Neutrinos at TLEP

29 October 2013

IOP TLEP Meeting
UCL

Silvia Pascoli
IPPP – Durham University

Outline

Sterile neutrinos are the simplest extension of the Standard Model which can also accommodate neutrino masses.

1. Neutrino masses and sterile neutrinos
2. Tests of sterile neutrinos
3. First thoughts about sterile neutrinos at TLEP
4. Conclusions

Neutrino masses BSM

Neutrino Masses in the Standard Model

In the SM, neutrinos do not acquire a mass and mixing:

- like the other fermions as there are no right-handed neutrinos.

$$m_e \bar{e}_L e_R \qquad\qquad m_\nu \bar{\nu}_L \cancel{\nu_R}$$

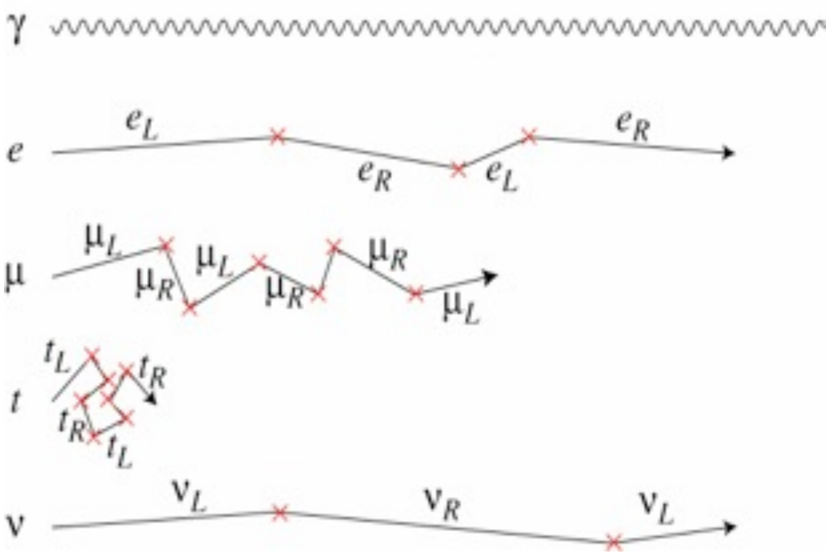
Solution: Introduce ν_R for Dirac masses

- they do not have a Majorana mass term

$$M \nu_L^T C \nu_L$$

as this term breaks the SU(2) gauge symmetry.
Solution: Introduce an SU(2) scalar triplet or gauge invariant non-renormalisable terms (D>4).

Neutrino masses in the sub-eV range cannot be explained naturally within the SM. If neutrinos had the same interactions with the Higgs as the top quark, they would be **100000000000** times heavier!



Thanks to Murayama

$$\mathcal{L} = -y_\nu \bar{L} \cdot \tilde{H} \nu_R + \text{h.c.}$$

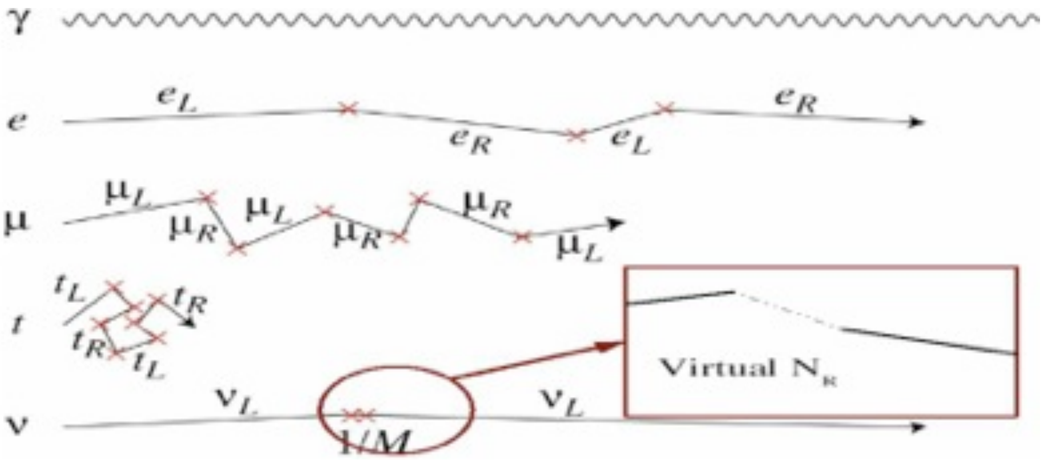
$$y_\nu \sim \frac{\sqrt{2} m_\nu}{v_H} \sim \frac{0.2\ \text{eV}}{200\ \text{GeV}} \sim 10^{-12}$$

1. why the coupling is so small????
2. why the mixings are large? (instead of small as in the quark sector)
3. why neutrino masses have at most a mild hierarchy if they are not quasi-degenerate? instead of what happens to quarks?

Many theorists consider this explanation of neutrino masses unnatural, unless an explanation can be given for the extreme smallness of the coupling (e.g. large or warped extra-D models).

Majorana Masses

In order to have an SU(2) invariant mass term for neutrinos, it is necessary to introduce a Dimension 5 operator (or to allow for new scalar fields, e.g. a scalar triplet):



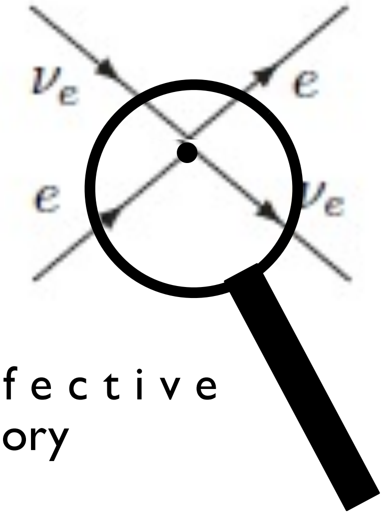
Thanks to
H. Murayama

D=5 term

$$-\mathcal{L} = \lambda \frac{\nu_L H \, \nu_L H}{M} = \frac{\lambda v^2}{M} \nu_L^T C \nu_L$$

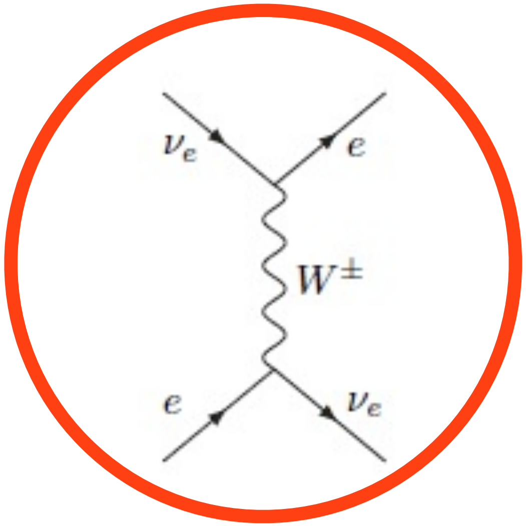
Lepton number violation!

If neutrino are Majorana particles, a **Majorana mass** can arise as the **low energy realisation of a higher energy theory (new mass scale!)**.



