Sterile neutrino oscillations after first MiniBooNE results

GDR Neutrino, APC Paris, 22 June 2007

Thomas Schwetz

CERN

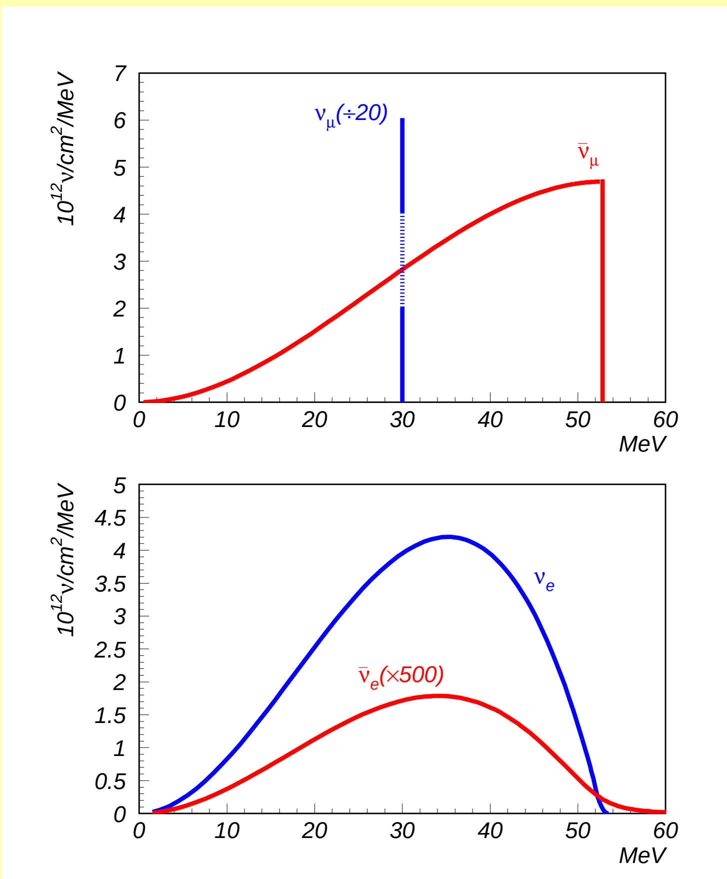
Outline

- Introduction to the LSND problem
- Recent results from MiniBooNE
  Talk at Fermilab, April 11, 2007
  A.A. Aguilar-Arevalo et al., arXiv:0704.1500 [hep-ex]
- Short-baseline data and sterile neutrino oscillation
  4-neutrinos, 5-neutrinos, 6-neutrinos
  M. Maltoni, T. Schwetz, arXiv:0705.0107 [hep-ph]
- Comments on exotic solutions
- Summary and outlook

The LSND puzzle

The LSND signal

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

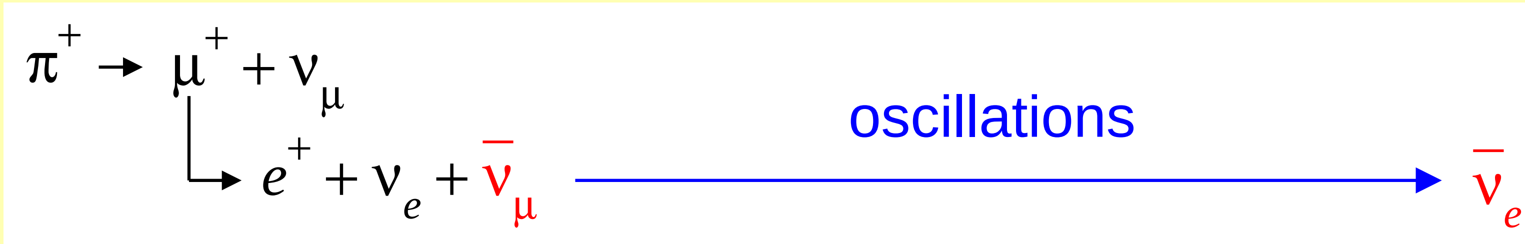


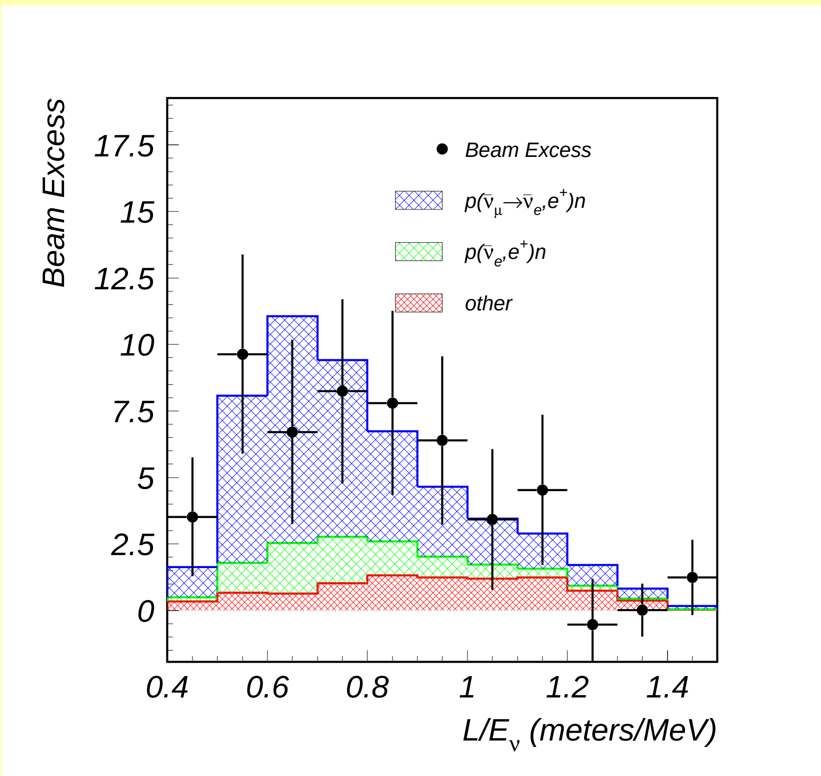
$L \simeq$ 35 m

signal:

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

The LSND signal





$L \simeq$ 35 m

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

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

$87.9 \pm 22.4 \pm 6.0$ excess events

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

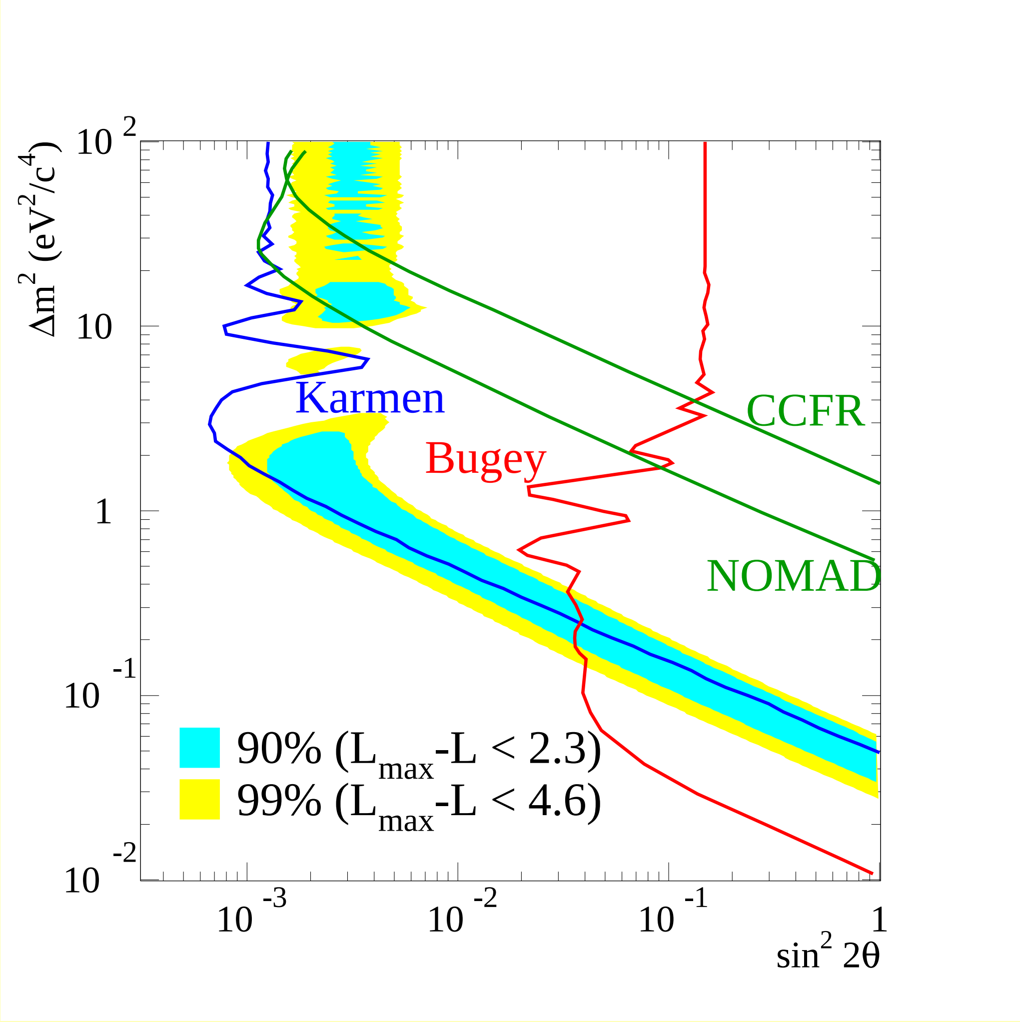
$\sim 3.3\sigma$ away from zero

Oscillation interpretation of LSND

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

combined analysis of LSND and KARMEN:

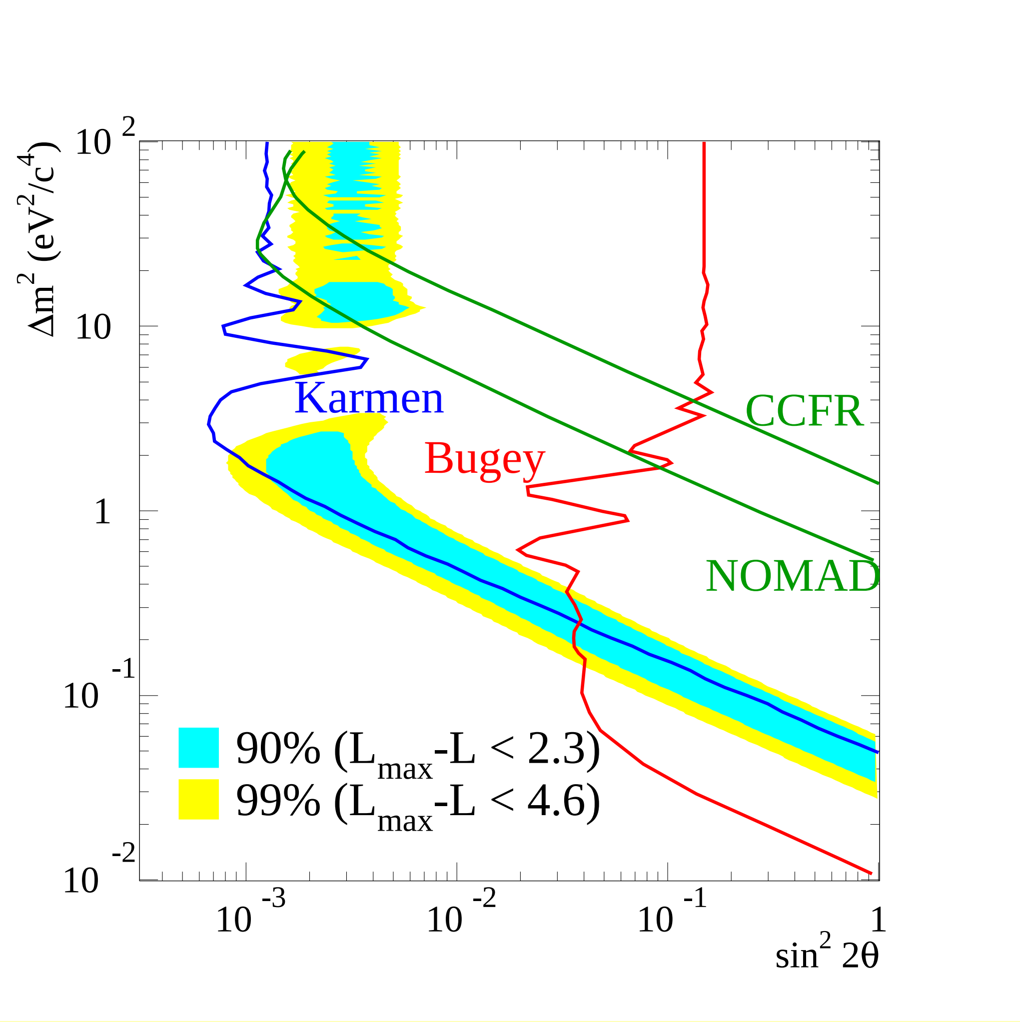
Church, Eitel, Mills, Steidl, PRD (2002)



Oscillation interpretation of LSND

the problem:

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

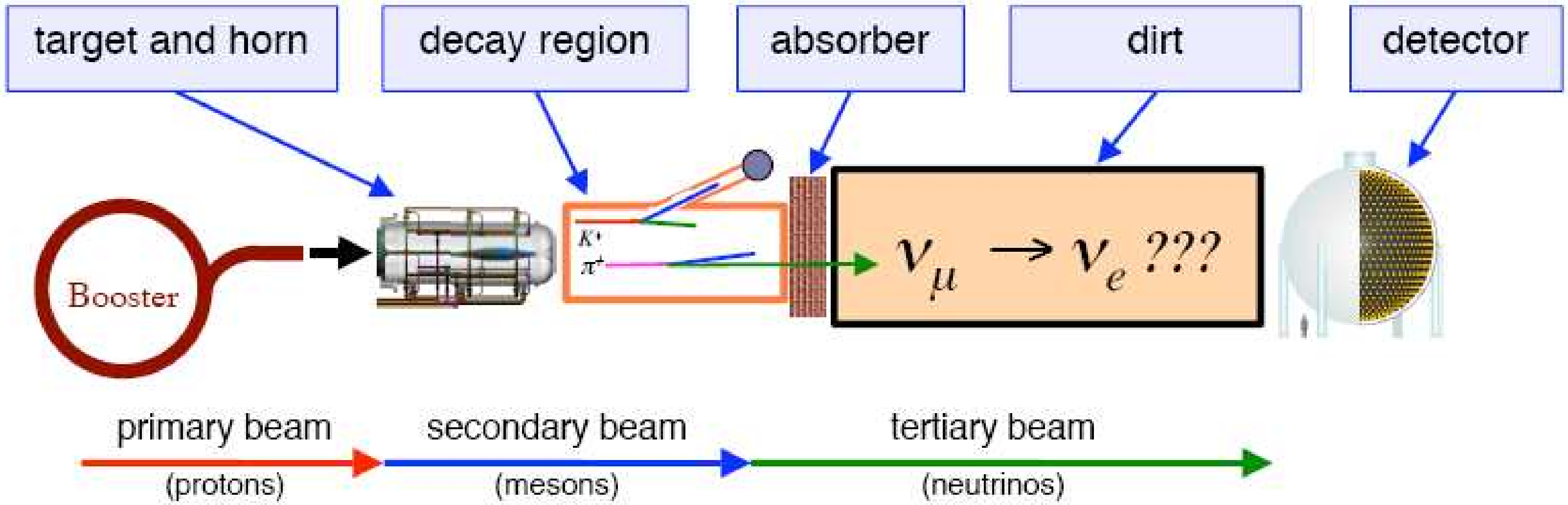


MiniBooNE

MiniBooNE's Design Strategy...

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

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

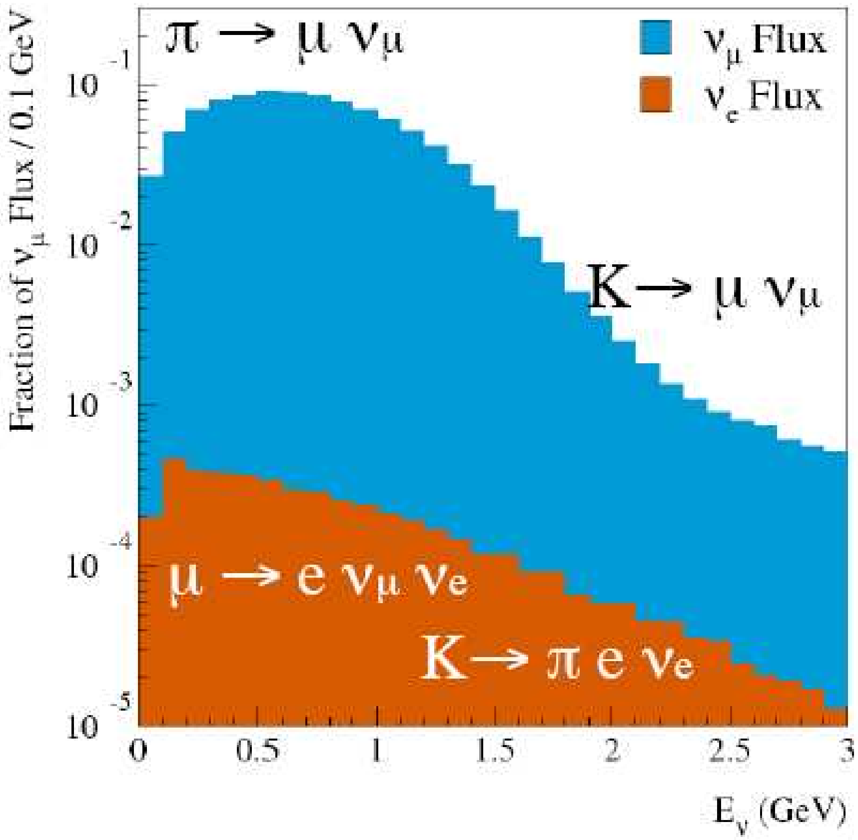


Order of magnitude
higher energy (~500 MeV)
than LSND (~30 MeV)

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

W. Louis, J. Conrad, talk @ Fermilab, April 11, 2007

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%)

W. Louis, J. Conrad, talk @ Fermilab, April 11, 2007

MiniBooNE background

estimated background for $475 < E_\nu^{\rm QE} < 1250\,{\rm MeV}$

process	events
ν_μ CCQE	10 ± 2
$\nu_\mu e \to \nu_\mu e$	7 ± 2
misc. ν_μ events	13 ± 5
NC π^0	62 ± 10
NC $\Delta \to N\gamma$	20 ± 4
dirt events	17 ± 3
ν_e from μ	132 ± 10
ν_e from K^+	71 ± 26
ν_e from K_L^0	23 ± 7
ν_e from π	3 ± 1
total background	385 ± 35
signal for 0.26% $\nu_\mu \to \nu_e$	163 ± 21

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$$\frac{\text{signal}}{\text{error}} = \frac{163}{\sqrt{385 + 35^2 + 21^2}} = 3.6$$

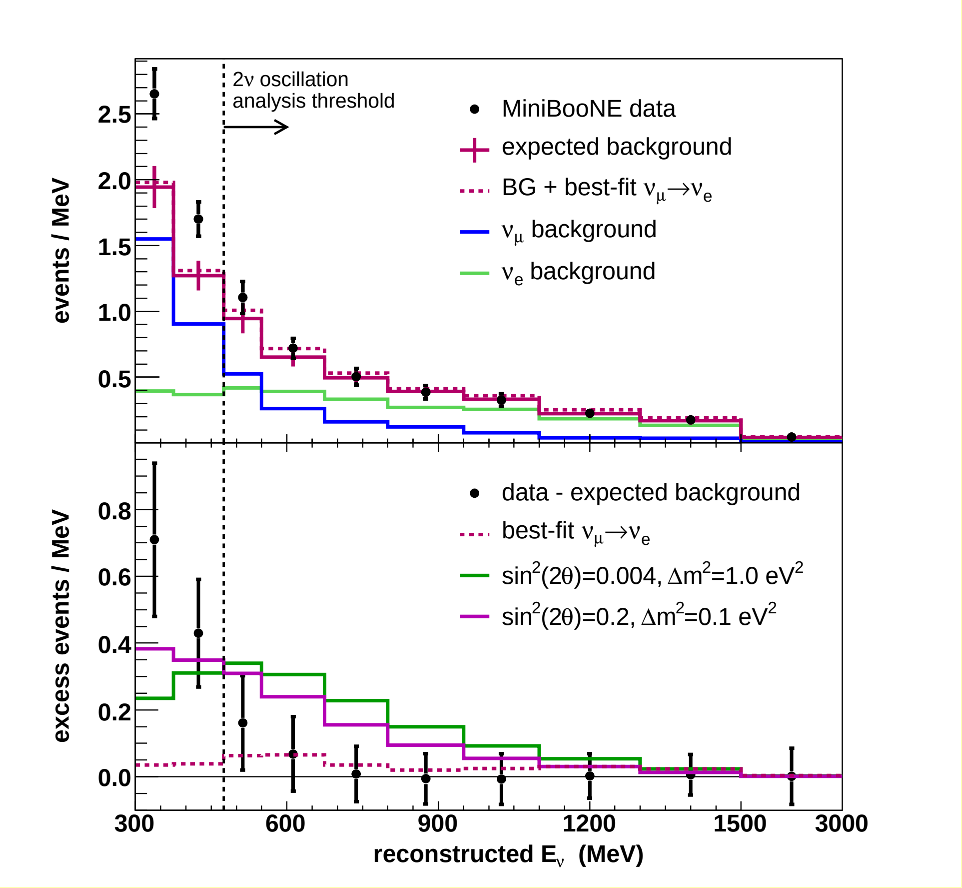
MB should see a 3.6σ effect

MiniBooNE results

obs. events minus background:

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

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



The event excess at low energies

- Two-neutrino oscillations cannot account for the sharp rise of the spectrum.
- Before fully opening the box they found that the full range gives a very poor fit of the E_{vis} distribution ($< 1\%$).
- Decided to restrict the two-neutrino analysis to $E_\nu^{\mathrm{QE}} > 475\,\mathrm{MeV}$.

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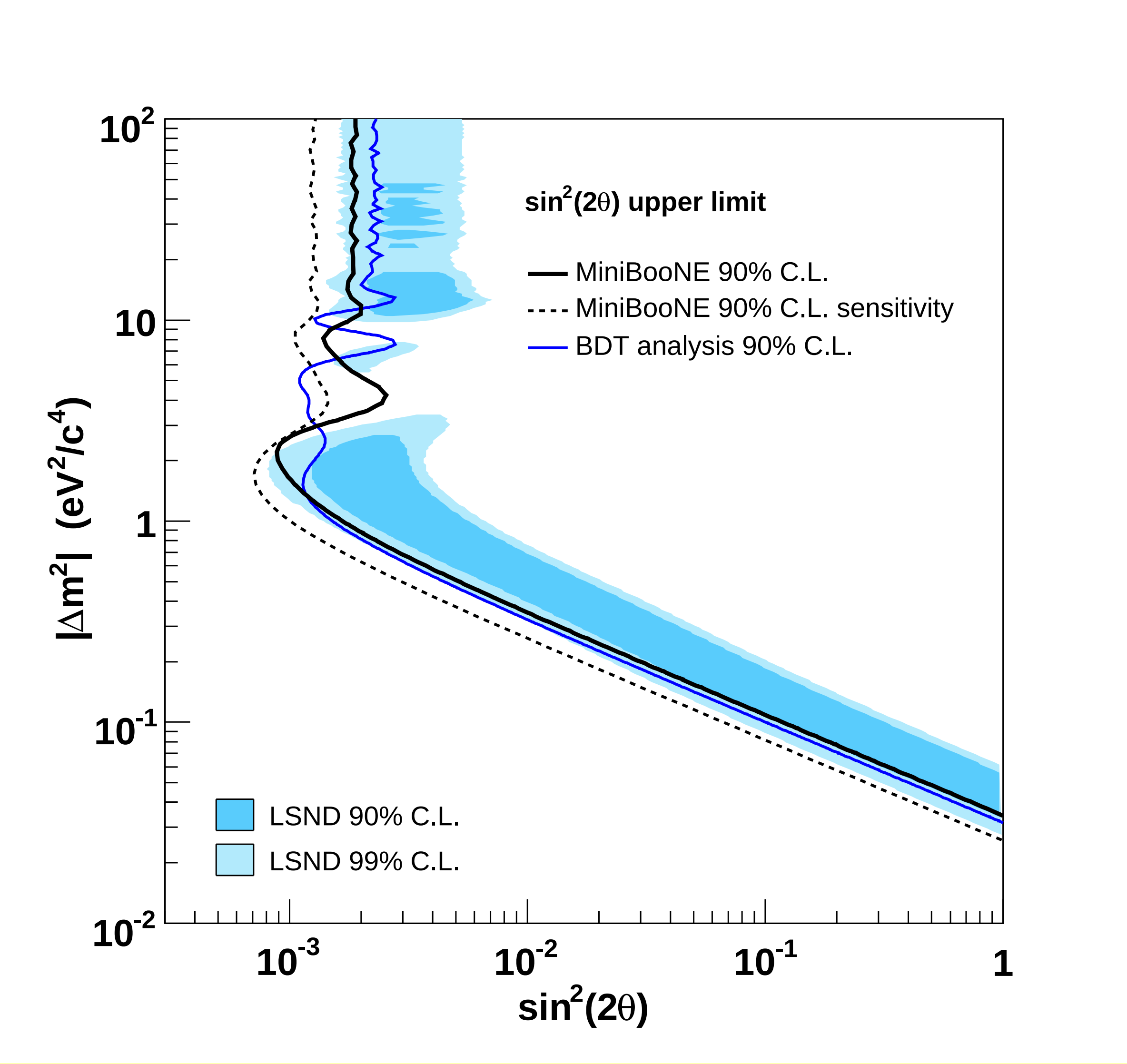
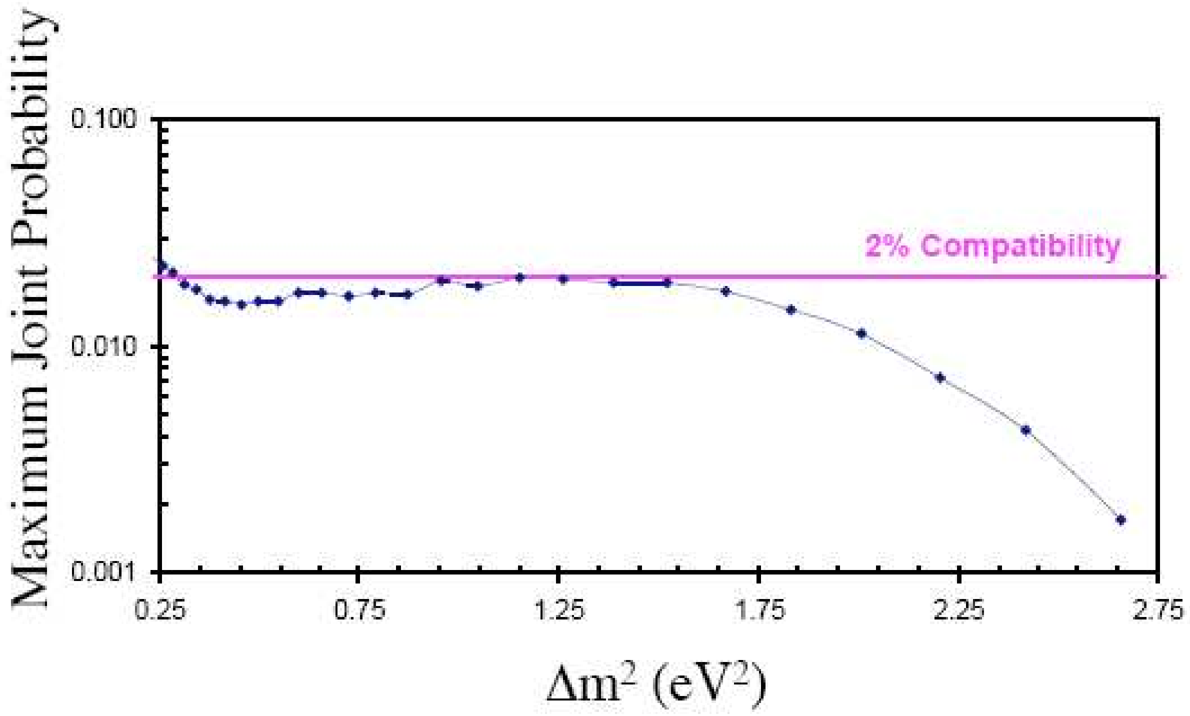
Backgrounds are difficult to estimate in the low energy region, all possible sources are under investigation.

