Neutrino Mixing and Quark-Lepton Complementarity

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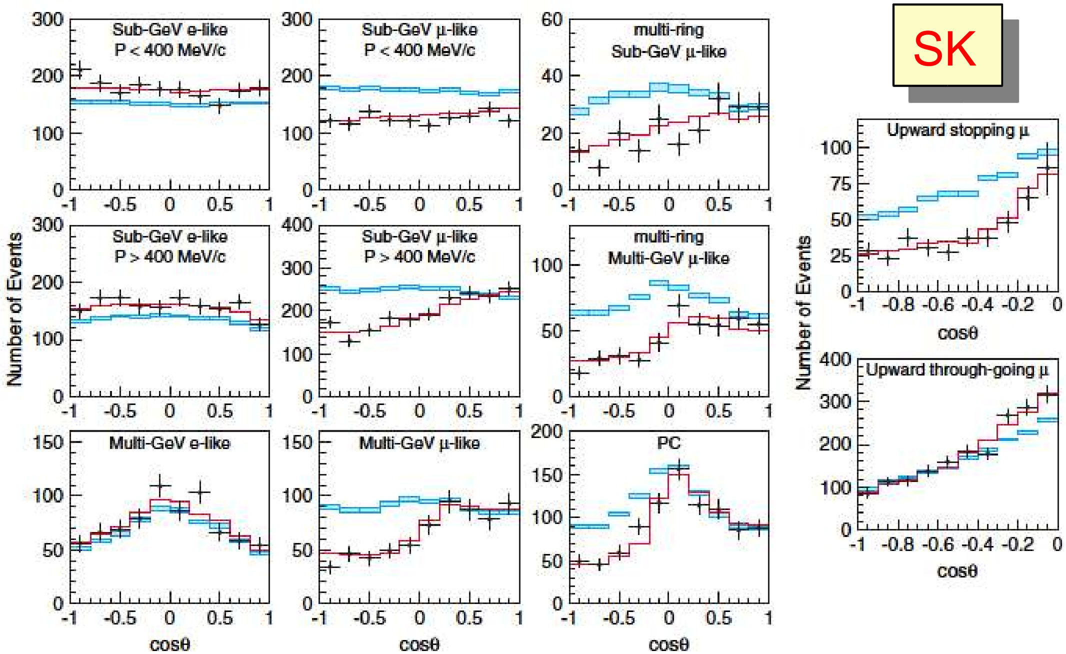
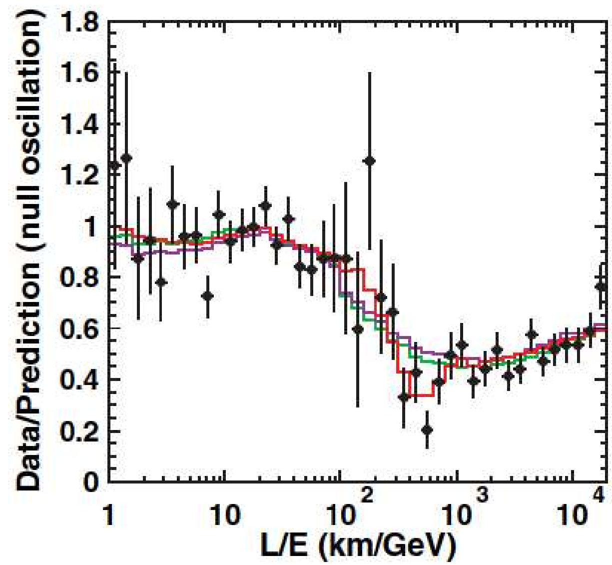
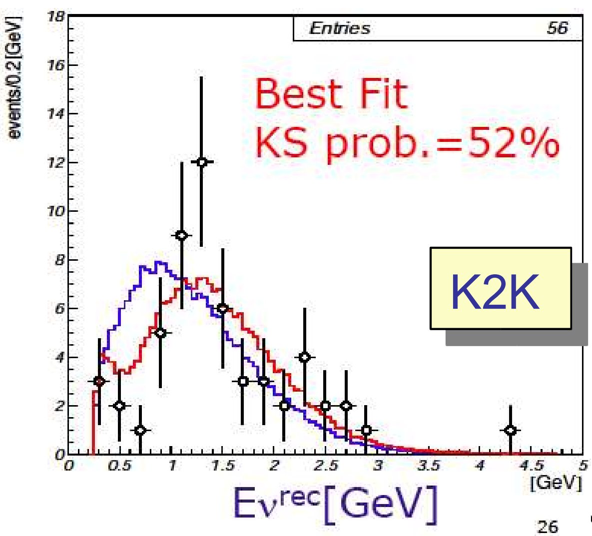
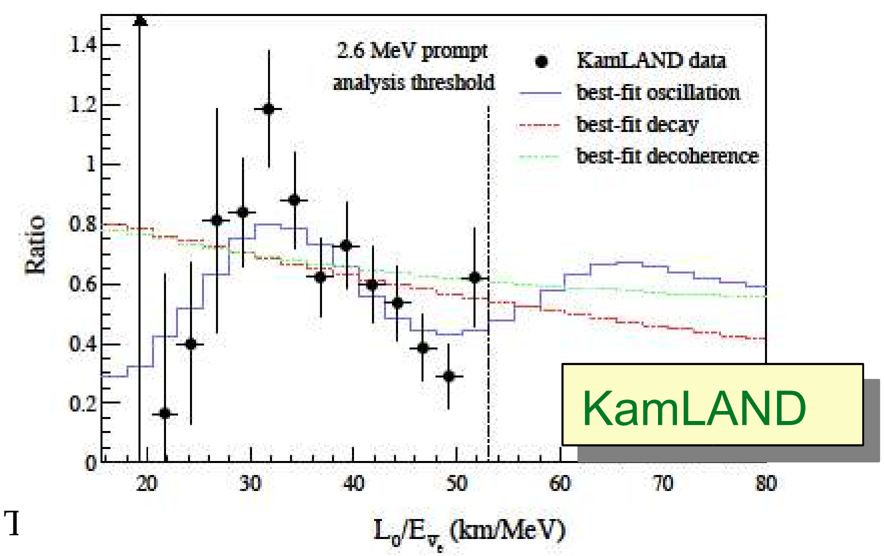
ν oscillatory behavior has been seen!







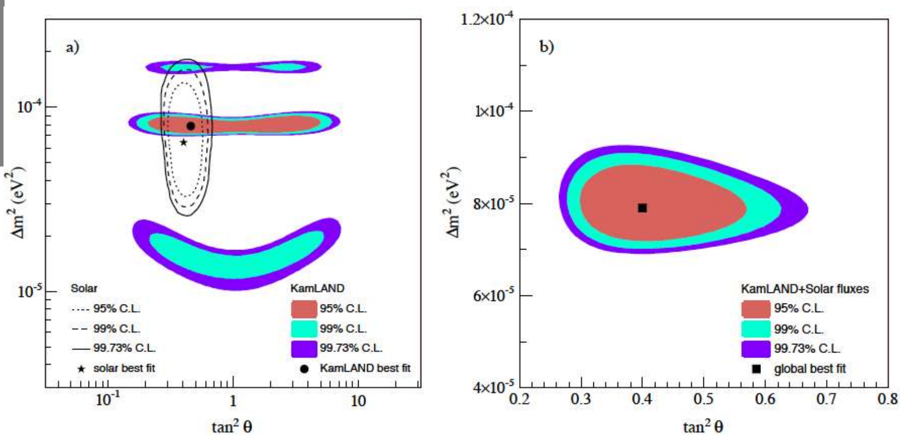


Mysterious relation between quark and lepton mixing angles

$\theta_C + \theta_{solar} = 45.1^o$ +/- 2.4^o (1σ)

=> $2\theta_C$ and $2\theta_{solar}$ are complementary => QLC

Thanks to all the solar & KamLAND experiments ==>



<=Really maximal?

