Neutrino masses and mixing: a theoretical perspective

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Silvia Pascoli

IPPP - Durham University

Outline

1. The discovery of theta13 and present status of neutrino physics

2. Neutrino masses beyond the Standard Model: Dirac versus Majorana masses

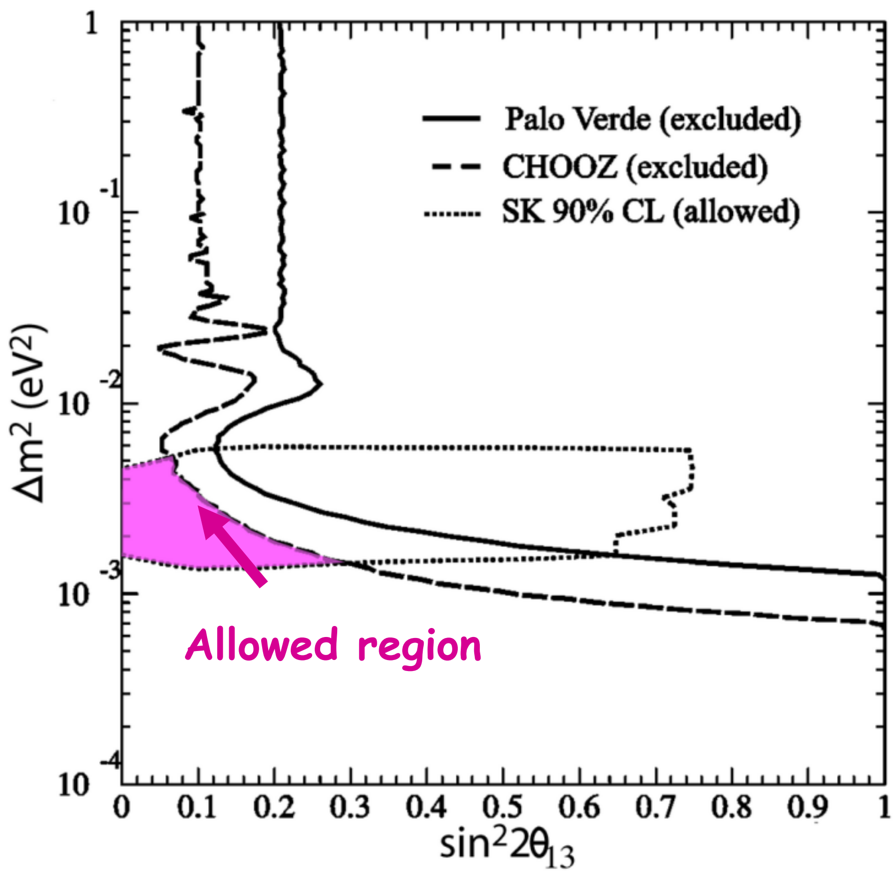
4. See-saw models and other mechanisms for the origin of neutrino masses

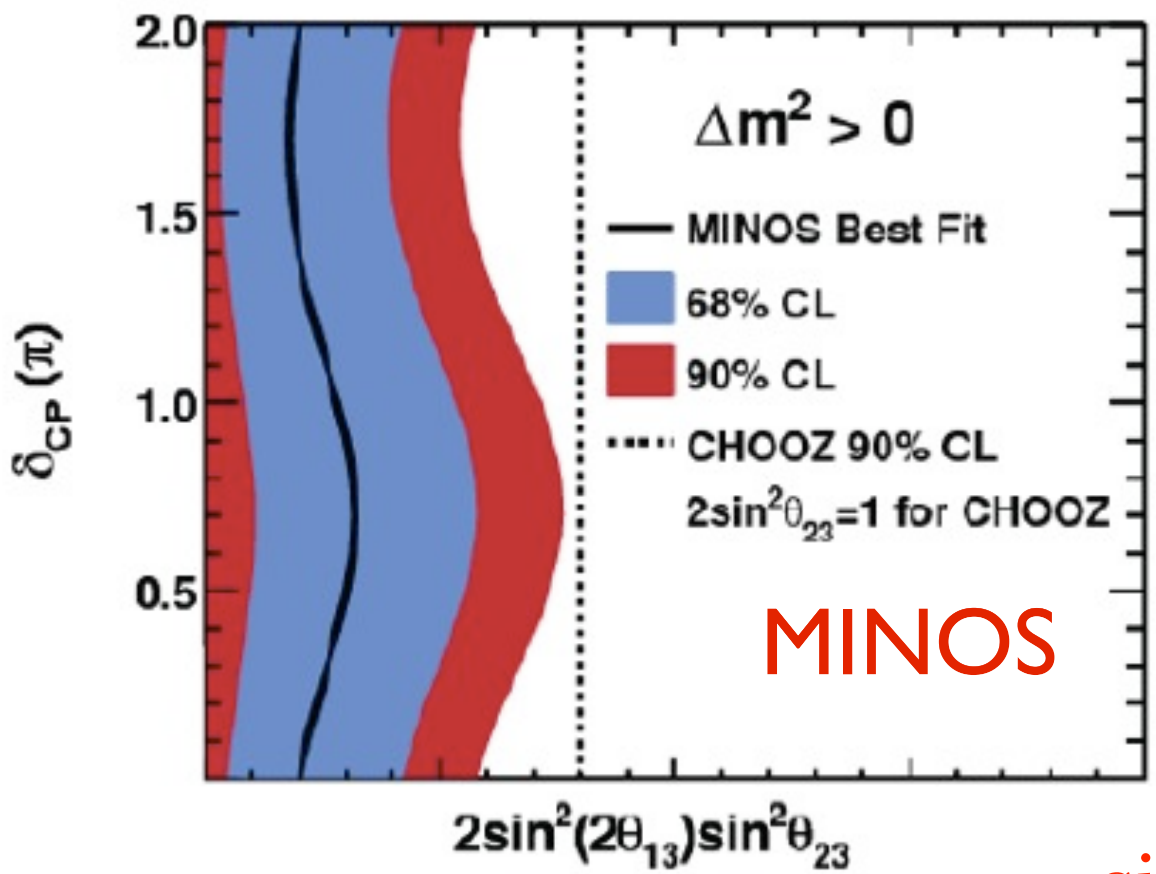
4. The leptonic flavour problem

5. Conclusions

The discovery of large theta13

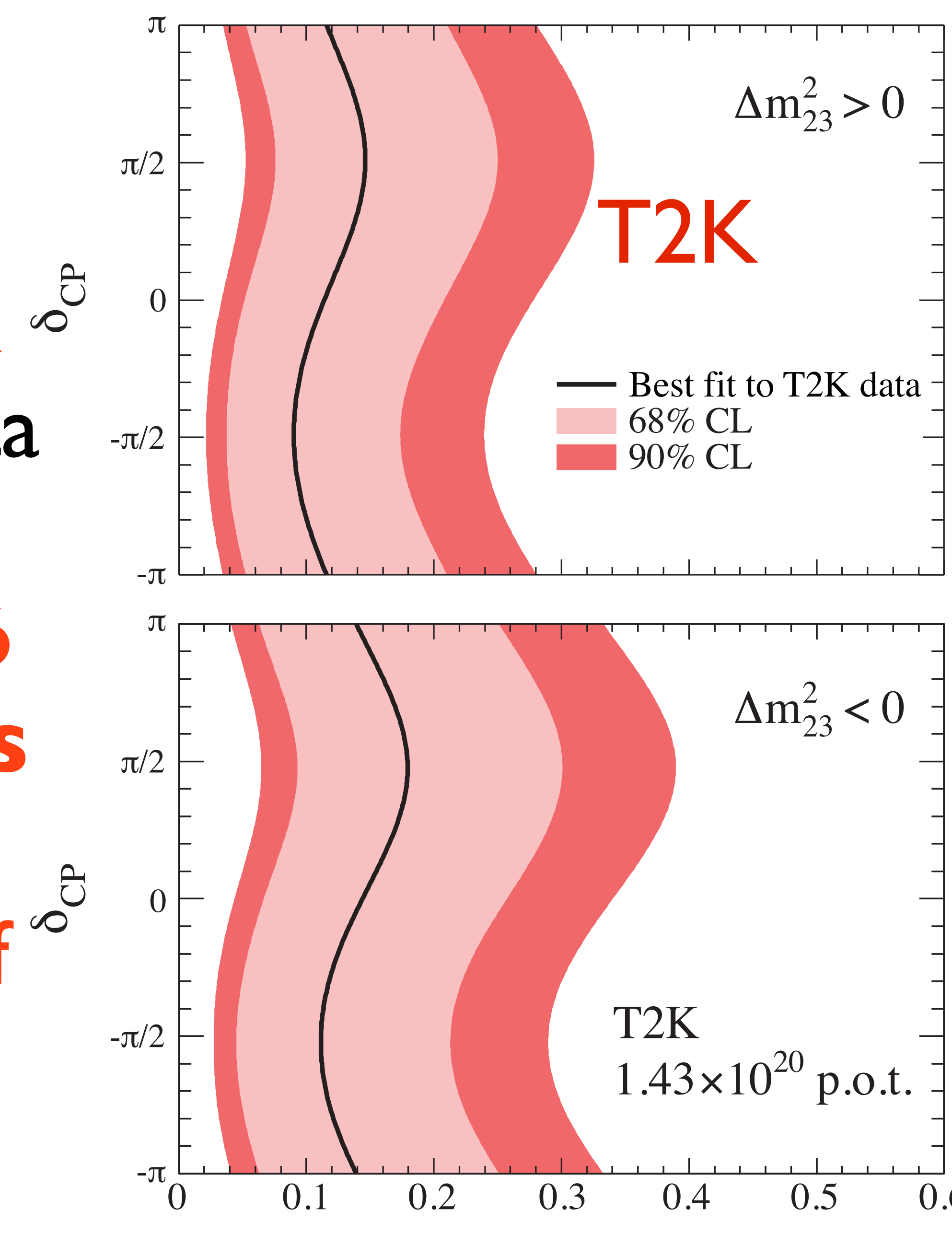
Up to 2011, oscillation experiments had measured with good precision 2 mixing angles. First hints of theta13 by T2K, MINOS.





MINOS Coll, 1108.0015

- T2K first data in May 2011: **6 events** with a bckg of 1.5



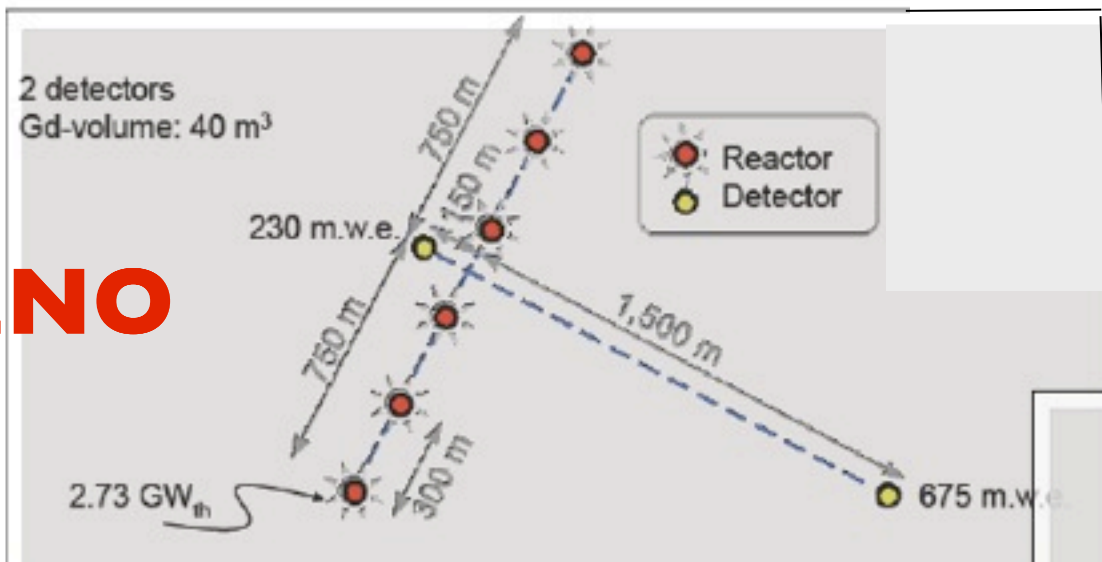
$$\sin^2 2\theta_{13}|_{BF} = 0.11$$

PRL 107 (2011)

First Results from DChooz (9/11/11)

$$\sin^2 2\theta_{13} = 0.085 \pm 0.051$$

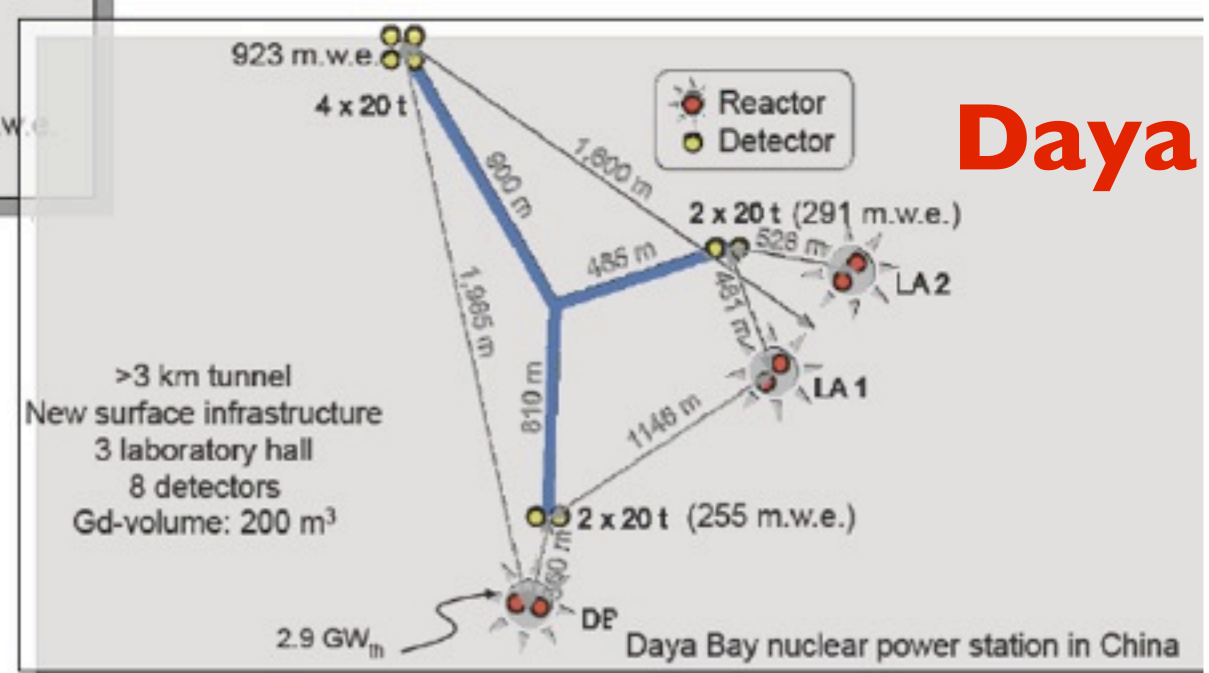
RENO

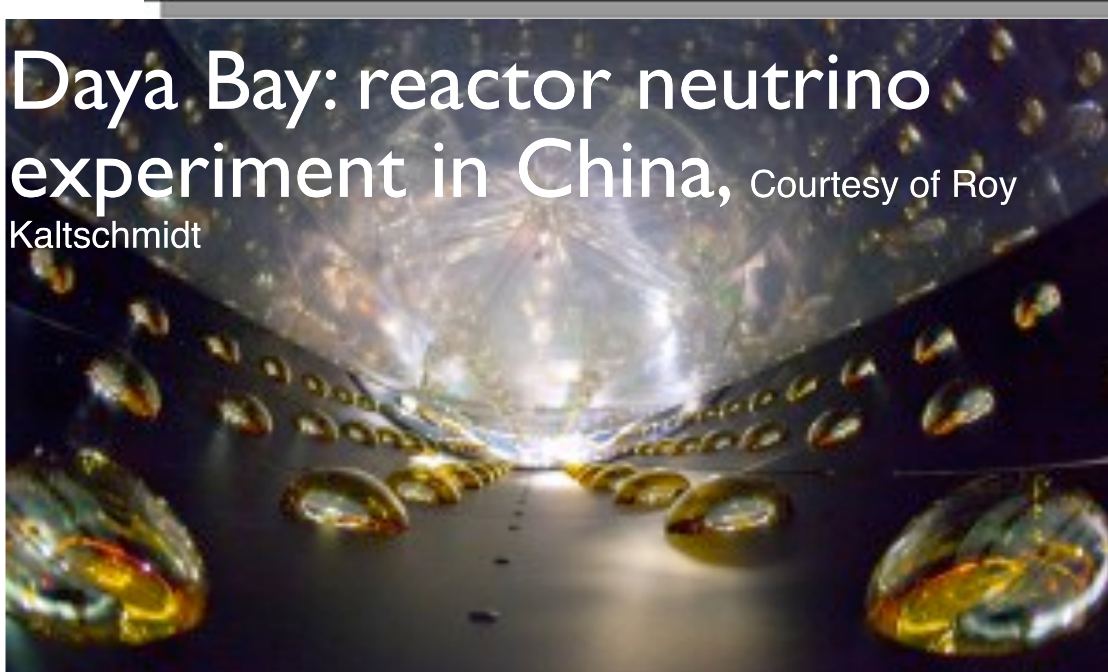


Two near detector data taking

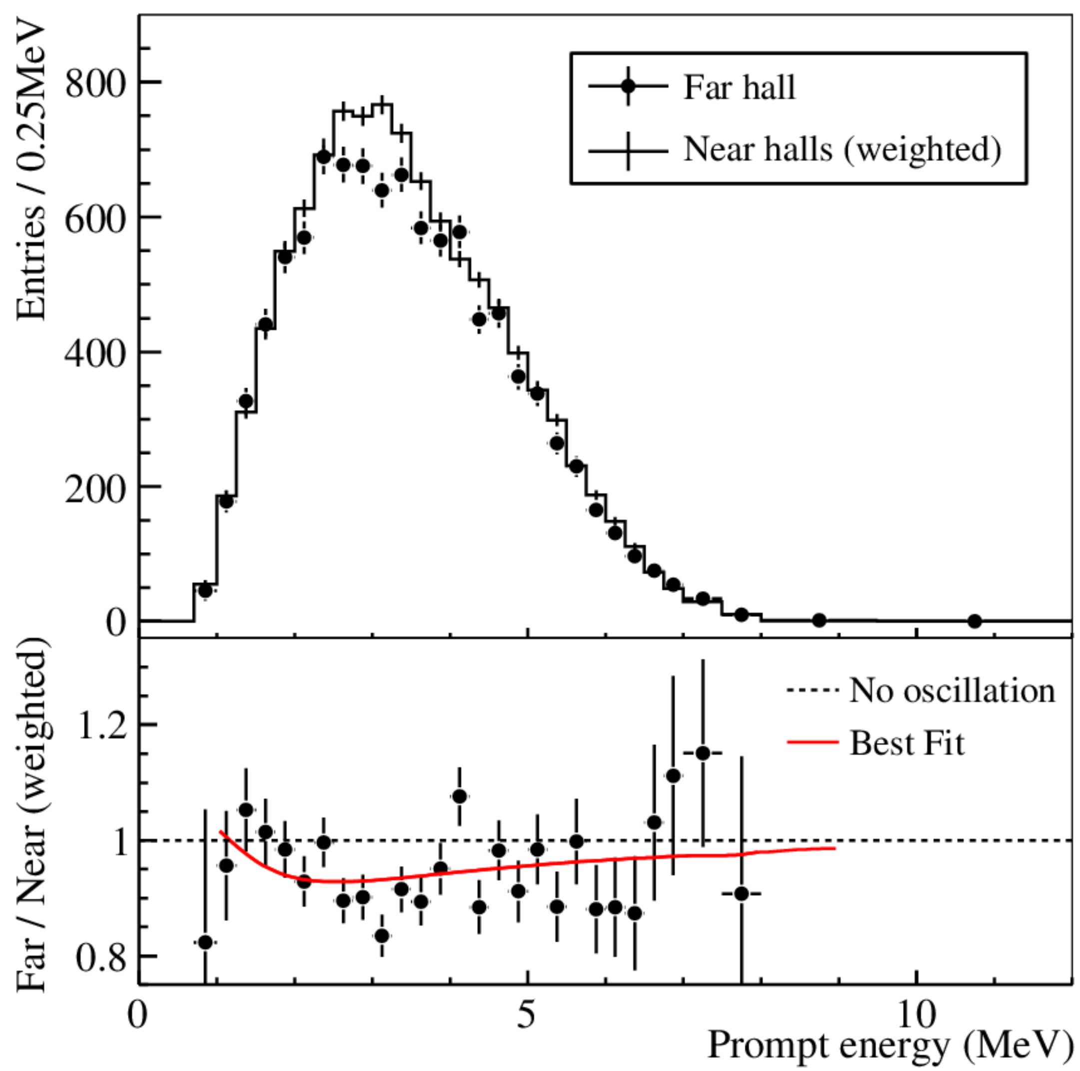
Daya Bay (China)

