Neutrino mass models
Lecture II

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Outline

1. Recap of previous lecture

2. See-saw mechanism and GUT theories

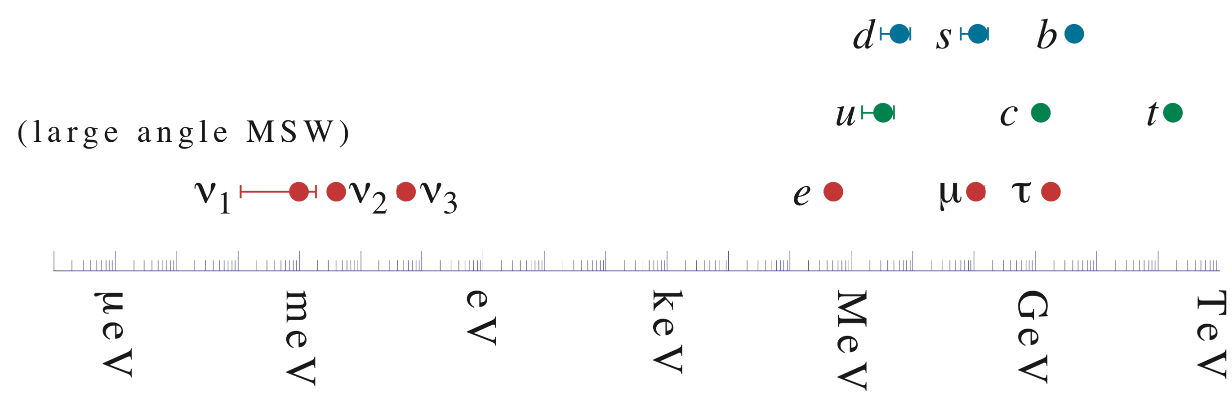
3. Tests of neutrino mass models
   - LFV processes
   - Leptogenesis
   - TeV scale: collider searches
   - below TeV scale

4. Other mechanisms of neutrino masses
   - Radiative masses
   - SUSY with R-parity violation

Open window on Physics beyond the SM

Neutrinos have mass and mix. Open problems:

1. Origin of masses



Why neutrinos have mass?
and why are they so much lighter?
and why their hierarchy is at most mild?

2. Problem of flavour

$$\begin{pmatrix} \sim 1 & \lambda & \lambda^3 \\ \lambda & \sim 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & \sim 1 \end{pmatrix} \quad \lambda \sim 0.2$$

$$\begin{pmatrix} 0.8 & 0.5 & 0.16 \\ -0.4 & 0.5 & -0.7 \\ -0.4 & 0.5 & 0.7 \end{pmatrix}$$

Why leptonic mixing is so different from quark mixing?

This information is **complementary** with the one from flavour physics experiments and from colliders.

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Summary of neutrino mass terms

Dirac masses

$$\mathcal{L}_{mD} = -m_\nu(\bar{\nu}_R \nu_L + \mathrm{h.c.})$$

This term conserves lepton number.

Majorana masses

$$\mathcal{L}_{mM} \propto -M_M \bar{\nu_L^c} \nu_L + \mathrm{h.c.} = M_M \nu_L^T C^{-1} \nu_L$$

This term breaks lepton number.

Dirac + Majorana masses

$$\mathcal{L}_{mD+M} = -m_\nu \bar{\nu}_R \nu_L - \frac{1}{2} \nu_L^T M_{M,L} C^{-1} \nu_L - \frac{1}{2} \nu_R^T M_{M,R} C^{-1} \nu_R + \mathrm{h.c.}$$

Lepton number is broken -> Majorana neutrinos.

Neutrino Masses in the SM and beyond

In the SM, neutrinos do not acquire mass and mixing.

- Introduce a Dirac mass like for all other fermions:

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

but tiny couplings are needed.

- Introduce a Dimension 5 operator for Majorana masses

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

Lepton number violation!

This can emerge as the **low energy realisation of a higher energy theory (new mass scale!)**.

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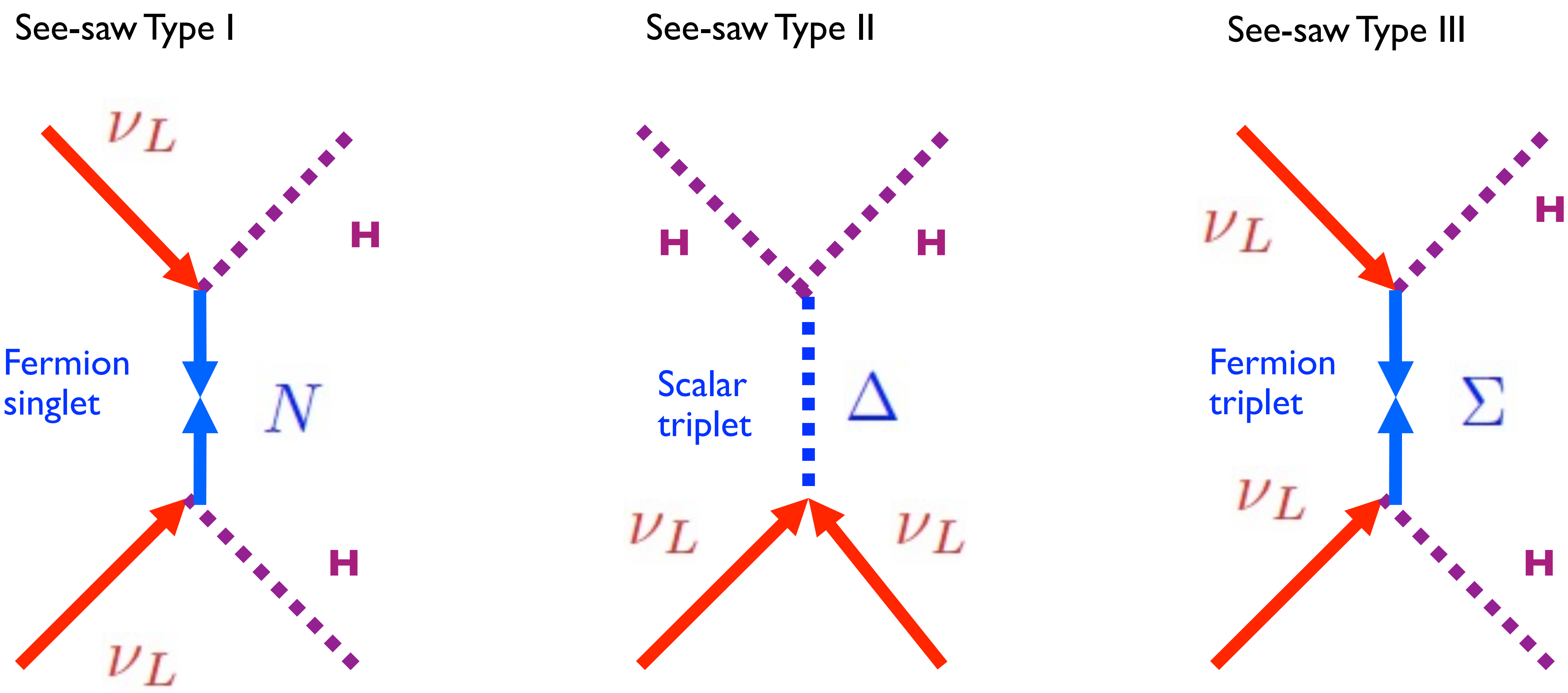


$$m_\nu \sim y_\Delta v_\Delta$$

The simplest case is the see-saw type I models

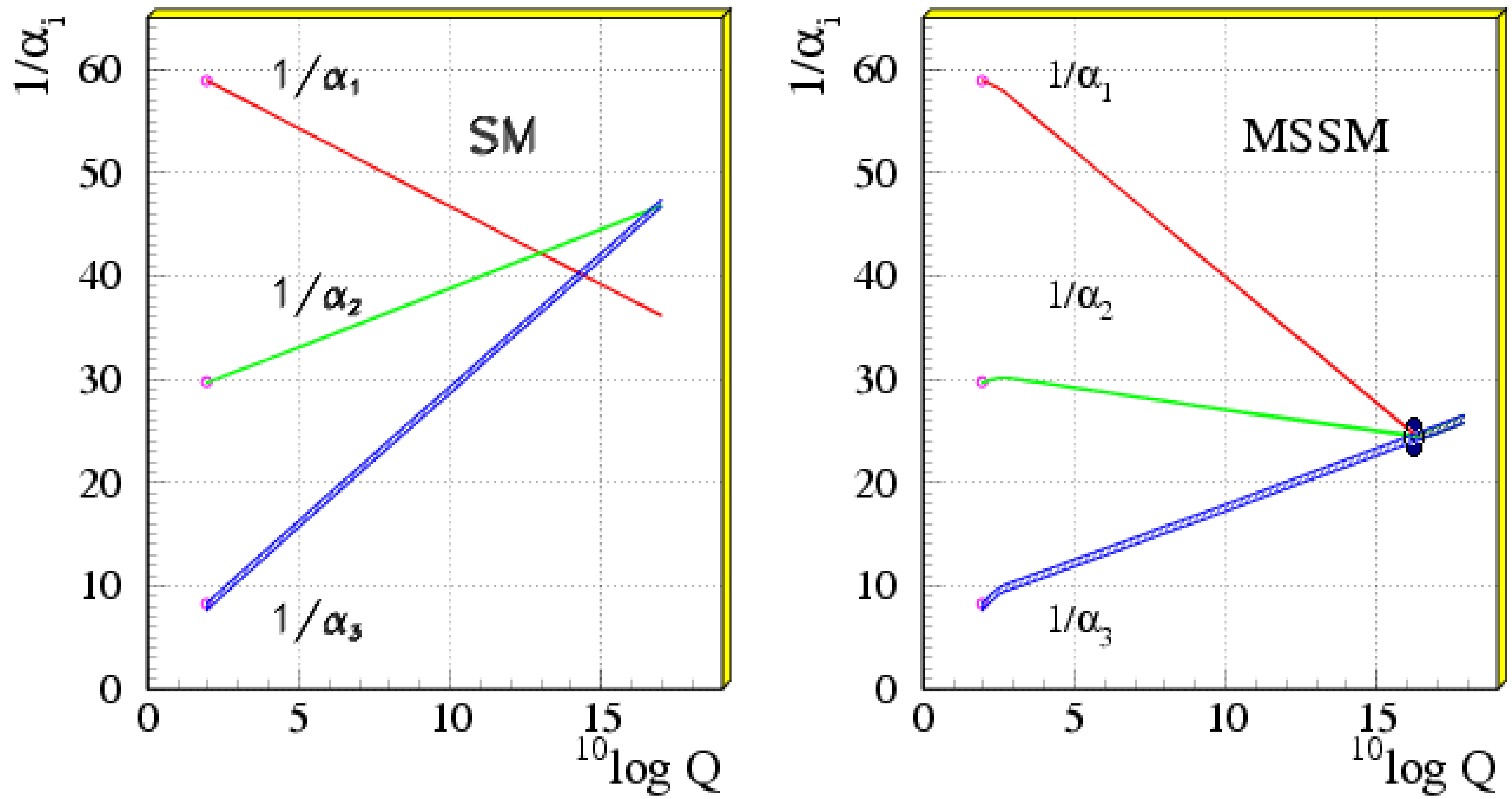
$$\mathcal{L} = (\nu_L^T N^T) \begin{pmatrix} 0 & m_D \\ m_D^T & M \end{pmatrix} \begin{pmatrix} \nu_L \\ N \end{pmatrix}$$

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

Extended-type of see-saw models allow for large couplings and “low” masses: extended, inverse, linear see-saw.

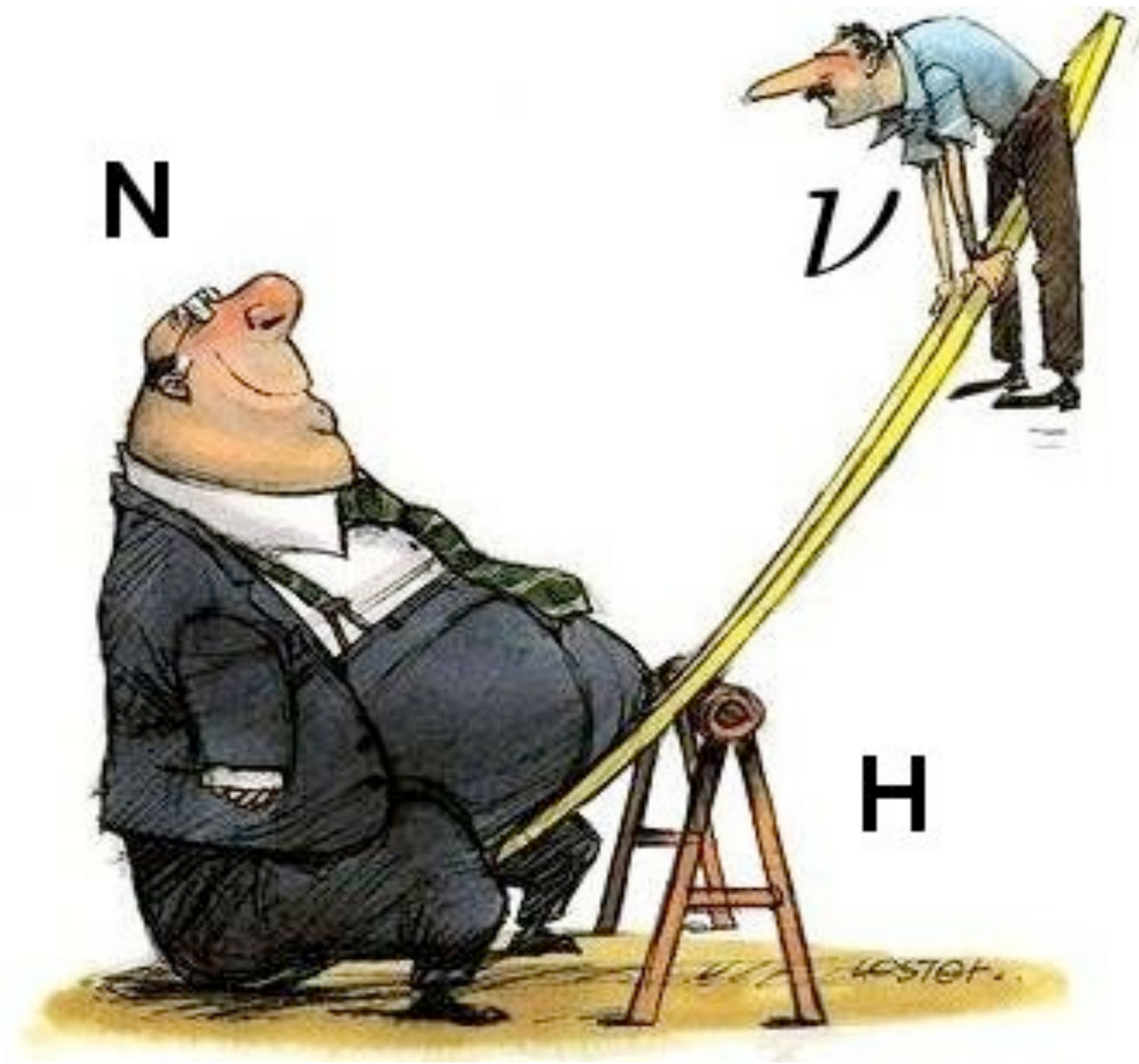
GUT theories and the see-saw mechanism

The SM has a very complex gauge structure (3 gauge couplings) and charge assignments for the fields. GUT aim at providing a unified picture.



