TESTING NON-STANDARD NEUTRINO OSCILLATIONS AT DAYA BAY REACTOR

David Vanegas Forero[1]

[1]AHEP Group. Instituto de Física Corpuscular-CSIC/UVEG

in collaboration with **M. Tórtola[1]**, **S. Agarwalla[2]** and **P. Bagchi[2]**

[2]Institute of physics, Bhubaneswar

INTRODUCING THE NSI

Motivation

Models that generate neutrino masses can also introduce new neutrino interactions [1,2]. Even for massless neutrinos, in a popular extensions of the Standard Model, NSI affects neutrino propagation [2,3]. It is then expected that at low energy the interchange of new particles leave a 'finger print' in the form of NSI.

Four fermion interactions

Effective Fermi interactions for neutrinos can be introduced, conserving the Standard Model structure of the low energy Charged (CC) and Neutral Current (NC) interactions, with a new couplings. The four fermion or NSI Lagrangian is given by [3]:

$$\mathcal{L}_{V\pm A} = \frac{G_F}{\sqrt{2}} \sum_{f,f'} \tilde{\varepsilon}_{\alpha\beta}^{S(D),f,f',V\pm A} \left[\bar{\nu}_\beta \gamma^\rho (1-\gamma^5) \ell_\alpha\right] \left[\bar{f}' \gamma_\rho (1 \pm \gamma^5) f\right] + \frac{G_F}{\sqrt{2}} \sum_f \tilde{\varepsilon}_{\alpha\beta}^{m,f,V\pm A} \left[\bar{\nu}_\alpha \gamma^\rho (1-\gamma^5) \nu_\beta\right] \left[\bar{f} \gamma_\rho (1 \pm \gamma^5) f\right] + \text{h.c.}$$

were strength of the interaction is parametrized in terms of the SM effective interaction through the Fermi constant. First line corresponds to CC interaction with the S and D upper index for Source and Detector, respectively. In the second line, the Lagrangian for NC NSI interaction that will affect neutrino propagation in matter (m).

NSI at reactor experiments

The production (detection) of reactor neutrinos is a CC process: beta (inverse beta) decay. Additionally the baseline is short enough to neglect neutrino interactions with matter, then along this work when referring to reactor NSI it corresponds to CC NSI Lagrangian with the definition [5]:

$$\tilde{\varepsilon}_{e\beta}^{S(D),u,d,V\pm A} \rightarrow \varepsilon_{e\beta}^{S(D)}$$

Antineutrino state and probability

When a neutrino is created in a CC process together with a lepton of the same flavor, in the presence of NSI, it has an additional flavor component that in general can be different to the original with a coefficient given by the dimensionless coupling :

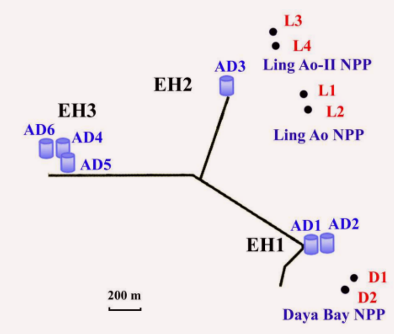
$$|\bar{\nu}_\alpha^s\rangle = |\bar{\nu}_\alpha\rangle + \sum_\gamma \varepsilon_{\alpha\gamma}^{s*} |\bar{\nu}_\gamma\rangle$$

$$\langle \bar{\nu}_\beta^d| = \langle \bar{\nu}_\beta| + \sum_\eta \varepsilon_{\eta\beta}^{d*} \langle \bar{\nu}_\eta|$$

Finally, we can calculate the probability of the new state in the source (S) be detected (D) as another new flavor state:

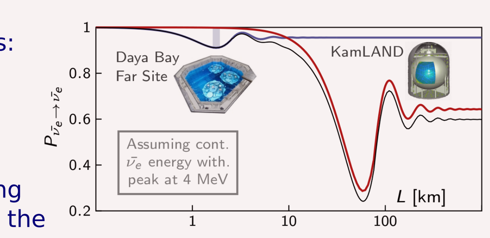
$$P_{\bar{\nu}_\alpha^s \rightarrow \bar{\nu}_\beta^d} = |\langle \bar{\nu}_\beta^d| \exp\left(-i\,\mathcal{H}\,L\right) |\bar{\nu}_\alpha^s\rangle|^2$$

DAYA BAY REACTOR NEUTRINO EXPERIMENT



Reactor antineutrinos are produced from beta decay of mainly four isotopes: ^{235}U, ^{239}Pu, ^{241}Pu and ^{238}U and detected via the inverse process.

