A measurement of muon neutrino disapperance rate with MINOS

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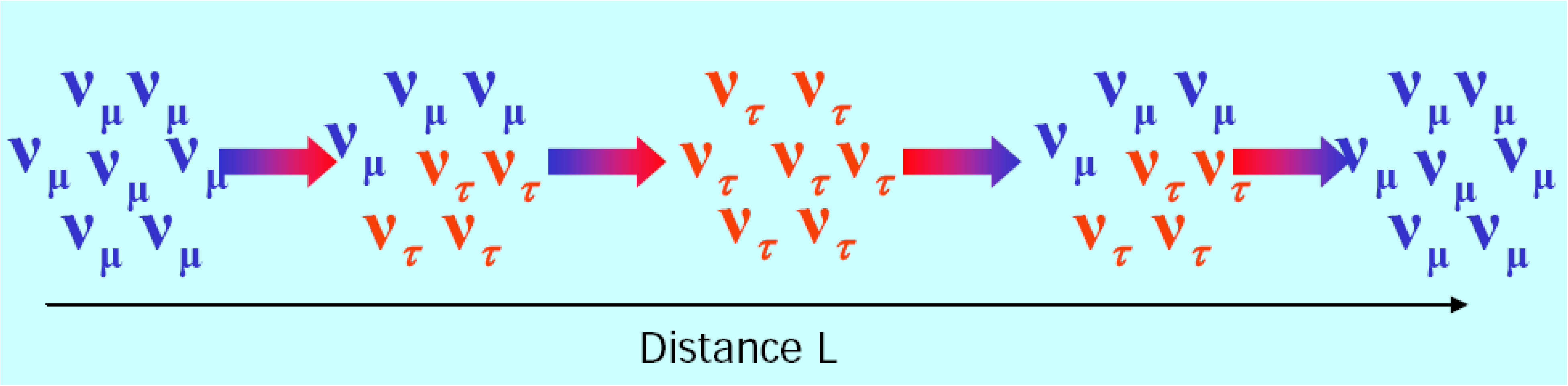
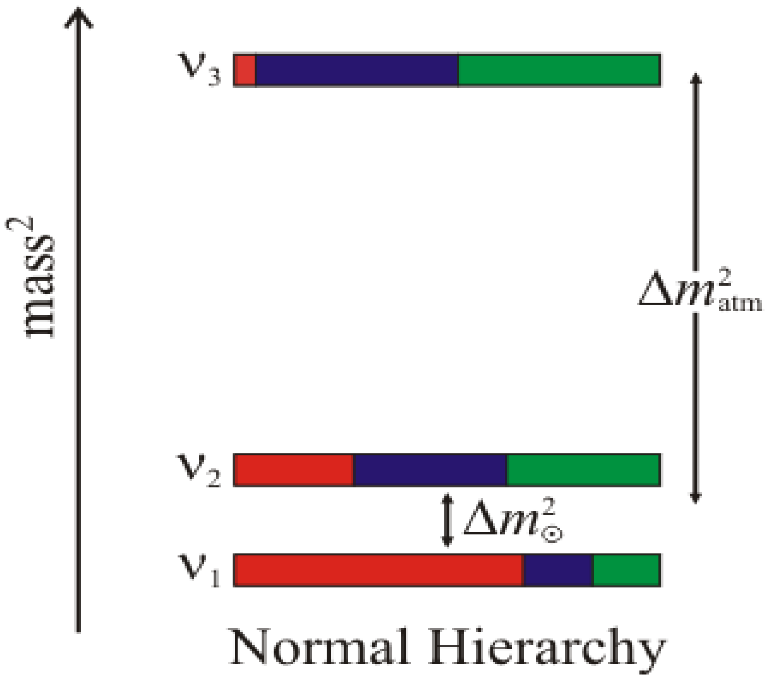
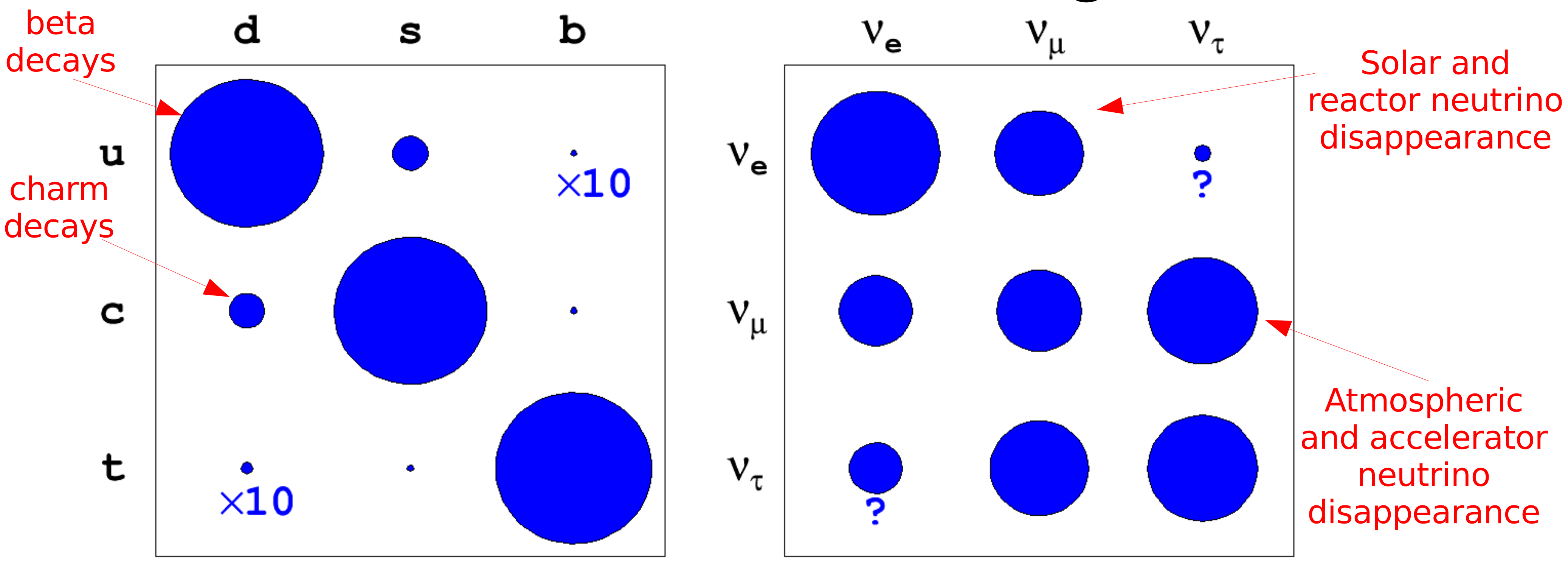
Neutrino masses



- If neutrinos have mass then flavor and mass eignenstates can mix: quantum mechanical interfence
- Amplitude depends on neutrino mass squared differences and mixing angles
- Observation of neutrinos oscillations implies at least two non-zero neutrino masses



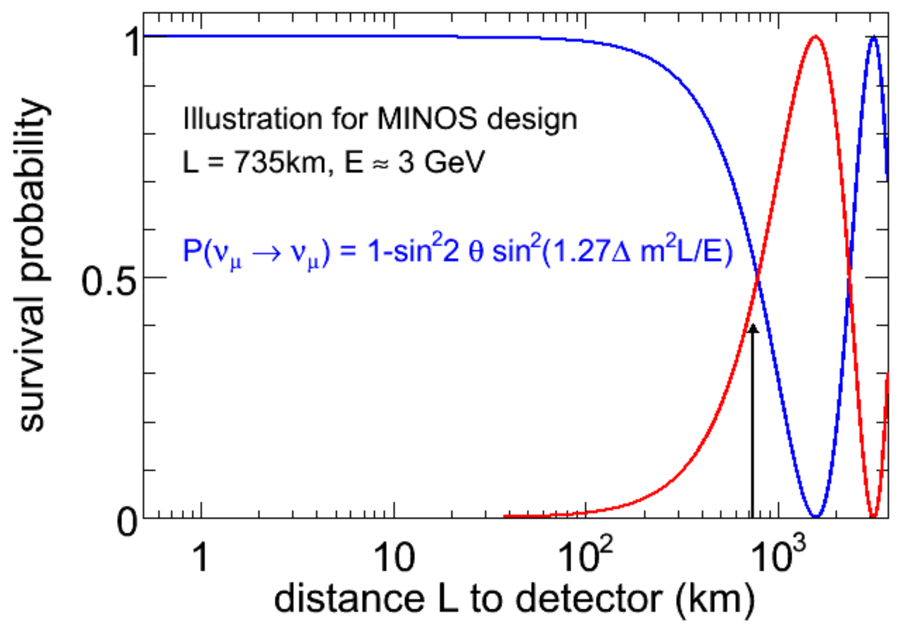
Quark and neutrino mixing matrices

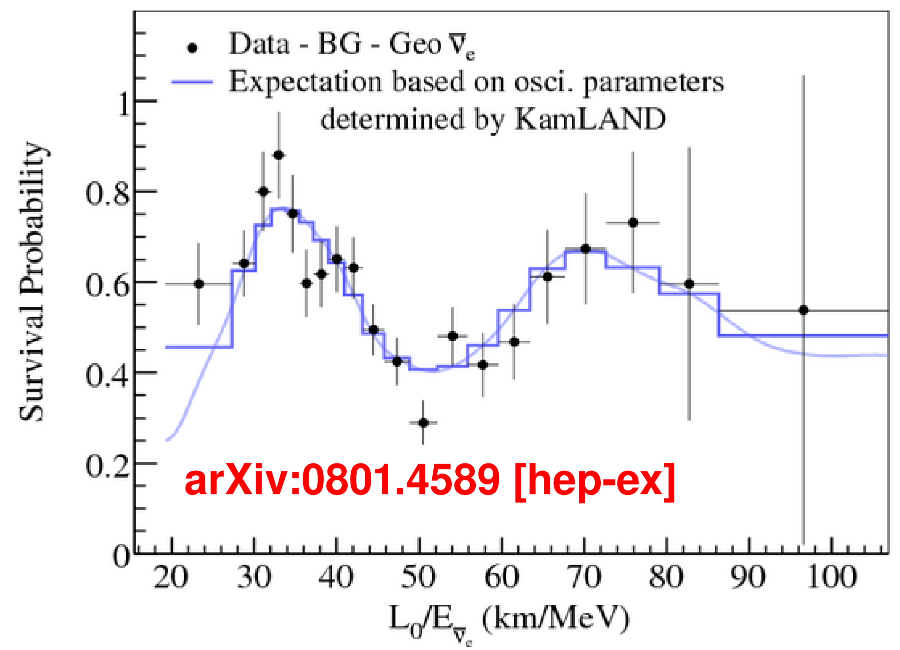


- CKM matrix gives strength of charged current W interactions to physical quark states: measured by many different experiments
- Neutrino mixing matrix is measured together with neutrino mass squared differences: depending on experiment's L/E that experiment is mostly sensitive to 2x2 mixing matrix as shown above in very simplified view of mixing matrix

Neutrino oscillations: disappearance

- Experiments in Homestake, Kamioka and Sudbury established deficit of ν_e from the sun
- Total solar flux measured by SNO agrees with predicted flux
- KamLAND measured L/E form of reactor anti-ν_e disappearance rate
- Super-K, K2K and MINOS have measured L/E form of ν_μ disappearance rate

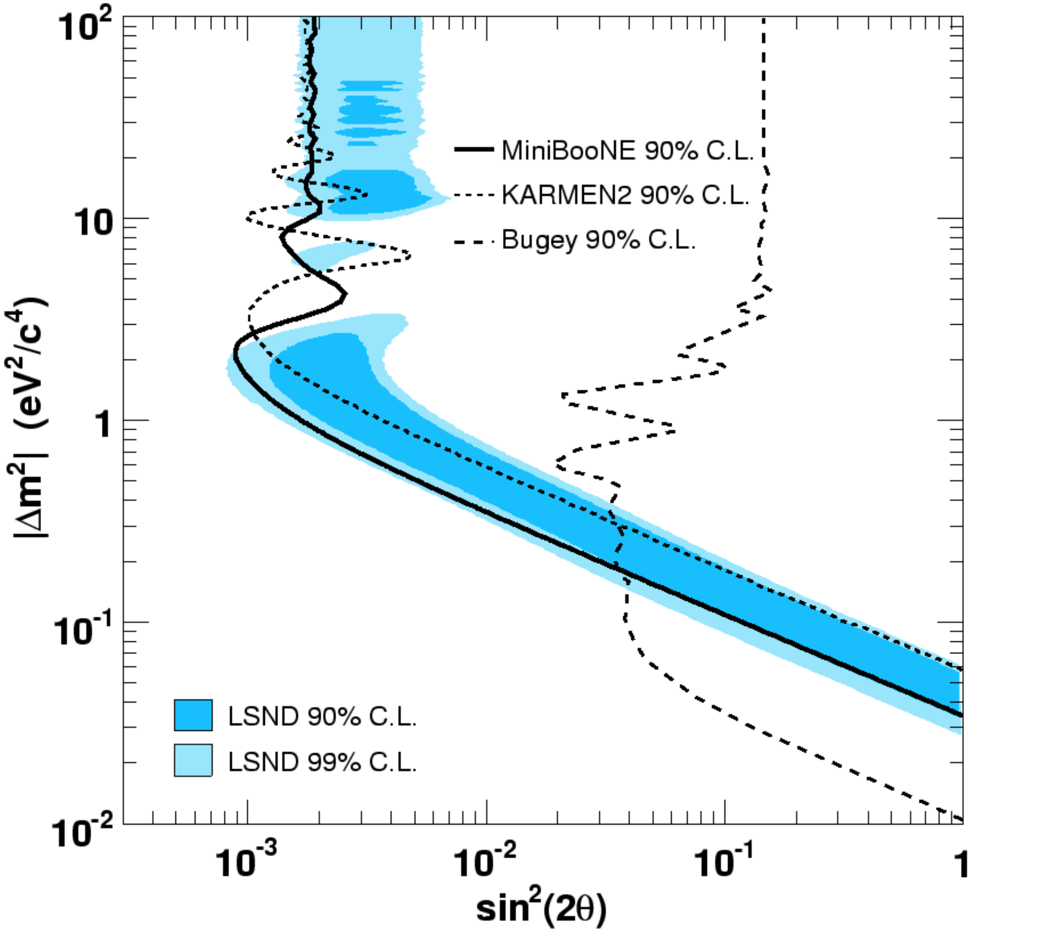


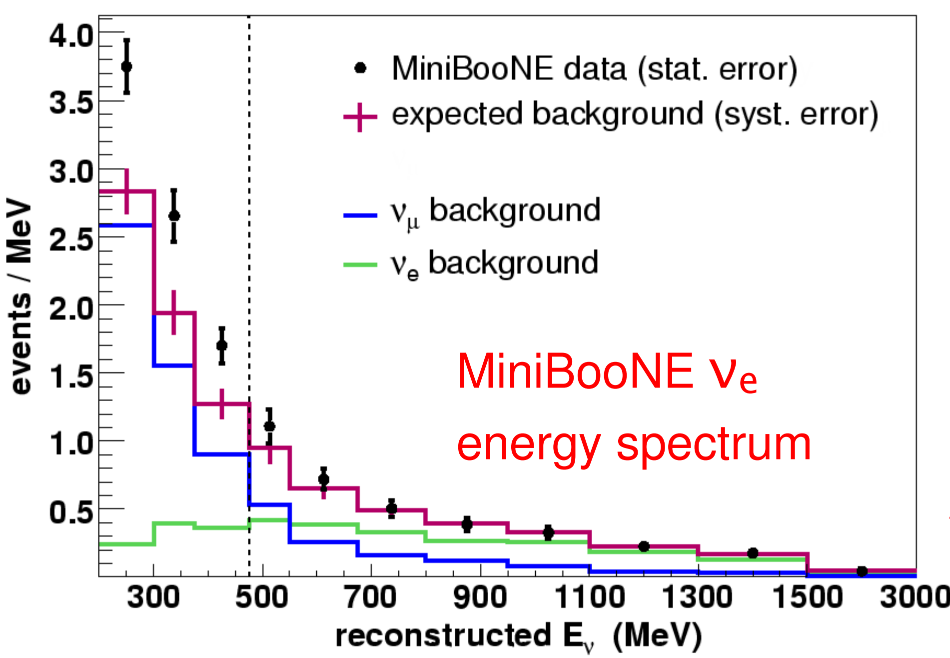


Neutrino oscillations: appearance

- Another signature of neutrino oscillation is apperance of "wrong" flavor neutrinos
- LNSD observed excess of anti-ν_e in anti-ν_μ beam but

MiniBOONe did not confirm this signal with ν_μ beam





Mixing for two neutrino flavors:

$$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta)\sin^2(1.27\Delta m^2 L/E)$$

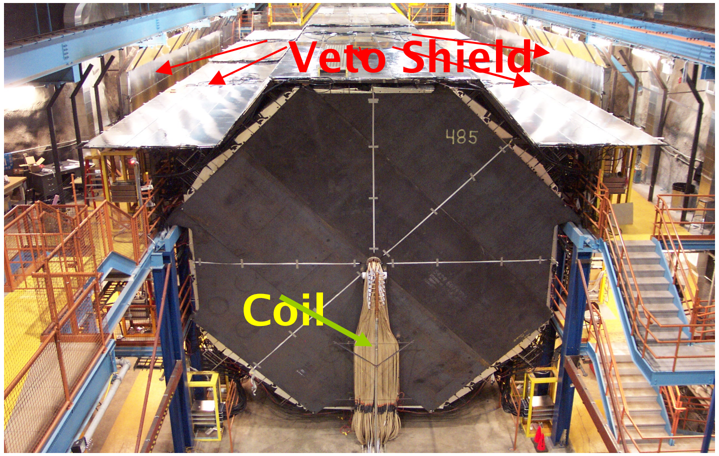
Main Injector Neutrino Oscillation Search (MINOS)

- Investigate oscillations with high intensity ν_μ beam
- Measure ν_μ and anti-ν_μ disappearance rates
- Search for $\nu_\mu \rightarrow \nu_e$ appearance
- Search for $\nu_\mu \rightarrow \nu_s$ transition
- Cosmic ray physics
- Neutrino cross-section measurements

Near Detector

Two functionally identical magnetized iron-scintillator calorimeters

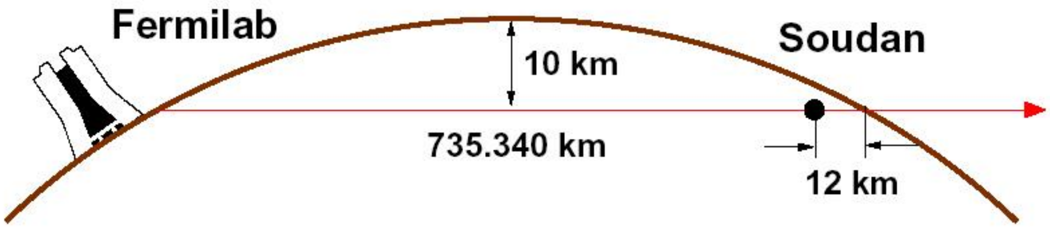
Far Detector



980 tons

1 km from target

100 m deep

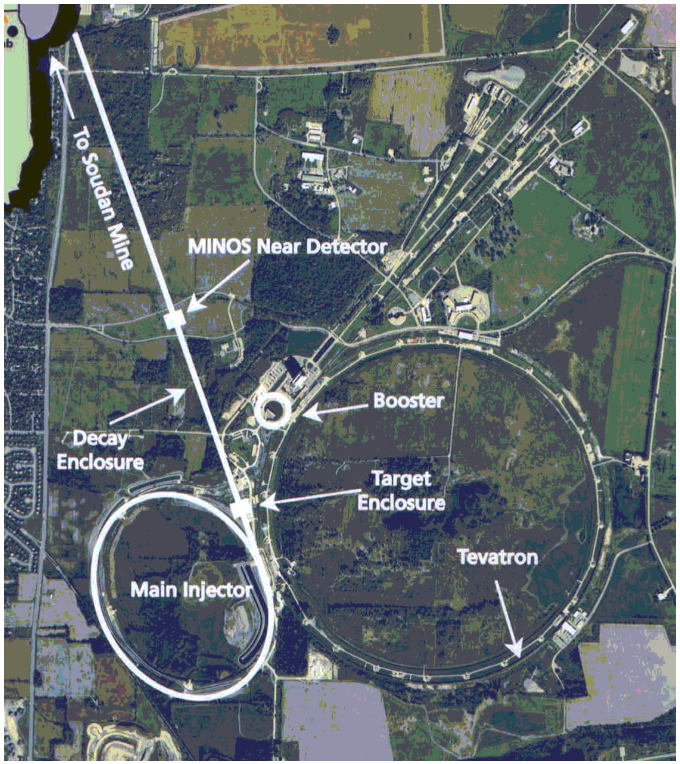


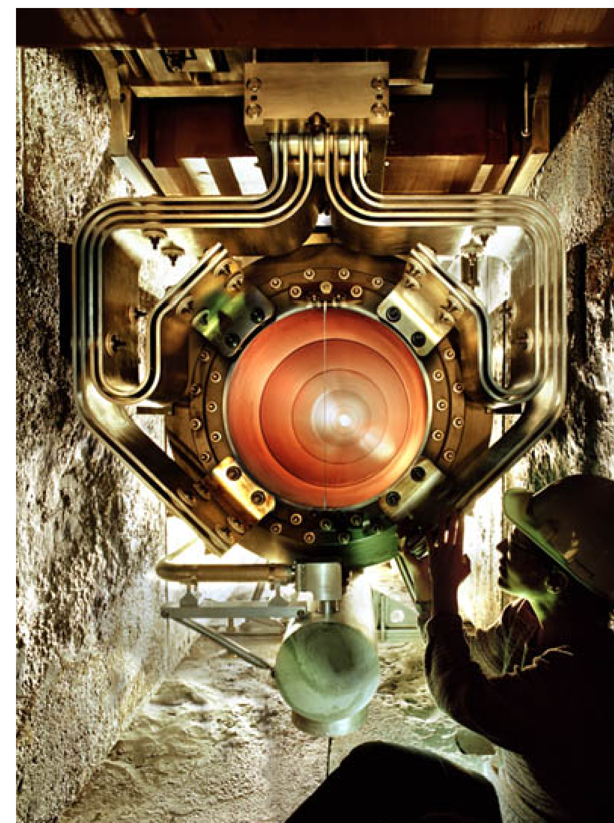
5400 tons

735 km away

700 m deep

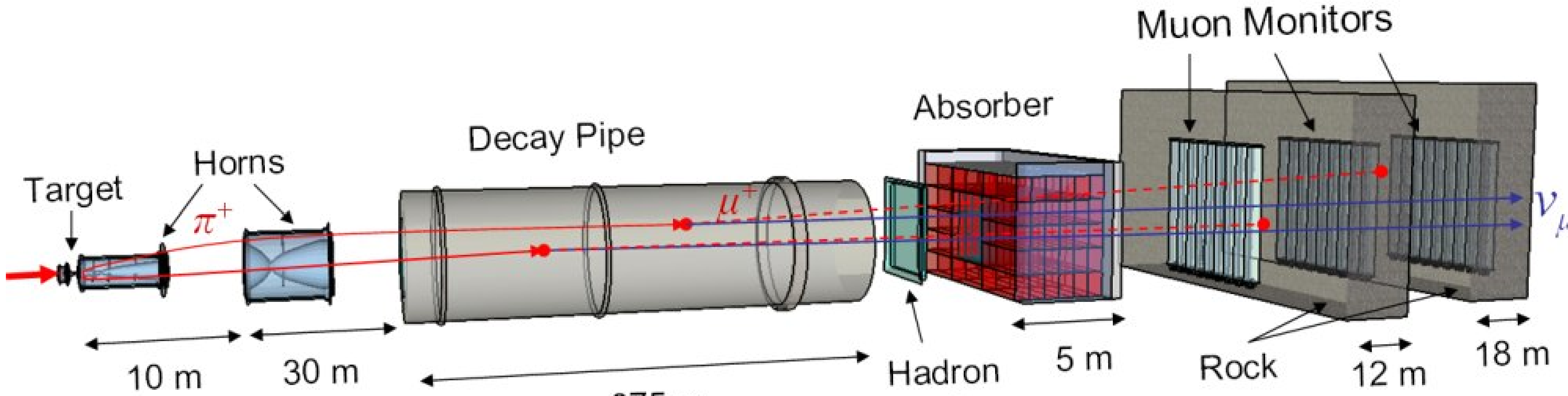
Neutrinos at Main Injector (NuMI)





- Advance neutrino beamline uses 120GeV/c Main Injector protons
- 2.4×10^{13} protons/spill every ~2.4s
- ~0.2 MW average beam power

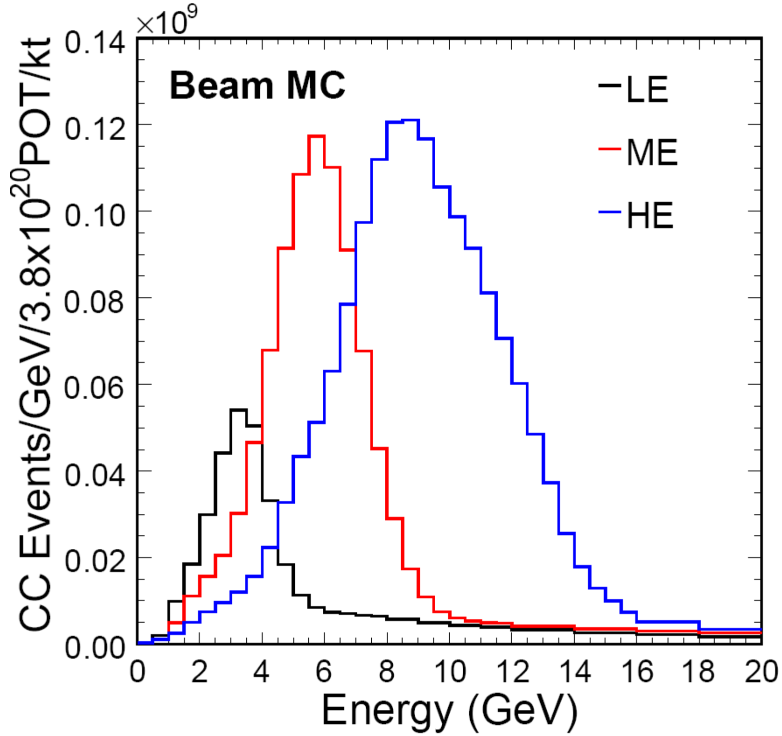
NuMI beamline



Z. Pavlovic

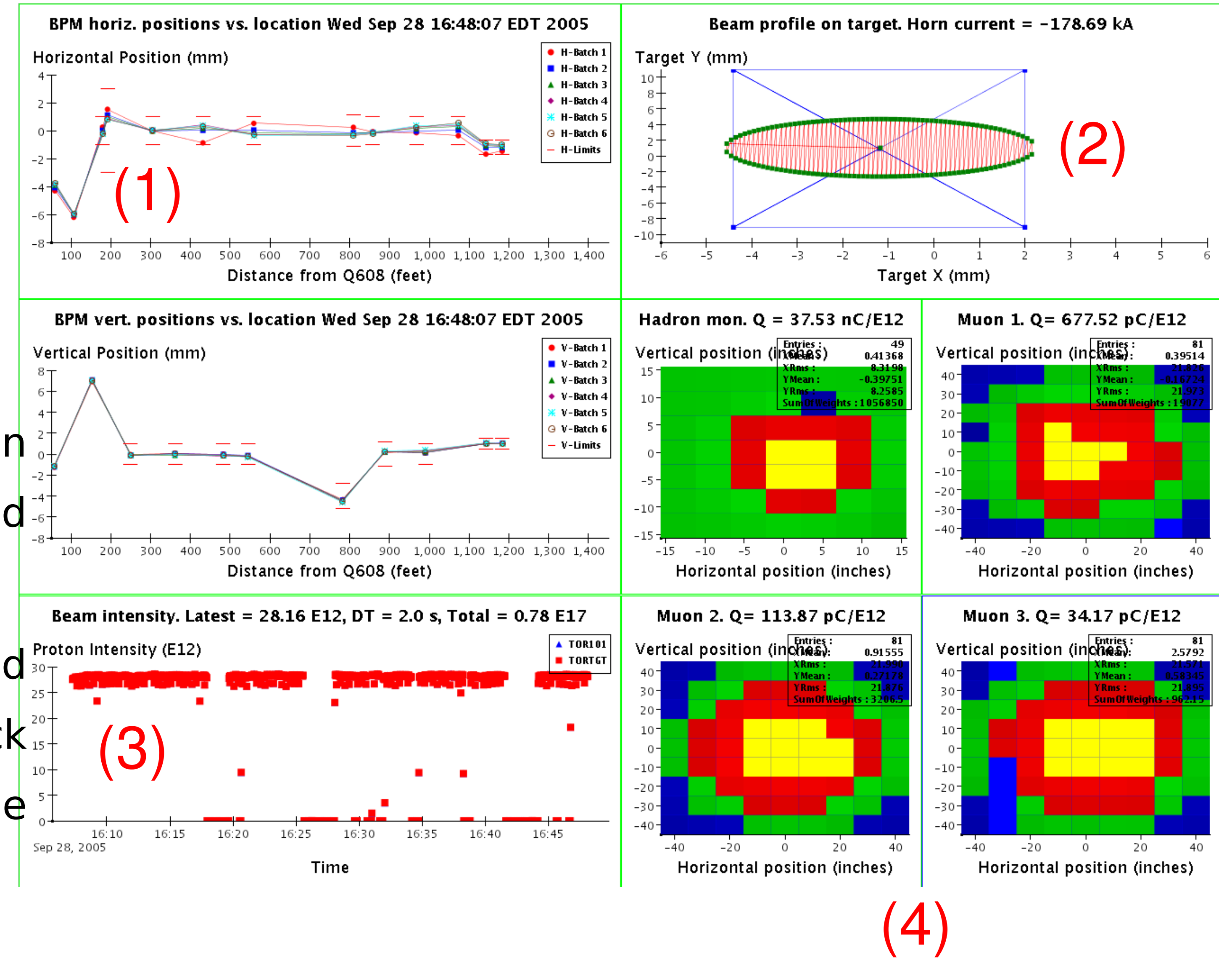
- Water cooled graphite target
- 2 pulsed parabolic magnetic horns
- Hadron and muon monitors
- Change beam flux by changing relative positions of target and horns
- Mostly run in Low Energy (LE) beam

