Search for Sterile Neutrinos in Trilepton Final States at Hadron Colliders

Kechen Wang

DESY, Hamburg, Germany
CFHEP, IHEP, CAS, Beijing, China

1st FCC Physics Workshop, Jan 18, 2016

Based on [Phys. Rev. D **94** (2016) 013005, hep-ph/1701.XXXXX]
with C.S. Kim, C. Dib and J. Zhang

Outline

- ★ Introduction of Sterile Neutrinos
  - ◆ Simplified Model
- ★ Discovering/Excluding N
  - ◆ Dirac
  - ◆ Majorana
- ★ Distinguishing Dirac/Majorana N
- ★ Summary

→ Results @ HL-LHC today
→ Can be extended to 100 TeV, like FCC-hh

Theory Model

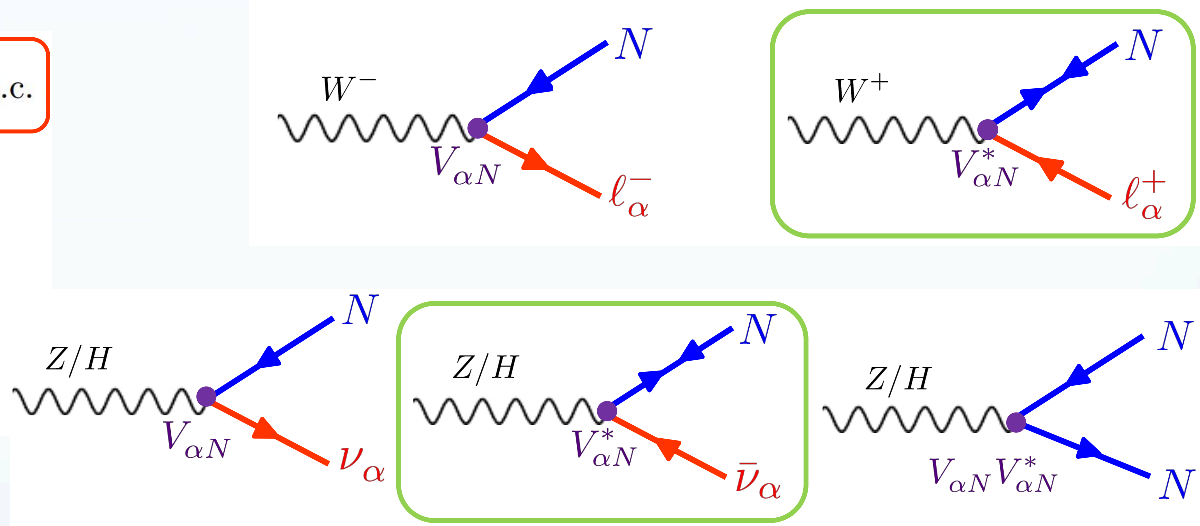
Discovery of neutrino oscillations => neutrinos have mass
→ In SM, neutrinos are massless
→ A window to BSM physics

Type-I see-saw: Singlet (Sterile) Fermions

$$-\mathcal{L} = h_{\ell\alpha}\bar{L}_\ell\widetilde{\Phi}N_\alpha + \frac{1}{2}M_{N_{\alpha\beta}}\bar{N}^C_\alpha N_\beta + \text{H.c.}$$

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & M_D \\ M_D^\intercal & M_N \end{pmatrix}$$

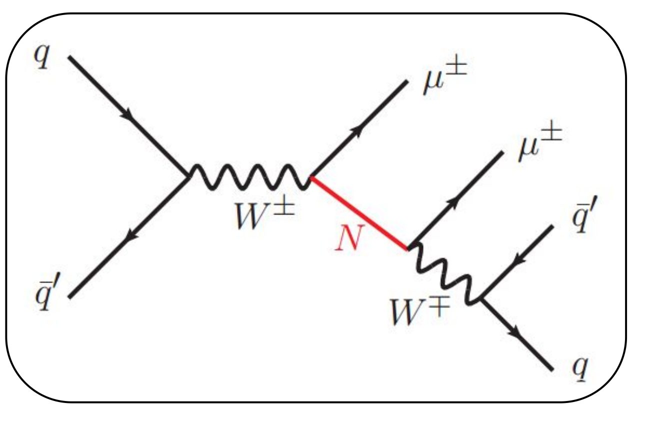
Interactions: [0901.3589]



Simplified model with assumptions:
Only 1 generation of sterile neutrinos is light & within experimental reach;
$U_{N\tau} = 0$;
3 free parameters: m_N, U_{Ne}, $U_{N\mu}$, Dirac/Majorana.

Studies @ LHC

Main Search Channels:



2l + 2j need well isolated energetic 2 jets;
need SS di-lepton to suppress BG;
→ better for Majorana N with $m_N > m_W$.

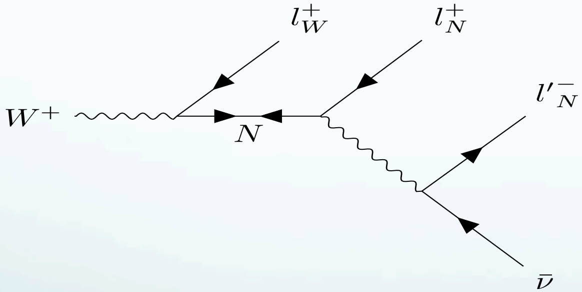
[CMS: 1207.6079, 1501.05566]
[ATLAS-CONF-2012-139]

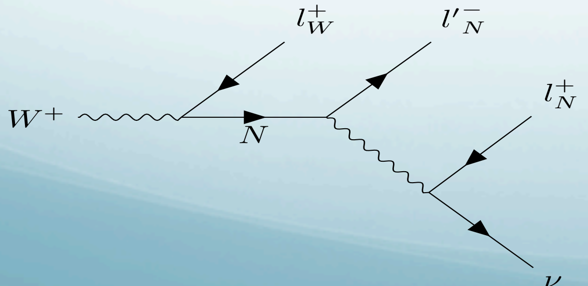
Majorana:

$$pp \to W^\pm \to l^\pm N \to l^\pm l^\pm jj \quad (l = e, \mu)$$

Dirac:

$$pp \to W^\pm \to l_1^\pm N \to l_1^\pm l_2^\mp jj \quad (l_{1,2} = e, \mu)$$





3l + MET

→ better for Majorana or Dirac N with $m_N < m_W$

$m_N < m_W$: [1504.02470]
$m_N > m_W$: [0809.2096, 0910.2720, 1112.6419 ...]