At sketch of Daya Bay reactor core distribution (in red) and the six operating antineutrino detectors (AD) is shown at the left panel.



Antineutrino disappearance probability is given by the expression:

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{ee} L}{4E}\right) + solar\ terms$$

Daya Bay Far Detectors are located near the first dip in the probability, which allows to measure the reactor mixing angle. Additionally, Daya Bay is a multi-detectors facility what is used to cancel systematical errors in the reactor, detector and mainly minimizing the impact of the absolute flux normalization.

In order to determine the oscillation parameters, the total event rate measurements (M) are compare statistically with the theoretical expectation T [6]:

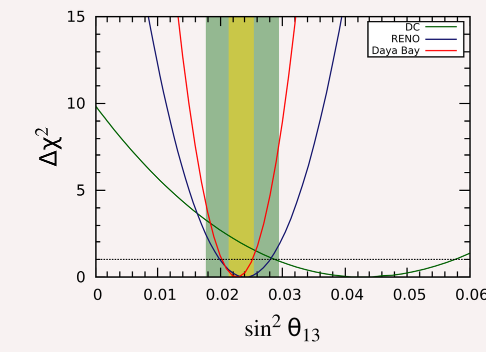
$$\chi^2 = \sum_{d=1}^{6} \frac{\left[M_d - T_d\left(1 + a + \sum_r \omega_r^d \alpha_r + \xi_d\right) + \beta_d\right]^2}{M_d + B_d} + \sum_{r=1}^{6} \frac{\alpha_r^2}{\sigma_r^2} + \sum_{d=1}^{6} \left(\frac{\xi_d^2}{\sigma_d^2} + \frac{\beta_d^2}{\sigma_B^2}\right)$$

where the r index refers to the reactors.

The minimization of the chi square function over all the systematical errors:

$$(\alpha, \xi, \beta)$$

related to a detector (d), reactor and the absolute normalization a (free parameter), produces the determination of the reactor mixing angle:



$$\sin^2\theta_{13}^{DYB} = 0.023 \pm 0.004$$

An interesting setting is:

$$\varepsilon_{e\alpha}^s = \varepsilon_{\alpha e}^{d*}$$

because the detection is the 'conjugate' process of the production.

For a fixed value of the mass square splitting, the NSI effect can be parametrized as a shift in the reactor mixing angle [7].

First order (in epsilon) expressions are shown for the shift angle in each case.

Three cases were considered:

$$\varepsilon_e \neq 0,\ \varepsilon_{\mu,\tau} = 0$$

$$\varepsilon_{\mu,\tau} \neq 0,\ \varepsilon_e = 0$$

$$\varepsilon_e = \varepsilon_{\mu,\tau} = \varepsilon$$

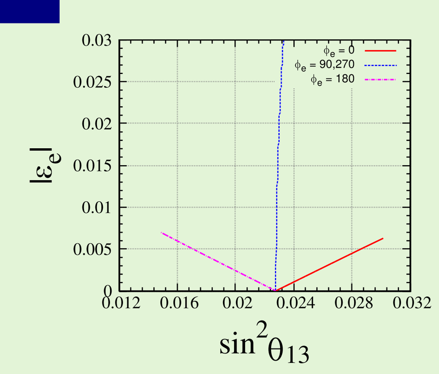
Finally, we fix the the pull of the absolute normalization a=0 in the statistical analysis.

Only electron coupling 'on'

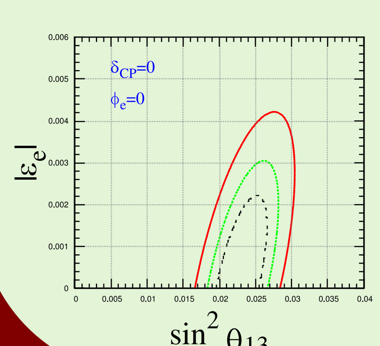
In this case, the shift function is given by:

$$\tilde{s}_{13}^2 = s_{13}^2 - \frac{|\varepsilon_e|\ \cos\phi_e}{\sin^2\Delta_{31}}$$

The Iso-probability plot at the right upper corner shows (anti)correlations when the cosine of the new phase is (negative)positive.



