Towards Neutrino Mass Origin with Higgs decays at the LHC

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with Alessio Maiezza (IFIC) and Fabrizio Nesti (IRB)

arXiv:1503.06834

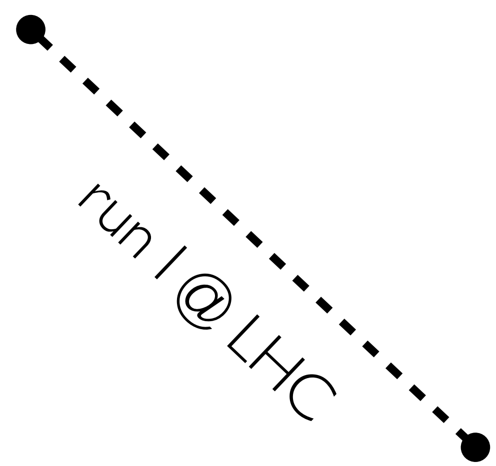
PRL 115 (2015) 081802

and 1603.00360

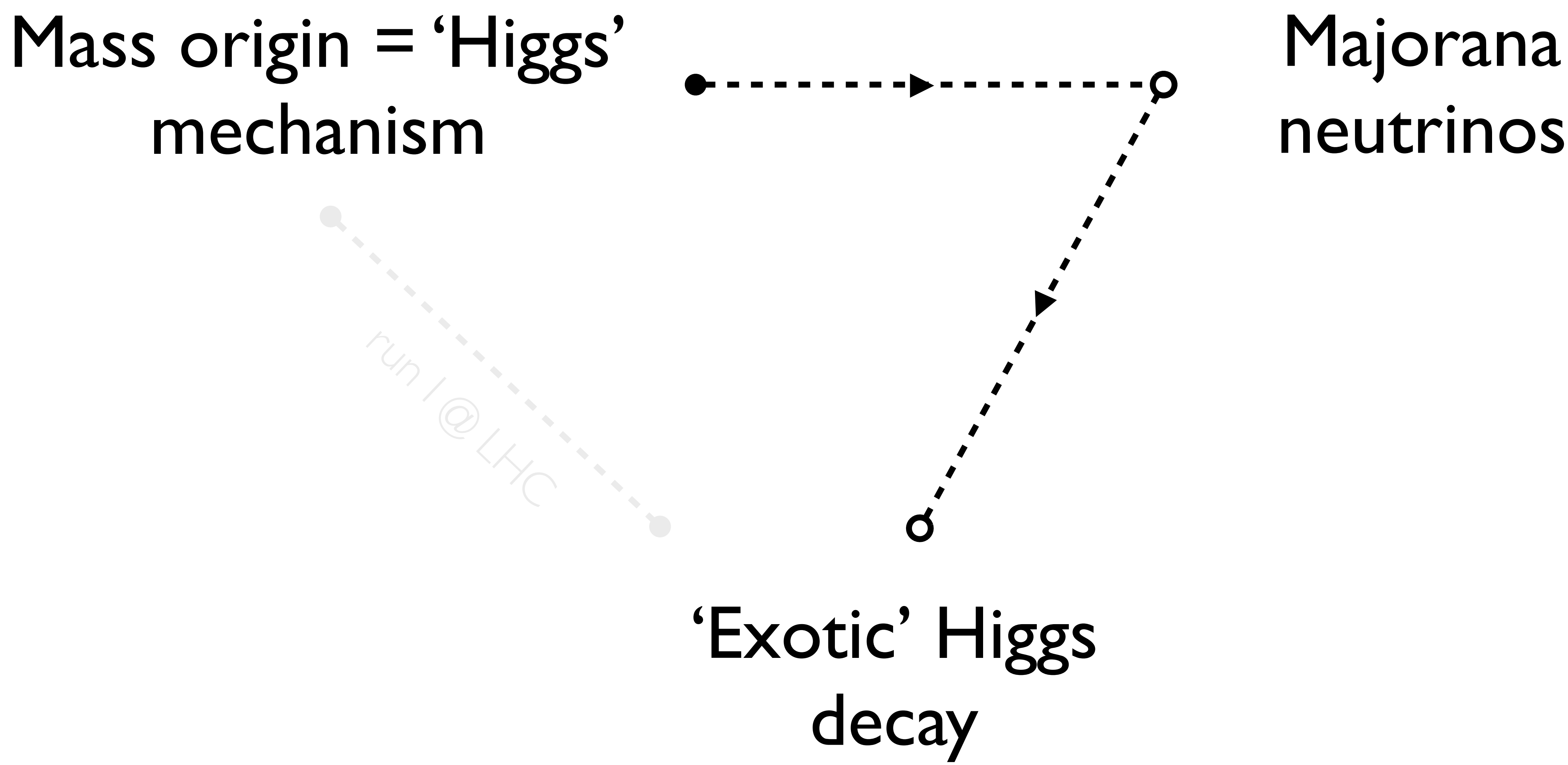
Genova

March 3rd 2016

Mass origin = Higgs mechanism



Higgs decay

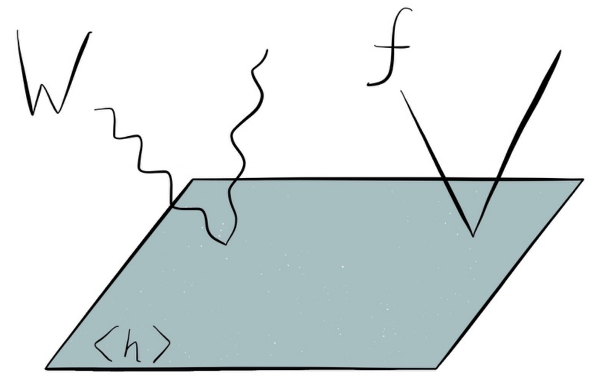

Mass origin = ‘Higgs’ mechanism
Majorana neutrinos
run 1 @ LHC
‘Exotic’ Higgs decay

Mass origin

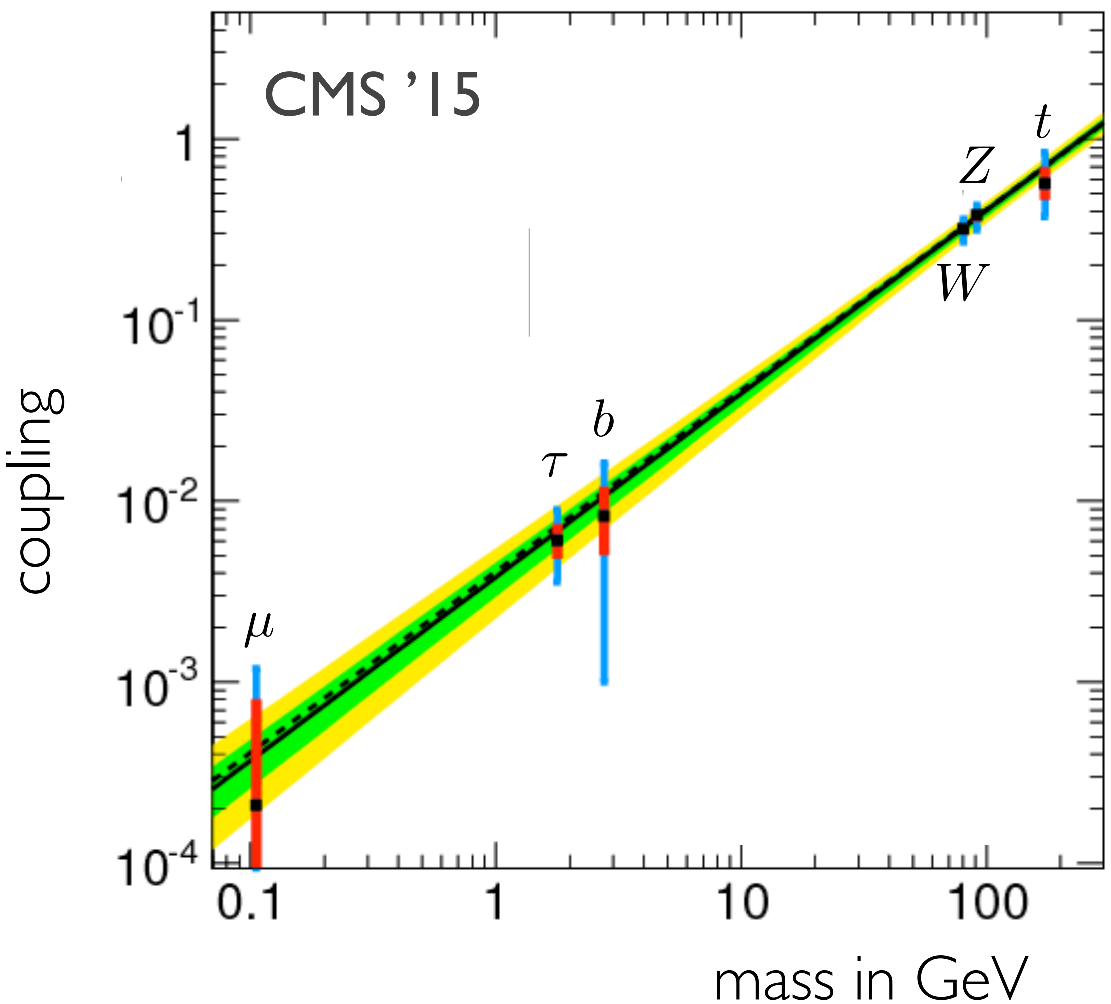
Higgs '64
Weinberg '67

$$\mathcal{L}_y = y\,\overline{f}_L\,h\,f_R$$

$$\Gamma_{h\to ff} \propto m_f^2$$



$$m_f = y\,v$$



Higgs mass origin discovery

L number conserved

Neutrinos massless

Neutrino Mass

Neutral fermions $m_M \, \nu^T C \nu$ Majorana ’37

Implication of *LNV* $0\nu 2\beta$ Racah, Furry ’37

⋮

colliders, mesons, Higgs

Neutrino Mass origin

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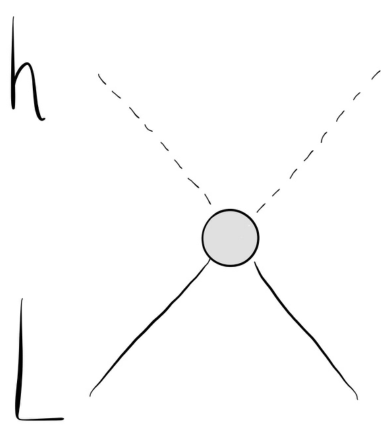
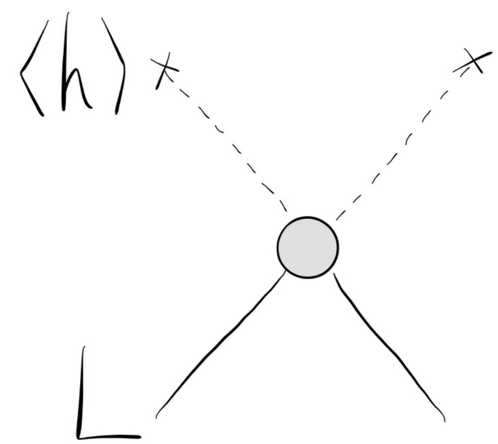
⋮

colliders, mesons, Higgs

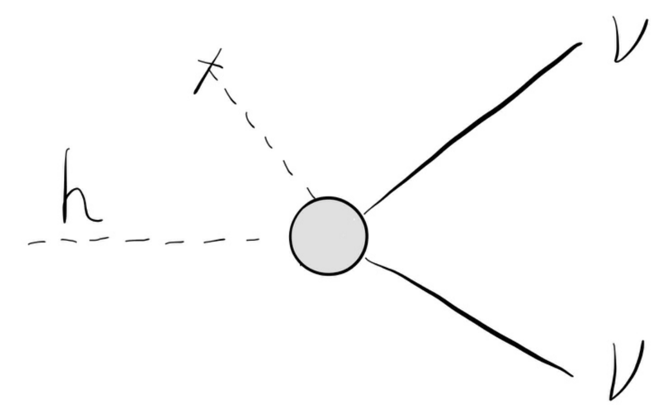
EFT: no light states $\Lambda \gg v$ Weinberg '79



$$\tilde{y}\frac{LHLH}{\Lambda}$$



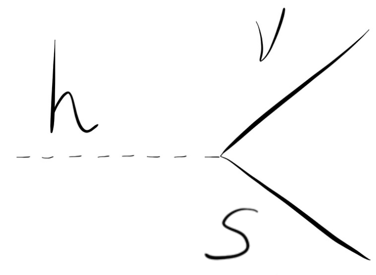
$$m_\nu = \tilde{y}\frac{v^2}{\Lambda}$$

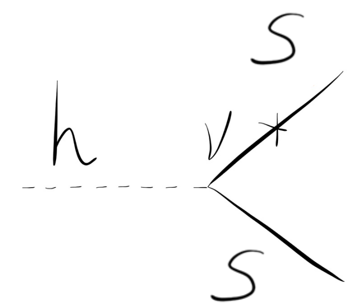


$$\Gamma_{h\to\nu\nu} \propto m_\nu^2$$

Neutrino Mass origin

type I





type III **ruled out**

$$M_\nu = -M_D^T\, m_S^{-1}\, M_D$$

Casas-Ibarra '01

$$\Gamma_{h\to\nu S} \propto M_D^2$$

Dev, Franceschini, Mohapatra '12
Cely, Ibarra, Molinaro, Petcov '12

$$\Gamma_{h\to SS} \propto M_D^2 \left(\frac{M_D}{m_S}\right)^2$$

Pilaftsis '91

Ambiguous relation

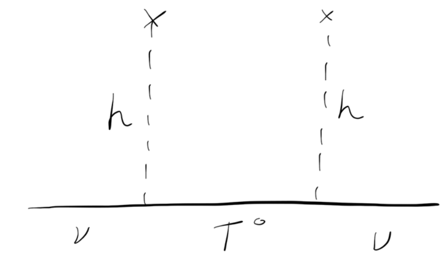
Fine-tuned, 'inverse'

LNV mode forbidden

Delphi '91, CMS '15

Neutrino Mass origin

type I



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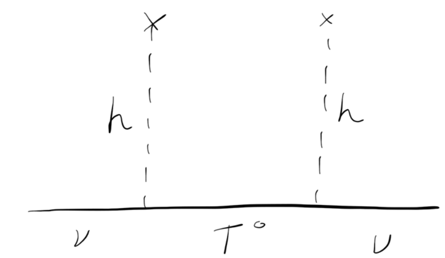

