Model comparison and experimental constraints

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Based mainly on:

-Ballett, King, Luhn, Pascoli , Schmidt,
Phys.Rev. D89, 016016 (2014)

-D.M., Phys.Lett. B728 (2014) 118-124

Big question

Is it possible to identify the flavor model "responsible" for the measured values of ν mixing?

Two different <u>but equivalent</u> approaches to study the problem:

- sum rules among mixing angles: are they satisfied?
- direct comparison of different flavor models

↓

Experimental precision is the key issue

Also important: choice of the variables to perform the check

Approach based on sum rules

Theory invariant under a flavor group G_F

- permutation groups like A4 and S4 suitable for TBM

Residual symmetry in the neutrino sector: $G_\nu \rightarrow U_\nu$

Residual symmetry in the charged lepton sector $G_l \rightarrow U_l$

$$U_{PMNS} = U_l^+ U_\nu$$

At this step: quite often a vanishing reactor angle

Appropriate breaking of the residual symmetries generates a non-vanishing th13, whose value is related to the shift of th23 from maximal mixing

Approach based on sum rules

Ballett, King, Luhn, Pascoli , Schmidt, Phys.Rev. D89, 016016 (2014)

$$s_{23} = \left(\frac{1 + a_0}{\sqrt{2}}\right) + \lambda s_{13} \cos\delta$$

→ no dependence on th12

- a_0 and lambda are model-dependent parameters

$a_0 = 0, \;\; \lambda = 1/2$ → $s_{23}^2 = \frac{1}{2} + \frac{1}{\sqrt{2}} s_{13} \cos\delta$ Yin Lin, Nucl.Phys. B824 (2010) 95-110

$a_0 = 0, \;\; \lambda = 1$ → $s_{23}^2 = \frac{1}{2} + \sqrt{2} s_{13} \cos\delta$ Hernandez and Smirnov, Phys.Rev.D86, 053014 (2012)

Compatibility with data

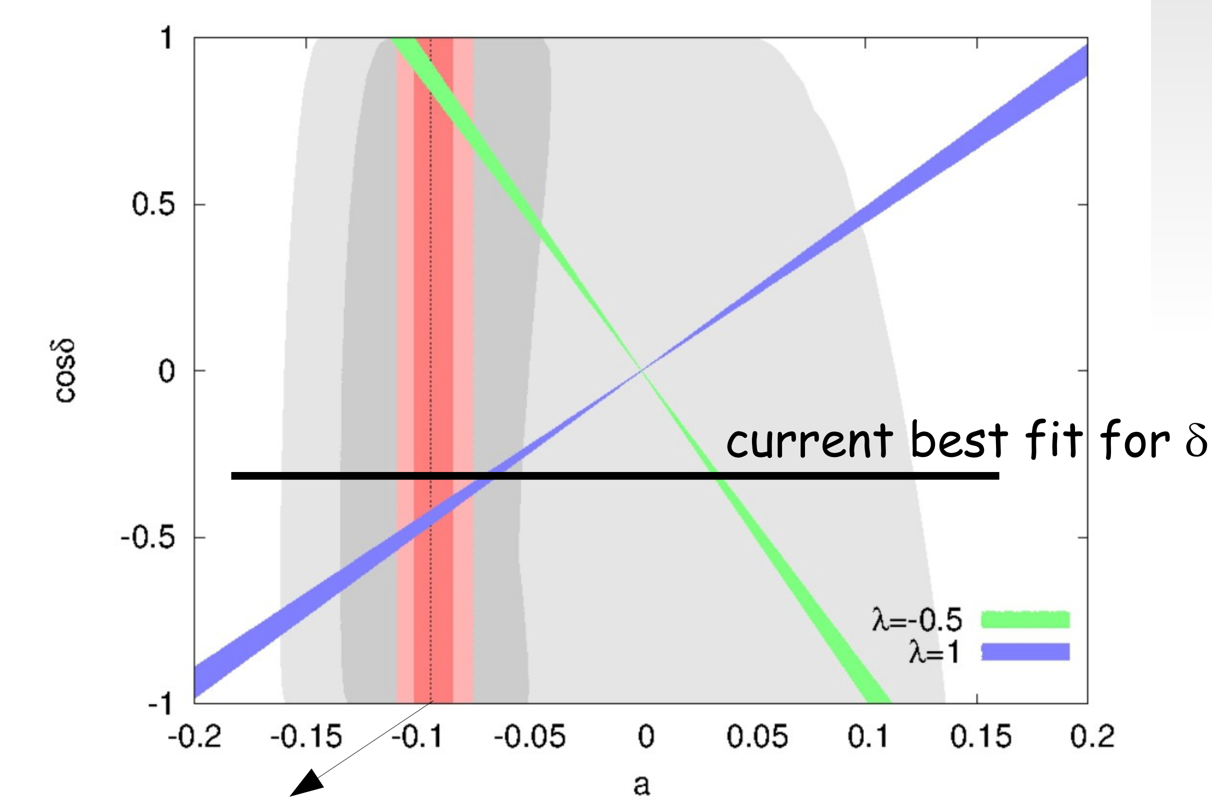
$$s_{23} = \left(\frac{1+a_0}{\sqrt{2}}\right) + \lambda\, s_{13} \cos\delta$$

$$a_0 = 0,\ \ \lambda = -1/2,\ \ \lambda = 0$$

Red areas:
projected sensitivities based on T2K, NOνA, Double Chooz, Reno and Daya Bay