Daya Bay

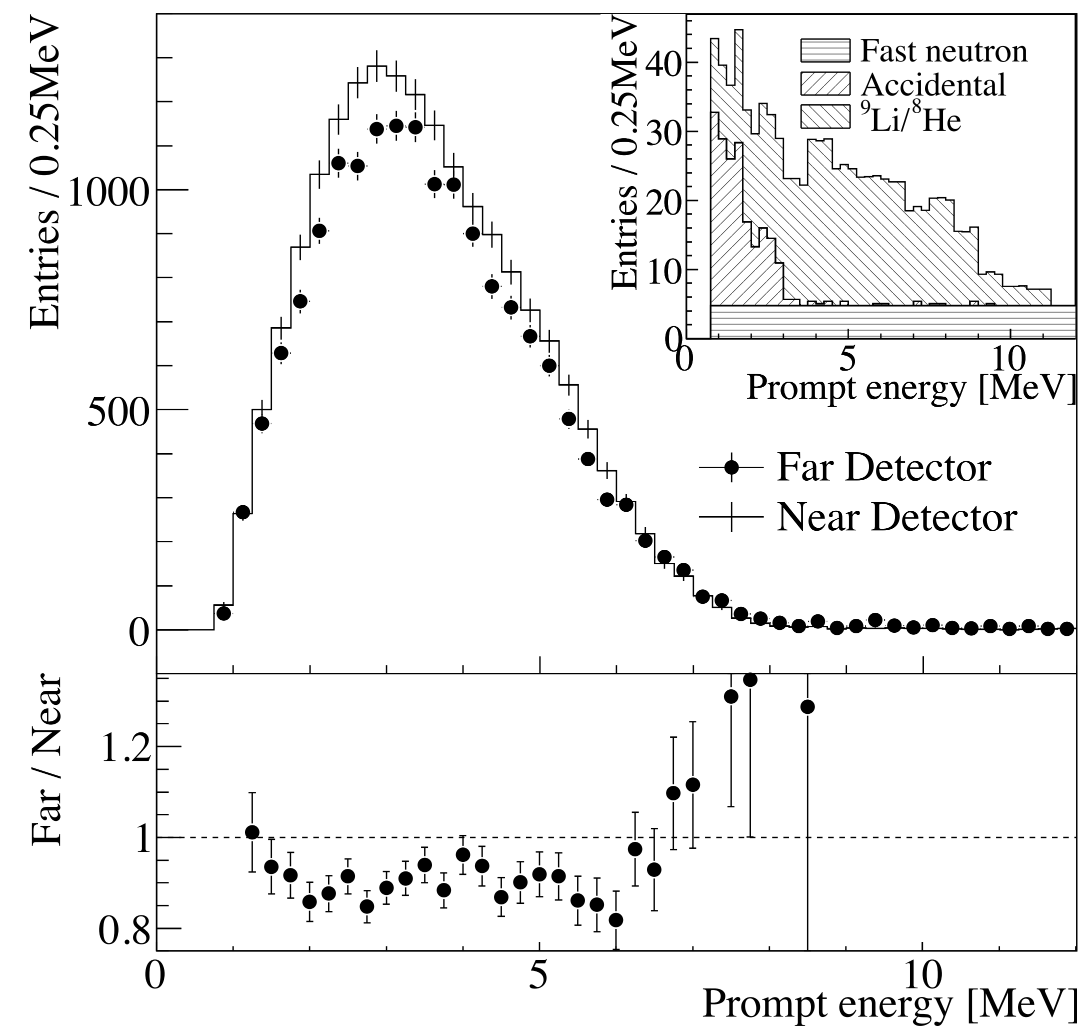



Daya Bay: reactor neutrino experiment in China, Courtesy of Roy Kaltschmidt

In 2012, previous hints (DoubleCHOOZ,T2K, MINOS) for a nonzero third mixing angle were confirmed by Daya Bay and RENO: important discovery.



Daya Bay, PRL 108 (2012)



RENO, PRL 108 (2012)

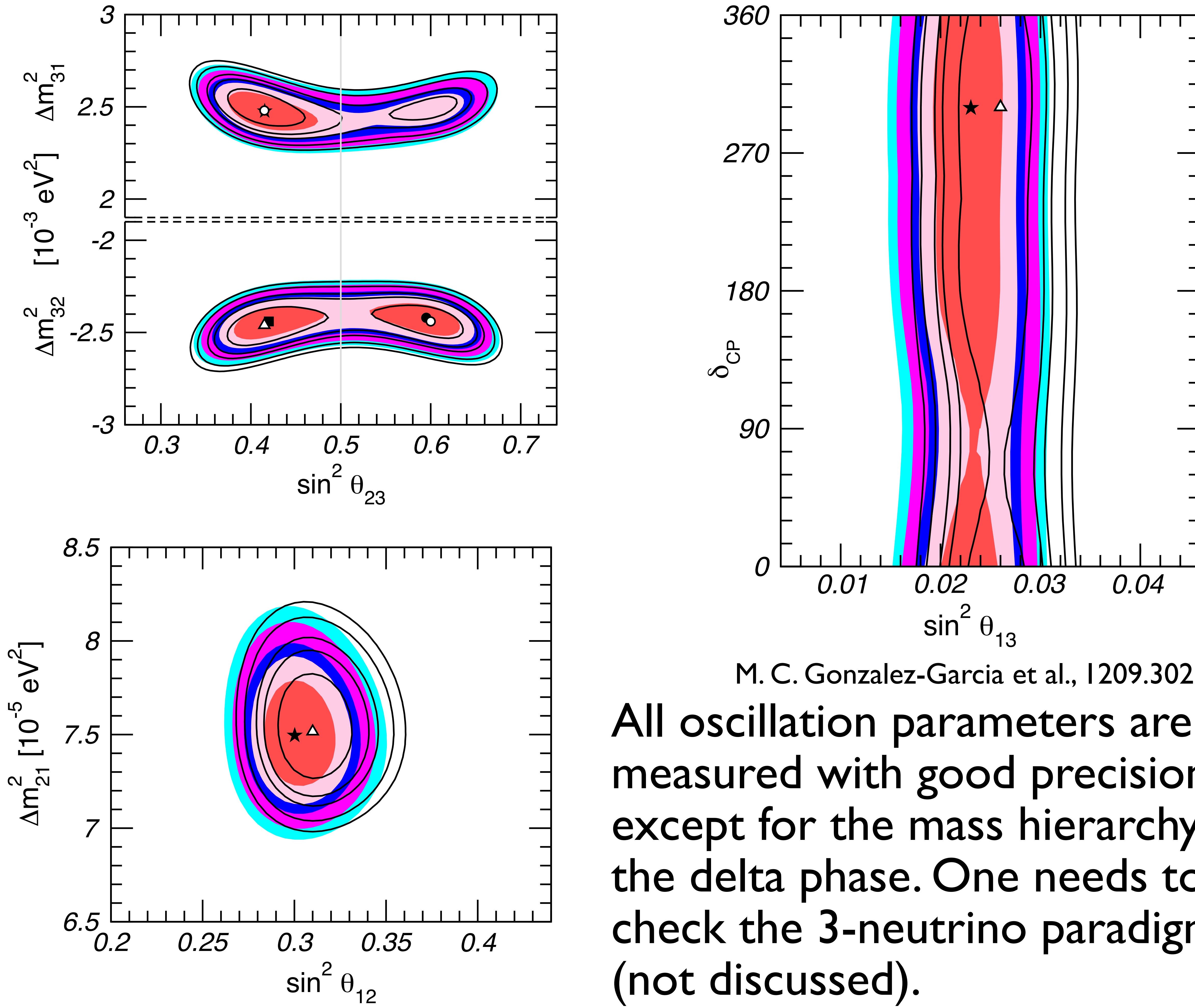
Observed: 9901 neutrinos at far site,

Prediction: 10530 neutrinos if no oscillation

R = 0.940 ±0.011 (stat) ±0.004 (syst)

Y. Wang, March 2012

$$\sin^2 2\theta_{13} = 0.092 \pm 0.016 \pm 0.005$$

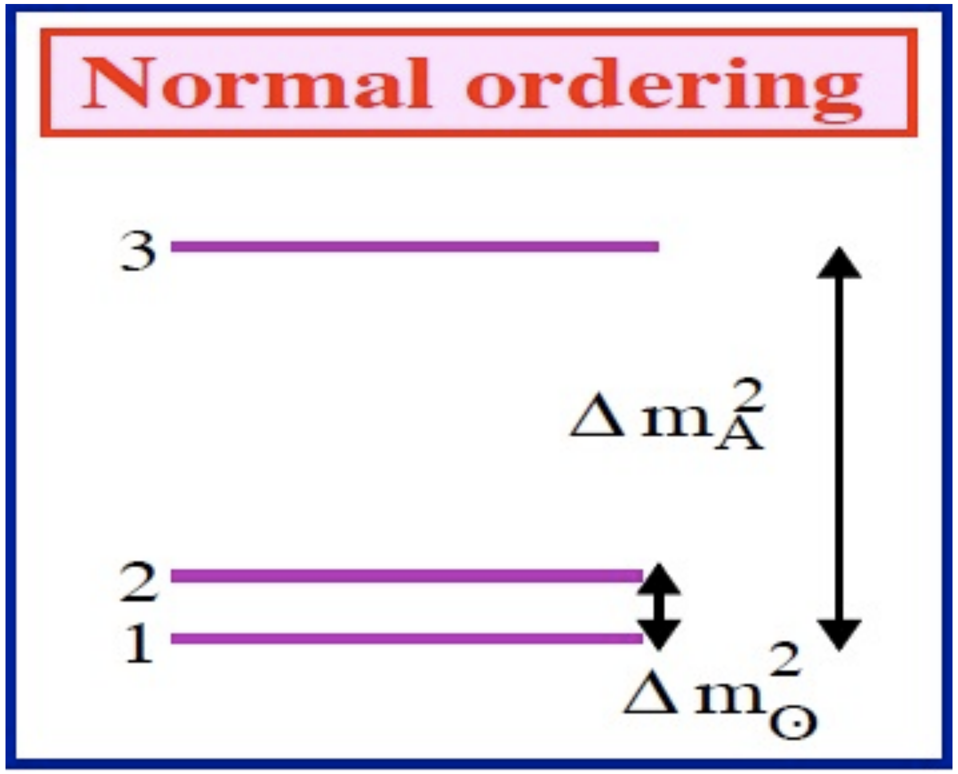


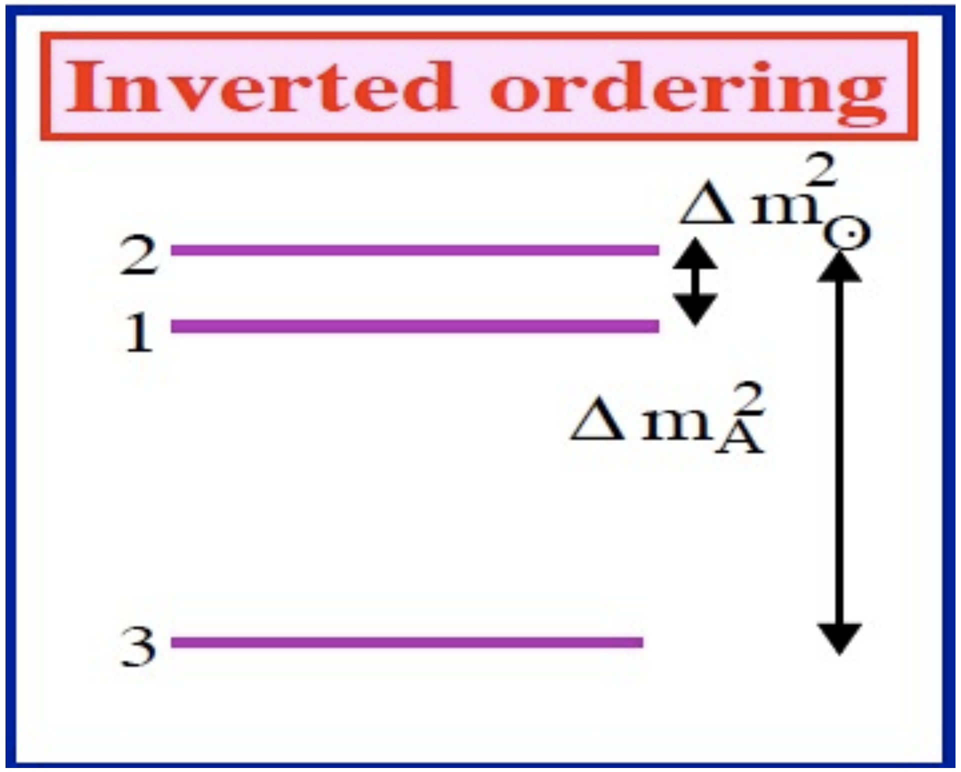
M. C. Gonzalez-Garcia et al., 1209.3023

All oscillation parameters are measured with good precision, except for the mass hierarchy and the delta phase. One needs to check the 3-neutrino paradigm (not discussed).

Present status of (standard) neutrino physics

$\Delta m^2_{\rm s} \ll \Delta m^2_{\rm A}$ implies at least 3 massive neutrinos.





$$m_1 = m_{\rm min}$$
$$m_2 = \sqrt{m^2_{\rm min} + \Delta m^2_{\rm sol}}$$
$$m_3 = \sqrt{m^2_{\rm min} + \Delta m^2_{\rm A}}$$

$$m_3 = m_{\rm min}$$
$$m_1 = \sqrt{m^2_{\rm min} + \Delta m^2_{\rm A} - \Delta m^2_{\rm sol}}$$
$$m_2 = \sqrt{m^2_{\rm min} + \Delta m^2_{\rm A}}$$

Measuring the masses requires: $m_{\rm min}$ and the ordering .

Neutrino mixing

Mixing is described by the Pontecorvo-Maki-Nakagawa-Sakata matrix, which enters in the CC interactions

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i}|\nu_i\rangle$$

$$\mathcal{L}_{CC} = -\frac{g}{\sqrt{2}}\sum_{k\alpha}\left(U^*_{\alpha k}\bar{\nu}_{kL}\gamma^\rho l_{\alpha L}W_\rho + \text{h.c.}\right)$$

Large angles

CPV?

$$U = \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Solar, reactor } \theta_\odot \sim 30^o} \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{Atm, Acc. } \theta_A \sim 45^o}$$

$$\underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{-i\delta} \end{pmatrix}}_{\text{CPV phase}} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix}}_{\text{Reactor, Acc. } \theta_{13} \sim 9^o} \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\alpha_{21}/2} & 0 \\ 0 & 0 & e^{-i\alpha_{31}/2+i\delta} \end{pmatrix}}_{\text{CPV Majorana phases}}$$

CPV is a fundamental question to answer, possibly related to the origin of the baryon asymmetry.

Phenomenology questions for the future

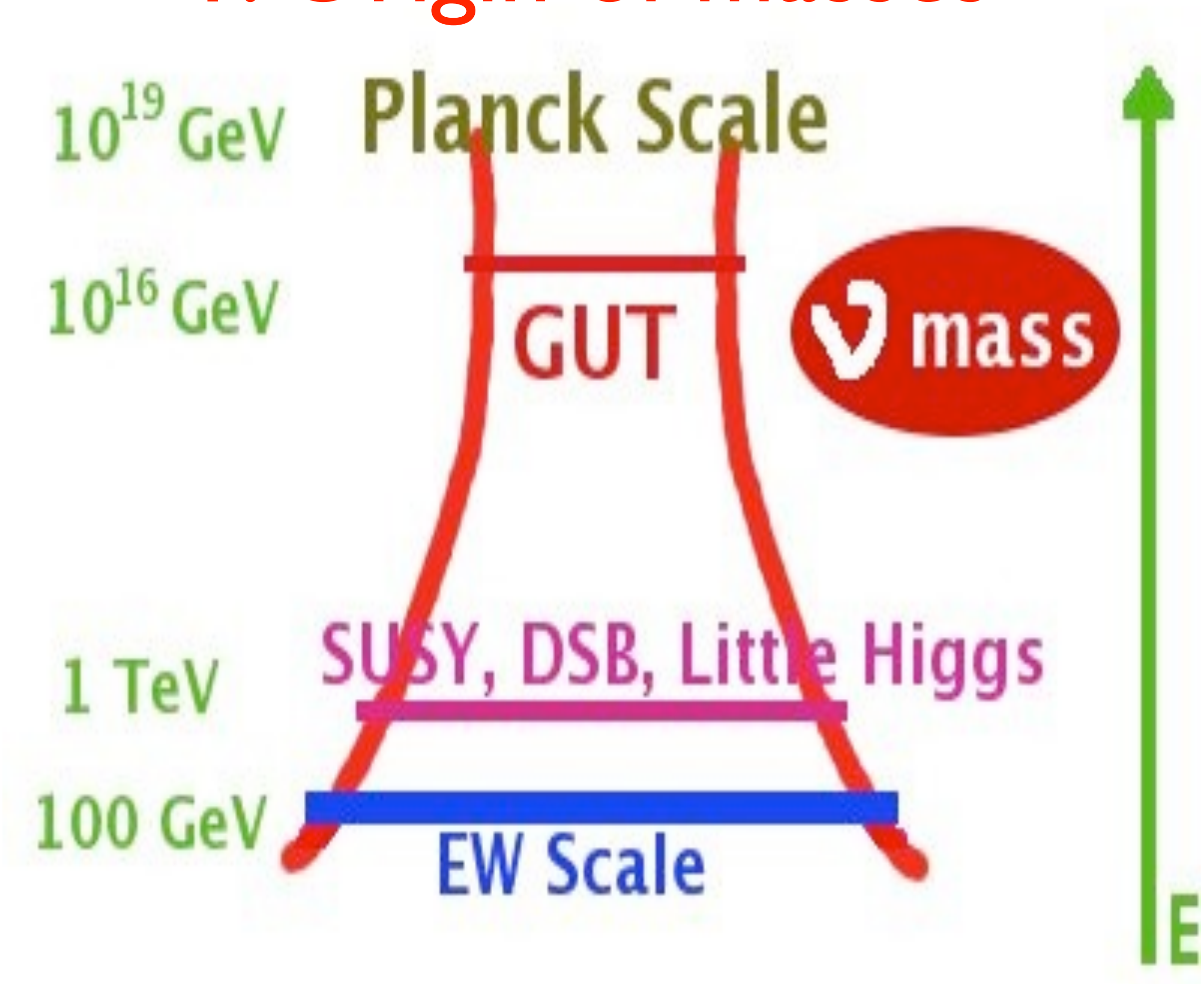
- **What is the nature of neutrinos? Dirac vs Majorana?**
- **What are the values of the masses?** Absolute scale (KATRIN, ...?) and the ordering.
- **Is there CP-violation?** Its discovery in the next generation of LBL depends on the value of delta.
- **What are the precise values of mixing angles?** Do they suggest a underlying pattern?
- **Is the standard picture correct?** Are there NSI? Sterile neutrinos? Other effects?

A wide experimental programme is under way.
See D. Wark's talk.

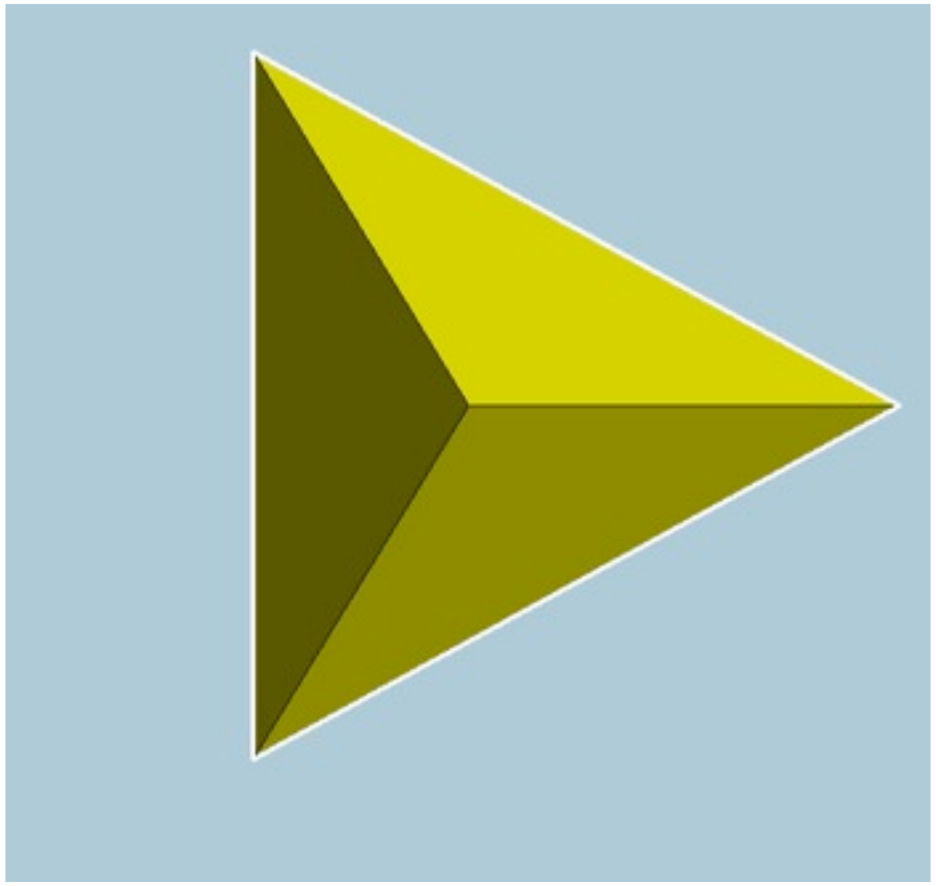
Open window on Physics beyond the SM

Neutrino physics gives a new perspective on physics BSM.

