CP violation in neutrino oscillations and new physics

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Based on

G. Altarelli & D.M.,

Nucl.Phys.B809:158-182,2009

Neutrino oscillation searches: present and future

- **The present**
  - Solar sector

$$\Delta m^2_{21} = 7.67^{+0.67}_{-0.61} \times 10^{-5}\, eV^2$$
$$\theta_{12} = 34.5^{+4.8}_{-4.0}$$

Gonzalez-Garcia&Maltoni,
Phys.Rept.460:1-129,2008

  - Atmospheric sector

$$\Delta m^2_{31} = 2.46^{+0.47}_{-0.42} \times 10^{-3}\, eV^2$$
$$\theta_{23} = 42.3^{+11.3}_{-7.7}$$

- **The future**

$$\theta_{13} \quad - \quad \delta_{CP}$$

And also
- mass hierarchy
- octant of the atmospheric angle

In this talk, we will look at the future of neutrino oscillation searches

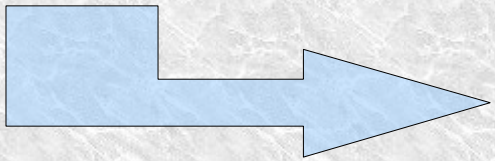
- **Our starting point:**

  1 - a positive signal of CP violation has been established in neutrino oscillation experiments

  2 – θ_{13} has been measured

- **Our question:**

  are the observed phenomena compatible with the simple picture where all CP quantities in ν oscillation sector are described in terms of one parameter only?



$$\delta_{CP} \quad \text{or} \quad \text{equivalently}$$

$$J \sim \cos\theta_{13} \sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12} \sin\delta$$

Strategy to face the problem

- **Our observables are CP asymmetries**

  from one of them we can measure δ

we get predictions for the other asymmetries !

- **We measure them and:**

- If the results are compatible with expectations:

  the Standard Model picture is right

- if the results are not compatible with expectations

  New Physics is at work !

Strategy to face the problem

To perform the test we need

- ✔ A predictive model for new physics in ν oscillation to compute asymmetries
- ✔ Experimental facilities where to make the test

Many possible choices in both cases

We decide to use:

- Minimal Unitarity Violating model (MUV)

  sufficiently structured to provide indicative estimates of new physics effects
- The same experimental facilities proposed to measure δ and solve the problem of degeneracies

Summary of the MUV model

Antush et al., JHEP 0610:084,2006

Fernandez Martinez et al.,Phys.Lett.B649:427-435,2007

- **Main assumption:**

the complete theory of ν oscillation is unitary but the effective low energy mixing matrix in NOT

Low energy mixing matrix

$$N = (1+\eta)\,U_{PMNS}$$

Hermitian matrix:
9 new parameters

Unitary matrix:
4 independent parameters

Summary of the MUV model

- The structure of the matrix elements of *N* can be obtained from **oscillation experiments** (especially disappearance) and **weak decays**

$$N = (1+\eta) U_{PMNS}$$

Phases unconstrained

$$|\eta| = \begin{pmatrix} |\eta_{ee}| < 1.5\cdot 10^{-3} & |\eta_{e\mu}| < 3.6\cdot 10^{-5} & |\eta_{e\tau}| < 8.0\cdot 10^{-3} \\ |\eta_{\mu e}| < 3.6\cdot 10^{-5} & |\eta_{\mu\mu}| < 2.5\cdot 10^{-3} & |\eta_{\mu\tau}| < 4.9\cdot 10^{-3} \\ |\eta_{\tau e}| < 8.0\cdot 10^{-3} & |\eta_{\tau\mu}| < 4.9\cdot 10^{-3} & |\eta_{\tau\tau}| < 2.5\cdot 10^{-3} \end{pmatrix}$$

Main features: all new moduli at O(10^{-2}-10^{-3}) but $\eta_{e\mu}$ which is of O(10^{-5})

Experimental facilities

To perform the check, the "experiments" should be so that they are:

- ✔ **Able to measure θ_{13} and the standard CP phase**
- ✔ **Able to measure e, μ and τ neutrinos**

	Available channels	Experiments	L (Km)	<Eν>(GeV)
Super-Beams (Conventional beam from π decay)	$\nu_\mu \to \nu_\mu$ $\nu_\mu \to \nu_e$	T2HK SPL	295 130-732	0.75 0.3
β-Beams (ν from radioactive ion decay)	$\nu_e \to \nu_e$ $\nu_e \to \nu_\mu$ +CP conjugates	LEβB(low energy) HEβB(high energy)	130 732	0.4 1
Neutrino Factories (ν from μ decay)	$\nu_e \to \nu_{e,\mu,\tau}$ $\bar{\nu}_\mu \to \bar{\nu}_{e,\mu,\tau}$ +CP conjugates	NF@4000 (suitable for small θ_{13}) NF@1500 (suitable for large θ_{13})	4000 1500	30 (ν_e) / 35 (ν_μ)

Asymmetries: Standard vs MUV

- **preliminaries**

We work "close" to the tri-bimaximal mixing $U_{PMNS} \sim U_{TBM} = \begin{pmatrix} \sqrt{\frac{2}{3}} & \sqrt{\frac{1}{3}} & 0 \\ -\sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}} \\ \sqrt{\frac{1}{6}} & -\sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}} \end{pmatrix}$

Harrison et al,Phys.Lett.B 530 (2002)

The deviation from TBM are parametrized as follows

King,Phys.Lett.B 659 (2008)

$$s_{13} = \frac{r}{\sqrt{2}} \qquad s_{12} = \frac{1}{\sqrt{3}}(1+s) \qquad s_{23} = \frac{1}{\sqrt{2}}(1+a)$$

For the sake of simplicity, we work expanding probabilities and asymmetries up to second order in these small quantities:

$$r, s, a \sim O(10\%), \quad \xi = \Delta m^2_{21} / \Delta m^2_{31} \sim 1/30, \quad \eta_{\alpha\beta}$$

$$\Delta m^2_{21} \, L/E_\nu << 1$$

Asymmetries: Standard vs MUV

- **We work in the vacuum limit to give more transparent analytical formulae**

$$A_{e\mu} = \frac{P(\nu_e -> \nu_\mu) - P(\bar{\nu}_e -> \bar{\nu}_\mu)}{P(\nu_e -> \nu_\mu) + P(\bar{\nu}_e -> \bar{\nu}_\mu)}$$

$$A^{SM}_{e\mu} = \frac{N^{SM}_{e\mu}}{D^{SM}_{e\mu}} = \frac{12\, r\, \Delta_{21} \sin\delta \sin^2\Delta_{31}}{4\Delta^2_{21} + 9 r^2 \sin^2\Delta_{31} + 6r\,\Delta_{21}\cos\delta \sin 2\Delta_{21}}$$

$$A^{MUV}_{e\mu} = \frac{N^{SM}_{e\mu} + 18 r\, \eta_{e\mu} \sin 2\Delta_{31} \sin(\delta - \delta_{e\mu})}{D^{SM}_{e\mu} + 18\, r \sin^2\Delta_{31}[\eta_{e\tau}\cos(\delta - \delta_{e\tau}) - \eta_{e\mu}\cos(\delta - \delta_{e\mu})]}$$

