Experimental study of decoherence effects in neutrino oscillations in Daya Bay

Konstantin Treskov on behalf of the Daya Bay collaboration
Joint Institute for Nuclear Research, Dubna, Russia

NEUTRINO 2018, Heidelberg, 3-10 June

Conventional neutrino oscillations

- Convetional approach to neutrino oscillations relies on a number of assumptions:
  - Flavor state is a superposition of mass states with identical energies:
  $$|\nu_\alpha\rangle = \sum_{i=1}^{3} V^*_{\alpha i}\,|\nu_i(p)\rangle$$
  - Production and detection proccesses occur coherently.
  - Mass states travel at speed of light.
- This leads to the extensively experimentally studied oscillation probability
$$P_{\alpha\beta}(L) = \sum_{i,k=1}^{3} V^*_{\alpha i} V_{\beta i} V^*_{\beta k} V_{\alpha k} \exp\left(-2\pi i \frac{L}{L^{\mathrm{osc}}_{ik}}\right), \quad L^{\mathrm{osc}}_{ik} = \frac{4\pi E}{\Delta m^2_{ik}}$$
- There are internal inconsistencies within this approach:
  - Distance L can't be defined with delocalized states.
  - The coherence of production and detection should be proven.
  - Equal energy assumption is not Lorentz-invariant.

Neutrino oscillation with wave packets

- The issues above can be addressed when one considers neutrino flavor state as coherent superposition of mass states with different momenta:
$$|\nu_i(k)\rangle \to \int \frac{dk}{2\pi} f(k,p,\sigma^2)|\nu_i(k)\rangle$$
- Assuming form factor is Gaussian the oscillation probability reads:
$$\mathrm{P}_{\alpha\beta}(L) = \sum_{k,j=1}^{3} \frac{V_{k\beta}V^*_{\alpha k}V_{j\alpha}V^*_{\beta j}}{\sqrt[4]{1+\left(L/L^{\mathrm{d}}_{kj}\right)^2}} \exp\left[-\frac{\left(L/L^{\mathrm{coh}}_{kj}\right)^2}{1+\left(L/L^{\mathrm{d}}_{kj}\right)^2} - \mathrm{D}^2_{kj}\right] \mathrm{e}^{-i(\varphi_{kj}+\varphi^{\mathrm{d}}_{kj})}$$
$$\varphi^{\mathrm{d}}_{kj} = -\frac{L/L^{\mathrm{d}}_{kj}}{1+\left(L/L^{\mathrm{d}}_{kj}\right)^2}\left(\frac{L}{L^{\mathrm{coh}}_{kj}}\right)^2 + \frac{1}{2}\arctan\frac{L}{L^{\mathrm{d}}_{kj}}, \quad \varphi_{kl} = 2\pi\frac{L}{L^{\mathrm{osc}}_{kj}},$$
  - $\sigma_{rel} = \sigma_p/p$ is the relative momentum dispersion of wave packet. σ_p is the intrinsic momentum dispersion of wave packet. It depends on the kinematics of production and detection proccesses. In this work $\sigma_p = \mathrm{const}$ is assumed.
  - $L^{\mathrm{coh}} = \frac{L^{\mathrm{osc}}_{kj}}{\sqrt{2}\pi\sigma_{\mathrm{rel}}}$ is coherence length. At this distance separation of wave packets due to different group velocities suppresses interference between mass states.
  - $L^{\mathrm{d}}_{kj} = \frac{L^{\mathrm{coh}}_{kj}}{2\sqrt{2}\sigma_{\mathrm{rel}}}$ is dispersion length of wave packet. At this distance coherence between mass states is partially restored due to spacial broadening of wave packet.
  - $\mathrm{D}^2_{kj} = \frac{1}{2}\left(\frac{\Delta m^2_{kj}}{4p^2\sigma_{\mathrm{rel}}}\right)^2$ suppresses the coherence of mass states due to spacial localization of production and detection regions.

What do we know about σ_p?