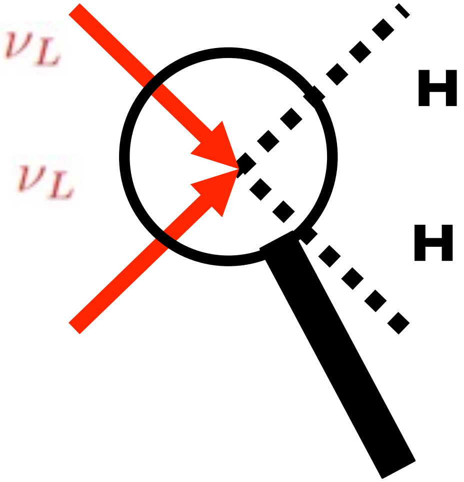
effective theory

$$\mathcal{L} \propto G_F(\bar{e}_L\gamma_\mu\nu_L)(\bar{\nu}_L\gamma^\mu e_L)$$



Standard Model: W exchange

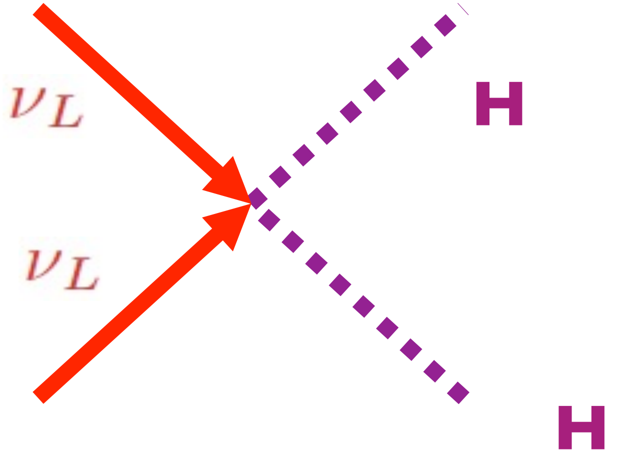
$$\mathcal{L}_{SM} \propto g\bar{\nu}_L\gamma^\mu e_L W_\mu \Rightarrow G_F \propto \frac{g^2}{m_W^2}$$



Neutrino mass

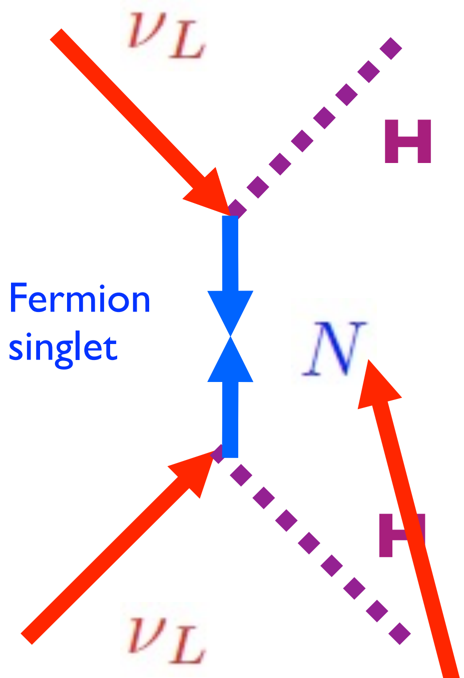
$$-\mathcal{L} = \lambda\frac{\nu_L H\,\nu_L H}{M} = \frac{\lambda v^2}{M}\nu_L^T C\nu_L$$

New theory: new particle exchange with mass M



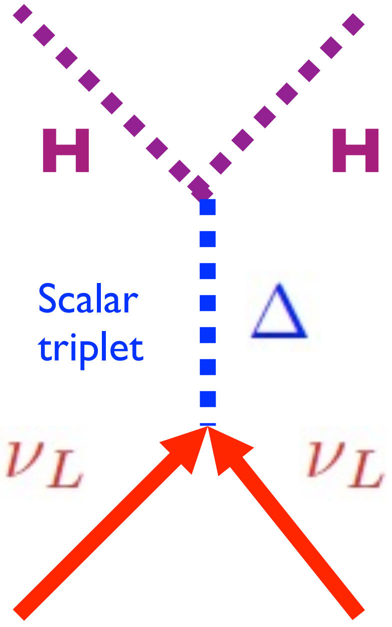
$$\frac{\nu_L H \, \nu_L H}{\Lambda}$$

See-saw Type I



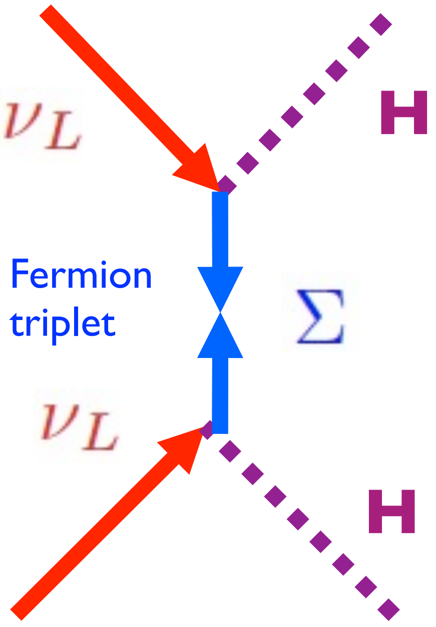
Minkowski, Yanagida, Glashow, Gell-Mann, Ramond, Slansky, Mohapatra, Senjanovic

See-saw Type II



Magg, Wetterich, Lazarides, Shafi. Mohapatra, Senjanovic, Schecter, Valle

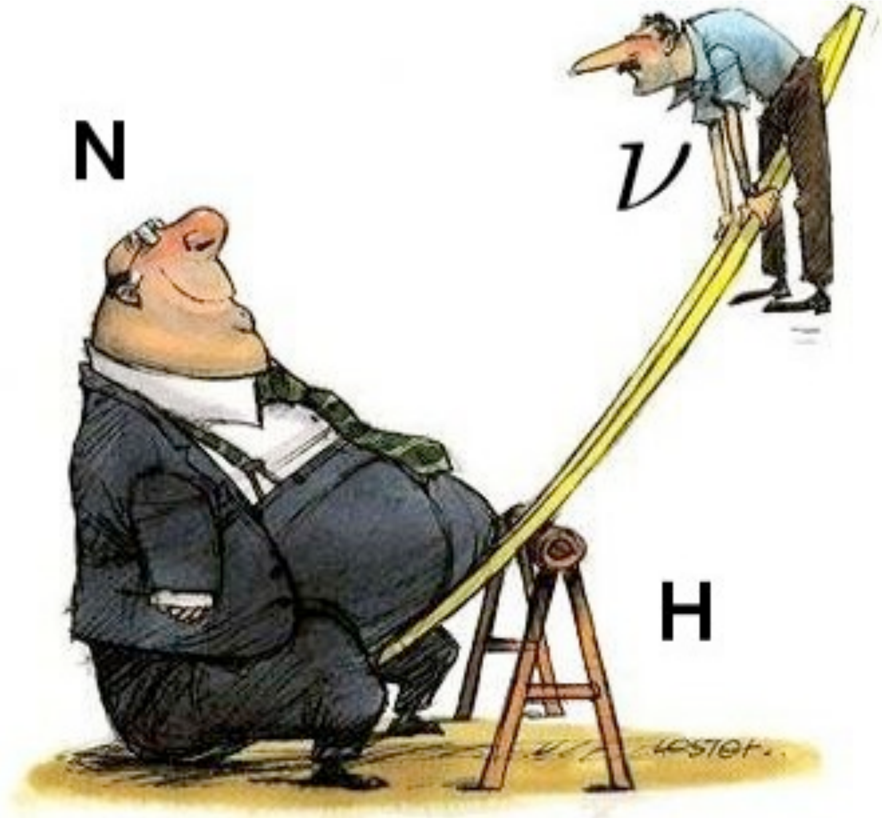
See-saw Type III



Ma, Roy, Senjanovic, Hambye

Sterile neutrino

The simplest see saw mechanism: type I



- Introduce a right handed neutrino **N (sterile neutrino)**
- Couple it to the Higgs and left handed neutrinos

The Lagrangian is

breaks lepton number

$$\mathcal{L} = -Y_\nu \bar{N} L \cdot H - \boxed{1/2\bar{N}^c M_R N}$$

When the Higgs boson gets a vev, Dirac masses will be generated and the mass matrix will be

$$\mathcal{L} = (\nu_L^T N^T) \begin{pmatrix} 0 & m_D \\ m_D^T & M \end{pmatrix} \begin{pmatrix} \nu_L \\ N \end{pmatrix}$$

One massive state remains very heavy, the light neutrino masses acquires a tiny mass!

$$m_\nu \simeq \frac{m_D^2}{M} \sim \frac{1\,\mathrm{GeV}^2}{10^{10}\,\mathrm{GeV}} \sim 0.1\,\mathrm{eV}$$

