Neutrinos at LHC

Theory and Experiment

Fabrizio Nesti
Ruđer Boškovic Institute

LHC Days in Split 2014

Journey

- Neutrino masses already *are* New Physics
- Majorana?
- What is the mechanism?
- Probable Theories?
- Connection with LHC?

Lesson of simplicity from the SM

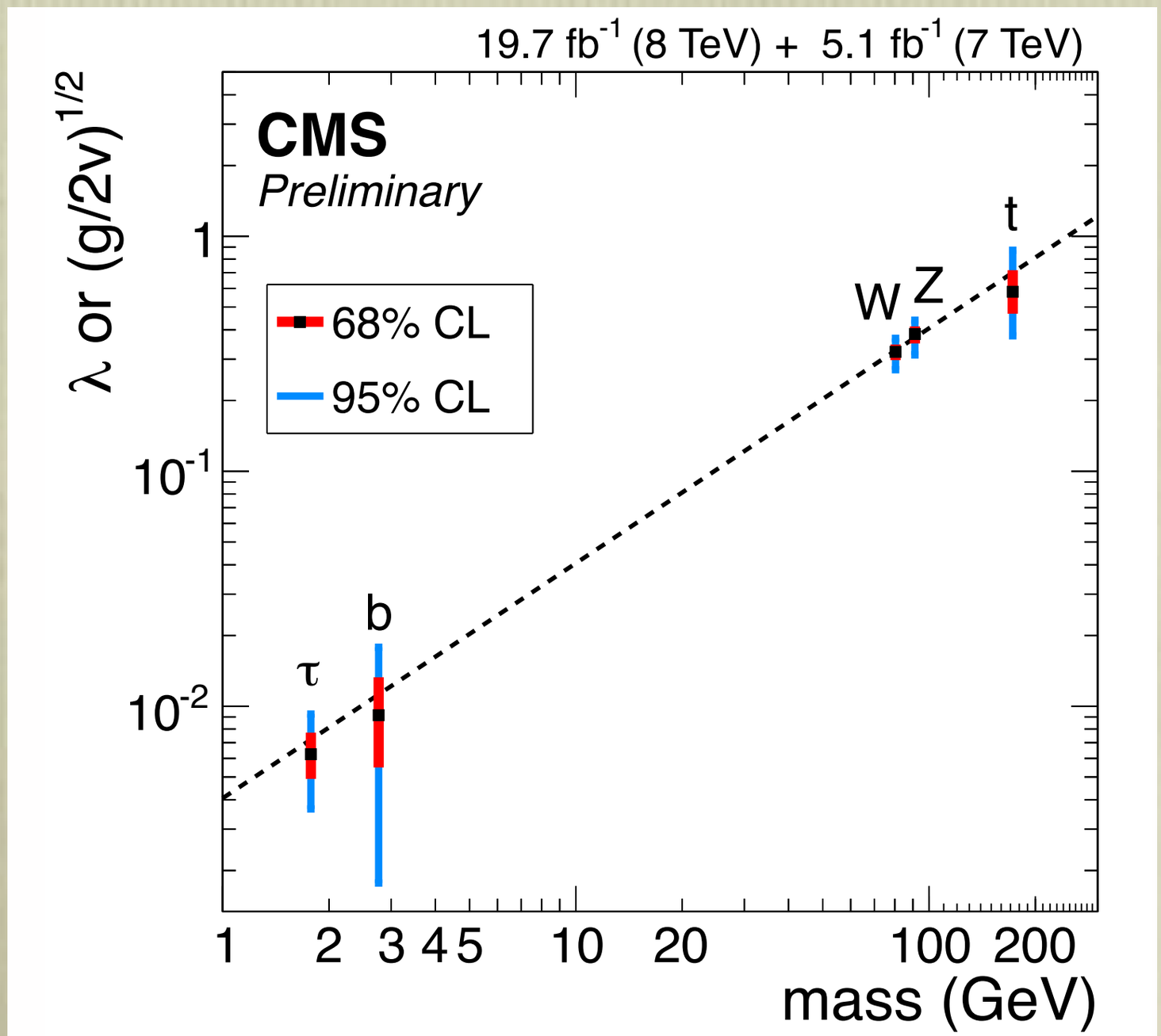
- Fundamental mass generation in the SM correlates two measures:

  - Masses generated by higgs couplings

  - Couplings can be checked

Indeed

The triumph of the SM



Mass and Higgs couplings as expected

H→ττ ATLAS-CONF-2013-108

H→bb ATLAS-HIGG-2013-23-003

H→ττ CMS arXiv:1401.5041

H→bb CMS arXiv:1310.3687

CMS PAS HIG-14-009

Anything similar for neutrino masses?

- We measure neutrino mass differences (oscillations)
  ...thus nonzero neutrino mass.

- SM has only LH neutrinos...
  ...no Higgs coupling

$$M_\nu = 0$$

Need to go Beyond the SM...

but *which* BSM theory

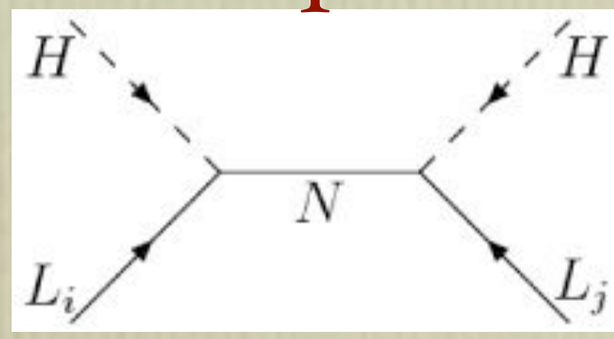
Need new states...

- Dirac neutrinos: requires light states, ν_R (no LHC)
- Majorana neutrinos: requires heavy states ($\gg M_\nu$)

Al theories rely in some way on building blocks

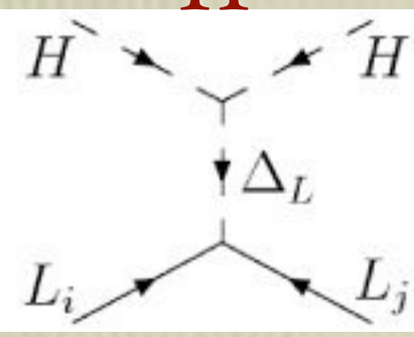
Seesaws - single particle tree-level UV completions, realizing Weinberg effective operator *(LH)(LH)/M*:

I



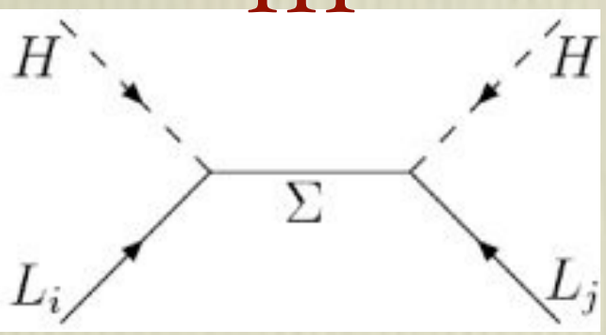
Minkowski '77
Mohapatra, Senjanović '80
Yanagida '79, Glashow '79
Gell-Mann + '79

II



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

III



Foot + '89

SUSY

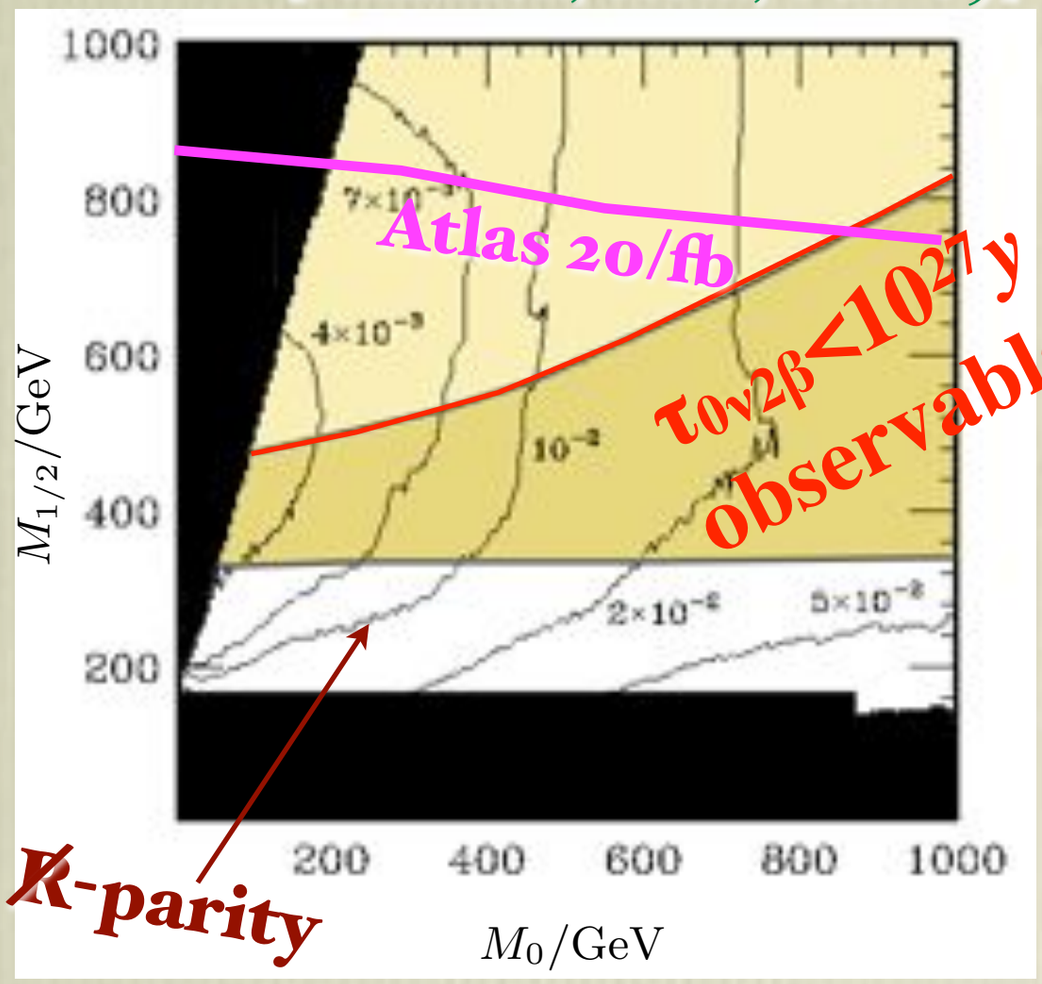
- Neutrino is massless in the MSSM with exact R-parity.

- Relax R-parity, allow LNV
  LH_u, $L_iL_je_k$, $L_iQ_jd_k$
  (+soft terms)

- Neutrino masses: "sneutrino VEV seesaw", loops (mixed!)

- Superpartners unconstrained
  (even asking for DM) [Bajc+ '10]

- A certain link between 0ν2β and slepton production
  [Allanach, Kom, Pas '09]



- No direct link m_ν - phenomenology. And of course full parameter scan impossible, only benchmarks...

(need to wait and hope? And all this for naturalness?)

Neutrino with naturalness

- Want naturalness from *N* down to EW scale?
- Easy - say SUSI: Super Singlets

sterile neutrino + sterile scalar (singlet)

[Fabbrichesi Petcov '14]

- Improve naturalness
- And gives neutrino a mass
- The scalar may be a DM candidate (w/ tuning)

However, naturalness is a high scale concern...
hardly testable if at high scale -- weak argument if at low

Radiative neutrino masses

- Tree level neutrino masses forbidden by some tuning (assumption of Z_2, etc) [after Zee '80]
- LN broken typically by some VEV ➛ radiative ν mass
- More (discrete) symmetries lead to more sophisticated/ realistic textures of mass matrices.
- Typically a number of fields, some/many brought at TeV
- So, a number of LHC predictions, very model specific.

We have pileup of modeling of neutrinos

Seesaws

http://www.zazzle.co.uk/

Seesaw type I

Sterile Neutrinos

- Add 3 fermion singlets *N* (or two)
- Small M_ν from large Majorana mass M_N, and Dirac mass M_D

$$M_\nu \simeq -M_D^t\, M_N^{-1}\, M_D$$

- scenario of large $M_N \sim 10^{10}\,\mathrm{GeV}$ (quite unobservable)
- Dirac mass (Yukawa) is ambiguous, orthogonal complex *O*

[Casas Ibarra]

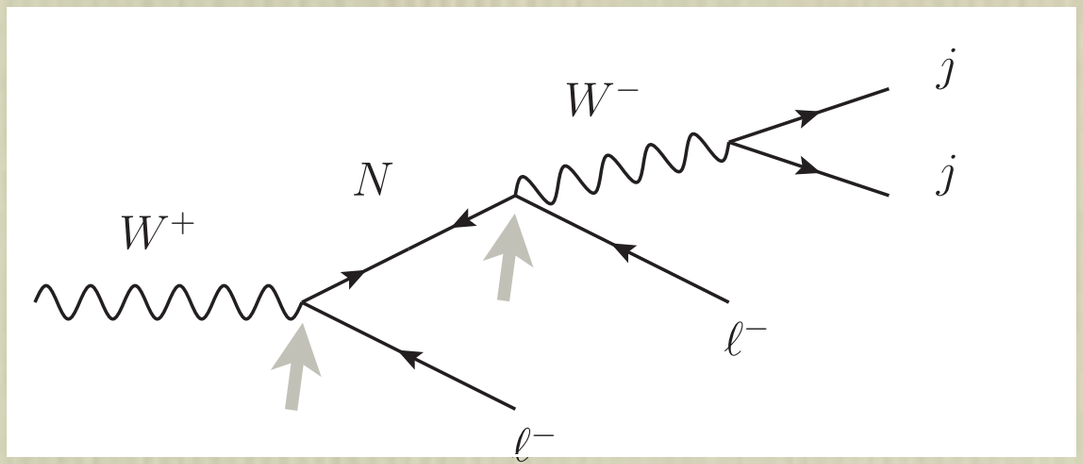
$$M_D = i\,\sqrt{m_N}\,O\,\sqrt{m_\nu}$$

Still M_N can be at weak scale...

