6TH IDPASC SCHOOL
Slovenia, Vipava, 23 May - 01 June 2016

JSI

Neutrino Mass and colliders

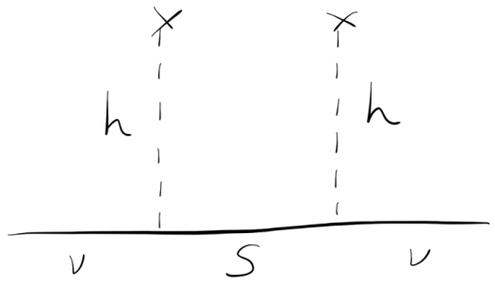
Miha Nemevšek

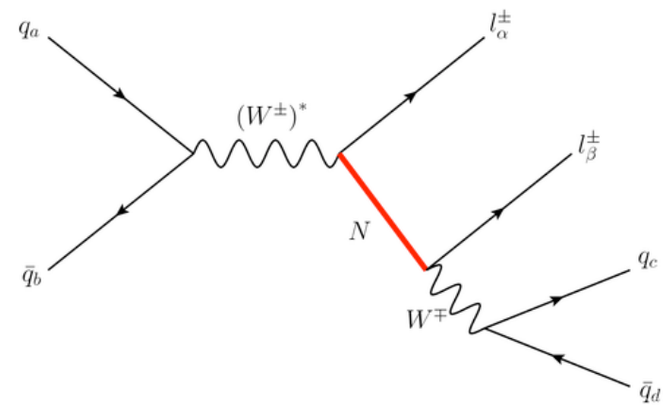
University of Nova Gorica
Summer School

Vipava, May 28th 2016

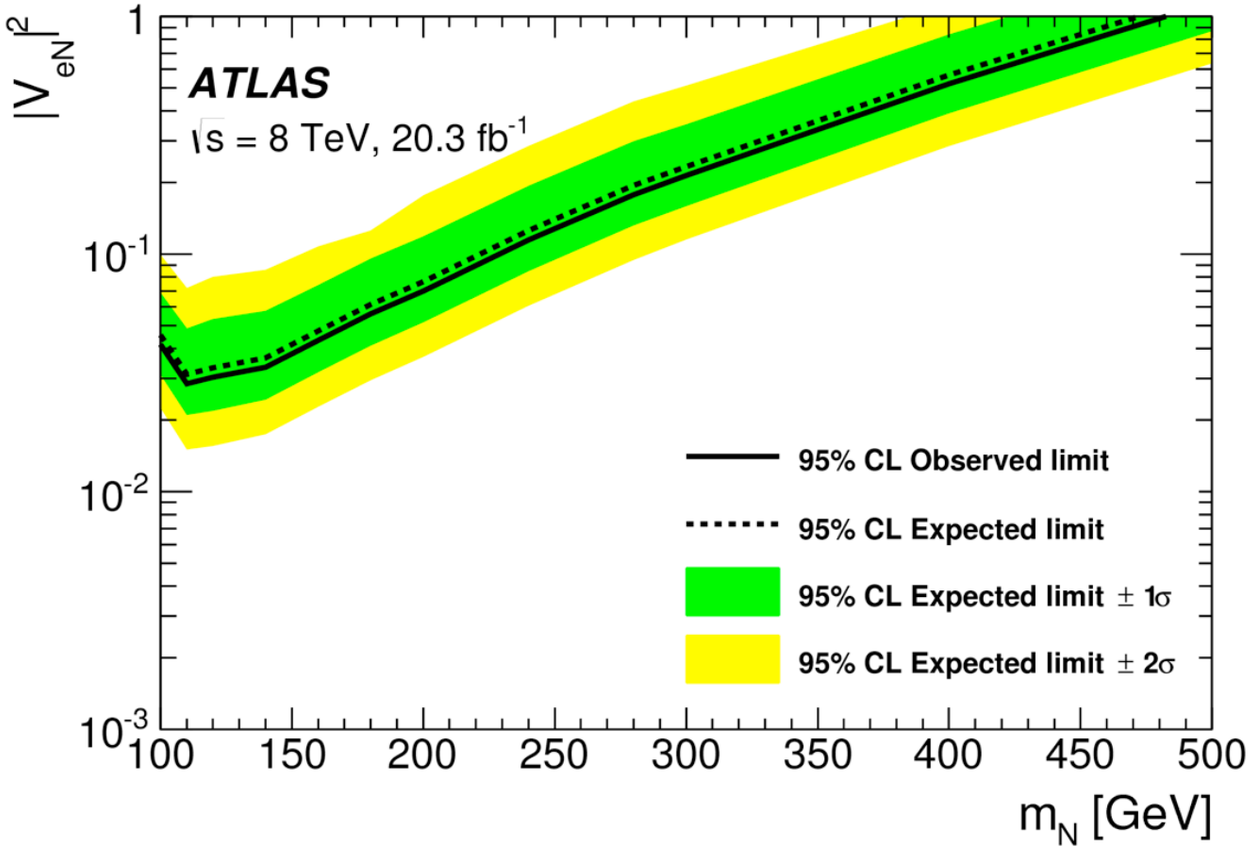
type I

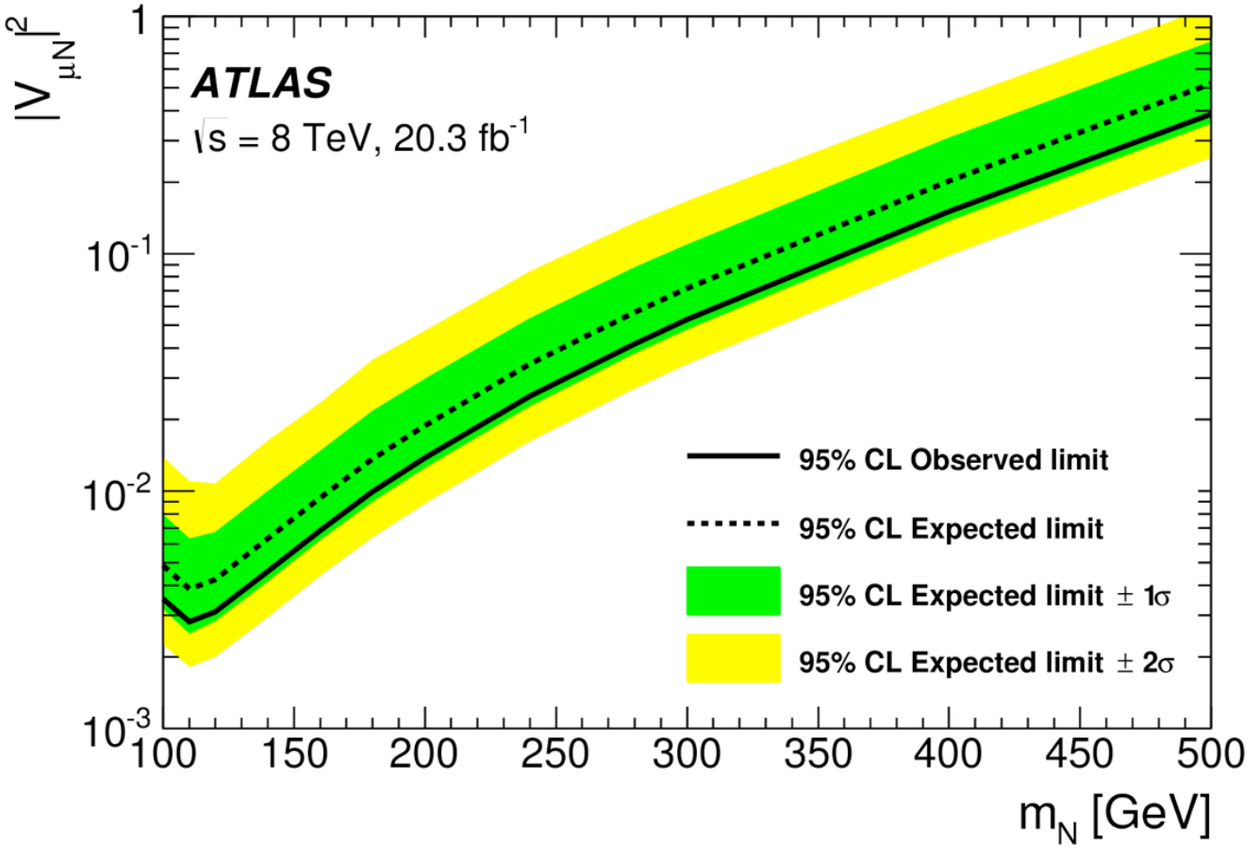
type I





ATLAS 1506.06020

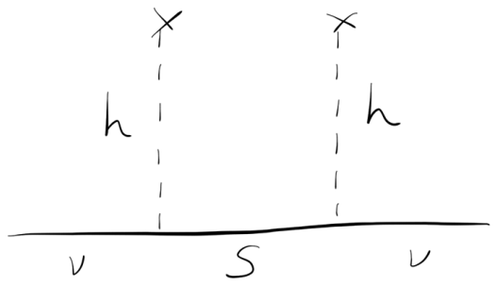


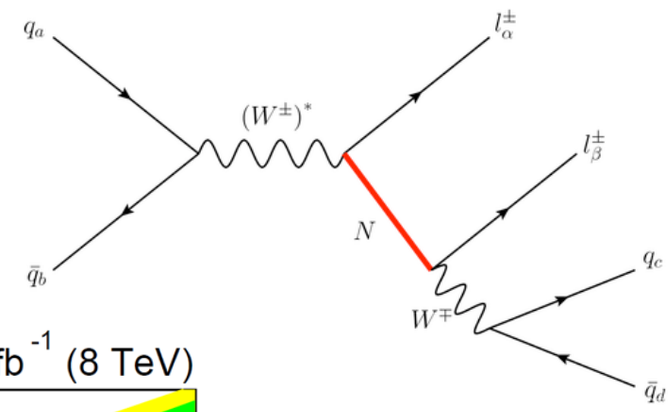


electrons a bit worse, larger *B*s

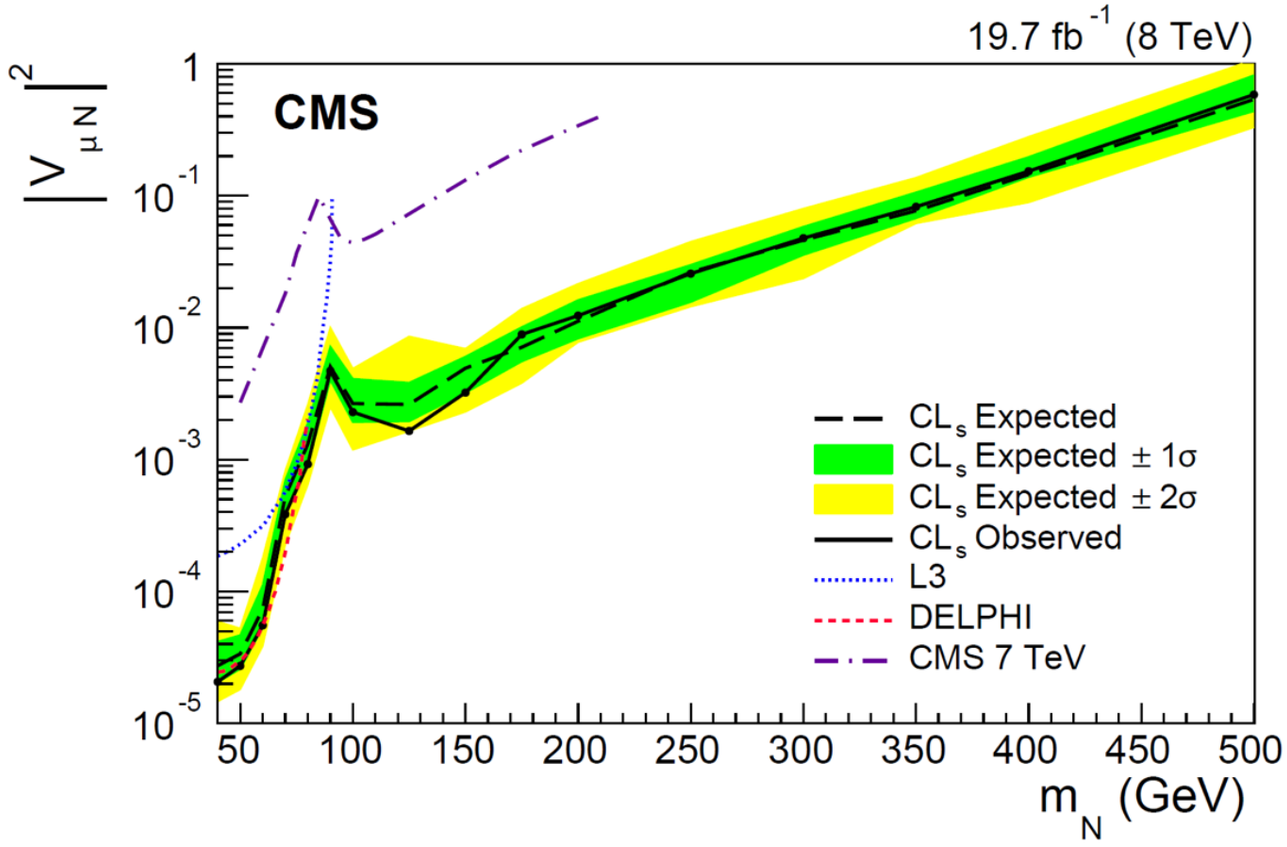
jet fakes, secondary photoproduction

type I



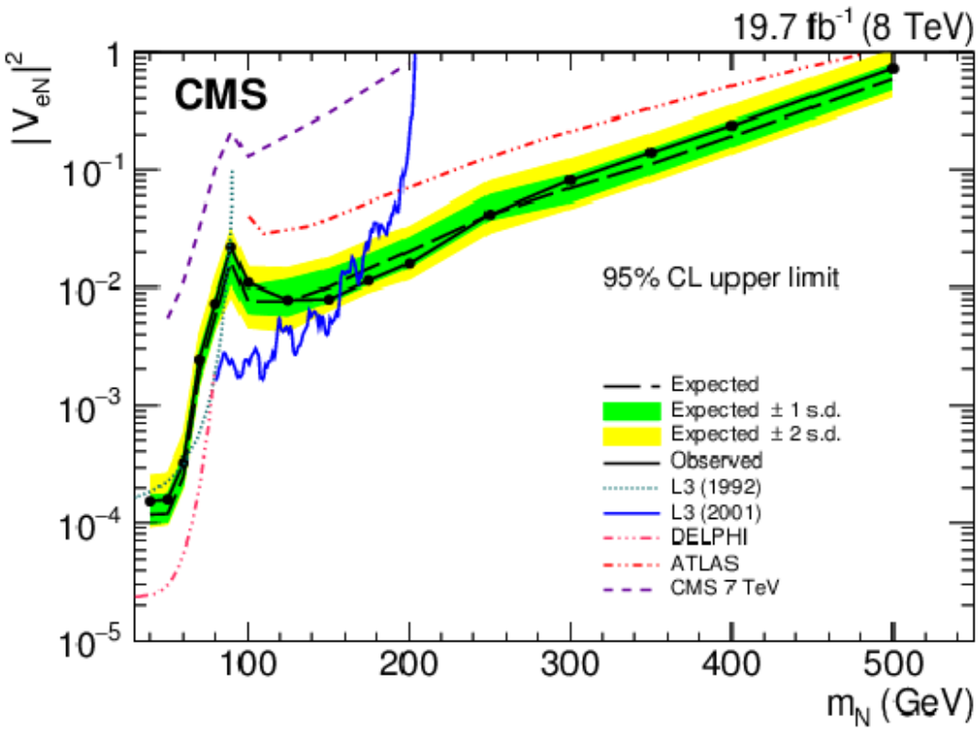


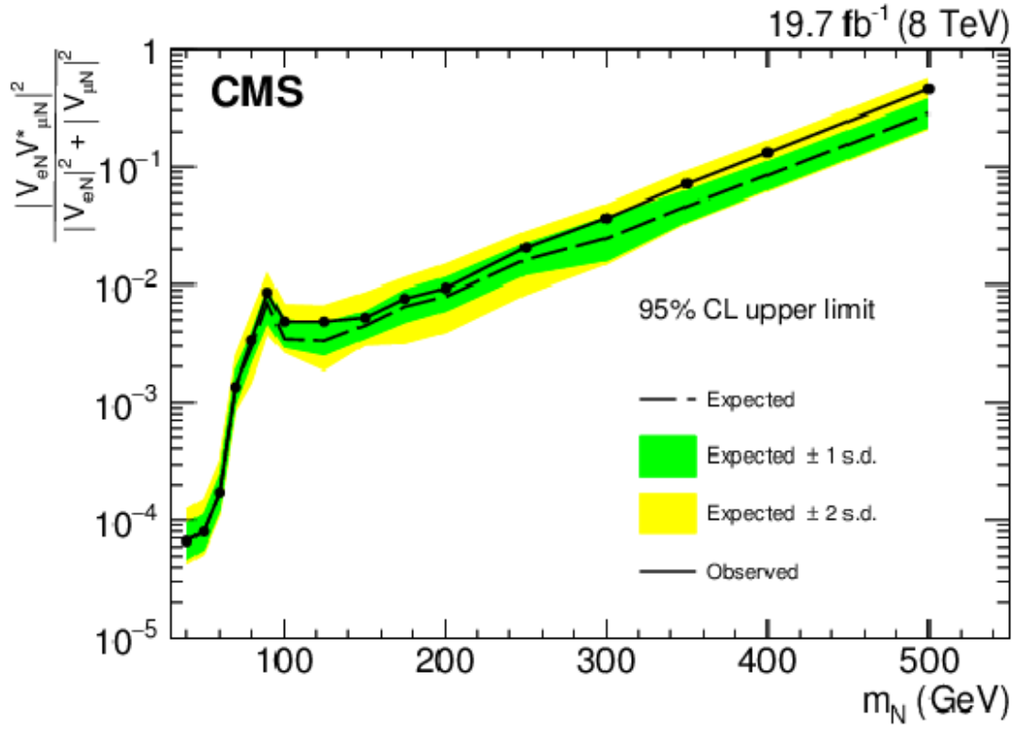
sensitive below W



CMS 1501.05566

CMS 1603.02248





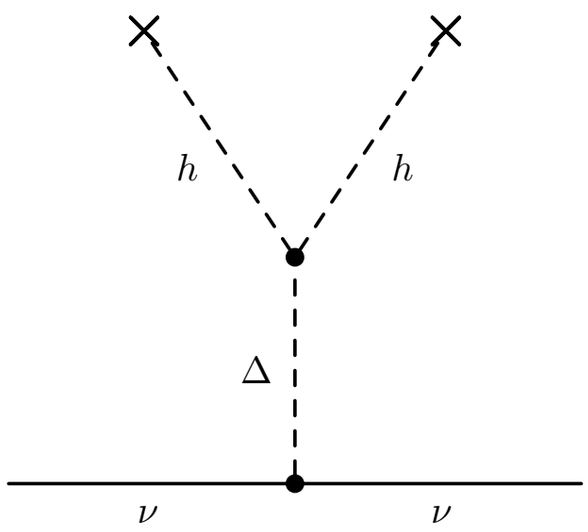
type II

type II

2 x 2 = 1+3, the only rep. apart from Higgs

simple(st) one rep. addition to SM

Cheng, Li '80
Magg, Wetterich '80



possible remnant of

SO(10)	126_H	Lazarides, Shafi, Wetterich '81
SU(5)	15_H	Glashow '79, ...
Left-Right	$\Delta_L(3,1,2)$	Mohapatra, Senjanović '81

tests at the LHC

open issues?

LNV @ LHC needs luck

type II

$$\Delta_L = \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 + v_L & -\Delta^+/\sqrt{2} \end{pmatrix}$$

$$\mathcal{L}_\Delta = |D\Delta_L|^2 - Y_\Delta\, L^T C \Delta_L L - V(\Delta, \varphi)$$

gauge production

decays to g.b.s

neutrino mass

decays to leptons

mass spectrum

cascade decays

$W, Z \to \Delta\Delta$

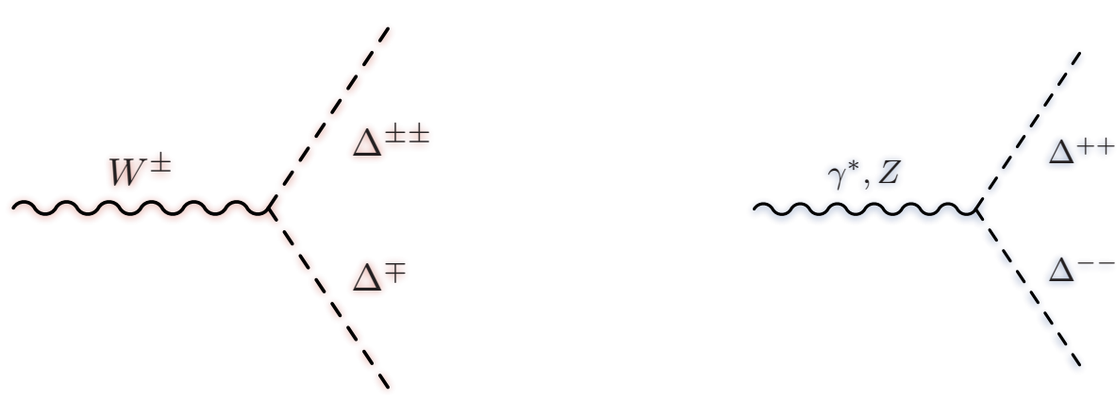
$v_L < \mathcal{O}(\mathrm{GeV})$

$$M_\nu = Y_\Delta v_L = V_L^T m_\nu V_L$$

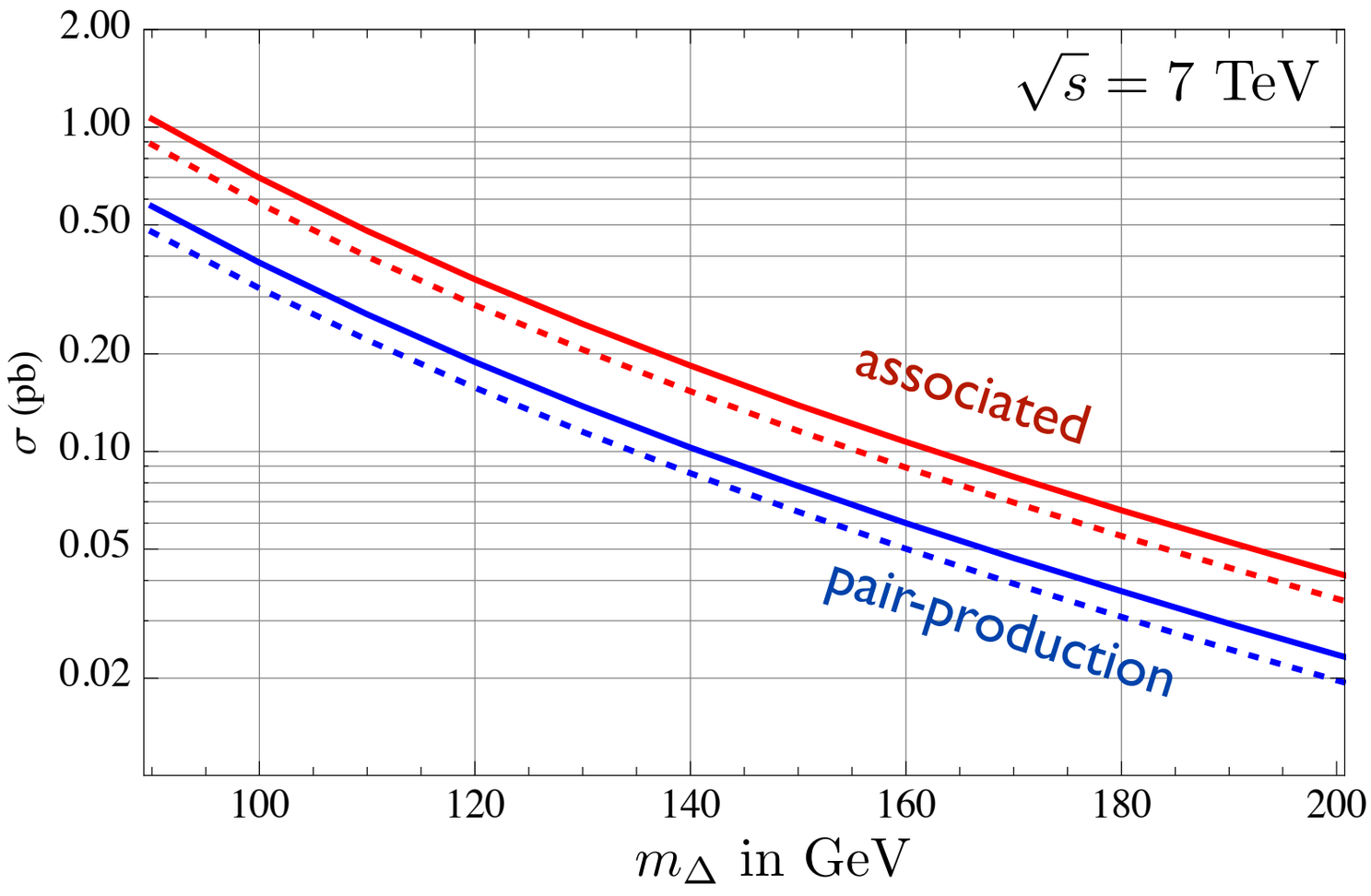
$$m_+^2 - m_{++}^2 \simeq$$
$$m_0^2 - m_+^2 \simeq \beta v^2/4$$

