Open Questions – The Big Picture (III)

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Neutrino Physics Summer School

Fermilab, July 2–13, 2007

Outline for this Lecture

1. What We Don't Know We Don't Know: Tests of Fundamental Laws
   - Lorentz Invariance Violation.
   - Do Neutrinos and Antineutrinos Have the Same Mass?
2. What Can We Learn from Charged Lepton Processes?
3. Neutrinos Have Mass – So What?
   - Neutrinos As Physics Beyond the Standard Model
   - What is the ν Standard Model?
4. Concluding Remarks, Summary, and the Road Ahead

[note: Questions are ALWAYS welcome]

1 – What We Don't Know We Don't Know

Are we missing anything? Is our picture of the ν world qualitatively incomplete?

Is there more new physics out there that can be best probed by neutrino experiments? What kind of experiments?

Neutrinos are expected to add non-trivial information, especially via neutrino oscillations. Remember the quantum interferometer aspect of neutrino oscillations – "deep" probe of very small effects. (This is the ONLY WAY we have been able to see neutrino masses after all!).

Example: **Tests of Lorentz Invariance Violation**

Violation of Lorentz-invariance would lead to a modified neutrino dispersion relation ($E^2 - |\vec{p}|^2 \neq m^2$) in a CPT-invariant or violating way.

Modified dispersion relations for the neutrino lead to deviations from the characteristic L/E–oscillatory behavior, which means that precision oscillation measurements can set unprecedented bounds on such effects!

One example

Spontaneous breaking of Lorentz invariance [Coleman+Glashow 1997, Colladay+Kostelecký 1997, Barger *et al.* 1998, also Bahcall, Barger, Marfatia 2002, AdG 2002]

$$\mathcal{L}_{\rm CPTV} \supset A^{ij}_{\mu}\bar{\nu}_i\gamma^{\mu}\nu_j + B_{\mu\nu}\bar{\nu}\sigma^{\mu\nu}\nu + H.c. + \ldots$$

where A_μ is interpreted as having a vacuum expectation value in the "time" direction $A^{\mu}_{ij} = (V_{ij}/2, \vec{0})$, (in the reference frame where we perform experiments), $B_{\mu\nu}$ can have a vev in some ij direction, etc...

In the limit $E, |\vec{p}| \gg m, V$,

$$E = |\vec{p}| + \frac{m^2}{2|\vec{p}|} \pm \frac{V}{2}$$

This looks just like matter effects!

$\pm$ refers to neutrinos/antineutrinos $\rightarrow$ CPT violation (Does NOT fit LSND + ATM + SOL).

By the way, taylor-made Lorentz violation does fit all neutrino data (including LSND, Mini-BooNE), but it is very, very ugly! [AdG, Grossman, hep-ph/0602237]

We can use intuition of matter effects to understand what is going on (V_{ij} are "ether" potentials). *E.g.*, two-flavor "ether" oscillations

$$P_{ex} = \sin^2\theta_{\rm eff}\sin^2\left(\frac{\Delta_{\rm eff}}{2}L\right)$$

$$\Delta_{\rm eff} = \sqrt{(\Delta\cos 2\theta - V)^2 + (\Delta\sin 2\theta + V_{ex})^2}$$

$$\Delta_{\rm eff}\sin 2\theta_{eff} = \Delta\sin 2\theta + V_{ex}$$

$$\Delta_{\rm eff}\cos 2\theta_{eff} = \Delta\cos 2\theta - V_{ex}$$

where $\Delta = \Delta m^2/(2E)$, $V = 2(V_{ee} - V_{xx})$, and for antineutrinos $V_{ij} \to -V_{ij}$

$\Rightarrow$ neutrinos and antineutrinos have different effective mixing angles (which are energy dependent), and the L/E oscillatory behavior is violated!)

One can probe these "ether effects" through several oscillation measurements. Order of magnitude estimates of bounds are easy to make $\Delta m^2/(2E) > V_{ij}$ (conservative!, read "certainly bigger/less than"):

- Atmospheric: $V_{\mu\tau,\mu\mu,\tau\tau} < 10^{-3}$ eV^2/GeV$\rightarrow$ $< 10^{-21}$ GeV
- Solar + KamLAND: $V_{e\mu,e\tau} < 10^{-6}$ eV^2/MeV$\rightarrow$ $< 10^{-21}$ GeV

detailed analysis see, *e.g.* Gonzalez-Garcia, Maltoni, hep-ph/0404085

This is a MUCH richer phenomenon. There are even studies of whether you can explain all the neutrino data with Lorentz invariance violation (and no neutrino masses)! Keep in mind that there are MANY free parameter you can tune.

[*e.g.* Kostelecký+Mewes, 2003, Barger *et al.*, 2007]

(Specific) Test of CPT-invariance: is $m_\nu = m_{\bar{\nu}}$?

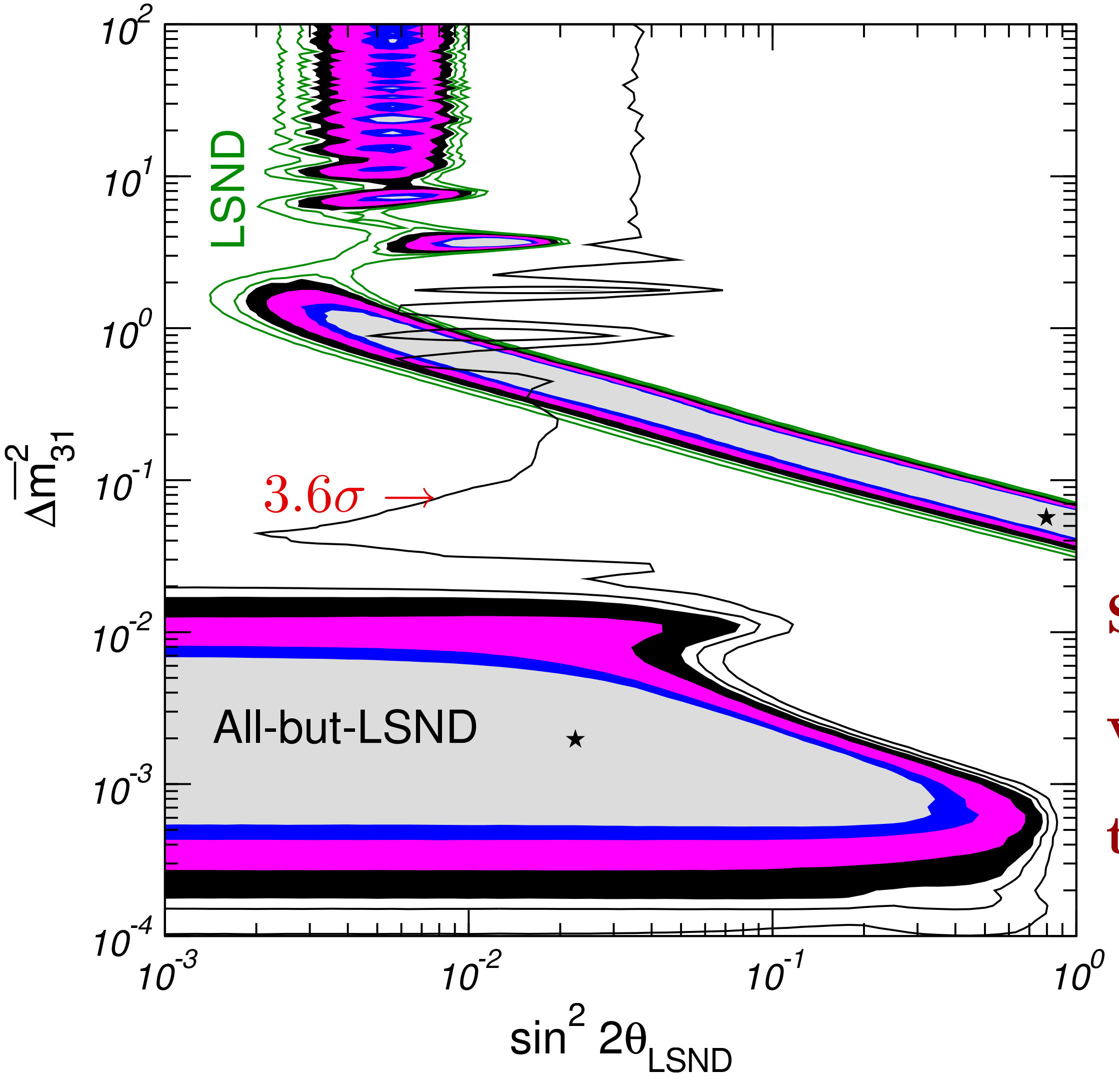
Different masses for neutrinos and antineutrinos were postulated as a potential solution to the LSND anomaly (and also helped address a small problem with SN1987A data) in Murayama+Yanagida (2001), and further pursued in Barenboim *et al.*(2001–2003).

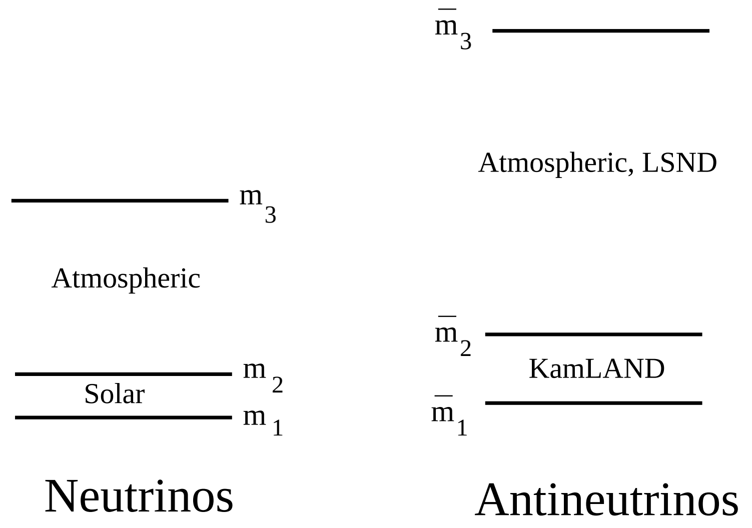
Currently, this form of CPT-violating solution to all neutrino puzzles plus LSND (and only active (anti)neutrinos) is experimentally severely disfavored

- KamLAND and solar data "agree" ($\Delta m^2_{\rm sol} = \Delta\bar{m}^2_{\rm Kam}$)
- $\Delta\bar{m}^2_{\rm atm} \ll \Delta\bar{m}^2_{\rm LSND}$

+ Given that there is no evidence for CPT violation, these (and other) "precision neutrino oscillation experiments" allows one to bound how much CPT can be violated in the neutrino sector.

