Neutrino Oscillation Phenomenology

Enrique Fernández Martínez

Why Neutrinos?

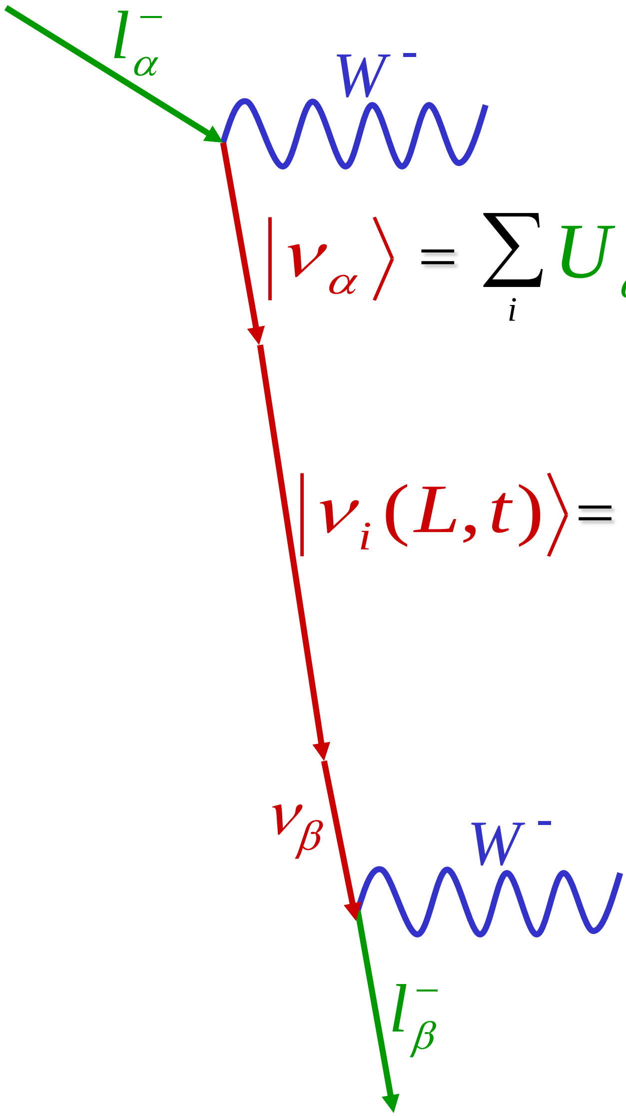
- Evidence of physics beyond the SM
- Many open questions:
  - Masses? Why so small??
    - Absolute mass scale?
    - Normal or inverted hierarchy?
  - Mixing?
    - Large compared with CKM
    - $\theta_{23} = 45^{o}$? $\theta_{13} = 0^{o}$?
    - CP violation?
  - Dirac or Majorana particles?

→ Flavour

→ Origin of matter

- New generation of neutrino experiments to address these questions is now running!

Neutrino Oscillations



Massive neutrinos can change flavour in flight

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i}^* |\nu_i\rangle$$

$$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta)\sin^2\left(\Delta m^2 \frac{L}{4E}\right)$$

$$|\nu_i(L,t)\rangle = e^{-i(E_i t - p_i L)} |\nu_i\rangle$$

$$\langle \nu_\beta | \nu_\alpha(L)\rangle \approx \sum_i U_{\beta i}\, e^{\frac{-i m_i^2 L}{2E}} U_{\alpha i}^* \neq 0$$

Neutrino Parameters

Interaction Basis		Mass Basis	
$\lvert \nu_e \rangle$	U_{PMNS} $\longrightarrow$	$\lvert \nu_1 \rangle$	m_1
$\lvert \nu_\mu \rangle$		$\lvert \nu_2 \rangle$	m_2
$\lvert \nu_\tau \rangle$		$\lvert \nu_3 \rangle$	m_3

$\lvert \nu_\alpha \rangle = U^*_{\alpha i} \lvert \nu_i \rangle$ with $\alpha = e, \mu, \tau$ i = 1, 2, 3

Atmospheric — Mixing — Solar — Majorana Phases

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & e^{i\alpha_3/2} \end{pmatrix}$$

With $c_{ij} = \cos\theta_{ij}$ y $s_{ij} = \sin\theta_{ij}$

The atmospheric neutrino problem

- Cosmic rays produce neutrinos upon reaching the atmosphere:

$$\pi^+ \rightarrow \mu^+ \nu_\mu \qquad \mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$

- We expect ≈ 2 ν_μ for each ν_e
- A ν_μ deficit is measured in SK

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Neutrino oscillations with

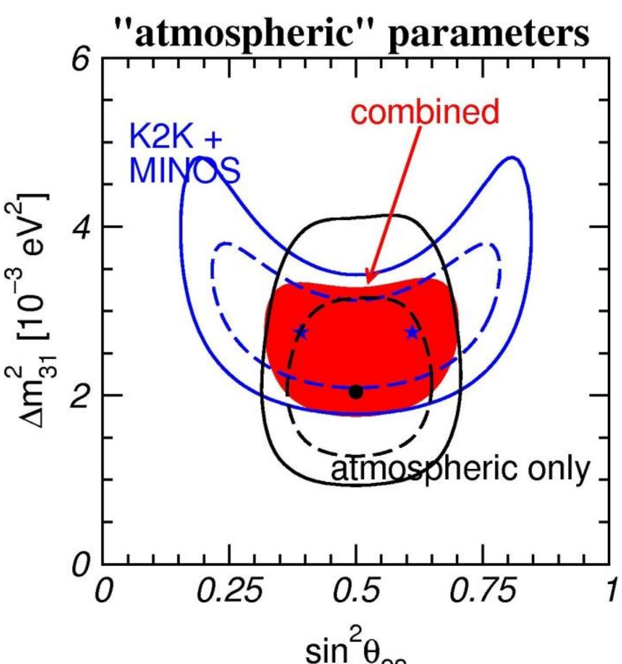
$$\Delta m^2_{23} = 2.5\cdot 10^{-3} eV^2 \qquad \sin^2\theta_{23} = 0.52$$

$$\nu_\mu \longrightarrow \nu_\tau$$

Confirmed by K2K, MINOS, T2K and OPERA with ν_μ from accelerators

$$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta)\sin^2\left(\Delta m^2 \frac{L}{4E}\right)$$

octant? sign?



T. Schwetz hep-ph/0606060

The Solar Neutrino Problem

- The sun produces ν_e together with photons in nuclear reactions in its core

$$4p \rightarrow {}^4\mathrm{He} + 2e^+ + 2\nu_e + 2\gamma$$

- SNO and SK and now Borexino have measured a ν_e deficit:

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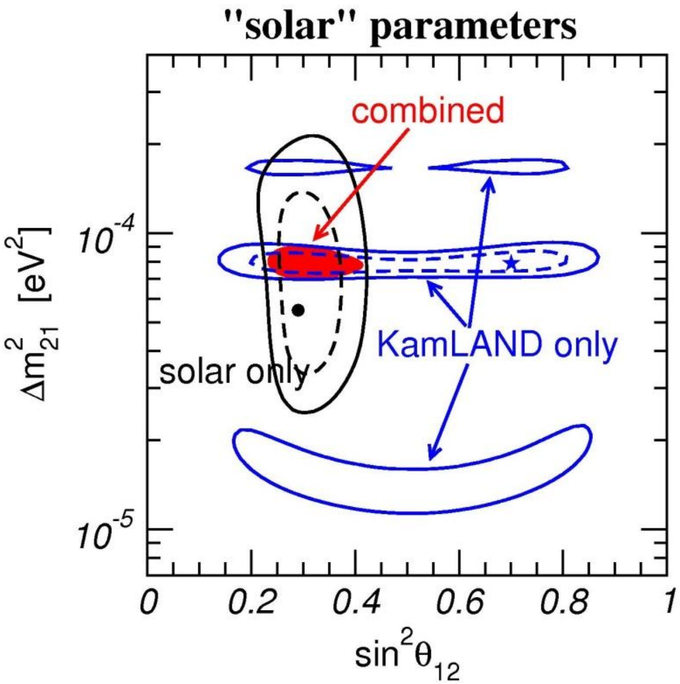
Neutrino Oscillations with

$$\sin^2\theta_{12} = 0.31 \qquad \Delta m^2_{12} = 7.6\cdot 10^{-5}\,\mathrm{eV}^2$$

$$\nu_e \longrightarrow \nu_\mu, \nu_\tau$$

Confirmed by KamLand with reactor $\bar{\nu}_e$



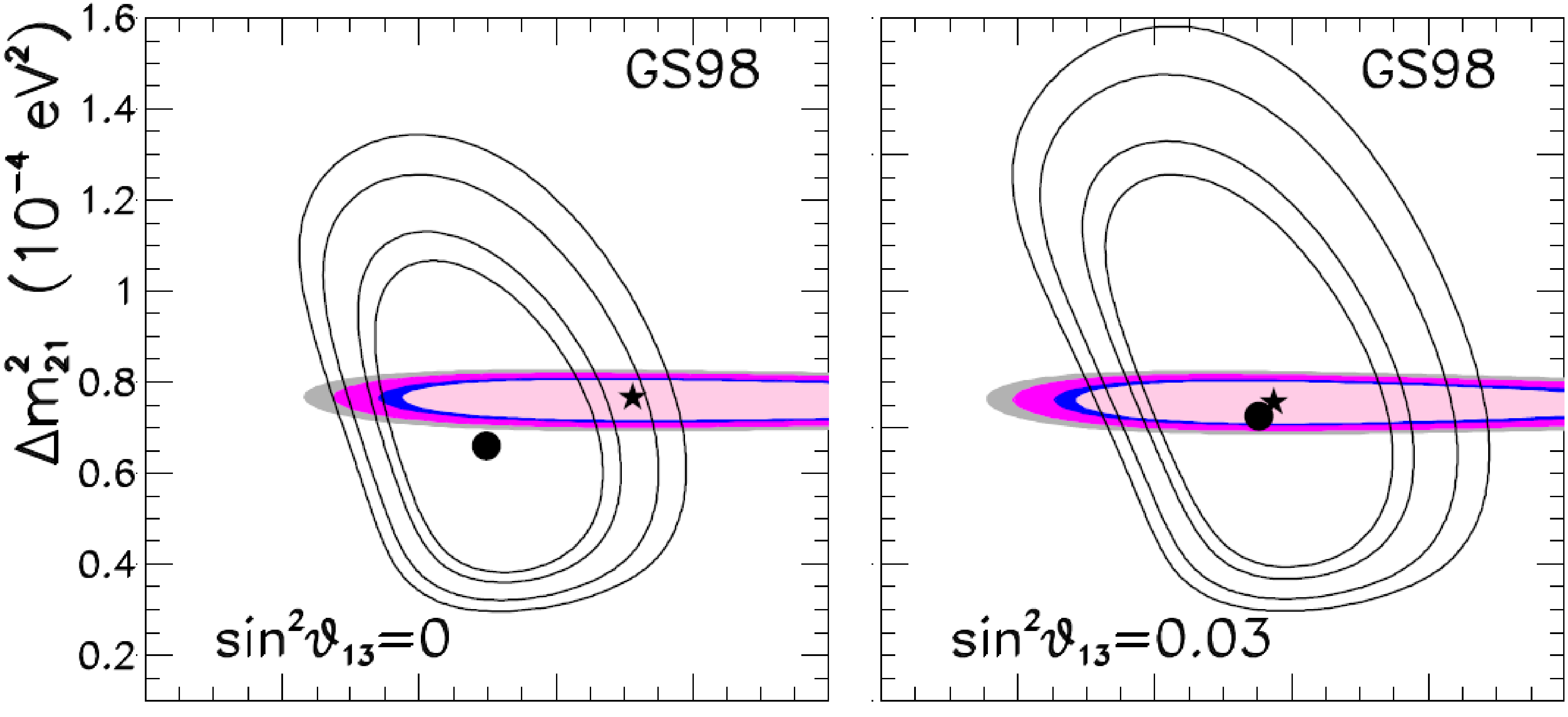
T. Schwetz hep-ph/0606060

Oscillation Parameters

- What we already know (1σ)
  - Solar sector
    $$\begin{cases} \Delta m_{21}^2 = 7.59_{-0.18}^{+0.20} \cdot 10^{-5} \mathrm{eV}^2 \\ \sin^2\theta_{12} = 0.312_{-0.015}^{+0.017} \end{cases}$$
  - Atm. sector
    $$\begin{cases} \Delta m_{31}^2 = 2.5_{-0.16}^{+0.09} \cdot 10^{-3} / -2.4_{-0.08}^{+0.09} \cdot 10^{-3}\ \mathrm{eV}^2 \\ \sin^2\theta_{23} = 0.52_{-0.07}^{+0.06} \end{cases}$$

T. Schwetz, M. Tortola and J. Valle 1108.1376

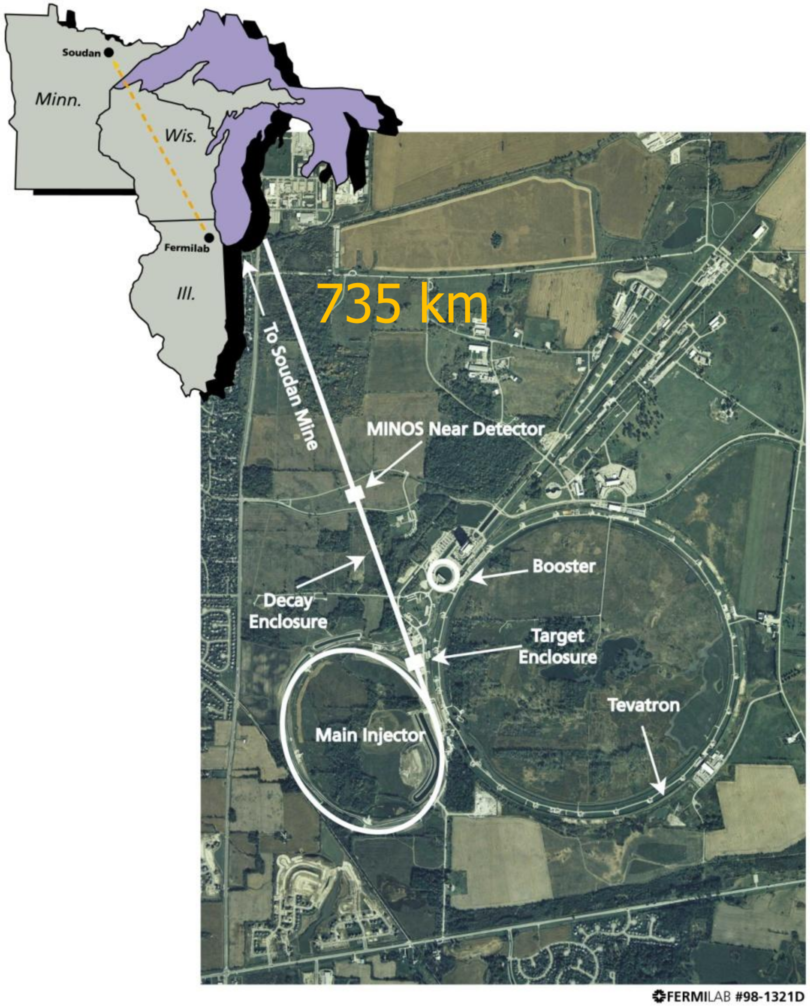
Large θ_{13}?