Need Yukawa and v_L to break LNV

type II production



Azuelos et al. '05
Akeroyd, Aoki '05



Single production small

Godfrey, Moats '10
Bhambaniya et al. 1504.03999

Production studies

del Aguila, Aguilar-Saavedra, Pittau '07, '08
Han, Fileviez-Perez, Huang, Li, Wang '08

LHC reach @ 14 TeV

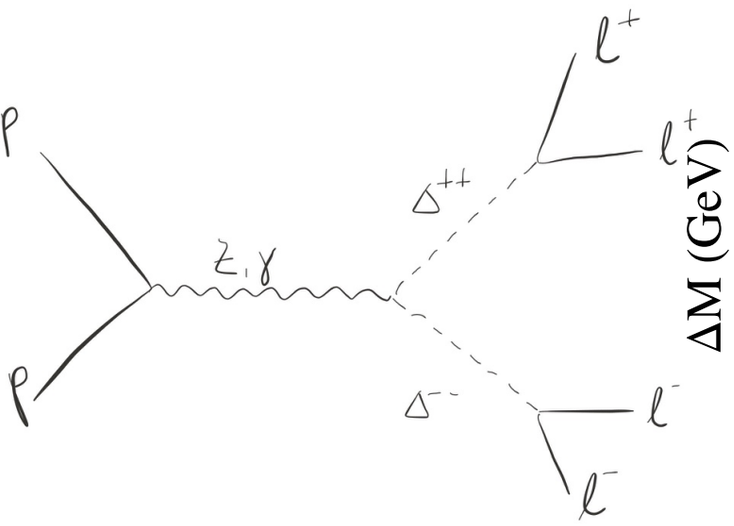
$$m_\Delta \lesssim 700 \text{ GeV} - 1 \text{ TeV}$$

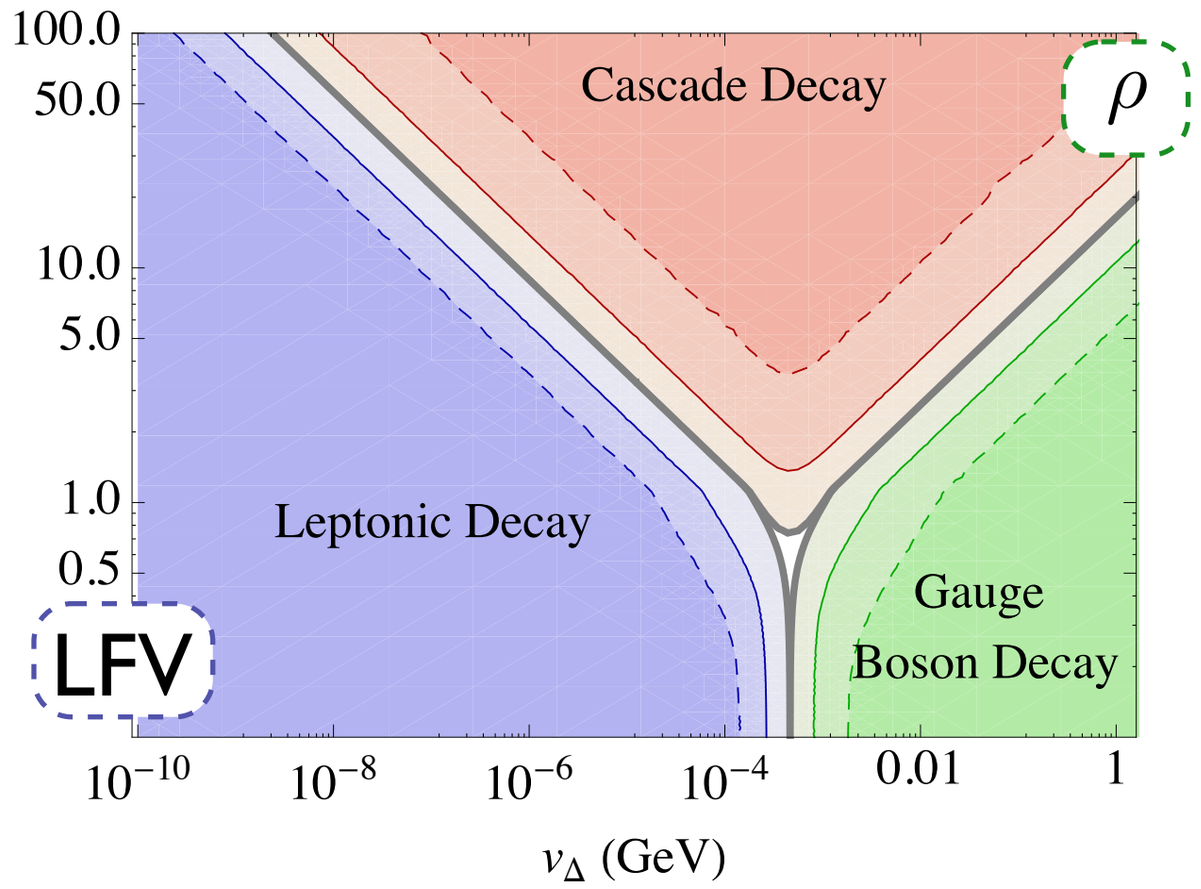
type II decays

$$\Delta m^2 = m_+^2 - m_{++}^2$$
$$\simeq m_0^2 - m_+^2 \simeq \beta v^2/4$$

spectacular two same-sign di-leptons

Melfo, MN, Nesti, Senjanović, Zhang '11





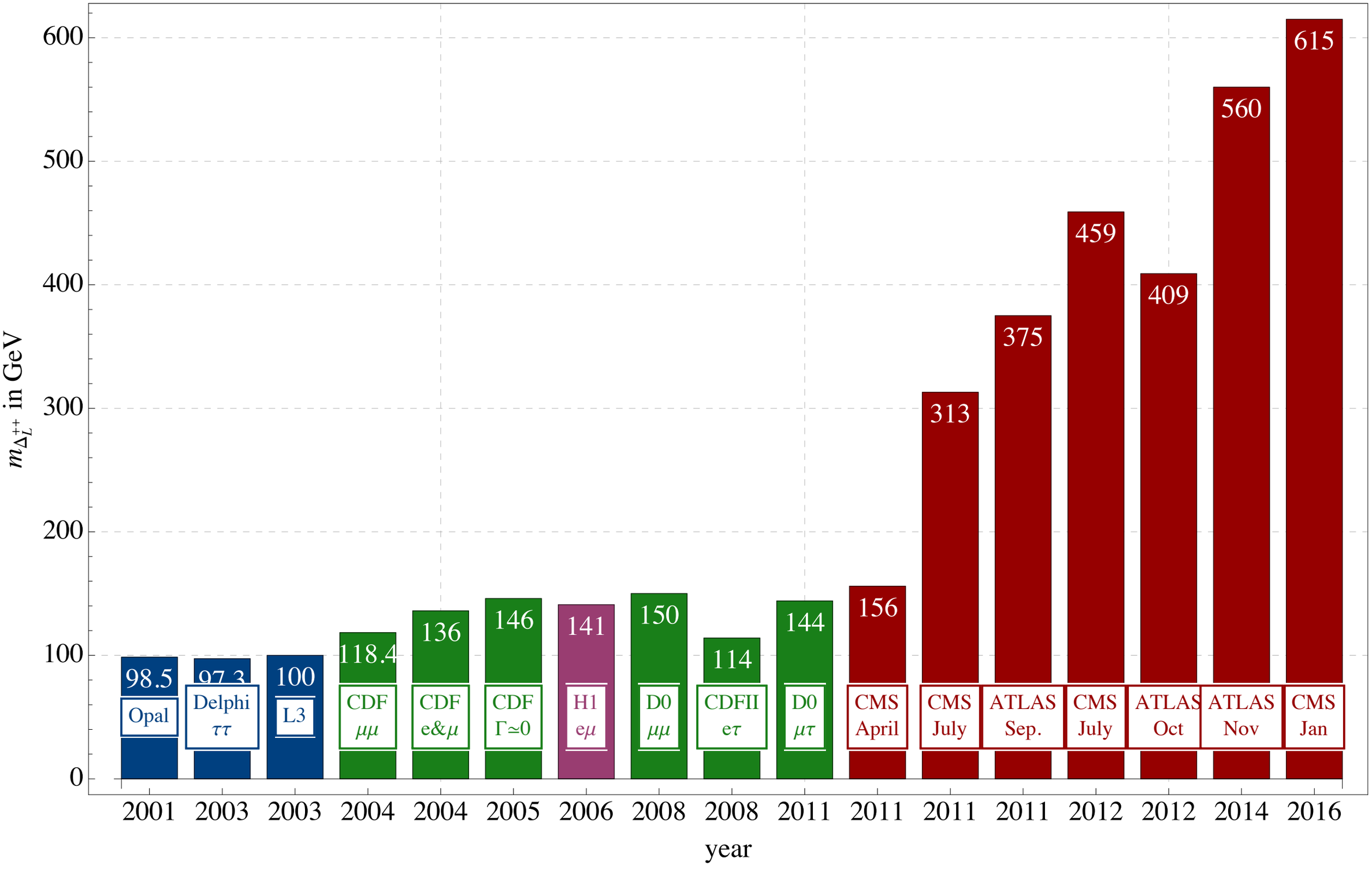
all flavors - LFV

no $\not{E}$ and no LNV

probes Majorana phases & hierarchy $\Gamma \propto |M_\nu|^2$

Chun, Lee, Park '03
Garayoa, Schwetz '07
Kadastik, Raidal, Rebane '07

type II history of searches - assumes degeneracy and small v_L



1207.2666 CMS (7 TeV / 4.9)
1201.1091 ATLAS (7 TeV / 1.6)

1412.0237 ATLAS (8 TeV / 20.3)
1210.5070 ATLAS (7 TeV / 4.8)

CMS-PAS-HIG-14-039 (8 TeV/19.7)