The decision not to use the low energy bins is based on the hypothesis of two-flavour oscillations!

The MiniBooNE 2-neutrino limit



MiniBooNE - LSND compatibility



MiniBooNE is incompatible with a $\nu_\mu \rightarrow \nu_e$ appearance only interpretation of LSND at 98% CL

W. Louis, J. Conrad, talk @ Fermilab, April 11, 2007

Going beyond simple 2-neutrino oscillations

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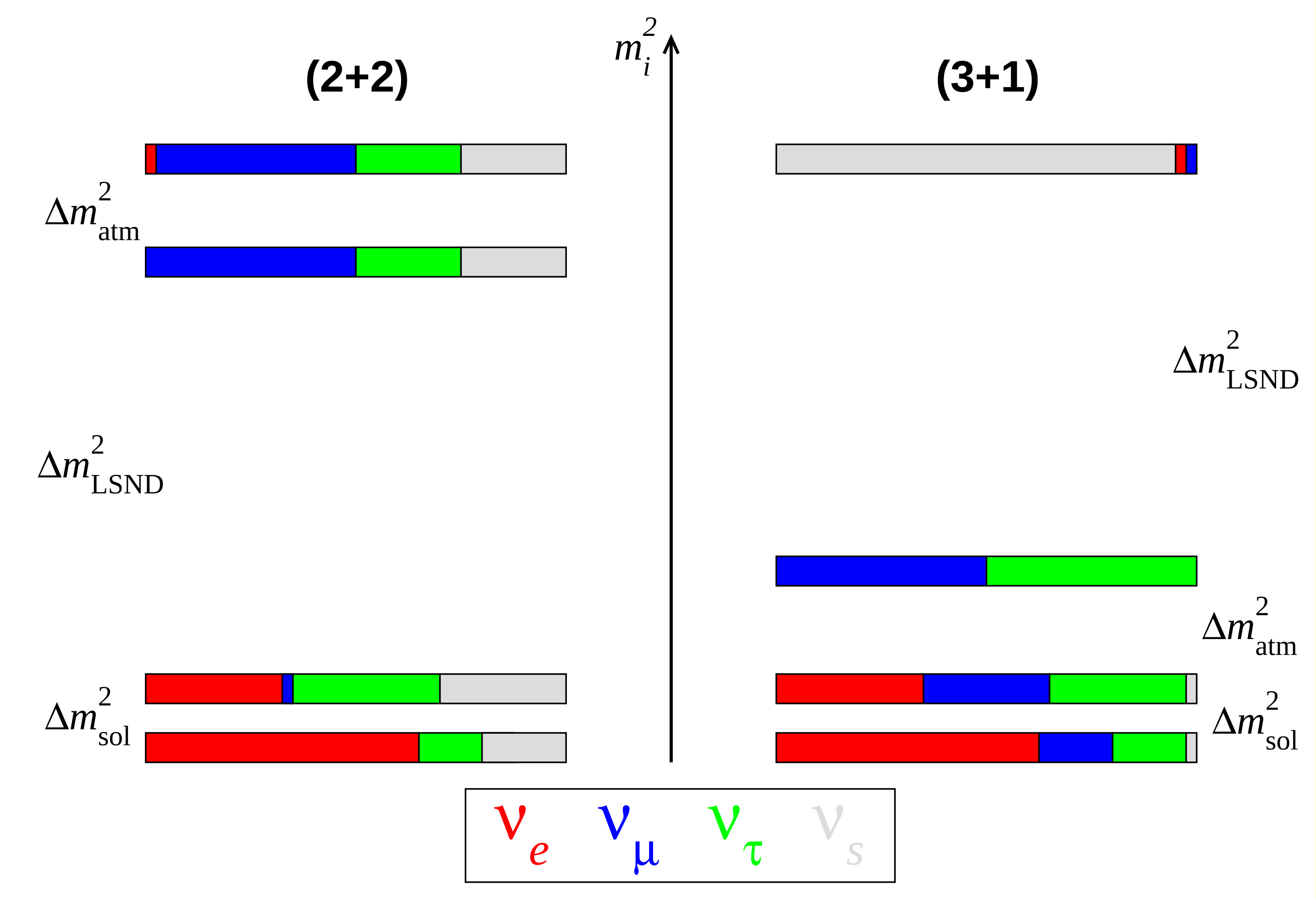
4-neutrino oscillations?

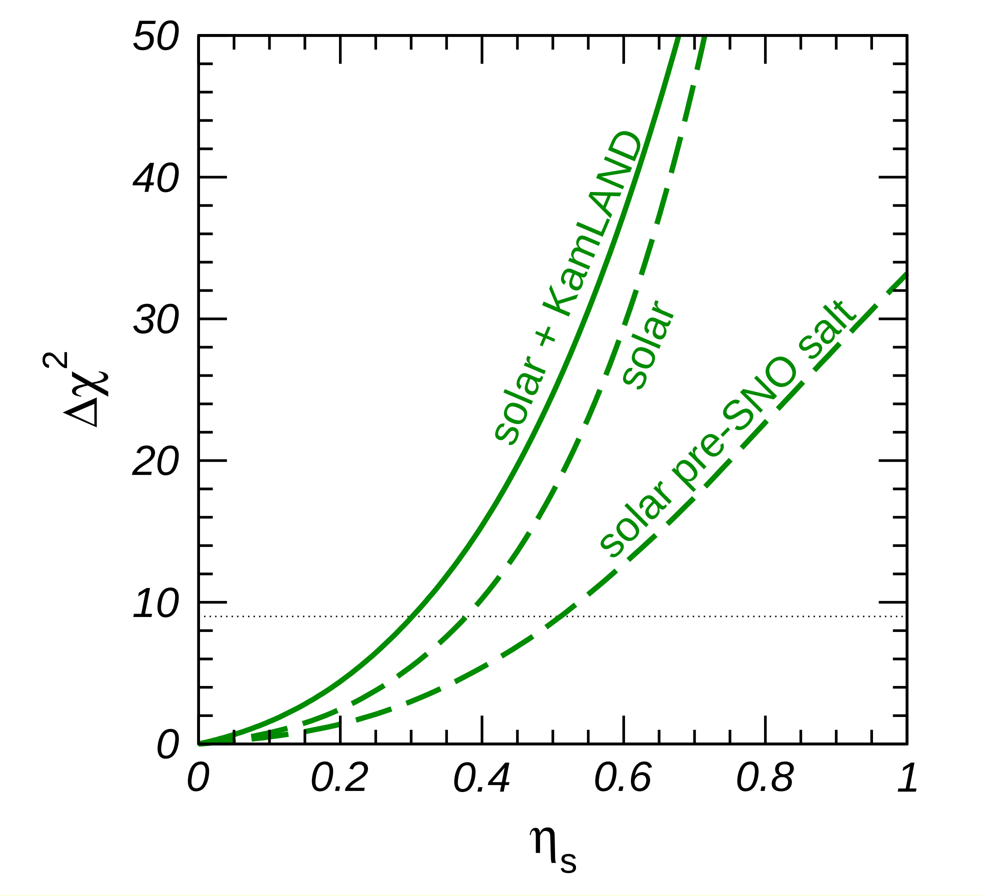
Adding a sterile neutrino

4-neutrino mass schemes:



(2+2): ruled out by solar and atmospheric data

Maltoni, Schwetz, Tortola, Valle, hep-ph/0207157, hep-ph/0405172



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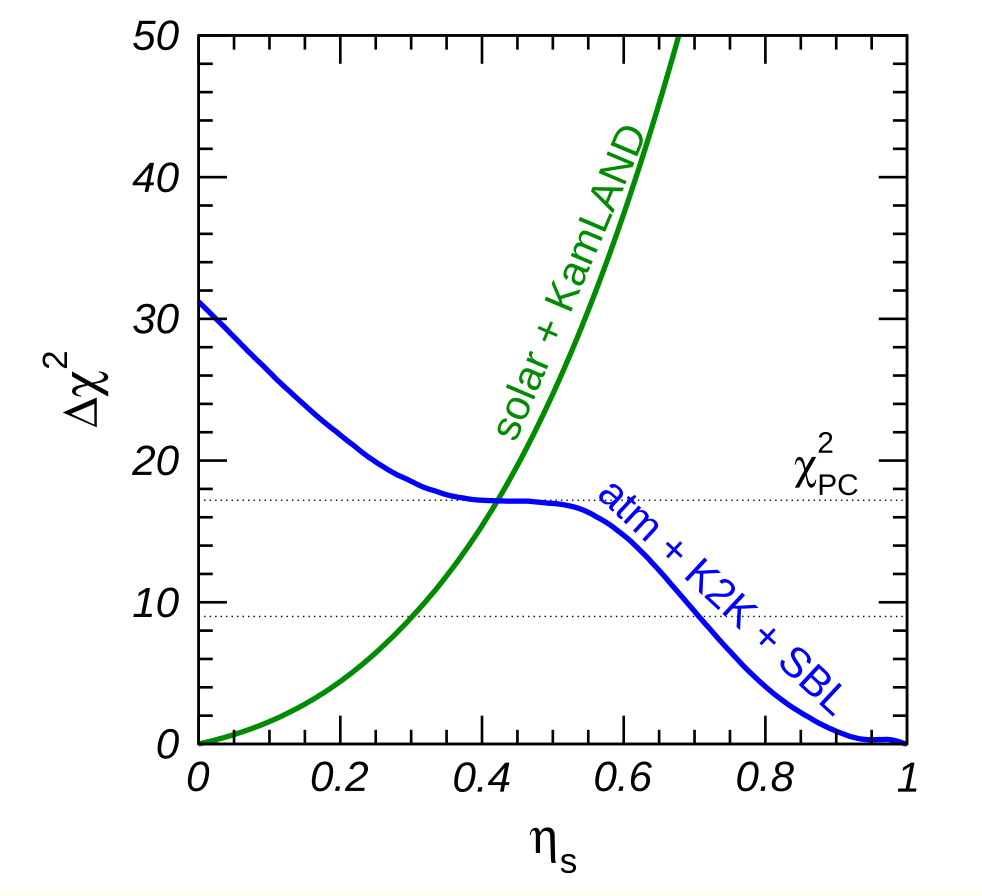

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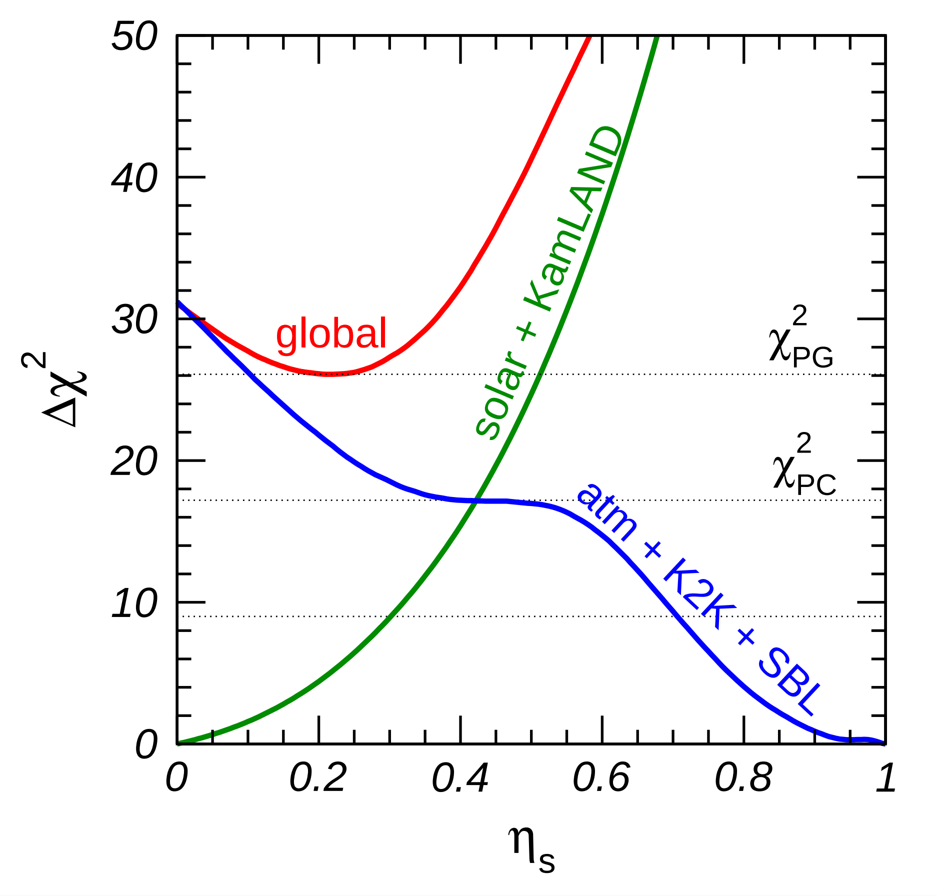

