Neutrino and Antineutrino Charged-Current Inclusive Cross Sections & Flux Measurements in MINERvA

Jeff Nelson

Fermilab JETP Seminar, 1/8/16

WILLIAM & MARY

CHARTERED 1693

A MINERvA "natural hat trick" on interrelated topics …

Date	Speaker	Title
Dec. 11	Phil Rodrigues U. of Rochester	Identification of Multinucleon Effects in Neutrino-Carbon Interactions at MINERvA
Dec. 18	Leo Aliaga William & Mary	Flux Results from MINERvA
Dec. 25	No Seminar	Happy Holidays!
Jan 1		Happy New Year!
Jan 8	Jeff Nelson William & Mary	Neutrino and Antineutrino Charged Current Inclusive Cross Sections and Flux Measurements in MINERvA

BONUS:
"*Measurement of Neutrino Flux from Neutrino-Electron Elastic Scattering*"
[arXiv:1512.07699]

Outline

- ## Introduction
  - > Neutrino interactions
  - > Status of charged-current inclusive scattering
  - > The low-ν method
- ## The analysis
  - > MINERvA/NuMI
  - > Analysis design
  - > Systematic uncertainties
- ## Results
  - > Fluxes and comparisons
  - > Cross sections and comparisons

This analysis is the subject of Josh Devan's W&M dissertation Fermilab-Thesis-2015-29

Goals of the long-baseline program

- **Targets**
  - > Quadrant of θ_{23} (most uncertain of the angles)
  - > Hierarchy of neutrino mass spectrum
  - > CP violation in the neutrino sector
- **Later two driven by electron appearance measurements at long baselines at few-GeV energies**
  - > Comparisons of neutrino/antineutrino appearance
  - > Understanding background systematic uncertainties
  - > Oscillation parameters (esp. the quadrant) have significant impact on parameter measurements
- **Pushes most systematics to regimes we've never achieved!**
  - > Flux, interactions, energy scales, background, near/far extrapolation…
  - > e.g. Both NOvA and T2K report 11% syst on their sample backgrounds

50% CP Violation Sensitivity

DUNE Sensitivity
Normal Hierarchy
$\sin^2 2\theta_{13} = 0.085$
$\sin^2 \theta_{23} = 0.45$

CDR Reference Design
Optimized Design

$\sigma = \sqrt{\Delta \chi^2}$

Exposure (kt-MW-years)

5%@1%
5%@2%
5%@3%

DUNE CDR, Fig 3.23 (2015)
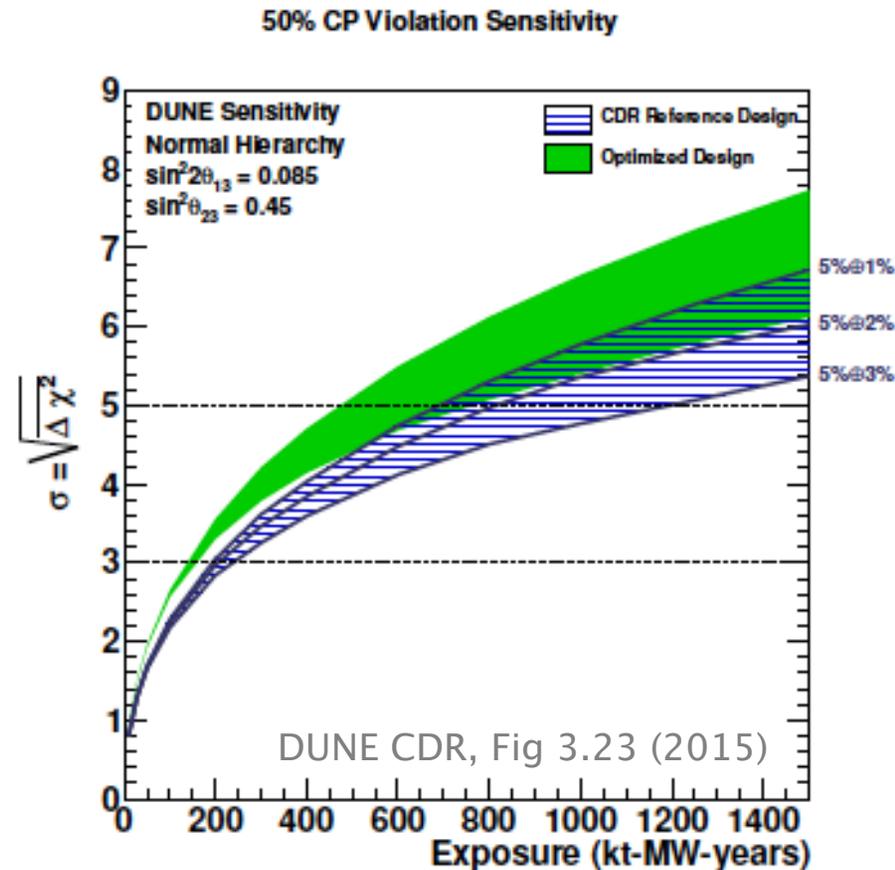
State of scattering (ca. 2016)

- ## Final SPS and TeVatron results
  - > Many GeV to hundreds of GeV
- ## Final results from MINOS
  - > Down into the few GeV region
- ## Final results from MiniBooNE, K2K, and SciBooNE
  - > All these are for E < ~1 GeV
  - > Dearth of antineutrino data starting to be addressed
- ## MINERvA, ArgoNeut, T2K results rolling in
  - > Dozens of papers
  - > Starting to get the right nuclei
  - > Can't fit it all on one plot anymore… a good thing!!!

A. Schukraft, G. Zeller

A. Schukraft, G. Zeller
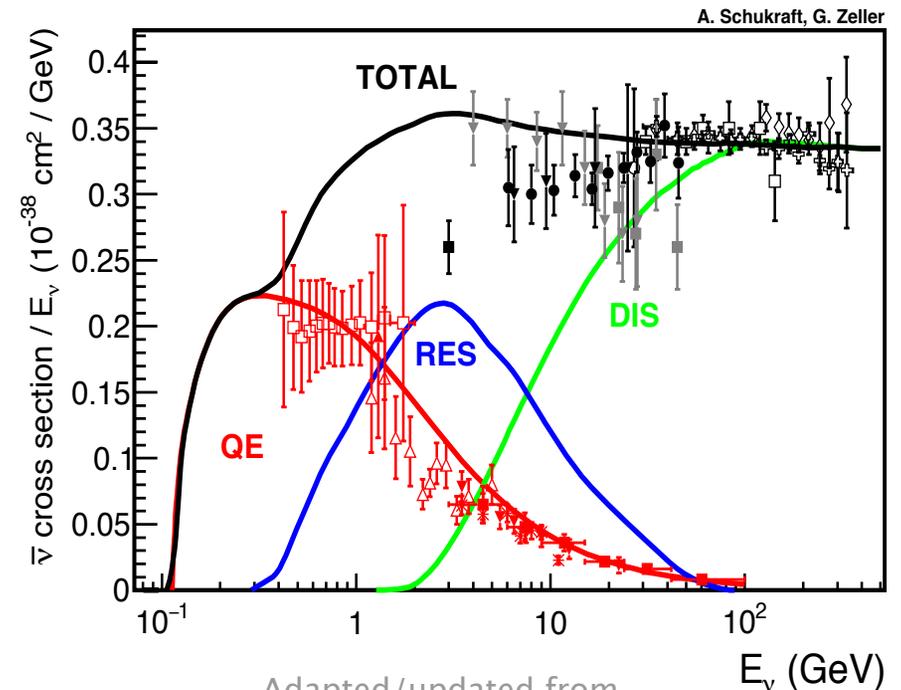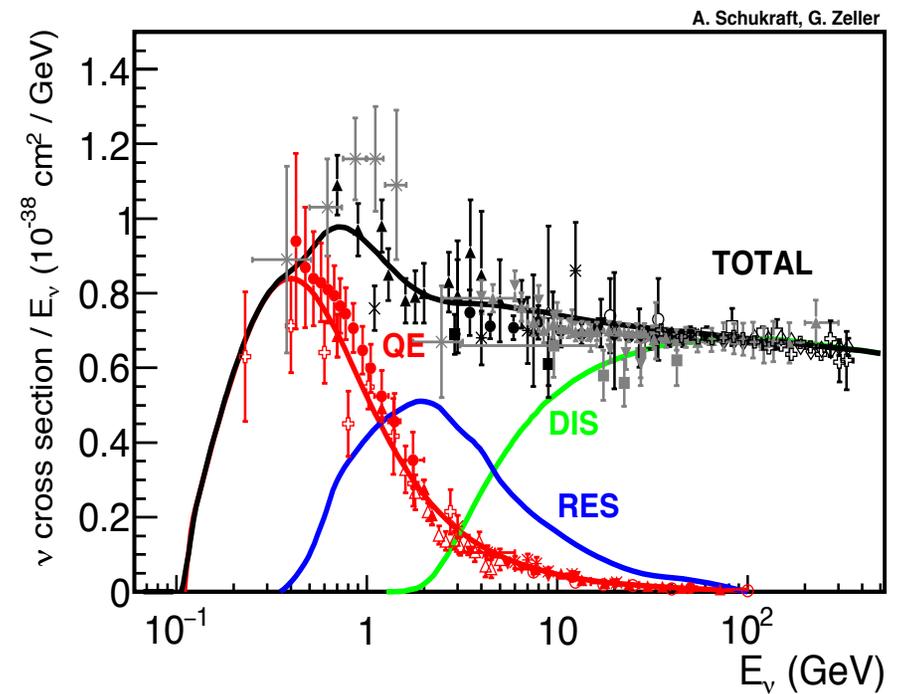
Adapted/updated from
J.A. Formaggio, G.P. Zeller, Rev. Mod. Phys. 84 (2012) 1307

Neutrino event generators

- Neutrino experiments have are few *in situ* physics handles
  - > MIP/muon, muon decay (Michel) electrons, neutral pions
  - > Only know the incoming neutrino direction accurately
- We rely heavily on full simulations of neutrino interactions to understand:
  - > Signal selection
  - > Background rejection
  - > Energy reconstruction
  - > Near/far extrapolation
- In the US program we most often use **GENIE**
  - > C. Andreopoulos et al, NIM A, 614, 87 (2010)
  - > We will use version v2r6p2 as the reference today
- Many other generators exist
  - > Some with fully specified final states
  - > Some only with computed physics distributions
- Central values for the generators are fits to scattering data

Our generators (models) do not accurately reflect recent exclusive cross section data

Adapted from PRD 81, 092005 (2010)
by P. Rodrigues
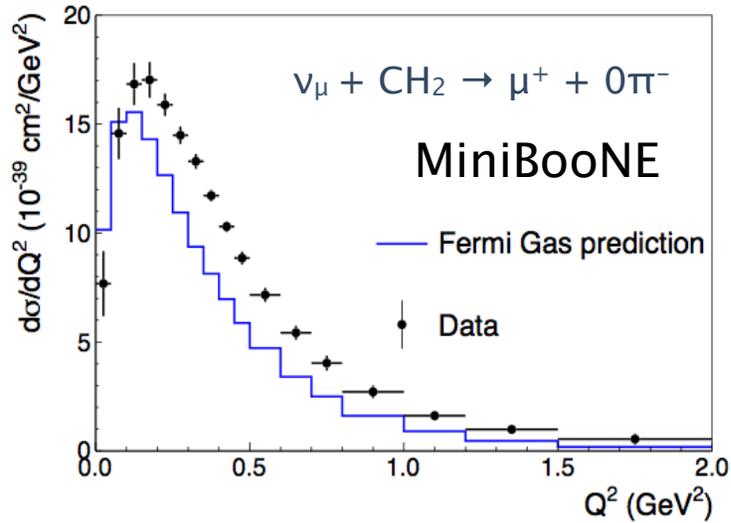
These examples are all charge pion production

$\nu_\mu + CH_2 \rightarrow \mu^+ + 0\pi^-$

MiniBooNE

— Fermi Gas prediction

• Data

Adapted from PRD 83, 052007 (2011)
by P. Rodrigues

MiniBooNE

Resonant π^0
Resonant π^+
Coherent
Quasielastic
Multi-π
Other

$\nu_\mu + CH_2 \rightarrow \mu^+ + 1\pi^-$

$\nu_\mu + CH \rightarrow \mu^+ + CH + \pi^-$

• DATA
CC coherent π
CC resonant π
Other
CC QE

SciBooNE
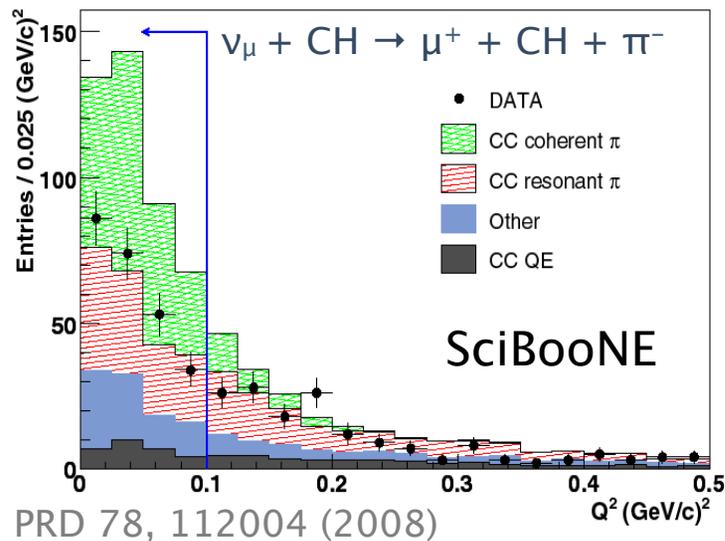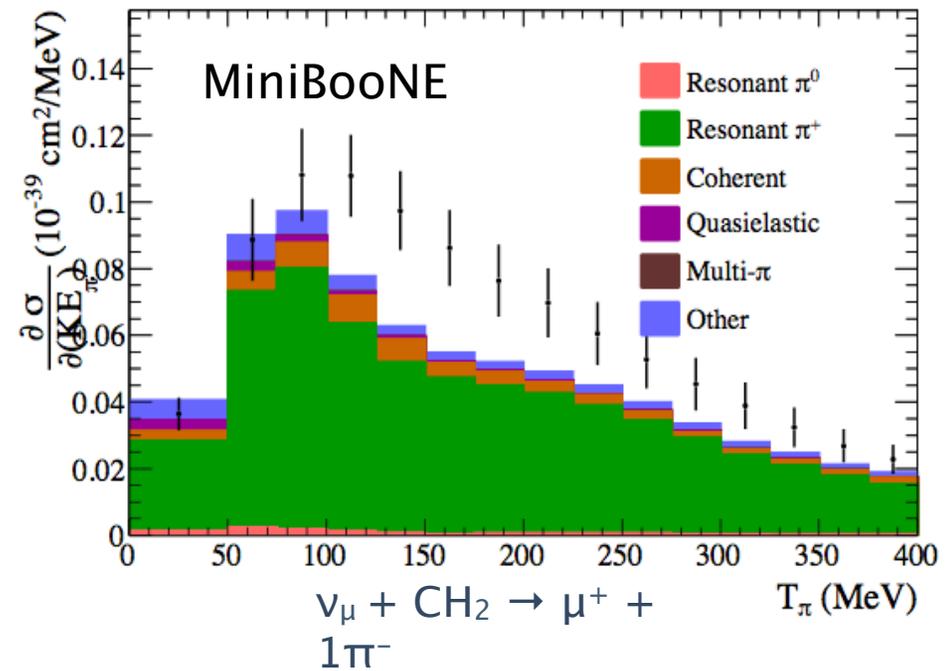
PRD 78, 112004 (2008)

We now, however, know a lot more about what works well and what doesn't

- QE-like and nuclear effects analyses favor a 2p2h process and RPA-type nuclear effects

- Pion data shows reasonable agreement on the strength of effects of intranuclear rescattering

MINERvA Preliminary • ν Tracker → CCQE

$1.5 < E_\nu < 10$ GeV

PRD 92, 092008 (2015)
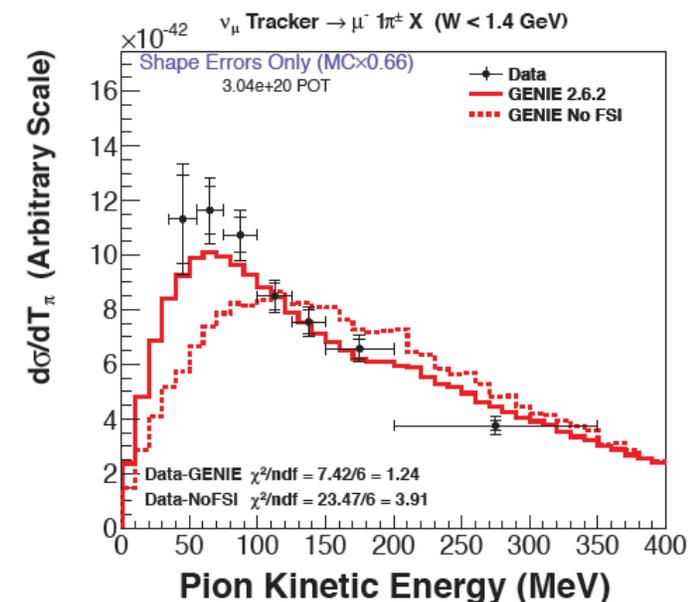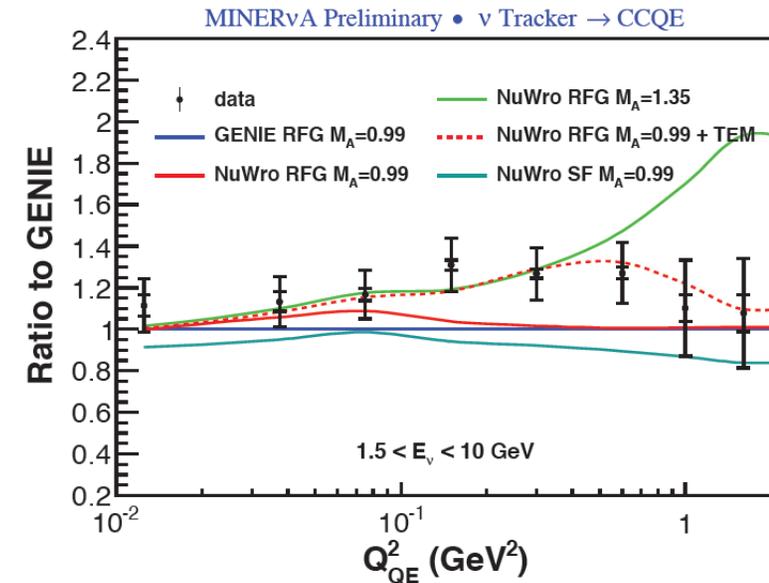
The role of inclusive scattering

- Generators require data to tune their models
  - > They/We need more/better data!
- The current and future long-baseline neutrino program focuses on the few GeV region
- This region offers a particularly interesting mix of processes
  - "it's complicated"

- In that context, one particularly useful constraint for tuning is the inclusive (total) charged-current scattering cross section

FHC Neutrinos
Minerva Preliminary
Monte Carlo

GENIE's predicted composition in NuMI LE flux

Number of Events/1E20 POT vs True E_ν (GeV)

Coherent Pion

Resonance

Quasielastic

Low W Inelastic: W<2GeV

Low Q^2 DIS: W>2GeV Q^2<1GeV^2

DIS: W>2GeV Q^2>1GeV^2
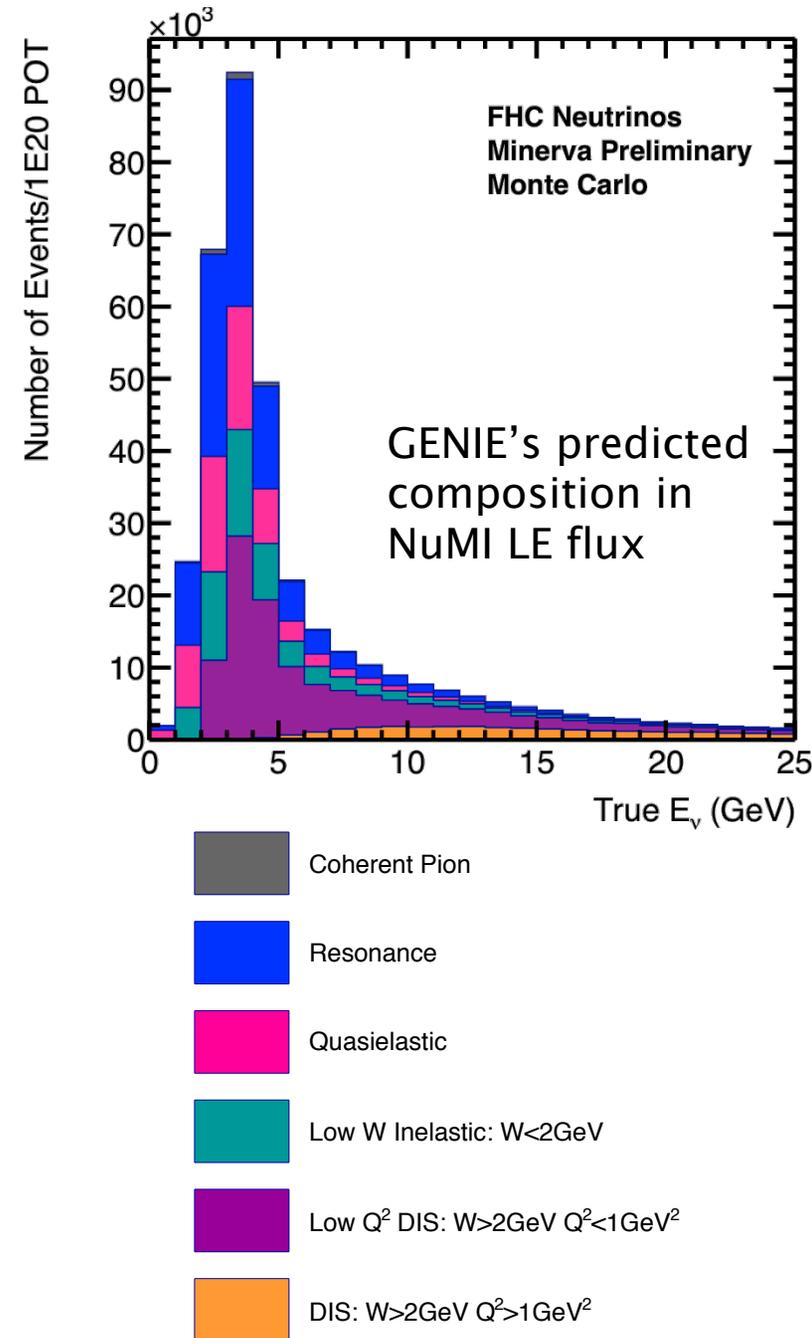
World inclusive cross section measurements for neutrinos & antineutrinos

Legend:
- ✚ T2K (Fe) PRD 90, 052010 (2014)
- ✚ T2K (CH) PRD 90, 052010 (2014)
- ☆ T2K (C), PRD 87, 092003 (2013)
- △ ArgoNeuT PRD 89, 112003 (2014)
- ● ArgoNeuT, PRL 108, 161802 (2012)
- ★ ANL, PRD 19, 2521 (1979)
- ○ BEBC, ZP C2, 187 (1979)
- ▲ BNL, PRD 25, 617 (1982)
- ◇ CCFR (1997 Seligman Thesis)
- □ CDHS, ZP C35, 443 (1987)
- ■ GGM-SPS, PL 104B, 235 (1981)
- ■ GGM-PS, PL 84B (1979)
- ▼ IHEP-ITEP, SJNP 30, 527 (1979)
- ▼ IHEP-JINR, ZP C70, 39 (1996)
- ● MINOS, PRD 81, 072002 (2010)
- ▲ NOMAD, PLB 660, 19 (2008)
- ⛣ NuTeV, PRD 74, 012008 (2006)
- ✕ SciBooNE, PRD 83, 012005 (2011)
- ✳ SKAT, PL 81B, 255 (1979)

$\nu_\mu\ N \rightarrow \mu^-\ X$

$\overline{\nu}_\mu\ N \rightarrow \mu^+\ X$

PDG 2016 Preview!

Thanks Sam!

She says this is the first unveiling!

Note: σ/E approaches a well-determined asymptotic value at high energies

Neutrino flux measurement

Neutrino flux critical for any absolute cross section measurement

$$\sigma(E) = \frac{U(D-B)}{\epsilon \Phi T \times \Delta E}$$

- D is data event yield
- B is background estimate
- U( ) unfolding operation
- Φ is flux (AKA the hardest part)
- ε is efficiency/acceptance correction
- ΔE is the bin width
- T is number of targets

How to know your neutrino flux?

