Theoretical physics scenarios in view of second generation ν-oscillation and p-decay experiments

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We focus on 2 topics of fundamental physics: the supersymmetric decay of the proton and the perspectives of improving what we know on neutrino properties. The unifying theoretical links are the physics at ultra-high scale and the flavor (fermion mass) problem. We also discuss the interest of supernova neutrinos in connection with oscillations and in view of future detectors.

1 On SUSY GUT p-decay modes

$p \to K^+\bar{\nu}$ can be improved with $M_{\rm Ar} \cdot T > 20$ kton·years

Why it is interesting? [Sakai-Yanagida & Weinberg, 1982]

- SU(3)$_c$-triplets implied by SU(2)$_L$-higgs doublet in GUT.
- Fermionic triplets (higgsinos) implied in SUSY GUT.
- Addition of SUSY breaking effects gives proton decay operators, such as:

$$G \cdot qqql, \quad \text{with } G = \frac{\alpha/4\pi}{M_{susy}} \cdot \frac{Y^2}{M_{GUT}}$$

Higgs couples to fermion masses $Y_f = m_f/v$ and similarly does triplet higgsino. τ_p is known to be generically quite fast.

1.1 Crucial theoretical issues

We would like to know τ_p, the branching ratio into $K^+\bar{\nu}$, and their uncertainties. We confront with the open questions:

(1) Is SUSY broken at the electroweak scale?

(2) What is the gauge group (of the GUT)?

(3) More particularly: What is its higgs sector?
Should we include M_{GUT}/M_{Planck} effects?

(4) How to validate the selected SUSY GUT model?

(1) SUSY at low scale.

Helps with the electroweak mass scale,

decoupled from M_{heavy} (M_{ν_R}, M_{GUT} or M_{Planck}). SU(2) breaking connected to SUSY scale; in many models happens through radiative corrections.

SUSY scale not precisely predicted.

The nature of SUSY breaking: gravity/gauge mediation? $M_{susy} \sim M_W$, $M_{susy} = M_{Planck}$ or 'split' spectra? Some predictivity with GUT.

Main tests:

Supersymmetric particles in accelerators.

WIMP as DM; DM direct detection and annihilation into $e, \gamma, \nu, \bar{p}$.

If LHC finds SUSY, motivations for $p \to K\bar{\nu}$ search even stronger.

(2) The gauge group.

One simple possibility is $\mathbf{SU(5)}$. It is amazing that low energy SUSY is consistent with gauge coupling unification, as needed.

> The most attractive GUT is $\mathbf{SO(10)}$ that unifies the 16 fermions of a family, including ν_R (more later).

SO(10) can have **intermediate scales**. *This opens more possibilities but it is also a problem for predictivity. SUSY unification suggests we are close to SU(5) chain of breaking.*

(3) Which higgs fields? Non-renormalizable operators?

These two questions go together, at least in SO(10):

$$\begin{cases} \text{a renormalizable theory needs } 126_H; \\ \text{a theory with small-reps.-only needs non-ren. operators.} \end{cases}$$

Either options have difficulties or drawbacks:

⋆ *the first has typically big threshold effects; the number of higgs fields is at least (probably more) than 4; needs of fine-tunings.*

⋆ *the second needs more physics as "flavor groups" to keep under control the effective operators; to know the cutoff; has the issue of R parity.*

(4) How to validate the model.

Of course gauge couplings and fermion masses (included ν's) have to be reproduced. The possible tests of SUSY GUTs are:

- dim-5 proton decay;
- neutrino mass scale;
- leptogenesis;
- possibly $\mu \to e\gamma$, $b \to s\gamma$, e.d.m.'s.

These observables regard GUT mass scale but also flavor physics (i.e., Yukawa couplings). Monopoles, probably, are out of reach.

1.2 Provisional summary

In many SUSY GUTs, proton decays preferentially to strange mesons; the generic expectation is that the decay is fast.