Today !

LNV: $W^+ \to e^+ e^+ \mu^- \bar{\nu}_\mu$

non-trival ←
flavor of ν undetectable

distinguishable?

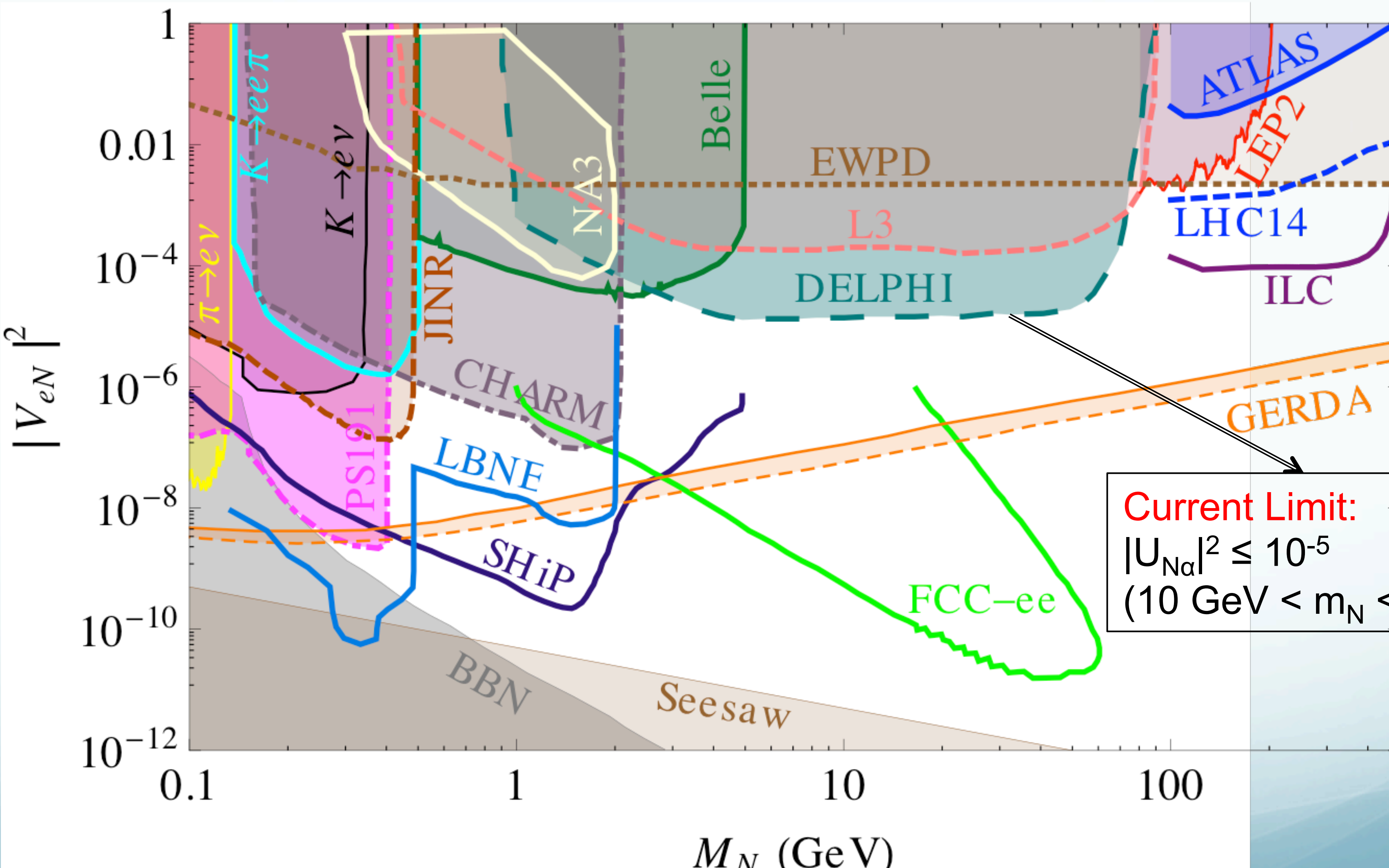
LNC: $W^+ \to e^+ e^+ \mu^- \nu_e$

[0809.2096, 1509.05981]

Global Constraints

from [Deppisch, Dev and Pilaftsis, New J. Phys. 17 (2015) 085019]

m_N: 0.1 ~ 500 GeV



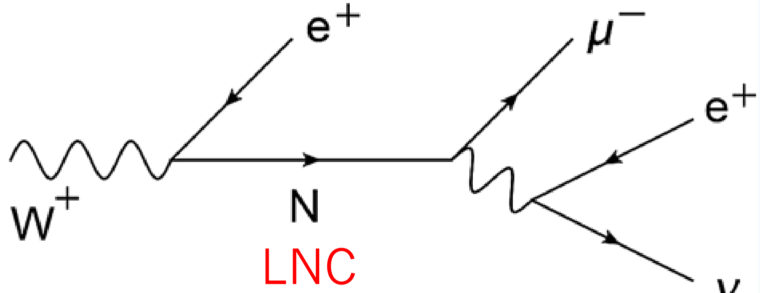
Current Limit:
$|U_{N\alpha}|^2 \leq 10^{-5}$
(10 GeV < m_N < m_W)

