Flavourful searches for seesaw at LHC

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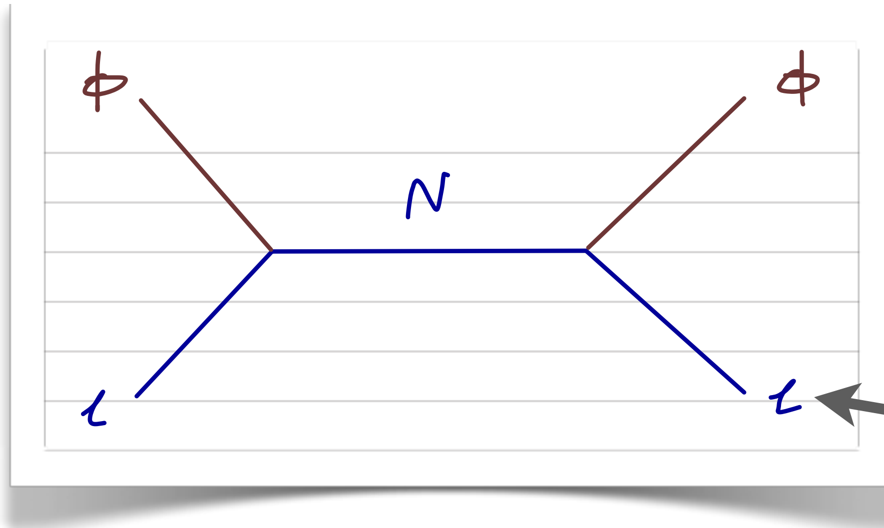
Introduction

- We know about neutrino masses.
  - Neutrinos have masses and this experimental evidence demands for a satisfactory theoretical explanation.
  - "Satisfactory" means no huge fine-tuning or parameter hierarchy.
  - The most popular such explanation is provided by the seesaw mechanism.
- We have the LHC.
  - The LHC has been running for two years, and many searches (including some for seesaw mediators) have been performed.
  - It is now being upgraded to 13.5 ± 0.5 TeV.
- This talk is about that: seesaw searches at the LHC.

Minimal seesaw models

Seesaw mediators

Type I

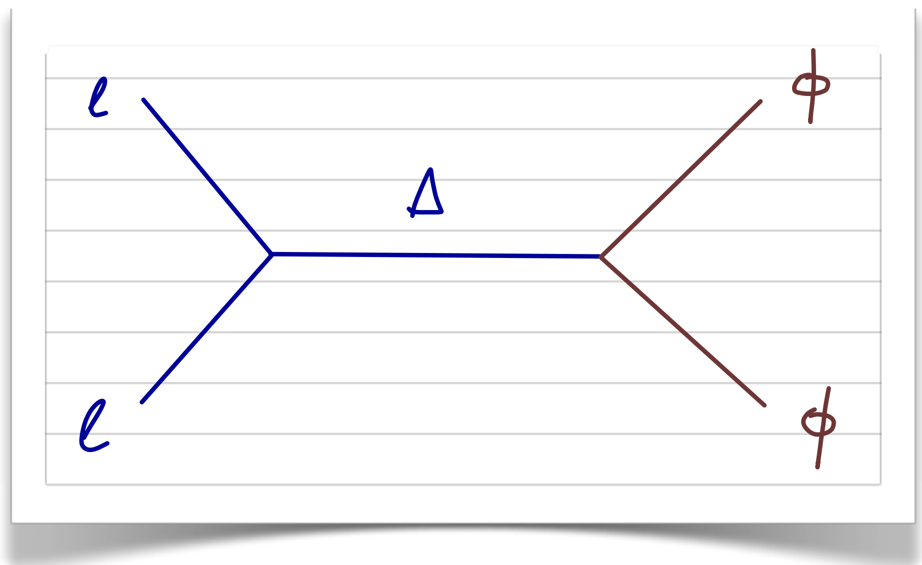


Majorana

N_i

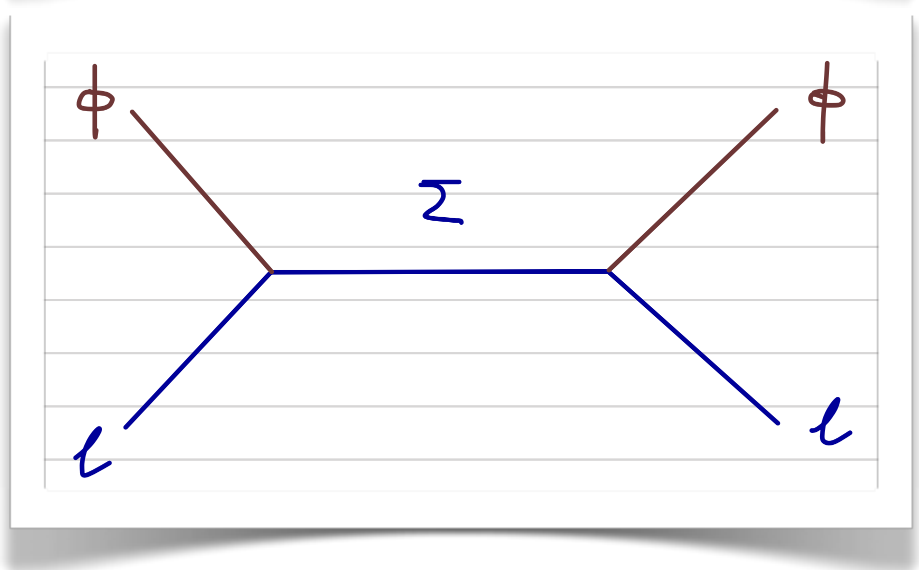
lepton doublet

Type II



$$\Delta = \begin{pmatrix} \Delta^{++} \\ \Delta^{+} \\ \Delta^{0} \end{pmatrix}$$

Type III



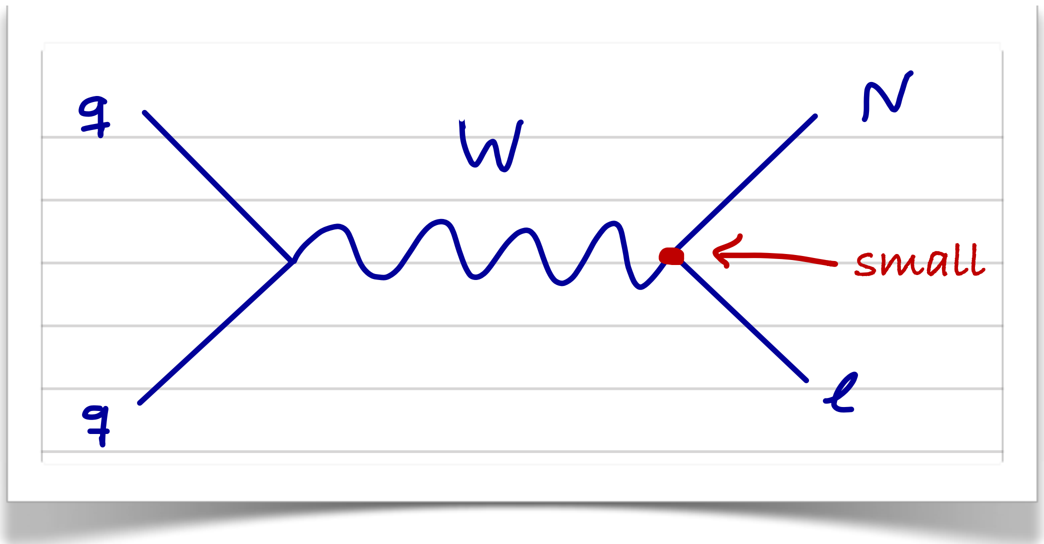
Majorana

$$\Sigma_i = \begin{pmatrix} E_i^{+} \\ N_i \\ E_i^{-} \end{pmatrix}$$

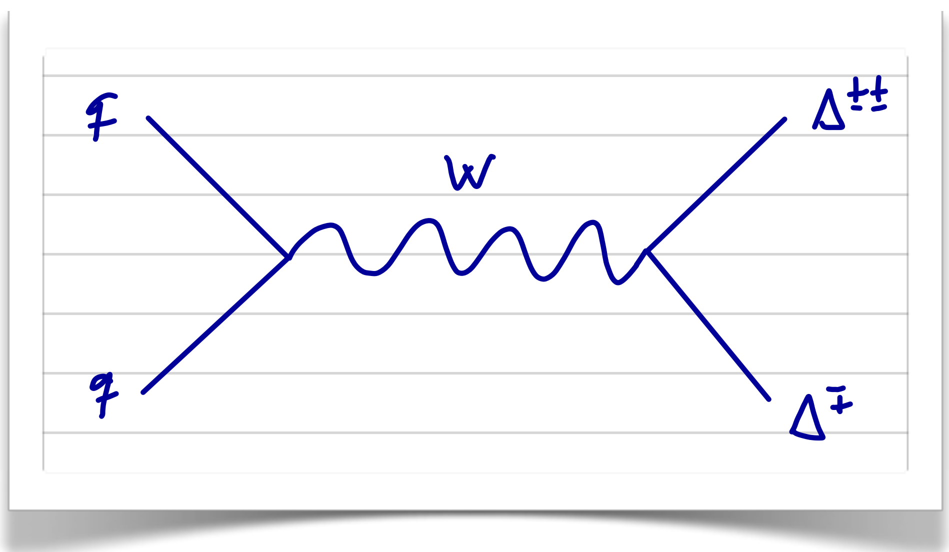
Dirac

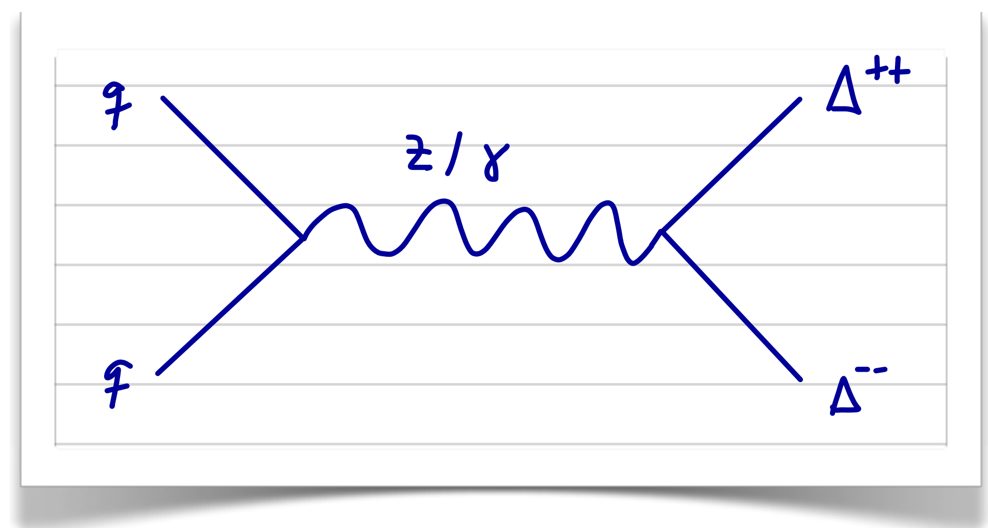
If they are light enough, seesaw mediators can be produced at LHC

Type I

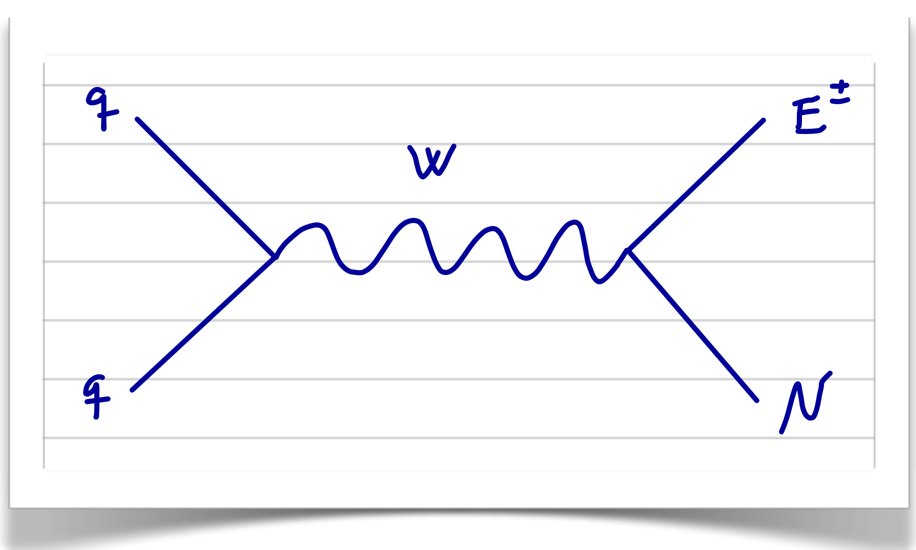


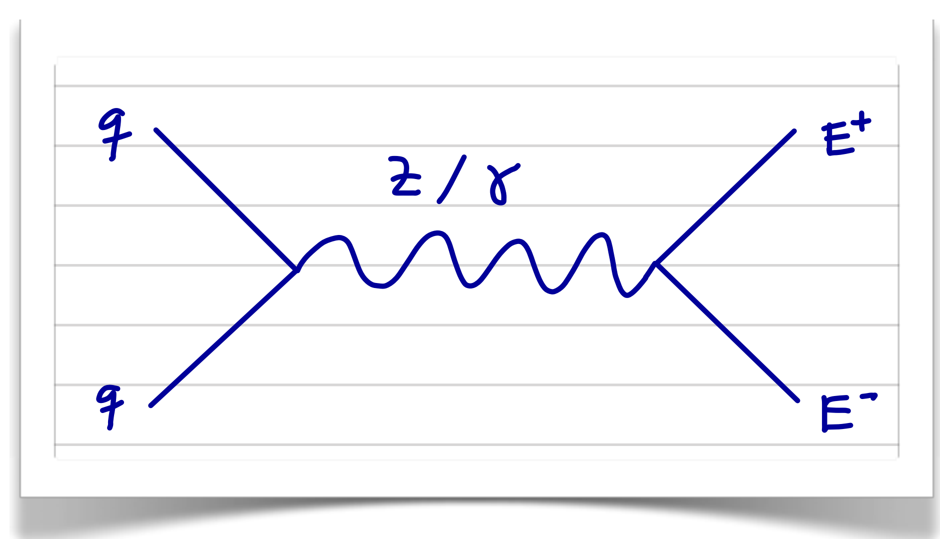
Type II





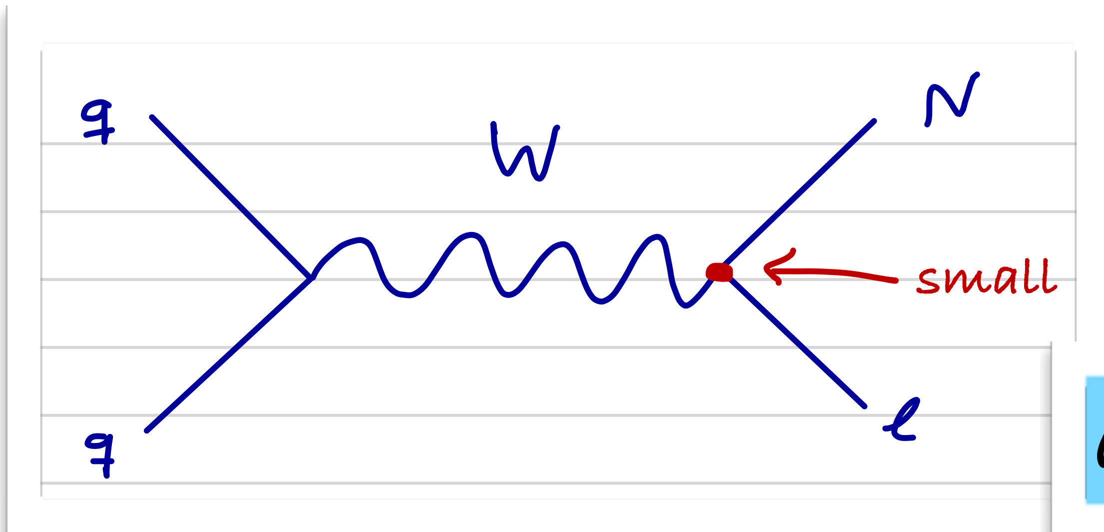
Type III





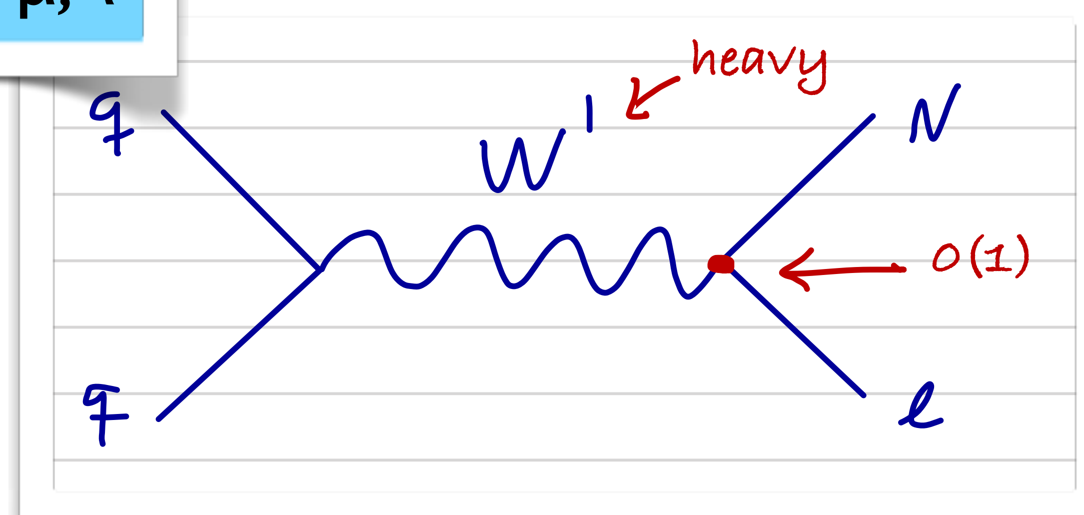
Extra interactions

The presence of extra interactions is crucial for type-I seesaw where N production is suppressed by their small mixing with SM leptons $\ell = e, \mu, \tau$.



