Prospects for the fine-grained detector neutrino-scattering program

Jeff Nelson
William & Mary

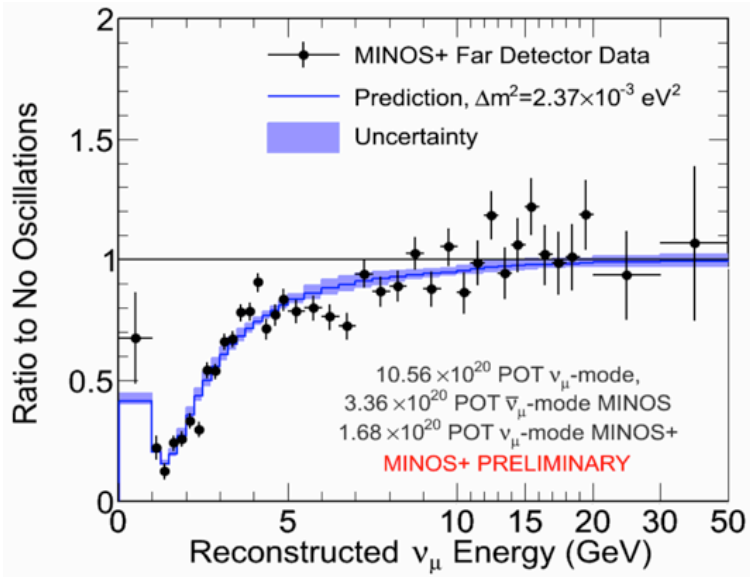
WINP2015
Brookhaven National Laboratory
February 5, 2015

Outline

- Where are we? What do we need for the future?
  - LB physics, data for model/generator improvements, nuclear physics
- Reminder of results
  - A few notes on fluxes and cross sections
- Output with current data (near term)
  - NOMAD
  - T2K ND280 neutrino
  - MINERvA LE
- Currently running (medium term)
  - NOvA ND
  - MINERvA ME neutrino and antineutrino
  - T2K antineutrinos
- Proposed redeployment (intermediate term)
  - CAPTAIN-MINERvA
- Beyond (long term)
  - nuPRISM
  - LBNF ND

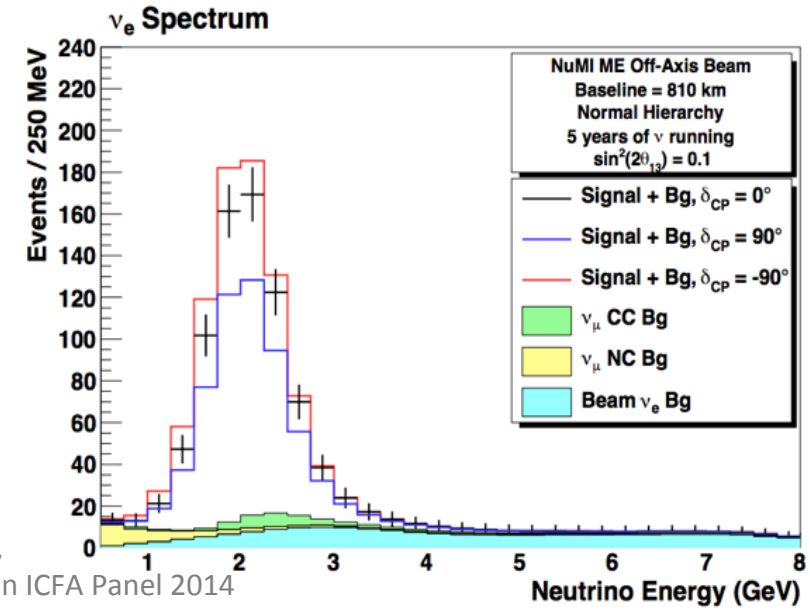
Cross sections (both signal & background) are becoming limiting factors in precision measurements

MINOS+



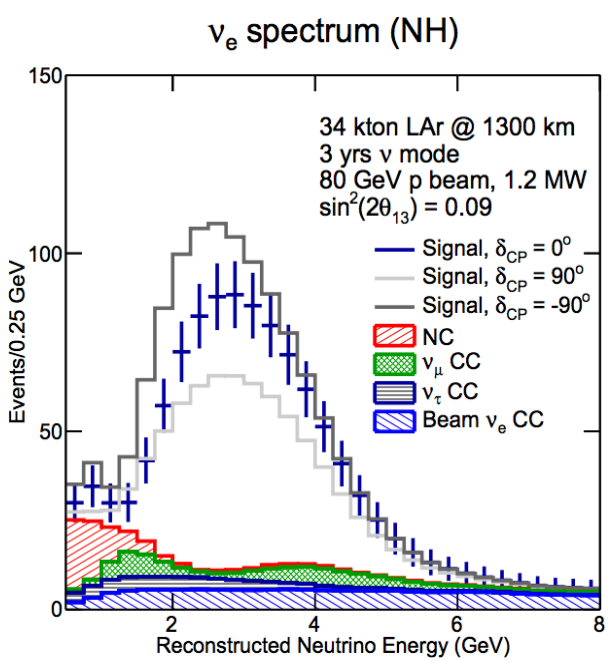
Sousa, Neutrino2014

NOvA



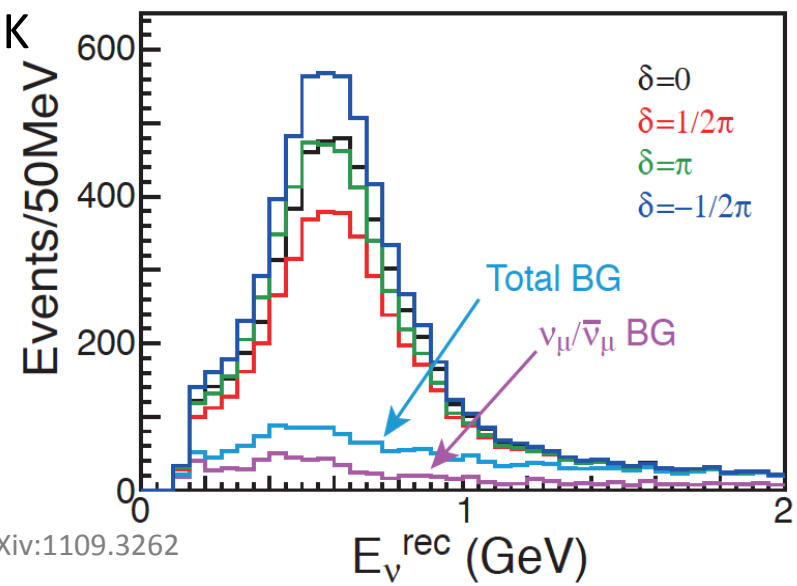
Thomas, European ICFA Panel 2014

LBNE



arXiv:1307.7335

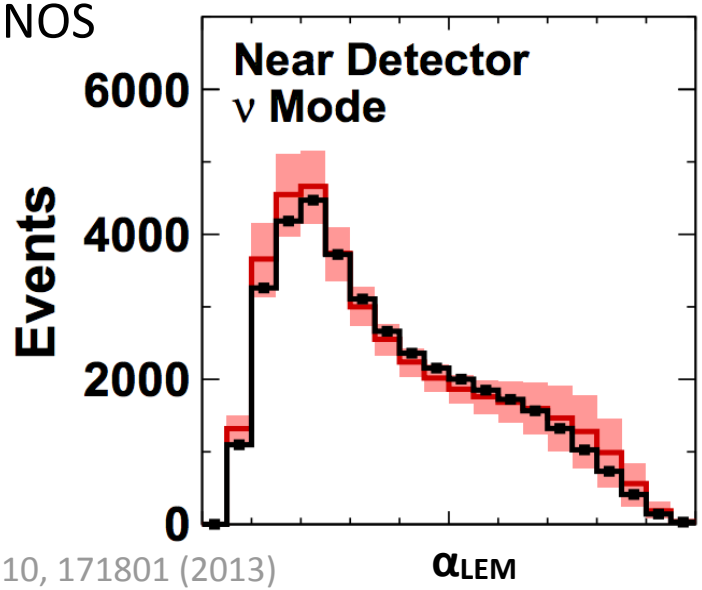
T2HK



arXiv:1109.3262

Uncertainties on signal predictions in ν_e appearance measurements: now & goals

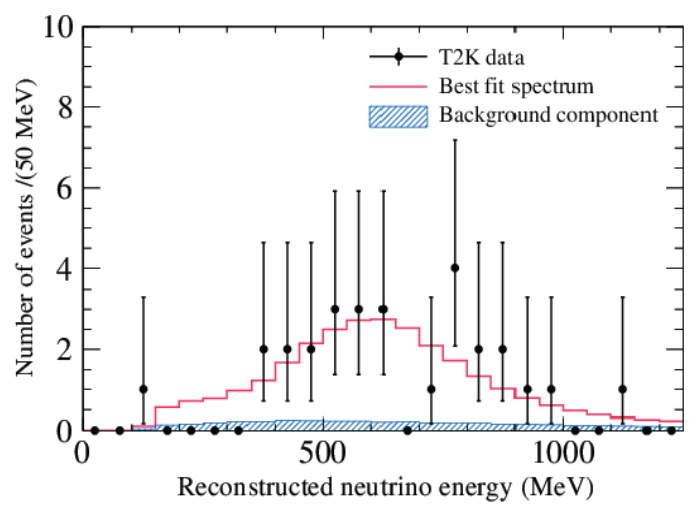
MINOS



PRL 110, 171801 (2013)

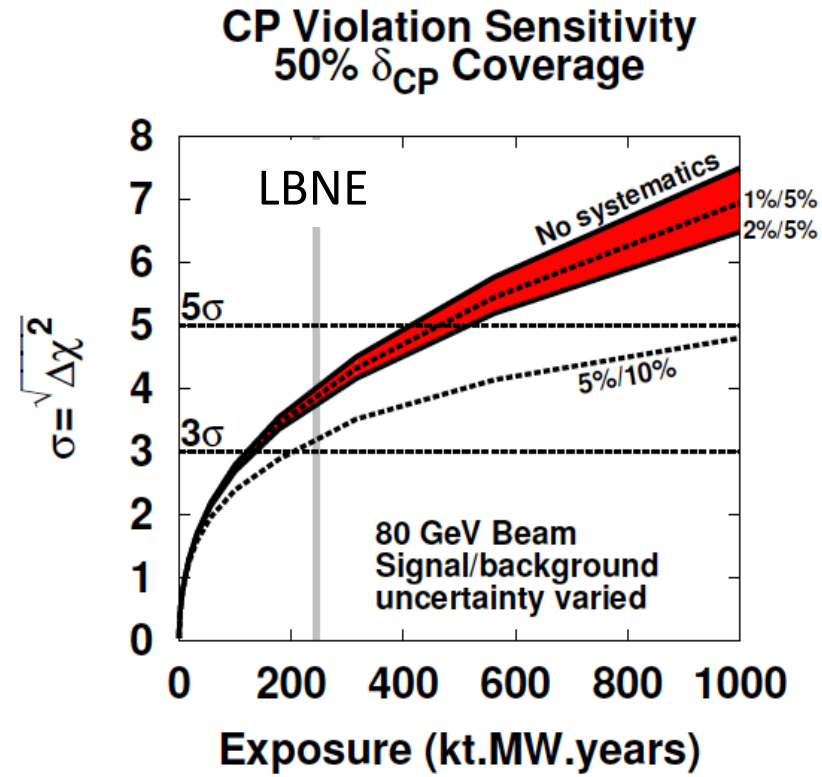
5.6% uncertainty on signal prediction

T2K



PRL 112, 061802 (2014)

