Flavor and neutrinos

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Plan

- Flavor in the Standard Model and beyond
  - (The charged flavor sector: beyond CKM)
- Neutrinos observables: what do we know
- Neutrinos observables: how do we know
- The origin of neutrino masses
- Understanding the pattern of neutrino masses and mixings

(Pedagogical) references

- Useful web-pages:
  Giunti's http://www.nu.to.infn.it/ (source of references)
  http://www.hep.anl.gov/ndk/hypertext/nuindustry.html (experiments)
  Bahcall's http://www.sns.ias.edu/~jnb/ (*)
- General: M.C. Gonzalez-Garcia, Y. Nir Rev.Mod.Phys.75:345-402,2003, SV (to come)
- Matter effects (classic): T.K. Kuo , J. Pantaleone Rev.Mod.Phys.61:937,1989
- Supernova neutrinos: G. Raffelt, Stars as Laboratories for Fundamental Physics, University of Chicago Press (astrophysics) (astrophysics)
- $0\nu2\beta$ decay: S. T. Petcov, New J. Phys. 6 (2004) 109
- Cosmology: W. Buchmuller, P. Di Bari, M. Plumacher, Annals Phys. 315 (2005) 305; Brian Fields, Subir Sarkar, Phys. Lett. B592 (2004) 202; S. Hannestad, New J. Phys. 6 (2004) 108
- Model building: G. Altarelli, F. Feruglio, New J. Phys. 6 (2004) 106
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The Standard Model (at the ren. level)

$$\begin{array}{rccc} & & \bar{\Psi}_i i\hat{D}\Psi_i - \frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} & \text{gauge} \\ \mathcal{L}^{\text{ren}}_{\text{SM}} & = & +|D_\mu H|^2 - V(H) & \text{symmetry breaking} \\ & & +\lambda_{ij}\bar{\Psi}_i\Psi_j H & \text{flavor} \end{array}$$

- An extremely successful synthesis of particle physics
- (in compact notations)
- i = 1,2,3: family index

Fermion content

- Ψ_i = (e_i ν_{ei} d_i u_i) (Dirac spinors) (e_i) = (e μ τ), (ν_i) = (ν_e ν_μ ν_τ), ...
- A 4-component Dirac spinor Ψ has 2x 2-components with definite chirality (γ_5):

$$\Psi_{L,R} = \frac{1 \mp \gamma_5}{2} \Psi$$

- A gauge symmetry can mix all the fields with same Lorentz quantum numbers ⇒ can act independently on ψ_L, ψ_R (chiral symmetry):

SO(3,1) = SU(2) x SU(2) →

$$\Psi + \bar{\Psi} \to \Psi_L + \Psi_R + (\bar{\Psi})_L, (\bar{\Psi})_R \to \overbrace{\Psi_L, (\bar{\Psi})_L}^{(0,1/2)} + \overbrace{(\bar{\Psi})_R, \Psi_R}^{(1/2,0)}$$

$$= \Psi_L, \overline{\Psi_R} + \overline{\Psi_L}, \Psi_R$$

or

$$\Psi_L = \begin{pmatrix} 0 \\ \psi \end{pmatrix} \qquad \Psi_R = \begin{pmatrix} i\sigma_2 \psi_c^* \\ 0 \end{pmatrix}$$

$$\underbrace{\Psi_L, \overline{\Psi_R}}_{(0,1/2)} + \underbrace{\overline{\Psi_R}, \Psi_L}_{(1/2,0)} \leftrightarrow \boxed{\psi, \psi_c} + \psi^*, \psi_c^*$$

2-component Weyl fermions
(the fundamental objects)

Fermion quantum numbers

$$\begin{array}{rcl} & \bar{\Psi}_i i\hat{D}\Psi_i - \frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} & \text{gauge} \\ \mathcal{L}^{\text{ren}}_{\text{SM}} = & +|D_\mu H|^2 - V(H) & \text{symmetry breaking} \\ & +\lambda_{ij}\bar{\Psi}_i\Psi_j H & \text{flavor} \end{array}$$

G = SU(3)$_C$ x SU(2)$_W$ x U(1)$_Y$

$$L = \begin{pmatrix} \nu \\ e \end{pmatrix} \qquad Q = \begin{pmatrix} u \\ d \end{pmatrix}$$

$$q = q_a$$

$$a = 1, 2, 3 \text{ (color)}$$

	SU(3)	SU(2)	U(1)
L_i	1	2	-1/2
e^c_i	1	1	1
Q_i	3	2	1/6
u^c_i	3*	1	1/3
d^c_i	3*	1	-2/3

Y

Fermion mass terms

ψ_i Weyl fermions

ψ

Most general mass term: $\frac{m_{ij}}{2}\psi_i\psi_j$

$\frac{m}{2}\psi\psi$

$$\psi_i\psi_j \equiv \psi_i^\alpha \epsilon_{\alpha\beta}\psi_j^\beta$$

"Majorana"

breaks any charge of ψ

Fermion mass terms

ψ_i Weyl fermions

ψ, ψ^c

Most general mass term: $\frac{m_{ij}}{2}\psi_i\psi_j$

$$\underbrace{\frac{m_1}{2}\psi\psi + \frac{m_2}{2}\psi^c\psi^c}_{\text{“Majorana”}} + \underbrace{m\psi^c\psi}_{\text{“Dirac”}}$$

$$\psi_i\psi_j \equiv \psi_i^\alpha \epsilon_{\alpha\beta} \psi_j^\beta$$

$Q(\psi) + Q(\psi^c) = 0$

Dirac spinors turn out useful (all the SM fermions except ν)

e.g. electron mass term: me^ce

Family replication

$$\mathcal{L}^{\rm ren}_{\rm SM} = \begin{array}{cc} \bar{\Psi}_i i\hat{D}\Psi_i - \frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} & \text{gauge} \\ +|D_\mu H|^2 - V(H) & \text{symmetry breaking} \\ +\lambda_{ij}\bar{\Psi}_i\Psi_j H & \text{flavor} \end{array}$$

$\Psi_i = (L_i\ e^c_i\ Q_i\ u^c_i\ d^c_i)$ ↔ 1 family

3 families ↔ 3 identical copies

of the same (reducible) repr

WHY?

	SU(3)	SU(2)	U(1)
L_i	1	2	-1/2
e^c_i	1	1	1
Q_i	3	2	1/6
u^c_i	3^*	1	1/3
d^c_i	3^*	1	-2/3

Y

U(3)^5

$$\mathcal{L}_{\rm SM}^{\rm ren} = \begin{array}{cc} \bar\Psi_i i\hat{D}\Psi_i - \frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} & \text{gauge} \\ +|D_\mu H|^2 - V(H) & \text{symmetry breaking} \\ +\lambda_{ij}\bar\Psi_i\Psi_j H & \text{flavor} \end{array}$$

Family replication ↔ the gauge lagrangian cannot tell families ↔ is U(3)^5 invariant:

$$U(3)^5: \begin{array}{l} L_i \to U^L_{ij}L_j \\ e^c_i \to U^{e^c}_{ij}e^c_j \\ Q_i \to U^Q_{ij}Q_j \Rightarrow \mathcal{L}_{\rm SM}^{\rm gauge} \to \mathcal{L}_{\rm SM}^{\rm gauge} \\ u^c_i \to U^{u^c}_{ij}u^c_j \\ d^c_i \to U^{d^c}_{ij}d^c_j \end{array}$$

(U(3)^5 → U(3) in SO(10) gauge-unified models)

$U(3)^5$

$$\mathcal{L}_{\rm SM}^{\rm ren} = \begin{array}{ll} \bar\Psi_i i\hat{D}\Psi_i - \frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} & \text{gauge} \\ +|D_\mu H|^2 - V(H) & \text{symmetry breaking} \\ +\lambda_{ij}\bar\Psi_i\Psi_j H & \text{flavor} \end{array}$$

The symmetry breaking lagrangian is $U(3)^5$ invariant:

$$U(3)^5 : \begin{array}{l} L_i \to U^L_{ij}L_j \\ e^c_i \to U^{e^c}_{ij}e^c_j \\ Q_i \to U^Q_{ij}Q_j \\ u^c_i \to U^{u^c}_{ij}u^c_j \\ d^c_i \to U^{d^c}_{ij}d^c_j \end{array} \Rightarrow \mathcal{L}^{\rm SB}_{\rm SM} \to \mathcal{L}^{\rm SB}_{\rm SM}$$

The symmetry breaking itself $H = \begin{pmatrix} G^+ \\ v + \frac{h+iG^0}{\sqrt{2}} \end{pmatrix}$ is also $U(3)^5$ invariant

U(3)⁵

$$\mathcal{L}_{\text{SM}}^{\text{ren}} = \begin{array}{ll} \bar{\Psi}_i i\hat{D}\Psi_i - \frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} & \text{gauge} \\ +|D_\mu H|^2 - V(H) & \text{symmetry breaking} \\ +\lambda_{ij}\bar{\Psi}_i\Psi_j H & \text{flavor} \end{array}$$

The flavor lagrangian is not U(3)⁵ invariant (unless λij = 0)

$$\mathcal{L}_{\text{SM}}^{\text{flavor}} = \lambda^E_{ij} e^c_i L_j H^\dagger + \lambda^D_{ij} d^c_i Q_j H^\dagger + \lambda^U_{ij} u^c_i Q_j H + \text{h.c.}$$

$$\begin{array}{lllll} & L_i \to U^L_{ij} L_j & & & \\ & e^c_i \to U^{e^c}_{ij} e^c_j & & \lambda_E \to U^T_{e^c}\lambda_E U_L \\ U(3)^5: & Q_i \to U^Q_{ij} Q_j & \Rightarrow & \lambda_D \to U^T_{d^c}\lambda_D U_Q \\ & u^c_i \to U^{u^c}_{ij} u^c_j & & \lambda_U \to U^T_{u^c}\lambda_U U_Q \\ & d^c_i \to U^{d^c}_{ij} d^c_j & & \end{array}$$

The flavor sector (at the ren. level)

- Despite the rich flavor structure:
  - **No** lepton or baryon number violation
  - **No** individual lepton number or CP violation in the lepton sector
  - All family violation and CP violating effects (neglecting ϑ_{QCD})
    - reside in the quark charged current
    - are encoded in a unitary 3x3 matrix **V**

- Individual lepton numbers: e.g. L_e corresponds to $e^c \to e^{-i\alpha} e^c, \quad L_e \to e^{i\alpha} L_e,$

  Total lepton number $L = L_e + L_\mu + L_\tau$: corresponds to $e^c_i \to e^{-i\alpha} e^c_i, \quad L_i \to e^{i\alpha} L_i \quad (\forall\ i)$

  Baryon number B: corresponds to $u^c_i \to e^{-i\alpha} u^c_i, \quad d^c_i \to e^{-i\alpha} d^c_i, \quad Q_i \to e^{i\alpha} Q_i \quad (\forall\ i)$

- The transformations corresponding to L_e L_μ L_τ L B are all part of $U(3)^5$

B & L

$$\mathcal{L}_{\text{SM}}^{\text{flavor}} = \lambda_{ij}^{E} e_i^c L_j H^\dagger + \lambda_{ij}^{D} d_i^c Q_j H^\dagger + \lambda_{ij}^{U} u_i^c Q_j H + \text{h.c.}$$

$$L_i \longrightarrow e^{i\alpha_L} L_i$$

$$e_i^c \longrightarrow e^{-i\alpha_L} e_i^c$$

$$Q_i \longrightarrow e^{i\alpha_B} Q_i$$

$$u_i^c \longrightarrow e^{-i\alpha_B} u_i^c$$

$$d_i^c \longrightarrow e^{-i\alpha_B} d_i^c$$

are both symmetries of $\mathcal{L}_{\text{SM}}^{\text{flavor}}$

Leptons

$$\begin{aligned}\mathcal{L}^{\text{flavor}}_{\text{SM}} &= \lambda^E_{ij} e^c_i L_j H^\dagger + \lambda^D_{ij} d^c_i Q_j H^\dagger + \lambda^U_{ij} u^c_i Q_j H + \text{h.c.} \\ &= m^E_{ij} e^c_i e_j \quad + m^D_{ij} d^c_i d_j \quad + m^U_{ij} u^c_i u_j \quad + \text{h.c.} \qquad m^{E,D,U}_{ij} = \lambda^{E,D,U}_{ij} v \\ &\qquad +\text{Higgs interactions}\end{aligned}$$

- **Lepton mass eigenstates:**

$$m^E = U^T_{e^c} m^E_{\text{diag}} U_e \text{ , with } U_{e^c},\, U_e \text{ unitary, } m^E_{\text{diag}} = \text{Diag}(m_{e_i}) \geq 0$$

$$\begin{cases} e^{c\prime}_i = U^{e^c}_{ij} e^c_j \\ e'_j = U^e_{ij} e_j \end{cases} \quad \rightarrow m^E_{ij} e^c_i e_j + \text{h.c.} = m_{e_i} e'^c_i e'_i + \text{h.c.} = m_{e_i} \bar{E}'_i E'_i,\; m_\nu = 0$$

↑

phase ambiguity

- **Extend to an U(3)⁵ transformation**

$$\begin{cases} e^{c\prime}_i = U^{e^c}_{ij} e^c_j \\ L'_j = U^e_{ij} L_j \end{cases} \quad \rightarrow \lambda^E_{ij} e^c_i L_j H^\dagger = \lambda_{e_i} e^{c\prime}_i L'_i H^\dagger$$

- **⇒ Conservation of individual lepton numbers and of leptonic CP**

CP: $\psi \rightarrow i\sigma_2 \psi^*$ (no preferred phase convention)

$\lambda_{ij} \psi_i \psi_j h + \text{h.c.} \rightarrow \lambda^*_{ij} \psi_i \psi_j h + \text{h.c.}$

Quarks

- Mass eigenstates:

$$m^D = U_{d^c}^T m^D_{\rm diag} U_d \qquad m^U = U_{u^c}^T m^U_{\rm diag} U_u$$

$$\begin{cases} d_i^{c\prime} = U_{ij}^{d^c} d_j^c \\ d_j^{\prime} = U_{ij}^d d_j \end{cases}, \begin{cases} u_i^{c\prime} = U_{ij}^{u^c} u_j^c \\ u_j^{\prime} = U_{ij}^u u_j \end{cases} \to m_{ij}^D d_i^c d_j + m_{ij}^U u_i^c u_j + \text{h.c.} = m_{d_i} d_i^{c\prime} d_i^{\prime} + m_{u_i} u_i^{c\prime} u_i^{\prime} + \text{h.c.}$$

- Cannot extend to an U(3)^5 transformation (both u$_L$, d$_L$ $\in$ Q)

$$\text{e.g.} \begin{cases} u_i^{c\prime} = U_{ij}^{u^c} u_j^c \\ d_i^{c\prime} = U_{ij}^{d^c} d_j^c \\ Q_j^{\prime} = U_{ij}^d Q_j \end{cases} \to \begin{array}{l} \lambda_{ij}^D d_i^c Q_j H^\dagger = \lambda_{d_i} d_i^{c\prime} Q_i^{\prime} H^\dagger \qquad \text{but} \\ \lambda_{ij}^U u_i^c Q_j H^\dagger = \lambda_{u_i} V_{ij} u_i^{c\prime} Q_i^{\prime} H^\dagger \end{array}$$

$$\boxed{V = U_u U_d^\dagger}$$

Cabibbo Kobayashi Maskawa (CKM) matrix

- In terms of mass eigenstates:

$$j^{\mu}_{\mathrm{c,had}} = \overline{u_{iL}}\gamma^{\mu}d_{iL} = V_{ij}\overline{u}'_{iL}\gamma^{\mu}d'_{jL}$$

$$j^{\mu}_{\mathrm{n,had}} = (j^{\mu}_{\mathrm{n,had}})'$$

$$j^{\mu}_{\mathrm{em,had}} = (j^{\mu}_{\mathrm{em,had}})'$$

- All flavor and CP violating effects originate from the unitary 3x3 matrix V in the quark charged current

Physical parameters in V

$$m_{d_i} d_i^c d_i + m_{u_i} u_i^c u_i + \frac{g}{\sqrt{2}} V_{ij} \overline{u}_i \hat{W} d_j + \text{h.c.}$$

$$V = \underbrace{\begin{pmatrix} e^{i\tau_1} & & \\ & e^{i\tau_2} & \\ & & e^{i\tau_3} \end{pmatrix}}_{\text{unphysical}} \begin{pmatrix} \text{standard par.} \end{pmatrix} \underbrace{\begin{pmatrix} 1 & & \\ & e^{i\sigma} & \\ & & e^{i\rho} \end{pmatrix}}_{\text{unphysical}}$$

9 = 3 + 3 + 1 + 2

With N families

Families	Pars in V	Phys. pars	Angles	Phases
N	N^2	$N^2-(2N-1)$	$N(N-1)/2$	$(N^2-3N+1)/2$
2	4	1	1	0
3	9	4	3	1

Standard parameterizations

$$V = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}s^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}s^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

Experimentally: V ~ 1

$$V = \begin{pmatrix} 1 - \lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \lambda^2/2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

$$\lambda = 0.22$$

$$A, \rho, \eta = \mathcal{O}\left(1\right)$$

Back to the point

- In terms of mass eigenstates:

$$j^{\mu}_{\mathrm{c,had}} = \overline{u_{iL}}\gamma^{\mu} d_{iL} = V_{ij} u'_{iL}\gamma^{\mu} d'_{jL}$$

$$j^{\mu}_{\mathrm{n,had}} = (j^{\mu}_{\mathrm{n,had}})'$$

$$j^{\mu}_{\mathrm{em,had}} = (j^{\mu}_{\mathrm{em,had}})'$$

- All flavor and CP violating effects originate from the unitary 3x3 matrix V in the quark charged current

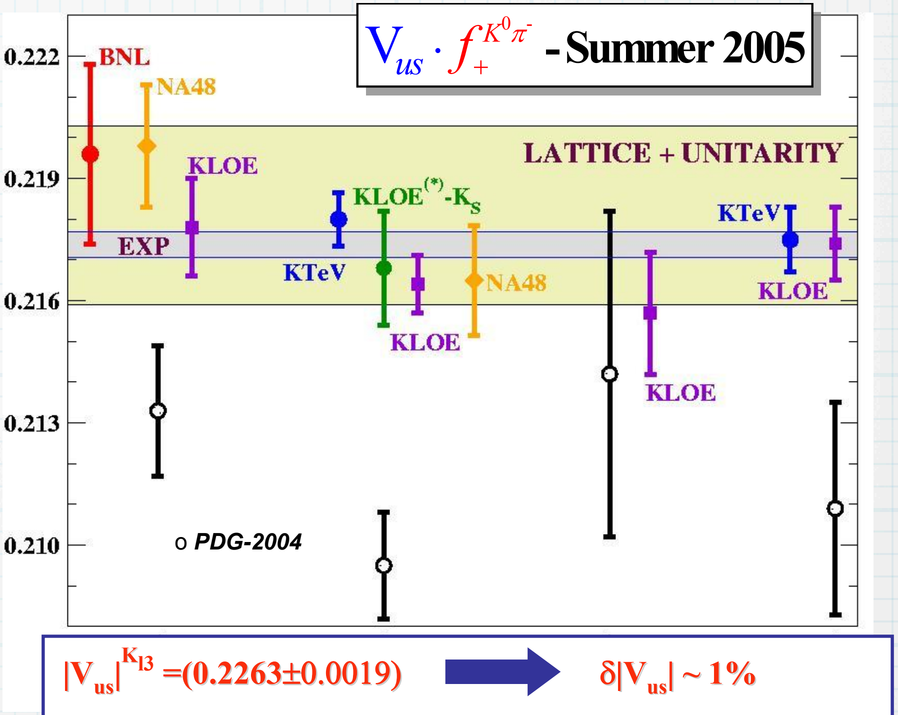
Is that so?

