Lepton Flavor Violation beyond the Z pole

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wip with Alessio Maiezza (IFIC Valencia), Fabrizio Nesti (IRB, Zagreb)

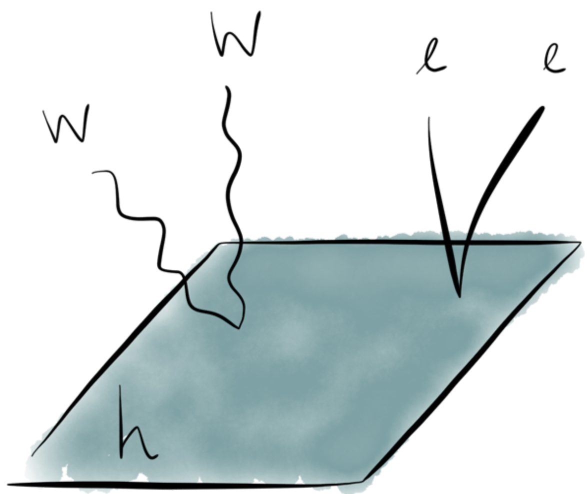
9th FCC-ee (TLEP) Physics Workshop (TLEP9)
Pisa, 3-5 February 2015

Higgs boson found and
remains to be studied

Mystery of neutrino
mass origin unsolved

LHC and FCCs
indispensable hep tools

Origin of Mass



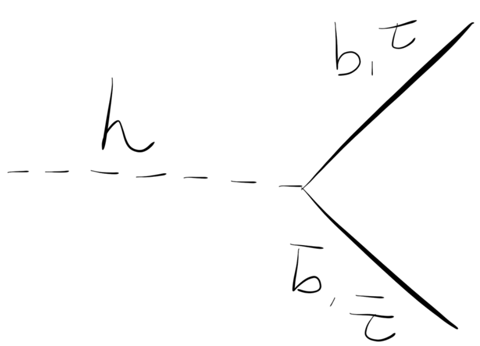
Charged fermions = Dirac mass

$$\mathcal{L}_{m_D} = y_f \, \overline{f}_L \, h \, f_R$$

Weinberg '67

$$\boxed{m_\nu = 0}$$

Being tested at LHC



$$\Gamma(h \to f f) \propto y_f^2 \qquad \tau \begin{cases} > 3\,\sigma \\ 4.5\,\sigma \end{cases}$$

CMS '14

ATLAS '15

Neutral fermions

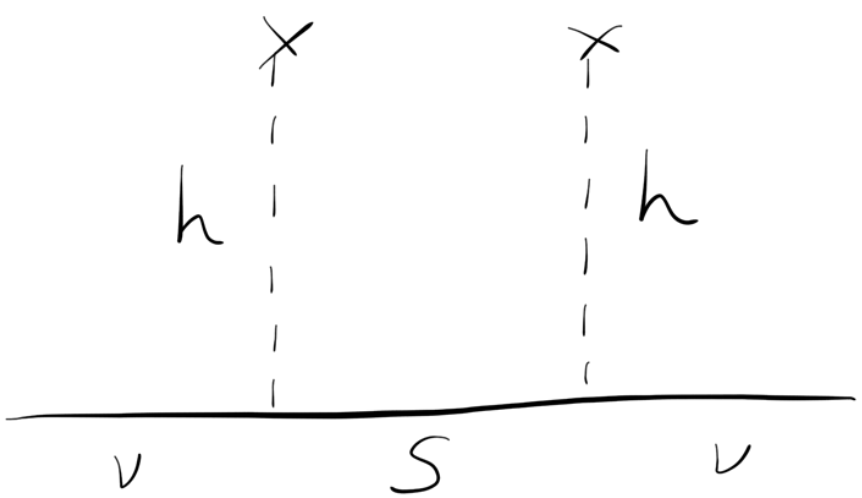
$$\mathcal{L}_{m_M} = m_{\nu_M} \, \overline{\nu}_L^T \, C \, \nu_L$$

Majorana '37

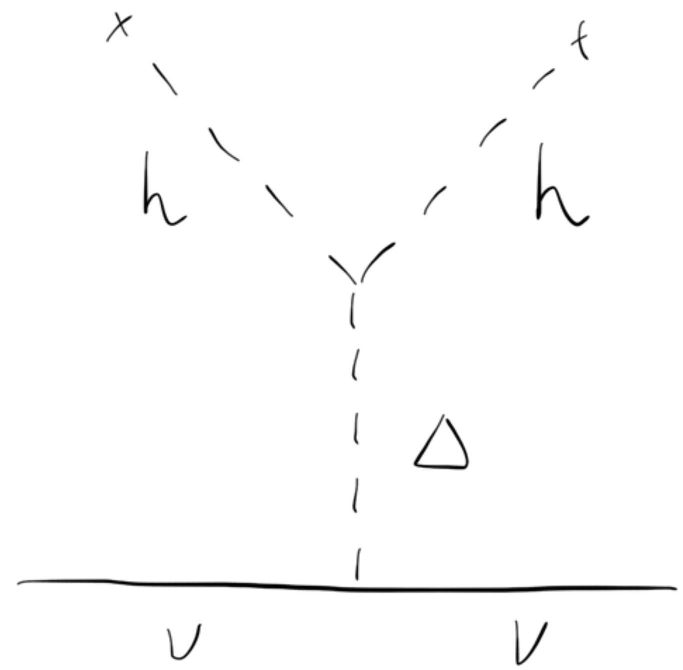
See-saw

a simple single particle UV completion

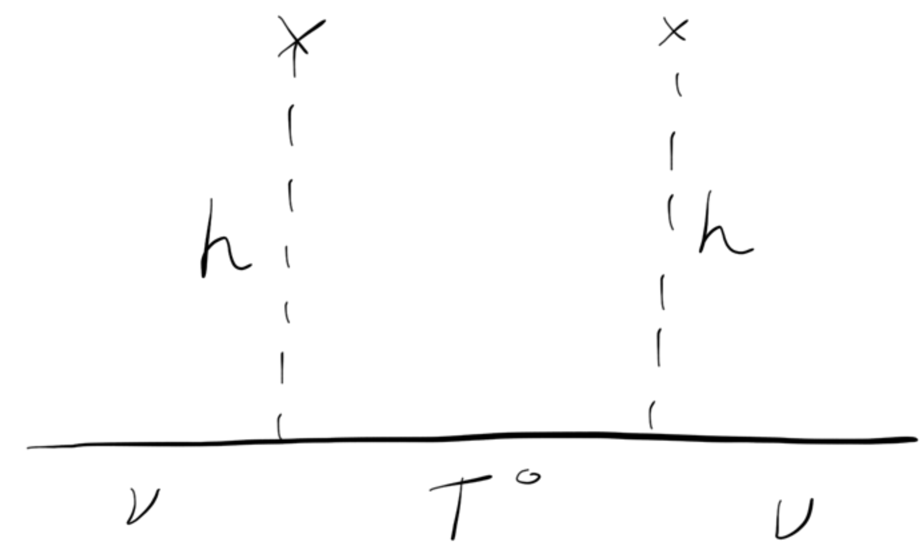
type I



type II



type III



Left-Right

Minkowski ’77
Mohapatra, Senjanović ’80
Yanagida ’79, Glashow ’79
Gell-Mann, Ramond, Slansky ’79