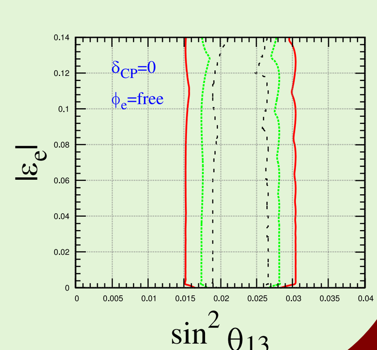
Allowed regions in the parameter space



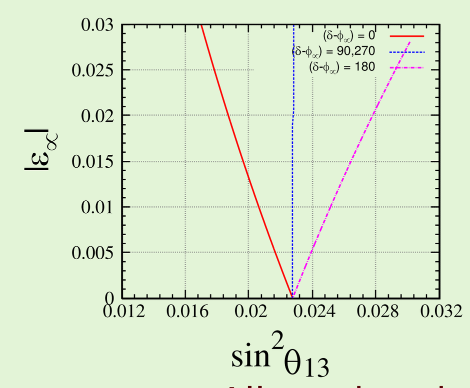
Confidence Level of 68,90 and 99 in black, green and red, respectively.

For the real case in left, the NSI coupling is constrained, and the bound is ~10^{-3}.

When marginalizing over the new phase the constraints are diluted, as it is shown in the right panel.



only muon(tau) nsi coupling 'on'

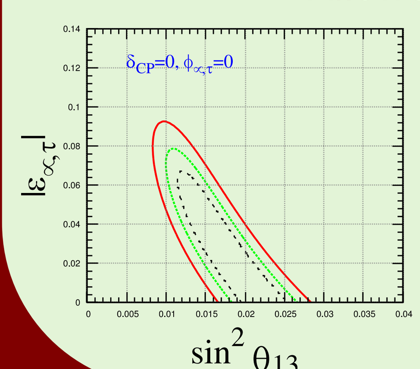


In this case, the shift function is given by:

$$\tilde{s}_{13}^2 = s_{13}^2 + 2 s_{13} s_{23} |\varepsilon_{\mu,\tau}| \cos\phi_{\mu,\tau}$$

The Iso-probability plot at the left upper corner shows (anti)correlations when the cosine of the difference between the new phase and the Dirac cp phase is (positive) negative.

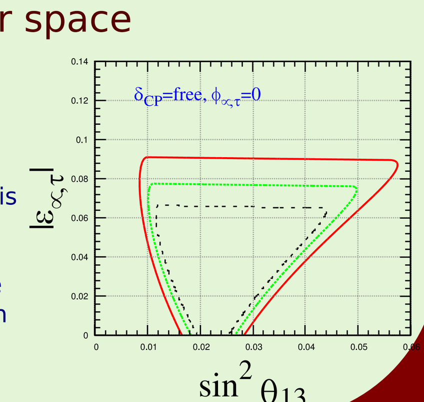
Allowed regions in the parameter space



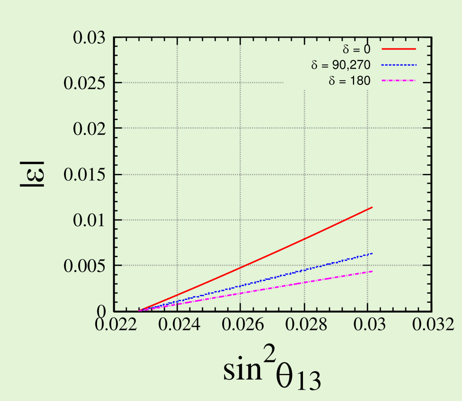
Confidence Level of 68,90 and 99 in black, green and red, respectively.

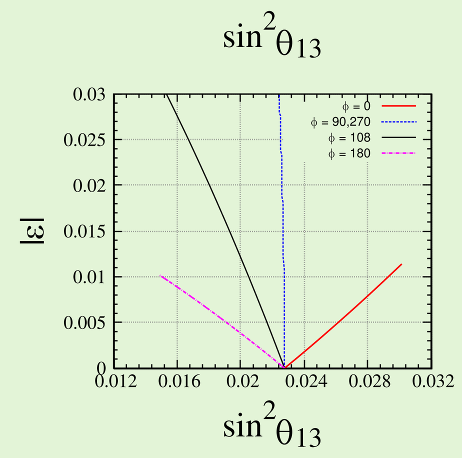
For the real case in left, the NSI coupling is constrained, and the bound is ~10^{-1}.

When marginalizing over the new phase the constraints are diluted, as it is shown in the right panel.



All nsi couplings with the same strenght or Flavor Universal (FU)





In this case, the shift function is given by:

$$\tilde{s}_{13}^2 = s_{13}^2 - |\varepsilon| \left[\frac{\cos\phi}{\sin^2\Delta_{31}} - 4 s_{13} s_{23} \cos\left(\delta - \phi\right)\right]$$

The Iso-probability plots at left shows the magnitude and the shifting in the reactor mixing angle according to the phase values. The left lower panel shows only correlations independent of the Dirac phase variation, for a zero value of the new phase.

