The Abdus Salam International Centre for Theoretical Physics

JSI

Neutrino Mass Origin and the LHC

Miha Nemevšek

GDR Neutrino Meeting
Caen, October 2012

LHC discovered a fundamental boson.

We are seeing the origin of particle masses.

What about neutrino?

Fermion Mass Origin

Charged fermions mass described by

Dirac '28

$m_f \overline{f}_L f_R$ Dirac term

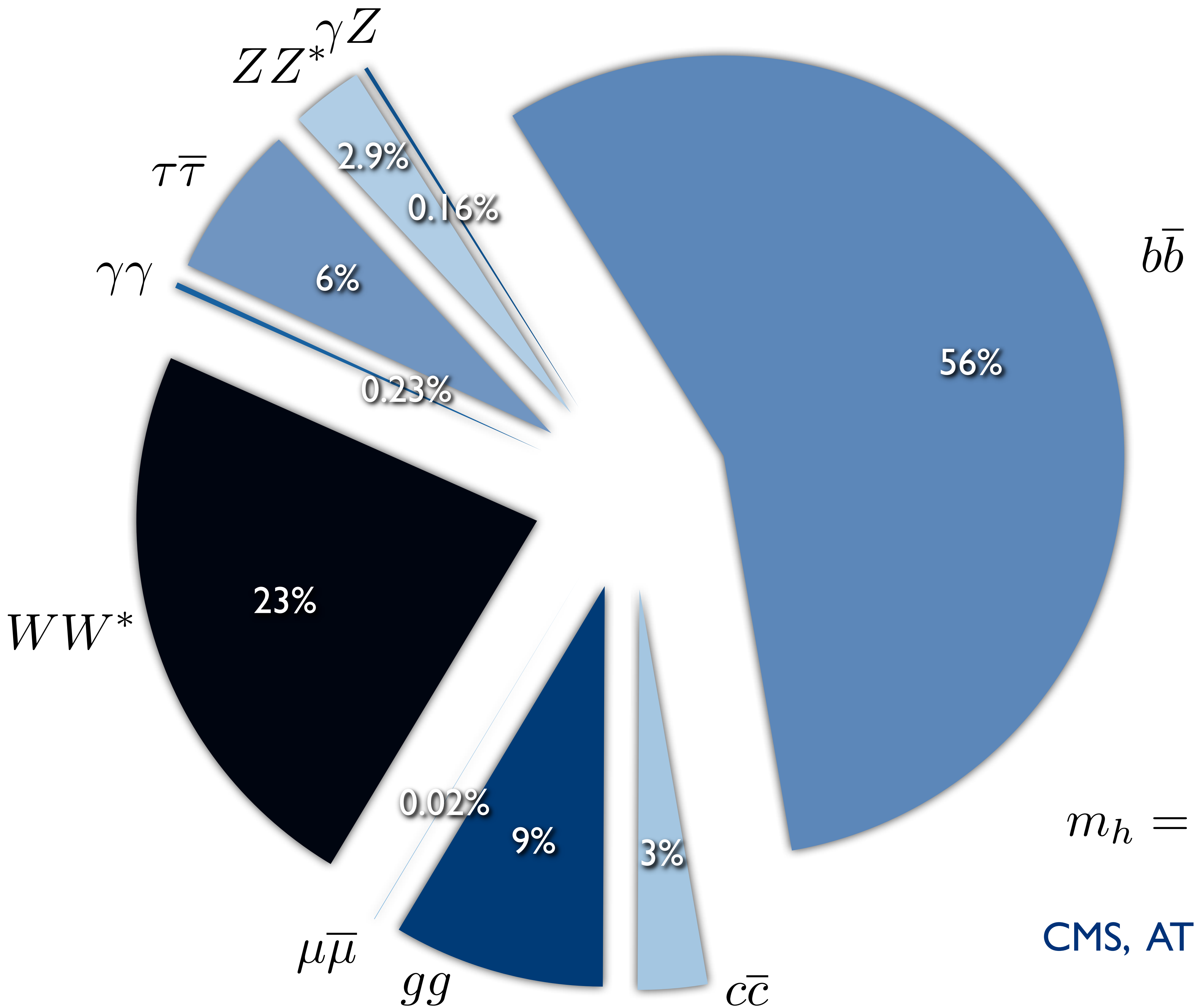
EBH mechanism of SSB within GWS model

$y_D \, \overline{f}_L \phi f_R$ $m_F = y_D v$ mass dynamical quantity

prediction

$\Gamma(\phi \to f\overline{f}) \propto \frac{m_f}{v}$ test at LHC

SM Higgs boson

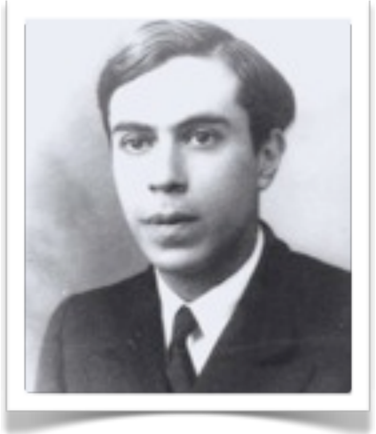


$m_h = 126\ \mathrm{GeV}$

CMS, ATLAS July '12

Neutrino Mass Origin

Neutral fermions — Majorana '32



$m_M f^T \mathcal{C} f$ — Majorana term

Effective theory, like Fermi operator for the SM

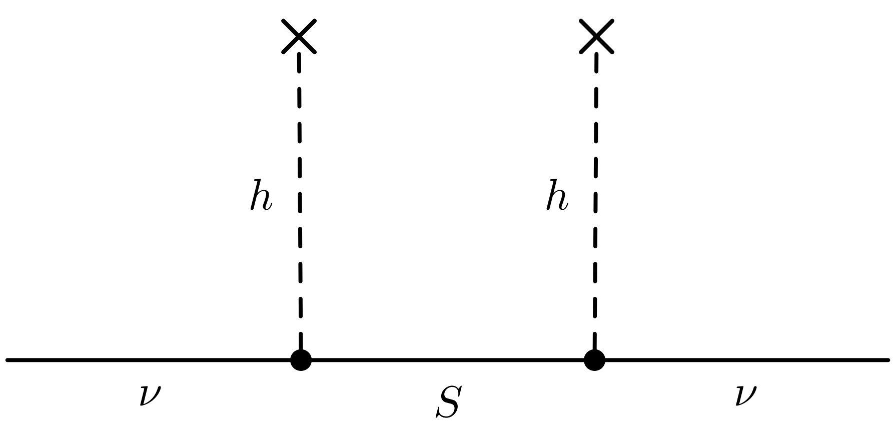
$$\mathcal{O}_W = y \frac{\ell\phi\,\ell\phi}{\Lambda}$$ Weinberg operator — Weinberg '79

$\Lambda \gg v$ hard to probe, GUT — $\Lambda \simeq \text{TeV}$ LHC?

See-saw

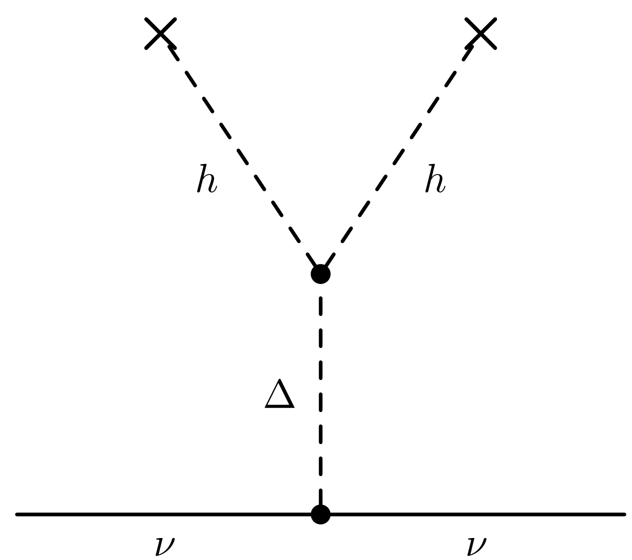
Simple tree-level UV completions of $\mathcal{O}_W$ ~ toy scenarios

type I



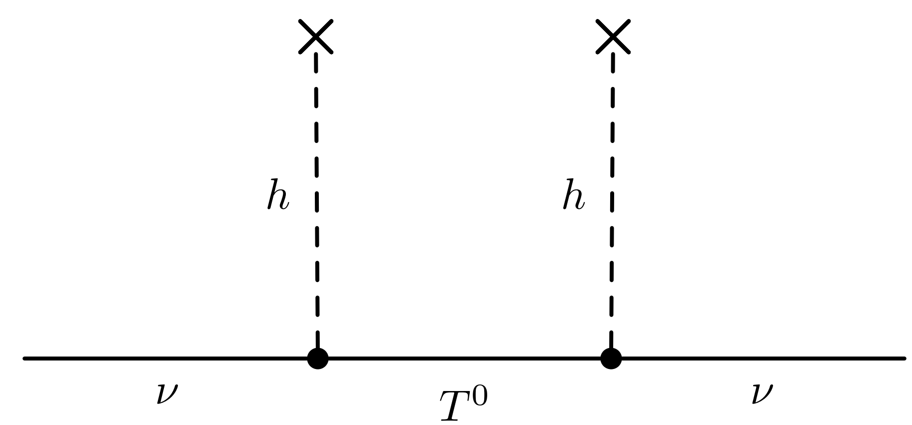
Minkowski '77
Mohapatra, Senjanović '80
Yanagida '79, Glashow '79
Gell-Mann, Ramond, Slansky '79

type II



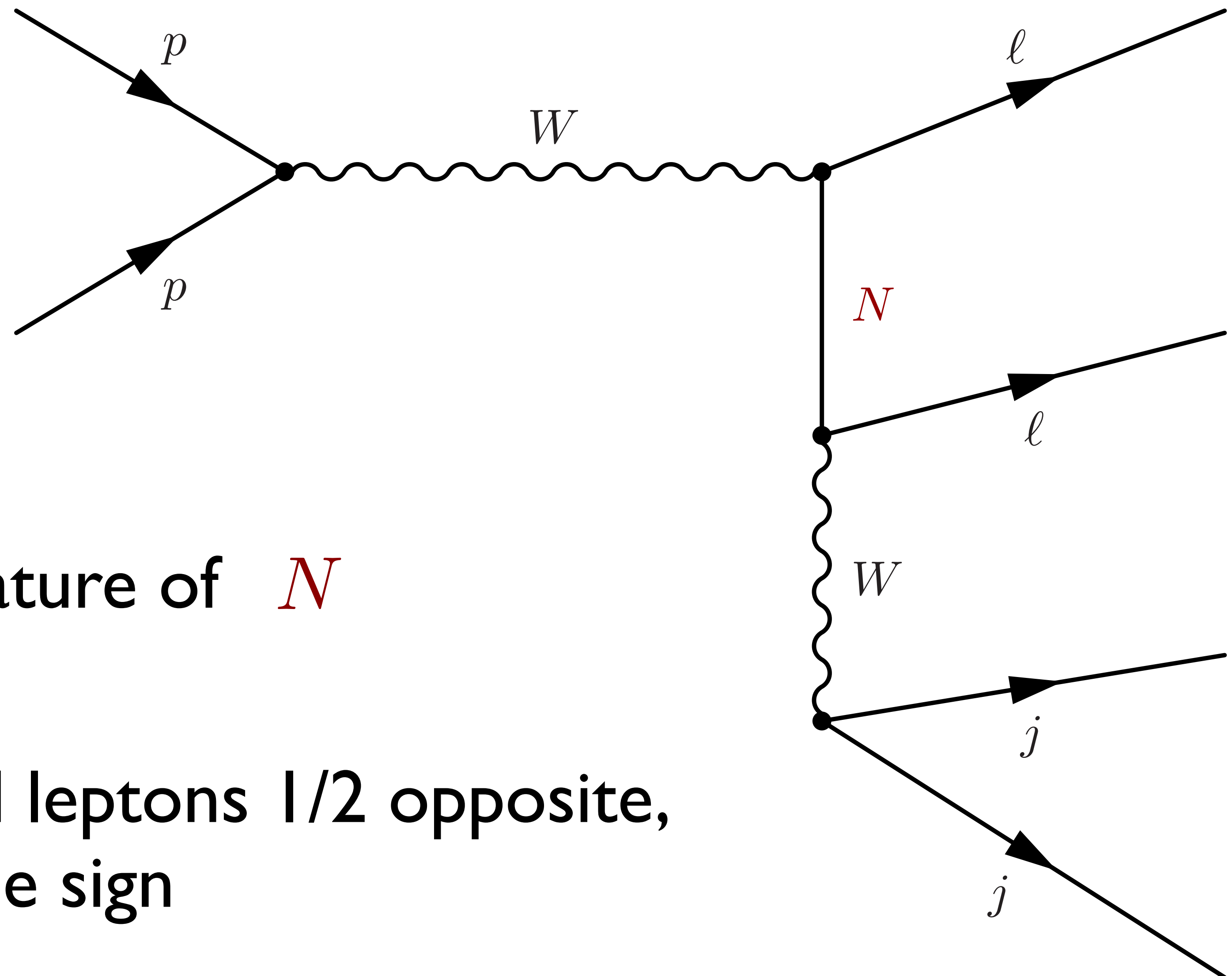
Magg, Wetterich '80
Lazarides, Shafi, Wetterich '81
Mohapatra, Senjanović '81

type III



Foot, Lew, He, Joshi '89

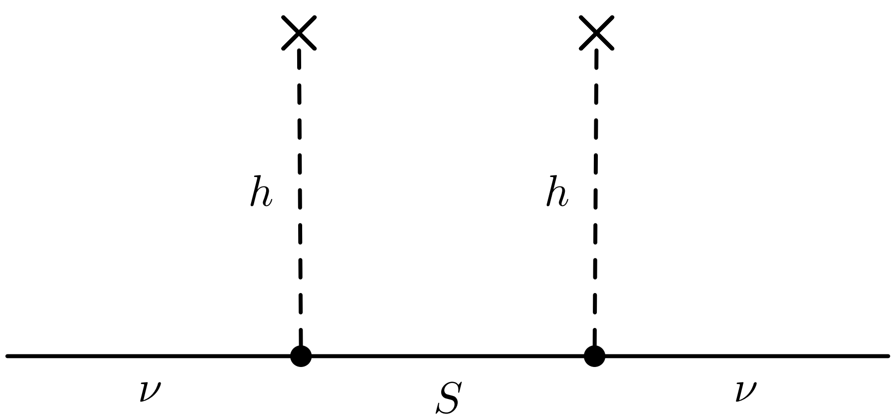
Heavy Neutrino Search



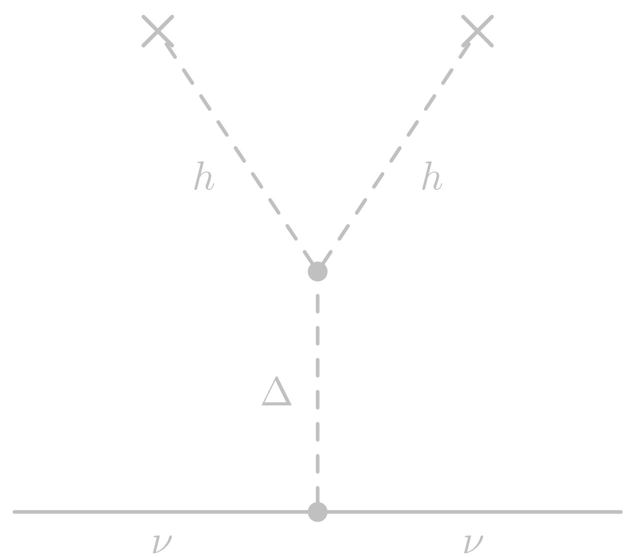
- Majorana nature of N
  - charged leptons 1/2 opposite, 1/2 same sign
- Lepton number violation at colliders
- Proposed in context of LR, generic signal