> *Surely, a discovery of $p \to K^+\bar{\nu}$ would be a strong point in favor of SUSY GUT.*

Several models already constrained, but it is difficult to proceed with WČ. We would need systematic investigation of realistic models a completely reliable prediction of the rate seems almost impossible now. Prospects more clear after LHC.

(Remarks on ν masses later).

Workshop on Grand Unification and Proton Decay
ICTP, Miramare, Trieste, Italy

July 22-26, 2007

Scientific Purpose

Accumulated data on fermion masses and mixings in recent years allow today for the construction of well-defined and verifiable grand unified models. Many of them strongly indicate the possibility of observable proton decay. At the same time, a number of proposals for the next generation of proton decay experiments, improving the limits on proton lifetime have been put forward. The time is ripe for an in-depth discussion of both the theoretical and the experimental relevant issues in grand unification. We plan to bring together a number of leading experts in both theory and experiment in order to assess the present day status of grand unified theories, with focus on the feasibility of testing them in the near future.

http://users.ictp.it/∼smr1854/

2 On neutrino properties

[see hep-ph/0606054 for an on-line review]

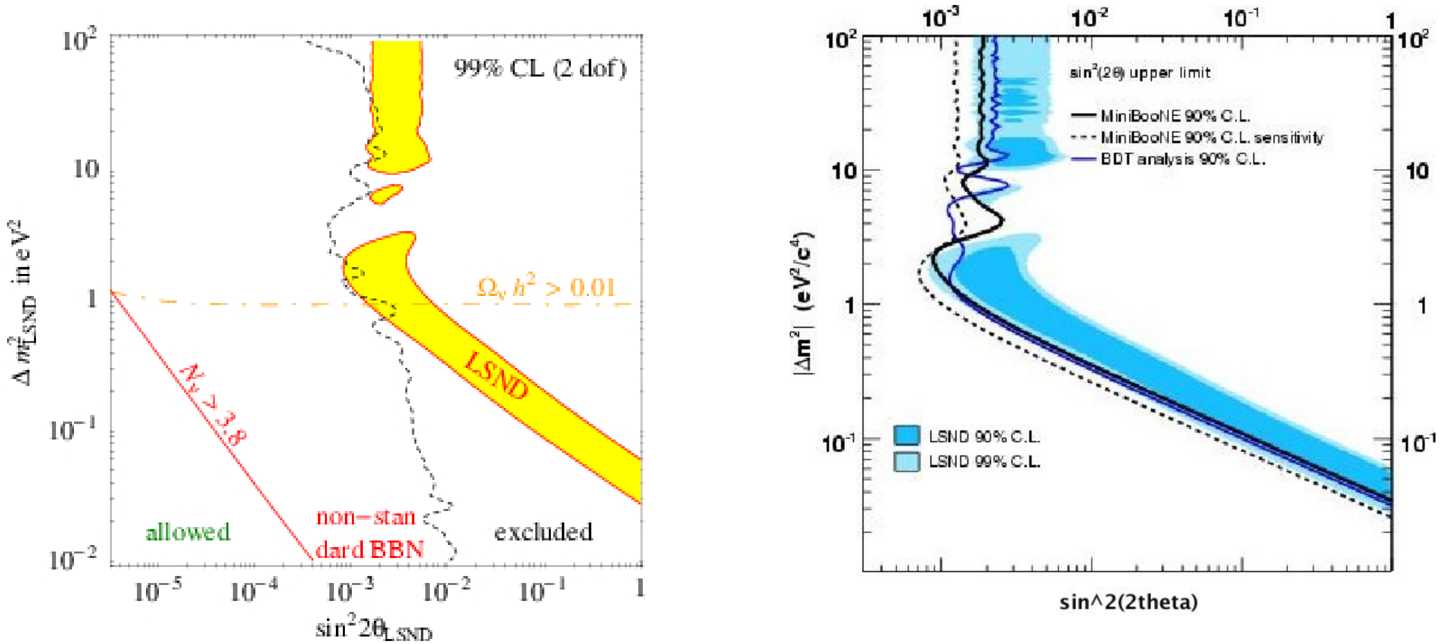


Figure 1: 4 ν framework and LSND hint for $\bar{\nu}_e$ appearance: (a) Exclusion regions from disappearance, BBN, cosmology (Cirelli *et al*, 2004). (b) Comparison with MiniBOONE neutrino data (2007).