type II

1412.0237 ATLAS
(8 TeV / 20.3)

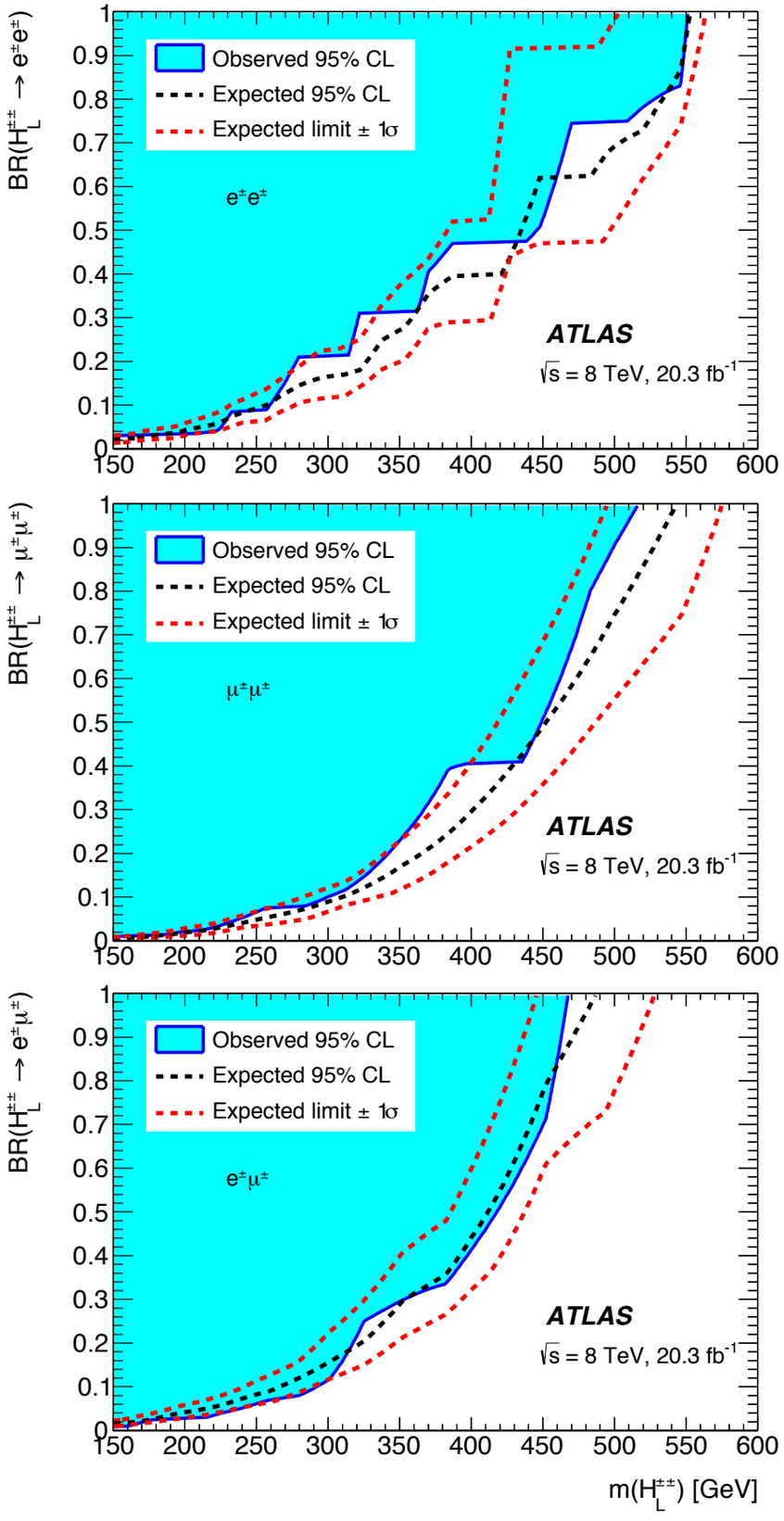
Δ_L^{++}

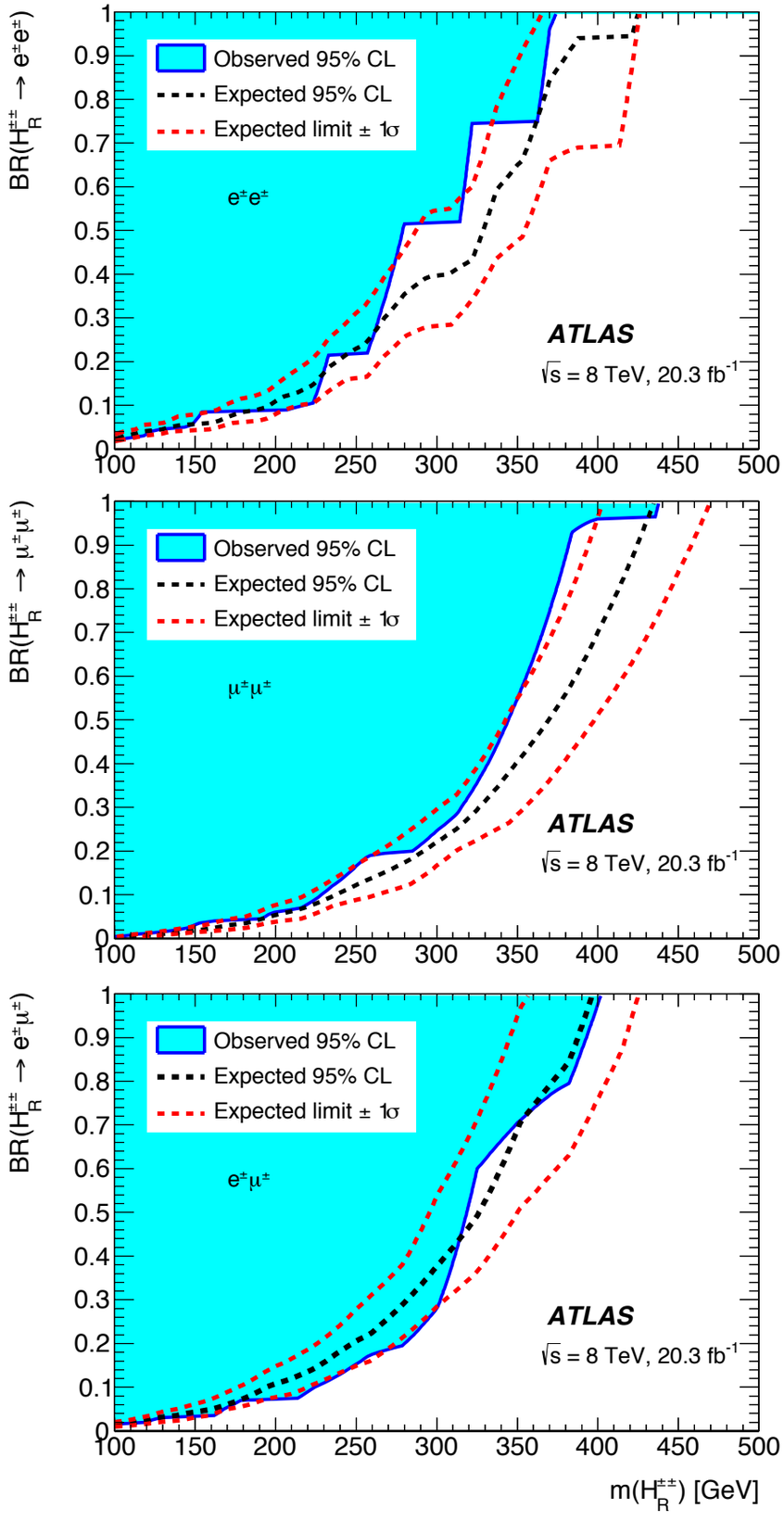
Δ_R^{++}

ee

$\mu\mu$

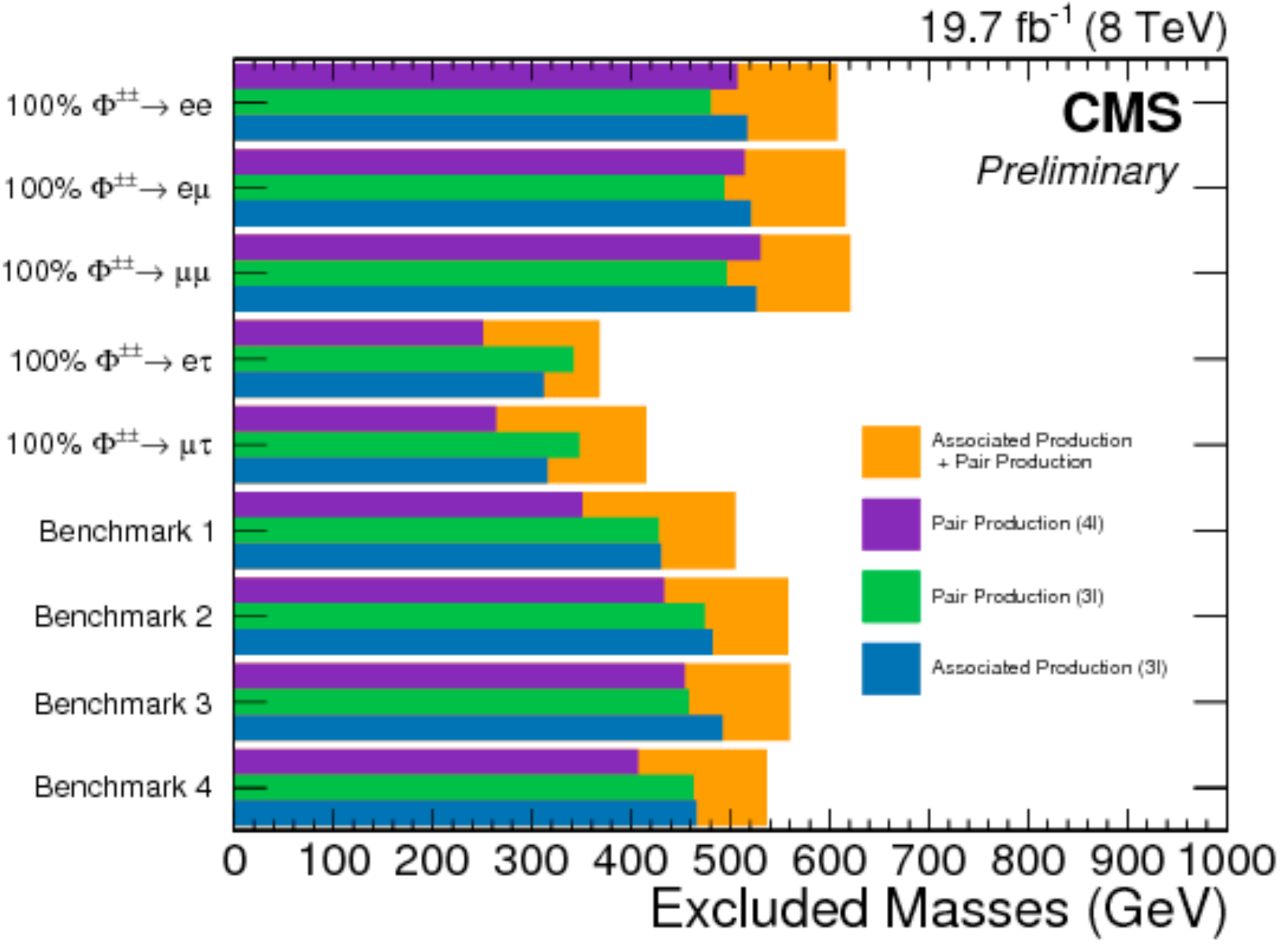
$e\mu$





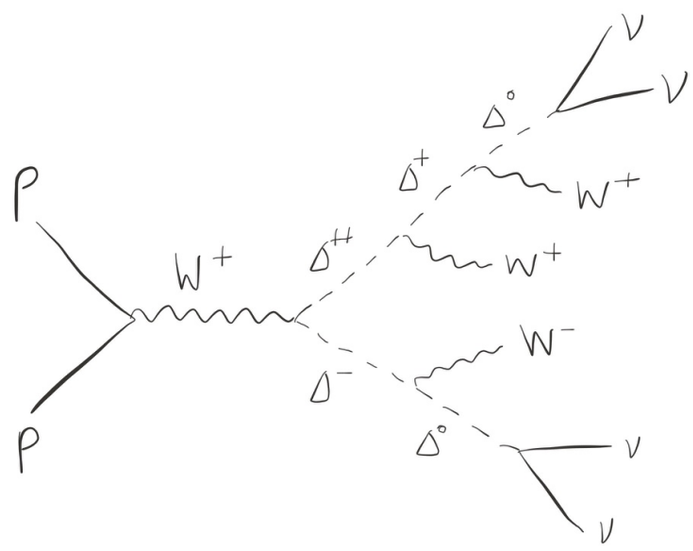
CMS also has τ s CMS 1207.2666

type II Δ_L^{++}



CMS-PAS-HIG-14-039

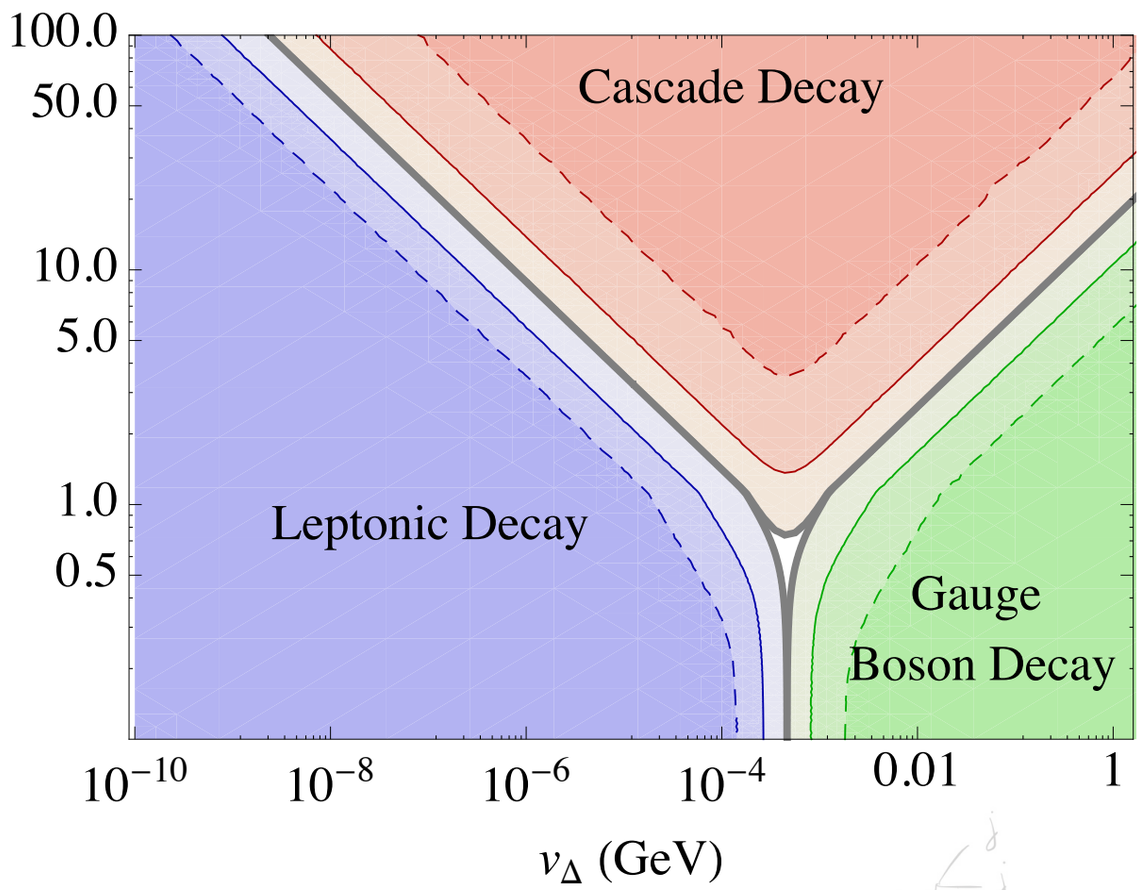
type II decays



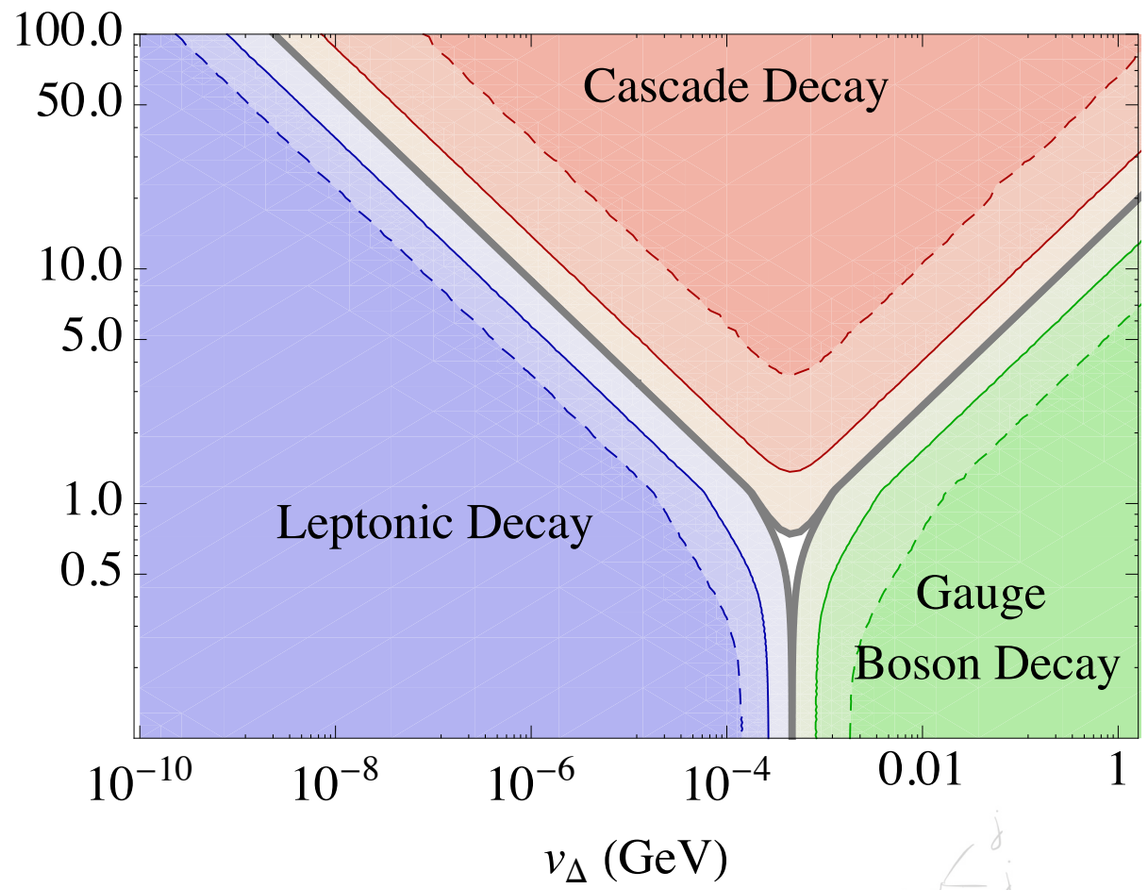
~soft jets/leptons

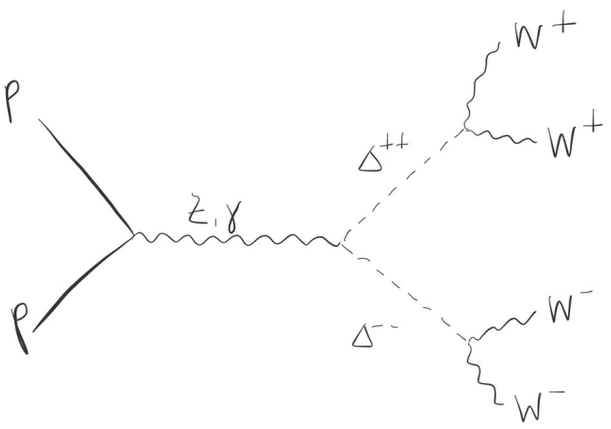
missing energy - large bckg

bounds strengthen/weaken



type II decays



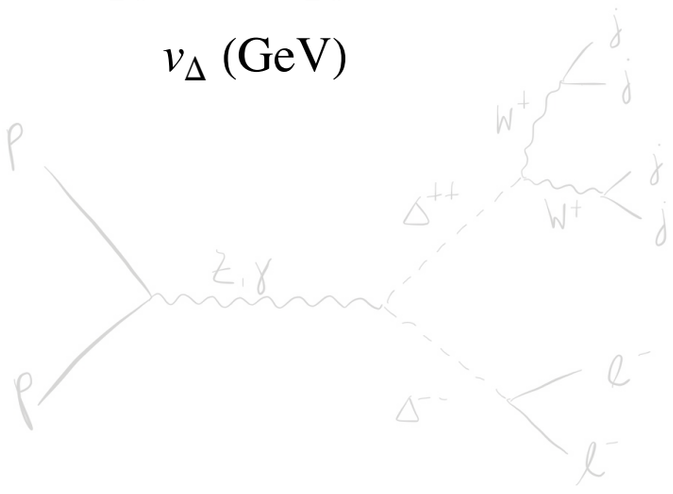


soft Ws, bcgk

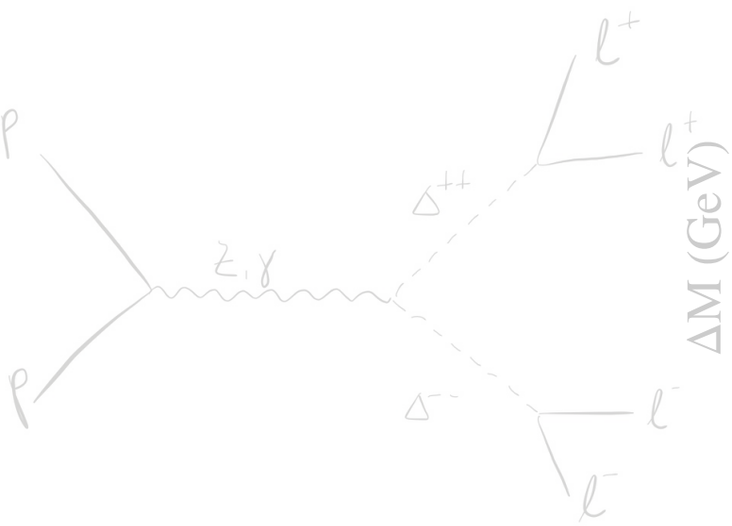
some sensitivity

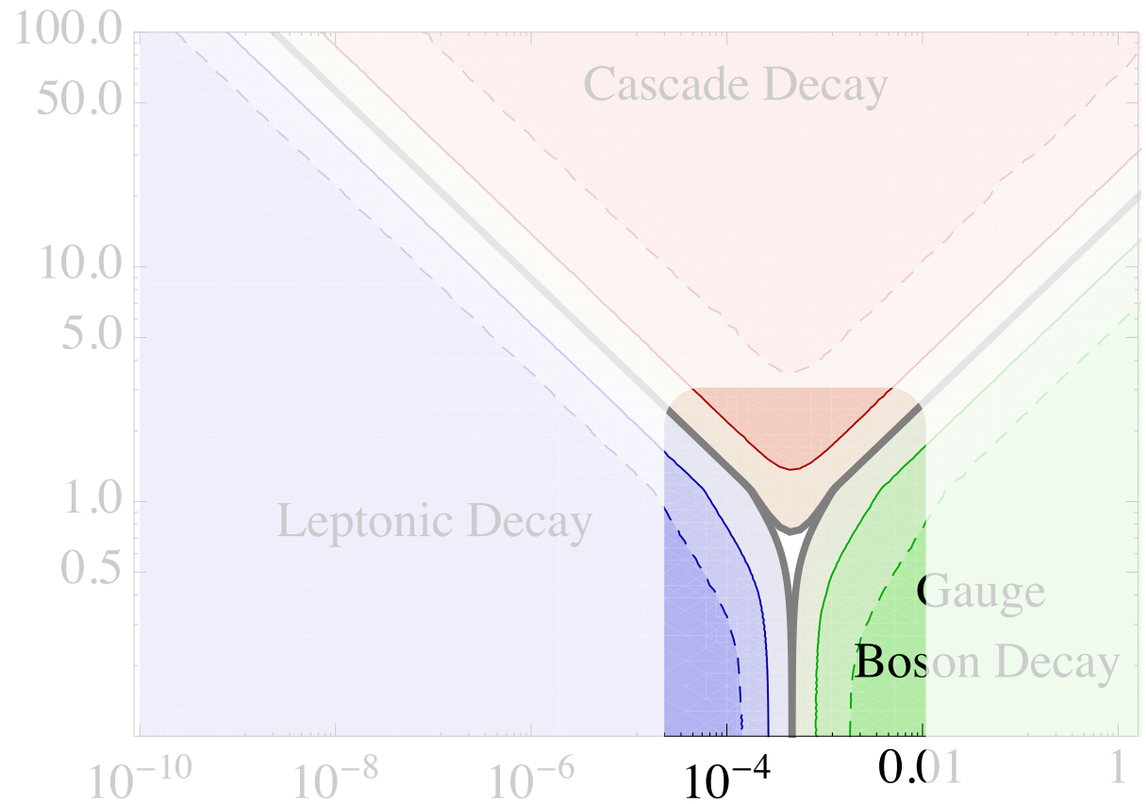
$m_\Delta \lesssim 90$ GeV

Kanemura et al.
1407.6547



type II decays

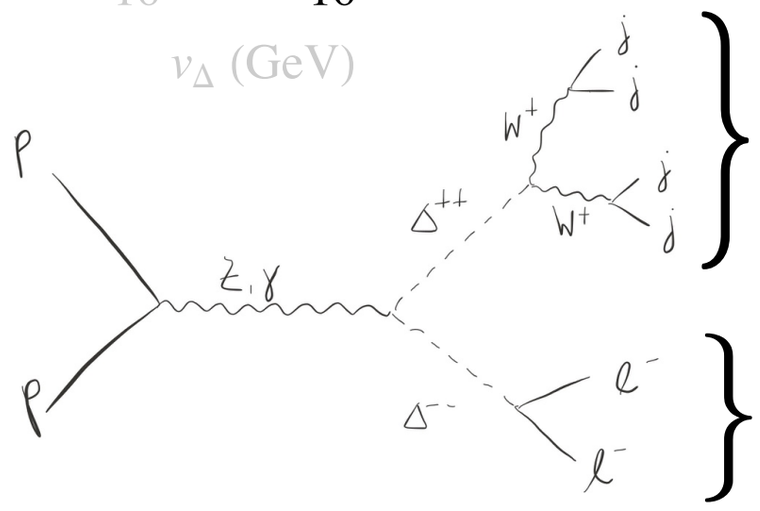




Y_Δ and v_L give LNV

same-sign di-leptons + 4j

no missing energy

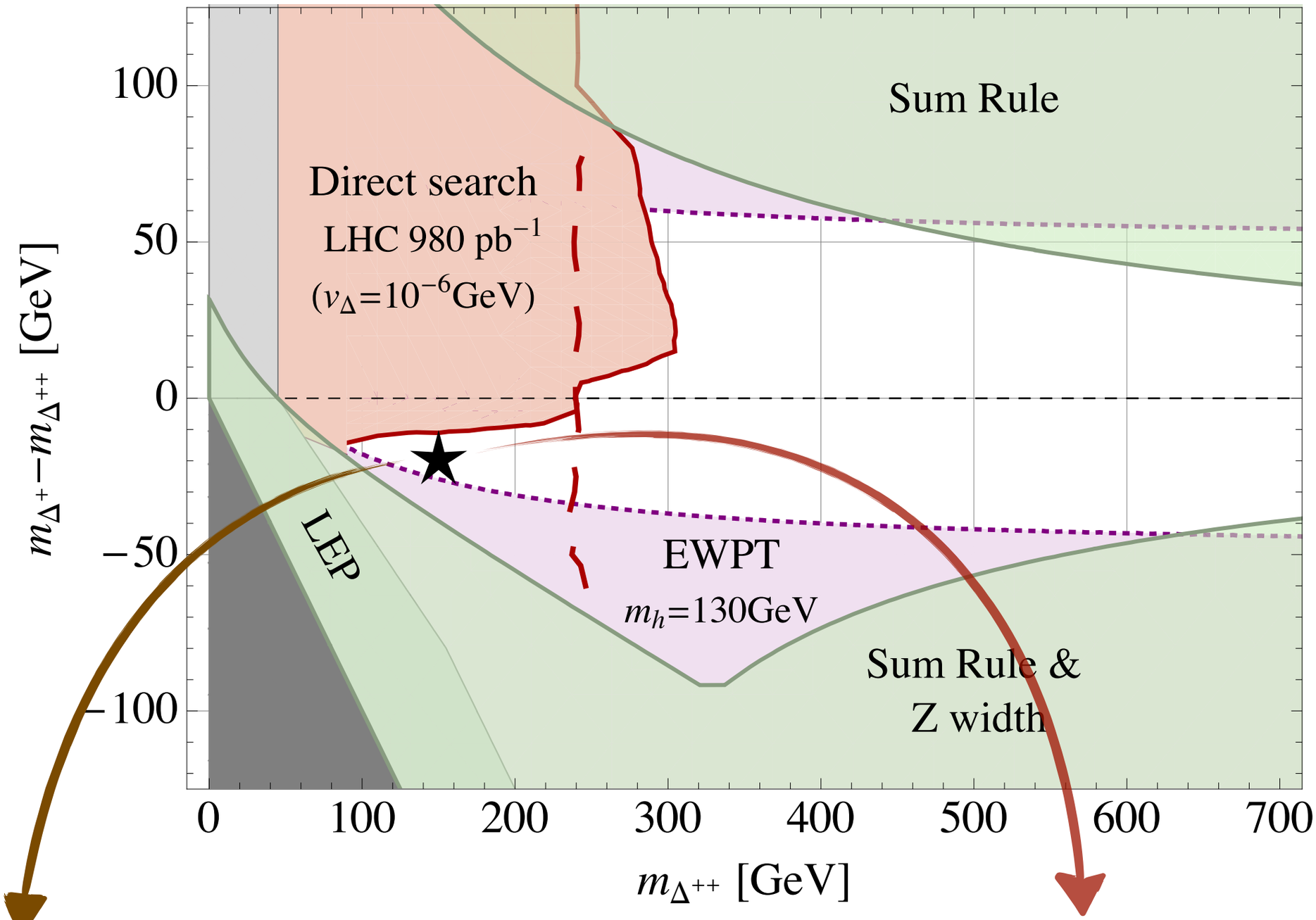


$$m_{\ell\ell} = m_\Delta$$

$$m_{jjjj} = m_\Delta$$

type II LHC roadmap

Melfo, MN, Nesti, Senjanović, Zhang '11



limited sensitivity

Han, Ding, Liao 1502.05242, 1506.08996

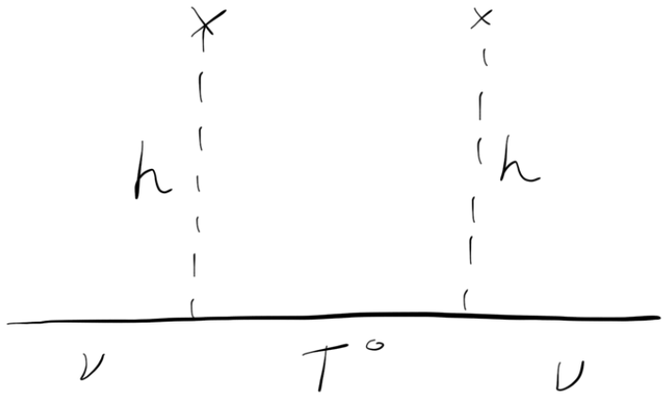
enhanced $h \to \gamma\gamma$

Melfo, MN, Nesti, Senjanović, Zhang '11

..., Akeroyd, Moretti 1206.0535

type III

type III



same logic as type I, need two reps

Foot, Lew, Joshi '89

predicted light remnant of

SU(5) 24_F

Bajc, Senjanović '06
Bajc, MN, Senjanović '07

$$\mathcal{L}_T = i\overline{T}\not{D}T - \frac{1}{2}m_T\, T^T C T + y_T\, \overline{L} H T$$

gauge production

mass splitting & cascades

neutrino mass

need m_T and y_T for LNV

$$M_\nu = -v^2\, y_T^T\, m_T^{-1}\, y_T$$

Tests at the LHC

LNV @ LHC ~automatic

type III production

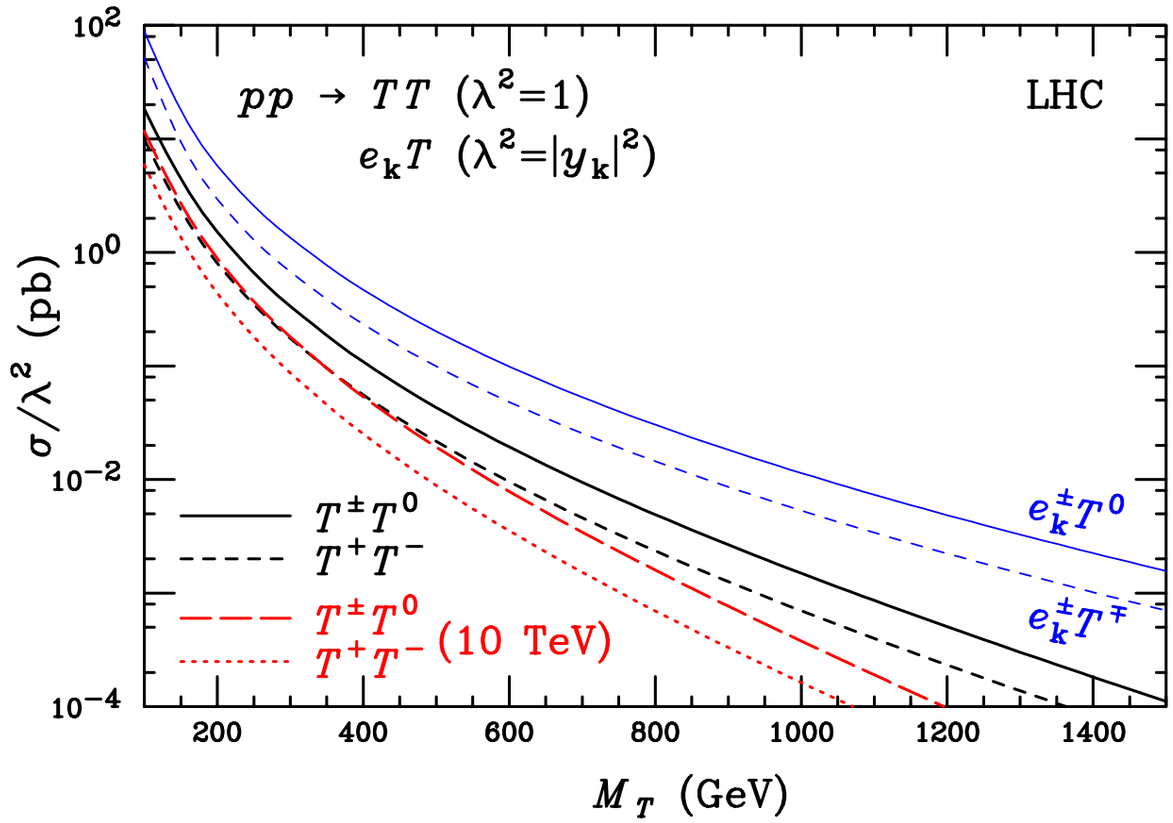
Franceschini, Hambye, Strumia '08
Arhrib, Bajc, Ghosh, Han, Huang, Puljak, Senjanović '09

