Neutrino factory near detector simulation

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Neutrino oscillations

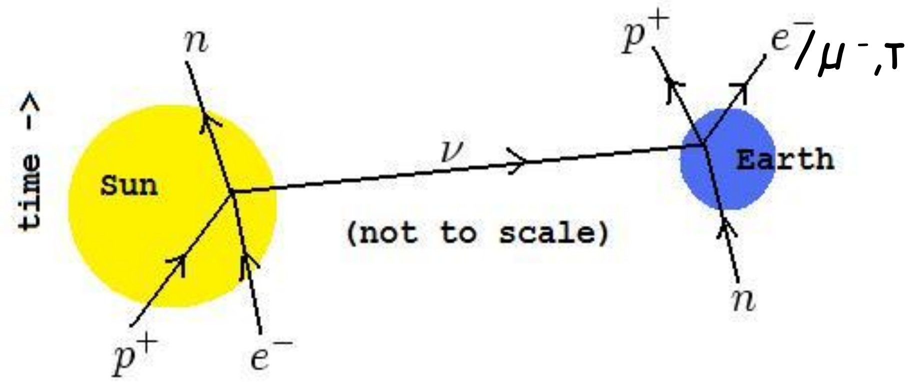
- If the neutrino has a non-zero mass then the mass and weak interaction eigenstates can be mixed.

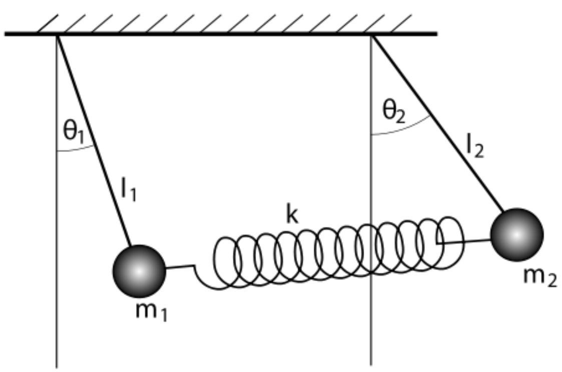
$$|\nu_\alpha\rangle = \sum_\alpha U_{\alpha i}|\nu_i\rangle$$

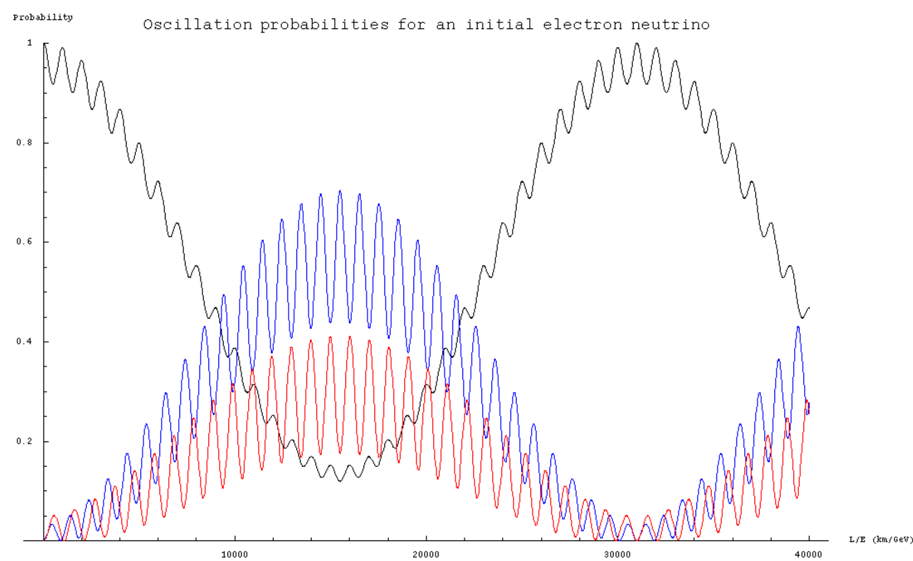
$$\nu_e - \nu_\mu - \nu_\tau$$

Neutrino oscillations

- Neutrinos are produced in weak interactions (e.g. in the sun) and start their travel with a given flavor. However when they propagate, the different mass values interfere with each other and the probability of measuring a particular flavor for a neutrino varies periodically. This phenomena is called **neutrino oscillations**.

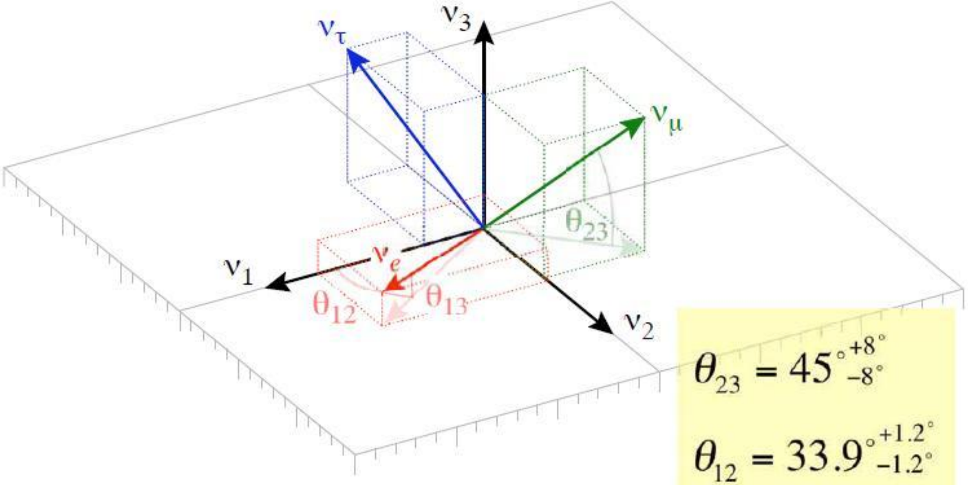






Neutrino oscillations

- The Neutrino oscillations can be used to measure the three mixing angles and the two mass differences.



