MIND analysis

Andrew Laing, ICRR

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University of Glasgow | Experimental Particle Physics

ICRR Institute for Cosmic Ray Research University of Tokyo

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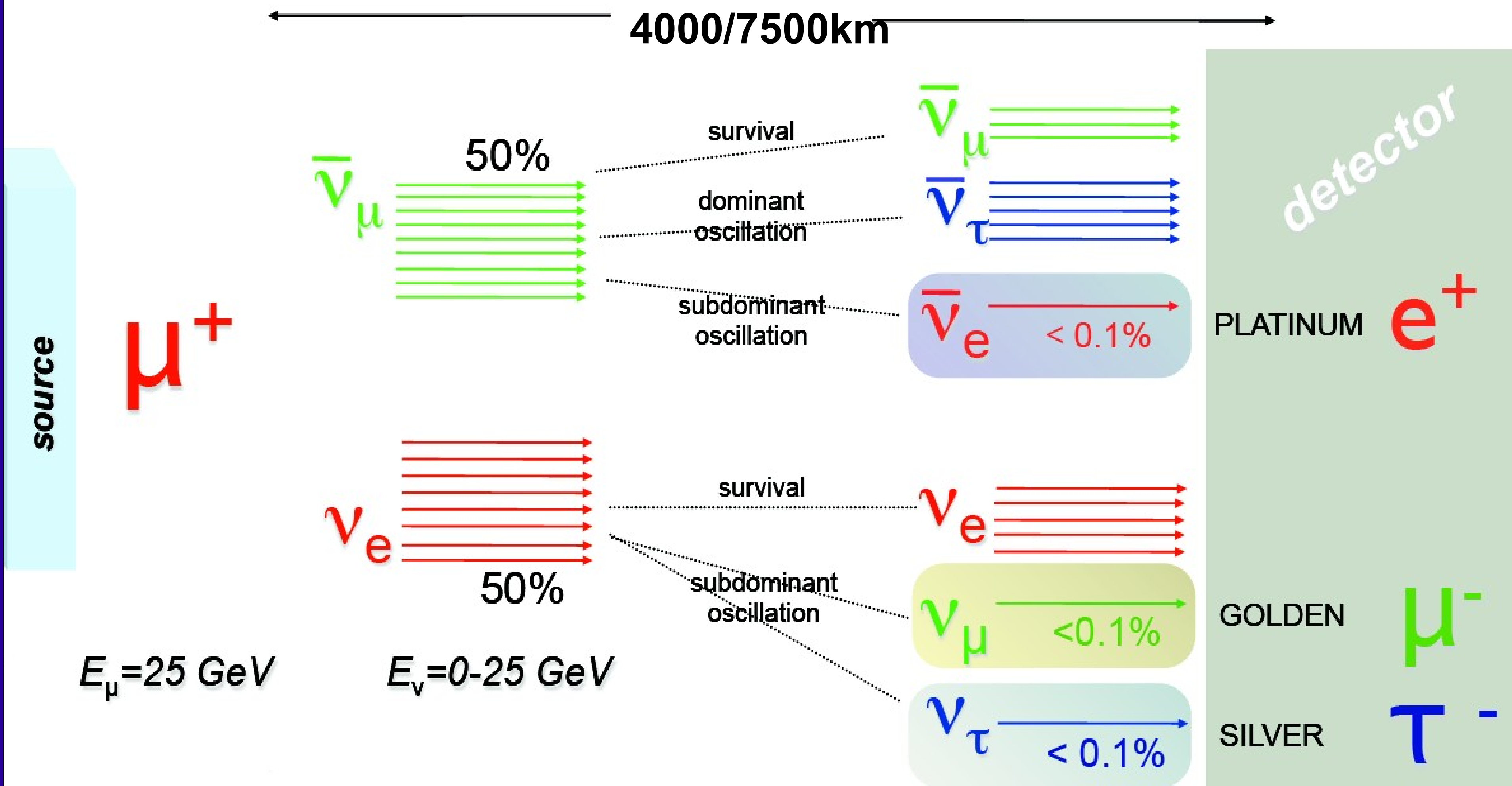
- Current simulation status
  - Envisaged design and motivation for assumptions
- Digitization
- Reconstruction and analysis

Oscillation Channels



The beam contains a flux of disappearance muons ~3 orders of magnitude larger than that of the appearance signal. Significant reduction of this and other potential backgrounds is required.

General detector requirements

- Large Mass.
  - Although the flux is large the distances are large too.
- Magnetic field.
  - Without event by event separation analysis impossible.
- Good muon identification.
- Efficiency from $E_{\tau\rho\upsilon\varepsilon}$ = 3 GeV.
- Backgrounds suppressed to at least 10^{-3} level.

MIND: Motivation for a MINOS-like detector

High mass and relative ease of magnetization.

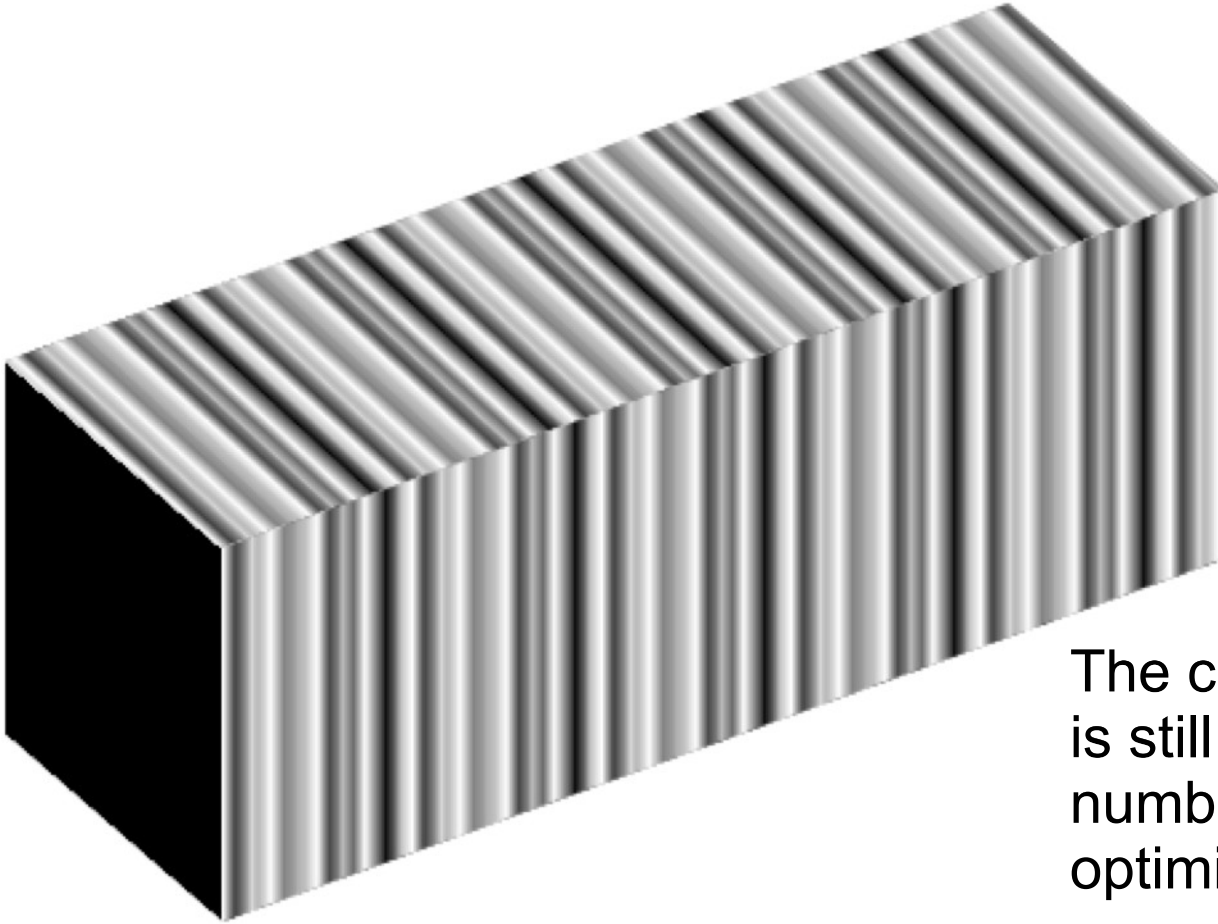
Technology well understood.

Limitations:
Does not allow direct study of ν_e and ν_τ in the Neutrino Factory.
Photo-detectors used in MINOS do not allow for certain studies.

MIND: Improvements needed over MINOS

- Charge identification requirement is more stringent.
  - Must improve tracking resolution and fitting.
- Need better photo-detectors for improved angular resolution (see analysis section).
  - SiPM?

MIND simulation design



The current detector geometry is still simplified but contains a number of features to aid its optimisation

One of the primary differences to MINOS motivated by the required improvement in performance is the inclusion of 2 orthogonal readout layers per iron plane. This reduces the amount of iron between readings and should improve tracking resolution.