6.8% uncertainty on signal prediction

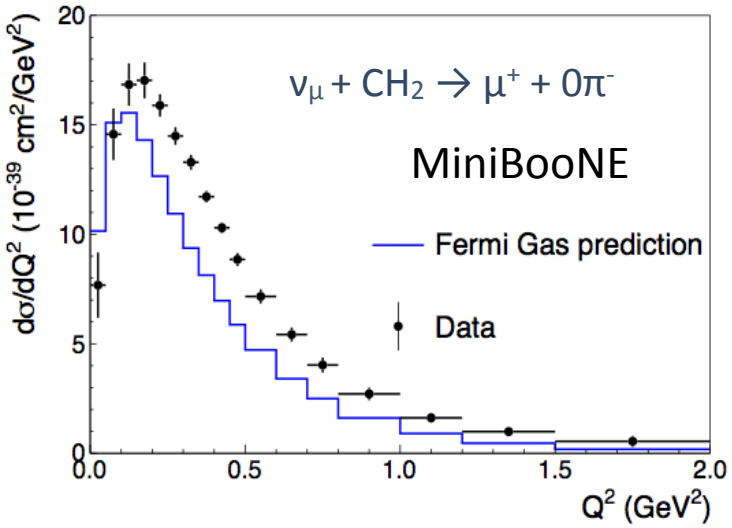


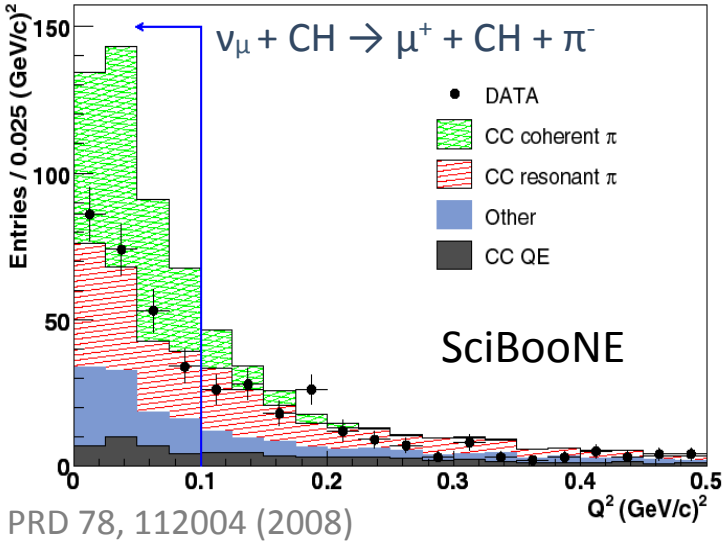
Bass, NuInt2014

- **LBNE's goal is 1%** for total systematic uncertainty on signal prediction
- Sensitivity to CP violation is strongly impacted by uncertainties in signal & background predictions

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

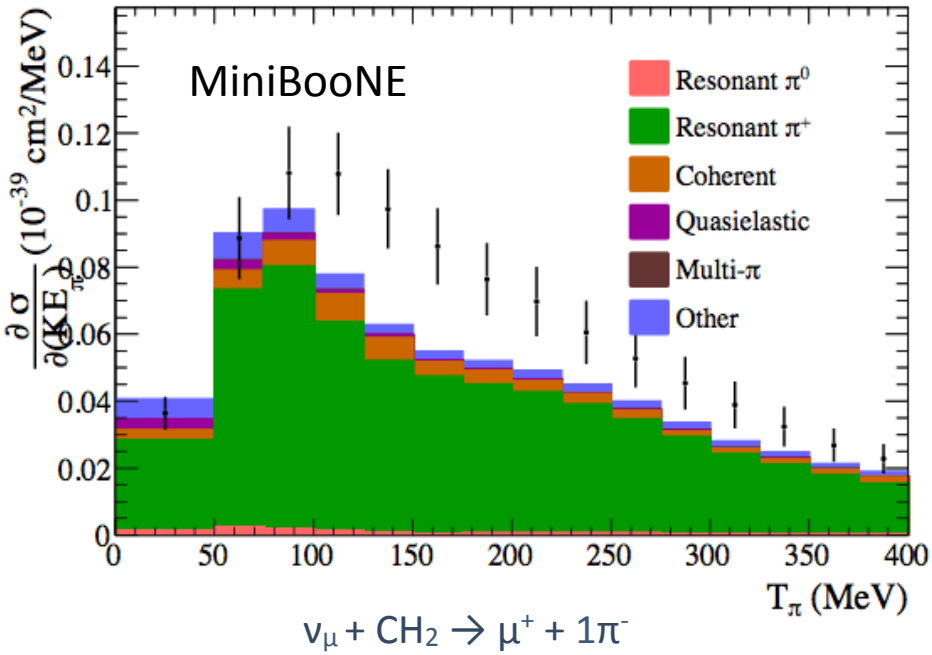
Adapted from PRD 81, 092005 (2010)
by P. Rodrigues





PRD 78, 112004 (2008)

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



2014 was an exciting year for the neutrino-nuclear scattering program…

- New results
  - > T2K, MINERvA, NOMAD, and ArgoNeuT
  - > NuINT2014, Neutrino2014, NuFact2014
- Steps toward the future
  - > Commissioning of NOvA's Near Detector
  - > Installation of MicroBooNE
  - > Ramp up of NuMI in ME tune
  - > T2K antineutrino run

Flux: critical for any absolute measurement

- Current tools
  - > Hadron production data
    - NA61/SHINE for T2K/JPARC energies (thin and thick)
    - Thin & Thick target data: MIPP & NA49
      - Clear tension between the data
      - Implies secondary interactions are not well modeled
    - Program for US-NA61 for MI energies [c.f. G. Mills today]
  - > Multiple simulations
  - > Special beam tunes
- Can also use standard-candle cross sections
  - > Neutrino-electron scattering
  - > Low ν (low recoil) events rates

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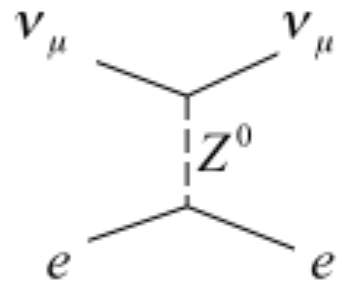
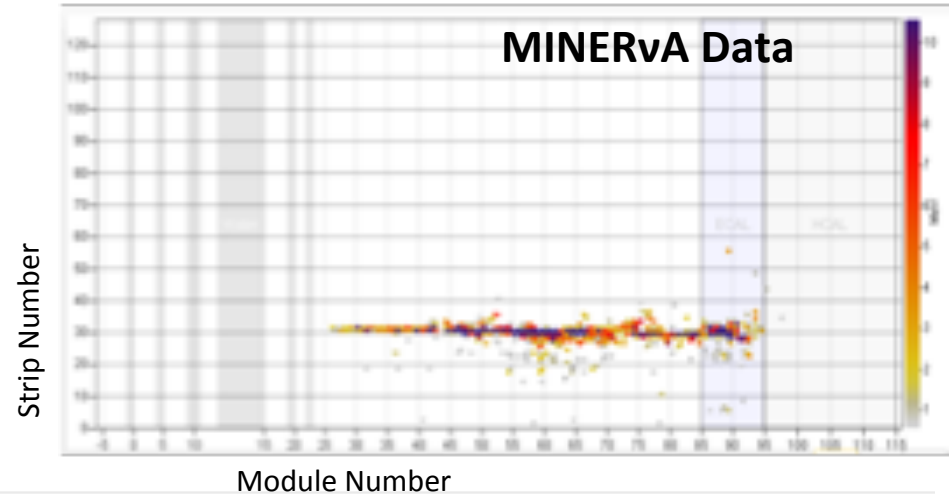
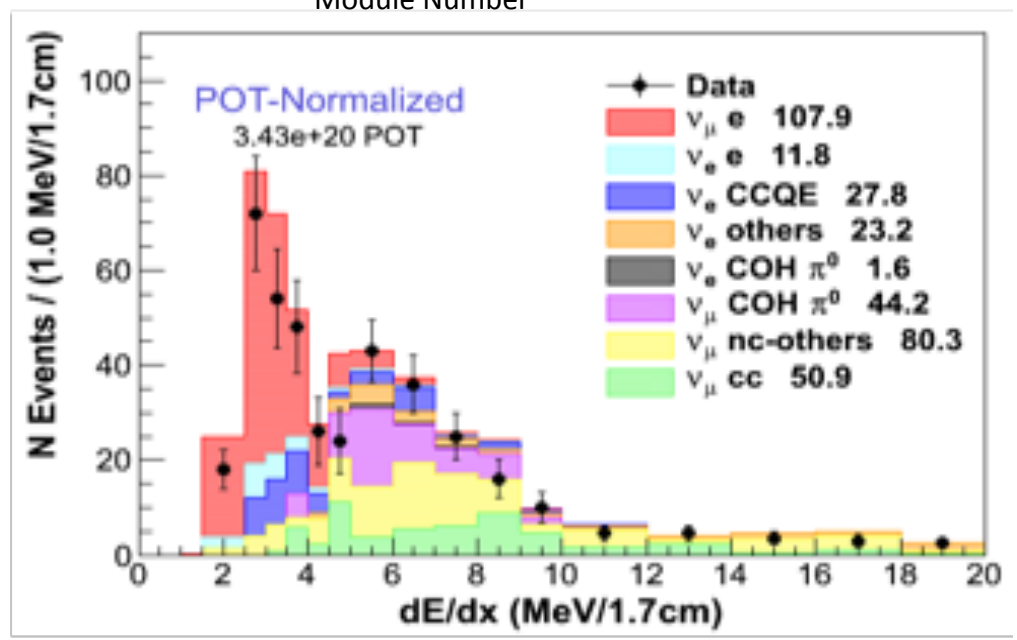
Flux: *ν*-e scattering