1. Origin of masses



2. Problem of flavour



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

Nature of Neutrinos: Majorana vs Dirac

Neutrinos can be **Majorana** or **Dirac** particles. In the SM only neutrinos can be Majorana because they are neutral.

Majorana condition $\nu = C\bar{\nu}^T$

The **nature** of neutrinos is linked to the conservation of the **Lepton number (L)**.

- This is crucial information to understand the **Physics BSM**: **with or without L-conservation**?

- Lepton number violation is a necessary condition for **Leptogenesis**.

- Tests of LNV:
  - At low energy, **neutrinoless double beta decay,**
  - LNV tau and meson decays,
  - collider searches.

Neutrino Masses in the SM and beyond

In the SM, neutrinos do not acquire 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

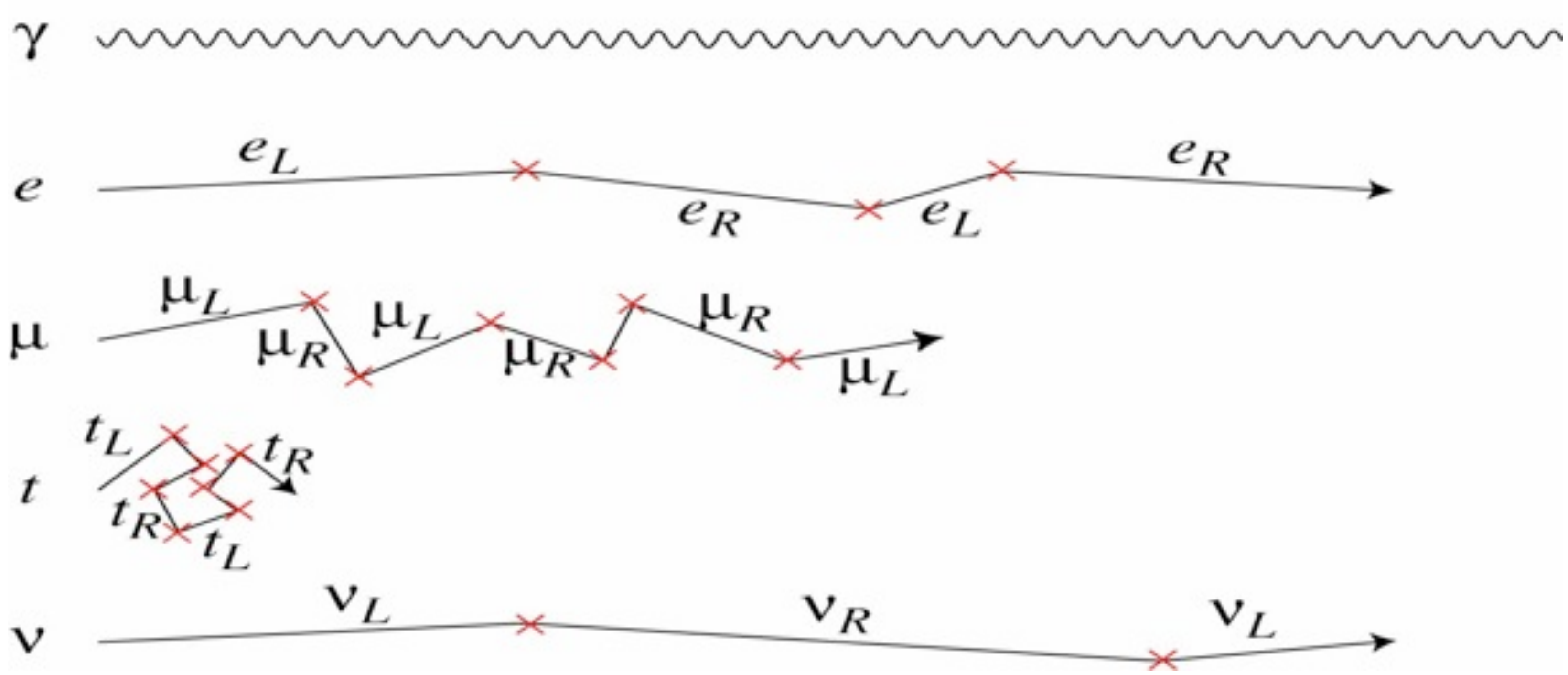
- they do not have a Majorana mass term

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

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

Dirac Masses

Neutrino masses in the sub-eV range cannot be explained naturally within the SM.



Thanks to
H. Murayama

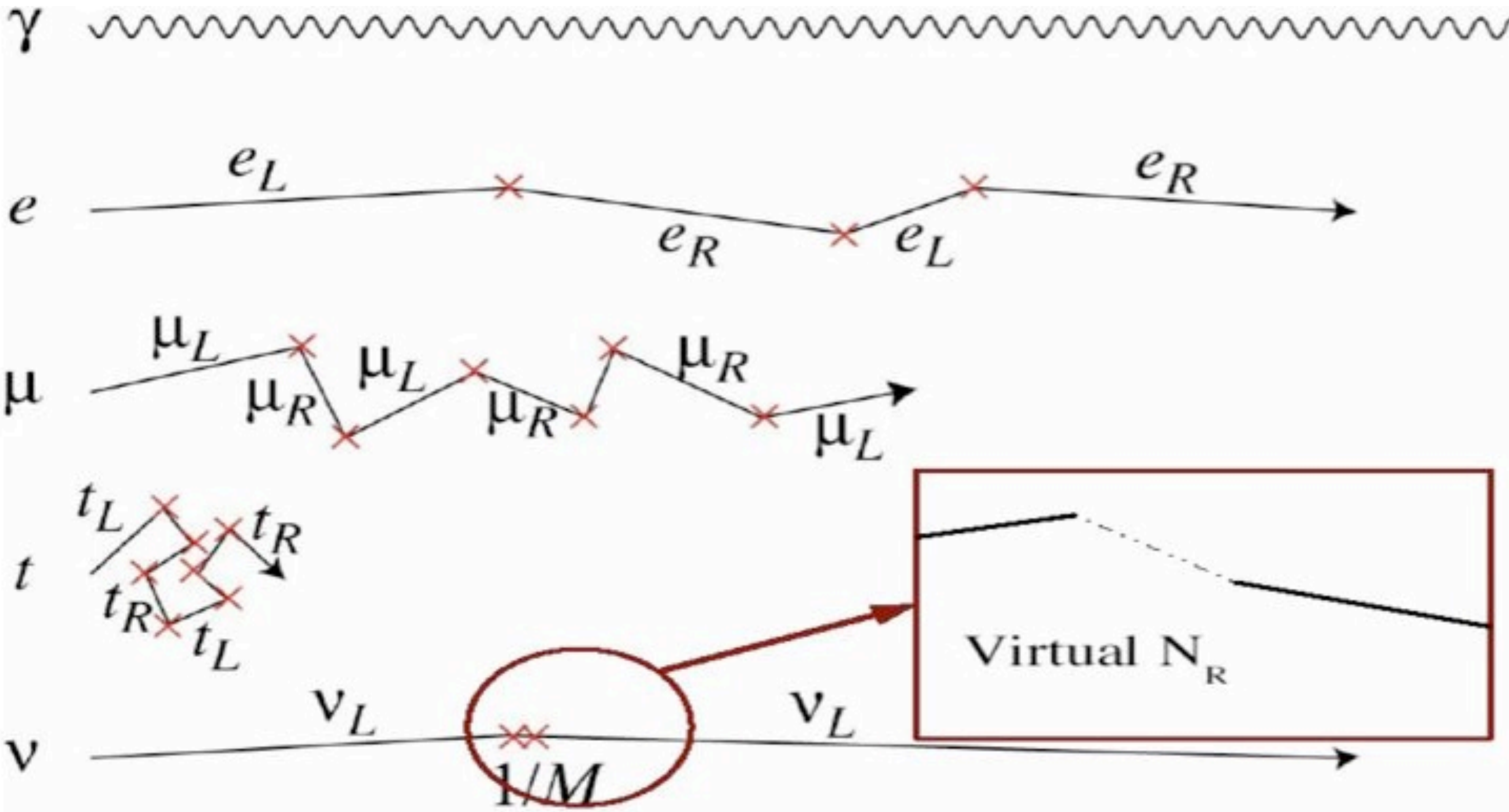
$$\mathcal{L} = y_\nu \bar{L} \cdot H \nu_R + \text{h.c.}$$

$$y_\nu = \frac{m_\nu}{v} = \frac{0.1\,\text{eV}}{250\,\text{GeV}} = 4 \times 10^{-13}$$

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).

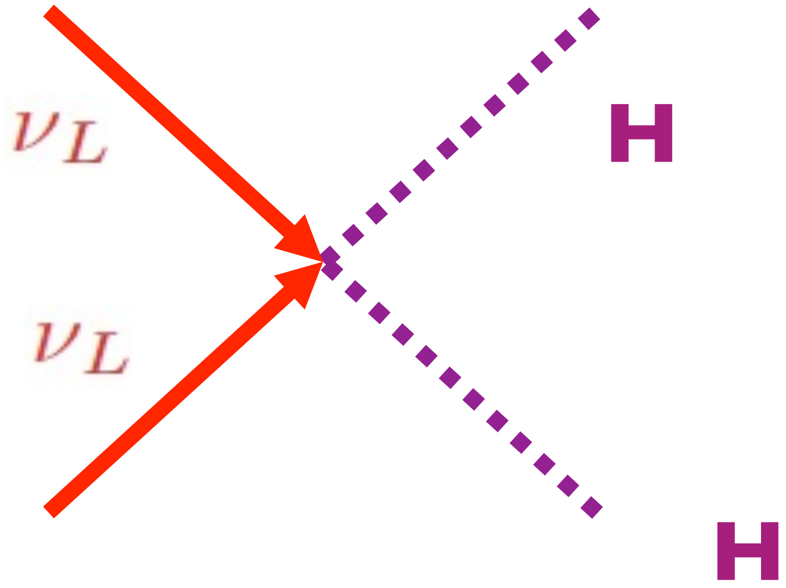
Majorana Masses

If neutrino are Majorana particles, a **Majorana mass** can be generated and can arise as the **low energy realisation of a higher energy theory**.



Thanks to H. Murayama

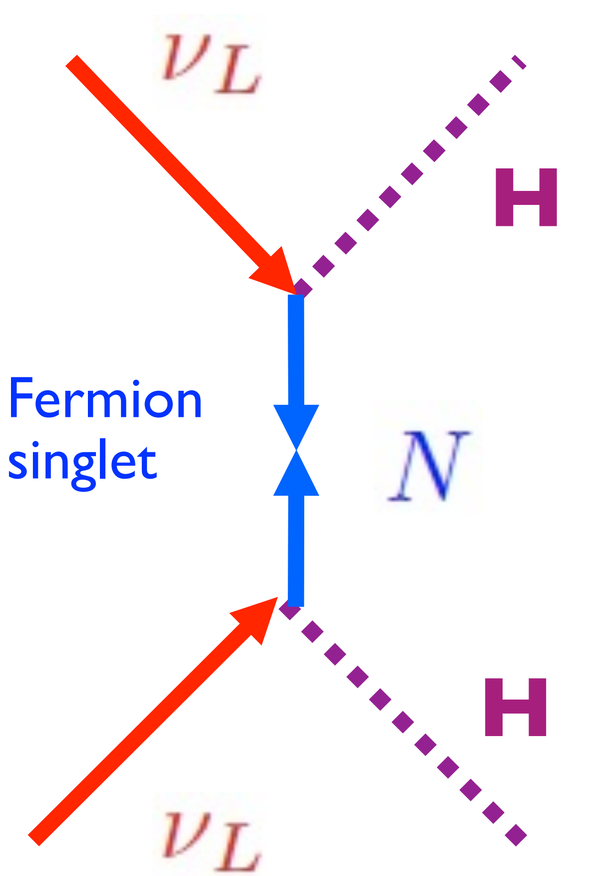
$$-\mathcal{L} = \lambda \frac{\nu_L H \, \nu_L H}{M} = \frac{\lambda v^2}{M} \nu_L^T C \nu_L$$ D=5 term



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

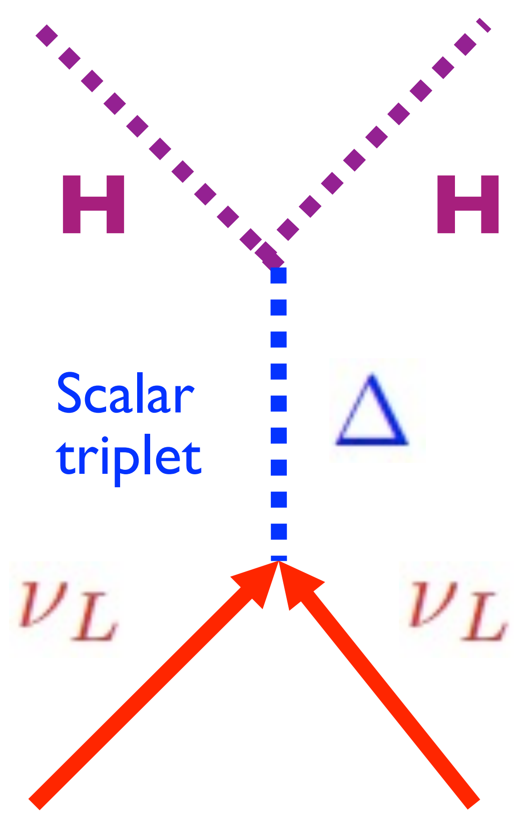
Lepton number violation!

See-saw Type I



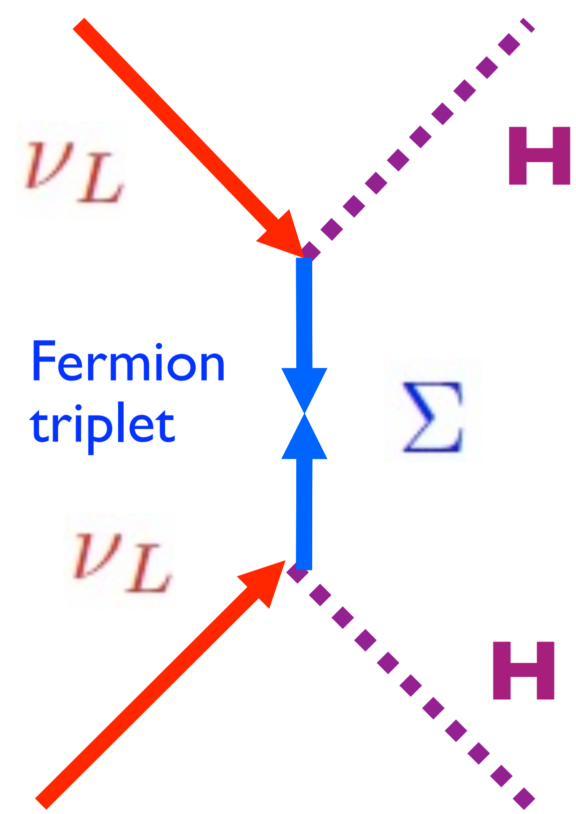
Minkowski, Yanagida, Glashow, Gell-Mann, Ramond, Slansky, Mohapatra, Senjanovic

See-saw Type II



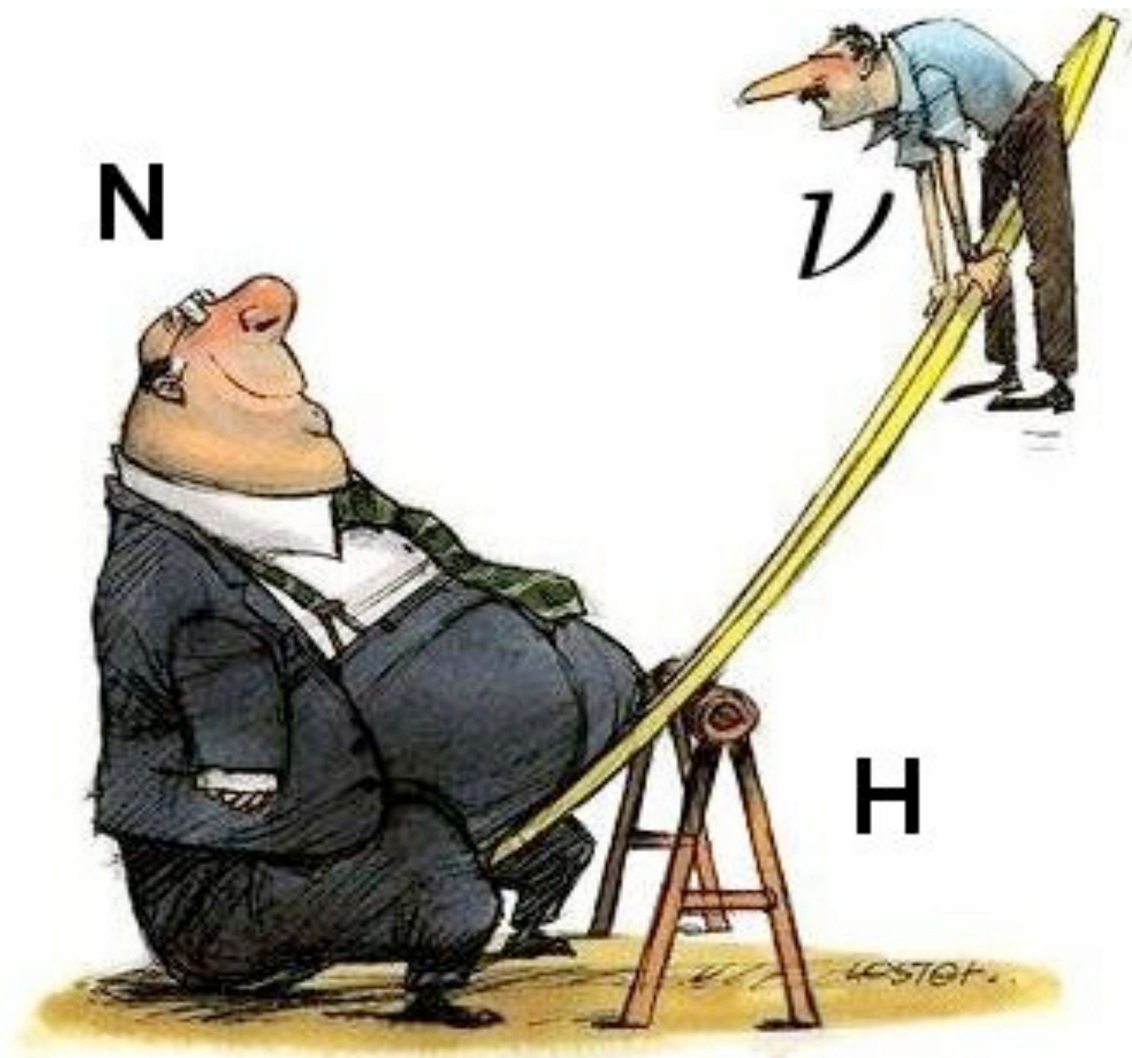
Magg, Wetterich, Lazarides, Shafi. Mohapatra, Senjanovic, Schecter, Valle

