Searching for Heavy Neutral Leptons at A Future Muon Collider

with Tsz Hong Kwok, Lingfeng Li, and Tao Liu

Based on 2301.05177

February 13, 2023

THE HONG KONG UNIVERSITY OF SCIENCE AND TECHNOLOGY

HKUST JOCKEY CLUB INSTITUTE FOR ADVANCED STUDY

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**See also Peiran Li, Zhen Liu and Kunfeng Lyu 2301.07117
and Krzysztof Mękała, Juergen Reuter and Aleksander Filip Żarnecki 2301.02602*

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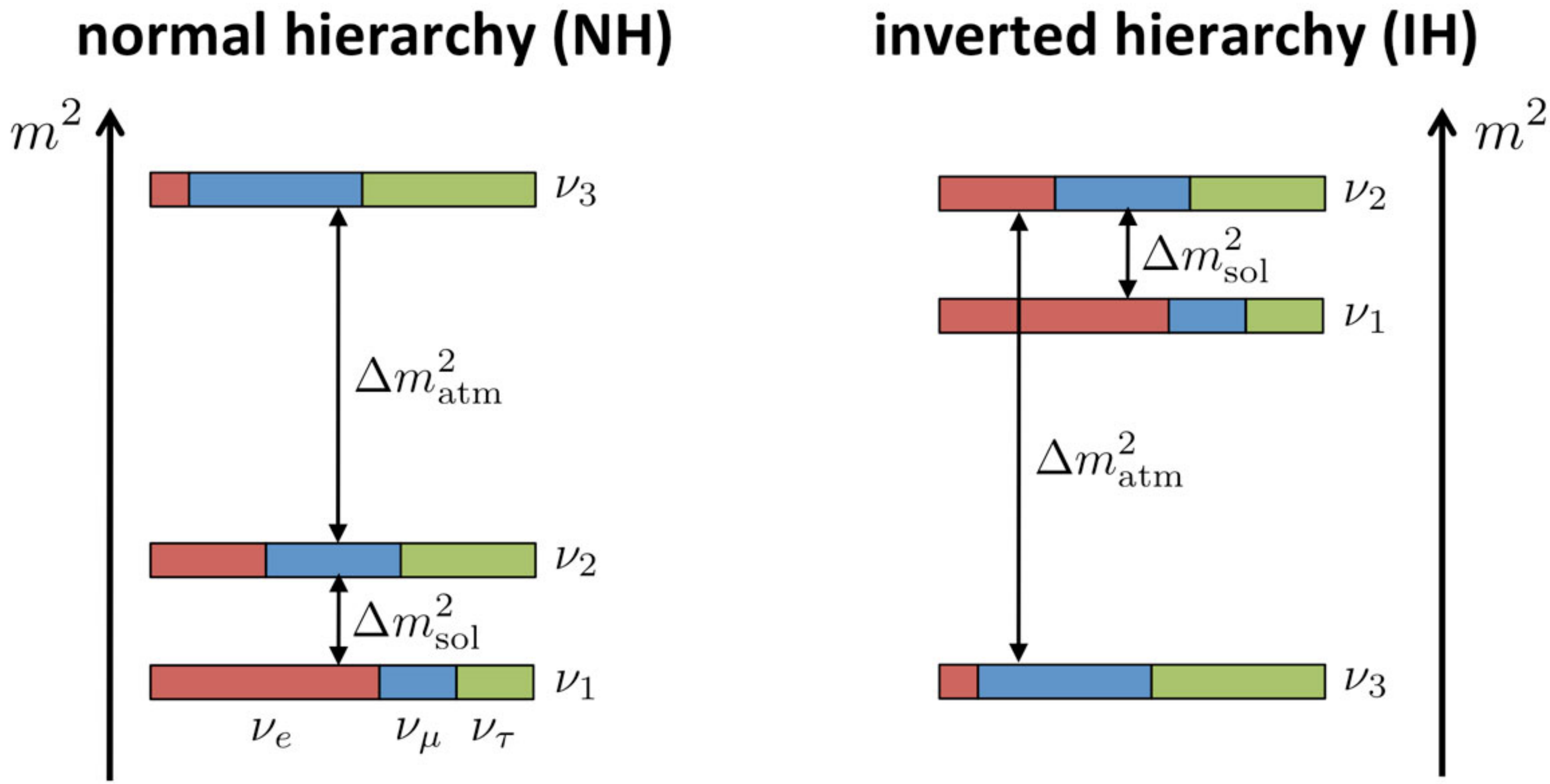
Outline

- Heavy Neutral Leptons
- Simulation Framework
  - Signal
  - Background
  - Detector
- Analysis and Reconstruction
- Sensitivity Results
- Conclusion and Future Outlook

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 ...

Creating Neutrino Masses

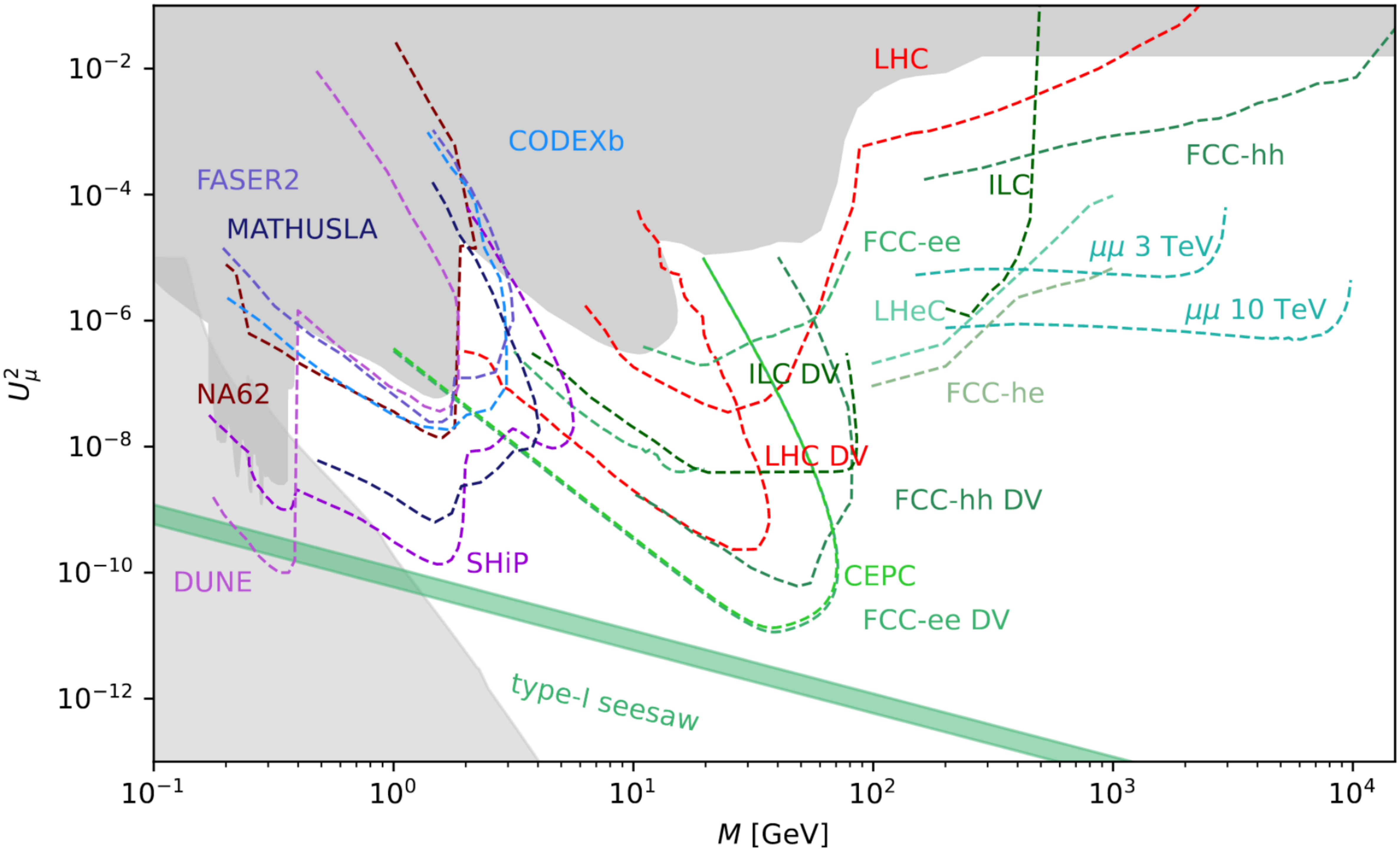
- How to introduce neutrino masses?

Weinberg 1979

  - Lowest order using only SM fields, introduce d=5 Weinberg operator $-\frac{Y}{\Lambda}\left(\bar{L}\tilde{H}L^{c}H\right)$,
  - $SU(2)$ indices can be contracted in multiple ways — hinting at different UV physics
    - Seesaws Type I,II,III *Ma 1998*
  - Type I Seesaw — Weinberg operator descended from integrating out heavy sterile Majorana Neutrinos, $\Lambda = m_N$ *Minkowski 1977, Gell-Mann et al. 1979, Yanagida 1979, Mohapatra et al. 1980*
    - SM Neutrino Mass $m_\nu \sim \frac{Y^2 v^2}{m_N}$
    - Mixing with SM Neutrinos $V \sim \frac{v}{m_N} Y \sim \sqrt{\frac{m_\nu}{m_N}}$

Current and Future Bounds

Snowmass Energy Frontier: 2211.11084



Why Muon Collider?

