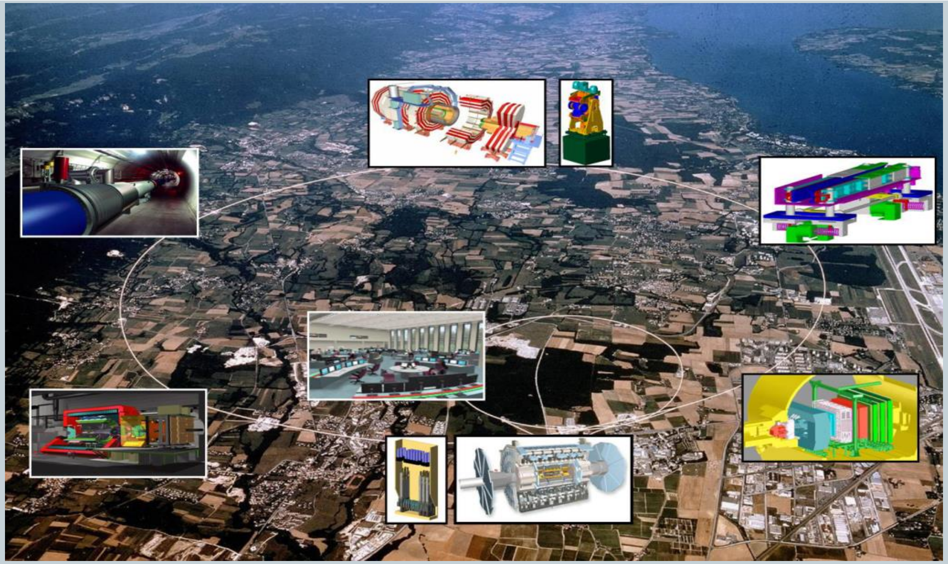
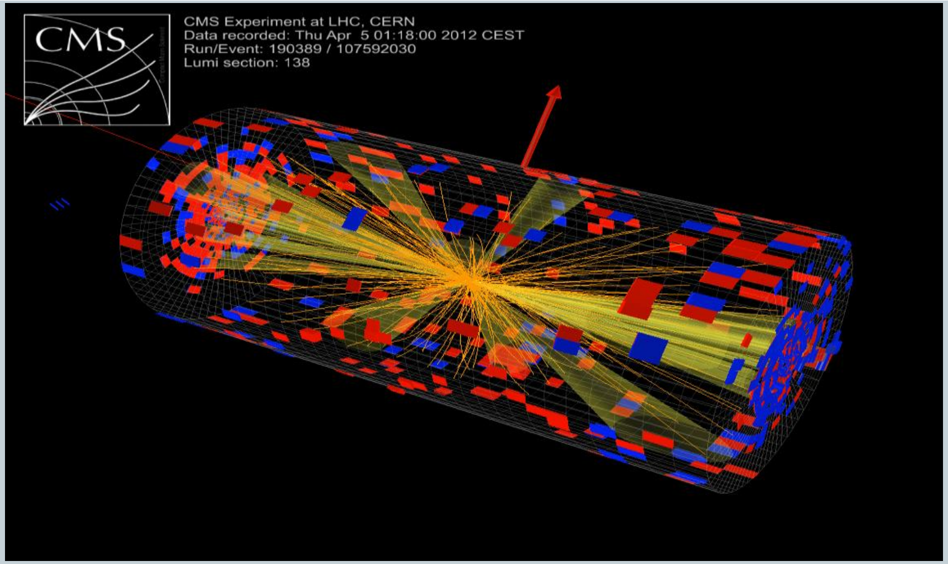
Sterile Neutrinos Searches at Proton Colliders





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Particle Physics Workshop

SYSU, Guangzhou, Jan. 22, 2019

Based on [JHEP 1810 (2018) 067; PRD 95 (2017) 115020, CPC 41 (2017) 103103, PRD 94 (2016) 013005]

Outline

★ Introduction

- ♦ Sterile Neutrinos Productions @ pp colliders

★ $3l$+MET @ HL-LHC

[C. Dib, C. S. Kim, **K. Wang** and J. Zhang, PRD 95 (2017) 115020, CPC 41 (2017) 103103, PRD 94 (2016) 013005]

★ $2l+2j$ @ HL-LHC & SppC/FCC-hh

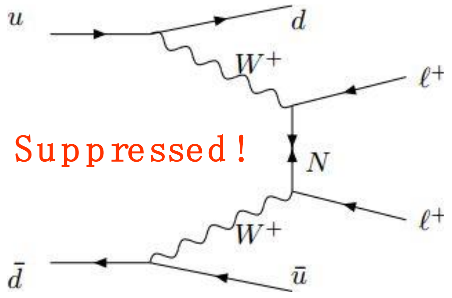
[S. Antusch, E. Cazzato, O. Fischer, A. Hammad and **K. Wang**, JHEP 1810 (2018) 067]

★ Summary

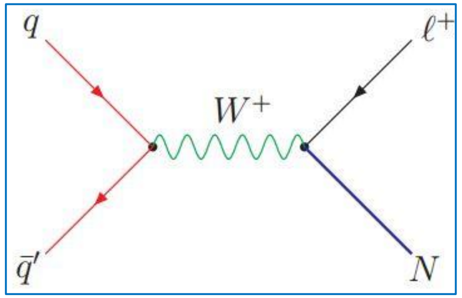
Sterile Neutrino Productions @ pp Colliders

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

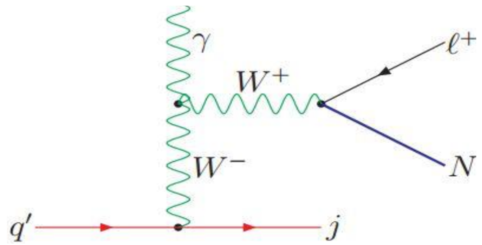
almost unobserved
(l^+l^- or $l^\pm$+MET suffer from huge BG)



(no resonance enhancement)



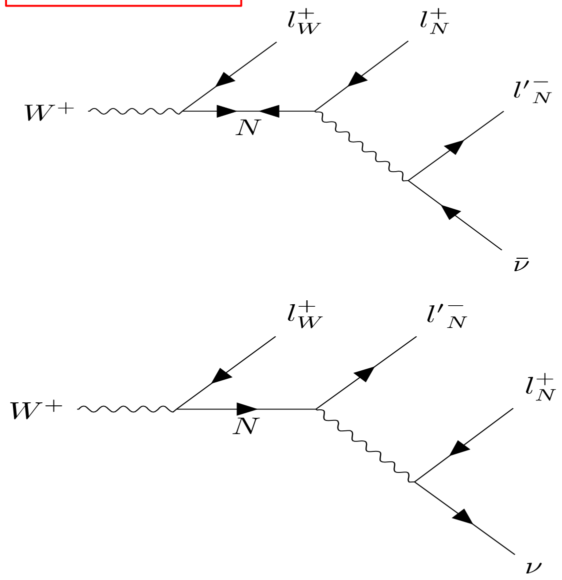
Mostly studied
(important for m_N < 1 TeV)



More important for m_N > 1 TeV

Main Search Channels @ pp Colliders

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 ...]

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

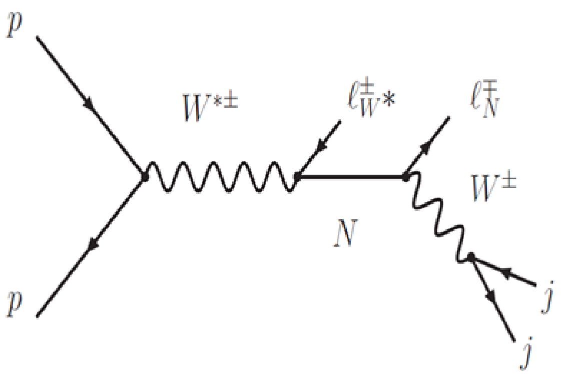
non-trival ←
flavor of ν undetectable

distinguishable?

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

[0809.2096, 1509.05981]

2l + 2j



need well isolated energetic 2 jets;
→ better for $m_N > m_W$

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

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

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

Collider Limits on Sterile Neutrinos

[**LHC, CMS experiment:** Phys.Rev.Lett. 120 (2018) no.22, 221801,
"Search for heavy neutral leptons in events with three charged leptons in proton-proton collisions at 13 TeV"]

3*l* + MET

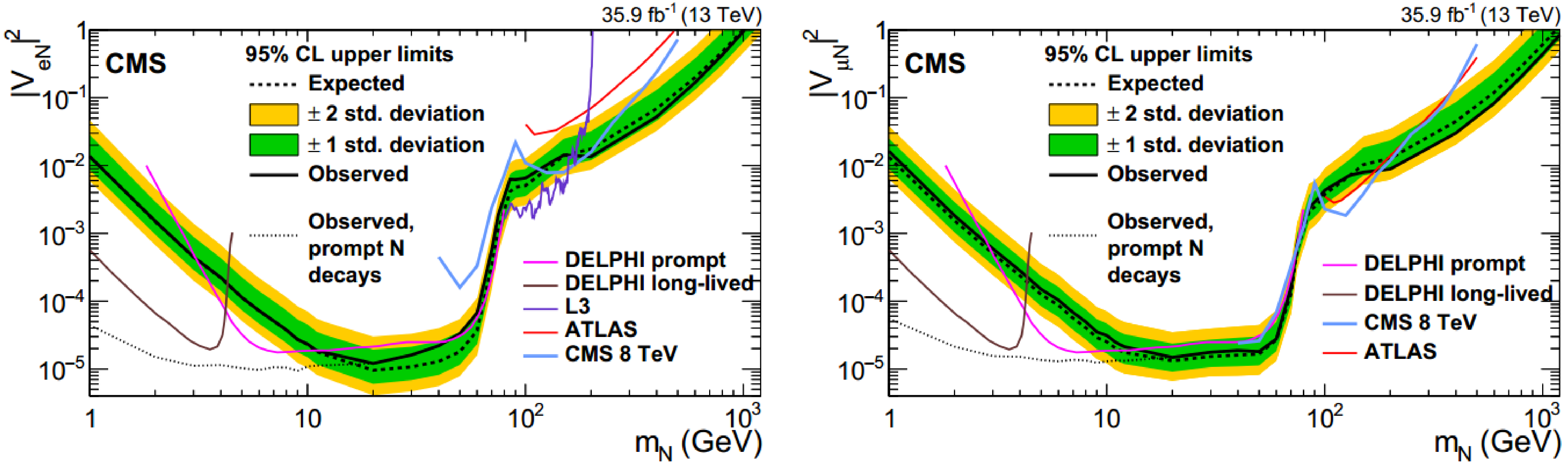


Figure 2: Exclusion region at 95% CL in the $|V_{eN}|^2$ vs. m_N (left) and $|V_{\mu N}|^2$ vs. m_N (right) planes. The dashed black curve is the expected upper limit, with one and two standard-deviation bands shown in dark green and light yellow, respectively. The solid black curve is the observed upper limit, while the dotted black curve is the observed limit in the approximation of prompt N decays. Also shown are the best upper limits at 95% CL from other collider searches in L3 [41], DELPHI [38], ATLAS [28], and CMS [27].

