NSI at running reactor and beam-based neutrino oscillation facilities

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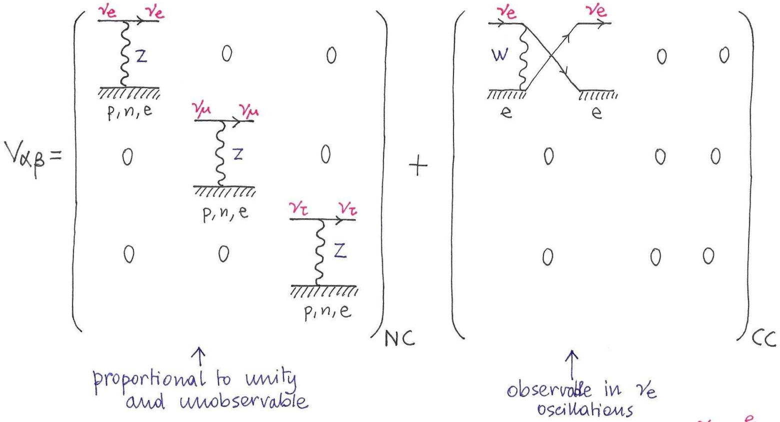
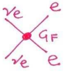
Within the Standard Model, and in ordinary matter:



Relevant term is the $\nu_e - \nu_{\mu,\tau}$ energy difference: $V_{CC} \simeq$ 

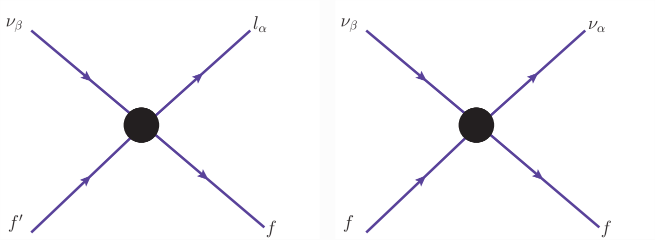
(No analogous for μ,τ, which are absent in ordinary matter)

Outline

1. The pheno approach to the NSI
   - CC-Like NSI pheno approach
   - What are the current limits?
   - NC-Like NSI pheno approach
2. Where the CC-like NSI can be probed?
   - Example I, results
3. Where the NC-like NSI can be probed?
   - Example II, results

The pheno approach to the NSI

L. Wolfenstein (PRD **17**(1978)), J.W.F Valle (PLB **199**(1987))
M.M Guzzo *et al.* (PLB **260**(1991)), E. Roulet (PRD **44**(1991))



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

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

Also, see J. Kopp *et al.* (PRD **77**(2008)).

CC-like NSI pheno approach

Redefining the neutrino states

A 'new' state $|\nu_\beta\rangle$ can appear with the usual state $|\nu_\alpha\rangle$ in a CC weak process together with l_α. That flavor 'admixture' is incorporated to the anti-neutrino flavor states:

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

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

where the standard flavor states are related to mass eigenstates by:

$$|\bar{\nu}_\alpha\rangle = \sum_k U_{\alpha k}|\bar{\nu}_k\rangle$$

The anti-neutrino transition probability for the new states is:

$$P_{\bar{\nu}^s_\alpha \to \bar{\nu}^d_\beta} = |\langle\bar{\nu}^d_\beta|\exp\left(-i\,\mathcal{H}\,L\right)|\bar{\nu}^s_\alpha\rangle|^2.$$

Current bounds

CC-like NSI

Biggio, Blennow, Fernández-Martínez (JHEP **090**(2009))

Bounds extracted from:

- V^{ud} determination: From Kaon decays $\to$ V^{us} (and asumming CKM unitarity) compared with the derivation from beta decays (affected by NSI).
- Universality tests: Ratios $\pi \to e(\mu)\nu$ and $\tau \to \pi\nu$ decay rates modified by quark CC-like NSI.
- Non-observation of flavor change at NOMAD ('zero distance effect'). Channels $\nu_\mu \to \nu_e$ ($|\varepsilon^{ud\,A}_{\mu e}|$, $|\varepsilon^{ud\,L(R)}_{e\mu}|$), $\nu_e \to \nu_\tau$ ($|\varepsilon^{ud}_{\tau e}|$), and $\nu_\mu \to \nu_\tau$ ($|\varepsilon^{ud\,A}_{\mu\tau}|$, $|\varepsilon^{ud\,L(R)}_{\tau\mu}|$).