Gray areas:
1 and 2 sigma intervals

Ballett, King, Luhn, Pascoli , Schmidt, Phys.Rev. D89, 016016 (2014)



current best fit for a

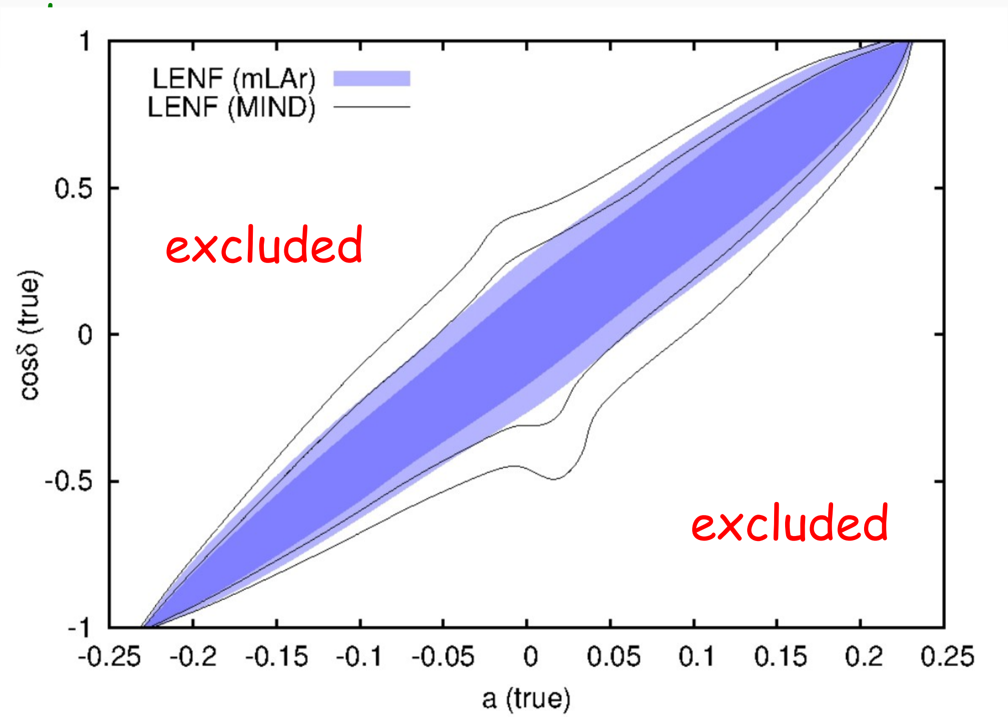
$$a = \sqrt{2}\, s_{23} - 1$$

Excluding sum rules

Strategy:

Plot already shown by Christoph...

- "cos δ" and "a" (or equivalently s_{23}) are varied in their allowed ranges
- for every (δ,a) pairs the best fitting set of oscillation parameters obeying a given sum-rule is found
- the corresponding χ^2 is computed and, if above a reference value, the sum-rule is exclud



$\lambda=1$

Ballett, King, Luhn, Pascoli , Schmidt, Phys.Rev. D89, 016016 (2014)

The Hernandez-Smirnov approach

Hernandez and Smirnov,
Phys.Rev.D86, 053014 (2012)

- Mass terms $\mathscr{L} = \frac{g}{\sqrt{2}} \bar{\ell}_L U_{PMNS} \gamma^\mu \nu_L W^+_\mu + \bar{E}_R m_\ell \ell_L + \frac{1}{2} \bar{\nu^c}_L m_\nu \nu_L + \ldots + \text{h.c.}$
- nu-mass: $S_i^T m_n S_i = m_n$ (i=1,2) → $Z_2 \times Z_2$ → $S^2=1$
- charged leptons: $l_L \to T\, l_L$, $l_R \to T\, l_R$ → $U(1)^3$ (or Z_m for the discrete case) → $T^m=1$

$$S_1 = \begin{pmatrix} 1 & & \\ & -1 & \\ & & -1 \end{pmatrix}, \quad S_2 = \begin{pmatrix} -1 & & \\ & 1 & \\ & & -1 \end{pmatrix} \qquad T = \begin{pmatrix} e^{2\pi i \frac{k_1}{m}} & & \\ & e^{2\pi i \frac{k_2}{m}} & \\ & & e^{2\pi i \frac{k_3}{m}} \end{pmatrix} \to T_e,\ T_\mu,\ T_\tau$$

- Assumptions: the residual symmetries are 1-generator groups

→ $\{S_i, T_\alpha\}$ generate the flavor group

The Hernandez-Smirnov approach

Hernandez and Smirnov,
Phys.Rev.D86, 053014 (2012)

- The definition of G requires: $(S_i, T_\alpha)^p = I$

D(2,m,p)

$$D(2,2,3) = \mathbf{S}_3\,,$$
$$D(2,3,3) = \mathbf{A}_4$$
$$D(2,3,4) = \mathbf{S}_4\,,$$
$$D(2,3,5) = \mathbf{A}_5$$

- Consequence of the 1-g assumption: mixing angles not all fixed !