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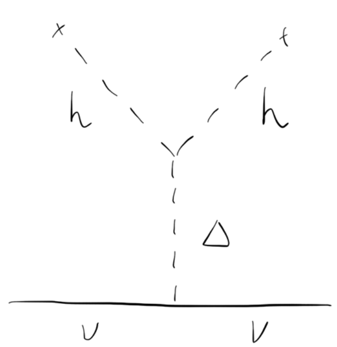
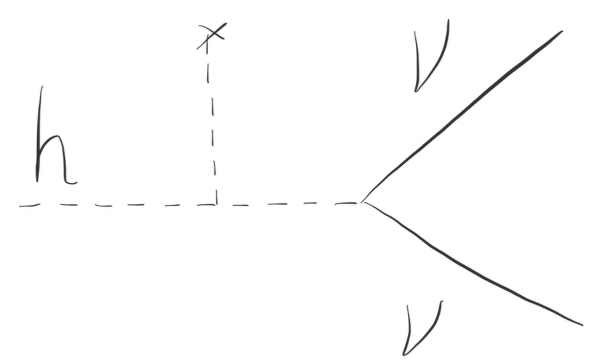


type II

$$m_\nu = Y_\Delta v_L$$



$$\Gamma_{h\to\nu\nu} \propto \frac{m_\nu^2}{v^2}$$

no LNV

Neutrino Mass origin

Seesaw

Left-Right

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

$N \in L_R$

Minkowski '77
Mohapatra, Senjanović '79

GUTs

$SO(10)$

$N \in 16_F$

Gell-Mann, Ramond, Slansky '79

$SU(5)$

$\Delta_L \in 15_H$

Glashow '79

Horizontal symmetry

$SU(n)_F$

Yanagida '79

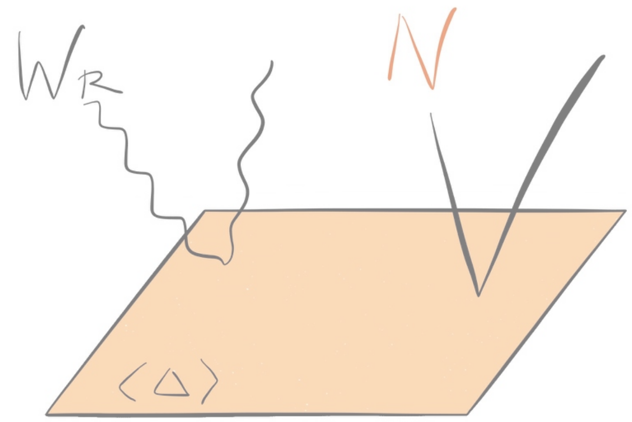
Left-Right

Pati, Salam '74
Mohapatra, Pati '75

Minimal model

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

Minkowski '77
Mohapatra, Senjanović '79



Spontaneous parity breaking

Senjanović, Mohapatra '75

$$\mathcal{P}: \begin{cases} \Delta_L \leftrightarrow \Delta_R,\ \Phi \to \Phi^\dagger \\ Q_L \leftrightarrow Q_R,\ L_L \leftrightarrow L_R \end{cases}$$

Left-Right

Pati, Salam '74
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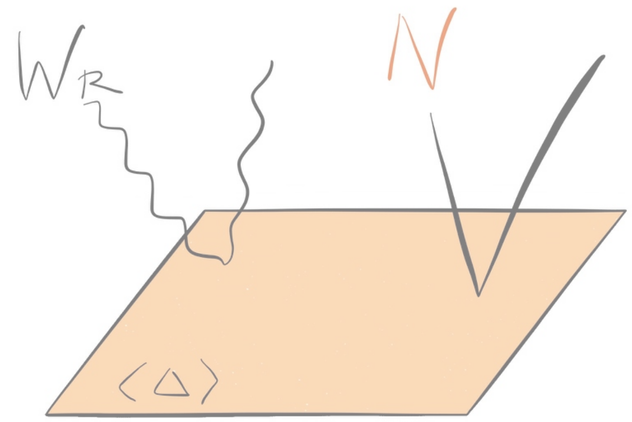

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$$\mathcal{P}:\begin{cases}\Delta_L \leftrightarrow \Delta_R,\ \Phi \to \Phi^\dagger\\ Q_L \leftrightarrow Q_R,\ L_L \leftrightarrow L_R\end{cases}$$

$$\Phi = \begin{pmatrix}\phi_1^0 & \phi_2^+\\ \phi_1^- & \phi_2^0\end{pmatrix} \qquad \langle\Phi\rangle = \begin{pmatrix} v & 0\\ 0 & 0\end{pmatrix} \qquad V \in \lambda\,(\Phi^\dagger\Phi)^2 + \alpha(\Phi^\dagger\Phi)(\Delta_R^\dagger\Delta_R) + \rho\,(\Delta_R^\dagger\Delta_R)^2$$

same for $\mathcal{C}$-symmetry

$$\Delta_R = \begin{pmatrix}\Delta^+/\sqrt{2} & \Delta^{++}\\ \Delta^0 & -\Delta^+/\sqrt{2}\end{pmatrix}_R \qquad \langle\Delta_R\rangle = \begin{pmatrix}0 & 0\\ v_R & 0\end{pmatrix}$$

$h-\Delta$ mixing: $\theta \simeq \left(\frac{\alpha}{2\,\rho}\right)\left(\frac{v}{v_R}\right) \lesssim .44$

Left-Right

Pati, Salam '74
Mohapatra, Pati '75

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Spontaneous
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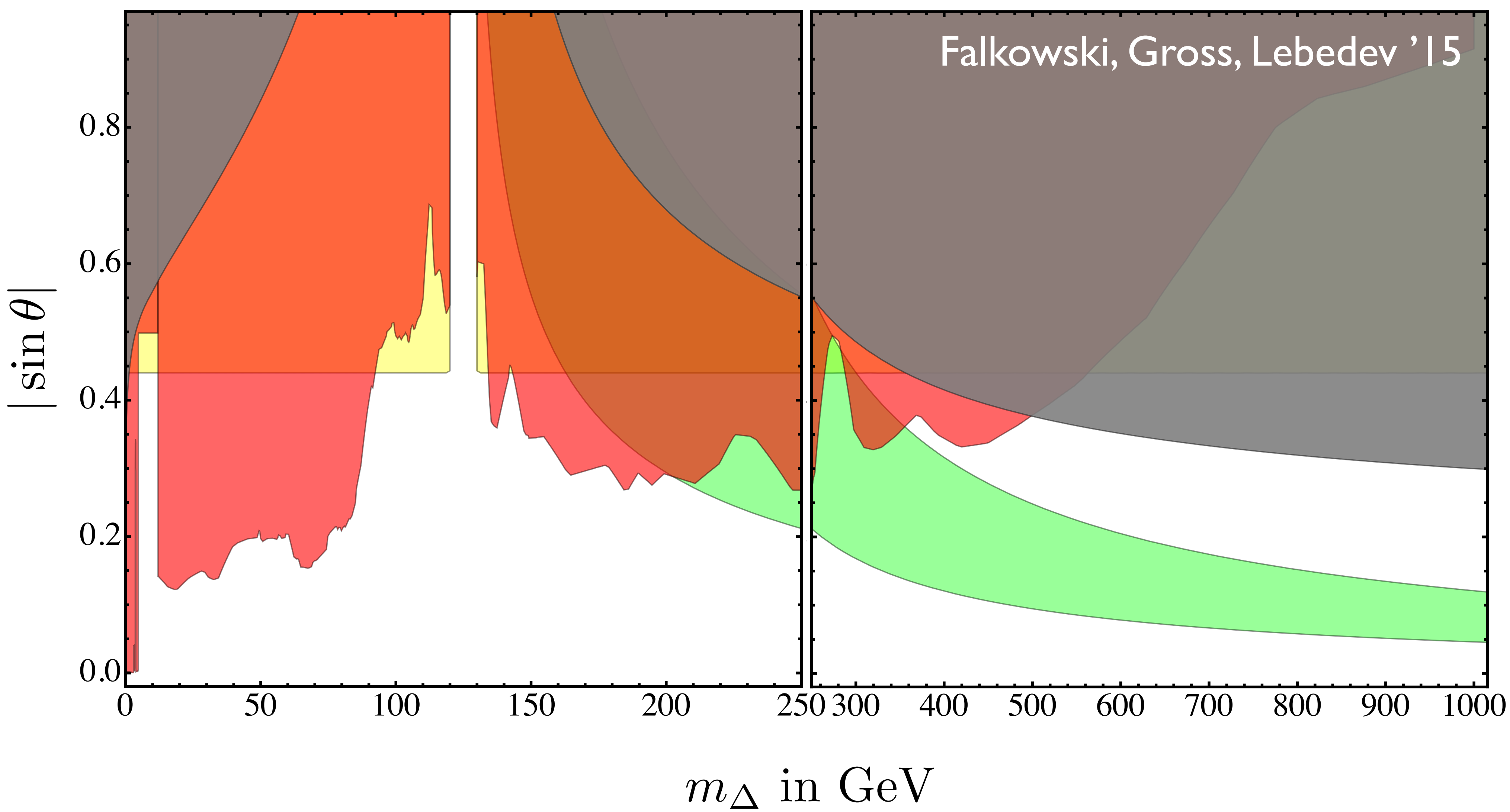


Future collider
outlook

$|\sin\theta| < .34$

Buttazzo, Sala, Tesi '15

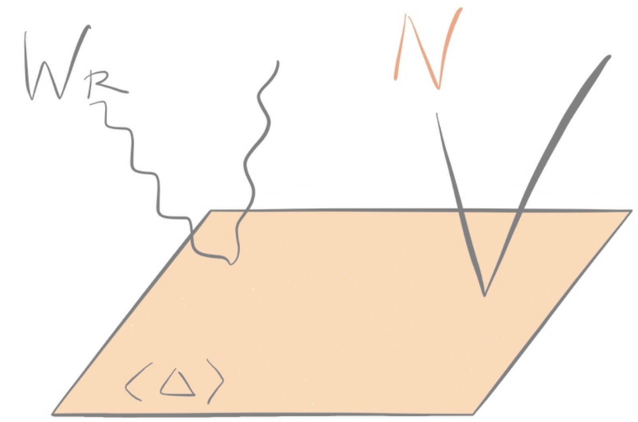
Left-Right

Pati, Salam '74
Mohapatra, Pati '75

Minimal model

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

Minkowski '77
Mohapatra, Senjanović '79



Spontaneous parity breaking

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$$\langle\Phi\rangle = \begin{pmatrix} v & 0 \\ 0 & 0 \end{pmatrix}$$

$$V \in \lambda\,(\Phi^\dagger\Phi)^2 + \alpha(\Phi^\dagger\Phi)(\Delta_R^\dagger\Delta_R) + \rho\,(\Delta_R^\dagger\Delta_R)^2$$

$$V(\Delta_L, \Phi, \Delta_R)$$

same for $\mathcal{C}$-symmetry

$$\langle\Delta_R\rangle = \begin{pmatrix} 0 & 0 \\ v_R & 0 \end{pmatrix}$$

$h-\Delta$ mixing: $\theta \simeq \left(\frac{\alpha}{2\rho}\right)\left(\frac{v}{v_R}\right) \lesssim .44$

e.g. Falkowski, Gross, Lebedev '15

Indirect limits

early $M_{W_R} > 1.6$ TeV

Beal, Bander, Soni '82, ...

to $M_{W_R} \gtrsim 3$ TeV *

Zhang et al. '07, Maiezza, MN, Nesti, Senjanović '10
Bertolini, Nesti, Maiezza '14

*barring strong CP

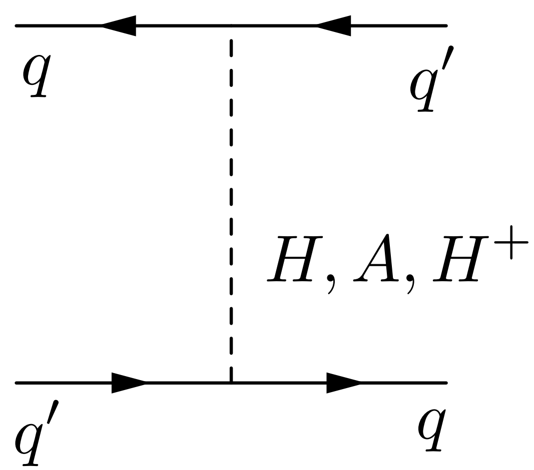
Maiezza, MN '14

H

$$\Phi \simeq \begin{pmatrix} h & H^+ \\ \chi^- & H + IA \end{pmatrix} \qquad \mathcal{V} \in \alpha_3 \left(\Phi^\dagger \Phi\right)\left(\Delta_R^\dagger \Delta_R\right) \qquad m^2_{H,A,H^+} \simeq \alpha_3 v_R^2$$

Tree-level FCNCs

Senjanović, Senjanović '80, ...



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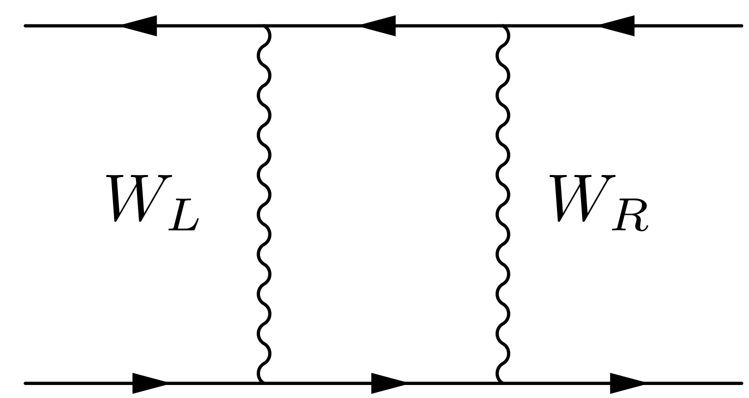


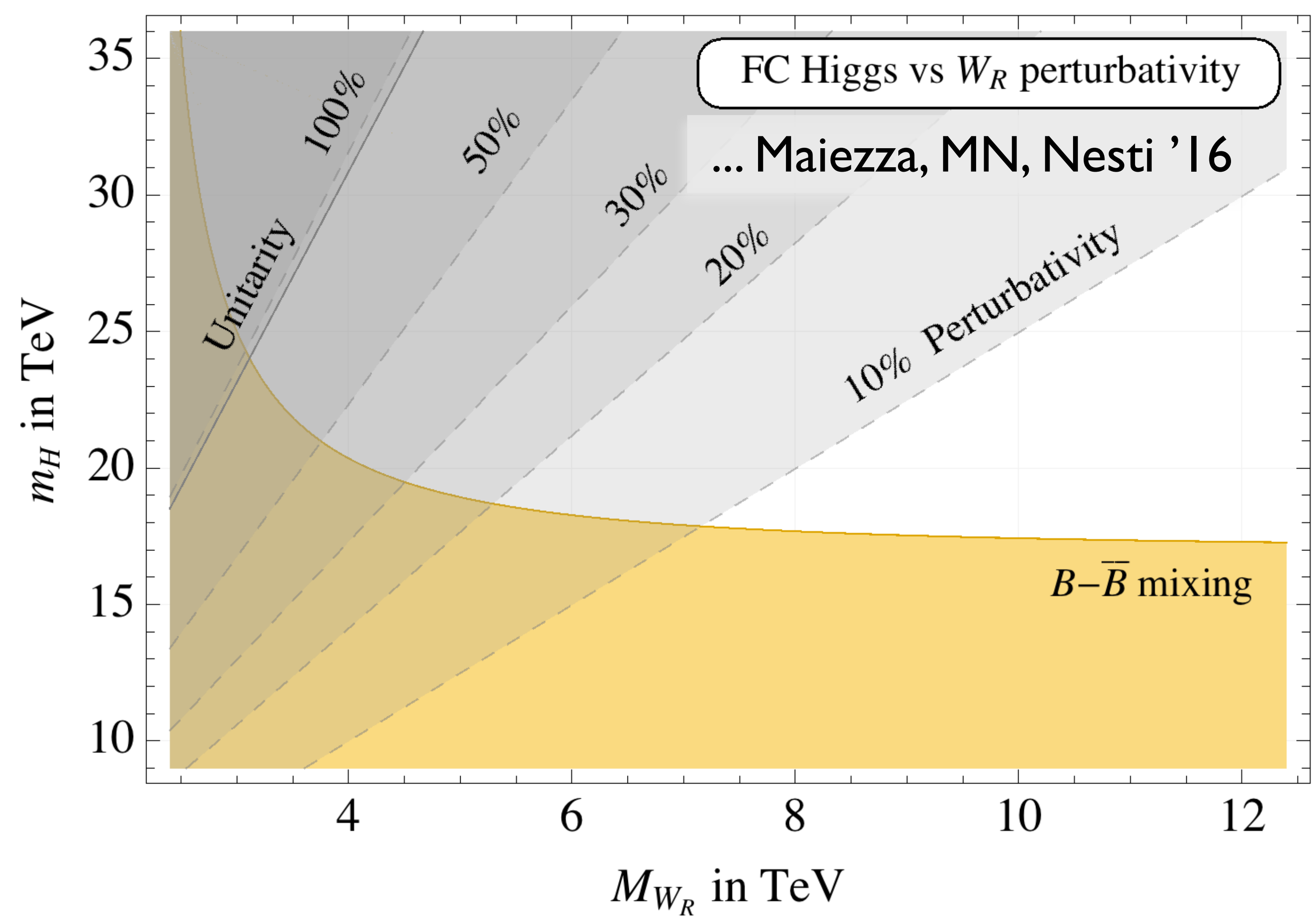
All couplings computable with $\mathcal{P}$ and $\mathcal{C}$