- The new CP-violating terms in the numerator contain $\eta_{e\mu}$ and $\eta_{e\tau}$ and the corresponding CP phases
- They show a different L/E_ν dependence
- The denominator also contains new (CP-conserving) terms in $\delta_{e\mu}$ and $\delta_{e\tau}$ (only important for very small θ_{13})

Asymmetries: Standard vs MUV

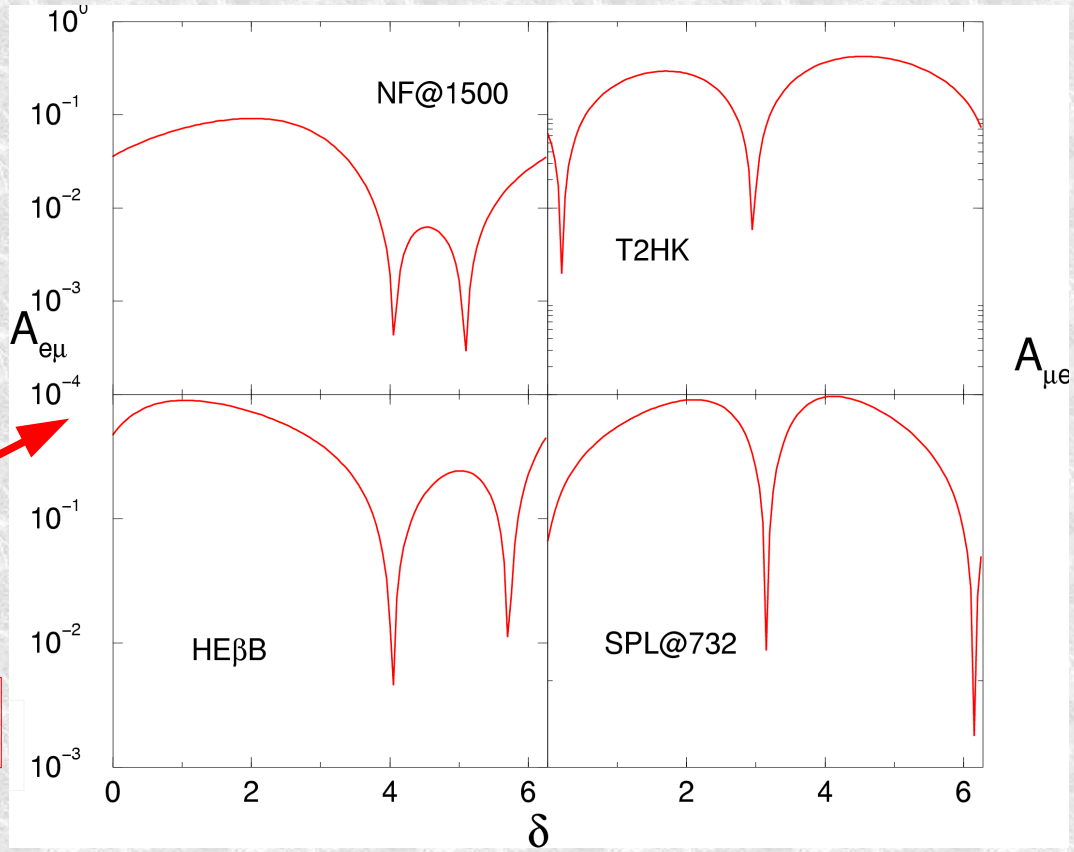
however

$\eta_{e\mu}$ is strongly constrained

$A_{e\mu}^{MUV}$ does not deviate much from the Standard Model result !

✯ To prove this numerically, we evaluated the asymmetry in both SM and MUV models as a function of δ

Standard Model $\sin(\theta_{13})=0.1$



Results obtained using EXACT probabilities

Asymmetries: Standard vs MUV

however

$\eta_{e\mu}$ is strongly constrained

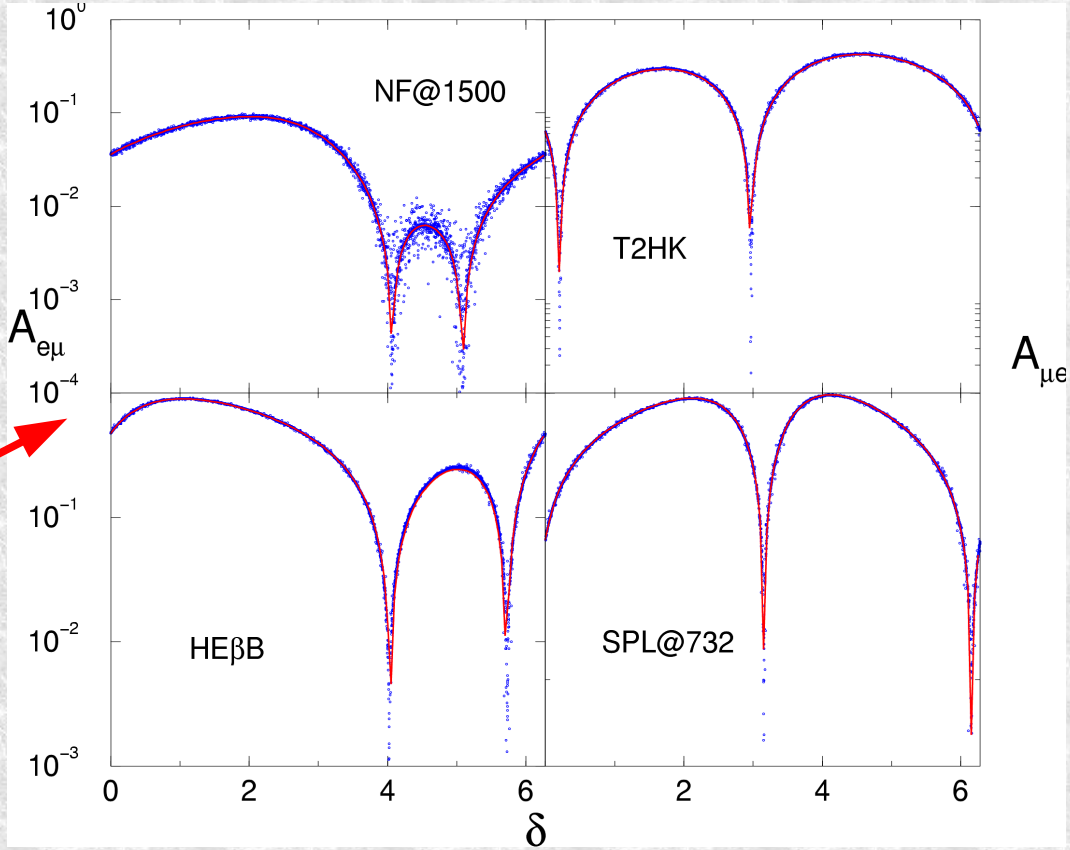
$A_{e\mu}^{MUV}$ does not deviate much from the Standard Model result !