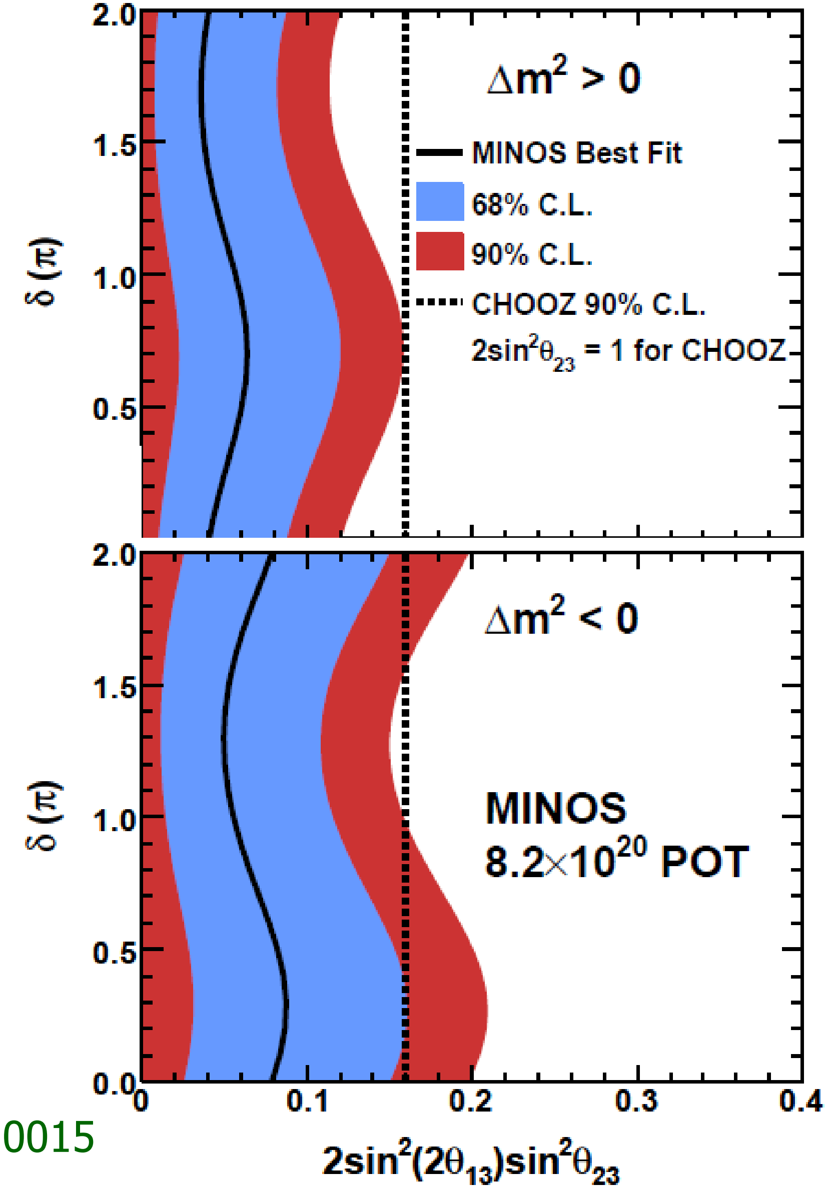


Solar + kamLAND data

From M. C. Gonzalez García, M. Maltoni and J. Salvado 1001.4524

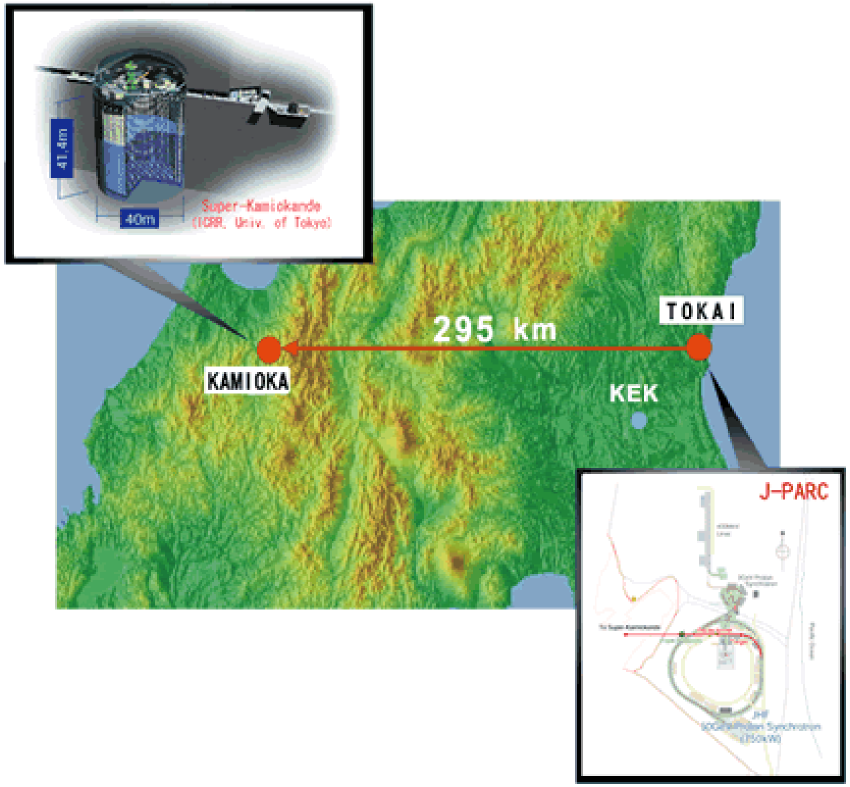
Large θ_{13}?

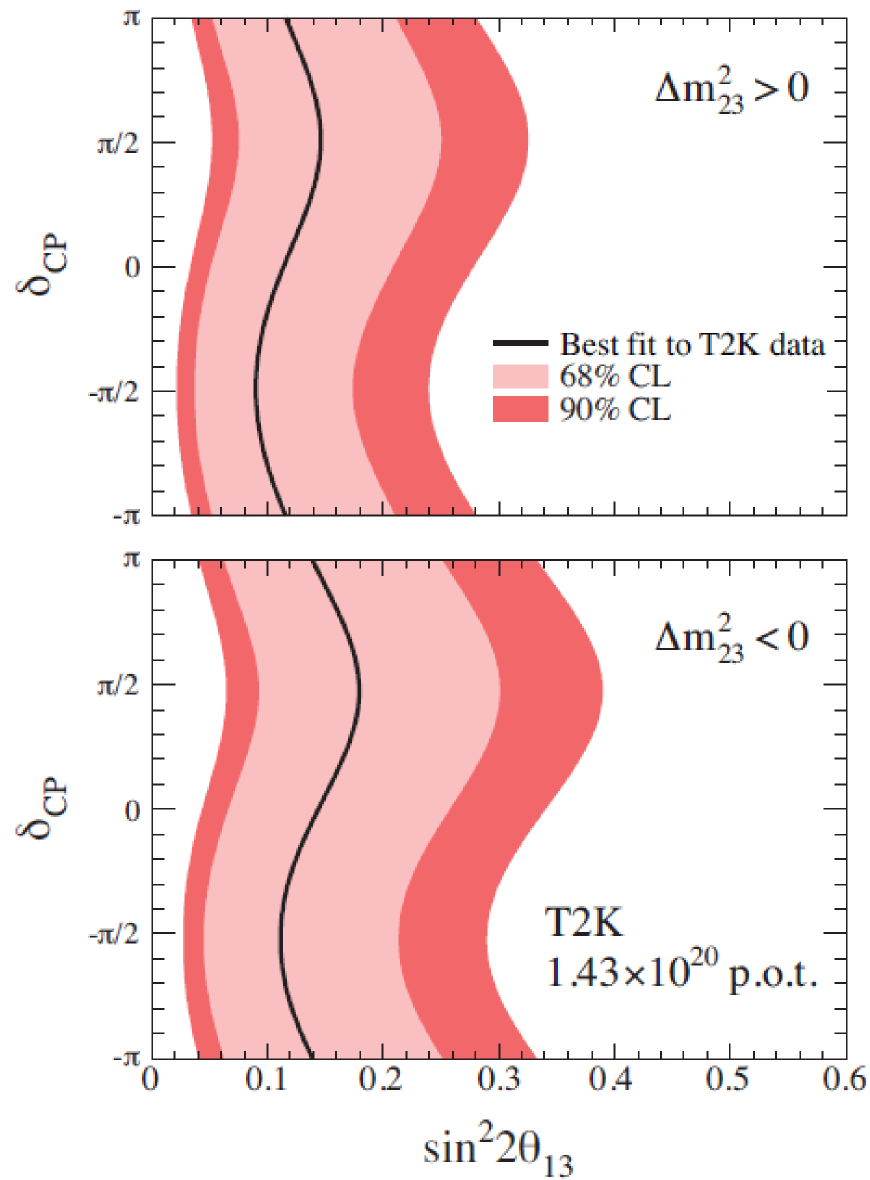




Adamson et al. (MINOS collaboration) 1108.0015

Large θ_{13}?





Abe et al. (T2K collaboration) 1106.2822

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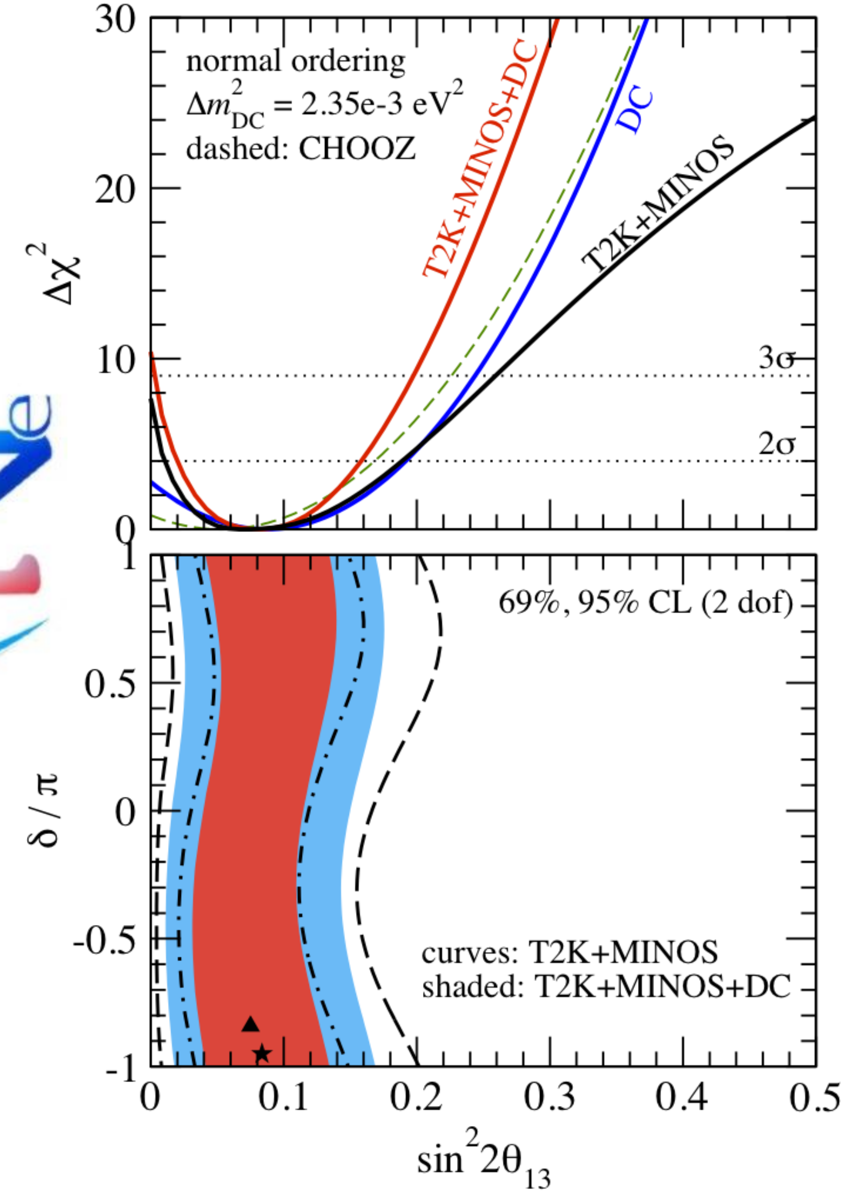

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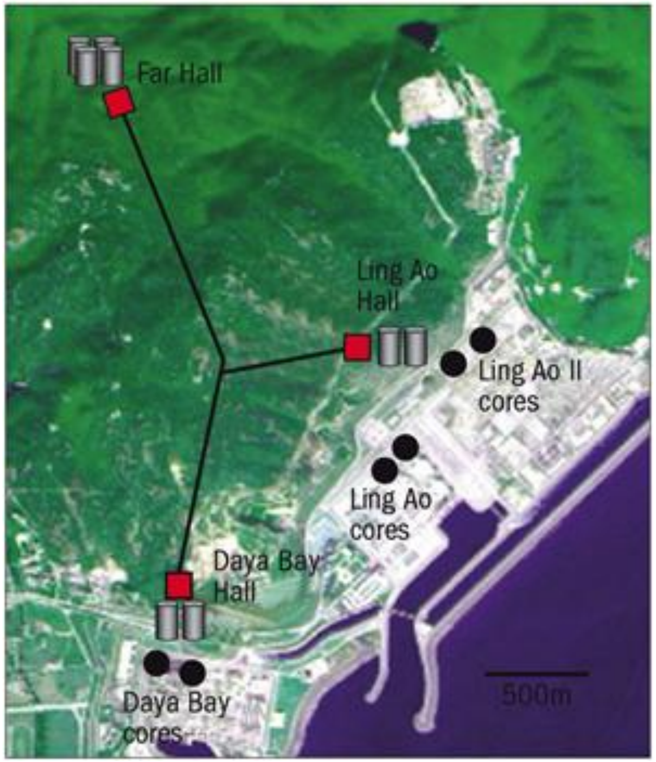
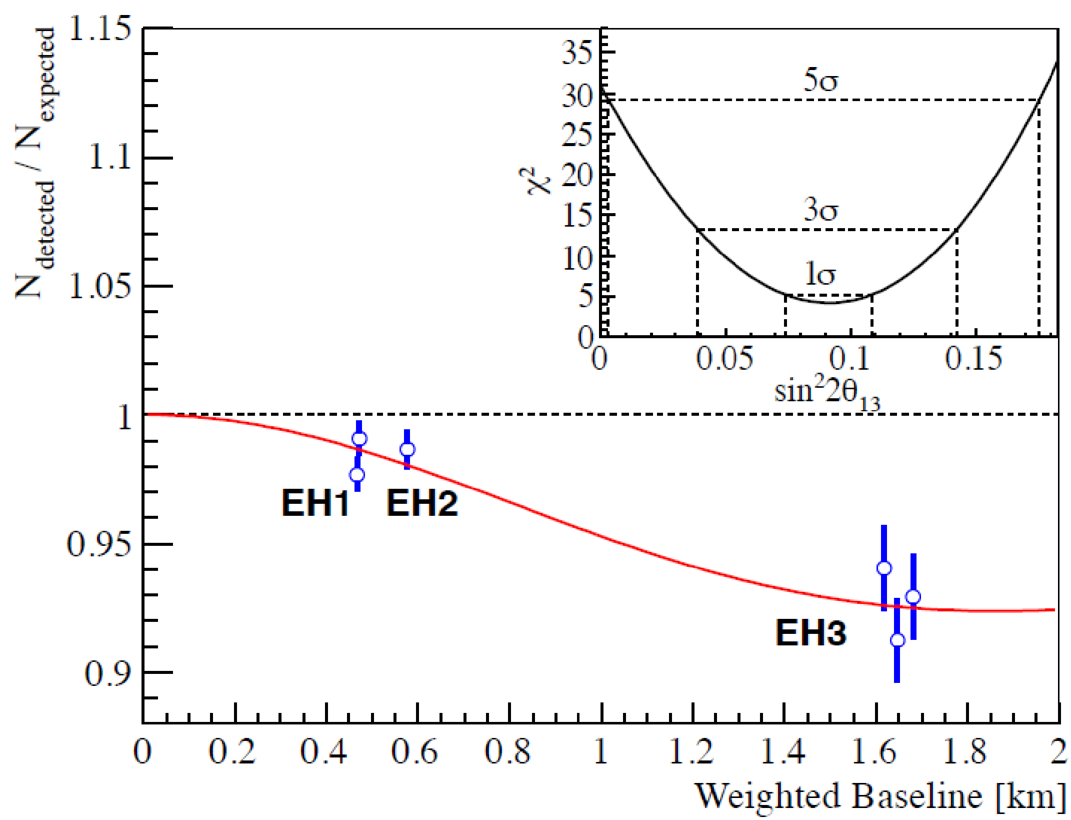


Daya Bay

$\sin^2 2\theta_{13} = 0.092 \pm 0.016 \pm 0.005$

No oscillations excluded at 5.2 σ!!