$$\theta_{23} = 45^{\circ}{}^{+8^{\circ}}_{-8^{\circ}}$$

$$\theta_{12} = 33.9^{\circ}{}^{+1.2^{\circ}}_{-1.2^{\circ}}$$

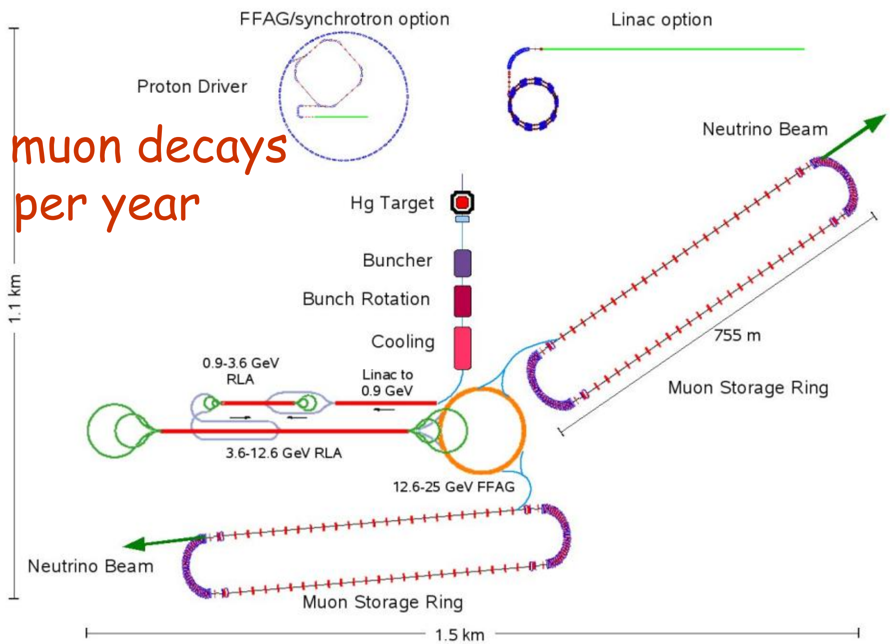
$$\theta_{13} < 13^{\circ}$$

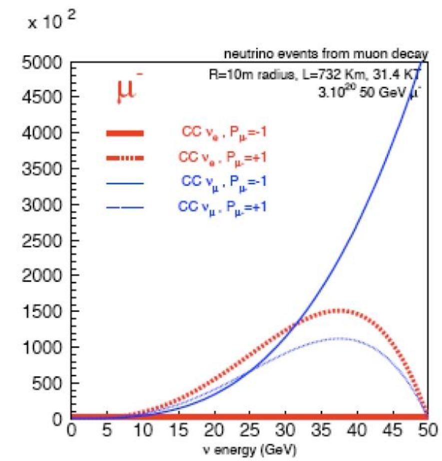
$$\Delta m^2_{12} = 7.67^{+0.22}_{-0.21} \left(^{+0.67}_{-0.61}\right) \times 10^{-5}\ eV^2$$

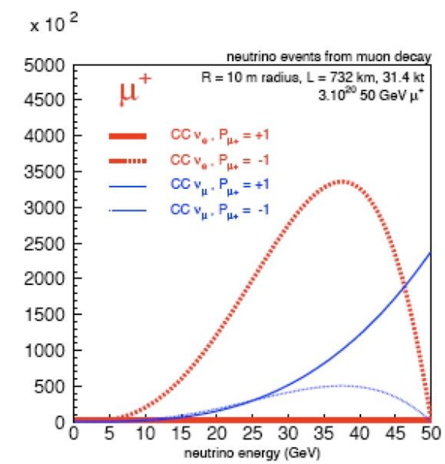
$$\Delta m^2_{23} = \begin{cases} -2.37 \pm 0.15 \left(^{+0.43}_{-0.46}\right) \times 10^{-3}\ eV^2 \\ +2.46 \pm 0.15 \left(^{+0.47}_{-0.42}\right) \times 10^{-3}\ eV^2 \end{cases}$$

