Distinguishing Dirac/Majorana Sterile Neutrinos at the LHC

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Based on [Phys. Rev. D **94** (2016) 013005]

Outline

★ Introduction of sterile neutrinos
  - Simplified Model
  - Productions @ LHC
  - Current limits

★ Distinguishing Dirac/Majorana
  - Basic idea
  - Collider simulation & background
  - Results

★ Summary

Theory Model

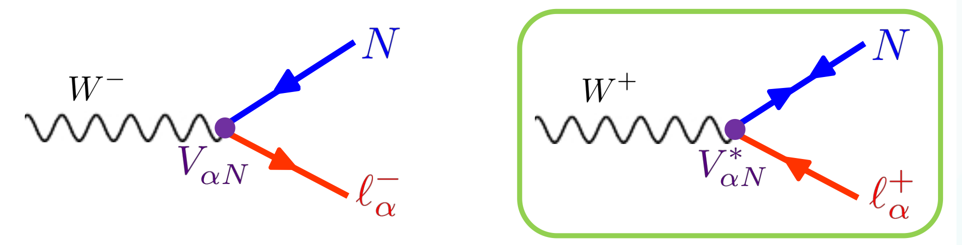
Discovery of neutrino oscillations => neutrinos have mass
→ In SM, neutrinos are massless
→ A window to BSM physics

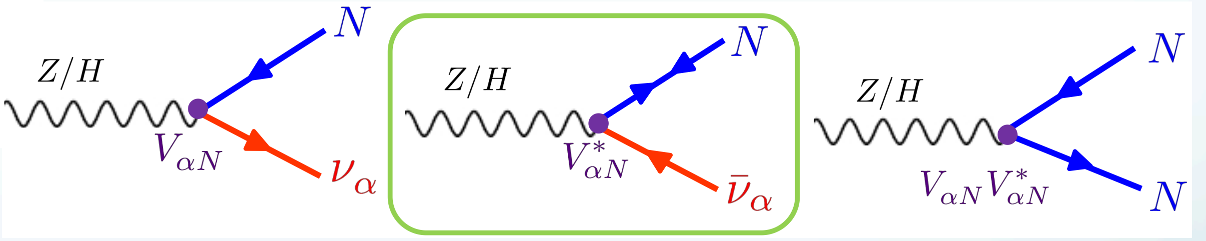
Type-I see-saw: Singlet (Sterile) Fermions

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

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

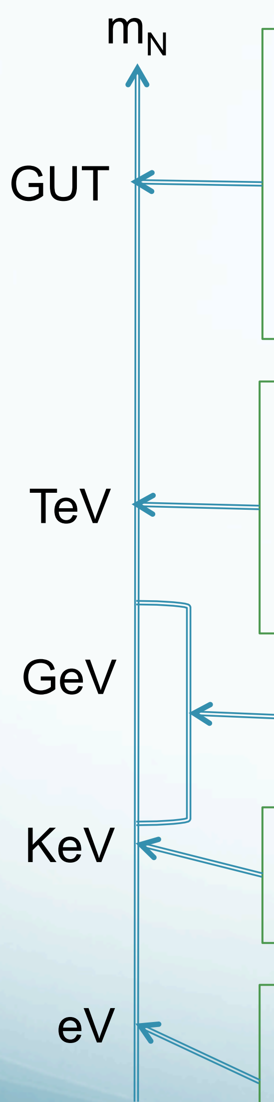
Interactions: [0901.3589]





Simplified model with assumption:
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.

Interesting Mass Scales of 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)

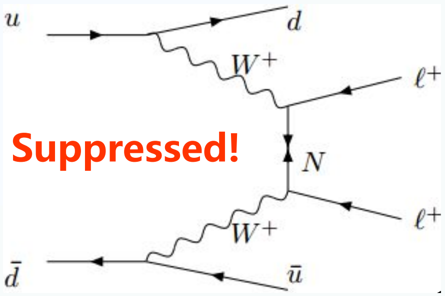
eV:

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

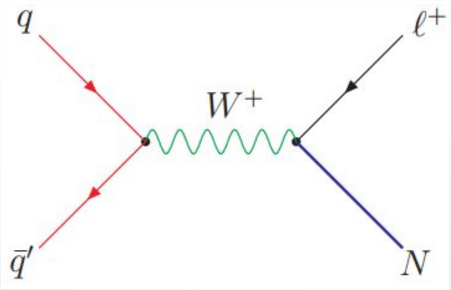
Productions @ LHC

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

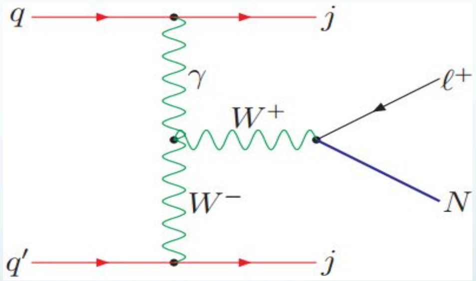
almost unobserved
(final states l^+l^-, $l^\pm$ suffer from huge background)



(no resonance enhancement)



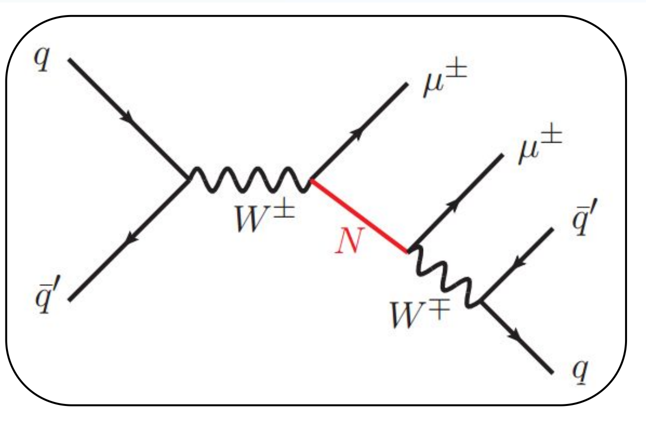
Mostly studied
(important for m_N < 1 TeV)



More important for m_N > 1 TeV

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 $m_N > m_W$.

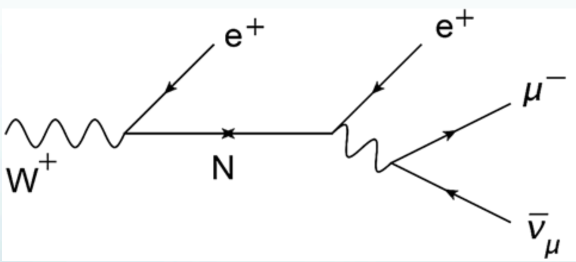
[CMS: 1207.6079, 1501.05566]
[ATLAS-CONF-2012-139]

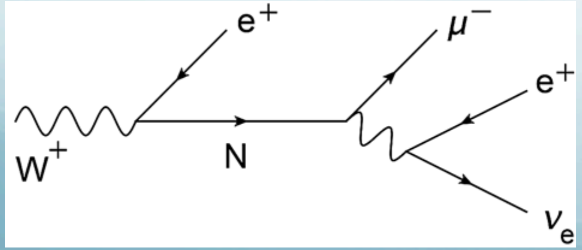
Majorana:

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

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 ...]

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

distinguishable?

Today !

