ISAPP

Valencia, 2008

Neutrino Oscillation Phenomenology - II

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Outline

Lecture 1:

- Neutrino oscillations
  oscillations in vacuum and matter
- Present neutrino oscillation experiments
  solar, atmospheric, reactor, accelerator

Lecture 2:

- θ_{13} and global three flavour analysis
  discussion of three flavour effects
  summary of present status and open questions
- the LSND puzzle and MiniBooNE results

3-flavour oscillation parameters

$$\Delta m^2_{31} \qquad\qquad\qquad \Delta m^2_{21}$$

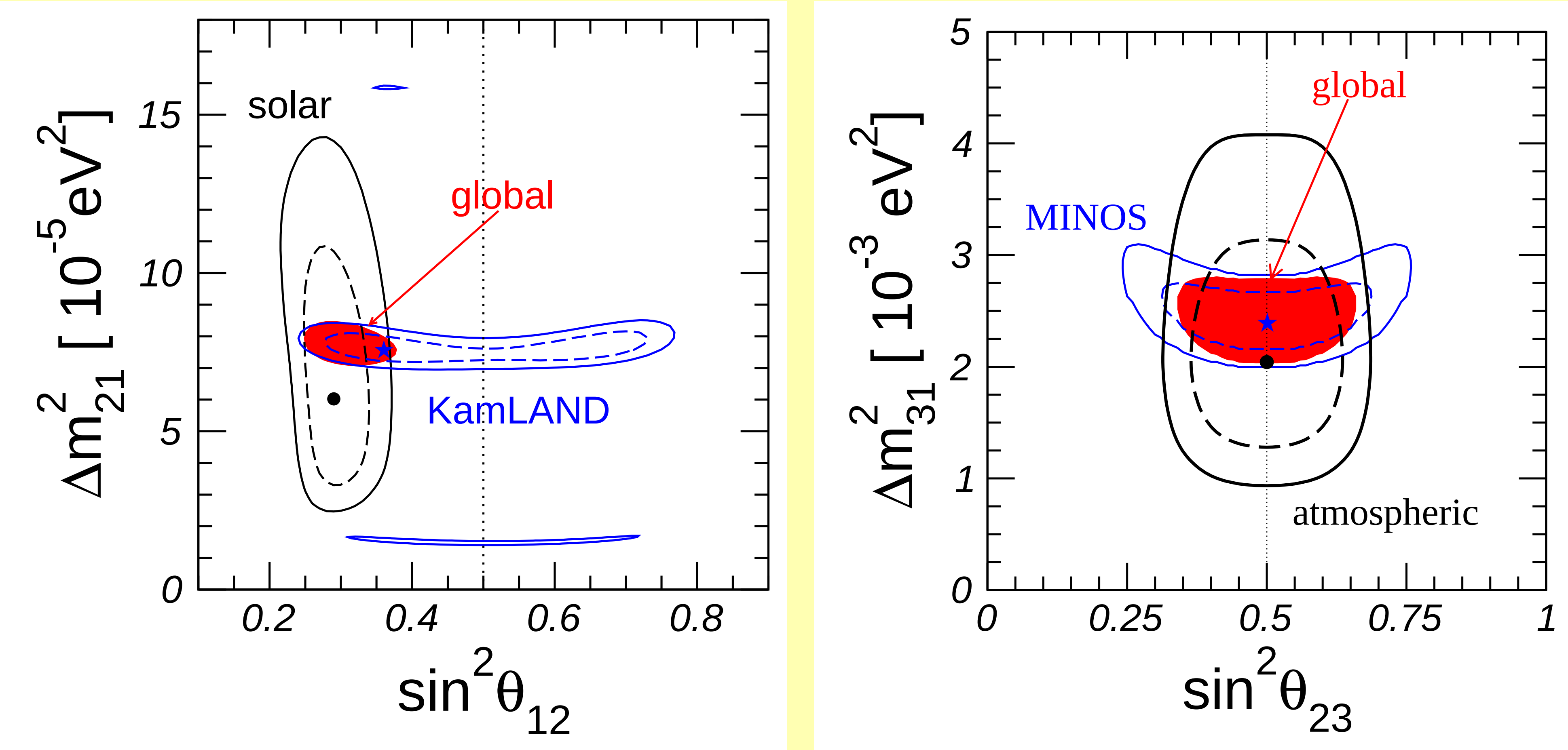
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & e^{-i\delta} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta} s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

3-flavour effects are suppressed because
$\theta_{13} \ll 1$ und $\Delta m^2_{21} \ll \Delta m^2_{31}$

$\Rightarrow$ dominant oscillations are well described by effective two-flavour oscillations

Dominat oscillations

90% and 99.73% CL contours



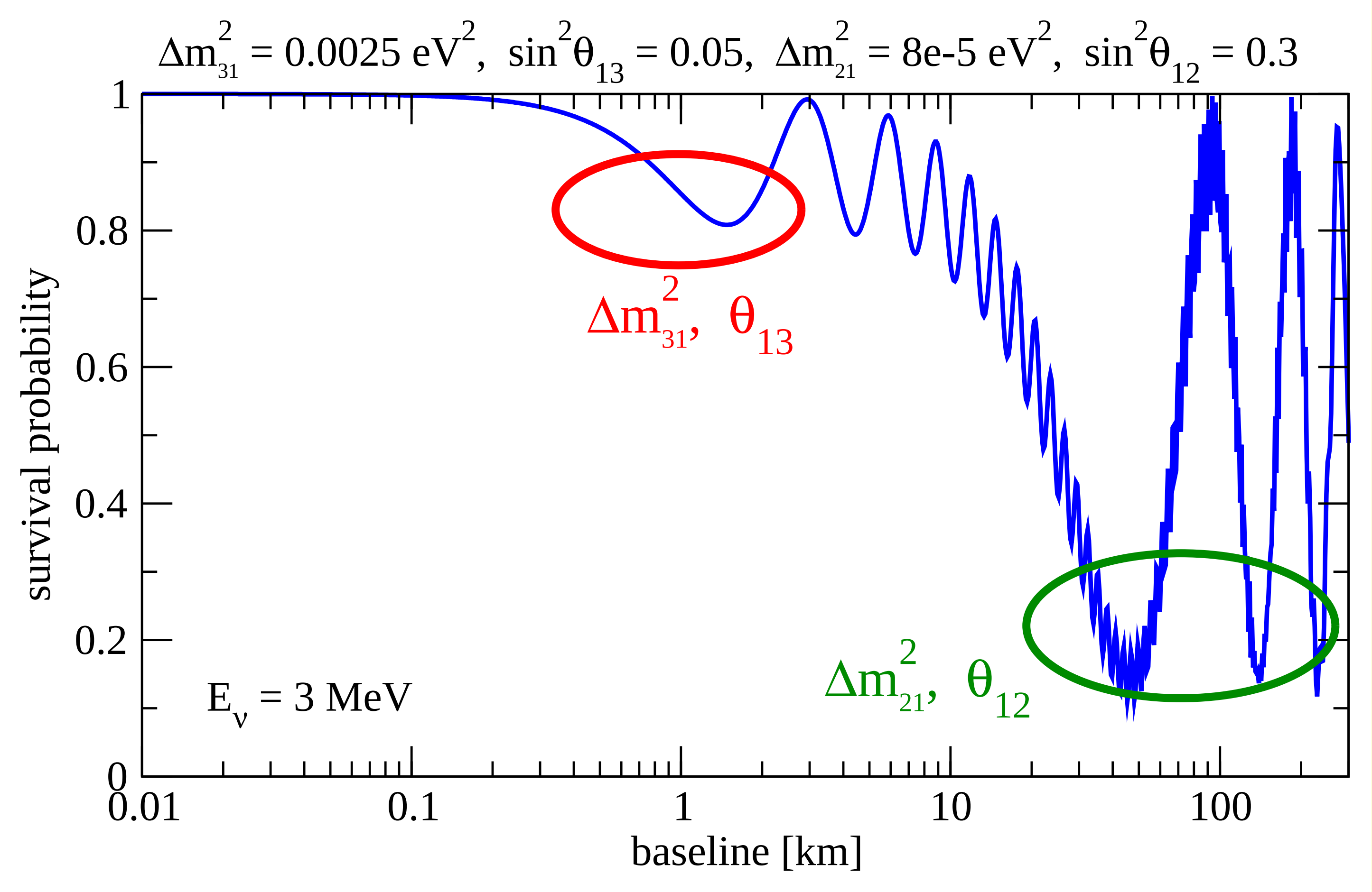
θ_{13} and 3-flavour effects

Three flavour effects

- θ_{13} effects in oscillations with Δm^2_{31}
- θ_{13} effects in oscillations with Δm^2_{21}
- Δm^2_{21} effects in oscillations with Δm^2_{31}
- effects of $\delta_{\rm CP}$

P_{ee} at reactors

The 3-flavour $\bar{\nu}_e \to \bar{\nu}_e$ survival probability:



The Chooz reactor experiment

reactor experiment with a baseline of 1 km:

$$\frac{E_\nu}{L} \sim \frac{4\,\mathrm{MeV}}{1\,\mathrm{km}} \sim 4 \times 10^{-3}\,\mathrm{eV}^2$$

$\bar{\nu}_e$ disappearance at the “atmospheric” Δm^2 scale

$$P_{ee} = 1 - \sin^2 2\theta_{13} \underbrace{\sin^2 \frac{\Delta m^2_{31} L}{2E_\nu}}_{\mathcal{O}(1)\mathrm{@CHOOZ}} + \mathcal{O}(\Delta m^2_{21}/\Delta m^2_{31})$$

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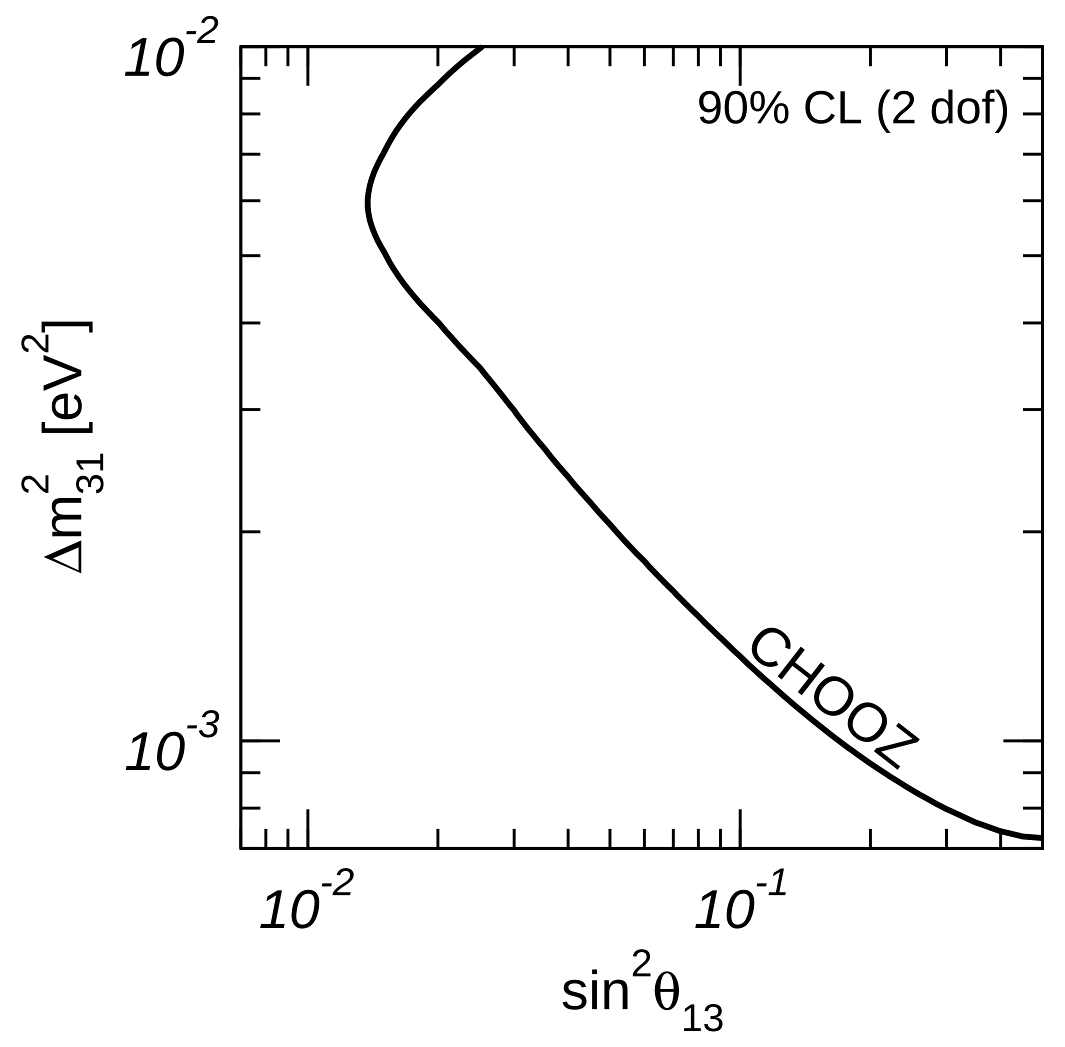
CHOOZ Result: observed over expected number of events:

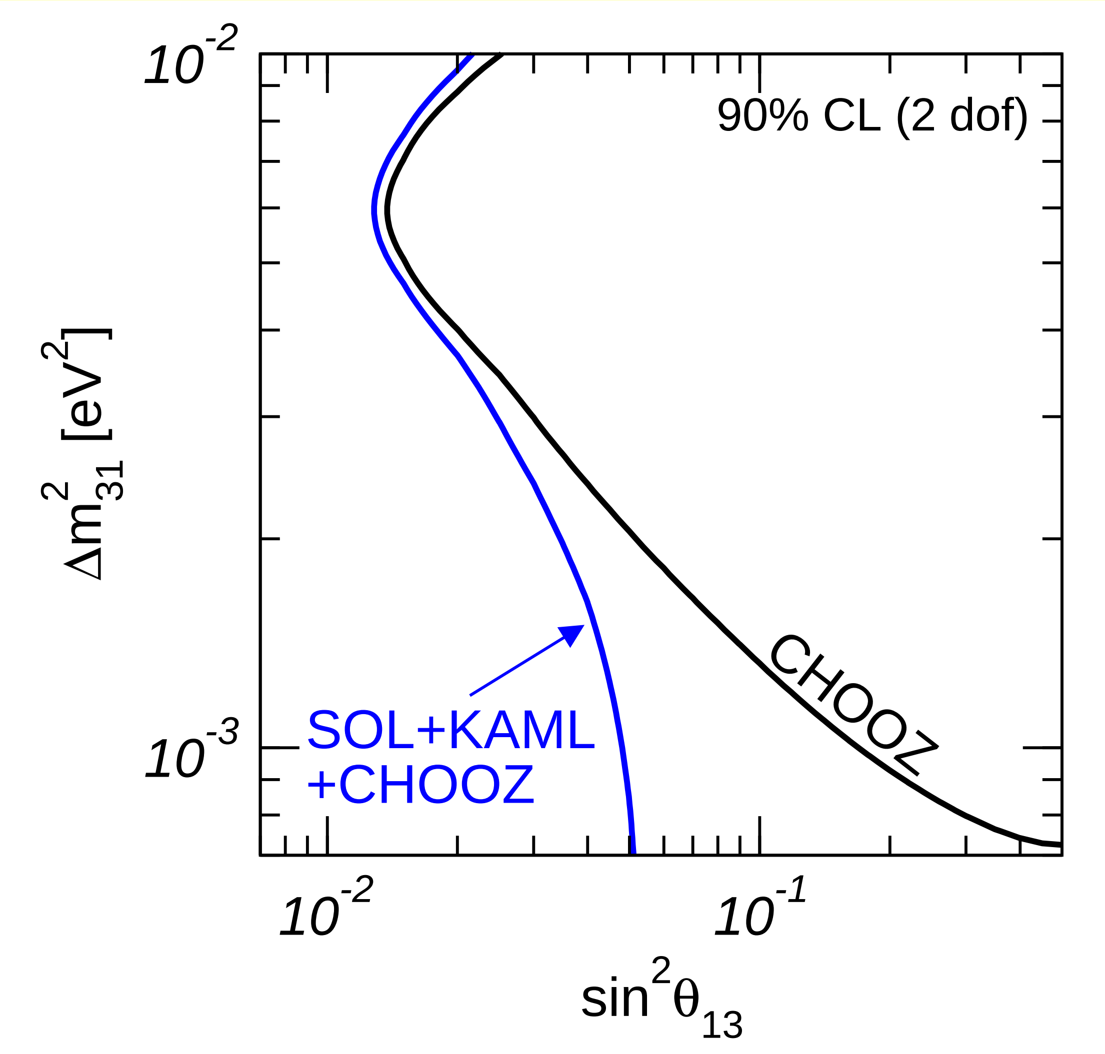
$$R = 1.01 \pm 2.8\% \pm 2.7\%$$

The bound on θ_{13}



The bound on θ_{13}

… from interplay of global data:



The bound on θ_{13}

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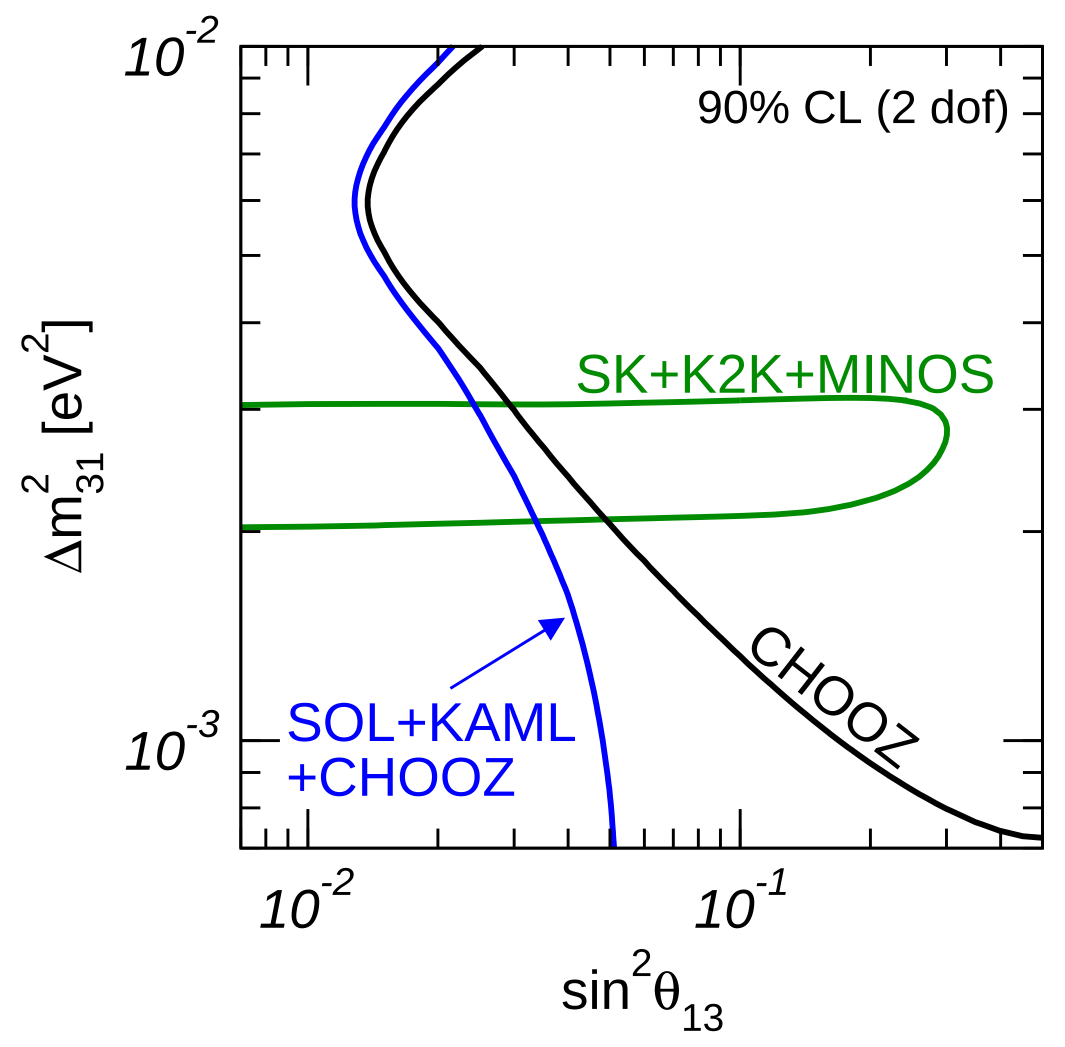

The bound on θ_{13}

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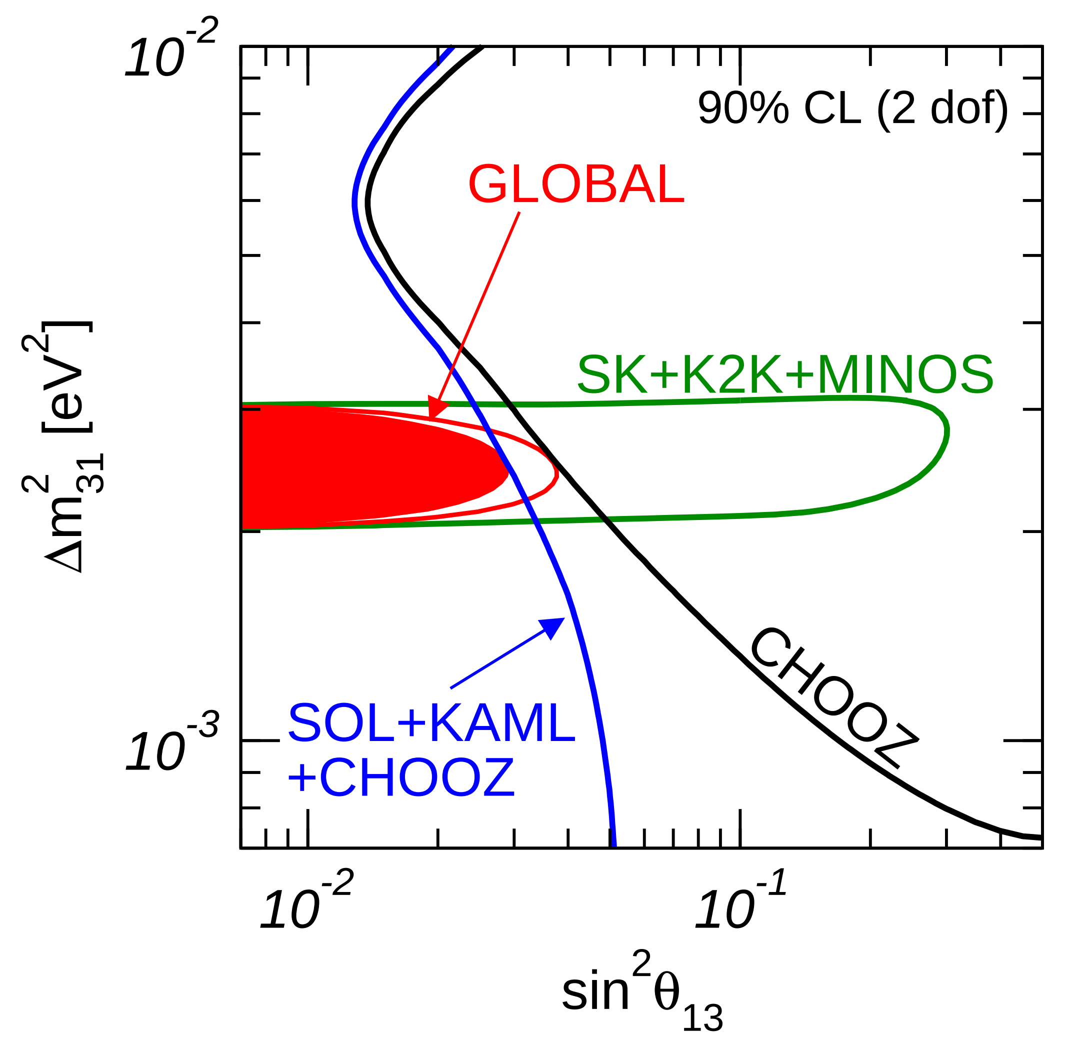

θ_{13} *in Solar and KamLAND*

$$\begin{aligned} H^{\nu}_{\rm mat} &= U_{23}U_{13}U_{12}\textsf{diag}\left(0,\Delta_{21},\Delta_{31}\right)U_{12}^{\dagger}U_{13}^{\dagger}U_{23}^{\dagger}+\textsf{diag}(V,0,0) \\ &= U_{23}U_{13}\left[U_{12}\left(0,\Delta_{21},\Delta_{31}\right)U_{12}^{\dagger}+U_{13}^{\dagger}(V,0,0)U_{13}\right]U_{13}^{\dagger}U_{23}^{\dagger} \end{aligned}$$

θ_{13} in Solar and KamLAND

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for solar and KamLAND:

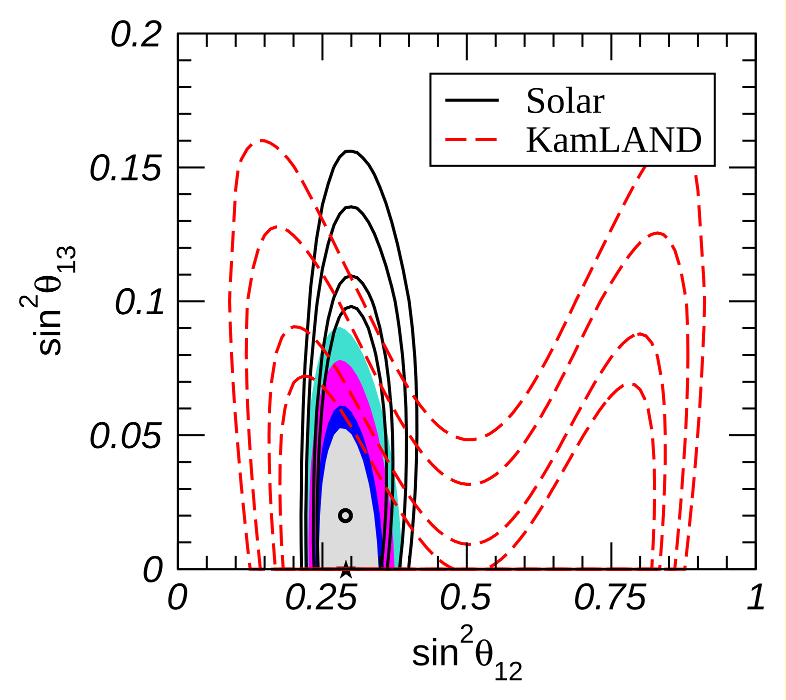
$$\frac{|\Delta m_{31}^2|L}{2E} \gg \frac{\Delta m_{21}^2 L}{2E} \sim 1\,, \qquad |\Delta m_{31}^2| \gg EV_{\mathrm{sun}} \sim \Delta m_{21}^2$$

$\Rightarrow$ can set $\Delta m_{31}^2 \to \infty$

$$P_{ee}^{\mathrm{sun,KL}} = c_{13}^4 P_{ee}^{2\nu}(\theta_{12}, \Delta_{12}) + s_{13}^4 \quad \text{with} \quad V \to c_{13}^2 V$$

θ_{13} *in Solar and KamLAND*

complementarity between solar and KamLAND data



Maltoni et al., hep-ph/0405172

see also Goswami and Smirnov, hep-ph/0411359

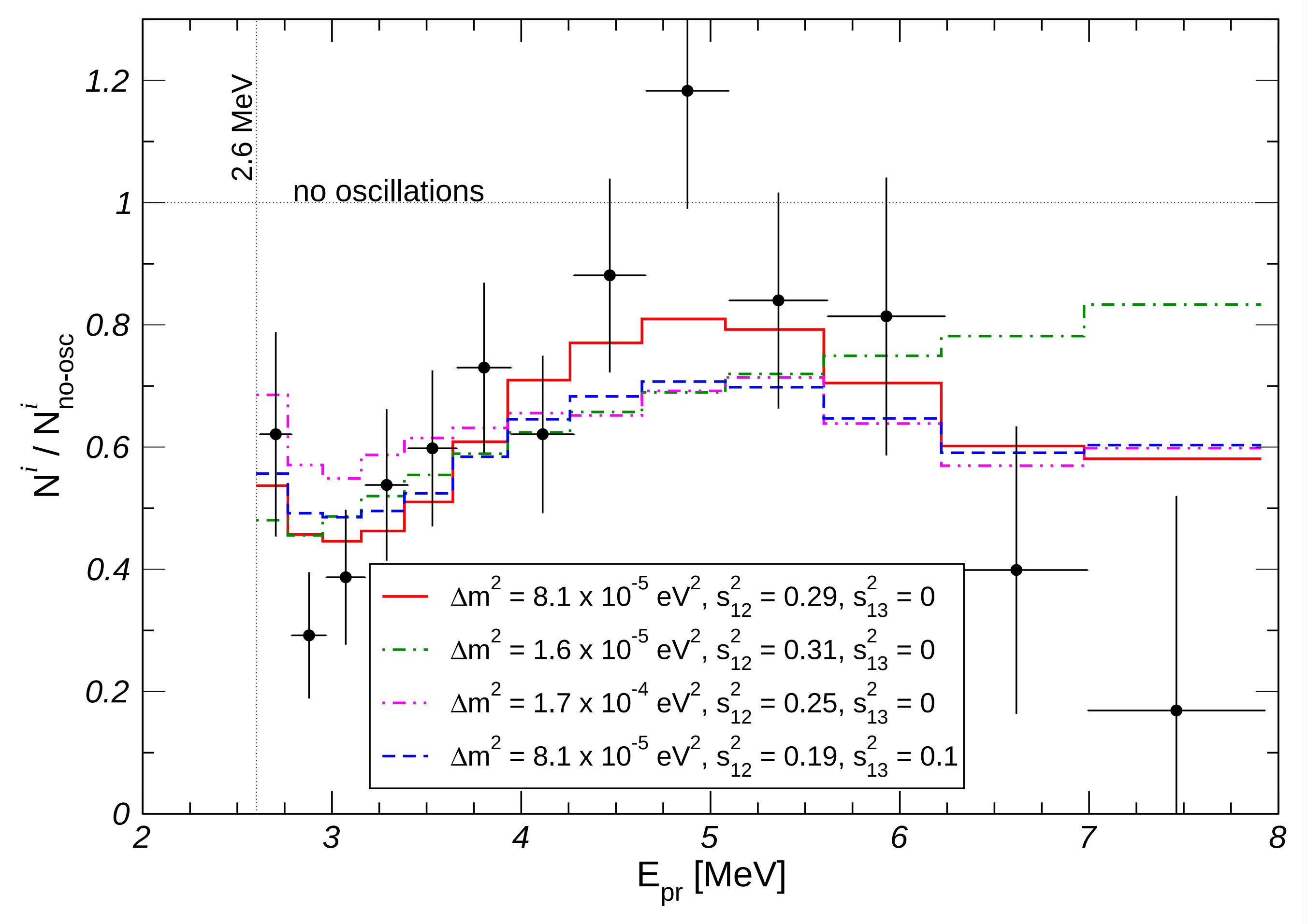
KamLAND spectrum $\Rightarrow$

$$P_{\text{KL}} \approx (1 - 2\sin^2\theta_{13}) \left(1 - \sin^2 2\theta_{12} \, \sin^2 \frac{\Delta m^2_{21} L}{4E_\nu}\right)$$

$$P_{\text{Sol}} \approx (1 - 2\sin^2\theta_{13}) \begin{cases} \sin^2\theta_{12} & \text{high } E_\nu \\ (1 - 0.5\sin^2 2\theta_{12}) & \text{low } E_\nu \end{cases}$$

The KamLAND energy spectrum

θ_{13} leads to a flatter energy spectrum



3-flavour effects in Δm^2_{31} oscillations

$$H^\nu_{\rm mat} = U_{23}U_{13}U_{12}\text{diag}\,(0, \Delta_{21}, \Delta_{31})\, U^\dagger_{12}U^\dagger_{13}U^\dagger_{23} + \text{diag}(V, 0, 0)$$

for $\Delta m^2_{12} = 0$ and $\theta_{13} = 0$ one gets $\nu_\mu \to \nu_\tau$ vacuum oscillations:

$$H^\nu_{\rm mat} = \begin{pmatrix} V & 0 \\ 0 & H^{2\nu} \end{pmatrix}, \quad \text{with} \quad H^{2\nu} = O_{23} \begin{pmatrix} 0 & 0 \\ 0 & \Delta m^2_{31} \end{pmatrix} O^T_{23}$$

$$\Rightarrow \qquad P_{ee} = 1,\ P_{\mu\mu} = P^{2\nu}$$

θ_{13} *in MINOS*

let's keep $\Delta m^2_{21} \approx 0$ but allow for $\theta_{13} \neq 0$:

$$P_{\mu\mu} = \sin^2 2\theta_{\text{eff}} \sin^2 \frac{\Delta m^2_{31} L}{4E} \,, \qquad \sin^2\theta_{\text{eff}} = \sin^2\theta_{23}\cos^2\theta_{13}$$

neglect matter effect

θ_{13} in MINOS

let's keep $\Delta m^2_{21} \approx 0$ but allow for $\theta_{13} \neq 0$:

$$P_{\mu\mu} = \sin^2 2\theta_{\rm eff} \sin^2 \frac{\Delta m^2_{31} L}{4E} \,, \qquad \sin^2\theta_{\rm eff} = \sin^2\theta_{23}\cos^2\theta_{13}$$

neglect matter effect

ν_e appearance:

$$P_{\mu e} = \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{31} L}{4E} + \mathcal{O}(\Delta m^2_{21}\theta_{13}, \Delta m^2_{21})$$

MINOS analysis in progress (e^- detection is difficult)

expect minor improvement on CHOOZ

$\Rightarrow$ main goal of future LBL experiments (T2K, NOvA)

Sub-leading effects in atmospheric neutrinos

$$\begin{aligned}\phi_e^{\rm obs} &= \phi_e^0 P_{ee} + \phi_\mu^0 P_{\mu e}\\ \phi_\mu^{\rm obs} &= \phi_\mu^0 P_{\mu\mu} + \phi_e^0 P_{e\mu}\end{aligned}$$

e-like events are a good place to look for 3-flavour effects

Sub-leading effects in atmospheric neutrinos

excess of electron-like events:

$$\begin{aligned} \frac{N_e}{N_e^0} - 1 \simeq & \; (r\, s_{23}^2 - 1)\, P_{2\nu}(\Delta m_{31}^2, \theta_{13}) && \theta_{13}\text{-effects} \\ + & \; (r\, c_{23}^2 - 1)\, P_{2\nu}(\Delta m_{21}^2, \theta_{12}) && \Delta m_{21}^2\text{-effects} \\ - & \; 2 s_{13} s_{23} c_{23}\, r\, \mathrm{Re}(A_{ee}^* A_{\mu e}) && \text{interference: } \delta_{\mathrm{CP}} \end{aligned}$$