MUV

$\sin(\theta_{13})=0.1$

MUV predictions are computed as follows:

- η's and phases are extracted randomly flat in their allowed ranges
- For each set of values of η's and phases we get a MUV prediction, which is a point in the $(\delta, A_{e\mu})$-plane



Results obtained using EXACT probabilities

Asymmetries: Standard vs MUV

- **The other two asymmetries are more interesting because they can differ quite a lot from the SM results !!!**

$A_{e\tau}$

$$A_{e\tau}^{SM} = \frac{N_{e\tau}^{SM}}{D_{e\tau}^{SM}} = \frac{12\, r\, \Delta_{21} \sin\delta \sin^2\Delta_{31}}{-4\Delta_{21}^2 - 9 r^2 \sin^2\Delta_{31} + 6r\,\Delta_{21}\cos\delta \sin 2\Delta_{21}}$$

$$A_{e\tau}^{MUV} = \frac{N_{e\tau}^{SM} - 6\eta_{e\tau}\left[3r \sin 2\Delta_{31} \sin(\delta - \delta_{e\tau}) + \Delta_{21} \sin\delta_{e\tau}(3 + \cos 2\Delta_{31})\right]}{D_{e\mu}^{SM} + 6\eta_{e\tau}\left[3r \sin^2\Delta_{31} \cos(\delta - \delta_{e\tau}) + \Delta_{21} \sin 2\Delta_{31}\right]}$$

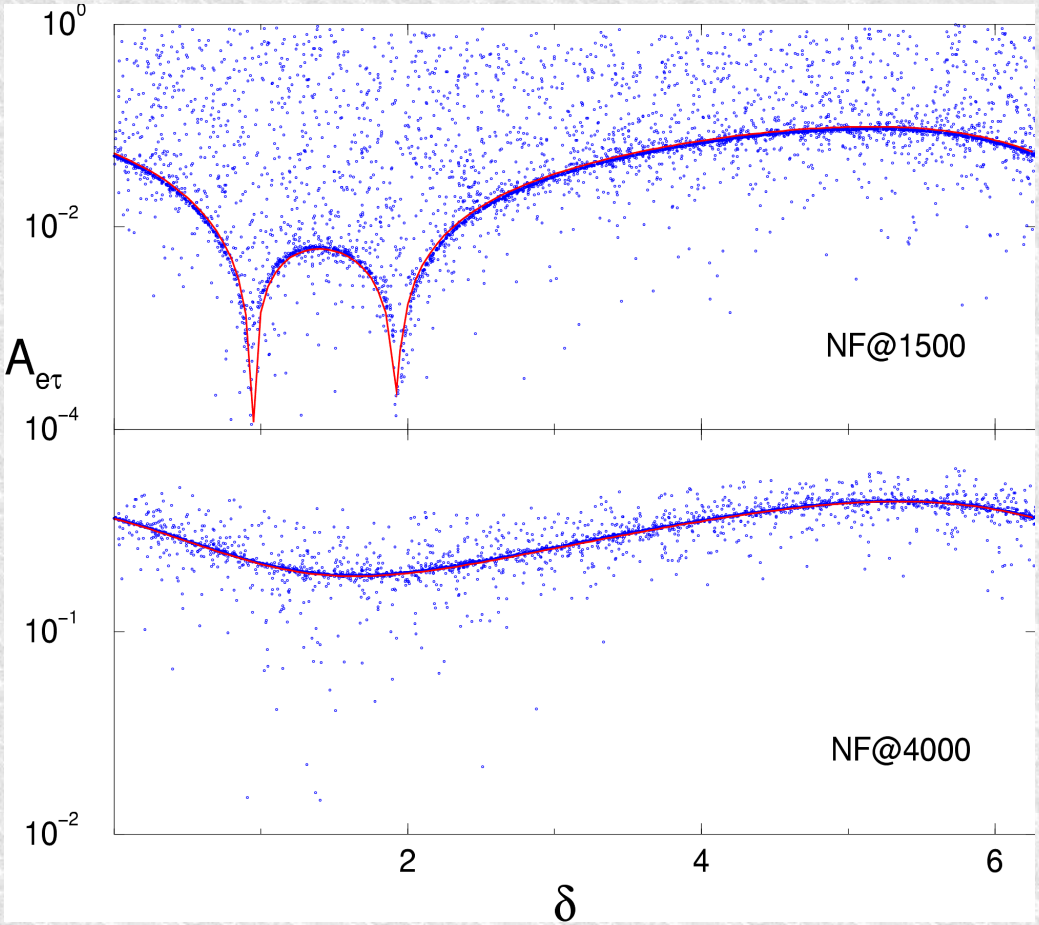
- The new CP-violating terms are only linearly suppressed in the small $\eta_{e\tau}$ parameter
- Whenever $\Delta_{21} \sim \eta_{e\tau}$, the $A_{e\tau}^{MUV}$ can be quite different with respect to the SM result ---> <u>better at smaller baselines</u>

Asymmetries: Standard vs MUV

- **The other two asymmetries are more interesting because they can differ quite a lot from the SM results !!!**

$A_{e\tau}$

$\sin(\theta_{13})=0.1$



- Higher density points around the SM results (solid red lines)
- Larger deviations from SM results for smaller baselines, as expected

Asymmetries: Standard vs MUV

- the μτ asymmetry behaves even better...