Keung, Senjanović '83

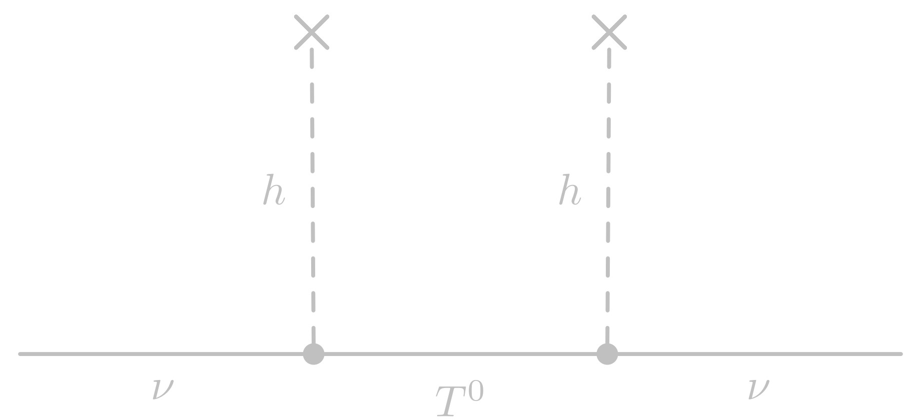
type I



type II



type III



type I Singlet Majorana fermion S

Only interaction with the SM via Yukawa

$$M_\nu = -v^2 \, {y_S}^T {m_S}^{-1} y_S$$

Ambiguous relation of Higgs coupling to neutrino mass

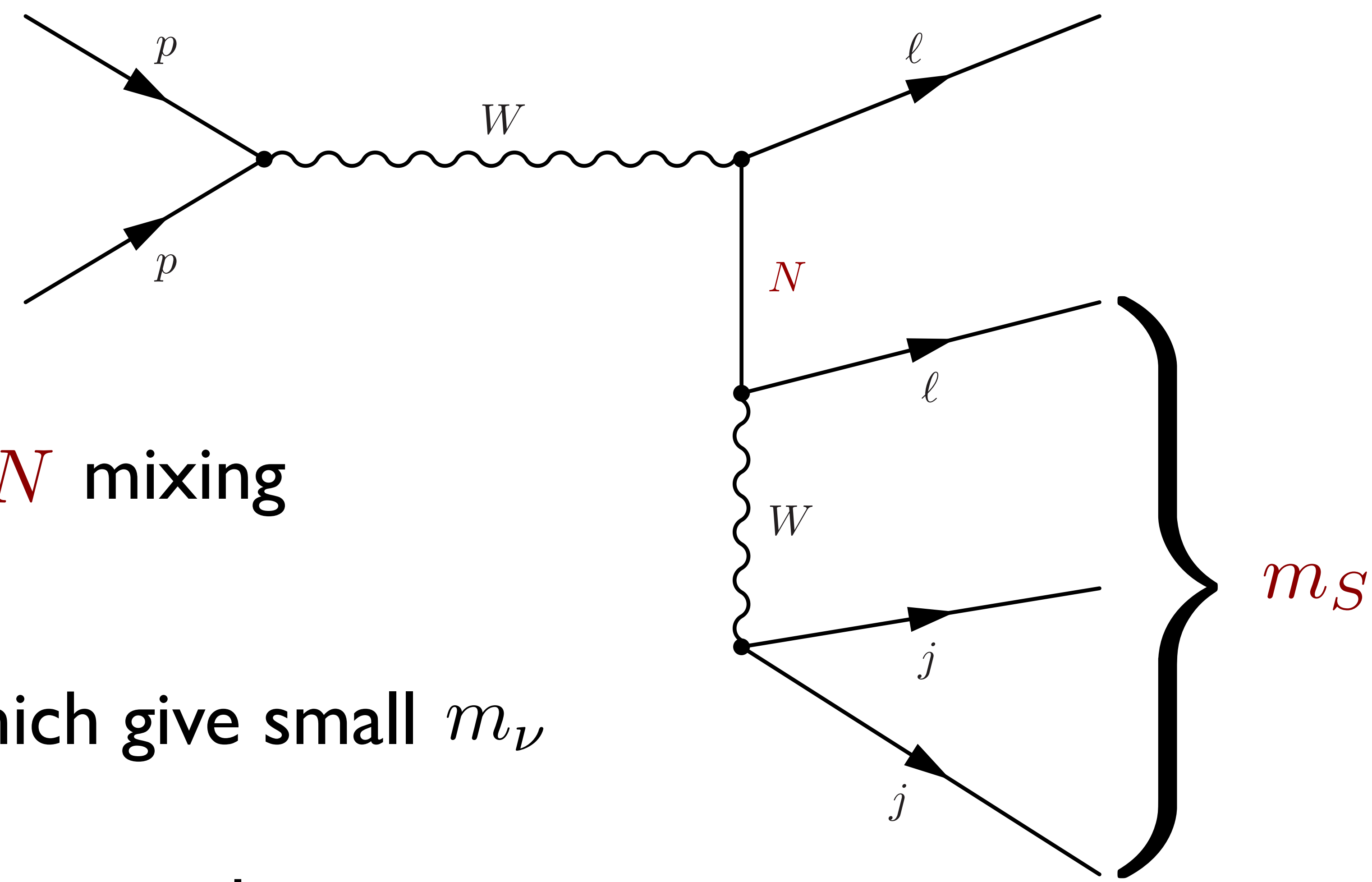
$$y_S = \frac{i}{v} \sqrt{m_S} \, O \, \sqrt{m_\nu} \, {V_L}^\dagger$$

Casas, Ibarra '01

Unknown up to an orthogonal matrix

- typically small $\quad y_S \sim \sqrt{\frac{m_S m_\nu}{v^2}} \simeq 10^{-6} \sqrt{\frac{m_S}{100 \text{ GeV}}}$
- could be large if O is large

type I @ LHC



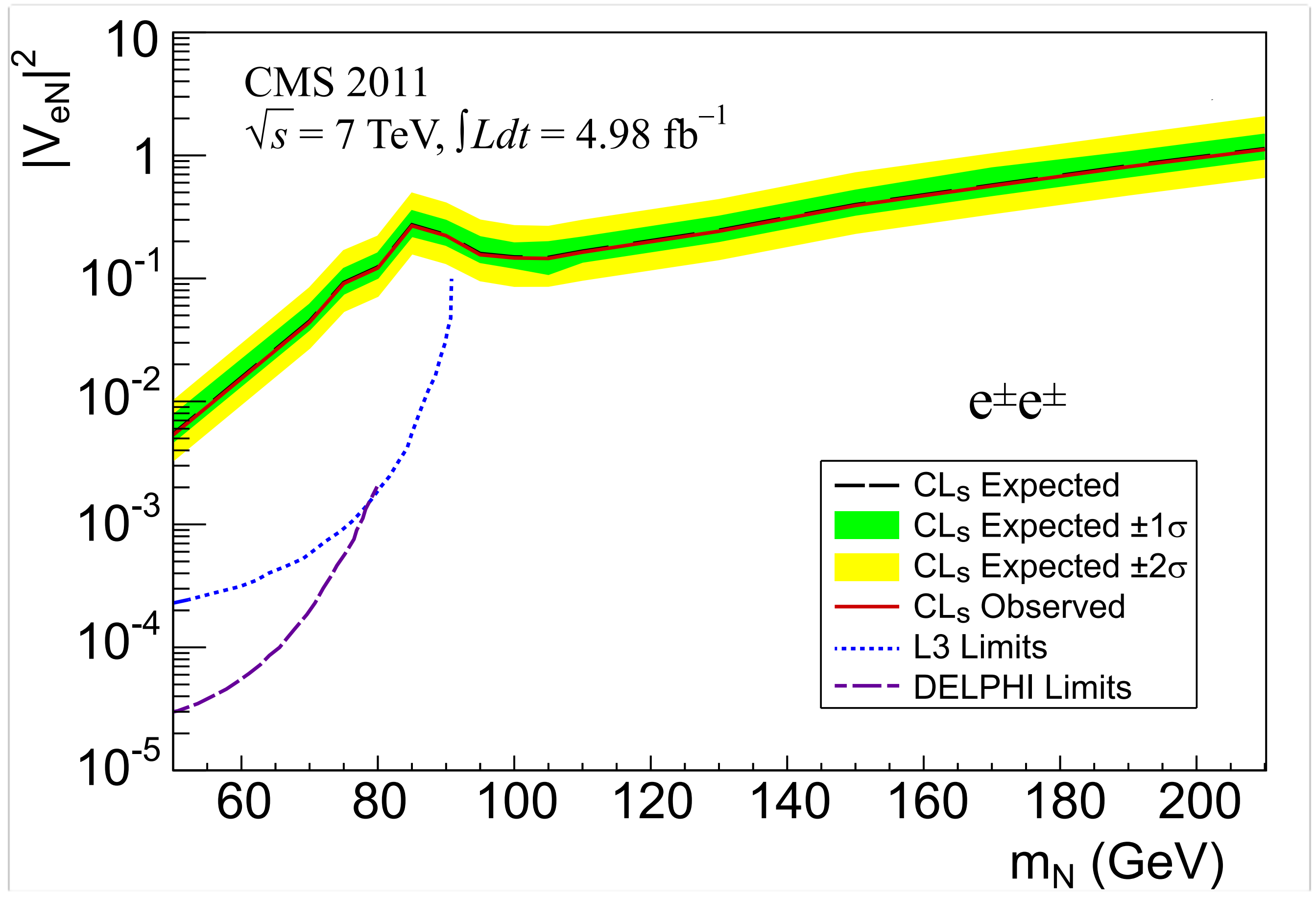
- Production through $\nu - N$ mixing
  - requires large y_S which give small m_ν
  - *L* is approximately conserved Kersten, Smirnov '07
- Flavor of charged leptons probes y_S, $m_{\ell jj} = m_S$
- Limited low energy phenomenology, mostly $0\nu 2\beta$

Atre, Han, Pascoli, Zhang '09

Mitra, Senjanović, Vissani '11

type I searches at LHC

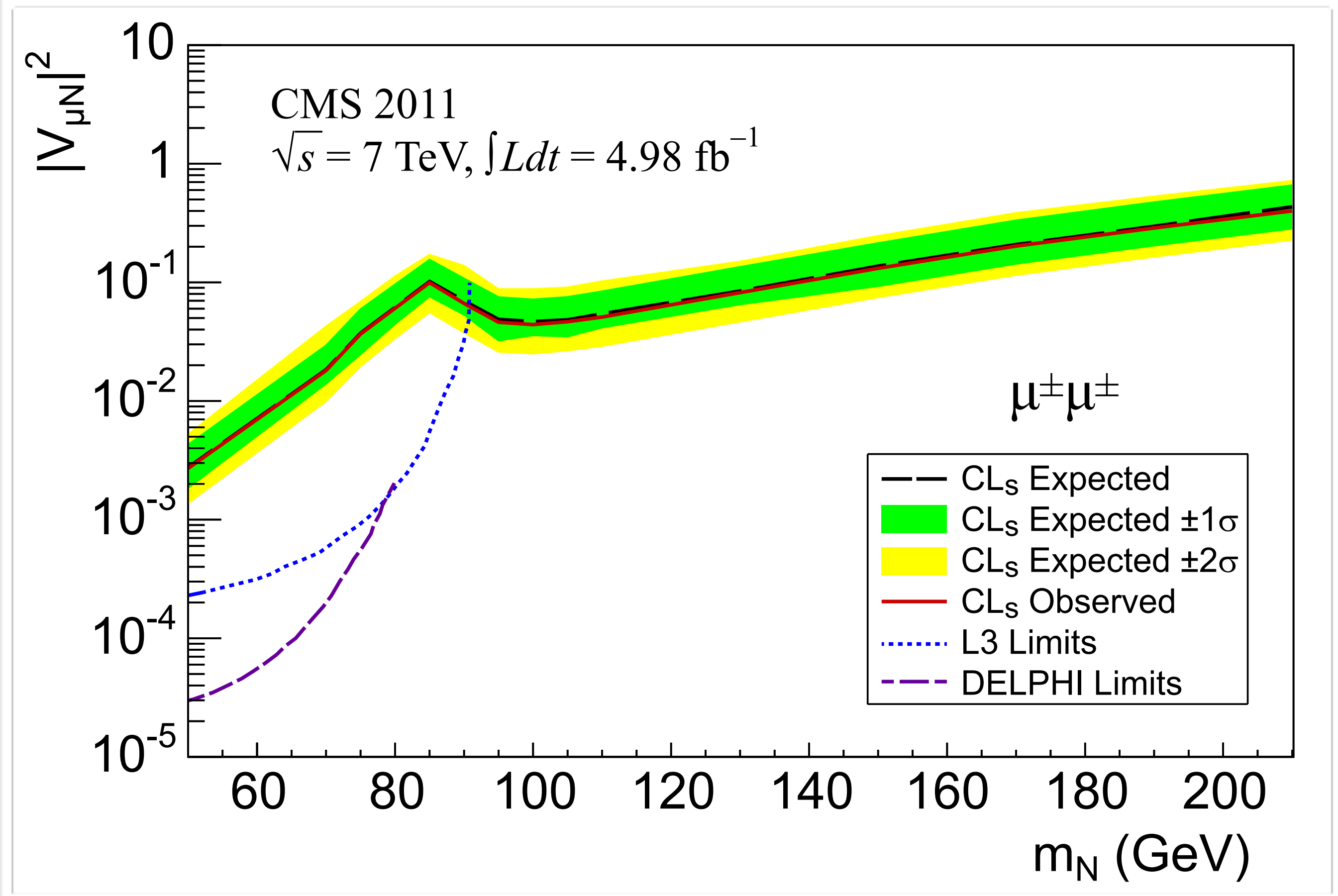
CMS-EXO-11-076



- Heavy N signal: two isolated charged leptons and two hard jets

Backgrounds

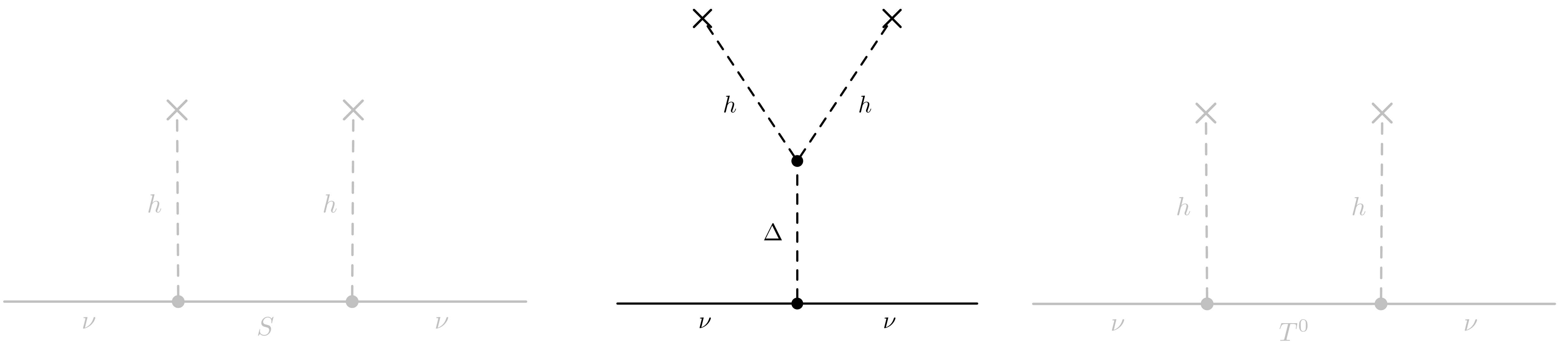
$$t\bar{t},\ Z+j,\ \text{QCD jets}$$



LHC reach

$$m_S \simeq \mathcal{O}(100)\ \text{GeV}$$

Aguila, Aguilar-Saavedra, Pittau ’07, ’08 type I type II type III



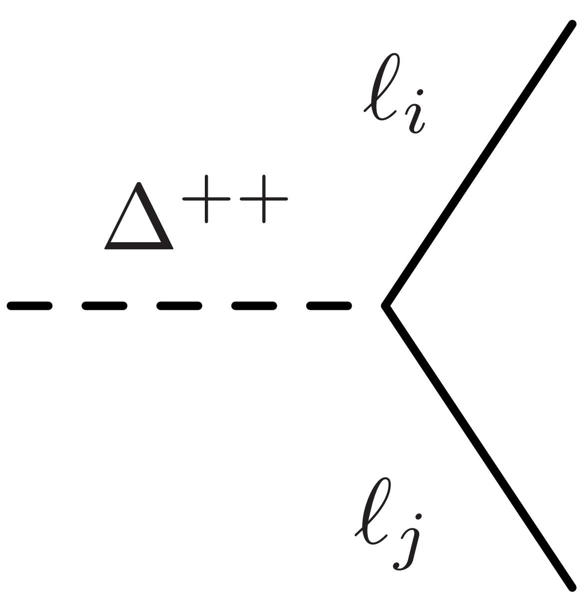
type II triplet Higgs scalar Δ_L with $Y = 2$