- *Ex situ* via Hadron production data
  - \> External thin & thick target hadron production data can be used to modify off-the-shelf simulation packages
  - \> Subject of previous JETP by Leo Aliaga (more later)
- Measuring muon spectra at the end of the decay volume
  - \> Get a muon for each muon neutrino so sampling the muon rate at various ranges allows evaluation of flux
  - \> NuMI has three thresholds for its muon counters (not very finely grained)
- Can also use standard-candle cross sections
  - \> Neutrino-electron scattering (more later)
  - \> Low recoil event rates: subject of the seminar

The principle of the low-ν method

- ν is the energy transferred to the recoil system

$$\nu \equiv E - E_\mu$$

- In the limit of small ν, the charged-current cross section for neutrinos and antineutrinos is approximately constant as a function of neutrino energy (will show this shortly)
  > That this is constant is needs to be true because we know that cross sections can be expressed by a set of structure functions
- A measurement of the low-ν interaction rate as a function of neutrino energy is equivalent to a measurement of the shape of the neutrino flux as a function of energy

The cross section for charged-current inclusive neutrino-nucleon scattering ...

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}x\mathrm{d}y} = \frac{G_F^2 M E}{\pi}\left(\left[1 - y\left(1 + \frac{Mx}{2E}\right) + \frac{y^2}{2}\left(\frac{1 + (2Mx/Q)^2}{1 + R_L}\right)\right]F_2 \pm \left[y - \frac{y^2}{2}\right]xF_3\right)$$

- Where the "+" is for neutrino scattering; "−" is for antineutrino
- E is the neutrino energy, M is the mass of the nucleon, x (scaling variable) and y (inelasticity) are given by

$$y = \nu/E \qquad x = \frac{Q^2}{2M\nu}$$

- The internal structure of the nucleon is describe by structure functions $F_2(x,Q^2)$, $xF_3(x,Q^2)$, and $R_L(x,Q^2)$.
- R_L is the ratio of the cross section for scattering from longitudinally polarized W bosons to transversely polarized and is defined in terms of F_1 and F_2

$$R_L(x,Q^2) = \frac{F_2(x,Q^2)(1 + 4M^2x^2/Q^2) - 2xF_1(x,Q^2)}{2xF_1(x,Q^2)}$$

Then some algebra happens...

- Substitute $y = \nu/E$ and and $Q^2 = 2M\nu x$, group terms into ν/E, and integrate over x

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\nu} = \frac{G_F^2 M}{\pi}\left(\int_0^1 F_2\,\mathrm{d}x - \frac{\nu}{E}\int_0^1 [F_2 \mp xF_3]\,\mathrm{d}x \right.$$
$$\left. + \frac{\nu}{2E^2}\int_0^1 \left[\frac{Mx(1-R_L)}{1+R_L}F_2\right]\mathrm{d}x + \frac{\nu^2}{2E^2}\int_0^1\left[\frac{F_2}{1+R_L} \mp xF_3\right]\mathrm{d}x\right)$$

- Integrating this to low ν (i.e. $\nu_0 << E$) causes the terms proportion ν/E, ν/E^2 and ν^2/E^2 to be vanishingly small
- Therefore $\sigma(\nu < \nu_0, E)$ is approximately constant
- It deviates modestly due to Q^2 dependence of the structure functions (Bjorken scaling violation)

Game plan…

- The charged-current cross section for events with low hadronic recoil (ν) is nearly energy independent
  - > The low-ν cross section is a (nearly) standard-candle process!
- Due to the energy independence, the interaction rate is proportional to the flux:

$$N(\nu < \nu_0, E) = \Phi(E) \times \sigma(\nu < \nu_0, E) \propto \Phi(E)$$

- Use the extracted event rates to measure the neutrino and antineutrino fluxes
- Then extract inclusive scattering cross sections using those fluxes

This picture isn't quite so simple

- Can't cut at exactly ν=0
- So you have to put in corrections from other structure functions

$$S(\nu_0, E) = \frac{\sigma(\nu < \nu_0, E)}{\sigma(\nu < \nu_0, E \to \infty)}$$

- For this analysis, these are calculated using the GENIE model
- You have to normalize the flux somewhere
  - Can use precision external measurements as an anchor
  - Can use GENIE (which itself is based on data)

Some recent examples of the low-ν technique in action

- NuTeV (and CCFR before them)
  - They examined neutrino energies from 30 to 360 GeV and used a 5 – 20 GeV low-ν cut so all their "flux sample" events firmly in the DIS regime
  - These energies mean the recoil systems have fairly high multiplicity and fairly linear calorimetric responses with Gaussian resolutions
  - NuTeV Collaboration (M. Tzanov at al.) Phys. Rev. D 74 (2006) 012008
- MINOS
  - They examined neutrinos (antineutrinos) energies from 3(5) to 50 GeV and used low-ν cuts as low as 1 GeV
  - The lowest energy application of the technique to date
  - MINOS Collaboration (P. Adamson et al.) Phys. Rev. D 81, (2010) 072002

But isn't your low-ν cross section is part of you the CC cross section you wish to measure?!?

- Successful history of the method in CCFR, NuTeV, MINOS
- Seems like a circular argument …
  - > Your standard candle is also part of the inclusive sample (at the tens of percent level in MINOS)
  - > One must use the simulation and external normalization to correct for this part of the sample
- Leads to a balancing act…
  - > Try to keep the fraction of low-ν events small by decreasing the ν cut
  - > Try to keep the statistical uncertainty of the flux low by increasing the ν cut
  - > Try to keep away from the lowest energy recoils where the uncertainties in the models "blows up"

Why use Low-ν in MINERvA?

- MINERvA
  - > It is a fine-grained detector with better hadron energy resolution
  - > Ran in both neutrino and antineutrino enhanced sample
  - > Extend down to neutrinos energies as low as 2 GeV
- To go this low in energy …
  - > Need to extend the low-ν limit to as low as 300 MeV
  - > Recoil systems with single particle final states are a significant probability so we get non-Gaussian response that depends on details of initial state
  - > Pushes into areas that were fully murky in 2009
- How to address?
  - > We evaluate the uncertainties in this method based on the data/mc discrepancies that we do see in these other channels and using new models for the effects people think we're seeing.
  - > New results and theoretical progress give us better, model-motivated systematic uncertainties (both nuclear effects and process models)
  - > New generators (like GENIE) have better tools to do more complete analysis of theoretical uncertainties
  - > Study of using low-ν method in MINERvA was performed
    - A. Bodek, *et al.* Eur. Phys. J. C 72 (2012) 1973

At the 12/11 MINERvA JETP seminar…

- A theory based description of unmolded effects in GENIE (Valencia model) that improves agreement at the lowest emerges (top)

- Neutrino cross sections (bott) in bins of momentum transfer as a function of recoil energy (ν)
  - > Shows us where the issues are lurking

- From earlier in the year we also saw that the modern final–state interaction (FSI) model in GENIE works better too
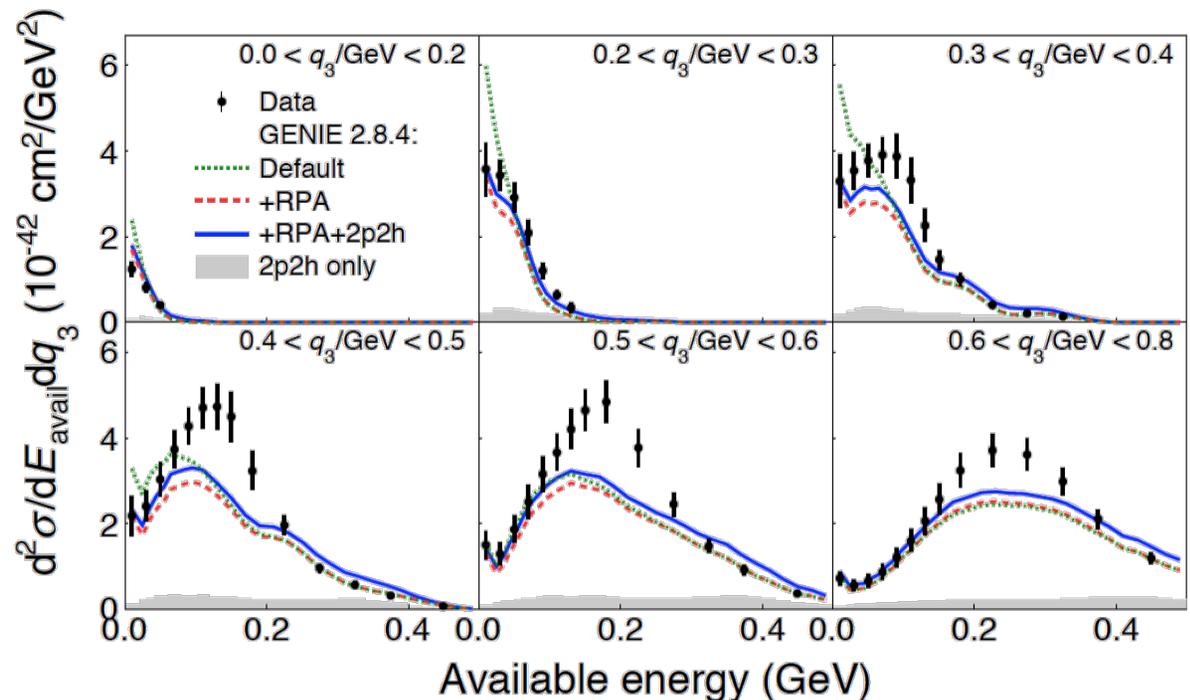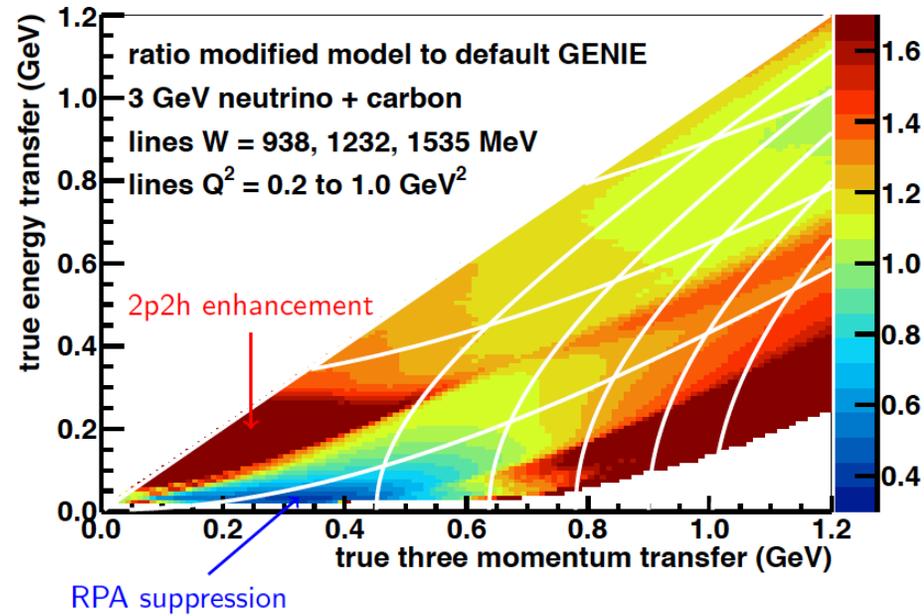
See arXiv:1511.05944 &
Carrie McGivern's 6/26/15 for pion based tests of FSI models

The MINERvA neutrino-nucleus scattering experiment

The MINERvA Collaboration

MINERvA

- Finely segmented solid scintillator (CH) detector on axis in NuMI
  - Active tracker is all scintillator
  - Calorimeters are scintillator w/ Fe or Pb
- MINOS detector for muon spectrometer
- Test beam program for energy scale/detector model
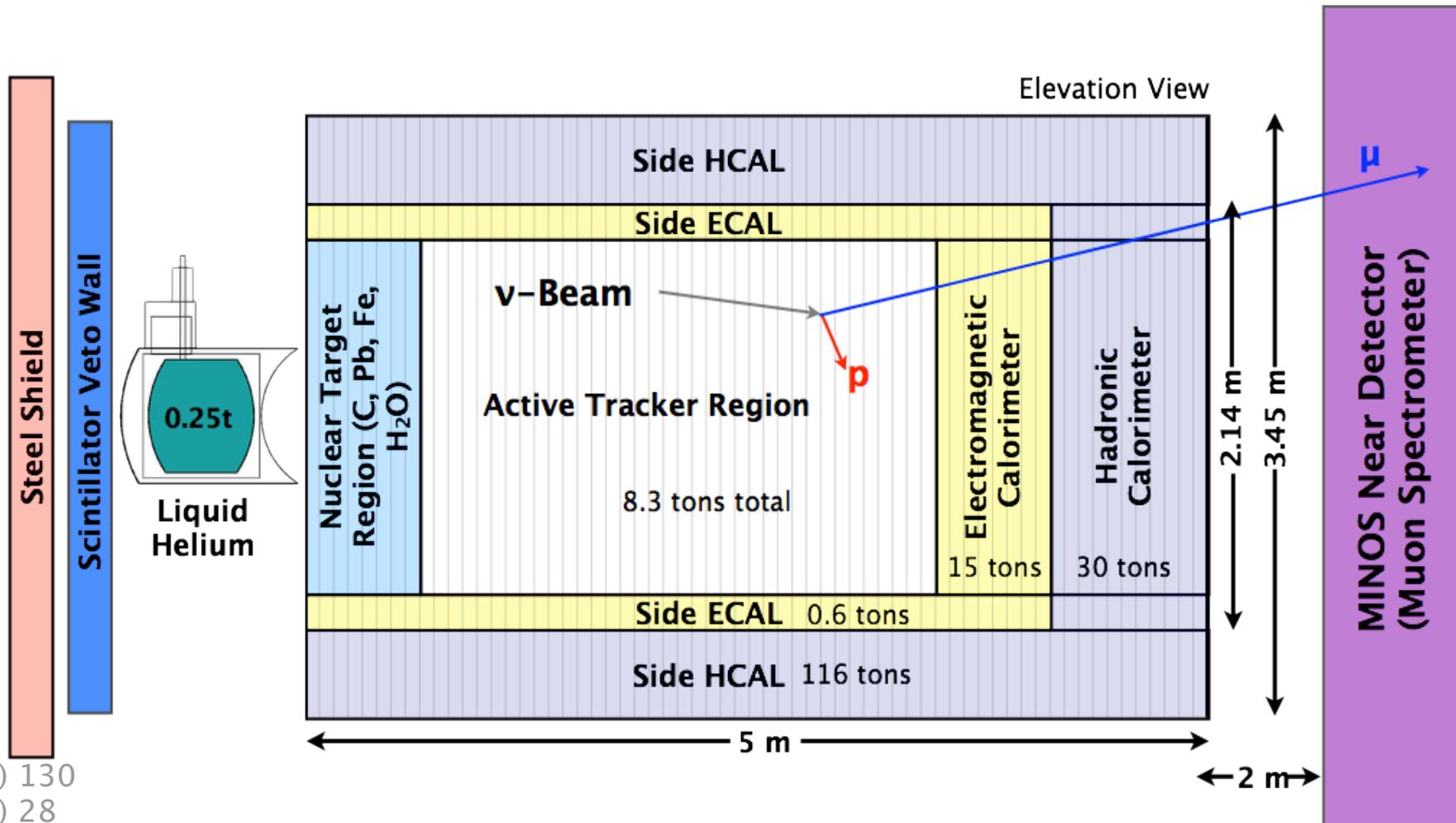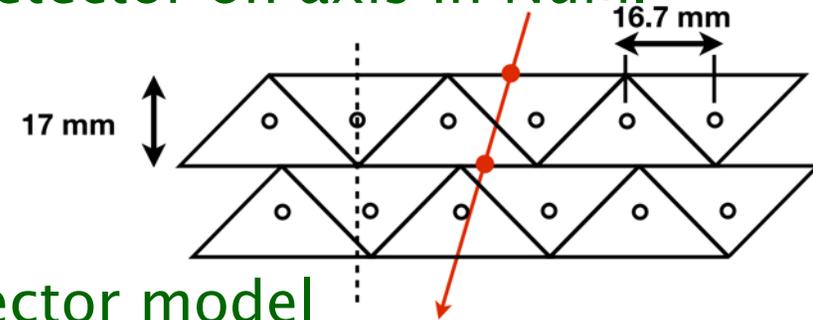
NIM A743 (2014) 130
NIM A789 (2015) 28

NuMI Neutrino Beam

$$p + C \rightarrow \pi \rightarrow \mu + \nu_\mu$$
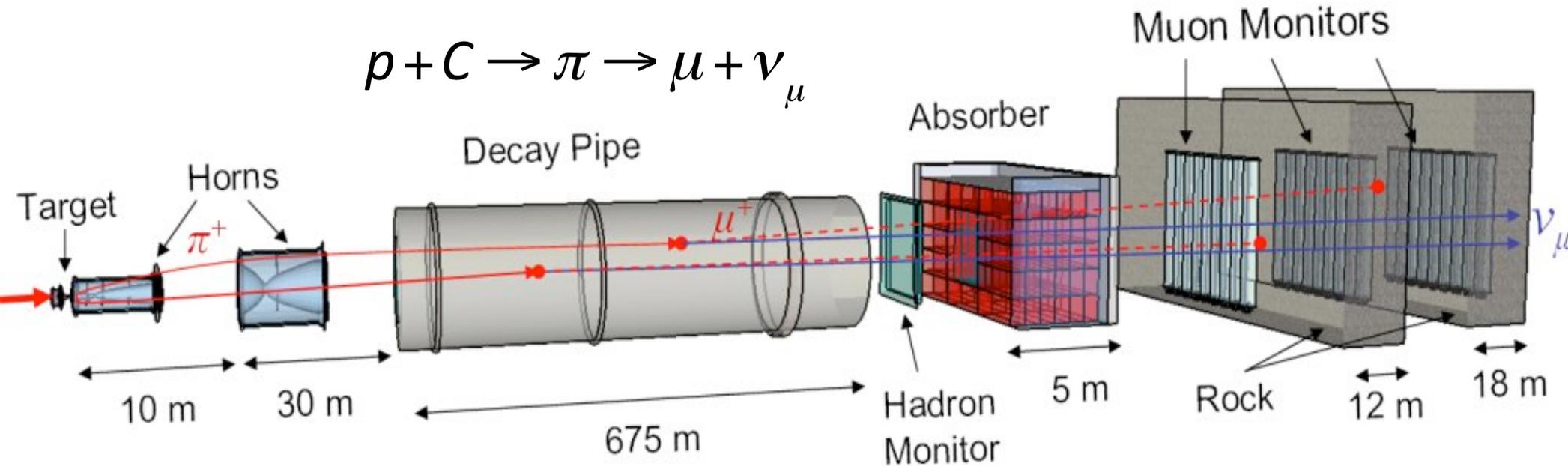
- 120 GeV protons impinge on a 2 interaction length graphite target
- Mesons produced in the target are focused by two magnetic horns
- The beam composition is selected by the polarity of the current in the horns
  - > Forward Horn Current (**FHC**) focuses π⁺ creating a neutrino−enhanced beam
  - > Reverse Horn Current (**RHC**) focuses π⁻ creating an antineutrino−enhanced beam
- Can also change the target−horn configuration (and horn current) to focus different energy pions & change the neutrino energy spectrum

Image courtesy of Z. Pavlovic

The data set

- NuMI low–energy tune (LE) data collected from 2010–2012

- **RHC** 1.09×10^{20} POT

- **FHC** 3.18×10^{20} POT

- Since then we have been collecting data in NuMI's medium energy (ME) tune
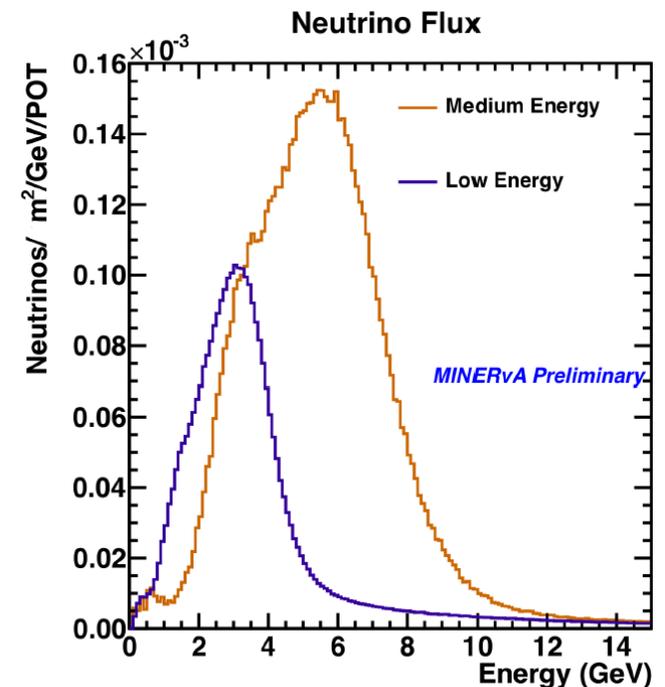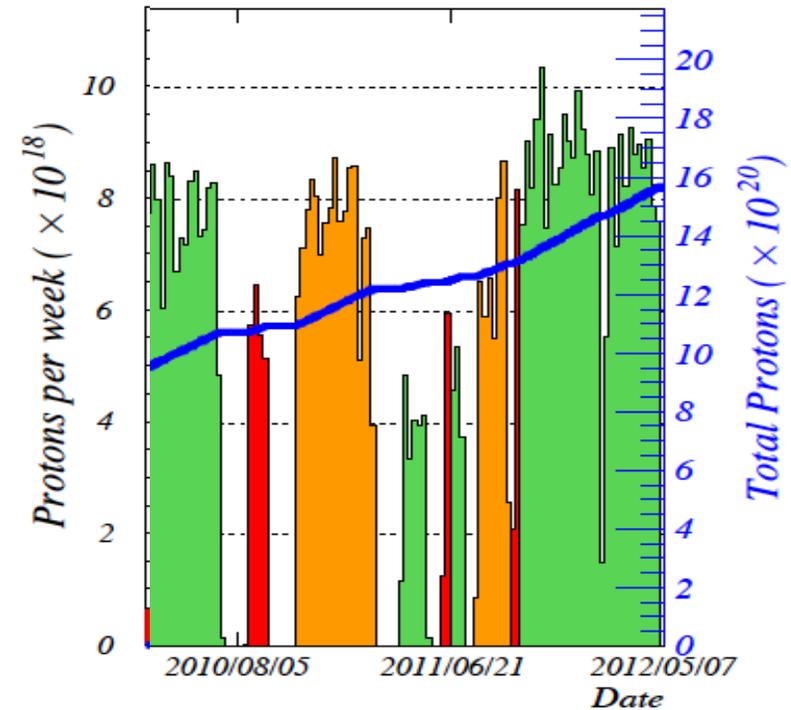
# MINERvA analysis chain

A MINERvA event
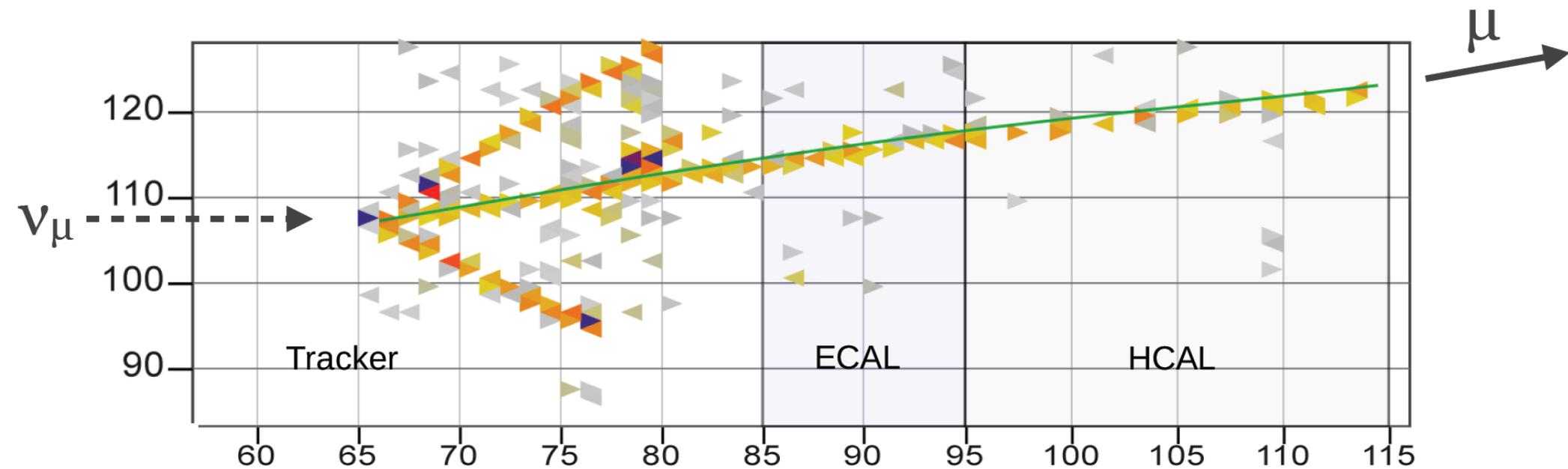
In this plot the color reflects the energy recorded in the strip