Outline

- ★ Introduction of Sterile Neutrinos
  - Simplified Model
- ★ Discovering/Excluding N
  - Dirac
  - Majorana
- ★ Distinguishing Dirac/Majorana N
- ★ Summary

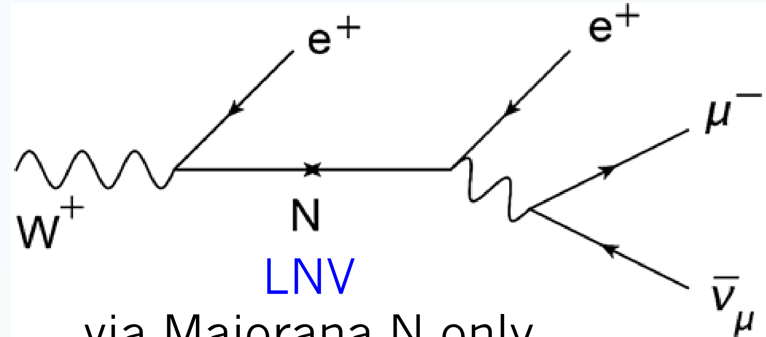
Production Rates

tri-lepton + MET with no-OSSF lepton pairs



via Majorana or Dirac N

$$\mathbf{Br}\left(W^+ \to e^+ e^+ \mu^- \nu_e\right) \propto \frac{|U_{Ne} U_{N\mu}|^2}{|U_{Ne}|^2 + |U_{N\mu}|^2}$$



via Majorana N only

$$\mathbf{Br}\left(W^+ \to e^+ e^+ \mu^- \bar{\nu}_\mu\right) \propto \frac{|U_{Ne}|^4}{|U_{Ne}|^2 + |U_{N\mu}|^2}$$

Scale factors for different tri-lepton states

	Dirac (LNC)	Majorana (LNC+LNV)
$e^+ e^+ \mu^- \nu$	s	$s\,(1 + r)$
$\mu^+ \mu^+ e^- \nu$	s	$s\,(1 + \frac{1}{r})$

normalization factor

$$s \equiv 2 \times 10^6 \times \frac{|U_{Ne} U_{N\mu}|^2}{|U_{Ne}|^2 + |U_{N\mu}|^2}$$

disparity factor $r \equiv \frac{|U_{Ne}|^2}{|U_{N\mu}|^2}$

For benchmark point

$|U_{Ne}|^2 = |U_{N\mu}|^2 = 10^{-6}$ → $r = s = 1$

Collider Simulation

Simulation
MadGraph (jet matching up to 2 extra partons) + PYTHIA + Delphes

Signal:
tri-lepton + MET with no OSSF lepton pairs
$e^+ e^+ \mu^- / \mu^+ \mu^+ e^- / e^- e^- \mu^+ / \mu^- \mu^- e^+$ + MET.

SM backgrounds:
→ Leptonic τ decay:
WZ -> (l ν) (τ τ) -> 3 l + MET

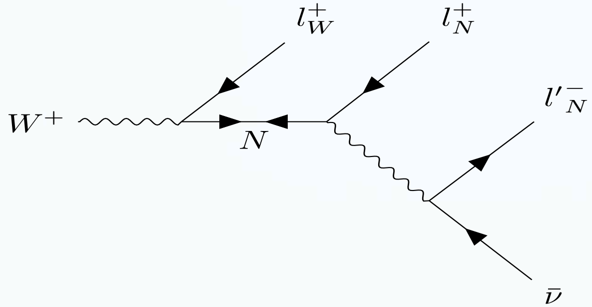
→ Fake leptons from jets containing heavy-flavor mesons:
γ^*/Z+jets: γ^*/Z (-> τ τ) + a 3rd faked lepton
t tBar+jets: prompt decay of t tBar + a 3rd fake lepton

Strategy

Apply various cuts to reduce BG

→ 3 leptons $l^\pm l^\pm l'^\mp$, veto b-jets.

→ Cut-and-Count or MVA



correct lep from N & $p_{z,\nu}$

← by minimizing the

$M(l^\pm l^\pm l'^\mp \nu)$ $M(l^\pm l'^\mp \nu)$

$$\chi^2 = \left(\frac{M_W - m_W}{\sigma_W}\right)^2 + \left(\frac{M_N - m_N}{\sigma_N}\right)^2$$

MVA input observables:

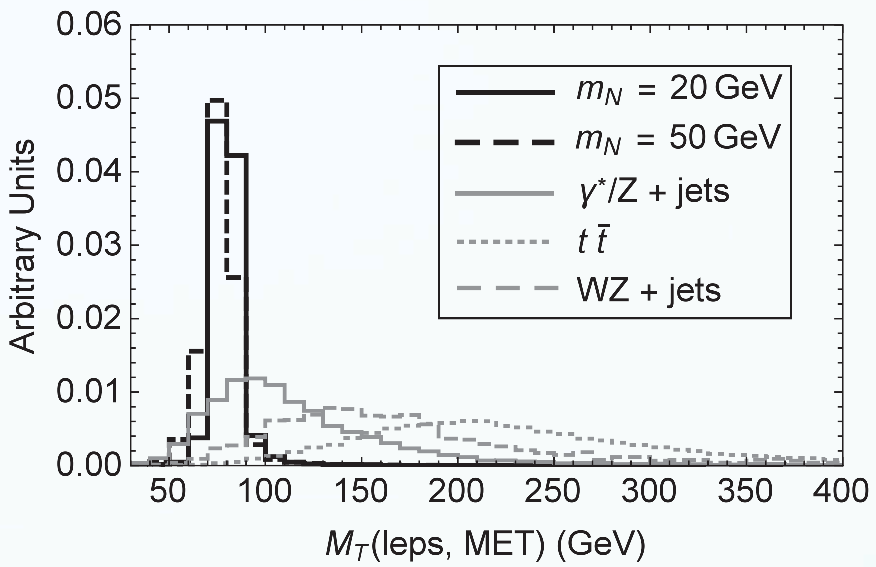
→ met, H_T;