Gauge interactions, EW production

$$W \to \Delta^{++}\Delta^{-}, \Delta^{+}\Delta^{0}$$
$$Z \to \Delta^{++}\Delta^{--}, \Delta^{+}\Delta^{-}, \Delta^{0}\Delta^{0}$$

Azuelos et al. '05
Akeroyd, Aoki '05

Direct relation of Higgs coupling to neutrino mass



$$M_\nu = v_L Y_\Delta$$

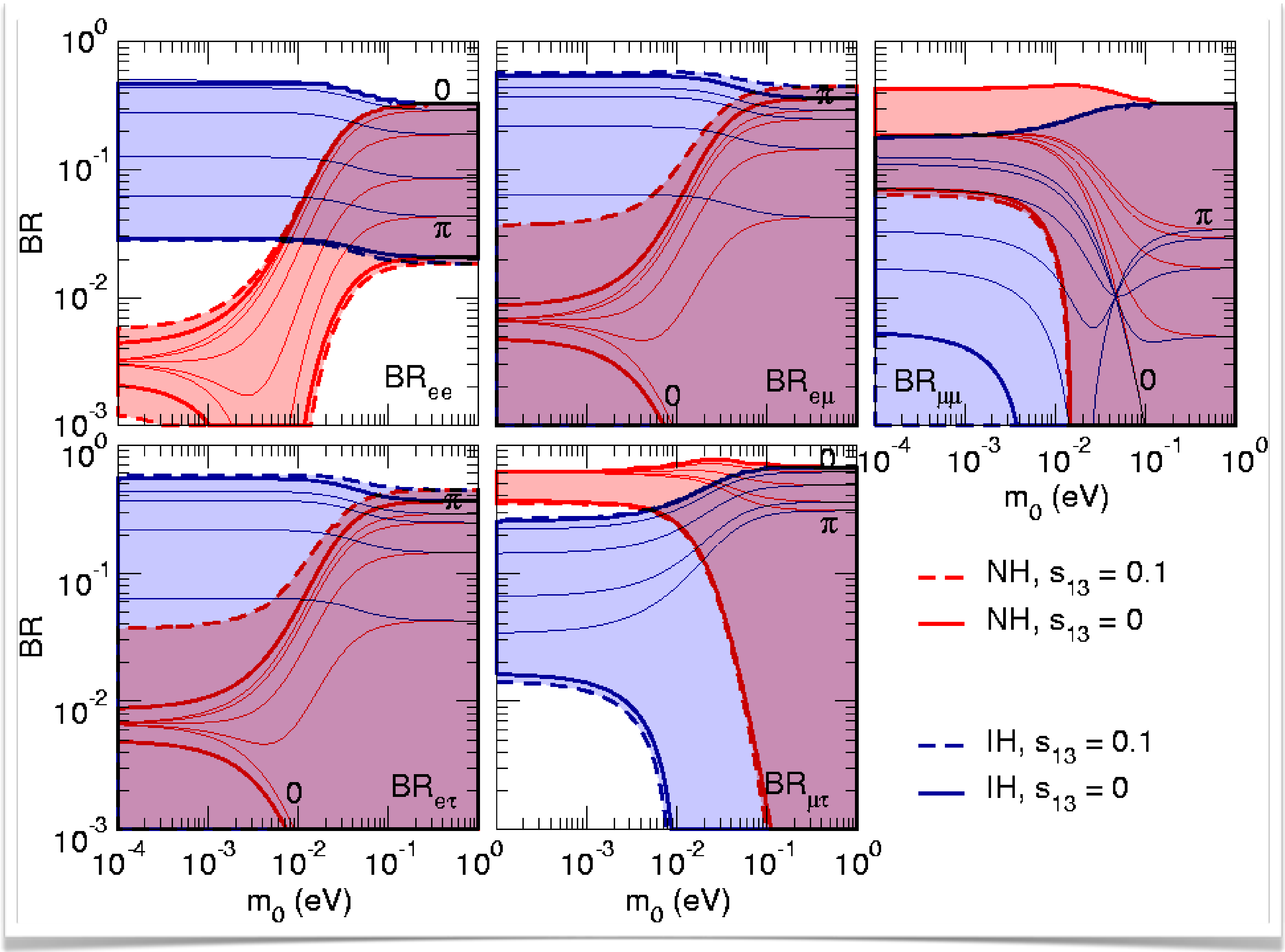
Chun, Lee, Park '03

- LNV hard to probe, needs v_L and Y_Δ

Collider studies Han, Fileviez-Perez, Huang, Li, Wang '08 type II

direct connection to neutrino mass

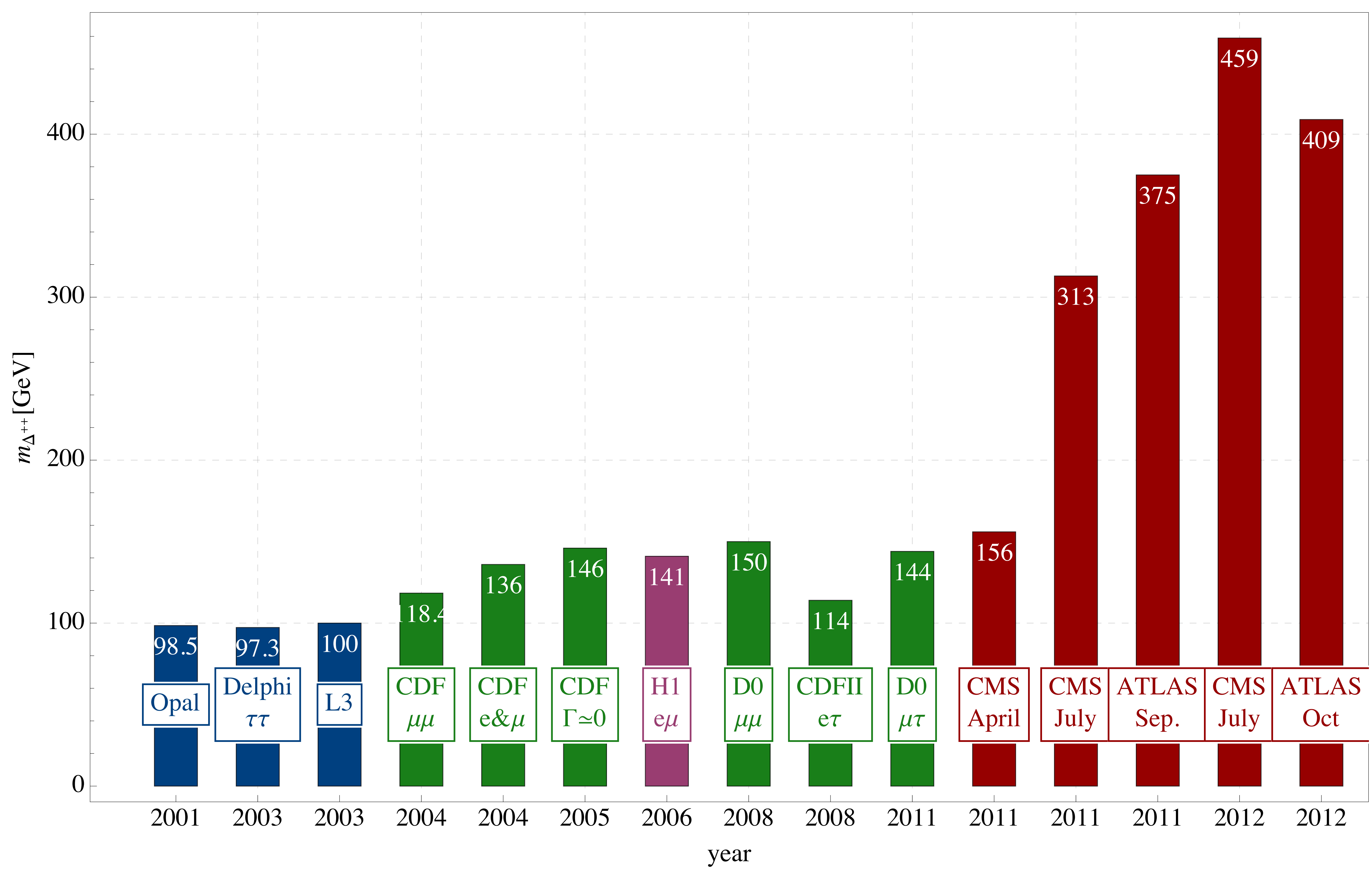
from Garayoa, Schwetz '07



sensitive to hierarchy & the Majorana phase

see also Kadastik, Raidal, Rebane '07

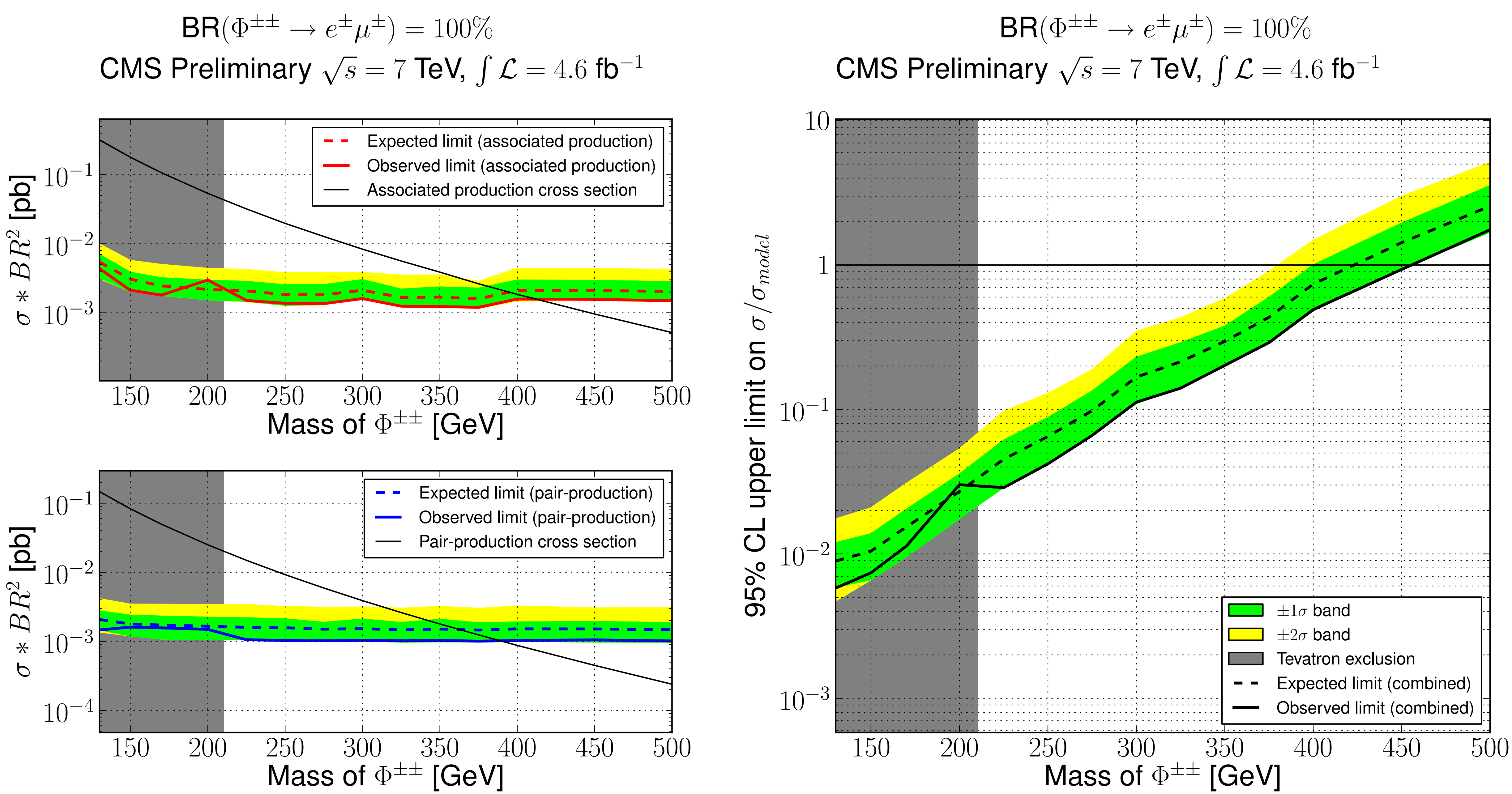
type II history of searches



type II searches at LHC

CMS PAS-HIG-12-005

~ Degeneracy of components assumed



see also ATLAS 1210.5070 - pair production only

type II caveat for searches

fermions $\Gamma_{\Delta \to \ell\ell} \propto m_\Delta \frac{{V_L}^* m_\nu {V_L}^\dagger}{v_L}$ small vev $v_L \lesssim 10^{-3}\ \mathrm{GeV}$

gauge bosons $\Gamma_{\Delta \to VV} \propto \frac{{m_\Delta}^3 v_L^2}{v^4}$ 'large' vev $v_L \gtrsim 10^{-3}\ \mathrm{GeV}$