Collider Limits on Sterile Neutrinos

[**LHC, CMS experiment:** hep-ex/1806.10905, CMS-EXO-17-028,
"Search for heavy Majorana neutrinos in same-sign dilepton channels in proton-proton collisions at 13 TeV"]

2*l*(SS) + ≥ 1 j

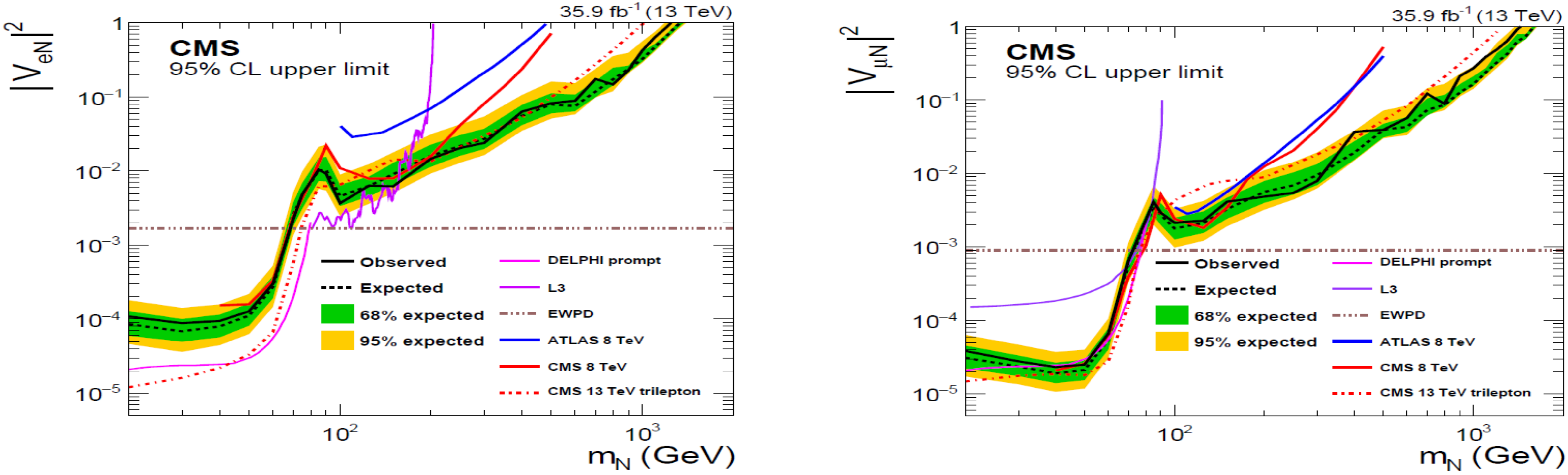
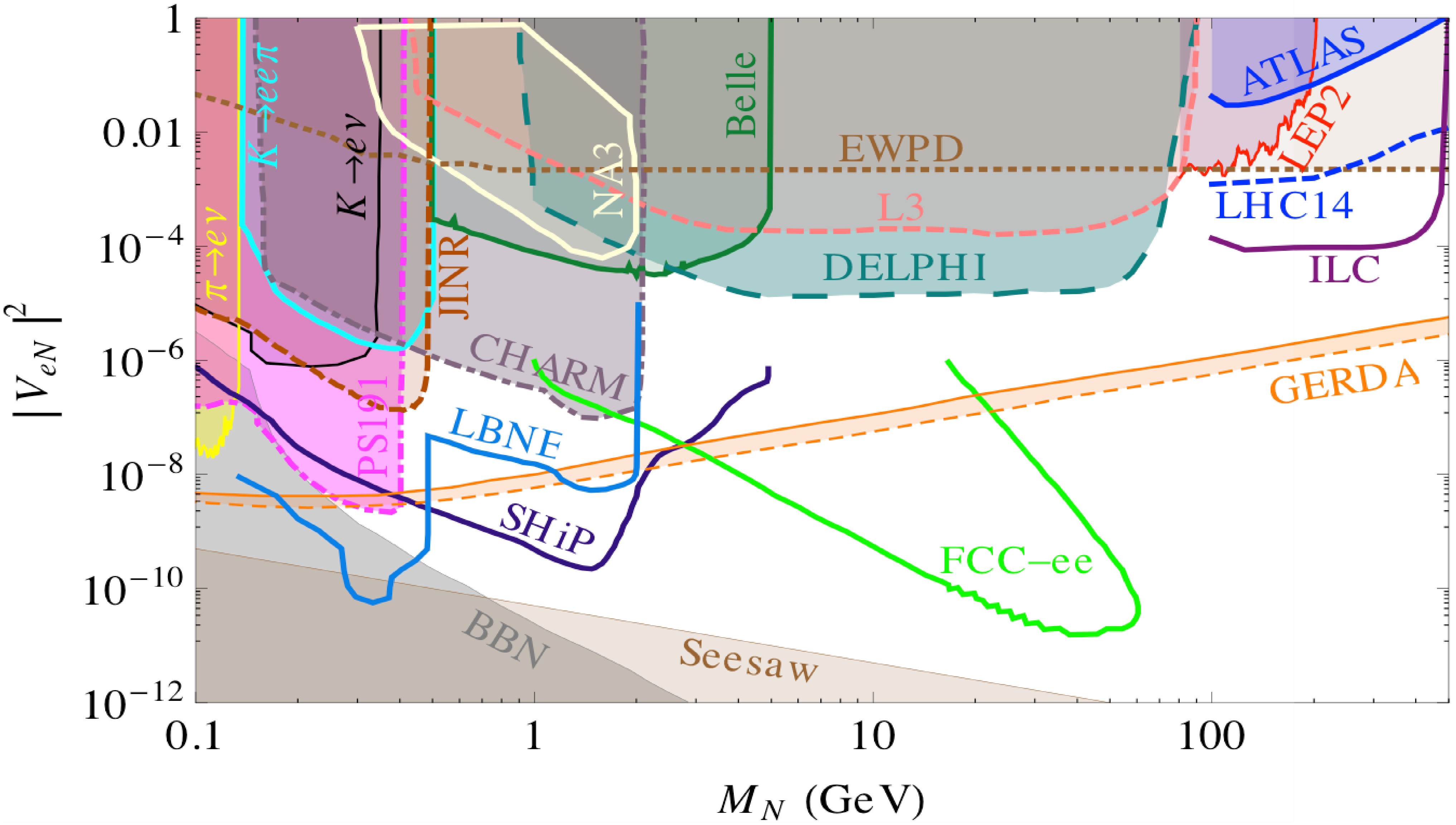


Figure 4: Exclusion region at 95% CL in the $|V_{eN}|^2$ (upper) and $|V_{\mu N}|^2$ (lower) vs. m_N plane. The dashed black curve is the expected upper limit, with one and two standard-deviation bands shown in green and yellow, respectively. The solid black curve is the observed upper limit. The brown line shows constraints from EWPD [83]. Also shown are the upper limits from other direct searches: DELPHI [30], L3 [31, 32], ATLAS [36], and the upper limits from the CMS $\sqrt{s}$ = 8 TeV 2012 data [35] and the trilepton analysis [37] based on the same 2016 data set as used in this analysis.

Global Constraints

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

m_N: 0.1 ~ 500 GeV



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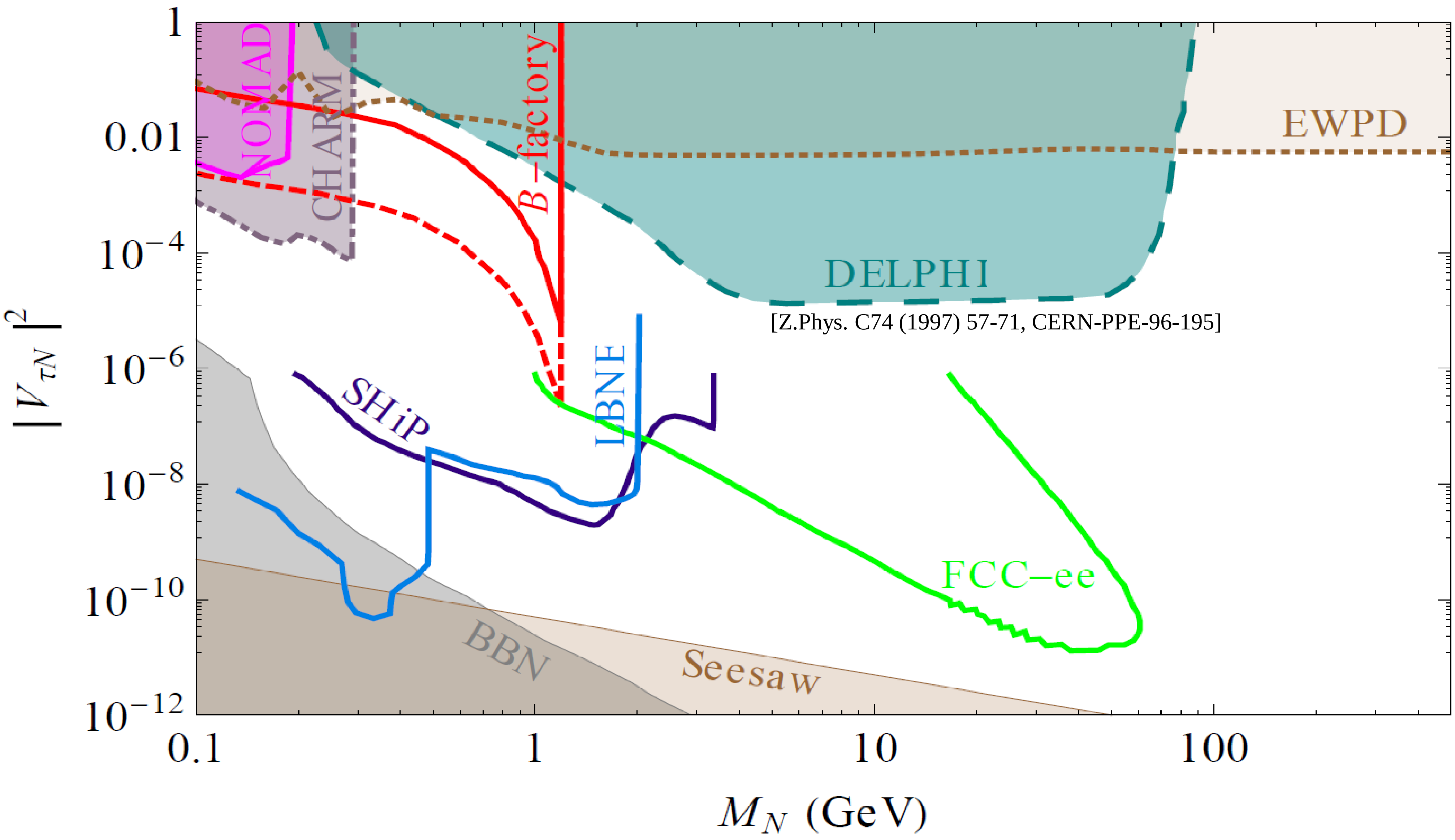
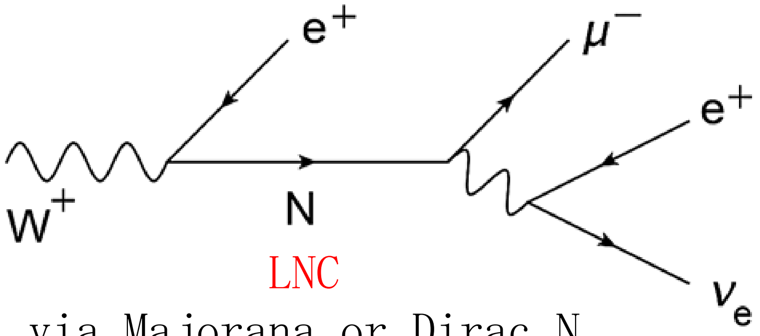


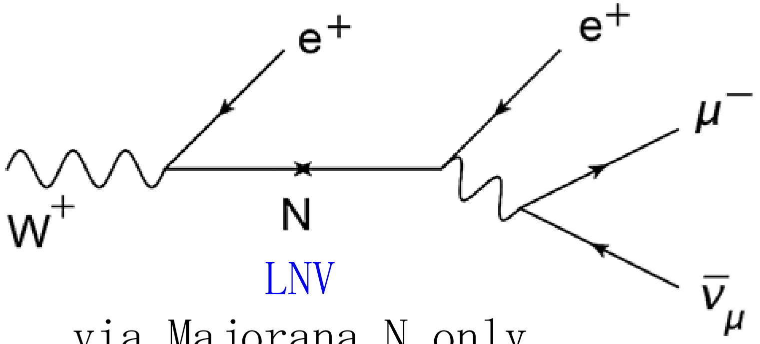
Production Rates

3l + 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)
$e^\pm e^\pm \mu^\mp \nu$	s	$s\,(1 + r)$
$\mu^\pm \mu^\pm e^\mp \nu$	s	$s\,(1 + \frac{1}{r})$

normalization factor

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

disparity factor

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

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

→ When r >> 1, or << 1, Dirac vs. Majorana via production rates, details see [Phys. Rev. D **94** (2016) 013005]

Collider Simulation

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

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

Signal:
3l + MET with no OSSF lepton pairs
$e^+ e^+ \mu^- / \mu^+ \mu^+ e^- / e^- e^- \mu^+ / \mu^- \mu^- e^+$ + MET.