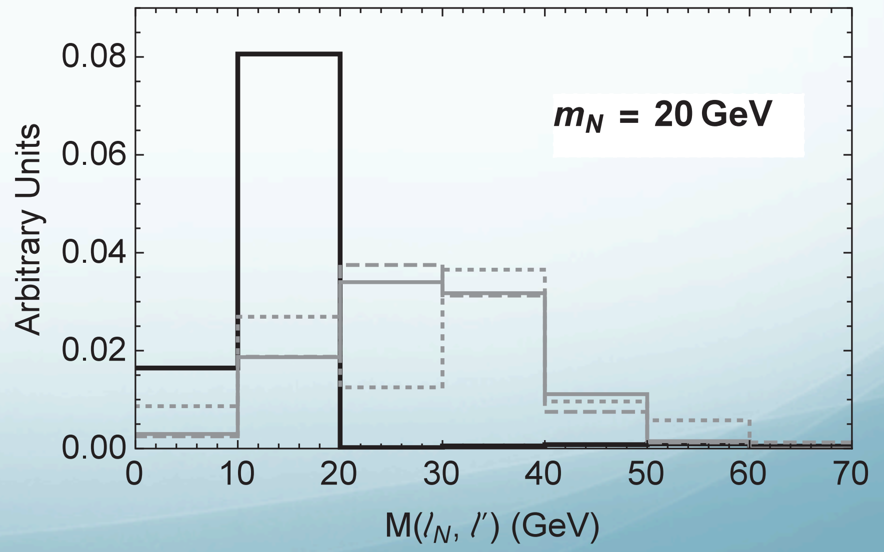
→ M_T(met, lep(s));

→ Δφ(met, lep(s));

→ M(leps);

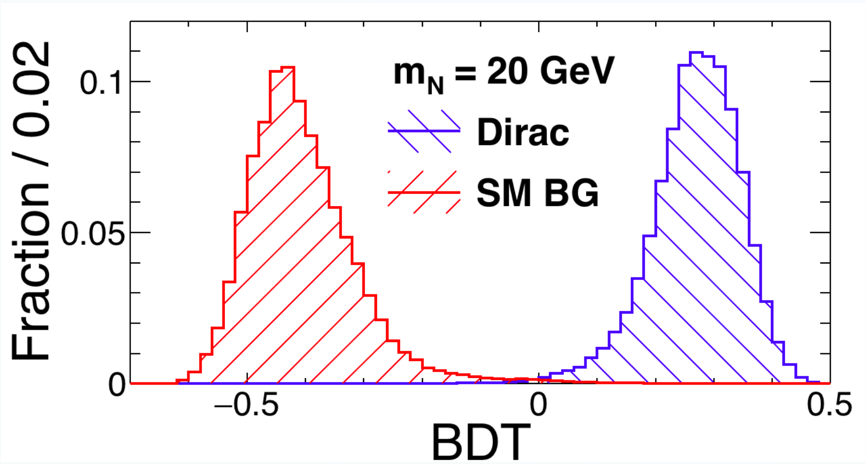
→ Δφ(lep, lep).