- Intensity and Energy Frontier

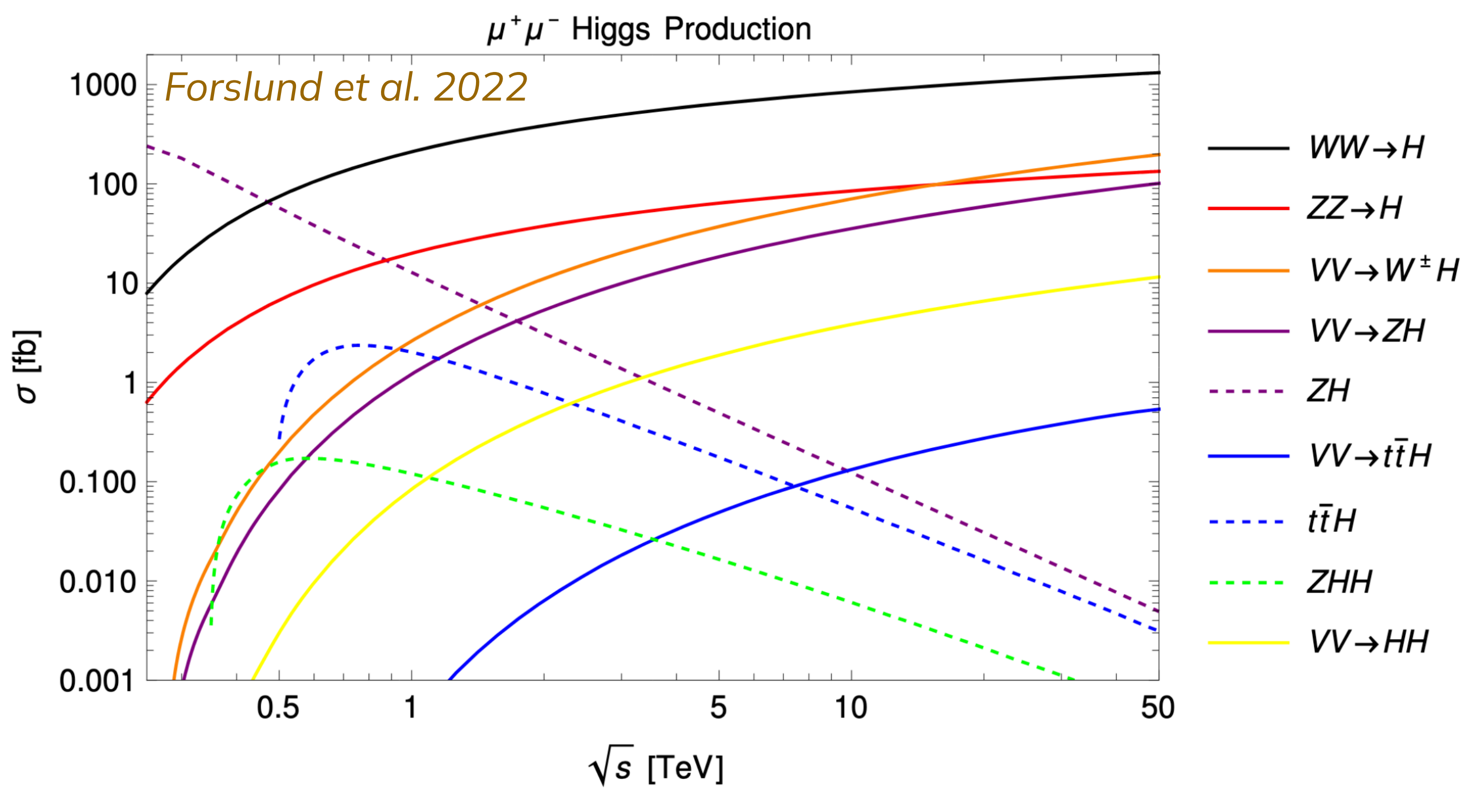
Skrinsky et al. 1981, Neuffer 1983, Neuffer 1987, Barger et al. 1995, Chen 1996, Palmer 1996, Barger et al. 1997, Ankenbrandt et al. 1999

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

- Negligible Beamstrahlung

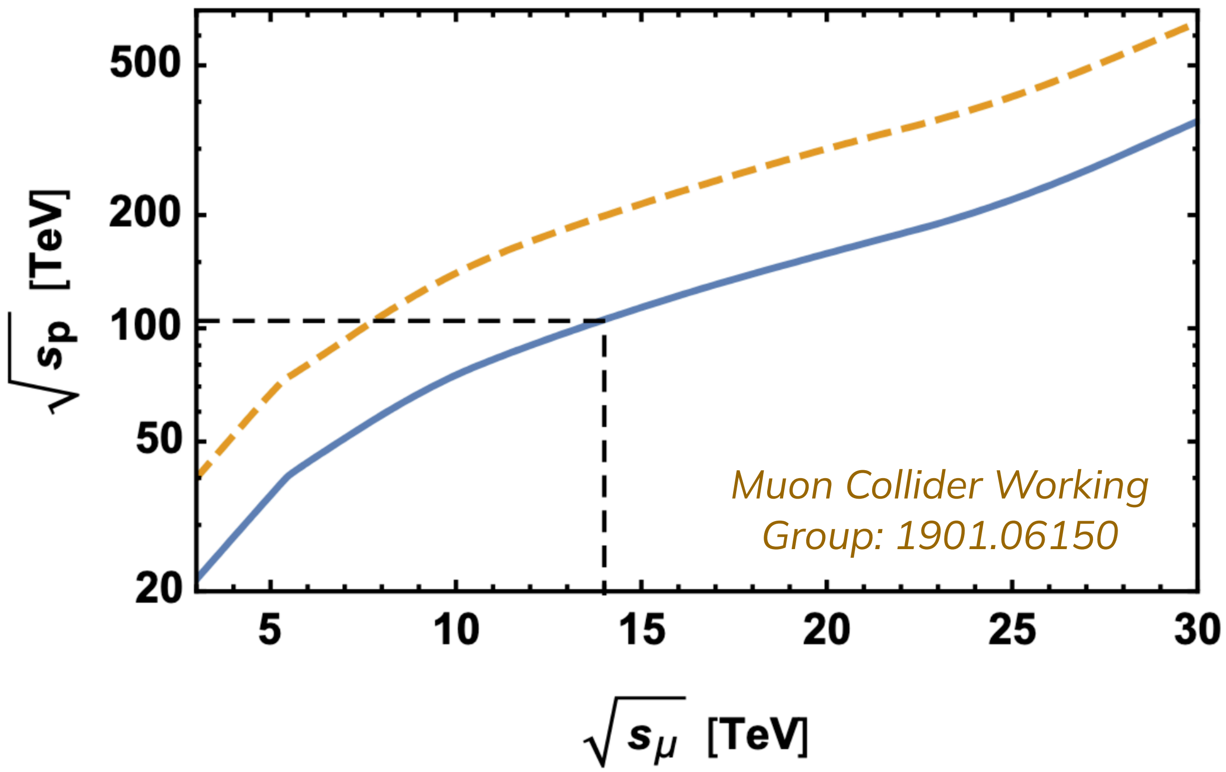
- Muon is itself fundamental — less suppressed by PDF

The Physics Case



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}

“Pheno” Type I Seesaw

◆ Effective Lagrangian

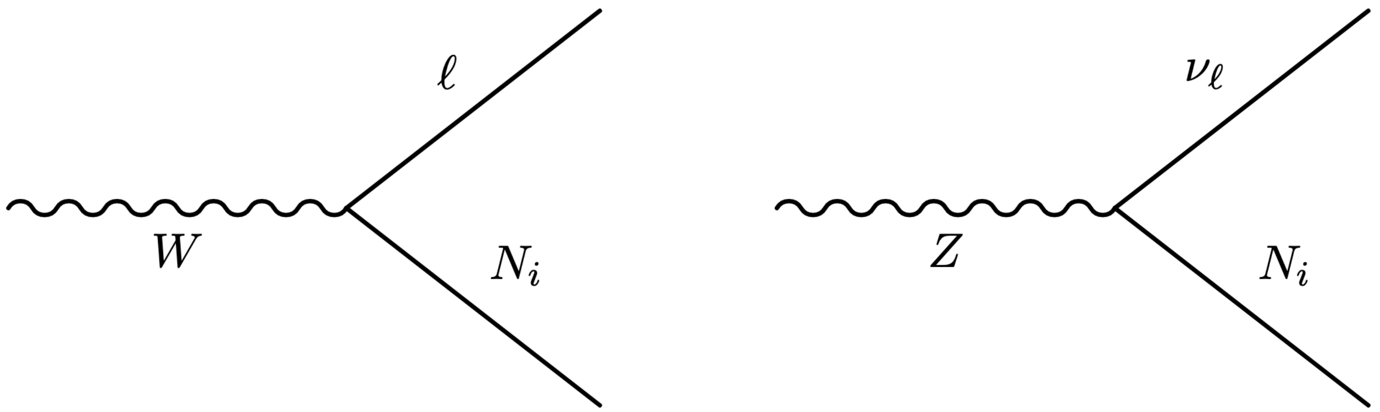
$$-\mathcal{L}_{\text{int,EW}} = \frac{g}{\sqrt{2}} W^{\mu +} \sum_{\ell=e}^{\tau} \left(\sum_{m=1}^{3} U^{*}_{\ell m} \bar{\nu}_m \gamma^{\mu} P_L \ell + \sum_{m=1}^{3} V^{*}_{\ell m} \bar{N}^{c}_{m} \gamma^{\mu} P_L \ell \right)$$