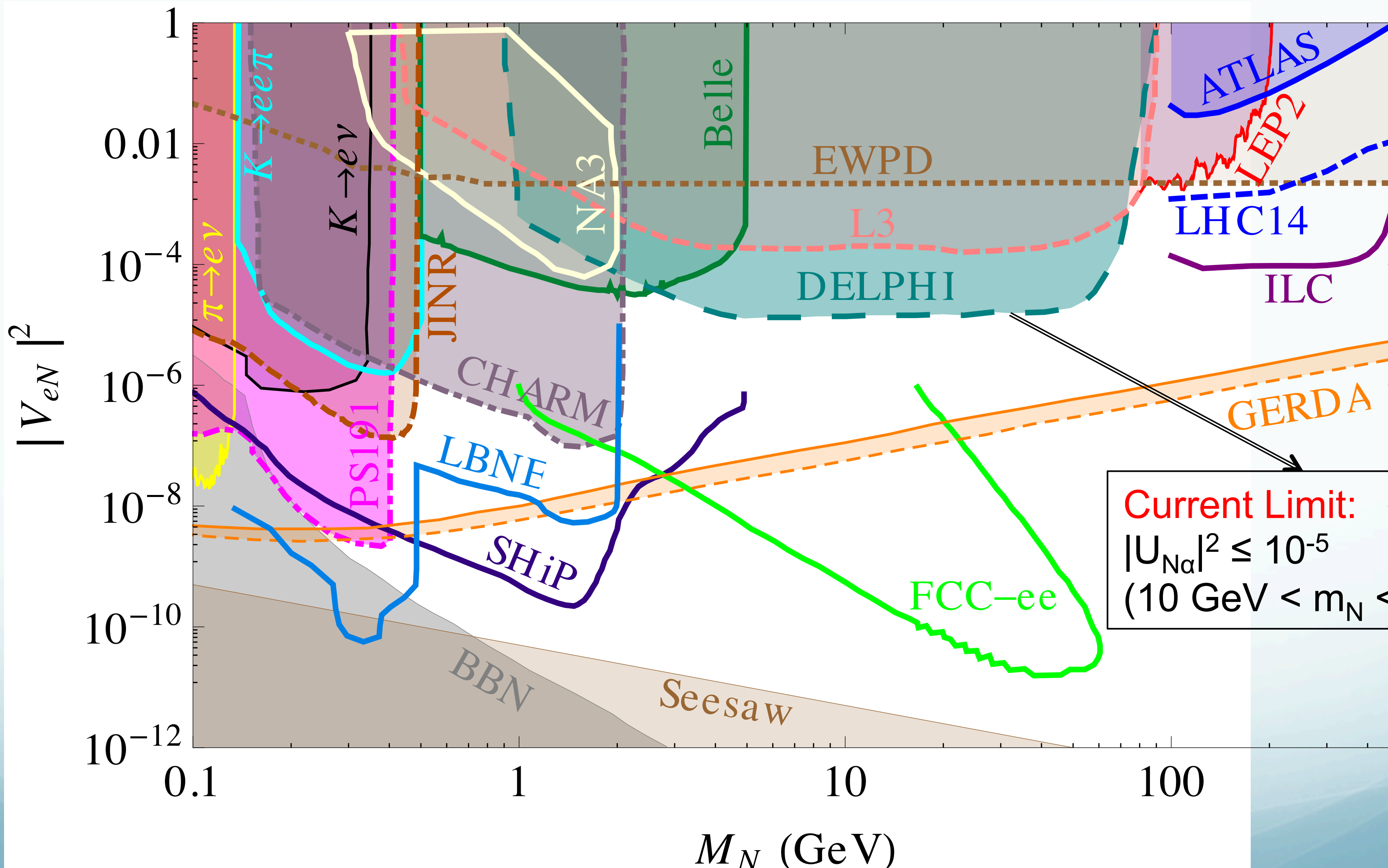
Dirac: $W^+ \to e^+ e^+ \mu^- \nu_e$

[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)

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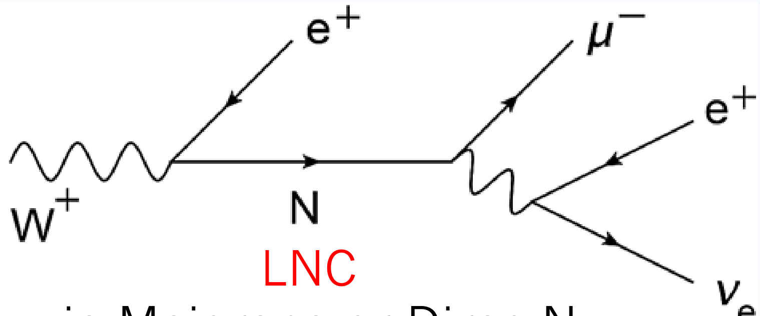
Basic Idea

