.0$
  - Or, two narrow jets $J = j_1 + j_2$, with $R = 0.2, \beta = \gamma = 1.0$
- Choose method with invariant mass closest to m_W
  - Keep all jet information for use in BDT



Preselection

- Reconstructed events pass preselection if:
  - $p_{T,\ell,J} > 100$ GeV
  - $|M_J - m_W| < 5\Gamma_W$
- Final HNL candidate is combination of J and ℓ

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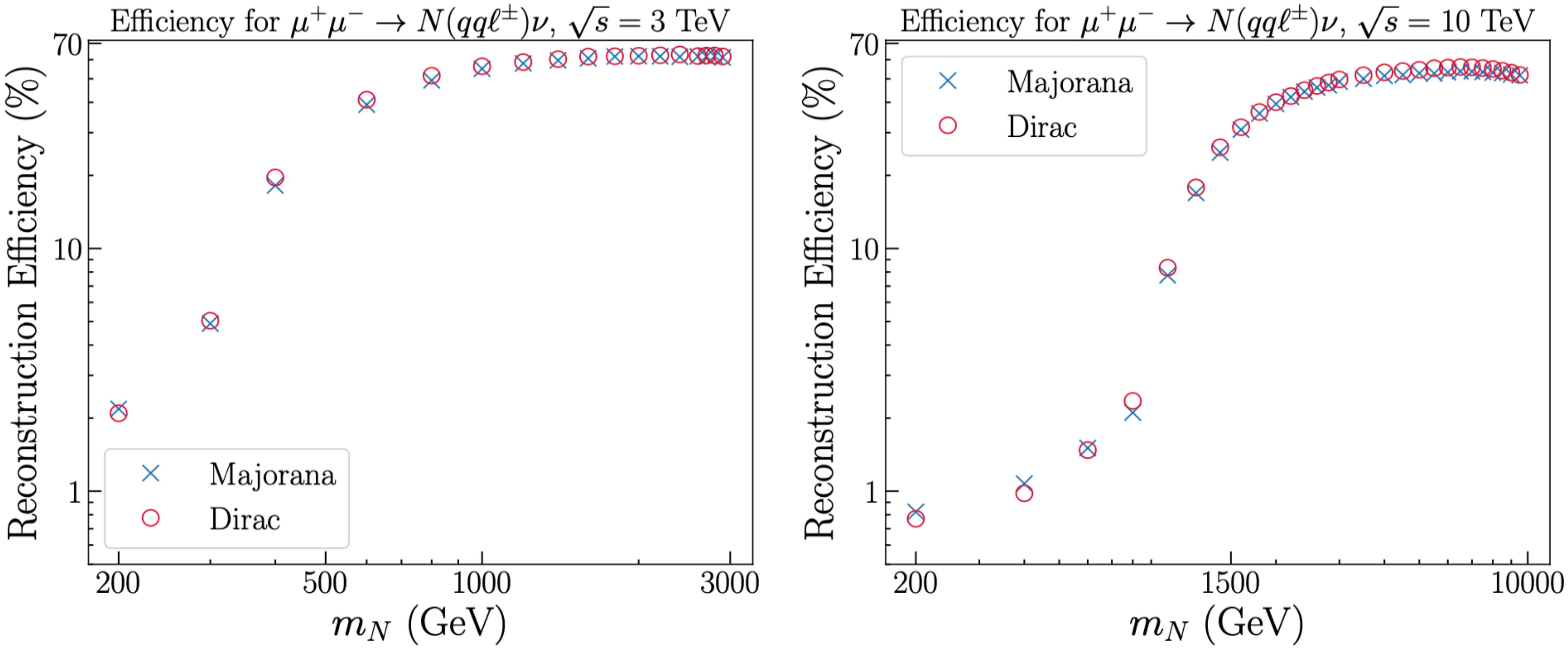
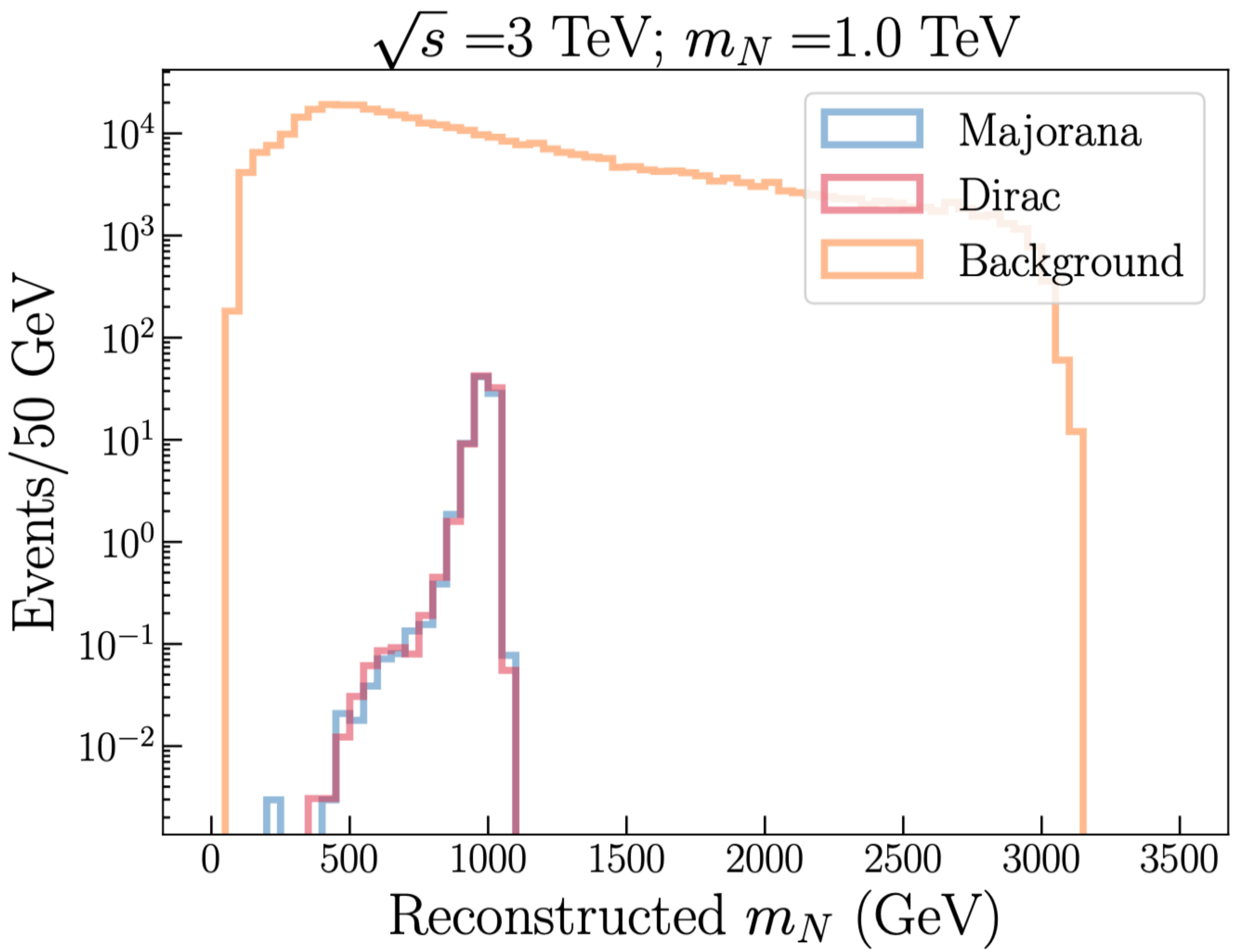