Here I consider two different models:

1T: S_1, Te, (m,p)=(3,4) -->S_4

2T: S_2, Te, (m,p)=(3,3) -->A_4

1T vs 2T

1T

$$\cos^2\theta_{12} = \frac{2}{3\cos^2\theta_{13}}$$

$$\tan 2\theta_{23} = \frac{-1+5s_{13}^2}{2\cos\delta\, s_{13}\sqrt{2(1-3s_{13}^2)}}$$

(a_0=0, λ=1)

Yin Lin, Nucl.Phys. B824 (2010) 95-110

Altarelli, Feruglio, Merlo, Stamou,
JHEP 1208(2012)021

2T

$$\sin^2\theta_{12} = \frac{1}{3\cos^2\theta_{13}}$$

$$\tan 2\theta_{23} = \frac{1-2s_{13}^2}{\cos\delta\, s_{13}\sqrt{2-3s_{13}^2}}$$

(a_0=0, λ=1/2)

Ma, Rajasekaran, Phys.Rev.D64,113012(2001)

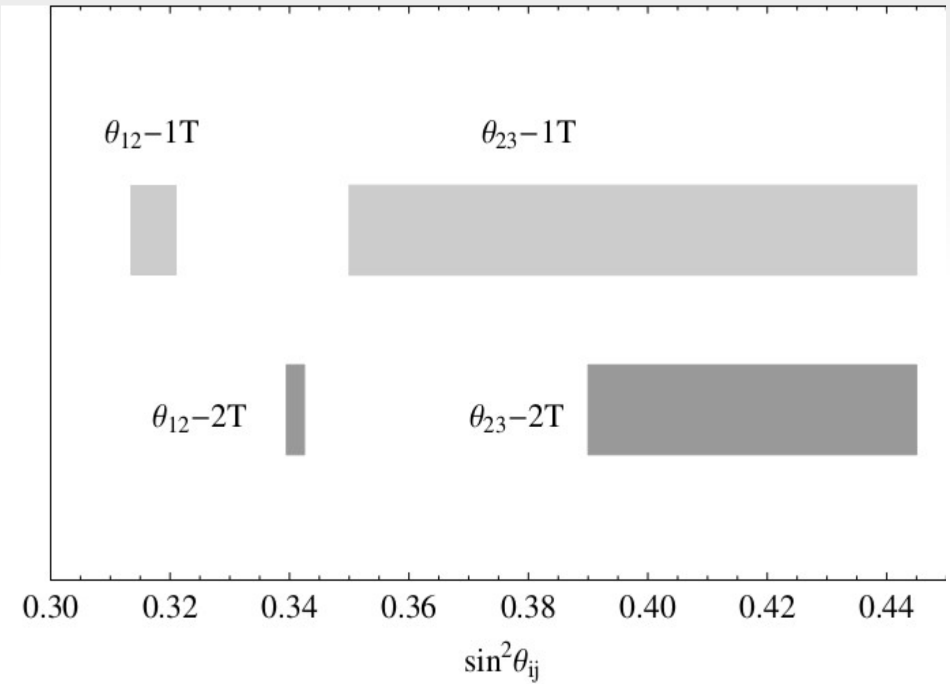
Babu,Ma,Valle, Phys.Lett.B552,207(2003)

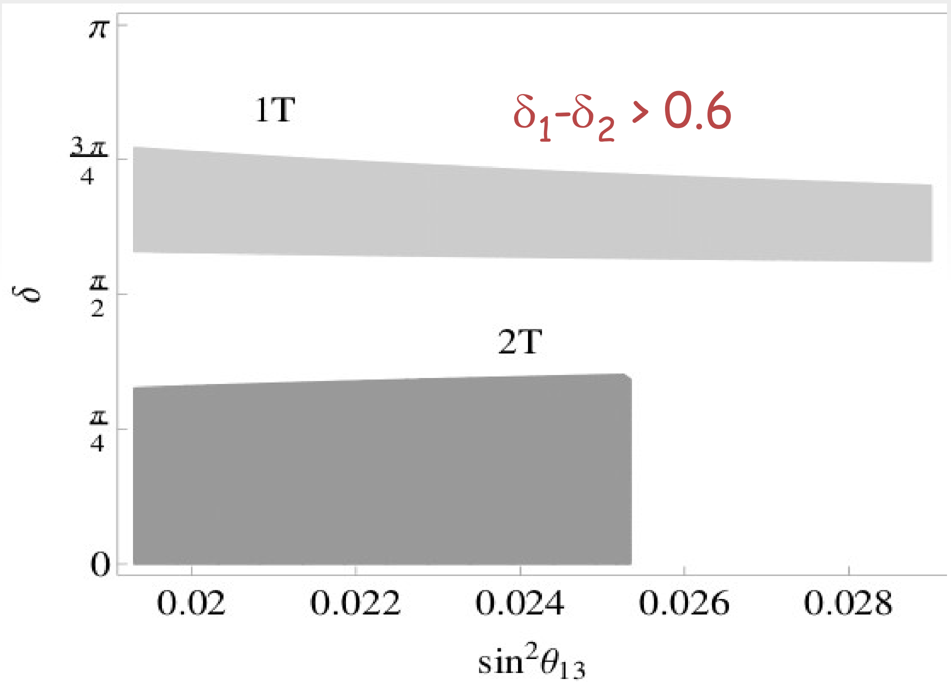
Ma, Phys.Rev.D73,057304(2006)

Main message of this talk

D.M., Phys.Lett. B728 (2014) 118-124

It is not enough that the models gives different intervals on the allowed mixing angles to distinguish them





th12's are not overlapping: not guaranteed that a precise measurement can tell 1T from 2T

Where to look for the largest effects?

