Big Issues in particle physics:

neutrino physics

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1 – Outline

- The Standard Model and Beyond
- Neutrino oscillations are evidence of physics BSM
- Neutrinos are unique: they provide a new window on physics at very high energy scales and a different perspective on the flavour problem
- A wide experimental program is going to give the information on the neutrino parameters. The synergy and complementarity of the various experiments should be fully exploited.

2 – Standard Model and Beyond

The SM of particle physics explains very well the electroweak precision data.

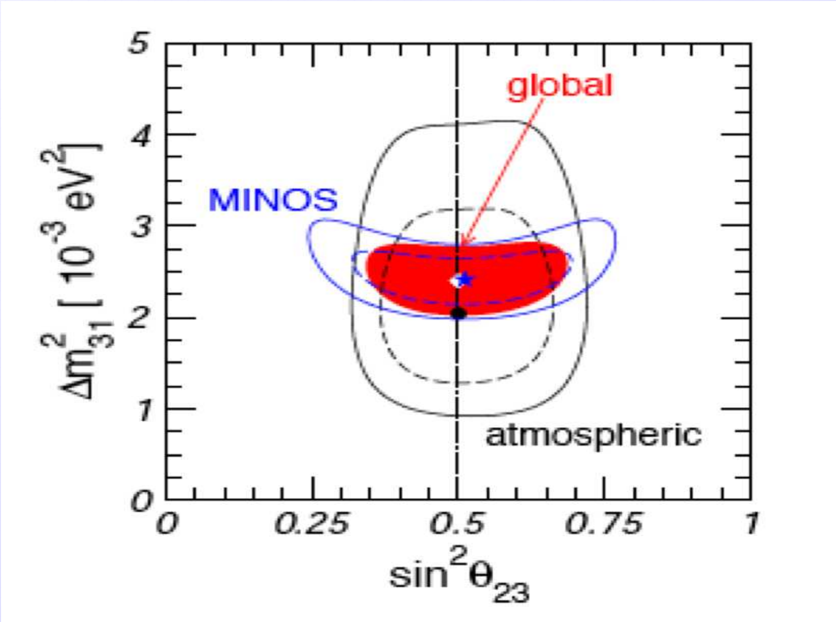
No surprises yet but we might have them soon at Tevatron/LHC.

There is strong theoretical prejudice for physics BSM:

- hierarchy problem
- gauge unification
- flavour physics

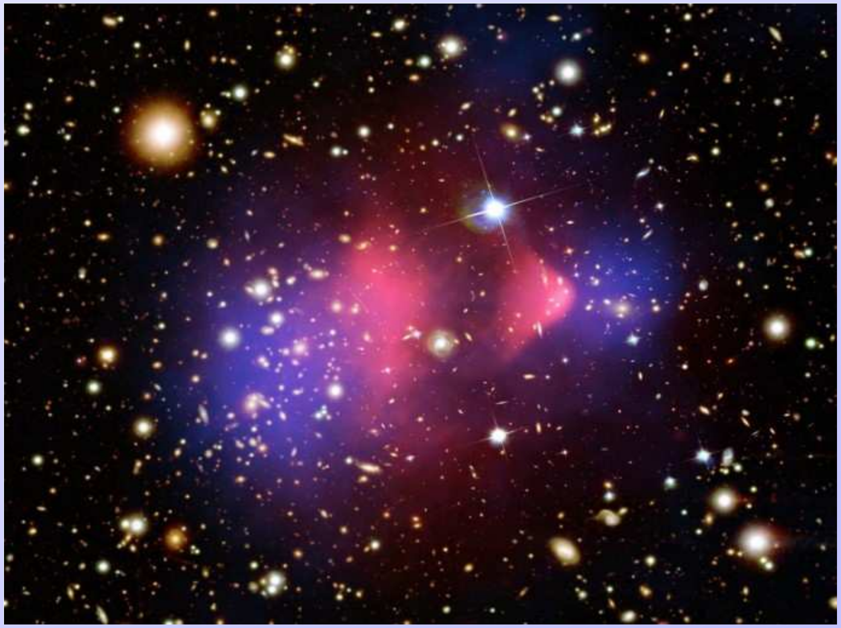
Evidence of physics BSM

neutrino oscillations



M. Maltoni and T. Schwetz, 0812.3161

dark matter

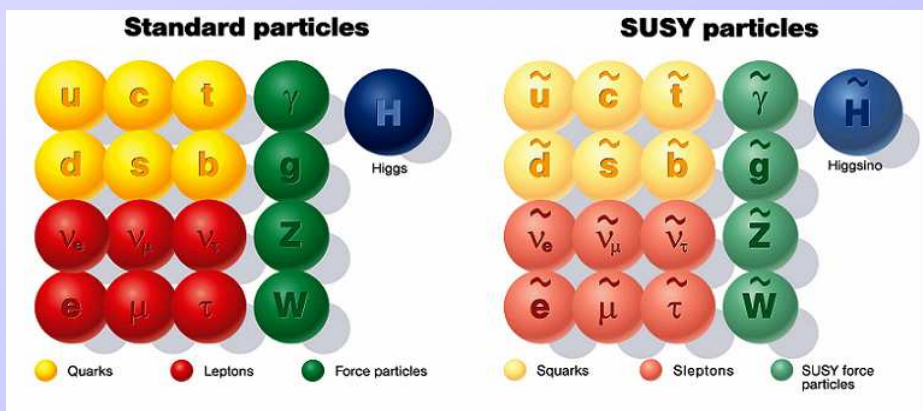


NASA

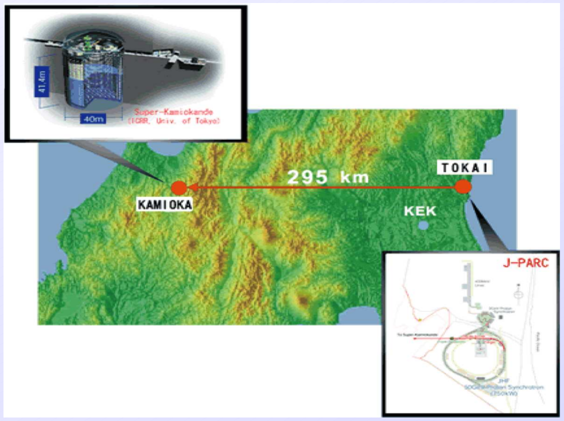
- We need to extend the SM to explain theoretically the origin of neutrino masses and dark matter. Ultimate goal: identify the theory BSM.

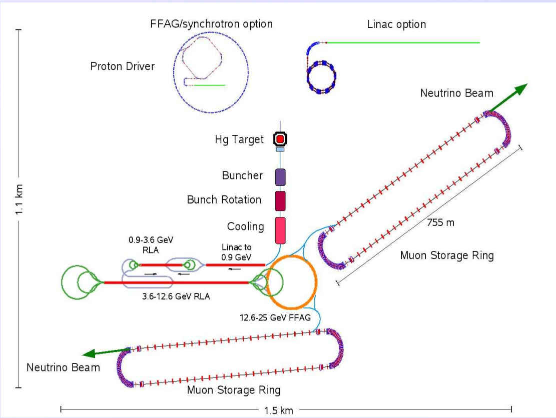
[http://lhc-machine-outreach.web.cern.ch/lhc-machine-outreach/lhc_in_pictures.htm]