- Unitarity of V (I)

$$\sum_{i \text{ or } a} |V_{ai}|^2 = 1$$

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

0.9739(3) + 0.2263(19) + small = 0.9997(10)



$|V_{us}|^{K_{l3}}$ =(0.2263±0.0019) → $\delta|V_{us}|$ ~ 1%

(dominated by the $f_+(0)$ theoretical uncertainty)

[Mescia]

$|V_{ud} f^{ud}(0)|$ from $N \to N' e\nu$ $\quad (\delta f^{ud}(0) = \mathcal{O}(0.1\%))$

$|V_{us} f^{us}(0)|$ from $K \to \pi e\nu$ $\quad (\delta f^{us}(0) = \mathcal{O}(1\%))$

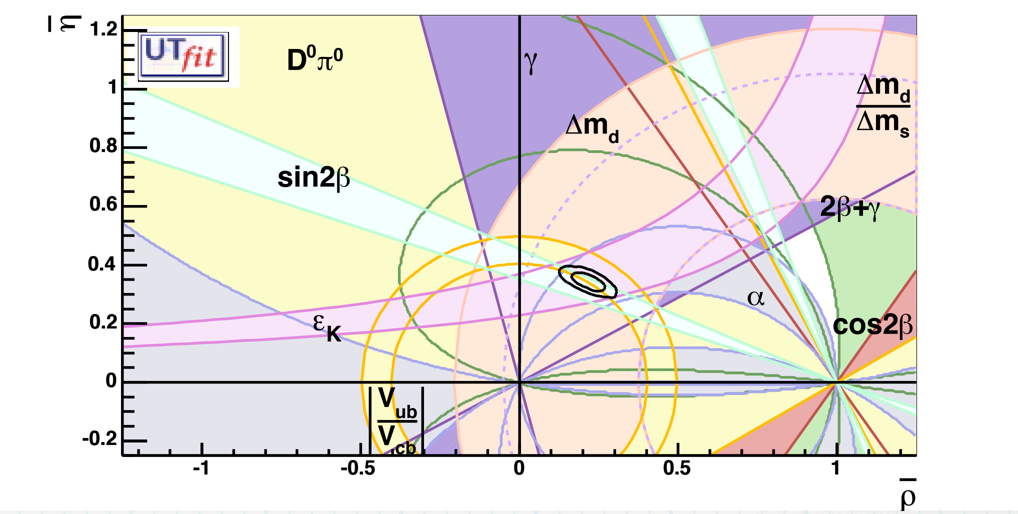
$|V_{ub}|$ from $b \to ul\bar{\nu}$ $\quad$ (subdominant)

Is that so?

- Unitarity of V (II)

$$\sum_i V_{ai}V^*_{bi} = 1 \quad (a \neq b)$$

$$\sum_a V_{ai}V^*_{aj} = 1 \quad (i \neq j)$$



$$V_{ud}V^*_{ub} + V_{cd}V^*_{cb} + V_{td}V^*_{tb} = 0$$

A triangle in the complex plane
(when properly normalized, it has vertex in (ρ,η)

$$-\frac{V_{ud}V^*_{ub}}{V_{cd}V^*_{cb}} - \frac{V_{cd}V^*_{cb}}{V_{cd}V^*_{cb}} - \frac{V_{td}V^*_{tb}}{V_{cd}V^*_{cb}} = 0$$

Is that so?

- $BR(\mu \to e\,\gamma) < 1.2 \times 10^{-11}$ ✓

- $d_e < 10^{-27}$ e cm ~ $10^{-11}\ \mu_B$ ✓

- $\nu_{ei} \leftrightarrow \nu_{ej}$ $(i \neq j)$ ✗

Neutrino physics

- New data!
- New physics!
- Data interpretation (now) pretty clean
- Cosmology (baryogenesis, CMB, LSS, BBN,...)
- Astrophysics (probe of SUN, SNe, HE sources,...)
- Particle physics (access $\Lambda \sim M_{GUT}$, unification, flavor, LFV)

Neutrino masses (E ≪ ‹H›)

- In the broken EW phase, the most general fermion mass term is

$$\frac{m^\nu_{ij}}{2}\nu_i\nu_j + m^E_{ij}e^c_i e_j + m^D_{ij}d^c_i d_j + m^U_{ij}u^c_i u_j$$

- (a Dirac mass term would require a ν^c)
- The neutrino Majorana mass term breaks L: $L_i \to e^{i\alpha}L_i \Rightarrow \nu_i\nu_j \to e^{2i\alpha}\nu_i\nu_j$
- and the L_i's:

$$m^\nu = U^T_\nu m^D_{\mathrm{diag}} U_\nu \qquad m^e = U^T_{e^c} m^E_{\mathrm{diag}} U_e$$

$$\nu_i{}' = U^\nu_{ij}\nu_j, \begin{cases} e^{c\prime}_i = U^{e^c}_{ij}e^c_j \\ e'_j = U^e_{ij}e_j \end{cases} \to \frac{m^\nu_{ij}}{2}\nu_i\nu_j + m^E_{ij}e^c_i e_j + \mathrm{h.c.} = \frac{m_{\nu_i}}{2}\nu_i{}'\nu'_i + m_{e_i}e^{c\prime}_i e'_i + \mathrm{h.c.}$$

$$j^\mu_{\mathrm{c,lep}} = \overline{\nu_{iL}}\gamma^\mu e_{iL} = U_{ij}\overline{\nu}'_{iL}\gamma^\mu e'_{jL}$$

$$j^\mu_{\mathrm{n,lep}} = (j^\mu_{\mathrm{n,lep}})'$$

$$j^\mu_{\mathrm{em,lep}} = (j^\mu_{\mathrm{em,lep}})'$$

$U = U_\nu U_e^\dagger$ Pontecorvo Maki Nakagawa Sakata (PMNS) matrix

Physical parameters in U

$$\frac{m_{\nu_i}}{2}\nu_i\nu_i + m_{e_i}e_i^c e_i + \frac{g}{\sqrt{2}}U_{ij}\bar{e}_i\hat{W}\nu_j + \text{h.c.}$$

$$U = \underbrace{\begin{pmatrix} e^{i\gamma_1} & & \\ & e^{i\gamma_2} & \\ & & e^{i\gamma_3} \end{pmatrix}}_{\text{unphysical}} \begin{pmatrix} \text{standard par.} \end{pmatrix} \underbrace{\begin{pmatrix} 1 & & \\ & e^{i\alpha} & \\ & & e^{i\beta} \end{pmatrix}}_{\text{physical (Majorana)}}$$

9 = 3 + 3 + 1 + 2

Physical parameters in the lepton sector

$$-\mathcal{L} \supset \frac{m_{\nu_i}}{2}\nu_i\nu_i + m_{e_i}e^c_i e_i + \frac{g}{\sqrt{2}}U_{ij}\bar{e}_i\hat{W}\nu_j + \text{h.c.}$$

$$m_e,\ m_\mu,\ m_\tau,\ m_{\nu_1},\ m_{\nu_2},\ m_{\nu_3},\ \theta_{23},\ \theta_{12},\ \theta_{13},\ \delta,\ \alpha,\ \beta$$

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}s^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}s^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha} & 0 \\ 0 & 0 & e^{i\beta} \end{pmatrix}$$

$$0 \leq \theta_{23}, \theta_{12}, \theta_{13} \leq \frac{\pi}{2}, \quad 0 \leq \delta < 2\pi, \quad 0 \leq \alpha, \beta < 2\pi$$

Physical parameters: what do we know?

Accessible
to oscillations

Charged
sector

$m_{e,\mu,\tau}$

Δm_{12}^2

$|\Delta m_{23}^2|$

$\mathrm{sign}(\Delta m_{23}^2)$

$\theta_{12}, \theta_{23}, \theta_{13}, \delta$

Not accessible
to oscillations

m_{lightest}

α

β

$$\left(\Delta m_{ij}^2 \equiv m_{\nu_j}^2 - m_{\nu_i}^2\right)$$

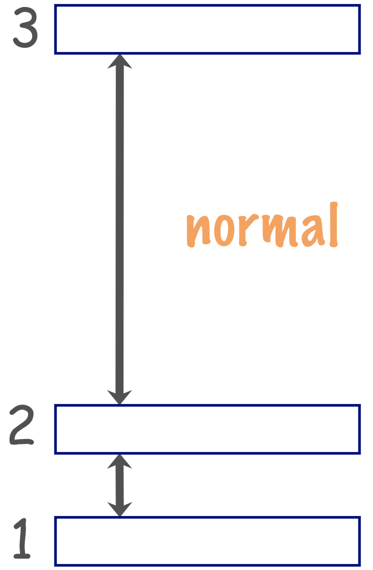
Standard labeling of eigenstates

$0 < \Delta m^2_{12} < |\Delta m^2_{23}|$ **uniquely defines the labeling**

$\Delta m^2_{12} > 0$ **by definition;** Δm^2_{23} **can have both signs**

$$\left(\begin{array}{c}\Delta m^2_{\mathrm{SUN}} \equiv \Delta m^2_{12} \\ \Delta m^2_{\mathrm{ATM}} \equiv \Delta m^2_{23}\end{array}\right)$$

$\Delta m^2_{23} > 0$



e.g.:

$m_1 < m_2 \ll m_3$

(hierarchical)

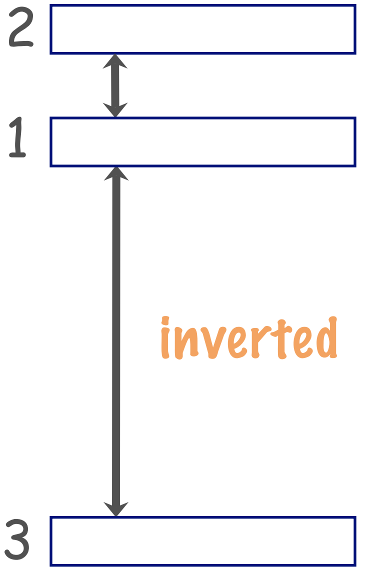
$m_1 \approx m_2 \approx m_3$

(degenerate)

$m_1 \approx m_2 < m_3$

(neither)

$\Delta m^2_{23} < 0$



e.g.:

$m_1 \approx m_2 > m_3$

(inverse hierarchical)

$m_1 \approx m_2 \approx m_3$

(degenerate)

Charged sector

$m_{e,\mu,\tau}$

Well known

Accessible to oscillations

Δm^2_{12}

$|\Delta m^2_{23}|$

$\mathrm{sign}(\Delta m^2_{23})$

$\theta_{12}, \theta_{23}, \theta_{13}, \delta$

Not accessible to oscillations

m_{lightest}

α

β

Known

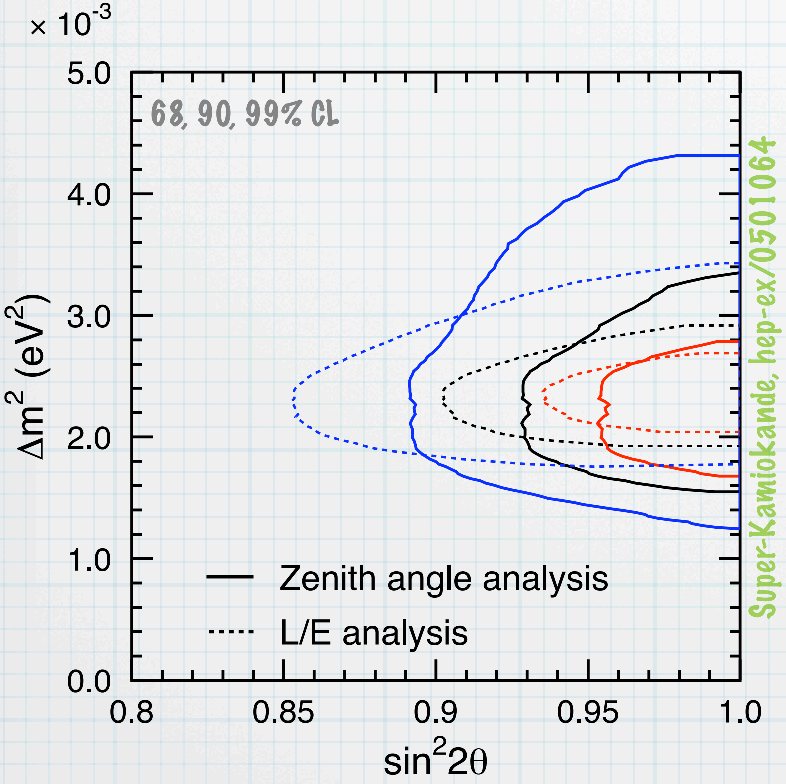
Bounds

Experimental constraints (oscillations)

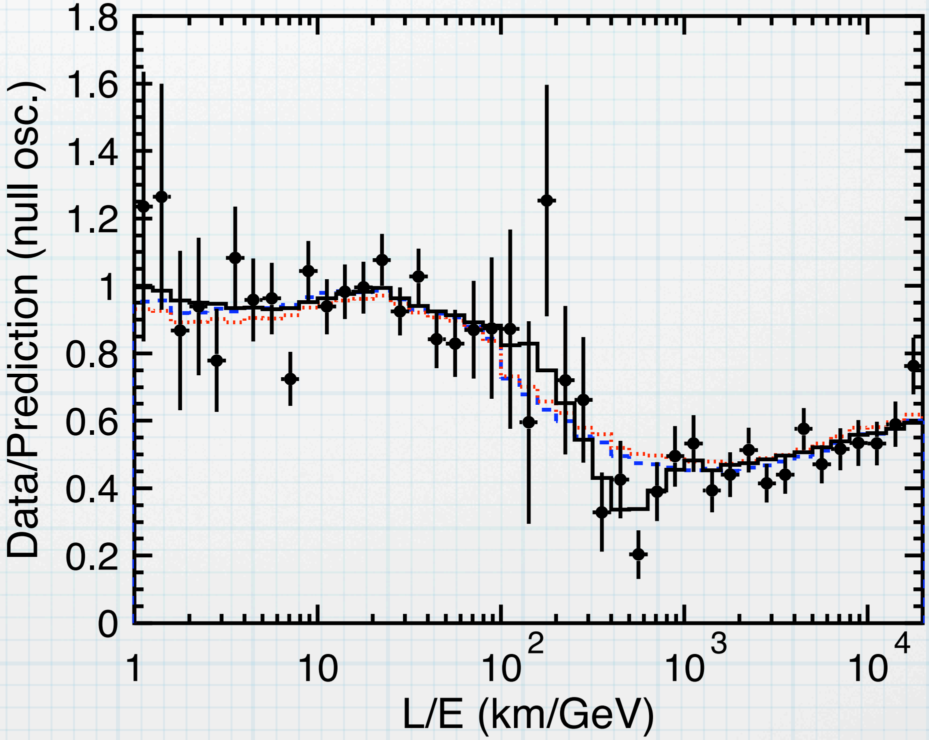
$\Delta m^2_{23} \sim 2.5 \times 10^{-3}\,\mathrm{eV}^2 \quad \theta_{23} \sim 45°$ **(ATM, K2K)**

$\Delta m^2_{12} \sim 0.8 \times 10^{-4}\,\mathrm{eV}^2 \quad \theta_{12} \sim 30°–35°$ **(SUN,KamLAND)**

$\theta_{13} < 10°$ **(CHOOZ, Palo Verde + ATM)**



Super-Kamiokande, hep-ex/0501064



Super-Kamiokande, hep-ex/0404034

Experimental constraints (oscillations)

$\Delta m^2_{23} \sim 2.5 \times 10^{-3}\,\mathrm{eV}^2 \quad \theta_{23} \sim 45°$ (ATM, K2K)

$\Delta m^2_{12} \sim 0.8 \times 10^{-4}\,\mathrm{eV}^2 \quad \theta_{12} \sim 30°–35°$ (SUN,KamLAND)

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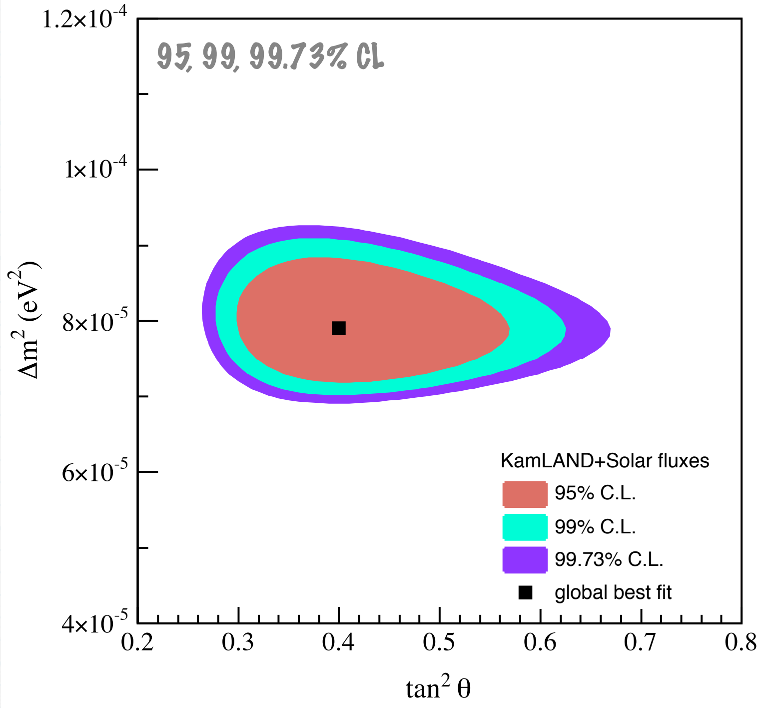
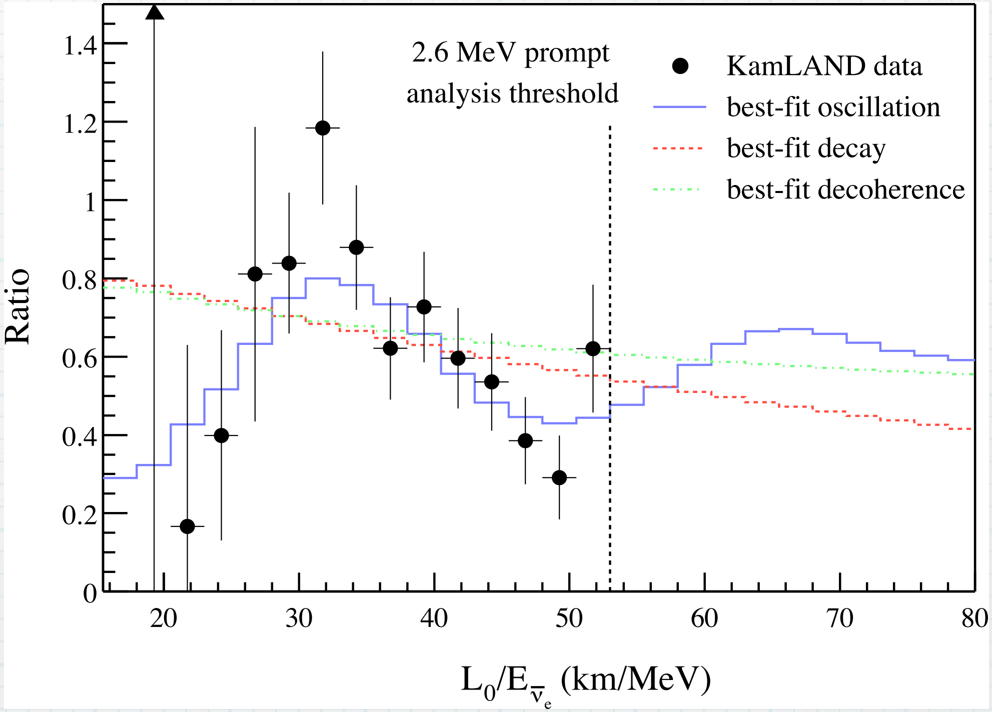


LamLAND, hep-ex/0406035



LamLAND, hep-ex/0406035

Experimental constraints (oscillations)