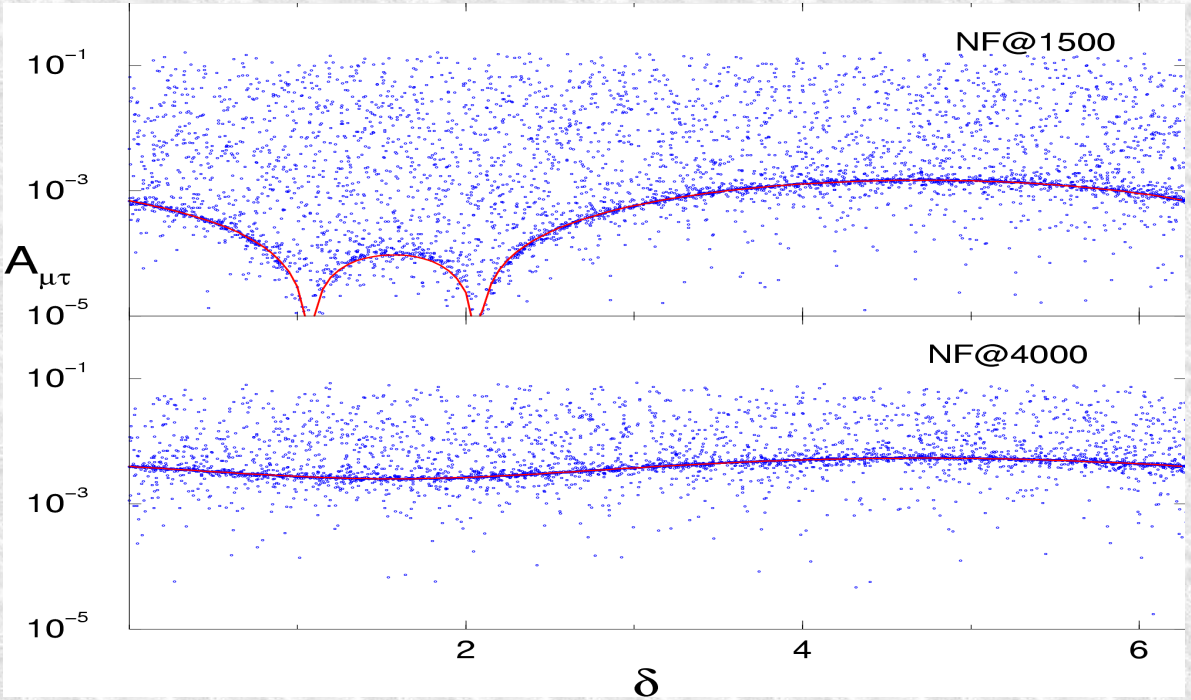
$A_{\mu\tau}$

$$A_{\mu\tau}^{SM} = \frac{4}{3} r \Delta_{21} \sin\delta$$

Very small because doubly suppressed by r and Δ_{21} ~ O(10^{-3})

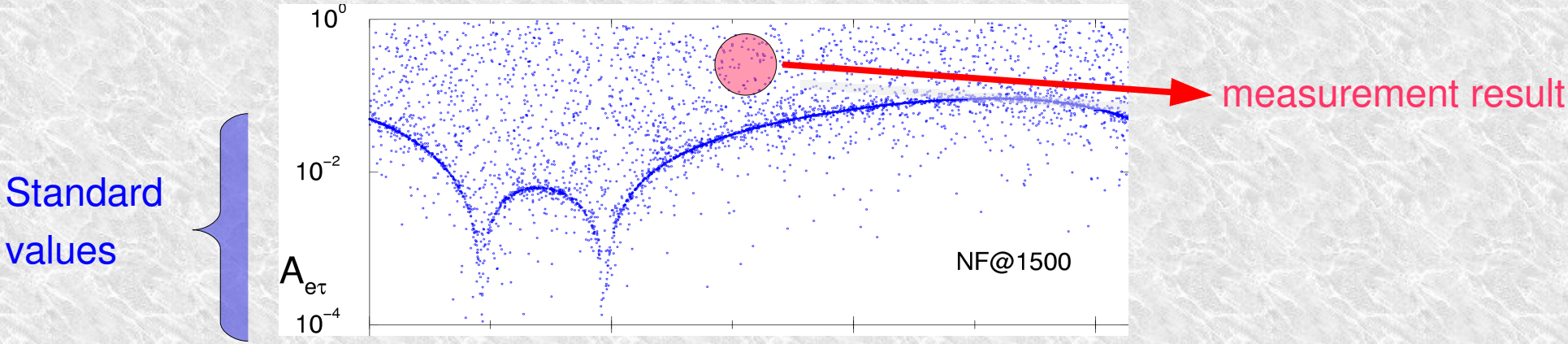
$$A_{\mu\tau}^{MUV} = A_{\mu\tau}^{SM} - 4\eta_{\mu\tau} \cot\Delta_{31} \sin\delta_{\mu\tau}$$

Can reach values as large as ~ O(10^{-1})!



Consistency check of the Standard Model

- the easiest situation: one or more asymmetries are not compatible with the standard bound



- A more difficult situation: any measured asymmetry is compatible with the bounds. Then the question is:

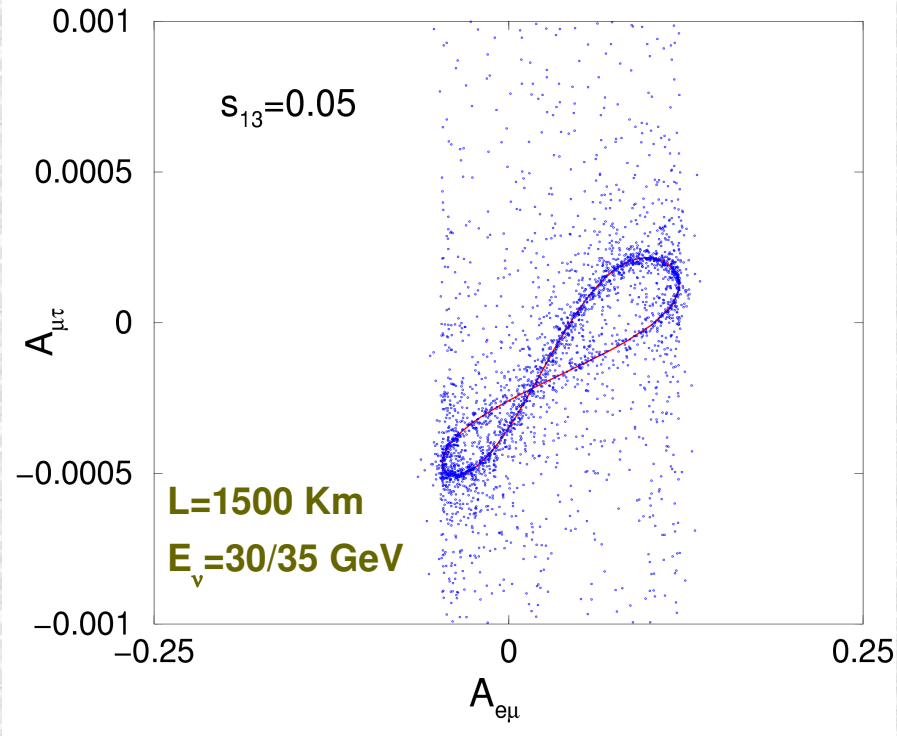
are they compatible to each other?

To answer both questions simultaneoulsy we eliminate δ and study $A_{e\tau}$ and $A_{\mu\tau}$ as a function of $A_{e\mu}$

