The Abdus Salam International Centre for Theoretical Physics

JSI

Neutrino mass and the LHC

Miha Nemevšek, ICTP & JSI

with Bajc, Senjanović, Nesti, Zhang, Maiezza, Tello, Vissani and Kamenik

Corfu 2012 School and Workshop

Neutrino mass *is* Beyond the SM physics.

LHC found a Higgs, we are starting to probe the origin of mass.

What about neutrinos?

Fermion mass

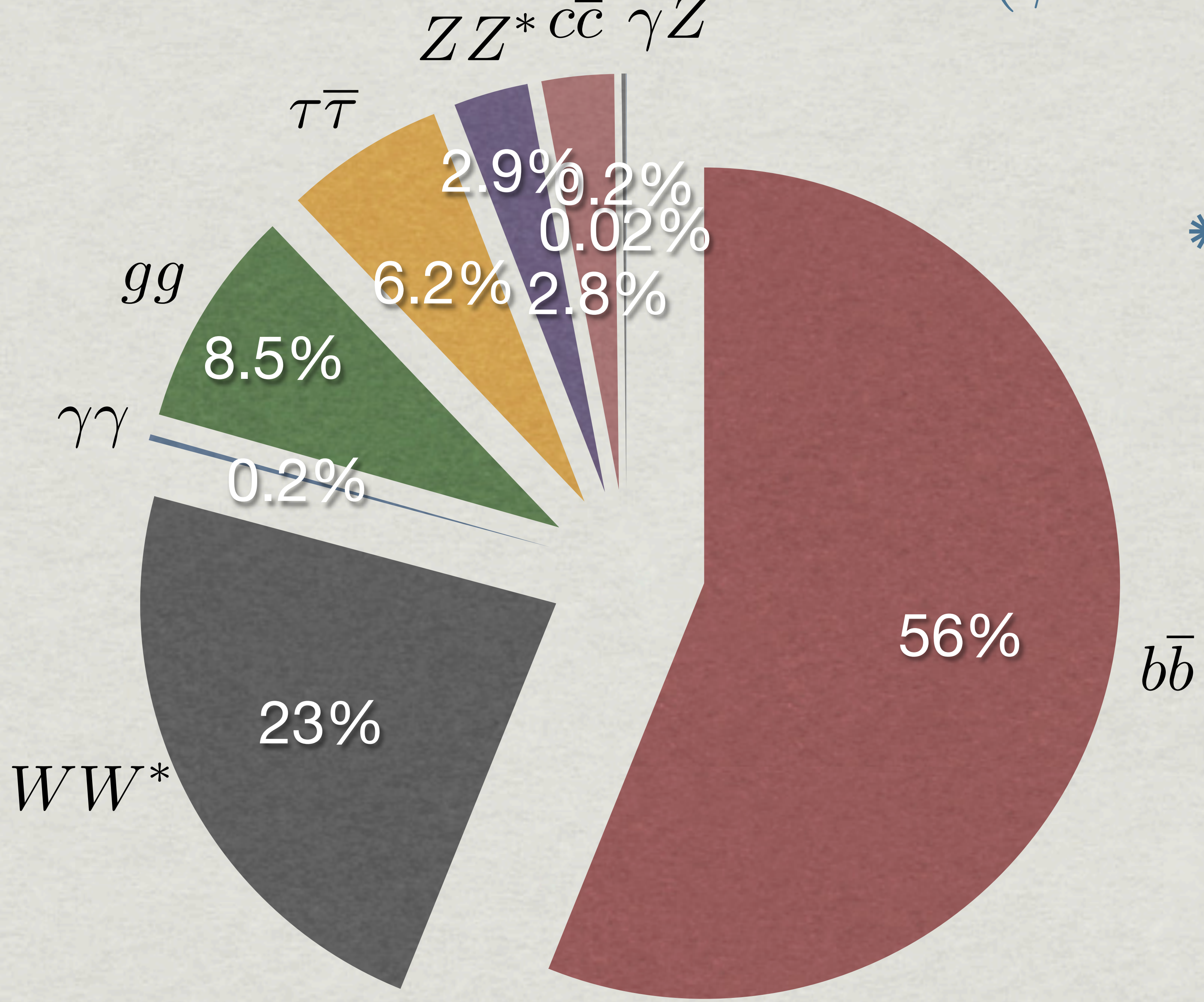
- Charged fermions Dirac

$$\mathcal{L}_m = y_f \overline{f}_L \phi f_R + h.c. \Rightarrow m_f = y_f v$$

  - Yukawa predicted, probe with $\phi \to f\overline{f}$

- Minimality requires ν_L only $m_\nu = 0$
  - Majorana?
  - if not SM, what is the theory of neutrino mass...
  - ...and how to probe it?

SM EBH boson Br



$$\Gamma(\phi \to xx) \propto \frac{m_x}{v}$$

- ATLAS & CMS data circa 2012

$m_h \simeq 126\ \mathrm{GeV}$

CMS, ATLAS ’12

Neutrino mass

- EFT approach: *d=5* operator

Weinberg '79

$$\mathcal{L}_\nu = y_{ij} \frac{\ell\phi\,\ell\phi}{\Lambda}$$

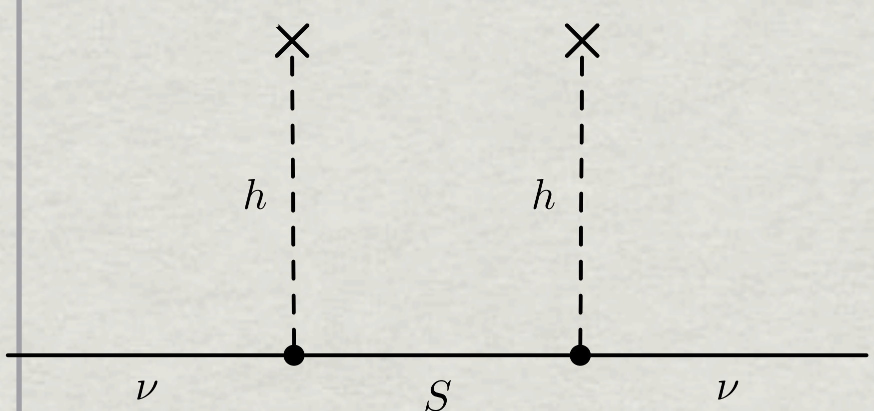
  - valid when $\Lambda \gg v$
  - nearly impossible to probe directly

- Low scale completions
  - accessible to LHC
  - connected to other (LNV, LFV) low energy processes

A theory of neutrino mass?

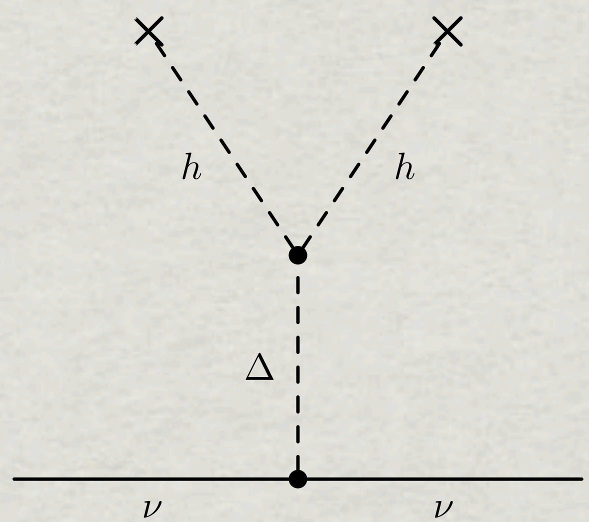
- Seesaw scenarios - toy models, not a theory

type I



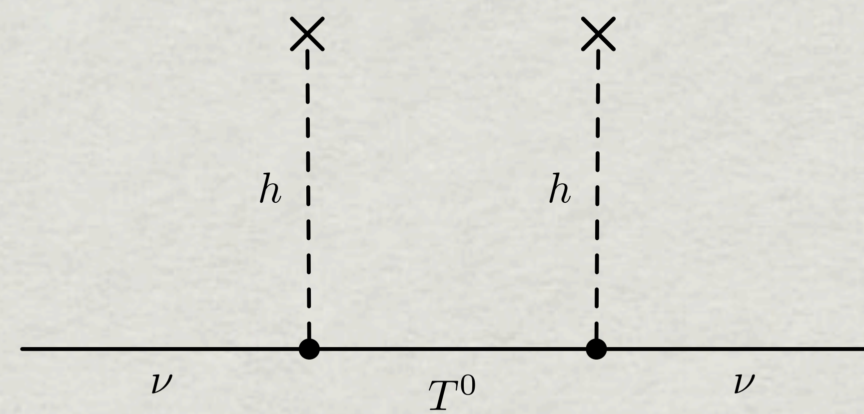
Minkowski ’77,
Mohapatra, Senjanović ’79,
Yanagida ’79, Glashow ’79,
Gell-Mann, Ramond, Slansky ’79,

type II



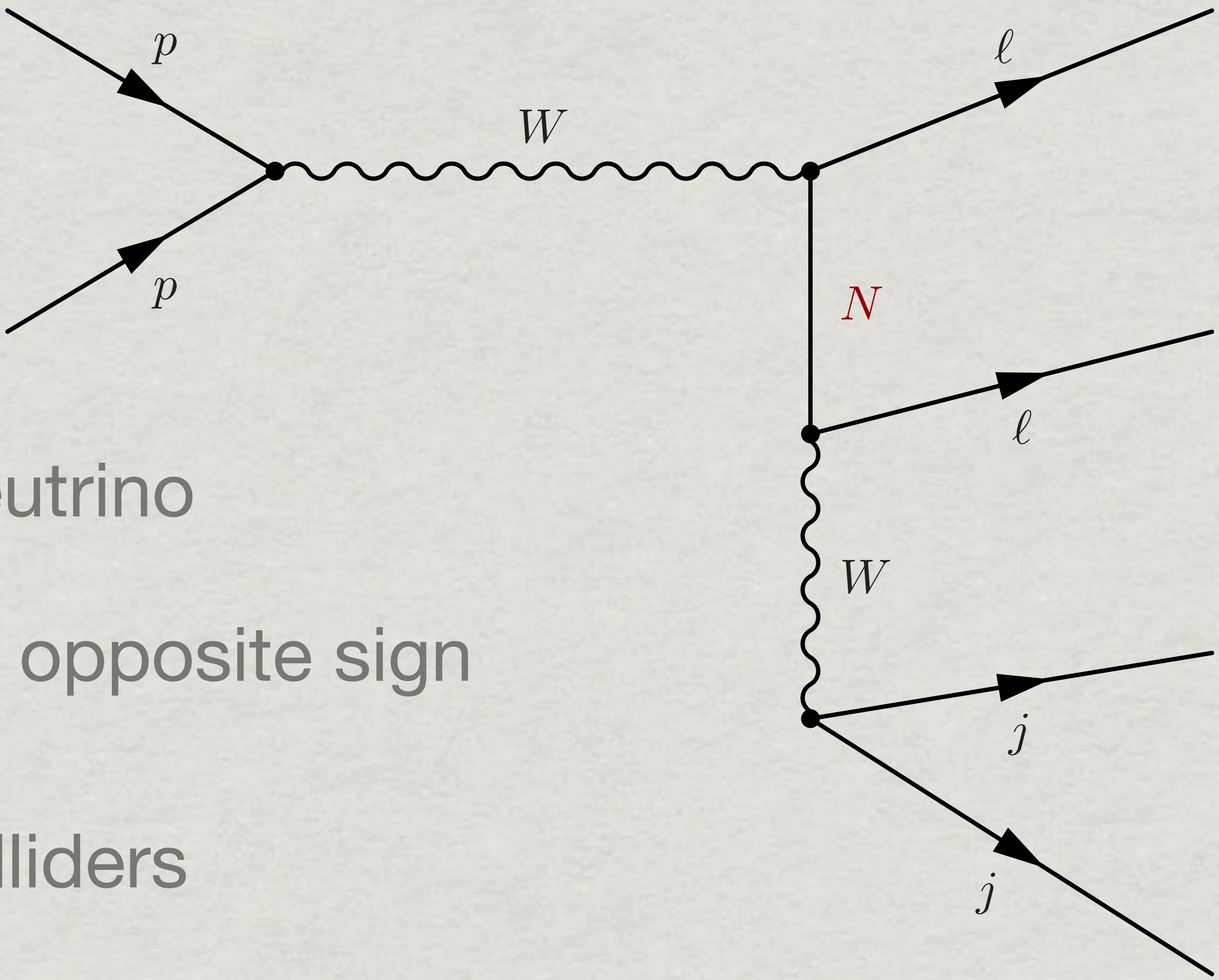
Magg, Wetterich ’80,
Lazarides, Shafi, Wetterich ’81,
Mohapatra, Senjanović ’81

type III



Foot, Lew, He, Joshi ’89

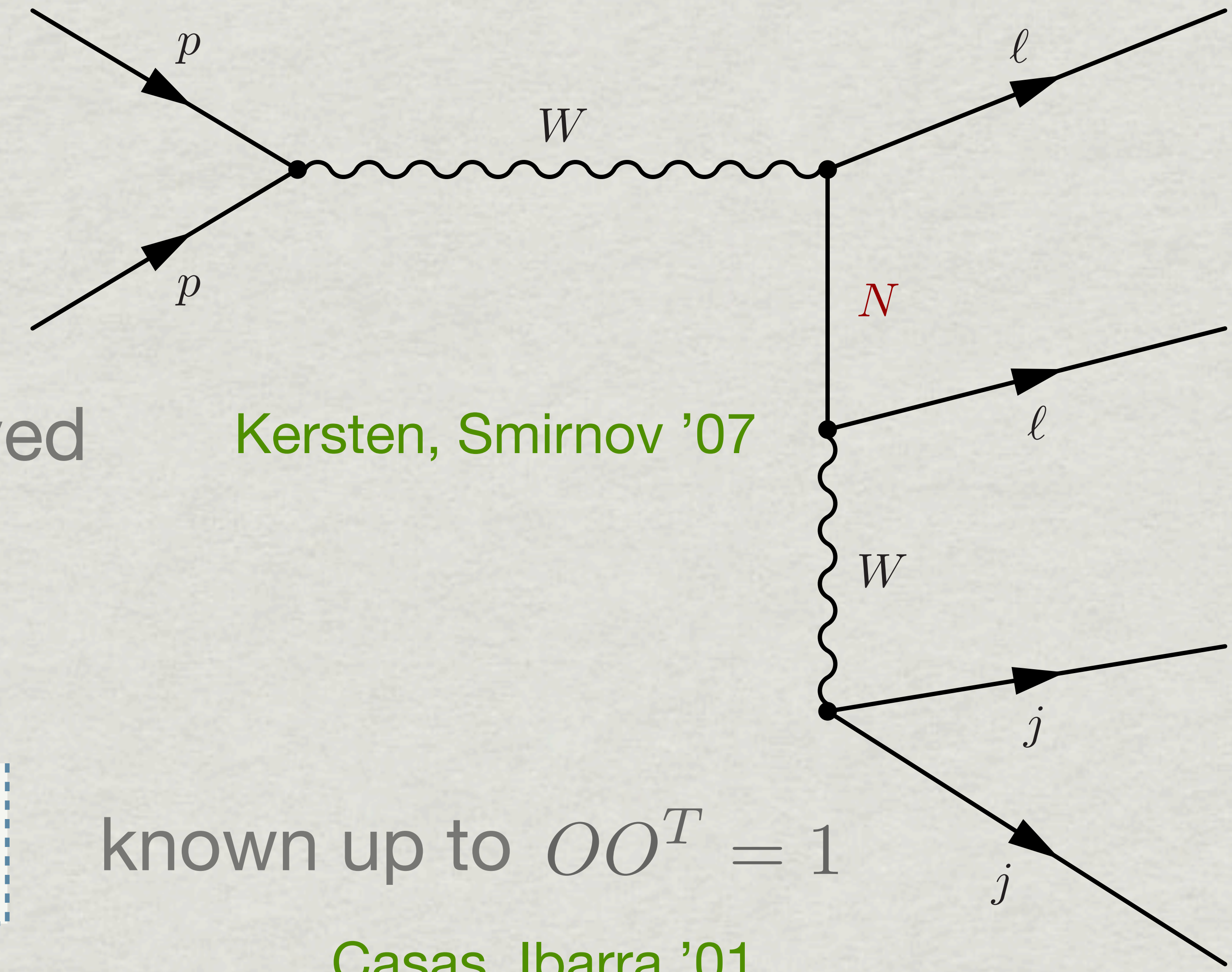
Probing seesaw @ LHC



- Heavy Majorana neutrino
  - 50% same, 50% opposite sign
- Observe LNV at colliders
- Analog of seeing *W* in the Fermi theory
- Proposed in context of LR, generic

Keung, Senjanović '83

type I



- L approximately conserved

Kersten, Smirnov '07

- Dirac term not predicted

$$M_D = \sqrt{m_N} O \sqrt{m_\nu} V_L^\dagger$$

known up to $OO^T = 1$

Casas, Ibarra '01

- Studies at colliders; need fine-tuning
  - LHC reach $\sim 100\ \mathrm{GeV}$

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

- Low energy mostly $0\nu 2\beta$

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

Left-Right

Pati, Salam ’74
Mohapatra, Pati ’75

- Breaks parity spontaneously

Mohapatra, Senjanović ’75

  - Anomaly requires RH neutrino $L_R = \begin{pmatrix} \nu_R \\ \ell_R \end{pmatrix}$
  - Predicted m_ν, originated seesaw