[Gonzalez-Garcia, Maltoni, Schwetz (2003)]





SuperK atmospheric data exclude values of $\Delta\bar{m}^2_{13}$ required to address the LSND anomaly at 3σ

Solar and KamLAND data, interpreted in terms of two-flavor neutrino oscillations, agree!!!!! This is a remarkable achievement of Physics.

"new SM" assumed (including CPT-invariance)

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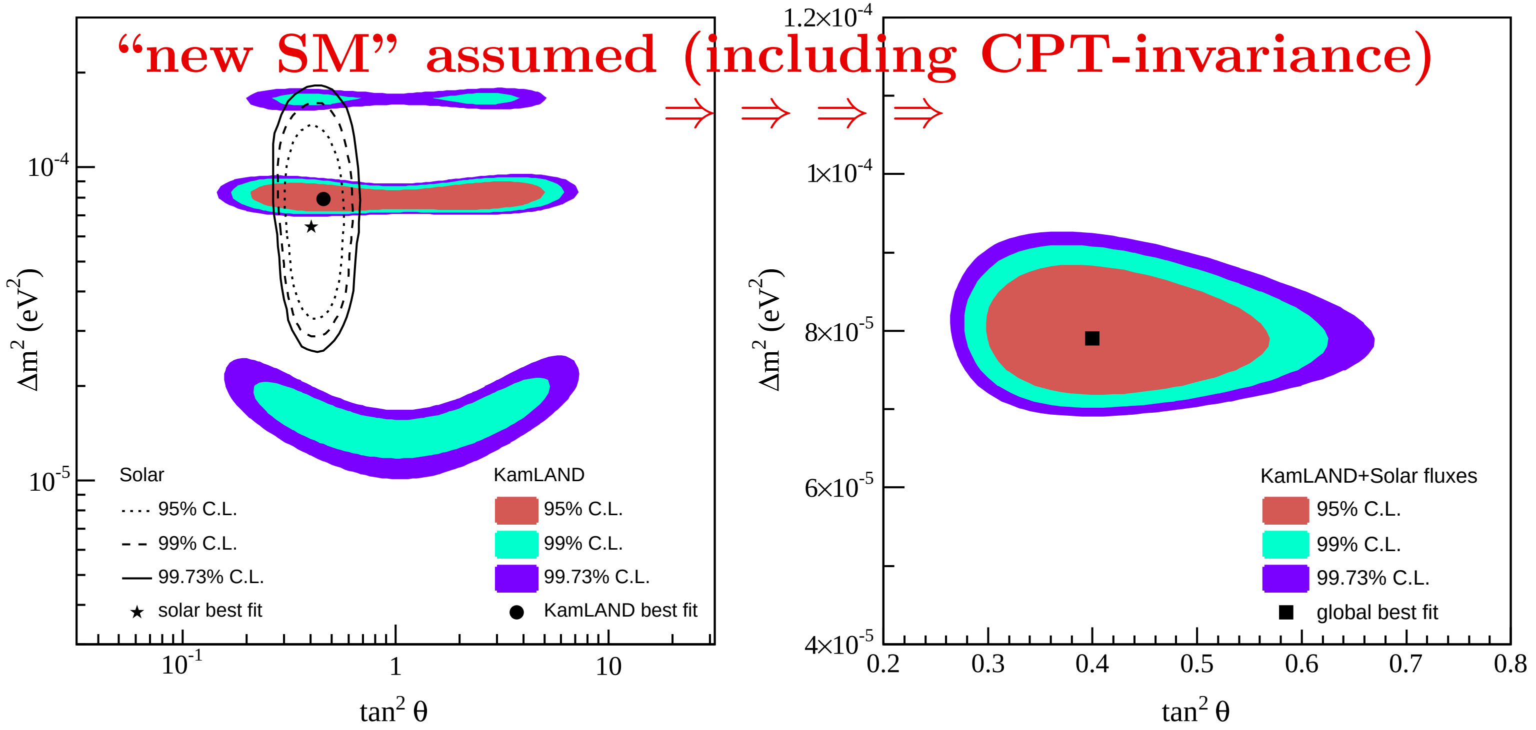


example:

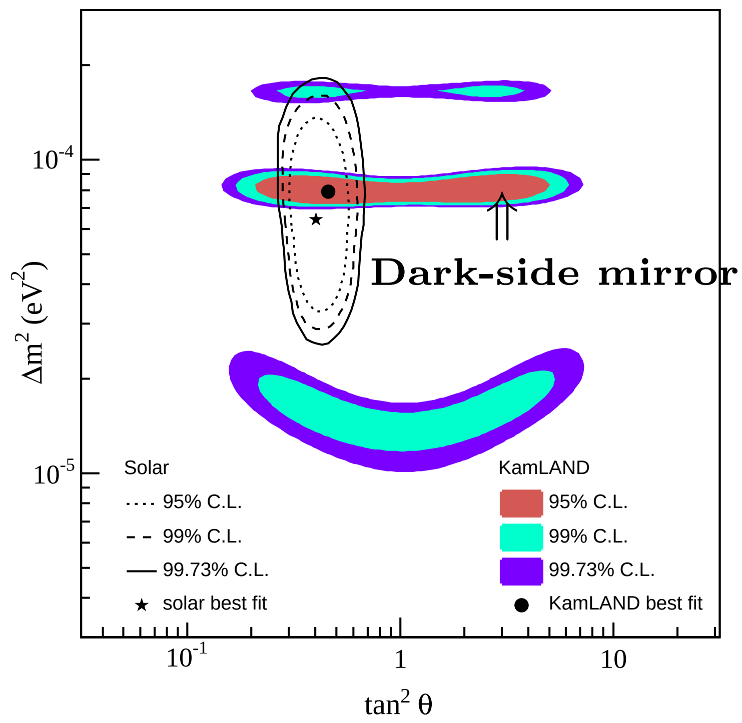
Assuming CPT-Invariance, we can bound CPT-violating observables

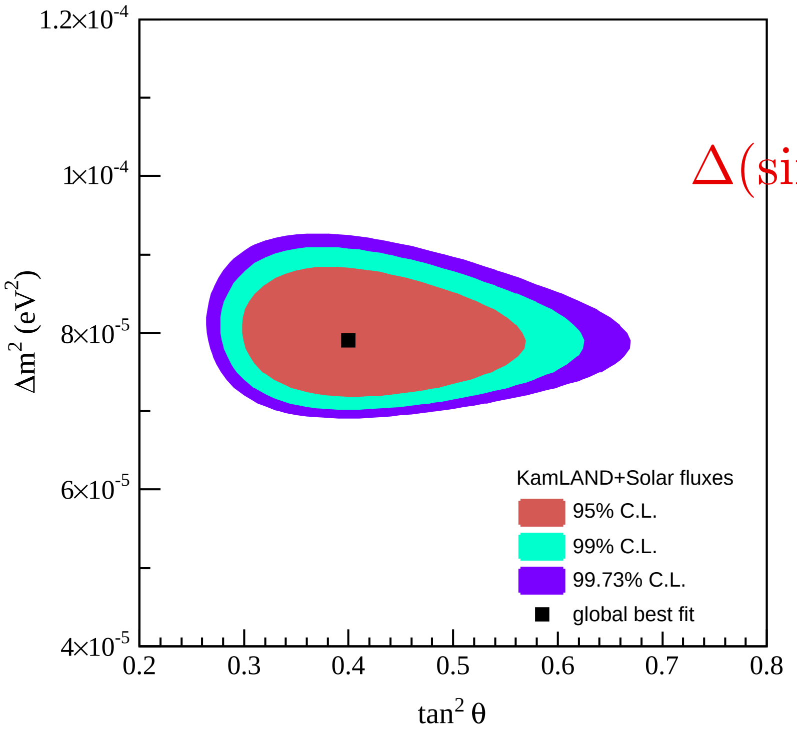
$$\Delta(\Delta m^2) < 1.2 \times 10^{-4}\ \mathrm{eV}^2$$

From solar data!

$$\Delta(\sin^2\theta) < 0.7$$

will not improve much – matter efffects do not matter!





