Higgs sector signatures of neutrino mass models

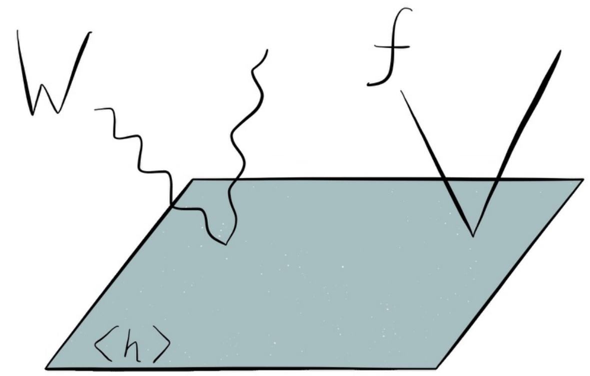
Miha Nemevšek (IJS)

"Neutrinos at the High Energy Frontier" workshop
UMass, ACFI, July 18th 2017

Mass origin

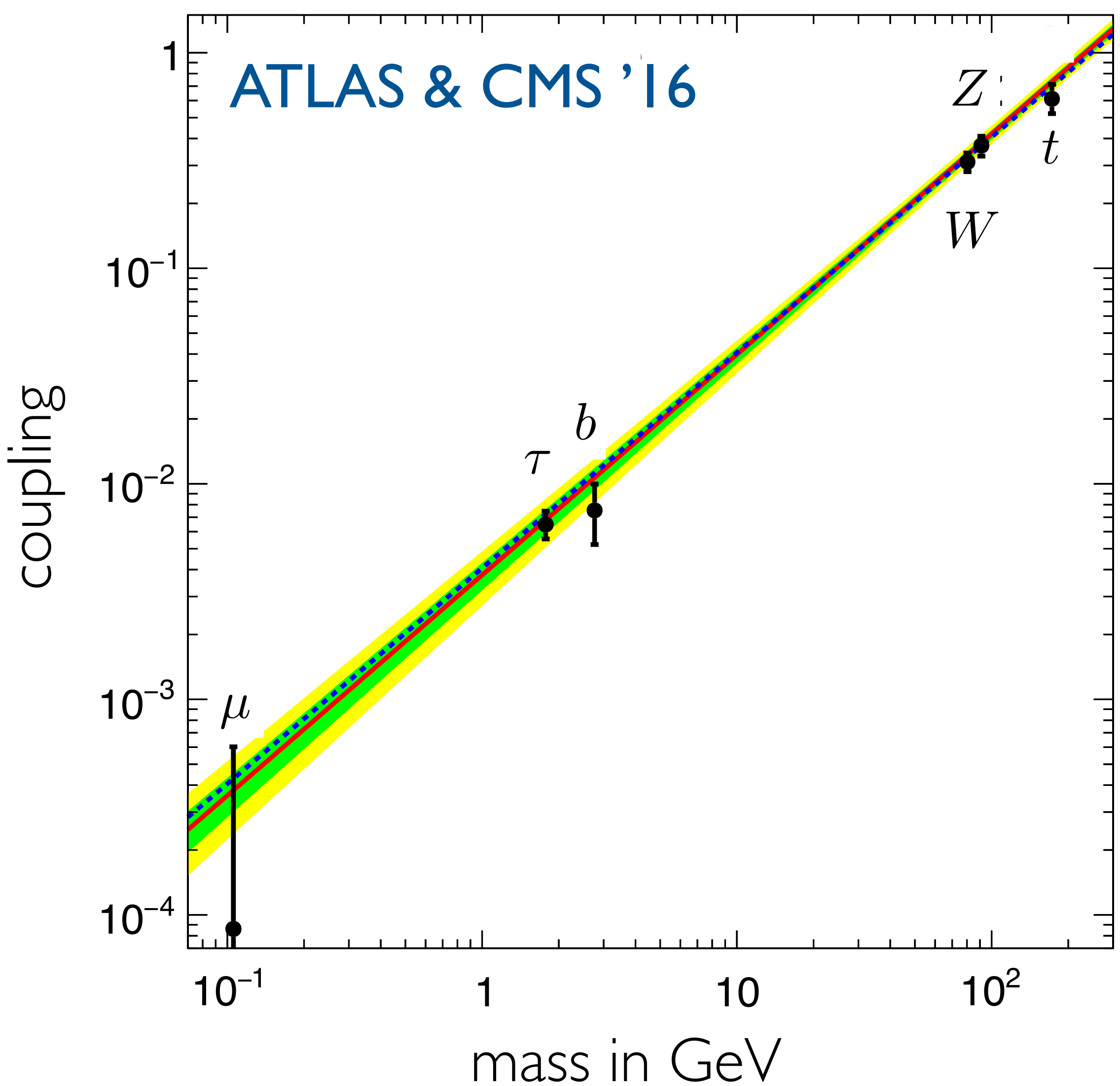
Higgs '64
Weinberg '67

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



$$m_f = y\,v$$

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



Higgs era: discovery of mass origin

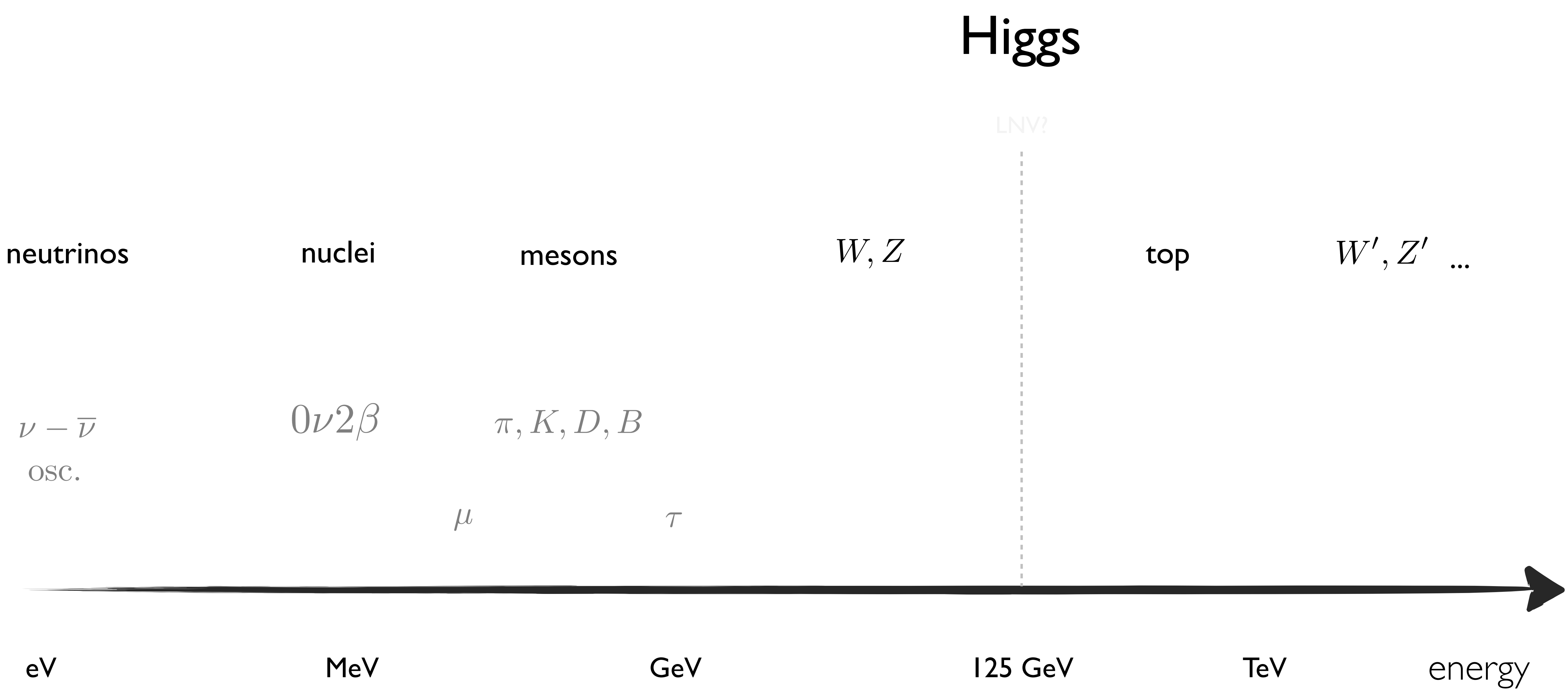
L number conserved

Neutrinos massless

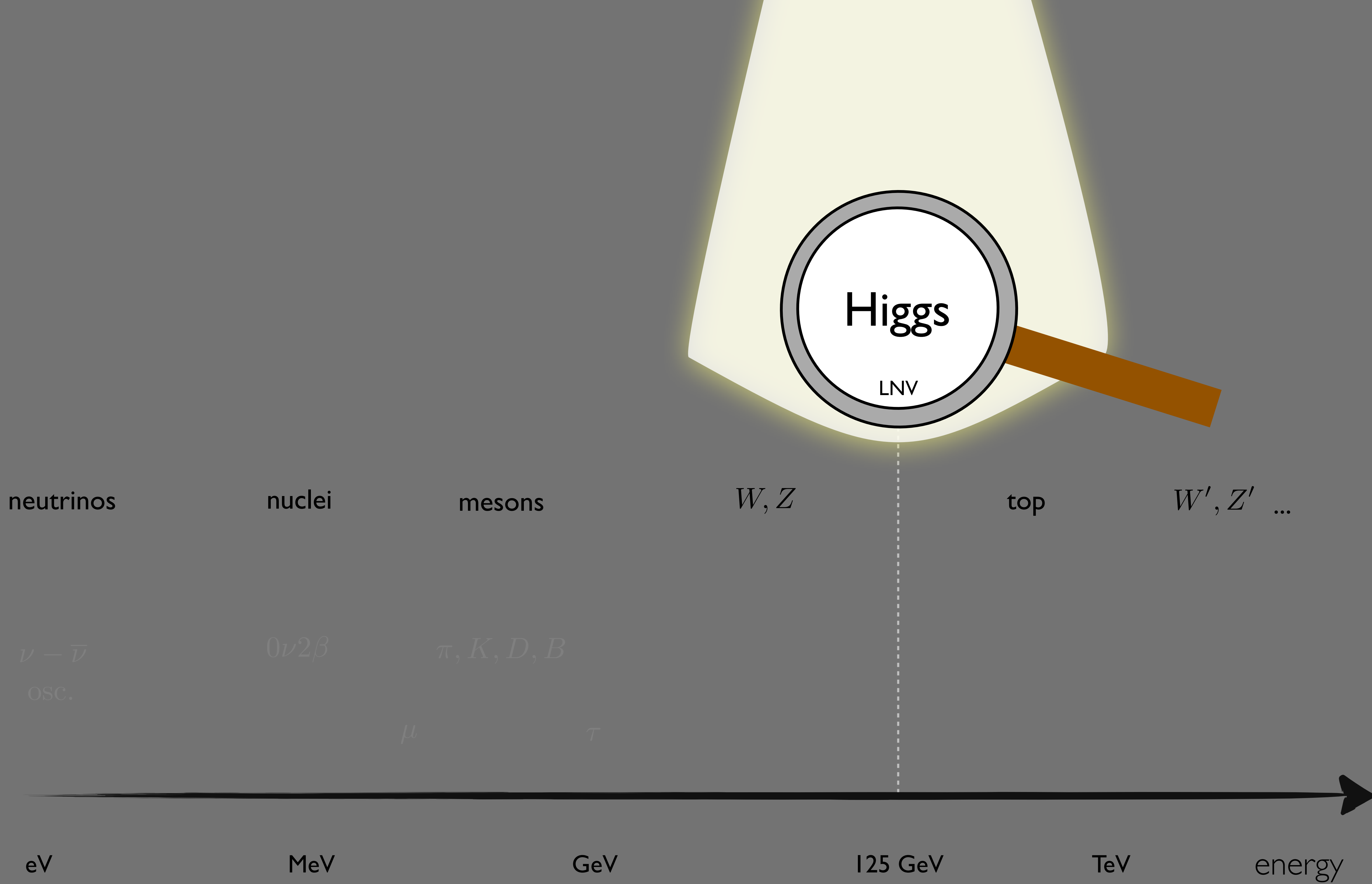
Neutrino Mass

Neutral fermions	$m_M \, \nu^T C \nu$	Majorana '37
Implication is *LNV*	$0\nu 2\beta$	Racah, Furry '37

Lepton number violation searches



Lepton number violation searches



Higgs and Neutrino Mass origin

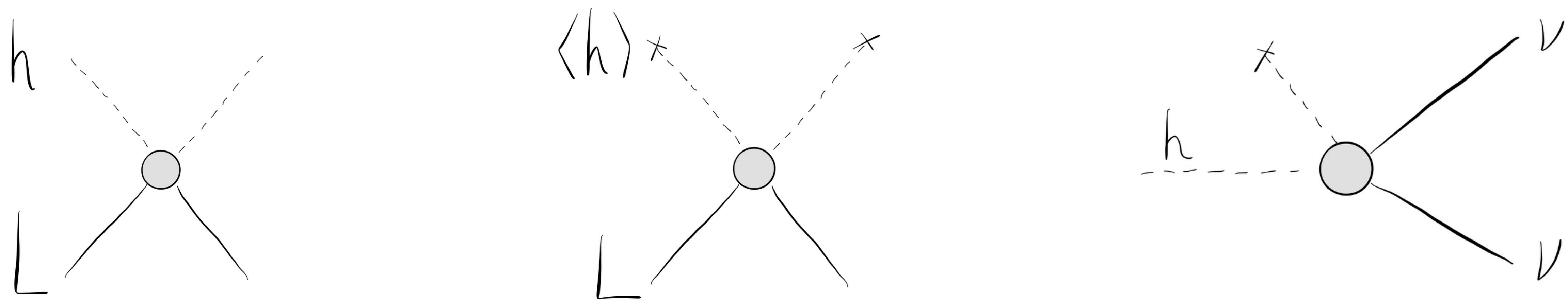
Neutral fermions $m_M \, \nu^T C \nu$ Majorana '37

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

⋮

colliders, mesons, Higgs

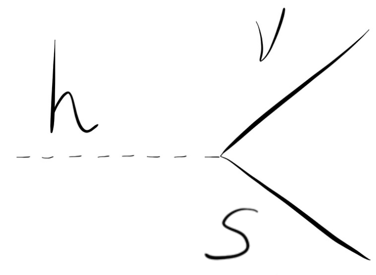
EFT: no light states $\Lambda \gg v$ Weinberg '79

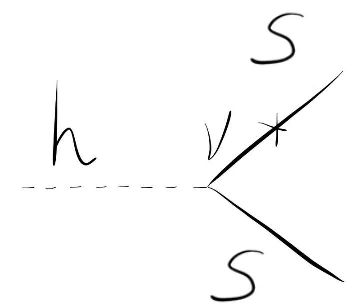


$\tilde{y} \frac{LHLH}{\Lambda}$ $m_\nu = \tilde{y} \frac{v^2}{\Lambda}$ $\Gamma_{h \to \nu\nu} \propto m_\nu^2$

Higgs and Neutrino Mass origin

type I





type III ruled out

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

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

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

Casas-Ibarra ’01

Dev, Franceschini, Mohapatra ’12
Cely, Ibarra, Molinaro, Petcov ’12
talk by Das

Pilaftsis ’91

Ambiguous relation

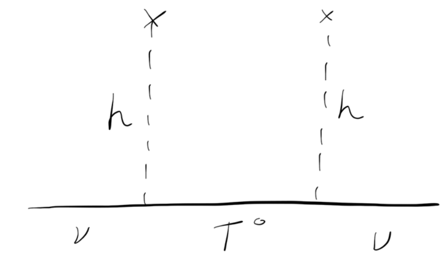
Fine-tuned, ‘inverse’

LNV mode forbidden

Delphi ’91, CMS ’15

Higgs and Neutrino Mass origin

type I



type III **ruled out**

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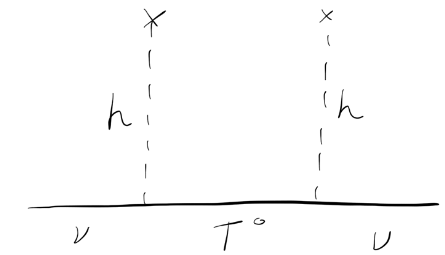

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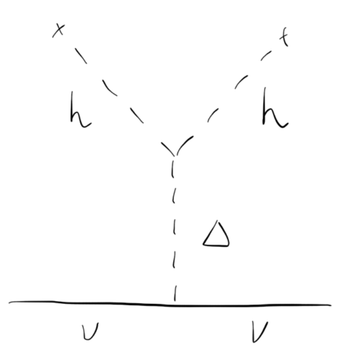
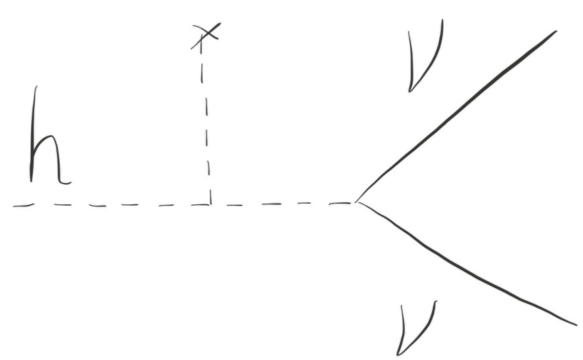


type II

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



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

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

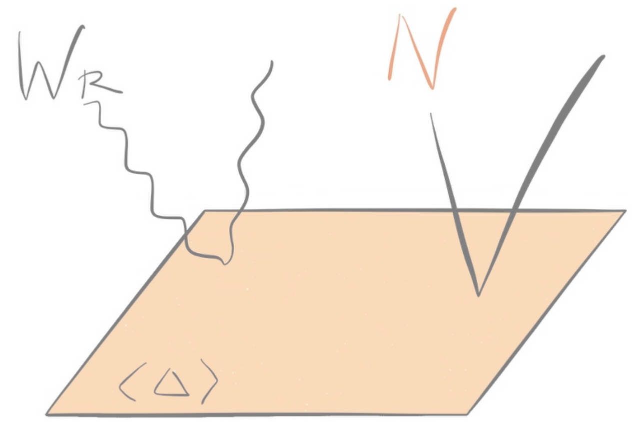
Left-Right

Pati, Salam '74
Mohapatra, Pati '75
talk by Rabi

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
Mohapatra, Pati '75
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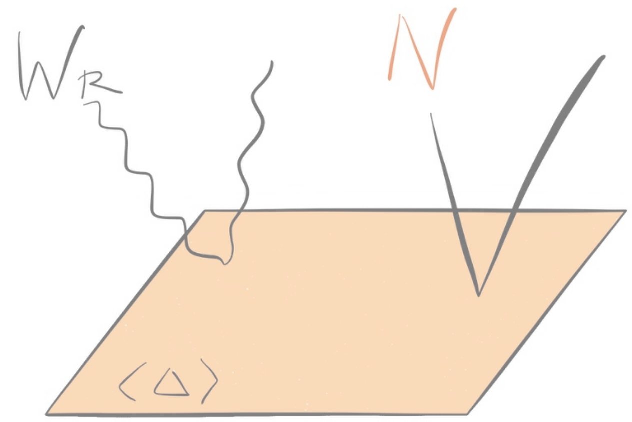


Spontaneous parity breaking

Senjanović, Mohapatra '75

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

$$\Phi = \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix} \qquad \langle \Phi \rangle = \begin{pmatrix} v & 0 \\ 0 & 0 \end{pmatrix}$$

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

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

see appendix for $\phi_2^0, \Delta_L, \Delta_R^{++}$

Left-Right

Pati, Salam '74
Mohapatra, Pati '75

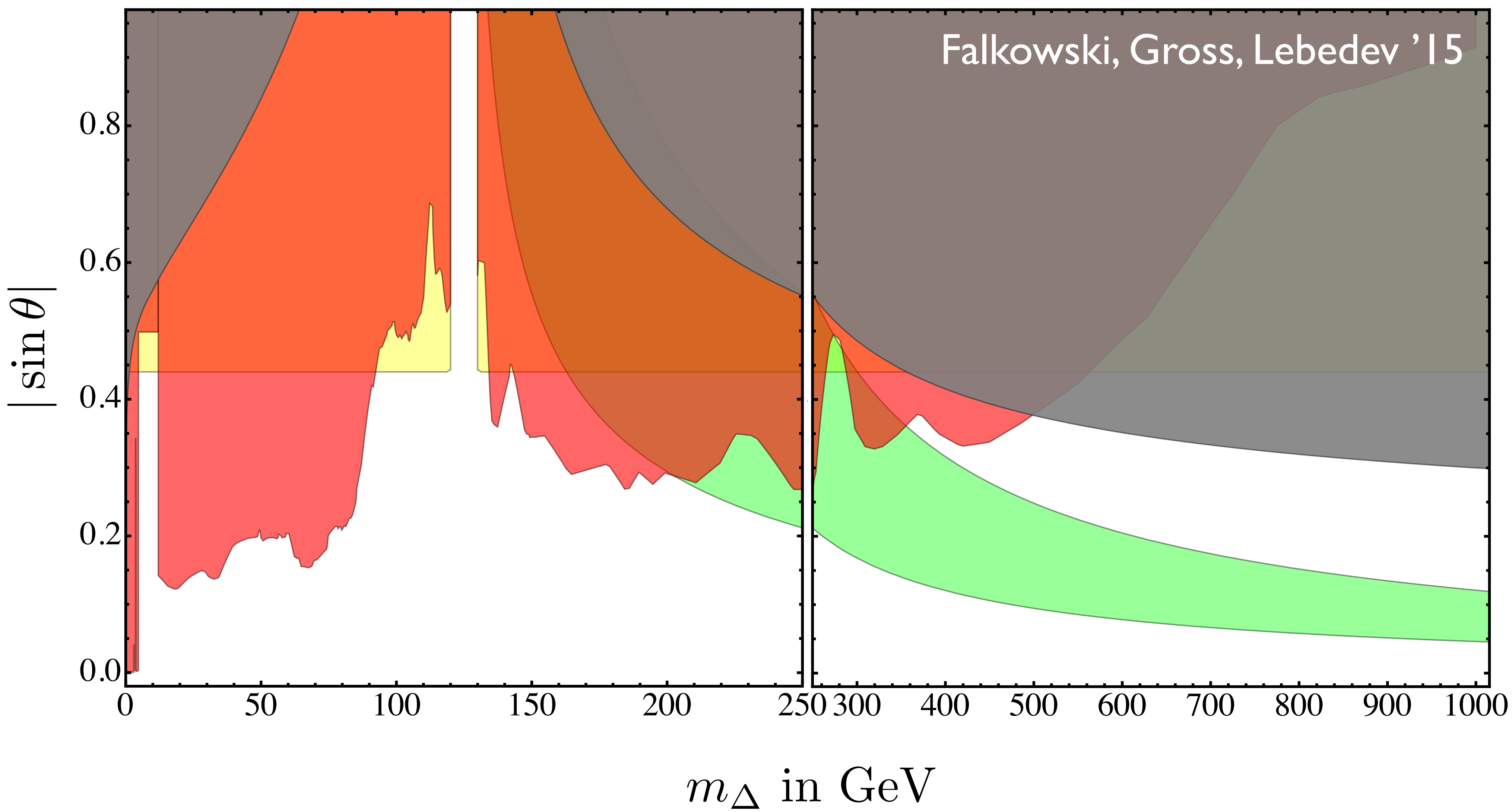
talk by Rabi

Minimal model

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

Spontaneous
parity breaking

Senjanović, Mohapatra '75



Future collider
outlook

$|\sin\theta| < .34$

Buttazzo, Sala, Tesi '15

Left-Right

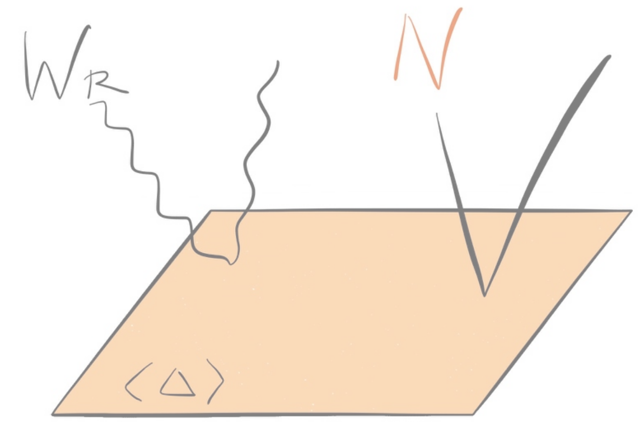
Pati, Salam ’74
Mohapatra, Pati ’75

talk by Rabi

Minimal model

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

Minkowski ’77
Mohapatra, Senjanović ’79



Spontaneous parity breaking

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

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

same for $\mathcal{C}$-symmetry

$$\langle\Delta_R\rangle = \begin{pmatrix} 0 & 0 \\ v_R & 0 \end{pmatrix} \qquad h-\Delta \text{ mixing: } \theta \simeq \left(\frac{\alpha}{2\rho}\right)\left(\frac{v}{v_R}\right) \lesssim .44$$

e.g. Falkowski, Gross, Lebedev ’15

Indirect flavor limits

early $M_{W_R} > 1.6\ \text{TeV}$

Beal, Bander, Soni ’82, ...