S. Rabi, PDG

Due to the renormalisation of the couplings, they “run” and unify at a very high energy scale, typically 10^{16} GeV.
Ingredients: gauge group (only one group and one coupling), fermion representations, Higgs sector, symmetry breaking.



See-saw mechanisms and GUTS

- Introduce a right handed neutrino **N (sterile neutrino) with a very heavy mass scale**
- Couple it to the Higgs and left handed neutrinos

$$M = \frac{m_D^2}{m_\nu} \sim \begin{array}{l} \frac{(100\mathrm{GeV})^2}{10^{-10}\mathrm{GeV}} \sim 10^{14}\ \mathrm{GeV} \\ \frac{1\mathrm{GeV}^2}{10^{-10}\mathrm{GeV}} \sim 10^{10}\ \mathrm{GeV} \end{array}$$

The new mass scale turns out to be naturally large and suggests the embedding of the model in GUT theories.

Let's make a parallel with the SM.

1. Gauge group: $SU(2)_L \times U(1)_Y$

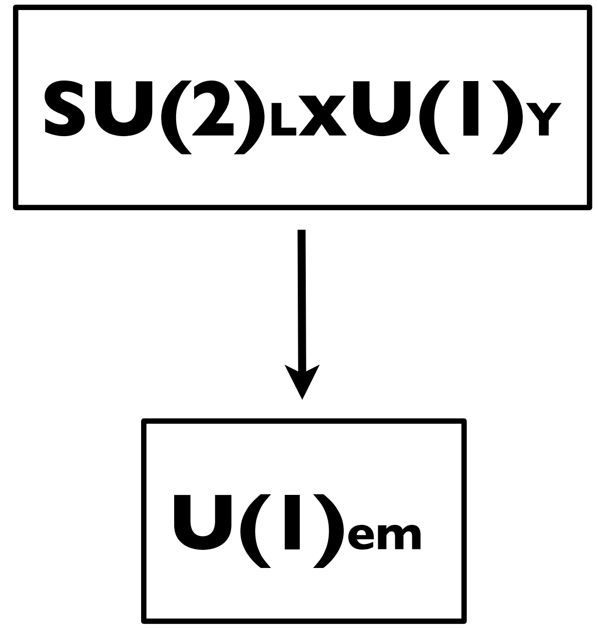
2. Choose representations of the group and assign the fermions to it.

SU(2) singlet: e.g. $e_R, \quad u_R, \quad d_R$

SU(2) doublet: e.g. $\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$

3. Introduce a scalar Higgs sector. This breaks the symmetry to a subgroup. To break $SU(2)_L$, the scalar needs to be a doublet and to preserve $U(1)_{em}$ it needs to have a neutral component. $\begin{pmatrix} H^0 \\ H^- \end{pmatrix}$

4. H_0 gets a vev and the symmetry is broken



5. Invariance w.r.t. the gauge group dictates the type of terms in the Lagrangian: both the gauge interactions and the Yukawa ones.

E.g.

$$\mathcal{L}_{\nu H} = -y_\nu (\bar{\nu}_L, \bar{\ell}_L) \cdot \begin{pmatrix} H^{0*} \\ -H^- \end{pmatrix} \nu_R + \mathrm{h.c.}$$

6. Masses for the gauge bosons, the Higgs field and the fermions result from it and depend on v_H.

Left-right models

This is a very simple model in which the see-saw can be naturally embedded.

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

2. Fermion assignment:

$$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$$ Doublet, singlet, -1

$$\begin{pmatrix} \nu_R \\ e_R \end{pmatrix}$$ Singlet, doublet, -1

and so on for the quarks.

3. Introduce a scalar Higgs sector.
As we want to break the symmetry from $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ to $SU(2)_L \times U(1)_Y$, the Higgs needs to be a singlet of $SU(2)_L$ and transform non-trivially w.r.t. $SU(2)_R$.
We take a triplet of $SU(2)_R$.

$$\begin{pmatrix} \xi^+/\sqrt{2} & \xi^{++} \\ \xi^0 & \xi + /\sqrt{2} \end{pmatrix}$$

4. The symmetry is broken

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

↓

$SU(2)_L x U(1)_Y$

The EW breaking is a achieved by a Higgs boson, doublet of $SU(2)_L$ and $SU(2)_R$.

5. Invariance of the Yukawa couplings

$$\mathcal{L} \propto y_1 \bar{L}_R H L_L + \ldots + y_\xi \bar{L}_R^c i\sigma_2 \xi L_R + \text{h.c.}$$

6. Masses for neutrinos

$$\mathcal{L} \propto y_1 v_H \bar{\nu}_R \nu_L + \ldots + y_\xi v_\xi \bar{\nu}_R^c \nu_R + \text{h.c.}$$

Usual Dirac mass term

Majorana mass term for N

Remembering that $v_{xi} >> v_H$, the usual see-saw structure has emerged and neutrino mass will be given by

$$m_\nu \simeq \frac{(y_1 v_H)^2}{2 y_\xi v_\xi}$$

SO(10) GUT models

SO(10) contains $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ and therefore a right-handed neutrino and can easily implement the see-saw mechanism.

The leptons and quarks belong to the same representation, their masses come from the same source and will be related.

The scale of breaking (and consequently the mass for the right-handed neutrino) is at a very high energy scale: see-saw naturally implemented.

1. Gauge group: SO(10)
only one gauge coupling g!!!

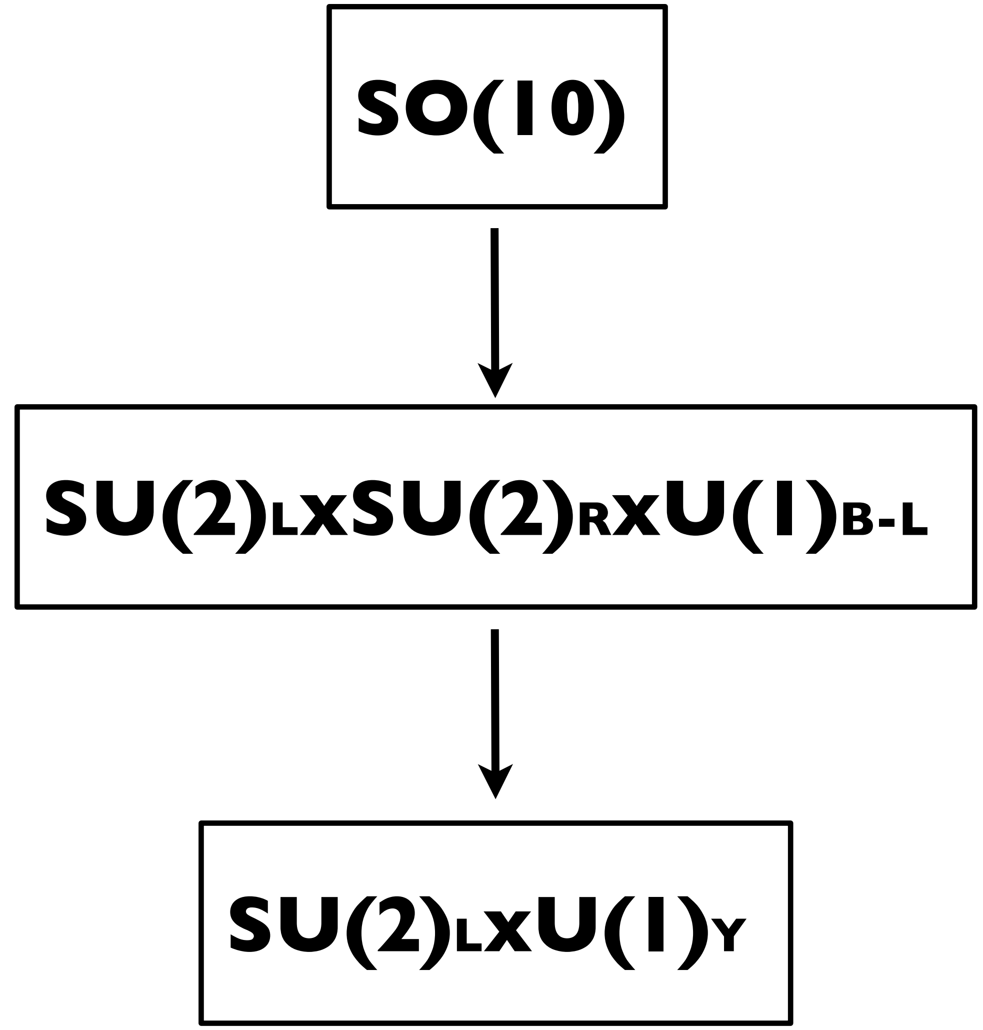
2. Fermion assignment:

$$f(16)_L = \left(\begin{pmatrix}\nu_L \\ e_L\end{pmatrix}, \begin{pmatrix}u_L \\ d_L\end{pmatrix}, \begin{pmatrix}\nu^c_R \\ e^c_R\end{pmatrix}, \begin{pmatrix}u^c_R \\ d^c_R\end{pmatrix}\right)$$

Quarks and leptons belong to the same representation! Their behaviour is related.
The right-handed neutrino is present and belongs also to this representation.

3. Introduce a scalar Higgs sector.
We want to break the symmetry from SO(10) to $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$. This is achieved using a Higgs in the 45-representation.
There are also other useful scalar representations: H(10), H(120), H(126)... Some of their components can also get vevs.

4. The symmetry is broken.



5. Invariance of the Yukawa couplings

Neutrino masses require two fermions (so 2 f(16)).

$$f(16) \otimes f(16) = f(10) + f(120) + f(126)$$

$$\mathcal{L} \propto g_{10} f(16) f(16) H(10) + g_{126} f(16) f(16) H(126)$$

6. Masses for neutrinos

Once the H(10) gets a vev, Dirac masses emerge for the quarks and leptons. They are related

$$M_u(GUT) = M_d(GUT) = M_l(GUT) = M_\nu(GUT)$$

Usual Dirac mass term

This relation is in conflict with data. So we need to introduce also H(126) to give a large mass to the right-handed neutrino: $M_N = g_{126} v_{126}$

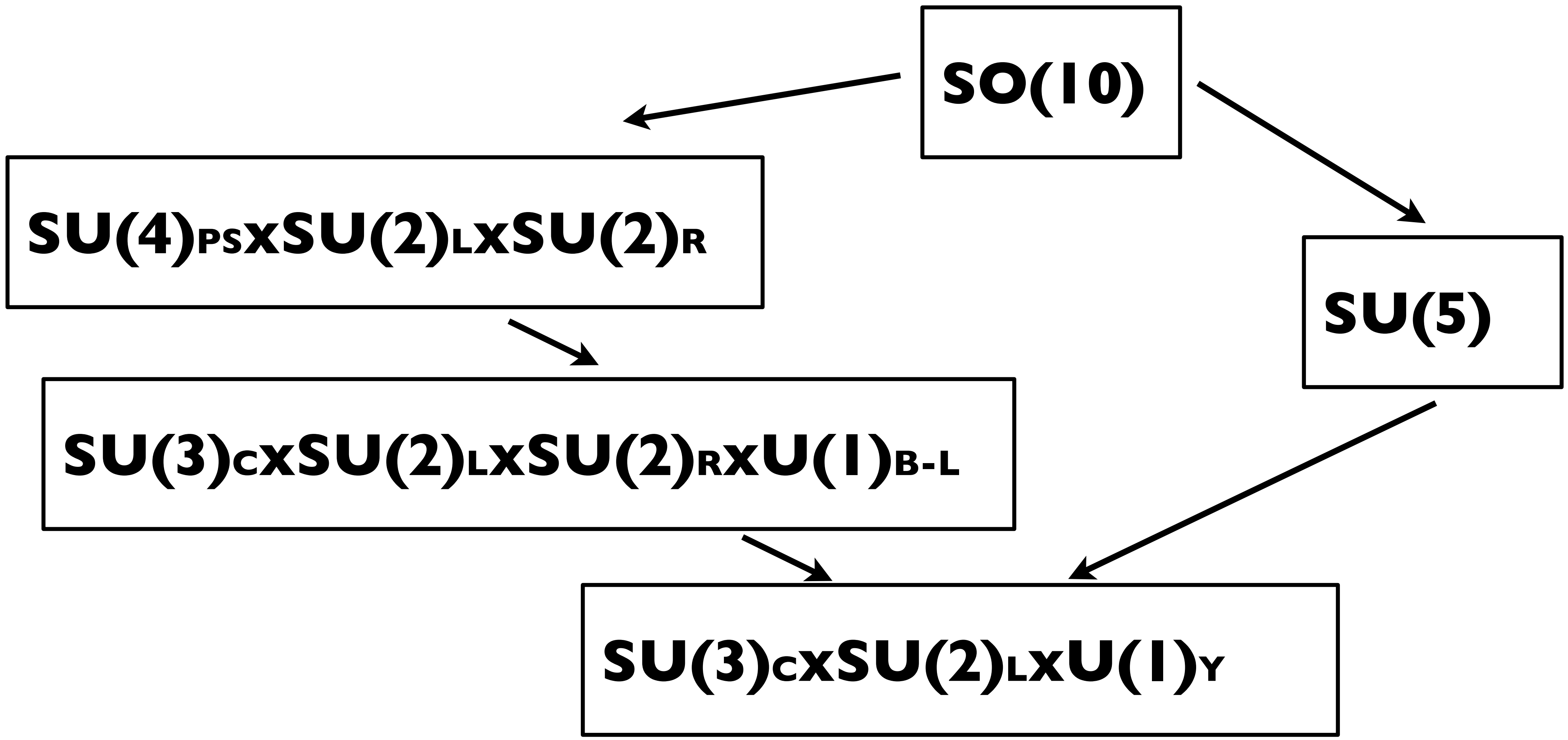
Majorana mass term for N

The usual see-saw structure is present and neutrino mass will be given by

$$m_\nu \sim \frac{g_{10}^2 v_H^2}{g_{126} v_{126}} \propto m_q^2 \quad \Rightarrow \quad m_{\nu_e} : m_{\nu_\mu} : m_{\nu_\tau} = m_u^2 : m_c^2 : m_t^2$$

This relation can be relaxed via H(10)+H(126), a direct Majorana mass and/or a specific structure for M_N.