Muon reconstruction

- For this analysis we require that the muon track be matched to a track in MINOS
  - > Imposes a roughly 1.5 GeV threshold to punch through the MINERvA calorimeters and be above the MINOS tracking threshold
  - > Limits the maximum muon angle to be within roughly 20° of the beam direction
- MINOS returns momentum based on either range or curvature and charge based on curvature
- Systematic uncertainties in MINOS muons
  - > 2% uncertainty on muon momentum from range due to mass model and dE/dx model in MINOS
  - > 0.6% (2.5%) uncertainty on muon momentum from curvature for momentum below (above) 1.5GeV
    - Based on comparing magnetic field maps to magnetic induction measurements
    - Based on comparisons between range and curvature for tracks stopping
   - Added in quadrature to range uncertainty

Calorimetry

Energy not on the muon road (or on the road and too energetic to be a muon) within a timing window in the tracker/downstream ECAL/ downstream HCAL
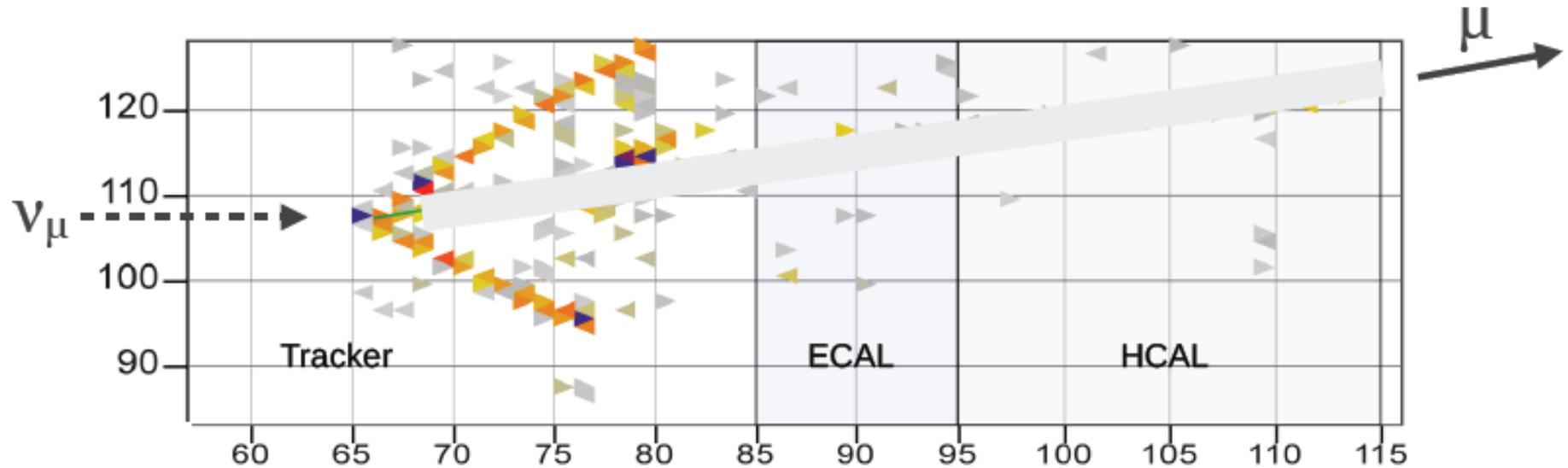
Reconstructed recoil energy

Calorimetric constant (per subdetector)

$$\nu_{reco} \equiv \alpha \times \sum_i C_i E_i$$

Overall scale (fit from simulation)

Cluster energy

$C_{tracker} = 1.222$
$C_{ECAL} = 2.013$
$C_{HCAL} = 10.314$

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# Low energy calorimetric response constrained by test beam experiment

- This analysis uses a preliminary MC to the test beam response
  - 10% proton uncertainty
  - 5% pion uncertainty
  - 3% for electron-magnetic response (also tested using Michel electrons and the neutral pion peak)
  - n.b. errors are 3%/5%/3% with tuning

- Other particle responses were validated by comparing GEANT to external inelastic scattering data
  - Sample samples also used to validate GENIE final-state interaction model
  - 15% neutron response uncertainty
  - Higher energy inelastic pion/proton data
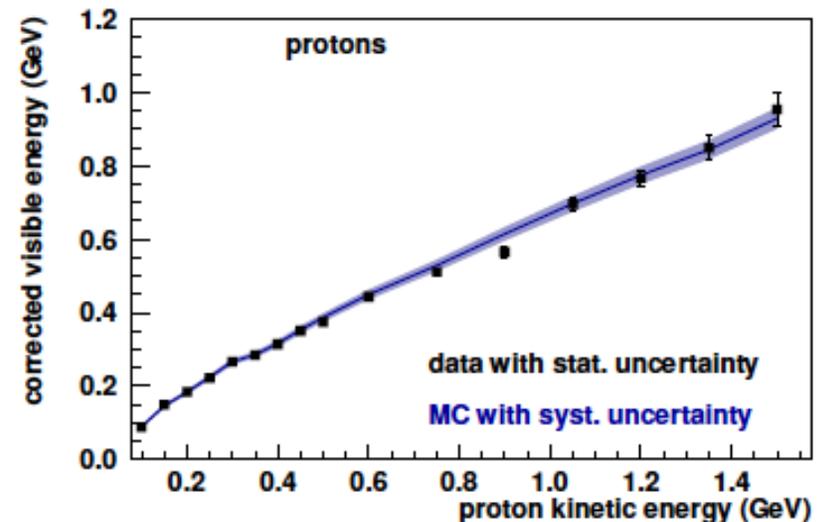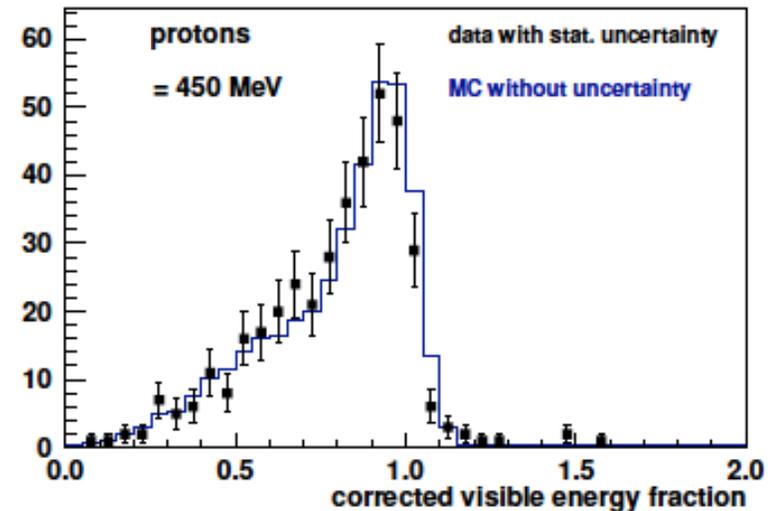

NIM A 789, 28 (2015)

Average energy carried by particle type in the CC inclusive recoil system (MINERvA flux/ GENIE)
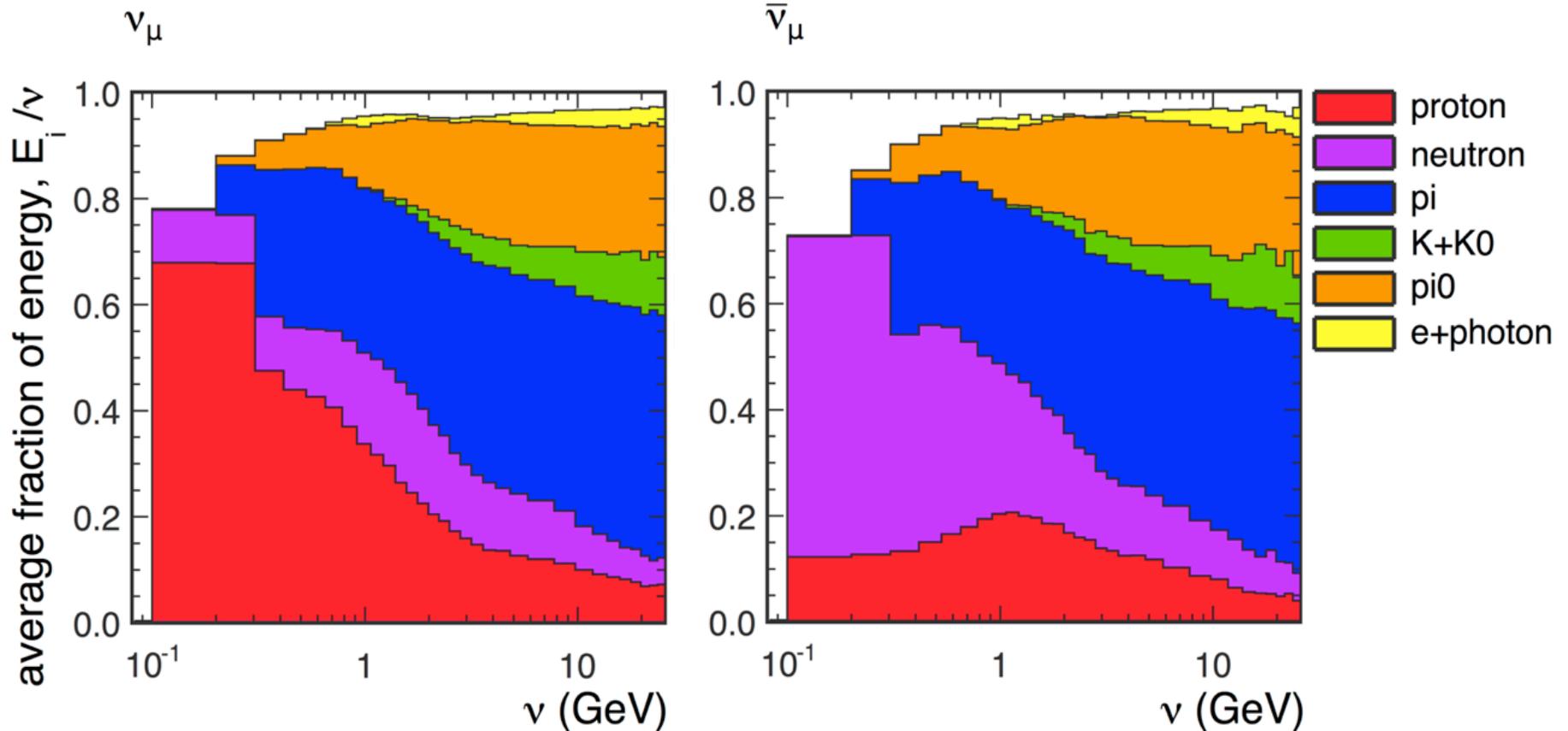
Deficit at low energy is due to FSI, binding energy, and excitation of the nucleus

Fractional recoil system energy resolution (neutrino CC inclusive)

From simulation

ν_μ

$$\frac{\sigma}{\nu} = 0.132 \oplus \frac{0.329}{\sqrt{\nu}}$$

calorimetric resolution, σ/ν

true recoil energy, ν_{true} (GeV)

$\overline{\nu}_\mu$

$$\frac{\sigma}{\nu} = 0.163 \oplus \frac{0.283}{\sqrt{\nu}}$$

true recoil energy, ν_{true} (GeV)
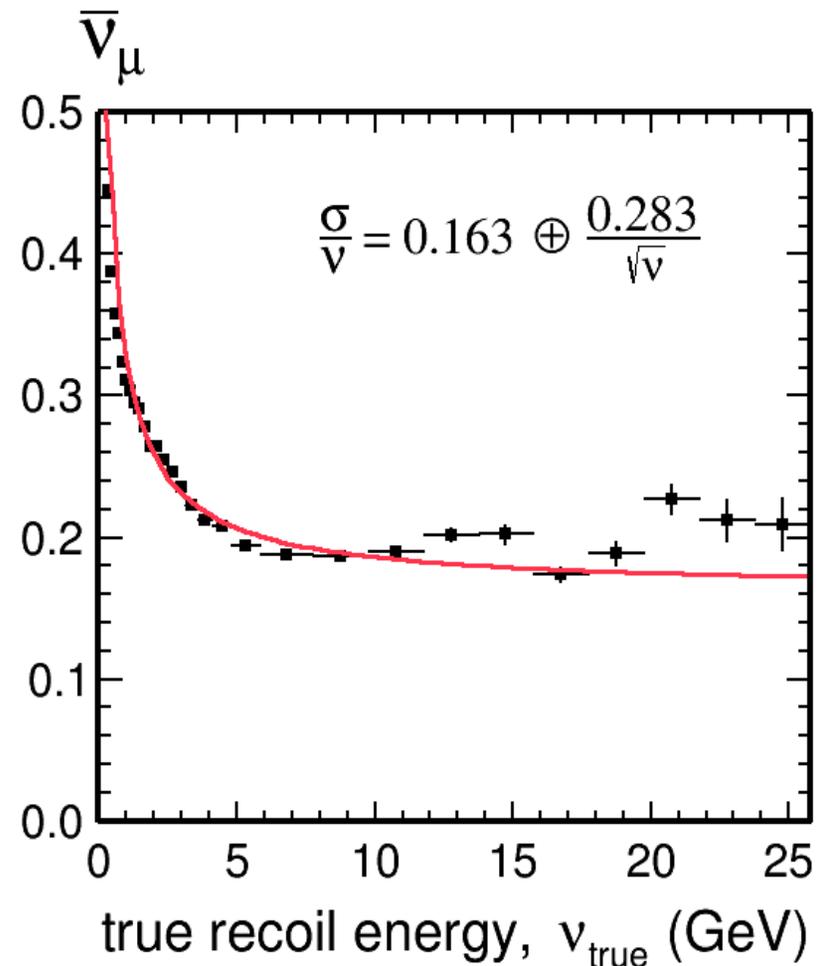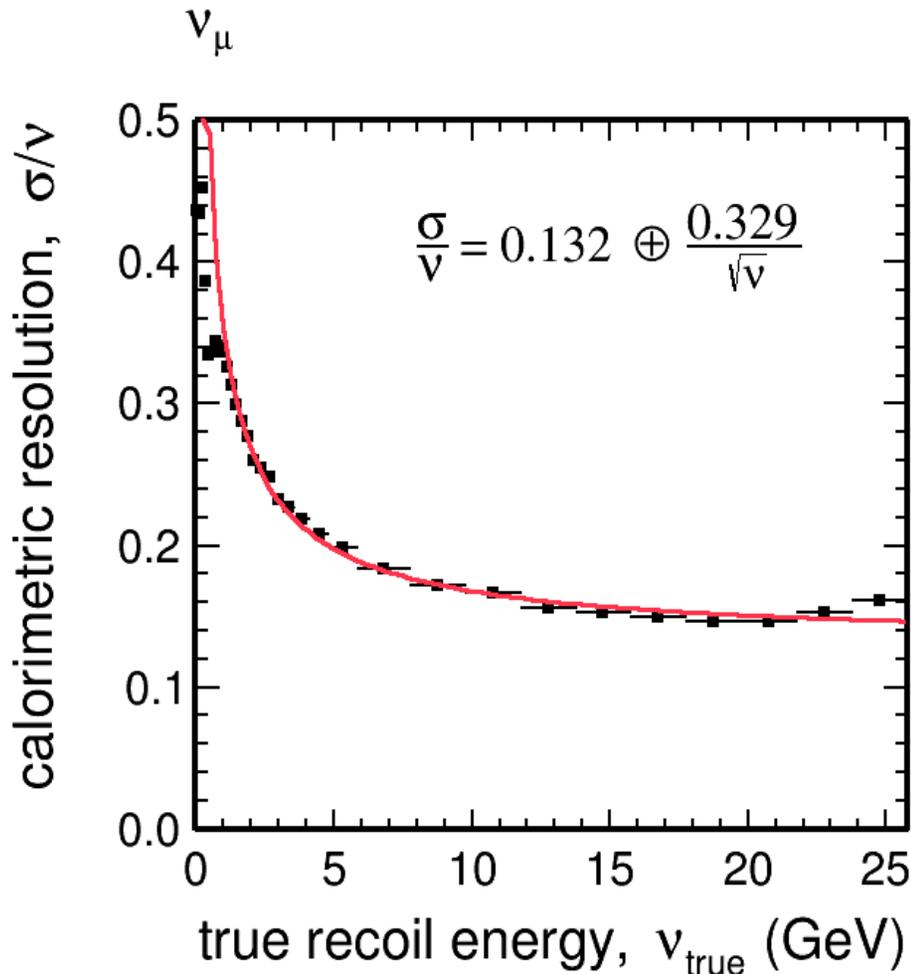
Uncertainty on calorimetric reconstruction of the recoil system


From simulation
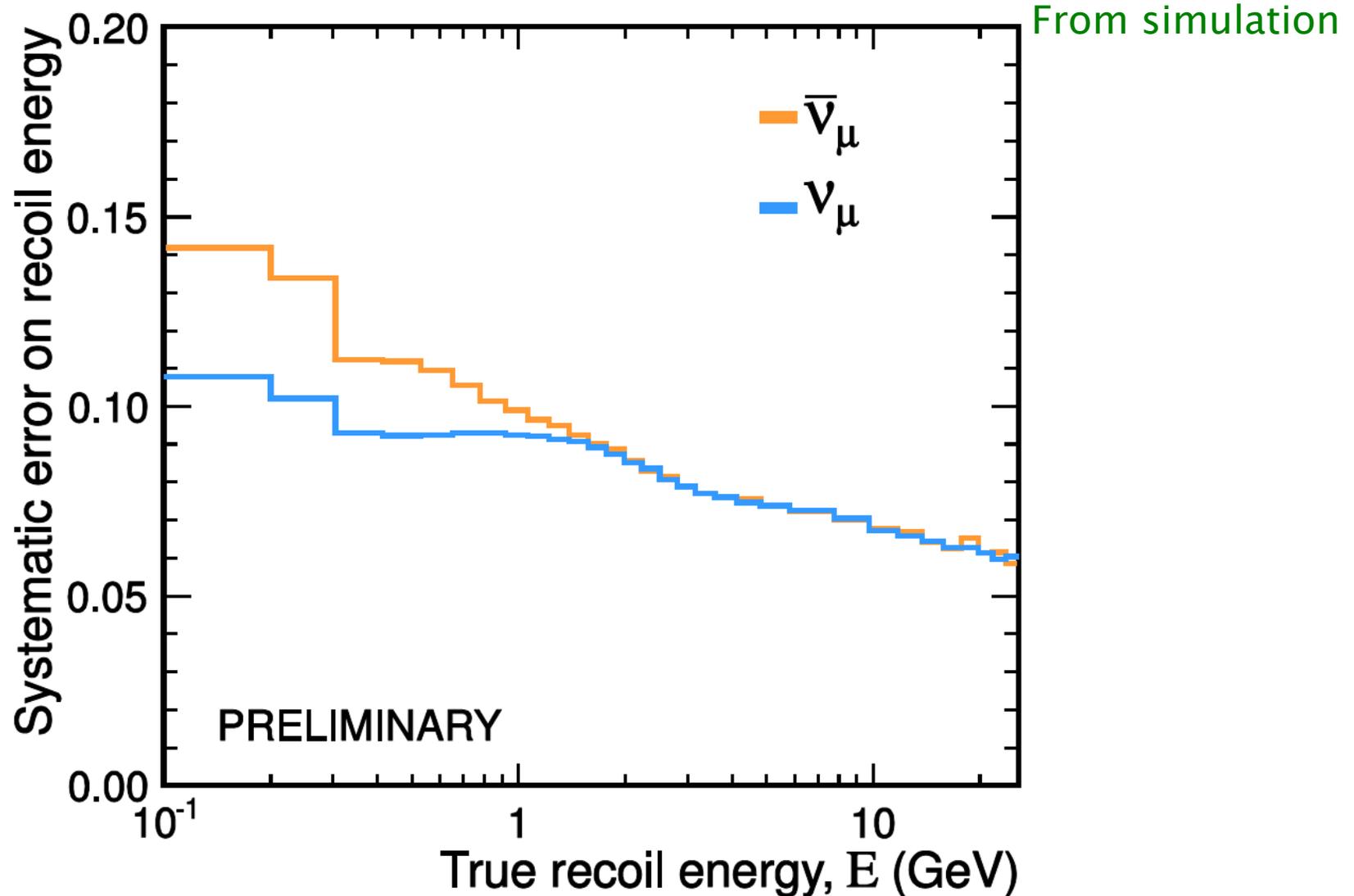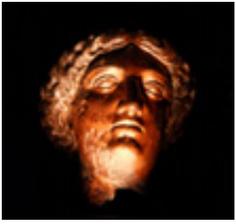
The analysis

Low-ν method for flux determination

The absolute normalization of the flux is set such that the extracted cross section matches a target value at high neutrino energy.

$$\Phi(E) = \eta \frac{U(D_\nu - B_\nu)}{\epsilon \sigma_\nu T \times \Delta E}$$

Unfolding

Neutrino flux (function of neutrino energy)