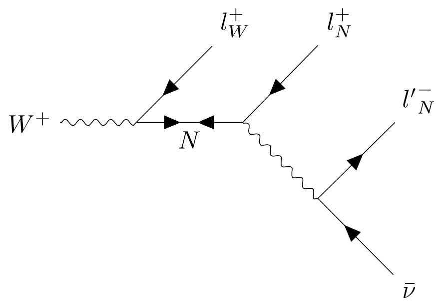
SM backgrounds:
→ Leptonic τ decay:
WZ -> (l ν) (τ τ) -> 3 l + MET

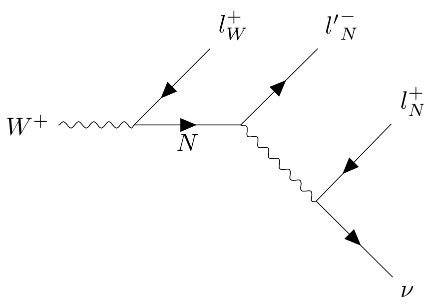
→ Fake leptons from jets containing heavy-flavor mesons:
γ^*/Z+jets: γ^*/Z (-> τ τ) + a 3rd faked lepton
t tBar+jets: prompt decay of t tBar + a 3rd fake lepton

Search Strategy

→ Selecting 3 leptons $l^{\pm}l^{\pm}l'^{\mp}$ & veto b-jets;
→ Identifying correct lepton from N & calculating $p_{z,\nu}$
→ Constructing various observables
→ Input observables to perform MVA-BDT analysis

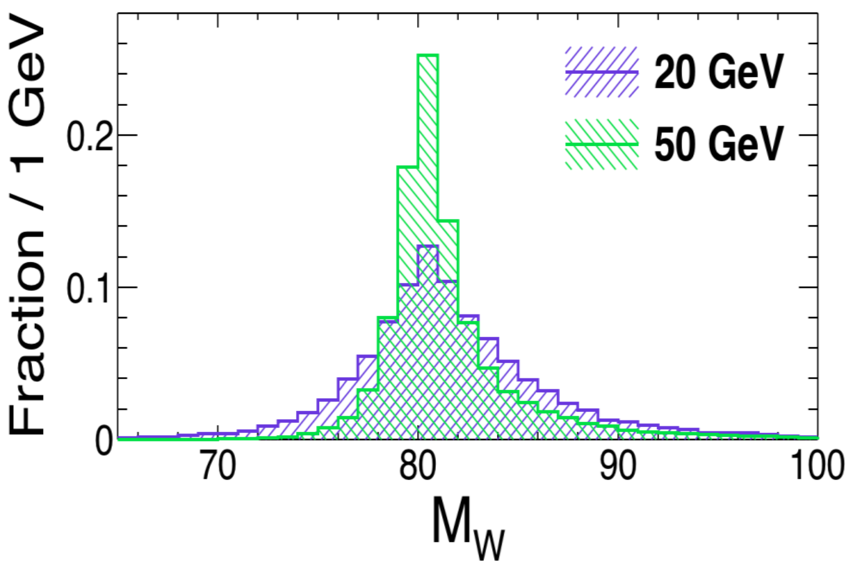
← by minimizing the

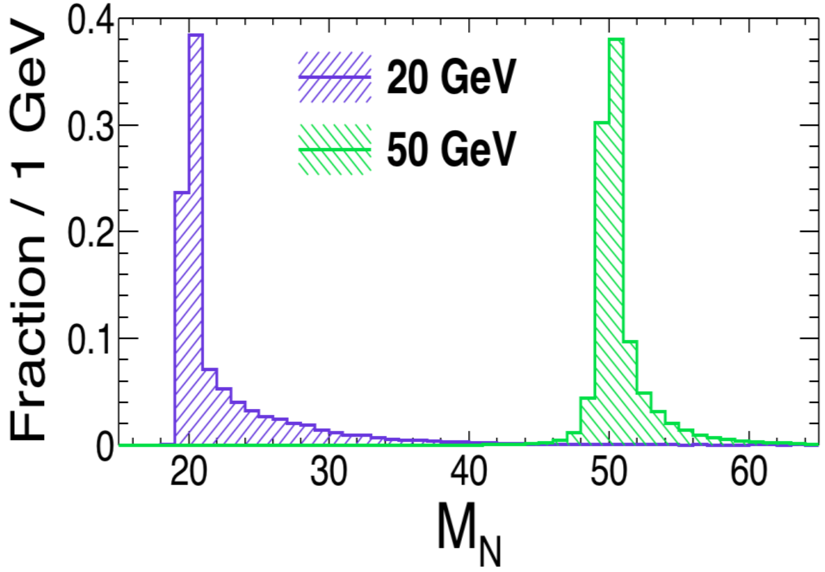




$M(l^{\pm}l^{\pm}l'^{\mp}\nu)$ $M(l^{\pm}l'^{\mp}\nu)$

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

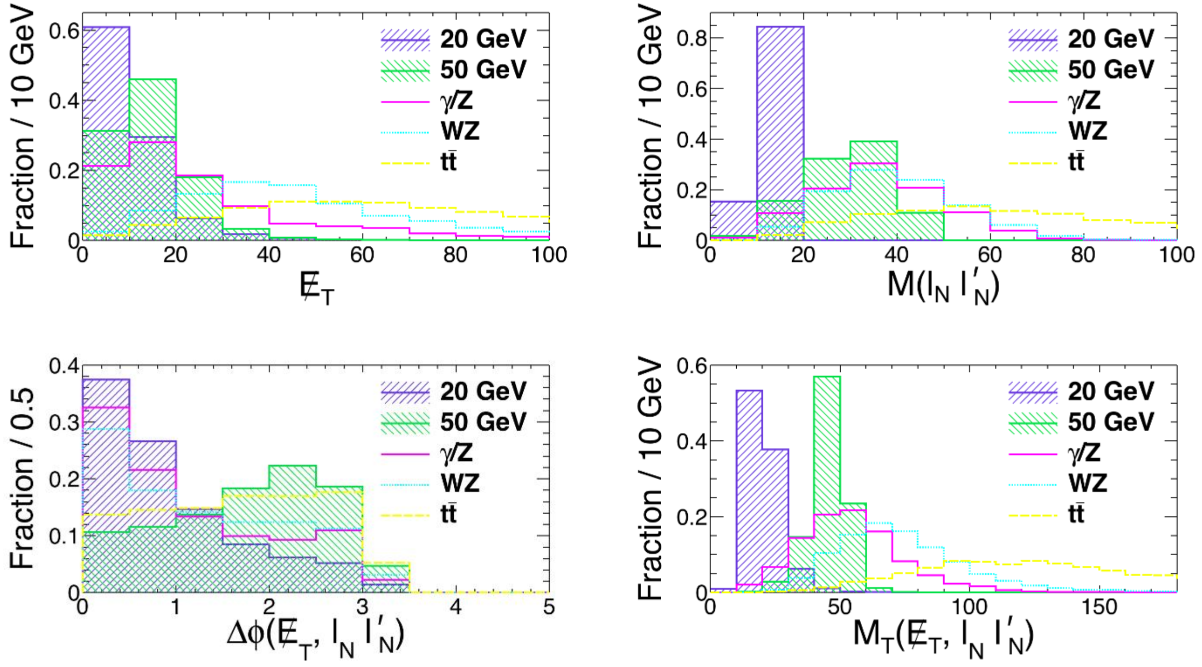




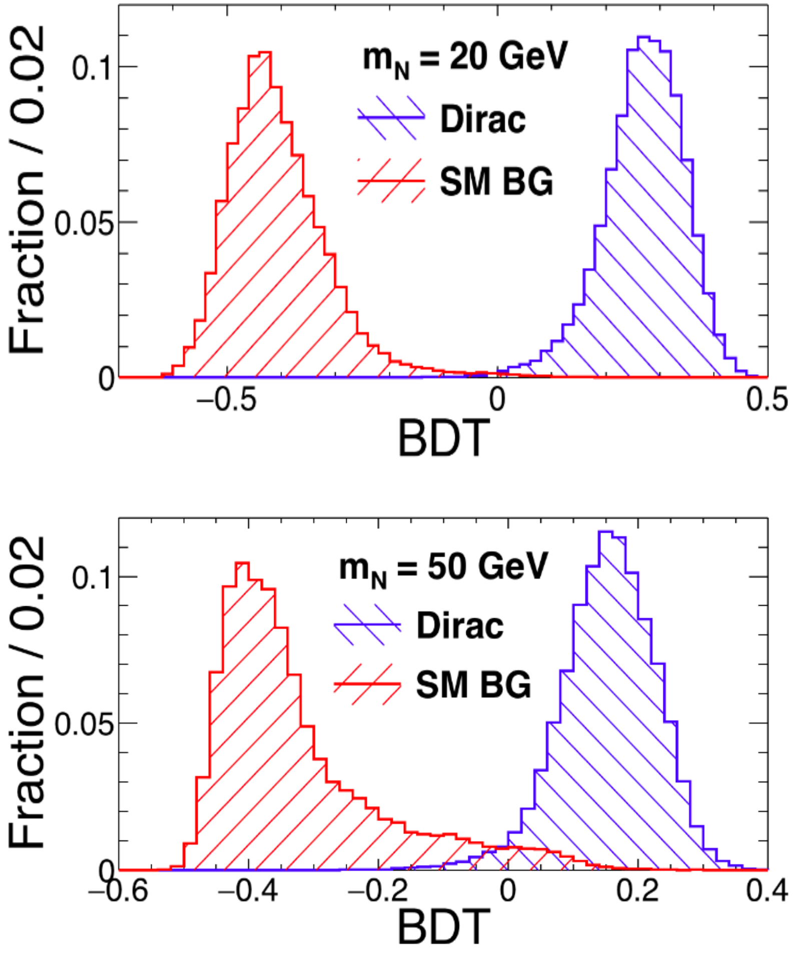
BDT Analysis

Input observables for BDT:
→ MET, H_T;
→ M(leps), Δφ(lep, lep);
→ M_T(met, lep(s)), Δφ(met, lep(s));