$\nu_\mu = 93\%, \overline{\nu}_\mu = 6\%, \nu_e + \overline{\nu}_e = 1\%$

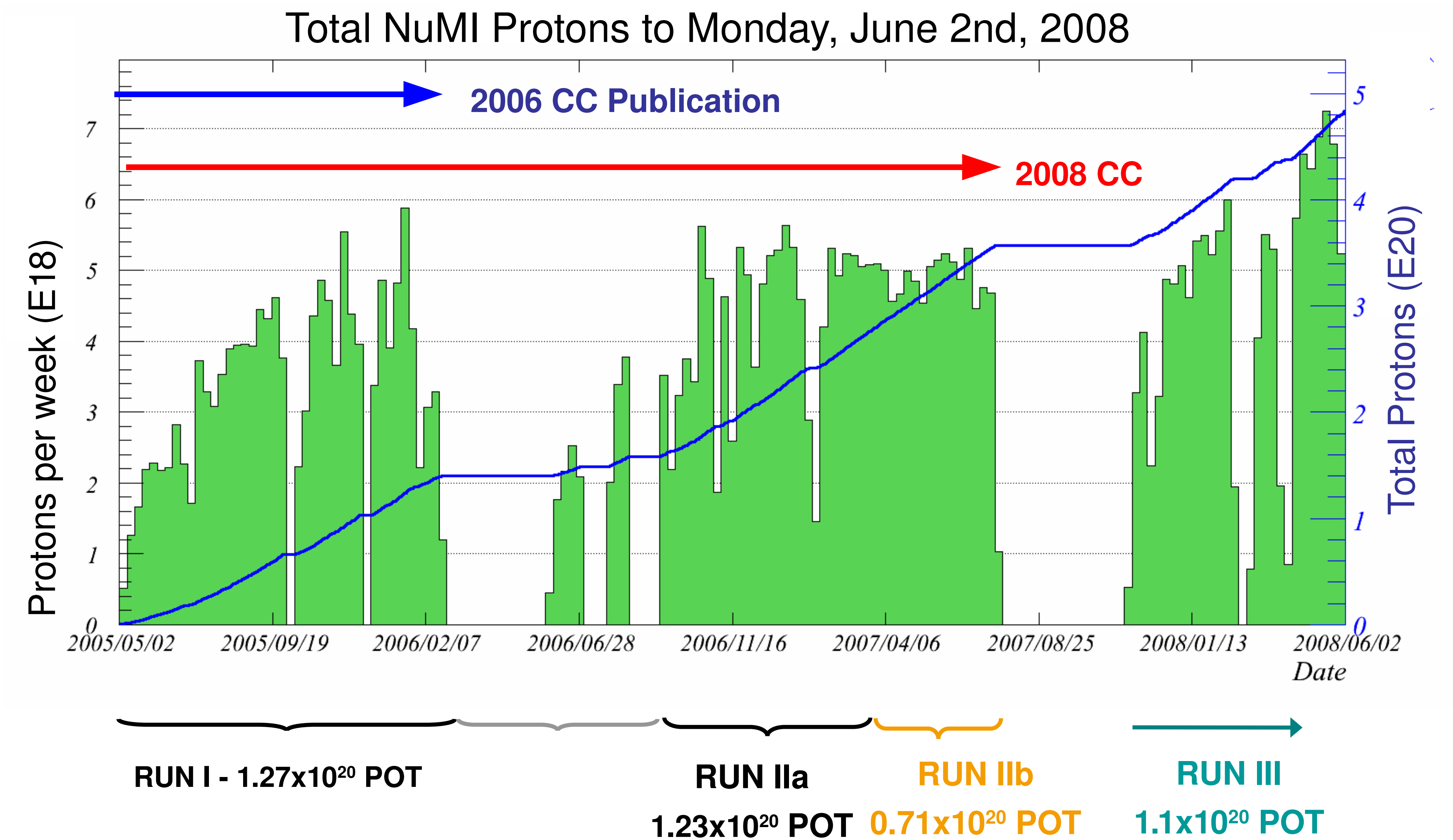


Monitoring NuMI beamline

- Each spill we monitor:
  1) Beam trajectory
  2) Beam position and profile at target
  3) Intensity
  4) Hadron and muon monitors
- This information is then used offline to select good beam quality spills
- Use GPS, gyroscopes and muon monitors to check the beam alignment to the far detector



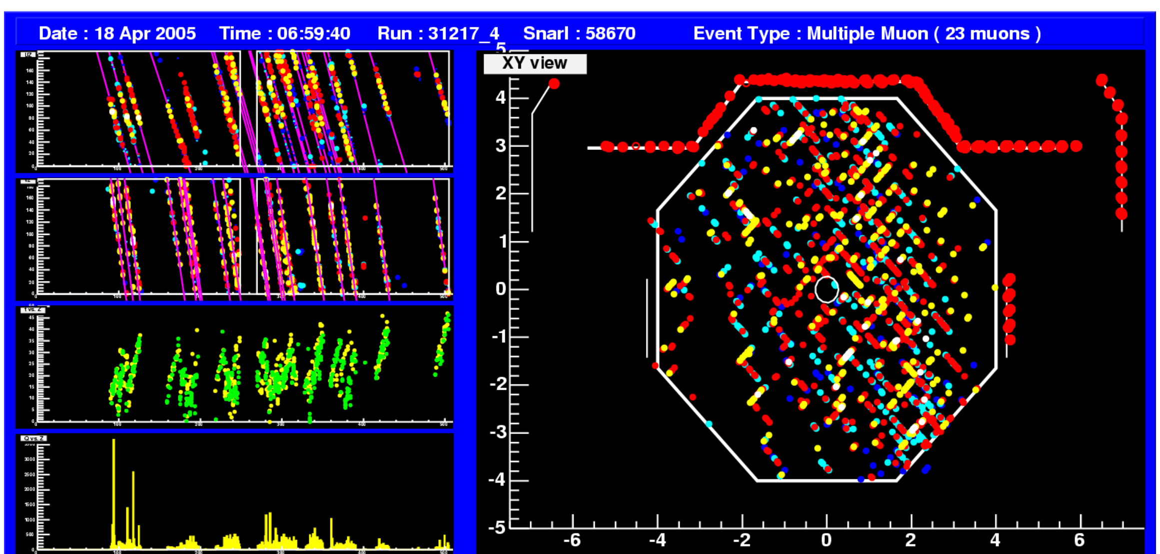
NuMI Beam Performance

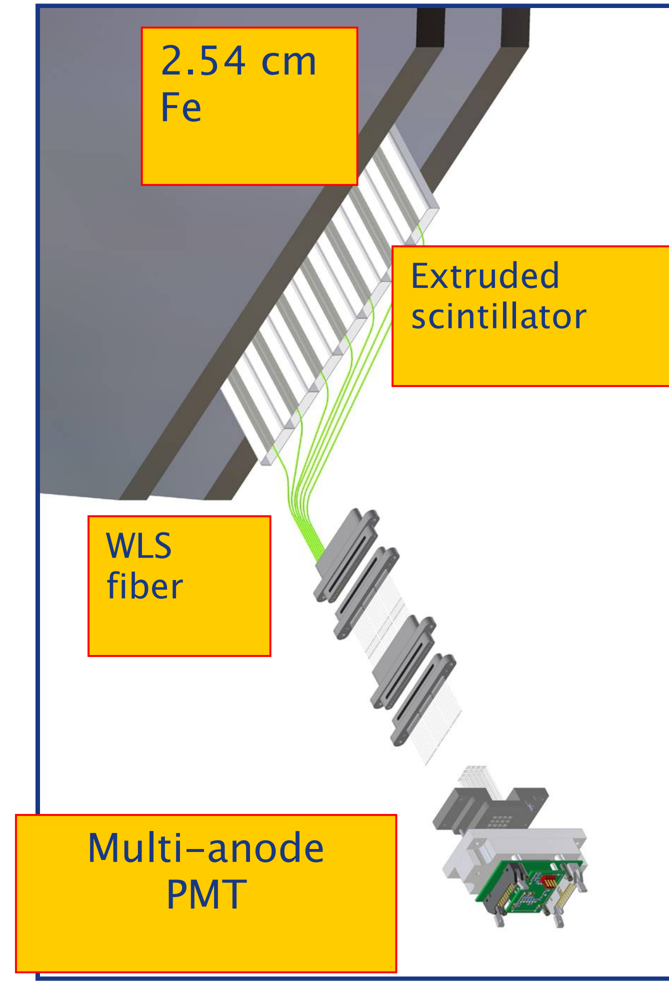


Many thanks to Fermilab staff for the great beam perfomance!

MINOS detectors

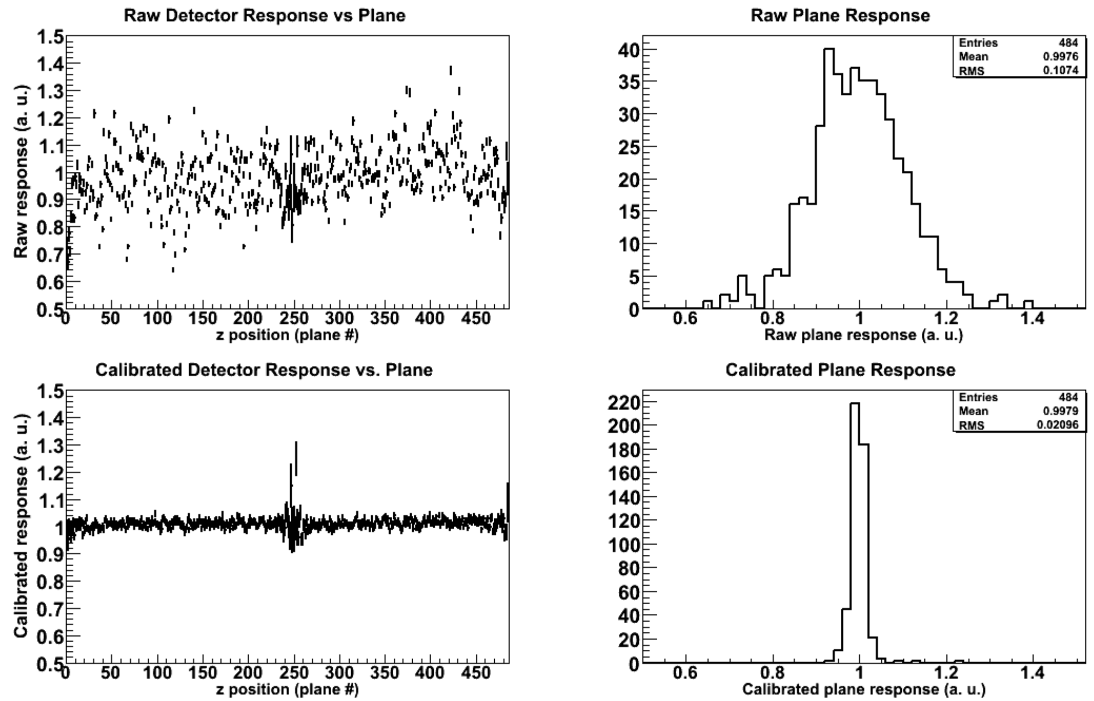
- MINOS uses far/near ratio to reduced errors
- Two detectors use same steel and scintillator
- Toroidal magnetic field with ~1.2T
- Orthogonal strip orientation in alternating planes allows 3d tracking
- Shower energy = sum of scintillation light
- Muon momentum = range or curvature

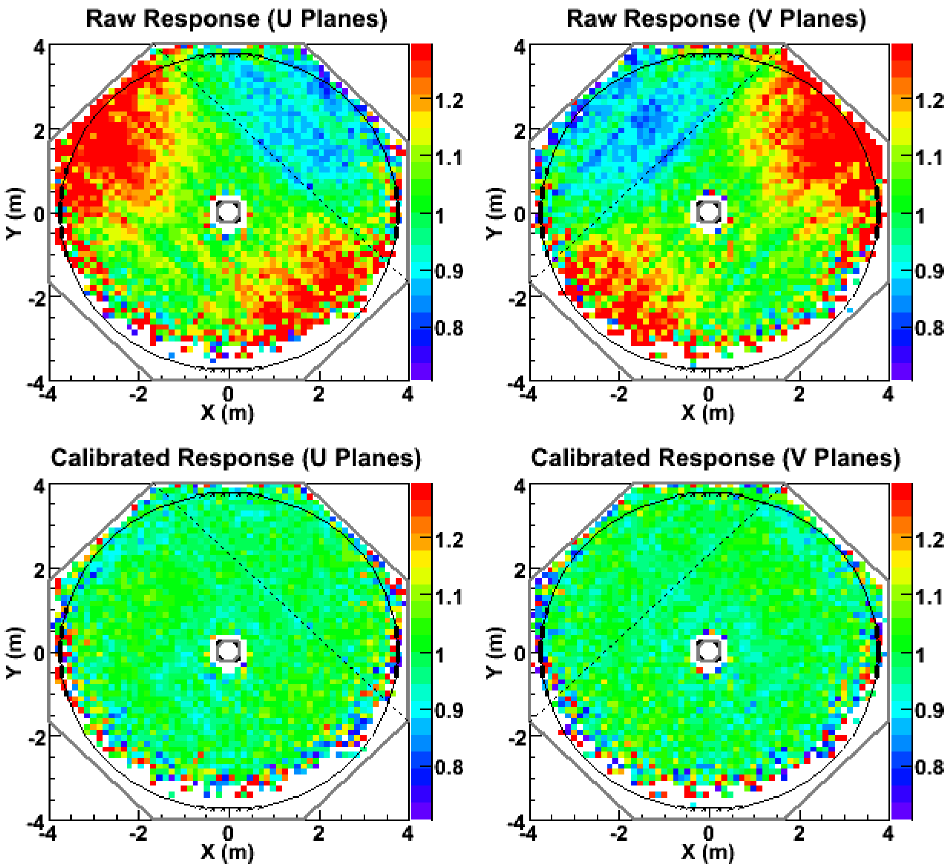




MINOS calibration

- Detectors are calibrated using LED ligh injection system and cosmic ray muons
- Absolute calibration with stopping muons



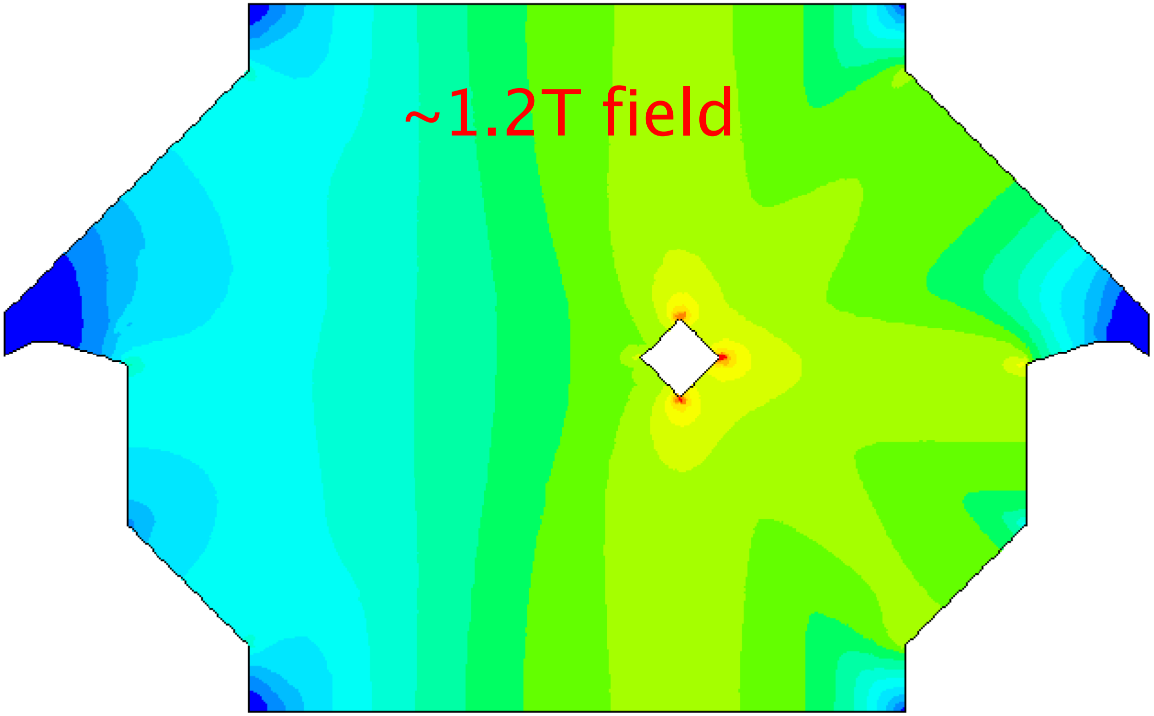


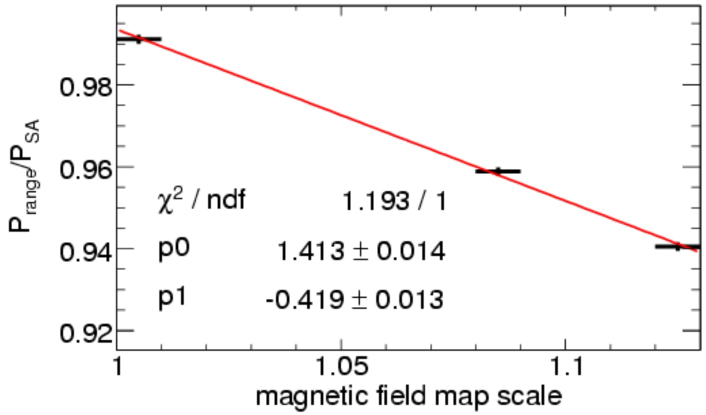
Energy scale calibration:

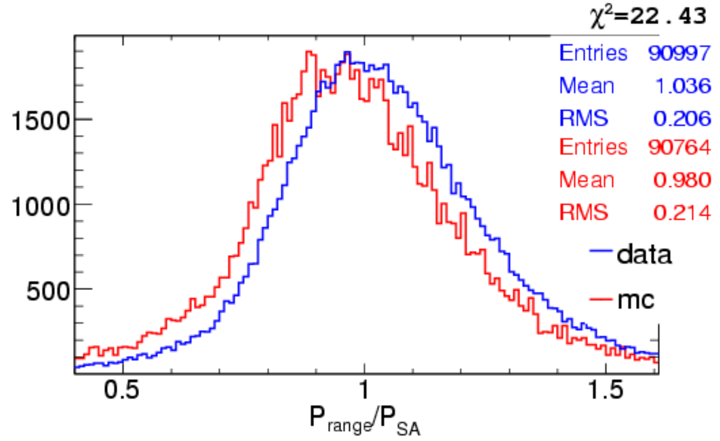
- **3.1 % absolute error in ND**
- **2.3 % absolute error in FD**
- **3.8 % relative**

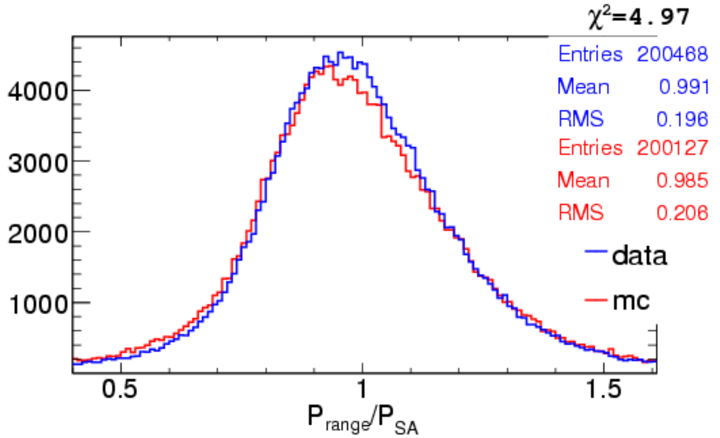
MINOS magnetic field

- MINOS measured magnetic properties of steel and used that data for finite element simulation of the field map
- Calibrate overall field strength by comparing range and curvature of stopping muons



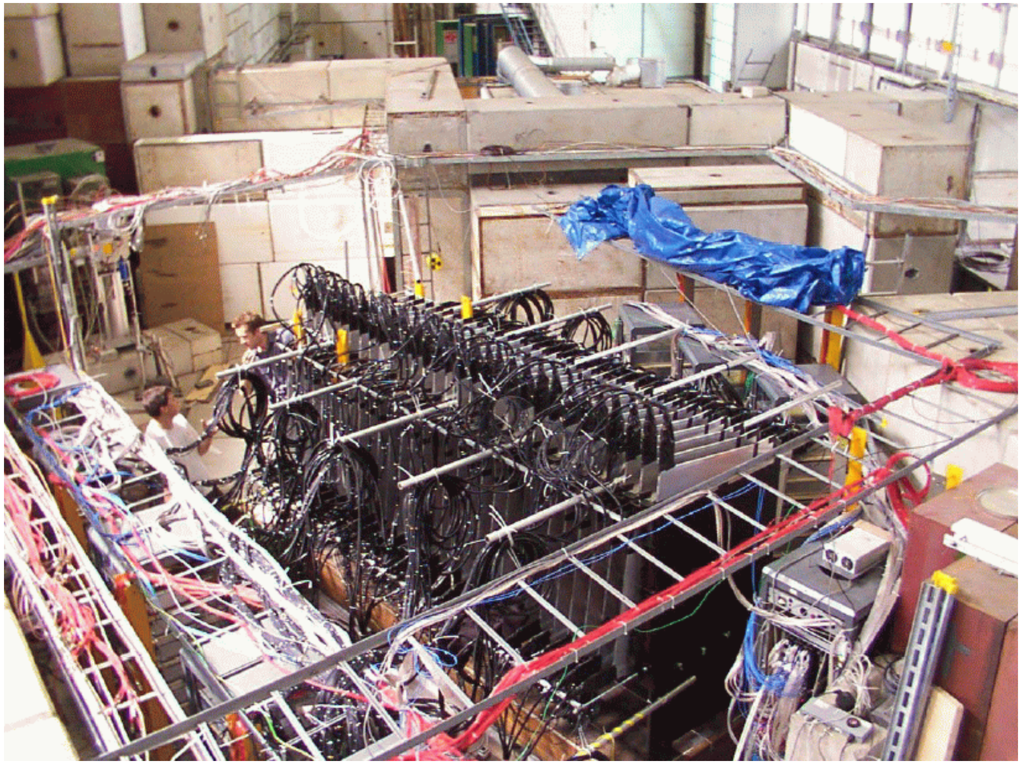


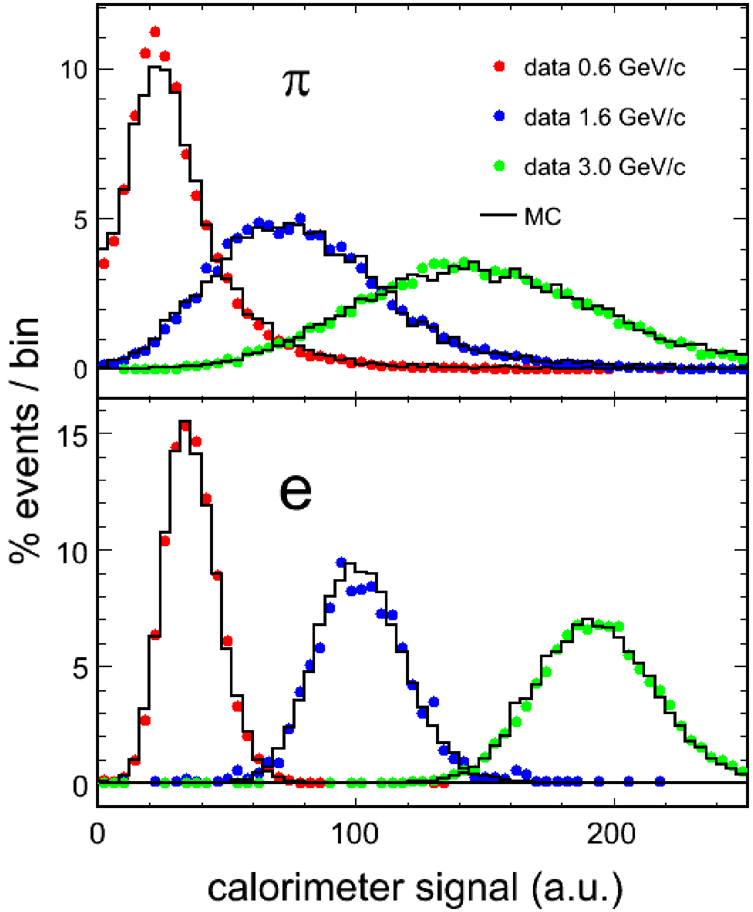


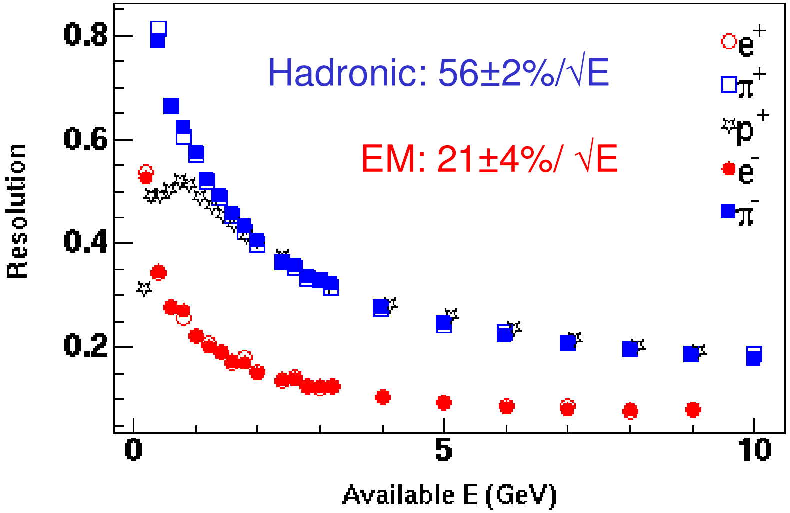


Caldet

- 60-plane 'micro-MINOS'
  - has taken data at T7 & T11 test beam lines at CERN during 2001, 2002, 2003
- Instrumented with both Near and Far Detector electronics
  - To provide cross-calibrations between two detectors







Charged Current Analysis

Precision measurement of Δm^2 and $\sin^2(2\theta)$

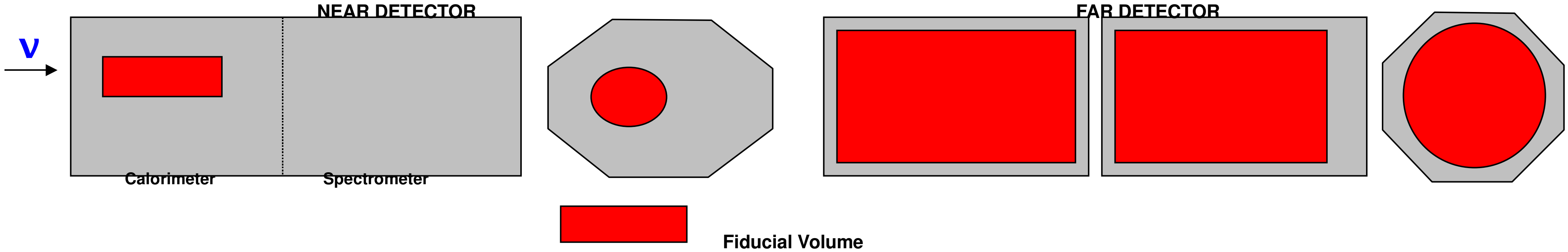
Testing the oscillation hypothesis

CC Event Selection

ν_μ CC-like events are selected in the following way:

Event must contain at least one good reconstructed track

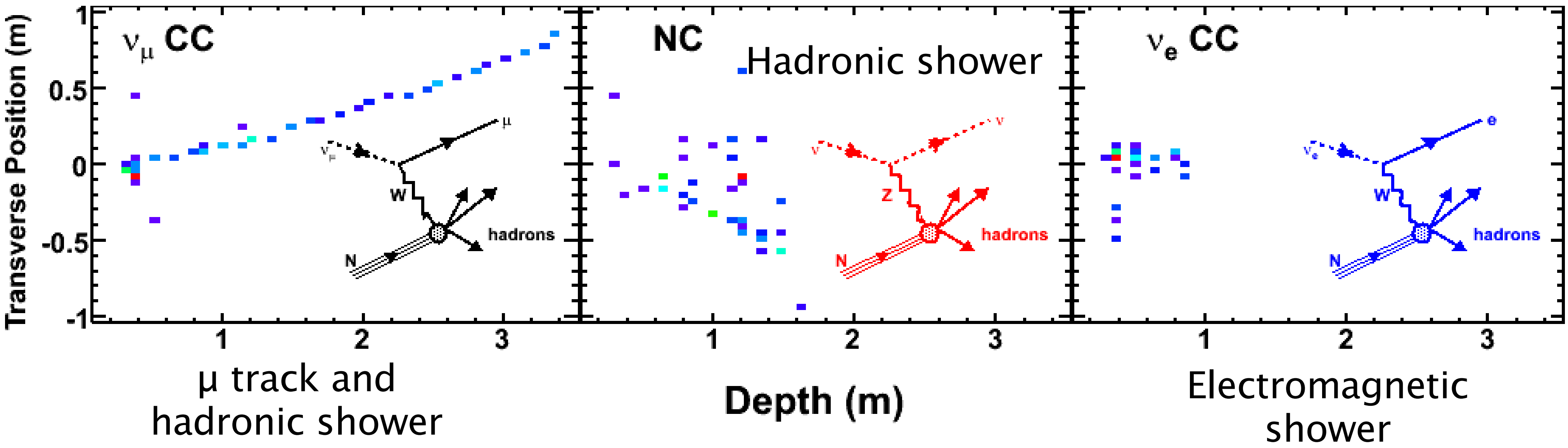
The reconstructed track vertex should be within the fiducial volume of the detector:



The fitted track should have negative charge (selects ν_μ)

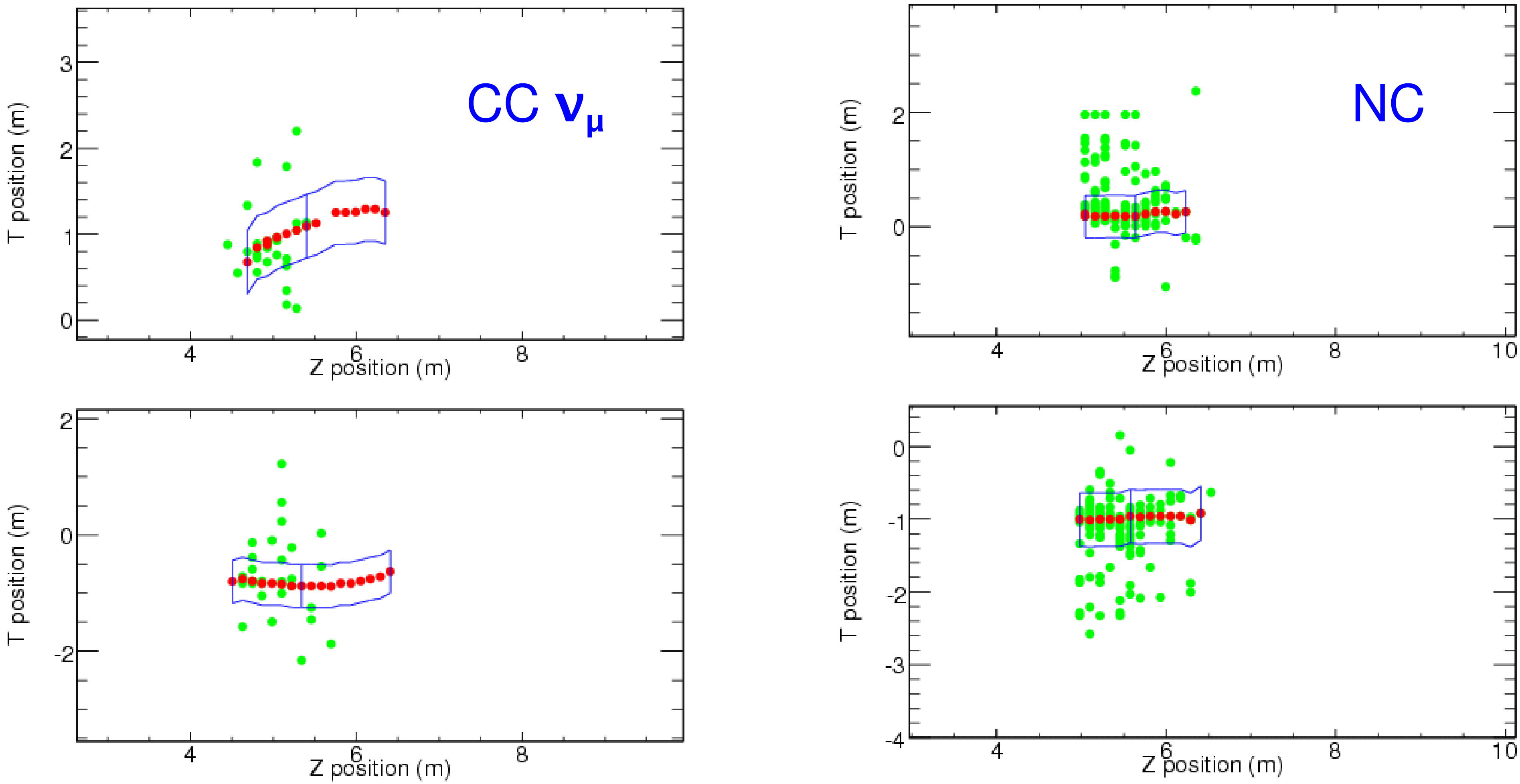
Cut on multi-variate Particle ID parameter which is used to separate CC and NC events.

Event classification



- Three types of interactions:
  - Charged current ν_μ and anti-ν_μ
  - Neutral current interactions
  - Charged current ν_e
- Use pattern of hits and pulse height of energy depositions to select charged current ν_μ events

Identifying muon track

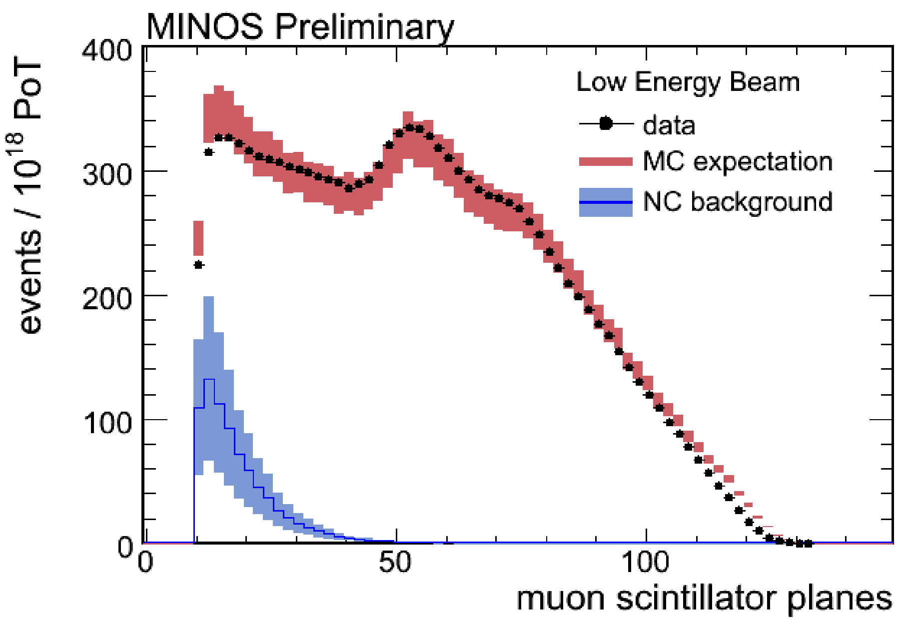


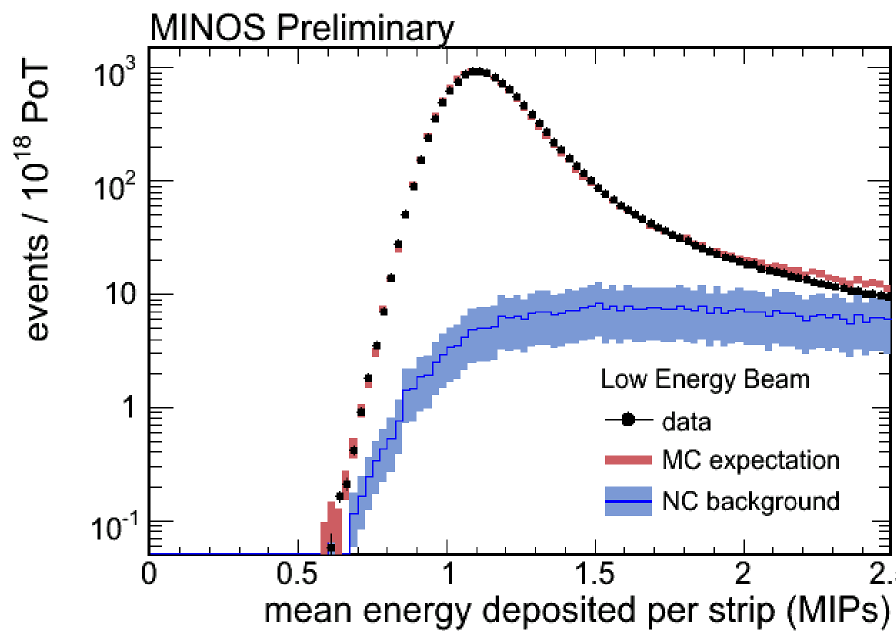
- Ignore track planes near vertex that contain shower hits
- Construct variables using hits on and around track
- Compare thousands of combinations to optimize selection

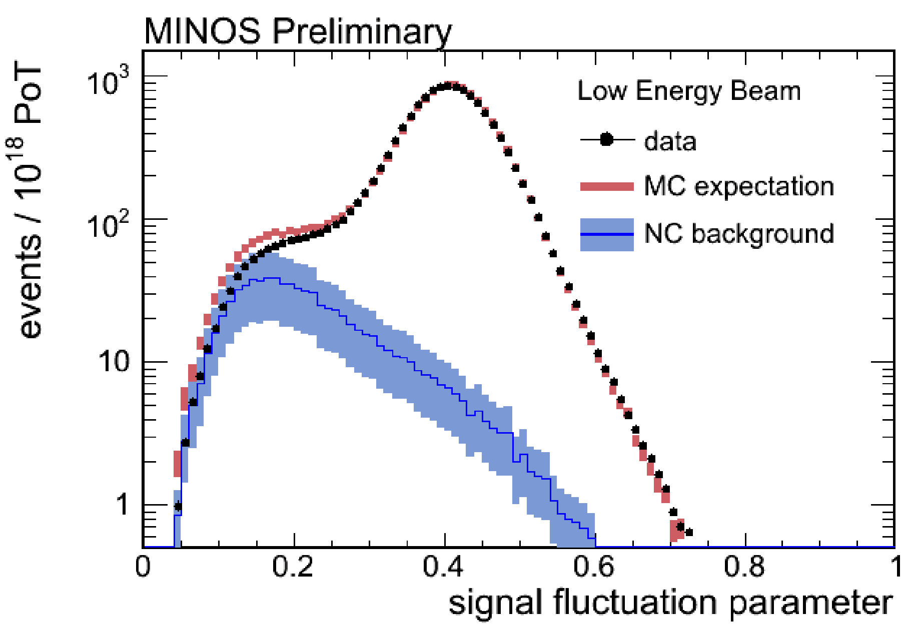
Event classification

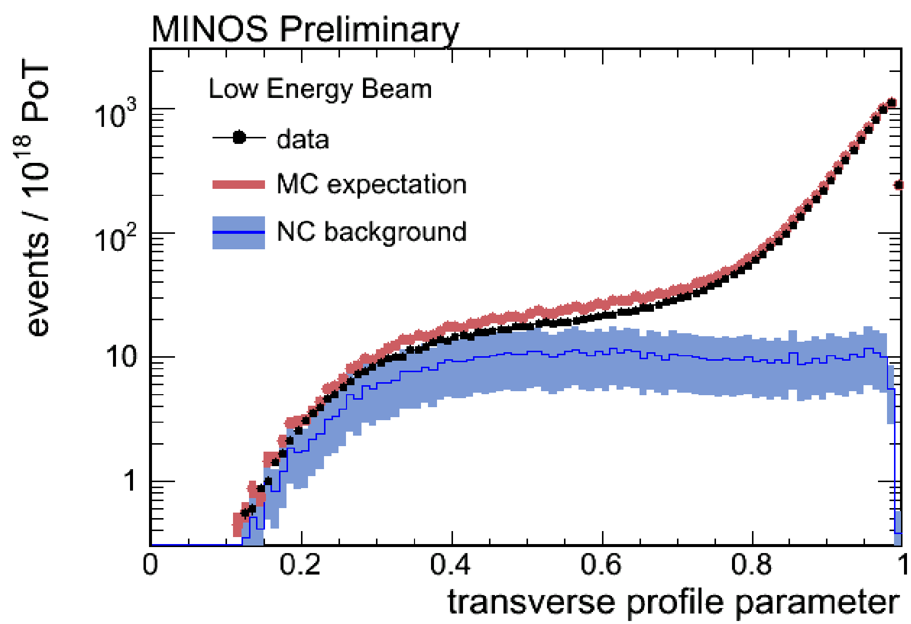
- Create 4 track variables to identify muon tracks:
  - Number of steel planes crossed
  - Mean of scintillator strips' pulse height
    - ~ mean of Landau distribution for muons
  - Fluctuation in scintillator strips' pulse height
    - ~ width of Landau distribution for muons
  - Transverse track profile
    - ~ single muon propagation versus multi-particle hadronic shower
- These 4 variables are inputs to the k-Nearest Neighbour algorithm (kNN)

Event classification variables



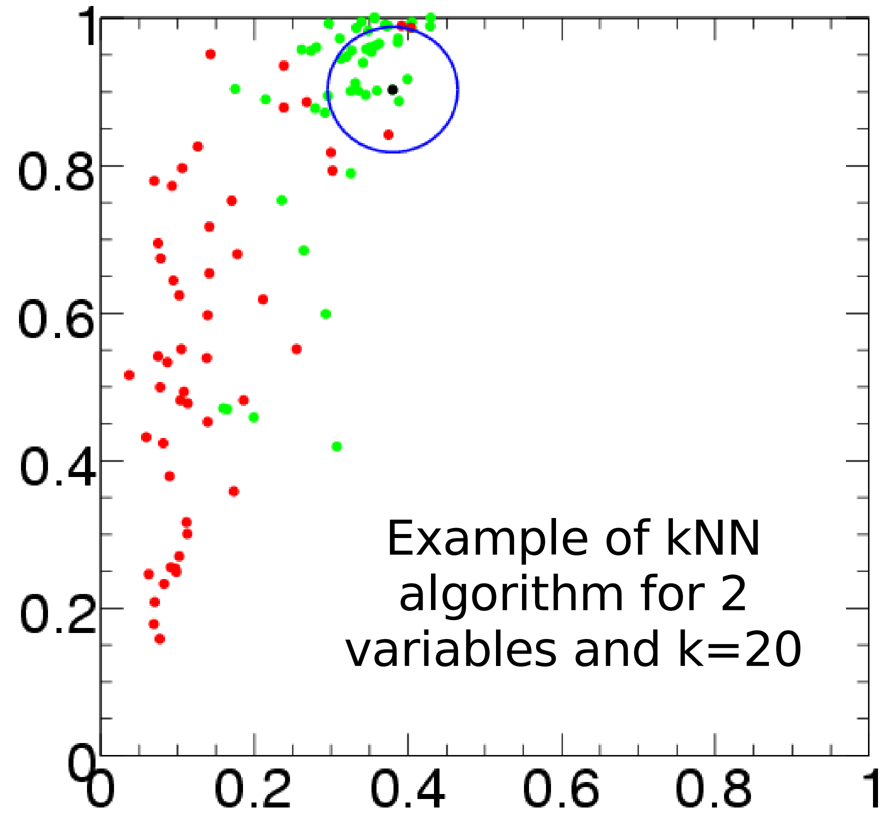






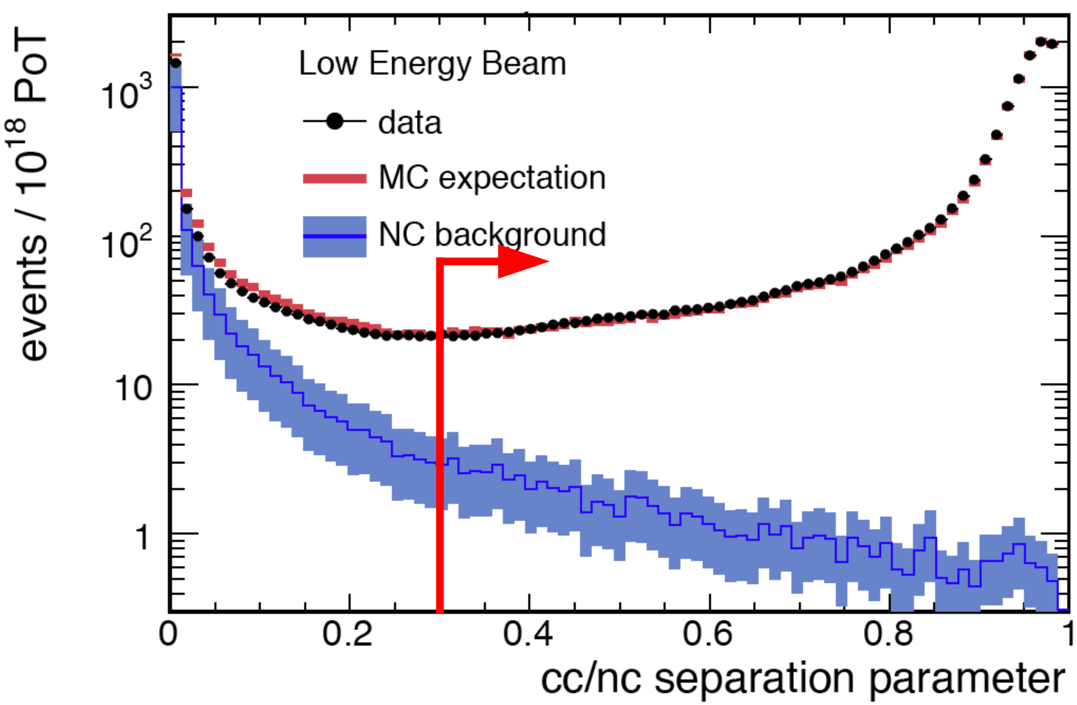
k-Nearest Neighbour algorithm

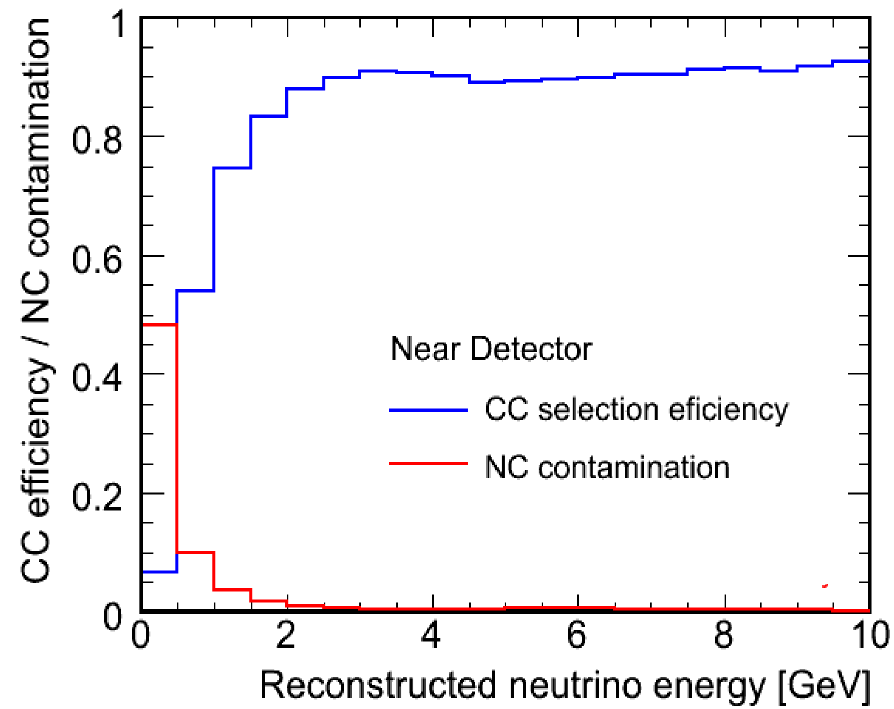
- For general kNN algorithm populate multi-dimensional parameter space with signal and background events
- Search for k neighbours and classify event by majority vote of k-neighbours
- kNN algorithm must be fast to search through thousands Monte-Carlo events (500k for MINOS)
- The algorithm's code is based on paper by J.H. Freidman, J.L. Bentley and R.A. Finkel and is added to TMVA/ROOT



Charged current ν_μ event selection

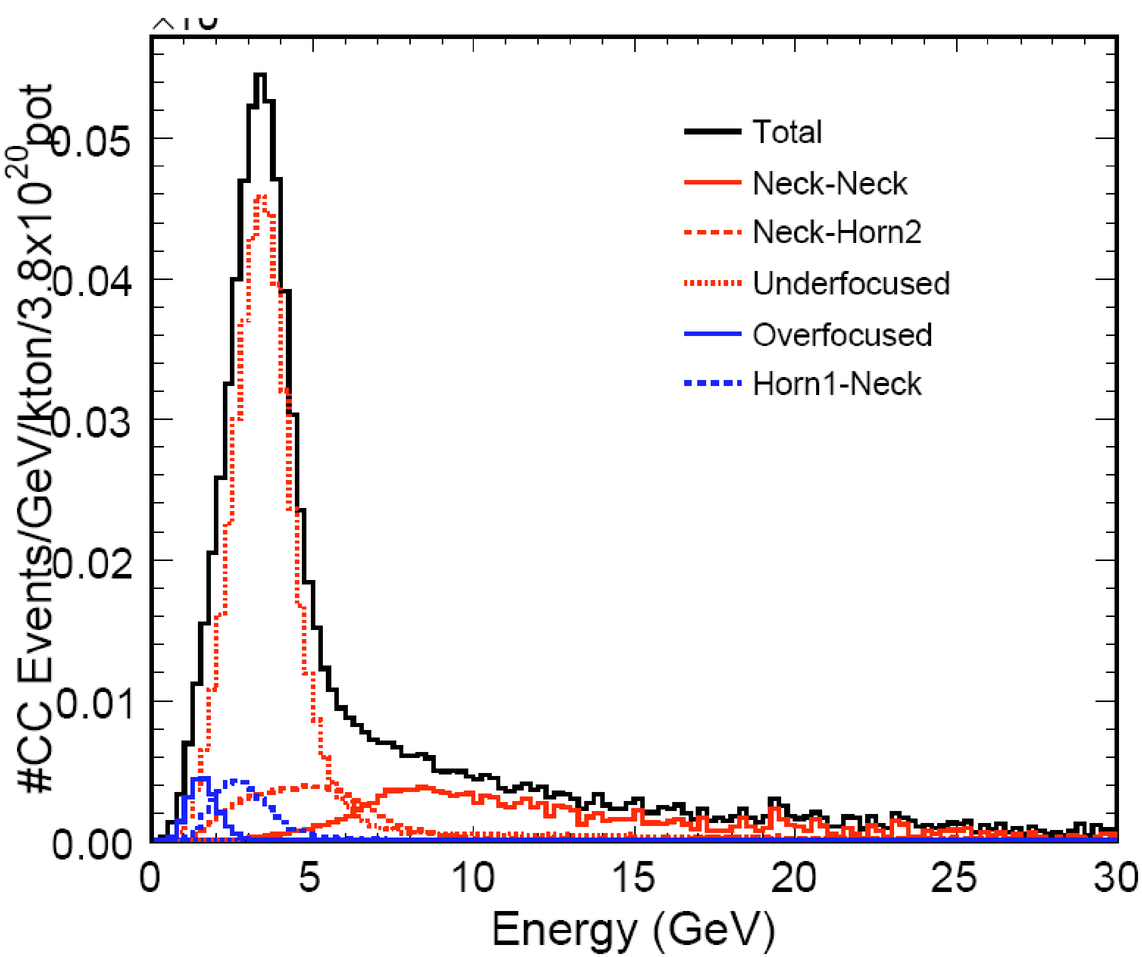
- Select events using kNN variable: fraction of true Monte-Carlo muon muon tracks that are similar to this track
- NC background is <0.6% ± 0.3% (data driven estimate)
- Energy threshold is ~0.5 GeV or ~24 cm of steel

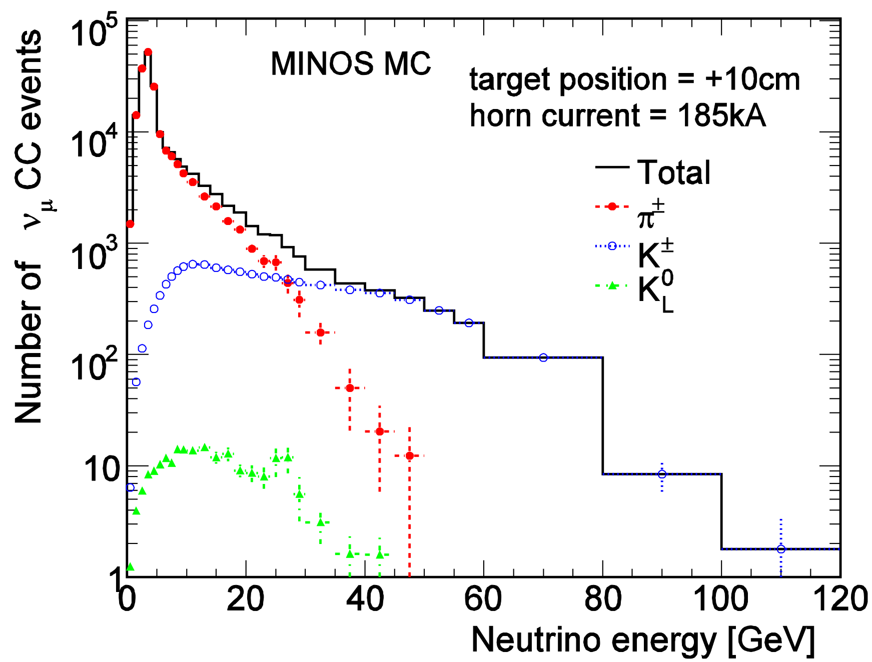




NuMI Flux prediction

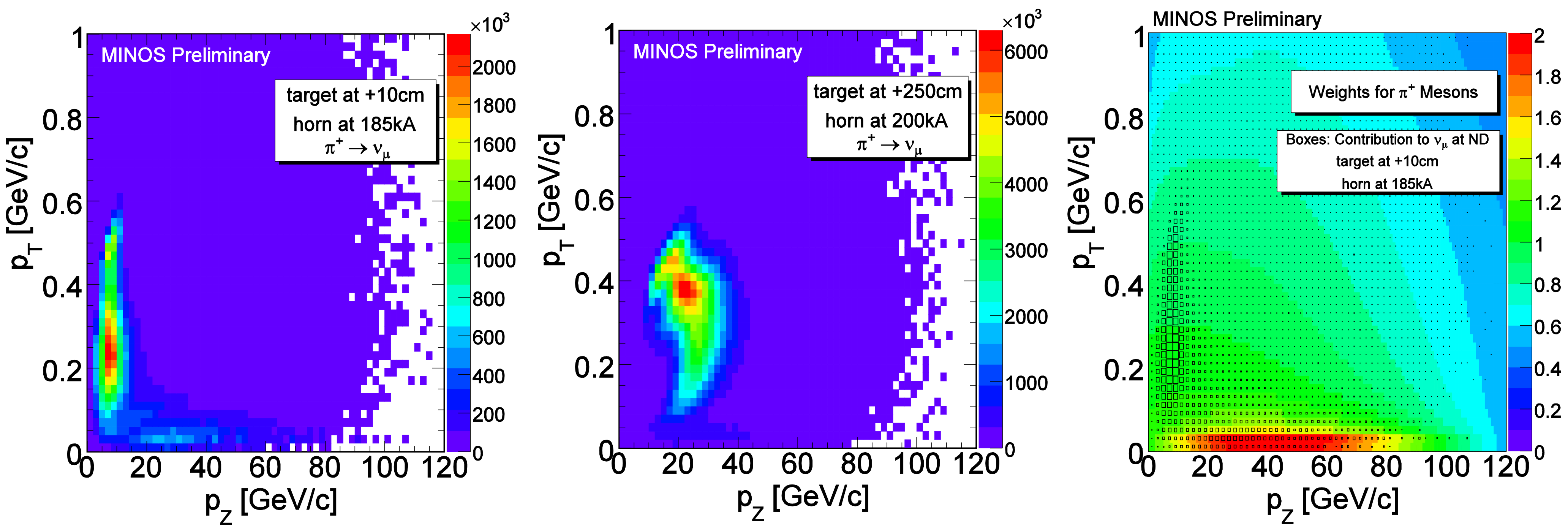
- Fluka05 simulation of 120GeV protons hitting graphite target
- Geant3 propagates secondary pions and kaons through magnetic horns, target assembly elements and decay pipe