Assuming only <u>one parameter at a time</u> (90% C.L. for 1 d.o.f):

$$\mathcal{X} = \begin{bmatrix} V & L(R) & V \\ A & A & A \\ L(R) & L(R) & A \end{bmatrix}, \; |\varepsilon^{ud\,\mathcal{X}_{ij}}_{\alpha\beta}| < \begin{bmatrix} \boxed{0.041} & \underline{0.026(0.037)} & \underline{0.041} \\ 0.026 & 0.078 & 0.013 \\ 0.087(0.12) & 0.013(0.018) & 0.13 \end{bmatrix}$$

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WARNING: The bounds are '$\mathcal{X}_{ij}$ dependent'! Are the assumptions (and process(es) involved) clear in each case?

NC-Like NSI pheno approach

Generalizing the effective matter potential

The general matter interaction Hamiltonian can be written as

$$H_{\text{int}} = V \begin{pmatrix} 1 + \varepsilon^m_{ee} & \varepsilon^m_{e\mu} & \varepsilon^m_{e\tau} \\ (\varepsilon^m_{e\mu})^* & \varepsilon^m_{\mu\mu} & \varepsilon^m_{\mu\tau} \\ (\varepsilon^m_{e\tau})^* & (\varepsilon^m_{\mu\tau})^* & \varepsilon^m_{\tau\tau} \end{pmatrix}$$

with $V = \sqrt{2}\, G_F\, N_e$, and:

$$\varepsilon^m_{\alpha\beta} = \sum_{f=e,u,d} \left\langle \frac{Y_f}{Y_e} \right\rangle \varepsilon^f_{\alpha\beta} = \varepsilon^e_{\alpha\beta} + Y_u \varepsilon^u_{\alpha\beta} + Y_d \varepsilon^d_{\alpha\beta}$$

How many new degrees of freedom do we have now ‘in the game’?

Current bounds

NC-like NSI

Gonzalez-Garcia and Maltoni (JHEP **152** (2013))

From a global fit, using only neutrino oscillation data, the 90% of C.L bounds for the LMA solution are:

$$\varepsilon_{\alpha\beta} - \varepsilon_{\mu\mu}\Big|^{f=d(u)} \in \begin{bmatrix} [0.02(0.00), 0.51] & [-0.09, 0.04] & [-0.14, 0.14] \\ \times & 0 & [-0.01, 0.01] \\ \times & \times & [-0.01, 0.03] \end{bmatrix}$$

Thus, for instance, one of the less constrained and non-diagonal NSI coupling is $\varepsilon^{m}_{e\tau} \sim \mathcal{O}(1)$.

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Constrains on $\varepsilon^{f=e}_{\alpha\beta}$ also come from 'ν–e' scattering (not cover them here), see for instance table III in Ref:

Miranda and Nunokawa (NJP **17**(2015))

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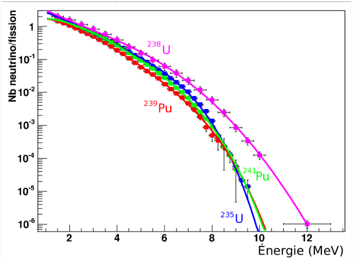
Reactor $\bar{\nu}_e$ production and detection