$\Delta m^2_{23} \sim 2.5 \times 10^{-3}\,\mathrm{eV}^2 \quad \theta_{23} \sim 45°$ (ATM, K2K)

$\Delta m^2_{12} \sim 0.8 \times 10^{-4}\,\mathrm{eV}^2 \quad \theta_{12} \sim 30°\text{–}35°$ (SUN,KamLAND)

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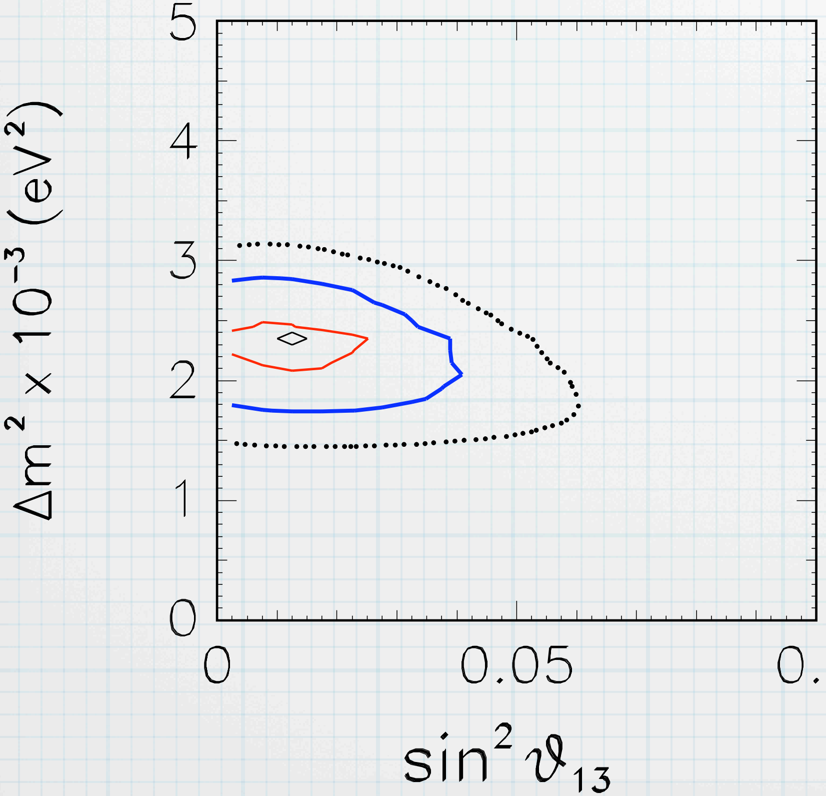
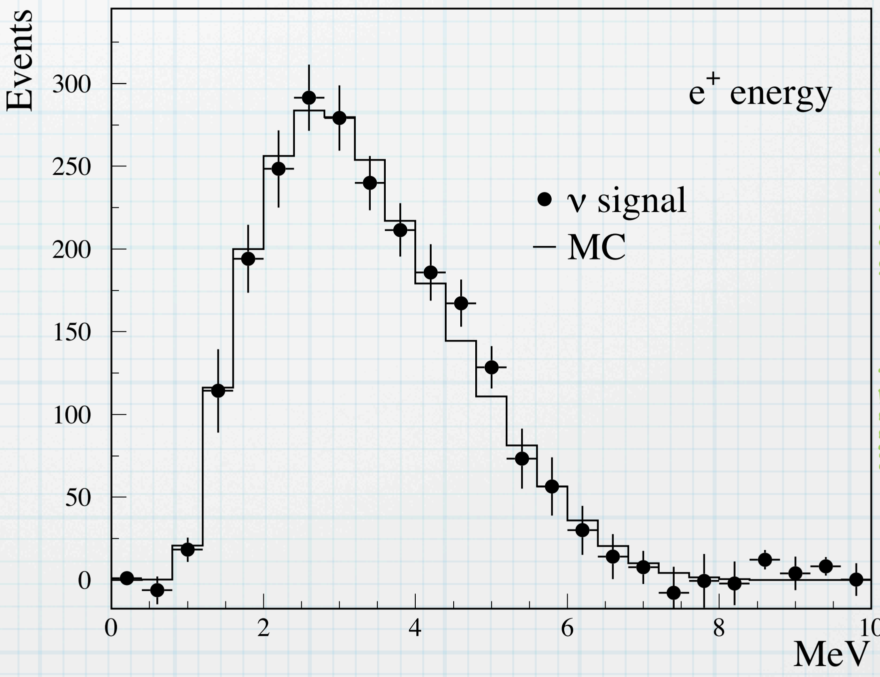


Fogli, Lisi, Marrone, Palazzo, hep-ph/0506083



CHOOZ, hep-ex/0301017

Experimental constraints

$\Delta m^2_{\rm ATM} \sim 2.5 \times 10^{-3}\,{\rm eV}^2 \quad \theta_{23} \sim 45^\circ$	(ATM, K2K)
$\Delta m^2_{\rm SUN} \sim 0.8 \times 10^{-4}\,{\rm eV}^2 \quad \theta_{12} \sim 30^\circ$–$35^\circ$	(SUN,KamLAND)
$\theta_{13} < 10^\circ$	(CHOOZ, Palo Verde + ATM)
$\|m_{ee}\| = \|U^2_{ei} m_{\nu_i}\| < \mathcal{O}\,(1) \times 0.4\,{\rm eV}$	(Heidelberg-Moscow)
$(m^\dagger m)_{ee} = \|U_{ei}\|^2 m^2_{\nu_i} < (2.2\,{\rm eV})^2$	(Mainz, Troitsk)
$\sum_i m_{\nu_i} < 0.6\,{\rm eV}\ \ ({\rm priors})$	(Cosmology)
${\rm sign}(\Delta m^2_{23})? \quad \delta? \quad \alpha, \beta?$	Unknowns

Physical parameters: how do we know?

Flavor and mass eigenstates

ν_e, ν_μ, ν_τ

"flavor eigenstates", paired to charged leptons in CC:

$$j^\mu_{\mathrm{c,lep}} = \bar{e}_i \gamma^\mu P_L \nu_{e_i}$$

ν_1, ν_2, ν_3

"mass eigenstates", diagonalize the neutrino mass matrix:

$$m^\nu_{ij} \nu_{e_i} \nu_{e_j} = m_{\nu_h} \nu_h \nu_h$$

$$\boxed{\nu_{e_i} = U_{ih} \nu_h}$$

U unitary (PMNS)

$$(\overline{\nu}_i = U^*_{ih} \overline{\nu}_h)$$

Oscillations

$$|\nu_{e_i}\rangle = U^*_{ih}|\nu_h\rangle \Rightarrow e^{-iHt}|\nu_{e_i}\rangle = U^*_{ih}e^{-iE_h t}|\nu_h\rangle \qquad \left(E_h \approx p + \frac{m_h^2}{2E}\right)$$

$$P(\nu_{e_i} \to \nu_{e_j}) = \left|\langle\nu_{e_j}|e^{-iHt}|\nu_{e_i}\rangle\right|^2, \ \langle\nu_{e_j}|e^{-iHt}|\nu_{e_i}\rangle = U_{jh}e^{-iE_h t}U^\dagger_{hi}$$

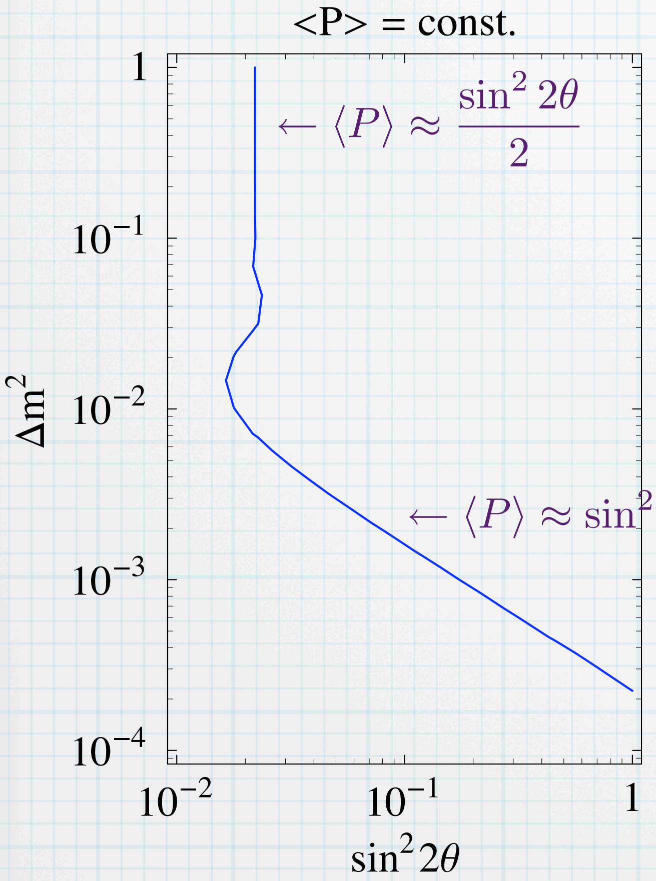
In the simplest case:

$$\begin{aligned}\nu_e &= \nu_1 \cos\theta + \nu_2 \sin\theta \\ \nu_\mu &= -\nu_1 \sin\theta + \nu_2 \cos\theta\end{aligned} \Rightarrow \boxed{P(\nu_e \to \nu_\mu) = \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{4E}}$$

(to be integrated over energy, position and convoluted with cross section, resolution, efficiency...)

$$\lambda = \frac{4\pi E}{\Delta m^2} = 2.48\text{km}\frac{E(\text{ GeV})}{\Delta m^2(\text{eV}^2)}, \qquad \frac{\Delta m^2 L}{4E} \approx 1.27\frac{\Delta m^2(\text{eV}^2)L(\text{km})}{E(\text{ GeV})}$$

A typical sensitivity plot



$\leftarrow \langle P \rangle \approx \frac{\sin^2 2\theta}{2}$

$\leftarrow \langle P \rangle \approx \sin^2 2\theta (\Delta m^2)^2 \left\langle \frac{L}{4E} \right\rangle_{E,L}$

$$\langle P \rangle = \langle P(\nu_e \to \nu_\mu) \rangle_{E,L} = \left\langle \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{4E} \right\rangle_{E,L}$$

In order to measure $\sin^2 2\theta$ and Δm^2:

- <P> alone is not sufficient
- need E or L
- best to be in the $\frac{\Delta m^2 L}{4E} \sim 1$ regime

Caveats

- In vacuum only
- Coherence can be lost
  - because of averaging over the oscillation phase (averaged coherence)
  - because the wave packets corresponding to different mass eigenstates travel at different velocities
  - because of reduction to the neutrino subsystem
- Simplified derivation: p constant? E constant? It does not really matter (change of variable in the wave packet integral)
  - e.g., if coherence is not lost

$$
\begin{aligned}
\langle \nu_{e_j}, x | e^{-iHt} | \psi_0 \rangle &= \int \frac{dp}{2\pi} U_{e_j k} e^{i(px - E_k(p)t)} U^\dagger_{k e_i} f(p) \\
&= \int \frac{dp}{2\pi} \left[U_{e_j k} e^{-i\frac{m_k^2 t}{2p}} U^\dagger_{k e_i} \right] e^{ip(x-t)} f(p) \\
&= U_{e_j k} e^{-i\frac{m_k^2 t}{2\bar{p}}} U^\dagger_{k e_i} \psi_0(x-t)
\end{aligned}
$$

3ν → 2ν

Exact (cumbersome) 3ν formulae:

$$P(\nu_{e_i} \to \nu_{e_j}) = P(\overline{\nu}_{e_j} \to \overline{\nu}_{e_i}) = P_{\mathrm{CP}} + P_{\cancel{\mathrm{CP}}}$$
$$P(\overline{\nu}_{e_i} \to \overline{\nu}_{e_j}) = P(\nu_{e_j} \to \nu_{e_i}) = P_{\mathrm{CP}} - P_{\cancel{\mathrm{CP}}}$$

$$P_{\mathrm{CP}} = \delta_{ij} - 4\,\mathrm{Re}(J^{ji}_{12})S^2_{12} - 4\,\mathrm{Re}(J^{ji}_{23})S^2_{23} - 4\,\mathrm{Re}(J^{ji}_{31})S^2_{31}$$
$$P_{\cancel{\mathrm{CP}}} = 8\sigma_{ij}J_{\mathrm{CP}}S_{12}S_{23}S_{31}$$

$$S_{hk} = \sin\frac{\Delta m^2_{hk}L}{4E}$$

$$J^{ji}_{12} = U_{jh}U^{\dagger}_{hi}U_{ik}U^{\dagger}_{kj}, \quad \mathrm{Im}(J^{ji}_{hk}) = \sigma_{ji}\sigma_{hk}J_{\mathrm{CP}}, \quad \sigma_{ij} = \sum_k \epsilon_{ijk} = \pm 1, 0$$

CHOOZ: $S^2_{12} \ll 1,\ S^2_{23} \approx S^2_{13}:$ $$P(\nu_e \to \nu_e) \approx 1 - \sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{23}L}{4E}$$

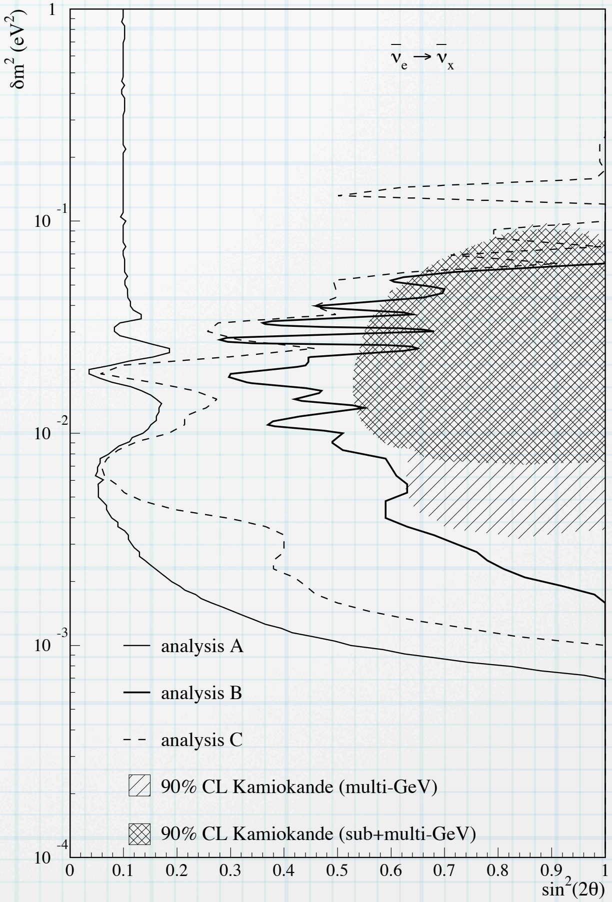
ATM: $S^2_{12} \ll 1,\ S^2_{23} \approx S^2_{13},\ \theta_{13} \ll 1:$ $$P(\nu_\mu \to \nu_\tau) \approx \sin^2 2\theta_{23}\sin^2\frac{\Delta m^2_{23}L}{4E}$$
$$P(\nu_e \to \nu_{\mu,\tau}) \ll 1$$

SUN: S^2_{23}, S^2_{13} terms suppressed by $\theta_{13}:$ $$P(\nu_e \to \nu_e) \approx 1 - \sin^2 2\theta_{12}\sin^2\frac{\Delta m^2_{12}L}{4E}$$

Experiments

CHOOZ

- $\overline{\nu}_e \longrightarrow \overline{\nu}_e$ disappearance reactor experiment
- L ~ 1 km, E ~ few MeV
- Detection: $\overline{\nu}_e p \rightarrow e^+ n$ (scintillator)
  - e^+ signal + annihilation → 2γ(511 keV)
  - n capture → γ (8 MeV) (delayed coincidence)



CHOOZ, hep-ex/0301017

CHOOZ

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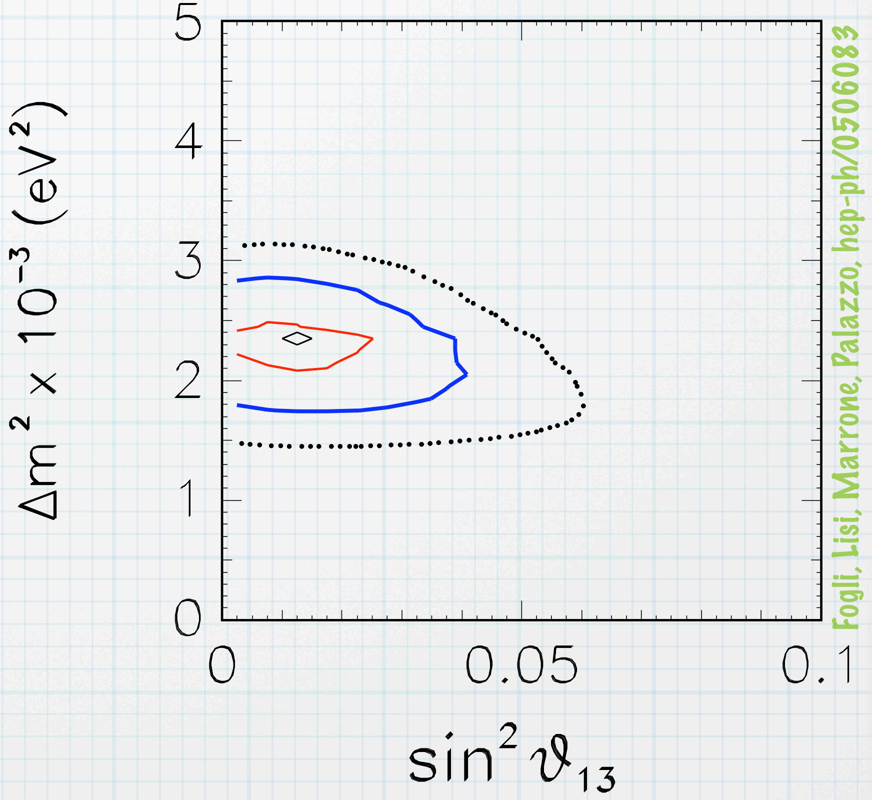
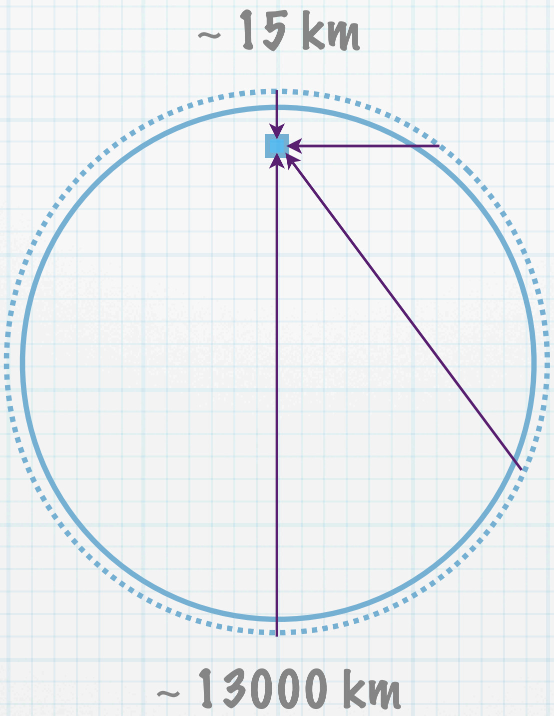


Fogli, Lisi, Marrone, Palazzo, hep-ph/0506083

What are atmospheric neutrinos?

$$\begin{tikzcd} \pi^+ \arrow[r] & \mu^+ \nu_\mu \arrow[d] \\ & e^+ \nu_e \overline{\nu}_\mu \end{tikzcd}$$

$2\ \nu_\mu$ for each ν_e



Allow to test neutrino flavor transitions

Actually:

- Energetic μ are long-lived
- Kaons are also produced

so that the ratio is > 2

Need to measure:

- neutrino flavor
- neutrino direction
- possibly energy range

$$L = 10^{2\div 4}\ \mathrm{km}$$
$$E = (0.1 \div 10)\ \mathrm{GeV} \qquad \rightarrow \frac{\Delta m^2_{23} L}{4E} = 10^{-2\div 2}$$
$$\Delta m^2_{23} \sim 2.5 \times 10^{-3}\ \mathrm{eV}^2$$

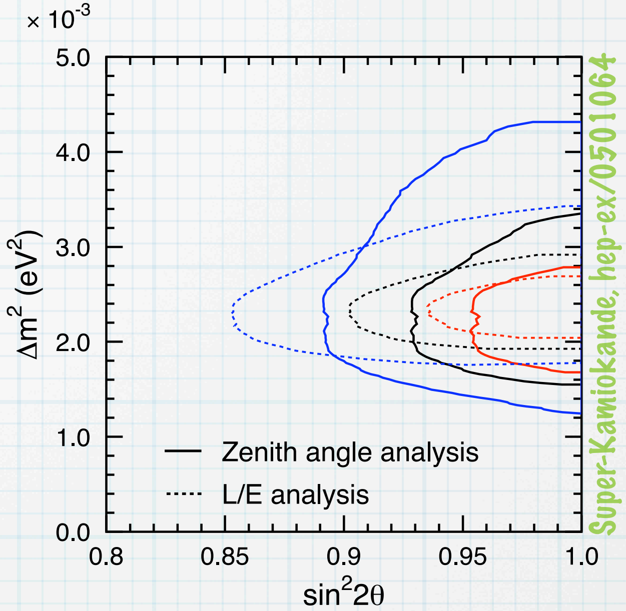
Super-Kamiokande

Super-Kamiokande: detection

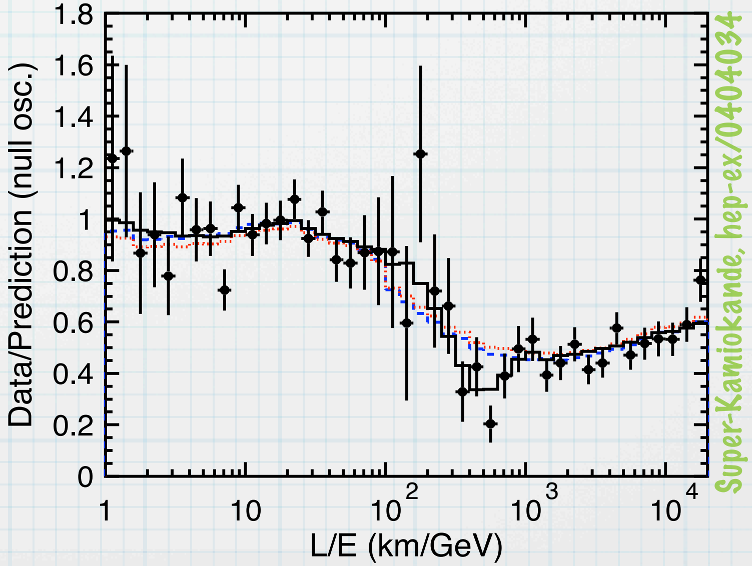
- CC-interactions on nuclei: $\nu + N \rightarrow l + N'$
- Neutrino **type**:
  - $\nu_\mu \rightarrow \mu \rightarrow$ clean Cherenkov ring
  - $\nu_e \rightarrow e \rightarrow$ fuzzy Cherenkov ring
- ν **direction**: correlated with the direction of l if $E \gg$ GeV
- ν **energy**: classify the events in sample with different E distribution:
  - Fully Contained sub-GeV
  - Fully Contained multi-GeV
  - Partially Contained μ ($E \sim$ few GeV)
  - Upgoing stopping μ ($E \sim 10$ GeV)
  - Up & through going μ ($E > 10$ GeV)

Super-Kamiokande: results

- Osc. pars: $\Delta m^2_{\rm ATM} \sim 2.5 \times 10^{-3}\,{\rm eV}^2,\ \theta_{23} \sim 45^\circ$
- Hint of oscillation dip
- Exotic effects (steriles, decay, Lorenz violation, CPT) are marginal
- Sterile neutrino analysis:
  - matter effects (relevant for sterile at high energy: resonance and then suppression)
  - neutral currents (only affected by sterile)
  - τ appearance sample
- No electron neutrino transition, compatible with CHOOZ bound



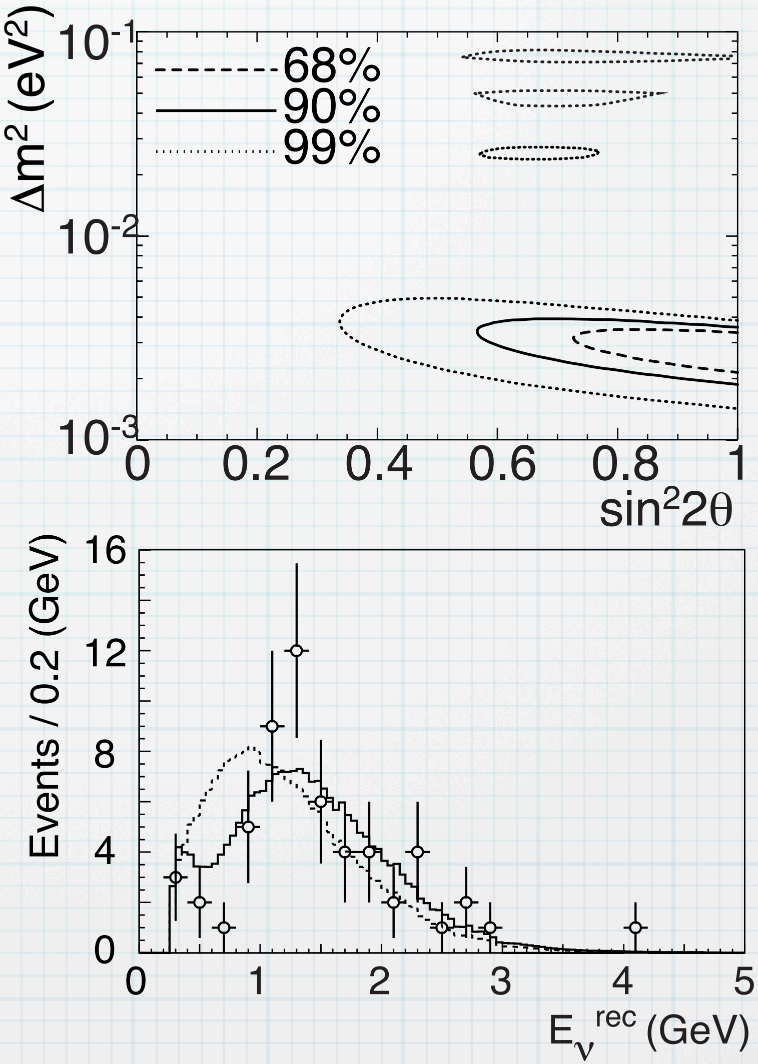
Super-Kamiokande, hep-ex/0501064



Super-Kamiokande, hep-ex/0404034

K2K

- KEK → SK pulsed ν_μ beam
- L ~ 250km, E ~ 1.3 GeV
- Measure $\Delta\theta$, E_μ → **reconstruct E_ν**
- Competitive with SK on Δm^2



Future

- More K2K
- NuMI
- CNGS
- Monolith
- ...

Matter effects

Incoherent scattering - typical mean free paths

(depend on flavor, "simplified" energy dependence):

$\lambda(E) \sim 10$ cm $(100\ \mathrm{MeV}/E)^2$	in proto-neutron star cores
$\lambda(E) \sim 10^{10}$ km $(10\ \mathrm{MeV}/E)^2$	in the Sun
$\lambda(E) \sim 10^9$ km GeV/E	in the Earth's mantle

Coherent forward scattering is enhanced by $1/(G_F E^2)$

$$\begin{array}{ll} \text{incoherent:} & dP_{\rm sc}/dx \sim G_{\rm F}^2 E^2 n \\ \text{coherent:} & d\phi_{\rm co}/dx \sim G_{\rm F} n \end{array} \rightarrow \frac{dP_{\rm sc}}{d\phi_{\rm co}} \sim G_{\rm F} E \sim 10^{-5} \left(\frac{E}{\rm GeV}\right)$$

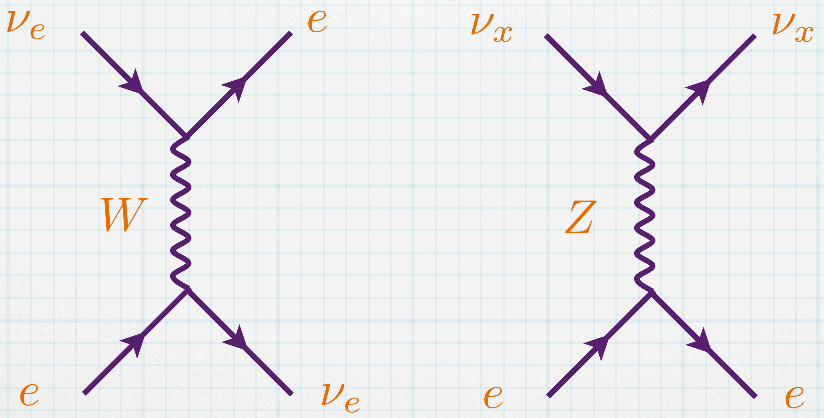
It affects the neutrino phases in a flavor dependent way

In matter:

$$H = \underbrace{\frac{1}{2E} U \begin{pmatrix} m_1^2 & & \\ & m_2^2 & \\ & & m_3^2 \end{pmatrix} U^\dagger}_{\text{Free Hamiltonian}} + \underbrace{\begin{pmatrix} V & & \\ & 0 & \\ & & 0 \end{pmatrix}}_{\text{MSW potential}} + \text{univ. terms}$$

$$V = V_e - V_\mu = \sqrt{2} G_\mathrm{F} n_e \quad (\text{neutral matter, } n_\nu \ll n_e)$$

$$V_\mu = V_\tau \quad (\text{tree level, neutral matter, } L_\mu = L_\tau)$$



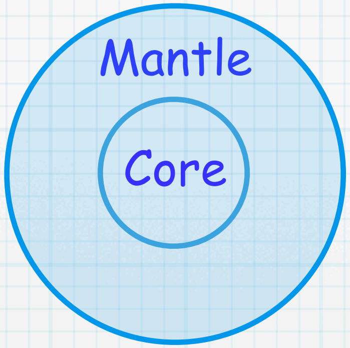
+ u, d,...

$$\text{for } \overline{\nu}: \begin{cases} U \to U^* \\ V \to -V \end{cases}$$

Propagation in constant density

Oscillation formulae still hold with $\vartheta \to \vartheta_m$, $\Delta m^2 \to (\Delta m^2)_m$, where ϑ_m, $(\Delta m^2)_m$ depend on the neutrino energy

The Earth:



$\rho_m \sim$ 3-5 g/cm^3

$\rho_c \sim$ 10-15 g/cm^3

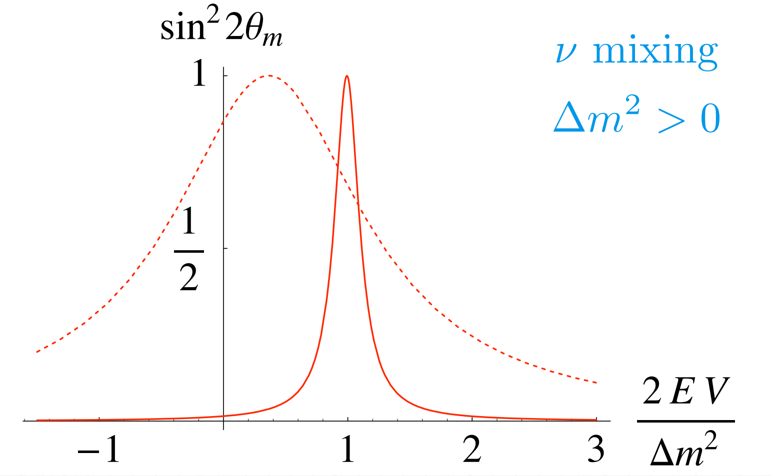
Propagation in the Earth affects

- Atmospheric ν's (only through the subdominant $\nu_e \leftrightarrow \nu_{\mu,\tau}$)
- Solar, SN ν's (D/N effect)
- Terrestrial experiments (Long Baseline)

Resonance (2ν)

$$H = \begin{pmatrix} \sin^2\theta + \frac{2EV}{\Delta m^2} & \sin\theta\cos\theta \\ \sin\theta\cos\theta & \cos^2\theta \end{pmatrix} \frac{\Delta m^2}{2EV} + \text{universal terms}$$

Resonant enhancement of the mixing angle: $\frac{2EV}{\Delta m^2} = \cos 2\theta \Rightarrow \begin{cases} (\sin 2\theta)_m = 1, \\ (\Delta m^2)_m = \Delta m^2 \sin 2\theta \end{cases}$



Also: $(\Delta m^2)_m = \Delta m^2 \frac{\sin 2\theta}{(\sin 2\theta)_m}$

- Resonance width = tan 2ϑ ($\sin^2 2\vartheta > 1/2$)
- $\vartheta < 45^0 \Rightarrow$ resonance only if $V \times \Delta m^2 > 0$
- SUN: $V > 0$, $(\Delta m^2)_{12} > 0 \Rightarrow$ resonance only if $\vartheta < 45^0$
- Note also: $(2EV)/(\Delta m^2)_{12} \gg 1 \Rightarrow \nu_e \approx (\nu_2)_m$

Resonance: formulae

$$\sin^2 2\theta_m = \frac{\sin^2 2\theta}{1 + \left(\frac{2EV}{\Delta m^2}\right)^2 - 2\cos 2\theta \frac{2EV}{\Delta m^2}} \qquad (\Delta m^2)_m = \Delta m^2 \left[1 + \left(\frac{2EV}{\Delta m^2}\right)^2 - 2\cos 2\theta \frac{2EV}{\Delta m^2}\right]^{1/2}$$

$$\frac{2EV}{\Delta m^2} = \frac{E}{E_{\text{res}}}\cos 2\theta \qquad E_{\text{res}} = \frac{\Delta m^2}{2V}\cos 2\theta \approx 8\,\text{GeV}\left(\frac{\Delta m^2(\text{eV}^2)}{2\cdot 10^{-3}\,\text{eV}^2}\frac{n_e}{1.65\,\text{gr/cm}^3}\right)$$

$$\frac{(\sin^2 2\theta)_m}{\sin^2 2\theta} = \left[\frac{\Delta m^2}{(\Delta m^2)_m}\right]^2$$

- Matter effects are negligible:
  - when $E \ll E_{res}$
  - when $L \ll \lambda_m$ (sin x ≈ x)

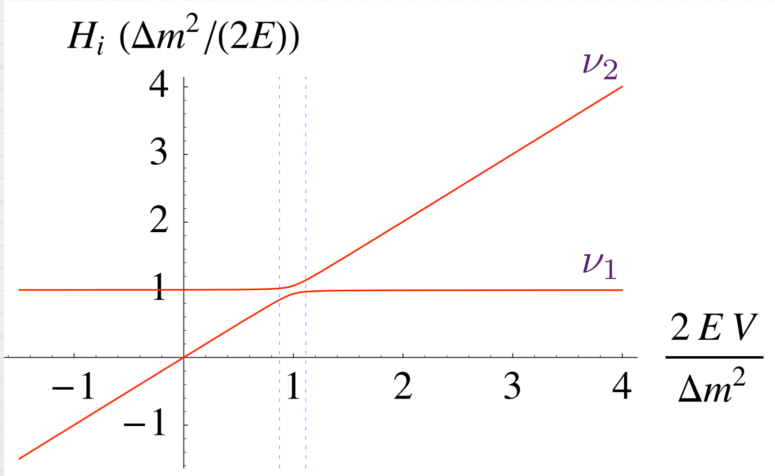
Propagation in varying density (2 ν)

$H(t) = H_{free} + V_{MSW}(t)$ time-dependent hamiltonian

Adiabatic evolution: no $\nu_1 \leftrightarrow \nu_2$ transitions

Adiabaticity condition: $\frac{d\theta_m}{dx} \ll \frac{(\Delta m^2)_m}{2E}$

Adiabatic resonance crossing → large flavor swap even for small ϑ



$$E \gg E_{\rm res} \rightarrow V = 0$$

$$\nu_e \approx (\nu_2)_m \rightarrow \nu_2 = \nu_e \sin\theta + \nu_\mu \cos\theta$$

$$P(\nu_e \rightarrow \nu_\mu) \approx \cos^2\theta$$

The adiabatic approximation must break at small ϑ

Level crossing

- The adiabatic approximation $\frac{d\theta_m}{dx} \ll \frac{(\Delta m^2)_m}{2E}$ is worst at the resonance

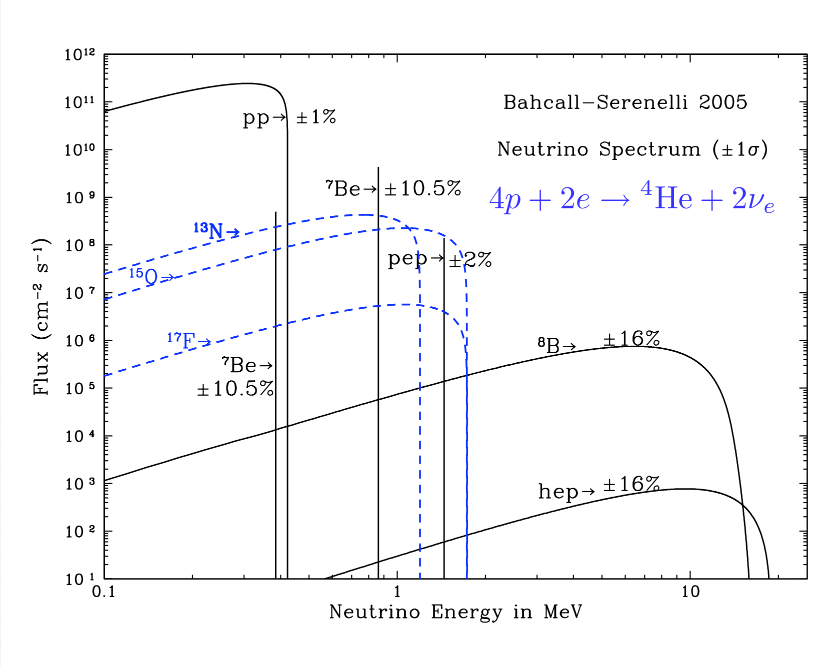
- Adiabatic condition at the resonance: $\gamma \equiv \frac{\Delta m^2}{2E(V'/V)_{\rm res}} \frac{\sin^2 2\theta}{\cos 2\theta} \gg 1$

- If $\gamma \lesssim 1$ but $\gamma \gg 1$ at production and detection $P(\nu_1 \to \nu_2) \equiv P_c \approx e^{-\gamma/2}$

  Landau-Zener

- Example: SN neutrinos ($\Delta m^2 > 0$) or antineutrinos ($\Delta m^2 > 0$) for $\vartheta_{13} < 10^{-3}$