2.1 Next steps with oscillations

The 3 massive neutrino framework is predictive and seems reliable.

In this framework we still need to probe:

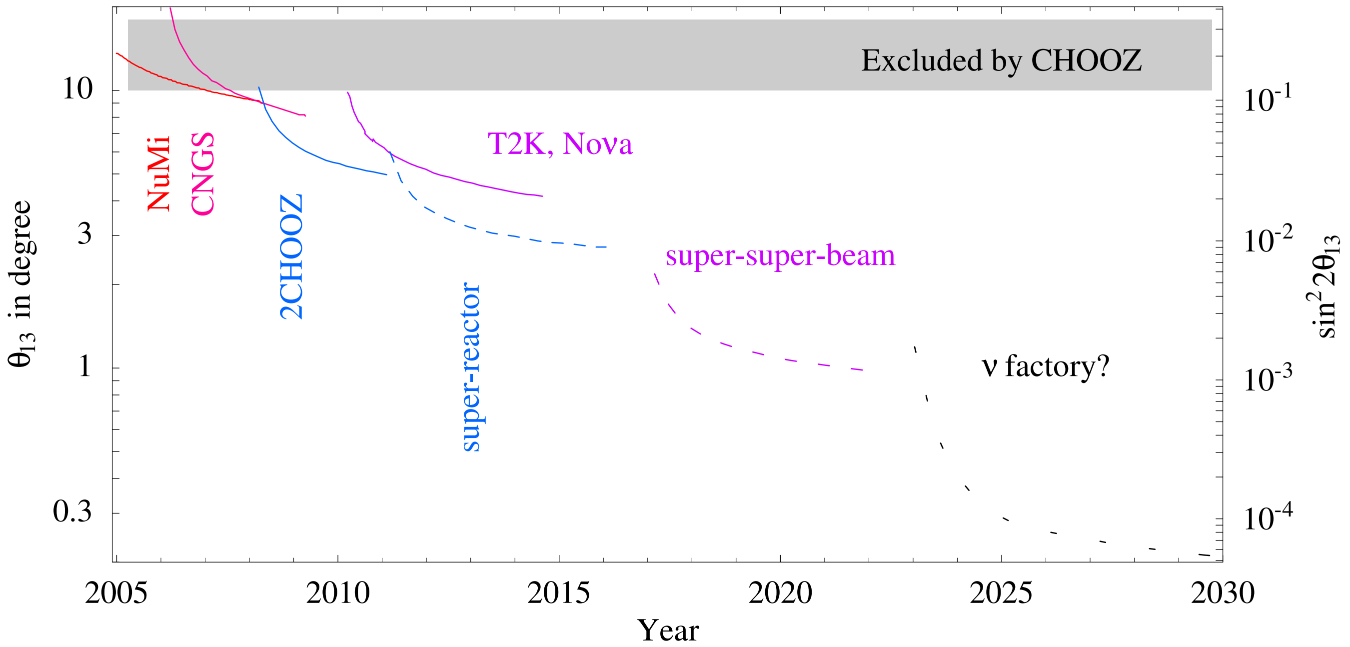
$\theta_{13} < 10^\circ$	(at 99% C.L.)
$\mid \theta_{23} - 45^\circ \mid < 9^\circ$	(at 99% C.L.)
$\mathcal{I} = \pm 1$	hierarchy parameter
$\delta = 0^\circ - 360^\circ$	CP violation

More important tests at Borexino, OPERA, MiniBOONE.

To access mass scale and nature of the mass, we further need non-oscillation experiments.

The key parameter is θ_{13}.

The prospects to improve on it depend on beam and on the detector, and will be discussed in the workshop.