See-saw Type III



Ma, Roy, Senjanovic, Hambye

See-saw mechanism: type I at the GUT scale



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

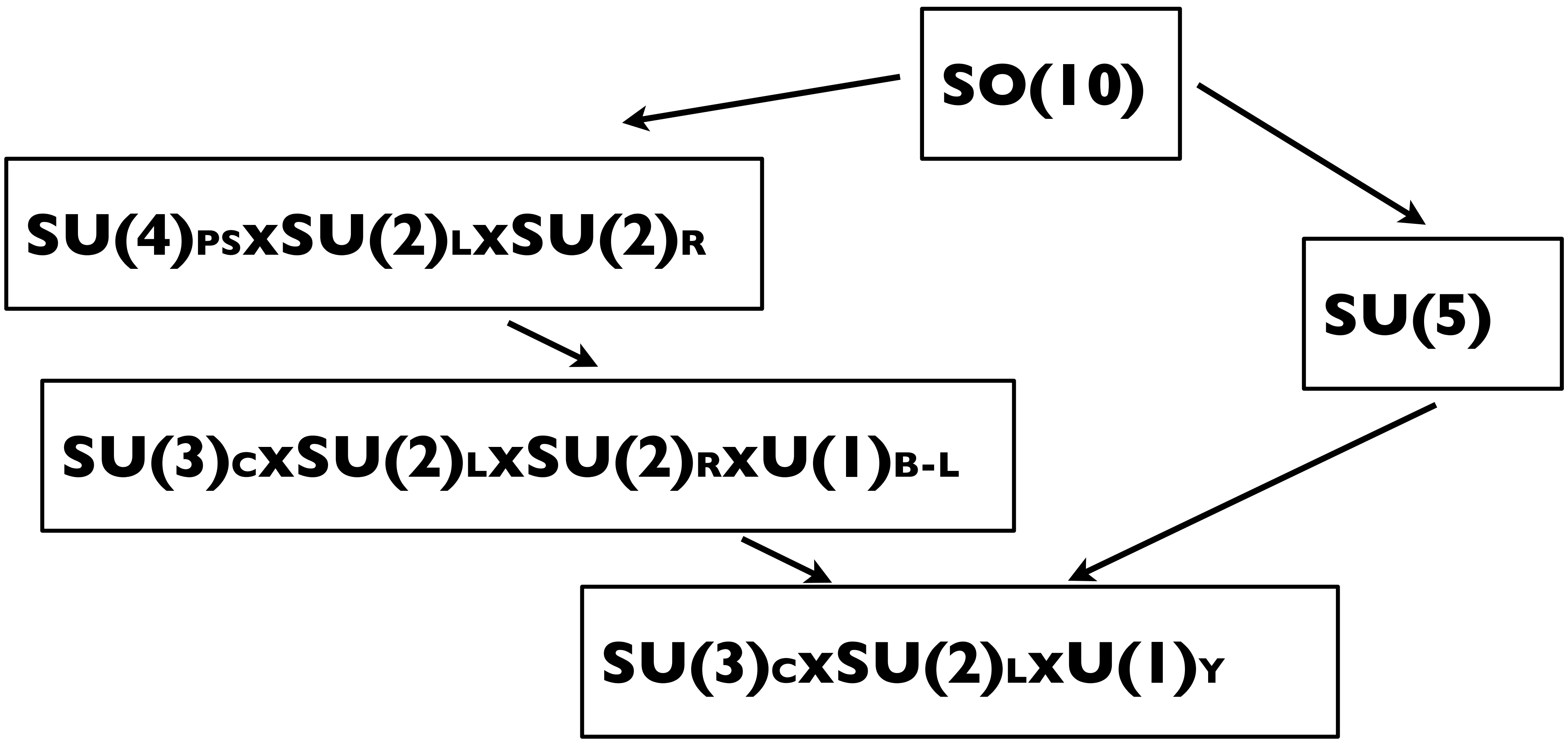
$$\mathcal{L} = -Y_\nu \bar{N} L \cdot H - 1/2 \bar{N}^c M_R N$$

$$\begin{pmatrix} 0 & m_D \\ m_D^T & M_N \end{pmatrix}$$

$$m_\nu = \frac{y_\nu^2 v_H^2}{M_N}$$

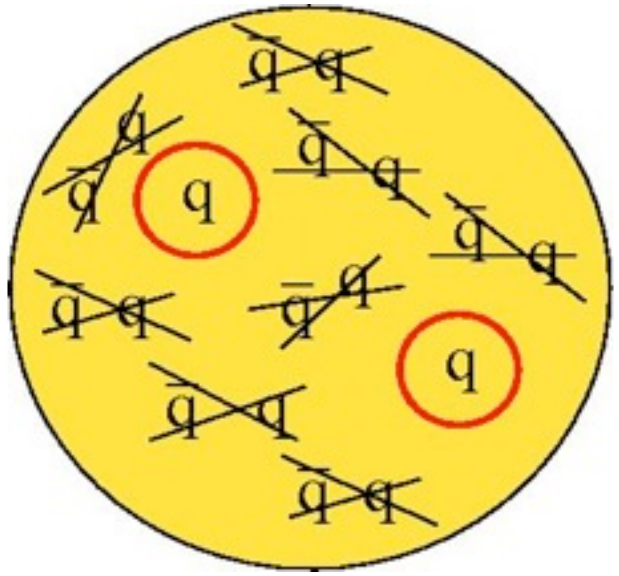
$$M_N \sim 10^{14}\ \mathrm{GeV}$$

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 relations between quark and lepton masses. Understanding the origin of neutrino masses might shed light on the physics at energy scales which could not be tested directly in any experiments.

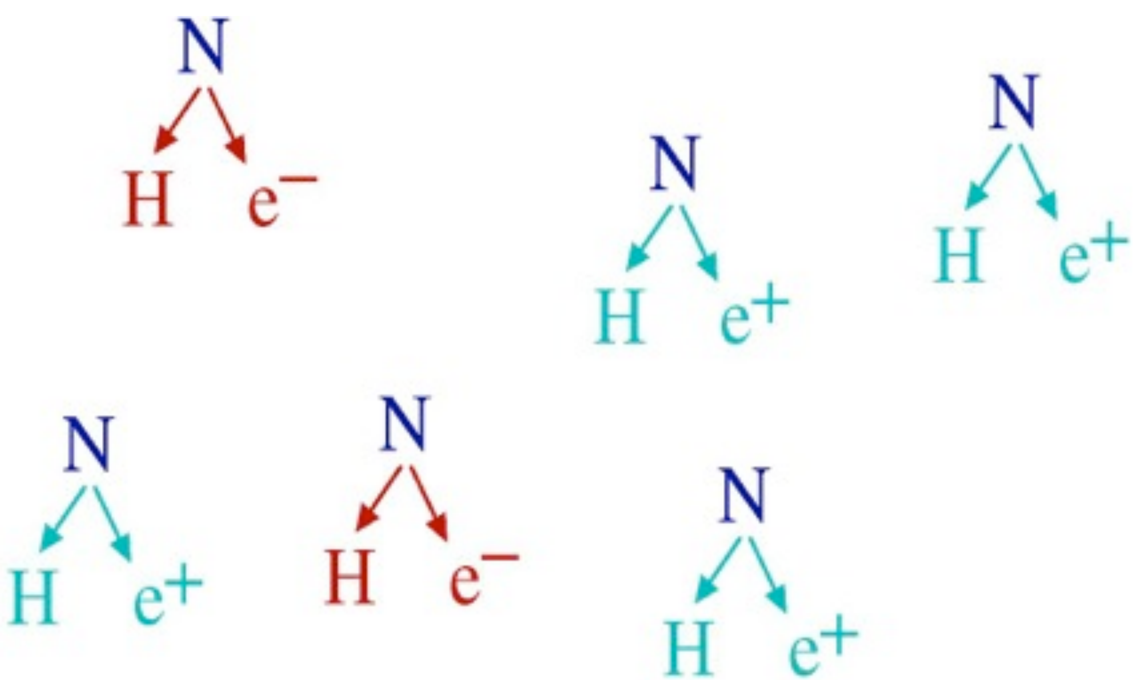
In the Early Universe



As the temperature drops, only quarks are left:

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

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

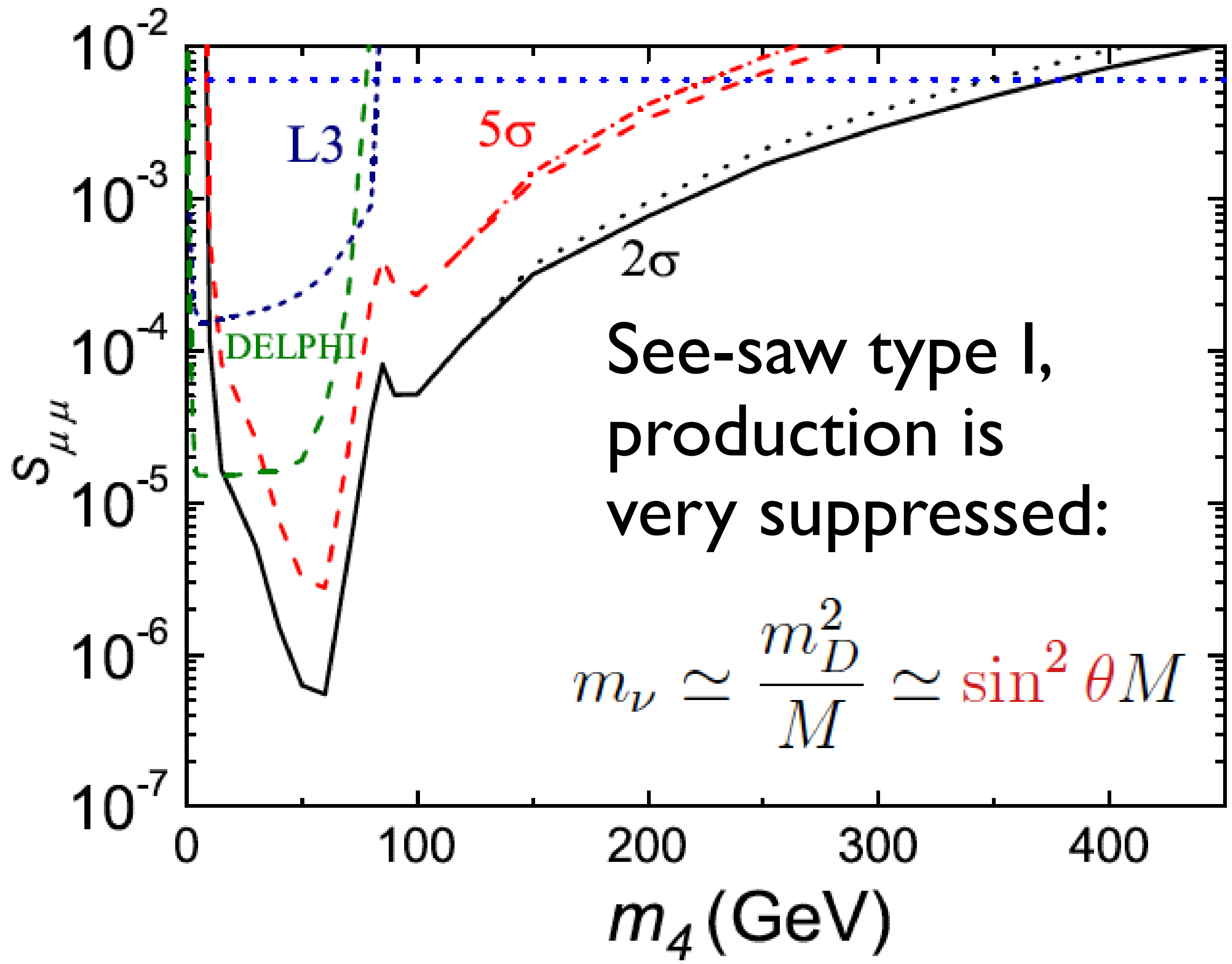


Excess of $e^+ \longrightarrow$ excess of q over $\bar{q}$

Observing L violation and CPV would constitute a **strong hint in favour of leptogenesis as the origin of the baryon asymmetry**.

Neutrino masses at the TeV scale

For smaller Yukawa couplings, small masses can arise from new physics at the TeV scale: in principle testable at the LHC by looking at same-sign dileptons.



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

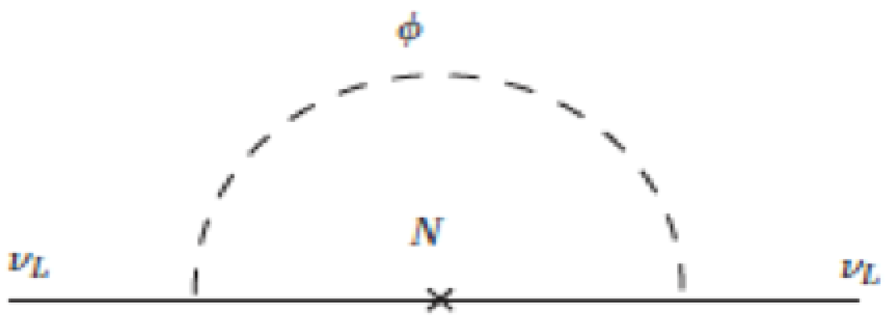
$$pp \to N^+ N^0 \to \ell_1^+ \ell_2^+ Z W^-$$

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

Other models of Neutrino Masses

There are also other possibilities for generating neutrino masses. For example

- via loops in models in which Dirac masses are forbidden



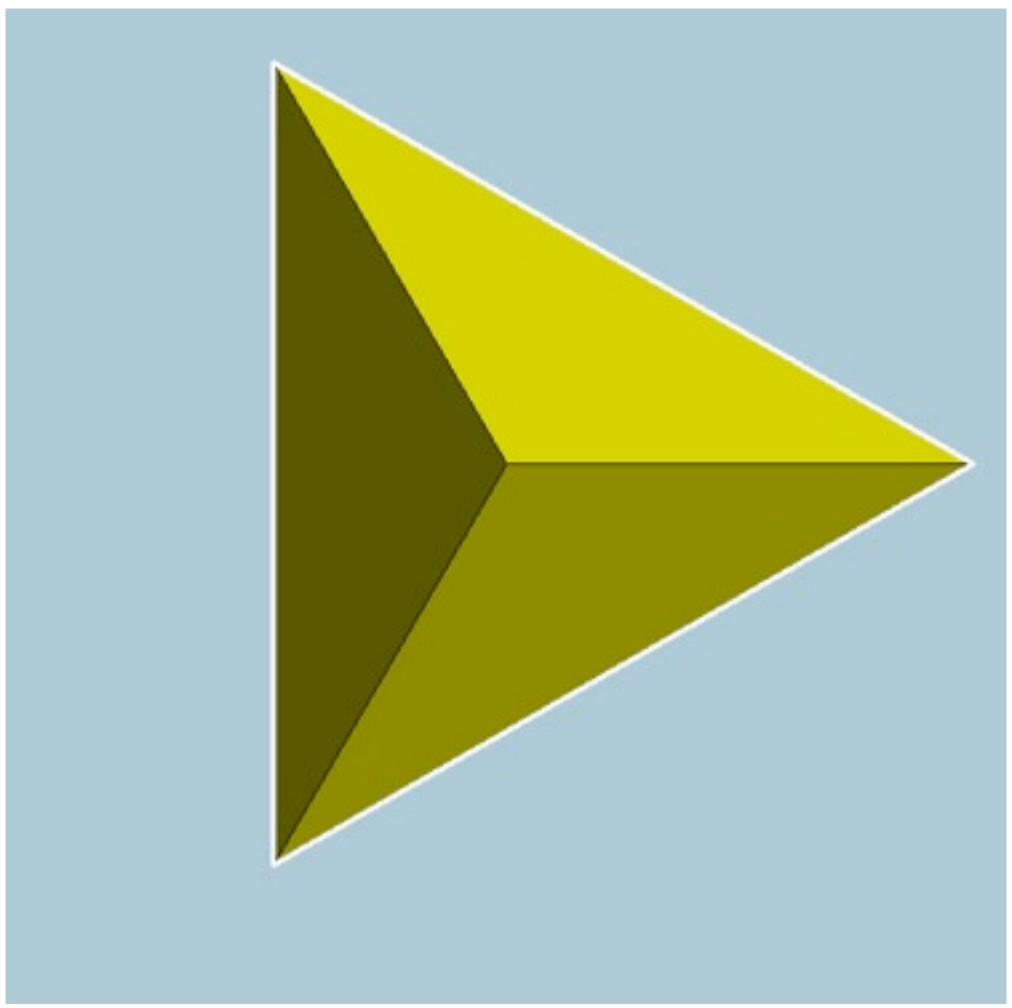
- Low energy see-saw: sterile neutrinos m<< GeV

- R-parity violating SUSY: neutrinos can mix with neutralinos

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, ...).

The problem of flavour

Mixing in the leptonic sector is very different from the quark one: angles are large (even θ_{13} !) and there can be new sources of CP-violation. Neutrinos provide a different perspective on the flavour problem.



Why three generations?

Why massive and flavour states are not the same?

Why the angles have the values measured?

What is the origin of CPV?

Trying to understand the leptonic flavour structure and its relation to the one present in the quark sector.

Tri-(bi)maximal mixing:
implies the existence of flavour symmetries, e.g. A4.

Quark-Lepton complementarity:
quark + lepton mixing ~maximal

Quark-Lepton universality:
the difference between mixing might be due to smallness of masses and mild hierarchy

Anarchy:
all entries in mass matrix of O(1)

The precise values of the mixing angles have a strong theoretical impact for understanding the flavour problem. Symmetry motivated patterns:

$$U_{BM} = \begin{pmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 \\ -\frac{1}{2} & \frac{1}{2} & \frac{1}{\sqrt{2}} \\ \frac{1}{2} & -\frac{1}{2} & \frac{1}{\sqrt{2}} \end{pmatrix} \Rightarrow \theta_{23} = 45^o, \theta_{12} = 45^o, \theta_{13} = 0$$

$$U_{TBM} = \begin{pmatrix} \frac{\sqrt{2}}{\sqrt{3}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{6}} & -\frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix} \Rightarrow \theta_{23} = 45^o, \theta_{12} \sim 35^o, \theta_{13} = 0$$

$$U_{GR} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -\frac{s_{12}}{\sqrt{2}} & -\frac{c_{12}}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \frac{s_{12}}{\sqrt{2}} & -\frac{c_{12}}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix} \Rightarrow \theta_{23} = 45^o, \theta_{12} = 32^o, \theta_{13} = 0$$

Deviation from these patterns is expected theoretically, e.g. GUTs, and is required by experimental data. Theoretical models typically lead to correlations between parameters (sum rules) or specific predictions for their values.

Conclusions

- Neutrino masses cannot be accommodated in the SM (at least in its minimal form): this is the **first particle physics evidence of physics BSM**.

- Masses are much smaller than those of other fermions. Mixing is large, differently from the quark sector.

- Understanding the origin of neutrino masses will shed light on the physics beyond the standard model possibly at scales which might not be tested in direct experiments or in models reachable at the LHC.

Connecting masses and mixing

In some models, the masses (and the type of neutrino mass hierarchy) can be connected to the mixing. For example

$$m_\nu = m_0 \begin{pmatrix} \epsilon & \epsilon & \epsilon \\ \epsilon & 1+\epsilon & 1 \\ \epsilon & 1 & 1 \end{pmatrix}$$

Normal mass hierarchy

maximal θ_{23}, large θ_{12}

$\epsilon \sim \lambda$

$$m_\nu = m_0 \begin{pmatrix} \epsilon & c_{23} & s_{23} \\ c_{23} & \epsilon & \epsilon \\ s_{23} & \epsilon & \epsilon \end{pmatrix}$$

Inverted mass hierarchy

maximal θ_{23}, large θ_{12}

$L_e - L_\mu - L_\tau$

Determining the mass hierarchy and the values of angles is of critical importance to understand the physics BSM.