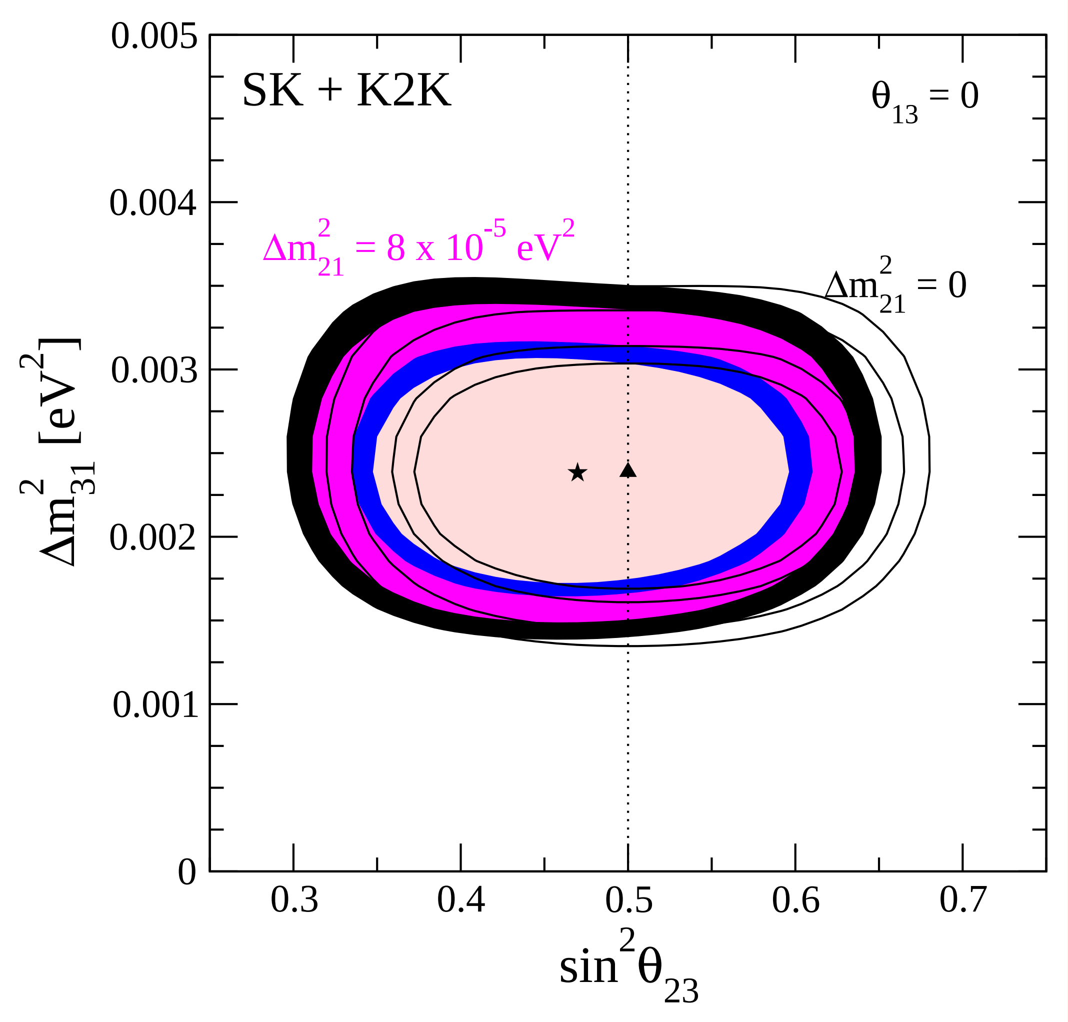
$$r = r(E_\nu) \equiv \frac{\phi_\mu^0(E_\nu)}{\phi_e^0(E_\nu)}$$

$r \approx 2$ (sub-GeV)

$r \approx 2.6 - 4.5$ (multi-GeV)

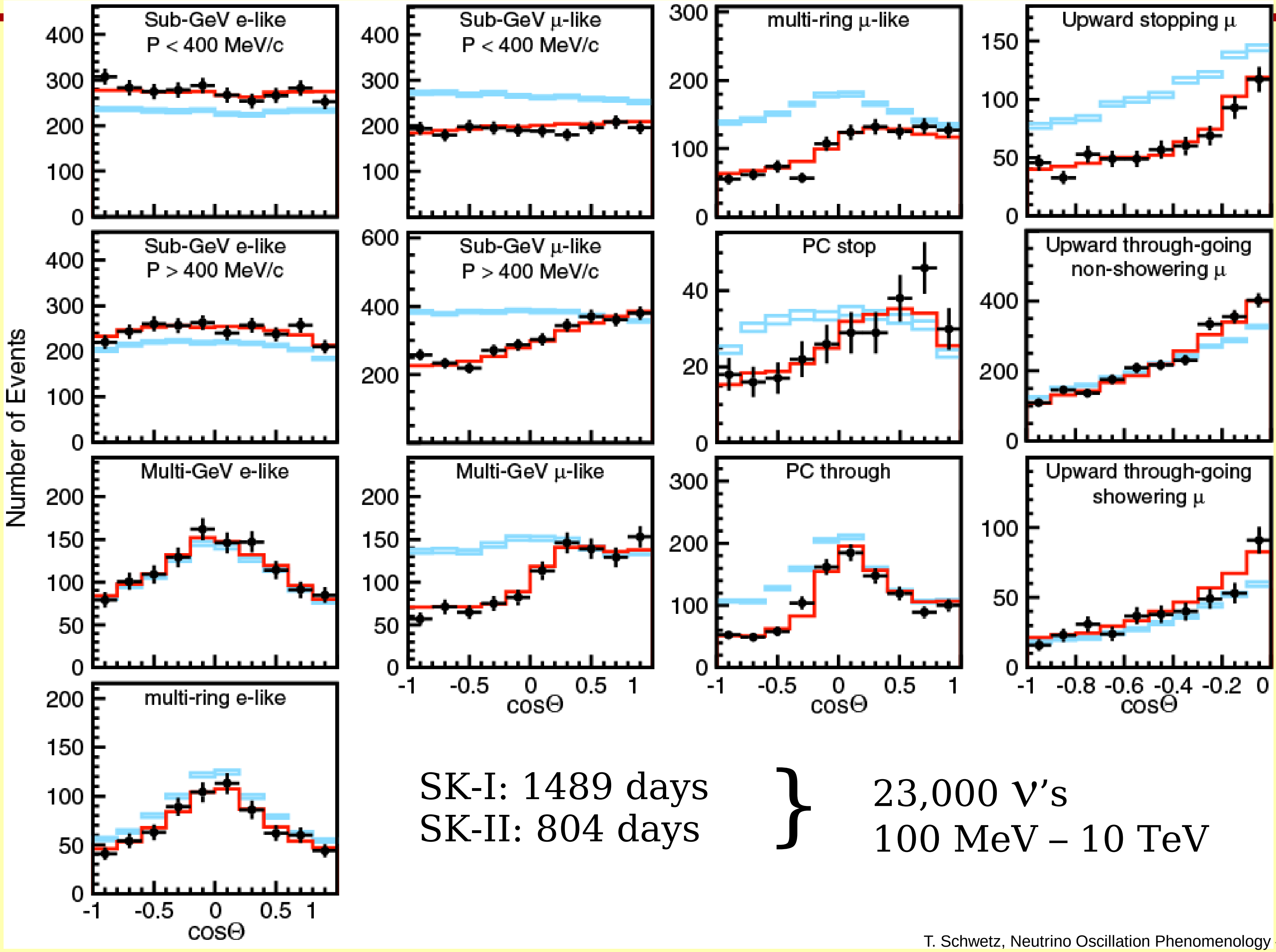
Fogli, Lisi, Marrone, Palazzo, hep-ph/0506083

Taking into account Δm^2_{21}



Gonzalez-Garcia, Maltoni, Smirnov, hep-ph/0408170

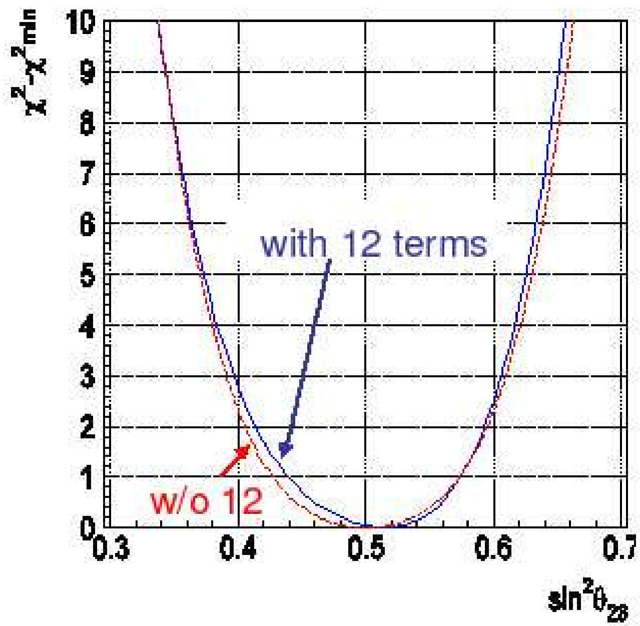
Super-K atmospheric neutrino data

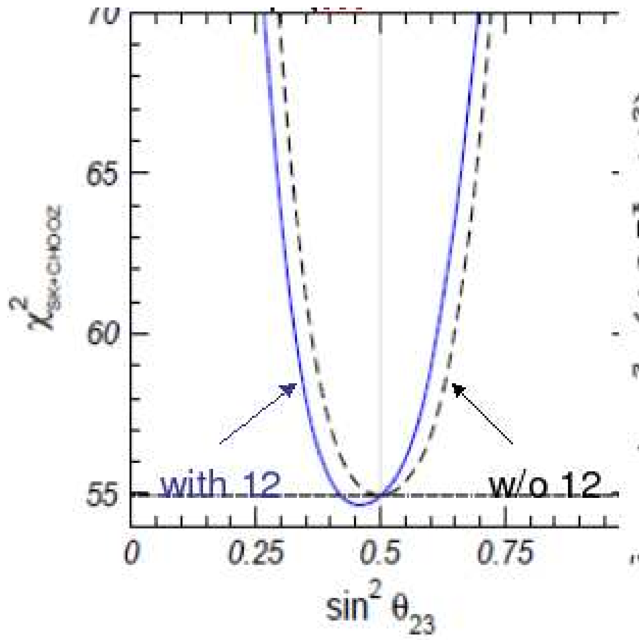


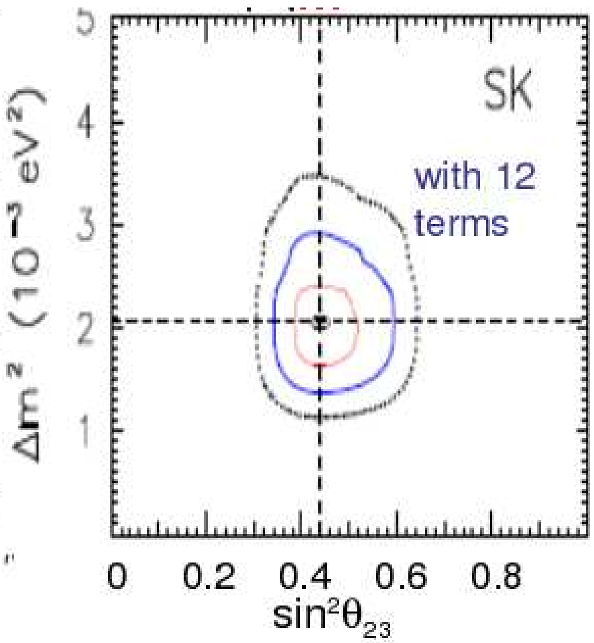
SK-I: 1489 days
SK-II: 804 days } 23,000 ν's
100 MeV – 10 TeV

Is there an indication for a non-max θ_{23}?

Super-K Coll. T. Kajita, NuFact05	Gonzalez-Garcia, Maltoni, Smirnov hep-ph/0408170	Fogli et al., hep-ph/0506083

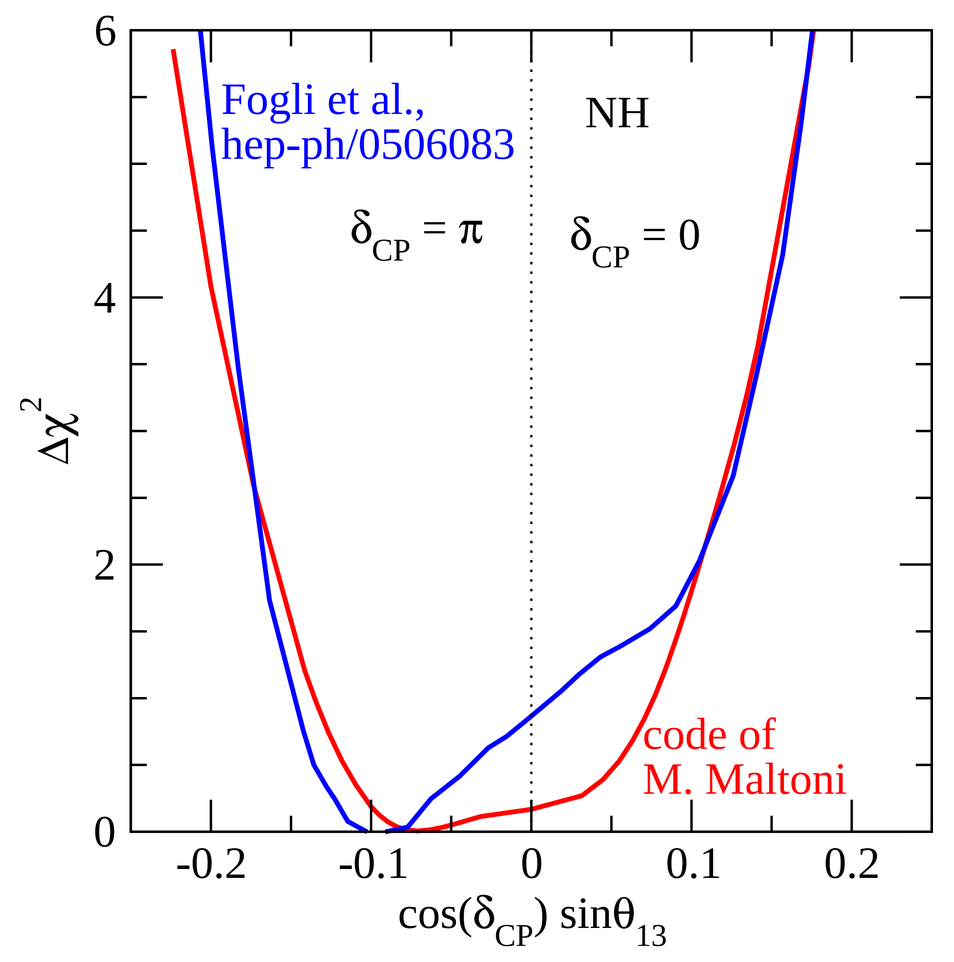






best fit: $\sin^2\theta_{23} = 0.51$	$\sin^2\theta_{23} = 0.46$	$\sin^2\theta_{23} = 0.44$
max θ_{23}: $\Delta\chi^2 \approx 0.1$	$\Delta\chi^2 \approx 0.3$	$\Delta\chi^2 \approx 0.8$

Is there an indication for $\theta_{13} \neq 0$?



Bari: best fit: $\sin^2\theta_{13} \approx 0.01$, $\Delta\chi^2 \approx 0.85$ for $\theta_{13} = 0$

Maltoni: best fit: $\sin^2\theta_{13} \approx 0.005$, $\Delta\chi^2 \approx 0.16$ for $\theta_{13} = 0$

Effects of $\delta_{\rm CP}$

To observe an effect of $\delta_{\rm CP}$ one needs

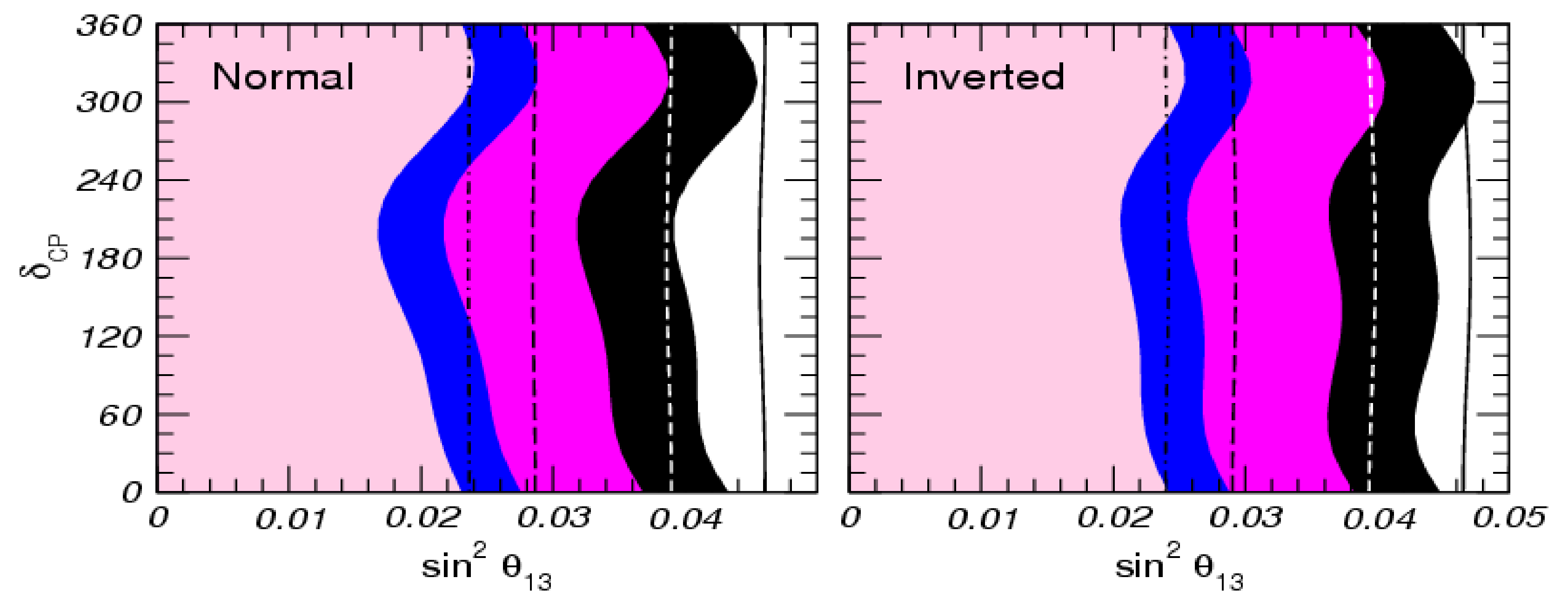
- $\theta_{13} \neq 0$, and
- sensitivity to Δm^2_{21}