Seesaw type I

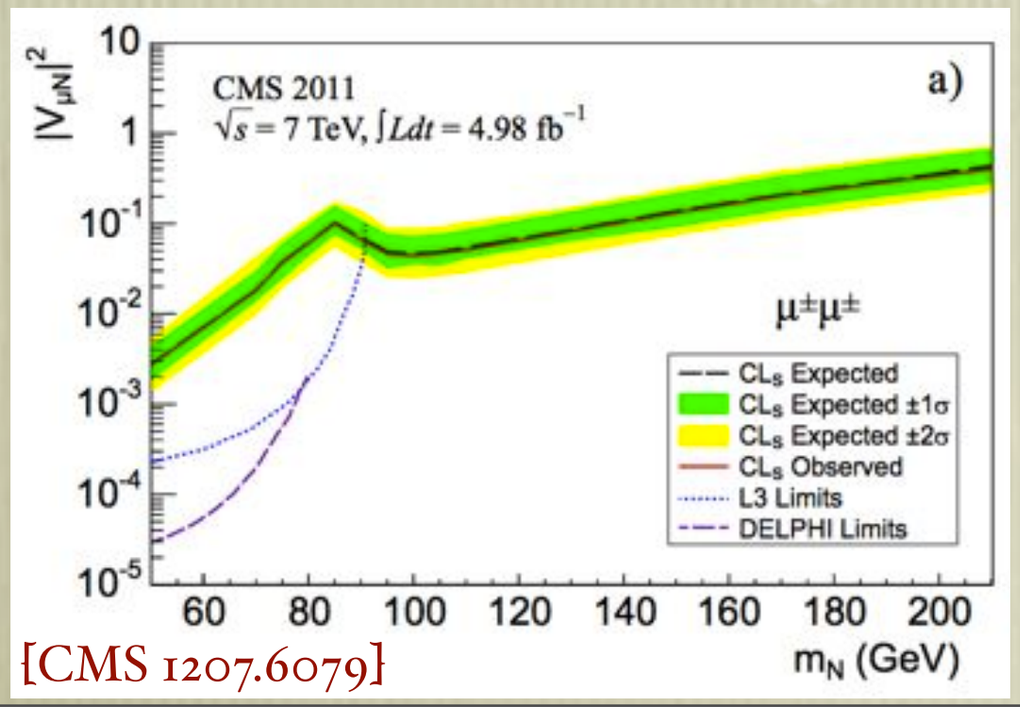
Sterile Neutrinos

LNV@LHC!



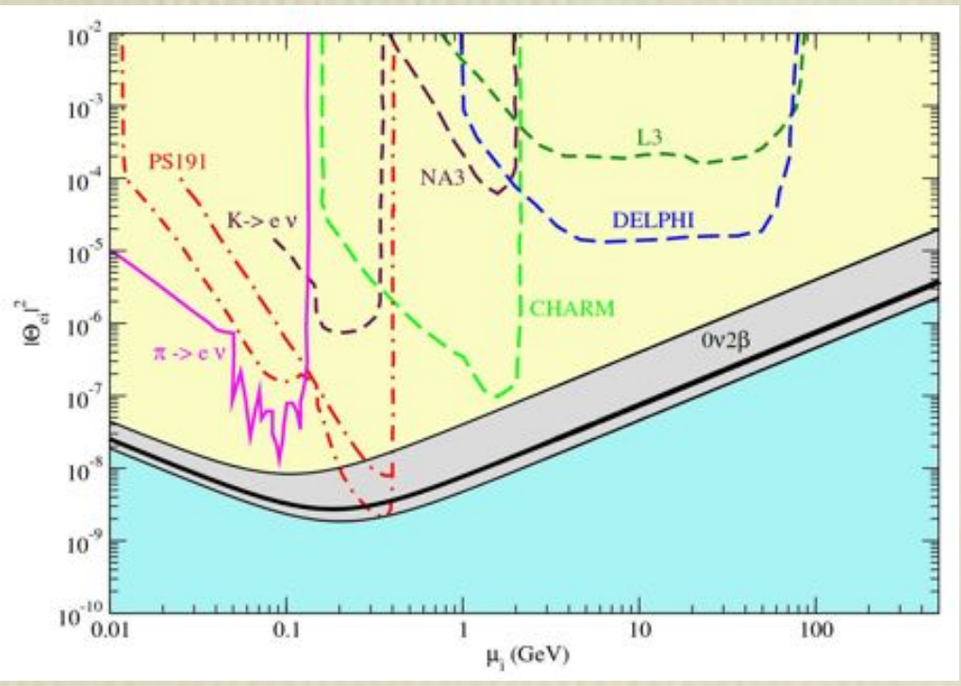
[Keung, Senjanović '83]
as in LR, see below.

- BUT: N couples via Dirac mass, tiny if m_N ~ TeV. $M_D = i\sqrt{m_N} O \sqrt{m_\nu}$
- Hard to see at LHC, need to boost O [Kersten, Smirnov '07]
- LHC reach *100 GeV* [Aguila+ '07, '08]



[CMS 1207.6079]

- Signals in 0ν2β [Atre + '09] [Mitra+ '11]



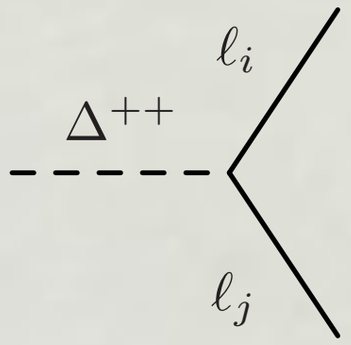
Seesaw type II

Scalar Triplet

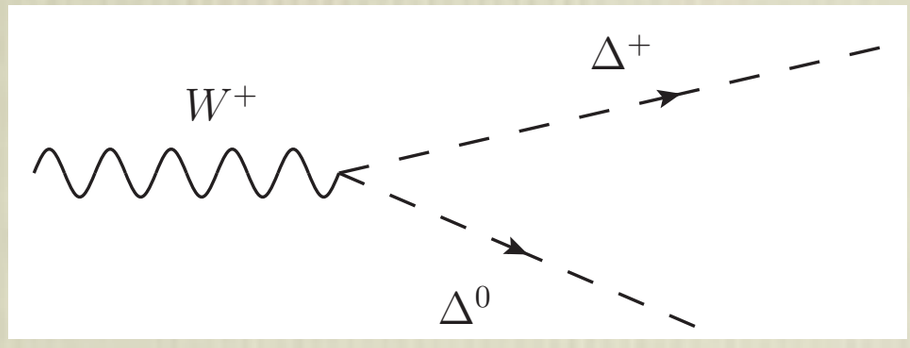
- Describes small neutrino via the coupling to a Scalar Δ_L with small VEV $\langle H \rangle^2/M$

- Neutrino mass matrix drives decay into leptons: Yukawa connection with LHC

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



- Production practically only pairwise

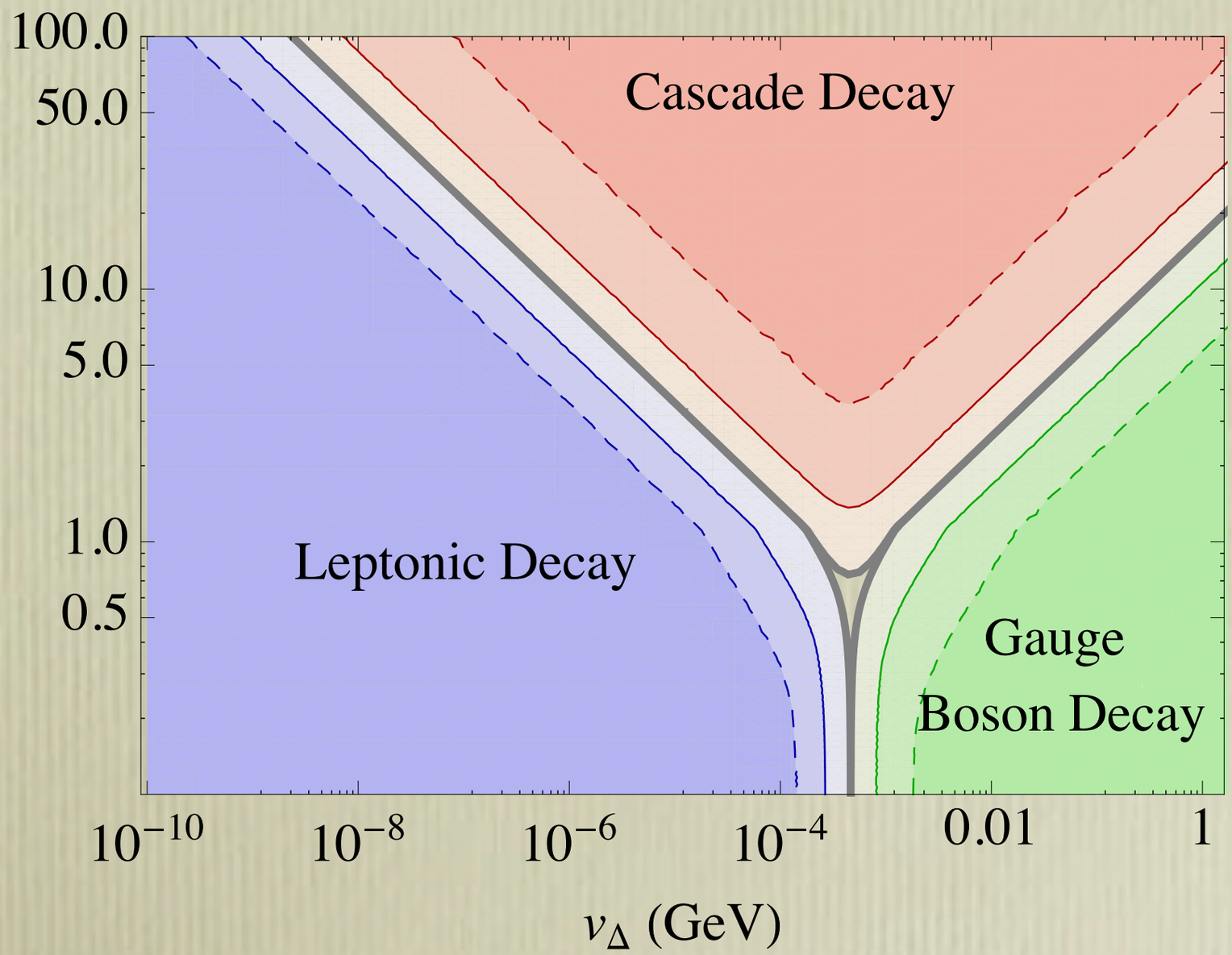


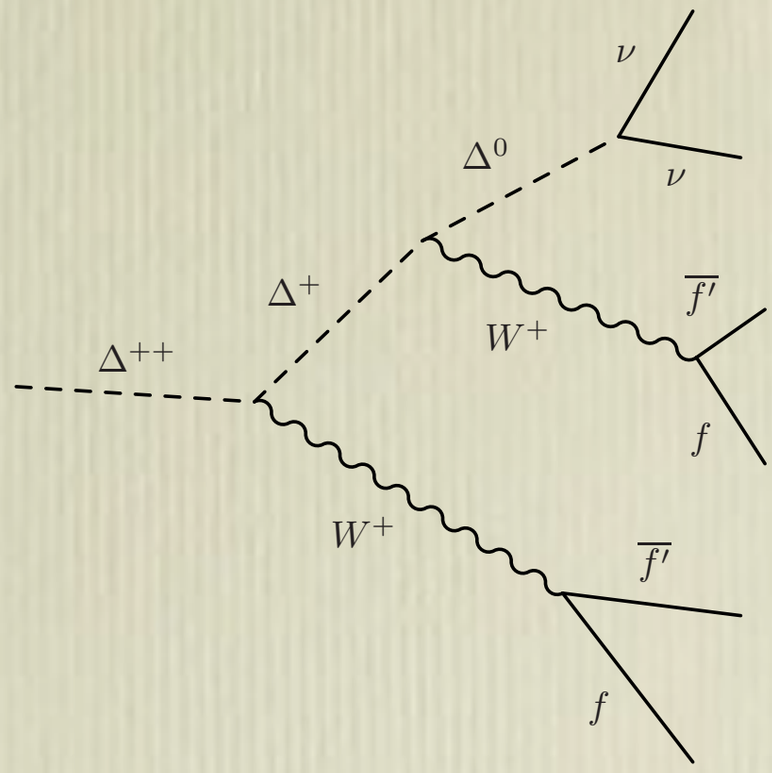
- Search limited by kinematics, to <~TeV

Seesaw type II

But... cascade decays! Depends on mass splitting in triplet

$$\text{-}\Delta M = \; m^2_{\Delta^+} - m^2_{\Delta^{++}} \simeq m^2_{\Delta^0} - m^2_{\Delta^+} \simeq \beta\, v^2/4$$