- No first principle QFT calculations.
- Only phenomenological estimates such as:
  - $\sigma_p \sim 1\,\mathrm{MeV}$, $\sigma_x \sim 10^{-11}\,\mathrm{cm}$ — uranium atom size;
  - $\sigma_p \sim 1-10\,\mathrm{keV}$, $\sigma_x \sim 10^{-8}-10^{-7}\,\mathrm{cm}$ — atomic scale;
  - $\sigma_p \sim 0.1\,\mathrm{eV}$, $\sigma_x \sim 10^{-4}\,\mathrm{cm}$ — pressure broadening.
- Lack of experimental studies.

Reference

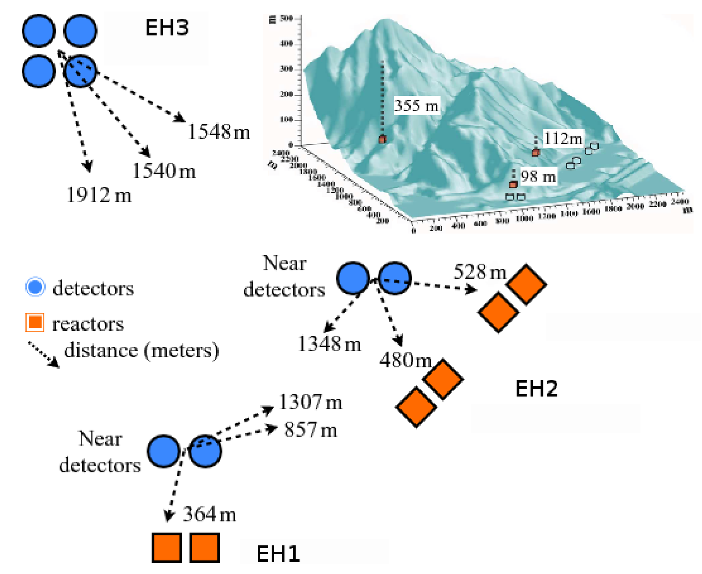
- **Study of the wave packet treatment of neutrino oscillation at Daya Bay**, Eur.Phys.J. C77 (2017), 606

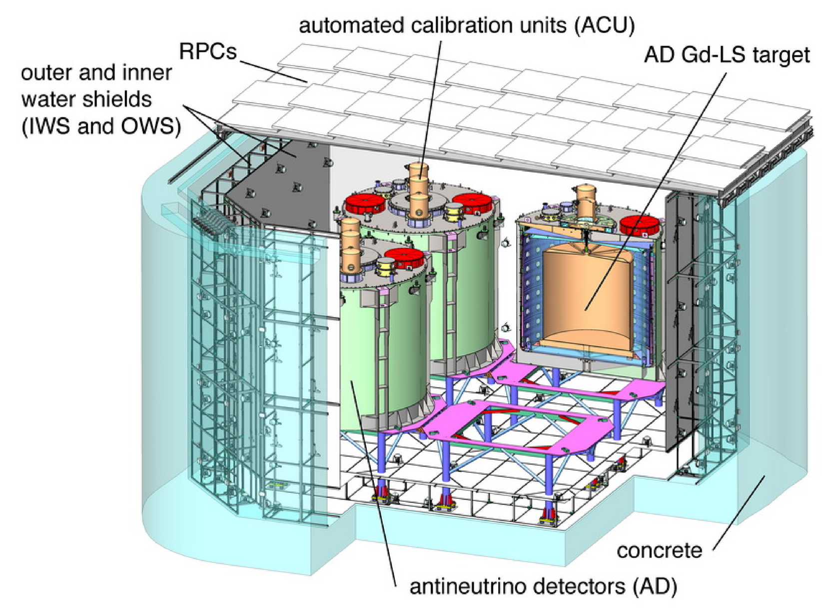
Daya Bay setup

- 8 detectors each with 20 tons of Gd-doped liquid scintillator.
- 6 nuclear reactors each with 2.9 GW of thermal power.
- $\bar{\nu}_e$ detection through IBD
$$\bar{\nu}_e + p \to e^+ + n$$
- Use coincidence of prompt and delayed signals in time to select $\bar{\nu}_e$ events.
- $\bar{\nu}_e$ sample based on 621 days:

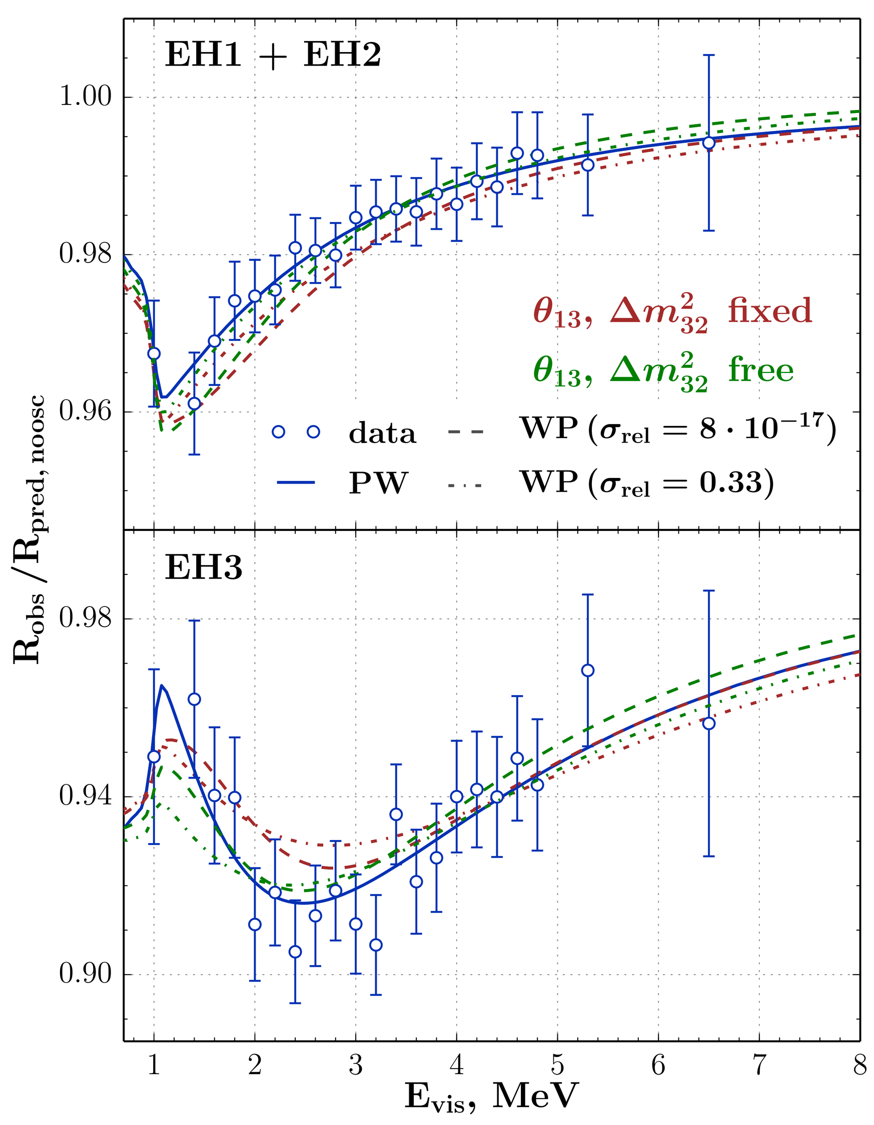
	EH1	EH2	EH3
Events	613813	477144	150255

- Energy resolution $\sim 8\,\%$ at 1 MeV.