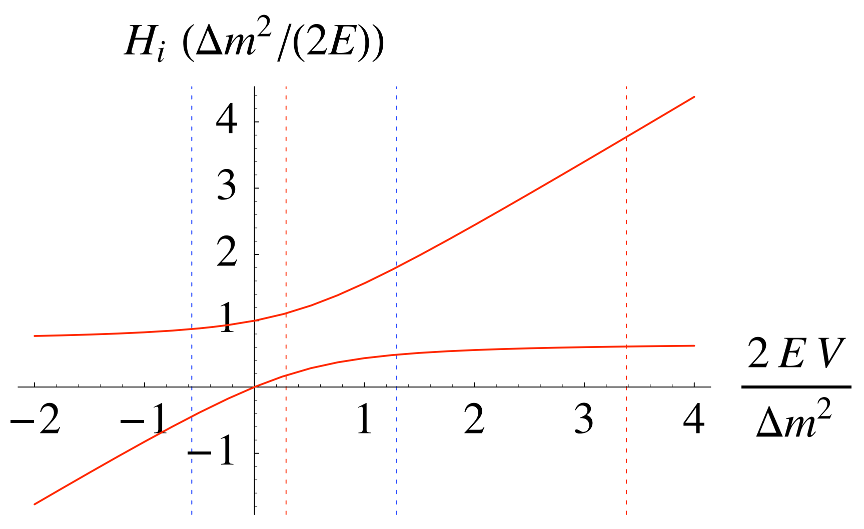
Solar neutrinos

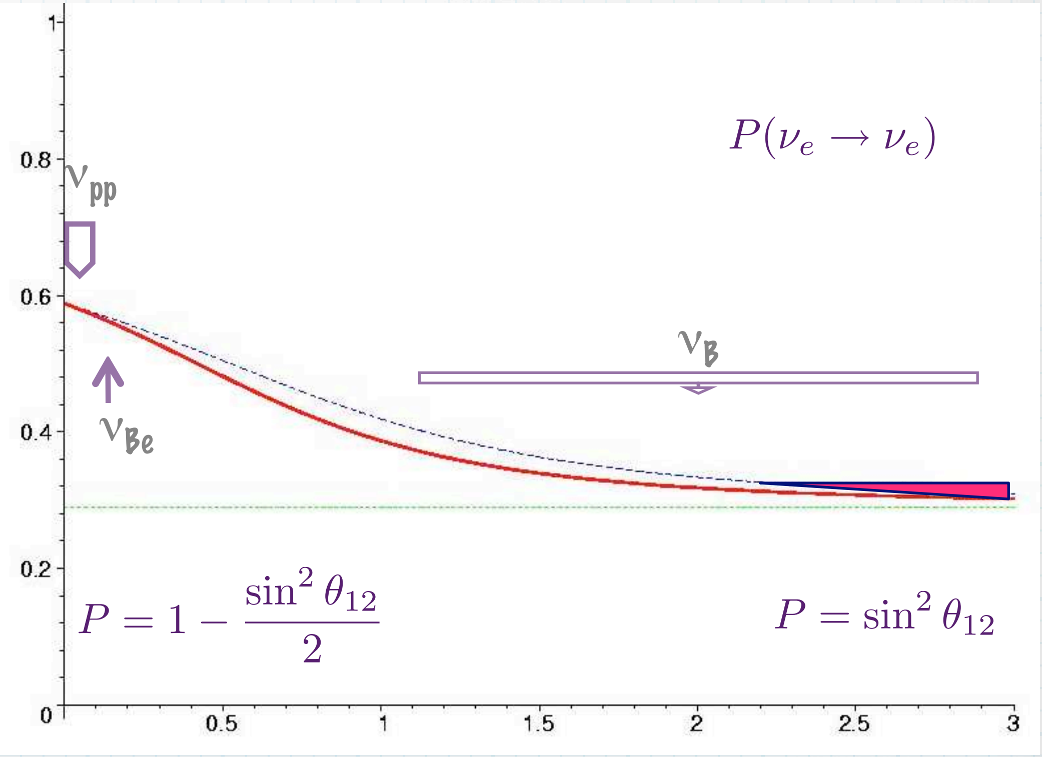


$$0\,\text{MeV} < E_\nu < 14\,\text{MeV}$$

$$E_{\text{res}}(\text{core}) \sim 3\,\text{MeV}$$

$$(\Delta m^2_{12} = 0.8 \times 10^{-4}\,\text{eV}^2)$$

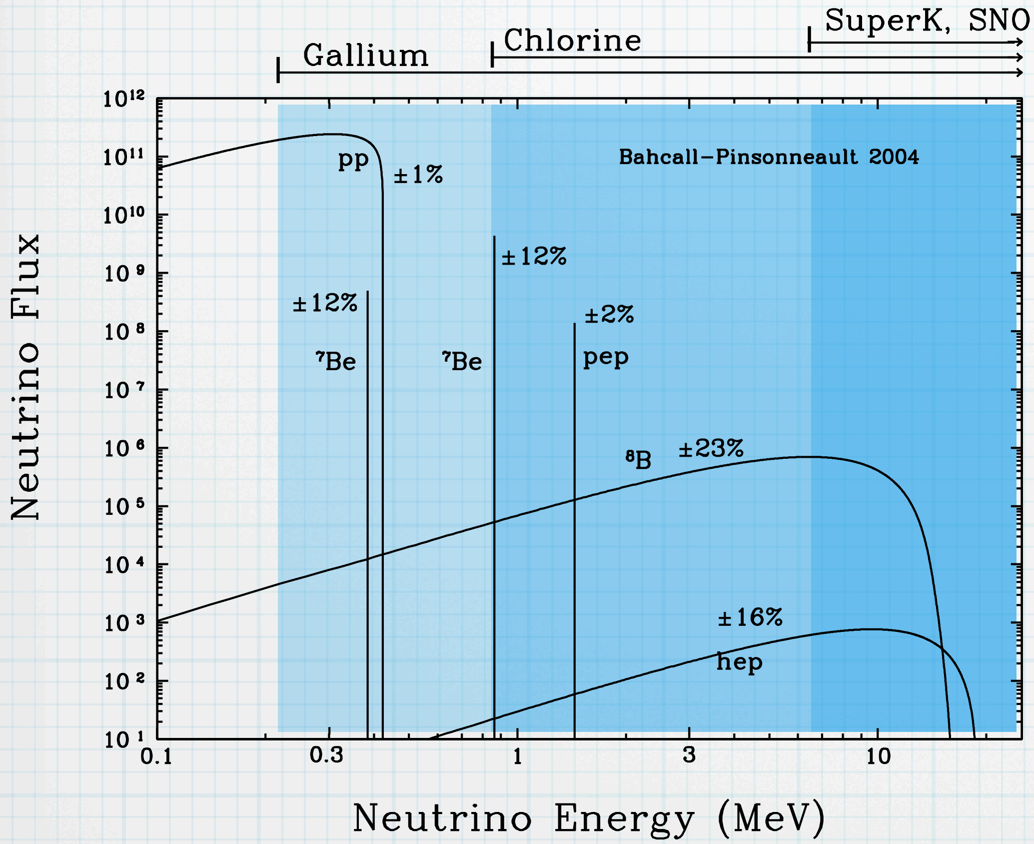




Smirnov

$$\frac{2EV}{\Delta m^2_{12}}$$

Solar neutrino experiments



Chlorine: Homestake (68)

$\nu_e\,{}^{37}\mathrm{Cl} \to e\,{}^{37}\mathrm{Ar}$

$E_\nu > 0.814\,\mathrm{MeV}$

Gallium: SAGE, Gallex/GNO

$\nu_e\,{}^{71}\,\mathrm{Ga} \to e\,{}^{71}\,\mathrm{Ge}$

$E_\nu > 0.233\,\mathrm{MeV}$

H_2O: K, SK

$\nu_e e \to \nu_e e$

$E_\nu > 5.5\,\mathrm{MeV}$

D_2O: SNO

$\nu_e e \to \nu_e e$

$\nu_e D \to ppe$

$\nu_x D \to \nu_x pn$

SNO

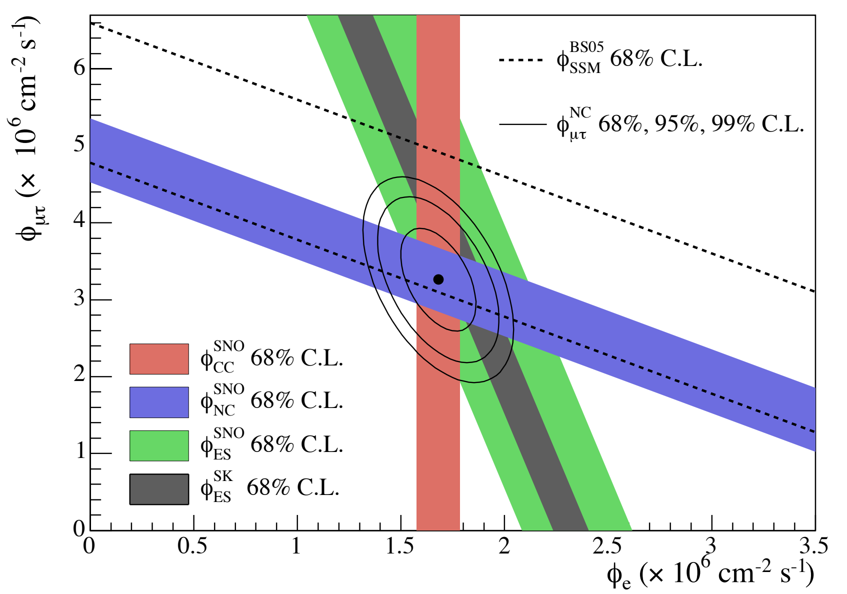
- Measurement of total solar neutrino flux in agreement with the prediction of the SSM

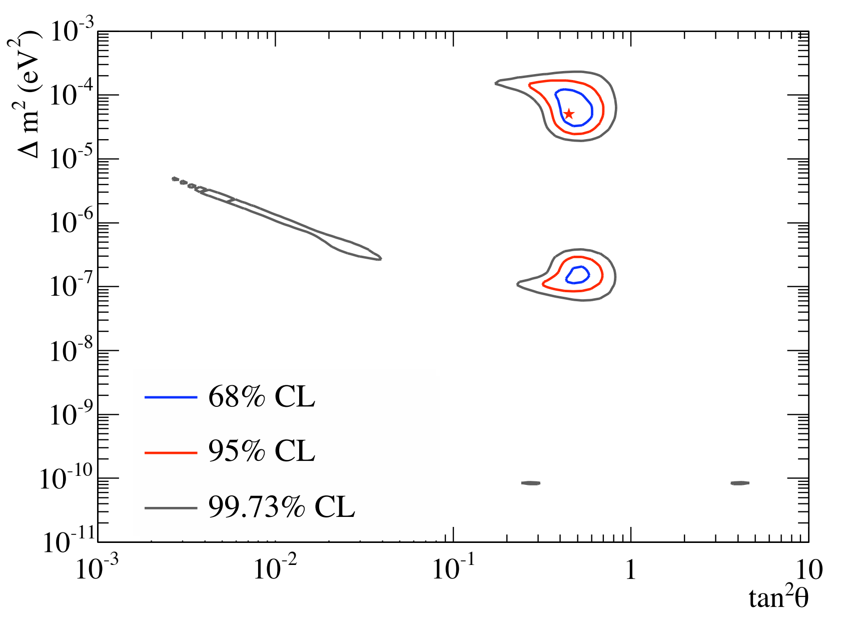
$$\Phi(\nu) = \Phi(\nu_e) + 2\Phi(\nu_{\mu,\tau})$$

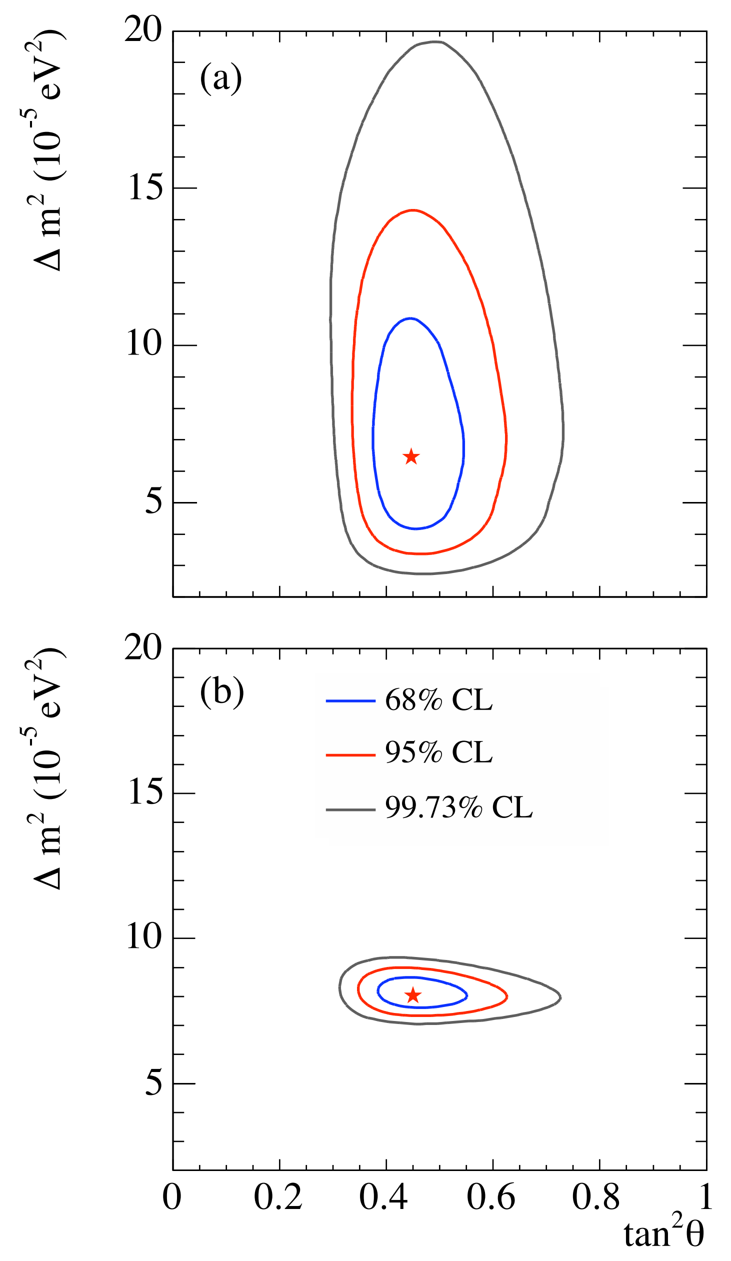
- ES (direction): $\nu_x e \rightarrow \nu_x e \Rightarrow \Phi(\nu_e) + 2\Phi(\nu_{\mu,\tau})/(6\text{–}7)$

- CC (energy): $\nu_e D \rightarrow ppe \Rightarrow \Phi(\nu_e)$

- NC (ring shape): $\nu_x D \rightarrow \nu_x pn \Rightarrow \Phi(\nu_e) + 2\Phi(\nu_{\mu,\tau})$ neutron capture and detection improved in the salt phase


ϕ_{SSM}^{BS05} 68% C.L.
$\phi_{\mu\tau}^{NC}$ 68%, 95%, 99% C.L.
ϕ_{CC}^{SNO} 68% C.L.
ϕ_{NC}^{SNO} 68% C.L.
ϕ_{ES}^{SNO} 68% C.L.
ϕ_{ES}^{SK} 68% C.L.
$\phi_{\mu\tau}$ ($\times$ 10^6 cm^{-2} s^{-1})
ϕ_e ($\times$ 10^6 cm^{-2} s^{-1})
0
1
2
3
4
5
6
0
0.5
1
1.5
2
2.5
3
3.5


Δ m^2 (eV^2)
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
68% CL
95% CL
99.73% CL
10^{-3}
10^{-2}
10^{-1}
1
10
tan$^2\theta$

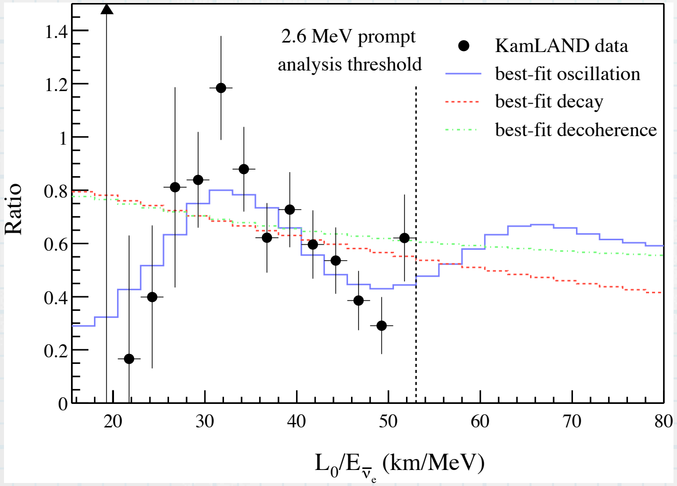

(a)
Δ m^2 (10^{-5} eV^2)
20
15
10
5
(b)
68% CL
95% CL
99.73% CL
Δ m^2 (10^{-5} eV^2)
20
15
10
5
0
0.2
0.4
0.6
0.8
1
tan$^2\theta$

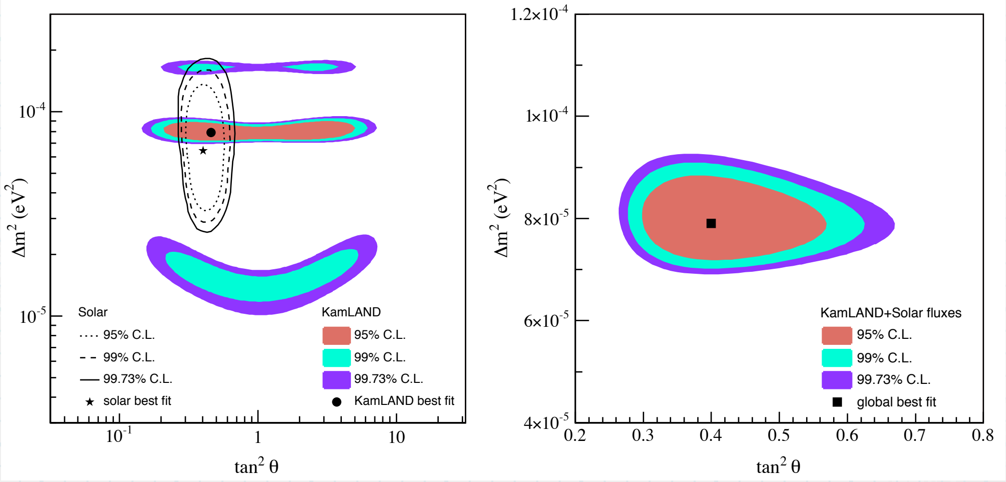
KamLAND

- $\overline{\nu}_e$ from several reactors (E ~ few MeV) at L ~ 200 km $\frac{\Delta m_{12}^2 L}{4E} = \mathcal{O}\left(1\right)$ (initial flux well known)

- $\overline{\nu}_e p \to e^+ n$ in scintillator

- $E_{\nu_e} = E_{e^+} + m_n - m_p \;\to$ good determination of Δm_{12}^2





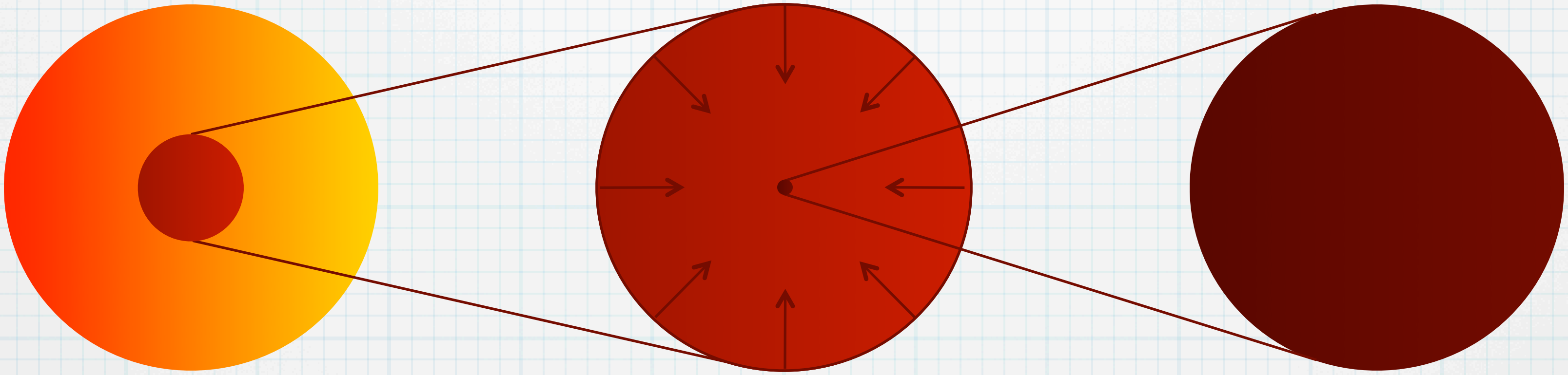
KamLAND, hep-ex/0406035

Future solar neutrino experiments

- More KamLAND
- Borexino: measure Berillium flux
  - If LMA, no seasonal variation, no D/N effect
  - Surprises? Non-LMA physics?
- sub-MeV experiments
  - measure averaged oscillations → ϑ