$\Downarrow$

$$\Delta(\sin^2\theta) = |\cos 2\theta|?$$

$$(\theta + \bar{\theta} = \pi/2?)$$

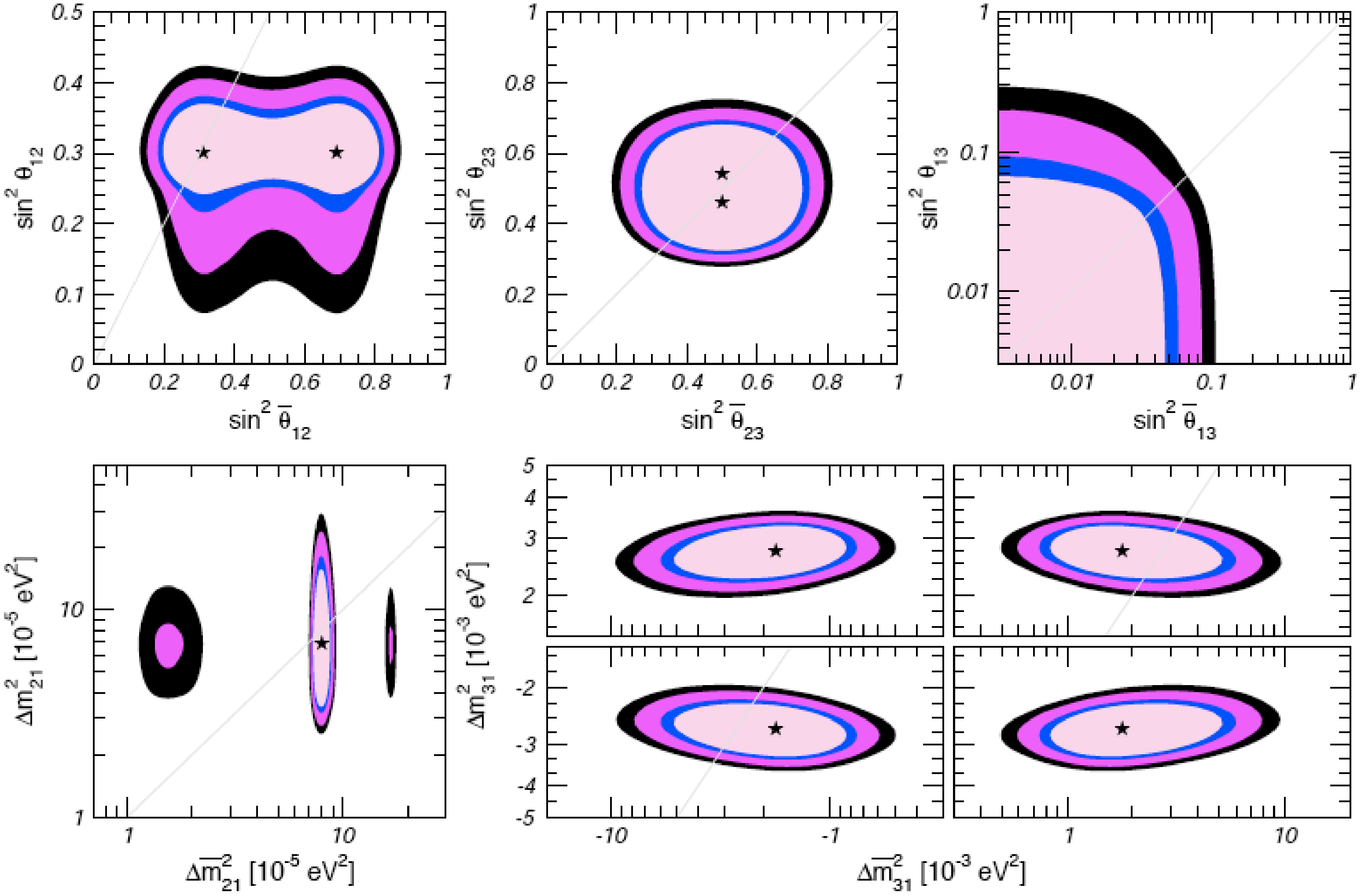


Fig. 49. Allowed regions for neutrino and anti-neutrino mass splittings and mixing angles in the CPT violating scenario. Different contours correspond to the two-dimensional allowed regions at 90%, 95%, 99% and 3σ CL. The best fit point is marked with a star.

Gonzalez-Garcia, Maltoni, hep-ph/0704.1800

In More Detail: Can We Do Better?

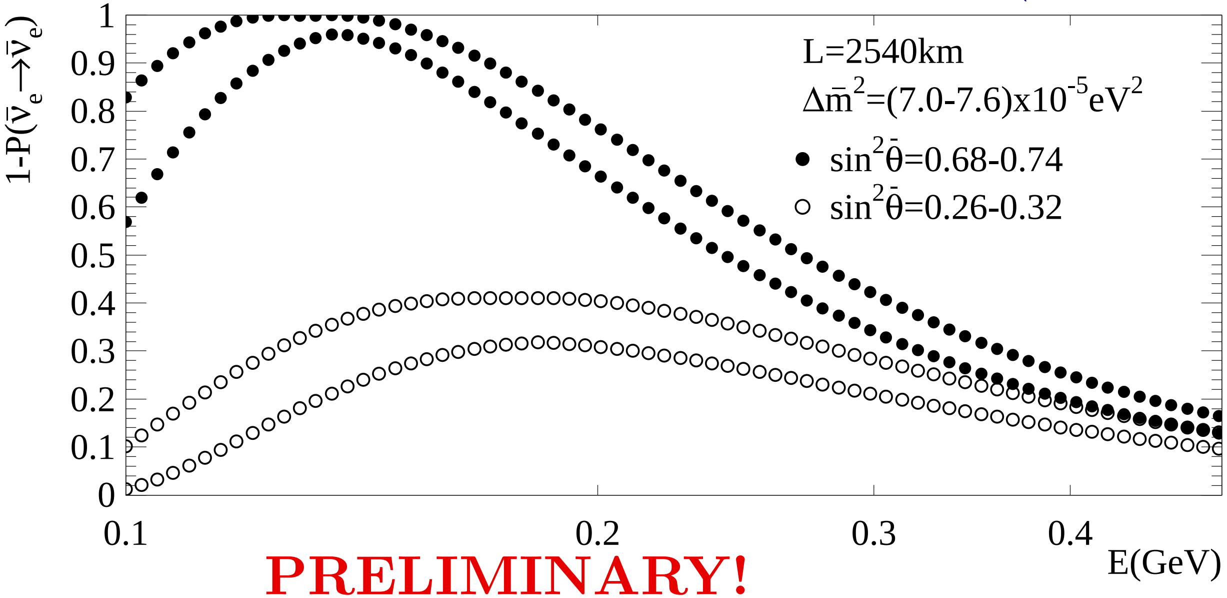
In order to address whether CPT-invariance is "maximally violated" in the solar mixing we need:

- Antineutrinos
- Matter effects

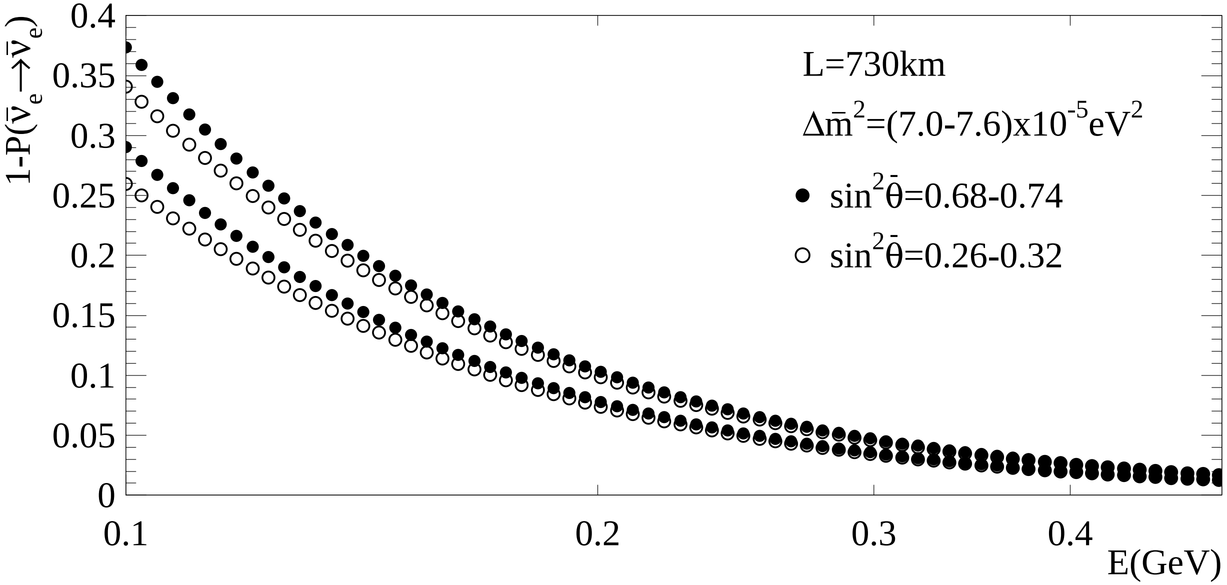
Possible experiments include

- Supernova neutrinos $\Rightarrow P_{\bar{\nu}_e} \simeq \cos^2\theta$; can it really be done?
- Very long baseline $\bar{\nu}_e \leftrightarrow \bar{\nu}_{\mu,e}$ searches with frequency $\Delta\bar{m}^2_{\rm Kam}$ $\Rightarrow$
- ?

$(\bar{U}_{e3} = 0)$



PRELIMINARY!



"KamLAND" LBL Oscillations

- low energies
- very long baselines
- antineutrinos

$\Downarrow$

Small statistics, hard to detect, large backgrounds,...

BNL-setup, β-beams, NuFact ?

[AdG+Peña-Garay, hep-ph/0406301]

Summary: How Powerful are These Tests Anyway?

- "Order one" CPT-violating observables are allowed: improvements expected from more "precision neutrino data" (which we expect to get a hold of with more oscillation data)
- $\Delta(\Delta m^2_{12}) \equiv \Delta(m^2_2) - \Delta(m^2_1)$ – Need to ignore "conspiracies" in order to interpret bound
- *cf.* with $|m^2(K^0) - m^2(\bar{K}^0)| < 0.25$ eV^2 – neutrino bounds much better? This is a "model dependent" question.
- Bounding CPT-violating leptonic mixing angles may be very challenging – Is this another job for (next-)next-generation LBL experiments?

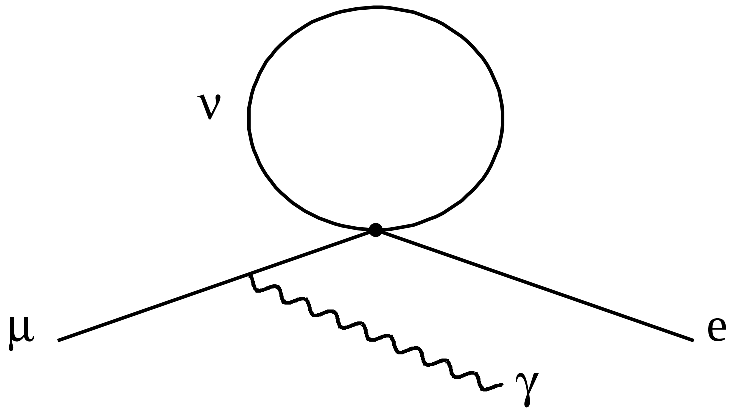
2 – What Can We Learn From Charged Lepton Processes

We have established beyond reasonable doubt that **flavor mixing in the lepton sector is large**. We did this by observing neutrino oscillations. Can we see evidence for this phenomenon in **charged leptons**? Are there processes in the charged lepton sector that violate lepton flavor?