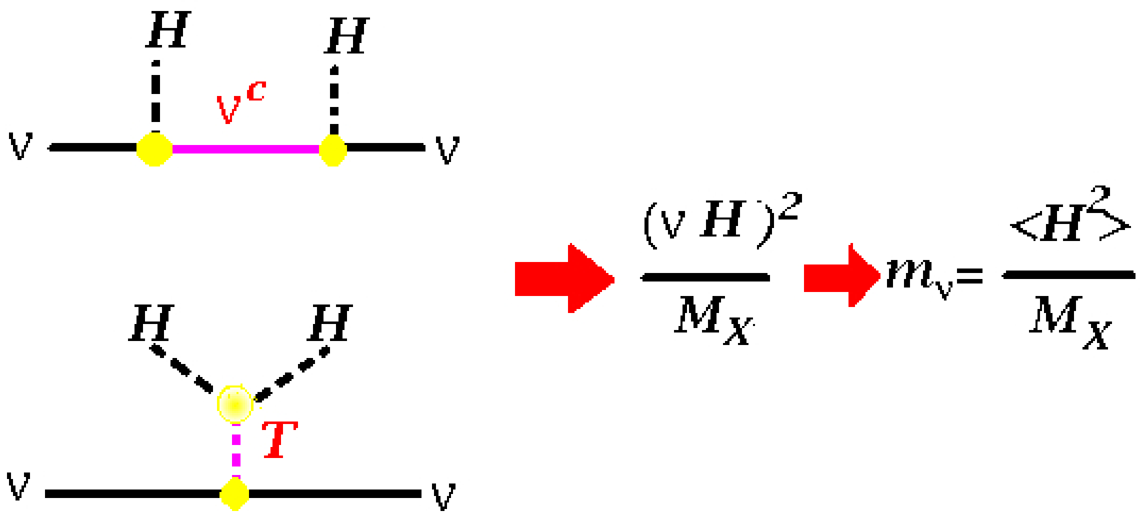


My personal formulation/check-list (or list of prejudices) is simply:

- ⋆ probe $\theta_{13} > 5^\circ$ ($\sin^2 2\theta_{13} \sim 3\%$);
- ⋆ find if $|\theta_{23} - 45^\circ| > 5^\circ$ ($\sin^2 2\theta_{23} \sim 1 - 3\%$ or $|\sin^2\theta_{23} - 1/2| > 9\%$);
- ⋆ demonstrate that the mass hierarchy is normal.

2.2 Last points on the physics at ultrahigh scale

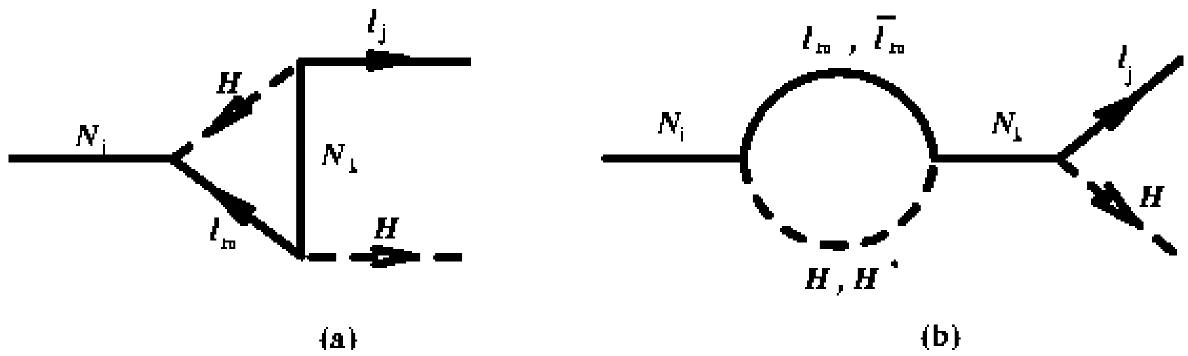
Physics at ultra-high scale explains neatly why m_ν are very small in comparison to charged fermion masses:



this is the "seesaw" of Minkowski 77; Yanagida, GellMann-Ramond-Slansky, Mohapatra-Senjanovic 79.

