Neutrino Induced Coherent NC(π^0) Production in MINOS

$$\nu + \mathrm{Fe} \rightarrow \nu + \mathrm{Fe} + \pi^0$$
$$\hookrightarrow \gamma\gamma$$

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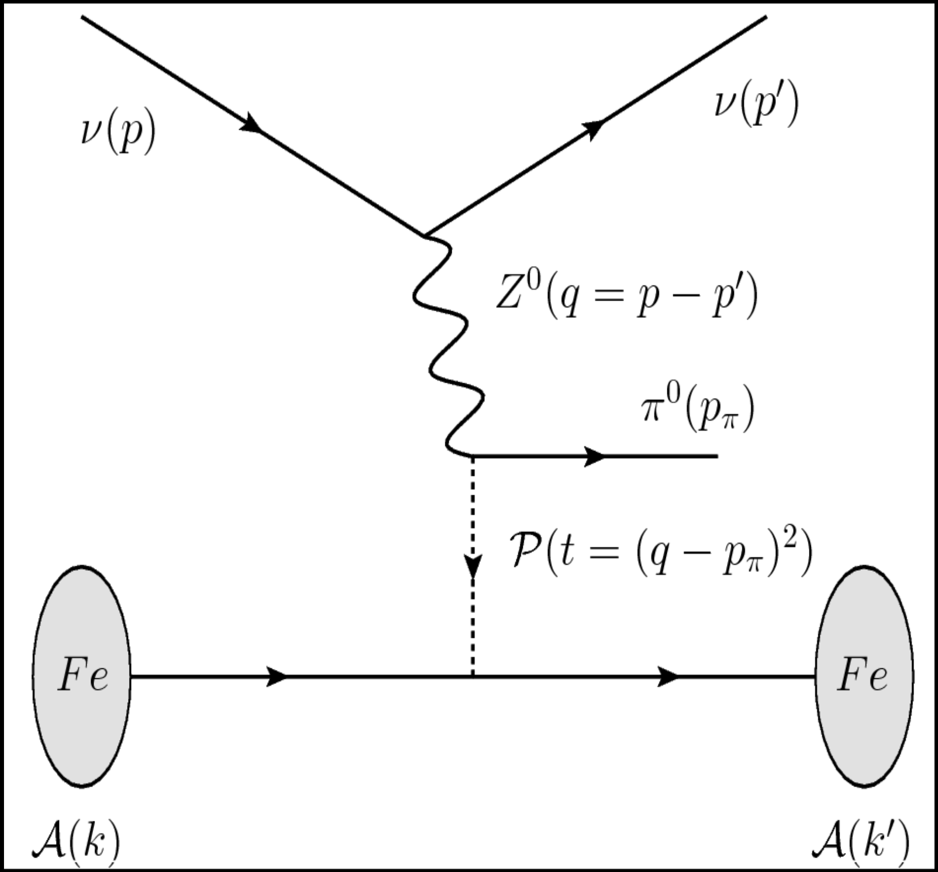
Outline

- **Introduction**
  - Phenomenology
  - The beam and detector
- **Event selection**
  - Coherent NC(π^0) signal
  - Background interactions
  - Support vector machines
  - The selected sample
- **Fitting the background model**
- **Extracting the coherent NC(π^0) event rate**
- **Systematic error studies**
- **Sensitivity studies**
- **Determination of cross sections**

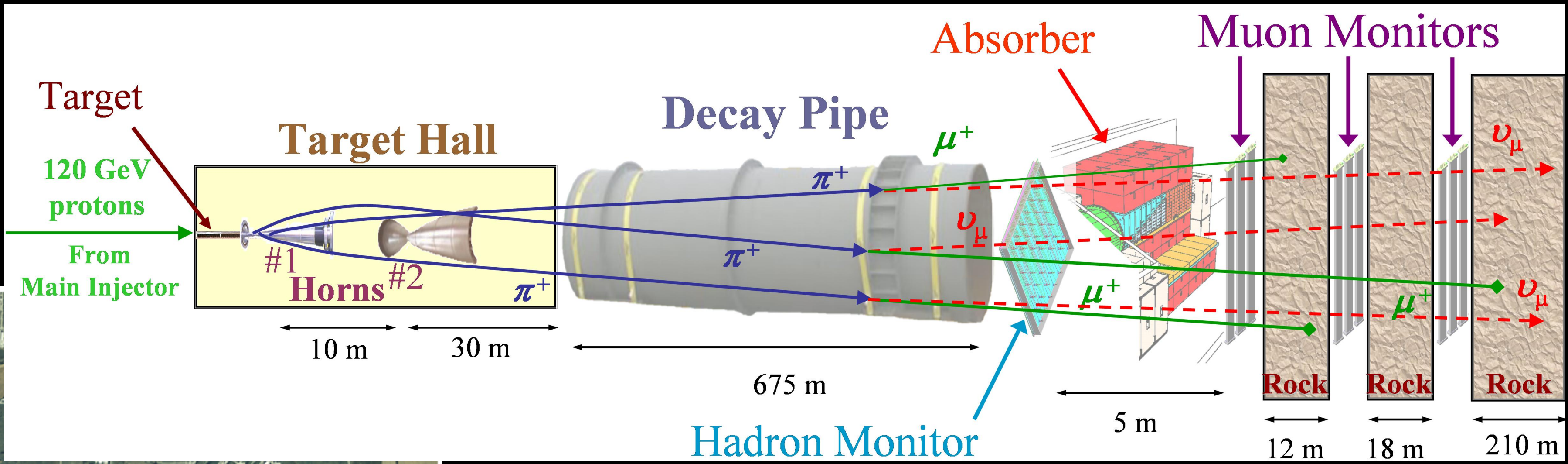
Coherent NC(π^0) Scattering: Phenomenology

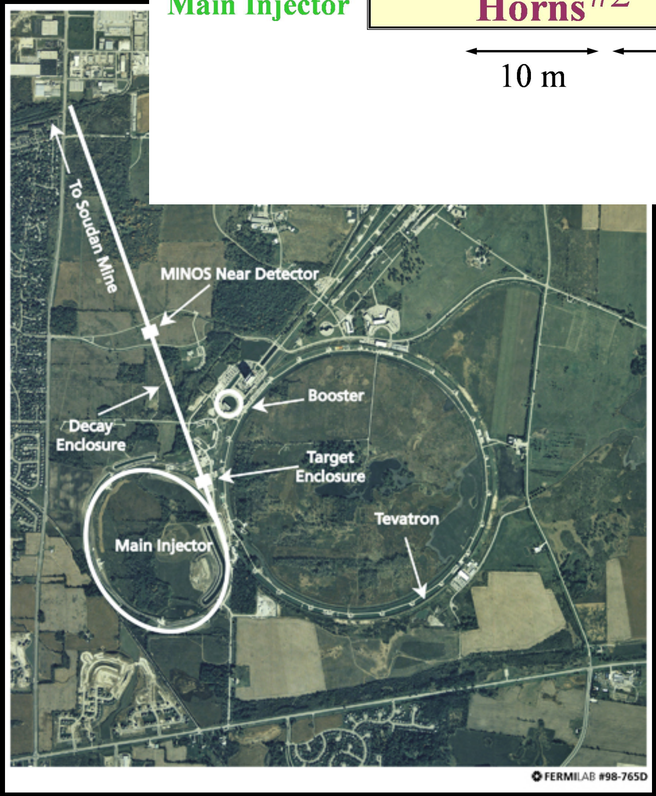
- No transfer of quantum numbers
- Small momentum transfer
- Nucleus remains in the ground state
- Single detectable final state reaction product



$$\frac{d^2\sigma(\nu A \rightarrow \nu \pi A)}{dQ^2\, dy\, d|t|} = \frac{G_F^2}{4\pi^2}\frac{(1-y)}{y}\left(\frac{m_A^2}{Q^2+m_A^2}\right) f_\pi^2 \frac{d\sigma(\pi A \rightarrow \pi A)}{d|t|}$$

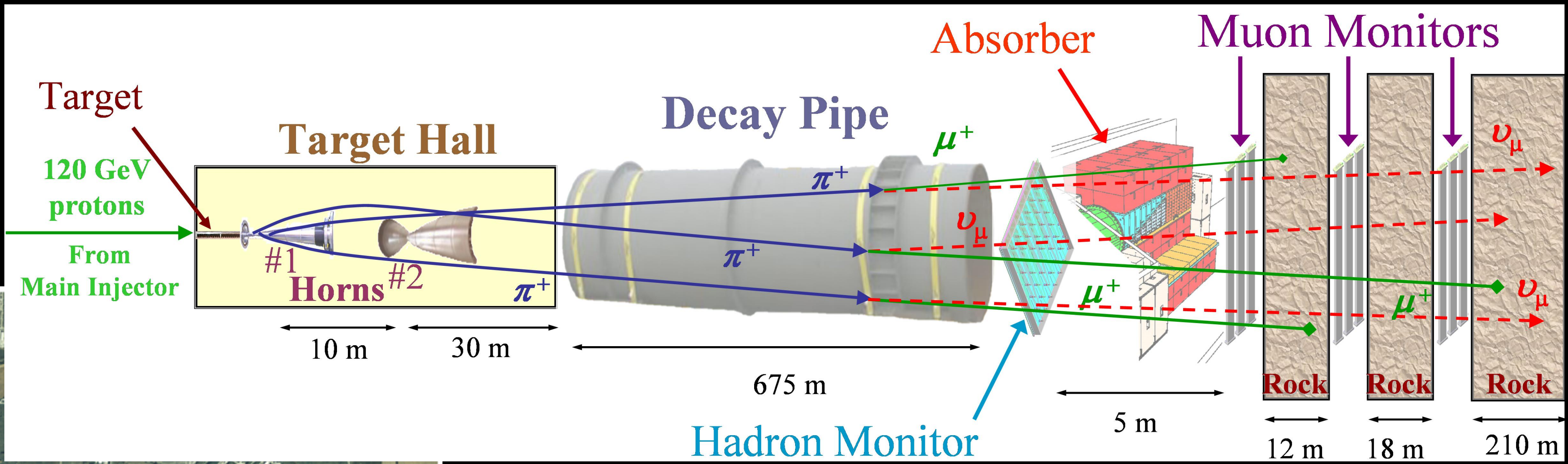
The NuMI Beam

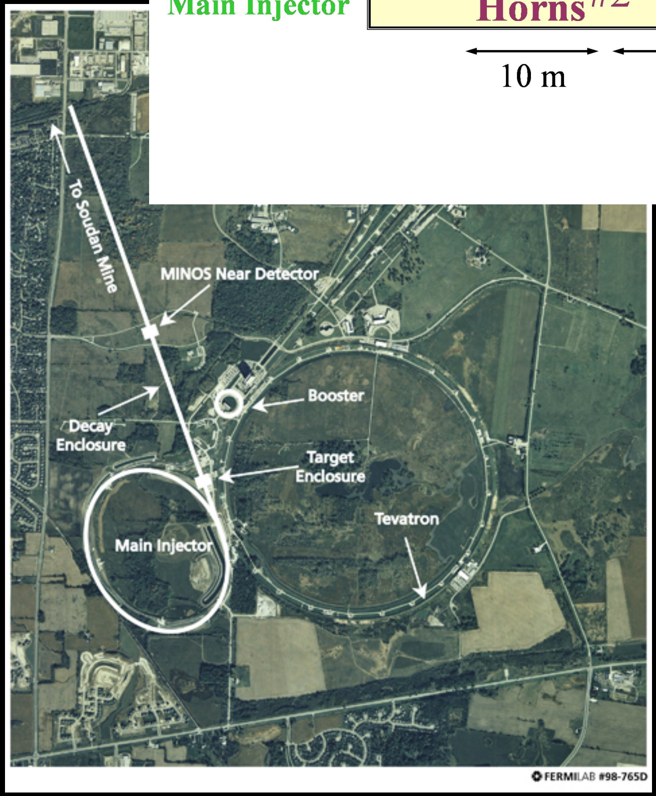


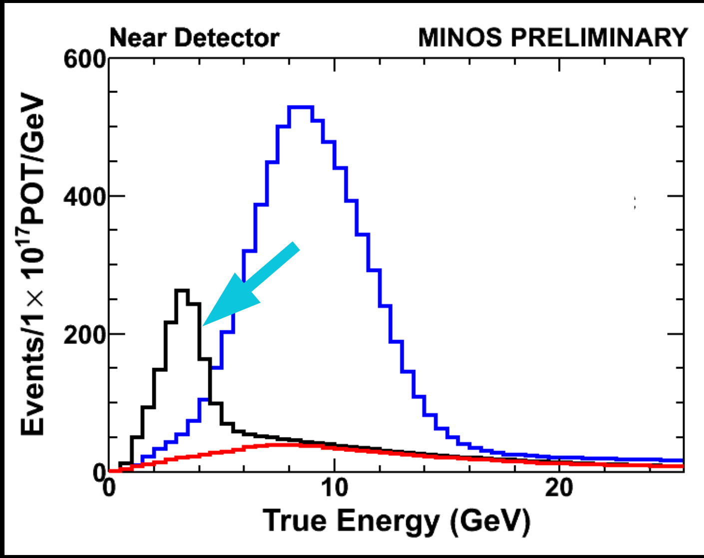


- 120 GeV protons directed to the target
- Protons strike the graphite target; produce π's and K's
- Hadrons focused using magnetic horns
- Hadrons decay to μ's and ν_μ's

The NuMI Beam



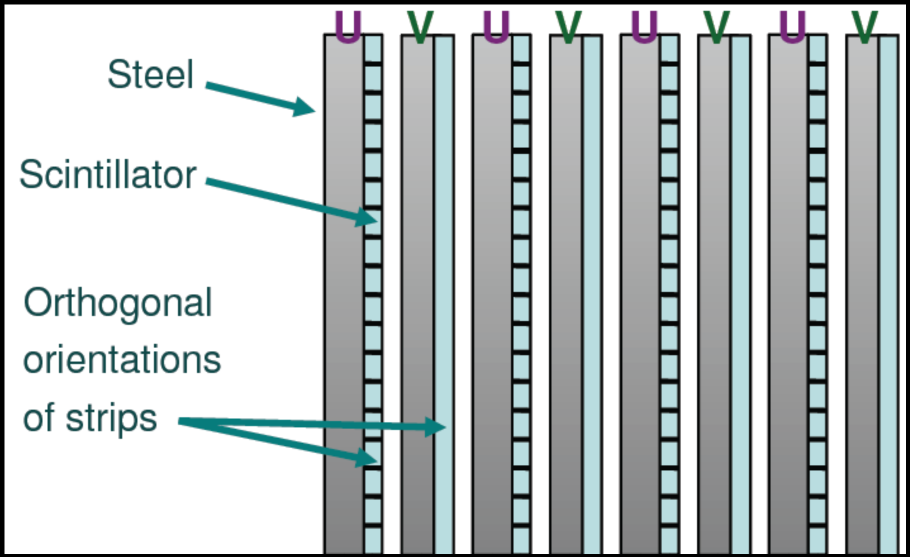


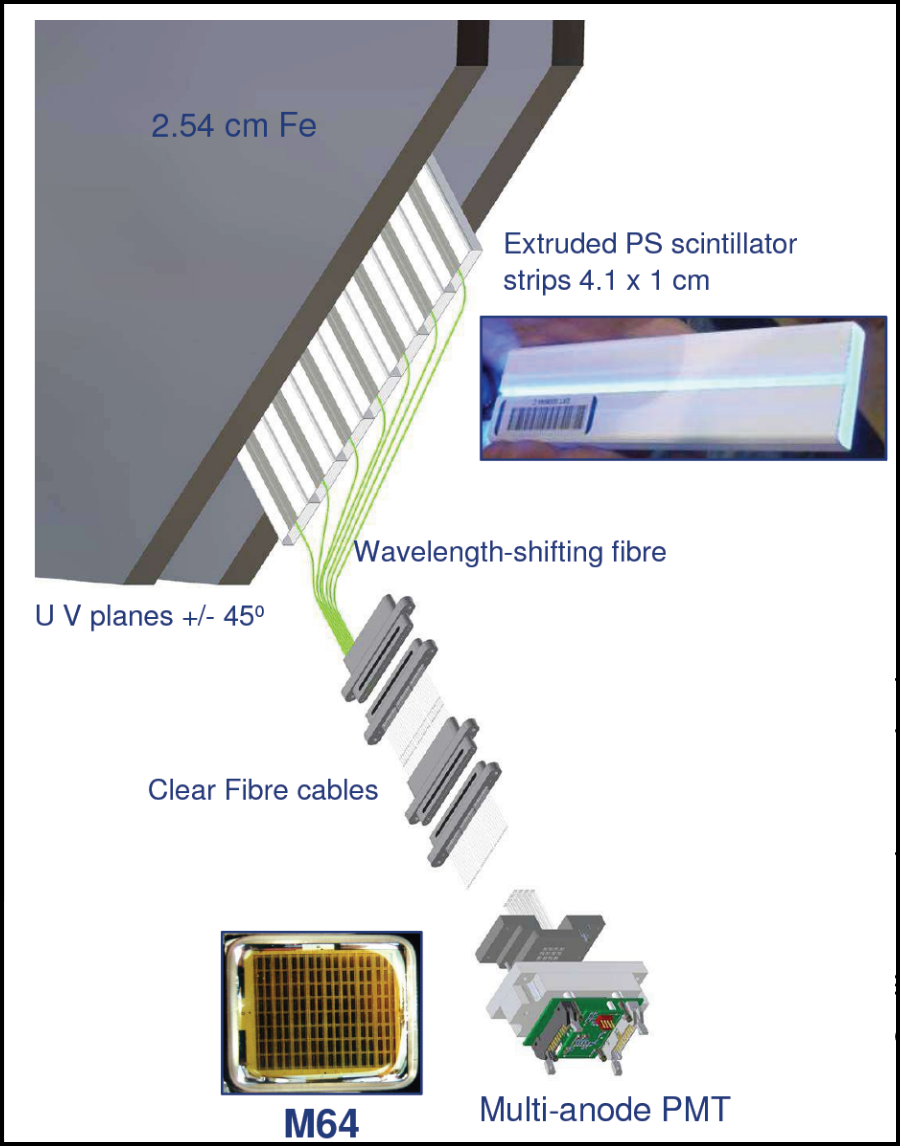


Beam Configurations:

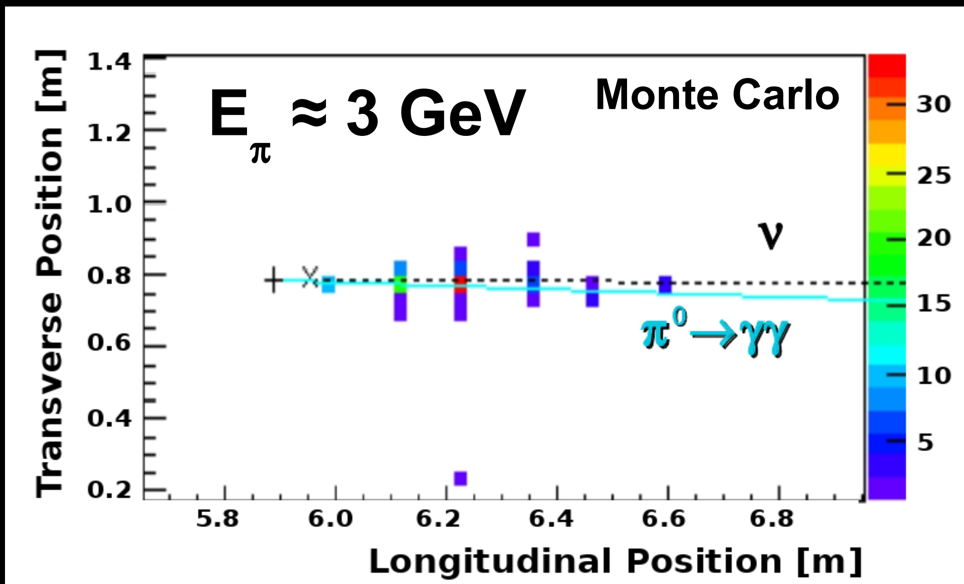
Low Energy
High Energy
Horns Off

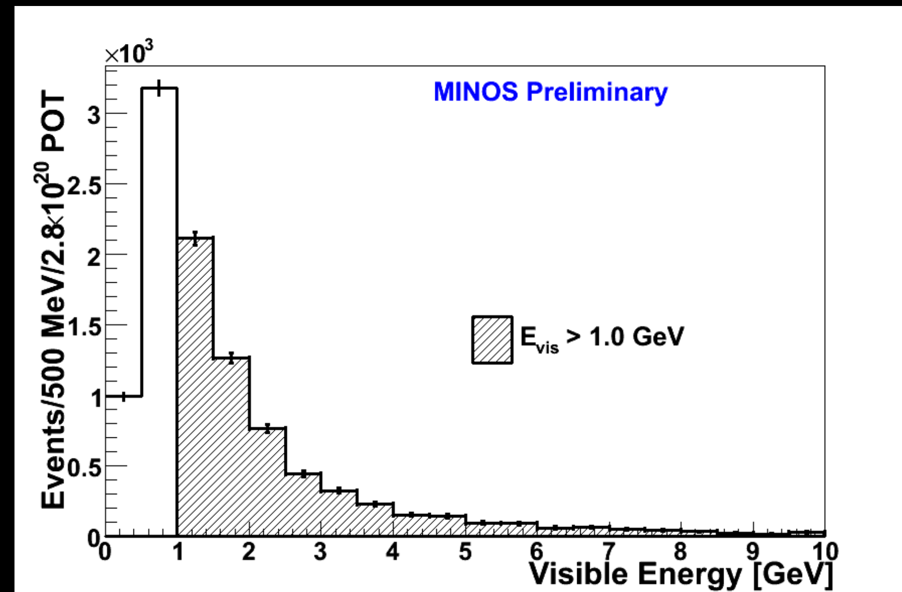
The MINOS Near Detector

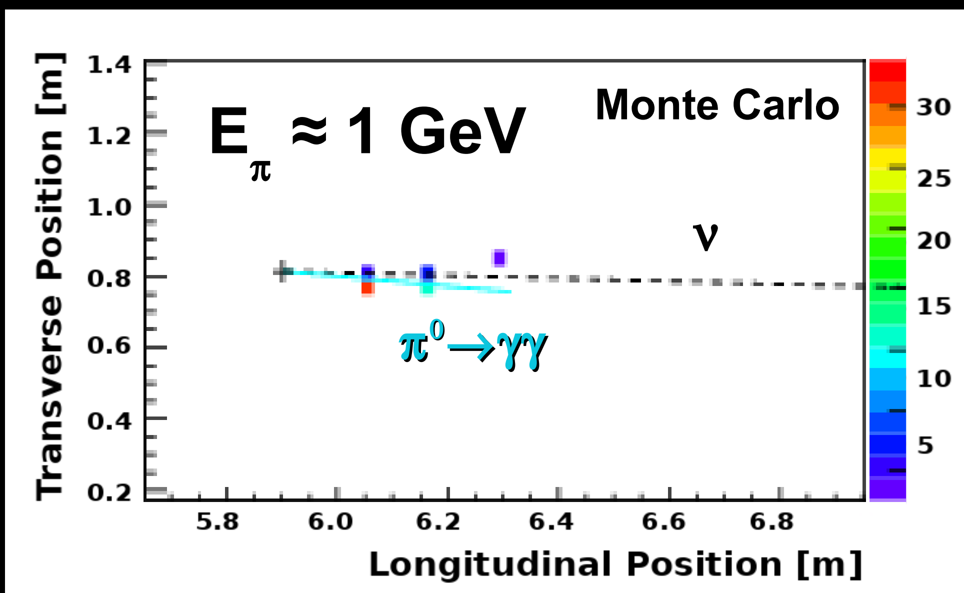


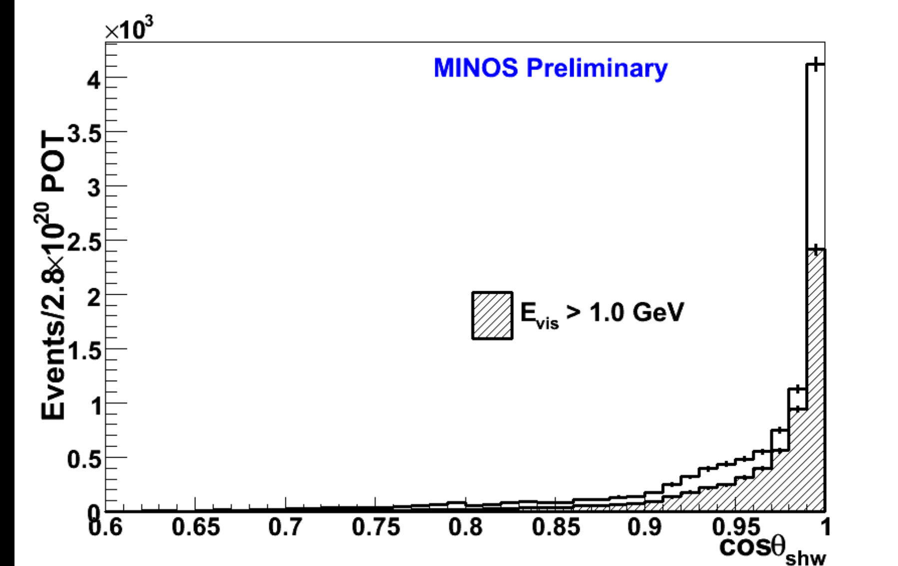


Coherent NC(π^0) Scattering in MINOS



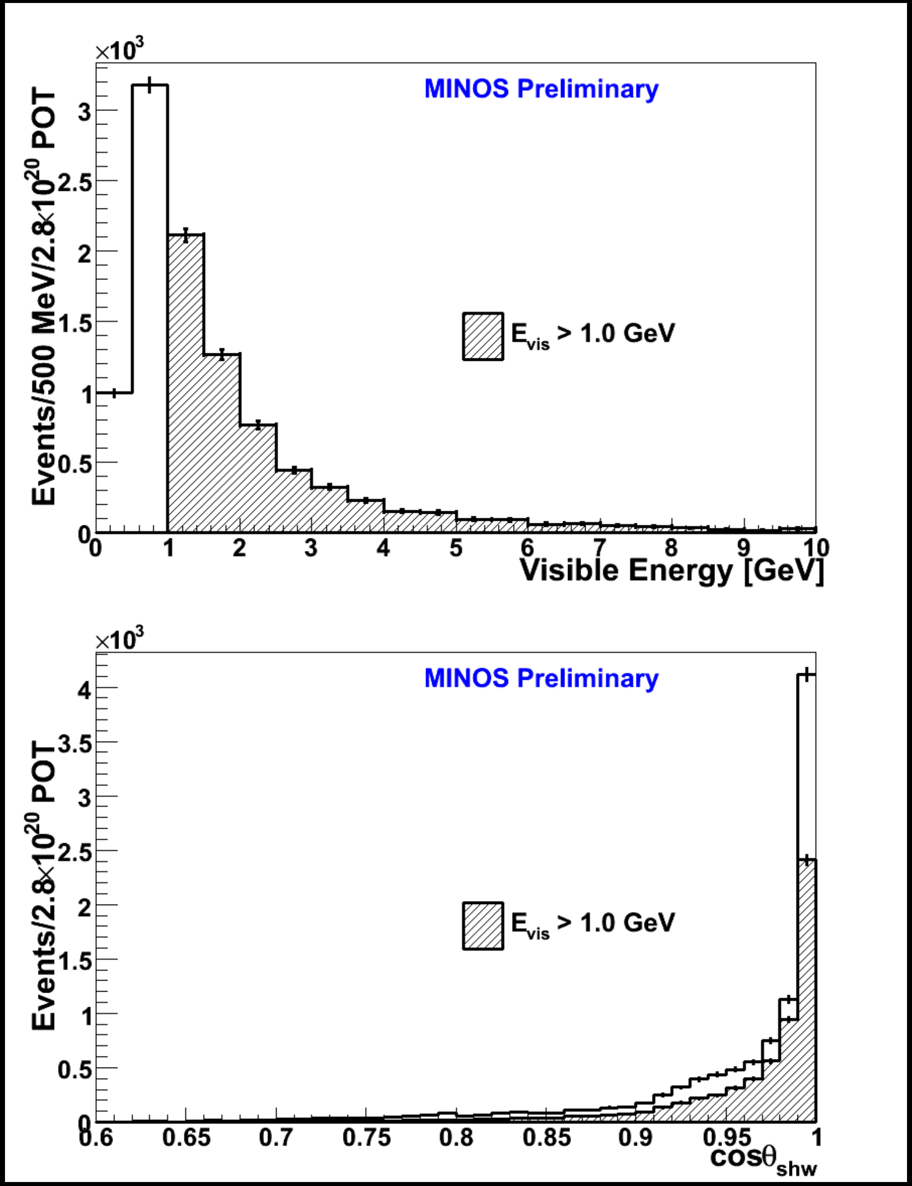




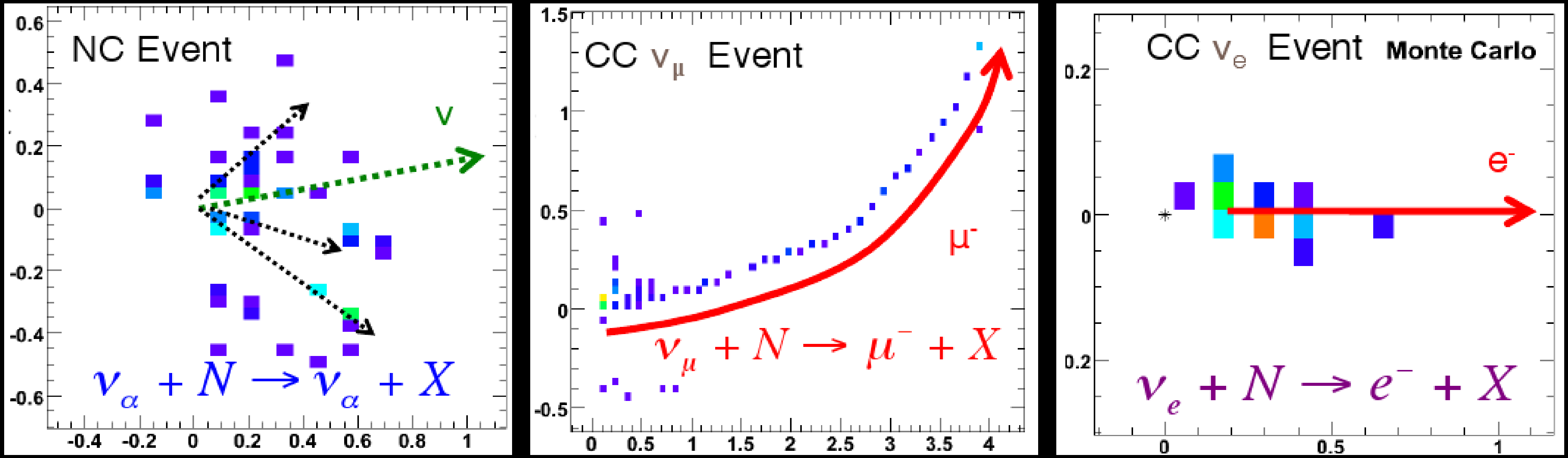


Coherent NC(π^0) Scattering in MINOS

- MC event rates (2.8×10^{20} POT)
  - Roughly 13k coherent NC(π^0)
  - About 1 in 500 events
  - 1044 selected events
- $\pi^0 \rightarrow \gamma\gamma \rightarrow$ single EM shower
  - Most of the energy goes to one γ
  - Two showers overlap (density of steel)



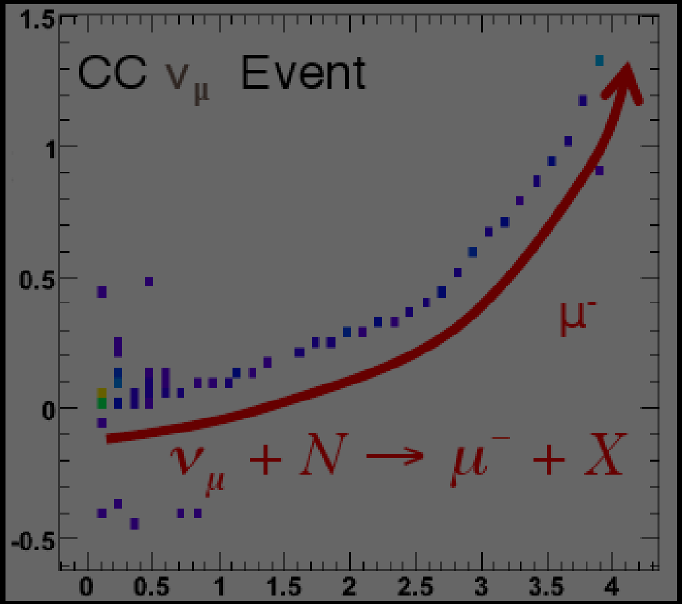
Background Reactions

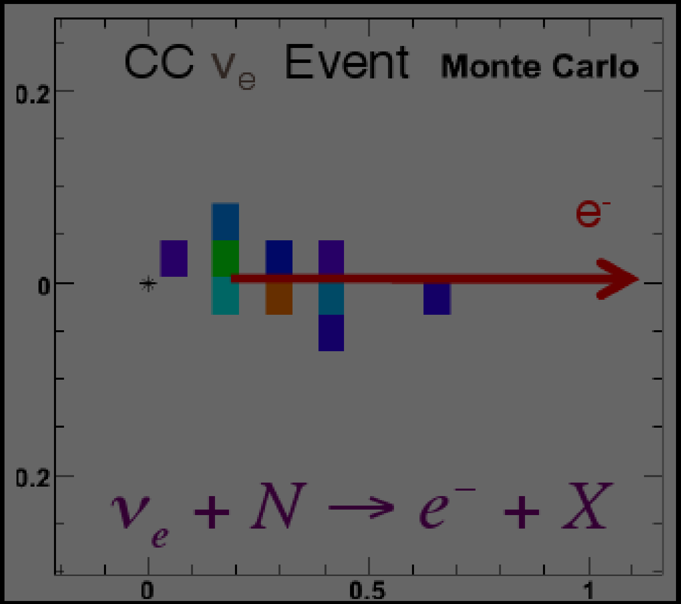


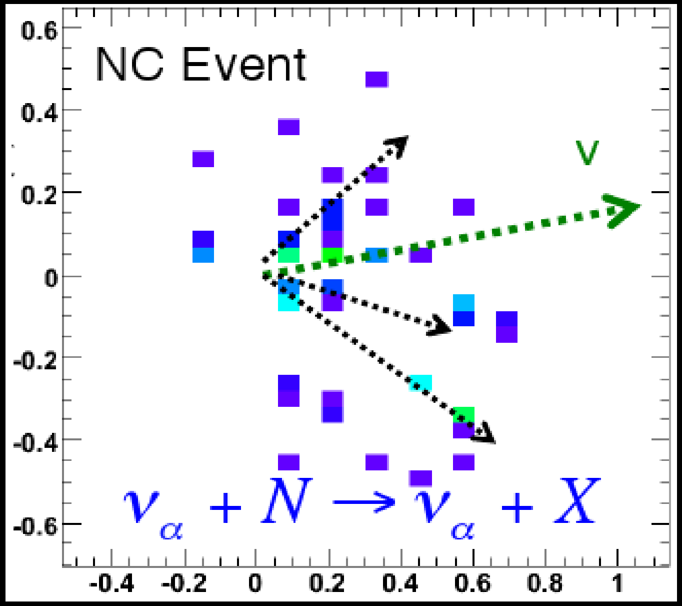
1,388,311 Fiducial Volume Events	**4,976,668** Fiducial Volume Events	**86,178** Fiducial Volume Events
780,960 Pre-selected Events	**930,761** Pre-selected Events	**68,967** Pre-selected Events
4,233 Selected Events	**454** Selected Events	**469** Selected Events

Background Reactions

- No visible leptons
- EM shower dominated
- No additional visible particles

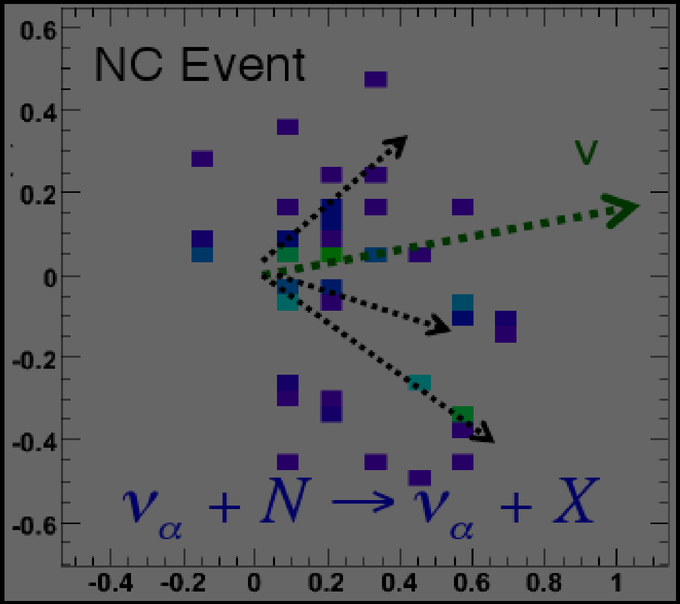




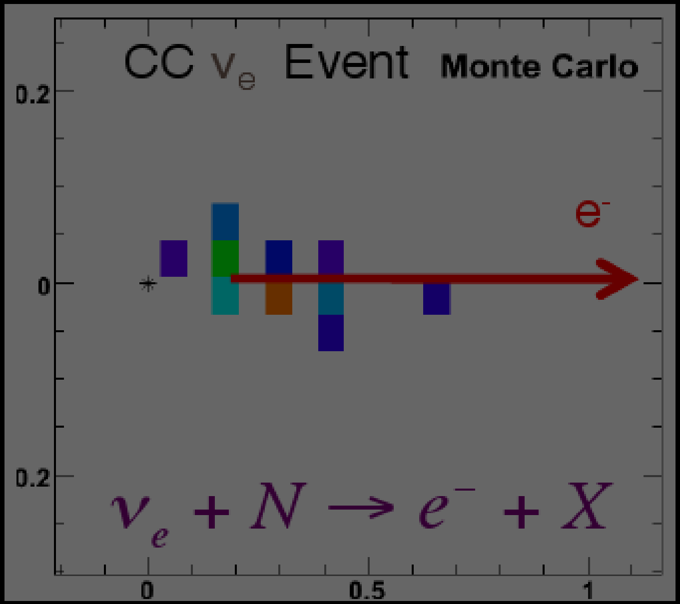


Neutral Current

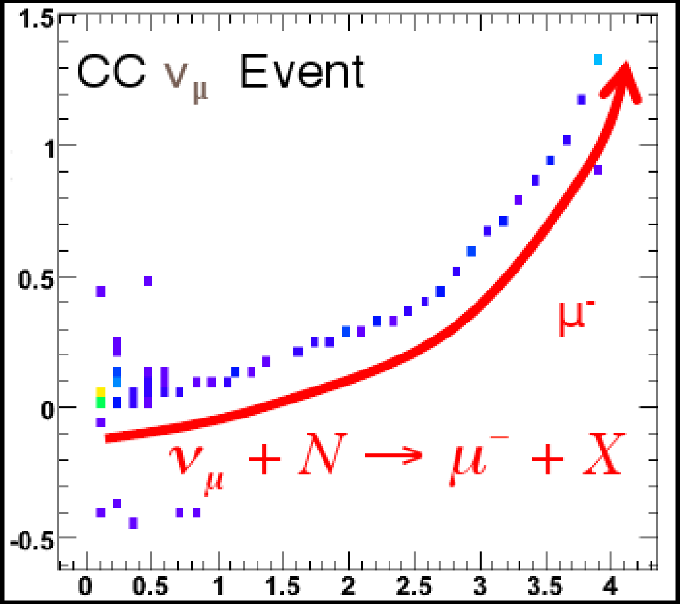
Background Reactions



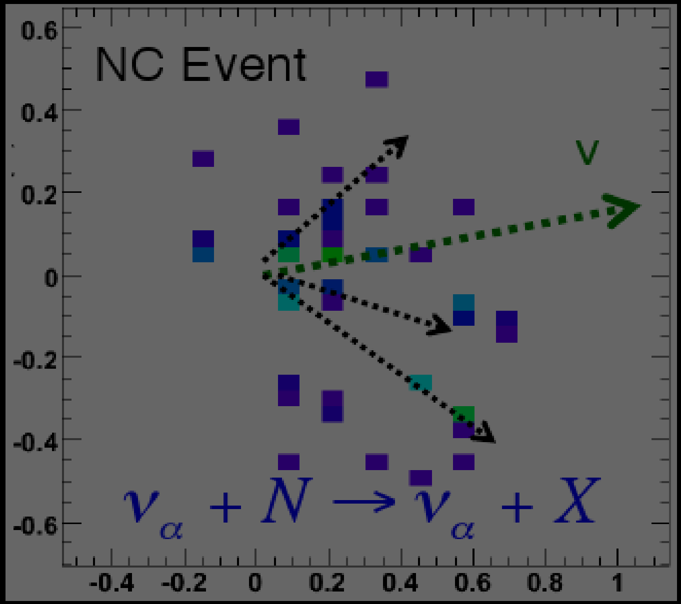
- Long μ tracks easily rejected
- Short μ tracks can mimic NC topologies

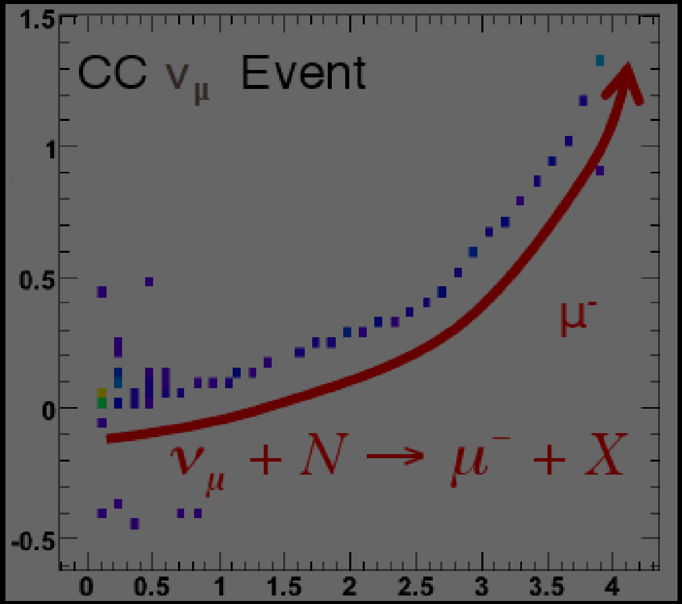


Charged Current - ν_μ

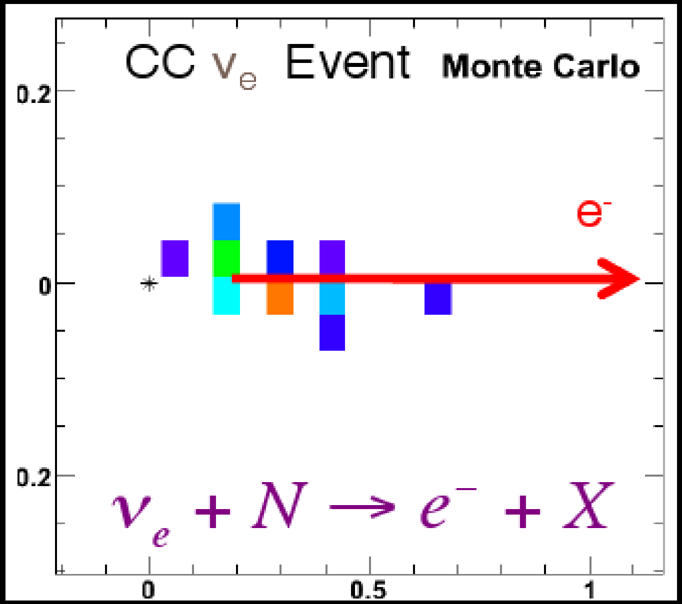


Background Reactions





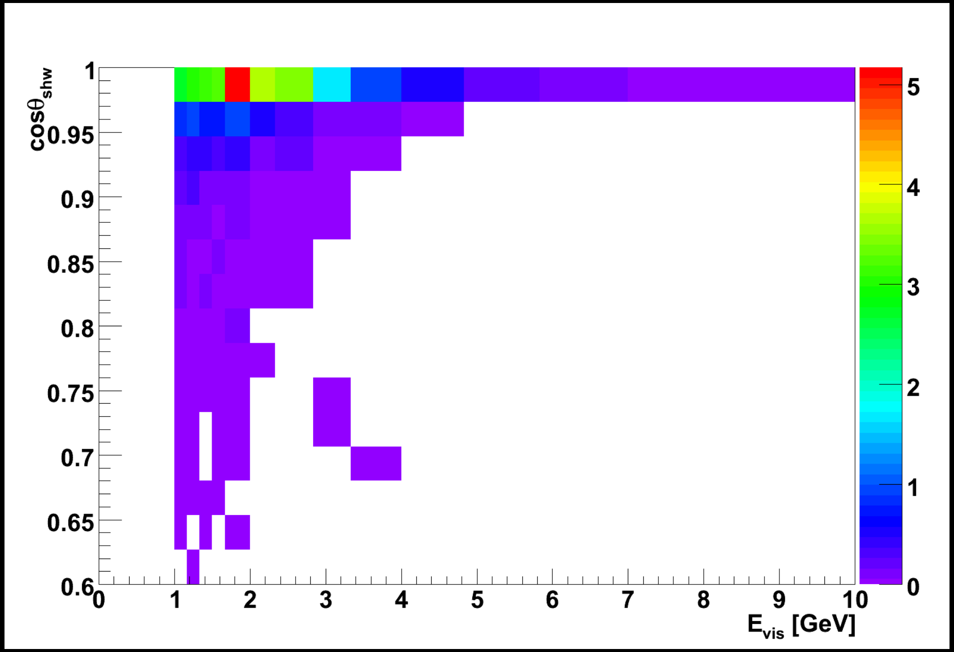
- Electron produced EM shower
- QE - like topologies



Charged Current - ν_e

$\nu + e^- \rightarrow \nu + e^-$ Scattering Backgrounds

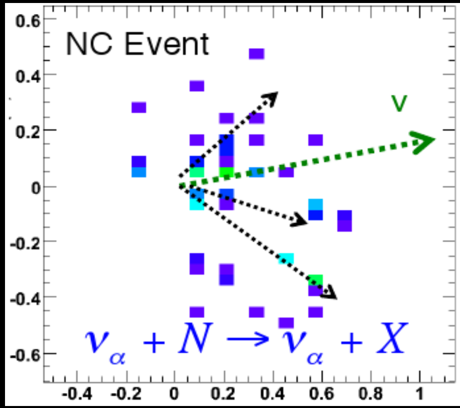
- Neutrino – electron scattering not included in the Monte Carlo
- Theoretical cross sections are well constrained