Simulation and digitization specifications

Current design:	Planned Improvement:
Square cross-section	Hexagonal cross-section
1 T dipole field	STL toroidal field (See B.Wands' talk)
Virtual boxes for matched hits	Full simulation of light transport in scintillator
30% QE and 6% energy sigma	Parameterization of PMT response

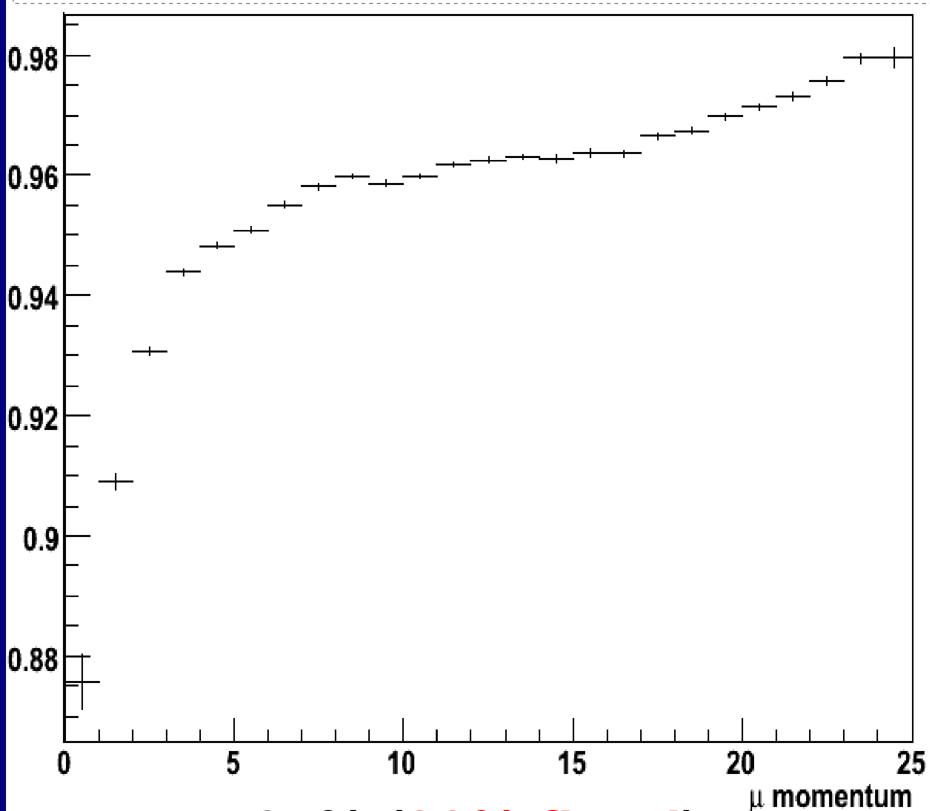
Many of the improvements to the simulation are now underway at Glasgow and the merging of the simulations for MIND and TASD will aid this development (M.Ellis' talk(?)).

Reconstruction

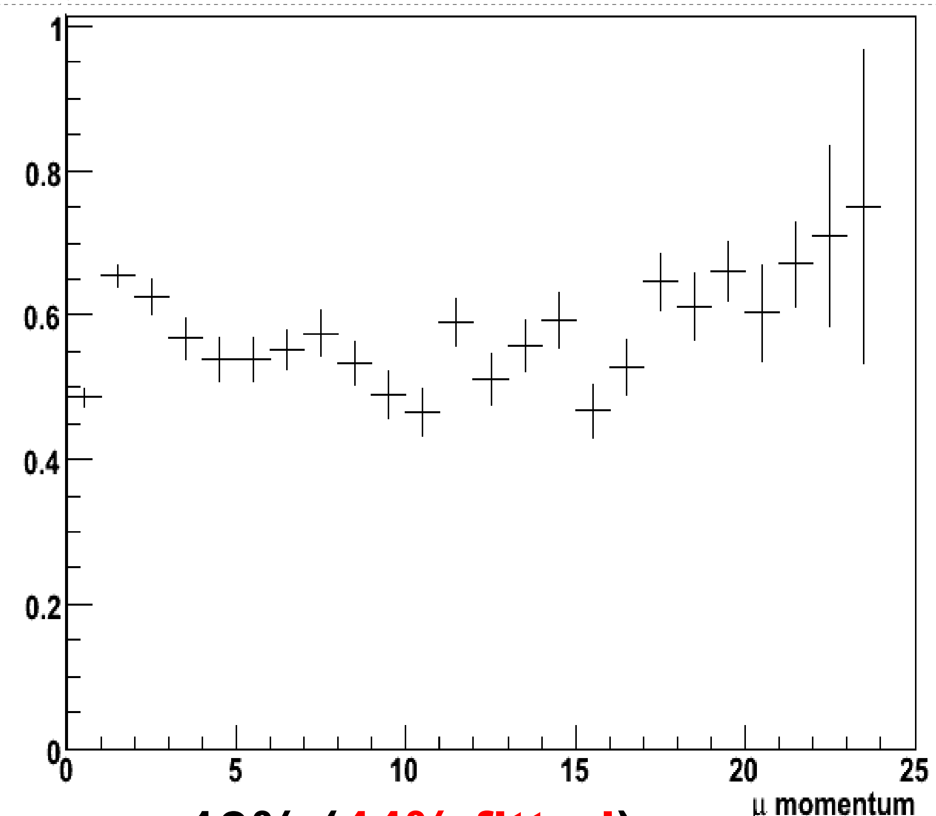
- Recpack used to filter back through hadronic activity.
- Cellular automaton to try and recover extra low energy/high y events.
- Kalman fit (Recpack)
  - Fitted in forward direction. Attempt to recover failed fits by re-seeding and fitting backwards.
- Neutrino energy rec.
  - Quasi-elastic formula.
  - Rec from hadronic activity (smear)

Pattern recognition

Kalman method
All events with a section of 5 consecutive single occupancy planes within 10% of event endpoint



Cellular automaton
Others. Trajectories from nearest neighbour subject to “muonness” test



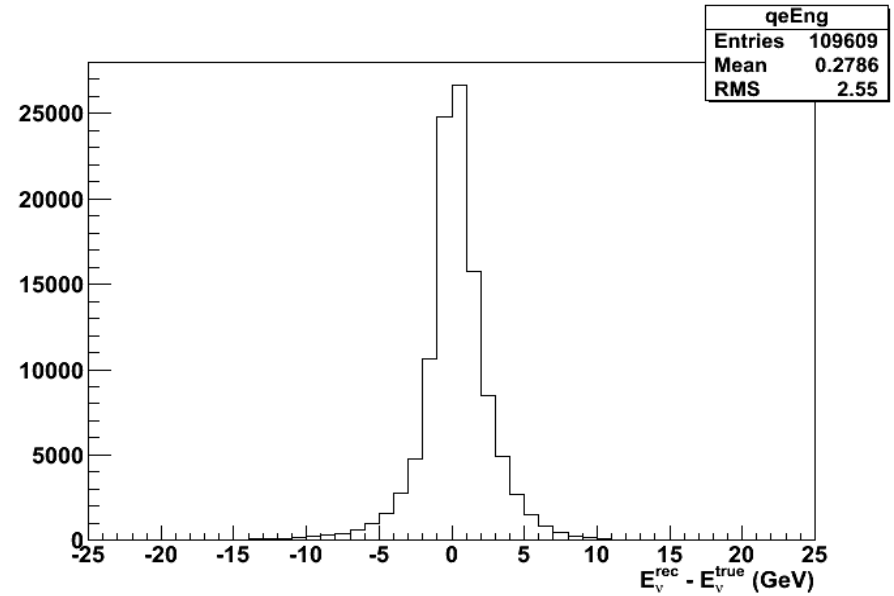
	Kalman method	Cellular automaton
ν_μ :	87% (99% fitted)	13% (44% fitted)
$\bar{\nu}_\mu$:	95% (99% fitted)	5% (47% fitted)
NC:	2.4% (61% fitted)	83% (28% fitted)

~13% of NC rejected before pattern recognition (<1% CC).

Neutrino energy reconstruction

Events comprised of a single track are reconstructed using the quasi formula:

$$E_\nu = \frac{m_N E_\mu + \frac{m_{N_X}^2 - m_\mu^2 - m_N^2}{2}}{m_N - E_\mu + |p_\mu| \cos\vartheta}$$



Otherwise, reconstruction from hadronic activity. Currently reconstruct hadron energy and direction using a smear of the true quantities assuming similar performance to MINOS and Monolith:

$$\frac{\delta E}{E} = \frac{0.55}{\sqrt{E}} + 0.03$$

$$\delta\theta = \frac{10.4}{\sqrt{E}} + \frac{10.1}{E}$$

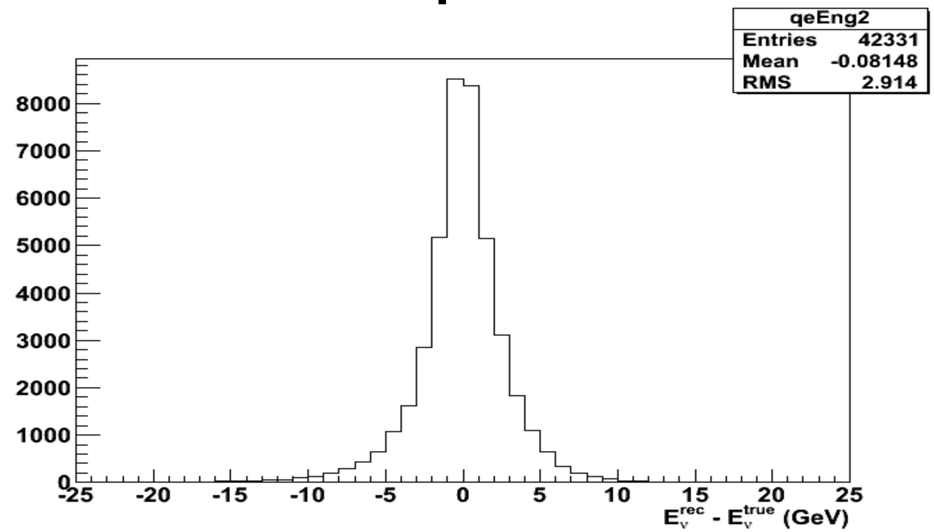
From MINOS CalDet result.