Reconstruction



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Signal m_N and total SM Background

BDT

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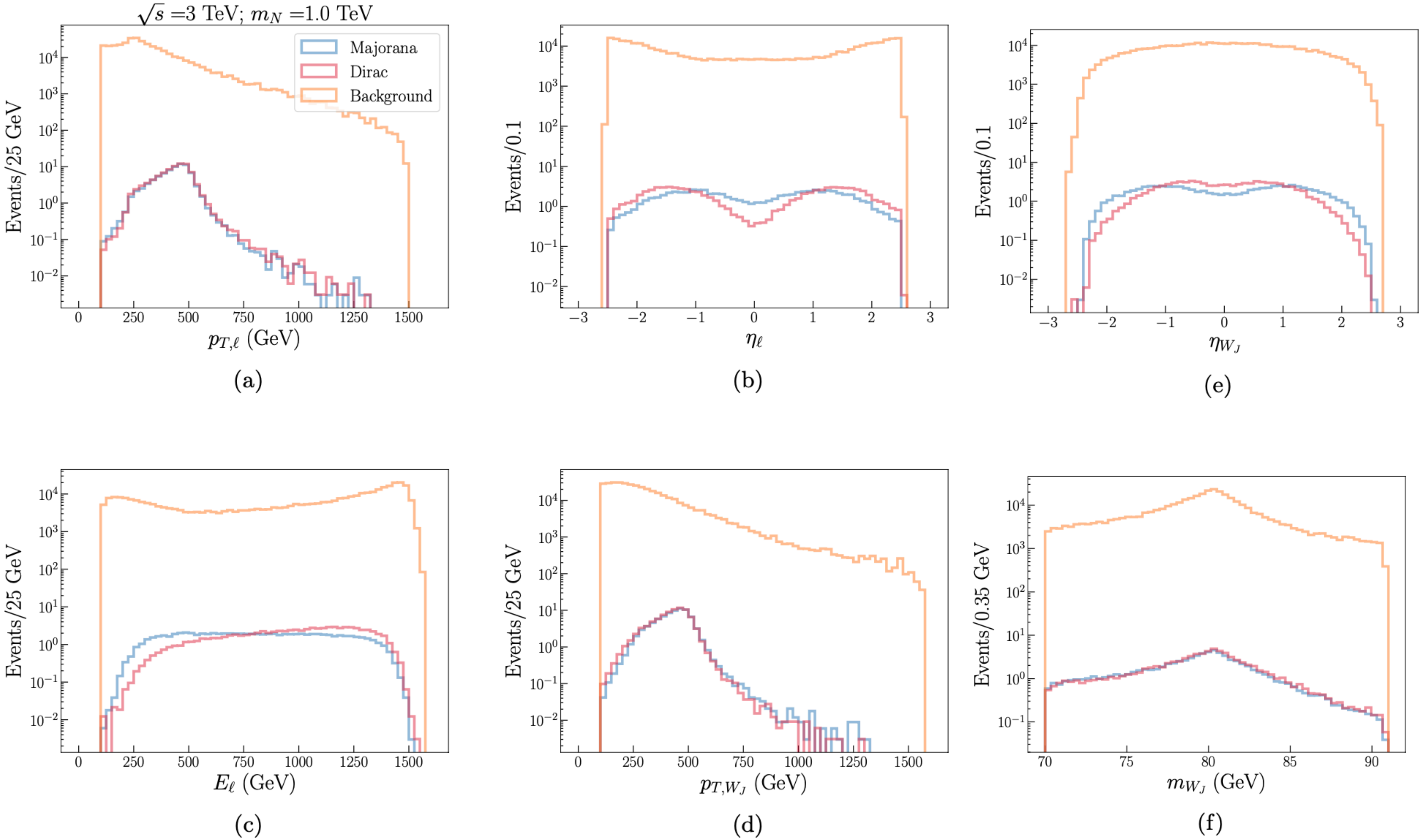

BDT Variable Distributions (1/2)