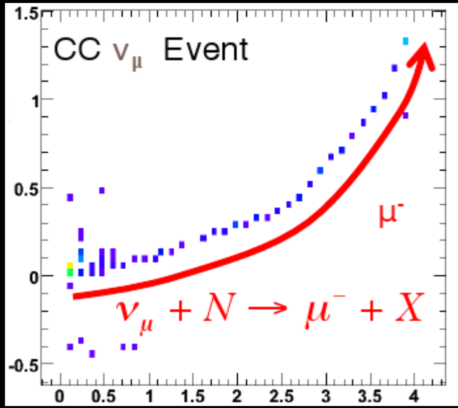


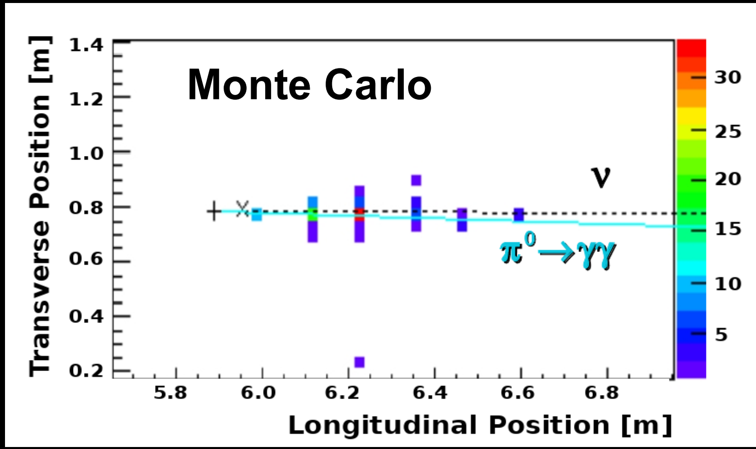
- Special MC samples used to estimate the cosθ-vs-E_{vis} distribution
- Subtracted prior to fitting to the data
- Not included in either fit MC or mock data – studies still valid

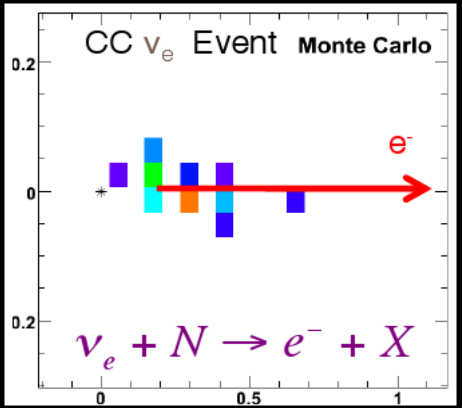
Event Selection:
Attribute Categories

- Shower Size
- Shower Shape
- Fits to the energy profiles
- Vertex Activity
- Energy Dispersion
- Track Length and Curvature



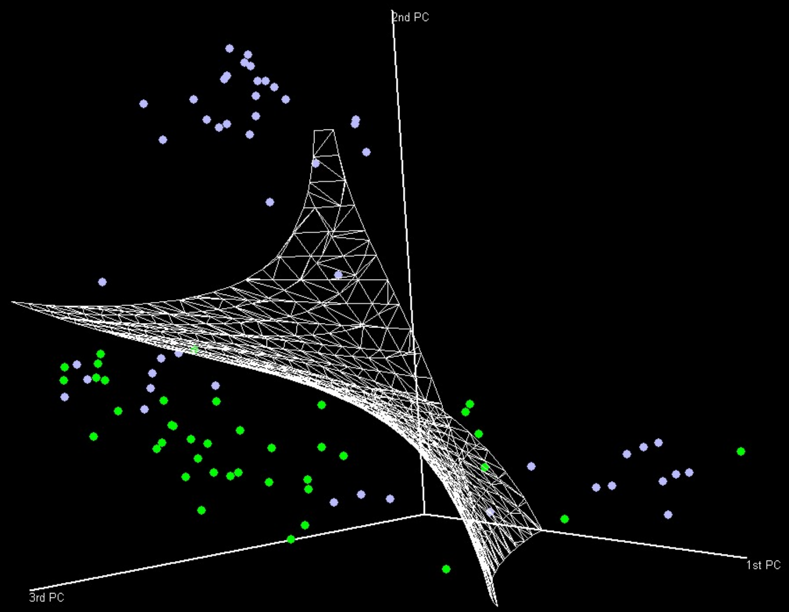




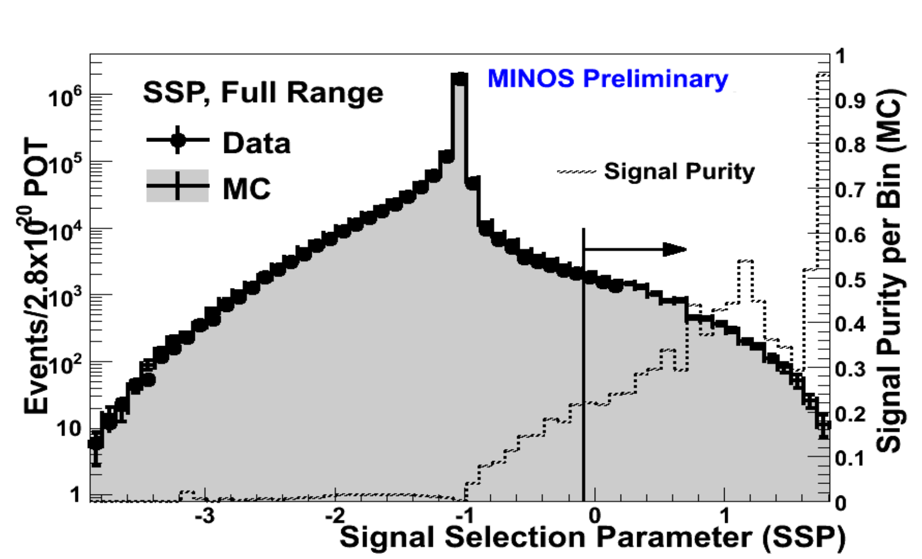


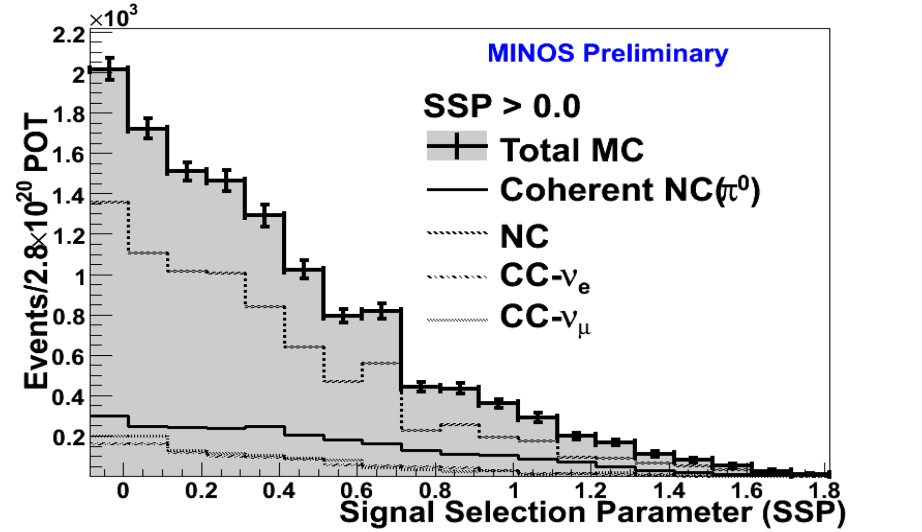
Support Vector Machines

- Multivariate classification algorithm
- Similar to:
  - Neural networks
  - k-Nearest neighbor
- Train based on MC
  - Plot events in attribute space
  - Draw borders between regions of signal and background
- Input: attributes for an event
- Output: distance to the nearest border
- Output used to select a sample of coherent NC(π^0) events



Event Selection:
Signal Selection Parameter

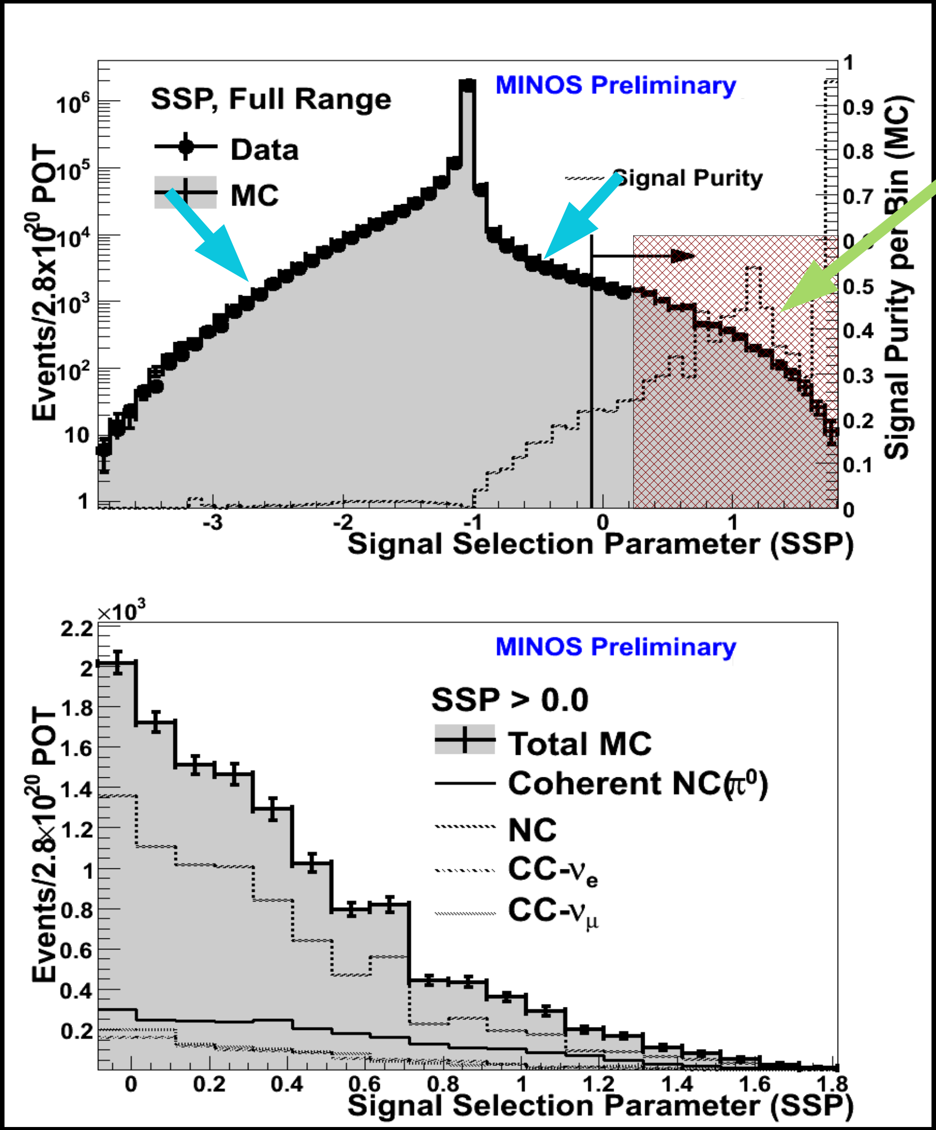




Event Selection

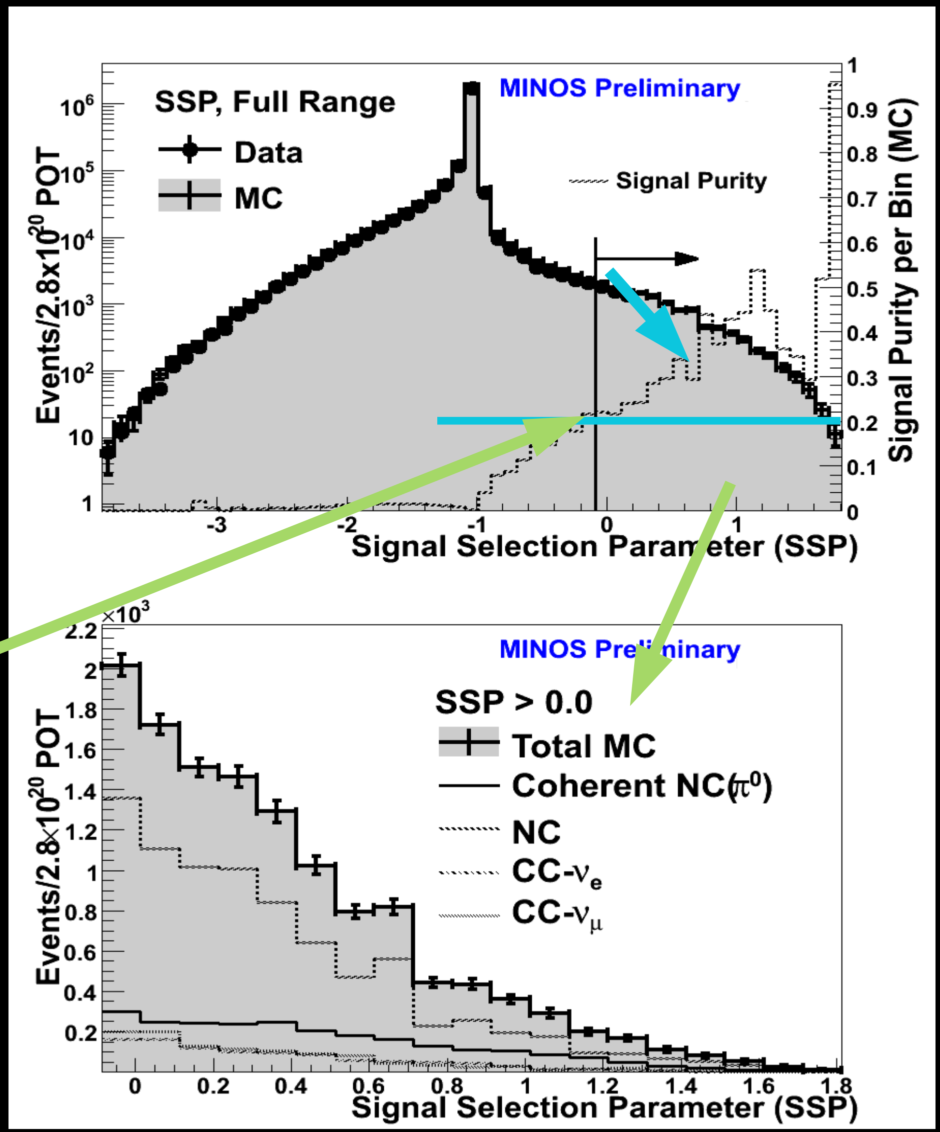
Data and MC are in agreement in the unblinded region

Blinded



Event Selection

Signal purity increases with increases values of the SSP



Blind regions with ρ > 20%

Signal purity (ρ):