Magg, Wetterich ’80
Lazarides, Shafi, Wetterich ’81
Mohapatra, Senjanović ’81

Foot, Lew, He, Joshi ’89

Flavor of see-saw

or testing neutrino mass origin at colliders

$$M_\nu = V_L m_\nu V_L^T$$

V_L non-trivial, LFV decays naturally expected

~Higgs: produce the mediator (scattering or decays), observe its decays and connect to M_ν

type I and III

$$\mathcal{L}_S = M_D \, \overline{\nu}_L \, h \, S + m_S \, \overline{S}^T \, C \, S + \text{ h.c.}$$

all flavor in M_D

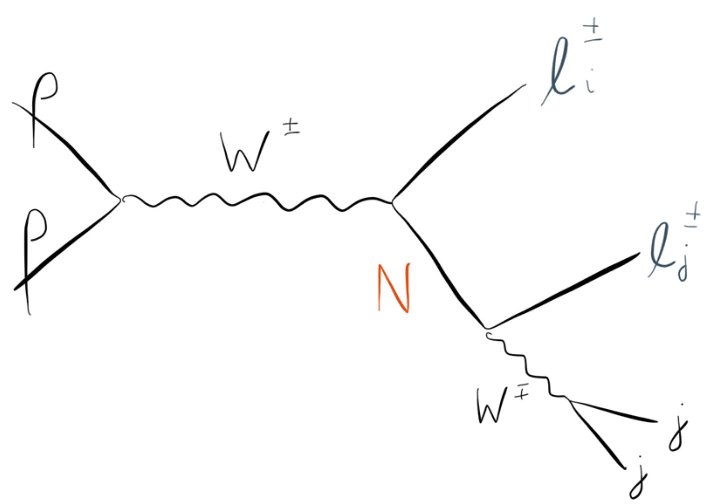
$$M_\nu = -{M_D}^T {m_S}^{-1} M_D = -({m_S}^{-1/2} M_D)^T \underbrace{({m_S}^{-1/2} M_D)}_{O \times S}$$

symmetric part fixed $\quad S = i\sqrt{M_\nu}$

orthogonal part O arbitrary $\quad M_D = i\sqrt{m_S}\, O \, \sqrt{M_\nu}$ $\quad$ and ambiguous

Heavy Neutrino at LHC

Keung, Senjanović '83



probes directly M_D

possibly large couplings

Kersten, Smirnov '07

$0\nu2\beta$

Atre, Han, Pascoli, Zhang '09
Mitra, Senjanović, Vissani '11

backgrounds

$$t\bar{t}, VV, Z^*, \gamma^* + j, \text{mis-id jets}$$

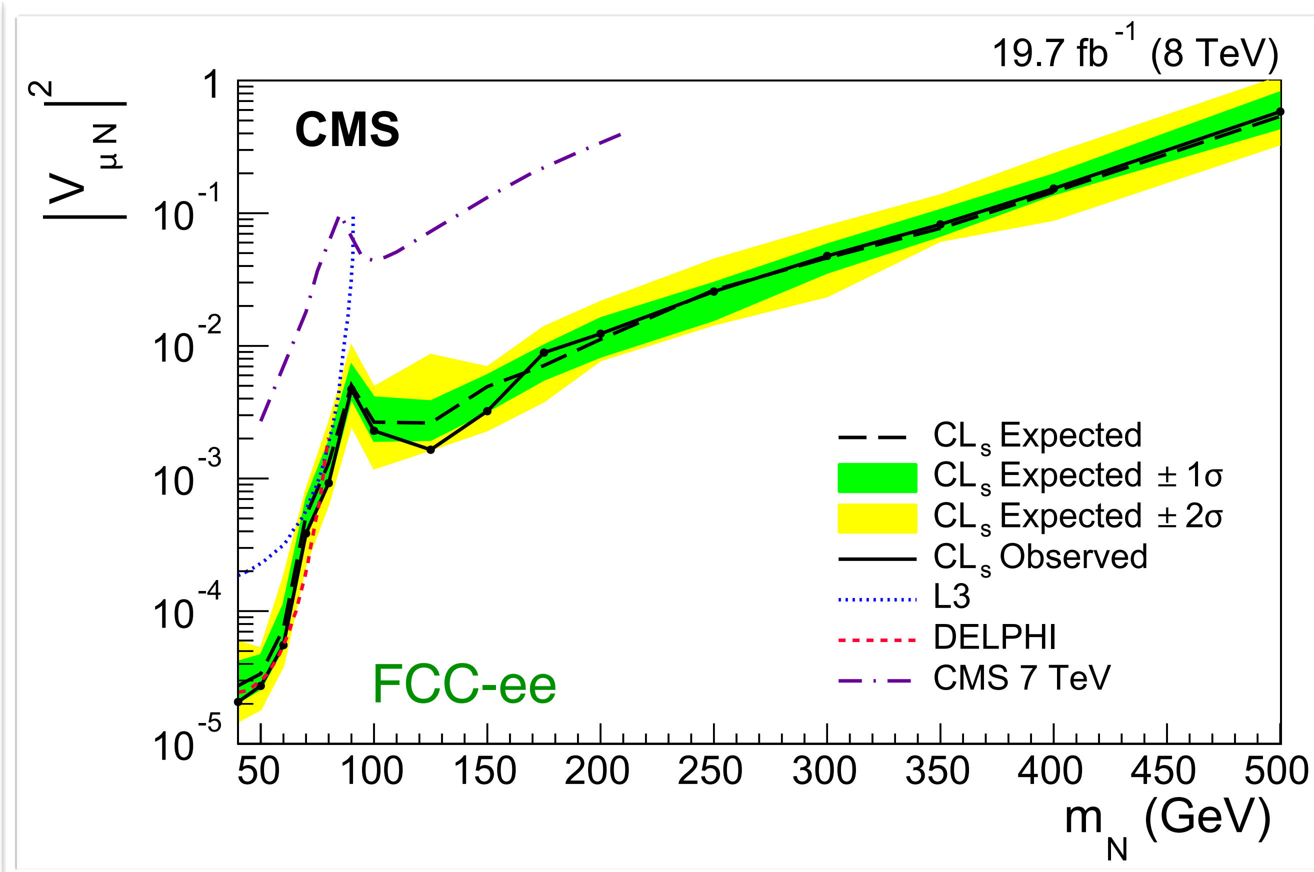
LHC reach

$$\sqrt{s} = 14 \text{ TeV and } \mathcal{O}(100) \text{ fb}^{-1}$$

$$m_N \lesssim \mathcal{O}(100) \text{ GeV}$$

del Aguila, Aguilar-Saavedra, Pittau '07, '08

CMS 1501.05566



Left-Right

$$SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$$

Pati, Salam '74
Mohapatra, Pati '75

parity restoration, heavy RH neutrino *N* necessary — Senjanović, Mohapatra '75

theory originally led to seesaw $M_\nu = -M_D {M_N}^{-1} M_D$ — Minkowski '77, Mohapatra, Senjanović '80