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

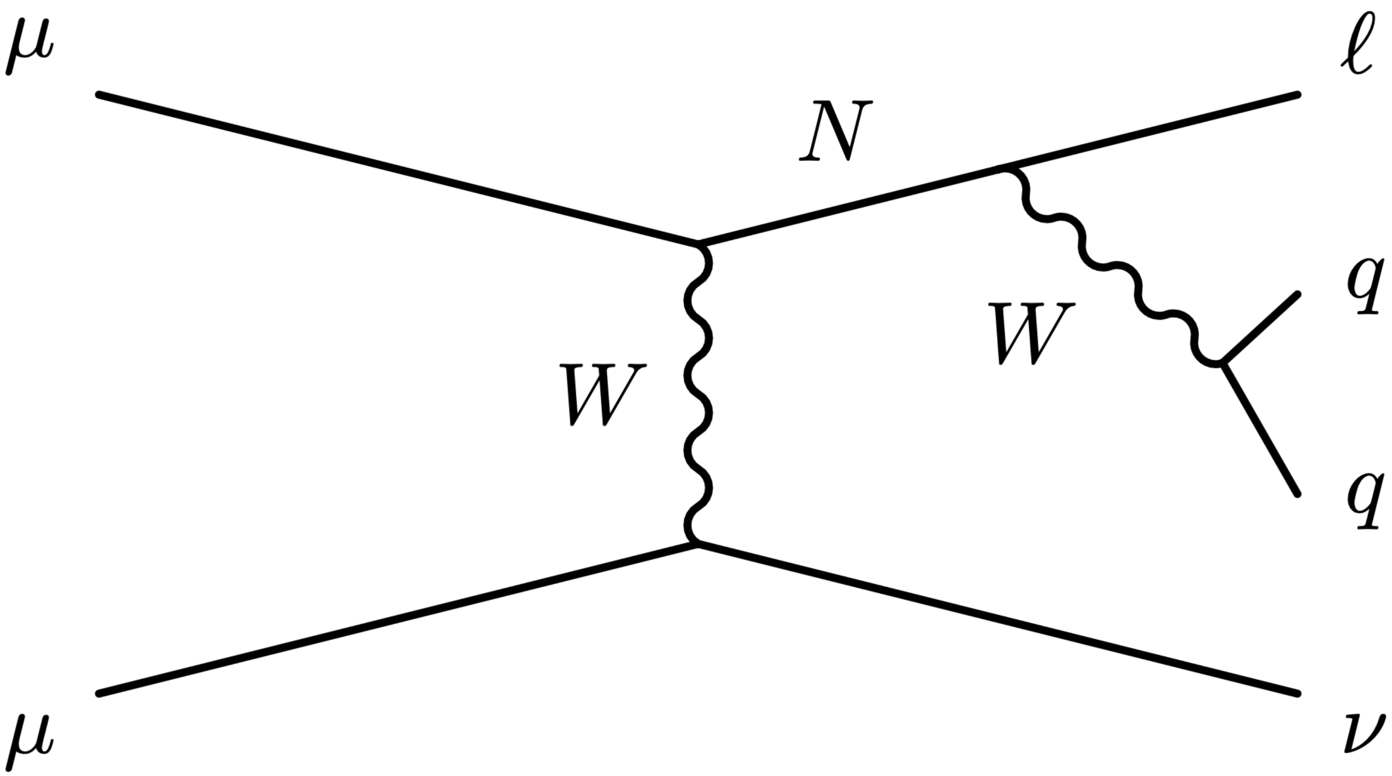
◆ Neutrino Mixing

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

◆ New Vertices

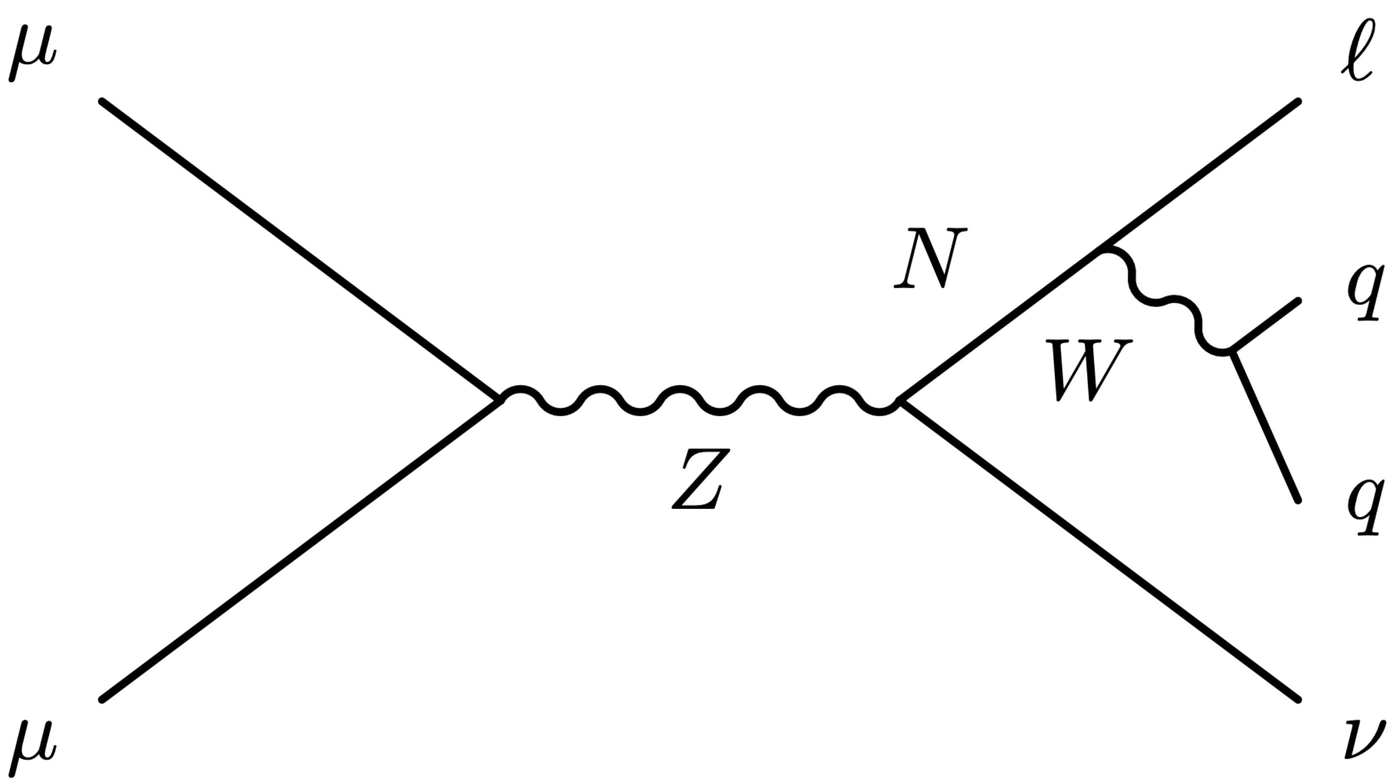


Signal



Dominant above Z-pole

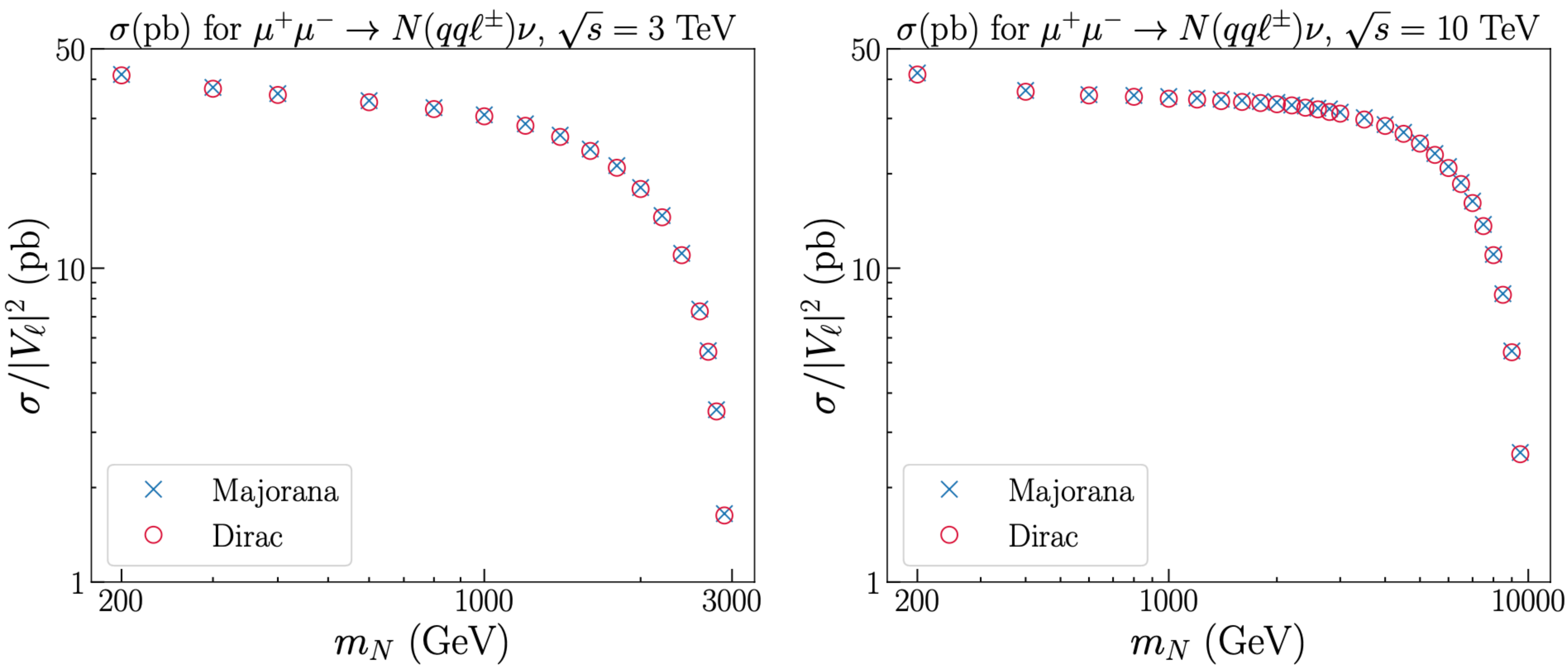
Signal: $\mu^+\mu^- \to N(qq\ell)\nu$



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



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

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Background Generation

Process	Generator Level Cuts	Method
$\mu^+\mu^- \to qq\ell\nu$	$M_{qq,\ell\ell} > 10$ GeV, $p_{T,\ell} > 4$ GeV, $\lvert\eta_\ell\rvert < 8$, $q_\ell > 4$ GeV	ME + ISR
$\mu^+\mu^- \to qq\ell\ell$		
$\mu^+\mu^- \to qq\ell\ell\nu\nu$	$M_{qq,\ell\ell} > 40$ GeV, $p_{T,\ell} > 4$ GeV, $\lvert\eta_\ell\rvert < 8$, $q_\ell > 4$ GeV	ME + ISR
$\mu^+\mu^- \to qq\ell\ell\ell\nu$		
$\gamma\gamma \to qq\ell\nu$	$M_{qq} > 10$ GeV, $q_\gamma < 4$ GeV	EPA
$\gamma\mu^\pm \to qq\ell$	$M_{qq} > 10$ GeV, $q_\gamma < 4$ GeV, $3^\circ < \theta_\ell < 177^\circ$	EPA + ISR