BDT

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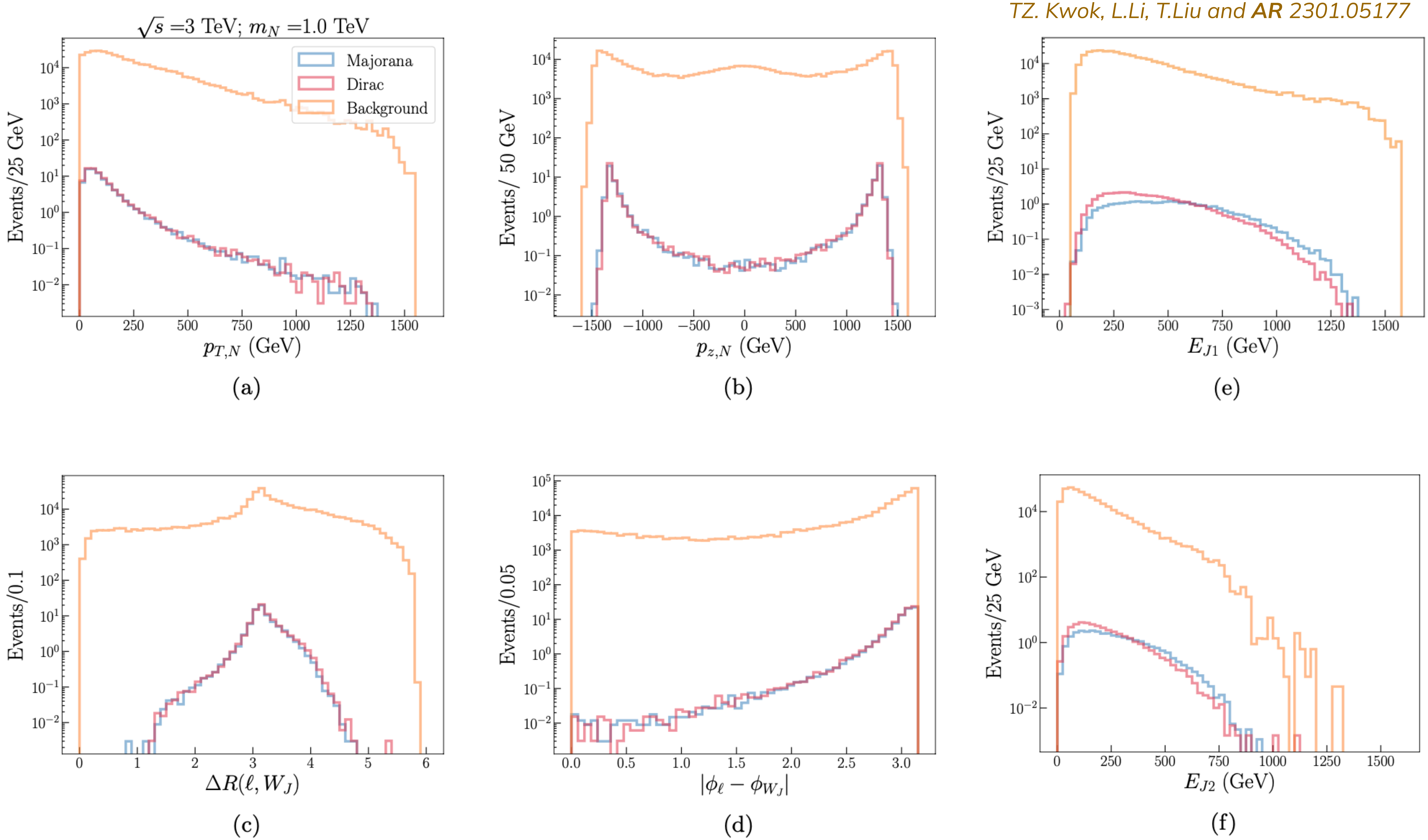
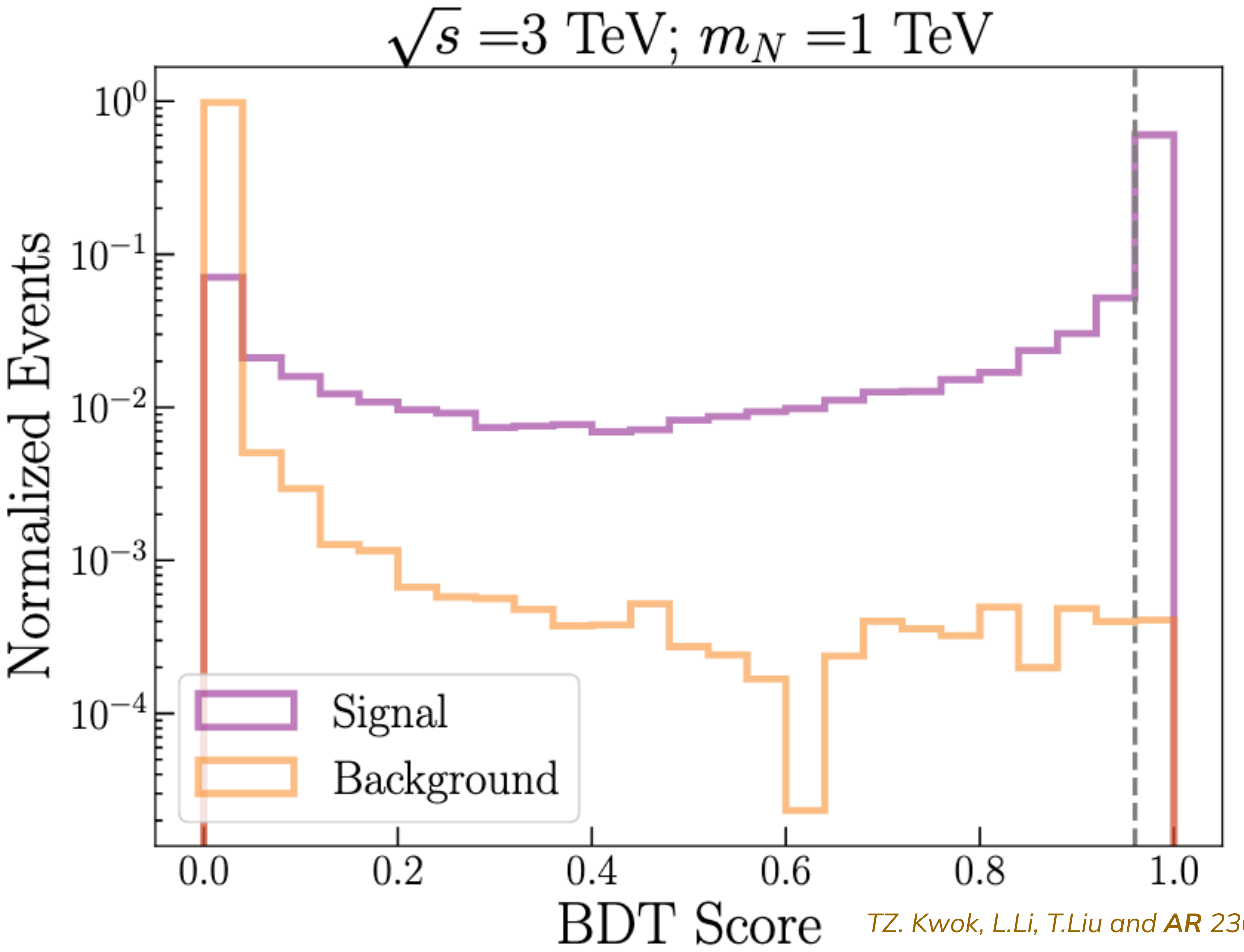