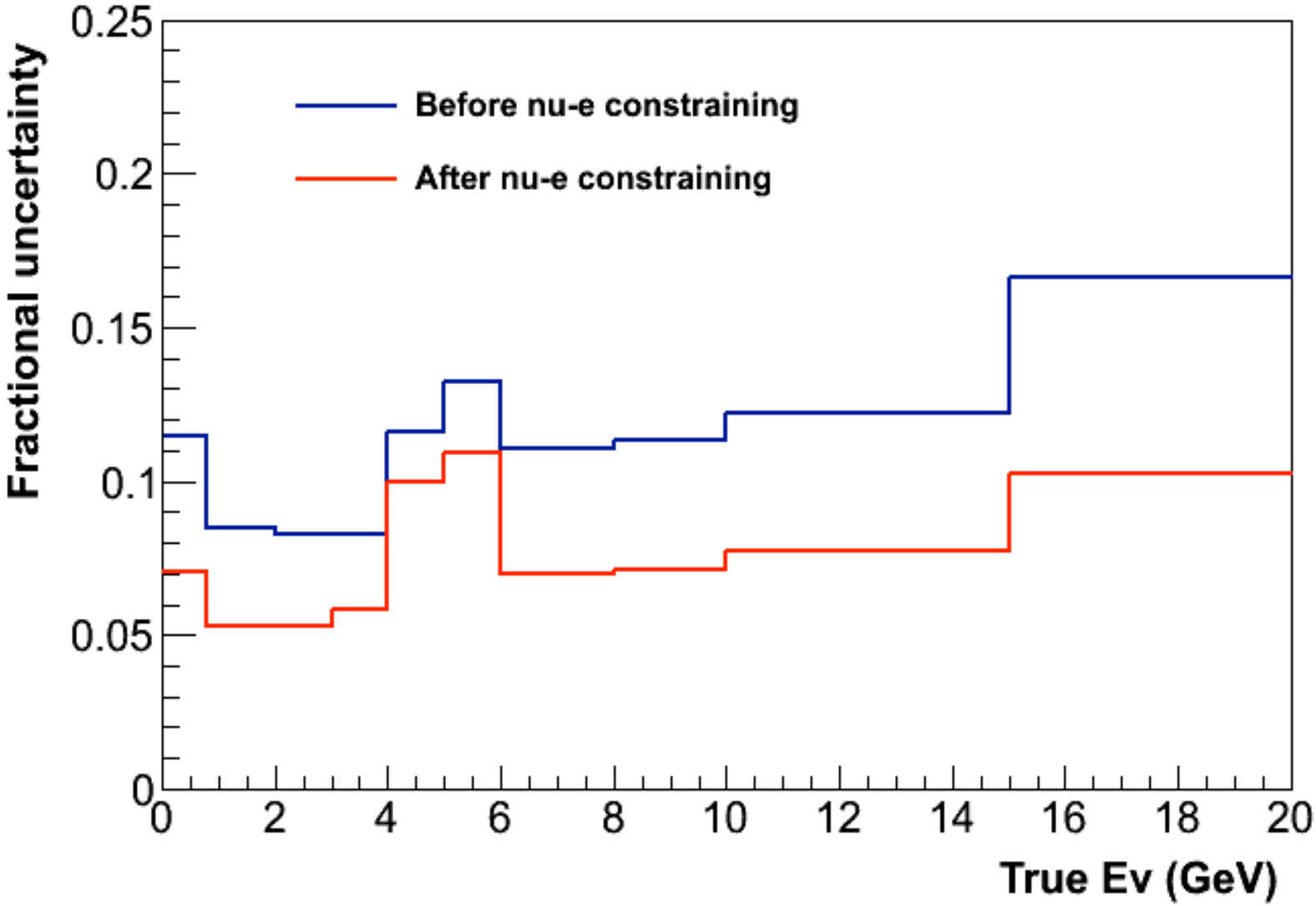
- Signal is a single electron moving in beam direction
- Process cross section is smaller than nucleus scattering by a factor of 2000
- Improves MINERvA's flux uncertainties
- Statistically limited
- Important proof of principle for future experiments
- Especially for NuMI medium energy and LBNF beams





J. Park FNAL JETS, Dec 20, 2013

Flux: *ν*-e scattering



J. Park FNAL JETS, Dec 20, 2013

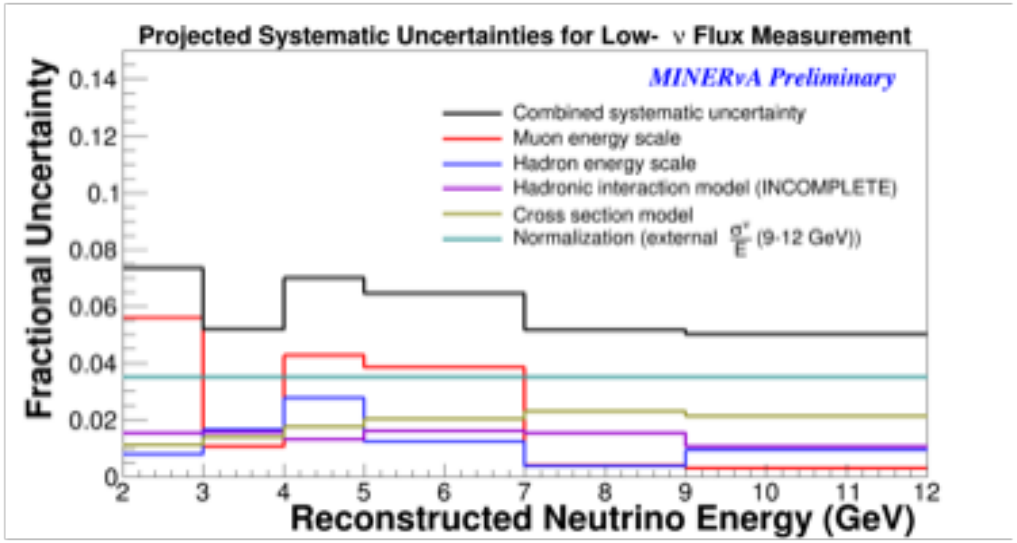
Flux: low *ν*

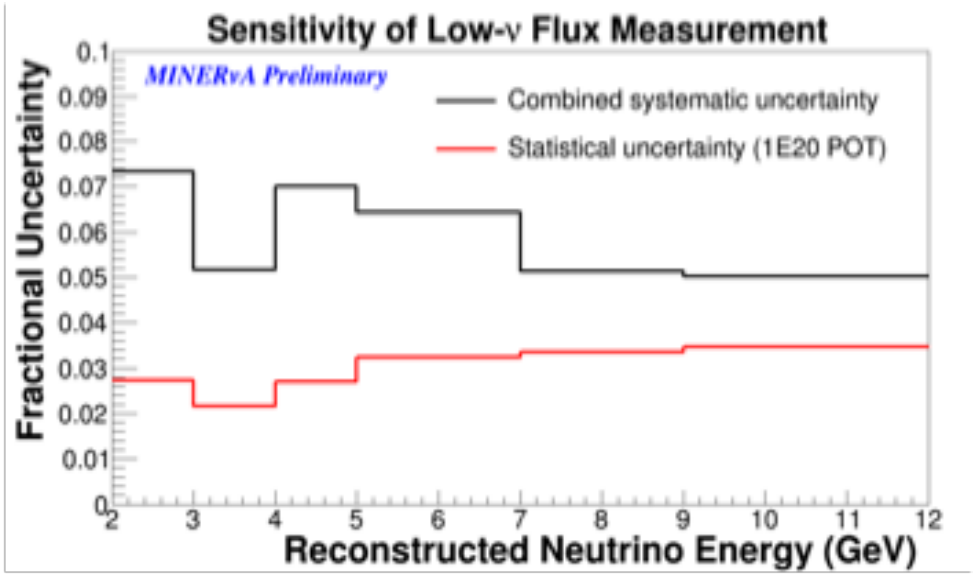
- Charged-current scattering with low hadronic recoil energy (*ν*) is flat

$$\frac{d\sigma}{d\nu} = A(1 + \frac{B}{A}\frac{\nu}{E} - \frac{C}{A}\frac{\nu^2}{2E^2})$$

  > Gives a measurement of the flux's shape
  > Normalization tied to external measurements at high energy

- Preliminary estimates of systematic uncertainty are promising at fairly low energies