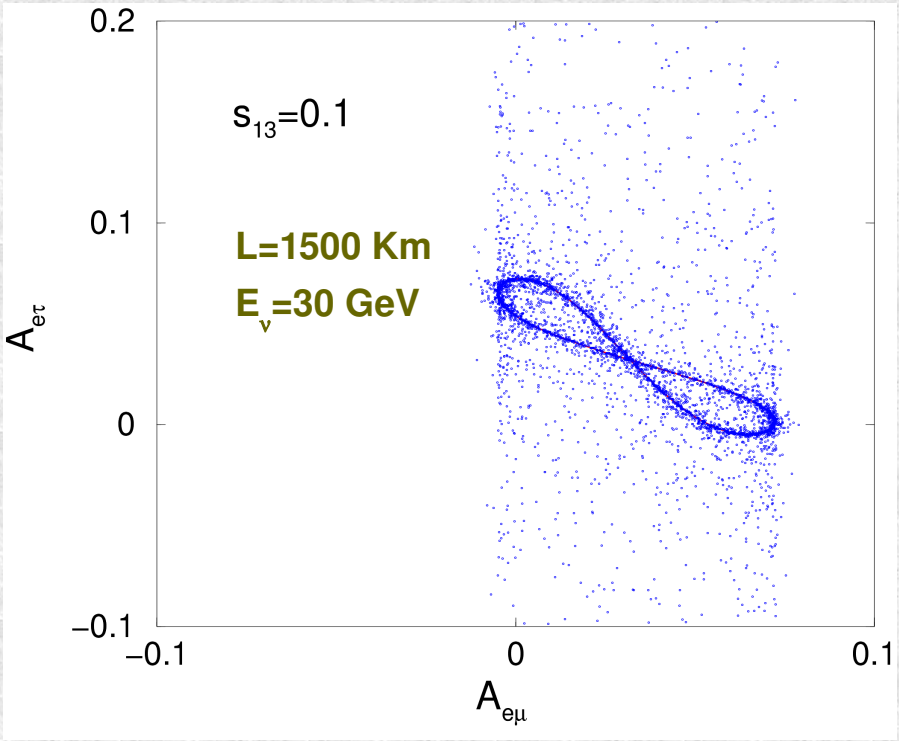
Consistency check of the Standard Model

- In the Standard Model the resulting plots are in the form of closed lines
- The MUV effects is to fill a larger parameter space

$(A_{e\mu}, A_{\mu\tau})$



$(A_{e\mu}, A_{e\tau})$



Due to the large spread induced by MUV, even with a moderate precision a meaningful test of the PMSN mechanism can be achieved

But what is the expected precision on $A_{\alpha\beta}$?

- Let us make some estimate based on simulations of ν-factory
- We work with *integrated* asymmetries

$$A_{\alpha\beta} = \frac{N_\beta - \bar{N}_\beta}{N_\beta + \bar{N}_\beta}$$

where

$$N_\beta = \int dE_\nu P_{\alpha\beta} \sigma_\beta \frac{d\phi_\alpha}{dE_\nu} \varepsilon_\beta \qquad \bar{N}_\beta = \int dE_\nu P_{\bar{\alpha}\bar{\beta}} \sigma_{\bar{\beta}} \frac{d\phi_{\bar{\alpha}}}{dE_\nu} \varepsilon_{\bar{\beta}}$$

σ_β = cross section for producing the lepton β

ε_β = detector efficiency to reveal the lepton β

ϕ_α = initial neutrino flux

β can be μ or τ → **We need different detector technologies**

But what is the expected precision on $A_{\alpha\beta}$?

About detector technologies

for $\nu_e \rightarrow \nu_\mu$ transition

(golden channel)

- We use a magnetized iron detector (MIND)
- Efficiencies and backgrounds
  as described in A.Cervera at "Golden07"

See also:

ISS Physics Working Group, arXiv:0710.4947

for ν_τ in the final state

$\nu_e \rightarrow \nu_\tau$

(silver channel)

- We use an OPERA-like detector, as described in A.Donini, D.M., P.Migliozzi, Nucl.Phys.B646:321-349,2002 and A.Autiero et al.,Eur.Phys.J.C33:243-260,2004

$\nu_\mu \rightarrow \nu_\tau$

(discovery channel)

Detailed studied is still missing; we assume X 5 the statistics and backgrounds of the silver channel

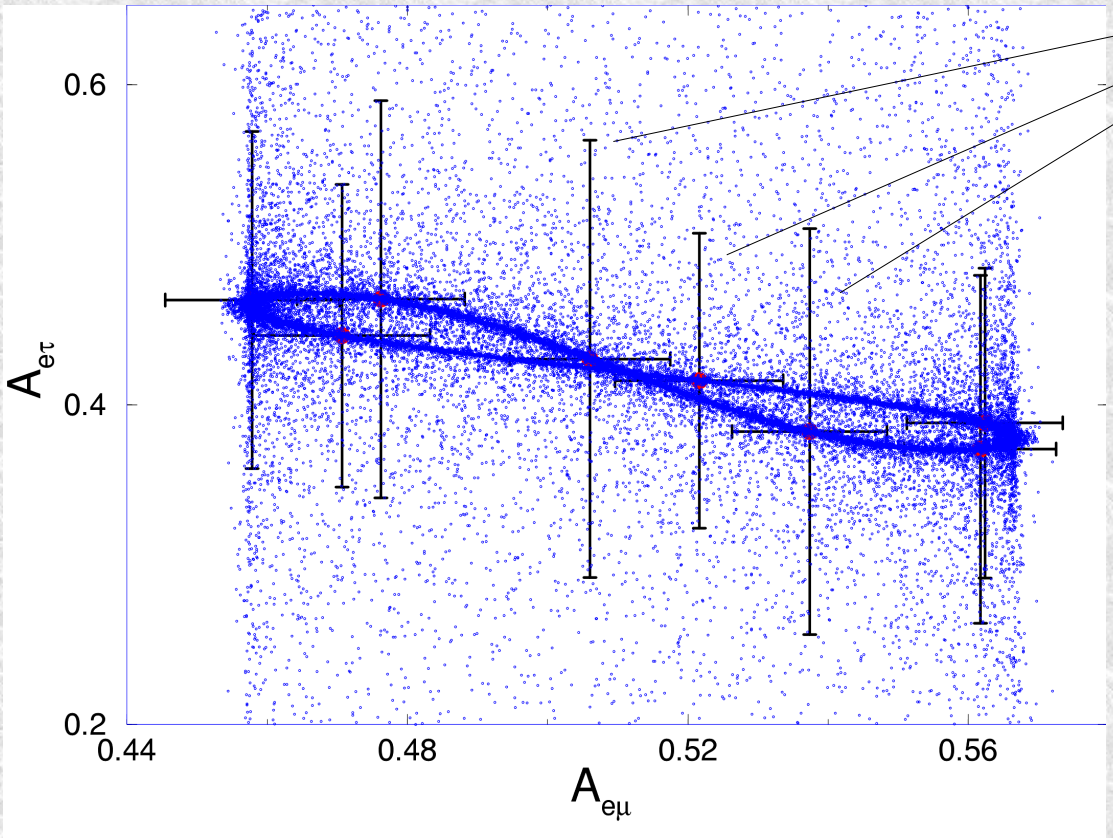
But what is the expected precision on $A_{\alpha\beta}$?