Production: β decay of
$k = ^{235}$U, ^{239}Pu, ^{241}Pu and ^{238}U

`T. Lasserre @INSS2011`

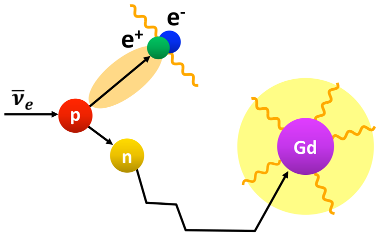


Flux parametrizations: $\Phi_k(E)$

P. Huber (PRC **84** (2011))

T. Mueller *et al.* (PRC **83** (2011))

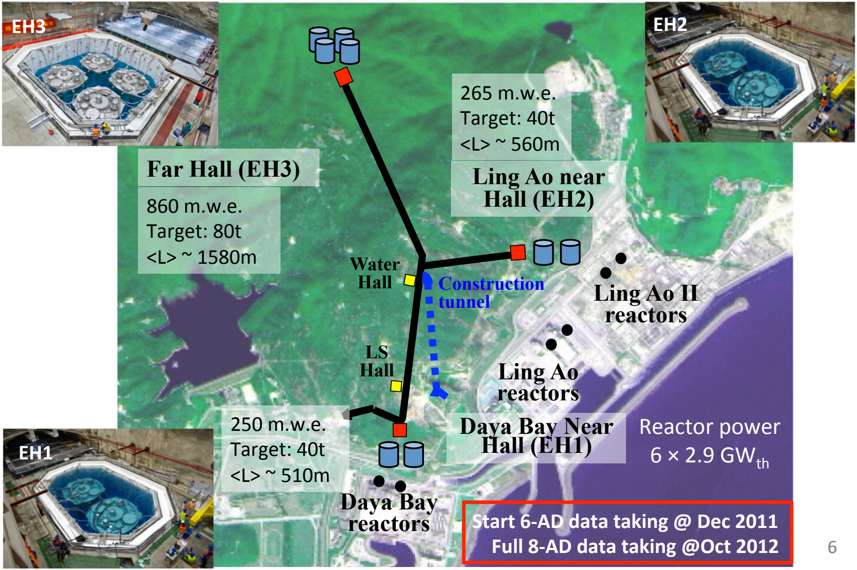
Detection: Inverse β decay,
$\bar{\nu}_e + p \rightarrow n + e^+$



Coincidence signals: Prompt e^+-annihilation and delayed n-capture.

For $\sim$ 1km baseline, Antineutrino propagate to FD practically in Vacuum!

Daya Bay Experimental Setup



Analysis details

$$\tilde{\varepsilon}_{\alpha\beta}^{m,f,V\pm A} \to 0 \quad \text{and} \quad \tilde{\varepsilon}_{e\beta}^{S(D),u,d,V\pm A} \to \varepsilon_{e\beta}^{S(D)}$$

Assumptions in the analysis:

- $\varepsilon^s_{e\alpha} = \varepsilon^{d*}_{\alpha e} \equiv \varepsilon_\alpha = |\varepsilon_\alpha| e^{i\phi_\alpha}$
- $|\bar{\nu}^s_\alpha\rangle = |\bar{\nu}_\alpha\rangle + \sum_\gamma \varepsilon^{s*}_{\alpha\gamma} |\bar{\nu}_\gamma\rangle$
- The effective oscillation probability is given by:

$$P^{eff.}_{\bar{\nu}^s_e \to \bar{\nu}^d_e} \simeq 1 + \overbrace{4|\varepsilon_e|\cos\phi_e}^{\text{'zero distance term'}} - 4\left[\sin\theta_{13} + s_{23}|\varepsilon_\mu|\cos(\delta - \phi_\mu) + c_{23}|\varepsilon_\tau|\cos(\delta - \phi_\tau)\right]^2 \sin^2\Delta_{31} + \mathcal{O}(\varepsilon)^2$$

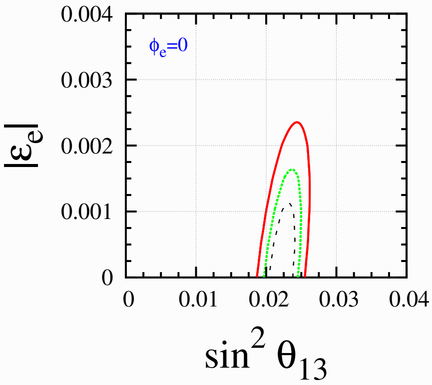
- Ours is a total rate analysis.