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

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

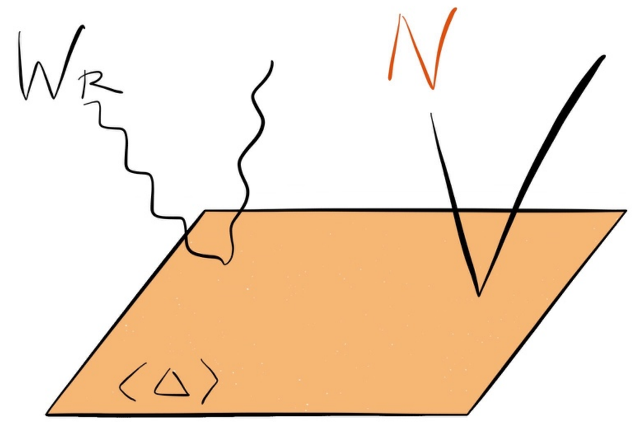
*barring strong CP

Maiezza, MN ’14

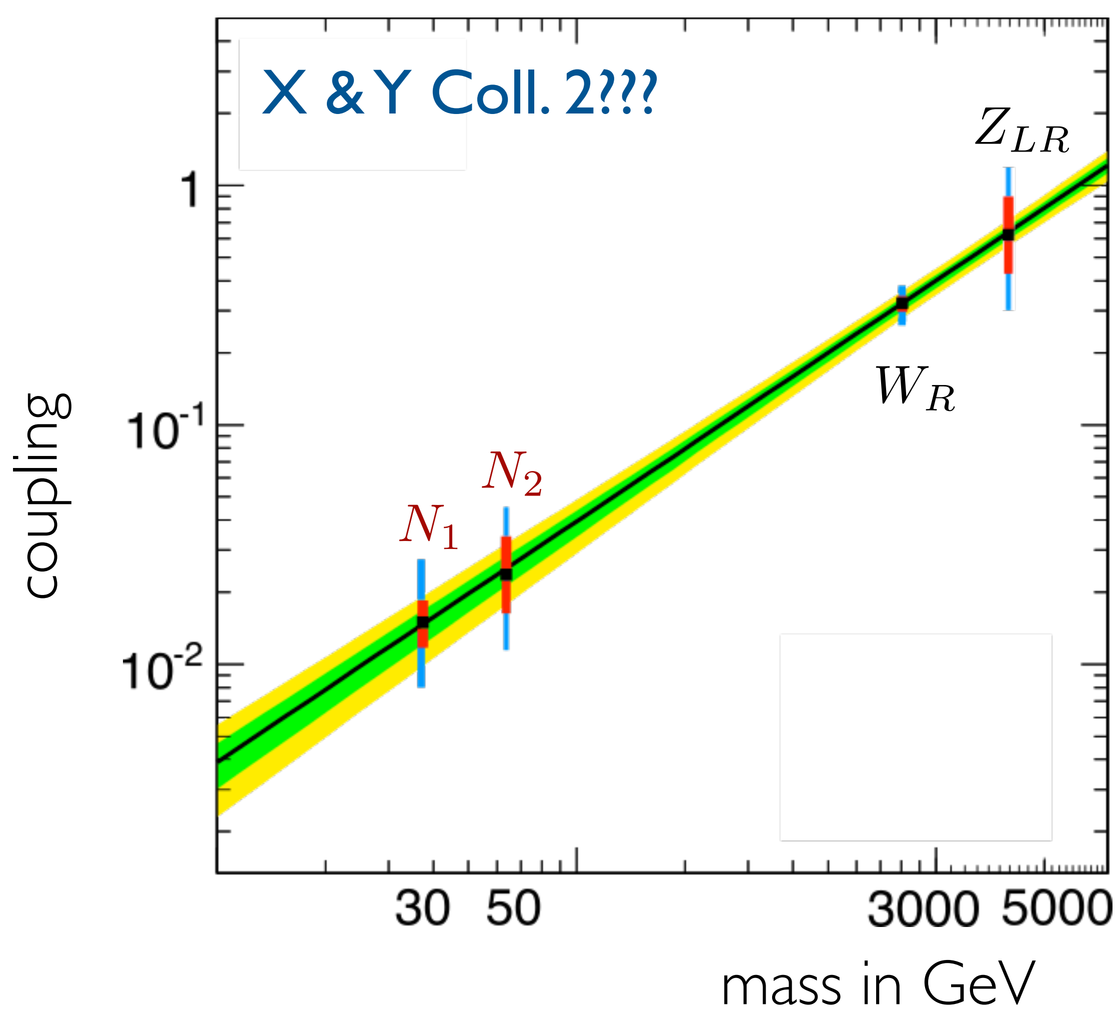
Neutrino mass origin

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

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



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



‘Higgs‘ origin of Majorana neutrinos

$$m_N \, , m_\nu$$

$$\Downarrow$$

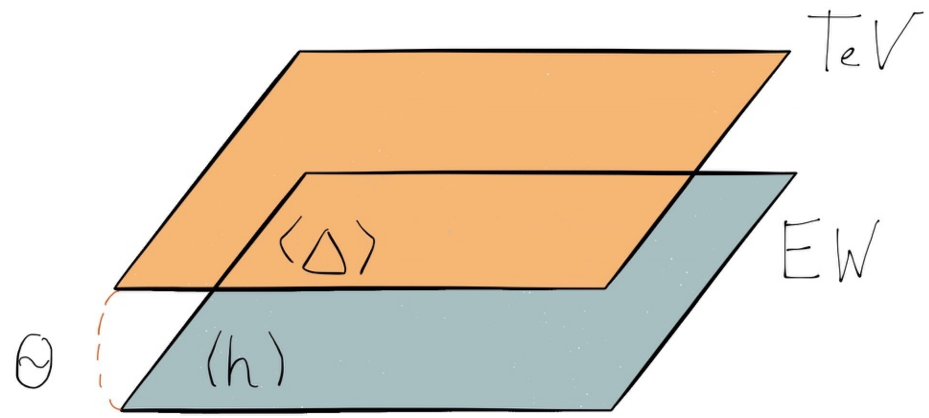
‘Majorana’ Higgses

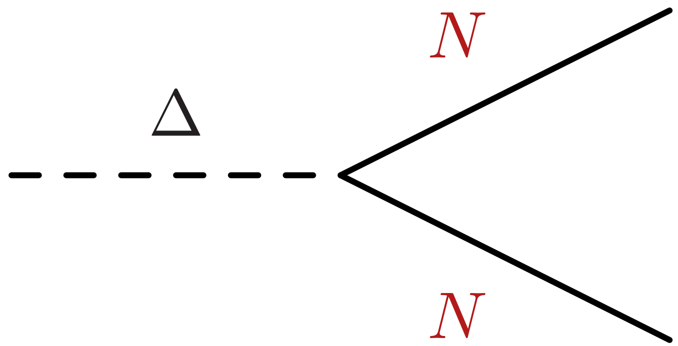
$$h, \; \Delta$$

‘Majorana’ Higgses

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

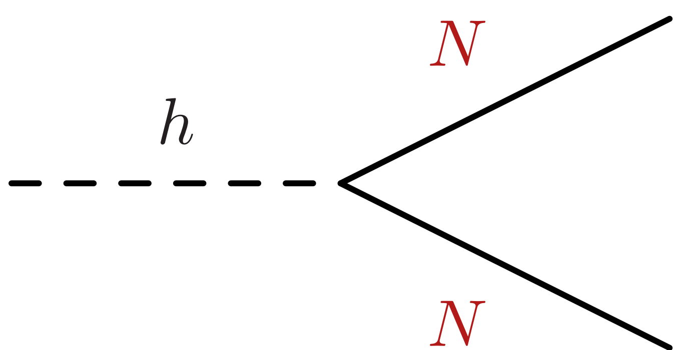
$$m_\Delta = ?$$



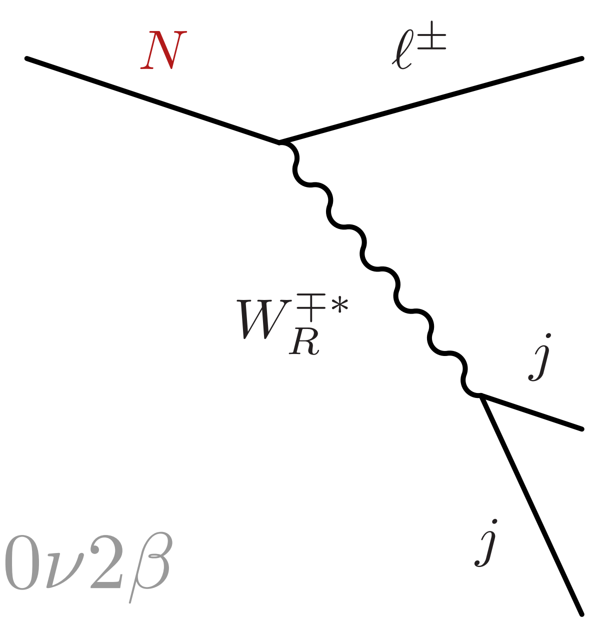


$$\Gamma_{h\to NN} \propto s_\theta^2\, {m_N}^2$$

$$m_h = 125 \text{ GeV}$$

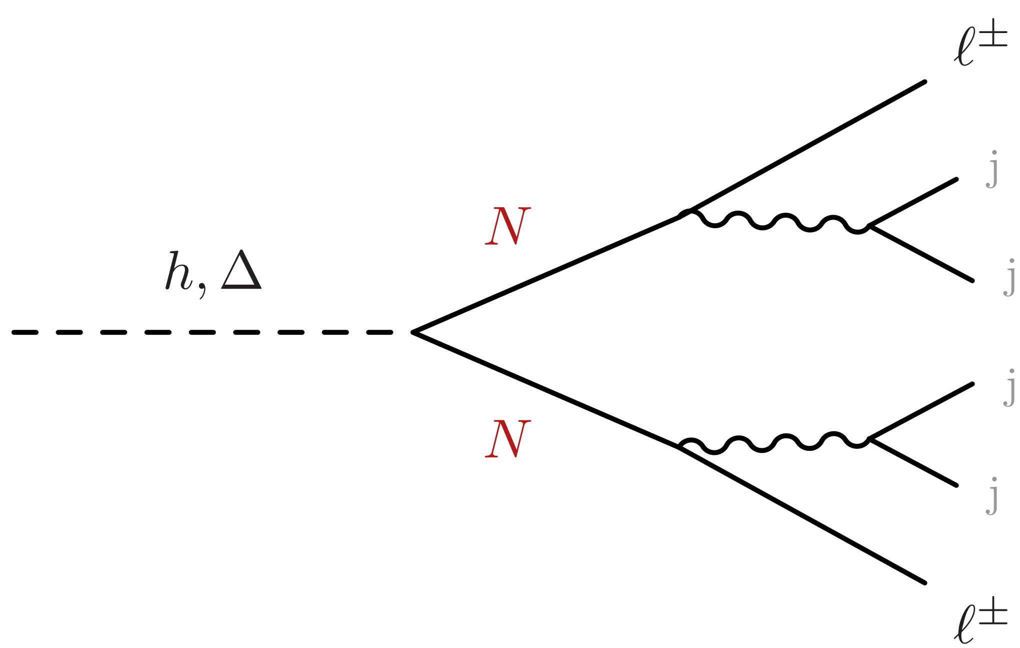


Majorana connections



$0\nu 2\beta$

Neutrino mass origin LNV decays

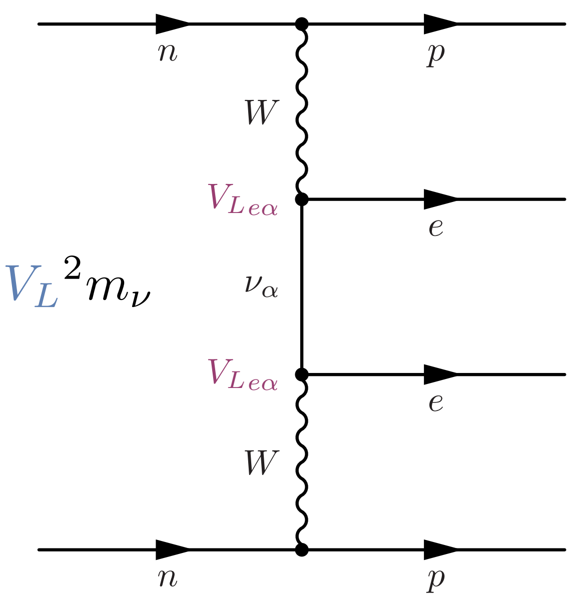


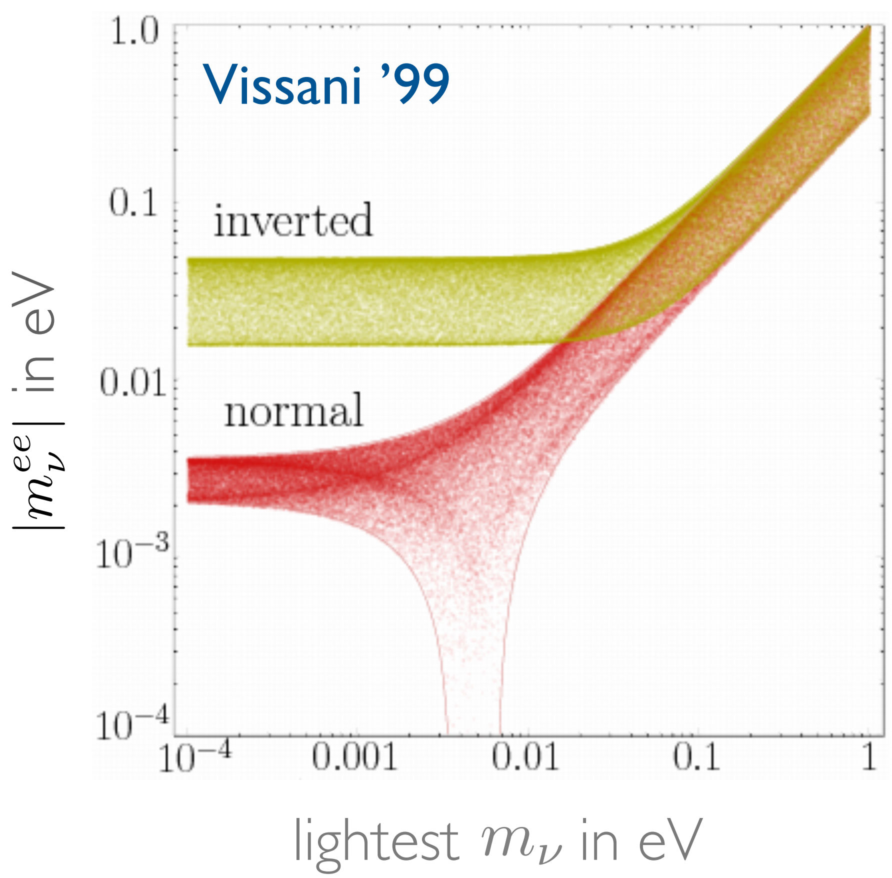
$\Delta L = 0, 2$

Majorana LNV connections

Standard

$$m_\nu^{ee} = \sum_\nu V_L{}^2 m_\nu$$



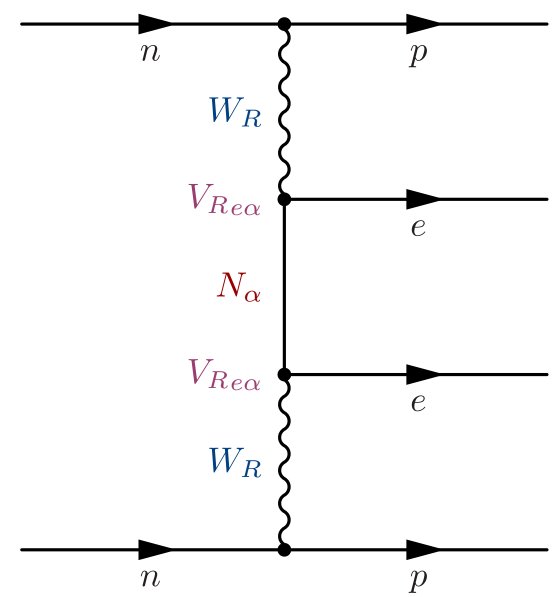


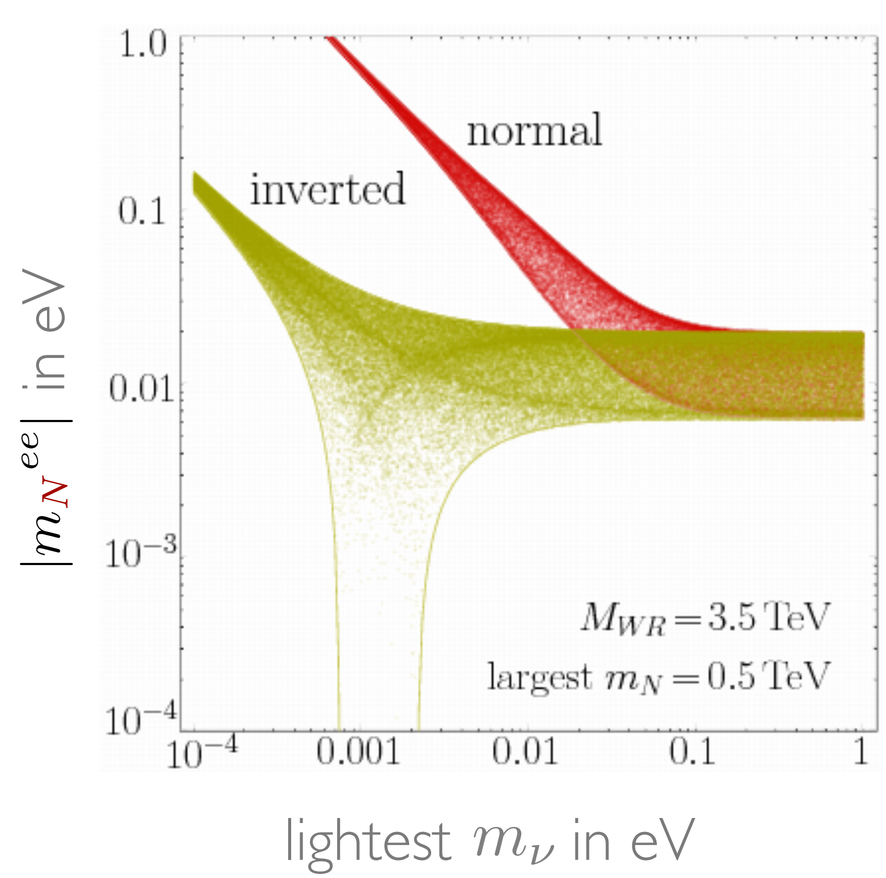
New physics

talk by Rabi

Mohapatra, Senjanović '79, '80

$$m_N^{ee} = p^2 \frac{M_{W_L}^4}{M_{W_R}{}^4} \sum_N \frac{V_R{}^2}{m_N}$$





includes LFV and triplets

Tello, MN, Nesti, Senjanović, Vissani '10

Dirac mass predicted in LR

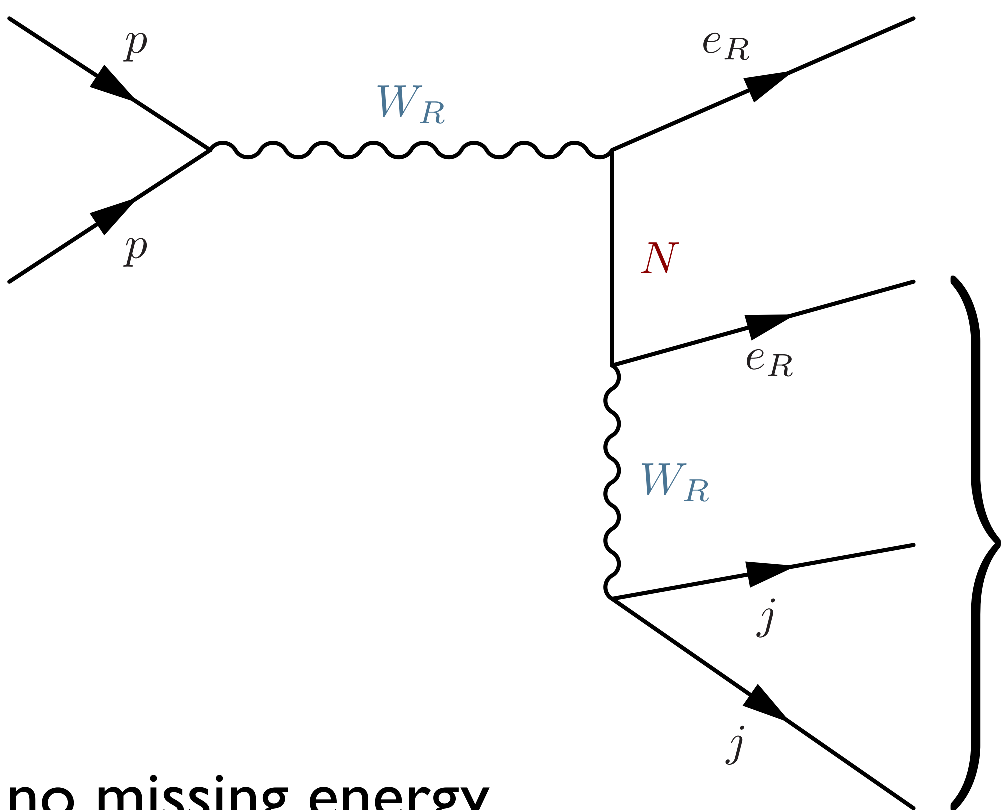
Tello, MN, Senjanović '12

Majorana LNV connections

talks by Rabi, Das

LHC

Keung, Senjanović, '83



no missing energy

$$m^{\text{inv}}_{e_R jj} = m_N$$

reach of 5-6 TeV at 14 TeV

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

Neutrino jets

Mitra et al. '16

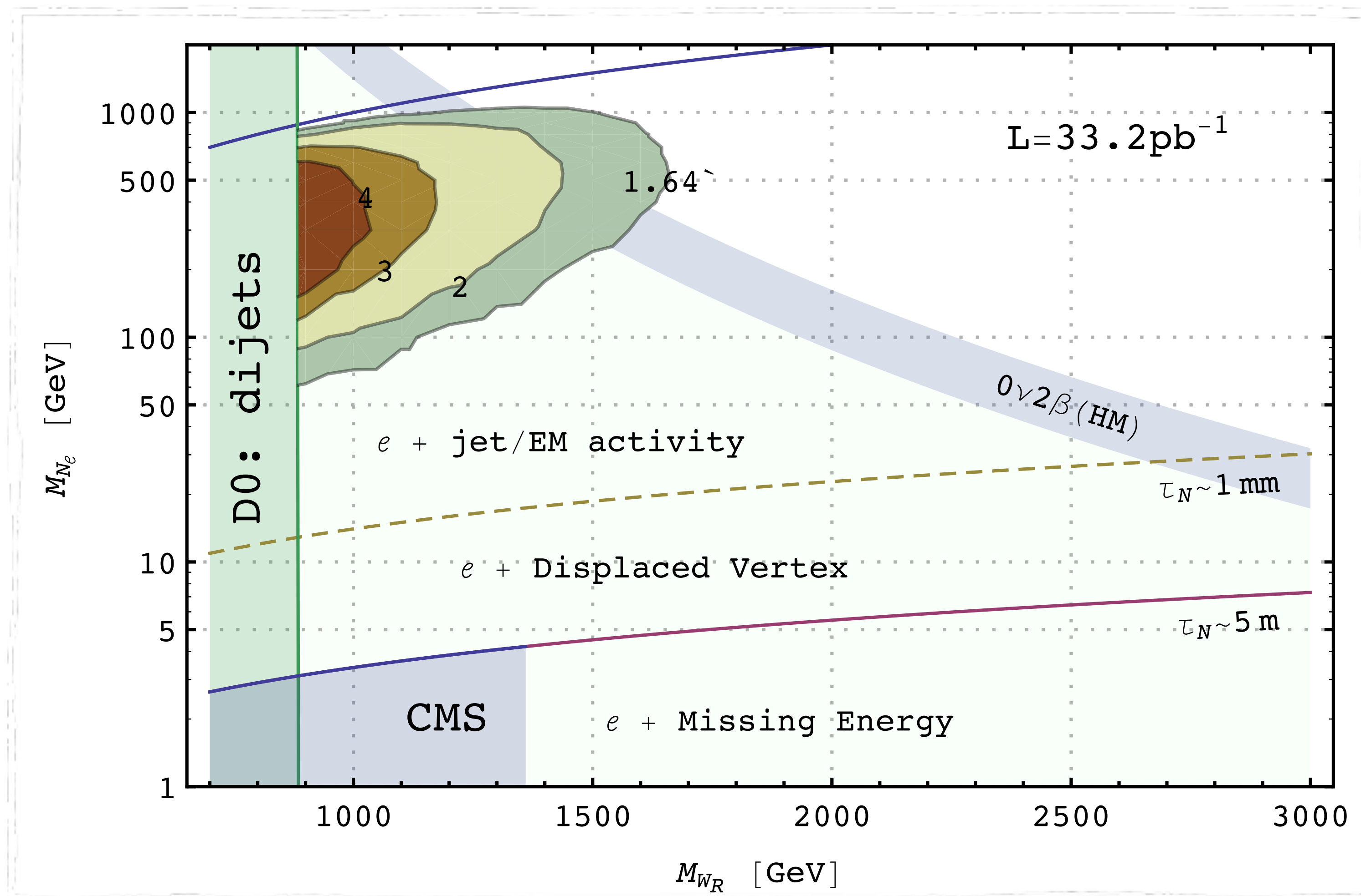
Measure M_N directly

MN, Nesti, Senjanović, Zhang '10

Unambiguous seesaw

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

MN, Senjanović, Tello '12



missing E channel $M_{W'} > 4.7\ \text{TeV}$ ATLAS 1703.09127

di-jet channel $M_{W'} > 5.11\ \text{TeV}$ ATLAS CONF-2017-016

Majorana LNV connections

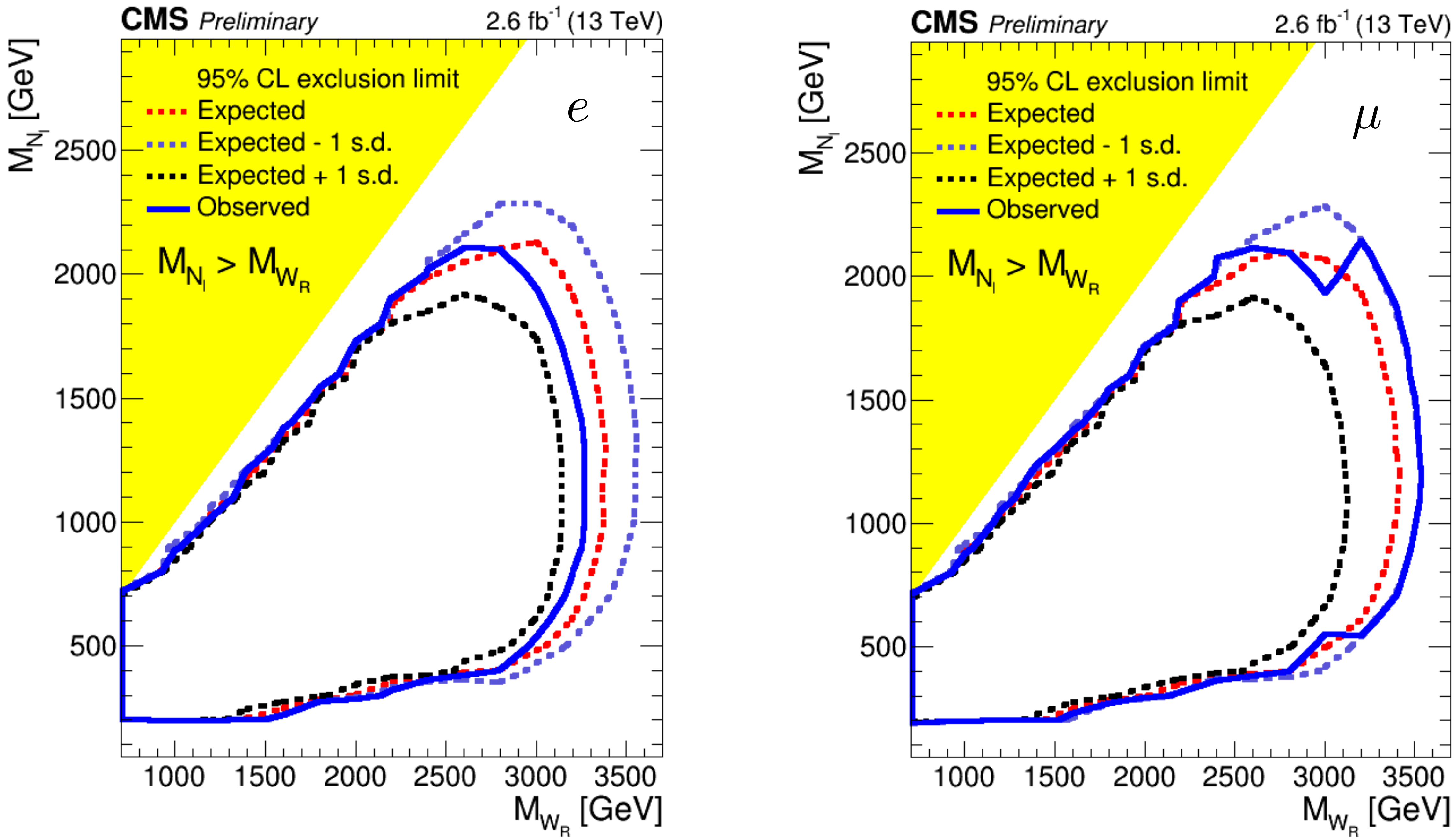
LHC

Keung, Senjanović, ’83

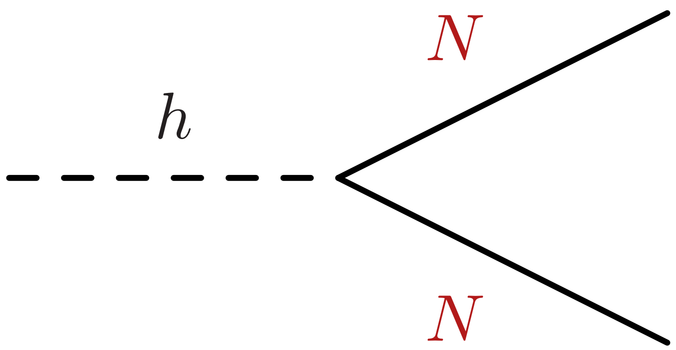
CMS PAS-EXO-12-017
CMS 1210.2402
ATLAS 1203.54203