The see-saw can emerge naturally in **GUTheories**: e.g. SO(10). They provide the necessary elements: N, large M and L violation.



They typically lead to proton decay and to relations between quark and lepton masses. Understanding the origin of neutrino masses might shed light on energy scales which could not be tested directly in any experiments.

What is the new physics scale?

The **new Standard Model** will contain

- new particles at a new physics scale
- new interactions.

sub-eV eV keV MeV GeV TeV GUT scale

See-saw I (tiny couplings)

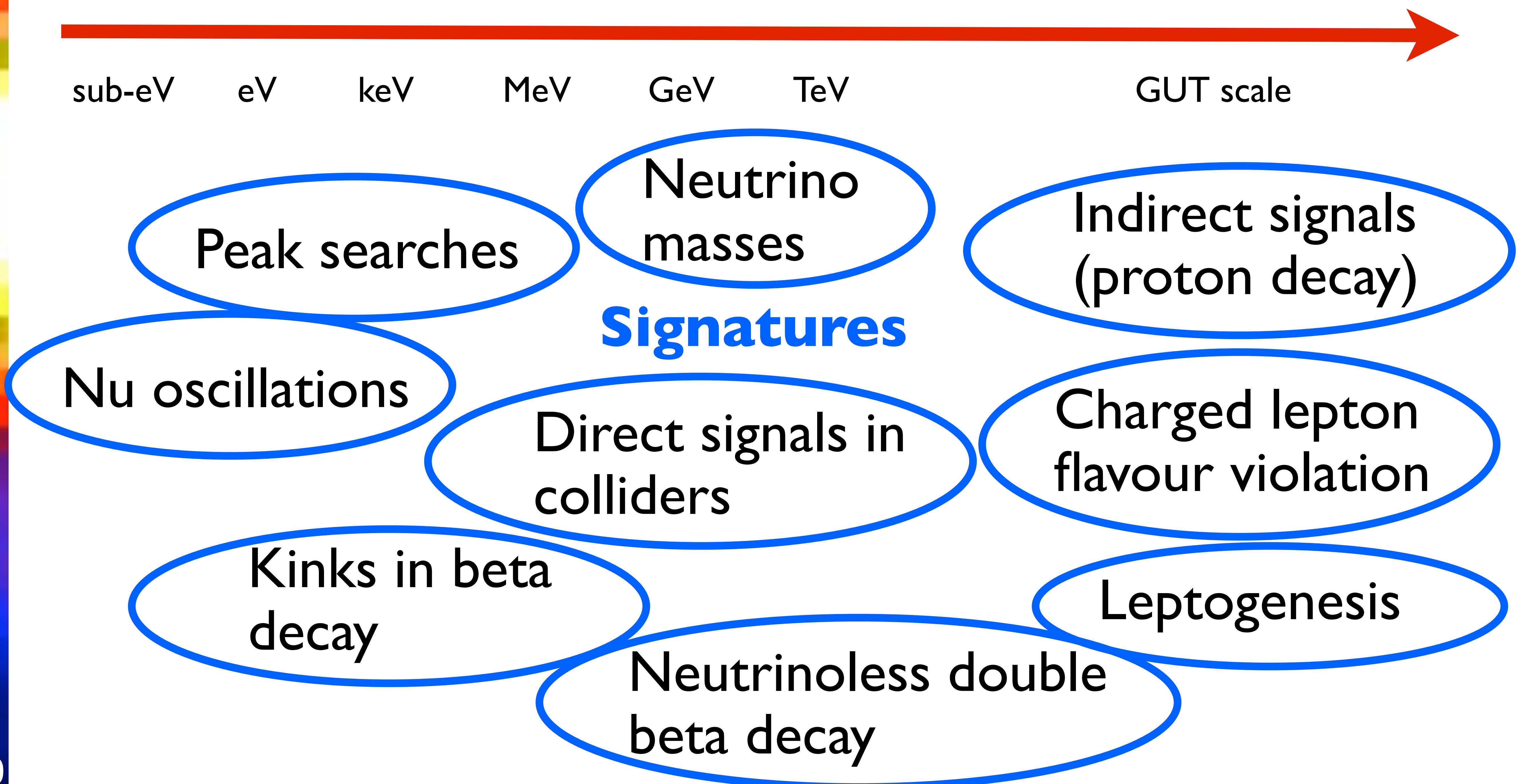
GUT see-saw I

TeV see-saw I (small couplings)
see-saw II
see-saw III
extended-type seesaws

Here I focus on see-saw models, but similar considerations apply also for other models of neutrino masses.

What is the new physics scale?

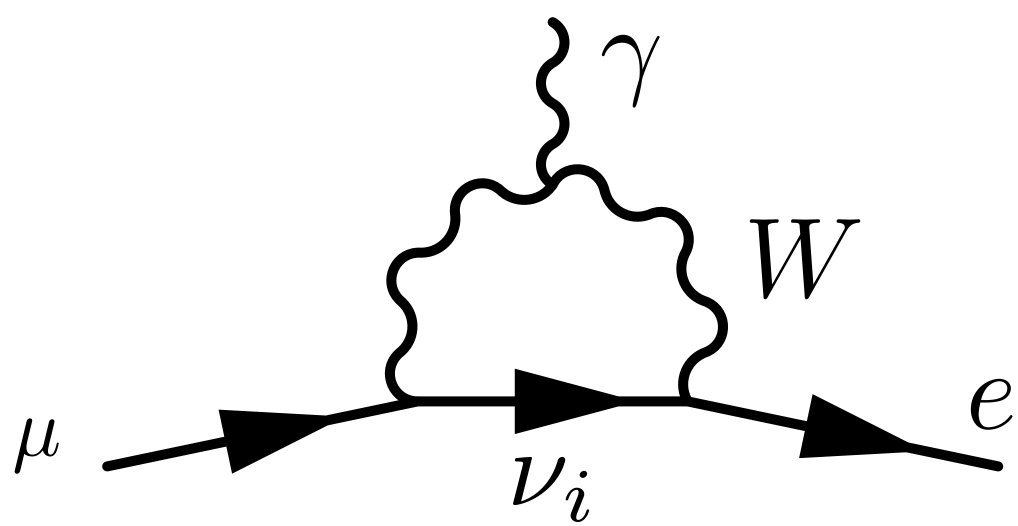
It is necessary to combine information from different experimental strategies.



Charged lepton flavour violation

Establishing the origin of neutrino masses requires to have as much information as possible about the masses and to combine it with other signatures of the models (proton decay, LHC searches, LFV, sterile neutrinos, ...).

CLFV plays a special role. Neutrino masses induce LFV processes but they are very suppressed.



$$Br(\mu \to e\gamma)$$

$$\sim \frac{3\alpha}{32\pi} \left(\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta^2 m_{i1}}{m_W^2}\right)^2 \sim 10^{-53}$$

Any observation of LFV would indicate new physics BSM and provide clues about the origin of neutrino masses.

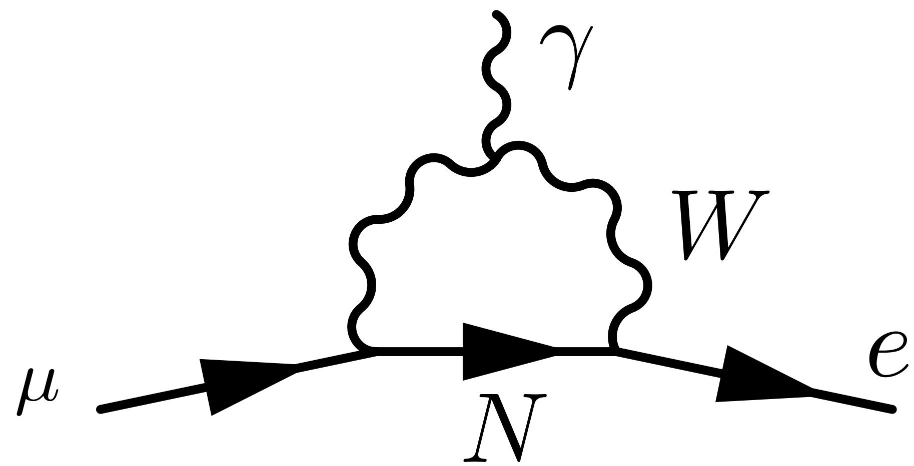
LFV at GUT scale

LFV at intermediate scale

Suppressed

LFV in neutrino masses

As an example, extension of the SM with singlet neutrinos N



$$Br(\mu \to e\gamma) \sim \frac{3\alpha}{8\pi}\left(\sum_j U^*_{\mu j} U_{ej}\, g\left(\frac{M_N^2}{m_W^2}\right)\right)^2$$

Many models of neutrino masses give raise to sizable LFV:

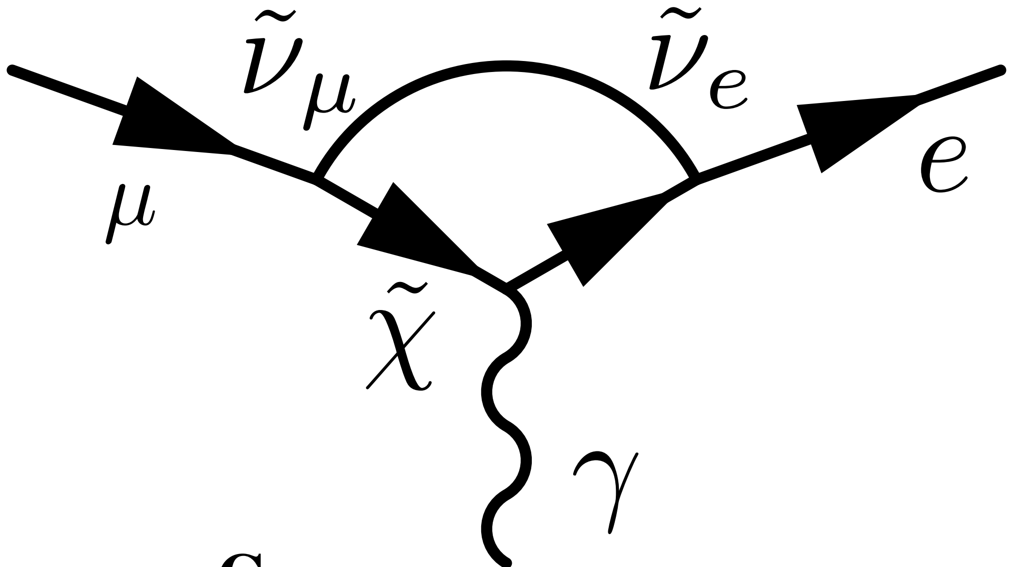
models at the TeV scale with large mixing

Radiative neutrino mass models

SUSY GUT see-saw models (LFV is communicated to the SUSY TeV sector which mediates the process)

Extra D, extra Higgs etc.

Example I: SUSY see-saw with R-parity : misalignment between lepton and slepton mass matrices

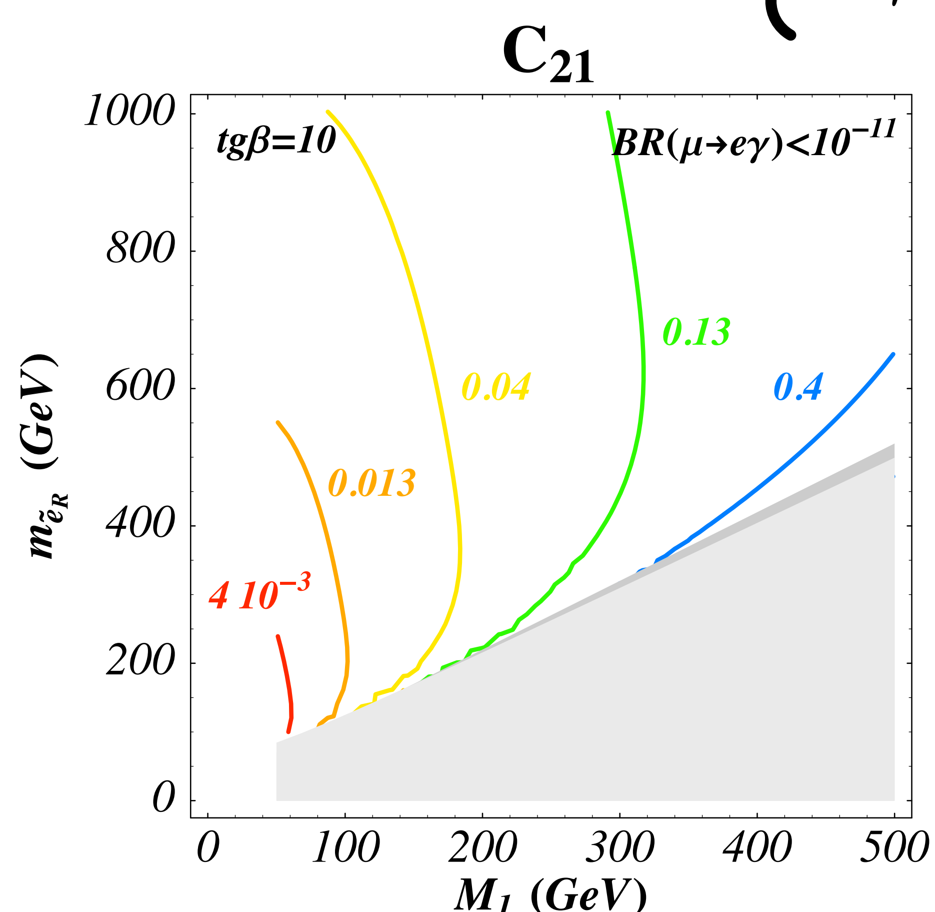


$$Br \sim 10^{-5} \frac{m_W^4}{M_{SUSY}^4} \left| \frac{\tilde{m}_{e\mu}^2}{m_\ell^2} \right|^2 \tan^2 \beta$$

$$\propto \left| \sum_N Y_{N\mu}^* Y_{Ne} \ln(m_0/m_N) \right|^2$$

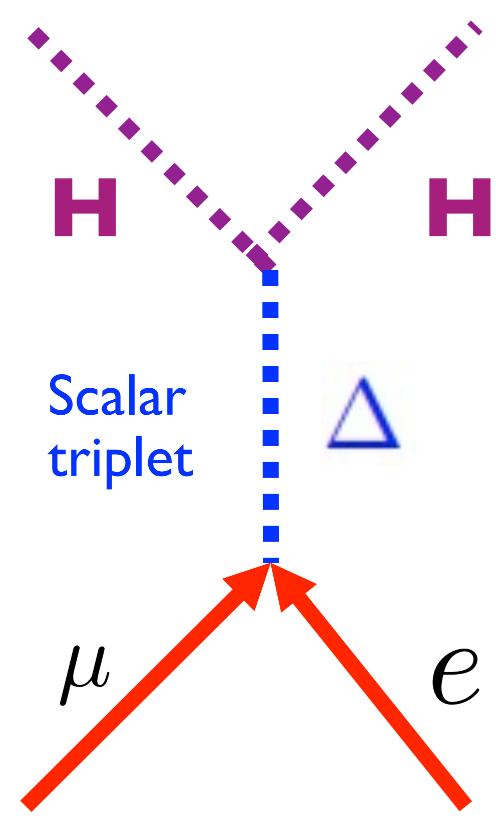
Borzumati, Masiero

The same parameters enter in LFV, neutrino masses and leptogenesis.