From Monolith proposal.

Ideas for development of E_ν reconstruction

- Can a jet fitter be adapted to reconstruct energy and direction?
  - What activity is required for a reliable reconstruction?
  - Displacement, charge centre, opening angle, number of planes etc. could be useful variables.
- Is a parameterisation more reliable?
- How much can the use of the quasi-formula be generalised?

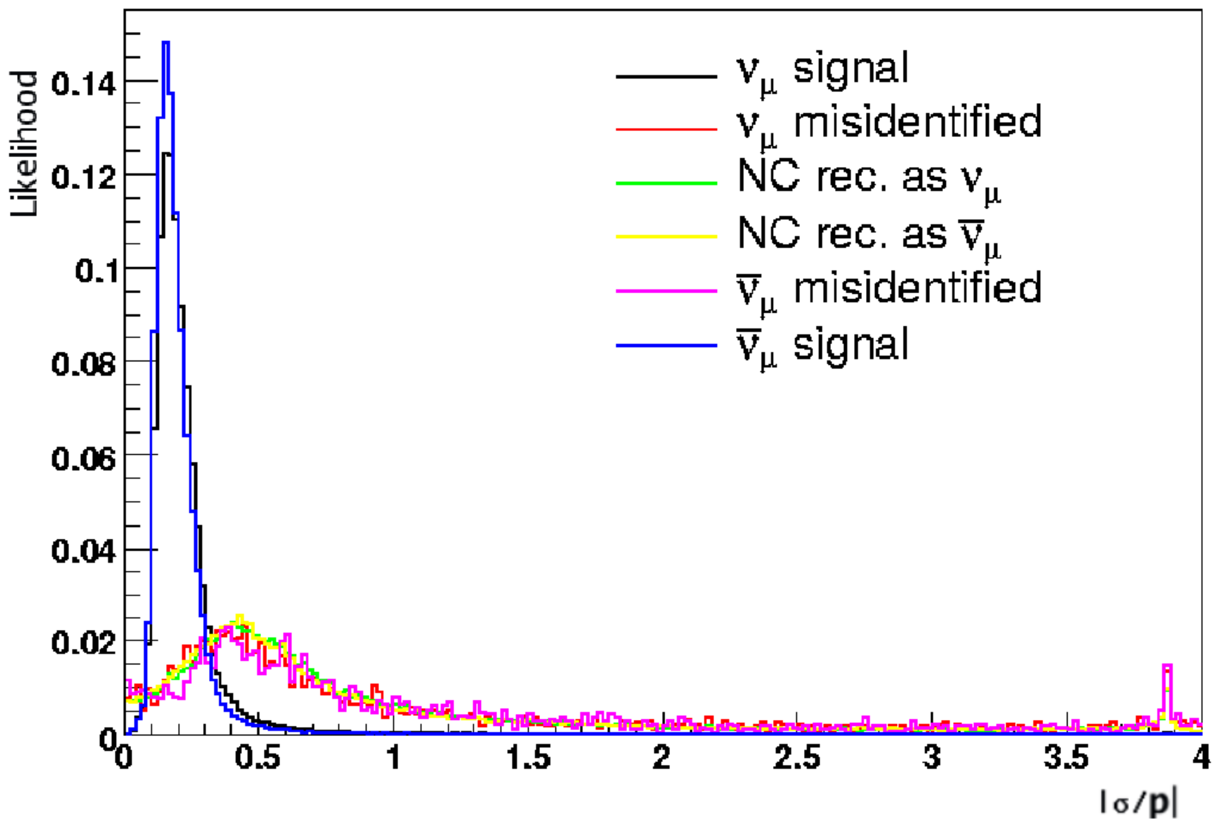
Events not in normal quasi sample but with only 1-3 deposits not associated with the candidate muon



Analysis

- Currently neutrino and antineutrino are subject to identical analyses.
- Fit quality
  - Reconstructed momentum (40 GeV).
  - Q/P.
  - Displacement in bending plane.
  - Parabola fit.
- Neutral current
  - Candidate length.
  - Generalisation to include energy variables.
- Kinematic cuts
  - Isolation of candidate from rest of event (Q_t).

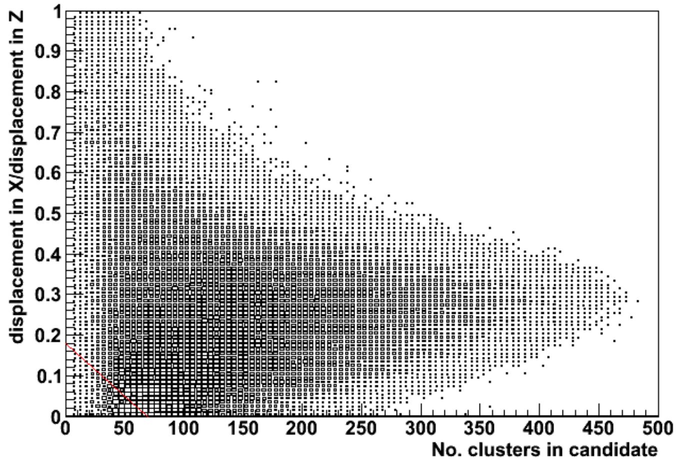
Q/P

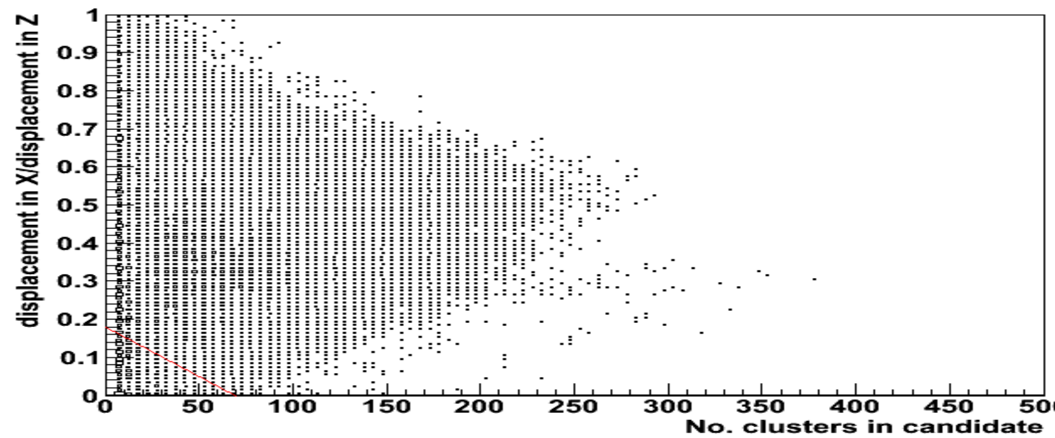


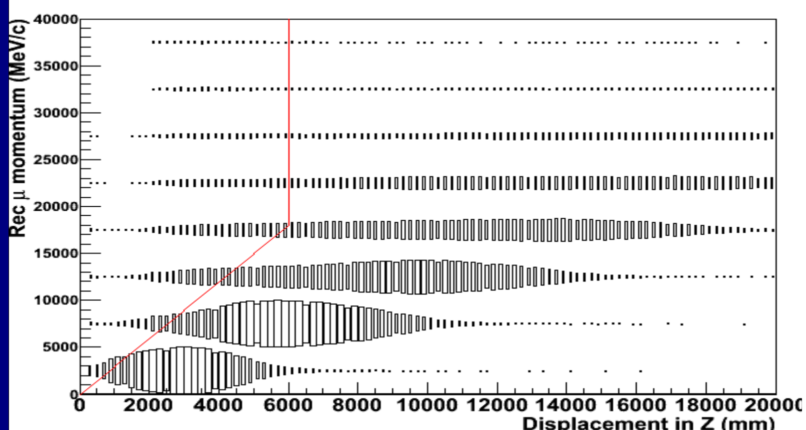
Form PDFs from the combination of the two signals and the combinations of the backgrounds and use a log likelihood to reject background like events. This has more flexibility than a straight cut on the parameter.

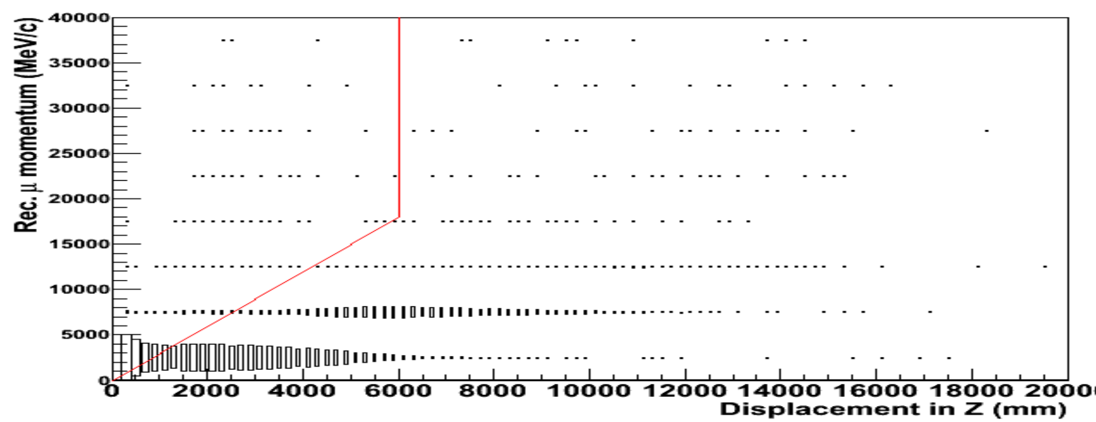
This is a powerful cut, how much is it affected by reduction in tracking resolution?