Results for the ε_e case

$0.020 \leq \sin^2\theta_{13}^{DYB} \leq 0.024$

Agarwalla, Bagchi, DVF, Tórtola

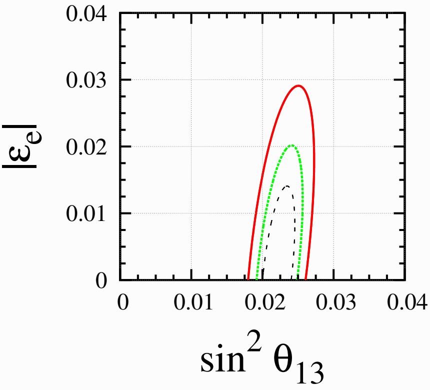
(JHEP **060** (2015))



C.L = 68.3, 90, 95%; 2 d.o.f

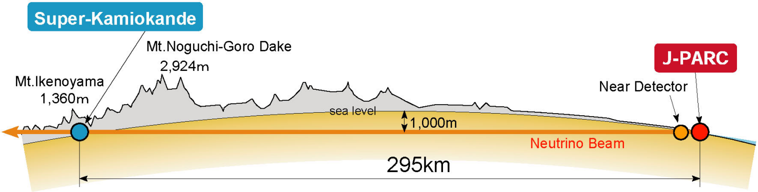
$a_{norm} = 0$
$|\varepsilon_e| \leq 0.0012$ @90% C.L
$0.020 \leq \sin^2\theta_{13} \leq 0.024$

$\sigma_a = 5\%$
$|\varepsilon_e| \leq 0.015$ @90% C.L
$0.020 \leq \sin^2\theta_{13} \leq 0.025$

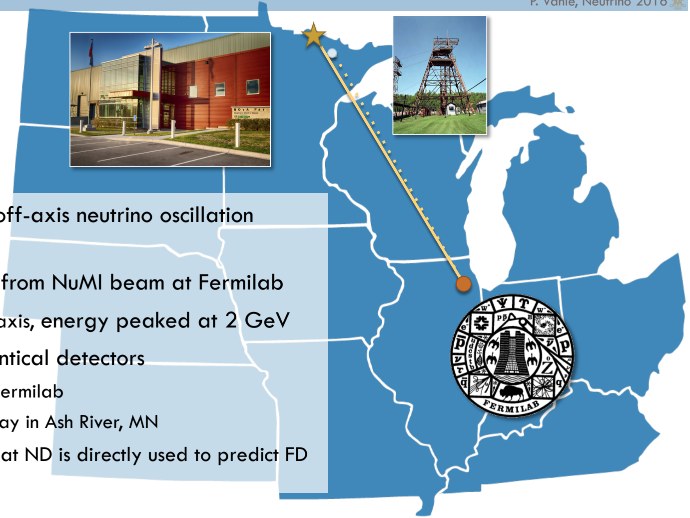


Outline

T2K Experiment



NOvA



- Long-baseline, off-axis neutrino oscillation experiment
- Study neutrinos from NuMI beam at Fermilab
- At 14 mrad off-axis, energy peaked at 2 GeV
- Functionally identical detectors
  - ND on site at Fermilab
  - FD 810 km away in Ash River, MN
  - Measurement at ND is directly used to predict FD

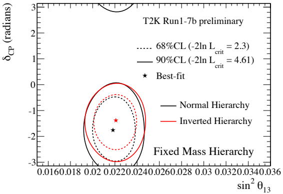
More importantly . . .

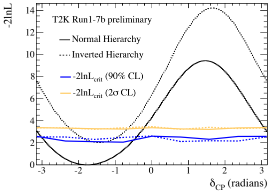
$\boldsymbol{\theta_{13}}$ and $\boldsymbol{\delta_{cp}}$

K. Iwamoto @ ICHEP 2016

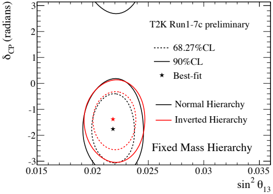
- T2K result with reactor constraint ($\sin^2 2\theta_{13} = 0.085 \pm 0.005$)

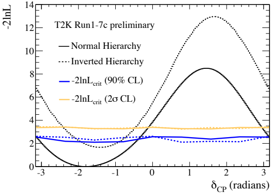
Neutrino 2016





ICHEP 2016





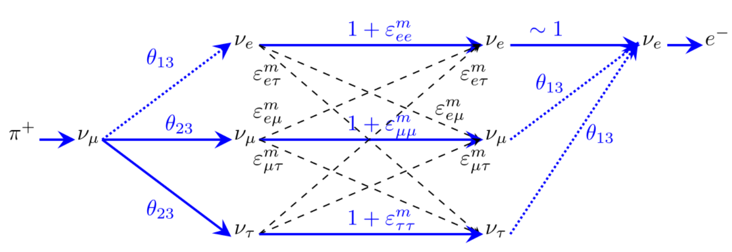
Neutrino 2016: $\delta_{cp} = [-3.02, -0.49](NH), [-1.87, -0.98]\ (IH)$ at 90% CL