CMS-EXO-16-023 e and mu

CMS-EXO-16-016, 2.2 fb^{-1} (13 TeV) $M_{W_R,N_\tau} > 2.3$ TeV
CMS-EXO-16-023, 12.9 fb^{-1} (13 TeV) $M_{W_R,N_\tau} > 3.2$ TeV



‘Majorana’ SM Higgs

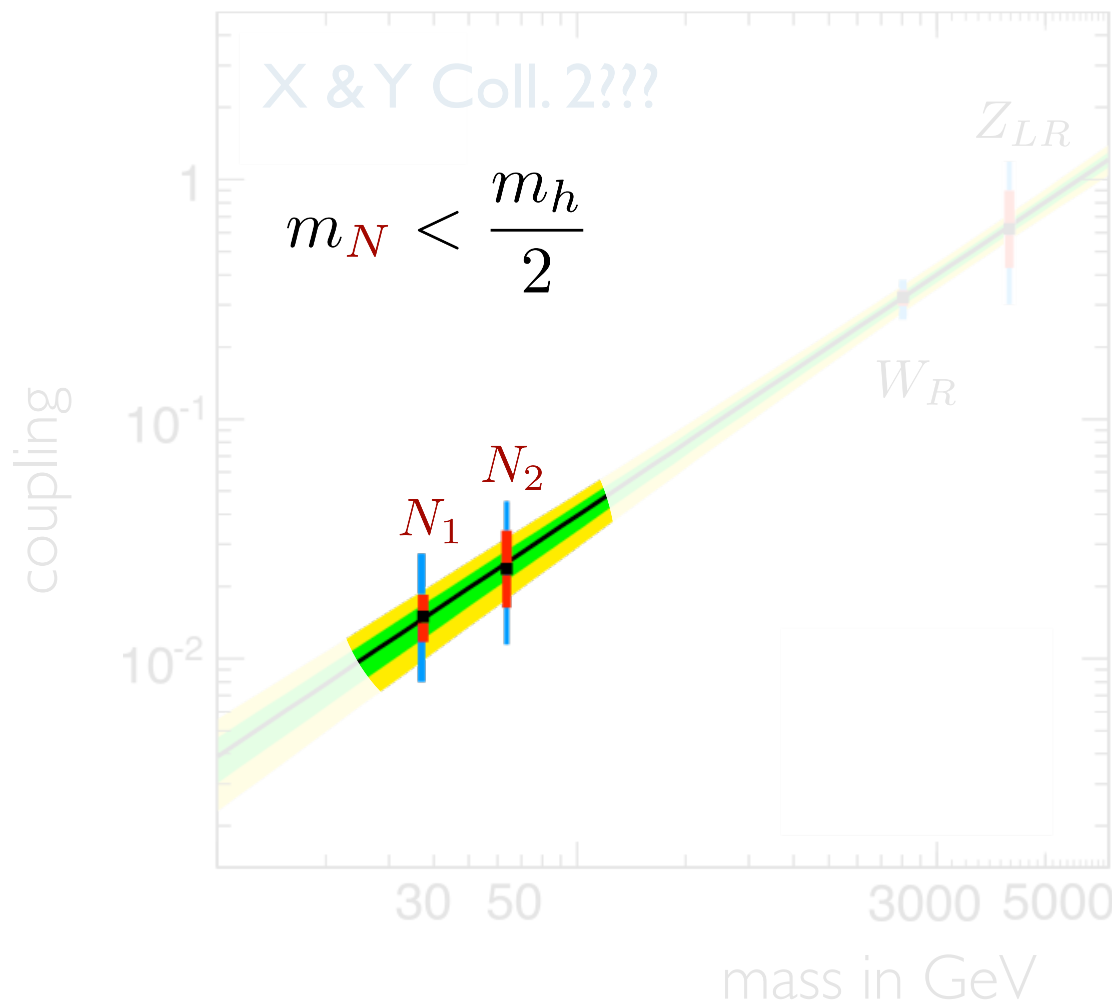


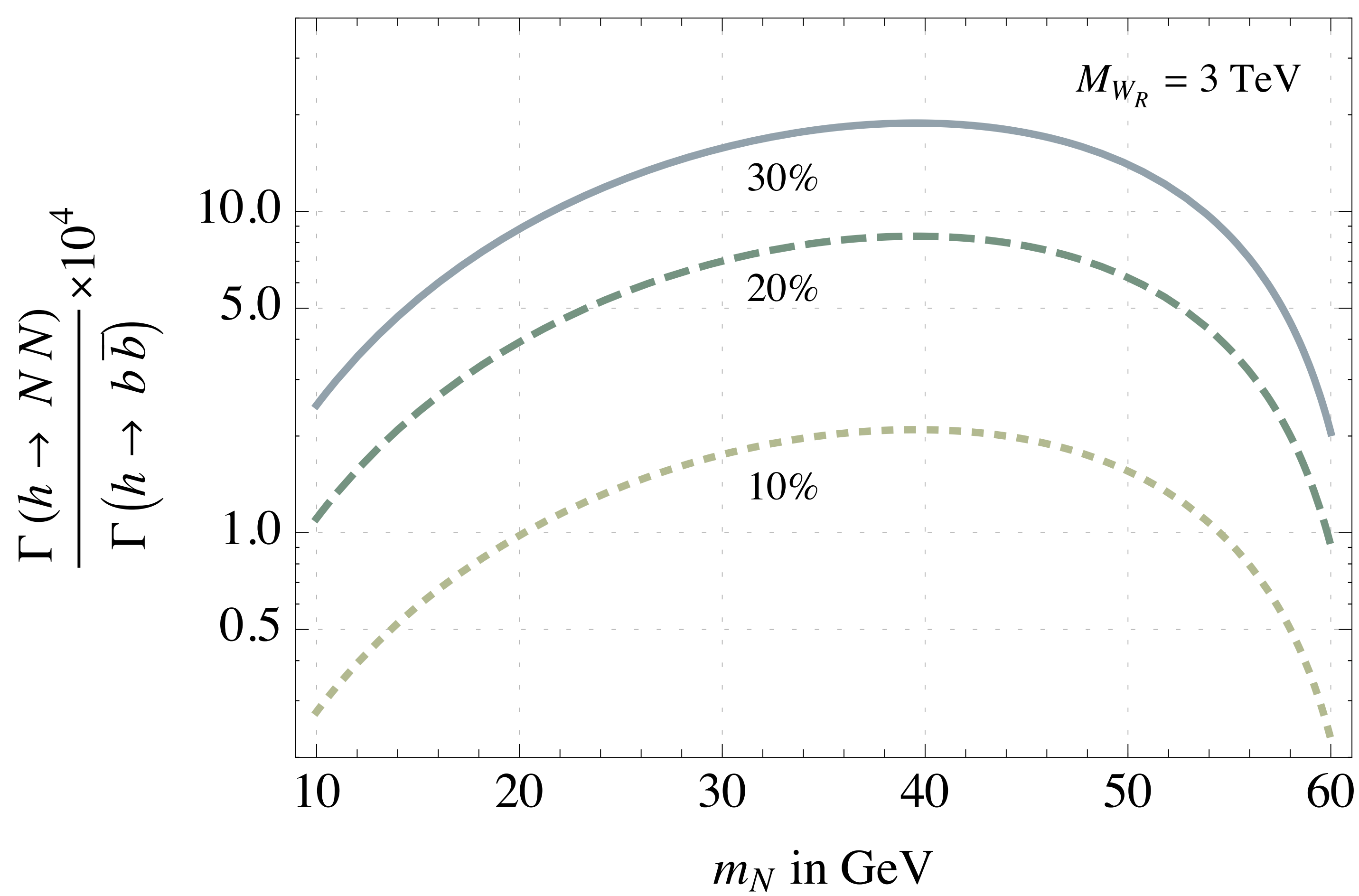
h decays

$$\Gamma_{h\to NN} \propto s_\theta^2\, {m_N}^2 \qquad \frac{\Gamma_{h\to NN}}{\Gamma_{h\to b\bar b}} \simeq \frac{\theta^2}{3}\left(\frac{m_N}{m_b}\right)^2\left(\frac{M_W}{M_{W_R}}\right)^2$$

Gunion et al. Snowmass ’86

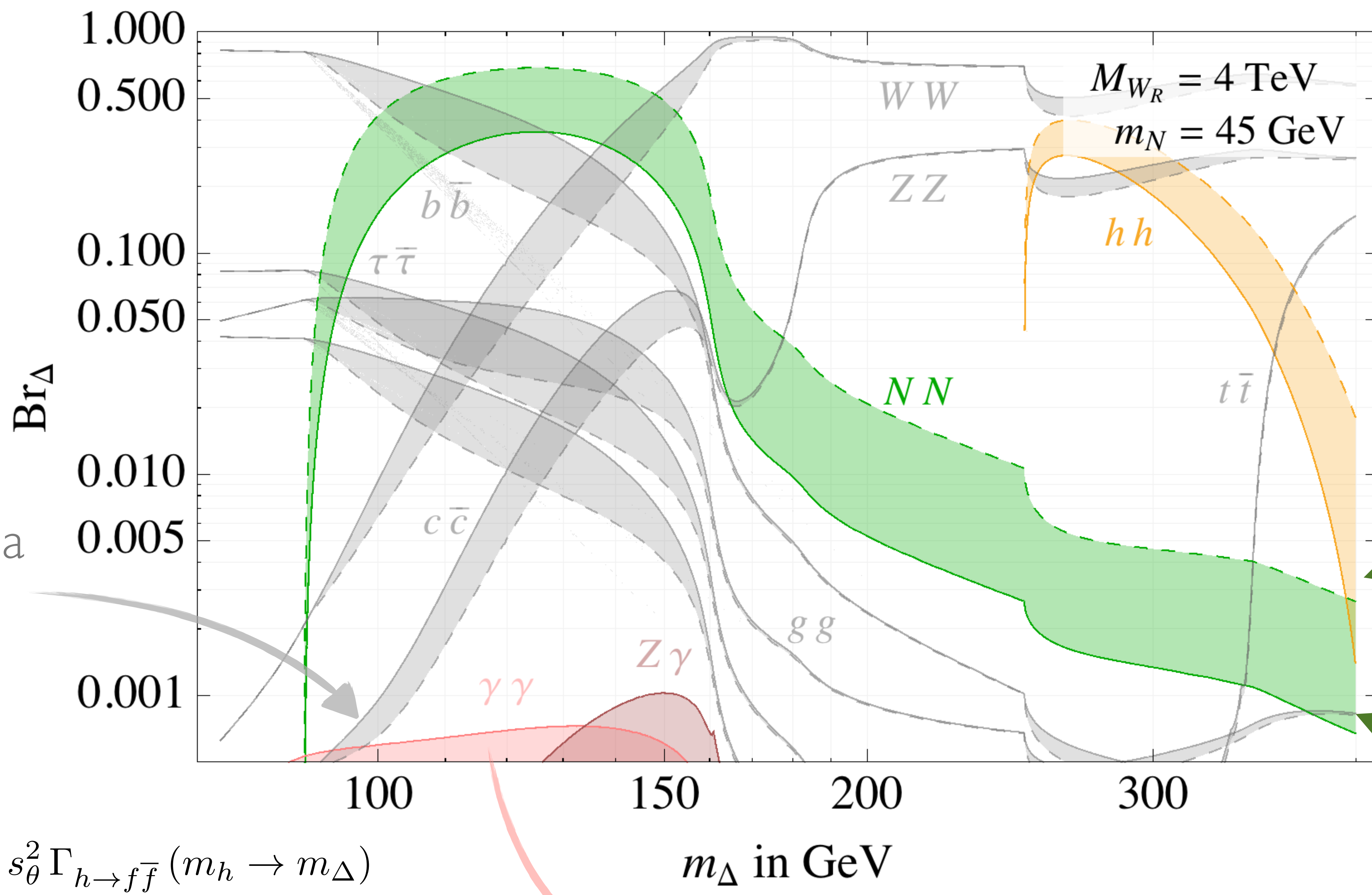
EFT SM+h+N Graesser ’07





‘Right-handed’ Higgs

Δ decays



to SM via mixing

$s_\theta = 5\%$

10%

$$\Gamma_{\Delta\to f\bar{f}} = s_\theta^2\,\Gamma_{h\to f\bar{f}}\,(m_h \to m_\Delta)$$

radiative loops
$(\mathrm{SM}, W_R, \Delta^{++}_{L,R})$

$$\Gamma_{\Delta\to\gamma\gamma} = \frac{m_\Delta^3}{64\pi}\left(\frac{\alpha}{4\pi}\right)^2 |F_\Delta|^2$$

Displaced photons Dev, Mohapatra, Zhang ’16,

‘Right-handed’ Higgs

Δ decays

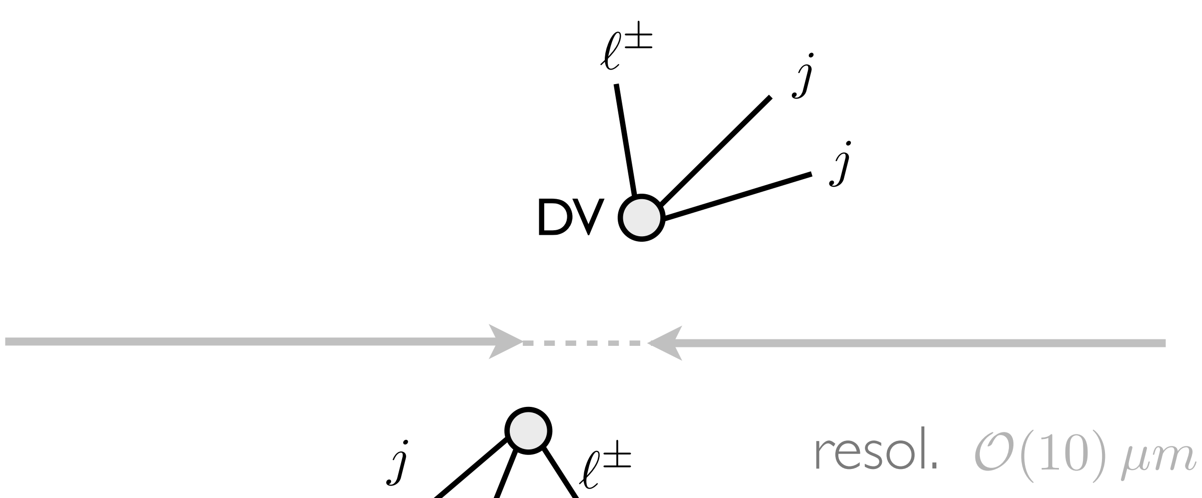
Region of interest for $\Delta \to NN$

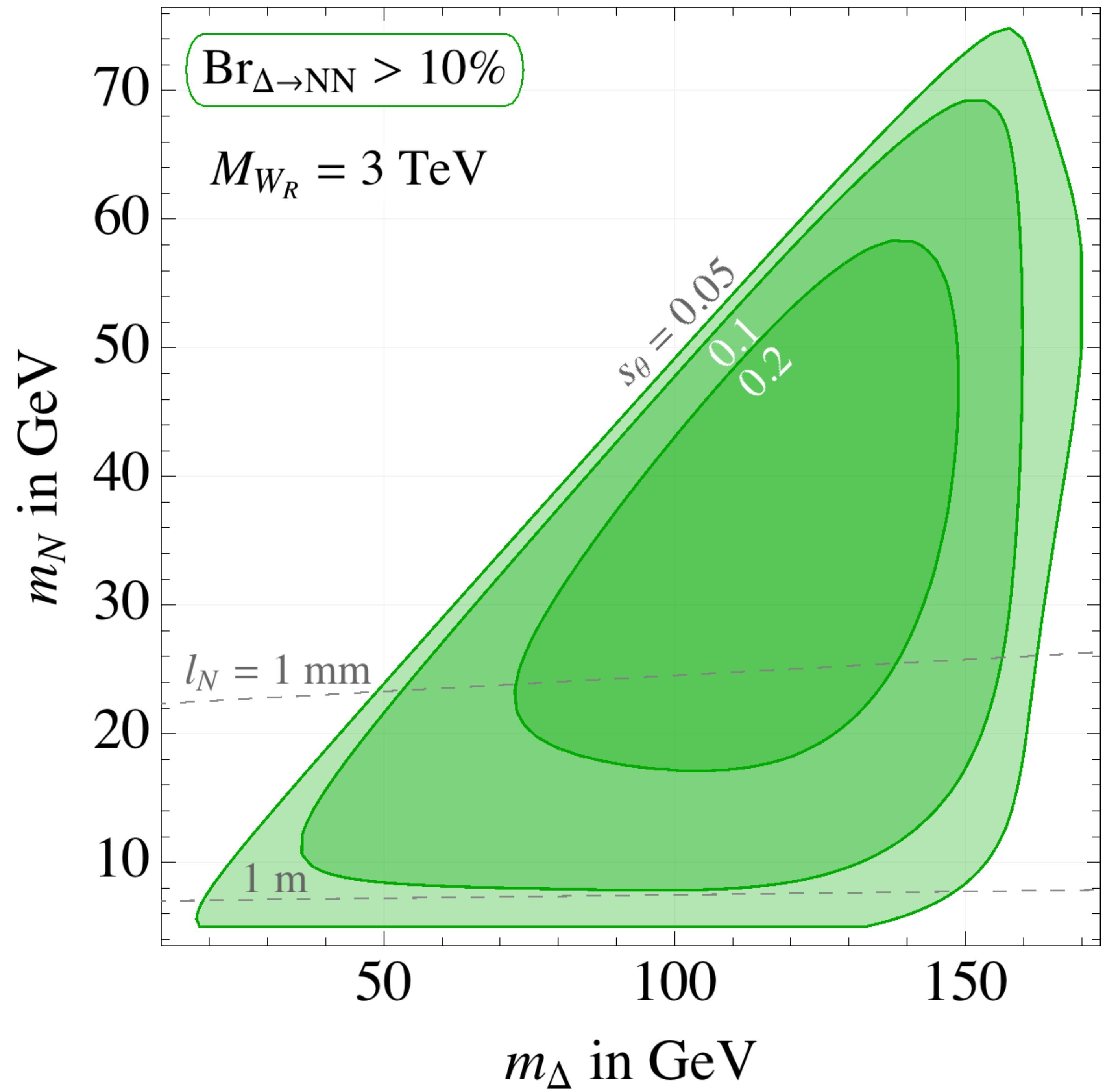
$$20 \text{ GeV} \lesssim m_\Delta \lesssim 170 \text{ GeV}$$

Decay length

$$c\tau_N^0 \simeq 0.1 \text{ mm} \left(\frac{40 \text{ GeV}}{m_N}\right)^5 \left(\frac{M_{W_R}}{5 \text{ TeV}}\right)^4$$

Leads to two DV with LNV





‘Right-handed’ Higgs

Δ production

single

$$\sigma(gg \to \Delta) = s_\theta^2\, \sigma(gg \to h) \qquad \text{N}^3\text{LO} \qquad \text{Anastasiou et al. '16}$$

$$\sigma(pp \to V\Delta) = s_\theta^2\, \sigma(pp \to Vh)$$

pair & associated

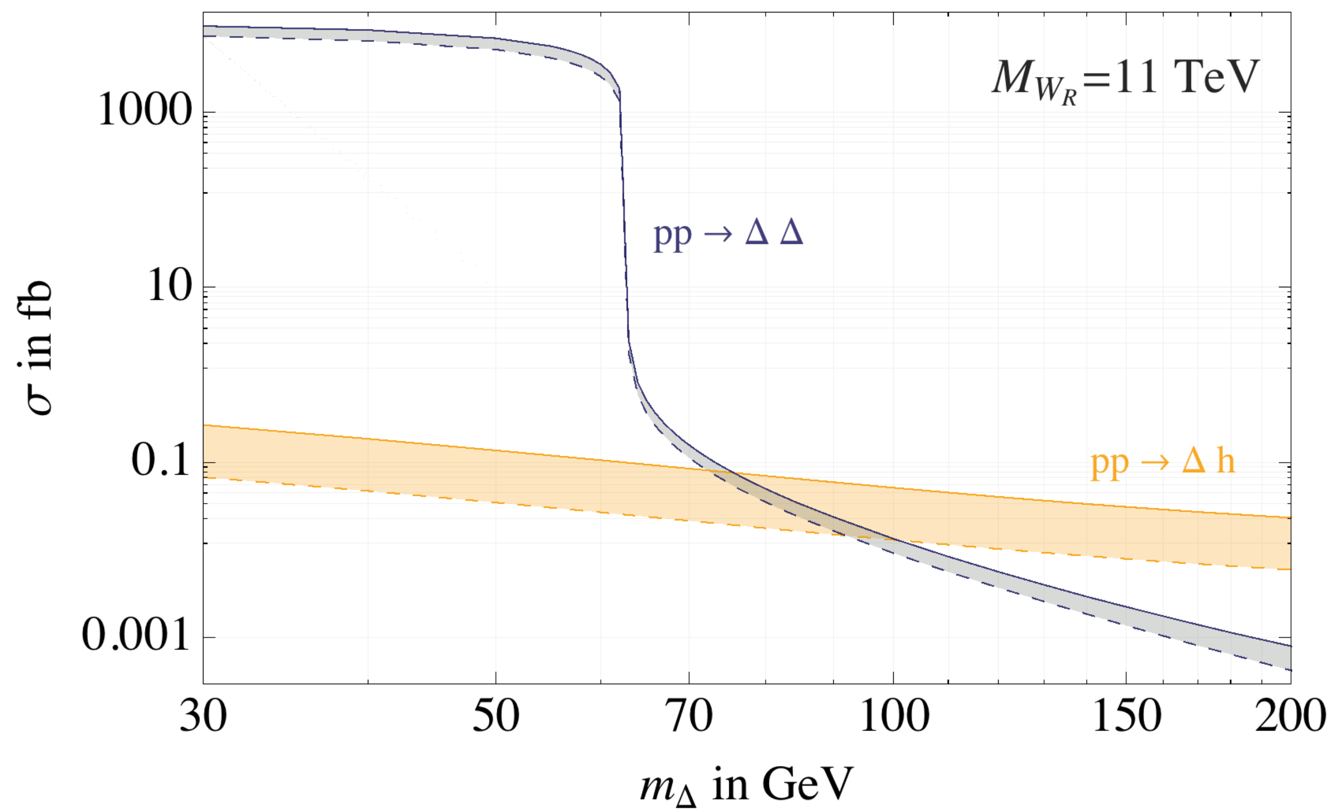
$$\hat{\sigma}_{gg\to\Delta S} \simeq \frac{c_\theta^2}{64\pi(1+\delta_{\Delta S})}\, \hat{s} \left(\frac{\alpha_s}{4\pi}\right)^2 \frac{v_{hS\Delta}^2}{(\hat{s}-m_h^2)^2 + \hat{s}\Gamma_h^2} |F_b + F_t|^2 \sqrt{\beta_{\hat{s}\Delta S}}$$

large rate for $m_\Delta < m_h/2$

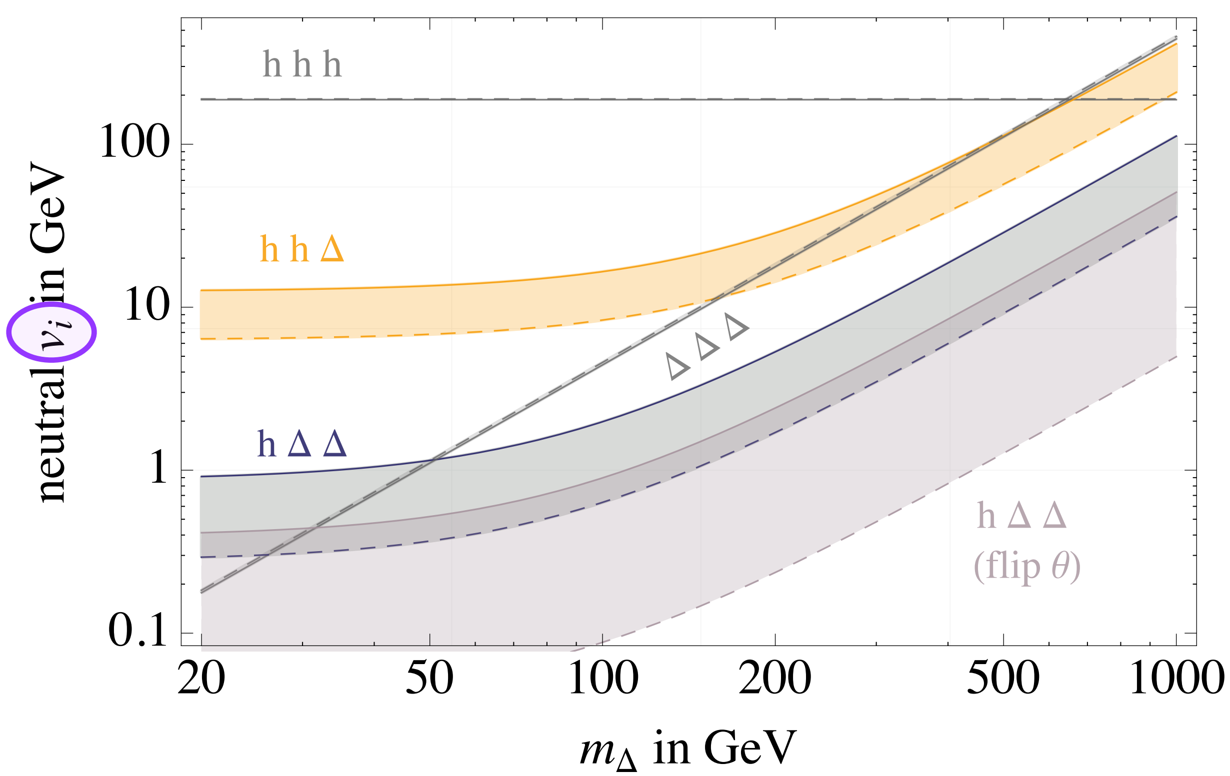
$$\sigma_{gg\to\Delta\Delta} \simeq \sigma_{gg\to h}\, \text{Br}_{h\to\Delta\Delta}$$