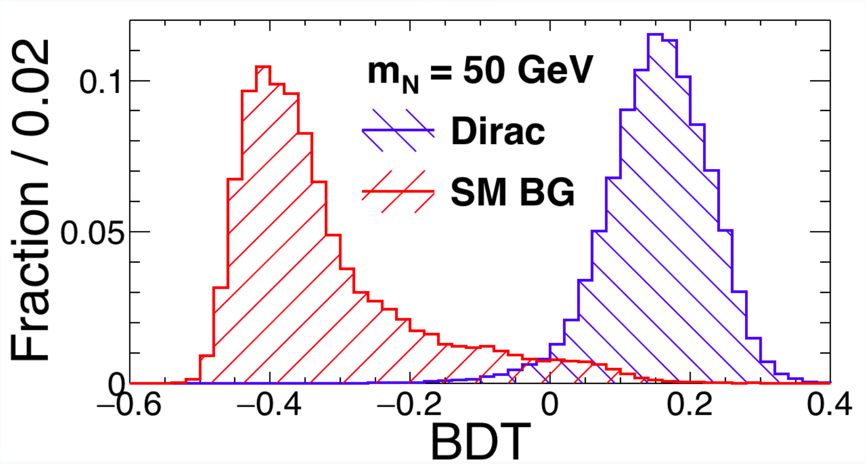




Cut Flow Tables

BDT from TMVA package



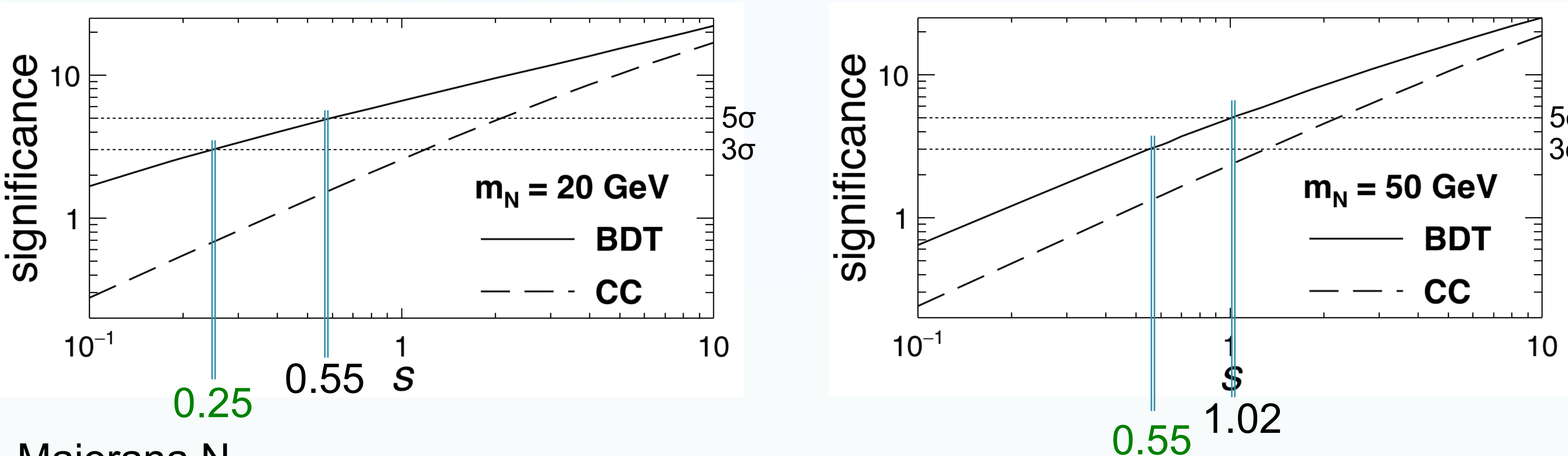


# of events, 14 TeV, 3000 fb^{-1} m_N = 20 GeV

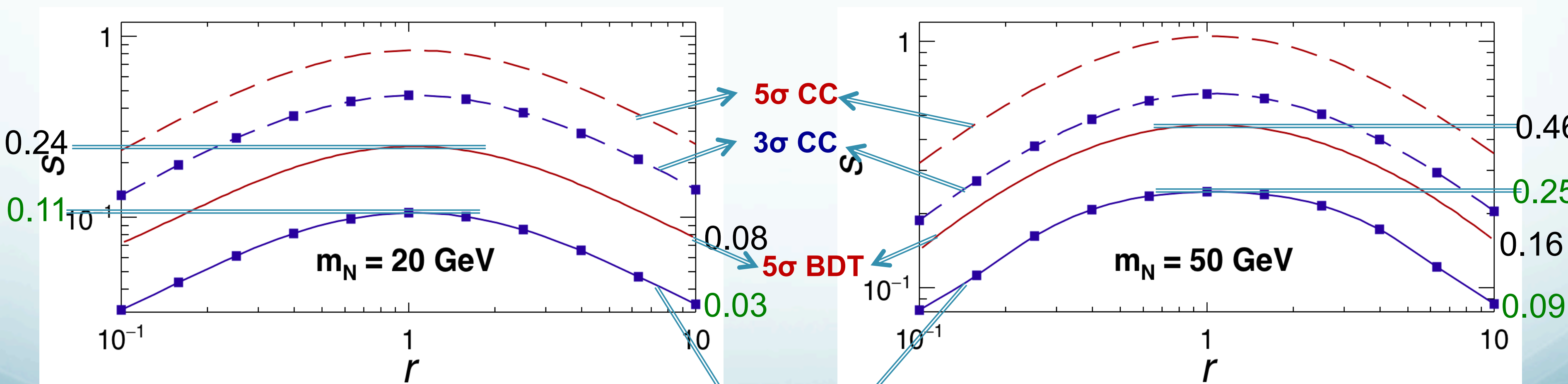
Cuts	Dirac	Majorana	γ^*/Z	WZ	$t\bar{t}$	SS
Basic cuts	54.0	133.2	4220	2658	68588	
N(b-jets)=0	53.1	131.1	4063.0	2497.1	31953.5	
CC	44.2	110.9	209.8	25.3	16.9	2.6 (5.8)
BDT > 0.1825	46.7	-	1.9	1.3	0.0	6.6
BDT > 0.1705	-	120.7	5.1	1.7	0.8	10.7