Other parameters of the simulation:

- **L=1500 Km for both detectors**
- **Detector mass = 50 Kton for golden and 10 Kton for silver**
- **Overall systematic errors: 2% and 10% for golden and silver, resp.**

$(A_{e\mu}, A_{e\tau})$

$\sin(\theta_{13})=0.1$

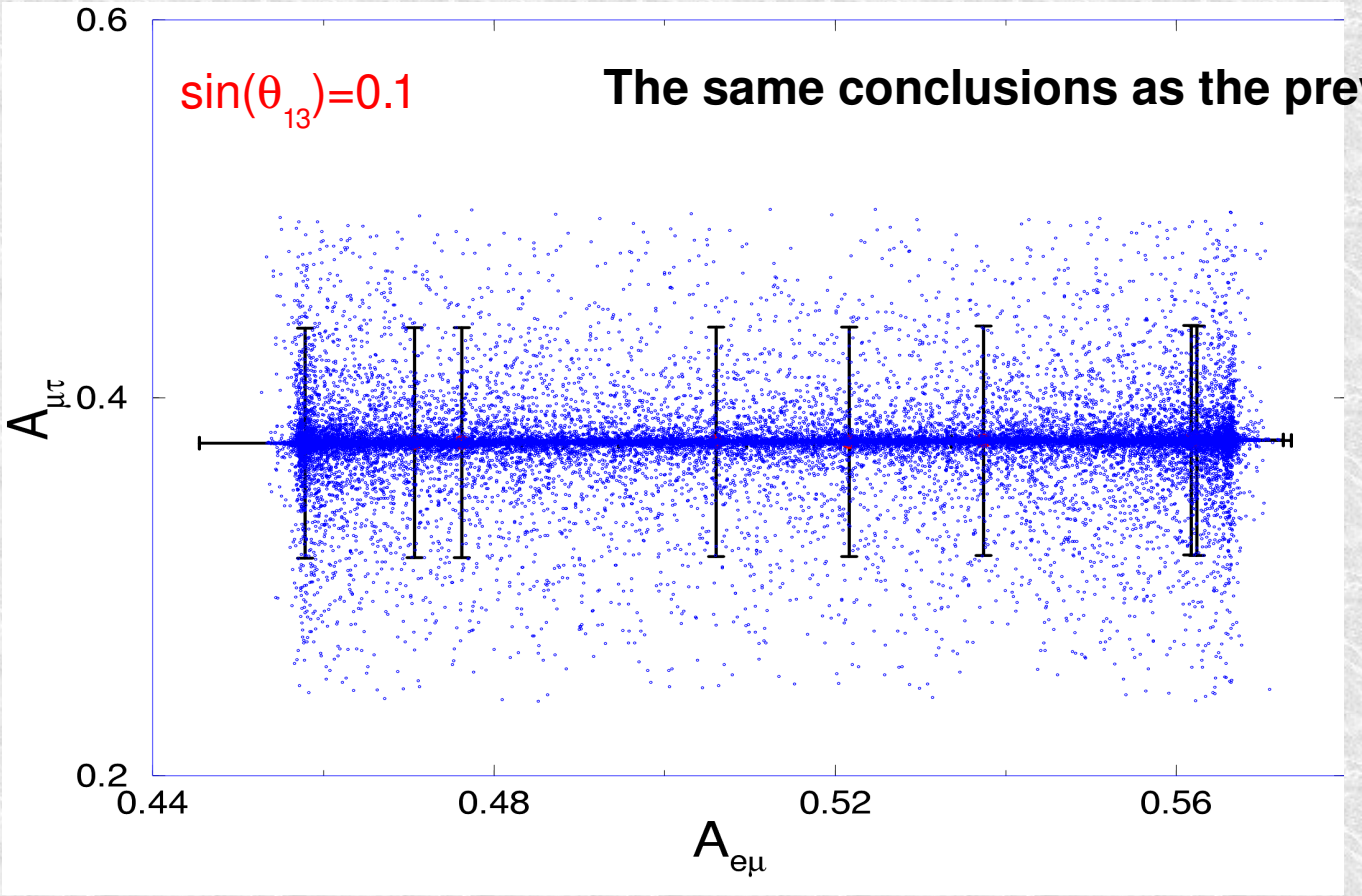


Estimated uncertainties

The asymmetry uncertainty is not as big as to spoil the possibility to see substantial deviation from Standard Model expectations

But what is the expected precision on $A_{\alpha\beta}$?

$(A_{e\mu}, A_{\mu\tau})$



Output of the analysis

the conclusions obtained looking at the asymmetries at the probability level are not invalidated when reliable error estimated are taken into account

The impact of the degeneracies

It could happen that one measures "incompatible" values of asymmetries

new physics is at work

The result is perfectly compatible with the Standard Model but, due to our ignorance about θ_{23} and the sign$[\Delta m^2_{31}]$, we "missed" the correct interpretation of the data

We have to discuss the role of the degeneracies in performing the test !!!

The sign and octant degeneracies

– Suppose (θ_{13},δ)–bar are the values chosen by Mother Nature

– Other (θ_{13},δ) pairs can give the same transition probabilities for neutrinos and antineutrinos at the same time

- Sign degeneracy

The fake (θ_{13},δ) solutions are obtained solving

$$P_{\nu_\alpha \nu_\beta}(\theta_{13}, \delta, -|\Delta m^2_{23}|) = P_{\nu_\alpha \nu_\beta}(\bar{\theta}_{13}, \bar{\delta}, |\Delta m^2_{23}|)$$

- Octant degeneracy

It comes from the fact that the atmospheric angle is measured via the disappearance channel which depends on $\sin^2(2\theta_{23})$

$$P_{\nu_\alpha \nu_\beta}(\theta_{13}, \delta, \tfrac{\pi}{2} - \theta_{23}) = P_{\nu_\alpha \nu_\beta}(\bar{\theta}_{13}, \bar{\delta}, \bar{\theta}_{23})$$