$36.8^o < \theta_{atm} < 53.2^o$ (90% CL)

$2.3^o < \theta_{23}^q < 2.5^o$ (90% CL)

$\theta_{23}^q + \theta_{atm} = 47.4^o$ +/- 8.3^o (90% CL)

What does it mean?

Naturally point to "new" bimaximal mixing

- Old bimaximal mixing

$\theta_{solar} = \theta_{atm} = 45^o$

Vissani, Barger et al., Baltz et al., Georgi-Glashow, …..

- New bimaximal mixing

A.Smirnov in NOVE03

$\theta_C + \theta_{solar} = 45^o$

$\theta_{atm} (\text{or } \theta_{23}^q + \theta_{atm}) = 45^o$

- Bi-large or large-maximal mixing between neighboring families (1- 2) (2- 3):

$$\boxed{\theta_{12} + \theta_C = \theta_{23} \sim 45^o}$$

Pedagogical bimaximal mixing

$$U_{bimax} = \begin{pmatrix} \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & 0 \\ \frac{1}{2} & \frac{1}{2} & -\frac{1}{\sqrt{2}} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

$$U_{bimax}\,\mathrm{diag}[m1,m2,m3]\,U_{bimax}^{+} =$$

$$\begin{pmatrix} \frac{m1}{2} + \frac{m2}{2} & \frac{m1}{2\sqrt{2}} - \frac{m2}{2\sqrt{2}} & \frac{m1}{2\sqrt{2}} - \frac{m2}{2\sqrt{2}} \\ \frac{m1}{2\sqrt{2}} - \frac{m2}{2\sqrt{2}} & \frac{m1}{4} + \frac{m2}{4} + \frac{m3}{2} & \frac{m1}{4} + \frac{m2}{4} - \frac{m3}{2} \\ \frac{m1}{2\sqrt{2}} - \frac{m2}{2\sqrt{2}} & \frac{m1}{4} + \frac{m2}{4} - \frac{m3}{2} & \frac{m1}{4} + \frac{m2}{4} + \frac{m3}{2} \end{pmatrix}$$

Simplification; normal vs. inverted hierarchies

Normal

$$\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & m3 \end{pmatrix} \Rightarrow \begin{pmatrix} 0 & 0 & 0 \\ 0 & \frac{m3}{2} & -\frac{m3}{2} \\ 0 & -\frac{m3}{2} & \frac{m3}{2} \end{pmatrix}$$

Inverted1

$$\begin{pmatrix} m2 & 0 & 0 \\ 0 & m2 & 0 \\ 0 & 0 & 0 \end{pmatrix} \Rightarrow \begin{pmatrix} m2 & 0 & 0 \\ 0 & \frac{m2}{2} & \frac{m2}{2} \\ 0 & \frac{m2}{2} & \frac{m2}{2} \end{pmatrix}$$

Inverted2

$$\begin{pmatrix} m2 & 0 & 0 \\ 0 & -m2 & 0 \\ 0 & 0 & 0 \end{pmatrix} \Rightarrow \begin{pmatrix} 0 & \frac{m2}{\sqrt{2}} & \frac{m2}{\sqrt{2}} \\ \frac{m2}{\sqrt{2}} & 0 & 0 \\ \frac{m2}{\sqrt{2}} & 0 & 0 \end{pmatrix}$$

L_e-$L\mu$-$L\tau$ symmetry!

Perturbative QLC correction; varying scenarios

Normalized mass matrix $\widehat{\mathcal{M}}_\nu$	zero term $\widehat{\mathcal{M}}_\nu^{\rm atm}$	solar mass correction $\widehat{\mathcal{M}}_\nu^{\rm sol}$	QLC correction $\widehat{\mathcal{M}}_\nu^{\rm QLC}$	Eigenvalues
normal hierarchy	$\begin{bmatrix} 0 & 0 & 0 \\ 0 & \frac{1}{2} & -\frac{1}{2} \\ 0 & -\frac{1}{2} & \frac{1}{2} \end{bmatrix}$	$\frac{\gamma}{2}\begin{bmatrix} 1 & -\frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{2}} & \frac{1}{2} & \frac{1}{2} \\ -\frac{1}{\sqrt{2}} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}$	$\frac{\gamma}{2}\begin{bmatrix} -4\lambda_\nu & 0 & 0 \\ 0 & \lambda_\nu & \lambda_\nu \\ 0 & \lambda_\nu & \lambda_\nu \end{bmatrix}$	$(0,\gamma,1)$ $\gamma \approx \lambda$
inverted hierarchy with same CP parities	$\begin{bmatrix} 1 & 0 & 0 \\ 0 & \frac{1}{2} & \frac{1}{2} \\ 0 & \frac{1}{2} & \frac{1}{2} \end{bmatrix}$	$\frac{\gamma}{2}\begin{bmatrix} 1 & -\frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{2}} & \frac{1}{2} & \frac{1}{2} \\ -\frac{1}{\sqrt{2}} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}$	$\frac{\gamma}{2}\begin{bmatrix} -2\lambda_\nu & 0 & 0 \\ 0 & \lambda_\nu & \lambda_\nu \\ 0 & \lambda_\nu & \lambda_\nu \end{bmatrix}$	$(1,(1+\gamma),0)$ $\gamma \approx \lambda^2/2$
inverted hierarchy with opposite CP parities	$\begin{bmatrix} 0 & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} & 0 & 0 \\ \frac{1}{\sqrt{2}} & 0 & 0 \end{bmatrix}$	$\frac{\gamma}{\sqrt{2}}\begin{bmatrix} -\frac{1}{\sqrt{2}} & \frac{1}{2} & \frac{1}{2} \\ \frac{1}{2} & -\frac{1}{2\sqrt{2}} & -\frac{1}{2\sqrt{2}} \\ \frac{1}{2} & -\frac{1}{2\sqrt{2}} & -\frac{1}{2\sqrt{2}} \end{bmatrix}$	$\begin{bmatrix} 2\lambda_\nu & 0 & 0 \\ 0 & -\lambda_\nu & -\lambda_\nu \\ 0 & -\lambda_\nu & -\lambda_\nu \end{bmatrix}$	$(1,-(1+\gamma),0)$ $\gamma \approx \lambda^2/2$

Relative size of correction different

- Perturbative mass generation:
- $M_\nu = M_\nu^{\rm atm} + M_\nu^{\rm solar} + M_\nu^{\rm QLC}$

Ferrandis-Pakvasa 04

QLC as indication of quark-lepton unification?

Raidal, HM-Smirnov 04

- Unexplored aspect of QLC

→

" Quarks and leptons are unified in such a way that QLC is satisfied"

If true, tremendous implications to unification of forces!

RIKEN BNL
Research Center

QLC embedded into GUTs

$U_{MNS}=U_{lepton}^{+}\ U_{\nu}$ $V_{CKM}=V_{up}^{+}\ V_{down}$

- Lepton-induced bimaximal

$$U_{\nu} = V_{CKM}^{\dagger}$$
$$U_{lepton} = U_{bimaximal}$$

<= GUTs =>

<= Lopsided

$$V_{up} = V_{CKM}^{\dagger}$$
$$V_{down} = I$$

- Neutrino-induced bimaximal

$$U_{\nu} = U_{bimaximal}$$
$$U_{lepton} = V_{CKM}$$

Seesaw enhance?

