Neutrino flux monitoring by CC and NC scattering off electrons in a high resolution scintillating fibres tracker

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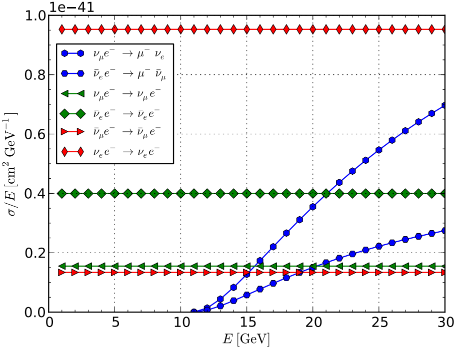
Neutrino flux measurement

Neutrino electron scattering off electrons can be used to measure the flux, because its absolute cross-section can be calculated theoretically with enough confidence.

$$\nu_\mu + e^- \longrightarrow \nu_e + \mu^- \qquad \text{(IMD)}$$
$$\bar{\nu}_e + e^- \longrightarrow \bar{\nu}_\mu + \mu^- \qquad \text{(ANH)}$$
$$\nu_{e,\mu} + e^- \longrightarrow \nu_{e,\mu} + e^- \qquad \text{(ES)}$$
$$\bar{\nu}_{e,\mu} + e^- \longrightarrow \bar{\nu}_{e,\mu} + e^- \qquad \text{(ES)}$$



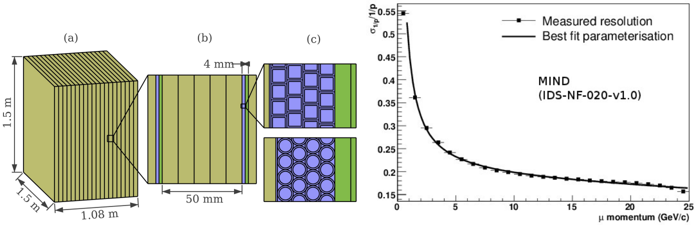
Muon neutrino and anti-neutrino CC total cross section is at the level of $0.5 \times 10^{38} E(\mathrm{GeV})\ \mathrm{cm}^2$.

Design motivation

To distinguish between the leptonic events and inclusive CC neutrino interactions with nuclei the detector needs to have the following properties:

- solid to provide enough interaction rate;
- tracker-like design to measure precisely the primary lepton's scattering angle;
- dipole magnetic field to measure the momentum of the primary lepton;
- precise calorimeter to separate background events based on recoil energy;
- low Z material to minimize multiple scattering and electromagnetic showering.

Scintillating fiber tracker (design in IDR)

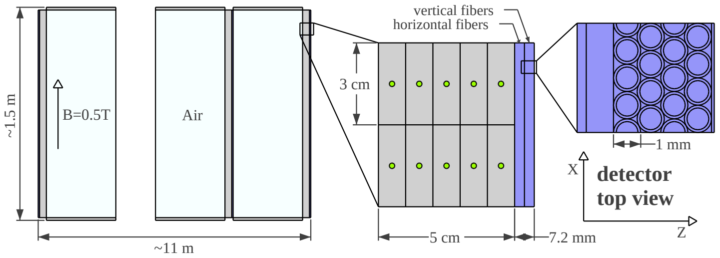


- 20 modules
- 5 scintillating slabs in absorber section (5 cm thick)
- 4+4 layers of round/square, 0.5 mm thick scintillating fibers in tracker station
- $\sim$ 2.5 tons of polystyrene ($\sim 1.5 \times 1.5 \times 1\ \mathrm{m}^3$)

Drawbacks:

- Momentum of final state lepton is not measured in the detector
- Poor signal from 0.5 mm thick scintillating fibers