Neutrino Factory

10^{21} muon decays per year



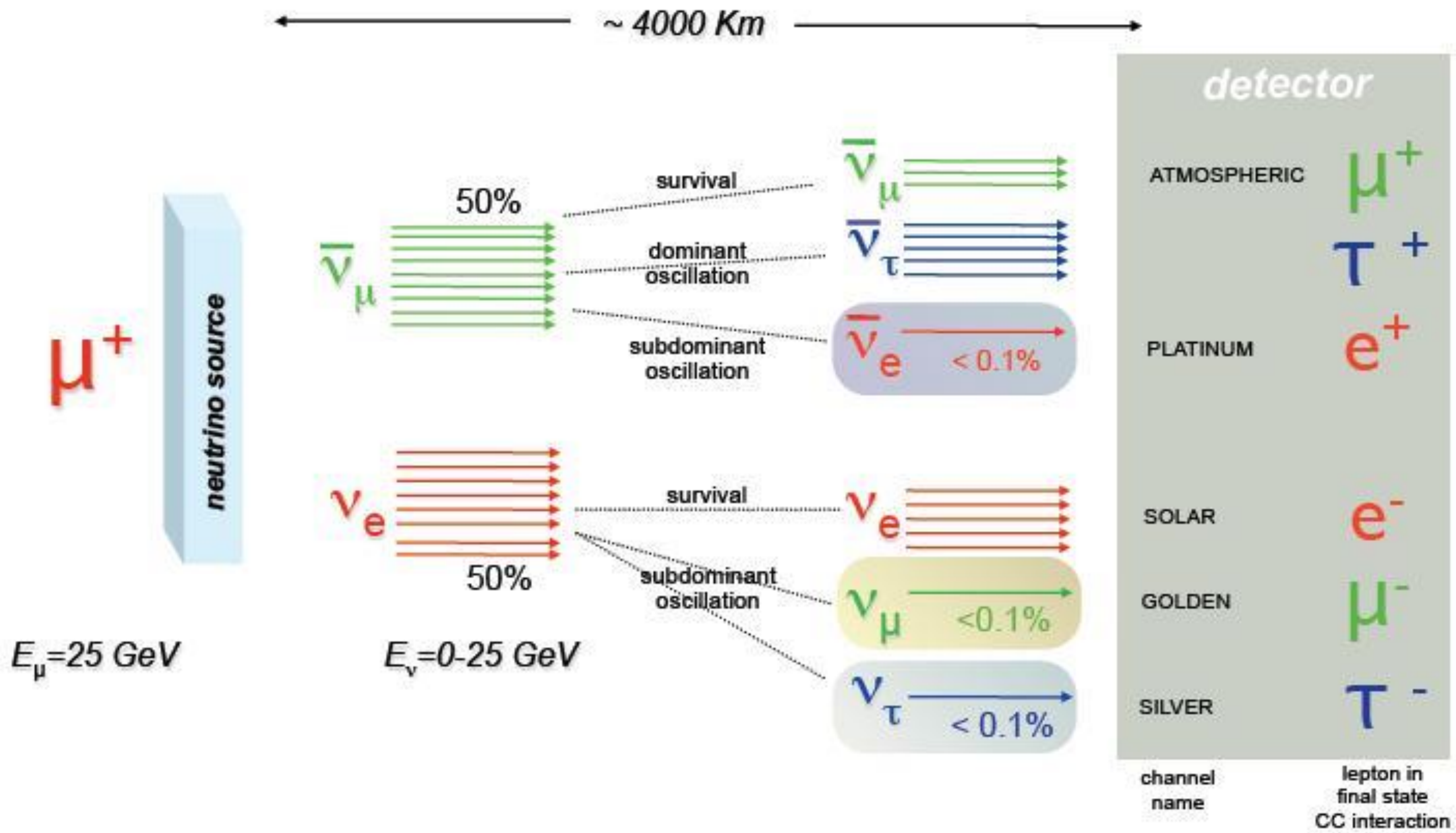




- Measure θ_{13};
- Determine the mass hierarchy;
- Discover CP-violation in the leptonic sector (if exists).

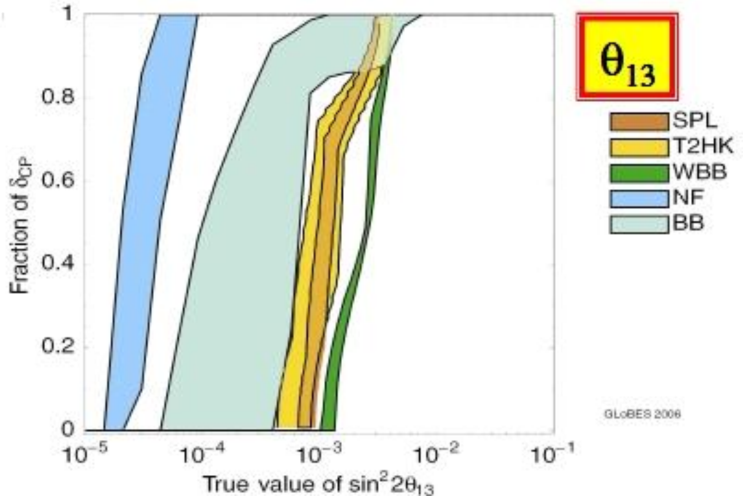
Oscillations channels

The CP violation search requires the study of the subdominant oscillations

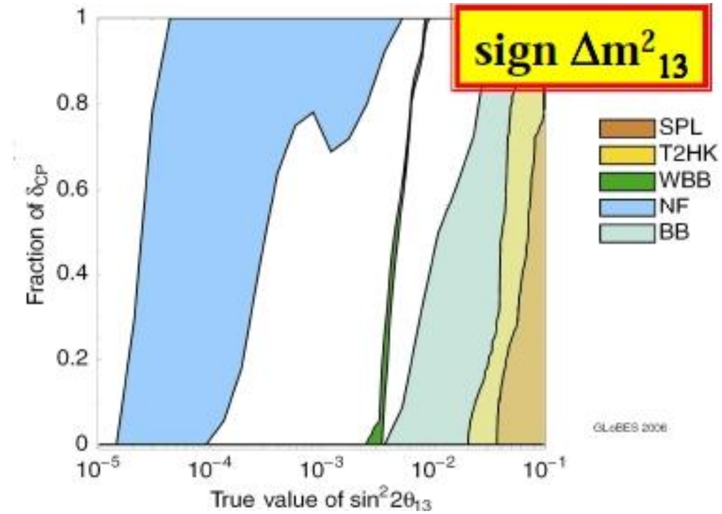


Discovery potential of the neutrino factory

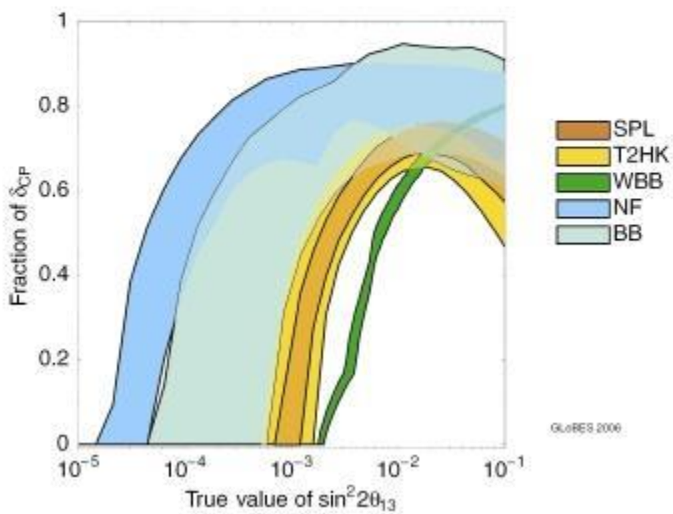
θ_{13}



sign Δm^2_{13}



CP phase δ



- Neutrino factory does it all…

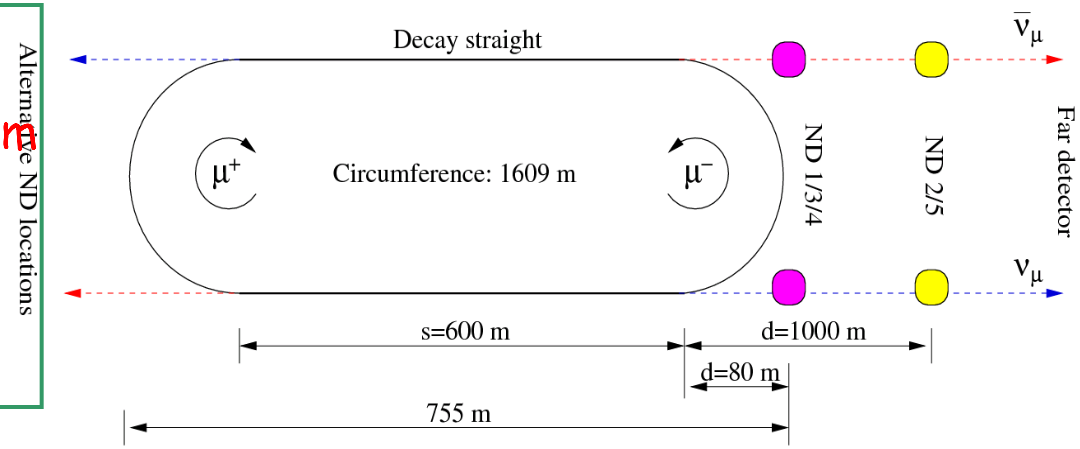
Neutrino Factory Near Detector

E_μ = 25 GeV 80 MeV

Straight section length = 600 m

Muon angular spread 0.5 mrad

5×10^{20} muon decays/year



Neutrino Factory Near Detector aims:

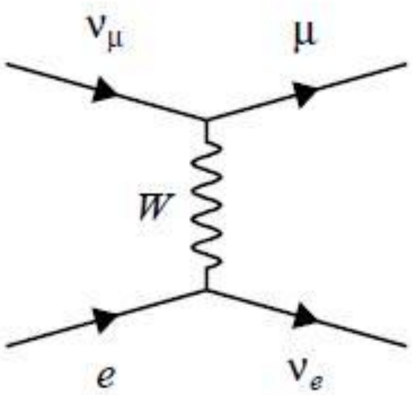
- Measurement of neutrino flux with ~1% precision and extrapolation to the Far Detector;
- Measurement of charm production(main background to oscillation signal);
- Cross-section measurements: DIS, QEL, RES scattering;
- Search for Non Standard Interactions (NSI).

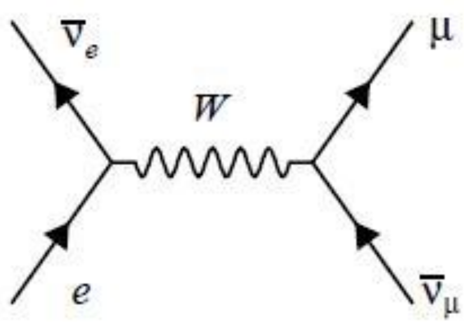
Neutrino Factory Near Detector

Neutrino Factory Near Detector components:

- Vertex detector for charm and tau interactions for NSI;
- Low Z high resolution target (ie scintillating fibre tracker or capillary tube tracker) for flux and cross-section measurement (ν_μ and ν_e);
- Magnetic field for muon momentum measurement ($\delta p/p \sim 1\%$);
- Need muon catcher and electron identification;
- Good energy resolution for flux extrapolation (better than Far Detector) – aspire to $\delta E/E \sim 1\%$.

Measurement of the neutrino flux in the Near detector





$$\nu_\mu + e^- \rightarrow \nu_e + \mu^- \qquad \bar{\nu}_e + e^- \rightarrow \bar{\nu}_\mu + \mu^-$$

$$\sigma = \frac{G_F^2}{\pi}\frac{(s - m_\mu^2)^2}{s}$$

$$\frac{d\sigma}{dcos\theta} = \frac{G_F^2}{\pi}\frac{(s - m_\mu^2)^2}{s} \times$$

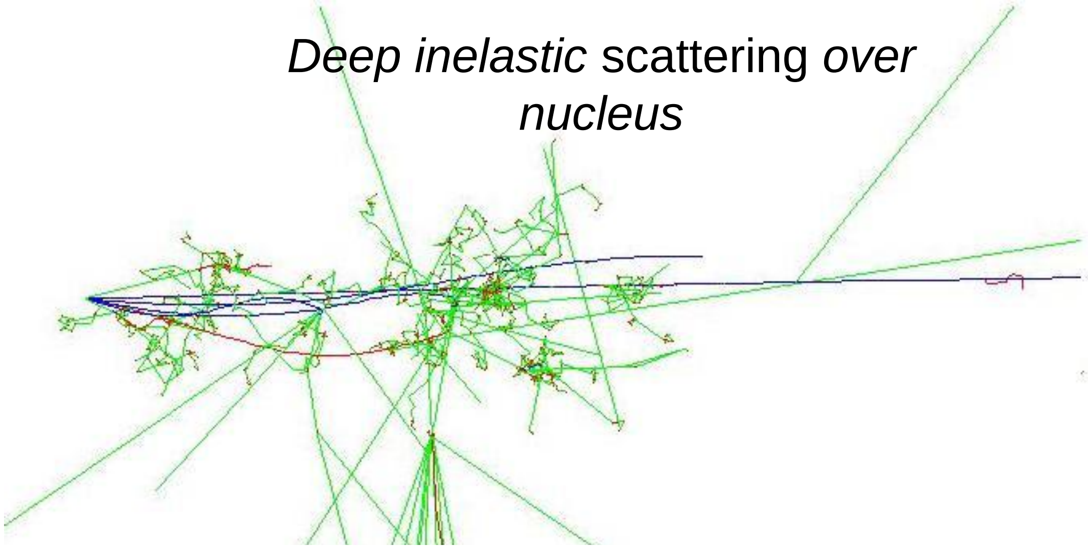
$$\times \ (1 + \frac{s - m_\mu^2}{s + m_\mu^2} cos\theta)(1 + \frac{s - m_e^2}{s + m_e^2} cos\theta)$$

$$\sigma = \frac{G_F^2}{\pi}\frac{(s - m_\mu^2)^2}{s^2}(E_e E_\mu + \frac{1}{3} E_{\bar{\nu}_\mu} E_{\bar{\nu}_e})$$

- The quasielastic scattering off electrons can be used to measure the flux, because its absolute cross-section can be calculated theoretically with great confidence.