Data interaction rate

Background interaction rate

Normalization

Efficiency × acceptance

Low-ν cross section

Neutrino energy bin width

# Target nucleons

Many ν's

ν_μ in FHC

ν̄_μ in RHC
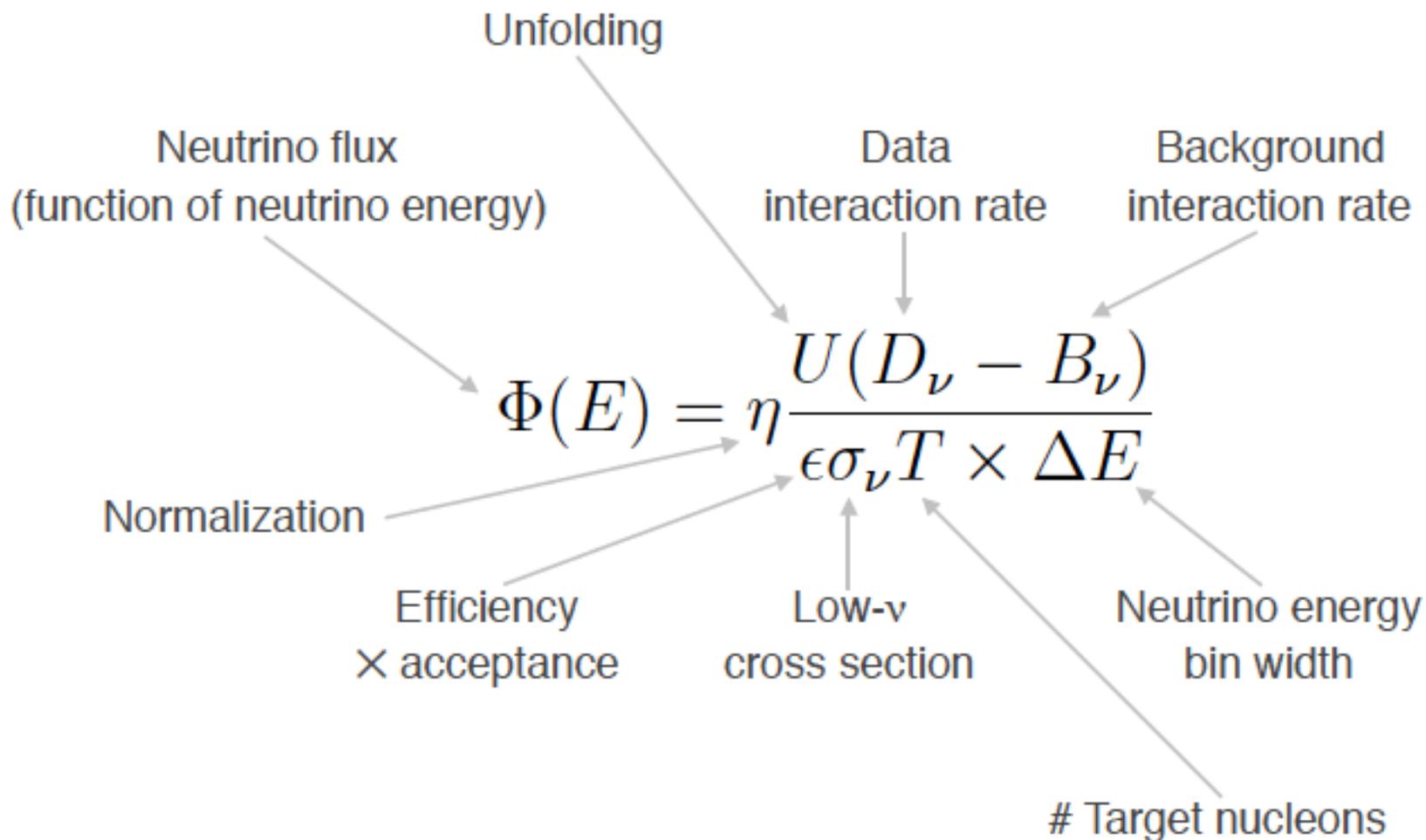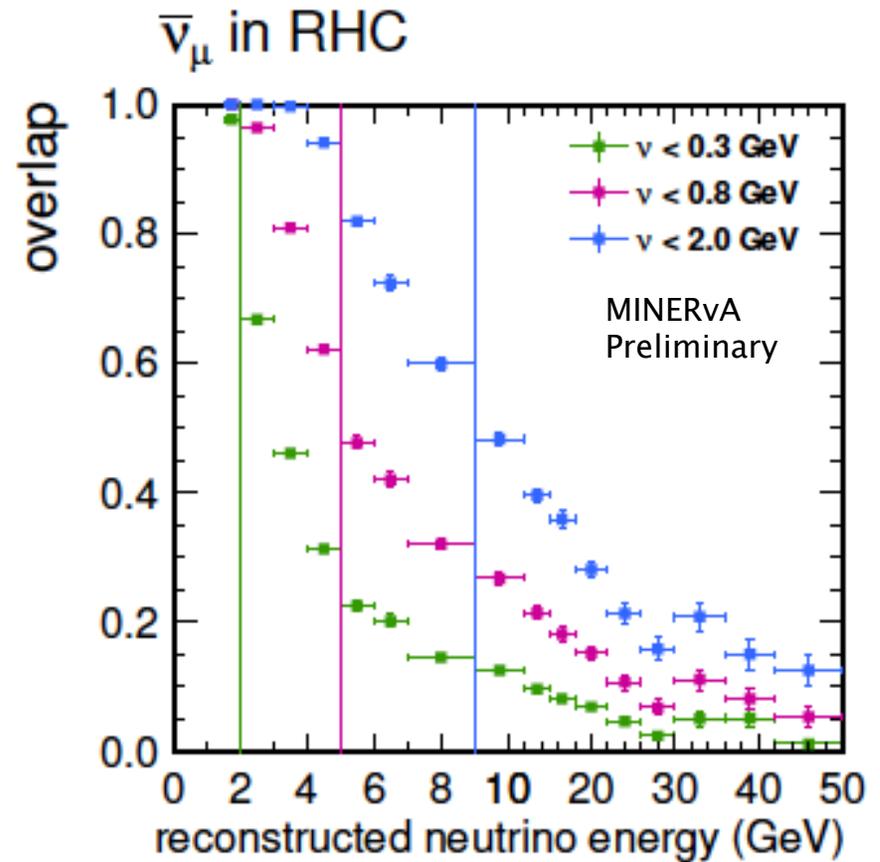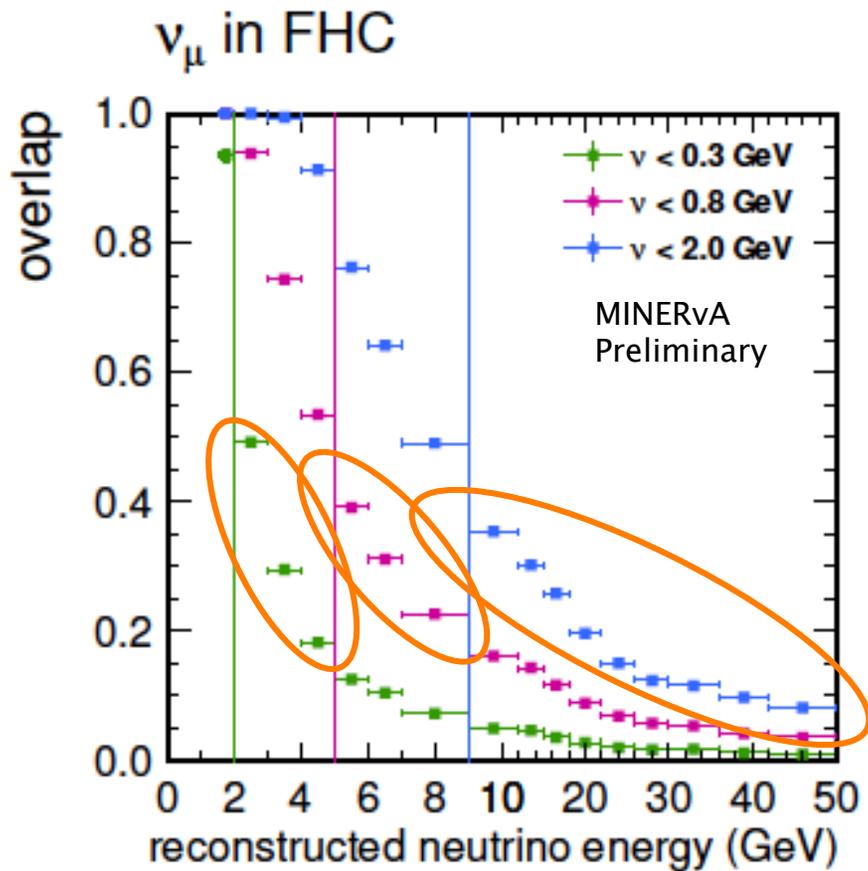
Three ν cuts are used: 300 MeV, 800 MeV and 2 GeV.

"Overlap" is the fraction of the inclusive data sample with ν less than the cut.

Event yields (inclusive)

ν_μ in FHC, inclusive

MINERvA Preliminary

$\bar{\nu}_\mu$ in RHC, inclusive

MINERvA Preliminary
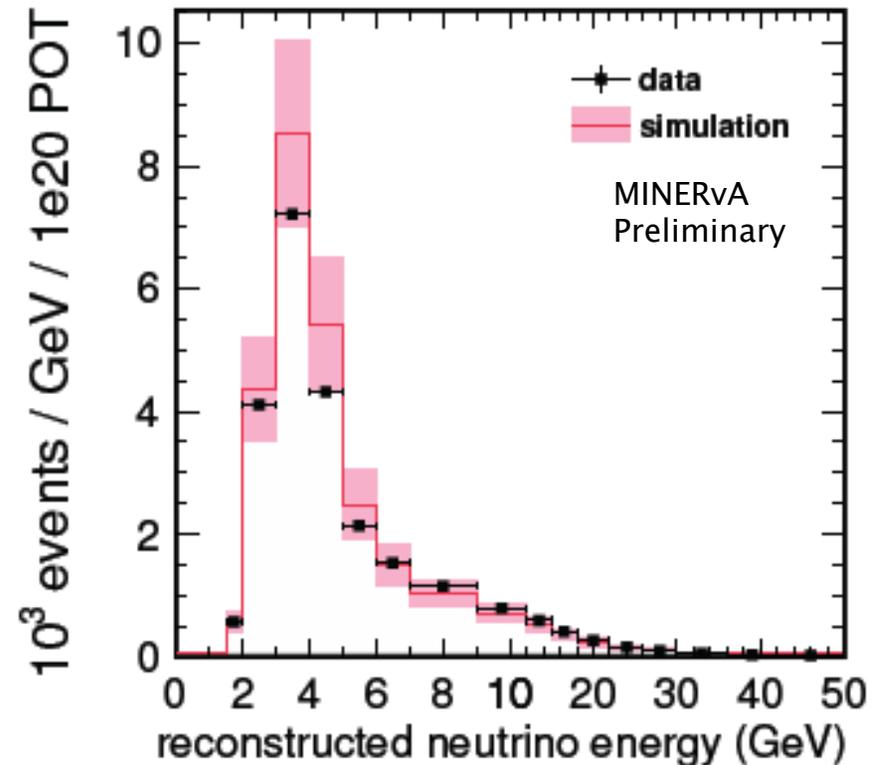
$$\sigma(E) = \frac{U(D - B)}{\epsilon \Phi T \times \Delta E}$$

$$\Phi(E) = \eta \frac{U(D_\nu - B_\nu)}{\epsilon \sigma_\nu T \times \Delta E}$$

Event yields
(lowest of the 3 low *v* cuts)

ν_{μ} in FHC, $\nu < 0.3$ GeV

MINERvA
Preliminary

$\overline{\nu}_{\mu}$ in RHC, $\nu < 0.3$ GeV

MINERvA
Preliminary
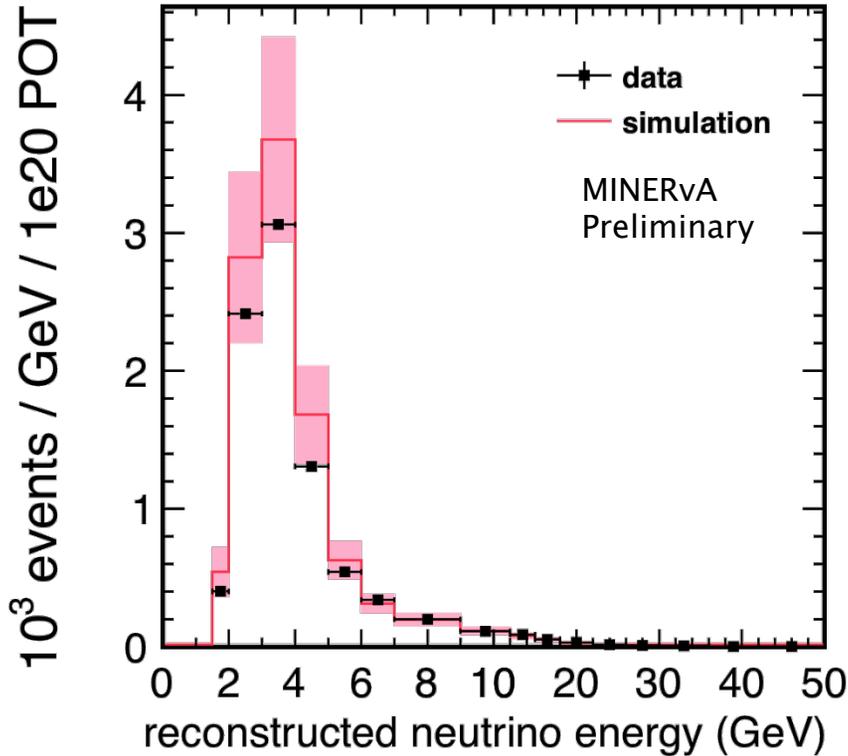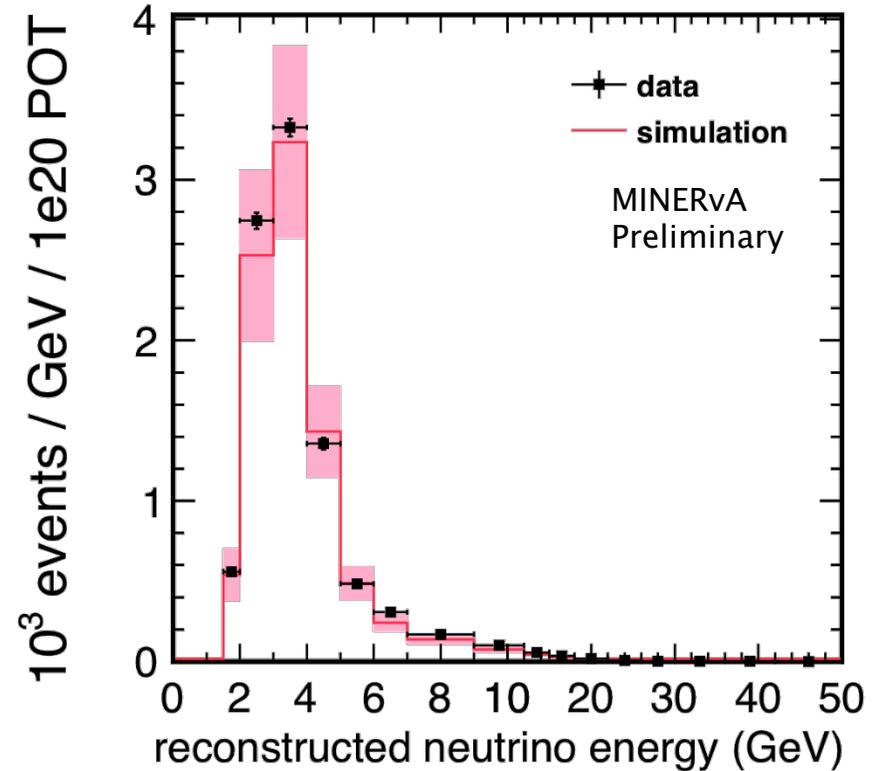
$$\sigma(E) = \frac{U(D - B)}{\epsilon \Phi T \times \Delta E}$$

$$\Phi(E) = \eta \frac{U(D_{\nu} - B_{\nu})}{\epsilon \sigma_{\nu} T \times \Delta E}$$

Unfolding

Unfolding removes the effects of detector resolution on a distribution using a simulated model of detector response.

$$\sigma(E) = \frac{U(D - B)}{\epsilon \Phi T \times \Delta E}$$

$$\Phi(E) = \eta \frac{U(D_\nu - B_\nu)}{\epsilon \sigma_\nu T \times \Delta E}$$

Unfolding

ν$_\mu$ in FHC, inclusive

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Preliminary

true neutrino energy (GeV)

reconstructed neutrino energy (GeV)

$\overline{\nu}_\mu$ in RHC, inclusive

MINERvA
Preliminary

true neutrino energy (GeV)

reconstructed neutrino energy (GeV)

$$\sigma(E) = \frac{U(D-B)}{\epsilon \Phi T \times \Delta E}$$

$$\Phi(E) = \eta \frac{U(D_\nu - B_\nu)}{\epsilon \sigma_\nu T \times \Delta E}$$

Acceptance correction

Not accepted μ

Elevation View

Steel Shield

Scintillator Veto Wall

Liquid Helium

0.25t

Nuclear Target Region (C, Pb, Fe, H₂O)

Side HCAL

Side ECAL

Active Tracker Region

8.3 tons total

Side ECAL   0.6 tons

Side HCAL   116 tons

Electromagnetic Calorimeter

Hadronic Calorimeter

15 tons   30 tons

2.14 m   3.45 m

MINOS Near Detector (Muon Spectrometer)

Accepted μ

5 m   2 m

The acceptance correction accounts for the acceptance of muons into MINOS, which requires a forward trajectory and at least 1.5 GeV energy.

$$\sigma(E) = \frac{U(D-B)}{\epsilon \Phi T \times \Delta E}$$

$$\Phi(E) = \eta \frac{U(D_\nu - B_\nu)}{\epsilon \sigma_\nu T \times \Delta E}$$

Acceptance correction

ν_μ in FHC

$\overline{\nu}_\mu$ in RHC

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Preliminary

- ν < 0.3 GeV
- ν < 0.8 GeV
- ν < 2.0 GeV
- inclusive

MINERvA
Preliminary

- ν < 0.3 GeV
- ν < 0.8 GeV
- ν < 2.0 GeV
- inclusive

$$\sigma(E) = \frac{U(D - B)}{\epsilon \Phi T \times \Delta E}$$

$$\Phi(E) = \eta \frac{U(D_\nu - B_\nu)}{\epsilon \sigma_\nu T \times \Delta E}$$

Low-ν correction

ν_μ in FHC

ν̄_μ in RHC

MINERvA
Preliminary

- $\nu < 0.3$ GeV
- $\nu < 0.8$ GeV
- $\nu < 2.0$ GeV
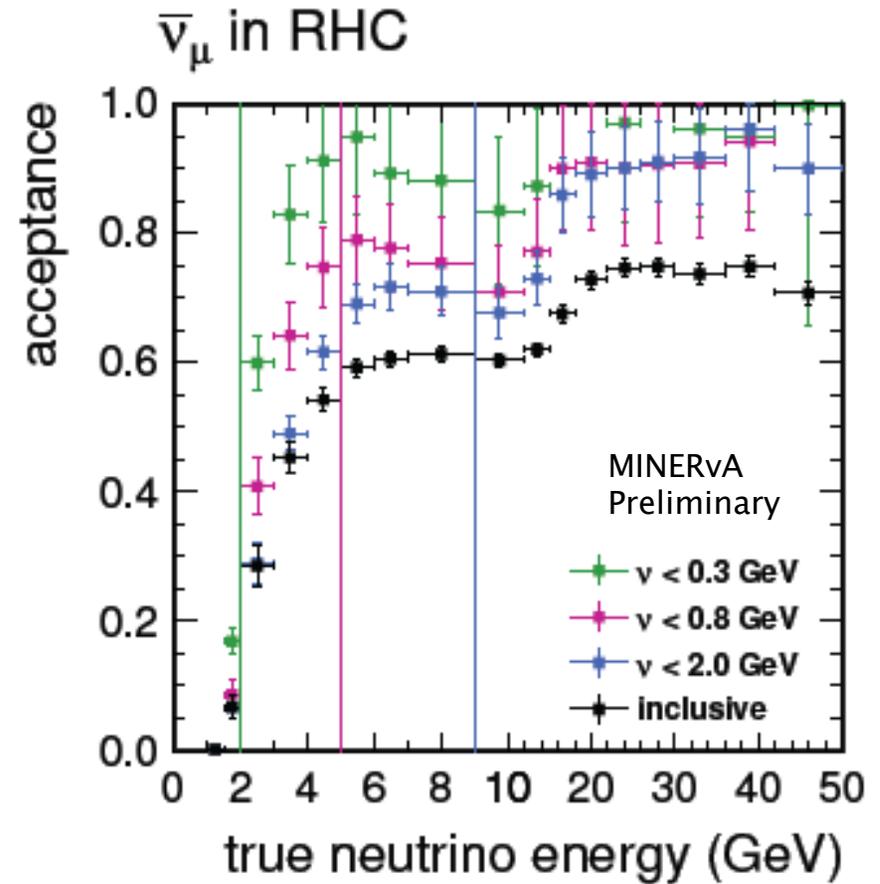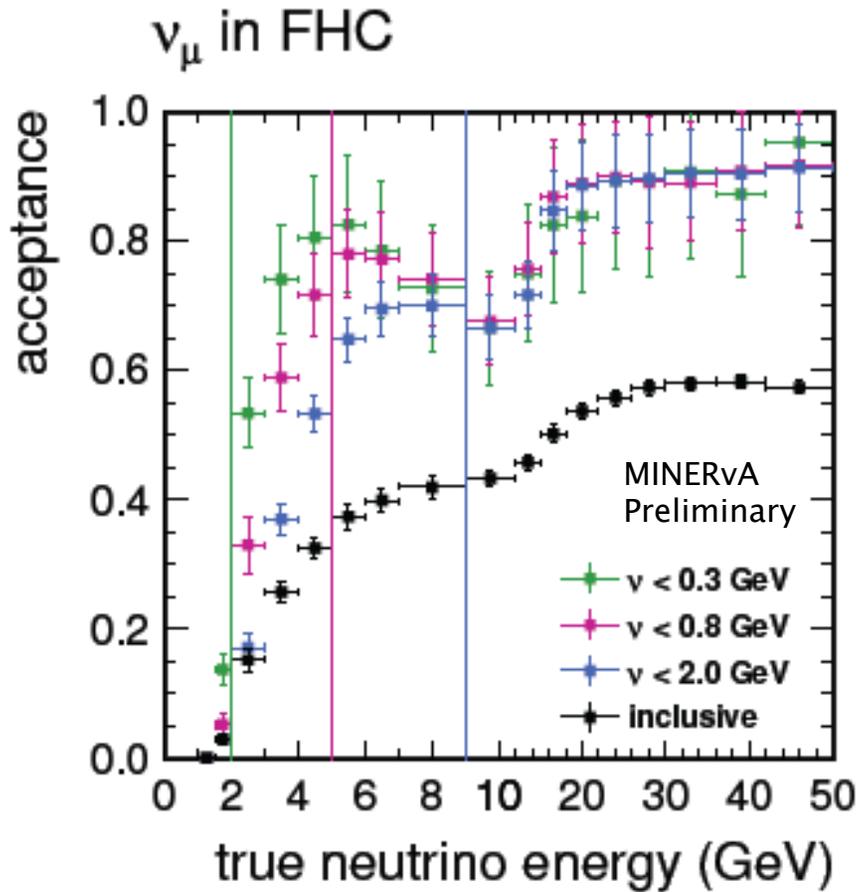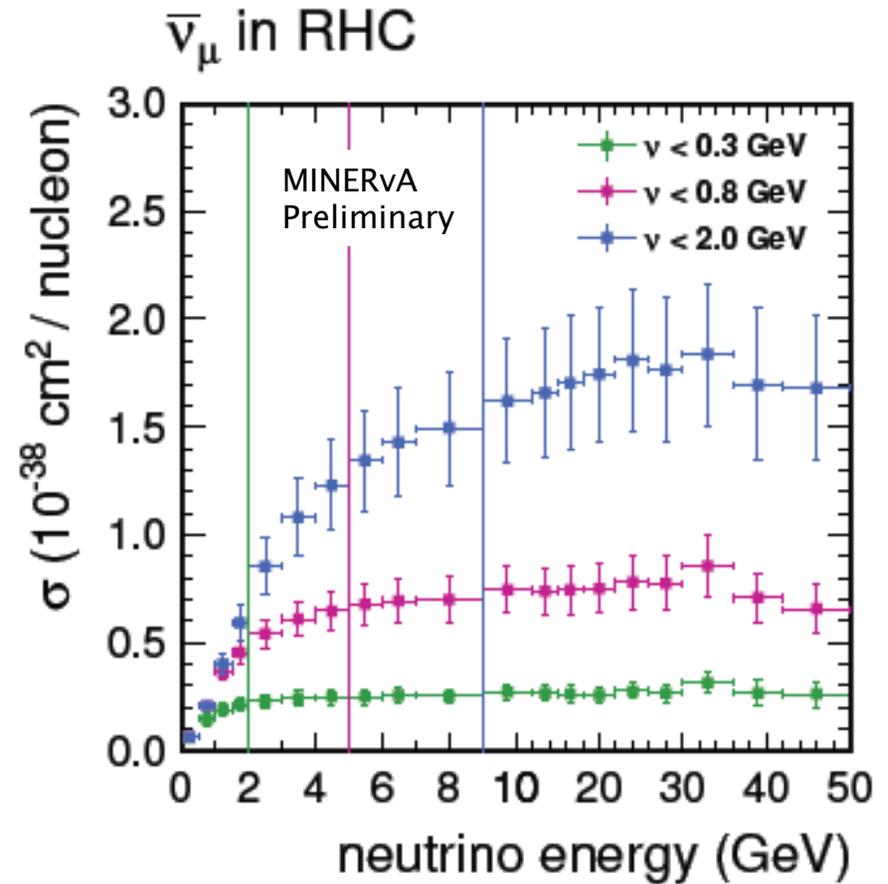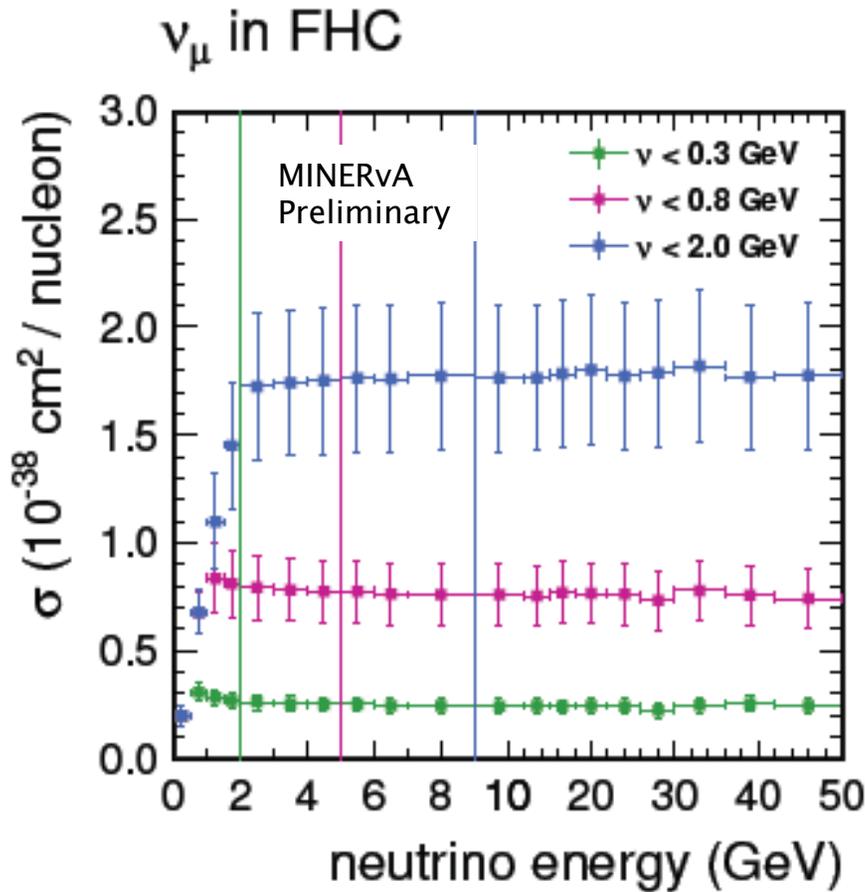
$$\sigma(E) = \frac{U(D-B)}{\epsilon \Phi T \times \Delta E}$$

$$\Phi(E) = \eta \frac{U(D_\nu - B_\nu)}{\epsilon \sigma_\nu T \times \Delta E}$$