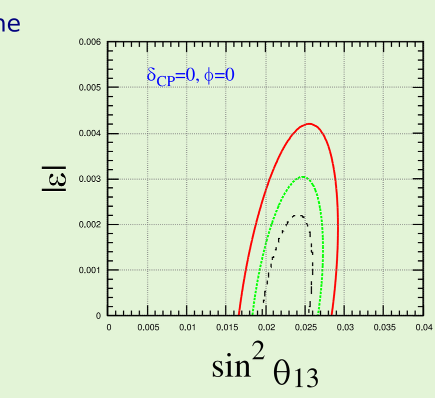
For the Dirac phase set to zero, when the cosine of the new phase is (negative)positive we found (anti)correlations between the reactor mixing angle and the NSI FU coupling. A bigger shift in the range of reactor mixing angle is expected in this case compared with the Dirac cp variation case in the upper panel.

Allowed regions in the parameter space

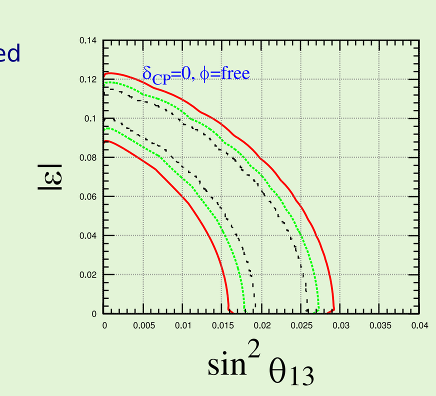
Confidence Level of 68,90 and 99 in black, green and red, respectively.

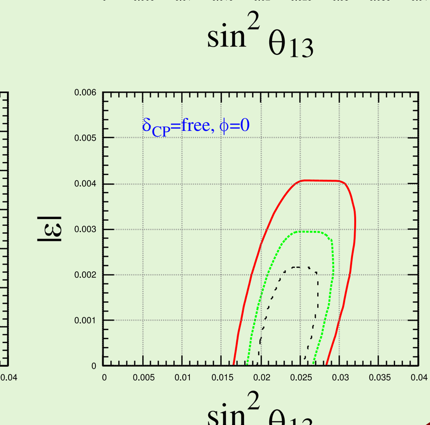
For the real case in the upper right pannel, the NSI coupling is constrained, and the bound is ~10^{-3}.

In the bottom panels the effect of the phases is shown. In the right bottom panel the Dirac cp phase effect is shown. Comparing with the upper plot for the real case, the bound on the NSI FU coupling is approximately equal but with a slightly bigger shift in the reactor angle.



When marginalizing over the new phase, a bigger values for the NSI FU coupling are allowed by the data, as it is shown in the left bottom panel. When comparing with the iso-probabilty plot at bottom the result is compatible with a negative cosine of the new phase. A particular value of 108 degrees reproduce the behavior preferred by the data. That specific phase value cancels the 'zero distance' term in the probability.





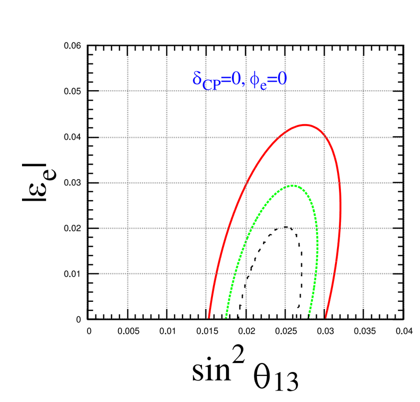
A COMMENT ABOUT THE NORMALIZATION

Reactor flux uncertainties in the absolute normalization in reactor experiments can be ~3% [8] or slightly bigger ~4% [9].
In order to include the error in the absolute normalization we modify the chi square function:

$$\chi^2 = \sum_{d=1}^{6} \frac{\left[M_d - T_d\left(1 + a + \sum_r \omega_r^d \alpha_r + \xi_d\right) + \beta_d\right]^2}{M_d + B_d} + \sum_{r=1}^{6} \frac{\alpha_r^2}{\sigma_r^2} + \sum_{d=1}^{6} \left(\frac{\xi_d^2}{\sigma_d^2} + \frac{\beta_d^2}{\sigma_B^2}\right) + \left(\frac{a}{\sigma_a}\right)^2$$

and we include a conservative 5% error in the absolute normalization.

As a consequence, the constraints we have found for each case are relaxed until on order of magnitude. See the right panel and compare it with the case studied before.



Summary

The measured reactor angle by Daya Bay is modified by the presence of NSI.

For the case of study, we found the strongest constraints for the electron and FU case, with the phases set to zero. In those cases there is an important 'zero distance' contribution to the probability.

The constraints we found depend on the uncertainty in the absolute normalization in the event calculation.

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