ICHEP 2016: $\delta_{cp} = [-3.13, -0.39](NH), [-2.09, -0.74]\ (IH)$ at 90% CL

Analysis details

(Anti)neutrino appearance

Figure taken from: J. Kopp *et al.* (PRD **77**(2008))



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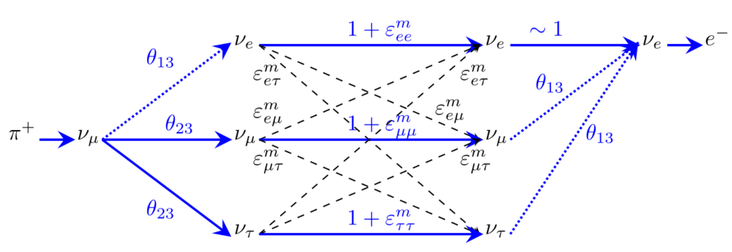
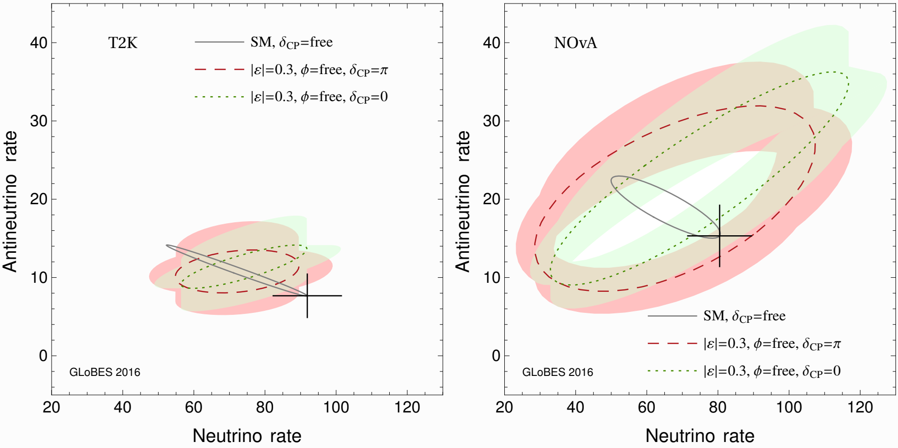


- We considered only the (Anti)neutrino appearance channel.
- Only the off-diagonal NSI parameter $\varepsilon^m_{e\tau} \equiv |\varepsilon| \exp(i\phi) \neq 0$.
- We simulated true neutrino events including NSI and we compare them to the test SM events in both T2K (scaled 5 yrs) and NOvA (3ν+$3\bar{\nu}$).

Results

Bi-rate plots

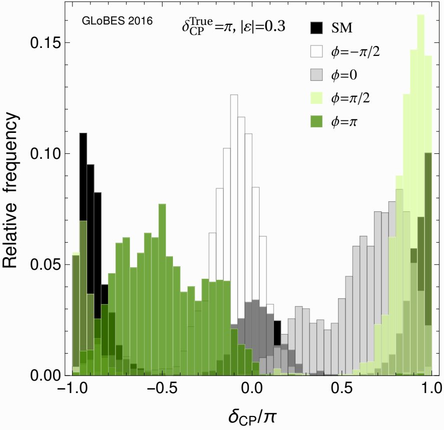
DVF and Huber (PRL 117 (2016))

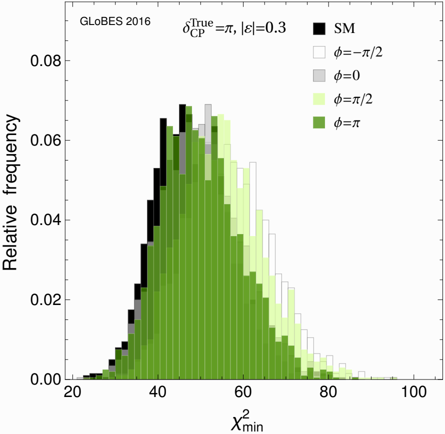


Results

Histograms

DVF and Huber (PRL 117 (2016))