Lavignac, Masina, Savoy

Example II: See-saw type II. A direct connection is present with neutrino masses, inducing correlations between different observables. Rossi



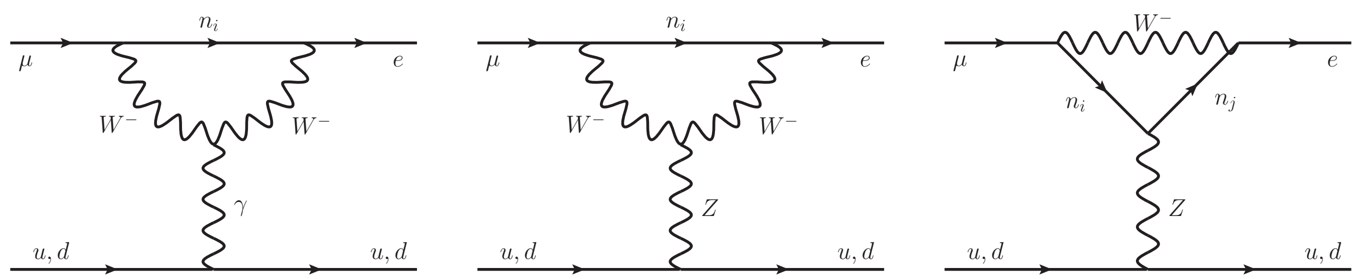
Other processes can also take place:

$\mu - e$ conversion

$\mu \to eee$

LFV τ decay

Their relative Br depend on the underlying new physics BSM and flavour structure.

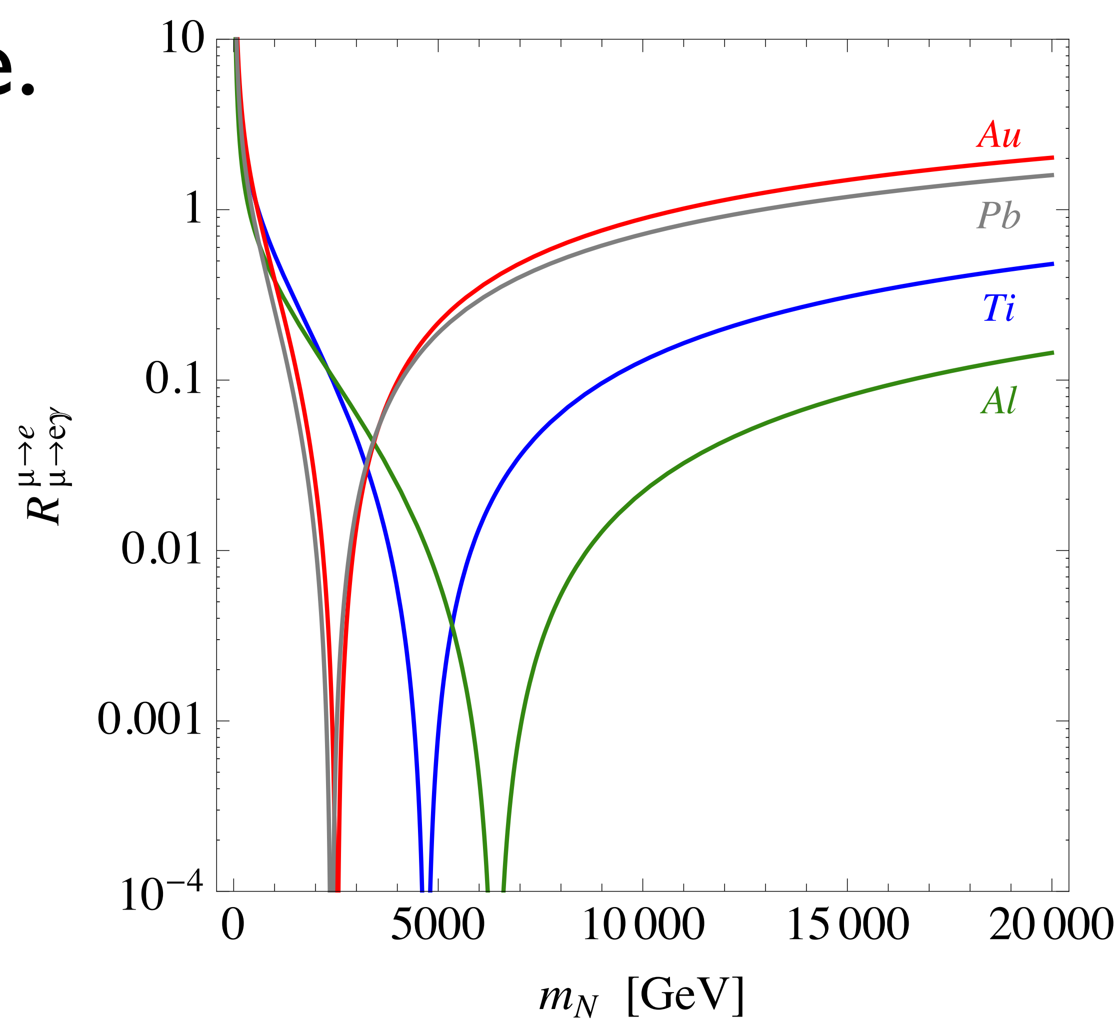


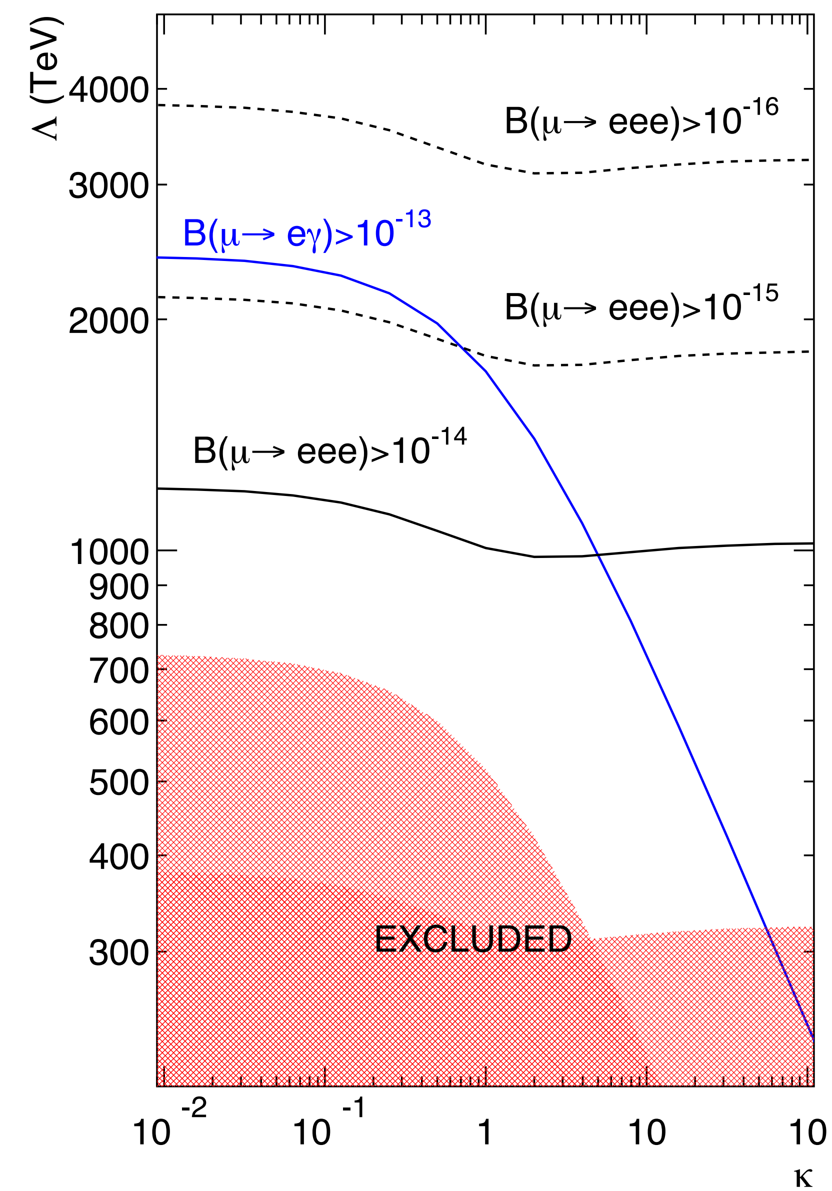
(a) Photon Penguin Diagram (b) Z Penguin Diagram (c) Z Penguin Diagram

Alonso, Dhen, Gavela, Hambye

$$\mathcal{L}_{\text{CLFV}} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + $$
$$+ \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L \bar{e}\gamma^\mu e$$

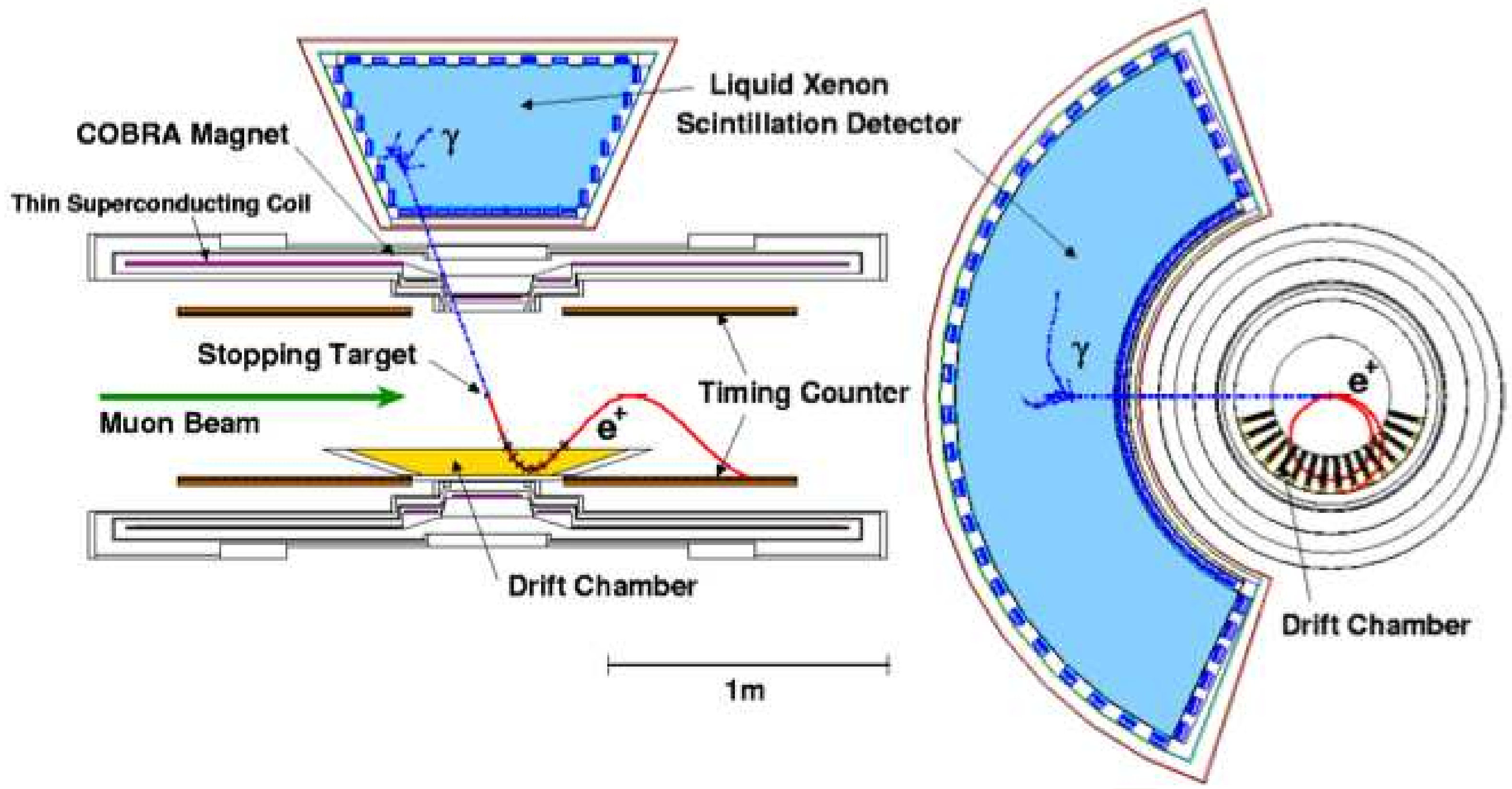
A. de Gouvea





Alonso, Dhen, Gavela, Hambye, 1209.2679

Searches for mu->e gamma and other rare decays



MEG at PSI

MEG has recently provided the best limit on this LFV decay channel.