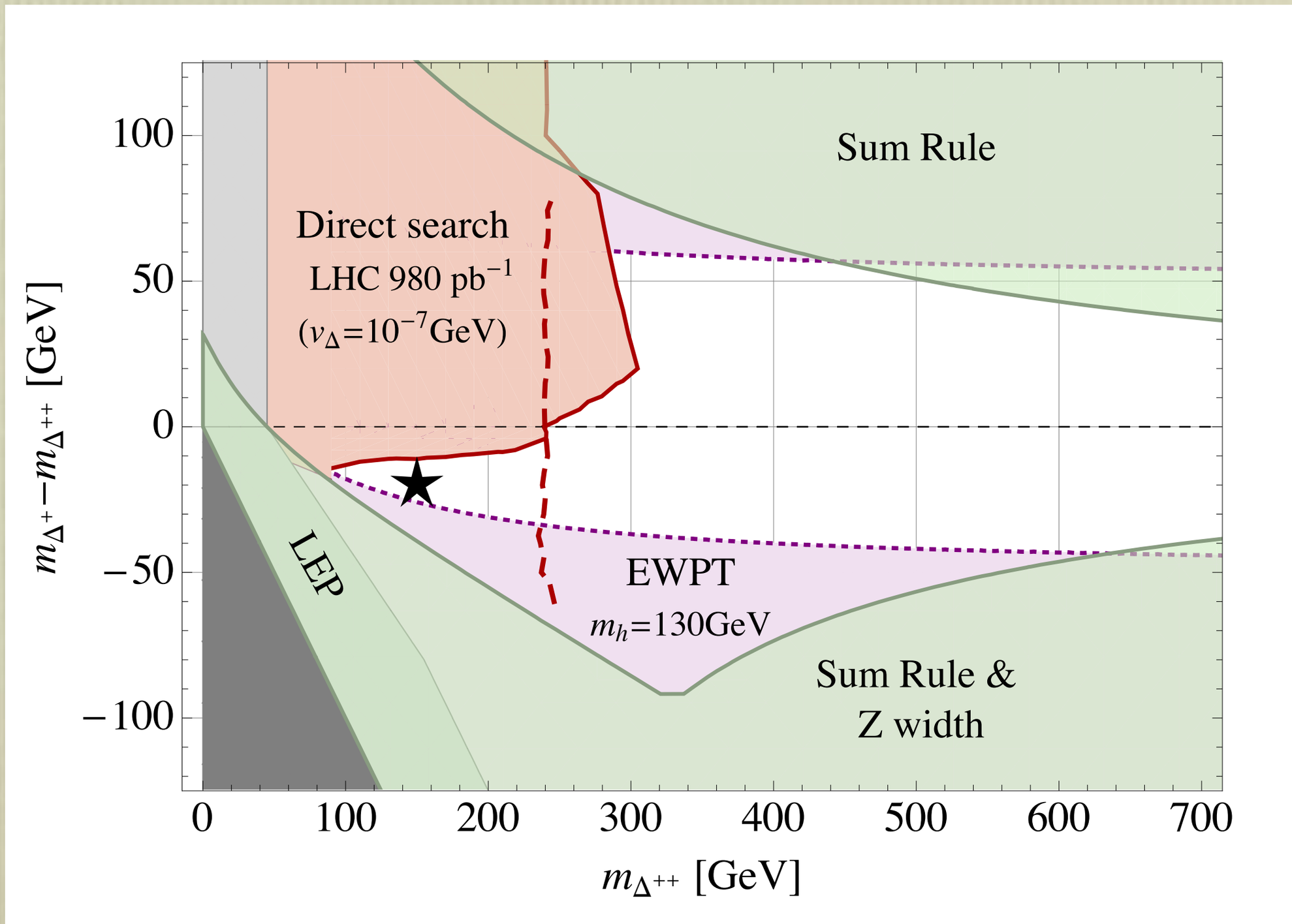




[Melfo, Nemevšek, FN, Senjanović, Zhang '11]

Seesaw type II

Even in such a simple model: a three-parameters space.



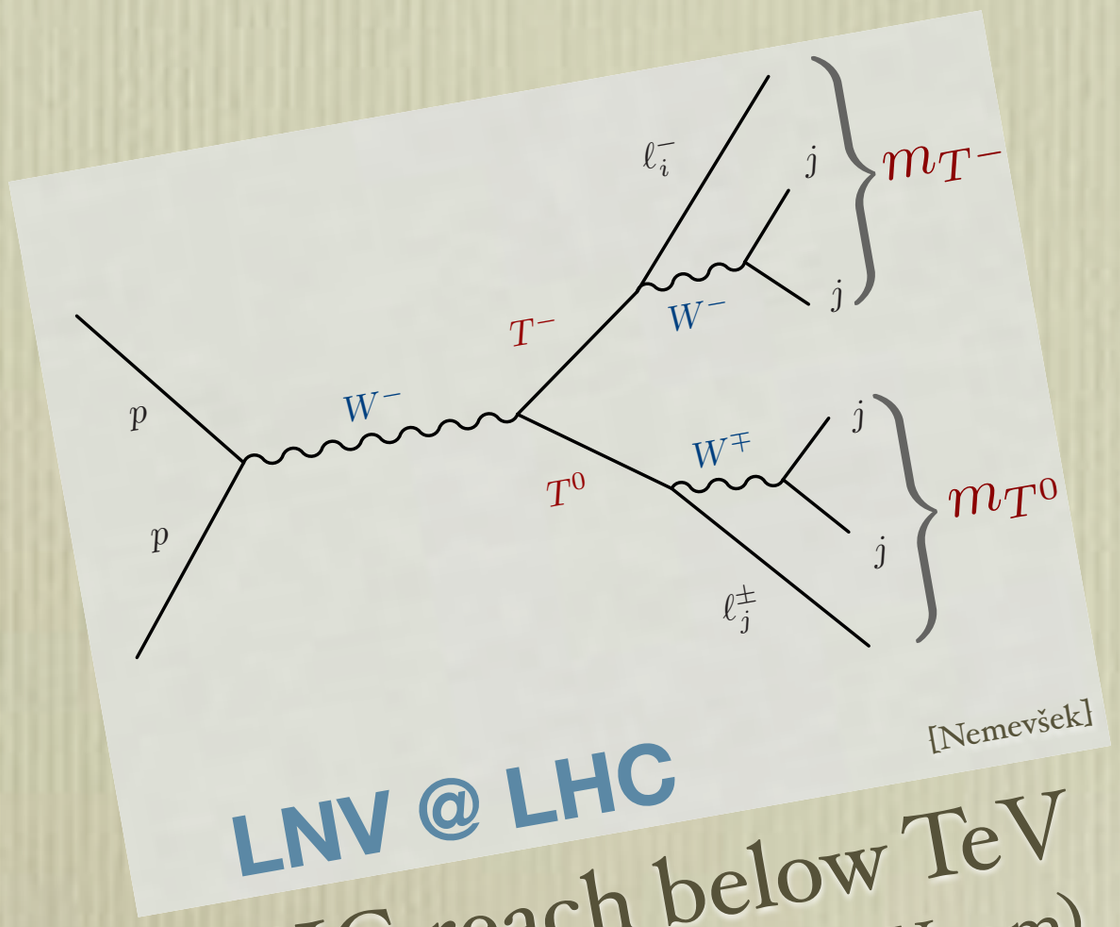
[Melfo, Nemevšek, FN, Senjanović, Zhang '11]

Seesaw type III

E.g. realistic SU(5) GUT + Fermion Masses + Safe p-decay ...

...predictes seesaw type-III with a Fermionic Triplet at TeV

[Bajc, Nemevšek, Senjanović '07]



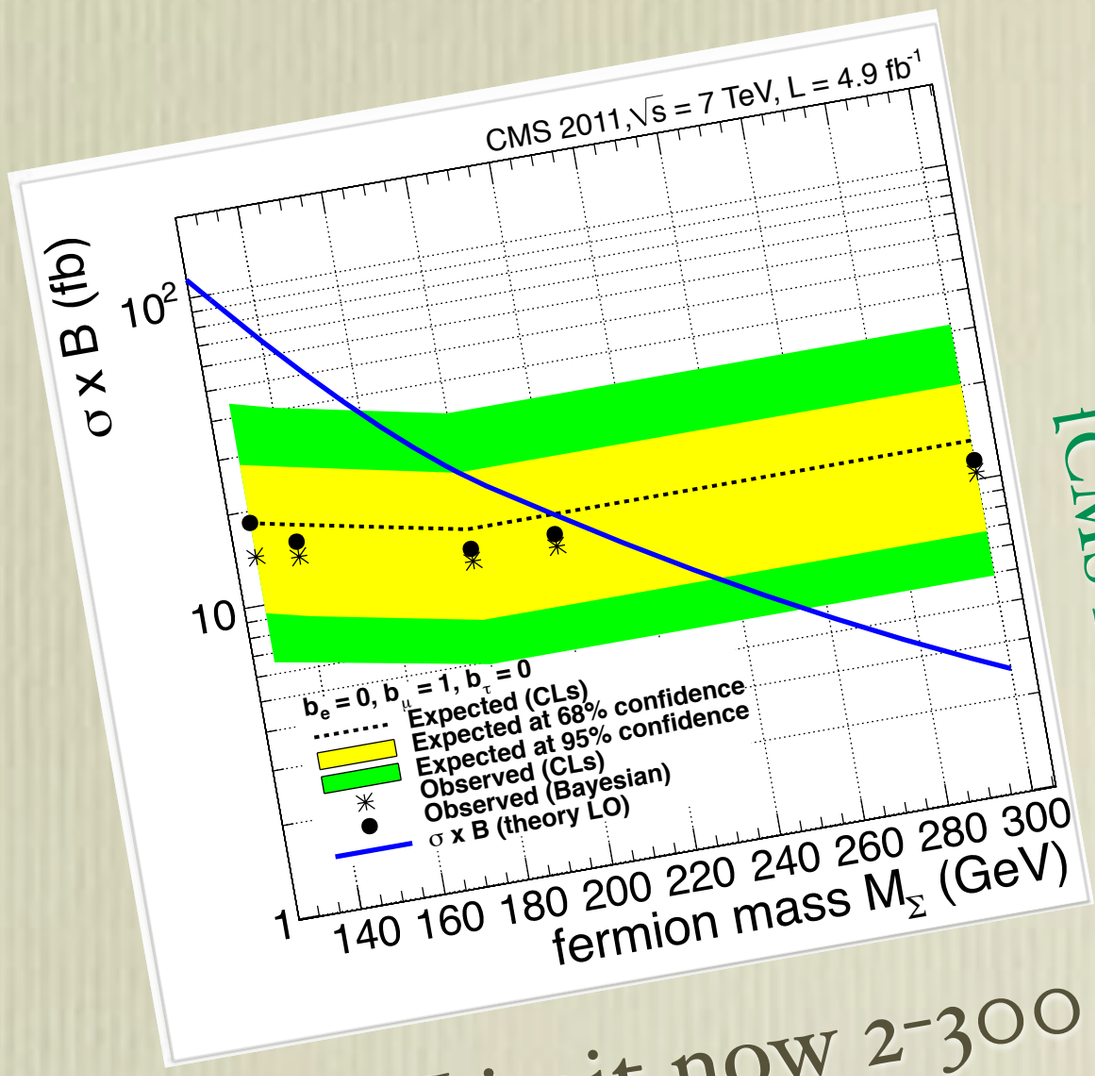
LNV @ LHC

LHC reach below TeV

(14TeVcom)

[Franceschini+ '08]

[Arhrib+ '09]



[CMS 1207.1797]

Limit now 2-300 GeV

A complete theory: Left-Right Symmetry

A complete theory: Left-Right symmetry

Tello's talk tomorrow afternoon

[Pati, Salam '74] [Mohapatra, Pati '75]
[Senjanović, Mohapatra '75]

- Spectrum *has to be* symmetric

$$L_L = \begin{pmatrix} \nu \\ \ell \end{pmatrix}_L \qquad L_R = \begin{pmatrix} \nu \\ \ell \end{pmatrix}_R$$

- Spontaneous parity breaking is understood

$$W_L \qquad W_R$$

- Neutrino are massive via seesaws:
  & no ambiguity [Nemevšek+ PRL '13]

$$M_\nu = M_L - M_D^T \frac{1}{M_N} M_D$$

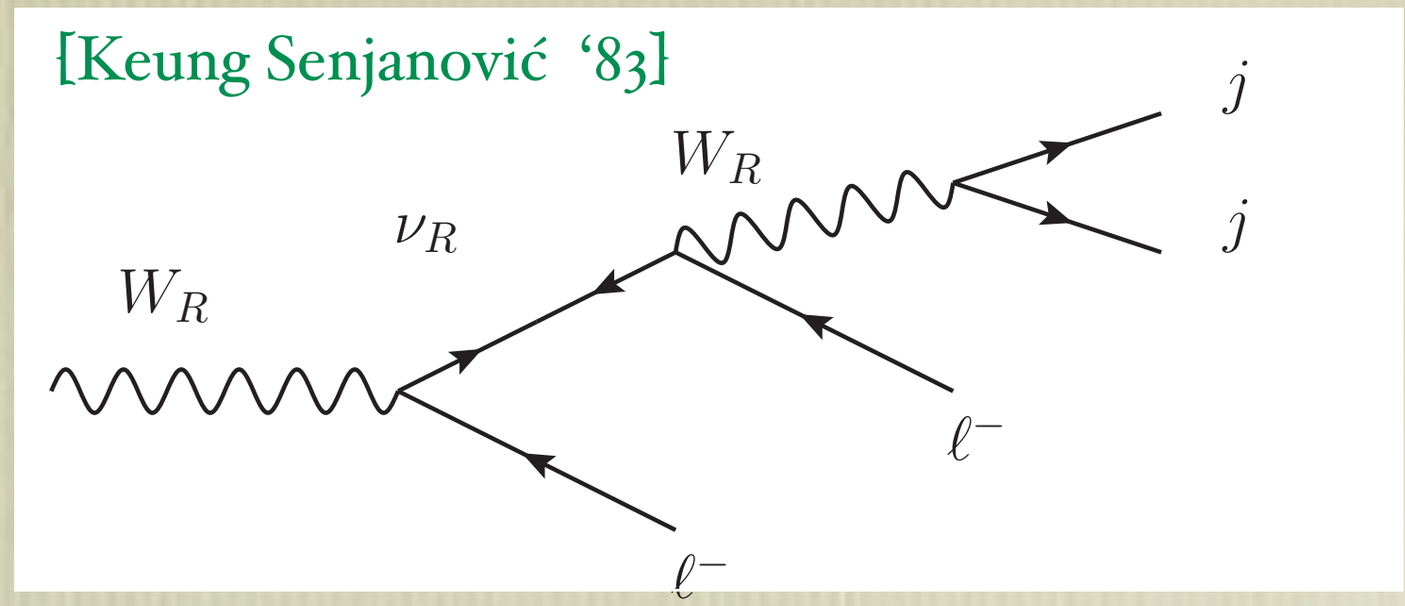
Vasquez' talk this afternoon

- Genuine LNV, collider can say something

A complete theory: Left-Right symmetry

LNV@LHC!