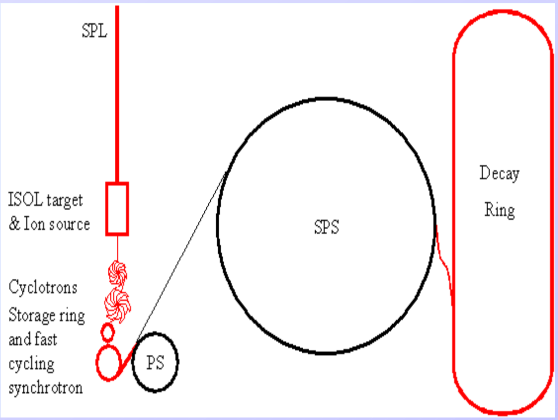
- The LHC will test the physics at the **EW–TeV scale**.
- search for the Higgs boson which is responsible for the masses of particles
- search for physics BSM: SUSY, extra-dimension models, other extensions

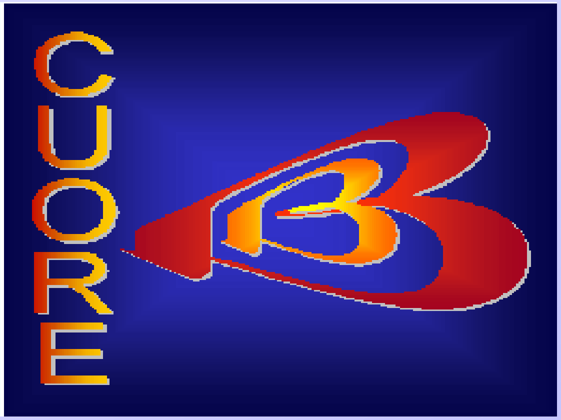


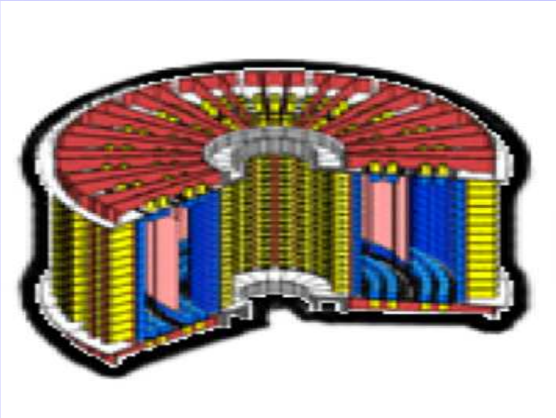
- We have a wide experimental program ongoing and under study in other areas of particle physics and astroparticle physics.







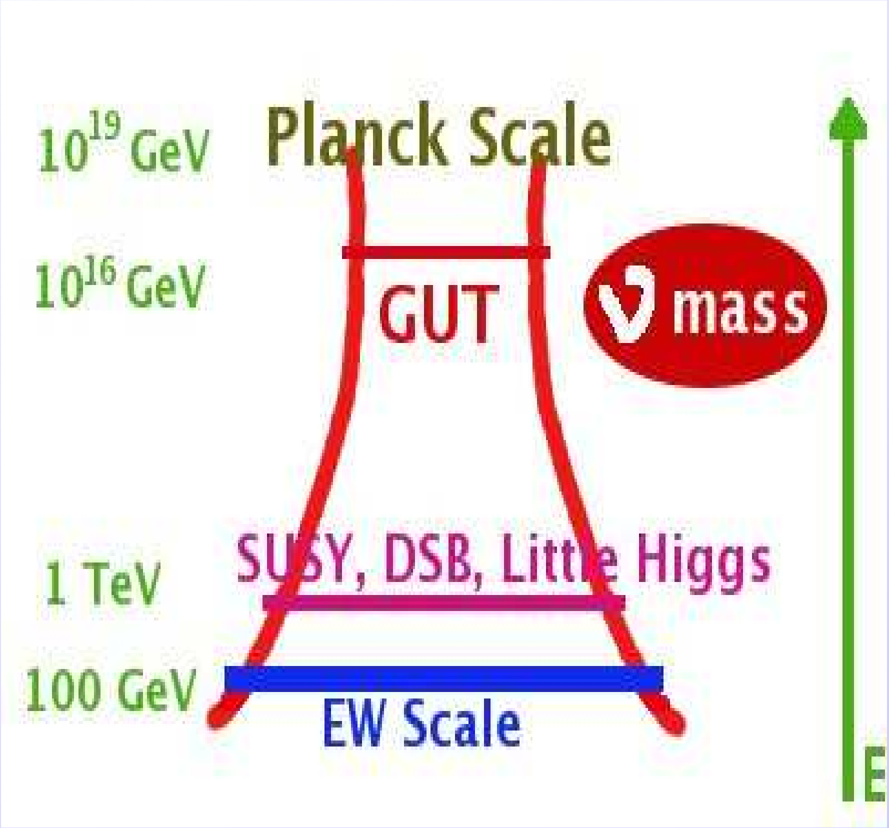




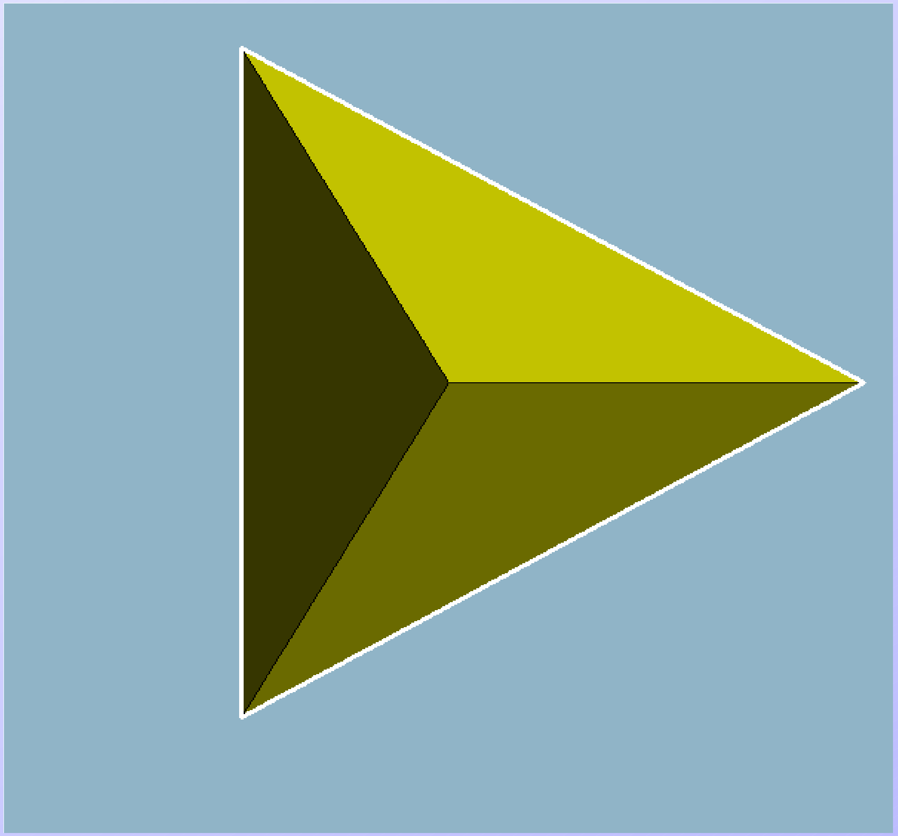
3 – Neutrino physics: an open window on BSM

Neutrino physics gives a new perspective on physics BSM.