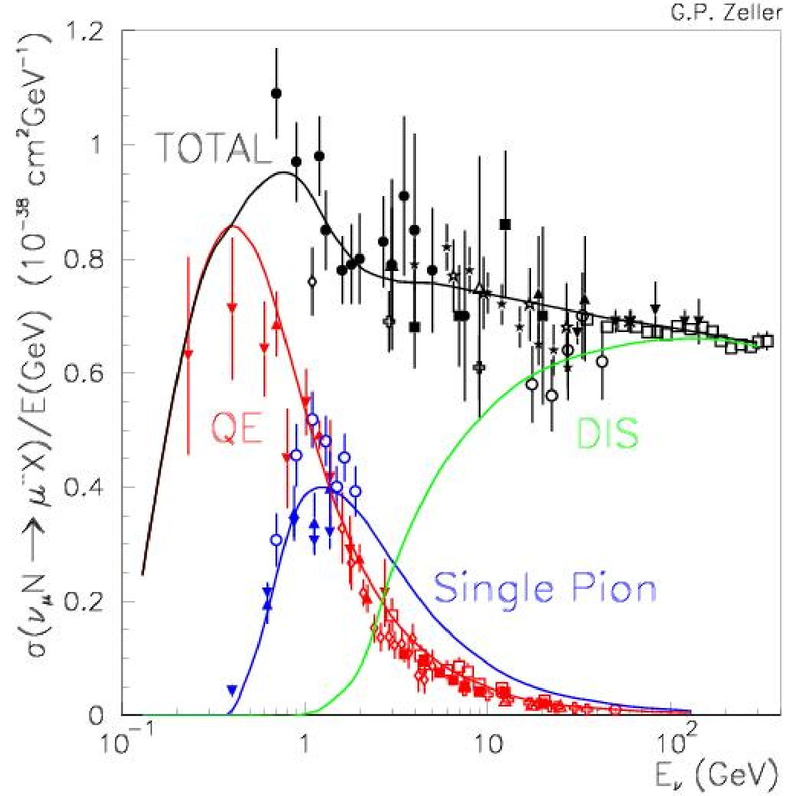
NuMI Flux prediction

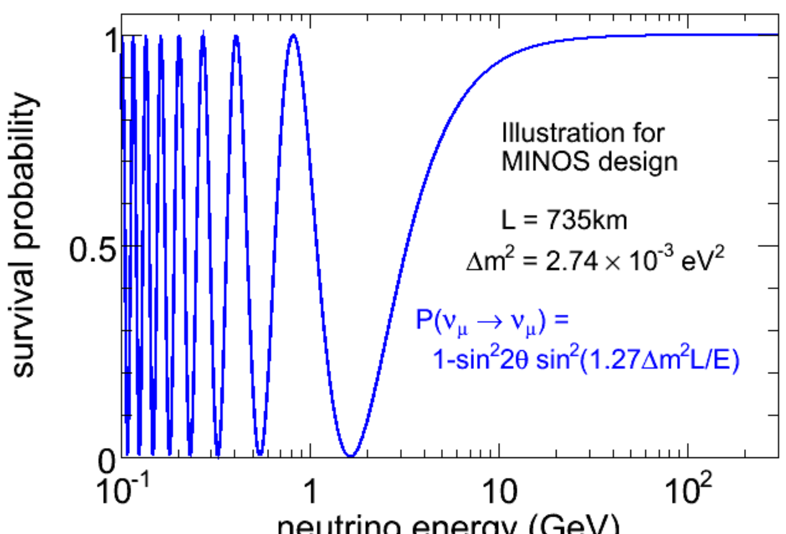
- Distribution of pions's p_t and p_z momentum off the target
- Flux fit change weights in p_t-p_z plane for pions and kaons
- Multiple beam configuration have sensitivity to different regions of p_t-p_z space



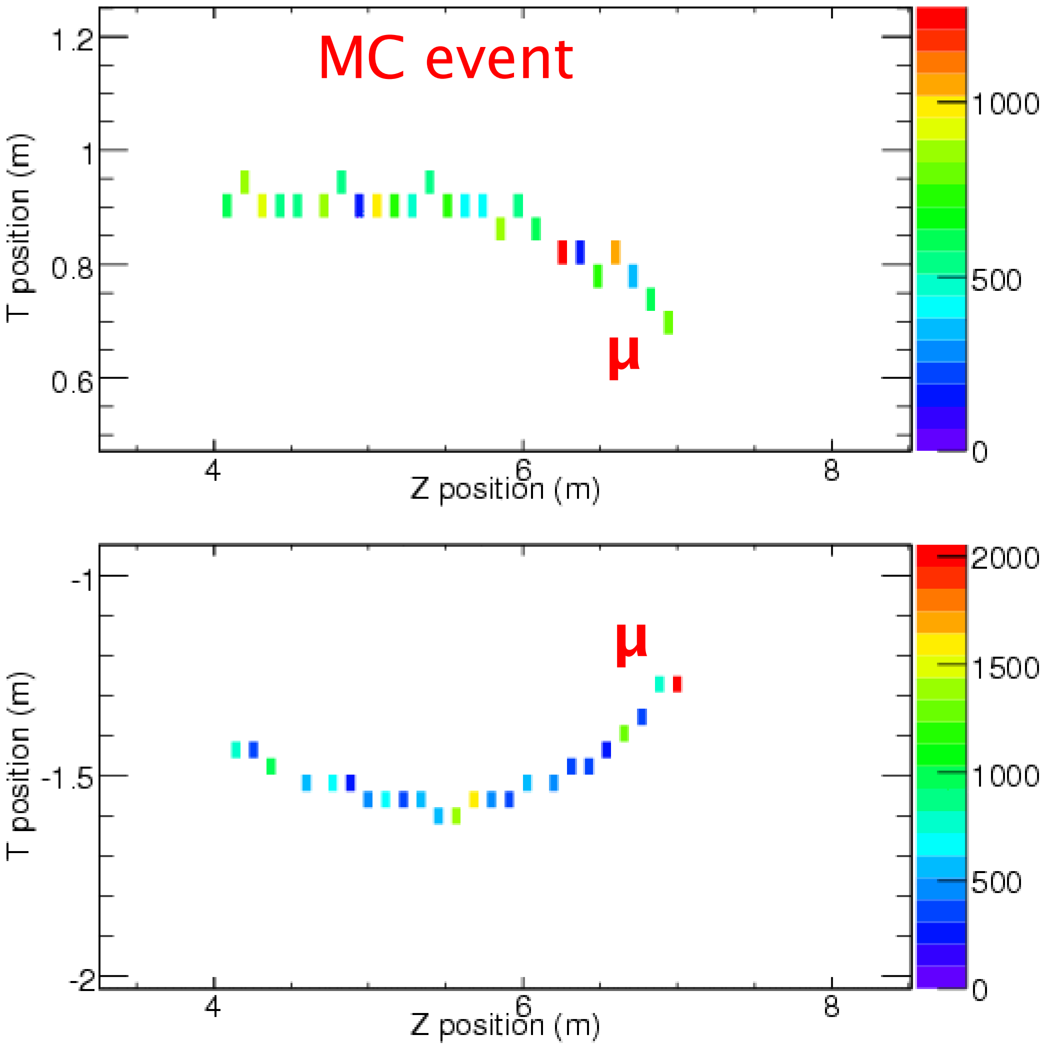
Neutrino CC cross-sections

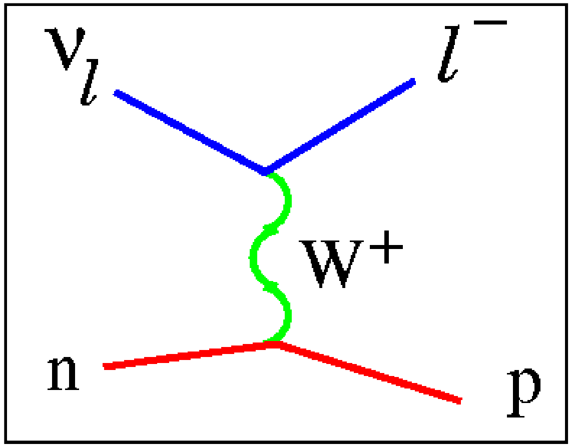
- Cross-section and hadronization models are tuned to world ν data
- 3 types of charged current ν_μ interactions:
  - Quasi-elastic scattering: target proton stays intact
  - Single pion production: production of delta resonance that decay to single pion
  - Deep inelastic scattering: multiple hadronic final states, generates hadronic shower





Quasi-elastic scattering

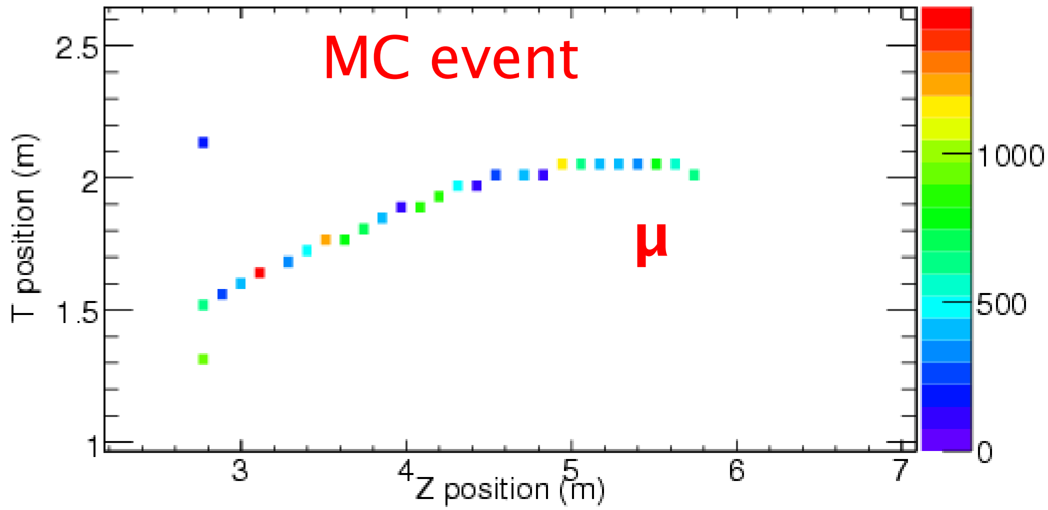


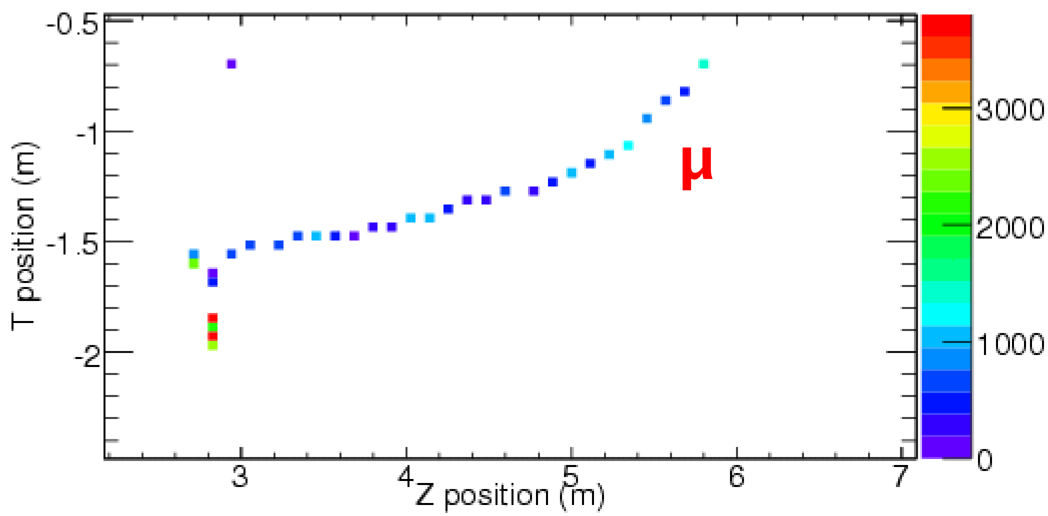


- Apply cut on shower energy: Ehad < 150Mev
- MINOS steel is 2.54cm thick
- Most protons range out in steel
- Use muon momentum and angle to reconstruct neutrino energy

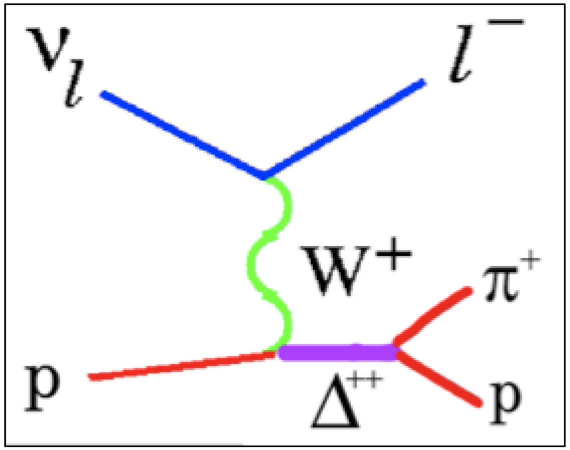
$$E_{QES} = \frac{(M_p - E_{bin})E_\mu + \frac{1}{2}(M_p^2 - (M_p - E_{bin})^2 - m_\mu^2)}{M_p - E_{bin} - E_\mu + P_\mu cos\theta_\mu}$$

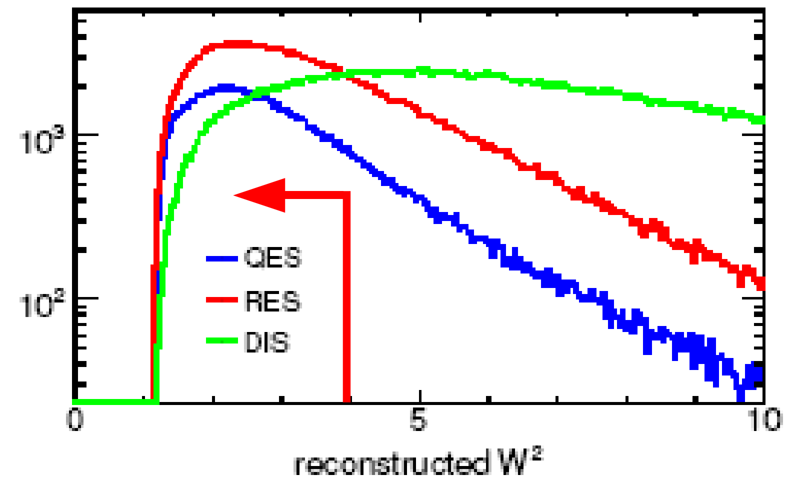
Resonance production





$$E_\nu = E_\mu + E_{had}$$

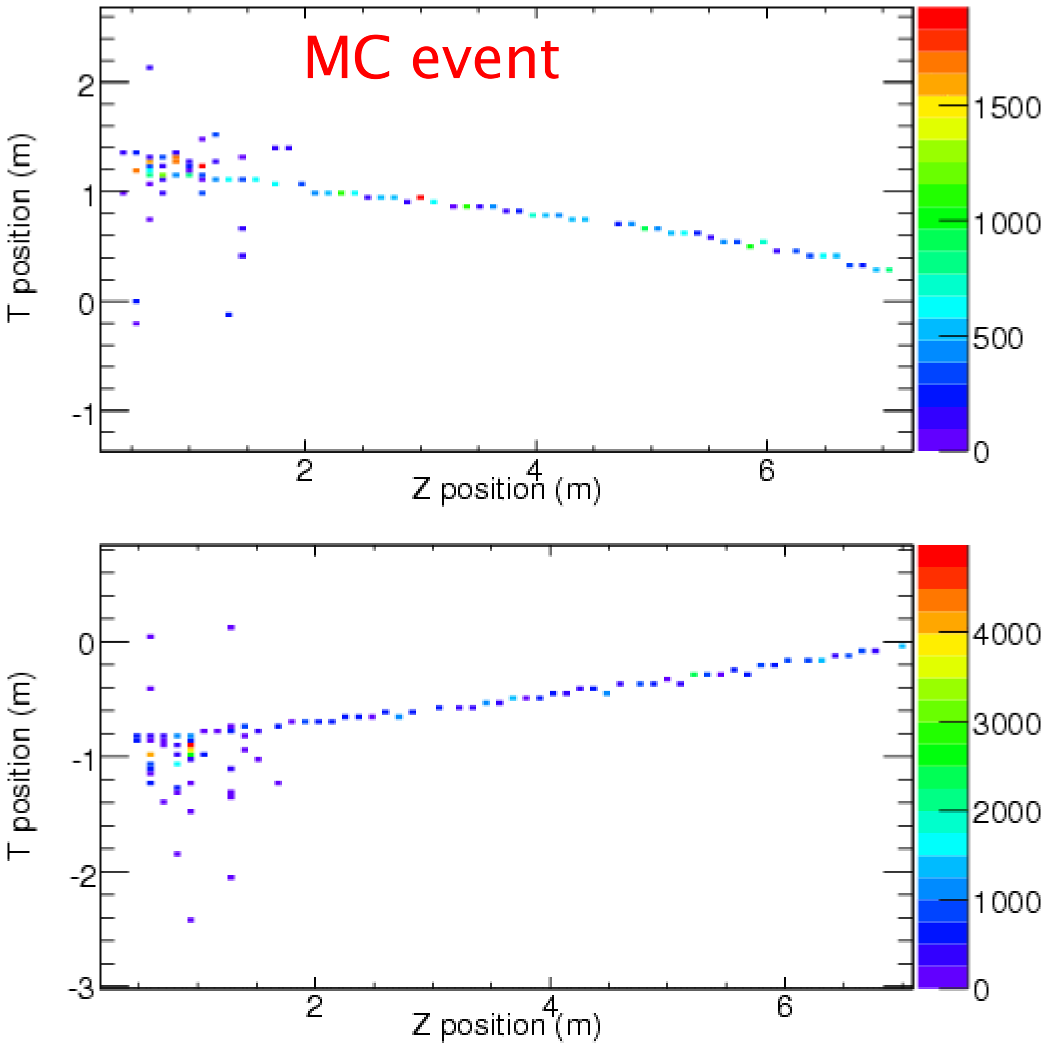




$$Q^2 = 2E_\nu E_\mu(1 - cos\theta_\mu)$$

$$W^2 = M_p^2 + 2M_p E_{had} + Q^2$$

Deep inelastic scattering

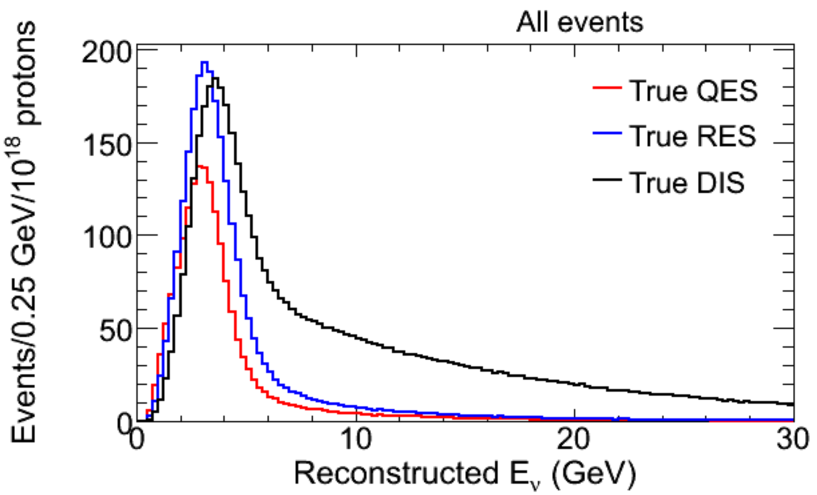


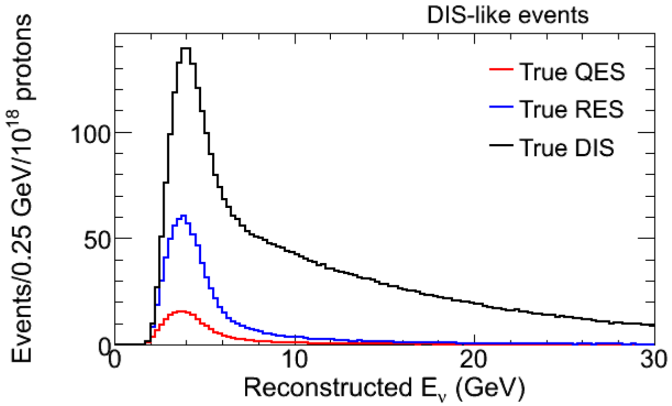
- All other events are classified as DIS: typically have substantial showers
- Tune MINOS Monte-Carlo to the world's data
- Tune single particle response Monte-Carlo to the calibration detector data in CERN test beam facility

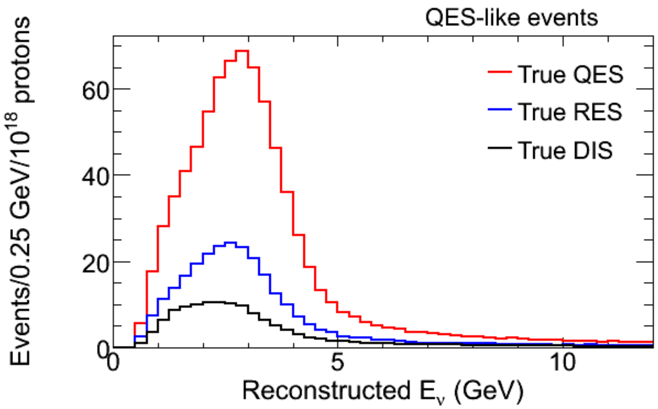
$$E_\nu = E_\mu + E_{had}$$

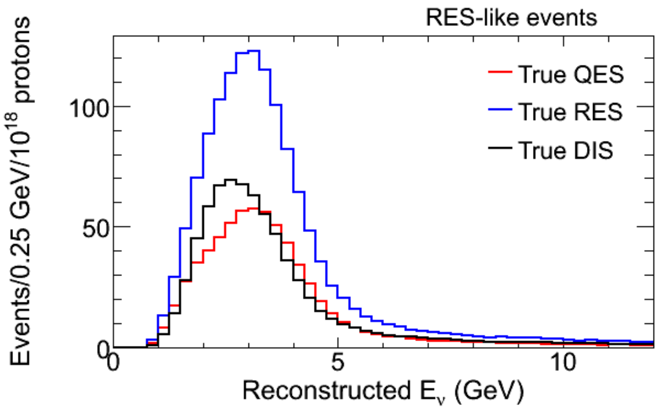
Monte-Carlo tuning

- Use near detector data to tune
  - Flux parametrization
  - QES and RES normalization
  - QES, RES and DIS energy scales
- 9 beam configurations
- 3 spectra enriched with QES, RES and DIS events
- Basic modelling of the detector is not changed by tuning

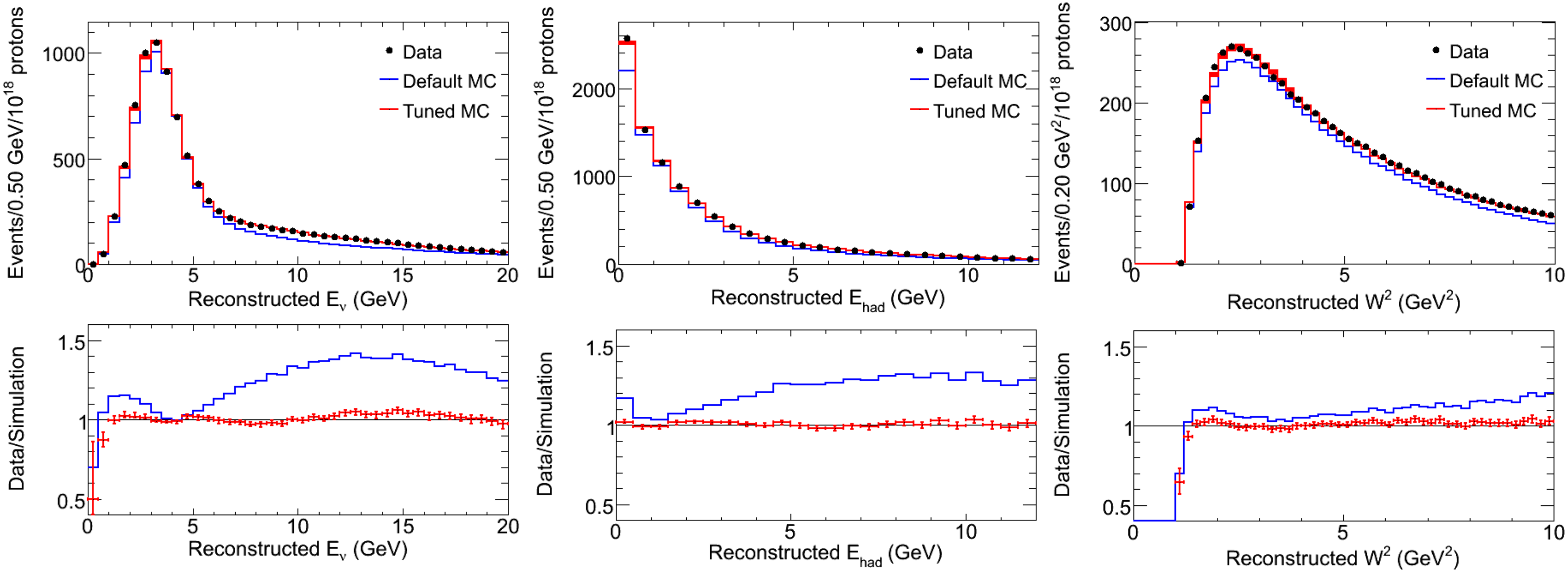






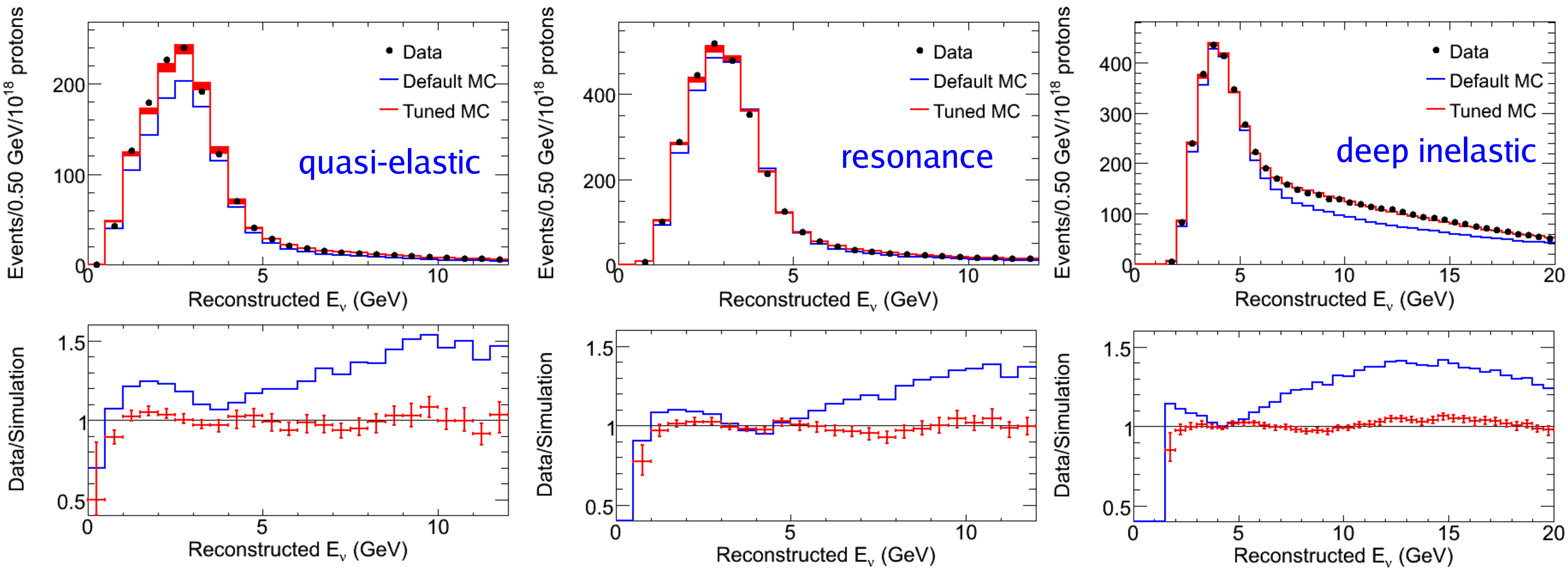


Low energy beam events



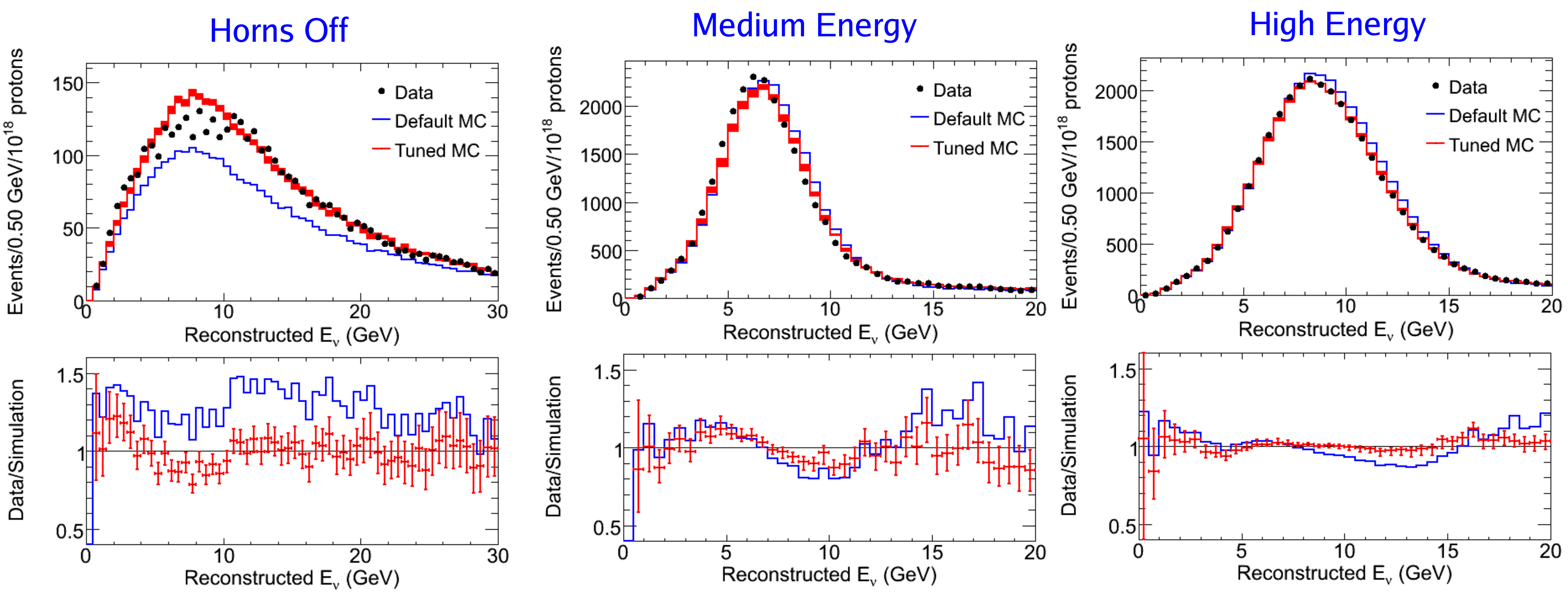
- Energy spectrum, hadronic energy and invariant mass squared agree well after tuning procedure
- Tuned MC errors include statistical errors and variation in fit parameters from selection uncertainty