Normalization technique

Normalize fitting
lower-cut sample to the
upper-cut sample
up to 22 GeV

Merge the higher –
cut sample
with the new
normalized points

$$\Phi(E) = \eta \frac{U(D_\nu - B_\nu)}{\epsilon \sigma_\nu T \times \Delta E}$$
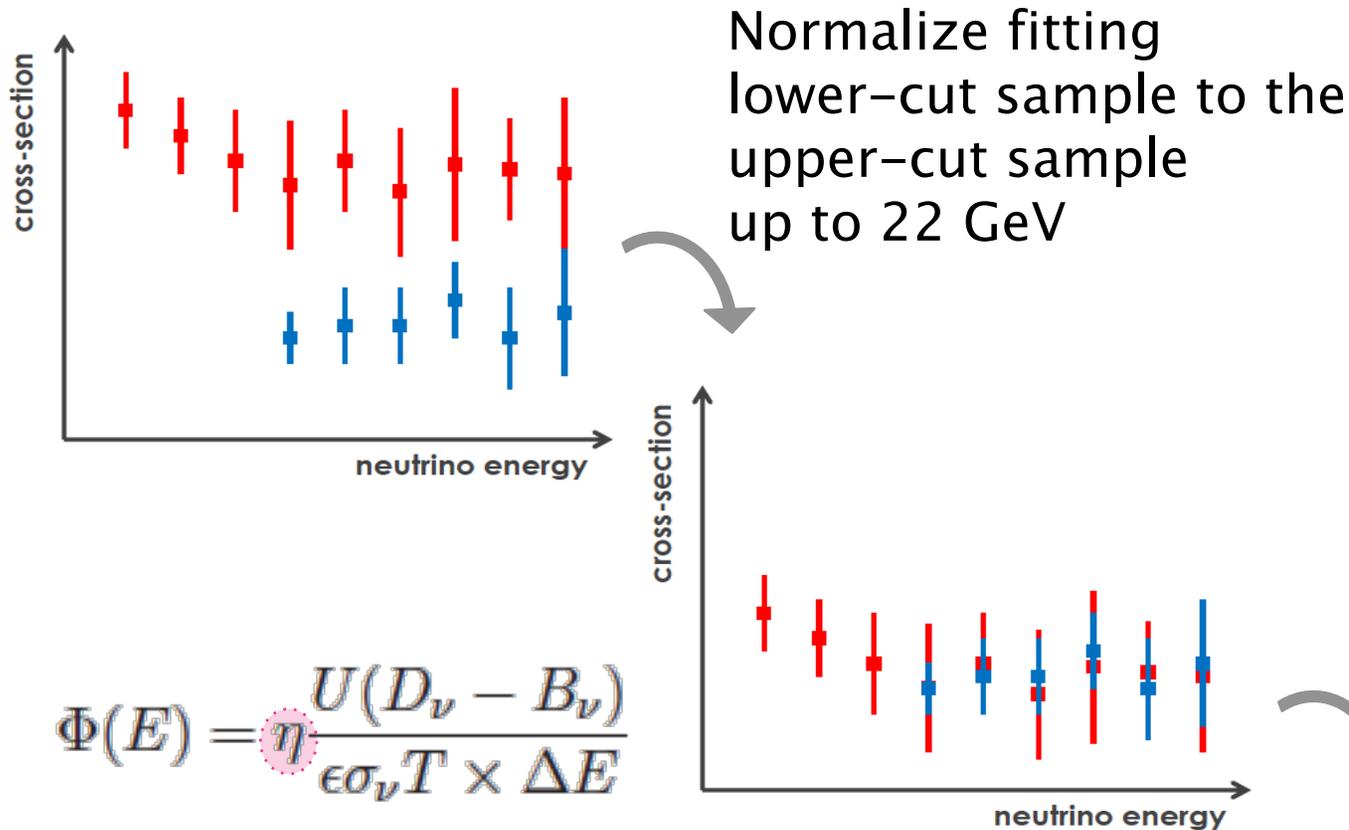
This is a shape measurement:
The flux is normalized such that
the extracted inclusive cross
section matches an ***external*** target
value at high neutrino energy

Fit error is a
uncertainty on the
lower-cut samples
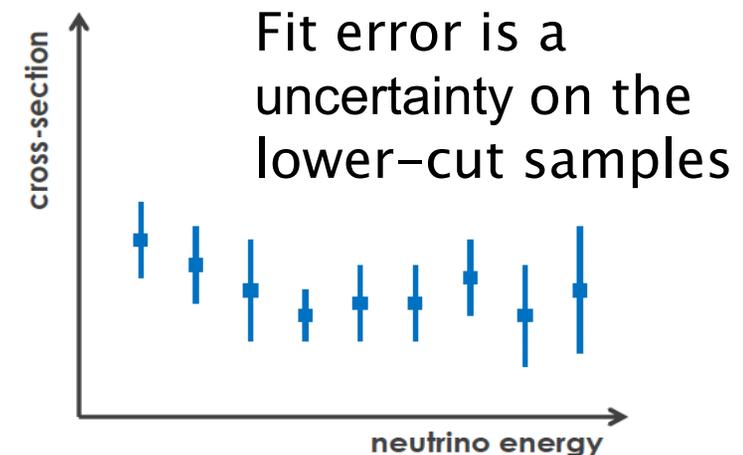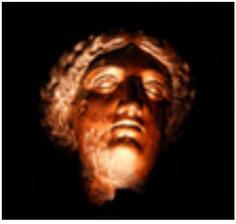
Systematic uncertainties

Systematic uncertainties

- Flux
  - > Hadron production, focusing
    - Largely unimportant since, in this analysis, we derive our own flux based on the low-ν sample
  - > Will address this assertion in a bit
- Detector
  - > Muon energy scale
  - > Hadronic energy scale
  - > Saturation and cross talk
  - > Efficiency/normalization
- Interaction model
  - > GENIE gives a recommended set of parameter variations for systematic uncertainties
    - c.f. GENIE Collaboration, arXiv:1510.05494
  - > In light of the "nuclear effects" analysis we have updated these for the low-recoil region
  - > More on this in a bit…

- Will show breakdowns of these uncertainties with results

Low recoil reconstruction – validation

- **Off–track "muon fuzz" on rock muons**
  - **> Knock–on electrons and brems can feed into the recoil**
  - **> Tests accidental and cross talk models too**
  - **> We find our GEANT model doesn't produce muon fuzz often enough**

- **Add in fuzz from real rock muons to MC to make the spectrum agree with data**
 - **> Take 50% of the correction as an uncertainty**

$E_\mu = [0,10]$ GeV

data
default simulation
corrected simulation

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probability per bin
calorimetric recoil energy (MeV)

$E_\mu = [10,120]$ GeV

data
default simulation
corrected simulation

MINERvA
Preliminary

probability per bin
calorimetric recoil energy (MeV)
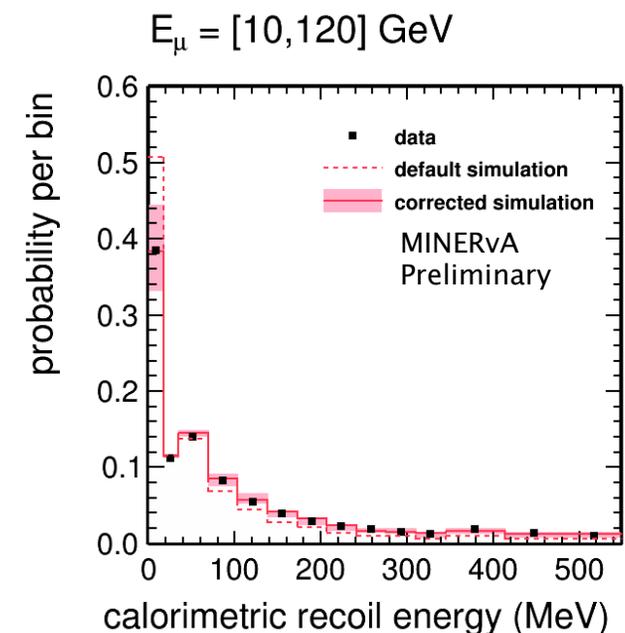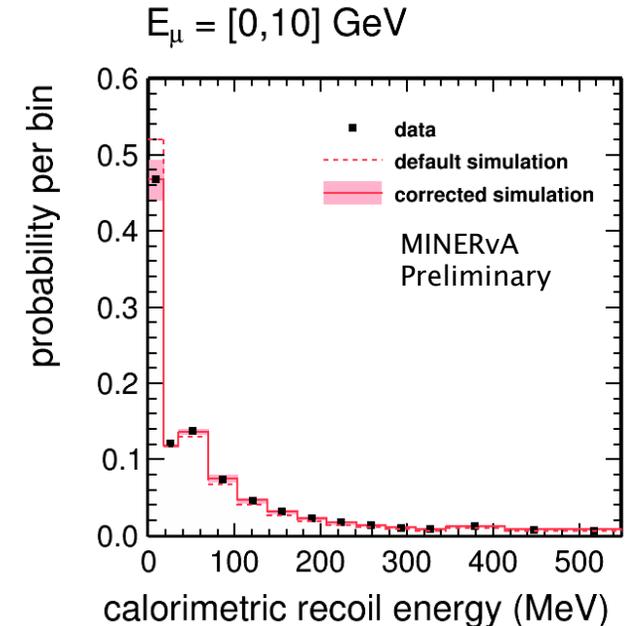
Standard GENIE parameter "knobs" (Not really meant to be read!)

Description	$\pm 1\sigma$ Uncertainty
Charged-current quasi-elastic (CCQE) axial mass, M_A^{CCQE}	-15% +25%
CCQE electromagnetic form factor	BBBA2005 (default) or dipole
Charged-current resonance axial mass, M_A^{CCRES}	±20%
Charged-current resonance vector mass, M_V^{CCRES}	±10%
Non-resonance 1π production in νp interactions	±50%
Non-resonance 1π production in νn interactions	±50%
Non-resonance 2π production in νp interactions	±50%
Non-resonance 2π production in νn interactions	±50%
Intranuclear absorption probability for nucleons	±20%
Intranuclear absorption probability for pions	±20%
Intranuclear charge exchange probability for nucleons	±50%
Intranuclear charge exchange probability for pions	±50%
Intranuclear elastic scattering probability for nucleons	±30%
Intranuclear elastic scattering probability for pions	±10%
Intranuclear inelastic scattering probability for nucleons	±40%
Intranuclear inelastic scattering probability for pions	±40%
Intranuclear π-production probability for nucleons	±20%
Intranuclear π-production probability for pions	±20%
Intranuclear mean free path for nucleons	±20%
Intranuclear mean free path for pions	±20%
Feynman x_F distribution in 1π states in AGKY model	±20%
π angular distribution in $\Delta \to \pi N$	isotropic (default) or Rein-Sehgal
Radiative decay branching ratio, $\Delta \to \gamma X$	±50%
Random phase approximation model	off (default) or on
Random phase approximation and meson exchange currents model	off (default) or on
Effective nuclear radius for intranuclear interactions	±0.6 fm
Formation zone time (when a quark is free in the nucleus)	±50%
Hadronization model with more isotropic final states	off (default) or on

arXiv:1510.05494

Model–based estimate of the uncertainties in QE–like events

- In normal analyses we use a large (GENIE recommended) M_A (axial mass) uncertainty as an effective uncertainty to encompass uncertainties in QE–like processes
- For this analysis we implemented a different systematic uncertainty on QE–like events based on the modified version of GENIE used in our nuclear effects analysis
  - > Sets of weights to account for RPA and MEC effects in QE events based in the Valencia model
- Use difference between standard GENIE and the "Valencia" GENIE as the uncertainty due to unmodeled QE–like effects
  - > Ran the analysis both ways and used the difference as an uncertainty
  - > It is ***not*** implemented as a central-value weight for this analysis (use standard GENIE)
- Residual uncertainty on M_A is based on NOMAD and bubble chamber data (3%)

RPA weights

2p2h weights
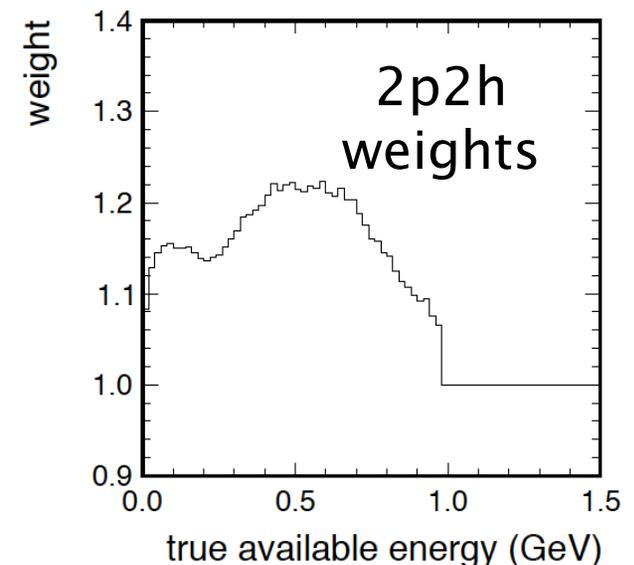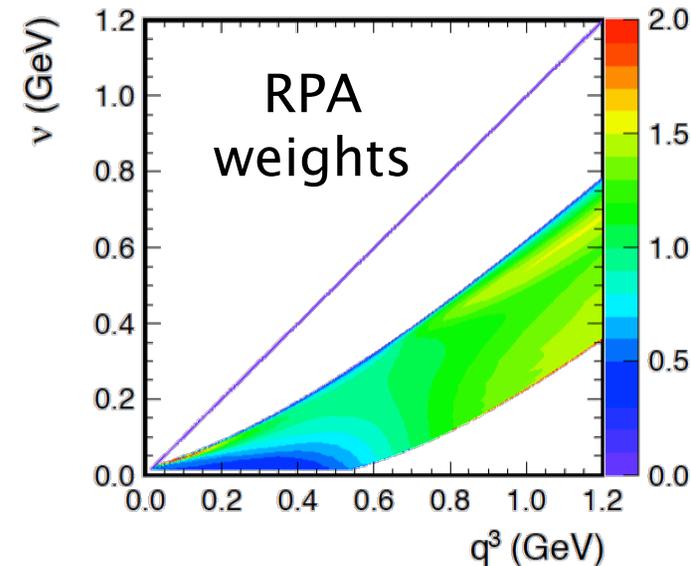
Examples of QE-like uncertainty vs the rest of the uncertainties

ν_μ, E = [2.0,3.0] GeV

ν_μ, E = [7.0,9.0] GeV

MINERvA
Preliminary
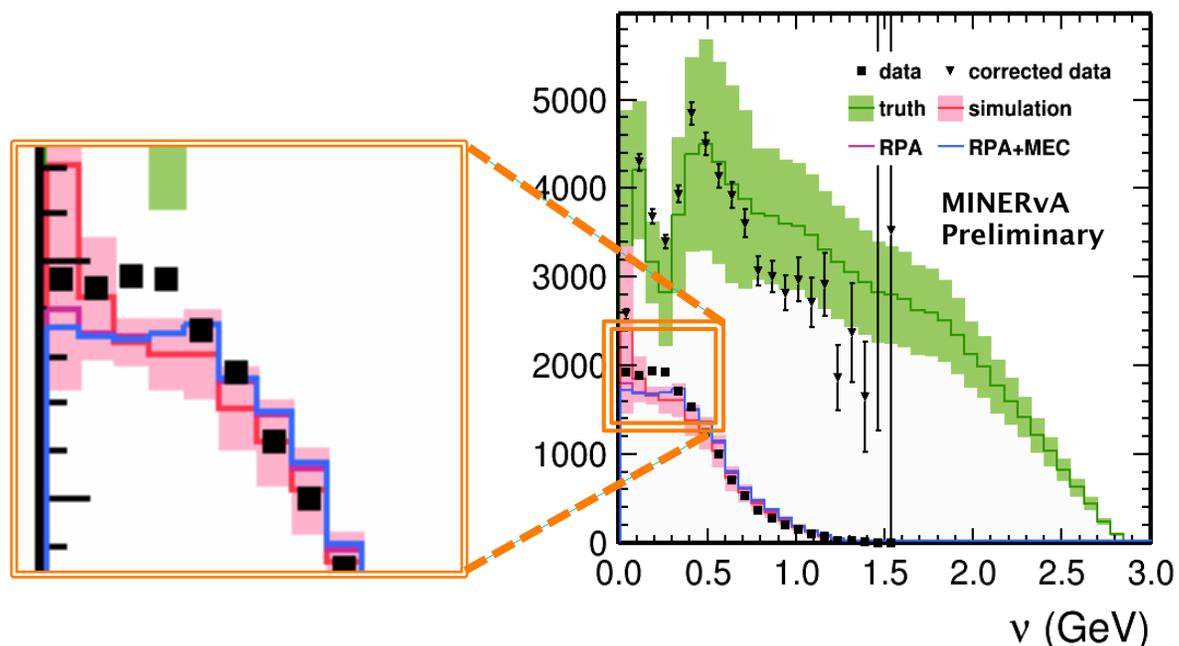
ν (GeV)
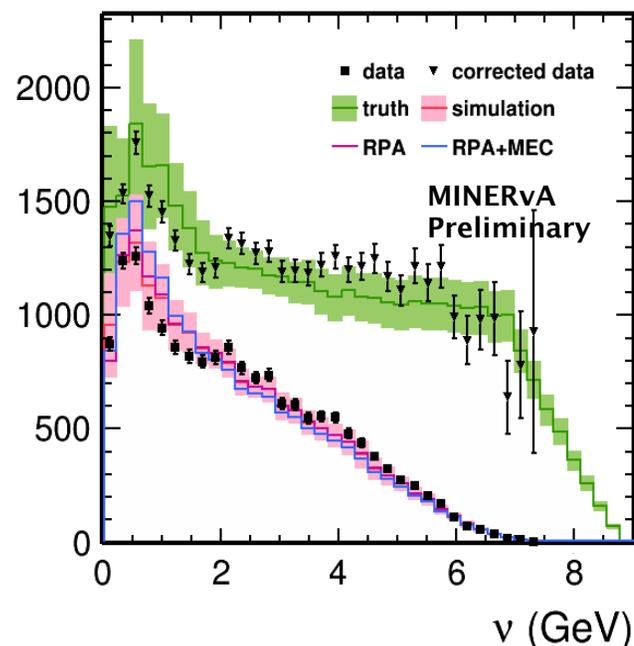
Selected data events (black squares stat errors)
Simulation from standard GENIE (pink/squares)
Valencia-weighted GENIE (blue)
Uncertainty implemented as: red-blue

Also shown: Acceptance corrected data and true GENIE (green/triangles)

We have these plots for each point in the analysis (see Josh's thesis)
the two points that go beyond the envelop are the worst in any distribution

Flux results

Extracted neutrino flux by subsample
(there ARE points under the pink and blue)
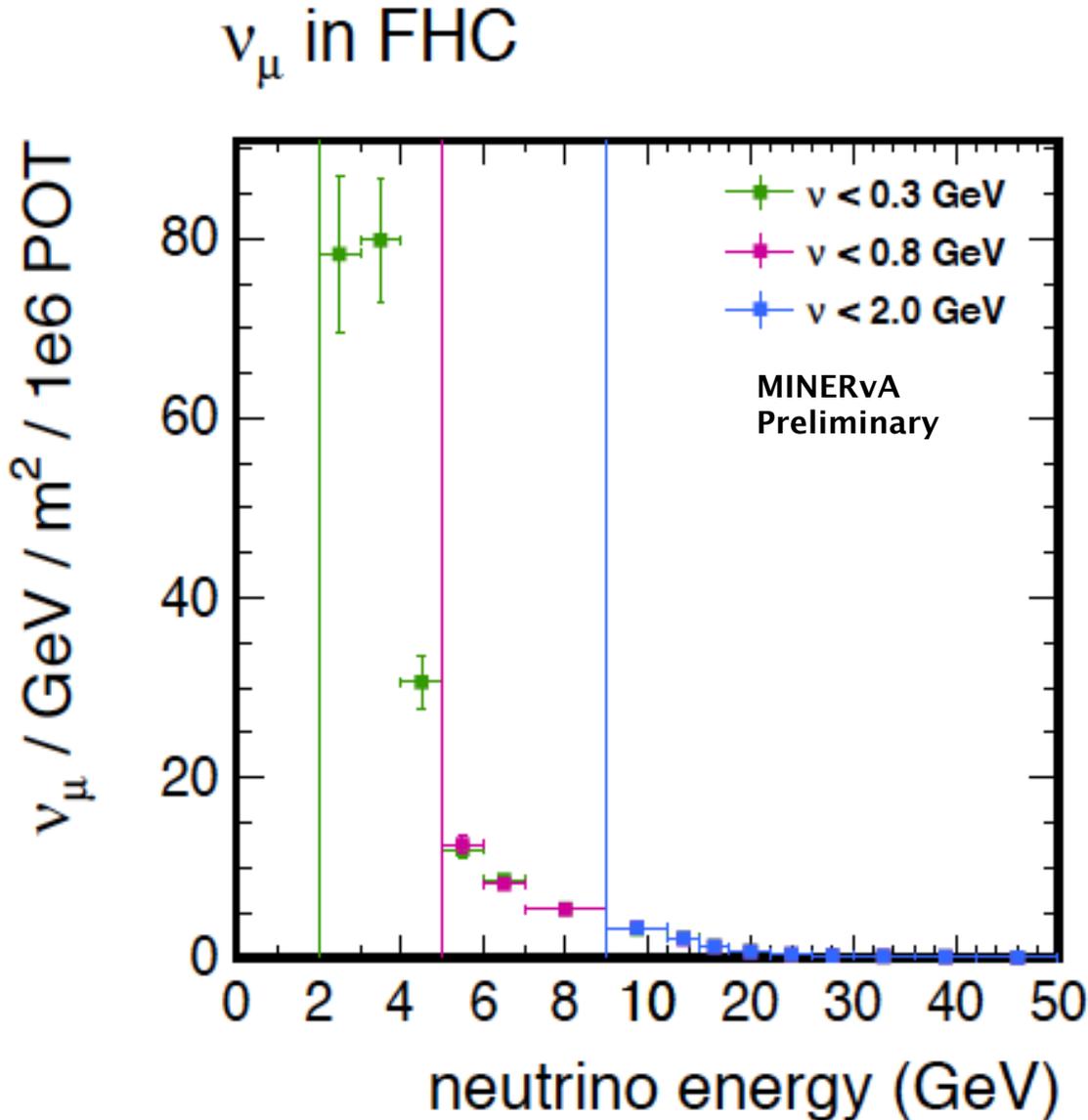
ν_μ in FHC

Normalization WRT GENIE
(at 9–12 GeV bin)

<1 means data favors a
lower low-v cross section
than modeled in GENIE

Statistical uncertainties in
table

ν cut	FHC ν_μ
$\nu < 2\,\mathrm{GeV}$	0.925 ± 0.009
$\nu < 800\,\mathrm{MeV}$	0.958 ± 0.009
$\nu < 300\,\mathrm{MeV}$	0.946 ± 0.012