2 weeks ago



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$$\sin^2\theta_{13} = 0.024 \pm 0.004$$

T. Schwetz, M. Tortola and J. Valle 1108.1376

Oscillation Parameters

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  - $\sin^2\theta_{13} = 0.024 \pm 0.004$
- What we still don't know
  - δ
  - Mass hierarchy $s_{atm} = sign\left(\Delta m^2_{31}\right)$

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The Golden channel in matter

$$P\left(\overset{(-)}{\nu}_e \rightarrow \overset{(-)}{\nu}_\mu\right) = s_{23}^2 \sin^2 2\theta_{13} \left(\frac{\Delta_{atm}}{\tilde{B}_\mp}\right)^2 \sin\left(\frac{\tilde{B}_\mp L}{2}\right)^2$$

$$+ c_{23}^2 \sin^2 2\theta_{12} \left(\frac{\Delta_{sol} L}{A}\right)^2 \sin^2\left(\frac{AL}{2}\right)$$

$$+ \tilde{J} \frac{\Delta_{sol}}{A} \frac{\Delta_{atm}}{\tilde{B}_\mp} \sin\left(\frac{AL}{2}\right) \sin\left(\frac{\tilde{B}_\mp L}{2}\right) \cos\left(\pm\delta - \frac{\Delta_{atm} L}{2}\right)$$

Expanded in

$$\sin 2\theta_{13} \sim 0.3 \qquad \left(\frac{\Delta_{sol} L}{2}\right) \cong 0.05$$

where

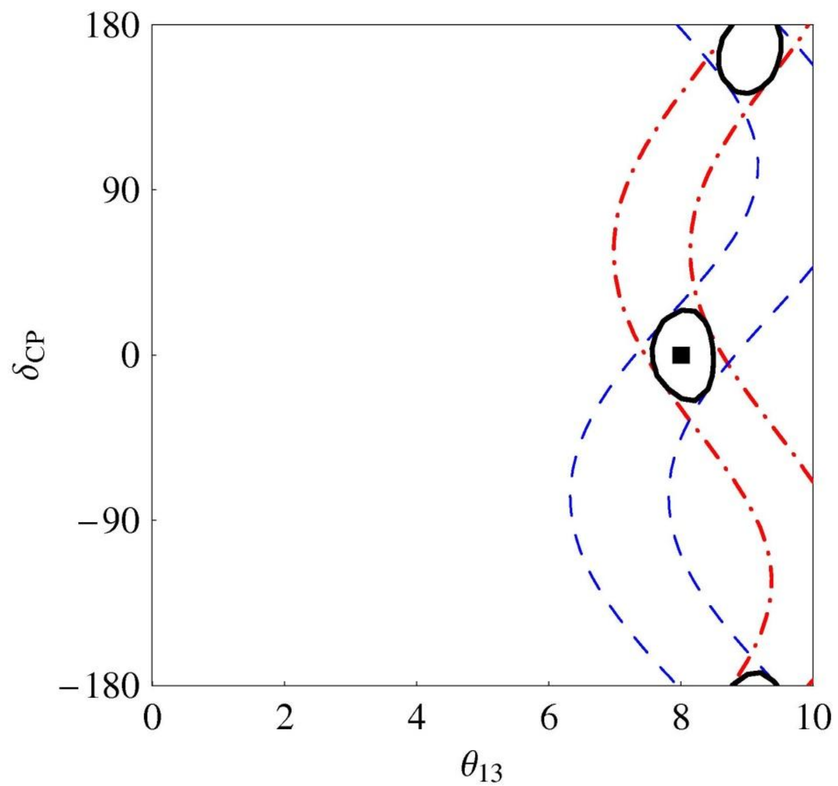
$$\tilde{J} = \cos\theta_{13} \sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \qquad \Delta_{atm} = \frac{\Delta m_{23}^2}{2E} \qquad \Delta_{sol} = \frac{\Delta m_{12}^2}{2E}$$

$$A = \sqrt{2} G_F n_e \qquad \tilde{B}_\mp = \left|A \mp \Delta_{atm}\right|$$

A. Cervera *et al.* hep-ph/0002108

The degeneracy problem

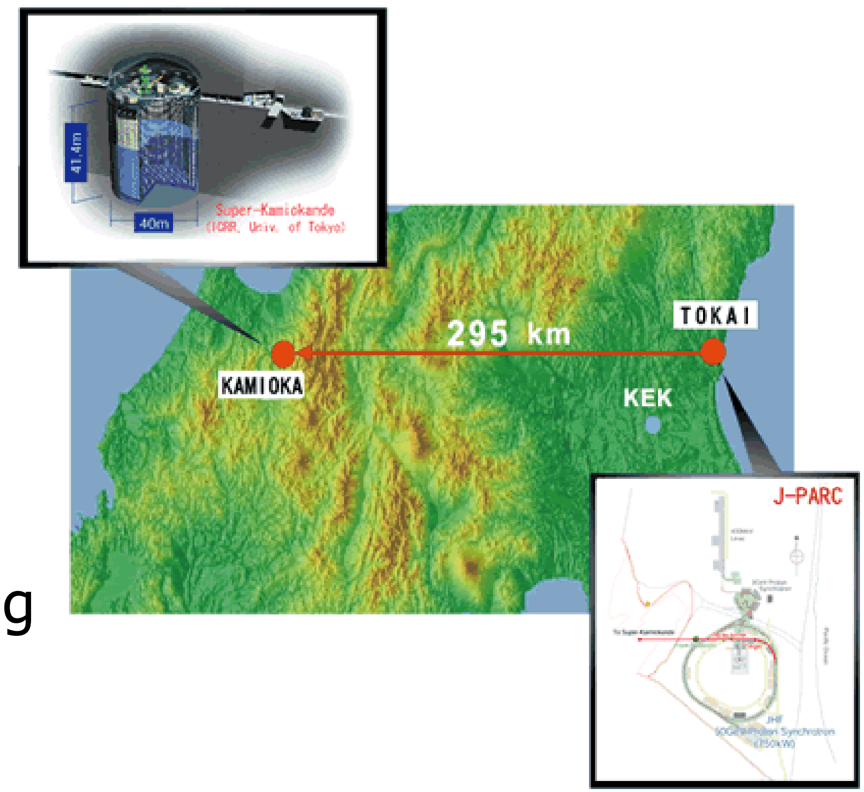
- Black square = input "true" value
- There is a curve of solutions
- If we add antineutrinos the two curves intersect in 2 regions: The *true* solution and an *intrinsic degeneracy*



J. Burguet-Castell *et al.* hep-ph/0103258

Present (and near future) ν beams

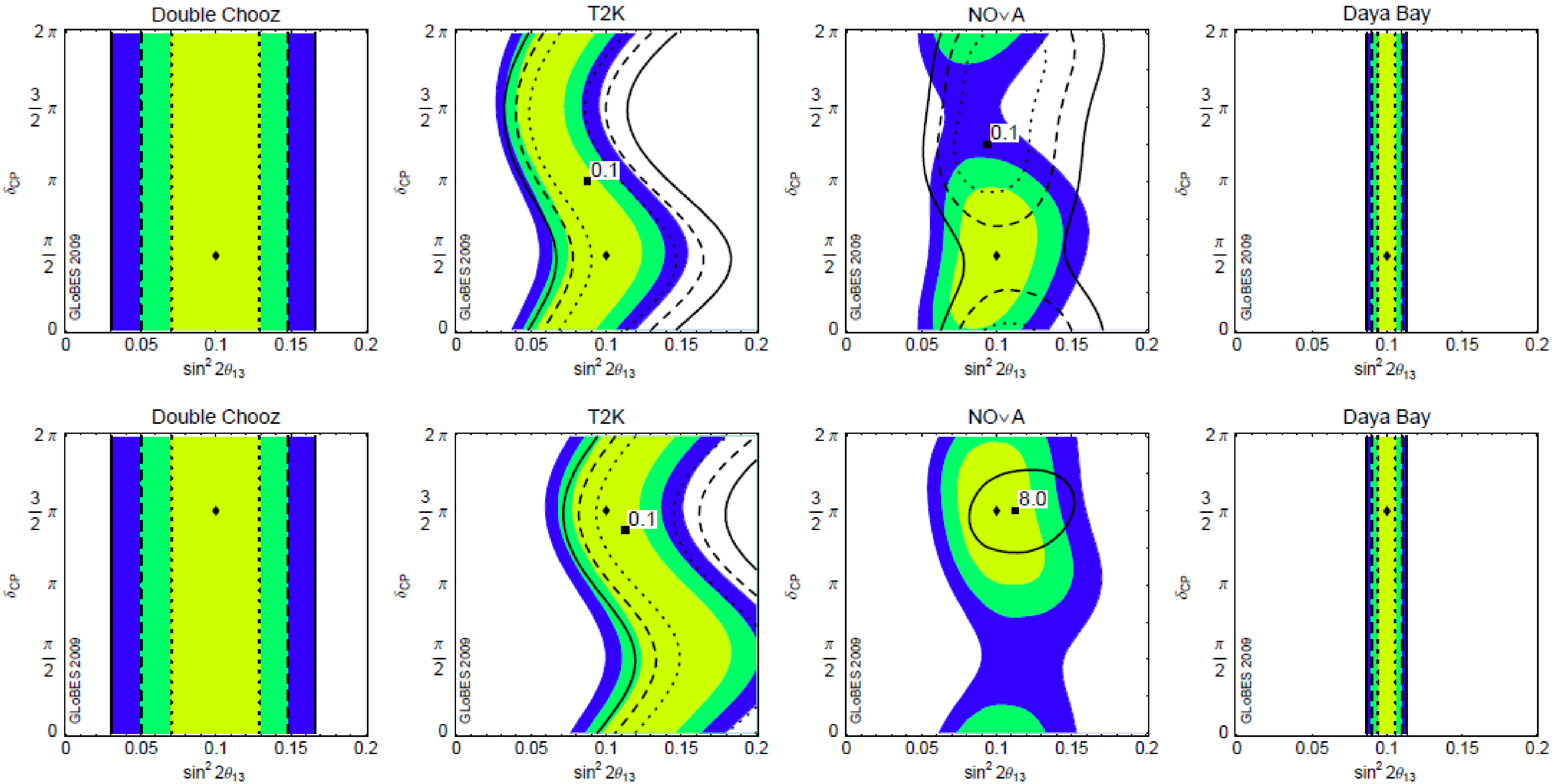
- T2K: L=295 Km, E= 0.4-1.2 GeV
  SK 22 kt water Cerenkov detector
  ν_μ beam → no sensitivity to δ



- Nova: L=810 Km E= 1.5-3 GeV
  3 + 3 yr run. 2013 starts data taking
  15 kt active scintillator detector

Sensitivities with present experiments

1, 2 and 3 σ

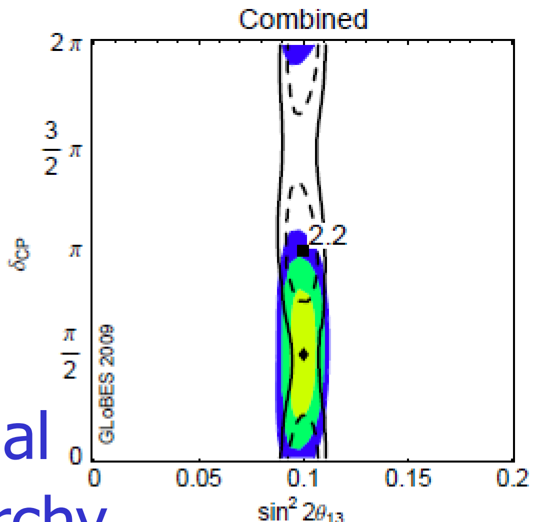


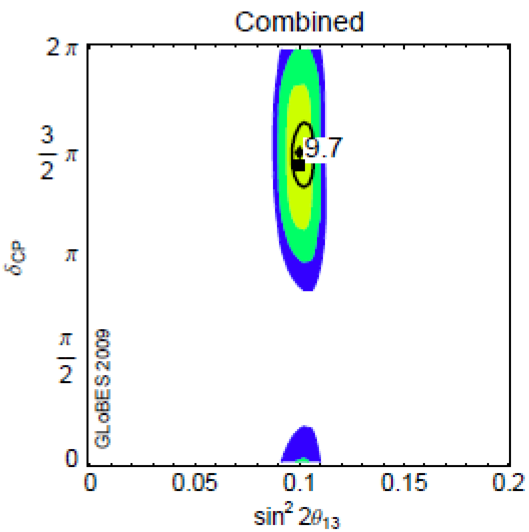
From P. Huber *et al.* 0907.1896

Sensitivities with present experiments

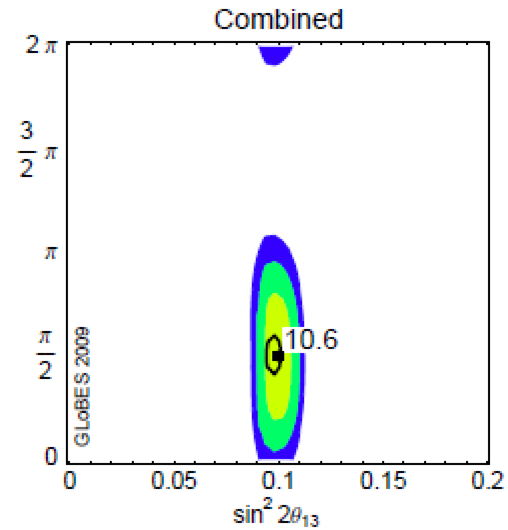
1, 2 and 3 σ

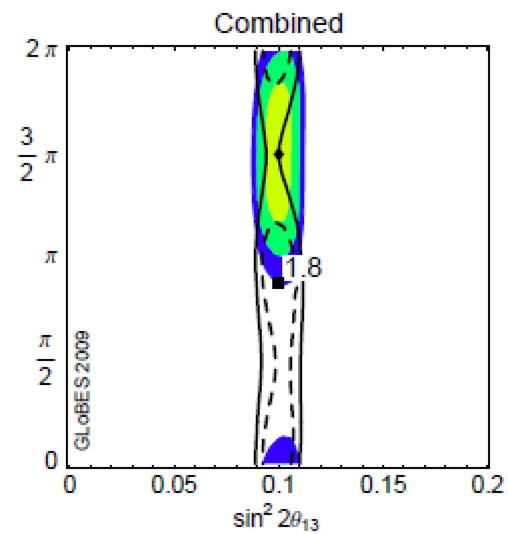
Normal hierarchy





Inverted hierarchy

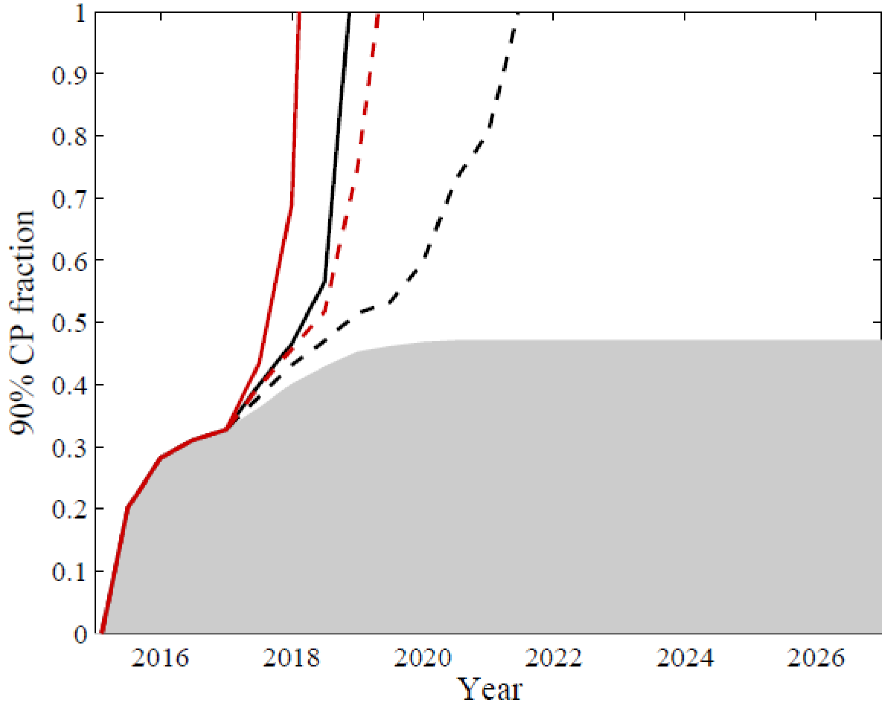


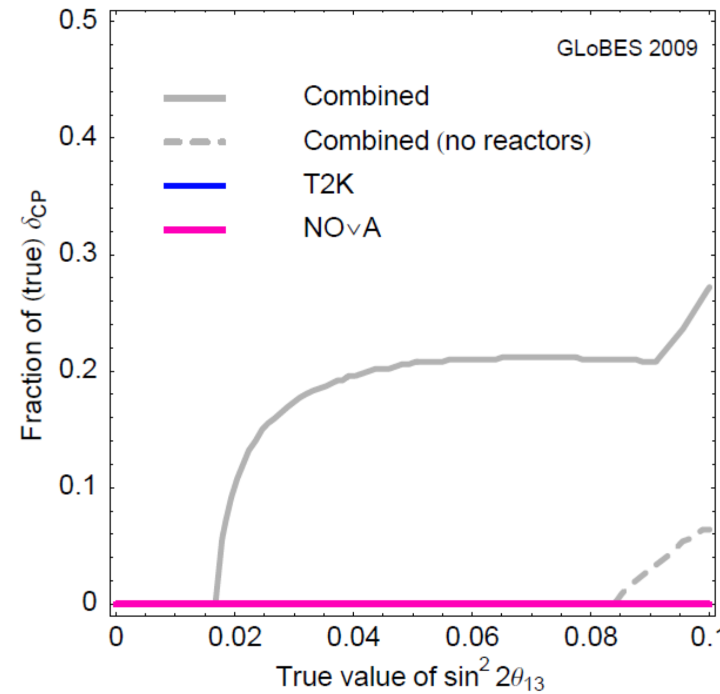


From P. Huber *et al.* 0907.1896

CP and mass hierarchy in the next 10 years

Mass hierarchy   90 % CL   CPV





Red 100 kt INO   Solid: high res INO ($\sigma_E/E = 0.15$, $\sigma_\theta = 15^o$)