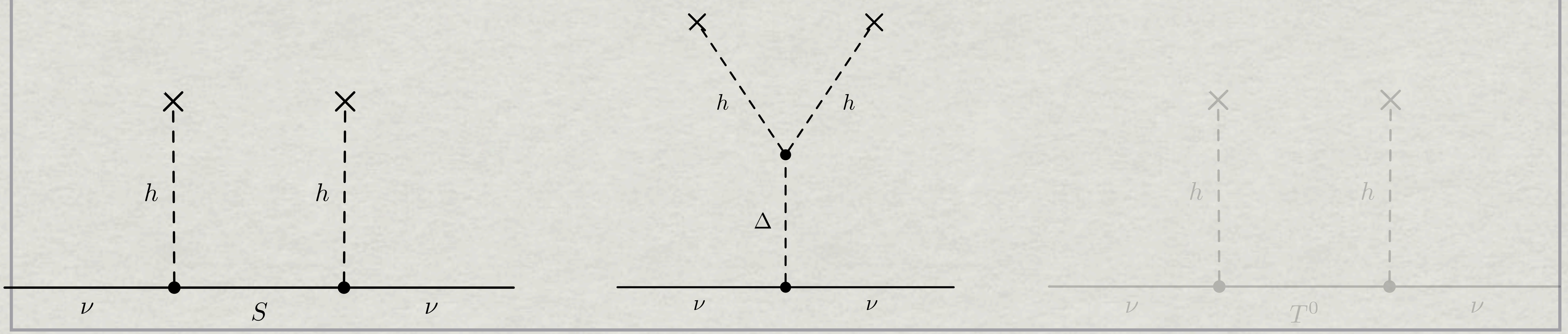
- Minimal model with triplets Δ_L, Δ_R

- Warm DM with ν_R

type I

type II

type III



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

- Parity invariance: *P*arity or Charge conjugation
  - Broken by $v_R \equiv \langle \Delta_R(1,3,2) \rangle \approx \text{TeV},\ v_L = 0$

$$M_{W_R} = g\, v_R, \quad m_N = y\, v_R$$

  - Down to SM via

$$\langle \Phi(2,2,0) \rangle \equiv \text{diag}(v_1, v_2 e^{i\alpha}), \quad v^2 = v_1^2 + v_2^2$$

$$M_W = g\, v, \quad m_f = y_f\, v$$

  - Seesaw

$$m_\nu = -m_D {m_N}^{-1} m_D^T + \frac{v_L}{v_R} m_N$$

- New Interactions $g \equiv g_R \simeq g_L$

$$\mathcal{L}_{cc} = \frac{g}{\sqrt{2}} \left(\overline{N}\, V_R{}^\dagger\, \not{W}_R\, \ell_R + \overline{u}_R\, V_R^q\, \not{W}_R\, d_R \right) + \text{h.c.}$$

  - Parity in Yukawa sector fixes the flavor

$$\mathcal{L}_Y = \overline{f}_L \left(Y\Phi + \tilde{Y}\tilde{\Phi} \right) f_R + \text{h.c.}$$

  - Due C: $Y = Y^T$ $\quad V_R^q = V_L^q \equiv V_{ckm}$

- Limits from meson mixing

Beall, Bander, Soni ’82, ...

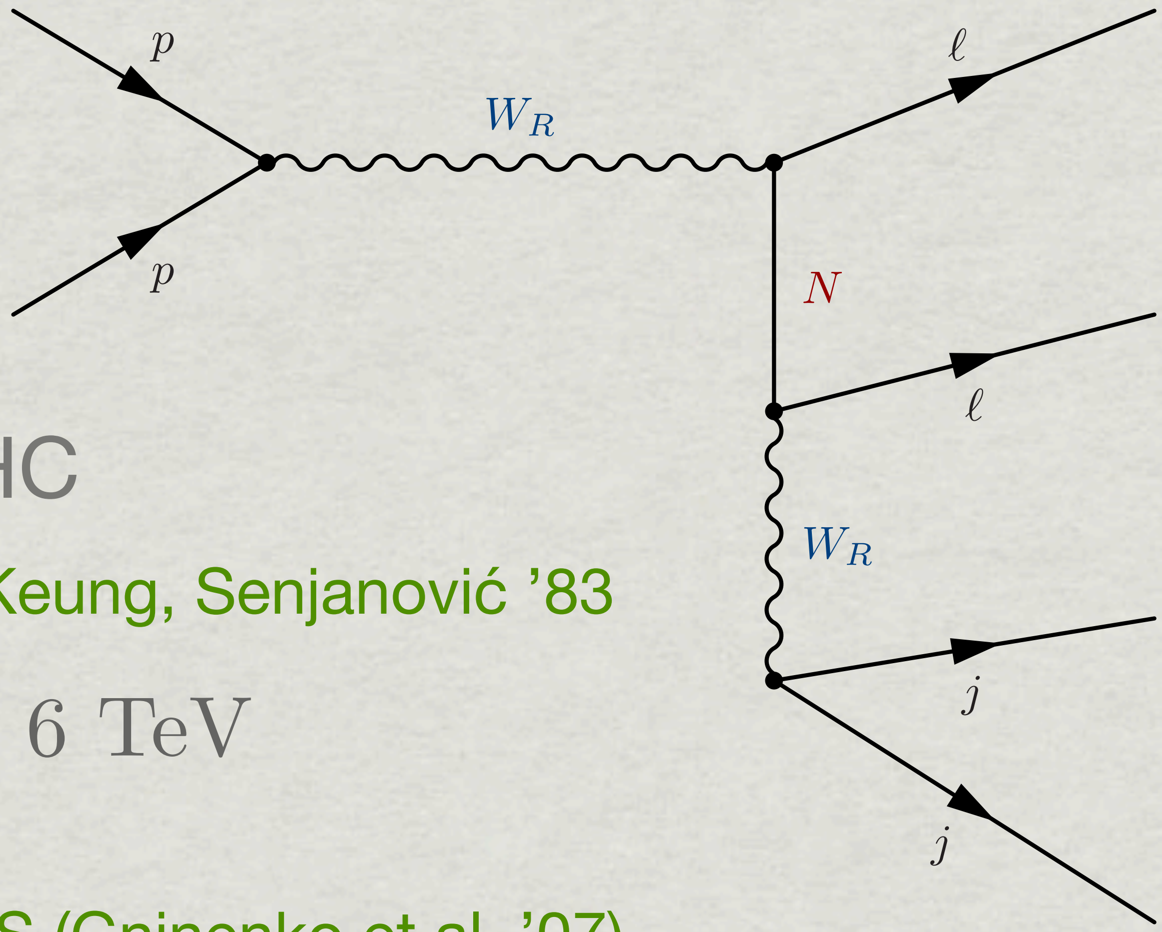
$$M_{W_R} > 1.6 \ \text{TeV}$$

  - Re-examine with CP violation

$$M_{W_R} > 2.5 \ \text{TeV}$$

..., Zhang, An, Mohapatra, Ji ’07
Maiezza, MN, Nesti, Senjanović ’09

- Left-Right



  - s-channel production at LHC

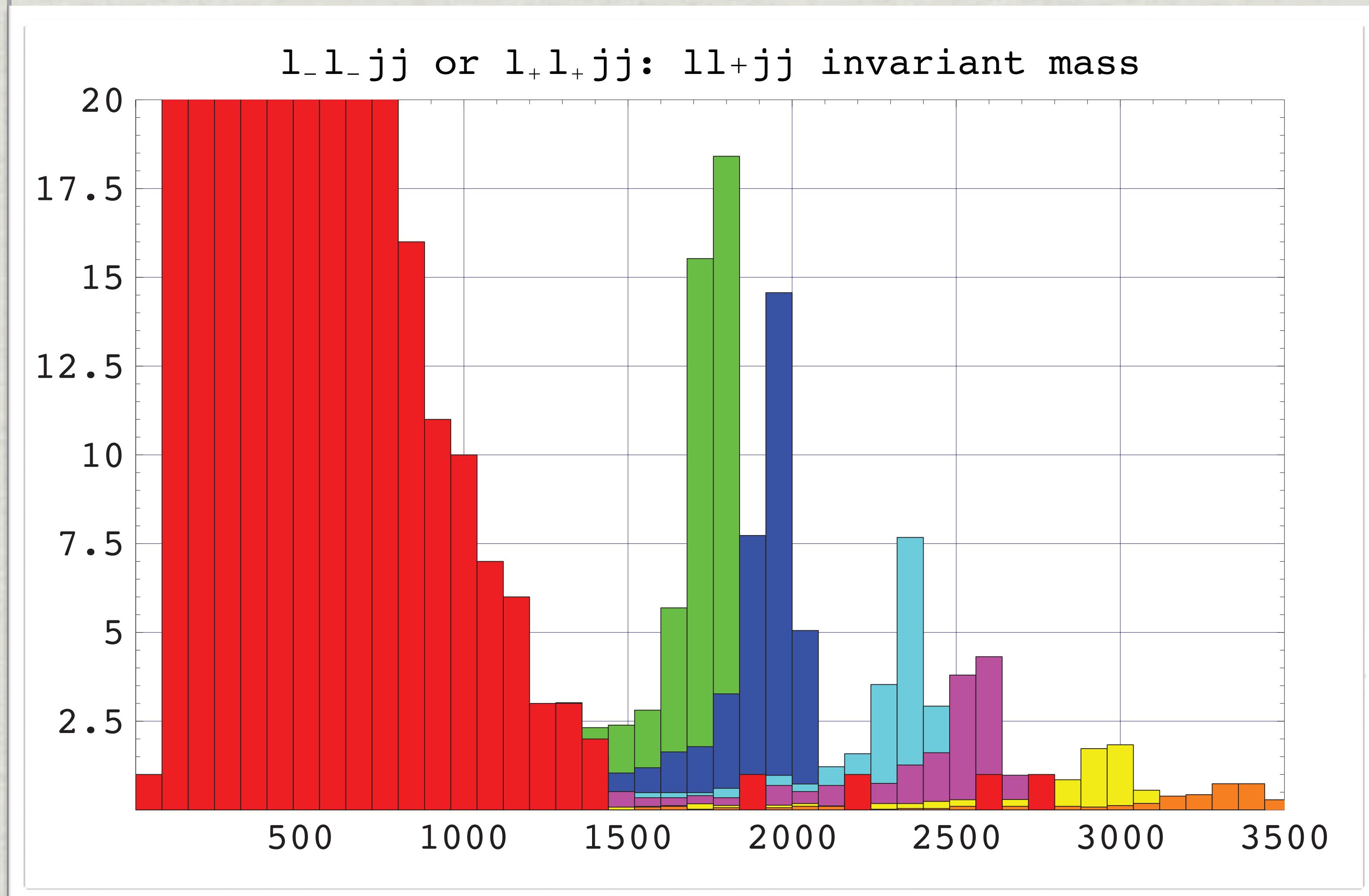
    Keung, Senjanović ’83

  - dedicated studies, reach $\gtrsim 6\ \mathrm{TeV}$

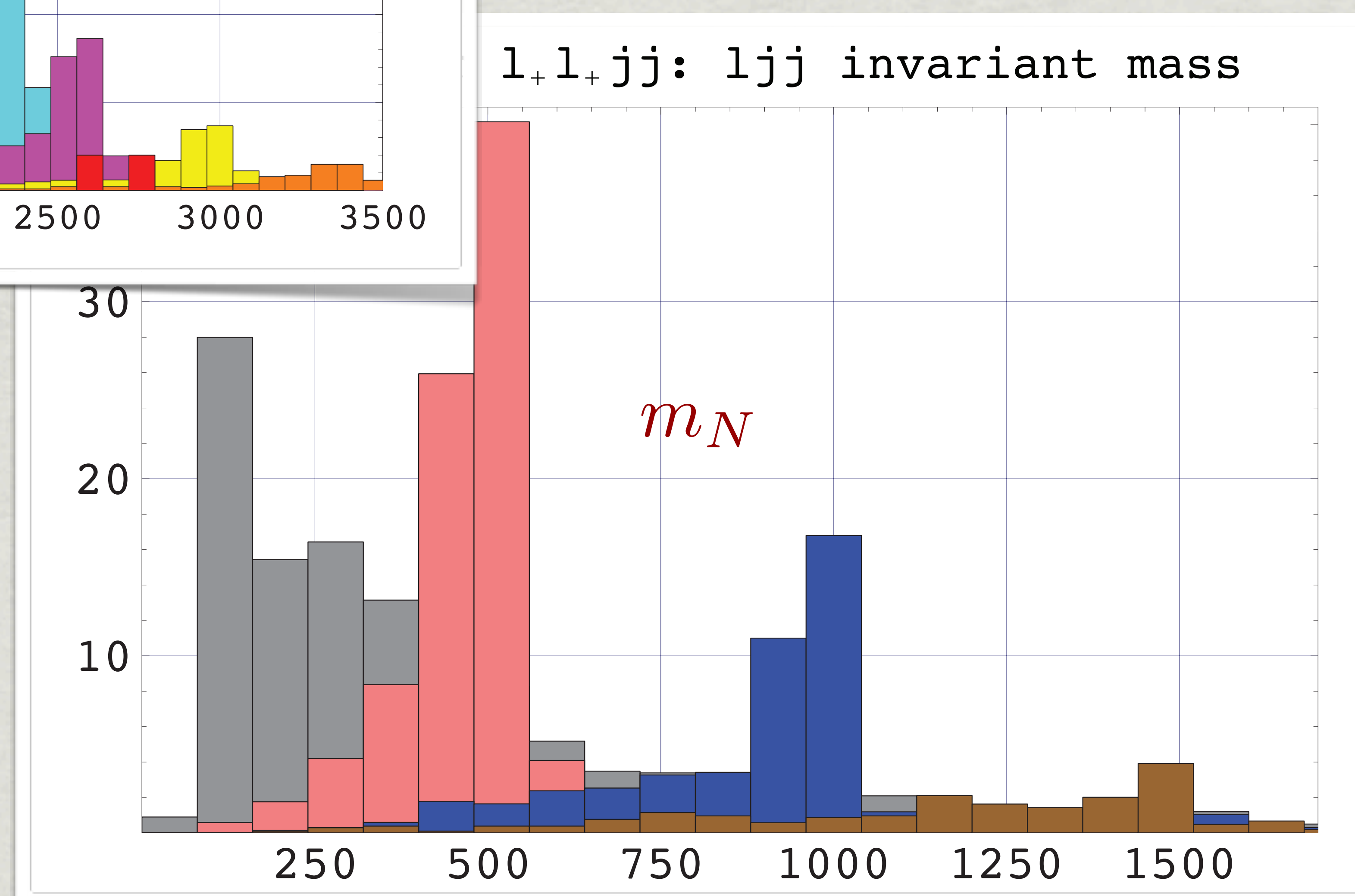
    ATLAS (Ferrari et al. ’00) & CMS (Gninenko et al. ’07)

  - LNV at colliders, Majorana nature
    - mass of W_R and N
    - no missing energy
  - Flavor channels give V_R, govern LNV & LFV at low E