Limits

Dirac N



Majorana N



$$|U_{Ne}|^2 = \frac{1}{2\times10^6}\times(1+r)\times s$$

$$|U_{N\mu}|^2 = \frac{1}{2\times10^6}\times\left(1+\frac{1}{r}\right)\times s$$

Outline

★ Introduction of Sterile Neutrinos
  ◆ Simplified Model

★ Discovering/Excluding N
  ◆ Dirac
  ◆ Majorana

★ Distinguishing Dirac/Majorana N

★ Summary

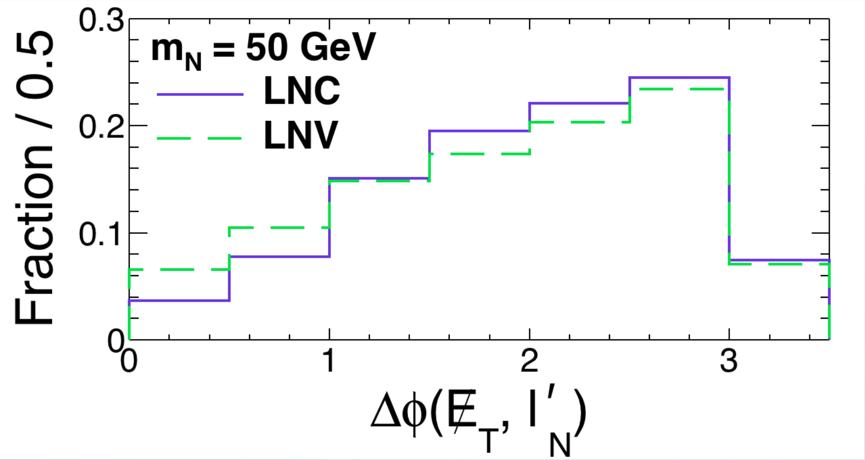
Basic Idea

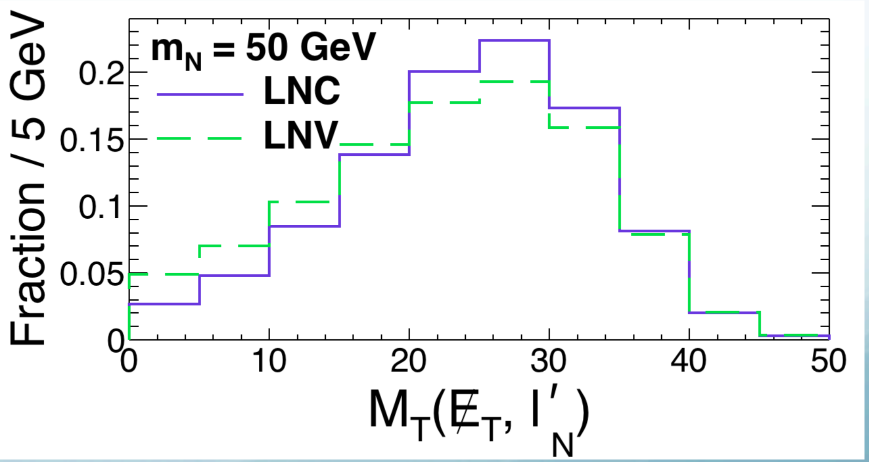
(1) 1st BDT -> reduce SM BG

# of events, 14 TeV, 3000 fb^{-1} m_N = 20 GeV

Cuts	$e^+e^+\mu^-$ LNC	$e^+e^+\mu^-$ LNV	$\mu^+\mu^+e^-$ LNC	$\mu^+\mu^+e^-$ LNV	$e^-e^-\mu^+$ LNC	$e^-e^-\mu^+$ LNV	$\mu^-\mu^-e^+$ LNC	$\mu^-\mu^-e^+$ LNV	$l^\pm l^\pm l'^\mp$ γ^*/Z	$l^+l^+l'^-$ W^+Z	$l^-l^-l'^+$ W^-Z	$l^\pm l^\pm l'^\mp$ $t\bar{t}$
Basic cuts	13.6	19.5	15.0	22.0	12.1	18.2	13.3	19.5	1055.0	779.0	550.0	17147.0
N(b-jets)=0	13.4	19.2	14.7	21.7	11.9	17.9	13.1	19.2	1015.8	731.8	516.7	7988.4
BDT1 > 0.1709	12.2	17.7	13.5	20.0	10.9	16.5	12.0	17.7	1.2	0.5	0.4	0.2

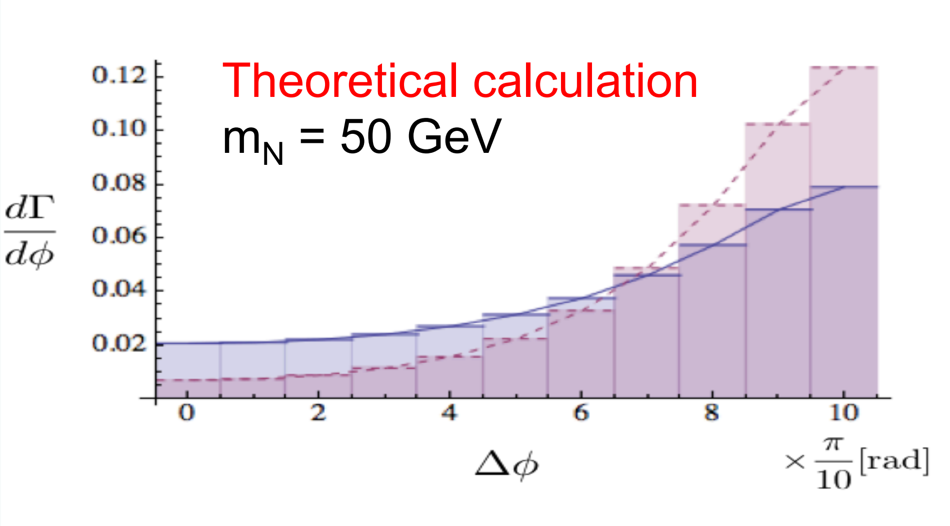
(2) 2nd BDT: kinematical distributions differing between LNC & LNV,
M_T(met, lep(s)) & Δφ(met, lep(s))