Black 50 kt INO   Dashed: low res INO ($\sigma_E/E = 0.10$, $\sigma_\theta = 10^o$)

From M. Blennow and T. Schwetz 1203.3388
P. Huber *et al.* 0907.1896

Super-Beams

- Intense conventional ν_μ beams from π decay with MW proton drivers

- T2HK: Beam power x2
  mass x25 (560 kt) Hyper-K
  Abe et al 1109.3262

- SPL: CERN - Frejus L=130 km
  E= 0.1-0.5 GeV
  500 kt water Cerenkov detector

- LBNE: Wide Band Beam
  E= 1-5 GeV
  Fnal – Dusel L=1300 km
  Liquid Ar detector 33.4 kt

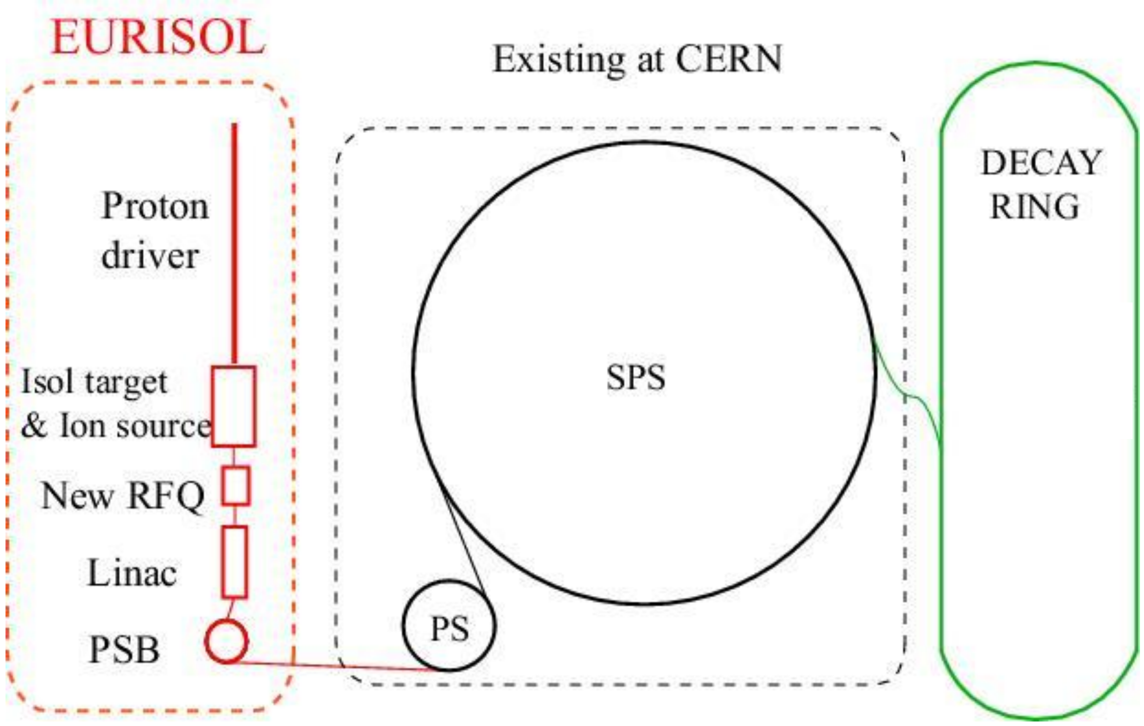
- LAGUNA-LBNO: Wide Band Beam E= 1-8 GeV
  CERN – Pyhäsalmi L=2300 km
  Liquid Ar detector 100 kt

β-Beams

- Pure ν_e beams from the β decay of radiactive ions

$$^{6}He \rightarrow {}^{6}Li + \bar{\nu}_e + e^- \qquad {}^{18}Ne \rightarrow {}^{18}F + \nu_e + e^+$$

$$\nu_e \rightarrow \nu_\mu \qquad \nu_e \rightarrow \nu_e$$



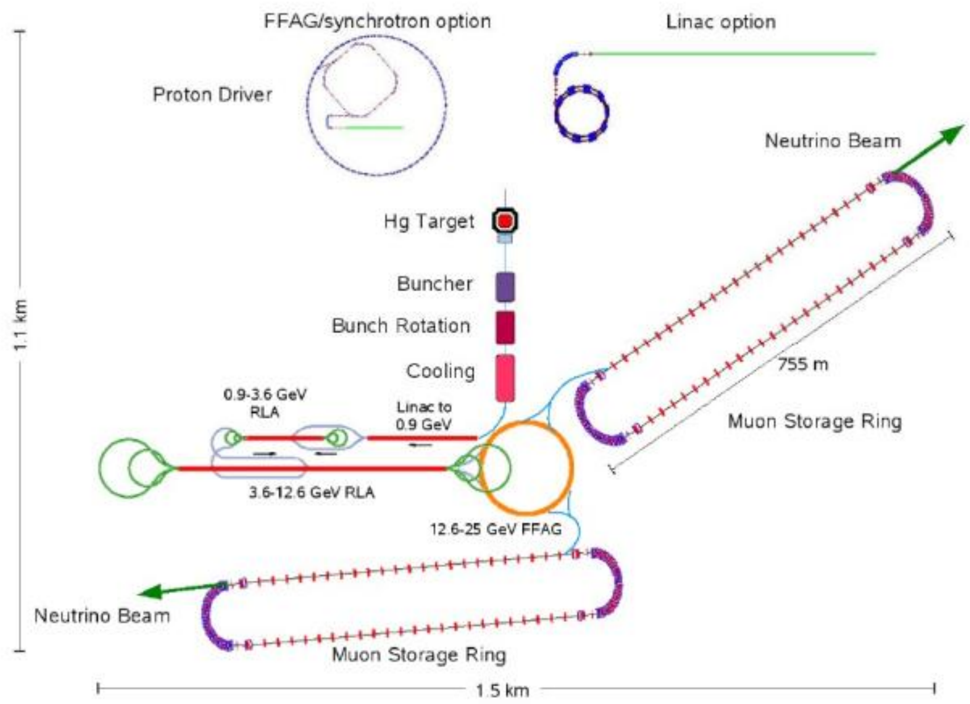
P. Zucchelli 2002

Neutrino Factory

- Pure ν_e and ν_μ from the μ decay accelated to 25 GeV

$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu \qquad L = 4000\text{km}$$

- Lots of channels could be observed
  - *golden channel:* $\nu_e \rightarrow \nu_\mu$
  - *silver channel:* $\nu_e \rightarrow \nu_\tau$
  - $\nu_\mu \rightarrow \nu_\mu$
  - $\nu_\mu \rightarrow \nu_\tau$



- Needs to measure the lepton charge to identify the original flavour
- Magnetized iron detector for $\nu_e \rightarrow \nu_\mu$ and ECC for $\nu_e \rightarrow \nu_\tau$

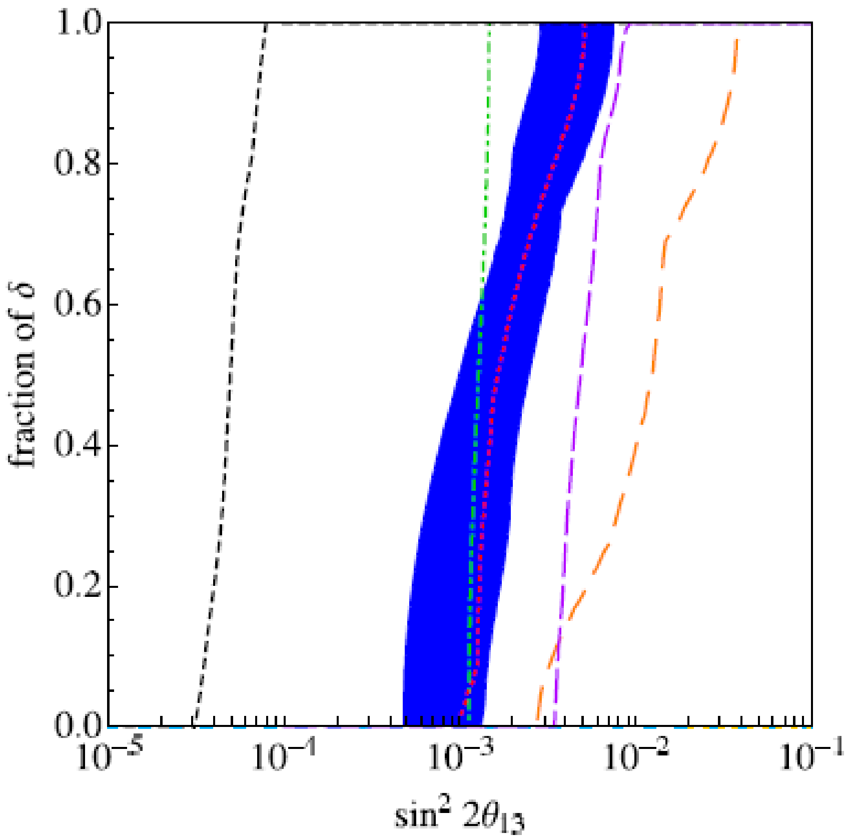
S. Geer hep-ex/9712290 A. de Rujula, B. Gavela and P. Hernandez hep-ex/9811390