<= GUTs =>

$$V_{up} = I$$
$$V_{down} = V_{CKM}$$

Predictions of various scenarios

- Lepton-induced bimaximal

$$U_{MNS} = R_{23}^m \Gamma_\delta R_{12}^m V^{CKM\dagger} = R_{23}^m \Gamma_\beta R_{12}(\pi/4 - \theta_{12}^{CKM}) R_{13}^{CKM\dagger} R_{23}^{CKM\dagger}$$

- Neutrino-induced bimaximal

$$U_{MNS} = V^{CKM\dagger} \Gamma_\delta R_{23}^m R_{12}^m = R_{12}^{CKM\dagger} R_{13}^{CKM\dagger} R_{23}^{CKM\dagger} \Gamma_\delta R_{23}^m R_{12}^m,$$

Scenarios	$\Delta \sin^2\theta_{12}$	$\sin^2 2\theta_{13}$	$D_{23} \equiv \frac{1}{2} - s_{23}^2$	$J_{lep}/\sin\delta$
neutrino bi-maximal (27)	0.051	0.10 ± 0.032	0.025	1.5×10^{-3}
lepton bi-maximal (41)	-6×10^{-4}	2×10^{-3}	0.035*	5×10^{-3}
hybrid bi-maximal (52)	1.4×10^{-4}	3.3×10^{-4}	0.04*	2.1×10^{-3}
neutrino max+large (58)	0.057 ± 0.023	0.10 ± 0.032	SK bound	$\leq 6.8 \times 10^{-3}$
lepton max+large (67)	-6×10^{-4}	2×10^{-3}	SK bound	$\leq 5 \times 10^{-3}$
hybrid max+large	1.4×10^{-4}	3.3×10^{-4}	SK bound	$\leq 2.1 \times 10^{-3}$
single maximal (72)	0.015	0.034	$0.06 - 0.16$	9.1×10^{-3}

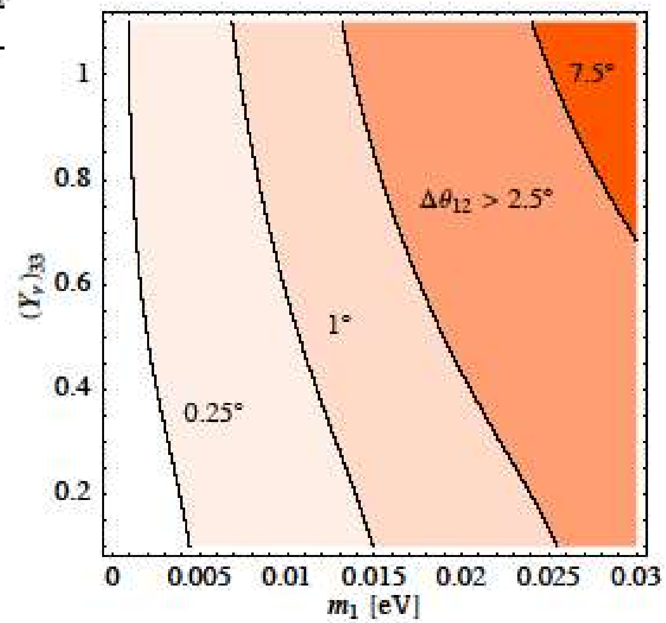
HM-Smirnov 04

Renormalization group effect

- QLC at GUT scale does not necessarily mean QLC at low energies
- RG stability required

$$\frac{d\theta_{12}}{dt} \approx -\frac{Cy_\tau^2}{32\pi^2}\sin 2\theta_{12}\sin^2\theta_{23}\frac{|m_1 e^{i\phi_1}+m_2 e^{i\phi_2}|^2}{\Delta m^2_{sun}}$$

$$\frac{Cy_\tau^2}{32\pi^2} \approx \begin{cases} 0.3\cdot 10^{-6}, & \text{SM} \\ 0.3\cdot 10^{-6}(1+\tan^2\beta), & \text{MSSM} \end{cases}$$



Antusch et al 03, 05

RG stability seems OK

There are problems, …

- Neutrino-induced bimaximal

$U_{lepton} = V_{down} = V_{CKM}$ but

$m_e/m_\mu \sim (1/10)\ m_d/m_s$

$U_{lepton} = V_{down} = V_{CKM}$ but

$m_e/m_\mu \sim (1/10)\ m_d/m_s$

Example given by Ferrandis-Pakvasa 04

Suppose

$$\sin\theta_C = \sqrt{\frac{m_d}{m_s}} \Leftarrow M = \begin{bmatrix} 0 & \sqrt{m_d m_s} \\ \sqrt{m_d m_s} & m_s \end{bmatrix}$$

$$\sin\theta_{12} = \sqrt{\frac{m_e}{m_\mu}} \simeq \frac{1}{3}\sqrt{\frac{m_d}{m_s}} = \frac{1}{3}\sin\theta_C \Rightarrow \theta_{solar} = \frac{\pi}{4} - \frac{\theta_C}{6}$$

Hierarchical vs. not-so-hierarchical masses

Model realization & stability of QLC etc.

- A natural way of model realization
- At zeroth-order:

$U_{MNS}=U_{bimax}$, $V_{CKM}=1$

- First-order correction brings common rotation to U_{MNS} and V_{CKM}:

$U_{MNS}=U_{bimax}$ x $V_{CKM\text{-like}}$

$V_{CKM}=1$ x $V_{CKM\text{-like}}$

<=Frampton-Mohapatra 04

- More generic stability mechanism of QLC?

Accident al!

New parametrization of MNS matrix

- QLC ansatz $$U_{MNS}V_{CKM} = U_{bimaximal}$$
  or $$U_{MNS} = U_{bimaximal}V_{CKM}^{\dagger}$$
  may be generalized to

$$\Rightarrow \quad U_{MNS} = U_{bimaximal}(V'_{CKM-like})^{\dagger}$$

with CKM-like matrix V'_{CKM} which can be parametrized with "Wolfenstein form"

New form of MNS matrix !

Many references => next page

Many relevant references, ….

[10] R. Barbieri *et al.*, JHEP **9812**, 017 (1998); G. Altarelli and F. Feruglio, JHEP **9811**, 021 (1998); S. Davidson and S. F. King, Phys. Lett. B **445**, 191 (1998); R. N. Mohapatra and S. Nussinov, Phys. Rev. D **60**, 013002 (1999); C. H. Albright and S. M. Barr, Phys. Lett. B **461**, 218 (1999); Y. Nomura and T. Yanagida, Phys. Rev. D **59**, 017303 (1999); A. S. Joshipura and S. D. Rindani, Eur. Phys. J. C **14**, 85 (2000); R. N. Mohapatra, A. Perez-Lorenzana and C. A. de Sousa Pires, Phys. Lett. B **474**, 355 (2000); A. Aranda, C. D. Carone and P. Meade, Phys. Rev. D **65**, 013011 (2002); R. Kitano and Y. Mimura, Phys. Rev. D **63**, 016008 (2001); K. S. Babu and S. M. Barr, Phys. Lett. B **525**, 289 (2002); H. S. Goh, R. N. Mohapatra and S. P. Ng, Phys. Lett. B **542**, 116 (2002); S. Antusch *et al.*, Phys. Lett. B **544**, 1 (2002); T. Miura, T. Shindou and E. Takasugi, Phys. Rev. D **68**, 093009 (2003); B. Stech and Z. Tavartkiladze, hep-ph/0311161.

[11] S. F. King, JHEP **0209**, 011 (2002).

[12] Z. z. Xing, Phys. Rev. D **64**, 093013 (2001).

[13] C. Giunti and M. Tanimoto, Phys. Rev. D **66**, 053013 (2002).