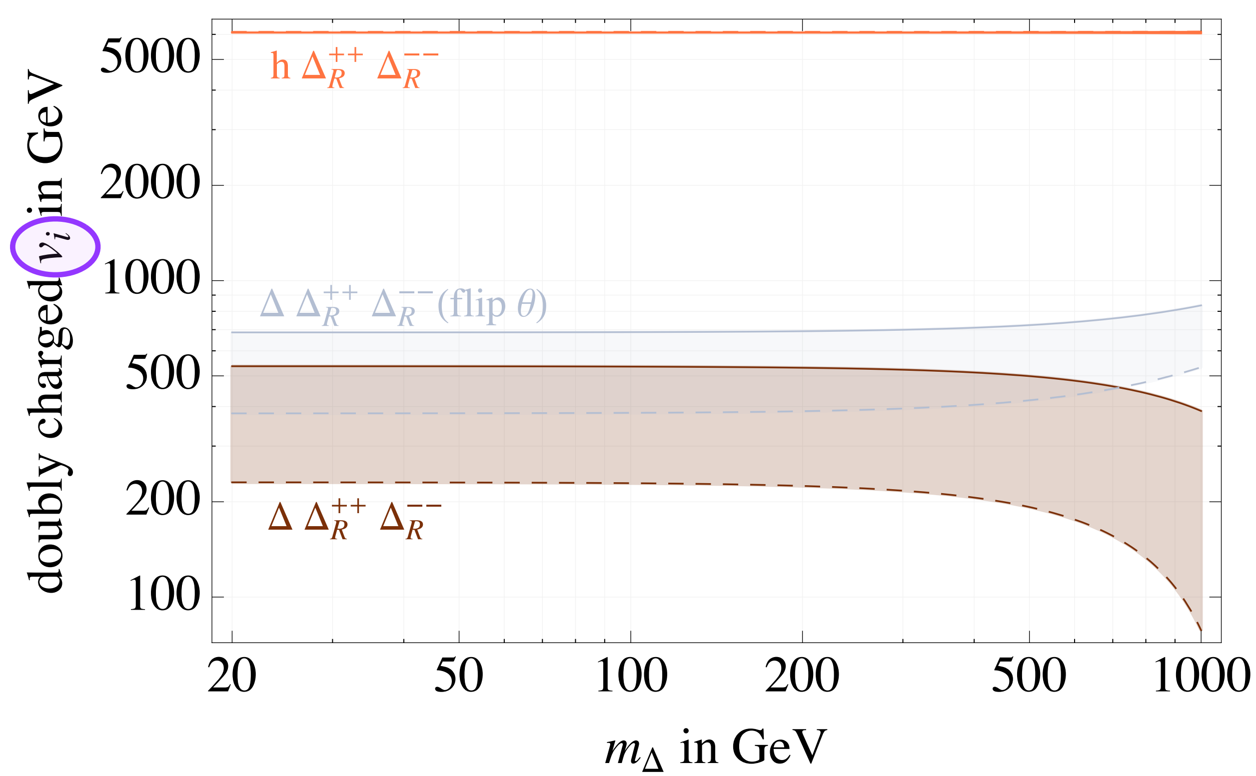
not very significant

(accidental cancellation)



Tri-linear Higgs couplings





2 x 2 matrix, mixing suppressed by flavor and $\langle \Delta_L \rangle$

tree level

$$v_{hhh} = \frac{3g}{2} m_h^2 \left[\frac{c_\theta^3}{M_W} - \sqrt{2} \frac{s_\theta^3}{M_{W_R}} \right]$$

$$v_{hh\Delta} = \frac{g}{4} s_{2\theta} \left(m_\Delta^2 + 2m_h^2 \right) \left[\frac{c_\theta}{M_W} + \sqrt{2} \frac{s_\theta}{M_{W_R}} \right] \xrightarrow{\theta \to 0} 0$$

$$v_{h\Delta\Delta} = \frac{g}{4} s_{2\theta} \left(m_\Delta^2 + 2m_h^2 \right) \left[\frac{s_\theta}{M_W} - \sqrt{2} \frac{c_\theta}{M_{W_R}} \right] \xrightarrow{\theta \to 0} 0$$

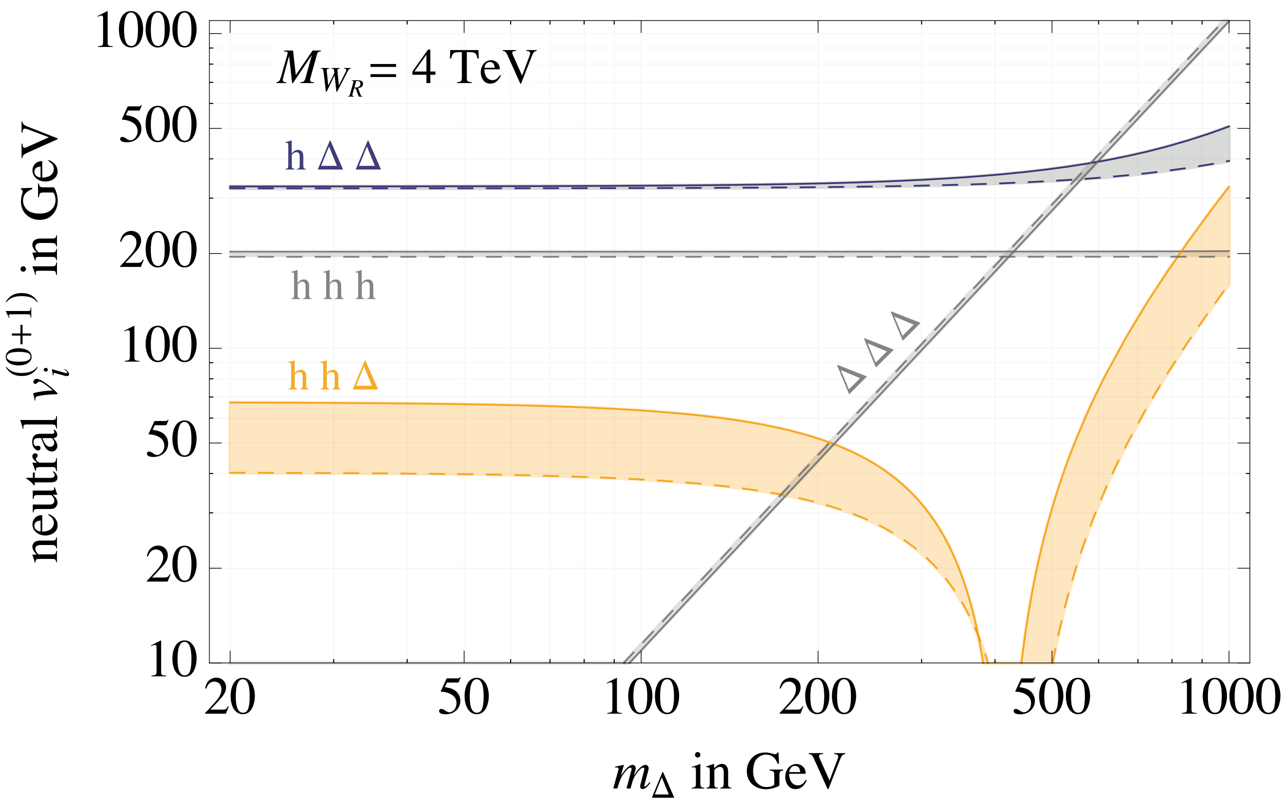
$$v_{\Delta\Delta\Delta} = \frac{3g}{2} m_\Delta^2 \left[\frac{s_\theta^3}{M_W} + \sqrt{2} \frac{c_\theta^3}{M_{W_R}} \right]$$

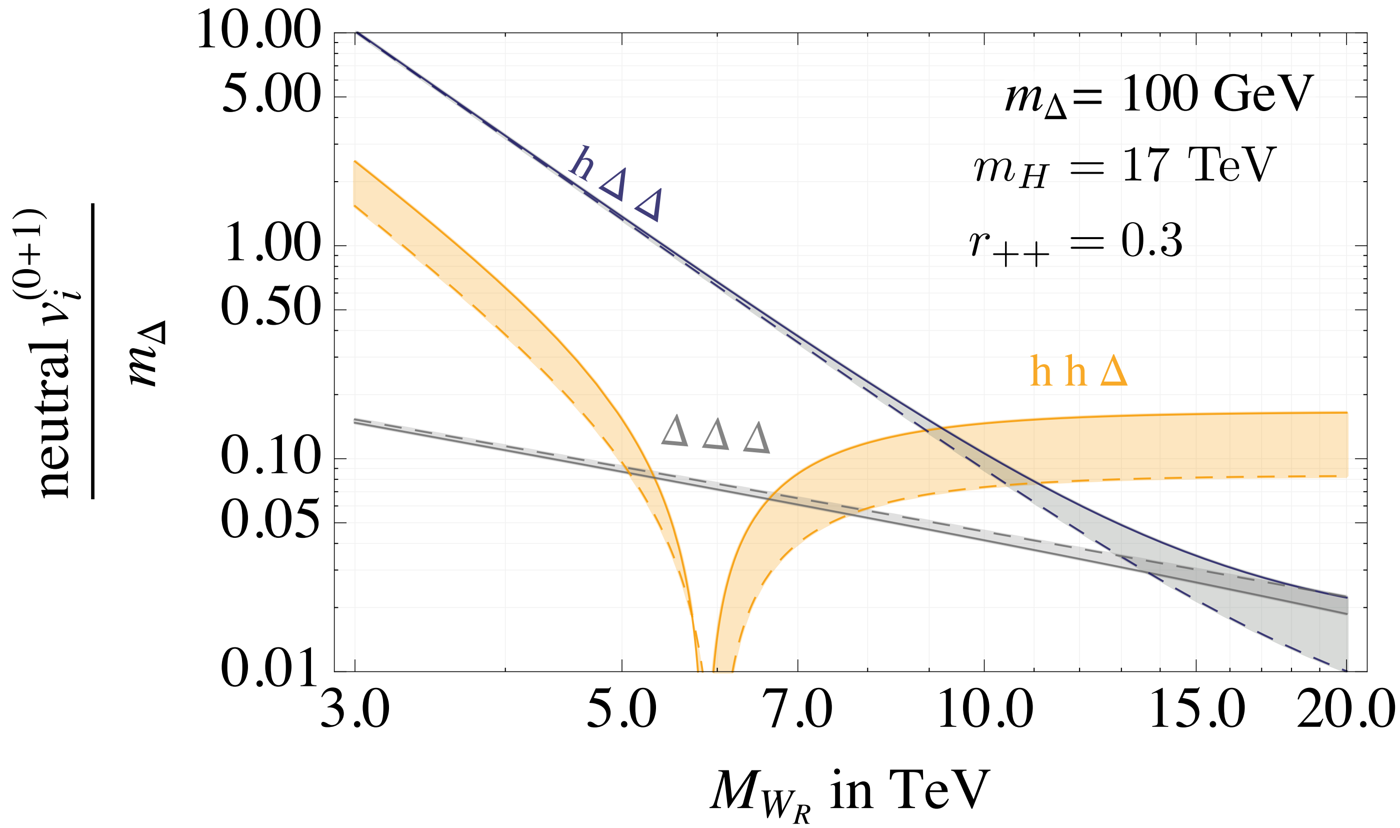
cancellation

+ corrections due to H mixing

Tri-linear Higgs couplings

loop corrections, ~top in the hhh vertex of the SM





$$v^{(1)}_{hhh} \simeq c^{(1)} \left(1 + \frac{17}{3}\frac{1}{r_{++}}\right)\left(\frac{v}{v_R}\right)^2 v \qquad v^{(1)}_{hh\Delta} \simeq c^{(1)}\, 11 \left(\frac{v}{v_R}\right) v$$

decouple with v_R

$$v^{(1)}_{h\Delta\Delta} \simeq c^{(1)}\,(4 + 10\, r_{++})\, v \qquad v^{(1)}_{\Delta\Delta\Delta} \simeq c^{(1)}\,(8 + 16\, r_{++}^2)\, v_R$$

$$c^{(1)} = \frac{1}{\sqrt{2}(4\pi)^2}\left(\frac{m_H}{v_R}\right)^4, \qquad r_{++} = \left(\frac{m_{\Delta^{++},\Delta_L^{0,+,++}}}{m_H}\right)^2$$

upper bound $v^{(1)}_{\Delta\Delta\Delta} \leq \left(\frac{7}{3}\right) v^{\text{tree level}}_{\Delta\Delta\Delta}$ from vacuum stability

Linde ’76, Weinberg ’76
Mohapatra ’86
Basecq, Wyler ’89

Δ production

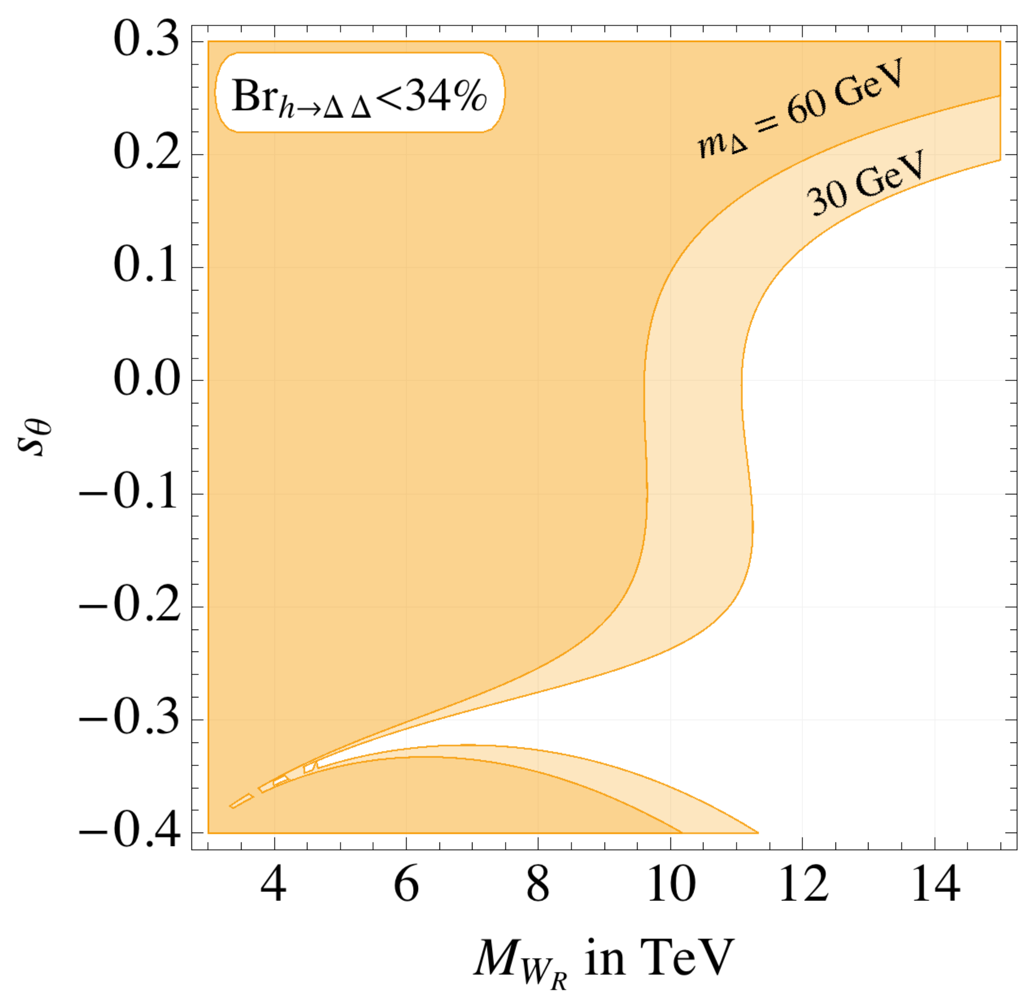
Δ^* suppressed

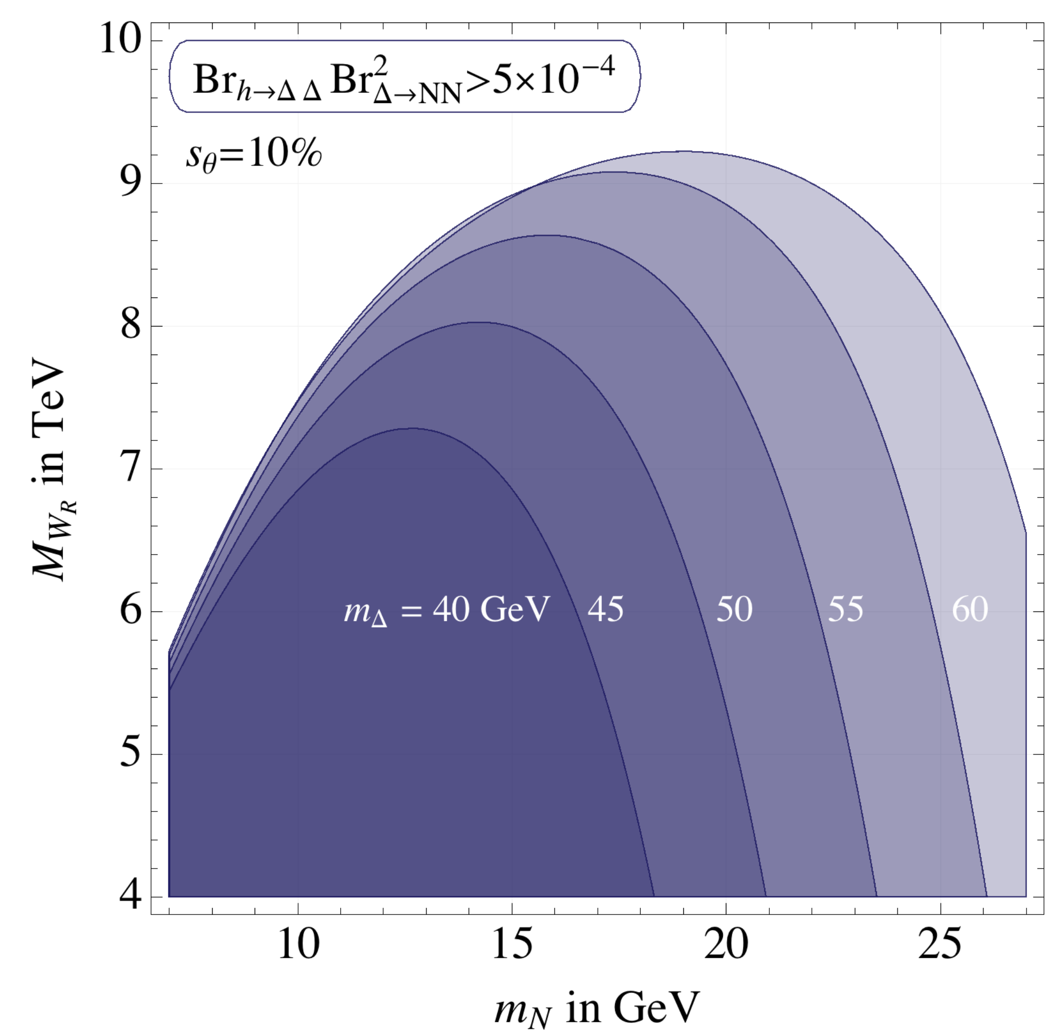
pair & associated

$$\hat{\sigma}_{gg\to\Delta S} \simeq \frac{c_\theta^2}{64\pi(1+\delta_{\Delta S})}\,\hat{s}\left(\frac{\alpha_s}{4\pi}\right)^2 \frac{v_{hS\Delta}^2}{(\hat{s}-m_h^2)^2+\hat{s}\Gamma_h^2}\,|F_b+F_t|^2\sqrt{\beta_{\hat{s}\Delta S}}$$

$\sigma_{gg\to\Delta\Delta} \simeq \sigma_{gg\to h}\,\mathrm{Br}_{h\to\Delta\Delta}$ leads to $pp \to NNNN$

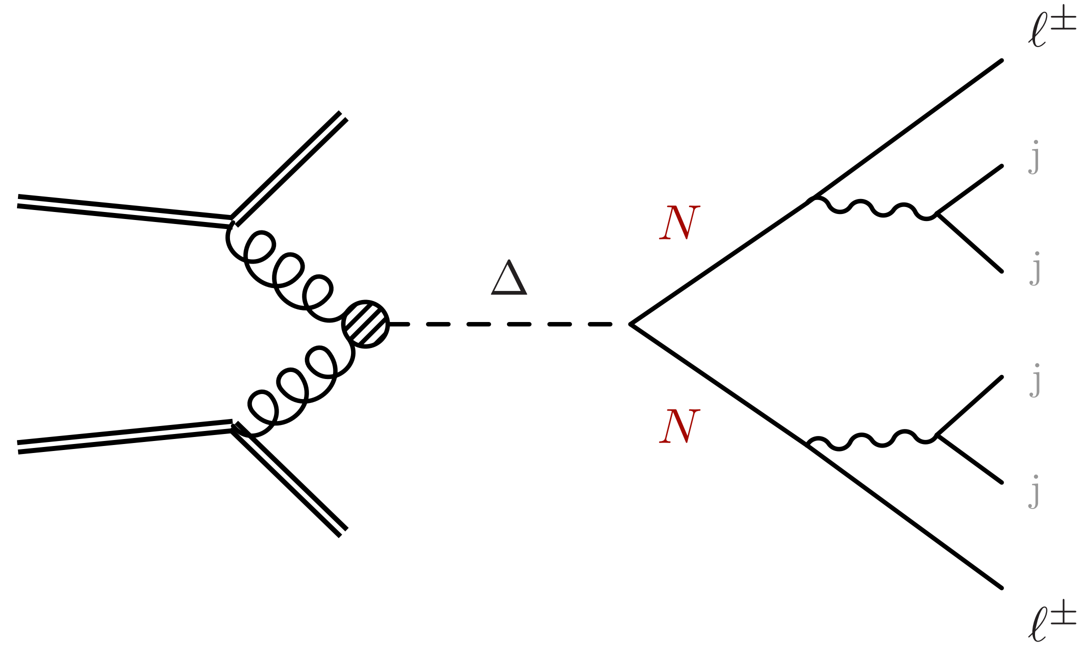
$\sigma_{gg\to h}$ N^{3}LO Anastasiou et al. '16