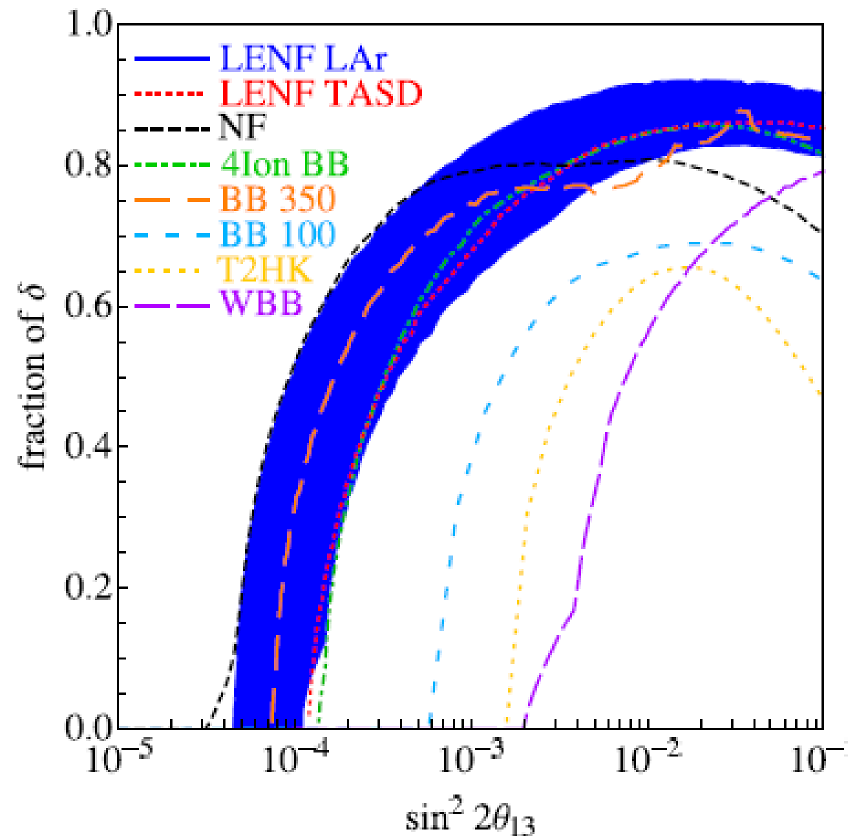
Sensitivities with future experiments

Mass hierarchy

3 σ

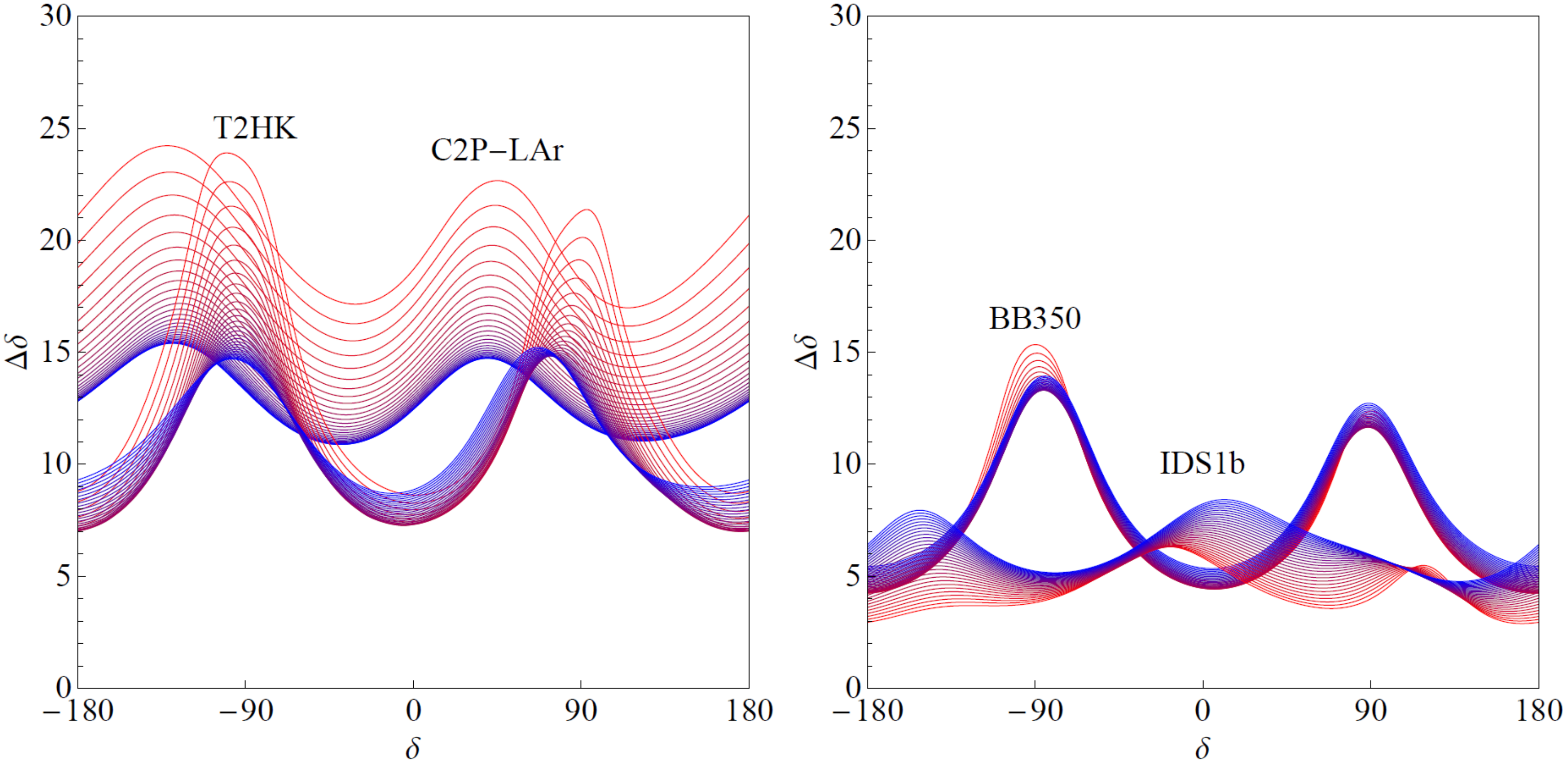
CP violation





From EFM, T. Li, O. Mena and S. Pascoli 0911.3776

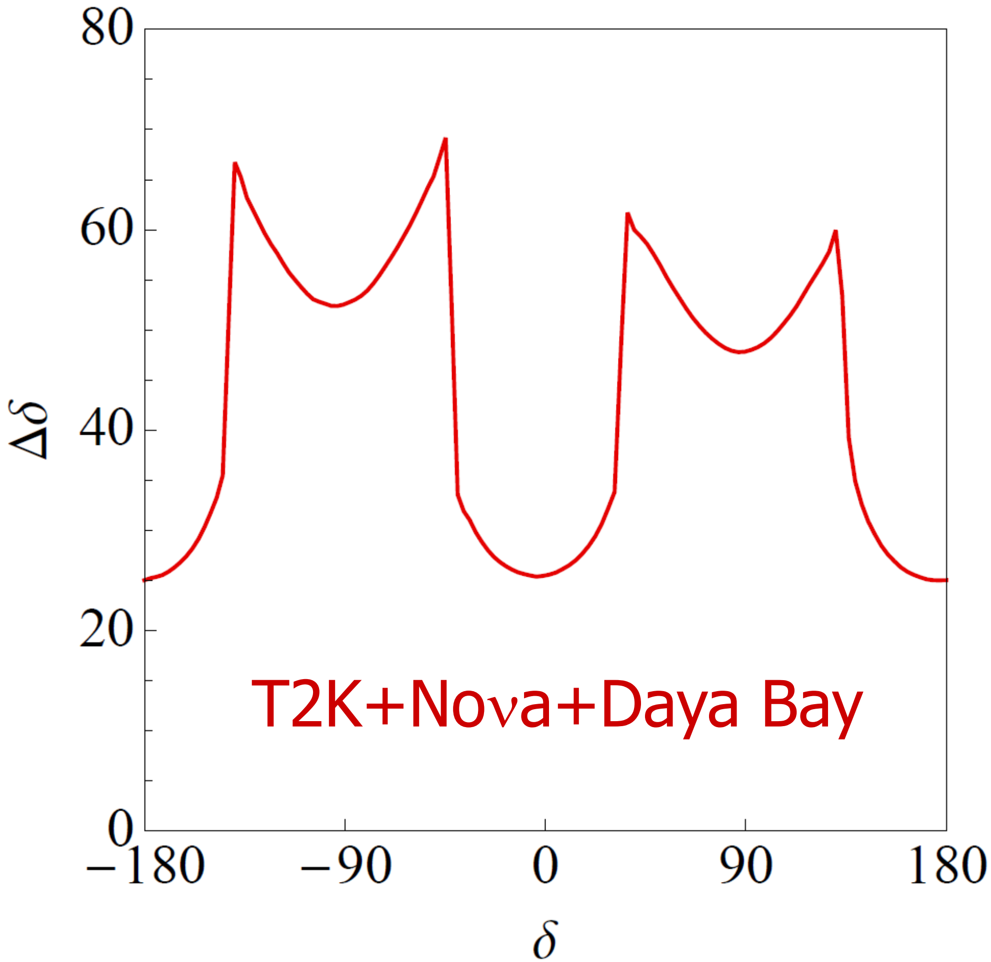
Precision

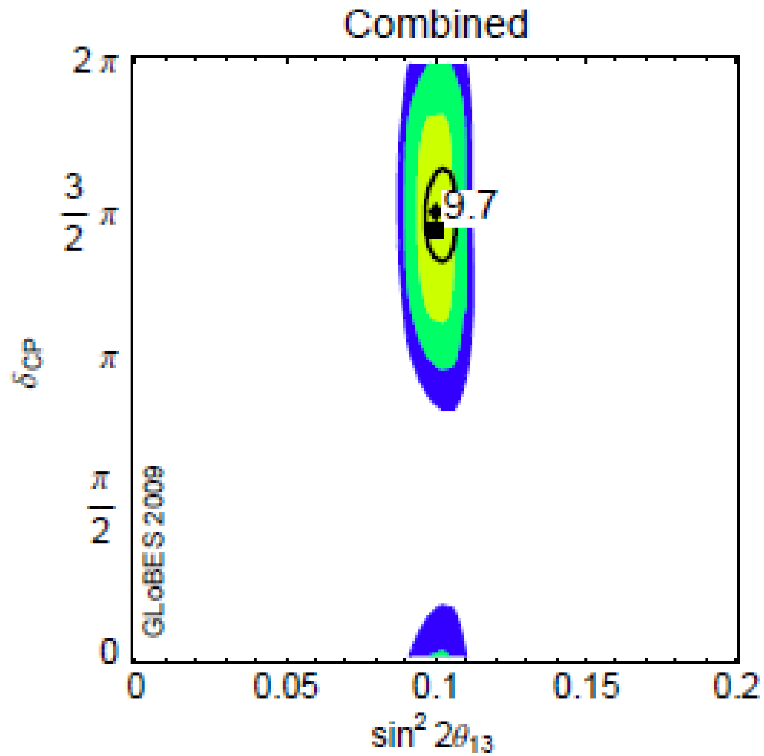


θ_{13}: 3º - 10º

P. Coloma, A. Donini, EFM and P. Hernandez in preparation

Precision





From P. Huber *et al.* 0907.1896

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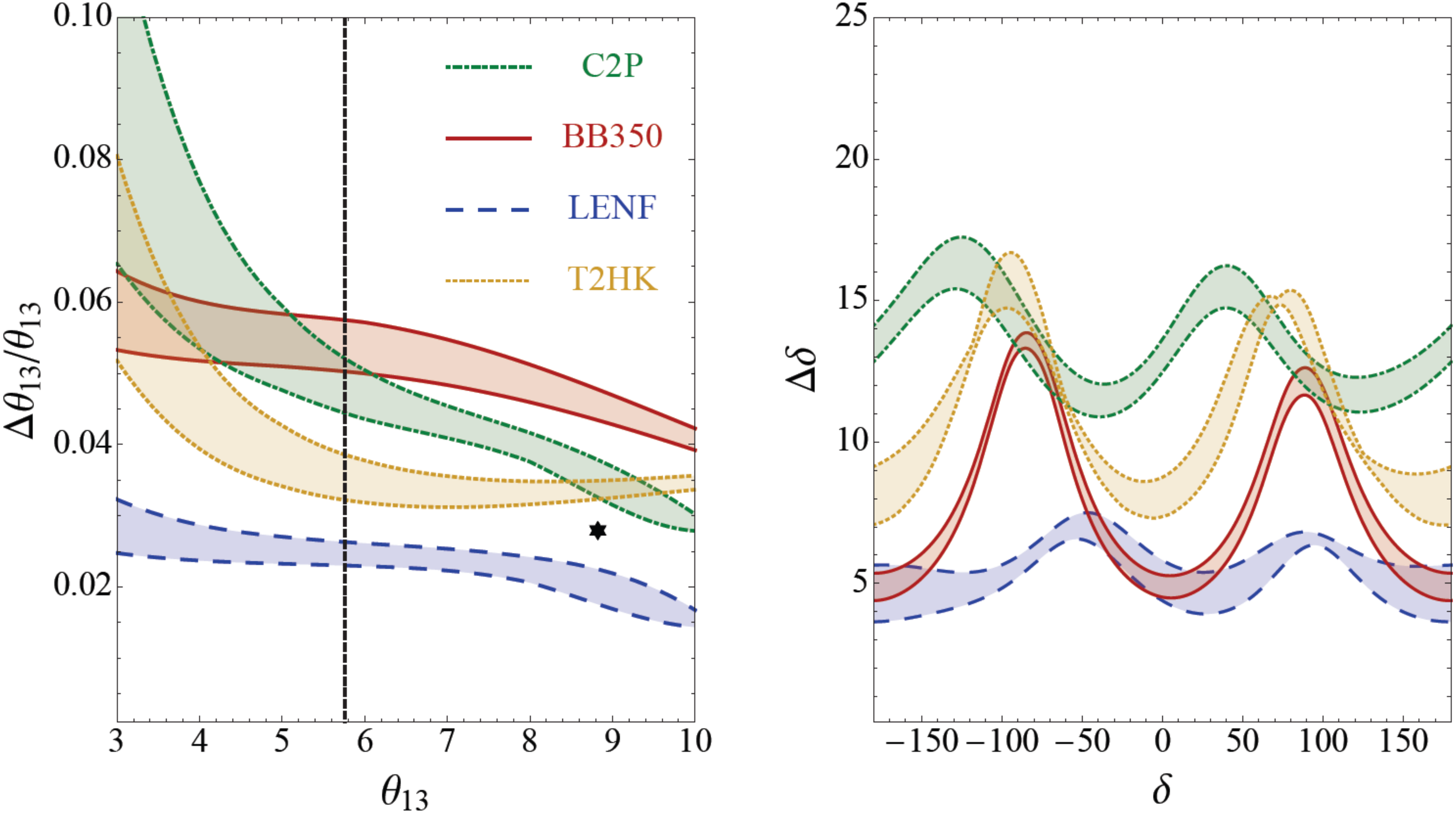
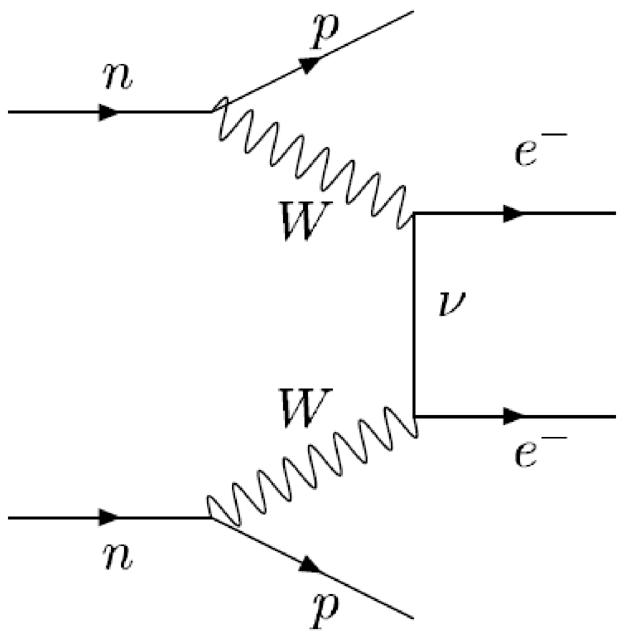
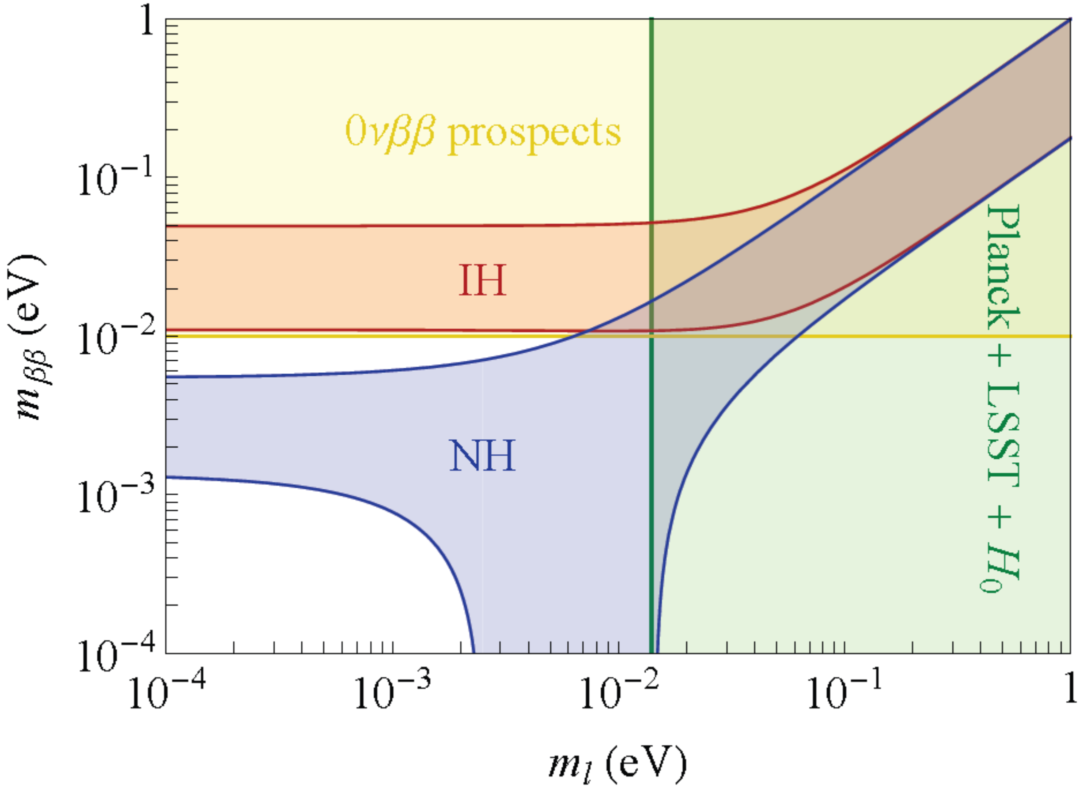


P. Coloma, A. Donini, EFM and P. Hernandez in preparation

Neutrinoless double β decay





$$m_{\beta\beta} = m_1 c_{12}^2 c_{13}^2 + m_2 s_{12}^2 c_{13}^2 e^{2i\alpha_1} + m_3 s_{13}^2 e^{2i\alpha_2}$$

Adapted from M. Blennow, EFM, J. Lopez and J. Menendez 1005.3240

Future with weak lensing from LSST (survey ~2020) and prospective 0νββ experiments

Conclusions

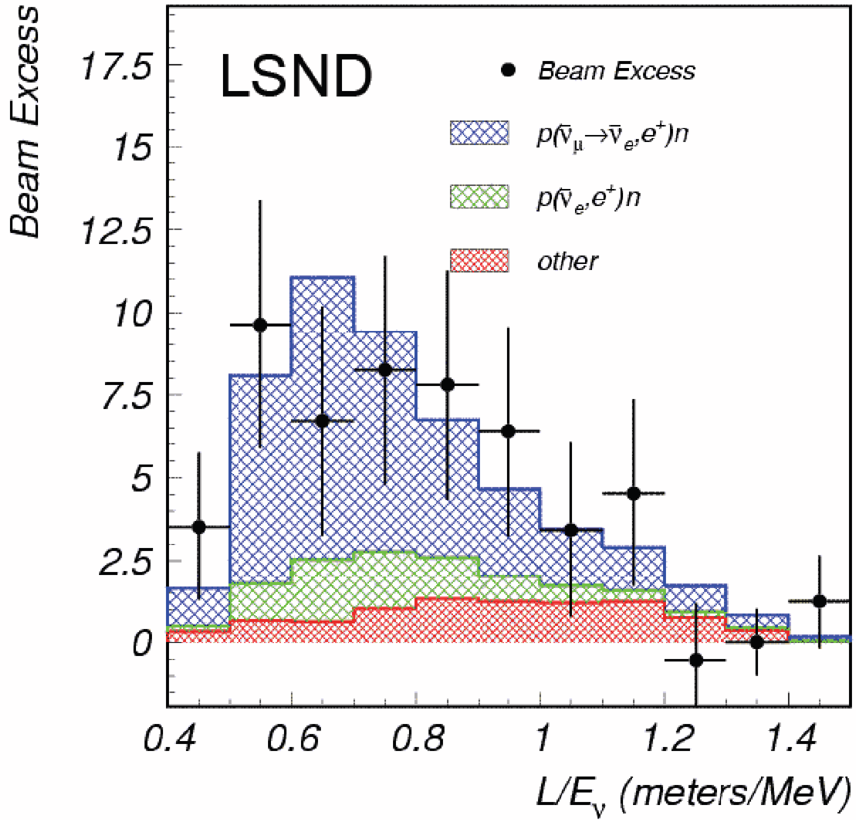
- The large value of θ_{13} discovered by Daya Bay opens the window to the measurement of the neutrino mass hierarchy and leptonic CP violation.

- T2K and Noνa will provide the first ~90% CL indications over the next 8 years.