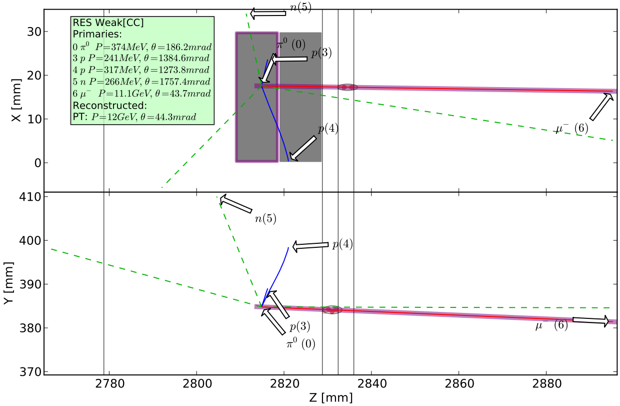
Scintillating fiber tracker (new design)



- 0.5 T dipole magnetic field
- 20 modules with $\sim$ 50 cm air gaps in between
- 5 layers of scintillating bars ($3 \times 1\ \mathrm{cm}^2$) in absorber section
- 4+4 layers of round, 1 mm thick scintillating fibers in tracker station
- air gaps are covered by one layer of scintillating bars
- overall detector dimensions are $\sim 1.5 \times 1.5 \times 11\ \mathrm{m}^3$
- $\sim$ 2.7 tons of polystyrene

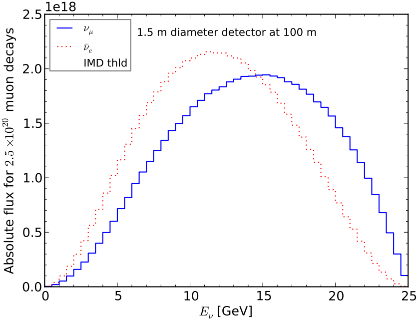
Simulation chain

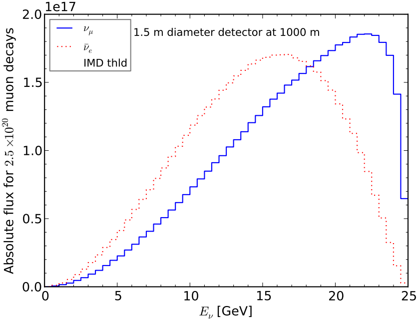
1. Neutrino flux simulation
2. Genie event generation
3. Geant4 transport
4. Digitization
5. Reconstruction
6. Background rejection and signal extraction



Flux simulation

- 2.5×10^{20} muon decays (per year per ND)
- Straight section length 600 m
- Mean muon energy 25 GeV with Gaussian spread of 80 MeV
- Gaussian beam divergence of 0.5 mrad
- Zero beam polarization





Genie and Geant4 Monte Carlo

- For neutrino event generation we have used out of the box Genie 2.6.2.
- Annihilation channel ($\bar{\nu}_e\ e^- \rightarrow\ \bar{\nu}_\mu\ \mu^-$) is not implemented.
- Particle transport by Geant4 4.9.4.p01 with physics list "Simple and Fast Physics List", D.H. Wright (SLAC)

Digitization

Fiber signal digitization. For each hit in fibers

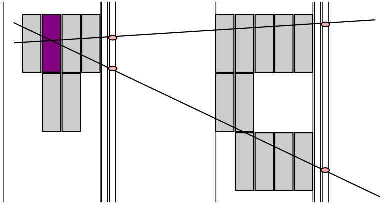
- draw number of photons,
- multiply by trapping efficiency and attenuation,
- account for optical coupling to SiPM (needs to be calibrated),
- account for photon detection efficiency (PDE),
- use Gaussian SiPM pixel response

Dark counts are also simulated. It seems they are not a major problem for 1 mm fibers and modern SiPMs (< 1 *MHz* dark count rate for 1 mm^2 at room temperature). Only signals with amplitude larger than threshold equivalent to 2.5 fired pixels are recorded.

Bar signal digitization. Bar signals are naively digitized by smearing the energy deposit with 20% gaussian. Signals with amplitude less than 0.5 *MeV* equivalent are discarded.