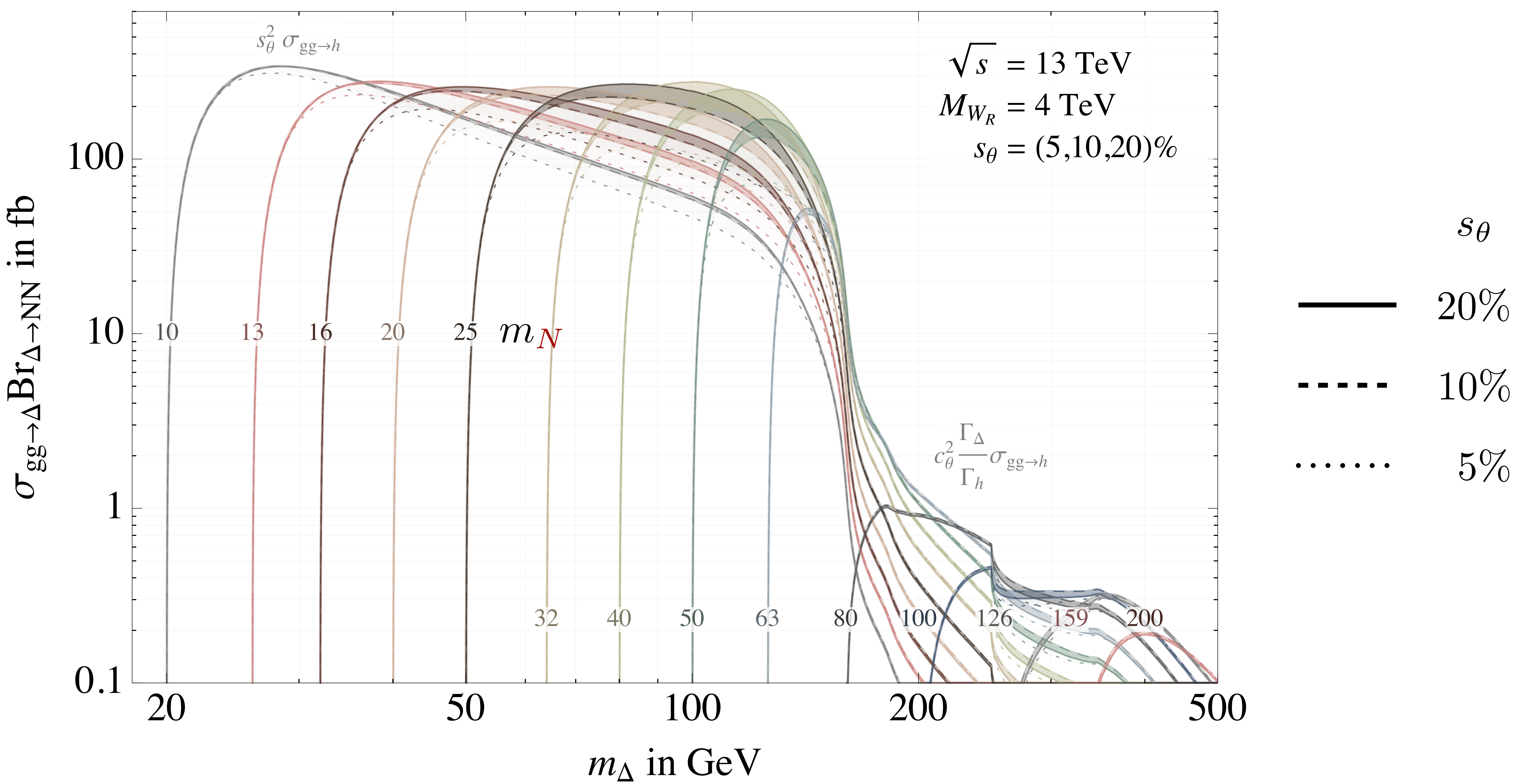


Δ signals

single

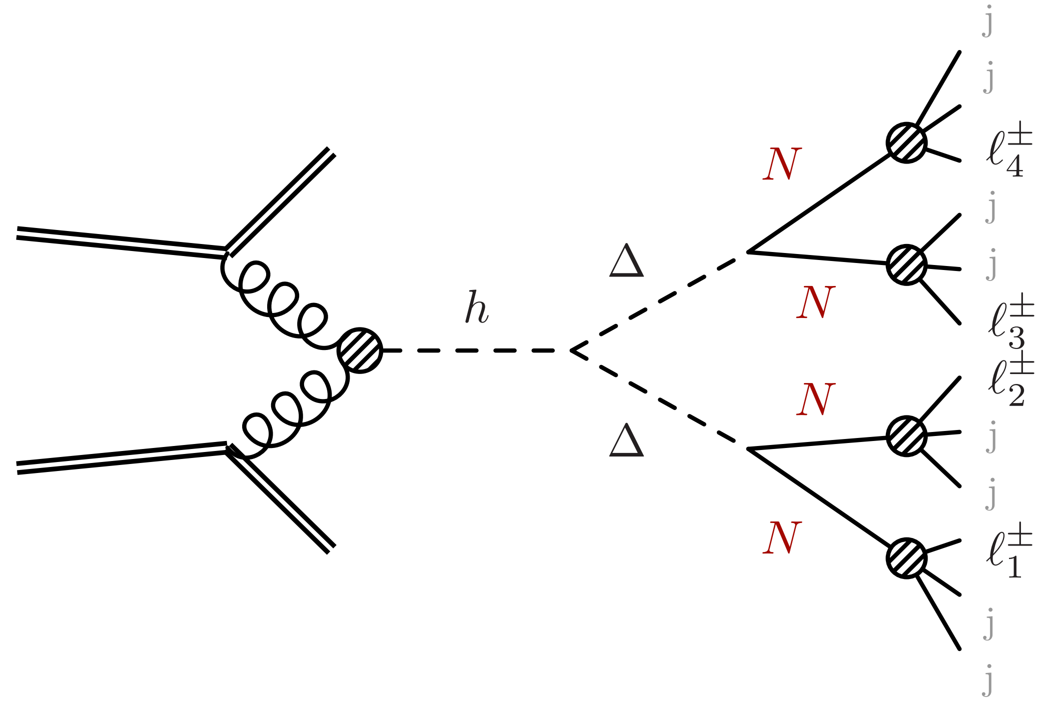


$\Delta L = 0, 2$

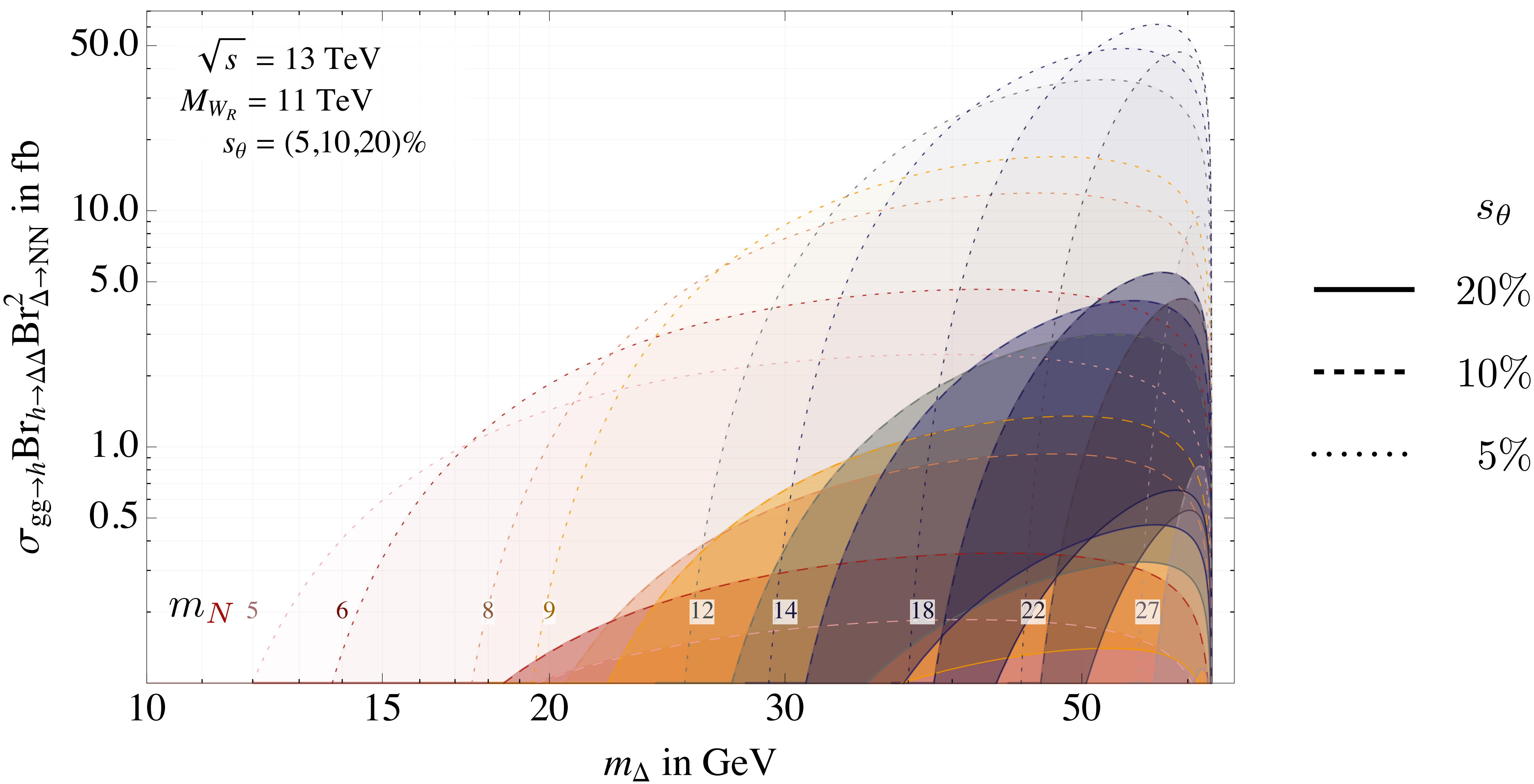


Δ signals

pair



$\Delta L = 0, 2, 4$



LHC projections

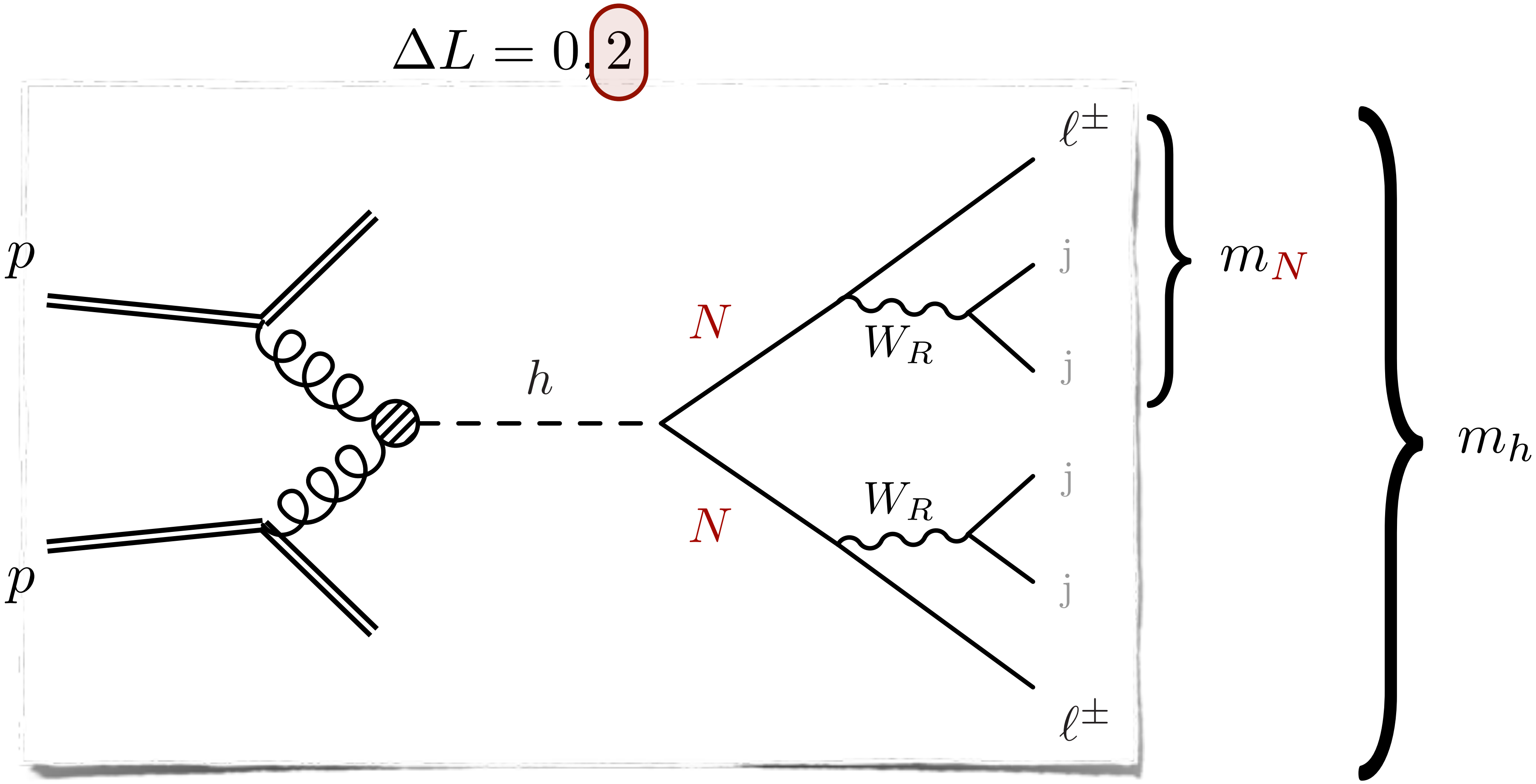
(Higgs mediated LNV)

‘Majorana’ Higgses at LHC

ggF production $\sigma_{gg\to h} \simeq 45$ pb N^{3}LO Anastasiou et al. ’14

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

$\mathrm{Br}_{h\to NN} \simeq 10^{-3}$



small couplings, no tuning

light jets only $V_L^q = V_R^q$

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

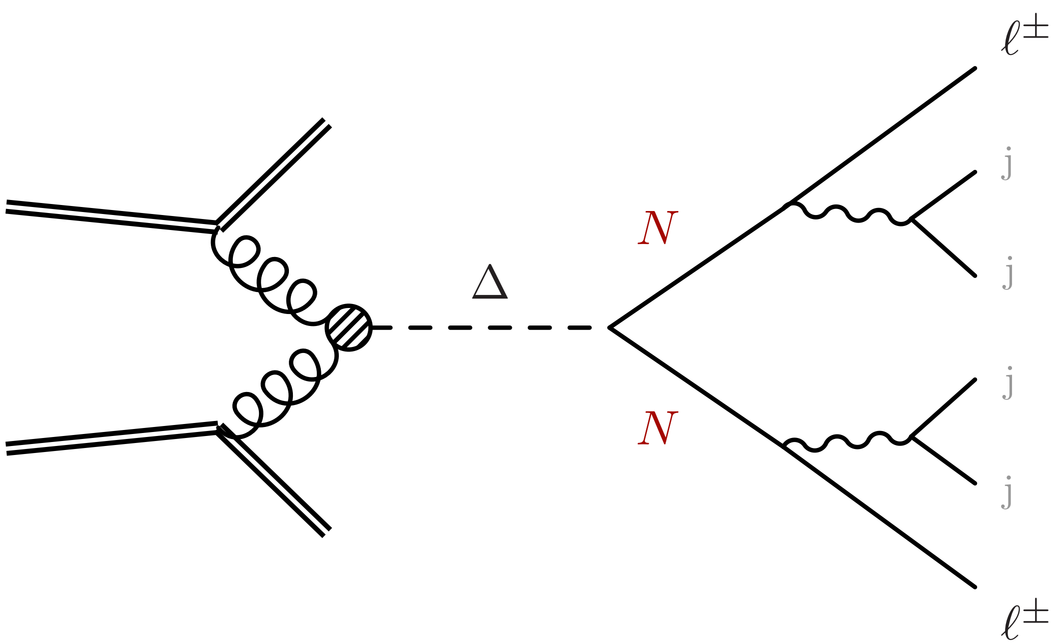
no missing energy

soft products $p_T \simeq m_h/6 \sim 20$ GeV

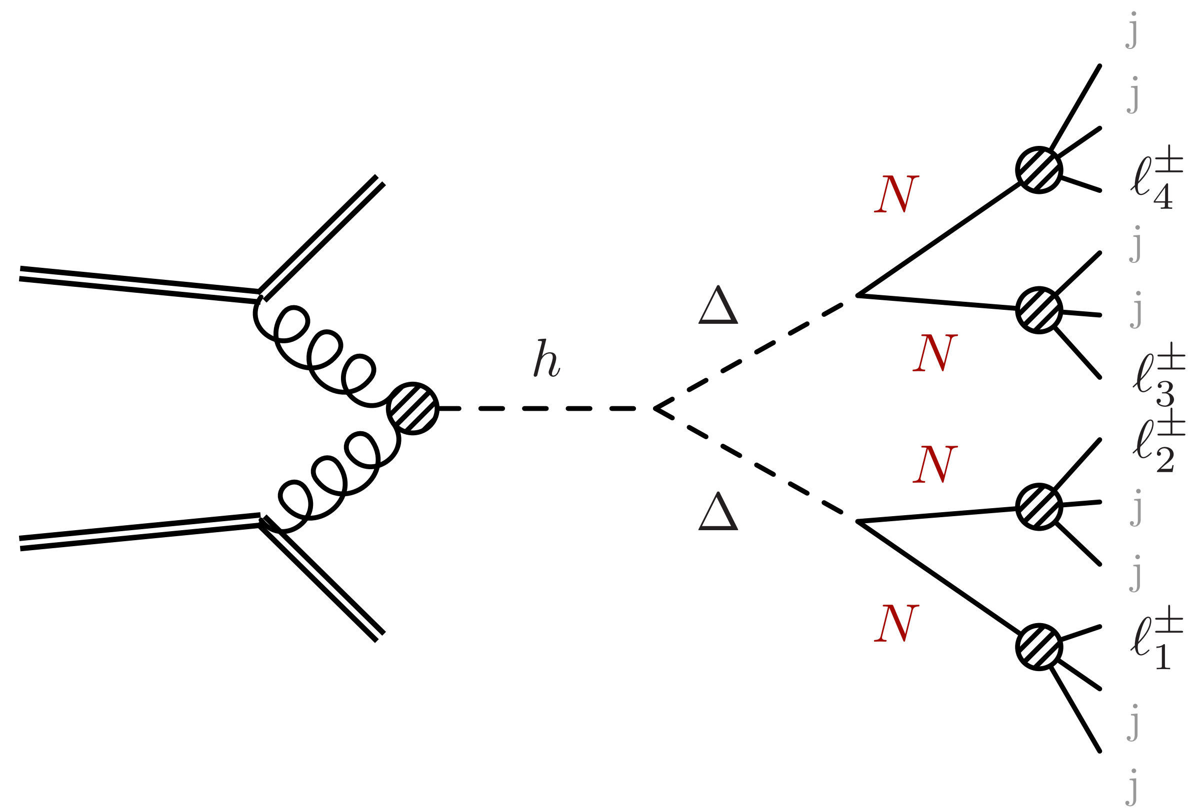
low background (LNV)

‘Majorana’ Higgses at LHC

$\Delta L = 0, 2$



$\Delta L = 0, 2, 4$



similar to $h \to NN$

(same-sign) multi-leptons

ggF of CP even scalar

$2^4 = 16$ possibilities

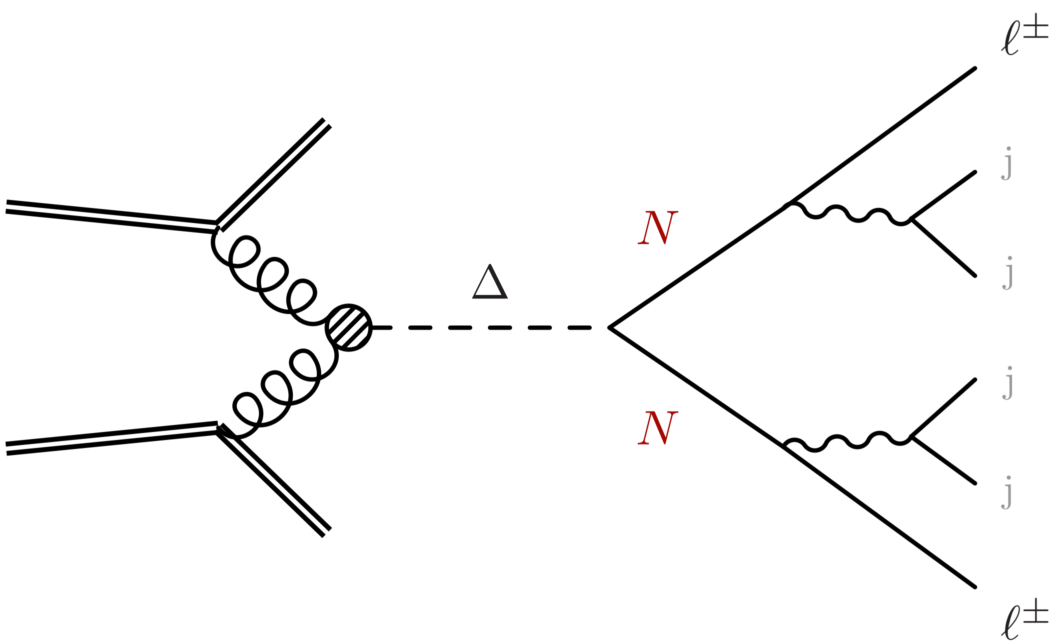
Anastasiou et al. ’16

$\Delta L_0 : \Delta L_2 : \Delta L_4 = 3 : 4 : 1$

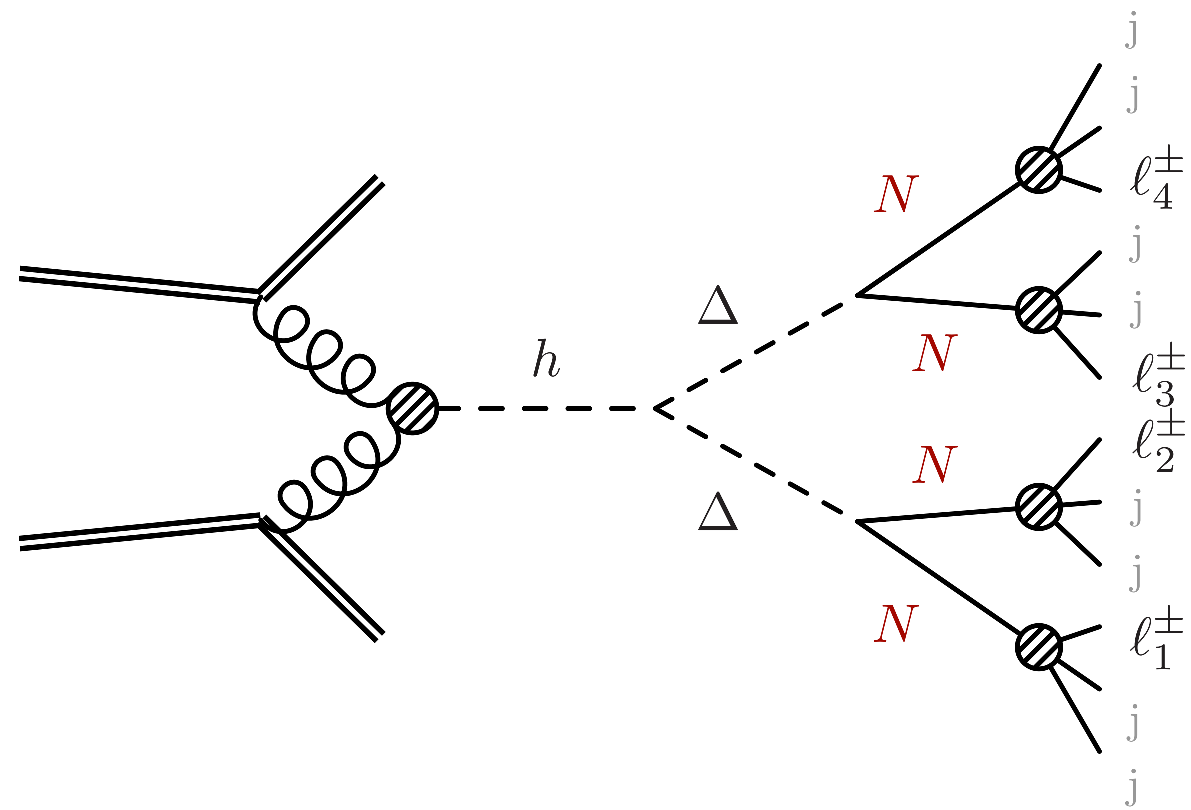
$\mathcal{R}^{\#\ell}_{\Delta L} \Rightarrow \mathcal{R}^2_2, \mathcal{R}^3_3, \mathcal{R}^4_2, \mathcal{R}^4_4$

‘Majorana’ Higgses at LHC

$\Delta L = 0, 2$



$\Delta L = 0, 2, 4$



LRSM Feyncalc adaptation

Roitgrund, Eilam, Bar-shalom 1401.3345

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

MadGraph5 Pythia6 Delphes3 MadAnalysis5

Detector simulation

Modified Delphes3 ATLAS card

leptons

reconstruction efficiencies

electrons ATLAS-CONF-2016-024

muons 1603.05598

tight (loose) isolation

electrons $p_T^{\text{varcone20}} < 0.06(0.15)$

muons $p_T^{\text{varcone30}} < 0.06(0.15)$

mono & di-lepton triggers

ATL-DAQ-PUB-2016-001

jets

anti-k_T $\Delta R = 0.4$

$p_T^{j\,\text{min}} = 20\ \text{GeV}$

$n_j = 1, 2, 3$

missing energy

$\not{E}_T \simeq 15\ \text{GeV}$

Backgrounds

Selection criteria

	$t\bar{t}$	$t\bar{t}h$	$t\bar{t}Z$	$t\bar{t}W$	WZ	Wh	ZZ	Zh	$WWjj$	fakes

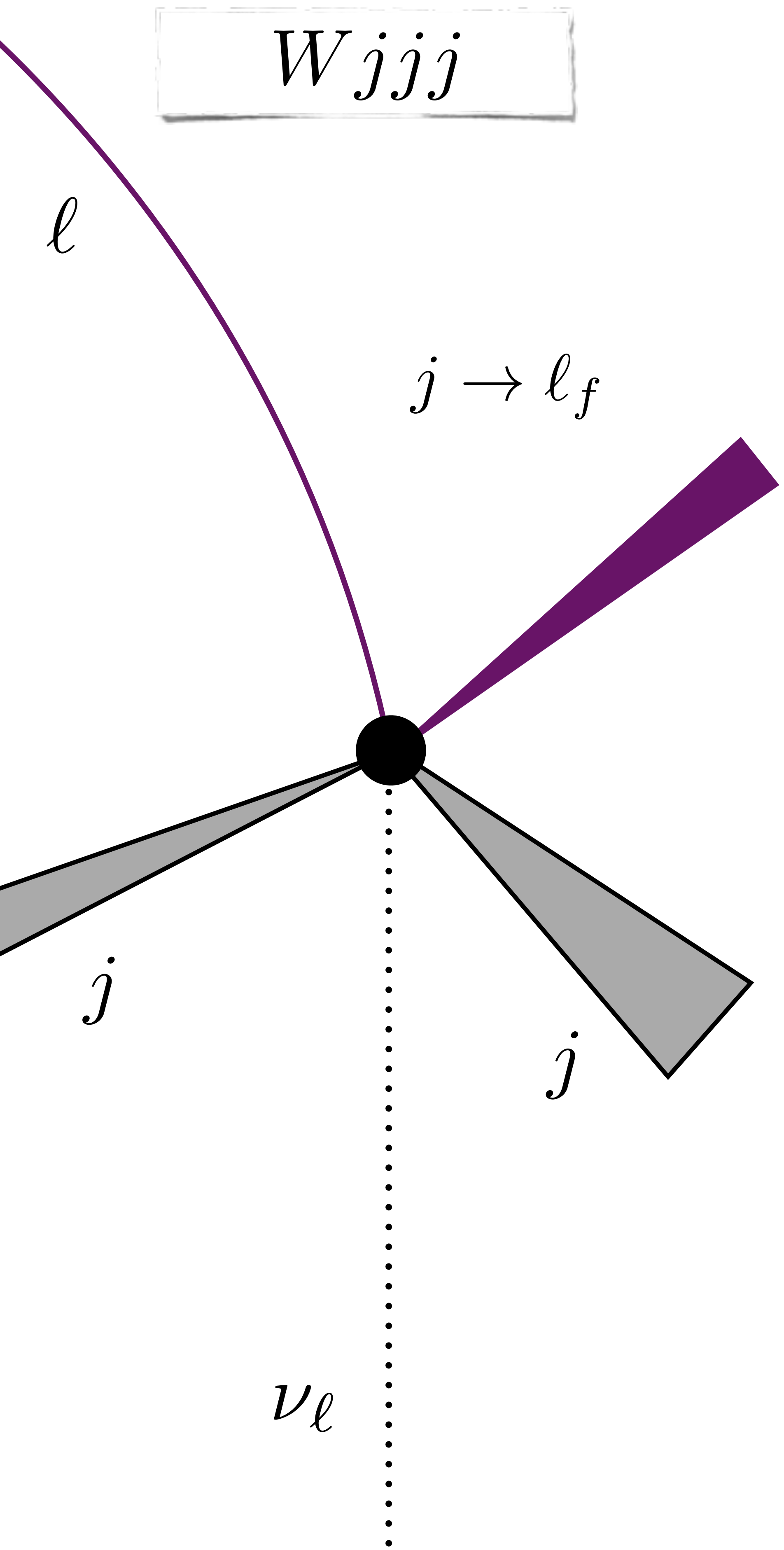
Selection	$\ell^\pm \ell^\pm + n_j$
$\not{E}_T$	$\not{E}_T < 30\,\mathrm{GeV}$
p_T	$p_T(\ell_1) < 55\ \mathrm{GeV}$
m_T	$m^T_{\ell \not{p}_T} < 30\,\mathrm{GeV}$
$m_{\rm inv}$	$m_{\ell\ell} < 80\,\mathrm{GeV}$ $m_{\ell \not{p}_T} < 60\,\mathrm{GeV}$
$l_{T\ell}$	$l_{T\ell} > 0.1\ \mathrm{mm}$

all contain missing energy

one prompt, one displaced lepton

Backgrounds

jet fakes



conversion rate

$$\varepsilon_{j\to\ell}(p_T, \eta)$$

softened momentum

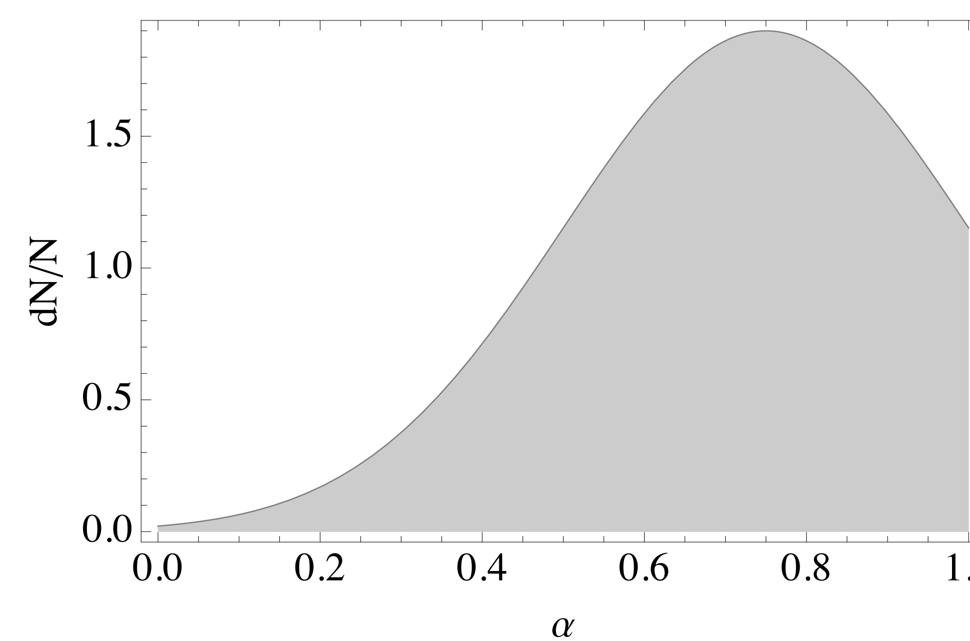
$$p_{T\ell} = (1-\alpha)p_{T\text{jet}}$$