- ME — Full Matrix Element
- ISR — Initial State Radiation
- EPA — Equivalent Photon Approximation *Budnev et al. 1975*
- q_ℓ — Momentum Transfer
- q_γ — EPA Upper Cutoff
- EPA Lower Cutoff at m_μ

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Detector Simulation

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”

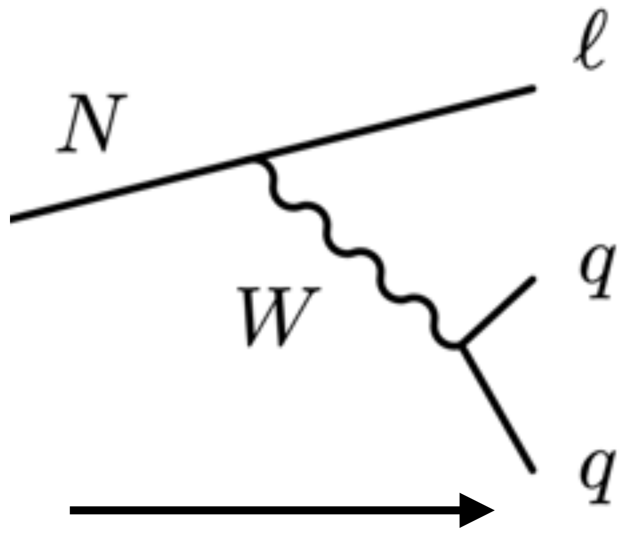
- We use the included Muon Collider Card

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

    Selvaggi 2020 Roloff et. al 2018

Lepton Reconstruction

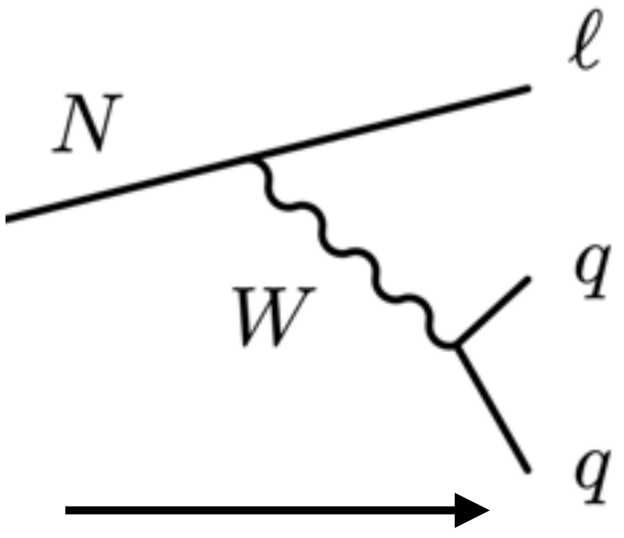
- At least 1 isolated $\ell = e, \mu$ candidate
  - $p_{T,\ell} > 0.5$ GeV
  - $\sum_{\neq \ell} p_T / p_{T,\ell} < 0.2$ within cone of $\Delta R = 0.1$
- If > 1 ℓ, choose largest $p_{T,\ell}$



W-Jet Reconstruction

Boronat et al. 1404.4294

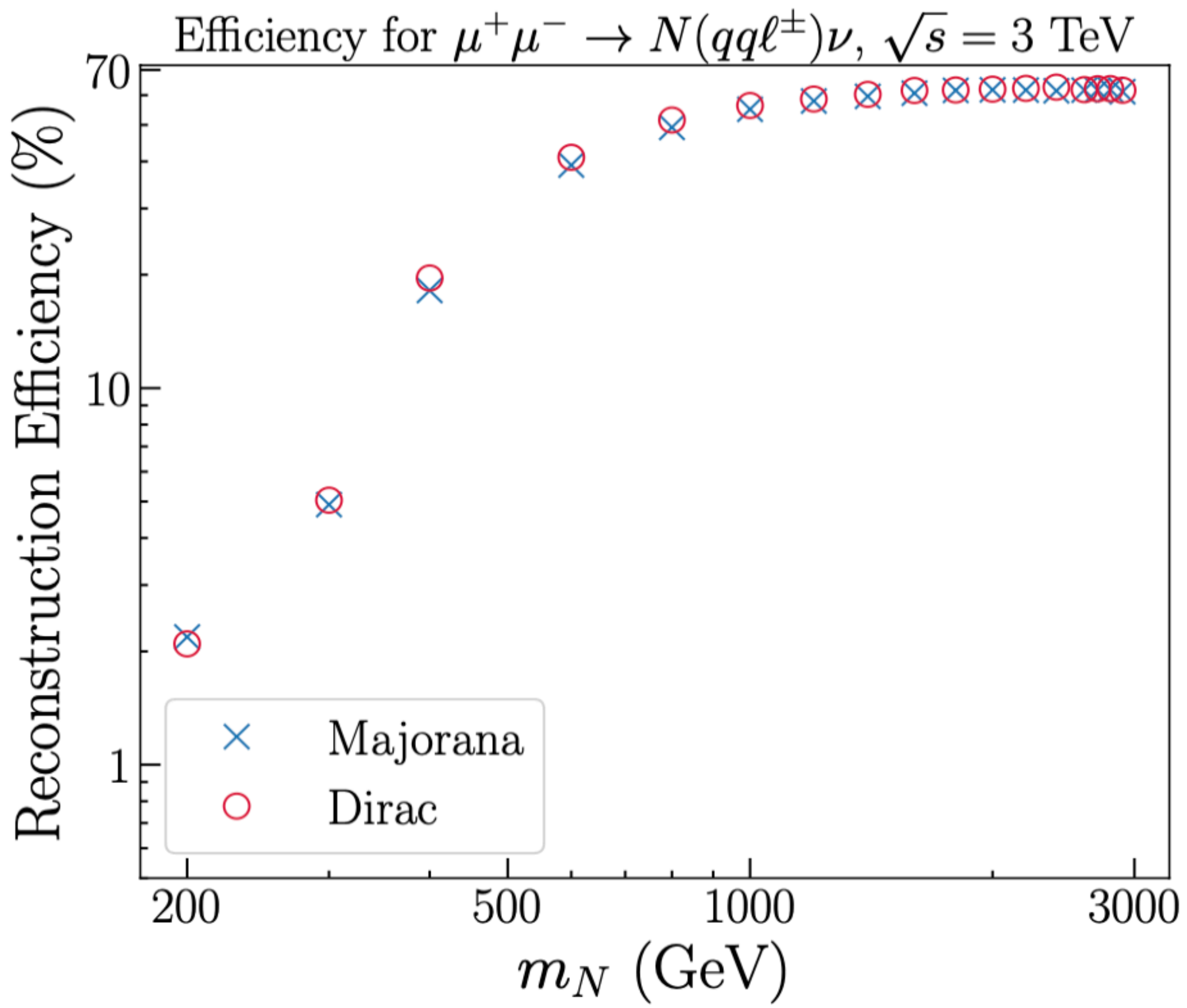
- Reconstruct jet system J using VLC algorithm
  - Two options, dependent on W boosting
    - Single fat jet, $J = J_{\text{fat}}$, with $R = 1.2, \beta = \gamma = 1.0$
    - Two narrow jets $J = j_1 + j_2$, with $R = 0.2, \beta = \gamma = 1.0$
- If both reconstructed, choose method with invariant mass closest to m_W
  - Keep all jet information for use in BDT