Spectra for low energy beam



- Energy spectra for QE, Resonance and DIS events from Low Energy beam configuration
- Tuning changes spectrum of secondary pions and kaons: improves data and MC agreement for energy greater than 4GeV
- QES and RES normalization improves agreement below 4GeV

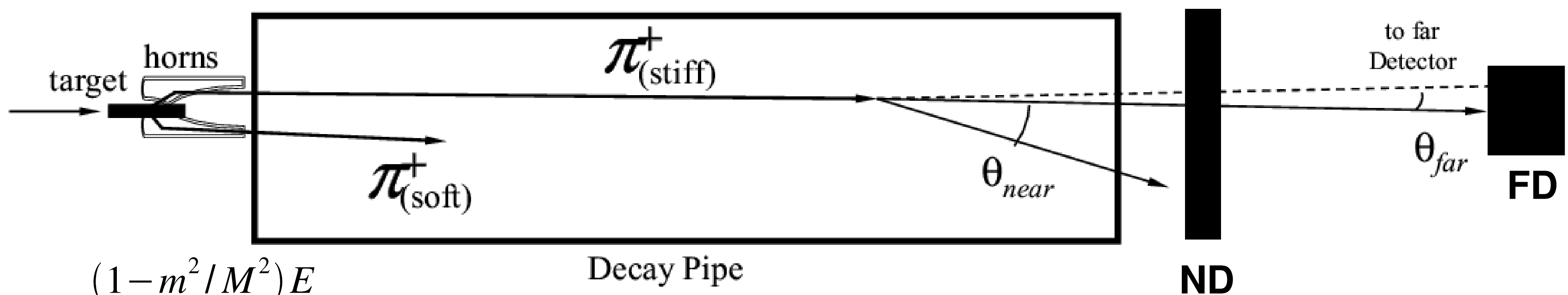
Different beam configurations



- Horns Off, Medium Energy and High Energy beams
- See horn focusing effect: number of interactions in Horns Off beam is signficantly less than in beams where secondary pions are focused forward by horns
- Default MC sees deficit of forward pions

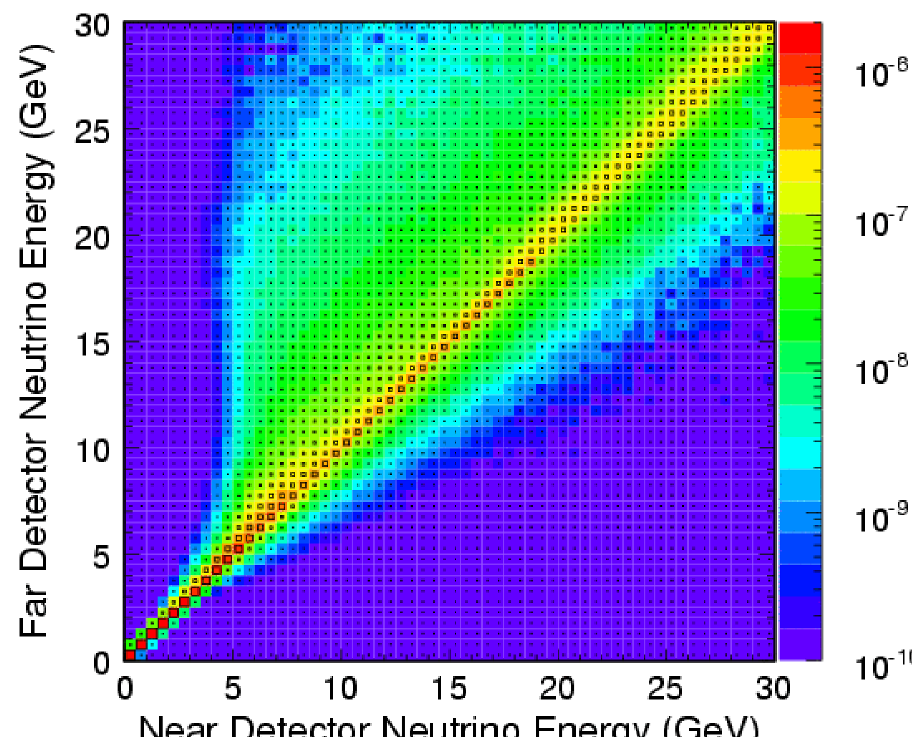
Near to far extrapollation

Rely on relativistic kinematics of pion and kaon decays
to project near detector observed spectra to far detector



$$E_\nu = \frac{(1 - m_\mu^2/M^2)E}{1 + \gamma^2 \tan^2 \theta_\nu^2}$$

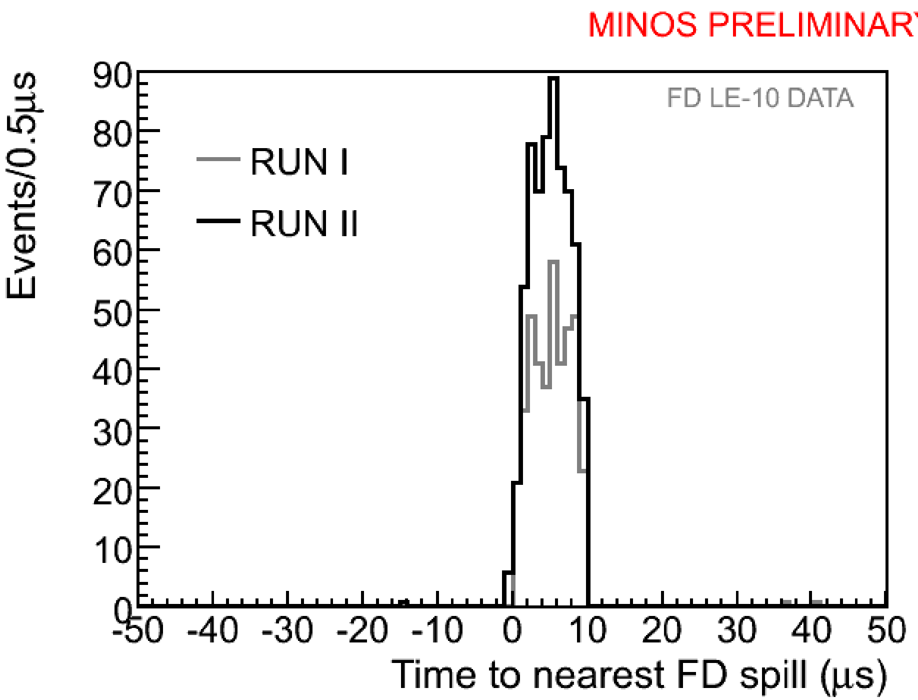
- Use near detector data to extrapolate near spectra to far detector
- MC provides acceptance, purity and energy smearing corrections
- Using near detector data reduces systematic errors from flux and cross-section uncertainties

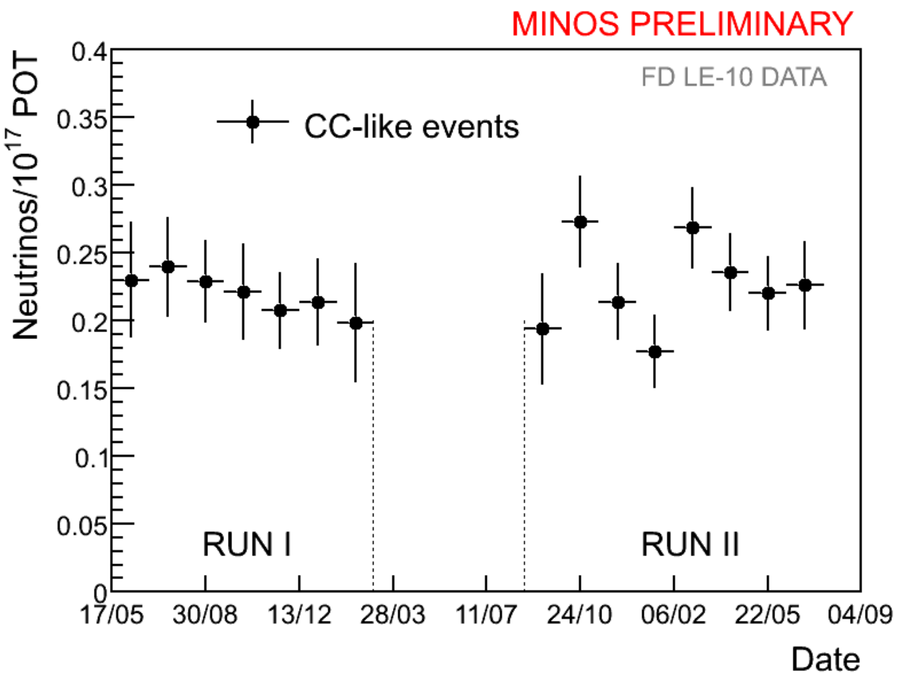


Far detector trigger

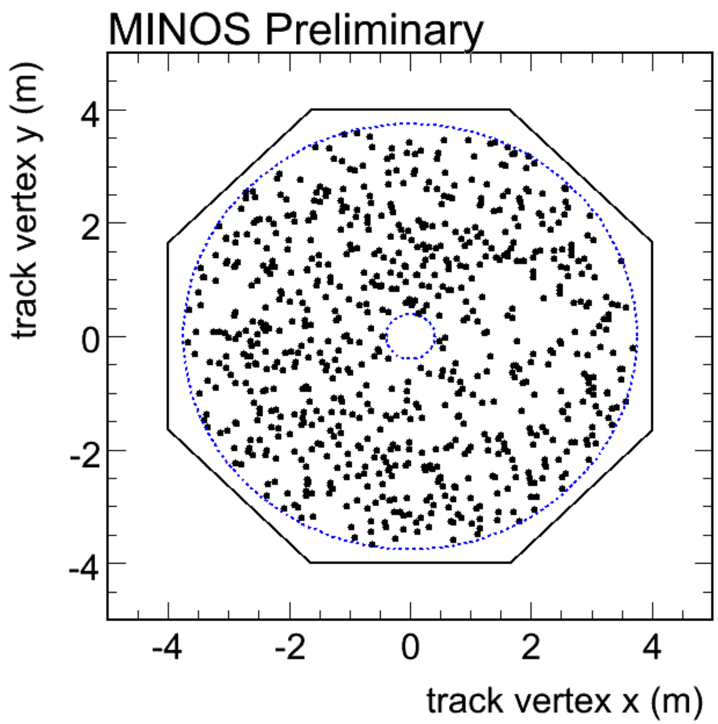
- Sync clocks at the near and far detector with GPS receivers
- Send to far detector GPS time of the incoming beam spill
- Use energy trigger when near-to-far communication fails
- Use "fake" triggers to study cosmic backgrounds:

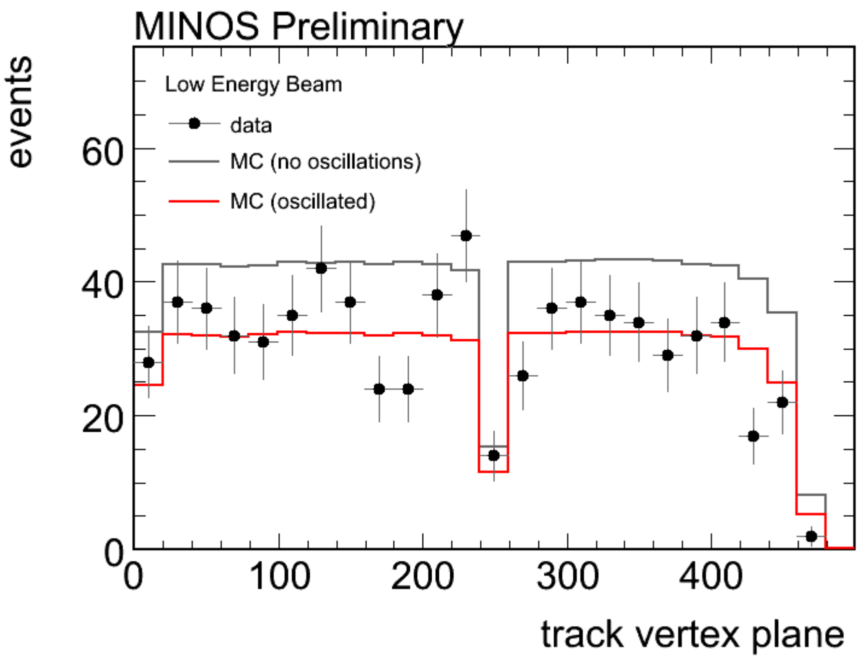
  $\sim 10^6$ background suppression

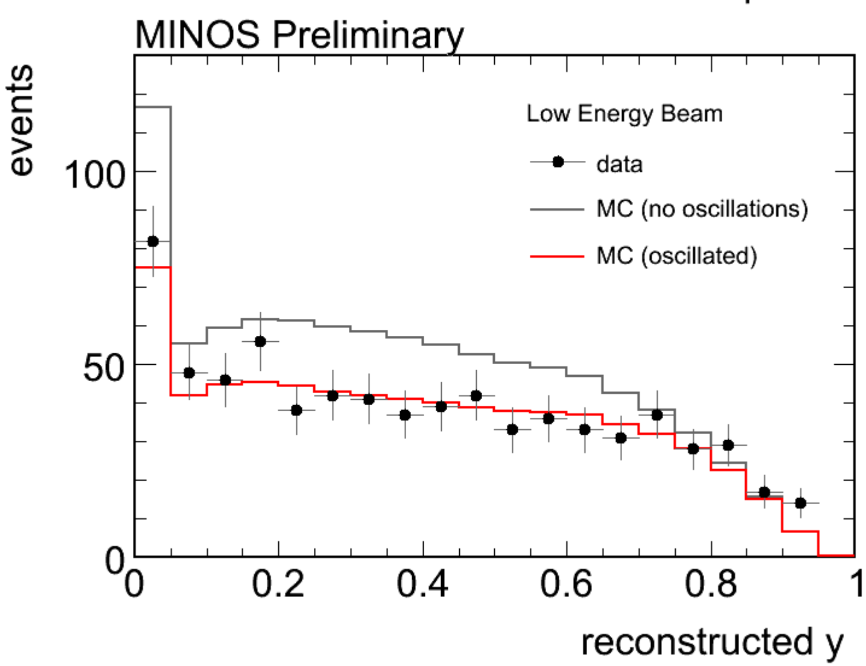




Far detector data quality

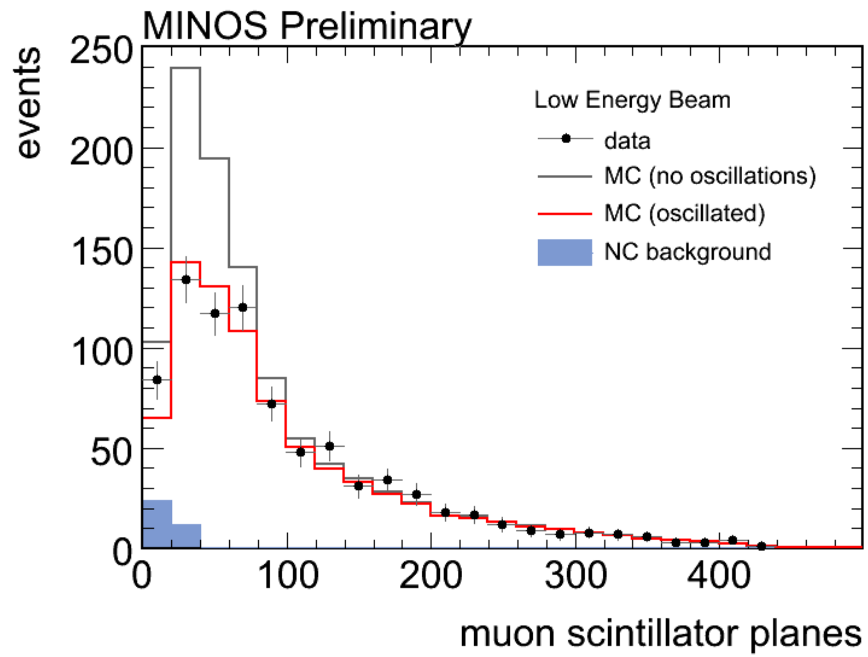


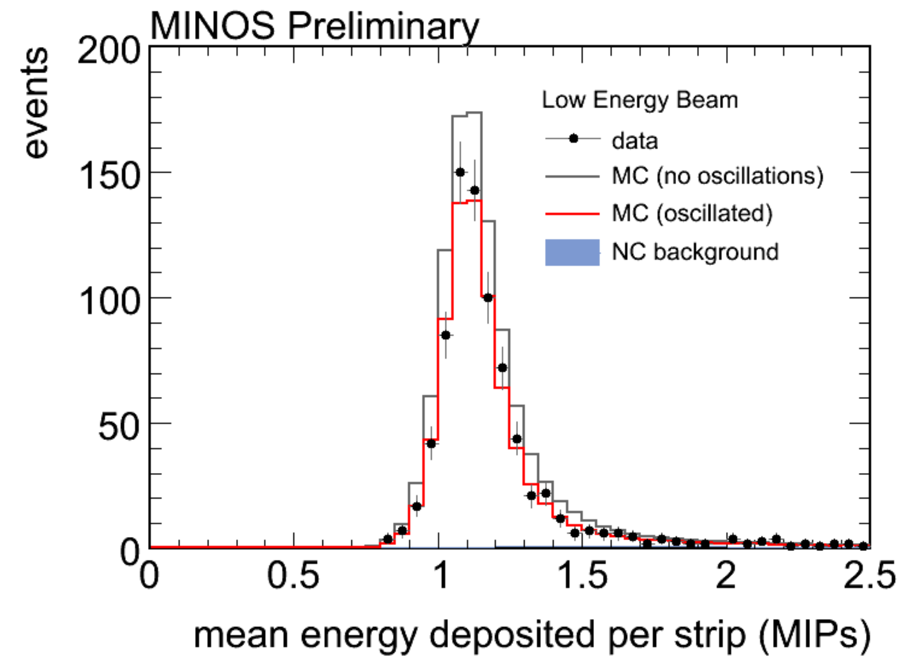


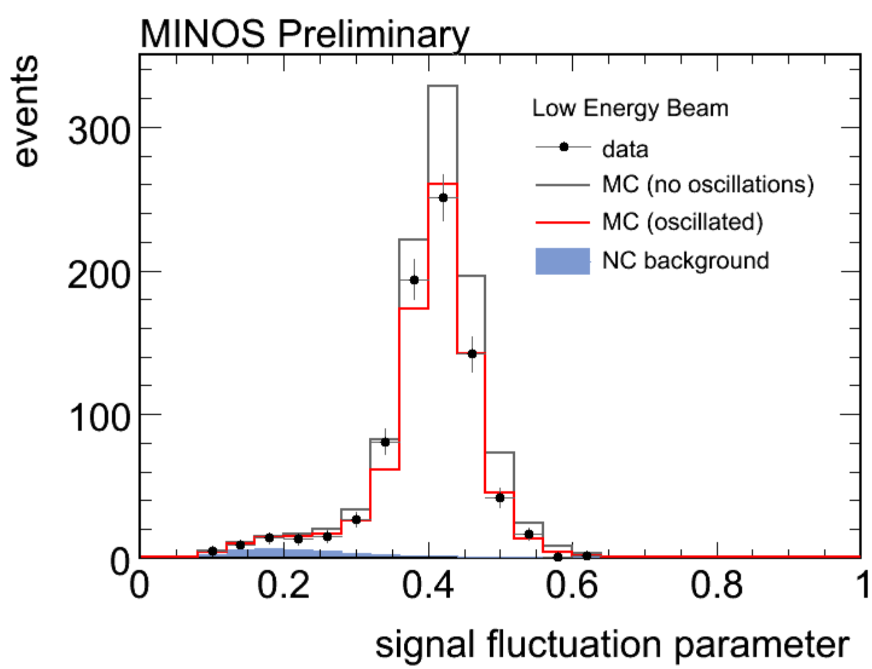


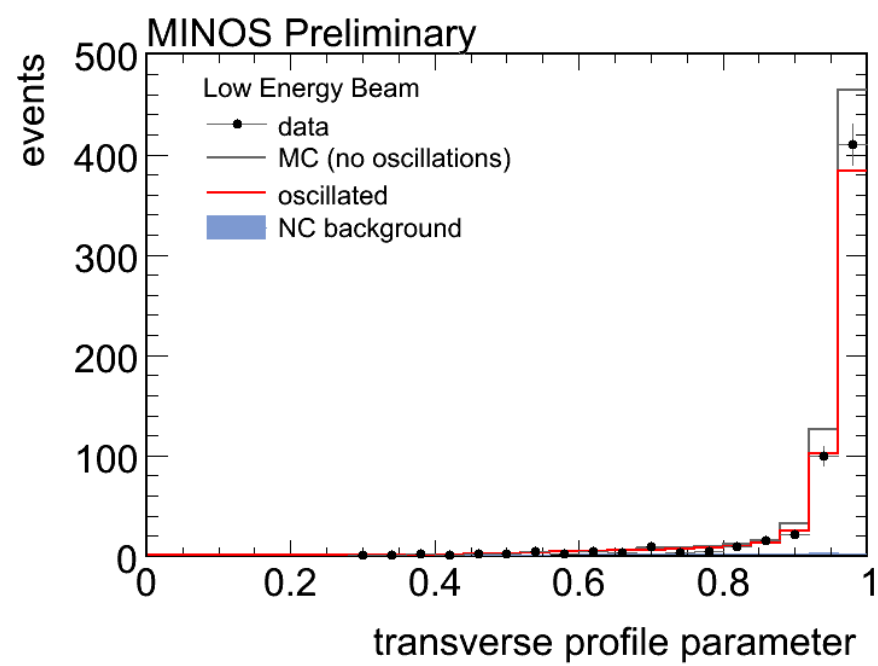
- Follow number of steps to check data quality gradually revealing more information about data
- If no problems observed in data then proceed to oscillation analysis