$$P(\alpha) = \frac{1}{\mathcal{N}}\, e^{\frac{(\alpha-\mu)^2}{2\sigma^2}}$$

Curtin, Galloway, Wacker '13
Izaguirre, Shuve, '15

$$\ell^\pm + \not{E}_T + j + j + j$$

prompt lepton + jets

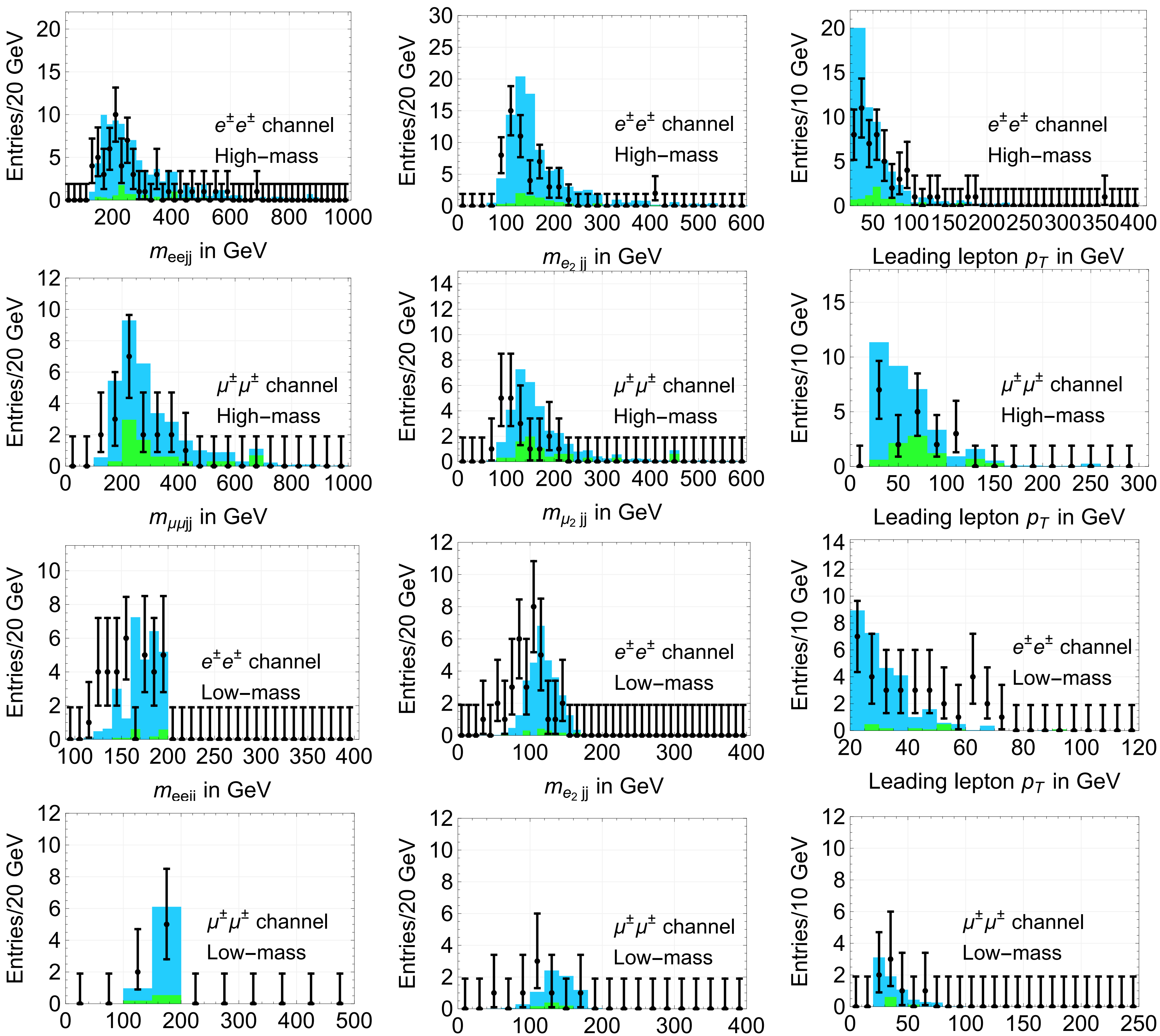


$$\ell^\pm + \ell_f^\pm + \not{E}_T + j + j$$

prompt + softer fake lepton + jets

Backgrounds

jet fakes



$Wjjj$

$jjjj$

$t\bar{t}+j+jj$

$VV+j+jj$

$$\varepsilon(j \to e) = 5 \times 10^{-4\,*}$$

*overestimated for Q mis-id

$$\varepsilon(j \to \mu) = 3 \times 10^{-4}$$

$\alpha = 0.75 \qquad \sigma = 0.25$

data from CMS
mumu 1501.05566
ee, emu 1603.02248

Backgrounds

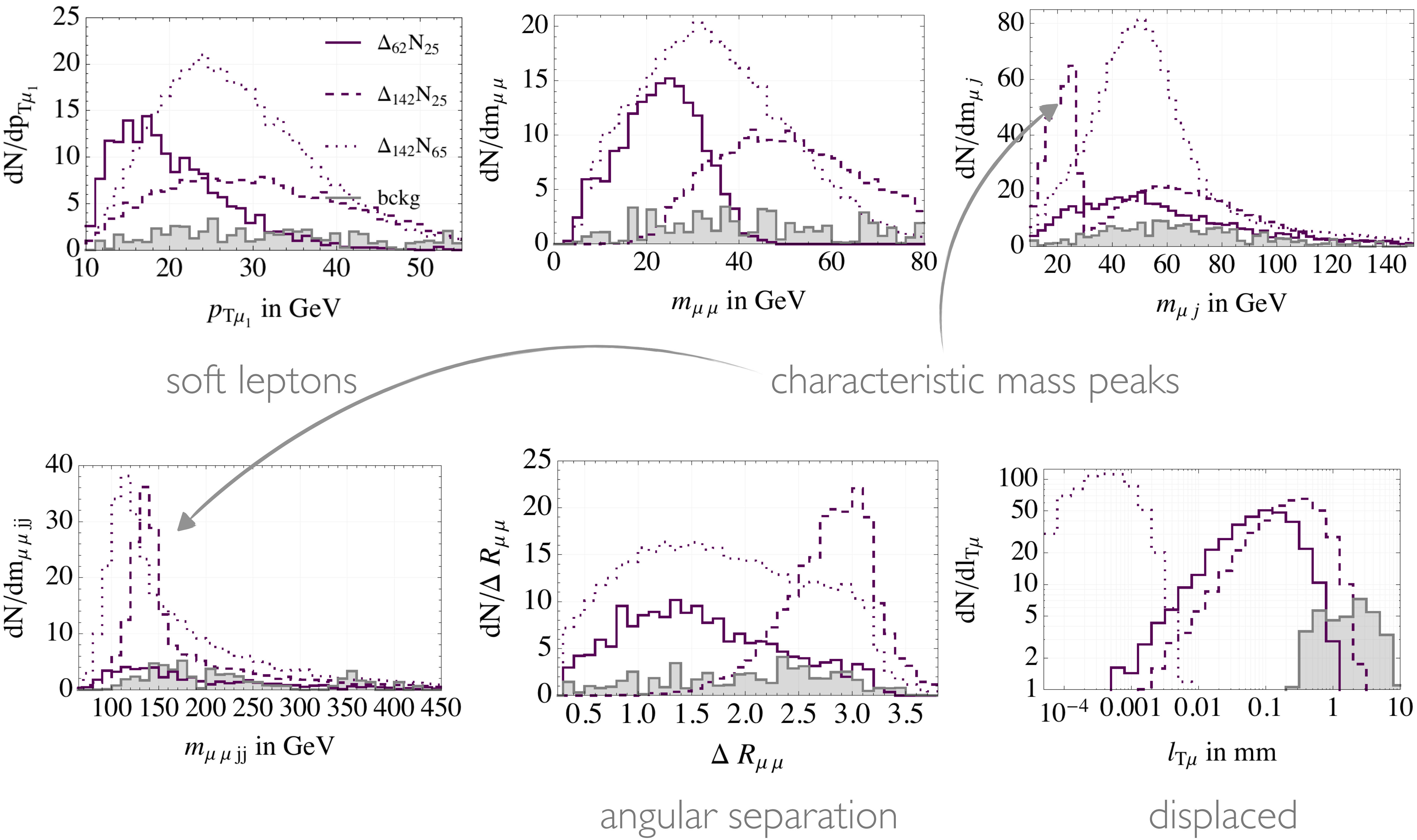
$\ell^{\pm}\ell^{\pm} + n_j$

	$t\bar{t}$	$t\bar{t}h$	$t\bar{t}Z$	$t\bar{t}W$	WZ	Wh	ZZ	Zh	$WWjj$	fakes
select	806	4	5	26	1241	87	147	16	1.5	2651
$\not{E}_T$	313	0.5	0.7	3	400	21	129	7	0.2	782
p_T	112	0.2	0.1	0.7	174	8.4	63	4	0.05	284
m_T	60	0.1	0.04	0.3	80	4	56	2	0.03	106
m^{inv}	35	0.03	0.03	0.2	25	2	36	2	0	80
l_{Te}	0	0	0	0	0.7	0.1	0.9	0.05	0.001	2
	$t\bar{t}$	$t\bar{t}h$	$t\bar{t}Z$	$t\bar{t}W$	WZ	Wh	ZZ	Zh	$WWjj$	fakes
select	670	4	6	32	750	133	68	16	2	1676
$\not{E}_T$	130	0.5	0.9	3.5	200	32	33	6	0.3	391
p_T	57	0.2	0.2	1	95	17	16	3	0.1	152
m_T	32	0.1	0.1	0.5	51	9	12	2	0.05	49
m^{inv}	17	0.04	0.04	0.2	23	5	8	1	0.01	40
$l_{T\mu}$	0	0	0	0	1.4	0.4	1	0.15	0.005	3

all contain missing energy

one prompt, one displaced lepton

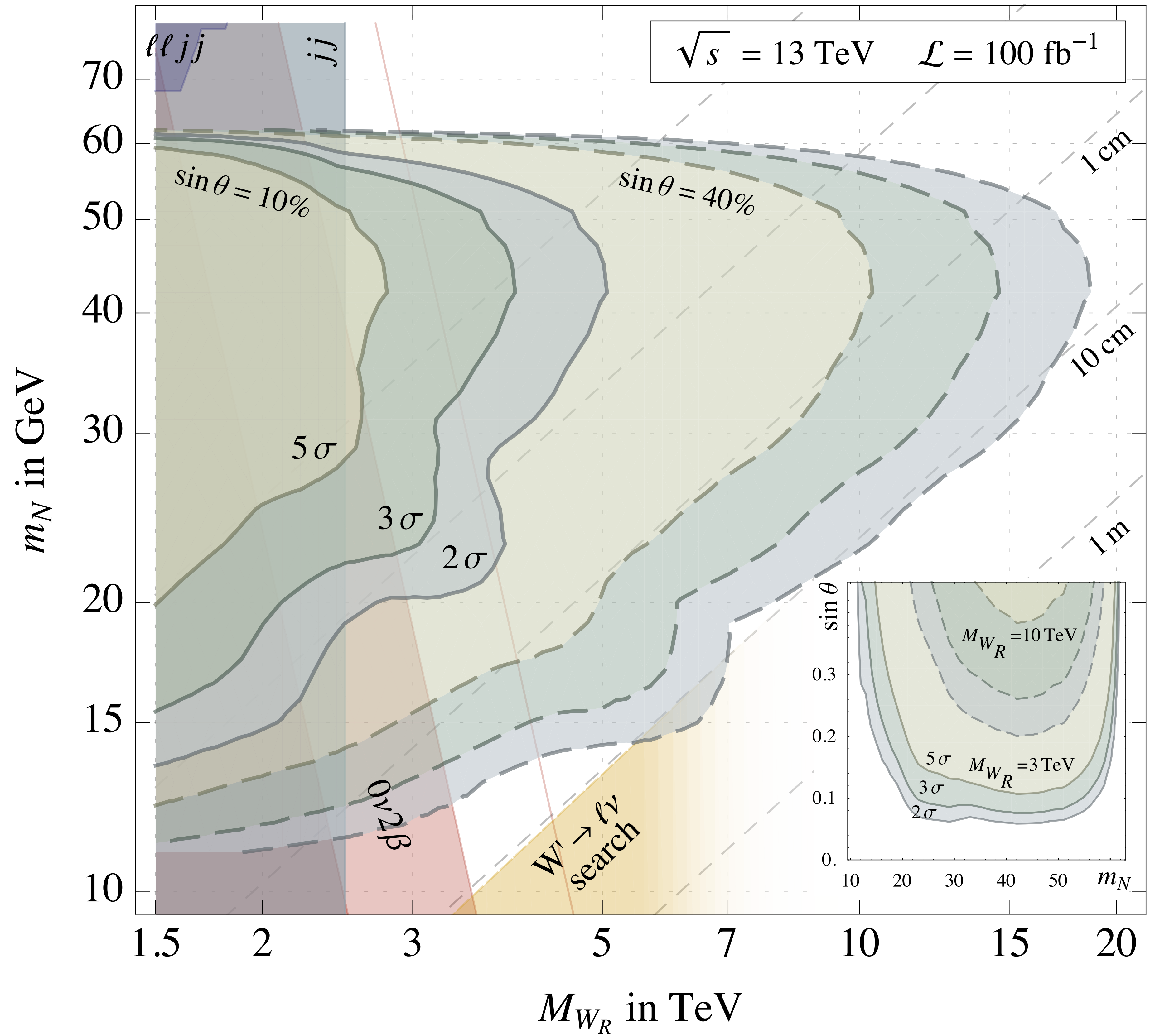
Signal features



Sensitivity

$h \to NN$

Maiezza, MN, Nesti '14

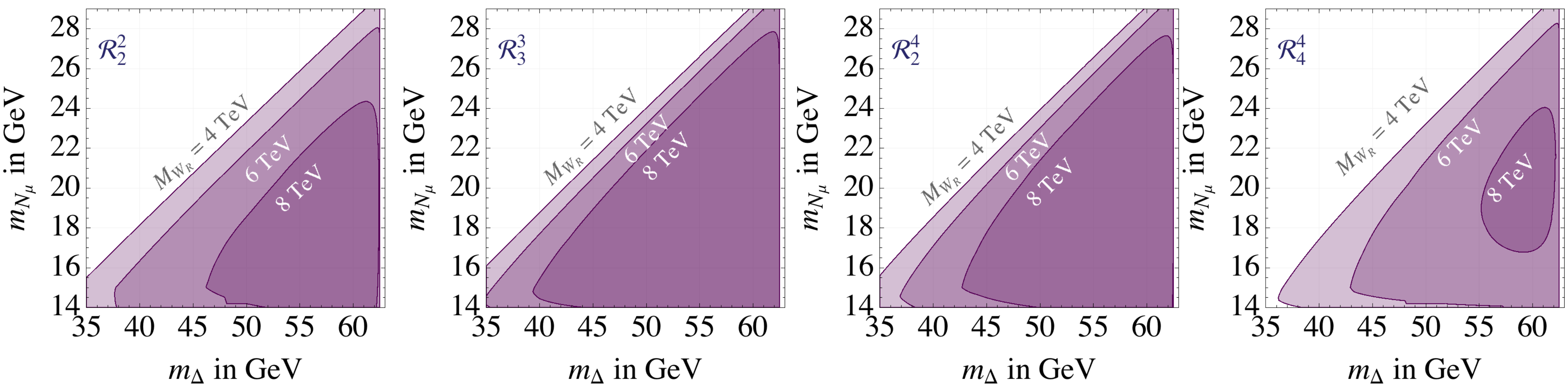


Sensitivity

$h \to \Delta\Delta \to NNNN$ @ $3\sigma, s_\theta = 0.2$

SM background ~zero $(t\bar{t}Z, t\bar{t}h, WZZ, VVVV, t\bar{t}t\bar{t}, VVtt)$

muons



backgrounds | optimal | $\Delta L \simeq 3$ | spectacular

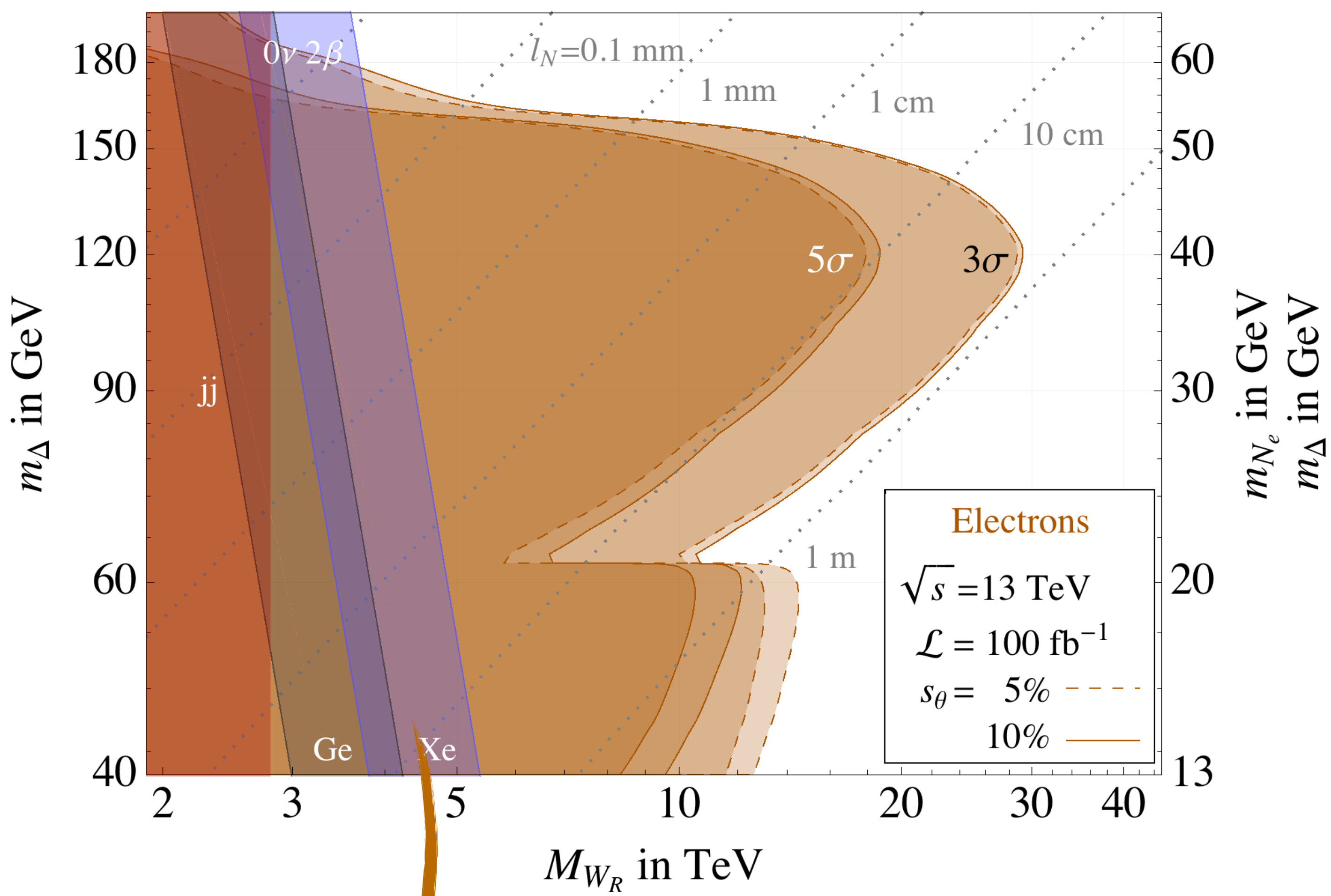
geometric & kinematic acceptance

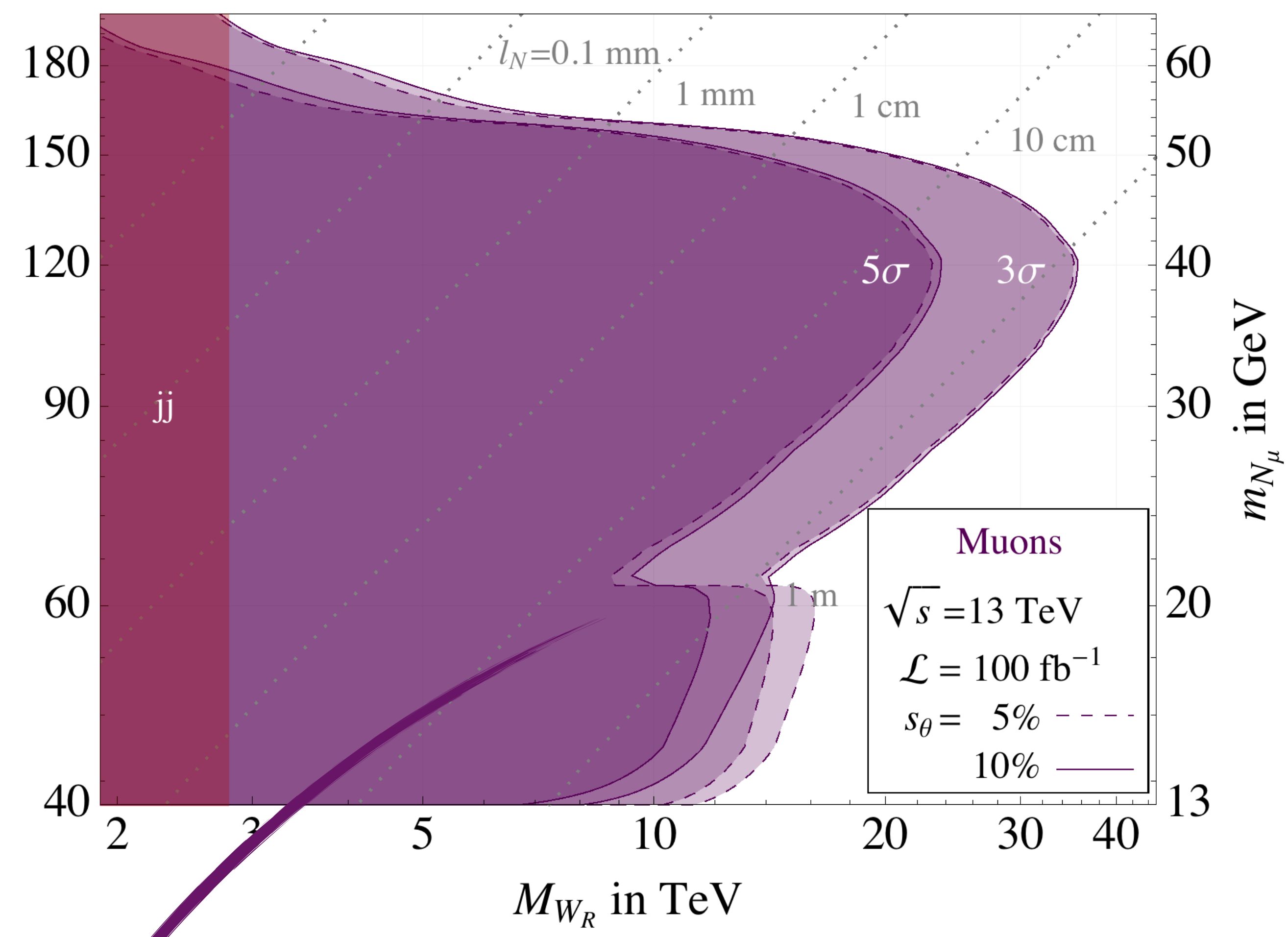
$\Delta L = 4$

electrons bit less feasible

Sensitivity

Combined $h \to NN$ $\Delta \to NN$ $\Delta\Delta \to NNNN$





connection to $0\nu 2\beta$

GERDA, Neutrino '16

KamLAND-Zen '16

$h \to \Delta\Delta \to NNNN$

displaced 0.01 mm - >1m

discovery reach beyond direct searches

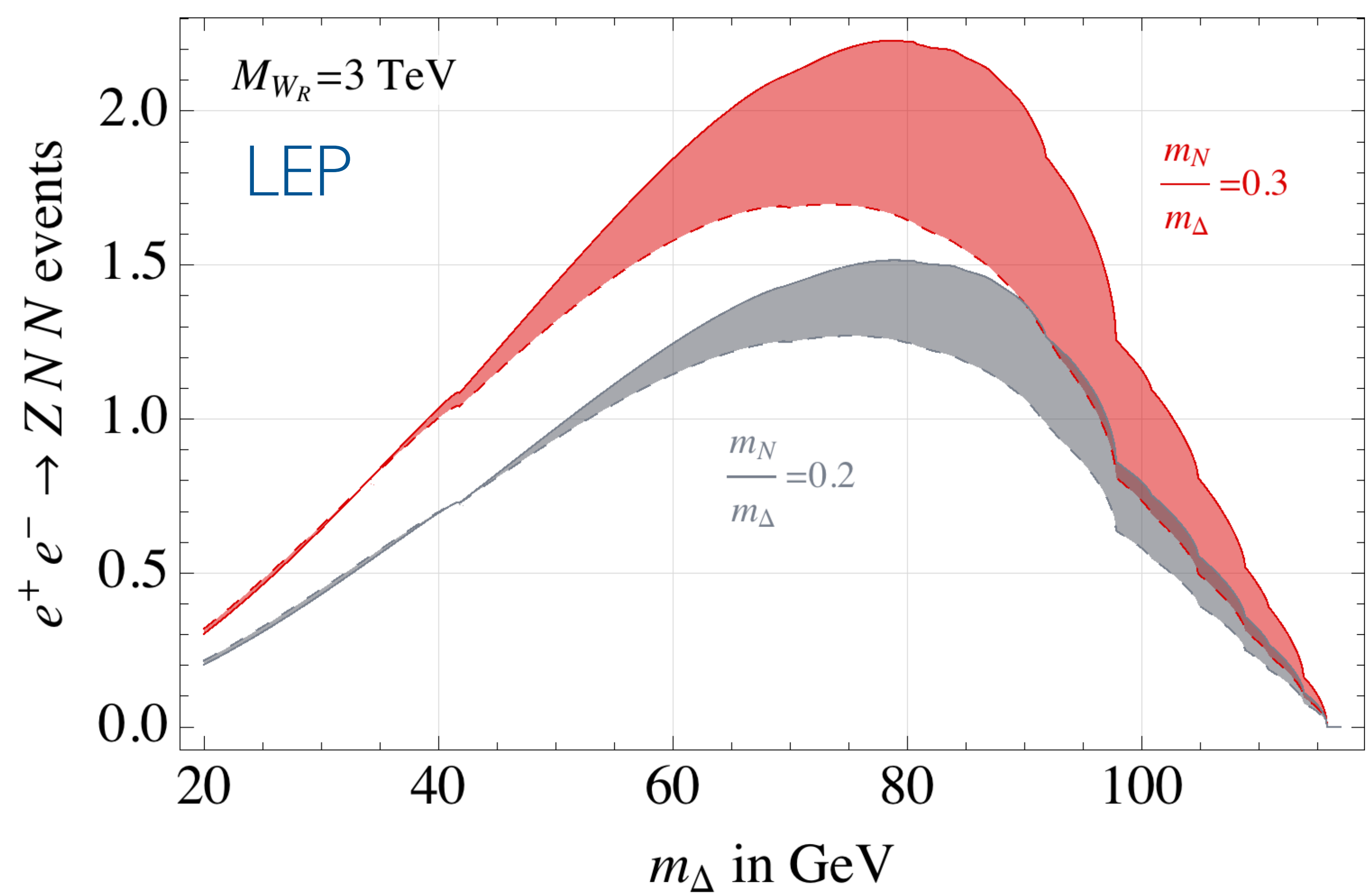
Leptonic colliders

Leptonic colliders

Dominant production modes

$e^+e^- \to Zh, Z\Delta$ $\sqrt{s} \simeq 500$ GeV $e^+e^- \to \nu\nu h, \nu\nu\Delta$