Signal and background estimation

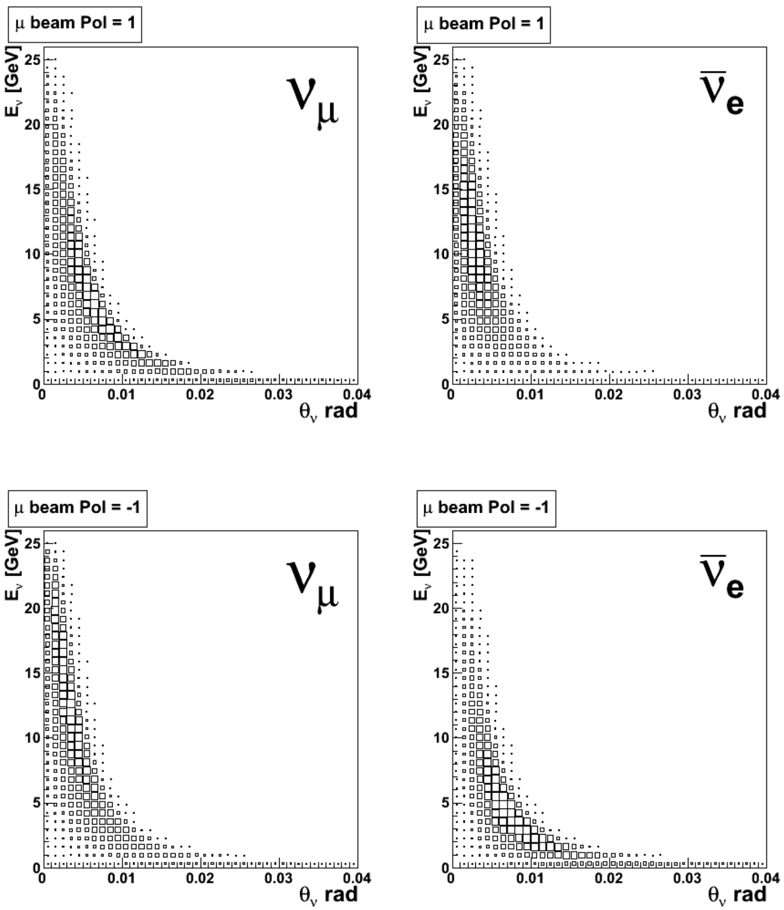
Deep inelastic scattering *over nucleus*



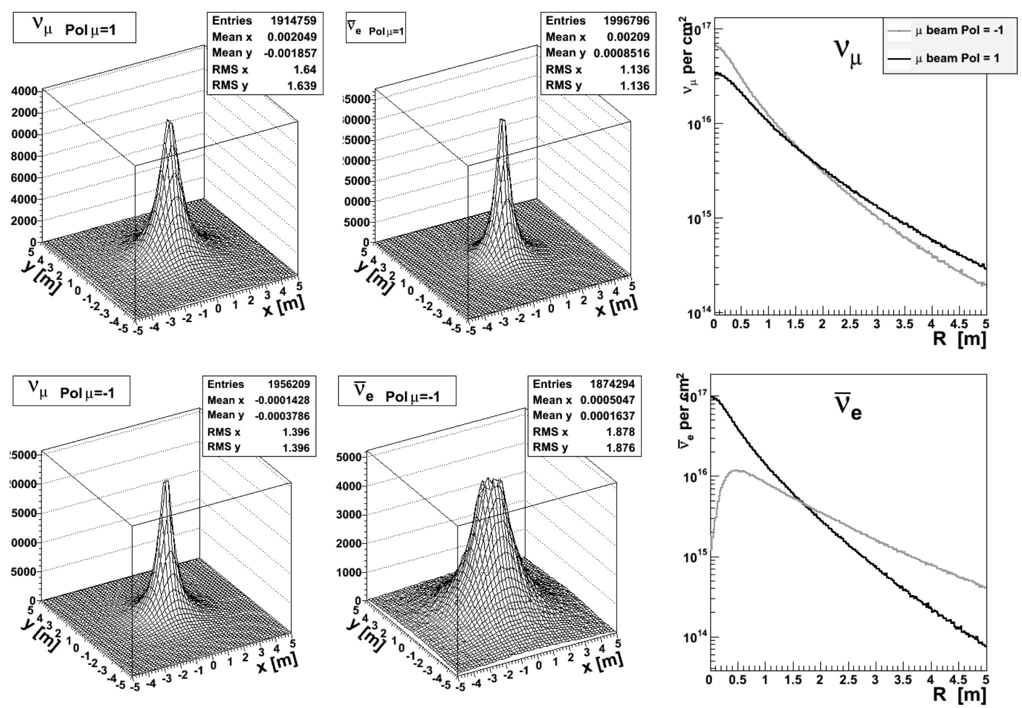
Quasielastic scattering off electrons

If we want to measure the neutrino flux by using the quasielastic scattering off electrons, the detector has to be able to distinguish between these two events.