Vertex reconstruction

- **Clustering.** Fired neighboring fibers are grouped into clusters.
- **Vertex position reconstruction.** The volume containing the vertex is found. The two most upstream stations with clusters are considered. The most upstream fired bar consistent with clusters is labeled as vertex bar.



86 % of the signal events (IMD and ES) have their vertex volume reconstructed.

Vertex Z coordinate resolution

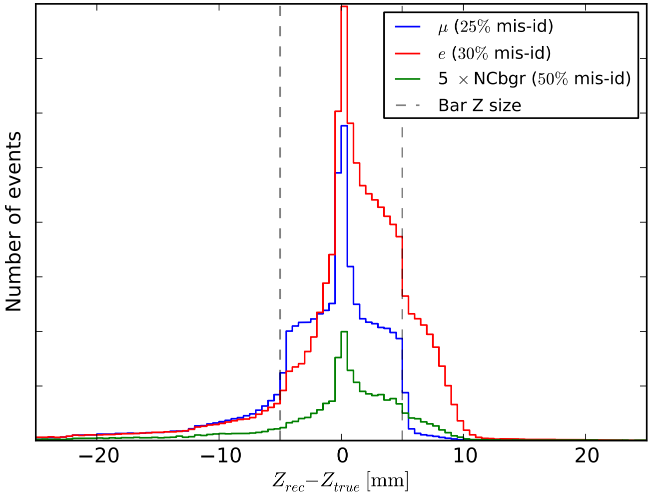


Figure: Vertex Z coordinate resolution for μ^- beam.

Track reconstruction

- Only events with one cluster per orientation in the first two stations are passed. This is a very strong background rejection criterion.
- Selection has efficiency **61% for IMD muons and 52% for ES electrons**.
- Measure angle and curvature of track from first three points only.
- Overall reconstruction efficiency (remaining signal events) is **53% for IMD and 45% for ES**
- Efficiency and resolution can be improved with more sophisticated reconstruction (pattern recognition of clusters, Kalman filter for fitting)

Angular resolution

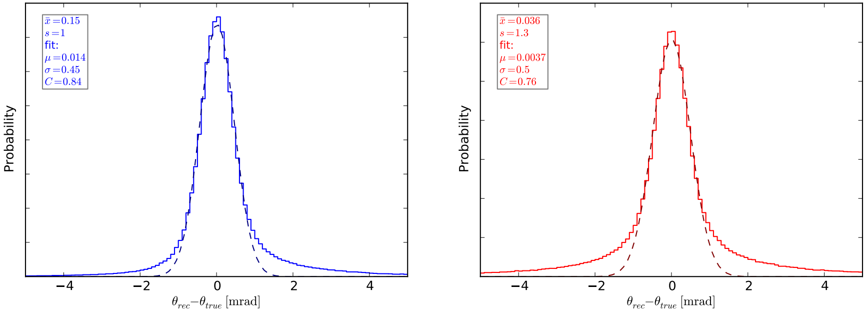


Figure: Obtained angular resolution for muons (left) and electrons (right).

Momentum resolution

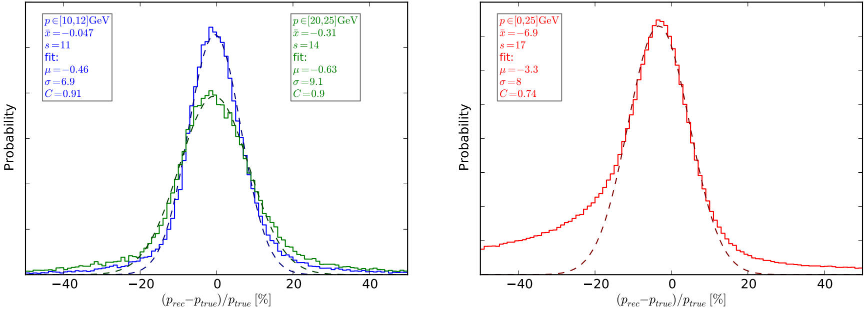
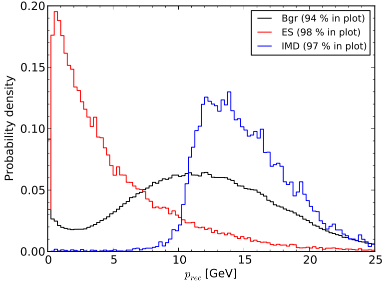