- In order to reach discovery, upgraded or new facilities will be needed. But "moderate" improvements like T2HK can be sufficient.

Neutrino anomalies

Sterile neutrinos? LSND



LSND 3.8 σ excess

E ~ 30 MeV L ~ 30 m

Assuming 2 family oscillations

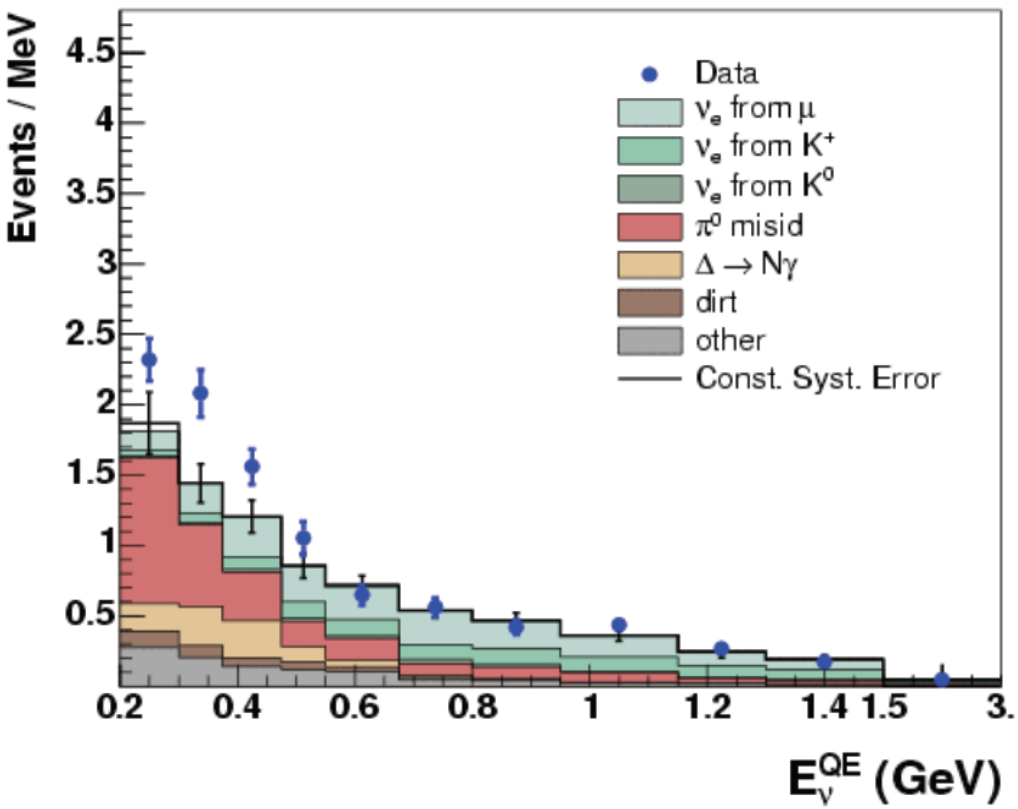
$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = \sin^2(2\theta)\sin^2\left(\frac{1.27\, L\, \Delta m^2}{E}\right)$$

$$= 0.245 \pm 0.067 \pm 0.045\ \%$$

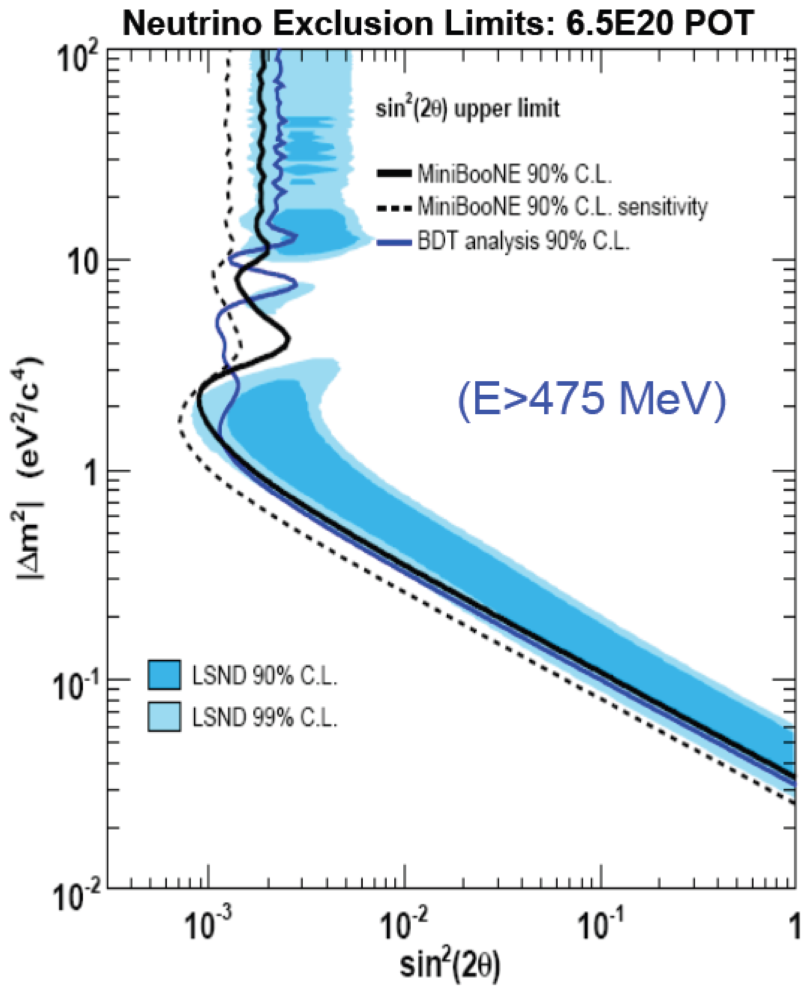
Selection	Beam-On Events	Beam-Off Background	ν Background	Event Excess
$R_\gamma > 1$	205	106.8 ± 2.5	39.2 ± 3.1	$59.0 \pm 14.5 \pm 3.1$
$R_\gamma > 10$	86	36.9 ± 1.5	16.9 ± 2.3	$32.2 \pm 9.4 \pm 2.3$
$R_\gamma > 100$	27	8.3 ± 0.7	5.4 ± 1.0	$13.3 \pm 5.2 \pm 1.0$

Sterile neutrinos? MiniBooNE

MiniBooNE E ~ 500 MeV L ~ 500 m neutrino mode

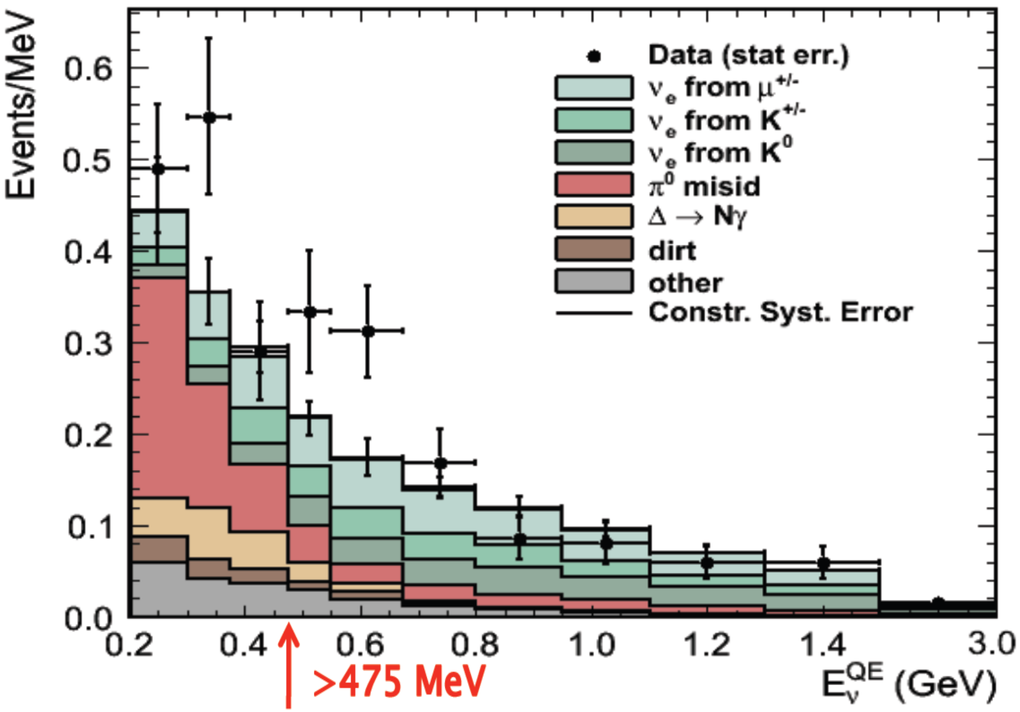


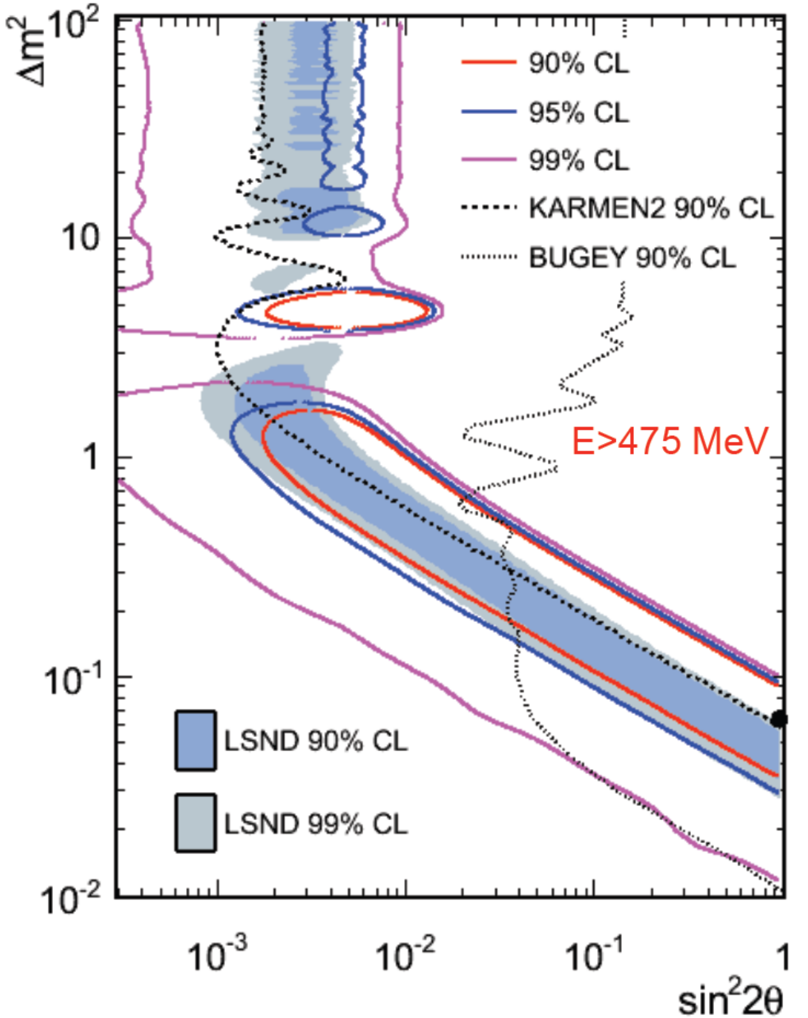
2009



Sterile neutrinos? MiniBooNE

MiniBooNE E ~ 500 MeV L ~ 500 m antineutrino mode





2010

Sterile neutrinos? MiniBooNE

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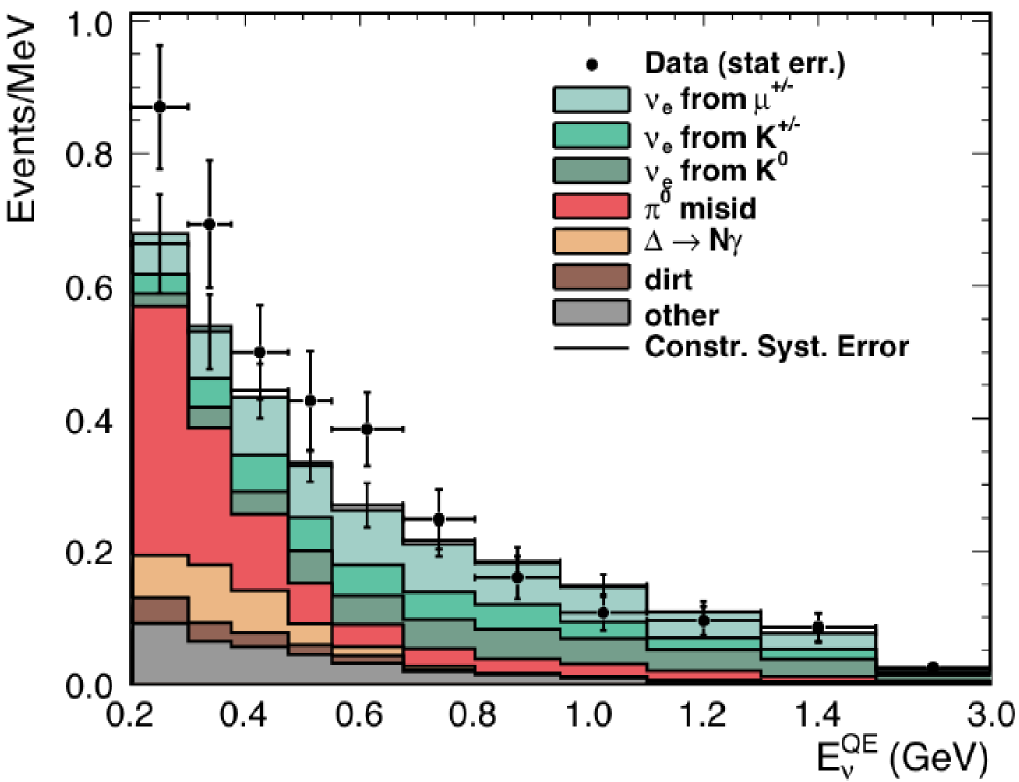
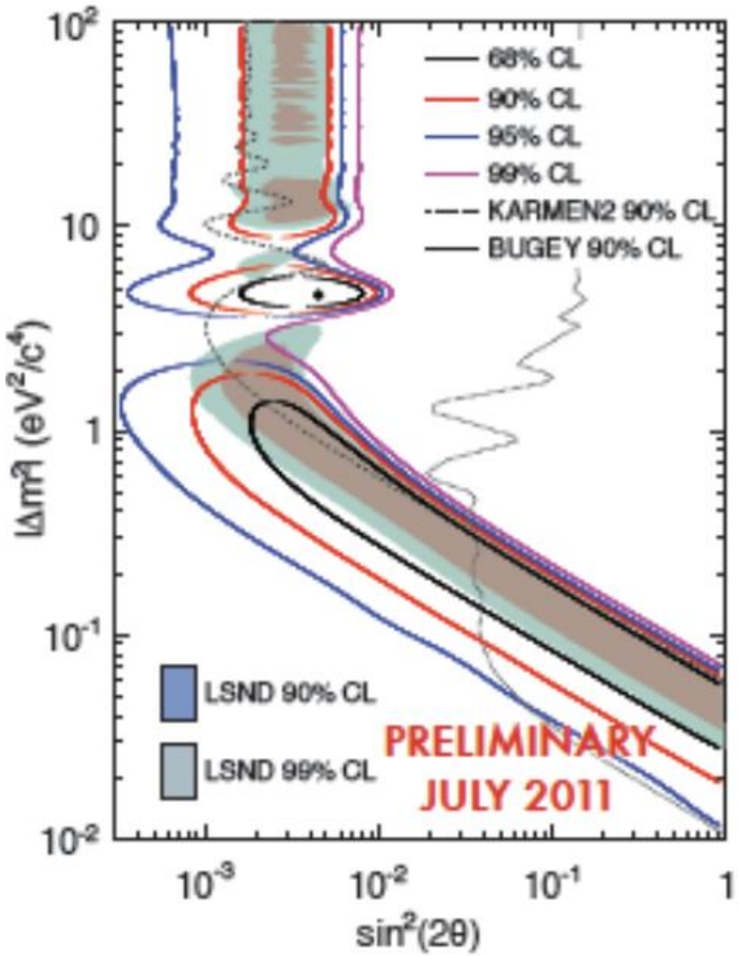