$\mathcal{C}$ parity requires $M_D = {M_D}^T$

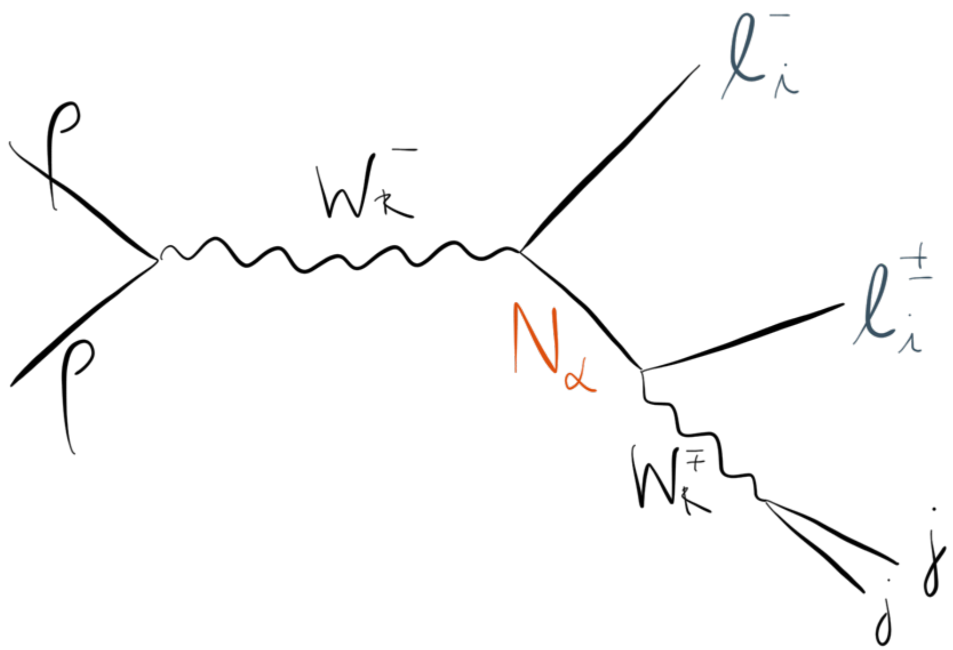
removes ambiguity and predicts $M_D = i M_N \sqrt{{M_N}^{-1} M_\nu}$ — MN, Tello, Senjanović '12

Flavor basis well defined in Left-Right

$$\mathcal{L}_W = \frac{g}{\sqrt{2}} \bar{e}_R \not{W}^-_R V_R N \qquad M_N = V_R^T m_N V_R$$

Left-Right

Heavy Neutrino at LHC



$$m_{\ell jj}^{\text{inv}} = m_N$$

Keung, Senjanović '83

LNV and LFV at LHC

flavor tag measures V_R 6 channels / *N*

$$M_N = V_R^T m_N V_R$$

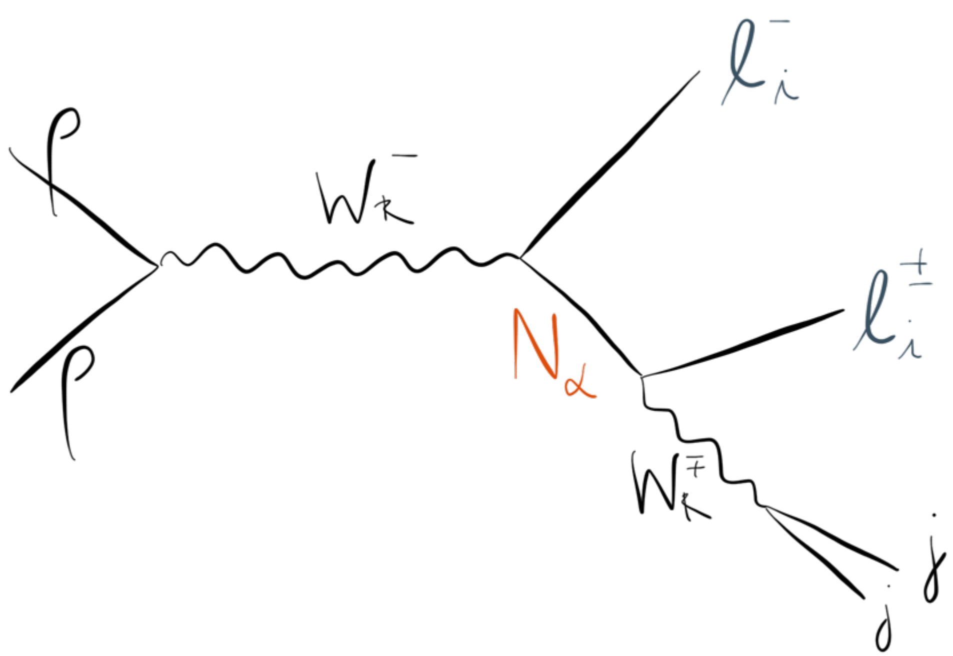
$\not{E} = 0$ at parton level
high total invariant mass

