Studies of ν Cross-Sections by the MINOS Near Detector

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on behalf of the
MINOS Collaboration

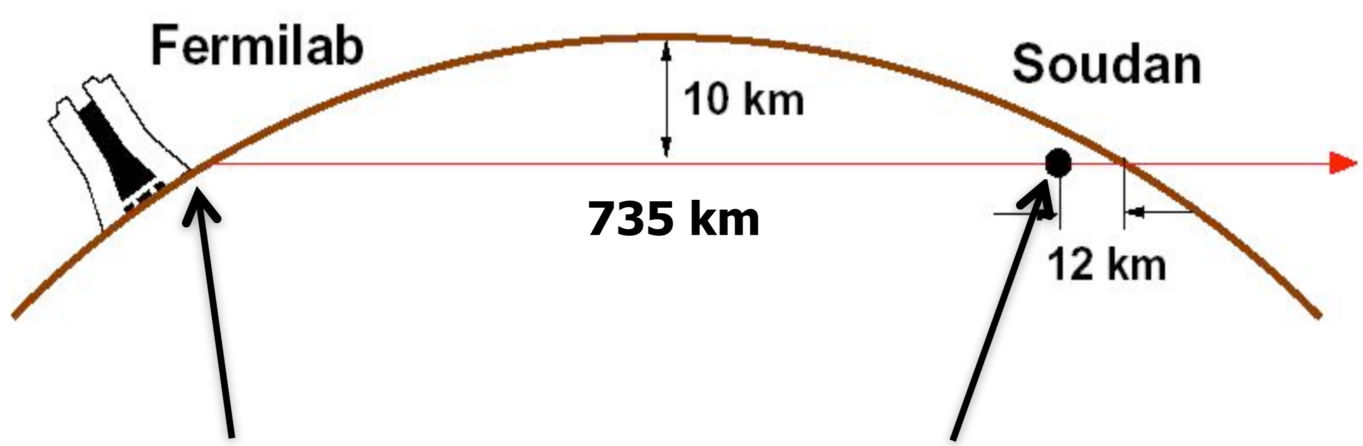
ॐ Inclusive ν_μ-CC Cross-section ($3 \le E_\nu \le 50$ GeV)
Inclusive Anti-ν_μ-CC Cross-section ($5 \le E_\nu \le 50$ GeV)

Status of:

ॐ M_A-Parameter of the Quasi-Elastic ν_μ-CC Interaction

ॐ Coherent-π^0 in ν-NC Interaction

Main **I**njector **N**eutrino **O**scillation **S**earch



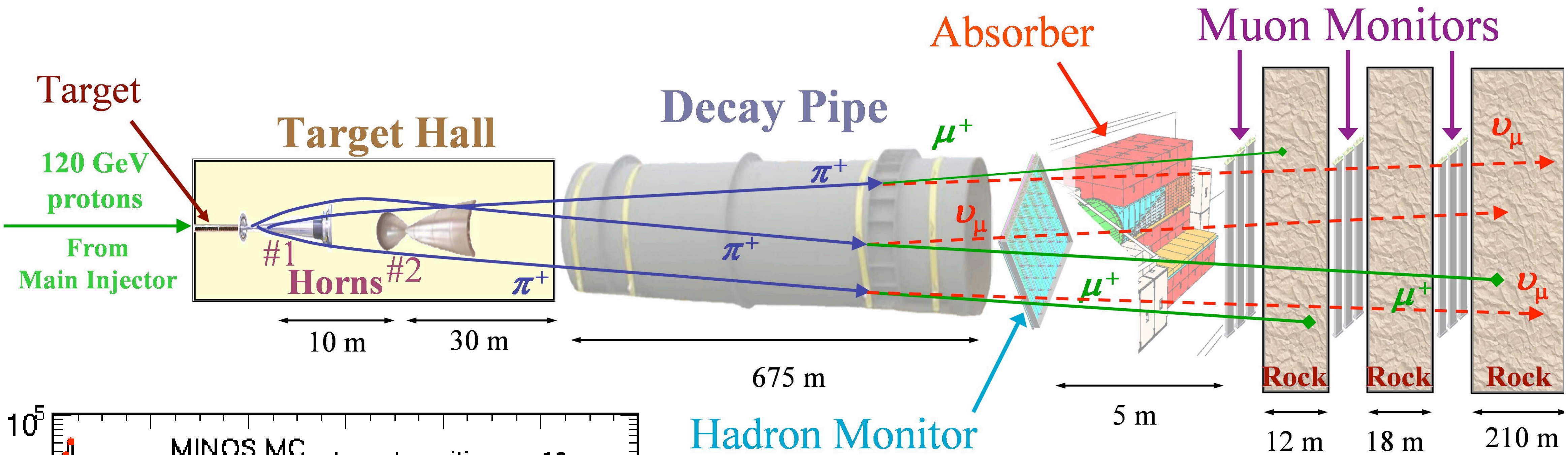
Neutrinos are produced by the **NuMI beam.** The beams composition and energy are measured by the **Near Detector**

The oscillated neutrino beam is measured by the **Far Detector**, at a mine in Minnesota.

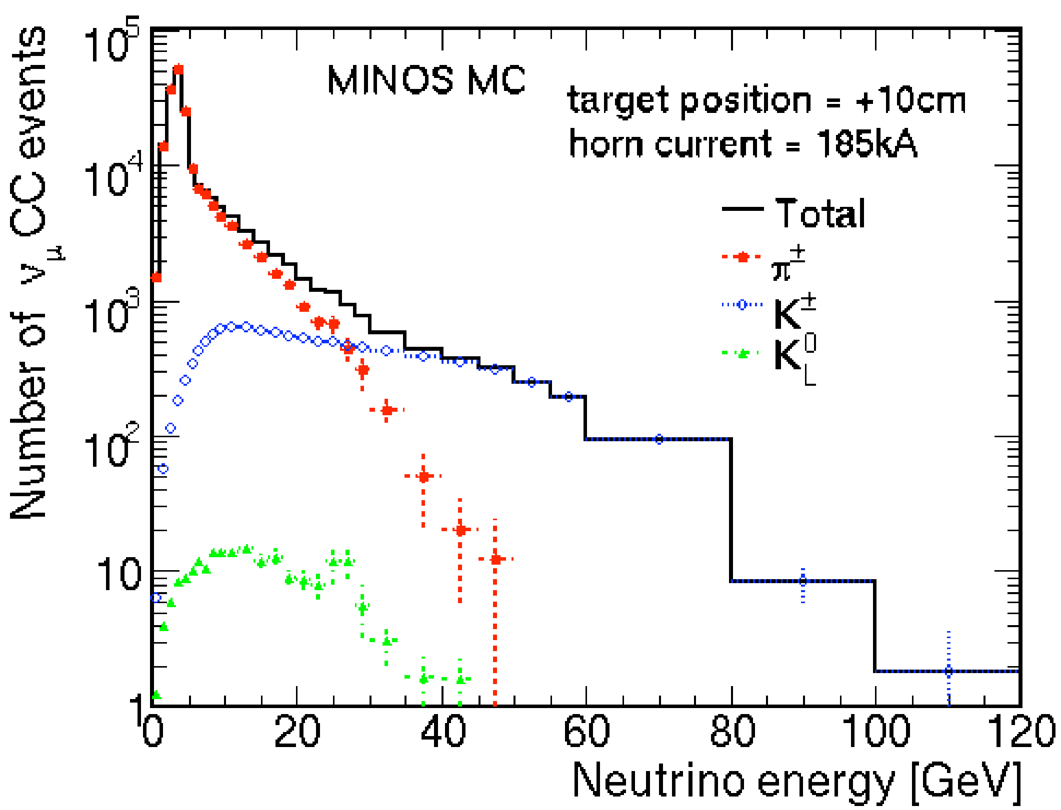
Measurements and limits include:

Δm^2_{32}, $\sin^2 2\theta_{32}$, $\Delta \overline{m}^2_{32}$, $\sin^2 2\overline{\theta}_{32}$, θ_{13}, sterile neutrinos, CPT conservation, cross-sections...

The NuMI neutrino beam



to Near Detector



- Variable target position = variable beam energy!
- Two magnetic focusing horns
- Sign selected beam: neutrino or anti-neutrino enriched

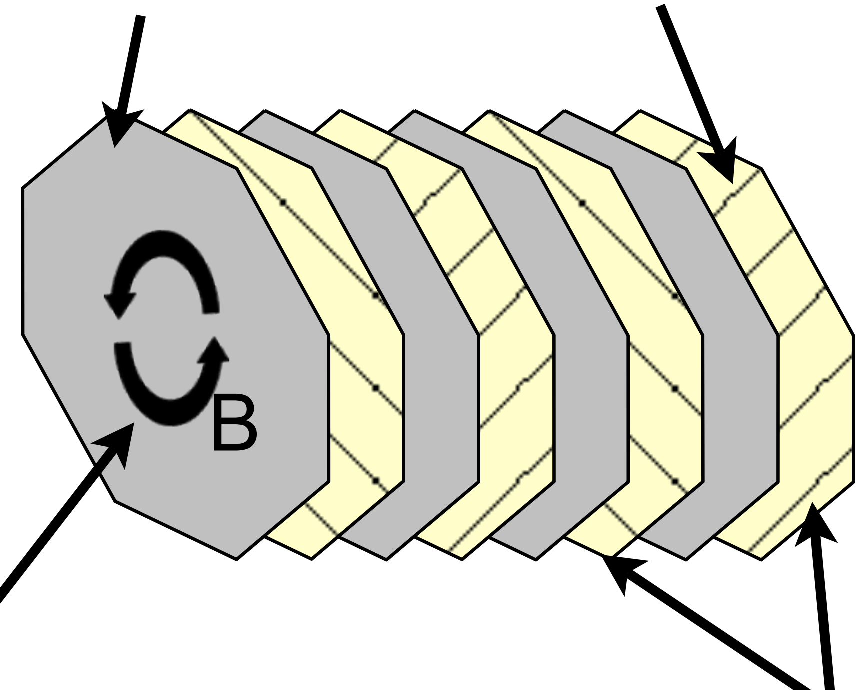
Foc+ ⇒ ν_μ ⇒ 91.7% Anti-ν_μ ⇒ 7% (Anti-)ν_e ⇒ 1.3%

MINOS Near and Far Detectors

Both detectors are functionally equivalent, in order to reduce systematics.

Near Detector	**Far Detector**
‣At Fermilab, IL	‣At Soudan, MN
‣282 Planes	‣486 Planes
‣980 Ton	‣5400 Ton

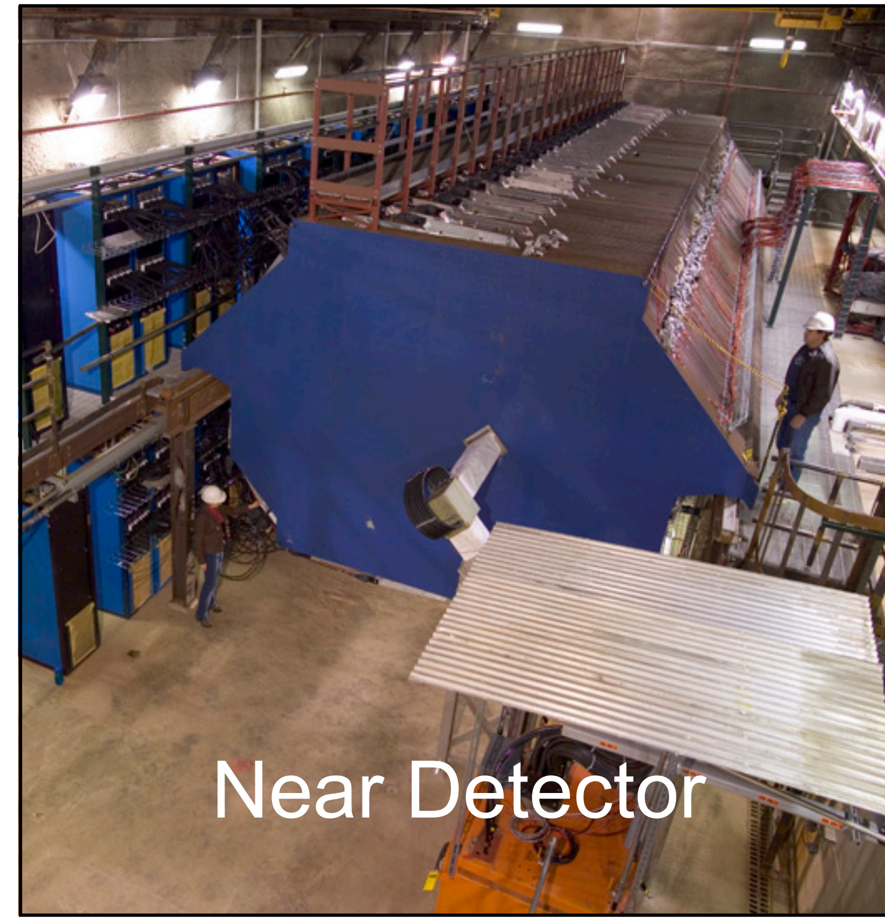
Planes of 2.54cm Steel and 1cm Scintillator