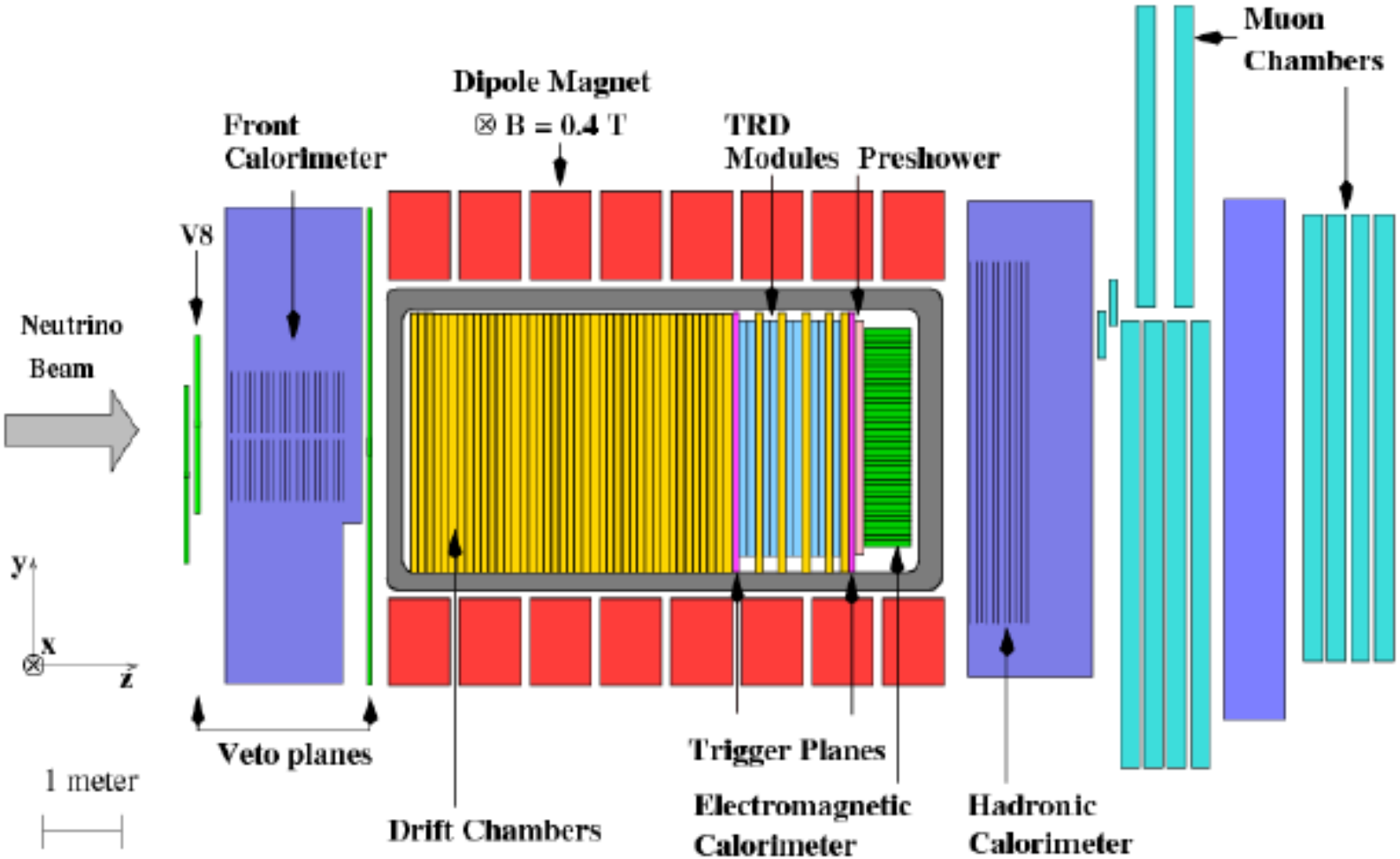


Fields, FNAL User's Meeting, 2014

Currently producing results: Near Term

NOMAD, MINERvA, T2K

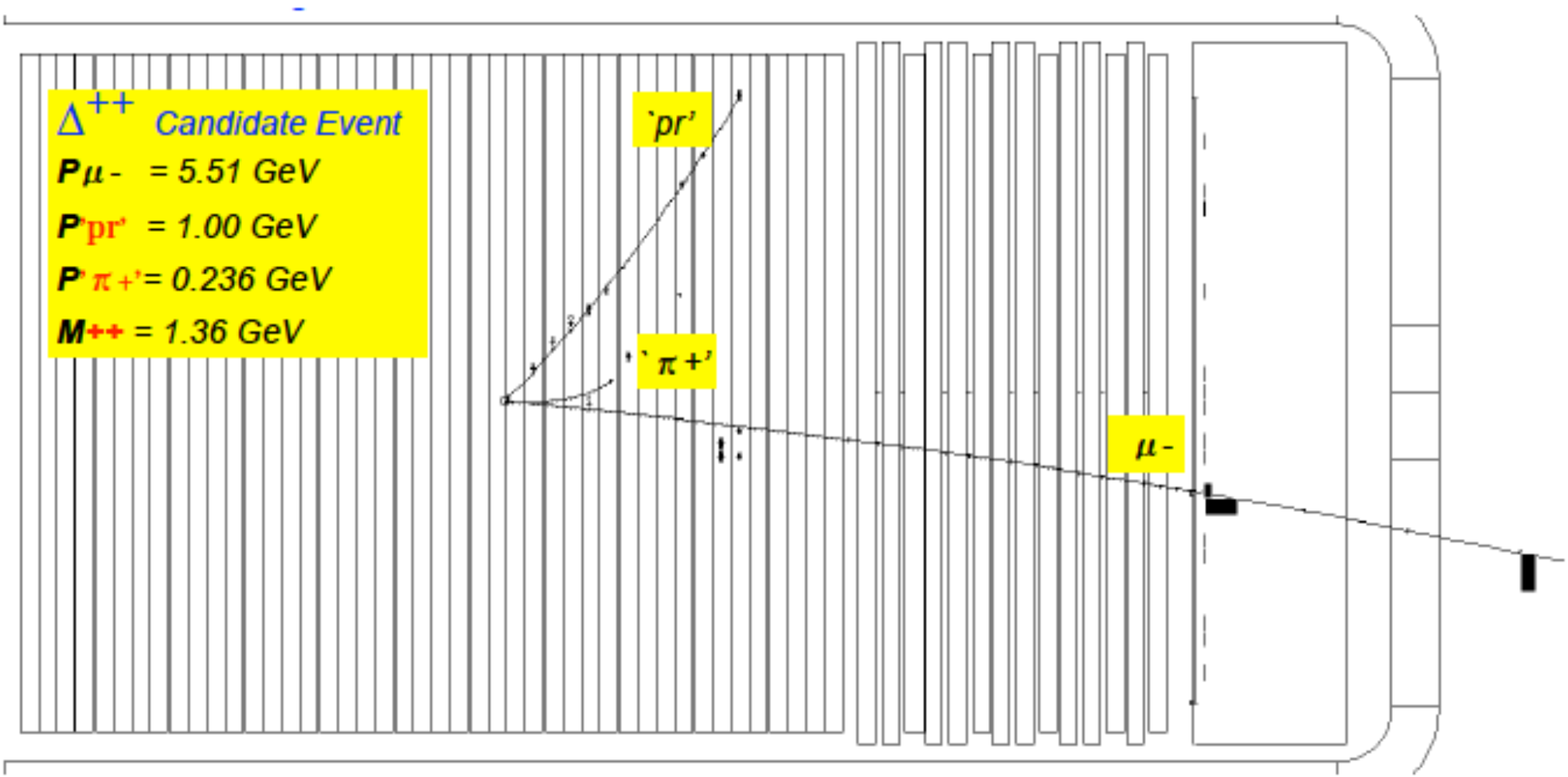
The NOMAD detector



- A classic: low-density fine-grain tracking detector in a magnetic field
- CERN SPS WBB in the **1990s** - 2M events recorded
- Famous for it's role in the QE model discussions for the last half decade
- A couple groups still work on this data

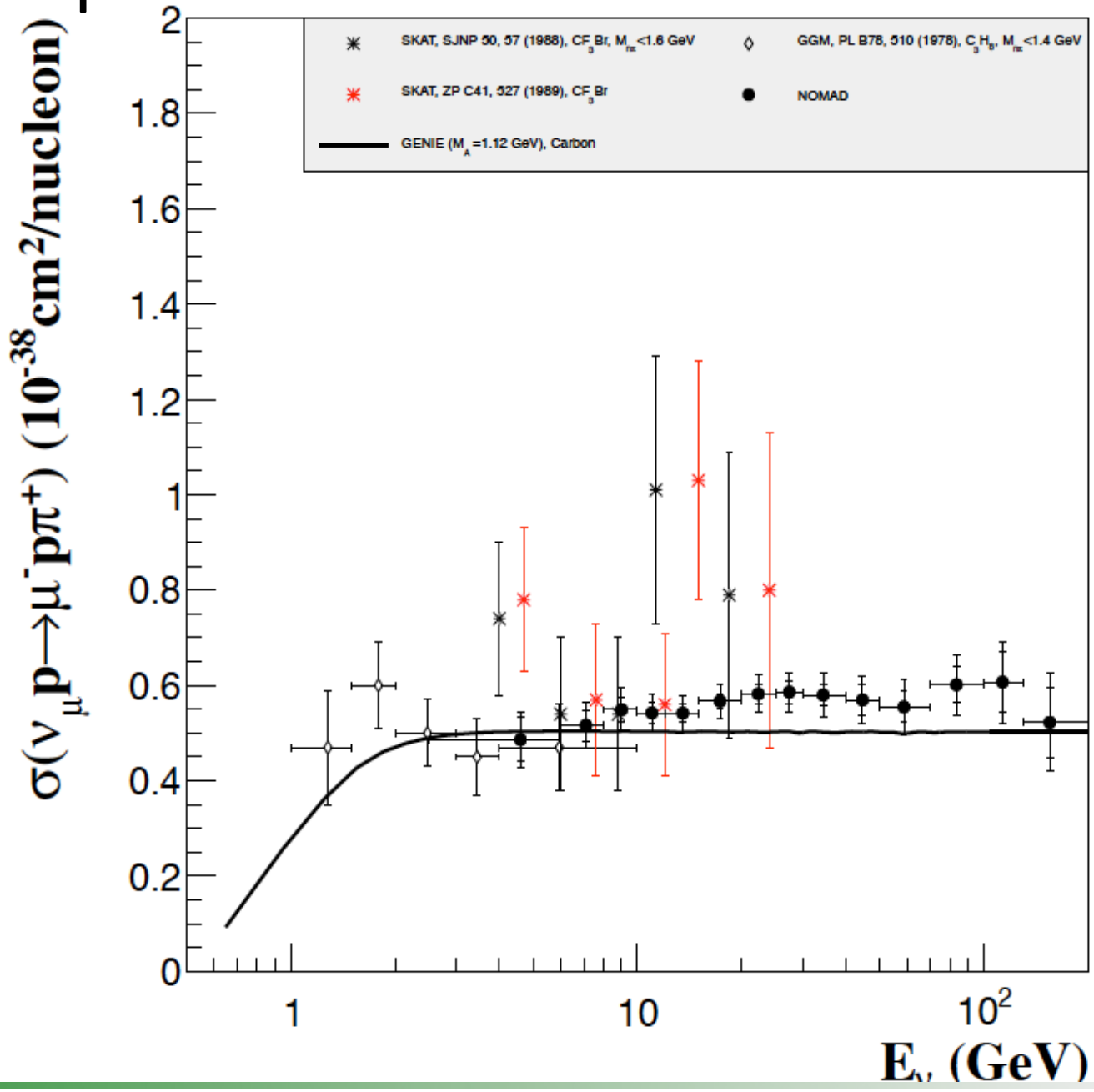
– so much **physics "left on the vine"**

NOMAD – 3 track single-pion event



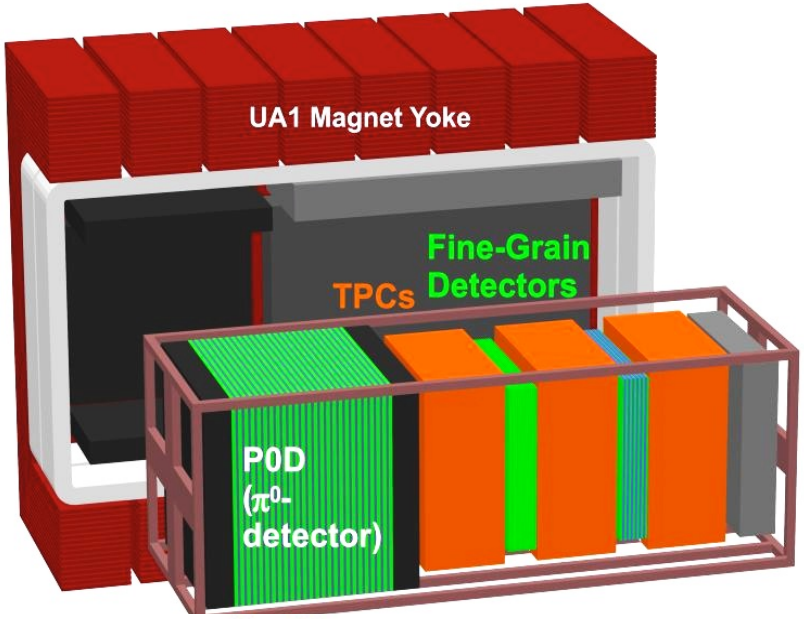
Preliminary:
3-track resonance production on Carbon

~60k events in sample



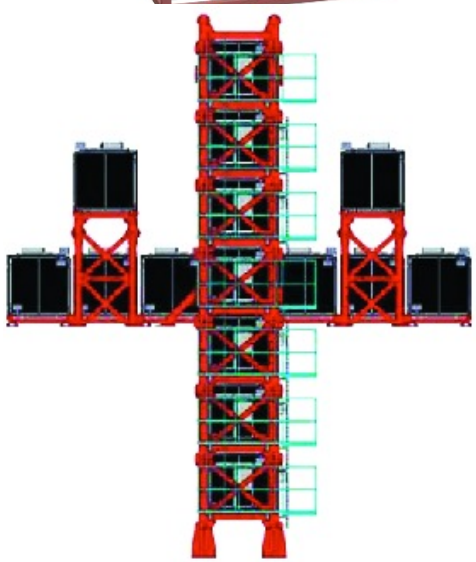
H. Duyang, Nufact2014

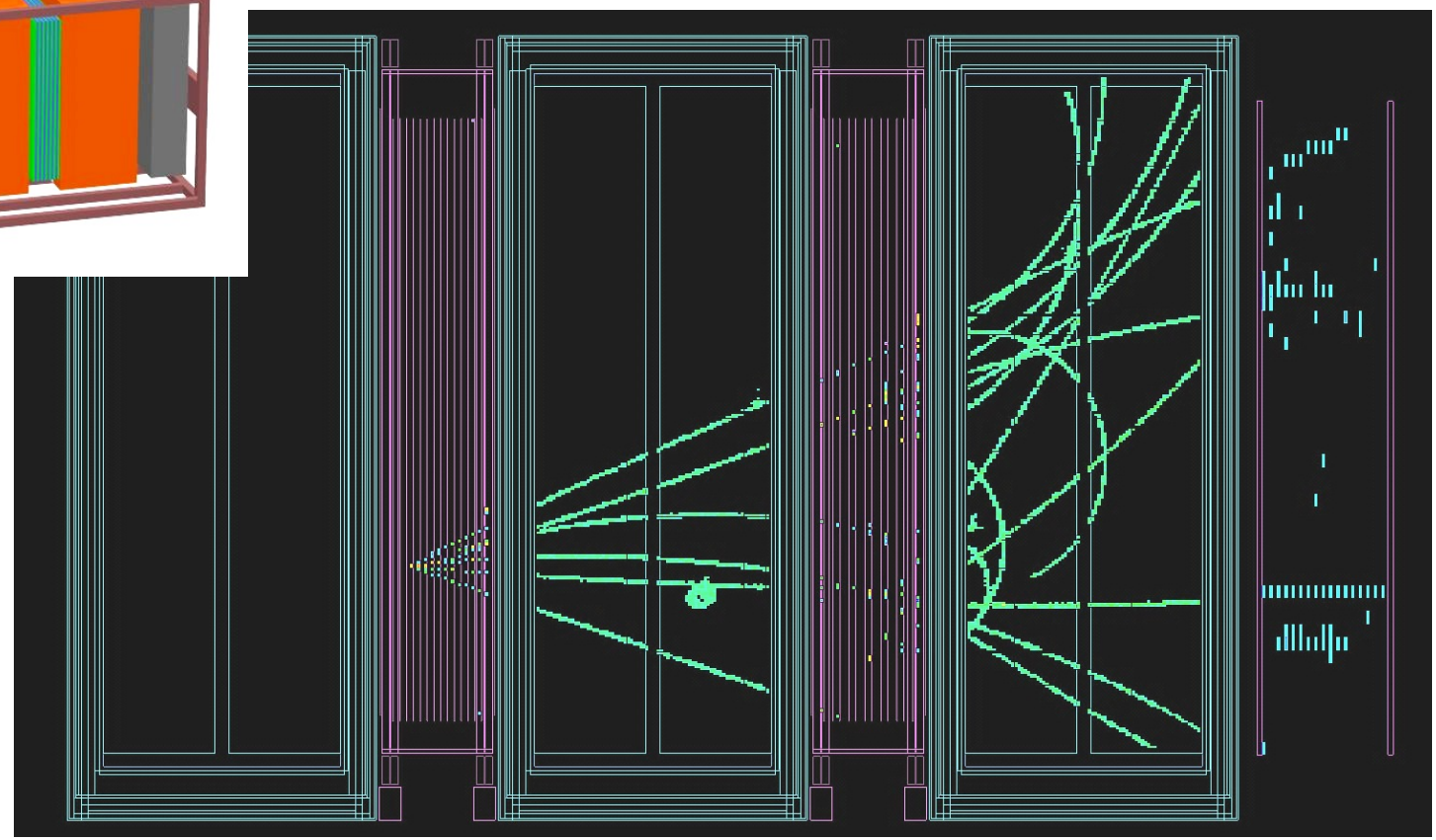
T2K near detectors
ND280 (off axis) and INGRID (on axis)