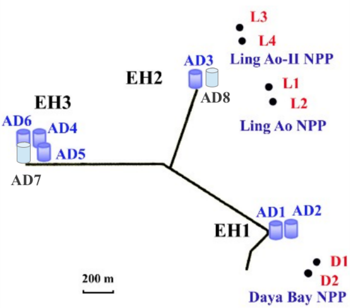


Summary

- A pheno approach to the NSI has been discussed. For a ‘model building approach’ do not miss Y. Farzan talk.
- NSI phenomenology with current neutrino oscillation experiments were presented. Two cases were shown, one for CC-like NSI and the other for NC-like NSI. For and additional possible study of CC-like NSI do not miss M. Blennow talk.
- Multidetector reactor neutrino experiments offer a clean probe of CC-like NSI. The θ_{13} determination is robust under CC-like NSI while the value of the NSI constraint is limited by our current knowledge of the (total normalization) reactor neutrino fluxes.
- Thanks to ‘parameter degeneracies’ (after including NC-like NSI in the 3ν-framework) if the current prefer value for $\delta_{\rm CP}^{\rm True} \sim -\pi/2$ were established, with current facilities, we can not disentangle whether the origin of the CP violation comes from the usual Dirac CP violating phase or from the NSI couplings (even with $\phi = \pi$).

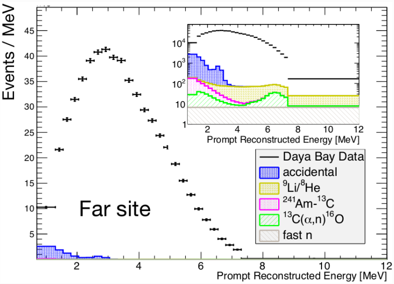
THANK YOU

Daya Bay $\bar{\nu}_e \to \bar{\nu}_e$



$$\frac{N_F}{N_N} = \frac{N_{p,F}}{N_{p,N}} \times \frac{\epsilon_F}{\epsilon_N} \times \frac{L_N^2}{L_F^2} \times \frac{\int \Phi(E)\sigma(E)P_{ee}(E,L_F)}{\int \Phi(E)\sigma(E)P_{ee}(E,L_N)}$$

Chao Zhang @neutrino2014



$$\chi^2 = \sum_{d=1}^{8} \frac{\left[M_d - T_d\left(1 + a_{\text{norm}} + \sum_r \omega_r^d \alpha_r + \xi_d\right) + \beta_d\right]^2}{M_d + B_d}$$

$$+ \sum_{r=1}^{6} \frac{\alpha_r^2}{\sigma_r^2} + \sum_{d=1}^{8}\left(\frac{\xi_d^2}{\sigma_d^2} + \frac{\beta_d^2}{\sigma_B^2}\right) + \left(\frac{a_{\text{norm}}}{\sigma_a}\right)^2$$

Constrained normalization analysis! $\sigma_a \sim 5\%$.

Oscillation Channels

$\bar{\nu}_e$ Disappearance

$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{ee} L}{4E}\right) + \text{solar term}$$

ν_e Appearance from a ν_μ-beam

Cervera *et al.* (NPB **579** (2000))

$$P(\nu_\mu \to \nu_e) \approx |\sqrt{P_{\text{atm}}} e^{-i(\Delta_{32}+\delta)} + \sqrt{P_{\text{sol}}}|^2$$

$$= P_{\text{atm}} + \underbrace{2\sqrt{P_{\text{atm}}}\sqrt{P_{\text{sol}}}\cos(\Delta_{32}+\delta)}_{P_{\sin\delta}+P_{\cos\delta}} + P_{\text{sol}}$$

$$\sqrt{P_{\text{atm}}} = \sin\theta_{23} \sin 2\theta_{13} \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \Delta_{31},$$

$$\sqrt{P_{\text{sol}}} = \cos\theta_{23} \sin 2\theta_{12} \frac{\sin(aL)}{(aL)} \Delta_{21}$$

with $a \equiv V_{CC}/2$ and $\Delta_{ij} \equiv (\Delta m^2_{ij} L)/(4E)$

ν_μ Disappearance

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2(2\theta_{23}) \sin^2 \Delta_{32} - \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2 \Delta_{31}$$