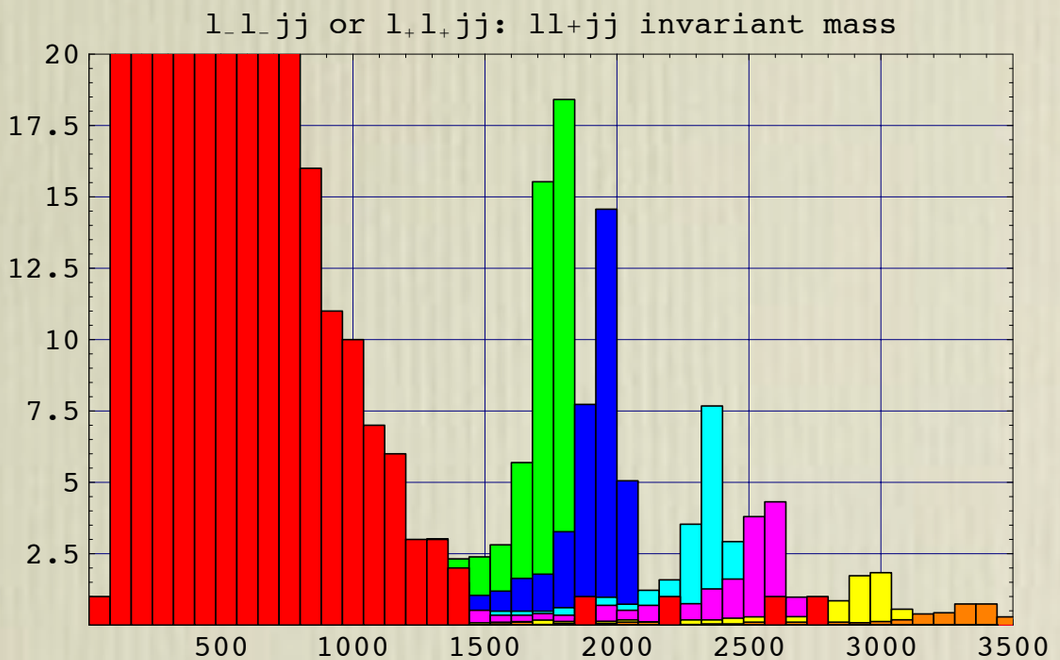
[Keung Senjanović '83]



- On shell W_R and ν_R.
- Invariant masses reconstruct W and ν masses. [Ferrari '00]

$$M_{W_R} \simeq m_{\ell\ell jj}$$
$$M_{\nu_R} \simeq m_{\ell jj}$$

- Probe of lepton flavour structure.
- LNV: Same sign leptons, 50%!
- Almost backgroundless
- Searches ongoing...



Recent Evidence :-)

CMS

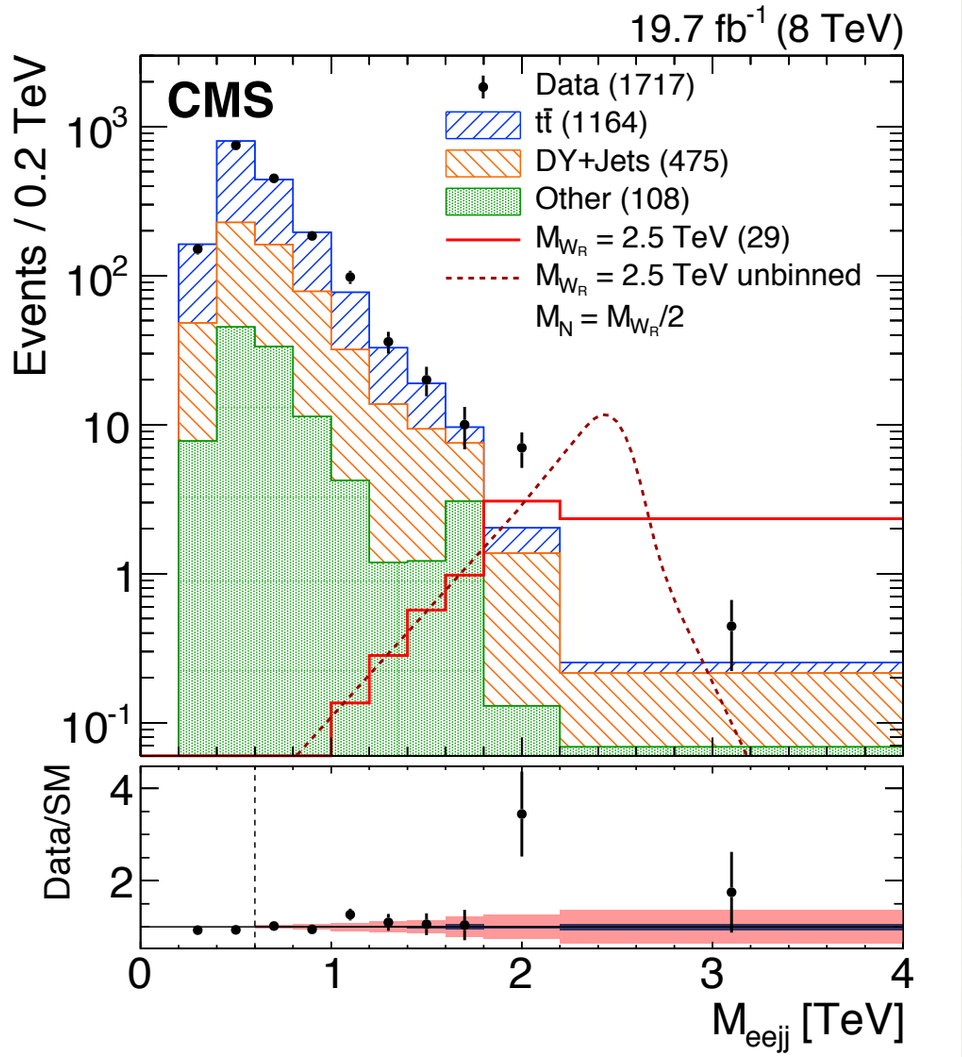
CERN-PH-EP/2014-161
2014/07/15

CMS-EXO-13-008

Search for heavy neutrinos and W bosons with right-handed couplings in proton-proton collisions at $\sqrt{s} = 8$ TeV

The CMS Collaboration*

14 Jul 2014



"The excess in the electron channel at approximately 2 TeV has a local significance of 2.8σ for a WR boson candidate with a mass of 2.1 TeV."

[CMS-EXO-13-008]

Recent Evidence (...)

Promptly speculated that the signal would be consistent with W_R, if the RH gauge coupling $g_R \sim 0.6\ g_L$, which can result in GUT from breaking of parity at high scale.

"A Signal of Right-Handed Charged Gauge Bosons at the LHC?"
[Deppisch+ 1407.5384]

"Testing Right-Handed Currents at the LHC"
[Heikinheimo +1407.6908]

More thorough analysis:

"A closer look at the possible CMS signal of a new gauge boson"
[Aguilar-Saavedra, Joaquim 1408.2456]

...from CMS:: "...In data events with $1.8 < M_{eejj} < 2.2$ TeV, we find same-sign electrons in only one of the 14 reconstructed events. ..."

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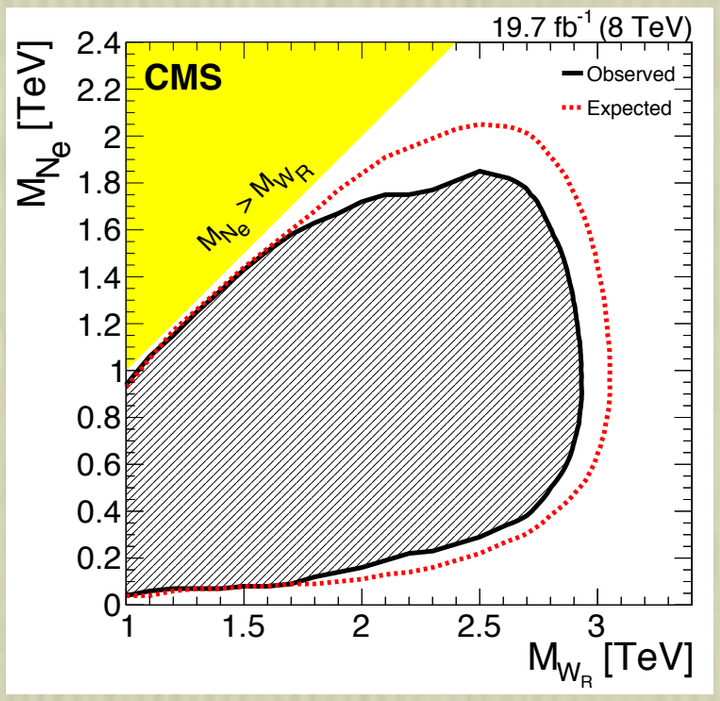
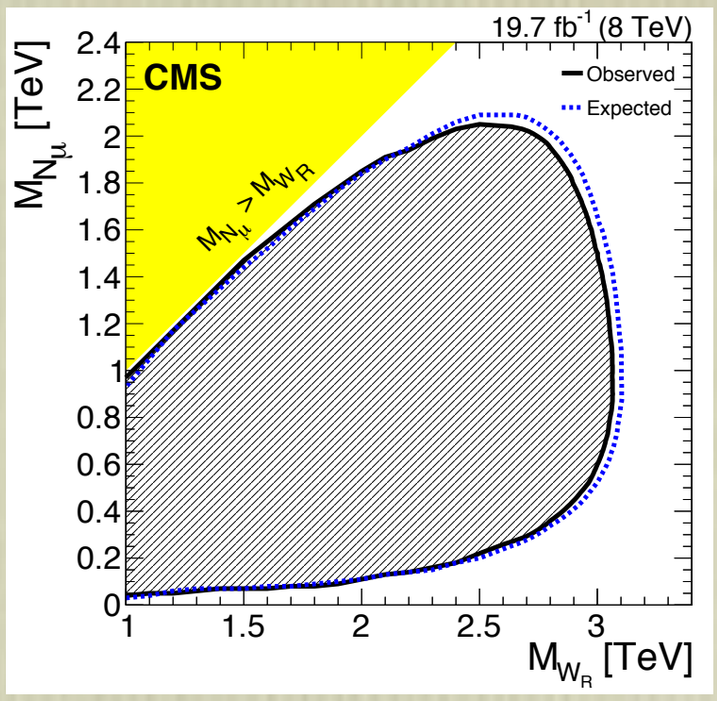
...so: Recent Limits





EXP

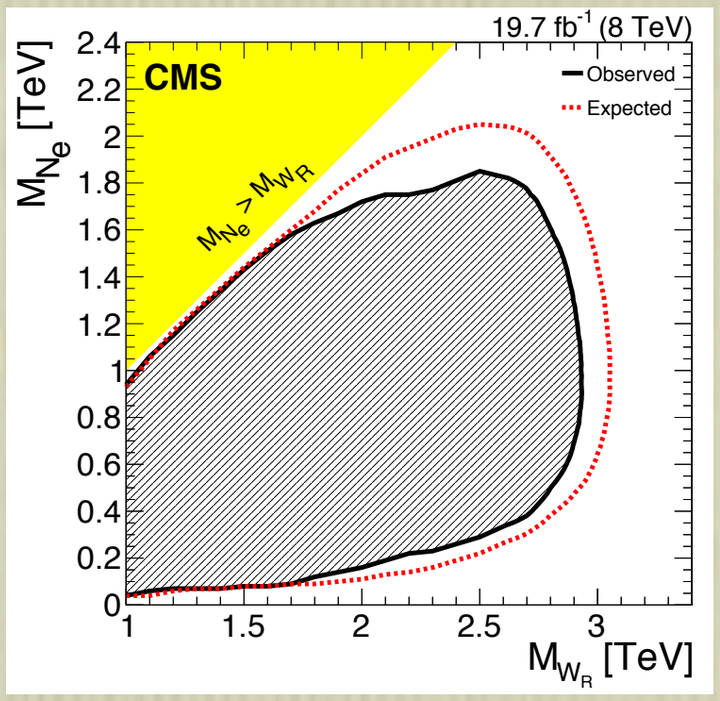
[CMS-EXO-13-008]