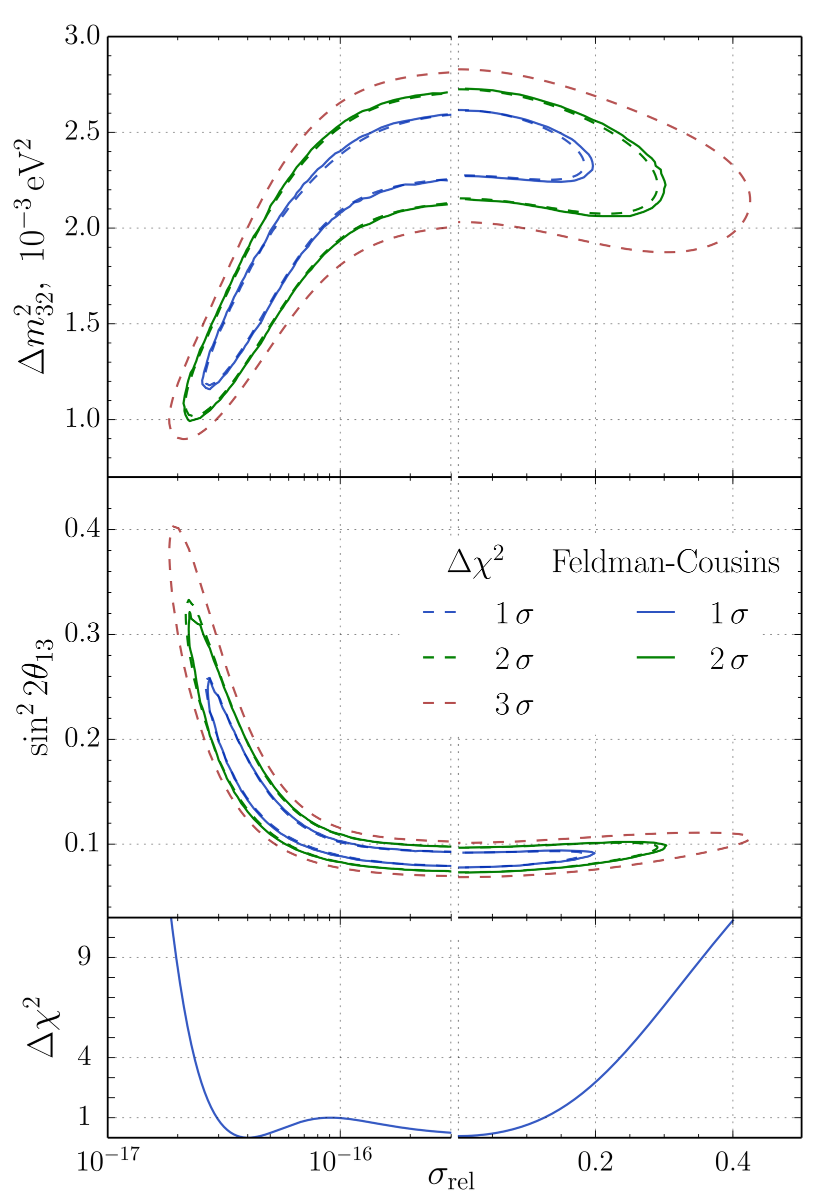
Statistical method



Test statistic is defined as:
$$\chi^2 = (\mathbf{d}-\mathbf{t}(\boldsymbol{\eta}))^T V^{-1}(\mathbf{d}-\mathbf{t}(\boldsymbol{\eta}))$$

- Free parameters:
  - σ_{rel}
  - $\sin^2 2\theta_{13}$
  - Δm^2_{32}
  - Flux normalization N
- Systematical uncertainties are propagated via covariance matrix V.
- Confidence levels are constructed via fixed-level $\Delta\chi^2$ and Feldman-Cousins methods.

Results and Discussion



- There are 3 distinct regions on σ_{rel}:
  - $\sigma_{\mathrm{rel}} < 10^{-16}$ – oscillations are suppressed by D^2.
  - $10^{-16} < \sigma_{\mathrm{rel}} < 0.1$ – no impact on oscillations.
  - $\sigma_{\mathrm{rel}} > 0.1$ – loss of coherence due to spacial separation L^{coh} and dispersion L^{d}.
- Allowed region for σ_{rel} at 95% C.L.:
$$2.38\cdot10^{-17} < \sigma_{\mathrm{rel}} < 0.232$$
- The lower limit can be improved with constraints from reactor cores and detector dimensions. Combined limits are:
$$10^{-11}\,\mathrm{cm} \lesssim \sigma_x \lesssim 2\,\mathrm{m}$$
- The upper limit on σ_{rel} is
$$\sigma_{\mathrm{rel}} < 0.2 \text{ at } 95\%\text{ C.L.}$$

Conclusion

- First experimental limits on σ_{rel} are obtained.
- Insignificance of decoherence effect ensures unbiased measurent of oscillation parameters using the standard approach in Daya Bay.