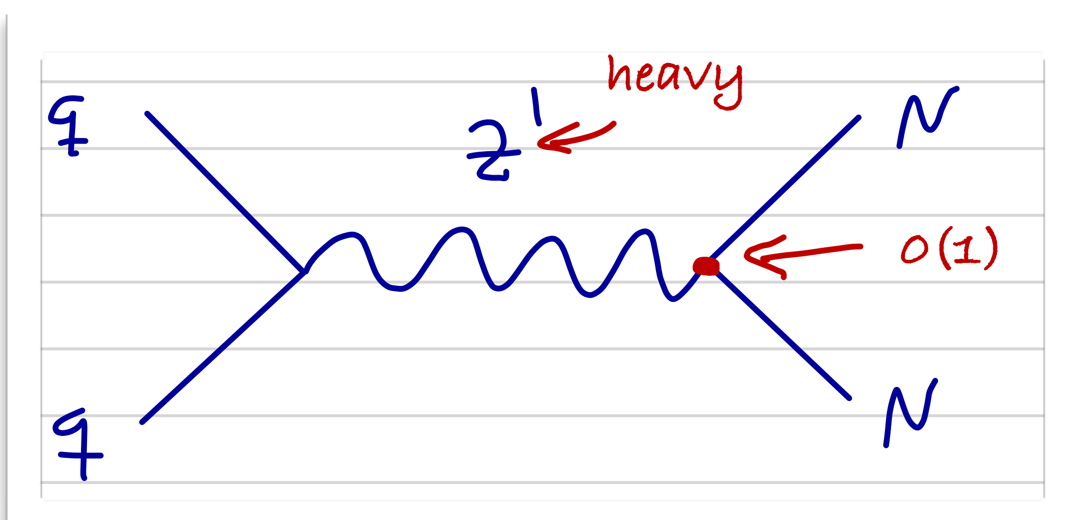
only SM interactions

$\ell = e, \mu, \tau$



extra W′: W_R, …

Keung & Senjanovic '86



extra Z′: $U(1)_{B-L}$, …

Once produced, they decay. Example: decays of a heavy *N*

via small coupling to SM bosons and light leptons

$$\left\{ \begin{array}{l} N \to W^+ \ell^- \\ N \to W^- \ell^+ \\ N \to Z\nu \\ N \to H\nu \end{array} \right.$$

relative BR depend mildly on N mass

relative importance depends on coupling to SM bosons and masses

LNV, not present if *N* Dirac particle

via large coupling to new heavy bosons (if any)

$$\left\{ \begin{array}{l} N \to (W_R^+)^* \ell^- \to jj\ell^-, t\bar{b}\ell^- \\ N \to (W_R^-)^* \ell^+ \to jj\ell^+, \bar{t}b\ell^+ \end{array} \right.$$

relative BR depend mildly on N, W_R mass

ℓ = e, μ, τ *any* lepton flavour in principle

Interlude #1

Heavy *N* can also be Dirac particles in seesaw I and III

Type I inverse seesaw

Mohapatra & Valle '86

Majorana

quasi-Dirac

$$N_i^1 + N_i^2 \to N_i$$

No LNV signals at LHC

Type III inverse seesaw

Aguila & JAAS '08

quasi-Dirac

$$\Sigma_i^1 + \Sigma_i^2 \to E_i^1, E_i^2, N_i$$

Dirac

Production and cascade decay of seesaw messengers yields multilepton signals

Fileviez et al. '08, Aguila & JAAS '08, JAAS '09

best expected sensitivity

	$\ell^\pm$	$\ell^+\ell^-$	$\ell^\pm\ell^\pm$	$\ell^\pm\ell^+\ell^-$	$\ell^+\ell^+\ell^-\ell^-$	$\ell^\pm\ell^\pm\ell^+\ell^-$
type I	✔	✔	✔	✔	✗	✗
type I inverse	✔	✔	✗	✔	✗	✗
type I (W')	✔	✔	✔	✔	✗	✗
type I inverse (W')	✔	✔	✗	✔	✗	✗
type I (Z')	✔	✔	✔	✔	✔	✗
type I inverse (Z')	✔	✔	✗	✔	✔	✗
type II (large Y)	✔	✔	✔	✔	✔	✗
type II (small Y)	✔	✔	✔	✔	✔	✗
type III	✔	✔	✔	✔	✔	✔
type III inverse	✔	✔	✔	✔	✔	✔

smaller signals

smaller backgrounds

Back to 2009...

Identifying new quarks and leptons at LHC: the role of multi-lepton signals

J. A. Aguilar-Saavedra

Departamento de Física Teórica y del Cosmos
Universidad de Granada

Corfu Summer Institute, September 3$^{\text{rd}}$ 2009

Today…

ATLAS CMS

only search for inverse seesaw

most popular channel

underrated channel

	$\ell^\pm$	$\ell^+\ell^-$	$\ell^\pm\ell^\pm$	$\ell^\pm\ell^+\ell^-$	$\ell^+\ell^+\ell^-\ell^-$	$\ell^\pm\ell^\pm\ell^+\ell^-$
type I	✔	✔	✔	✔	✗	✗
type I inverse	✔	✔	✗	✔	✗	✗
type I (W')	✔	✔	✔	✔	✗	✗
type I inverse (W')	✔	✔	✗	✔	✗	✗
type I (Z')	✔	✔	✔	✔	✔	✗
type I inverse (Z')	✔	✔	✗	✔	✔	✗
type II (large Y)	✔	✔	✔	✔	✔	✗
type II (small Y)	✔	✔	✔	✔	✔	✗
type III	✔	✔	✔	✔	✔	✔
type III inverse	✔	✔	✔	✔	✔	✔

no searches yet!

What's new in the talk? The τ lepton enters the game

It was always there, and the sensitivity was considered fairly insignificant.
But now:

- Some cases have been identified in which the sensitivity is interesting
- its role in explaining possible signals has been [again] highlighted

Review: flavour in type-II

In type II seesaw the flavour mixing of triplets with leptons (and then their decays) is fixed by neutrino data.

large Y $\quad \left\{ \begin{array}{l} \Delta^{++} \to \ell_i^+ \ell_j^+ \\ \Delta^{+} \to \ell_i^+ \bar{\nu}_j \end{array} \right.$ $\quad\longleftarrow\quad$ determined by MNS matrix and neutrino masses

small Y $\quad \left\{ \begin{array}{l} \Delta^{++} \to W^+ W^+ \\ \Delta^{+} \to W^+ Z, t\bar{b} \end{array} \right.$ $\quad\longleftarrow\quad$ flavour democratic

Garayoa & Schwetz '07
Akeroyd et al, '07
Kadastik et al. '07
Fileviez et al. '08
Aguila & JAAS '08
Melfo et al. '11
…

Then, once we assume normal or inverted hierarchy, the different branching ratios for flavours *i, j* is fixed and flavour-consistent searches for seesaw II can be performed by experiments. CMS actually did it.

Review: flavour in type-I, type-III

On the other hand, in type I, III seesaw the heavy-light mixing and neutrino mass matrix are not directly related.

$$V_{\ell_i N_j} = \frac{v}{\sqrt{2}} \frac{Y_{ij}}{M_j} \qquad (m_\nu)_{ij} = -\frac{v^2}{2} \frac{Y_{ik} Y_{jk}}{M_k}$$

$\Rightarrow$ "flavour benchmarks" commonly used for LHC searches

Although the mixing of a heavy neutrino *N* with e, μ, τ is in principle arbitrary, there are experimental constraints: del Aguila et al. '08

type I $\longrightarrow$

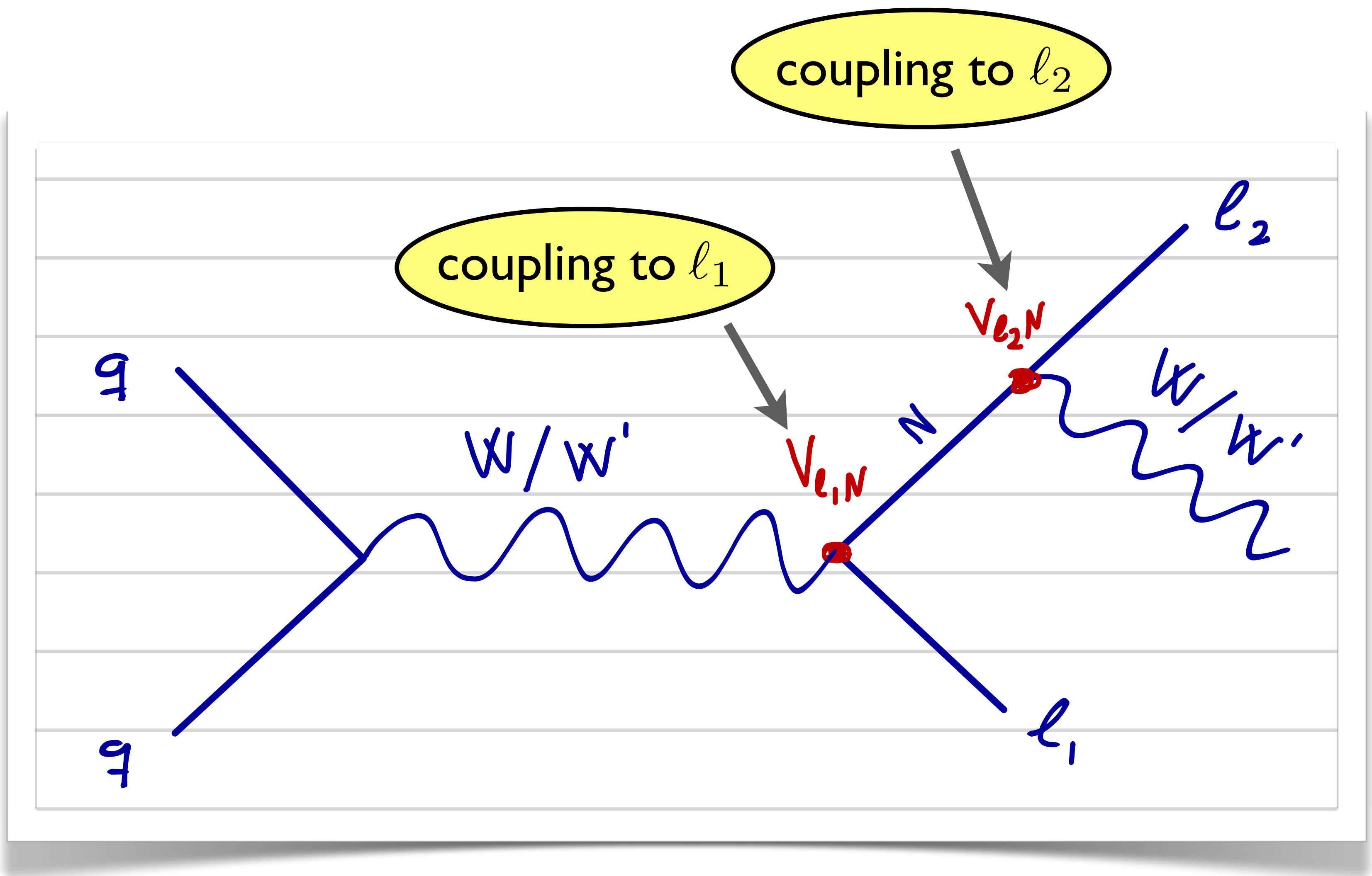
$$|V_{eN}| \leq 0.055 \quad |V_{\mu N}| \leq 0.057 \quad |V_{\tau N}| \leq 0.079$$

type III $\longrightarrow$

$$|V_{eN}| \leq 0.019 \quad |V_{\mu N}| \leq 0.017 \quad |V_{\tau N}| \leq 0.027$$

and very stringent limits (from low-energy LFV) for simultaneous mixing with e and μ.

Coupling of *N* (Σ in type-III seesaw) determines the flavour of the signals



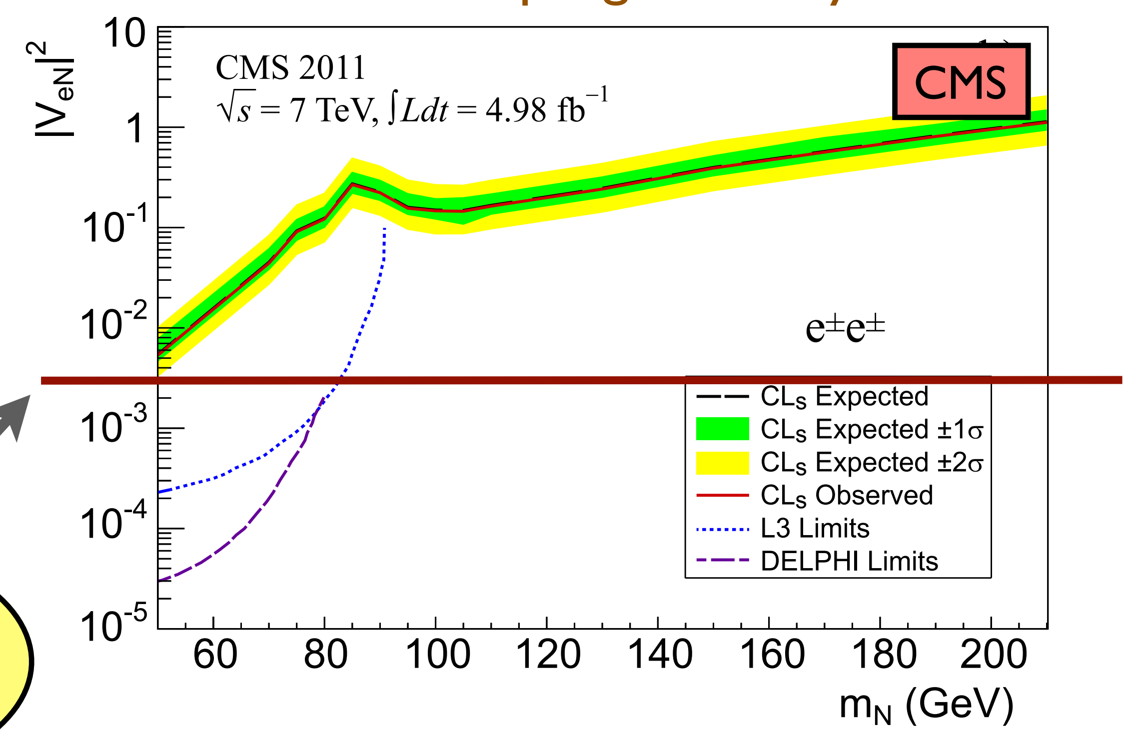
$$\sigma(\ell_1 \ell_2 X) \propto |V_{\ell_1 N}|^2 \frac{|V_{\ell_2 N}|^2}{|V_{eN}|^2 + |V_{\mu N}|^2 + |V_{\tau N}|^2}$$