Supernova neutrinos

- Probe of core-collapse supernova physics
- Some sensitivity to neutrino parameters (uncertainties on the source)
- Constraint on exotic (neutrino) physics

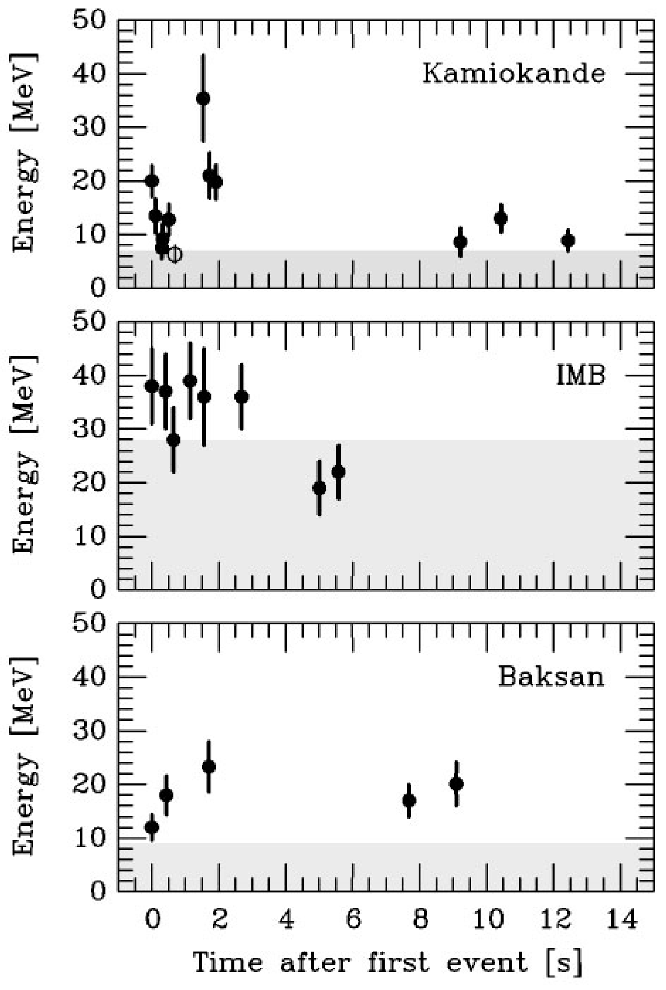


$$M \sim 1.5 M_{\mathrm{SUN}}$$
$$R \sim 8000\,\mathrm{km}$$
$$\rho \sim 10^9\,\mathrm{g/cm}^3$$
$$T \sim 0.7\,\mathrm{MeV}$$

$$E_{\mathrm{out}} \sim E_{\mathrm{b}} \sim 3 \times 10^{53}\,\mathrm{erg}$$
$$= \begin{cases} 0.01\%\ \text{photons} \\ 1\%\ \text{kinetic energy} \\ 99\%\ \text{neutrinos} \end{cases}$$
$$\lambda \sim 10\,\mathrm{cm} \Rightarrow t_{\mathrm{diff}} \sim \frac{3R^2}{\lambda} \sim 10\,\mathrm{sec}$$

$$R \sim 30\,\mathrm{km}$$
$$\rho \sim 3 \times 10^{14}\,\mathrm{g/cm}^3$$
$$T \sim 30\,\mathrm{MeV}$$

SN 1987A



Raffelt

Constraints on exotic scenarios

- Energy loss argument: $\frac{d\epsilon}{dt} < 10^{19}\,\mathrm{erg/s/g}$

- Constrains invisible escape channels
  - axions
  - KK gravitons
  - sterile neutrinos

- E.g.: $\sin^2 2\vartheta_s < 10^{-8}$ for large Δm^2

Future SNe

Future SNe (1/30yr?)				
Detector	SK	SNO	LVD	KamLAND
ν events (from 10kpc)	~ 8000	~ 800	~ 400	~ 330

@ neutrinosphere: $\langle E_{\nu_e}\rangle \sim 11\,\mathrm{MeV} < \langle E_{\overline{\nu}_e}\rangle \sim 16\,\mathrm{MeV} < \langle E_{\overline{\nu}_x}\rangle \sim 25\,\mathrm{MeV}$

@ Earth: the energy spectra depend on ϑ_{13} and sign$(\Delta m^2)_{23}$

e.g.: NH & $\vartheta_{13} > 0.05 \Rightarrow \Phi(\nu_e) = \Phi_0(\nu_{\mu,\tau})$

$(\Delta m^2)_{23}$ resonance crossed by neutrinos (antineutrinos) if NH (IH)

$P_C = 0$ ($P_C = 1$) if $\vartheta_{13} > 0.05$ ($\vartheta_{13} < 0.001$)

($(\Delta m^2)_{12}$ is always adiabatic)

($(\Delta m^2)_{23} = 2\,E\,(V_\mu - V_\tau)$ resonance plays a role if $\Phi(\nu_\mu) \neq \Phi(\nu_\tau)$)

Future

sign(Δm²) and matter effects

$$\Delta m^2_{12} = 0 : \;\; H_{\rm eff} = \frac{1}{2E}\left[U \begin{pmatrix} 0 & & \\ & 0 & \\ & & \Delta m^2_{23} \end{pmatrix} U^T \pm \begin{pmatrix} 2EV & & \\ & 0 & \\ & & 0 \end{pmatrix}\right]$$

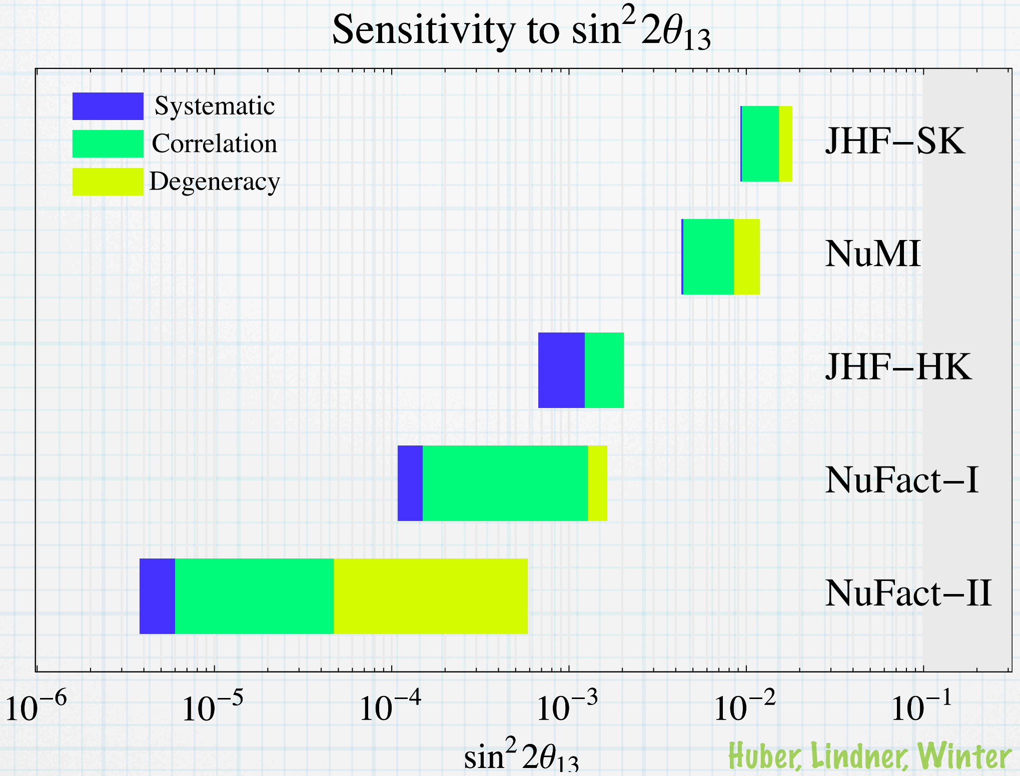
- Enhancement/suppression in neutrino/antineutrino channel depending on sign(Δm^2)
- A measurement of sign(Δm^2) needs
  - E ~ 10 GeV (resonance)
  - long baseline (sin(x) ≠ x)
  - $\nu_e \leftrightarrow \nu_{\mu,\tau}$
- sign(Δm^2) determines the pattern of neutrino masses and affects the
  - SN neutrino signal
  - terrestrial experiments
  - 0ν2β decay

ϑ_{13}

- Origin of masses and mixing
  - Discriminate models
  - Origin of solar and atmospheric angles
  - Neutrino mass pattern
- Phenomenology
  - Leptonic CP-violation
  - Supernova signals
  - Subleading effects
- Experiments
  - Rich experimental program available (subleading effect in SUN and ATM)

$$\left.\begin{aligned} P(\nu_\mu \leftrightarrow \nu_\tau) &\approx \sin^2\theta_{23}\sin^2\frac{\Delta m^2_{23}L}{4E} \\ P(\nu_e \leftrightarrow \nu_\mu) &\approx \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{23}L}{4E} \\ P(\nu_e \leftrightarrow \nu_\tau) &\approx \cos^2\theta_{23}\sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{23}L}{4E} \end{aligned}\right\} + \Delta m^2_{SUN}$$

Odds



Huber, Lindner, Winter

$$\theta_{13} = \lambda_c : \quad \sin^2 2\theta_{13} \approx 0.2$$

$$\theta_{13} = \lambda_c^2 : \quad \sin^2 2\theta_{13} \approx 0.01$$

$$\theta_{13} = \lambda_c^3 : \quad \sin^2 2\theta_{13} \approx 0.0005$$

bet: $\sin^2 2\theta_{13} > 0$

CP-violation

- Is there CP-violation in the lepton sector?

- Is it at the origin of the Baryon asymmetry in the universe?

- Can we observe it in neutrino experiments?
    - Dirac (CKM-like) CP-violation
    - Majorana CP-violation

CKM-like CP-violation

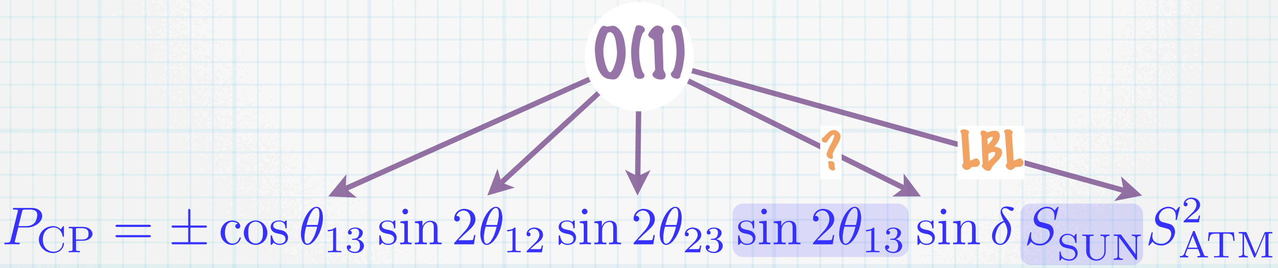
$$P(\nu_{e_i} \to \nu_{e_j}) = P(\overline{\nu}_{e_j} \to \overline{\nu}_{e_i}) = P_{\mathrm{CP}} + P_{\cancel{\mathrm{CP}}}$$
$$P(\overline{\nu}_{e_i} \to \overline{\nu}_{e_j}) = P(\nu_{e_j} \to \nu_{e_i}) = P_{\mathrm{CP}} - P_{\cancel{\mathrm{CP}}}$$

At accelerators, due to the smallness of $(\Delta m^2)_{12}/(\Delta m^2)_{23}$ and ϑ_{13} :

$$\left.\begin{aligned} P(\nu_\mu \leftrightarrow \nu_\tau)_{\mathrm{CP}} &\approx \sin^2\theta_{23}\sin^2\frac{\Delta m^2_{23}L}{4E} \\ P(\nu_e \leftrightarrow \nu_\mu)_{\mathrm{CP}} &\approx \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{23}L}{4E} \\ P(\nu_e \leftrightarrow \nu_\tau)_{\mathrm{CP}} &\approx \cos^2\theta_{23}\sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{23}L}{4E} \end{aligned}\right\} + \Delta m^2_{SUN}\ \mathrm{corr.}$$

CKM-like CP-violation

Large angles (unlike in quark sector) enhance CP-violation



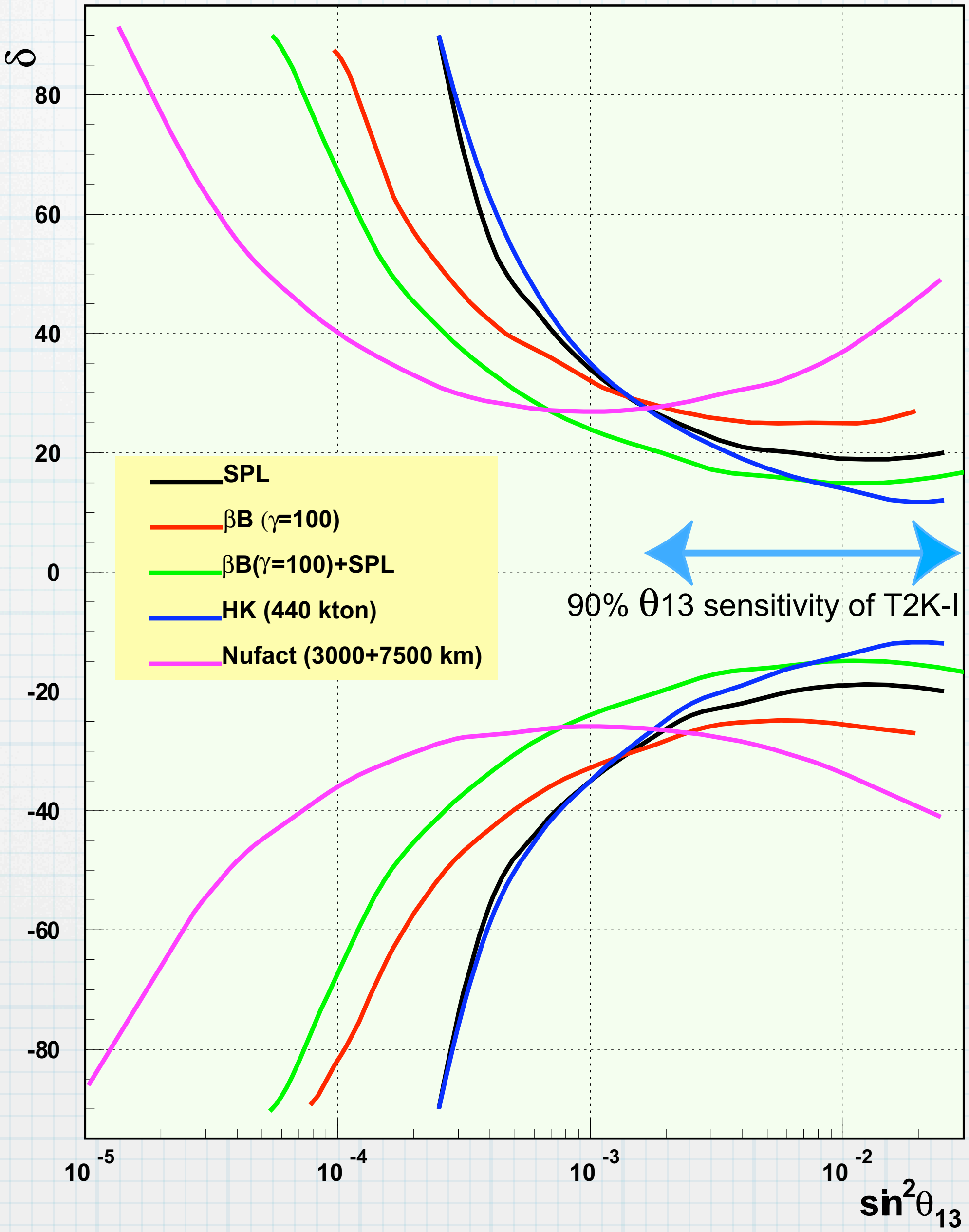
$$P_{\rm CP} = \pm \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \sin\delta \, S_{\rm SUN} S^2_{\rm ATM}$$

A small ϑ_{13} enhances the $\nu_e \leftrightarrow \nu_{\mu,\tau}$ CP-asymmetry

$$a_{\rm CP} = \frac{P(\nu_e \to \nu_\mu) - P(\overline{\nu}_e \to \overline{\nu}_\mu)}{P(\nu_e \to \nu_\mu) + P(\overline{\nu}_e \to \overline{\nu}_\mu)} \propto \frac{1}{\sin 2\theta_{13} + \ \text{corr.}}$$

The statistical sensitivity is independent of ϑ_{13} (on a wide range)

$$\delta a \sim \frac{1}{\sqrt{N}} \propto \frac{1}{\sin 2\theta_{13}} \to \text{stat. error} \sim \delta a / a \sim \text{constant with } \theta_{13}$$

δ
80
60
40
20
0
-20
-40
-60
-80
SPL
βB (γ=100)
βB(γ=100)+SPL
HK (440 kton)
Nufact (3000+7500 km)
90% θ13 sensitivity of T2K-I
10^{-5}
10^{-4}
10^{-3}
10^{-2}
$\sin^2\theta_{13}$

Fake CP-violation

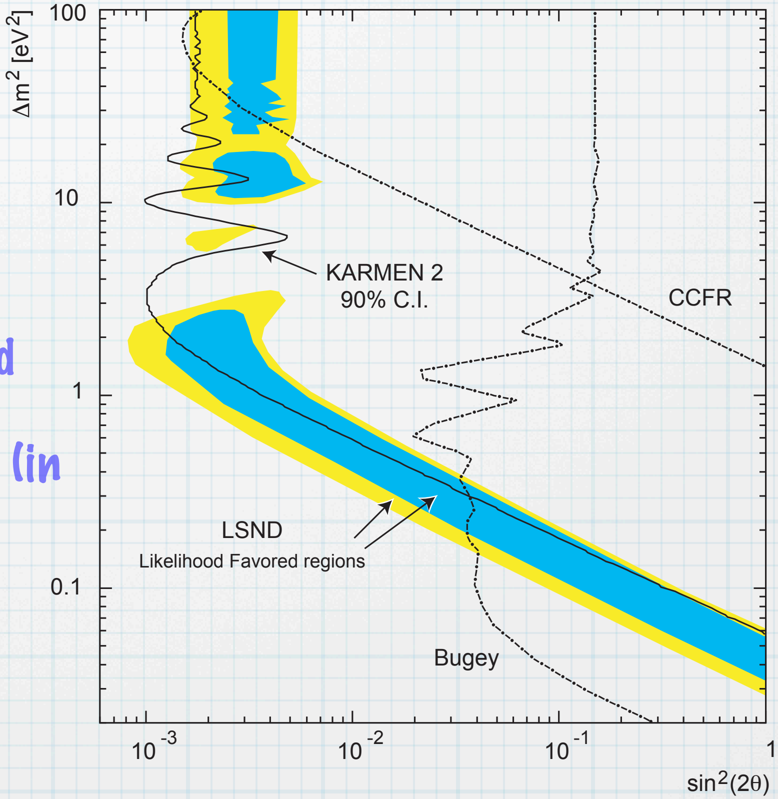
* In practice one has to take into account the contribution to the measured asymmetry from the CP-asymmetry of
  - the source
  - the matter along the path of neutrinos
  - the target
* That requires a good knowledge of
  - the initial fluxes
  - the Earth (electron) density profile
  - the neutrino cross sections
* Also useful are
  - the measurement of the energy spectrum
  - 2 baselines
  - additional channels