Heavy N @ LHC



- Pythia + PGS
- 14 TeV, 10/fb
- p_T cuts $t\bar{t}$ bckg



- Flavor channels

  $ee, \mu\mu, \tau\tau$

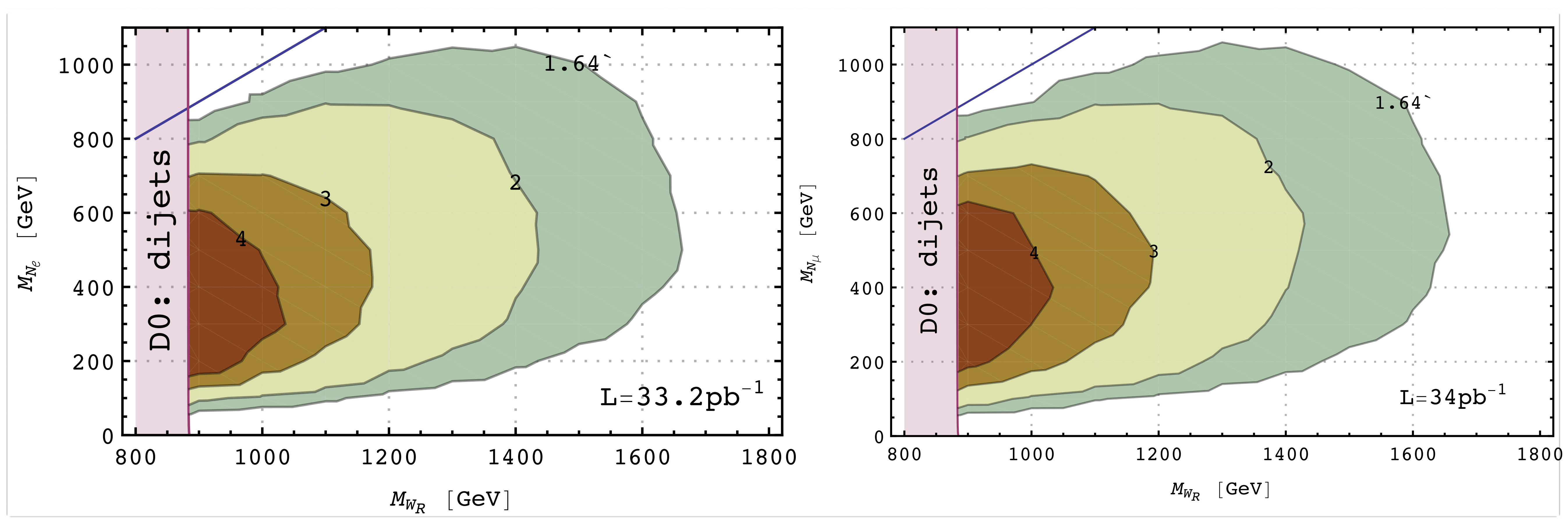
  $e\mu, e\tau, \mu\tau$

- Six per N

Left-Right searches @ LHC

- early data on LQ's, e and μ channel

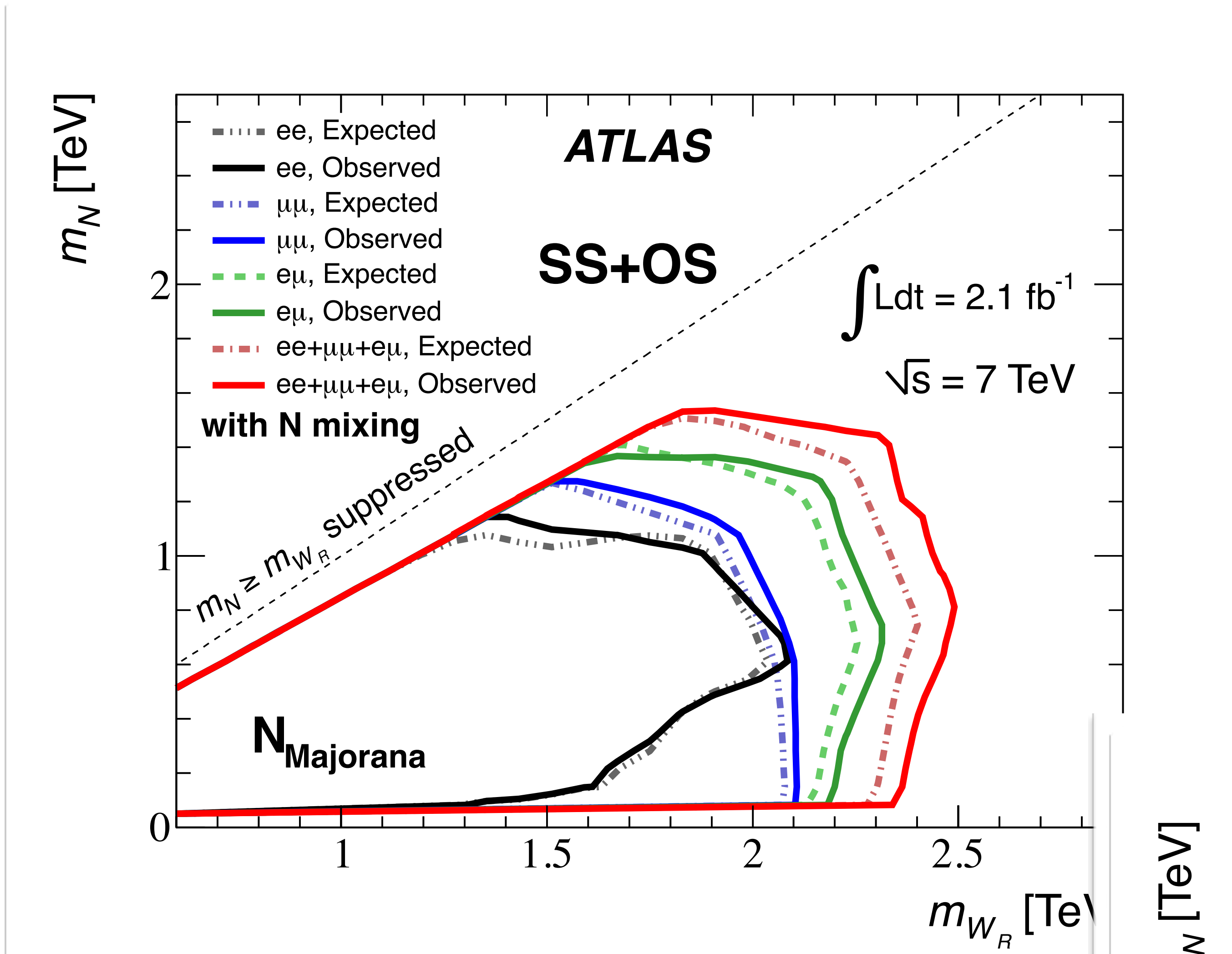
Nesti, MN,
Senjanović, Zhang '11



- low luminosity, theorist's roadmap

- τ channel feasible

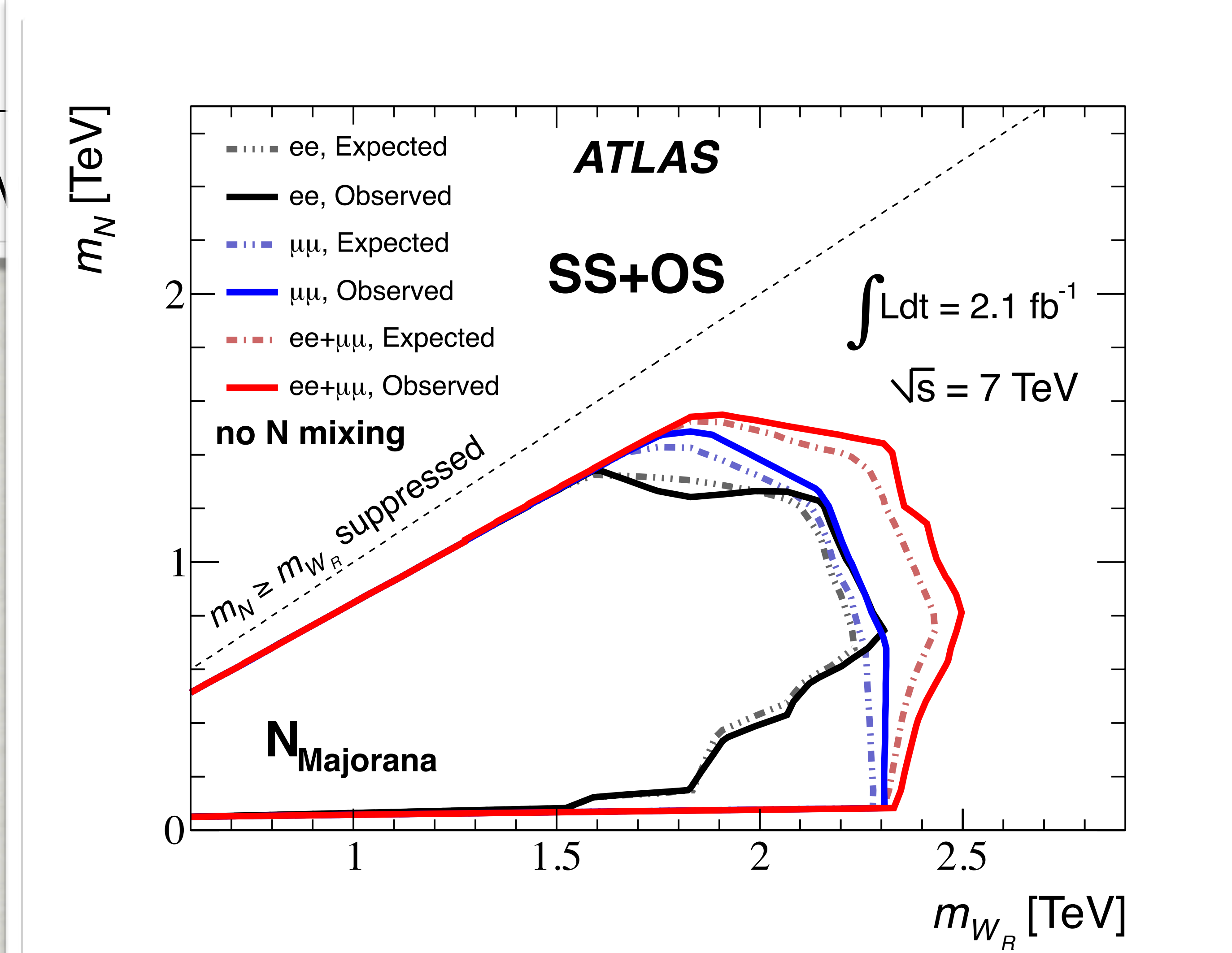
Aguilar-Saavedra,
Deppisch, Kittel, Valle '12



- Dedicated searches @ LHC

CMS-PAS-EXO-11-002

ATLAS 1203.5420

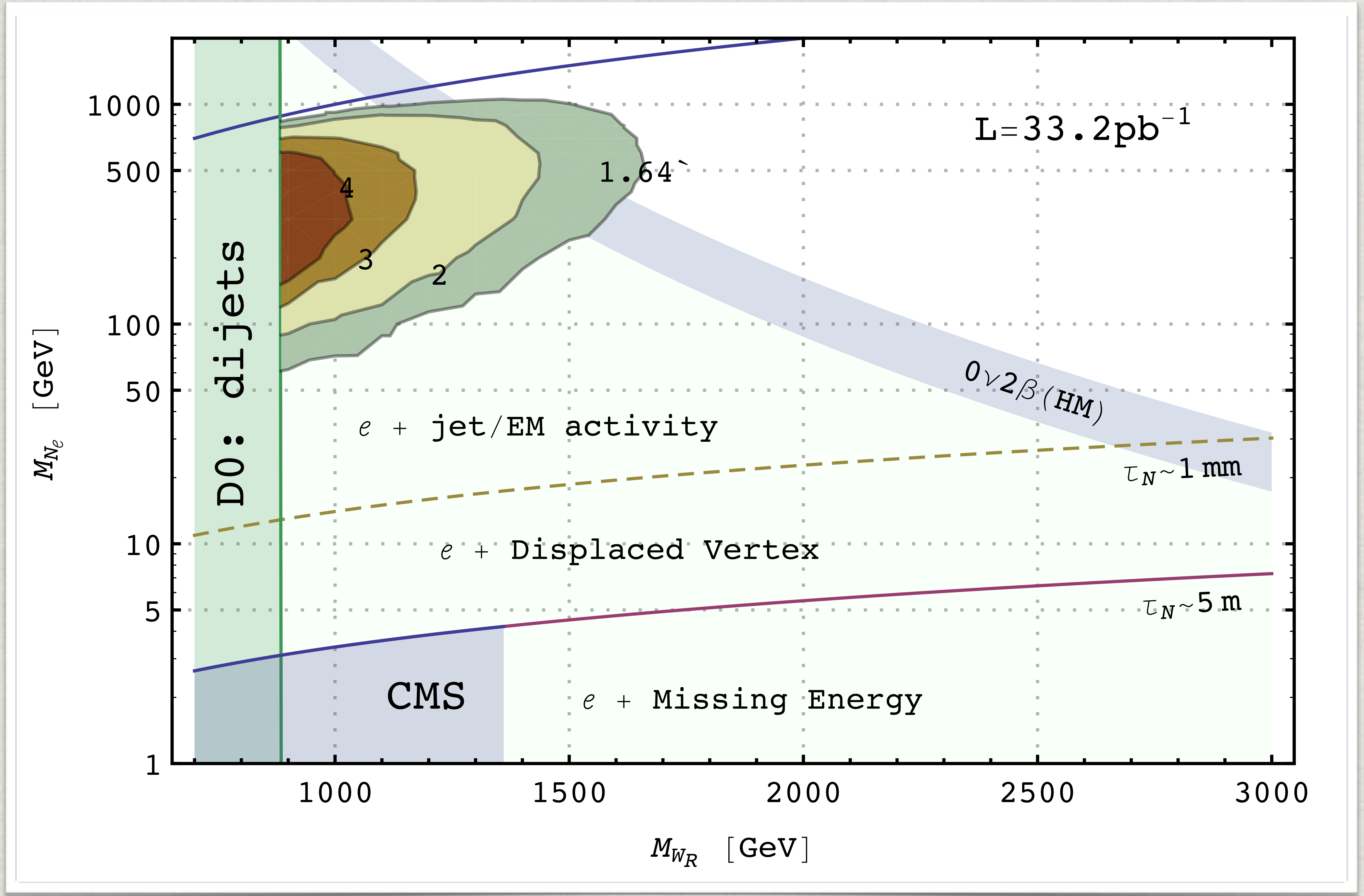


- Luminosity 9/11/2012

$$\mathcal{L} \approx 14 \text{ fb}^{-1}$$

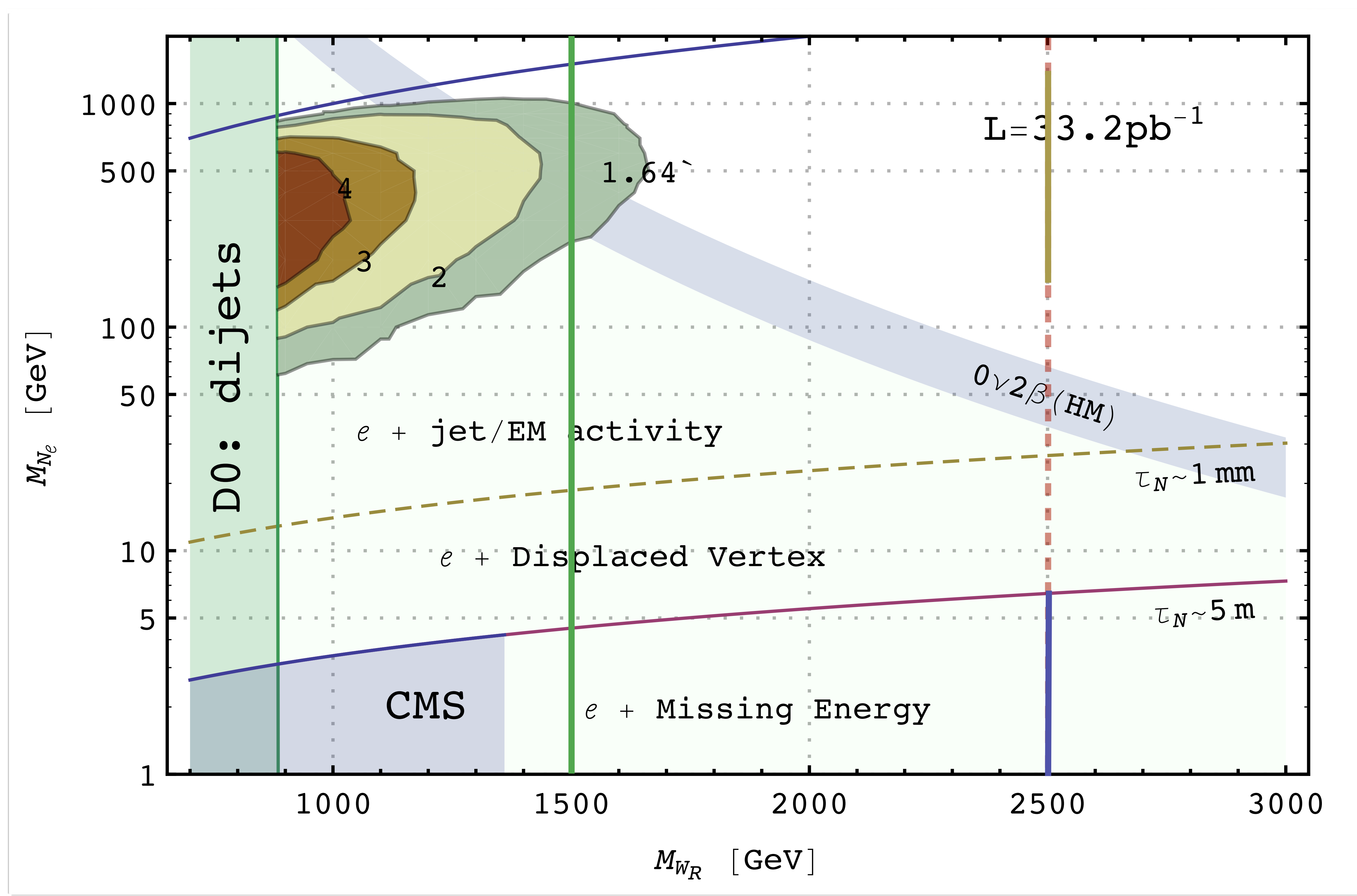
LR searches 2011-12

Nesti, MN, Senjanović, Zhang '11



LR searches 2011-12

Nesti, MN,
Senjanović, Zhang '11



LNV: $0\nu2\beta$ and LHC

- Neutrino less double beta decay

Furry '39

- Textbook: neutrino Majorana mass

$$m_\nu^{ee} = \sum_N m_N U_{eN}^2 \qquad \mathcal{A}_\nu \propto G_F^2 \frac{m_\nu^{ee}}{p^2} \qquad p \sim 100 \text{ MeV}$$