The neutrino Yukawa couplings can be similar to those of quarks and leptons, even if m_ν is small.

At one loop, the decay of the lightest right-handed neutrino leads to non-zero lepton asymmetry ΔL:



Then, non-perturbative, standard model transitions that violate (B+L) can convert ΔL into ΔB (Fukugita-Yanagida, 1986).

Seesaw or leptogenesis, taken alone, are not predictive.
Rather, I believe they are one of the few tests that a good (SUSY) GUT models should satisfy.

2.3 Neutrino-driven alternative scenarios

Suppose $0\nu2\beta$ experiments saw the transition. Suppose that $0\nu2\beta$ transition was faster than expected in the 3F picture. We could need to reconsider the interpretation of $0\nu2\beta$:

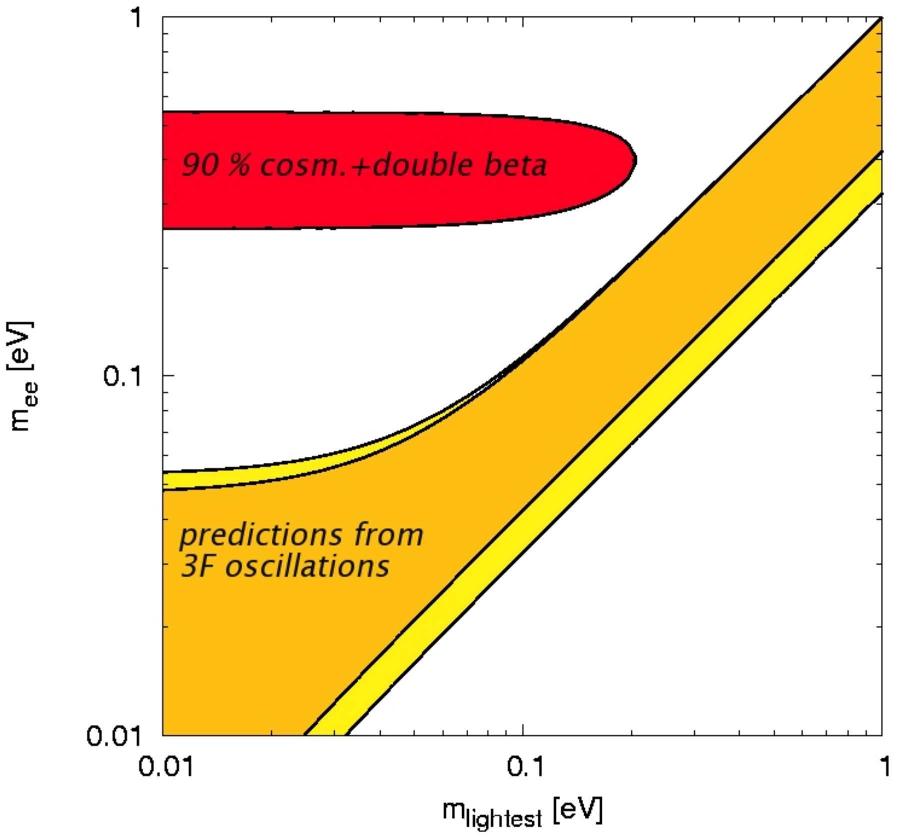
$\frac{(e\bar{d}u)^2}{M_X^5}$ a new, direct contribution to $0\nu2\beta$

$\frac{(\nu H)^2}{M_X}$ ν mass operator $\Rightarrow$ $(\bar{d}u \cdot \bar{\nu}e)\ (\nu\nu)\ (\bar{d}u \cdot \bar{\nu}e)$

The usual contribution $\mathcal{O}(G_F^2)$ could be subdominant if $M_X \sim M_W$: means 'low energy' physics!

A similar possibility considered by Pontecorvo, PLB26 (1968).