gauge pairs

$$W, Z \to TT$$

single production suppressed

$$W, Z \to \ell T \propto y^2$$



type III mass spectrum

m_T arbitrary, from minimal SU(5) $\lesssim 10^{3.5}$ GeV

$T^\pm$ and T^0 ~degenerate $\Delta m_T \sim 160$ MeV

type III decays

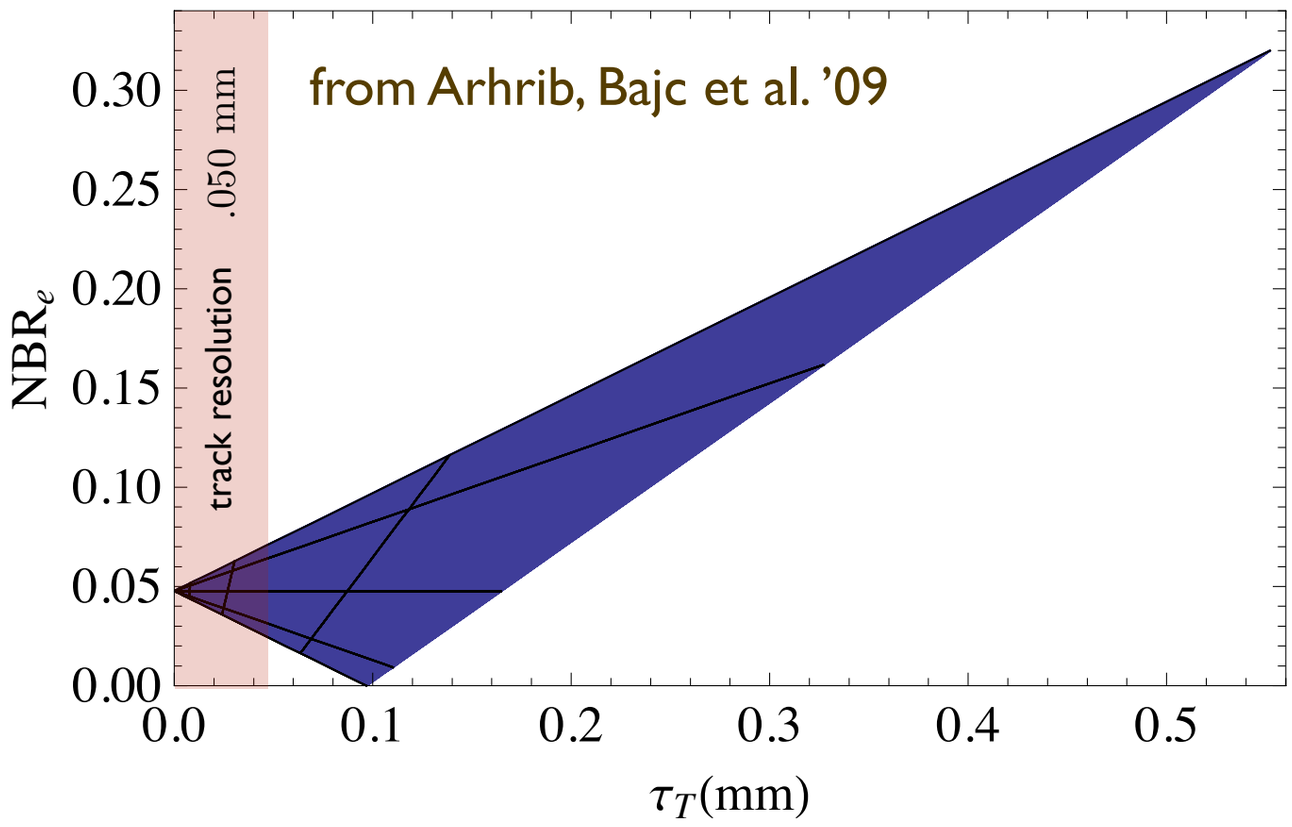
Bajc, MN, Senjanović '07

$$\left.\begin{array}{l}\boxed{\begin{array}{c}\Gamma(T^- \to Z\ell^-) \\ \wr \\ \Gamma(T^0 \to W\ell)\end{array}}\sim \dfrac{1}{2}\Gamma(T^- \to W^-\nu) \\ \\ \Gamma(T^0 \to W\ell) \sim 2\Gamma(T^0 \to Z\nu)\end{array}\right\} \propto |y_T|^2$$

ambiguous, sensitive to Majorana phases and the hierarchy

$$y_T^i = \frac{\sqrt{m}_T}{v}\begin{cases} U_{i2}\sqrt{m_2^\nu}\, c \pm U_{i3}\sqrt{m_3^\nu}\, s \\ U_{i1}\sqrt{m_1^\nu}\, c \pm U_{i2}\sqrt{m_2^\nu}\, s \end{cases}$$

$V \to jj$ explicit LNV



possibly displaced even in minimal I+III

cascades less important

$$\Gamma(T^\pm \to T^0\pi^\pm) < \Gamma(T \to V\ell)$$

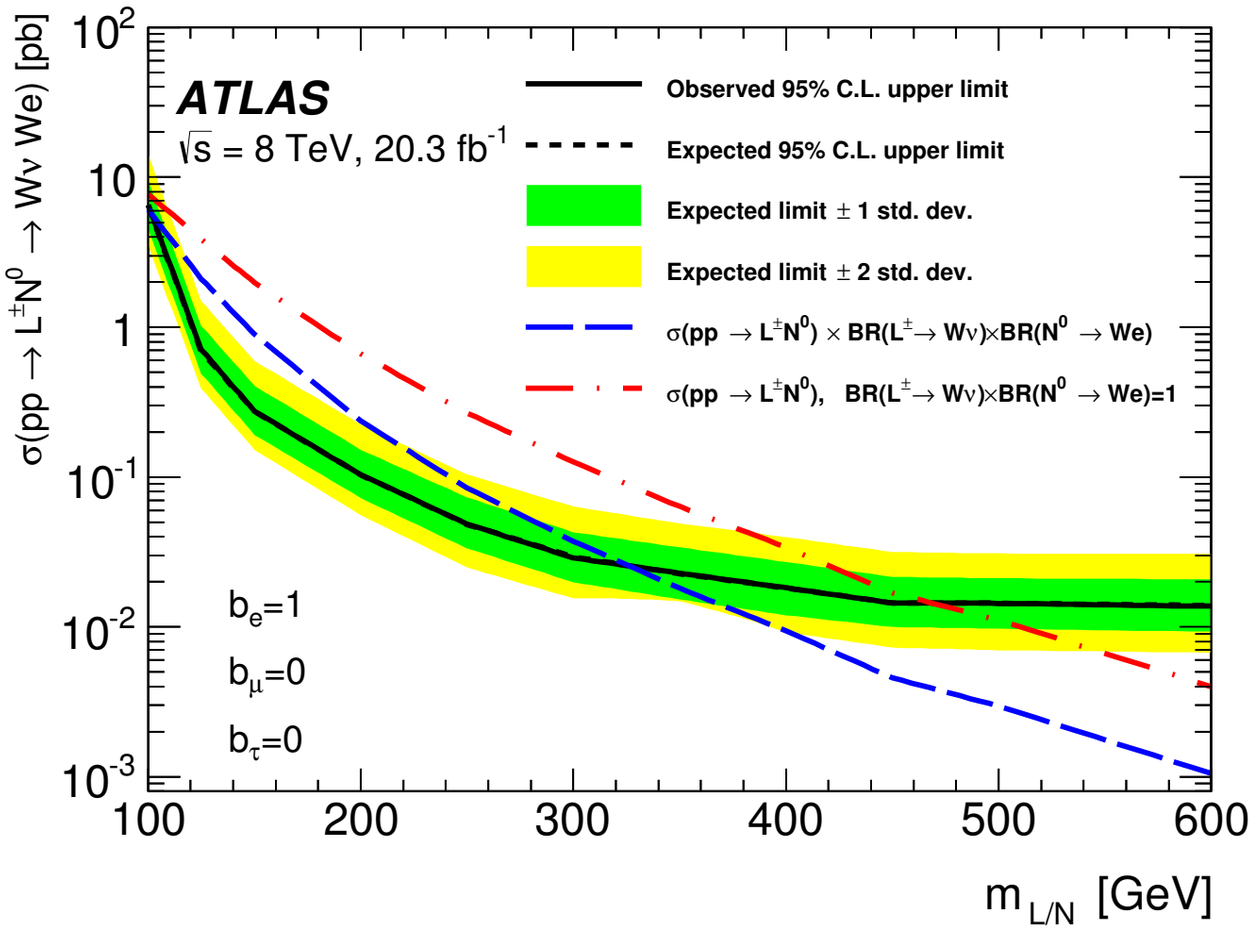
tri-leptons & seesaw comparisons

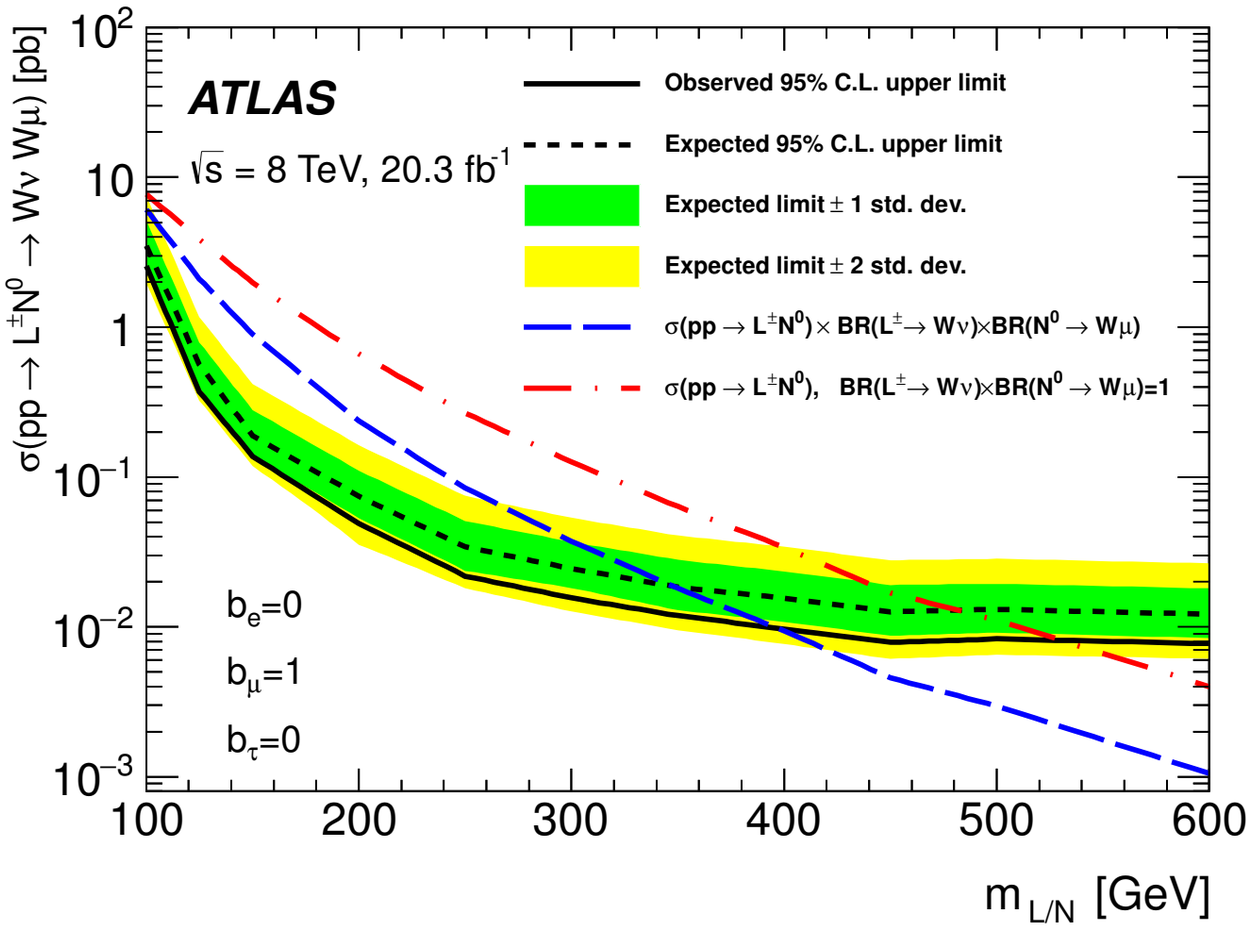
Del Aguila, Aguilar-Saavedra 0808.2468

type III decays

$$\left.\begin{array}{c} \Gamma(T^- \to Z\ell^-) \sim \frac{1}{2}\Gamma(T^- \to W^-\nu) \\ \wr \\ \Gamma(T^0 \to W\ell) \sim 2\Gamma(T^0 \to Z\nu) \end{array}\right\} \propto |y_T|^2$$

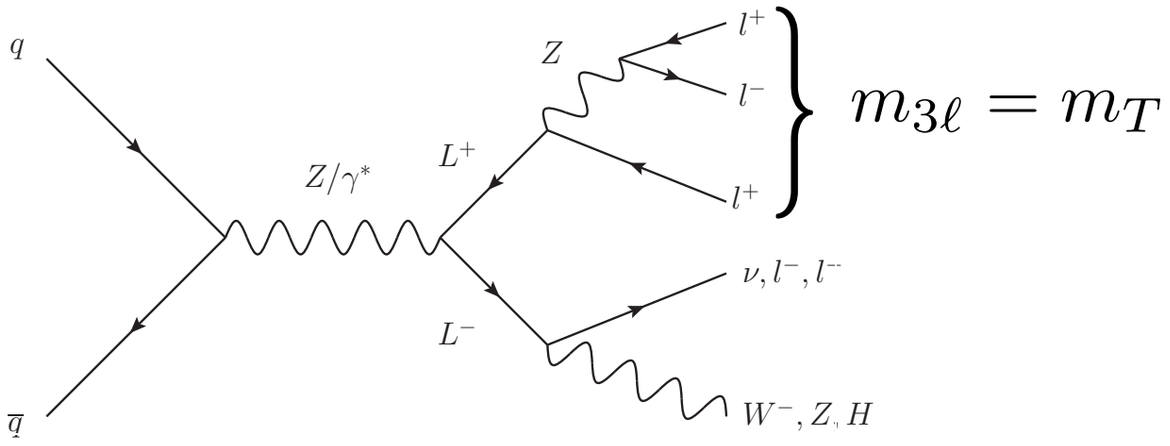
ATLAS 1506.01839



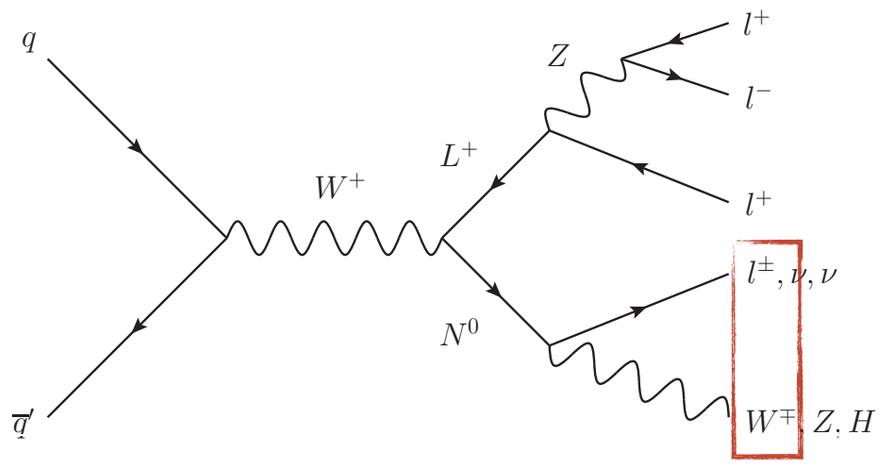


large Br, but $\not{E} \neq 0$ and LN conserved

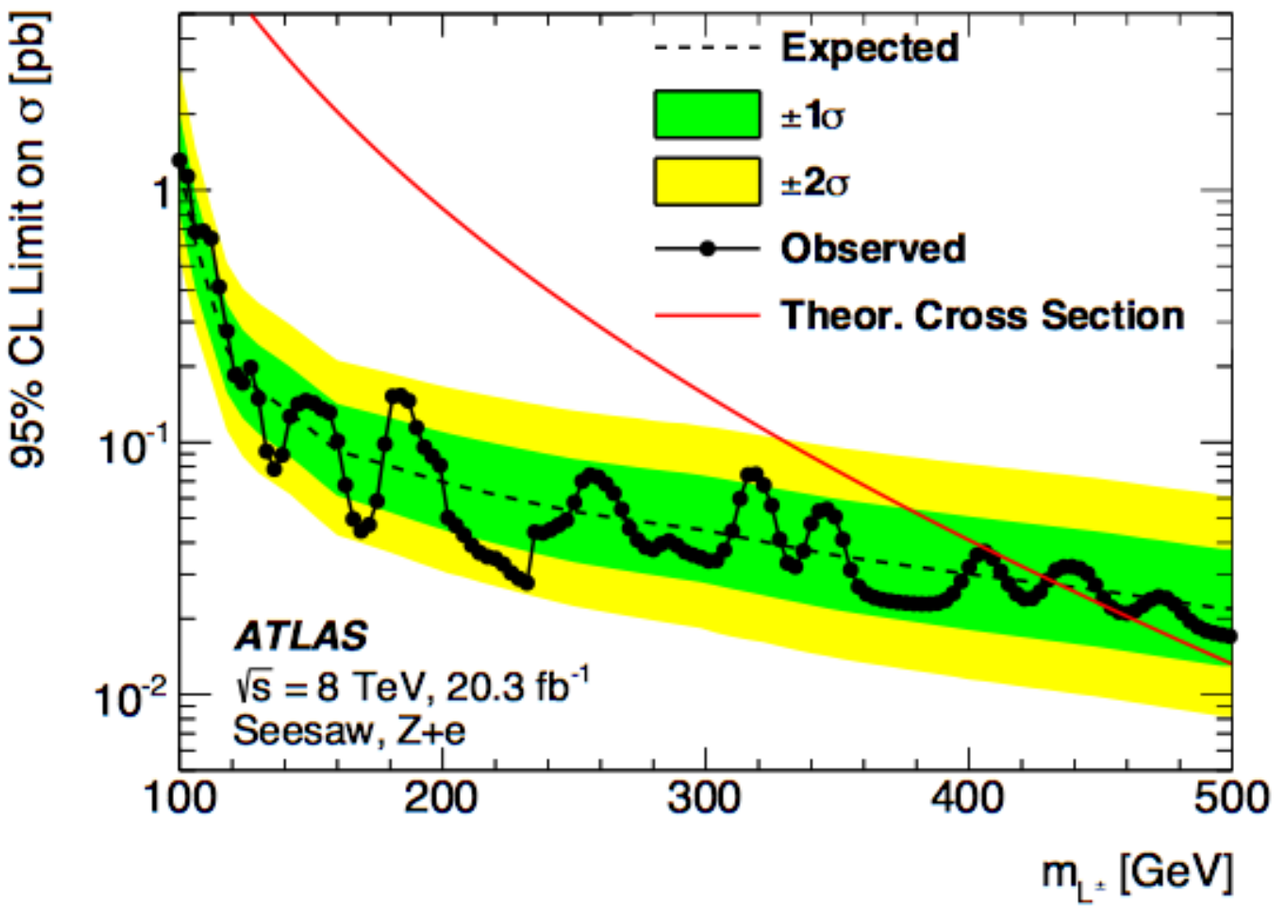
type III tri-leptons in ATLAS 1506.01291