LEP low energy and luminosity



Leptonic colliders

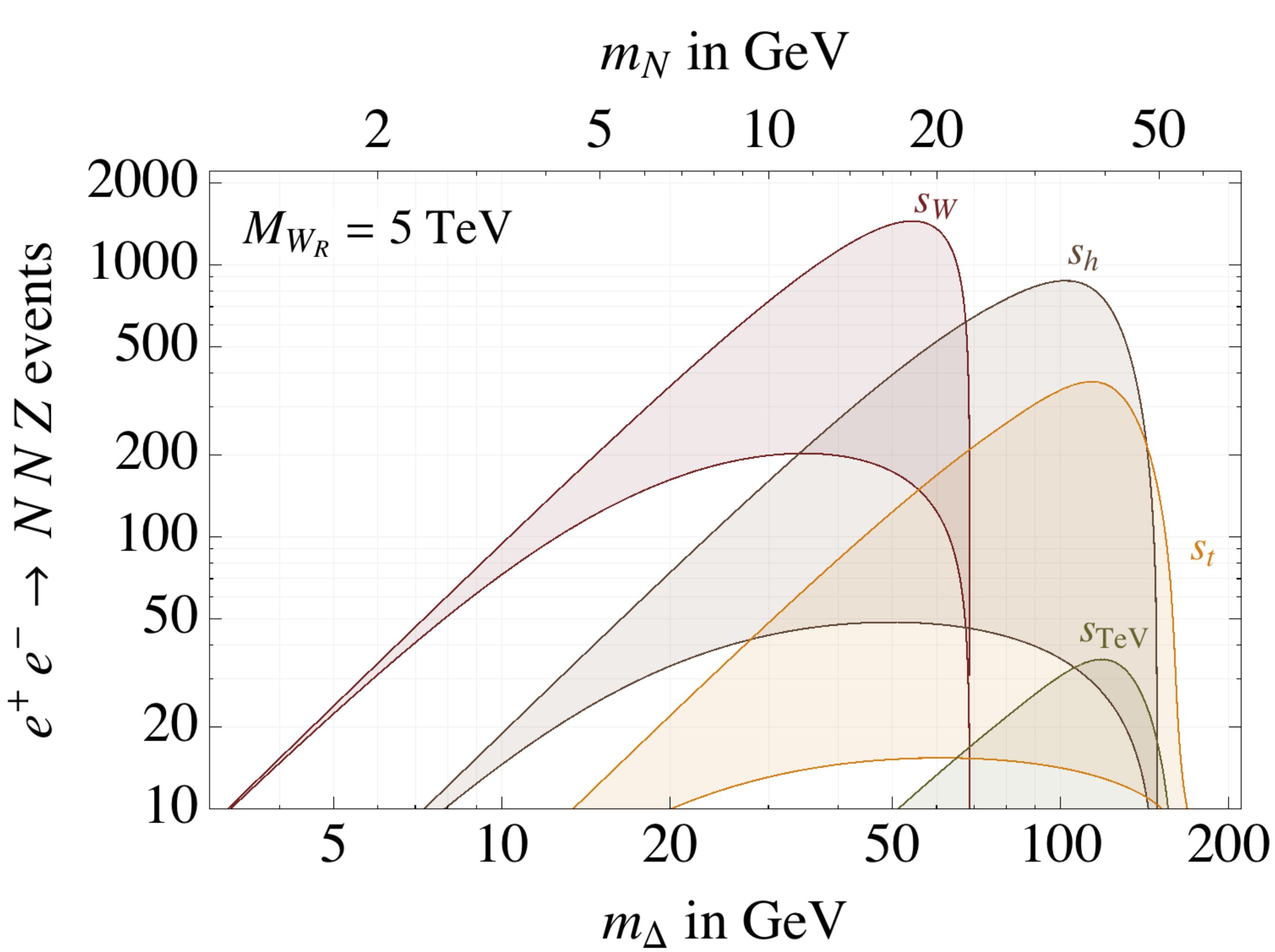
Dominant production modes

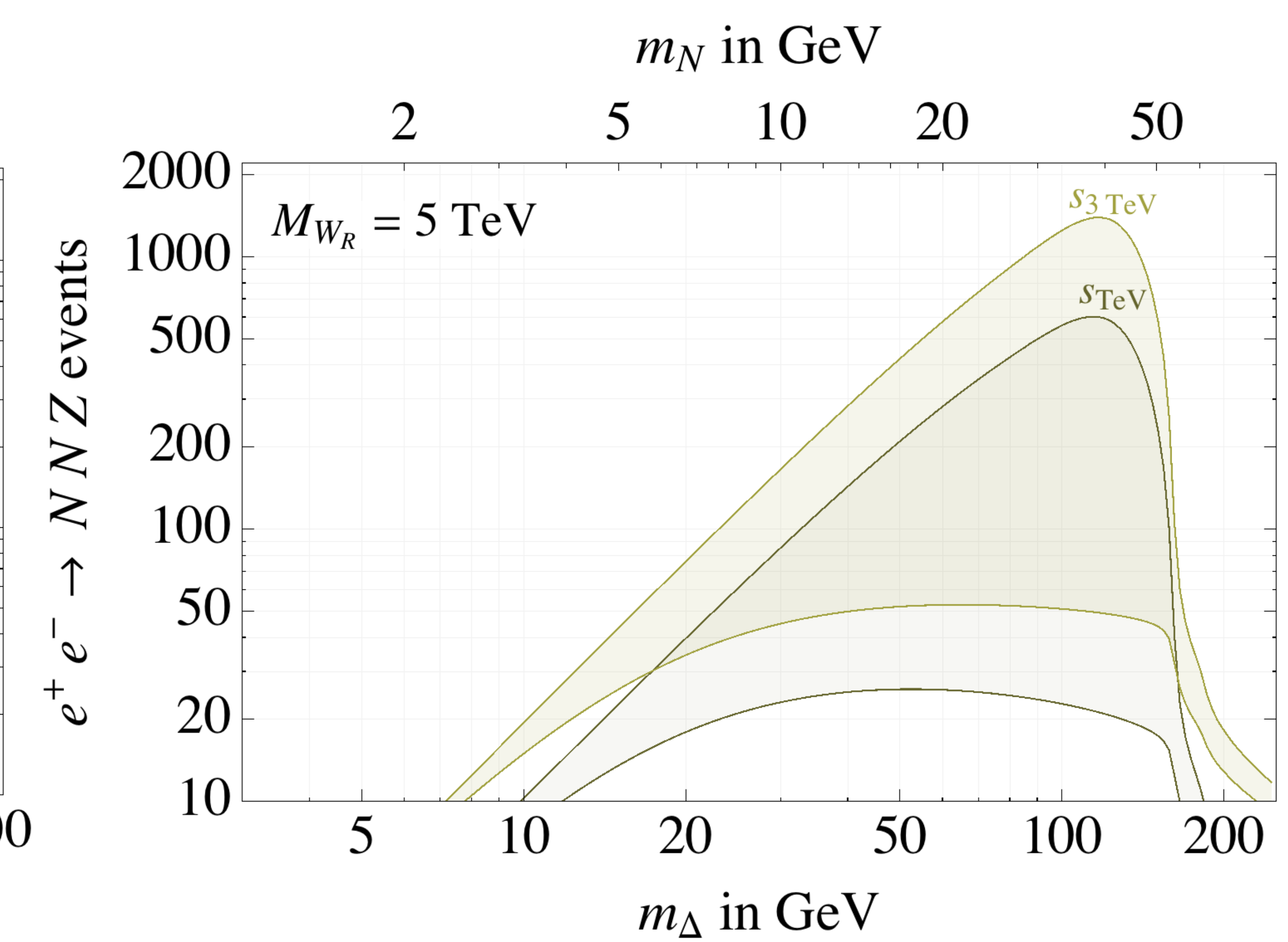
$e^+e^- \to Zh, Z\Delta$ $\sqrt{s} \simeq 500$ GeV $e^+e^- \to \nu\nu h, \nu\nu\Delta$

ILC, CLIC, CEPC, FCC-ee, ?

high energy and/or luminosity

no triggers, good energy resolution low p_T





other LNV Higgs candidates

No-go for vanilla see-saw(s)

Fourth generation $h \to \nu_4 \nu_4$

Pilaftsis '92
Carpenter '11

EFT from SM + *h* + *N*

Graesser '07
Caputo, Hernandez, Lopez-Pavon '17

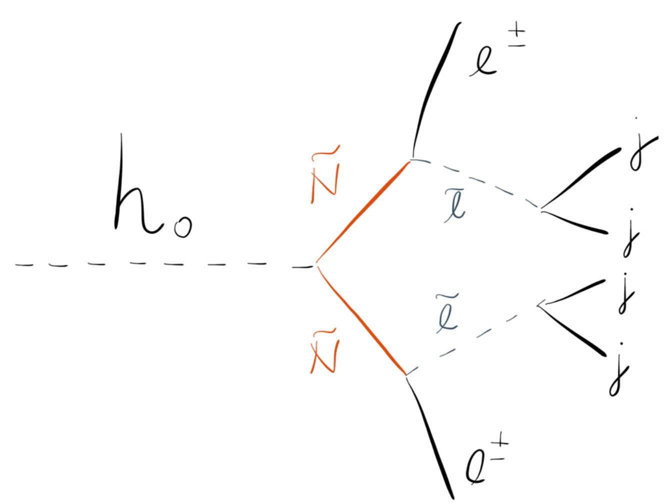
SM + *h* + *N* + singlet scalar

Shoemaker, Petraki, Kusenko '10

Spontaneous B-L

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

RPV Susy



LNV disfavored

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

needs post-LHC revision

Banks, Carpenter Fortin '08

Summary

Conclusions

Higgs sectors are a new frontier for neutrino mass models

No-go for vanilla see-saw(s)

Sensitive probe of the origin of neutrino mass within LRSM

Improvements

LFV and tau final states, displaced em-jets, include $\Delta L = 0$

improved detector simulation, vertexing, sophisticated searches (MVA, BDT), backgrounds from data

leptonic colliders promising

Thank you

Appendix slides

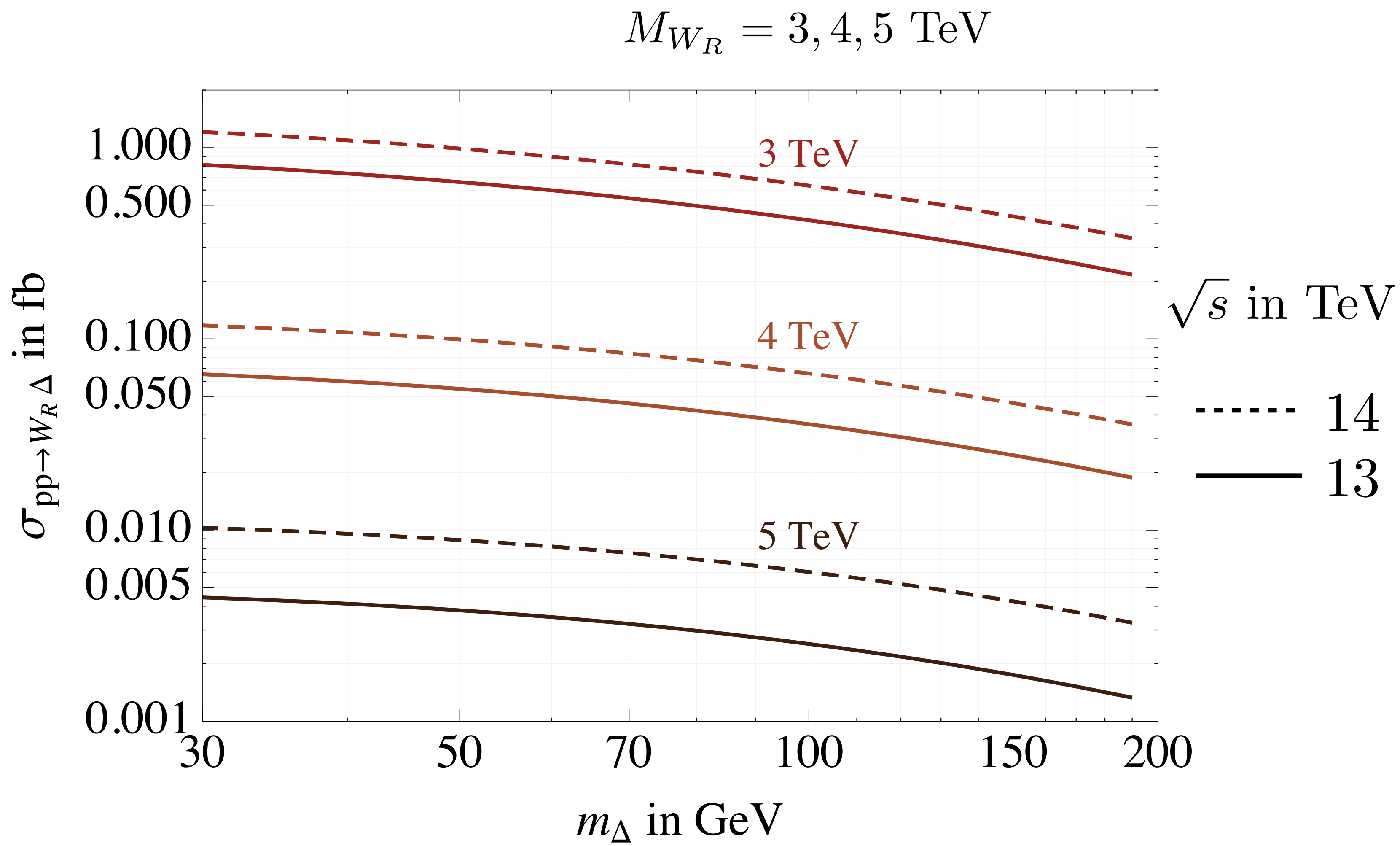
Δ production

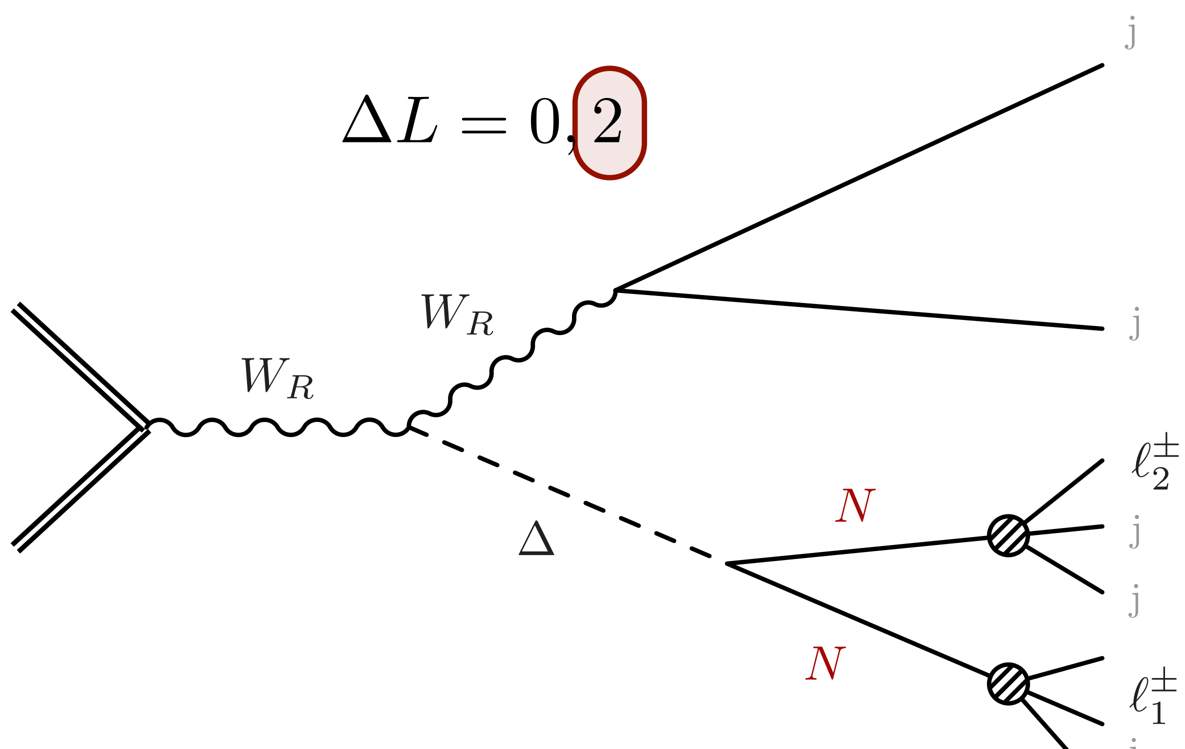
W_R strahlung, fusion small

no mixing required

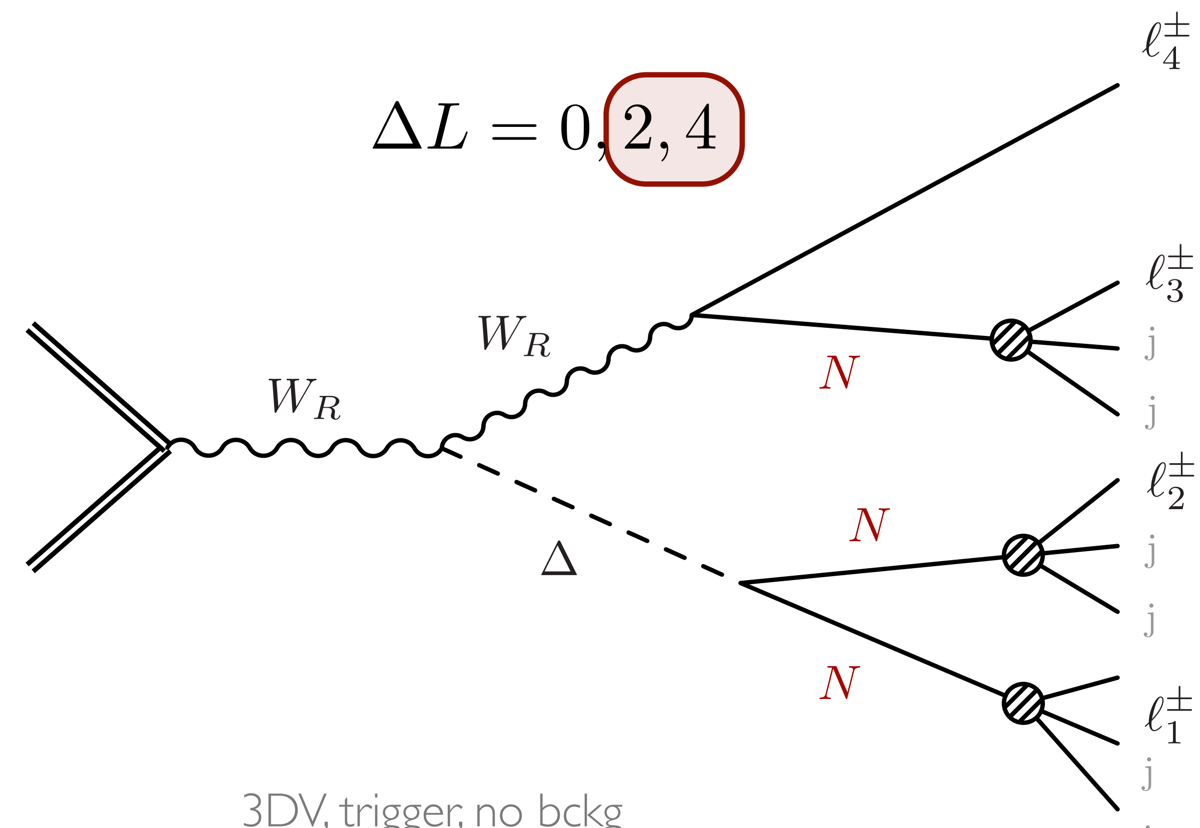
$\mathrm{Br}(\Delta \to NN) = \mathcal{O}(1)$

higher m_Δ



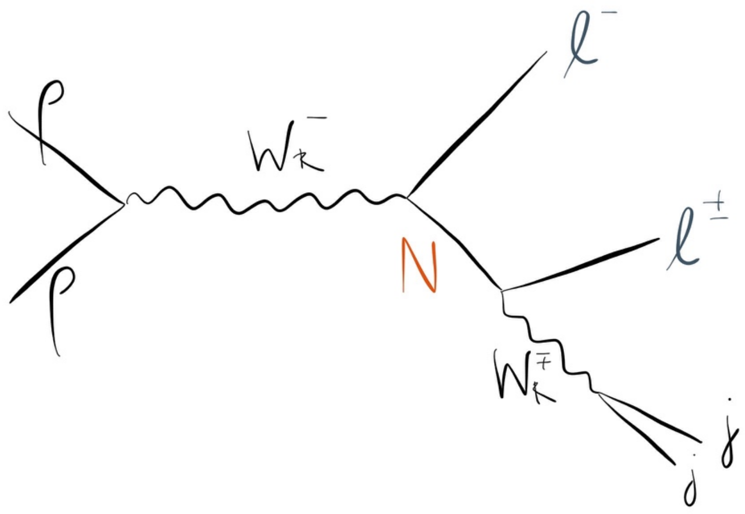


2DV, boost



3DV, trigger, no bckg

Neutrino Mass at LHC



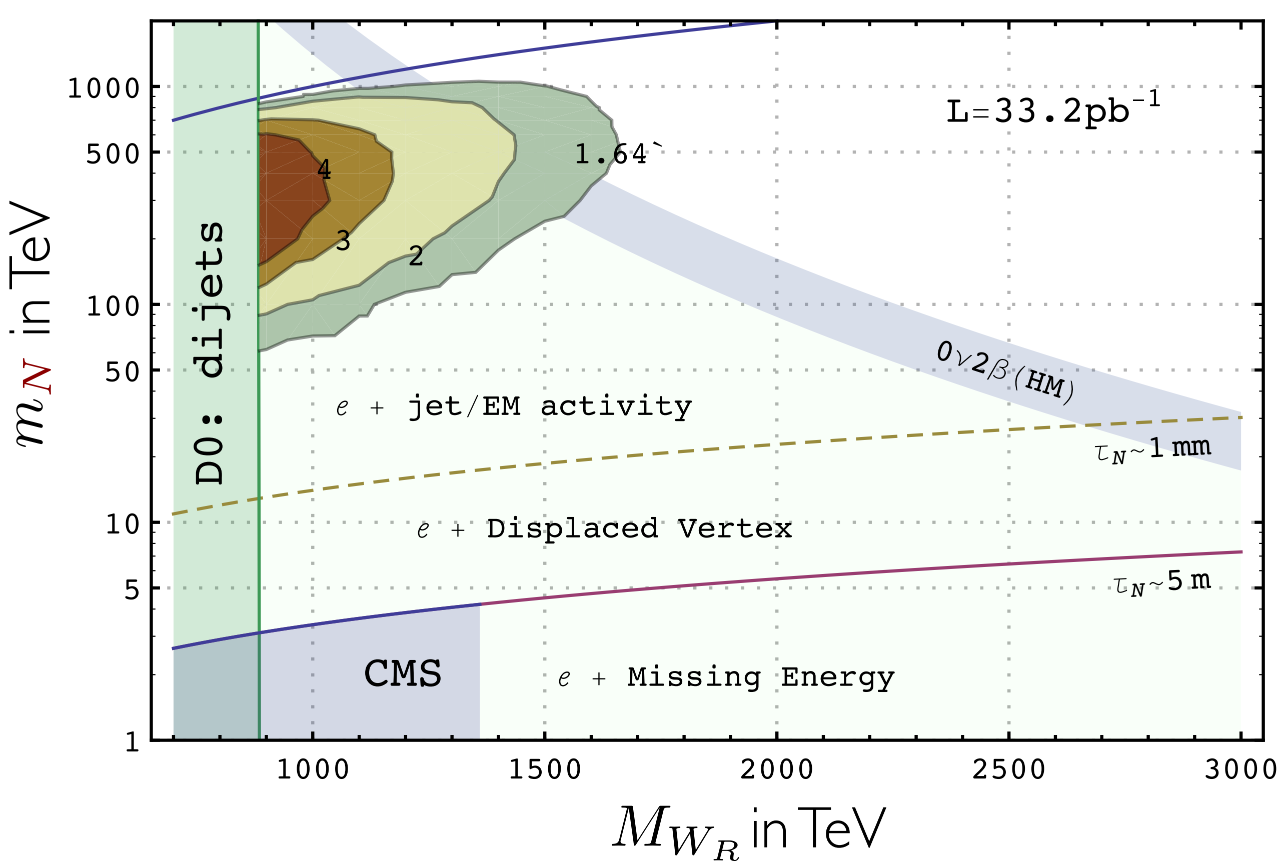
$$m_{\ell jj}^{\text{inv}} = m_N$$

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

LNV @ hadron colliders — Keung, Senjanović '83

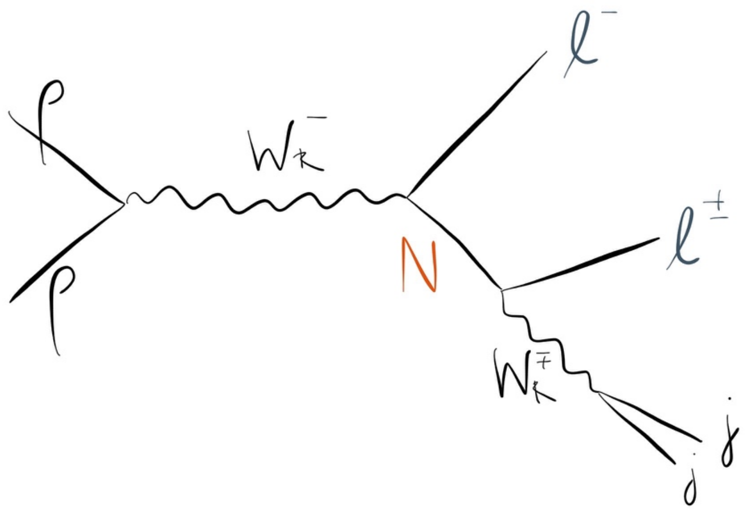
Unambiguous seesaw — MN, Senjanović, Tello '12

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



MN, Nesti, Senjanović, Zhang '11

Neutrino Mass at LHC



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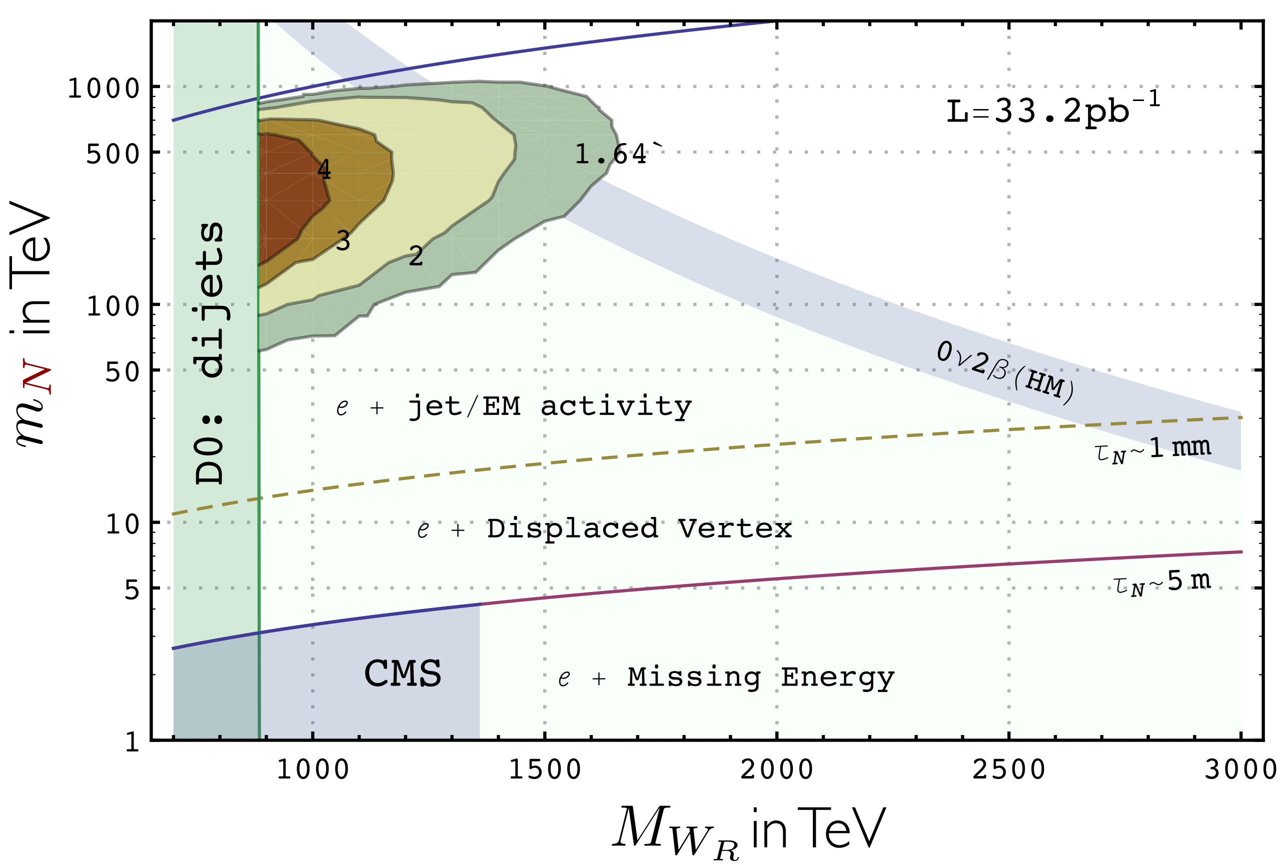
Unambiguous seesaw — MN, Senjanović, Tello '12