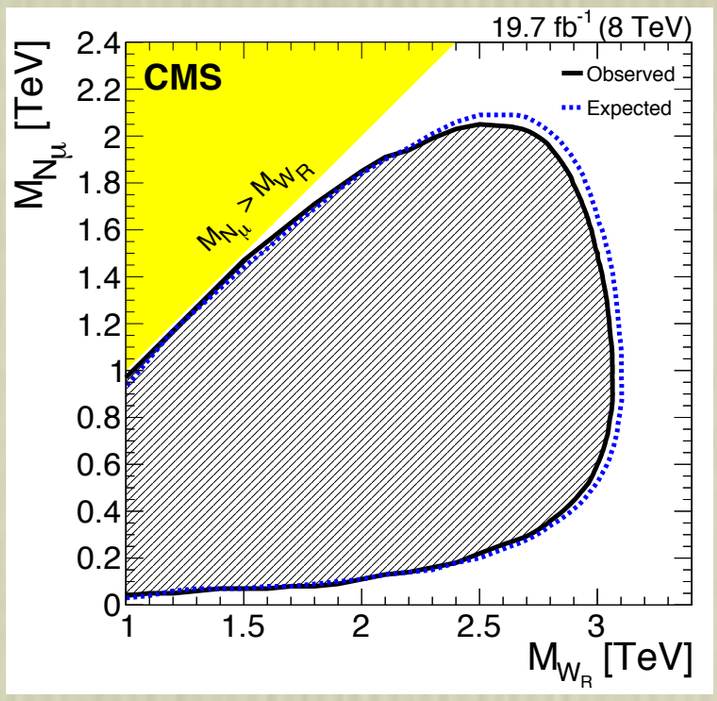
W_R-nu_R plane,
now beyond
theo bound 2.5TeV

[Maiezza+ '10]

[Bertolini Maiezza, FN '12,'13,'14]

...so: Recent Limits





EXP

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W_R-nu_R plane,
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But:

THEO

from $\Delta M(K, B_d, B_s)$
theoretical limit
now shifted up to
~ 3-4 TeV

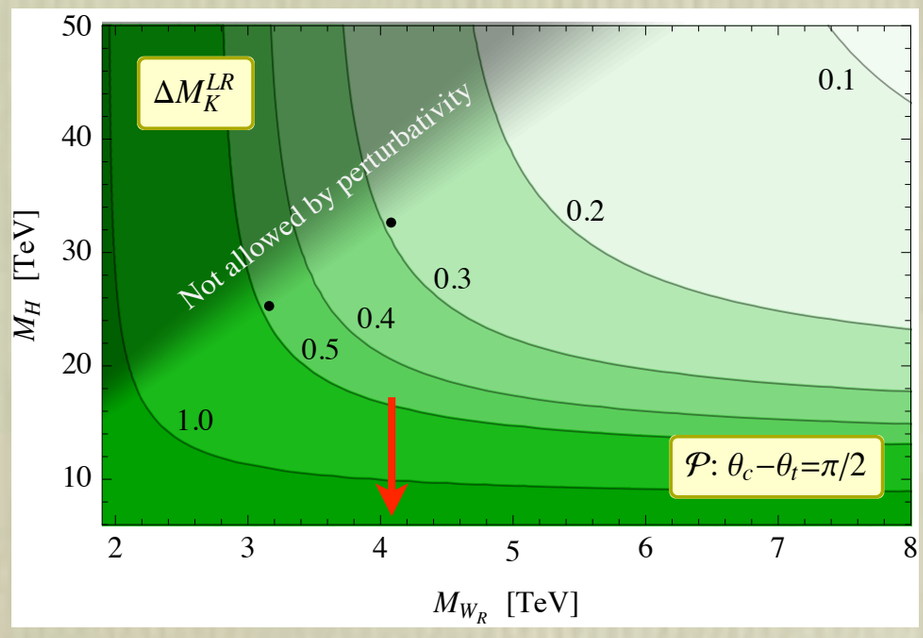


FIG. 9. Correlated bounds on M_R and M_{W_R} (region above the curves) for $\left|\Delta M_K^{LR}\right| / \Delta M_K^{exp} < 1.0, ..., 0.1$ and for $\theta_c - \theta_t = \pi/2$ in the case of $\mathcal{P}$ parity.

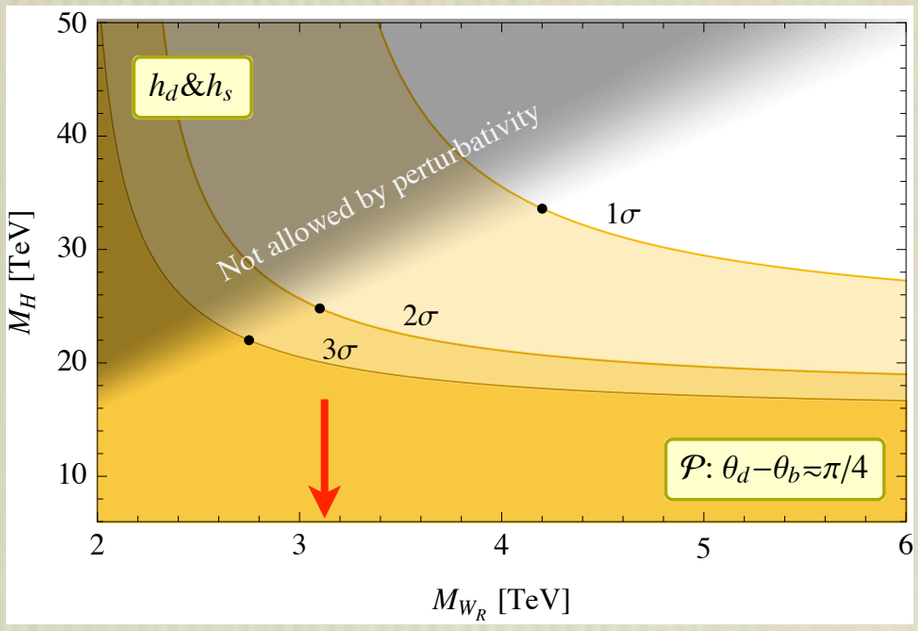
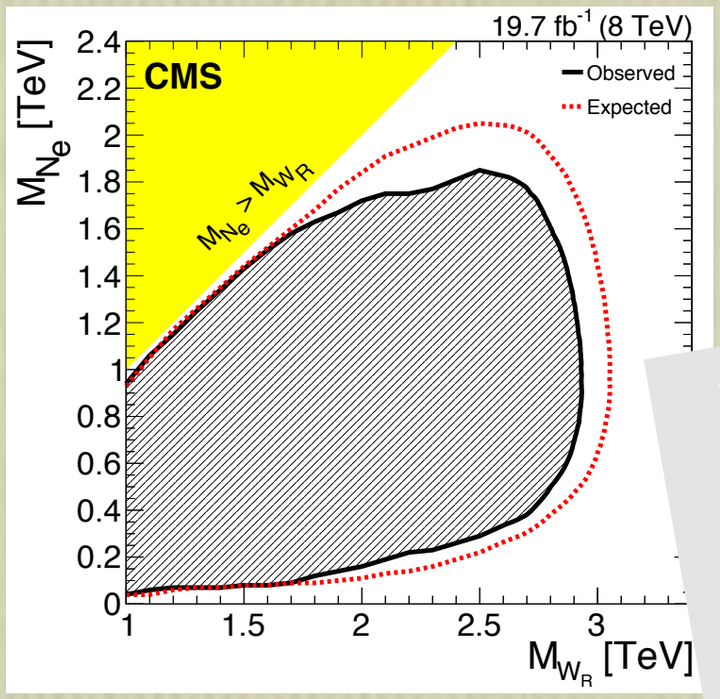
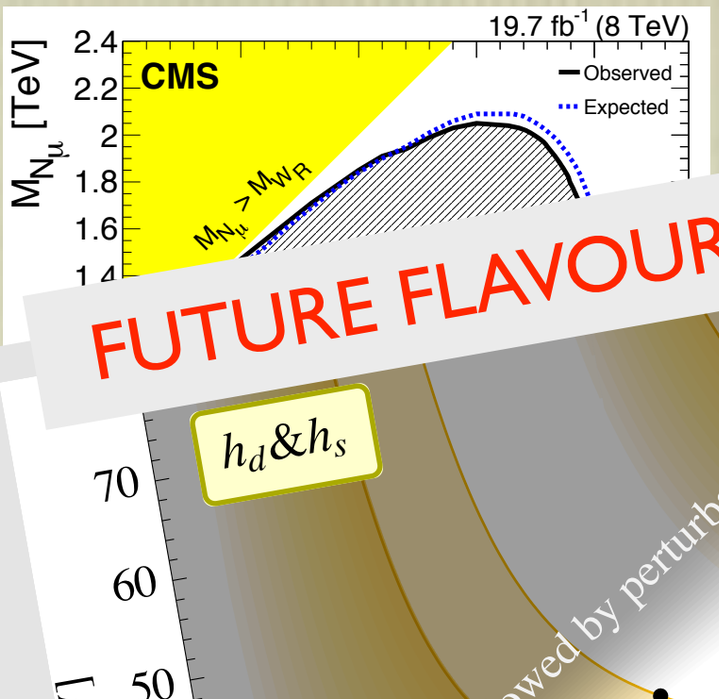


FIG. 10. Combined constraints on M_R and M_{W_R} from ε, ε' B_d and B_s mixings obtained in the $\mathcal{P}$ parity case from the numerical fit of the Yukawa sector of the model.

[Bertolini Maiezza, FN '12,'13,'14]

...so: Recent Limits





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from $\Delta M(K, B_d, B_s)$
theoretical limit
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~ 3-4 TeV

EXP

13-008]
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zza+ '10]

FIG. 11. Future constraints on M_R and M_{W_R} from the projected combined limits on h_d and h_s discussed in Ref. [77]. Stage I corresponds to a foreseen 7 fb^{-1} (5 ab^{-1}) data accumulation by LHCb (Belle II) by the end of the decade. Stage II assumes 50 fb^{-1} (50 ab^{-1}) data by the two experiments, achievable by mid 2020's.

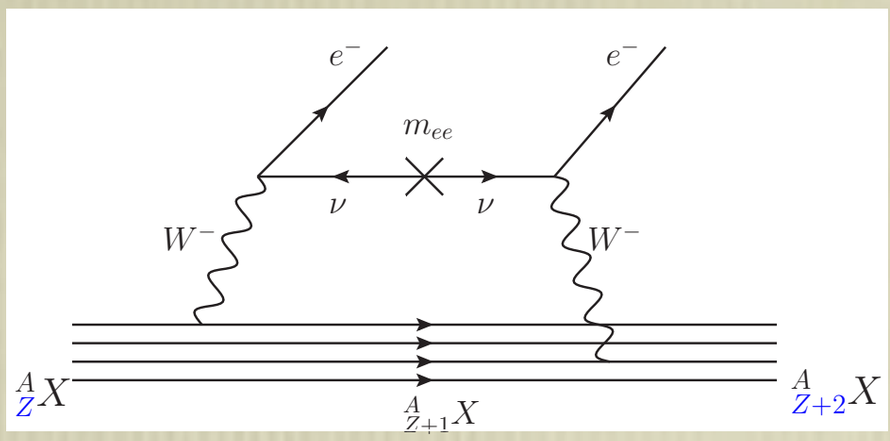
FIG. 9. Correl
the curves) for
$\theta_t = \pi/2$ in the

$_{W_R}$ from ε, ε'
the P parity case from the
Yukawa sector of the model.