$=$ low background

reach for W_R is 5-6 TeV

ATLAS: Ferrari et al. '00
CMS: Gninenko et al. '07

Heavy Neutrino at LHC



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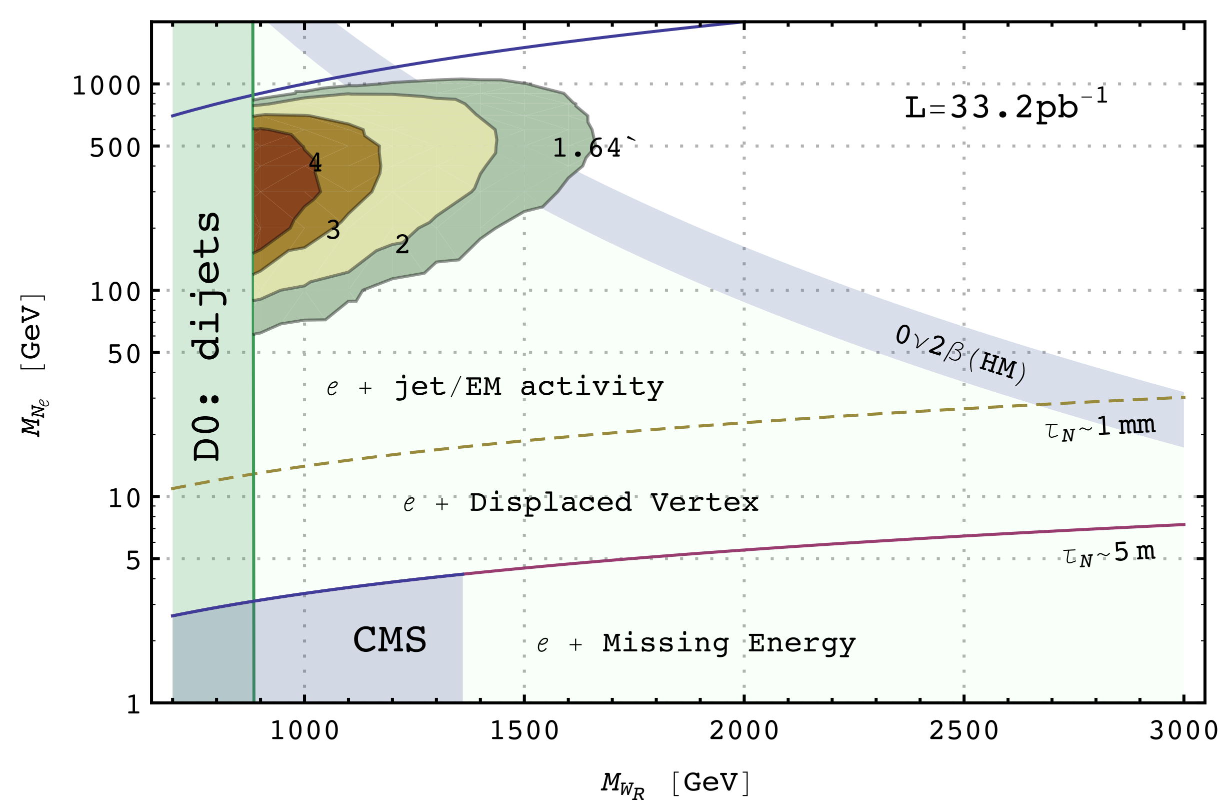
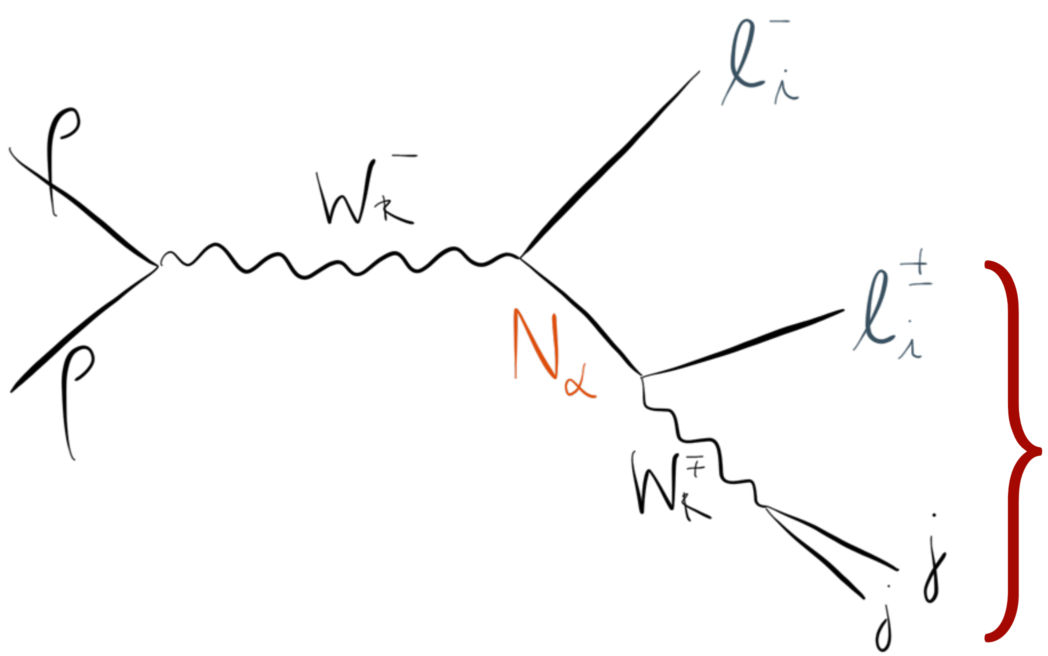


MN, Nesti, Senjanović, Zhang '11

Left-Right

Heavy Neutrino at LHC



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Keung, Senjanović '83

LNV and LFV at LHC

$0\nu 2\beta$ & LFV connection

Tello, MN, Nesti, Senjanović, Vissani '10
Cirigliano, Kurylov, Ramsey-Musolf, Vogel '04

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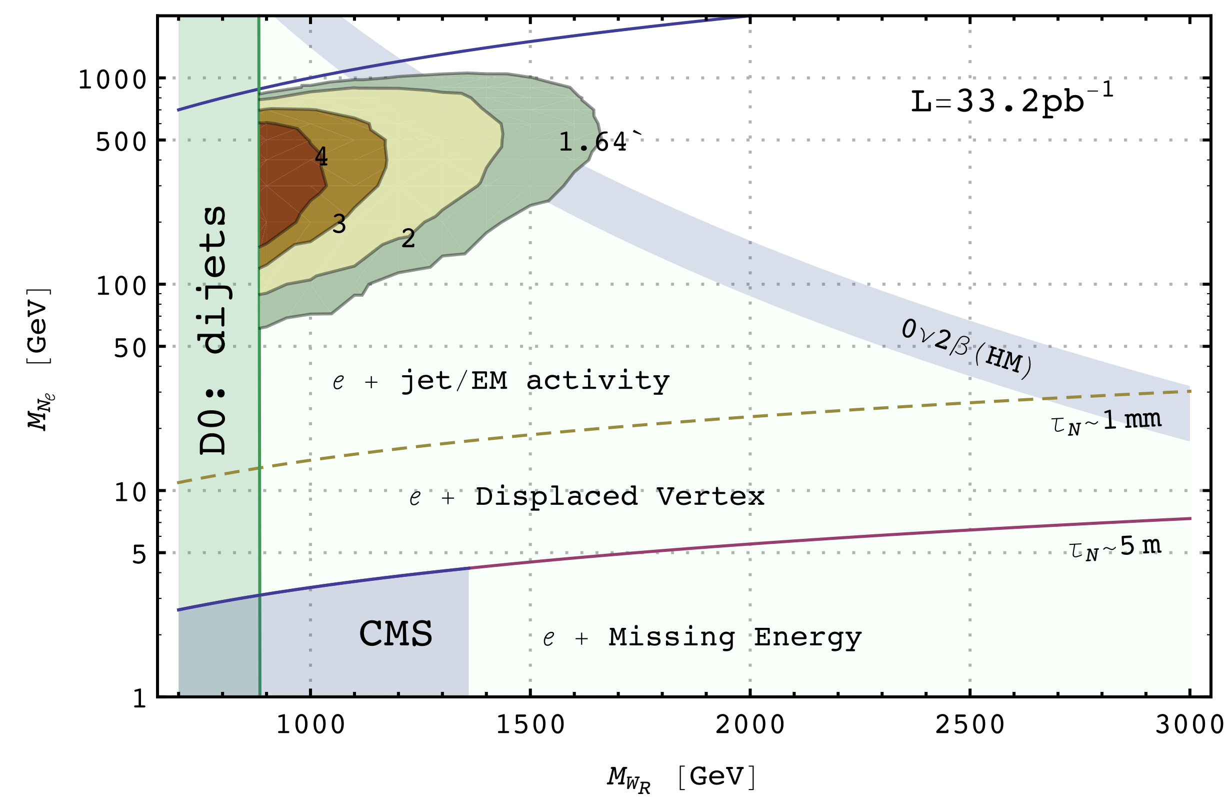