NuMI on-axis neutrino flux
from the low-ν method (merged)
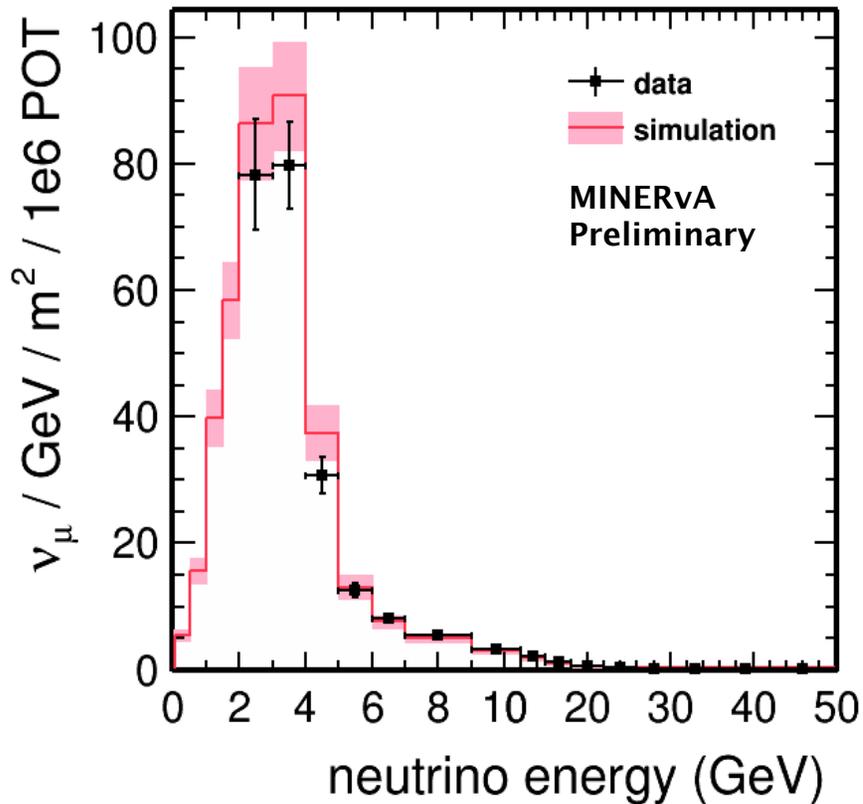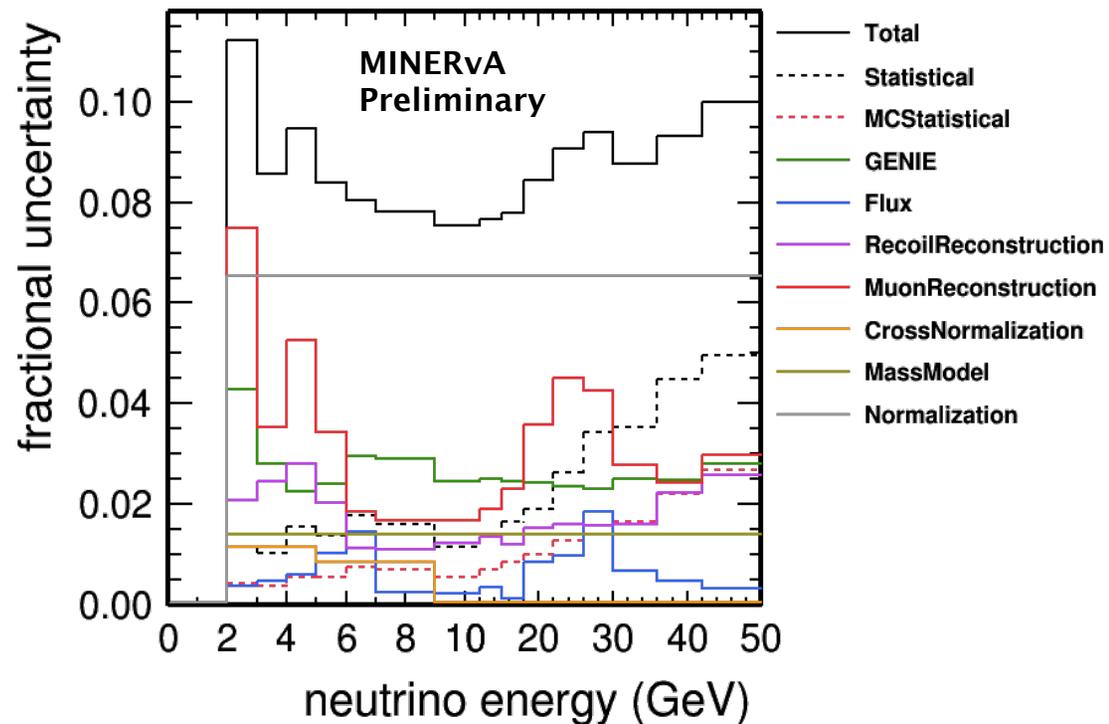
Extracted antineutrino flux by subsample
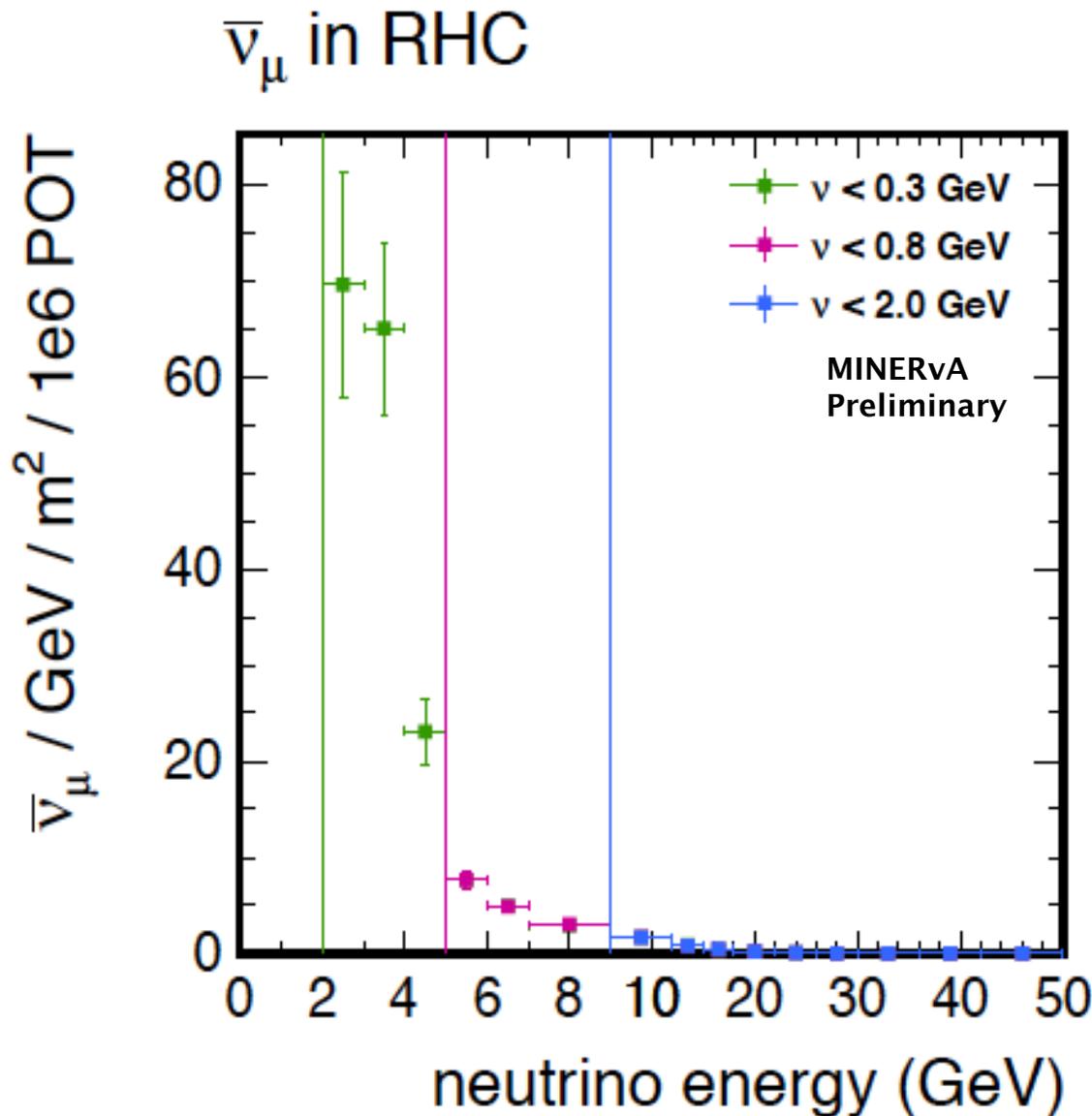
$\bar{\nu}_\mu$ in RHC

Legend:
- $\nu < 0.3$ GeV
- $\nu < 0.8$ GeV
- $\nu < 2.0$ GeV

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y-axis: $\bar{\nu}_\mu$ / GeV / m^2 / 1e6 POT

x-axis: neutrino energy (GeV)

Normalization WRT GENIE (at 9–12 GeV bin)

<1 means data favors a lower low-ν cross section than modeled in GENIE

Statistical uncertainties in table

ν cut	RHC $\bar{\nu}_\mu$
$\nu < 2\,\text{GeV}$	0.943 ± 0.021
$\nu < 800\,\text{MeV}$	1.085 ± 0.019
$\nu < 300\,\text{MeV}$	1.200 ± 0.020

NuMI on-axis antineutrino flux from the low-ν method (merged)

$\overline{\nu}_\mu$ in RHC

$\overline{\nu}_\mu$ in RHC

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MINERvA Preliminary

data

simulation

Total

Statistical

MCStatistical

GENIE

Flux

RecoilReconstruction

MuonReconstruction

CrossNormalization

MassModel

Normalization
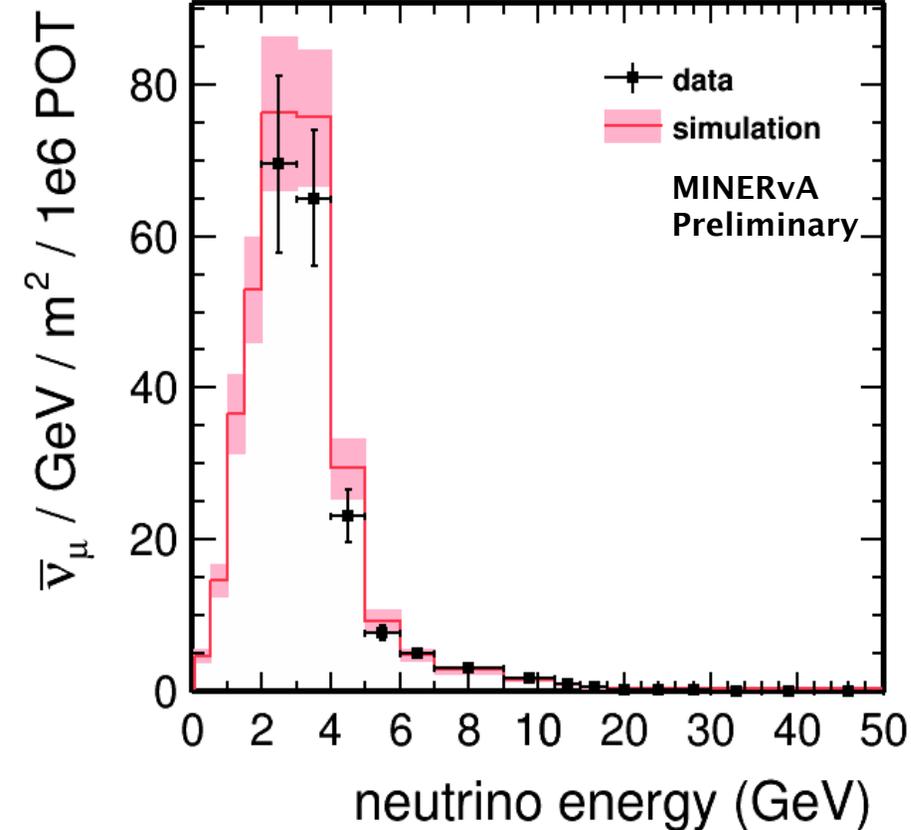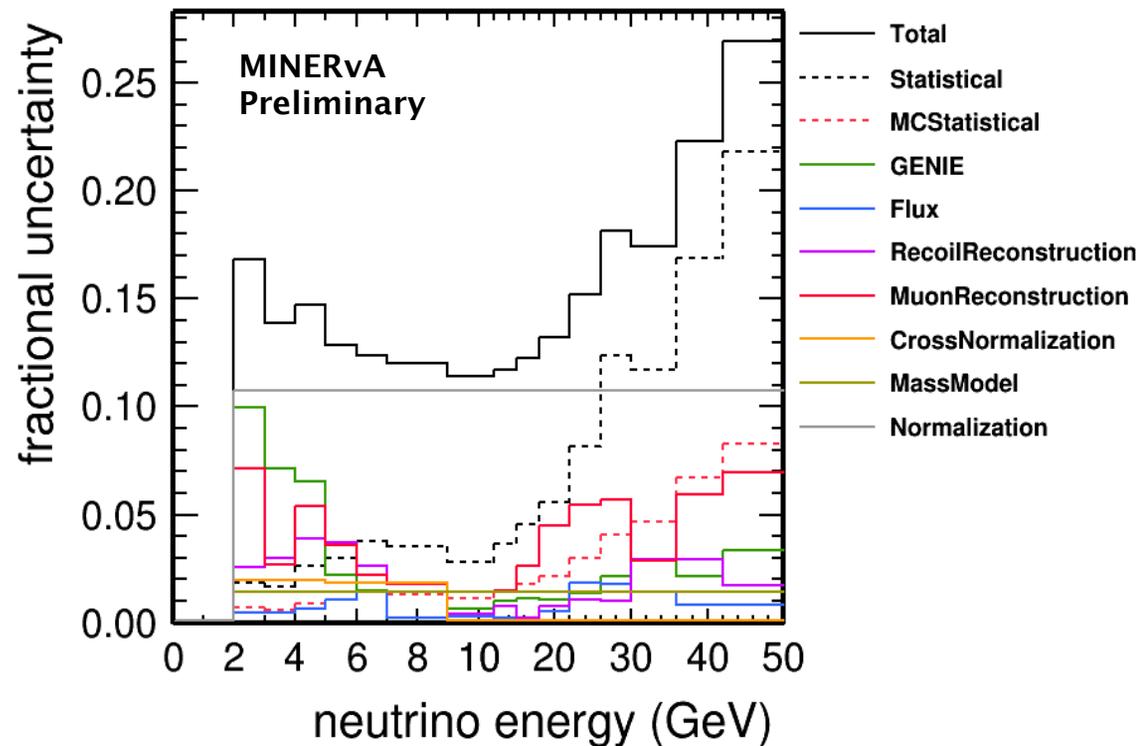
Fluxes of neutrinos from defocused pions
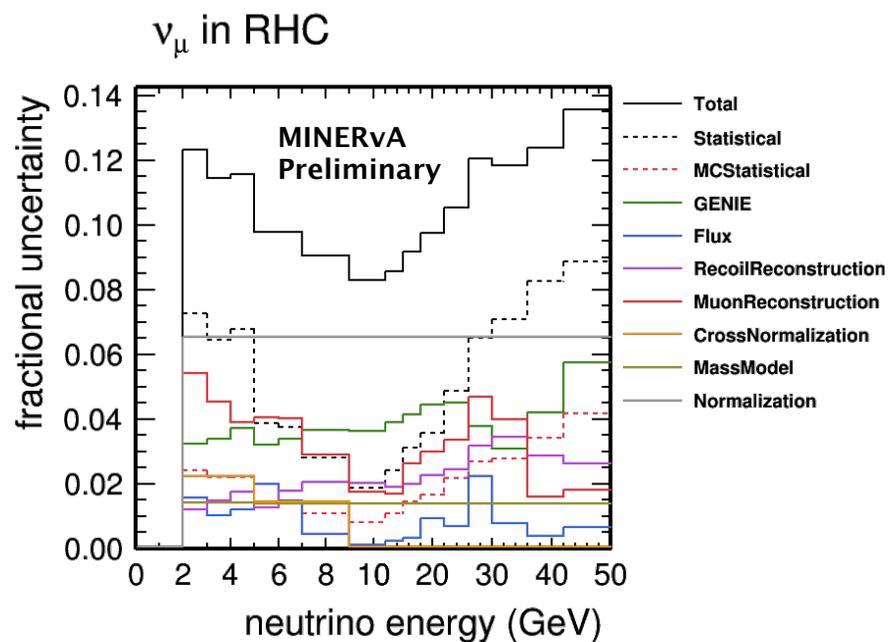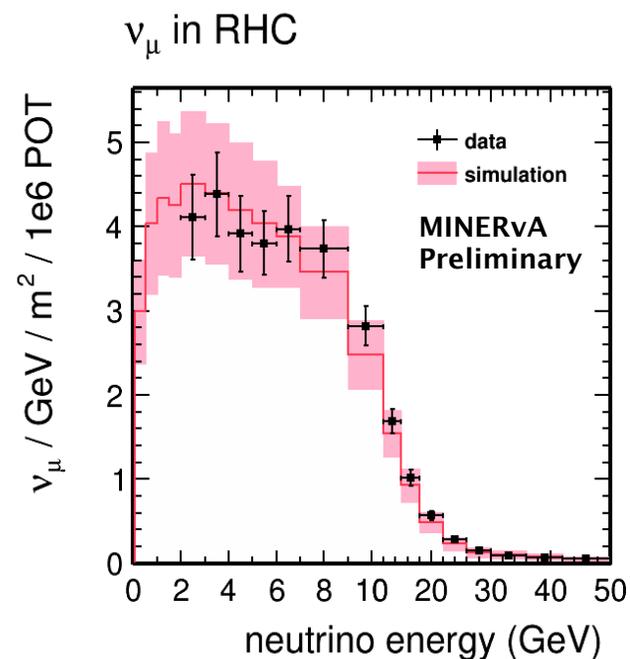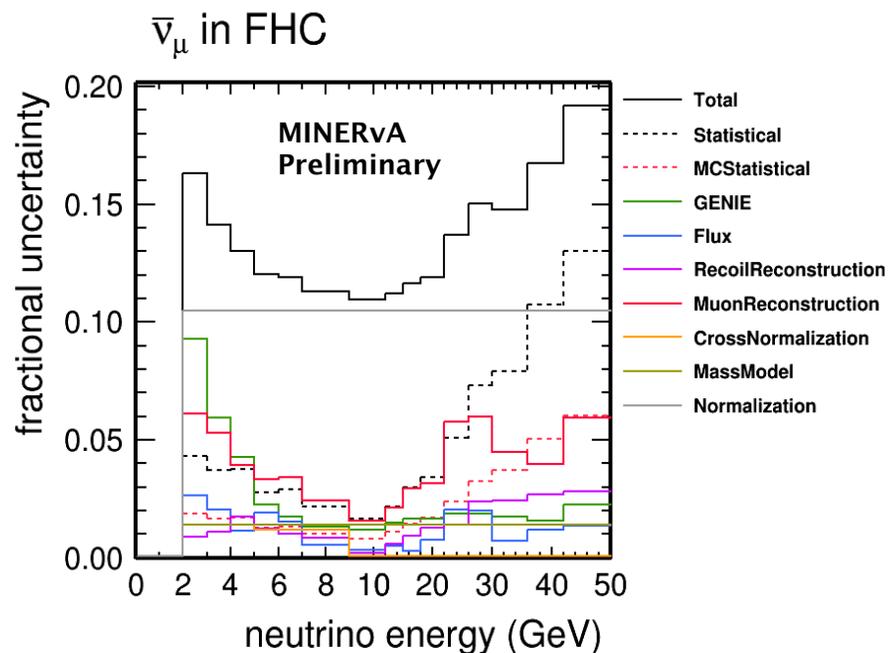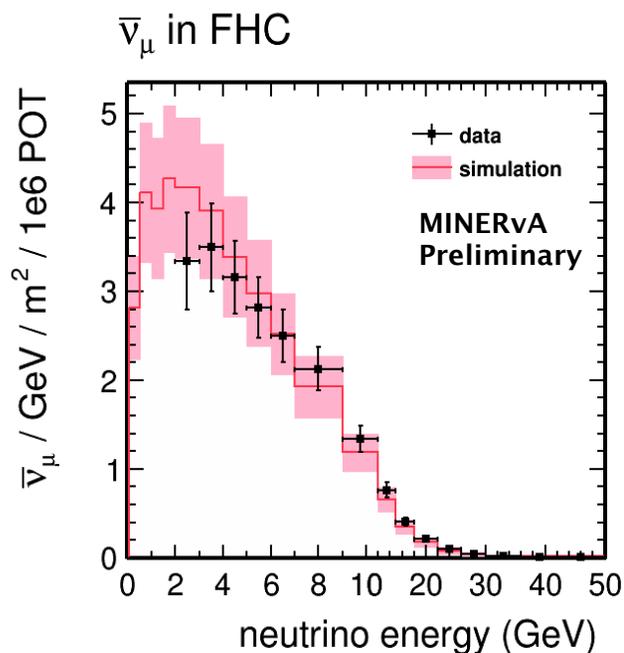
Comparisons between low-ν fluxes and other MINERvA flux constraints

MINERvA *a priori* flux estimation

- Leo provided a comprehensive JETP seminar (12/18/15) on the MINERvA flux
- Central value is based on *ex situ* data
  - > Using GEANT4 simulations
  - > Corrected using external hadron production data
  - > Errors based on experimental data
- Errors due to the beam line geometry evaluated using beam simulations and assumed survey/geometry errors

Calculating the NuMI Flux

Leo Aliaga
On behalf of the MINERvA Collaboration

December 18, 2015

WILLIAM & MARY
CHARTERED 1693

The MINERvA flux program has been a multi-year effort (some history)

MINERvA physics program produced physics results based on 2 prior snapshots of the flux and the newly-unveiled flux

GEN0
> Used for our 2013 quasi-elastic scattering papers

GEN1
> This flux was used for most MINERvA analyses
> This is the central-value flux used on the slides in this seminar

GEN2
> Subject of Leo's dissertation and seminar
> Completed this Fall
> Used for the recent nuclear-effects analysis
> Two versions a version using only thick-target data (GEN2thick) and one also using thick-target data (GEN2thin)
> We'll compare this flux to the low-v flux results

Low-ν flux and GEN2 (thin target) neutrino comparison
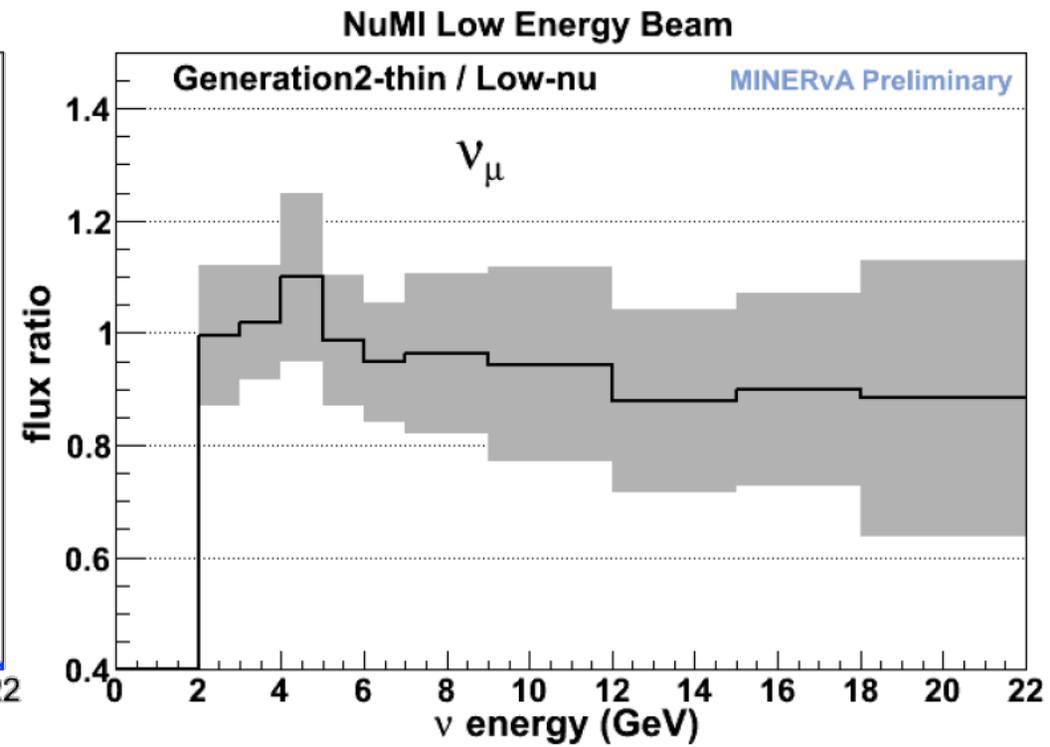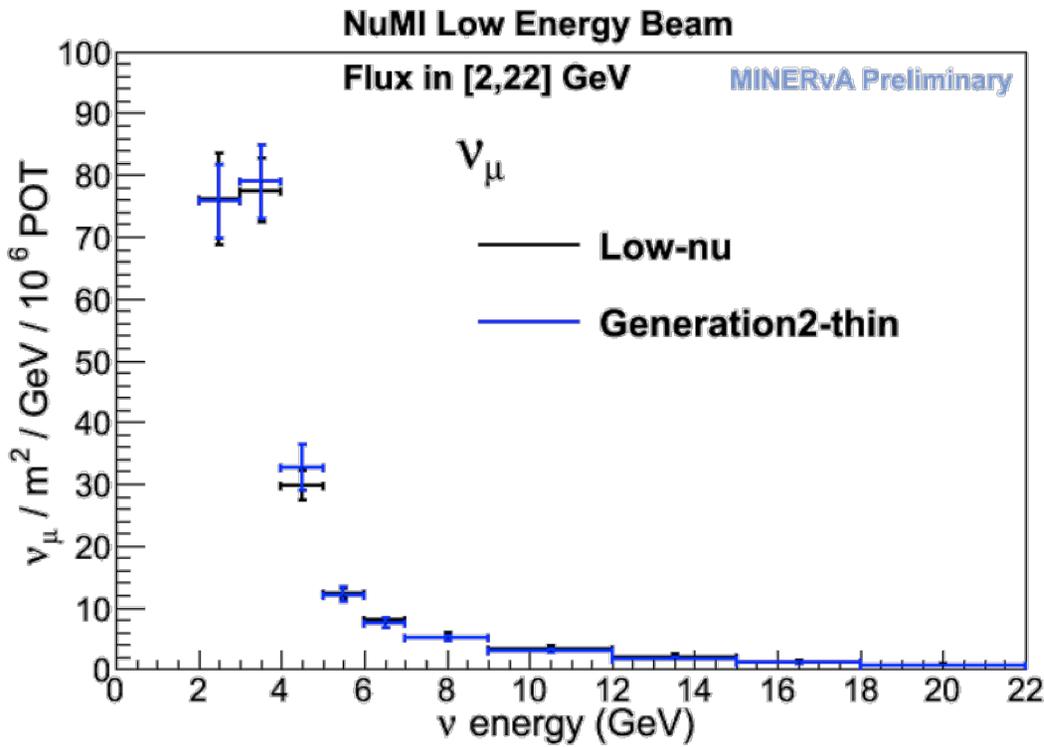