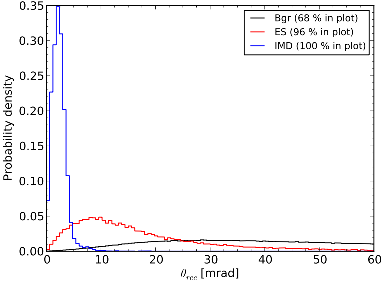
Figure: Obtained momentum resolution for muons (left) and electrons (right).

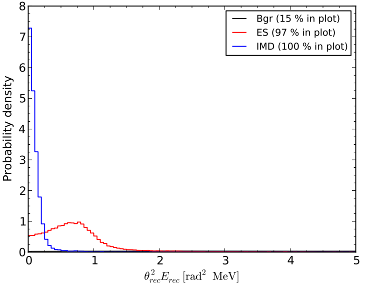
Background rejection

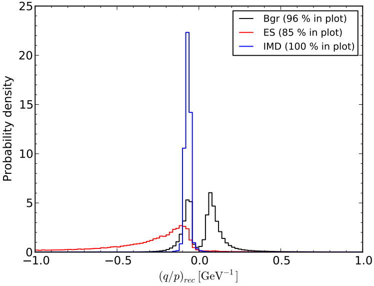
- No activity in bars covering air gaps adjacent to the vertex.
- Vertex activity - if vertex is in bar, require that energy deposit in the bar is no more than 4 MeV.
- Charge sign - only events with negative q/p of the primary track are selected.
- IMD specific cuts
  - mean of all slab deposits is less than 3 MeV;
  - maximum deposit in a slab is less than 12 MeV;
  - momentum of primary track is more than 10 $\mathrm{GeV/c}$;
  - transverse spread of calorimetric energy deposits relative to the primary track is less than 25 mm.
- ES specific cuts
  - transverse spread of calorimetric energy deposits relative to the primary track is less than 150 mm.