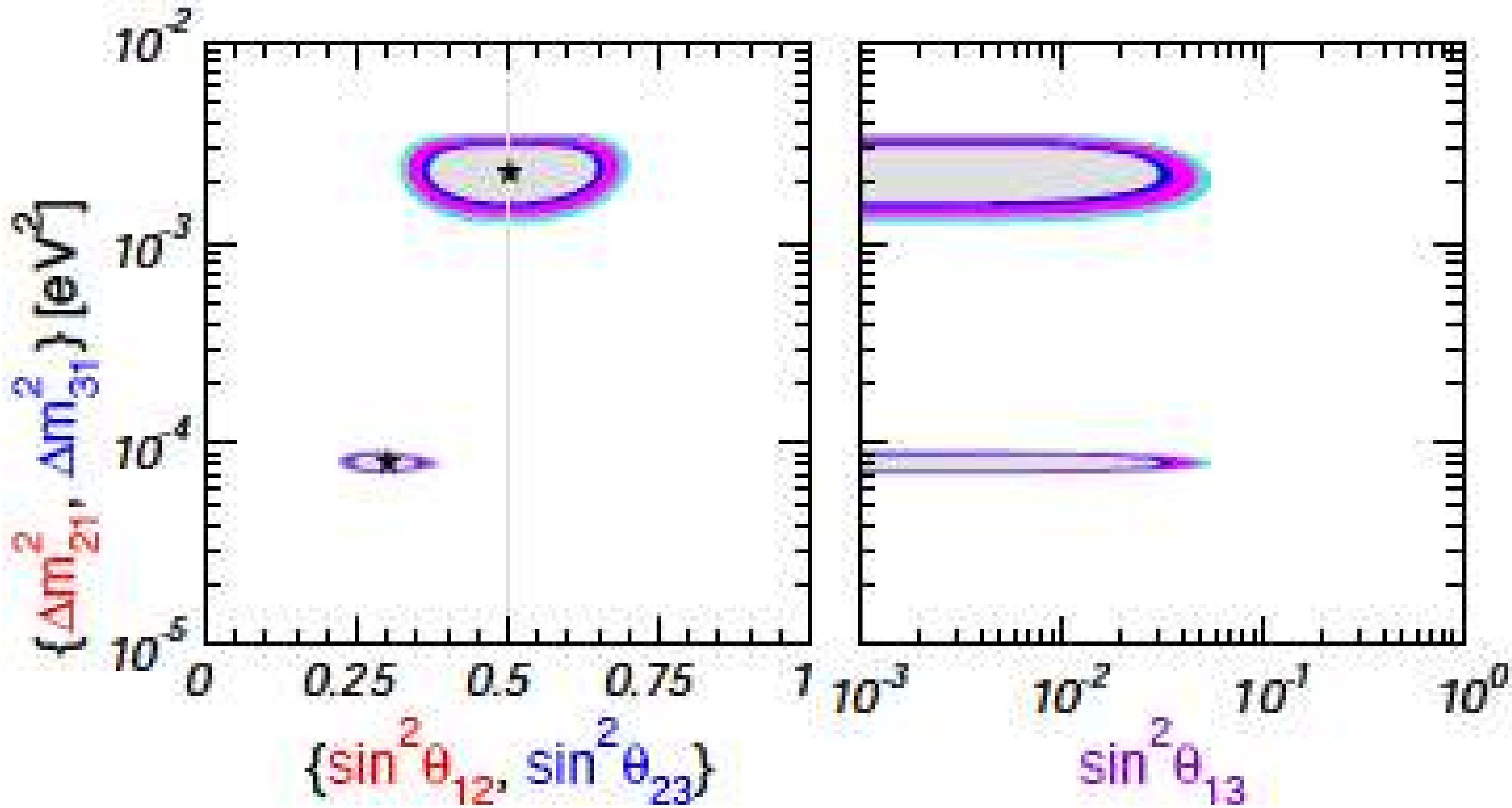
[14] C. Giunti and M. Tanimoto, Phys. Rev. D **66**, 113006 (2002).

As quoted by:

P.H. Frampton[a], S.T. Petcov[b*], and W. Rodejohann[b]

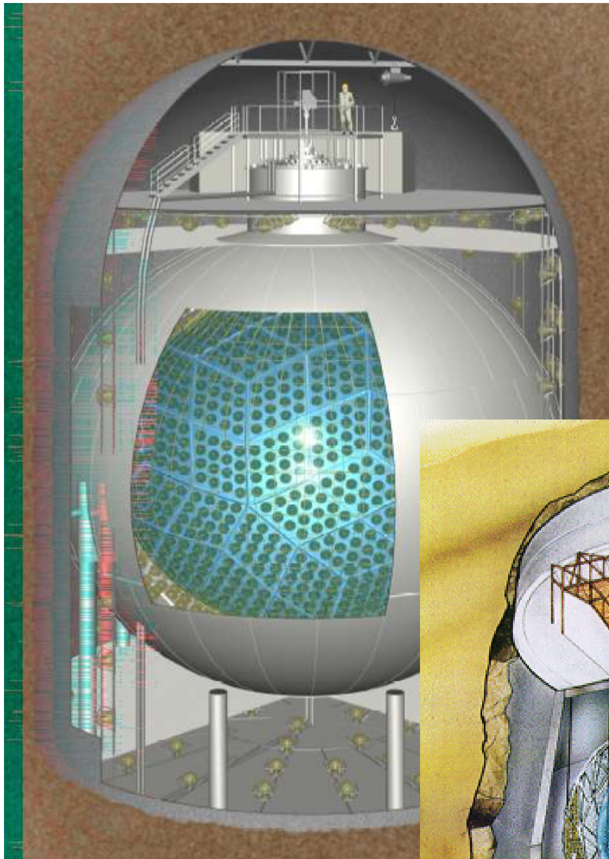
Are there ways for testing QLC?

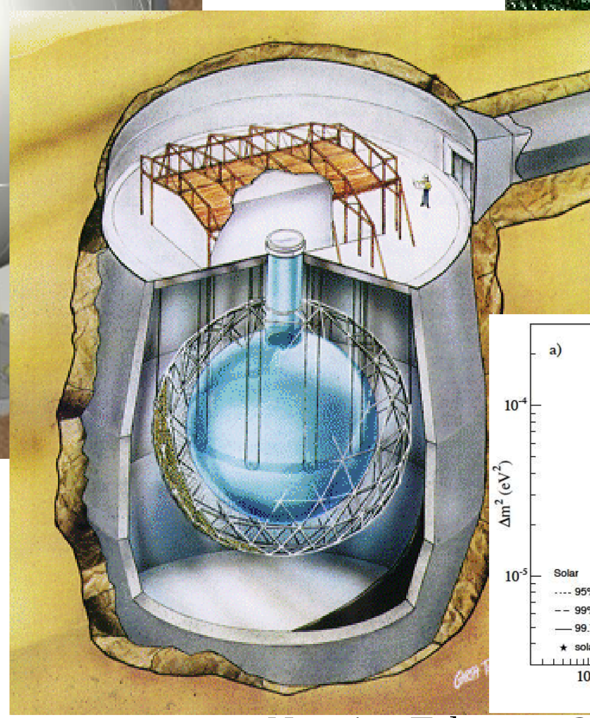
Present accuracy of determination of mixing angles