Maiezza, MN, Nesti, Senjanović '10
Senjanović, Tello '14

light W_R requires large α_3

(conservative) $\mathcal{V}_{eff}$ perturbativity

scalar scattering unitarity



Δ_L

$$\frac{m^2_{\Delta_L^{++}} - m^2_{\Delta_L^{+}}}{M_W^2} = \frac{m^2_{\Delta_L^{+}} - m^2_{\Delta_L^{0}}}{M_W^2} = \left(\frac{m_H}{M_{W_R}}\right)^2 > 0$$

Colliders

cascades dominate for large mass splittings

Melfo, MN, Nesti, Senjanović, Zhang '11

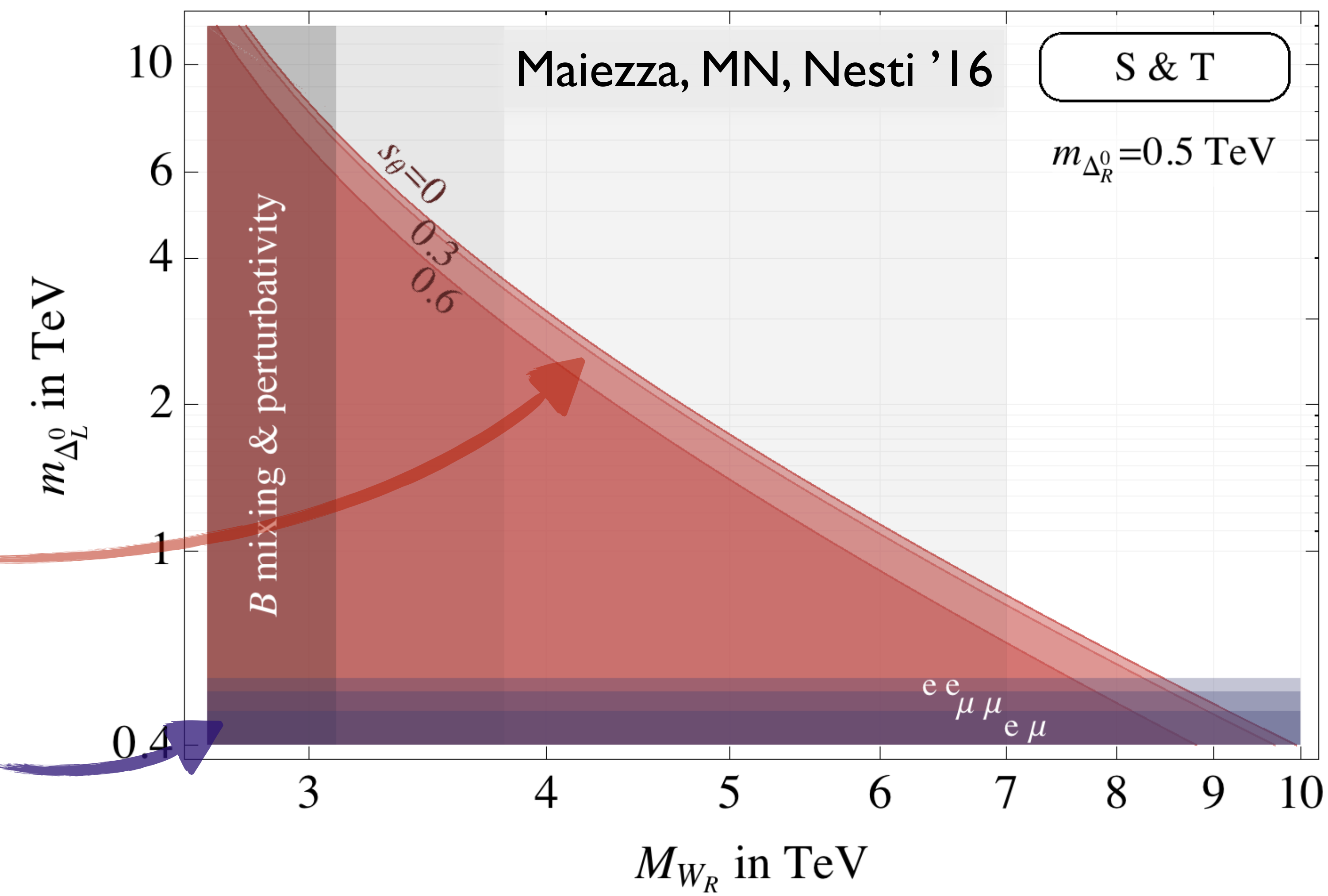
Δ_L^0 lightest, missing energy at LHC

$\boxed{\text{S \& T}}$ oblique parameters

decouple with m_{Δ_L}

partial cancellation with s_θ

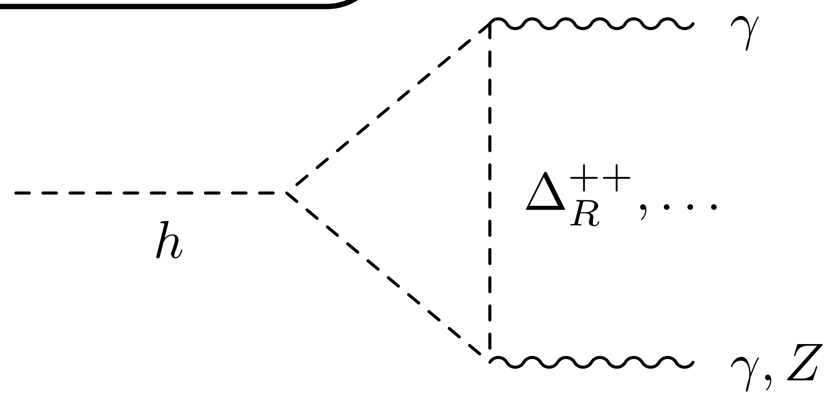
competes with direct searches



Δ_R^{++}

$$m^2_{\Delta_R^{++}} = 4\,\rho_2\,v_R^2 + \alpha_3\,v^2$$

$\boxed{h \to \gamma\gamma, \gamma Z}$



tree-level

$\mathcal{V}$ stability

$\rho_2 > 0$

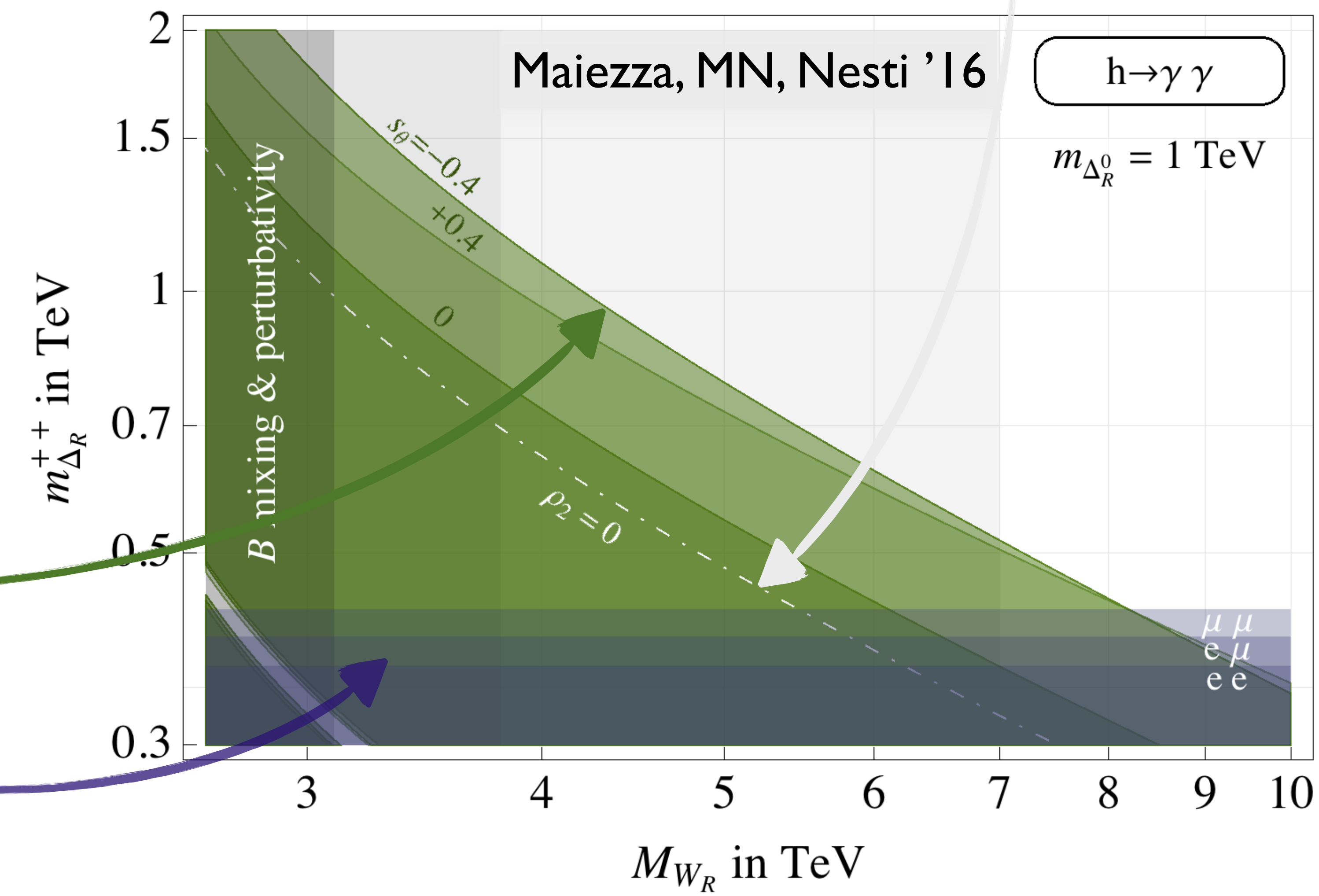
$\gamma\gamma$ data from CMS, ATLAS

γZ correlated, subdominant

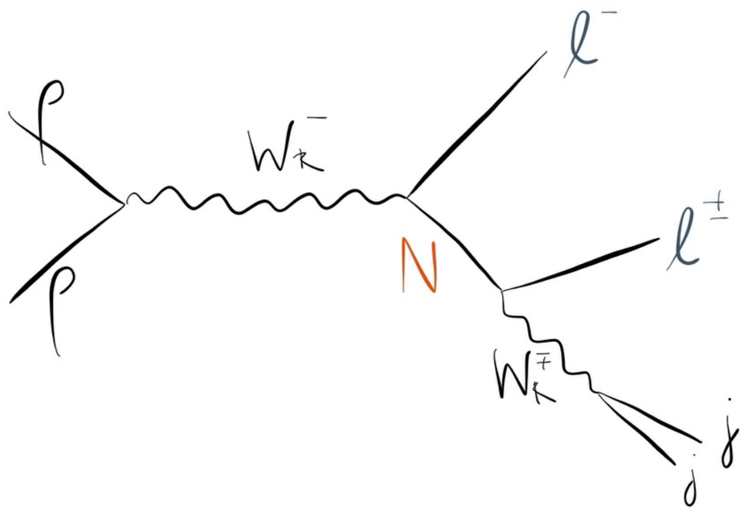
decouples with v_R

partial cancellation with s_θ

competes with direct searches



*N*eutrino Mass at LHC



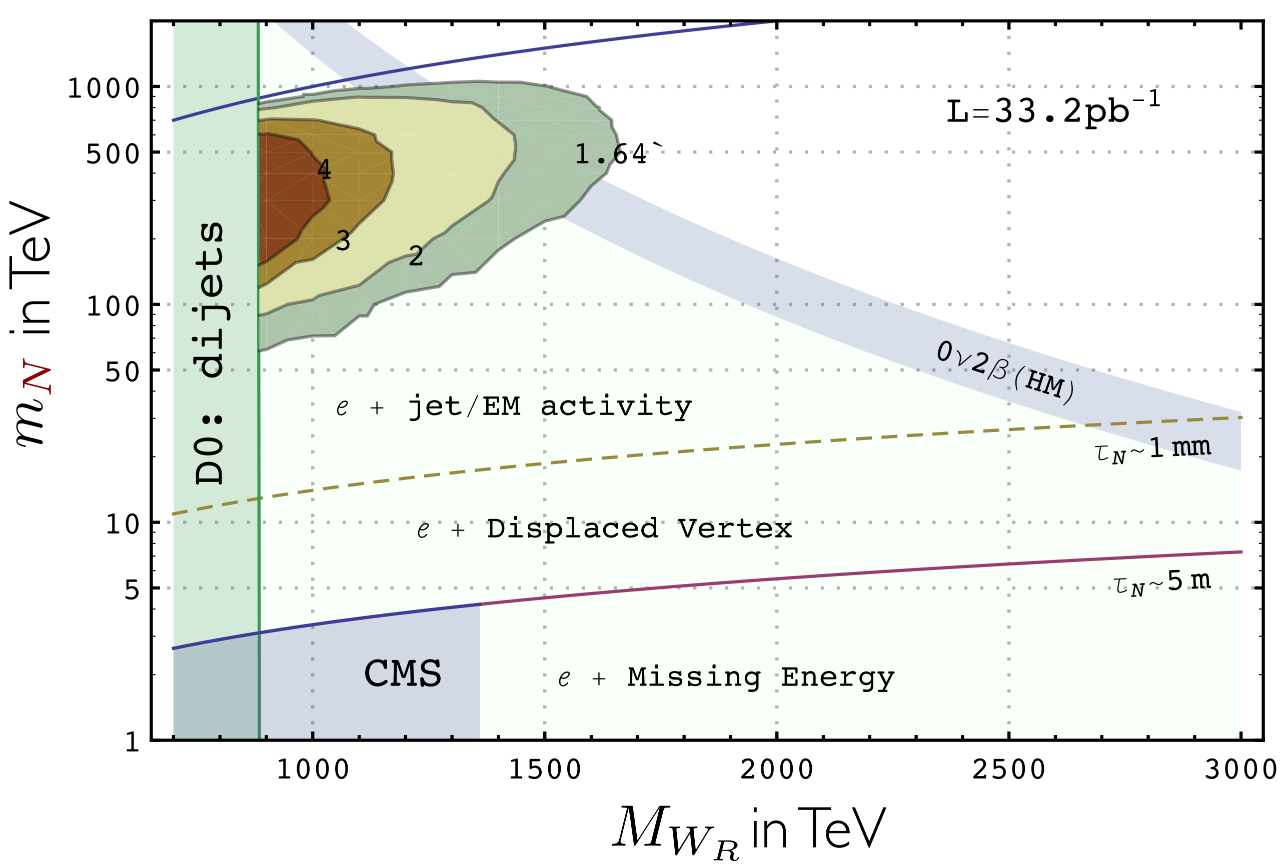
$$m_{\ell jj}^{\rm inv} = m_N$$

ℓ flavor measures V_R, $M_N = V_R^T m_N V_R$

LNV @ hadron colliders — Keung, Senjanović '83

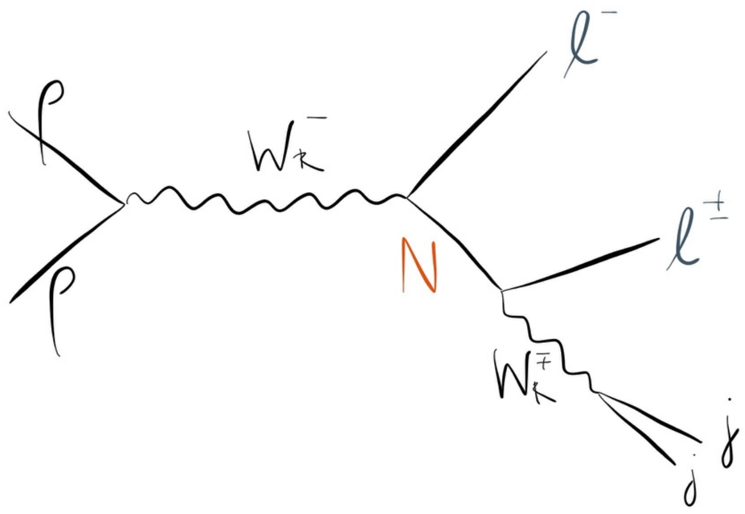