Far detector event selection

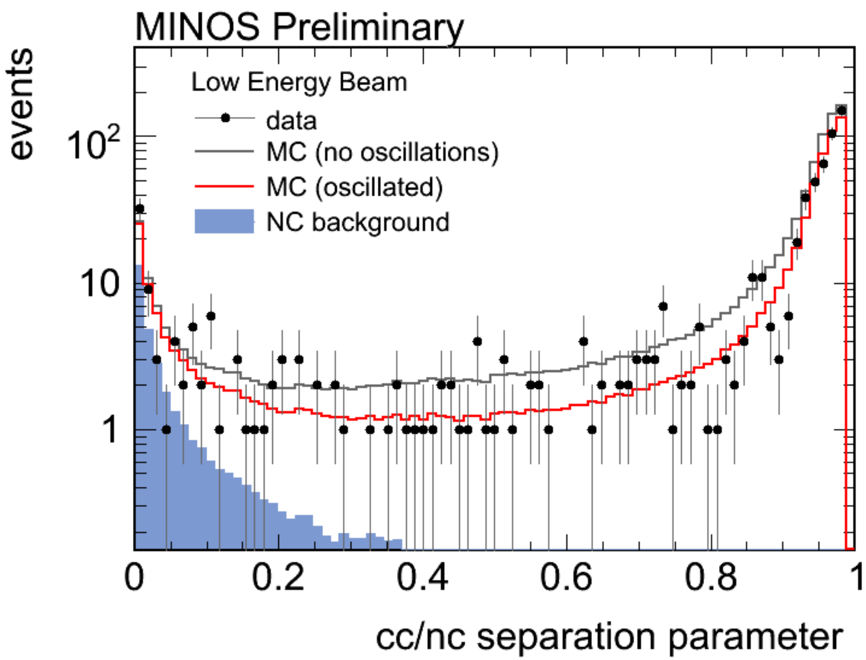




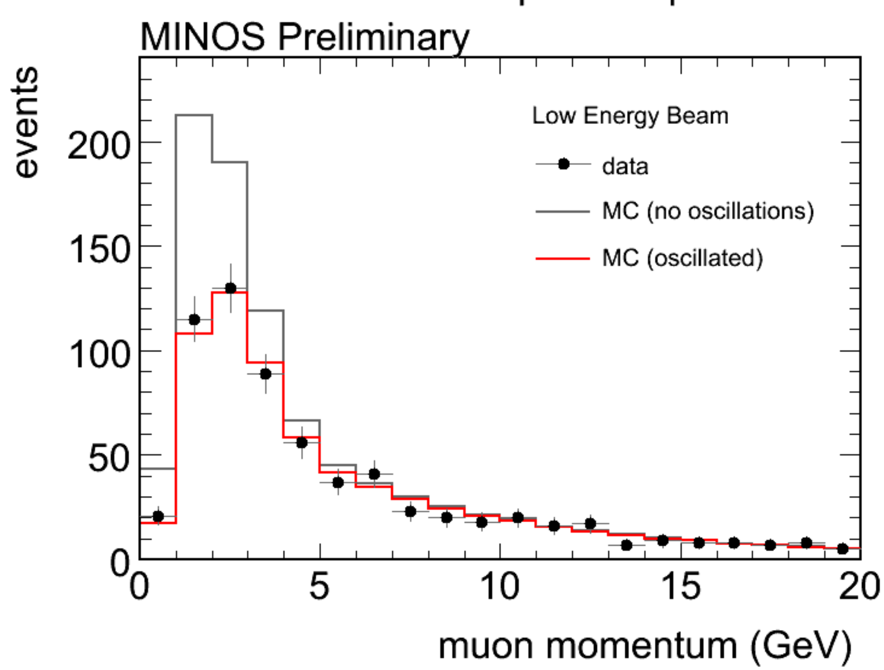


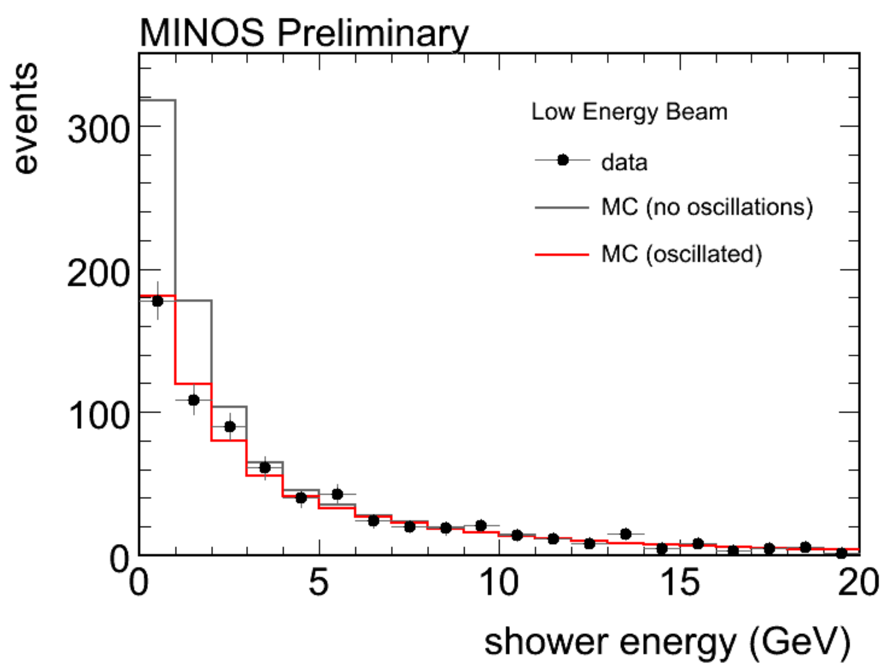


Far detector event selection

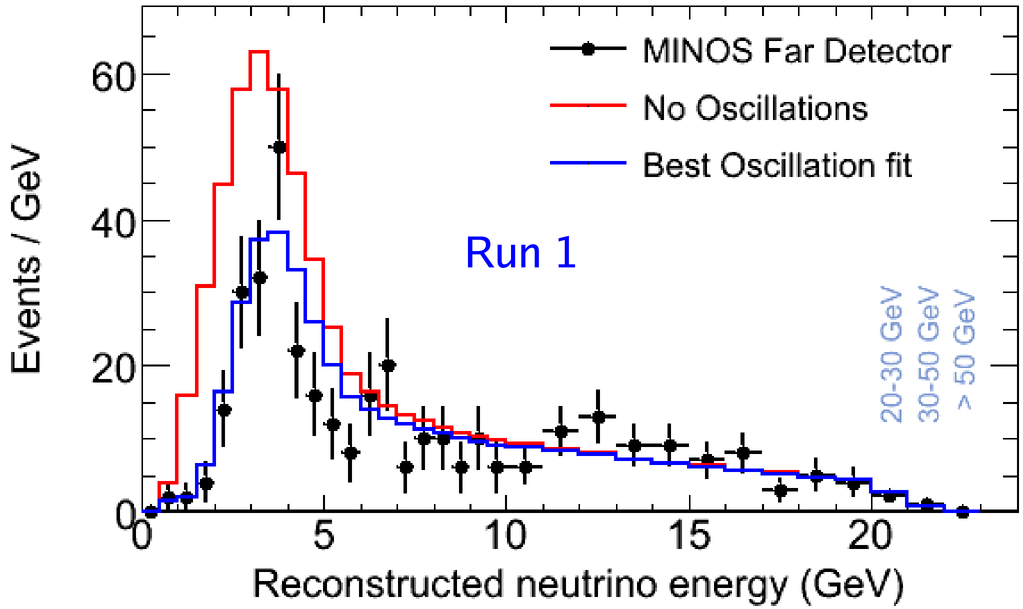


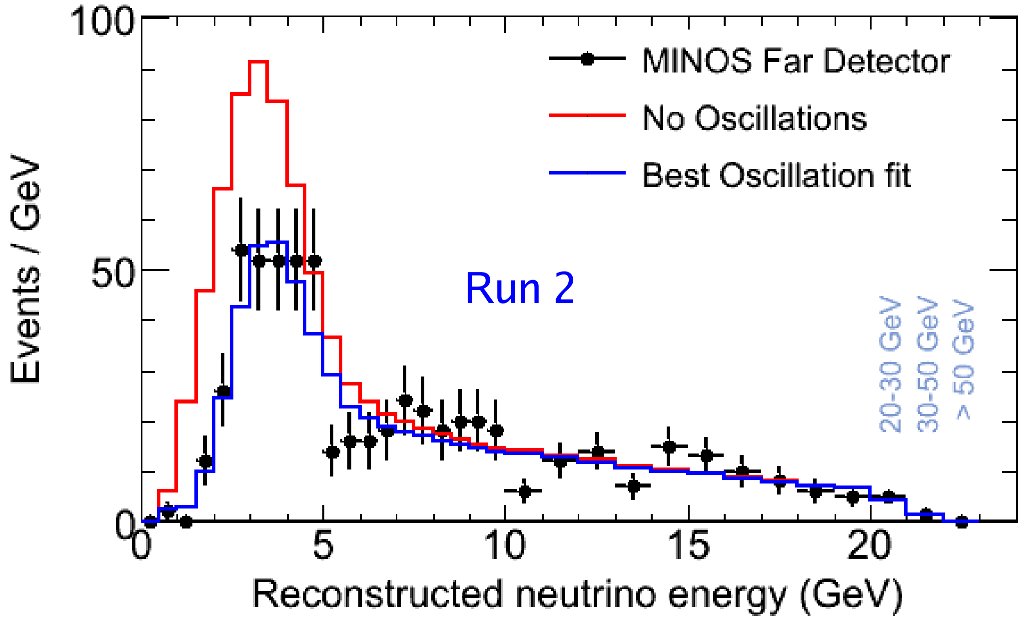
- Good agreement for event selection variables
- Good agreement is also seen in reconstructed quantities.
  - Numbers of tracks/showers
  - Track energies
  - Shower energies
  - Kinematic distributions





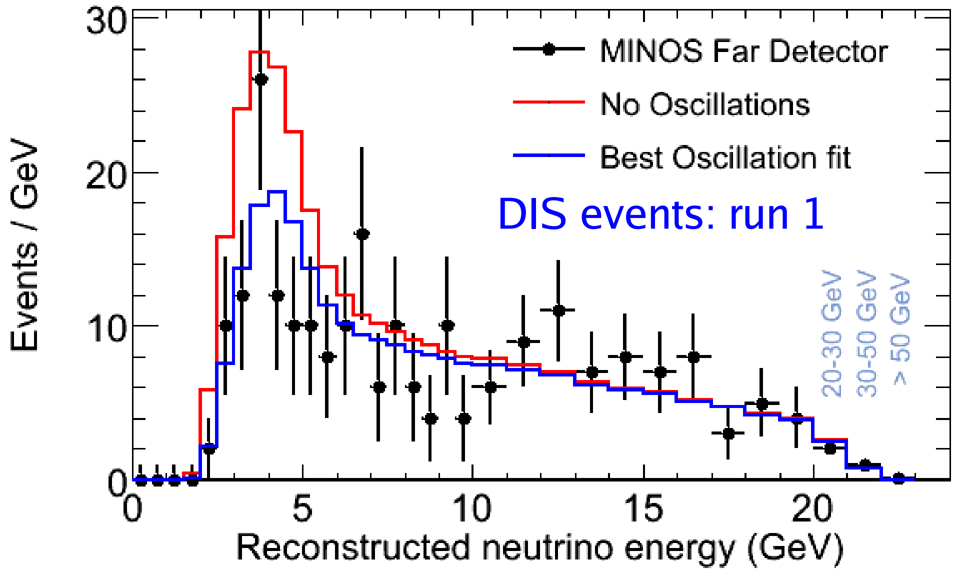
Far detector energy spectra

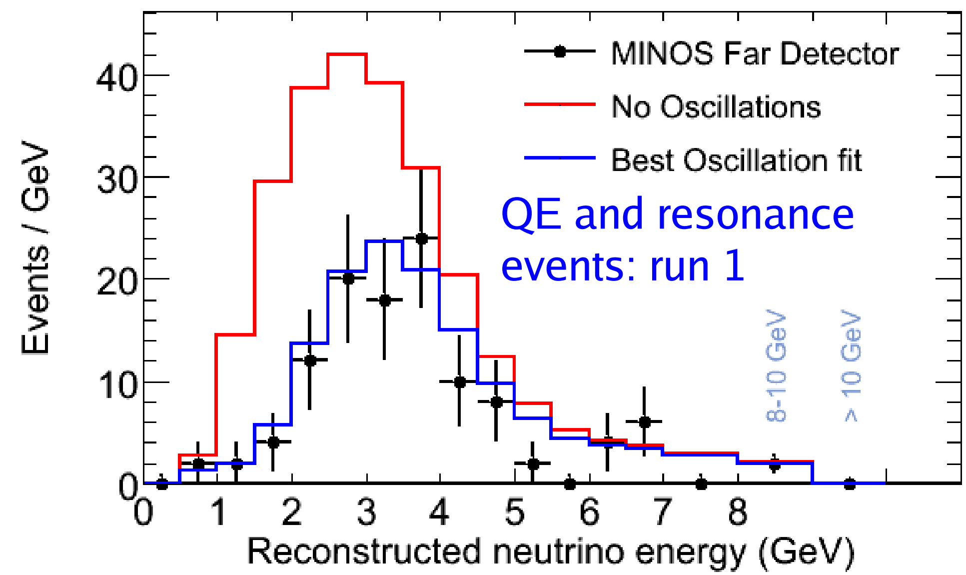


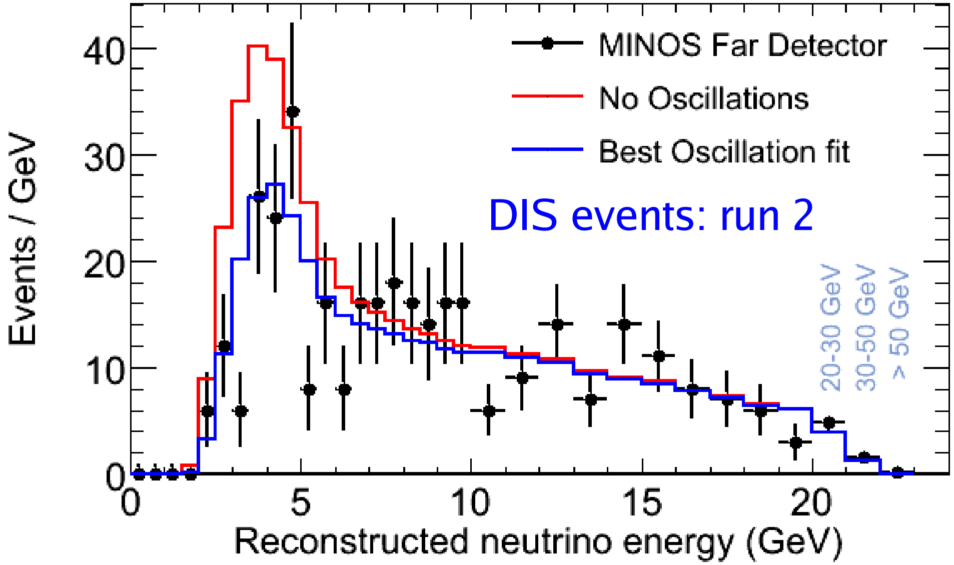


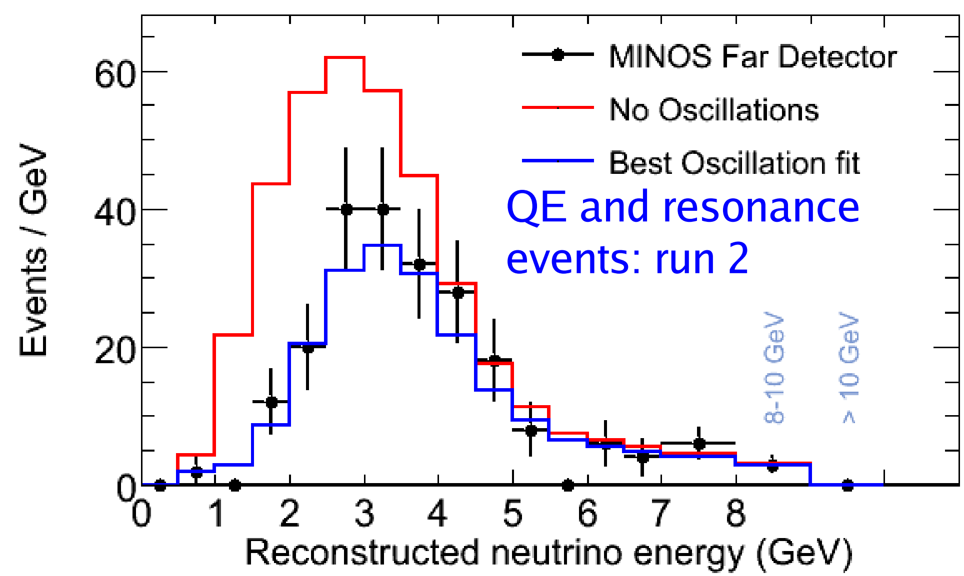
- All selected CC events for run 1 and run 2 data
- Deficit of data events compared to no oscillations hypothesis
- Expected 910 events
- Observed 702 events

Far detector energy spectra (2)

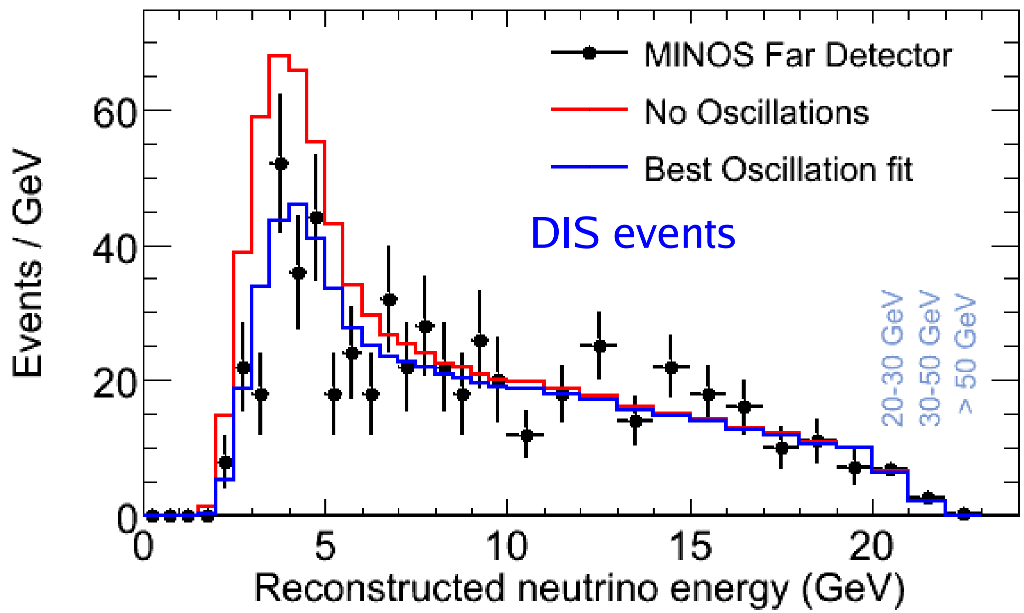


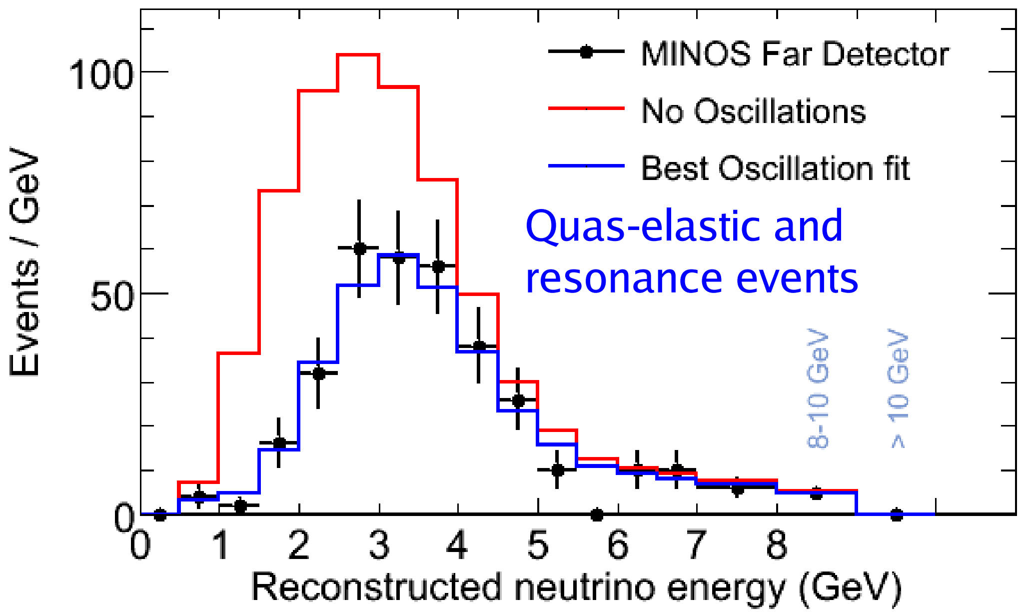






Far detector oscillation fit

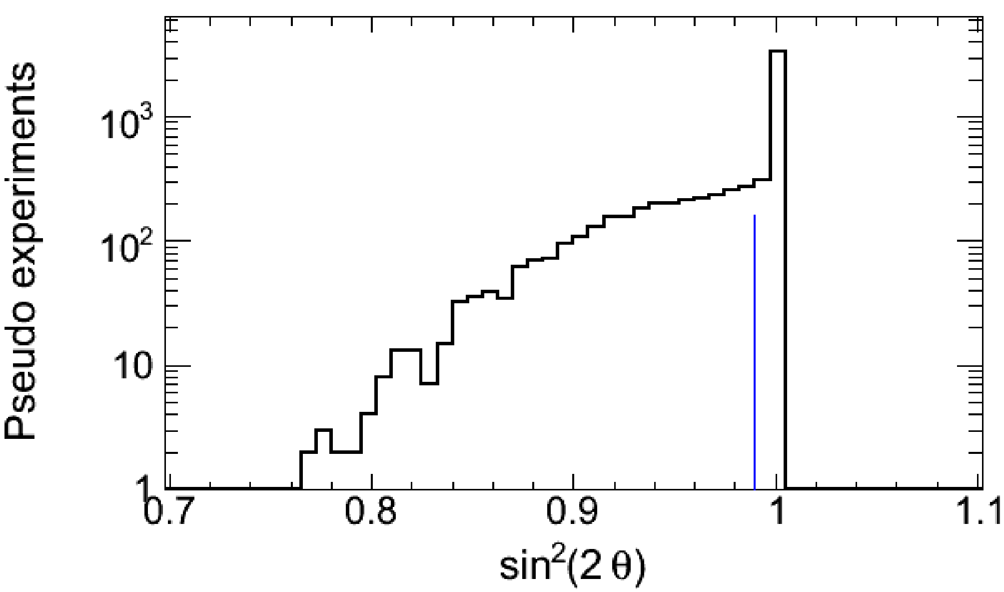


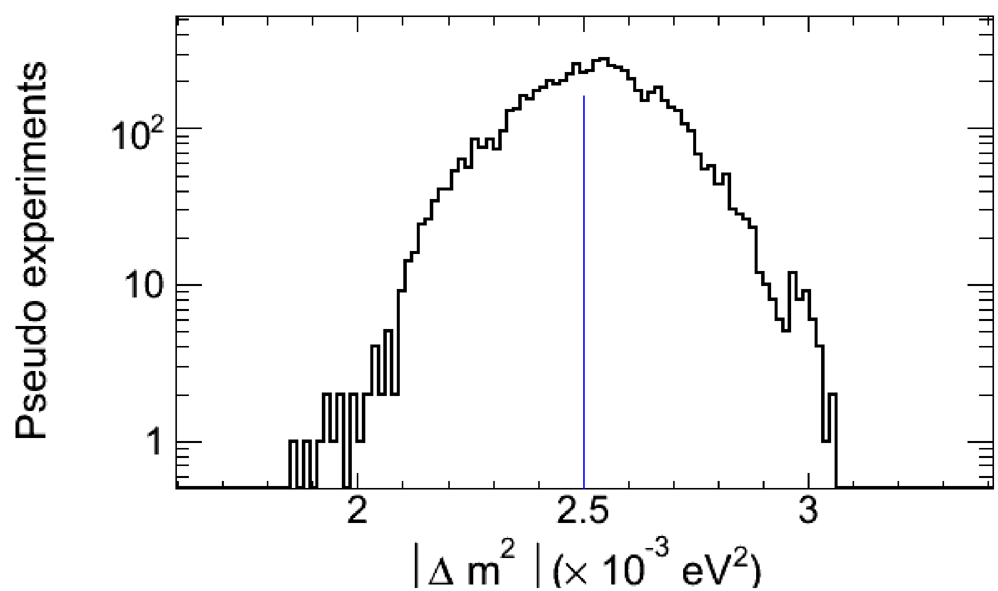


- Separate events for run 1 and 2:
  - DIS
  - QE and Resonance
- Fit total 4 histograms
- Two flavours neutrino oscillation hypothesis describes data very well

Extrapolation error

- Generate 9 additional sets of the near detector fits by varying selection cuts
- For default and 9 additional sets create 600 pseudo experiments
- Fit 6000 pseudo-experiments for two oscillation parameters

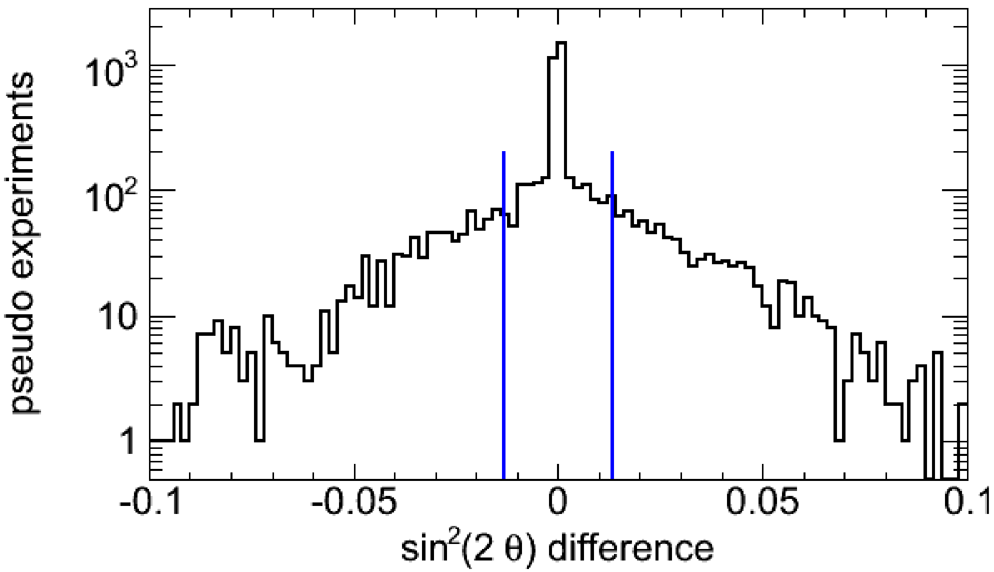




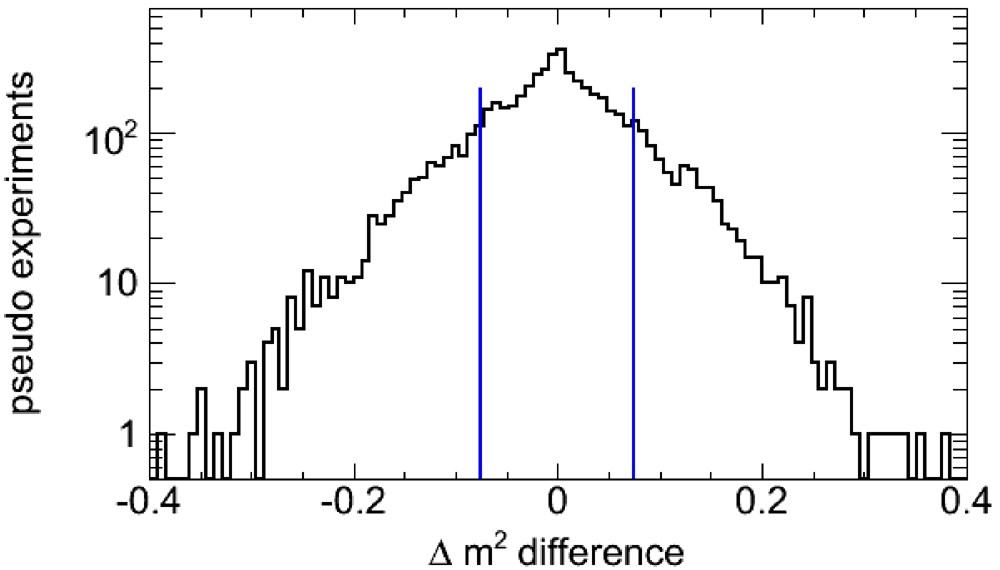
Extrapolation error

- For each statistically independent pseudo experiment compute difference between best fit oscillation parameter from the default extrapolation and each of the 9 additional sets
- Determine range that contains 68% of pseudo experiments

$$\sigma(\sin^2 2\theta) = 0.013$$



$$\sigma(\Delta m^2) = 0.075 \times 10^{-3}\, eV^2$$



Far detector systematic errors

- These are 6 largest sources of the systematic errors:
  - Absolute shower energy ±10.3%
  - Relative shower energy ±3.3%
  - Muon momentum from curvature ±3%
  - Muon momentum from range ±2%
  - Absolute event normalization ±4%
  - NC background ±50%
- Create 64 systematics sets by simultaneously varying all 6 systematic parameters by ± error
- For each set create 100 pseudo experiments

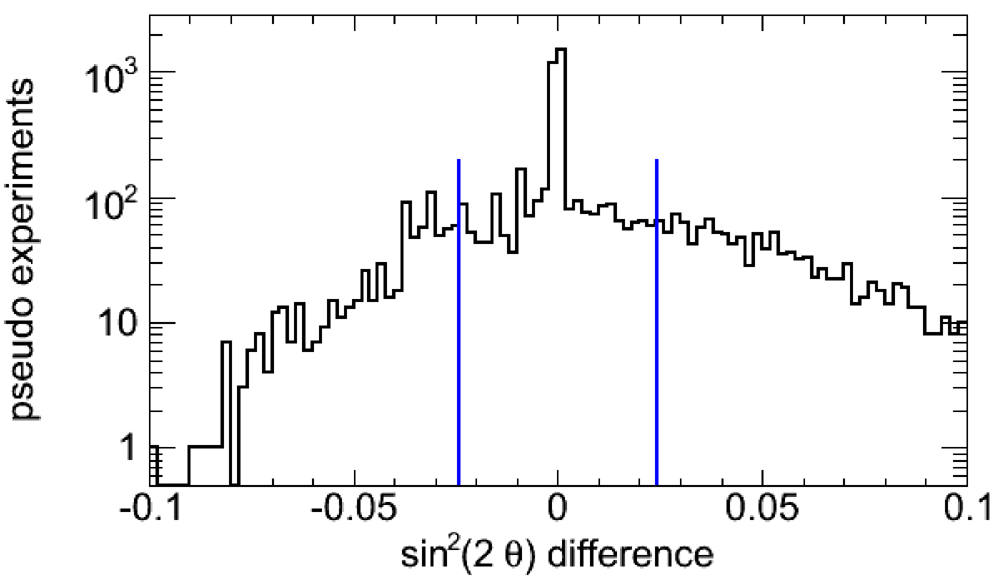
Far detector systematic errors

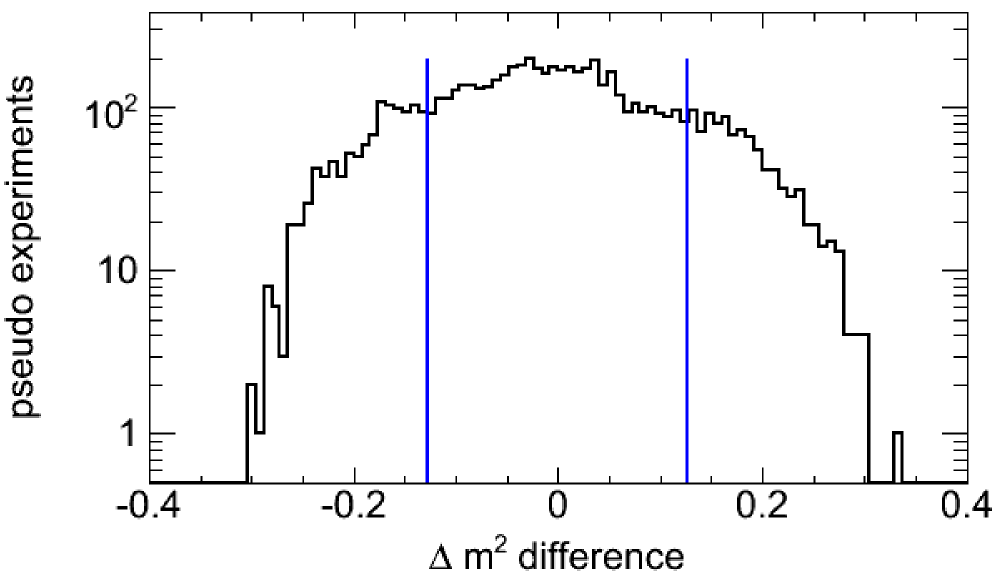
- For each of 64 systematics sets create 100 pseudo experiments
- Determine range that contains 68% of pseudo experiments
- Largest errors come from absolute hadronic energy scale uncertainty