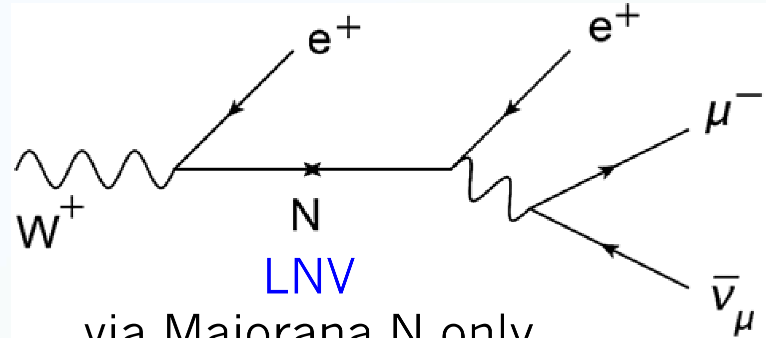
tri-lepton + MET with no OSSF lepton pairs



LNC

via Majorana or Dirac N

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



LNV

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

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

Basic idea: Distinguish Dirac/Majorana sterile neutrinos

by counting and comparing events in different channels !

Collider Simulation

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

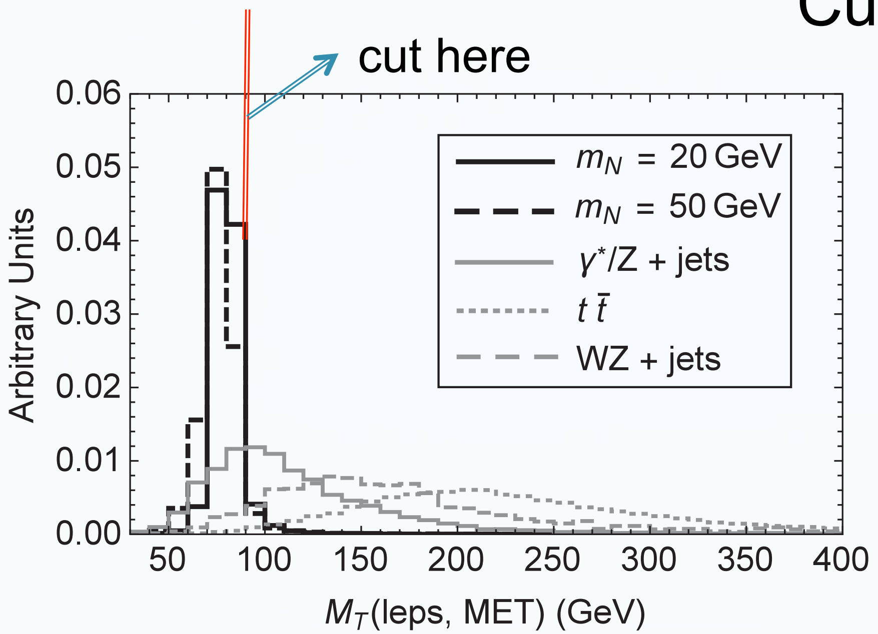
Signal:
tri-lepton + MET with no OSSF lepton pairs
$e^+ e^+ \mu^- / \mu^+ \mu^+ e^- / e^- e^- \mu^+ / \mu^- \mu^- e^+$ + MET.

SM background:

→ Leptonic τ decay:
WZ -> (l v) (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

Cuts



Apply various cuts to reduce BG

→ Basic cuts:

leptons, $p_{T,l}$ > 10 GeV & $|\eta_l|$<2.5;

jets, $p_{T,j}$ > 20 GeV & $|\eta_j|$<5.0.