Unambiguous seesaw — MN, Senjanović, Tello '12

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



MN, Nesti, Senjanović, Zhang '11

Neutrino Mass at LHC



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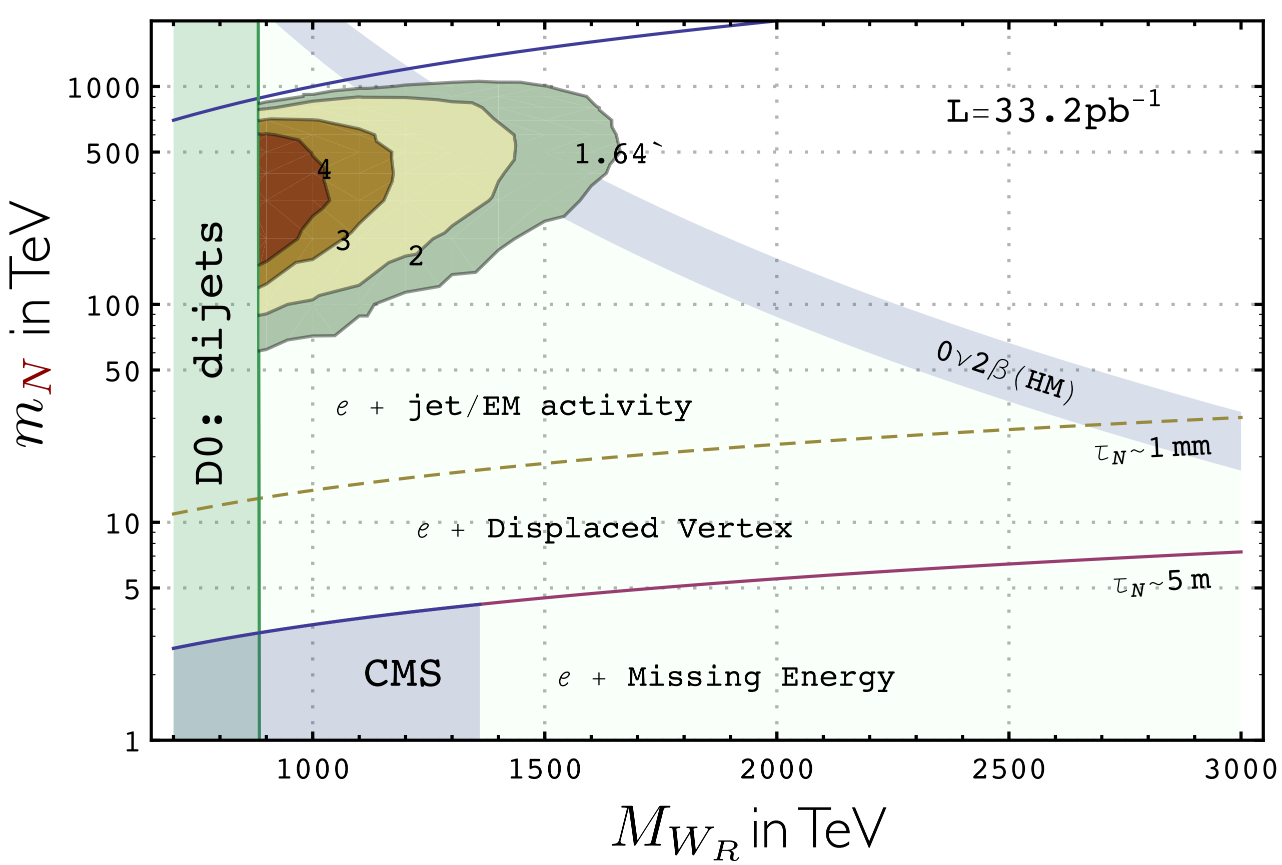
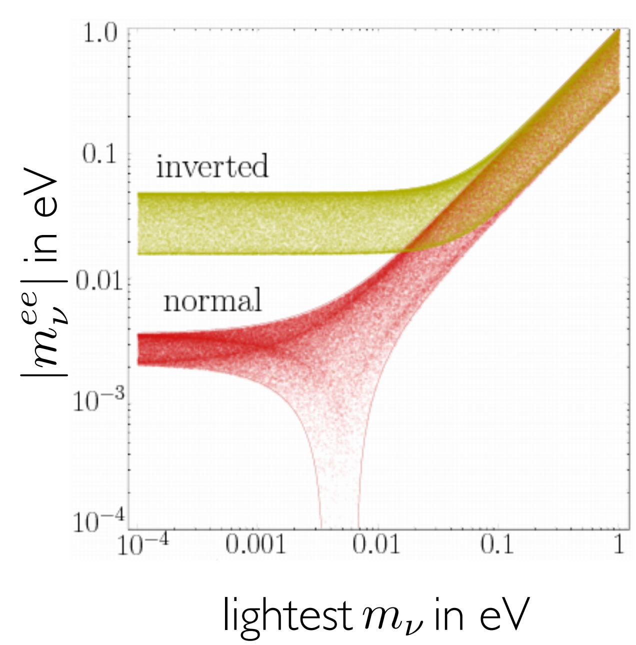


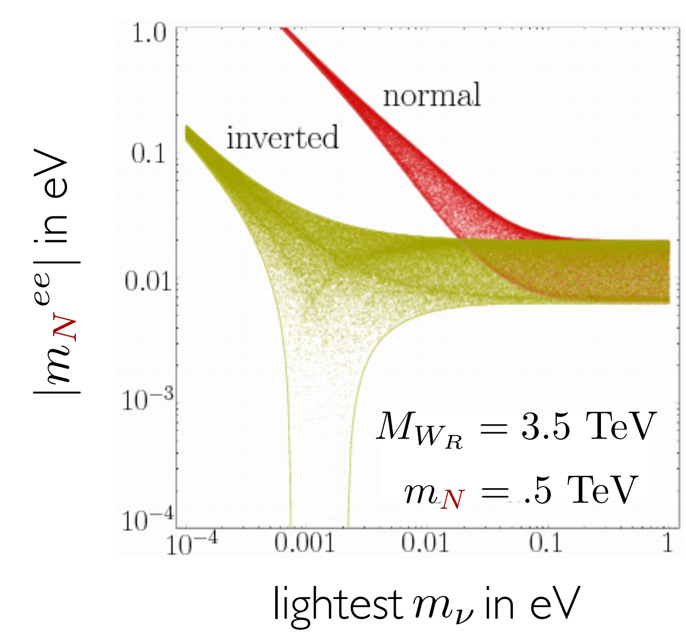
MN, Nesti, Senjanović, Zhang '11

Low energies: $0\nu 2\beta$, eEDM, LFV

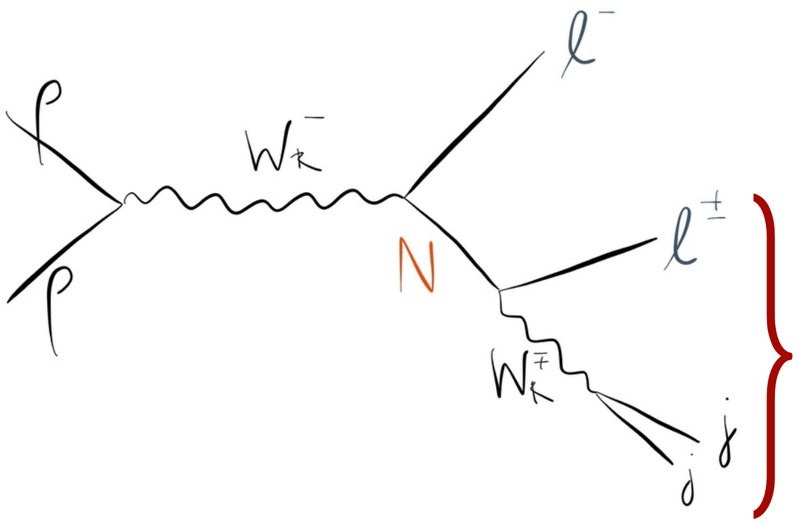
Mohapatra, Senjanović, '79, '80

Tello, MN, Nesti, Senjanović, Vissani '10





Neutrino Mass at LHC



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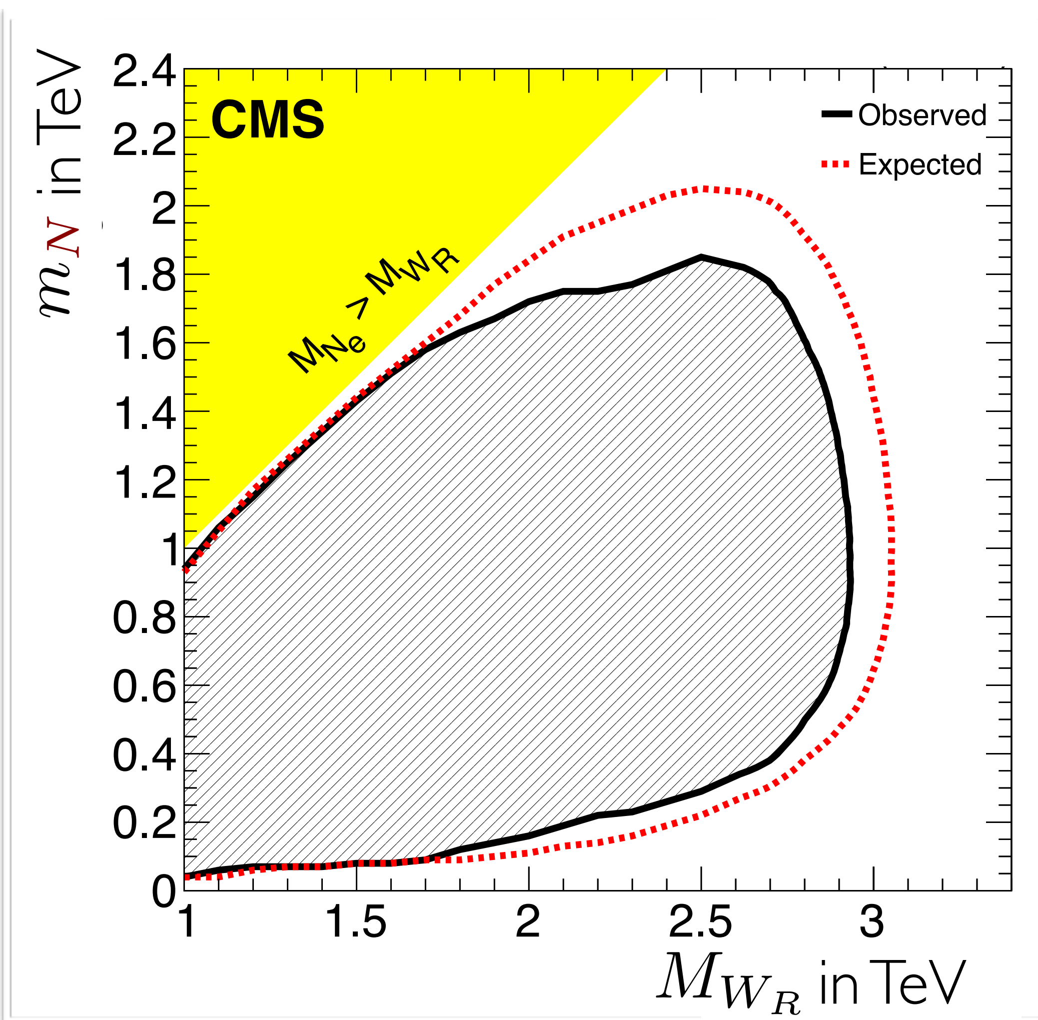

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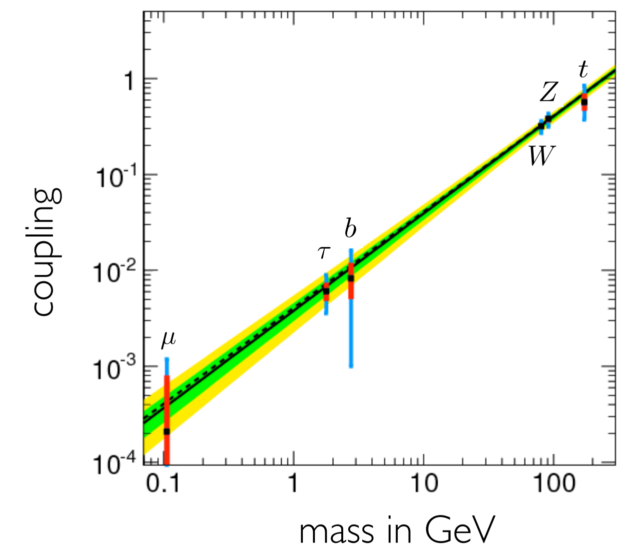
Mohapatra, Senjanović, '79, '80

Tello, MN, Nesti, Senjanović, Vissani '10

Majorana vs. Dirac

SM a *predictive* theory of charged fermion mass origin

$$\mathcal{L}_D = \frac{m_f}{v}\,\overline{f}_L\,h\,f_R \quad \xrightarrow{\text{unique}} \quad \Gamma_{h\to ff} \propto {m_f}^2 \quad \longrightarrow$$



Type I/III seesaw $\qquad \mathcal{L}_\nu = M_D\,\overline{\nu}_L\,h\,N + M_N\,NN + h.c.$

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

fixed $S = i\sqrt{M_\nu}$

$\mathcal{O}$ cancels out

$$M_D = i\sqrt{m_N}\,O\,\sqrt{M_\nu}$$ ambiguous, possibly large

not predictive...