BDT Variable Distributions (2/2)

BDT Results



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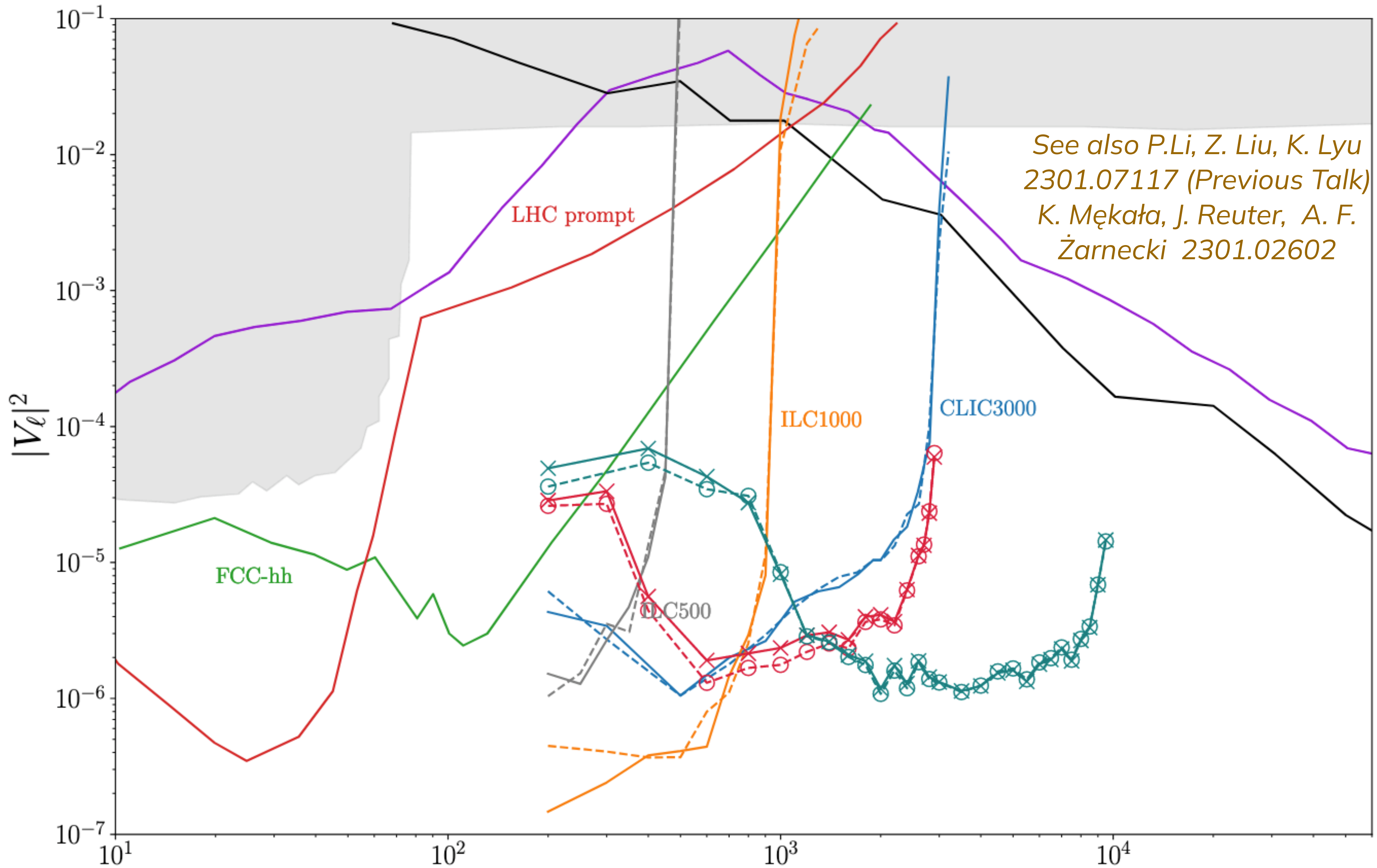
Predicted Sensitivity



See also P.Li, Z. Liu, K. Lyu 2301.07117 (Previous Talk) K. Mękała, J. Reuter, A. F. Żarnecki 2301.02602

m_N (GeV)

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$m_{\text{lightest}} = 0$ GeV
Thermal initial conditions
Vanishing initial conditions
μC 3 TeV Majorana 1 ab^{-1}
μC 3 TeV Dirac 1 ab^{-1}
μC 10 TeV Majorana 10 ab^{-1}
μC 10 TeV Dirac 10 ab^{-1}

Conclusion and Outlook

- The origin of neutrino masses is a fundamental question in BSM Physics
- Future muon collider would be a clean EW Intensity and Energy Frontier, promising environment for BSM physics searches
- Find exclusion limits for HNL-SM mixing to be as low as $\mathcal{O}(10^{-6})$
- Further Work:
  - Include couplings to Taus
  - Non-uniform mixing
  - Other production channels and observables (Double VBF, SS dilepton...)

Backup

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Reconstruction

Collider COM Energy	$\sqrt{s} = 3$ TeV			$\sqrt{s} = 10$ TeV		
Integrated Luminosity	$L = 1$ ab^{-1}			$L = 10$ ab^{-1}		
Process	σ (pb)	N_{events}	Eff. (%)	σ (pb)	N_{events}	Eff. (%)
$\mu^+\mu^- \to qq\ell\nu$	6.025	263400	4.373	9.534	932800	0.9784
$\mu^+\mu^- \to qq\ell\ell$	2.842	12160	0.4278	3.784	32090	0.0846
$\mu^+\mu^- \to qq\ell\ell\nu\nu$	0.02255	3201	14.20	0.07968	85100	10.68
$\mu^+\mu^- \to qq\ell\ell\ell\nu$	0.3133	90090	28.76	3.207	14950000	47.63
$\gamma\gamma \to qq\ell\nu$	0.1589	5068	3.190	0.4274	113600	2.658
$\gamma\mu^\pm \to qq\ell$	3.811	11390	0.2986	0.5823	21360	0.3668