- New physics *d=9*

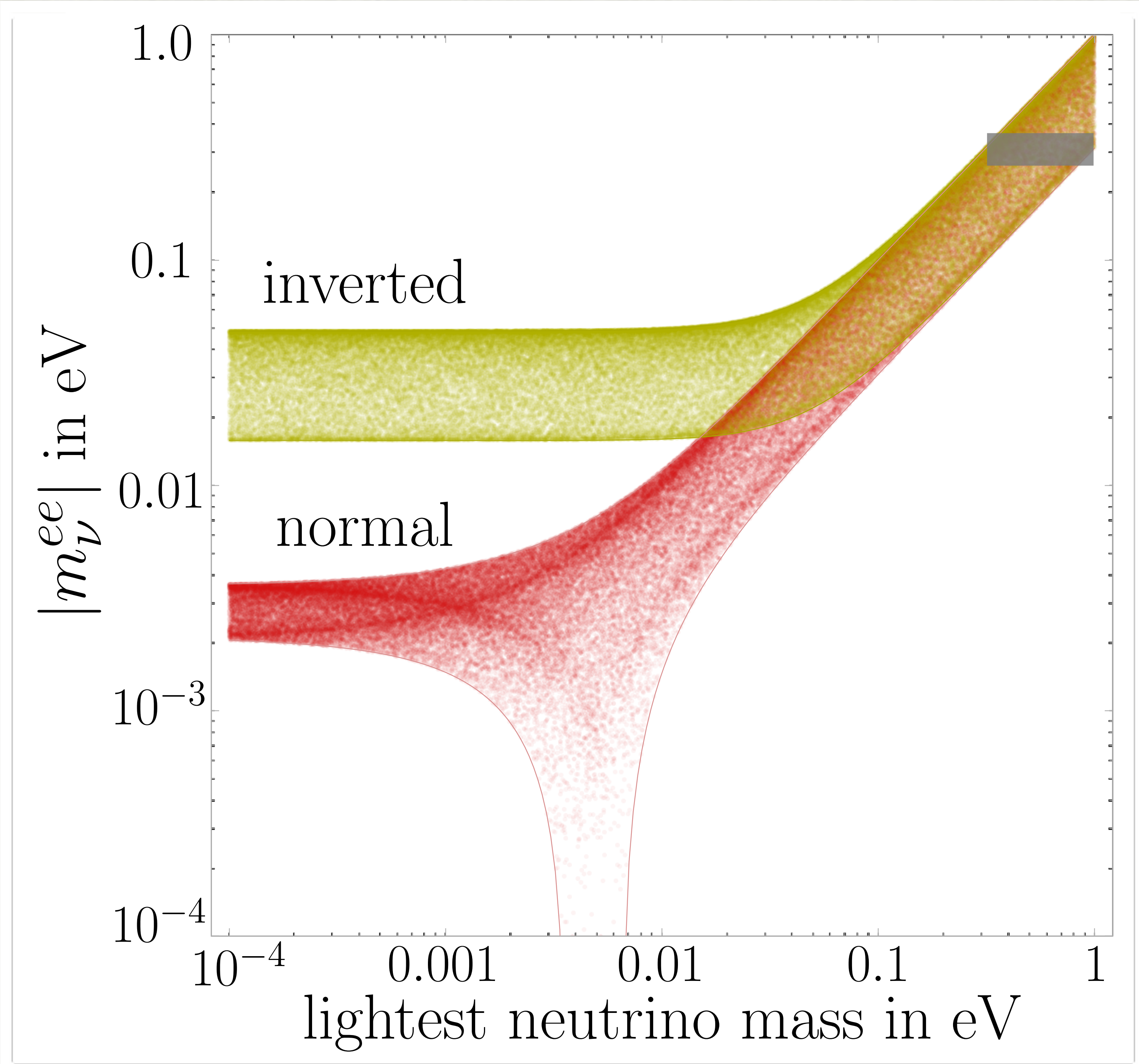
Feinberg & Goldhaber '59, Pontecorvo '64

$$\mathcal{A}_{\text{NP}} \propto G_F^2 \frac{M_W^4}{\Lambda^5}$$

$$m_\nu^{ee} \approx \text{eV} \Rightarrow \Lambda \approx \text{TeV}$$

- TeV scale is LHC

Majorana neutrino mass and $0\nu2\beta$



- claim of observation

  Klapdor et al. '06, '09

- cosmology

  $$\sum m_\nu < .17 - .44 \text{ eV}$$

  Seljak et al. '06

  Hannestad et al. '10

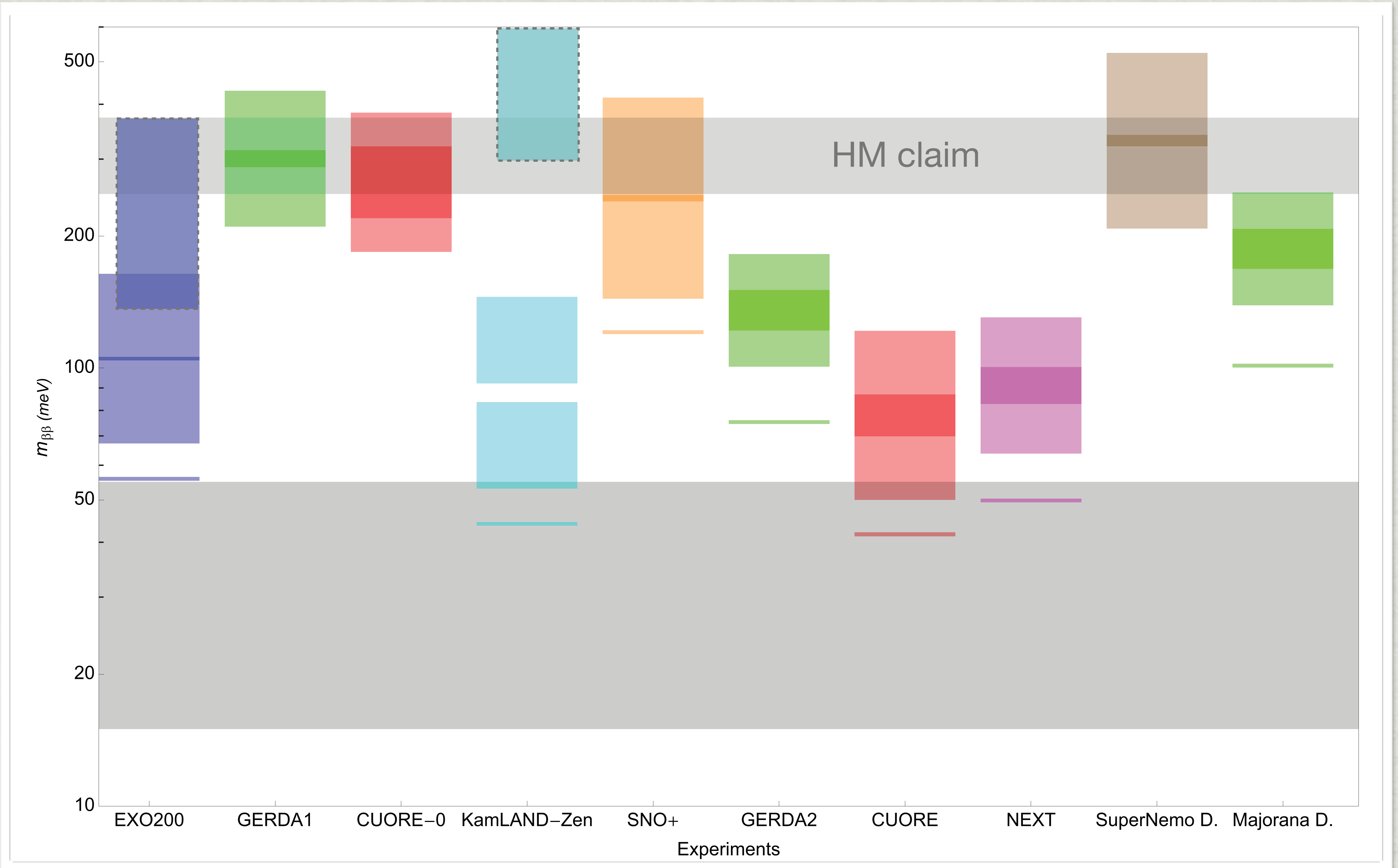
- large signal and cosmo = hint of NP

  Vissani '02

- Region to be explored by experiments

Experimental status circa 2012

Gomez-Cadenas et al. ’11

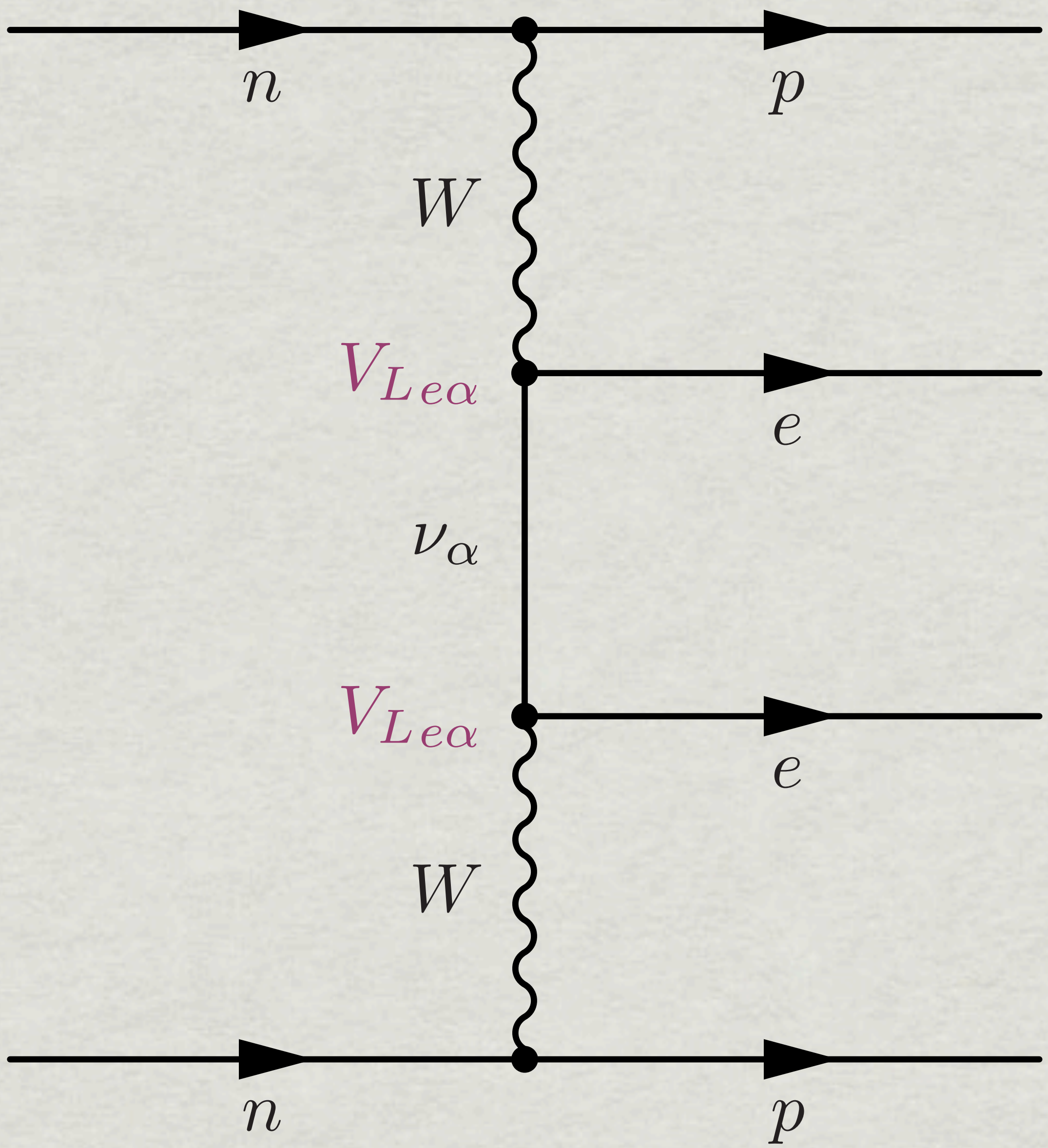


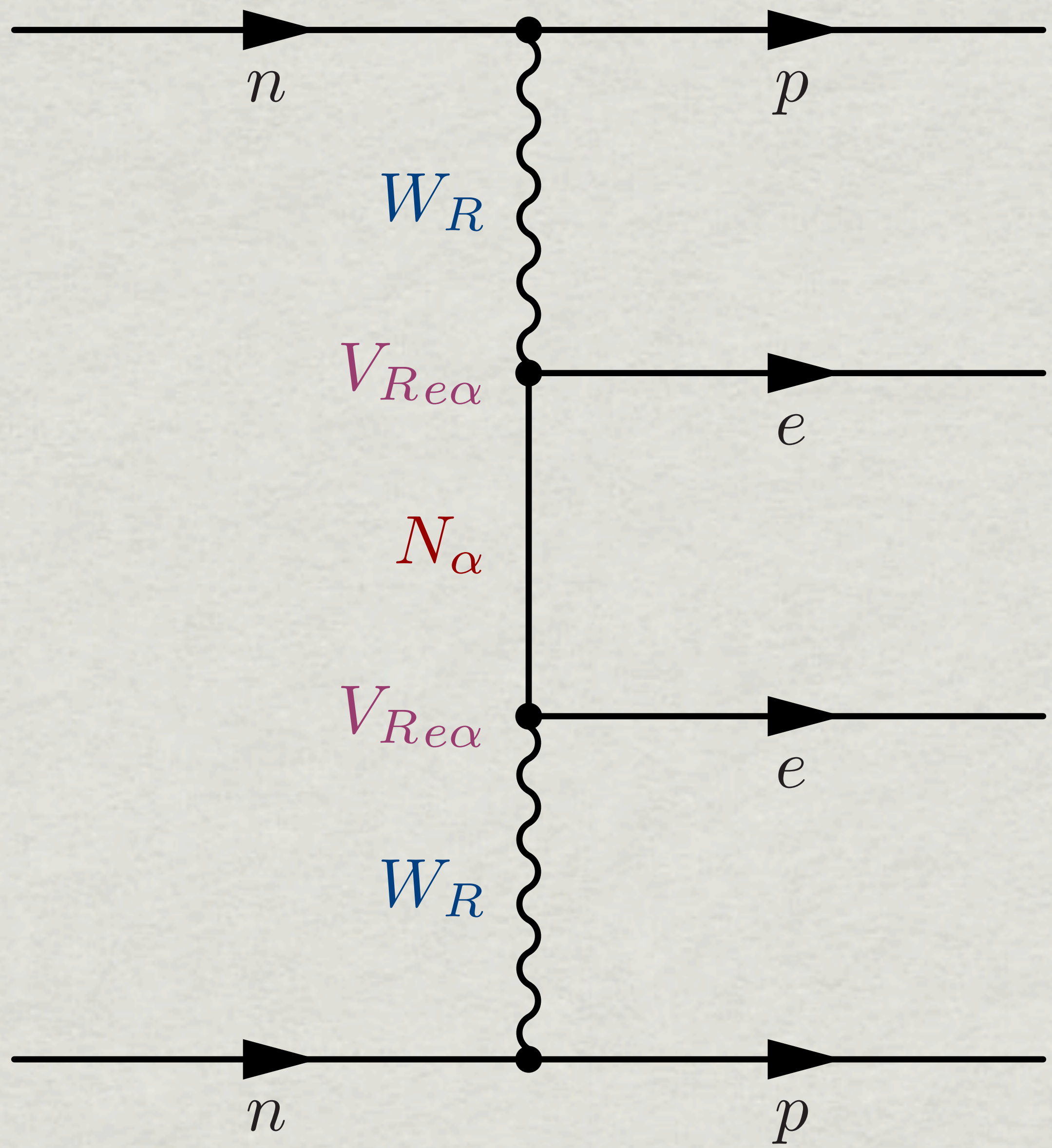
1205.5608

1201.4664

Left-Right and $0\nu 2\beta$

Mohapatra, Senjanović '81





$$\mathcal{A}_\nu \propto G_F^2 \frac{m_\nu^{ee}}{p^2}$$

$$\mathcal{A}_N \propto G_F^2 \left(\frac{M_W}{M_{W_R}}\right)^4 \frac{1}{m_N}$$

- Contribution from Δ_L^{++} tiny, Δ_R^{++} potentially there

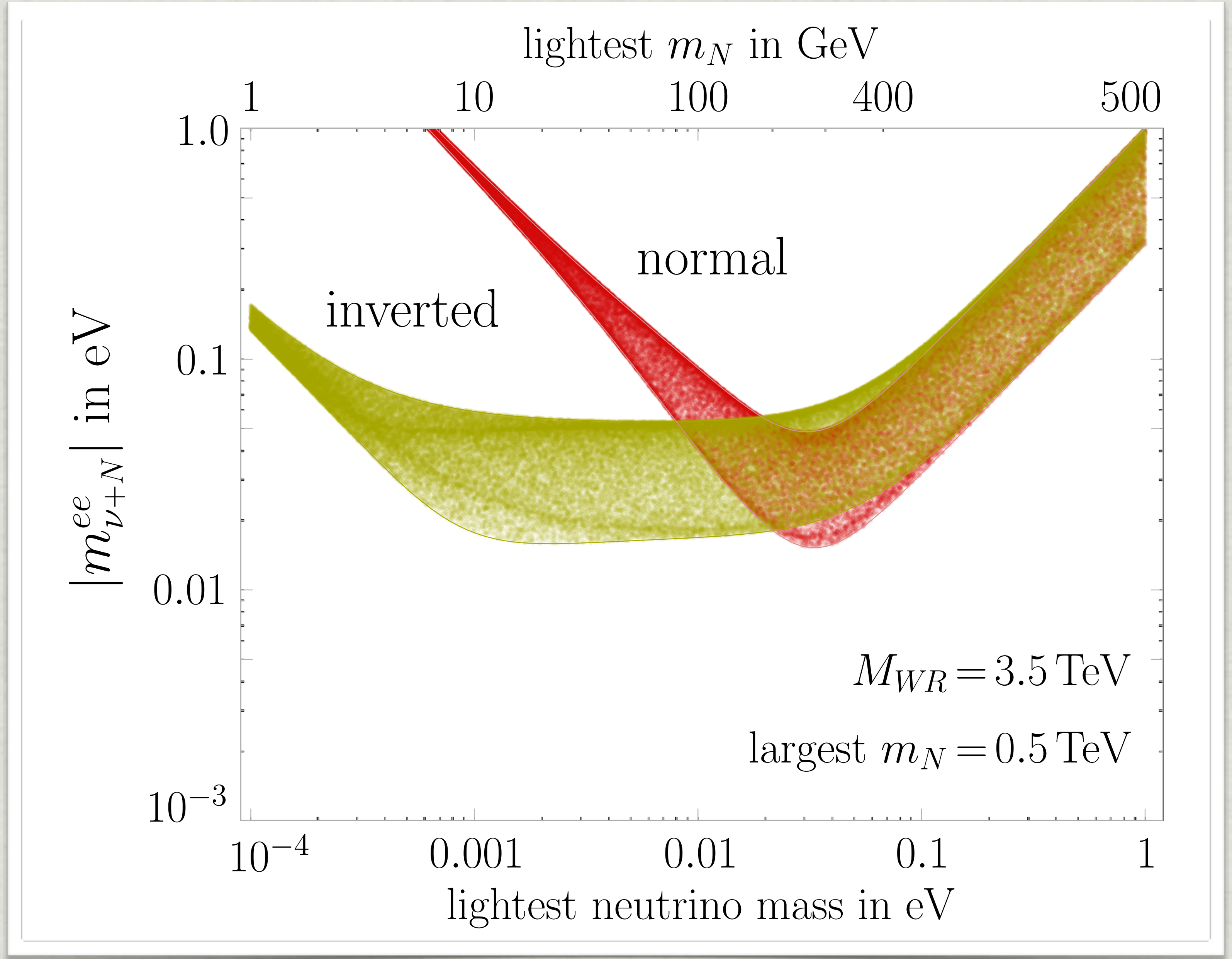
Tello, MN, Nesti, Senjanović, Vissani '11