$$\rho_i = \frac{N_i^{coh}}{N_i^{coh} + N_i^{bkg}}$$

For SSP bin i

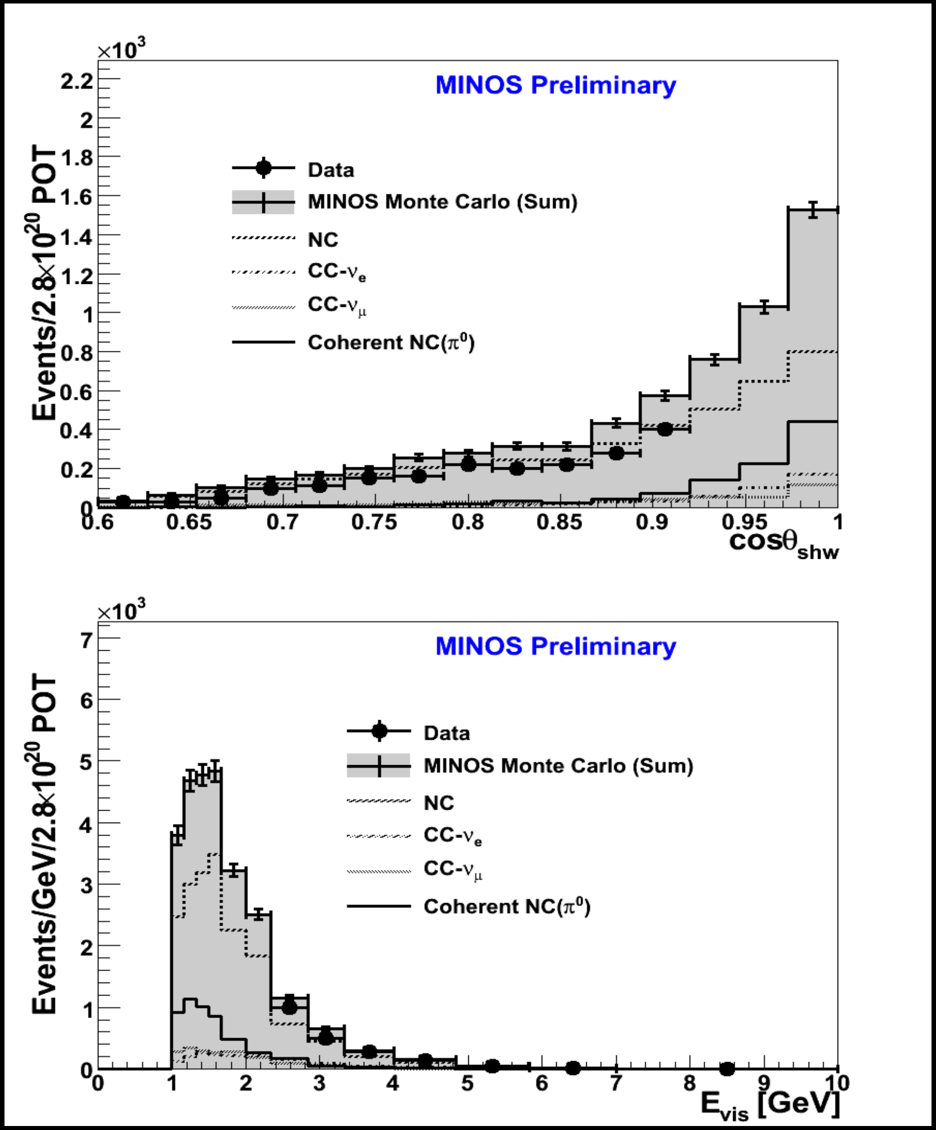
High SSP/High ρ region

NC – largest bkg

The Selected Sample
Relevant kinematic variables

cos θ$_{shw}$

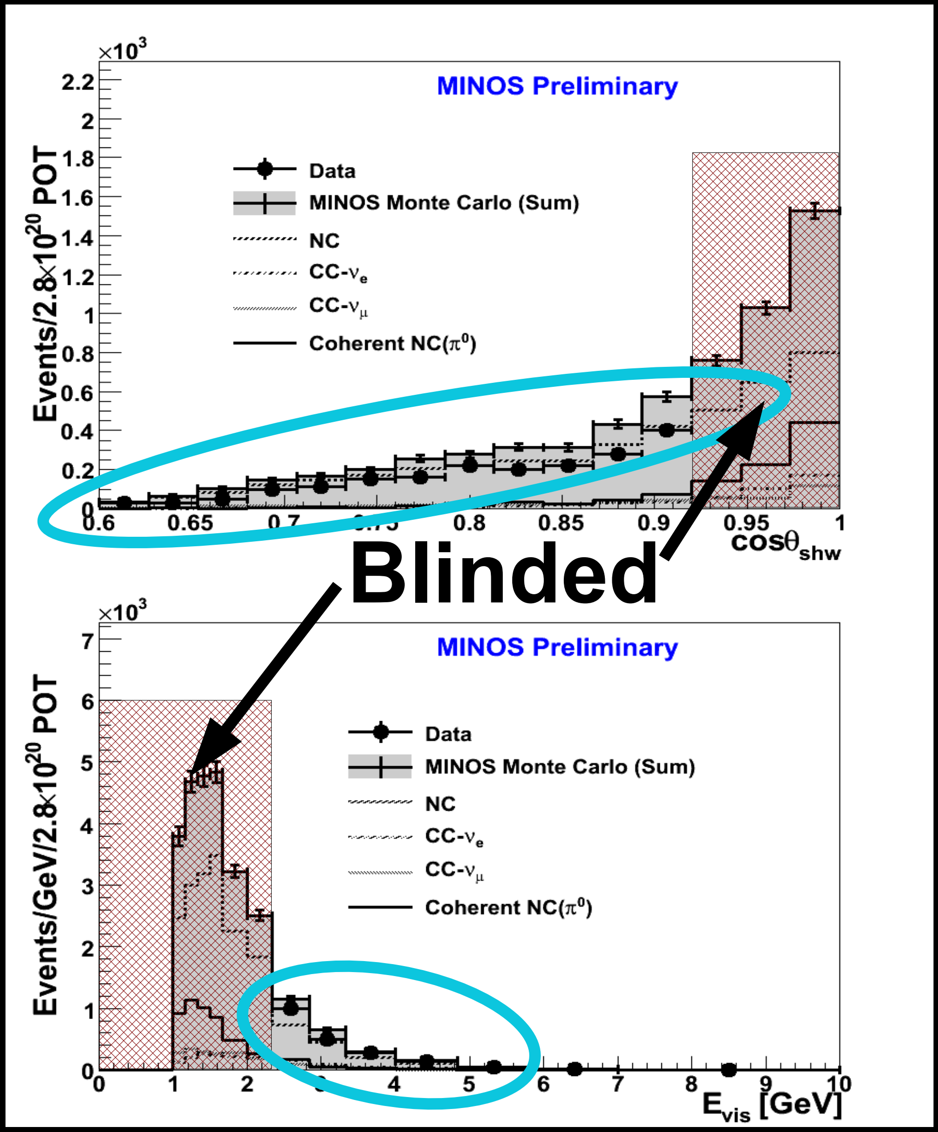
E$_{vis}$



Events selected based on SSP values

The Selected Sample

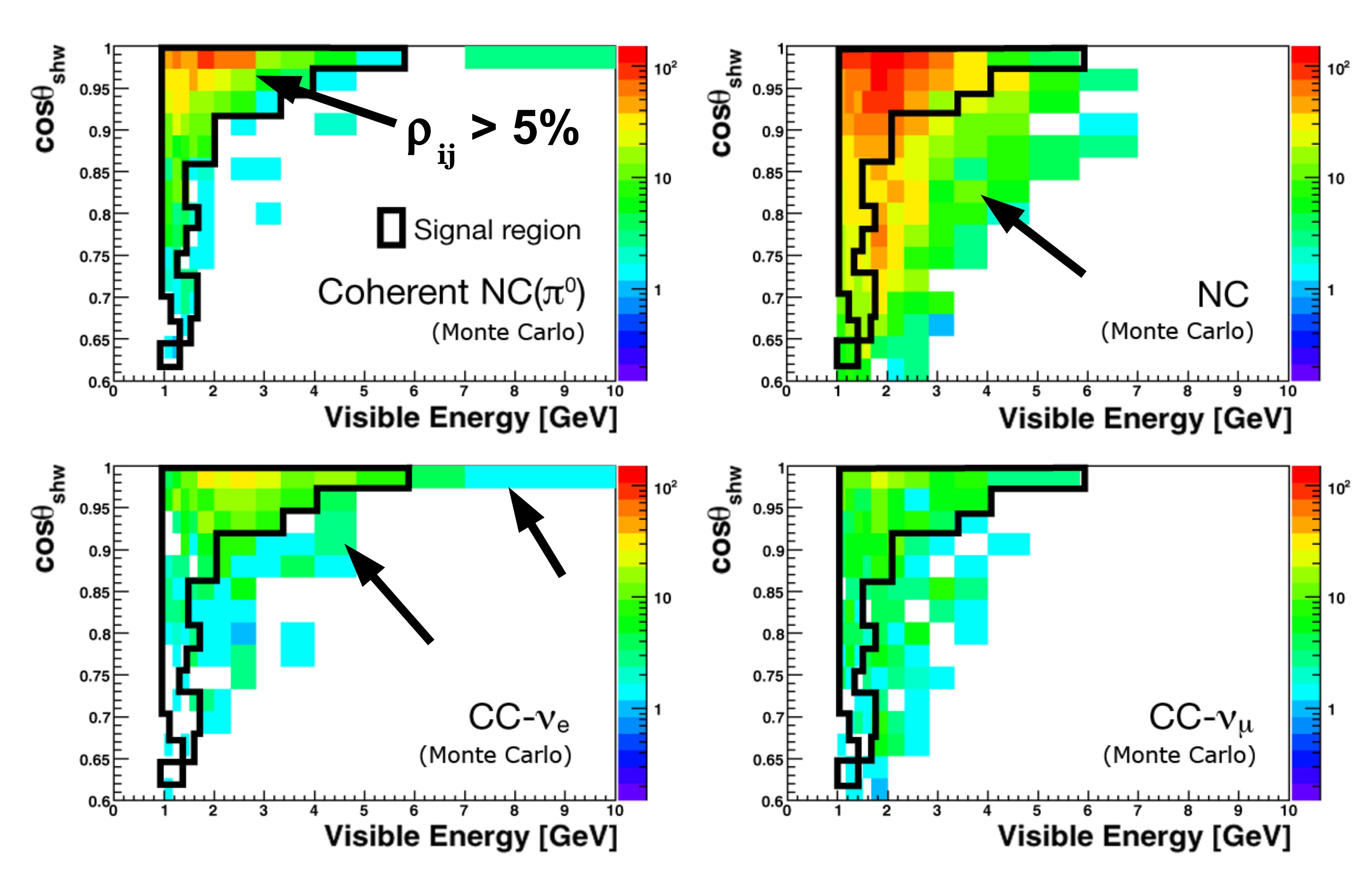
cos θ_{shw}



E_{vis}

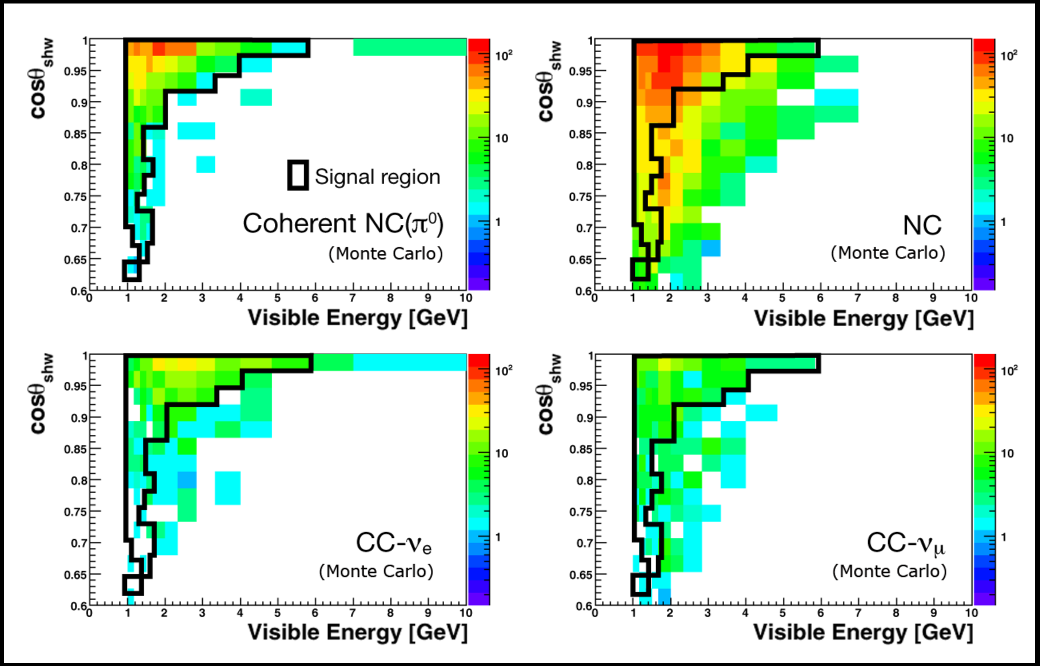
MC over-estimates the data in the selected sample by 20-30%

cosθ-vs-E_{vis}
Signal and Sideband Regions



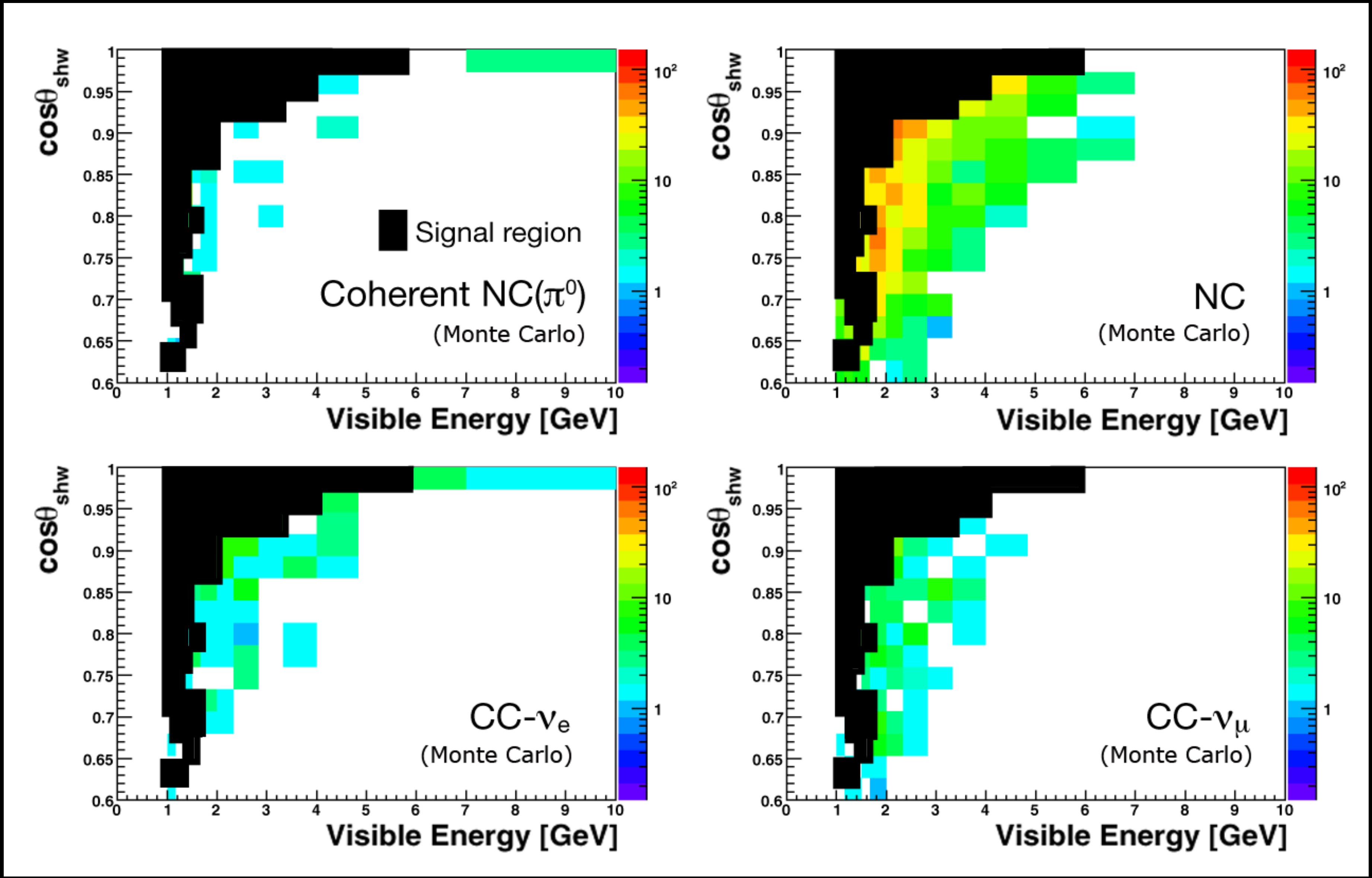
The Fitting Procedure

- Fit MC to the data
- Fit the sideband regions
- Fit Parameters – 5
  - Determined by systematics studies
  - Background template normalizations - 3
  - Background template shapes (systematics) - 2

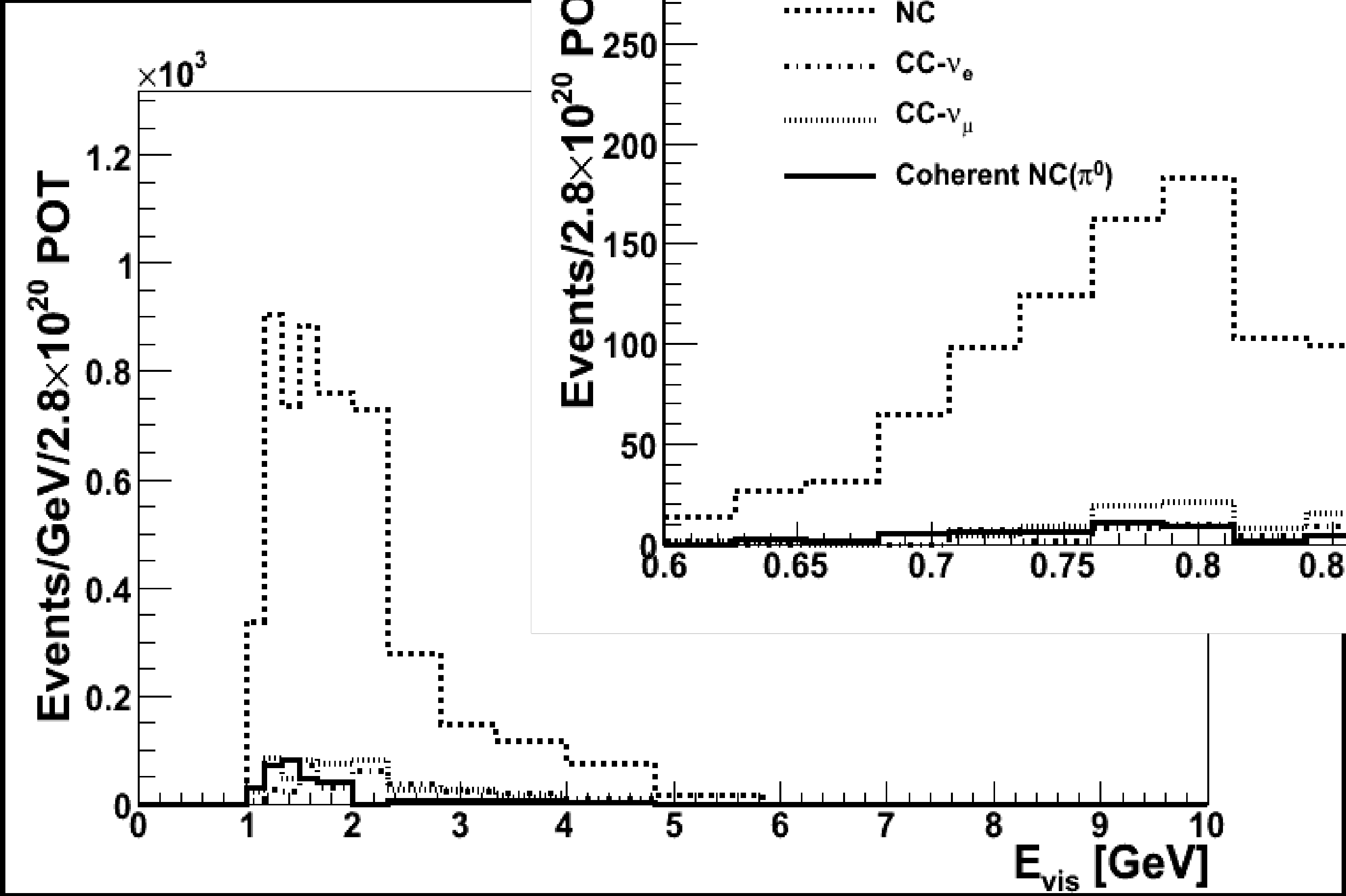


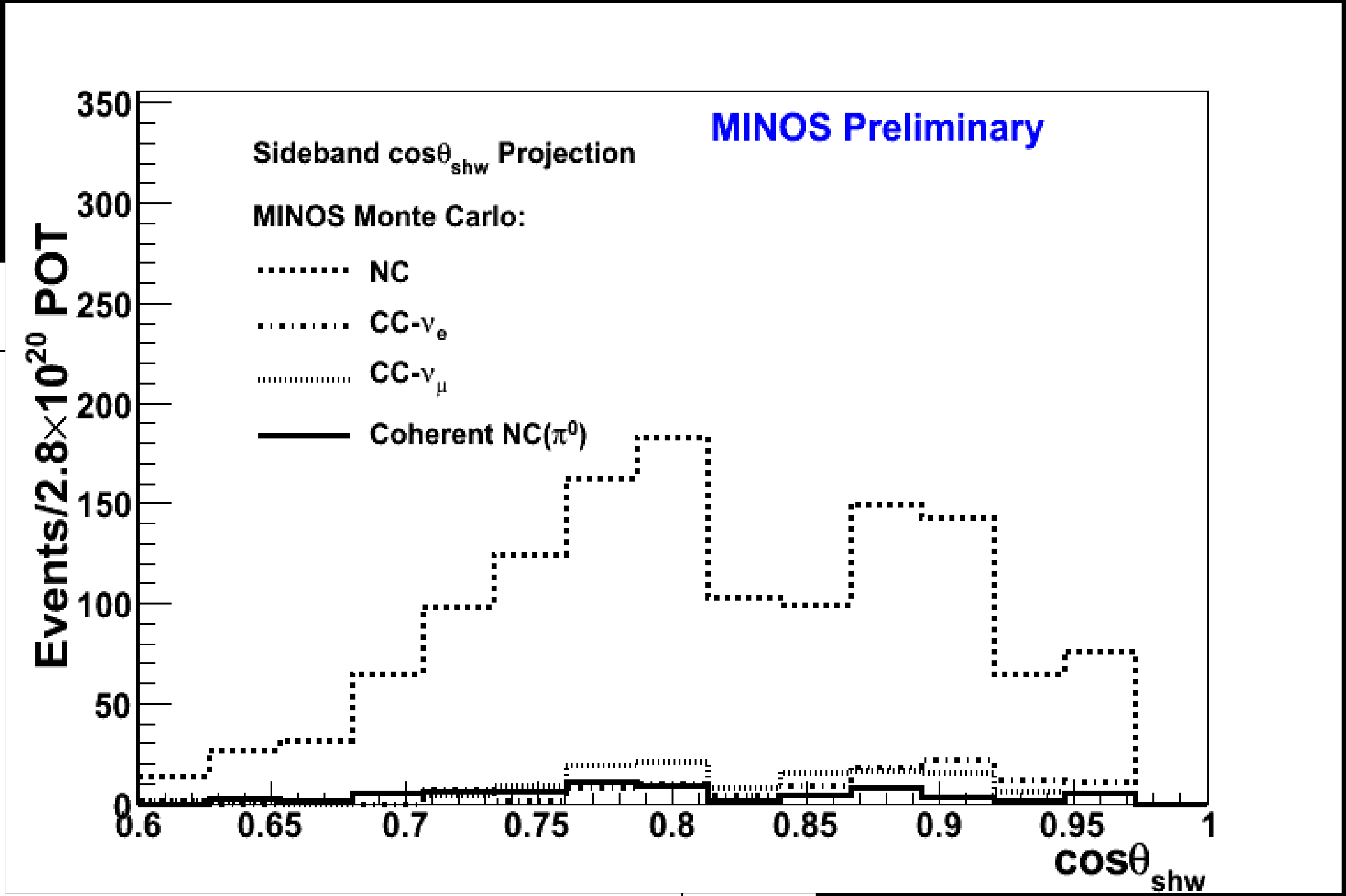
- Extrapolate backgrounds into the signal region
- Signal = Data - Backgrounds
- Apply acceptance corrections

cosθ-vs-E_{vis} Sideband Region: Projections

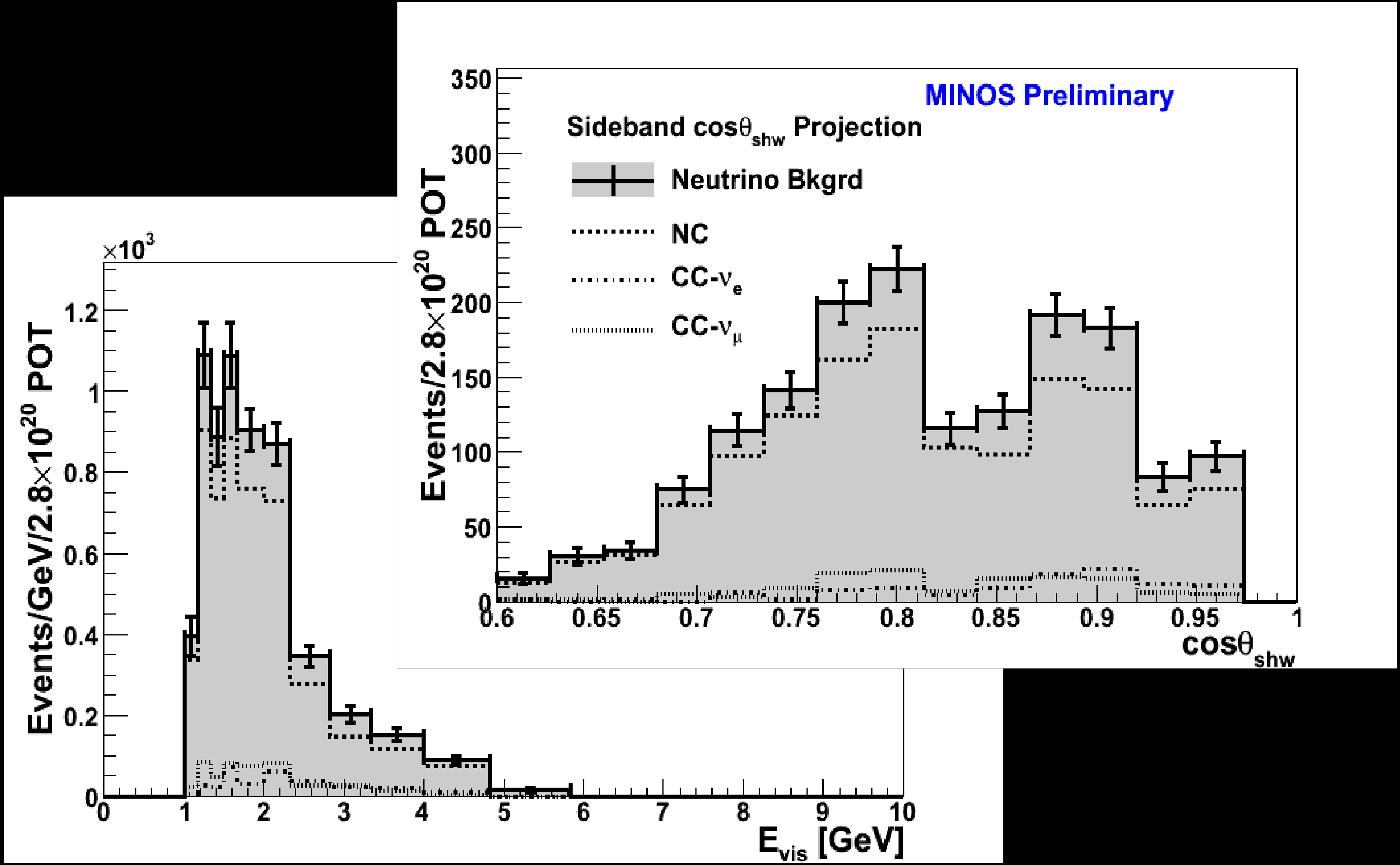


MC Sideband Projections

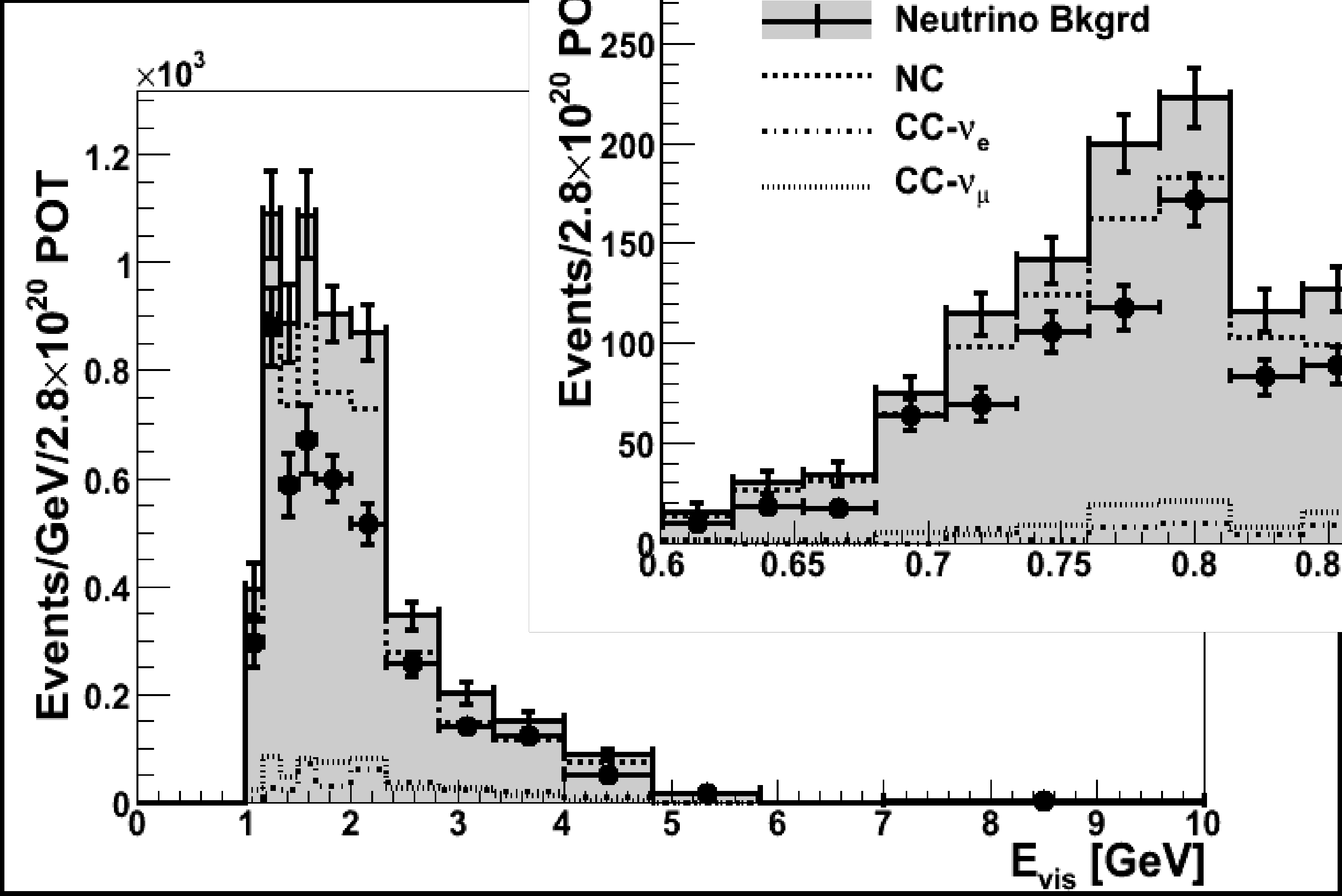


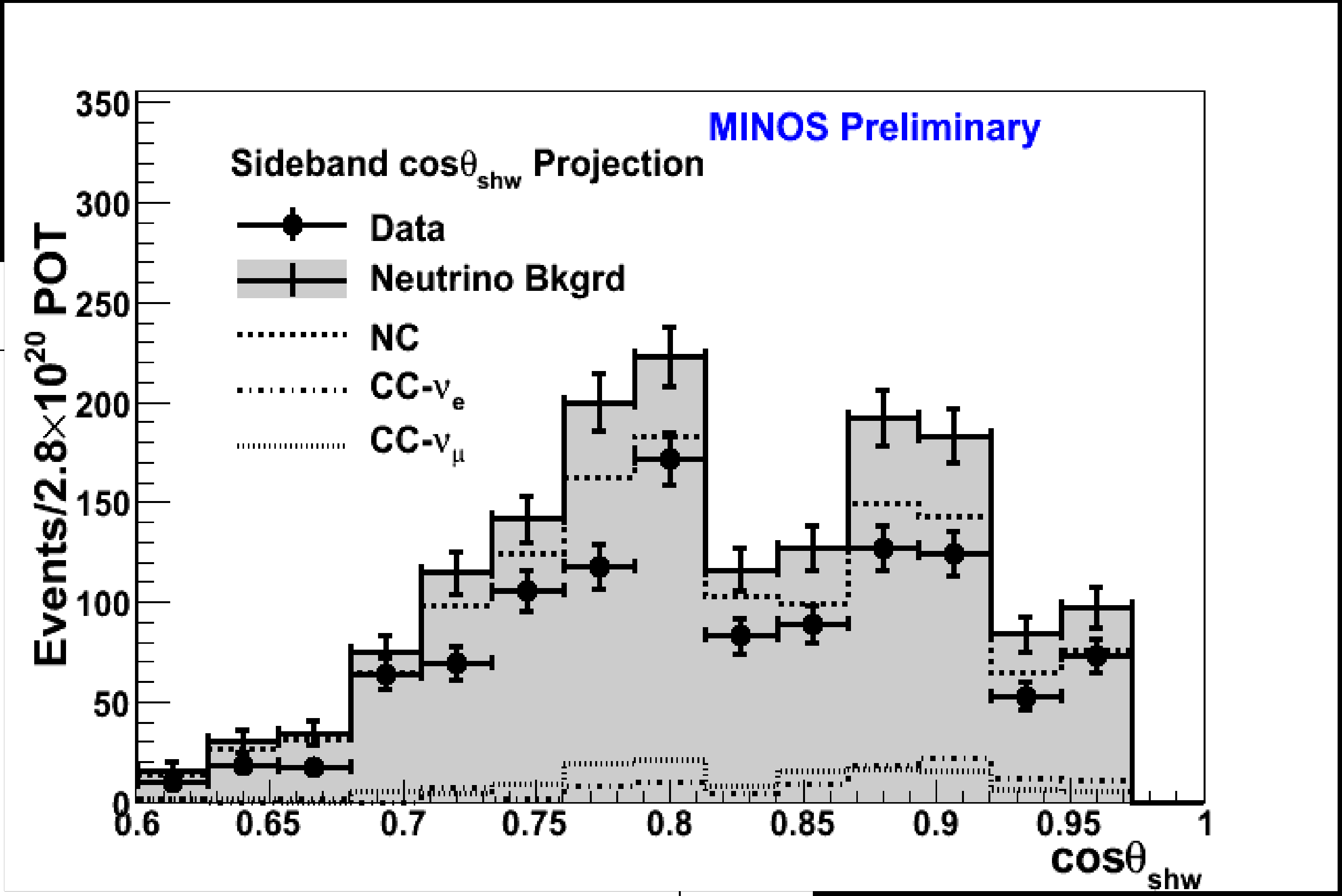


MC Sideband Projections (Sum)