LSND & MiniBooNE

The LSND evidence

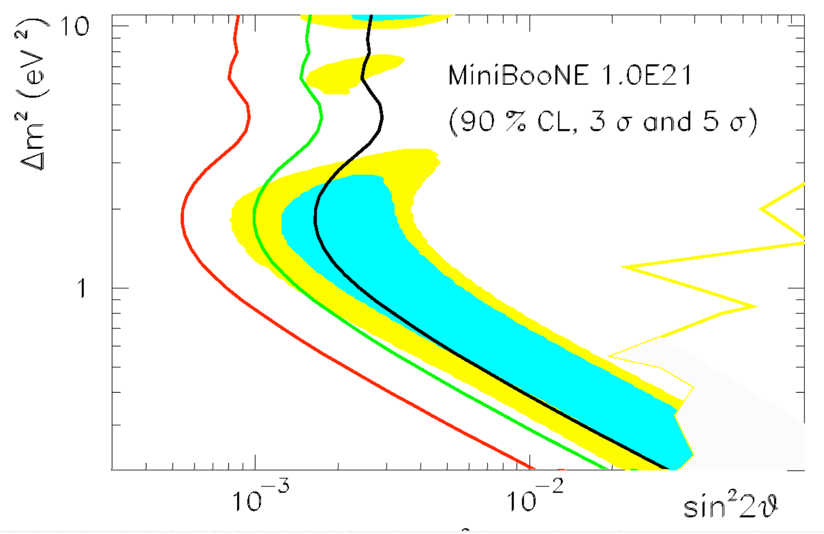
$$P(\overline{\nu}_\mu \to \overline{\nu}_e) = (2.6 \pm 0.8)10^{-3}, \text{ with } E \sim (10\text{–}50)\,\text{MeV and } L \approx 30\,\text{m}$$

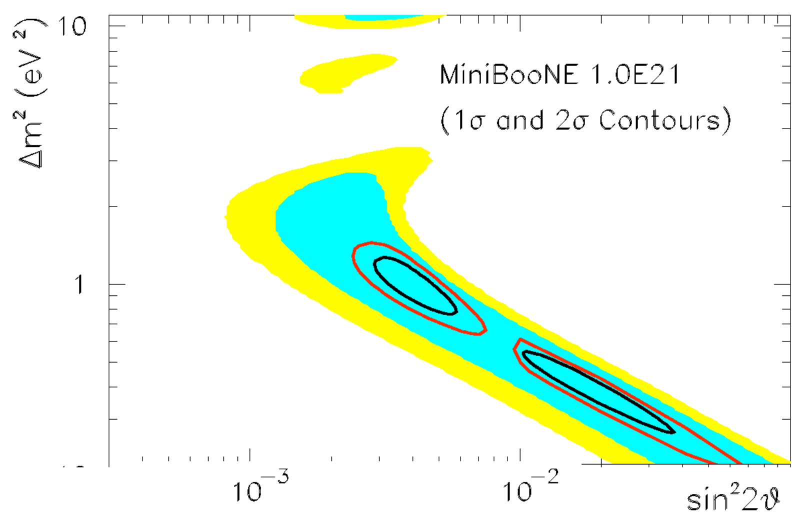
- does not fit in the 3 neutrino oscillation framework (large Δm^2)
- does not fit in a 4 neutrino oscillation framework
- depends on assumptions on the background
- is not confirmed by any other experiments (in particular Karmen)
- awaits confirmation (MiniBooNE: more statistics + pulsed beam)



Oscillation Sensitivity: Null and Positive Scenarios

- Fit energy distribution to extract signal. Estimates based on 10^{21} pot





Null MiniBooNE result:

- 4σ sensitivity to entire LSND 90% CL allowed region
- Combined analysis of MiniBooNE + LSND would show incompatibility at 99% CL, in CP and CPT-conserving scenarios

MiniBooNE confirms LSND:

- Should see $> 5\sigma$ excess at LSND central value
- Distinguish $1\,\mathrm{eV}^2$ from $0.4\,\mathrm{eV}^2$ at 2σ

Beyond oscillations

$$\Delta m^2_{12}$$

$$|\Delta m^2_{23}|$$

$$m_{e,\mu,\tau}$$

$$\mathrm{sign}(\Delta m^2_{23})$$

$$\theta_{12}, \theta_{23}, \theta_{13}, \delta$$

$$m_{\mathrm{lightest}}$$

$$\alpha$$

$$\beta$$

0ν2β decay

- Signals L-violation
- Probes the Majorana nature of neutrinos
- Allows to access parameters not accessible to oscillations:
  - Absolute mass scale
  - Majorana phases

Dirac vs Majorana (particle content)

- A Dirac fermion (e + e^c) corresponds to

  4 degrees of freedom = 2 x particle + 2 x antiparticle

- A Majorana fermion (ν) corresponds to

  2 degrees of freedom = 2 x particle = 2 x antiparticle

- The difference shows up only in the m ≠ 0 case:
  - Dirac (m = 0)

    $$\overline{\nu}_L|0\rangle = |\nu\, -\rangle \qquad \nu_L|0\rangle = |\overline{\nu}\, +\rangle$$

  - Majorana (m = 0)

    $$\overline{\nu}_L|0\rangle = |\nu\, -\rangle \qquad \nu_L|0\rangle = |\nu\, +\rangle$$

- In oscillations, once the O(m/E) terms have been neglected:
  - the elicity does not play a role
  - there is no L-violation
  - oscillation formulae are identical for Dirac and Majorana ν's

Dirac vs Majorana (particle content)

- A Dirac fermion (e + e^c) corresponds to

  4 degrees of freedom = 2 x particle + 2 x antiparticle

- A Majorana fermion (ν) corresponds to

  2 degrees of freedom = 2 x particle = 2 x antiparticle

- The difference shows up only in the m ≠ 0 case:
  - Dirac (m ≠ 0)

    $$\overline{\nu}_L|0\rangle = |\nu\,-\rangle + \mathcal{O}\left(m/E\right)|\nu\,+\rangle \qquad \nu_L|0\rangle = |\overline{\nu}\,+\rangle + \mathcal{O}\left(m/E\right)|\overline{\nu}\,-\rangle$$

  - Majorana (m ≠ 0)

    $$\overline{\nu}_L|0\rangle = |\nu\,-\rangle + \mathcal{O}\left(m/E\right)|\nu\,+\rangle \qquad \nu_L|0\rangle = |\nu\,+\rangle + \mathcal{O}\left(m/E\right)|\nu\,-\rangle$$

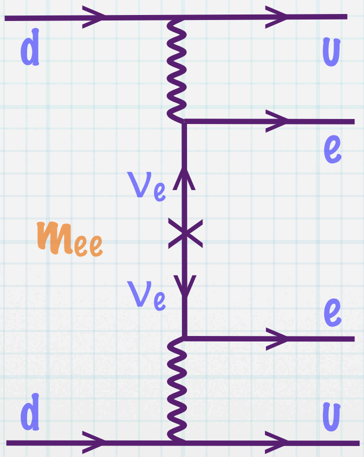
- In oscillations, once the O(m/E) terms have been neglected:
  - the elicity does not play a role
  - there is no L-violation
  - oscillation formulae are identical for Dirac and Majorana ν's

0ν2β decay

$$(A,Z) \to (A,Z+2) + 2e^-; \quad \text{e.g.: } {}^{76}\text{Ge} \to {}^{76}\text{Se} + 2e^-$$

$$\Gamma \propto |m_{ee}|^2 \langle Q \rangle^2$$

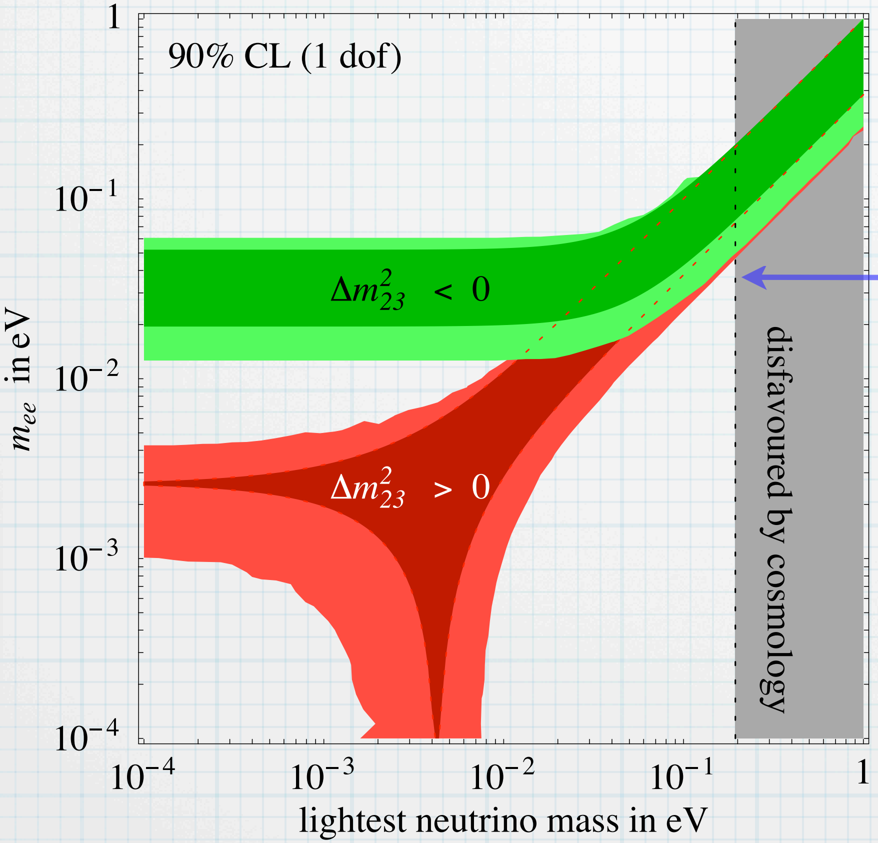
$$m_{ee} = U_{eh}^2 m_h = c_{13}^2(m_1 c_{12}^2 + m_2 s_{12}^2 e^{2i\alpha}) + m_3 s_{13}^2 e^{2i\beta'}$$



Expectations for m_{ee}

$$(m^\dagger m)_{ee} < (2.2\,\mathrm{eV})^2 \text{ (Mainz, Troitsk)} \to (0.3\,\mathrm{eV})^2 \text{ (Katrin)}$$

$$|m_{ee}| < \mathcal{O}(1) \times 0.4\,\mathrm{eV} \text{ (Heidelberg-Moscow)} \to \mathcal{O}(1) \times 0.01\,\mathrm{eV} \text{ (Genius)}$$



Feruglio Strumia Vissani

$$|m_{ee}| \approx \sqrt{\Delta m^2_{32}}\,\left|c^2_{12} + s^2_{12}e^{2i\alpha}\right|$$

Only IH and D are promising

Sensitivity to Majorana phases through CP-conserving quantity

Explicit models may relate CKM-like and Majorana phases

Potential to discriminate Dirac/M

β decay endpoint

$$(A, Z) \to (A, Z+1) + e^- + \overline{\nu}_e; \quad \text{e.g.: } {}^3\mathrm{H} \to {}^3\mathrm{He} + e^- + \overline{\nu}_e$$

$$\frac{dN}{dE} \propto \sum |U_{eh}|^2 \Gamma(m_h^2, E) \approx \Gamma((m^\dagger m)_{ee}, E)$$

$$(m^\dagger m)_{ee} = |U_{eh}|^2 m_h^2 = c_{13}^2 (m_1^2 c_{12}^2 + m_2^2 s_{12}^2) + m_3^2 s_{13}^2$$

Neutrinos and cosmology

- Big Bang Nucleosynthesis
  - The present relative abundance of p, n, light elements is determined by standard inverse beta reactions involving neutrinos at their decoupling temperature T ~ MeV
  - Agreement with 3 SM neutrinos in thermal equilibrium at T ~ MeV. Present accuracies do not allow to tell $N_\nu = 3$ from $N_\nu = 4$ even in the context of standard cosmology (not fully tested)

- Cosmic Microwave Background
  - Anisotropies in the photon radiation at decoupling (T ~ 0.3 eV) are sensitive to the total radiation density
  - Present fits (cosmological model dependent) give $N_\nu \sim 3 \pm 2$

- Large Scale Structure
  - Free streaming of relativistic non-interacting particles smoothes density fluctuation leading to the LSS observed today (and to the acoustic peaks in CMB)
  - The length scale of the effect depends on the neutrino masses, hence the limit $\sum m_i < 0.7\,\mathrm{eV}$
- Baryogenesis
  - $n_B/n_\gamma \sim 6 \times 10^{-10}$ means that a tiny Baryon asymmetry was present before complete annihilation at T < GeV
  - The asymmetry can be dynamically generated in presence of B, C and CP-violating processes out of equilibrium
  - EW baryogenesis in SM: not out of equilibrium enough for m_H > 70 GeV (and too small CP-violation); in extensions: LEP
  - GUT baryogenesis, Affleck-Dine, but most economical and elegant is...

Baryogenesis through leptogenesis

- Non-perturbative B-L-conserving processes relate L- and B-asymmetries.
- Right-handed neutrino L- and CP-violating decays generate a lepton asymmetry out of equilibrium. In a see-saw context with hierarchical R-handed neutrinos:

$$n_B/n_\gamma \propto \epsilon, \quad \epsilon \sim \frac{3}{16\pi}\frac{M_1}{v^2}\frac{\mathrm{Im}(\lambda_N m_\nu \lambda_N^T)_{11}}{(\lambda_N \lambda_N^\dagger)_{11}}$$

- The RH neutrino coupling are not fully determined by the low energy parameters. However, both come from the same see-saw lagrangian (model-dependent relation)
- Leptogenesis is a simple, elegant, economical and successful Baryogenesis mechanism

Other constraints on see-saw physics

- Lepton Flavour Violation in SUSY models
  - LFV associated to neutrino Yukawa couplings does not decouple at the RH neutrino mass scale in SUSY theories: they leave an imprint in the slepton soft masses
  - However, the effect depends on four powers of the unknown (model-dependent) overall scale of the couplings
  - Additional effects are also likely, e.g.
    - Non-universal soft term
    - Top Yukawa in SUSY-GUTs

- Bottom-Tau mass unification
  - The running is affected by the neutrino Yukawa couplings

The origin of neutrino masses
(data interpretation)

Experimental constraints

$\Delta m^2_{\text{ATM}} \sim 2.5 \times 10^{-3}\,\text{eV}^2 \quad \theta_{23} \sim 45^\circ$	(ATM, K2K)
$\Delta m^2_{\text{SUN}} \sim 0.8 \times 10^{-4}\,\text{eV}^2 \quad \theta_{12} \sim 30^\circ\text{–}35^\circ$	(SUN,KamLAND)
$\theta_{13} < 10^\circ$	(CHOOZ, Palo Verde + ATM)
$\lvert m_{ee}\rvert = \lvert U^2_{ei} m_{\nu_i}\rvert < \mathcal{O}(1) \times 0.4\,\text{eV}$	(Heidelberg-Moscow)
$(m^\dagger m)_{ee} = \lvert U_{ei}\rvert^2 m^2_{\nu_i} < (2.2\,\text{eV})^2$	(Mainz, Troitsk)
$\sum_i m_{\nu_i} < 0.6\,\text{eV}\ \ (\text{priors})$	(Cosmology)

Guidelines for theory:

$$m_{\nu_i} \ll 174\,\text{GeV}$$

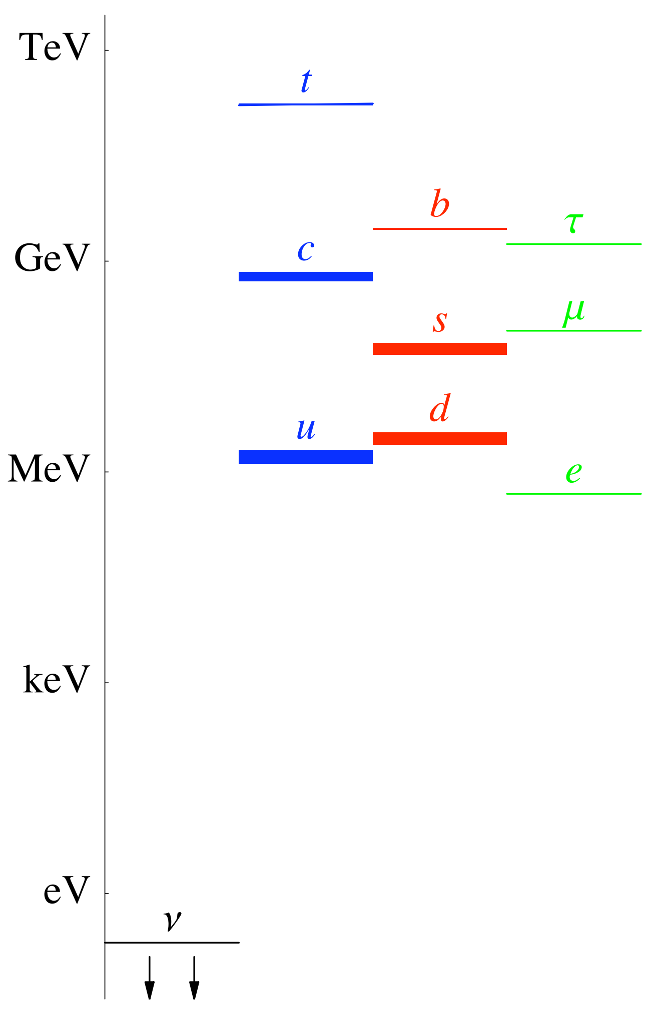
$$\theta_{23} \sim 45^\circ (= 45^\circ ?)$$

$$\theta_{12} \sim 30^\circ\text{–}35^\circ \neq 45^\circ\ \ (> 5\sigma)$$

$$\theta_{13} < 10^\circ$$

$$\lvert \Delta m^2_{12} / \Delta m^2_{23} \rvert \approx 0.035 \ll 1$$

Smallness of neutrino masses



- Natural scale of fermion masses: v = 174 GeV
- Why $m_\nu / v < 10^{-12}$?
- (must have a different origin than $m_e / v < 10^{-12}$ GeV $= 0.3 \times 10^{-5}$)

The SM as a renormalizable theory

B, L_e, L_μ, L_τ are accidentally conserved

- No proton decay (...)
- No lepton number violation (...)
- No individual lepton number violation, no $\nu_{ei} \leftrightarrow \nu_{ej}$, no neutrino masses

The SM as an effective theory

$$\mathcal{L}_{\rm SM}^{\rm eff} = \mathcal{L}_{\rm SM}^{\rm ren} + \frac{h_{ij}}{\Lambda}(HL_i)(HL_j) + \ldots$$

$$m_\nu = hv \times \frac{v}{\Lambda}$$

$$\Lambda \sim 0.5 \times 10^{15}\,\mathrm{GeV}h\left(\frac{0.05\,\mathrm{eV}}{m_\nu}\right)$$

- $M_{GUT} \approx 2 \times 10^{16}$ GeV
- L^{eff} is sensitive to the GUT scale only through L- and B-violating operators
- $\Lambda_L \sim 10^{15}$ GeV, $\Lambda_B > 4 \times 10^{15}$ GeV (no or small L, B violation at TeV scale)

Right-handed neutrinos

$$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} u^c \\ d^c \end{pmatrix} \quad \begin{pmatrix} \nu \\ e \end{pmatrix} \quad \begin{pmatrix} \nu^c \\ e^c \end{pmatrix}$$

$SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

Right-handed neutrinos

$$\begin{pmatrix} u \\ d \end{pmatrix} \qquad \begin{matrix} u^c \\ d^c \end{matrix} \qquad \begin{pmatrix} \nu \\ e \end{pmatrix} \qquad \begin{matrix} \nu^c \\ e^c \end{matrix}$$

$SU(3)_C$ x $SU(2)_W$ x $U(1)_Y$

$$\lambda \nu_c L H \rightarrow m_\nu = \lambda_\nu v$$

(like the other fermions)

ν_c is a SM singlet and can therefore be heavy

$$\mathcal{L}_{\mathrm{HE}} \supset -\frac{M}{2} \nu^c \nu^c$$

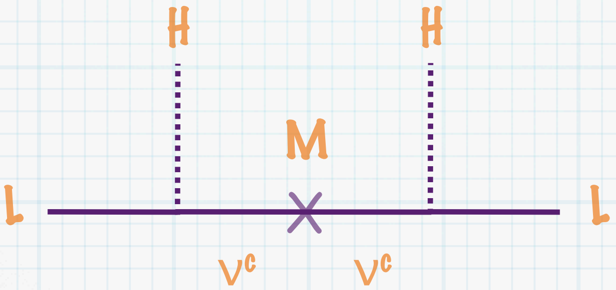
(unlike the other fermions)

If M is very small

- (meaning $M \ll m_\nu$, $M/M_{GUT} \ll 10^{-26}$)
- (why?)
- Neutrino have Dirac masses, which do not break L
- Their Yukawas are $< 10^{-12}$ (all families)
- (why?)
- Neutrinoless double beta decay may test the Majorana nature of neutrinos

See-saw

Integrate out ν^c:



$$\frac{h}{\Lambda}(HL)(HL)$$

$$\frac{h}{\Lambda} \rightarrow -\lambda^T \frac{1}{M} \lambda$$

$$\boxed{m_\nu = -m_{\rm D}^T \frac{1}{M} m_{\rm D}}$$

Majorana

Other options: additional singlets, triplets

Large angles?