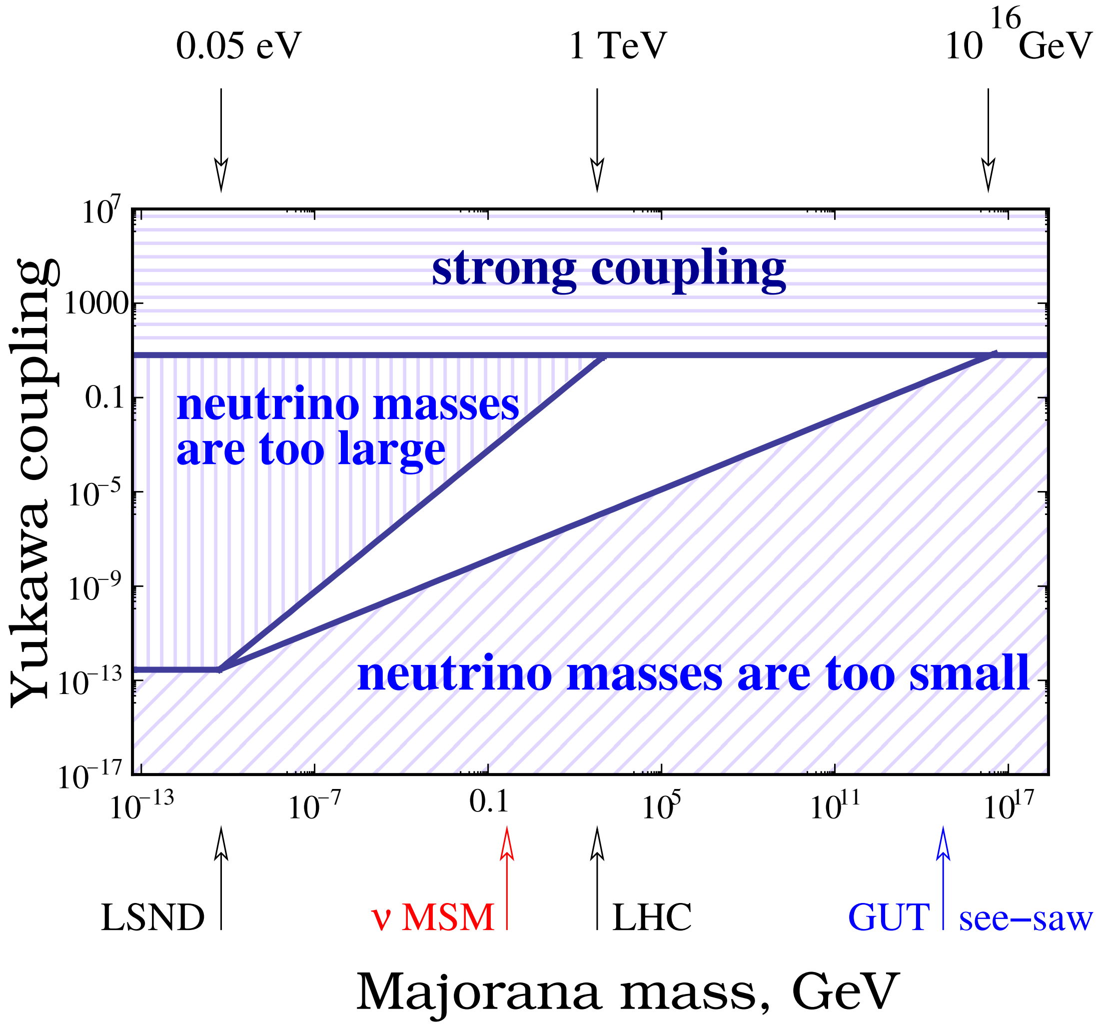
Mixing between active neutrinos and heavy neutrinos will emerge but it will be typically very small

$$\tan 2\theta = \frac{2m_D}{M}$$

Mixing can be related to neutrino masses

$$m_\nu \simeq \frac{m_D^2}{M} \simeq \sin^2\theta M$$

Important for searches



Models with enhanced mixing

The mixing-mass relation can be avoided if neutrino masses are suppressed. A typical example are the inverse see-saw and extended see-saw models, in which two sterile neutrinos are introduced.

$$\mathcal{L} = Y \bar{L} \cdot H N_1 + Y_2 \bar{L} \cdot H N_2^c + \Lambda \bar{N}_1 N_2 + \mu' N_1^T C N_1 + \mu N_2^T C N_2$$

The neutrino mass matrix is

$$\begin{pmatrix} 0 & Yv & Y_2 v \\ Yv & \mu' & \Lambda \\ Y_2 v & \Lambda & \mu \end{pmatrix}$$

Depending on the assignment one can have different lepton numbers:

N1=1, N2=1:
$$\begin{pmatrix} 0 & Yv & \boxed{Y_2 v} \\ Yv & \boxed{\mu'} & \Lambda \\ Y_2 v & \Lambda & \boxed{\mu} \end{pmatrix}$$

N1=0, N2=-1:
$$\begin{pmatrix} 0 & \boxed{Yv} & Y_2 v \\ Yv & \mu' & \Lambda \\ Y_2 v & \Lambda & \boxed{\mu} \end{pmatrix}$$

N1=1, N2=0:
$$\begin{pmatrix} 0 & Yv & \boxed{Y_2 v} \\ Yv & \boxed{\mu'} & \boxed{\Lambda} \\ Y_2 v & \Lambda & \mu \end{pmatrix}$$

This implies that neutrino masses require

- $Yv, \quad \mu'$ (= standard see-saw plus light sterile neutrino)
- $Yv, \quad \Lambda, \quad \mu, \quad \text{and/or } Y_2 v \quad \text{and/or } \mu'$

$$m_{tree} \simeq -m_D^T M^{-1} m_D \simeq \frac{v^2}{2(\Lambda^2 - \mu'\mu)} \left(\mu Y_1^T Y_1 + {}^{2}\mu' Y_2^T Y_2 - \Lambda\epsilon (Y_2^T Y_1 + Y_1^T Y_2)\right)$$

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Small neutrino masses associated to small breaking of L.

Two limits:

- **Inverse see-saw:** $\Lambda \gg \mu, Y_2 v, \mu'$

Gavela et al., 0906.1461; Ibarra, Molinaro, Petcov, 1103.6217

Two quasi-Dirac neutrinos with large mixing

$$m_4 \approx -m_5 \approx \tilde{M}_1 \approx -\tilde{M}_2 \approx \Lambda, \qquad U_{e4} \approx U_{e5} \approx Y_{1e} v / 2\Lambda,$$