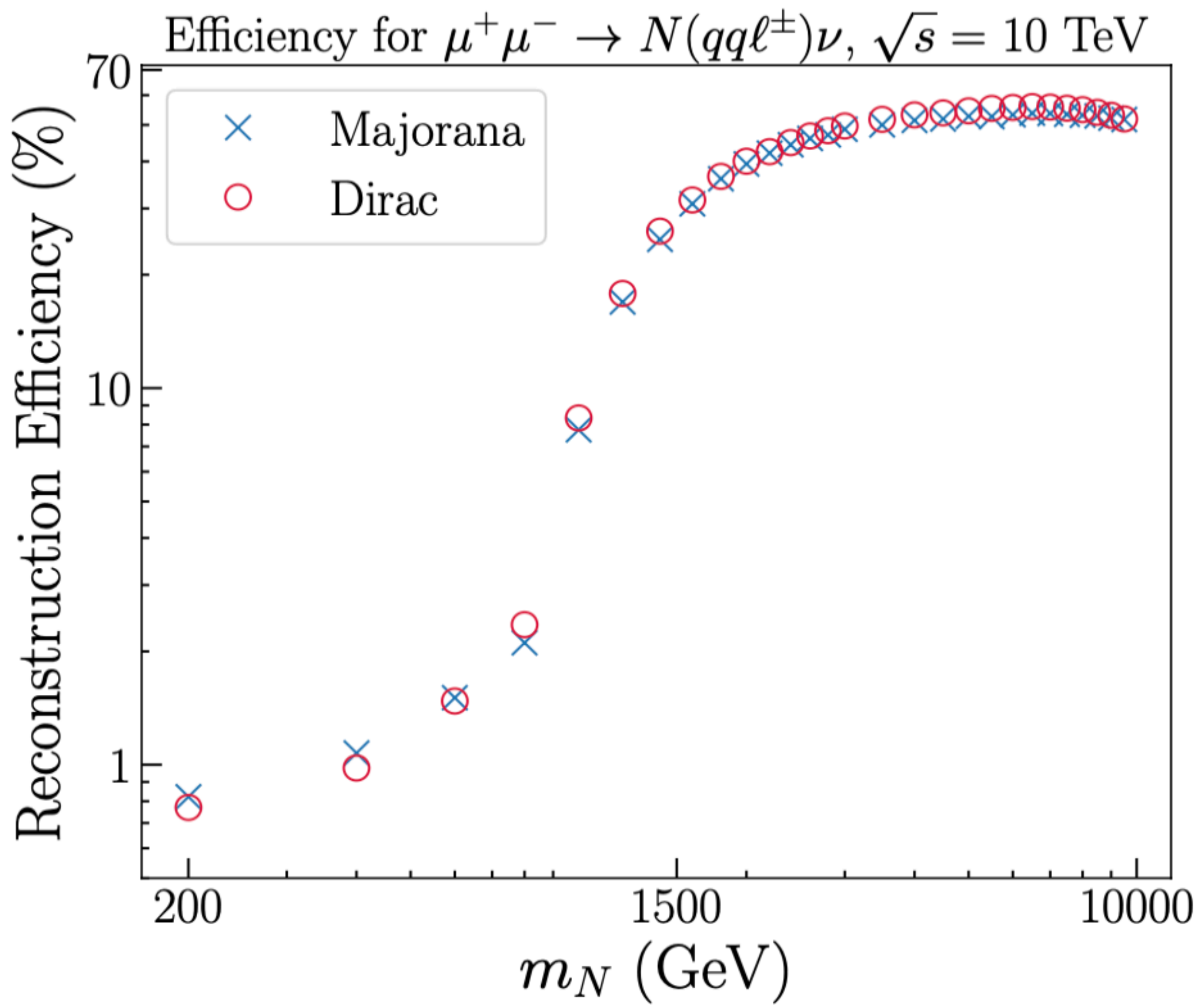


Preselection

- 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

Reconstruction





Signal Reconstruction and Preselection Efficiency

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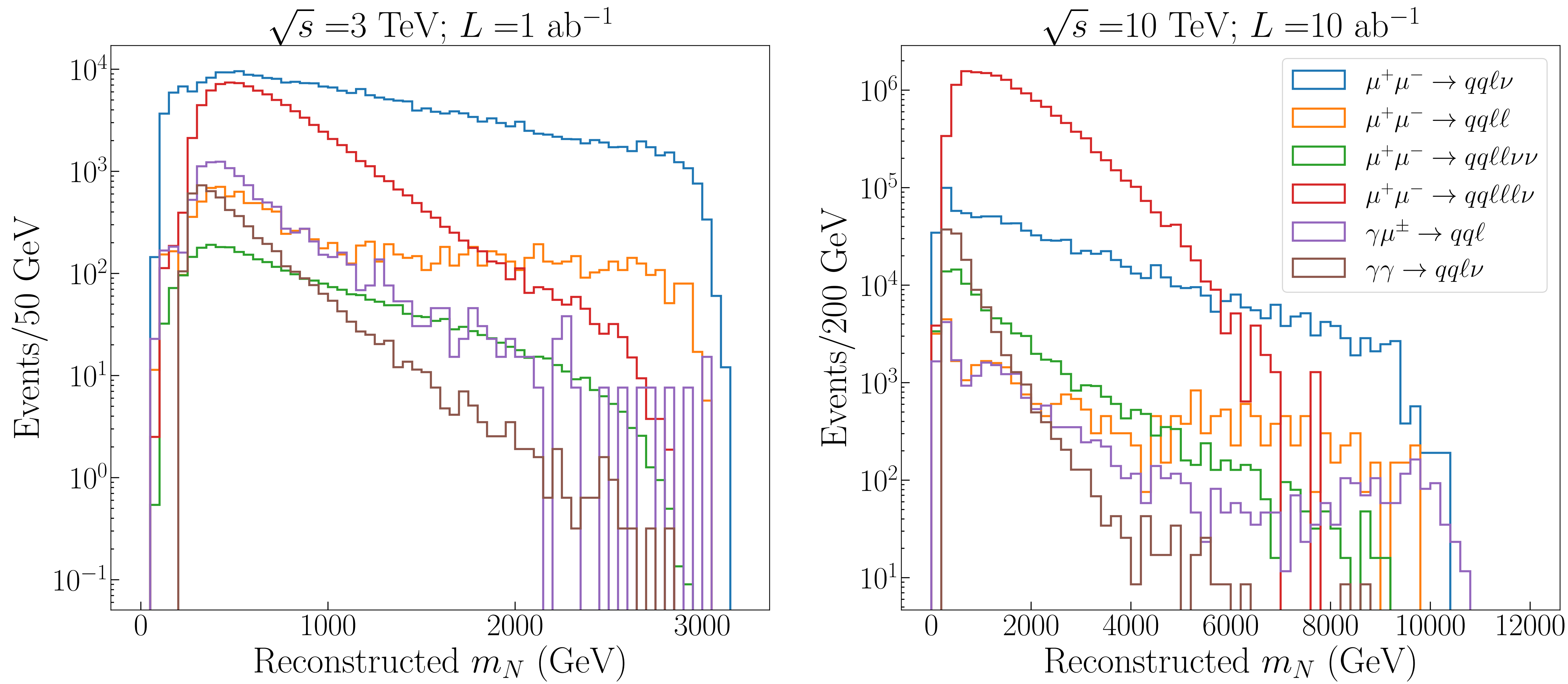
Reconstruction

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

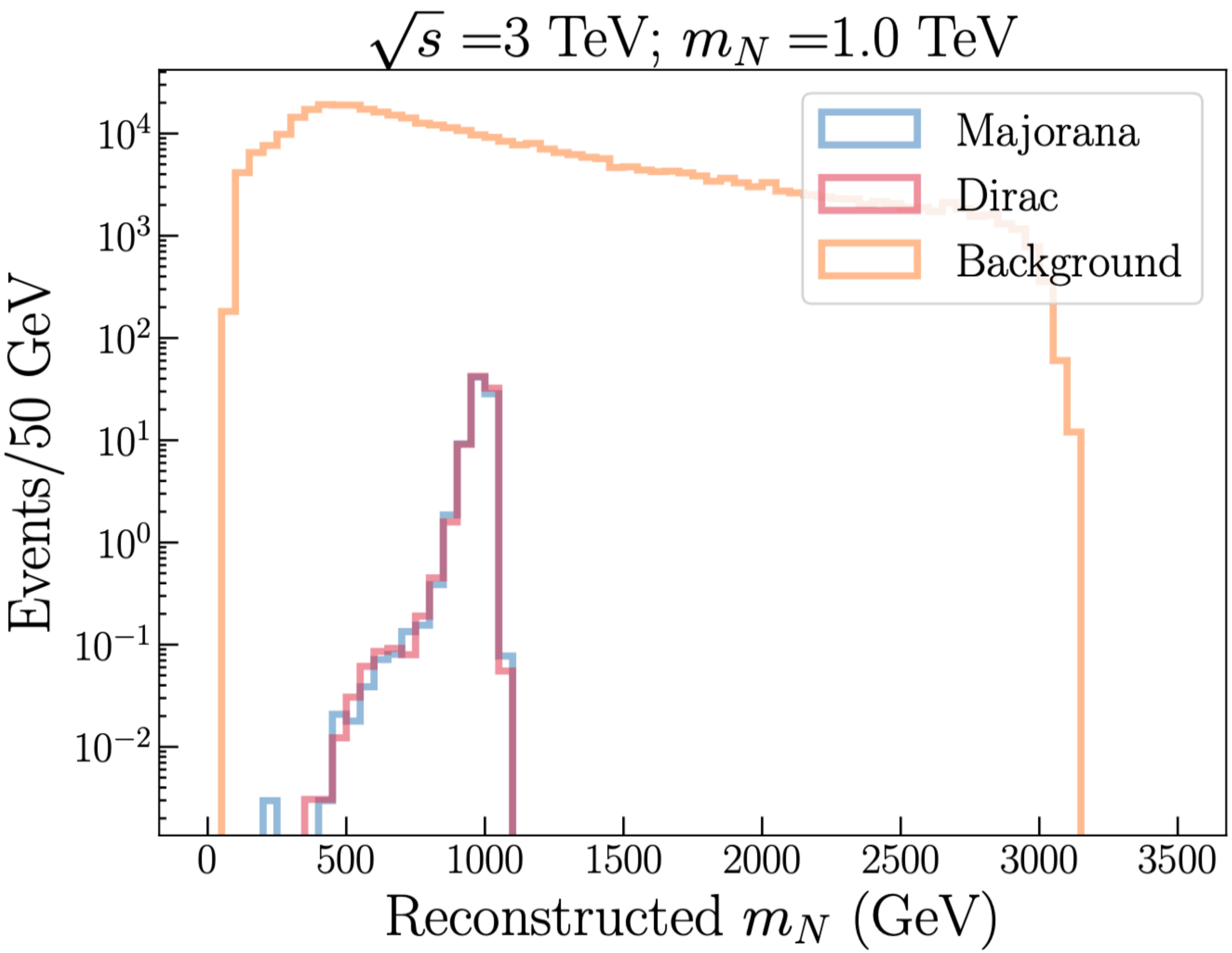
SM Background Yield and Total Reconstruction + Preselection Efficiency