High energy physics



Flavour problem

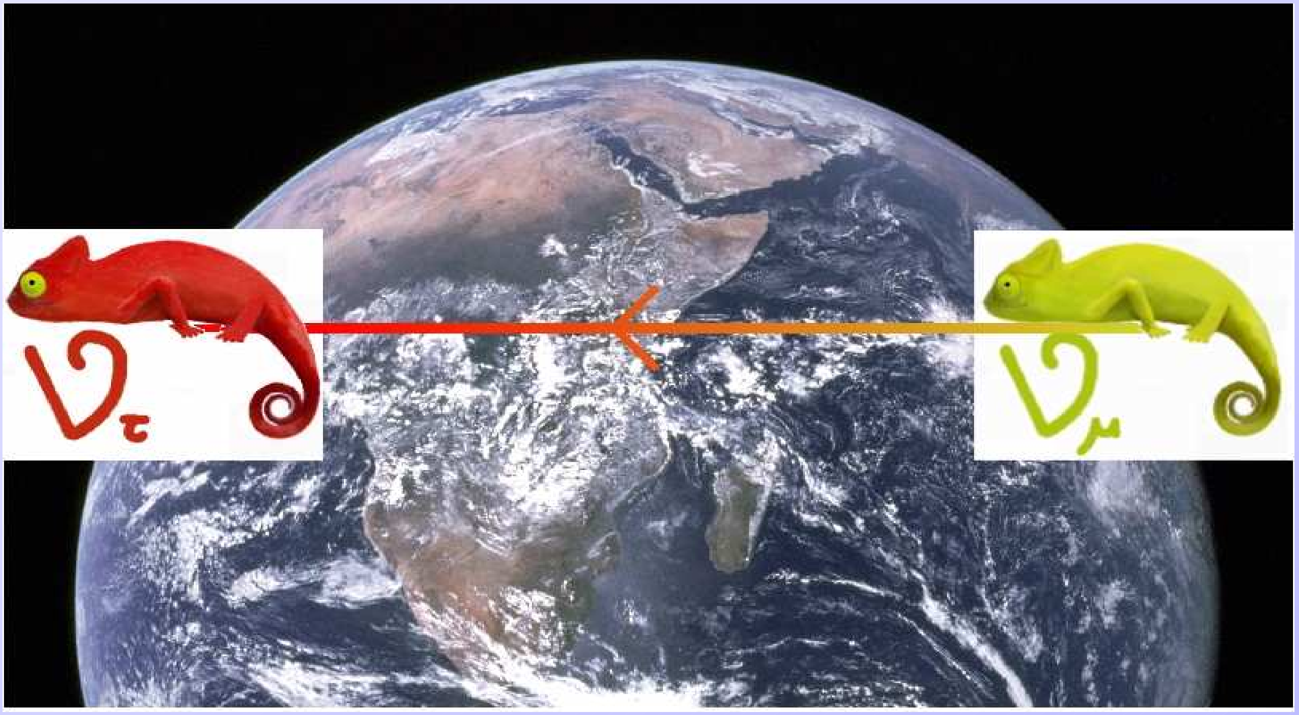


- This information is **complementary** with the one which comes from flavour physics experiments and from collider physics.

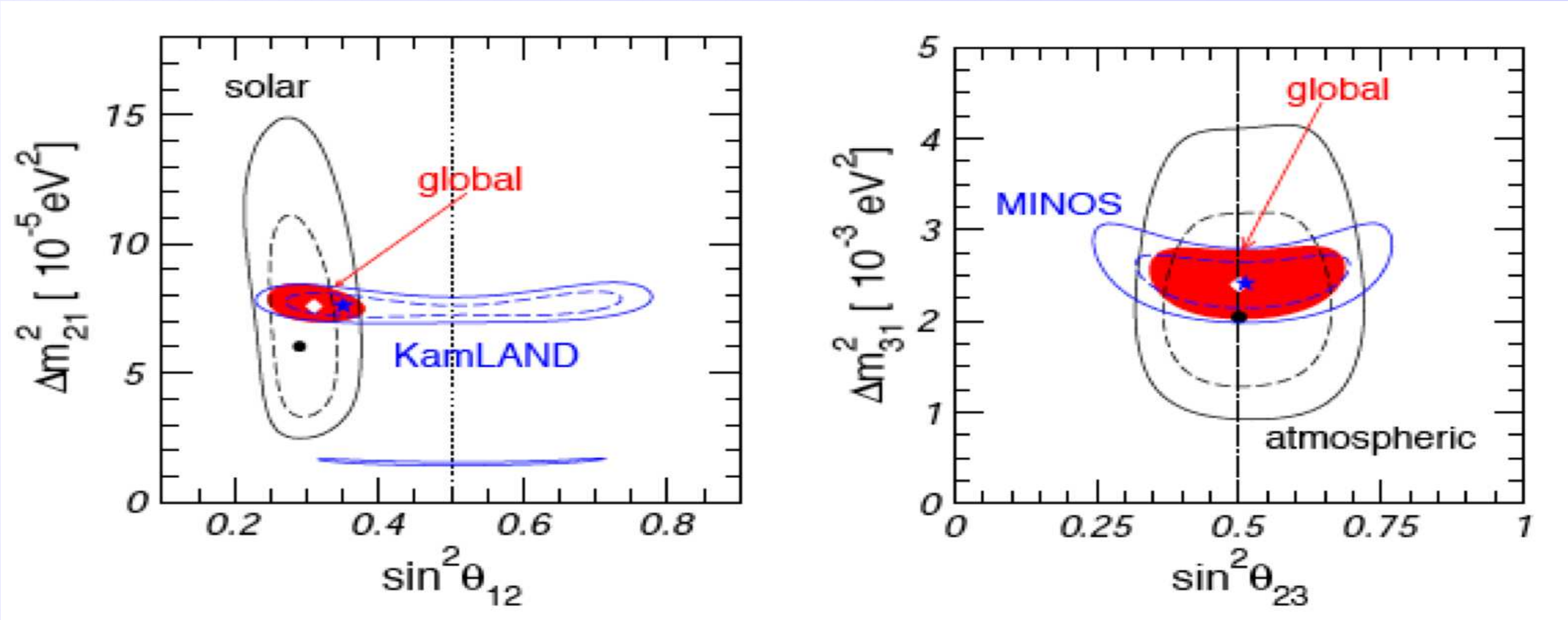
4 – Present status of neutrino physics

- We have compelling **evidence** of neutrino oscillations from atmospheric, solar, reactor and accelerator neutrino experiments.

Neutrinos are chamaleon particles: they change flavour (ν_e, ν_μ, ν_τ).

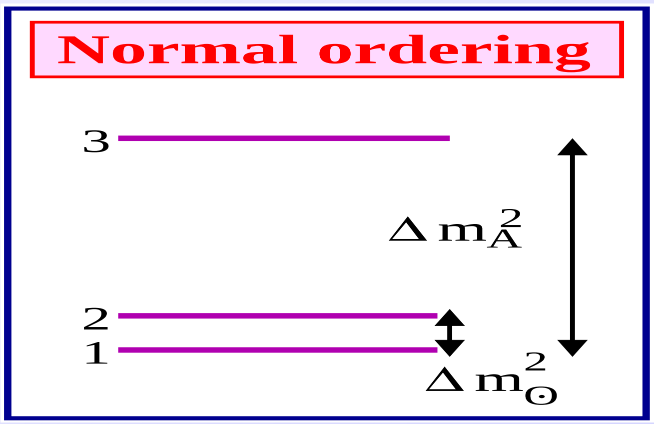


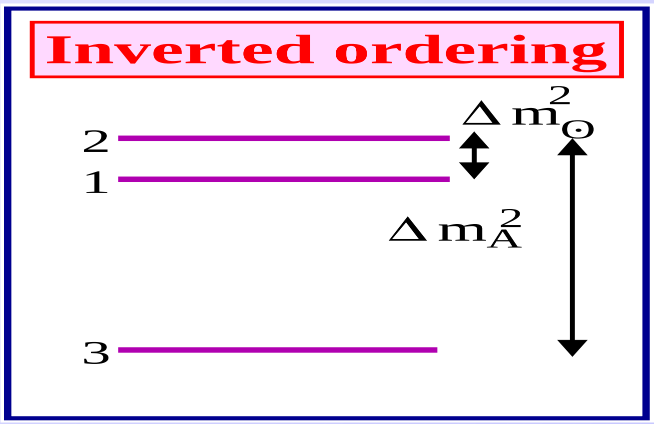
- Neutrino oscillations require neutrino **masses** ($\Delta m^2 \neq 0$) and neutrino **mixing** ($\theta \neq 0$): $P(\nu_e \to \nu_\mu) = \sin^2 2\theta \; \sin^2\left(\frac{\Delta m^2_{21}}{4E} L\right)$



[M. Maltoni and T. Schwetz, 0812.3161]

$\Delta m^2_\odot \ll \Delta m^2_A$ implies at least **3 neutrinos**.