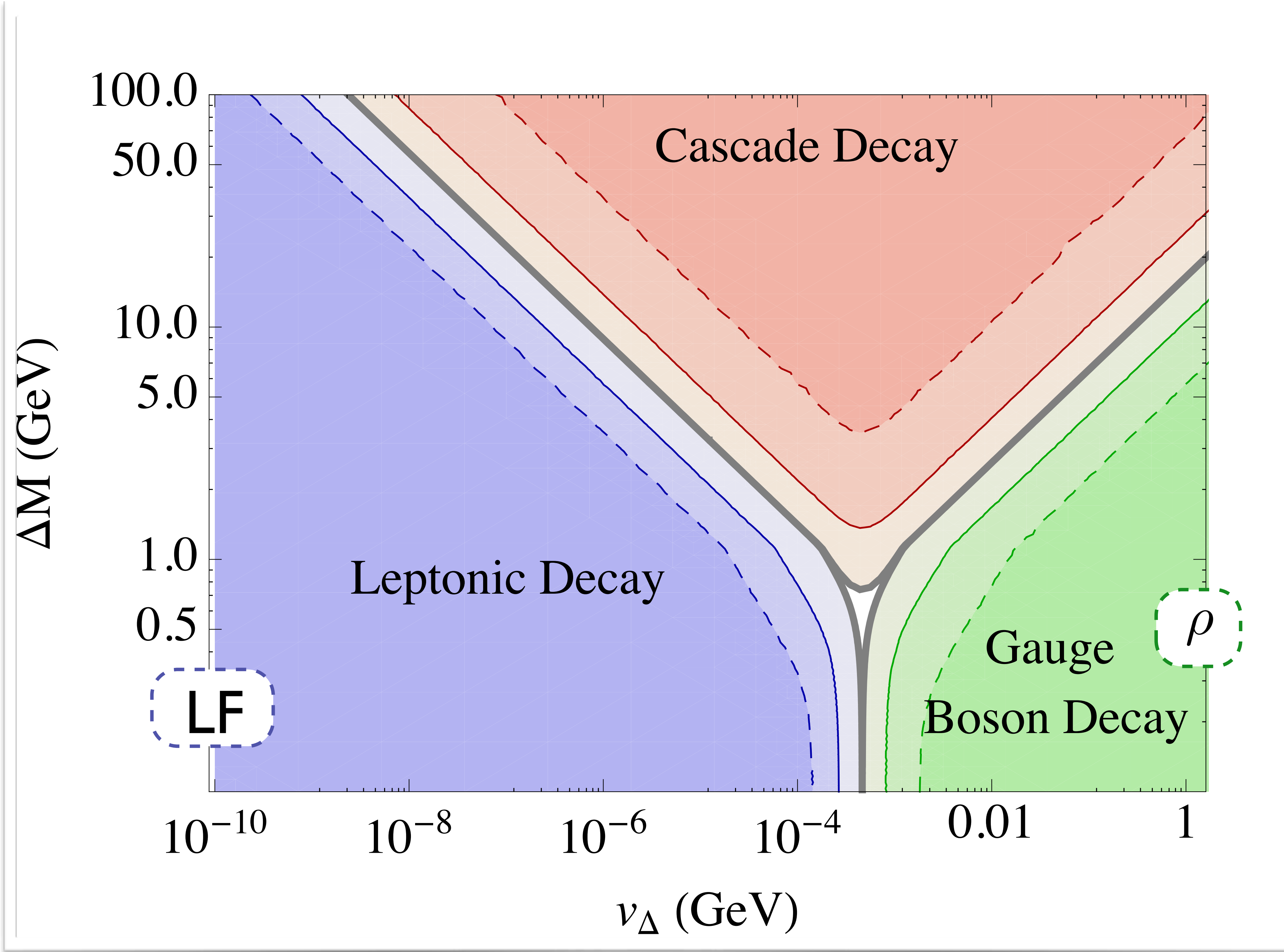
cascades $\Gamma_{\Delta \to \Delta' V} \propto \frac{\Delta {m_\Delta}^5}{v^4}$ mass split $\Delta m_\Delta > \mathcal{O}(\mathrm{GeV})$

- vev and mass splits define the phase space

Melfo, MN, Nesti, Senjanović, Zhang '11

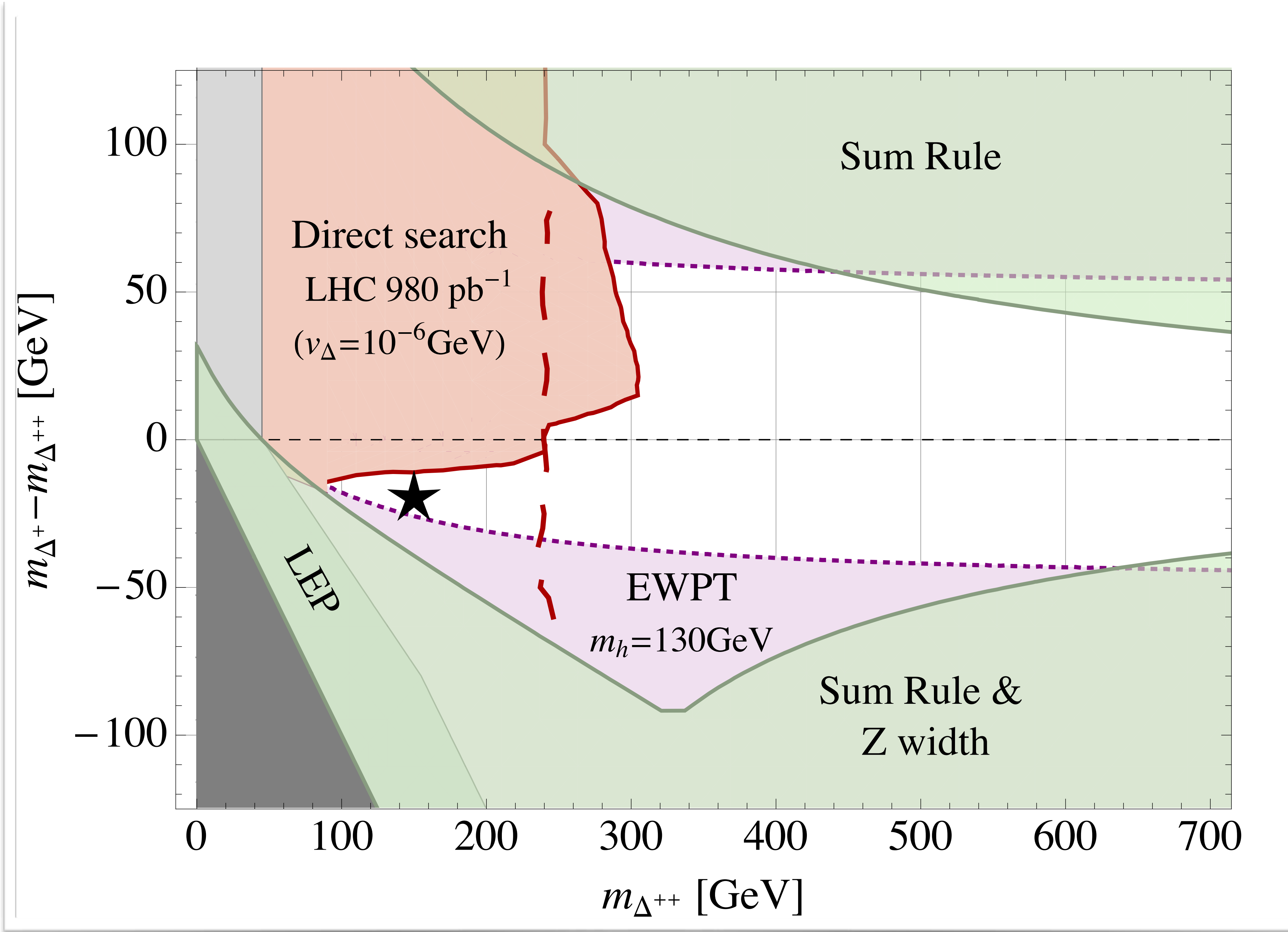
type II phase space

$$\Delta m_\Delta = {m_{\Delta^+}}^2 - {m_{\Delta^{++}}}^2 = m_{\Delta^0} - {m_{\Delta^+}}^2 \propto v^2$$

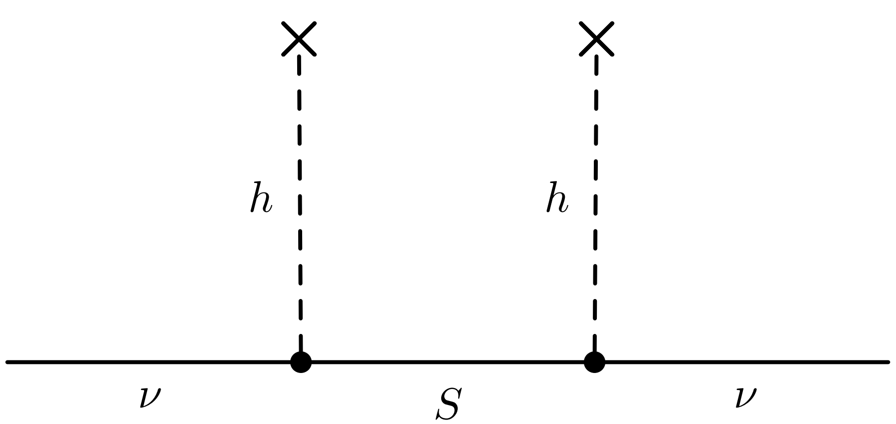


type II search prototype

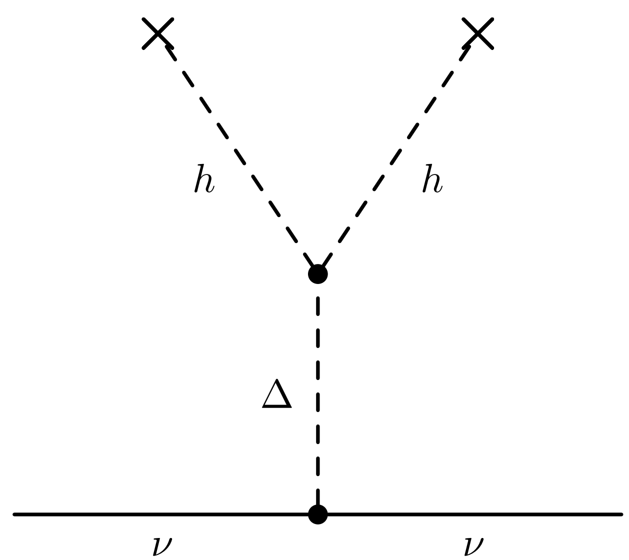
Melfo, MN, Nesti, Senjanović, Zhang '11



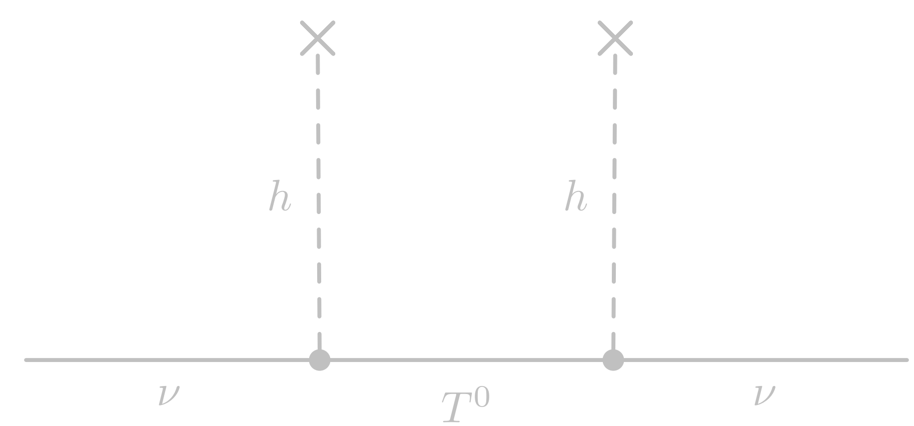
two-parametric limits: mass vs. splitting type I



type II



type III



Left-Right

Left-Right Symmetry

Understanding parity violation

Pati, Salam '74

Mohapatra, Pati '75

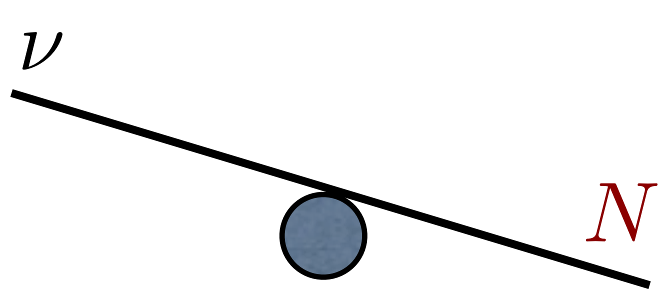
$$SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

Broken spontaneously, analogous to SM Higgs

Senjanović, Mohapatra '75

Senjanović '79

Predicted neutrino mass: a theory *of*, not *for* m_ν



LR gave see-saw

Minkowski '77

Mohapatra, Senjanović '79

LRSM and neutrino mass

Minkowski '77

Mohapatra, Senjanović '80

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

Parity broken spontaneously $\quad v_R \equiv \langle \Delta_R \rangle \quad\quad M_{W_R} = g\, v_R$

Anomalies: three RH
Majorana neutrinos $\quad m_N = Y_\Delta\, v_R$

LR parity $\quad \mathcal{P} : \psi_L \leftrightarrow \psi_R \quad$ or $\quad \mathcal{C} : \psi_L \leftrightarrow (\psi_R)^c$

Φ completes the breaking $\quad v_L \equiv \langle \Delta_L \rangle \propto \dfrac{v^2}{v_R}$

See-saw

$$M_\nu = \frac{v_L}{v_R} M_N - M_D \frac{1}{M_N} M_D \qquad (\mathcal{C})$$

LRSM bounds on the scale

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

LR parity in the Yukawa sector $\quad M_q = M_q^T \qquad (\mathcal{C})$

fixes the flavor in the gauge couplings $\quad V_R^q = V_L^{q\,*}$

- Limits from precision tests, kaon mixing

$M_{W_R} > 1.6 \text{ TeV}$ Beal, Bander, Soni '82, ...

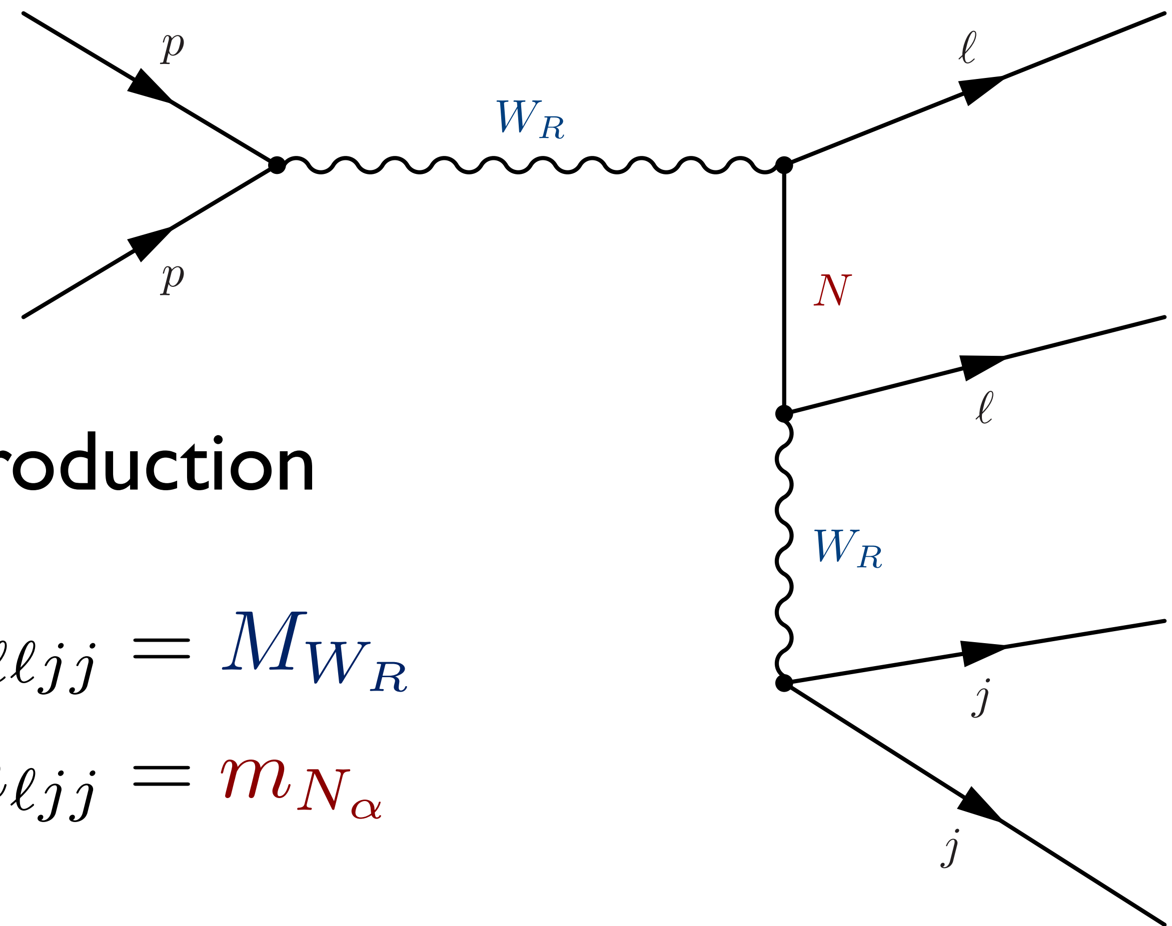
re-examined including CP violation

...Maiezza, MN, Nesti, Senjanović '09
Bertolini, Eeg, Nesti, Maiezza '12

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

Keung, Senjanović '83

LRSM @ LHC



- Drell-Yan resonance for W_R production

  Mass reconstruction $m_{\ell\ell jj} = M_{W_R}$ $m_{\ell jj} = m_{N_\alpha}$

  Flavor information $V_{R\ell\alpha}$ from N_α

  LHC reach $M_{W_R} \lesssim 6\ \text{TeV}$ Ferrari et al. '00, Gninenko et al. '07