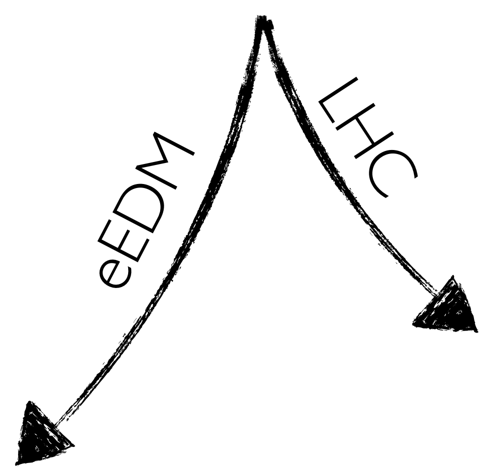
Majorana vs. Dirac

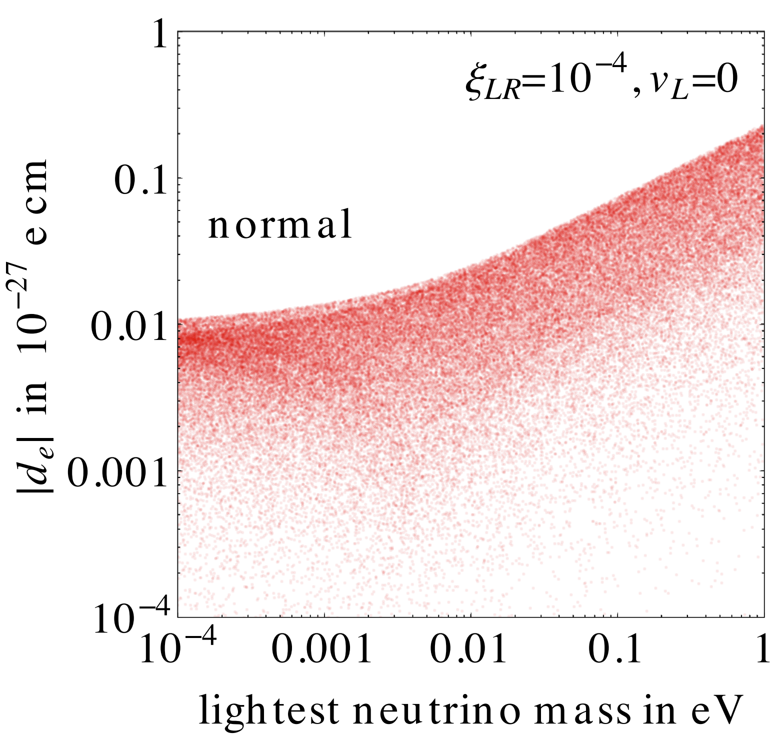
Left-Right gauge interaction defines the basis

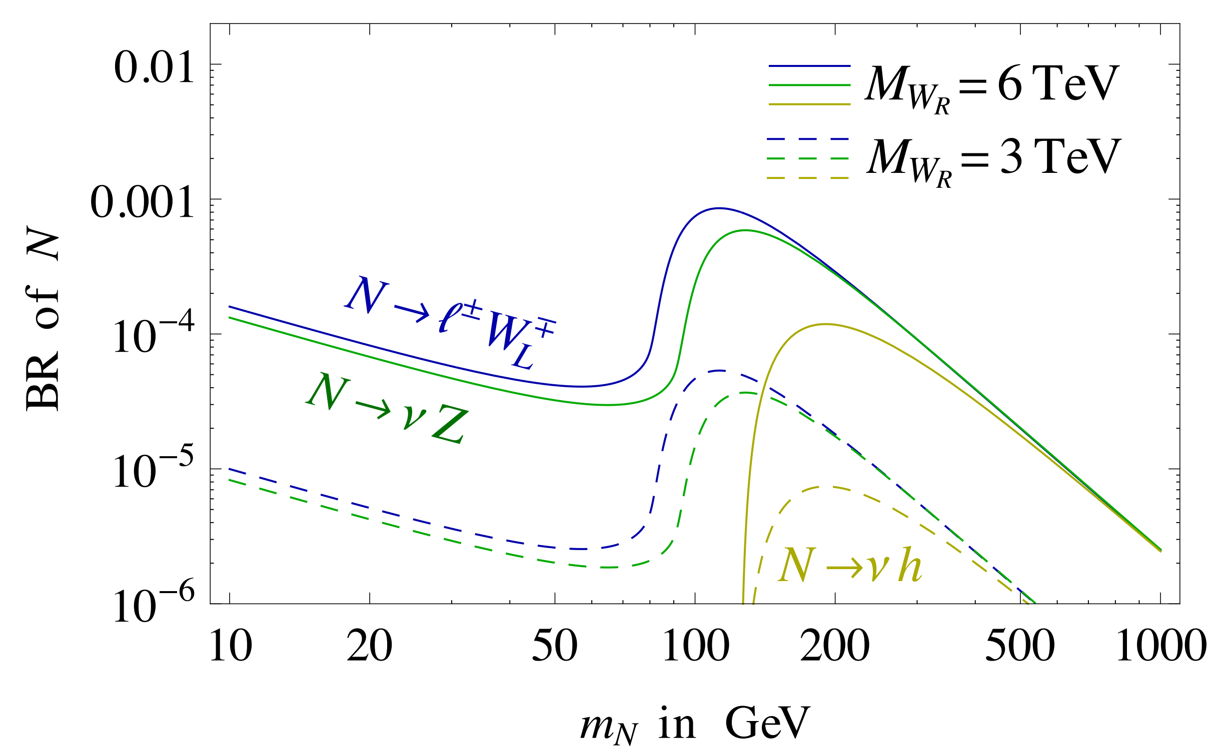
$$\mathcal{L}_W = \frac{g}{\sqrt{2}} \bar{\ell}_R \not{W}_R^- V_R N \qquad M_N = V_R^T m_N V_R$$

LR symmetry constrains the Dirac mass $\qquad M_D = M_D^T$

seesaw gives $M_D = i M_N \sqrt{M_N^{-1} M_\nu}$ $\qquad$ MN, Senjanović, Tello '12

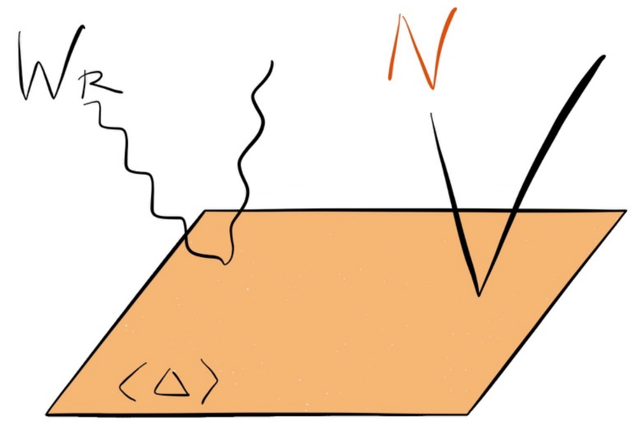






Neutrino Mass origin

$$\mathcal{L}_N = Y_\Delta \, L_R^T \, \Delta_R \, L_R$$



$$M_N = Y_\Delta \, v_R$$

$$\Gamma_{\Delta \to NN} \propto {m_N}^2$$

Neutrino Mass origin

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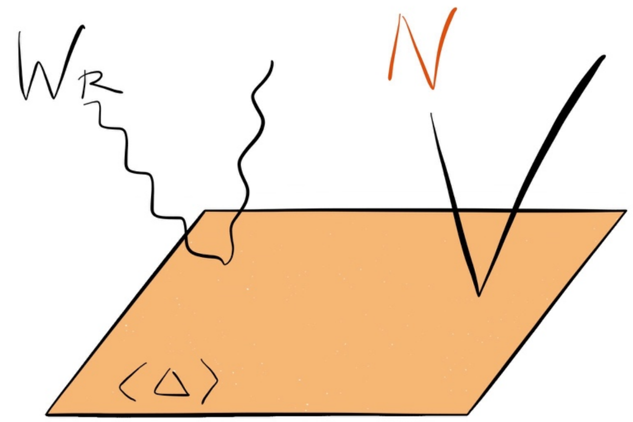

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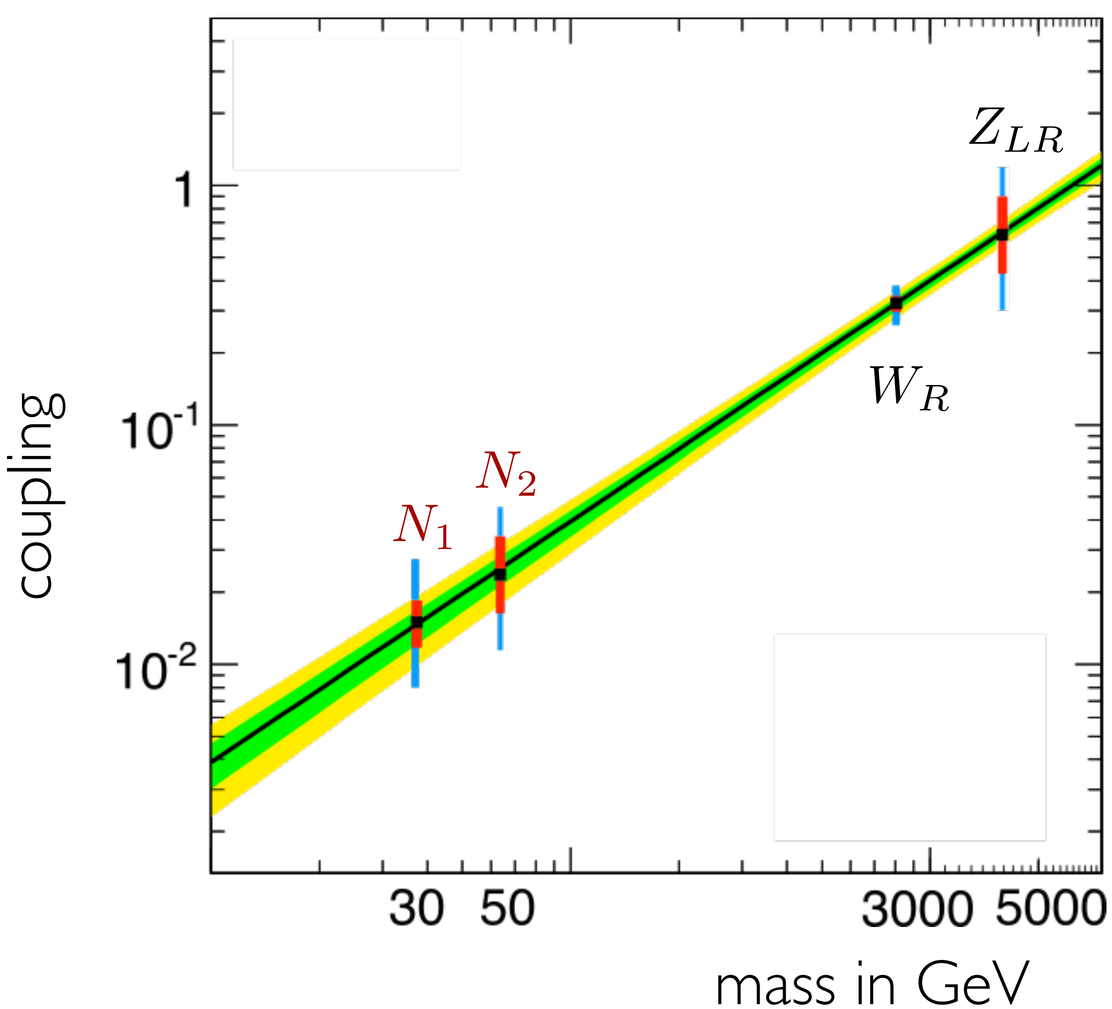
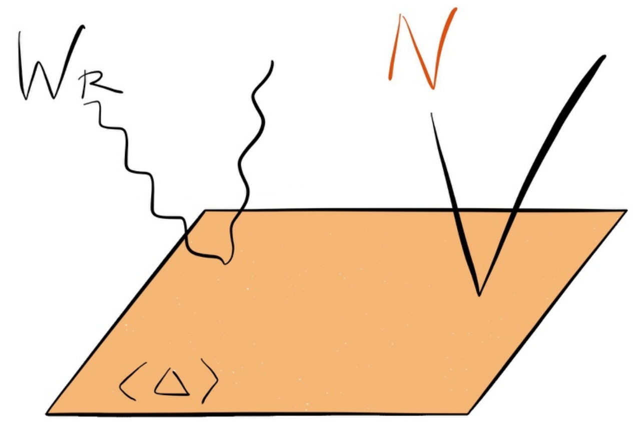


'Higgs' origin of m_N, m_ν

*N*eutrino Mass origin

Δ_R production limited

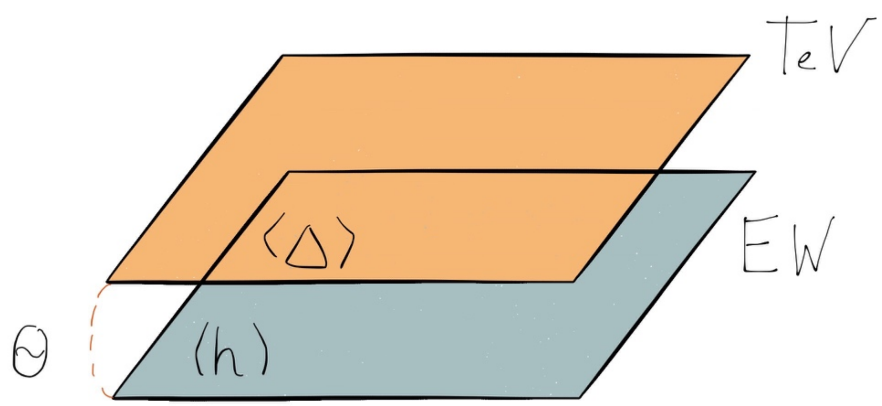
$$\Gamma_{\Delta \to NN} \propto {m_N}^2$$