But most flavour benchmarks used are actually *flavourless benchmarks*

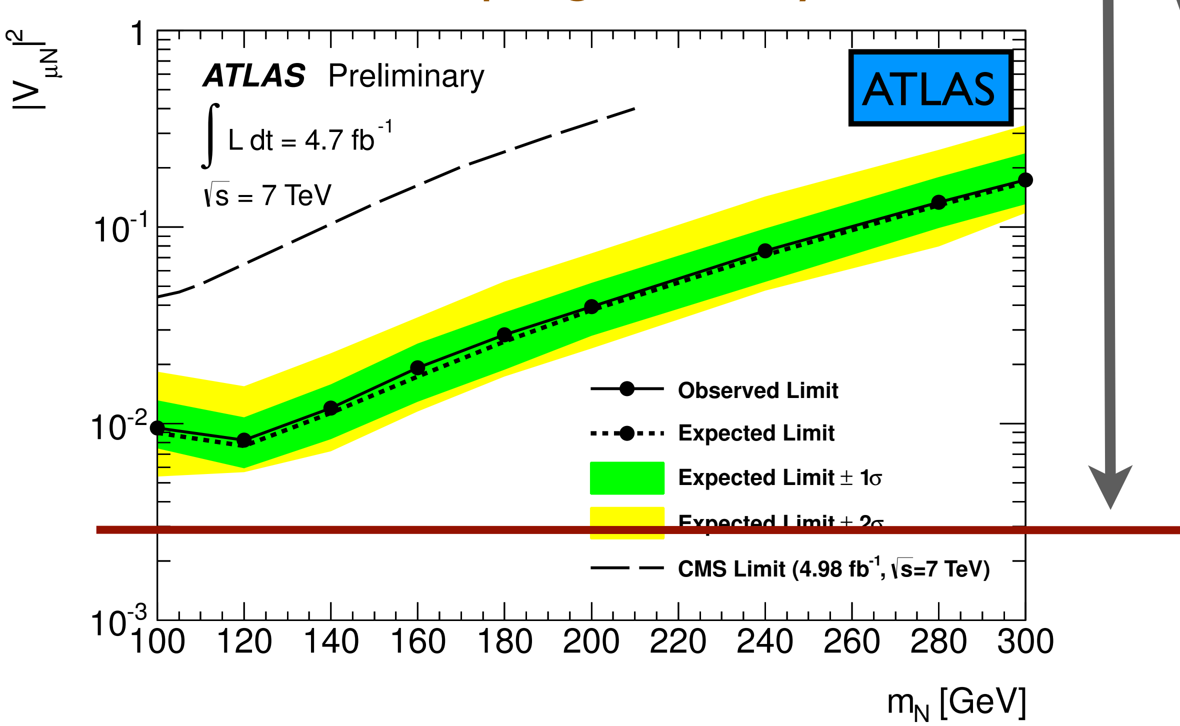
searches for type-I seesaw

$$|V_{eN}|^2 \leq 0.003$$
$$|V_{\mu N}|^2 \leq 0.0032$$

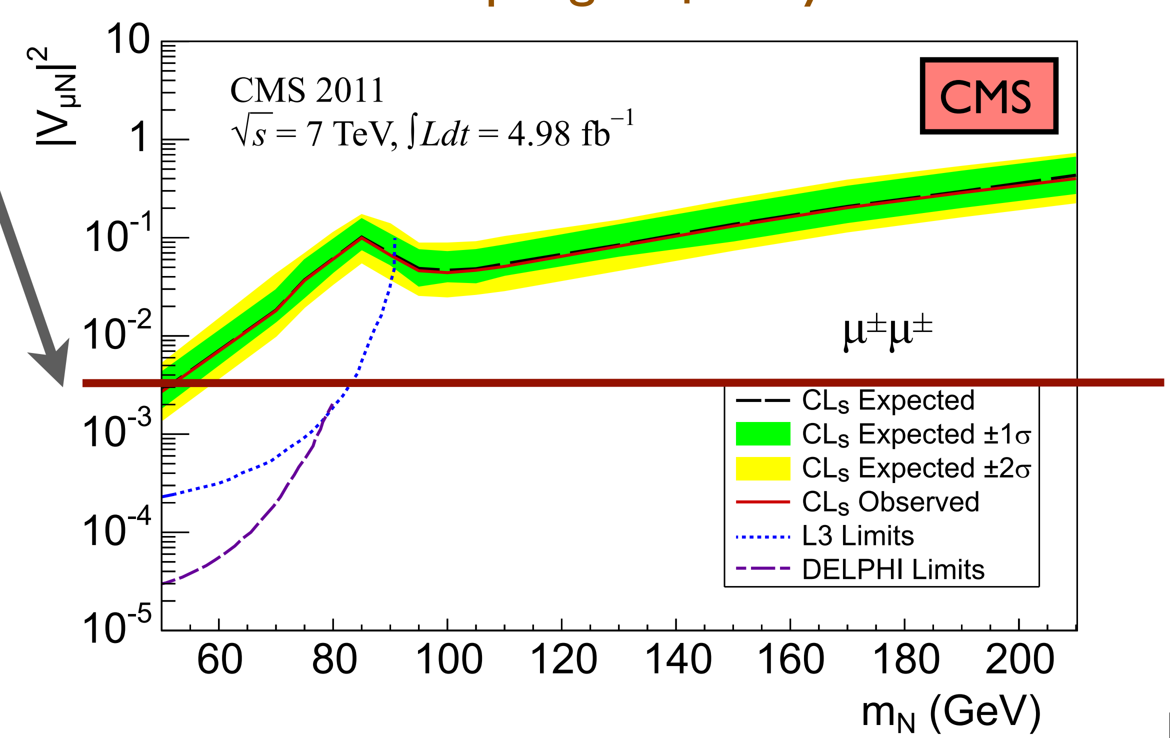
N coupling to e only



N coupling to μ only



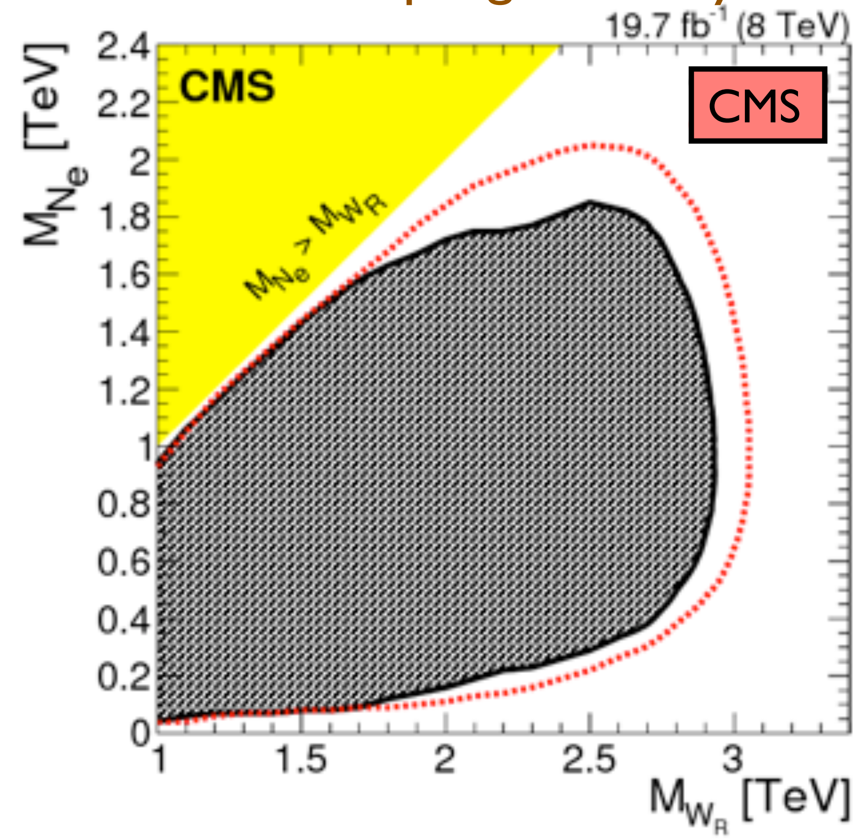
N coupling to μ only



Flavourless benchmarks are used even when not needed…

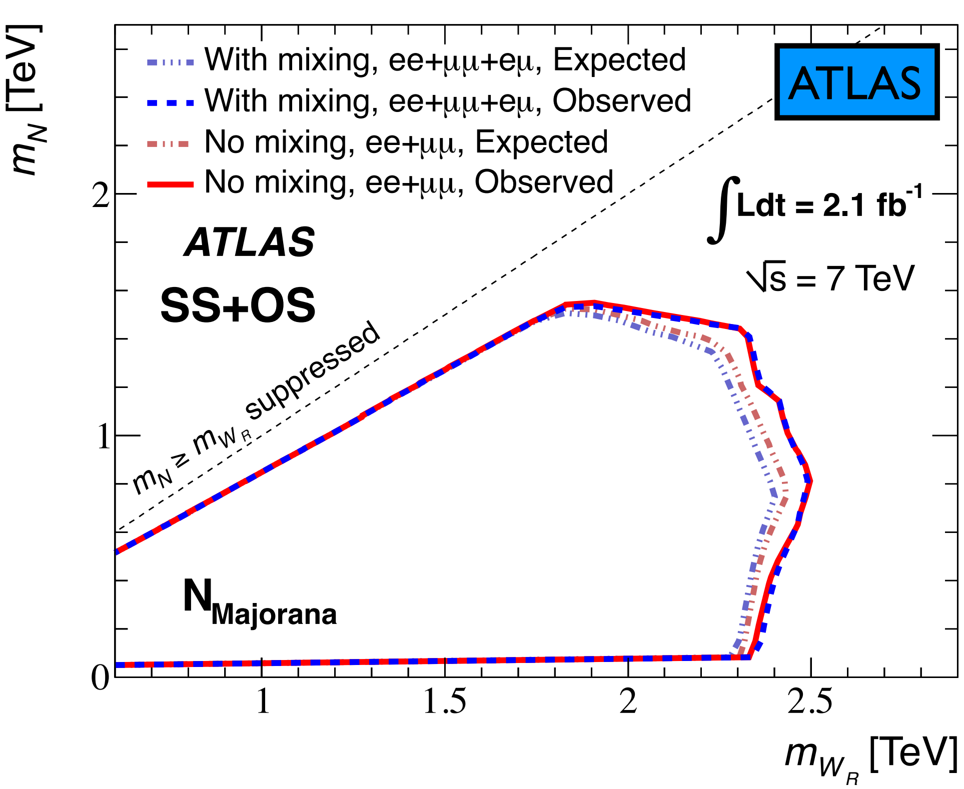
searches for type-I seesaw with W_R

N coupling to e only

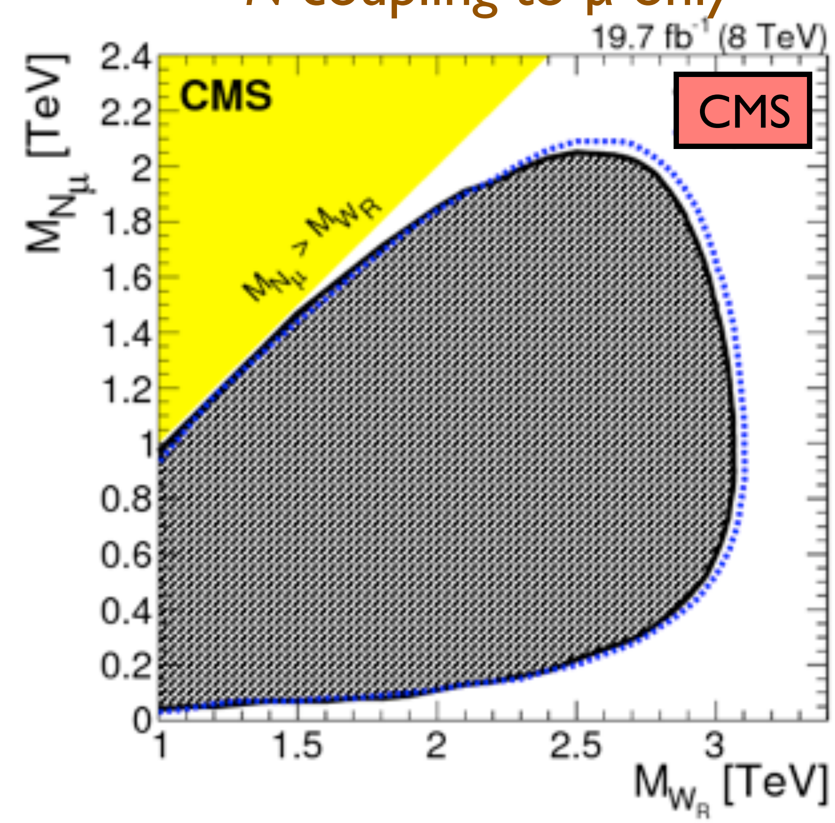


N_1 coupling to e and N_2 coupling to μ

Flavoured benchmark: N_1, N_2 coupling to e, μ



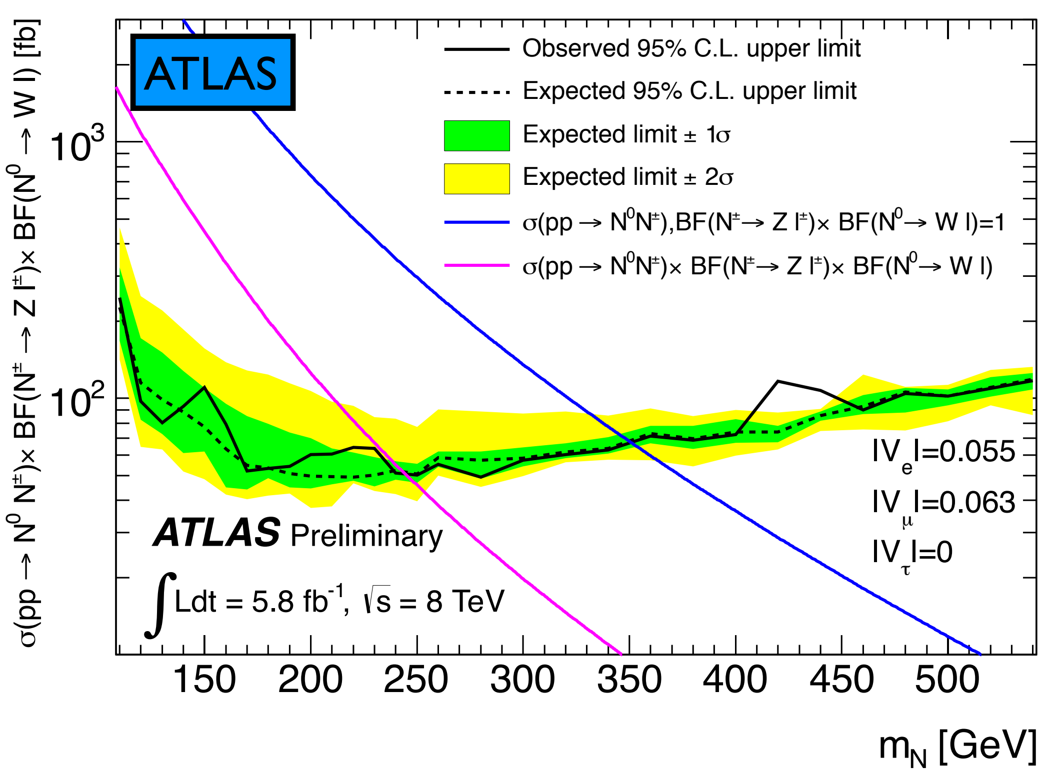
N coupling to μ only



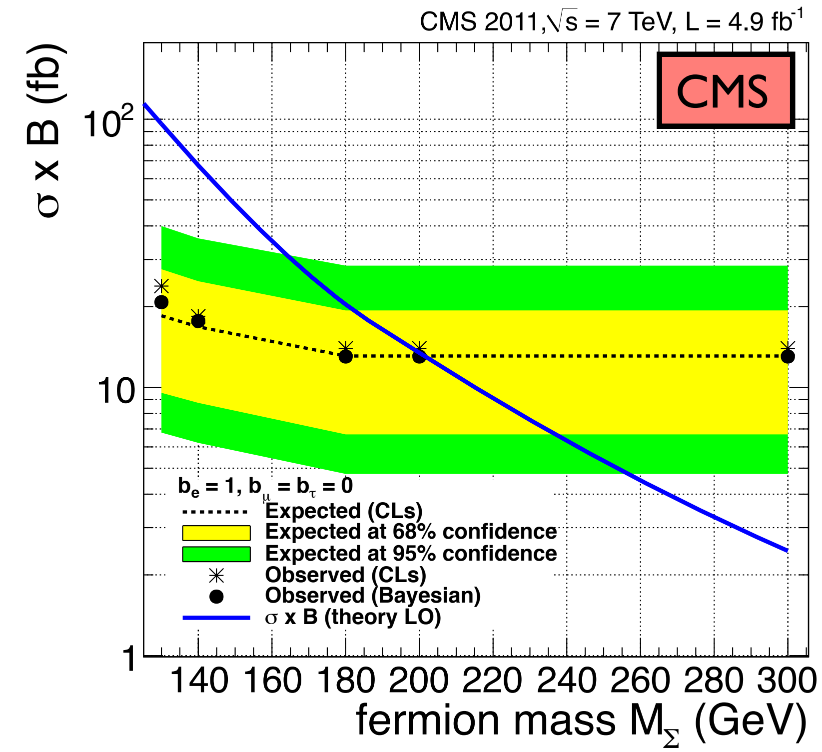
Flavourless benchmarks used in type-III seesaw too…

searches for type-III seesaw

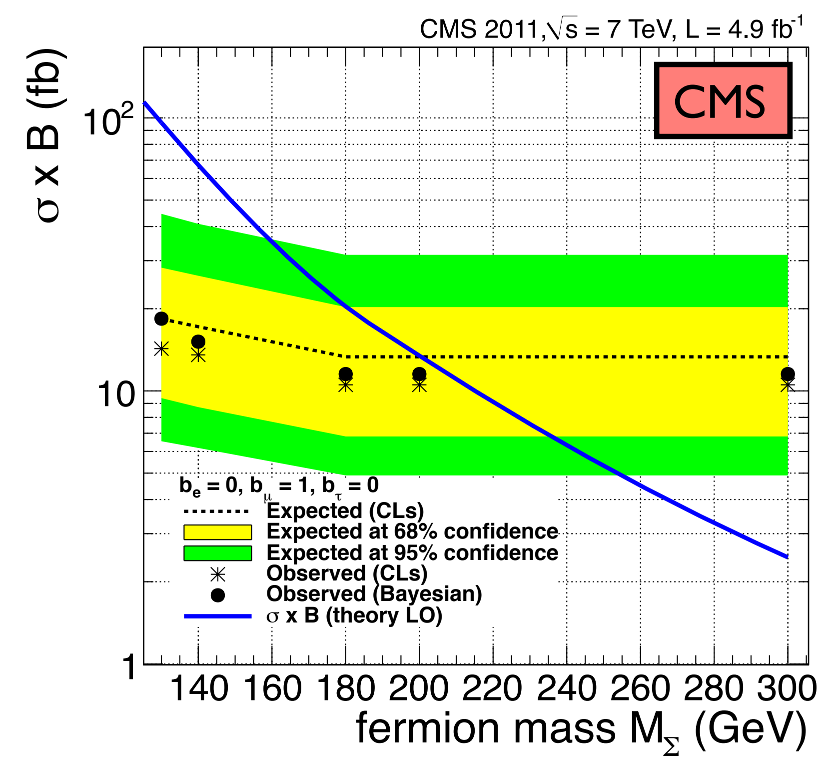
Flavoured benchmark violating $\mu \to e\gamma$ by 10^7 x