- neutrino masses are much smaller than the other fermion masses!

Mixing is described by the Pontecorvo-Maki-Nakagawa-Sakata matrix

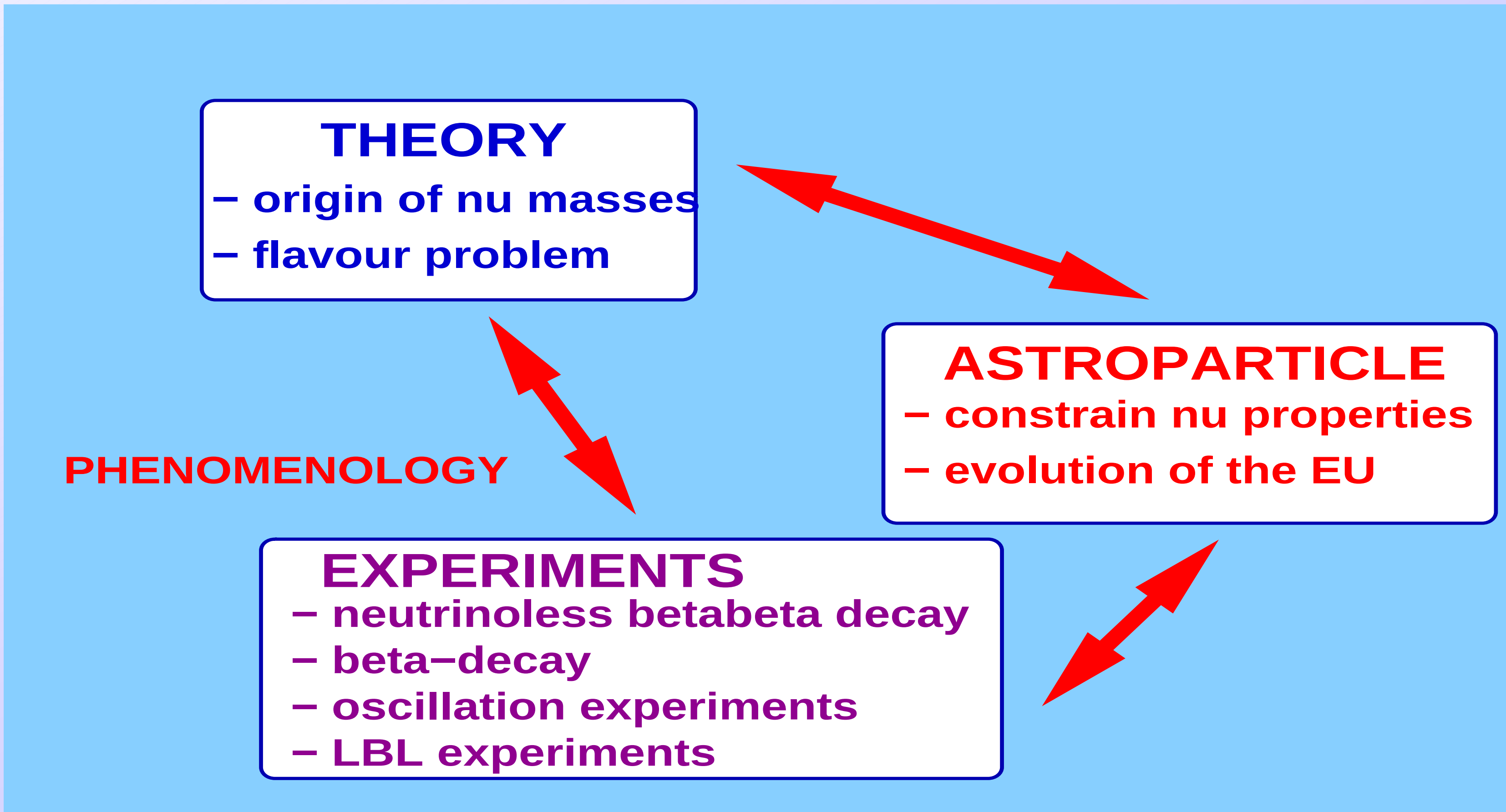
$$|\nu_l\rangle = \sum_i U_{li} |\nu_i\rangle$$

- It contains three angles: $\theta_{12} \sim 30^o$, $\theta_{23} \sim 45^o$ **and** θ_{13}.

and three CPV phases: δ, α_{21}, α_{31}.

- The flavour structure in the leptonic sector is very different from the quark one: large mixing angles.

Neutrinos can provide unique information on the physics BSM and the flavour problem.



5 – THEORY: Neutrino mass generation, going beyond the SM

- **How are neutrino masses generated?**
- **Why are they much smaller than the ones of the other SM particles?**
- **Are there other predictions for these models (leptogenesis)?**

Within the SM, neutrino masses cannot be explained and the SM needs to be extended.

We know that neutrinos have very small masses:

$$m_\nu \lesssim few\,\mathrm{eV} \quad \Rightarrow \quad \frac{m_\nu}{m_e} \sim 10^{-6}$$

Dirac Mass Term

- If the origin of neutrino masses is the same as the other fermions, we would expect large masses.

If the strength of the interaction between Higgs and neutrinos were as for the top quark, neutrinos would be 10^{12} times heavier!

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

- Why is the coupling so small compared to the other fermions?

Many theorists consider this explanation of neutrino masses unnatural.