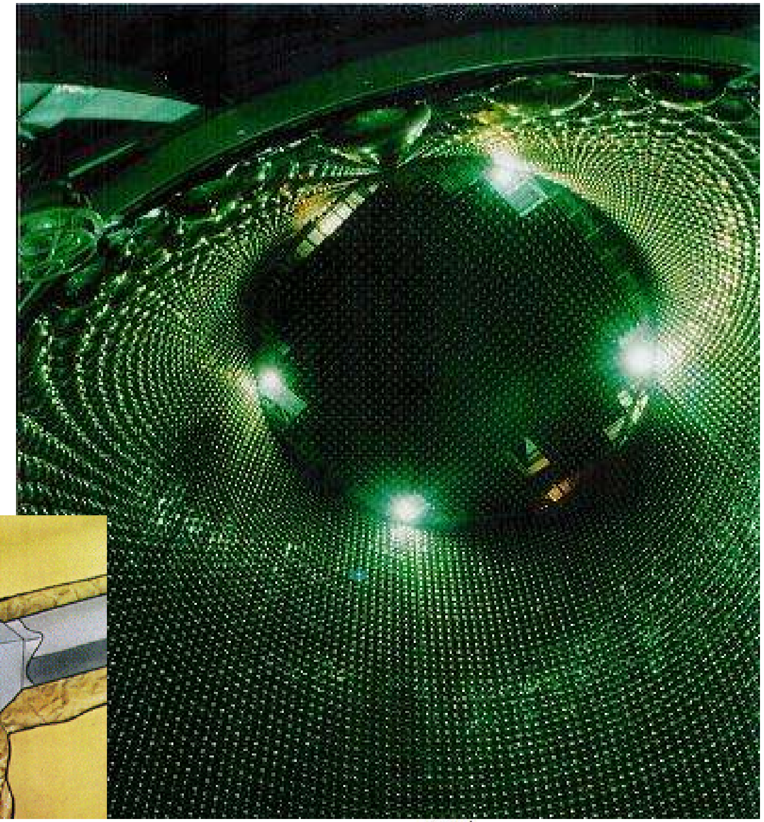


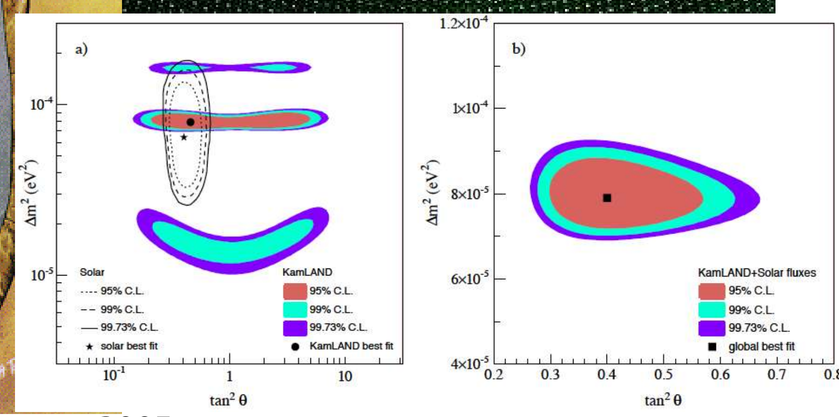
Maltoni et al., NJP 04

Measurement of θ_{12}









Feb. 22-25, 2005

Neutrino Telescope 2005

More precise measurement of $\theta_{12,}$ How?

Our knowledge of θ_{12} in quark and lepton sectors are not balanced:

$\delta(\sin^2\theta_C)$ = 1.4% (90%CL) <--> $\delta(\sin^2\theta_{12})$ = 10-20%

Future low energy solar neutrino experiments

experiment	reaction	detector
LENS	$\nu_e\,^{115}In \to e^-\,^{115}Sn, e, \gamma$	60 tons In-loaded scintillator
MOON	$\nu_e\,^{100}Mo \to e^-\,^{100}Tc(\beta)$	3.3 ton ^{100}Mo foil + plastic scintillator
Lithium	$\nu_e\,^{7}Li \to e^-\ ^{7}Be$	Radiochemical, 10 ton lithium
BOREXINO	$\nu e^- \to \nu e^-$	100 ton Liquid scintillator (^{7}Be only)
KAMLAND	$\nu e^- \to \nu e^-$	1000 ton Liquid scintillator (^{7}Be only)
XMASS	$\nu e^- \to \nu e^-$	10 ton Liquid Xe (pp, ^{7}Be)
HERON	$\nu e^- \to \nu e^-$	10 ton super-fluid He (pp, ^{7}Be)
CLEAN	$\nu e^- \to \nu e^-$	10 ton Liquid Ne (pp, ^{7}Be)
TPC type	$\nu e^- \to \nu e^-$	Tracking electron in gas target (pp, ^{7}Be)
SNO (Liq.scint.)	$\nu e^- \to \nu e^-$	1000 ton Liquid scintillator (pep, CNO)

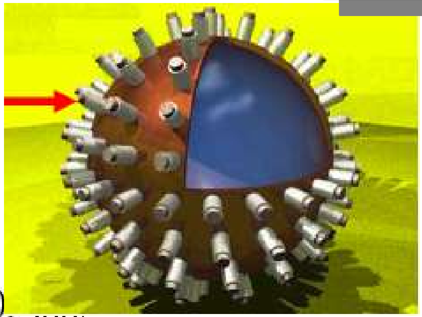
CC exp. (ν_e only) ve scattering exp. ($\nu_e + \alpha(\nu_\mu + \nu_\tau)$)

Reactor θ_{12} experi-ments

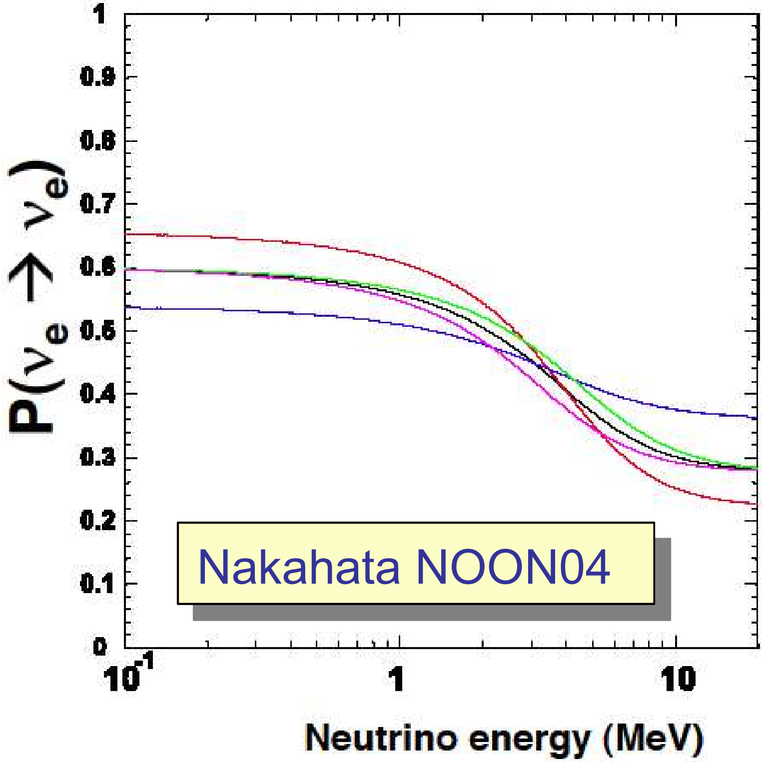
HM, Nunokawa, Teves, Zukanovich-Funchal, hep-ph/0407326

SADO = Several-tenth of km Antineutrino DetectOr

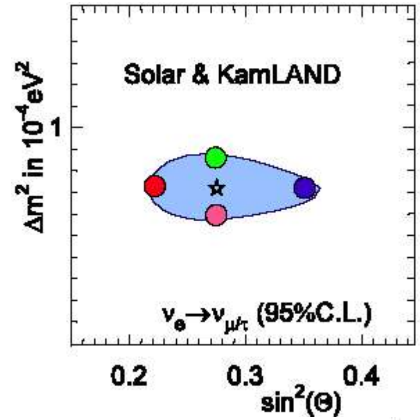
See also, Bandyopadhyay et al



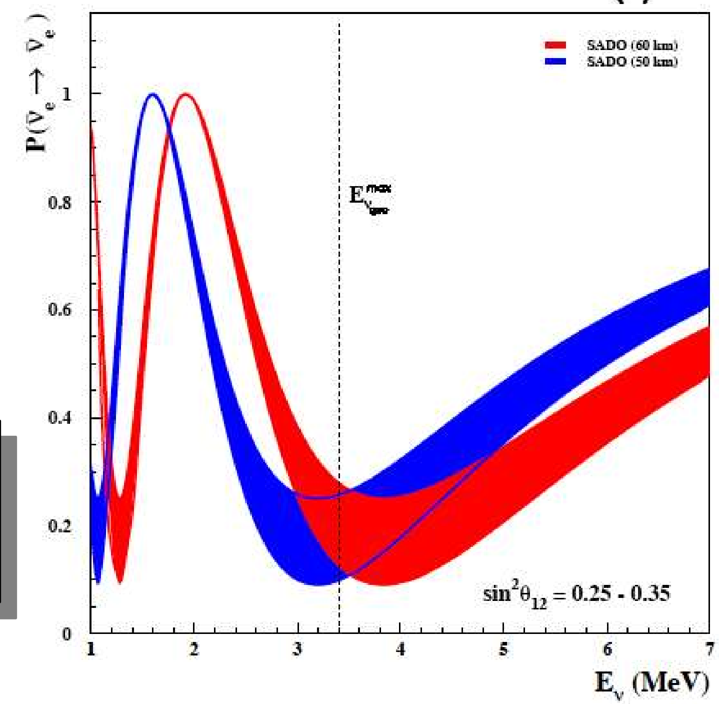
Low-E solar ν survival rate measures θ_{12}



