Neutrino energy reconstruction in long-baseline experiments

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in collaboration with

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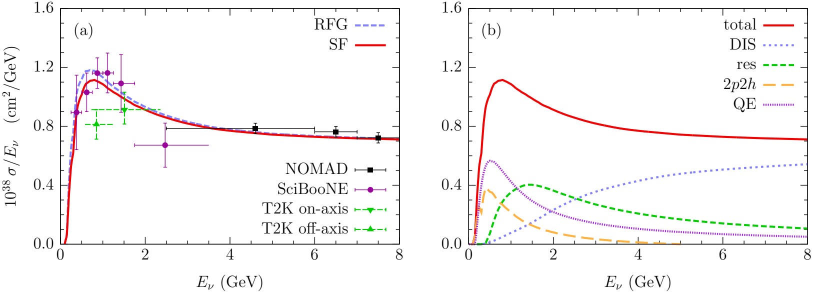
Introduction

- Neutrinos are produced as tertiary decay products
- Neutrino has a low cross section ($\propto 10^{-38}$ cm^2)

$$\nu_\ell + A \to \ell^- + X$$

- Neutrino cross section for ^{12}C as a nuclear target



The kinematic method

The generic final state resulting from neutrino-nucleus scattering in charged current, can be described by a state of N nucleons and M mesons

$$\nu_\ell(k_\nu) + A(p) \to \ell^-(k_\ell) + N(p') + M(h')$$

and the energy of the incoming neutrino can be reconstructed as

$$E_\nu^{kin} = \frac{W^2 - m_\ell^2 + 2(M - \epsilon_n)E_\ell - (M - \epsilon_n)^2}{2(M - \epsilon_n - E_\ell + |\mathbf{k}_\ell| \cos\theta_\ell)}$$

- The reaction mechanism is assumed to be quasi-elastic like $(\nu_\ell(k_\nu) + n(p) \to \ell^-(k_\ell) + p(p'))$
- The struck nucleon is assumed to be at rest
- W^2 is assumed to be equal to M^2 for meson-less events and to M_Δ^2 otherwise

The calorimetric method

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and the energy of the incoming neutrino can be reconstructed as

$$E_\nu^{cal} = \epsilon_n + E_\ell + \sum_i^N (E_{\mathbf{p_i}'} - M) + \sum_j^M E_{\mathbf{h_j}'}$$

- $\epsilon_n = 34$ MeV average single-nucleon separation-energy
- Note that mesons enter with the total energy, while for nucleons only the kinetic energy contribute
- Can be applied to any type of CC reactions

The calorimetric method

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HOWEVER

an accurate reconstruction of hadrons poses a formidable experimental challenge

- Neutrons are likely to escape detection
- Any undetected meson results as an underestimation of neutrino energy of ~ 135 MeV

Energy reconstruction: Strategy

Neutrino events are analyzed within two different assumptions

- Perfect reconstruction: with the exception of neutrons, all produced particles are observed, and their measured energies are equal to the true ones

Energy reconstruction: Strategy

Neutrino events are analyzed within two different assumptions

- Perfect reconstruction: with the exception of neutrons, all produced particles are observed, and their measured energies are equal to the true ones
- Realistic reconstruction: neutrons are assumed to escape detection and detector effects are taken into account
  - the measured energies and angles are smeared with respect to the true ones by a finite detector resolution

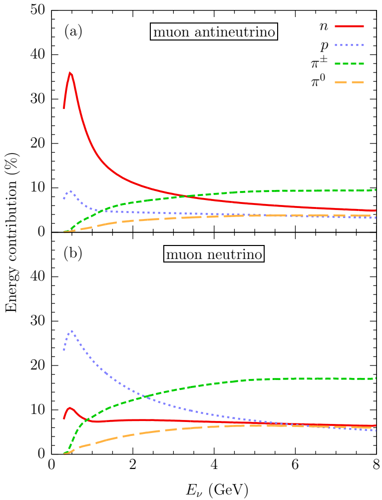
$$f(x_{meas}) = \frac{1}{\sqrt{2\pi}\sigma(x_{true})} \exp\left[-\frac{1}{2} \left(\frac{(x_{meas} - x_{true})}{\sigma(x_{true})} \right)^2 \right]$$

  - detection efficiencies (energy independent) and thresholds are taken into account

Thresholds for mesons (20 MeV) and protons (40 MeV)

Efficiencies for π^0 (60%), for other mesons (80%) and for protons (50%)