Σ coupling to e only



Σ coupling to μ only



Flavourless searches are clearly insufficient but flavoured reinterpretations [by theorists] are often possible

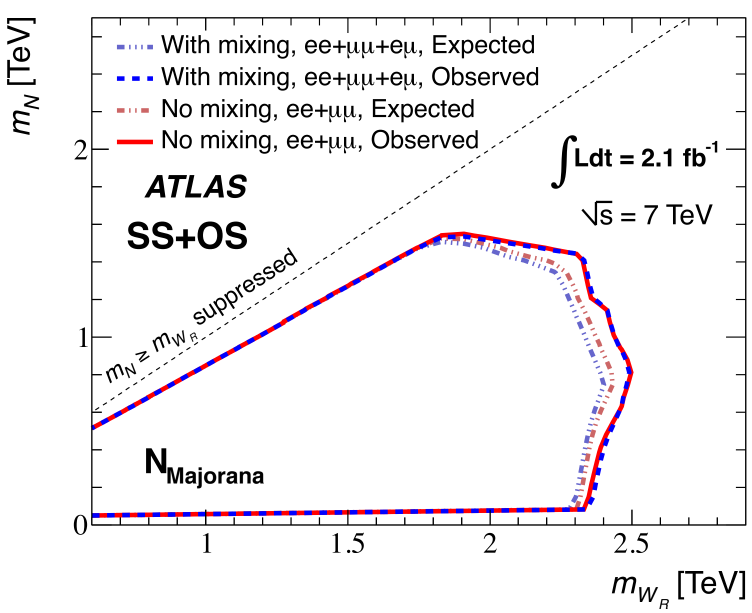
For heavy leptons coupling to the τ, the final states involve one or more τ, which subsequently can decay giving e, μ too, but

- the signals are smaller: $\mathrm{Br}(\tau \to e\nu\bar{\nu}, \mu\nu\bar{\nu}) \simeq 1/3$.
- the signals involve missing energy E_T.
- the resulting e, μ are softer.

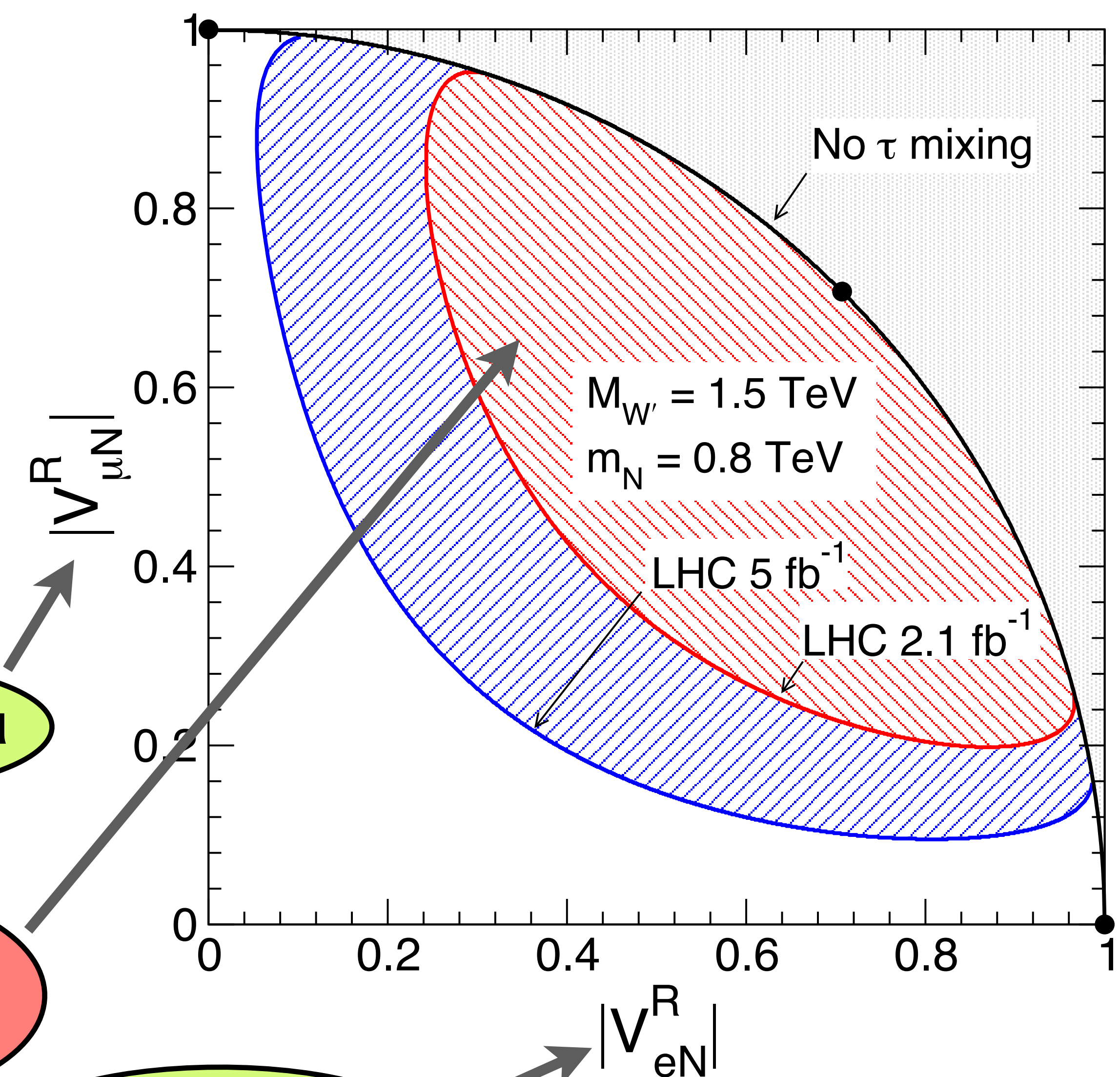
Reinterpretations of existing analyses (with fast simulation of new MC signals tuned to reproduce efficiencies in actual experiments) are possible if experimental analyses do not include a veto on E_T. JAAS et al. '12 '13 fix flavour structure and let m_N and $M_{W'}$ arbitrary

or

fix m_N and $M_{W'}$ and let flavour structure arbitrary



reinterpretation
of ATLAS results

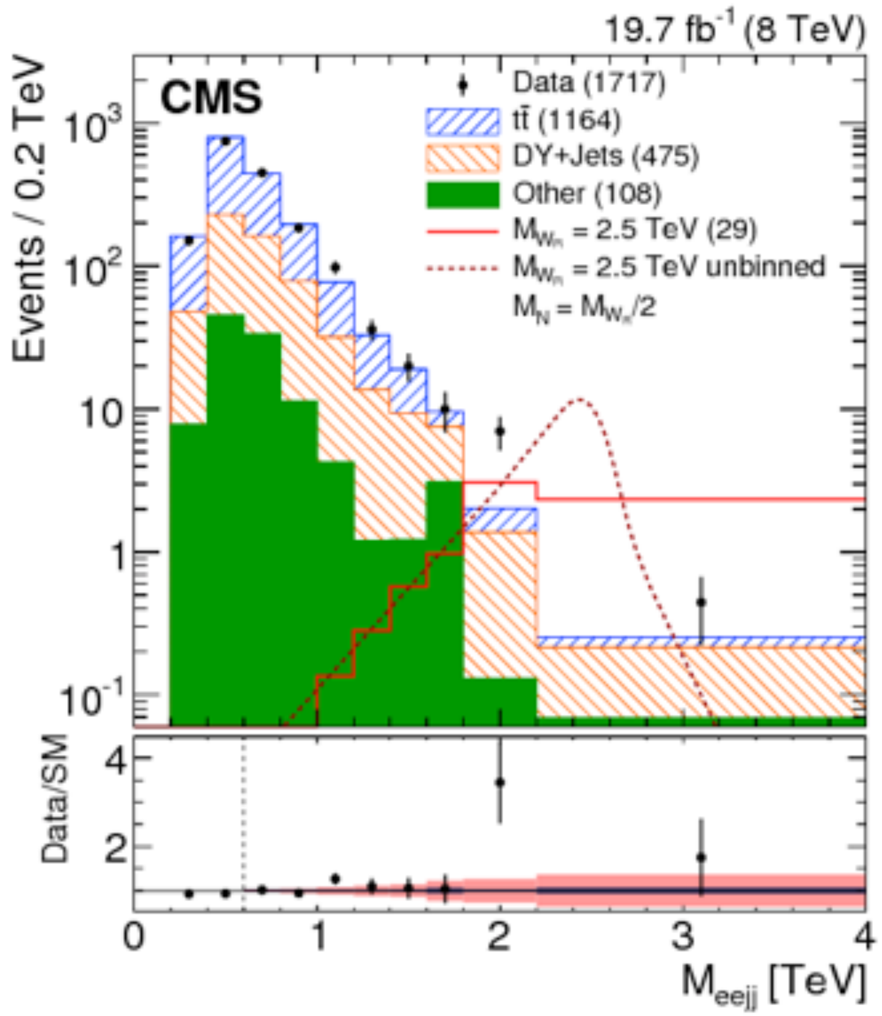


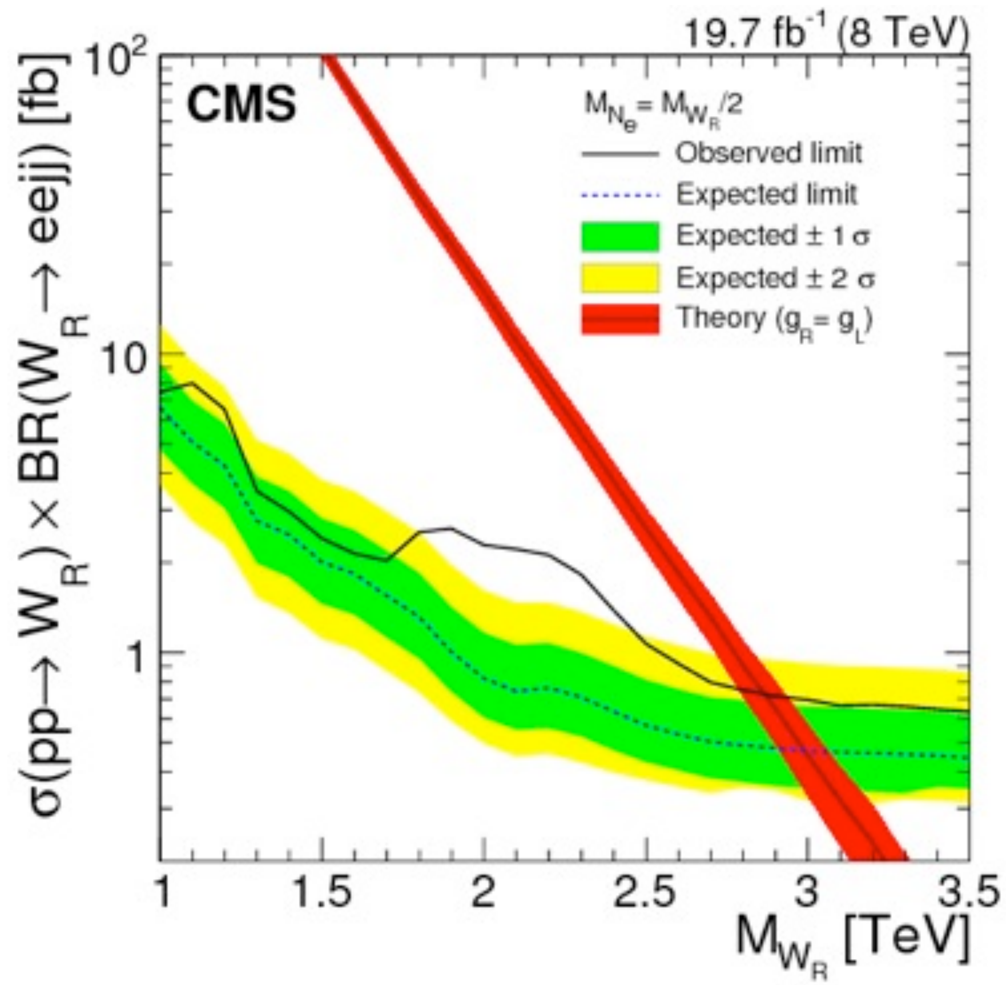
mixing with μ

exclusion region in flavour mixing space

mixing with e

The problem comes when one sees something like this…

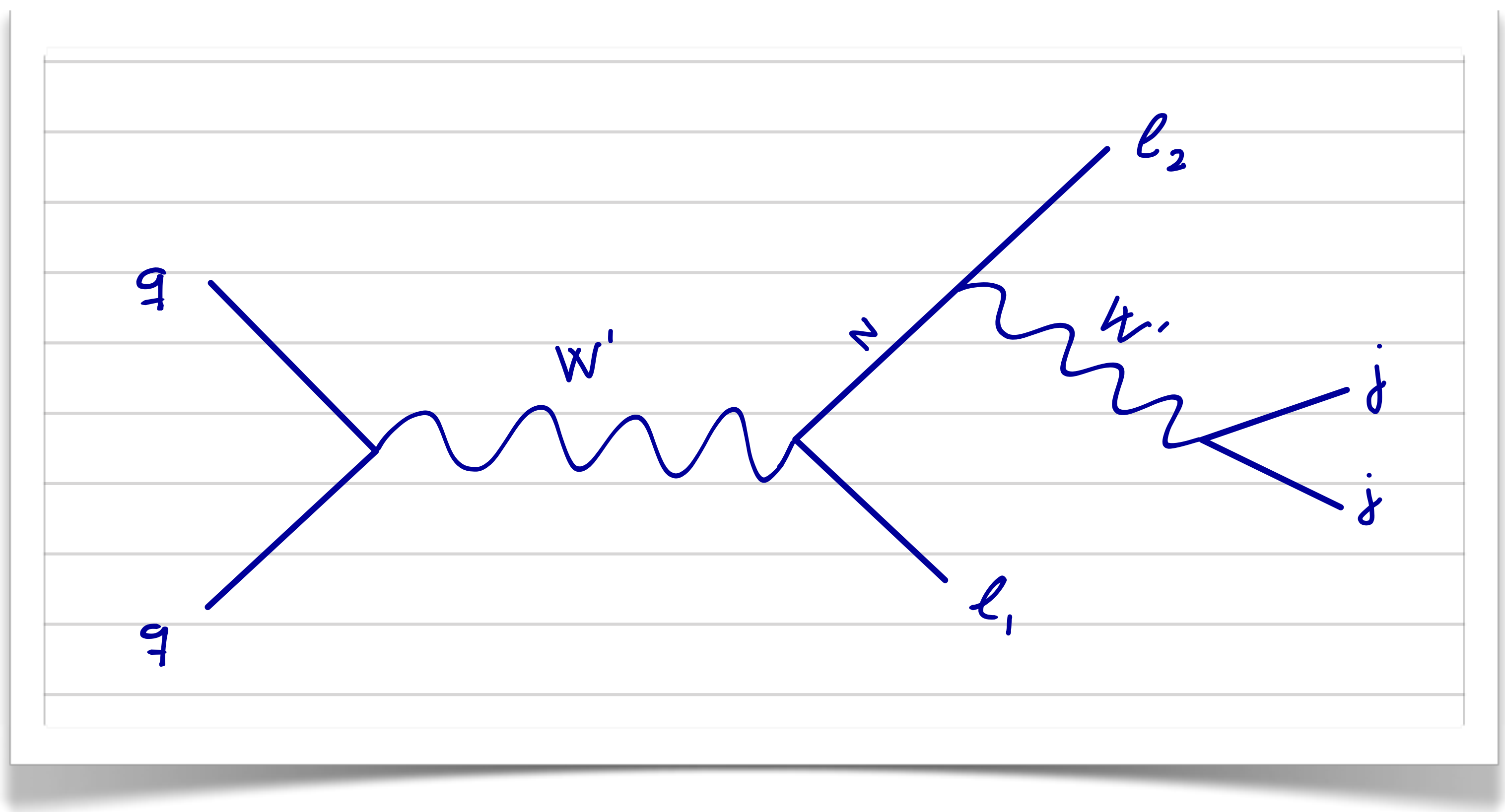




… with a disclaimer like that:

The $M_{\ell\ell jj}$ distributions for events satisfying all selection criteria appear in Fig. 2. A comparison of the observed data to SM expectations yields a normalized χ^2 of 1.4 (0.9) for electron (muon) channel events. We observe an excess of events in the electron channel with $1.8 < M_{eejj} <$ 2.2 TeV, with a local significance of 2.8σ using the method discussed in Section 7. This excess does not appear to be consistent with $W_R \to eN_e$ decay, as we find no localized excess in other distributions associated with these events. Examining the charge of the electrons used to build W_R boson candidates in data events with $1.8 < M_{eejj} < 2.2$ TeV, we find same-sign electrons in only one of the 14 reconstructed events.