These equations have in general two solutions in the (θ_{13},δ)–plane

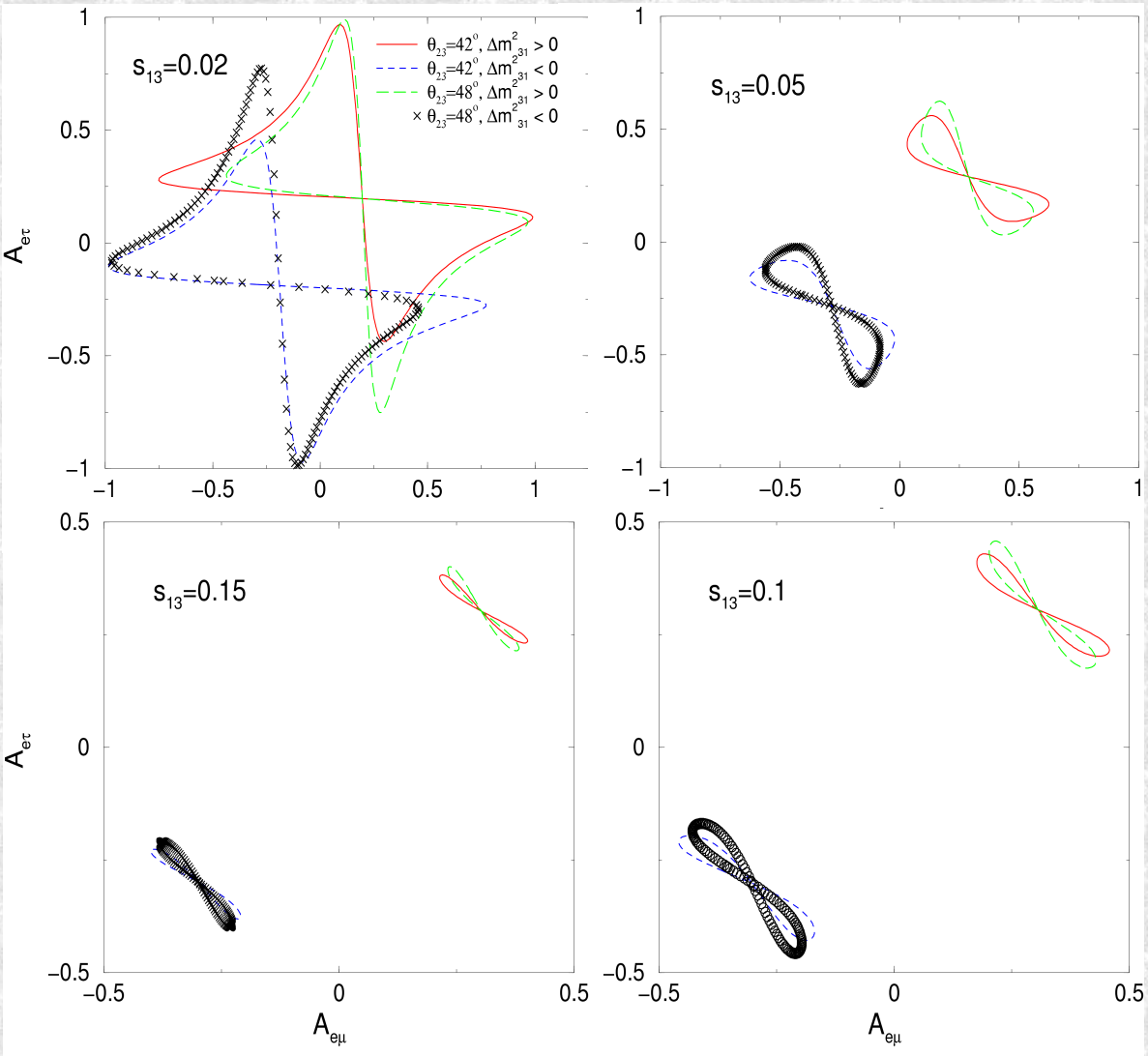
J.Burguet-Castell et al., Nucl.Phys. B 646, (2002) 301

A.Donini et al., JHEP 0406:011,2004.

The sign and octant degeneracies

In the asymmetry planes, they appear as follows

L= **4000** Km E_ν=30 GeV θ_{23}=42°/48° sin(θ_{13})=[0.02, 0.05, 0.1, 0.15]



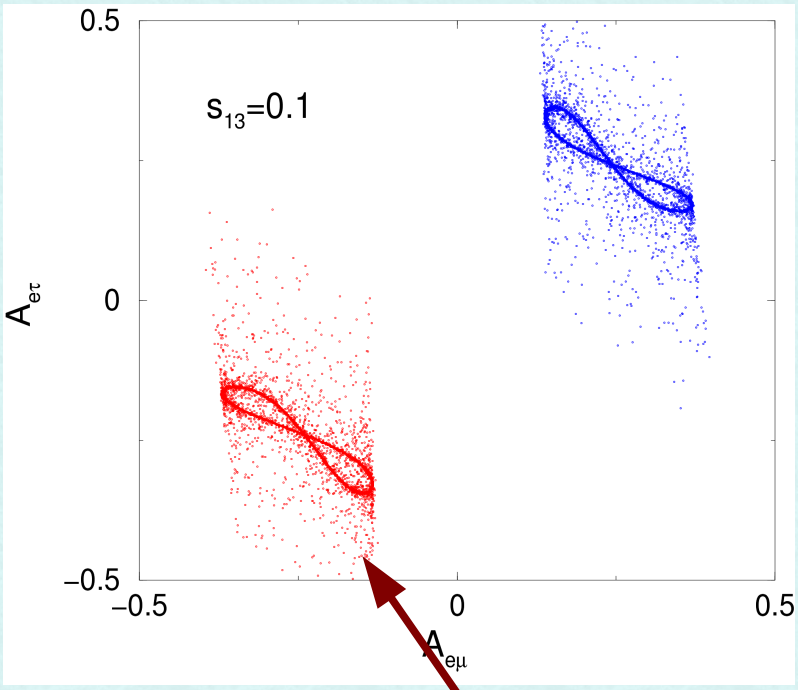
- θ23=42° Δm²31>0
- θ23=48° Δm²31>0
- θ23=42° Δm²31<0
- θ23=48° Δm²31<0

The octant degeneracy does not seem to be a problem because almost superimposed to the standard correlation

The sign degeneracy could be dangerous if MUV preditions fall close to the “sign degeneracy” values

The sign and octant degeneracies

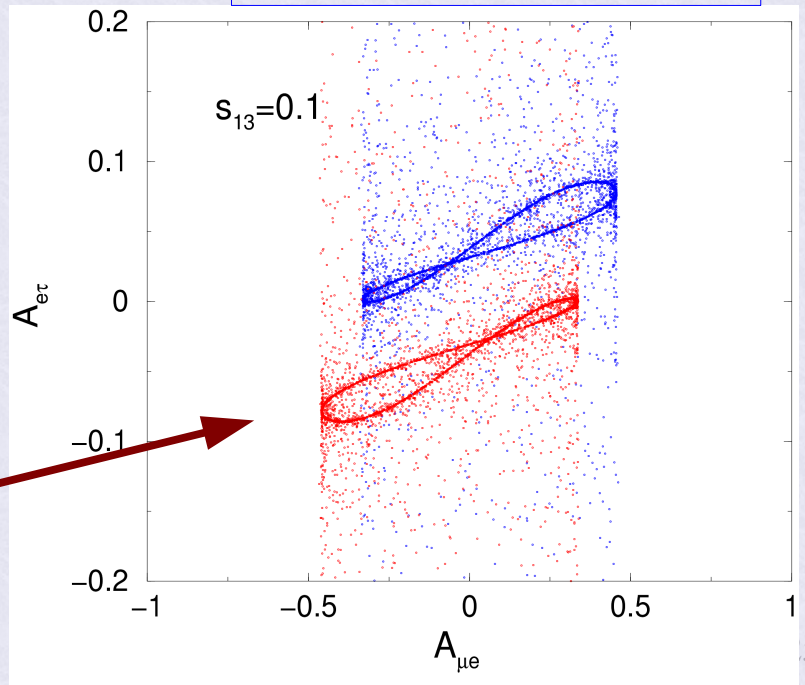
At **large** baseline (like L=4000 Km) the new physics is not large enough to fill the gap



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

Even at **smaller** baselines, where the matter effects do not help a lot in measuring the sign of the Δm^2_{31}, a meaningful test of standard picture is still possible (unless MUV prediction fall on the red "eight"...)