D.M., Phys.Lett. B728 (2014) 118-124

Consider $\nu_\mu \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_\mu$ transitions

in the regions where the mixing angles are overlapping (this case for simplicity):

$$\Delta P_{\mu e} = \left| P^{1T}_{\mu e} - P^{2T}_{\mu e} \right| \sim \sin\left(\frac{\delta_1 - \delta_2}{2}\right) \sin\left[\frac{1}{2}(2\Delta + \delta_1 + \delta_2)\right]$$

sensibly different from zero for $\delta_1 - \delta_2 \sim \pi$ → in the correct range (remember: $\delta_1 - \delta_2 > 0.6$)

$$\Delta P_{\mu\mu} \sim \cos\delta_2 - \cos\delta_1$$

sensibly different from zero for $\delta_1 \sim \pi/2 + \delta_2$ → in the correct range (remember: $\delta_1 - \delta_2 > 0.6$)

Where to look for the largest effects?

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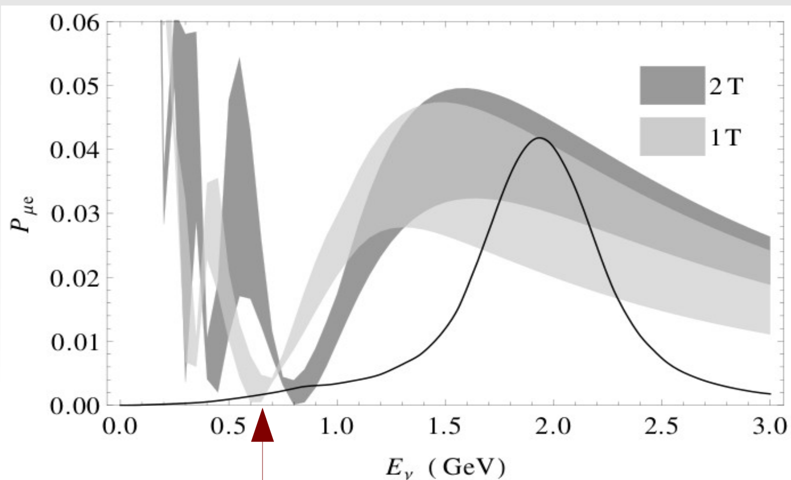
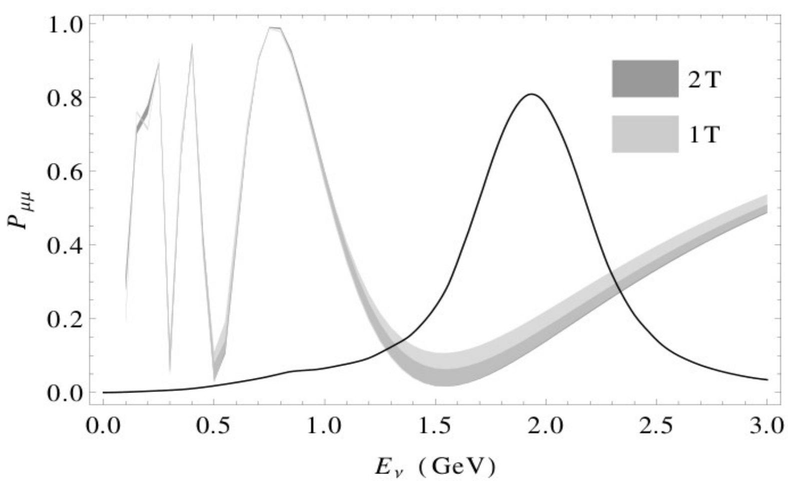
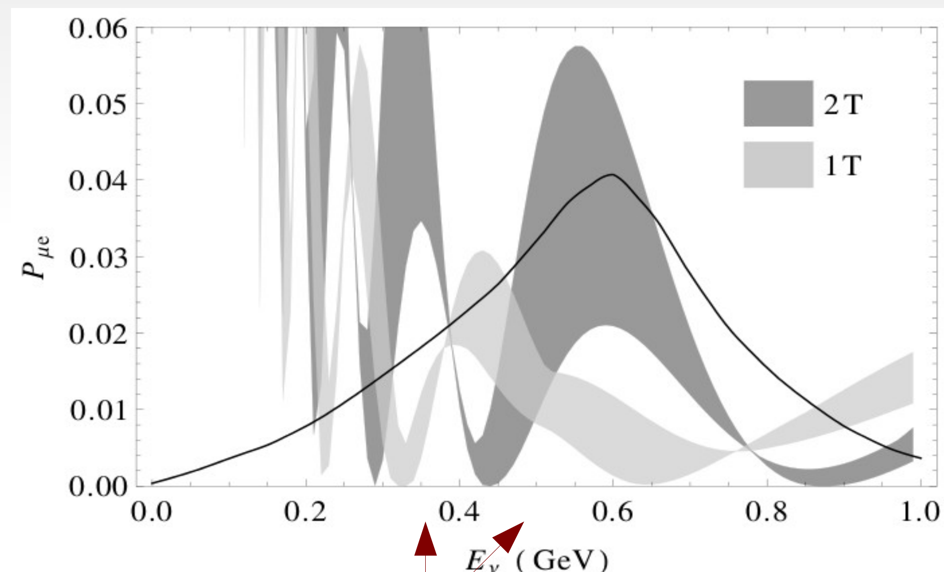
for the NOvA setup