Simulation of the neutrino beam



- Properties of the neutrino beam



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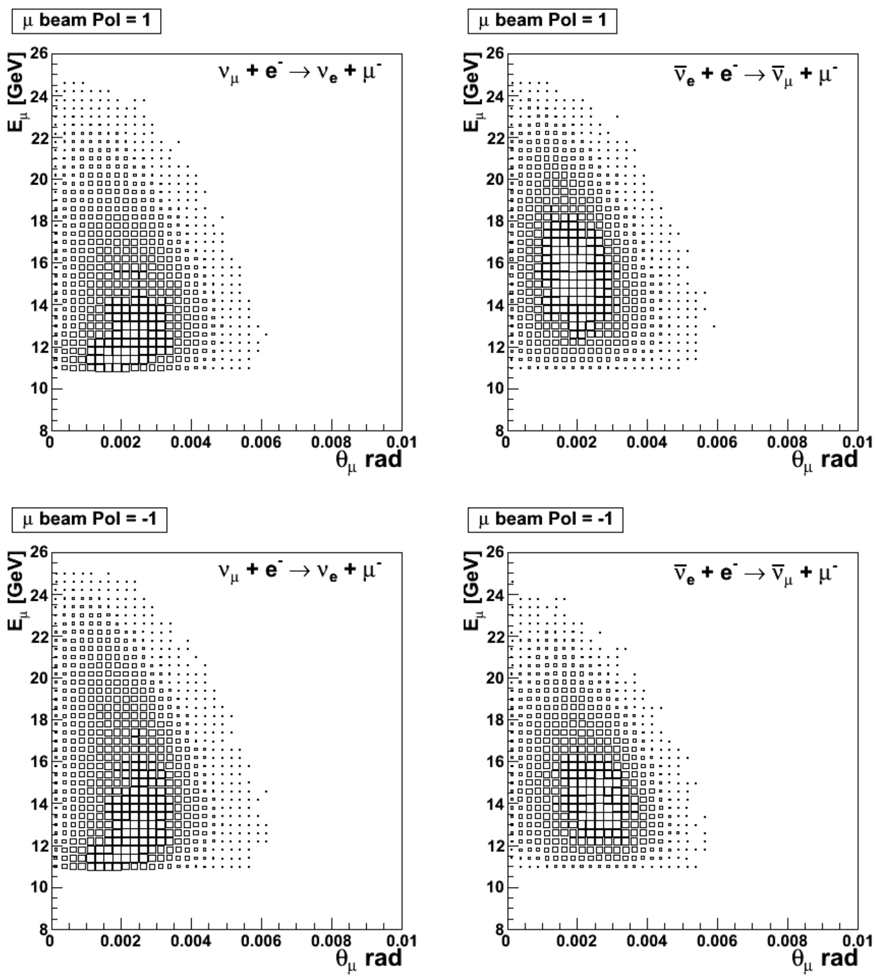
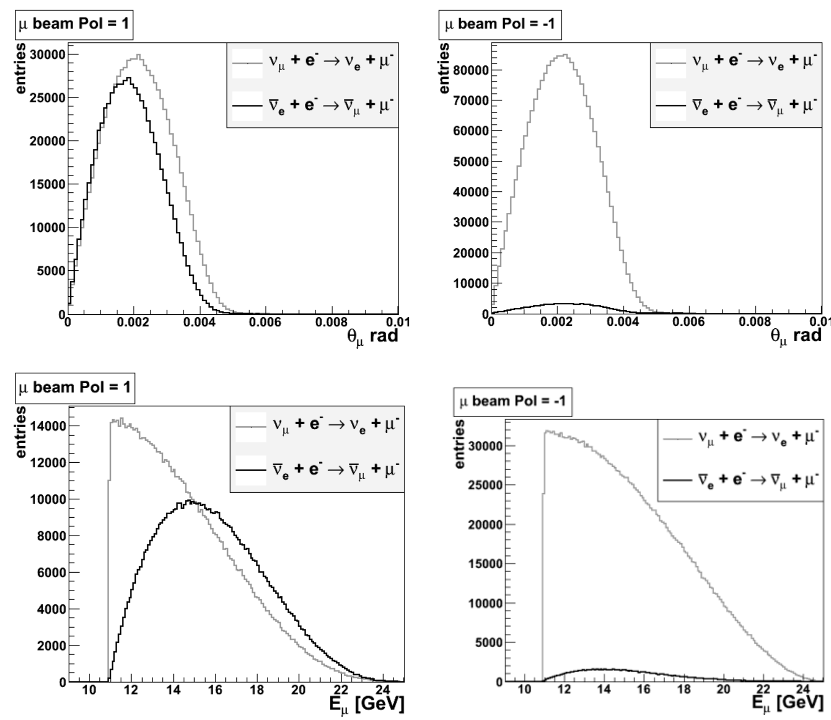
Quasielastic scattering off electrons



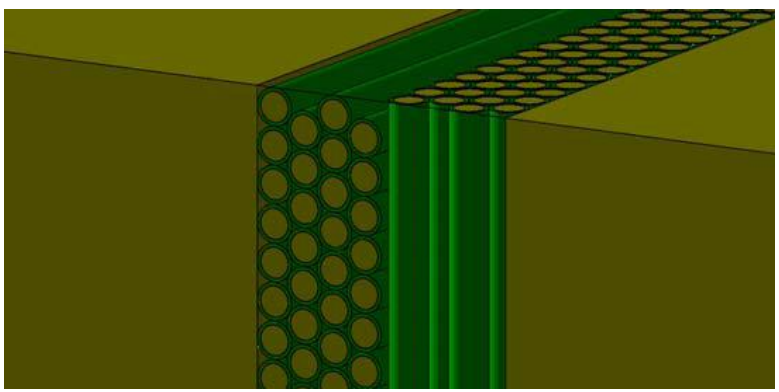


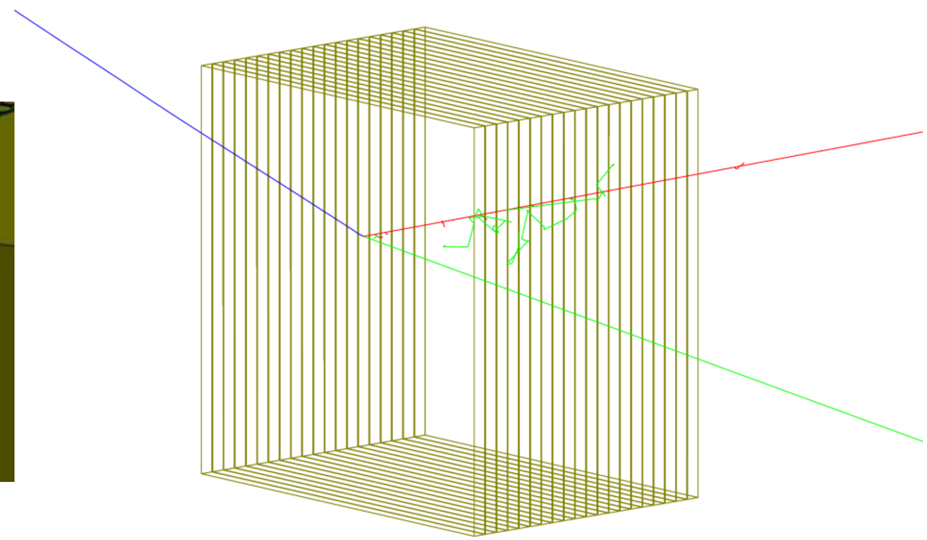
Distributions of the neutrinos over their energy and polar angle at the position of the near detector for the two polarizations of the decaying muons.

Neutrino Factory Near Detector

Low Z high resolution scintillating fibre tracker for flux and cross-section measurement

- 0.5 mm plastic fibers;
- 2x4 planes of fibers + 5 cm plastic slabs form a layer;
- 20 such layers are currently considered (~ 1.5x1.5x1 m3, 2.3 tones).





Summary of software status

Near detector flux simulation

↓ flux driver

Neutrino interactions GENIE

↓ GHEP

Detector simulation Geant 4

↓ root files

Digitization

↓ root files

Reconstruction

Possible to generate neutrino flux for different polarizations and distances.