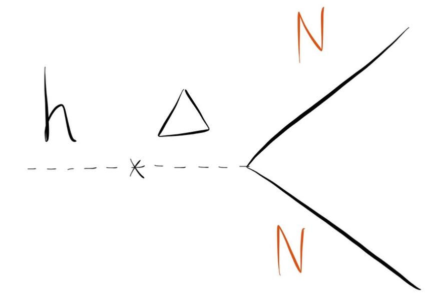


Neutrino Mass origin

$h - \Delta$ mixing

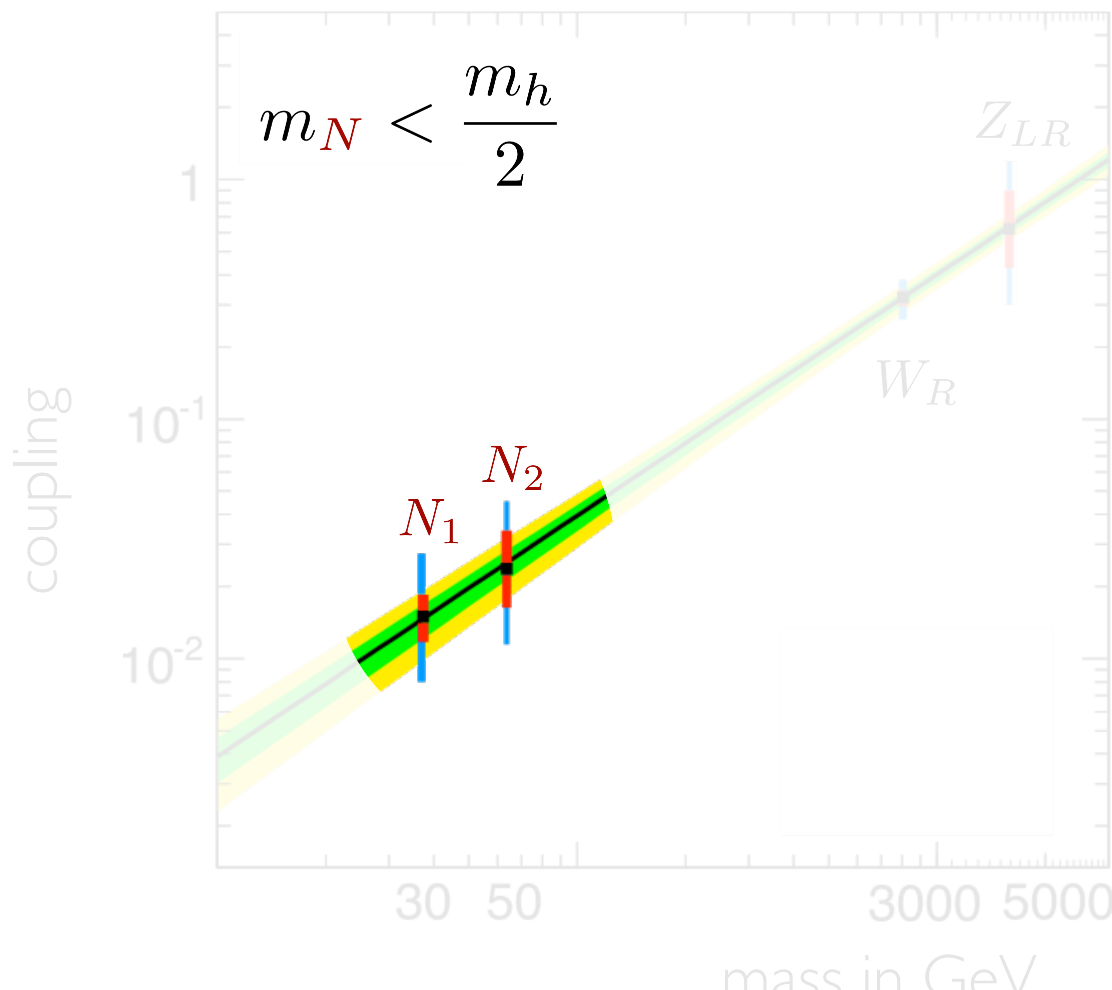
$\Gamma_{h \to NN} \propto \theta^2 \, {m_N}^2$





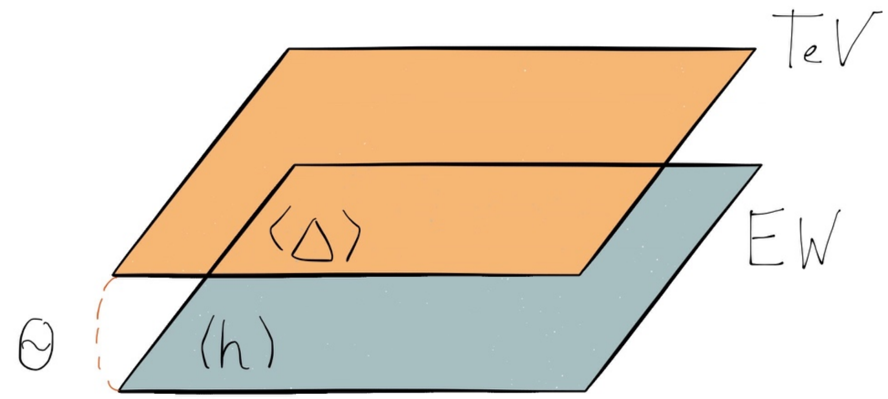
Gunion et al. Snowmass '86

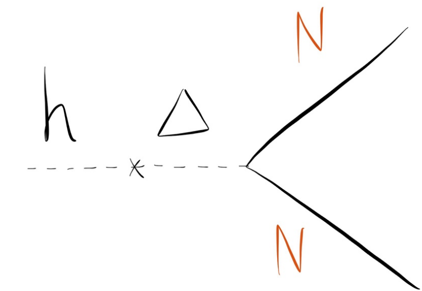
EFT SM+h+N Graesser '07



*N*eutrino Mass origin

$h - \Delta$ mixing

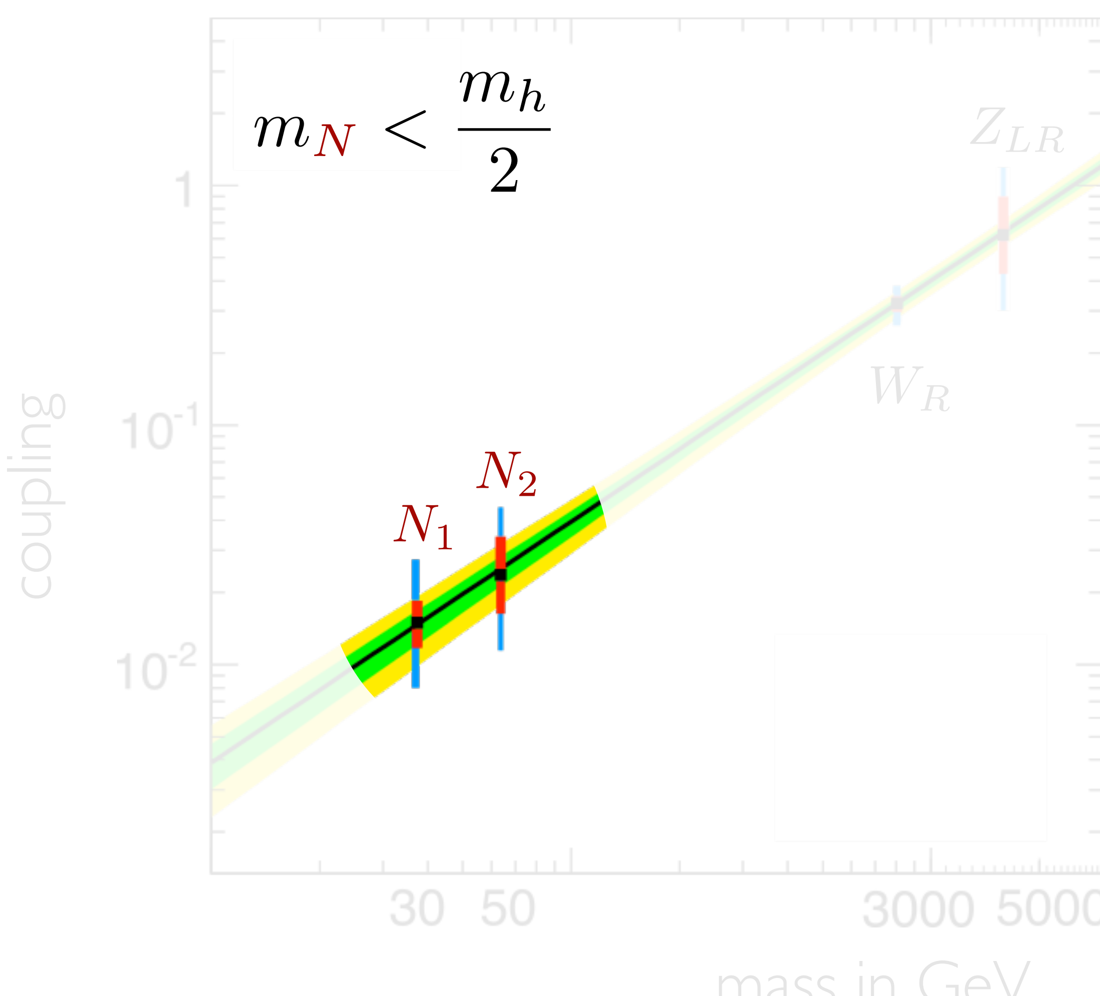




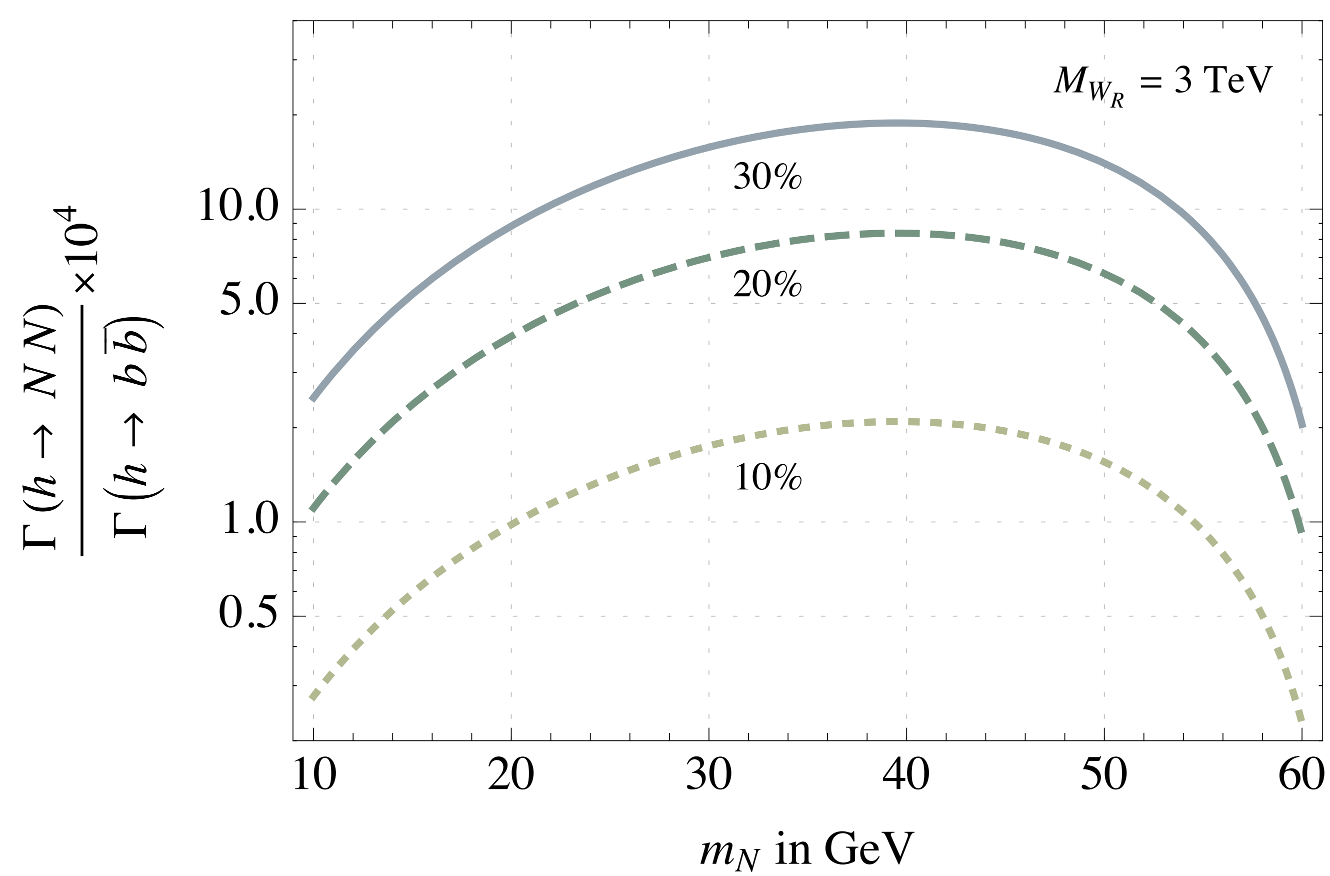
$$\Gamma_{h\to NN} \propto \theta^2\, {m_N}^2$$

Gunion et al. Snowmass '86

EFT SM+*h*+*N* Graesser '07



$$\frac{\Gamma_{NN}}{\Gamma_{b\bar b}} \simeq \frac{\theta^2}{3}\left(\frac{m_N}{m_b}\right)^2\left(\frac{M_W}{M_{W_R}}\right)^2$$



$h \to N N$ @ LHC

Production @ 13 TeV LHC

$$\sigma(gg \to h) = 45 \text{ pb}$$

$h \to {\color{red}NN}$ **event estimate** $m_{\color{red}N} = 40$ GeV $\begin{cases} \sin\theta = 10\,\% \Rightarrow 500 \\ \sin\theta = 20\,\% \Rightarrow 2000 \end{cases}$