TPCs, FG detector, fine-grained calorimetry & muon tagging in a magnetic field

[c.f. M. Wilking today]





NIMA 659, 106 (2011)

Recent T2K results

- Inclusive ν_μ CC on C
- Inclusive ν_e CC on C
- ν_μ CCQE on C
- Inclusive ν_μ CC on Fe and CH & their ratio
- ν_μ NC on Oxygen
  by observing nuclear deexcitation γ rays

Up coming T2K neutrino-scattering program

Off-axis (in progress)

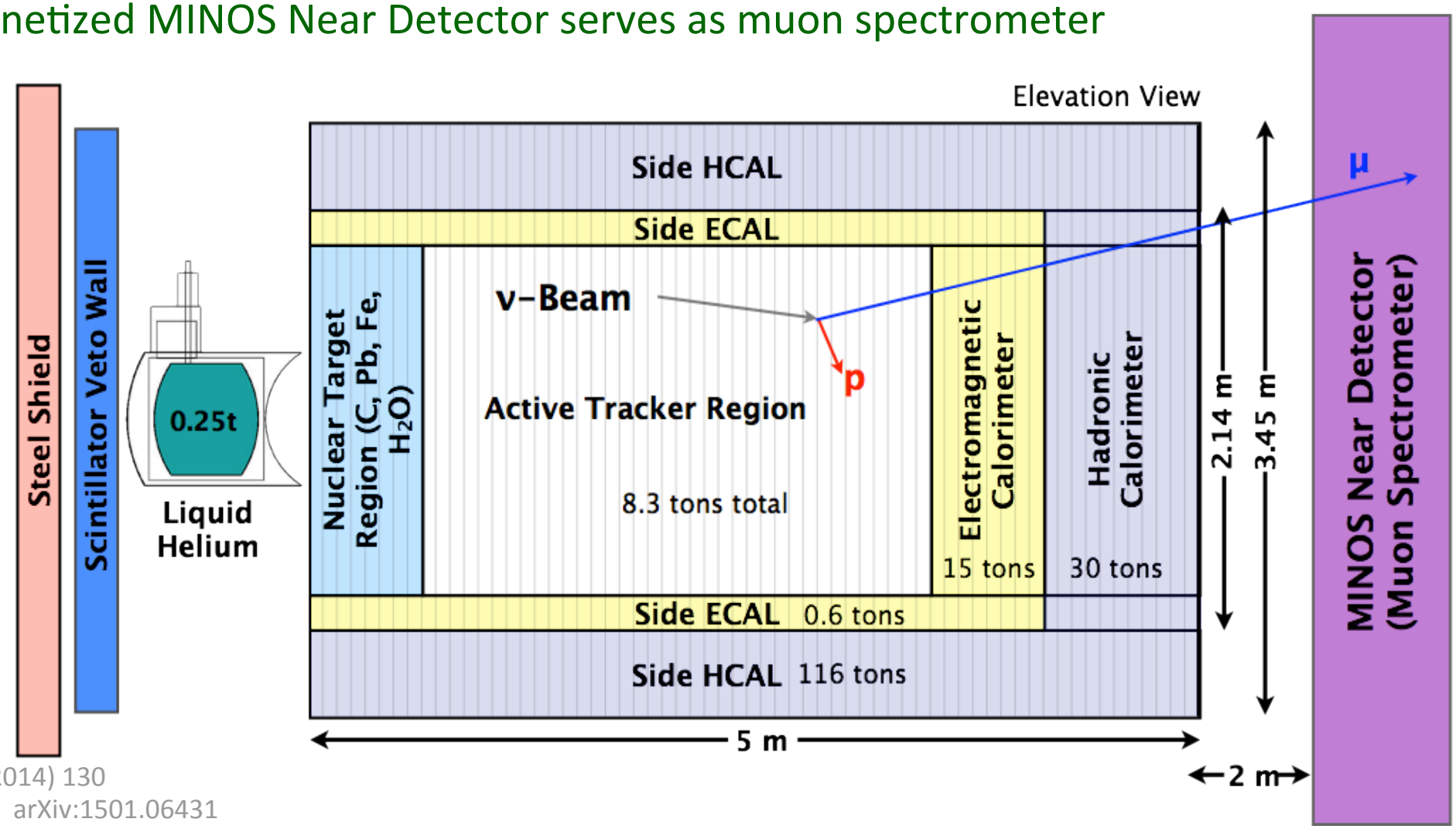
- QE two-track vs QE-like
  - > Multi-nucleon searches
- QE double differential
- Charged pion double differential
- Neutral pions
- Coherent charged (neutral?)
- More ν_e cross sections
- Nuclear ratios (w/H_2O, Pb, CH)
- INGRID (BBB) vs ND280 (NBB) for model comparisons
- Pion multiplicities

On axis (c.f. Suzuki, nufact2014)

- Energy dependent ν_μ CC inclusive on Fe
- ν_μ CC QE on C (one and two-track samples)
- ν_μ CC coherent on C
- ν_μ CC 0π differential on C

MINERvA

- Finely segmented solid scintillator detector in NuMI
  - Active tracker is made completely of scintillator
  - Calorimeters are scintillator with either Iron or Lead
- Upstream targets composed of Iron, Lead, Carbon, Water and Helium
- Magnetized MINOS Near Detector serves as muon spectrometer



NIM. A743 (2014) 130
Test beam: arXiv:1501.06431

MINERvA LE Program - Recent results

- CC QE
  - > Neutrino analysis (muon kinematic reco) on CH (single differential vs q^2)
  - > Antineutrino analysis (muon kinematic reco) on CH (single differential vs q^2)
  - > Neutrino two-track (proton kinematic reco) on CH (single differential vs q^2)
- CC Resonance
  - > Single and multiple charged pion production on CH (single differential vs T_π and θ_π)
  - > Single neutral pion production on CH (single differential vs T_π and θ_π)
- CC Coherent
  - > Neutrino/antineutrino charged-current coherent charged pion production on CH
- CC Inclusive
  - > Inclusive nuclear target ratios (single differential, E_ν and x) C/CH, Fe/CH, Pb/CH
- Neutrino-electron scattering
- Test beam experiment

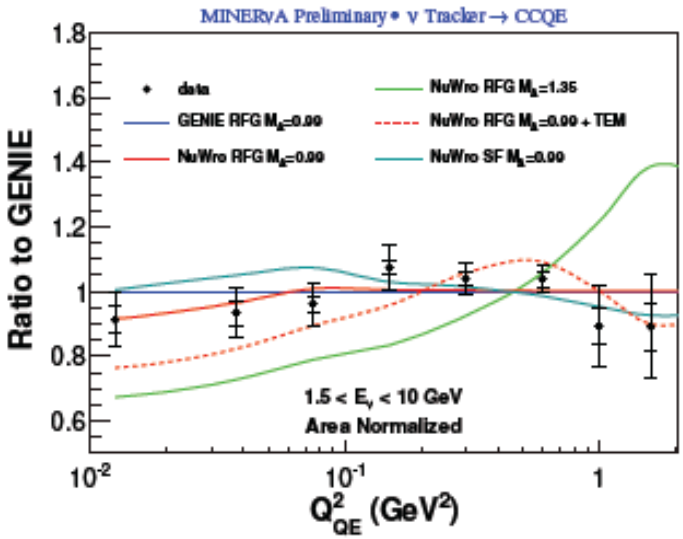
[c.f. Betancourt today]

c.f. Betancourt at this workshop

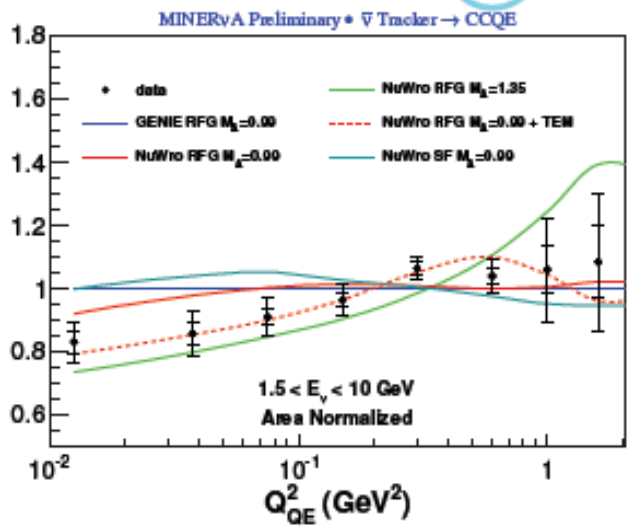
Charged Current Quasi-Elastic Scattering

- MINERvA uses the lepton kinematics and the hadronic part of the interaction to measure the CCQE single differential cross section and discriminates between nuclear models

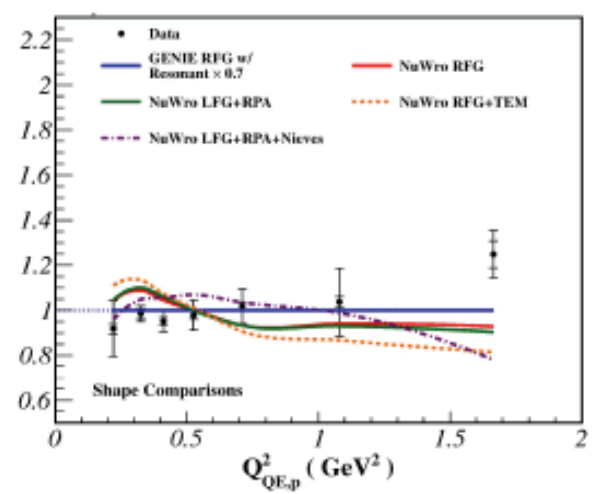
Neutrino $\nu_\mu + n \rightarrow \mu^- + p$ **AntiNeutrino** $\bar{\nu}_\mu + p \rightarrow \mu^+ + n$ **Neutrino** $\nu_\mu + n \rightarrow \mu^- + p$