Displacement in Bending plane & Momentum vs. length



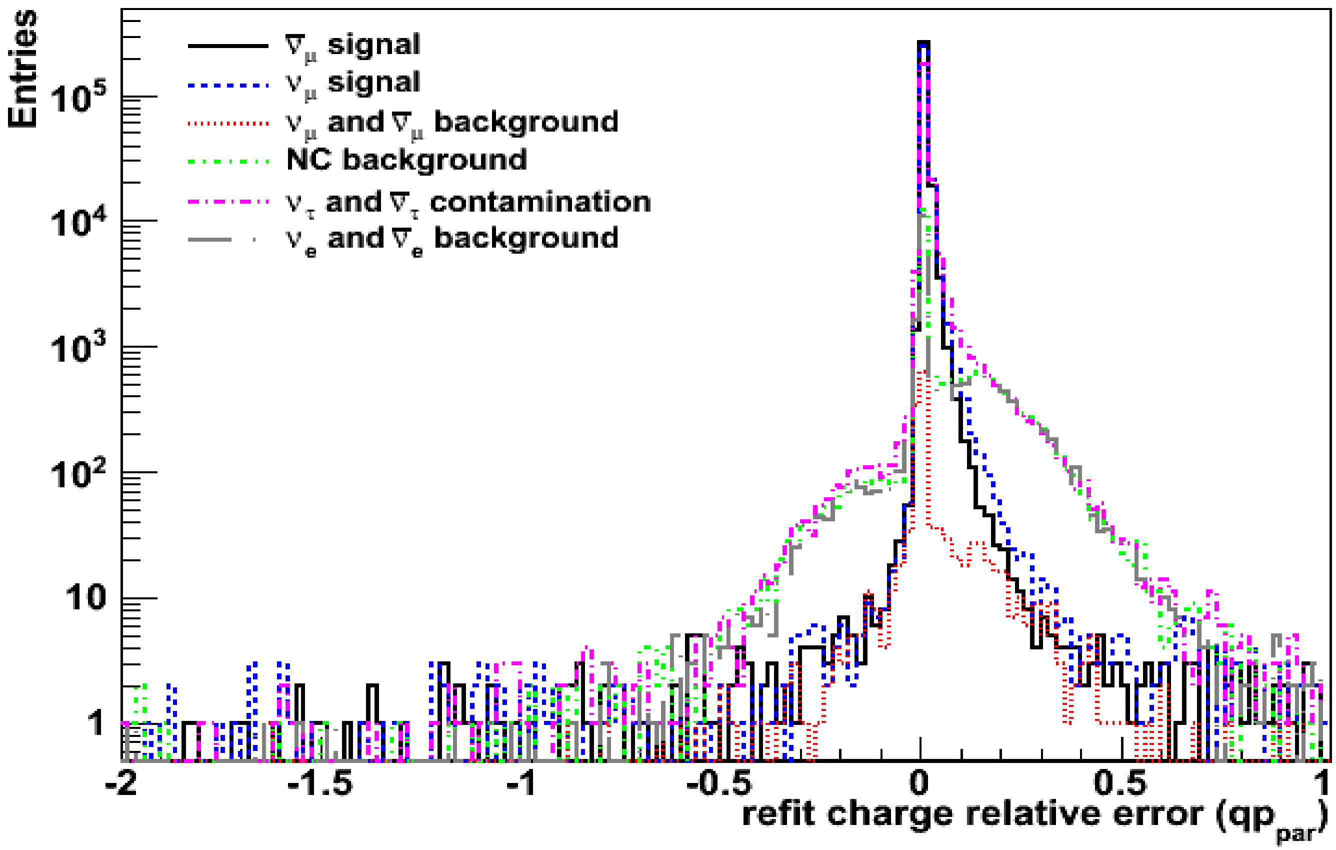






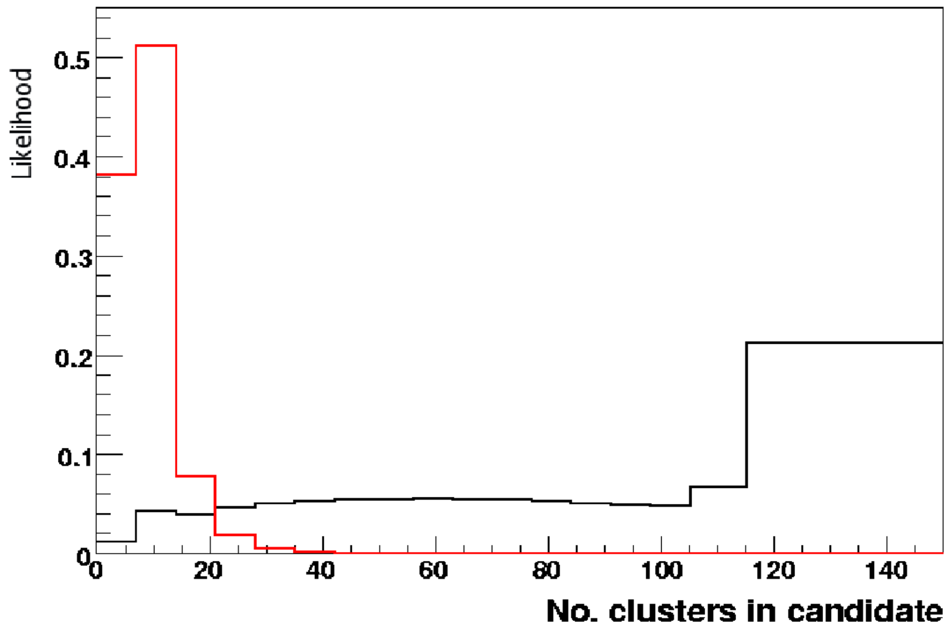
Remove short candidates reconstructed with high momentum and candidates which move little in the bending plane. Ultimately will be replaced with comparison of bending and track length measurements of the momentum.

Parabola fit

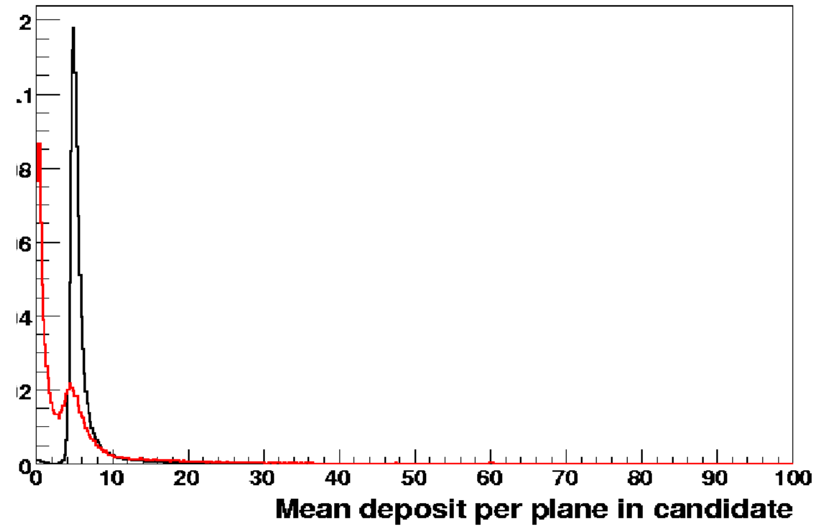


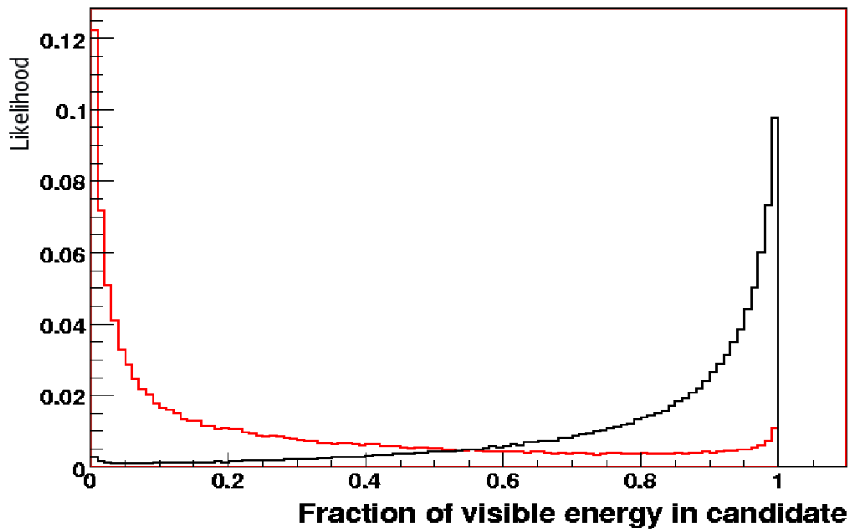
Refitting with a parabola and cutting those events which are fitted with the opposite curvature to that from the Kalman filter and a small relative error removes events with kinks not found by the kink finder.