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Left-Right

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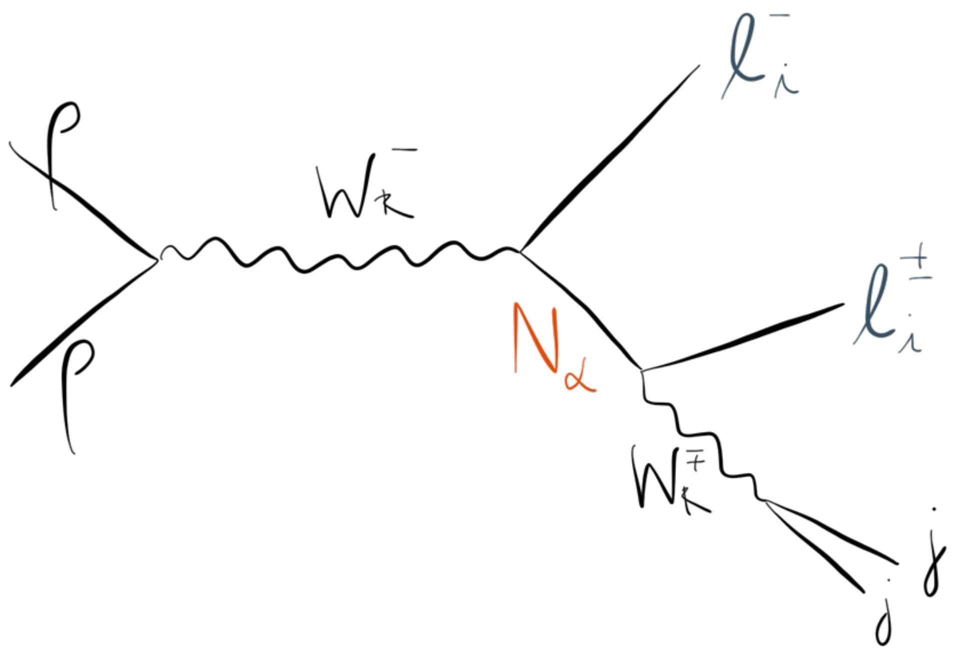

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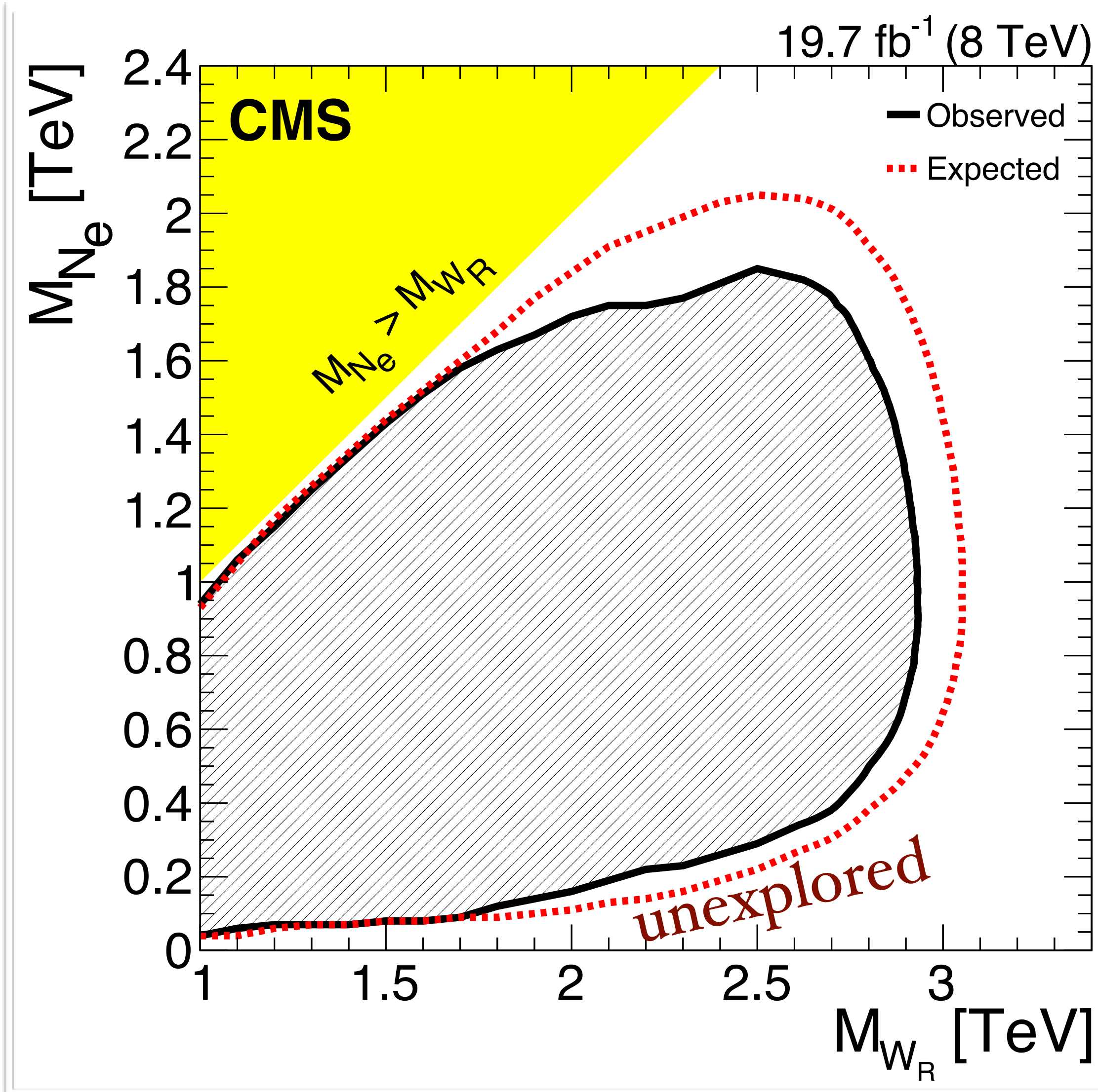


CMS '14

Higgs physics, LFV and LNV

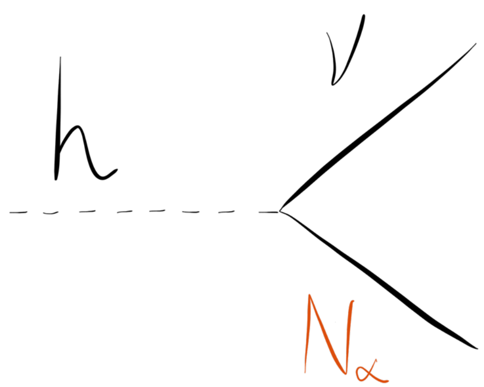
~ potential gateway to neutrino mass origin ~