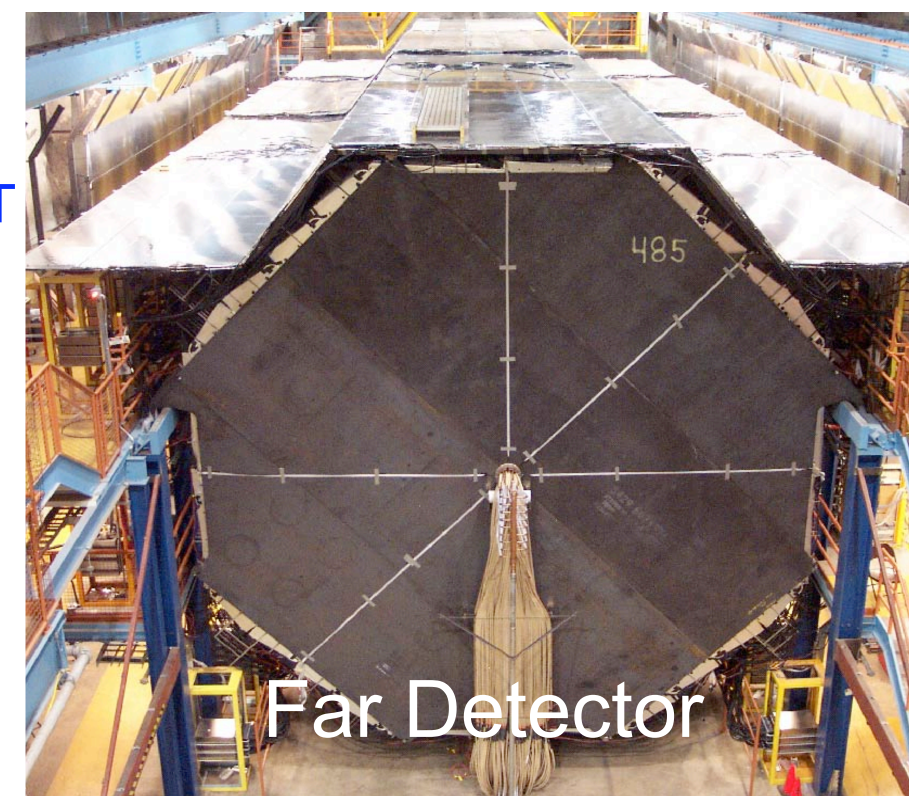


- 4.1 cm wide Sci
- WLS-fiber
- Multi-anode PMT
- B $\simeq$1.3T

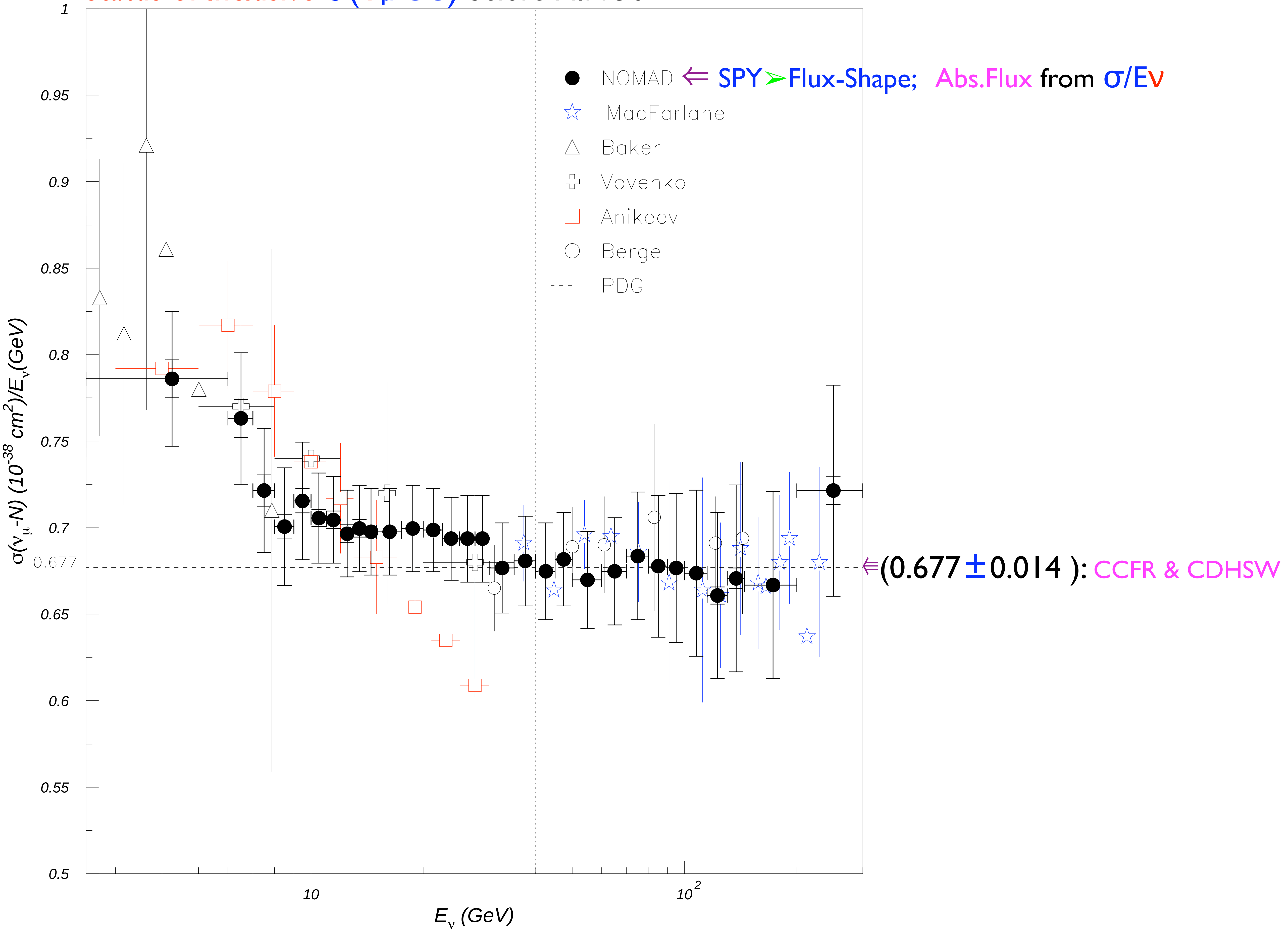
Toroidal magnetic field allows charge sign determination

Alternating scintillator planes in perpendicular directions for 3D event reconstruction





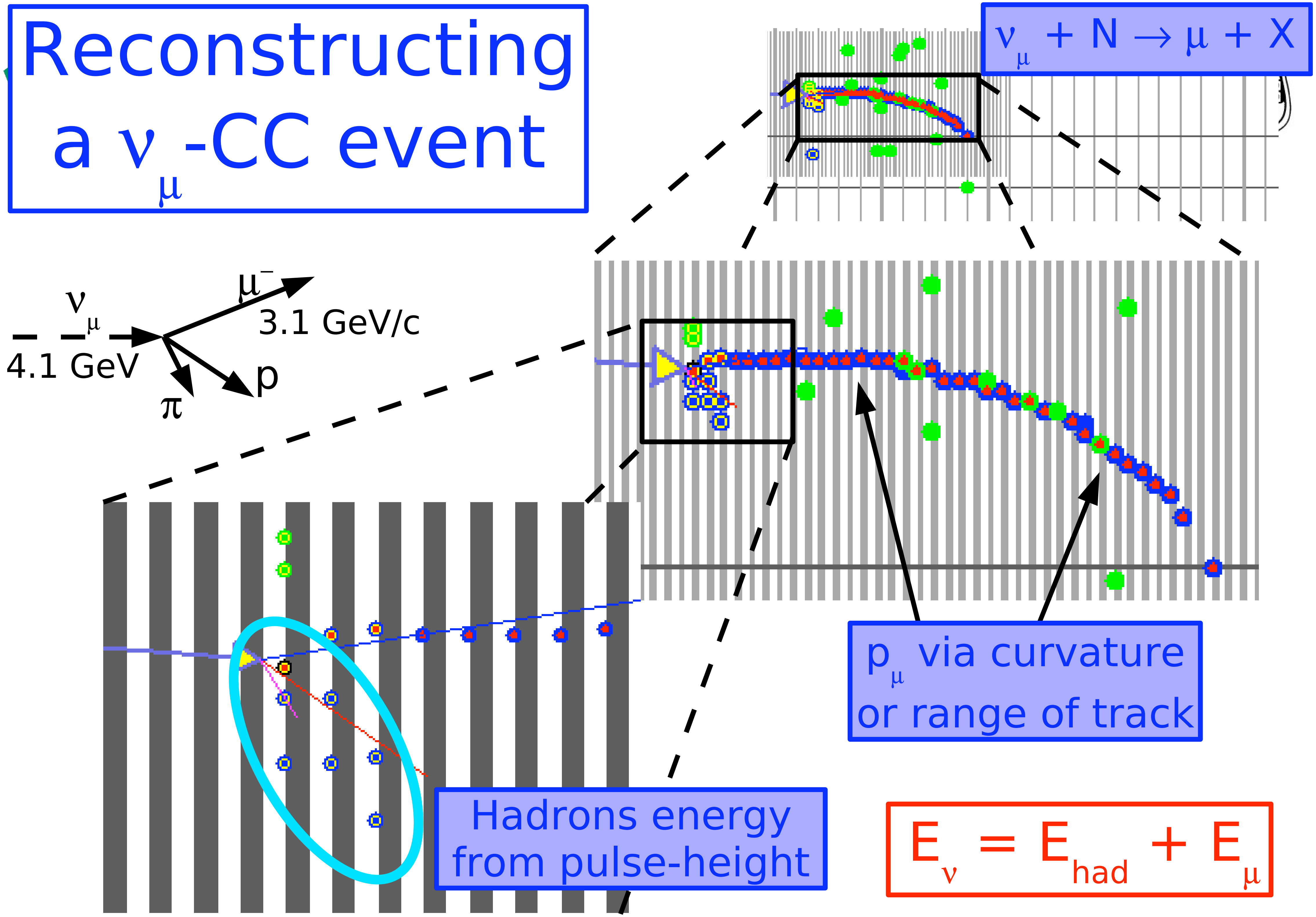
Status of Inclusive $\sigma(\nu_\mu\text{-CC})$ before MINOS