Some observables for Dirac Signal & Backgrounds

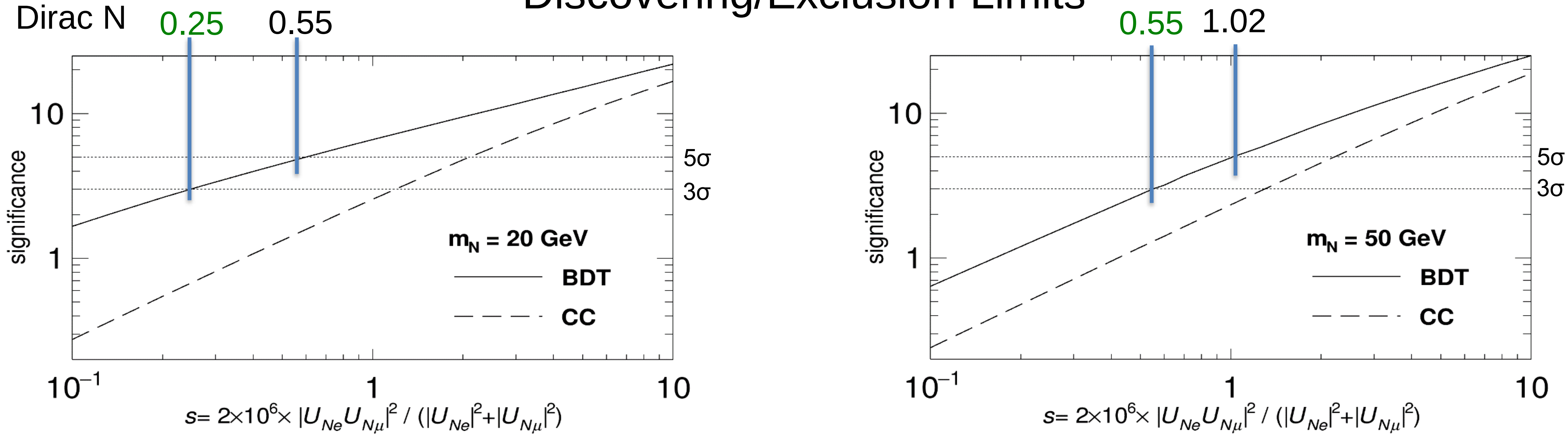


BDT from TMVA package



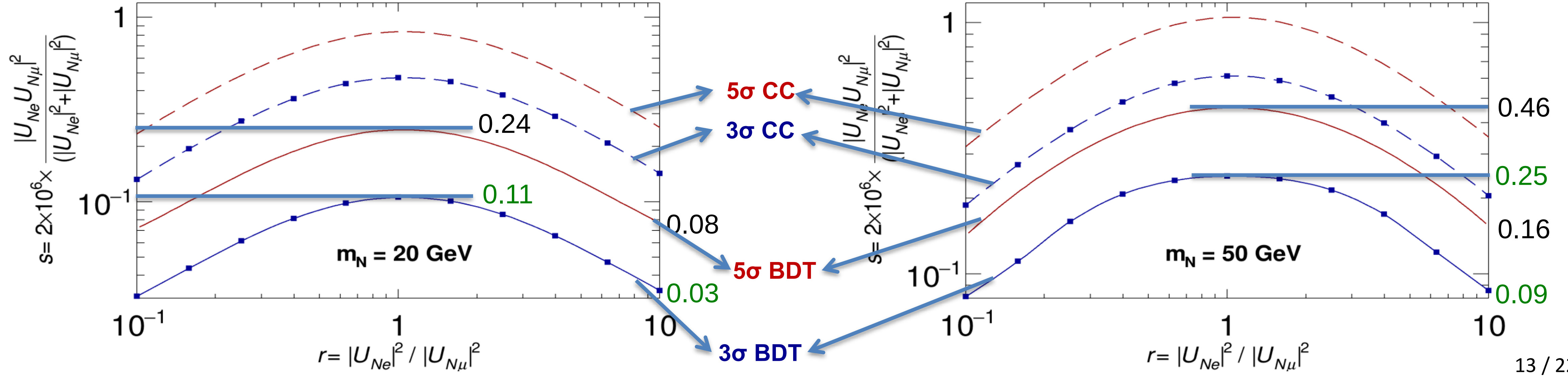
Discovering/Exclusion Limits

Dirac N



Majorana N

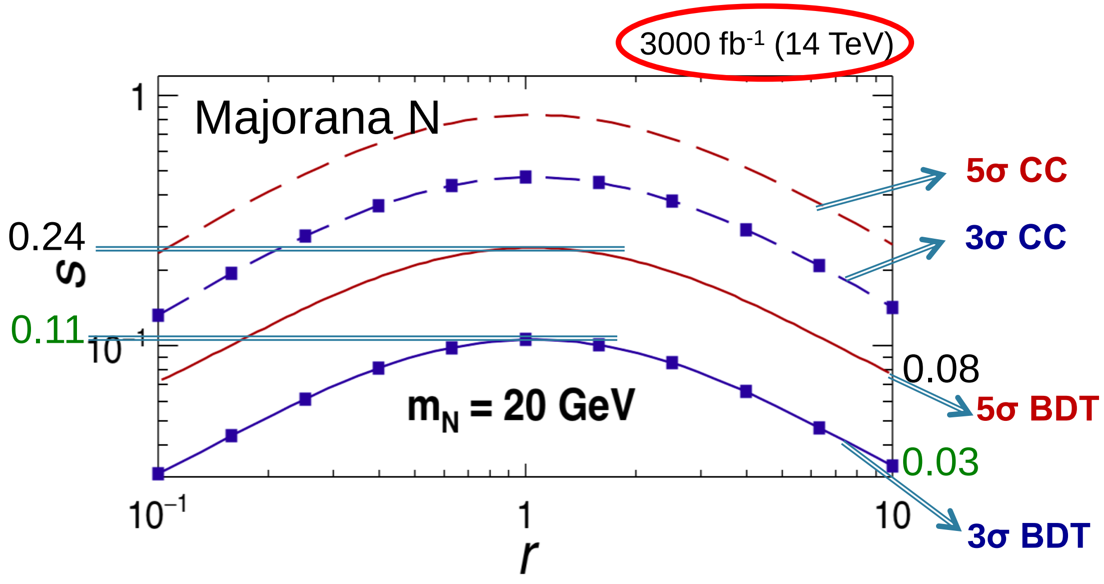
when r = 1, $|U_{Ne}|^2 = |U_{N\mu}|^2 = s \times 10^{-6}$



Sterile Neutrinos

Discovering/Excluding Majorana N

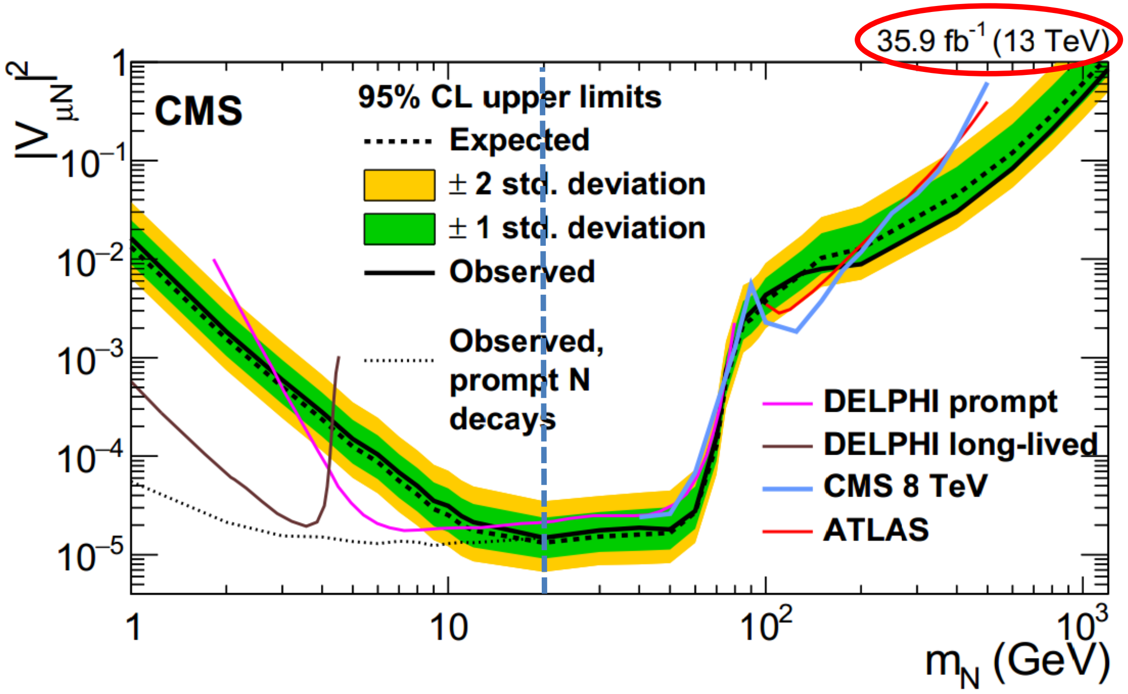
[**our study:** Phys.Rev. D95 (2017) no.11, 115020, cited by CMS collaboration]



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

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

[**LHC, CMS experiment:** Phys.Rev.Lett. 120 (2018) no.22, 221801]