Neutral current rejection likelihood



NC rejection based on MINOS parameters.





Considered:

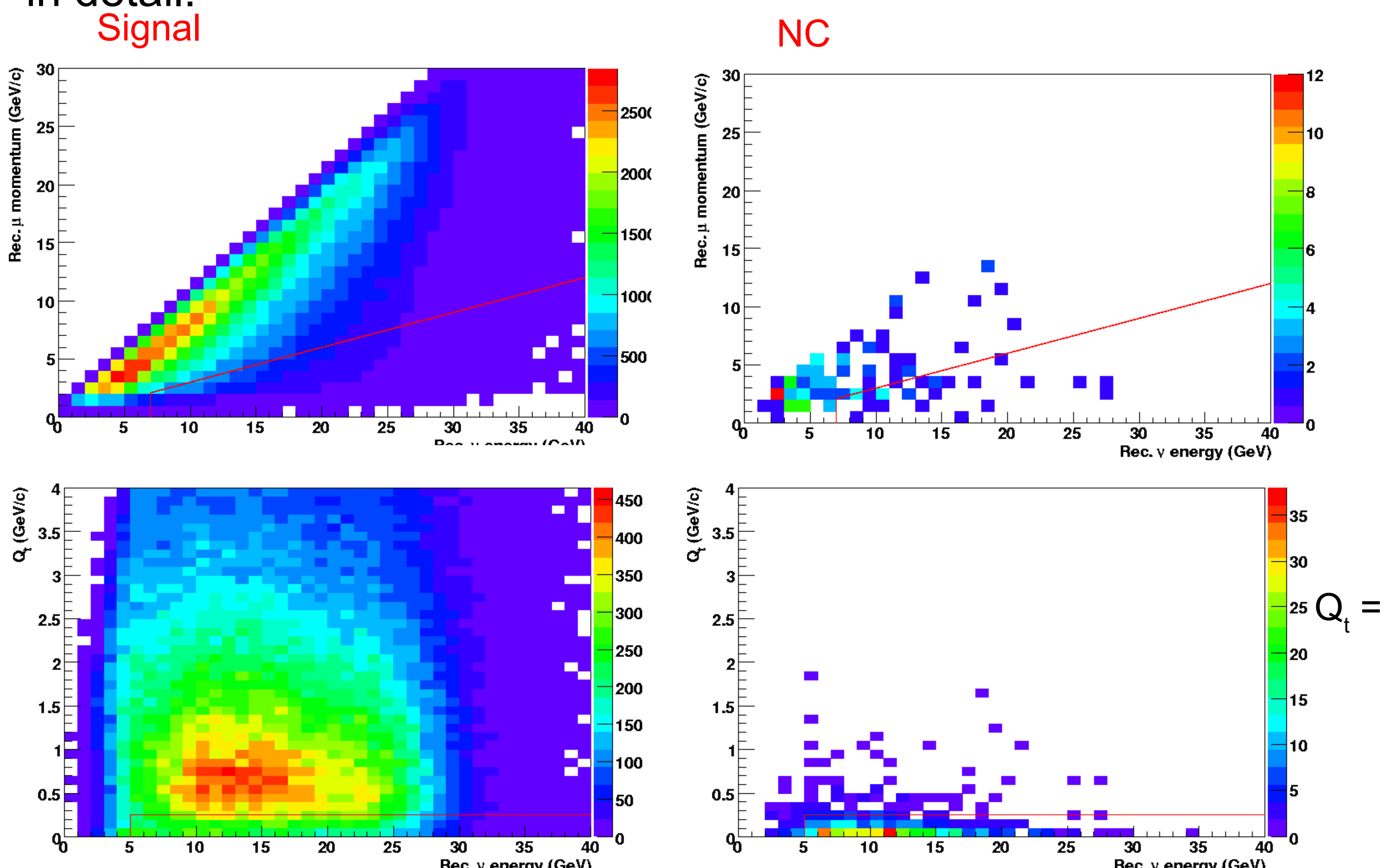
- number of clusters in candidate.
- fraction of energy deposit in muon.
- mean deposit of muon.

Since the treatment of energy deposits is still simplified in the simulation and due to correlations current analysis only uses first parameter.

“QE” events not subject to Q_t

Kinematic cuts

The cuts on the kinematical variables, particularly Q_t, are powerful against all backgrounds. These are sensitive to the hadronic reconstruction. Methods for the angular reconstruction must be studied in detail.



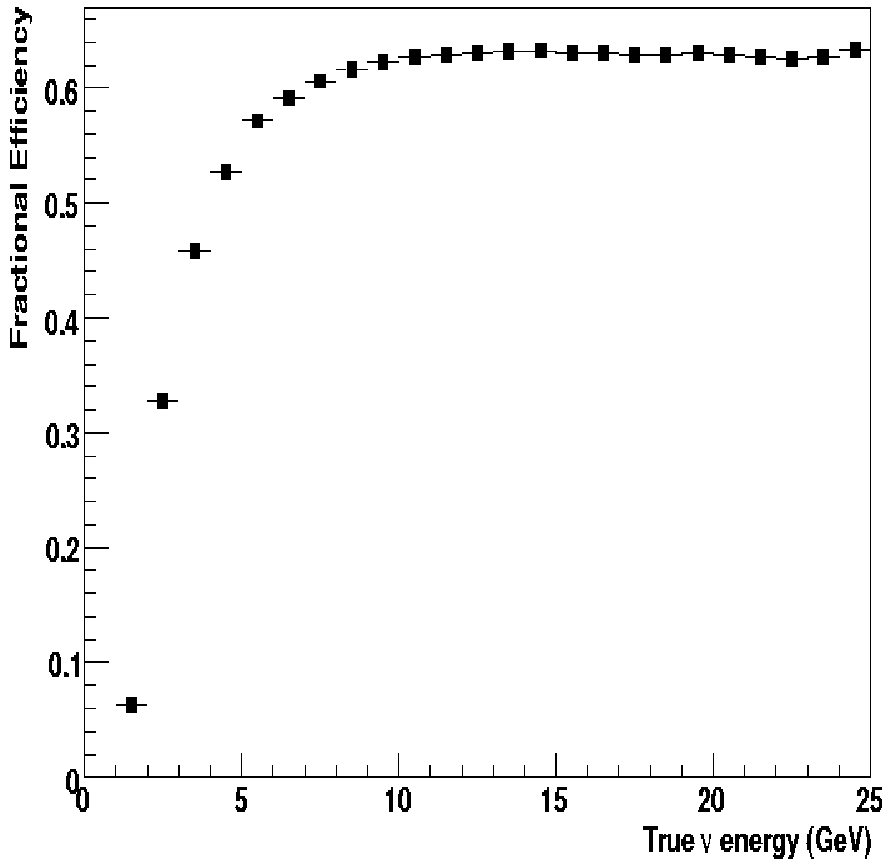
$Q_t = P\sin^2\vartheta$

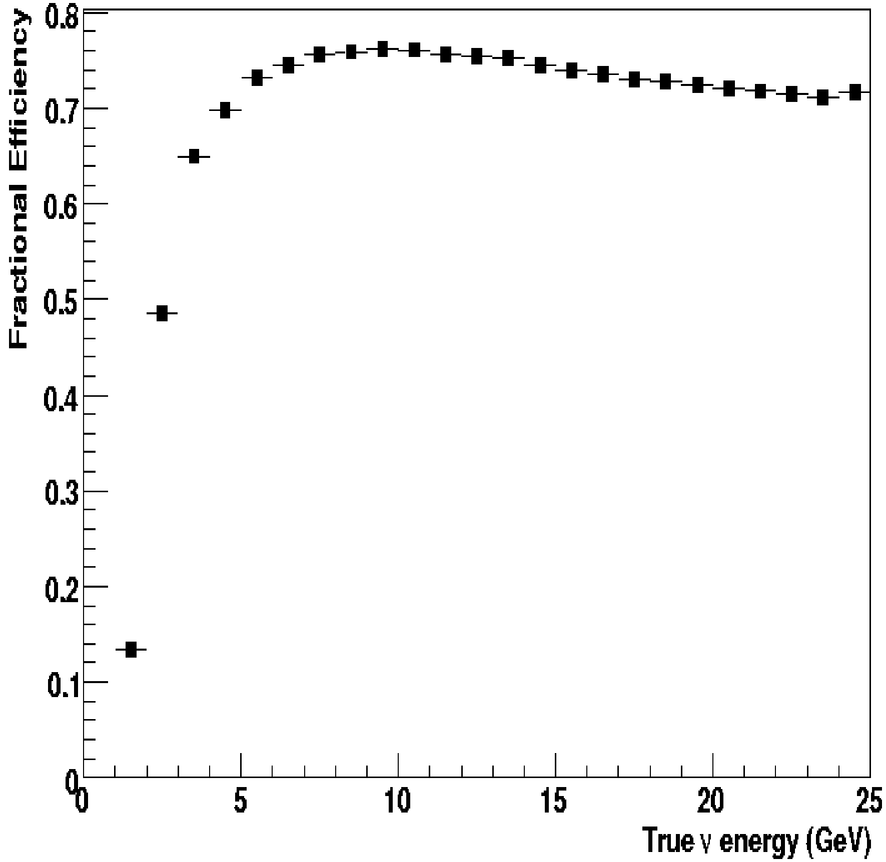
Cut summary

Table 1: Summary of cuts applied to select the golden channel appearance signals. The level of absolute efficiency and, for a 100 ktonne MIND 4000 km from the NF and $\theta_{13} = 5.7°$ and $\delta_{CP} = 45°$, the proportion of the total non-golden channel interactions remaining in the sample after each cut are also shown along with the species contributing th greatest number of interactions.