$$\Delta \tilde{M} \equiv |\tilde{M}_2| - |\tilde{M}_1| \approx \mu',$$

- **Extended see-saw:** $\mu' \gg \Lambda, \mu$

Kang, Kim, 2007; Majee et al., 2008; Mitra, Senjanovic, Vissani, 1108.0004

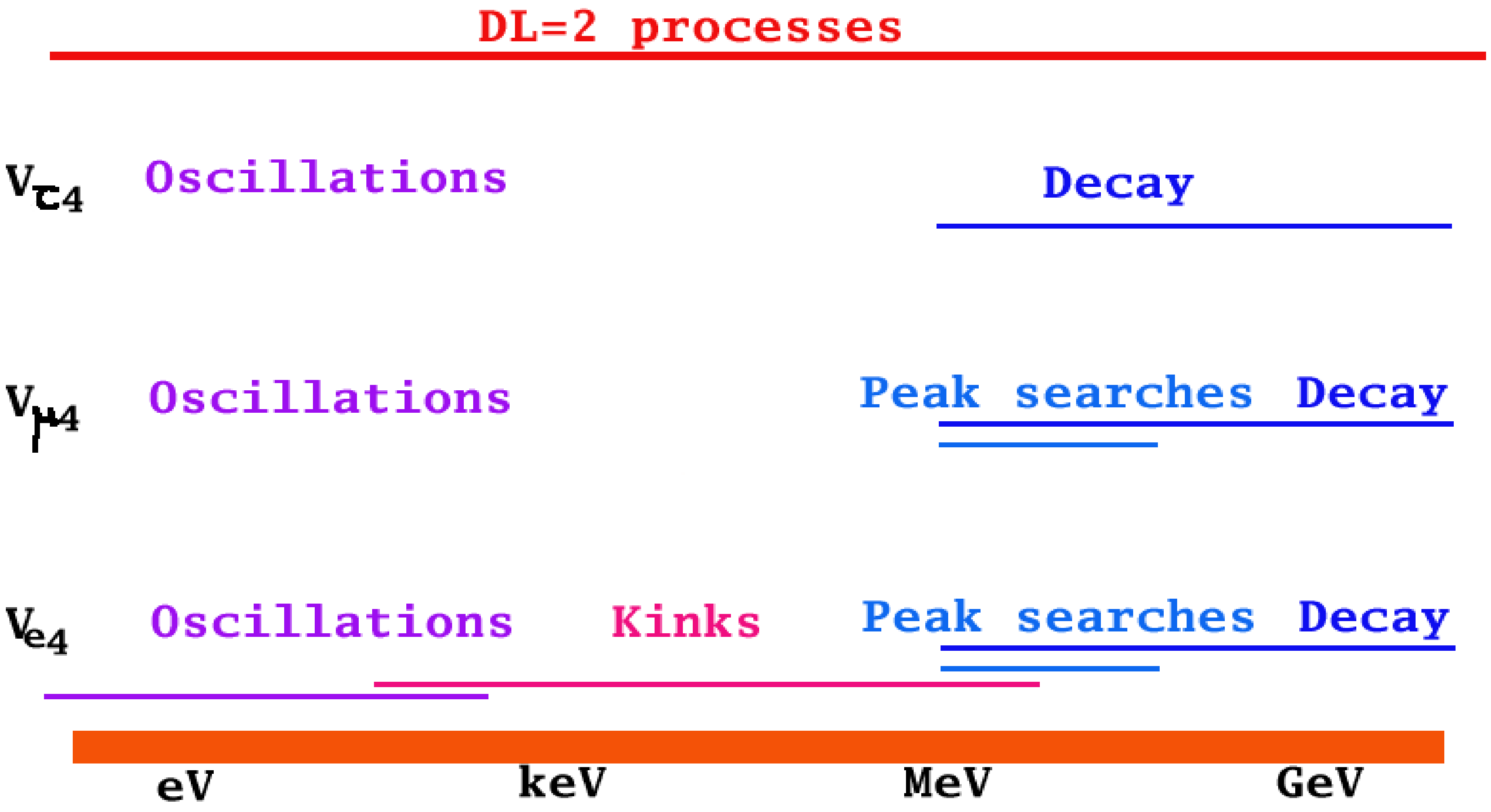
$$m_4 \approx \tilde{M}_1 \approx -\Lambda^2/\mu', \qquad U_{e4} \approx Y_{1e} v / \sqrt{2}\Lambda$$

$$m_5 \approx \tilde{M}_2 \approx \mu', \qquad U_{e5} \approx Y_{1e} v / \sqrt{2}\mu'$$

Other models with enhanced sterile neutrino production require new interactions (e.g. Z', see-saw type III...)

Testing sterile neutrinos

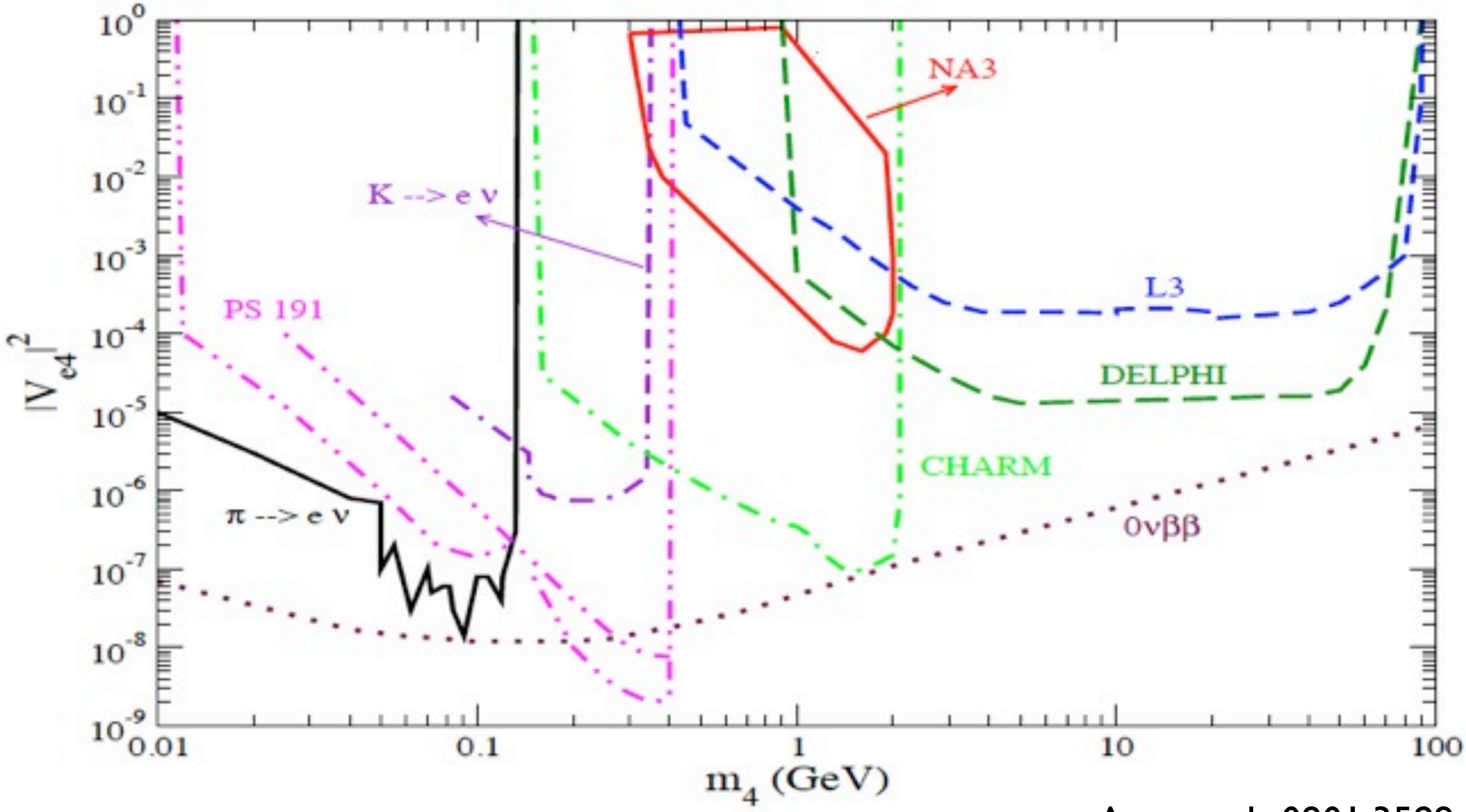
Searches of sterile neutrino depend on their masses.



Invisibles decay of Z for masses above mZ/2.

- Effects arise due to mixing with the active ones.

$$\begin{cases} |\nu_1\rangle = \cos\theta|\nu_e\rangle - \sin\theta|\nu_s\rangle \\ |N_2\rangle = \sin\theta|\nu_e\rangle + \cos\theta|\nu_s\rangle \end{cases}$$