Energy contribution



For the calorimetric reconstruction it is important to estimate the energy contribution coming from different species of hadrons

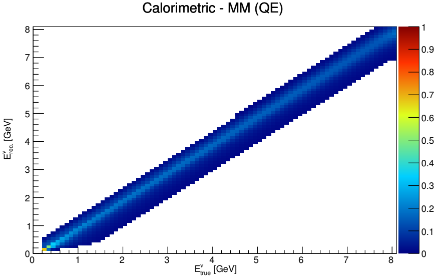
- In QE range the contribution of protons (neutrons) is dominant for neutrinos (anti-neutrinos)
- In the region of resonant and non-resonant pion production, charged pions gives the largest contribution
- At $E_\nu \gtrsim 1.5$ GeV neutrons contribute less than 15% to the (anti)neutrino energy

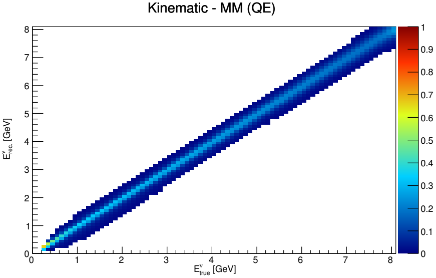
Migration Matrices

Define the probability that an event with a true neutrino energy in the bin j ends up being reconstructed in the energy bin i

$$\mathcal{M}_{ij} \equiv N(E_i^{rec}, E_j^{true})$$

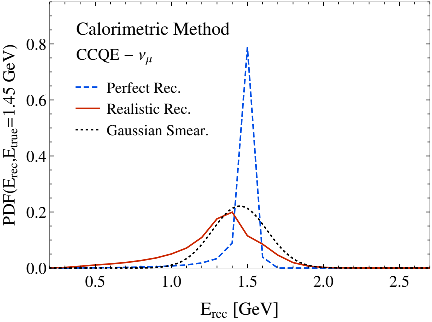
with events generated with GENIE

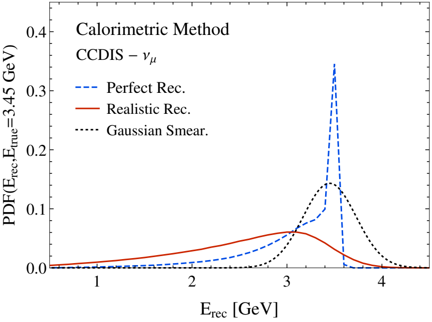




Migration Matrices

- Matrices are produced up to 8 GeV, with a bin size of 100 MeV
- Detector effects affect the probability for a neutrino event to be reconstructed in the correct energy bin
- Finite energy resolutions smear the measured energies
- Imperfect efficiencies and finite thresholds result in an energy partially carried away by undetected particles





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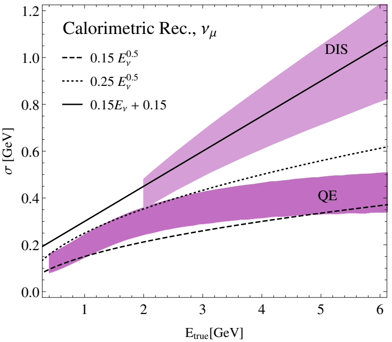

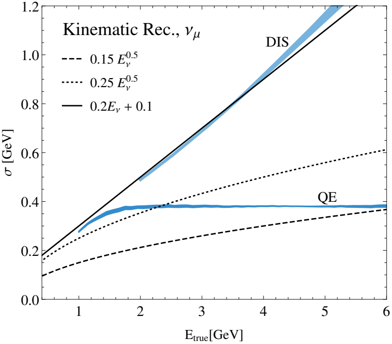

Neutrino oscillations

- mass eigenstates $\longleftrightarrow$ flavor eigenstates

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U_{\alpha i}|\nu_i\rangle \ ; \ i = 1,2,3 \quad \alpha = e, \mu, \tau$$

$$U = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{Atmospheric}} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}}_{\text{Reactor}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Solar}} \quad \begin{matrix} s_{ij} = \sin\theta_{ij} \\ c_{ij} = \cos\theta_{ij} \end{matrix}$$

- The evolution of the states

$$|\nu_i(t)\rangle = \exp(-itE_i)|\nu_i(0)\rangle \ ; \quad E_i \simeq p_i + \frac{m_i^2}{2p_i} \ \Rightarrow$$

$$\mathcal{A}(\nu_\alpha \to \nu_\beta) = \langle \nu_\beta(t)|\nu_\alpha(0)\rangle = \sum_j U_{\alpha j} U^*_{\beta j} \exp\left[-\frac{i m_j^2 L}{2E_\nu} \right]$$