Reconstruction



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

Reconstruction



Signal m_N and total SM Background

Boosted Decision Trees

- Three class Boosted Decision Tree (BDT) analysis to separate background from signal (Majorana vs Dirac vs SM Background)

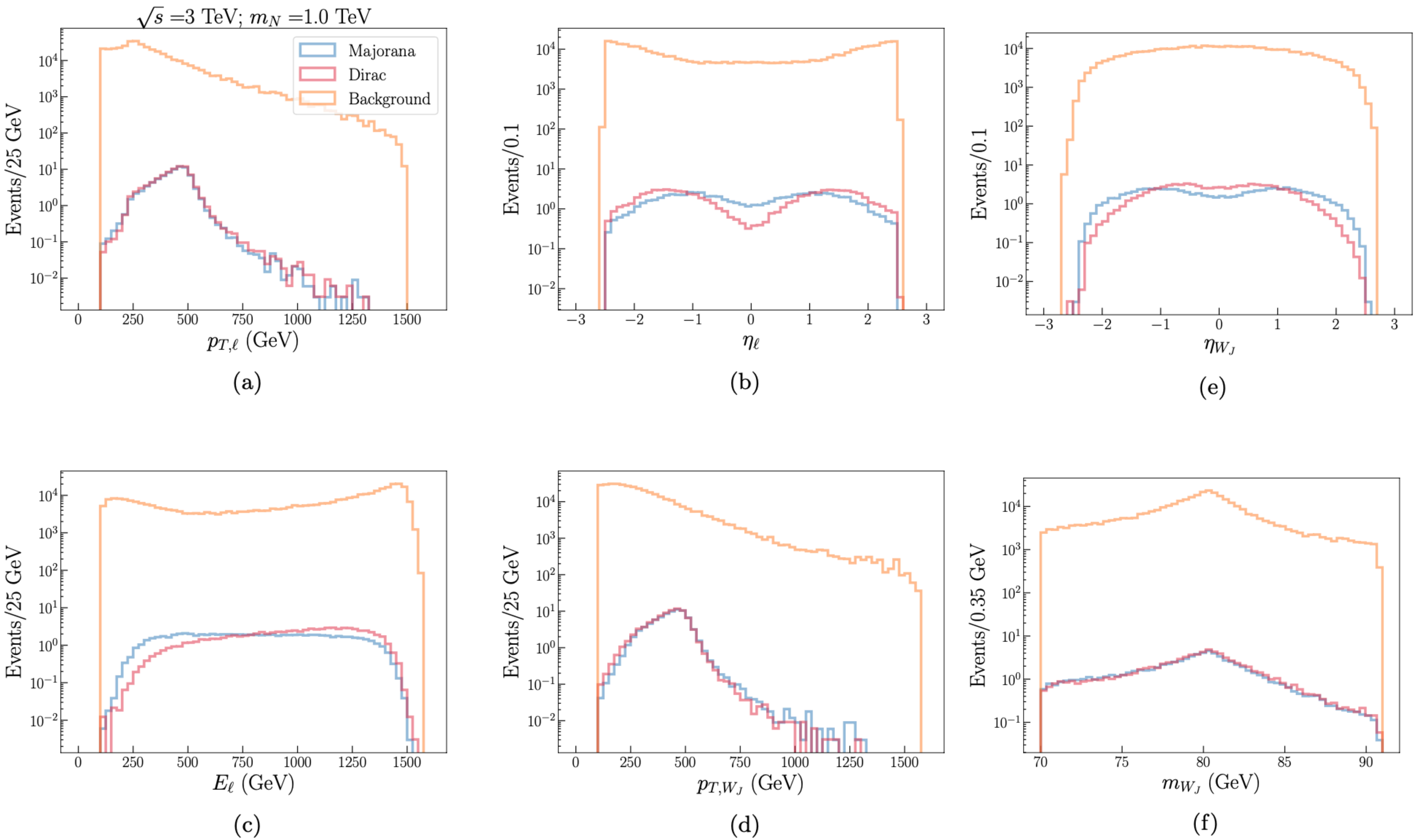
  Chen et al. 1603.02754

  - Python implementation of XGBoost
  - Supervised learning
    - Collection of decision trees
    - Loss function using gradient descent
  - Outputs probabilities: P_B, P_M, P_D

BDT Features

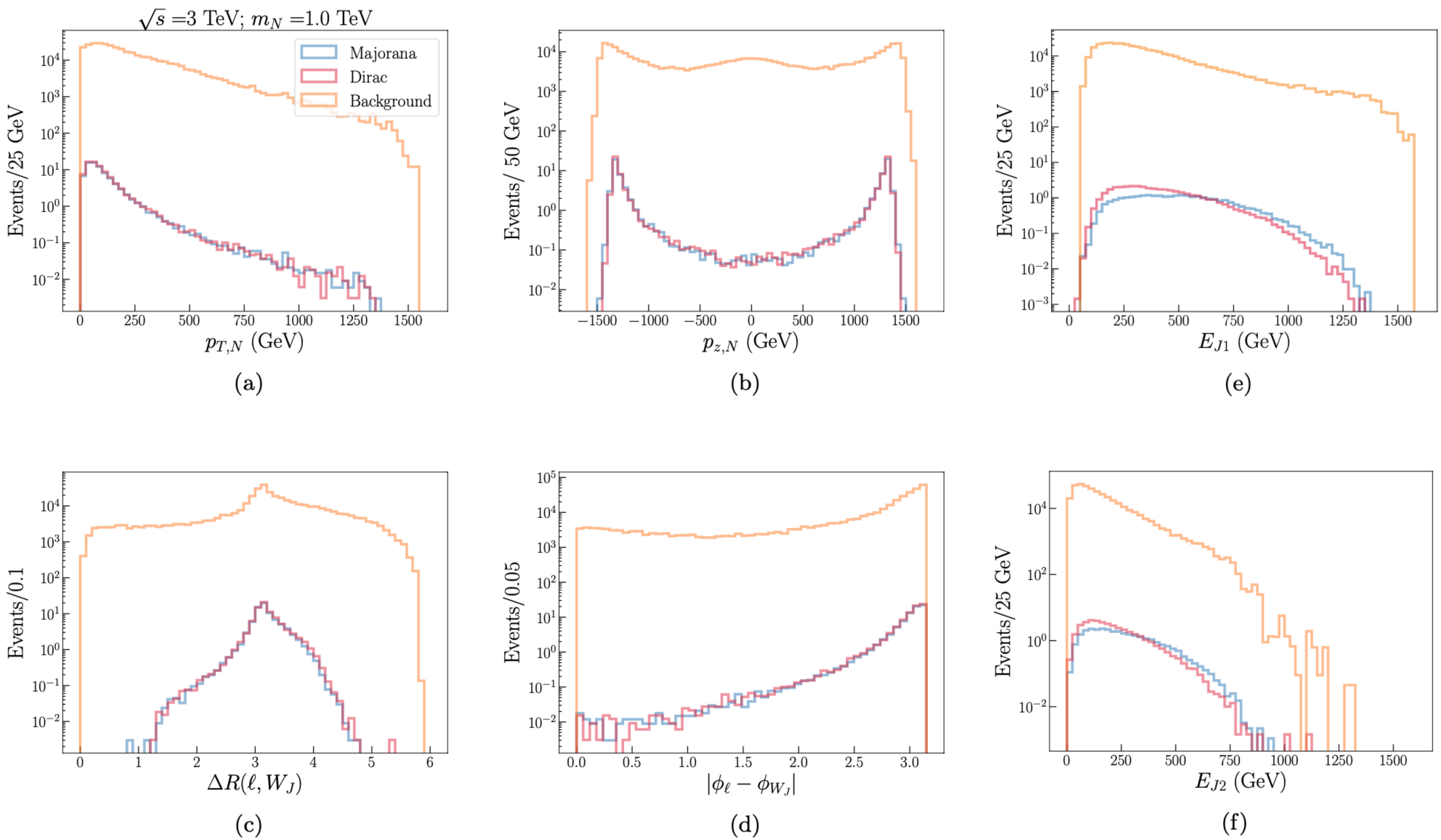
- Lepton
  - $p_{T,\ell}$, η_ℓ , E_ℓ , Charge, and Flavor
- W-Jets
  - p_{T,W_J} , η_{W_J} , and M_{W_J}
  - $E_{j1,2}$
- HNL
  - $p_{T,N}$ and $p_{z,N}$
- Geometry
  - $\Delta R(\ell, W_J)$ and $|\phi_\ell - \phi_{W_J}|$