Atre et al., 0901.3589

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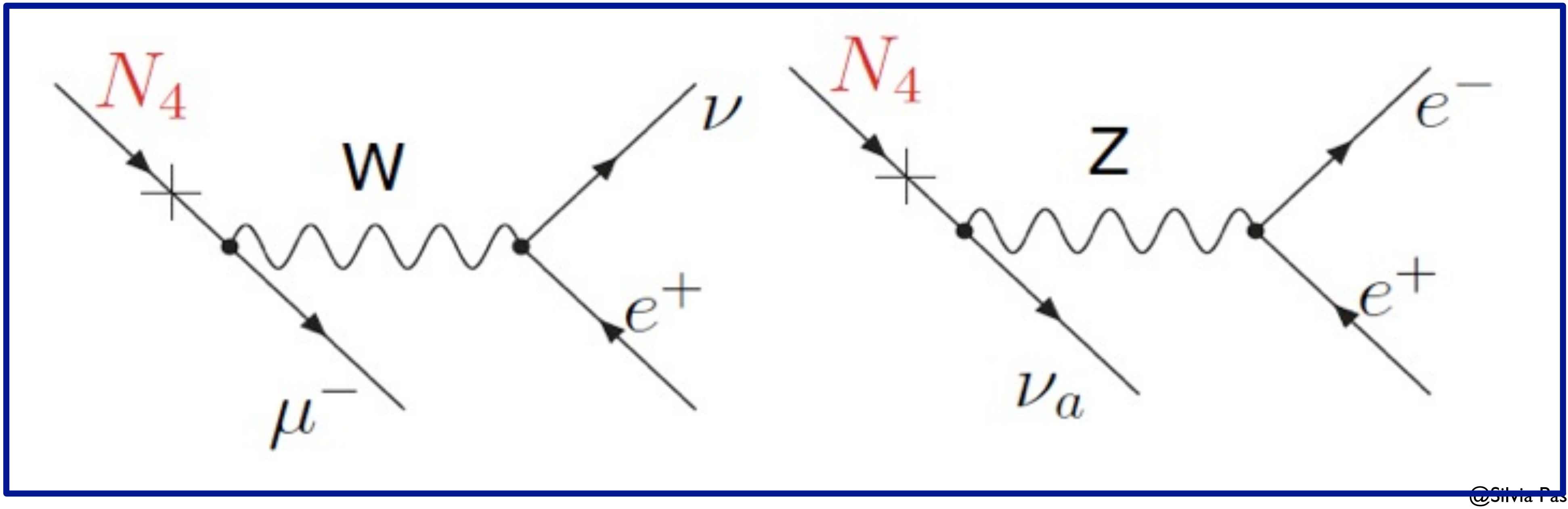
Decays and LNV at colliders

Sterile neutrinos can be produced and then decay into SM particles, due to mixing.

Decay signatures.

LNV processes have no SM backgrounds. They shows up as a same-sign dilepton signal with no missing energy.



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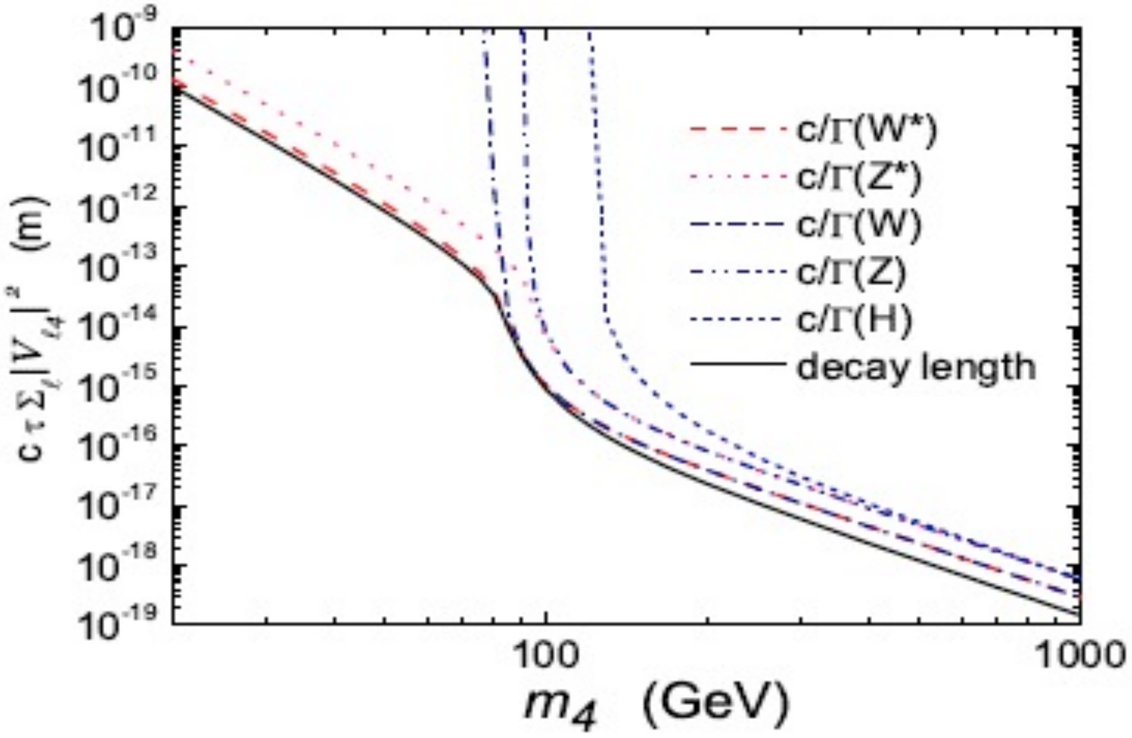
Even for very small mixing, the decay length is very small.

$$\Gamma_{N_4} \begin{cases} \approx \sum_\ell |V_{\ell 4}|^2 \dfrac{3G_F m_4^3}{8\pi\sqrt{2}} & \text{for } \ m_4 > m_W\,, \\ \propto \sum_\ell |V_{\ell 4}|^2\, G_F^2 m_4^3 (f_M^2 + m_4^2) & \text{for } \ m_4 \ll m_W\,, \end{cases}$$

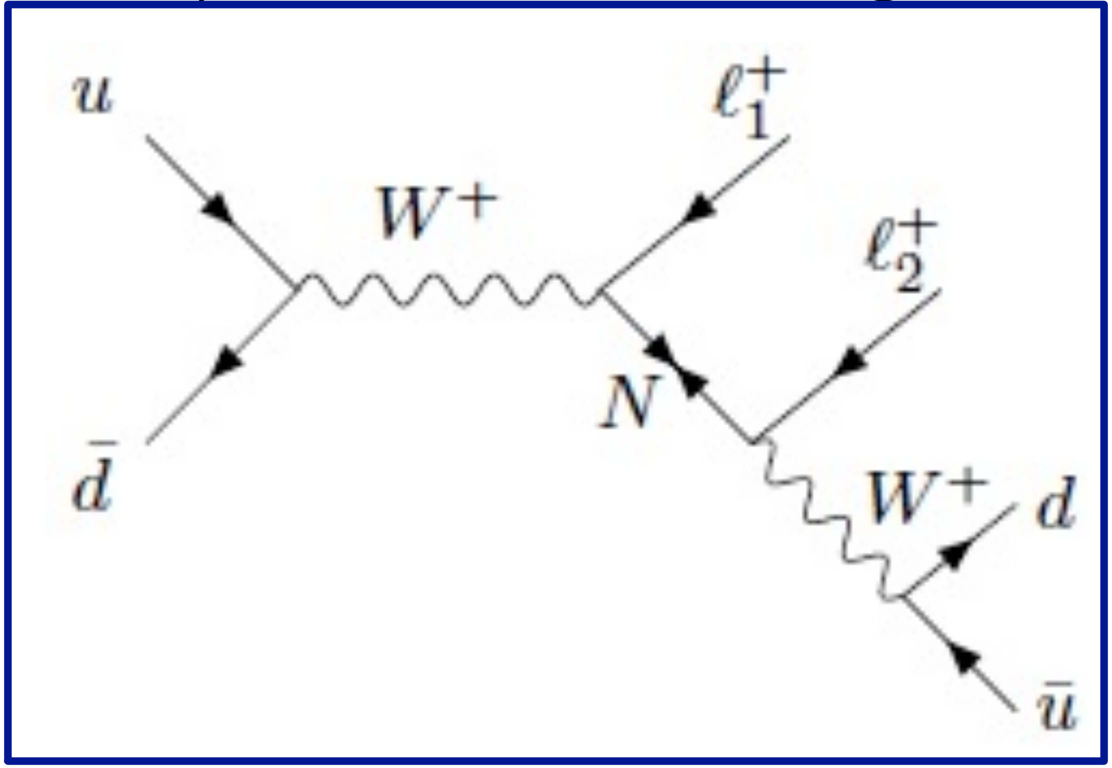


As the mass increases, more channels become kinematically available.

Atre et al., 0901.3589

If the decay length ~ few m, one could search for displaced vertices.

At the LHC, the dominant mechanism is W or Z-exchange (or BSM), at TLEP Z-exchange, or new physics.



where N goes on resonance and the cross section for the process can be approximated as

$$\sigma(pp \to \ell\ell W) \simeq \sigma(pp \to \ell N) Br(N \to \ell W) \sim |V_{\ell 4}|^2 \sigma_0$$

Searches will be controlled by **production** which depends on the mixing.