MINOS Inclusive $\sigma(\nu_\mu\text{-CC})$ Measurement Strategy

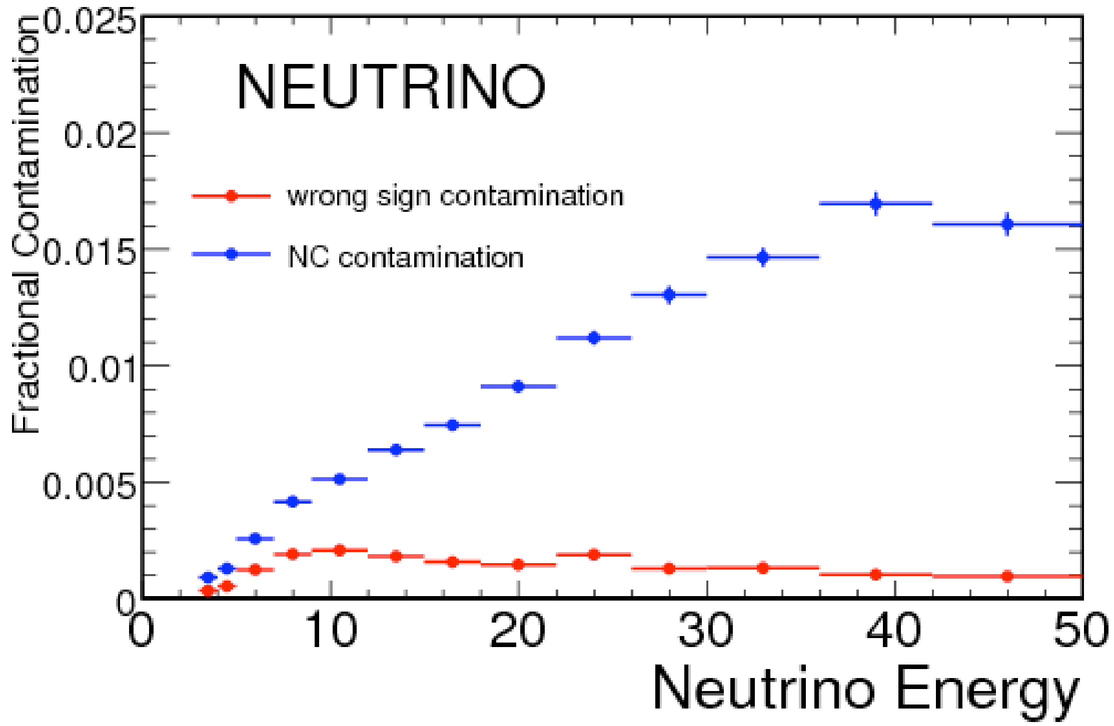
- Select Inclusive ν_μ-CC & Anti-ν_μ-CC Events
- Determine $\sigma(\nu_\mu\text{-CC})$ Cross-section at $3 \leq E\nu \leq 50$ GeV relative to $\sigma(\nu_\mu\text{-CC})$ at $40 \leq E\nu \leq 200$ GeV: ±2.1% precision
- Measure Relative-flux (Shape) using Low-$\nu 0$ Technique
- Fix the absolute level using high-$E\nu$ region
- Apply acceptance/smearing and model-corrections; evaluate systematic errors

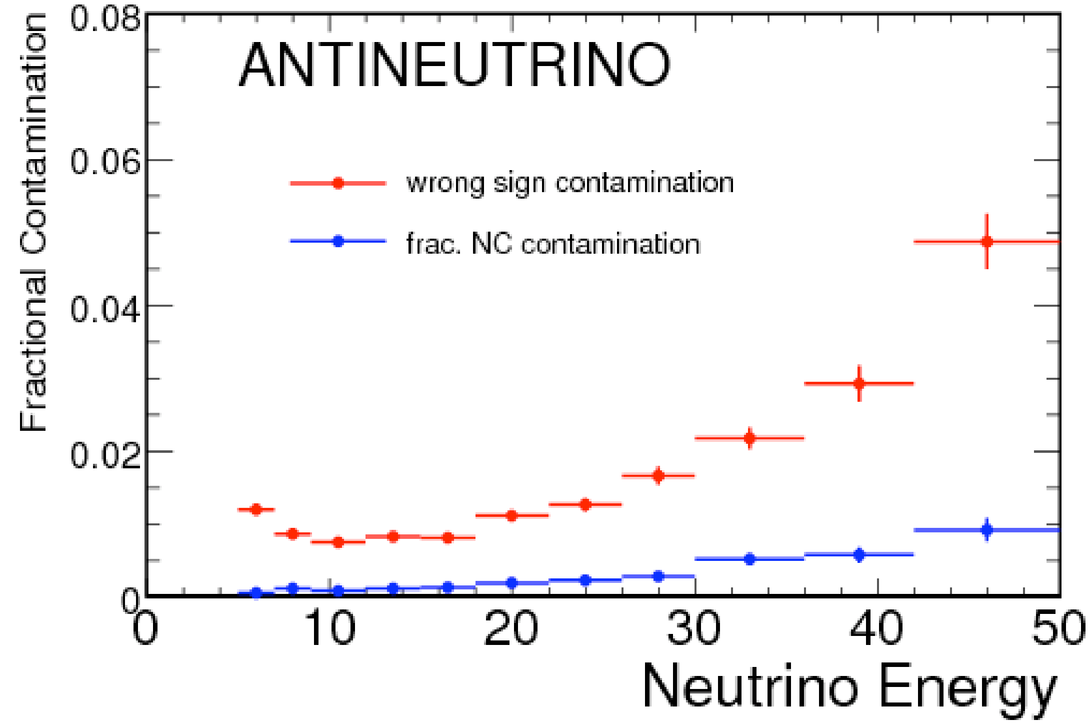
Reconstructing a ν_μ-CC event



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

Inclusive CC Sample Backgrounds





- $\nu_\mu \Rightarrow \mu^-$ Focussed; $P_\mu \geq 1.5$ GeV; $E_\nu \geq 3$ GeV
- Anti-$\nu_\mu \Rightarrow \mu^+$ defocussed; More Stringent μ-ID; $P_\mu \geq 1.5$ GeV; $E_\nu \geq 5$ GeV
- Background ➢ $\simeq$2% for ν_μ; $\simeq$5% for ν_μ
- Acceptance ➢ $\simeq$70% for ν_μ; $\simeq$60% for ν_μ at $E_\nu \simeq 10$ GeV

LOW-ν_0 METHOD

⇐Shape of ν_μ or Anti-ν_μ Flux

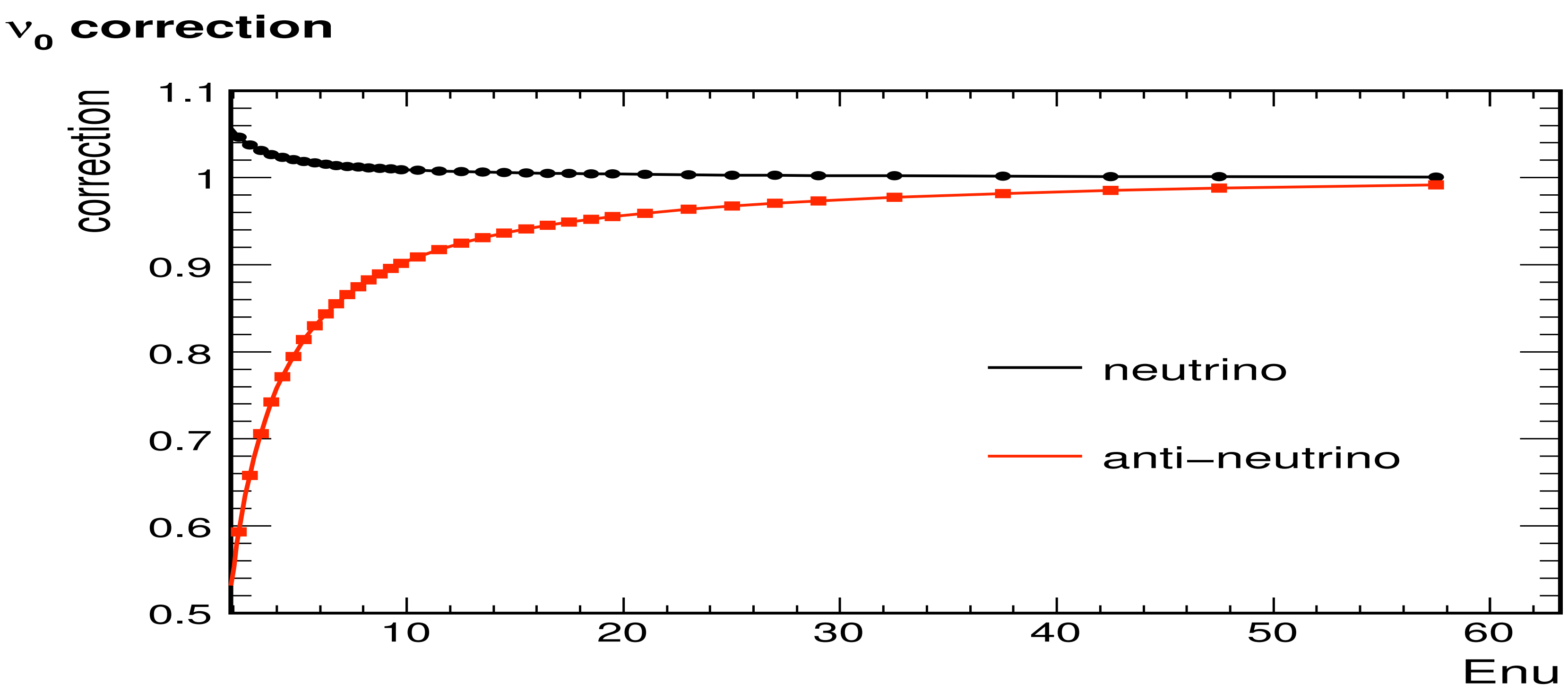
✦ *Relative flux vs. energy from low-ν_0 method:*

SRM, Wold.Sci. 84(1990), Ed.Geesman

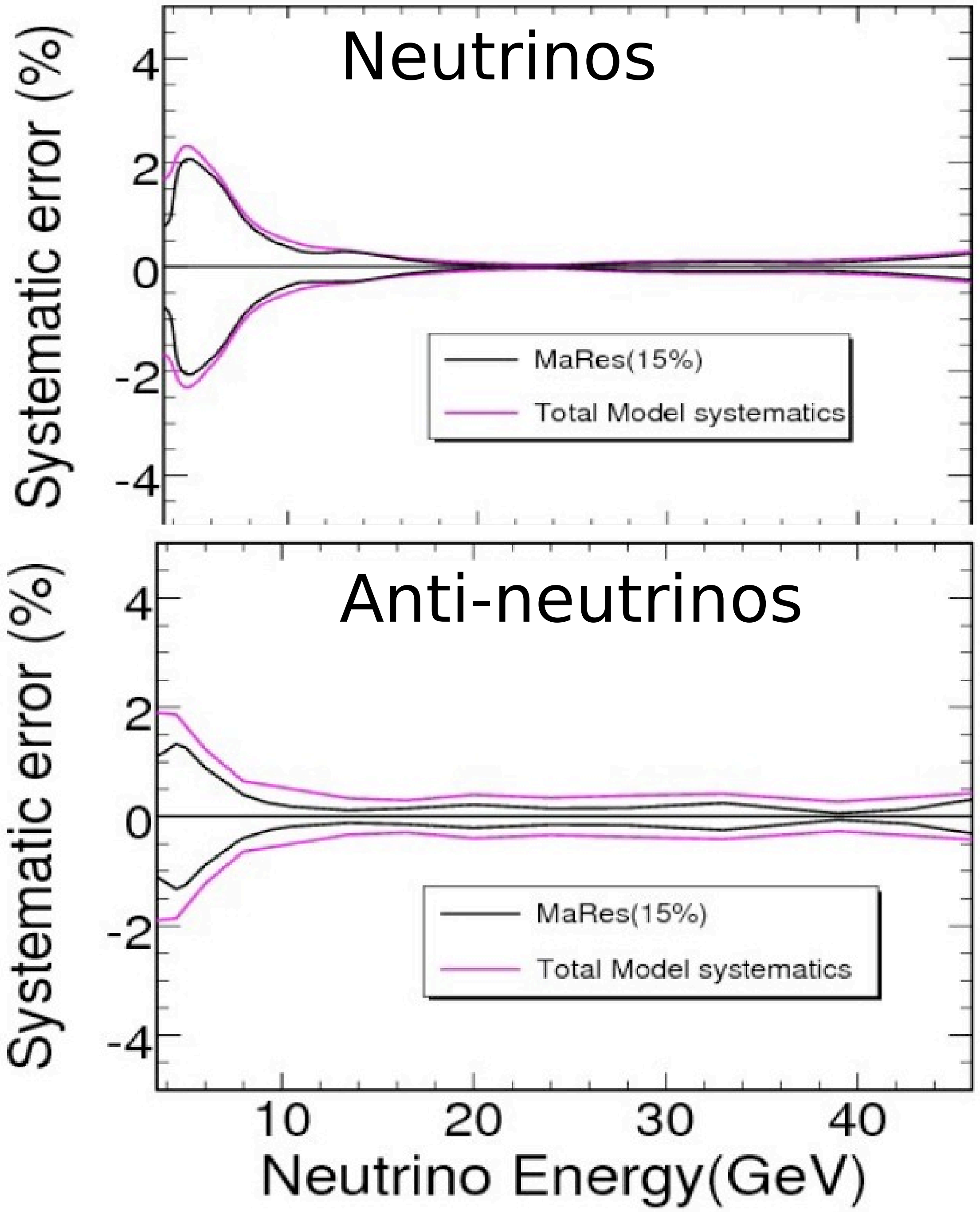
$$N(E_\nu : E_{\rm HAD} < \nu_0) = C\Phi(E_\nu) f(\frac{\nu_0}{E_\nu})$$

the correction factor $f(\nu_0/E_\nu) \rightarrow 1$ *for* $\nu_0 \rightarrow 0.$ ⇐CCFR, NOMAD, NuTeV, MINOS