BDT



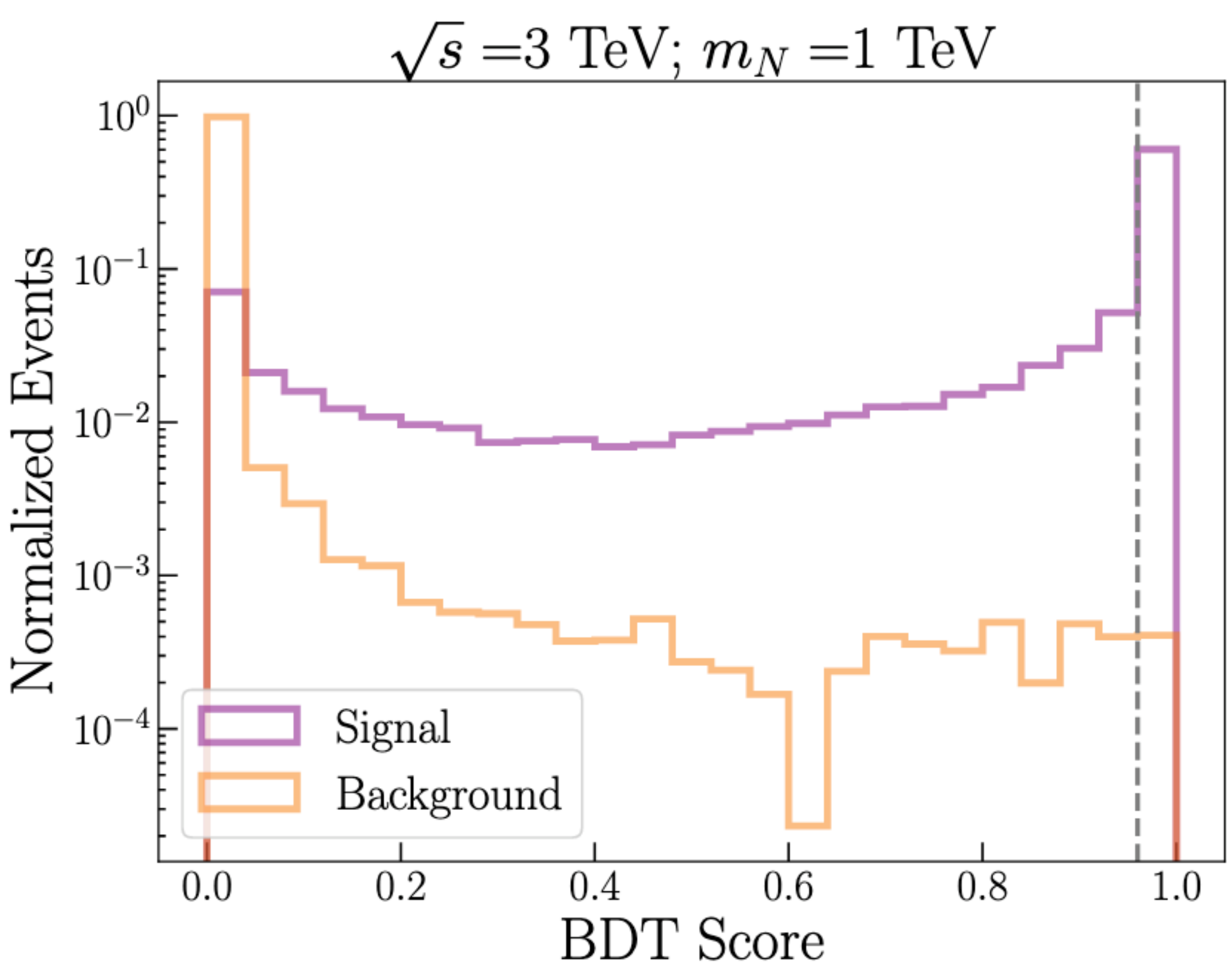
BDT Variable Distributions (1/2)

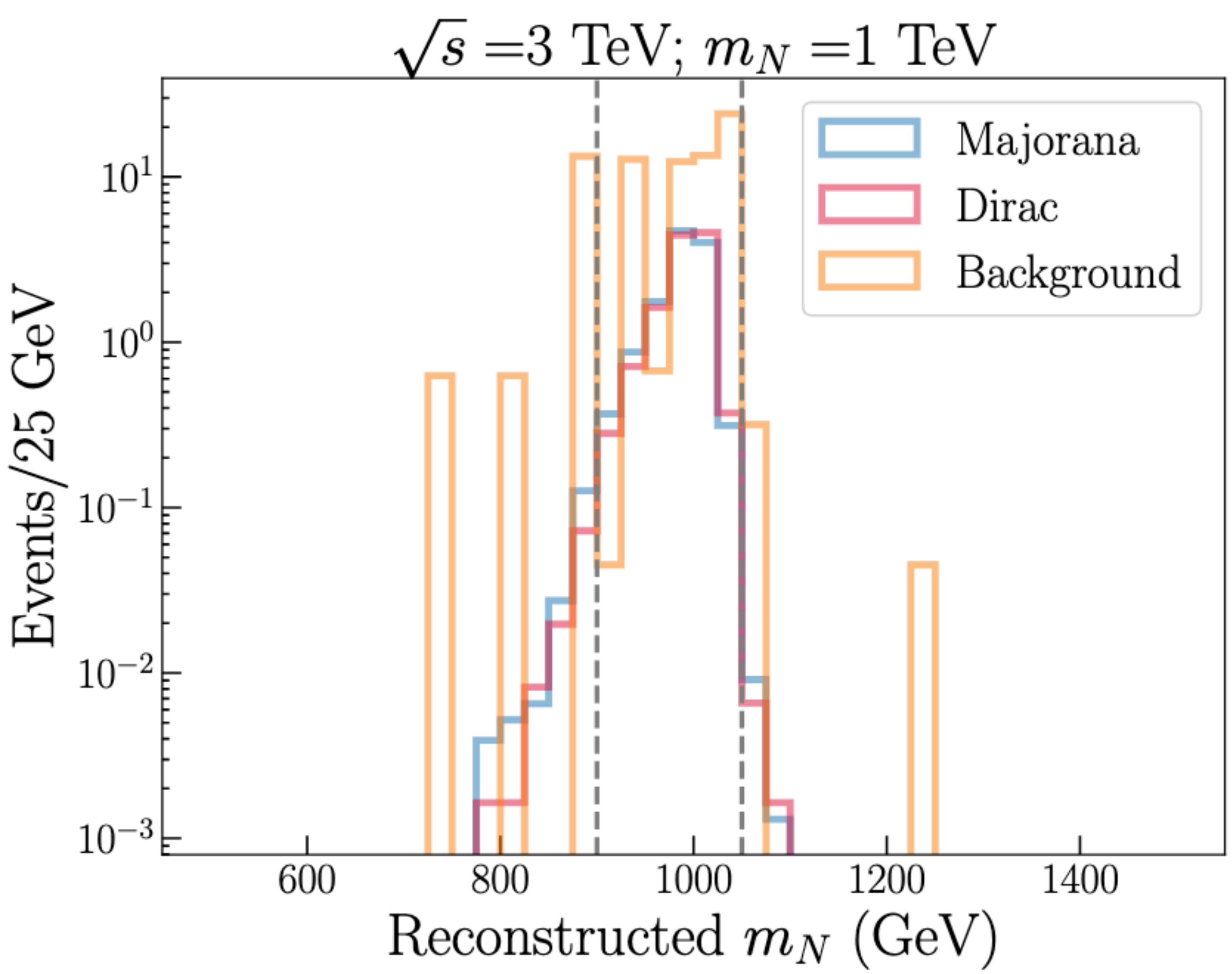
BDT



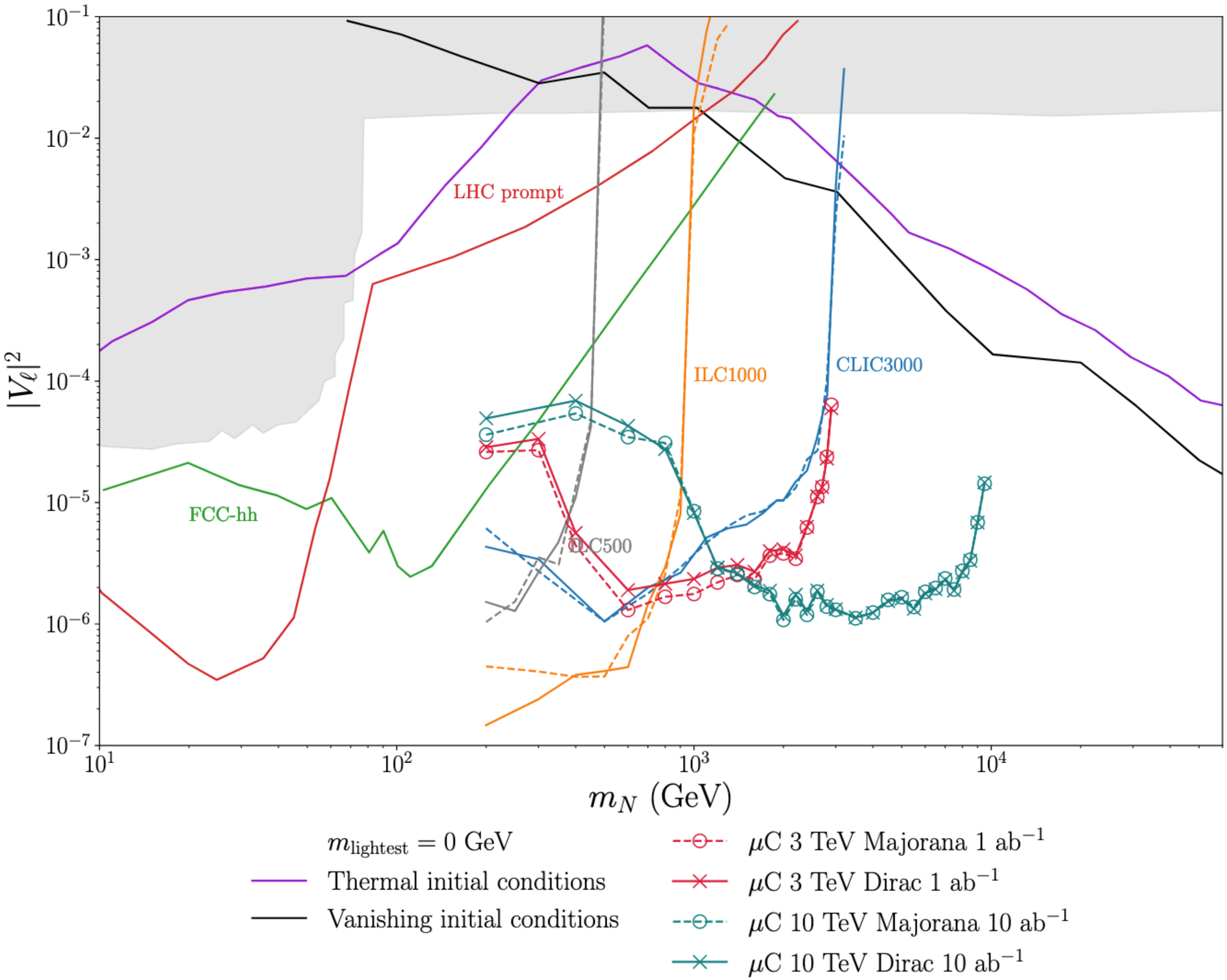
BDT Variable Distributions (2/2)