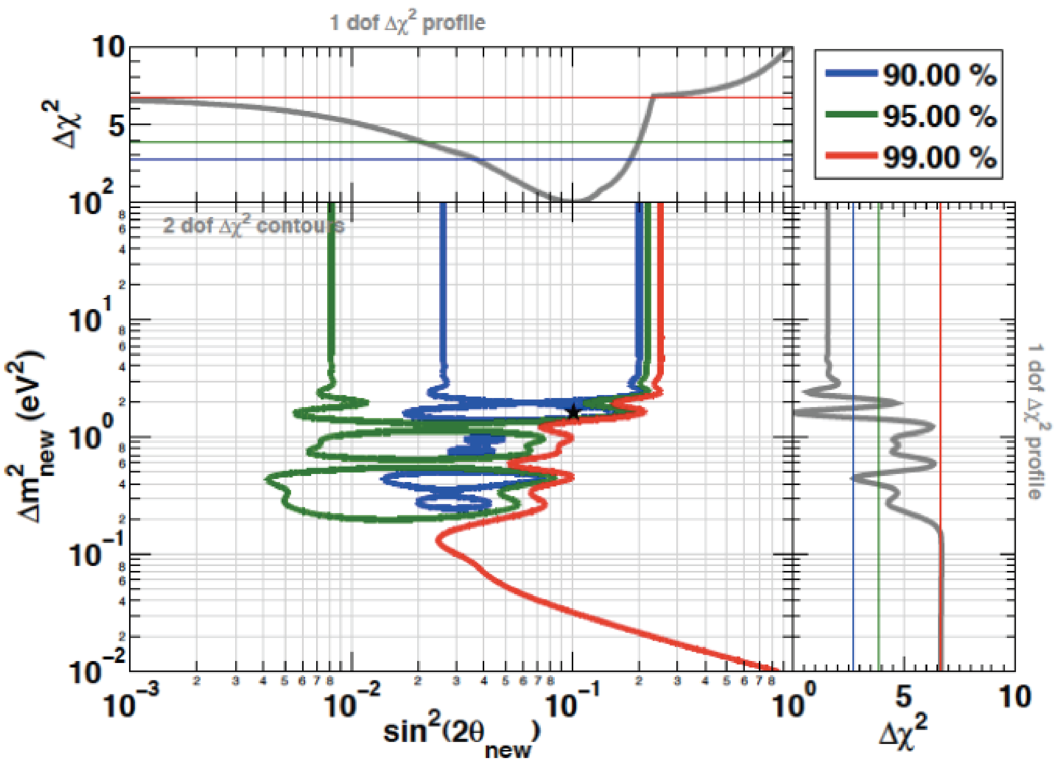
2011

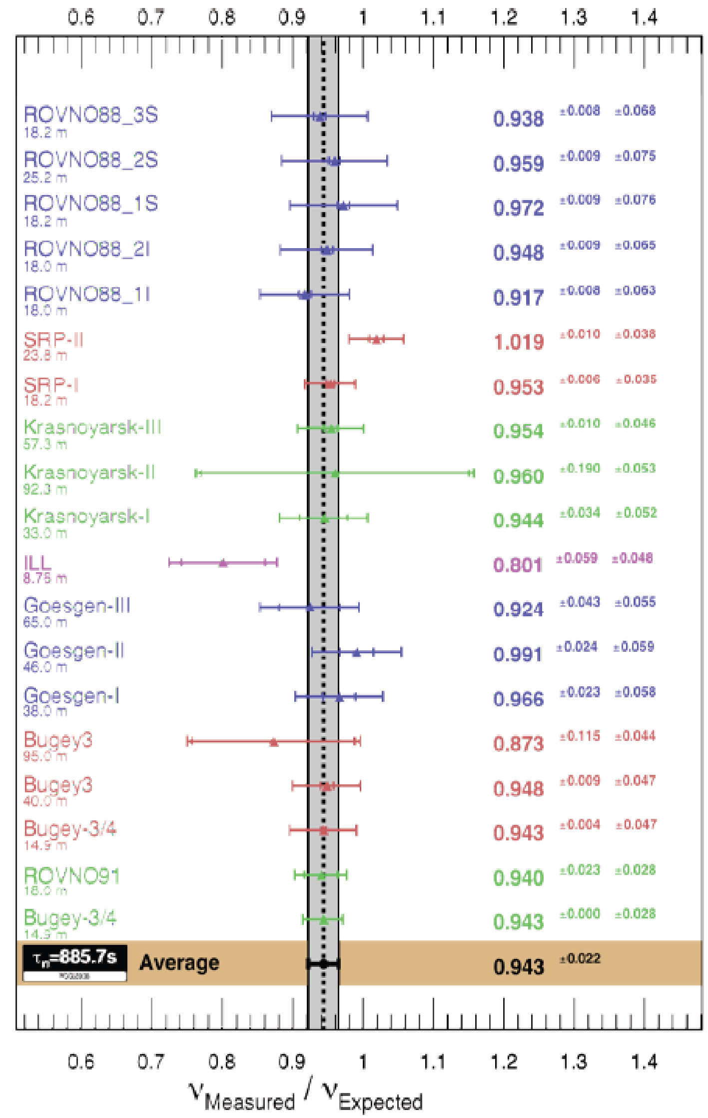


Sterile neutrinos? Reactors

- Inclusion of new beta decay estimates in reactor flux calculations
- Increases expected flux

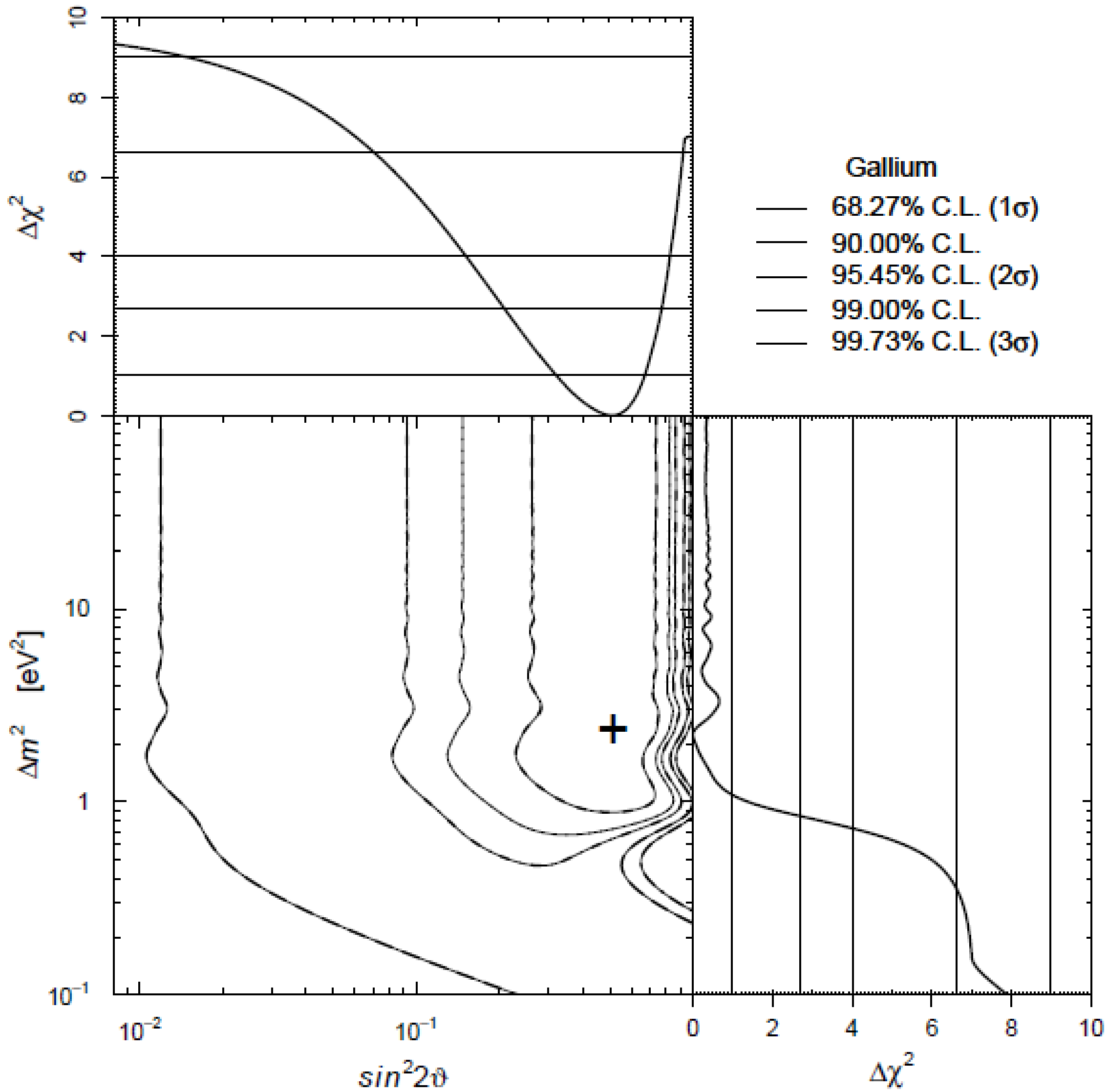
  Best fit: 0.943 ± 0.023





G. Mention et al 1101.2755

Sterile neutrinos? Gallium

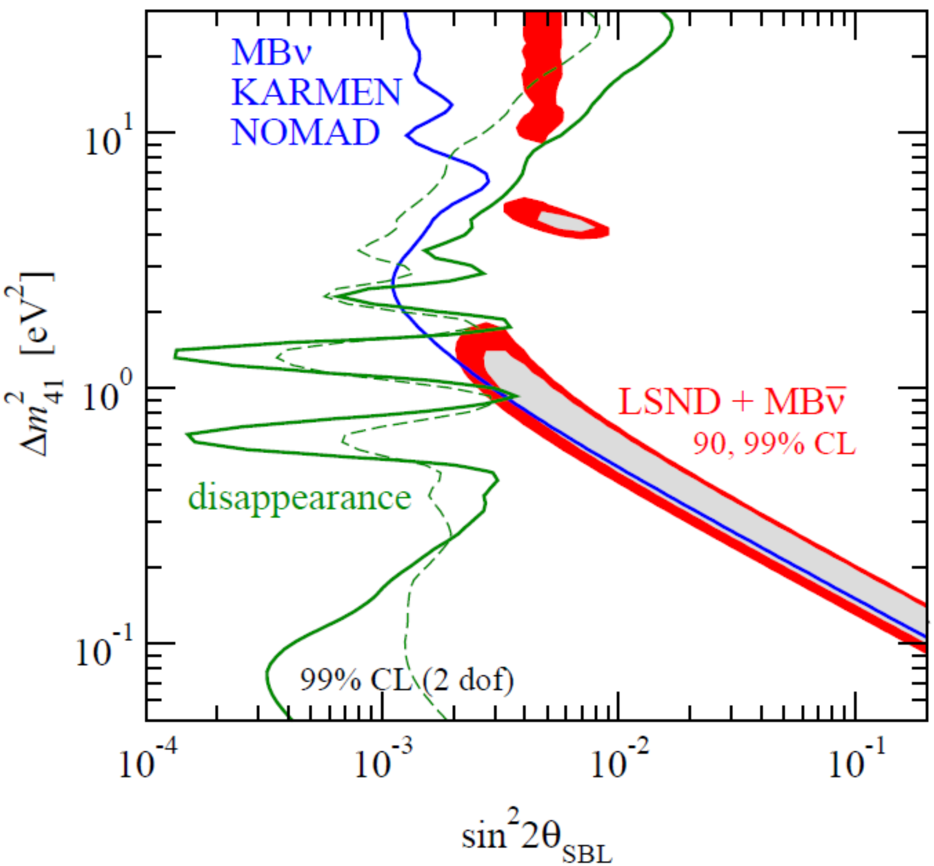


$$R_{\mathrm{B}}^{\mathrm{G1}} = 0.953 \pm 0.11\,,$$
$$R_{\mathrm{B}}^{\mathrm{G2}} = 0.812^{+0.10}_{-0.11}\,,$$
$$R_{\mathrm{B}}^{\mathrm{S1}} = 0.95 \pm 0.12\,,$$
$$R_{\mathrm{B}}^{\mathrm{S2}} = 0.791^{+0.084}_{-0.078}\,,$$

Callibration of Gallex and Sage detectors with radioactive sources

C. Giunti and M. Laveder
1006.3244

Sterile neutrinos? Everything together



	Δm^2_{41}	$\lvert U_{e4}\rvert$	$\lvert U_{\mu4}\rvert$	Δm^2_{51}	$\lvert U_{e5}\rvert$	$\lvert U_{\mu5}\rvert$	δ/π	χ^2/dof
3+2	0.47	0.128	0.165	0.87	0.138	0.148	1.64	110.1/130

	LSND+MB($\bar\nu$) vs rest		appearance vs disapp.	
	old	new	old	new
$\chi^2_{\mathrm{PG},3+2}$/dof	25.1/5	19.9/5	19.9/4	14.7/4
PG_{3+2}	10^{-4}	0.13%	5×10^{-4}	0.53%

J. Kopp, M. Maltoni and T. Schwetz 1103.4570

See also C. Giunti and M. Laveder 1107.1452

Majorana neutrinos?

General 3+2 scenario has 5 masses + 9 mixing angles +
6 Dirac phases + 4 Majorana phases

$$U_{\rm tot}^T \begin{pmatrix} 0 & m_D^T \\ m_D & M_N \end{pmatrix} U_{\rm tot} = \begin{pmatrix} m & 0 \\ 0 & M \end{pmatrix}$$

Adding 3 Majorana νR 6 masses + 6 angles + 4 + 2 phases

Can the 3+2 best fot point be reproduced with 3 Majorana νR?

Majorana neutrinos?

We generalized the Casas-Ibarra parametrization to work for any Majorana mass (away from Seesaw condition)

We scanned the parameter space via MCMC to reproduce the 3+2 best fit points

	$\lvert U_{e4}\rvert$	$\lvert U_{e5}\rvert$	$\lvert U_{\mu 4}\rvert$	$\lvert U_{\mu 5}\rvert$	ϕ/π	Δm^2_{41}	Δm^2_{51}
Ref. [26]	0.128	0.138	0.165	0.148	1.64	0.47	0.87
NH1	0.126	0.131	0.163	0.142	1.64	0.47	0.88
IH1	0.118	0.138	0.160	0.156	1.64	0.47	0.88
Ref. [27]	0.130	0.130	0.134	0.080	1.52	0.9	1.6
NH2	0.128	0.135	0.134	0.080	1.52	0.9	1.6
IH2	0.130	0.130	0.137	0.080	1.52	0.9	1.6

M. Blennow and EFM 1107.3992

See also A. de Gouvea hep-ph/0501039
A. Donini et al 1106.0064
J. Fan and P. Langacker 1201.6662

LSND/MiniBooNE via NSI

$$2\sqrt{2}G_F\varepsilon_{e\mu}^{ud}\left(\bar{\mu}\gamma^{\mu}P_L\nu_e\right)\left(\bar{u}\gamma_{\mu}P_{L,R}d\right)$$

Can be accommodated with production/detection NSI + sterile neutrinos

$\varepsilon_{e\mu} \sim 0.01$

E. Akhmedov and T. Schwetz 1007.4171

LSND/MiniBooNE via NSI

$$2\sqrt{2}G_F\varepsilon_{e\mu}\left(\bar{\mu}\gamma^\mu P_L\nu_e\right)\left(\bar{u}\gamma_\mu P_L d\right)$$

Can be accommodated with production/detection NSI + sterile neutrinos

$\varepsilon_{e\mu} \sim 0.01$

E. Akhmedov and T. Schwetz 1007.4171

is related to $2\sqrt{2}G_F\varepsilon_{e\mu}\left(\bar{\mu}\gamma^\mu P_L e\right)\left(\bar{q}\gamma_\mu P_{L,R} q\right)$

by gauge invariance → strong bounds < 10^{-4}

S. Antusch, J. Baumann and EFM 0807.1003

Proposals to probe steriles

- Add radioactive ν source near or inside Borexino
- BooNE: identical (or same) detector to miniBooNE located at 200 m to normalize flux and cross section
- MicroBooNE: LAr 62 tons detector starting 2013. At a latter stage use as near detector with larger far detector
- 2 ICARUS detectors @ CERN: 600 ton module moved from Gran Sasso to CERN 810 m baseline + near 150 ton module 127 m baseline