$\Delta\chi^2 = 26 \quad \rightarrow$ **(2+2) ruled out at the 5σ level** $\Rightarrow$

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

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

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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)

Tension between SBL appearance and disappearance experiments

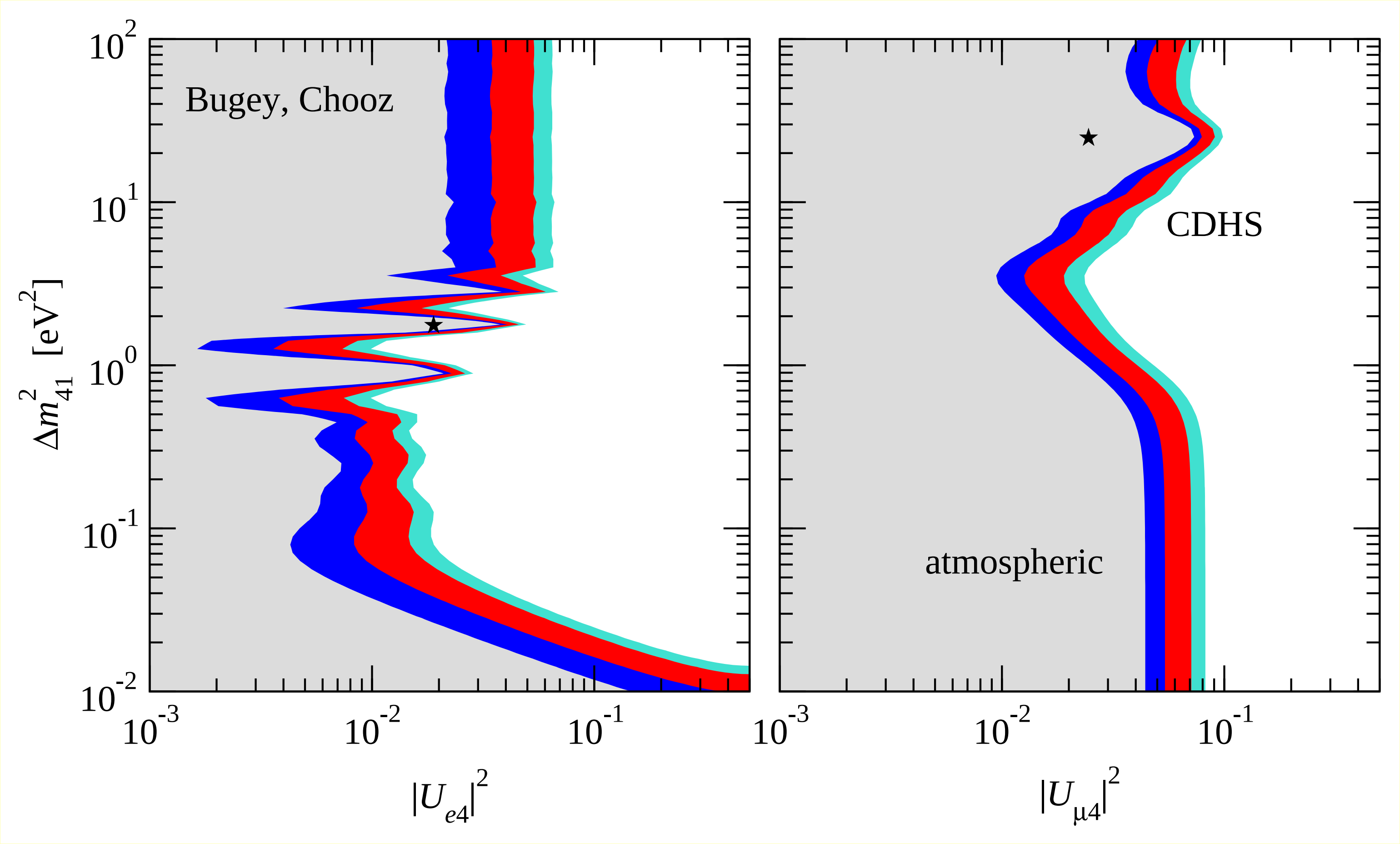
Bilenky, Giunti, Grimus, 96, 98; Okada, Yasuda, 1997; Barger *et al.*, 1998, 2000; Giunti, Laveder, 2001; Peres, Smirnov, 2001; Grimus, Schwetz, 2001

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

no-evidence (NEV) ν_e and ν_μ disappearance experiements bound $|U_{e4}|^2$ and $|U_{\mu 4}|^2$

$\Rightarrow$

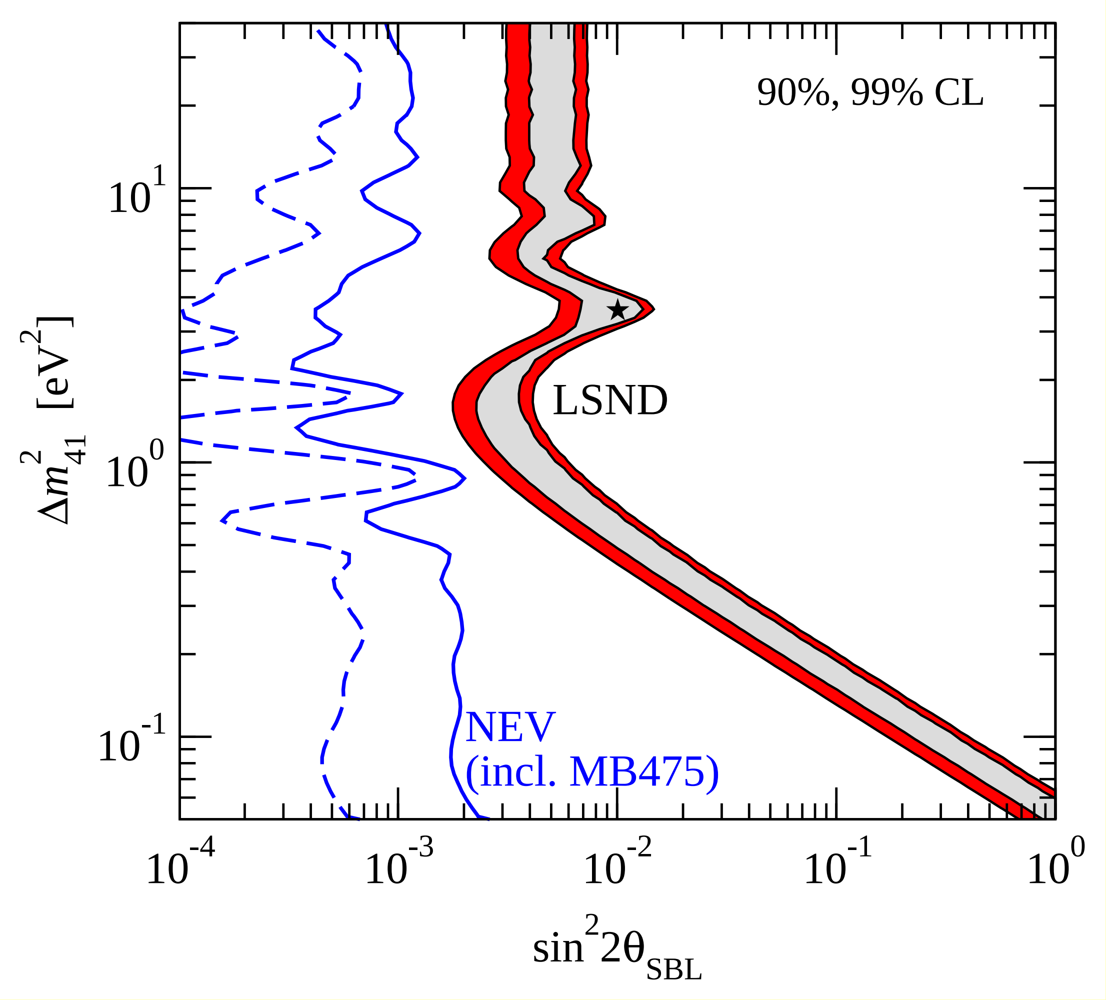
Disappearance bounds in (3+1)



atm. neutrinos give an important constraint on $|U_{\mu 4}|^2$ for low Δm^2

Bilenky, Giunti, Grimus, Schwetz, 1999; Maltoni, Schwetz, Valle, 2002

(3+1) global



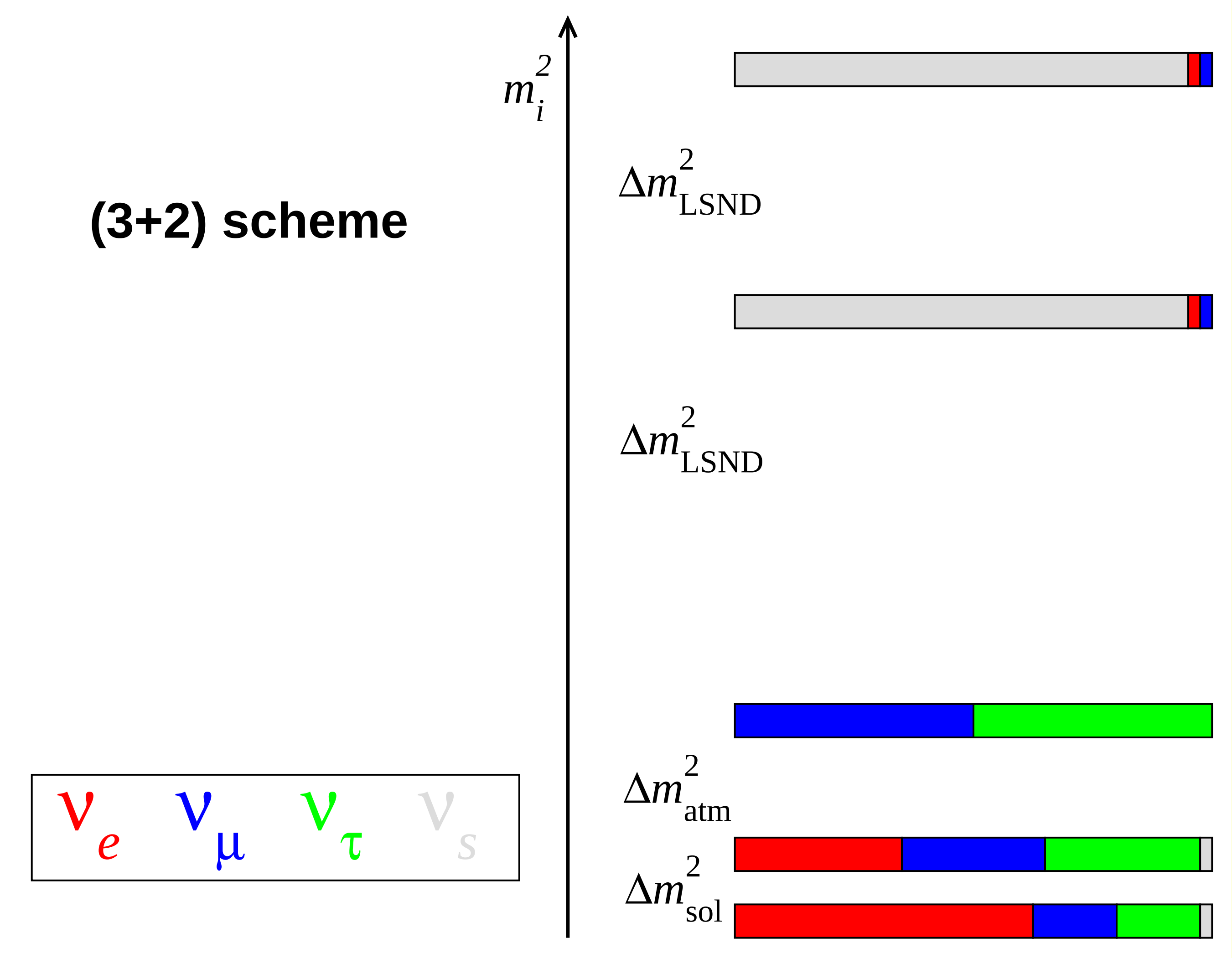
before MB:
$\chi^2_{\rm PG} = 20.9\,(2\,\rm dof)$