Neutrino oscillations

- mass eigenstates $\longleftrightarrow$ interactions eigenstates

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U_{\alpha i}|\nu_i\rangle \ ; \ i = 1,2,3 \quad \alpha = e, \mu, \tau$$

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$$|\nu_i(t)\rangle = \exp(-itE_i)|\nu_i(0)\rangle \ ; \quad E_i \simeq p_i + \frac{m_i^2}{2p_i} \ \Rightarrow$$

$$P(\nu_\alpha \to \nu_\beta) = |\langle \nu_\beta(t)|\nu_\alpha(0)\rangle|^2 = \sum_{i,j} U_{\alpha j}U^*_{\alpha i}U_{\beta i}U^*_{\beta j} \exp\left[-\frac{i\Delta m^2_{ij}L}{2E_\nu}\right]$$

Oscillation analysis

The extraction of the oscillation parameters is linked to the event rate

$$N^i_\beta = \int_{E^i_\nu}^{E^i_\nu + \Delta E_\nu} \mathrm{d}E_\nu \; \sigma_{\nu_\beta}(E_\nu) \; P_{\alpha\beta}(\{\Theta\}, E_\nu)\phi_{\nu_\alpha}(E_\nu)$$

- the event rate distribution is affected by detector capabilities
- the true rate is generated including experimental features implemented in the construction of the migration matrices

$$N^{true}_i = \sum_X \sum_j \mathcal{M}^X_{ij} \; N^X_j$$

where X describes the interaction channel

- the aim is to reproduce an event distribution obtainable with 'realistic' experimental setup

Oscillation analysis

The extraction of the oscillation parameters is linked to the event rate

$$N_\beta^i = \int_{E_\nu^i}^{E_\nu^i+\Delta E_\nu} \mathrm{d}E_\nu \; \sigma_{\nu_\beta}(E_\nu) \; P_{\alpha\beta}(\{\Theta\}, E_\nu)\phi_{\nu_\alpha}(E_\nu)$$

- the event rate distribution is affected by detector capabilities
- the fit is performed using a linear combination of the matrices obtained of the realistic and perfect reconstruction

$$N_i^{fit} = \sum_X \sum_j \left\{(1-\alpha)M_{ij}^{X,real} + \alpha M_{ij}^{X,perf}\right\} N_j^X$$

α is a purely phenomenological parameter

- this phenomenological approach is useful to quantify the impact of the incorrect estimation of detectors effect on the oscillation analysis

Oscillation analysis

- The oscillation analysis is performed in the disappearance channel $\nu_\mu \to \nu_\mu$, using the software GLoBES
- The χ^2 analysis is such that

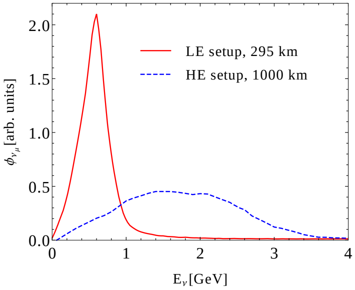
$$\Delta\chi^2(\Delta m^2_{31}, \theta_{23}) \equiv \chi^2(\Delta m^2_{31}, \theta_{23}) - \chi^2_{best-fit} < 2.30$$

- The pull method is used, with Gaussian priors for each systematic error
  - a 20% bin-to-bin uncorrelated systematic uncertainty
  - a 20% overall normalization uncertainty, which is bin-to-bin correlated
- A near detector is used
- The oscillation parameters used are

Δm^2_{21}	Δm^2_{31}	θ_{12}	θ_{23}	θ_{13}	δ
$7.50 \times 10^{-5}\text{eV}^2$	$2.46 \times 10^{-3}\text{eV}^2$	33.48 deg	42.30 deg	8.5 deg	0.0