FHC neutrinos

Low-ν flux and GEN2 (thick target) neutrino flux comparison
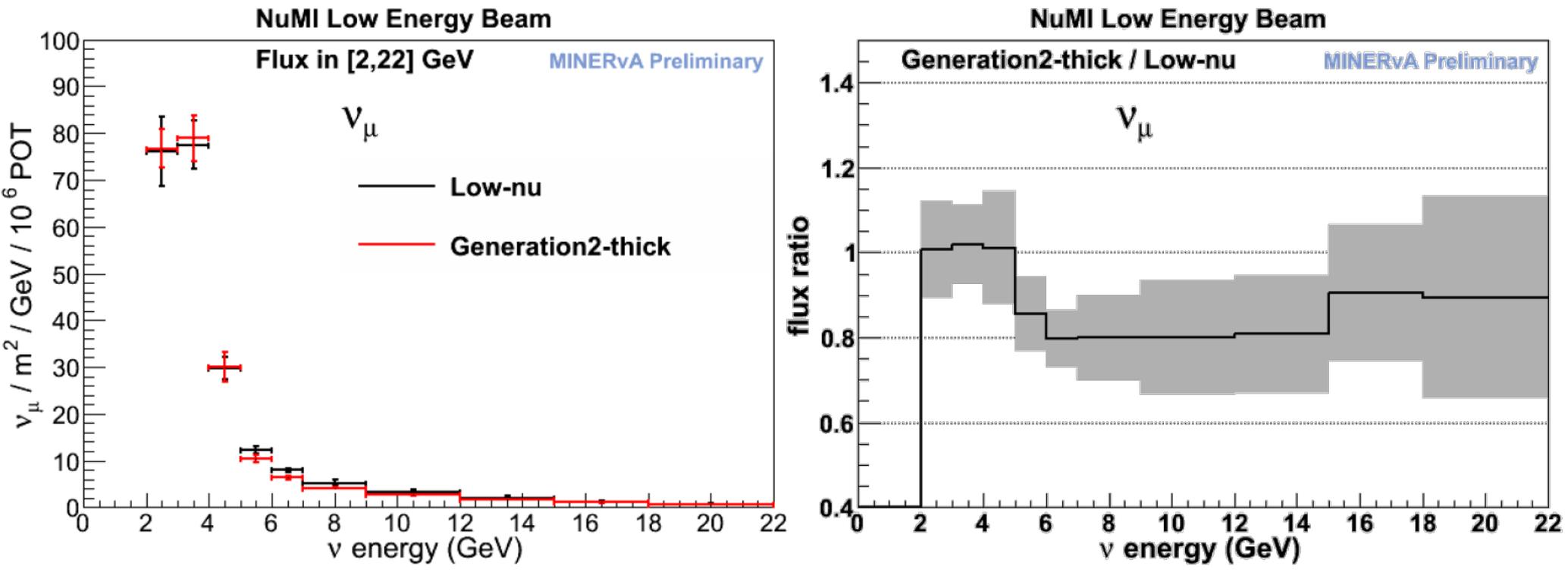
FHC neutrinos

Low-ν flux and GEN2 (thin-target) antineutrino flux comparison
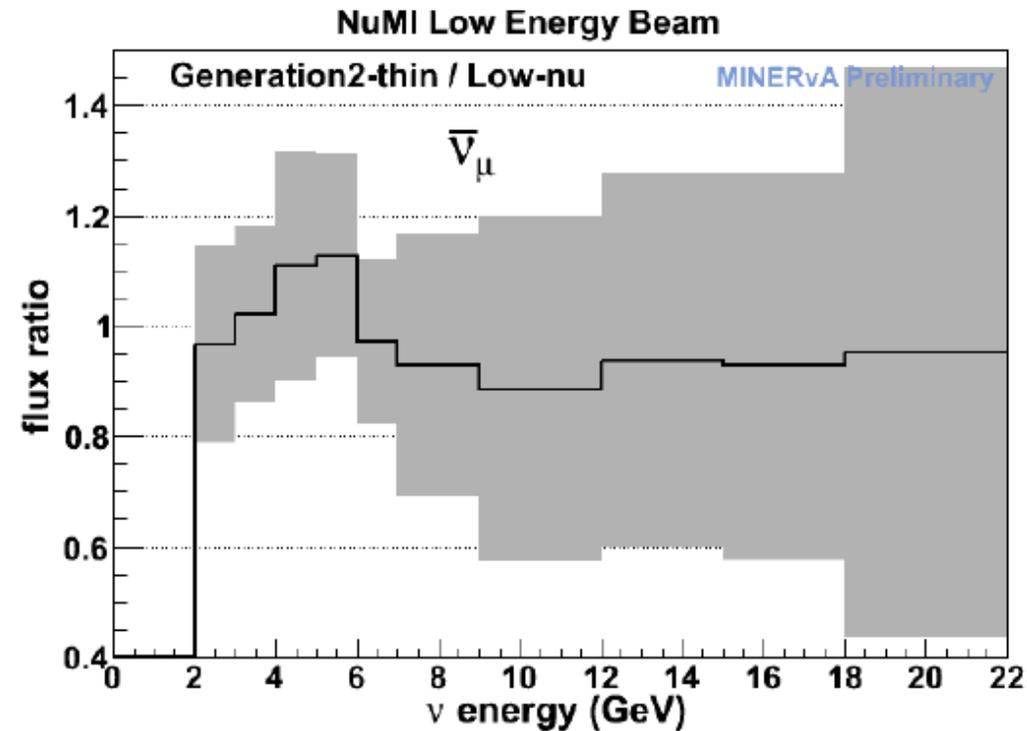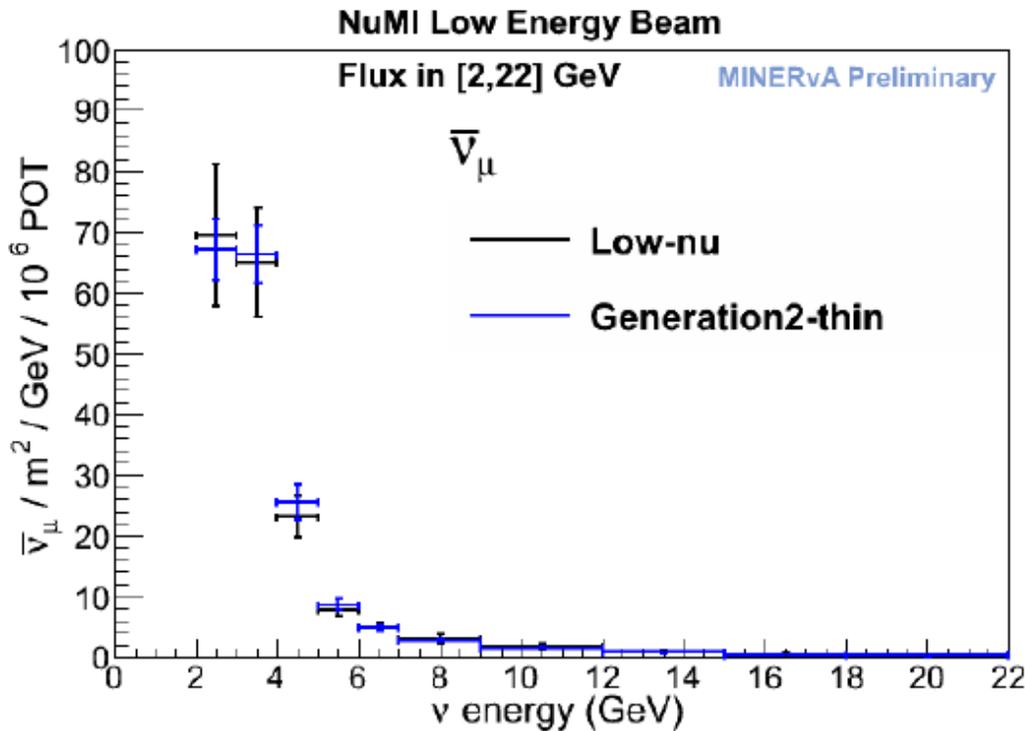
RHC antineutrinos

Low-ν flux and GEN2 (thick target) antineutrino flux comparison
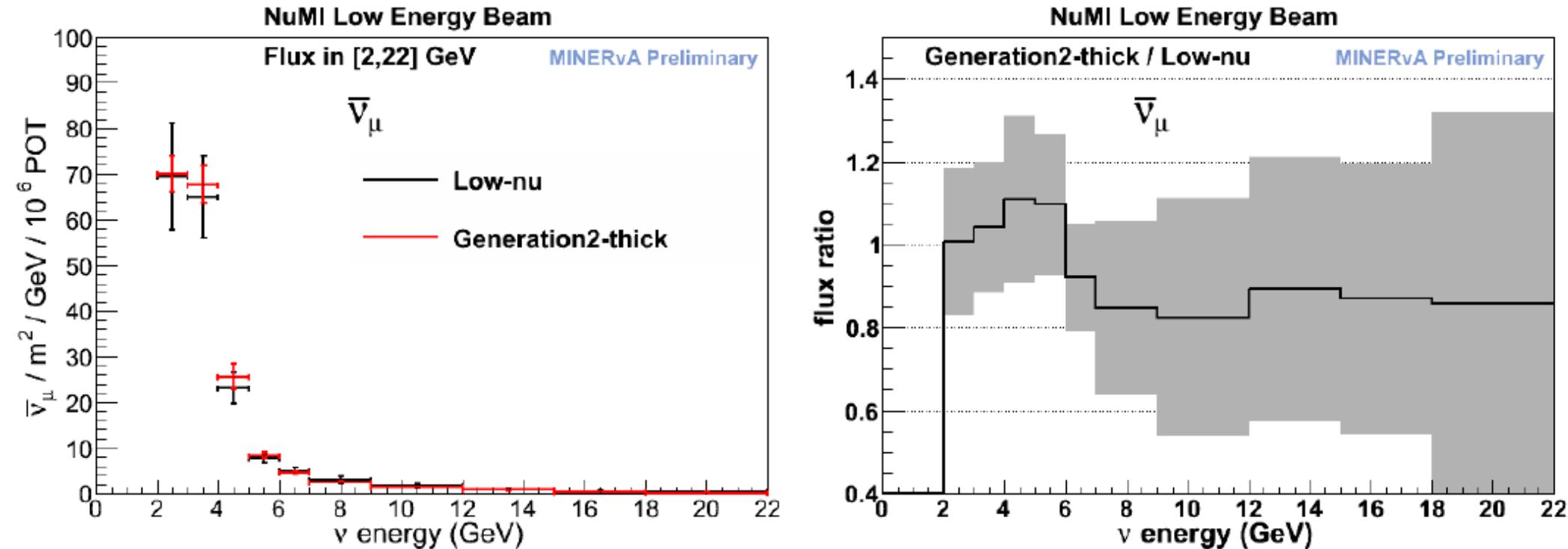
RHC antineutrinos

Results of flux comparisons

- Full covariance comparison (2–22 GeV)
  - > Both are systematics limited for these focused samples
  - > The uncertainties on these two fluxes are uncorrelated

|	Low–v vs GEN2 (thin)	Low–v vs GEN2 (thick)
X^2 / DoF	4.8/10	18.6/10

- Low–v flux is more compatible with the flux derived from thin–target hadron production data than that obtained from replica target (thick–target data)
  - > Thin–target data method is also directly applicable for other target geometries
  - > Thick–target data is, in general, more precise
 - > Hence, the US–NA61 program for NuMI/LBNE

Flux from ν–e scattering

$\nu_\mu \quad \nu_\mu$

Z^0

$e \quad e$
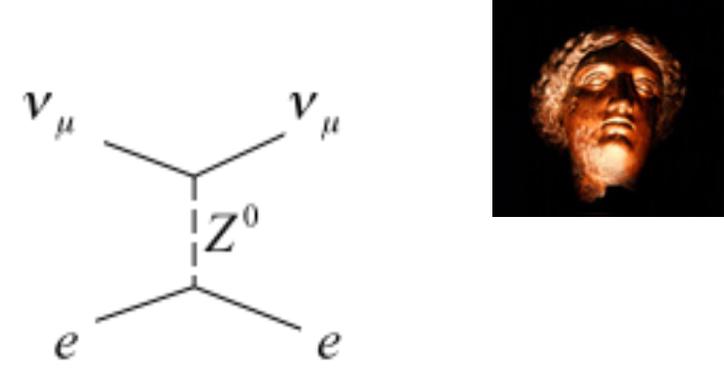
- Signal is a single electron moving in beam direction
  - > Purely electro–weak process
  - > Cross section is smaller than nucleus scattering by ~2000
  - > 123 ±17(stat) ±9(syst) events
- Independent *in situ* flux constraint
  - > Important proof of principle for future experiments
  - > Statistically limited in the MINERvA LE sample (~8% error)
  - > Results are consistent with new flux calculations
  - > Results are consistent with the *a priori* GEN2 (THIN) flux (~2%) and with the low ν flux
- Further confidence in flux!
 - > Three independent methods yield consistent results

MINERvA Data

Strip Number

N Events / 2.0 GeV

Data — Monte Carlo

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Electron Energy (GeV)

arXiv:1512.07699
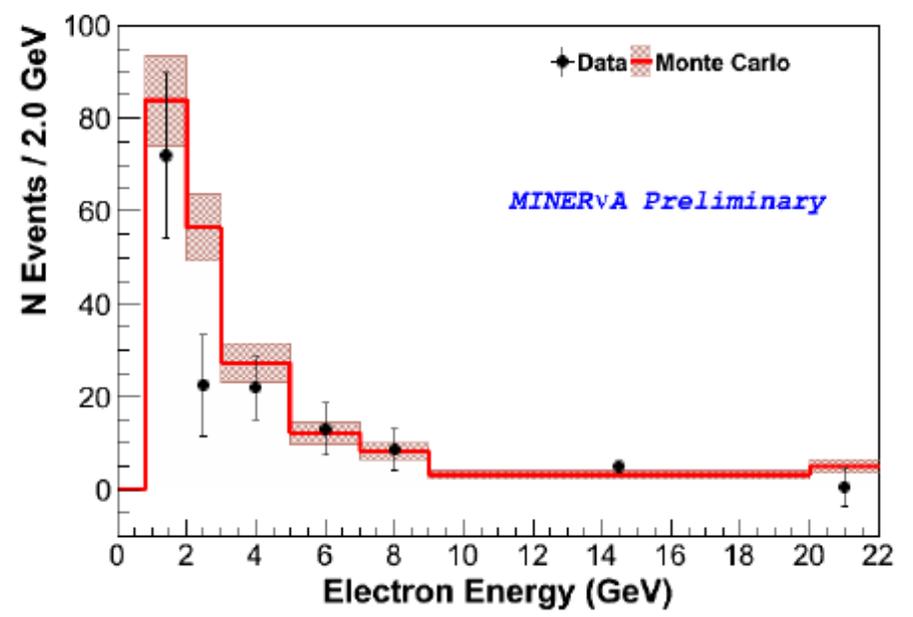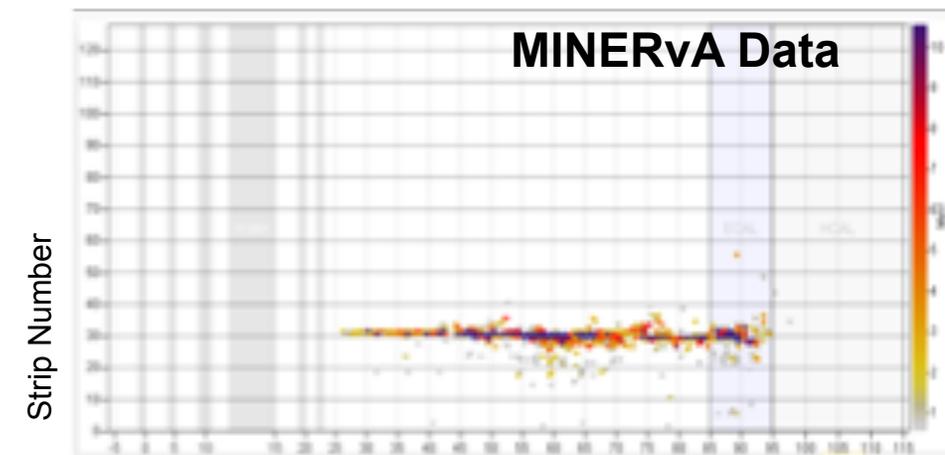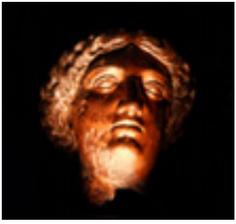
Cross section results

Neutrino cross section by low-ν cut
(plot is before data-to-data cross normalization)

GENIE
normalized

Antineutrino cross section by low-ν cut
(plot is before data-to-data cross normalization)


GENIE
normalized

Data plotted with stat+syst errors

Neutrino cross section – Normalized and merged

ν_μ in FHC

MINERvA Preliminary

MINERvA Preliminary
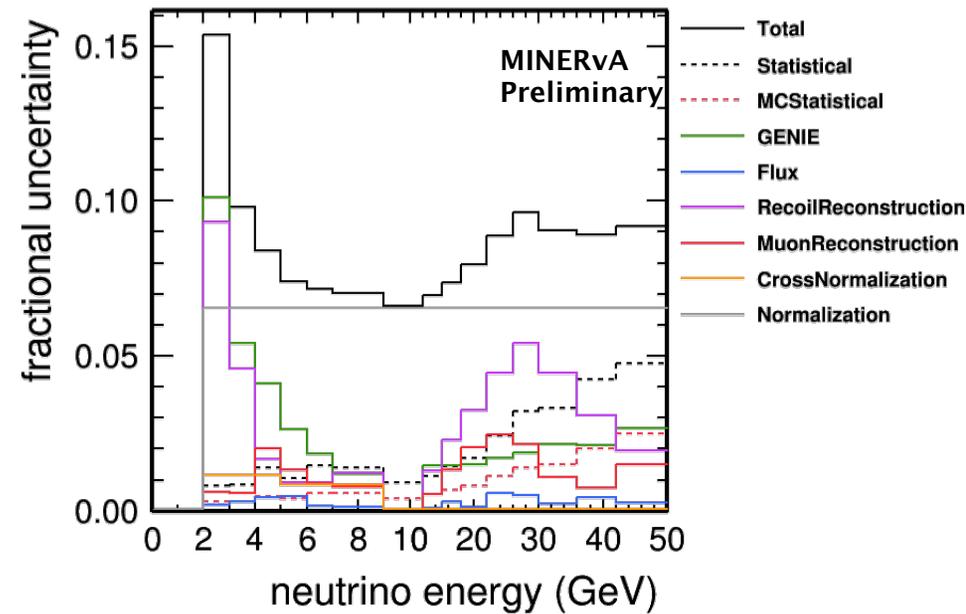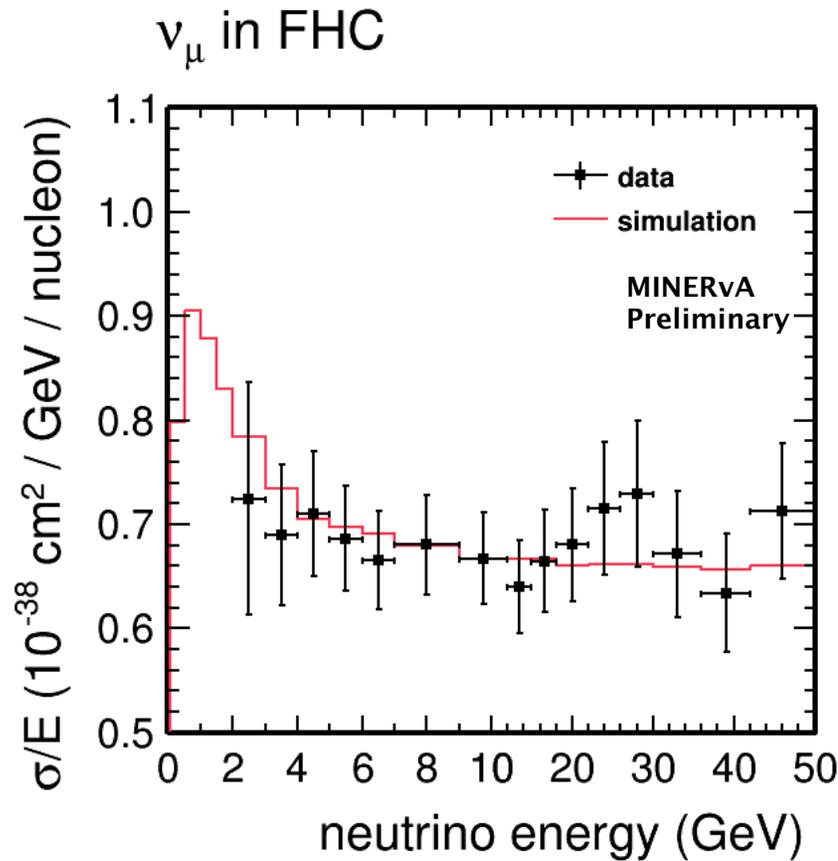
GENIE normalized

Data plotted with stat+syst errors

Antineutrino cross section – Normalized and merged

$\overline{\nu}_\mu$ in RHC

MINERvA Preliminary

data
simulation

MINERvA Preliminary

Total
Statistical
MCStatistical
GENIE
Flux
RecoilReconstruction
MuonReconstruction
CrossNormalization
Normalization
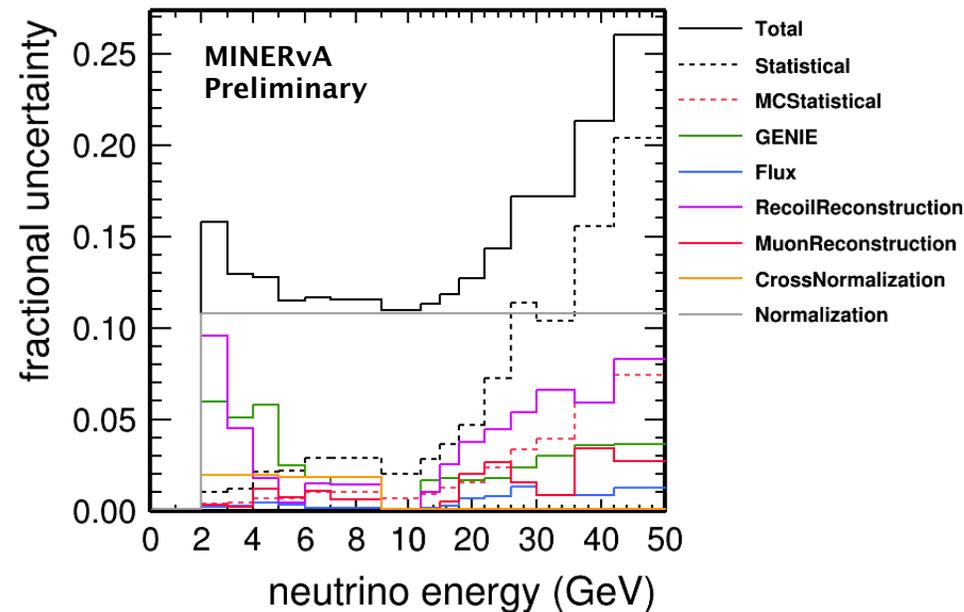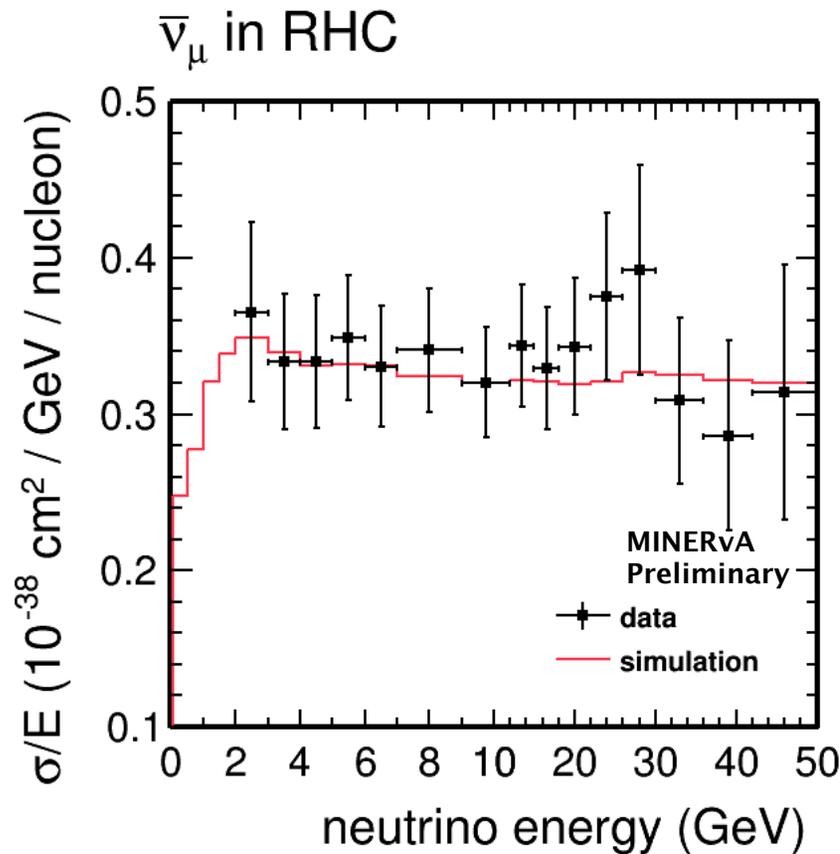
GENIE normalized