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

$$
\begin{aligned}
P_{\nu_\mu \to \nu_e} &= 4\,|U_{e4}|^2 |U_{\mu 4}|^2 \sin^2 \phi_{41} \\
&+ 4\,|U_{e5}|^2 |U_{\mu 5}|^2 \sin^2 \phi_{51} \\
&+ 8\,|U_{e4} U_{\mu 4} U_{e5} U_{\mu 5}| \sin \phi_{41} \sin \phi_{51} \cos(\phi_{54} - \delta)
\end{aligned}
$$

with the definitions

$$
\phi_{ij} \equiv \frac{\Delta m^2_{ij} L}{4E}, \qquad \delta \equiv \arg\left(U^*_{e4} U_{\mu 4} U_{e5} U^*_{\mu 5}\right) .
$$

(3+2) appearance probability

$$\begin{aligned} P_{\nu_\mu \to \nu_e} &= 4\,|U_{e4}|^2 |U_{\mu 4}|^2 \sin^2 \phi_{41} \\ &+ 4\,|U_{e5}|^2 |U_{\mu 5}|^2 \sin^2 \phi_{51} \\ &+ 8\,|U_{e4} U_{\mu 4} U_{e5} U_{\mu 5}| \sin \phi_{41} \sin \phi_{51} \cos(\phi_{54} - \delta) \end{aligned}$$

with the definitions

$$\phi_{ij} \equiv \frac{\Delta m^2_{ij} L}{4E}\,, \qquad \delta \equiv \arg\left(U^*_{e4} U_{\mu 4} U_{e5} U^*_{\mu 5}\right)\,.$$

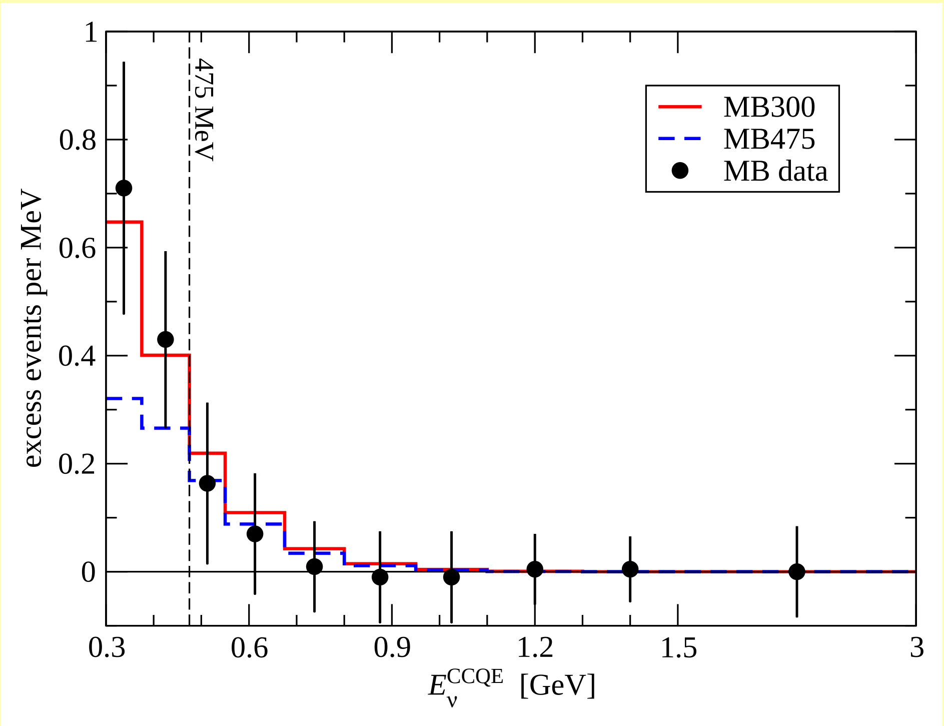
(3+2) osc. include the possibility of CP violation!

remember: MiniBooNE: neutrinos, LSND: anti-neutrinos

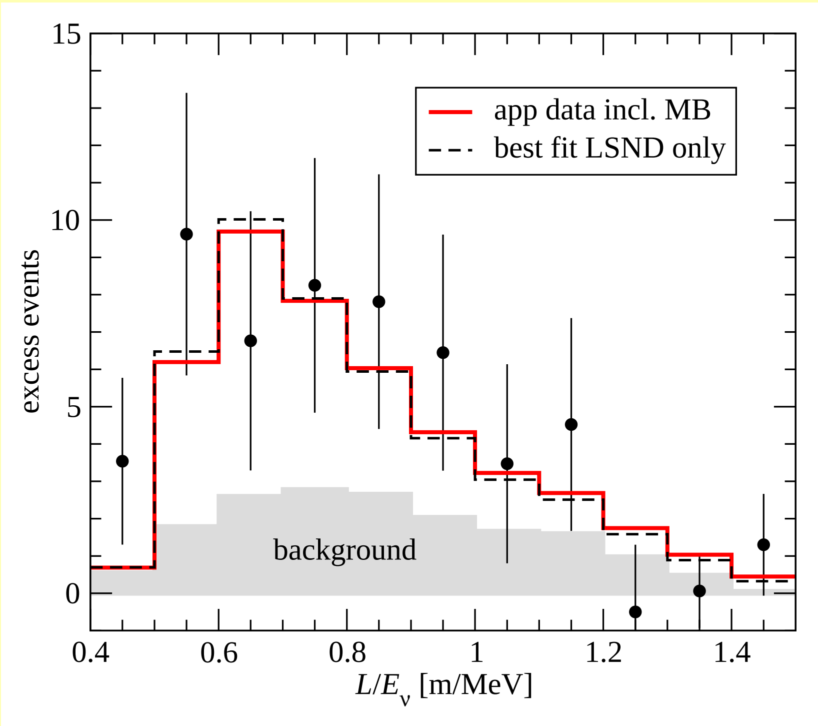
(3+2) appearance data

best fit point spectra:

MiniBooNE



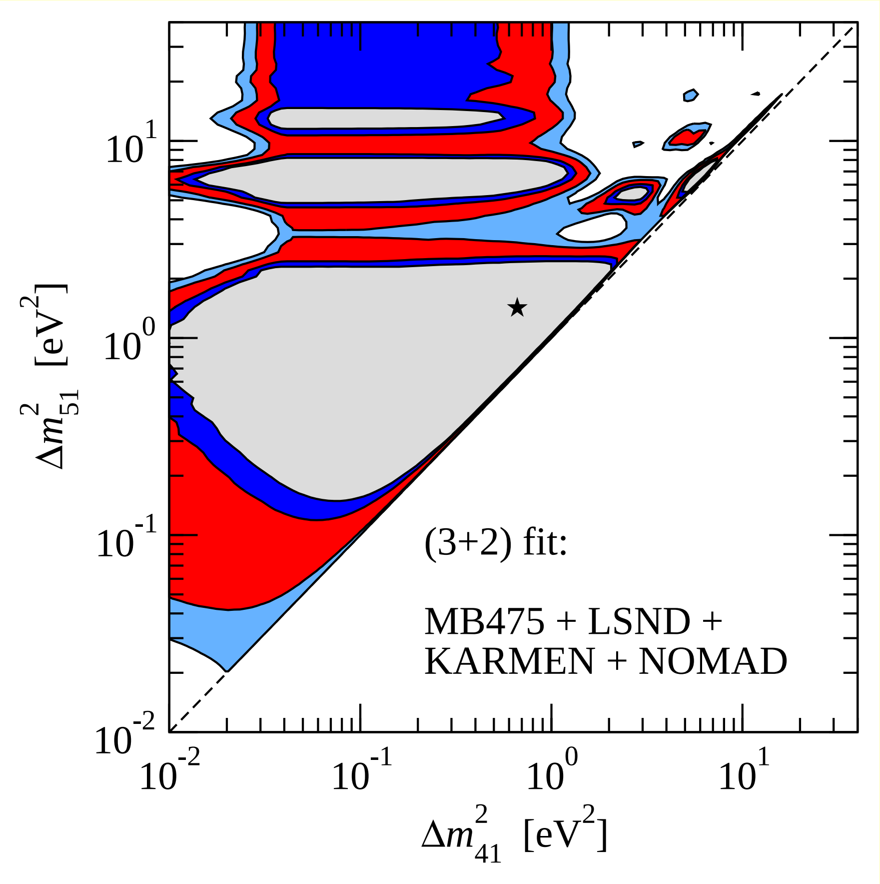
LSND



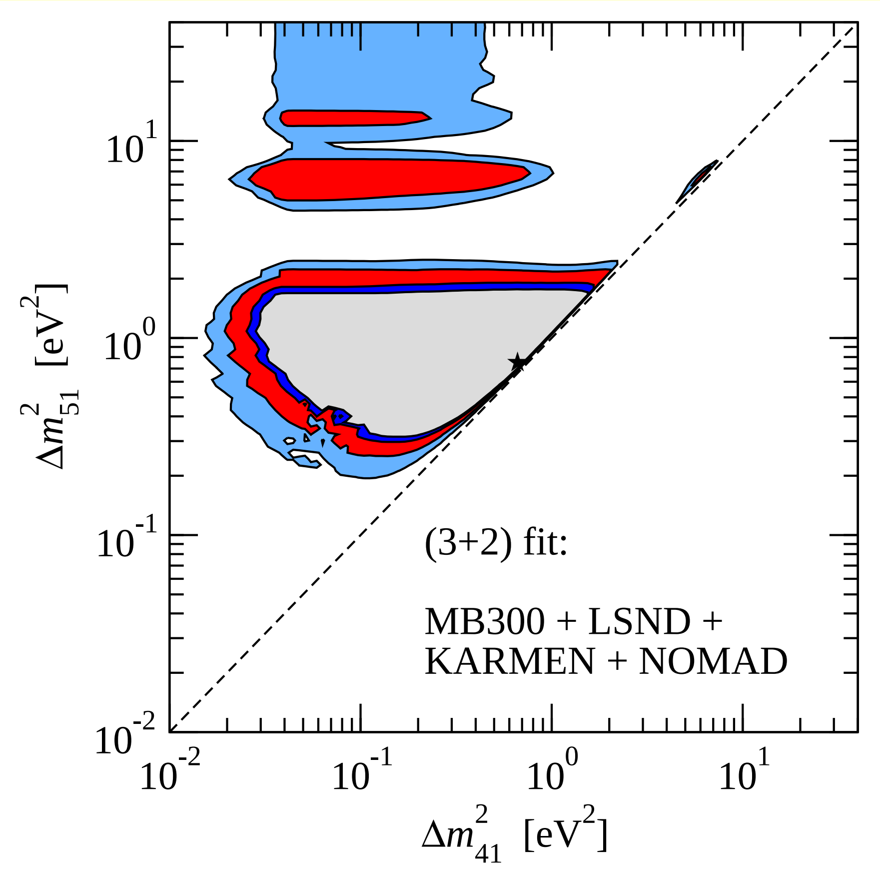
Perfect fit to appearance data

(MB with or without the low energy excess)

(3+2) appearance data



$$\chi^2_{\rm min} = 16.9/(29-5)$$



$$\chi^2_{\rm min} = 18.5/(31-5)$$

(3+2) disappearance data

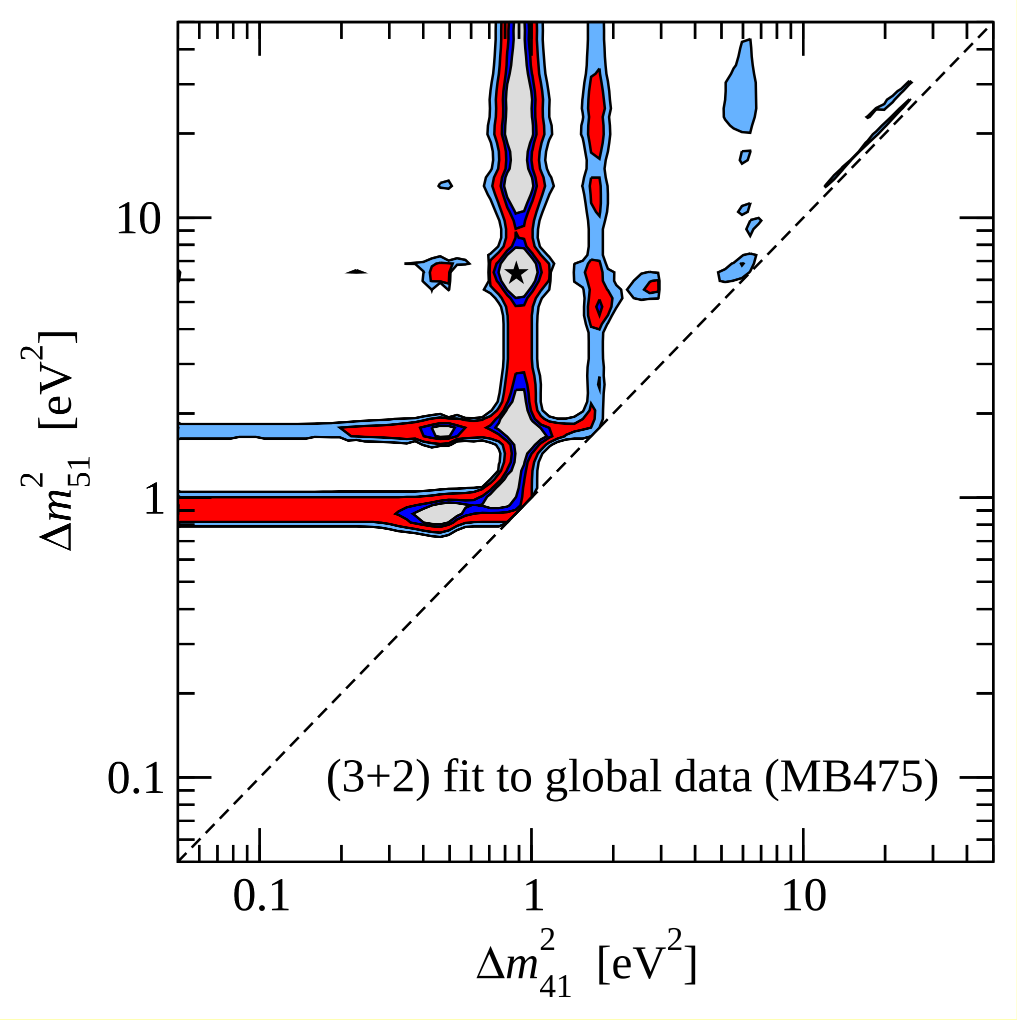
what about the disappearance data?