- A *direct* connection to LHC

$$M_{W_R},\ m_N,\ V_R$$

- Example: type II dominance

$$V_R = V_L^*$$

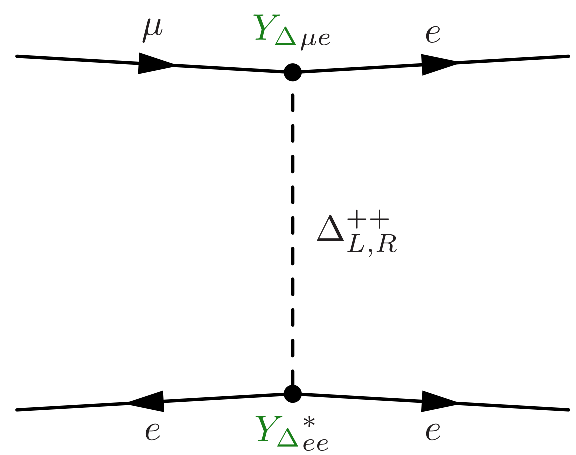
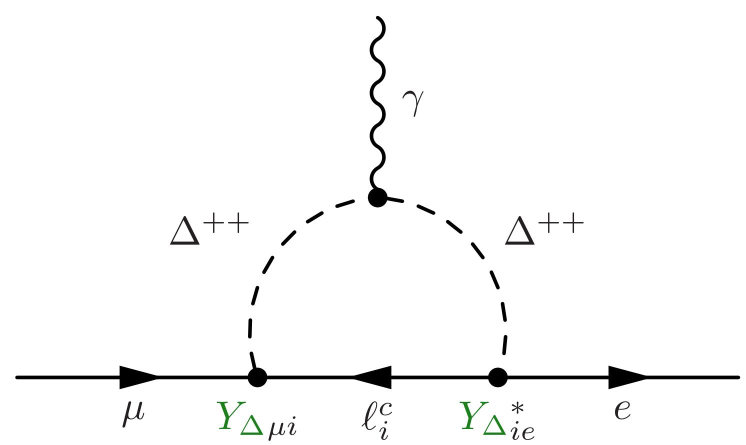
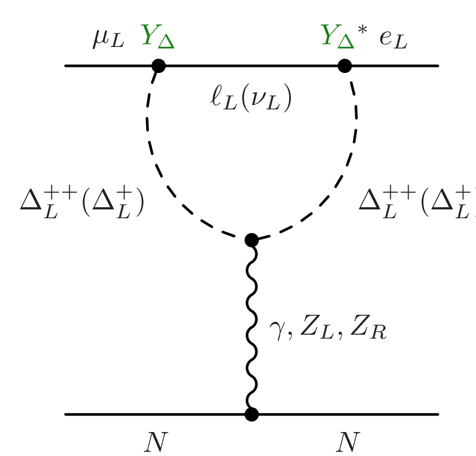


- Other sources (Δ_R^{++}) disfavored by LFV
    - no tension with cosmology
    - small interference, no cancellations

Lepton Flavor Violation

- rates computable in type II

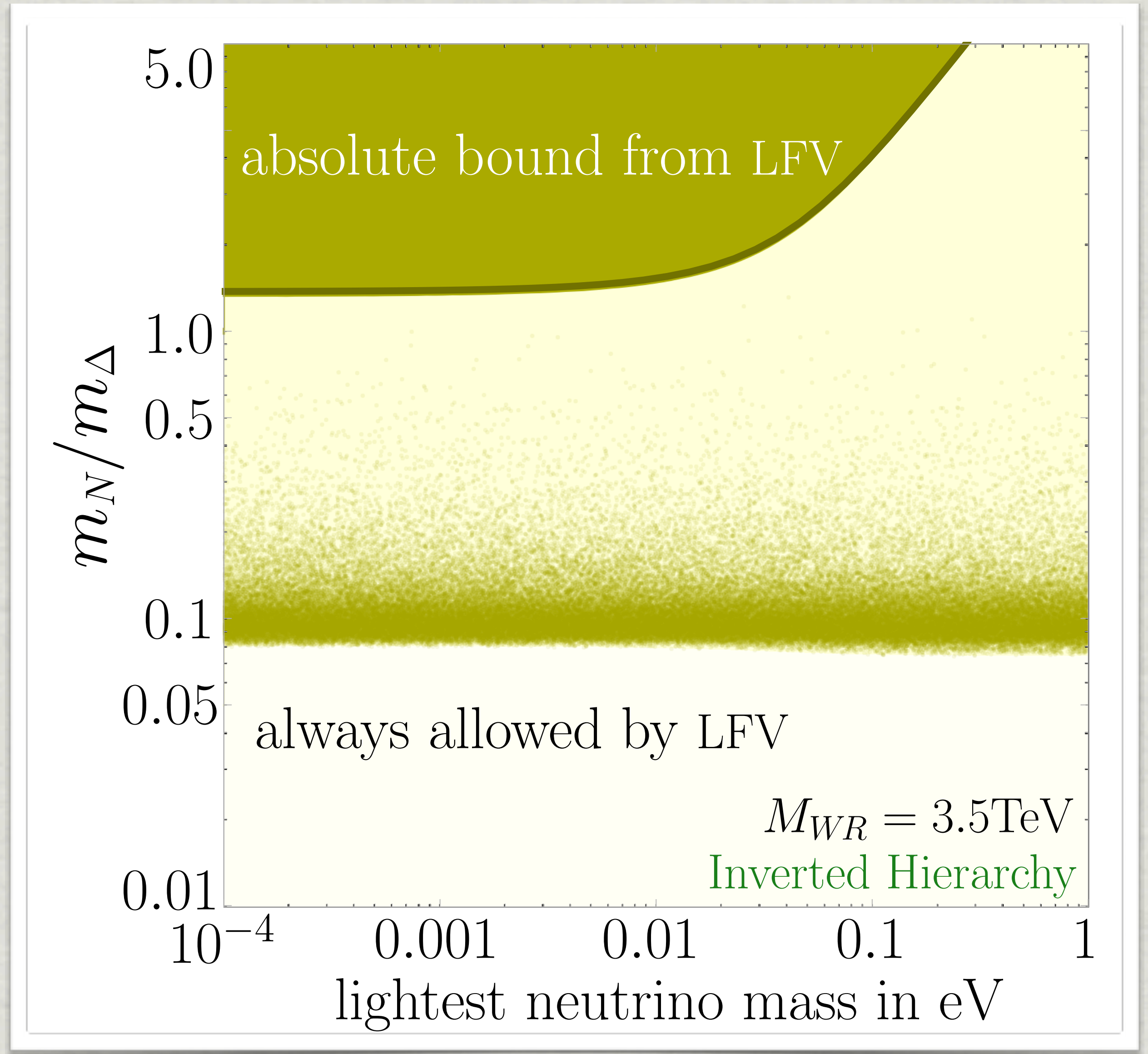
Cirigliano et al '04
Raidal, Santamaria '97

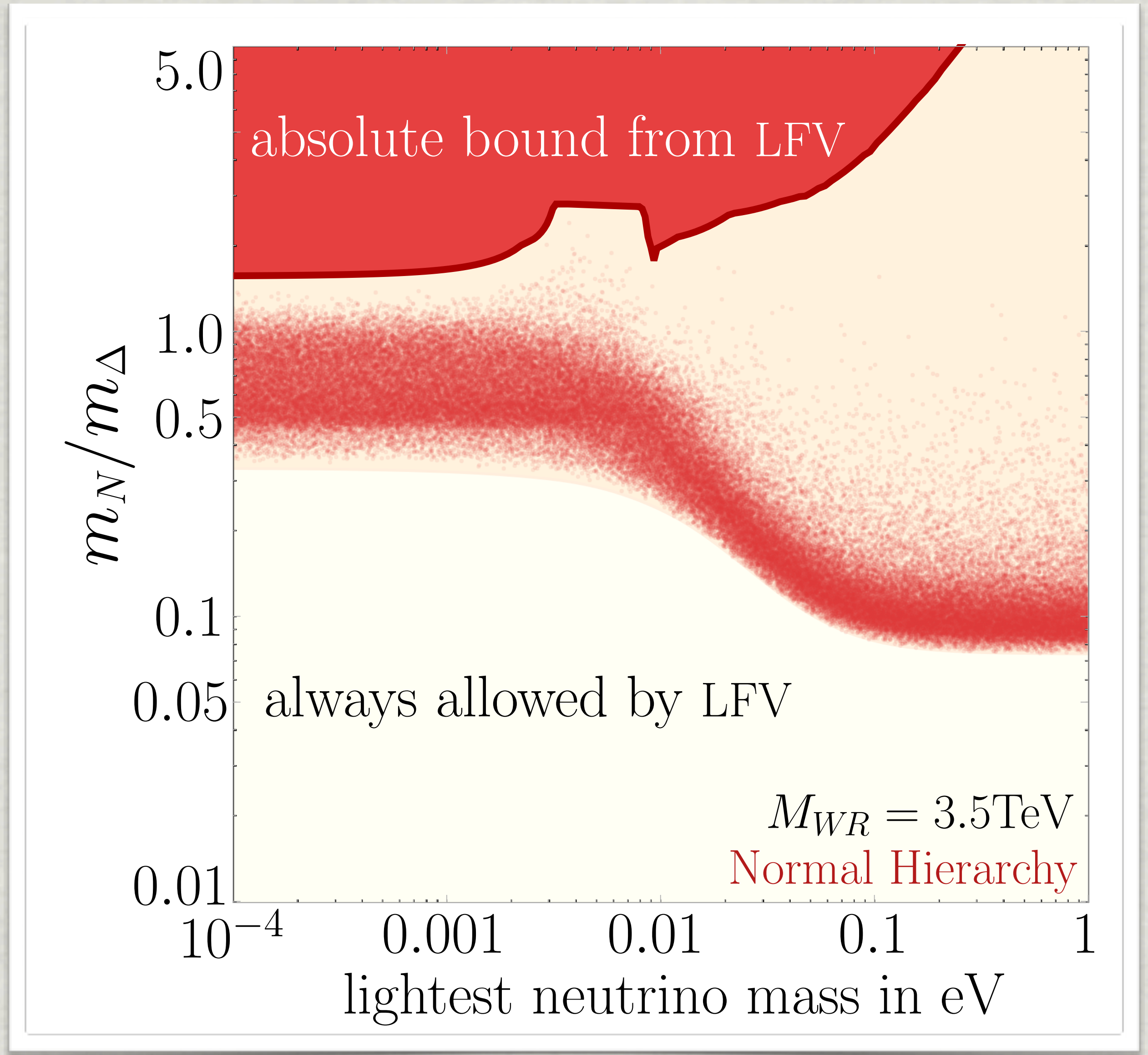
$\ell \to 3\ell$	tree		$V_L\, m_N / m_\Delta\, V_L{}^T$
$\ell \to \ell' \gamma$	loop		$V_L\, m_N / m_\Delta\, V_L{}^\dagger$
$\mu N - eN$	log		$V_L\, m_N / m_\Delta\, V_L{}^\dagger$

- Combined μ and τ channels

Tello, MN, Nesti, Senjanović, Vissani '11

- Flavor fixed by PMNS $V_R = V_L^*$

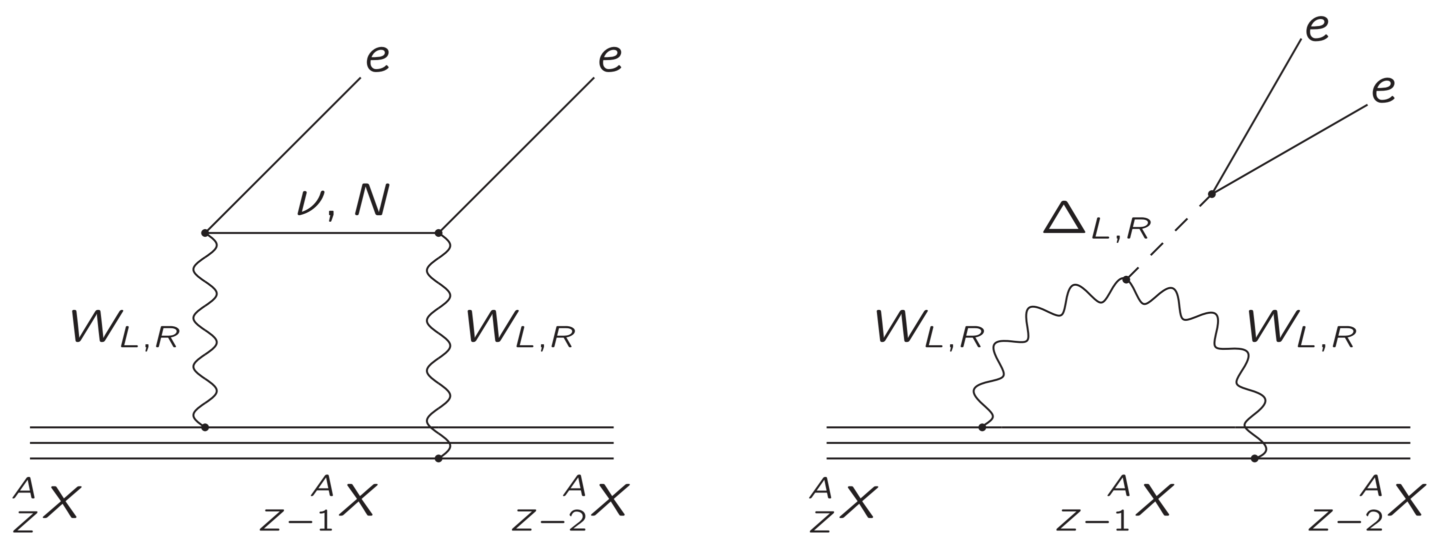




- TeV scale LR $\frac{m_N}{m_\Delta} < 1 \Rightarrow 0\nu2\beta$ due to Δ_R^{++} subdominant

LR contributions to $0\nu 2\beta$

- LR mixing small $\xi_{LR} < M_W / M_{W_R} < 10^{-3}$



$$\mathcal{H}_{\rm NP} = G_F^2 {V_R}_{ej}^2 \left[\frac{1}{m_{N_j}} + \frac{2\, m_{N_j}}{m_{\Delta_R}^2} \right] \frac{M_W^4}{{M_{W_R}}^4} J_{R\mu} J_R^\mu \, \overline{e_R} e_R^c$$