Figure 2: Predictions *versus* observations: $m_{\rm cosmo} < 0.73$ eV (Lyman α excluded) and $m_{\rm ee} = 0.2 - 0.6$ eV (Klapdor), both at 3σ.



If correct, does it mean surprises at LHC? Or: more than 3 νs?

3 On supernova neutrinos

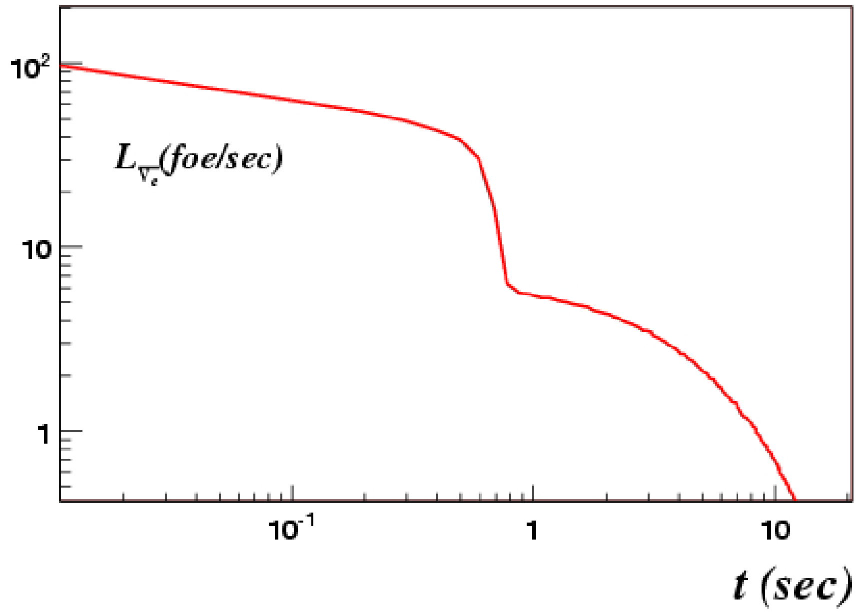


Figure 3: Expected $\bar{\nu}_e$ luminosity. The long-lasting, thermal phase (cooling) is preceded by the short non-thermal phase (accretion):

$$e^- p \to n\ \nu_e \quad \text{and} \quad e^+ n \to p\ \bar{\nu}_e$$

Accretion ν_e and $\bar{\nu}_e$ should be the key to understand the explosion.

3.1 SN1987A

About 20 years ago, Kamiokande-II, IMB and Baksan saw 16, 8 and 5 events respectively in a time window of 30 s.

After several hours, a supernova was seen in LMC.

The small background rate indicated that the excess was due to detection of supernova antineutrinos producing observable positrons ($\bar{\nu}_e p \to e^+ n$, *i.e.*, IBD reaction).

The number of events detected in the first second is 6, 3, and 2: namely, a considerable fraction.

3.2 New analysis of SN1987A

In 0705.4032 [astro-ph] accretion and cooling fluxes have been parameterized following Lamb & Loredo. SN1987A data were analyzed fitting times, energy, and angles of the observed positrons, considering background and oscillations. We got:

$$M_a \equiv 0.5\ M_\odot, \quad T_a = 2.1 \pm 0.1 \text{ MeV}, \quad \tau_a = 0.70^{+0.19}_{-0.20} \text{ s}$$

$$R_c = 13^{+8}_{-5} \text{ km}, \quad T_c = 5.1^{+0.9}_{-0.7} \text{ MeV}, \quad \tau_c = 4.4^{+1.6}_{-1.1} \text{ s}$$

Normal hierarchy: accretion involves a large mass and lasts about 0.7 s. PNS cools exponentially with time constant 4.4 s.
Total energy emitted $2.5 \cdot 10^{53}$ erg; 20-30% during accretion.