L=295 Km E_ν=0.75 GeV



Conclusions

- We have studied the possibility of testing whether the observed CP violation is consistent with the SM prediction that all CP violation observables must be proportional to the leptonic Jarlskog invariant
- As a quantitative model, we adopted the MUV framework with present bounds on its parameters
- We found that, although the model is a rather restricted model of new physics, the deviations from the standard picture of CP violation could be detected with realistic experimental accuracies
- To this aim, it is necessary to measure not only the golden channel $A_{e\mu}$ but at least one more channel ($A_{e\tau}$ and/or $A_{\mu\tau}$)
- The useful values of $L/\langle E_\nu \rangle$ should be small to enhance the new physics effects but also not too small to allow for a good counting rates
- A good compromise seems to be a ν-factory at L=1500 Km and E_μ=50 GeV

Backup slides

Summary of the MUV model

- **The structure of the matrix elements of *N* can be obtained from oscillation experiments (especially disappearance) and weak decays**

In fact, a part from normalization coefficients, the dis probability is

$$P_{\nu_\alpha \nu_\alpha} \sim \Sigma_i \left|N_{\alpha i}\right|^4 + 2\left|N_{\alpha 1}\right|^2 \left|N_{\alpha 2}\right|^2 \cos\Delta_{12} + (2 \Leftrightarrow 3) + (1 \Leftrightarrow 2)$$

$\Delta_{12} \simeq 0$ $\quad \left|N_{\alpha 1}\right|^2 + \left|N_{\alpha 2}\right|^2$ → ν_e dis, ν_μ dis: CHOOZ, SK, K2K, MINOS

$\Delta_{12} \neq 0,\ \Delta_{13} \gg 1$ → ν_e dis: KamLAND

$\Delta_{12} \simeq 0,\ \Delta_{13} \simeq 0$ → appearance: KARMEN, NOMAD, disappearance (near detector): MINOS, BUGEY

Summary of the MUV model

- Fits to oscillation data give the following *N* matrix

$$|N| = \begin{pmatrix} 0.75-0.89 & 0.45-0.66 & 0.00-0.27 \\ 0.00-0.69 & 0.22-0.81 & 0.57-0.85 \\ ? & ? & ? \end{pmatrix}$$

- Constraints from electroweak decays help!

- W decays

$$\Gamma(W \to l_\alpha \nu_\alpha) = \frac{G_F M_W^3}{6\sqrt{2}\pi} (N N^{dag})_{\alpha\alpha}$$

- Invisible Z decays

$$\Gamma(Z \to invisible) = \frac{G_F M_W^3}{12\sqrt{2}\pi} \Sigma_{ij} \left| (N^{dag} N)_{ij} \right|^2$$

- Rare charged lepton decays

$$l_\alpha \to l_\beta \gamma$$

Summary of the MUV model

$B(\tau \to e\,\gamma) < 1.1 \times 10^{-7}$

$B(\tau \to \mu\,\gamma) < 4.5 \times 10^{-8}$

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

The more stringent one

From these bounds, one can also get information on the last row of *N* and on the *moduli on the η matrix elements* (90% CL)

$$|\eta| = \begin{pmatrix} |\eta_{ee}| < 1.5\cdot 10^{-3} & |\eta_{e\mu}| < 3.6\cdot 10^{-5} & |\eta_{e\tau}| < 8.0\cdot 10^{-3} \\ |\eta_{\mu e}| < 3.6\cdot 10^{-5} & |\eta_{\mu\mu}| < 2.5\cdot 10^{-3} & |\eta_{\mu\tau}| < 4.9\cdot 10^{-3} \\ |\eta_{\tau e}| < 8.0\cdot 10^{-3} & |\eta_{\tau\mu}| < 4.9\cdot 10^{-3} & |\eta_{\tau\tau}| < 2.5\cdot 10^{-3} \end{pmatrix}$$

Background sources and rejection factors

Huber et al.,Phys.Rev.D74:073003, 2006
(adapted from A.Donini et al., Eur.Phys.J.C33:243–260,2004)

– silver channel

– neutrino induces charm production	10^{-8} x ($N_{CC}(\nu_e)$ +$N_{CC}(\nu_\mu)$)
- anti-neutrino induces charm production	3.7×10^{-7} x N_{CC}(anti ν_μ)
- τ^+ --> μ^+ decays	10^{-3} x N_{CC}(anti ν_τ)
- μ matched to hadron track	7×10^{-9} x N_{CC}(anti ν_μ)
- decay-in-flight and punch-trough hadrons	6.97×10^{-7} x N_{NC} + 2.1×10^{-8} x $N_{CC}(\nu_e)$
- large-angle muon scattering	10^{-8} x $N_{CC}(\nu_\mu)$

– golden channel

– neutral currents	5×10^{-6} x N_{NC}(anti ν_μ)
- wrong charge assignment	5×10^{-6} x N_{CC}(anti ν_μ)

Non-unitarity vs non-standard interactions

- **Flavour eigenstates in the case of MUV model**

$$\left|\nu_\alpha\right\rangle = \frac{(1+\eta)_{\alpha\beta}}{\left[1+2\eta_{\alpha\alpha}+(\eta^2)_{\alpha\alpha}\right]^{1/2}}\left|\nu_\beta^{SM}\right\rangle \qquad \nu_\alpha^{SM} = U_{\alpha i}\,\nu_i$$

- **Example: operators inducing new physics effects in the production and detection processes of neutrinos at ν-factories**

New physics terms

$$-L_{int} = \frac{4G_F}{\sqrt{2}}\Sigma_\alpha\left[(\delta_{\alpha\mu}+\frac{G^D_{\mu\alpha}}{G_F})(\bar{\nu}_\alpha\gamma_\mu P_L\mu)(\bar{d}\gamma^\mu P_L u)+(\delta_{\alpha e}+\frac{G^P_{e\alpha}}{G_F})(\bar{\nu}_\alpha\gamma_\mu P_L e)(\bar{\mu}\gamma^\mu P_L\nu_\mu)\right]$$

Standard terms

Non-unitarity vs non-standard interactions

- The effective production and detection states are given by

$$\left|\nu_e^P\right\rangle = \left(1+\varepsilon^P\right)_{e\beta}\left|\nu_\beta^{SM}\right\rangle$$

$$\left|\nu_\mu^D\right\rangle = \left(1+\varepsilon^D\right)_{\mu\beta}\left|\nu_\beta^{SM}\right\rangle \qquad \text{where} \qquad \varepsilon_{\alpha\beta}^{P,D} = \frac{G_{\mu\alpha}^D}{G_F}$$

and these expressions are very similar to the parameterization of the effects of a non-unitary mixing matrix

About θ_{13}

- We have assumed that θ_{13} will be known with sufficient precision by the time that a meaningful measurement of CP violation can be performed
- An obvious question is whether θ_{13} can be determined in a reasonably independent way
- In the MUV framework $P_{e\mu}$ is optimal as the new physics effects are bound to be small
- Alternatively, one can use reactor experiments:

$$P_{ee} = 1 - 2\sin^2\Delta_{31}\left[r^2 + \eta_{e\tau} + 2r\,\eta_{e\tau}\cos(\delta - \delta_{e\tau})\right] - \frac{8}{9}\Delta_{21}^2$$

The effects of new physics can be quite large and reactor experiments cannot guarantee a model independent determination of θ_{13}

- Reactor experiment results should be combined with other experiments