Phys. Rev. Lett. 111, 022501 (2013)



Phys. Rev. Lett. 111, 022502 (2013)



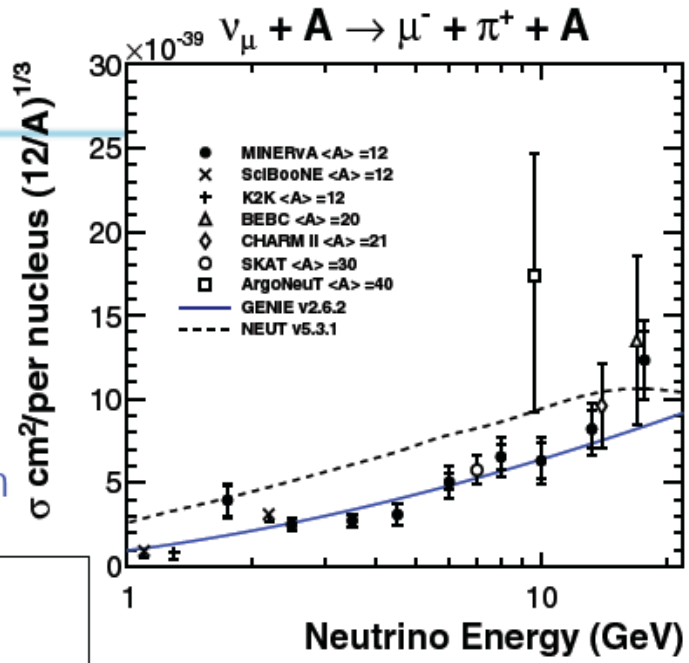
arXiv:1409.4497

- Neutrino data prefer extra vertex energy
- Muon-side kinematics prefer a model with nucleon-nucleon correlations
- Proton side kinematics consistent with GENIE – they prefer different models!!!

c.f. Betancourt at this workshop

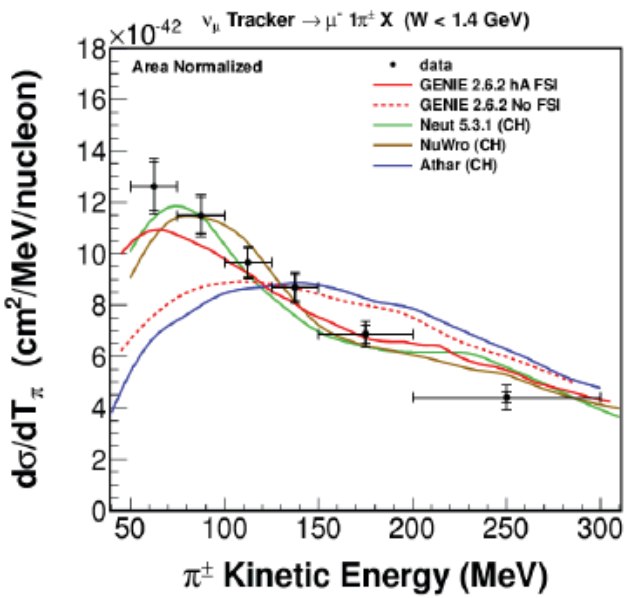
Pion Production

- MINERvA's pion production measurements:
  - Coherent cross section for neutrinos and antineutrinos
  - Differential cross section for neutrino single π^+ production and antineutrino single π^0 production



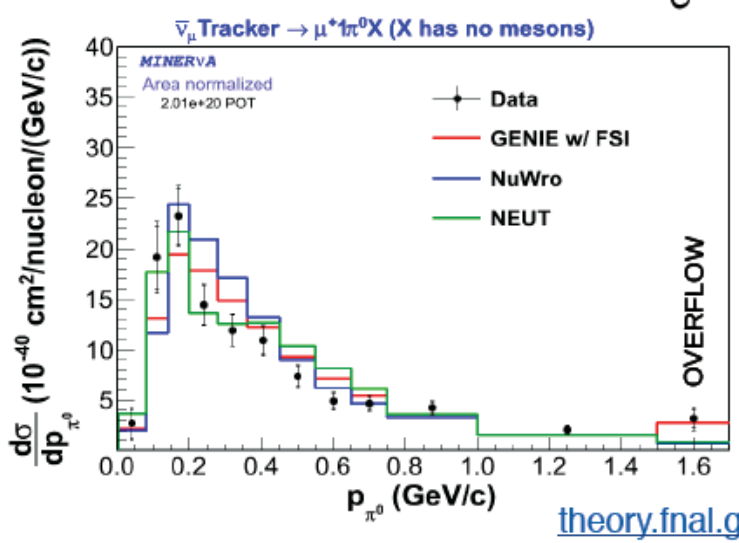
Phys. Rev. Lett. 113, 261802 (2014)

Neutrino CC single π^+ production



arXiv:1406.6415

AntiNeutrino CC single π^0 production



theory.fnal.gov/jetp/talks/WC_talk_Trung.ppt

Data prefer somewhat stronger nuclear effects

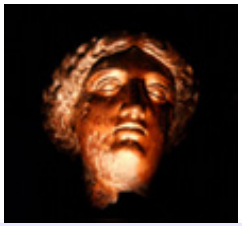
Low *x* summary

- At x = [0.0,0.1], observe a **deficit** that grows with the size of the nucleus
- This effect is not modeled in simulation

We expected neutrino differences

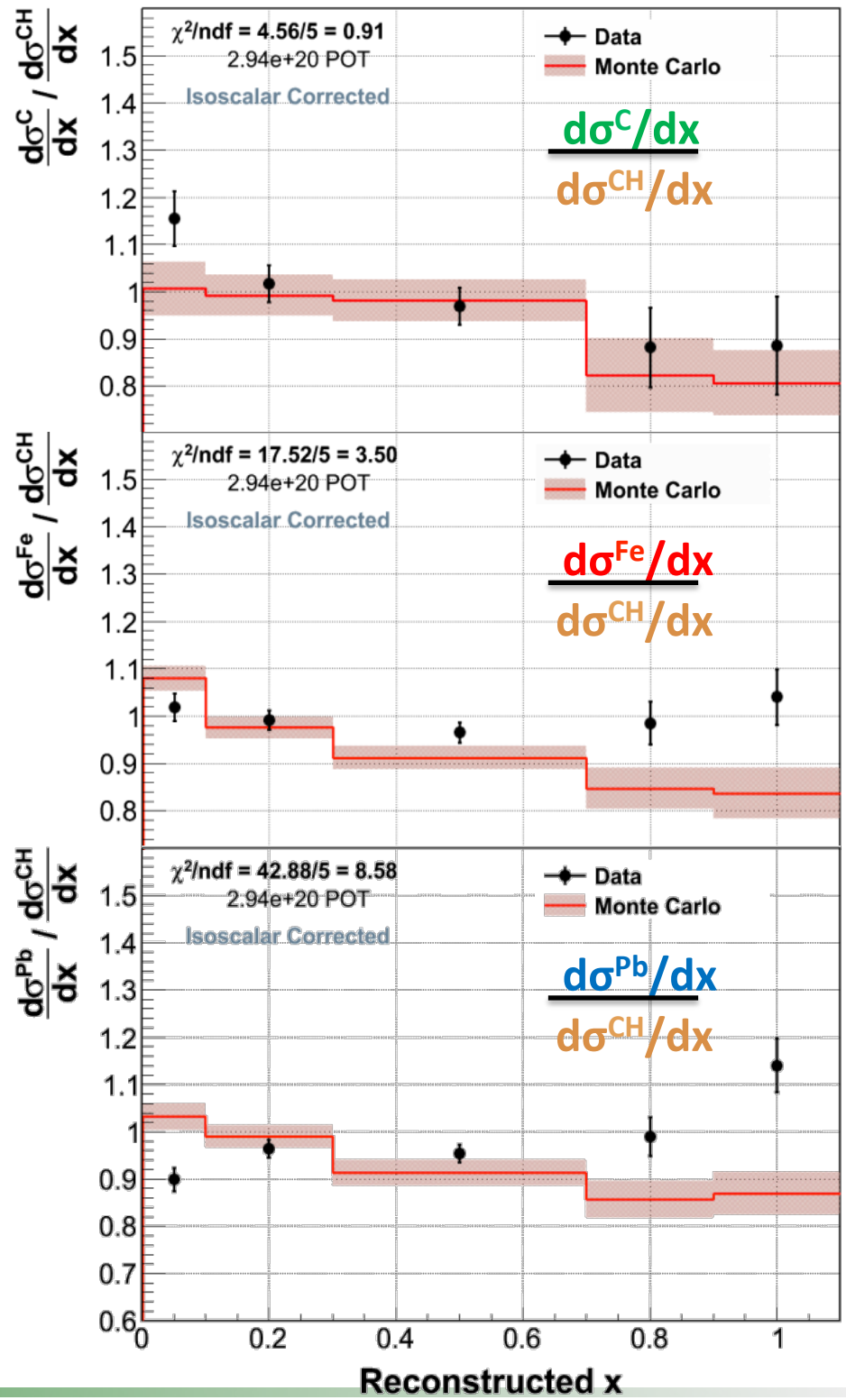
Neutrinos sensitive to structure function xF_3

Neutrinos sensitive to axial piece of structure function F_2



GENIE 2.6.2

PRL. 112 (2014) 231801



MINERvA LE dataset – Ongoing program

- Double differential CC QE for neutrino and antineutrino on CH
  - > Incorporation of Michel tag
- Low-nu CC neutrino, CC antineutrino & ratio
- CC DIS nuclear target ratios
- CC QE ratios in nuclear targets using the hadronic side of the interaction
- Kaon production
- Electron neutrino CC on CH
- Neutrino two-track CC on HE and H_20