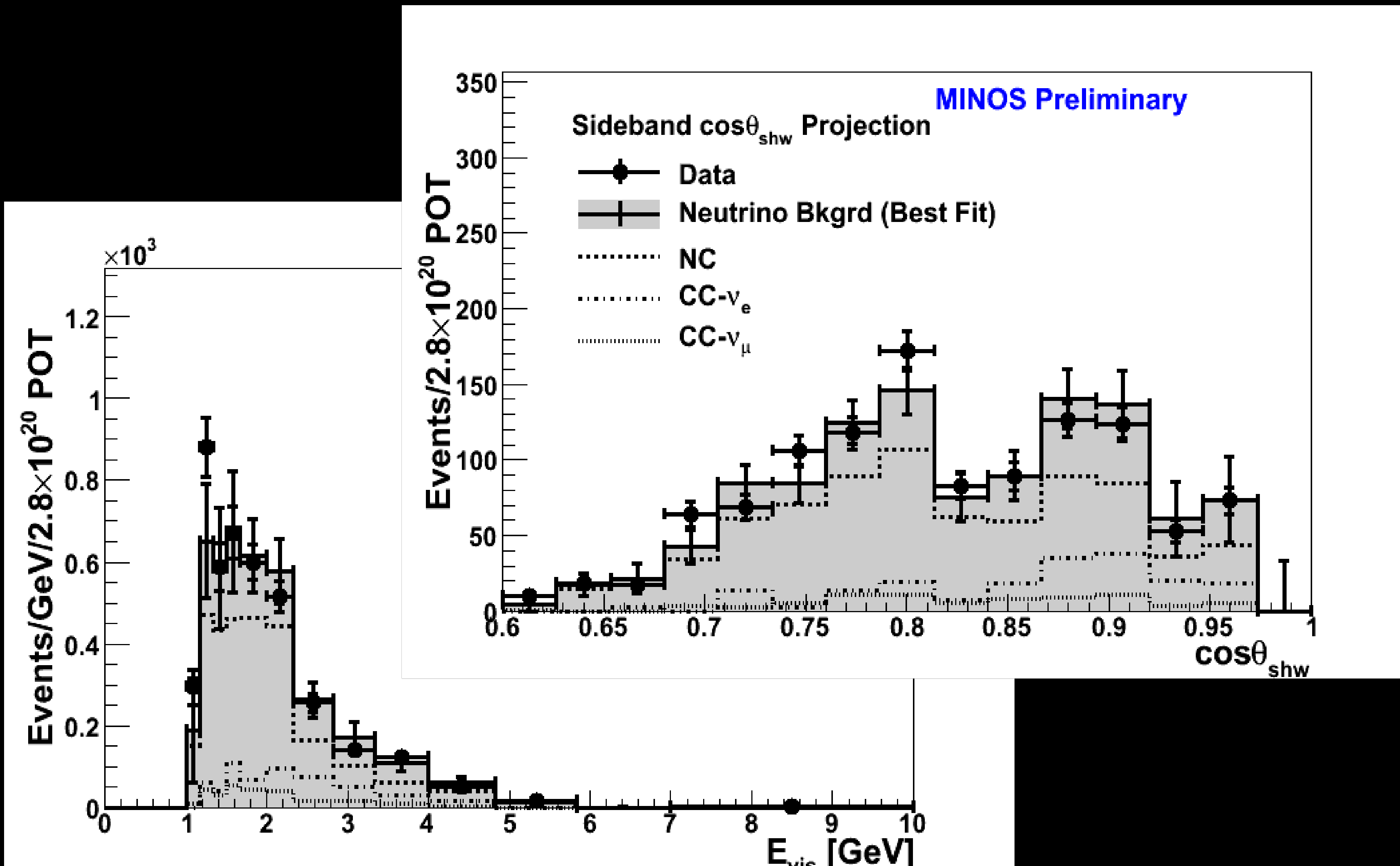


Data and MC in the Sidebands

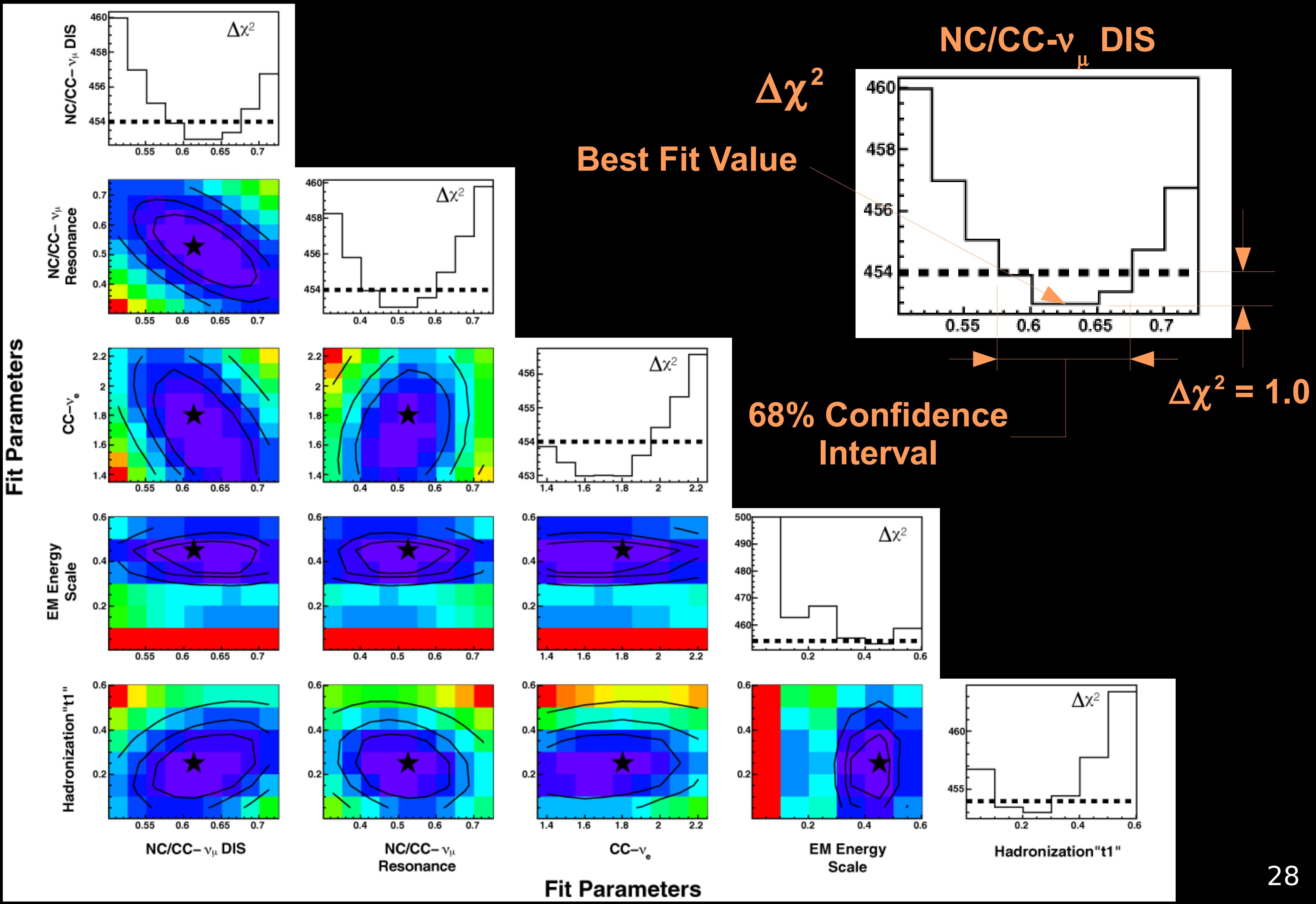




Sidebands: MC Fit to the Data



Fit Parameter $\Delta\chi^2$s



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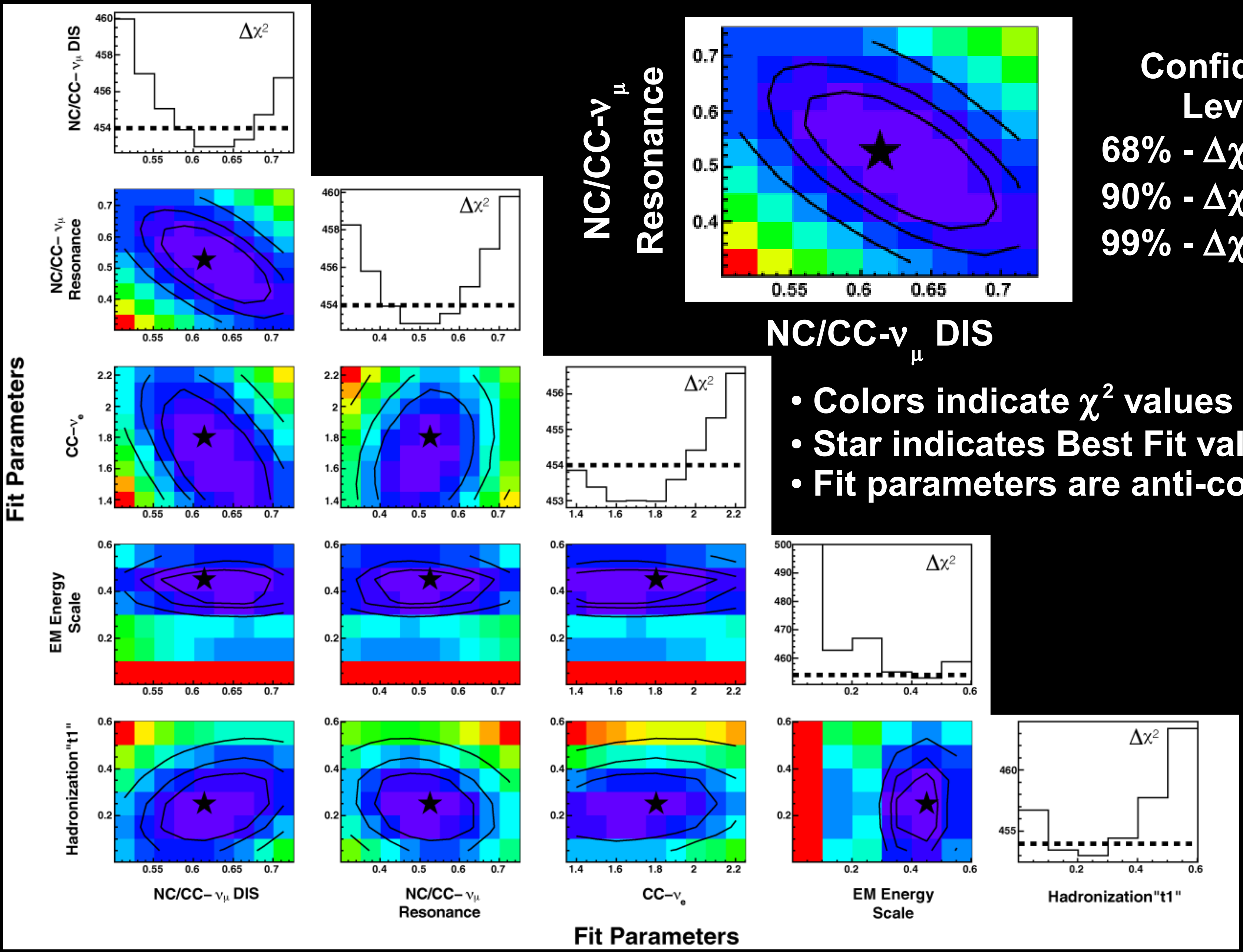


Confidence Levels

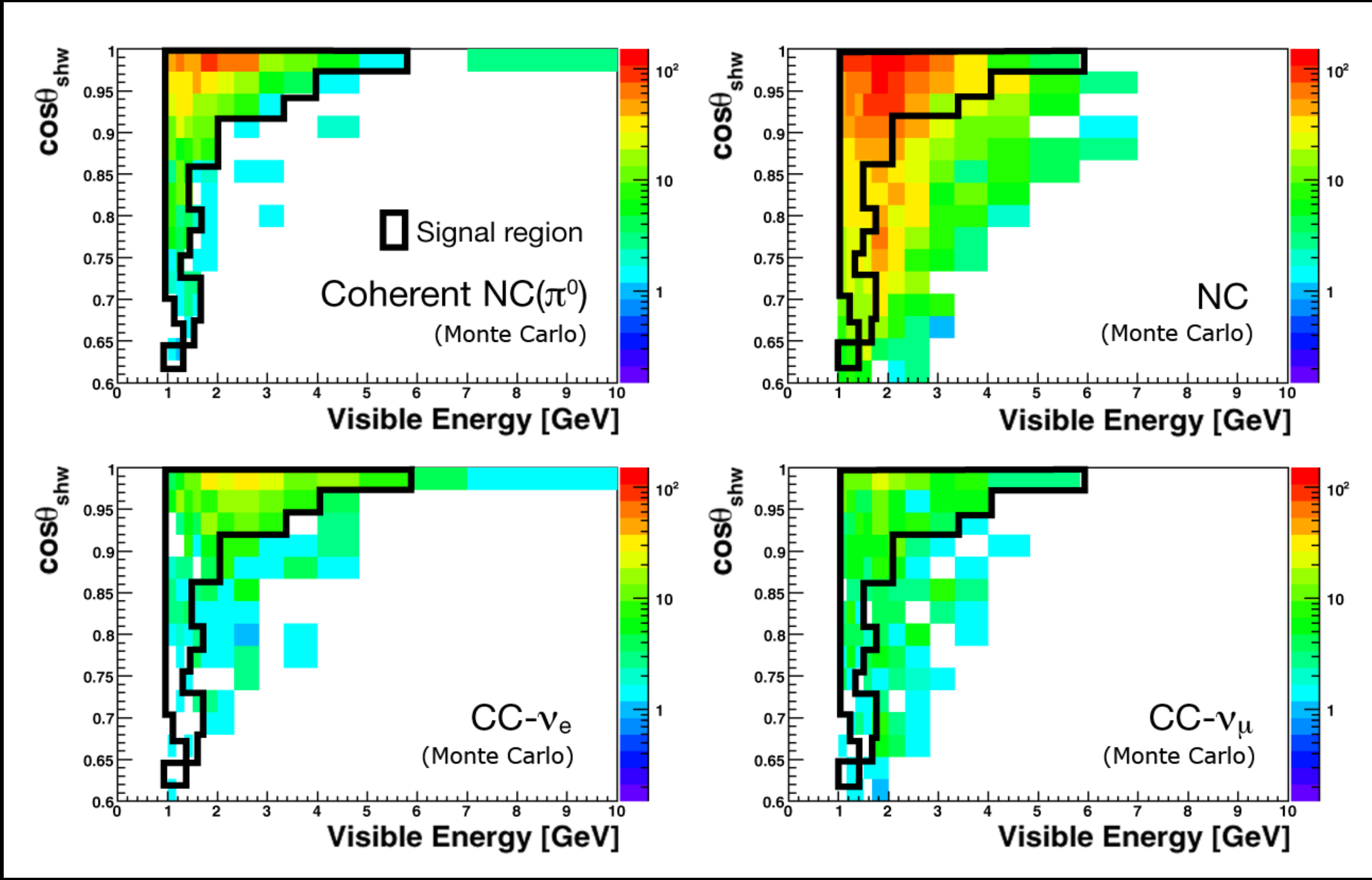
68% - $\Delta\chi^2$ = 2.30

90% - $\Delta\chi^2$ = 4.61

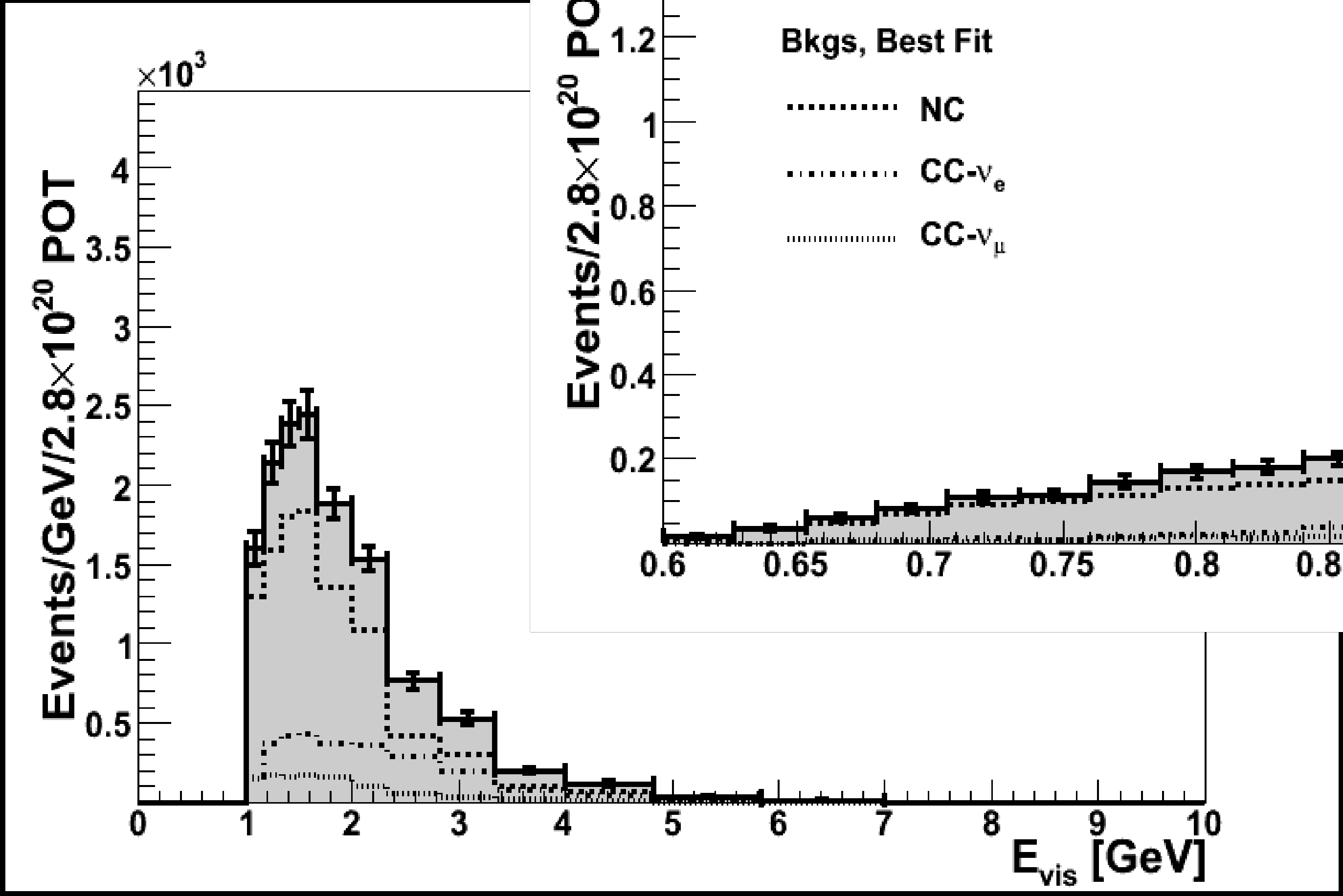
99% - $\Delta\chi^2$ = 9.21

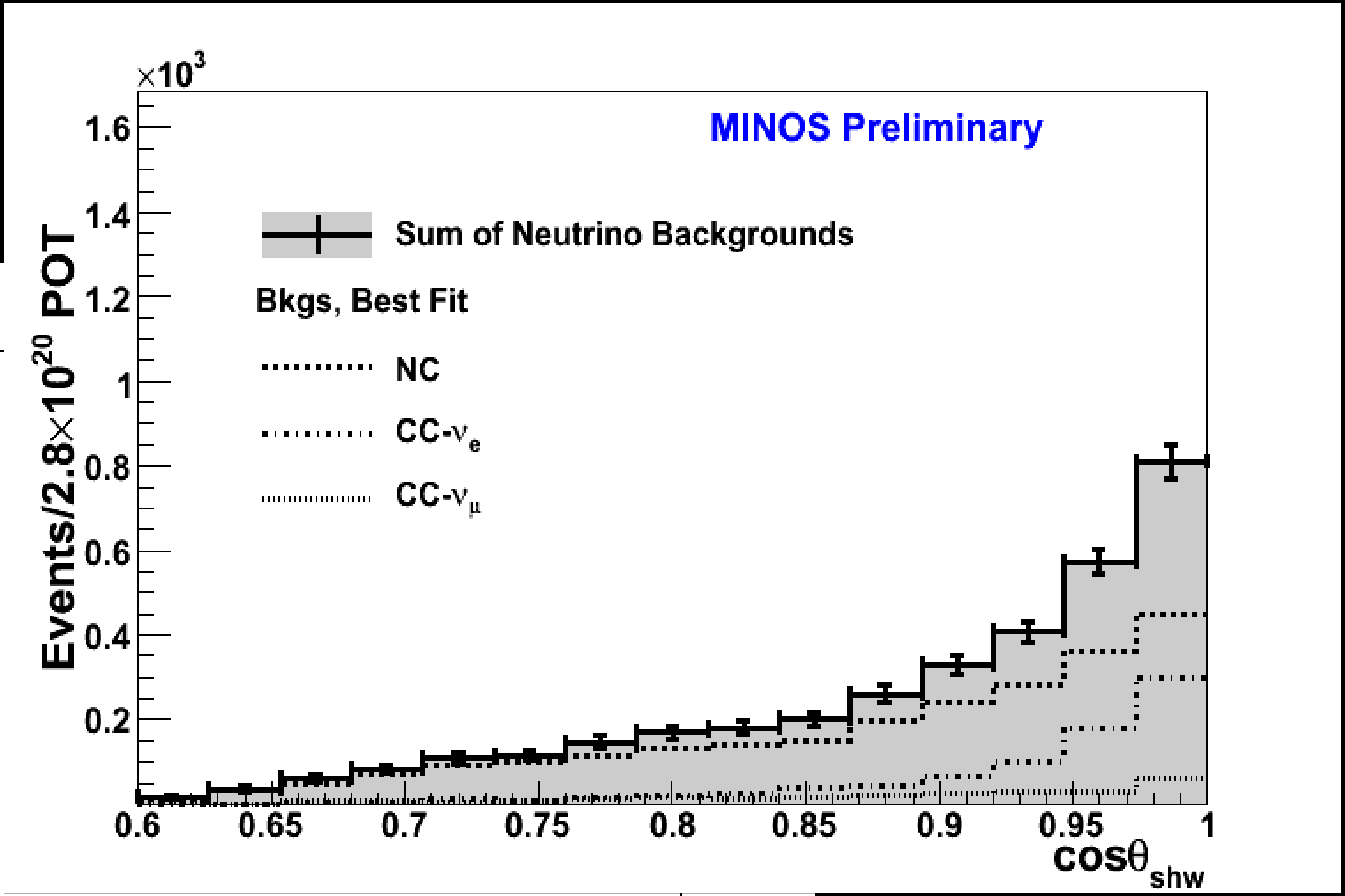
- **Colors indicate χ^2 values**
- **Star indicates Best Fit values**
- **Fit parameters are anti-correlated**