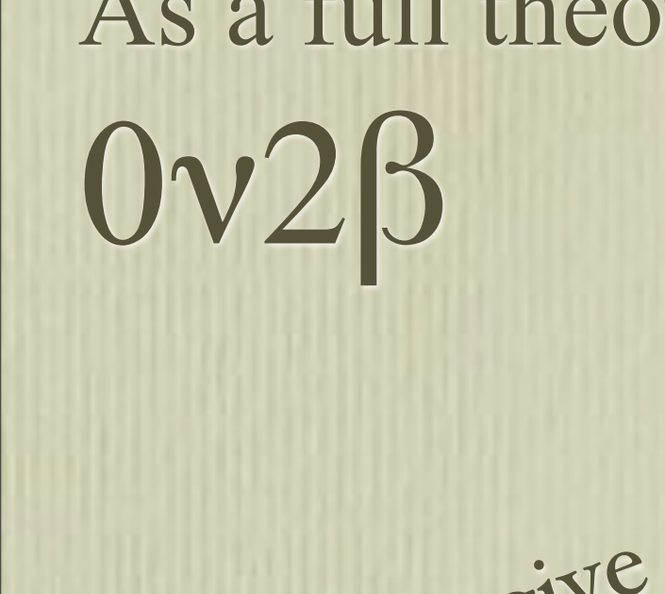
[Bertolini Maiezza, FN '12,'13,'14]

As a full theory, LR gives more

0ν2β

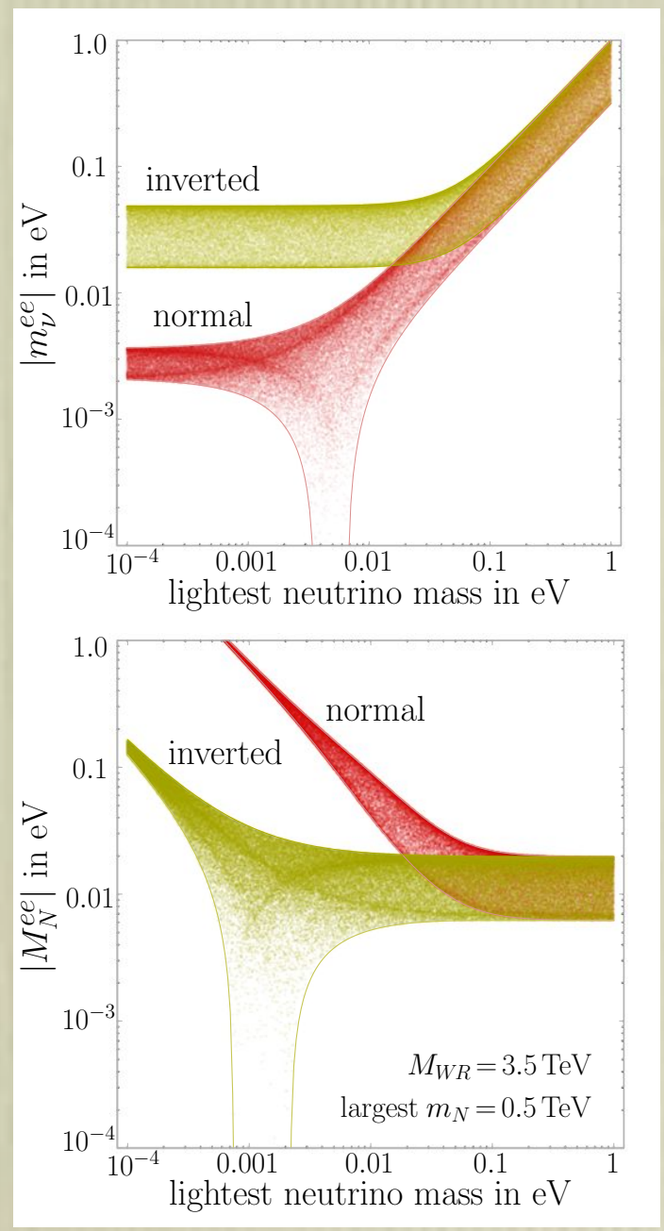


W_R & ν_R give new contributions



LL

RR



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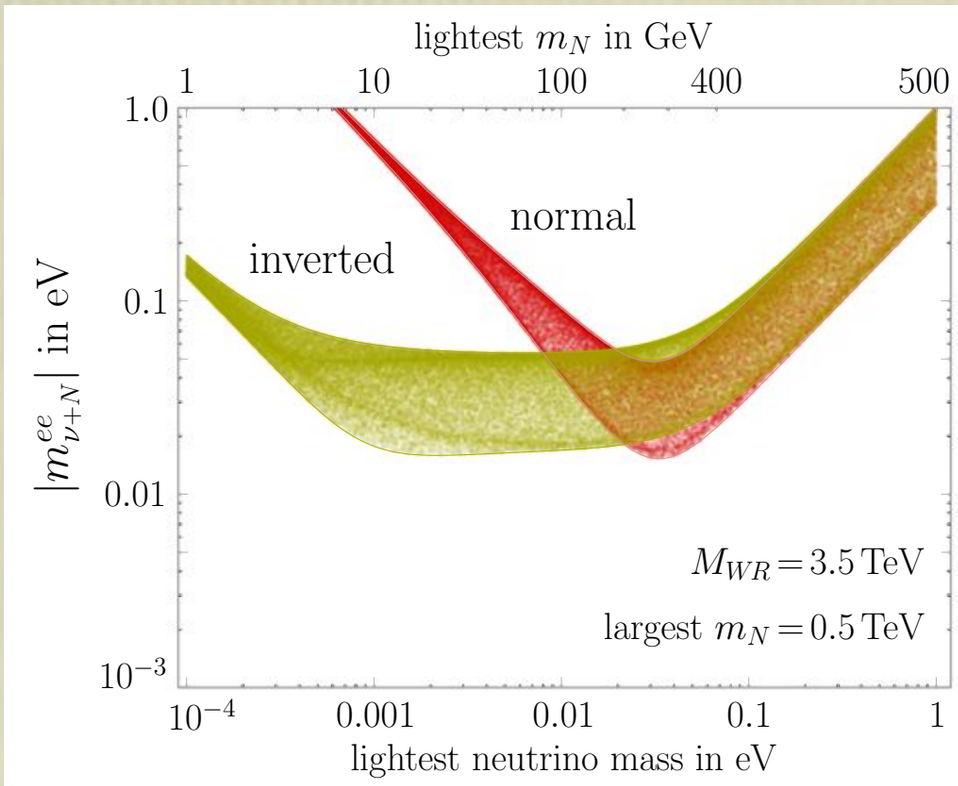

[Tello + '10] (type-II limit but see Tello's talk!)

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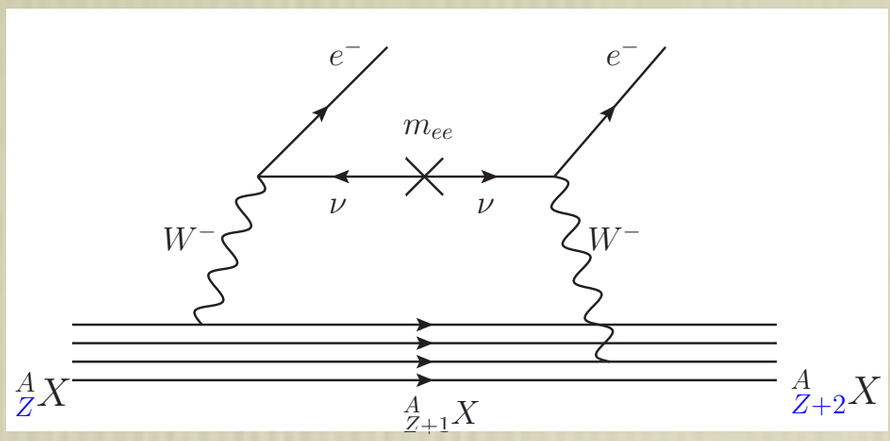

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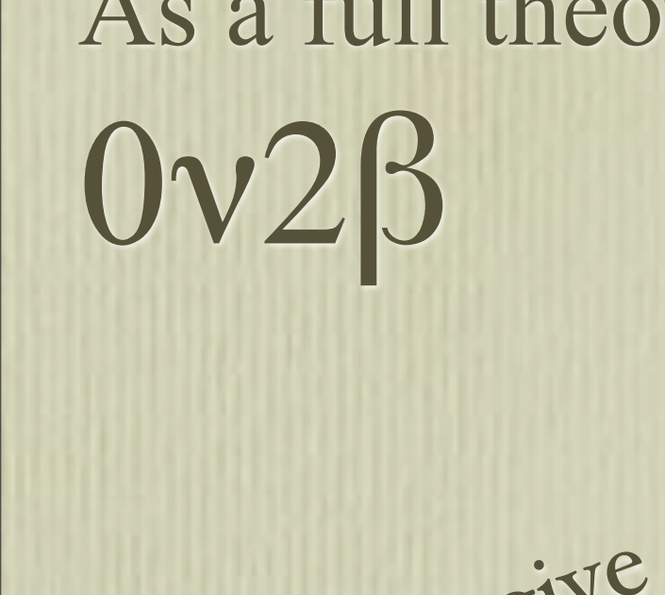

LL

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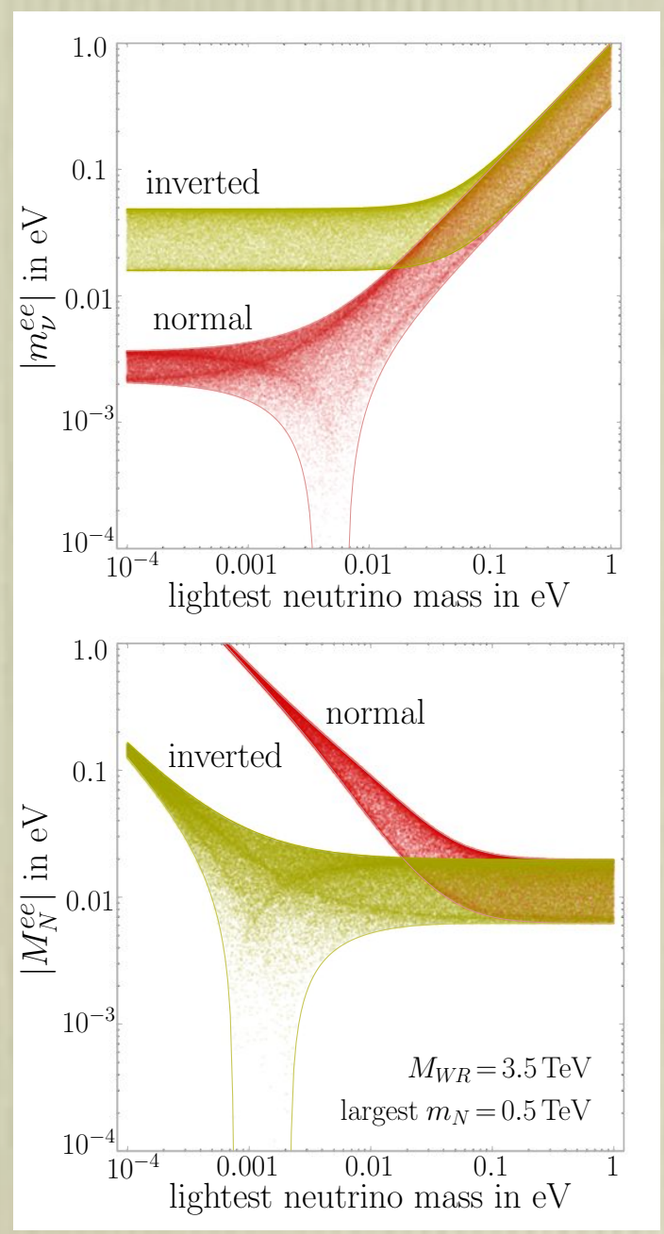

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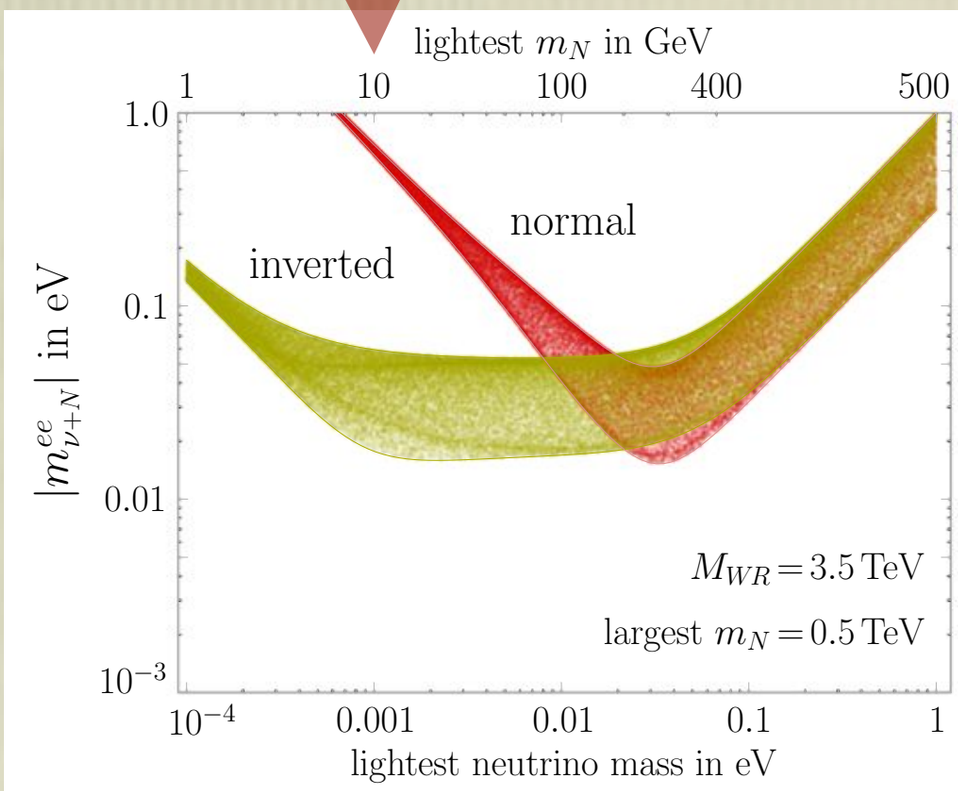
0ν2β points to W_R & m_N @LHC