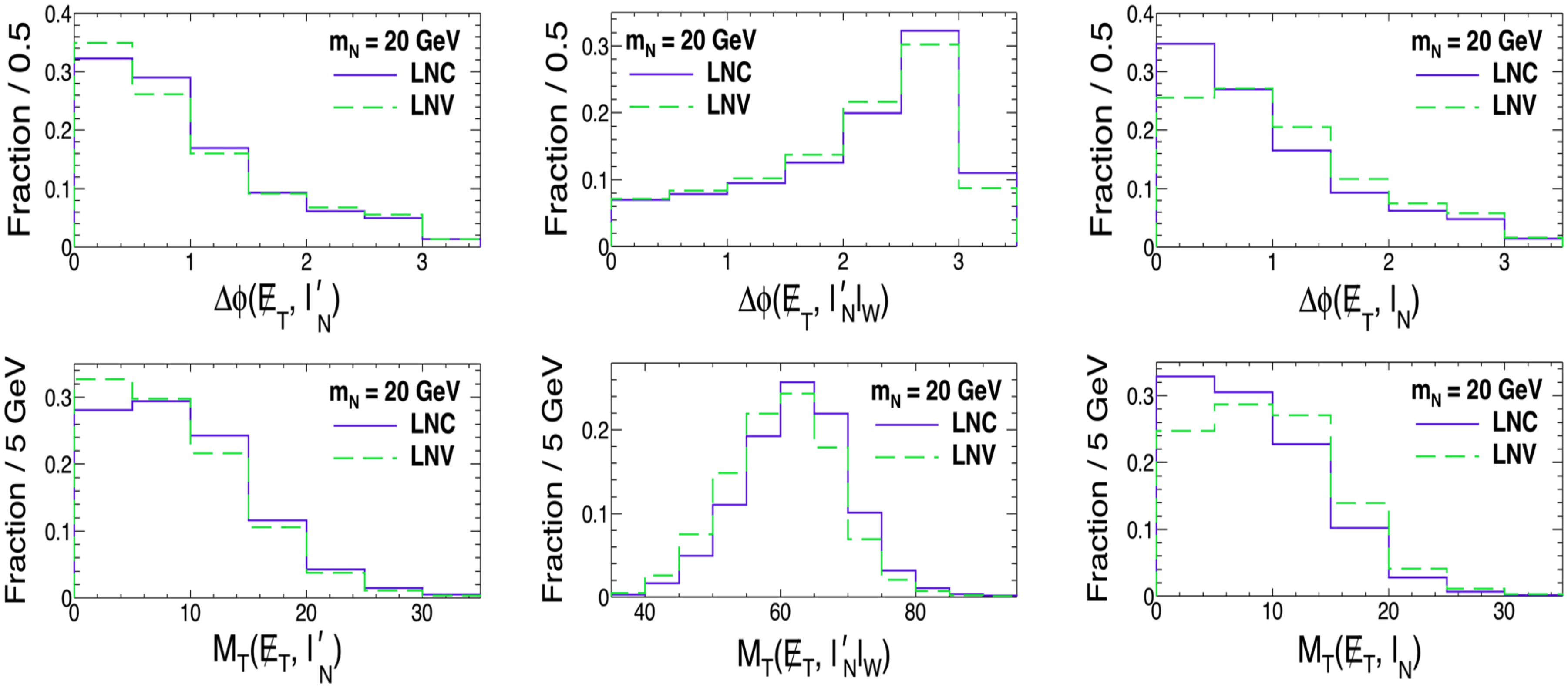


Distinguishing Dirac / Majorana

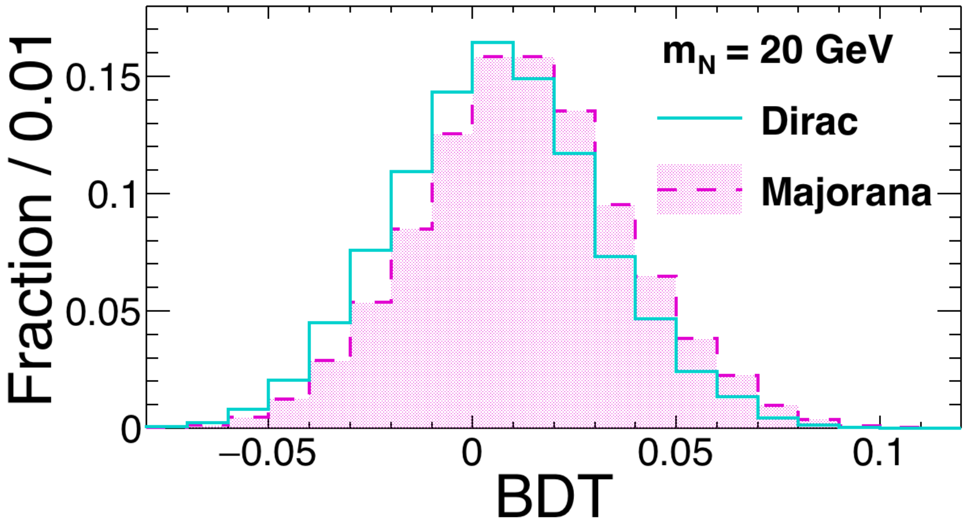
Basic Idea (1) 1st MVA -> reduce SM BG

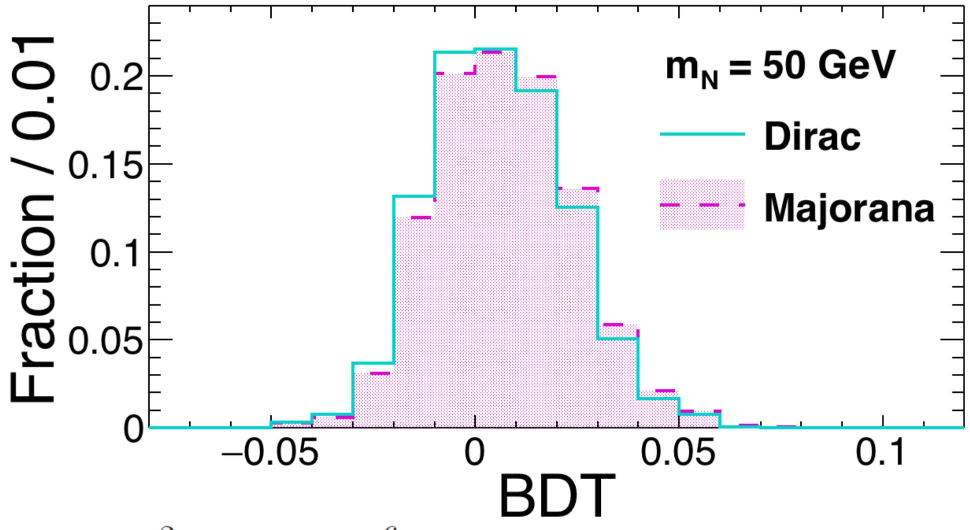
(2) 2nd MVA: exploiting kinematical distributions differing between LNC & LNV, M_T(met, lep(s)) & Δφ(met, lep(s))

Input observables:
$$(vii)\ M_T(\not{E}_T, l_N),\ M_T(\not{E}_T, l'_N),\ \text{and}\ M_T(\not{E}_T, l'_N l_W);$$
$$(viii)\ \Delta\phi(\not{E}_T, l_N),\ \Delta\phi(\not{E}_T, l'_N),\ \text{and}\ \Delta\phi(\not{E}_T, l'_N l_W).$$

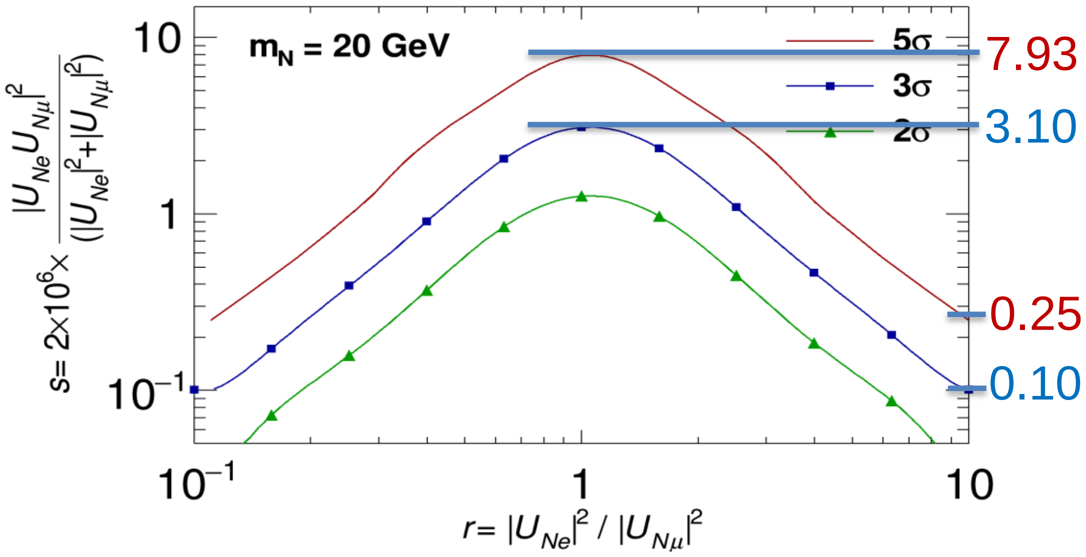


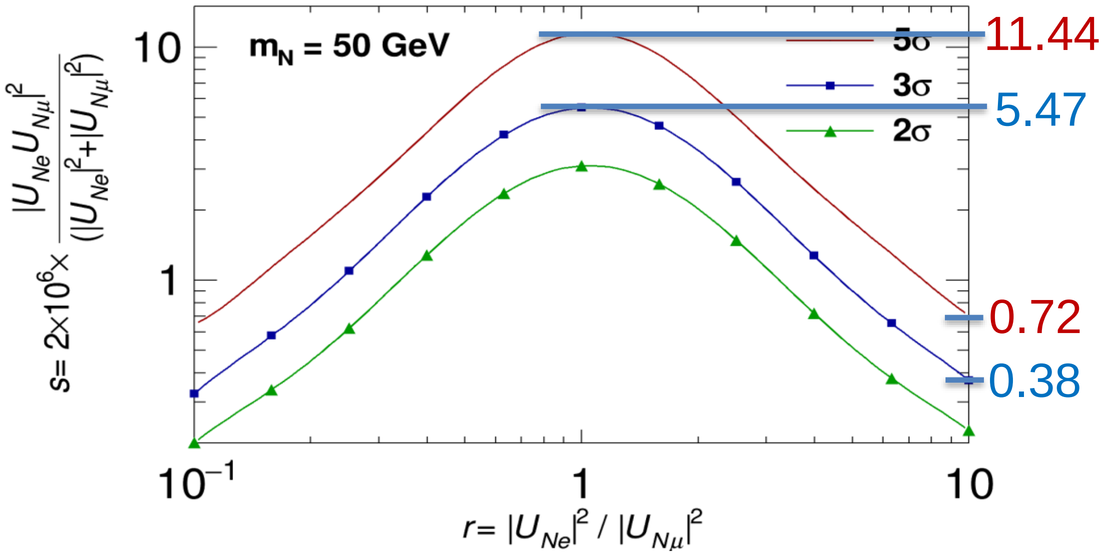
Distinguishing Limits





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





Signal in 2*l*+2*j* Final State

A symmetry protected seesaw model:

[S. Antusch, O. Fischer, JHEP 1505 (2015) 053]

→ Introducing one pair of sterile neutrinos N_R^1 & N_R^2
→ Possessing a "lepton-number like" (global) U(1) symmetry
→ N_R^1 (N_R^2) has the same (opposite) charge as the left-handed SU$_L$(2) doublets L_α, α = *e, μ, τ*

Lagrangian density in the symmetric limit

$$\mathscr{L} = \mathscr{L}_{\rm SM} - \overline{N_R^1} M_N N_R^{2\,c} - y_{\nu_\alpha} \overline{N_R^1} \widetilde{\phi}^\dagger L^\alpha + \text{H.c.} + \dots$$

After EWSB, $$\mathscr{L}_{\rm mass} = -\frac{1}{2} \begin{pmatrix} \overline{\nu^c_{e_L}} \\ \overline{\nu^c_{\mu_L}} \\ \overline{\nu^c_{\tau_L}} \\ \overline{N_R^1} \\ \overline{N_R^2} \end{pmatrix}^T \begin{pmatrix} 0 & 0 & 0 & m_e & 0 \\ 0 & 0 & 0 & m_\mu & 0 \\ 0 & 0 & 0 & m_\tau & 0 \\ m_e & m_\mu & m_\tau & 0 & M \\ 0 & 0 & 0 & M & 0 \end{pmatrix} \begin{pmatrix} \nu_{e_L} \\ \nu_{\mu_L} \\ \nu_{\tau_L} \\ (N_R^1)^c \\ (N_R^2)^c \end{pmatrix} + \text{H.c.}$$

Dirac masses $m_\alpha = y_{\nu_\alpha} v_{\rm EW}/\sqrt{2}$

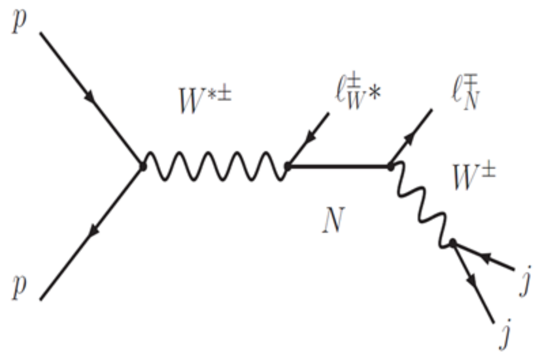
If exact symmetry,
→ Diagonalizing mass matrix $U^T \mathcal{M} U = \text{Diag}(0, 0, 0, M, M)$
→ SM neutrinos get zero masses
→ (complex) active-sterile mixing parameters $\theta_\alpha = \frac{y^*_{\nu_\alpha}}{\sqrt{2}} \frac{v_{\rm EW}}{M_N}$

If symmetry is slightly broken,
→ SM neutrinos achieve small masses
→ small mass "protected" by the symmetry -- technically natural

=> Mixing parameters & m_N can be free parameters in such models.