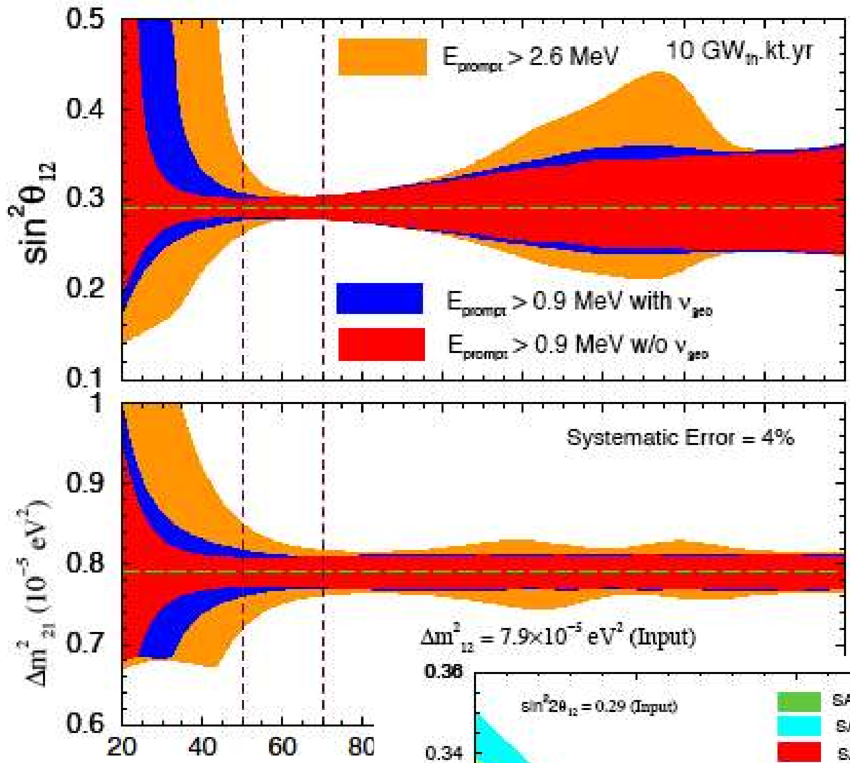
$\sin^2(\theta)$	Δm^2 (eV^2)
0.28	7.2×10^{-5}
0.22	7.2×10^{-5}
0.36	7.2×10^{-5}
0.28	8.5×10^{-5}
0.28	6.0×10^{-5}

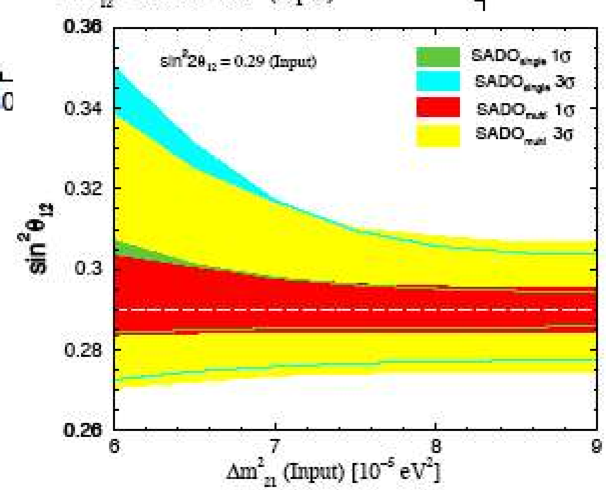


Reactor ν at oscillation maximum measures θ_{12} =>



Reactor measurement of θ_{12} at ~60km

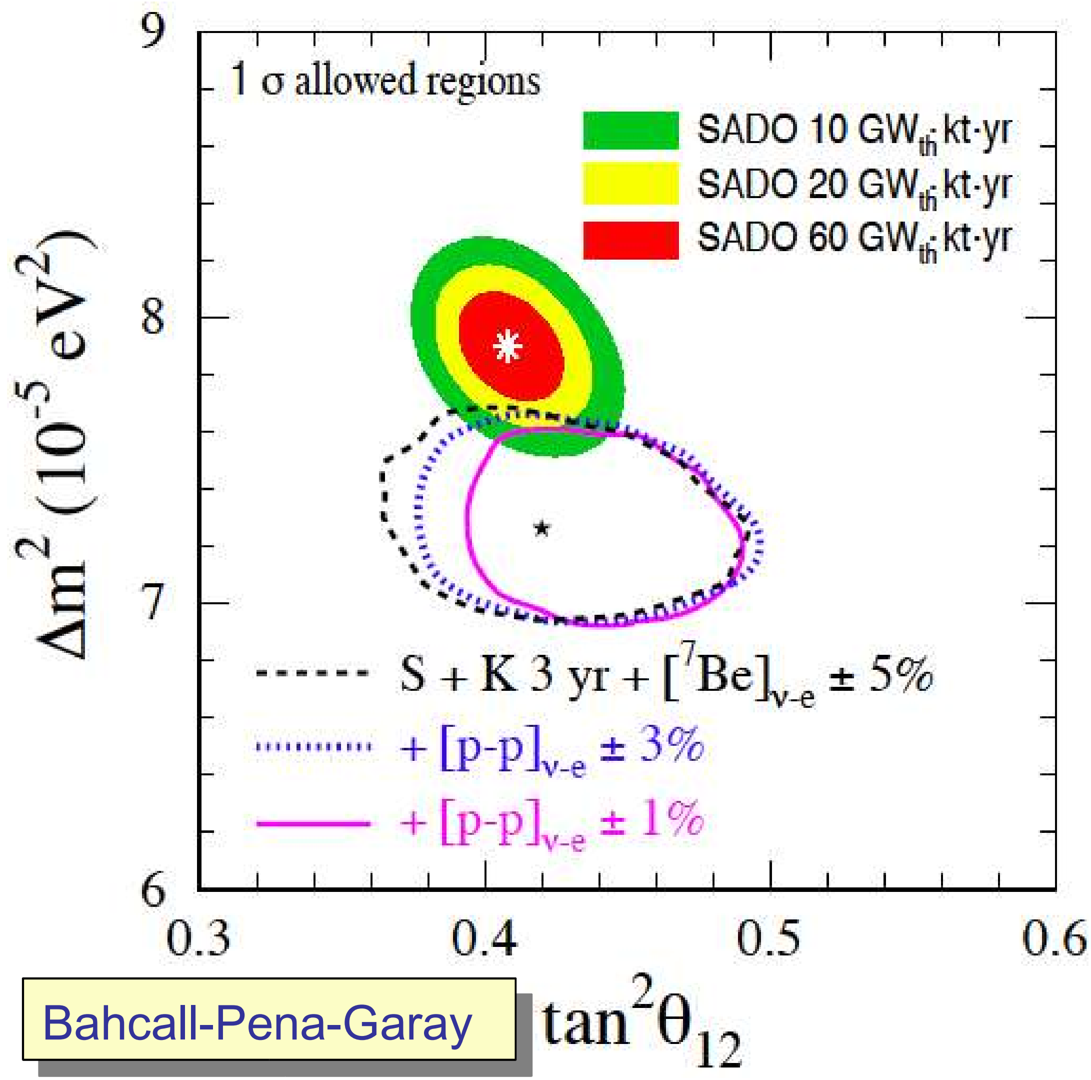




- Modest requirement on systematic error of 4% <= 6.5% of KL
- Feasible if no spectrum cut at E=2.6 MeV
- Geo-neutrino "BG" must be taken care of

HM, Nunokawa, Teves, Zukanovich-Funchal 04

Solar+KL and SADO are good competitors, but..