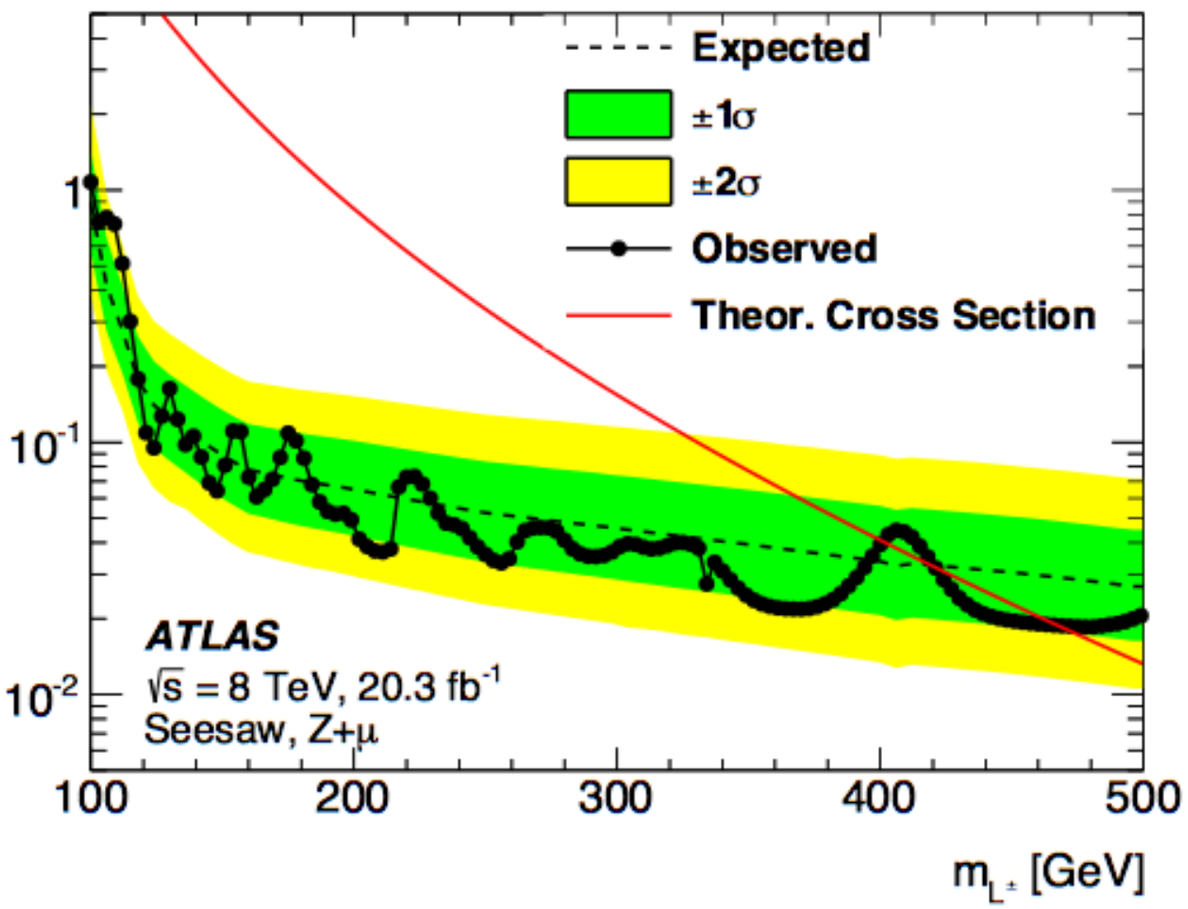


$m_{3\ell} = m_T$



searches for peaks in $\Delta m \equiv m_{3\ell} - m_{\ell^\pm \ell^\mp}$





type II

direct flavor relation with neutrino mass

need luck or luminosity for LNV

involved phase space, limited experimental searches

type III

ambiguous relation to neutrino mass

simpler searches, bounds more robust

LNV ubiquitous, possibly displacement

Left-Right

Mass origin = Higgs mechanism

run I @ LHC

Higgs decay

Mass origin = ‘Higgs’ mechanism

Majorana neutrinos

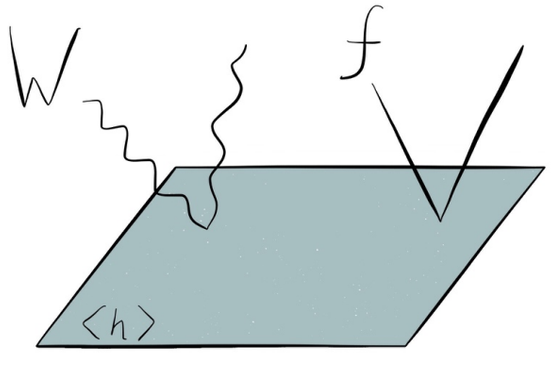
‘Exotic’ Higgs decay

Mass origin

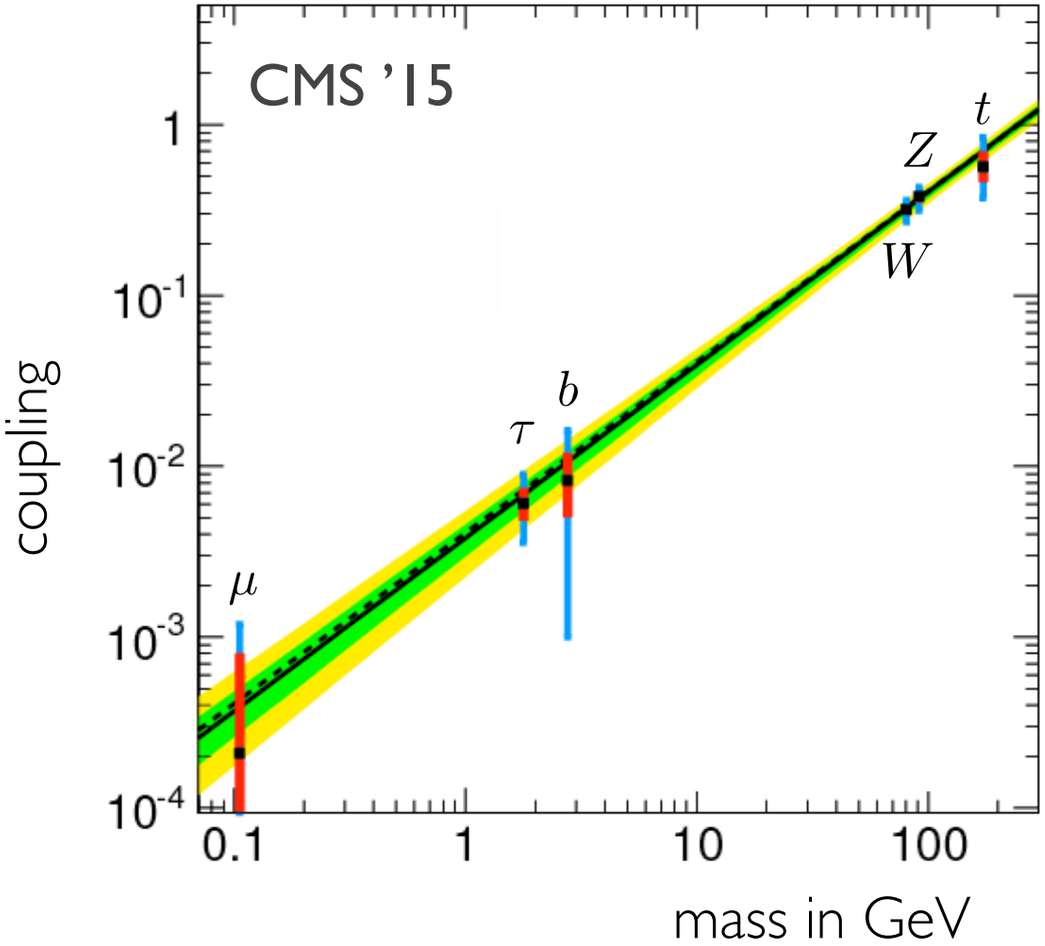
Higgs ’64
Weinberg ’67

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

$$\Gamma_{h\to f\,f} \propto m_f^2$$



$$m_f = y\,v$$



Higgs mass origin discovery

L number conserved

Neutrinos massless

Neutrino Mass

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

Implication of *LNV* $0\nu2\beta$ Racah, Furry ’37

⋮

colliders, mesons, Higgs

Neutrino Mass origin

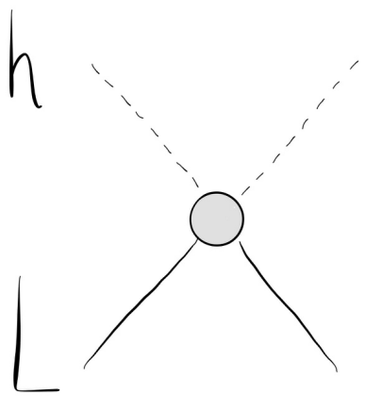
Neutral fermions $m_M \, \nu^T C \nu$ Majorana '37

Implication of *LNV* $0\nu2\beta$ Racah, Furry '37

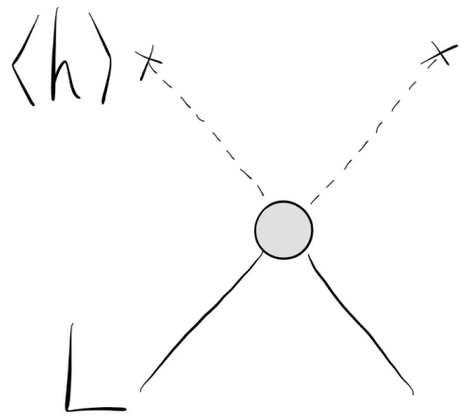
⋮

colliders, mesons, Higgs

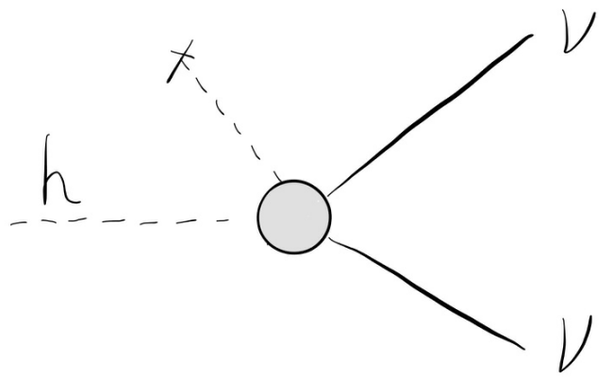
EFT: no light states $\Lambda \gg v$ Weinberg '79



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

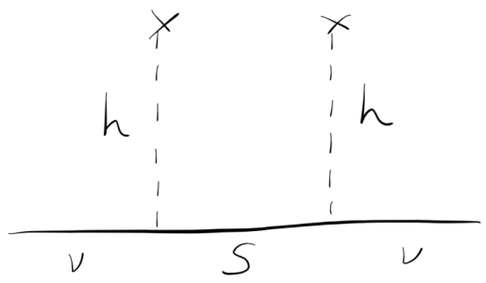


$$m_\nu = \tilde{y}\frac{v^2}{\Lambda}$$

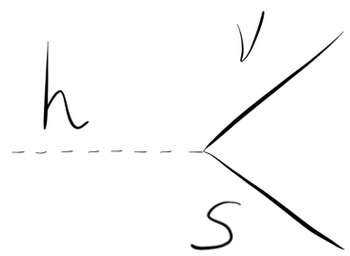


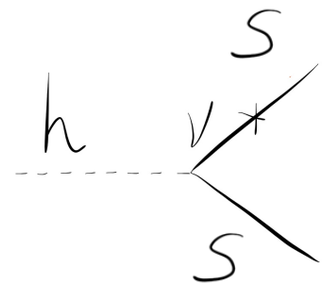
$$\Gamma_{h\to\nu\nu} \propto m_\nu^2$$

Neutrino Mass origin



type I





type III **ruled out**

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

Casas-Ibarra '01

Ambiguous relation

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

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

Fine-tuned, 'inverse'

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

Pilaftsis '91

LNV mode forbidden

Delphi '91, CMS '15

Neutrino Mass origin

type I

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

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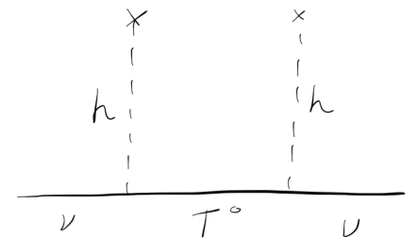

type III **ruled out**

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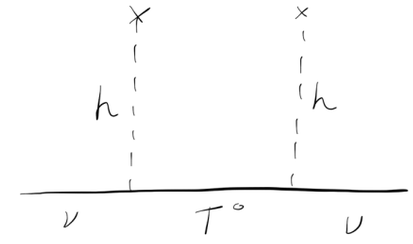
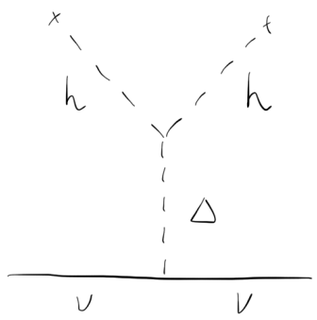


type III **ruled out**

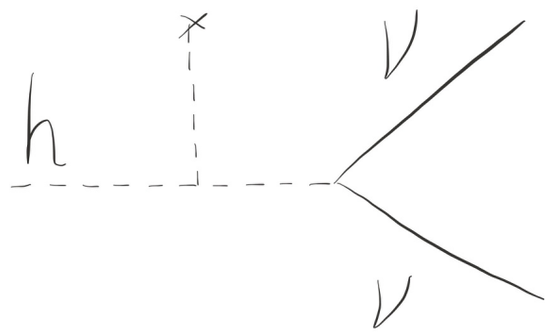
Ambiguous relation



type II

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

Fine-tuned, 'inverse'



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

LNV mode forbidden

Delphi '91, CMS '15

no LNV

Neutrino Mass origin

Seesaw

Left-Right	GUTs	Horizontal symmetry
$SU(2)_L \times SU(2)_R \times U(1)_{B-L}$	$SO(10)$	$SU(n)_F$
$N \in L_R$	$N \in 16_F$	
Minkowski '77 Mohapatra, Senjanović '79	Gell-Mann, Ramond, Slansky '79	Yanagida '79

$$SU(5)$$

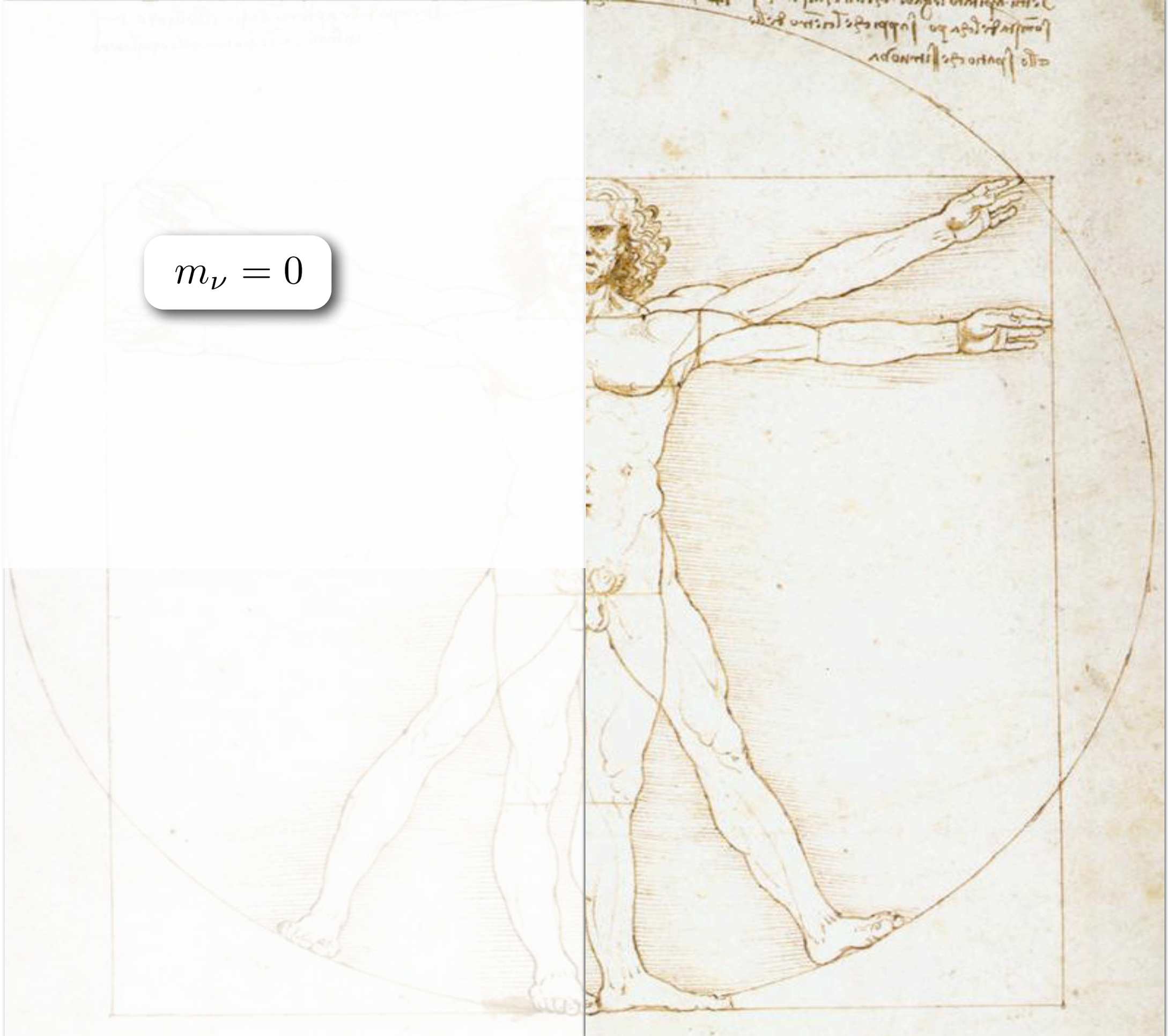
$$\Delta_L \in 15_H$$

Glashow '79

$$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$$

$$W_L$$

$$m_\nu = 0$$

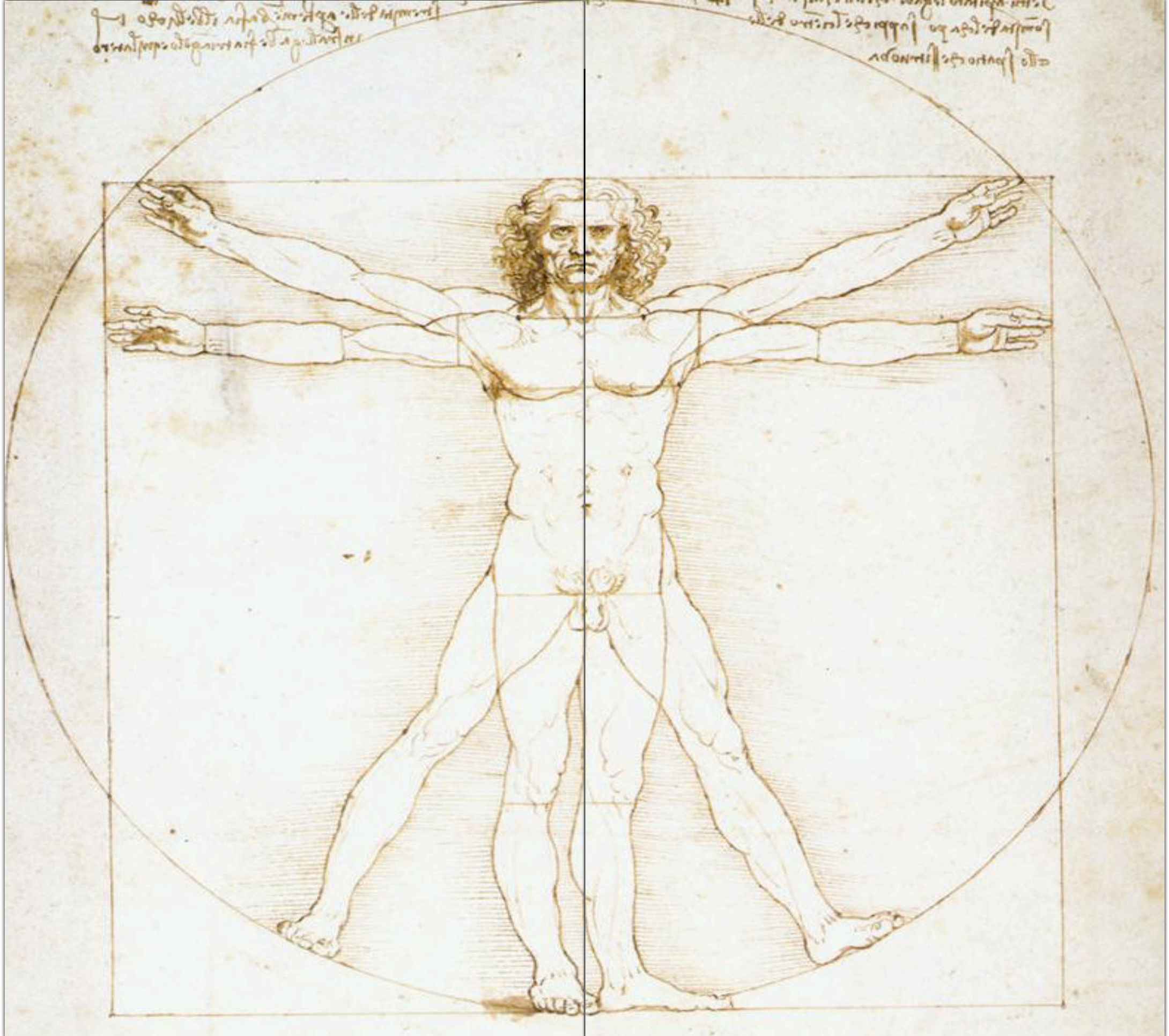


$$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$$

$$W_L$$

$\begin{pmatrix} \nu_R \\ e_R \end{pmatrix}$

W_R



$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$

W_L

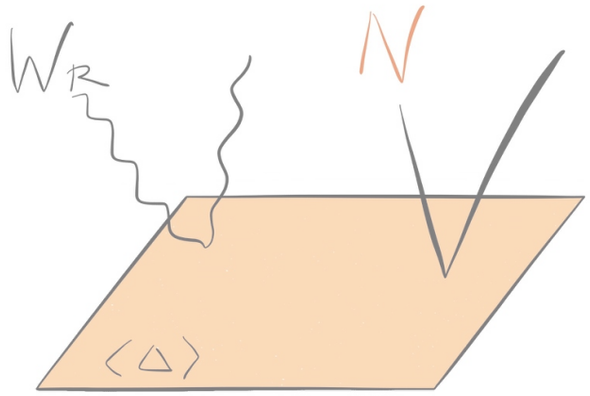
Left-Right

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

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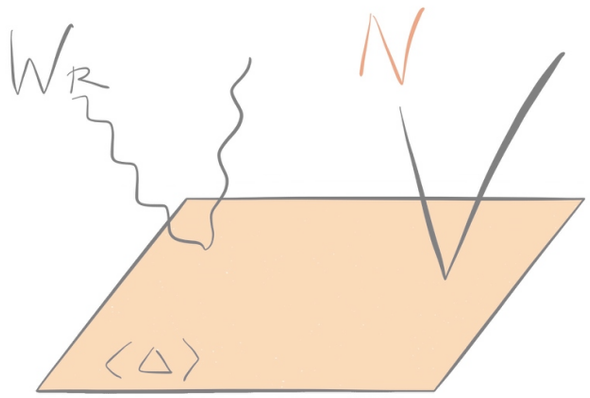

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$$\Phi = \begin{pmatrix}\phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0\end{pmatrix} \qquad \langle\Phi\rangle = \begin{pmatrix}v & 0 \\ 0 & 0\end{pmatrix} \qquad V \in \lambda\,(\Phi^\dagger\Phi)^2 + \alpha(\Phi^\dagger\Phi)(\Delta_R^\dagger\Delta_R) +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

same for $\mathcal{C}$-symmetry

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

Left-Right

Pati, Salam '74
Mohapatra, Pati '75

Minimal model

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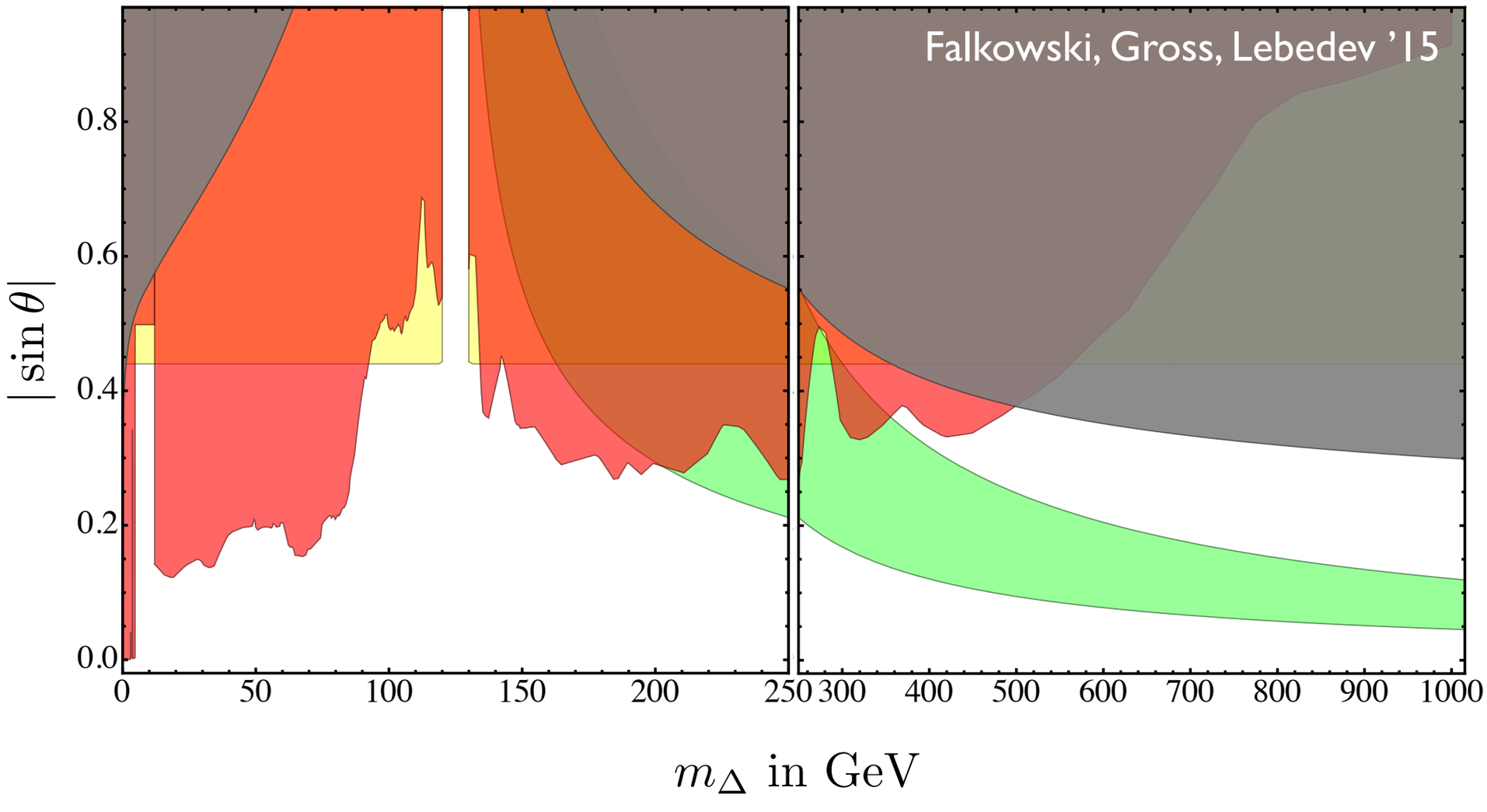