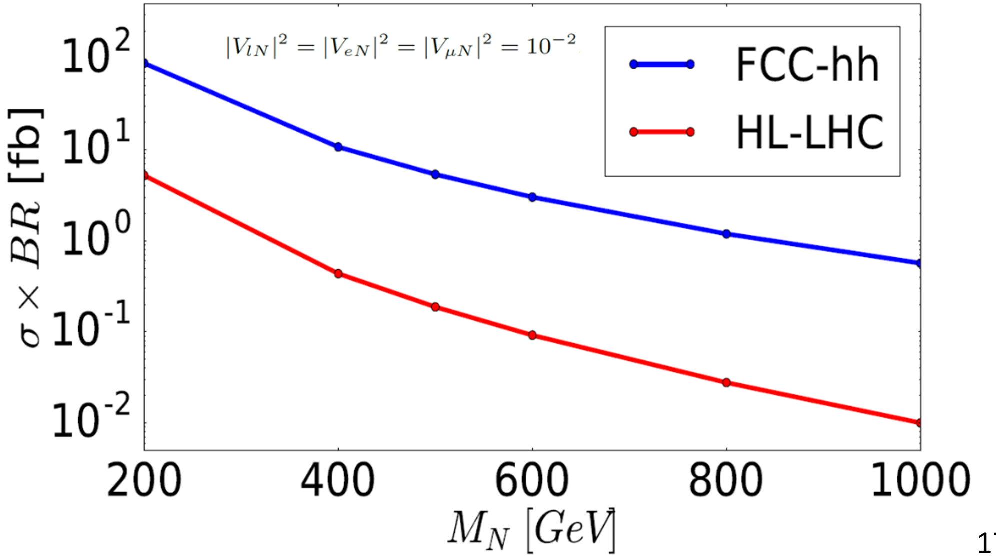
Signal: 2*l* (OSOF $e^\pm\mu^\mp$) + 2*j*

→ when m_N > 200 GeV
→ Dirac N



Production cross section times branching ratio

$\sigma(pp \to l^\pm N) \times \text{BR}(N \to l^\mp jj)$ includes ($e^\pm\mu^\mp$, e^+e^-, $\mu^+\mu^-$)



Search Strategy

Signal: 2l (OSOF $e^{\pm}\mu^{\mp}$) + 2j

SM Background:

2l + ≥ 2 j final state
→ with additional light neutrinos,
→ di-tau with both tau's decaying leptonically

1. di-top in fully leptonical decays:

   1.1. $pp \to t\bar{t} \to (bW^+)(\bar{b}W^-) \to (b\,l^+\nu)(\bar{b}\,l^-\bar{\nu})$, where both l can be either e or μ ;

2. di-boson with di-tau di-jet final states:

   2.1. $pp \to WZ \to (jj)(\tau^+\tau^-)$;

   2.2. $pp \to ZZ \to (jj)(\tau^+\tau^-)$;

3. tri-boson with at least 2 jets and at least 2 leptons (including taus):

   3.1. $pp \to WWZ \to (l\nu)(l\nu)(jj)$;

   3.2. $pp \to WWZ \to (jj)(jj)(\tau^+\tau^-)$;

   3.3. $pp \to WWZ \to (jj)(l\nu)(\tau^+\tau^-)$;

   3.4. $pp \to WWZ \to (jj)(l\nu)(l^+l^-)$.

3 leptons, contribute if one lepton is undetected

Simulation

MadGraph5 + Pythia6 + Delphes

Pre-selection cuts

1. exactly 1 muon, 1 electron with opposite charges $e^{\pm}\mu^{\mp}$; ≥ 2 j ; 0 b-jet; 0 taus;

2. $p_T(j) > 30$ GeV, $p_T(l) > 30$ GeV;

3. $\not{E}_T < 20$ GeV

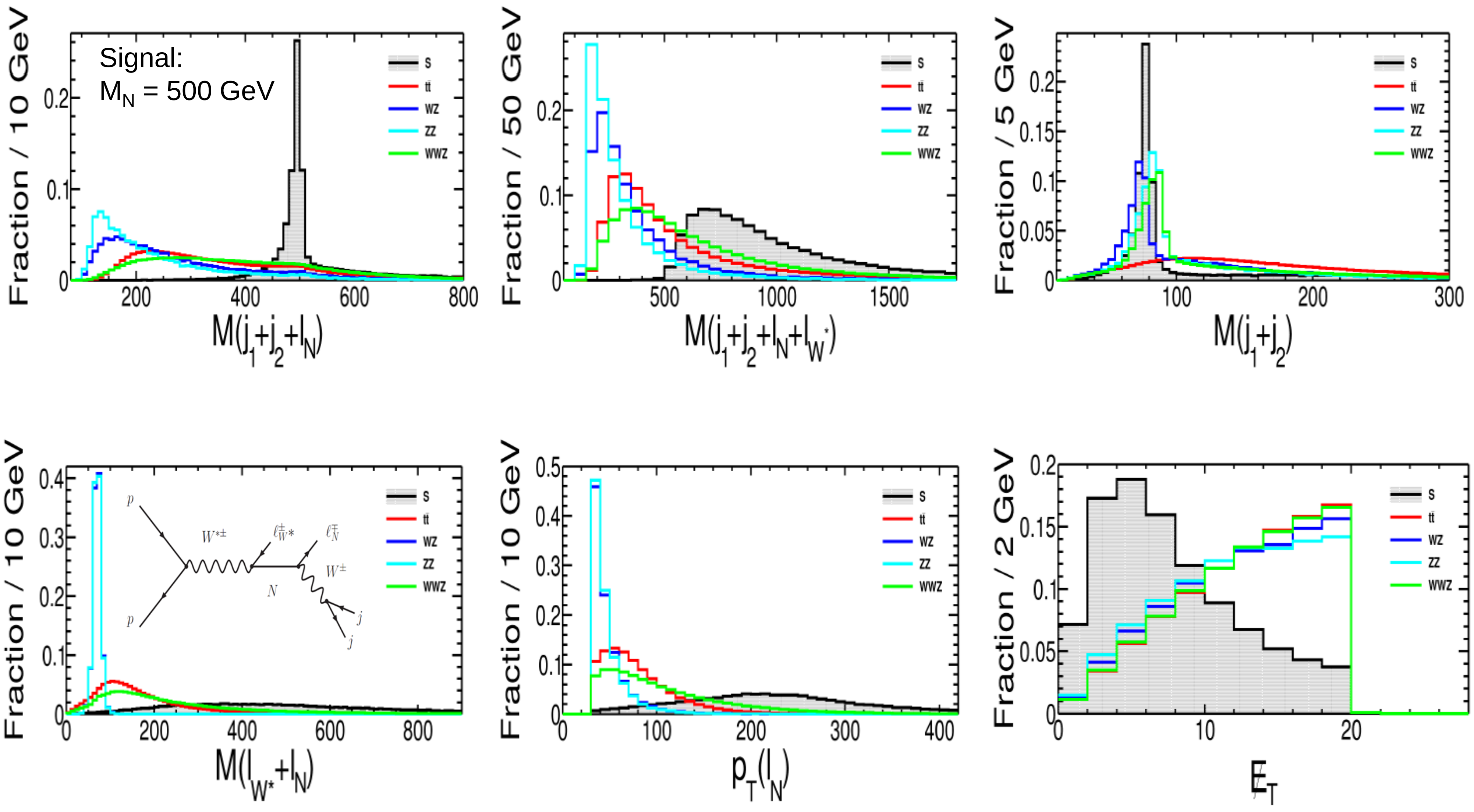
Strategy

→ Identifying correct lepton from N decay

→ Constructing various observables

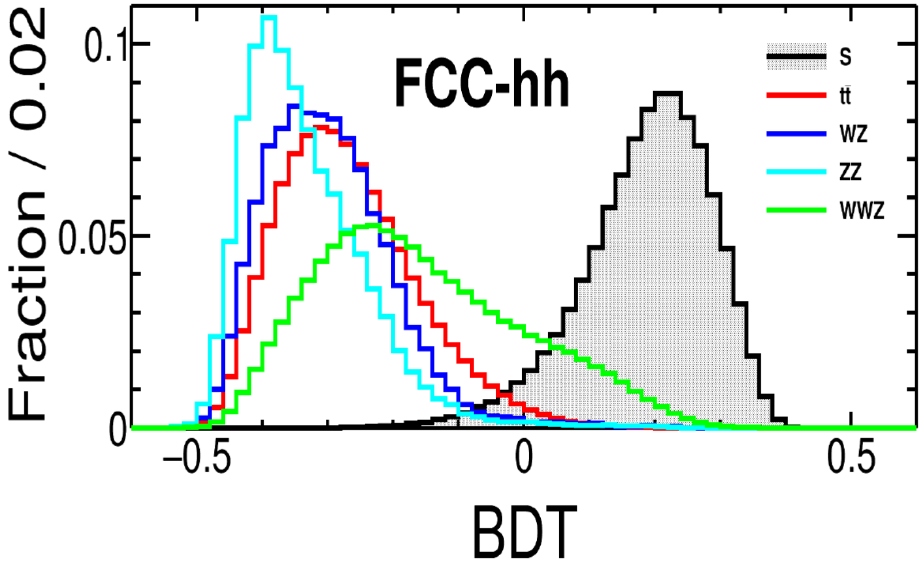
→ Input observables to perform MVA-BDT analysis