Bahcall-Pena-Garay

<= NOW05 Proc.

- "SADO" has better sensitivity with long-run because tuning L is powerful

2% (1σ) in $\sin^2\theta_{12}$ reachable!

Deviation from maximal θ_{23}; already seen?

$$(F^{osc}_e / F^0_e) - 1 = P_2 (r \cos^2\theta_{23} - 1)$$

screening factor for low energy ν $(r \sim 2)$

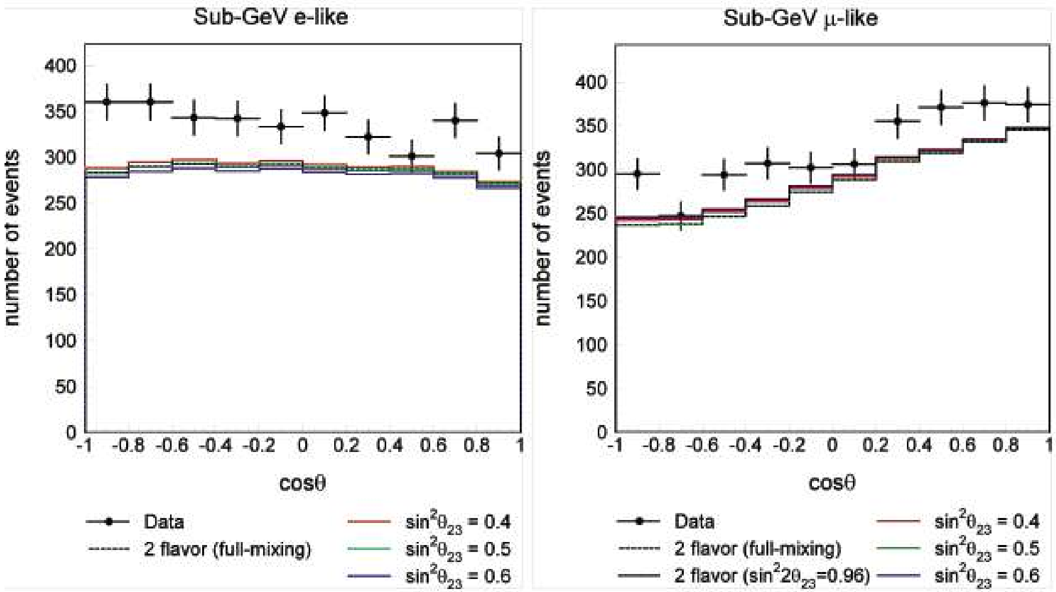
~ 0	if $\cos^2\theta_{23} = 0.5$	$(\sin^2\theta_{23} = 0.5)$
< 0	if $\cos^2\theta_{23} < 0.5$	$(\sin^2\theta_{23} > 0.5)$
> 0	if $\cos^2\theta_{23} > 0.5$	$(\sin^2\theta_{23} < 0.5)$

- If $\theta_{23} < 45^o$ =>enhancement of e-like events
- Explanation of e-excess at low energy?

Peres-Smirnov 99, 04

sub-GeV zenith angle distribution

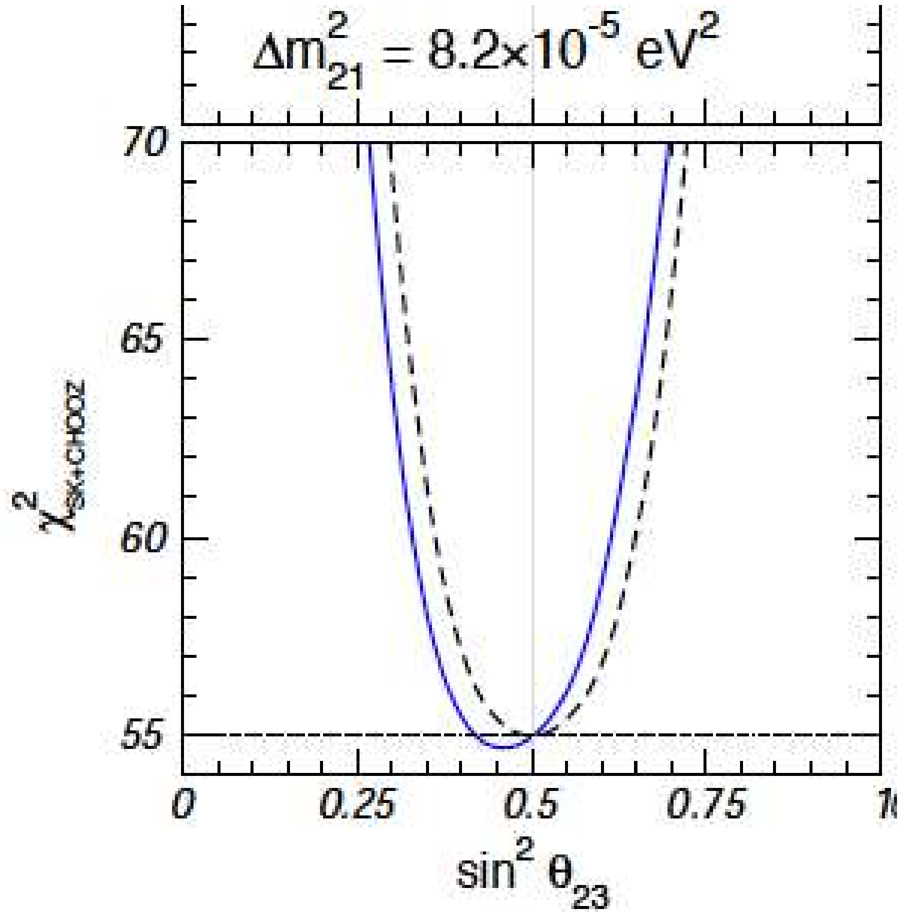
Nakayama@Sub-dominant WS, ICRR, Dec.04)

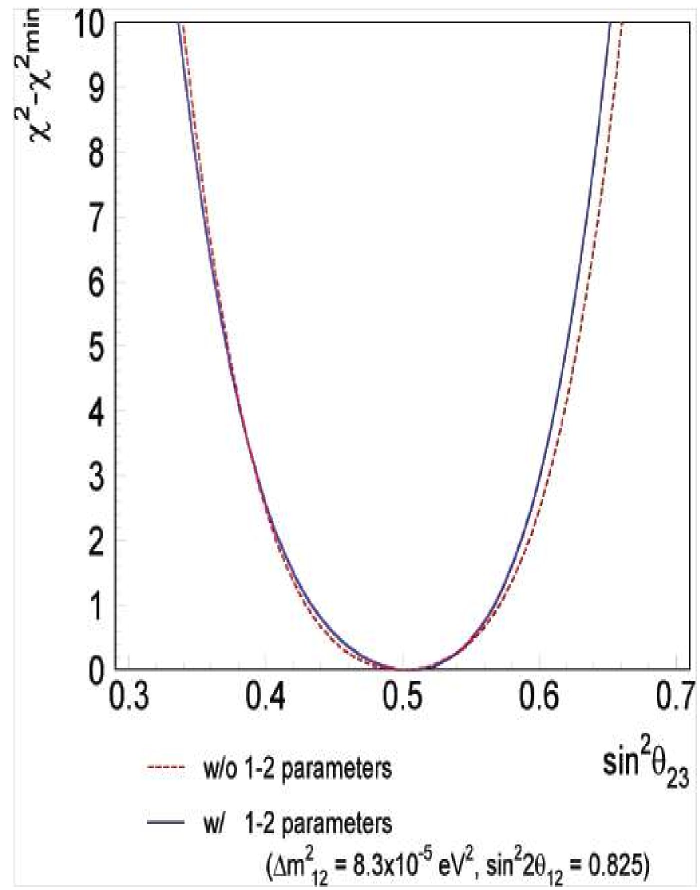


Two different results (why?)