$\cos\theta$-vs-E_{vis}
Extrapolate to the Signal Region

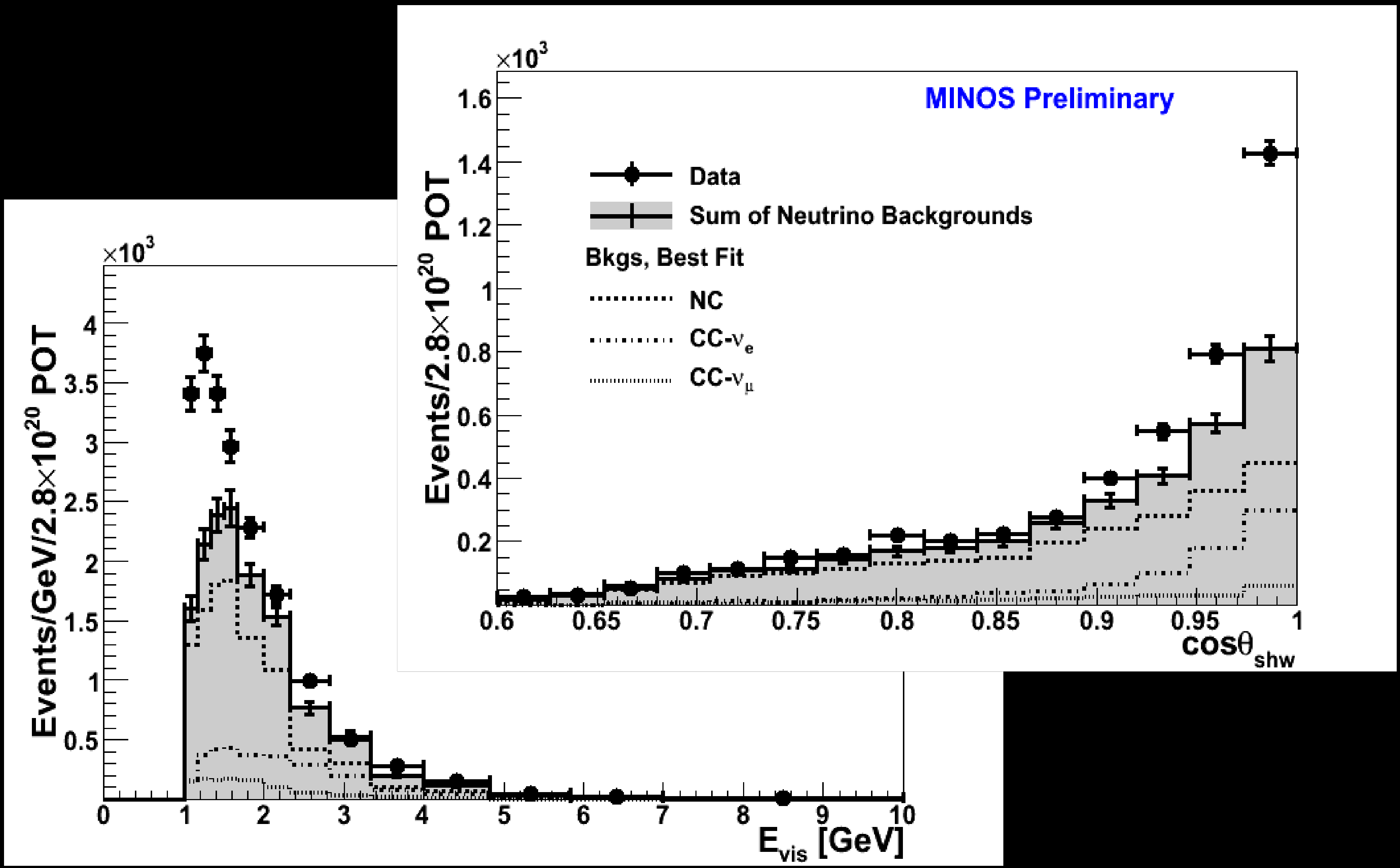


Best-Fit MC Backgrounds: Signal + Sideband

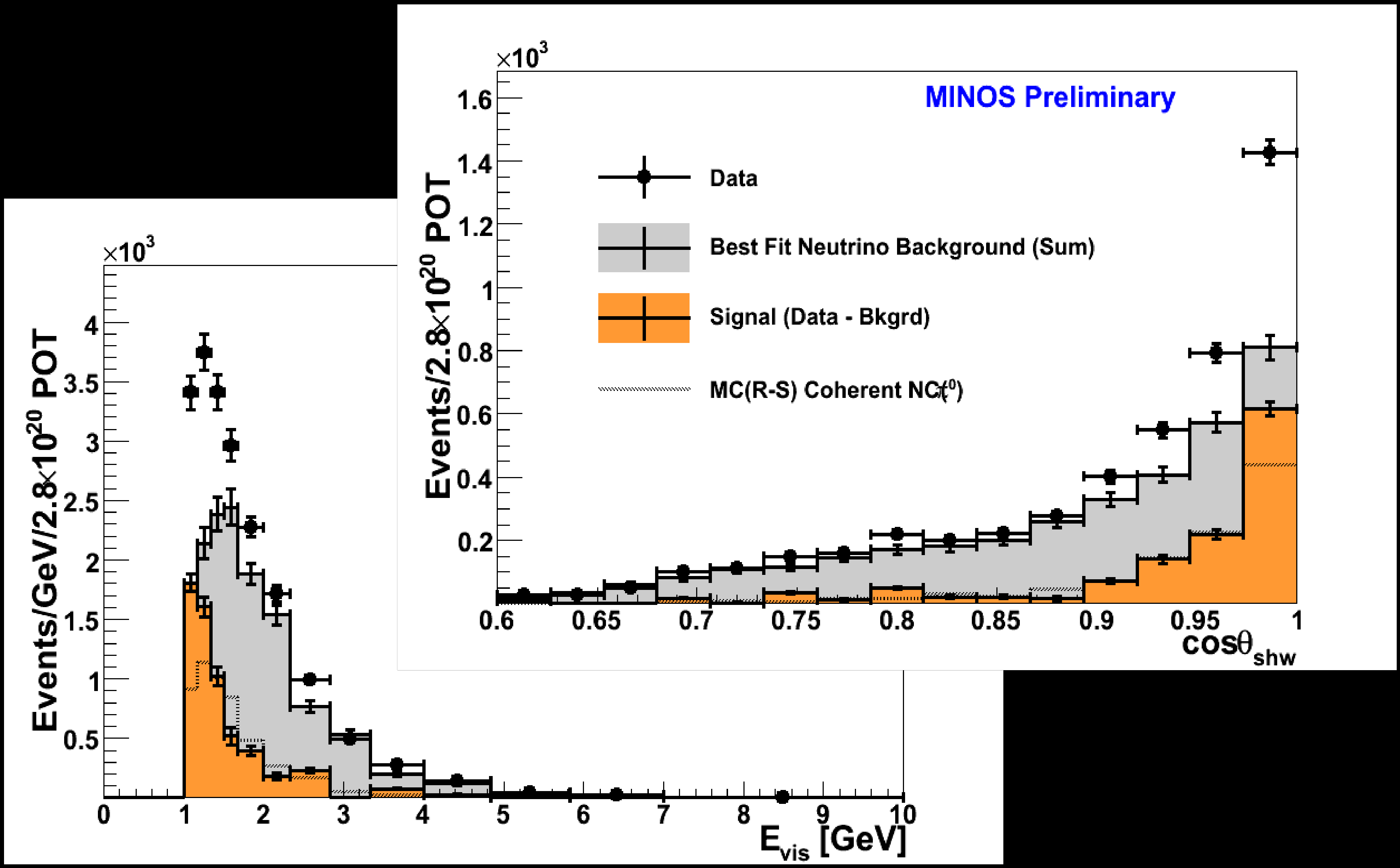




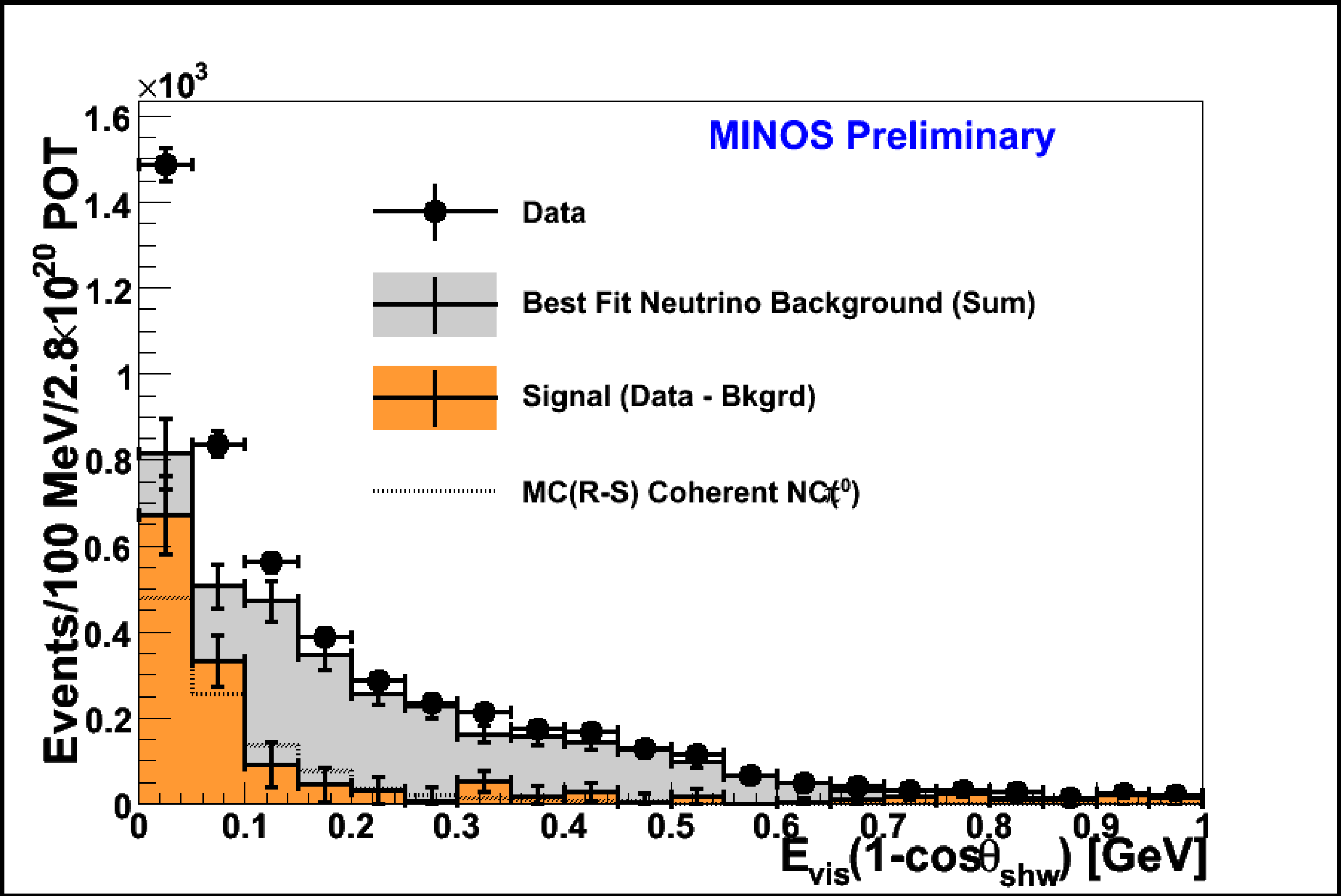
(Data) – (Best-Fit MC) = Signal



Measured Coherent NC(π^0) Event Rate



Measured Coherent NC(π^0) Event Rate: $\eta \equiv E_{vis}(1\text{-}\cos\theta_{shw})$

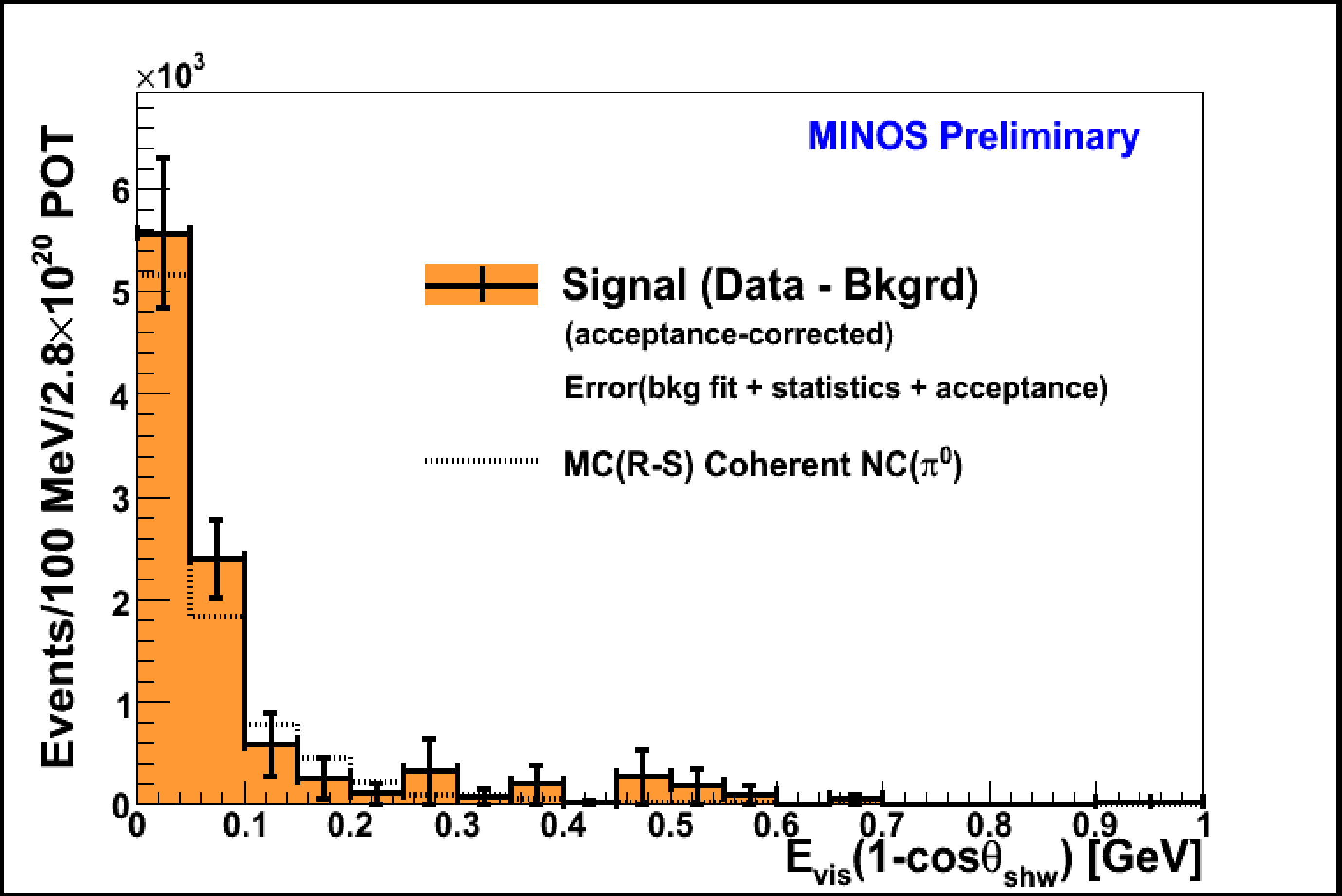


Selected Coherent NC(π^0) Event Rate:
1401±401 (29%)

Error Bars:
- **Fit Errors – $\Delta\chi^2$ 68% Confidence Interval**
- **Statistical Error on the data and MC**

Excess seen at low values of η

Acceptance Corrected Coherent NC(π^0) Event Rate



Total Coherent NC(π^0) Event Rate:
9241±2832 (29%)

Error Bars:

- **Fit Errors – $\Delta\chi^2$ 68% Confidence Interval**
- **Statistical Error on the data and MC**
- **Bin-by-bin Acceptance Correction Errors**

No acceptance correction for events with E_π < 1.0 GeV

Accounting for Systematic Errors

Sources of Systematic Error

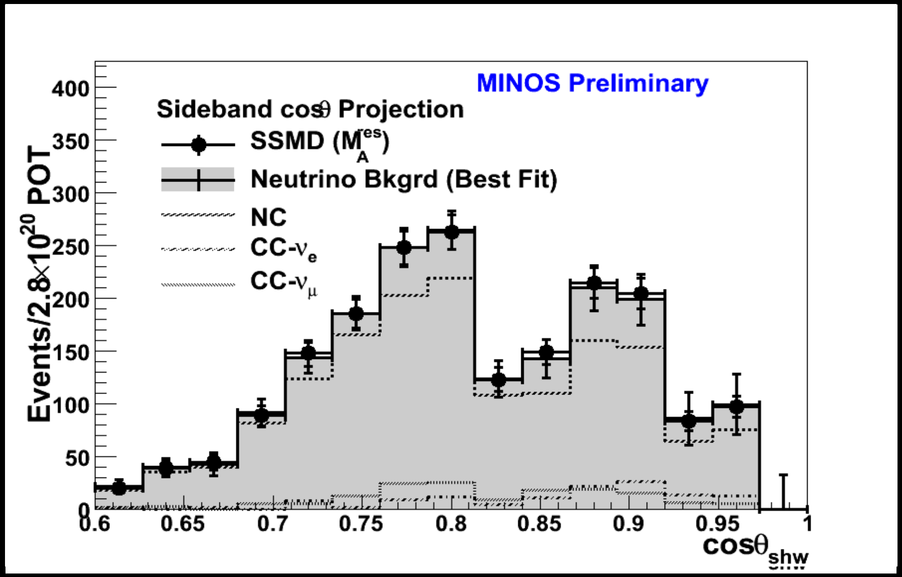
- Hadronization Model
- Cross Section Models
- Intranuclear Rescattering Model
- Detector Calibration
- NuMI ν Flux

Single Systematic Mock Data (SSMD)

- Pupose:
  - Optimize fits
  - Understand systematics
- Method:
  - Use Reweighted MC as data
  - Fit using 3 norm. fit params.
  - Analyze fit results

Single Systematic Mock Data Studies: Two Extremes

Axial Mass (res)



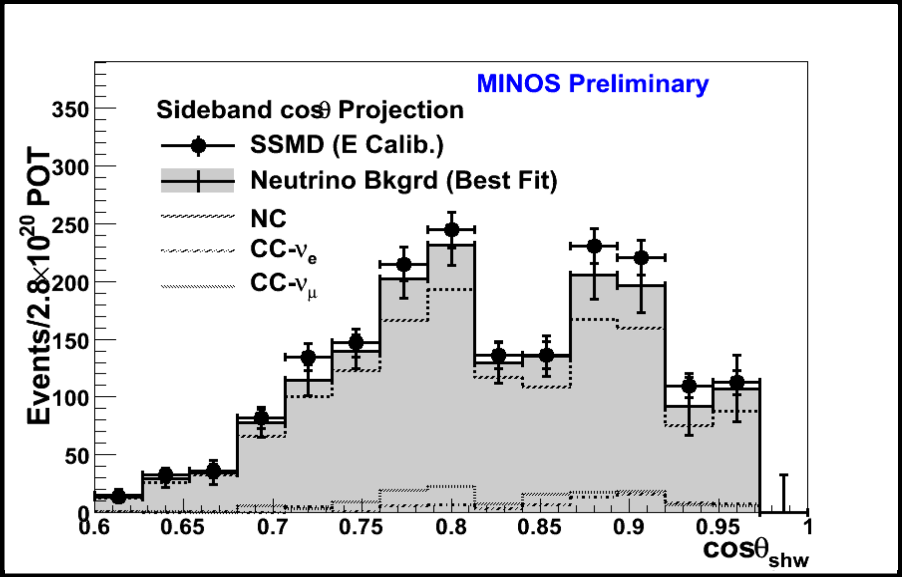
χ^2/ndf = 0.02

N_{fit} = 6696

N_{MC} = 7971

Changes to cosθ-vs-E_{vis} distributions accounted for by background template normalizations.

EM Energy Scale



χ^2/ndf = 3.34

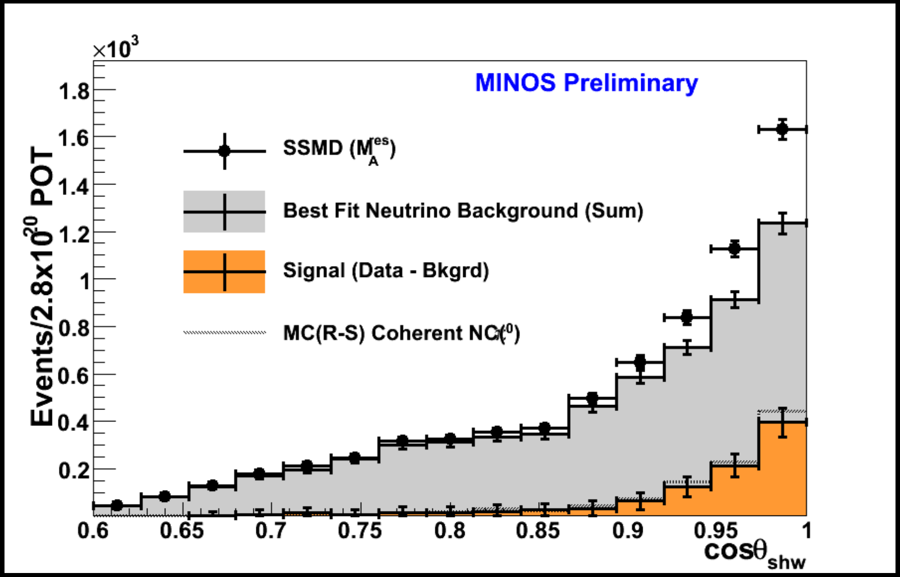
N_{fit} = 9645

N_{MC} = 7971

Causes shape changes to the cosθ-vs-E_{vis} distributions requires additional fit parameter.