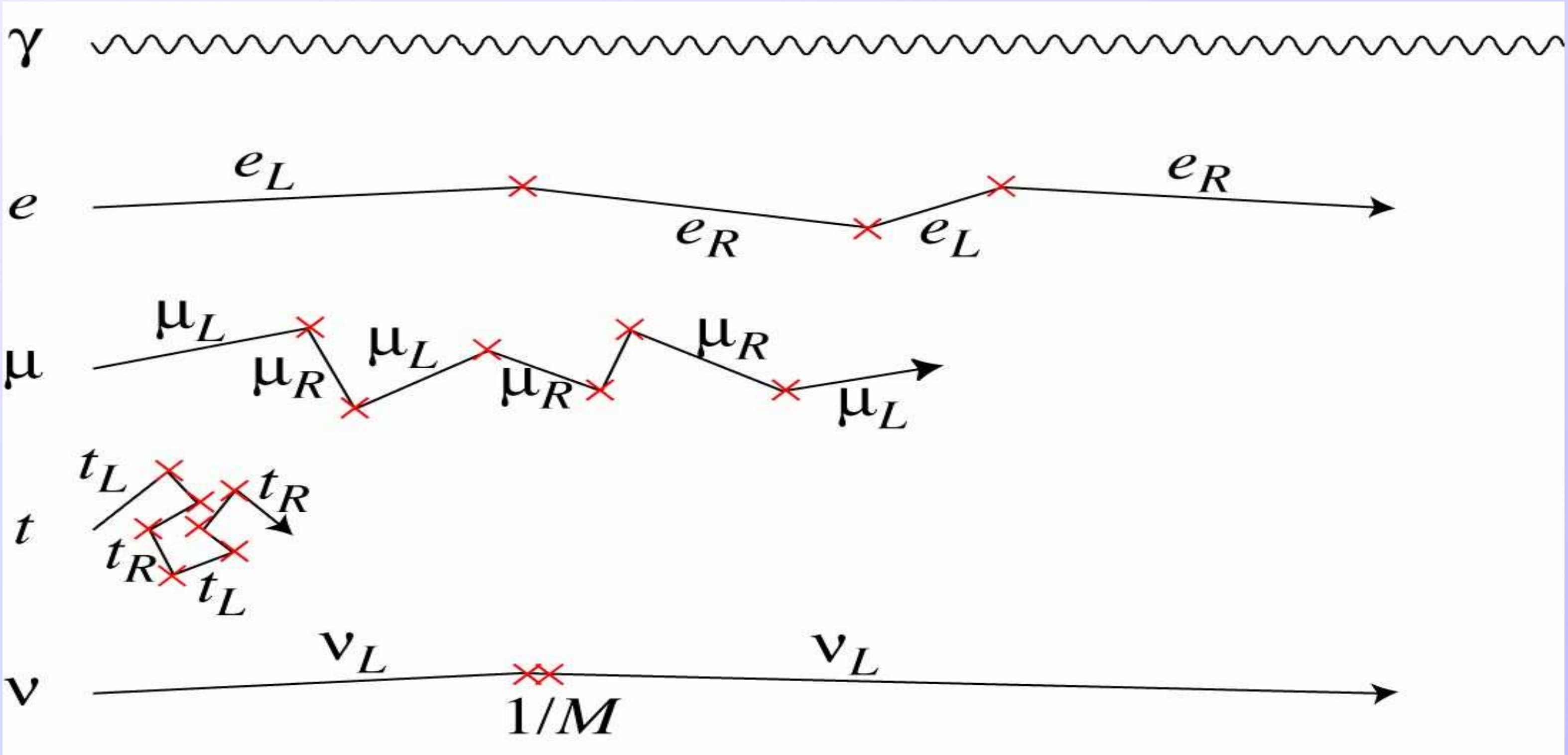
Majorana Mass Term

While an electron is distinguished from the positron by the charge, neutrinos are neutral:

- either there exist a new type of ”charge”, the **lepton number**, which distinguishes neutrinos from antineutrinos (Dirac particle)
- or there is no way to distinguish a neutrino from an antineutrino (Majorana particle): $\boxed{\nu_R = \nu_L^c}$
- **Establishing if lepton number is a conserved global symmetry is fundamental because it will guide us on how to extend the Standard Model to a more general theory.**

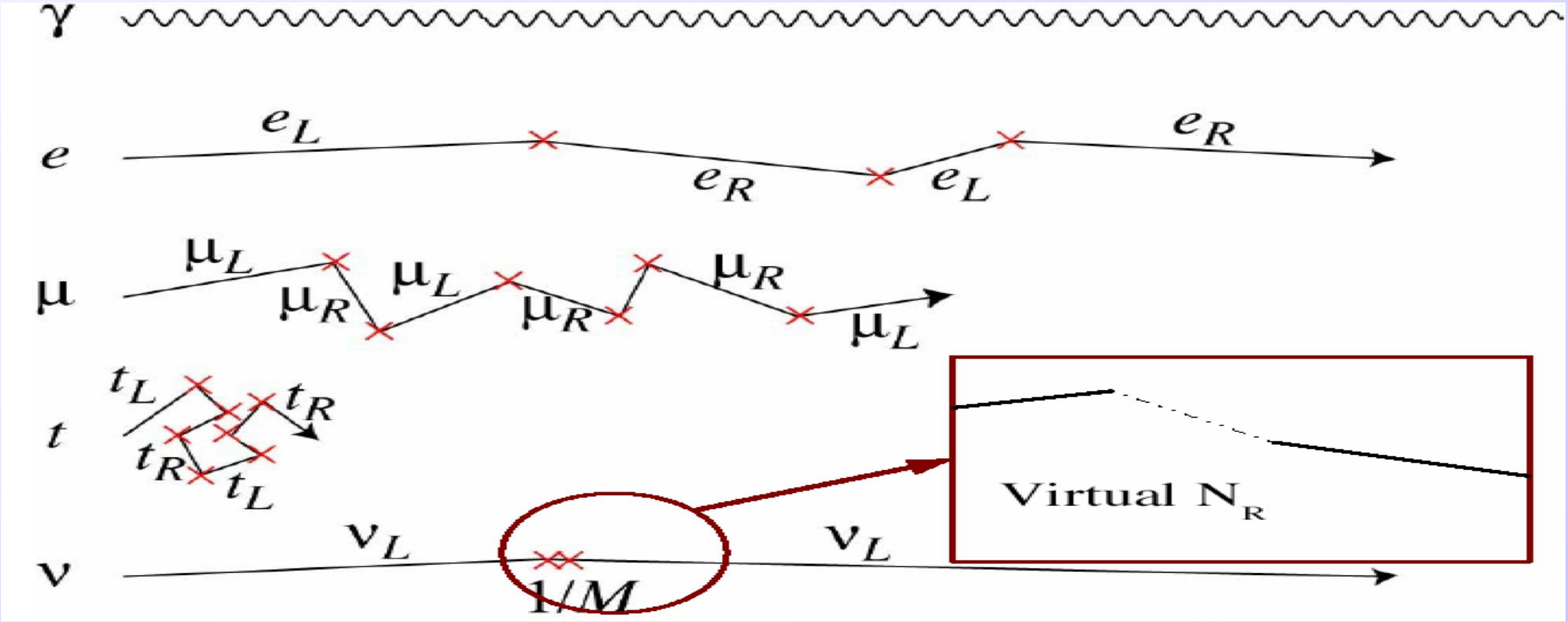
- In this case, a different type of neutrino mass can be generated:

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



[Thanks to H. Murayama]

The Majorana mass term arises as the low energy realisation of a higher energy theory.



- What is the scale of the new theory?

$$m_\nu = \frac{\lambda^2 v^2}{M} \rightarrow M \sim 10^{14}\,\mathrm{GeV}$$

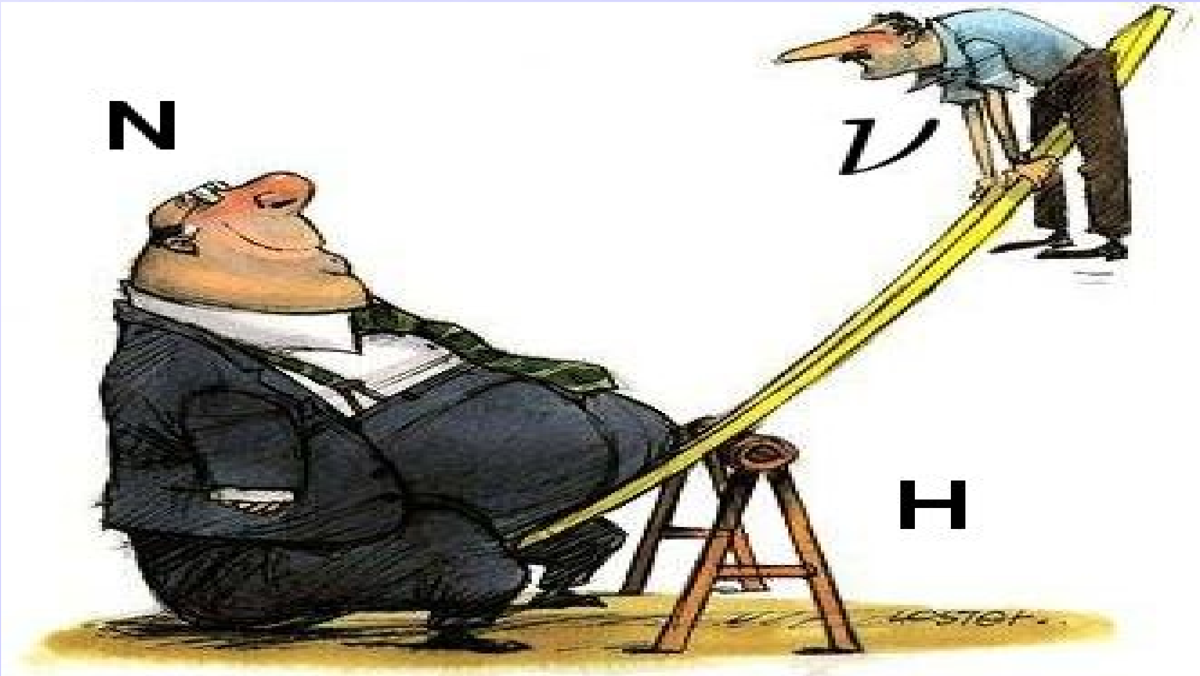
- **Neutrino masses are an open window on physics at or close to the grand unification (GUT) scale.**