Currently taking data: Medium term

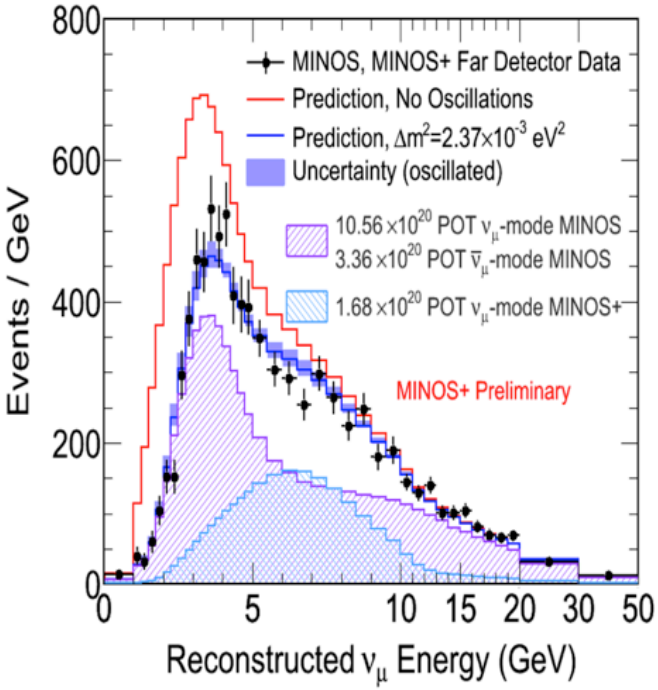
NOvA Near Detector

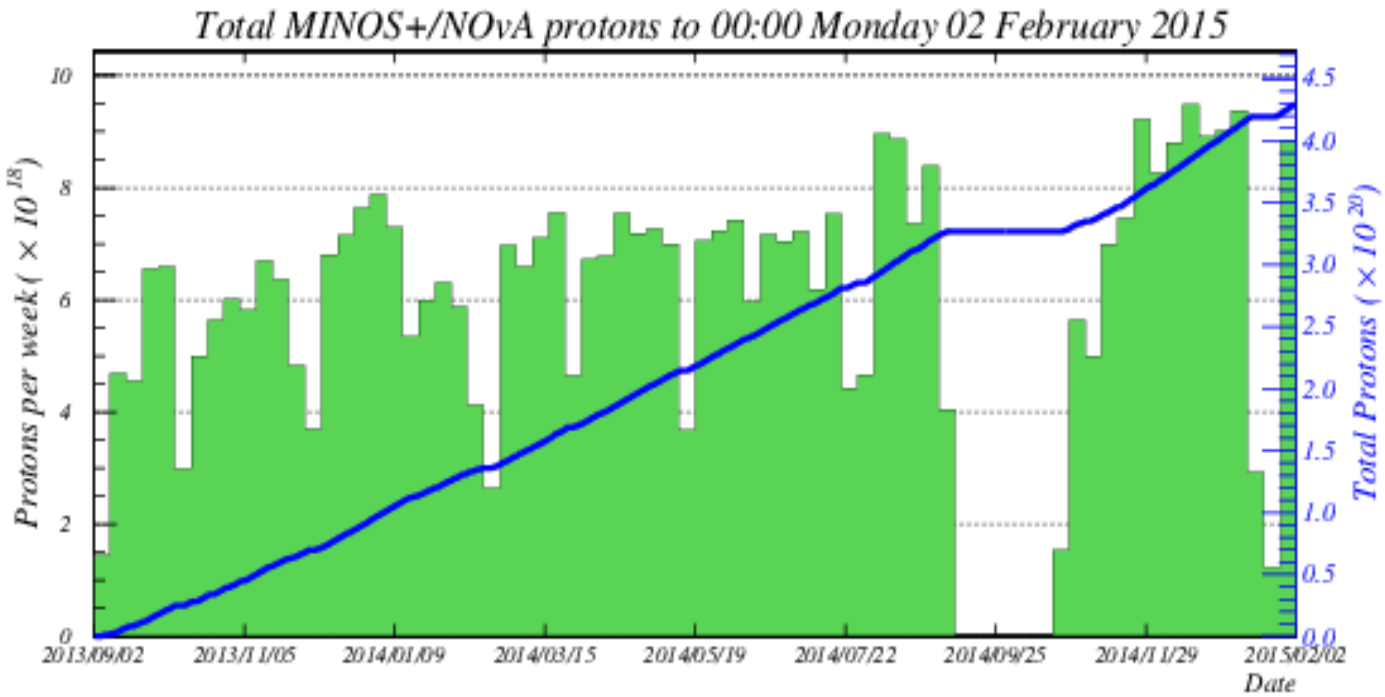
T2K antineutrino (0.5e20 in can)

MINERvA Medium Energy

NuMI running in ME era

- 4.28e20 POT since restart: MINERvA, MINOS+ & NOvA
  - > Reduced cycle time from 1.9s to 1.3s
  - > Ramping to design intensity by end of 2015
- As of 2/2/2015 NuMI cumulative exceeded 2e21 POT



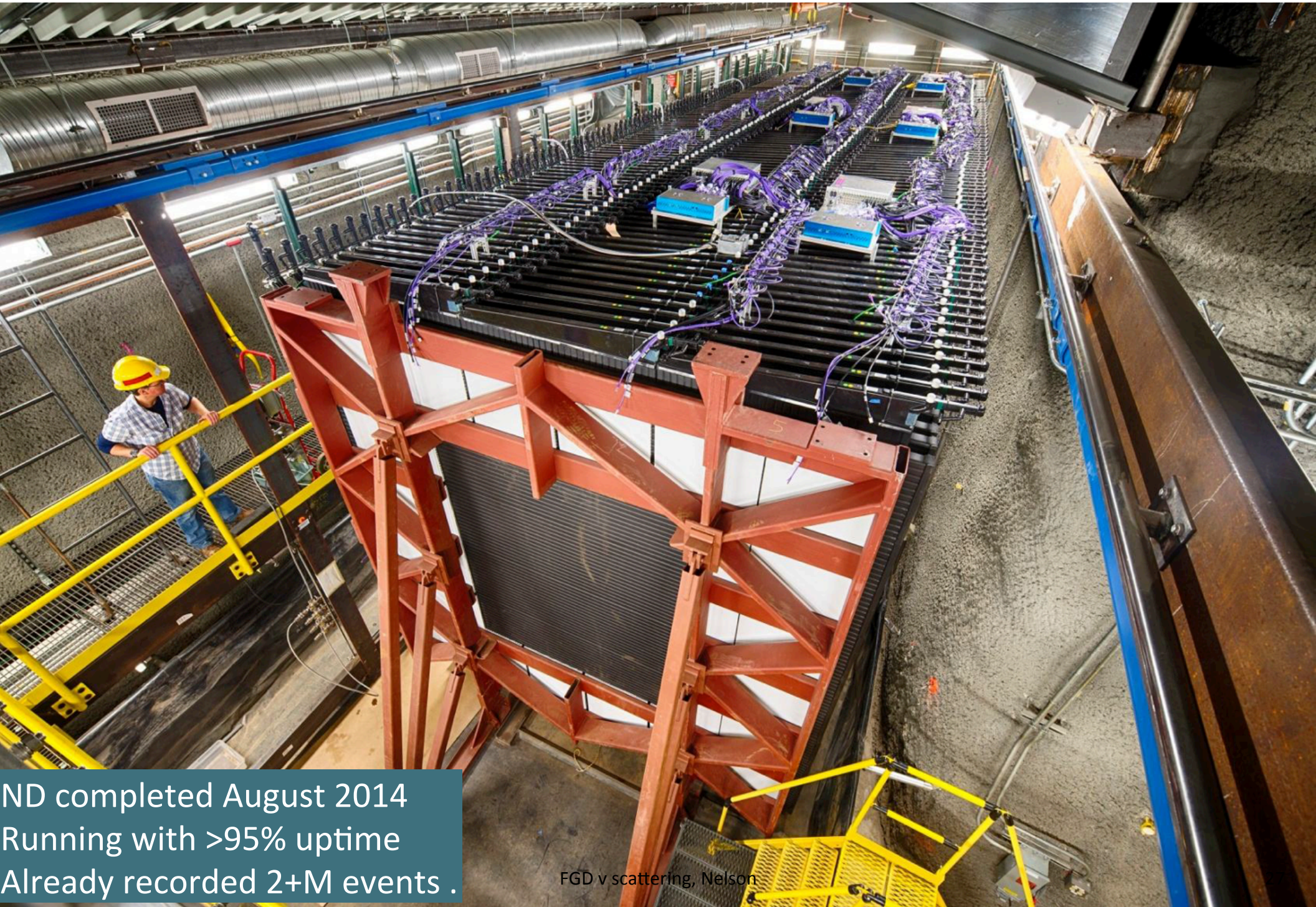


A. Sousa, Neutrino2014

[c.f. W. Flanagan today]

[c.f. C. Backhouse today]

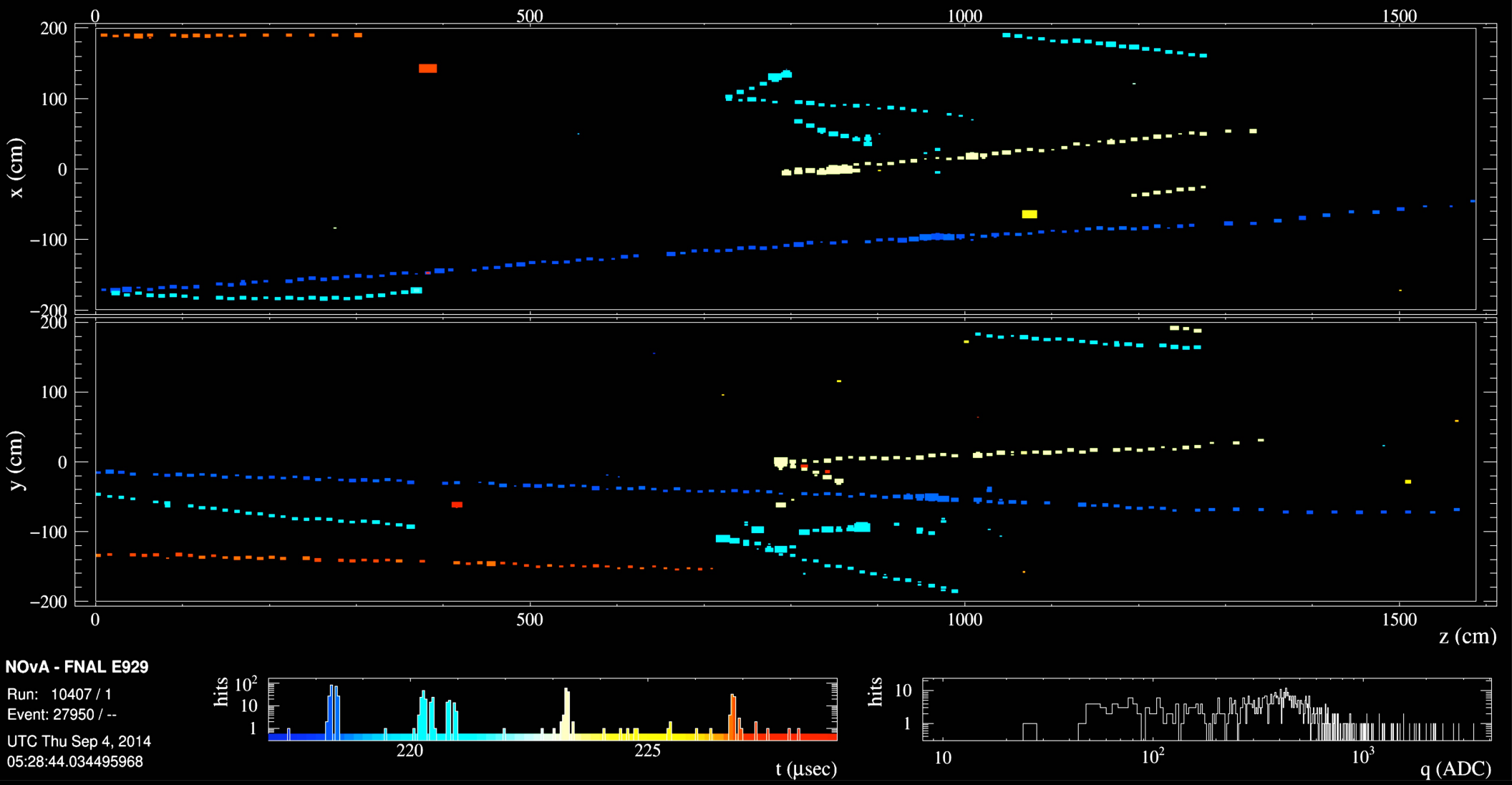
NOvA Near Detector



ND completed August 2014
Running with >95% uptime
Already recorded 2+M events .