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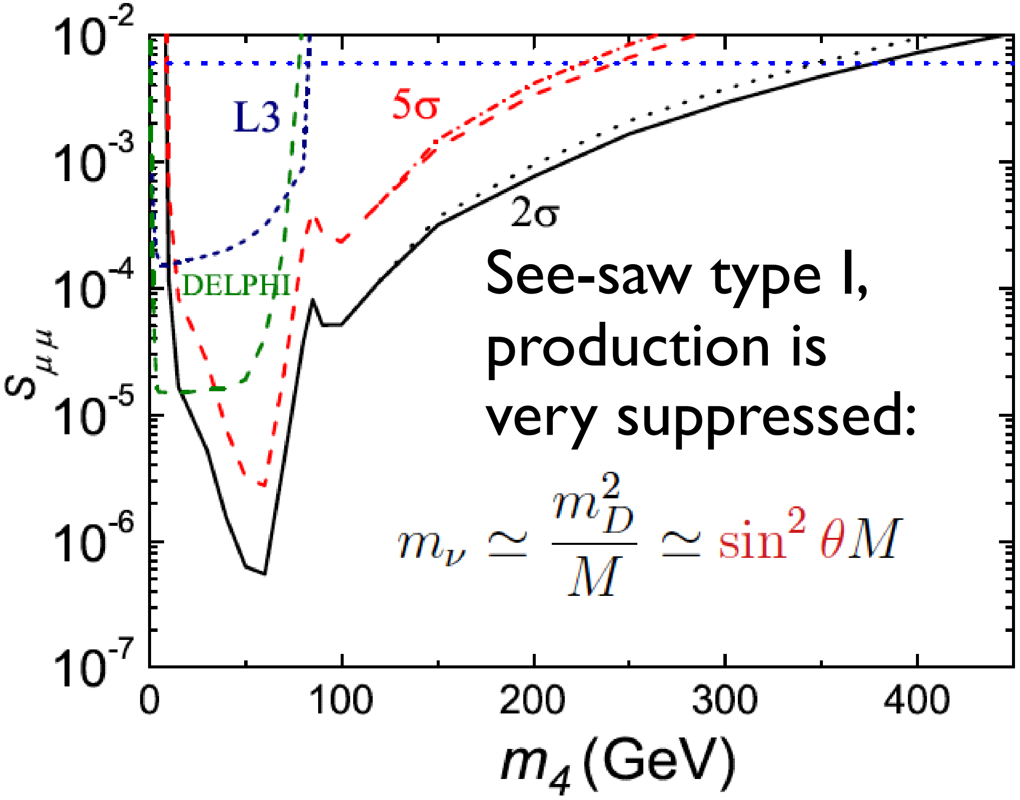
In see-saw type I, in which masses and mixing are directly related, production is suppressed by small mixing angles.

One should invoke some further extension of the SM.



See-saw type I, production is very suppressed:

$$m_\nu \simeq \frac{m_D^2}{M} \simeq \sin^2\theta M$$

Atre et al., 0901.3589

- Gauge B-L: pp → Z' → N N
- See-saw type II: Scalar Triplets
- Triplet see-saw. Triplet N produced in gauge interactions

$$pp \to N^+N^0 \to \ell_1^+\ell_2^+ZW^-$$

- Left-Right models via W_R
- Inverse or extended see-saw models

Invisibles decay of the Z

If sterile neutrinos are heavier than the Z mass, then they cannot be produced in its decay -> violation of unitarity.

C. Jarlskog, 1990

At the end of LEP:

Phys.Rept.427:257-454,2006

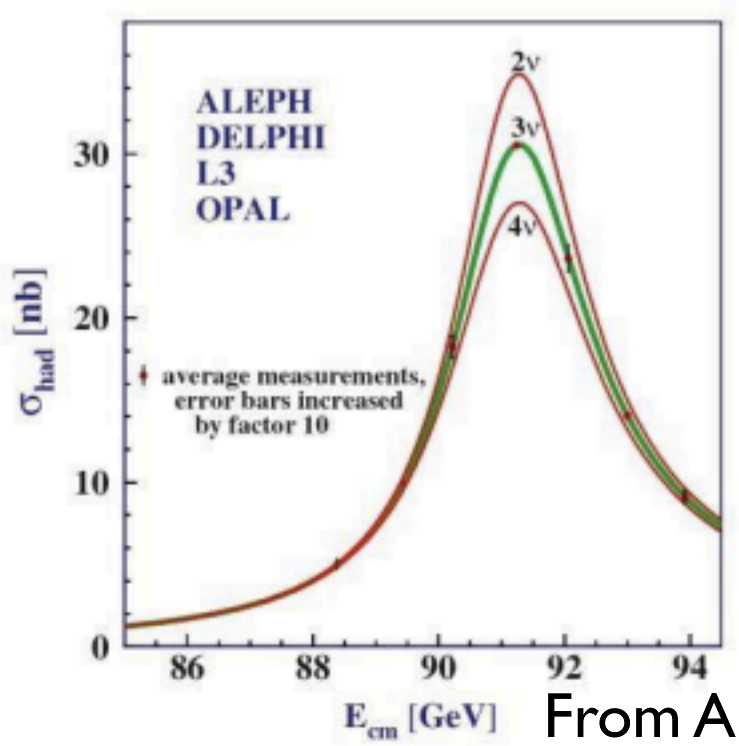
$N_\nu = 2.984 \pm 0.008$

-2σ :^) !!

This is determined from the Z line shape scan and dominated by the measurement of the hadronic cross-section at the Z peak maximum ➔

The dominant systematic error is the theoretical uncertainty on the Bhabha cross-section (0.06%) which represents an error of ± 0.0046 on N_ν

Improving on N_ν by more than a factor 2 would require a large effort to improve on the Bhabha cross-section calculation!



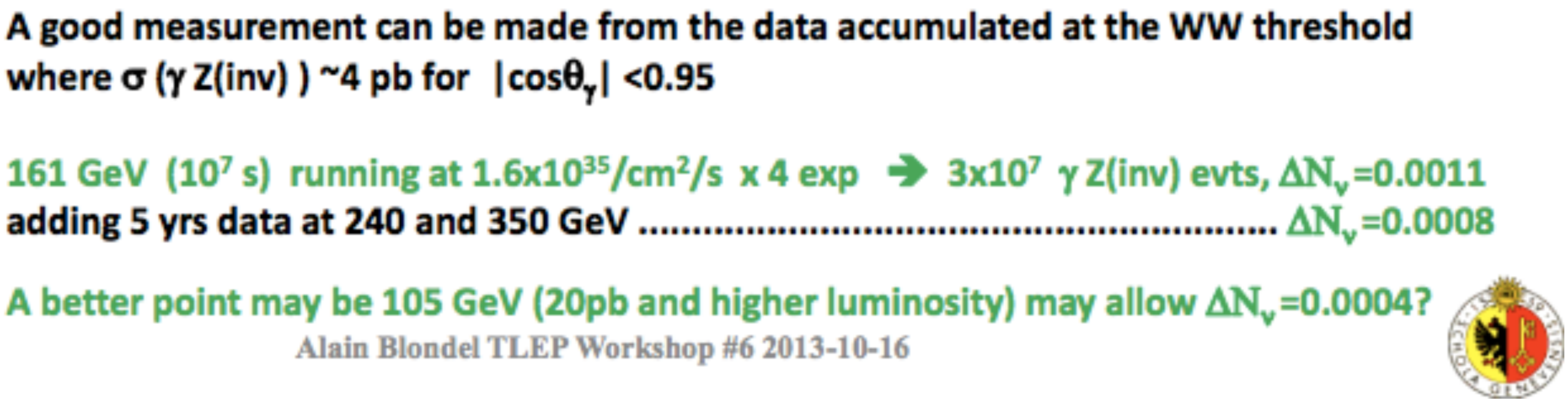
From A. Blondel, talk at TLEP meeting

Another technique looks at $e^+e^- \to \gamma Z(\nu\bar{\nu})$

$$N_\nu = 2.92 \pm 0.05$$

G. Barbiellini et al.

$$N_\nu = \frac{\dfrac{\gamma Z(\nu\bar{\nu})}{\gamma Z(ee,\mu\mu)}}{\dfrac{\Gamma_\nu(SM)}{\Gamma_{e\mu}(SM)}}$$



A good measurement can be made from the data accumulated at the WW threshold where σ (γ Z(inv)) ~4 pb for |$\cos\theta_\gamma$| <0.95

161 GeV (10^7 s) running at 1.6×10^{35}/cm²/s x 4 exp ➔ 3×10^7 γ Z(inv) evts, ΔN_ν=0.0011

adding 5 yrs data at 240 and 350 GeV .... ΔN_ν=0.0008

A better point may be 105 GeV (20pb and higher luminosity) may allow ΔN_ν=0.0004?