Future collider outlook

$|\sin\theta| < .34$

Buttazzo, Sala, Tesi '15

Left-Right

Pati, Salam '74
Mohapatra, Pati '75

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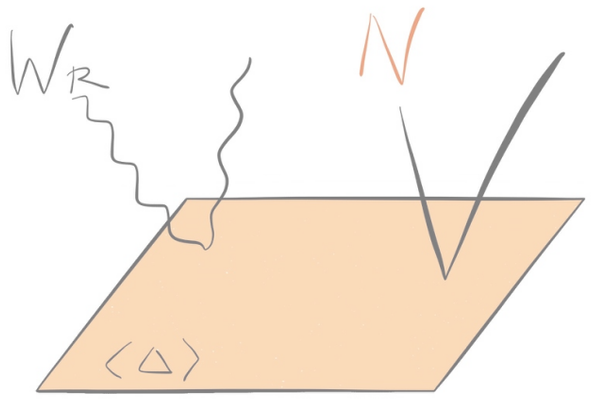

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$$\langle\Phi\rangle = \begin{pmatrix} v & 0 \\ 0 & 0 \end{pmatrix} \qquad V \in \lambda\,(\Phi^\dagger\Phi)^2 + \alpha(\Phi^\dagger\Phi)(\Delta_R^\dagger\Delta_R) + \rho\,(\Delta_R^\dagger\Delta_R)^2$$

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

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

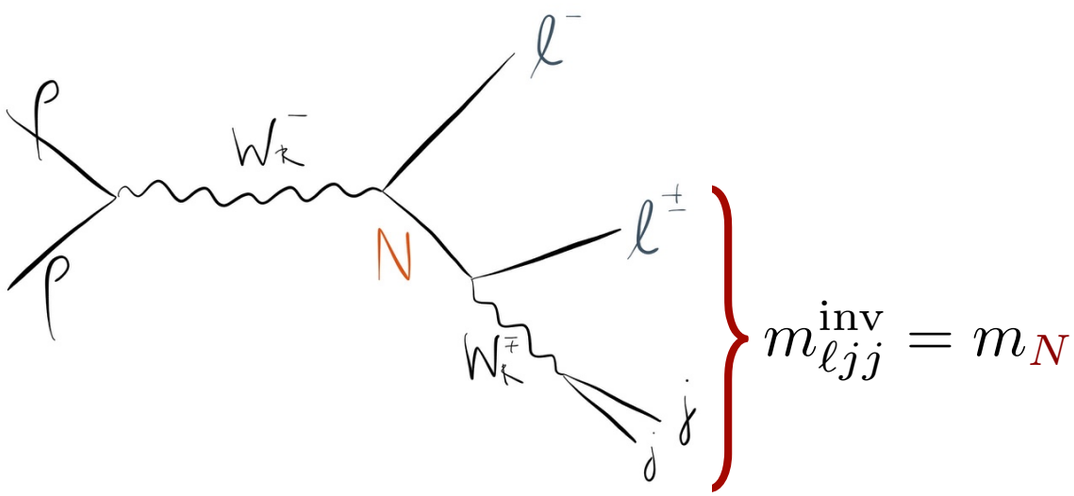
Indirect limits

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 at LHC



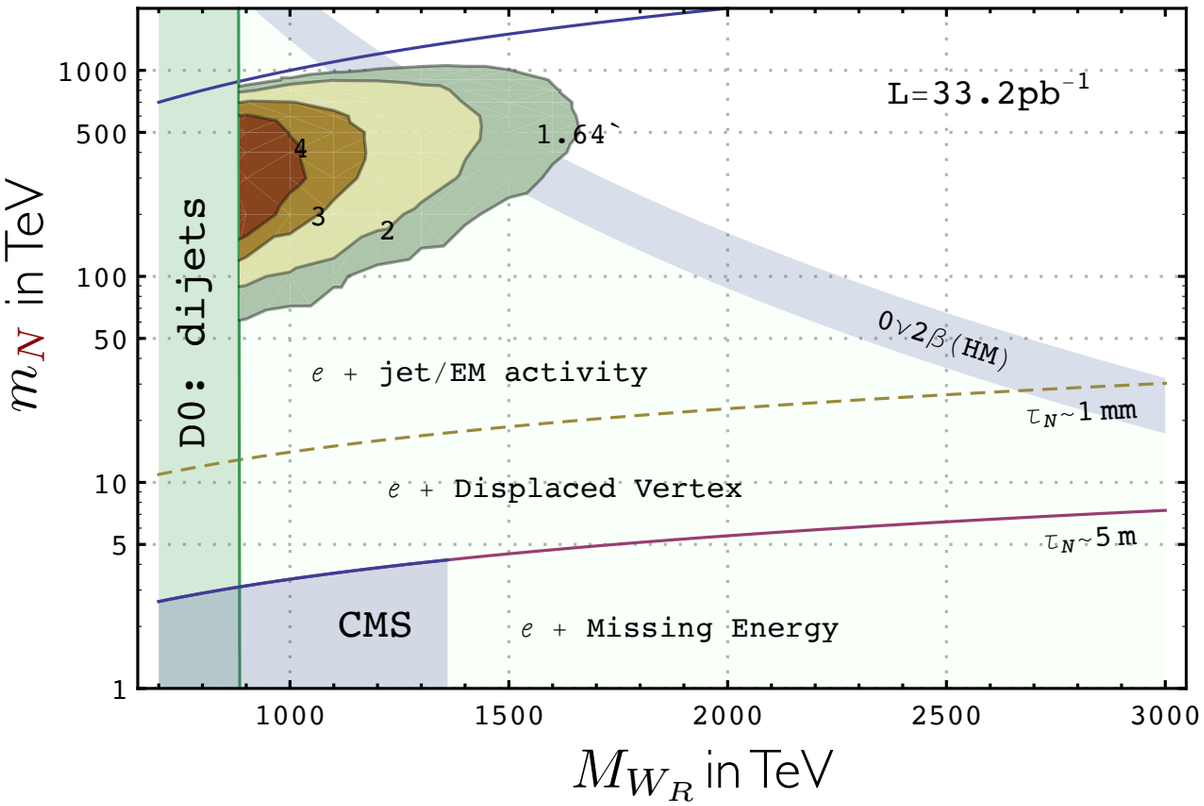
$m^{\rm inv}_{\ell jj} = m_N$

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

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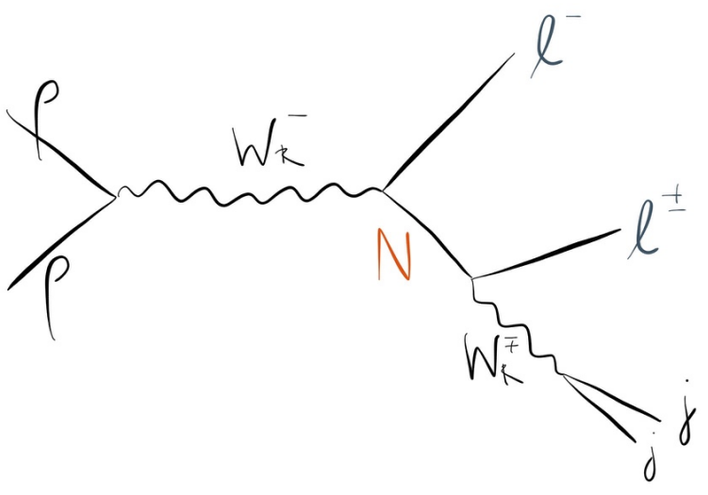

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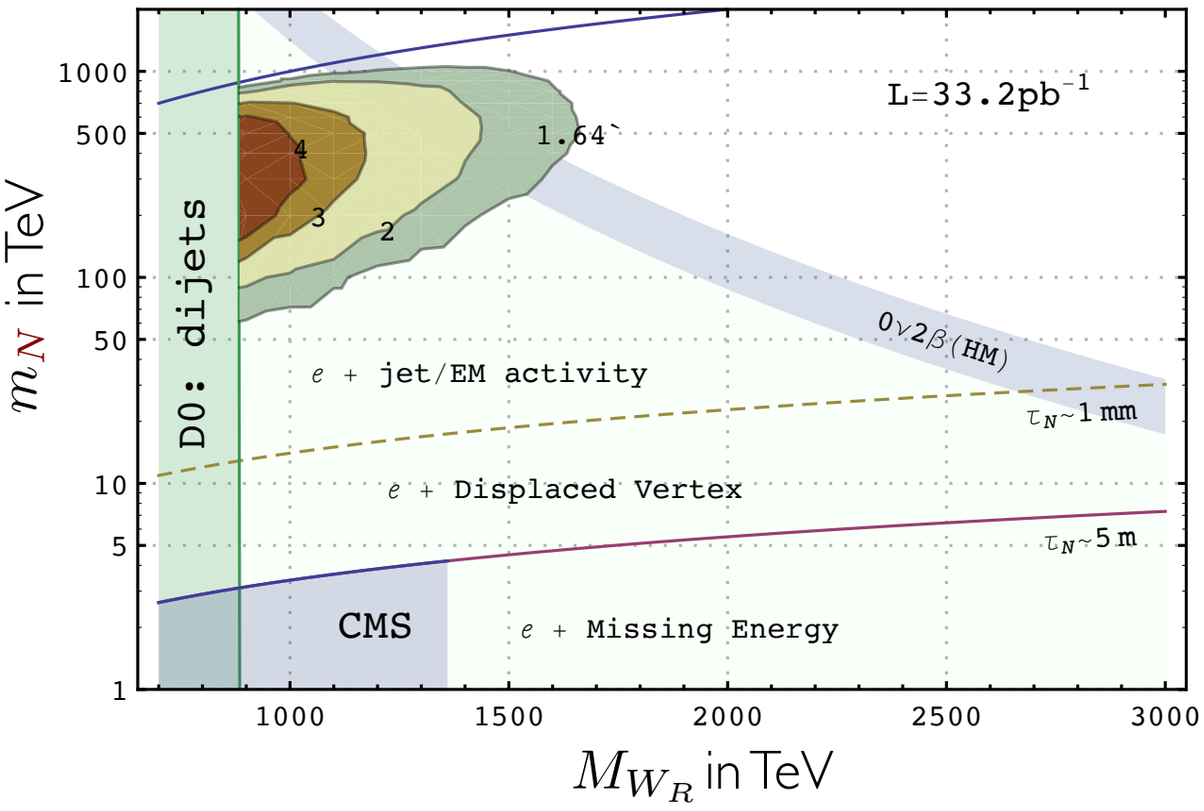
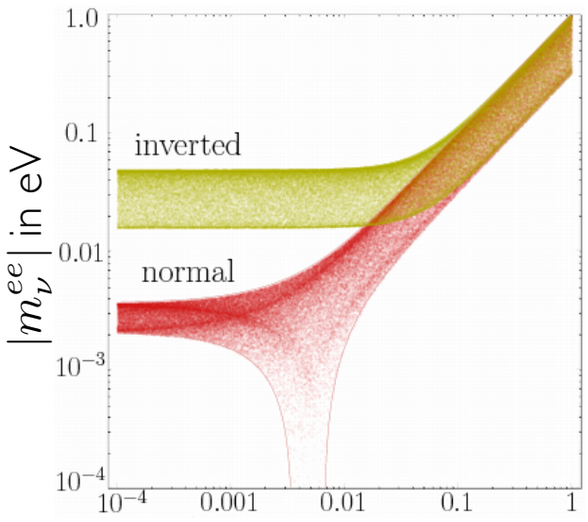


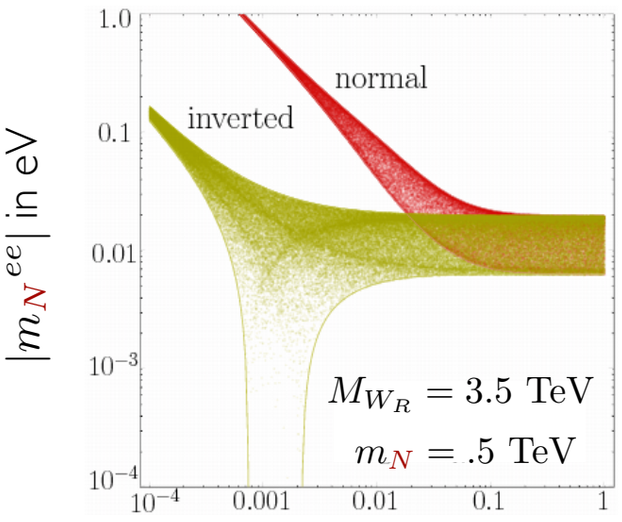
MN, Nesti, Senjanović, Zhang '11

Low energies: $0\nu2\beta$, eEDM, LFV

Mohapatra, Senjanović, '79, '80

Tello, MN, Nesti, Senjanović, Vissani '10





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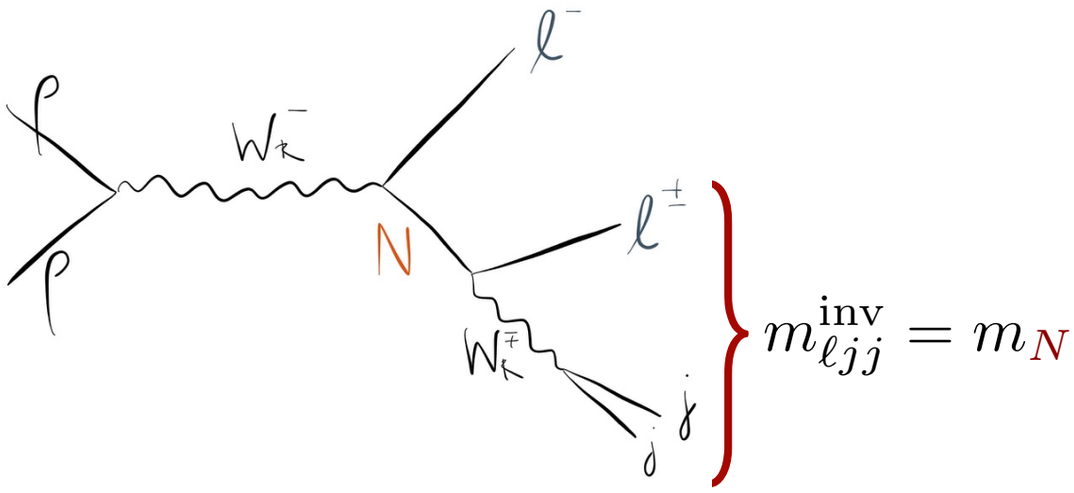

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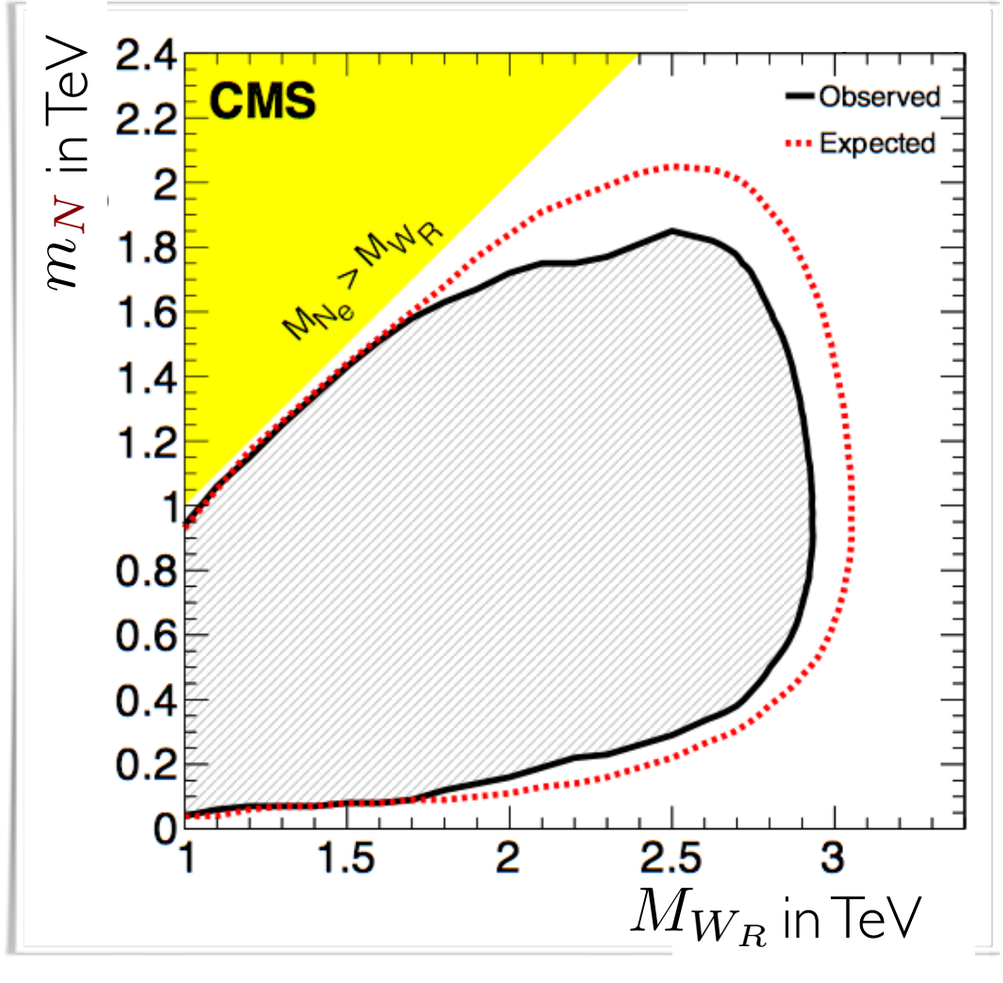

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Mohapatra, Senjanović, '79, '80

Tello, MN, Nesti, Senjanović, Vissani '10

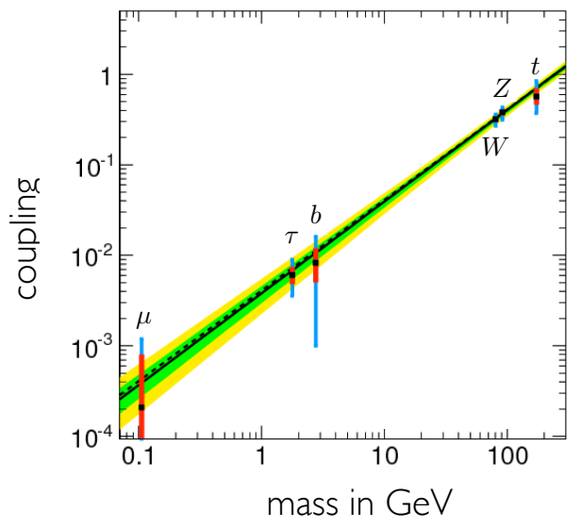
Majorana vs. Dirac

SM a *predictive* theory of charged fermion mass origin

$$\mathcal{L}_D = \frac{m_f}{v}\,\overline{f}_L\, h\, f_R$$

unique

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



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

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

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...