relevant differences here



for the T2K setup



relevant differences here

black lines: fluxes

as usual, energy dependence is relevant

A possible way to distinguish among 1T and 2T

D.M., Phys.Lett. B728 (2014) 118-124

The strategy

- Choose a pair of $(\overline{\theta}_{13},\overline{\delta})$ in the region allowed by the model 1T and compute the expected number of events per energy-bin $N^{1T}_{a,i}(\overline{\theta}_{13},\overline{\delta})$
  (th12 and th23 determined by the relations shown before)
- One then compute the events for the competing model $N^{2T}_{a,i}(\theta_{13},\delta)$ in the whole parameter space
- Minimize a χ^2 over the pair (θ_{13},δ)

Models can be distinguished in $(\overline{\theta}_{13},\overline{\delta})$ if χ^2_{min} >= χ^2_{cut}

$$\chi^2 = \Sigma_{\alpha,i} \frac{[N^{2T}_{\alpha,i}(\theta_{13},\delta) - N^{1T}_{\alpha,i}(\overline{\theta_{13}},\overline{\delta})]^2}{\sigma^2_{\alpha,i}}$$

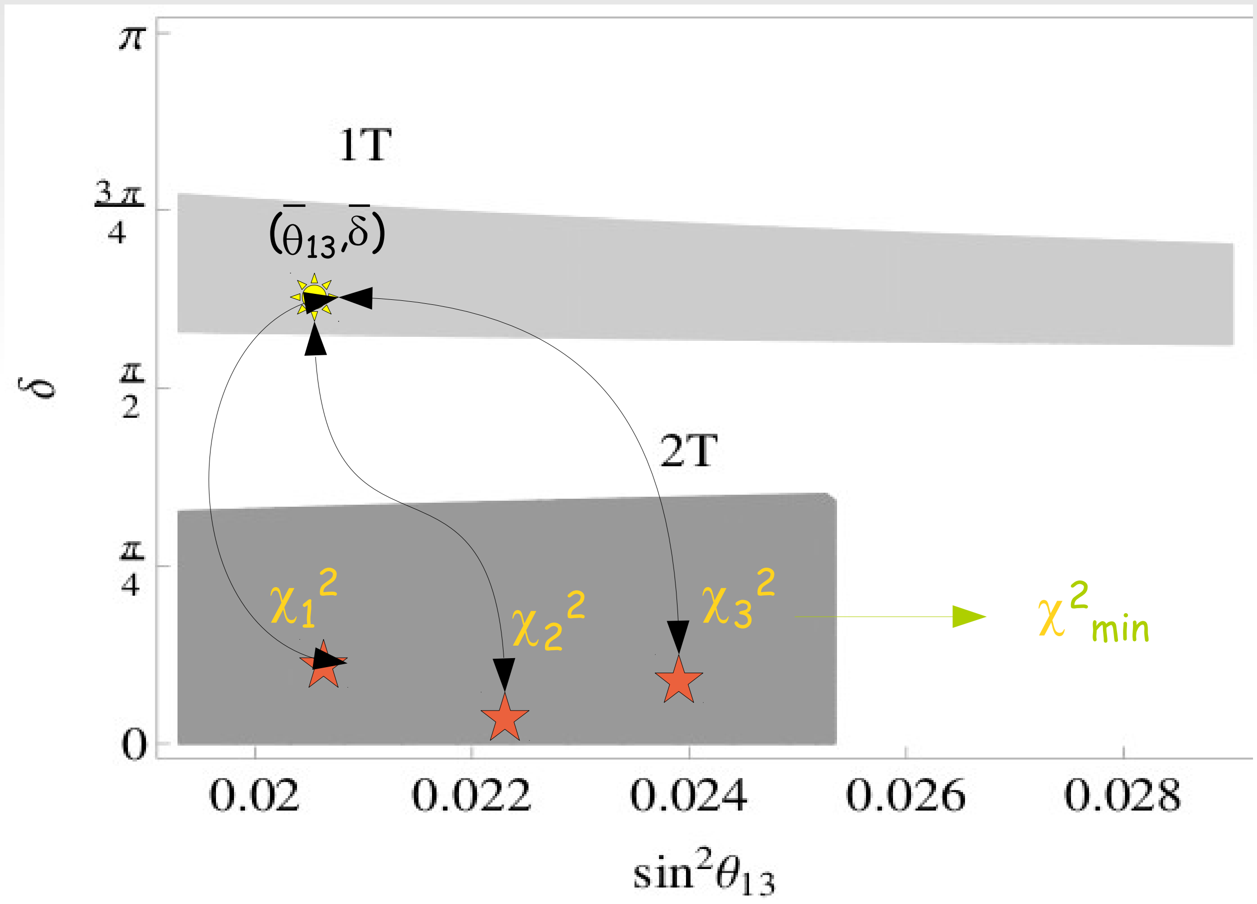
i=energy bin, α=flavor
n_a,b_a=overall systematic effects=0.05

$$\sigma^2_{\alpha,i} = N^{1T}_{\alpha,i}(\overline{\theta_{13}},\overline{\delta}) + B_{\alpha,i} + [n_\alpha N^{1T}_{\alpha,i}(\overline{\theta_{13}},\overline{\delta})]^2 + [b_\alpha B_{\alpha,i}]^2$$