BDT Results


$\sqrt{s}$ =3 TeV; m_N =1 TeV
Normalized Events
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
Signal
Background
0.0
0.2
0.4
0.6
0.8
1.0
BDT Score

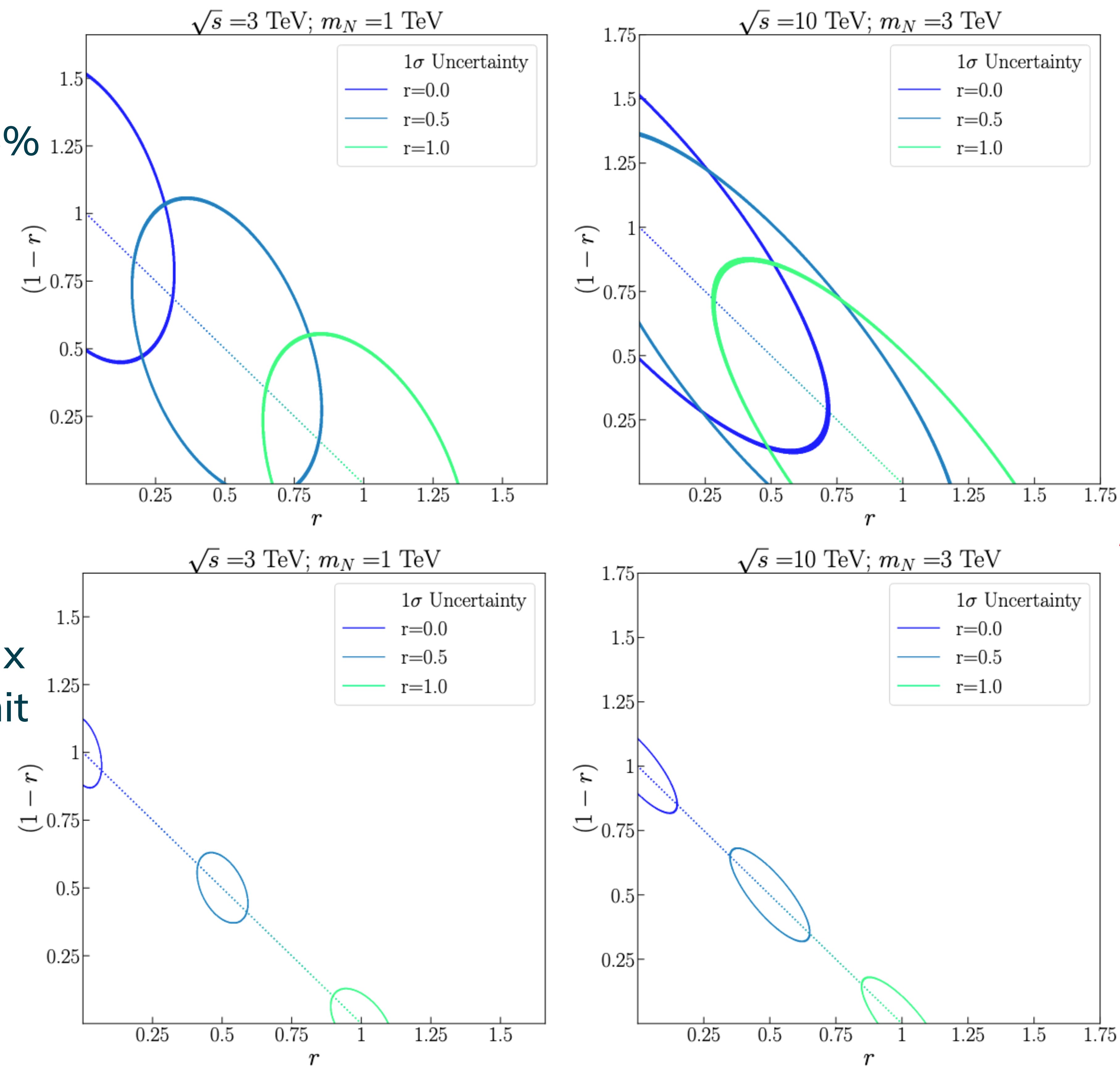

$\sqrt{s}$ =3 TeV; m_N =1 TeV
Events/25 GeV
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
Majorana
Dirac
Background
600
800
1000
1200
1400
Reconstructed m_N (GeV)

Predicted Sensitivity



Majorana vs Dirac Discrimination

$|V_\ell|^2$ at 95% Limit



$r = n_M/(n_M + n_D)$

$|V_\ell|^2$ at 5 x 95% CI Limit

Conclusion and Outlook

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

Backup

Technical Challenges

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- Muon is unstable — lifetime of 2 μs
  - How to produce and store?

    Delahaye et al. 1308.0494, Delahaye et al. 1502.01647, Dyne et al. 2015, Long et al. 2007.15684

    MICE Collaboration 1806.01807, 1806.04409, 1907.08562

    - Muon Accelerator Program (MAP, USA) + Muon Ionization Cooling Experiment (MICE, UK)
      - MAP — Proton beam on high-Z target creates pions, which decay to muons
      - MICE — Reduces muon phase space
      - Currently favored
    - Low Emittance Muon Accelerator (LEMMA) *Antonelli et al. 1509.04454*
      - Positron on fixed-target beam to produce muons at threshold
      - Long lifetime, low emittance
      - Low luminosity
      - Unfavored

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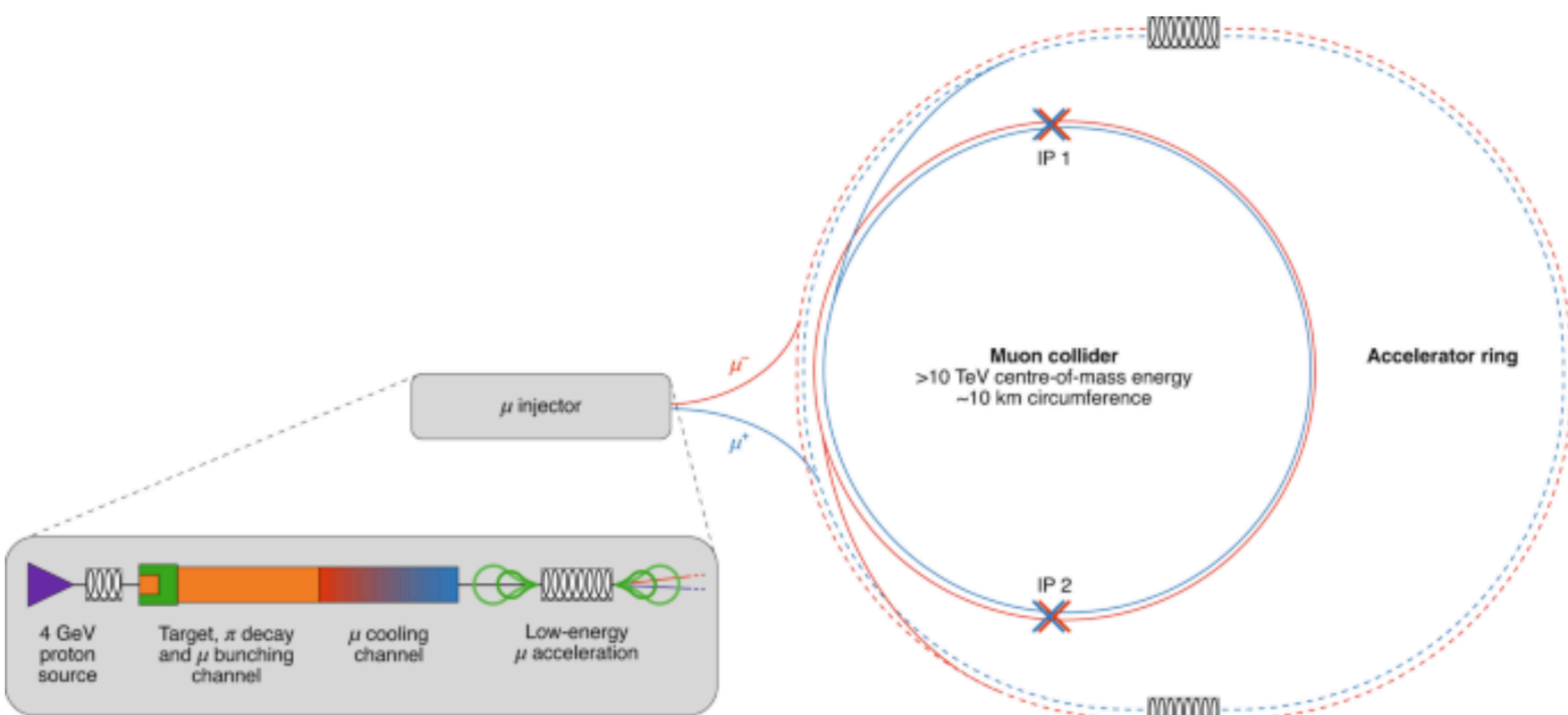
Muon Collider Schematics

Snowmass Muon Collider Forum Report: 2209.01318

Parameter	Unit	Higgs Factory	3 TeV	10 TeV
COM Beam Energy	TeV	0.126	3	10
Collider Ring Circumference	km	0.3	4.5	10
Interaction Regions		1	2	2
Est. Integ. Luminosity	ab^{-}1/year	0.002	0.4	4
Peak Luminosity	10^{34} cm^{-2} s^{-1}	0.01	1.8	20



https://muoncollider.web.cern.ch/

Potential Timeline

Snowmass Muon Collider Forum Report: 2209.01318