$\Longrightarrow$ *Need precise determination of the muon energy scale and good resolution at low* ν *values*

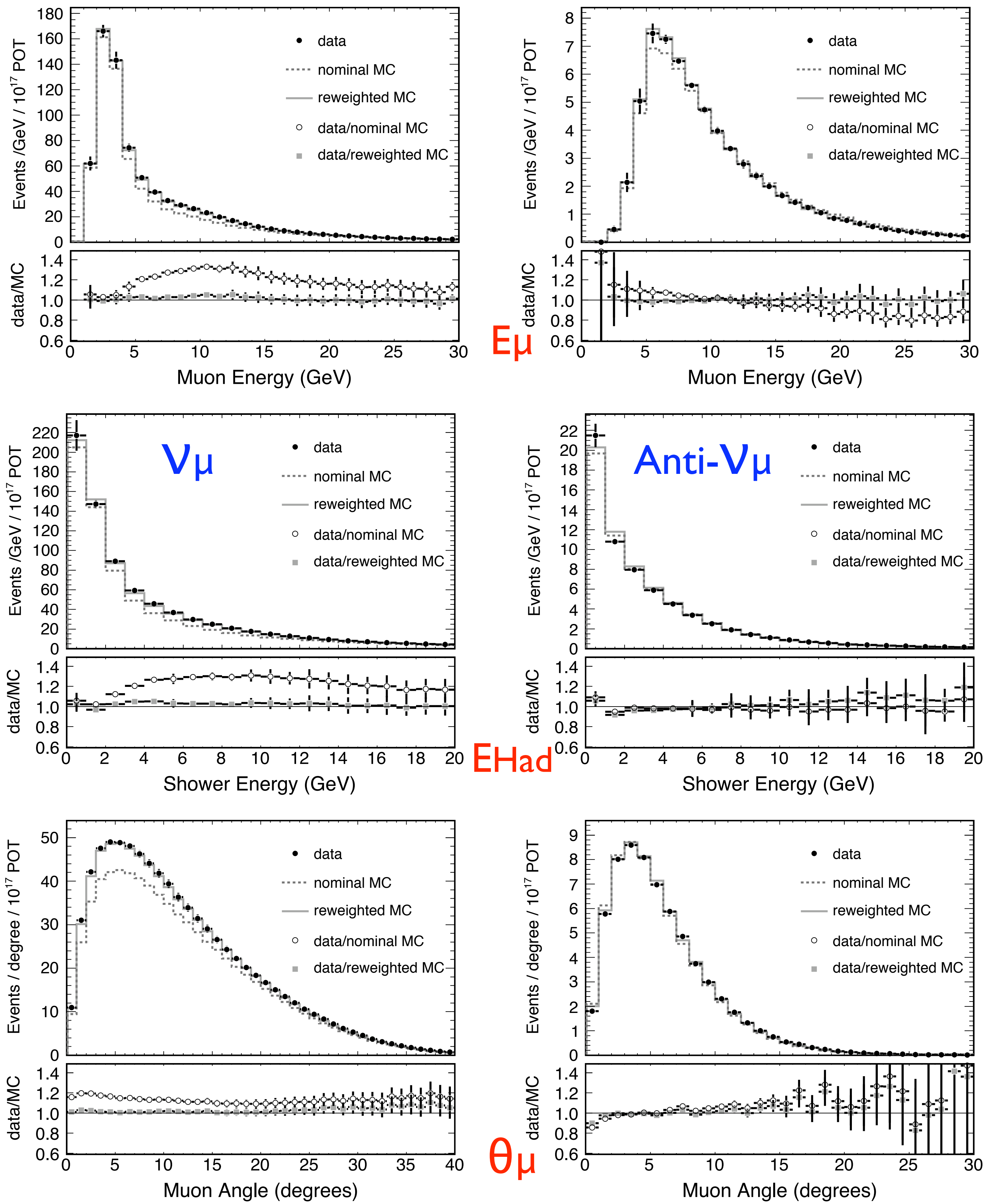


- Sliding $\nu 0$-Cut: $\nu 0=1$GeV for $3 \leq E\nu \leq 9$ GeV;
  $\nu 0=2$GeV for $9 \leq E\nu \leq 18$ GeV;
  $\nu 0=5$GeV for $18 \leq E\nu \leq 50$ GeV;
- Correct for Acceptance, smearing, background
- Correct for Low-$\nu 0$ → Flux Shape
- Iterate

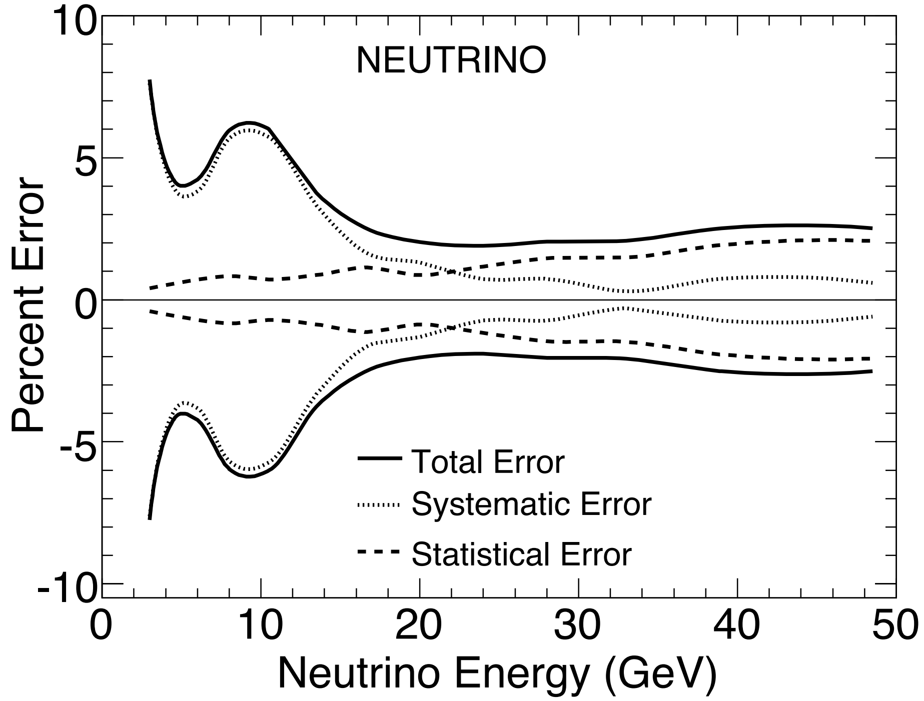


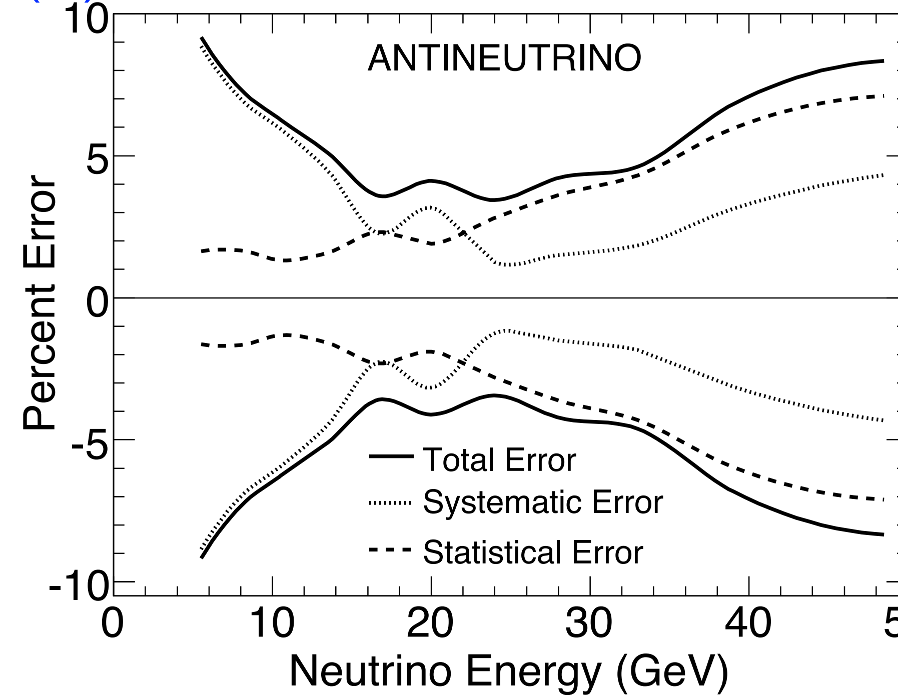
Systematic Errors assoc. with Low-ν0 Flux

- Model Parameters: QE, Res, DIS
- Energy Scale: Eμ & EHad
- Background
- Acceptance
-


Eμ
νμ
Anti-νμ
EHad
θμ
data
nominal MC
reweighted MC
data/nominal MC
data/reweighted MC
Events /GeV / 10^17 POT
Events / degree / 10^17 POT
data/MC
Muon Energy (GeV)
Shower Energy (GeV)
Muon Angle (degrees)