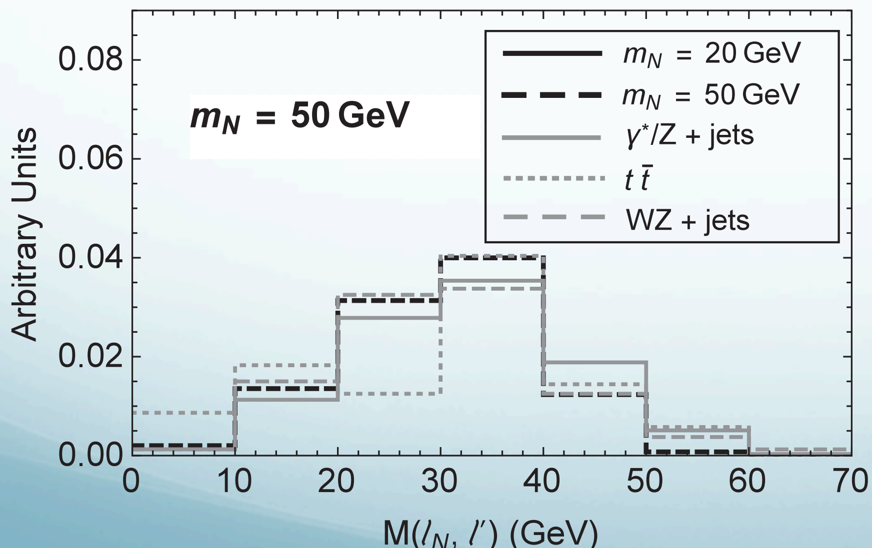
→ M_T(3l, MET) < 90 GeV

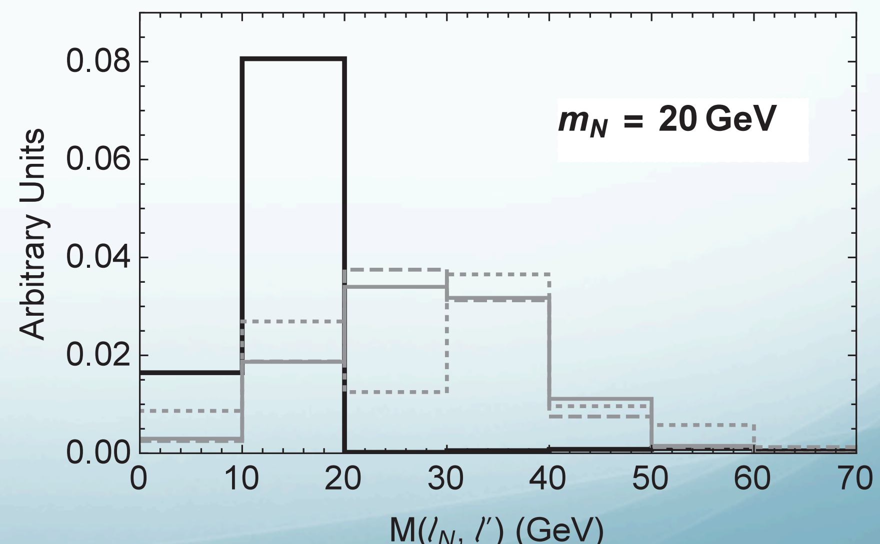
→ MET < 40 GeV

→ b-jet veto & H_T < 50 GeV

→ For mN = 20 GeV,

$M(l_N, l'_N)$ < 20 GeV





Cut Flow Tables

Signal 14 TeV, 3000 fb^{-1}

m_N = 50 GeV

Cuts	$e^+e^+\mu^-$		$\mu^+\mu^+e^-$		$e^-e^-\mu^+$		$\mu^-\mu^-e^+$	
	LNC	LNV	LNC	LNV	LNC	LNV	LNC	LNV
Basic cuts	27.7	30.7	30.7	33.3	23.7	26.6	26.3	29.8
M_t(leps, MET) $<$ 90 GeV	26.4	29.0	29.2	31.7	22.5	25.1	25.0	28.1
MET $<$ 40 GeV	26.1	28.7	28.9	31.4	22.3	25.1	24.8	28.1
N(b-jets) $=$ 0, H_t $<$ 50 GeV	23.7	26.0	26.2	28.4	20.1	22.8	22.4	25.5

m_N = 20 GeV

Cuts	$e^+e^+\mu^-$		$\mu^+\mu^+e^-$		$e^-e^-\mu^+$		$\mu^-\mu^-e^+$	
	LNC	LNV	LNC	LNV	LNC	LNV	LNC	LNV
Basic cuts	13.6	19.5	15.0	22.0	12.1	18.2	13.3	19.5
M_t(leps, MET) $<$ 90 GeV	12.7	18.3	13.9	20.3	11.3	17.0	12.3	18.3
MET $<$ 40 GeV	12.5	18.3	13.8	20.3	11.2	17.0	12.3	18.3
N(b-jets) $=$ 0, H_t $<$ 50 GeV	11.1	16.6	12.2	18.5	10.0	15.6	11.0	16.6
$M(\ell_N, \ell') < 20$ GeV	10.8	16.3	11.8	17.8	9.8	15.1	10.7	16.1