The See-Saw mechanism

- Introduce ν_R: singlet Majorana very heavy neutrino
- Couple it to the Higgs and $\nu_L \Rightarrow m_D = yv$

Very light neutrino masses are generated

$$m_{light} \simeq \frac{m_D^2}{M_R} \sim \frac{100\ \mathrm{GeV}^2}{10^{14}\ \mathrm{GeV}} \sim 0.1\ \mathrm{eV}$$



Baryon asymmetry of the Universe

A viable explanation for the baryon asymmetry of the Universe

$$\boxed{\eta_B = 6.5 \times 10^{-10}}$$

is the leptogenesis mechanism [Fukugita, Yanagida, 1986]. It requires L violation and CPV.

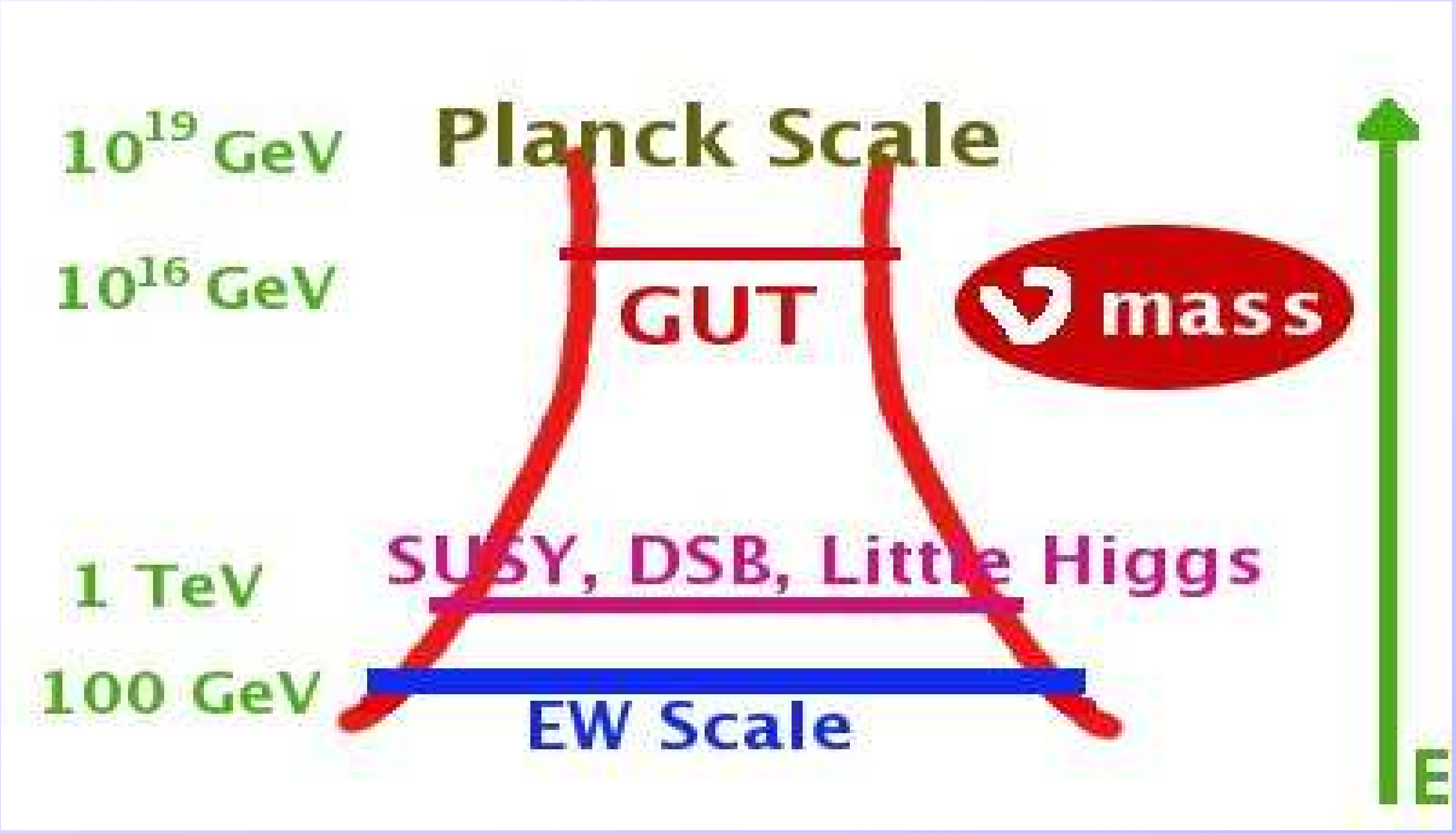
- In the early Universe, the heavy N_R of see-saw models decay generating a lepton asymmetry. This is then converted into the observed baryon asymmetry.
- Leptogenesis is implemented in see-saw models

- Is there any link between m_ν and the lepton asymmetry?

i) Generically there are more parameters at high energy than the ones we can measure at low energy. Explaining the flavour and mass structure requires to impose constraints on the parameters (e.g. symmetries): a direct connection between high energy and low energy parameters might be possible.

ii) Due to flavour effects, in see-saw type I, if we observe CPV in neutrino experiments, we know that a lepton asymmetry is generated (although we cannot predict exactly its magnitude).

- Understanding neutrino masses can give us information on physics at scales not accessible in any terrestrial or astrophysical experiment



- It might shed light on the origin of the baryon asymmetry at the very first instants of the Universe.