Error (%) on σ

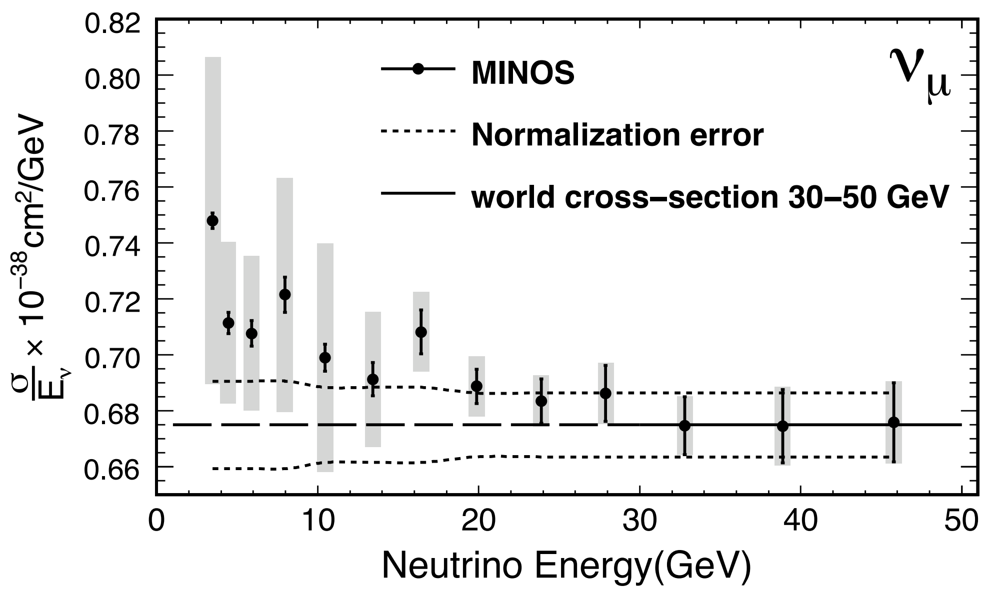


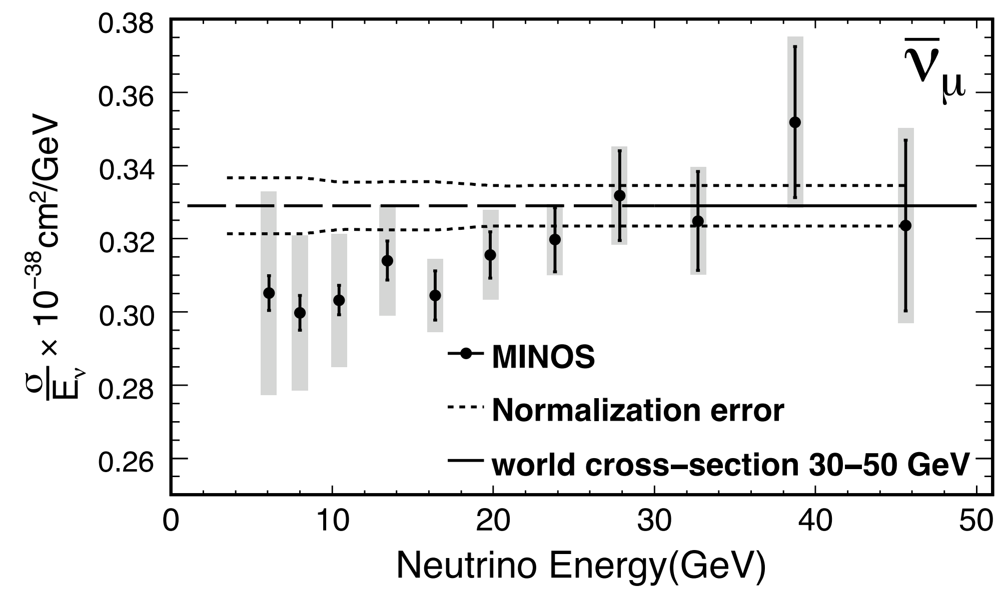


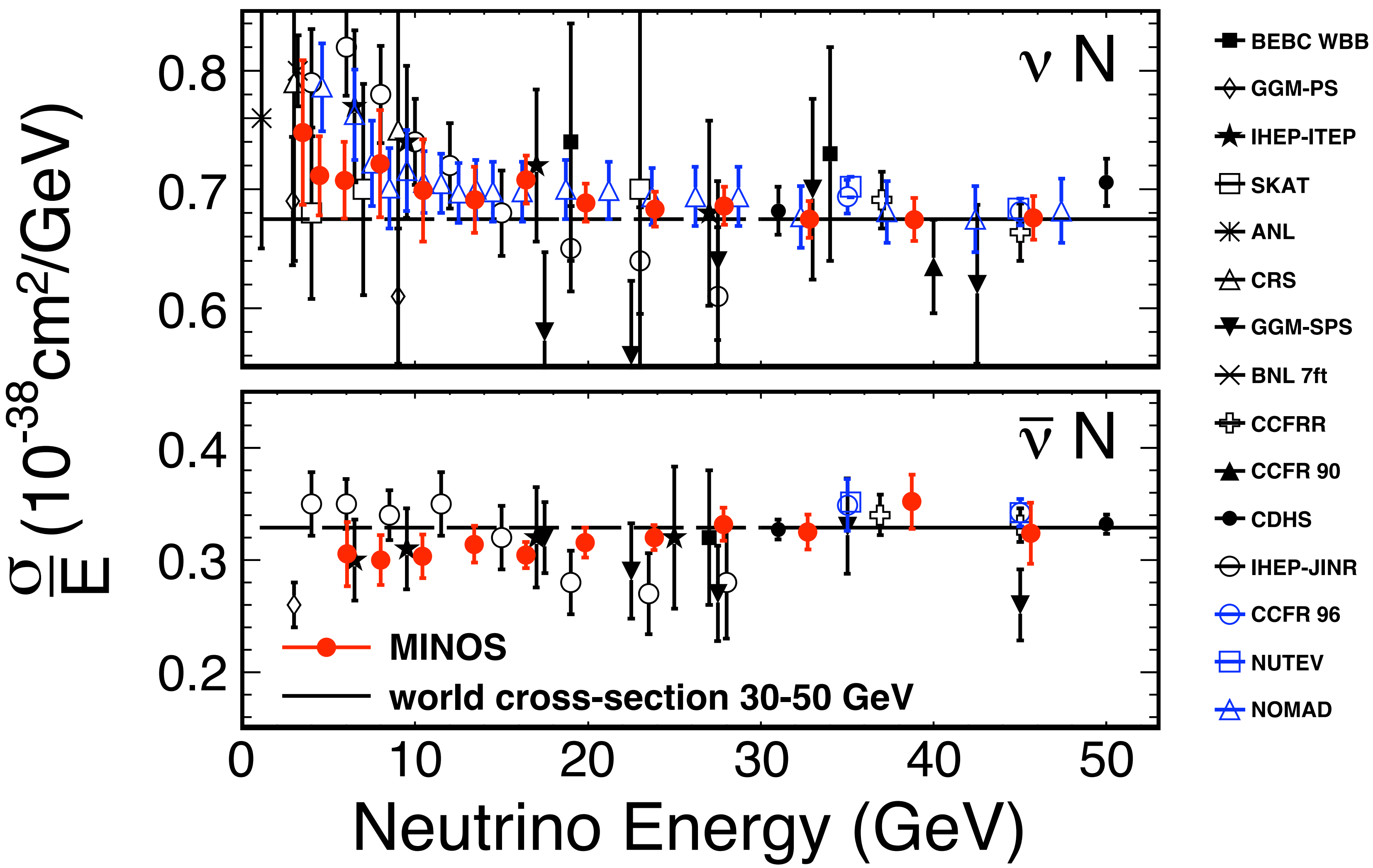
νμ

Anti-νμ

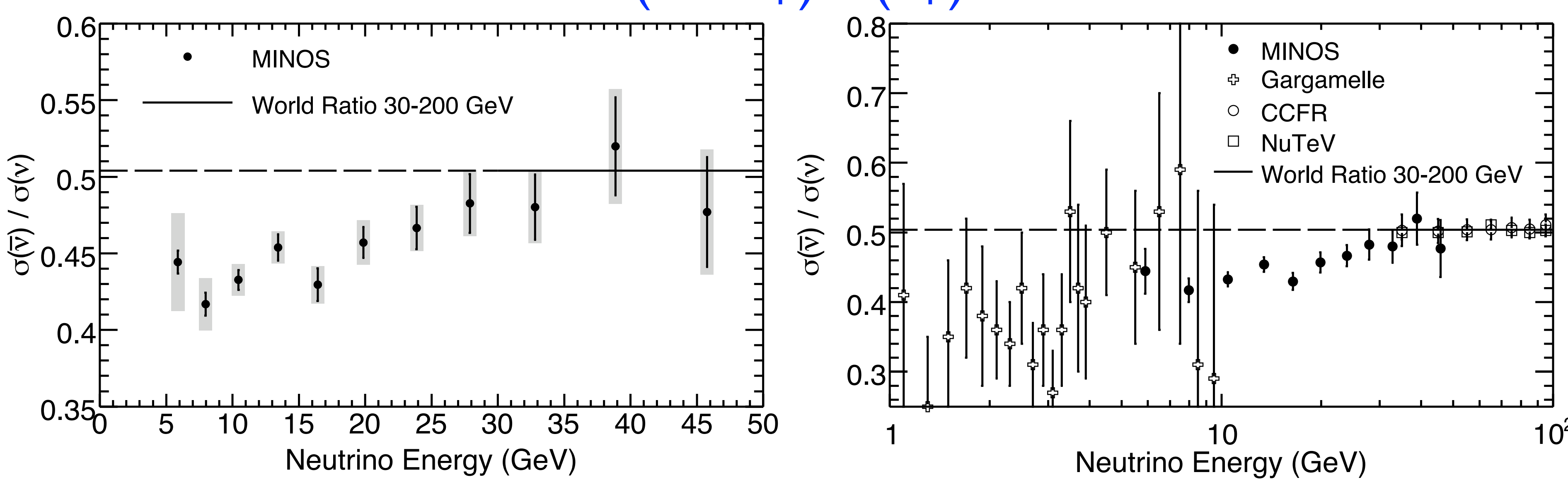
σ/E







$\sigma(\text{Anti-}\nu_\mu)/\sigma(\nu_\mu)$



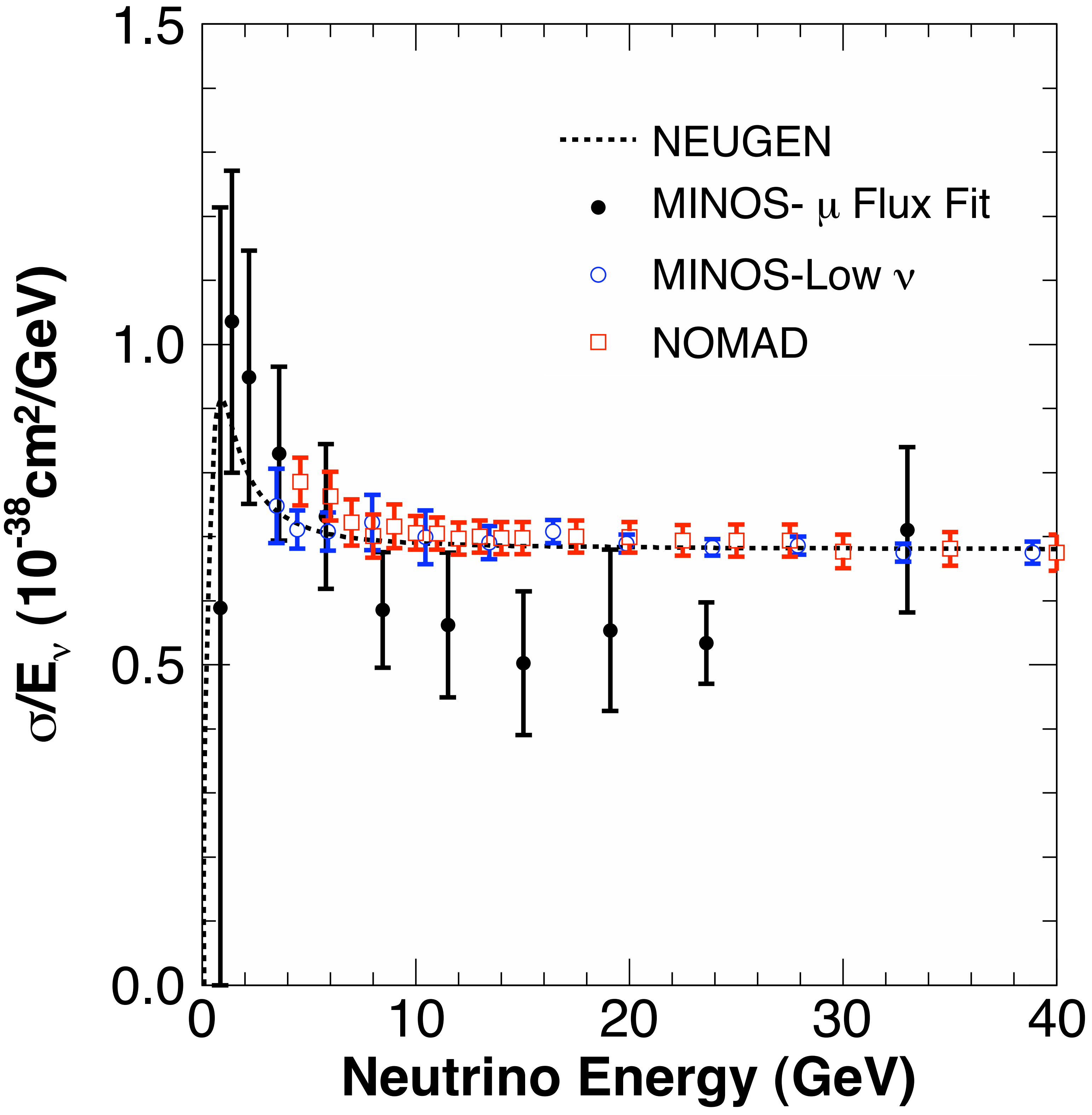
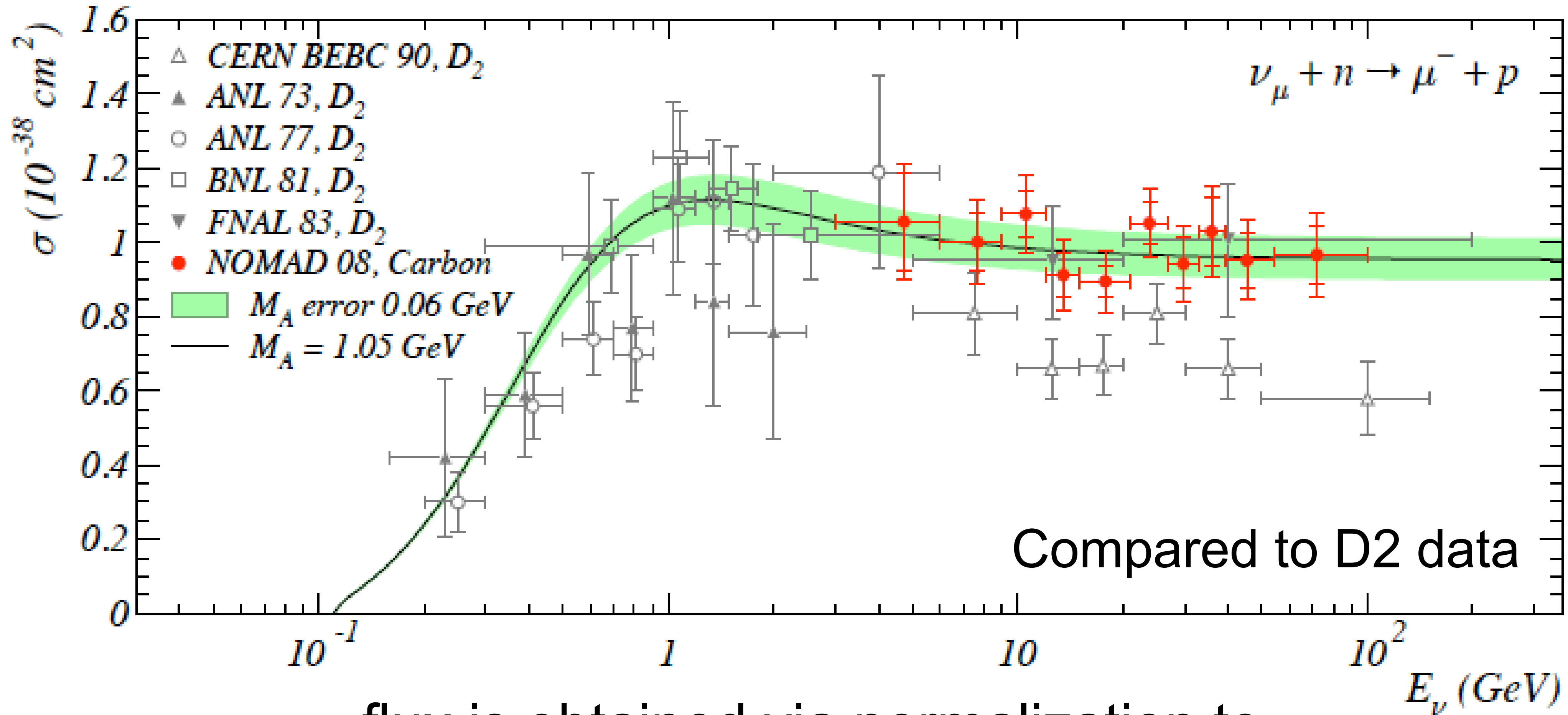