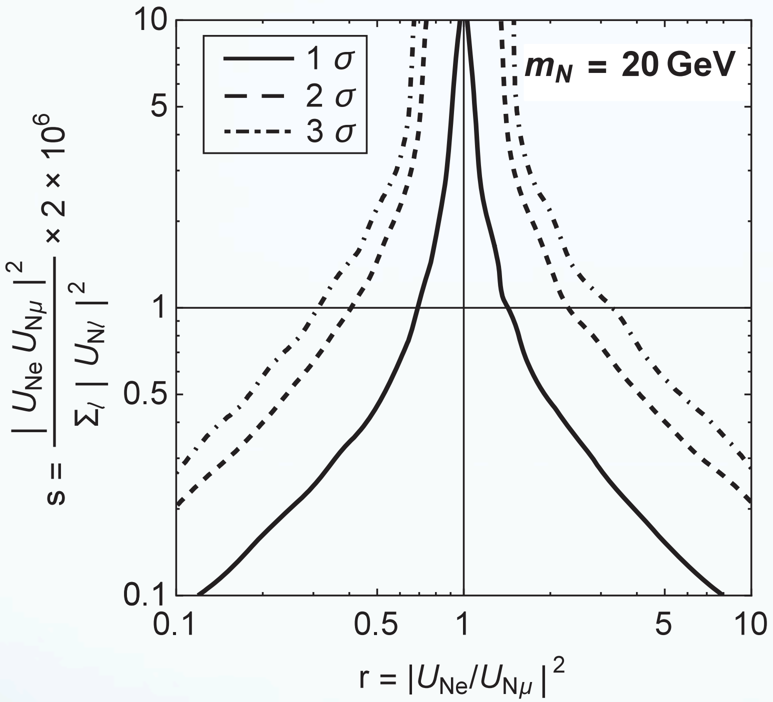
SM background l = e or μ

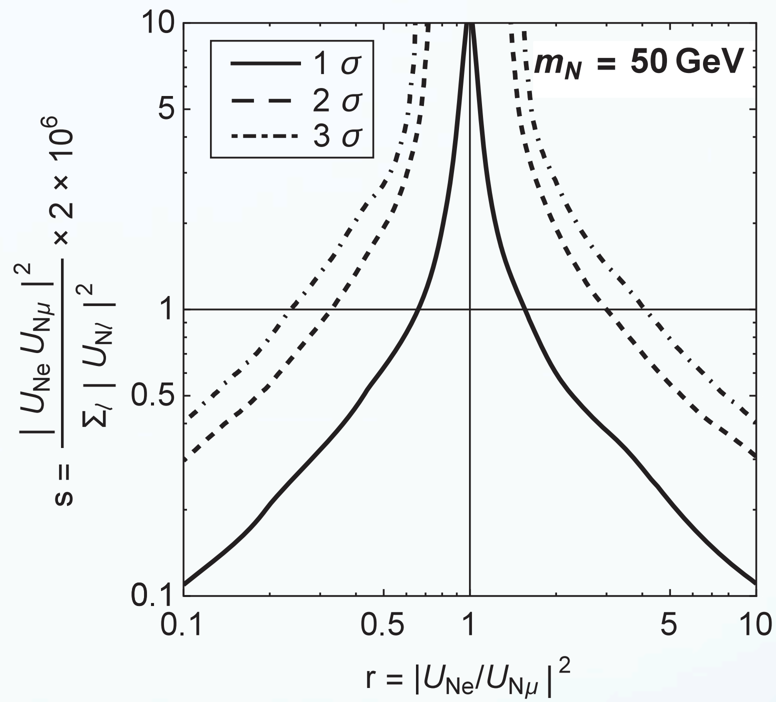
Cuts	WZ		$\gamma^*/Z+$jets	$t\bar{t}$
	$\ell^+\ell^+\ell'^-$	$\ell^-\ell^-\ell'^+$	$\ell^\pm\ell^\pm\ell'^\mp$	$\ell^\pm\ell^\pm\ell'^\mp$
Basic cuts	779	550	1055	17147
M_T(leps, $\not{E}_T$) $<$ 90 GeV	52	34	374	160
$\not{E}_T$ $<$ 40 GeV	46	28	356	113
N(b-jets) $=$ 0, H_T $<$ 50 GeV	39	23	323	15
$M(\ell_N, \ell') < 20$ GeV	7.4	4.4	62	2.7

dominant !