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

$$H^\nu_{\rm mat} = U_{23} U_{13} U_{12} \text{diag}\,(0, \Delta_{21}, \Delta_{31})\, U^\dagger_{12} U^\dagger_{13} U^\dagger_{23} + \text{diag}(V, 0, 0)$$

δ_{CP} *effects in present data*

bound on θ_{13} depends on δ_{CP} and on hierarchy:
(atmospheric data)



Gonzalez-Garcia, Maltoni, 0704.1800

Summary 3-flavour oscillation parameters

Three flavour osc. parameters summary

mass-squared differences:

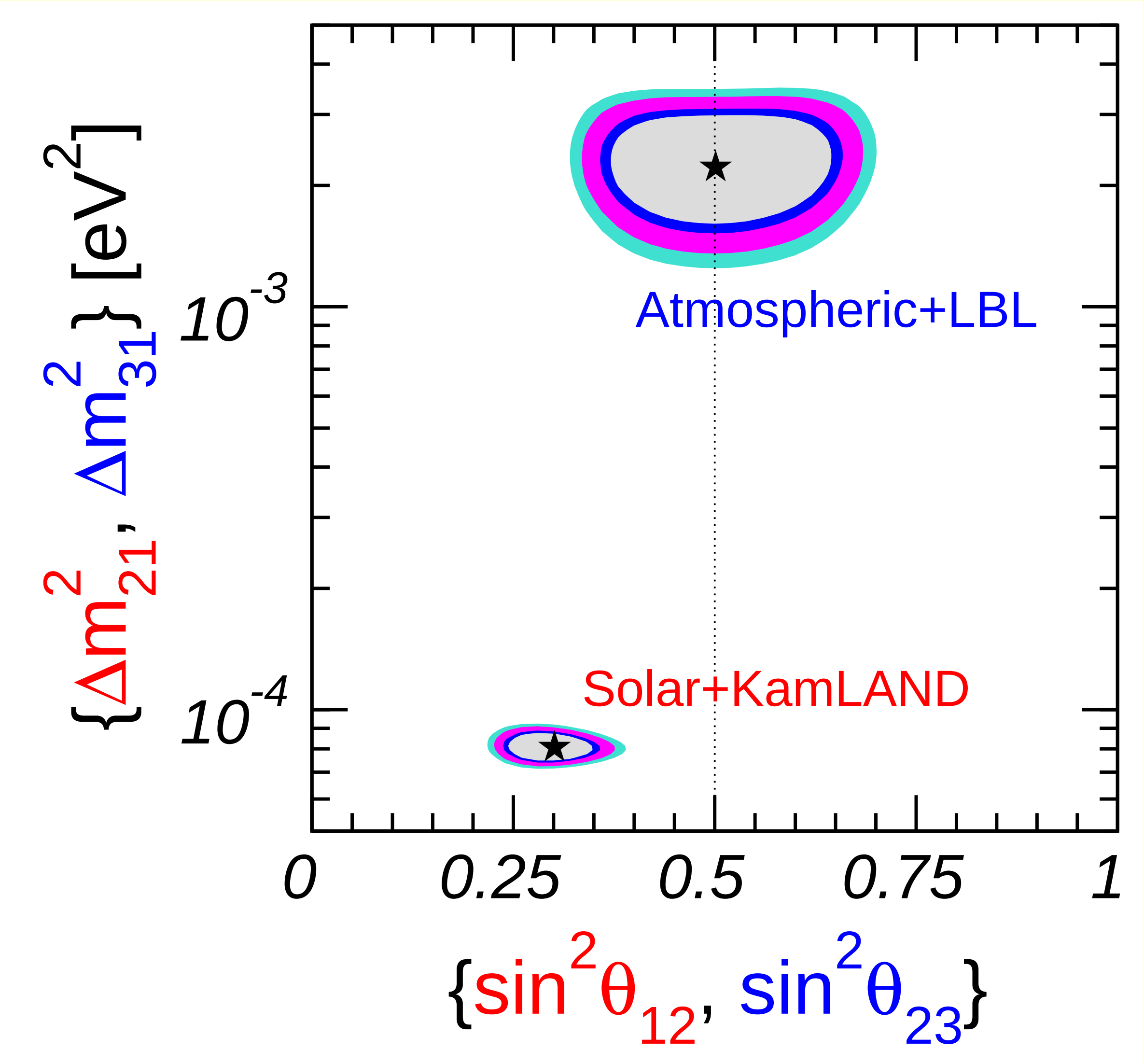
parameter	bf$\pm 1\sigma$	1σ acc.	3σ range
Δm^2_{21} $[10^{-5}\text{eV}^2]$	7.59 ± 0.21	2.8%	$7.05 - 8.35$
$\|\Delta m^2_{31}\|$ $[10^{-3}\text{eV}^2]$	$2.40^{+0.12}_{-0.10}$	4.6%	$2.07 - 2.76$

mixing angles:

parameter	bf$\pm 1\sigma$	1σ acc.	3σ range
$\sin^2\theta_{12}$	$0.31^{+0.016}_{-0.023}$	6.3%	$0.25 - 0.37$
$\sin^2\theta_{23}$	$0.50^{+0.07}_{-0.06}$	13%	$0.36 - 0.67$
$\sin^2\theta_{13}$	$0.01^{+0.016}_{-0.01}$	–	≤ 0.056

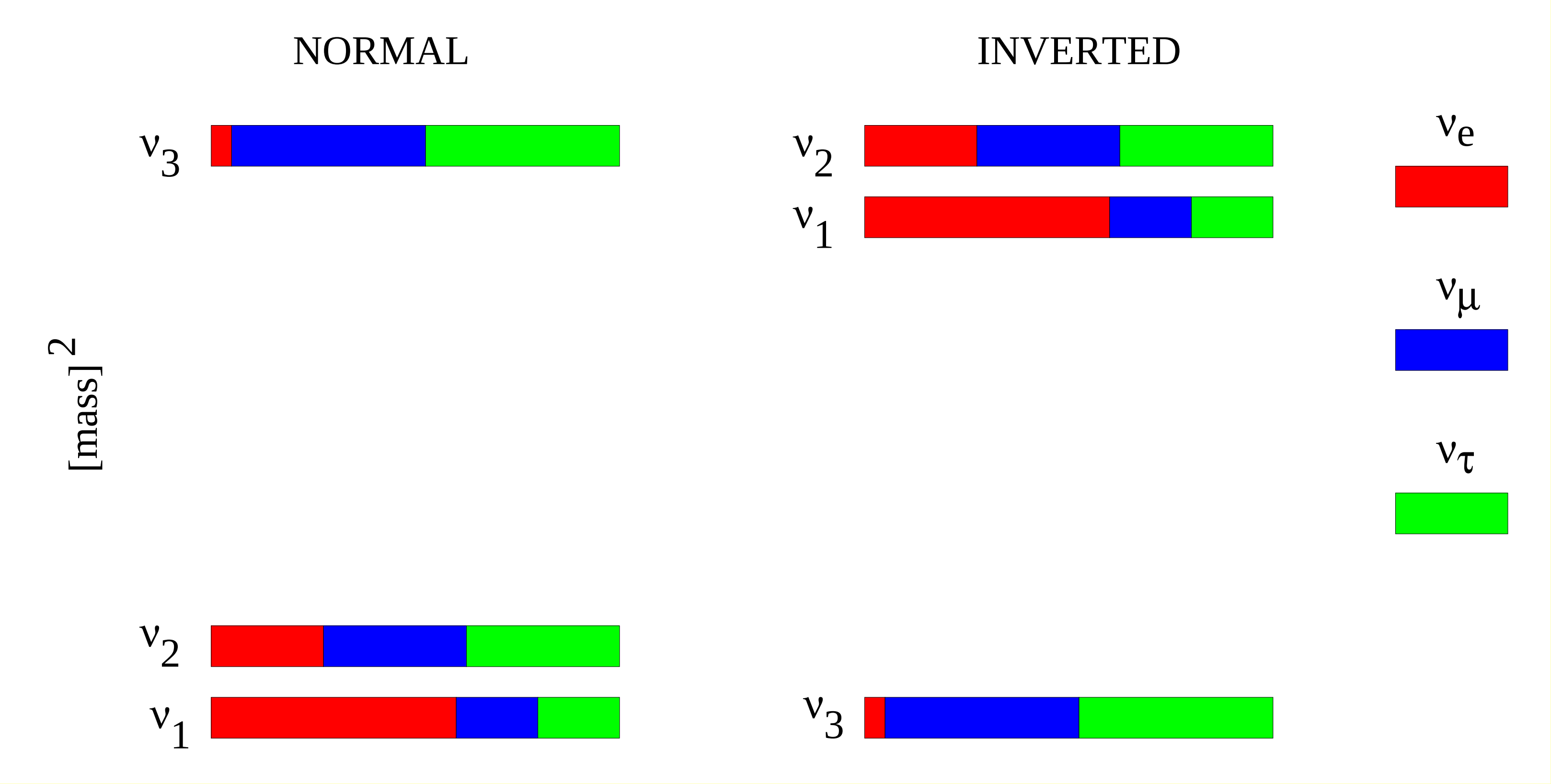
Schwetz, Tortola, Valle, in preparation

Three flavour osc. parameters summary



Three flavour osc. parameters summary

two possibilities for the neutrino mass spectrum



$\Delta m^2_{31} > 0$ $\Delta m^2_{31} < 0$

The 1-2 mass ordering

We know that the mass state containing most of ν_e is the lighter of the two "solar mass" states

$$\Delta m^2_{21} \equiv m^2_2 - m^2_1 > 0 \quad \text{and} \quad \theta_{12} < 45^o$$

thanks to the observation of the matter effect in the sun:

resonance condition:

$$\Delta m^2_{21} \cos 2\theta_{12} = 2E_\nu V \quad \Rightarrow \quad \Delta m^2_{21} \cos 2\theta_{12} > 0$$

The 1-3 mass ordering

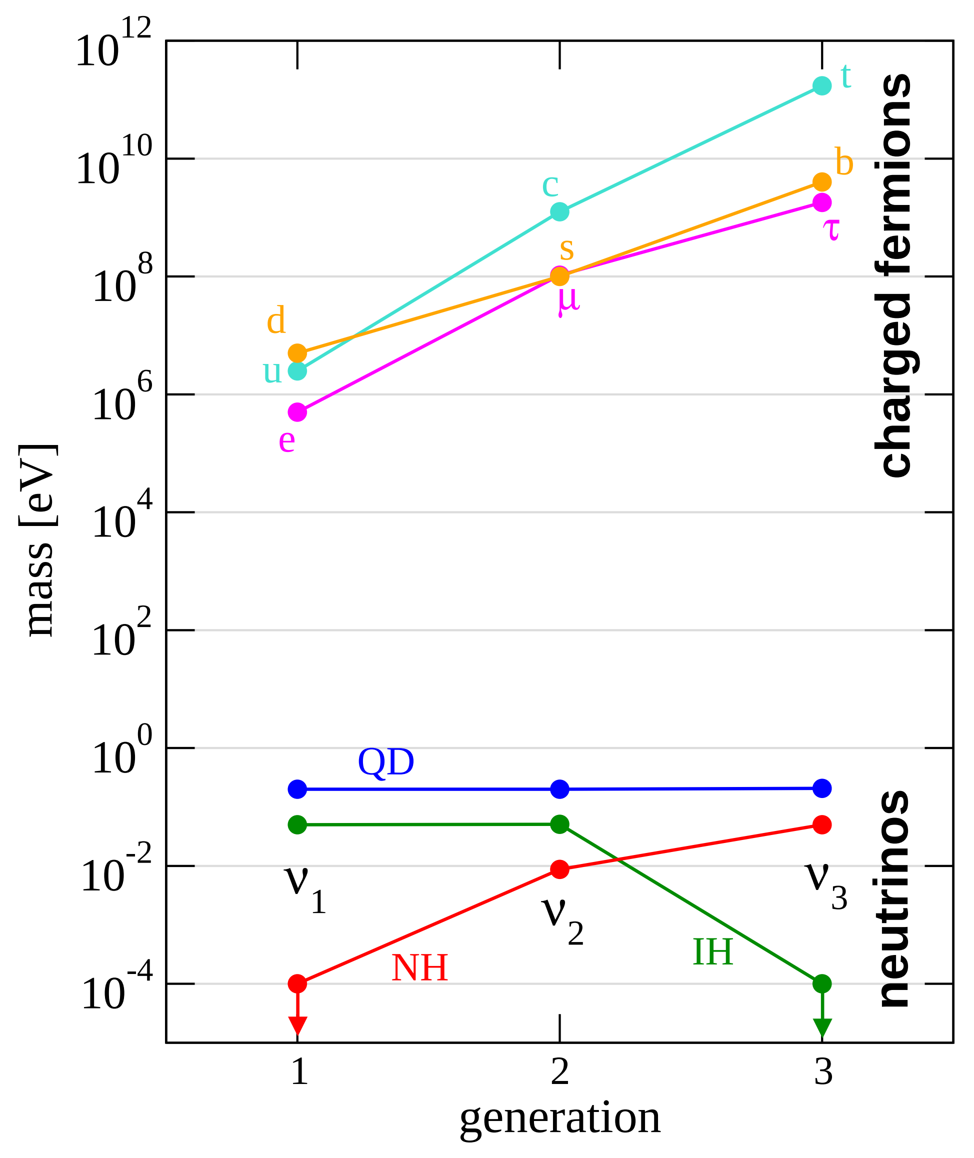
We do not know the sign of Δm^2_{31}!
(normal or inverted mass ordering)

No matter effect has been observed for oscillations with Δm^2_{31}, only “vacuum” $\nu_\mu \to \nu_\mu(\nu_\tau)$ oscillations:

$$P_{\mu\mu} \approx 1 - \sin^2 2\theta_{23} \sin^2 \frac{\Delta m^2_{31} L}{4E}$$

Has to look for matter effect in $\nu_e \leftrightarrow \nu_\mu$ oscillations due to $\Delta m^2_{31}, \theta_{13}$
$\Rightarrow$ future long-baseline experiments

Why are neutrino masses so small?



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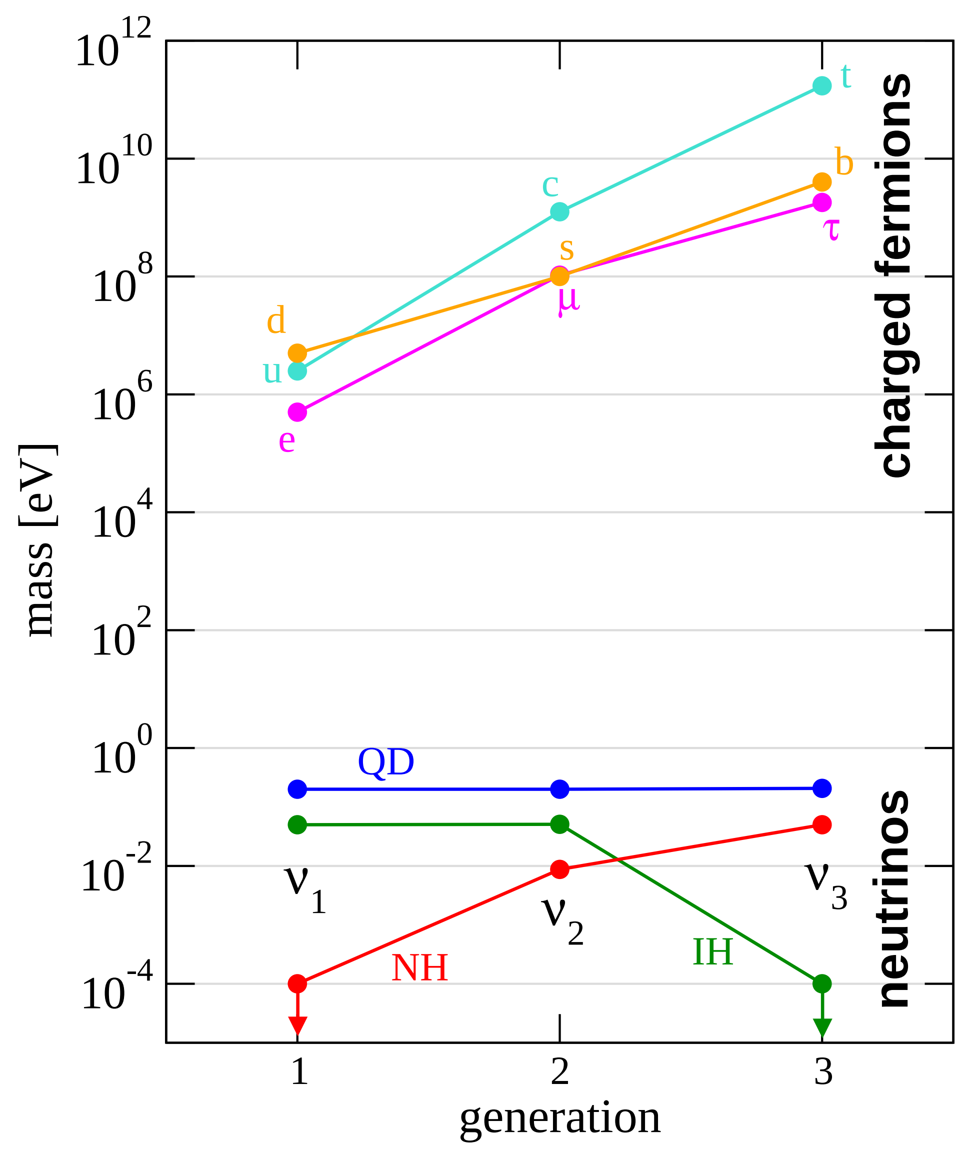
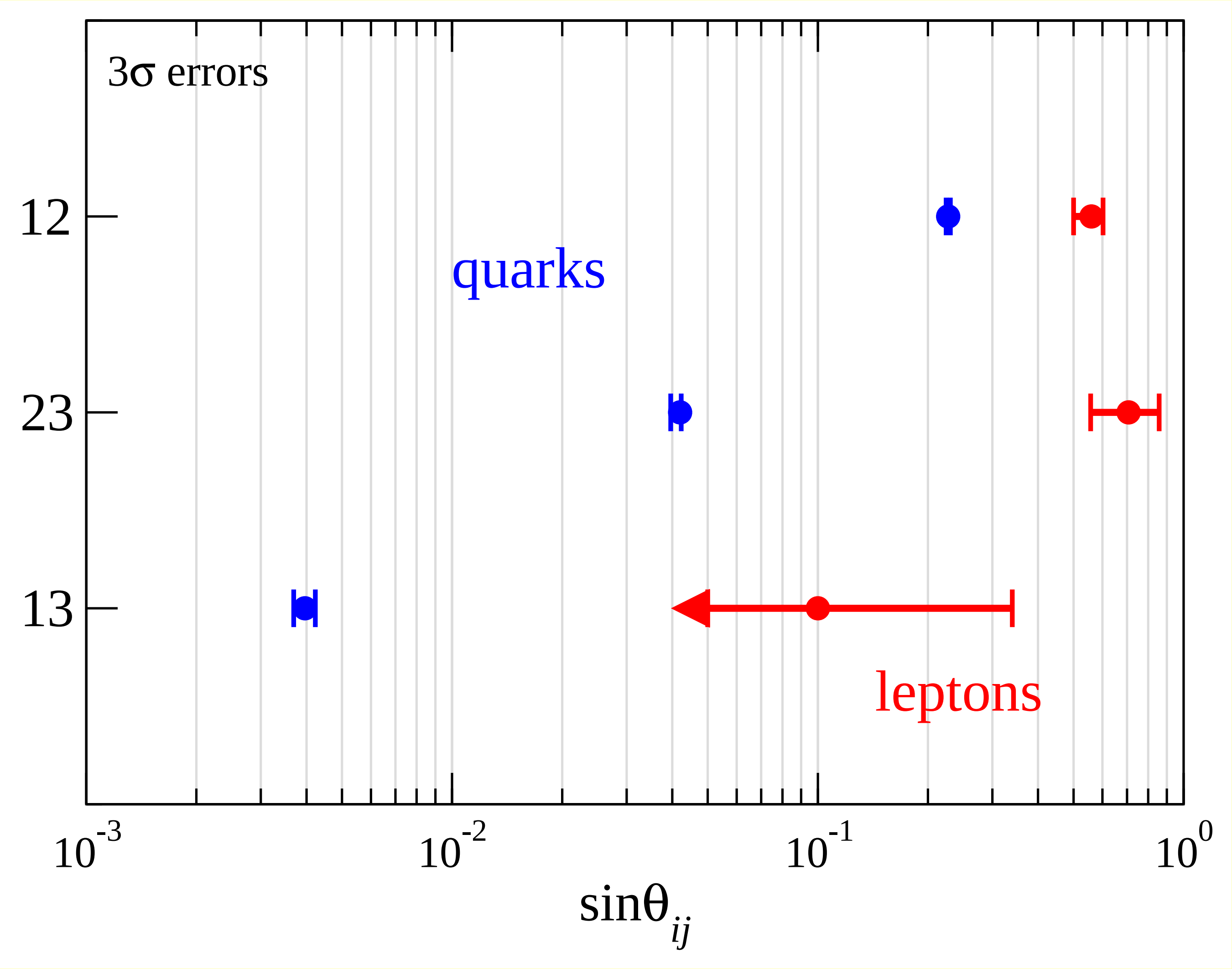