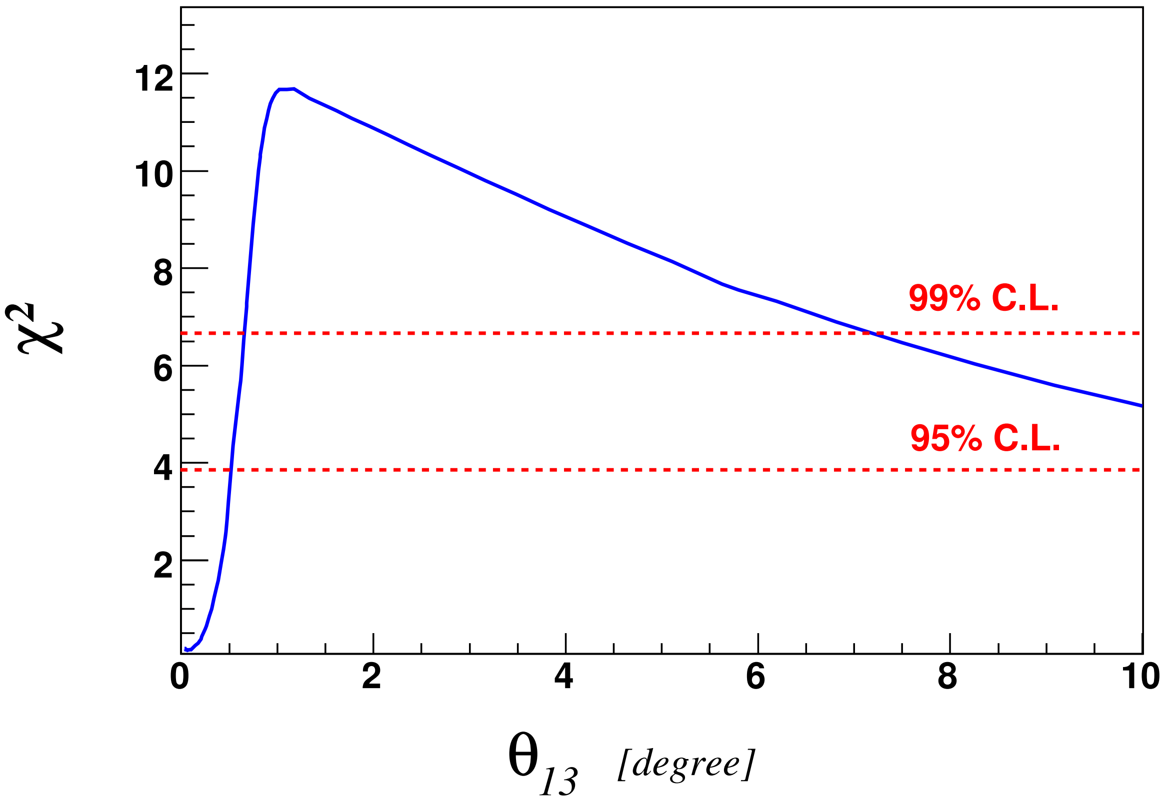


Figure 4: Inverted hierarchy: the first-second feature, seen in SN1987A data and due to accretion, disappears due to oscillation. (We assume no $\bar{\nu}_{\mu,\tau}$ during accretion and conventional form of $P_{\bar{\nu}_e \bar{\nu}_e}$.)

4 Points for a discussion

theoretical physics: Circumstantial evidence for high scale physics. Now need systematic classification of (SUSY) GUTs. Can we escape flavor problem?

$p \rightarrow K^+ \bar{\nu}$: Important to probe model predictions. New technique to proceed is needed. We should be ready to react to LHC findings.

oscillations: Assuming the correctness of the 3F picture, θ_{13} is the key to CP and mass hierarchy. Progresses are likely. "If the other leptonic angles are large, why this angle should be very small?"

absolute mass scale: Also very important for the general physical picture.

SN ν: Traditional $\bar{\nu}_e$ channel still rich of promises. However NC and ν_e detection important and not achieved. Theoretical progress expected/hoped.

Thanks for the attention!