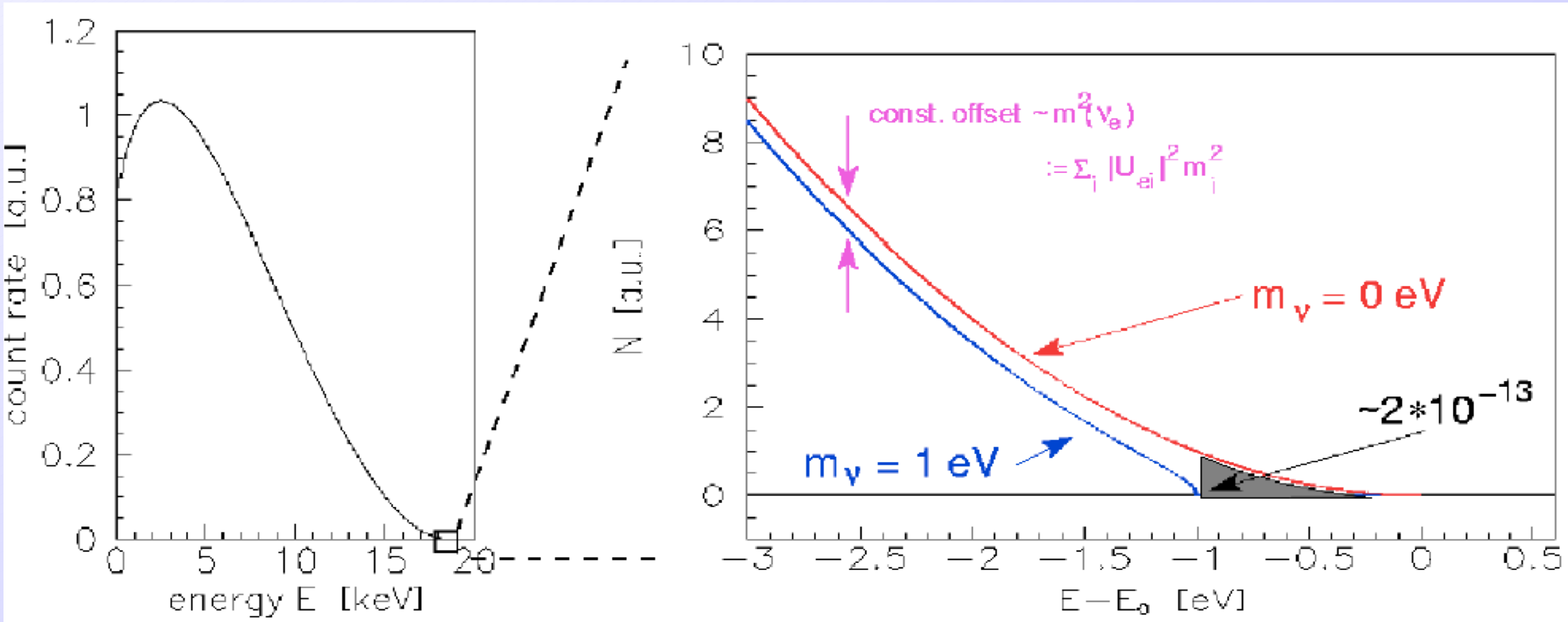
6 – EXPERIMENTS AND PHENOMENOLOGY

In order to identify the theory BSM responsible for neutrino masses and mixing, we need to measure the low energy neutrino parameters.

1. Nature of neutrinos: Majorana vs Dirac?
2. Testing the standard 3-ν picture: Are there sterile neutrinos? Do neutrinos have non-standard interaction?
3. Neutrino mass spectrum: NH, IH or QD?
4. CP-violation: $\delta \neq 0, \pi$ and/or $\alpha_{ij} \neq 0, \pi$?

Direct mass measurement in tritium beta decay

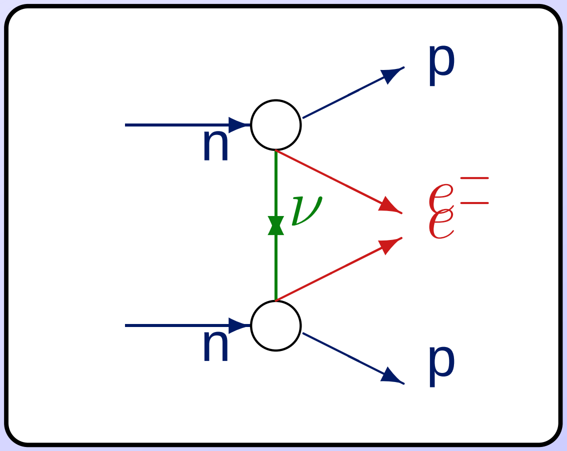
The spectrum of emitted electrons in a β-decay ($n \longrightarrow p\, e\, \nu$)



- present bound on masses: $m_\nu < 2.3\,\mathrm{eV}$ (Troitzk and Mainz)
- KATRIN is the next generation of ^{3}H-decay experiments with a sensitivity to $m_0 \sim 0.2$ eV (90% CL).

$(\beta\beta)_{0\nu}$-decay

neutrinoless double beta decay: $(A,Z) \rightarrow (A,Z+2) + 2e^-$, is the most sensitive of processes ($\Delta L = 2$) which can probe the **nature of neutrinos** (Dirac vs Majorana).



It can happen only if neutrinos and antineutrinos are indistinguishable (Majorana neutrinos).

The half-life time, $\mathrm{T}_{0\nu}^{1/2}$, of the $(\beta\beta)_{0\nu}$-decay depends on

$$|<m>| \equiv |\, m_1|U_{\mathrm{e}1}|^2 + m_2|U_{\mathrm{e}2}|^2 e^{i\alpha_{21}} + m_3|U_{\mathrm{e}3}|^2 e^{i\alpha_{31}} \,| \,,$$

The present bound on $|{<}m{>}|$ depends on the nuclei used:

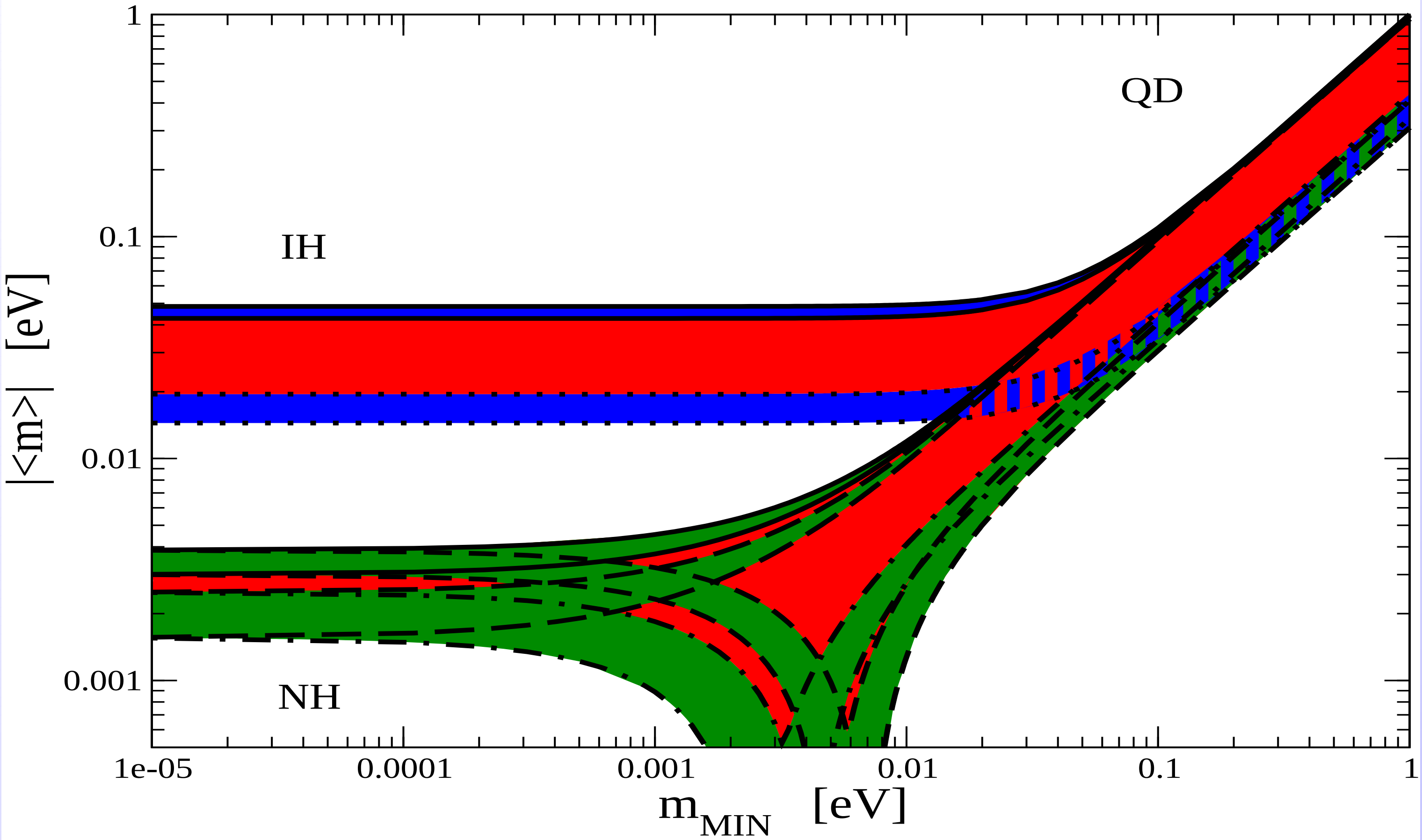
$|{<}m{>}| < (0.35 - 1.05)$ eV (Heidelberg-Moscow, ^{76}Ge),

$|{<}m{>}| < (0.20 - 0.68)$ eV (Cuoricino, ^{130}Te),

$|{<}m{>}| < (0.8 - 1.3)$ eV (NEMO3, ^{100}Mo).