Sensitivity of Excluding Dirac

(assuming Majorana)





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

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

→ 3σ level exclusion

Provided $s > 5$, $r = |U_{Ne}|^2 / |U_{N\mu}|^2 < 0.7$ (or $> 1/0.7 = 1.4$),

→ $|U_{Ne}| / |U_{N\mu}| < 0.84$ or > 1.20

Summary

★ Sterile neutrinos may exist over a wide range of masses

★ A simple method to discriminate Dirac / Majorana
→ @ LHC, $m_N < m_W$ & $r \neq 1$
→ trilepton channel
→ excluding the Dirac by counting and comparing the numbers of events in the e e μ and μ μ e channels

★ Sensitivities @ 14 TeV LHC, 3000 fb^{-1}
→ m_N = 20, 50 GeV
→ 3σ exclusion on Dirac for $|U_{Ne}|^2 < 0.7\ |U_{N\mu}|^2$ or $|U_{Ne}|^2 > 1.4\ |U_{N\mu}|^2$
→ provided $|U_{Ne}|^2 > 2 \times 10^{-6}$

★ Further directions
→ *r* ~ 1, challenging, kinematical distributions of final state leptons to enhance discriminating power

Thank you for your attention !

Any Questions ?

Backup Slide

Fake-lepton Simulation

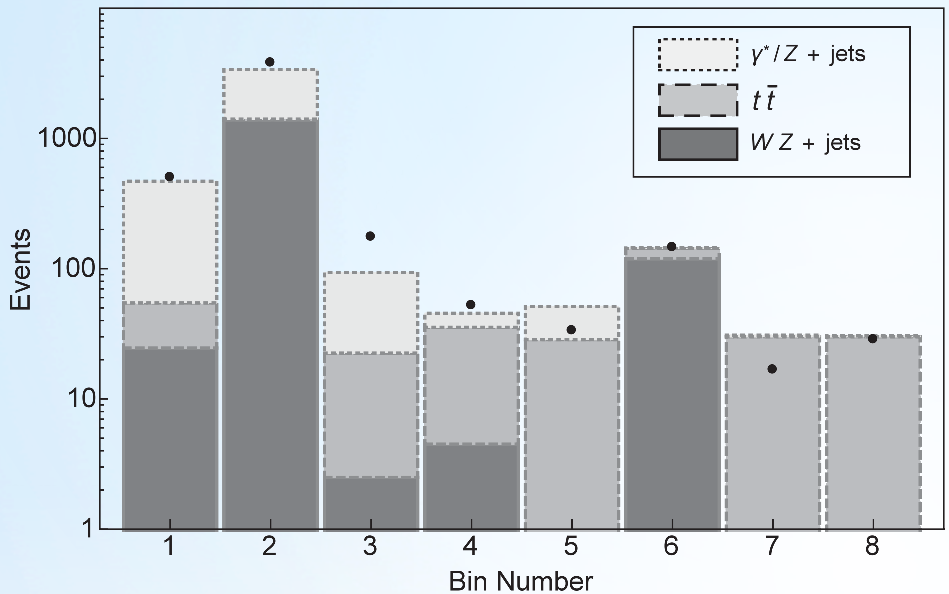


FIG. 6. Validation results for fake lepton simulation. Black dots indicate experimental results in Ref. [31]. Our simulated results for $\gamma^*/Z+$jets, $t\bar{t}$, and $WZ+$jets are given by upper light gray bars, middle brown bars, and bottom pink bars, respectively. Eight bin categories are (1) 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

→ 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)