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

$\Rightarrow$ 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) global



$$\Delta m^2_{41} = 0.89 \text{ eV}^2$$
$$\Delta m^2_{51} = 6.49 \text{ eV}^2$$

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

(3+2) global

testing consistency of disappearance and appearance (incl. MB475) data:

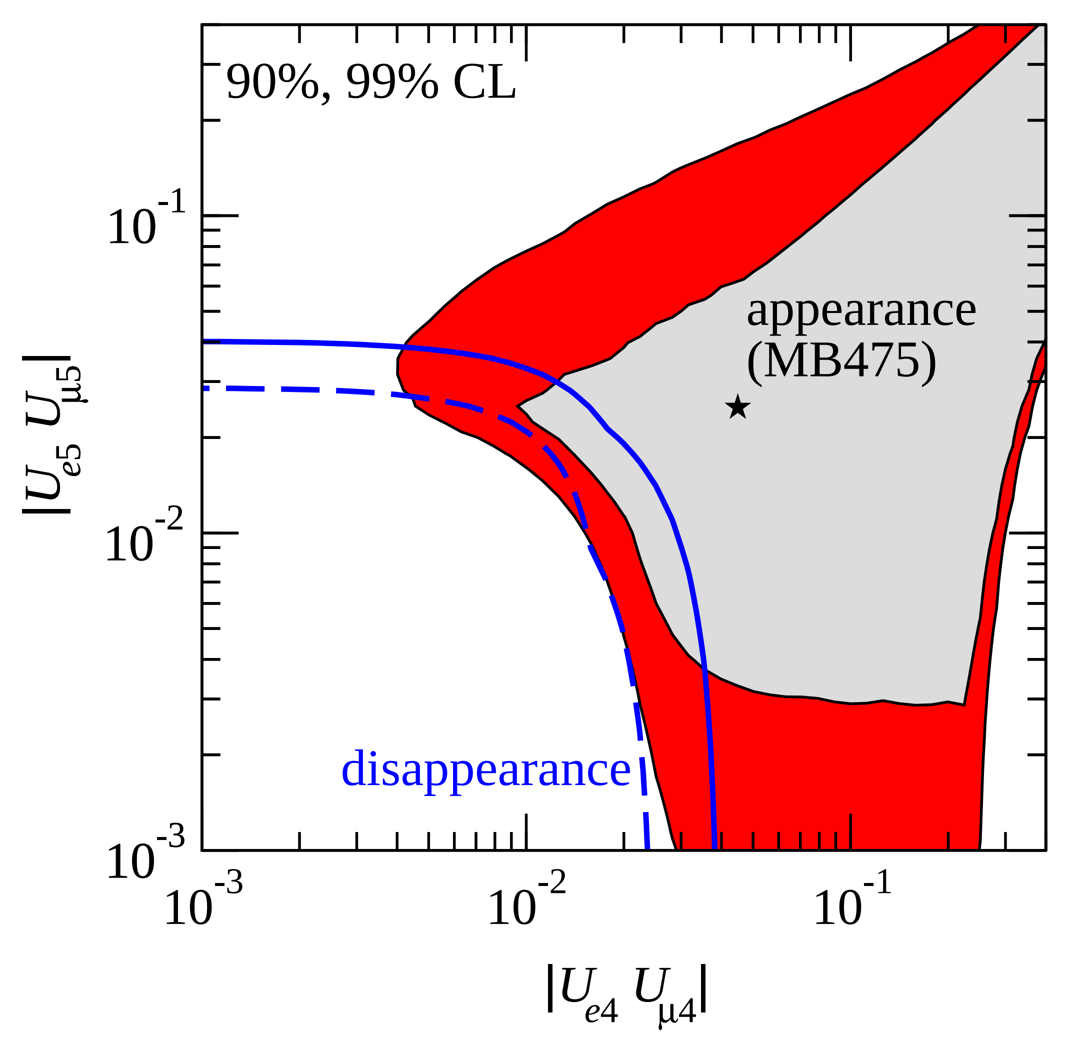
$$\chi^2_{\rm PG} = 17.2\,(4\,{\rm dof}) \qquad {\rm PG} = 0.18\%$$

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

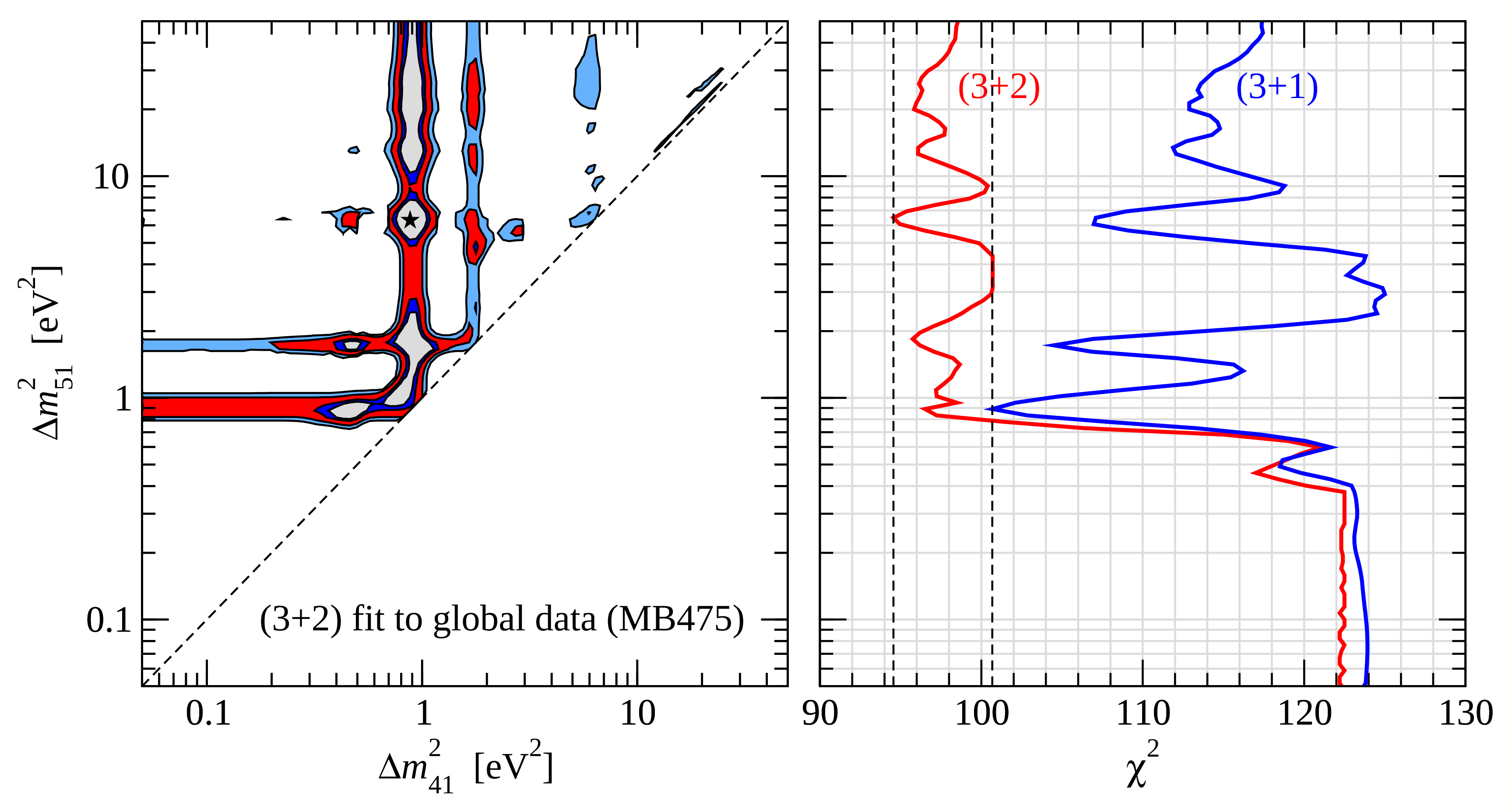
inconsistency at about 3.1σ

without MB: $\chi^2_{\rm PG} = 17.5$

(3+2) app vs disap



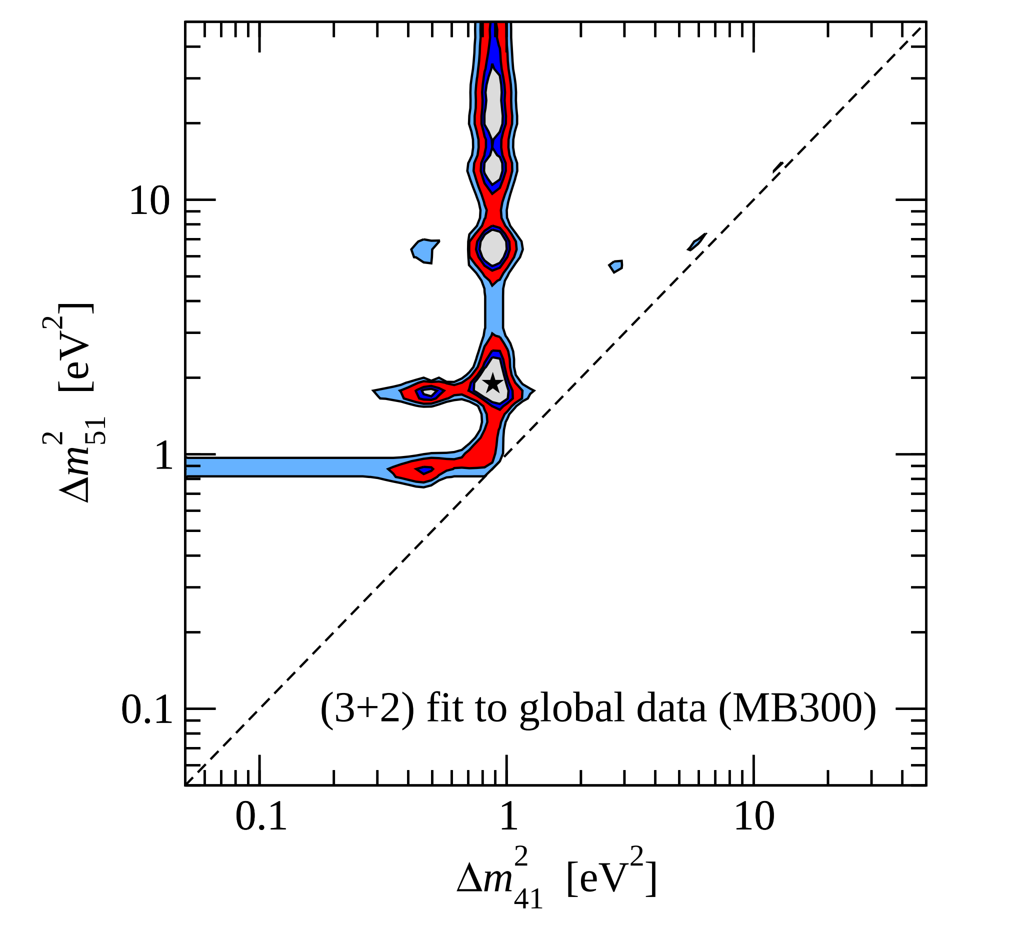
(3+2) vs (3+1)



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

MB300 in (3+2) schemes

including the full MB spectrum:



$\Delta m^2_{41} = 0.87$ eV^2
$\Delta m^2_{51} = 1.91$ eV^2

$\chi^2_{\rm min} = 104.4/(109-7)$
$(\chi^2_{\rm min,MB475} = 94.5)$

$\chi^2_{\rm PG} = 25.1/4$
$\rm PG = 4.8 \times 10^{-5}$ (4σ)