This is a search for type-I seesaw in LR models

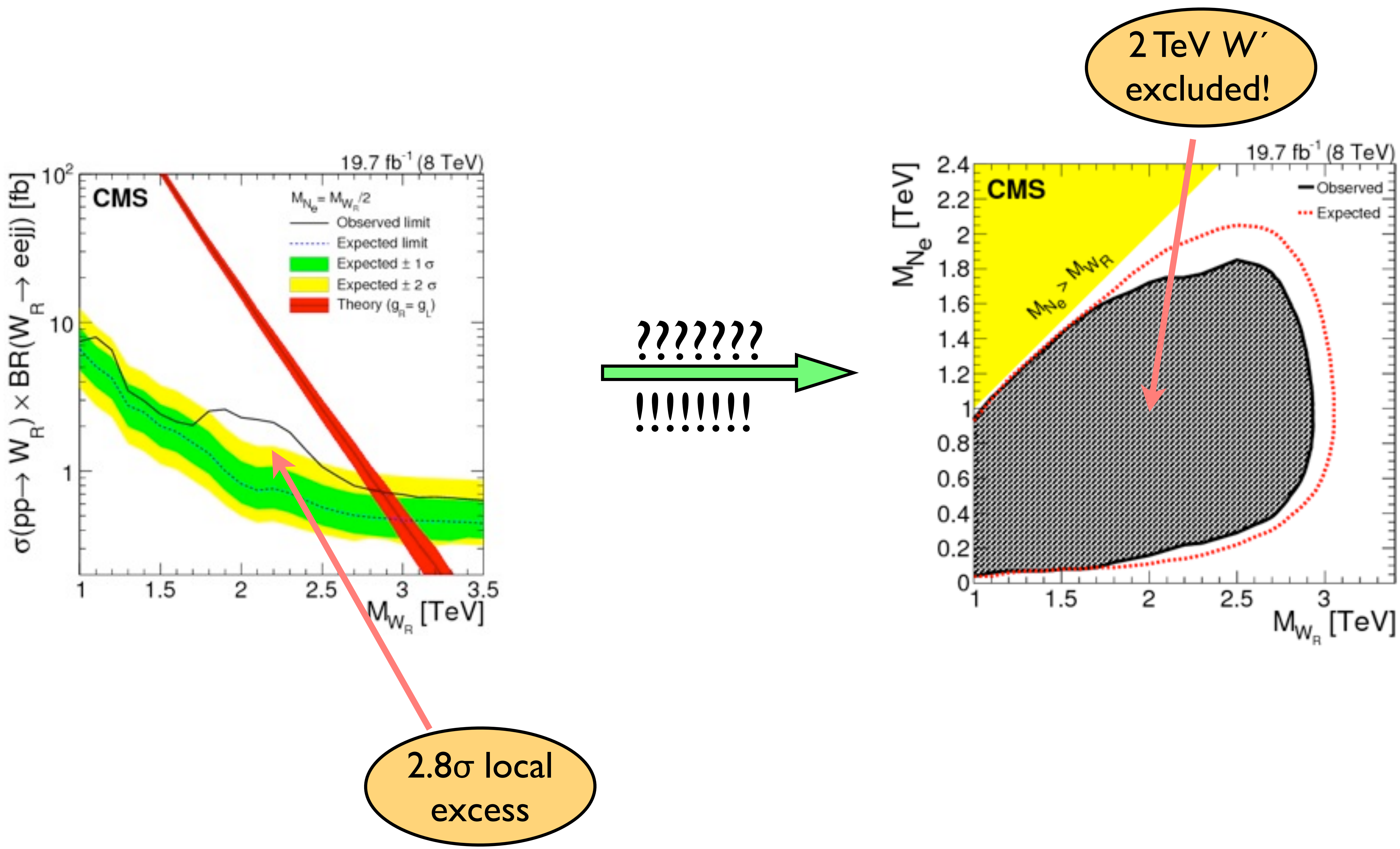


sensitive to quasi-Dirac N

focusing on same-flavour energetic leptons (ee, μμ) of either sign and jets

- $p_T \geq 60, 40$ GeV for leading and subleading lepton
- $p_T \geq 40$ GeV for jets
- dilepton invariant mass $m_{ll} \geq 100$ GeV
- W' reconstructed mass $m_{lljj} \geq 600$ GeV

And clearly, the flavourless approach is insufficient



The immediate question is whether this 2.8σ excess

— aside the fact that it might just be a statistical fluctuation —

is compatible or not with heavy neutrino production in a less restrictive framework. So, let us think what it could be in terms of seesaw.

- The excess only appears in *eejj*, and <u>not</u> in μμ*jj*. But eμ*jj* not analysed ☹

  ⇒ some new particle with non-universal lepton couplings

- The excess only appears in opposite-sign leptons

  ⇒ if this particle is heavy N, it has (quasi-)Dirac character

- The cross section is too large for type-III seesaw

  ⇒ new W' or Z' required

Interlude #2

Besides seesaw models, other explanations proposed every couple of days

- leptoquarks (2.4σ, 2.6σ excesses in other searches) Bai & Berger '14
- *R*-parity violating susy Chun et al. '14; Allanach et al. '14
- Z' + new leptons + new scalars Dobrescu & Martin '14

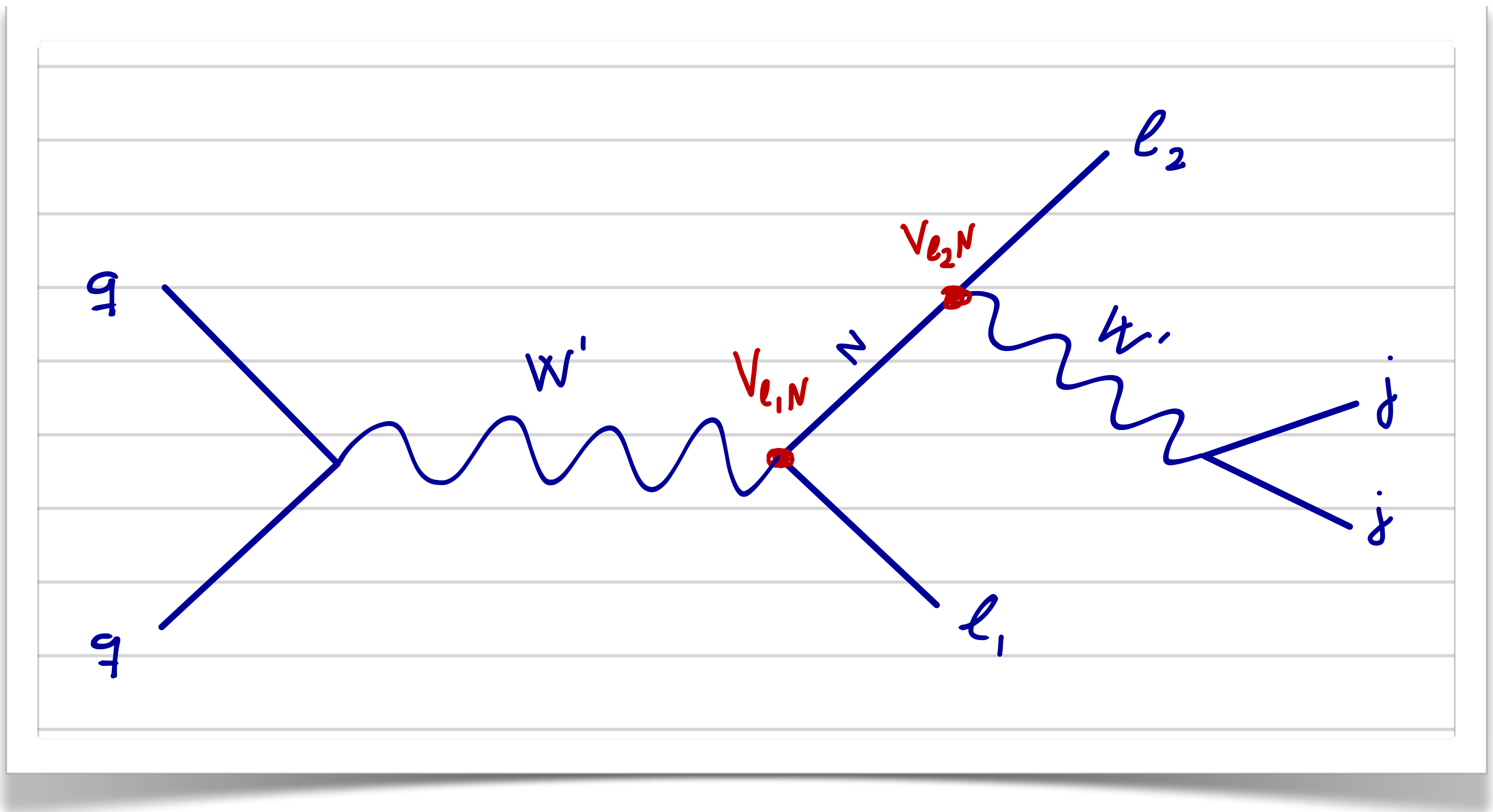
And other unflavoured W' explanations:

- LR model with $g' < g$ Deppisch et al. '14; Heikinheimo et al. '14

Plus some other related stuff Bhupal Dev et al. '14; Senjanovic & Tello '14 Fowlie & Marzola '14; Biswas et al. '14

W′ flavoured interpretation

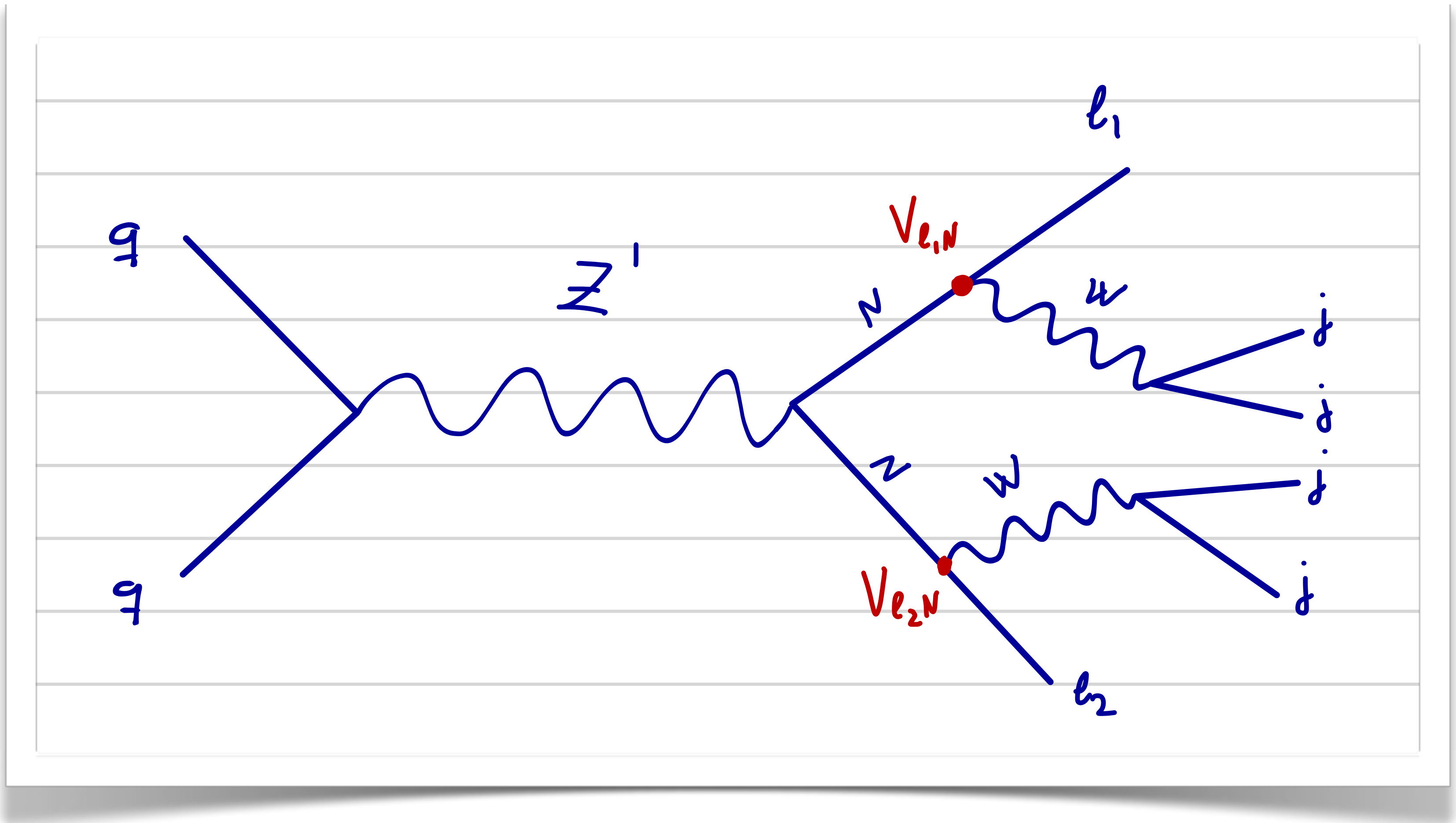
JAAS & Joaquim '14



- signal targeted by CMS search (left-right model)
- *m(eejj)* peaks at $M_{W'}$
- distributions smeared if significant τ mixing
- RH mixings satisfy $|V_{eN}|^2 + |V_{\mu N}|^2 + |V_{\tau N}|^2 = 1$