Data plotted with stat+syst errors

NOMAD–normalized inclusive neutrino cross section

- **NOMAD 9–12 GeV bin has 3.7% uncertainty**

- **GENIE systematic uncertainty in that bin is 6.5%**

- **NOMAD data point is 3.0% higher than the GENIE model**
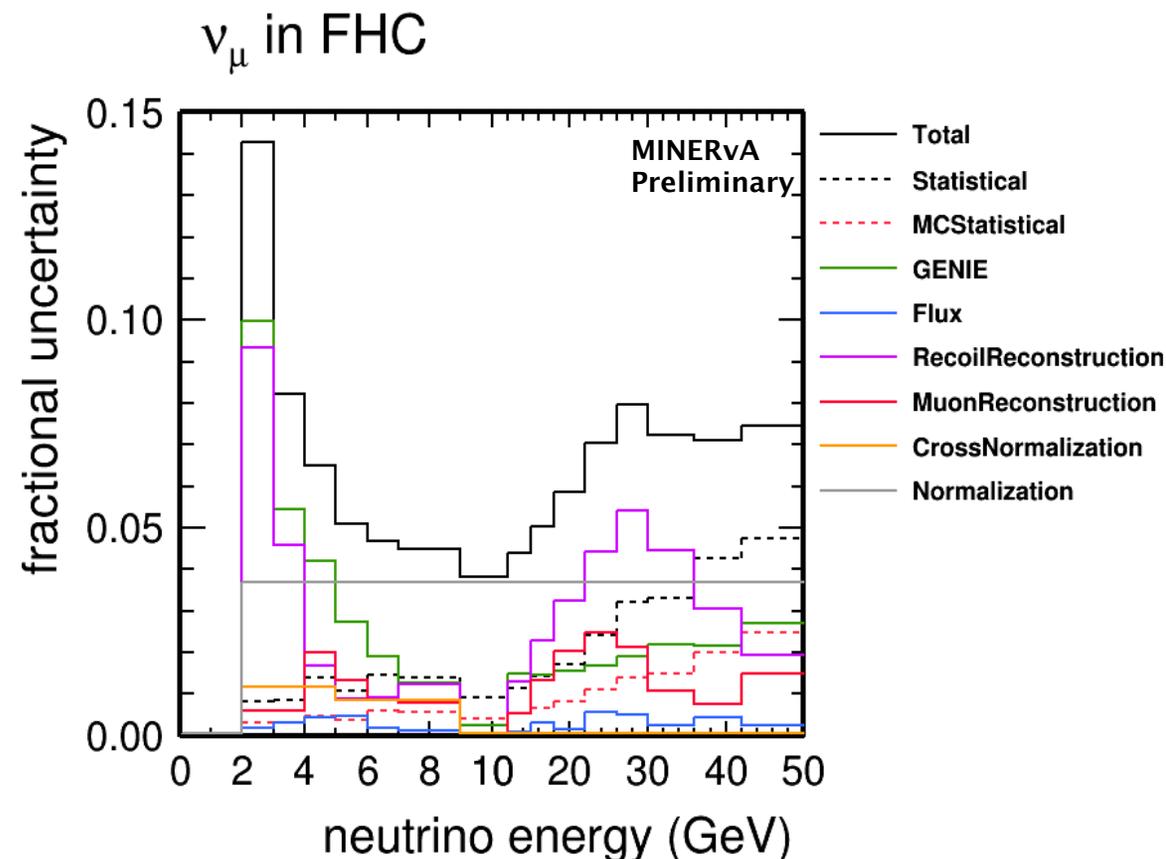
A data-driven normalization for the antineutrino cross section?

- Unfortunately there are no sufficiently precise external measurements (like NOMAD) in small enough bins in our normalization region
- Stick with GENIE value in the 9 – 12 GeV bin (superimposed as orange dot)
  - > GENIE's systematic uncertainty is 10.6%
  - > Normalization drives the errors
- Forthcoming analysis on neutrino/antineutrino cross section ratio will refine antineutrino normalization

$$\overline{\nu}_\mu \; N \rightarrow \mu^+ \; X$$
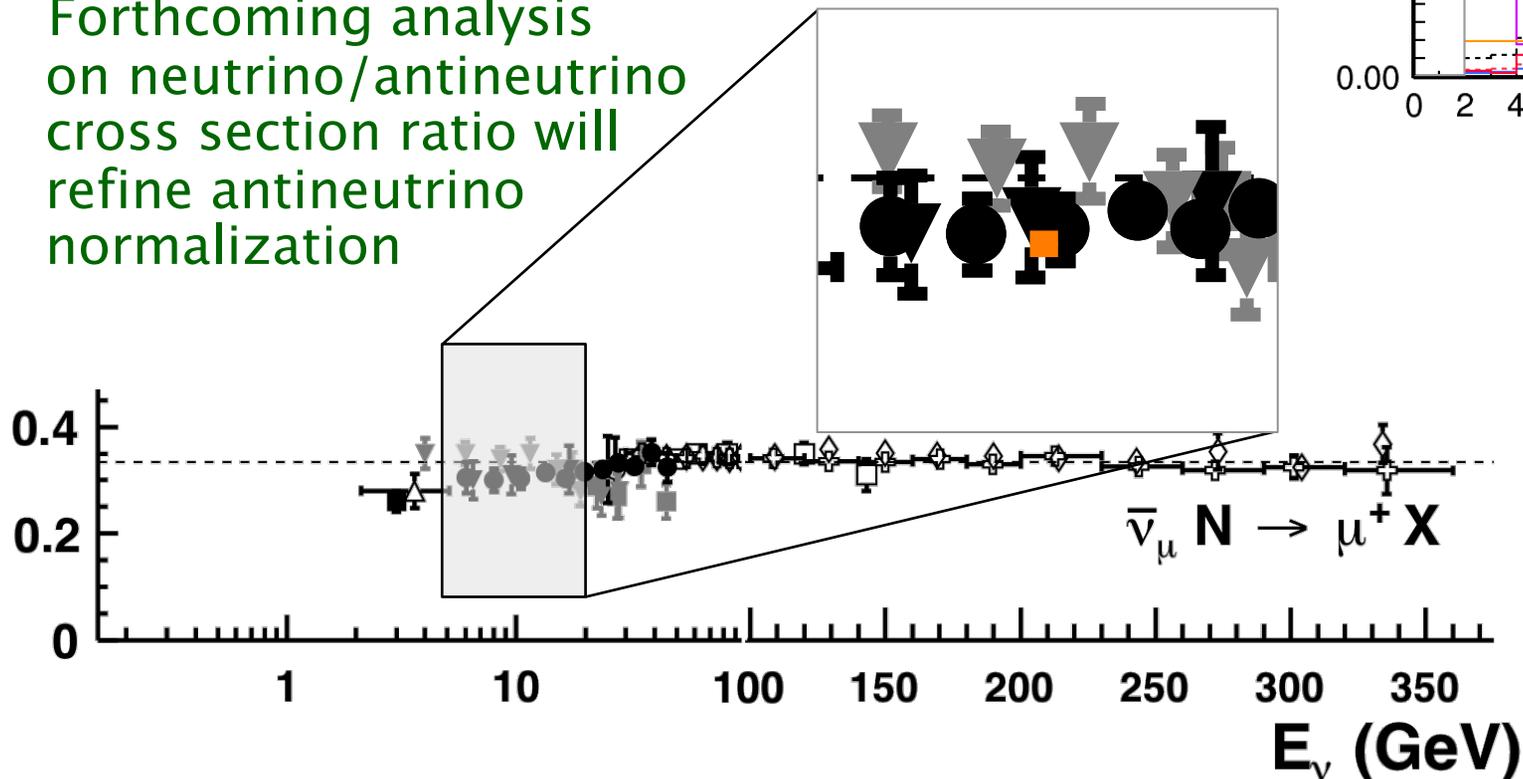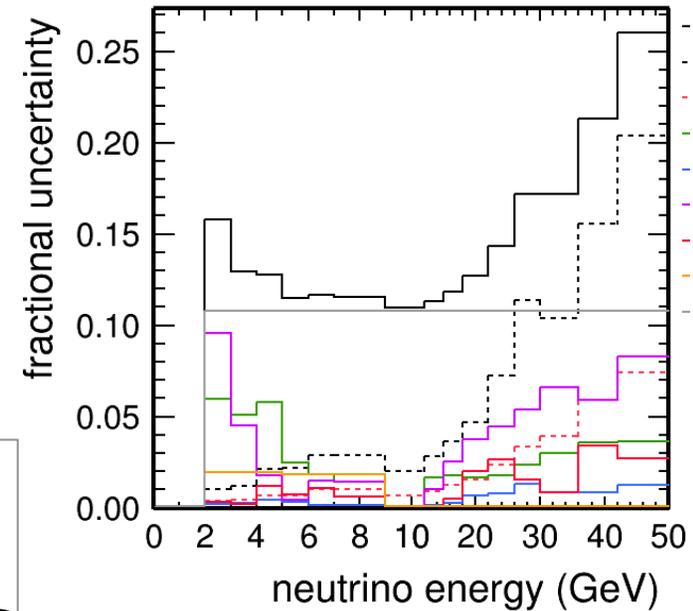
Cross checks

- Show that the extracted flux is not significantly dependent on the assumed initial flux
  - > Also can think of this as a closure test
  - > Use the extracted flux as the central value flux on MC and redo the entire low-ν analysis again

    ✓ Point-by-point the fluxes all agree to <1% level

- Redo the entire analysis and extract cross sections from "defocused" samples and compare
  - > RHC neutrinos and FHC antineutrinos
  - > Defocused pions in the beam so much different phase space for hadron production (and beam optics) hence much different fluxes
  - > MINOS magnetic field defocuses muons in these samples so most much different acceptances
  - > These are a small minority of the beam, so they are a stringent test of the backgrounds subtraction
  - > Tests unfolding with radically different energy spectra

✔ **It doesn't matter if the pions were focused or defocused, the measured cross sections are consistent!**

ν_μ, RHC / FHC

$\bar{\nu}_\mu$, FHC / RHC
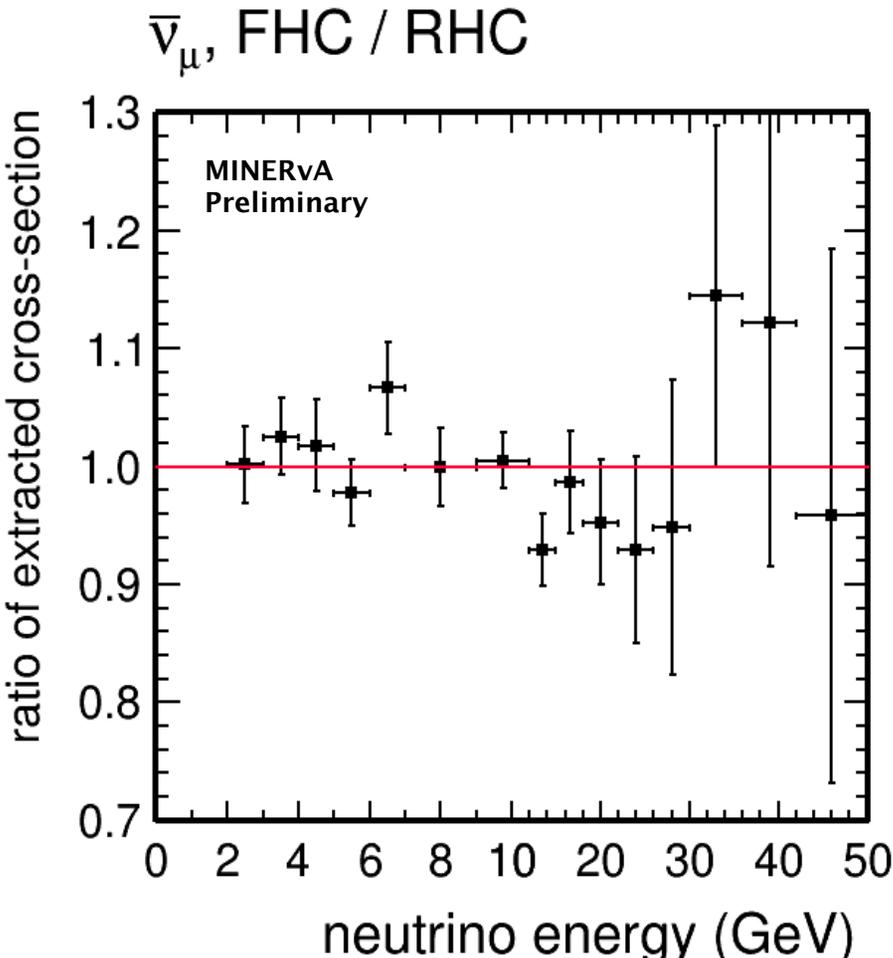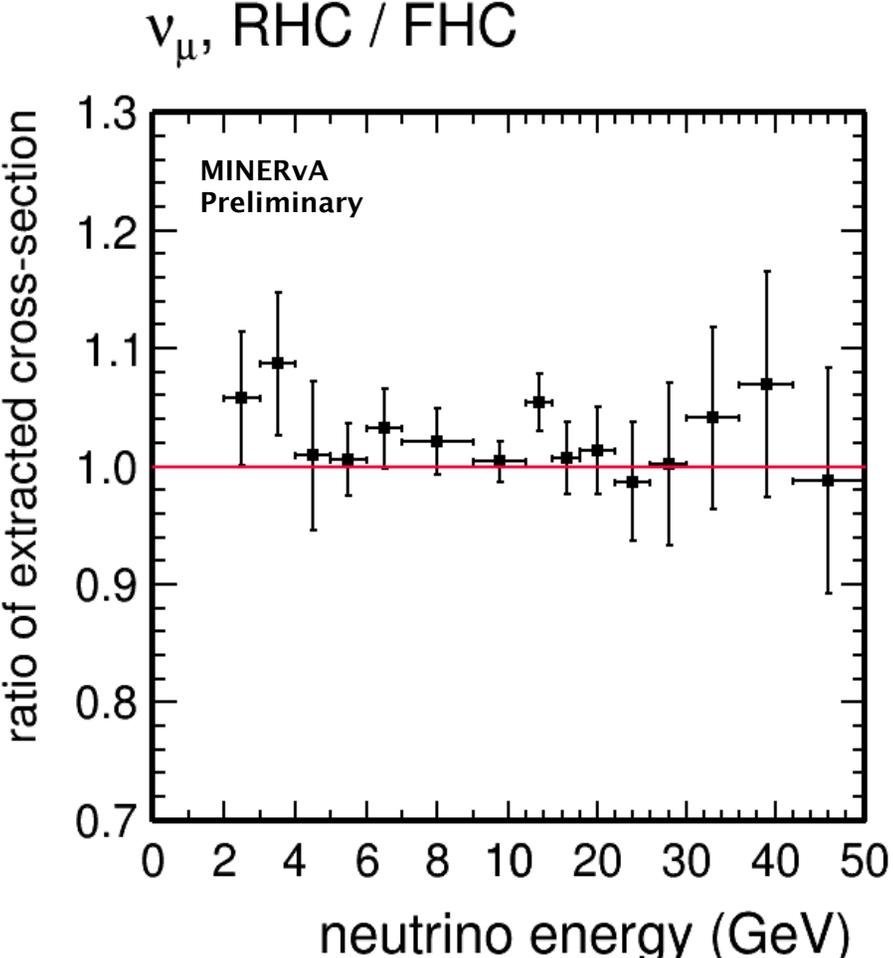
Data with statistical uncertainties only

Comparison to world data

Comparison to world data (the Big Picture)

Legend:
- **+** T2K (Fe) PRD 90, 052010 (2014)
- **+** T2K (CH) PRD 90, 052010 (2014)
- ☆ T2K (C), PRD 87, 092003 (2013)
- △ ArgoNeuT PRD 89, 112003 (2014)
- ● ArgoNeuT, PRL 108, 161802 (2012)
- ★ ANL, PRD 19, 2521 (1979)
- ○ BEBC, ZP C2, 187 (1979)
- ▲ BNL, PRD 25, 617 (1982)
- ◇ CCFR (1997 Seligman Thesis)
- □ CDHS, ZP C35, 443 (1987)
- ■ GGM-SPS, PL 104B, 235 (1981)
- ■ GGM-PS, PL 84B (1979)
- ▼ IHEP-ITEP, SJNP 30, 527 (1979)
- ▼ IHEP-JINR, ZP C70, 39 (1996)
- ● MINOS, PRD 81, 072002 (2010)
- ▲ NOMAD, PLB 660, 19 (2008)
- ✣ NuTeV, PRD 74, 012008 (2006)
- ✕ SciBooNE, PRD 83, 012005 (2011)
- ✳ SKAT, PL 81B, 255 (1979)
- ● MINERvA ν_μ (2016)
- ● MINERvA $\overline{\nu}_\mu$ (2016)

$\nu_\mu\ N \rightarrow \mu^-\ X$

$\overline{\nu}_\mu\ N \rightarrow \mu^+\ X$

Y-axis: $\sigma_{CC}\ /\ E_\nu\ (10^{-38}\ cm^2\ /\ GeV)$

X-axis: E_ν (GeV)

A. Schukraft, G. Zeller

Thank you for this personalized plot!

MINERvA results from select low-energy world data

ν_μ in FHC

$\overline{\nu}_\mu$ in RHC

MINERvA Preliminary
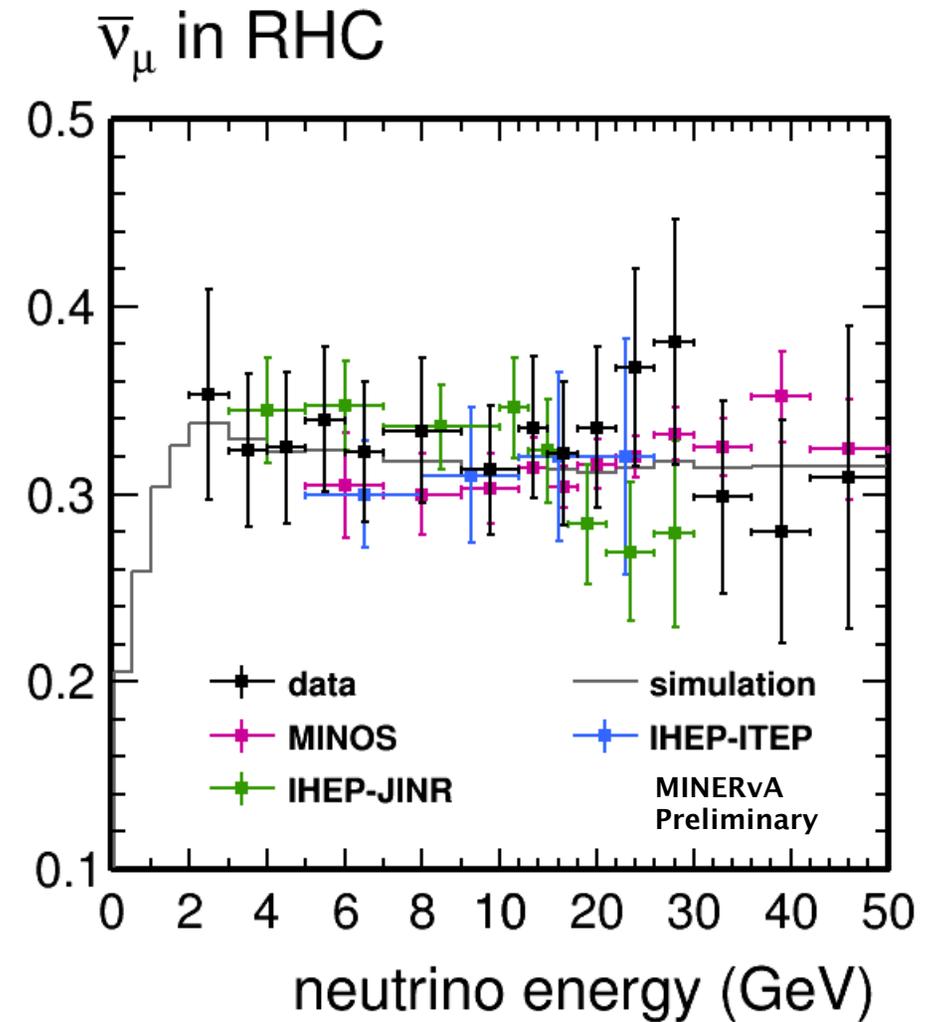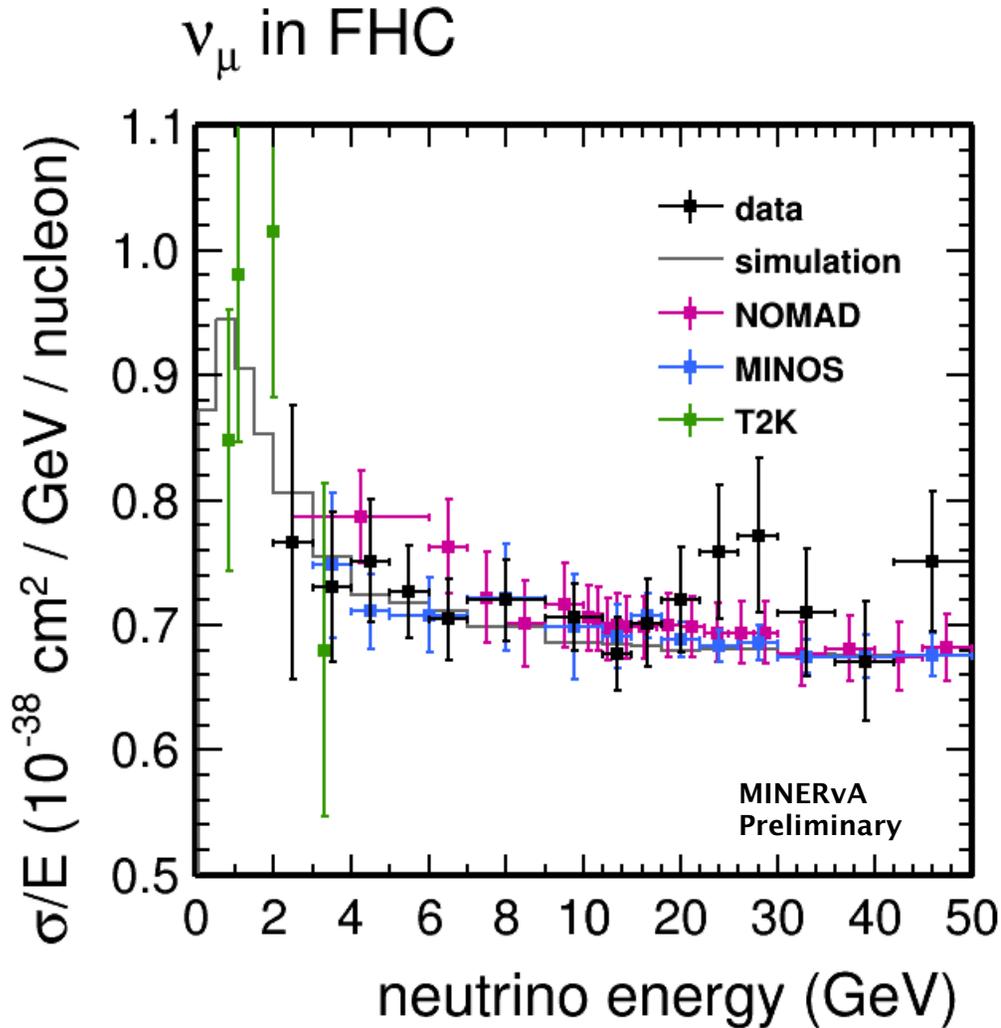
All points are isoscalar corrected

Simulation is GENIE

Summary

- Using the low-ν method, we extracted NuMI low-energy tune neutrino fluxes for muon neutrinos and antineutrinos or both focused and defocused samples
  - > 1st time this has been done for NuMI fluxes in the antineutrino-enhanced (RHC) beam
  - > Lowest energy application of this technique
  - > Lower than prior studies due to MINERvA's better resolution resolution
  - > These fluxes are consistent with the new MINERvA "GEN2" *a priori* fluxes & with our neutrino-electron scattering data
  - > These low-ν results helped to: validate the flux, pick the flux to use as our central value, and to validate revised horn conductor model

- Using the low-ν fluxes we extracted muon neutrino and antineutrino inclusive CC cross sections
  - > Extends inclusive data to lower energies (esp. antineutrinos)
  - > A forthcoming analysis will also measure the neutrino-antineutrino cross-section ratio with lower uncertainties