Predictions for betabeta decay

The predictions for |<m>| depend on the neutrino mass spectrum

- NH (m1<<m2<<m3): |<m>| ~ 2.5-3.9 meV

$$|<m>| \simeq \left| \sqrt{\Delta m^2_\odot} \cos^2\theta_{13} \sin^2\theta_\odot + \sqrt{\Delta m^2_{\mathrm{atm}}} \sin^2\theta_{13} e^{i\alpha_{32}} \right|$$

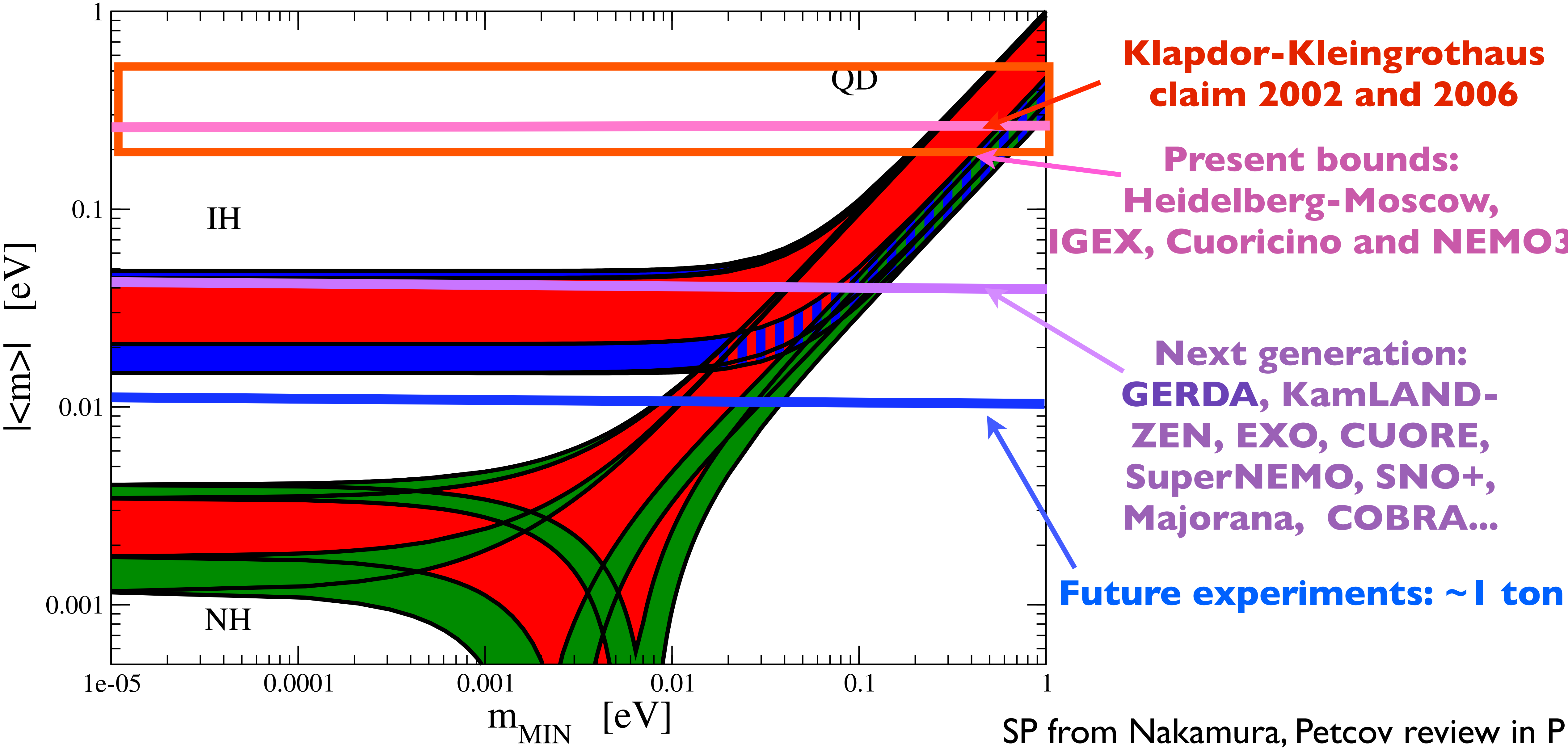
- IH (m3<<m1~m2): 10 meV < |<m>| < 50 meV

$$\sqrt{\Delta m^2_{\mathrm{atm}}} \cos 2\theta_\odot \leq |<m>| \simeq \sqrt{\left(1 - \sin^2 2\theta_\odot \sin^2\frac{\alpha_{21}}{2}\right)\Delta m^2_{\mathrm{atm}}} \leq \sqrt{\Delta m^2_{\mathrm{atm}}}$$

- QD (m1~m2~m3): 44 meV < |<m>| < m1

$$|<m>| \simeq m_{\bar{\nu}_e} \left| \left(\cos^2\theta_\odot + \sin^2\theta_\odot e^{i\alpha_{21}}\right) \cos^2\theta_{13} + \sin^2\theta_{13} e^{i\alpha_{31}} \right|$$

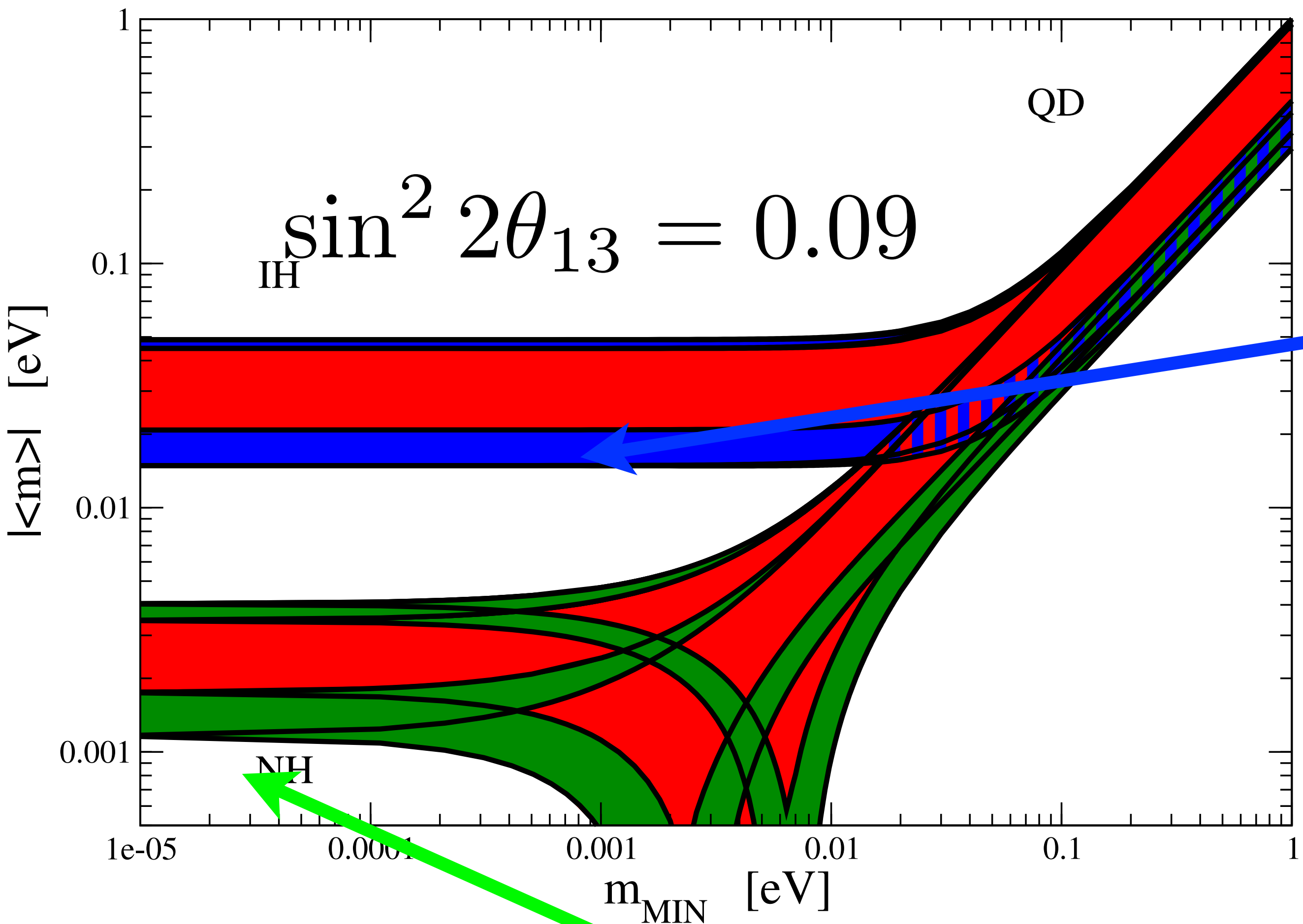
$$|\langle m\rangle| \sim |m_1 \cos^2\theta_{12} + m_2 \sin^2\theta_{12} e^{i\alpha_{21}} + m_3 \sin^2\theta_{13} e^{i\alpha_{31}}|$$

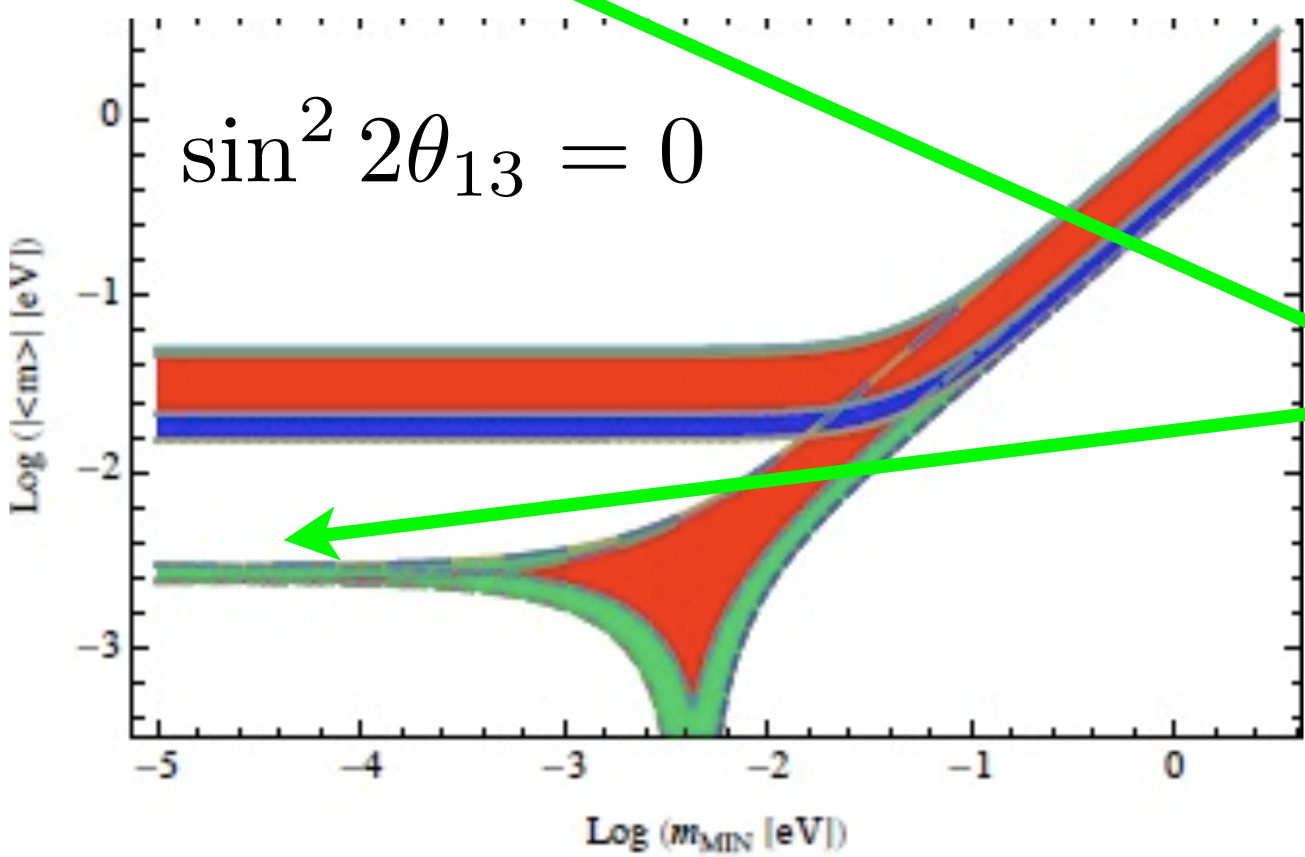


SP from Nakamura, Petcov review in PDG

Wide experimental program for the future: **a positive signal would indicate that L is violated!**

Dependence on the oscillation parameters



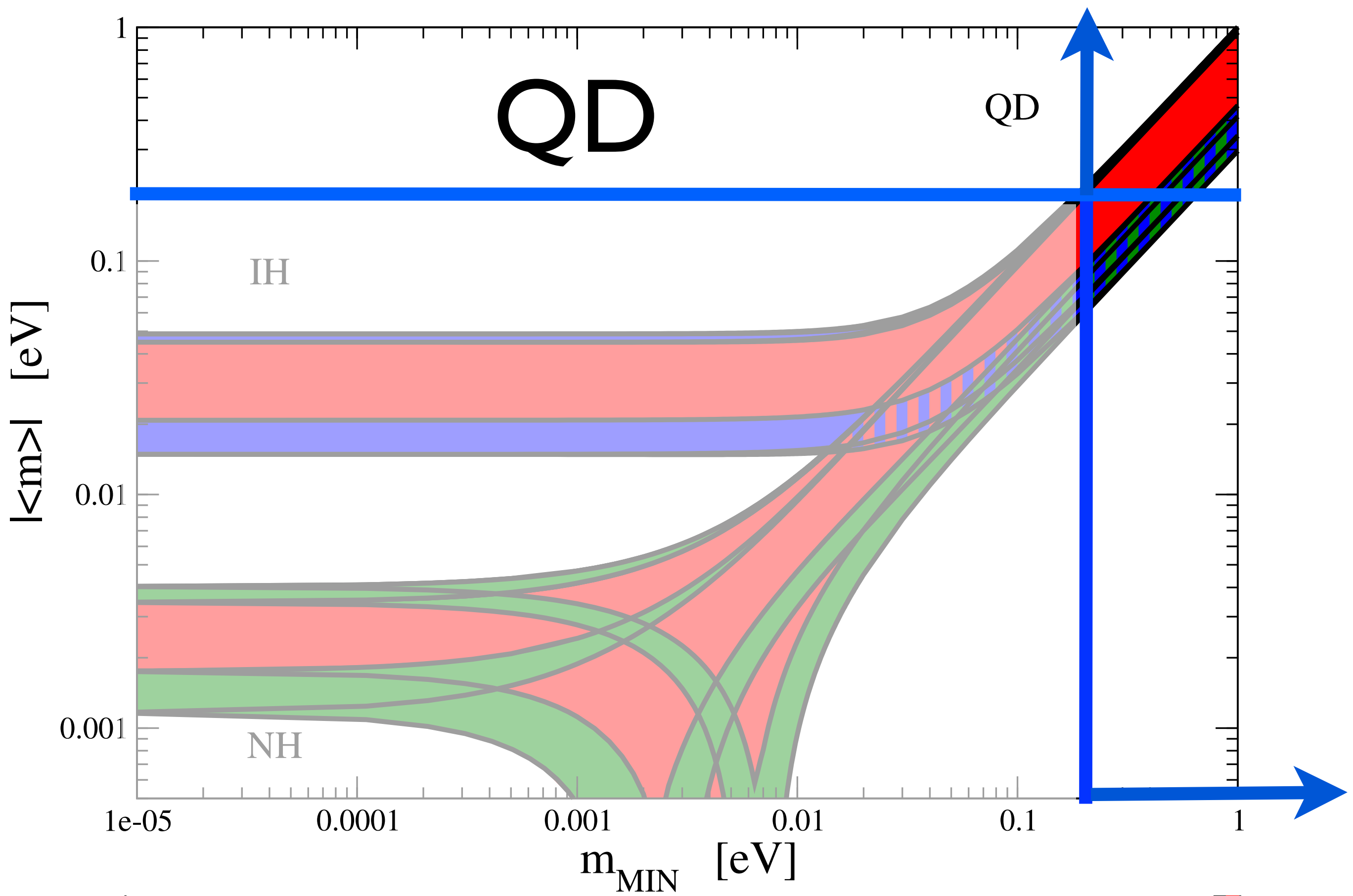


- $\cos 2\theta_{12}$ controls this term:

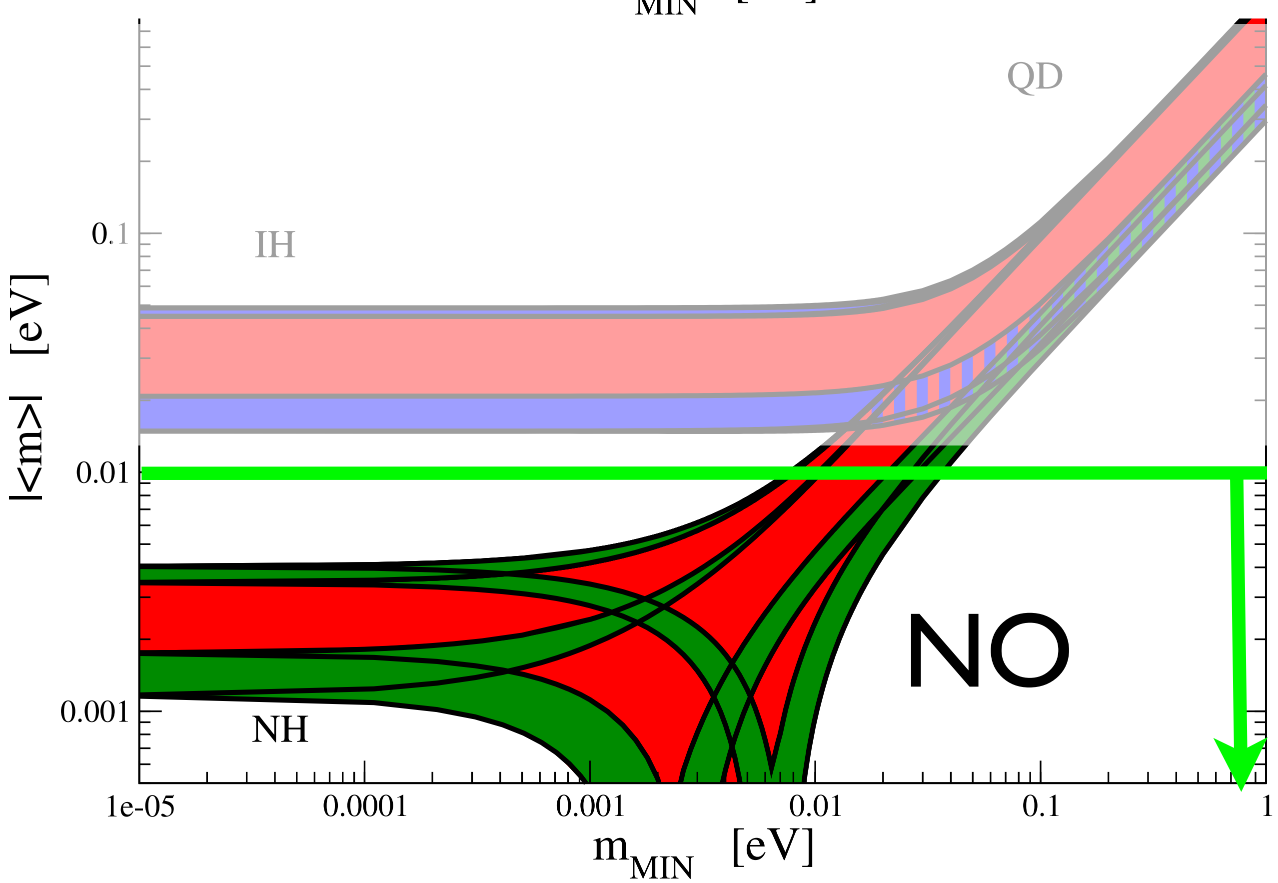
$$|\langle m\rangle|_{\min} = \sqrt{\Delta m^2_{31}}\cos 2\theta_{12}$$

- θ_{13} determines the cancellation in the NH spectrum and consequently the minimal value of |<m>|.

Determining neutrino masses with neutrinoless dbeta decay



- If |<m>| > 0.2 eV, then the neutrino spectrum is QD. The measurement of m1 is entangled with the value of the Majorana phase.

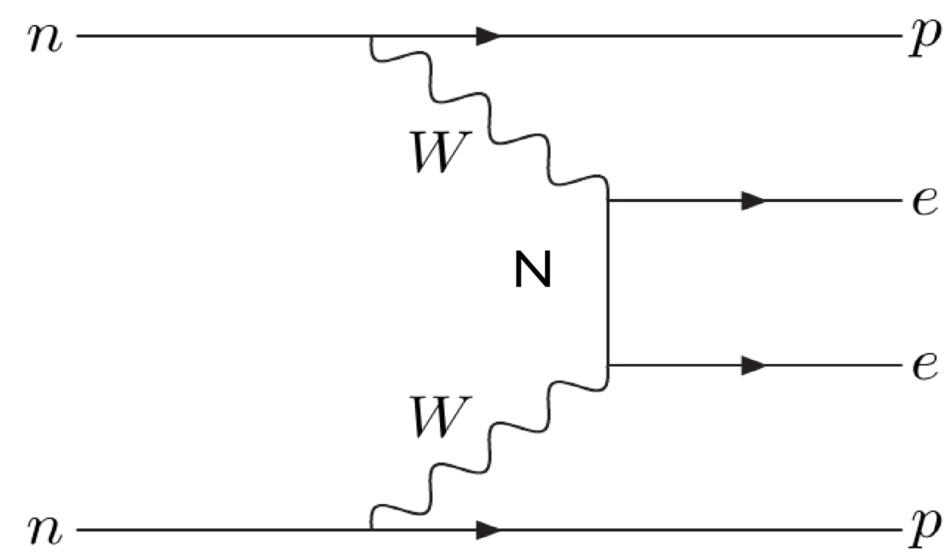


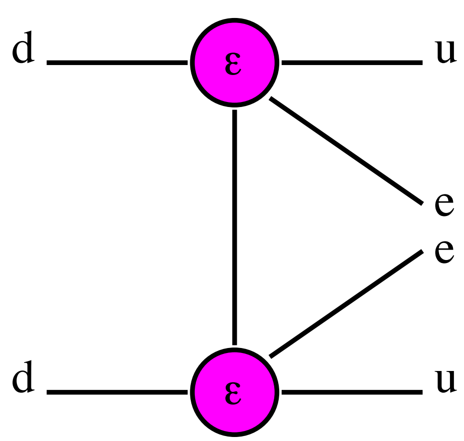
- • If no signal for |<m>| ~10 meV, then only NO is allowed.
  • If LBL experiments find IO, neutrino are Dirac particles (without fine-tuned cancellations).