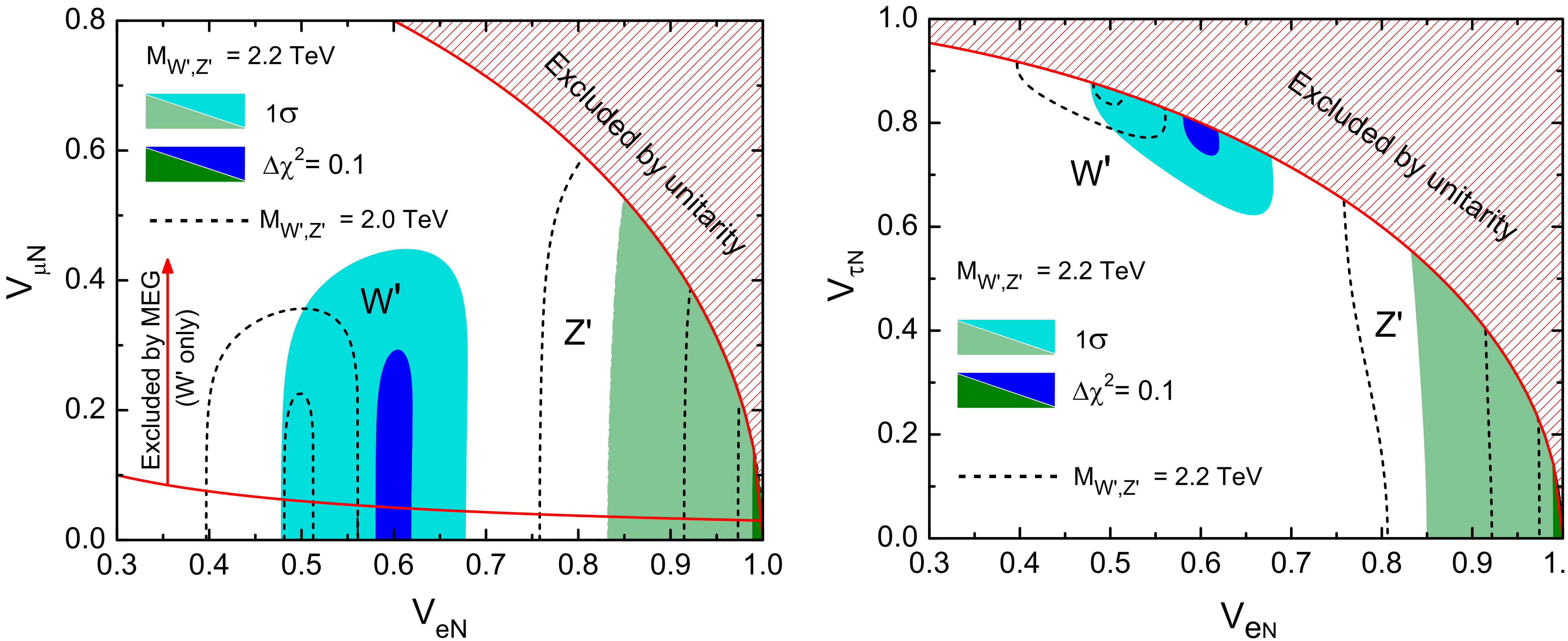
Z' flavoured interpretation

JAAS & Joaquim '14



- obviously requires leptophobic Z' — Aguila & JAAS '07
- *m(eejj)* still peaks close to $M_{Z'}$ because two highest p_T jets are chosen
- other distributions already smooth even if mixing only with e
- mixings are LH and can be normalised to $|V_{eN}|^2 + |V_{\mu N}|^2 + |V_{\tau N}|^2 = 1$

Reproducing the flavour of the signals



- fast sim slightly tuned to reproduce efficiencies of CMS analysis
- assuming $g' = g$ for the moment
- signal suggests $V_{\mu N} = 0$, which is in agreement with $\mu \to e\gamma$ bounds in the case of W'. For Z' no LFV problem because $V_{\ell N}$ can be small

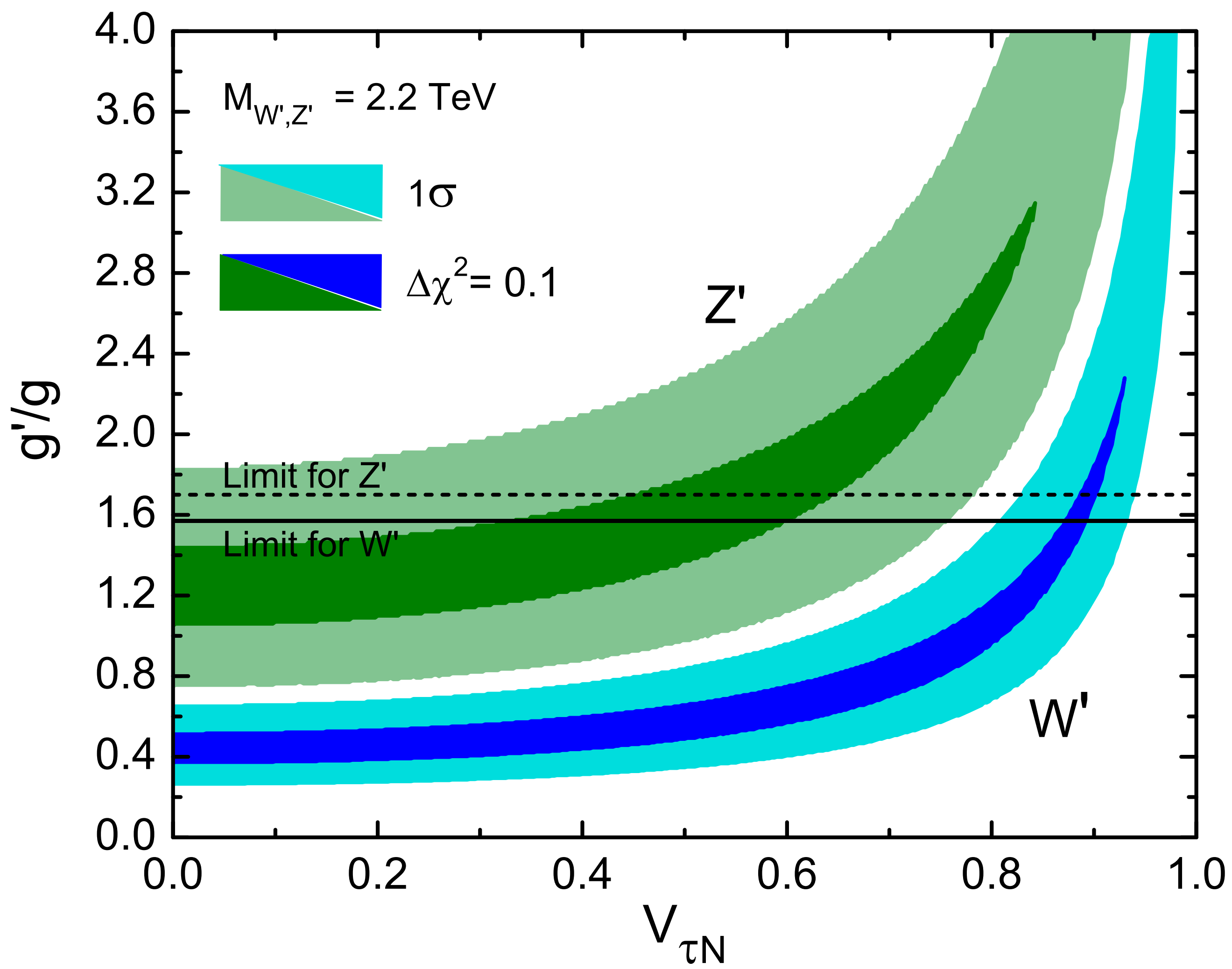
Interlude #3

Notice that even if $V_{\tau N}$ is sizable (but not close to one), dielectron signals are much larger than dimuon signals if $V_{\mu N} \simeq 0$

$$\sigma(ee) \propto \begin{cases} |V_{eN}|^4 \\ 2 \times |V_{eN}|^2 |V_{\tau N}|^2 \, \mathrm{Br}(\tau \to e\nu\bar{\nu}) \\ |V_{\tau N}|^2 \, \mathrm{Br}(\tau \to e\nu\bar{\nu})^2 \end{cases}$$

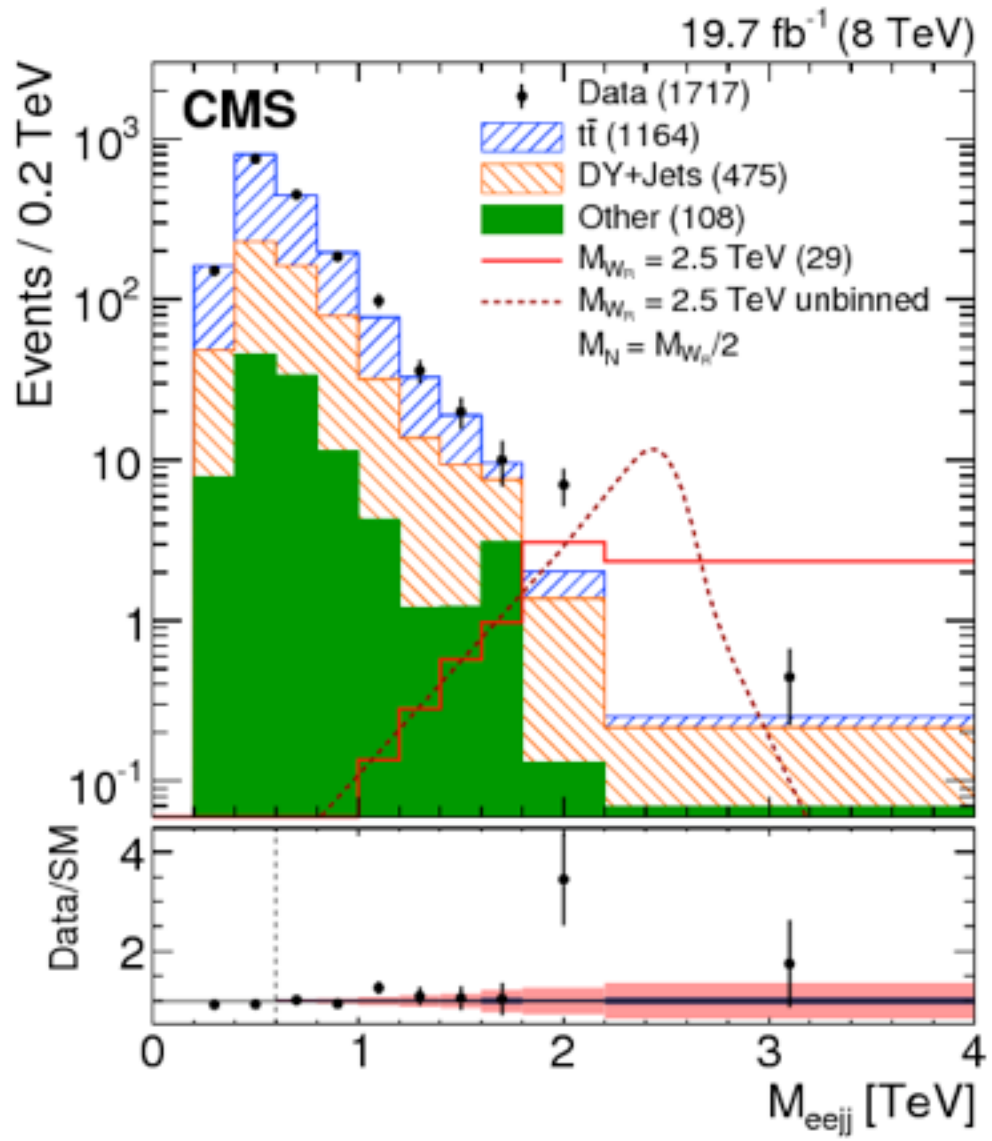
$$\sigma(\mu\mu) \propto |V_{\tau N}|^2 \, \mathrm{Br}(\tau \to \mu\nu\bar{\nu})^2$$

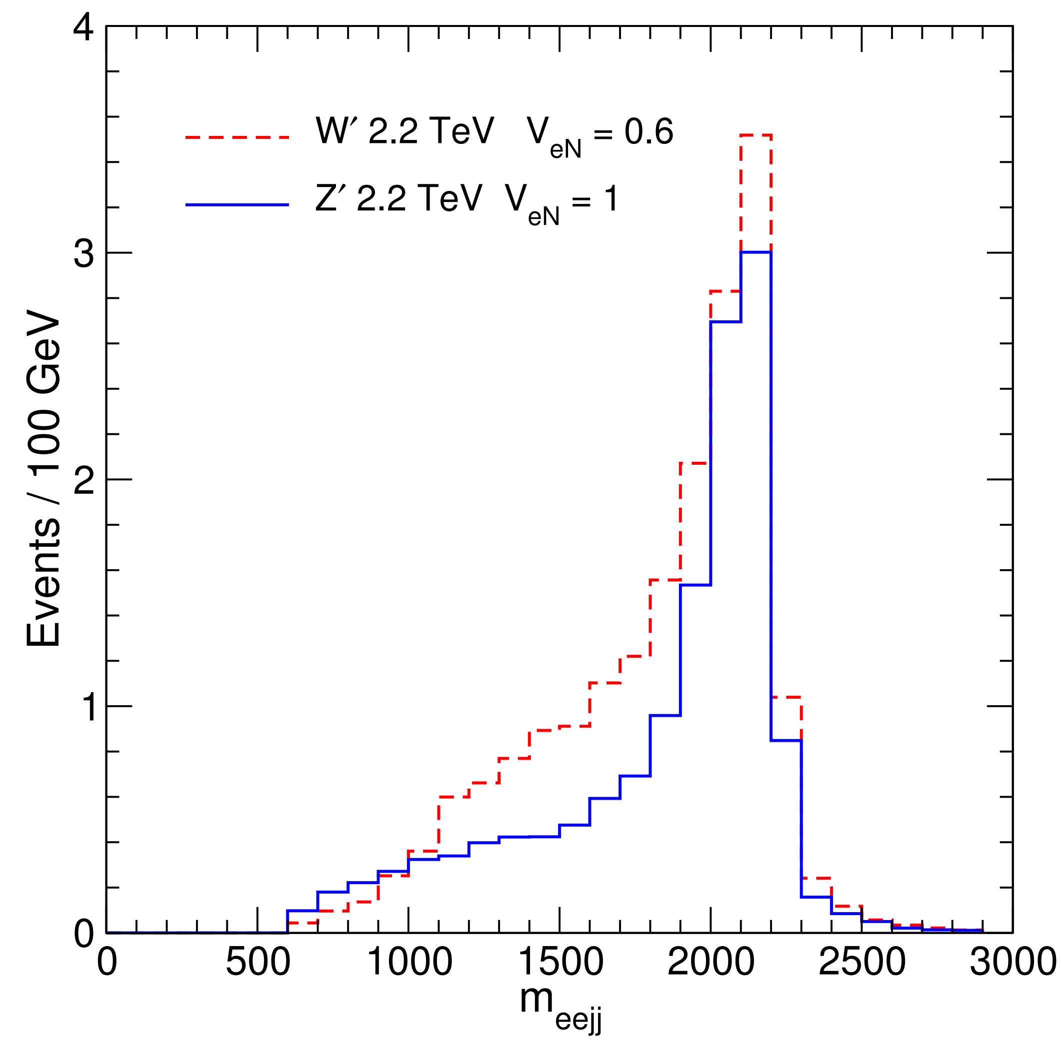
Constraints?



- assuming $V_{\mu N} = 0$ as suggested by the excess
- there is room to explain the size of the signal without conflicts with
  - dijets
  - $t\bar{t}, t\bar{b}$ resonances

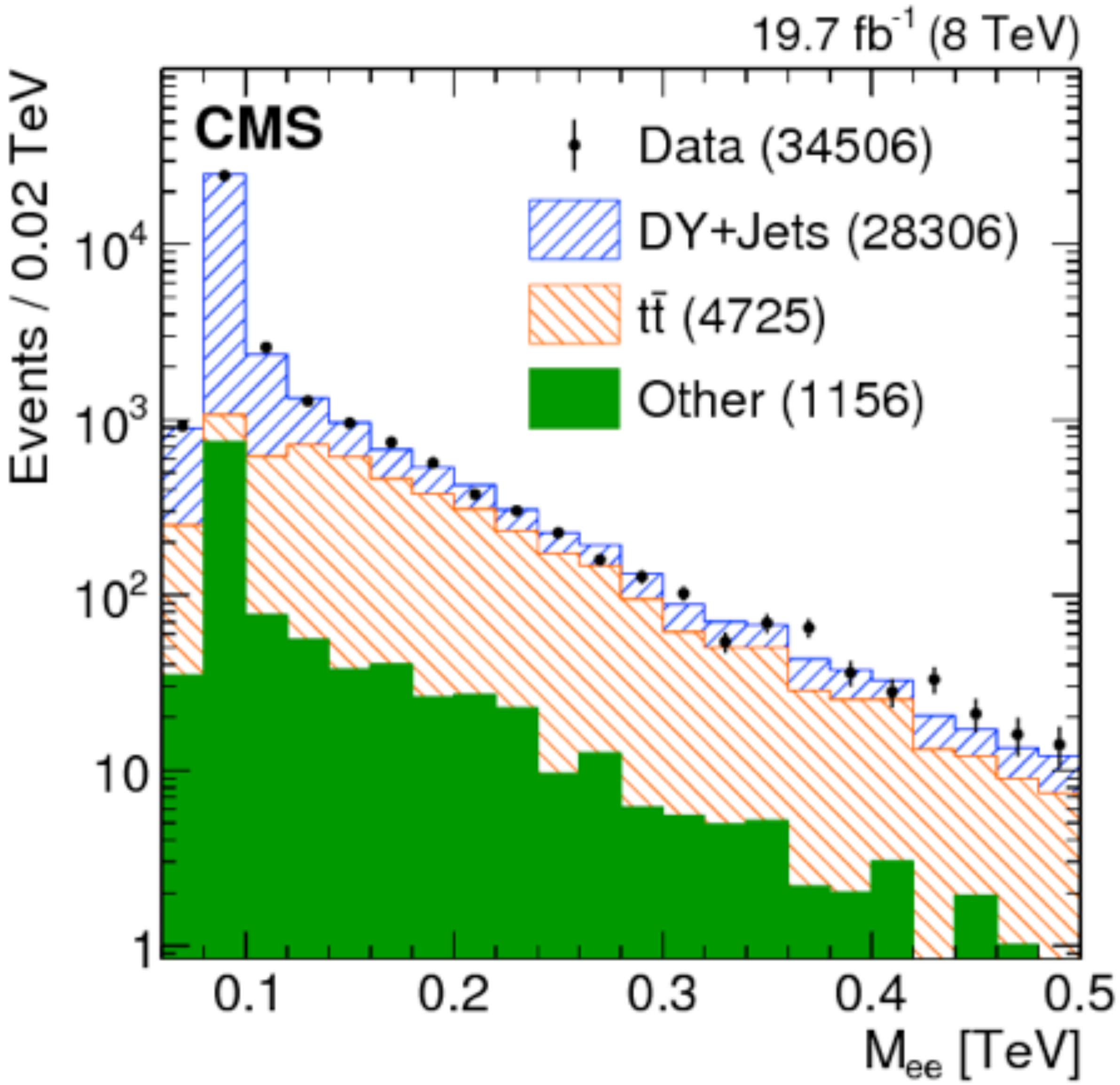
Distributions: W' reconstructed mass [m_{eejj}]