- $\vartheta_q\ \vartheta_l \ll 1 \not\Rightarrow \vartheta_\nu \ll 1$: Dirac and Majorana mass terms transform differently under symmetries

- Example: $L_\mu - L_\tau$. In the symmetric limit: $m_E \propto \begin{pmatrix} a & 0 \\ 0 & 1 \end{pmatrix}$ $\quad m_\nu \propto \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$

  $\theta_l = 0^\circ \qquad \theta_\nu = 45^\circ$

- However, it only works with degenerate ν's:
  - $m_2 \approx m_3$, $(\Delta m^2)_{12} \ll (\Delta m^2)_{23} \Rightarrow m_1 \approx m_2 \approx m_3$
  - Example: $m_\nu \propto \begin{pmatrix} 1 & & \\ & & 1 \\ & 1 & \end{pmatrix}$

Origin of large mixings

$$m_U = U_{u^c}^T m_U^{\rm diag} U_u$$

$$m_D = U_{d^c}^T m_D^{\rm diag} U_d$$

$$V = U_u U_d^\dagger$$

$$m_\nu = U_\nu^T m_\nu^{\rm diag} U_\nu$$

$$m_E = U_{e^c}^T m_E^{\rm diag} U_e$$

$$U = U_\nu U_e^\dagger$$

The large mixing angles can in principle originate from both m_E, m_ν

(the distinction is physical in terms of the physics giving rise to the mass matrices)

A large ϑ_{23} from m_ν - normal hierarchy

- ϑ_{23} large and $m_2 \ll m_3$ seems unnatural: $m_\nu \propto \begin{pmatrix} C & B \\ B & A \end{pmatrix}$

ϑ_{23} large : $A \sim B \sim C$

$m_2 \ll m_3$: $AC - B^2 \ll 1$

- However, in a see-saw context A, B, C are not fundamental parameters

$$m_\nu = -m_{\rm D}^T M^{-1} m_{\rm D}$$

$$[M]_{23} = \begin{pmatrix} M_2 & \\ & M_3 \end{pmatrix}, \quad [m_\nu]_{23} = \frac{1}{M_2} \begin{pmatrix} m_{22}^2 & m_{22}m_{23} \\ m_{22}m_{23} & m_{23}^2 \end{pmatrix} + \frac{1}{M_3} \begin{pmatrix} m_{32}^2 & m_{32}m_{33} \\ m_{32}m_{33} & m_{33}^2 \end{pmatrix}$$

det ≠ 0 det = 0 det = 0

- Natural option: $M_2 \ll M_3, \quad m_{22} \sim m_{23}$

King; Altarelli Feruglio Masina

A large ϑ_{23} from m_ν - inverse hierarchy

- ϑ_{23} large and $m_1 \approx m_2$ + no correlations: $m_\nu \propto \begin{pmatrix} & A & B \\ A & & \\ B & & \end{pmatrix} + \text{corr.}$

- $\tan \vartheta_{23} = B/A$

- Bonus: ϑ_{12} automatically large

- Potential problem: $(\vartheta_{12})_\nu = 45^0$

A large ϑ_{23} from m_E

$$m_E \propto \begin{pmatrix} & & \\ & & \epsilon' \\ & A & 1 \end{pmatrix} \qquad A = 1.0 \pm 0.3$$

$$m_D \propto \begin{pmatrix} & & \\ & & A' \\ & \epsilon & 1 \end{pmatrix} \qquad \epsilon \sim 0.04$$

Not incompatible even in SU(5), where $m_E \leftrightarrow (m_D)^T$ (up to JG factors)

[e.g. Altarelli Feruglio and refs]

Is ϑ_{23} large or maximal?

- Large = $O(\pi/4)$; maximal = $\pi/4 \pm$ correction $\ll 1$
- SK: $\sin^2 2\vartheta_{23} > 0.9$ - not enough

$$\tan\vartheta_{23} = B/A;\ A \sim B \leftrightarrow \text{large};\ A = B \leftrightarrow \text{maximal}$$

$$1 - \epsilon < B/A < 1 + \epsilon \ \Rightarrow \sin^2 2\vartheta_{23} > 1 - \epsilon^2$$

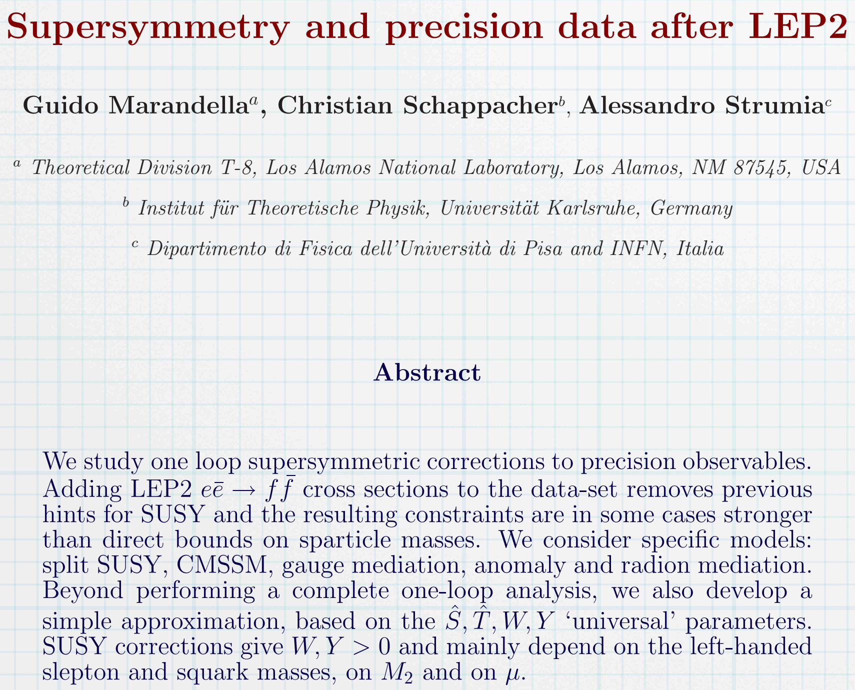
$$0.7 < B/A < 1.4 \Rightarrow \sin^2 2\vartheta_{23} > 0.9$$

$$0.9 < B/A < 1.1 \ \Rightarrow \sin^2 2\vartheta_{23} > 0.99$$

- Obtaining a maximal atm angle in a 3 neutrino context is non-trivial. A maximal angle would set a powerful constraint on the origin of lepton mixing (non-abelian horizontal symmetries?)

And dulcis in fundo...

quello che “la gente” fa



Supersymmetry and precision data after LEP2

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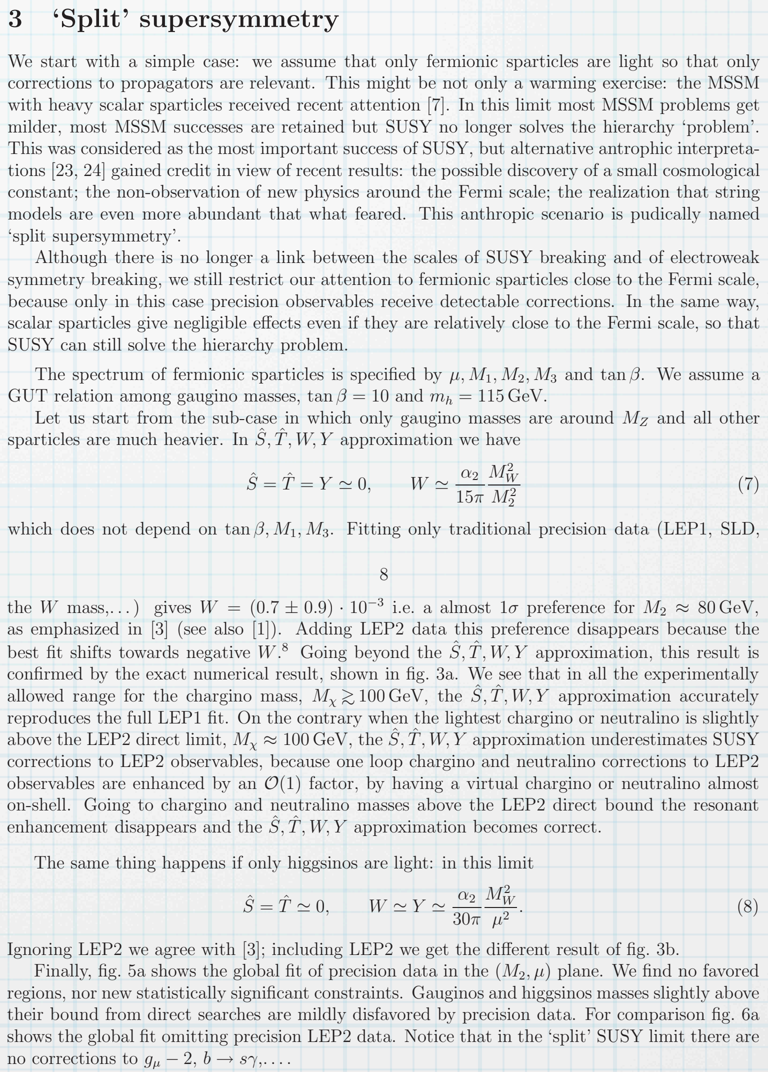
Abstract

We study one loop supersymmetric corrections to precision observables. Adding LEP2 $e\bar{e} \to f\bar{f}$ cross sections to the data-set removes previous hints for SUSY and the resulting constraints are in some cases stronger than direct bounds on sparticle masses. We consider specific models: split SUSY, CMSSM, gauge mediation, anomaly and radion mediation. Beyond performing a complete one-loop analysis, we also develop a simple approximation, based on the $\hat{S}, \hat{T}, W, Y$ 'universal' parameters. SUSY corrections give $W, Y > 0$ and mainly depend on the left-handed slepton and squark masses, on M_2 and on μ.



3 'Split' supersymmetry

We start with a simple case: we assume that only fermionic sparticles are light so that only corrections to propagators are relevant. This might be not only a warming exercise: the MSSM with heavy scalar sparticles received recent attention [7]. In this limit most MSSM problems get milder, most MSSM successes are retained but SUSY no longer solves the hierarchy 'problem'. This was considered as the most important success of SUSY, but alternative antrophic interpretations [23, 24] gained credit in view of recent results: the possible discovery of a small cosmological constant; the non-observation of new physics around the Fermi scale; the realization that string models are even more abundant that what feared. This anthropic scenario is pudically named 'split supersymmetry'.

Although there is no longer a link between the scales of SUSY breaking and of electroweak symmetry breaking, we still restrict our attention to fermionic sparticles close to the Fermi scale, because only in this case precision observables receive detectable corrections. In the same way, scalar sparticles give negligible effects even if they are relatively close to the Fermi scale, so that SUSY can still solve the hierarchy problem.

The spectrum of fermionic sparticles is specified by μ, M_1, M_2, M_3 and $\tan\beta$. We assume a GUT relation among gaugino masses, $\tan\beta = 10$ and $m_h = 115\,\text{GeV}$.

Let us start from the sub-case in which only gaugino masses are around M_Z and all other sparticles are much heavier. In $\hat{S}, \hat{T}, W, Y$ approximation we have

$$\hat{S} = \hat{T} = Y \simeq 0, \qquad W \simeq \frac{\alpha_2}{15\pi}\frac{M_W^2}{M_2^2} \tag{7}$$

which does not depend on $\tan\beta, M_1, M_3$. Fitting only traditional precision data (LEP1, SLD,

the W mass, ...) gives $W = (0.7 \pm 0.9) \cdot 10^{-3}$ i.e. a almost 1σ preference for $M_2 \approx 80\,\text{GeV}$, as emphasized in [3] (see also [1]). Adding LEP2 data this preference disappears because the best fit shifts towards negative W.[8] Going beyond the $\hat{S}, \hat{T}, W, Y$ approximation, this result is confirmed by the exact numerical result, shown in fig. 3a. We see that in all the experimentally allowed range for the chargino mass, $M_\chi \gtrsim 100\,\text{GeV}$, the $\hat{S}, \hat{T}, W, Y$ approximation accurately reproduces the full LEP1 fit. On the contrary when the lightest chargino or neutralino is slightly above the LEP2 direct limit, $M_\chi \approx 100\,\text{GeV}$, the $\hat{S}, \hat{T}, W, Y$ approximation underestimates SUSY corrections to LEP2 observables, because one loop chargino and neutralino corrections to LEP2 observables are enhanced by an $\mathcal{O}(1)$ factor, by having a virtual chargino or neutralino almost on-shell. Going to chargino and neutralino masses above the LEP2 direct bound the resonant enhancement disappears and the $\hat{S}, \hat{T}, W, Y$ approximation becomes correct.

The same thing happens if only higgsinos are light: in this limit

$$\hat{S} = \hat{T} \simeq 0, \qquad W \simeq Y \simeq \frac{\alpha_2}{30\pi}\frac{M_W^2}{\mu^2}. \tag{8}$$

Ignoring LEP2 we agree with [3]; including LEP2 we get the different result of fig. 3b.

Finally, fig. 5a shows the global fit of precision data in the (M_2, μ) plane. We find no favored regions, nor new statistically significant constraints. Gauginos and higgsinos masses slightly above their bound from direct searches are mildly disfavored by precision data. For comparison fig. 6a shows the global fit omitting precision LEP2 data. Notice that in the 'split' SUSY limit there are no corrections to $g_\mu - 2$, $b \to s\gamma, \ldots$

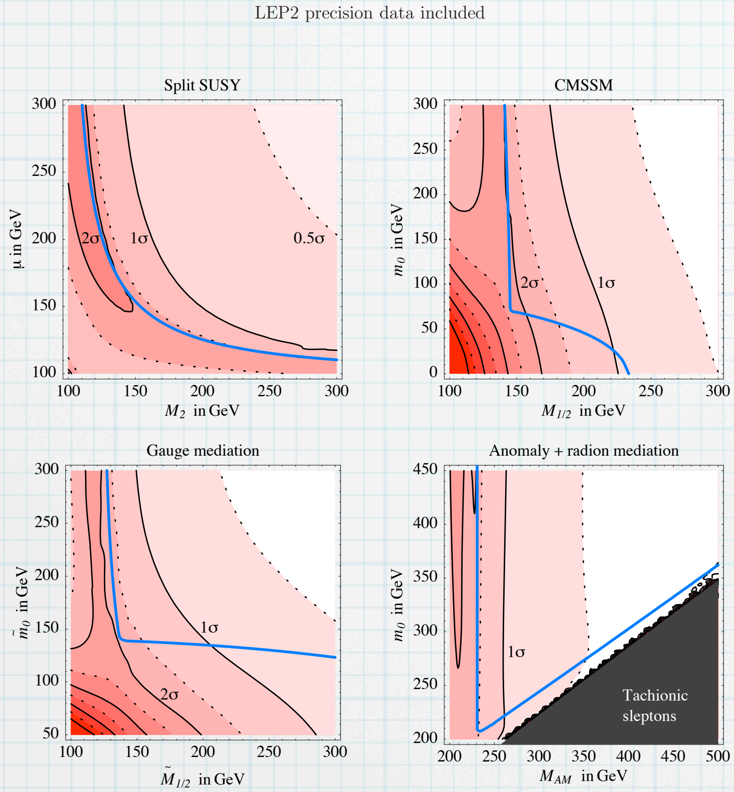


Figure 5: *Fits of precision data. Regions shaded in red are disfavored at* $1, 2, 3, \ldots \sigma$, *as indicated on the iso-lines. Regions below the thick blue line are excluded by LEP2 direct searches. We performed a full one-loop analysis, including LEP2 precision data. We kept fixed* $\tan\beta = 10$, $A_0 = 0$, $\lambda_t(M_{\rm GUT}) = 0.6$, $\text{sign}\,\mu = +1$, *the gauge-mediation scale* $M_{\rm GM} = 10^{10}\,\text{GeV}$.

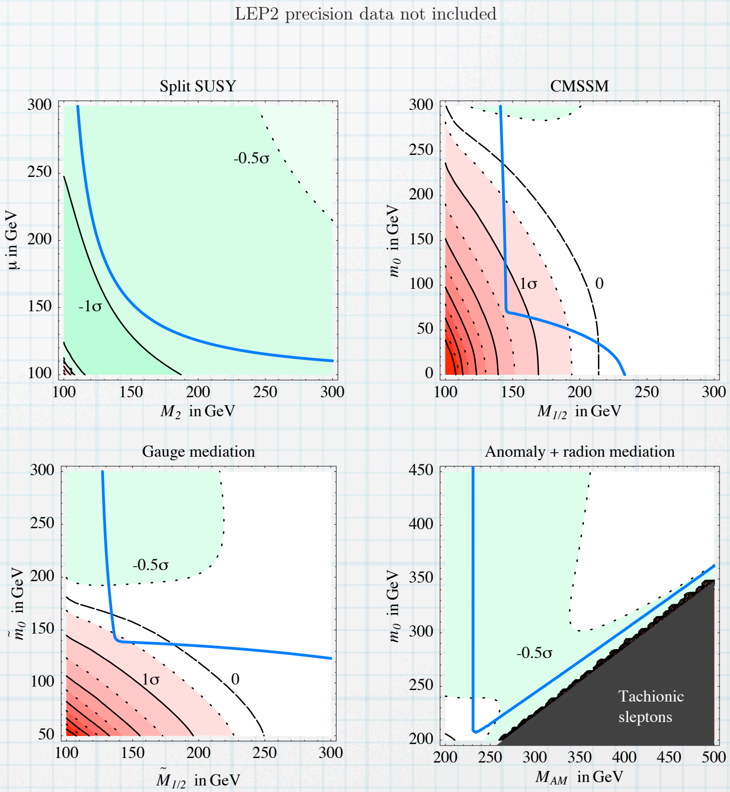


Figure 6: *As in fig. 5, but without including LEP2 precision data. Regions shaded in green are favored at* $-1, 2, 3, \ldots \sigma$.