A possible way to distinguish among 1T and 2T

D.M., Phys.Lett. B728 (2014) 118-124

The strategy



do it for (a discrete choice of) every $(\bar{\theta}_{13},\bar{\delta})$ and collect the good points

Choice of the facilities

- **NOvA**:

14 Kt totally active scintillator
Backgrounds:
- in appearance: intrinsic nue beam, mis-identified muons and single pi0 from NC
- in disappearance: wrong-sign muons from numubar contamination in numu beam, NC events

Agarwalla,Prakash,Raut,Sankar, 1208.3644; Patterson 1209.0716,
Coloma, Huber, Kopp, Winter, 1209.5973; Pilar Coloma, private communication

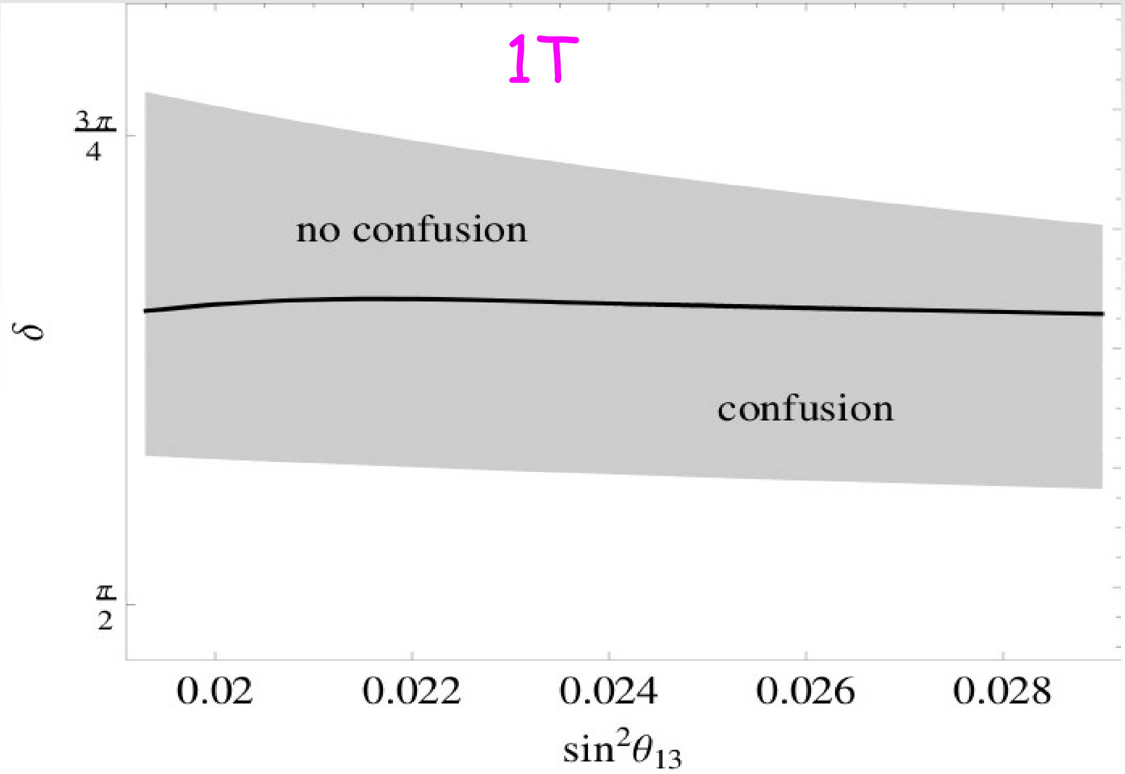
- **T2K**:

22.5 Kt water Cerenkov detector
Backgrounds:
- in appearance: nu_mu_disappearance_CC, NC, nu_e_beam, nu_e_bar_beam
- in disappearance: NC

Huber, Lindner,Schwetz,Winter, 0907.1896;
Fechner, DAPNIA-2006-01-Y

Results for a single experiment

D.M., Phys.Lett. B728 (2014) 118-124



similar results for NOvA and T2K 90% CL

- Discrimination possible for n_a < 5%
- The true δ_{CP} must be as distant as possible from the corresponding 2T model values: δ_{CP} >~2.06
- APP and DIS alone cannot determine any discrimination → synergy
- DIS helps with th23, slightly different among 1T and 2T