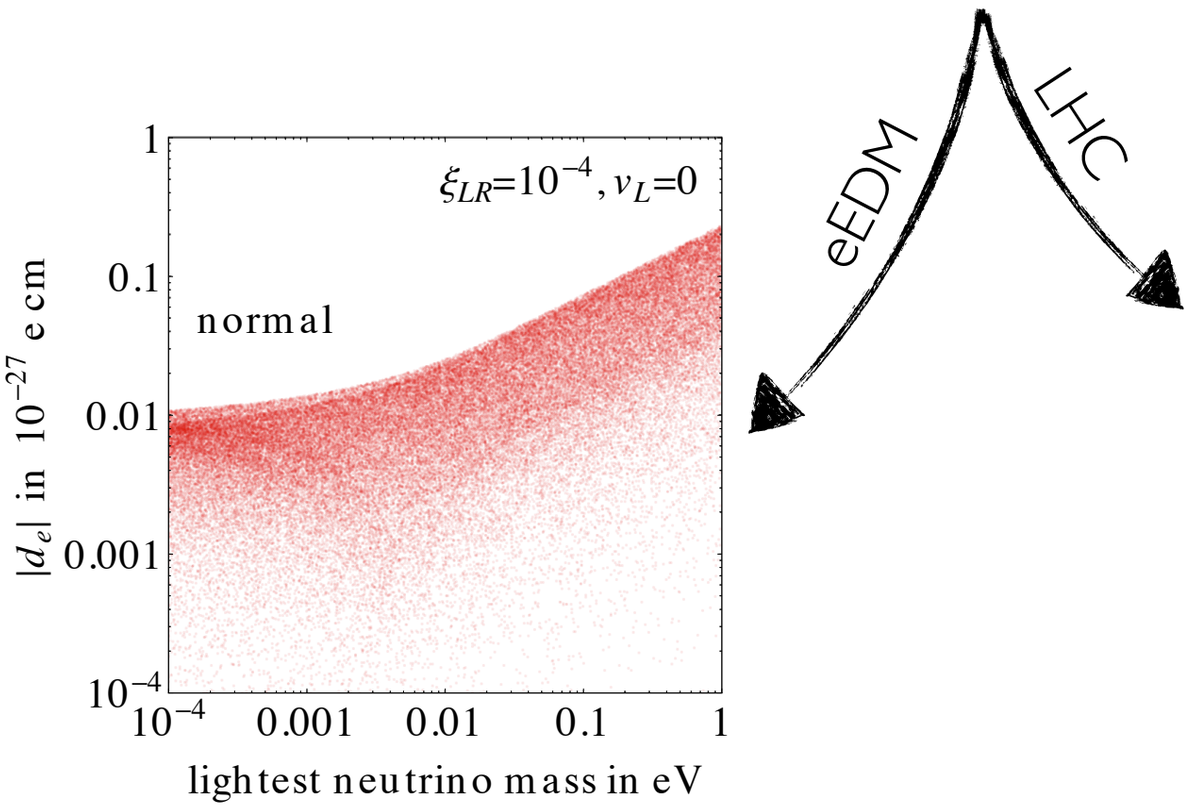
Majorana vs. Dirac

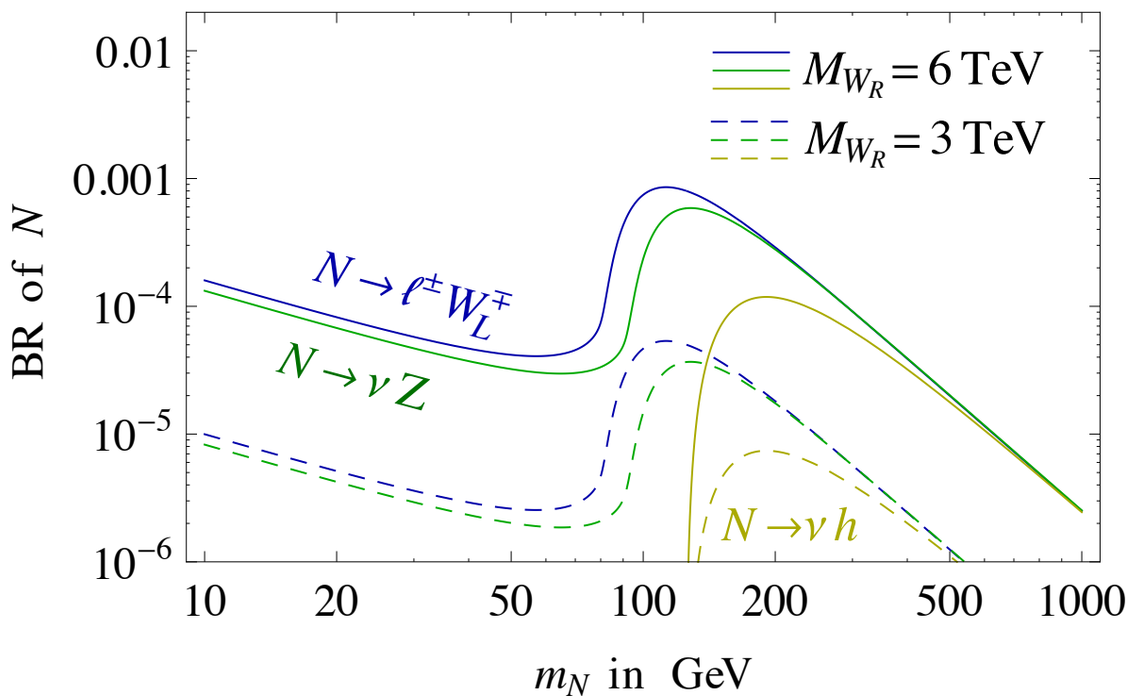
Left-Right gauge interaction defines the basis

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

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

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

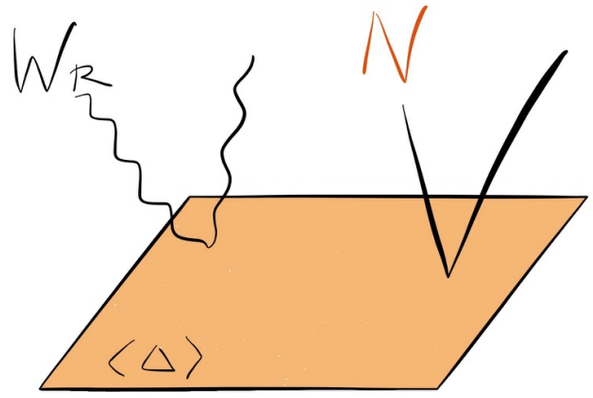




Neutrino Mass origin

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

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



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

Neutrino Mass origin

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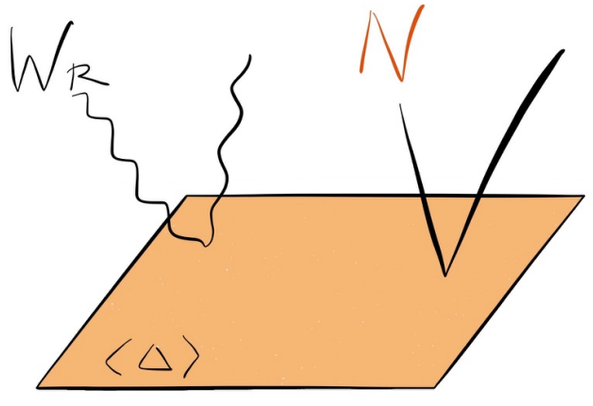
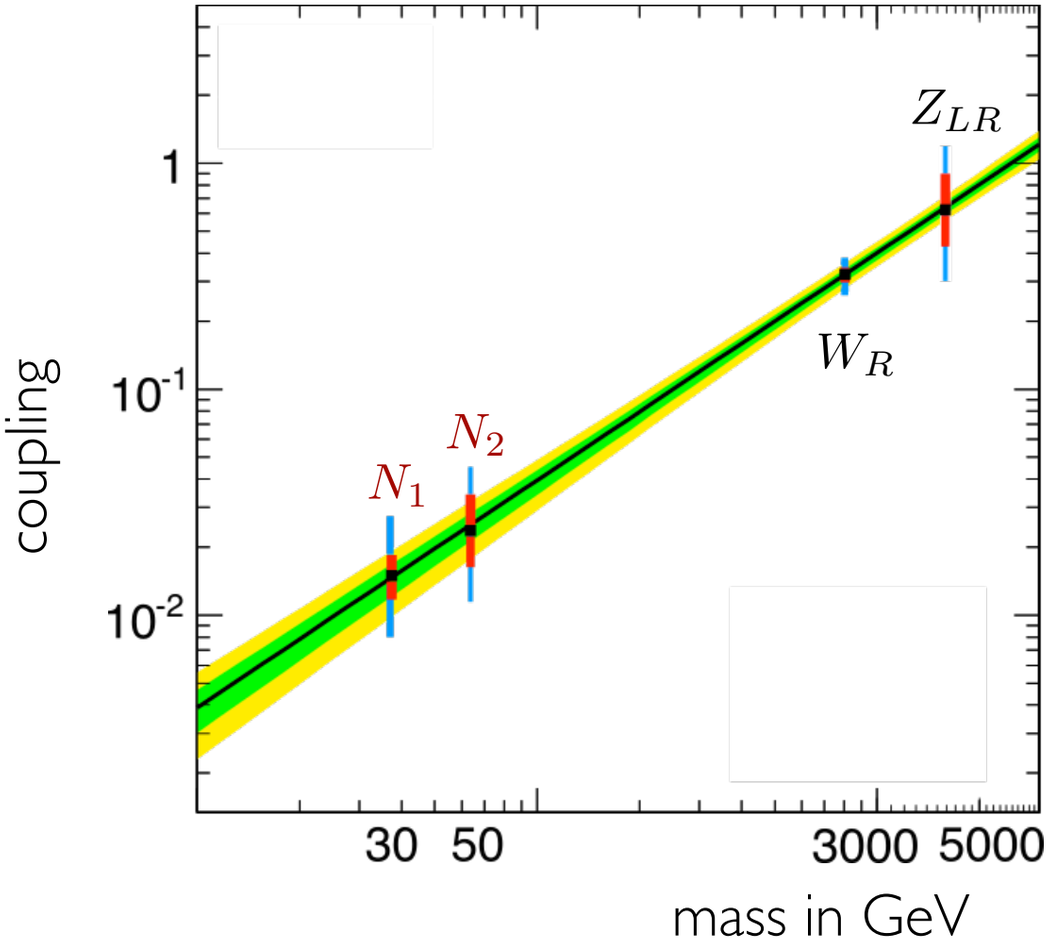


$$M_N = Y_\Delta \, v_R$$

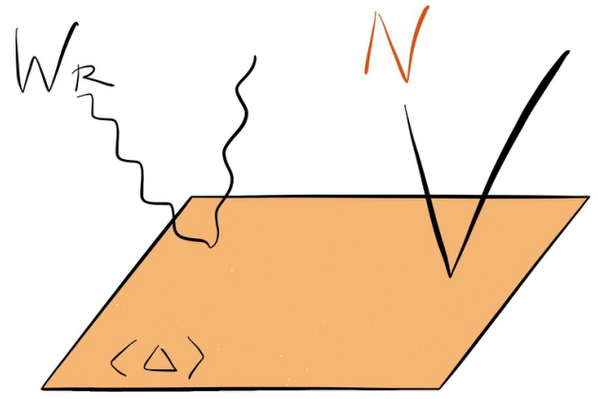


'Higgs' origin of m_N, m_ν

Neutrino Mass origin

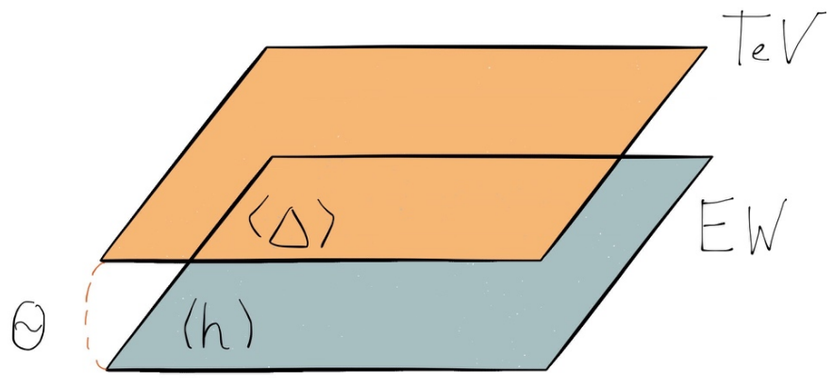
Δ_R production limited

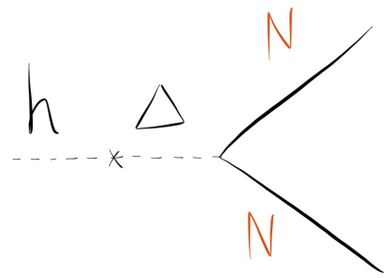
$\Gamma_{\Delta \to NN} \propto {m_N}^2$



Neutrino Mass origin

$h - \Delta$ mixing



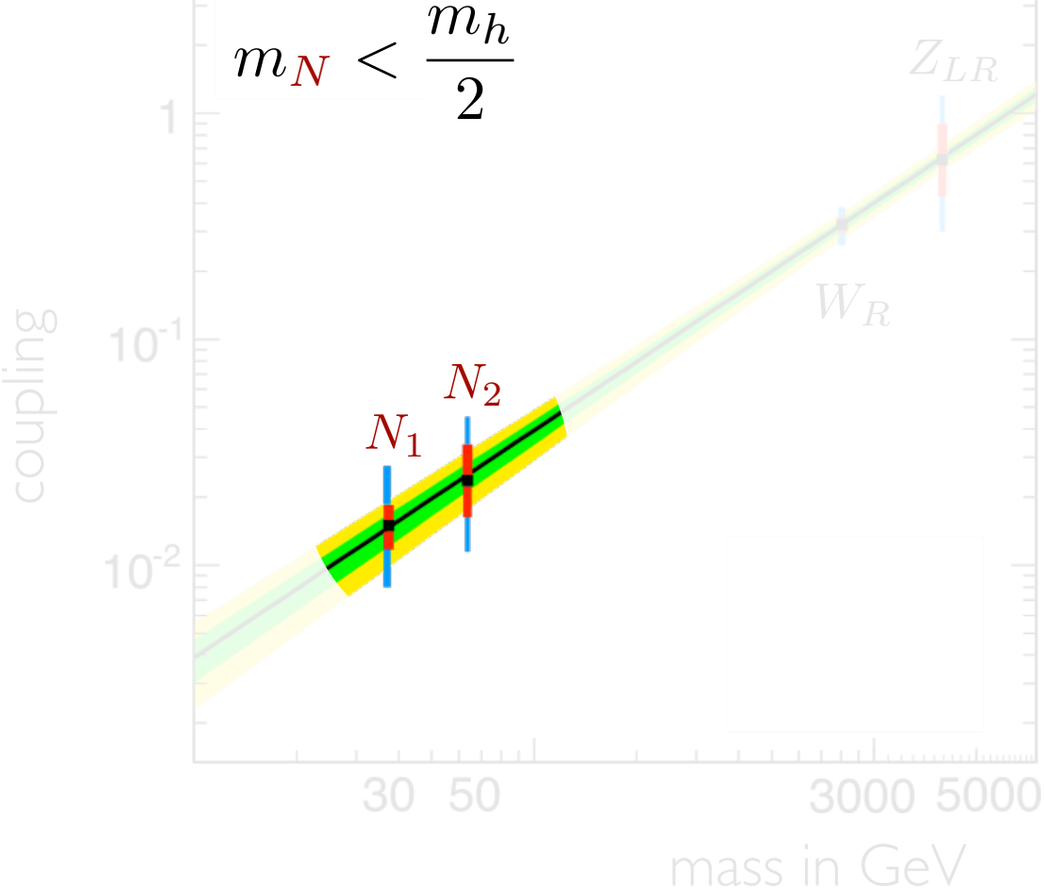


$\Gamma_{h \to NN} \propto \theta^2 \, {m_N}^2$

Gunion et al. Snowmass '86

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

$m_N < \dfrac{m_h}{2}$



Neutrino Mass origin

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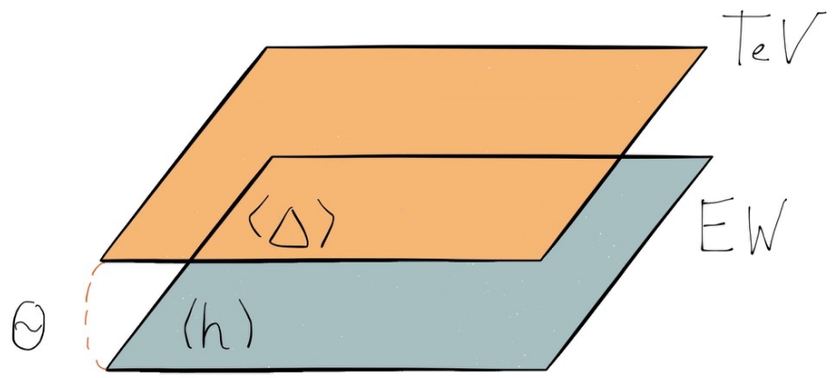
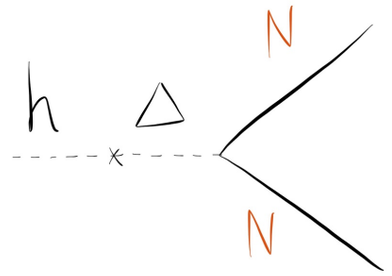


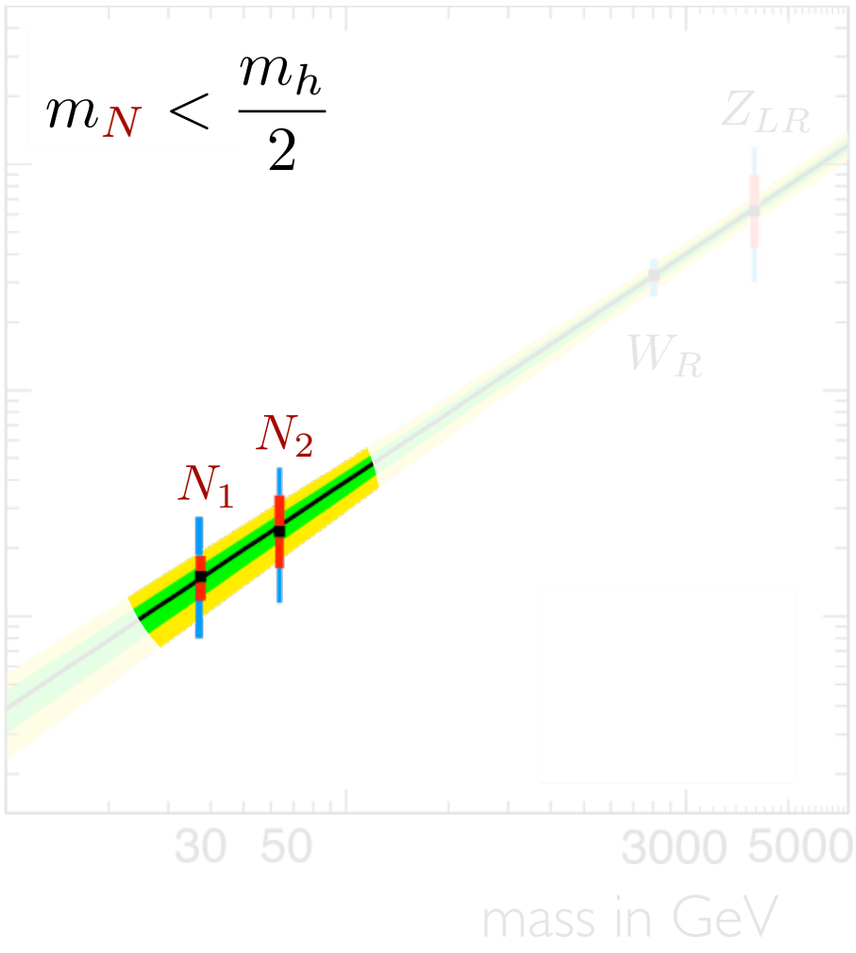


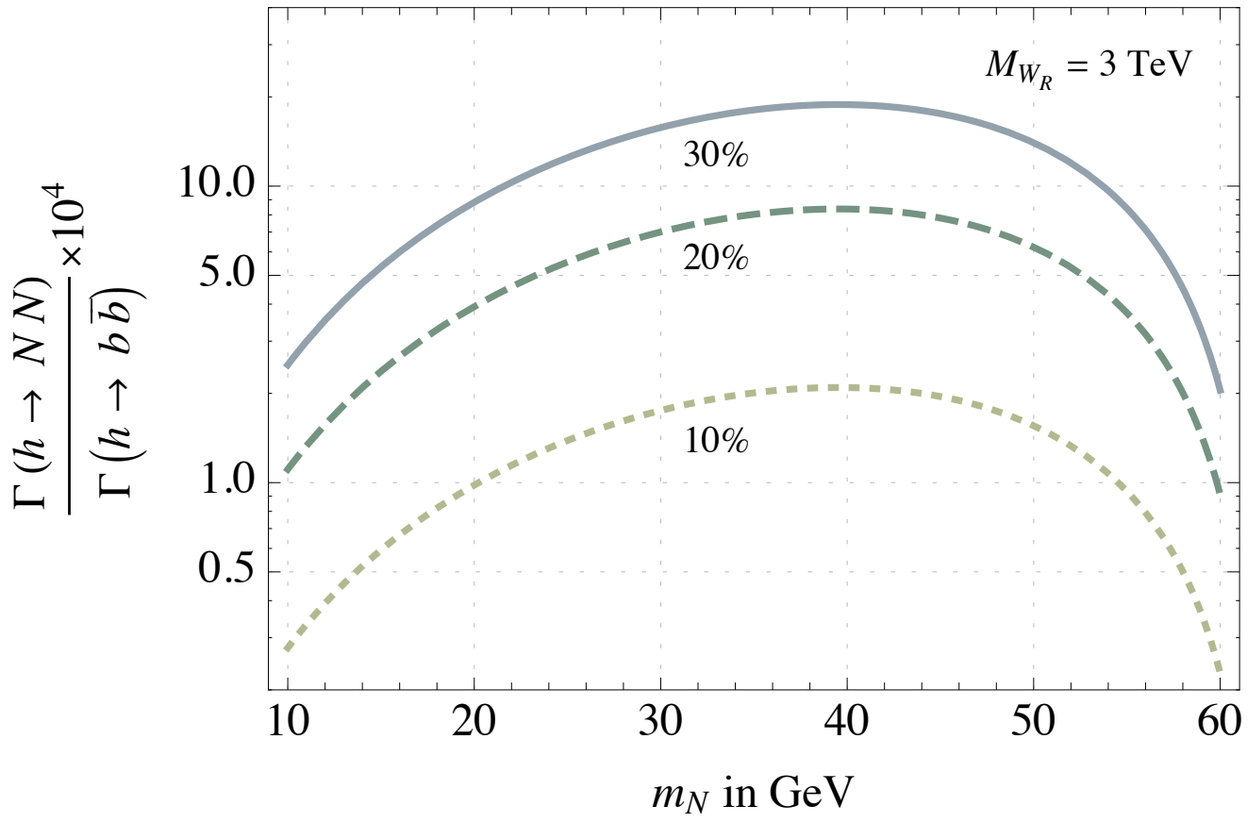
$\Gamma_{h \to NN} \propto \theta^2 \, {m_N}^2$

Gunion et al. Snowmass '86

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

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





$h \to NN$ @ LHC

Production @ 13 TeV LHC

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

$h \to NN$ **event estimate** $m_N = 40$ 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

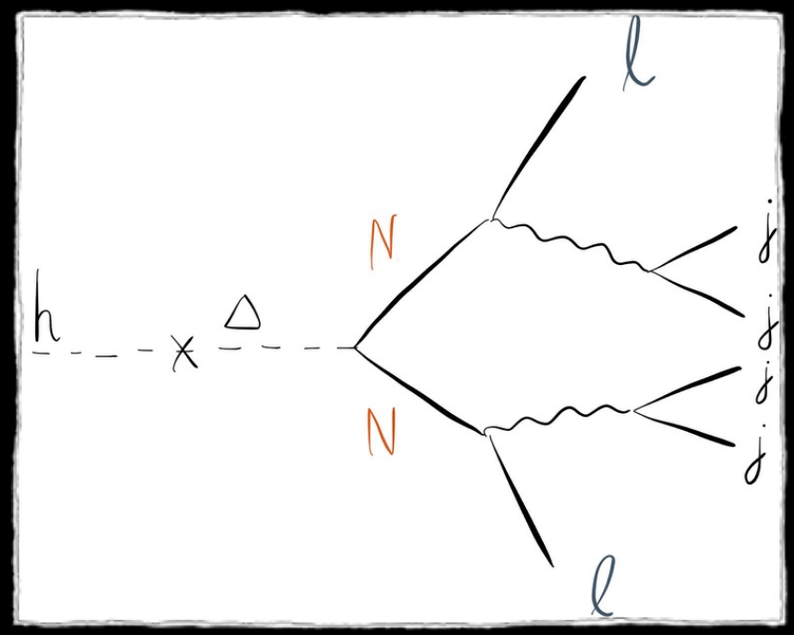
MadGraph5 Pythia6 Delphes3 MadAnalysis5

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

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N is Majorana

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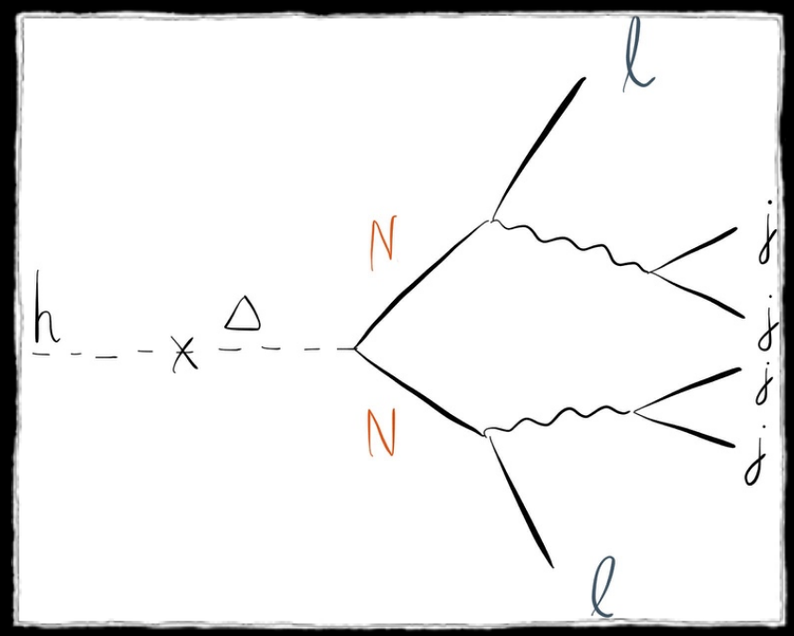
same-sign breaks *L*