Is the smallness of m_ν related to a high scale Λ (GUT scale?) via the seesaw mechanism?

$$m_\nu \sim \frac{v^2}{\Lambda}$$

$$v \sim 174\mathrm{GeV}$$

Why is lepton mixing large?



Why is lepton mixing large?

Lepton mixing:

$$U_{PMNS} = \frac{1}{\sqrt{3}} \begin{pmatrix} \mathcal{O}(1) & \mathcal{O}(1) & \epsilon \\ \mathcal{O}(1) & \mathcal{O}(1) & \mathcal{O}(1) \\ \mathcal{O}(1) & \mathcal{O}(1) & \mathcal{O}(1) \end{pmatrix}$$

Quark mixing:

$$U_{CKM} = \begin{pmatrix} 1 & \epsilon & {\scriptstyle \epsilon} \\ \epsilon & 1 & {\scriptstyle \epsilon} \\ {\scriptstyle \epsilon} & {\scriptstyle \epsilon} & 1 \end{pmatrix}$$

Is there a special pattern in lepton mixing?

example: Tri-bimaximal mixing

Harrison, Perkins, Scott, PLB 2002, hep-ph/0202074

$$\sin^2\theta_{12} = 1/3\,, \quad \sin^2\theta_{23} = 1/2\,, \quad \sin^2\theta_{13} = 0 \qquad \Rightarrow$$

$$U = \begin{pmatrix} \sqrt{2/3} & 1/\sqrt{3} & 0 \\ -1/\sqrt{6} & 1/\sqrt{3} & 1/\sqrt{2} \\ 1/\sqrt{6} & -1/\sqrt{3} & 1/\sqrt{2} \end{pmatrix}$$

3-flavour oscillations

Open questions:

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- Is this basic picture correct?
  LSND hint?
  non-standard effects beyond oscillations?

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- Increase the precision on solar and atmospheric parameters (e.g. Is θ_{23} exactly 45°?)

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- How small is θ_{13}?

3-flavour oscillations

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- How small is θ_{13}?
- What is the value of the CP phase δ?

3-flavour oscillations

Open questions:

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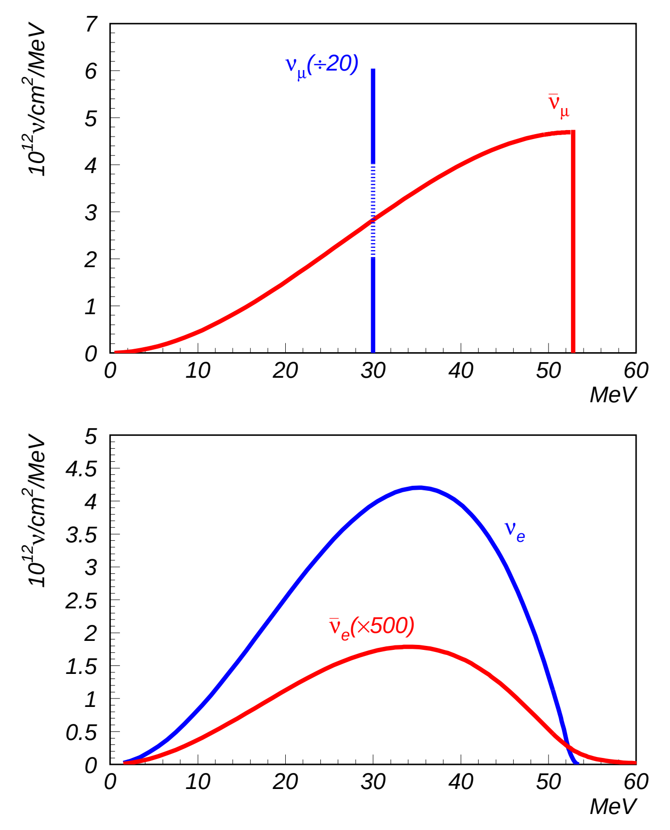
  non-standard effects beyond oscillations?
- Increase the precision on solar and atmospheric parameters (e.g. Is θ_{23} exactly 45°?)
- How small is θ_{13}?
- What is the value of the CP phase δ?
- Type of the neutrino mass ordering (sign of Δm^2_{31})

The LSND puzzle

The LSND signal

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \xrightarrow{\text{oscillations}} \bar{\nu}_e$$

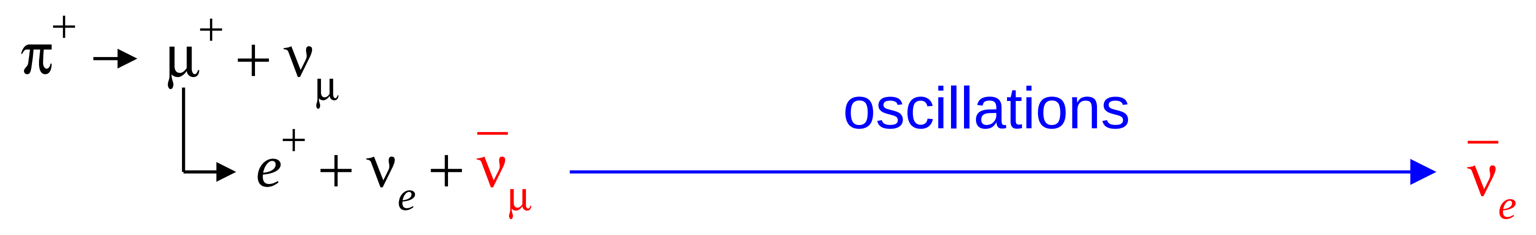


$L \simeq 35$ m

signal:

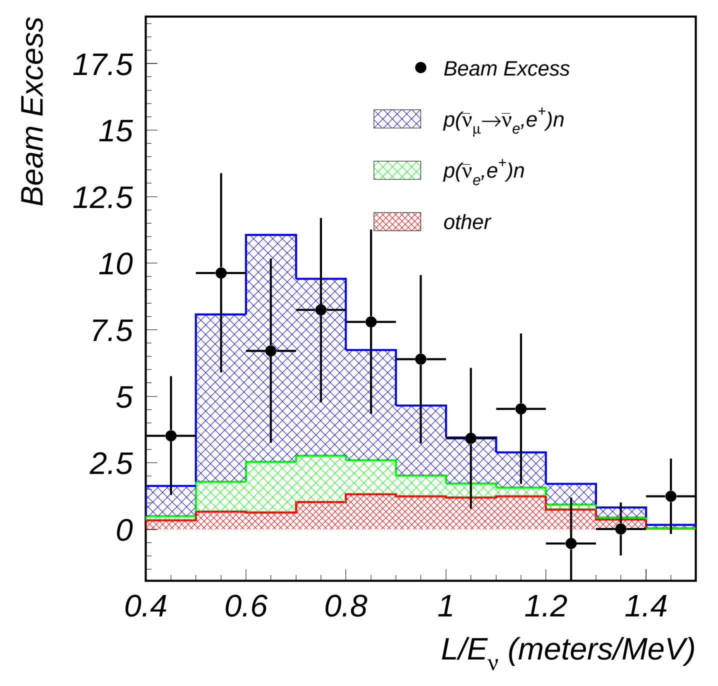
$$\bar{\nu}_e + p \longrightarrow e^+ + n$$

The LSND signal



$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu \xrightarrow{\text{oscillations}} \bar{\nu}_e$$



$L \simeq$ 35 m

evidence for $\bar{\nu}_\mu \longrightarrow \bar{\nu}_e$ oscillations

A. Aguilar *et al.*, PRD 64 (2001) 112007

$87.9 \pm 22.4 \pm 6.0$ excess events

$P = (0.264 \pm 0.067 \pm 0.045)\%$

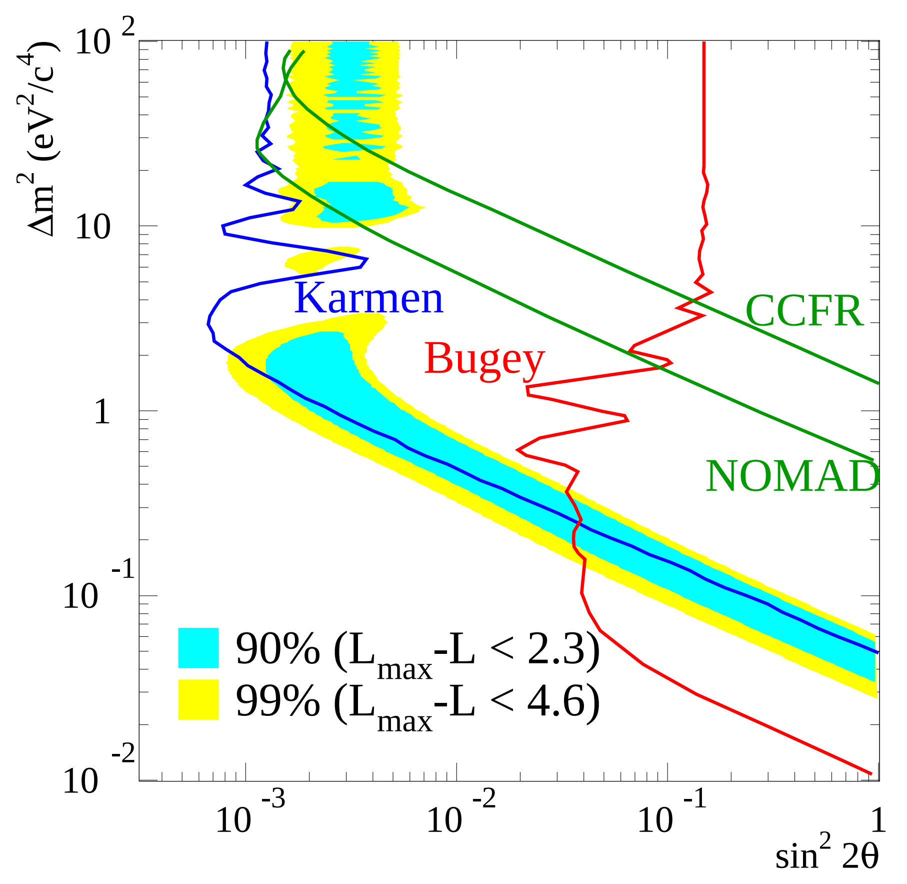
$\sim 3.3\sigma$ away from zero

Oscillation interpretation of LSND

several bounds from other no-evidence SBL experiments, (KARMEN)

combined analysis of LSND and KARMEN:

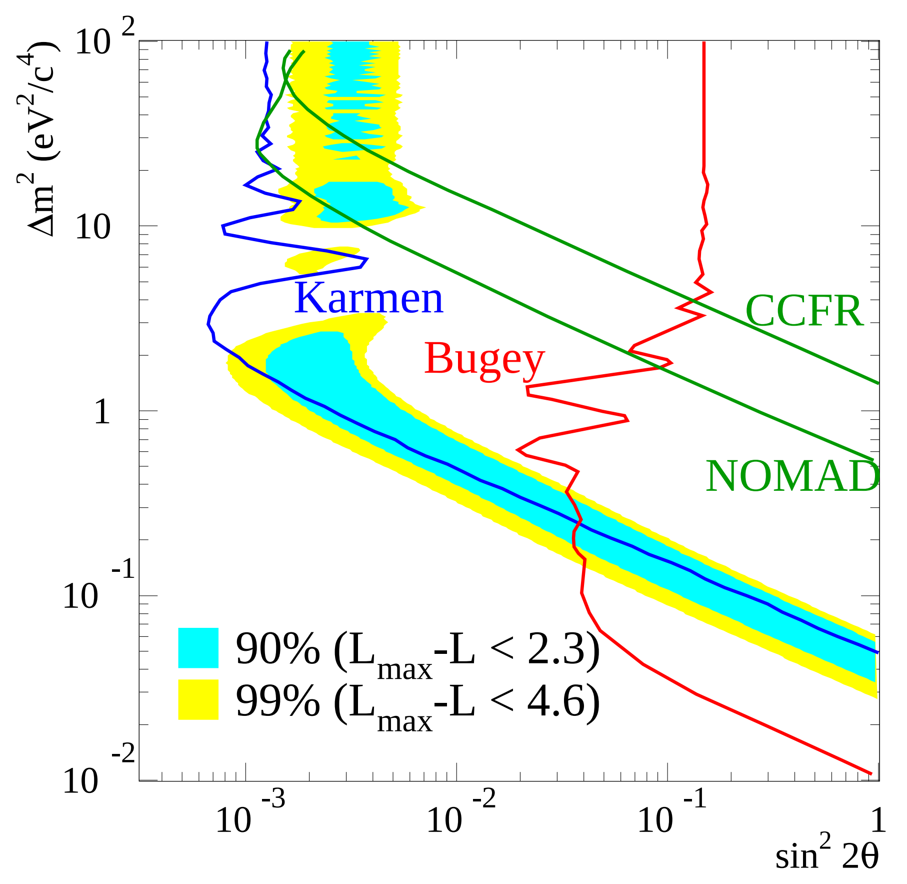
Church, Eitel, Mills, Steidl, PRD (2002)



Oscillation interpretation of LSND

the problem:

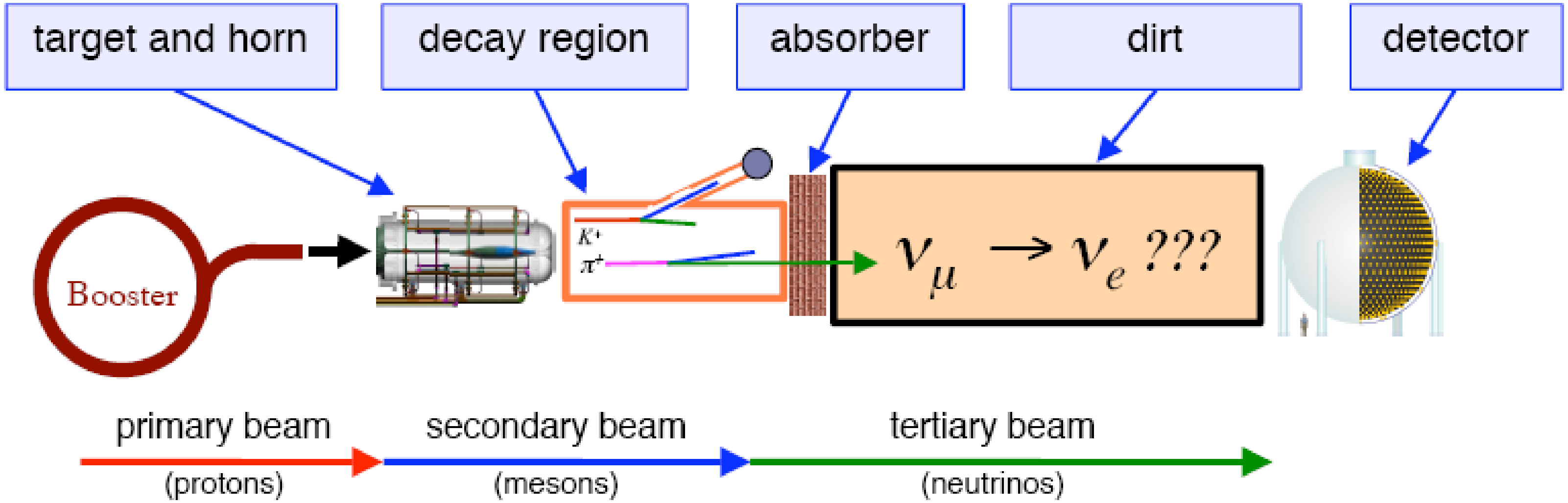
$\Delta m^2 \sim \mathrm{eV}^2$ not consistent with solar (8×10^{-5}) and atmospheric (2×10^{-3}) mass splittings for three neutrinos!