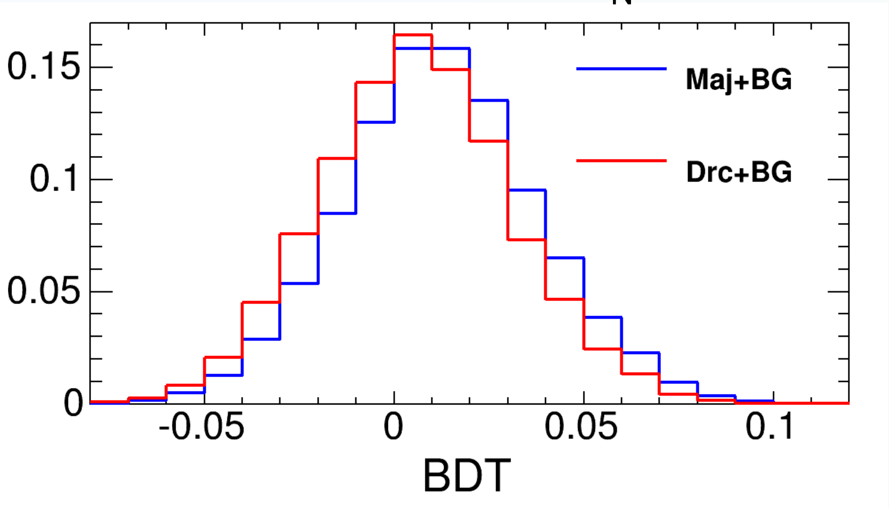


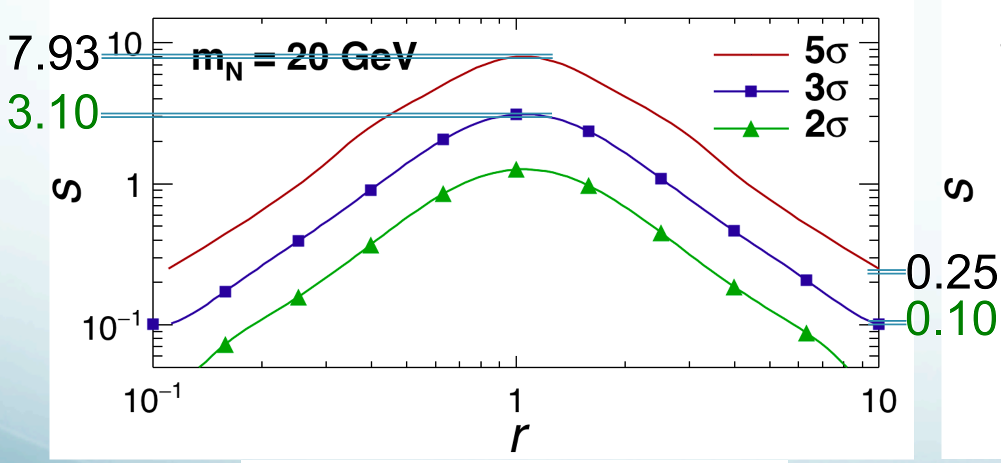


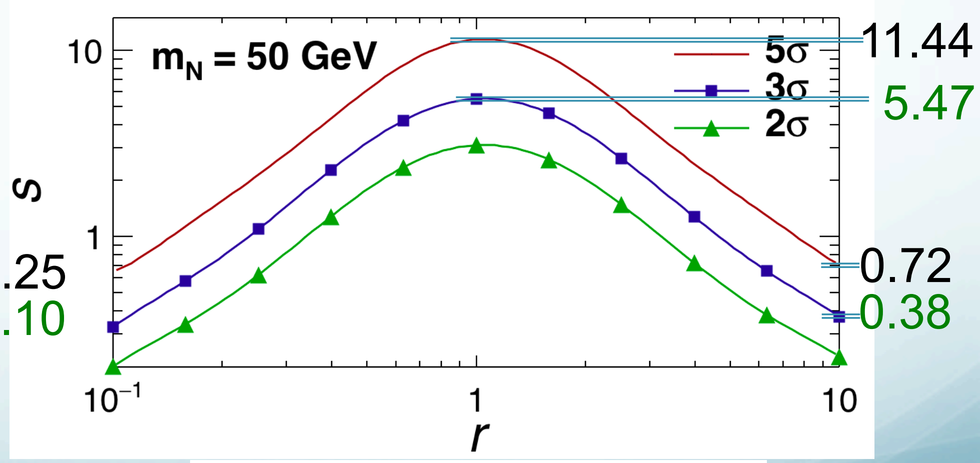
Limits

m_N = 20 GeV









$$|U_{Ne}|^2 = \frac{1}{2\times 10^6} \times (1+r) \times s$$

$$|U_{N\mu}|^2 = \frac{1}{2\times 10^6} \times \left(1+\frac{1}{r}\right) \times s$$

Summary

★ A complete search strategy for N from $W^{\pm} \to e^{\pm}e^{\pm}\mu^{\mp}\nu \,/\, \mu^{\pm}\mu^{\pm}e^{\mp}\nu$
→ m_N = 20, 50 GeV @ 14 TeV LHC, 3000 fb^{-1};
→ CC & MVA;
→ MVA greatly enhance the limits;
→ limits for 20 GeV better.

★ Discovering / Excluding N
→ Dirac: $s \geq 0.25$ @ 3σ;
→ Majorana $r \sim 1$: $s \geq 0.11$ @ 3σ
$r \sim 10$, limits on $|U_{N\mu}|^2$ stronger.

$$|U_{Ne}|^2 = \frac{1}{2\times10^6}\times(1+r)\times s$$

$$|U_{N\mu}|^2 = \frac{1}{2\times10^6}\times\left(1+\frac{1}{r}\right)\times s$$

★ Discriminating Dirac / Majorana
→ using kinematical distri. & MVA
→ non-trivial, flavor of ν undetectable;
→ $r \sim 1$: $s \geq 3.10$ @ 3σ;
→ $r \sim 10$, limits on $|U_{N\mu}|^2$ stronger.

★ Analysis can be extended to 100 TeV pp.

Thank you for your attention !

Any Questions ?