and absolute event normalization uncertainty

$\sigma(\sin^2 2\theta) = 0.024$

$\sigma(\Delta m^2) = 0.13 \times 10^{-3}\, eV^2$



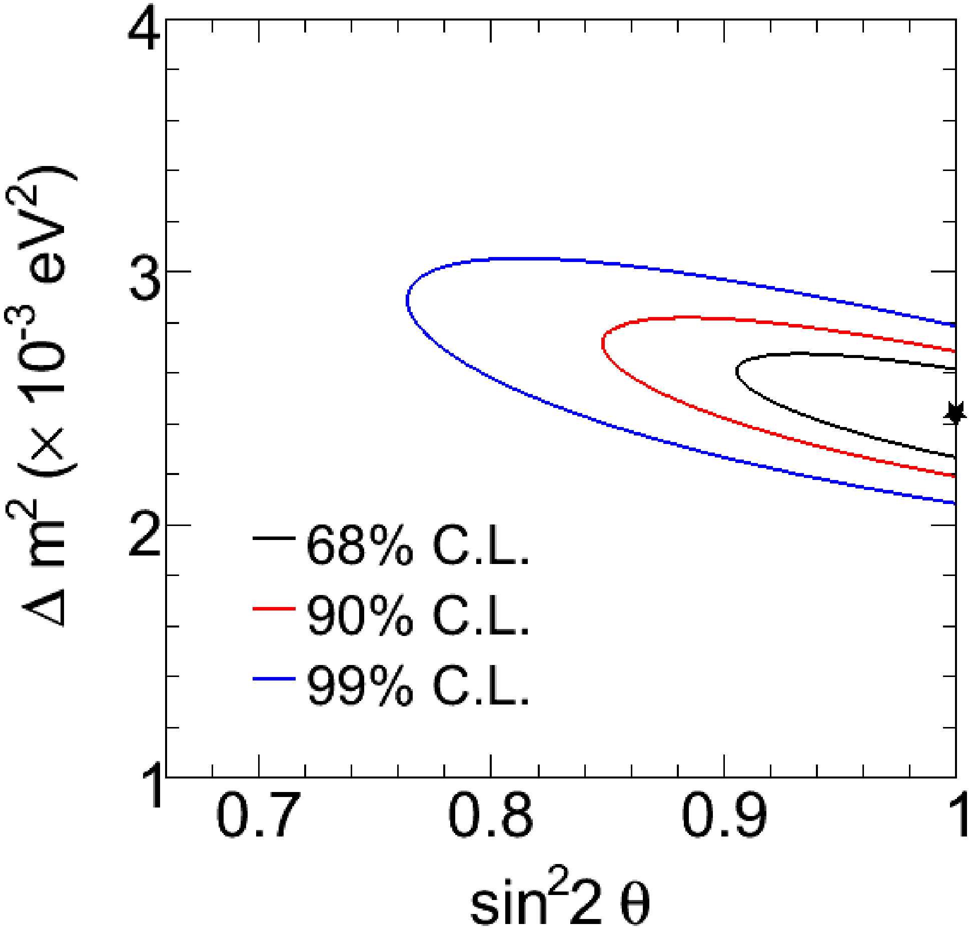


Far detector oscillation fit

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta \sin^2(1.27\,\Delta m^2 L/E)$$

$$\chi^2 = \sum 2(N_{\exp} - N_{obs}) - 2N_{obs}\ln(N_{obs}/N_{\exp})$$

- Fit data with 2 oscillation parameters
- Constrain to physical region
- Oscillation fit gives good description of data



$$|\Delta m^2_{atm}| = 2.44^{+0.12}_{-0.12}(\text{stat})^{+0.15}_{-0.15}(\text{syst}) \times 10^{-3}\, eV^2$$

$$\sin^2 2\theta = 1.000_{-0.038}(\text{stat})_{-0.028}(\text{syst})$$

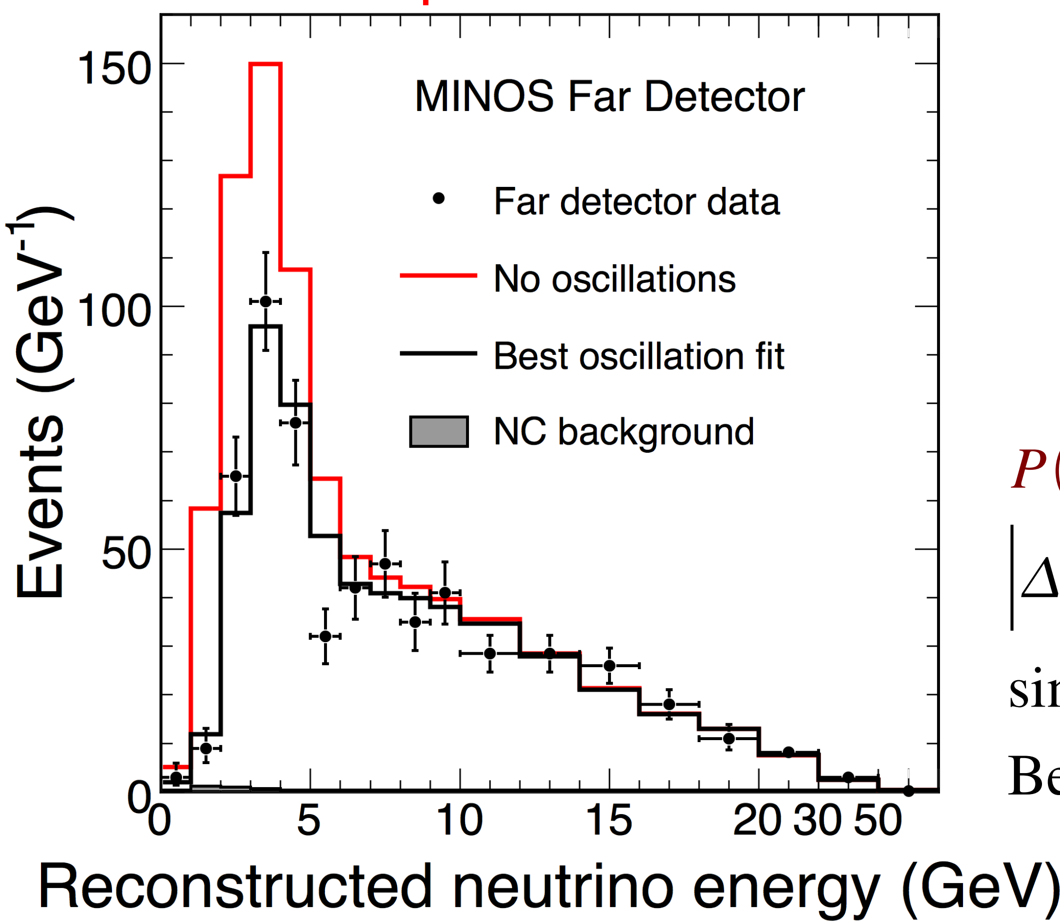
Best fit: $\chi^2/ndf = 86.5/92$

Null: $\chi^2/ndf = 239.9/92$

2008 CC result

$$\chi^2 = \sum 2(N_{exp} - N_{obs}) - 2N_{obs} \ln(N_{obs}/N_{exp})$$

arXiv:hep-ex/0806.2237



Including the three largest sources of systematic uncertainty as nuisance parameters:

- Absolute hadronic energy scale: 10.3%
- Normalization: 4%
- NC contamination: 50%

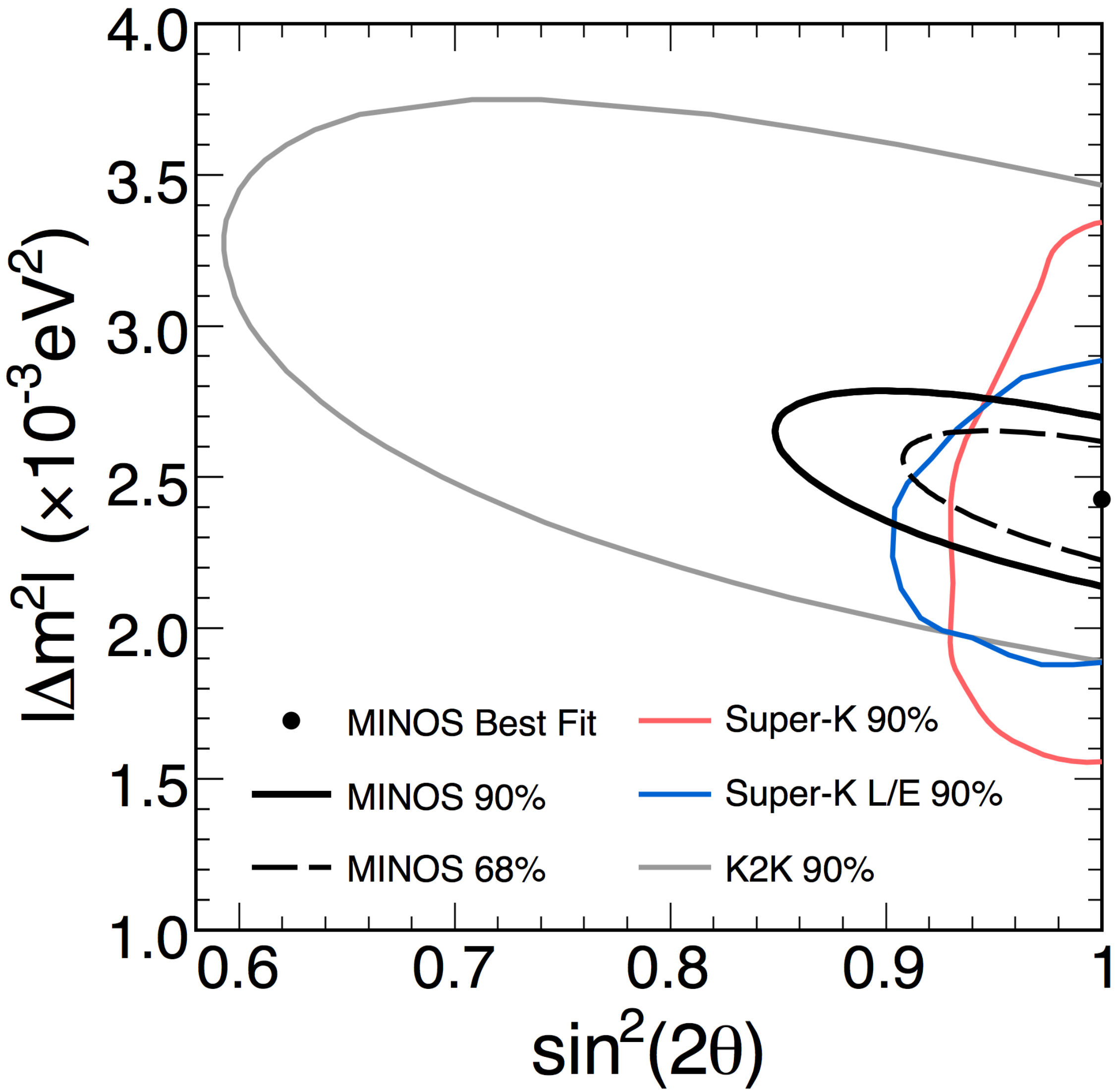
$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E)$$

$$|\Delta m^2_{atm}| = 2.43^{+0.13}_{-0.13}(\text{stat+syst}) \times 10^{-3} eV^2$$

$\sin^2 2\theta > 0.90$ at 90% C.L.

Best fit: $\chi^2/ndf = 90/97$

2008 CC result



$|\Delta m^2|$ =(2.43±0.13) x 10^{-3} eV^2
(68% C.L.)

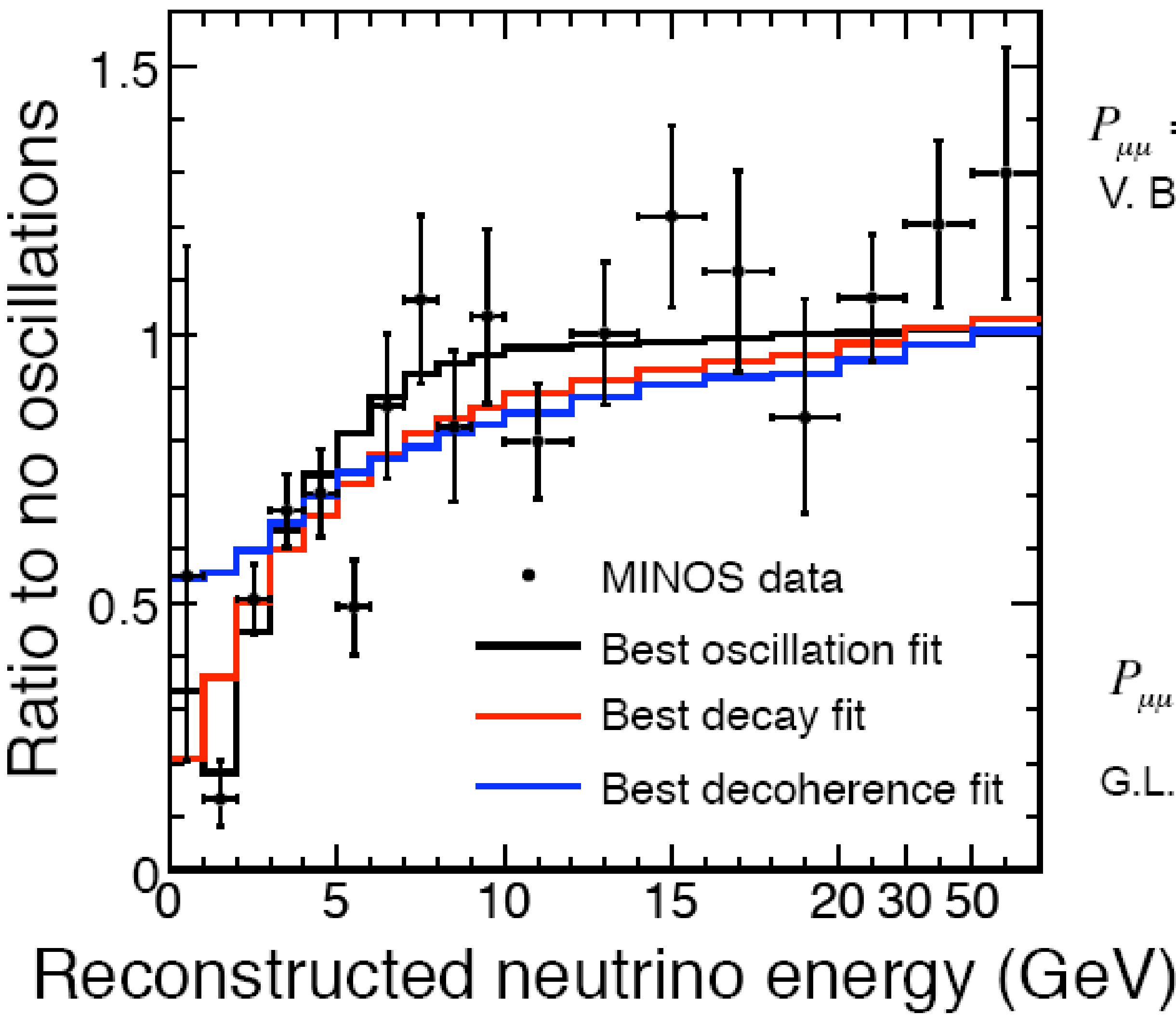
$\sin^2(2\theta)$ > 0.90
(90% C.L.)

χ^2/ndof = 90/97

Fit is constrained to the physical region.

Unconstrained:
$|\Delta m|^2$ = 2.33 x 10^{-3} eV^2
$\sin^2(2\theta)$=1.07
$\Delta\chi^2$=-0.6

2008 CC result



Decay:

$$P_{\mu\mu} = \sin^4\theta + \cos^4\theta \ \exp(-\alpha L/E)$$

V. Barger *et al.*, PRL82:2640(1999)

χ^2/ndof = 104/97

$\Delta\chi^2 = 14$

disfavored at 3.7σ

Decoherence:

$$P_{\mu\mu} = 1 - \frac{\sin^2 2\theta}{2}\left(1 - \exp\left(\frac{-\mu^2 L}{2E_\nu}\right)\right)$$

G.L. Fogli *et al.*, PRD67:093006 (2003)

χ^2/ndof = 123/97

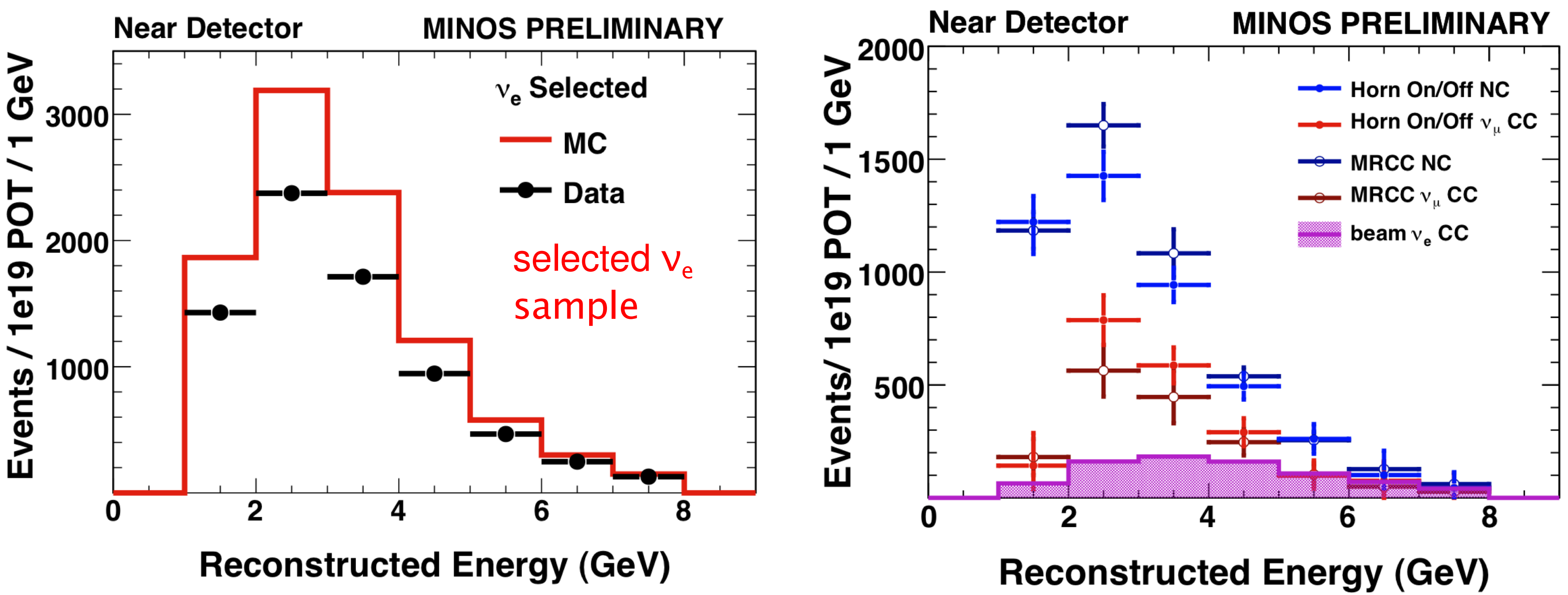
$\Delta\chi^2 = 33$

disfavored at 5.7σ

MINOS ν_e appearance search

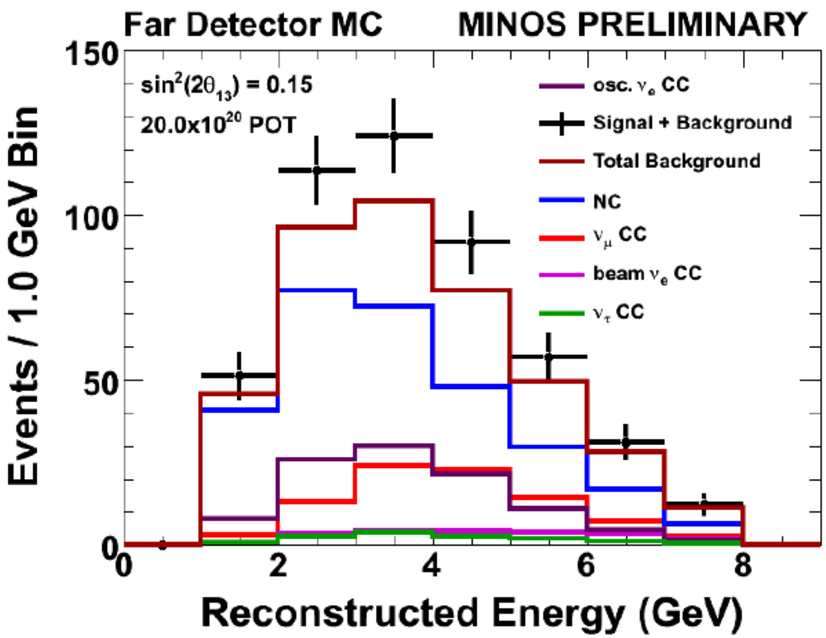
- Search for far detector ν_e apperance in initially 99% ν_μ beam
- Select ν_e with neural net based algorithm
- Selected near detector events are mostly $CC\nu_\mu$ and NC
- Use two independent data driven methods to estimate

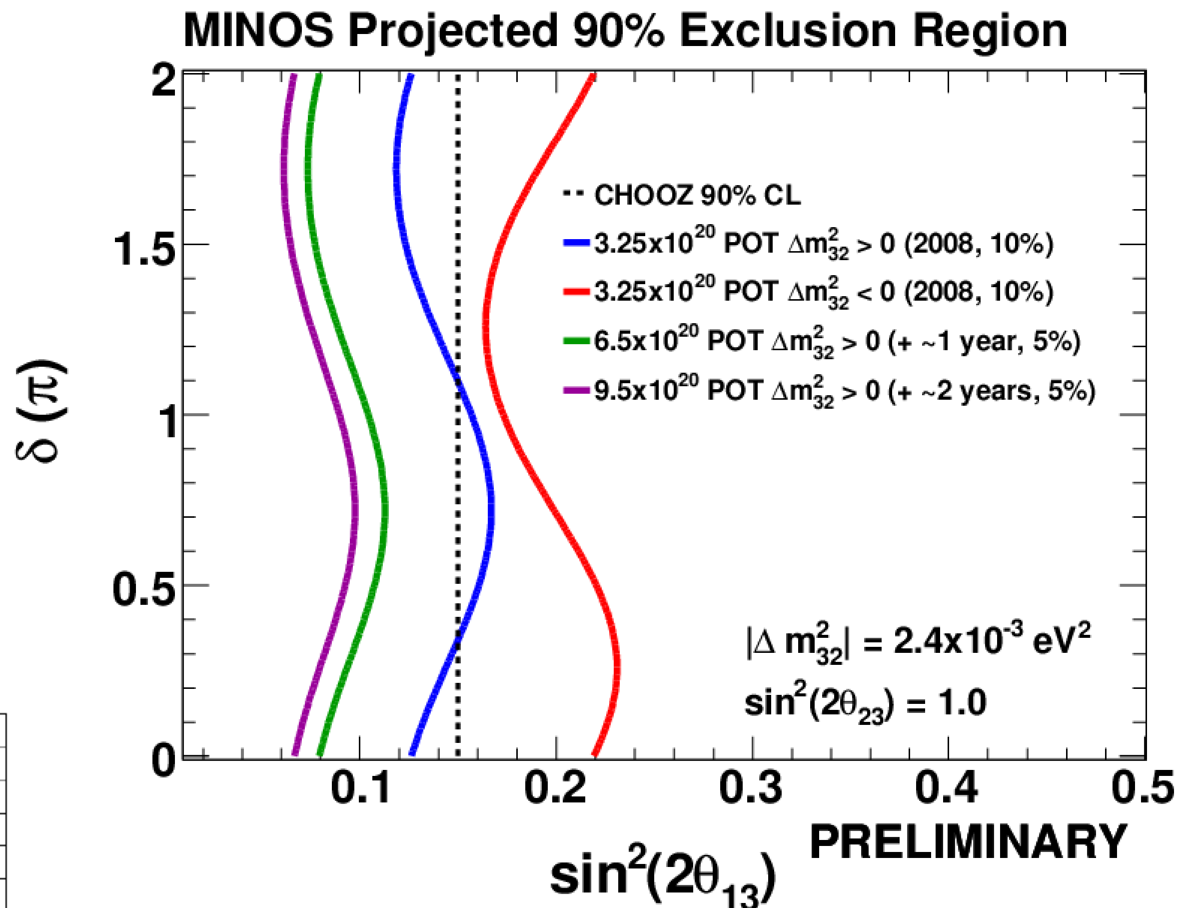
separately NC and CC backgrounds from near detector data



MINOS ν_e sensitivity

- Projected limits shown with current and expected MINOS exposure
- At CHOOZ limit expect 12 ν_e signal events and 42 background events with 3.25×10^{20} protons





- Use sidebands to study predicted far detector backgrounds
- Expect first result later this year

Summary and outlook

- The MINOS analysed data with $3.2x10^{20}$ protons on target and the results are consistent with standard oscillation pictutre:

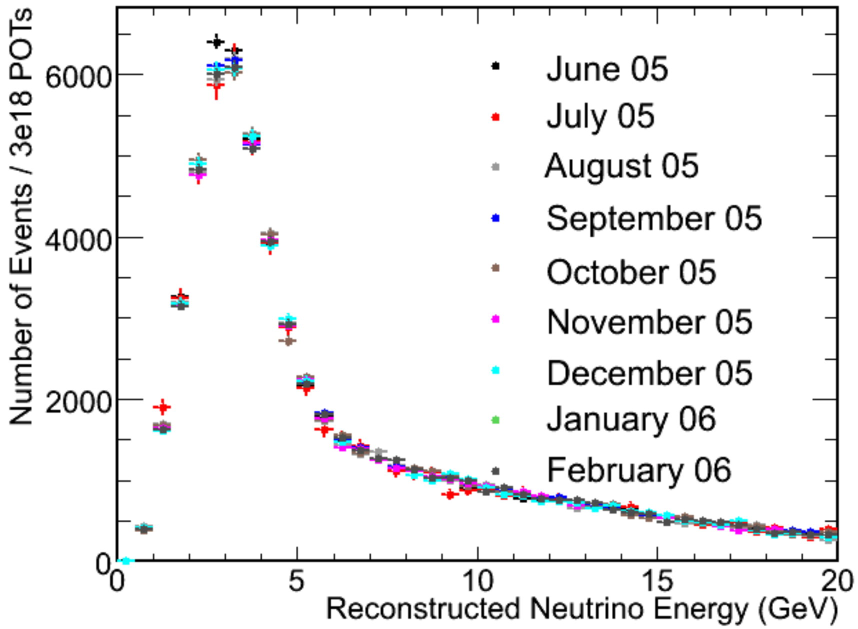
$$\left|\Delta m^2_{atm}\right| = 2.44^{+0.12}_{-0.12}(\text{stat})^{+0.15}_{-0.15}(\text{syst}) \times 10^{-3}\,eV^2$$

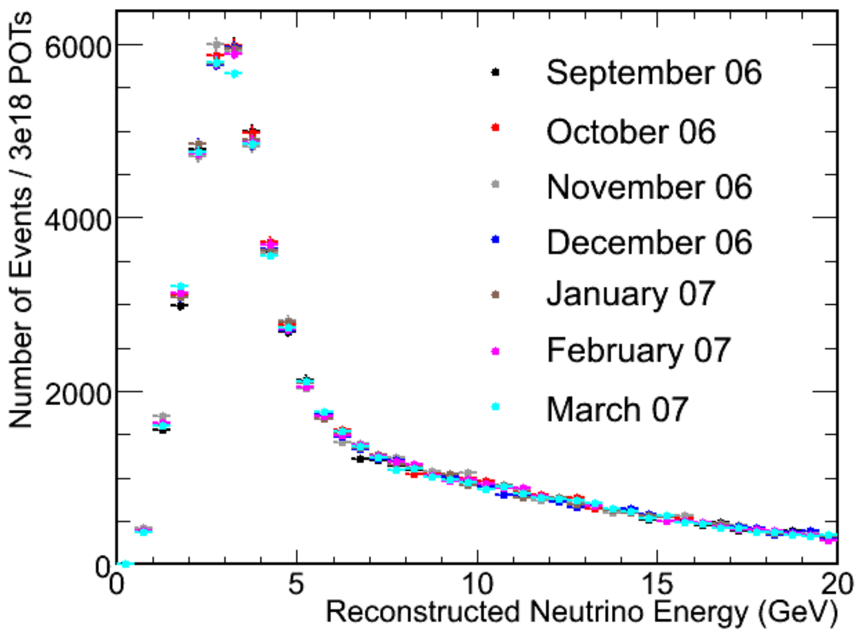
$$\sin^2 2\theta = 1.000_{-0.038}(\text{stat})_{-0.028}(\text{syst})$$

- Accumulating data and expect $>6x10^{20}$ by next Spring
- Electron neutrino apperance result later this year
- Many other MINOS physics measurements:
  - Cosmic ray muons
  - Measurement of neutrino disappearance to sterile neutrinos
  - Atmospheric ν_μ anti-ν_μ oscillations
  - Near detector neutrino cross-section