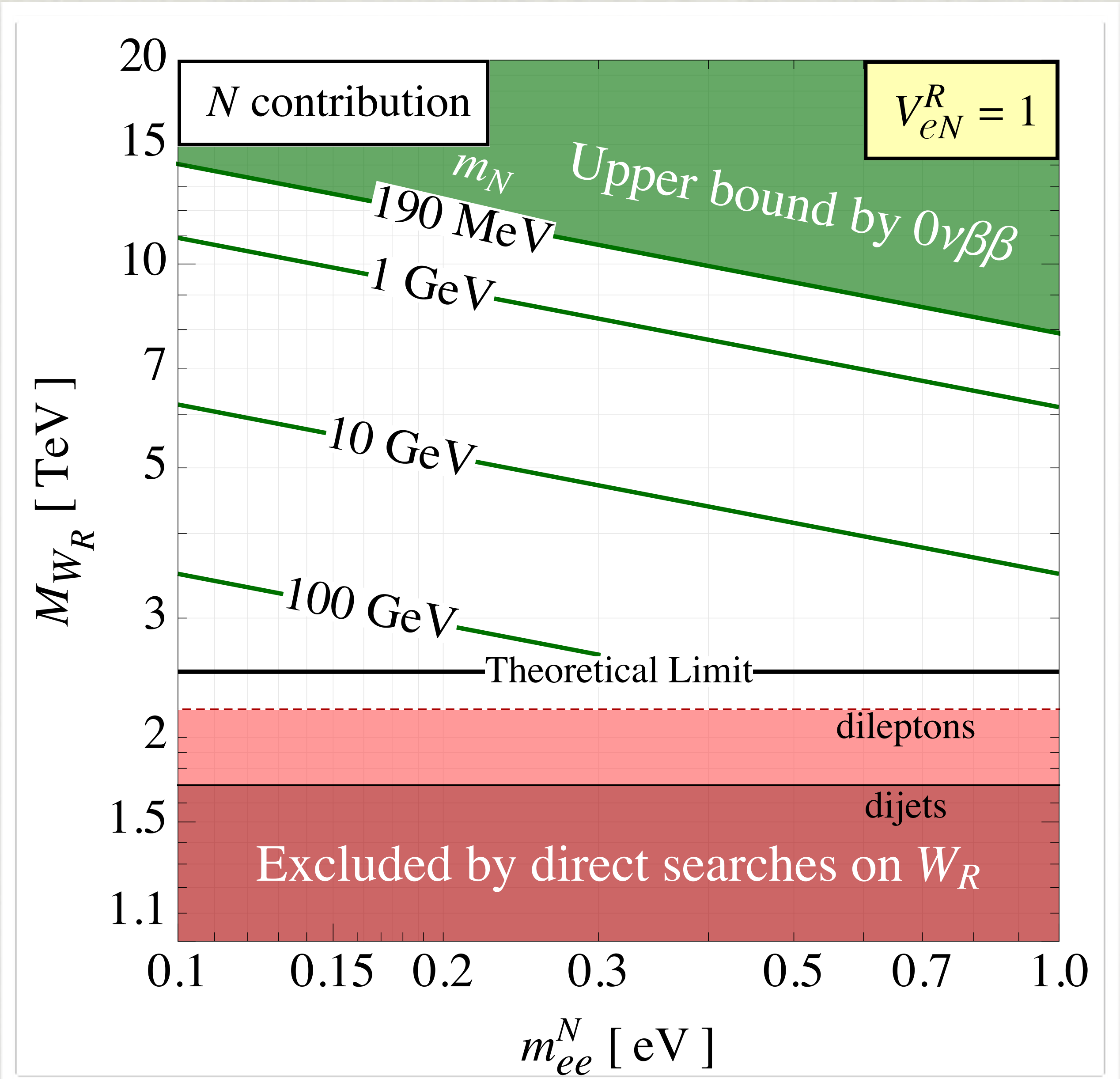
- Type II $V_R = {V_L}^*$
- Δ_L suppressed
- LFV $m_N / m_{\Delta_R} < 1$

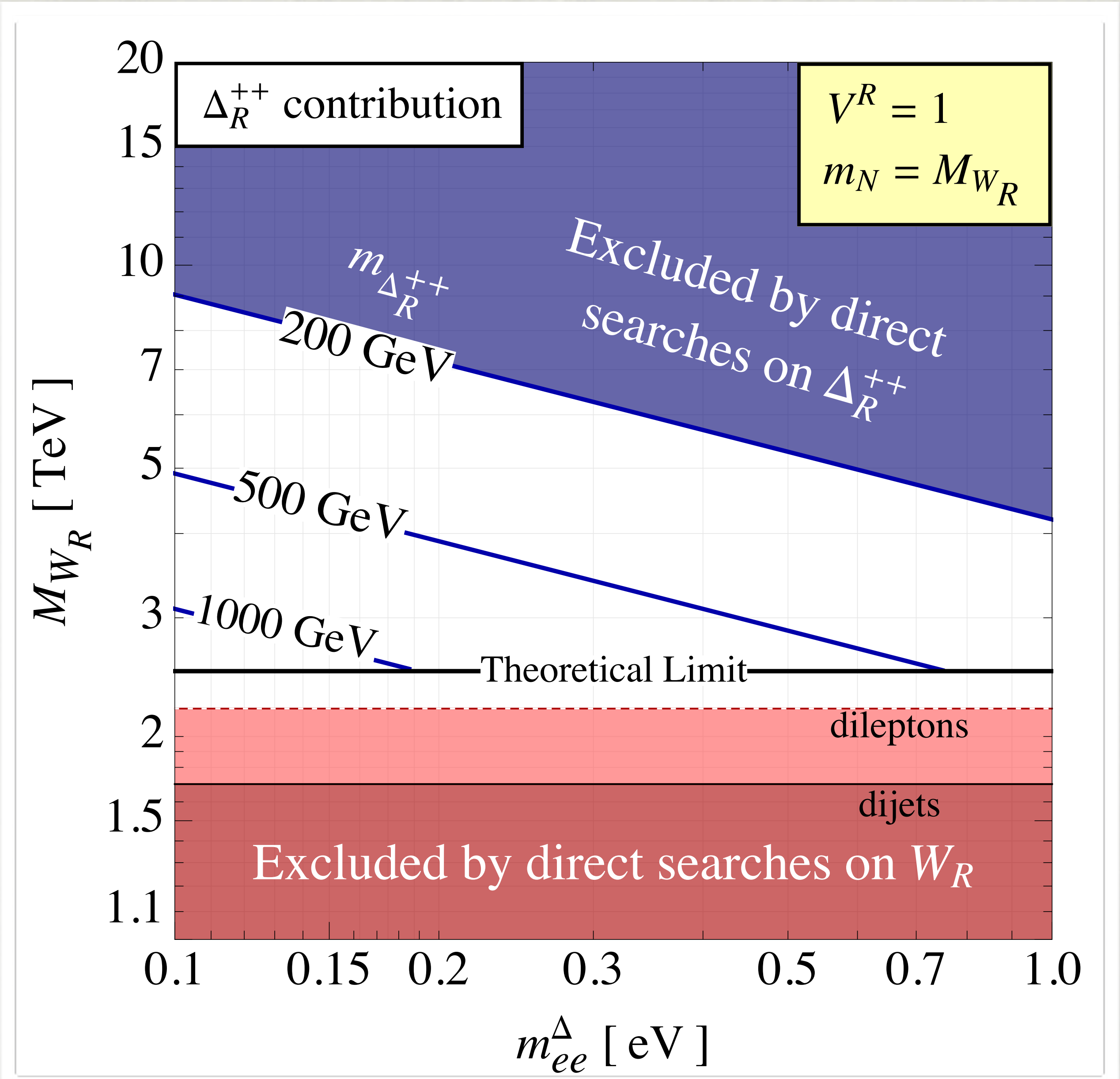
$m_\nu / m_{\Delta_L^{++}} \ll 1$

- Gauge contribution dominant

NP contribution and the LHC

Tello, MN, Nesti, Senjanović ’11

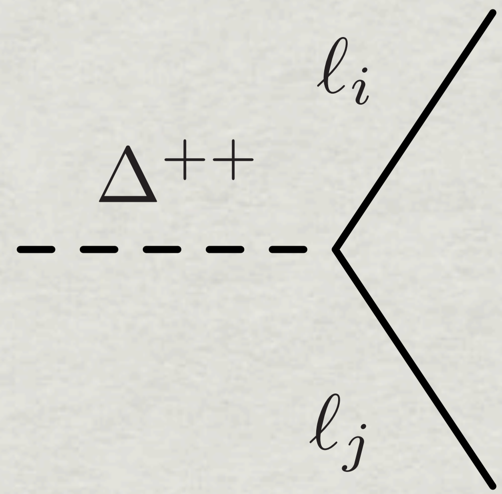




- LR signal of $0\nu2\beta$ testable

- Triplet contribution covered by LHC

Type II



- A direct probe of neutrino mass origin

  $$m_\nu = v_\Delta Y_\Delta$$

  Chun, Lee, Park '03, Garayoa, Schwetz '06
  Kadastik, Raidal, Rebane '07

- Hard to probe LNV at colliders
  - needs both Y and v_Δ — Han, Fileviez-Perez, Huang, Li, Wang '08

- $0\nu2\beta$ due to neutrino mass only

- Pair-production at LHC — Azuelos et al. '05, Akeroyd, Aoki '05

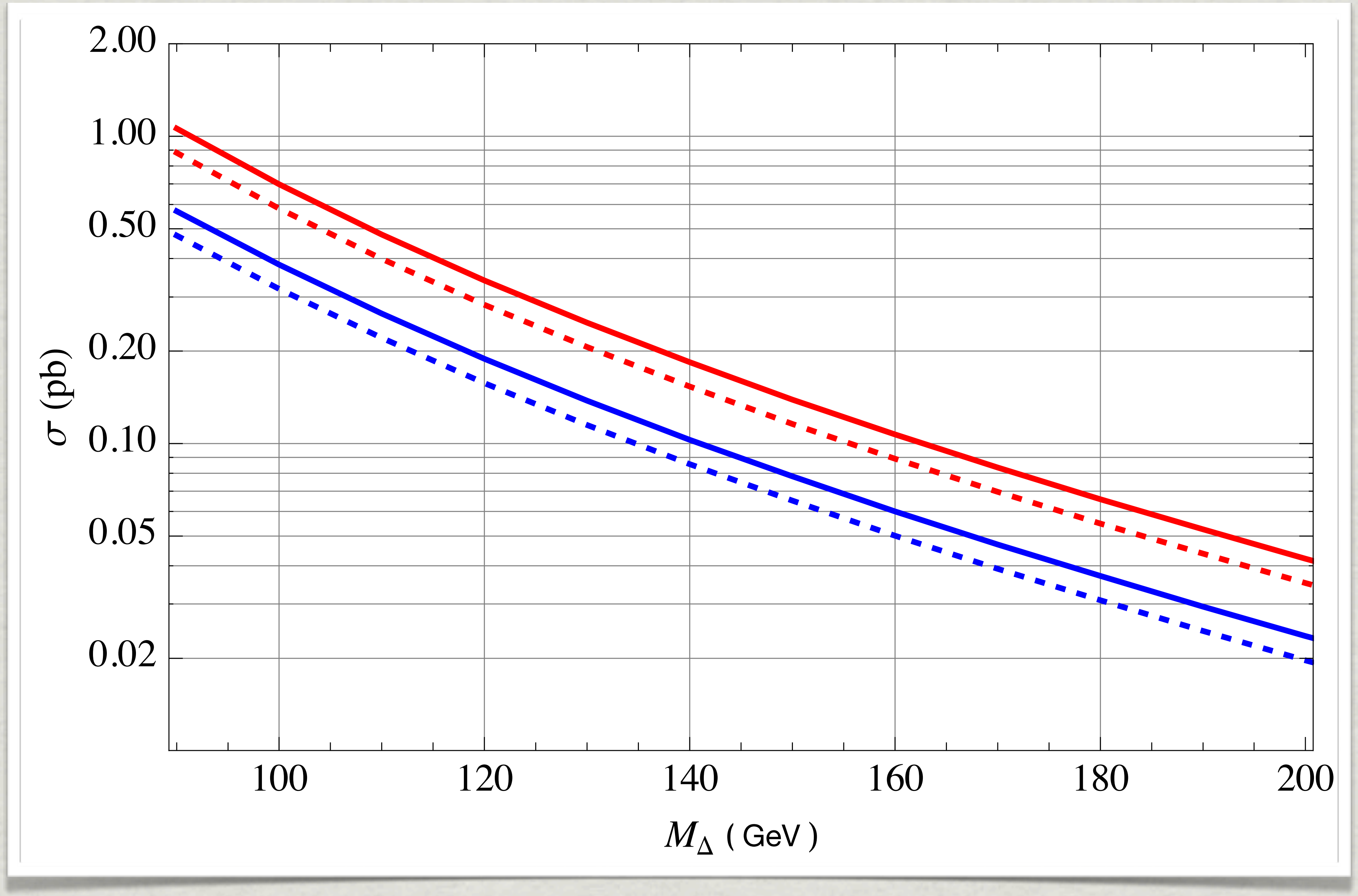
- Searches at colliders — CMS-HIG-12-005, ATLAS-CONF-2011-127

Production

- EW pair-production

$$W^{\pm} \to \Delta^{\pm}\Delta^{0}, \Delta^{\pm\pm}\Delta^{\mp}$$

$$(Z, \gamma^{*}) \to \Delta^{\pm\pm}\Delta^{\mp\mp},\ \Delta^{\pm}\Delta^{\mp},\ \Delta^{0}\Delta^{0}$$