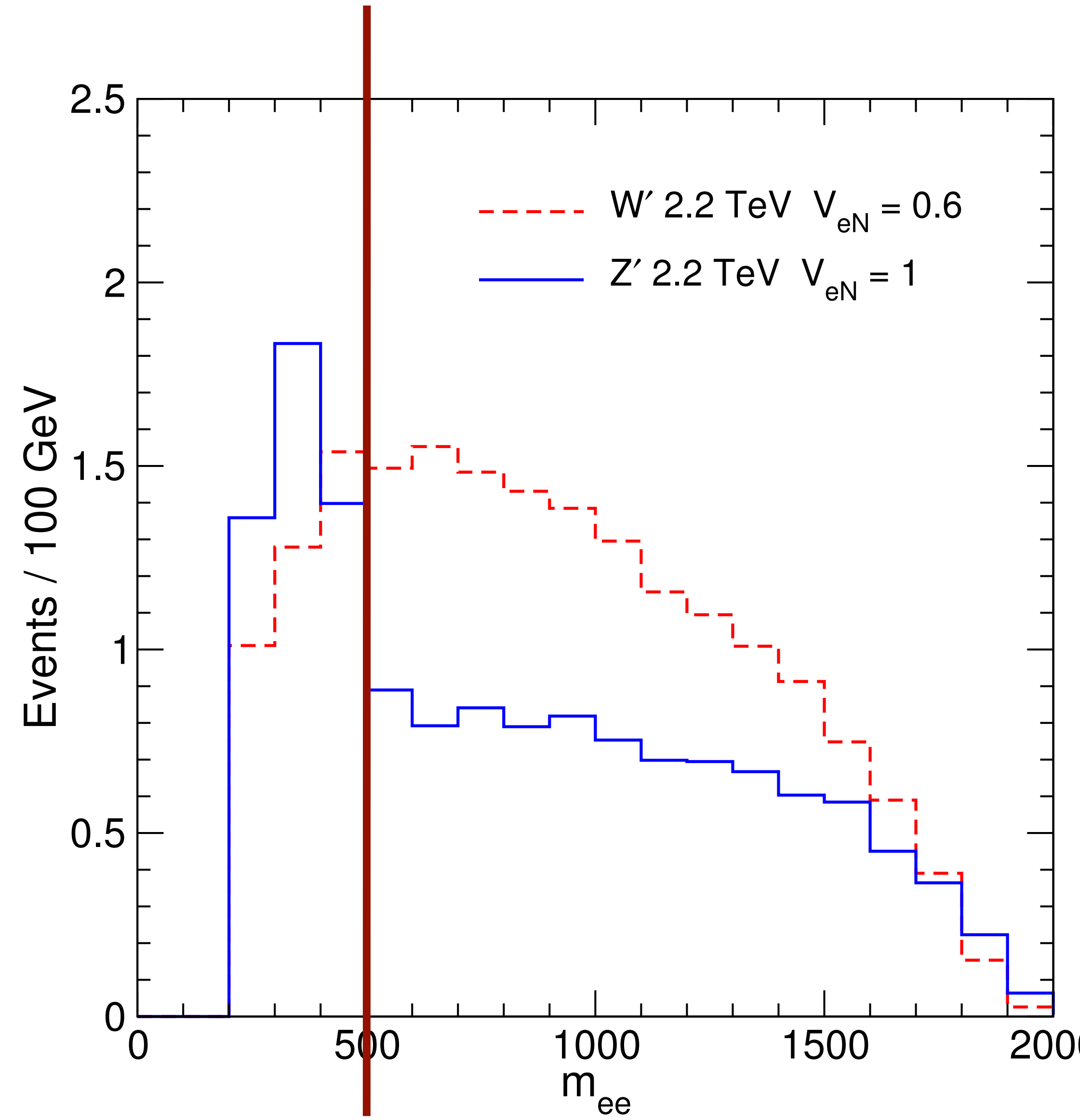




- W' and Z' masses of 2.2 TeV chosen so as to reproduce the excesses in the two bins: 1.8 TeV – 2.2 TeV / 2.2 TeV – 4.0 TeV
- peaks in both cases, excess well reproduced even if $V_{\tau N}$ significant

Distributions: dilepton invariant mass [m_{ee}]

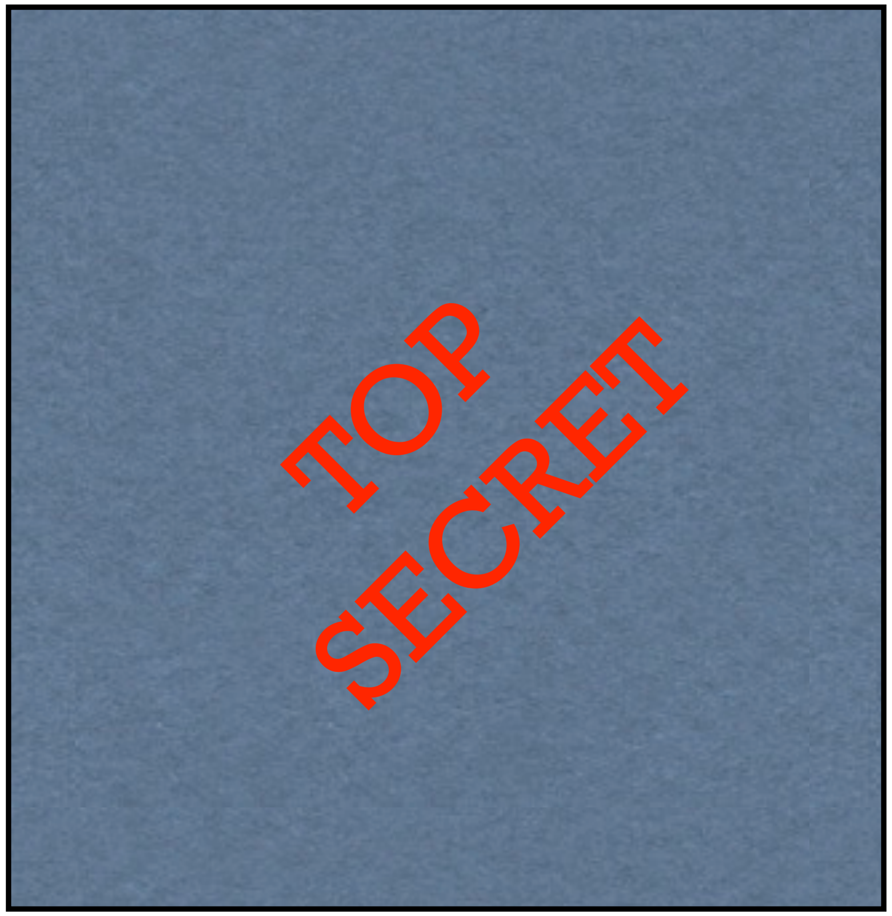


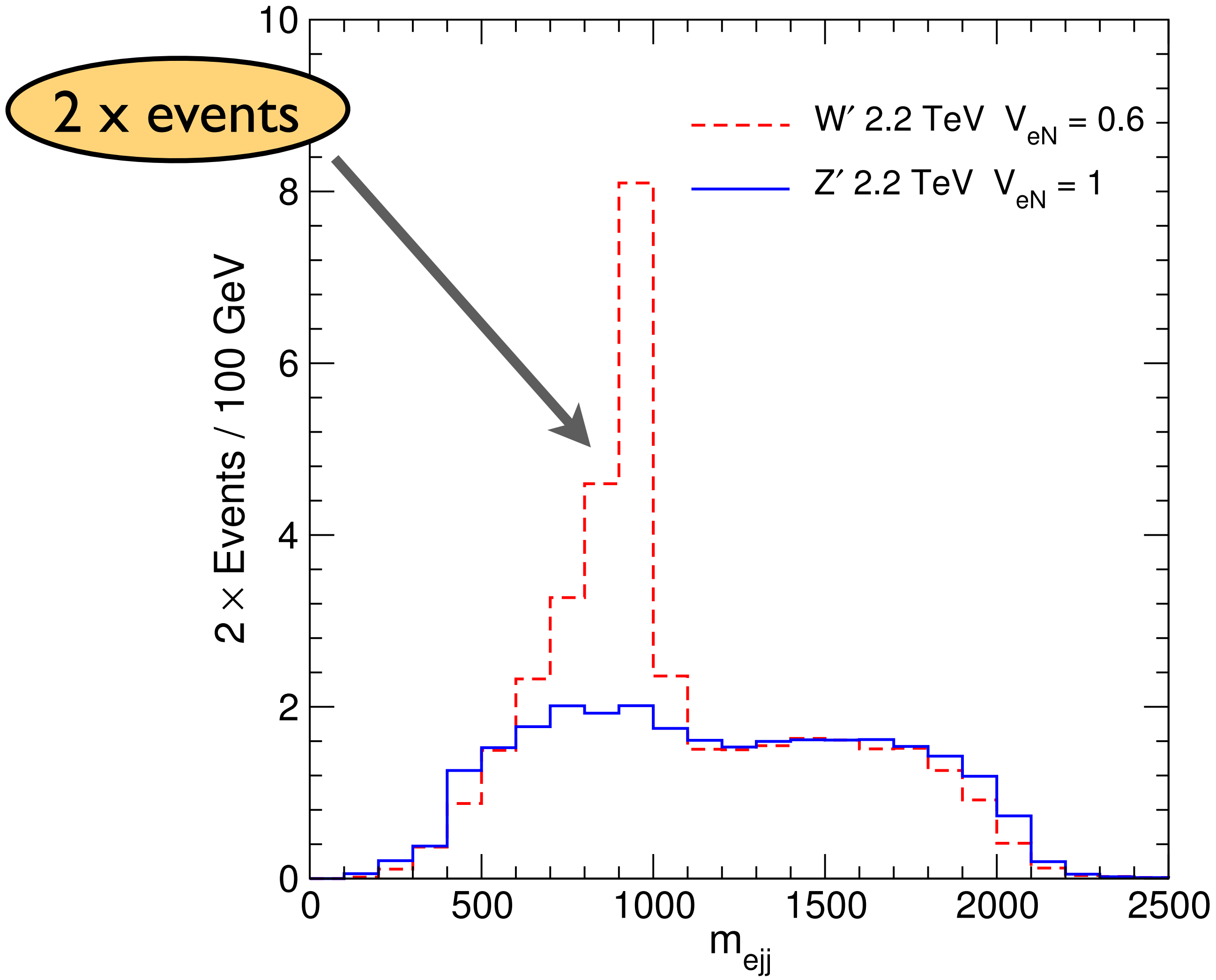


- big high-mass bump in W' model if $V_{eN} \simeq 1$, smeared if $V_{\tau N}$ sizeable or heavier N

- apparently consistent with the range shown in plot by CMS

Distributions: N reconstructed mass [m_{ejj} with either e]





- maybe this is is the *mysterious distribution* that CMS claims does not display a peak?
- peaks at m_N in the case of W', should the peak be visible?

Moral from this exercise [conclusions]

- If this excess were confirmed, we would be very happy:

media

citations

funding

- Even if it is not (which is quite possible), we should at least be warned once more that experimental searches should:
  - consider a wide scope of signals
  - be interpreted correctly!

Extra Slides

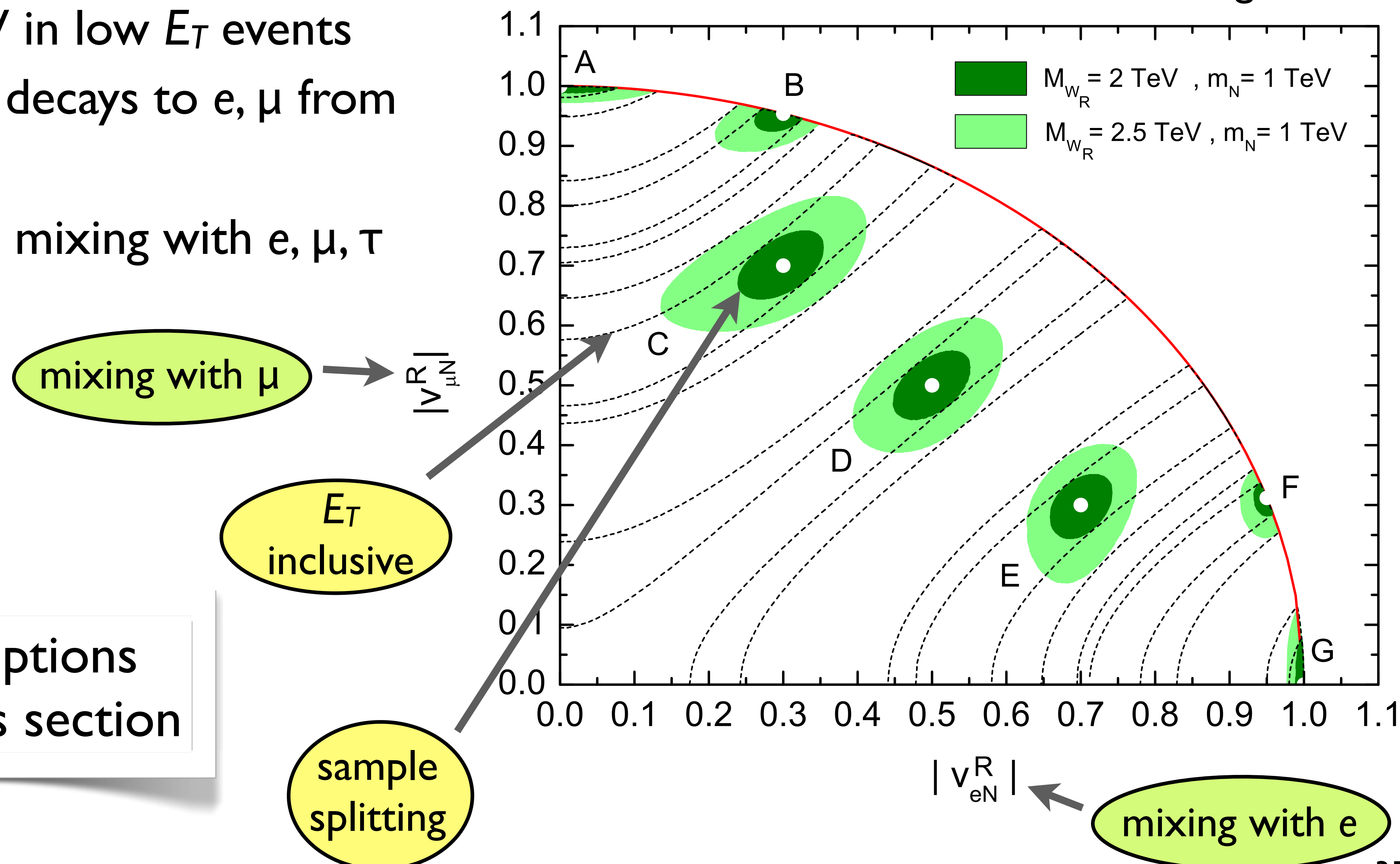
Wishlist for future analyses

JAAS & Joaquim '12

instead of being inclusive on E_T, one could split the event sample into high E_T and low E_T subsamples and combine results, to:

- probe LNV in low E_T events
- distinguish decays to e, μ from those to τ
- measure N mixing with e, μ, τ

Potential measurement of mixings



no assumptions about cross section

Reinterpretation of type-III seesaw searches

In type-III seesaw the trilepton signal has a good sensitivity to $V_{\tau N}$ because:

- the signal is clean: no hard pT cuts needed
- one of the leptons comes from W decay: high p_T even if $V_{\tau N} = 1$

Moreover, in type-III seesaw there are only three independent parameters (the multiplet mass and two mixings): it is possible to present general limits.