Let me add very quickly that, for all practical purposes, **charged leptons do not mix**. [see E.K. Akhmedov, hep-ph/0706.1216]

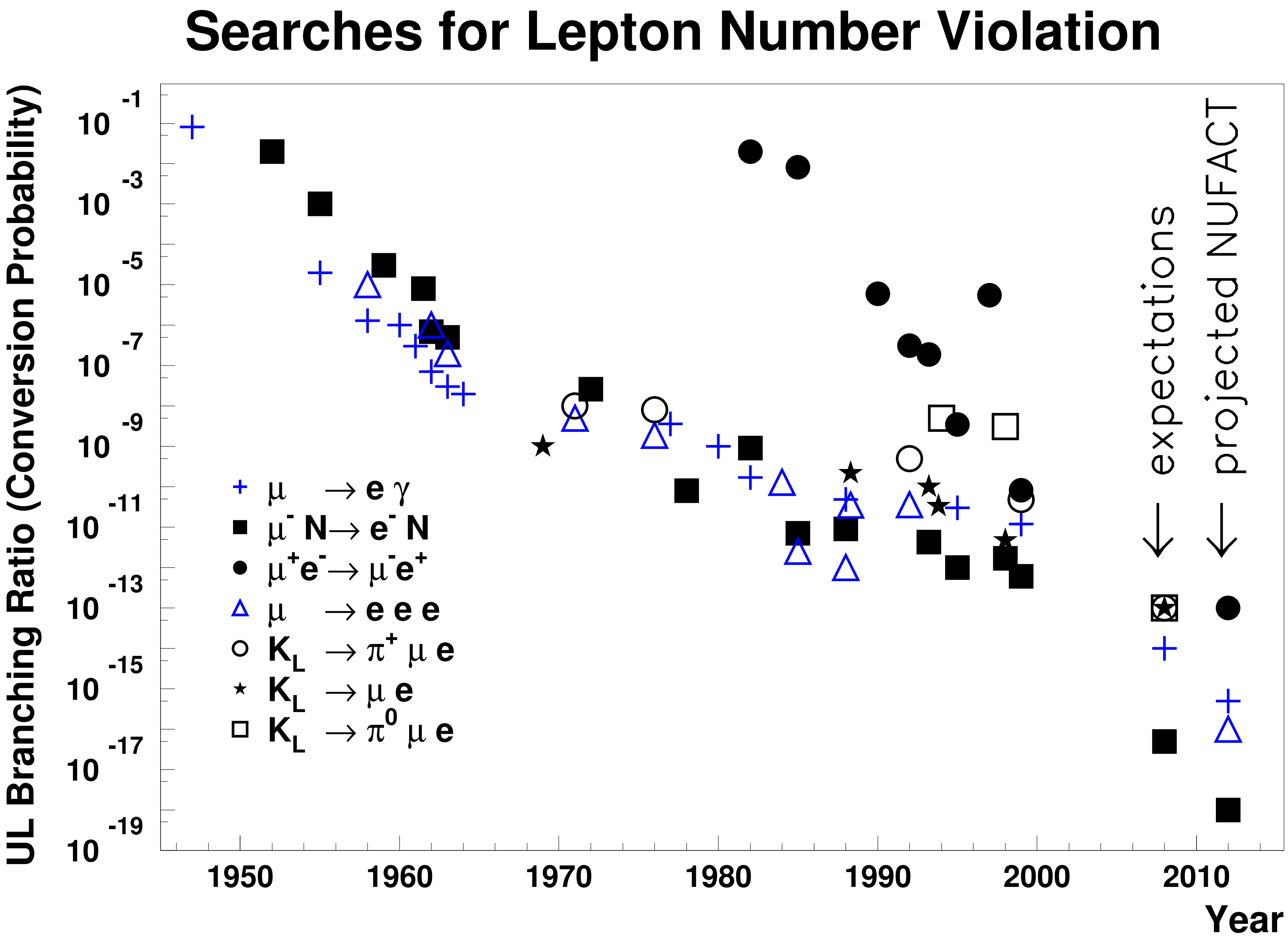
They do however, interact more readily than neutrinos, while the heavy charged leptons decay "fast." They are also much easier to see!

Ever since it was established that $\mu \to e\nu\bar{\nu}$, people have searched for $\mu \to e\gamma$, which was thought to arise at one-loop, like this:



The fact that $\mu \to e\gamma$ did not happen, led one to postulate that the two neutrino states produced in muon decay were distinct, and that $\mu \to e\gamma$, and other similar processes, were forbidden due to symmetries.

To this date, these so-called individual lepton-flavor numbers seem to be conserved in the case of charged lepton processes, in spite of many decades of (so far) fruitless searching…



[hep-ph/0109217]

SM Expectations

In the old SM, the rate for charged lepton flavor violating processes is trivial to predict. It vanishes because individual lepton number is conserved:

- $N_\alpha(\text{in}) = N_\alpha(\text{out})$, for $\alpha = e, \mu, \tau$.

However, the old SM is wrong: NEUTRINOS change flavor after propagating a finite distance.

- $\nu_\mu \to \nu_\tau$ and $\bar{\nu}_\mu \to \bar{\nu}_\tau$ — atmospheric experiments ["indisputable"];
- $\nu_e \to \nu_{\mu,\tau}$ — solar experiments ["indisputable"];
- $\bar{\nu}_e \to \bar{\nu}_{\text{other}}$ — reactor neutrinos ["indisputable"];
- $\nu_\mu \to \nu_{\text{other}}$ from accelerator experiments ["really strong"].

The simplest and **only satisfactory** explanation of **all** this data is that neutrinos have distinct masses, and leptons mix.

Hence, in the "New Standard Model" (νSM, equal to the old Standard Model plus operators that lead to neutrino masses) $\mu \to e\gamma$ is allowed, like other Flavor Changing Neutral Current processes which have already been observed in the quark sector (like $b \to s\gamma$).

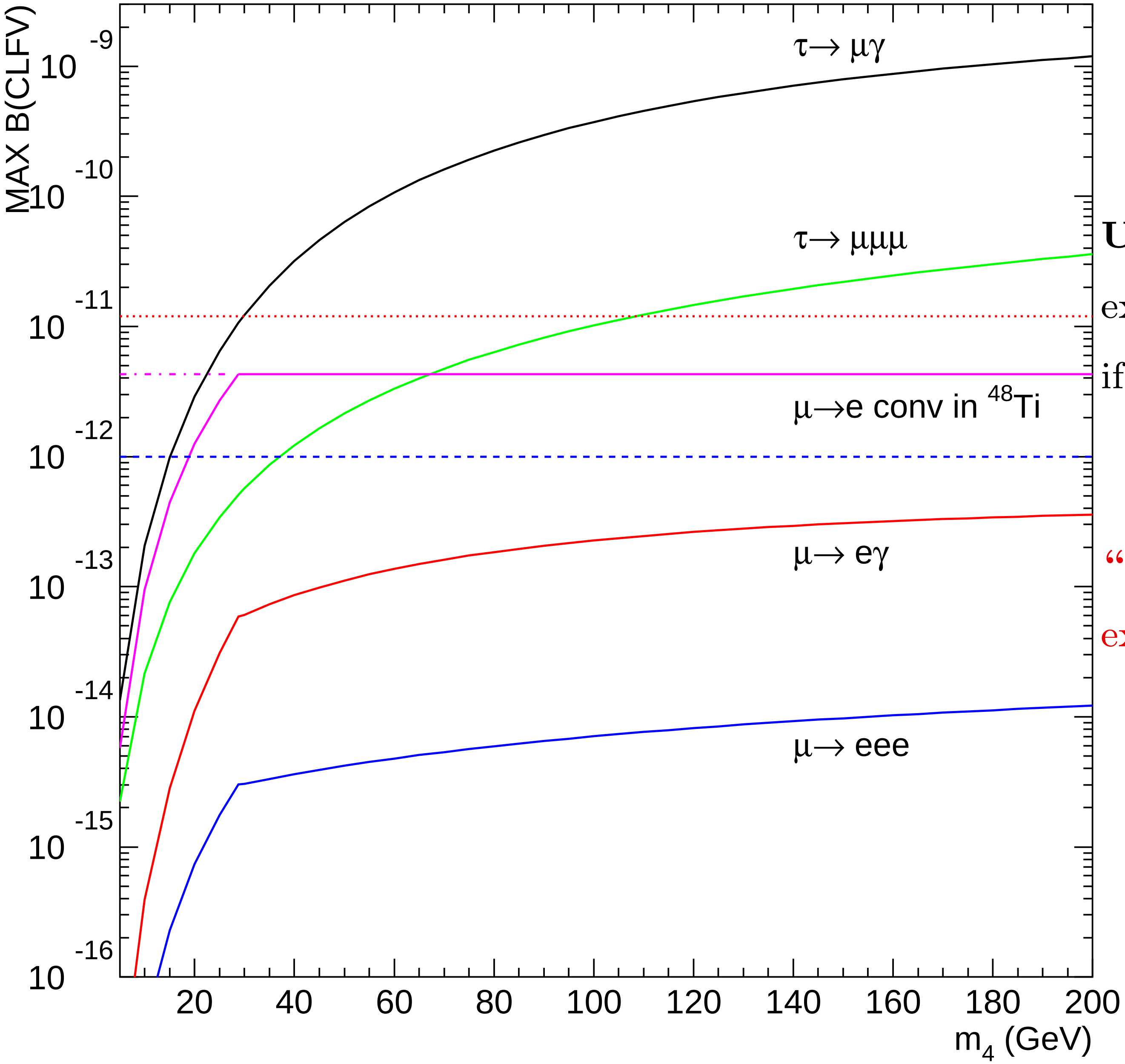
Unfortunately, we do not know the νSM expectation for charged lepton flavor violating processes $\to$ **we don't know the νSM Lagrangian !**

However, one contribution is known to be there: neutrino–W-boson loops (exact analog to the quark sector). In the case of charged leptons, the **GIM suppression is very efficient**. . .

$$Br(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i}U_{ei}\frac{\Delta m^2_{1i}}{M^2_W}\right|^2 < 10^{-54},$$

[$U_{\alpha i}$ are the elements of the leptonic mixing matrix, $\Delta m^2_{1i} \equiv m^2_i - m^2_1$, $i = 2, 3$ are the neutrino mass-squared differences]

Example: Seesaw Lagrangian, minus theoretical prejudices



(more on this later)

Upper bounds not far from experimental bounds if $M_N \sim M_{\rm weak}$

"Natural" bounds way below experimental bounds (not shown)

[AdG hep-ph/0706.1732]

Furthermore, there are strong theoretical reasons to believe that the expected rate for flavor changing violating processes is much, much larger than naive νSM predictions and that discovery is just around the corner.