Higgs decays

type I and III

Higgs decays to light & heavy neutrinos

Chen, He, Tandean, Tsai '10
Dev, Franceschini, Mohapatra '12



$$\frac{\Gamma_{h\to\nu N}}{\Gamma_{h\to b\bar{b}}} \simeq \frac{1}{N_c}\left(\frac{m_D}{m_b}\right)^2$$

needs 'large' m_D

fine-tune, inverse seesaw

final state depends on *N* decay mode $N \to 3\nu, N \to \nu\ell^+\ell^-, N \to \nu q\bar{q}, N \to \ell\bar{q}q'$

missing energy, significant SM background

LNV, LFV not observable

constraints from $\mu \to e\gamma$ and LEP

Garcia Cely, Ibarra,
Molinaro, Petcov '12

feasible for $m_S \in (90, 110)$ GeV

Left-Right

$$M_D = iM_N\sqrt{{M_N}^{-1}M_\nu}$$

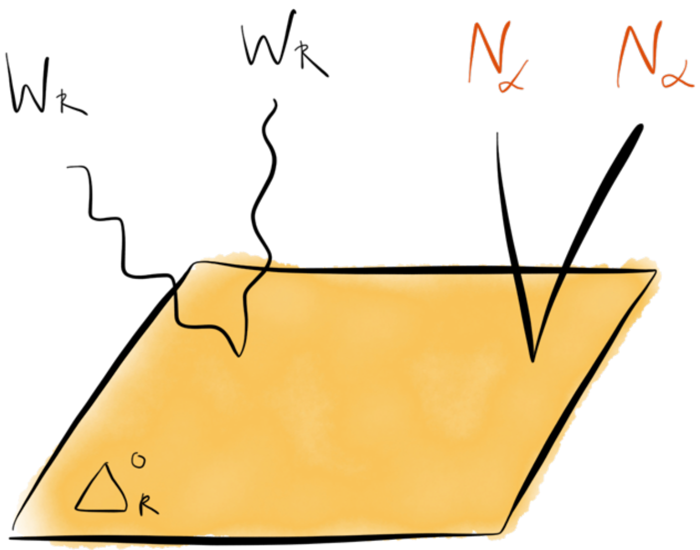
Dirac mass small

MN, Tello,
Senjanović '12

Left-Right

Higgs sector of the minimal model

wip Maiezza, MN, Nesti '15



$$\Phi(2,2,0),\ \Delta_L(3,1,2), \boxed{\Delta_R(1,3,2)}$$

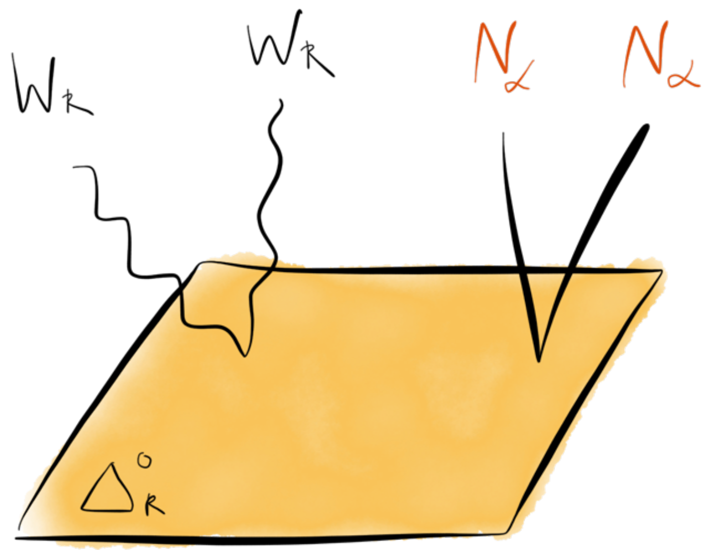
$\langle \Delta_R^0 \rangle$ breaks LR, gives mass to W_R and N

$$\mathcal{L}_N = Y_\Delta\, N^T C \Delta_R N \Rightarrow M_N = \langle \Delta_R^0 \rangle\, Y_\Delta$$

Left-Right

Higgs sector of the minimal model

wip Maiezza, MN, Nesti ’15



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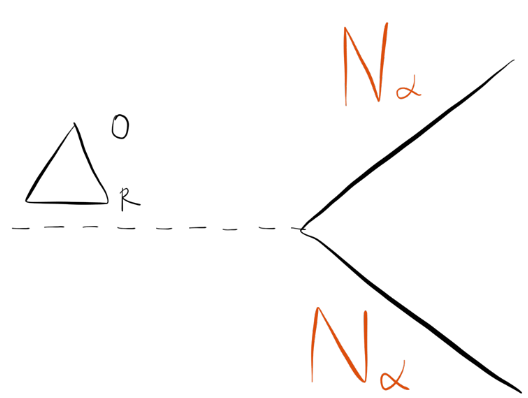
Heavy neutrino Higgs

Δ_R^0 SM singlet



decays

$$\Gamma(\Delta_R^0 \to NN) \propto {m_N}^2$$

$$\mathrm{Br}(\Delta_R^0 \to NN) = \mathcal{O}(1)$$

production suppressed

LR mixing

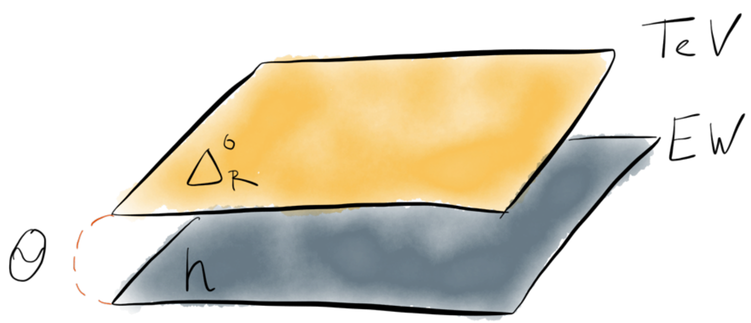
W_R fusion, Higgs-strahlung small

Left-Right

Δ_R^0 - Higgs mixing

wip Maiezza, MN, Nesti '15

$$V_{LR} \ni \alpha\ \left(\Phi\Phi^\dagger\right)\left(\Delta_R\Delta_R^\dagger\right) + \rho\left(\Delta_R\Delta_R^\dagger\right)^2$$



$$\boxed{\theta \simeq \left(\frac{\alpha}{\sqrt{2}\rho}\right)\left(\frac{M_W}{M_{W_R}}\right)}$$

can be sizable, allowed by other constraints, e.g. *EWPT*

Higgs-singlet mixing allowed at $\mathcal{O}(10\%)$

Left-Right Δ_R^0 - Higgs mixing

wip Maiezza, MN, Nesti '15

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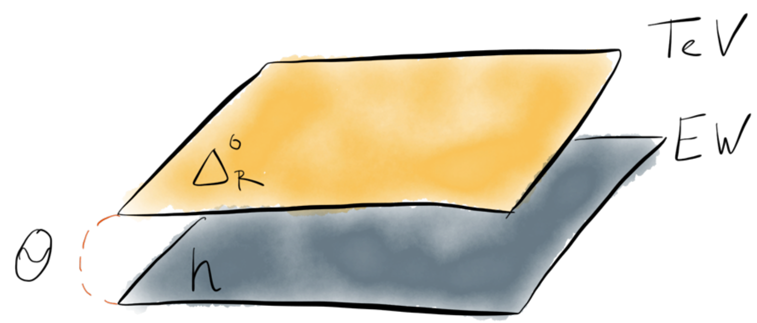