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same and opposite sign & four jets

LFV possible due to light m_N

mass peaks for N and h

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

~soft final state $p_T \simeq \frac{m_h}{6} \sim 20\ \mathrm{GeV}$

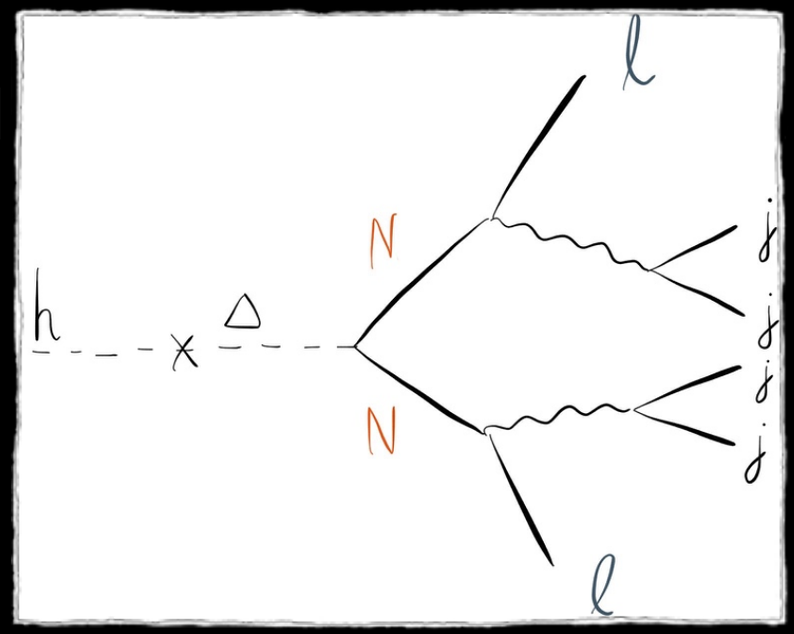
$\gamma(h) \simeq 3$

no missing energy

no SM background

LNV Higgs decay

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



Delphes3 ATLAS card

geometric acceptance

Leptons

no muons below $p_T < 10$ GeV

loss of signal by 50%

μ isolation $\Delta R = .3$

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

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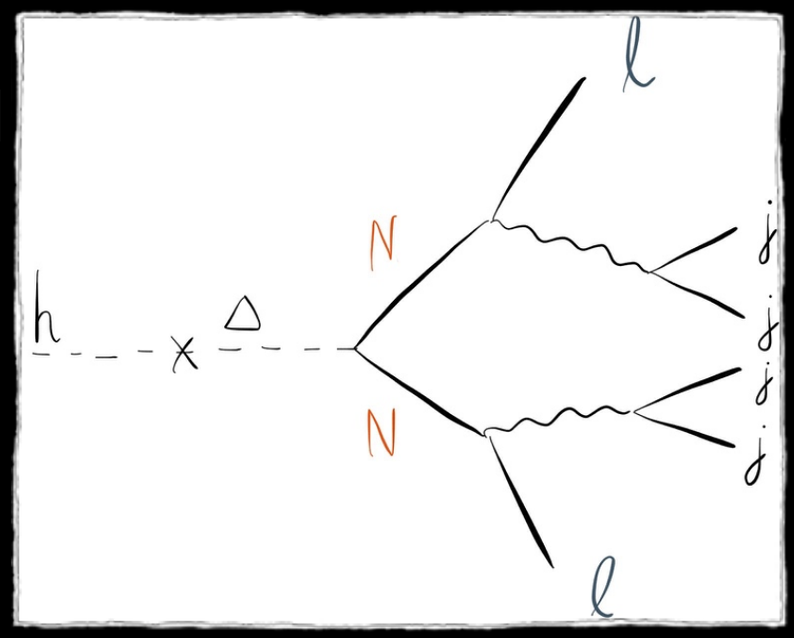

$m_{\ell jj} = m_N$

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

Delphes3 ATLAS card

geometric acceptance

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Jets

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

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

Missing E

$\not{E} \simeq 15$ GeV

Backgrounds

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

$W^\pm W^\pm jj$

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

contain missing energy

one lepton prompt, other from *b*

WZ, ZZ

simulated with MG5

$t\bar{t}$

Backgrounds

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

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

all contain missing energy

one lepton prompt, other from *b*

WZ, ZZ

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$t\bar{t}$

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 $\ell^\pm \ell^\pm + n_j j$

$W^\pm W^\pm jj$ $\quad\hookrightarrow \ell\, \nu_\ell$ $\qquad WZ, ZZ \qquad\qquad t\bar{t}$

all contain missing energy — simulated with MG5

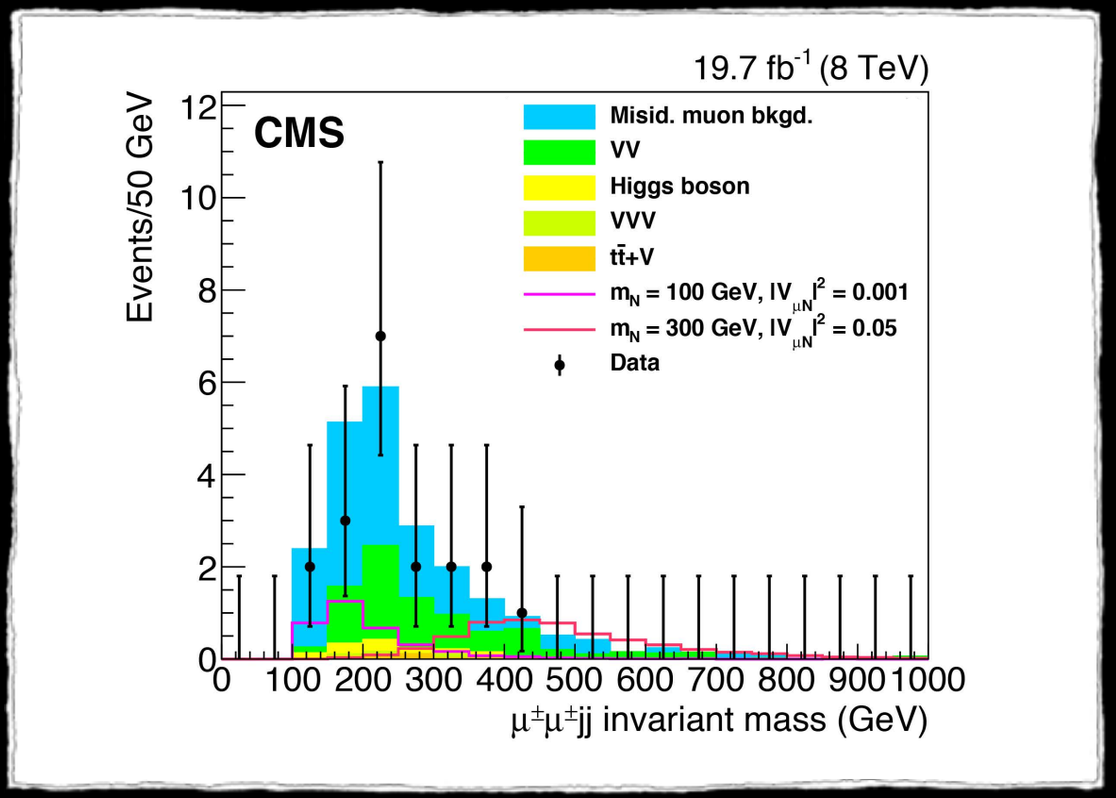
one lepton prompt, other from *b*

Jet mis-id

QCD jets mistaken for muons

Data-driven estimate — CMS 1501.05566

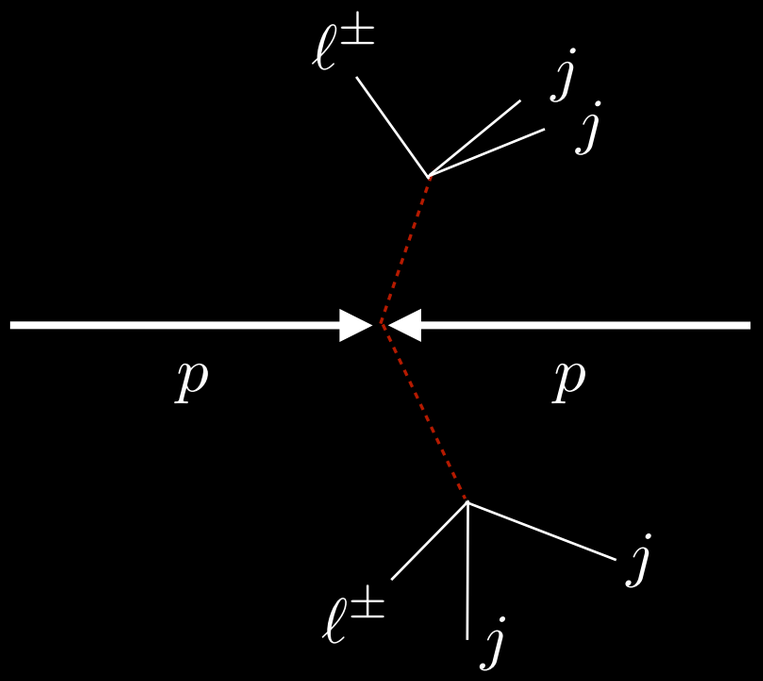
Theorist's approach $QCD = 2.5 \times (VV)$



Displacement

N lifetime significant

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



additional effective discriminant

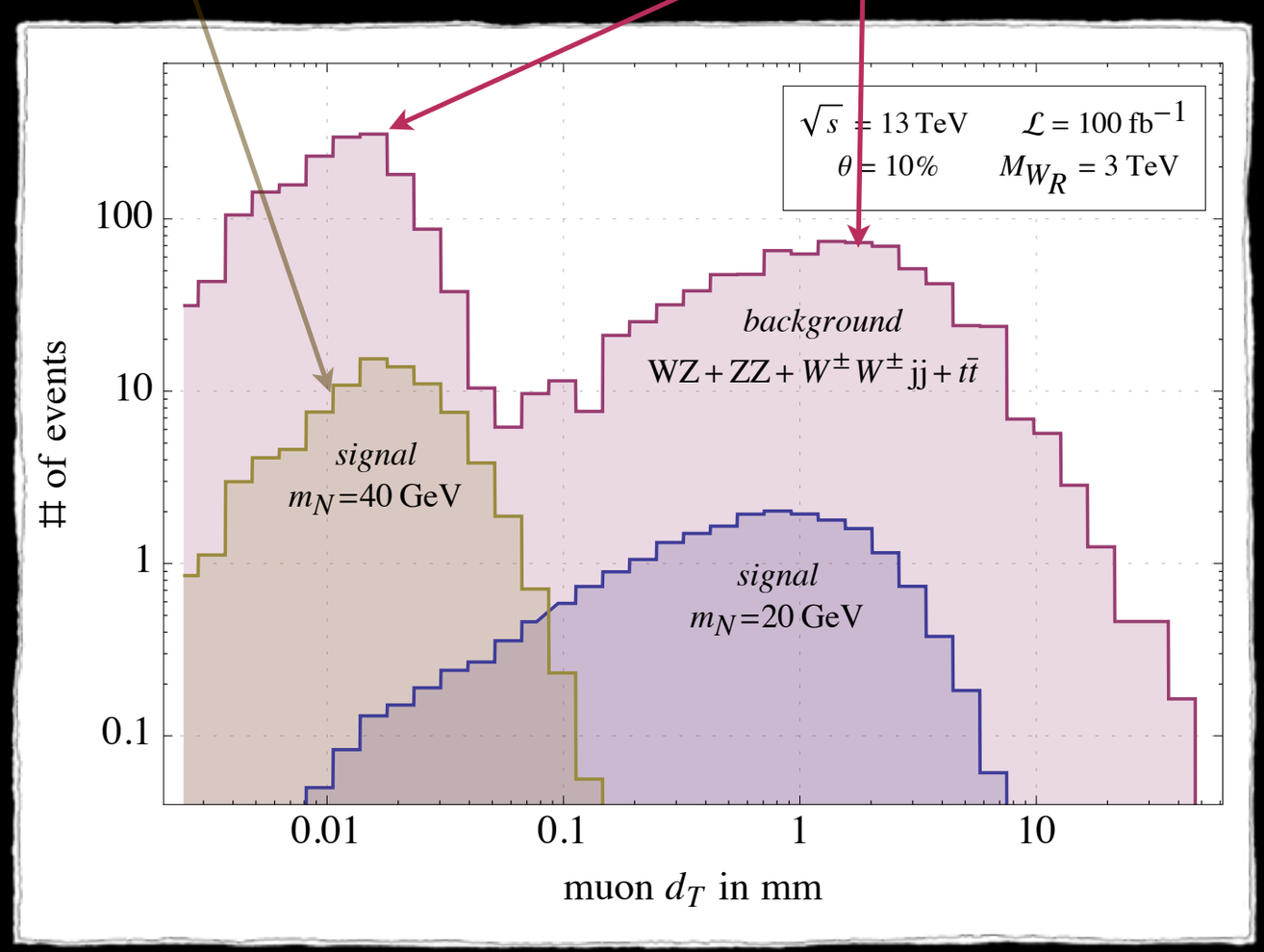
used on muons only

displaced jets wip

Resolution $O(10\mu m)$

Correlated

custom smearing module



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

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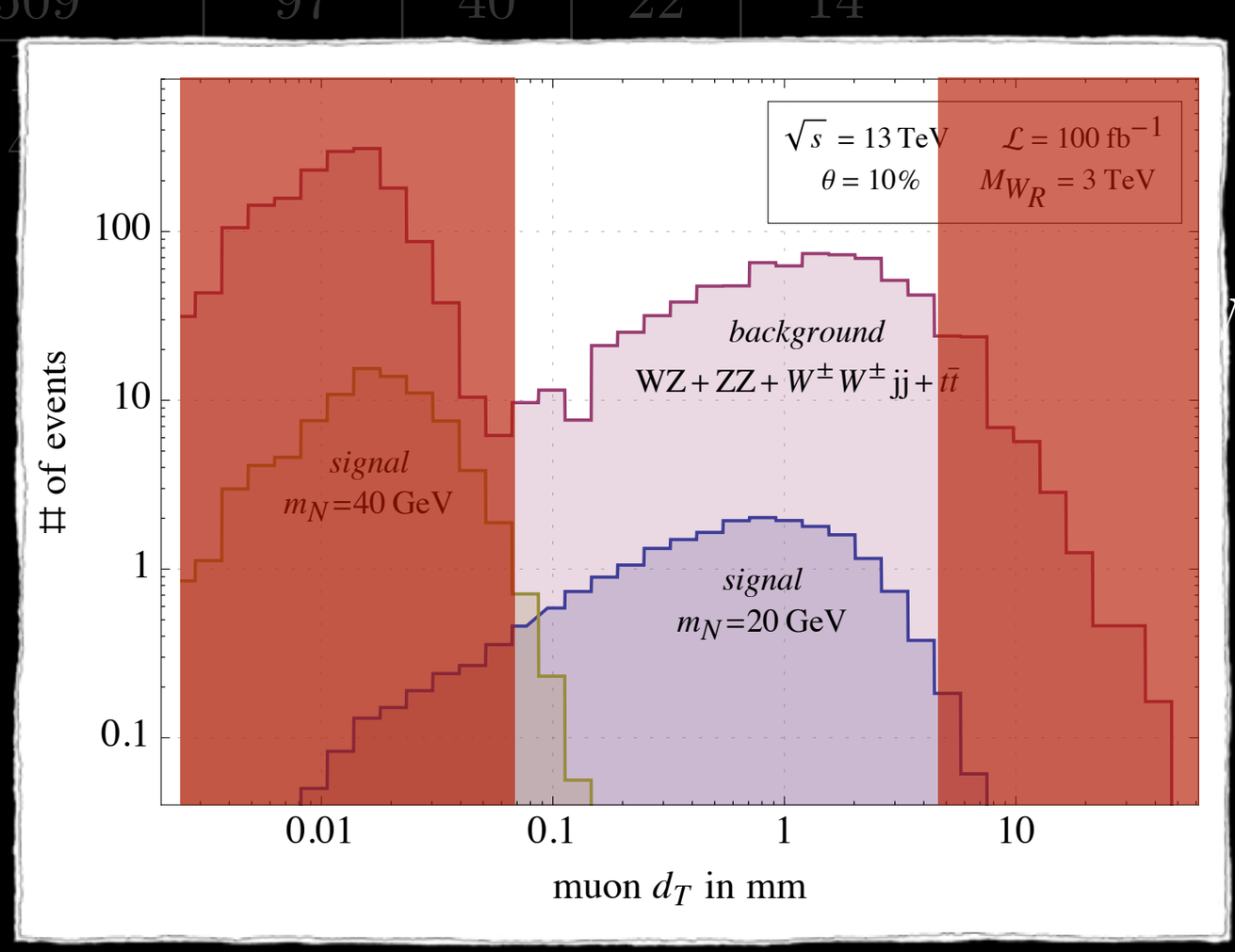
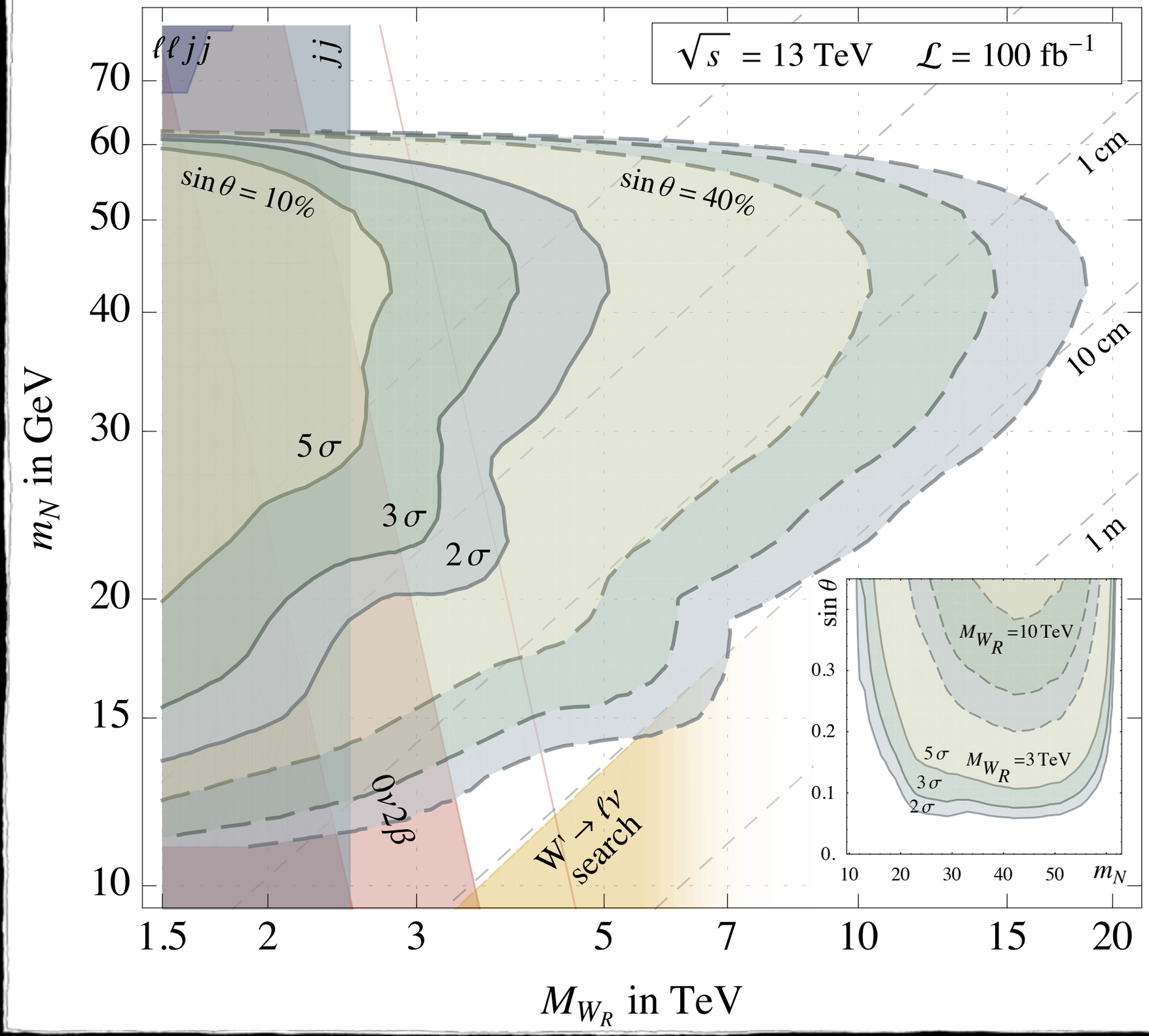
Jet mis-id $QCD \simeq 2.5 \times (VV)$

Sliding d_T window

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

optimize *L*




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

Thank you

Outlook

Room for improvement

electron, τ and LFV channels

sophisticated search methods

jet displacement

softer muons $p_T < 10$ 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

some LNV Higgs candidates

Simple see-saws excluded

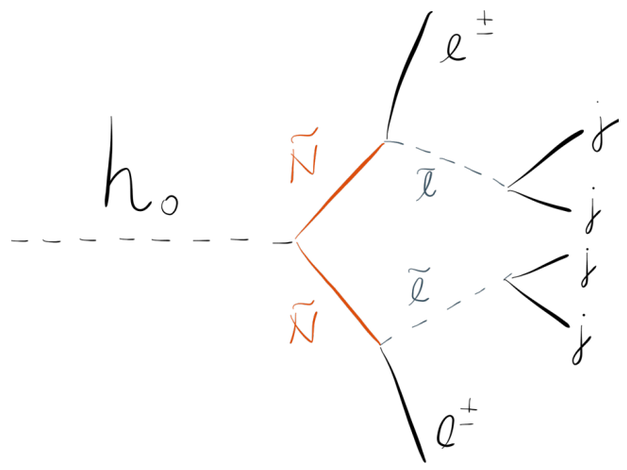
Fourth generation $h \to \nu_4 \nu_4$ — Pilaftsis '92, Carpenter '11

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