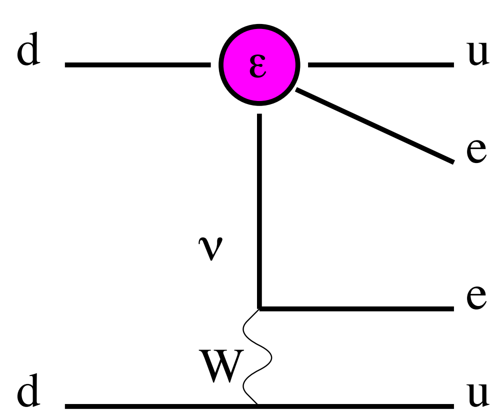
Other mechanisms

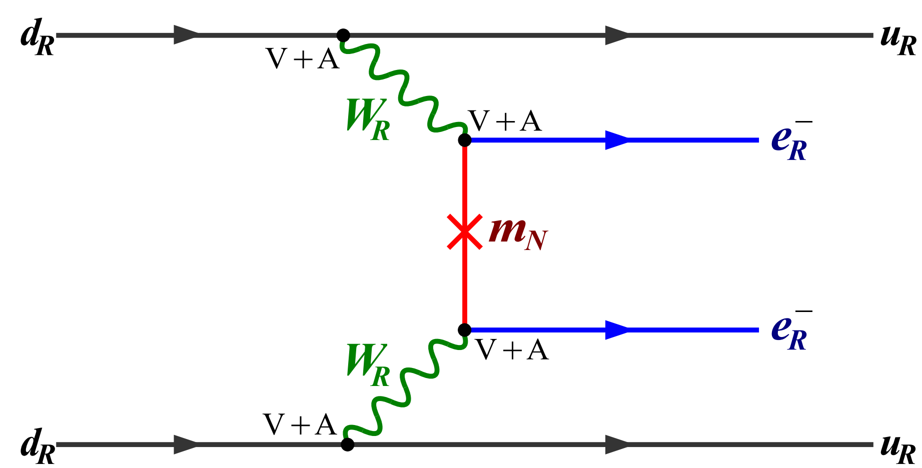
Neutrinoless double beta decay can also be mediated by other LNV mechanisms.

- Light sterile neutrinos
- Heavy sterile neutrinos
- R-parity violating SUSY
- Extra dimensional models
- Left-Right models





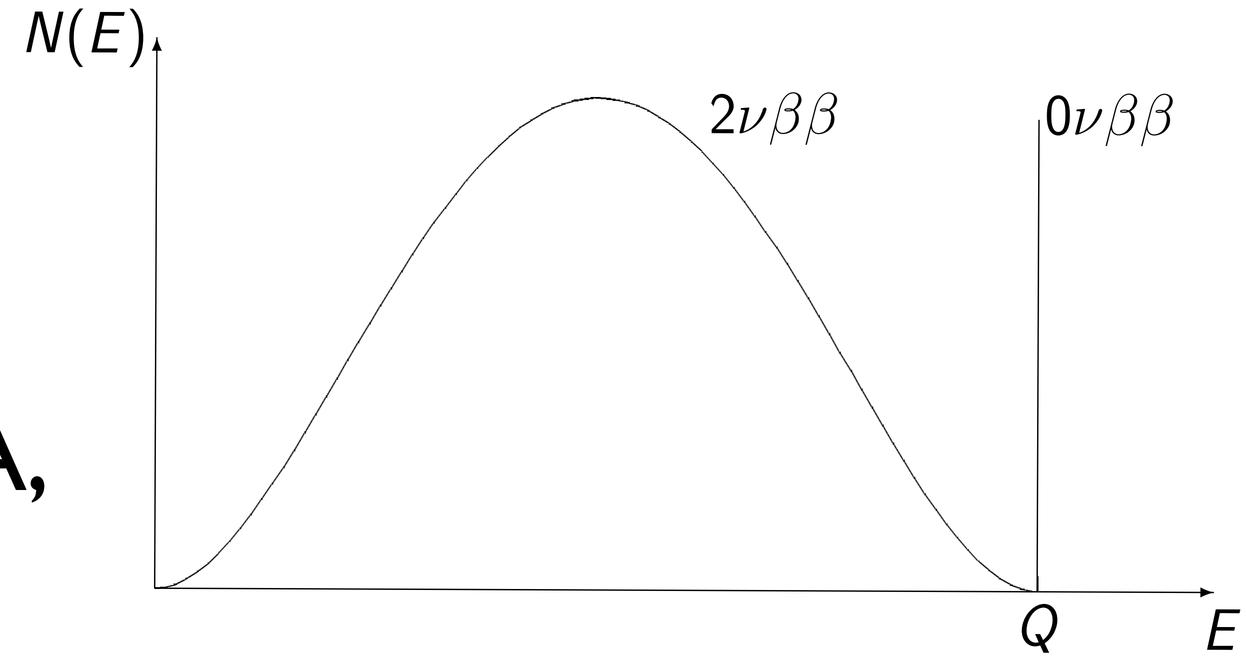




Deppisch, Hirsch, Pas, 1208.0727

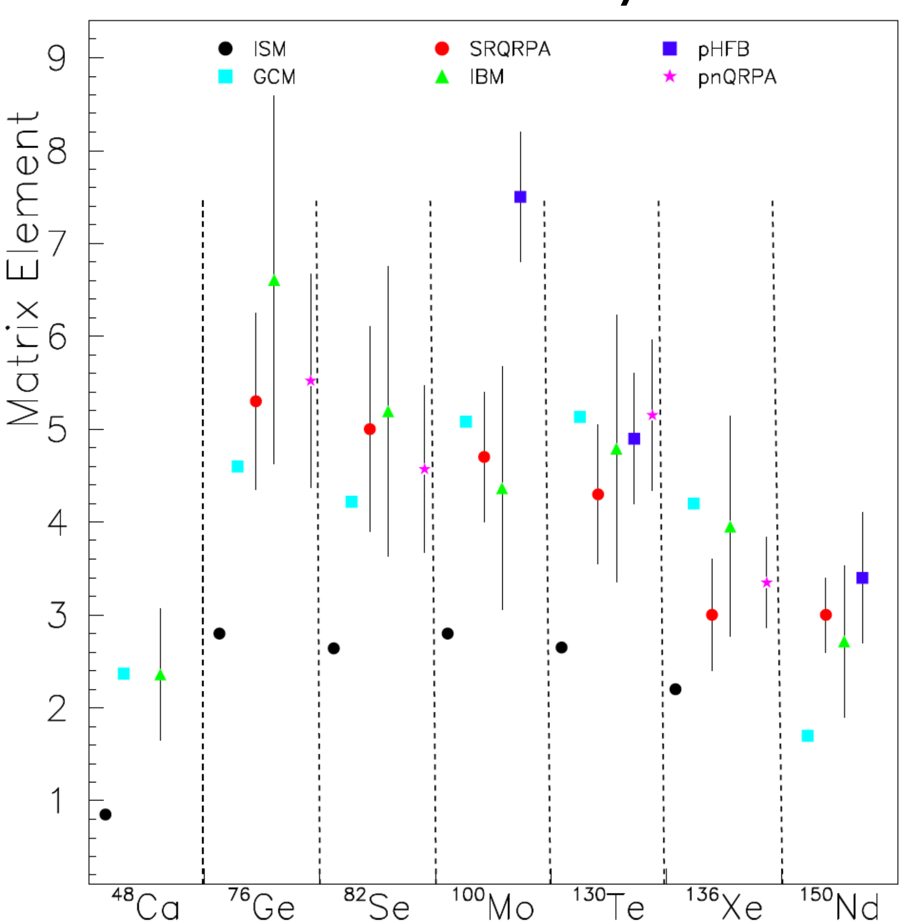
Experimental searches of betabeta decay

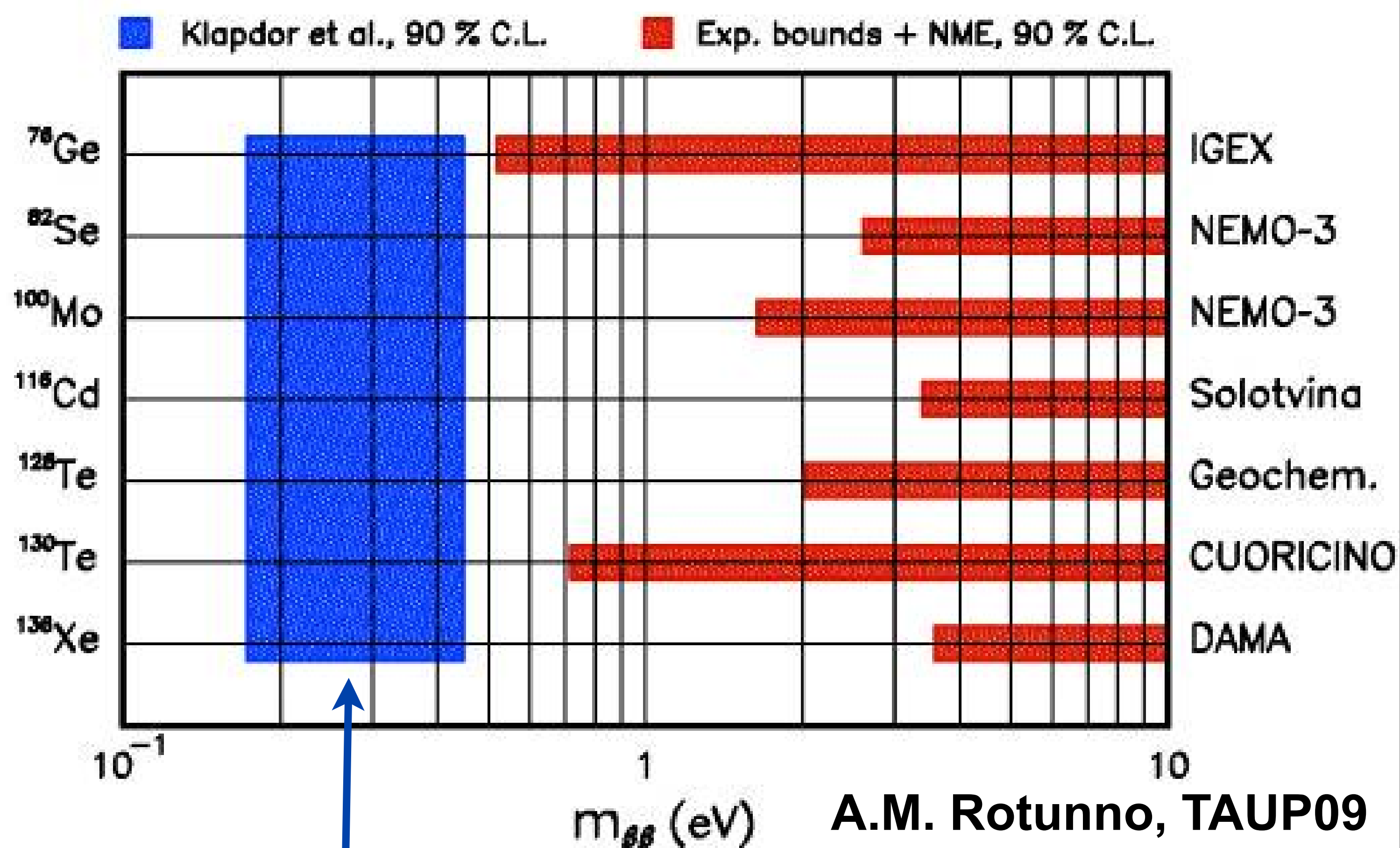
Neutrinoless double beta decay proceeds in nuclei in which single beta decay is kinematically forbidden but double beta decay (A, Z) → (A, Z+2) + 2 e + 2 v is allowed.



NMEs

B. Schwingenheuer, Annalen der Physik, 2012

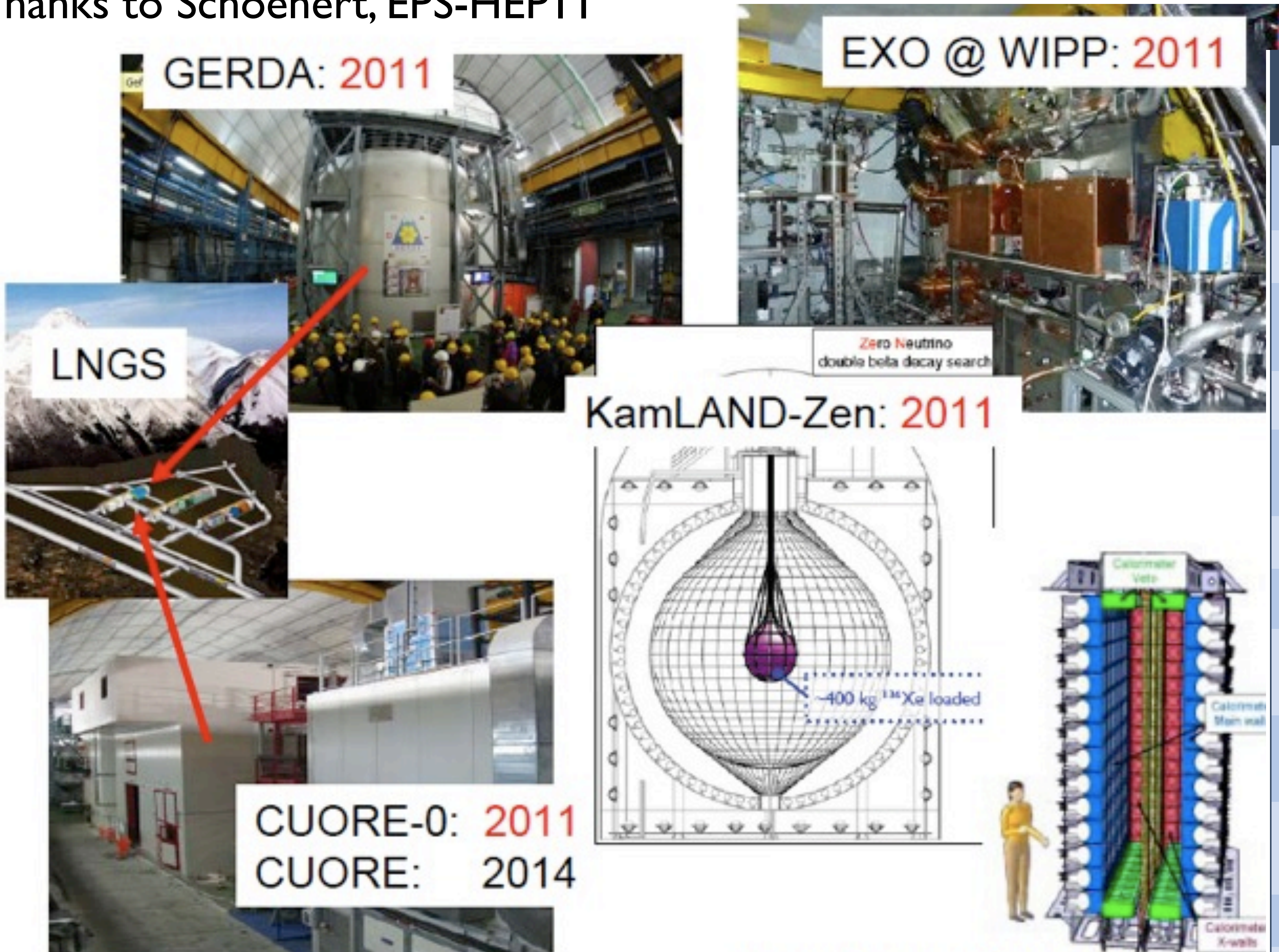




A.M. Rotunno, TAUP09

Depending on treatment of background, from 4.2 to 1.3 sigma

Thanks to Schoenert, EPS-HEP11



Super-Nemo @ LSM:
Demonstrator2014

The new generation of experiments is already taking data or nearly ready (e.g., EXO, KamLAND-ZEN, CUORE, GERDA,...) and more powerful ones are planned for the future (e.g., NExT, SNO+, SuperNEMO, COBRA,...)!!

Table 3 Selection of $0\nu\beta\beta$ experiments.

experiment	isotope	mass [kg]	method	start / end
		past experiments		
Heidelberg-Moscow	^{76}Ge	11	ionization	-2003
Cuoricino	^{130}Te	11	bolometer	-2008
NEMO-3	^{100}Mo, ^{82}Se	7,1	track. +calorim.	-2011
		current experiments		
EXO-200	^{136}Xe	175	liquid TPC	2011-
Kamland-Zen	^{136}Xe	330	liquid scintil.	2011-
GERDA-I/ GERDA-II	^{76}Ge	15/35	ionization	2011-/ 2013-
CANDLES	^{48}Ca	0.35	scint. crystal	2011-
		funded experiments		
NEXT	^{136}Xe	100	gas TPC	2015
Cuore0/ Cuore	^{130}Te	10/200	bolometer	2012- 2015-
Majorana Demo.	^{76}Ge	30	ionization	2013
SuperNEMO demo./total	^{82}Se	7/100	track.+calorin	2014- /??
SNO+	^{150}Nd	44	liquid scint.	2013

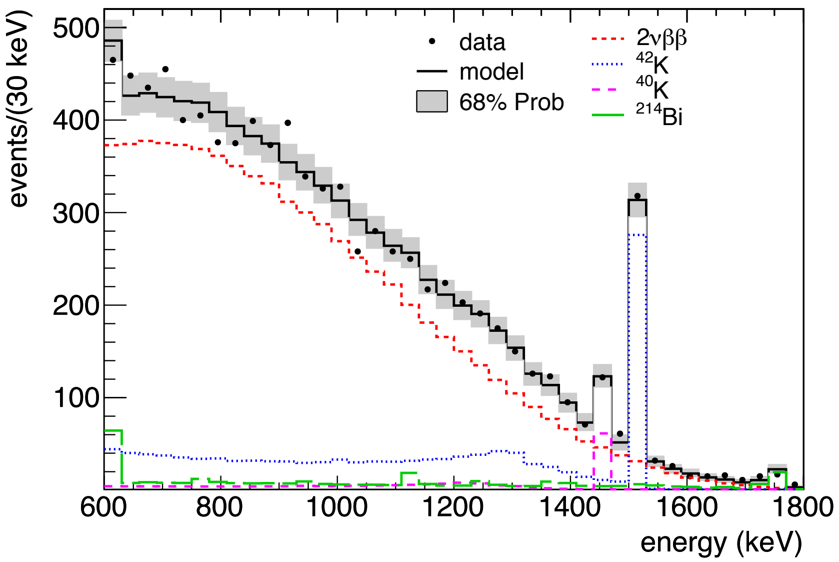
B. Schwingenheuer, Annalen der Physik, 2012

GERDA

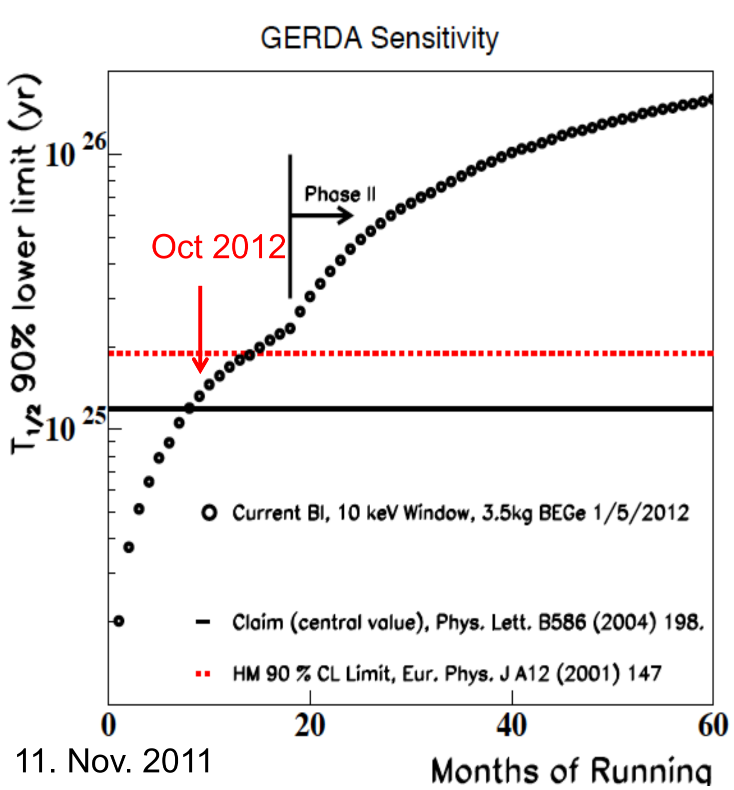
The GERmanium Detector Array

Phase	I	II
Exposure [kg ·yr]	15	100
Bg [counts/(keV·kg·yr)]	10^{-2}	10^{-3}
Upper limit $m_{\beta\beta}$ [eV]	0.23-0.39	0.09-0.15