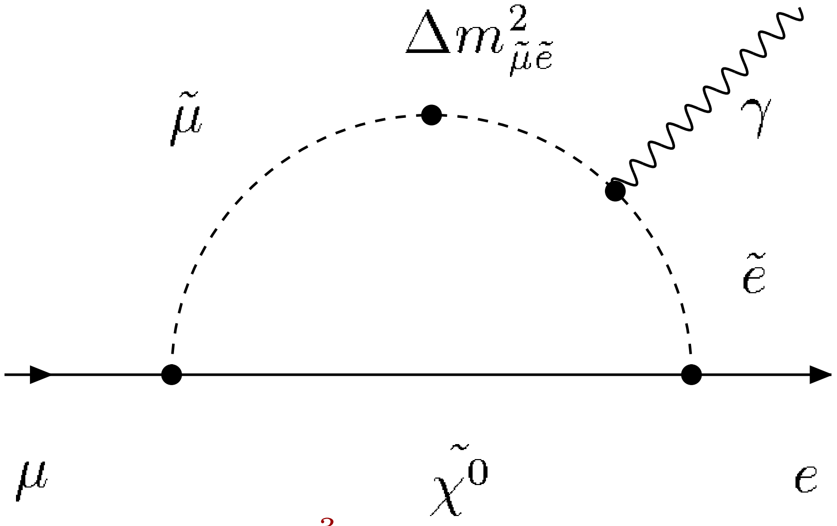
Due to the lack of SM "backgrounds," searches for rare muon processes, including $\mu \to e\gamma$, $\mu \to e^+e^-e$ and $\mu + Z \to e + Z$ (μ-e–conversion in nuclei) are considered ideal laboratories to probe effects of new physics at or even slightly above the electroweak scale.

Indeed, if there is new physics at the electroweak scale (as many theorists will have you believe) and if mixing in the lepton sector is large "everywhere" the question we need to address is quite different:

Why haven't we seen charged lepton flavor violation yet?

Theorists spend a lot of their creativity "protecting" new electroweak physics models from unacceptably large charged lepton flavor violation!

"Bread and Butter" SUSY plus High Energy Seesaw



$\rightarrow \ \theta_{\tilde{e}\tilde{\mu}} \sim \frac{\Delta m^2_{\tilde{e}\tilde{\mu}}}{\tilde{m}}$

$Br(\mu \to e\gamma) \simeq \frac{\alpha^3\pi}{G_F^2 \tilde{m}^4}\theta^2_{\tilde{e}\tilde{\mu}}$, $\tilde{m}^2$ is a typical supersymmetric mass.

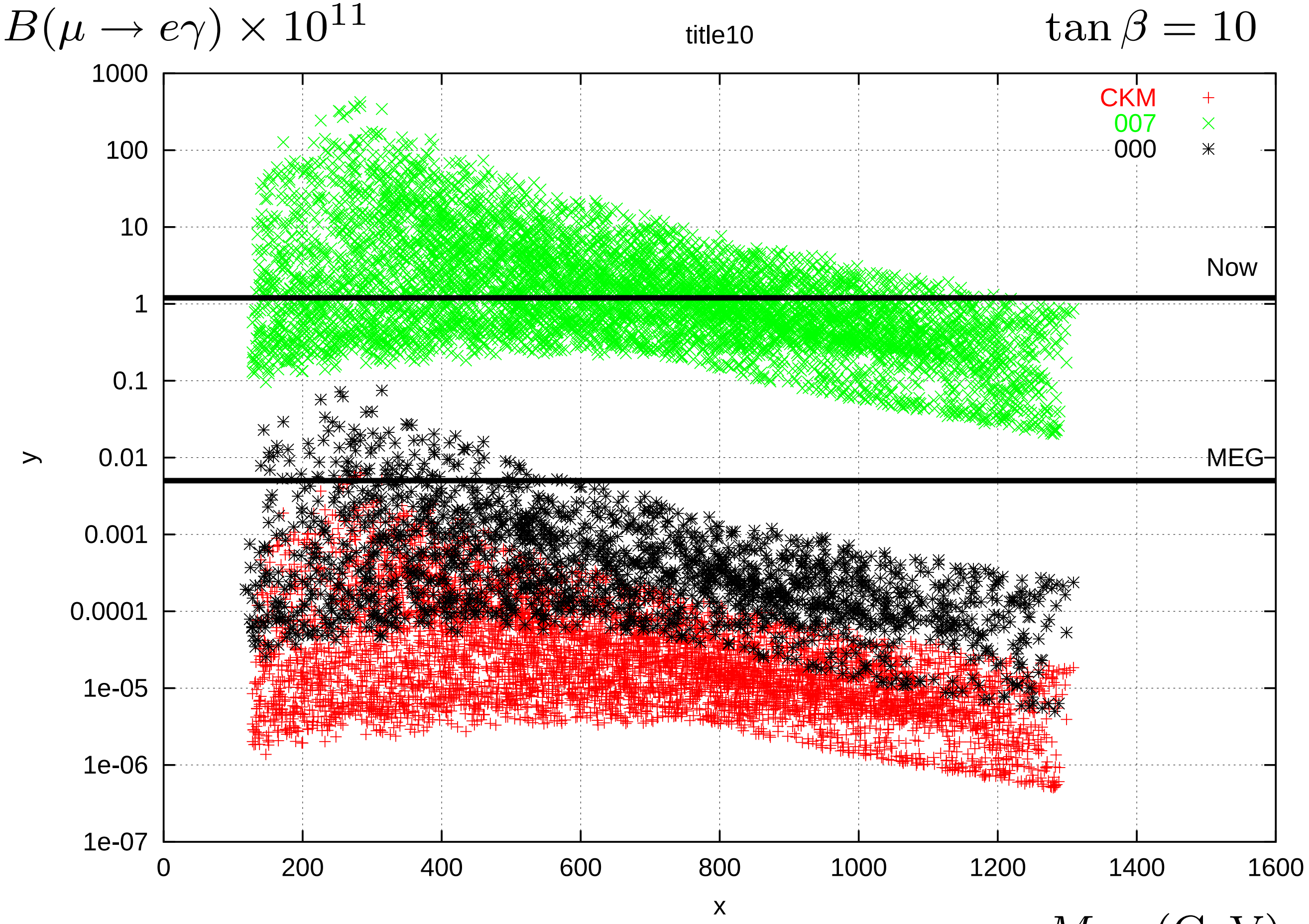
$\theta_{\tilde{e}\tilde{\mu}}$ measures the "amount" of flavor violation.

For $\tilde{m}$ around 1 TeV, $\theta_{\tilde{e}\tilde{\mu}}$ is severely constrained. Very big problem.

"Natural" solution: $\boxed{\theta_{\tilde{e}\tilde{\mu}} = 0}$ $\rightarrow$ modified by quantum corrections.

Rates calculable in seesaw model, after ansatz for Yukawa couplings

$B(\mu \to e\gamma) \times 10^{11}$ $\tan\beta = 10$



$M_{1/2}$(GeV)

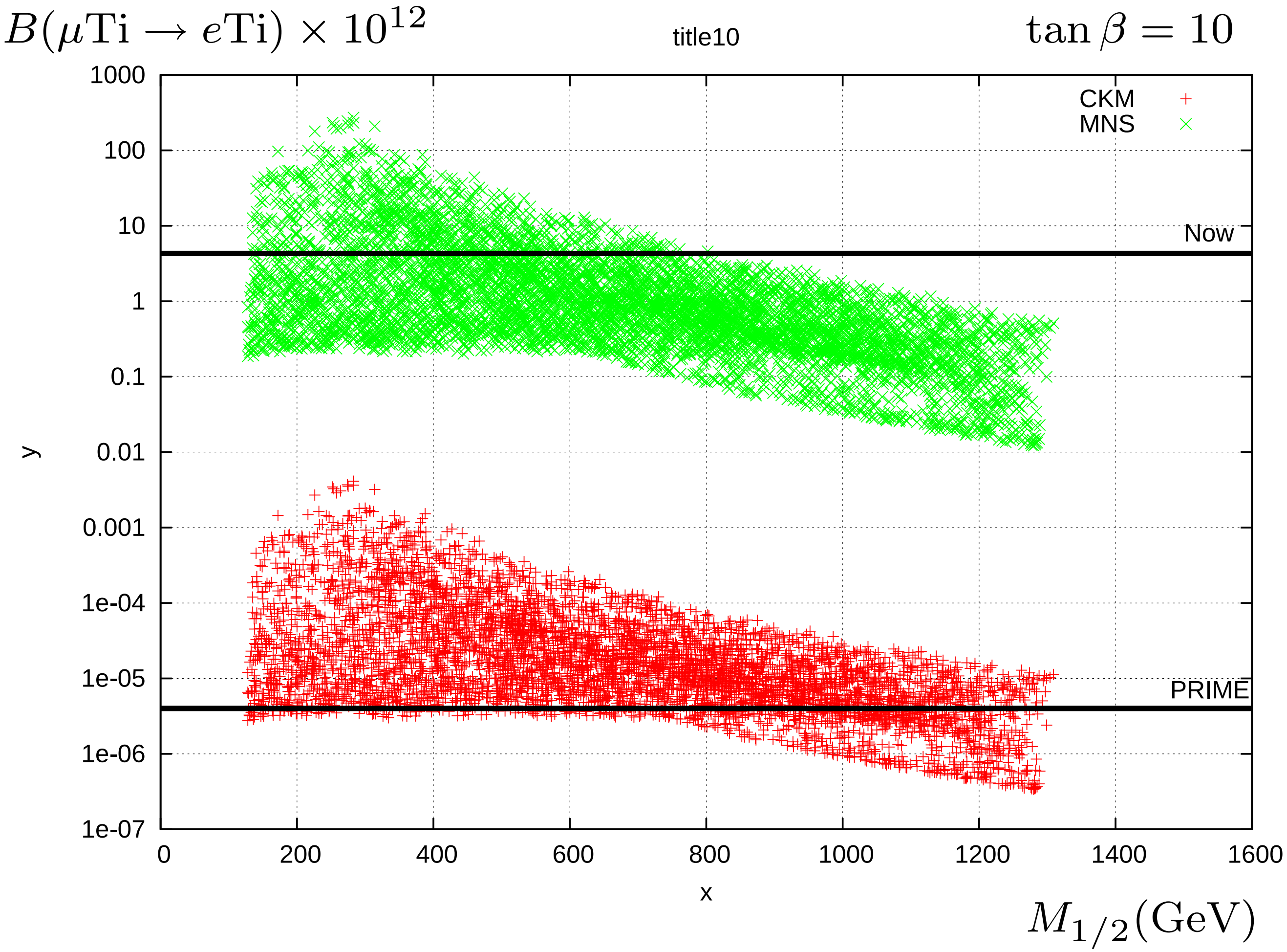
$SO(10)$ inspired model.

remember B scales with y^2.