- 7 TeV LHC

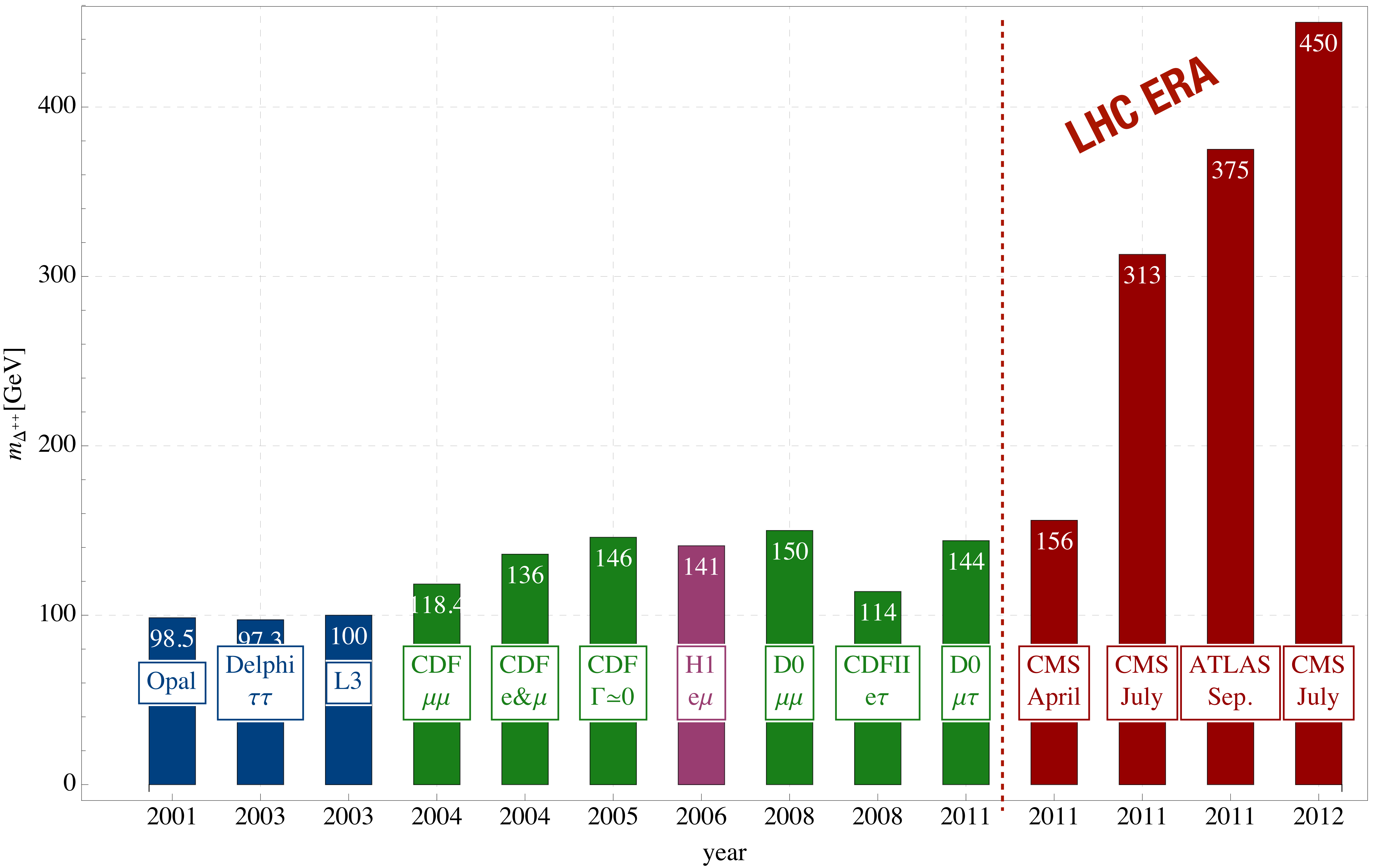
NLO

LO

associated

pair

History of searches

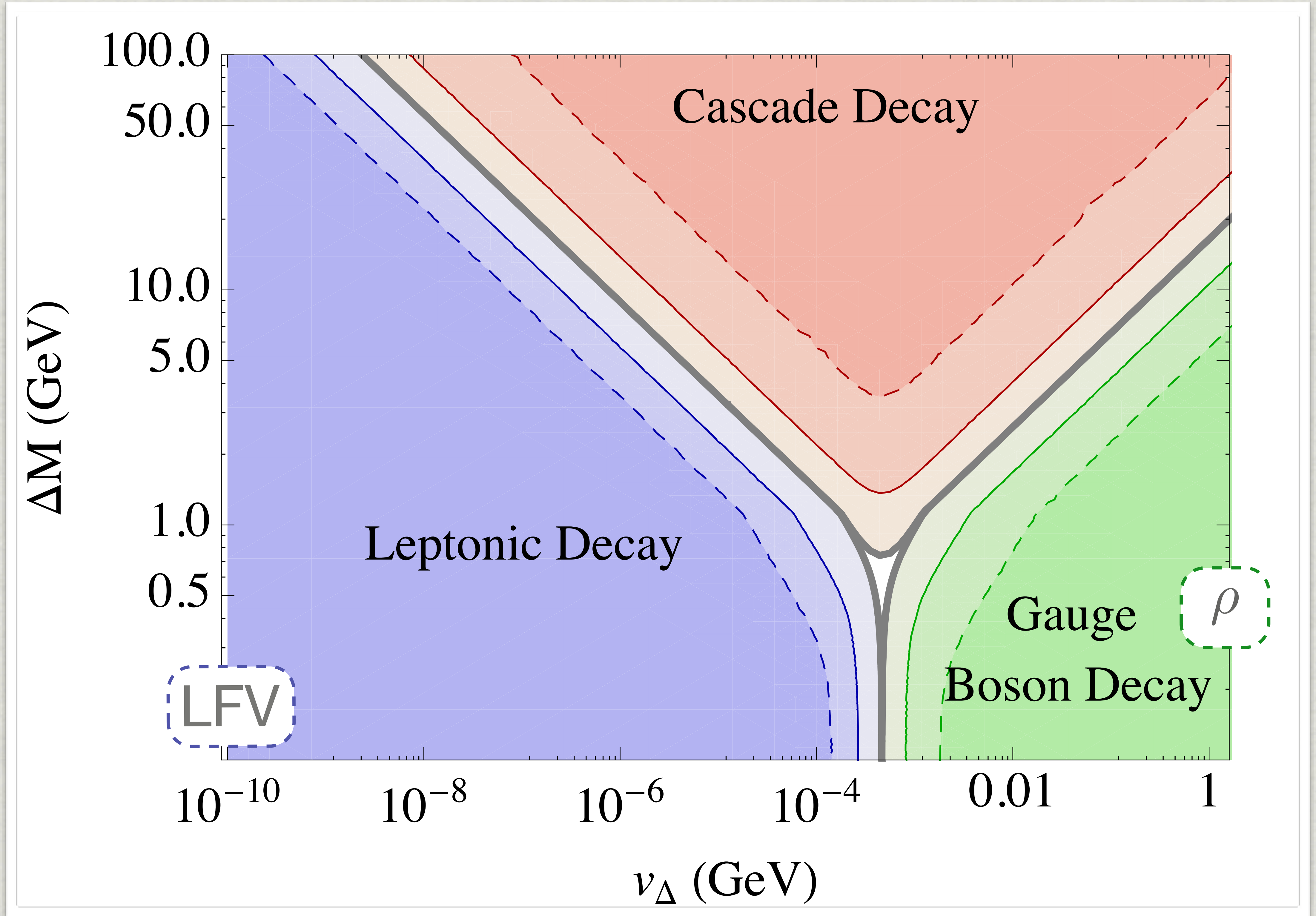


Decays

Han, Fileviez-Perez, Huang, Li, Wang '08
Melfo, MN, Nesti, Senjanović, Zhang '11

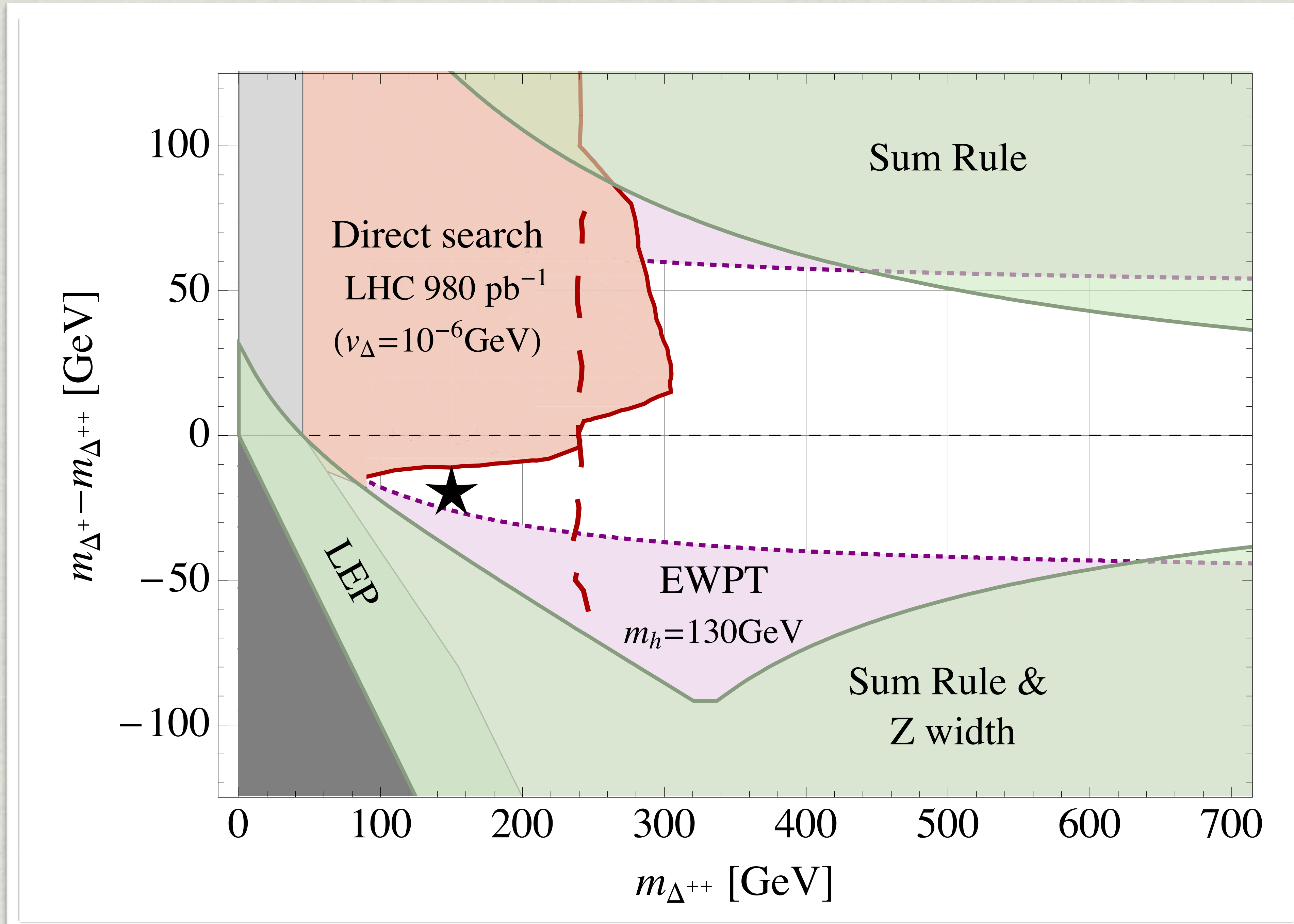
- Size of v_Δ determines Yukawa via $m_\nu = v_\Delta Y_\Delta$
  - Leptons $\Gamma_{\Delta\to\ell\ell} \propto m_\Delta \frac{{V_L}^* m_\nu {V_L}^\dagger}{v_\Delta}$ — small v_Δ
  - Gauge bosons $\Gamma_{\Delta\to VV} \propto \frac{m_\Delta^3 v_\Delta^2}{v^4}$ — $v_\Delta \gtrsim 10^{-4}$
  - Cascades $\Gamma_{\Delta\to\Delta' V} \propto \frac{\Delta m_\Delta^5}{v^4}$ — non-zero Δm
- Mass splits crucial to determine the final state

- $\Delta m^2 = \frac{\beta}{4} v^2, V \in \beta\, \phi^\dagger \Delta \Delta^\dagger \phi$ impact even for small β



Melfo, MN, Nesti, Senjanović, Zhang '11

❋ Caveat for setting of limits two-parametrical bound



$\beta < 0$

$m_{\Delta^0} > m_{\Delta^\pm} > m_{\Delta^{\pm\pm}}$

$\beta > 0$

$m_{\Delta^{\pm\pm}} > m_{\Delta^\pm} > m_{\Delta^0}$

Melfo, MN, Nesti, Senjanović, Zhang '11

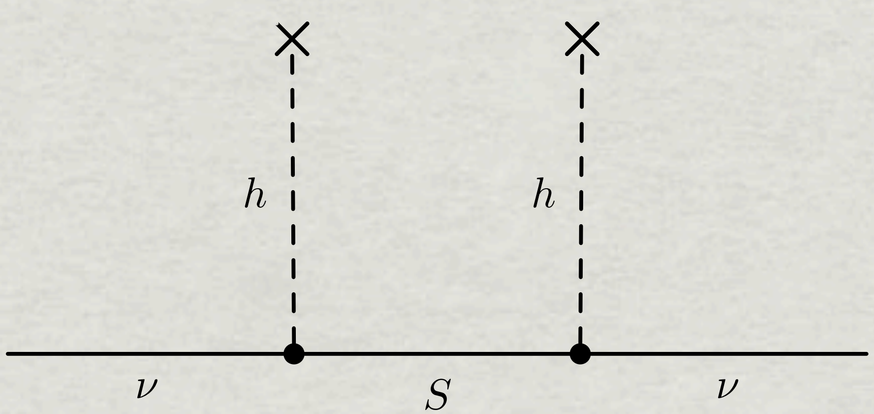
Minimal $SU(5)$

Georgi, Glashow '74

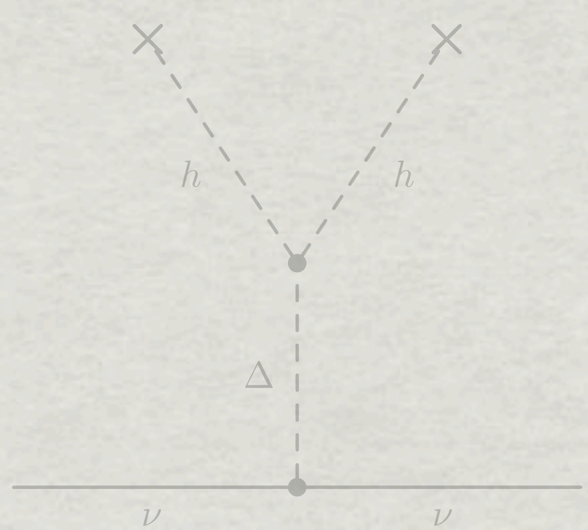
- Original mode beautiful, but wrong
  - Lack of unification, neutrinos massless

- Minimal extensions
  - Higgs sector 15_H — Fileviez-Perez, Doršner '06
  - Fermionic sector 24_F — Bajc, Senjanović '06

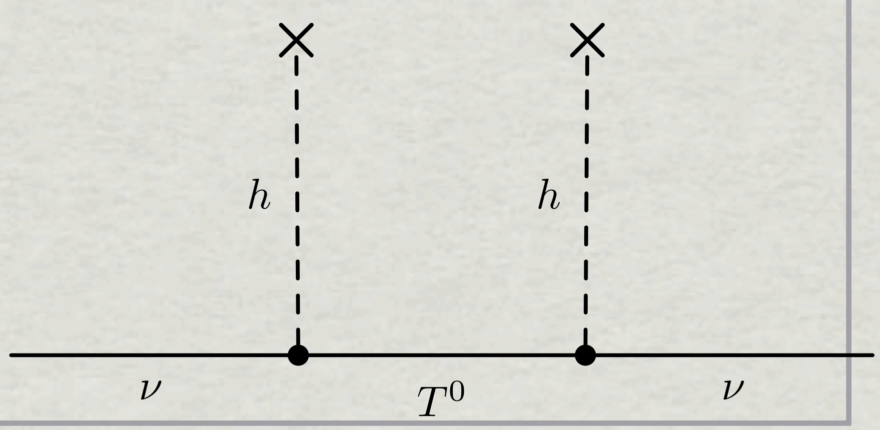
type I



type II



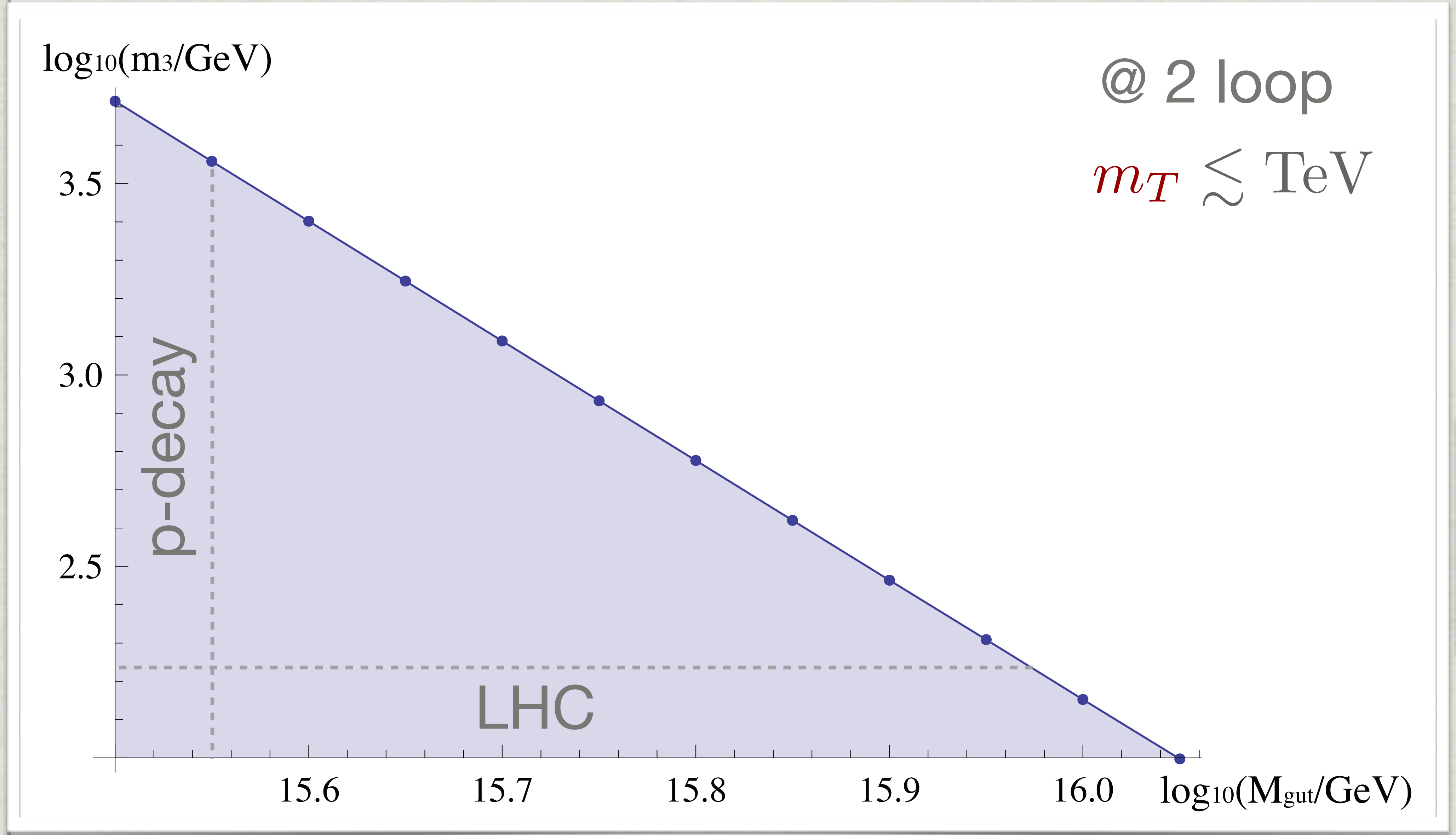
type III



Unification

- Matter states in 24_F and scalars in 24_H

$$24_F = (3,2)_{\pm 5/6} + (8,1)_0 + \underbrace{(1,3)_0}_{T} + \underbrace{(1,1)_0}_{S}$$