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

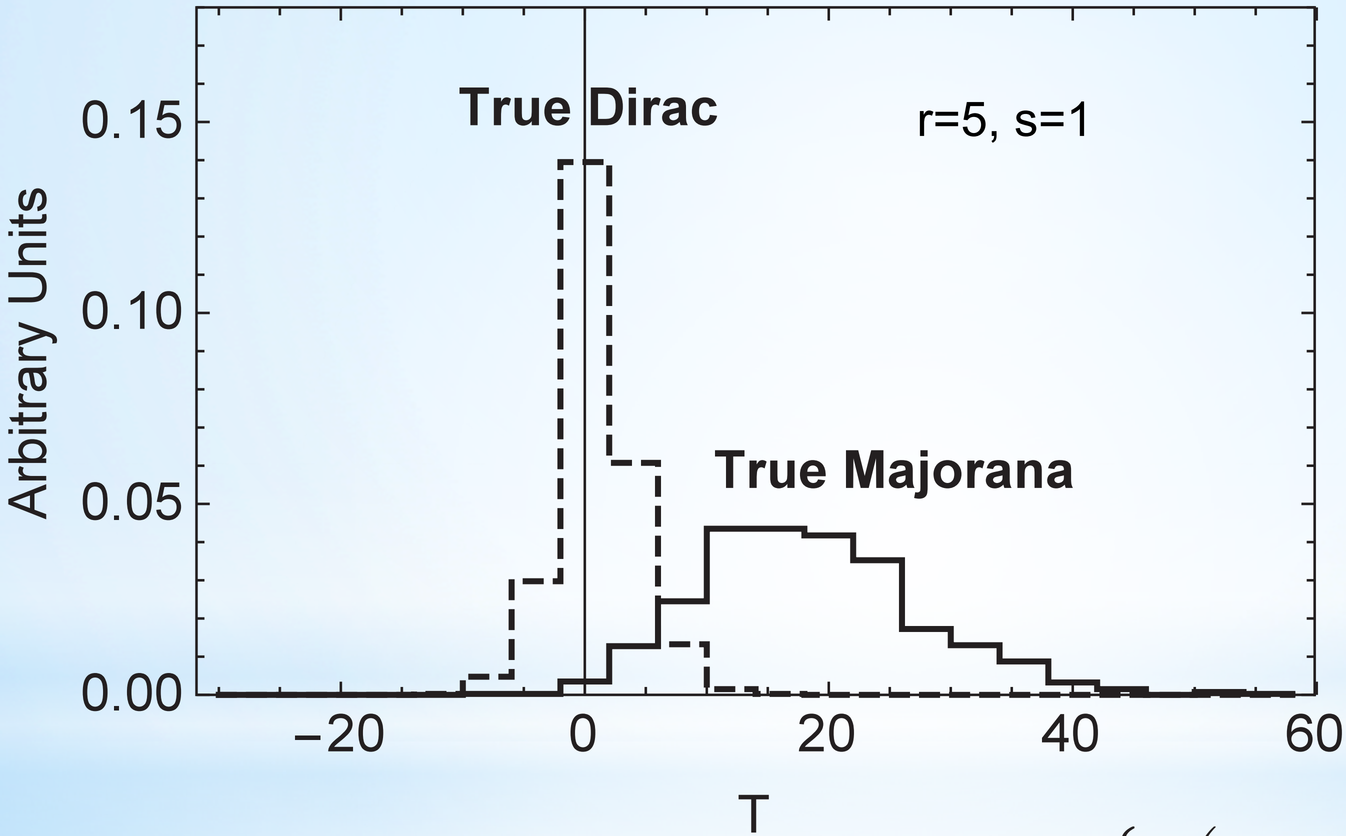
2. Transfer function
(how much p_T is transferred into the lepton)

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

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

Backup Slide

Calculating the Confidence Level of Excluding Dirac



Statistical fluctuation
→ spread of 2 distributions

Level of overlap
→ CL of discriminating
2 hypotheses

Median discrimination
→ T = 0, median possible
value for Dirac

CL = 1 – α
→ α, area under the Maj.
curve for T < 0.

A test statistic $T = \chi^2_{\mathrm{Dirac}} - \chi^2_{\mathrm{Maj}}$ $\quad \chi^2_H = -2 \min_{s,r \subset H} \left\{ \ln \left(\prod_i \mathrm{Poiss}[N_i^{\mathrm{expc}}(s,r;H), N_i^{\mathrm{obs}}] \right) \right\}$

→ To quantify how well the data sets are described within a given hypothesis.