$B(\mu \to e\gamma) \propto M_R^2[\ln(M_{Pl}/M_R)]^2$

[Calibbi, Faccia, Masiero, Vempati, hep-ph/0605139]

$\mu - e$ conversion is at least as sensitive as $\mu \to e\gamma$



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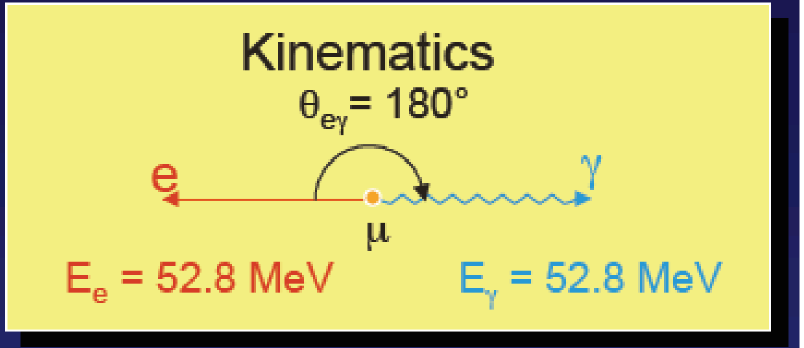
$B(\mu \to e\gamma) \propto M_R^2[\ln(M_{Pl}/M_R)]^2$

[Calibbi, Faccia, Masiero, Vempati, hep-ph/0605139]

Principal Features of $\mu^+ \to e^+\gamma$ Experiment

- Stop μ^+ in thin target
  - Measure energies of e^+ (E_e) and γ (E_γ)
  - Measure angle between e^+ and γ ($\Delta\theta$)
  - Measure time between e^+ and γ (Δt)



- Background from radiative decay – $\mu \to e\nu\nu\gamma$
  - Heavily suppressed for $E_\nu \to 0$, photon opposite electron
  - Not dominant background when rate high enough to reach 10^{-13} sensitivity
- Main source of background:
  - Accidental coincidences of e^+ from Michel decay ($\mu^+ \to e^+ \nu_e \nu_\mu$) + random γ from radiative decay or annihilation in flight
  - E_e distribution peaks near 53 MeV ($x = E_e / E_{max}$)
  - E_γ distribution in interval dy near y=1 given by $dN_\gamma \propto (1-y)dy$ ($y = E_\gamma / E_{max}$)

$\Rightarrow$ background/signal $\propto \Delta E_e \times (\Delta E_\gamma)^2 \times \Delta t \times (\Delta\theta)^2 \times$ Rate

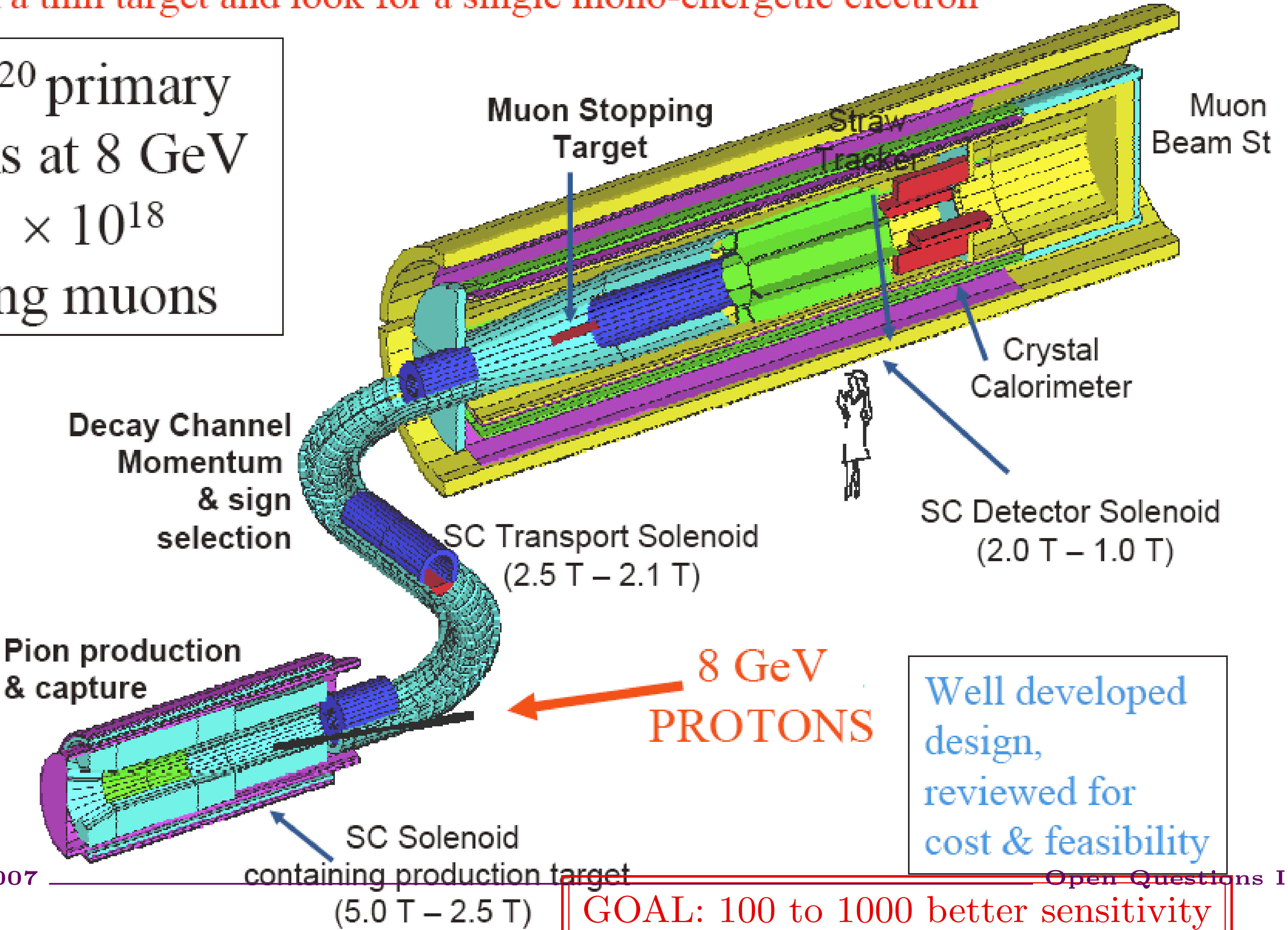
GOAL: 100 to 1000 better sensitivity

W. Molzon, UC Irvine NuFact 2006 - Status of the MEG Experiment August 28, 2006 3

MECO CONCEPT (Molzon et al.) ⇒ mu2e at FNAL?

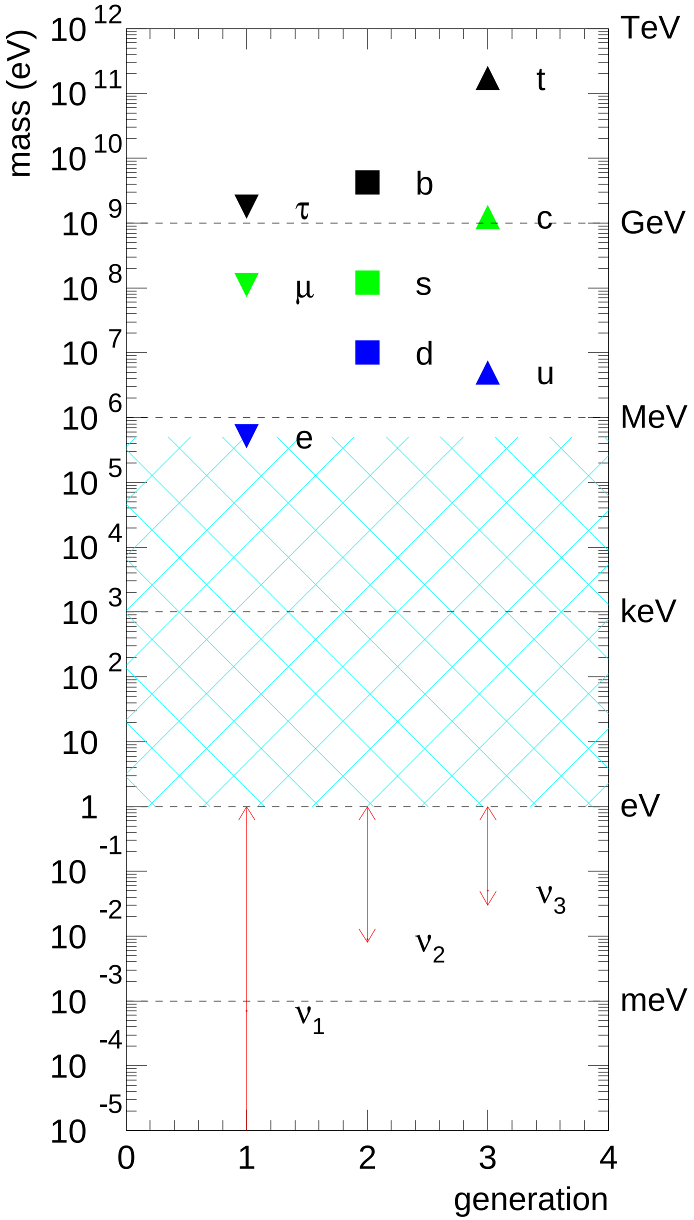
Stop muons in a thin target and look for a single mono-energetic electron

4×10^{20} primary protons at 8 GeV yield 1×10^{18} stopping muons



Well developed design, reviewed for cost & feasibility

GOAL: 100 to 1000 better sensitivity



3 – NEUTRINOS HAVE MASS

albeit very tiny ones...

SO WHAT?