MiniBooNE's Design Strategy...

Keep L/E same
while changing systematics, energy & event signature

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \, \sin^2(1.27 \Delta m^2 L/E)$$


target and horn

decay region

absorber

dirt

detector

primary beam (protons)

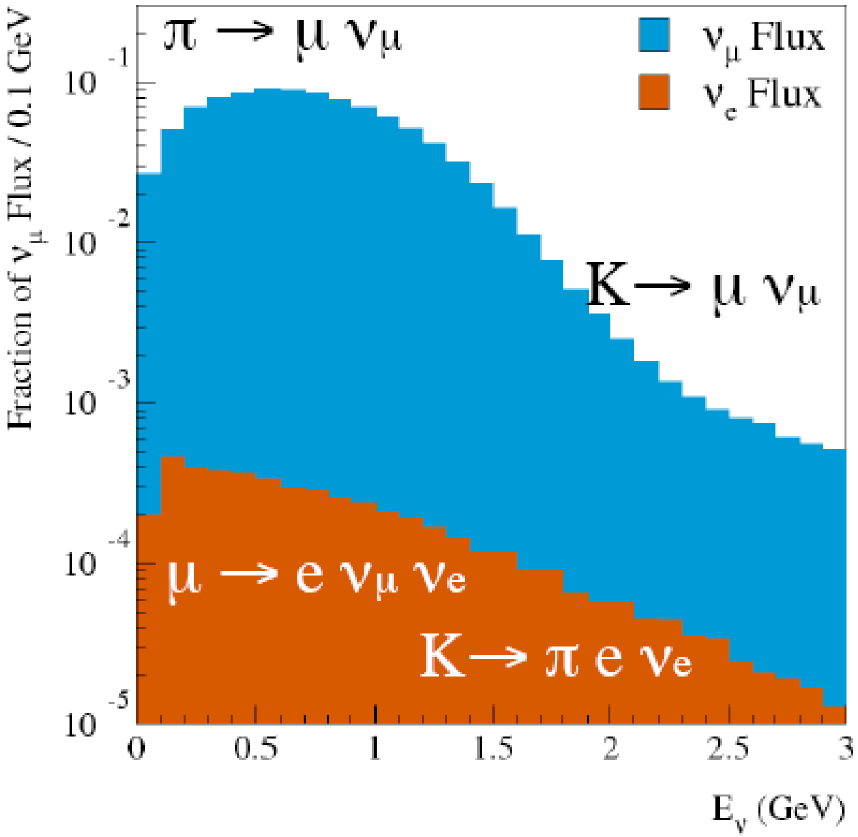
secondary beam (mesons)

tertiary beam (neutrinos)

Order of magnitude
higher energy (~500 MeV)
than LSND (~30 MeV)

Order of magnitude
longer baseline (~500 m)
than LSND (~30 m)

MiniBooNE neutrino flux



$\nu_e/\nu_\mu = 0.5\%$

Antineutrino content: 6%

“Intrinsic” $\nu_e + \bar{\nu}_e$ sources:

$\mu^+ \rightarrow e^+\, \bar{\nu}_\mu\, \nu_e$ (52%)

$K^+ \rightarrow \pi^0\, e^+\, \nu_e$ (29%)

$K^0 \rightarrow \pi\, e\, \nu_e$ (14%)

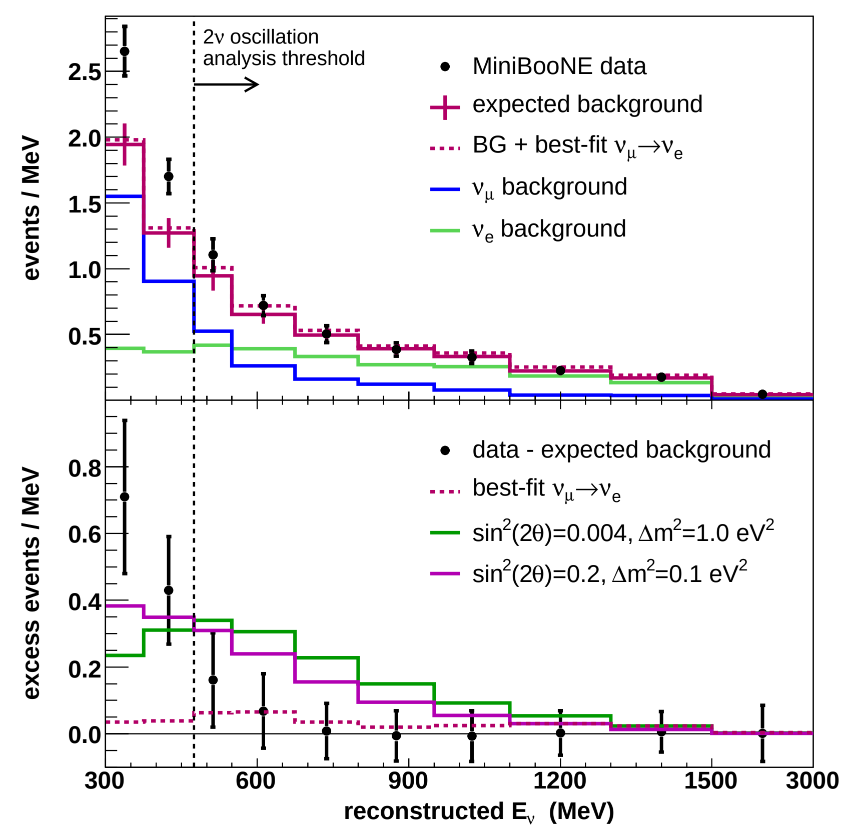
Other (5%)

MiniBooNE results, April 2007

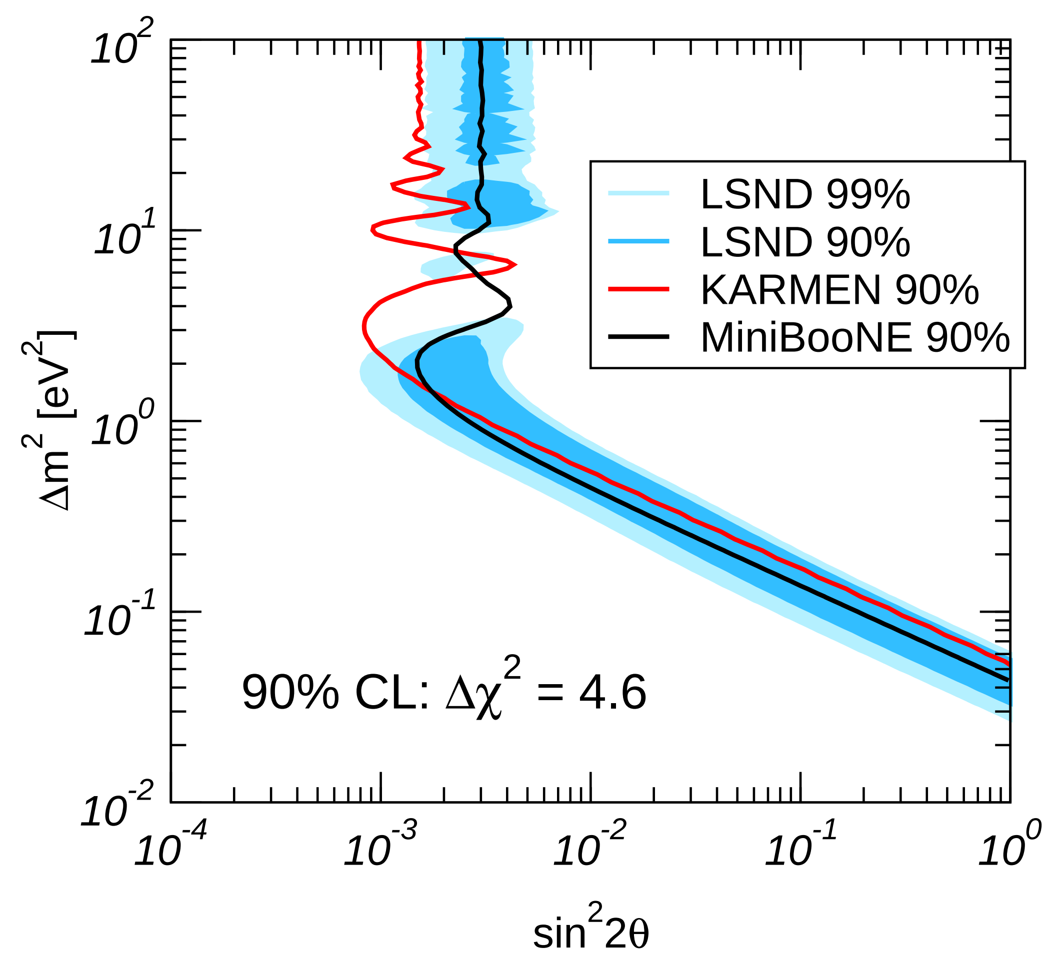
obs. events minus background:

$475 < E_\nu^{\rm QE} < 1250\,{\rm MeV}$:
$22 \pm 19 \pm 35$ events
(consistent with zero)

$300 < E_\nu^{\rm QE} < 475\,{\rm MeV}$:
$96 \pm 17 \pm 20$ events
(excess at 3.6σ)



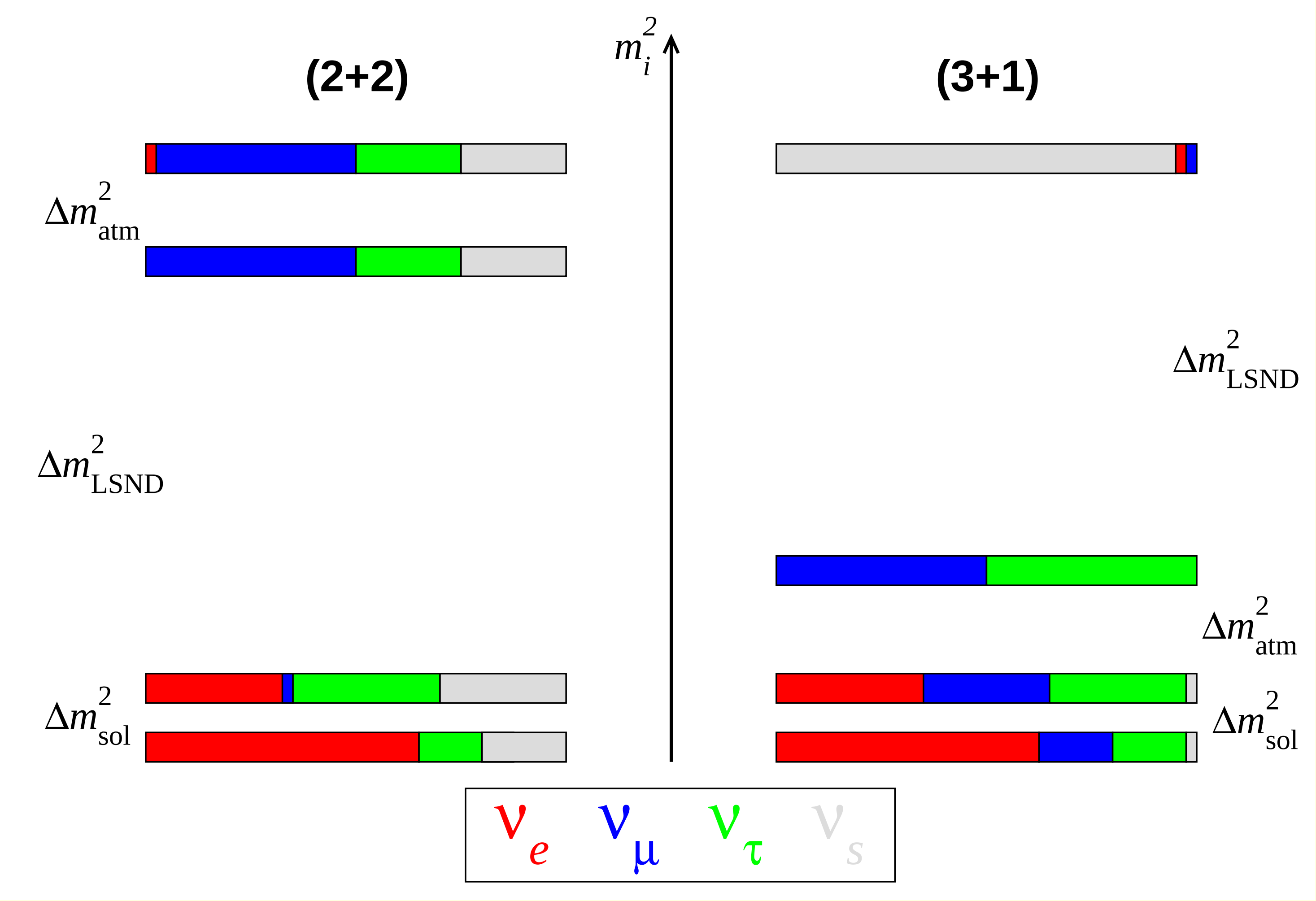
The MiniBooNE 2-neutrino limit



In the 2-neutrino framework MiniBooNE and LSND are incompatible at the 98% CL Aguilar-Arevalo et al., PRL08

Adding a sterile neutrino

4-neutrino mass schemes:



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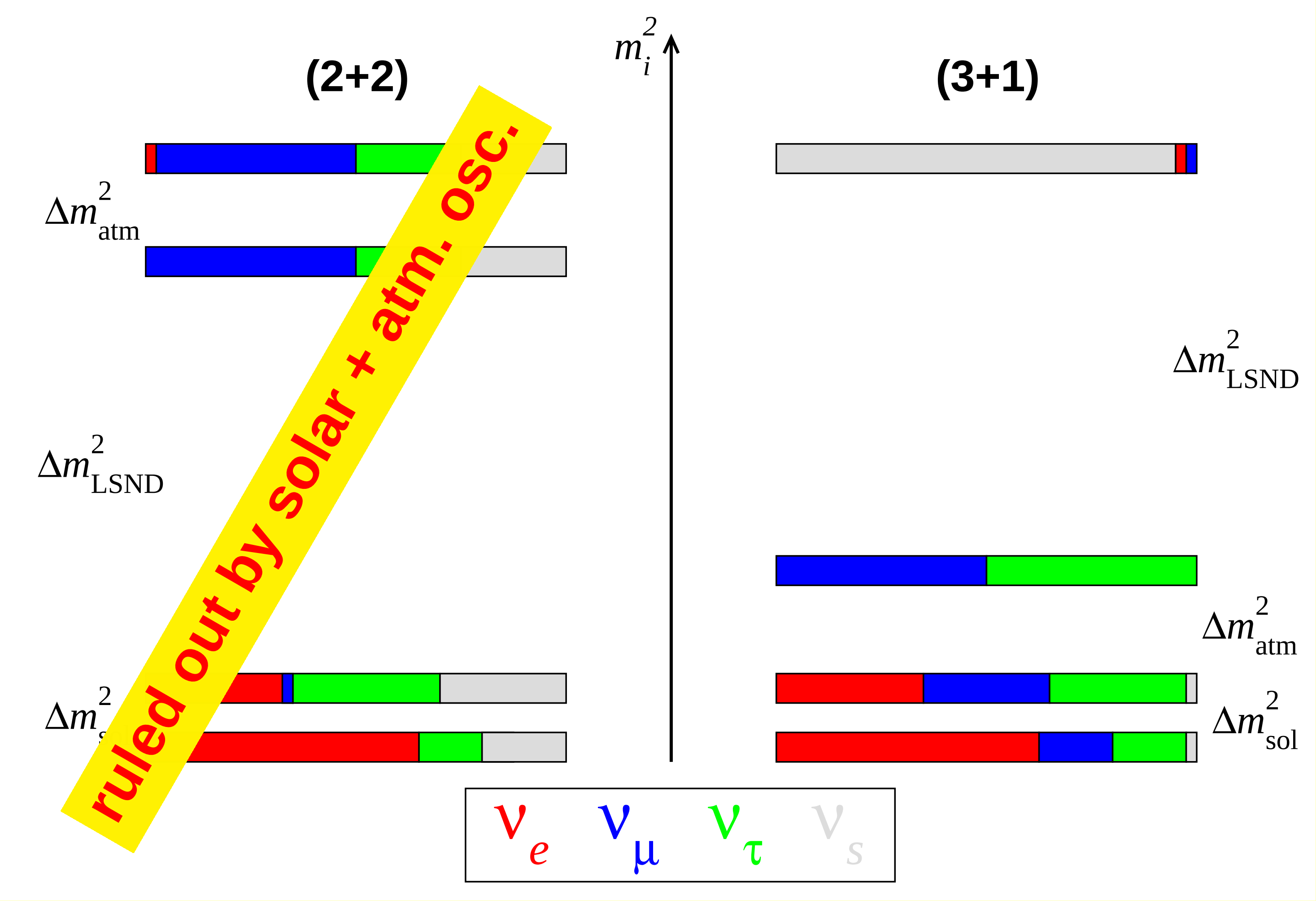