Backup Slide

Fake-lepton Simulation

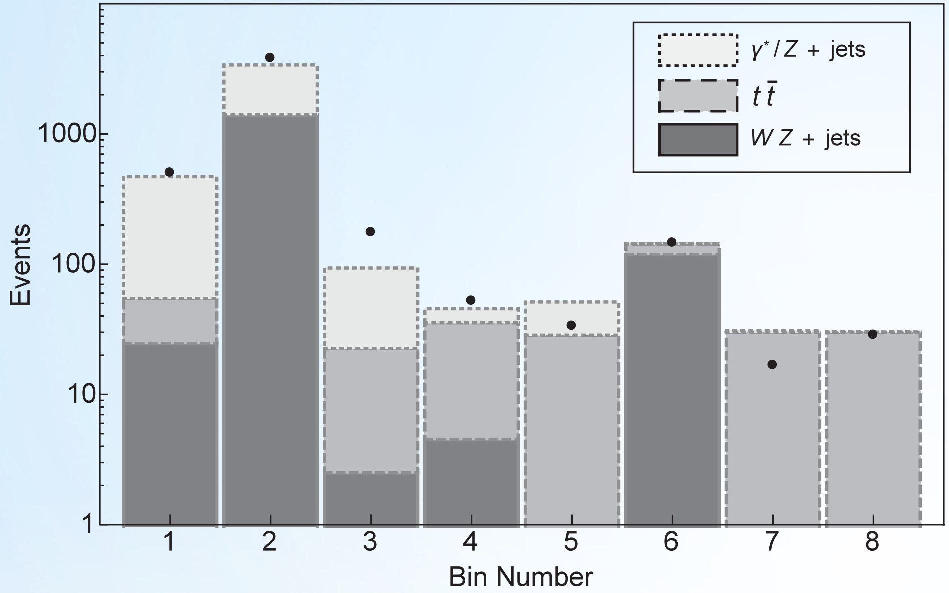


FIG. 6. Validation results for fake lepton simulation. Black dots indicate experimental results in Ref. [31]. Our simulated results for $\gamma^*/Z+$ jets, $t\bar{t}$, and $WZ+$ jets are given by upper light gray bars, middle brown bars, and bottom pink bars, respectively. Eight bin categories are (1) 0-bjet, 1-OSSF, $M_{\ell^+,\ell^-} < 75$ GeV, (2) 0-bjet, 1-OSSF, $|M_{\ell^+,\ell^-} - M_Z| < 15$ GeV, (3) 0-bjet, 1-OSSF, $M_{\ell^+,\ell^-} > 105$ GeV, (4) 0-bjet, 0-OSSF, (5–8) are the same as the first four bins, but with at least one b-jet.

A pheno. FL simulation method
[E. Izaguirre, B. Shuve, hep-ph/1504.0247]

→ data-driven methods to estimate the fake lepton contributions

→ modeling parameters, pinned down by validating simulated results against actual experimental ones.

1. Mistag rate
(probability of converting a jet to a lepton)

$$\epsilon_{j\to\ell}(p_{Tj}) = \epsilon_{200}\left[1-(1-r_{10})\frac{200-p_{Tj}/\mathrm{GeV}}{200-10}\right]$$

2. Transfer function
(how much p_T is transferred into the lepton)

$$p_{T\ell} \equiv (1-\alpha)p_{Tj}$$

$$\mathcal{T}_{j\to\ell}(\alpha) = \frac{1}{\mathcal{N}}\exp\left[-\frac{(\alpha-\mu)^2}{2\sigma^2}\right]$$

Backup Slide

Interesting Mass Scales of m_N

m_N

GUT

- Original Seesaw
- Fits well with GUTs
- Elegantly explains m_ν
- Leptogenesis

Hard to test experimentally !

TeV

- Models with small m_N

→ Inverse seesaw

→ Loop-induced neutrino models

Testable at the LHC !

$$\mathcal{M}_{ISS} = \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & 0 & M \\ 0 & M^T & \mu \end{pmatrix}$$

$$\mu \ll m_D,\ M$$

$$m_\nu \approx m_D^T \frac{1}{M} \mu \frac{1}{M^T} m_D$$

GeV – KeV

- νMSM (Neutrino Minimal SM)

→ Explains most BSM evidences

→ Fine-tuned model but testable

KeV

- DM candidate (warm or cold)
- X-ray bound (3.5 KeV line)

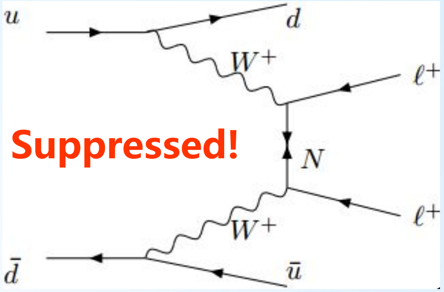
eV

- neutrino oscillation anomaly (LSND)
- reactor / gallium anomaly
- dark radiation

Backup Slide

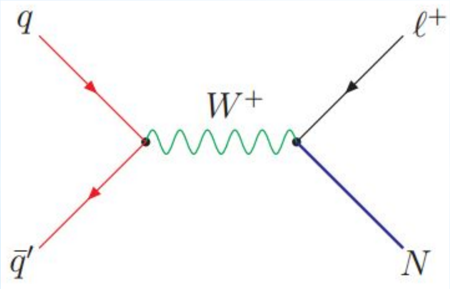
Productions @ pp Colliders

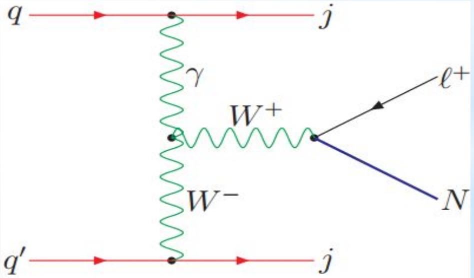
$$q\bar{q} \to Z^{(*)} \to \nu N$$
$$gg \to H^{(*)} \to \nu N$$



almost unobserved
(final states l^+l^-, $l^\pm$ suffer from huge background)

(no resonance enhancement)





Mostly studied
(important for m_N < 1 TeV)

More important for m_N > 1 TeV

Backup Slide

from [S. Antusch, E. Cazzato, O. Fischer, hep-ph/1612.02728]