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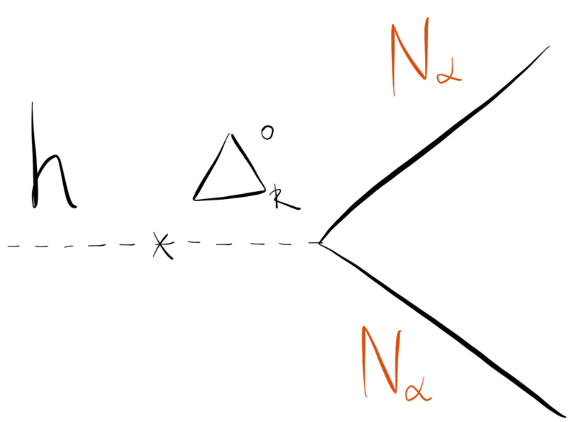
Higgs-singlet mixing allowed at $\mathcal{O}(10\%)$

Higgs decay to *N N*



sensitive to $m_N < \dfrac{m_h}{2}$ interesting for $0\nu2\beta$, safe from MEG

no need for large m_D

$$\frac{\Gamma_{h\to NN}}{\Gamma_{h\to b\bar{b}}} \simeq \frac{\theta^2}{N_c} \left(\frac{m_N}{m_b}\right)^2 \left(\frac{M_W}{M_{W_R}}\right)^2$$

disfavored in type I and III due to $m_D < .5 \text{ GeV}$

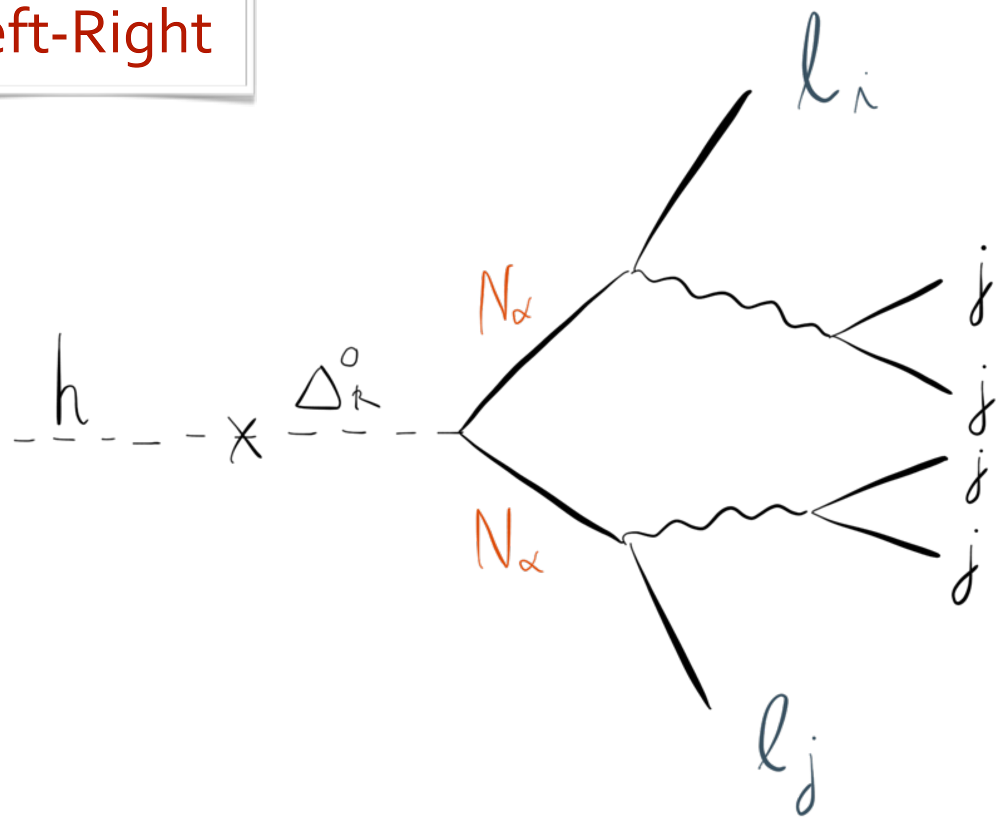
$$\frac{\Gamma_{h\to NN}}{\Gamma_{h\to b\bar{b}}} \simeq \frac{1}{N_c} \left(\frac{m_D}{m_b}\right)^2 \left(\frac{m_D}{m_N}\right)^2$$

Delphi '97
CMS '15

LNV Higgs decays

wip Maiezza, MN, Nesti '15

Left-Right



Signal selection

Majorana - LNV, same-sign

all flavors possible - LFV

1-3 jets

low missing energy

$\mathcal{O}(10\%)$

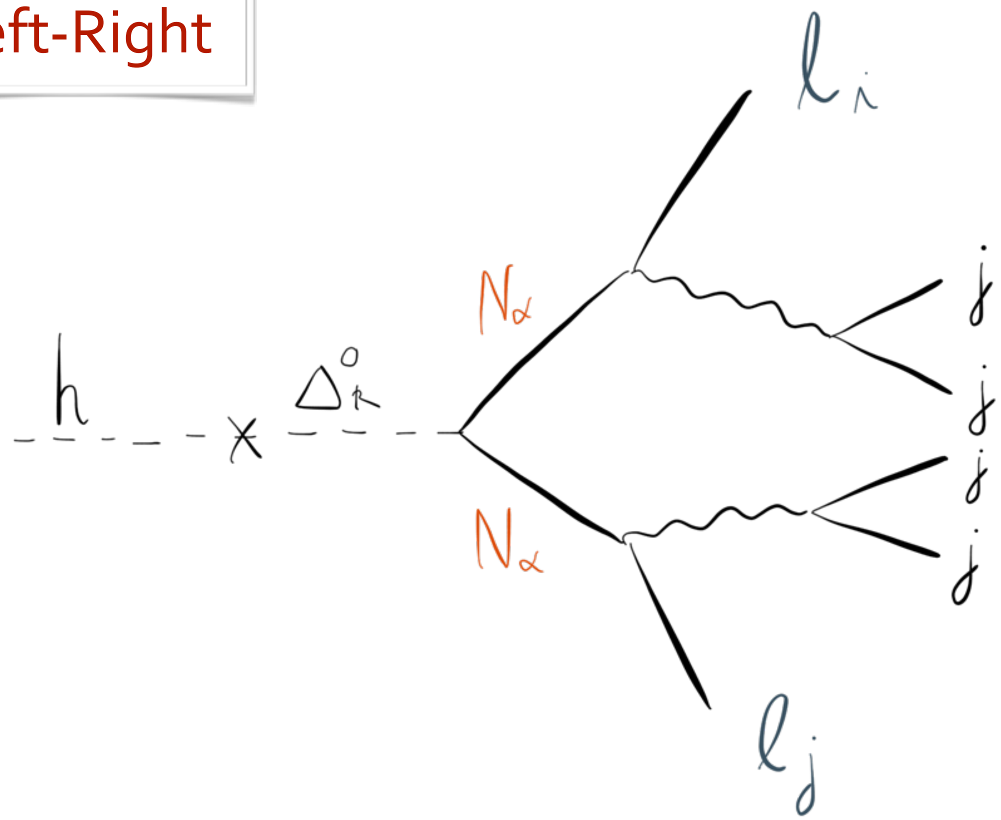
efficiency

$m_N \simeq 40~\mathrm{GeV}$

LNV Higgs decays

wip Maiezza, MN, Nesti ’15

Left-Right



Signal selection

Majorana - LNV, same-sign

all flavors possible - LFV

1-3 jets

low missing energy

$\mathcal{O}(10\%)$

efficiency

$m_N \simeq 40$ GeV

preliminarily

feasible @ LHC

SM di-lepton background

ATLAS 1412.0237

prompt same-sign	opposite-sign + mis-id	hadron mis-id	additional cuts
$VV, \quad V = W, Z$	$Z/\gamma^* + j$	QCD jets	$\not{E}_T < 20$ GeV
$t\bar{t}$	$Wt, W\gamma$	$W +$ jets	$\not{H}_T < 70$ GeV
	$W^\pm W^\mp$		