MB vs LSND in (3+1)

In (3+1) schemes the SBL appearance probability is effectively 2-ν oscillations:

$$P_{\mu e} = \sin^2 2\theta_{\rm SBL} \sin^2 \frac{\Delta m^2_{41} L}{4E}$$

with

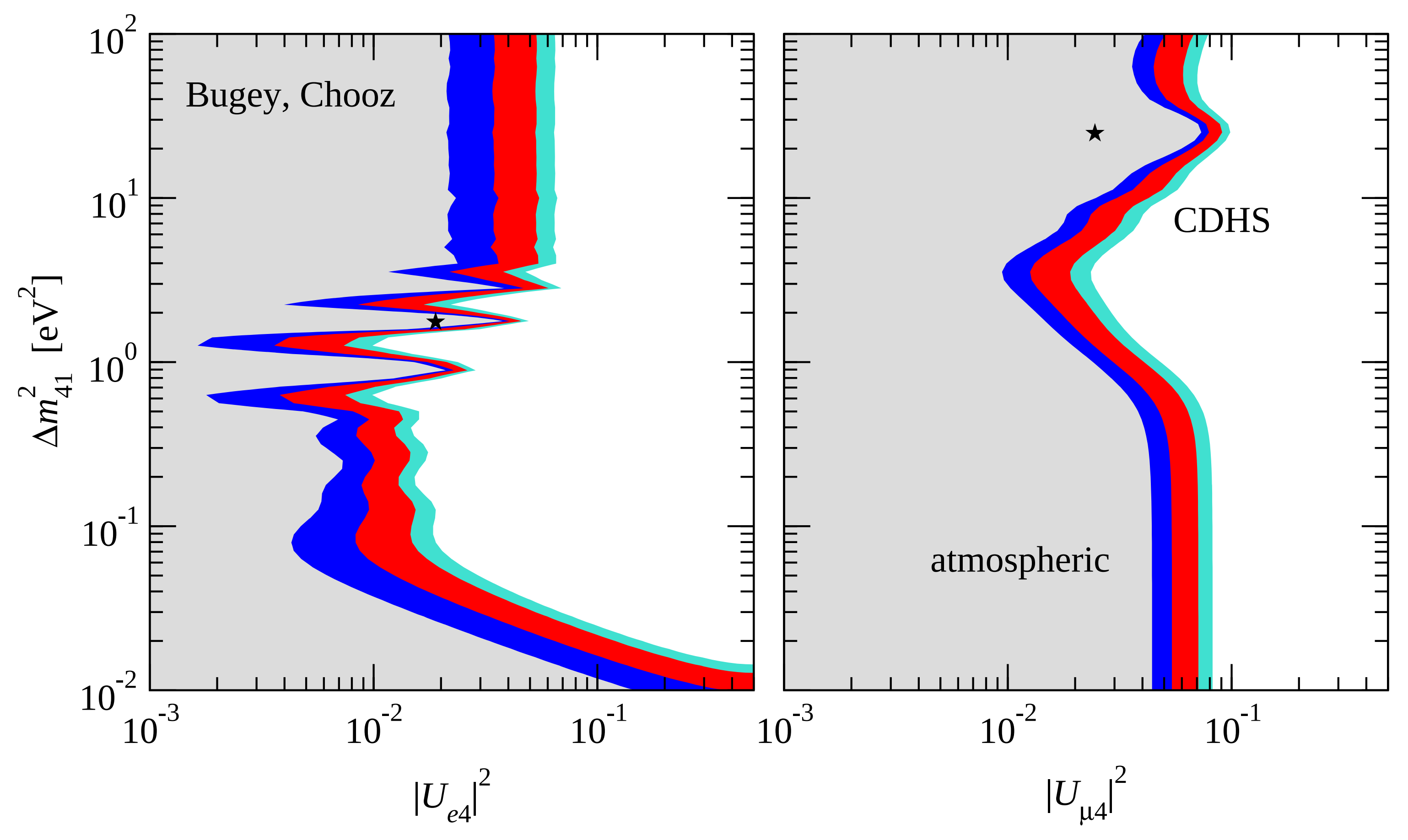
$$\sin^2 2\theta_{\rm SBL} = 4|U_{e4}|^2|U_{\mu 4}|^2$$

LSND / MiniBooNE inconsistency is the same as in the 2-flavour analysis presented by the MiniBooNE collaboration (98% CL)

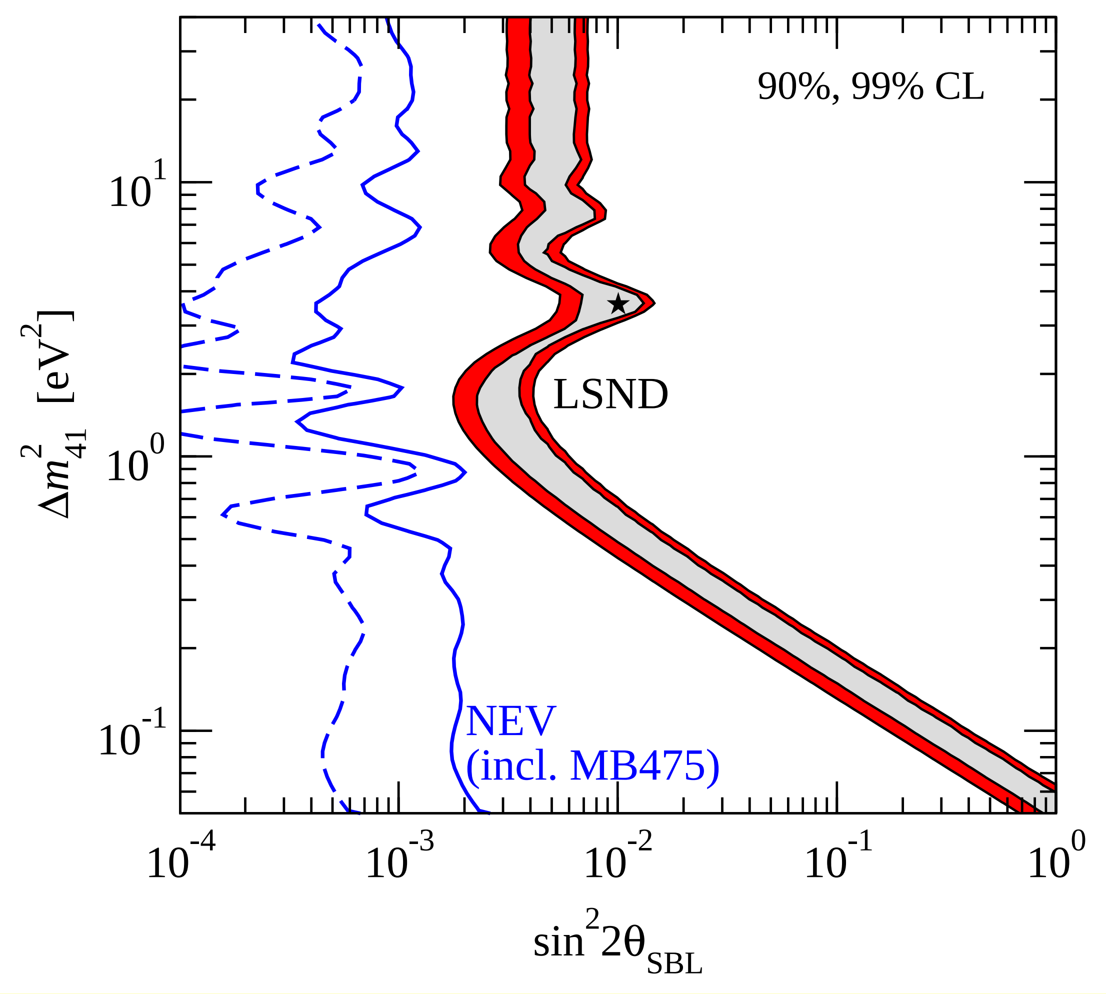
Appearance vs disappearance in (3+1)

appearance amplitude $\sin^2 2\theta_{\rm SBL} = 4|U_{e4}|^2|U_{\mu4}|^2$

disappearance experiments bound $|U_{e4}|^2$ and $|U_{\mu4}|^2$



(3+1) global



before MB:

$\chi^2_{\rm PG} = 20.9\,(2\,{\rm dof})$

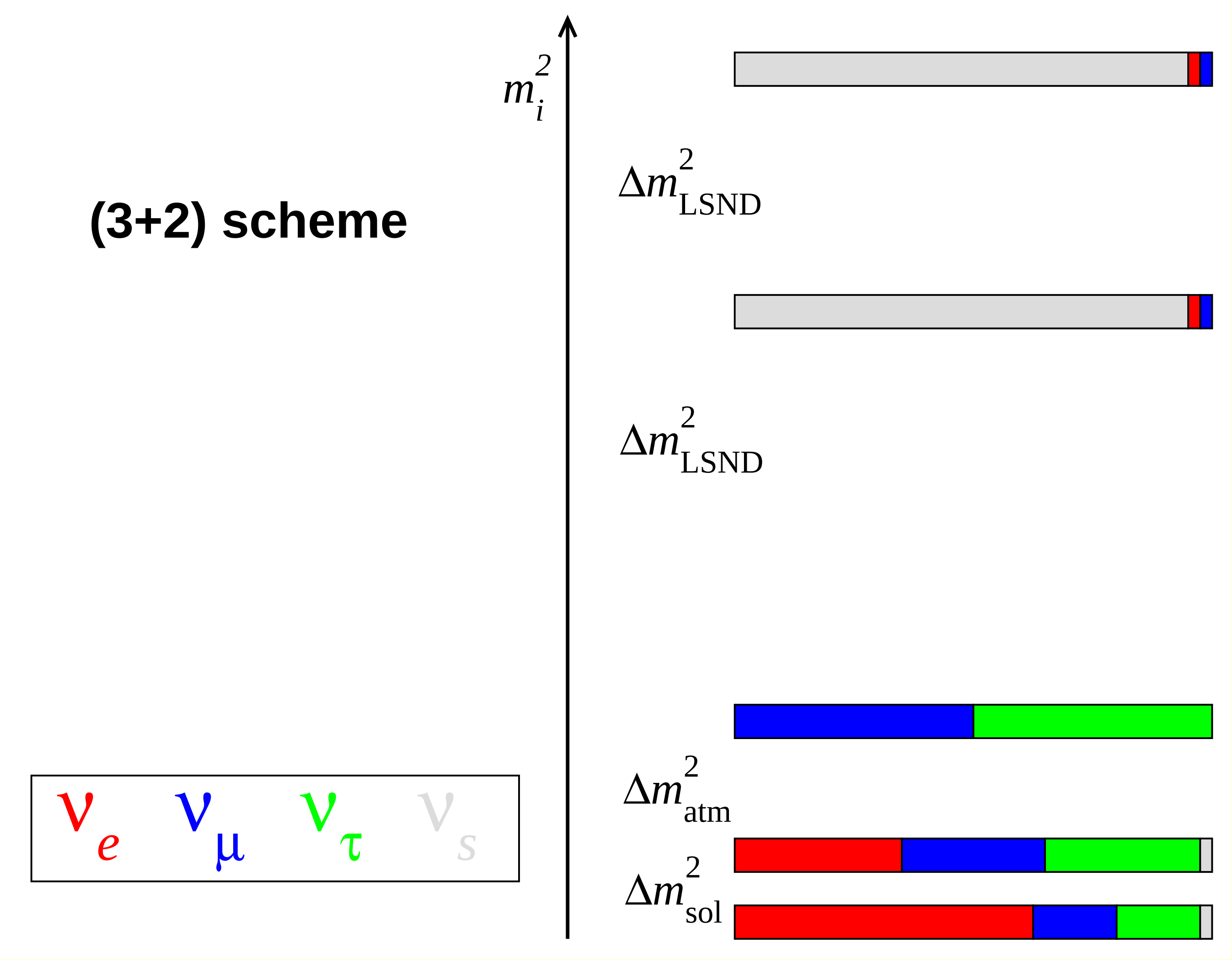
MB incl.:

$\chi^2_{\rm PG} = 24.7\,(2\,{\rm dof})$

disagreement at about 4σ

More sterile neutrinos?

5-neutrino oscillations



Sorel, Conrad, Shaevitz, hep-ph/0305255

(3+2) appearance probability

$$\begin{aligned} P_{\nu_\mu\to\nu_e} &= 4\,|U_{e4}|^2|U_{\mu4}|^2\sin^2\phi_{41} \\ &+ 4\,|U_{e5}|^2|U_{\mu5}|^2\sin^2\phi_{51} \\ &+ 8\,|U_{e4}U_{\mu4}U_{e5}U_{\mu5}|\sin\phi_{41}\sin\phi_{51}\cos(\phi_{54}-\delta) \end{aligned}$$

with the definitions

$$\phi_{ij}\equiv\frac{\Delta m^2_{ij}L}{4E}\,, \qquad \delta\equiv\arg\left(U^*_{e4}U_{\mu4}U_{e5}U^*_{\mu5}\right)\,.$$

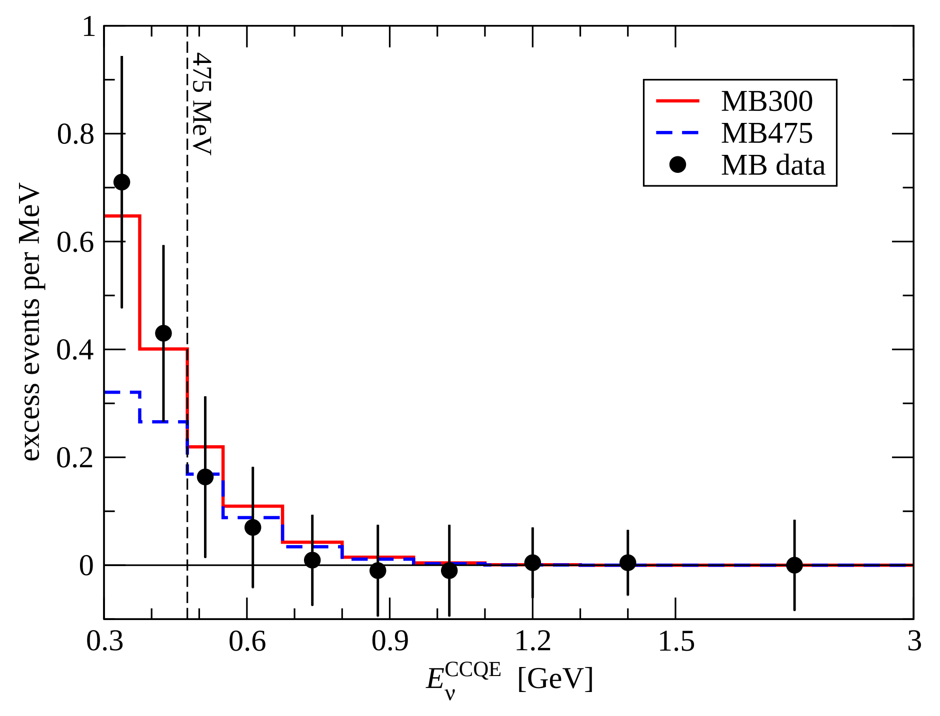
(3+2) osc. include the possibility of CP violation!

remember: MiniBooNE: neutrinos, LSND: anti-neutrinos

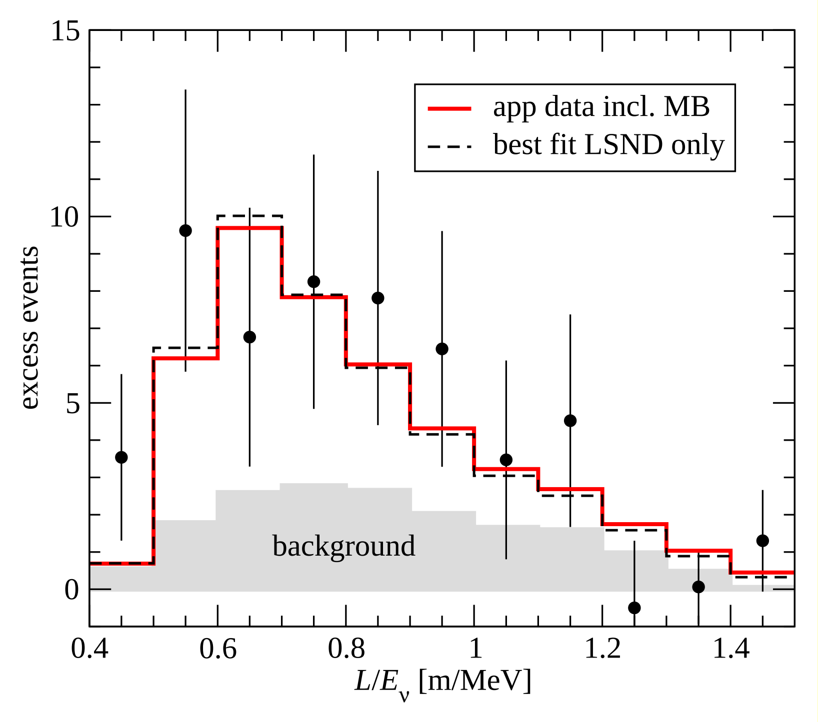
(3+2) appearance data

best fit point spectra:

MiniBooNE



LSND



Perfect fit to appearance data:

w/o MB low energy excess: $\chi^2_{\rm min} = 16.9/(29-5)$

with MB low energy excess: $\chi^2_{\rm min} = 18.5/(31-5)$

(3+2) disappearance data

what about the disappearance data?