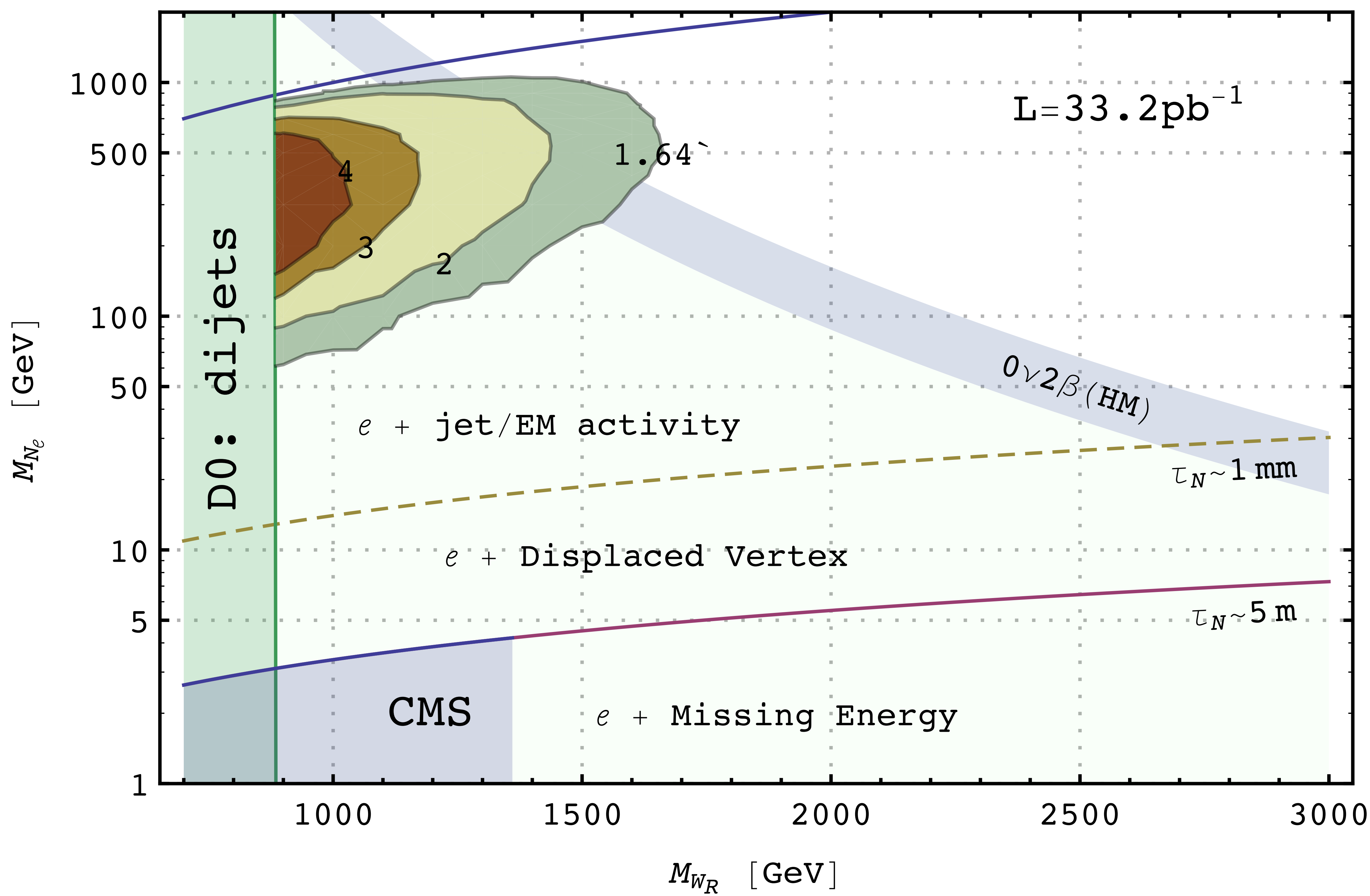
Relates directly to LFV & LNV at low energy