Background rejection - kinematic variables

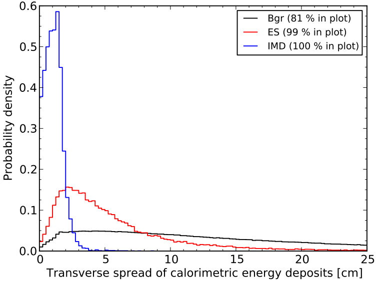


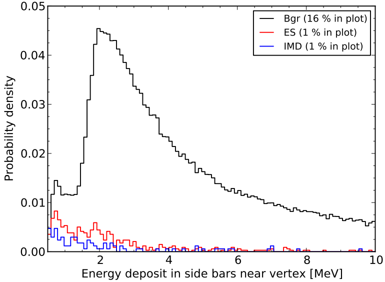


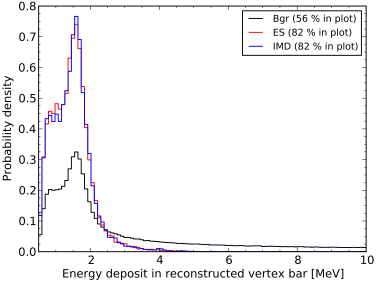




Background rejection - calorimetric variables

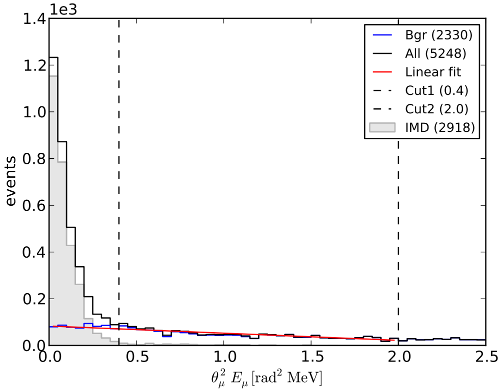






IMD signal extraction

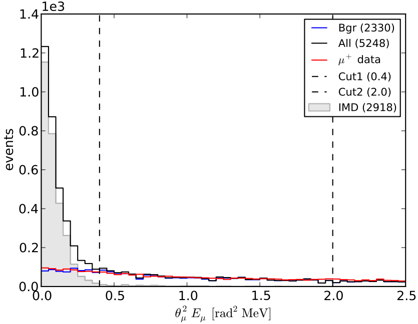
Use linear extrapolation of event rates in region between cut1 and cut2 to estimate background under the signal peak.

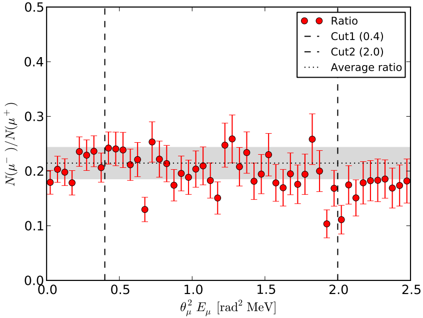


bgrrej&cut eff	overall eff	purity	all events	signal events	signal events from fit	μ decays
86 %	46 %	81 %	3498	2844	2880 ± 59	2.3×10^{19}

IMD signal extraction 2

Use μ^+ events to estimate background under the IMD peak. Number of μ^+ events is normalized to μ^- events by the average ratio between cut1 and cut2.

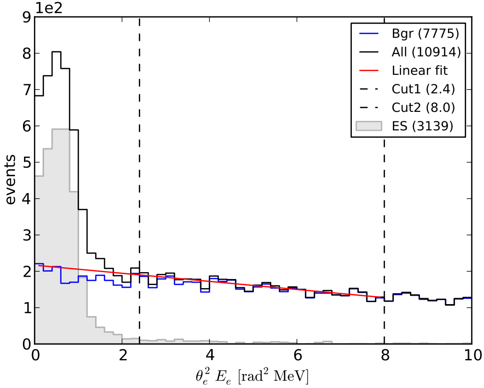




bgrrej&cut eff	overall eff	purity	all events	signal events	signal events from fit	μ decays
86 %	46 %	81 %	3498	2844	2820 ± 60	2.3×10^{19}

ES signal extraction in μ^- beam

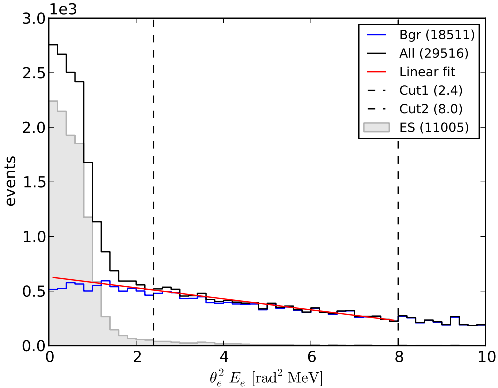
Use linear extrapolation of event rates in region between cut1 and cut2 to estimate background under the signal peak.



bgrrej&cut eff	overall eff	purity	all events	signal events	signal events from fit	μ decays
47 %	21 %	58 %	5202	2992	2760 ± 72	2.3×10^{19}

ES signal extraction in μ^+ beam

Use linear extrapolation of event rates in region between cut1 and cut2 to estimate background under the signal peak.



bgrrej&cut eff	overall eff	purity	all events	signal events	signal events from fit	μ decays
83 %	37 %	63 %	16964	10607	10124 ± 131	2.3×10^{19}