$\nu_\mu + e^- \to \nu_e + \mu^-$ is included in GENIE but $\bar{\nu}_e + e^- \to \bar{\nu}_\mu + \mu^-$ is not.

Interface between **GENIE** and **Geant4**.
Detailed Geant4 simulation of the neutrino events.

Simple digitization which does not include efficiency for registration.

Simple reconstruction with 100% effective pattern recognition (not very realistic).
Kalman filter for track fitting (**RecPack**).

Kalman Filter - RecPack

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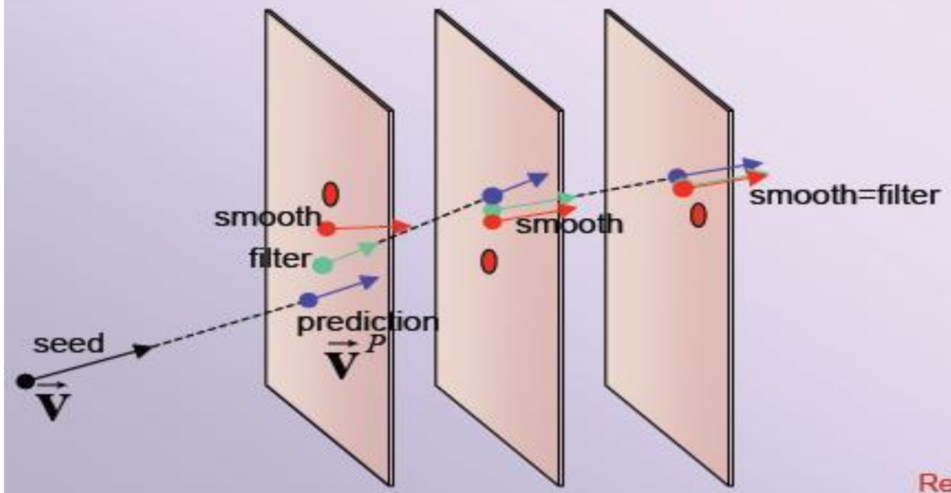
Fitting: Kalman Filter

- Used for track and vertex fitting by most of HEP experiments
- Easy to include random noise processes (*multiple scatt.*) and systematic effects (*eloss*)
- It is a local and incremental fit →
  - simultaneous pattern recognition and fitting
  - detection of outliers

Any other fitting algorithm can be plugged in



IPropagator

$$\vec{\mathbf{v}}^P = f(\vec{\mathbf{v}}) \xrightarrow{\text{linear}} \vec{\mathbf{v}}^P = \mathbf{F}\vec{\mathbf{v}}$$

Transport matrix

$$\mathbf{C}^P = \mathbf{FCF}^\mathrm{T} + \mathbf{Q}$$

Noise matrix (ms)

IProjector

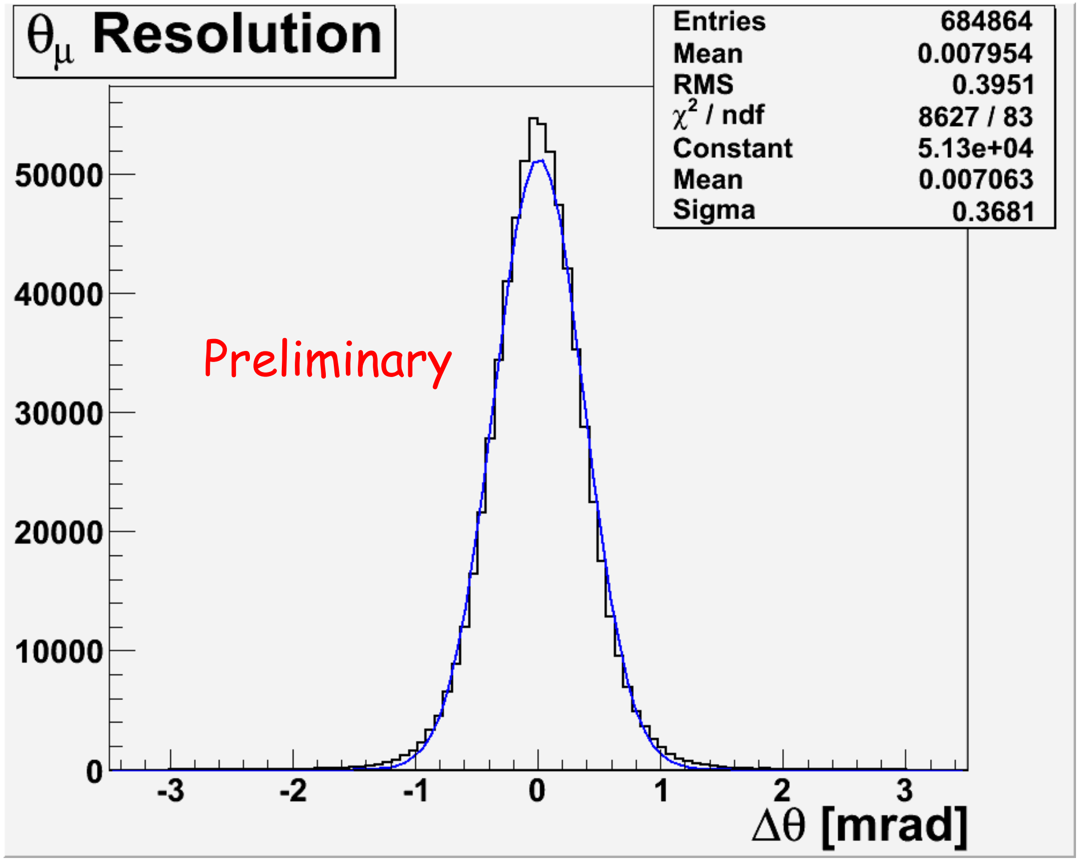
$$\vec{\mathbf{w}} = h(\vec{\mathbf{v}}) \xrightarrow{\text{linear}} \vec{\mathbf{w}} = \mathbf{H}\vec{\mathbf{v}}$$