$$Br(\mu \to e\gamma) < 5.7 \times 10^{-13}$$

Super-B factories can improve on rare tau decays.

$$Br(\tau \to \mu\gamma) < 4.4 \times 10^{-8}$$

$$Br(\tau \to e\gamma) < 3.3 \times 10^{-8}$$

Best limit from SINDRUM 1988

$$Br(\mu \to 3e) < 1 \times 10^{-12}$$

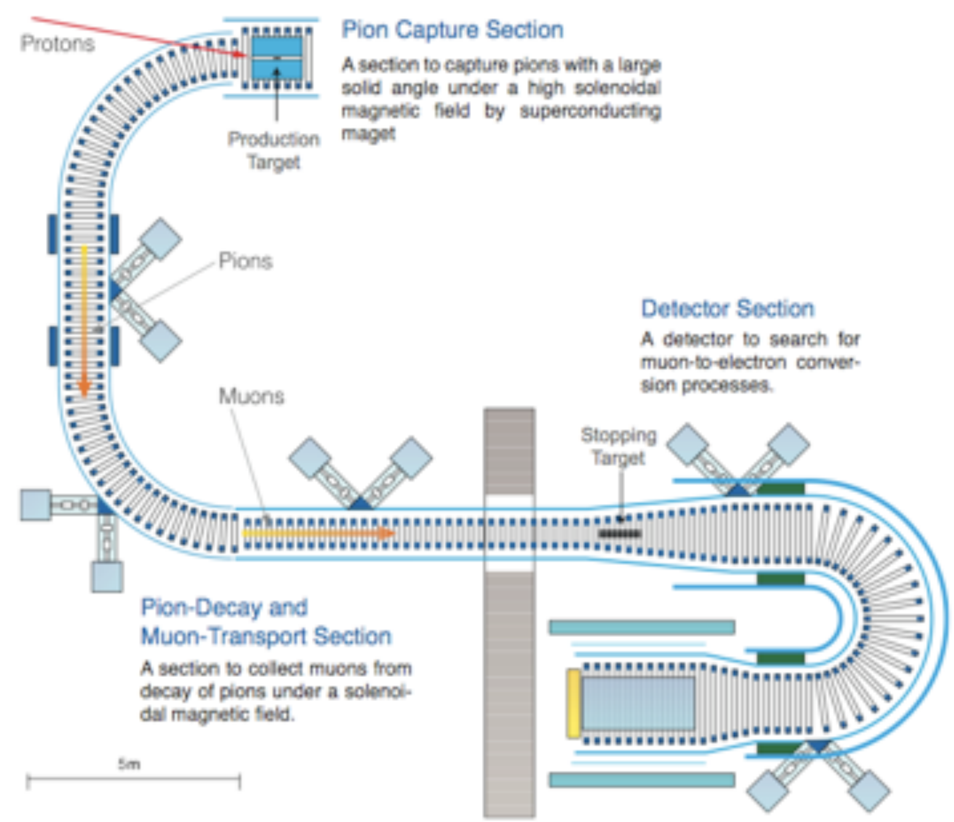
New proposal at PSI: mu3e.

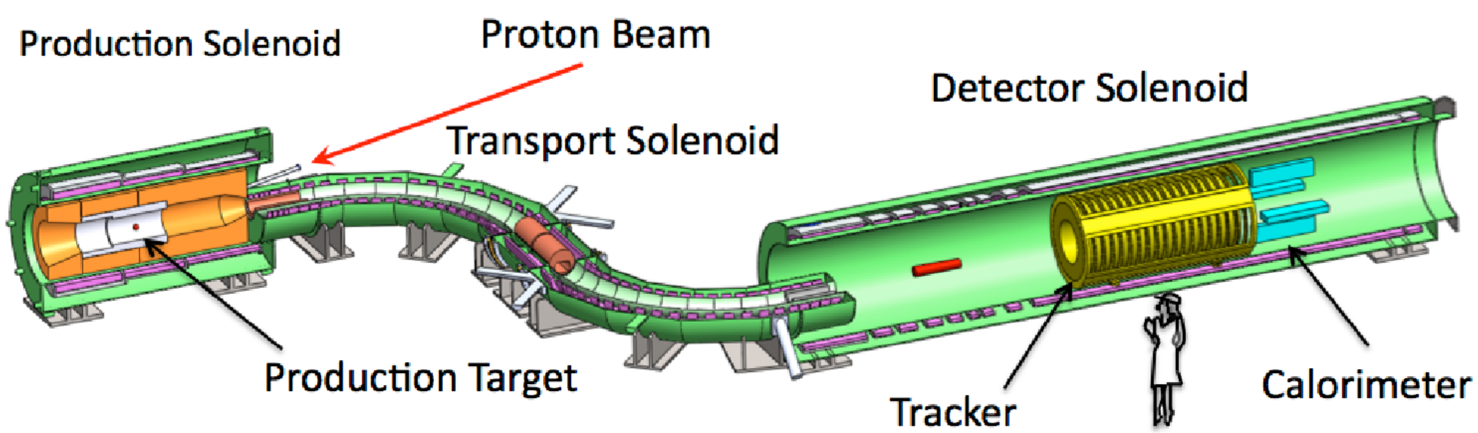
Searches for mu-e conversion

Limits from **SINDRUM-II**.
See PDG.

$\mu^- \ {}^{32}S \to e^- \ {}^{32}S$	$< 7 \times 10^{-11}$
$\mu^- \ Ti \to e^- \ Ti$	$< 4.3 \times 10^{-12}$
$\mu^- \ Ti \to e^+ \ Ca$	$< 3.6 \times 10^{-11}$
$\mu^- \ Pb \to e^- \ Pb$	$< 4.6 \times 10^{-11}$
$\mu^- \ Au \to e^- \ Au$	$< 7 \times 10^{-13}$

COherent Muon to Electron Transition (COMET) and PRISM
Expected sensitivity
Br< 10^-16 and 10^-18





Mu2e:
http://mu2e.fnal.gov/
11 July 2012: Approval of CD-1 by Office of Science Director
Expected sensitivity Br< 10^-17

Leptogenesis

There is evidence of the baryon asymmetry:

$$\eta_B \simeq \eta_B - \eta_{\bar{B}} = n_B / n_\gamma$$

- Observation of the acoustic peaks in CMB and at BBN:

$$\eta_B^{\text{CMB}} = \left(6.1^{+0.3}_{-0.2}\right) \times 10^{-10} \qquad \eta_B^{\text{BBN}} = (2.6 - 6.2) \times 10^{-10}$$

How can we explain the baryon asymmetry?

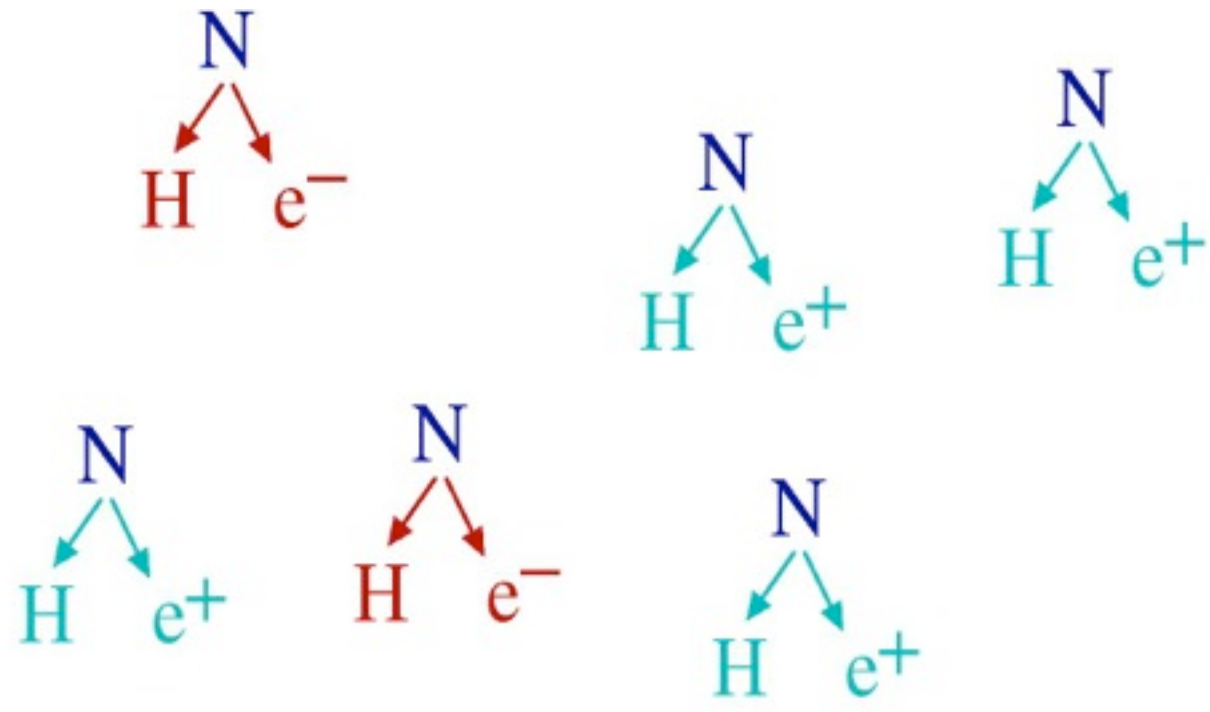
Sakharov conditions necessary for the dynamical creation of a B-asymmetry in the Early Universe:

- baryon (lepton) number violation
- C and CP violation
- deviation from thermal equilibrium (expansion of the EU)

The excess of quarks can be explained by **Leptogenesis** (Fukugita, Yanagida): the heavy N responsible for neutrino masses generate a lepton asymmetry.

In the Early Universe, there is a thermal plasma of particles. Its temperature T drops as the Universe expands.

- The Majorana right-handed neutrino N_i are in equilibrium in the Early Universe as far as the processes which produce and destroy them are efficient ($N \leftrightarrow lH$).
- When $T < M_1$, N_1 drops out of equilibrium as they cannot be produced efficiently anymore.

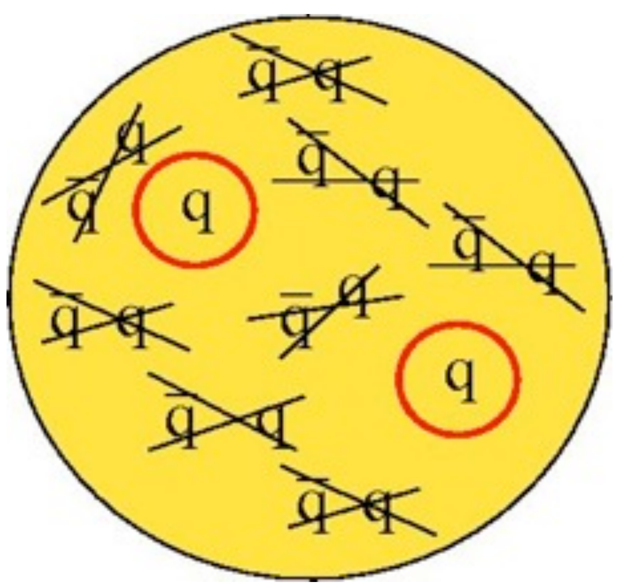


Excess of e^+ $\longrightarrow$ excess of q over $\bar{q}$

If the decay rate in to two channels (L violation) is different (CP-violation), a lepton asymmetry is generated.

- This lepton asymmetry is then converted into a baryon asymmetry by sphaleron processes.

In the Early Universe



As the temperature drops, only quarks are left:

$$Y_B = \frac{n_B}{n_\gamma} = (6.0 \pm 0.2) \times 10^{-10}$$

In order to compute the baryon asymmetry:

1. evaluate the CP-asymmetry:

$$\epsilon_1 \equiv \frac{\Gamma(N_1 \to lH) - \Gamma(N_1 \to \bar{l}H^c)}{\Gamma(N_1 \to lH) + \Gamma(N_1 \to \bar{l}H^c)}$$

2. solve the Boltzmann equation to take into account the wash-out of the asymmetry with a k washout factor:

$$Y_L = k\epsilon_1$$

3. convert the lepton asymmetry into baryon asymmetry.

$$Y_B = \frac{k}{g^*} c_s \epsilon_1 \sim 10^{-3} - 10^{-4} \epsilon_1$$

[Fukugita, Yanagida; Covi, Roulet, Vissani; Buchmuller, Plumacher]

The one-flavour approximation

For high T > 10^{12} GeV, charged leptons Yukawa interactions are out-of-equilibrium and **flavours are indistinguishable**.
Only the total decay asymmetry is relevant.