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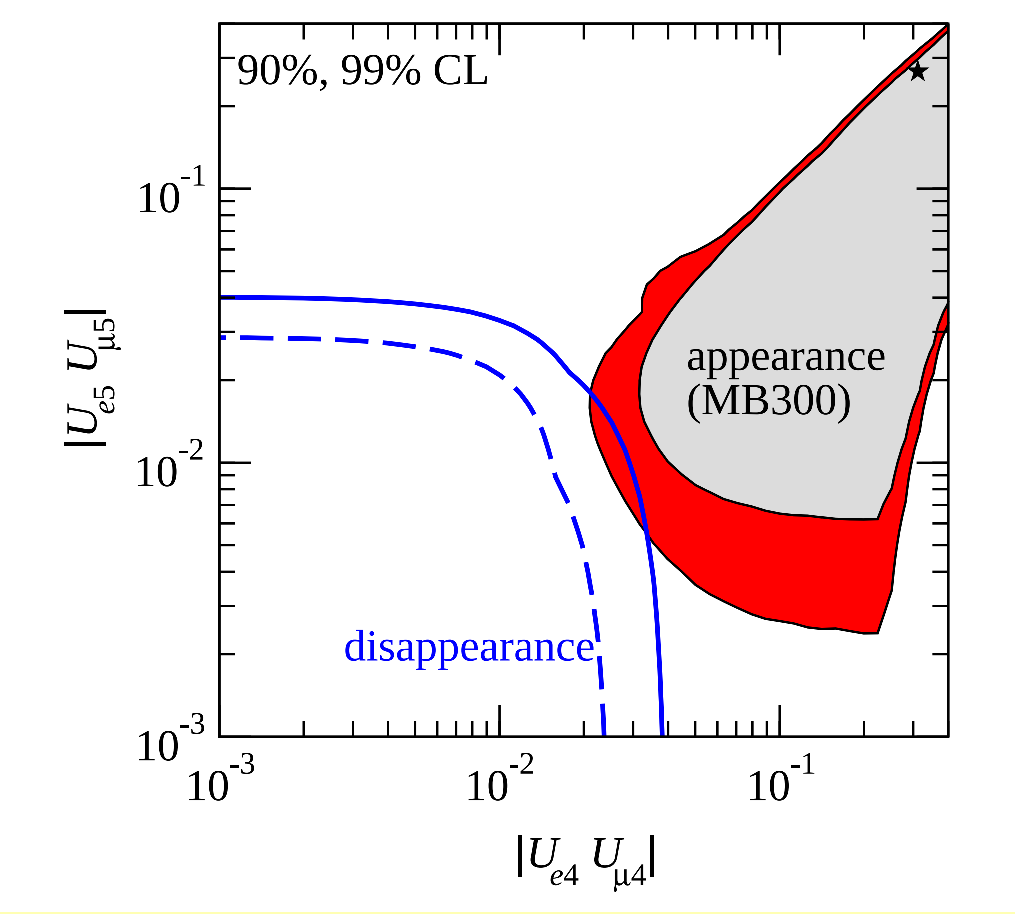

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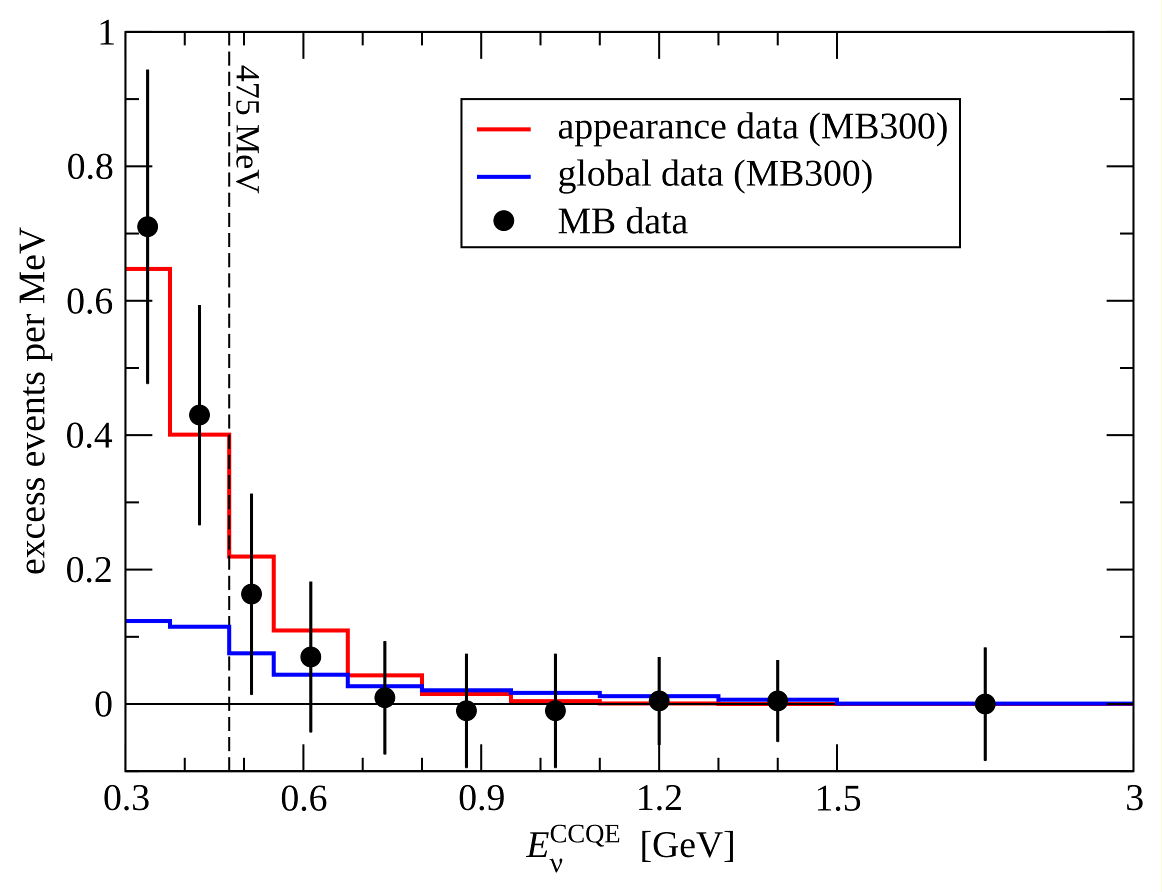
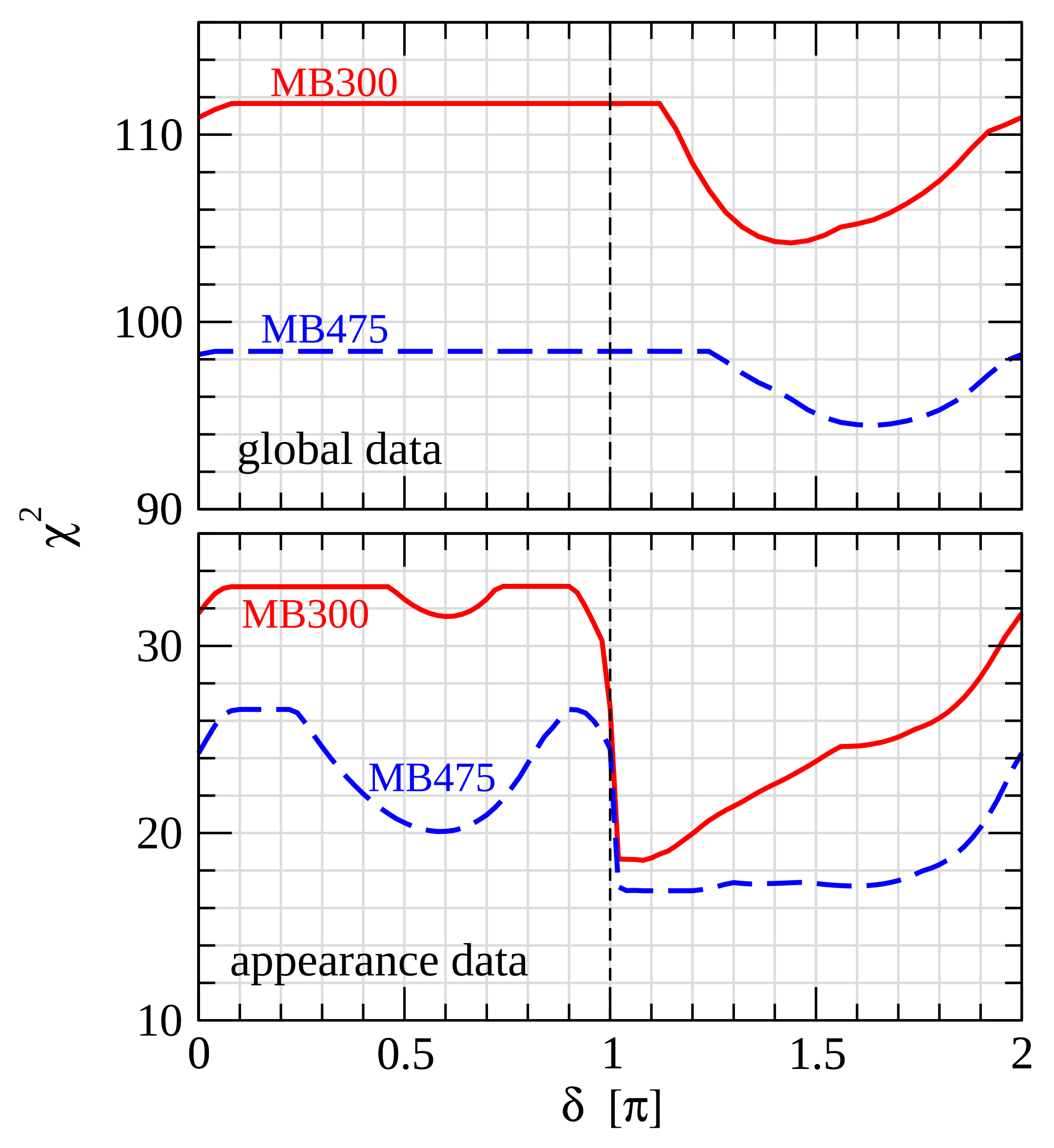


the MB low energy excess is not reproduced at the global best fit point

CP violation



adding another sterile: (3+3)

(3+3) probabilities

appearance prob.:

$$P_{\nu_\mu \to \nu_e} = 4 \sum_i |U_{ei} U_{\mu i}|^2 \sin^2 \phi_{i1}$$

$$+8 \sum_{i,j<i} |U_{ei} U_{\mu i} U_{ej} U_{\mu j}| \sin \phi_{i1} \sin \phi_{j1} \cos(\phi_{ij} - \delta_{ij}) \,, \qquad i,j = 4,5,6\,,$$

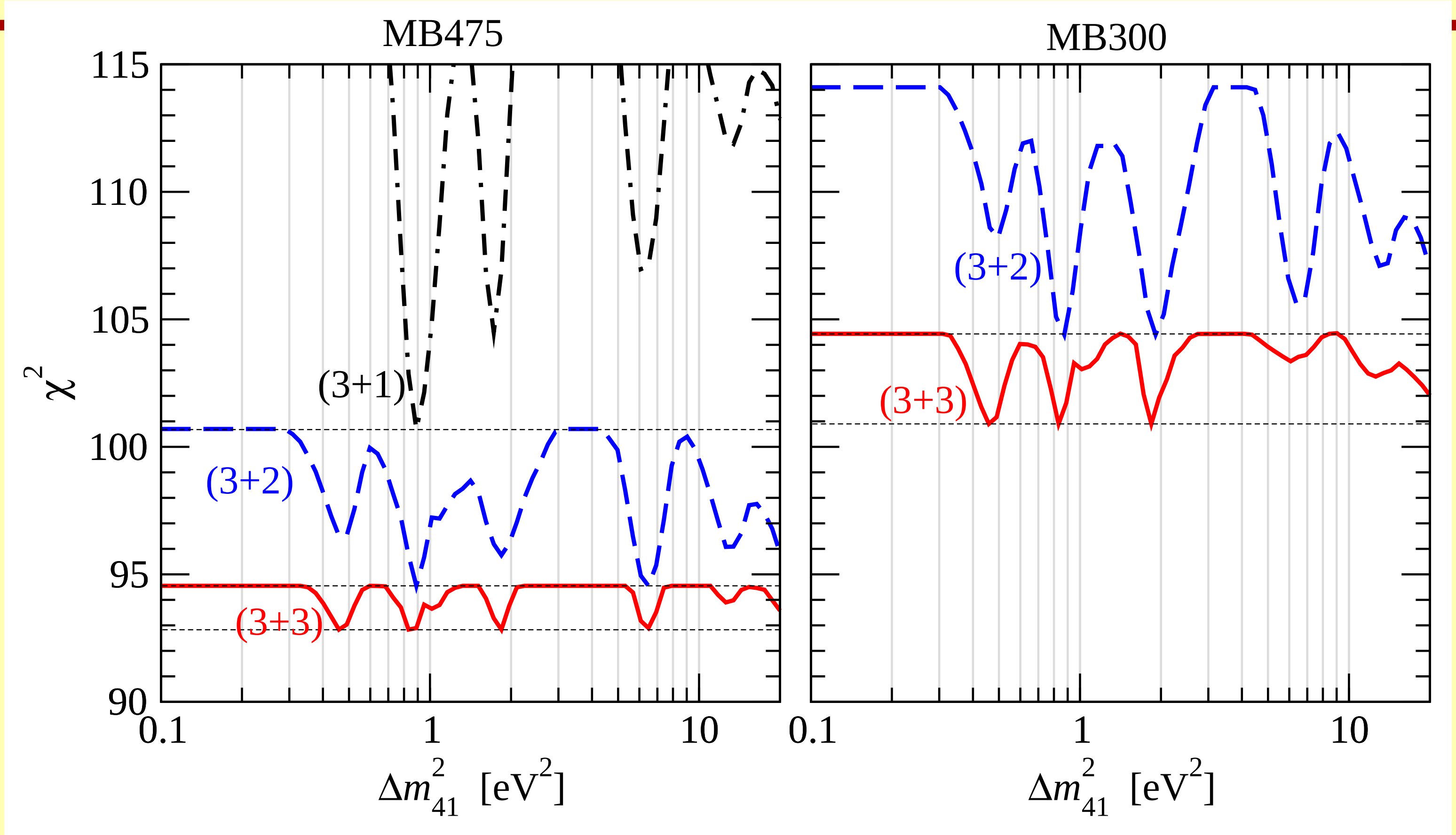
survival prob.:

$$P_{\nu_\alpha \to \nu_\alpha} = 1 - 4 \left(1 - \sum_i |U_{\alpha i}|^2\right) \sum_i |U_{\alpha i}|^2 \sin^2 \phi_{i1}$$

$$- 4 \sum_{i,j<i} |U_{\alpha i}|^2 |U_{\alpha j}|^2 \sin^2 \phi_{ij} \,, \qquad i,j = 4,5,6$$

with: $\phi_{ij} \equiv \dfrac{\Delta m^2_{ij} L}{4E} \,, \qquad \delta_{ij} \equiv \arg\left(U^*_{ej} U_{\mu j} U_{ei} U^*_{\mu i}\right)$