Tello, Nesti, MN, Senjanović, Vissani '11

m_{N_α} and V_R predict Dirac Yukawa couplings Tello, MN, Senjanović, to appear

LRSM search outline

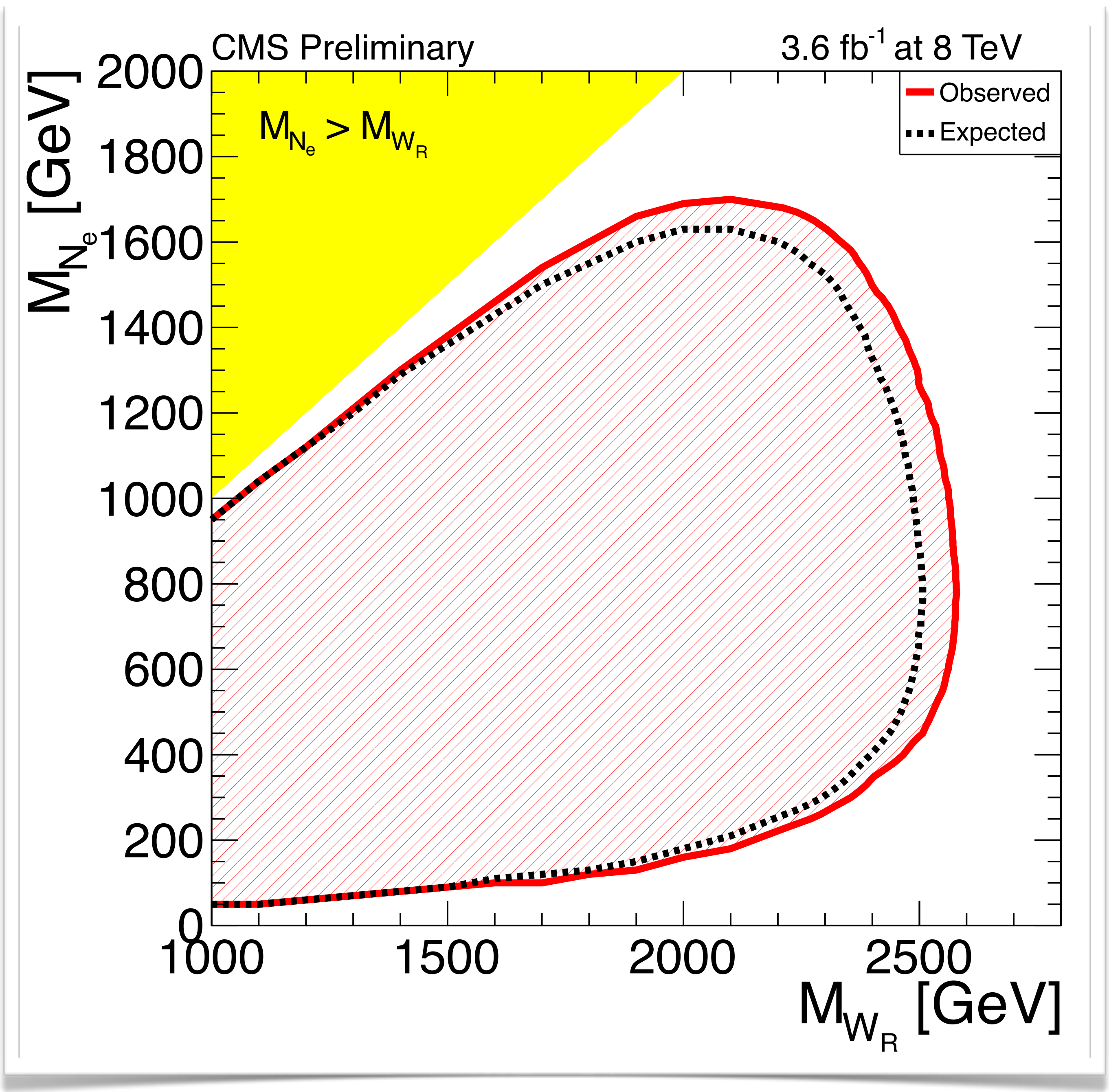
MN, Nesti, Senjanović, Zhang '11

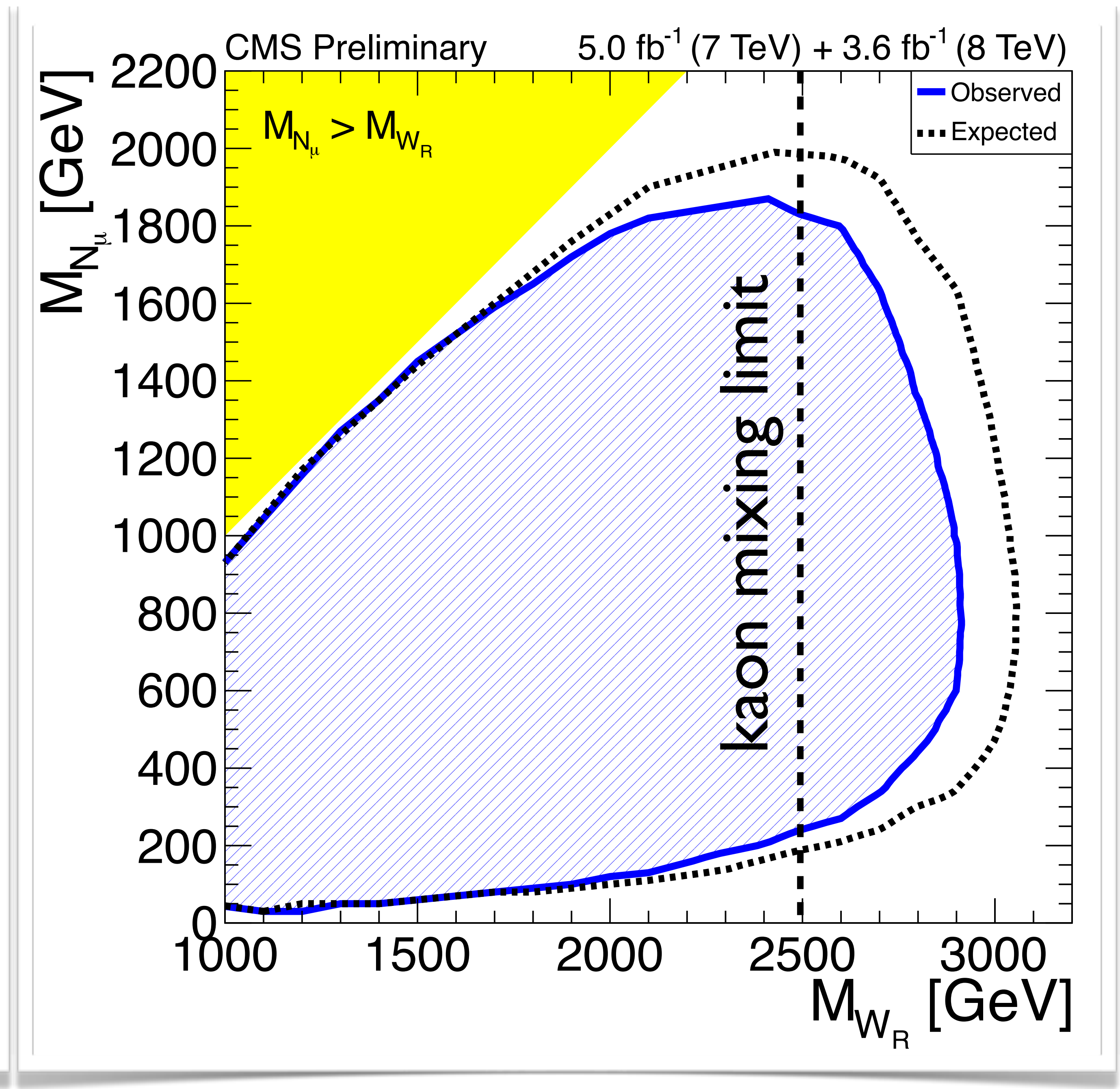


LRSM heavy N search - KS process

CMS PAS-EXO-12-017

CMS 1210.2402





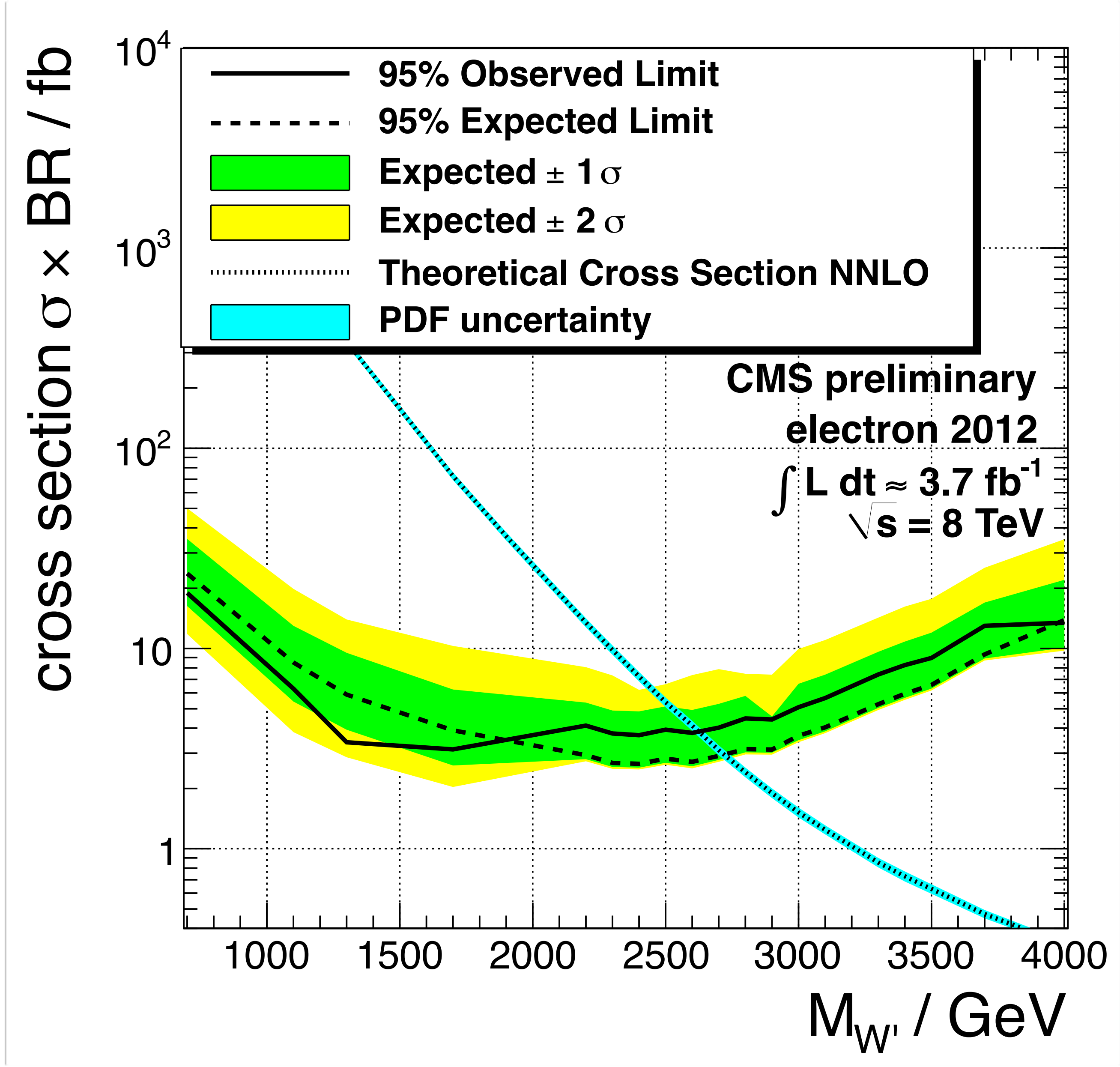
Background $t\bar{t}, Z/\gamma^*$

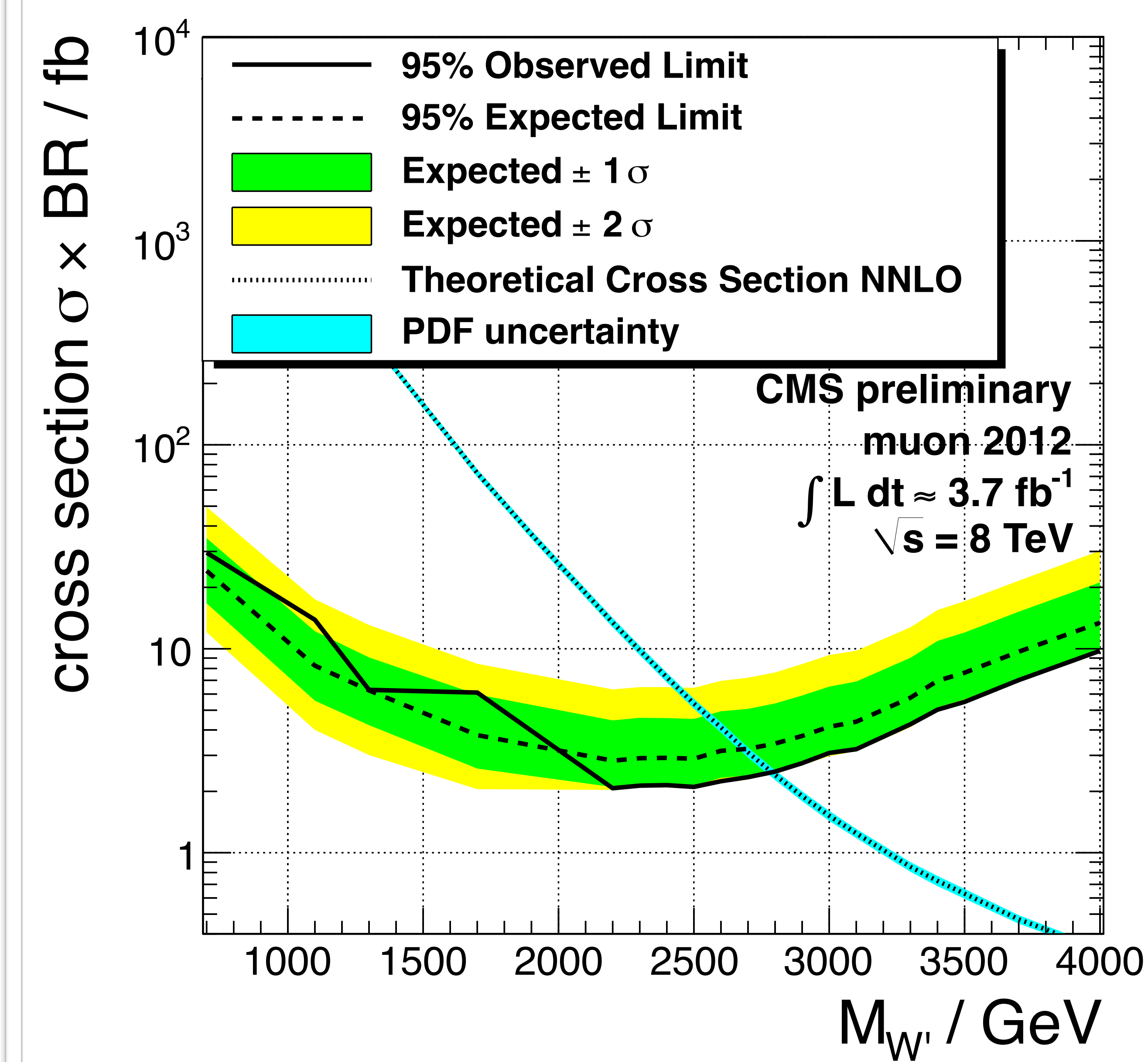
see also: ATLAS 1203.5420

Current luminosity $\mathcal{L} \simeq 17\ \mathrm{fb}^{-1}$

LRSM light *N* search - missing energy

CMS PAS-EXO-12-010
CMS 1210.2402



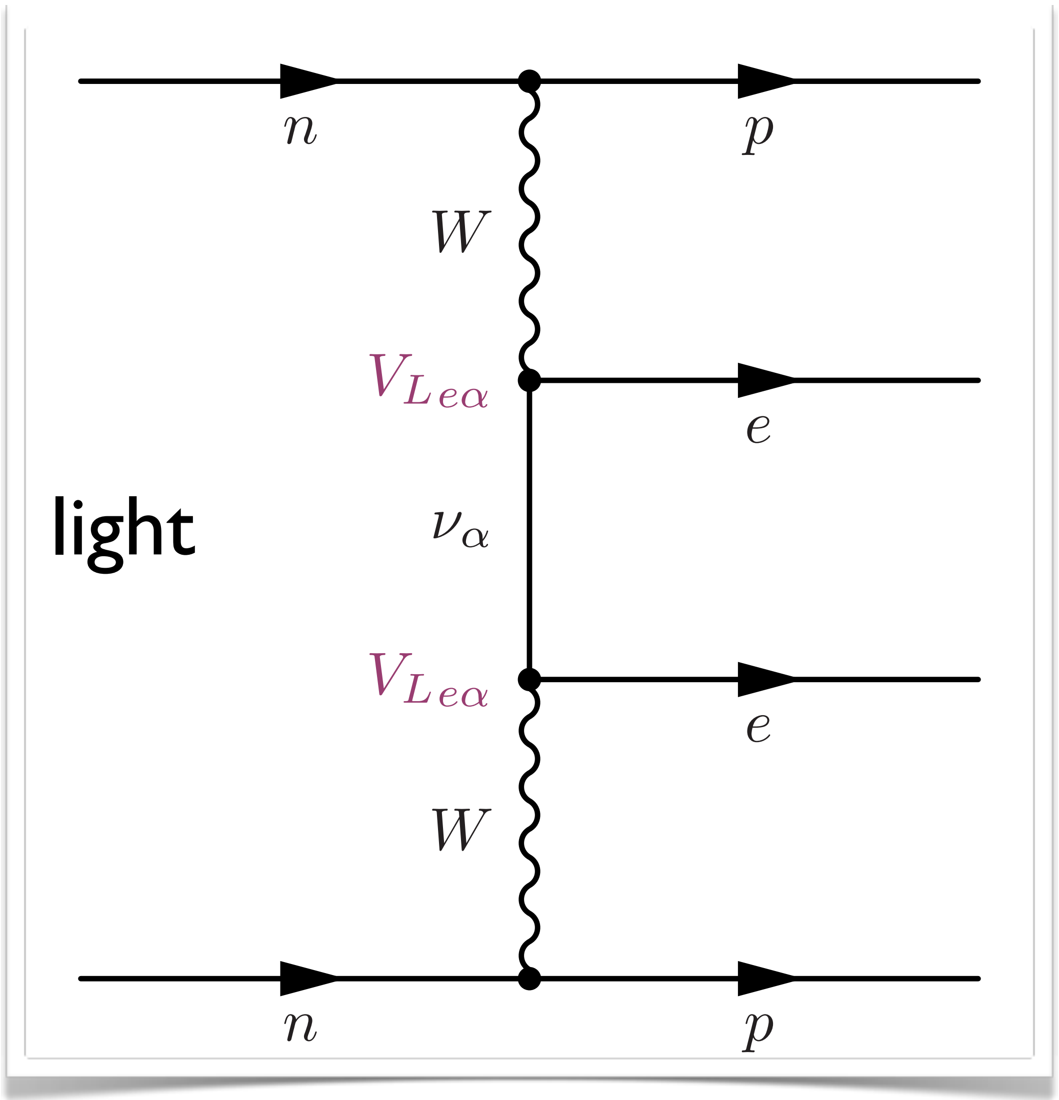


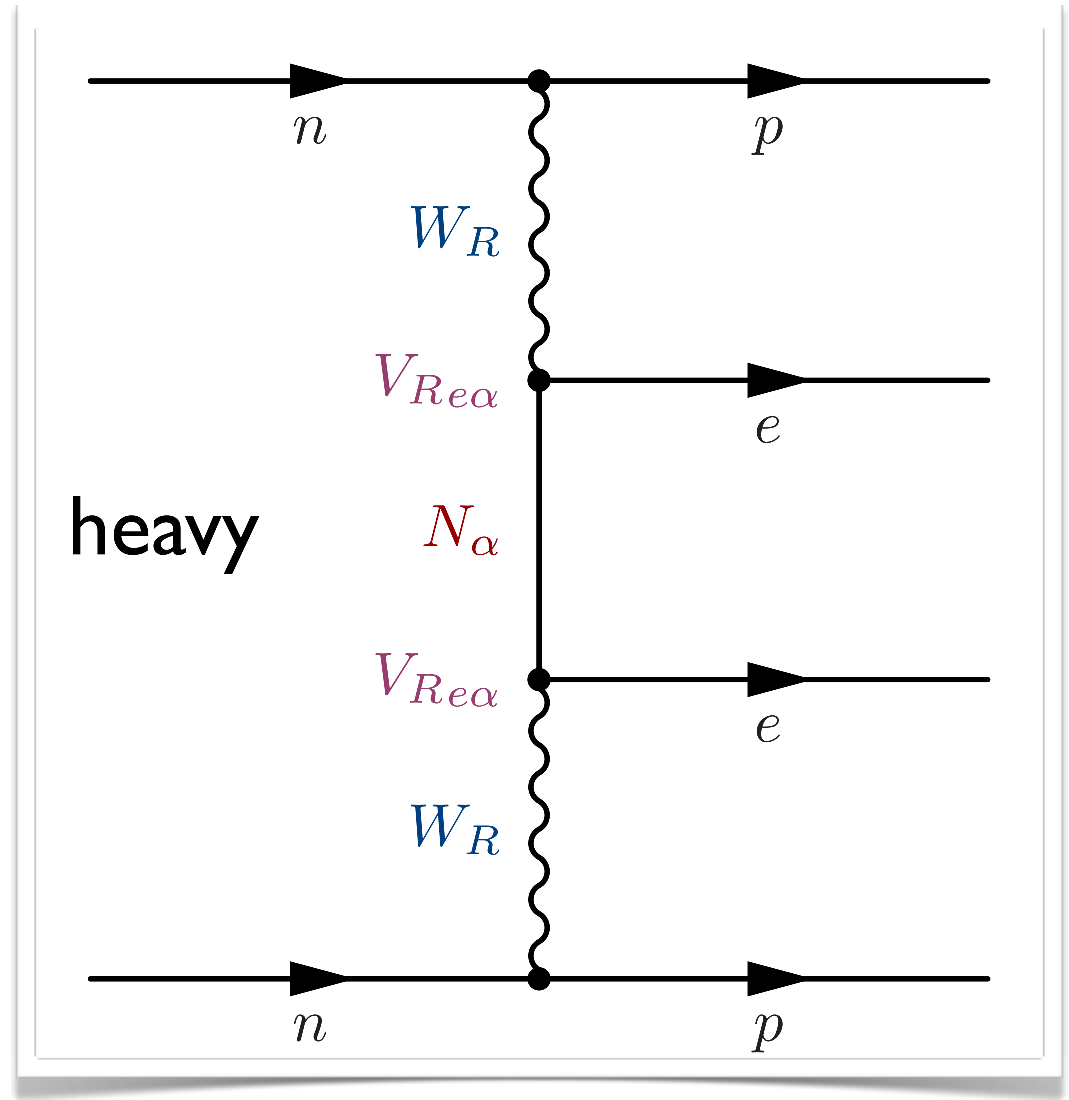
see also: ATLAS 1209.4446