Neutrino oscillation regimes

Δm^2_{13} fast oscillations - small L/E

$$\nu_\mu \xrightarrow{\theta_{23}} \nu_\mu$$

Atmospherics
K2K, MINOS, T2K

$$\nu_\mu \xrightarrow{\theta_{23}} \nu_\tau$$

OPERA

$$\nu_e \xrightarrow{\theta_{13}} \nu_e$$

Daya Bay
DCHOOZ

$$\nu_\mu \xrightarrow{\theta_{13}} \nu_e$$

T2K, Noνa

Δm^2_{12} slow oscillations - large L/E

$$\nu_e \xrightarrow{\theta_{12}} \nu_e$$

Solar
KamLAND

Neutrino oscillation regimes

Δm^2_{13} fast oscillations - small L/E

θ_{13} θ_{13} θ_{13} δ

$\nu_\mu \leftrightarrow \nu_e$

T2K, Noνa

Δm^2_{12} slow oscillations - large L/E

The Golden channel

$$P\left(\overset{(-)}{\nu}_e \to \overset{(-)}{\nu}_\mu\right) = s_{23}^2 \sin^2 2\theta_{13} \ \sin\left(\frac{\Delta_{atm} L}{2}\right)^2$$

$$+ c_{23}^2 \sin^2 2\theta_{12} \ \sin^2\left(\frac{\Delta_{sol} L}{2}\right)$$

$$+ \ \tilde{J} \ \sin\left(\frac{\Delta_{sol} L}{2}\right) \sin\left(\frac{\Delta_{atm} L}{2}\right) \cos\left(\pm\delta - \frac{\Delta_{atm} L}{2}\right)$$

Expanded in

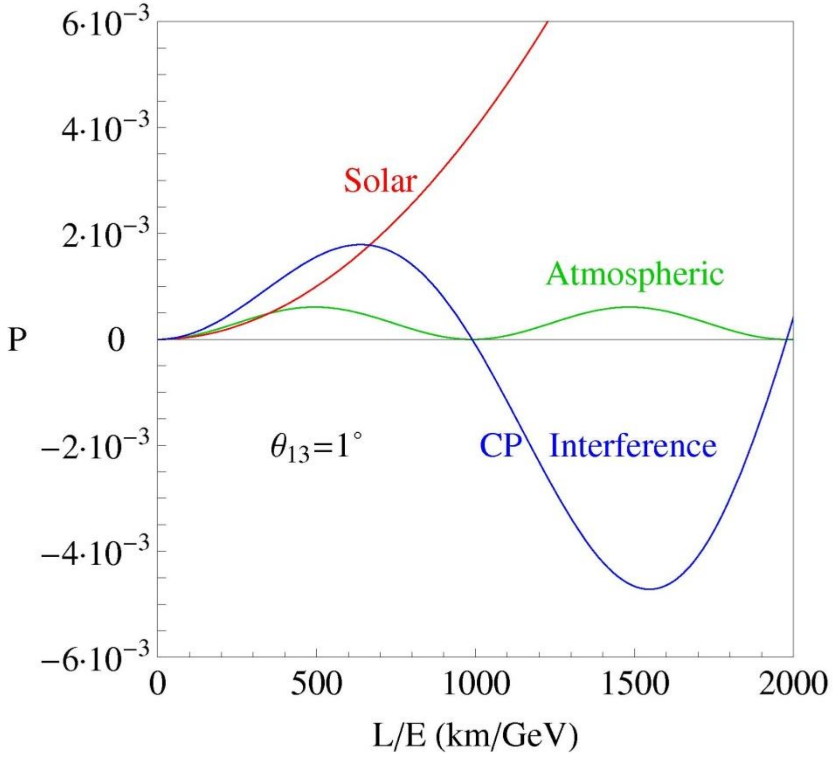
$$\sin 2\theta_{13} \qquad \left(\frac{\Delta_{sol} L}{2}\right)$$

where

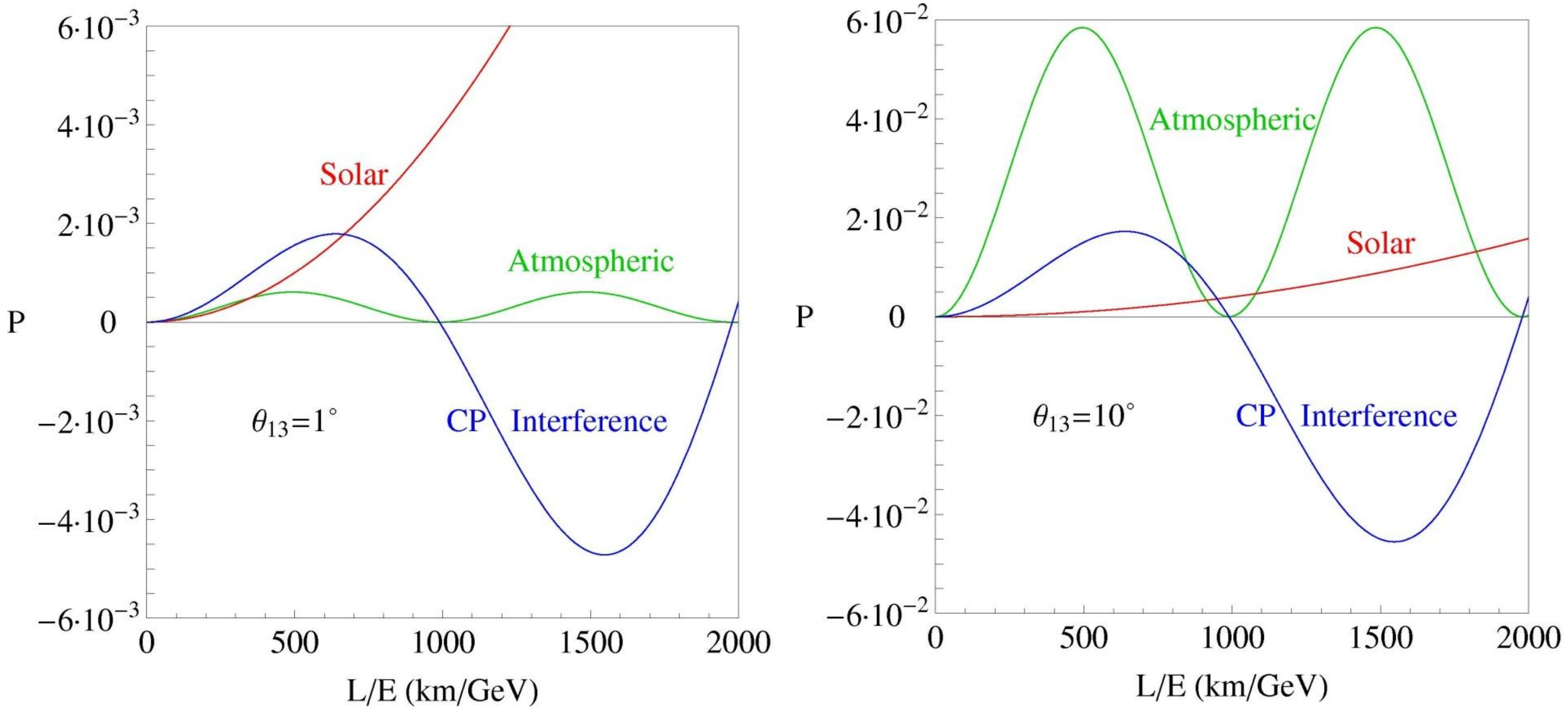
$$\tilde{J} = \cos\theta_{13} \sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \qquad \Delta_{atm} = \frac{\Delta m_{31}^2}{2E} \qquad \Delta_{sol} = \frac{\Delta m_{21}^2}{2E}$$

A. Cervera *et al.* hep-ph/0002108

Optimization of facilities for large θ_{13}

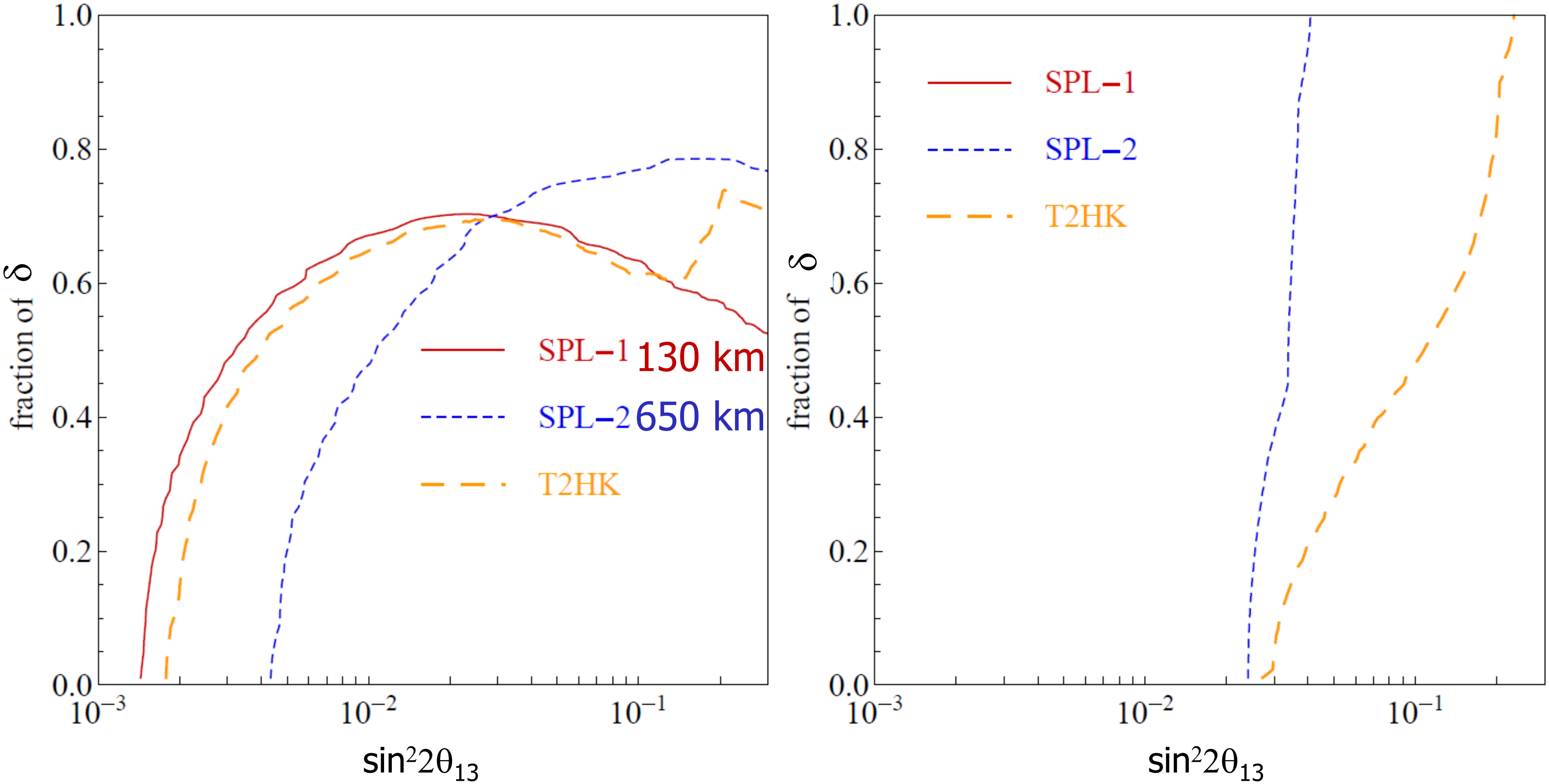


Optimization of facilities for large θ_{13}



Optimization of facilities for large θ_{13}

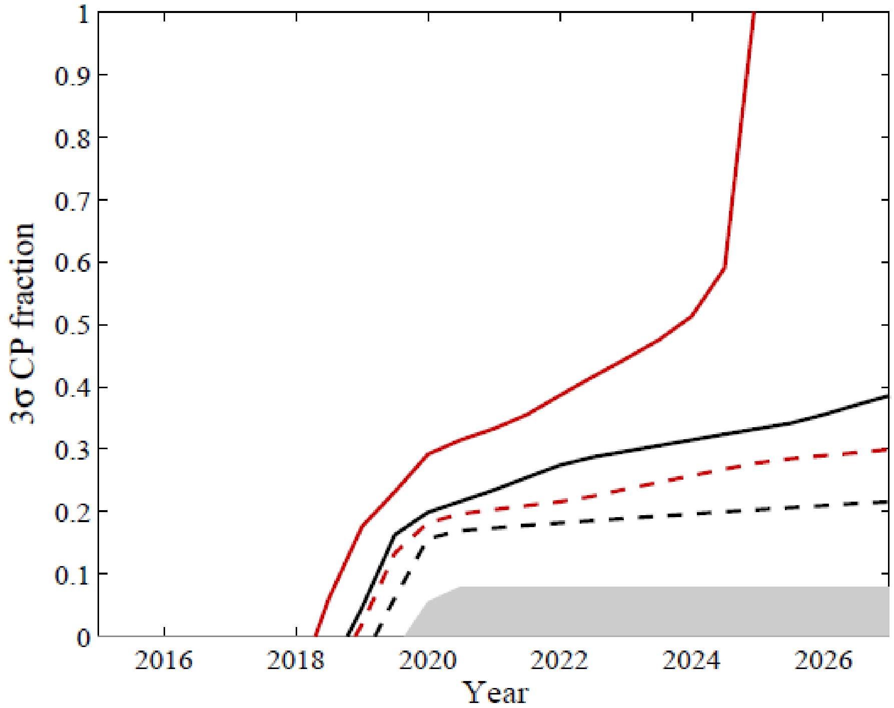
CP violation 3 σ Mass hierarchy



P. Coloma and EFM 1110.4583

Mass hierarchy with Novνa + T2K + INO

3 σ



Red 100 kt INO Solid: high res INO ($\sigma_E/E = 0.15$, $\sigma_\theta = 15^o$)

Black 50 kt INO Dashed: low res INO ($\sigma_E/E = 0.10$, $\sigma_\theta = 10^o$)

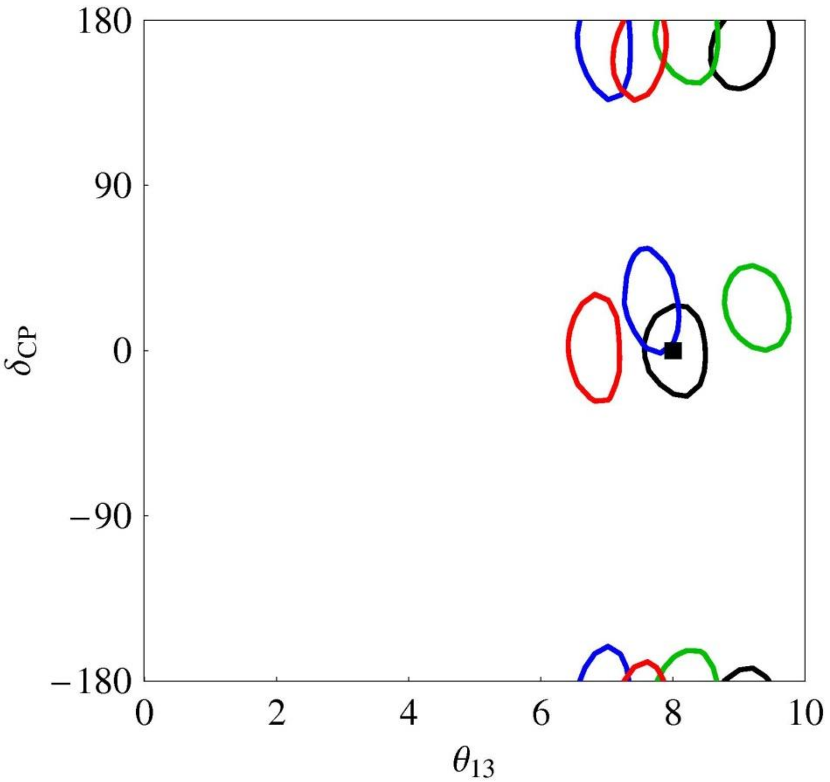
From M. Blennow and T. Schwetz 1203.3388

The degeneracy problem

Two other unknown parameters: sign and oct

- There are 4 different sets of curves for different choices of sign and octant
- 2 Intersections each

Eightfold degeneracy:
Intrinsic sign octant mixed



H. Minakata and H. Nunokawa hep-ph/0108085
G.L.Fogli and E. Lisi hep-ph/9604415
V. Barger and D. Marfatia hep-ph/0112119