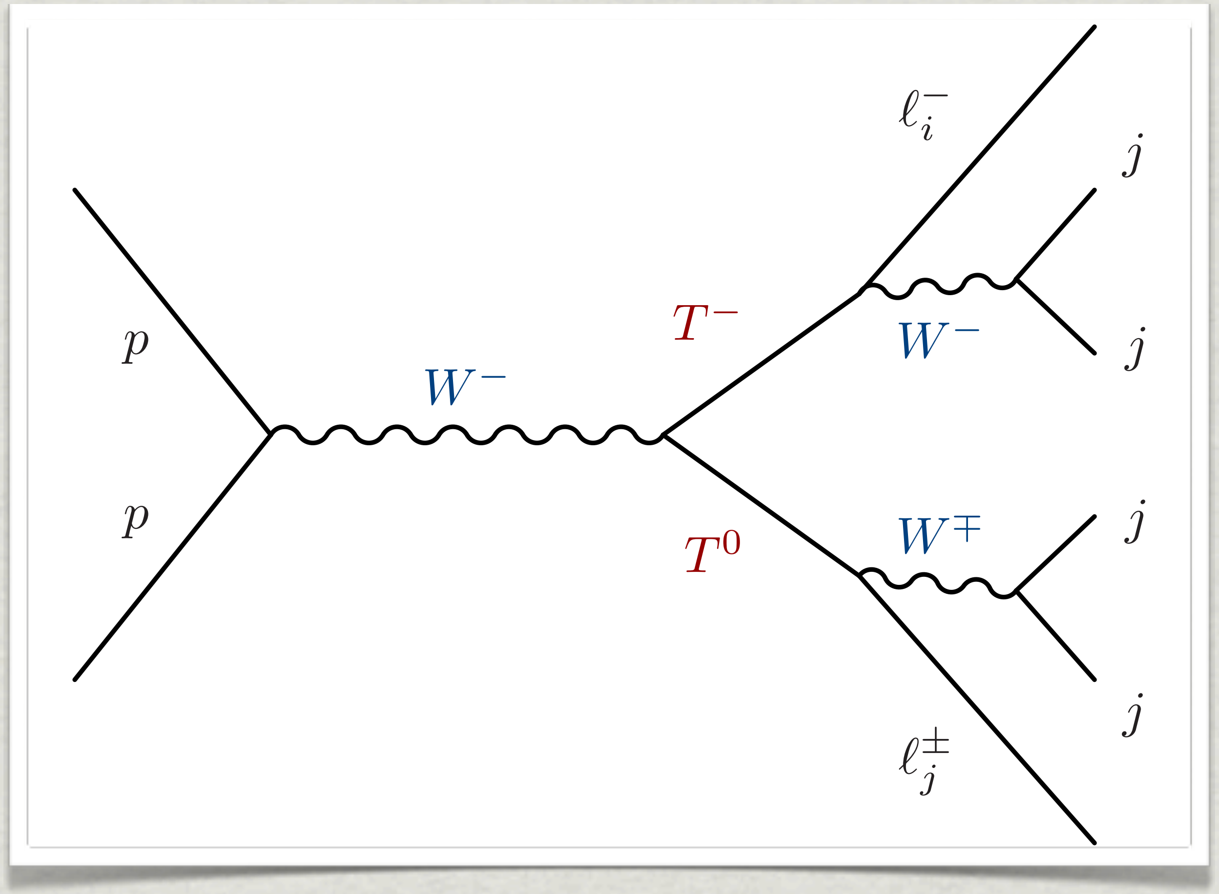


$$m_8 \simeq 10^8 \text{ GeV}$$
$$m_{3,2} \simeq M_{gut}$$

$SU(5)$ remnant at LHC

- EW pair-production

$$W^{\pm} \to T^{\pm}T^{0}$$
$$(Z,\gamma^{*}) \to T^{+}T^{-}$$

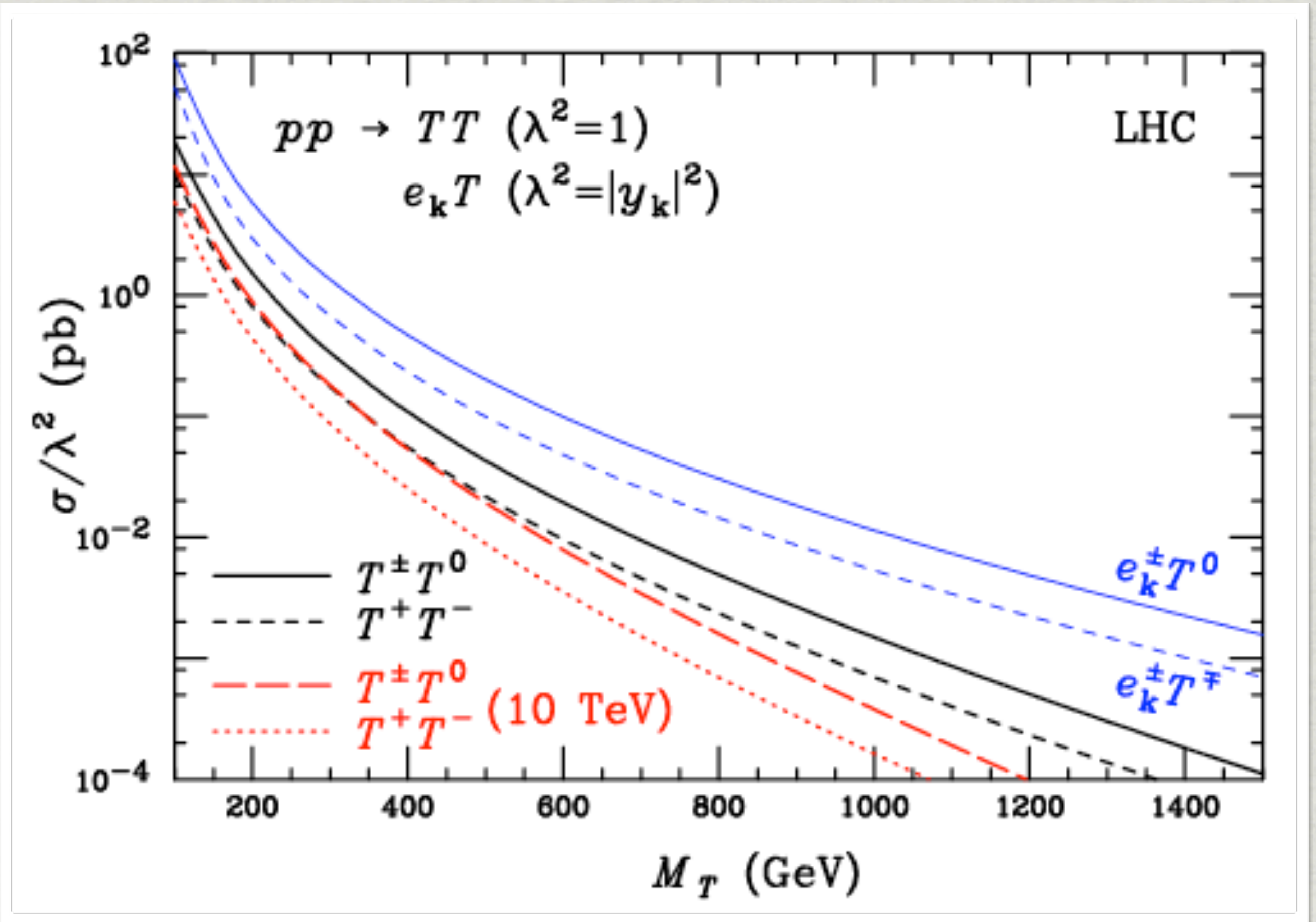


- Majorana nature & LNV

- Mass split radiative & small $\Delta m_T \simeq 170\ \mathrm{MeV}$

- Decays always through y_T in the minimal model

Arhrib, Bajc, Ghosh, Han, Huang, Puljak, Senjanović '09



- Reach of 450 (700) GeV for 10(100) fb^{-1} @ 10 TeV LHC
- Possibly long-lived, measure lifetime

Probing see-saw

- Neutrino mass simple

$$m_\nu^{ij} = \frac{v^2}{2}\left(\frac{{y_T}^i {y_T}^j}{m_T} + \frac{y_S^i y_S^j}{m_S}\right)$$

  - rank 2, one ~massless

$$ {y_T}^i = \frac{\sqrt{2m_T}}{v}\left(V_{i2}\sqrt{m_2^\nu}\cos z \pm V_{i3}\sqrt{m_3^\nu}\sin z\right)$$

NH

- Ambiguous, unknown parameter $z \in \mathbb{C}$

Ibarra, Ross '03

- Possible to probe z and φ

$$\tau \propto (|y_T^e|^2 + |y_T^\mu|^2 + |y_T^\tau|^2)^{-1} \approx \mathrm{mm}$$

$$\mathrm{Br}_e \propto |y_T^e|^2\,\tau, \quad \mathrm{Br}_\mu \propto |y_T^\mu|^2\,\tau$$

- $\mathrm{Im}\, z$ bounded by LFV / washout of *L*

Kamenik, MN '09
Aristizabal, Kamenik, MN '09

Conclusions

- Neutrino mass origin explorable at LHC
  - Pheno motivation, e.g. $0\nu 2\beta$ & cosmology
    - GUT predicted remnant $SU(5)$
- Majorana mass and LNV can be seen directly
  - Left-Right theory
    - Type II scenario
- Contemporary low energy experiments
  - LNV $0\nu 2\beta$
    - LFV $\mu - e,\ \ell \to \ell\gamma,\ \ell \to 3\ell$

Thank you.

Scales in LR

particle	final state	limit	collaboration
W_R	jj	1.5 TeV	CMS
W_R	$e/\mu + N$	2.5 TeV	CMS
W_R	$\ell\ell jj$	$\lesssim 2.5$ TeV	ATLAS, CMS
Z_{LR}	$e^+e^-/\mu^+\mu^-$	~ 2 TeV	ATLAS
Z_{LR}	e^+e^-	~ 3 TeV	LEP
Δ_L^{++}	$\ell_i^+\ell_j^+$	$\sim 100 - 460$ GeV	CMS
Δ_L^+	$\not{E}_T + j$	$\sim 70 - 90$ GeV	LEP
Δ_L^0	/	45 GeV	LEP
Δ_R^{++}	$\ell_i^+\ell_j^+$	$113 - 251$ GeV	ATLAS, CDF

Warm DM in LR

- DM might be a particle. What about N in LRSM?
  - Standard picture: thermal production

$$G'_F = G_F \frac{M_W^2}{{M_{W_R}}^2} \qquad T_f \simeq 400\ \text{MeV} \left(\frac{M_{W_R}}{5\ \text{TeV}}\right)^{4/3}$$

  - *Problem*: overabundance

$$\Omega_{N_1} = \frac{Y_{N_1} m_{N_1} s}{\rho_c} \simeq 3.3 \left(\frac{m_{N_1}}{\text{keV}}\right) \left(\frac{70}{g_*(T_{f1})}\right) \gg .229 \pm .04$$

  - *Solution*: dilution via long-lived $N_{2,3}$

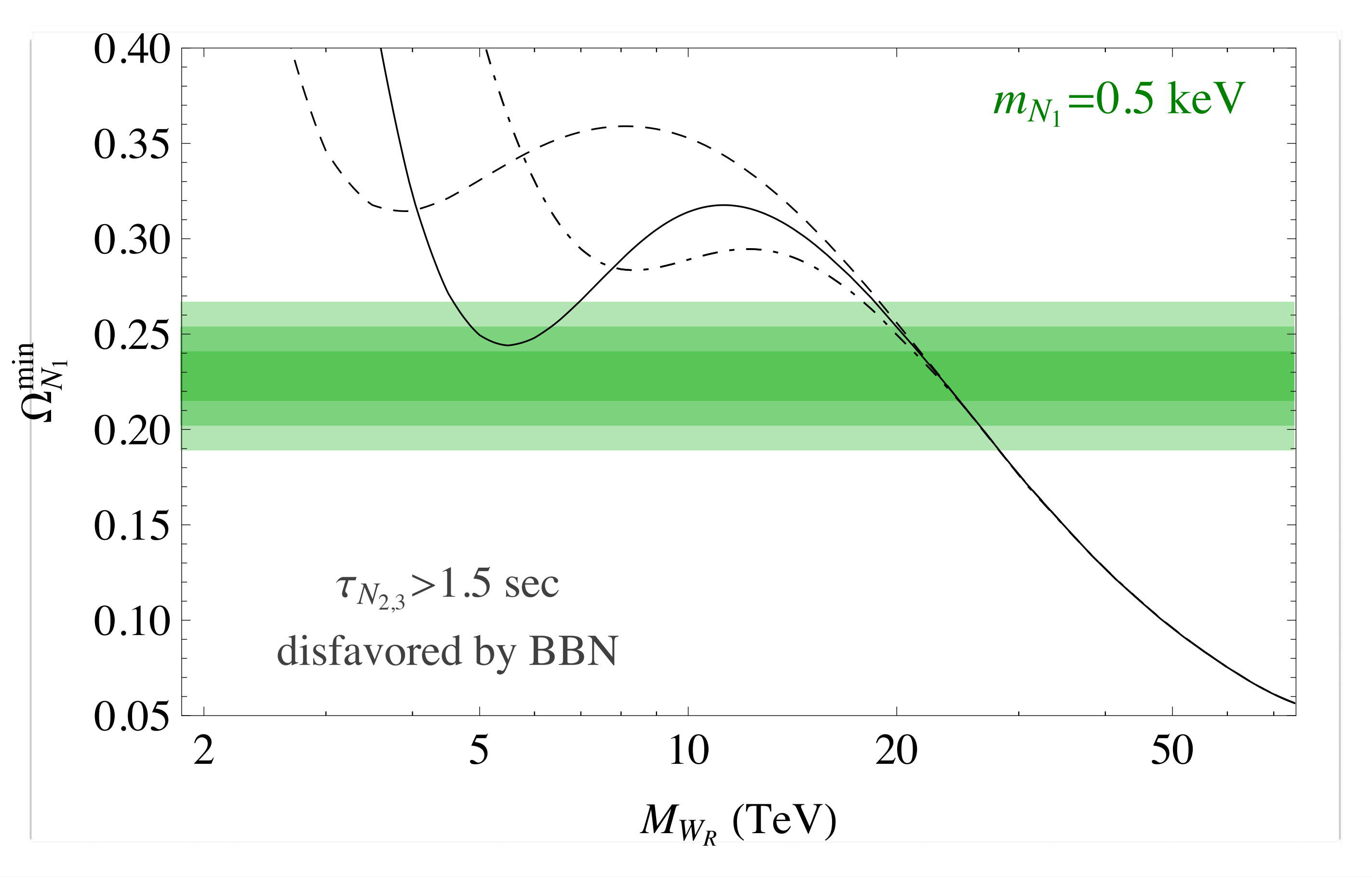
- *Result*: spectrum fixed, window for M_{W_R}

- Spectrum
  - wdm
  - diluters

$$m_{N_1} \simeq \text{keV}$$
$$m_{N_2} \simeq m_\pi + m_\mu$$
$$m_{N_3} \simeq m_\pi + m_e$$

$$V^R \approx \begin{pmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ 1 & 0 & 0 \end{pmatrix}$$

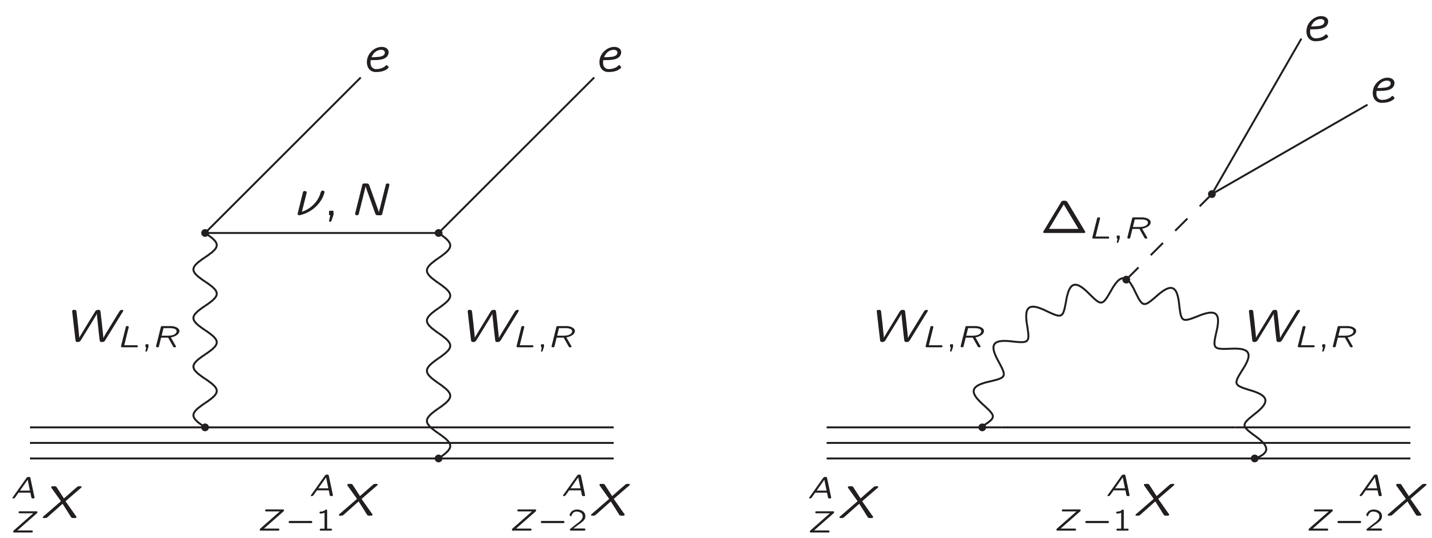
- Window



MN, Senjanović, Zhang '12

LR contributions to $0\nu 2\beta$

- LR mixing small $\xi_{LR} < M_W / M_{W_R} < 10^{-3}$



$$\mathcal{H}_{\rm NP} = G_F^2 {V_R}_{ej}^2 \left[\frac{1}{m_{N_j}} + \frac{2\, m_{N_j}}{m_{\Delta_R}^2} \right] \frac{M_W^4}{{M_{W_R}}^4} J_{R\mu} J_R^\mu \, \overline{e_R} e_R^c$$

- Type II $V_R = {V_L}^*$
- Δ_L suppressed
- LFV $m_N / m_{\Delta_R} < 1$

$m_\nu / m_{\Delta_L^{++}} \ll 1$

- Gauge contribution dominant