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

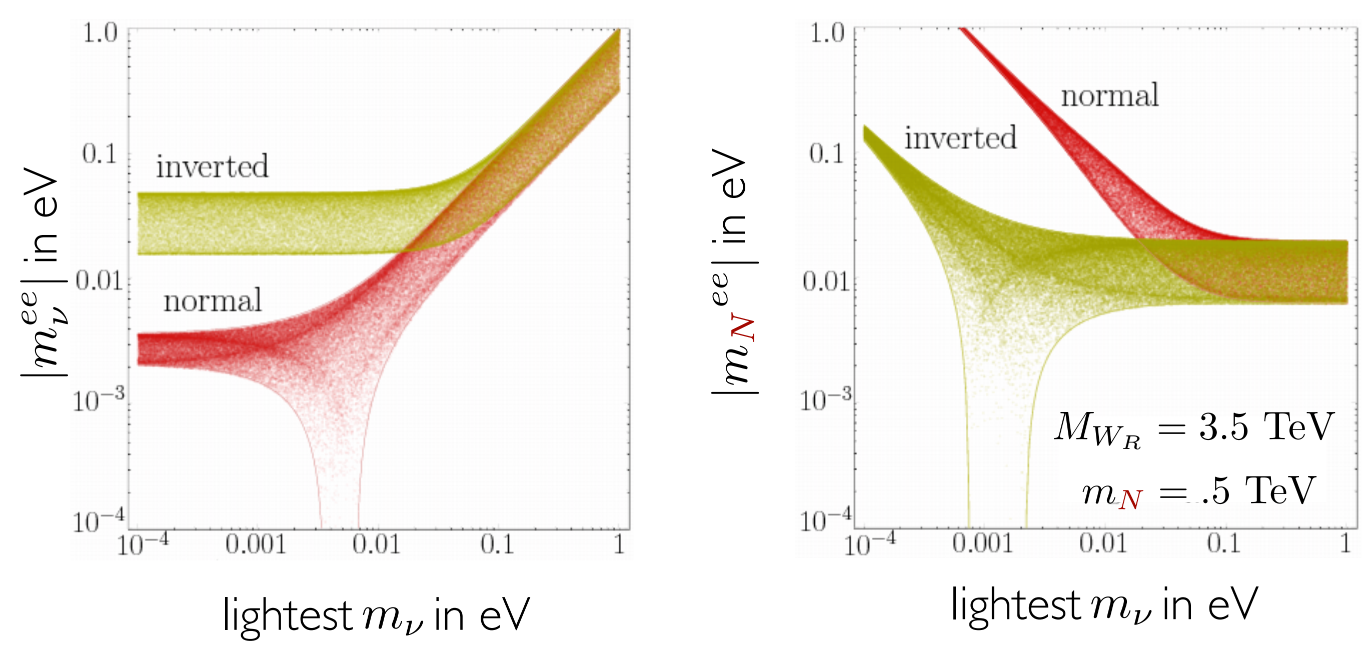
Low energies: $0\nu 2\beta$, eEDM, LFV

Mohapatra, Senjanović '79, '80

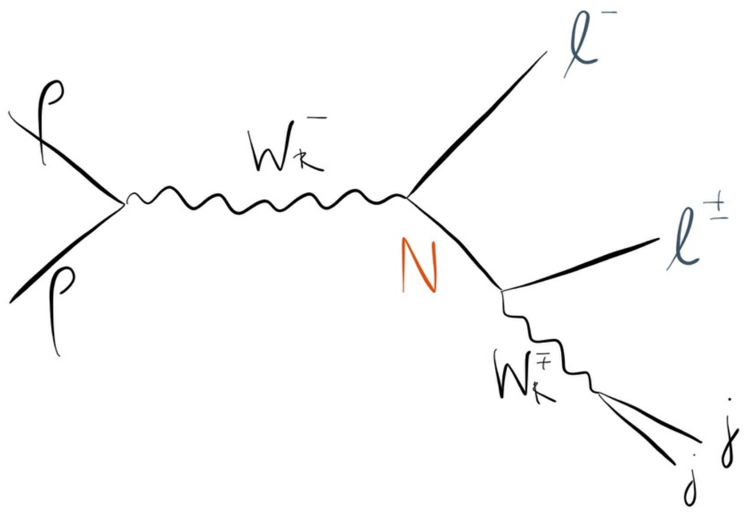
Tello, MN, Nesti, Senjanović, Vissani '10



MN, Nesti, Senjanović, Zhang '11



Neutrino Mass at LHC



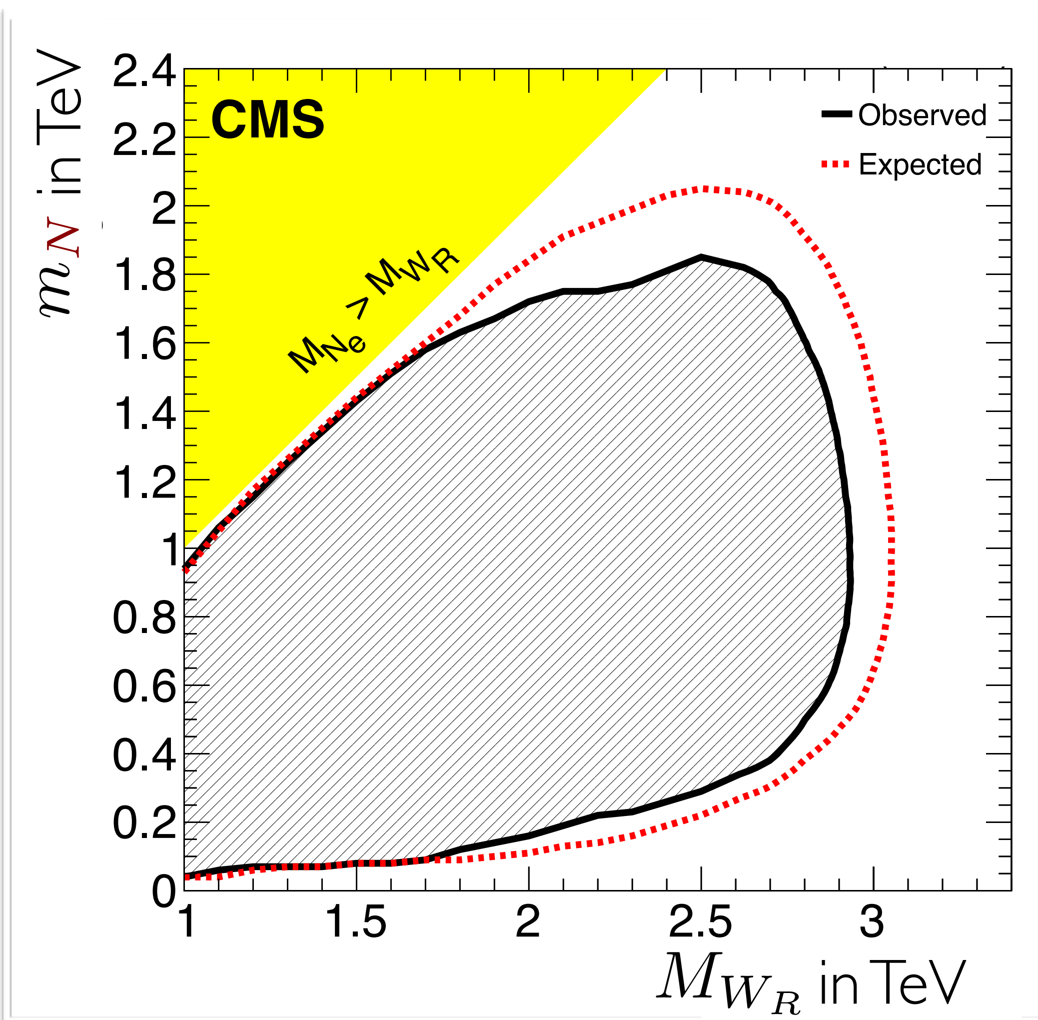
$$m_{\ell jj}^{\text{inv}} = m_N$$

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

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



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

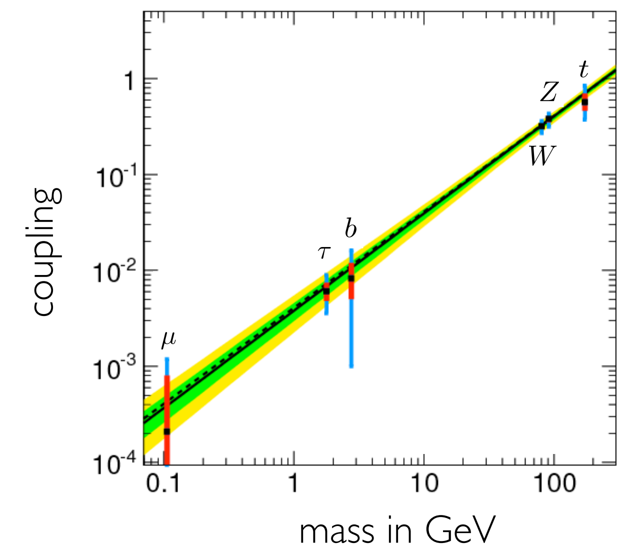
Mohapatra, Senjanović '79, '80

Tello, MN, Nesti, Senjanović, Vissani '10

Majorana vs. Dirac

SM a *predictive* theory of charged fermion mass origin

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



Type I/III seesaw

$$\mathcal{L}_\nu = M_D \overline{\nu}_L h N + M_N N N + h.c.$$

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

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...

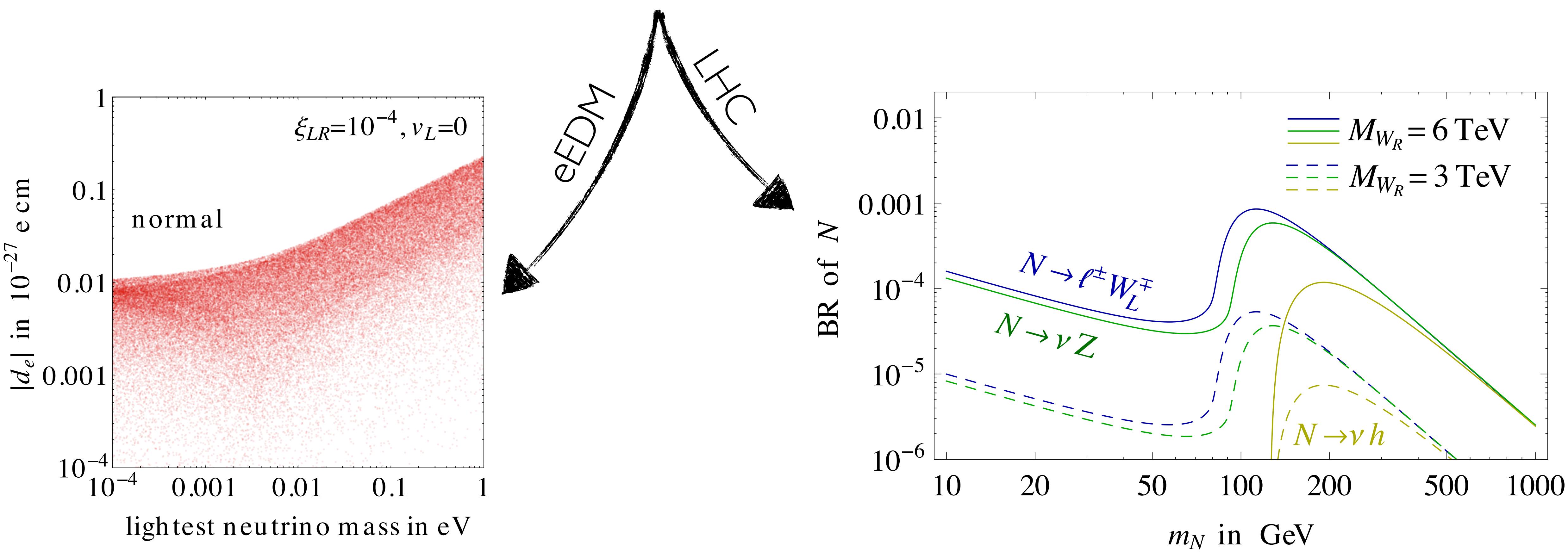
Majorana vs. Dirac

Left-Right gauge interaction defines the basis

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

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



small mixing   large mixing   decay length

$\ell\ell jj =$ KS search

CMS 1407.3683

$jj =$ dijet search

CMS 1501.04198

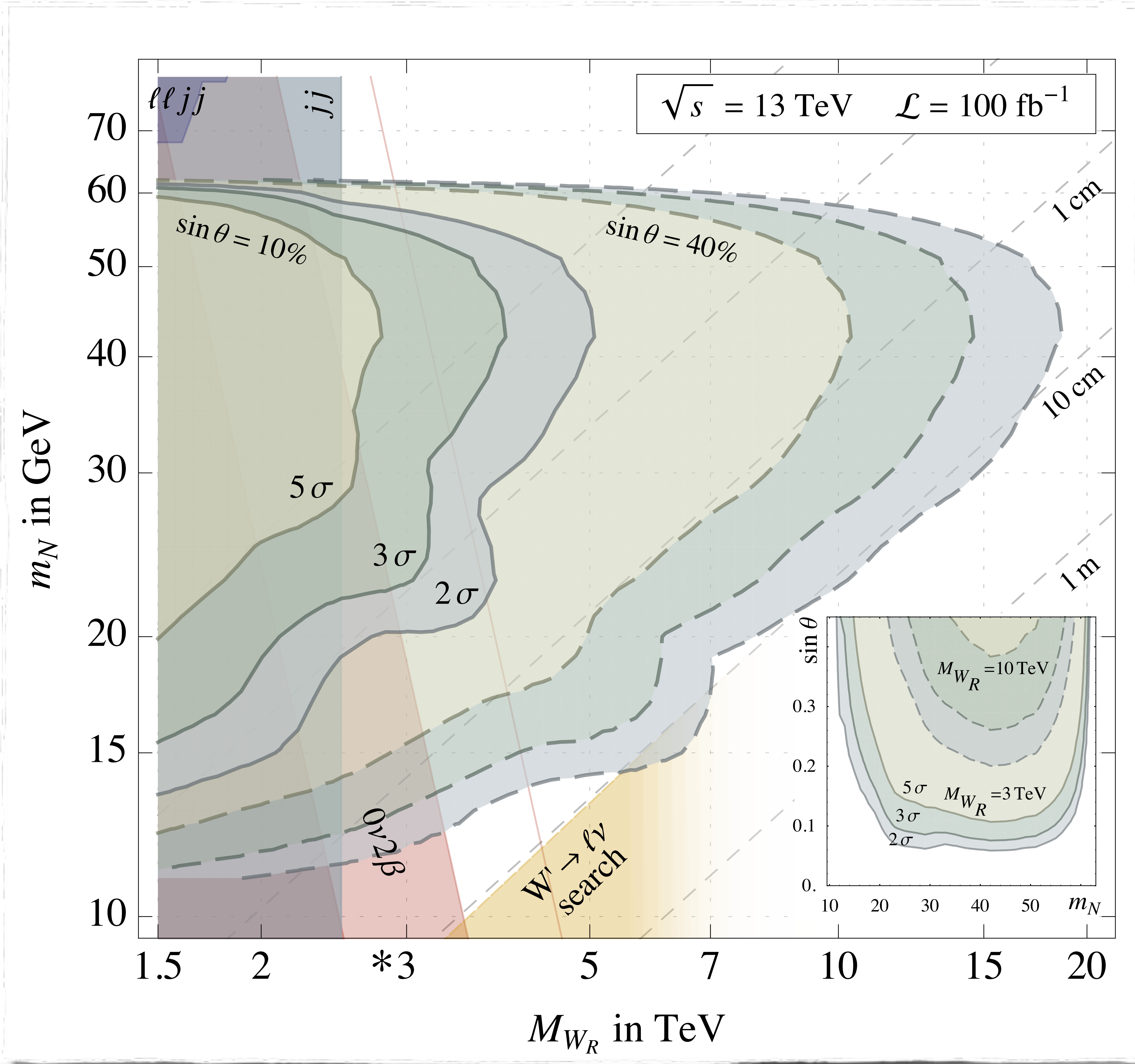
$0\nu2\beta =$ GERDA I & II

GERDA I 1307.4720

* NME uncertainty

$W' \to \ell\nu =$ search

CMS 1408.2745

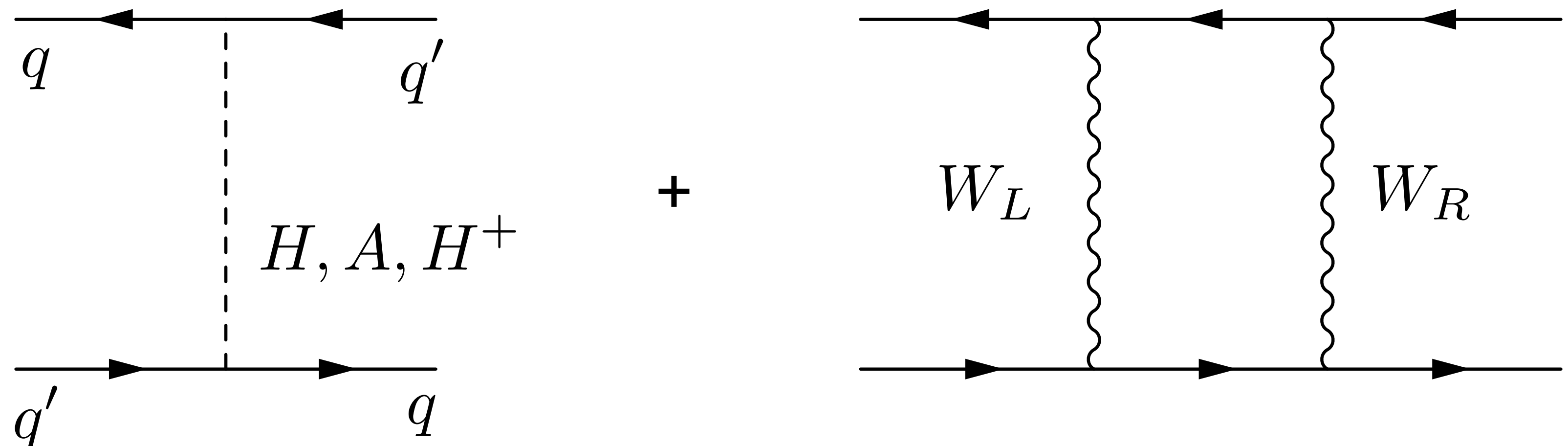


H

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

Tree-level FCNCs

Senjanović, Senjanović ’80, ...



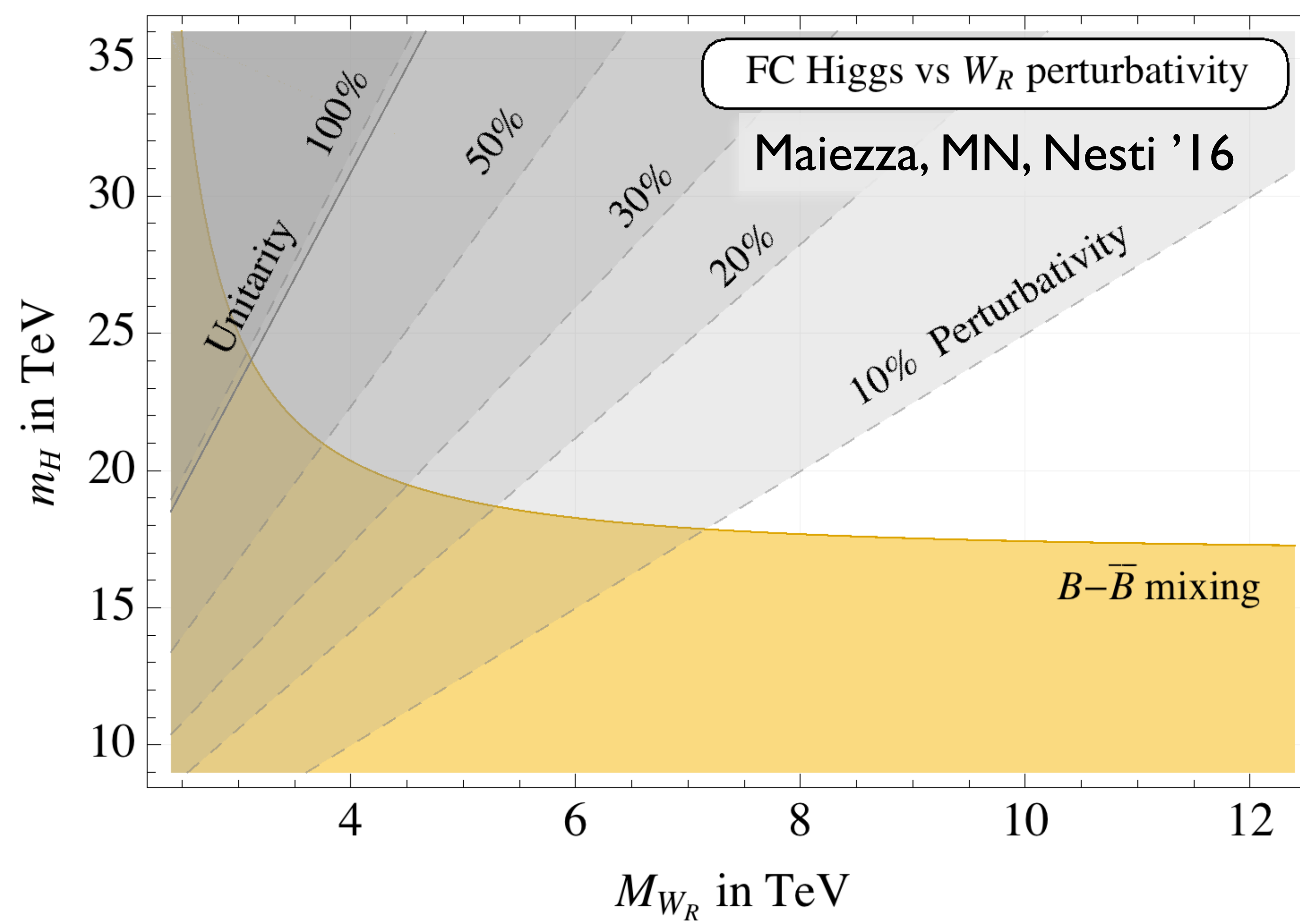
All couplings computable with $\mathcal{P}$ and $\mathcal{C}$

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

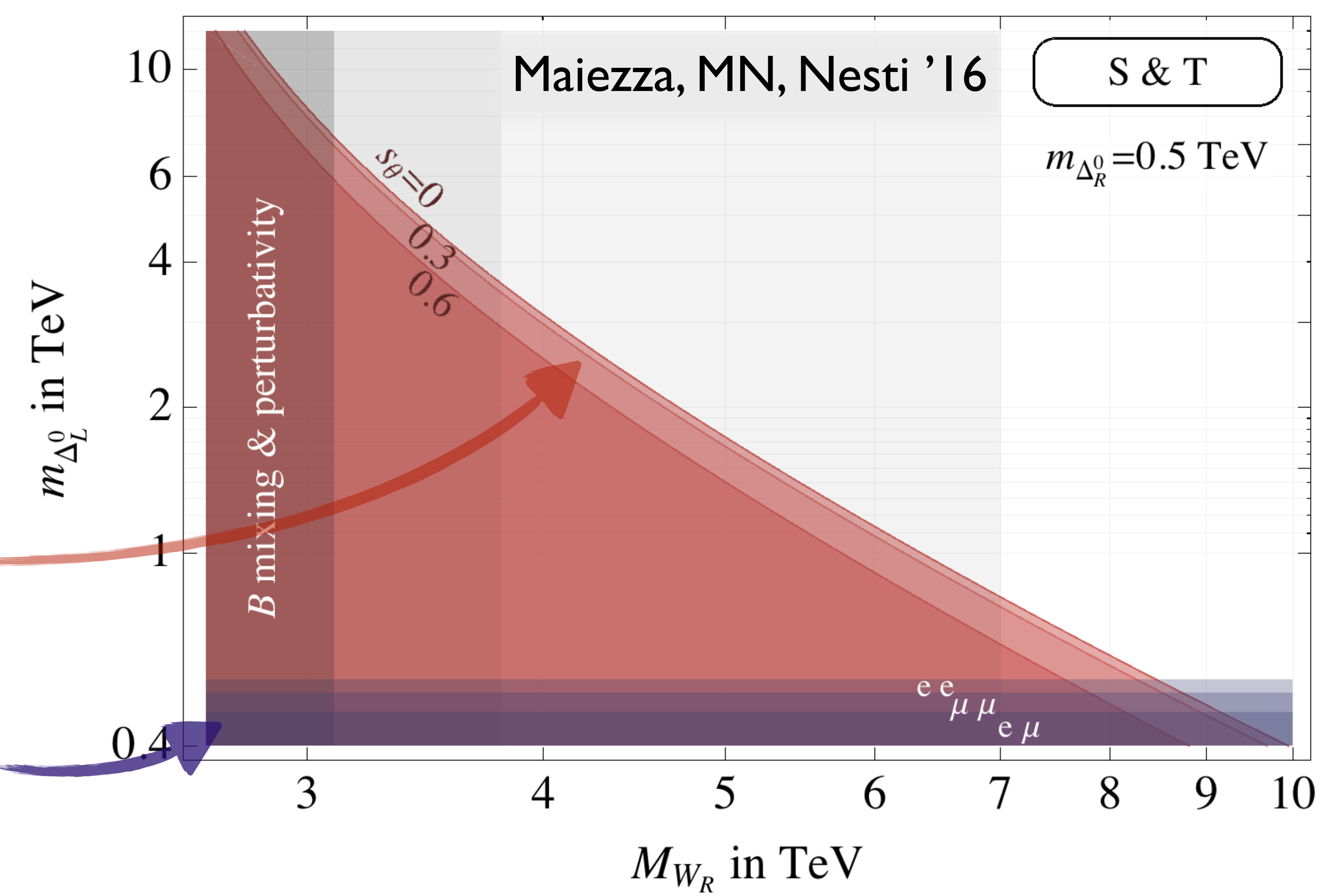
Δ_L^0 lightest, missing energy at LHC

S & T oblique parameters

decouple with m_{Δ_L}

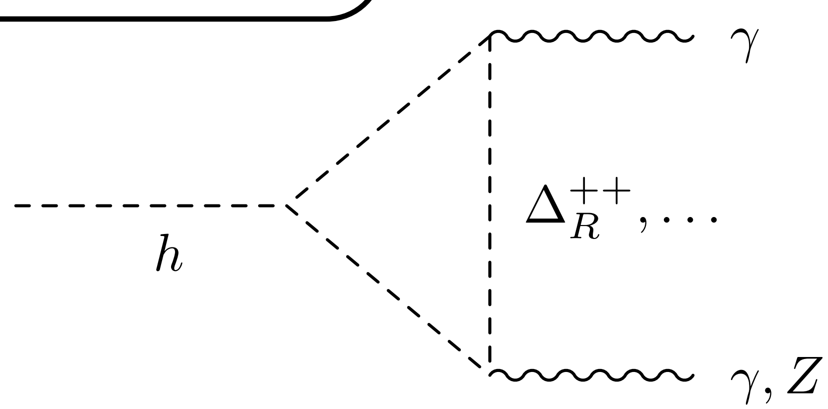
partial cancellation with s_θ

competes with direct searches



Δ_R^{++}

$h \to \gamma\gamma, \gamma Z$



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

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