It turns out that no distinction is possible in the 2T parameter space

Results for the NOνA + T2K combination

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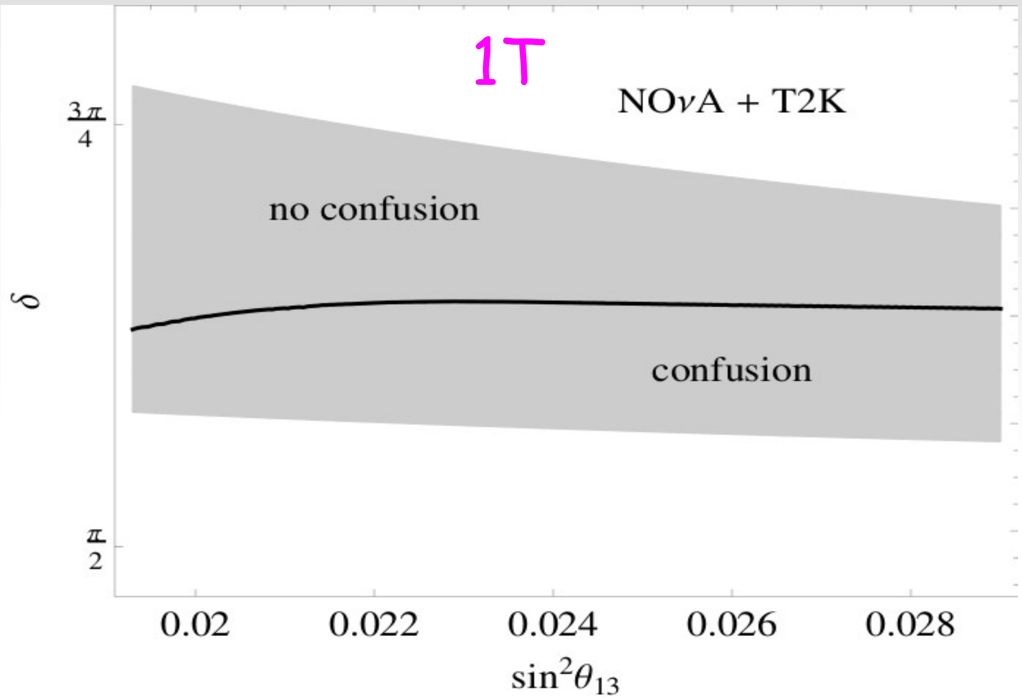
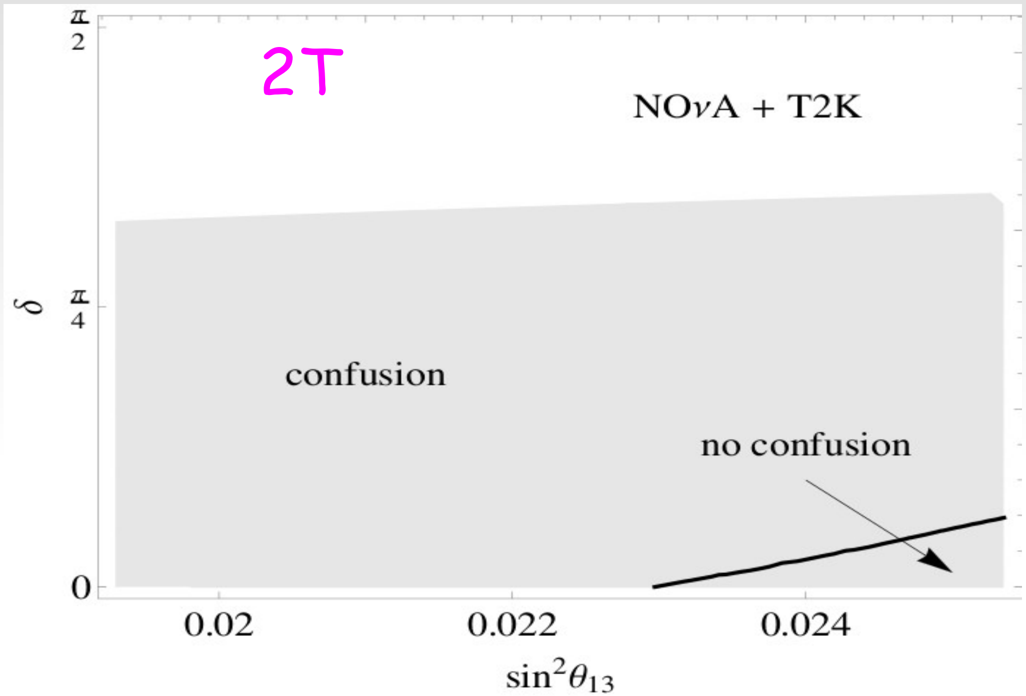




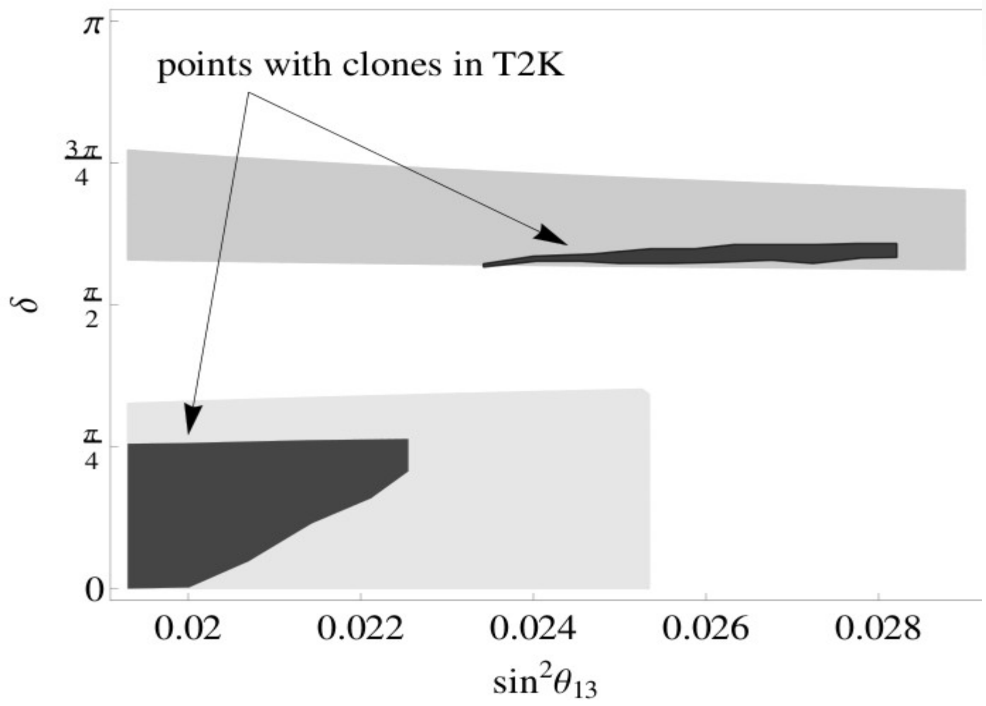
- Not a huge synergy in the 1T parameter space
- In the 2T case distinction is possible in a limited portion of the parameter space, for δ_{CP} <~0.2 and very large th13
- The different behavior is (partially) explained in terms of *intrinsic degeneracy*