Only* "Palpable" Evidence of Physics Beyond the Standard Model

The SM we all learned in school predicts that neutrinos are strictly massless. Hence, massive neutrinos imply that the the SM is incomplete and needs to be replaced/modified.

Furthermore, the SM has to be replaced by something qualitatively different.

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* There is only a handful of questions our model for fundamental physics cannot explain properly. These are in order of palpabiloity (these are personal. Feel free to complain)

- What is the physics behind electroweak symmetry breaking? (Higgs *or* not in SM).
- What is the dark matter? (not in SM).
- Why does the Universe appear to be accelerating? Why does it appear that the Universe underwent rapid acceleration in the past? (not in SM – Is this "particle physics?").

Standard Model in One Slide, No Equations

The SM is a quantum field theory with the following defining characteristics:

- Gauge Group ($SU(3)_c \times SU(2)_{\rm L} \times U(1)_{\rm Y}$);
- Particle Content (fermions: Q, u, d, L, e, scalars: H).

Once this is specified, the SM is unambiguously determined:

- Most General Renormalizable Lagrangian;
- Measure All Free Parameters, and You Are Done! (after several decades of hard experimental work. . .)

If you follow these rules, neutrinos have no mass. Something has to give.

What is the New Standard Model? [νSM]

The short answer is – WE DON'T KNOW. Not enough available info!

$$\Updownarrow$$

Equivalently, there are several completely different ways of addressing neutrino masses. The key issue is to understand what else the νSM candidates can do. [are they falsifiable?, are they "simple"?, do they address other outstanding problems in physics?, etc]

We need more experimental input, and it looks like it may be coming in the near/intermediate future!

The νSM – Take 1

SM as an effective field theory – non-renormalizable operators

$$\mathcal{L}_{\nu\text{SM}} \supset -\lambda_{ij}\frac{L^i H L^j H}{2M} + \mathcal{O}\left(\frac{1}{M^2}\right) + H.c.$$

There is only one dimension five operator [Weinberg, 1979]. If $M \gg 1$ TeV, it leads to only one observable consequence...

$$\text{after EWSB } \mathcal{L}_{\nu\text{SM}} \supset \frac{m_{ij}}{2}\nu^i\nu^j; \quad m_{ij} = \lambda_{ij}\frac{v^2}{M}.$$

- Neutrino masses are small: $M \gg v \rightarrow m_\nu \ll m_f$ ($f = e, \mu, u, d$, etc)
- Neutrinos are Majorana fermions – Lepton number is violated!
- νSM effective theory – not valid for energies above at most M.
- What is M? First naive guess is that M is the Planck scale – does not work. Data require $M < 10^{15}$ GeV (anything to do with the GUT scale?)

What else is this “good for”? Depends on the ultraviolet completion!

Note that this VERY similar to the "discovery" weak interactions.
Imagine the following model:

$U(1)_{E\&M} \ + \ e(q=-1),\ \mu(q=-1),\ \nu_e(q=0),\ \nu_\mu(q=0).$

The most general renormalizable Lagrangian explains *all* QED phenomena once all couplings are known (α, m_f).

New physics: the muon decays! $\mu^- \to e^-\bar{\nu}_e\nu_\mu$. This can be interpreted as evidence of effective four fermion theory (nonrenormalizable operators):

$$-\frac{4G_F}{\sqrt{2}}\sum_\gamma g_\gamma\left(\bar{e}\Gamma^\gamma\nu\right)\left(\bar{\nu}\Gamma_\gamma\mu\right), \qquad \Gamma_\gamma = 1, \gamma_5, \gamma_\mu, \ldots$$

Prediction: will discover new physics at an energy scale **below** $\sqrt{1/G_F} \simeq 250$ GeV. We know how this turned out $\Rightarrow$ $W^\pm, Z^0$ discovered slightly below 100 GeV!

Full disclosure:

All higher dimensional operators are completely negligible, **except** those that mediate proton decay, like:

$$\frac{\lambda_B}{M^2}QQQL$$

The fact that the proton does not decay forces M/λ_B to be much larger than the energy scale required to explain neutrino masses.

Why is that? We don't know...

The νSM – Take 2

Why don't we just enhance the fermion sector of the theory?

One may argue that it is trivial and simpler to just add

$$\mathcal{L}_{\rm Yukawa} = -y_{i\alpha} L^i H N^\alpha + H.c.,$$

and neutrinos get a mass like all other fermions: $m_{i\alpha} = y_{i\alpha} v$

- Data requires $y < 10^{-12}$. Why so small?
- Neutrinos are Dirac fermions. $B - L$ exactly conserved.
- νSM is a renormalizable theory.

This proposal, however, violates the rules of the SM (as I defined them)! The operator $\frac{M_N}{2} NN$, allowed by all gauge symmetries, is absent. In order to explain this, we are forced to add a symmetry to the νSM. The simplest candidate is a global $U(1)_{B-L}$.

$U(1)_{B-L}$ is upgraded from accidental to fundamental (global) symmetry.

Standard Model in One Slide, No Equations, Encore

The SM is a quantum field theory with the following defining characteristics:

- Gauge Group ($SU(3)_c \times SU(2)_{\rm L} \times U(1)_{\rm Y}$);
- Particle Content (fermions: Q, u, d, L, e, scalars: H).

Once this is specified, the SM is unambiguously determined:

- Most General Renormalizable Lagrangian;
- Measure All Free Parameters, and You Are Done.

This model has *accidental global symmetries*. In particular, the anomaly free global symmetry is preserved: $U(1)_{B-L}$.

New Standard Model, Dirac Neutrinos

The SM is a quantum field theory with the following defining characteristics:

- Gauge Group ($SU(3)_c \times SU(2)_{\rm L} \times U(1)_{\rm Y}$);
- Particle Content (fermions: Q, u, d, L, e, N, scalars: H);
- Global Symmetry $U(1)_{B-L}$.

Once this is specified, the SM is unambiguously determined:

- Most General Renormalizable Lagrangian;
- Measure All Free Parameters, and You Are Done.

Naively not too different, but nonetheless qualitatively different $\rightarrow$ enhanced symmetry sector!

On very small Yukawa couplings

We would like to believe that Yukawa couplings should naturally be of order one.

Nature, on the other hand, seems to have a funny way of showing this. Of all known fermions, only one (1) has a "natural" Yukawa coupling – the top quark!

Regardless there are several very different ways of obtaining "naturally" very small Yukawa couplings. They require the more new physics.

Massive Neutrinos and the Seesaw Mechanism

A simple[a], renormalizable Lagrangian that allows for neutrino masses is

$$\mathcal{L}_\nu = \mathcal{L}_{\rm old} - \lambda_{\alpha i} L^\alpha H N^i - \sum_{i=1}^{3} \frac{M_i}{2} N^i N^i + H.c.,$$

where N_i ($i = 1, 2, 3$, for concreteness) are SM gauge singlet fermions. $\mathcal{L}_\nu$ is the most general, renormalizable Lagrangian consistent with the SM gauge group and particle content, plus the addition of the N_i fields.

After electroweak symmetry breaking, $\mathcal{L}_\nu$ describes, besides all other SM degrees of freedom, six Majorana fermions: **six neutrinos.**

[a] Only requires the introduction of three fermionic degrees of freedom, no new interactions or symmetries.

To be determined from data: λ and M.

The data can be summarized as follows: there is evidence for three neutrinos, mostly "active" (linear combinations of ν_e, ν_μ, and ν_τ). At least two of them are massive and, if there are other neutrinos, they have to be "sterile."

This provides very little information concerning the magnitude of M_i (assume $M_1 \sim M_2 \sim M_3$)

Theoretically, there is prejudice in favor of very large M: $M \gg v$. Popular examples include $M \sim M_{\rm GUT}$ (GUT scale), or $M \sim 1$ TeV (EWSB scale).

Furthermore, $\lambda \sim 1$ translates into $M \sim 10^{14}$ GeV, while thermal leptogenesis requires the lightest M_i to be around 10^{10} GeV.

we can impose very, very few experimental constraints on M

What We Know About M:

- $M=0$: the six neutrinos "fuse" into three Dirac states. Neutrino mass matrix given by $\mu_{\alpha i} \equiv \lambda_{\alpha i} v$.

  The symmetry of $\mathcal{L}_\nu$ is enhanced: $U(1)_{B-L}$ is an exact global symmetry of the Lagrangian if all M_i vanish. Small M_i values are 'tHooft natural.

- $M \gg \mu$: the six neutrinos split up into three mostly active, light ones, and three, mostly sterile, heavy ones. The light neutrino mass matrix is given by $m_{\alpha\beta} = \sum_i \lambda_{\alpha i} M_i^{-1} \lambda_{\beta i}$.

  This the **seesaw mechanism.** Neutrinos are Majorana fermions. Lepton number is not a good symmetry of $\mathcal{L}_\nu$, even though L-violating effects are hard to come by.