Single Systematic Mock Data Studies: Two Extremes

Axial Mass (res)



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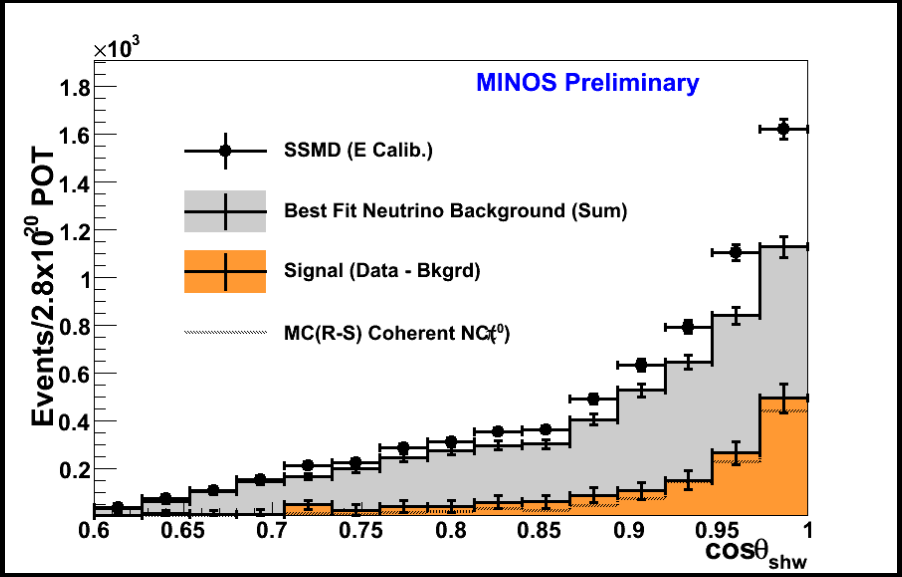

χ^2/ndf = 3.34

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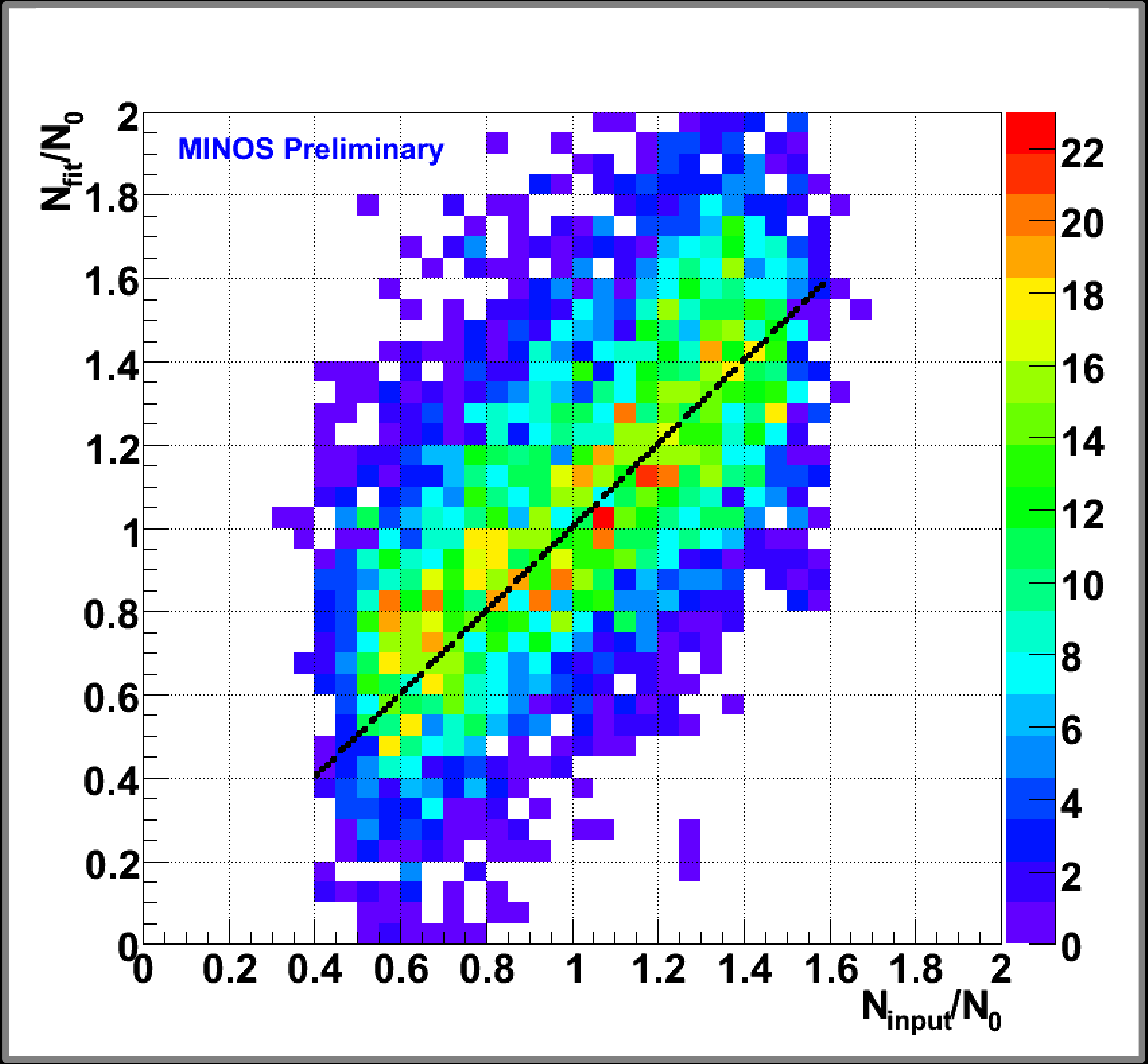
Measurement Sensitivity: Mock Data Studies

Random fluctuations of:

- The coherent NC(π^0) event rate (N_{input})
- 22 systematic error sources
- Bin counts (Poisson statistics)

Measured number of coherent NC(π^0) events (N_{fit})

Coherent NC(π^0) events in the MC (N_0)



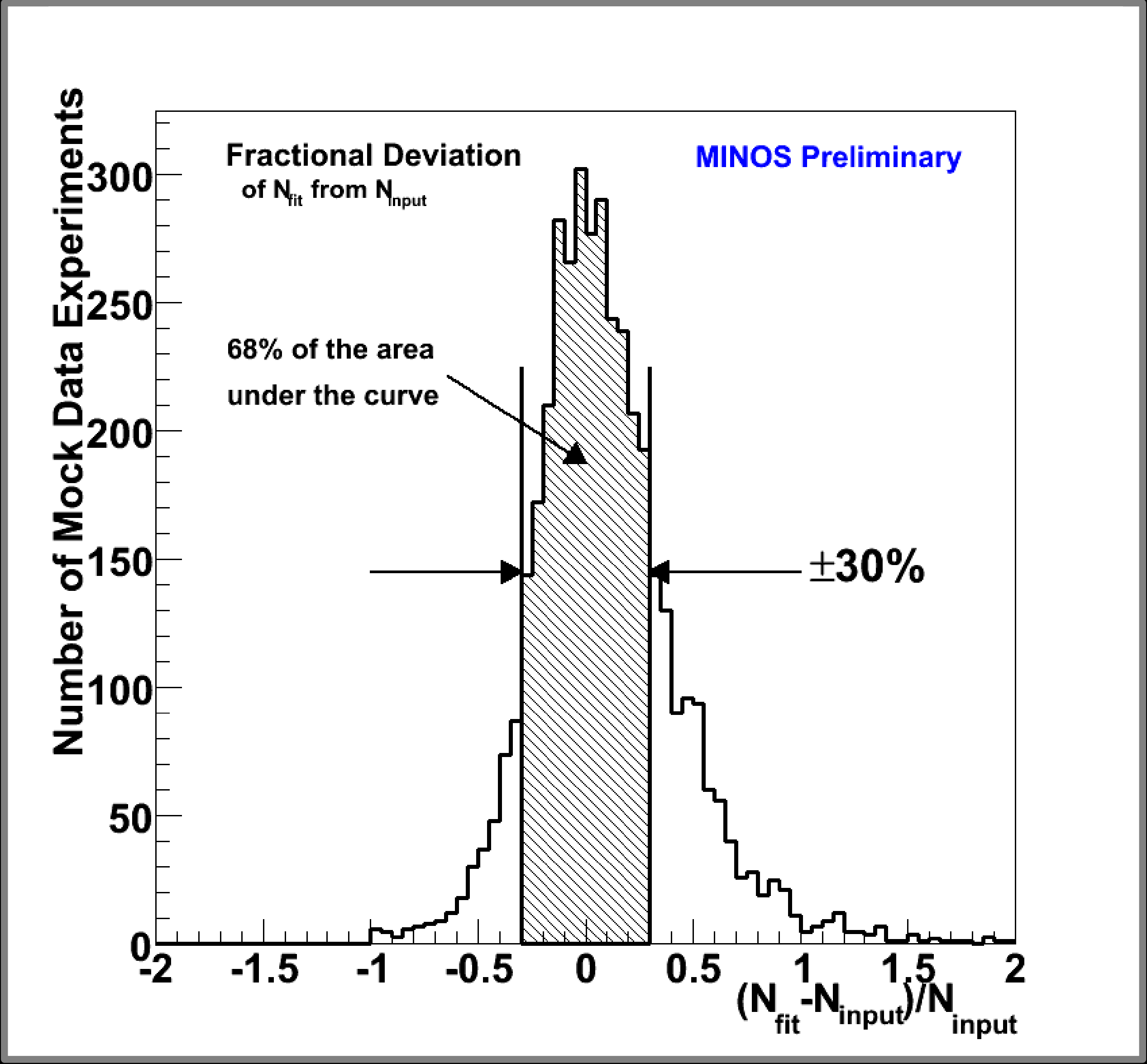
Measurement Sensitivity:
Mock Data Studies

Fractional Deviation (***f***) of N_{fit} from N_{input}

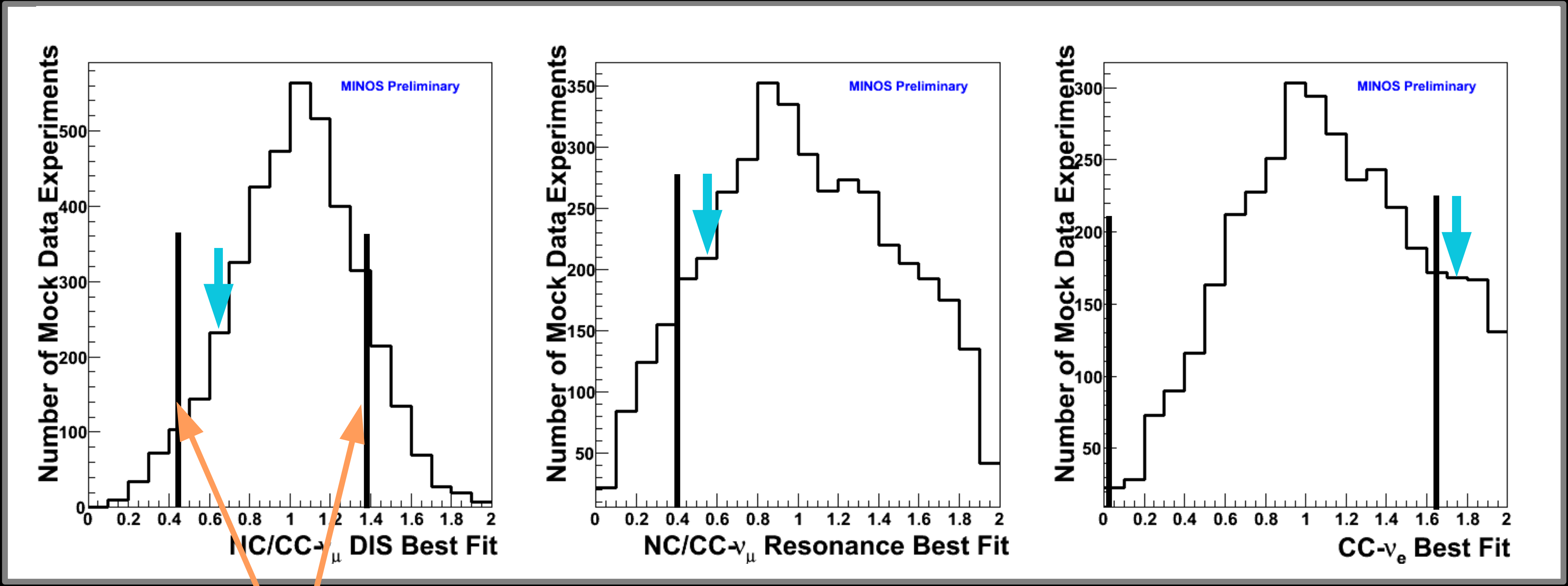
$$f = \frac{N_{fit} - N_{input}}{N_{input}}$$

Width of ***f*** used to determine the experimental error from:

- Statistical fluctuations
- Systematic error sources



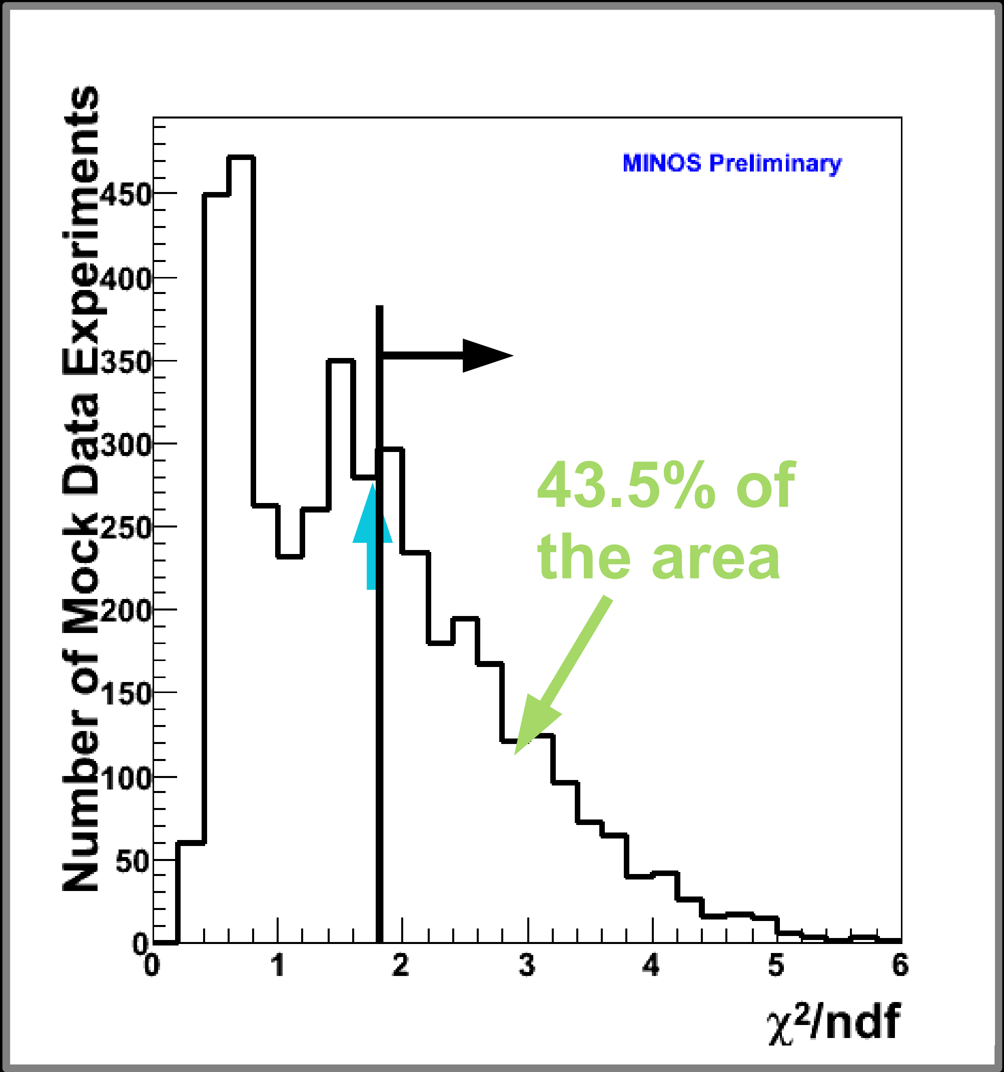
Mock Data Studies



One σ limits on fit parameters

- **Based on Systematic Error Studies**
- **Used in the penalty terms of the fits**

Mock Data Studies



The Coherent NC(π^0) Cross Section (E_π > 1.0 GeV)

- $\mathcal{E}$ = Neutrino exposure [PoT]
- $\mathcal{M}_\mathcal{T}$ = Target mass [nuclei]
- Φ = Integrated flux [ν/cm^2/PoT]

$$\sigma = \frac{N}{\mathcal{E}\,\mathcal{M}_\mathcal{T}\,\Phi}$$

- $\mathcal{E}$ = $(2.8 \pm 0.028) \times 10^{20}$ PoT
- $\mathcal{M}_\mathcal{T}$ = $(3.57 \pm 0.001) \times 10^{29}$ nuclei
- Φ = $(2.93 \pm 0.23) \times 10^{-8}$ ν/cm^2/PoT

- **Detector Makeup**
  - **~80% Fe^{56}**
  - **~20% C^{12}**
- **Avg Nucleus = 48**

$$\sigma = \frac{9241}{2.8 \times 3.57 \times 2.93 \times 10^{41}}$$

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- **Detector Makeup**
  - **~80% Fe^{56}**
  - **~20% C^{12}**
- **Avg Nucleus = 48**

$$\sigma = (\text{٣١.٦} \pm \text{١٠.٥}) \times \text{١٠}^{-\text{٤٠}} \frac{cm^{\text{٢}}}{Nucl.\,(A = \text{٤٨})}$$

The Coherent NC(π^0) Cross Section – on Fe^{56}

- NEUGEN3 Cross section ratio
- ~90.6% of events occur on Fe^{56}
- Additional 20% uncertainty

$$\sigma = \frac{N}{\mathcal{E} \mathcal{M}_{\mathcal{T}} \Phi}$$

- $\mathcal{E}$ = (2.8±0.028) x 10^{20} PoT
- $\mathcal{M}_{\mathcal{T}}$ = (2.89±0.001) x 10^{29} Fe^{56} nuclei
- Φ = (2.93±0.23) x 10^{-8} ν/cm^2/PoT

8372

Coherent NC(π^0) Events on Fe^{56}

$$\sigma = (35.3 \pm 12.4) \times 10^{-40} \frac{cm^2}{Fe^{56}\,Nucleus}$$

The Coherent NC(π^0) Cross Section – on C^{12}

- NEUGEN3 Cross section ratio
- ~9.4% of events occur on C^{12}
- Additional 20% uncertainty

$$\sigma = \frac{N}{\mathcal{E}\,\mathcal{M}_{\mathcal{T}}\,\Phi}$$

- $\mathcal{E}$ = (2.8±0.028) x 10^{20} PoT
- $\mathcal{M}_{\mathcal{T}}$ = (6.57±0.001) x 10^{28} C^{12} nuclei
- Φ = (2.93±0.23) x 10^{-8} ν/cm^2/PoT

869

Coherent NC(π^0) Events on C^{12}

$$\sigma = (16.1 \pm 8.5) \times 10^{-40} \frac{cm^2}{C^{12}\,Nucleus}$$

Cross Section on Fe^{56} and C^{12}

Experiment	$\mathcal{A}$ [amu]	Minimum π^0 Energy $E_{\pi^0}^{min}$ [GeV]	Number of Coherent NC(π^0) Interactions	Coherent Cross Section σ^{coh} [10^{-40}cm^2/A]	Total Fractional Uncertainty [%]	Rein-Sehgal (NEUGEN3) Cross Section [10^{-40}cm^2/A]
MINOS	48	1.0	9241	31.6±10.5	33.0	26.8
	56		8372 (0.906 × 9241)	35.3±12.4	35.1	30.3
	12		869 (0.094 × 9241)	16.1±8.5	52.8	11.2
	48	0.0	16,762 (1.814 × 9241)	57.3±22.2	38.7	49.5
	56		15,187 (0.906 × 16762)	64.0±25.9	40.5	55.8
	12		1576 (0.094 × 16762)	29.2±16.5	56.5	22.0

Fully Acceptance Corrected Coherent NC(π^0) Cross Section

- Monte Carlo correction factor
- 45% of coherent NC(π^0) events have $E_\pi < 1.0$ GeV
- Additional 20% uncertainty

$$\sigma = \frac{N}{\mathcal{E}\,\mathcal{M}_{\mathcal{T}}\,\Phi}$$

- $\mathcal{E} = (2.8 \pm 0.028) \times 10^{20}$ PoT
- $\mathcal{M}_{\mathcal{T}} = (3.57 \pm 0.001) \times 10^{29}$ nuclei
- $\Phi = (2.93 \pm 0.23) \times 10^{-8}$ $\nu/cm^2/PoT$