Cut	Acceptance level	Eff. after cut		background ($\times 10^{-3}$)	
		ν_μ	$\overline{\nu}_\mu$	ν_μ	$\overline{\nu}_\mu$
	successful pattern rec. and fit	0.88	0.93	108 (ν_e)	78.7 ($\overline{\nu}_e$)
Fiducial	$z1 \leq 18000$ mm where z1 is the lowest z cluster in the candidate	0.85	0.91	93.5 (ν_e)	71.6 ($\overline{\nu}_e$)
Max. momentum	$P_\mu \leq 40$ GeV	0.84	0.90	91.7 (ν_e)	63.4 ($\overline{\nu}_e$)
Fitted proportion	$N_{fit}/N_h \geq 0.6$	0.83	0.89	81.1 (ν_e)	55.2 (ν_μ)
Track quality	$\mathcal{L}_{q/p} > -0.5$	0.76	0.84	15.5 (ν_e)	11.2 ($\overline{\nu}_e$)
Displacement	$dispX/dispZ > 0.18 - 0.0026N_h$ $dispZ > 6000\ mm$ or $P_\mu \leq 3dispZ$	0.70	0.78	10.8 (ν_e)	7.76 ($\overline{\nu}_e$)
Quadratic fit	$qp_{par} < -1.0$ or $qp_{par} > 0.0$	0.70	0.78	9.51 (ν_e)	6.64 ($\overline{\nu}_e$)
CC selection	$\mathcal{L}_1 > 1.0$	0.68	0.77	0.94 (ν_e)	0.50 (ν_μ)
Kinematic	$E_{rec} \leq 5\ GeV$ or $Q_t > 0.25$ $E_{rec} \leq 7\ GeV$ or $P_\mu \geq 0.3E_{rec}$	0.58	0.71	0.09 (ν_τ)	0.07 (ν_μ)