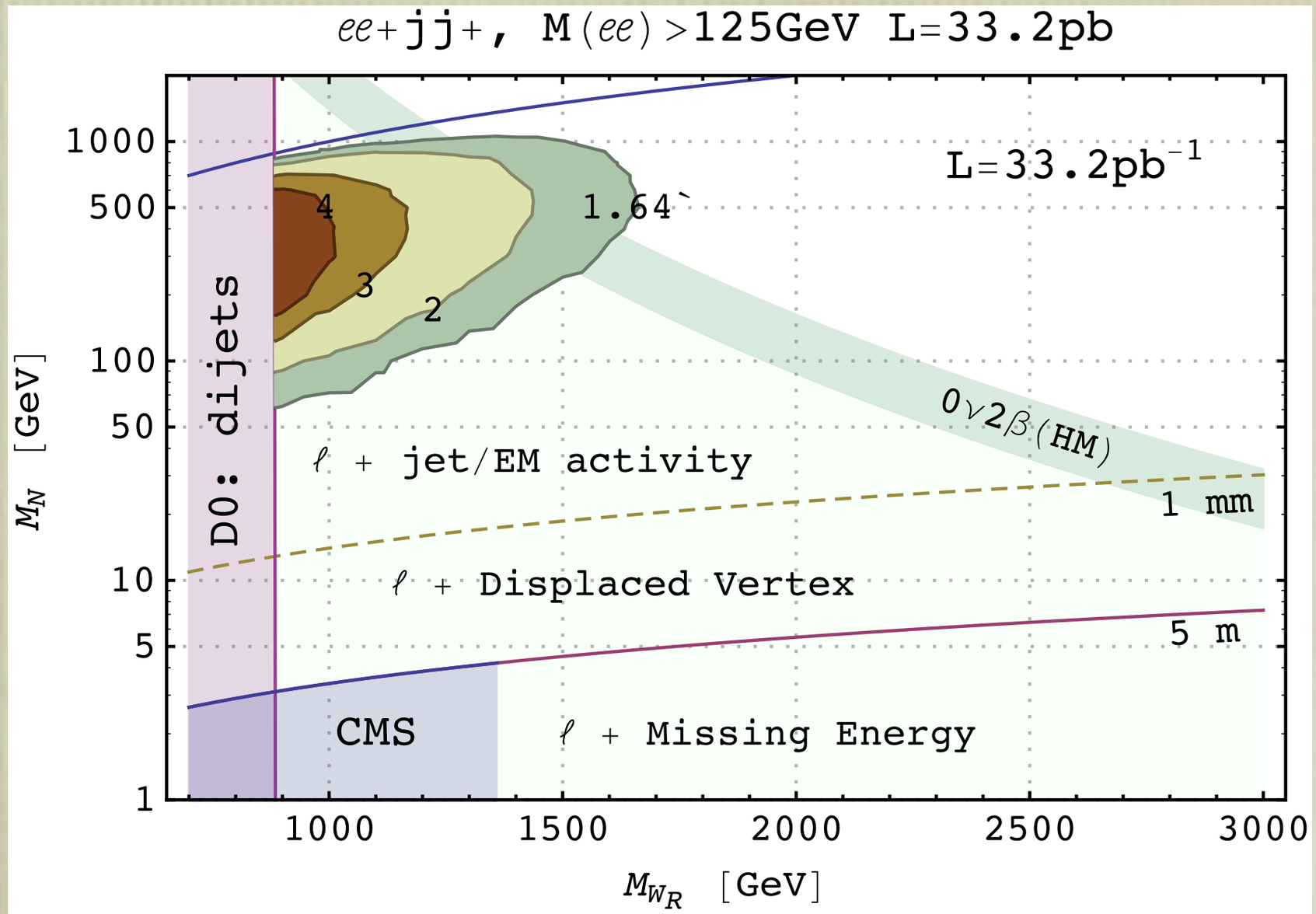


[Tello + '10] (type-II limit but see Tello's talk!)

Scenario @ 2011

from our older LR@LHC "roadmap"

[Nemevšek, FN, Senjanović, Zhang '11]



Scenario @ 2014

from our older LR@LHC "roadmap"

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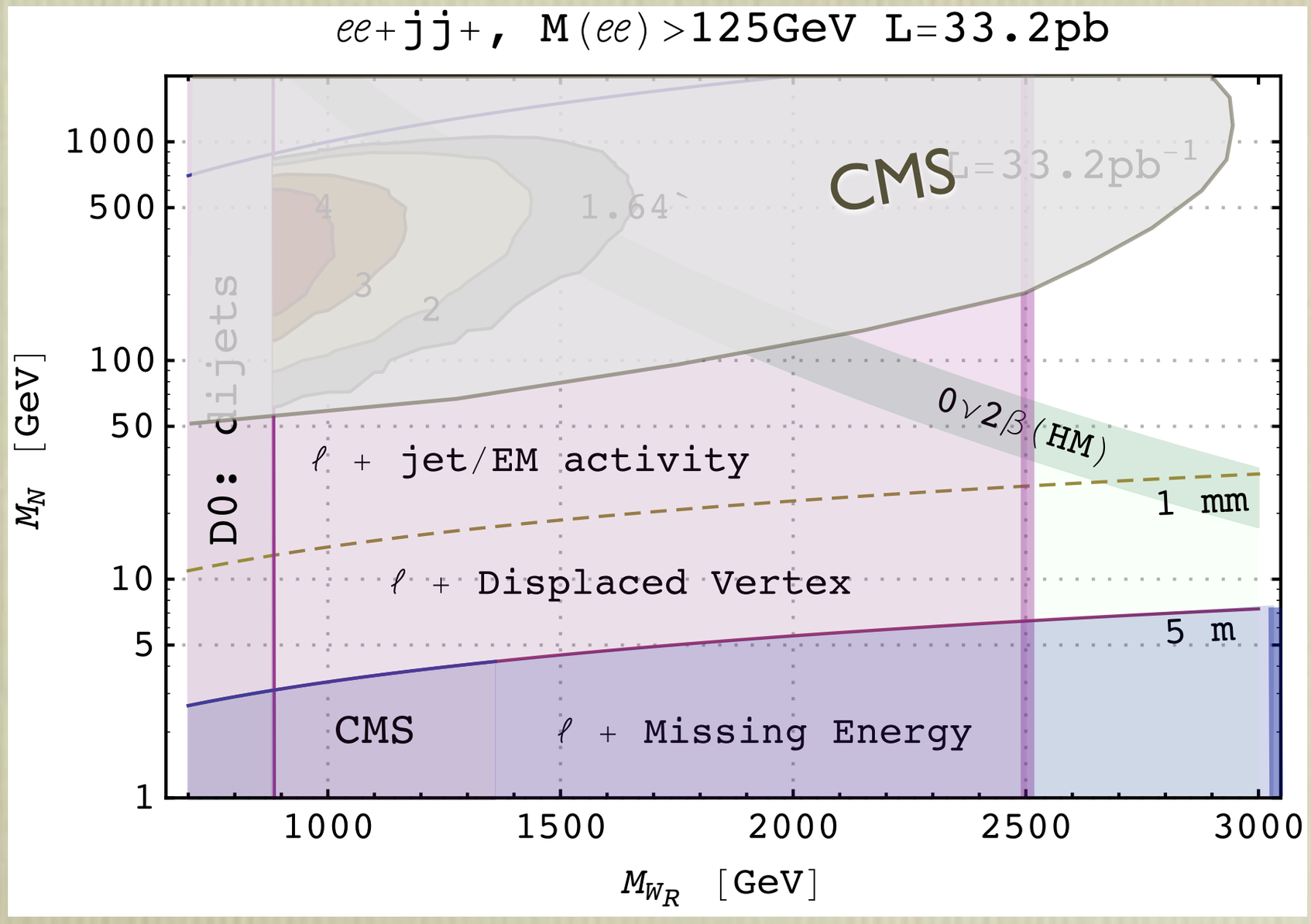

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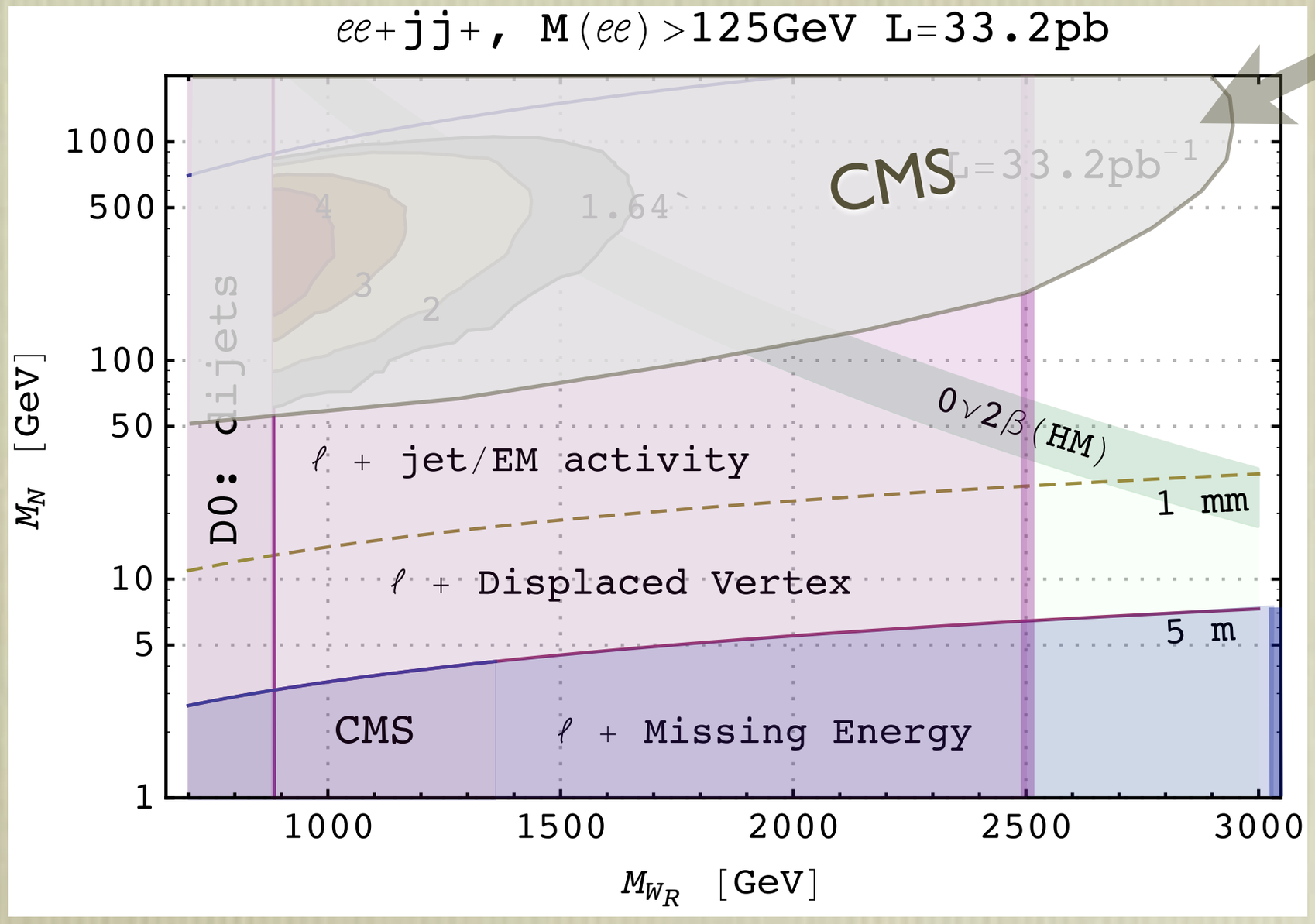

Keung-Senjanovic

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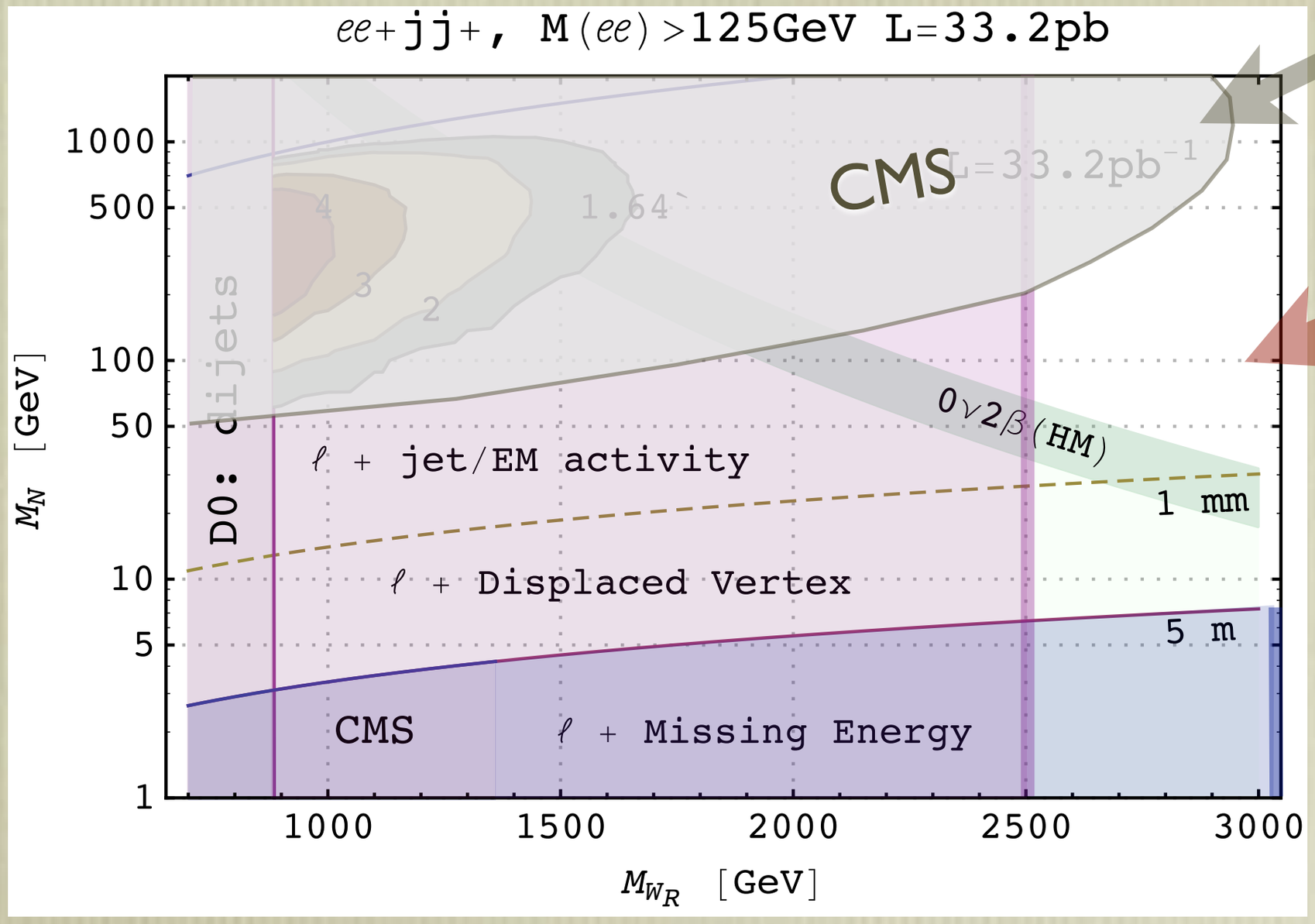