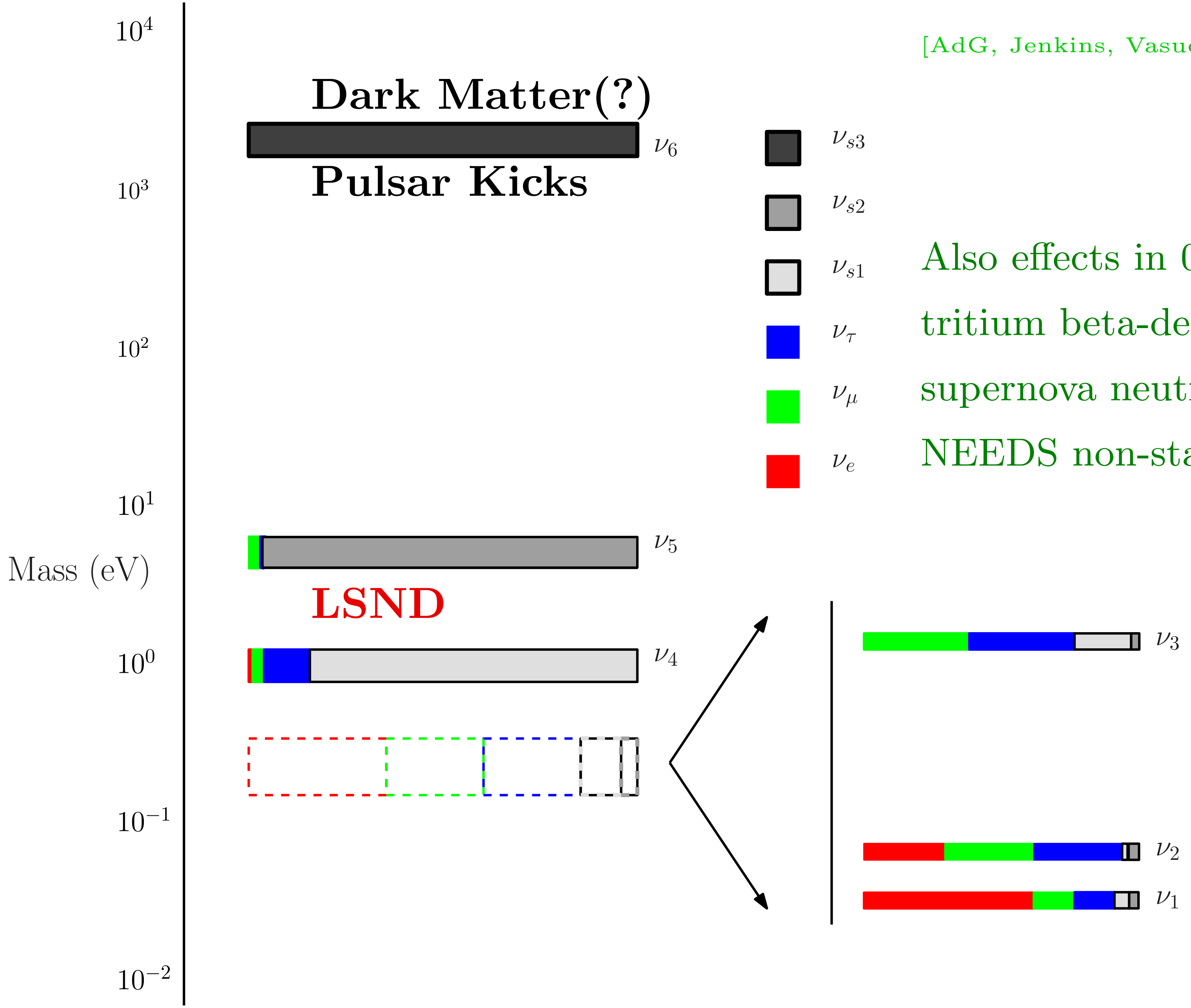
- $M \sim \mu$: six states have similar masses. Active–sterile mixing is very large. This scenario is (generically) ruled out by active neutrino data (atmospheric, solar, KamLAND, K2K, etc).

Low-Energy Seesaw [AdG PRD72,033005)]

Lets look at what happens if $M \ll$ weak scale. What do we get?

- Neutrino masses are small because the Yukawa couplings are very small $\lambda \in [10^{-6}, 10^{-11}]$;
- No standard thermal leptogenesis – right-handed neutrino way too light;
- No obvious connection with other energy scales (EWSB, GUTs, etc);
- Right-handed neutrinos are propagating degrees of freedom. They look like sterile neutrinos;
- Sterile–active mixing can be predicted – hypothesis is falsifyable.
- Sterile neutrinos could be Nature's answer to "all" our puzzles!
- Small values of M are natural (in the 'tHooft sense). In fact, theoretically, no value of M should be discriminated against!

[AdG, Jenkins, Vasudevan, hep-ph/0608147]



Also effects in $0\nu\beta\beta$,
tritium beta-decay,
supernova neutrino oscillations,
NEEDS non-standard cosmology.

4 – Concluding Remarks, Summary, and the Road Ahead

SUMMARY: The venerable Standard Model has finally sprung a leak – neutrinos are not massless!

1. we have a very successful parametrization of the neutrino sector, and we have identified what we know we don't know.

2. neutrino masses are very small – we don't know why, but we think it means something important.

3. lepton mixing is very different from quark mixing – we don't know why, but we think it means something important.

4. we need a minimal νSM Lagrangian. In order to decide which one is "correct" (required in order to attack 2. and 3. above) we must uncover the faith of baryon number minus lepton number ($0\nu\beta\beta$ is the best [only?] bet).

5. We need more experimental input – and more seems to be on the way (this is a truly data driven field right now). We only started to figure out what is going on.

6. The fact that neutrinos have mass may be intimately connected to the fact that there are more baryons than antibaryons in the Universe. How do we test whether this is correct?

7. There is plenty of room for surprises, as neutrinos are very narrow but deep probes of all sorts of physical phenomena. Remember that neutrino oscillations are "quantum interference devices" – potentially very sensitive to whatever else may be out there (e.g., $M_{\rm seesaw} \simeq 10^{14}$ GeV).

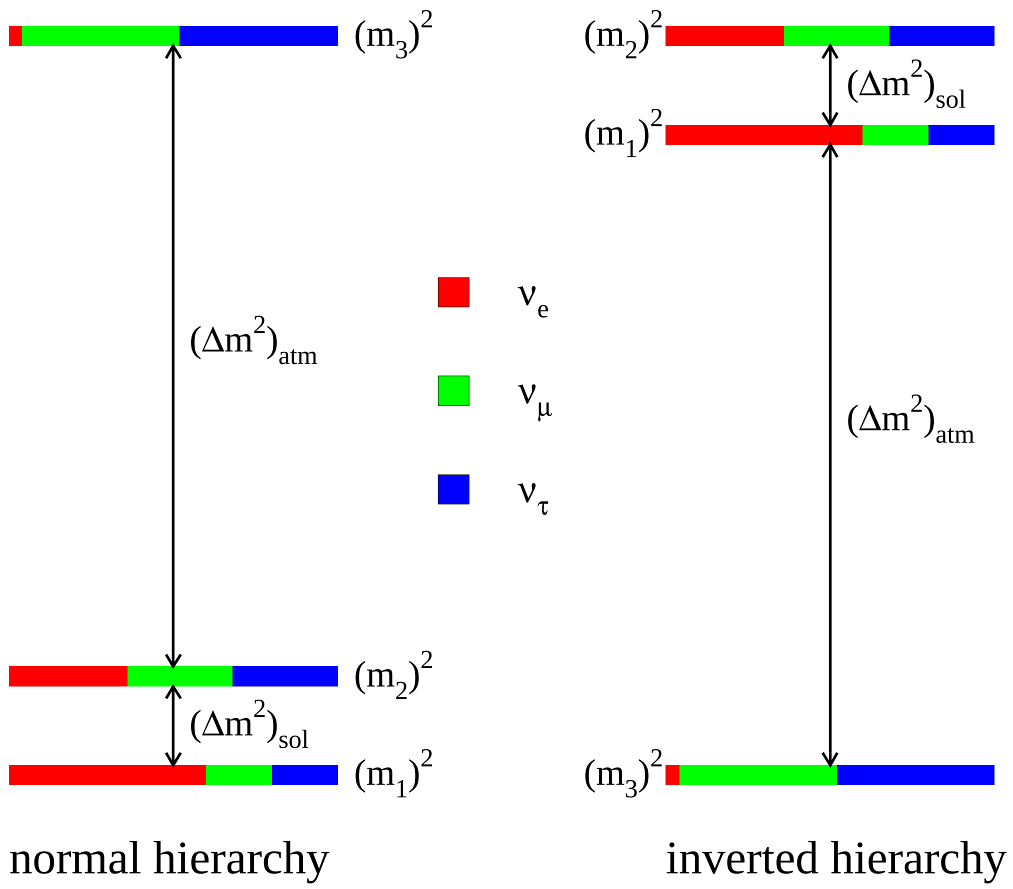
There is A LOT of work to be done, and several opportunities for unexpected discovery.

On the theory side, there are several questions we have no universally accepted answer for:

- Why are neutrino masses so small?
- Why is lepton mixing so large?
- How do we tell whether a certain idea is right (or wrong)?

The ultimate goal is to obtain a self-consistent, pleasant, deeper understanding of nature, and it seems clear to "most of us" that neutrinos will play a big role in this endeavor.

What We Know We Don't Know



- What is the ν_e component of ν_3? ($\theta_{13} \neq 0$?)
- Is CP-invariance violated in neutrino oscillations? ($\delta \neq 0, \pi$?)
- Is ν_3 mostly ν_μ or ν_τ? ($\theta_{23} > \pi/4$, $\theta_{23} < \pi/4$, or $\theta_{23} = \pi/4$?)
- What is the neutrino mass hierarchy? ($\Delta m^2_{13} > 0$?)
- Are neutrinos Majorana fermions?
- Do neutrinos decay?
- Are there more neutrino degrees of freedom (sterile neutrinos)?

Long, challenging, and diverse experimental program to address all of these!

Incomplete list of required activities.

- Very, very low background (deep underground) experiments $\to$ $0\nu\beta\beta$, study of low-energy solar neutrinos, synergy with searches for dark matter. New ideas: different targets and techniques, very deep underground labs.
- Precision measurements of reactor neutrinos $\to$ θ_{13}, neutrino magnetic moments, precision neutrino–matter scattering, synergy with geo-physics (?). New ideas: multiple, large detectors (movable(?)).
- Long and really long baseline experiments $\to$ reconstructing the neutrino mixing matrix, mass hierarchy, CP-violation, synergy with proton decay searches. New ideas: huge detectors capable of observing ν_e, new detector technologies (liquid argon), very intense neutrino sources, novel neutrino sources (NuFact, β-beams).
- Astrophysical and cosmological neutrino probes $\to$ supernova neutrinos, ultra-high energy neutrinos, studies of the energy budget of the universe. New ideas: humongous detectors underwater, under-ice, under-salt, etc. CMB studies, BAO, gravitational lensing. Ultra-high energy cosmic rays.

plus

- Searches for rare muon processes. Stopped muon experiments: $\mu \to e$ conversion in nuclei. $\mu \to e\gamma$, $\mu \to eee$. Rare tau processes ($\tau \to \mu\gamma$) – signficant progress would only (?) come from Super B factories. Also high precision kaon and pion decay experiments.
- Precision studies of neutrino interactions. $\nu + e$ scattering, ν DIS, ν scattering on nuclei.
- High energy collider physics (LHC, ILC). Understanding the phenomenon of electroweak symmetry breaking, direct searches for the (high energy) physics responsible for neutrino masses.

and of course

- Can we ever see relic neutrinos? Study their properties? How?
- Other activities I have not thought of / heard of, or which are yet to be invented (probably the most important and exciting stuff).