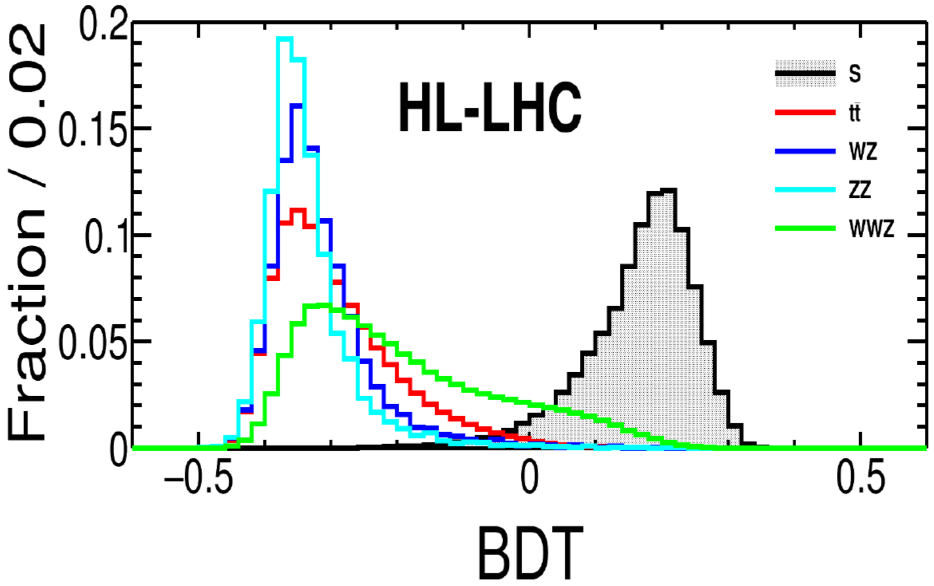
Input Observables at FCC-hh



BDT Analysis

Signal: M_N = 500 GeV



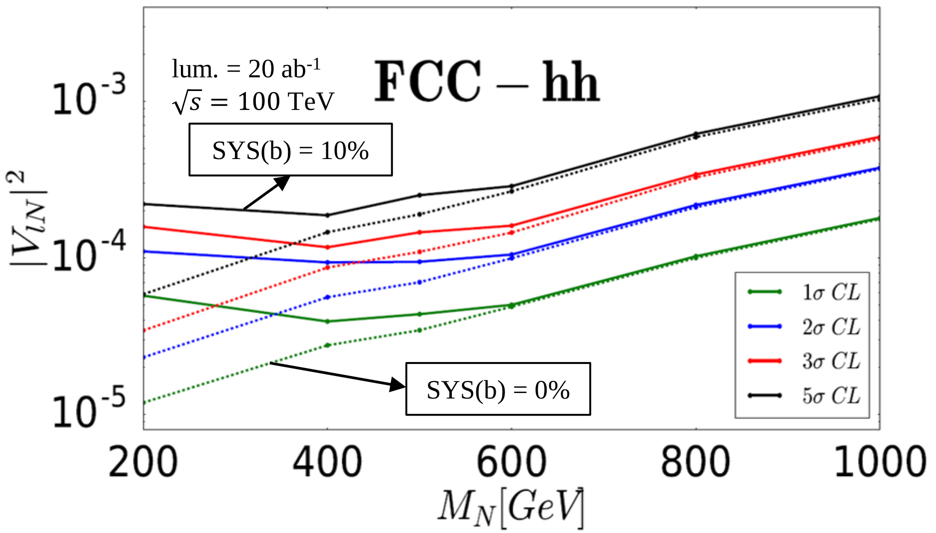


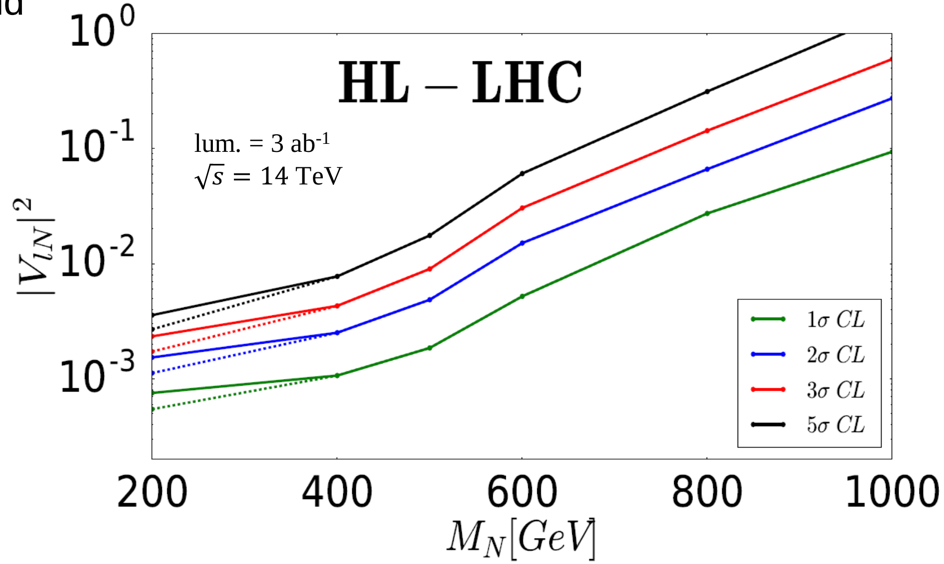
Cut flow table at FCC-hh, 20 ab^{-1} # of events for signal with $|V_{lN}|^2 = 10^{-2}$ & background

Cuts		M_N [GeV] 200	400	500	600	800	1000	Background $t\bar{t}$	WZ	ZZ	WWZ
initial		1.78×10^6	2.14×10^5	1.07×10^5	6.03×10^4	2.38×10^4	1.13×10^4	2.75×10^9	1.13×10^8	8.97×10^7	1.91×10^6
pre-sel.	cut 1	3.84×10^5	5.98×10^4	3.03×10^4	1.70×10^4	6347	2856	6.08×10^7	1.96×10^6	1.46×10^6	5.45×10^4
	cut 2	3.39×10^5	5.76×10^4	2.95×10^4	1.66×10^4	6257	2824	3.61×10^7	6.20×10^4	4.24×10^4	1.96×10^4
	cut 3	2.90×10^5	4.36×10^4	2.10×10^4	1.12×10^4	3722	1484	9.08×10^6	7090	5497	6657
BDT	> 0.2935	6611	-	-	-	-	-	238.4	0.6	0.5	15.9
	> 0.2827	-	5762	-	-	-	-	81.5	0.9	0.7	20.3
	> 0.2654	-	-	4666	-	-	-	53.8	0.3	0.5	16.4
	> 0.2611	-	-	-	2701	-	-	33.9	-	-	8.9
	> 0.2428	-	-	-	-	1261	-	27.1	0.3	-	6.7
	> 0.2262	-	-	-	-	-	693	27.6	0.3	-	6.7

limits on $|V_{lN}|^2$

Expected median limits with/without sys. unc. on background



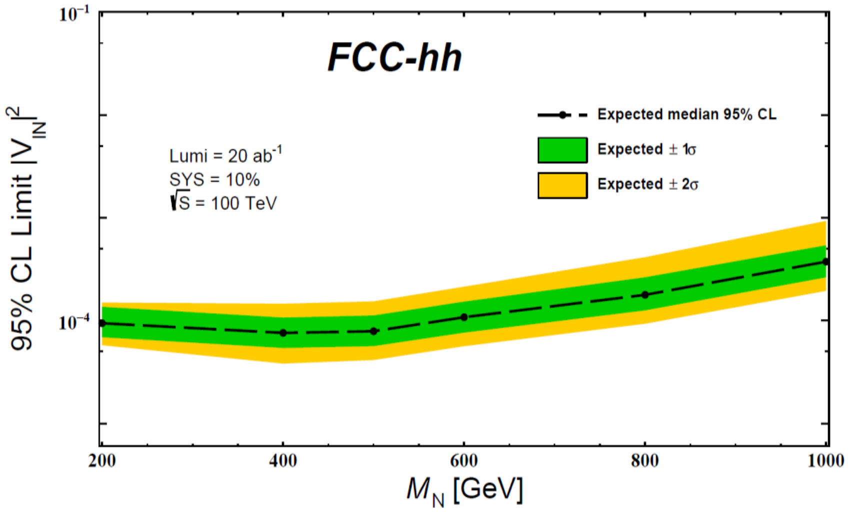


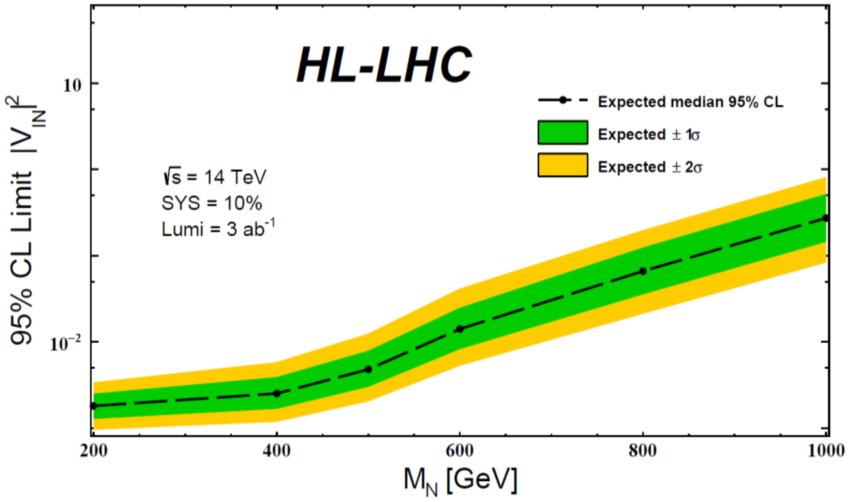
2 (5)-σ **limits on** $|V_{lN}|^2$
M_N = 500 GeV
0% sys. unc. on B.

→ FCC-hh, 20 ab^{-1}
7.0×10^{-5} (1.9×10^{-4})

→ HL-LHC, 3 ab^{-1}
4.9×10^{-3} (1.7×10^{-2})

Expected limits with stat. unc. & 10% sys. unc. on background





Summary

★ MVA-BDT searches for Sterile neutrinos & charged Higgs at colliders

★ Sterile neutrinos from 3*l*+MET @ *pp*

→ $e^{\pm}e^{\pm}\mu^{\mp}/\mu^{\pm}\mu^{\pm}e^{\mp}$ + MET

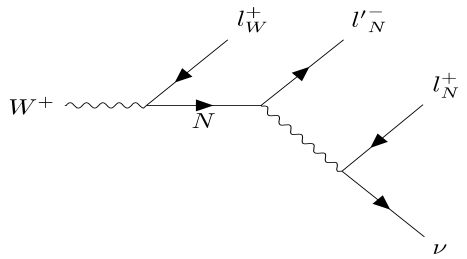
→ m_N = 20, 50 GeV @ 14 TeV LHC, 3 ab^{-1};

→ 3 (5)-σ limits on $|V_{lN}|^2$ for for m_N = 20 GeV with $|V_{lN}|^2 = |V_{eN}|^2 = \left|V_{\mu N}\right|^2$

2.5 (5.5)$\times 10^{-7}$ for Dirac N;

1.1 (2.4)$\times 10^{-7}$ for Majorana N;

3.1 (7.9)$\times 10^{-6}$ for distinguishing Dirac vs. Majorana



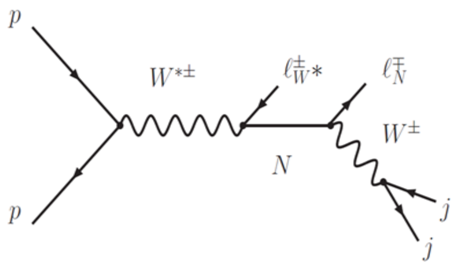
★ Sterile neutrinos from 2*l* + 2*j* @ *pp*

→ OSOF $e^{\pm}\mu^{\mp}$ + 2*j* for Dirac N

→ 2 (5)-σ limits on $|V_{lN}|^2$ for m_N = 500 GeV with $|V_{lN}|^2 = |V_{eN}|^2 = \left|V_{\mu N}\right|^2$

7.0×10^{-5} (1.9×10^{-4}) @ FCC-hh, 20 ab^{-1}

4.9×10^{-3} (1.7×10^{-2}) @ HL-LHC, 3 ab^{-1}



Thanks for your attention!

Backup Slides

Mass Scales of m_N

m_N

GUT

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

→ Hard to test experimentally !

TeV

- Inverse & Loop-induced SS
- Leptogenesis

→ Testable at the LHC !

GeV – **KeV**

- νMSM (Neutrino Minimal SM)
- EW precisions, $0\nu\beta\beta$, Leptogen.

→ Fine-tuned model but testable !