type I and III

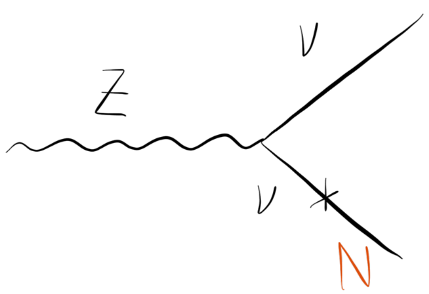
Heavy Neutrino at FCC-ee

on the Z-pole

Gronau, Leung, Rosner '84, ...

large statistics $n_Z \sim 10^{12} - 10^{13}$ over $n_Z \sim 10^6$ at LEP

Delphi '97

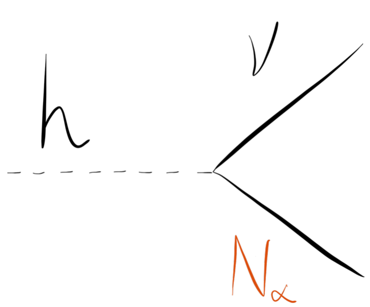


expect a limit of $\left(\frac{m_D}{m_N}\right)^2 < 10^{-11} - 10^{-12}$

Blondel, Graverini, Serra, Shaposhnikov 1411.5230

Higgs decays

FCC-ee $\sqrt{s} = 240\ \mathrm{GeV},\ \mathcal{L} = 10\ \mathrm{ab} \to 2.4 \times 10^6\ Zh$



$$\frac{\Gamma_{h\to\nu N}}{\Gamma_{h\to b\bar{b}}} \simeq \frac{1}{N_c} \underbrace{\left(\frac{m_D}{m_N}\right)^2}_{< 10^{-11}} \left(\frac{m_N}{m_b}\right)^2 < 10^{-9}$$

competitive between Z and h?

Left-Right

Heavy Neutrino at FCC-ee

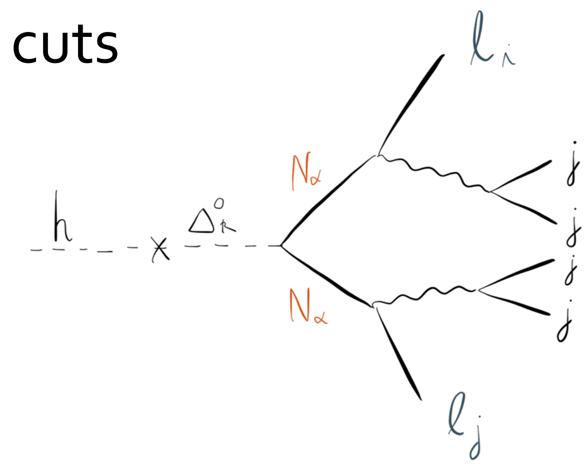
LNV Higgs decays

LHC

fair background, misid, need isolation + cuts

Higgs slightly boosted $\gamma_h \simeq 3$

inefficient for small *N* mass



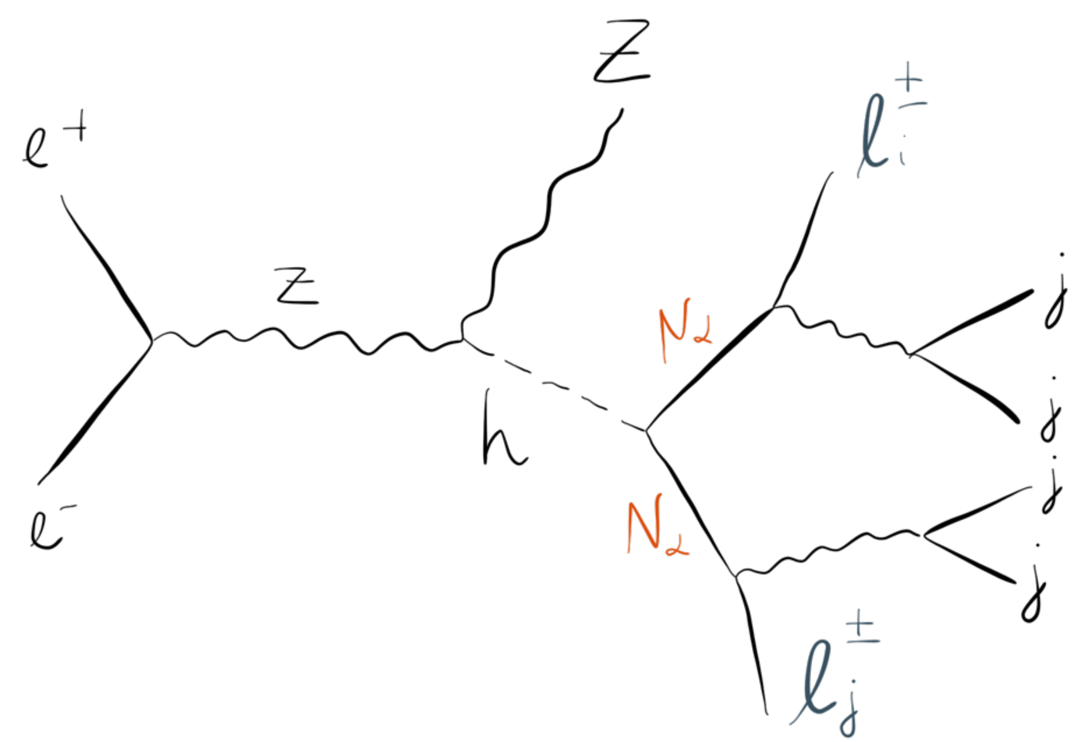
FCC-ee

less QCD background, prompt easier to handle

Higgs boost $\gamma_h = 1.08$

higher efficiency for lower masses

additional tagging *Z*



Conclusions

Theories of neutrino mass origin testable at colliders

flavor reconstruction required to connect to M_ν
leads to LFV signals

mediator searches at LHC (see-saw, LR)

Higgs decay searches

Higgs boson a (new) gateway to LNV

feasible at LHC via LR Higgs mixing , no tuning required

FCC-ee constrains see-saw on *Z* and *h* poles

FCC-ee prospect for LNV Higgs unexplored

Thank you