see talks by Schönert and Schönert

LRSM and $0\nu 2\beta$

Mohapatra, Senjanović '81





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

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

Δ_L negligible

$\nu - N$ mixing subdominant

Δ_R if no LFV

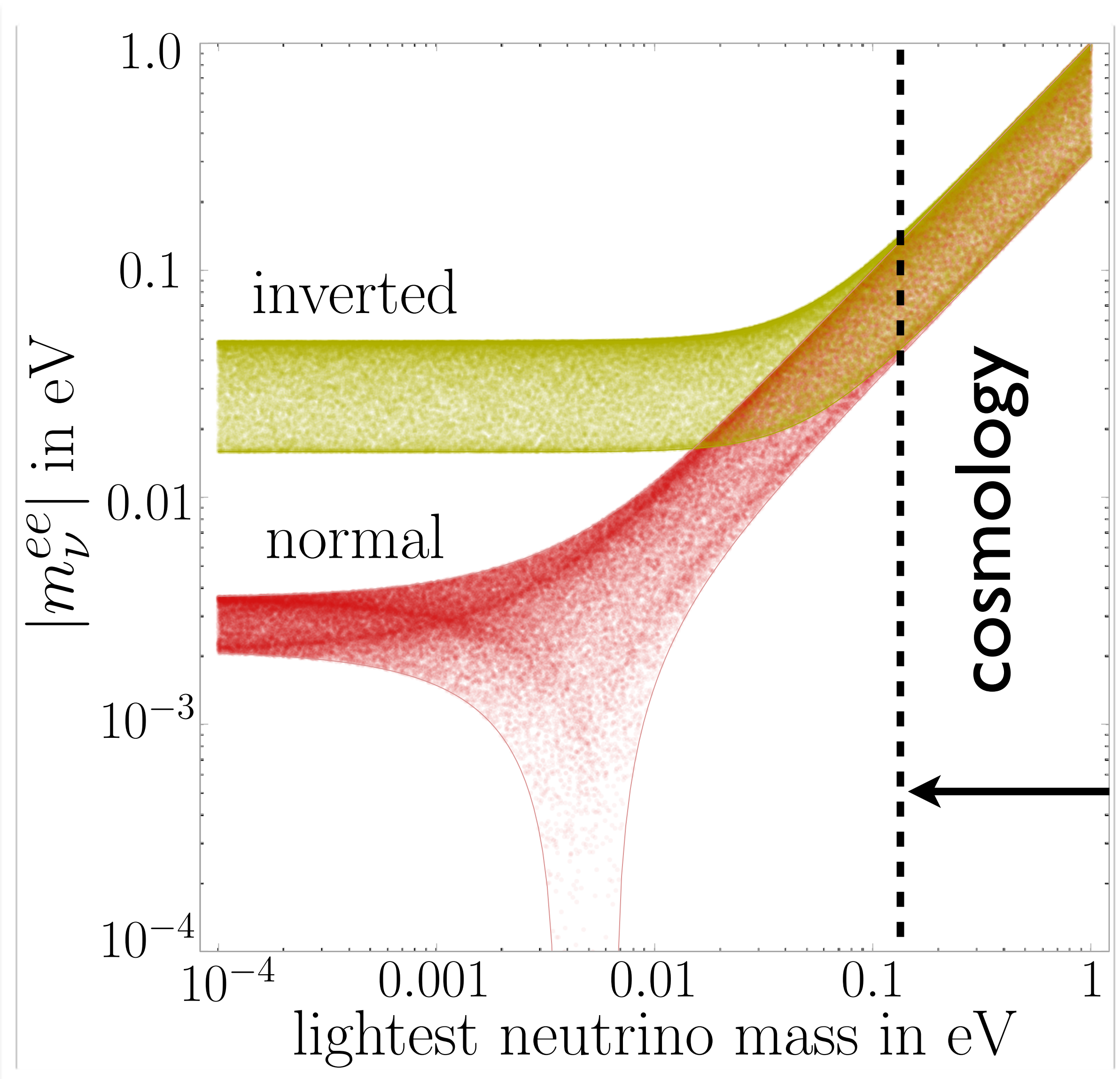
Tello, MN, Senjanović, to appear

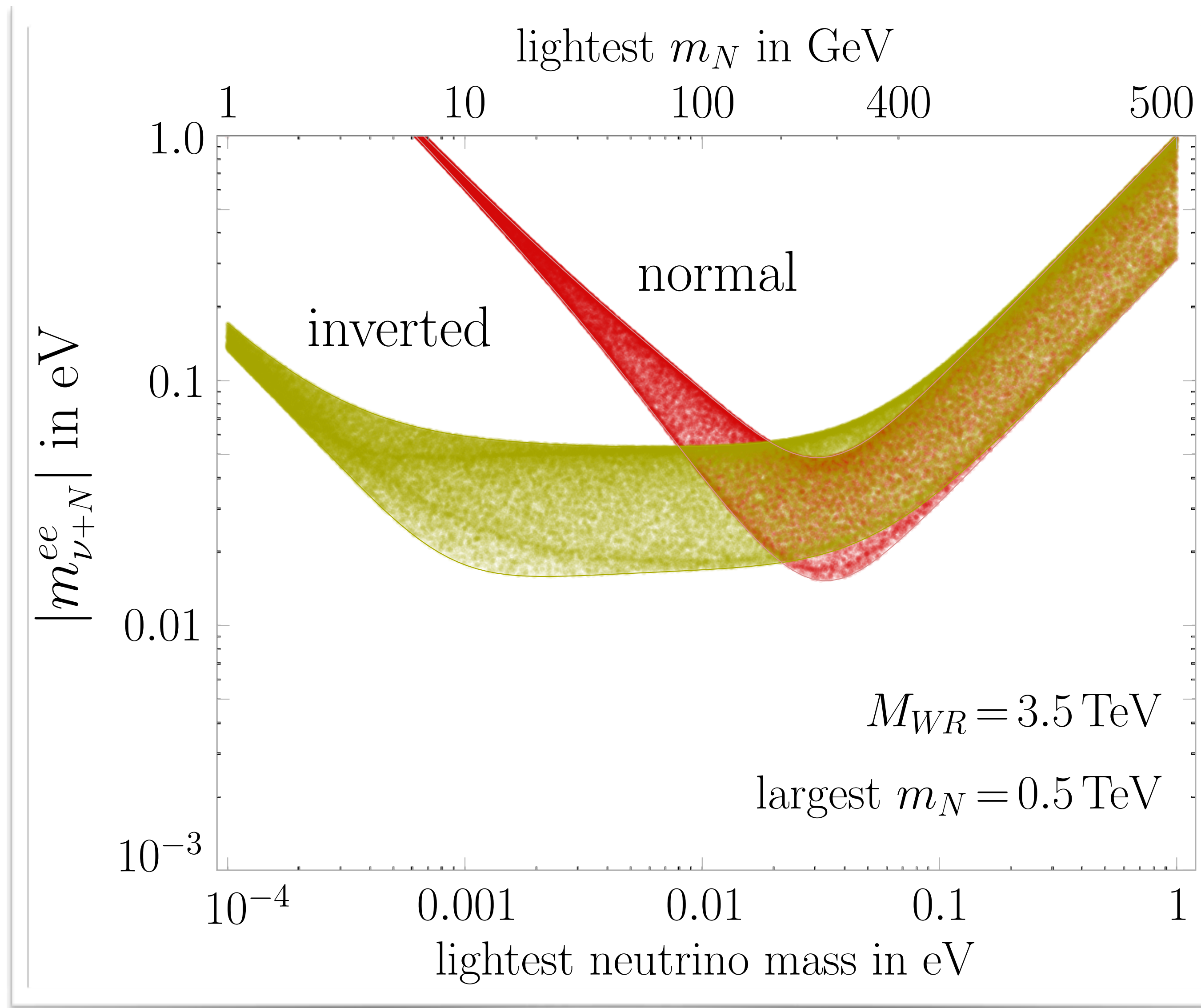
LRSM LHC - $0\nu2\beta$ connection

Tello, MN, Nesti, Senjanović, Vissani '11

M_{W_R}, m_N, V_R from colliders

e.g. type II: $V_R = {V_L}^*$





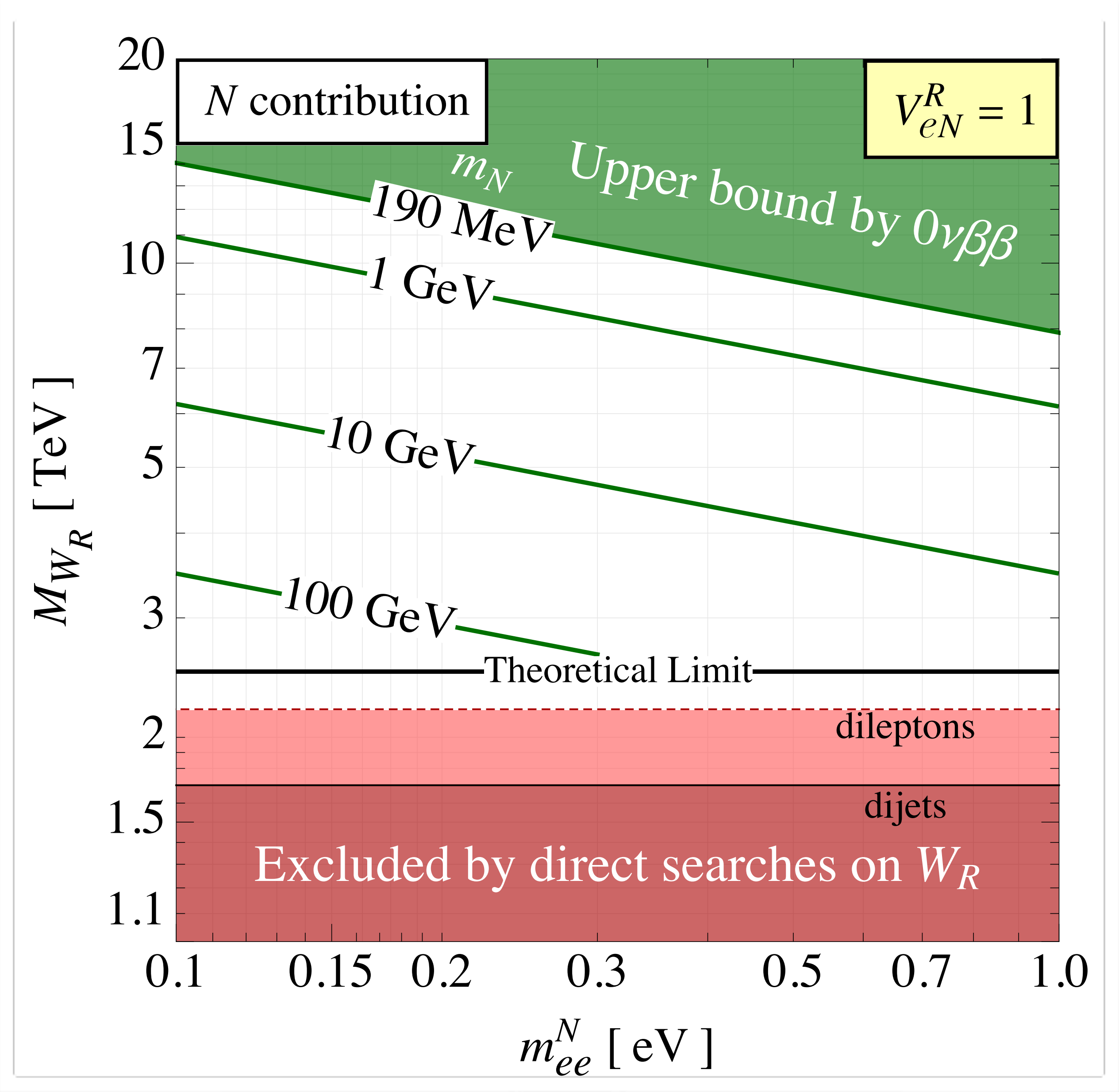
$$m_\nu^{ee} = \sum_\nu {V_L}^2 m_\nu$$

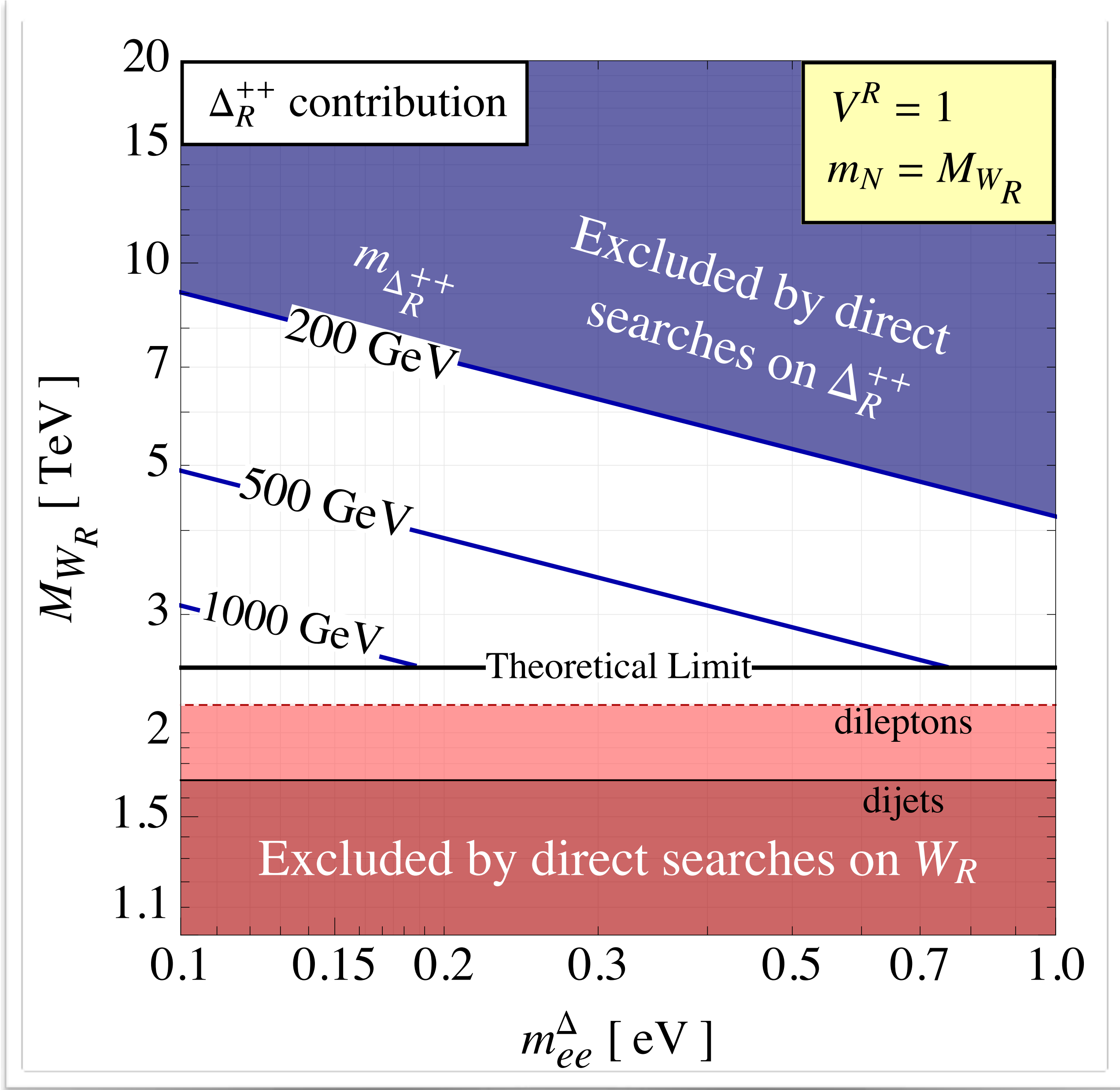
$$m_N^{ee} = p^2 \frac{M_{W_L}^4}{{M_{W_R}}^4} \sum_N \frac{{V_R}^2}{m_N}$$