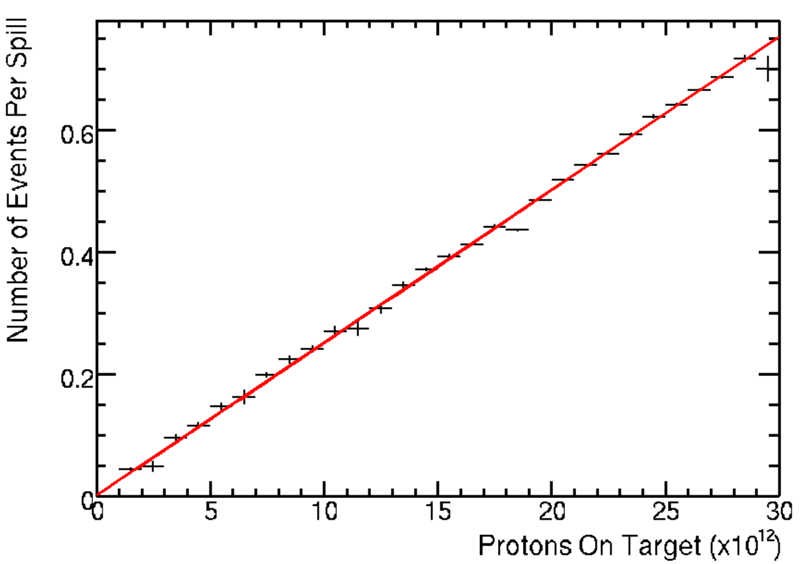
Backup slides

Near detector stability



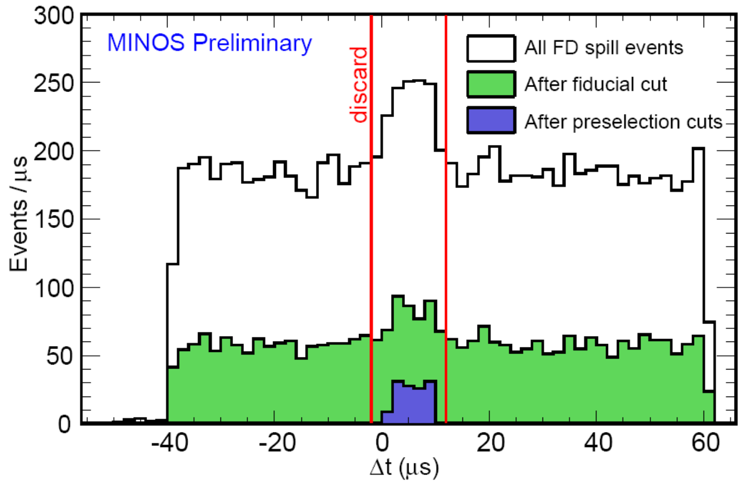


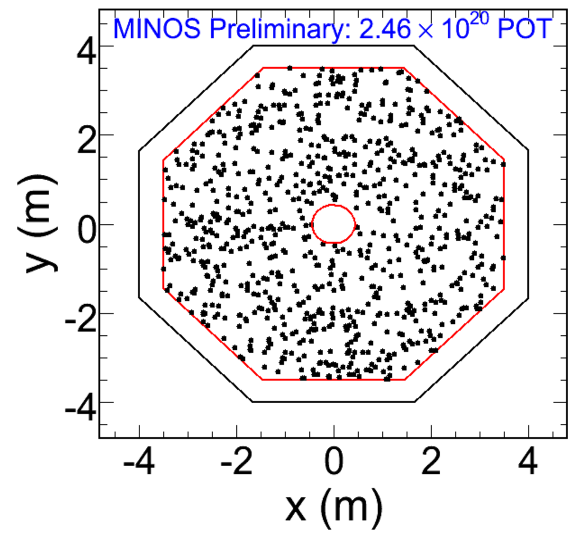
- Remove beam spills with "bad" beam properties: width and position at target, horn trips, etc
- Remove spills with bad detector state
- Selected spills are stabel with time
- Energy peak in Run 2 is 7%lower due to change in target position

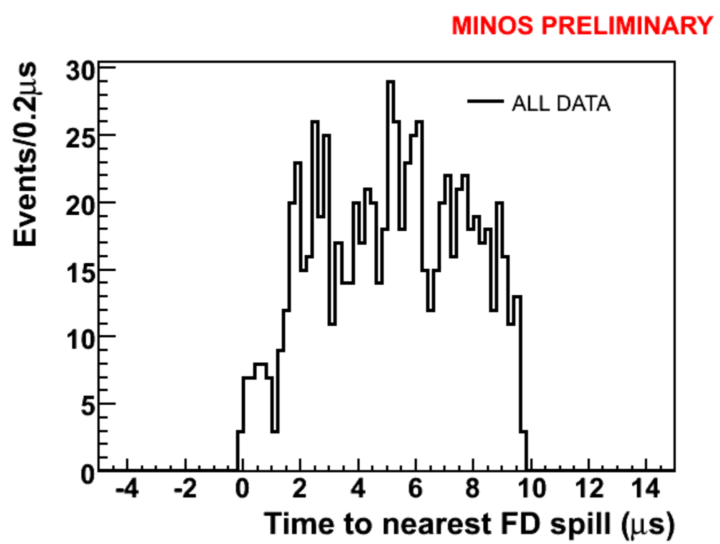


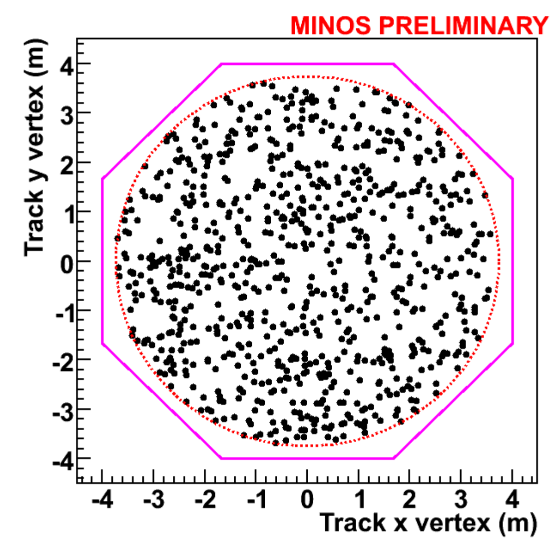
Far detector events

- Trigger far detector with GPS timestamp sent over Internet
- Select far detector events in time with beam spill using GPS clocks at near and far detectors
- Cosmic induced backgrounds are neglible in both NC(top) and CC (bottom) selected samples — check with "fake" spill triggers



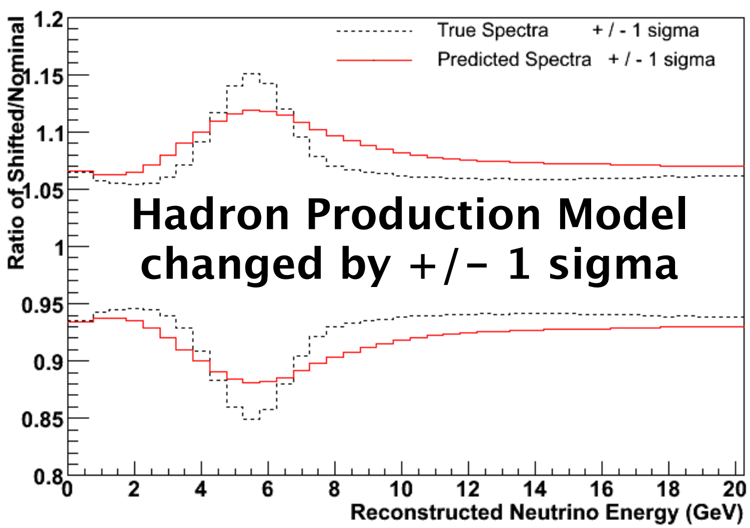


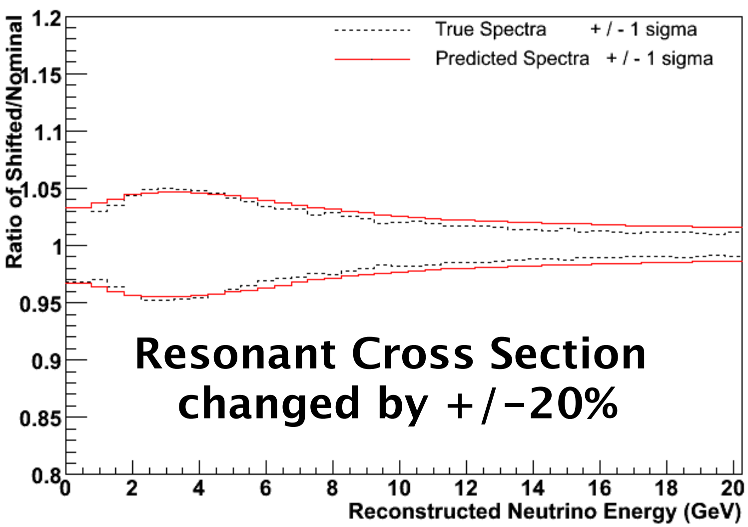




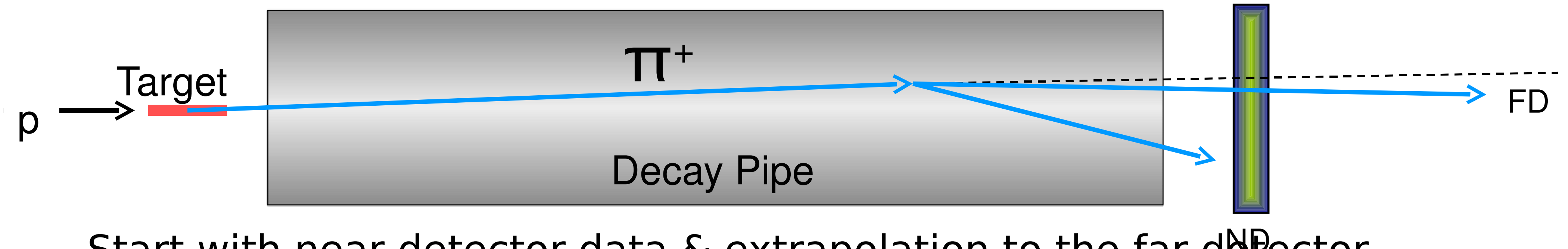
CC analysis systematic errors

Uncertainty	Shift in Δm^2 (10^{-3} eV^2)	Shift in $\sin^2(2\theta)$
Near/Far normalization ± 4%	0.065	<0.005
Absolute hadronic energy scale ± 10%	0.075	<0.005
NC contamination ± 50%	0.010	0.008
All other systematic uncertainties	0.041	<0.005
Total systematic (summed in quadrature)	**0.11**	**0.008**
Statistical error (data)	**0.17**	**0.080**



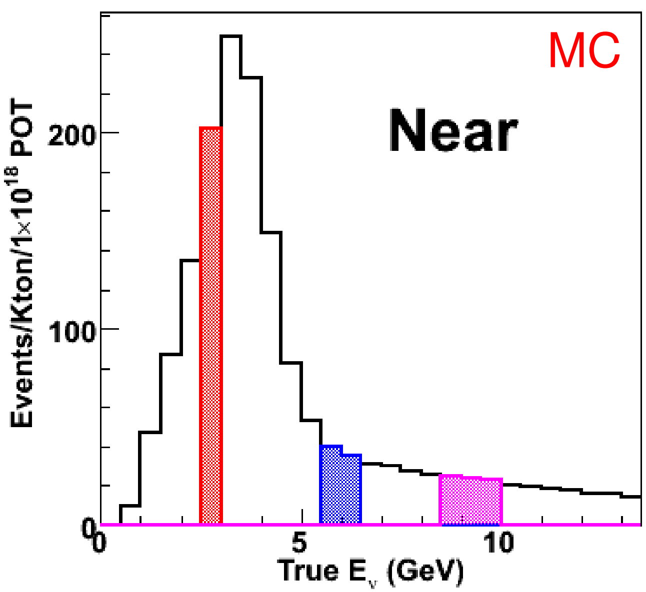


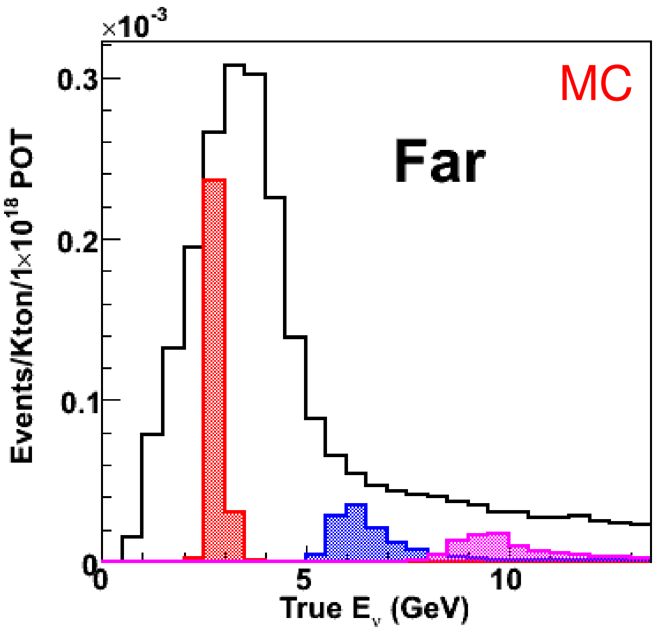
Near to Far Extrapolation

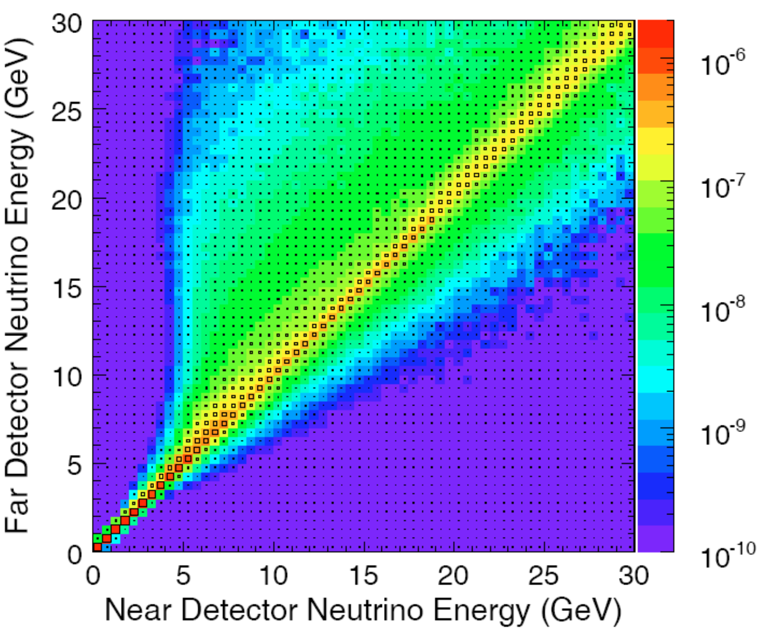


Start with near detector data & extrapolation to the far detector

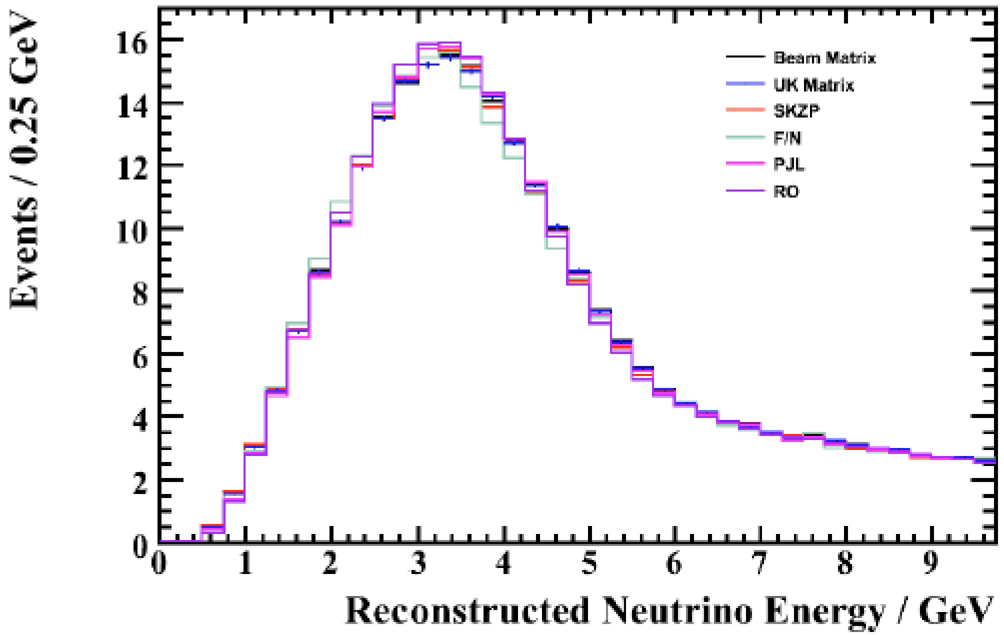
- Use Monte Carlo to provide corrections due to energy smearing and acceptance
- Encode pion decay kinematics & the geometry of the beamline into a matrix used to transform the ND spectrum into the FD energy spectrum

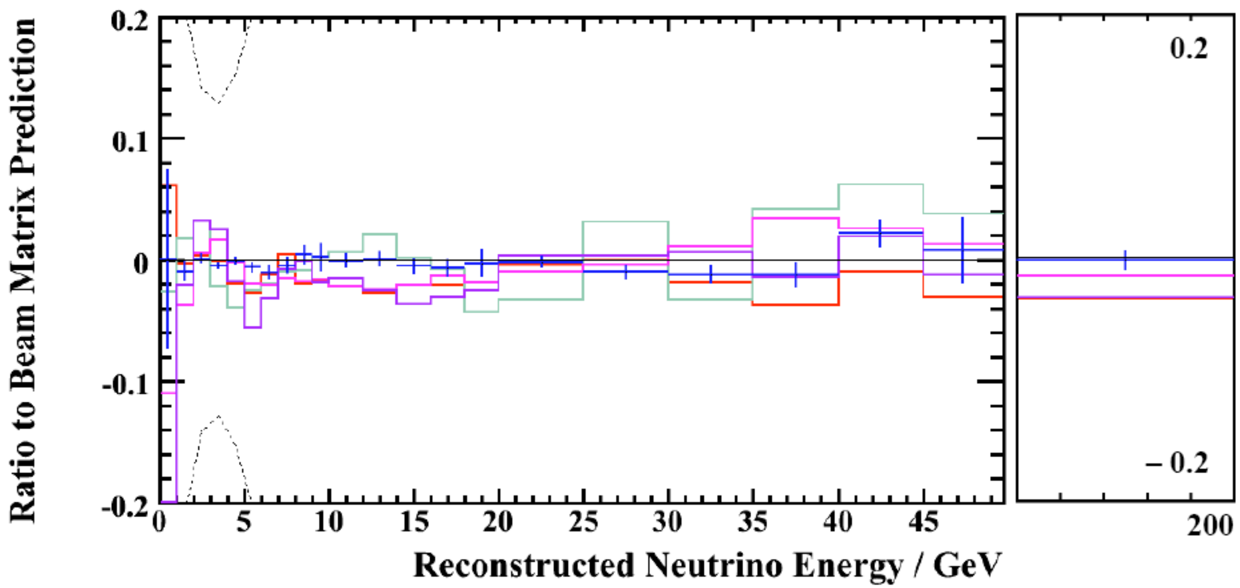






Many Extrapolations



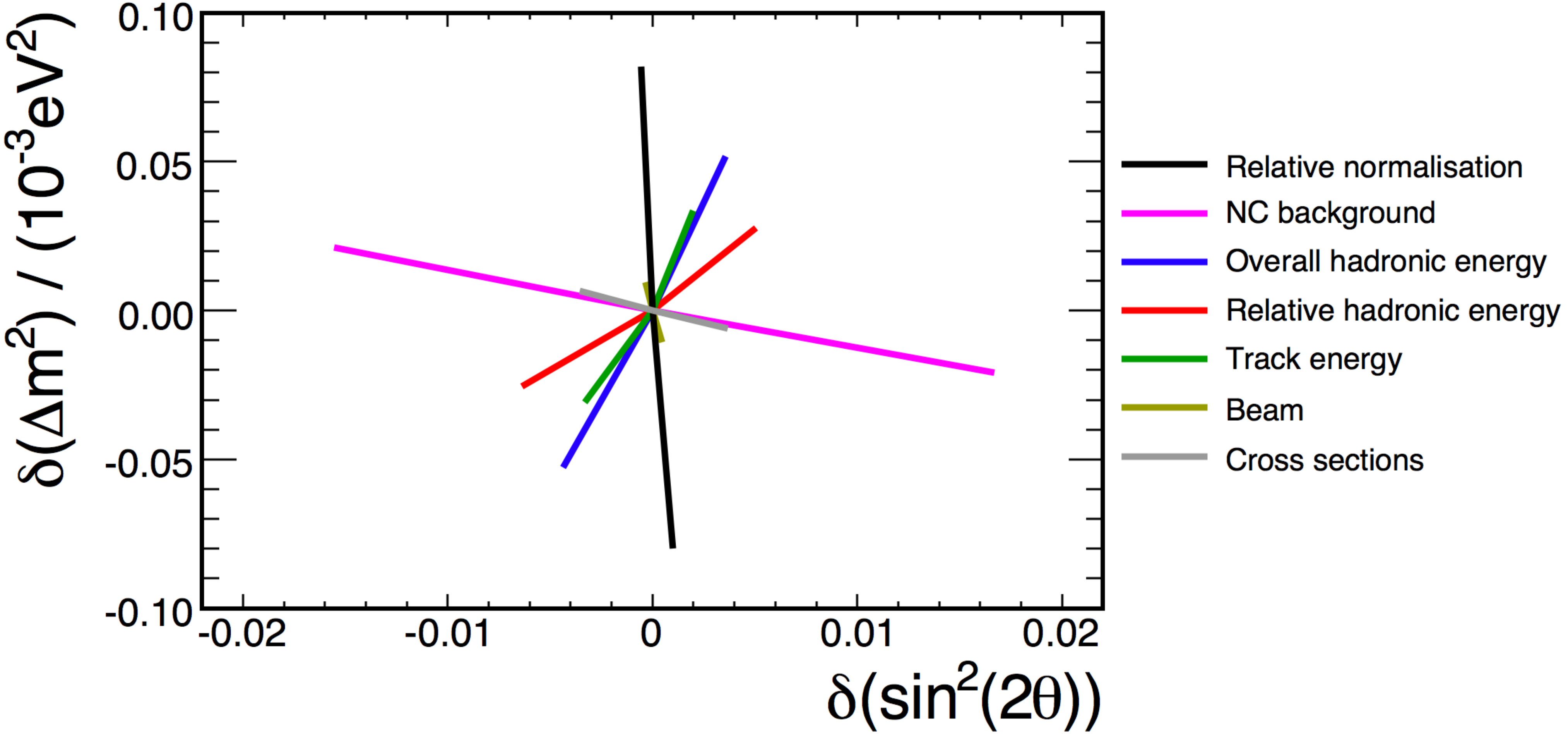


CC Systematics

Uncertainty	Δm^2 (10^{-4} eV^2)	$\sin^2 2\theta$
Near/Far normalization ± 4%	**0.43**	**0.004**
Muon momentum scale (range ± 2%, curvature ± 3%)	0.32	0.004
Absolute hadronic energy scale (±10.3%)	**0.67**	**0.003**
Near/Far shower energy scale ± 3.3%	0.35	0.006
NC contamination ± 50%	**0.20**	**0.017**
CC cross-section uncertainties	0.12	0.004
Beam uncertainties	0.25	0.005
Total Systematic (summed in quadrature)	0.96	0.019
Expected Statistical sensitivity	1.9	0.09

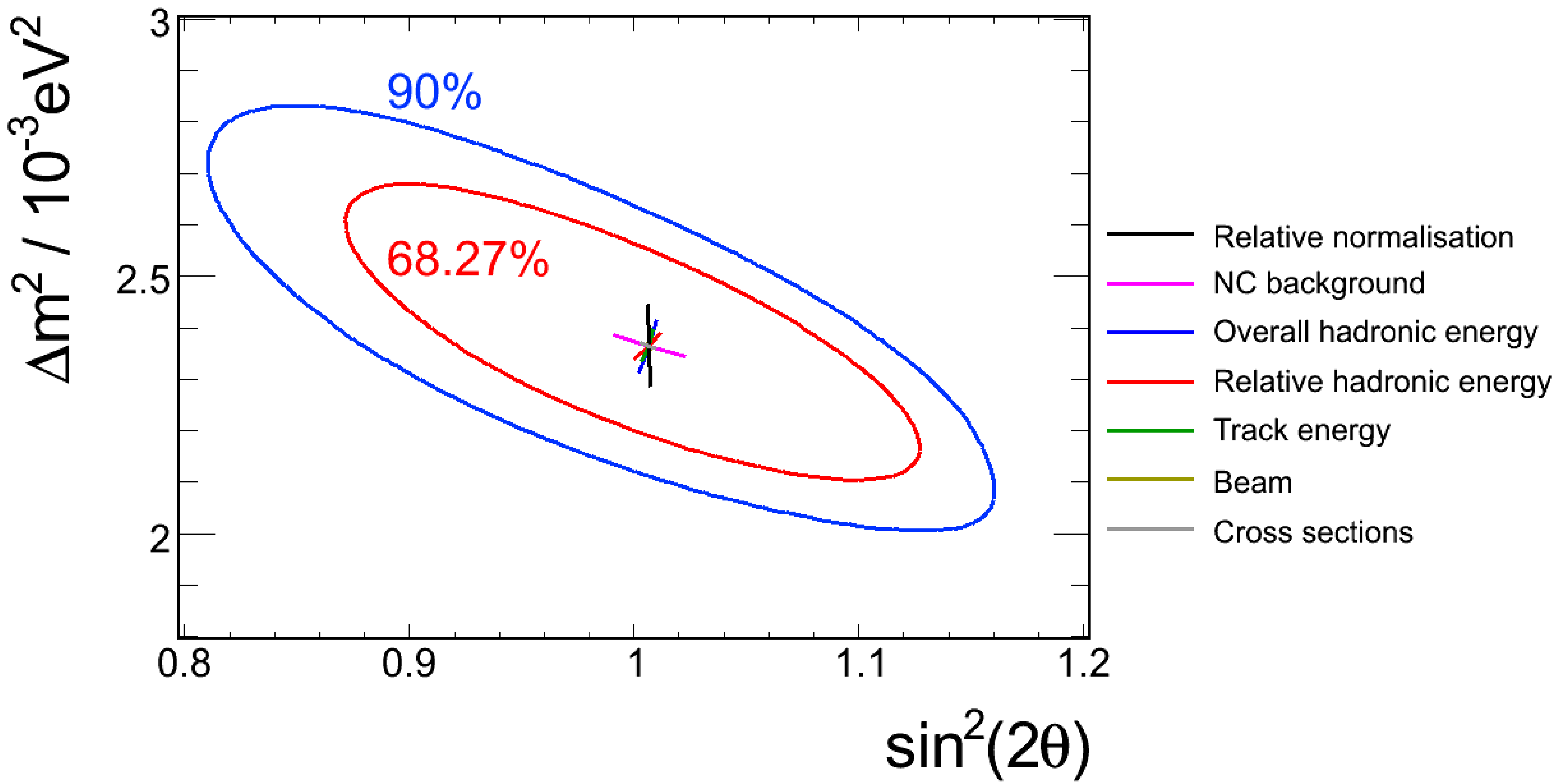
2008 CC result

Example of the impact of different sources of systematic uncertainty were evaluated by fitting modified MC in place of the data:

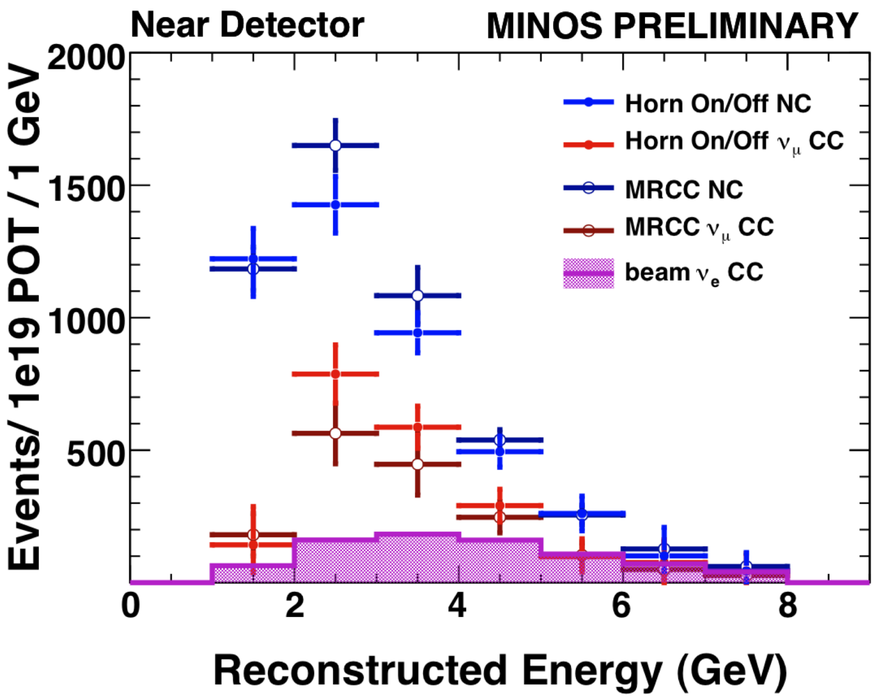


2008 CC result

Example of the impact of different sources of systematic uncertainty were evaluated by fitting modified MC in place of the data:



MINOS ν_e appearance



- Estimate two background components: NC and CCν_μ
- Two independent methods use near detector data events and agree with each other:
  - Muon removed events
  - Horn ON/Horn OFF beams