Signal selection Efficiency

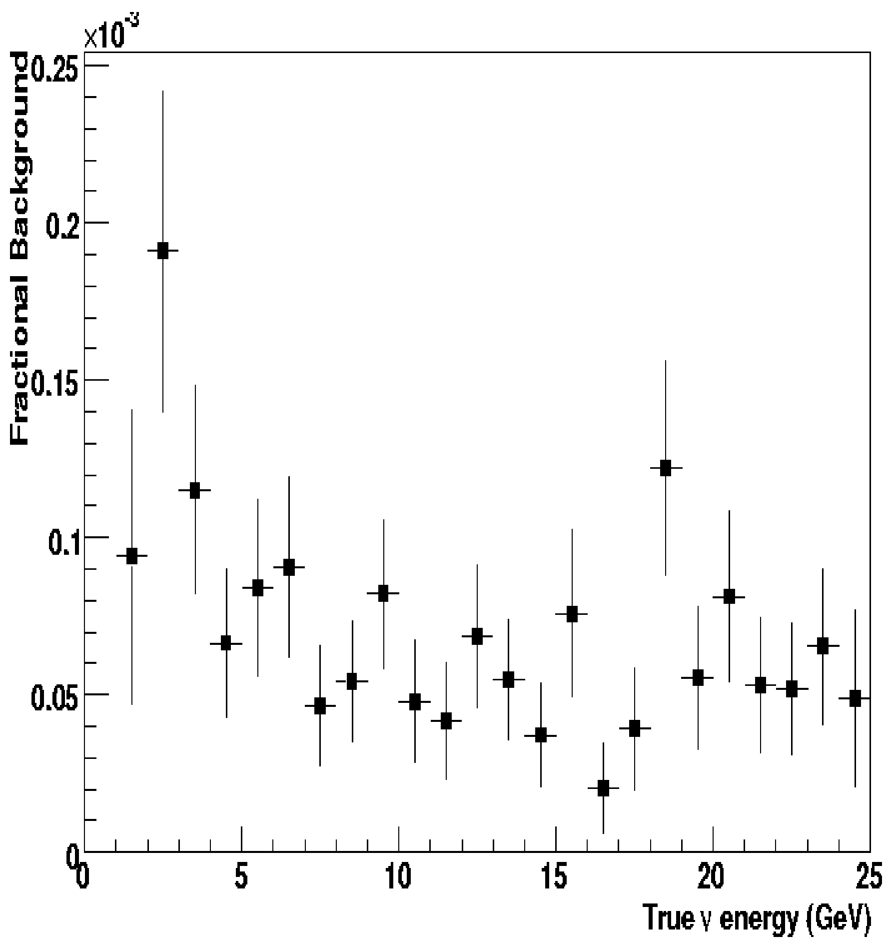




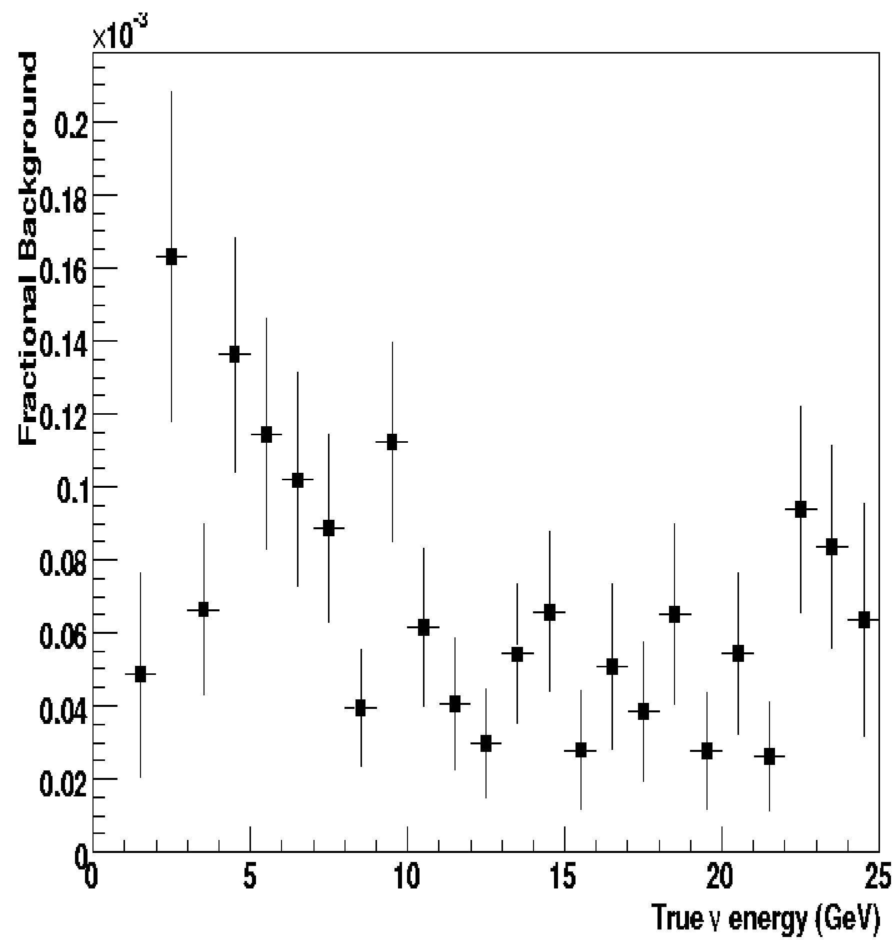
ν_μ appearance efficiency

$\bar{\nu}_\mu$ appearance efficiency

Background from opposite polarity ν_μ

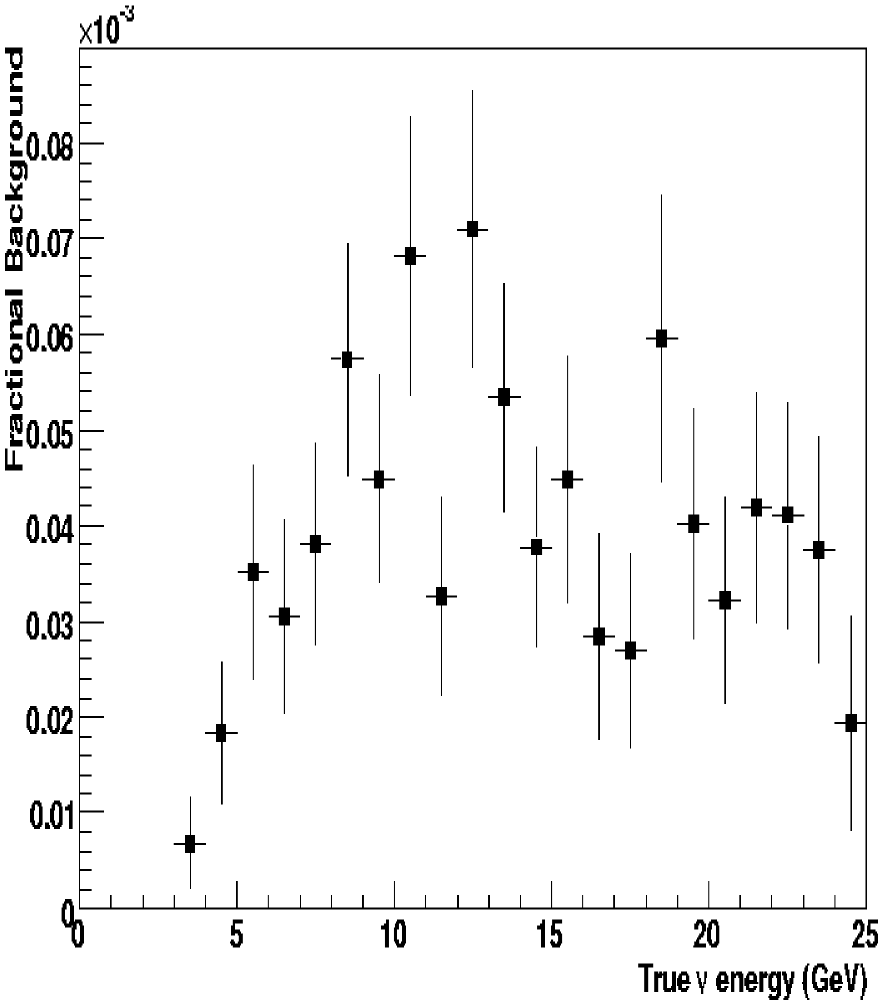


nu_mubar as nu_mu

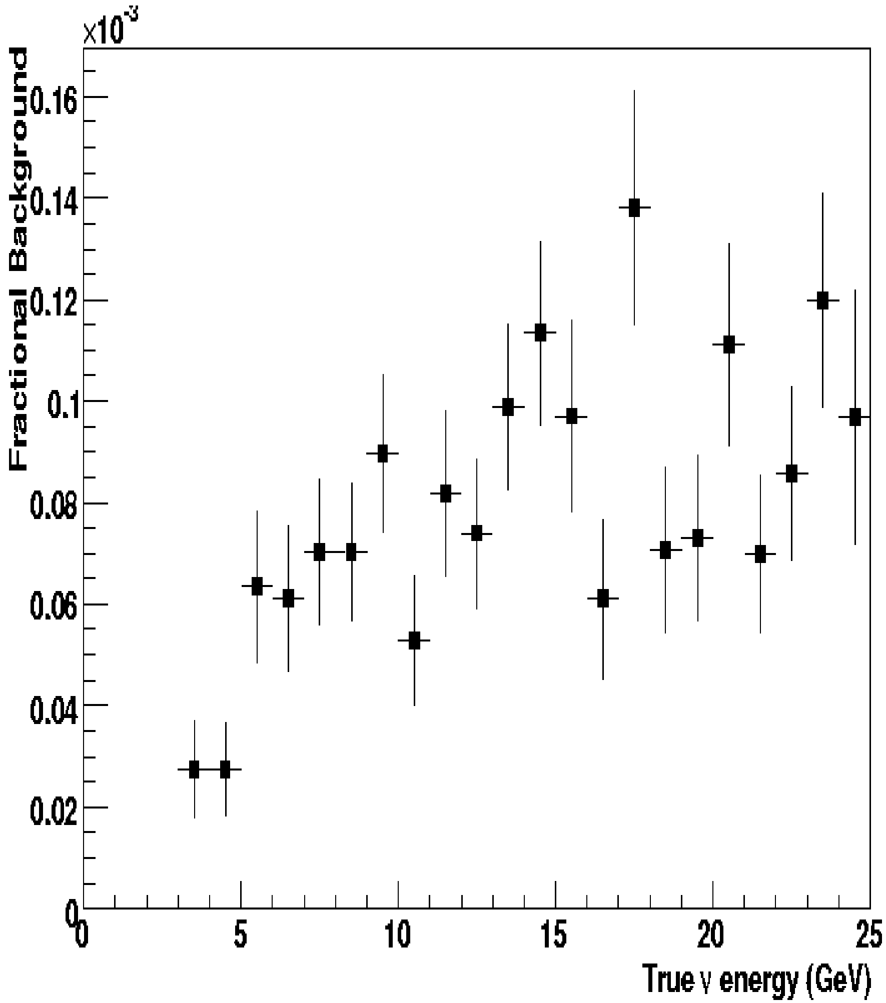


nu_mu as nu_mubar

NC background



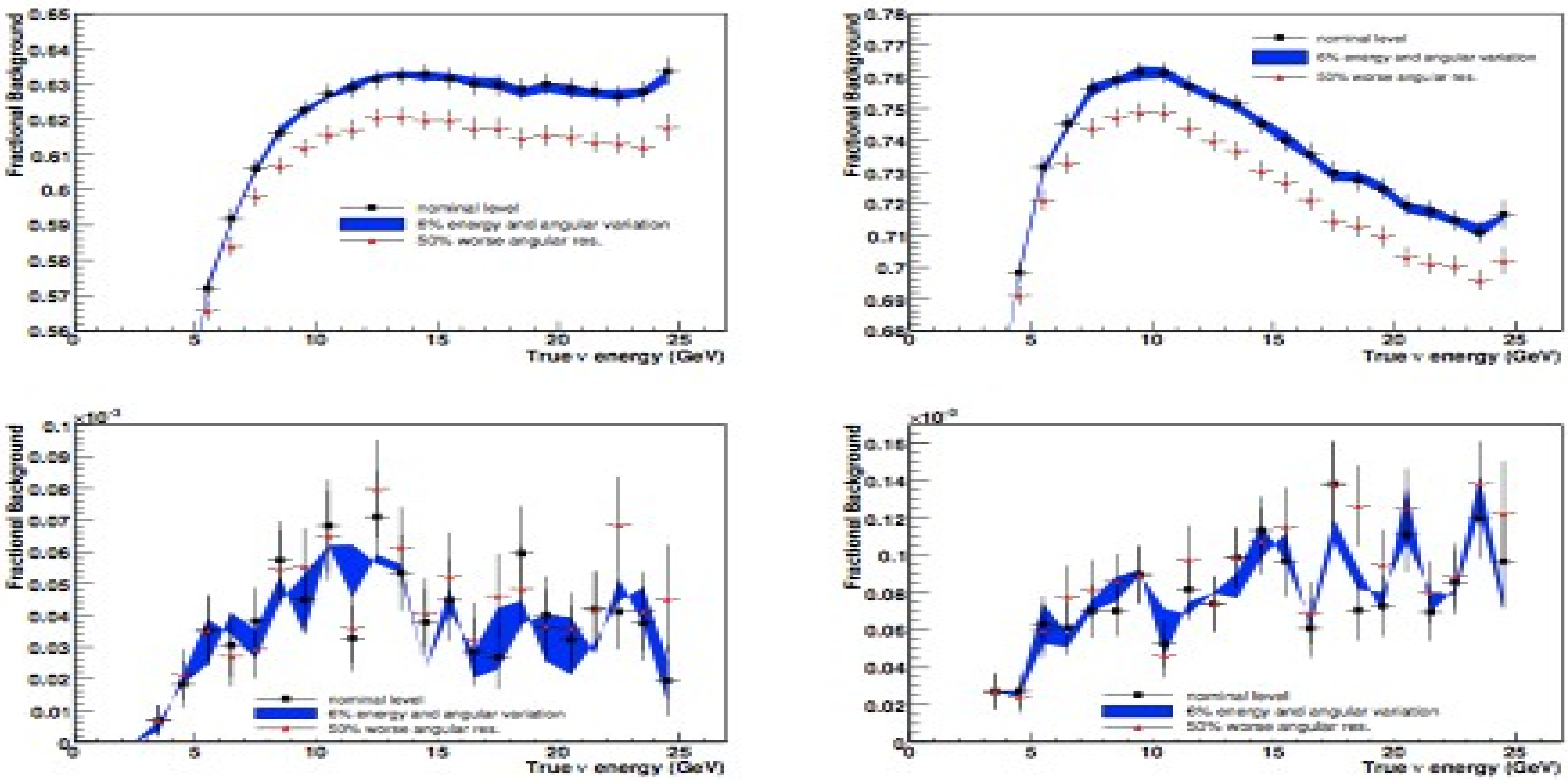
NC as nu_mu



NC as nu_mubar

Systematic

Worsening the hadronic angular resolution by 50% reduces efficiency by ~1%.