LRSM $0\nu 2\beta$ as a phenomenological motivation

MN, Nesti, Senjanović, Tello '11

Imminent signal possibly in tension with cosmology if sourced by m_ν^{ee}

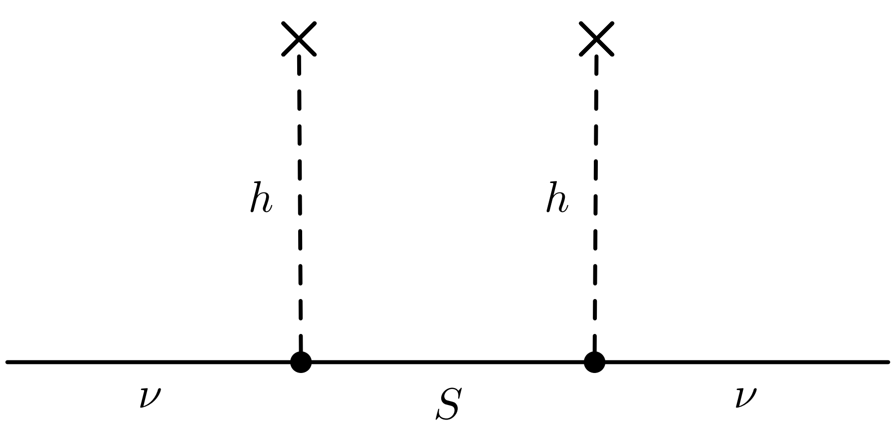




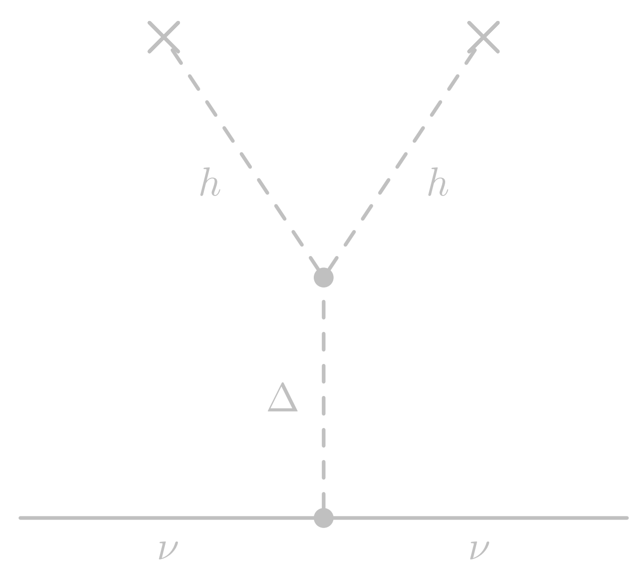
$0\nu 2\beta$ probes the TeV scale

LHC covers the Δ_R contribution

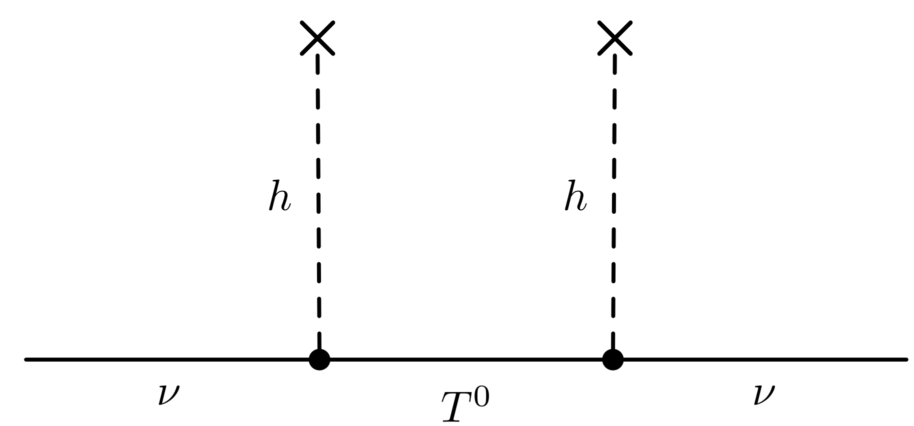
type I



type II



type III



Low scale motivated by grand unification

$SU(5)$

- Minimal GUT model, beautiful but wrong — Georgi, Glashow '74

  no unification - SM only

  $m_\nu = 0$ massless neutrinos

- Minimal extensions

  Higgs sector $15_H \in$ type II — Doršner, Fileviez-Perez '06

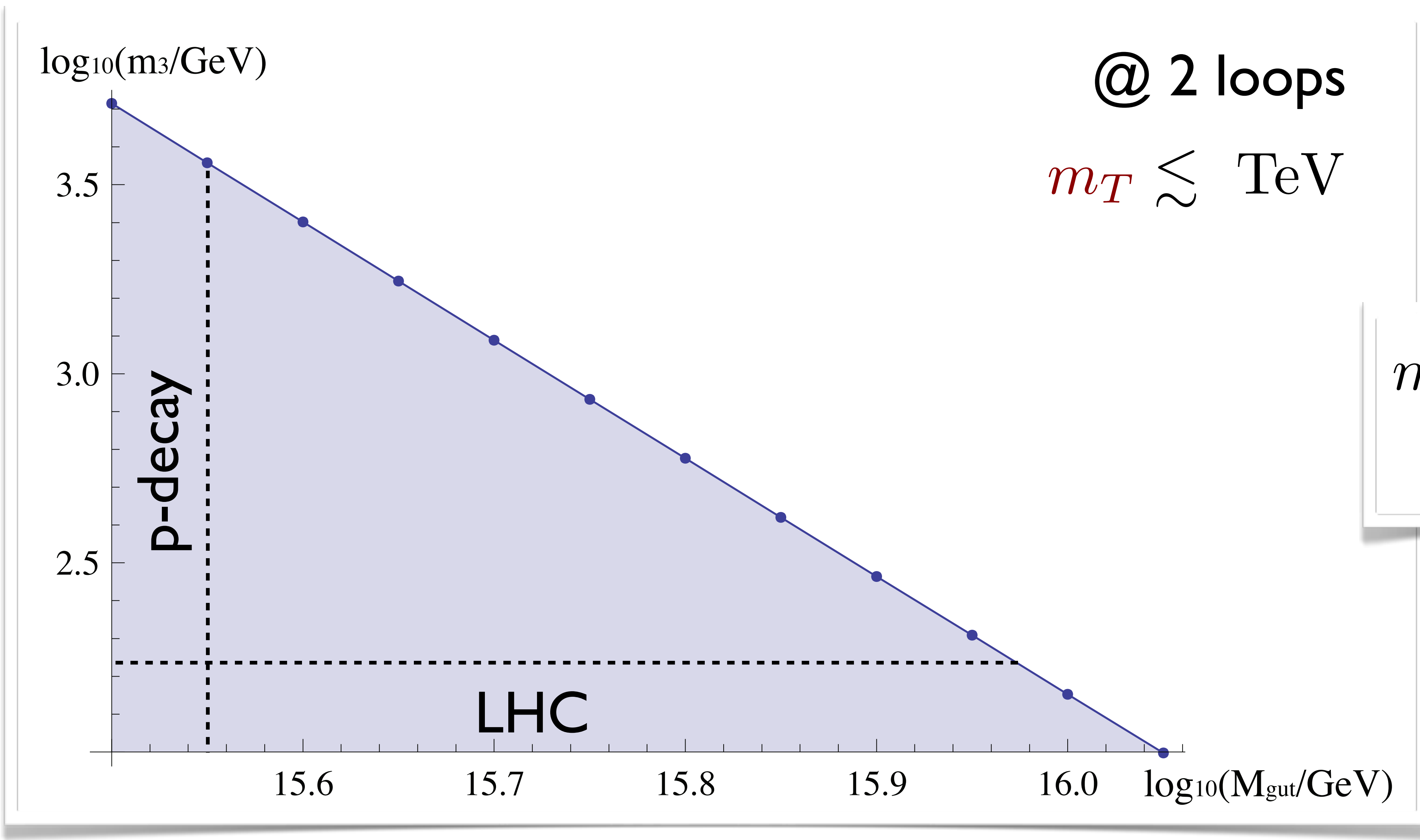
  arbitrary scale

  Fermionic sector $24_F \in$ type I & III — Bajc, Senjanović '06; Bajc, MN, Senjanović '07

  predicts TeV scale type III see-saw

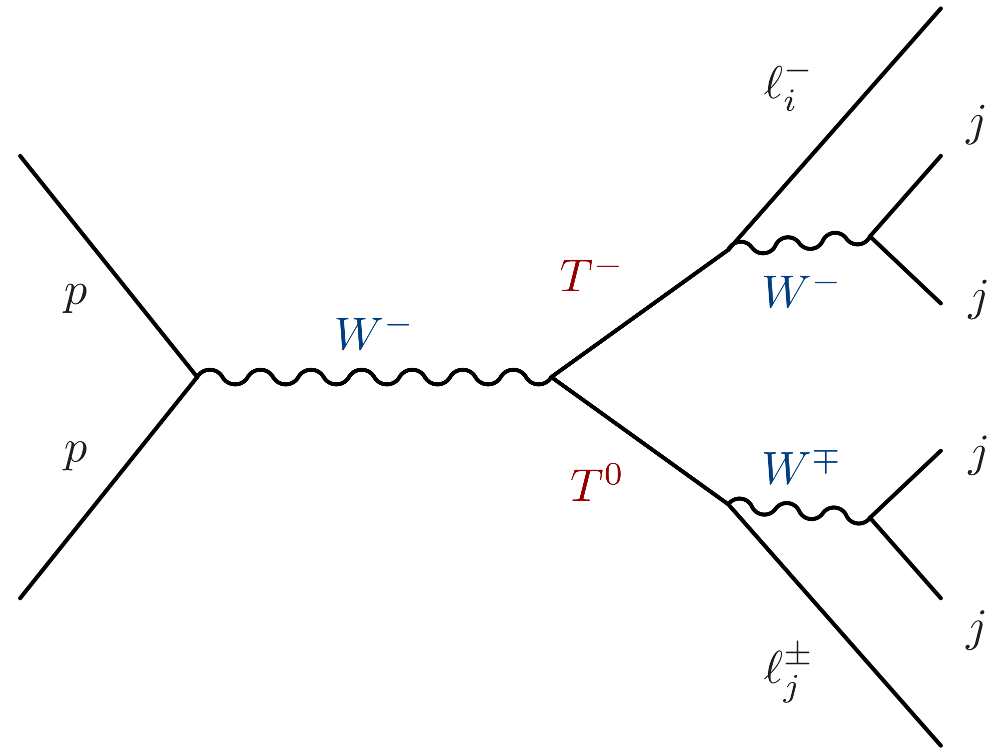
$SU(5)$ unification constraints

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



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

type III @ LHC



- EW pair-production

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

Mass reconstruction $m_{\ell jj} = m_T$

Decays via Yukawas in the minimal case

Bajc, MN, Senjanović '07

Mass splits radiative & small $\Delta m_T \simeq 170 \text{ MeV}$

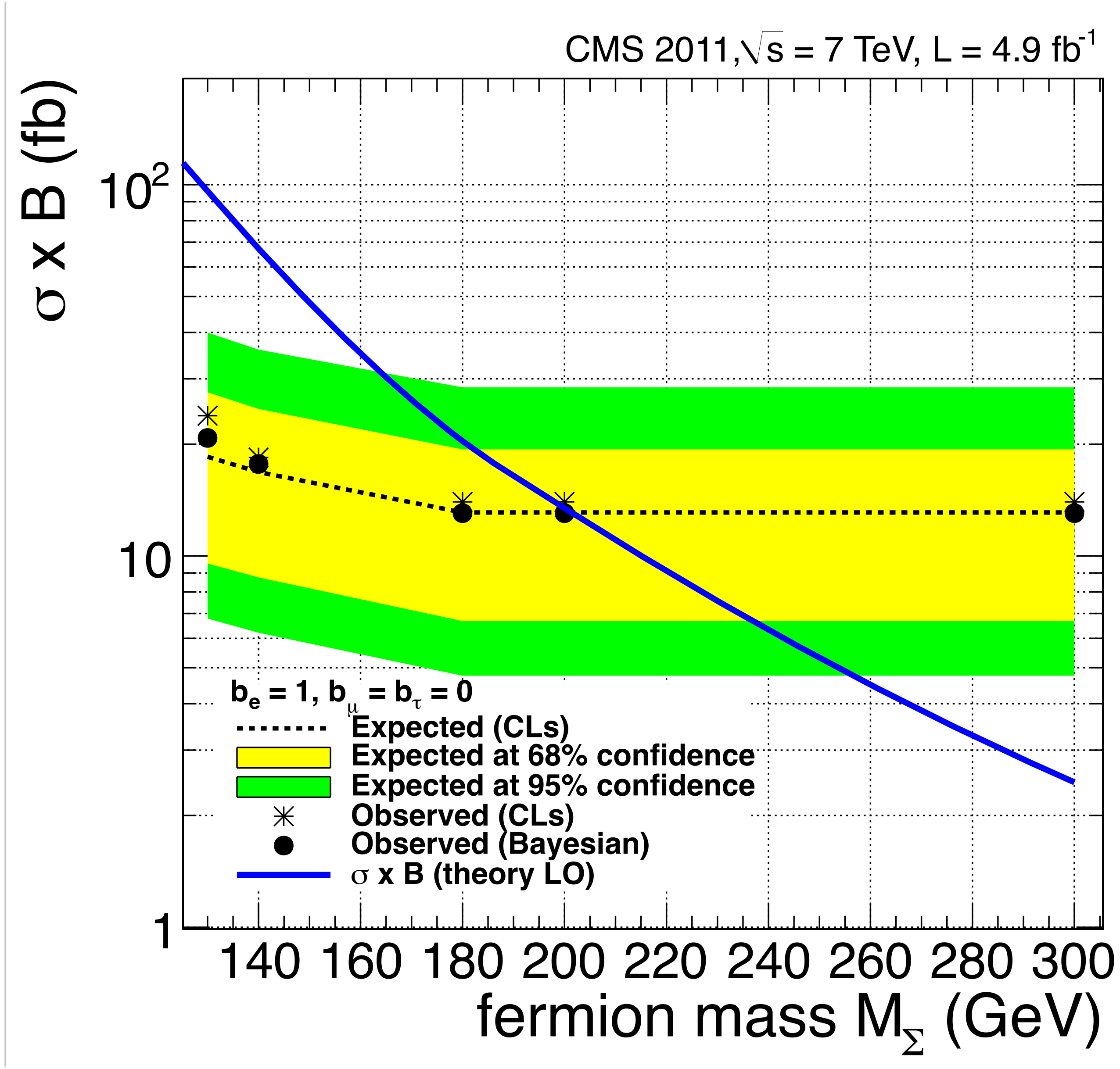
- Collider studies

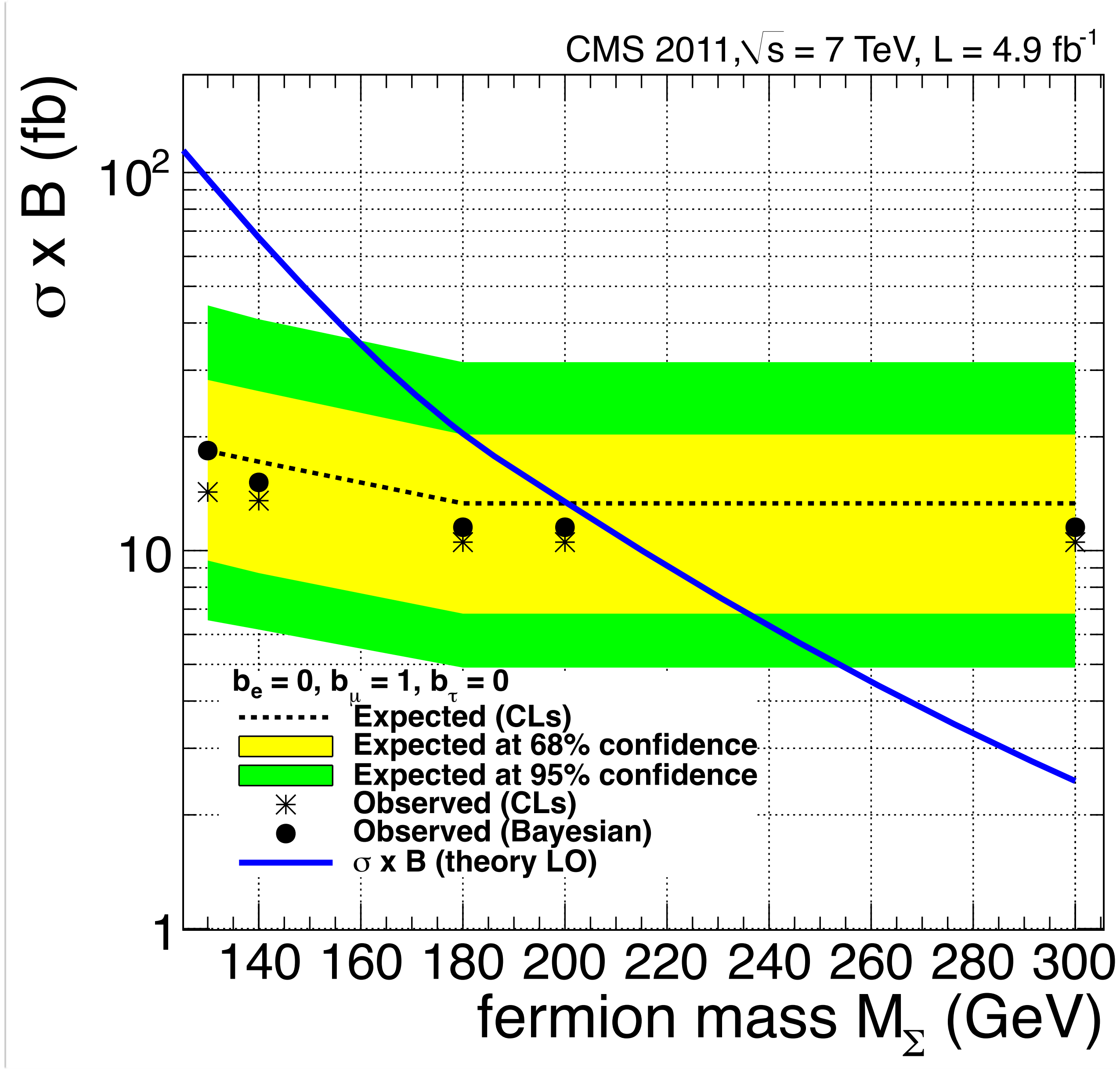
Reach ~ 700 GeV

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

type III searches at LHC

CMS PAS-EXO-11-073





Conclusions

LHC could probe neutrino mass origin

Majorana nature of heavy neutrinos

Lepton Number Violation

} *direct* probe @ colliders

type I negligible rates - no direct link to m_ν

type II possible, TeV scale not motivated by itself

+ direct connection to m_ν

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type I — negligible rates — - no direct link to m_ν

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LRSM — *fundamental* theory, best bet to probe

+ relates directly to m_ν and low E phenomena

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type I — negligible rates — - no direct link to m_ν

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$SU(5)$ — TeV scale predicted by GUT

+ can be ruled out