Alain Blondel TLEP Workshop #6 2013-10-16

From A. Blondel, talk at TLEP meeting

Conclusions

- **Sterile neutrino models are the minimal extension of the Standard Model and can explain neutrino masses.**

- Masses and mixing are related unless neutrino masses are suppressed.

- They are testable in neutrinoless double beta decay, rare tau and meson decays, and in colliders (LNV as same dilepton channels, N decays and invisible Z width).

- As mixing is linked to neutrino masses, effects at the LHC are suppressed unless production is enhanced due to new physics BSM.

Topical Research Meeting:
Prospects in Neutrino Physics
NuPhys2013

19–20 December 2013
Institute of Physics, London, UK

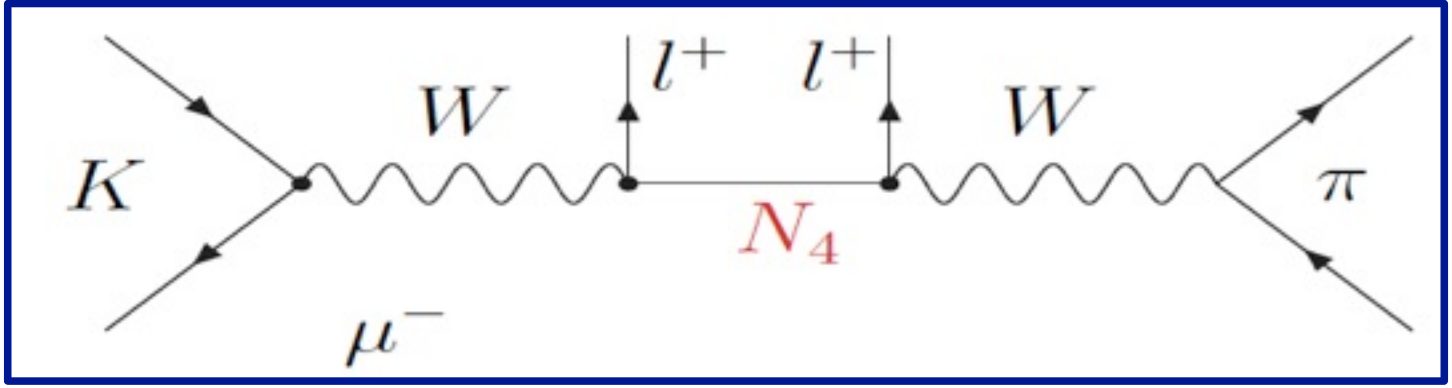
Confirmed speakers: F. Feruglio, E. Lisi, Y. Wang, M. Fallot, P. Huber, S. Soldner-Rembold, T. Nakaya, D. Wark, C. Backhouse, R. Wilson, T. Katori, A. Bross, A. Blondel, S. Petcov, J. Kopp, M. Pallavicini, G. Drexlin, M. Chen, F. Simkovic, F. Deppisch, L. Verde, J. Miller, Chang Kee.

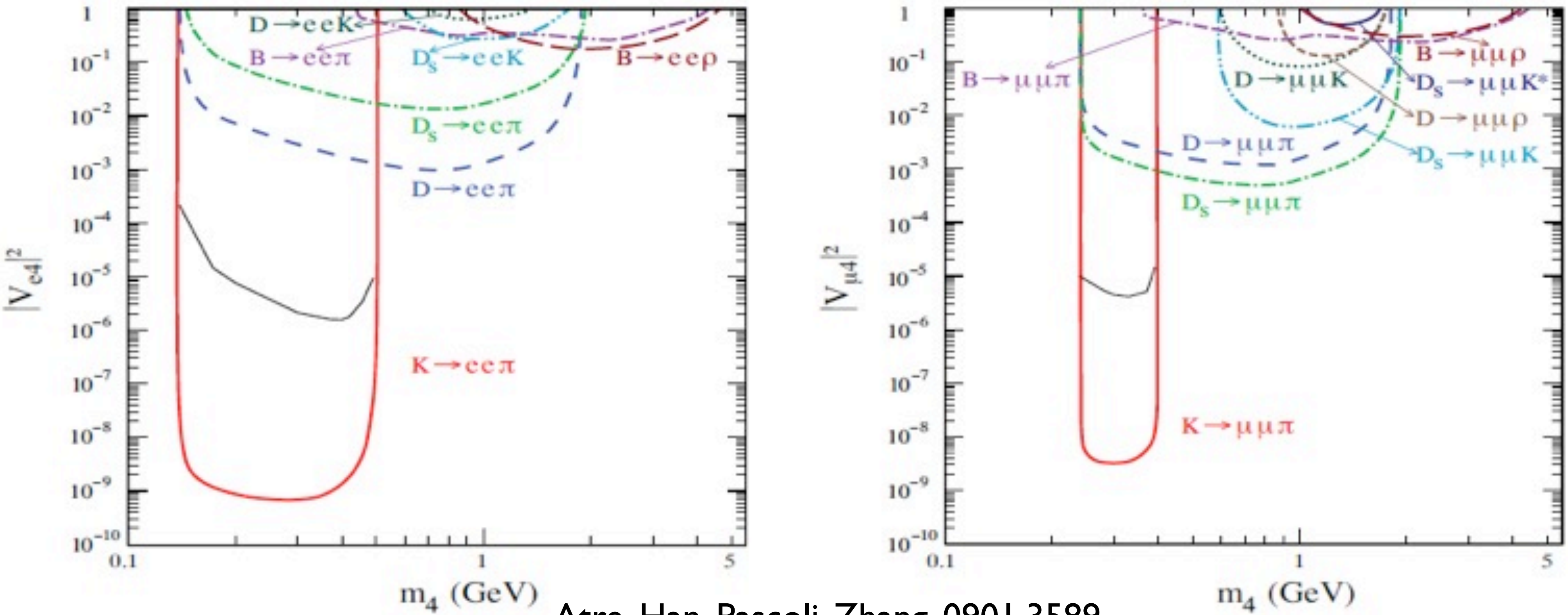
Deadline for submitting abstracts: November 18 2013.

http://nuphys2013.iopconfs.org

Rare tau and meson decays

LNV Tau and Meson decays get resonantly enhanced for M~ GeV. Violation of unitarity for heavy masses.

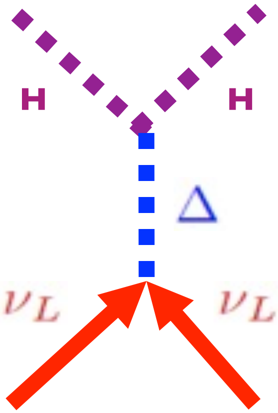




Atre, Han, Pascoli, Zhang, 0901.3589

See saw type II

We introduce a Higgs triplet which couples to the Higgs and left handed neutrinos. It has hypercharge 2.



$$\mathcal{L}_\Delta \propto y_\Delta L^T C^{-1} \sigma_i \Delta_i L + \mathrm{h.c.}$$

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

Once the Higgs triplet gets a vev, Majorana neutrino masses arise:

$$\boxed{m_\nu \sim y_\Delta v_\Delta}$$

Cons: why the vev is very small?
Pros: the component of the Higgs triplet could tested directly at the LHC.