Figure 24: The MINOS ν_μ charged current cross section measurement from utilizing the neutrino flux inferred from the muon monitors compared to the measurement from the MINOS Low-ν method [21] and from NOMAD [20].

σ(Anti-ν_μ) & $\sigma(\nu_\mu)$ Measurement by MINOS

- $\sigma(\nu_\mu)$: from 3.5 Gev (8.2%) to 30 GeV (2.4%)
- σ(Anti- ν_μ): from 5.9 Gev (9.5%) to 30 GeV (4.9%)
- $r = \sigma(\text{Anti-}\ \nu_\mu)/\sigma(\nu_\mu)$: from 5.9 Gev (7.2%) to 30 GeV (4.8%)

Status of Inclusive σ(νμ-CC) Quasi-Elastic



flux is obtained via normalization to
deep inelastic scattering and inverse muon decay

major systematics: 3.5% QE selection,
2.9% DIS background, 4.0% RES background, ~4% flux

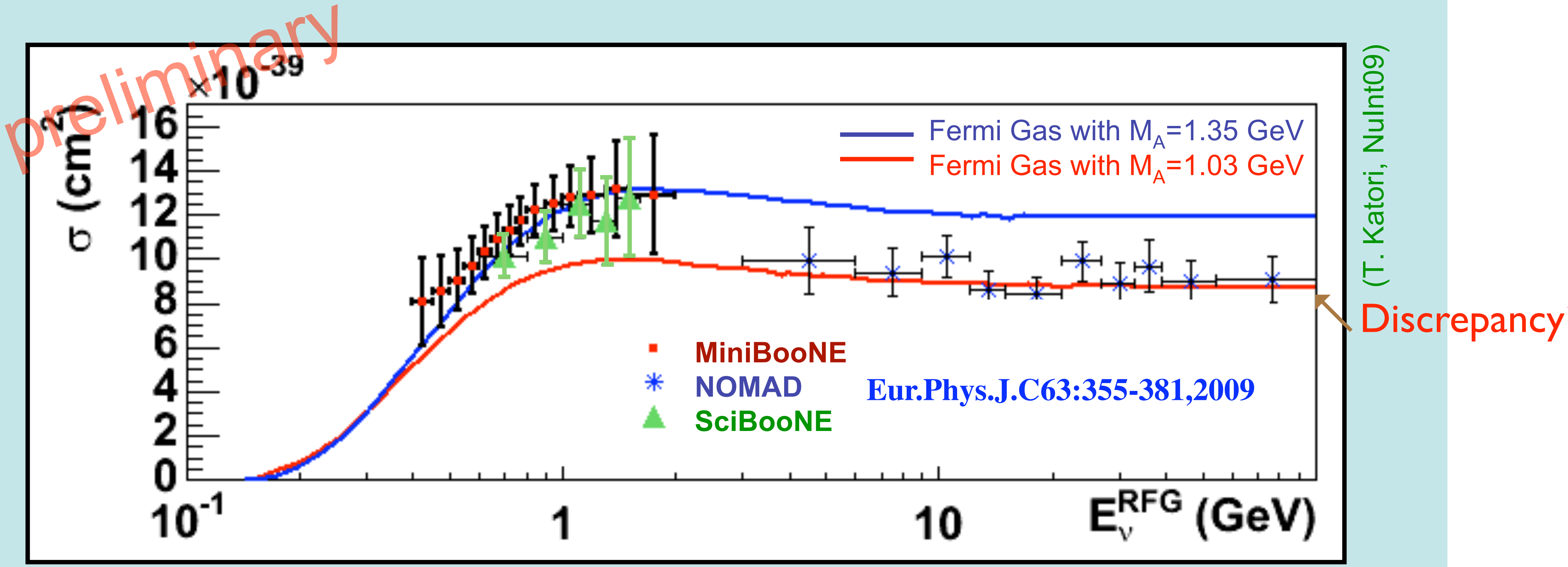
M_A ➢ an analysis-Parameter

Fit for M_A = 1.05 GeV ± 0.02 stat ± 0.06 syst

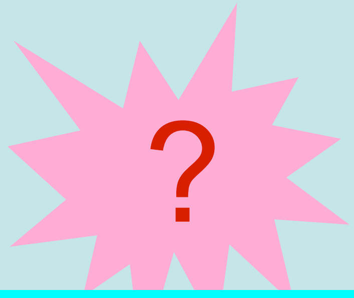
From Q**2 Fit ➢ M_A= 1.07 ± 0.06 (Stat) ± 0.07 (Syst)

Quasi-Elastic Scattering

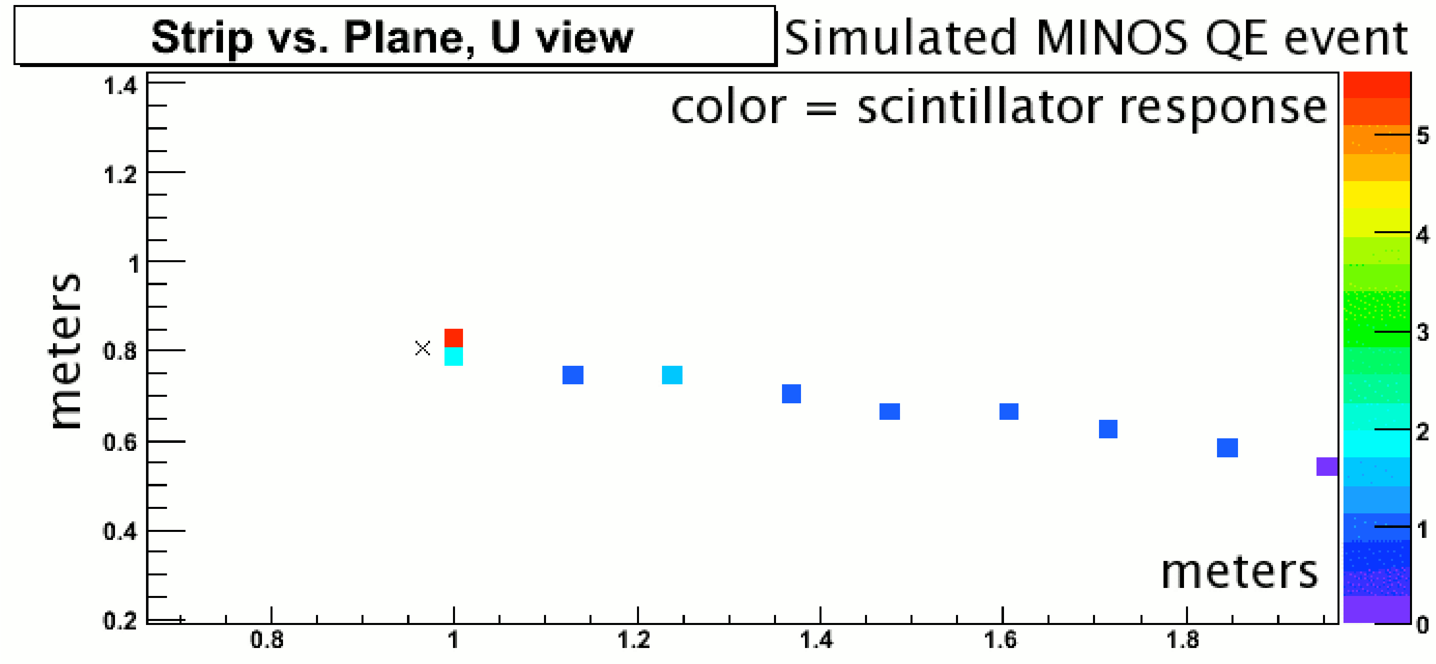
- new, modern measurements of QE σ at these energies (on ^{12}C)

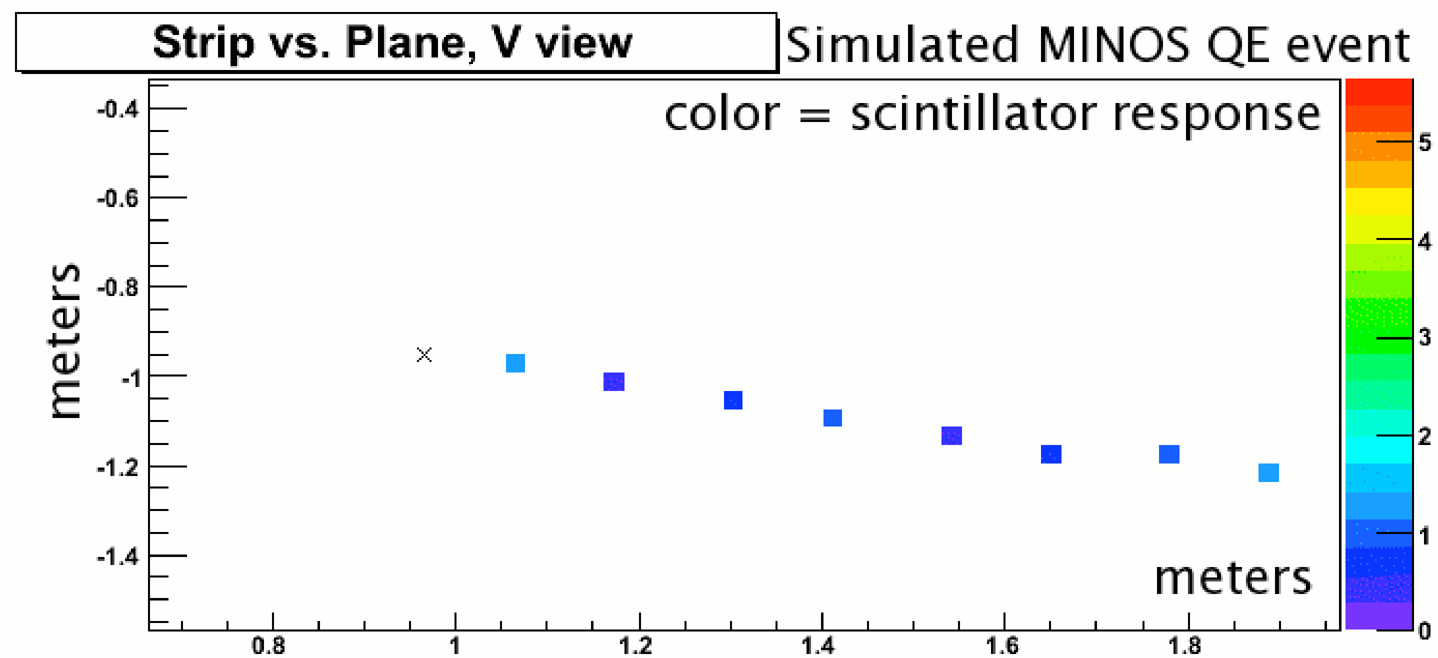


~ 30% difference between QE σ measured at low & high E on ^{12}C ?!