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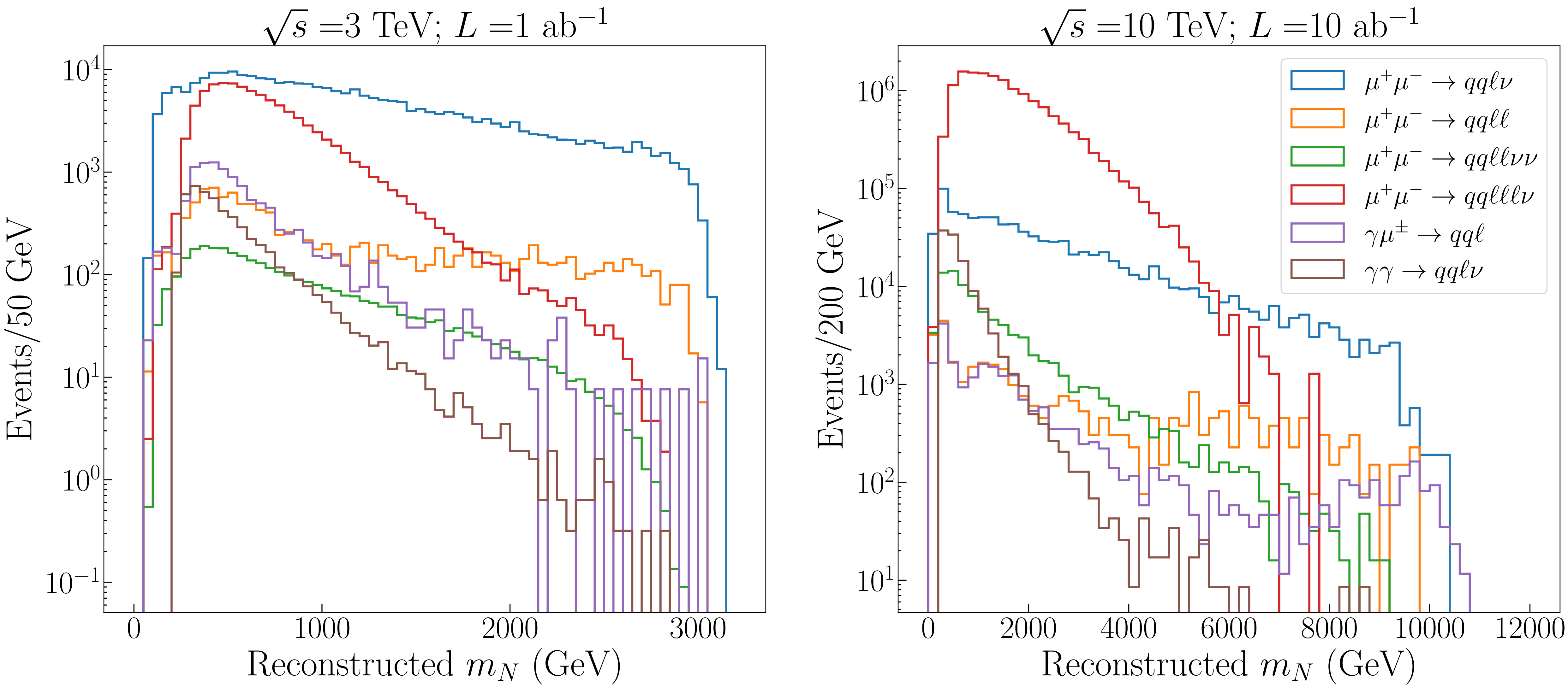
SM Background Yield and Total Reconstruction + Preselection Efficiency

BDT Features

- Lepton
  - $p_{T,\ell}$, η_ℓ , E_ℓ , Charge, and Flavor
- W-Jets
  - p_{T,W_J} , η_{W_J} , and M_{W_J}
  - $E_{j1,2}$
- HNL
  - $p_{T,N}$ and $p_{z,N}$
- Geometry
  - $\Delta R(\ell, W_J)$ and $|\phi_\ell - \phi_{W_J}|$

Reconstruction



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$m_N = m_{W_J+\ell}$ **SM Background by Channel**

Potential Timeline

Snowmass Muon Collider Forum Report: 2209.01318