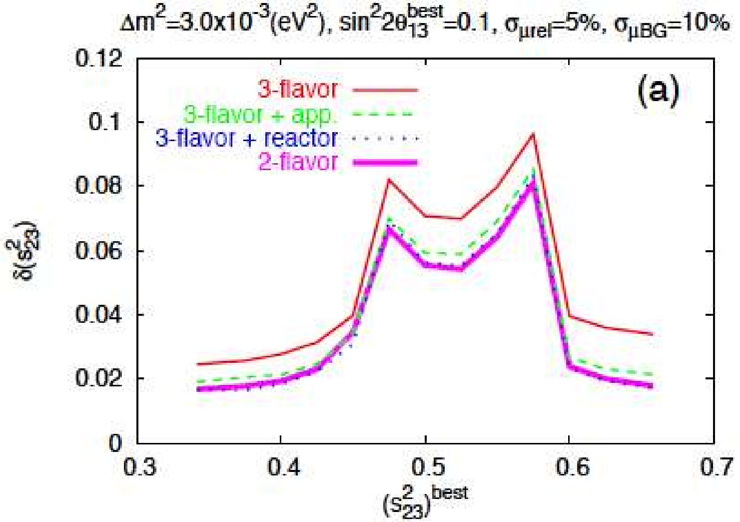
Concha-Maltoni-Smirnov 04

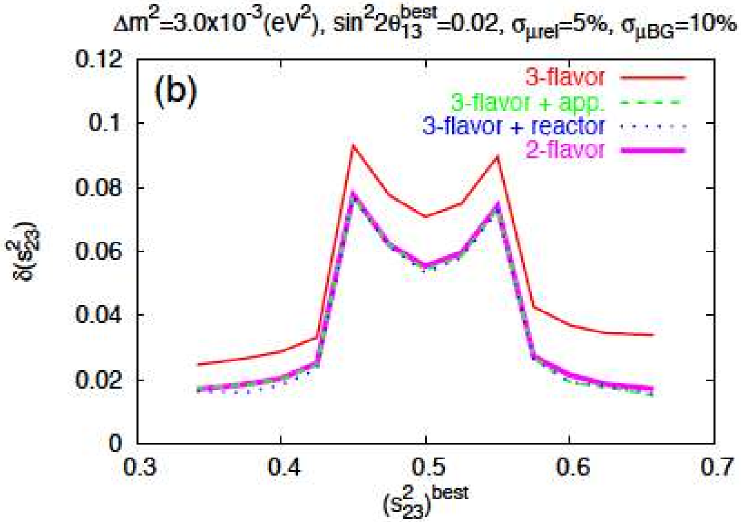
SK (Subdominant WS, ICRR, Dec.04)

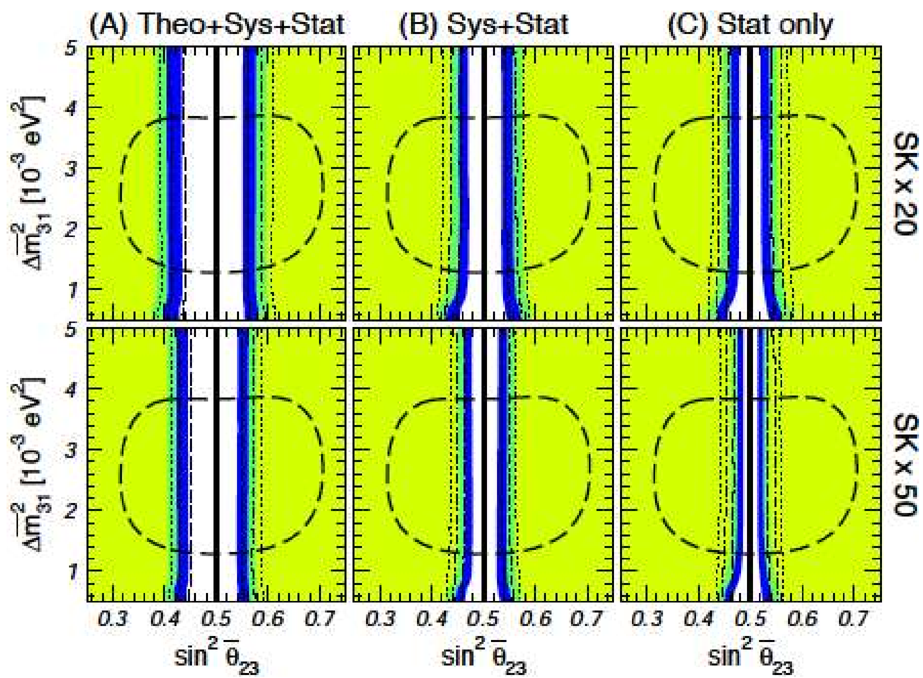




Future accelerator or atmospheric ν?







Concha-Maltoni-Smirnov 04

- Not an easy problem for both methods!

HM-Sonoyama-Sugiyama, Antusch et al. 04

Conclusion

- QLC, if not accidental, gives a new insight to unification of quarks and leptons
- QLC raises nontrivial issues if it is to be implemented into the unified model

$\Rightarrow$ model realization? (next talk)

- Experimental testing of QLC highly nontrivial $\Rightarrow$

θ_{12}: "SADO" and/or solar pp promising

θ_{23}: LBL+atm. and/or LBL+reactor (to which level do they reach?)

Lopsided lepton mass matrix (explanatory sheet)

- Consider SU(5) GUT

  $5^* = [d^c, (\nu, e)_L]$

  $10 = [u^c, (u, d)_L, e^c]$

- Quark mass

  $m_{LR}^{down} = 10 \cdot 5^* \langle H_1 \rangle$

- Charged lepton mass

  $m_{LR}^{lepton} = 5^* \cdot 10 \langle H_2 \rangle$

==> $m^{lepton} = (m^{down})^T$

==> lopsided structure; left-handed mixing of m^{lepton} = right-handed mixing of m^{down}

- $m^{d,l} m^{d,l+} = S\, m_i^2\, S^+$
- $U_{MNS} = S^{(lepton)+} S^{(\nu)}$

$$m^{\rm down} = c \begin{bmatrix} \lambda^4 & \lambda^3 & \lambda^4 \\ x & \lambda^2 & \lambda^2 \\ y & z & 1 \end{bmatrix}, \quad m^{\rm down}(m^{\rm down})^\dagger = c^2 \begin{bmatrix} \lambda^6 & \lambda^5 & \lambda^4 \\ \lambda^5 & \lambda^4 & \lambda^2 \\ \lambda^4 & \lambda^2 & 1 \end{bmatrix}$$

$$m^{\rm lepton}(m^{\rm lepton})^\dagger = c'^2 \begin{bmatrix} x^2+y^2 & yz+\lambda^2 x & y+\lambda^2 x \\ yz+\lambda^2 x & z^2 & z \\ y+\lambda^2 x & z & 1 \end{bmatrix}$$

$\lambda = 0.2$, x, y, z = O(1)==> Large lepton mixing arises from quark mass