MINOS-QE: details on the one-track selection

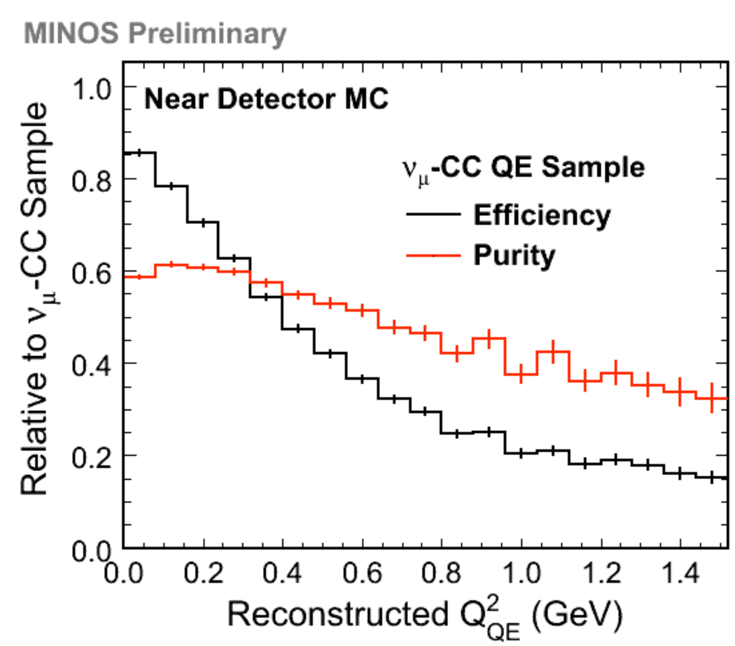




Require one reconstructed track.

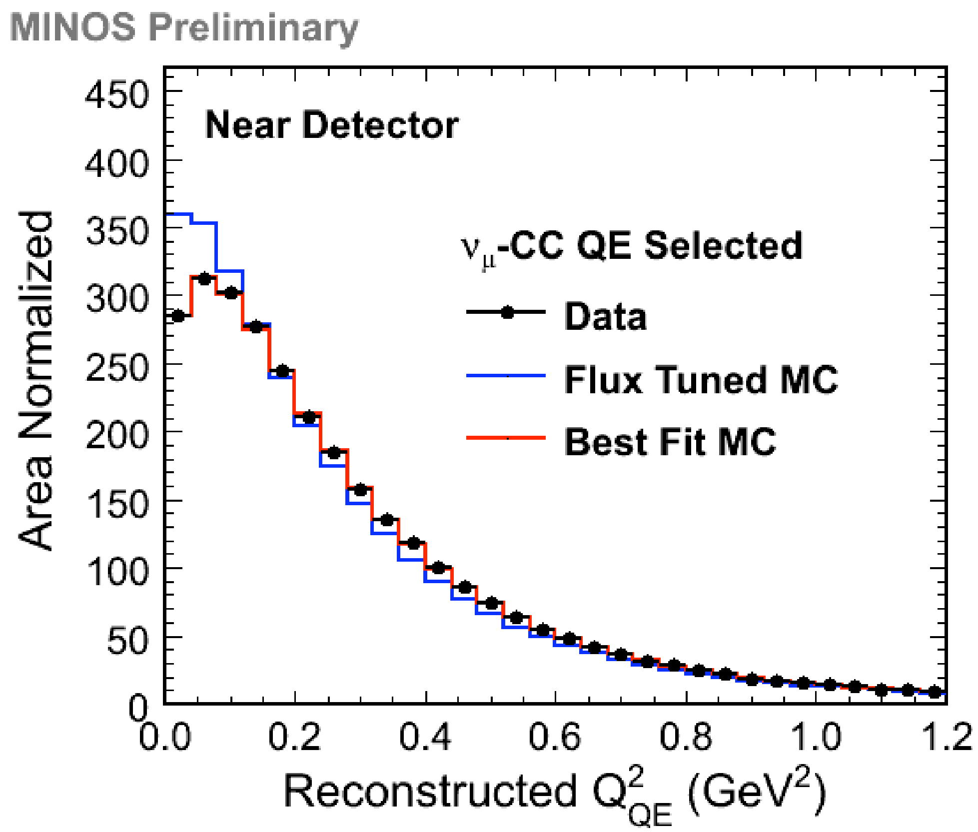
Visible shower energy < 250 MeV

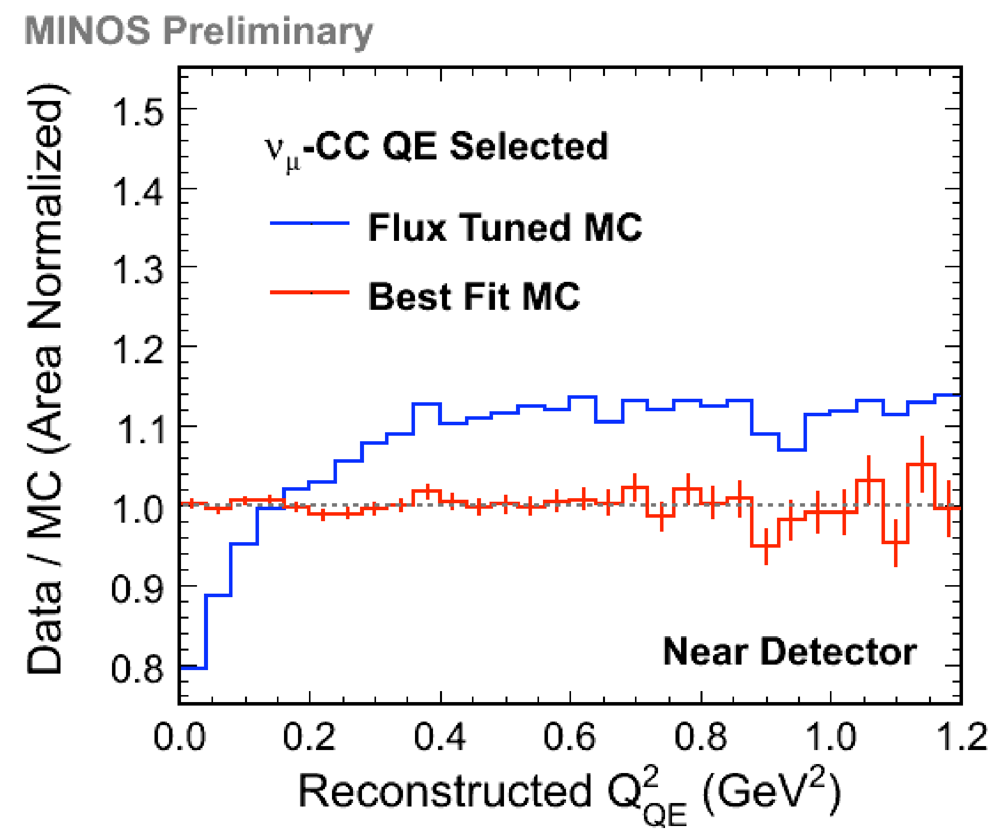
Event stops in near detector.



Efficiency 53%
Purity 61%

Best Q2 shape fit, including the lowest Q2 region





Best fit k_{Fermi} scale =1.28, E_μ scale 0.988, M_A Res=1.112
Largest additional systematics in this result are from
Hadronic energy scale errors and Intranuclear rescattering

- Effective MA = 1.19 GeV $^{+0.09}_{-0.10}$ (fit) $^{+0.12}_{-0.14}$ (syst)
- With Q**2>0.3 ⇒ M_A=1.26 0.11(Fit) 0.10 (Syst)

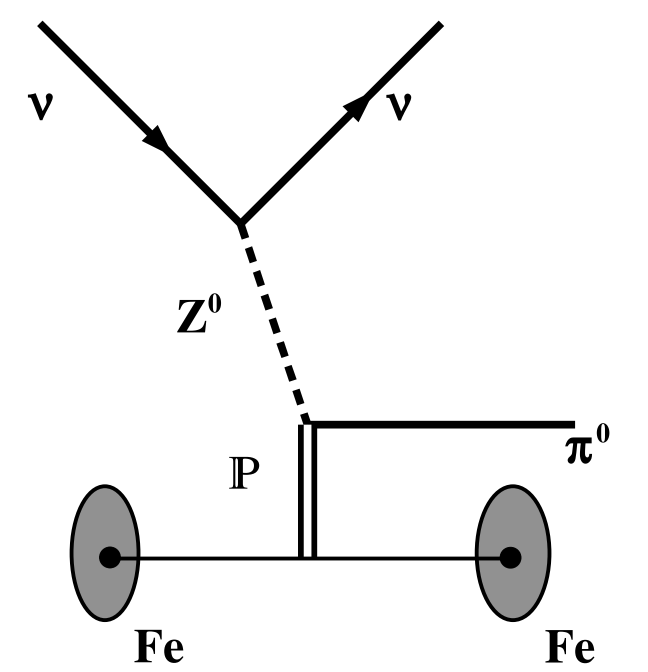
ν_μ QE-CC Measurement by MINOS

- $\sigma(\nu_\mu)$: Interpretation of the MINOS QE-data appear more consistent with MiniBOONE than NOMAD:
Higher M_A & suppression at Low-Q**2