Evidence of $(\beta\beta)_{0\nu}$-decay was reported [Klapdor-Kleingrothaus and Krivosheina, PLB 586 and MPLA 21]: $|{<}m{>}|_{\text{BF}} = (0.32 \pm 0.03)\,\text{eV}$.

The next generation of $(\beta\beta)_{0\nu}$-decay exp (GERDA, SNO+, SuperNEMO, EXO, Majorana, CUORE, Cobra ...) aim to $|{<}m{>}| \sim 10\text{–}30$ meV .



$(\beta\beta)_{0\nu}$**-decay has a special role in the study of neutrino properties,**

as it probes the violation of global lepton number,

and it might provide information on the neutrino mass spectrum,

absolute neutrino mass scale and CP-V.

LBL oscillations: mass hierarchy and CPV

δ and the sign of Δm^2_{31} can be measured in long baseline appearance ν-oscillation experiments: they use a manmade flux of neutrinos with detectors located at 100s-1000s of km away.

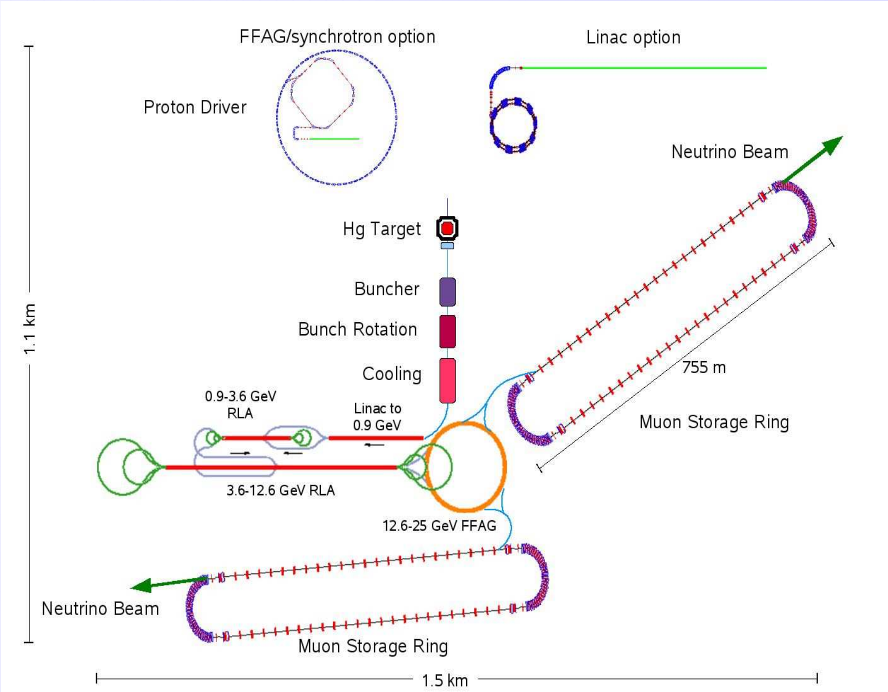
These accelerator neutrino experiments search for $\nu_\mu \longrightarrow \nu_e$ appearance:

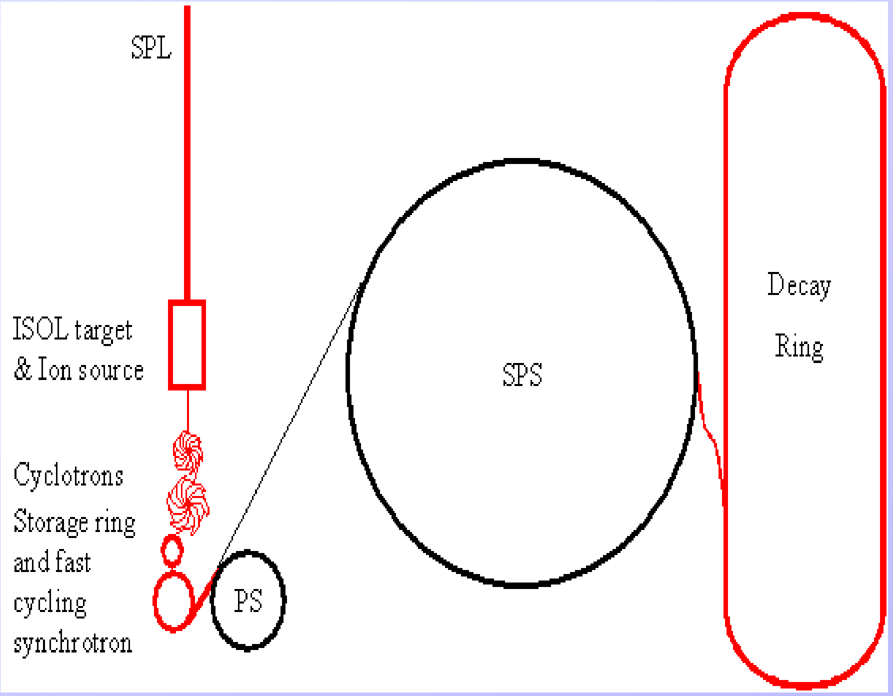
$$P(\nu_\mu \rightarrow \nu_e) = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{31} L}{4E}$$

for subdominant matter effects and CPV.

- CP-violating and matter effects are **controlled by the angle θ_{13}**.

- T2K will start this year hunting for θ_{13}
- Various more sensitive experimental configurations are under intensive study for the future.





Future long baseline experiments are unique as they can achieve

- **discovery**: find $\theta_{13} \neq 0$, CPV and the type of neutrino mass hierarchy
- **precision**: determine the oscillation parameters with great accuracy

- test the standard 3ν scenario

- give hints in favour of symmetries which can explain the flavour problem

7 – Synergy and complementarity in the neutrino exp program

- Neutrino experiments ($(\beta\beta)_{0\nu}$-decay, β-decay, LBL and other oscillation experiments) are **complementary** in the quest for ν-properties.

They exploit completely different physics effects.

- They have a strong sinergy: important information can be obtained from **combining** their results.

Each experiment individually might be affected by degeneracies which can be lifted by a joint analysis of the results.

The combination of the various experimental searches for neutrino properties will allow to reach a much better understanding of neutrino properties.

8 – Conclusions

- Neutrino masses and mixing require new physics beyond the SM:

Neutrino physics is a new window on physics BSM (high energy and flavour) with a different perspective with respect to flavour physics and collider searches.

- A wide experimental program is going to address the questions in neutrino physics in the next future: $(\beta\beta)_{0\nu}$-decay experiments, β-decay, LBL and other oscillation experiments.

- The synergy and complementarity between different experimental strategies need to be fully exploited and is very powerful in unveiling the properties of neutrinos.