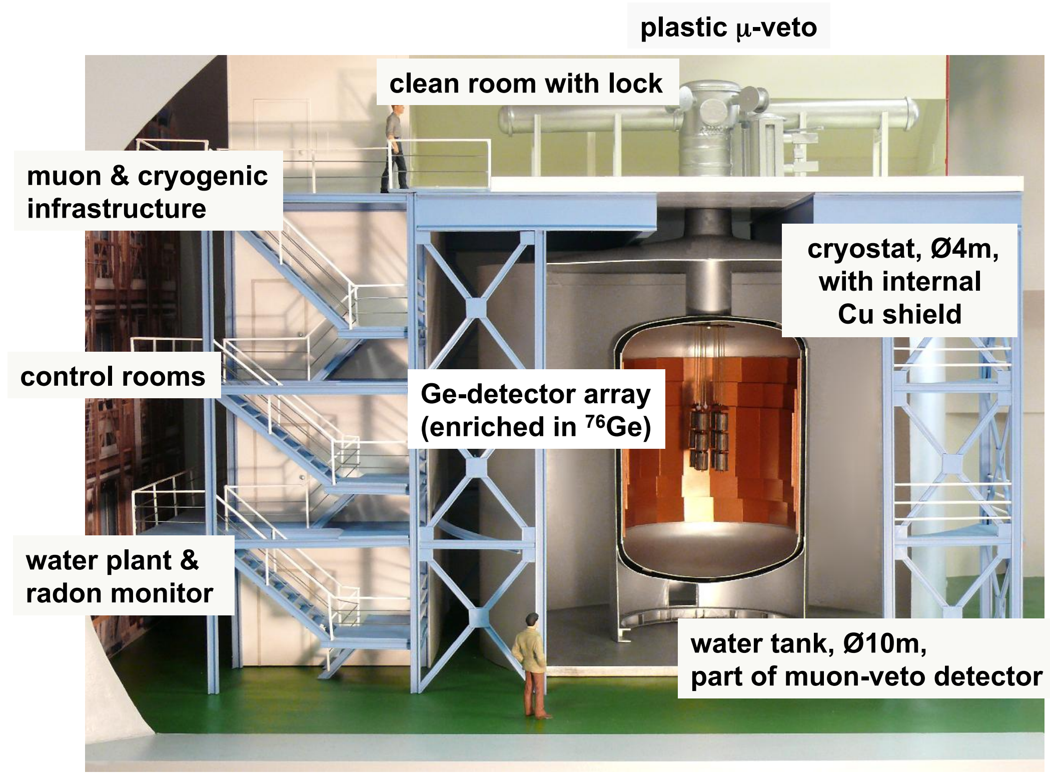
A. Smolnikov, P. Grabmayr PRC 81 028502(2010)



$T^{2\nu}_{1/2} = (1.88 \pm 0.10) \cdot 10^{21}$ yr (5.04 kg·yr)



11. Nov. 2011



GERDA. On Jul 6, 5 Ge diodes deployed at LNGS.

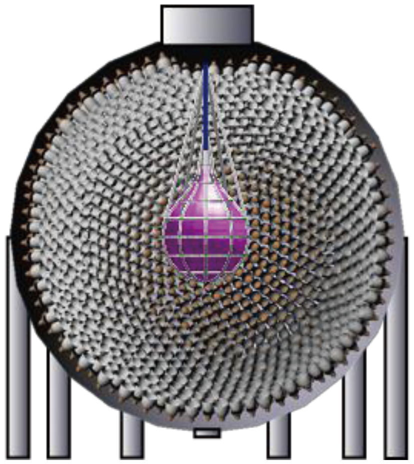
F. Cossavella, 16/10/12

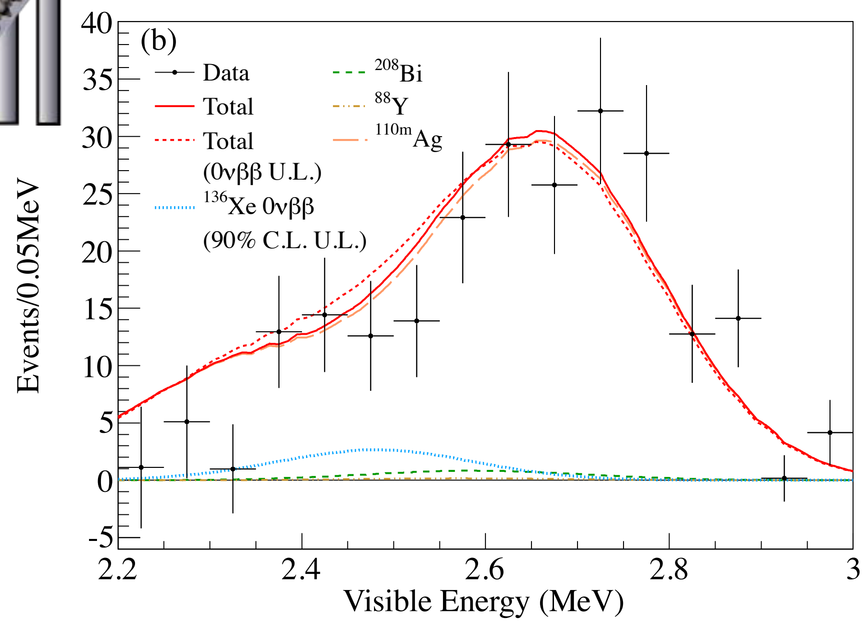
CUORE-0

From M. Pedretti, Neutrino 2012

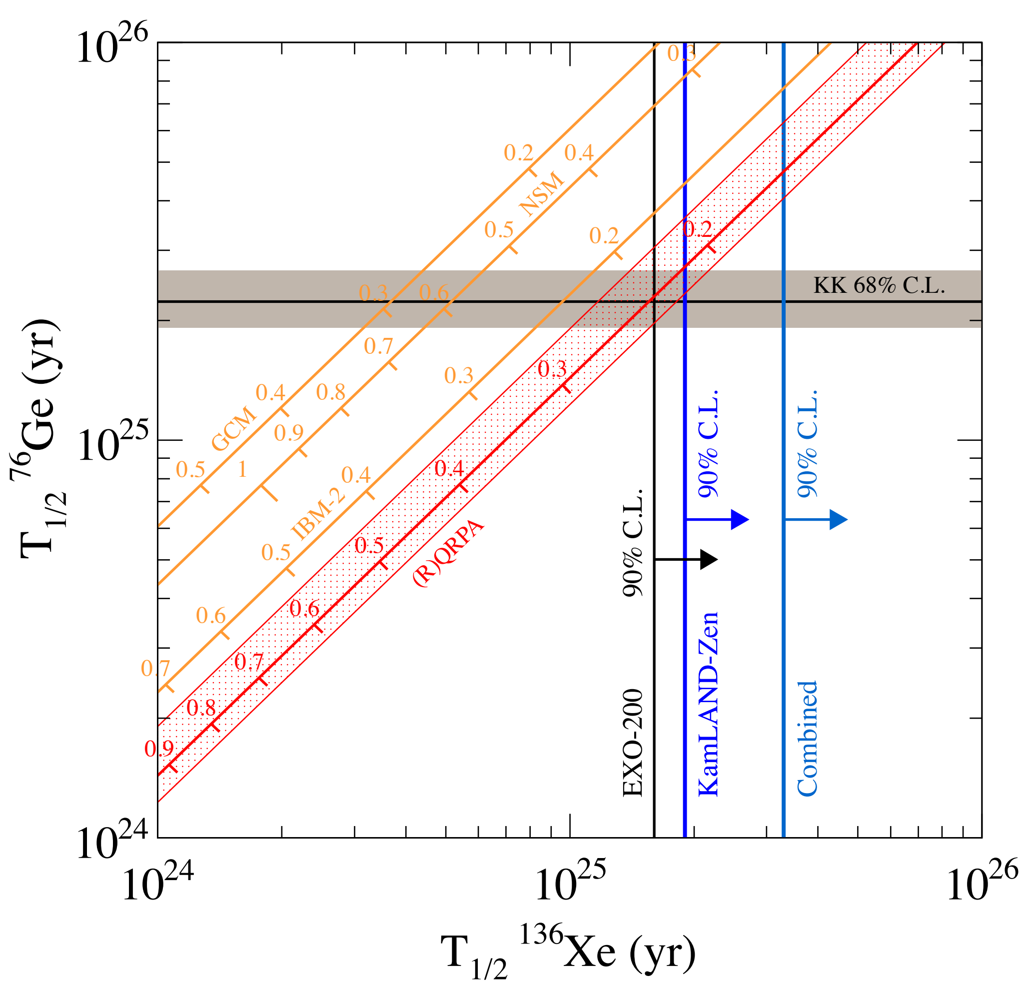
CUORE-0: the detector will consist of a complete CUORE tower: 52 TeO_2 cubic crystal absorbers, encapsulated in a dedicated copper shield at LNGS.

KamLAND-Zen





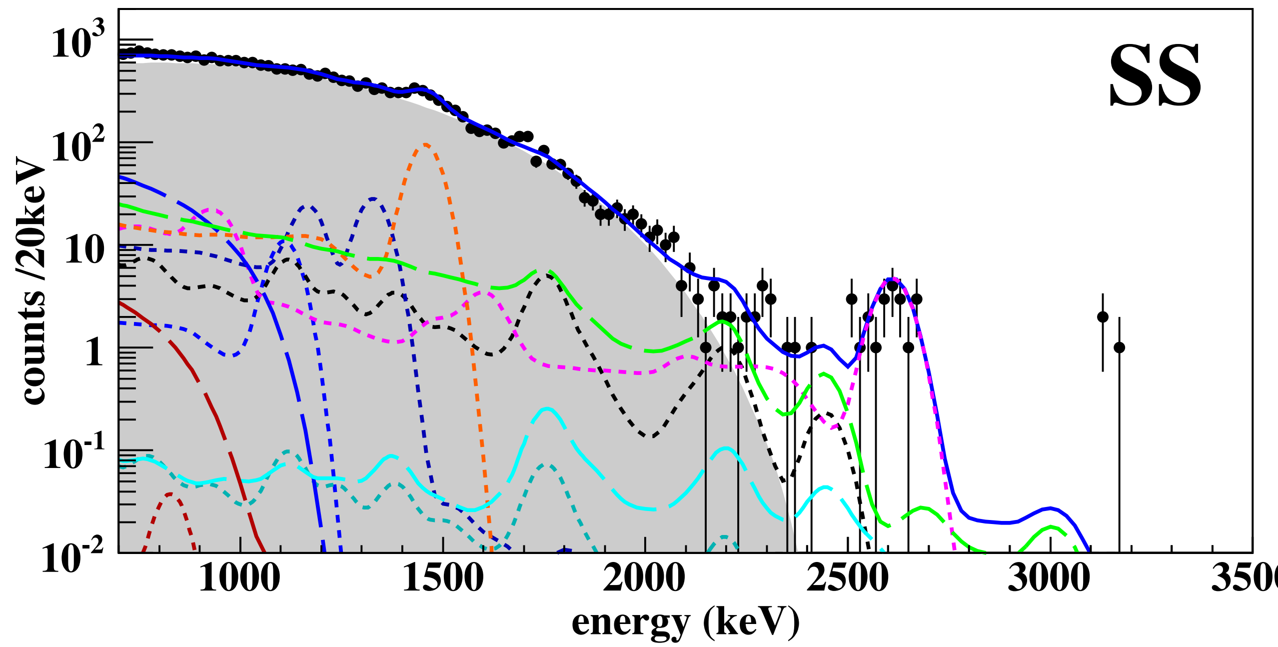
1211.3863



EXO

EXO-200 location, at the WIPP Site, USA, 1585 m.w.e.

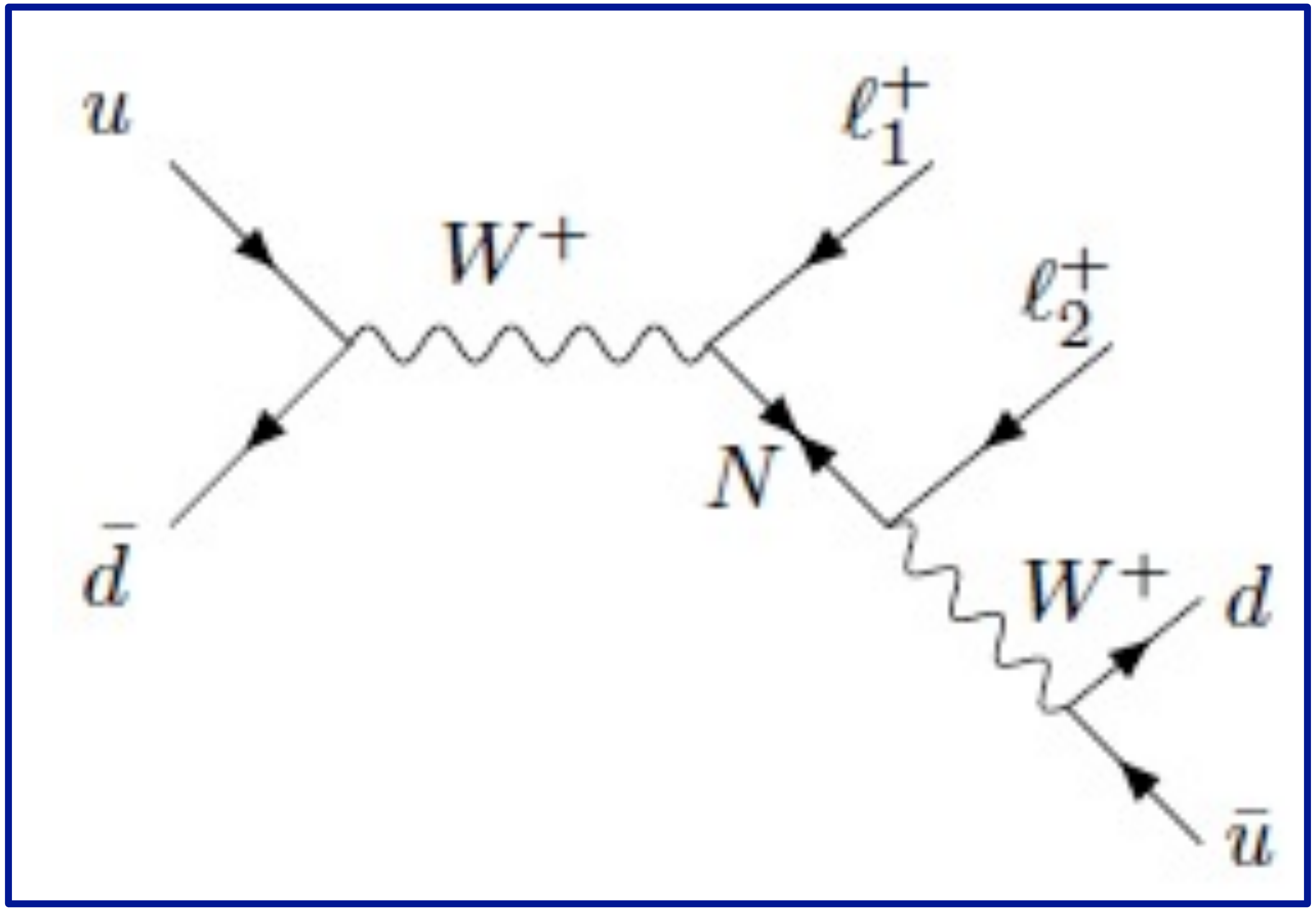
1205.5608



EXO-200 reported the first results last summer, T(0nu) >1.6 10^25 yrs for Xe136 and KamLAND-Zen last week: T(0nu) >1.9 10^25 yrs.

Collider searches

In colliders, the dominant mechanism due to mixing is

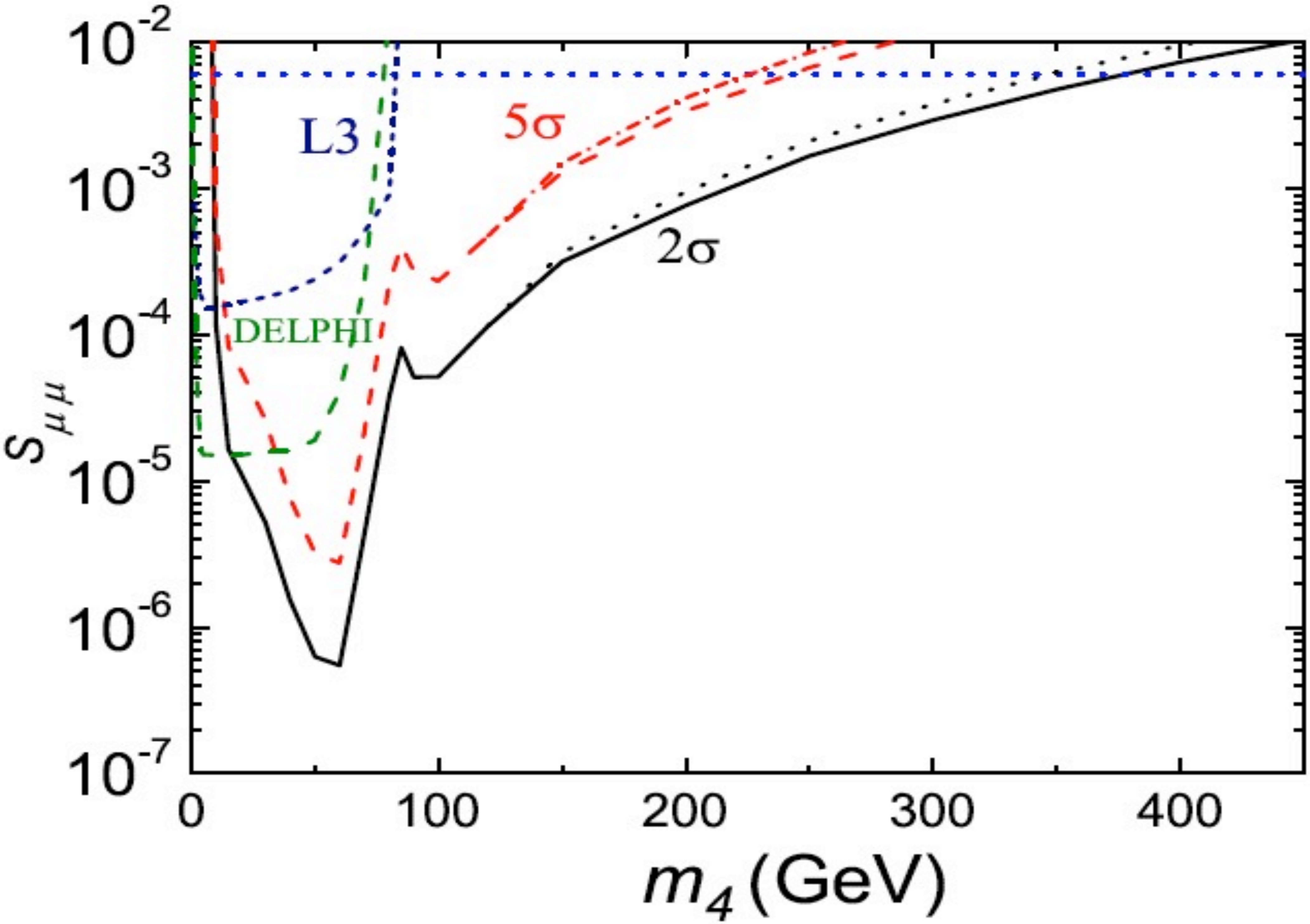


where N goes on resonance and the cross section for the process can be approximated as