JAAS et al. '13

Heavy lepton decays in type III seesaw

via small coupling to SM bosons and light leptons

$$\left\{\begin{array}{l} N \to W^+ \ell^- \\ N \to W^- \ell^+ \\ N \to Z\nu \\ N \to H\nu \end{array}\right.$$

LNV, not present in inverse seesaw

relative BR depend mildly on N mass

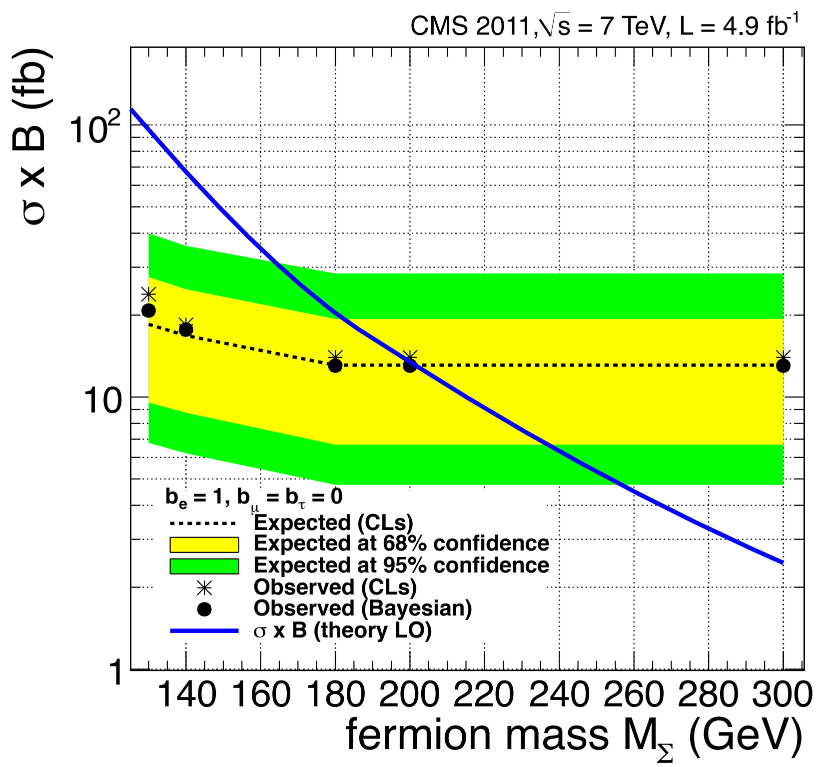
$$\left\{\begin{array}{l} E^- \to W^- \nu \\ E^- \to Z\ell^- \\ E^- \to H\ell^- \end{array}\right.$$

relative BR depend mildly on E mass

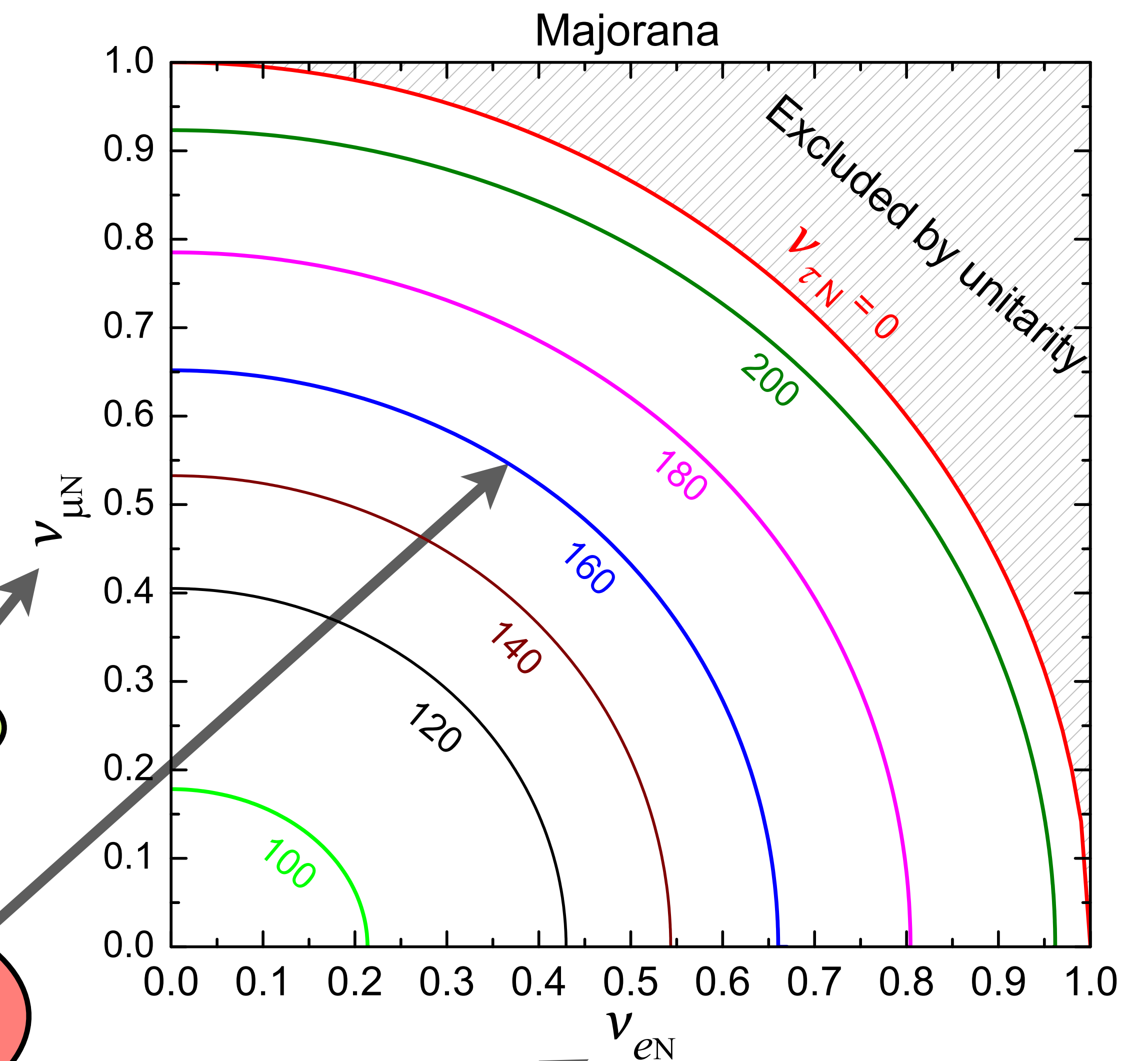
Additional decay modes present if new W′ or Z′.

fix flavour structure
and let m$_\Sigma$ arbitrary

fully general limits



reinterpretation
of CMS results

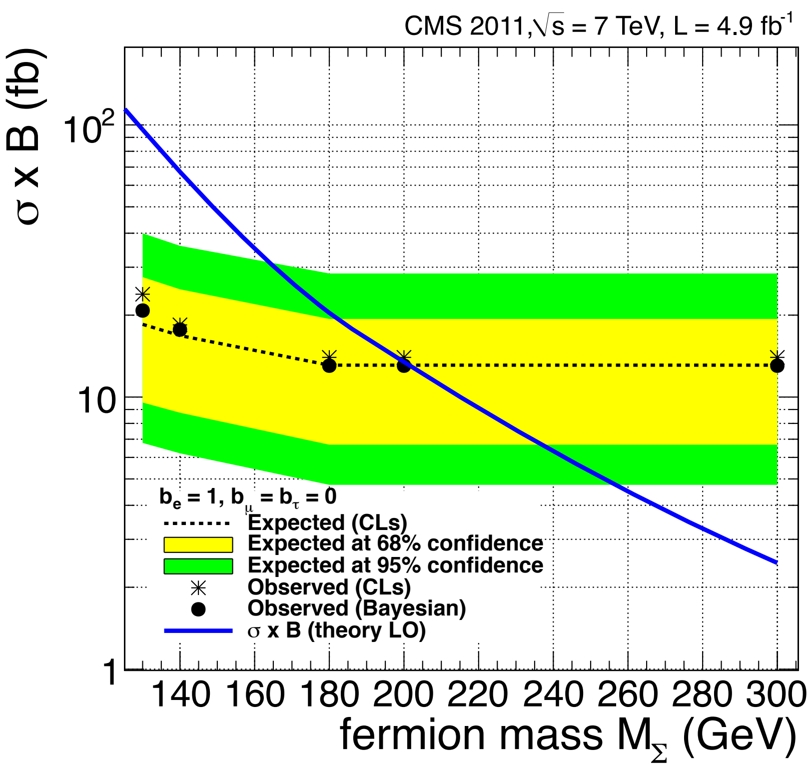


mixing with μ

exclusion regions
in flavour mixing
space for several m$_\Sigma$

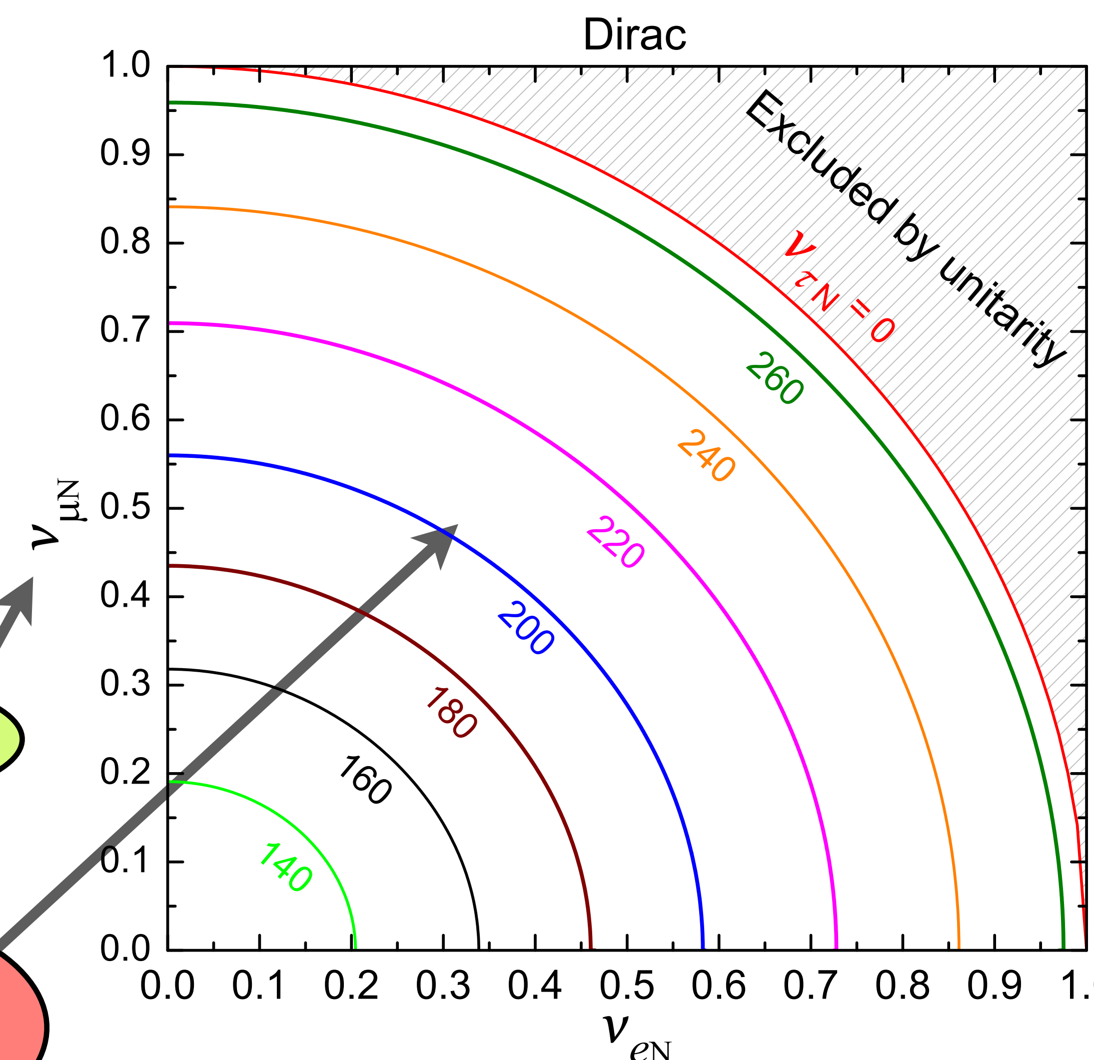
mixing with e

limits on minimal type III seesaw



reinterpretation of CMS results

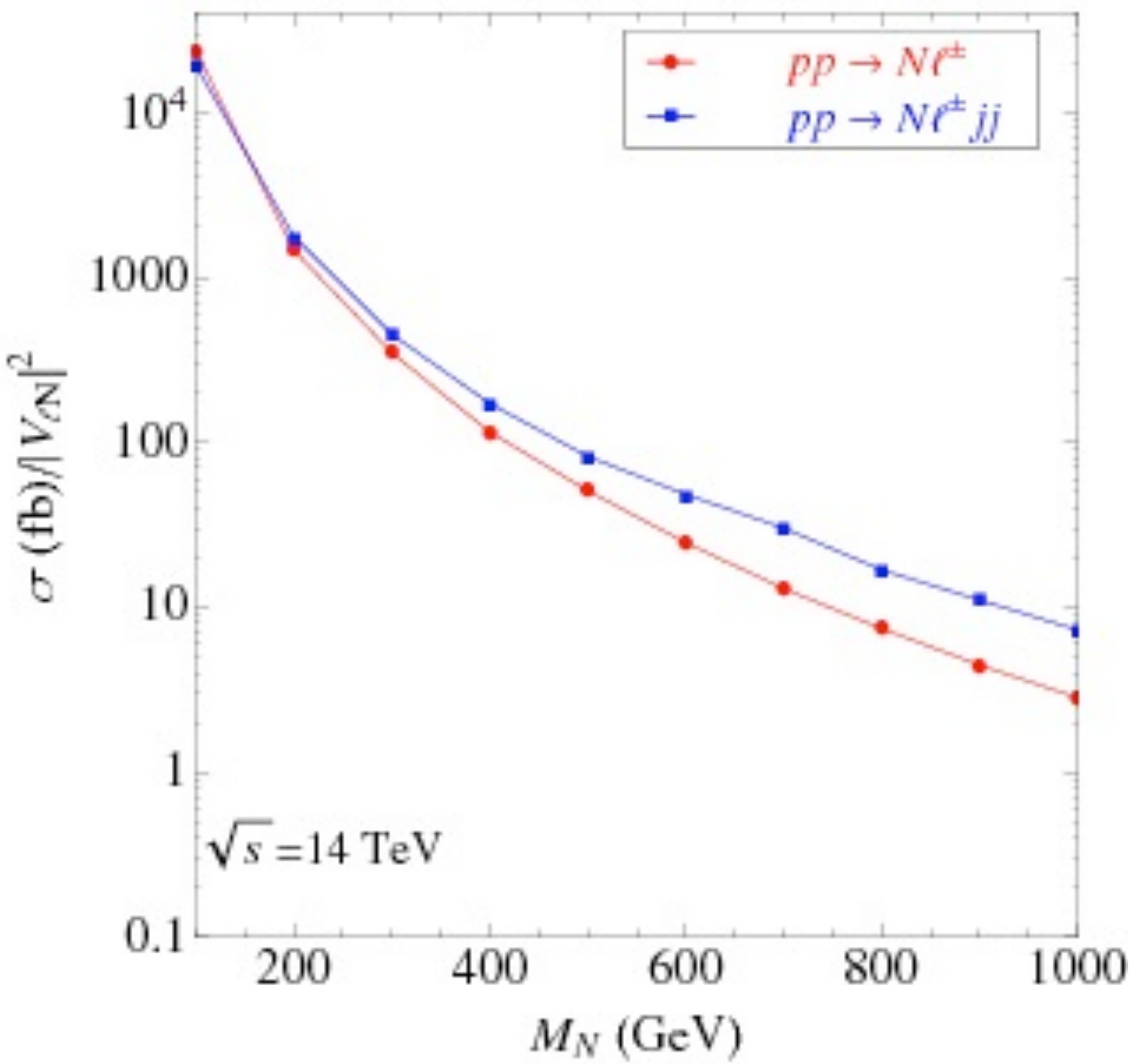
limits also on inverse type-III seesaw



mixing with μ

exclusion regions in flavour mixing space for several m$_\Sigma$

mixing with e



$pp \to N\ell^{\pm}$
$pp \to N\ell^{\pm} jj$
10^4
1000
100
10
1
0.1
σ (fb)/$|V_{\ell N}|^2$
$\sqrt{s}$ =14 TeV
200
400
600
800
1000
M_N (GeV)