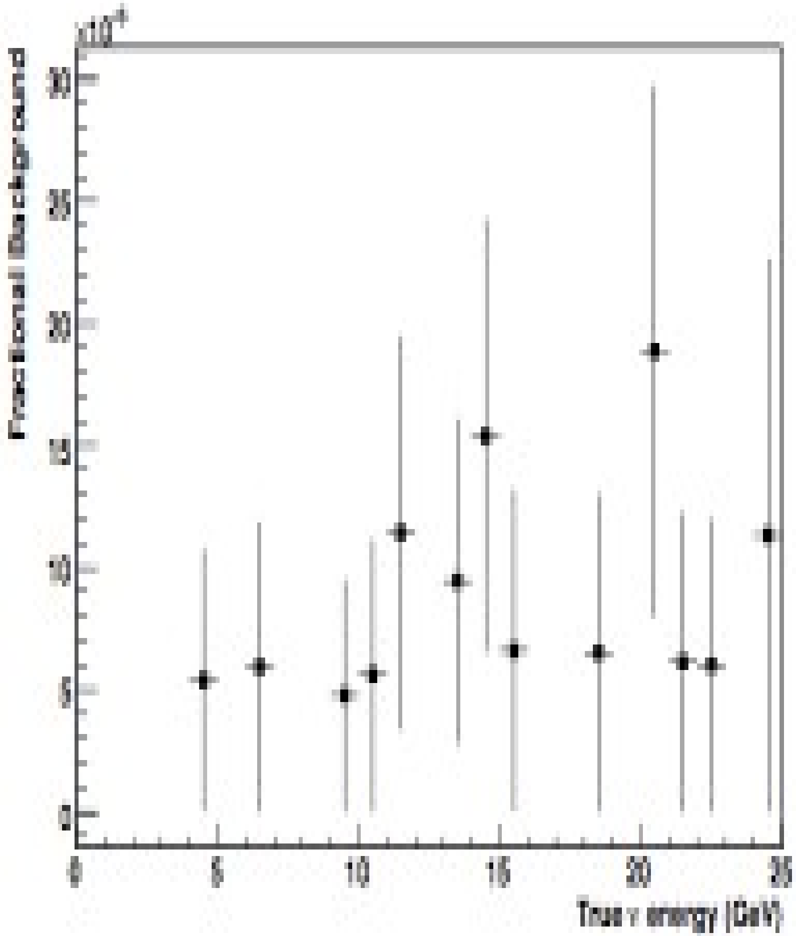
Neutral current background dominated by statistical error but systematic variation ~10^{-5} (~2% of absolute level).

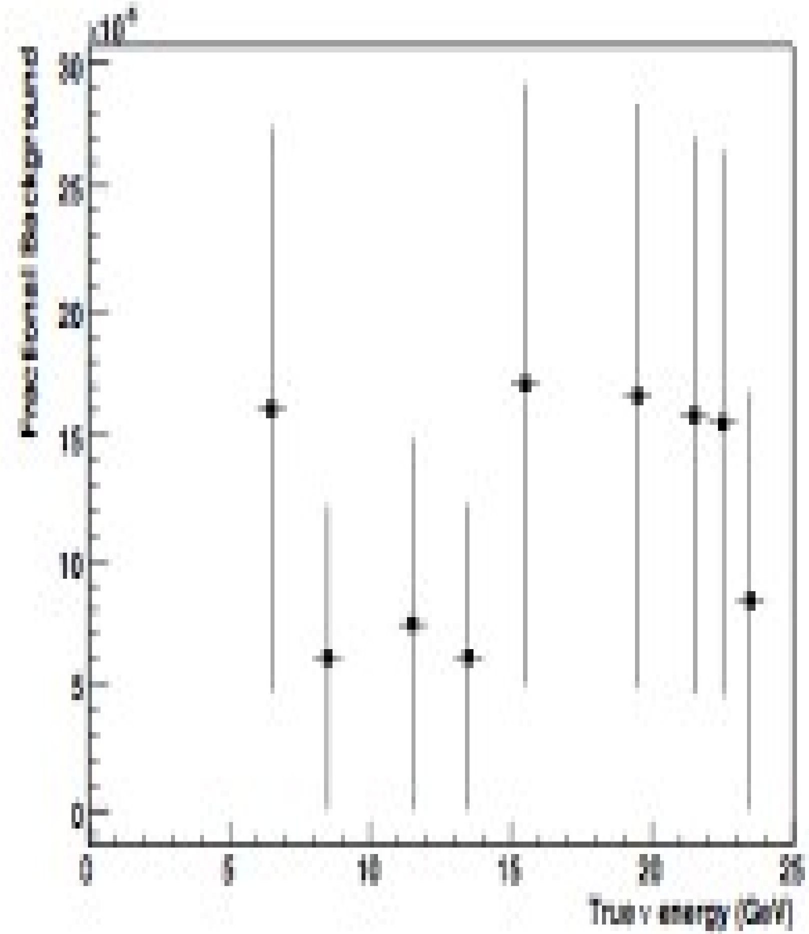
Summary

- Development of simulation, reconstruction and analysis underway.
  - A lot of ideas and assumptions at the moment but we believe they are robust.
- R&D for the detector and magnetic field will be discussed by B. Wands.

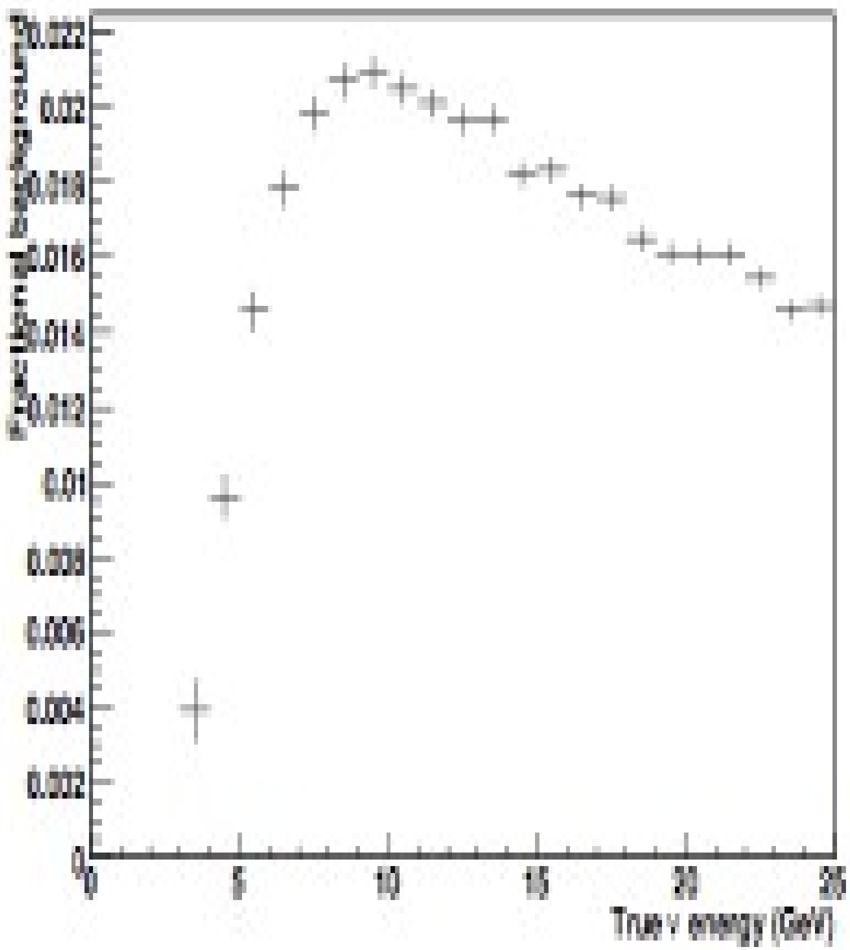
BACKUP

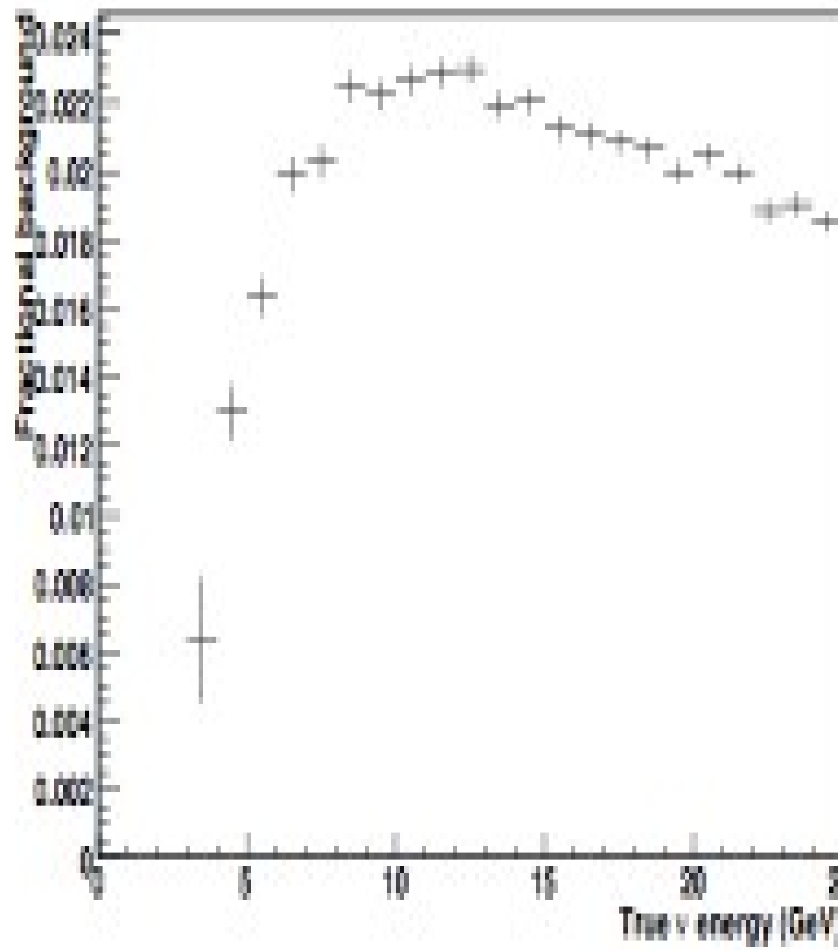
ν_e background





ν_τ contamination





Xsection systematic