Projection matrix

$$\vec{\mathbf{r}} = \vec{\mathbf{w}} - \vec{\mathbf{m}}$$

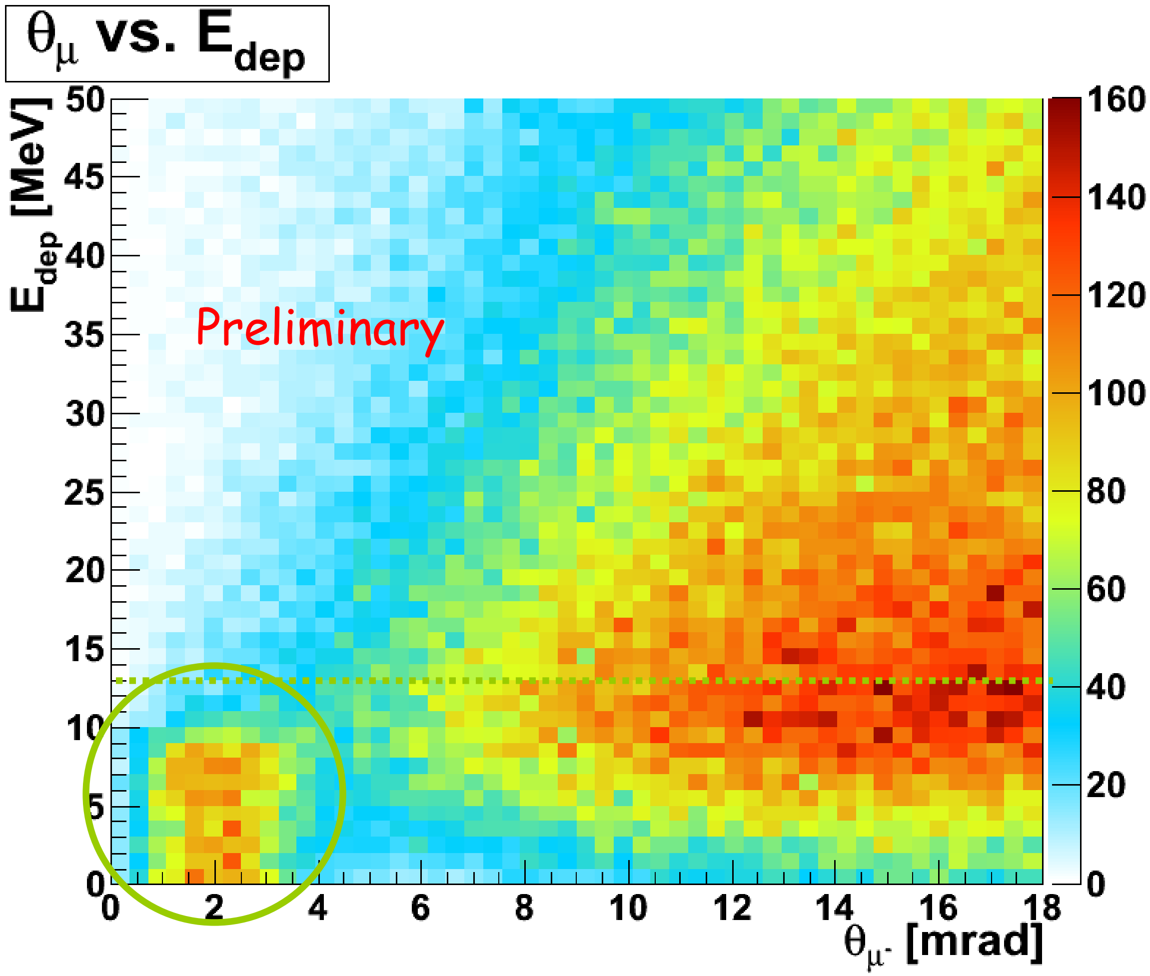
Residual = prediction-measurement

First results



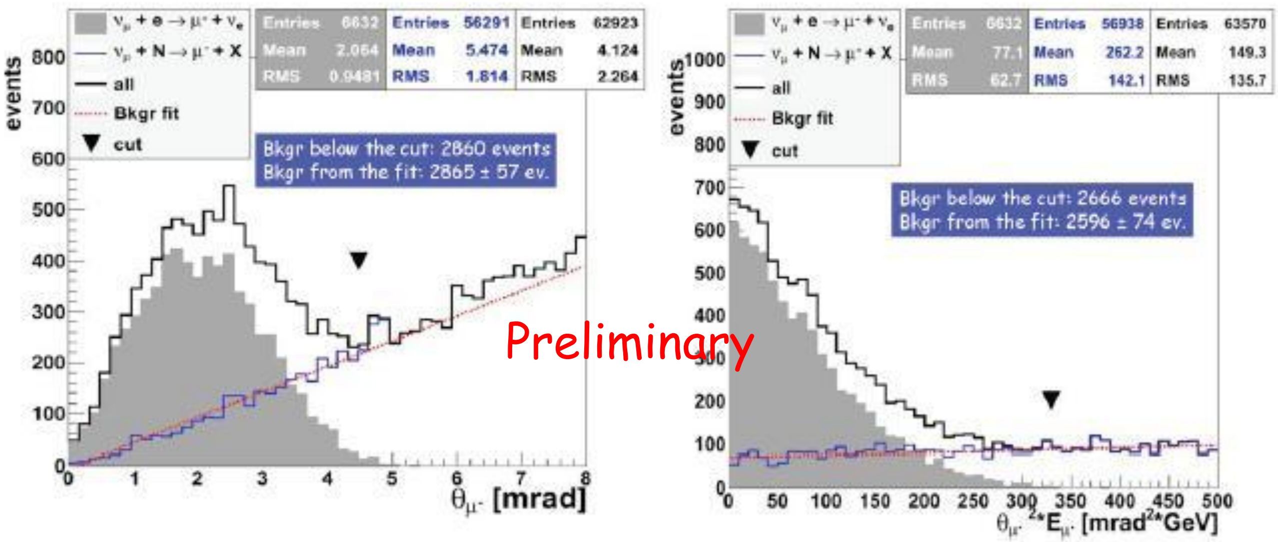
Simulations show ~0.5 mrad resolution in the measurement of the muon scattering angle.

Suppression of the background from inclusive CC reactions



Energy deposition in the first illuminated scintillating slab vs. reconstructed muon scattering angle.

Signal and background estimation



"Measured" distributions over the outgoing muon scattering angle. The leptonic events are filled with gray, the hadronic events are plotted in blue and the total spectrum is in black. Doted lines indicate the background extrapolation. Precision on the signal estimation after fitted background subtraction is ~1%.