Experimental setup

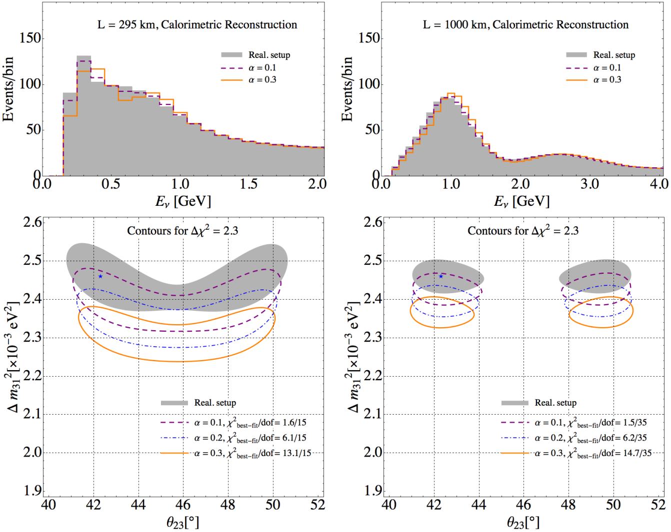
- *Low energy setup* (LE) with a narrow-band off-axis beam. The neutrino flux is peaked around 600 MeV with a baseline $L = 295$ km
- *High energy setup* (HE) with a broadband on-axis beam. The flux is peaked at $1 - 2$ GeV and the baseline is $L = 1000$ km



Number of un-oscillated events in the energy window under study [0.3, 2] GeV for LE and [0.3,4] GeV HE

	QE	2p2h	res	DIS	total
LE	49%	28%	21%	2%	4891
HE	26%	11%	37%	26%	4456

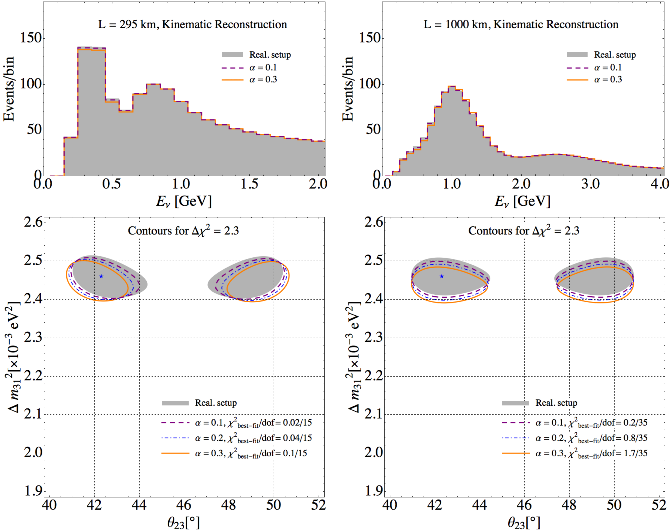
Results for the calorimetric method



Disappearance analysis: $\nu_\mu \to \nu_\mu$

[Phys. Rev. D **92** 073014 (2015)]

Results for the kinematic method



Appearance analysis

[Phys. Rev. D **92** 091301 (2015)]

- We consider $\nu_\mu \to \nu_e$ & $\overline{\nu}_\mu \to \overline{\nu}_e$
- A wide–band neutrino beam is considered with $L = 1300$ km
- The background is smeared according to a Gaussian with $\sigma(E_\nu) = 0.15\sqrt{E_\nu}$
- The signal efficiency is set to 80%

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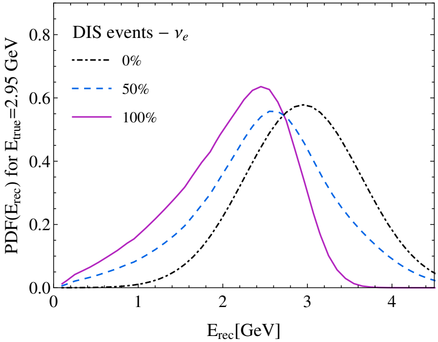

- The true rate is generated with realistic detector capabilities
- In the ideal case the neutrino energy would be smeared according to a Gaussian distribution

$$\Downarrow$$

$$\sigma(E_\nu) = a + b\sqrt{E_\nu} + cE_\nu$$

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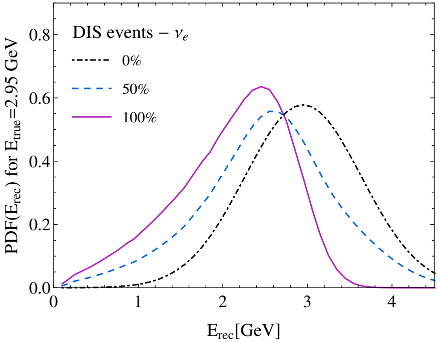

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- The fit is performed using a linear combination of the above cases

Appearance analysis

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$$N_i^{fit} = \sum_X \sum_j \left\{ (1-\alpha) M_{ij}^{X,real} + \alpha M_{ij}^{X,gauss} \right\} N_j^X$$