LRSM Feyncalc implementation

Roitgrund, Eilam, Bar-shalom '14

adaptation avilable: https://sites.google.com/site/leftrighthep/

MC toolbox

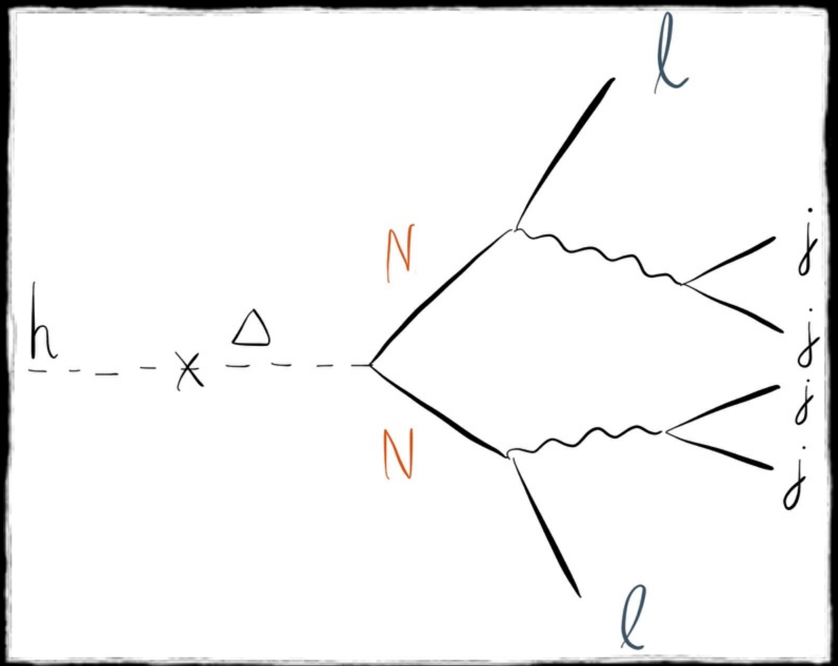
MadGraph5 Pythia6 Delphes3 MadAnalysis5

LNV Higgs decay

N is Majorana

decays via W_R

same-sign breaks *L*



$m_{\ell jj} = m_N$

$m_{\ell\ell 4j} = m_h$

$h \to \ell^\pm \ell^\pm jjjj$ at *parton* level

same and opposite sign & four jets

LFV possible due to light m_N

mass peaks for N and h

no b-jets $V_L^q = V_R^q$

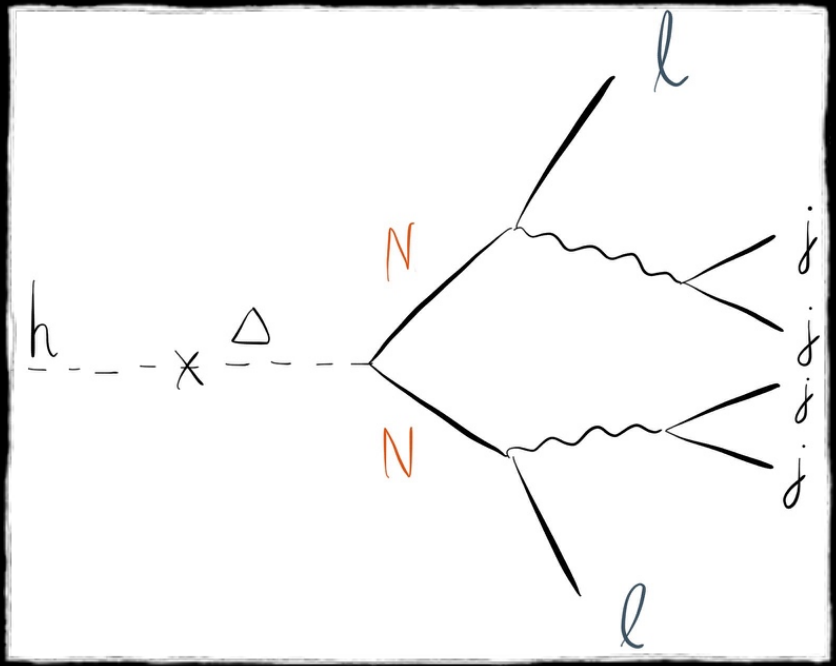
Kiers et al. '02, Zhang et al. '07
Maiezza et al. '10, Senjanović, Tello '14