- Plans: Finalize 1-Track analysis; include complementary 2-Track analysis

Neutrino-Nucleus Coherent NC(π^0) Scattering

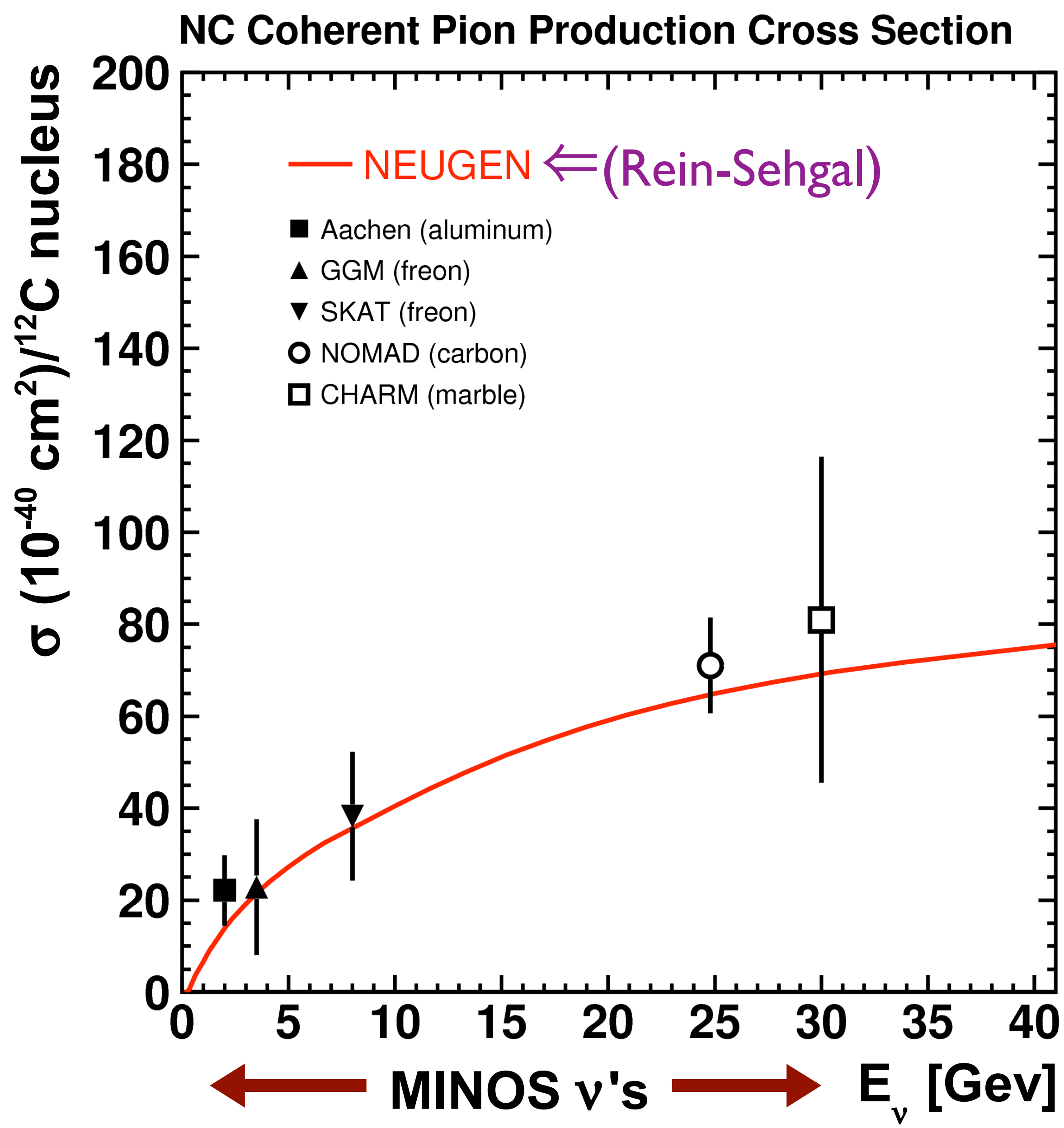
- Reaction Characterized by:
  - Single forward-going π^0
  - Nucleus remains in the ground state
  - No charge or isospin transfer
- Monte Carlo (NEUGEN3)
  - Rein-Sehgal (PCAC) model
  - Other models/implementations exist



Coherent NC(π^0) reaction

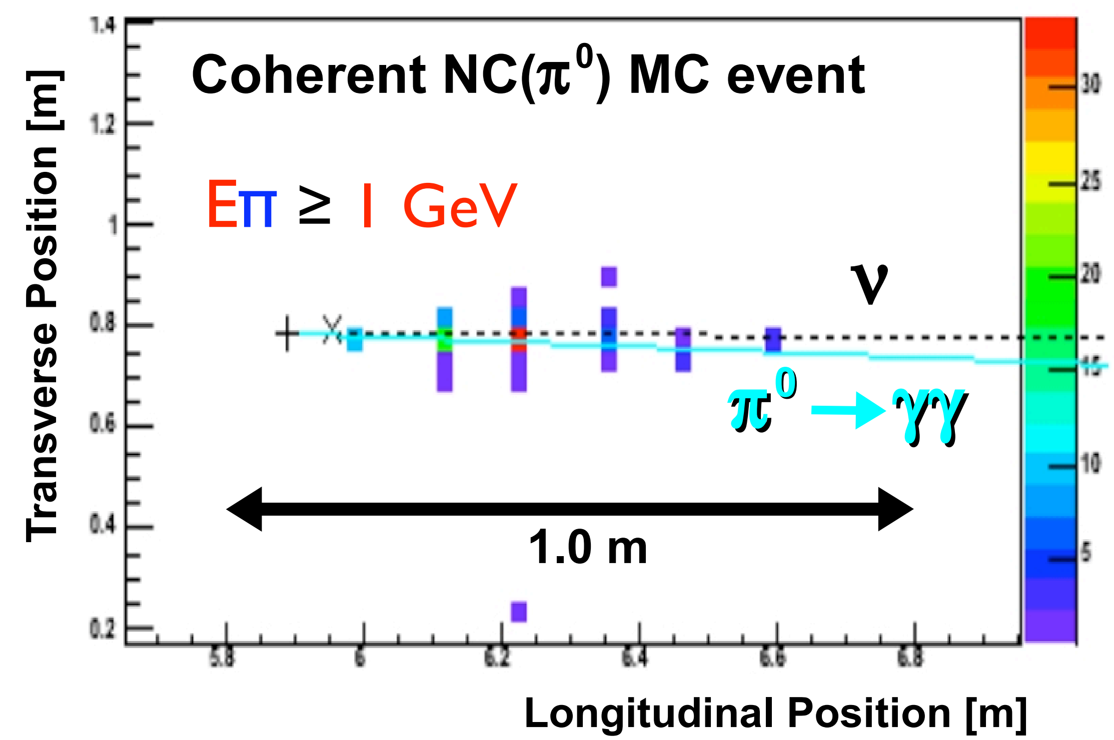
$$\frac{d^2\sigma(\nu A \to \nu \pi A)}{dQ^2\, dy\, d|t|} = \frac{G_F^2}{4\pi^2} \frac{(1-y)}{y} \left(\frac{m_A^2}{Q^2 + m_A^2} \right) f_\pi^2 \frac{d\sigma(\pi A \to \pi A)}{d|t|}$$

Status of Inclusive ν-NC Coherent-π0



Coherent NC(π^0) Interactions in the Near Detector

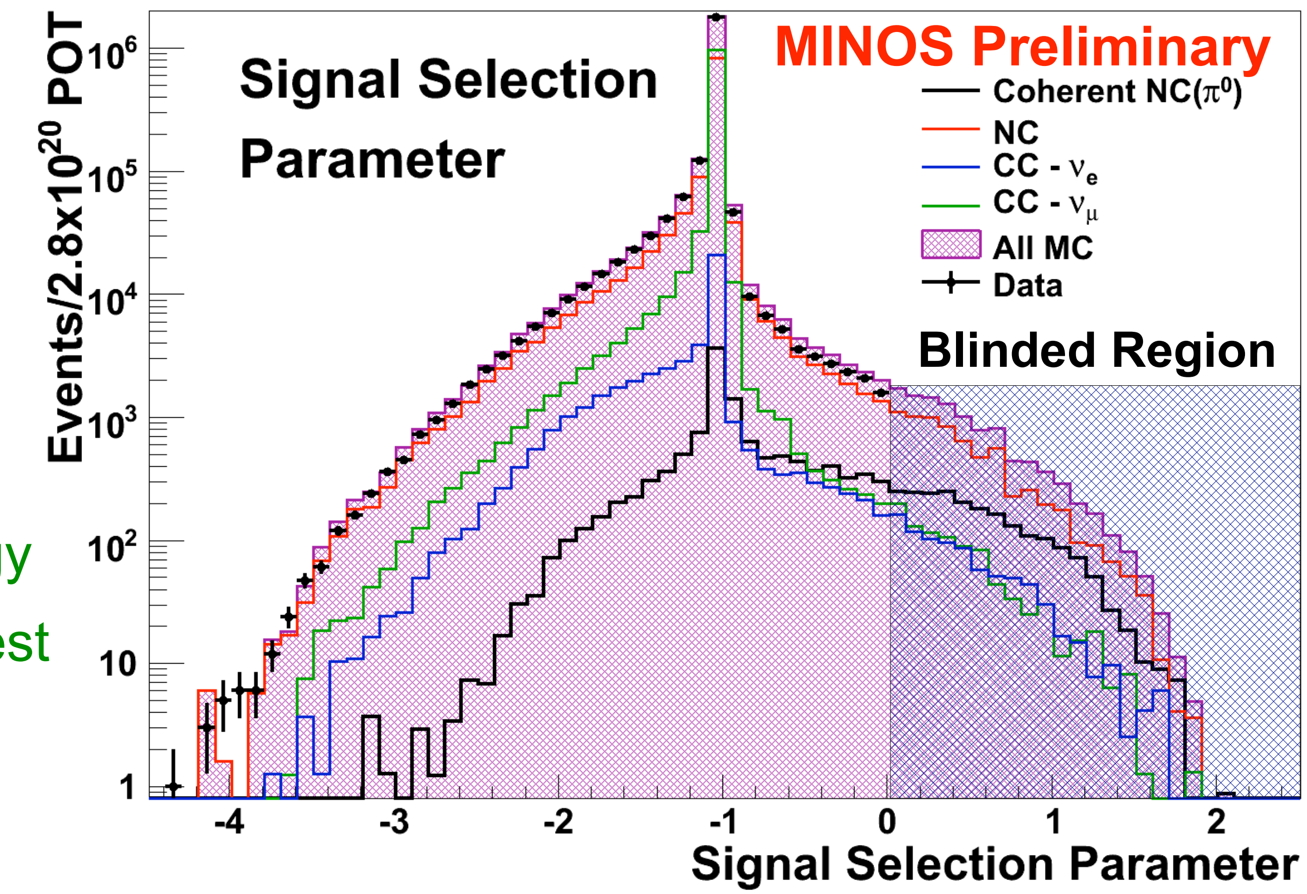
- Topological Signature:
  - Single electromagnetic shower
  - No additional hadronic activity
- Backgrounds Reactions with similar topology:
  - NC - single π^0 dominated
  - CC-ν_μ - high-y, single π^0 dominated
  - CC-ν_e - quasi-elastic like, no visible recoil proton
  - ν-e^- scattering



- MINOS event rates (2.8×10^{20} POT):
  - Roughly 13k coherent NC(π^0)
  - About 1 in every 500 events

SVM-Based Signal Selection

- Support Vector Machine (SVM) **input variables**
  - Shower size variables
    - Shower length
    - Shower width
  - Shower shape variables
    - Pattern of deposited energy
    - Fraction of energy in highest pulse height strips and planes
  - Shower fit variables:
    - Longitudinal profile
    - Transverse profiles
  - Vertex activity (recoil p)
  - Track variables



- The selected MC sample (2.8x10^{20} POT):
  - Coherent NC(π^0): 1,044 events
  - Backgrounds: 5,157 events

ν-NC Coherent-$\pi 0$ Analysis:

- Calibrate Backgrounds [NC-DIS $\pi 0$, CC-DIS, ν_e] Using Control samples
- Evaluate systematic Error: 33%
- Open the box and release the result soon

Backup Slides

Low-Nu0 Idea (1989 @ FNAL)

$$\frac{d\sigma^{\nu(\bar{\nu})}}{dxdy} = \frac{G_F^2 ME}{\pi} \times \left[\left(1 - y - \frac{Mxy}{2E}\right) F_2^{\nu(\bar{\nu})} + \frac{y^2}{2} 2xF_1^{\nu(\bar{\nu})} \pm y\left(1 - \frac{y}{2}\right) xF_3^{\nu(\bar{\nu})}\right]$$

=> Number of events < Nu0

$$\begin{aligned}\mathcal{N}(\nu < \nu_0) &= \Phi(E_\nu) \cdot \int_0^{\nu_0} \int_0^1 \frac{d\sigma}{dxd\nu} dxd\nu \\ &= C \cdot \Phi(E_\nu) \cdot \left[\left(\nu_0 - \nu_0^2/2E_\nu\right) \mathcal{F}_2 + \frac{\nu_0^3}{6E_\nu^2} \mathcal{F}_1 \pm \left(\frac{\nu^2}{2E_\nu} - \frac{\nu^3}{6E_\nu^2}\right) \mathcal{F}_3\right]\end{aligned}$$

Rearrange terms:

$$\begin{aligned}\mathcal{N}(\nu < \nu_0) &= C \cdot \Phi(E_\nu) \cdot \nu_0 \cdot \left[\mathcal{F}_2 - \frac{\nu_0}{2E_\nu}(\mathcal{F}_2 \mp \mathcal{F}_3) + \frac{\nu_0^2}{6E_\nu^2}(\mathcal{F}_2 \mp \mathcal{F}_3)\right] \\ &= C \cdot \Phi(E_\nu) \cdot \nu_0 \cdot \left[\mathcal{A} + \left(\frac{\nu_0}{E_\nu}\right)\mathcal{B} + \left(\frac{\nu_0}{E_\nu}\right)^2 \mathcal{C} + \mathcal{O}\left(\frac{\nu_0}{E_\nu}\right)^3\right]\end{aligned}$$

N(nu<nu0) is prop. Phi(Enu) up to..