KeV

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

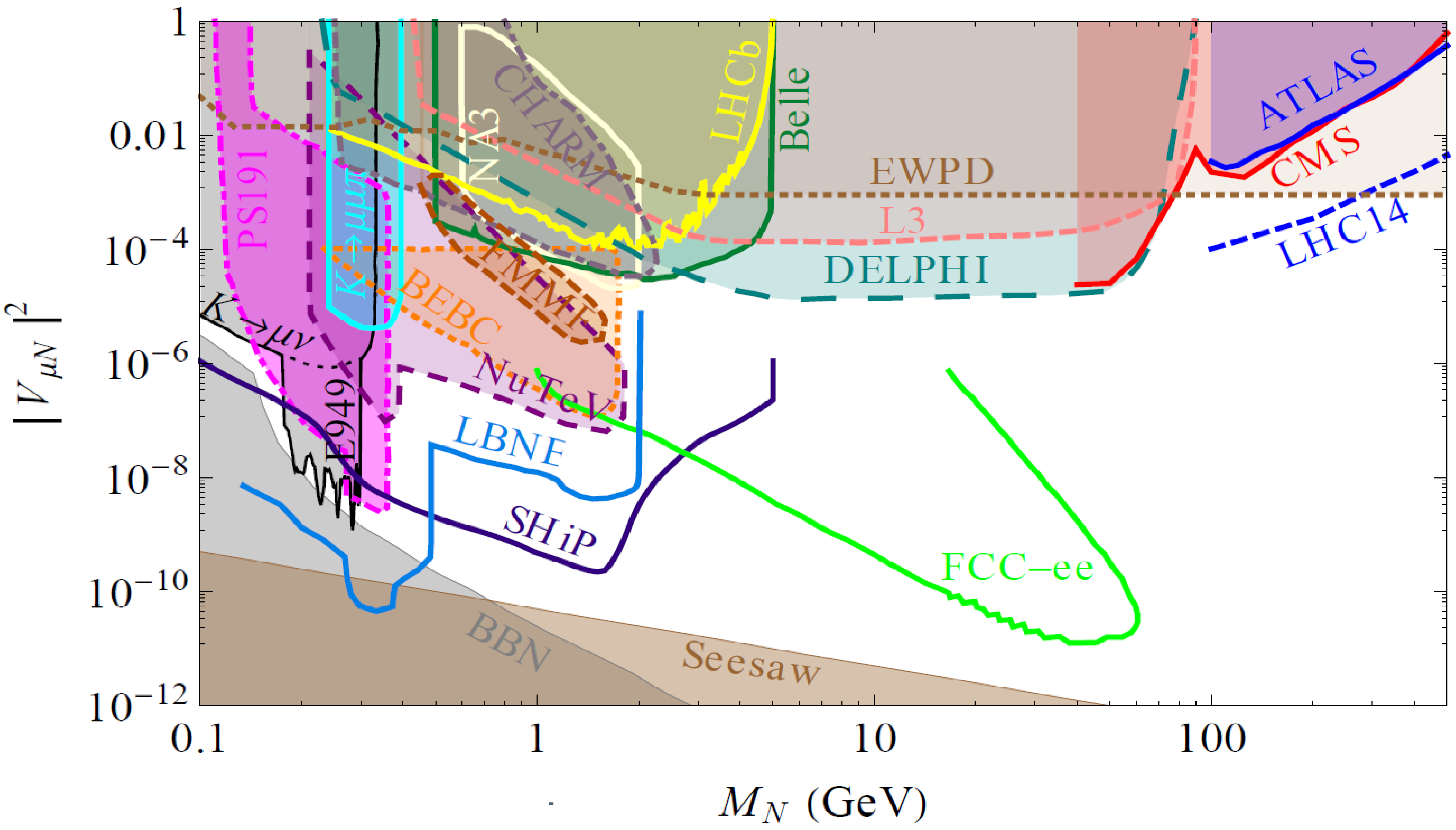
eV

- neutrino oscillation & reactor/gallium anomaly
- dark radiation
- explain $N_{eff} > 3$

Global Constraints

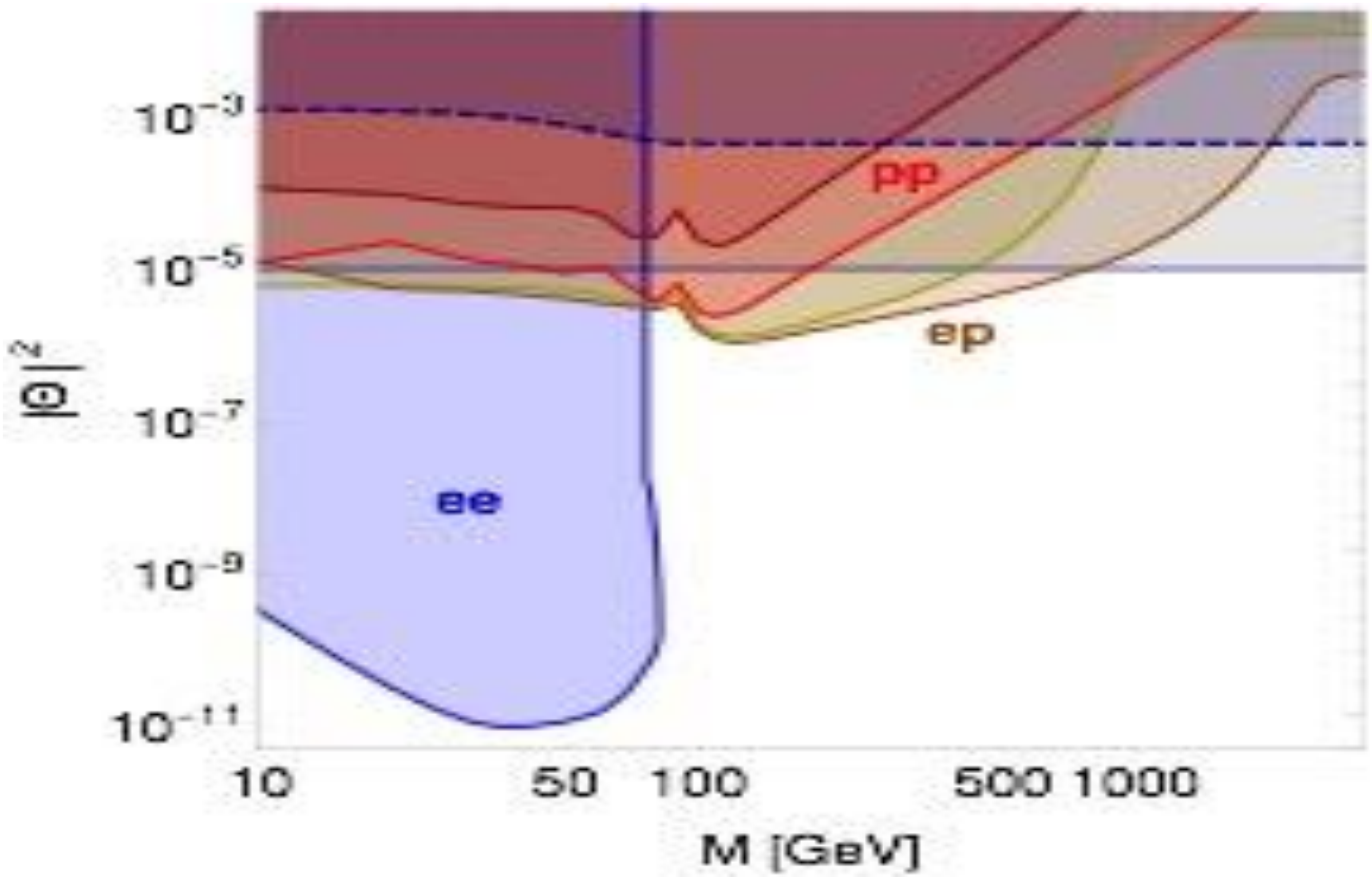
from [Deppisch, Dev and Pilaftsis, New J. Phys. 17 (2015) 085019]

m_N: 0.1 ~ 500 GeV

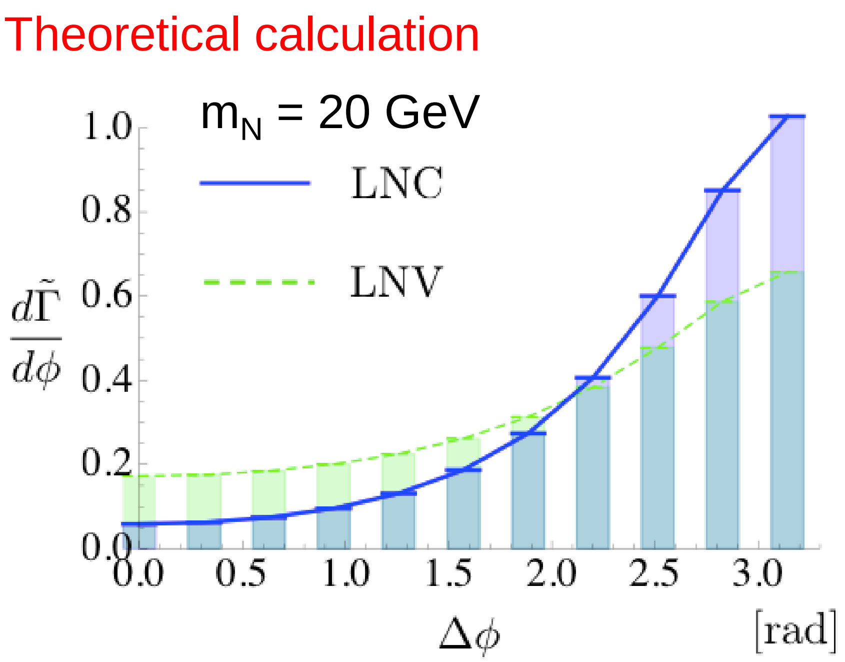


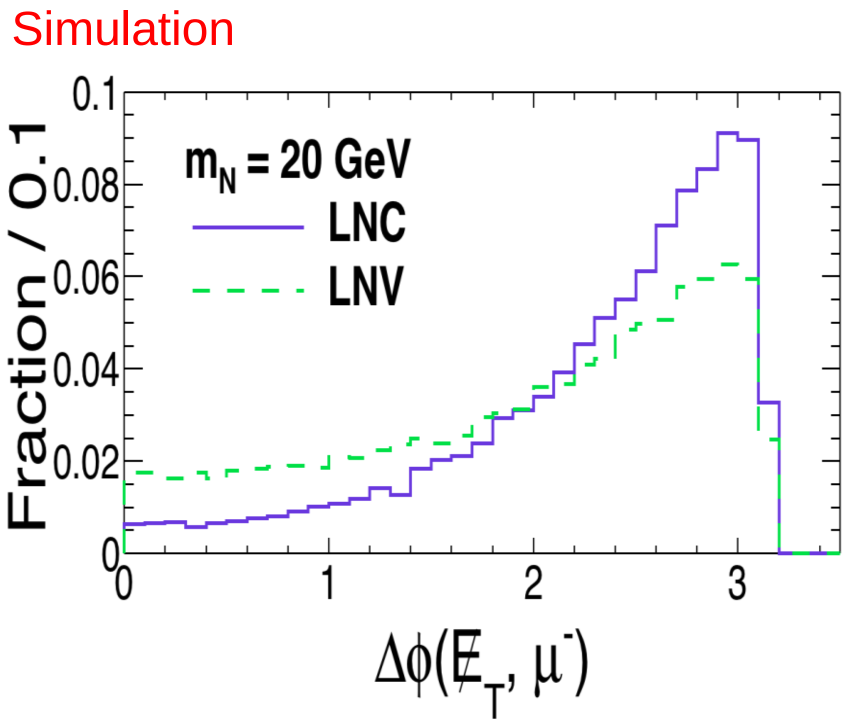
Limits at Different Colliders

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



Calculation vs. Simulation





distributions in the N rest frame from the $W^+ \to e^+ e^+ \mu^- \nu$ process

→ Distributions are verified by theoretical calculation
to make sure it is not just fluctuations.

Cut flow table at HL-LHC

\# of events for signal with $|V_{lN}|^2 = 10^{-2}$ & background, with lum. = 3 ab^{-1}

Cuts		M_N [GeV]						Background			
		200	400	500	600	800	1000	$t\bar{t}$	WZ	ZZ	WWZ
initial		1.56×10^4	1307	563	275	83.2	30.7	1.03×10^7	5.36×10^6	1.40×10^6	2.05×10^4
pre-sel.	cut 1	2545	260	109	50.6	14.1	5.0	3.26×10^5	2.63×10^4	6008	343
	cut 2	1830	229	97.7	45.2	12.4	4.4	1.83×10^5	1462	337	164
	cut 3	1376	130	46.9	18.5	3.7	0.99	5.44×10^4	265	64	58
BDT	> 0.2013	111	-	-	-	-	-	19.1	0.10	0.027	0.56
	> 0.2162	-	37.8	-	-	-	-	2.3	-	0.027	0.41
	> 0.2148	-	-	13.9	-	-	-	0.63	-	0.014	0.16
	> 0.2263	-	-	-	3.6	-	-	0.13	-	0.014	0.046
	> 0.2264	-	-	-	-	0.63	-	0.0068	-	-	0.013
	> 0.2348	-	-	-	-	-	0.15	0.00012	-	-	0.0041