ϵ_1 depends on the CPV phases in the Yukawa couplings:

$$\epsilon_1 \propto \sum_j \mathrm{Im}(y_\nu y_\nu^\dagger)^2_{1j} \frac{M_j}{M_1}$$

Flavour effects

At T < 10^{12} GeV, the τ charged lepton is a distinguishable mass eigenstate. The asymmetries in the τ and μ + e flavours need to be considered separately. [Abada et al.; Nardi et al.]

$$Y_B \simeq -\frac{12}{37 g_*} \left(\epsilon_\tau \eta \left(\frac{390}{589} \widetilde{m_\tau} \right) - \epsilon_2 \eta \left(\frac{417}{589} \widetilde{m_2} \right) \right)$$

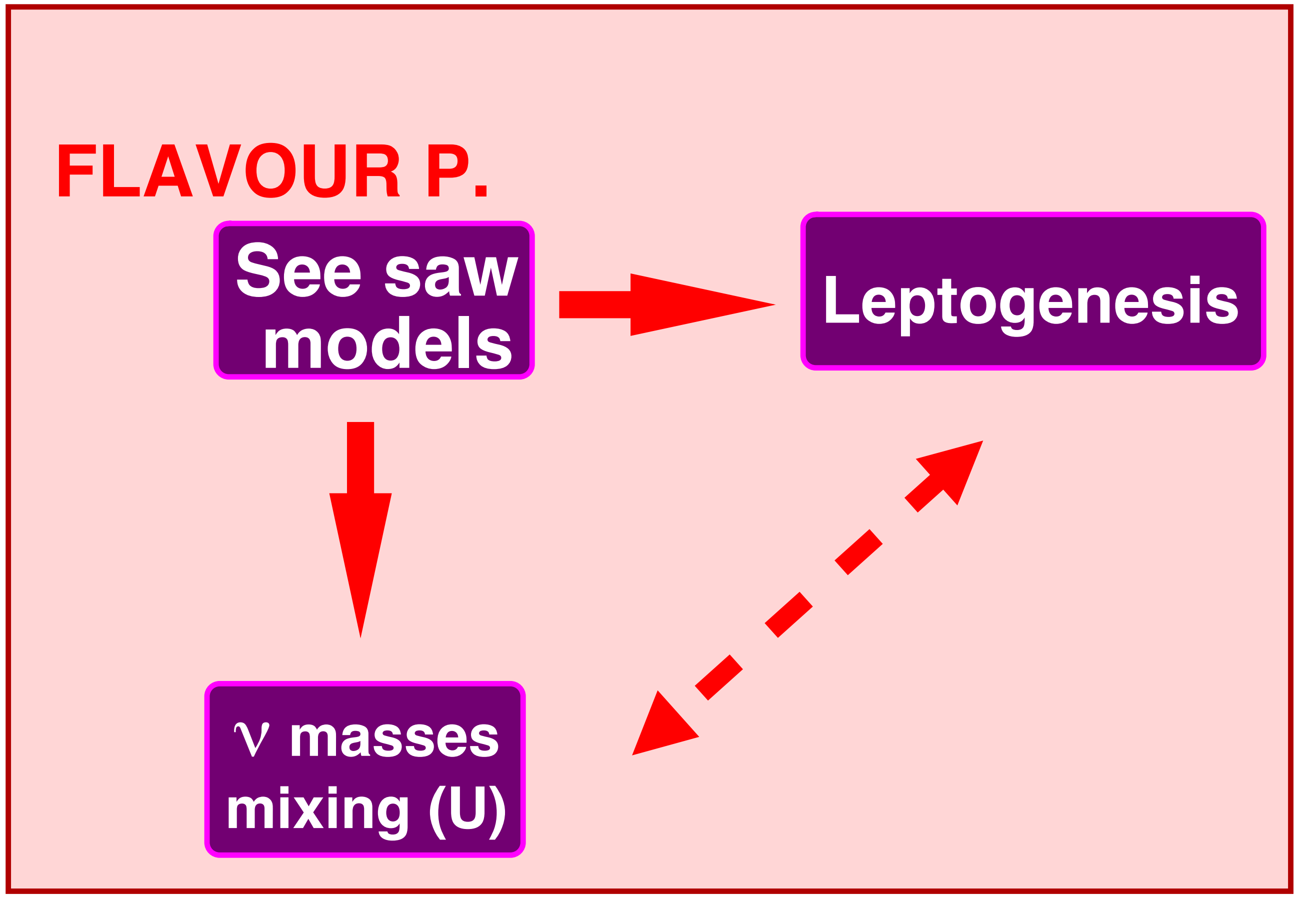
@Silvia Pascoli

Saturday, 10 August 13

Can we determine test directly leptogenesis in experiments? Parameter counting.

High energy parameters			Low energy parameters		
M_R	3	0	d_m	3	0
y_ν	9	6	U	3	3

At high energy there are 6 extra real parameters and 3 phases. So in a model independent way there is no direct connection.



However, in specific models of neutrino masses and flavour structure, the number of parameters will be reduced and a direct connection can be there.

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From observing leptonic CP-violation at low energy, can we infer that a baryon asymmetry (which can be as high as observed) is generated?

It is useful to use $y_\nu \simeq \frac{1}{v_H} d_M^{1/2} R d_m^{1/2} U^\dagger$

one-flavour

$$\epsilon_1 = -\frac{3M_1}{16\pi v^2} \frac{\mathrm{Im}\left(\sum_\rho m_\rho^2 R_{1\rho}^2\right)}{\sum_\beta m_\beta \left|R_{1\beta}\right|^2} = 0$$

with not CPV in R

with flavour

$$\epsilon_l = -\frac{3M_1}{16\pi v^2} \frac{\mathrm{Im}\left(\sum_{\beta\rho} m_\beta^{1/2} m_\rho^{3/2} U_{l\beta}^* U_{l\rho} R_{1\beta} R_{1\rho}\right)}{\sum_\beta m_\beta \left|R_{1\beta}\right|^2}$$

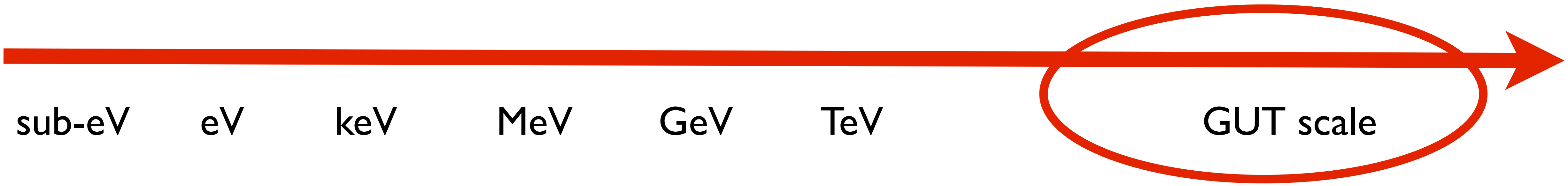
For example, Dirac CPV generates a baryon asymmetry

$$Y_B \sim 6 \times 10^{-10} |\sin\delta| \frac{\sin\theta_{13}}{0.15} \frac{M_1}{10^{11}\ \mathrm{GeV}}$$

for typical values of R.

Observing L violation and CPV would constitute a **strong hint in favour of leptogenesis as the origin of the baryon asymmetry, although not a proof**.

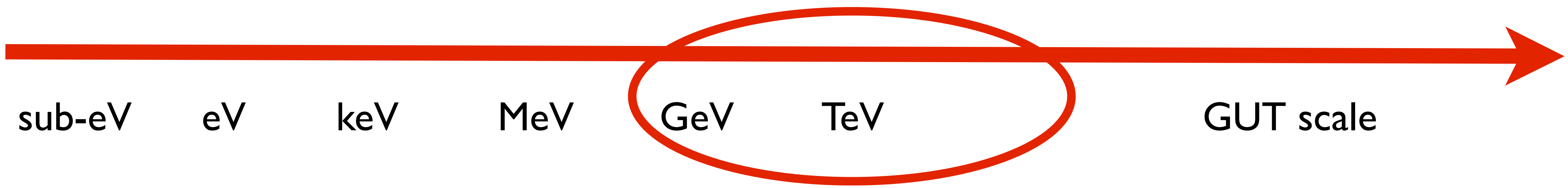
What is the new physics scale?



Signatures

- Neutrino masses
- Proton decay
- Charged lepton flavour violation, for SUSY models
- Leptogenesis

What is the new physics scale?



Signatures

Neutrino masses

Charged lepton flavour violation

Direct signals in colliders

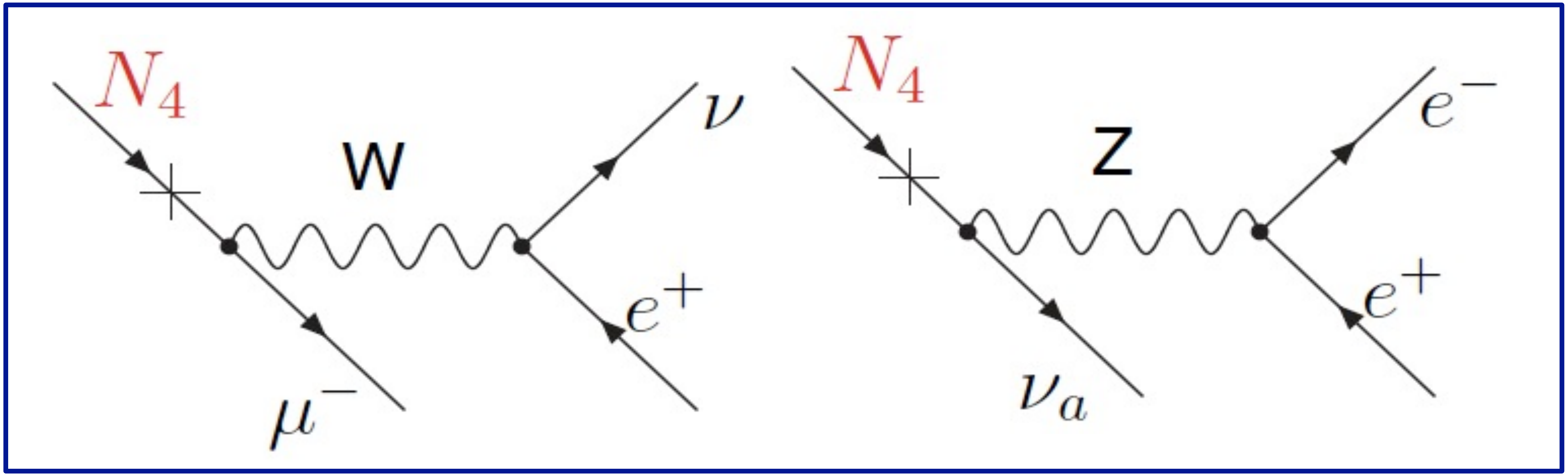
Leptogenesis with enhancements of effects

Signatures of TeV scale see-saw

The characteristic signature is LNV which shows up as a same-sign dilepton signal with no missing energy.

- LNV effects due to active neutrinos will depend on m1, m2, m3. Completely **negligible in colliders**.

- But can be relevant if sterile neutrinos are present. They are produced and decay into SM particles, due to mixing.



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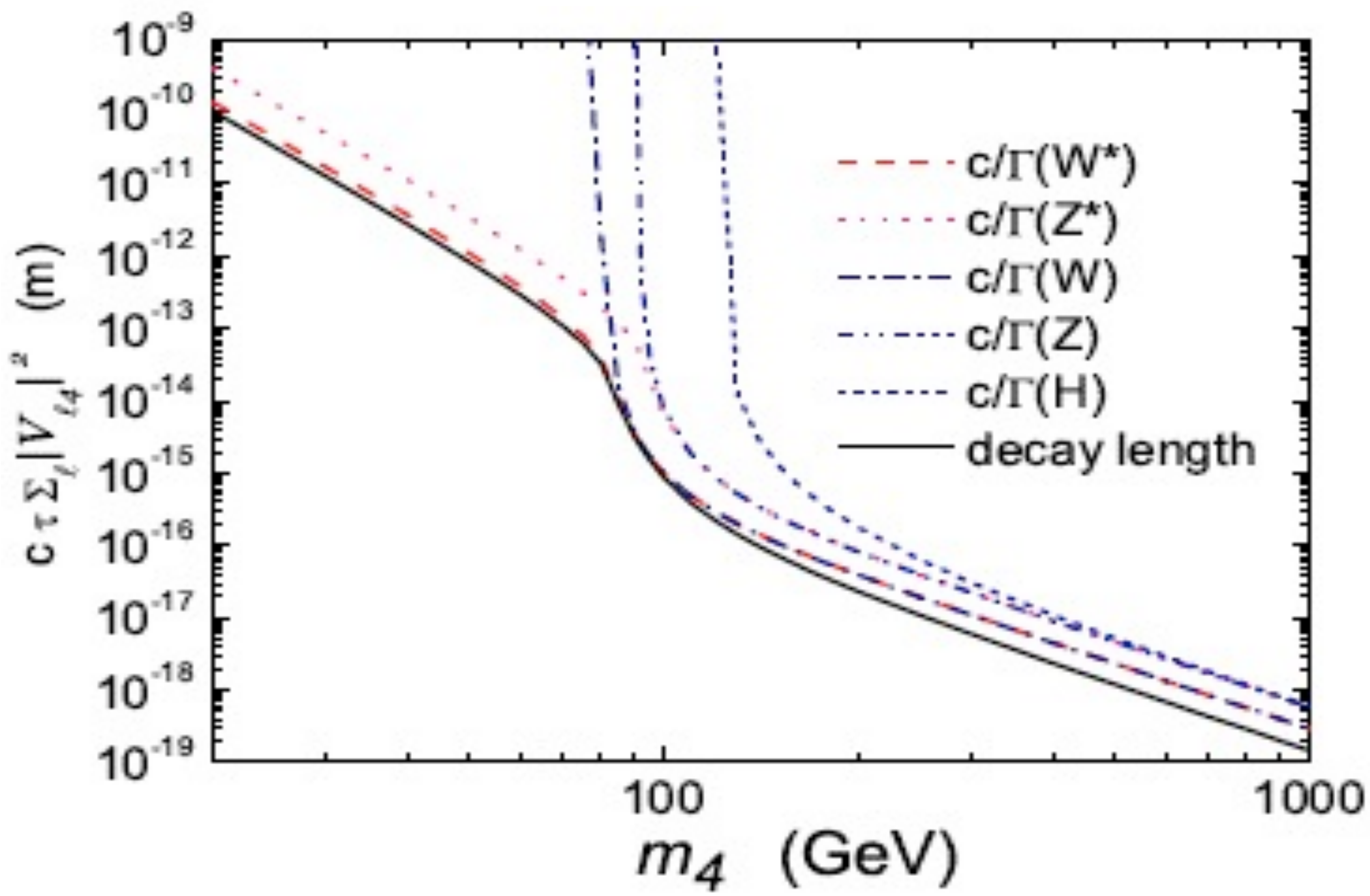
Saturday, 10 August 13