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

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

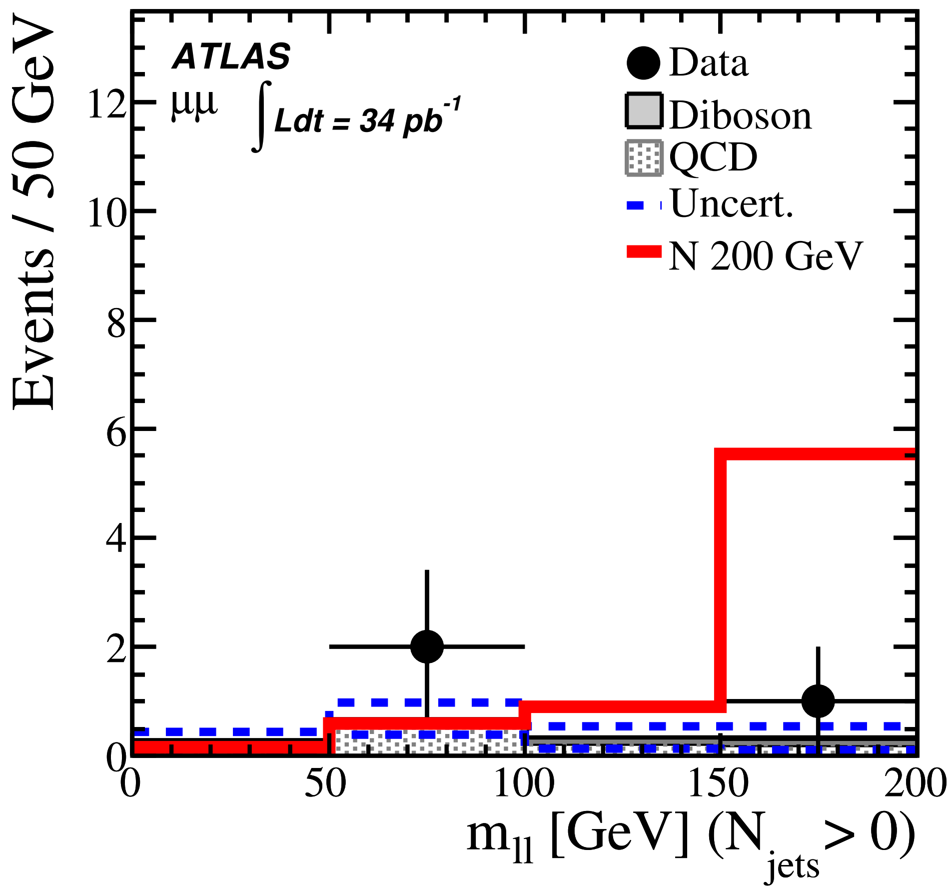
Sensitivity reachable at LHC

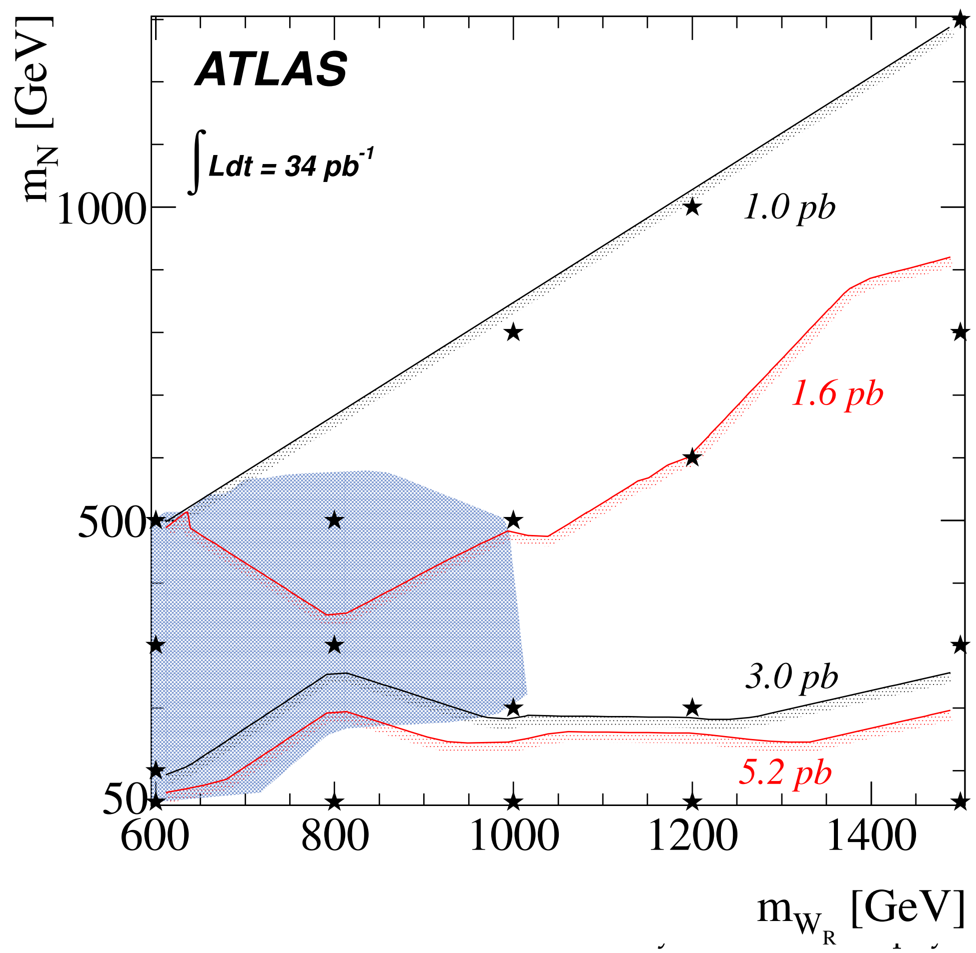


Atre et al., 0901.3589

Luminosity: 100 fb $^{-1}$.

Current limits from LHC





LHC at
E=7 TeV

ATLAS, 1108.0366

CMS, 1104.3168

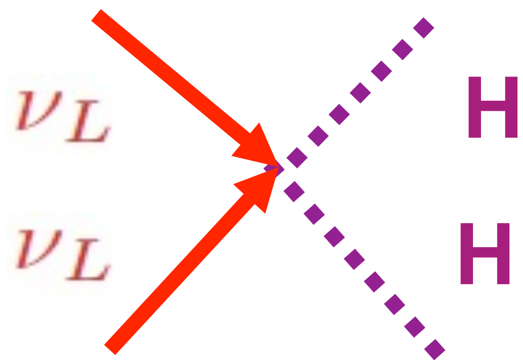
Luminosity: ATLAS 34 pb $^{-1}$
CMS 35 pb $^{-1}$

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.

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	$\mathbf{0.23^{+0.35}_{-0.23}}$	$\mathbf{0.23^{+0.26}_{-0.23}}$	$\mathbf{0.74 \pm 0.55}$	$\mathbf{1.2 \pm 0.8}$
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**

LNV and neutrino masses

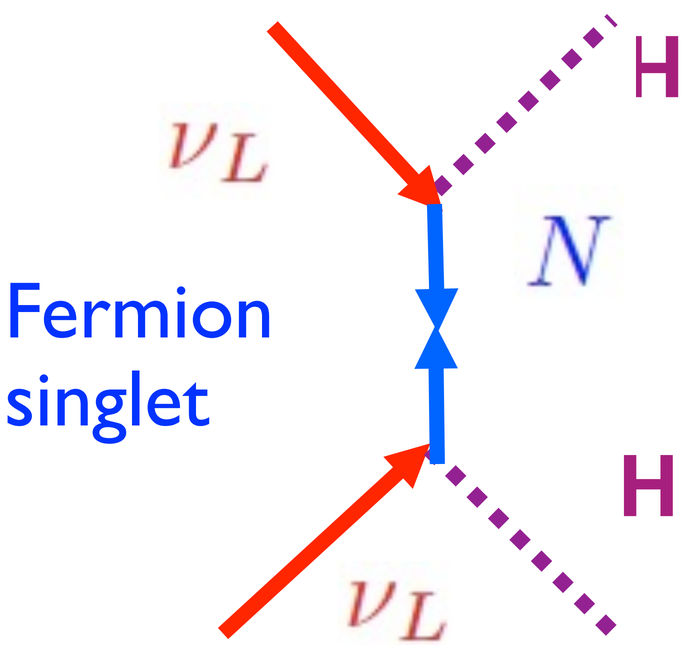
Majorana masses violate lepton number and conversely lepton number violation leads to Majorana masses.



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

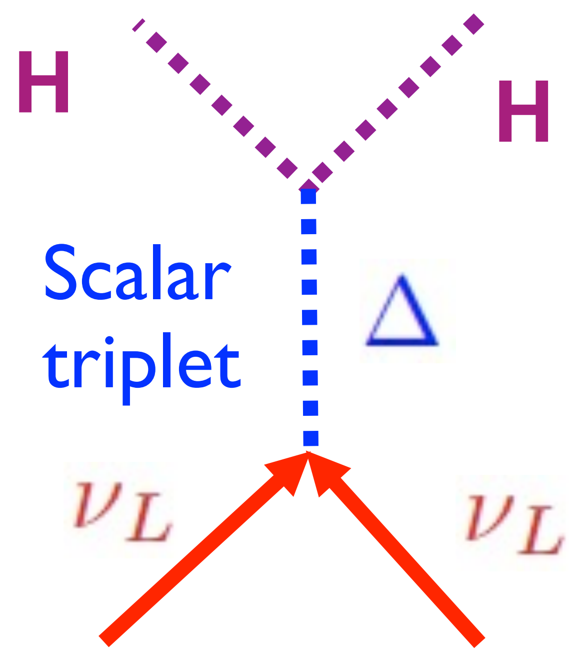
Lepton number violation!

See-saw Type I



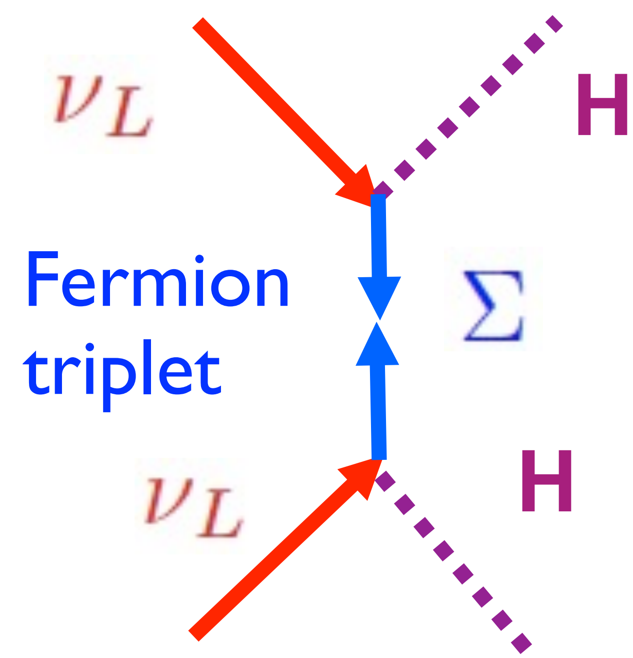
Minkowski, Yanagida, Glashow, Gell-Mann, Ramond, Slansky, Mohapatra, Senjanovic

See-saw Type II



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

See-saw Type III



Ma, Roy, Senjanovic, Hambye

For see-saw type I: $\mathcal{L} = -Y_\nu \bar{N} L \cdot H - 1/2 \bar{N}^c M_R N$

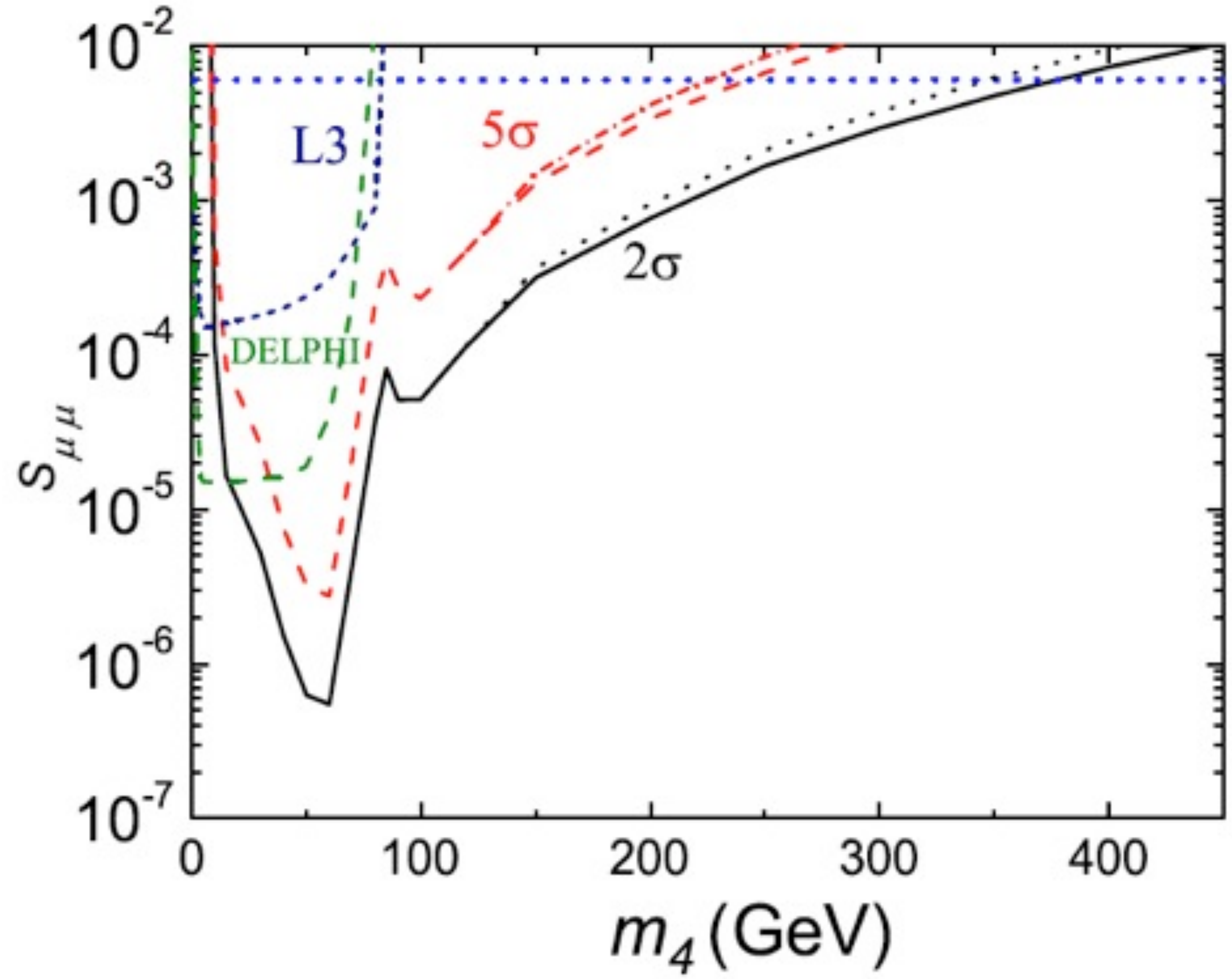
$$\mathcal{L} = \left(\nu_L^T N^T\right) \begin{pmatrix} 0 & m_D \\ m_D^T & M \end{pmatrix} \begin{pmatrix} \nu_L \\ N \end{pmatrix}$$

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; Mitra et al.

N production can be large if Ns have other interactions.
With 3 N, B-L can be gauged and N can be produced via Z'.
Other models: triplet see-saw, loop models, see-saw type II...

Even if neutrino masses are not generated at tree level, they will be at higher loops and the bounds typically remain significant. Example: see-saw with two heavy neutrinos.

$$\mathcal{L} = Y\bar{L}\cdot HN_1 + Y_2\bar{L}\cdot HN_2^c + \Lambda\bar{N}_1 N_2 + \mu' N_1^T C N_1 + \mu N_2^T C N_2$$

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

For

$\mu = 0$ and $Y_2 = 0$

tree-level masses are zero.

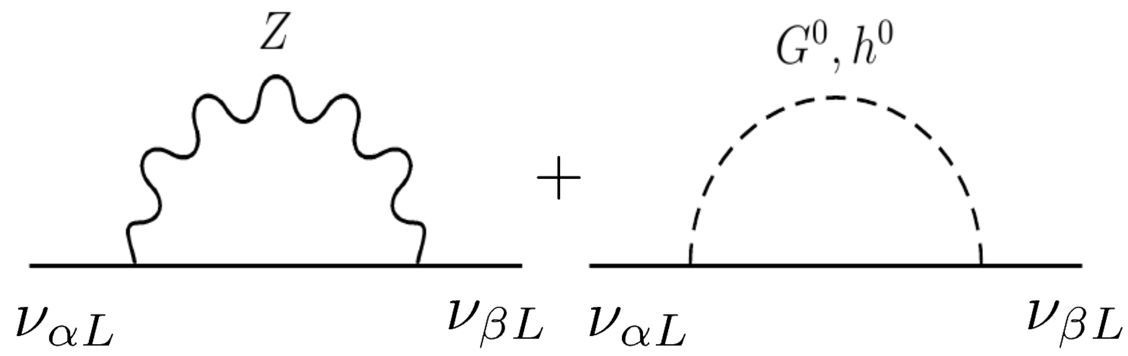
μ' can be very large inducing neutrinoless double beta decay without contradicting the bounds from neutrino masses:

$$A_{extra} \propto \frac{v^2 \mu' Y_{1e}^2}{2\Lambda^4}$$

Mitra, Senjanovic, Vissani; Ibarra, Molinaro, Petcov

Neutrino masses are generated at one loop.

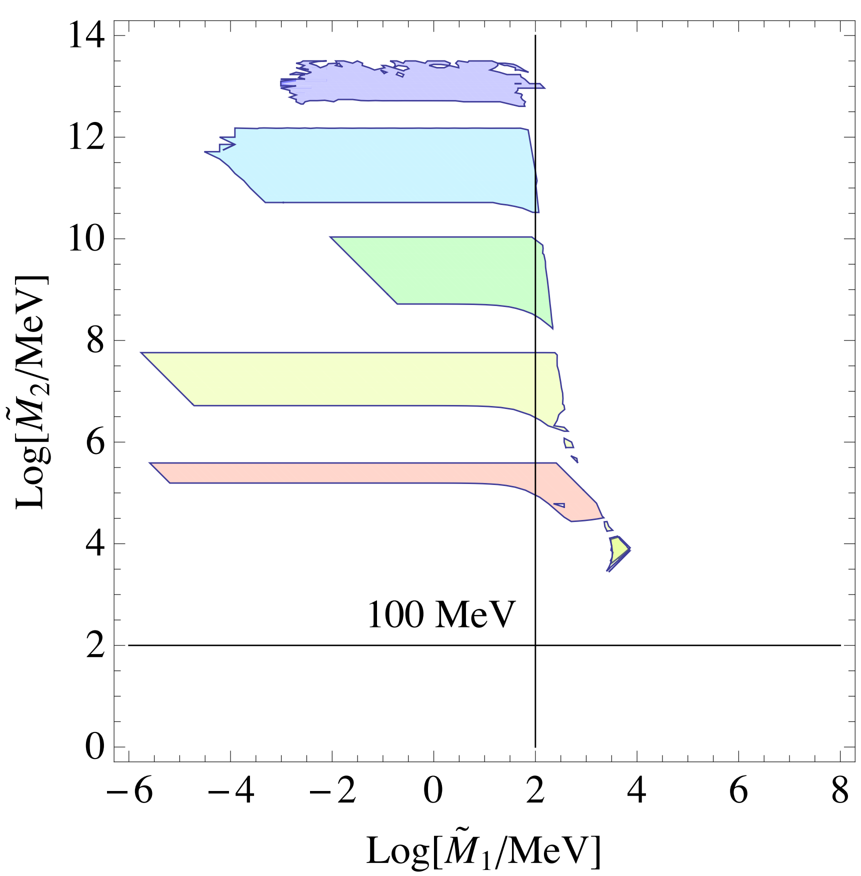
Grimus, Lavoura 2002;
Aristizabal Sierra, Yaguna 2011.



$$\delta m_{LL} = \frac{1}{(4\pi v)^2} m_D^T M \left\{ \frac{3\ln\left(M^2/M_Z^2\right)}{M^2/M_Z^2 - 1} + \frac{\ln\left(M^2/M_H^2\right)}{M^2/M_H^2 - 1} \right\} m_D$$

- Inverse see-saw: $\delta m_{LL} \approx \frac{1}{(4\pi)^2} \frac{Y_1^T Y_1}{2} \frac{M_H^2 + 3M_Z^2}{\Lambda^2} \mu'$

- Extended see-saw: $\delta m_{LL} \approx \frac{1}{(4\pi)^2} \frac{Y_1^T Y_1}{2} \left[\frac{3M_Z^2}{\mu'} \ln\left(\frac{\Lambda^4}{M_Z^4}\right) + \frac{M_H^2}{\mu'} \ln\left(\frac{\Lambda^4}{M_H^4}\right) \right]$



Allowed regions for heavy neutrino masses:
Inverse see-saw: small region around 5GeV.
Extended see-saw: one of the sterile neutrinos is very light, M1<100 MeV.

Lopez-Pavon, Pascoli, Wong