(3+3) global fit



	Δm^2_{41}	Δm^2_{51}	Δm^2_{61}	$\chi^2_{\min}$	$\chi^2_{(3+2)} - \chi^2_{(3+3)}$	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

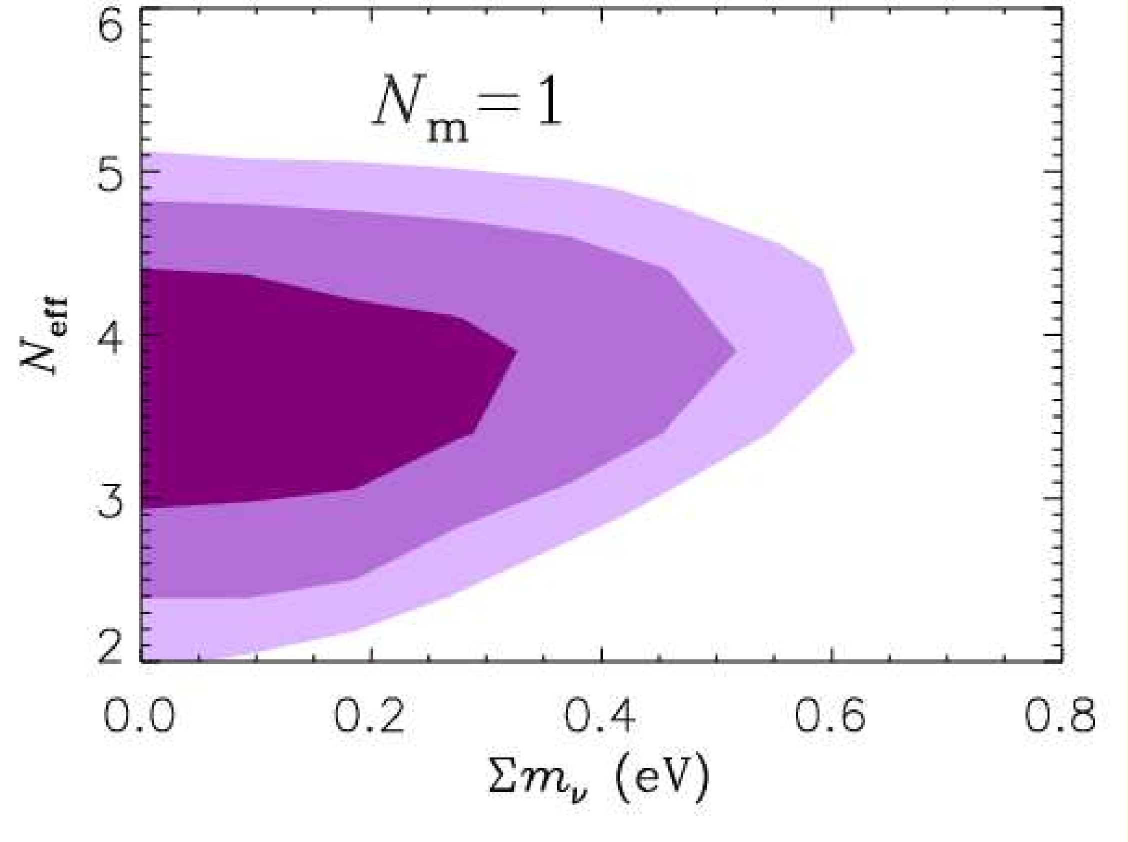
All these sterile neutrino schemes

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

Cosmology

one has to invoke some non-standard mechanism to prevent the equilibration of sterile neutrinos, e.g.,

- primordial lepton asymmetry

  Foot, Volkas, 95

- blocking active-sterile oscillations by some exotic particle physics

  Babu, Rothstein, 92; Bento, Berezhiani, 01

- low reheating temperature

  Gelmini, Palomares-Riuz, Pascoli, 04

More ’exotic’ proposals

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
- 2 decaying sterile neutrinos with CPV

More exotic proposals

KamLAND+atmospheric antineutrino data

- 3-neutrin… Murayama, Yanagida 01; Barenboim, B… Lykken 02; Gonzalez-Garcia, Maltoni, Schwetz 03
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KamLAND+atmospheric antineutrino data

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KARMEN, TWIST

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- Two decaying sterile neutrinos (CP violation)

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M. Maltoni, T. Schwetz, arXiv:0705.0107 [hep-ph]

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Thank you for your attention!

Additional slides

4-neutrino oscillation parameters

3 mass-squared differences + 6 mixing angles $\longrightarrow$ 9 parameters

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$$d_\alpha = 1 - \sum_i |U_{\alpha i}|^2 \quad \text{with } i \in \text{atmospheric mass states}$$

note that in (2+2): $\eta_\alpha = d_\alpha$

$$\longrightarrow \quad \boxed{\Delta m^2_{\rm sol},\ \Delta m^2_{\rm atm},\ \Delta m^2_{\rm LSND},\ \theta_{\rm sol},\ \theta_{\rm atm},\ \theta_{\rm LSND},\ \eta_s,\ \eta_e,\ d_\mu}$$

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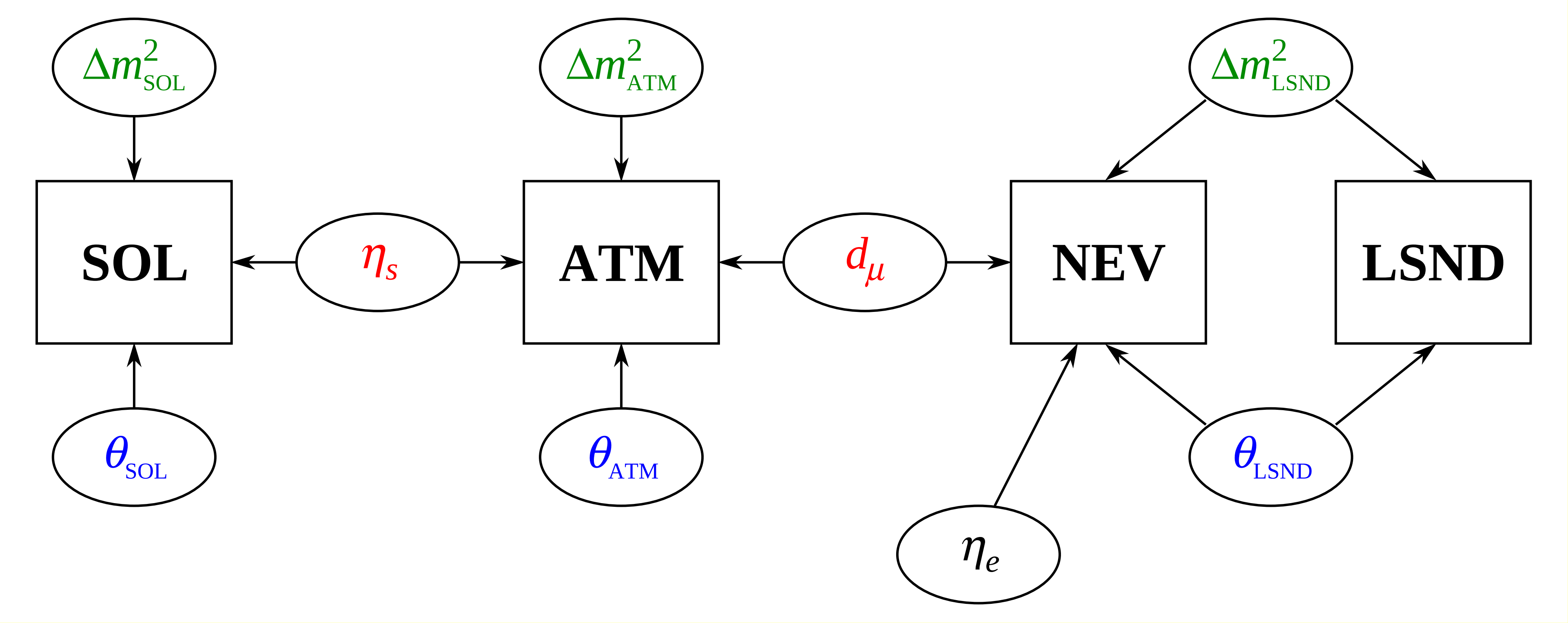
approximations:

- $\Delta m^2_{\rm sol} \ll \Delta m^2_{\rm atm} \ll \Delta m^2_{\rm LSND}$
- $\eta_e \approx 1$ for solar and atmospheric oscillations (reactor data)

Coupling of the data sets



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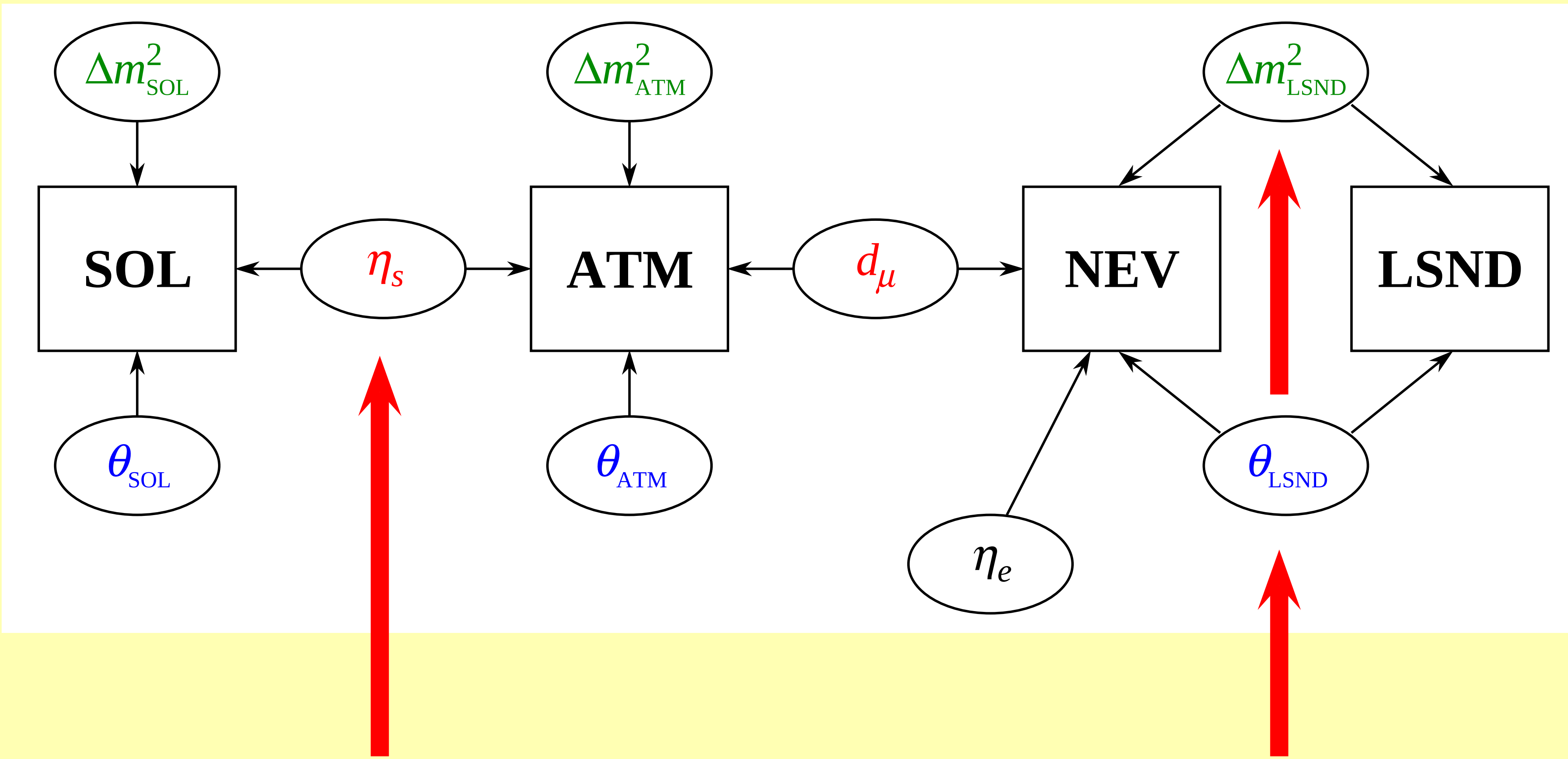

important for (2+2)

important for (3+1)

Compatibility of independent data sets

parameter goodness-of-fit (PG) Maltoni, Schwetz, hep-ph/0304176

$$\chi^2_{\mathrm{PG}} \equiv \chi^2_{\mathrm{min,global}} - \sum_i \chi^2_{\mathrm{min},i}$$

$$= \sum_i \Delta\chi^2_i(\mathrm{best\ fit})$$

i: data sets

evaluate χ^2_{PG} for # dof = # of params in comon

measure for the price one has to pay by the combination, relative to the fit of the sets individually