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

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

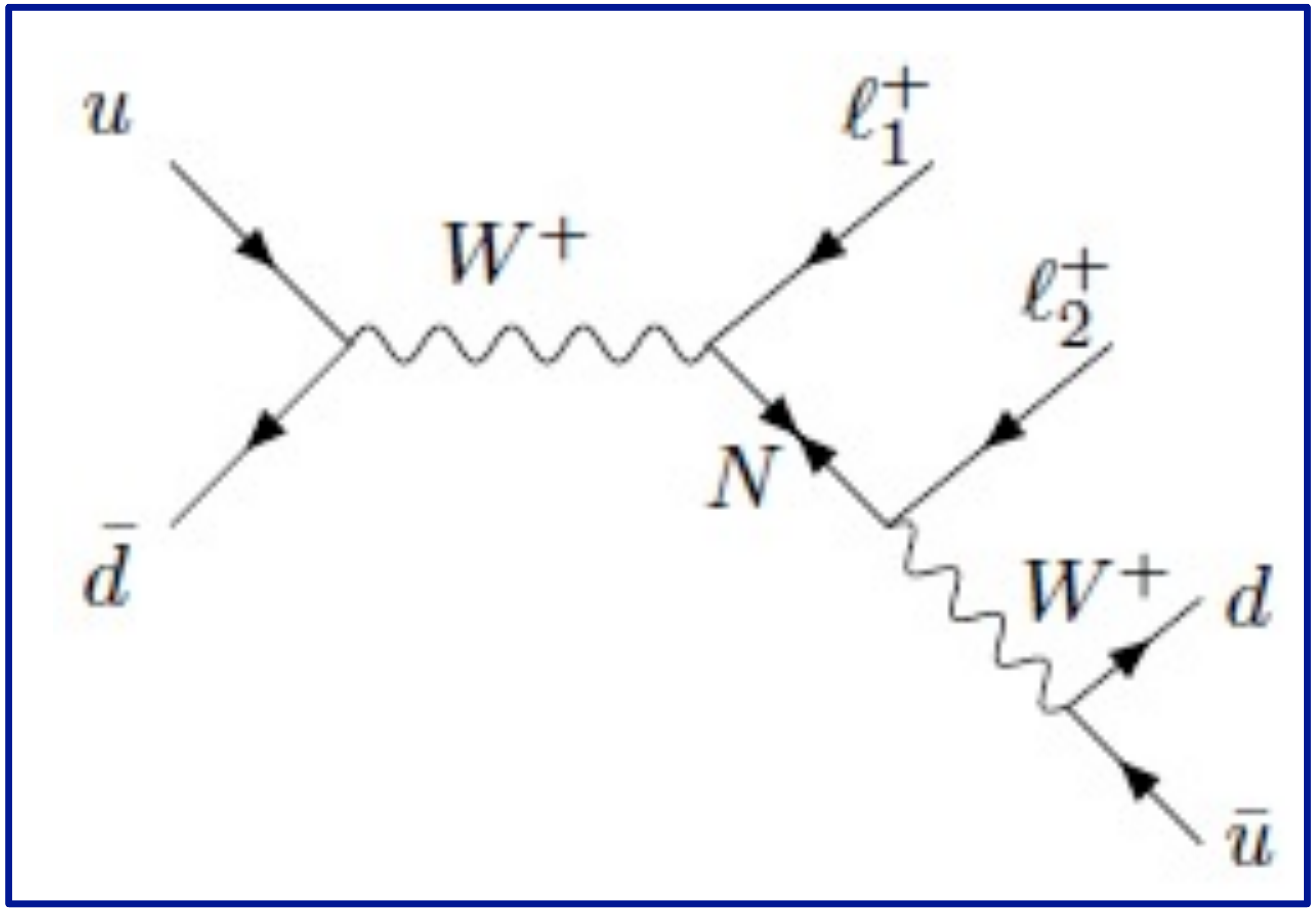


As the mass increases, more channels become kinematically available.

Atre et al., 0901.3589

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

In colliders, the dominant mechanism due to mixing is



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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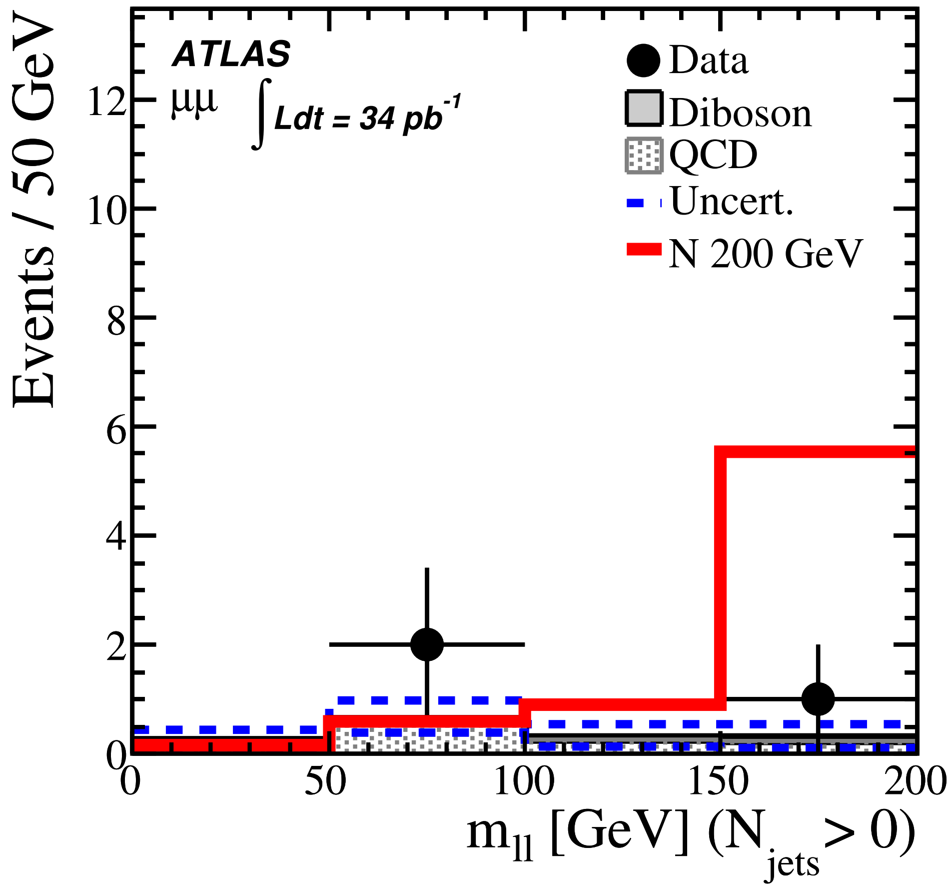
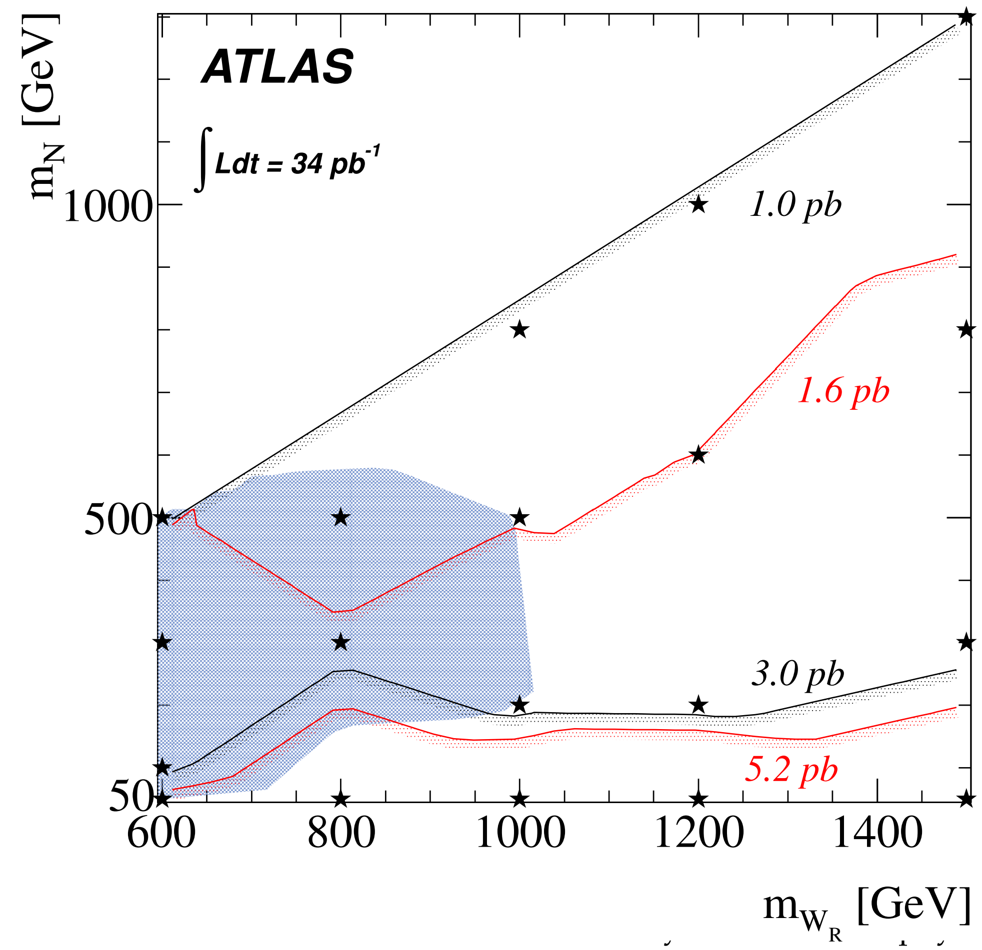
Current limits from LHC





LHC at E=7 TeV

ATLAS, 1108.0366

CMS, 1104.3168

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

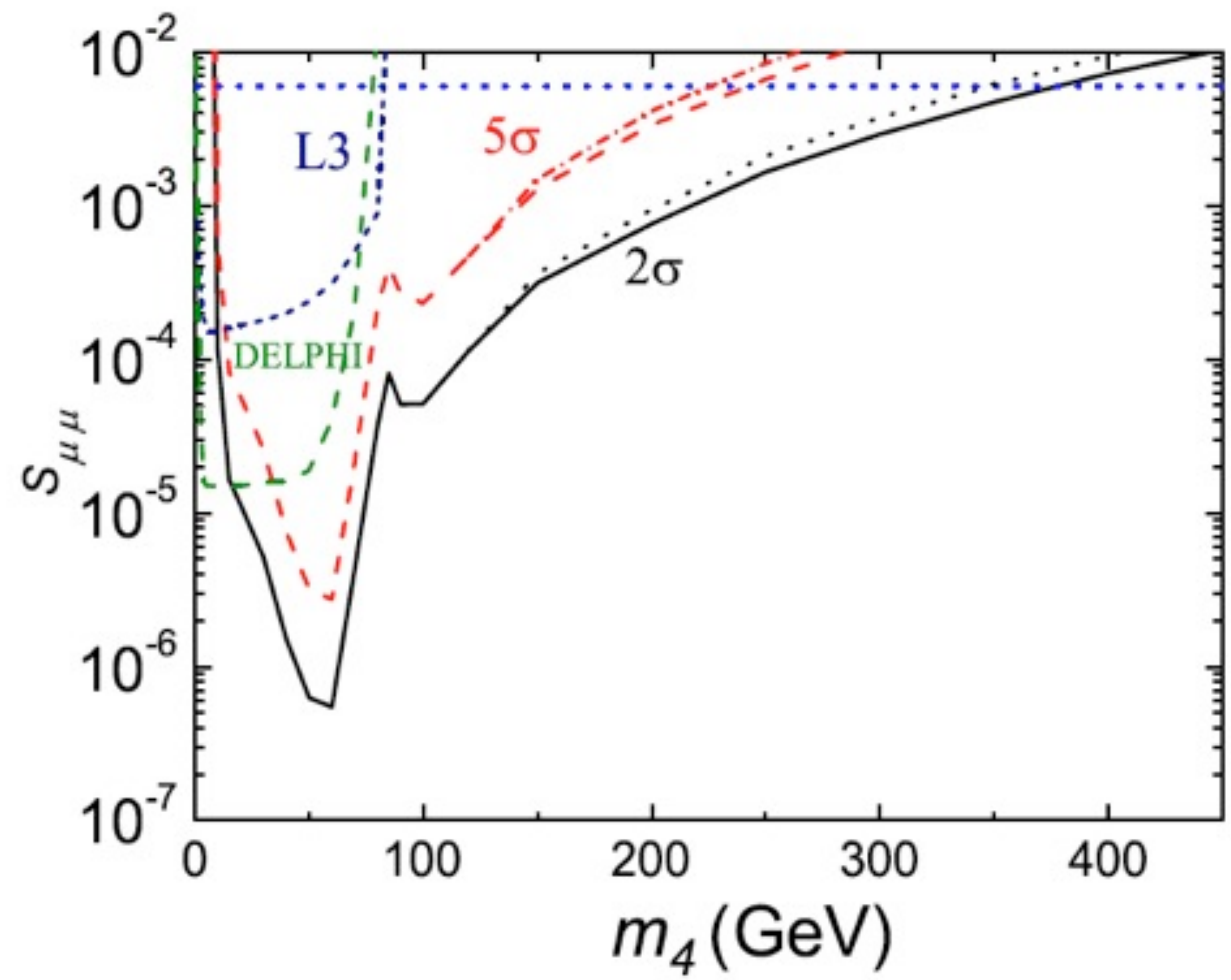
$$\mathcal{L} = (\nu_L^T N^T) \begin{pmatrix} 0 & m_D \\ m_D^T & M \end{pmatrix} \begin{pmatrix} \nu_L \\ N \end{pmatrix}$$

In general we expect mixing to be very small:

- Without cancellations, there is a contribution to neutrino masses:

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

- **Production is extremely suppressed**



In see-saw type I, all LNV effects are suppressed at colliders. Other production mechanisms need to be considered.

Kersten, Smirnov; Ibarra, Molinaro, Petcov

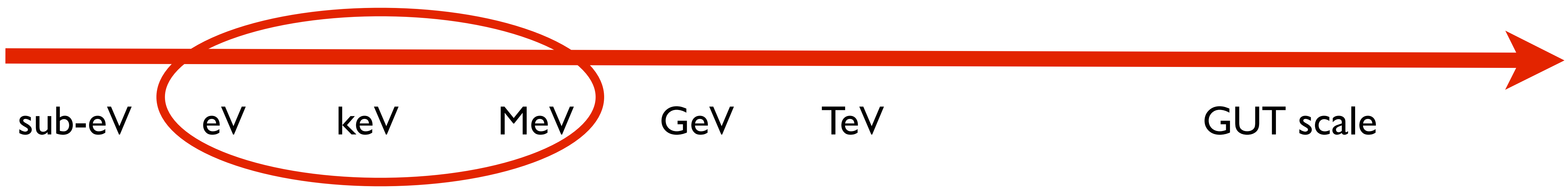
Sufficient N production can be achieved if Ns have additional interactions and the relation between LNV at collider and in neutrino masses is broken.