LNV Higgs decay

N is Majorana

decays via W_R

same-sign breaks *L*



$$\left.\right\} m_{\ell jj} = m_N \qquad \left.\right\} m_{\ell\ell 4j} = m_h$$

$h \to \ell^\pm \ell^\pm jjjj$ at *parton* level

same and opposite sign & four jets

~soft final state $p_T \simeq \dfrac{m_h}{6} \sim 20 \text{ GeV}$

$\gamma(h) \simeq 3$

LFV possible due to light m_N

mass peaks for N and h

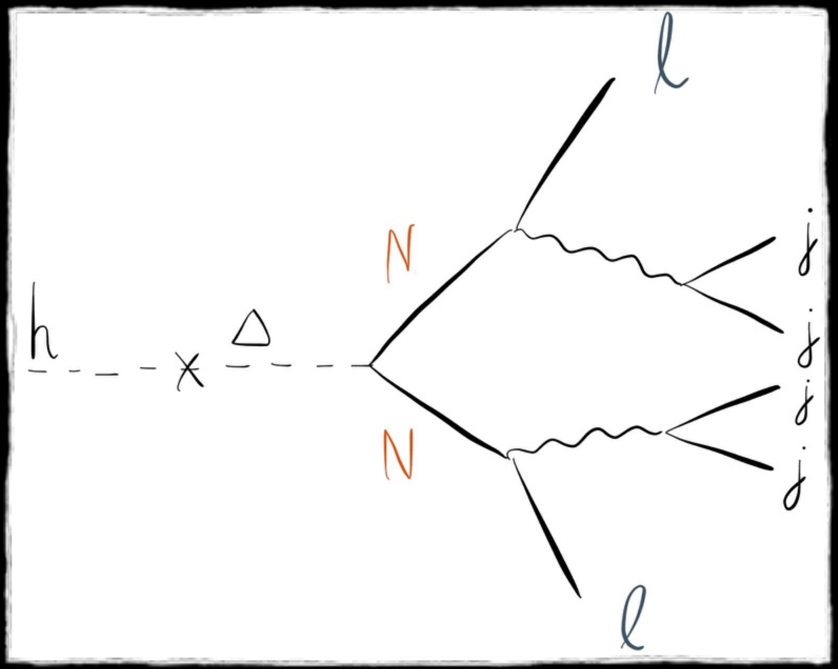
no missing energy

no b-jets $V_L^q = V_R^q$

no SM background

LNV Higgs decay

$h \to \ell^\pm \ell^\pm jjjj$ at *detector* level



$m_{\ell jj} = m_N$

$m_{\ell\ell 4j} = m_h$

Delphes3 ATLAS card

geometric acceptance

Leptons

no muons below $p_T < 10 \text{ GeV}$

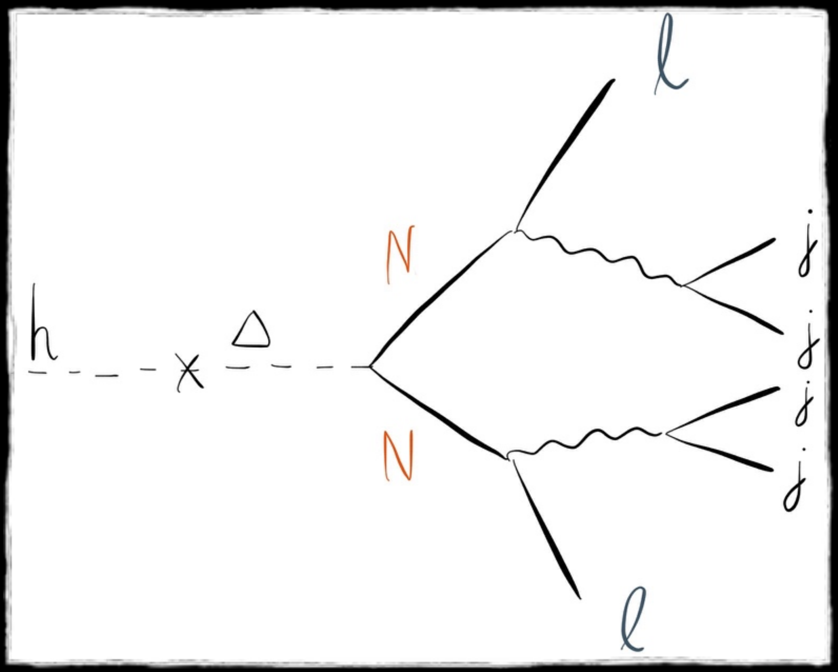
loss of signal by 50%

μ isolation $\Delta R = .3$

$p_T^{min} = 1 \text{ GeV} \quad p_T^{rat\, max} = .07$

LNV Higgs decay

$h \to \ell^\pm \ell^\pm jjjj$ at *detector* level



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loss of signal by 50%

μ isolation $\Delta R = .3$

$p_T^{min} = 1$ GeV $\quad p_T^{rat\,max} = .07$

Jets

anti-k$_T$ $\Delta R = .4$ $\quad p_T^{jmin} = 20$ GeV

loss of jets $n_j = 0, 1, 2, 3$

Missing E

$\not{E} \simeq 15$ GeV

Backgrounds

$\boxed{\text{SM parton level}}$ $\ell^\pm \ell^\pm + n_j j$

$W^\pm W^\pm jj$

$\hookrightarrow \ell \, \nu_\ell$

WZ, ZZ

$t\,\bar{t}$

contain missing energy

simulated with MG5

one lepton prompt, other from *b*

Backgrounds

SM parton level $\ell^{\pm}\ell^{\pm} + n_j j$

$W^{\pm}W^{\pm}jj$ $\hookrightarrow \ell\,\nu_\ell$

WZ, ZZ

$t\bar{t}$

all contain missing energy

simulated with MG5

one lepton prompt, other from *b*

Electron mis-id

Electron charge mis-id & photo-production

ATLAS 1412.0237
CMS 1501.05566

Significant same-sign background

Non-issue for muons

Backgrounds

SM parton level $\ell^\pm \ell^\pm + n_j j$

$W^\pm W^\pm jj$ $\hookrightarrow \ell \nu_\ell$

WZ, ZZ

$t\bar{t}$

all contain missing energy

simulated with MG5

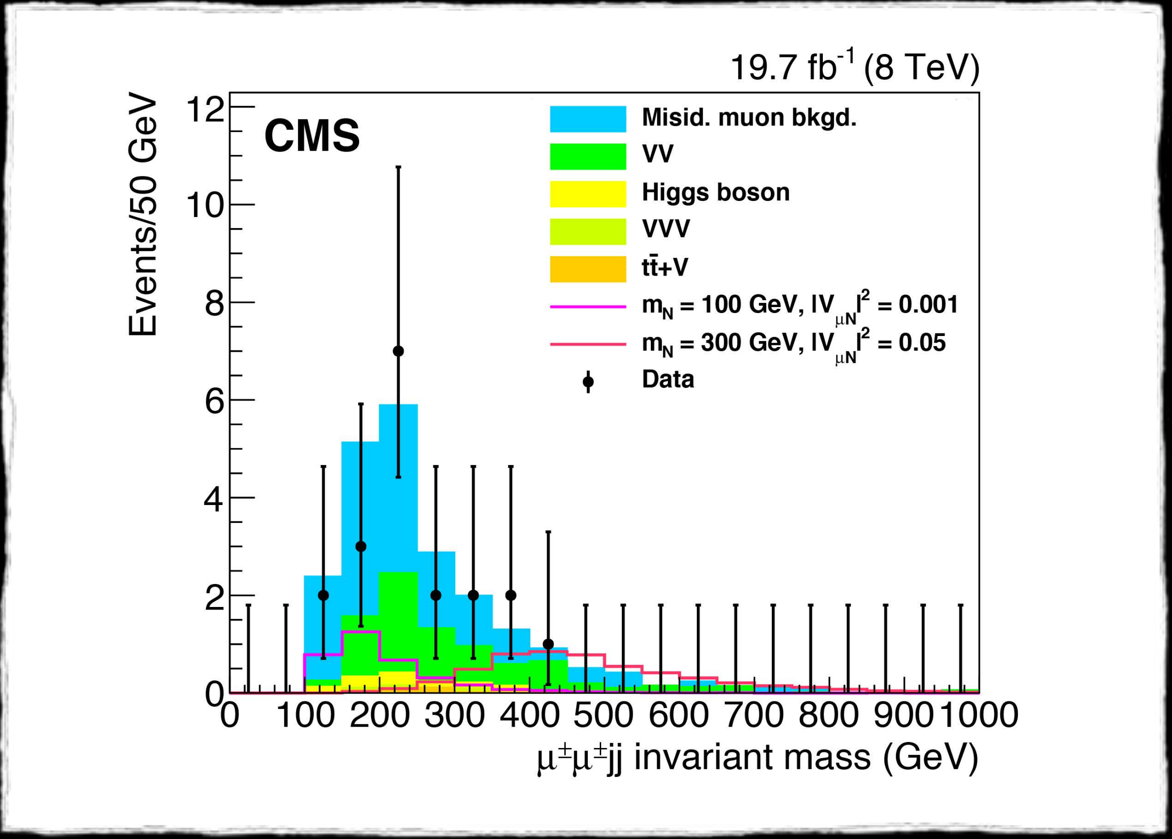
one lepton prompt, other from *b*

Jet mis-id

QCD jets mistaken for muons

Data-driven estimate

CMS 1501.05566

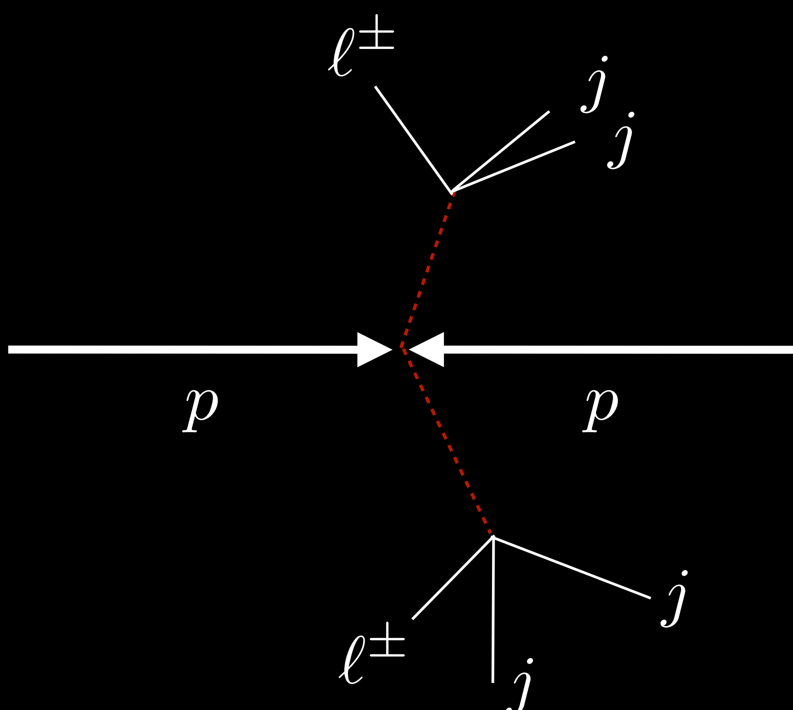


Theorist's approach $QCD = 2.5 \times (VV)$

Displacement

N lifetime significant

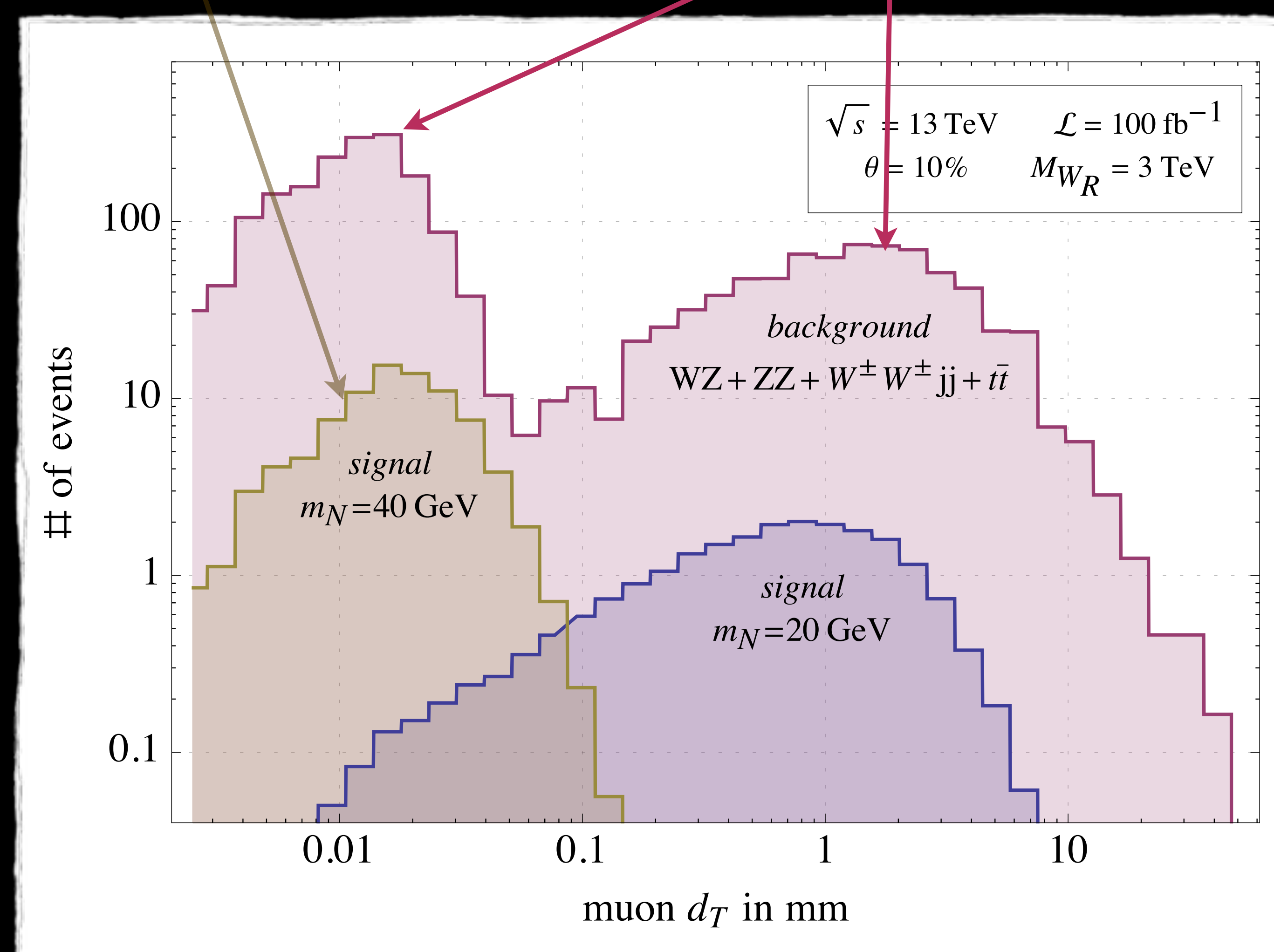
$$\Gamma_N \simeq 3 \times 2 \times 2\,\Gamma_\mu \left(\frac{m_N}{m_\mu}\right)^5 \left(\frac{M_W}{M_{W_R}}\right)^4$$



Resolution $O(10\mu m)$

Correlated

custom smearing module



additional effective discriminant

used on muons only

displaced jets wip

Significance

Cut & count

$$\mathcal{L} = 100\,\mathrm{fb}^{-1}, \quad \sin\theta = 10\,\%, \quad M_{W_R} = 3\,\mathrm{TeV}, \quad n_j = 1,2,3$$

Process	No cuts	Imposed cuts				
		$\mu^\pm\mu^\pm + n_j$	$\not{E}_T$	p_T	m_T	m_{inv}
WZ	2 M	544	143	78	40	20
ZZ	1 M	55	29	16	12	8
$W^\pm W^\pm 2j$	389	115	16	5	3	1
$t\bar{t}$	10 M	509	97	40	22	14
Signal (20)	254	11	11	10	9	8
Signal (40)	543	44	43	41	38	37

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require $\not{E}_T < 30$ GeV

leading μ : $p_T < 55$ GeV

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require $\not{E}_T < 30$ GeV

leading μ : $p_T < 55$ GeV

$$m^T_{\mu\not{p}_T} < 30\,\mathrm{GeV}$$

$$m_{\mu\mu} < 80\,\mathrm{GeV},\; m_{\mu\not{p}_T} < 60\,\mathrm{GeV}$$

Significance

Cut & count

$\mathcal{L} = 100\,\mathrm{fb}^{-1}, \quad \sin\theta = 10\,\%, \quad M_{W_R} = 3\,\mathrm{TeV}, \quad n_j = 1, 2, 3$

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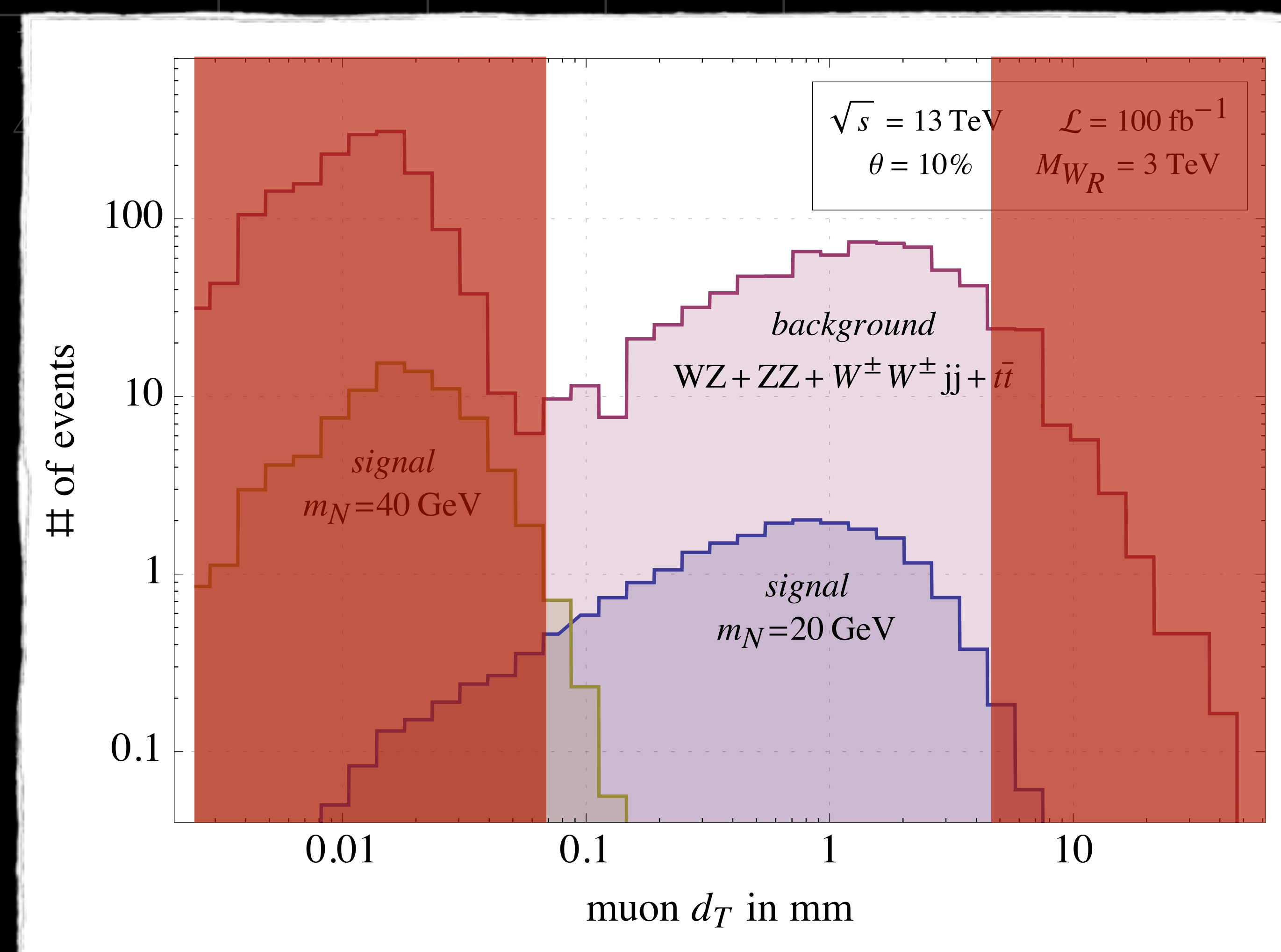
Signal (20)	254					
Signal (40)	543					

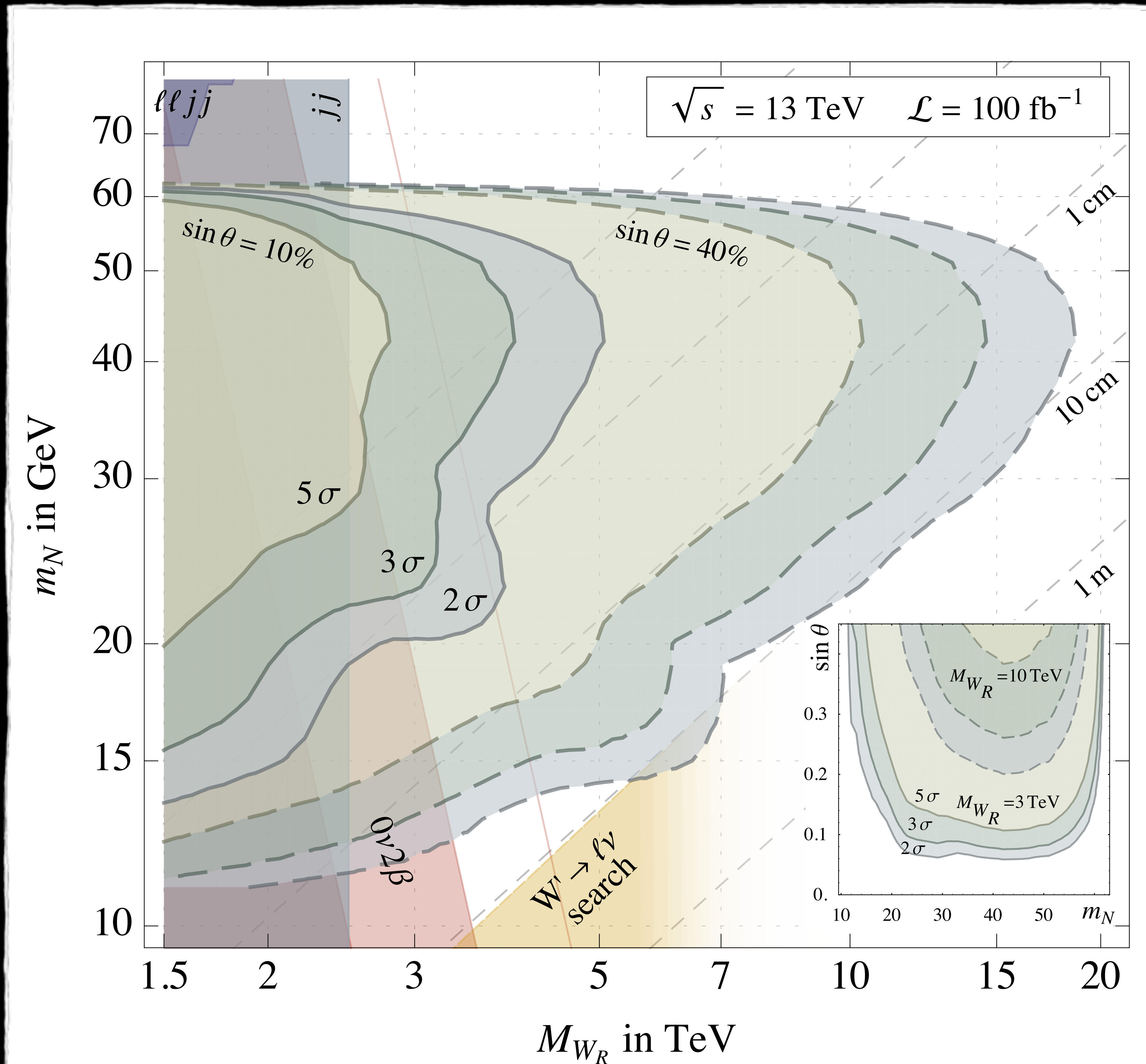
Jet mis-id $QCD \simeq 2.5 \times (VV)$

Sliding d_T window

$$L/10 < d_T < 5L$$

optimize *L*





$\sqrt{s}$ = 13 TeV $\mathcal{L}$ = 100 fb^{-1}
$\ell\ell jj$
jj
$\sin\theta = 10\%$
$\sin\theta = 40\%$
5σ
3σ
2σ
$0\nu2\beta$
$W' \to \ell\nu$ search
1 cm
10 cm
1 m
m_N in GeV
M_{W_R} in TeV
70
60
50
40
30
20
15
10
1.5
2
3
5
7
10
15
20
$\sin\theta$
M_{W_R} =10 TeV
M_{W_R} =3 TeV
0.3
0.2
0.1
0.
m_N

Outlook

Room for improvement

electron, τ and LFV channels

sophisticated search methods

jet displacement

softer muons $p_T < 10 \text{ GeV}$

lower missing energy cut

improved detector simulation

background estimation from data

Experimental search ongoing...

Triggering

trigger impact, specialized for run 2

Pile-up

peak resolution reduction

Appendix slides

some LNV Higgs candidates

Simple see-saws excluded

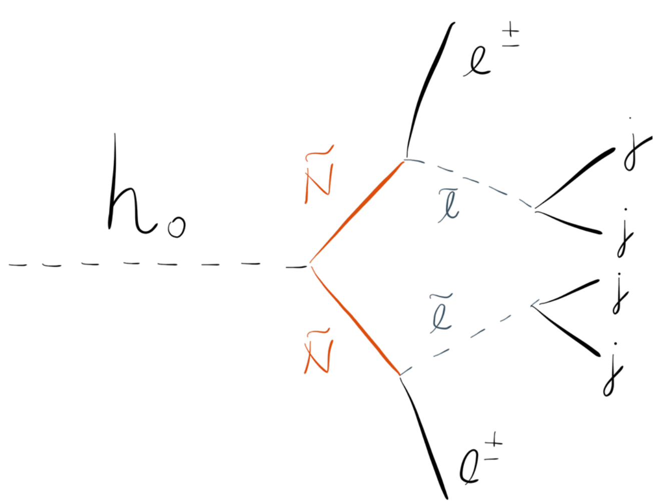
Fourth generation $h \to \nu_4 \nu_4$ — Pilaftsis '92, Carpenter '11

EFT SM + *h* + *N* — Graesser '07

SM + *h* + *N* + singlet scalar — Shoemaker, Petraki, Kusenko '10

Spontaneous *B-L* — $SU(2)_L \times U(1)_R \times U(1)_{B-L}$

RPV SUSY



LNV disfavored — Banks, Carpenter Fortin '08

$m_{\tilde{l}} \simeq m_{\tilde{\nu}}$

needs post-LHC revision

$\ell\ell jj$ = KS search

CMS 1407.3683

jj = dijet search

CMS 1501.04198

$0\nu 2\beta$ = GERDA I & II

GERDA I 1307.4720

* NME uncertainty

$W' \to \ell\nu = \not{E}$ search

CMS 1408.2745