Keung-Senjanovic

$l\,l\,j\,j$

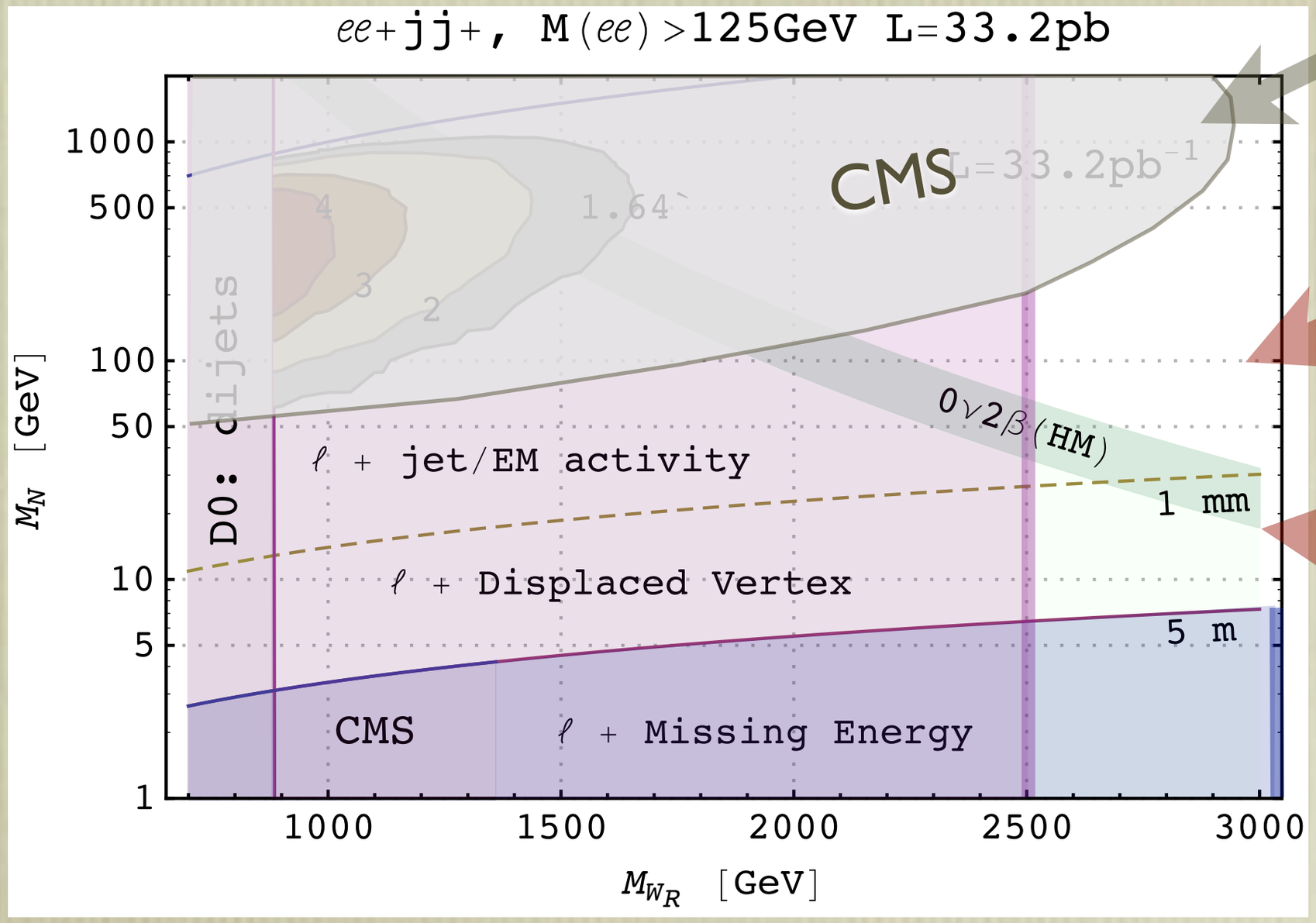
jets are merged

$l\,j$

Scenario @ 2014

from our older LR@LHC "roadmap"

[Nemevšek, FN, Senjanović, Zhang '11]



Keung-Senjanovic

$l\,l\,j\,j$

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l + jet from displaced vertex.. anyone?

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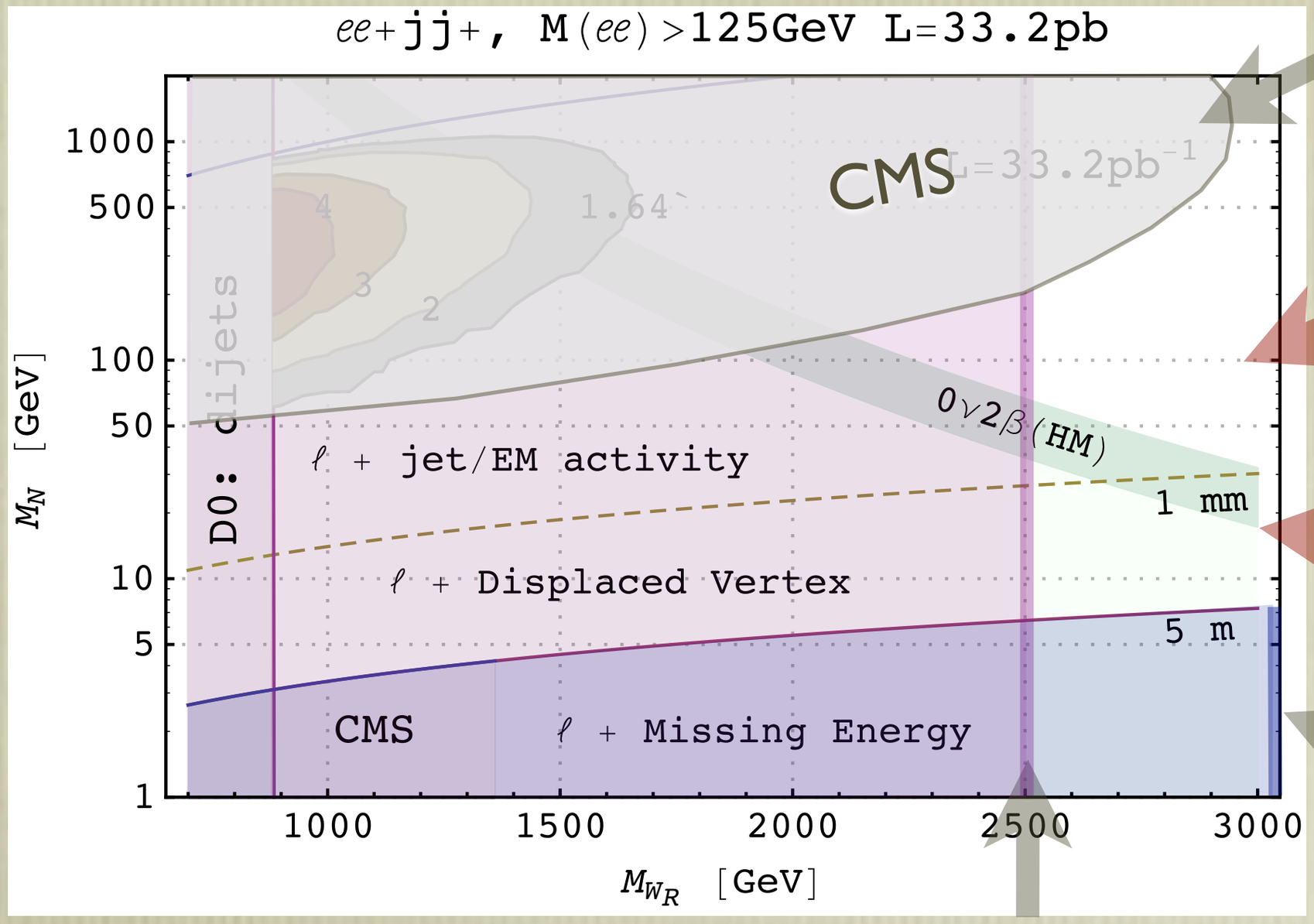

Keung-Senjanovic

$lljj$

jets are merged

lj

l + jet from displaced vertex.. anyone?

$W' \to l+\nu$ search

$W' \to$ dijet search

Scenario @ 2014

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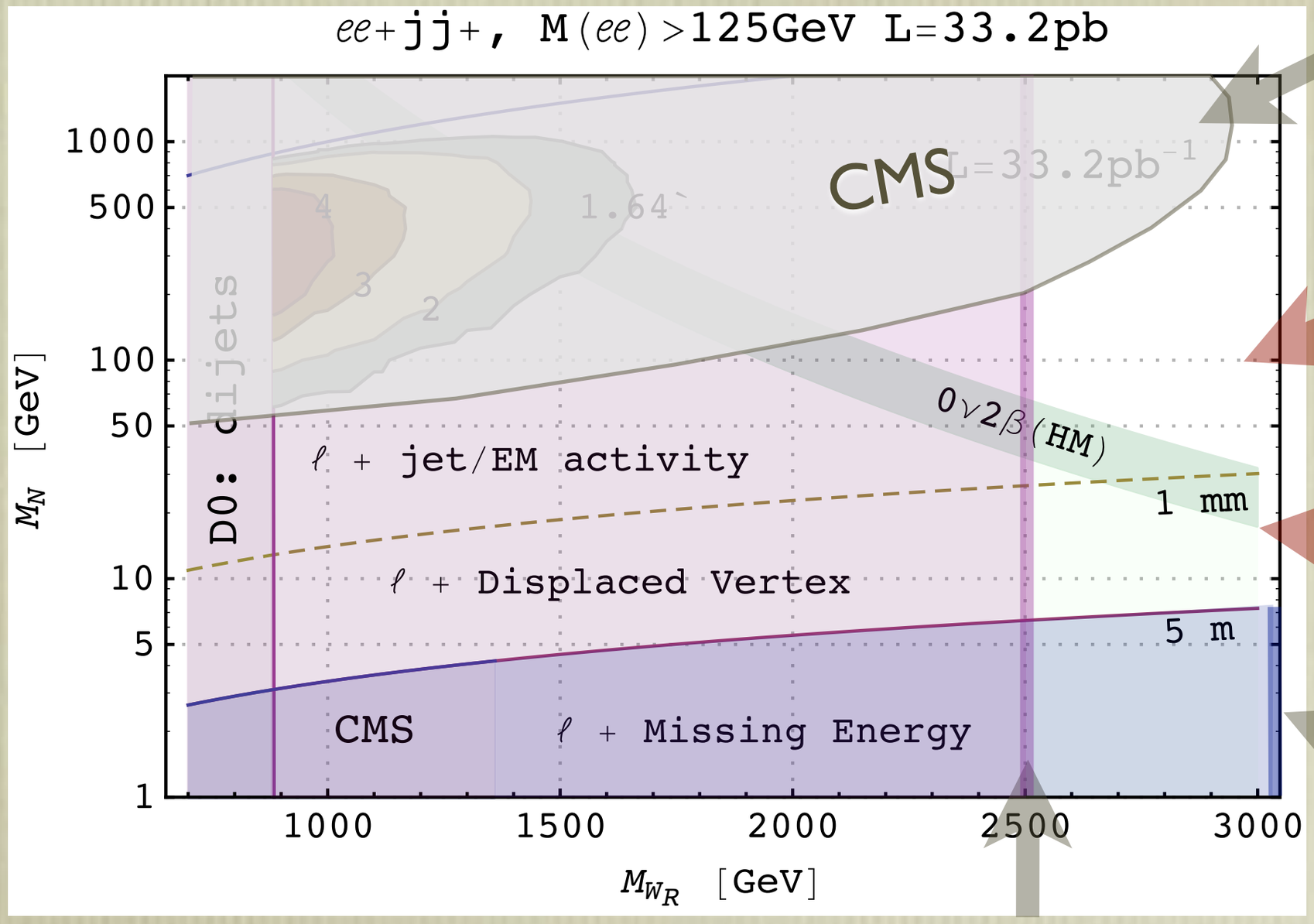

Keung-Senjanovic

l l j j

jets are merged

l j

l + jet from displaced vertex.. anyone?

W'➛*l*+ν search

W'➛dijet search

HRZZ project PhysMaB @ IRB (apply *now* for PhD!)

Outlook

- Neutrino masses exist
  and are in search for a theory.
- Low and high energy can be connected
  by Lepton Number Violation
- Challenges to theorists
  and to experimentalists.
- Nothing else to say...

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Thanks!