Results for the NOvA + T2K combination

D.M., Phys.Lett. B728 (2014) 118-124

- For a given $(\overline{\theta_{13}},\bar{\delta})$ in the 1T space, clone points are given by (θ_{13},δ) solving (consider rate-only for simplicity):

$$N_\mu^{1T}(\overline{\theta_{13}},\bar{\delta}) = N_\mu^{2T}(\theta_{13},\delta)$$
$$N_e^{1T}(\overline{\theta_{13}},\bar{\delta}) = N_e^{2T}(\theta_{13},\delta)$$

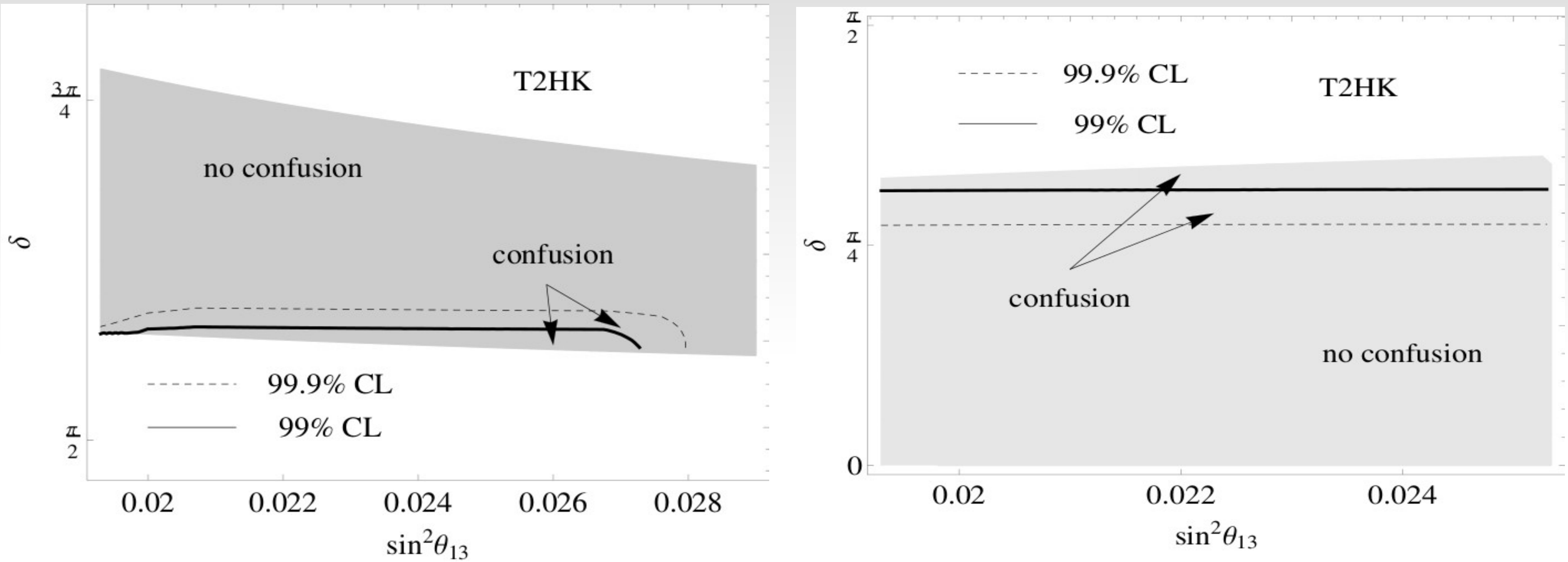


- Black regions resemble the "no-confusion" regions of the previous plots

- The real situation is more complicated, due to the energy dependence of the signal

Results for T2HK

D.M., Phys.Lett. B728 (2014) 118-124



▶ Much better discriminating power !

Conclusions

- Neutrino physics is an active field, from both experimental and theoretical point of views
- Many and precise data are now available, which in principle allow to discriminate among flavor models
- Two (or more) models can be distinguished by their predictions for the mixing angles but experiments with good energy resolution are necessary and systematics under control
- We started to investigate where the largest effects among two models can be seen at neutrino facilities: what about the mass difference? And matter effects?