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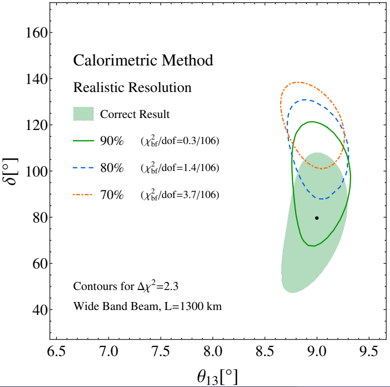

Effects of the missing energy

- $90\% \rightarrow \alpha = 0.1$
- $80\% \rightarrow \alpha = 0.2$
- $70\% \rightarrow \alpha = 0.3$

of the missing energy correctly accounted for

Conclusions

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- We compared two different energy reconstruction techniques: the reconstruction based on the kinematics of the outgoing lepton and the one based the calorimetric method
- Detectors effects have been taken into account
- The oscillation analysis has been performed in appearance and disappearance

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- We compared two different energy reconstruction techniques: the reconstruction based on the kinematics of the outgoing lepton and the one based the calorimetric method
- Detectors effects have been taken into account
- The oscillation analysis has been performed in appearance and disappearance

- Bias in the extraction of oscillation parameters
    - Effects of incorrect estimation of detector performances
    - Effects of incorrect estimation of missing energy

Backup

χ^2 analysis

The χ^2 values, in the energy bin i and for the detector D is calculated as

$$\chi^2_{i,D} = 2\left(T_{i,D}(\theta,\xi) - O_{i,D} + O_{i,D}\ln\frac{O_{i,D}}{T_{i,D}(\theta,\xi)}\right) .$$

- $T_{i,D}$ is the fitted rate

$$T_{i,D} = (1 + \xi_{\phi_i} + \xi_n)N_i(\theta)$$

  - ξ nuisance parameters
  - $N_i(\theta)$ is the event rate for a given energy bin computed with the test values θ
- $O_{i,D}$ is the effective *observed* rate and depends only on the oscillation values used as true input values

$$\chi^2 = \min_{\xi}\left\{\sum_{i,D}\chi^2_{i,D}(\theta,\xi) + \left(\frac{\xi_{\phi_i}}{\sigma_\phi}\right)^2 + \left(\frac{\xi_n}{\sigma_n}\right)^2\right\}$$

Gaussian Smearing

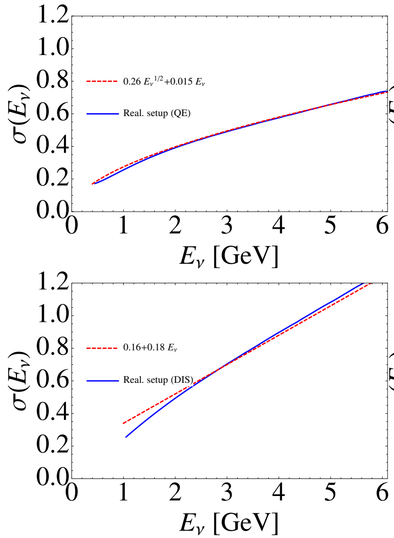
The behavior of the standard deviation, as a function of true neutrino energy can be fitted with a given function. The fitting function chosen is

$$\sigma(E_\nu) = a + b\sqrt{E_\nu} + cE_\nu \ , \quad \text{with} \quad a, b, c > 0 \ ,$$

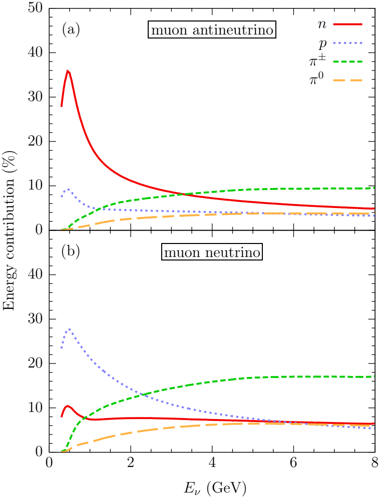
and the energy resolution $R(E_\nu, E')$

$$R(E_\nu, E') = \frac{1}{\sigma(E_\nu)\sqrt{2\pi}} e^{-\dfrac{E_\nu - E'}{2\sigma^2(E_\nu)}} \ .$$

Gaussian Smearing



Energy contribution



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- At $E_\nu \gtrsim 1.5$ GeV neutrons contribute less than 15% to the (anti)neutrino energy