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

$$pp \to N^+ N^0 \to \ell_1^+ \ell_2^+ Z W^-$$

- Left-Right models via WR
- Inverse or extended see-saw models
- R-parity violating SUSY

What is the new physics scale?



Signatures

Neutrino masses

Peak searches

Dark Matter, WDM, HDM

Nu oscillations

Kinks in beta decay

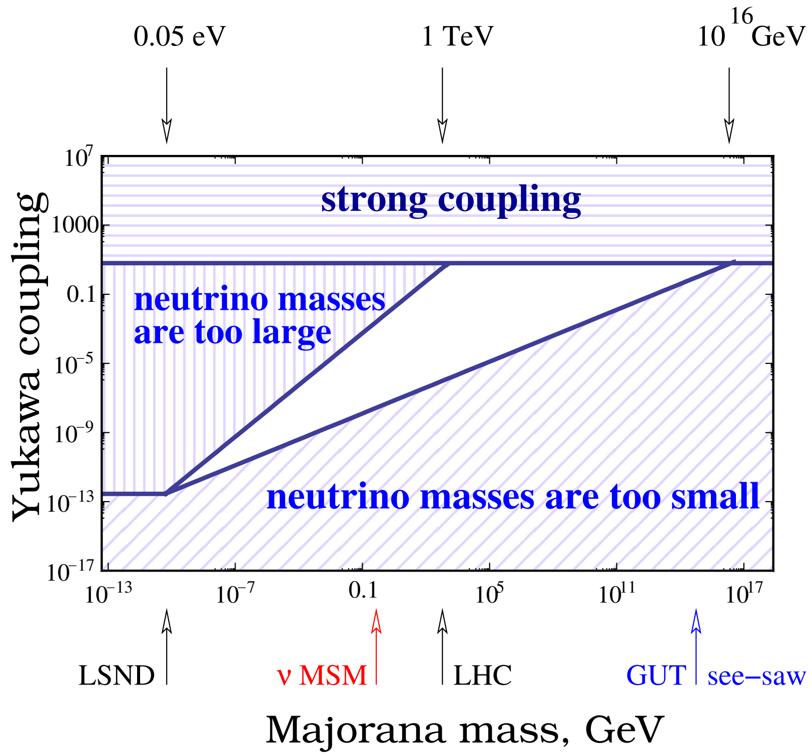
Neutrinoless double beta decay

Below the electroweak scale

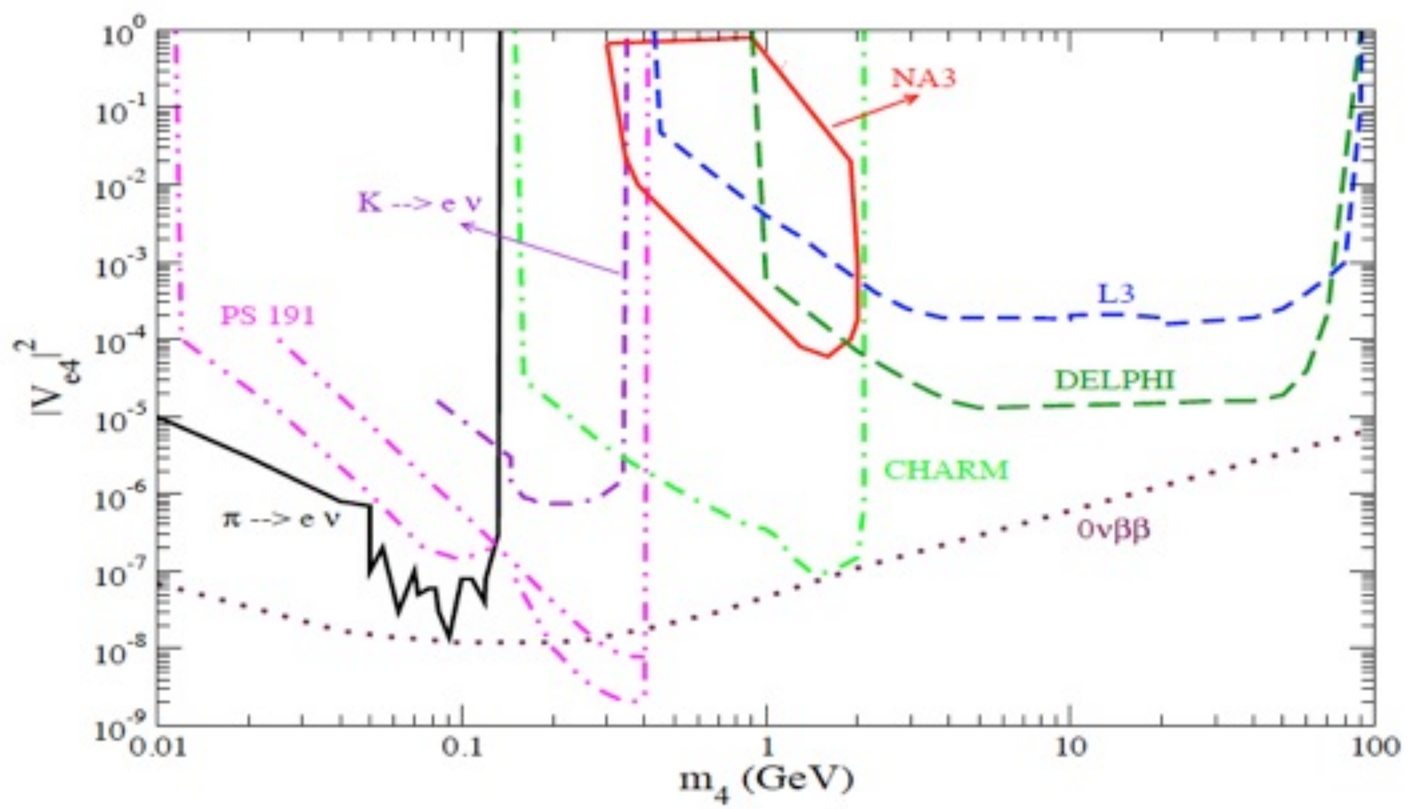
More on Monday.

Low energy see-saw: sterile neutrinos m<< GeV

Very small Yukawa couplings are required or specific cancellations in the masses (inverse or extended see-saw).

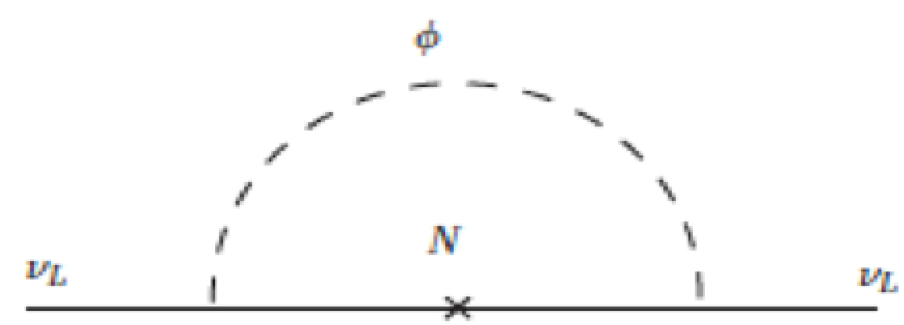


Light sterile neutrinos: a White Paper, 1204.5379



Atre et al., 0901.3589

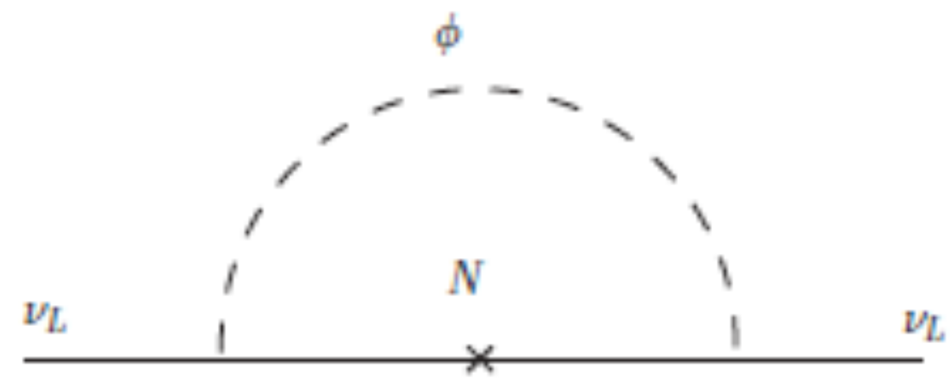
If neutrino masses emerge via loops, in models in which Dirac masses are forbidden, the scale can be lower than in the see-saw models, even at the MeV.



Radiative neutrino masses

Neutrino masses can arise at the electroweak scale **at loop level** and consequently are naturally suppressed.

$$\mathcal{L} = g\nu\phi N$$
$$\langle\phi\rangle = 0$$



A symmetry (e.g. Z2) prevents mixing and protects a **stable DM candidate**.

~~$\nu H^0 N$~~

Gauge invariance requires new particles at the electroweak scale, e.g. fermions, scalars.

Let's study the leptonic structure:

	ν_L	N_R	ϕ		
L1	$+1$	$+1$	0	$\Rightarrow$	MN^TCN
L2	$+1$	0	$+1$	$\Rightarrow$	$m_\phi^2\phi^\dagger\phi + \mu_\phi^2\phi^2$

Therefore, neutrino masses must depend on all terms which break the various lepton numbers (as in the inverse, extended see-saw...):

$$m_\nu \propto \frac{g^2}{16\pi^2} f(M, \mu_\phi^2)$$

A detailed computation gives

$$m_{\nu_L} = \frac{g^2}{32\,\pi^2}\, m_N \left[\frac{m_{\phi 1}^2}{(m_N^2 - m_{\phi 1}^2)} \ln(m_N^2/m_{\phi 1}^2) - \frac{m_{\phi 2}^2}{(m_N^2 - m_{\phi 2}^2)} \ln(m_N^2/m_{\phi 2}^2) \right]$$

At one-loop the Zee model and the Ma (and others) models provide neutrino masses. In the Ma (et al.) model we introduce a scalar doublet h without a vev!

$$\mathcal{L} \propto f \bar{L}_L \eta^\dagger N_R + \frac{1}{2} M N_R^T C N_R + \ldots + \lambda(\Phi^\dagger \Phi)(\eta^\dagger \eta) + \lambda'(\Phi^\dagger \eta)(\eta^\dagger \Phi) + \lambda''(\Phi^\dagger \eta)^2 + \text{h.c.}$$

Let's study the leptonic structure:

	ν_L	N_R	η		
L1	$+1$	$+1$	0	$\Rightarrow$	broken by M
L2	$+1$	0	$+1$	$\Rightarrow$	broken by λ''

So neutrino masses will be

$$m_\nu \sim \lambda'' f^2 \frac{v_H^2}{16\pi^2 M_i} \mathcal{O}(1)$$

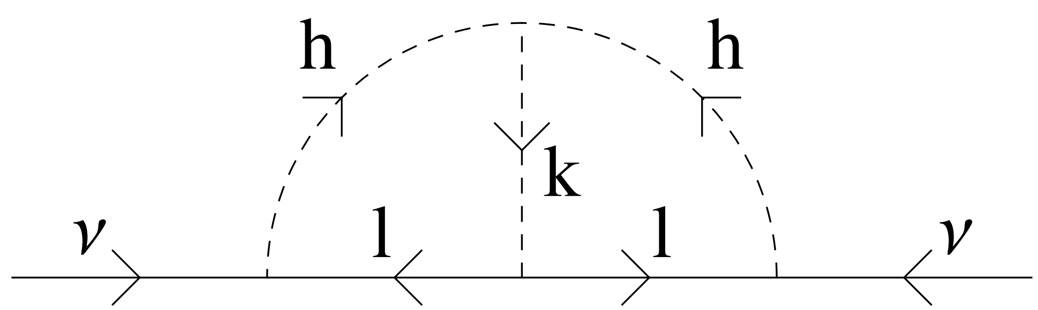
one loop → ($16\pi^2$)

Interesting connections can be found with dark matter (as the scalar does not get a vev, there is a conserved Z2 which guarantees the stability of the lightest new particle, the DM candidate) and LFV.

At too-loops complete (SU(2) conserving) is the Zee-Babu model.

We introduce two scalar singlets h^+ and k^{++}

$$\mathcal{L} = f_{ab} L_{La}^T C i\sigma_2 L_{Lb} h^+ + g_{ab} e_{Ra}^{\bar{c}} e_{Rb} k^{++} - \mu h^+ h^+ k^{--} + \text{h.c.}$$



Lepton number is broken by f, g and mu. So neutrino masses will be

$$m_\nu = \frac{8\mu}{(16\pi^2)^2 m_h^2} f^2 g m_l \mathcal{O}(1)$$

two loops

and will be suppressed by the couplings, loop factor and the lepton mass.

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R-parity violating SUSY and neutrino masses

In SUSY models, each particle has a super-partner with the same quantum numbers but different spin. For ex., the lepton will have a slepton, the Higgses the higgsinos etc.

R-parity is a symmetry of the Lagrangian defined as

$$R \equiv (-1)^{3B+L+2j}$$

In the MSSM, there are no neutrino masses.

But it is possible to introduce terms which violate R and therefore violate lepton number.

$$V = \ldots - \mu H_1 H_2 + \epsilon_i \tilde{L}_i H_2 + \lambda'_{ijk} \tilde{L}_i \tilde{L}_j \tilde{E}_k + \ldots$$

The bilinear term will induce mixing between neutrinos and higgsino and therefore neutrino masses, the trilinear term induces masses at the loop-level.

Summary and outlook

Today we have looked at

1. Embedding of the see-saw mechanism in GUT theories

2. Tests of neutrino mass models in order to identify the new physics scale: LFV processes, Leptogenesis, TeV scale: collider searches, below TeV scale (more tomorrow)

3. Other mechanisms of neutrino masses

   Radiative masses (general comments and one-loop and two-loop models)

   SUSY with R-parity violation (briefly)

On Monday we will focus on the connection between the mass matrix and the mixing structure. Various approaches can be adopted: mass textures, flavour symmetries; anarchy... And then we will consider models beyond 3-neutrino mixing (mainly sterile neutrinos and their models).