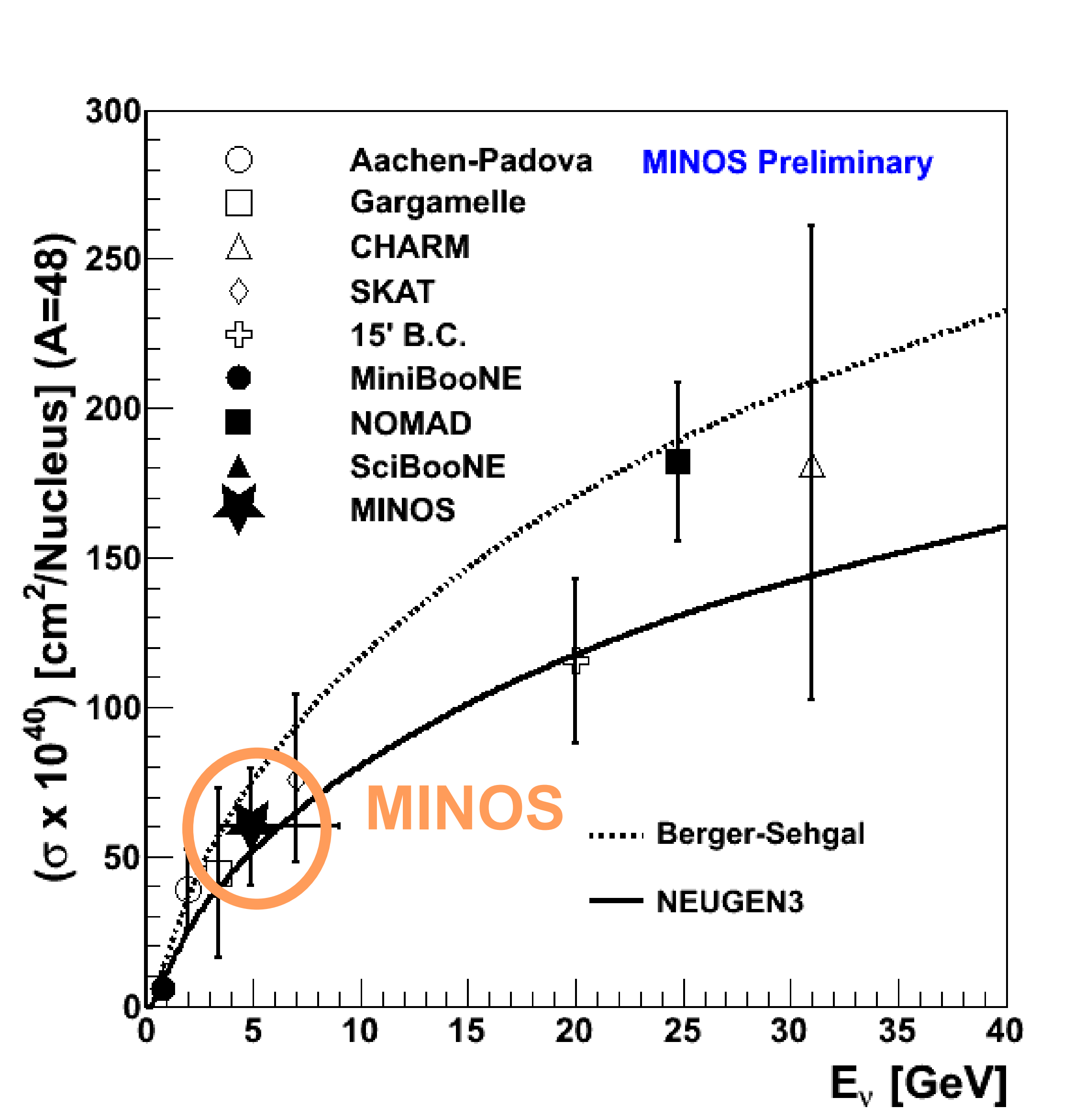
16,762

Coherent NC(π^0) Events (A = 48)

$$\sigma = (57.3 \pm 22.2) \times 10^{-40} \frac{cm^2}{Nucl.(A=48)}$$

Cross Section E_ν-Dependence

All results scaled to A = 48 with NEUGEN3 cross section ratios



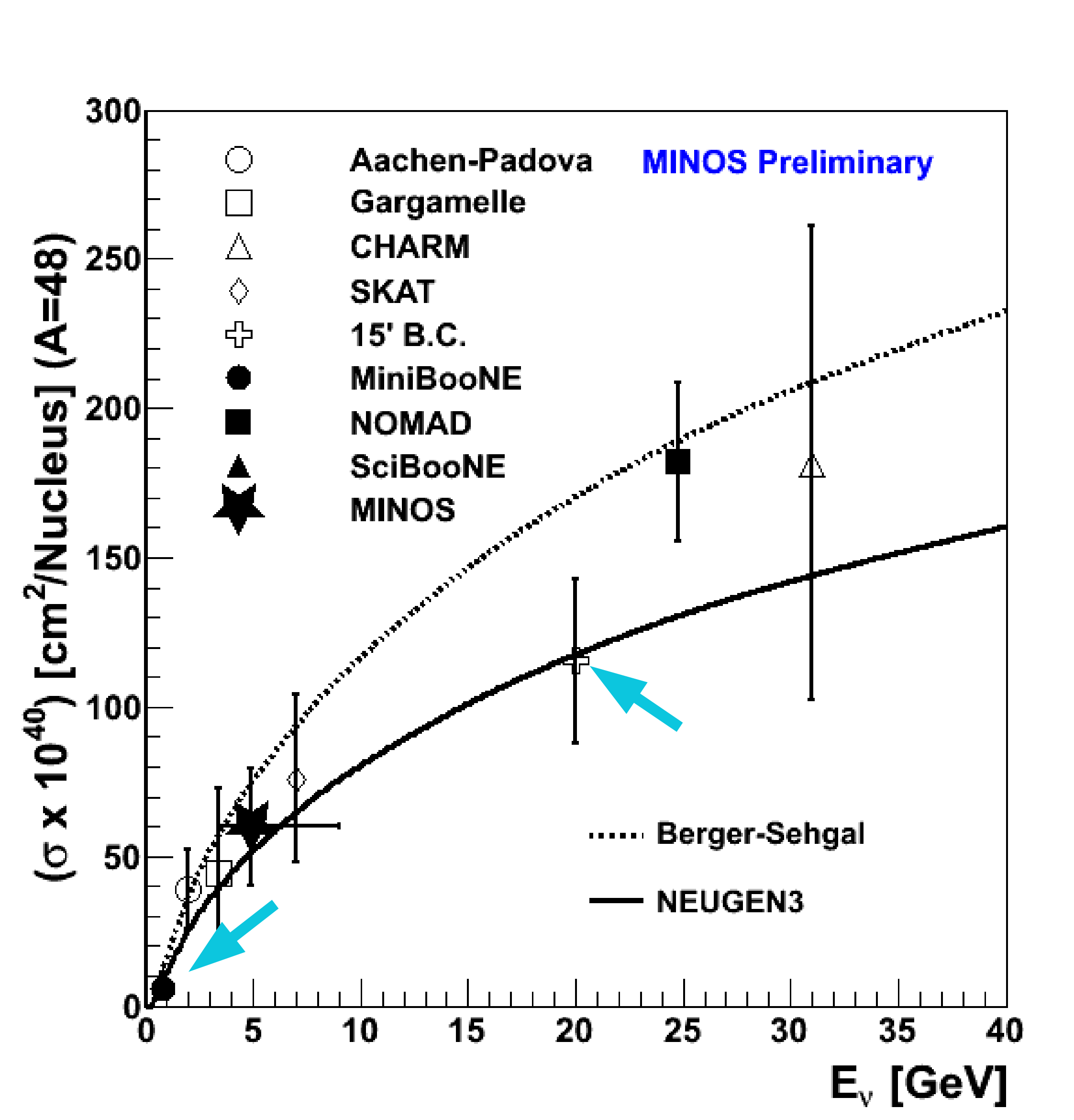
Cross Section E_ν-Dependence

All results scaled to $\mathcal{A}$ = 48 with NEUGEN3 cross section ratios

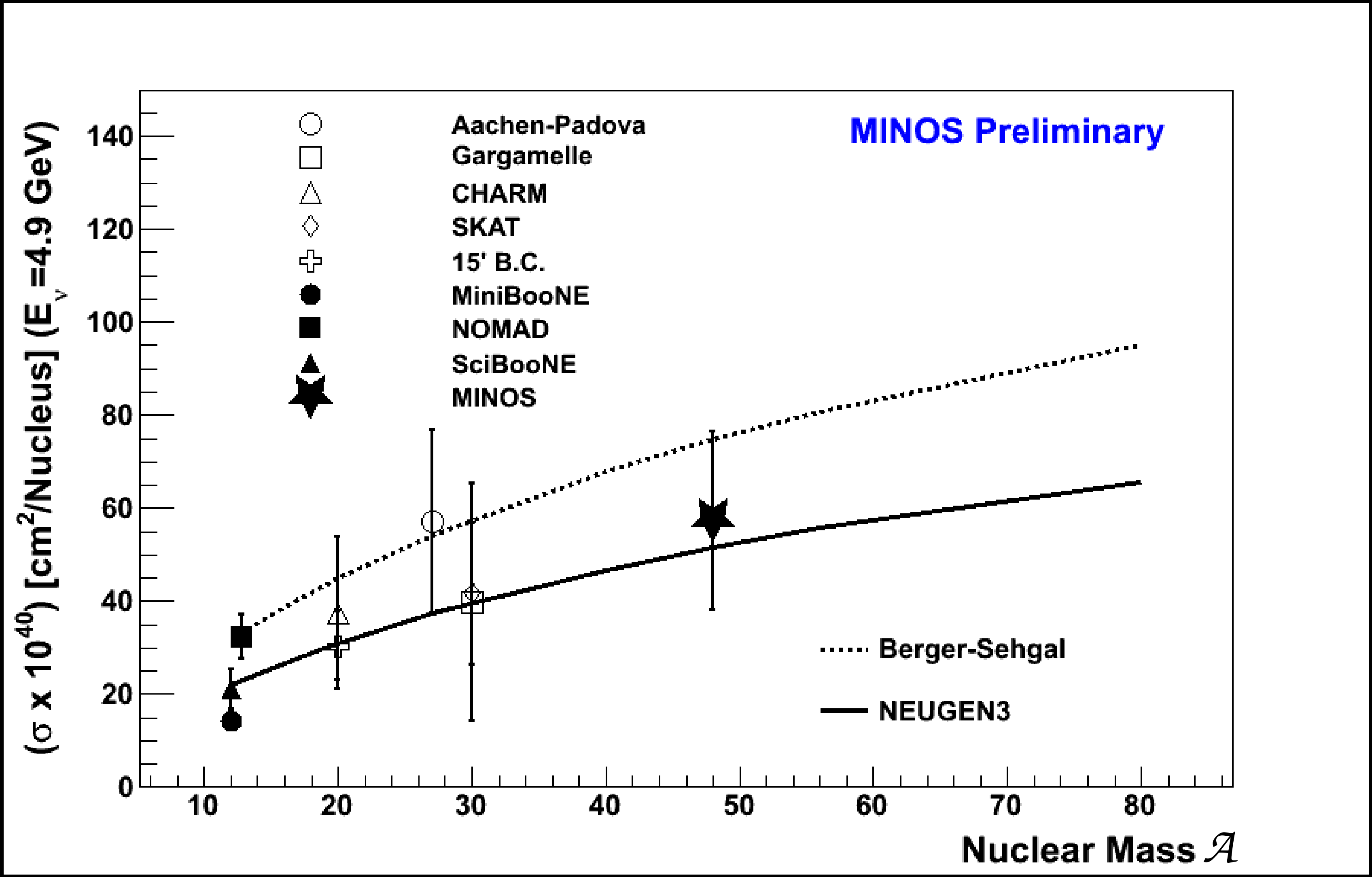
Several results reported relative to the Rein-Sehgal cross section

- **15 ft B.C.**
- **MiniBooNE**
- **SciBooNE**

Measurements scaled to the NEUGEN3 curve

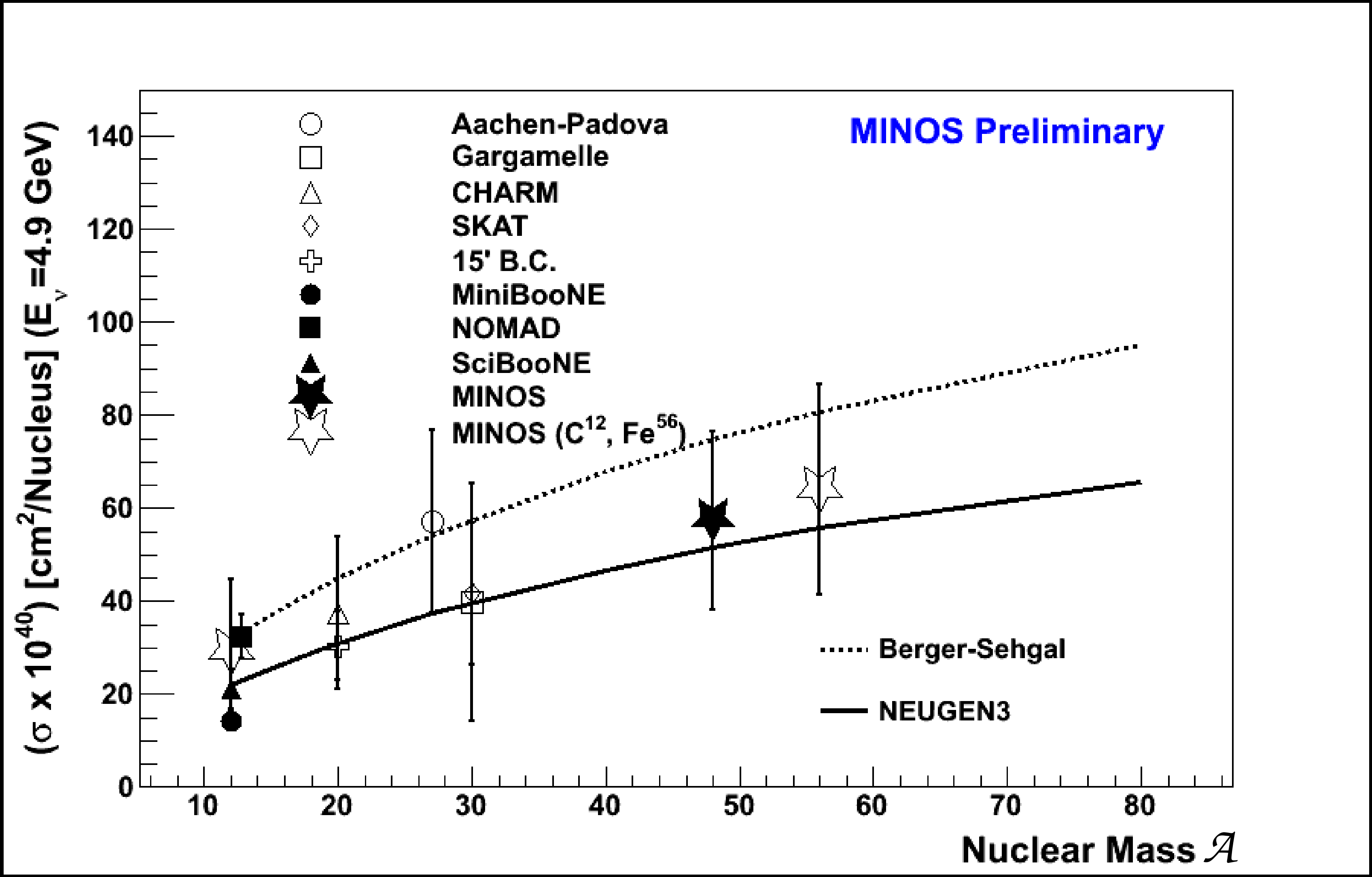


Cross Section $\mathcal{A}$-Dependence



All results scaled to E_ν = 4.9 GeV

Cross Section $\mathcal{A}$-Dependence



All results scaled to E_ν = 4.9 GeV

World Coherent NC(π^0) Cross Section Table

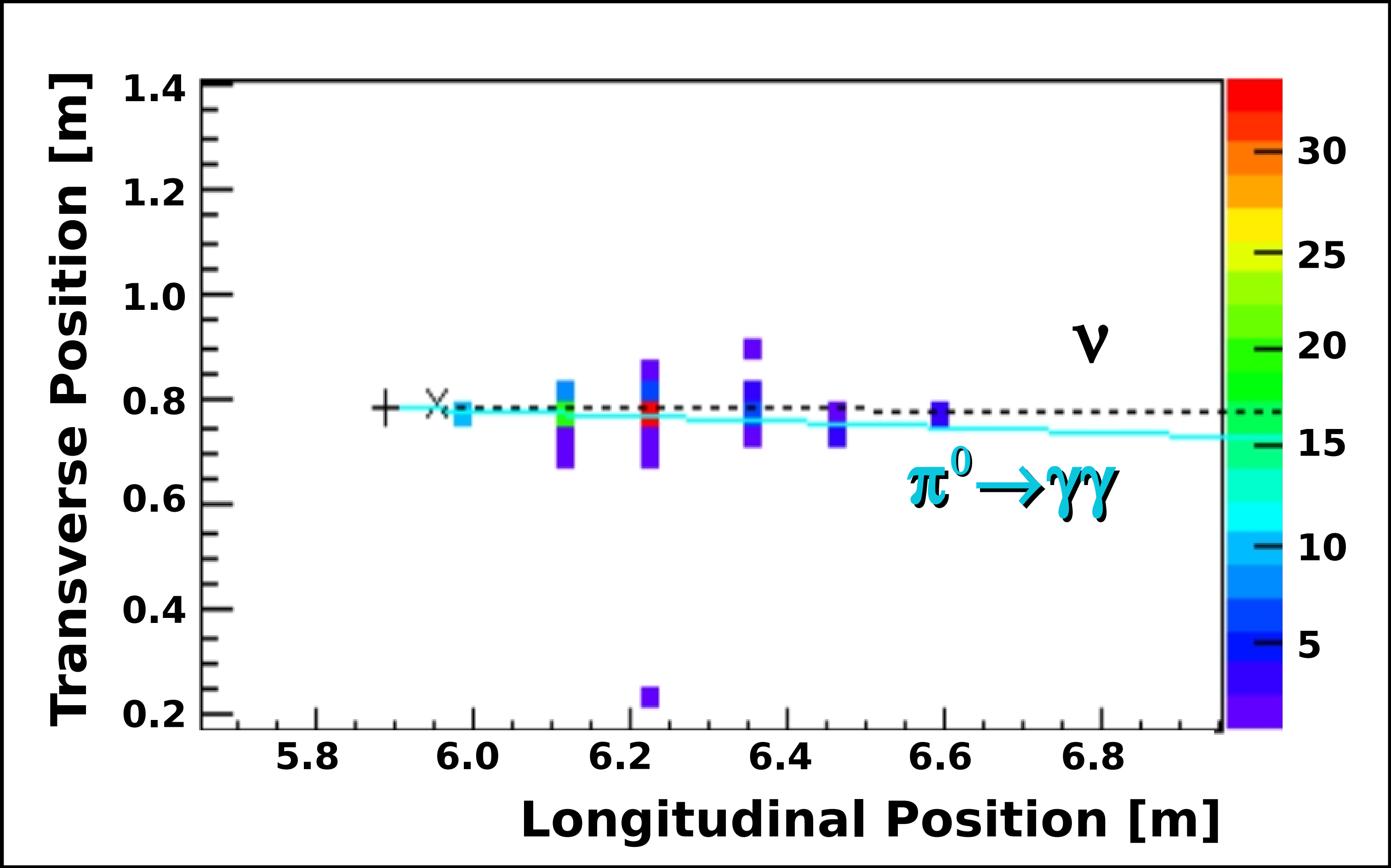
Experiment	Year	Average Neutrino Energy, $< E_\nu >$ [GeV]	Average Nucleus $\mathcal{A}$ [amu]	Minimum π^0 Energy, $E_{\pi^0}^{min}$ [GeV]	Coherent Cross Section, σ^{coh} $\nu/(\bar{\nu})$ $[10^{-40}\mathrm{cm}^2/A]$	Rein-Sehgal (NEUGEN3) Cross Section $[10^{-40}\mathrm{cm}^2/A]$
Aachen-Padova	1983	2	Aluminum 27	0.18	29±10 (25±7)	19.0
Gargamelle	1984	3.5	Freon CF_3Br - 30	0.2	31±20 (45±24)	27.7
CHARM	1985	31 24	Marble $CaCO_3$ - 20	6.0	96±42 (79±26)	76.2
SKAT	1986	7	Freon CF_3Br - 30	0.2	52±19	44.4
15' BC	1986	20	Neon NeH_2 - 20	2.0	RSx0.98±0.24	66.0
MiniBooNE	2008	0.8	Mineral Oil C_XH_Y - 12	0.0	RSx0.65±0.14 RSx0.65±0.14	4.4
NOMAD	2009	24.8	Carbon+ 12.8	0.5	72.6±10.6	52.1
SciBooNE	2010	0.8	Polystyrene C_8H_8 - 12	0.0	RSx0.96±0.20	4.4
MINOS	2010	4.9	Iron & Carbon - 48	1.0	57.3±22.2	49.5

Conclusions

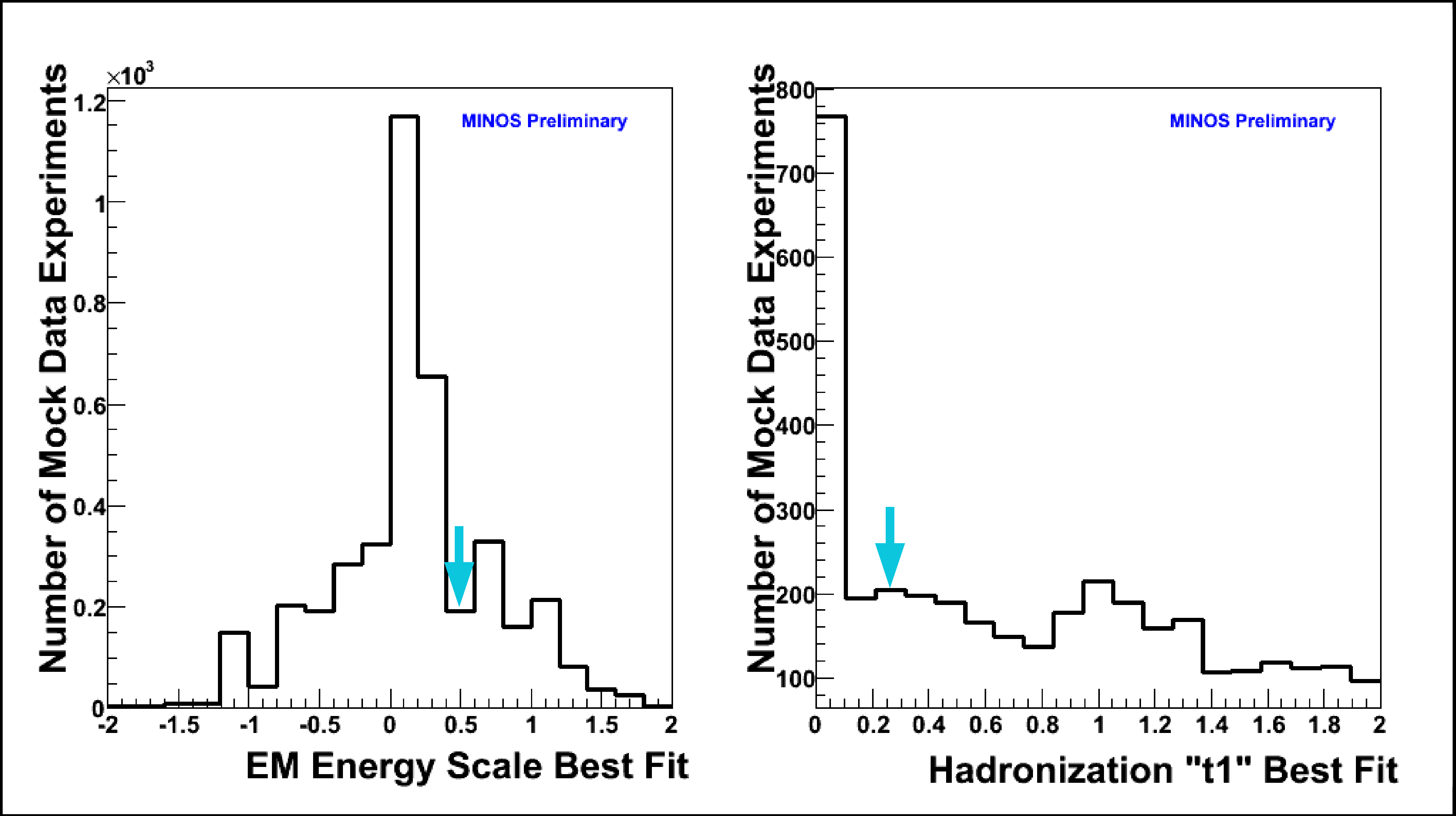
- First measurement of the coherent NC(π^0) scattering on nucleus with an average A > 30.
- First evidence for coherent NC(π^0) scattering on iron (Fe^{56}).
- Measurement consistent with the NEUGEN3 prediction and the Berger-Sehgal model.
- Confirmation of the PCAC hypothesis in the relevant kinematic ranges.
- MINOS anti-neutrino data can be used to make a follow-up measurement.

Backup Slides

Coherent NC(π^0) Event



Mock Data Studies



Calculating the Event Fractions

$$N = N_{Fe} + N_C \qquad M = M_{Fe} + M_C = 0.8\text{M} + 0.2\text{M}$$

$$r \equiv \frac{\sigma_{Fe}}{\sigma_C} \qquad \sigma_{Fe} = \frac{N_{Fe}}{E\,M_{Fe}\Phi} \qquad \sigma_C = \frac{N_C}{E\,M_C\Phi}$$

$$r = \left(\frac{N_{Fe}}{E\,M_{Fe}\Phi}\right)\left(\frac{E\,M_C\Phi}{N_C}\right) \Rightarrow N_{Fe} = N\left(\frac{M_{Fe}r}{M_C + M_{Fe}r}\right)$$