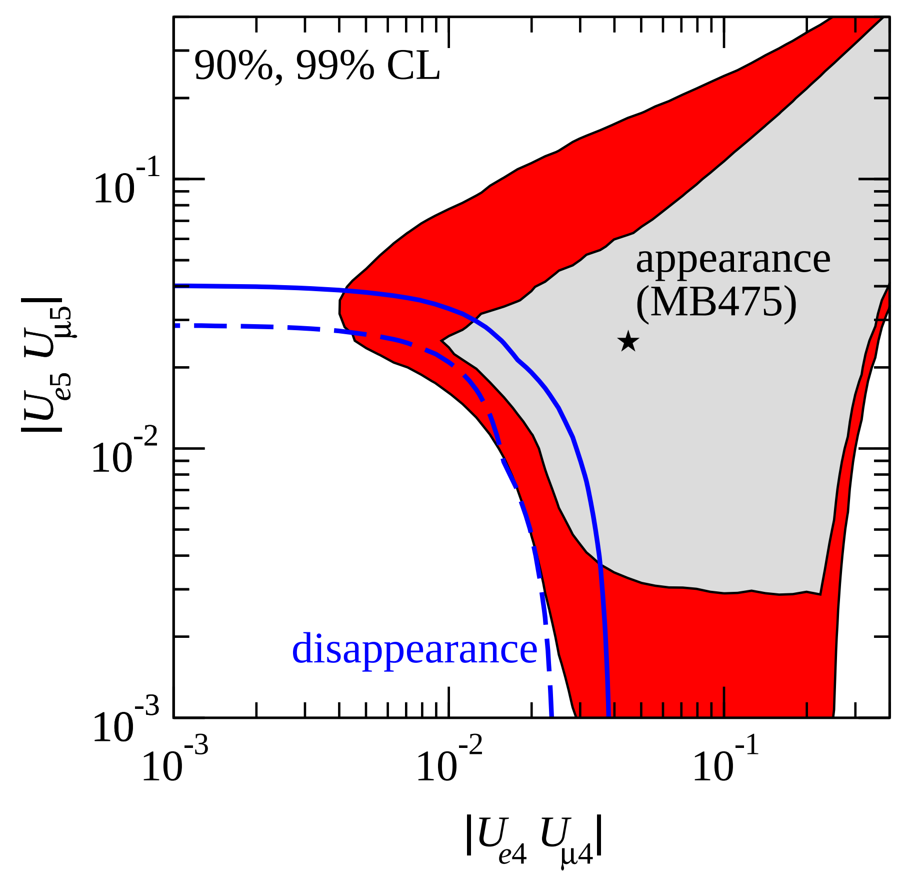
$$\begin{aligned} P_{\nu_\alpha \to \nu_\alpha} &= 1 - 4 \left(1 - \sum_{i=4,5} |U_{\alpha i}|^2 \right) \sum_{i=4,5} |U_{\alpha i}|^2 \sin^2 \phi_{i1} \\ &- 4\, |U_{\alpha 4}|^2 |U_{\alpha 5}|^2 \sin^2 \phi_{54} \end{aligned}$$

$\Rightarrow$ bound $|U_{ei}|$ and $|U_{\mu i}|$ ($i = 4, 5$), similar as in (3+1)

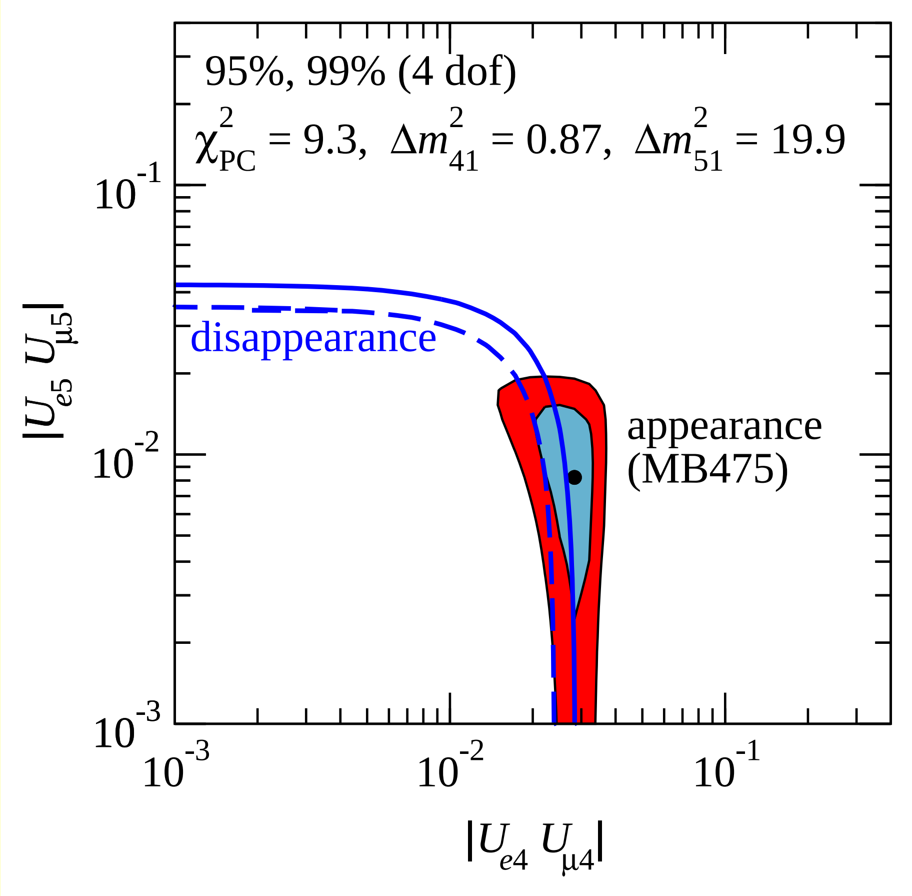
to be reconciled with appearance amplitudes $|U_{ei} U_{\mu i}|$

(3+2) app vs disap

projection



section



(3+2) global

testing consistency of disappearance and appearance data:

$$\chi^2_{\mathrm{PG}} = 17.2\,(4\,\mathrm{dof}) \qquad \mathrm{PG} = 0.18\%$$

(without MB: $\chi^2_{\mathrm{PG}} = 17.5$)

inconsistency at about 3.1σ

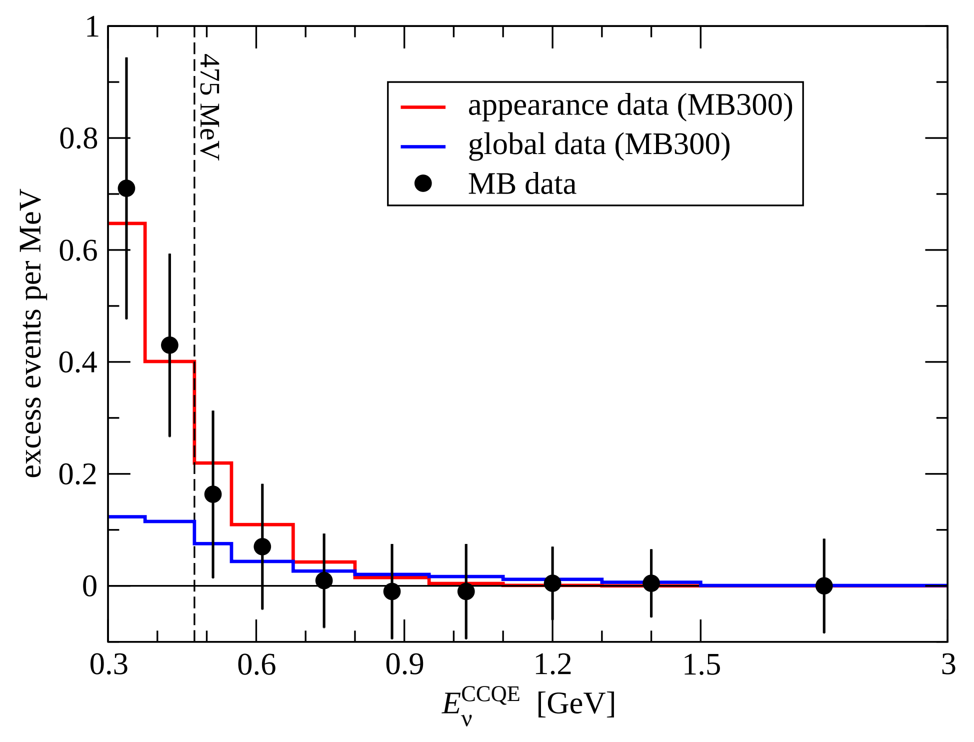
parameters in common $|U_{e4}U_{\mu 4}|, |U_{e5}U_{\mu 5}|, \Delta m^2_{41}, \Delta m^2_{51}$

best fit: $\Delta m^2_{41} = 0.9$ eV^2, $\Delta m^2_{51} = 6.5$ eV^2, $\chi^2_{\mathrm{min}} = 94.5/(107-7)$

$\chi^2_{\text{min, global}\,(3+1)} - \chi^2_{\text{min, global}\,(3+2)} = 6.1/4$ dof (81% CL)

the low energy MB excess in the (3+2) fit

the MB low energy excess is not reproduced at the global best fit point:



$$\chi^2_{\mathrm{MB300}} = 104.4/(109 - 7)$$

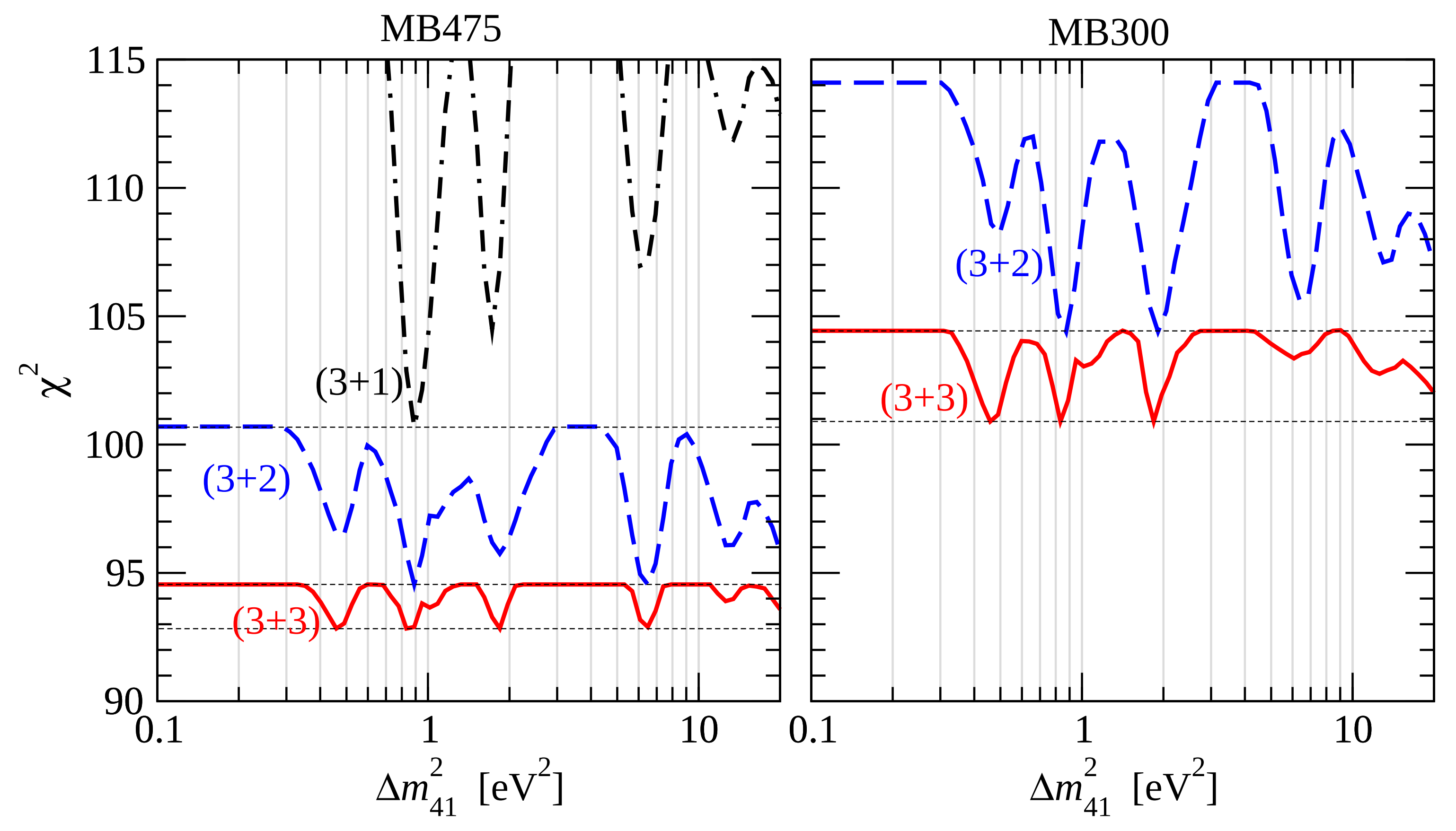
$$\chi^2_{\mathrm{MB475}} = 94.5/(107 - 7)$$

$$\chi^2_{\mathrm{PG}} = 25.1/4$$

$$\mathrm{PG} = 4.8 \times 10^{-5}\ (4\sigma)$$

adding another sterile: (3+3)

(3+3) global fit



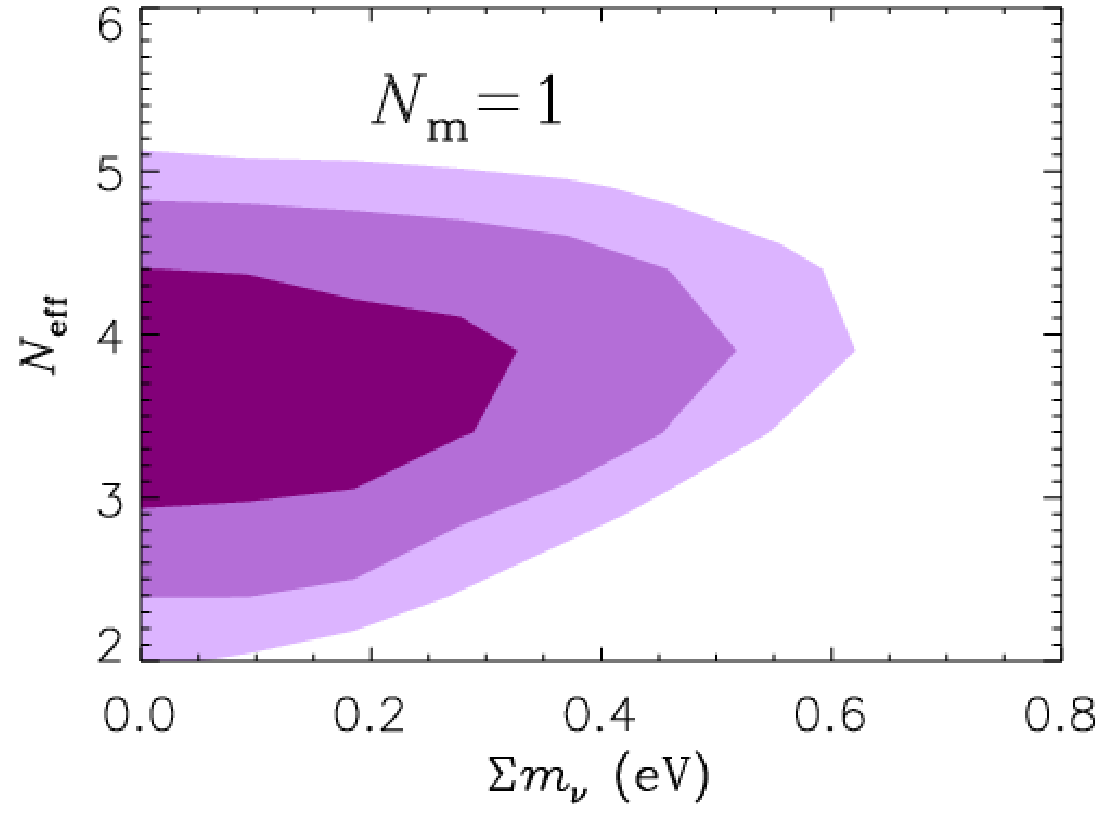
	Δm^2_{41}	Δm^2_{51}	Δm^2_{61}	$\chi^2_{\rm min}$	$\chi^2_{(3+2)} - \chi^2_{(3+3)}$	CL
MB475	0.46	0.83	1.84	92.8	$1.7/4$	20%
MB300	0.46	0.83	1.84	100.9	$3.5/4$	52%

All these sterile neutrino schemes have problems with cosmology

- sterile states contribute to the relativistic degrees of freedom (CMB, BBN)
- conflict with bound on the sum of neutrino masses from various cosmological data sets (LSS)

Cosmology

SN Ia, LSS (2dF, SDSS), BAO, CMB (WMAP, BOOMERANG)



68%, 95%, 99% CL

Hannestad, Raffelt, astro-ph/0607101

More ’exotic’ proposals

- 3-neutrinos and CPT violation Murayama, Yanagida 01; Barenboim, Borissov, Lykken 02; Gonzalez-Garcia, Maltoni, Schwetz 03
- 4-neutrinos and CPT violation Barger, Marfatia, Whisnant 03
- Exotic muon-decay Babu, Pakvasa 02
- CPT viol. quantum decoherence Barenboim, Mavromatos 04
- Lorentz violation
  Kostelecky, Mews, 04; Gouvea, Grossman, 06; Katori, Kostelecky, Tayloe, 06
- mass varying neutrinos
  Kaplan, Nelson, Weiner 04; Zurek 04; Barger, Marfatia, Whisnant 05
- shortcuts of sterile neutrinos in extra dimensions
  Paes, Pakvasa, Weiler 05
- 1 decaying sterile neutrino Palomares-Riuz, Pascoli, Schwetz 05
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KamLAND+atmospheric antineutrino data

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KARMEN, TWIST

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KARMEN, TWIST

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Sterile neutrino oscillations - outlook

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- sterile neutrinos with $\Delta m^2 \sim 1\,\mathrm{eV}^2$ might lead to large effects for high energy atmospheric neutrinos in IceCube S. Choubey, 0709.1937