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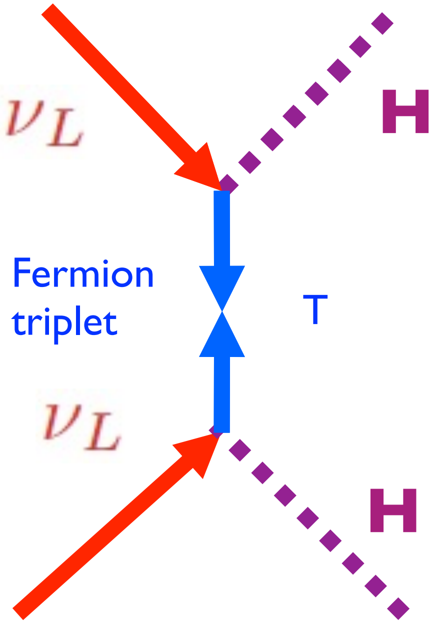
See saw type III

We introduce a fermionic triplet which has hypercharge 0.



$$\mathcal{L}_T \propto y_T \bar{L} \sigma H \cdot T + \text{h.c.}$$

with $T = \begin{pmatrix} T^0 & T^+ \\ T^- & -T^0 \end{pmatrix}$

Majorana neutrino masses are generated as in see-saw type I:

$$\boxed{m_\nu \simeq -y_T^T M_T^{-1} y_T v_H^2}$$

Pros: the component of the fermionic triplet have gauge interactions and can be produced at the LHC Cons: why the mass of T is very large?

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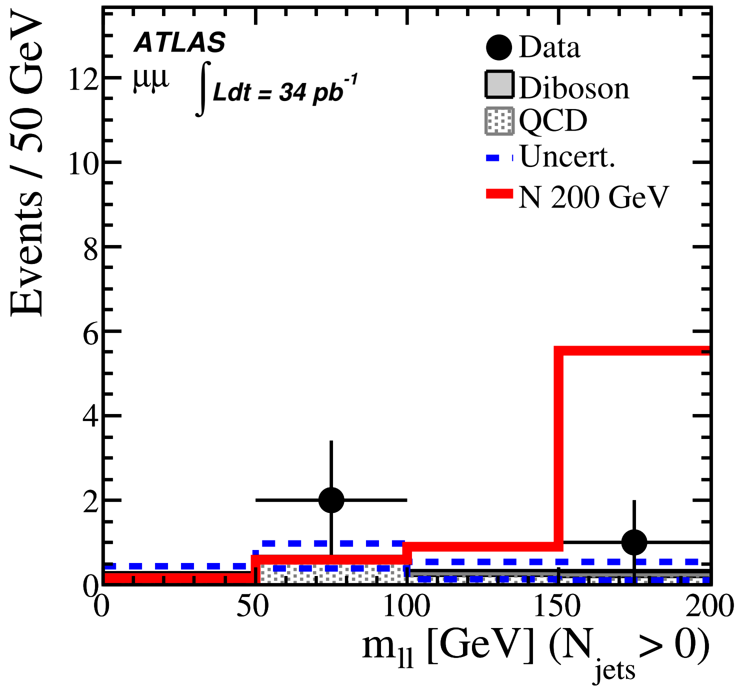
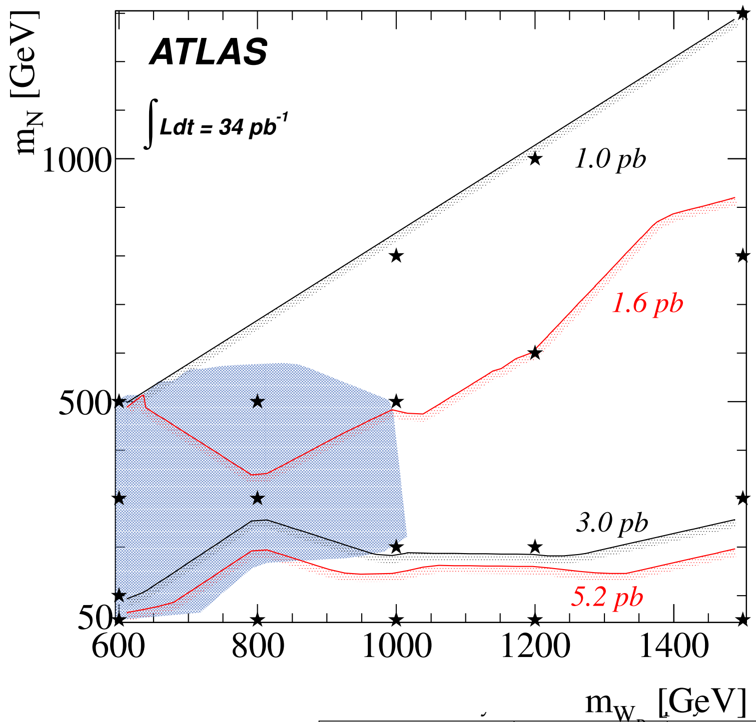
Current limits from LHC

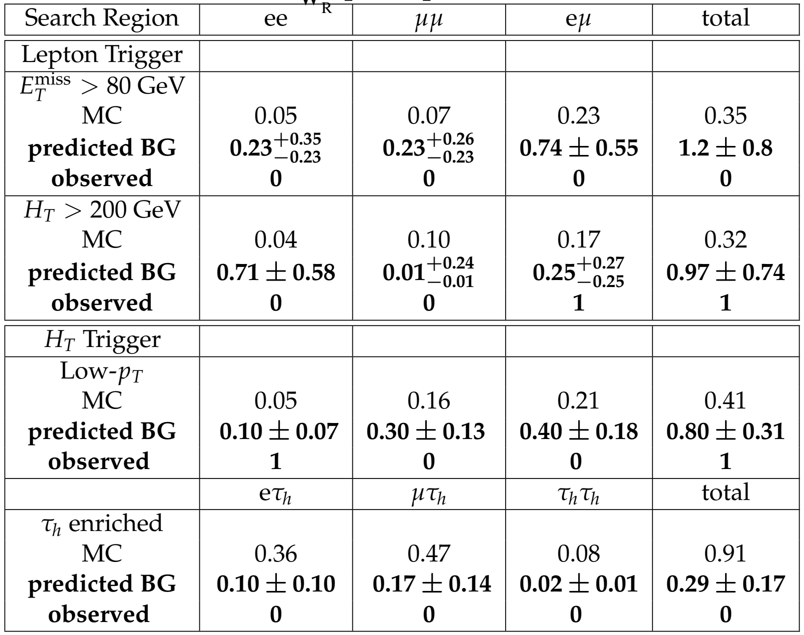




LHC at
E=7 TeV

ATLAS, 1108.0366

CMS, 1104.3168



Search Region	ee	$\mu\mu$	$e\mu$	total
Lepton Trigger				
$E_T^{\rm miss} > 80$ GeV				
MC	0.05	0.07	0.23	0.35
predicted BG	$\mathbf{0.23^{+0.35}_{-0.23}}$	$\mathbf{0.23^{+0.26}_{-0.23}}$	$\mathbf{0.74 \pm 0.55}$	$\mathbf{1.2 \pm 0.8}$
observed	**0**	**0**	**0**	**0**
$H_T > 200$ GeV				
MC	0.04	0.10	0.17	0.32
predicted BG	$\mathbf{0.71 \pm 0.58}$	$\mathbf{0.01^{+0.24}_{-0.01}}$	$\mathbf{0.25^{+0.27}_{-0.25}}$	$\mathbf{0.97 \pm 0.74}$
observed	**0**	**0**	**1**	**1**
H_T Trigger				
Low-p_T				
MC	0.05	0.16	0.21	0.41
predicted BG	$\mathbf{0.10 \pm 0.07}$	$\mathbf{0.30 \pm 0.13}$	$\mathbf{0.40 \pm 0.18}$	$\mathbf{0.80 \pm 0.31}$
observed	**1**	**0**	**0**	**1**
	$e\tau_h$	$\mu\tau_h$	$\tau_h\tau_h$	total
τ_h enriched				
MC	0.36	0.47	0.08	0.91
predicted BG	$\mathbf{0.10 \pm 0.10}$	$\mathbf{0.17 \pm 0.14}$	$\mathbf{0.02 \pm 0.01}$	$\mathbf{0.29 \pm 0.17}$
observed	**0**	**0**	**0**	**0**

Luminosity: ATLAS 34 pb^{-1}
CMS 35 pb^{-1}

Searches have resulted in no positive signal so far. LHCb has searched for di-muon decays of B, improving bounds by 30-40, PRL 108 and PRD.85.

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