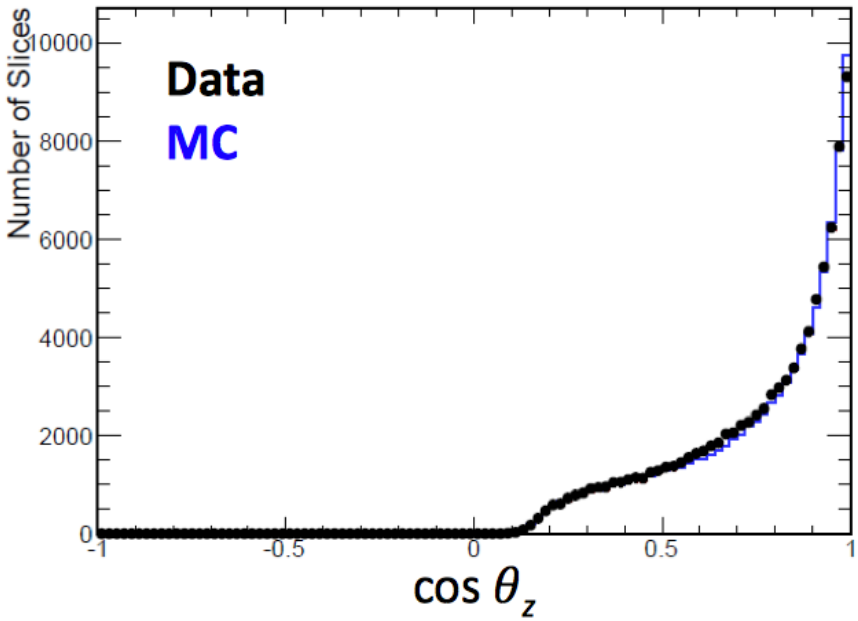
FGD ν scattering, Nelson

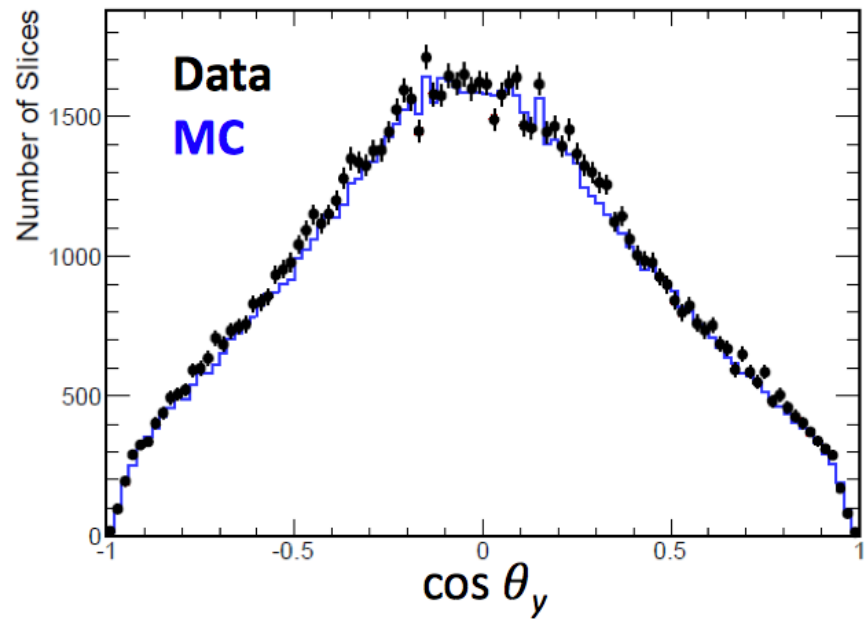
Near Detector Event Display

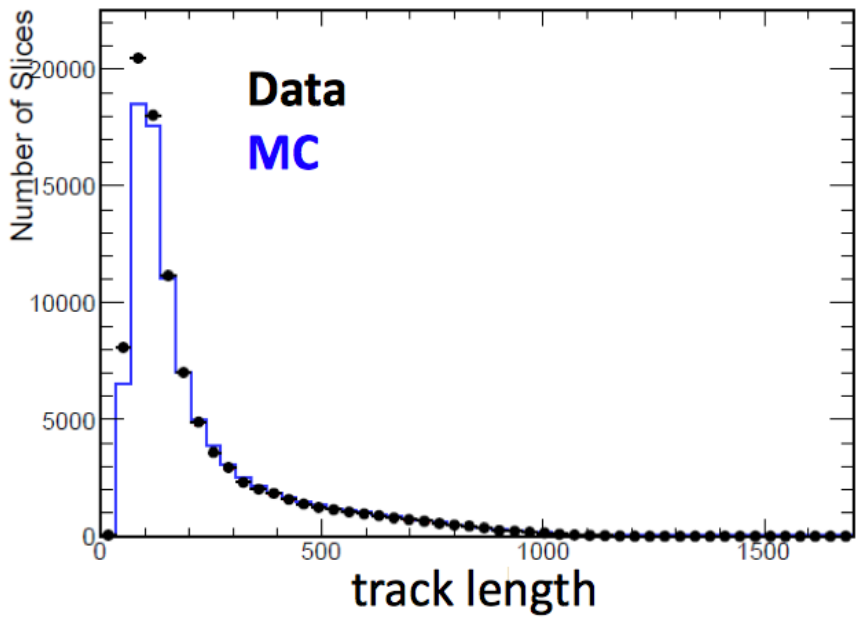


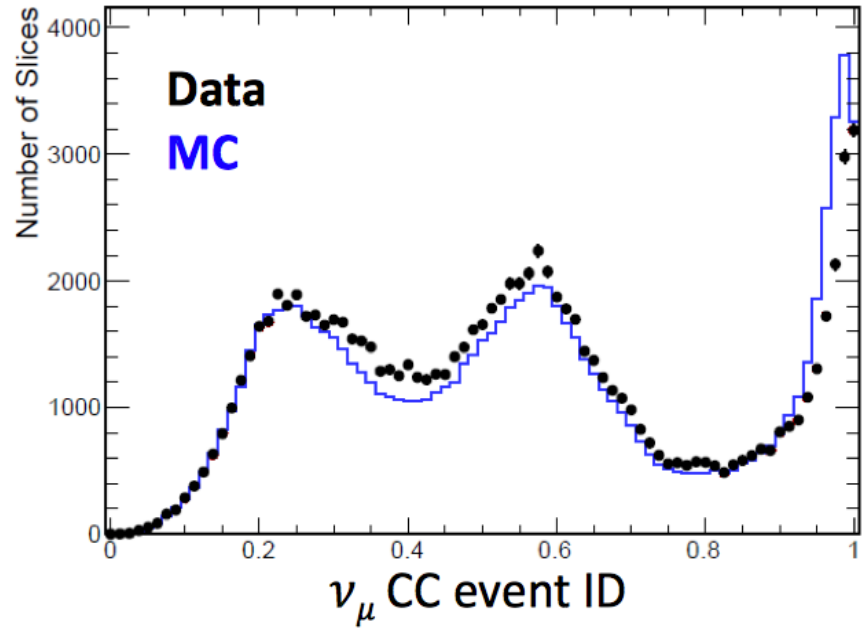
5 neutrino events in a spill separated in space and time

Near Detector Data/MC Distributions

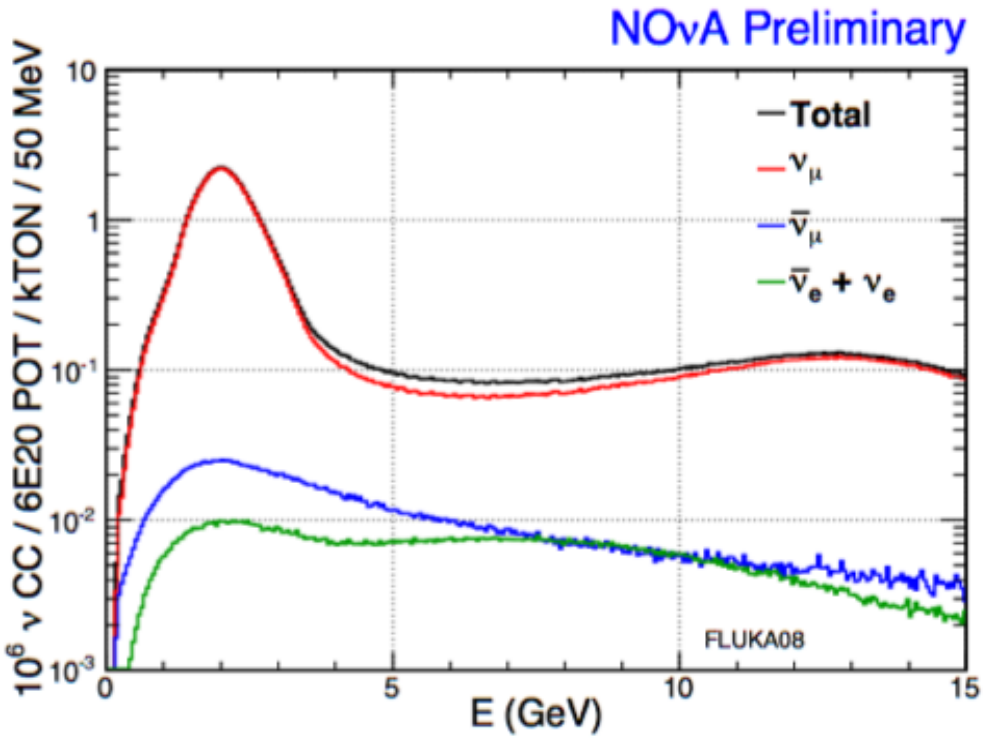


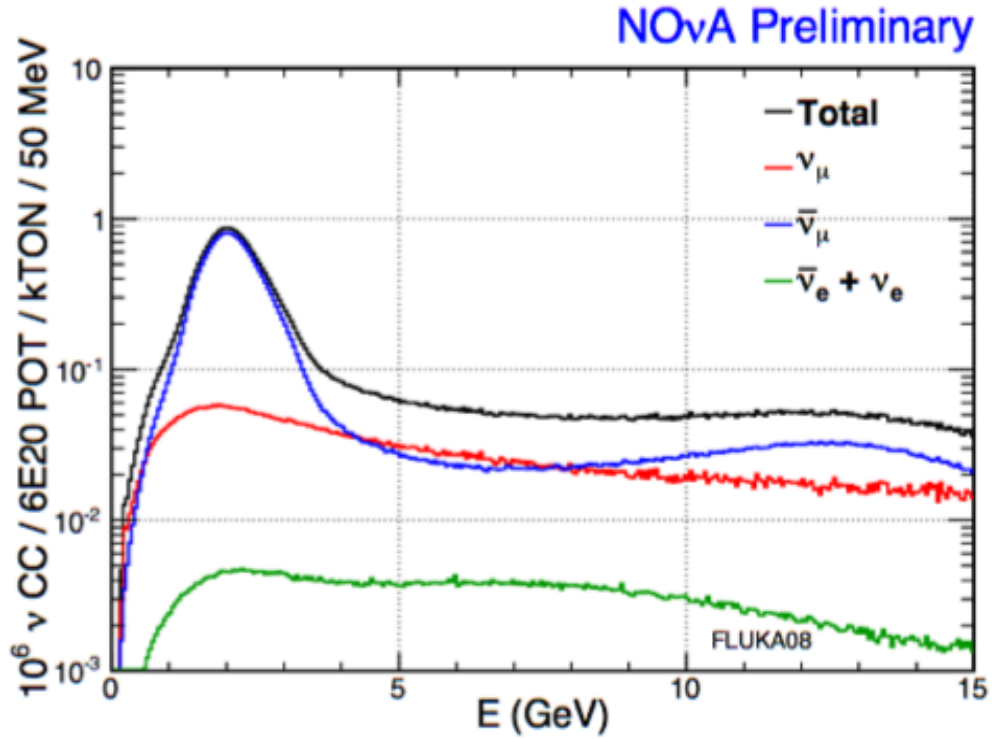






NOvA Near Detector
narrow-band beam, higher-energy



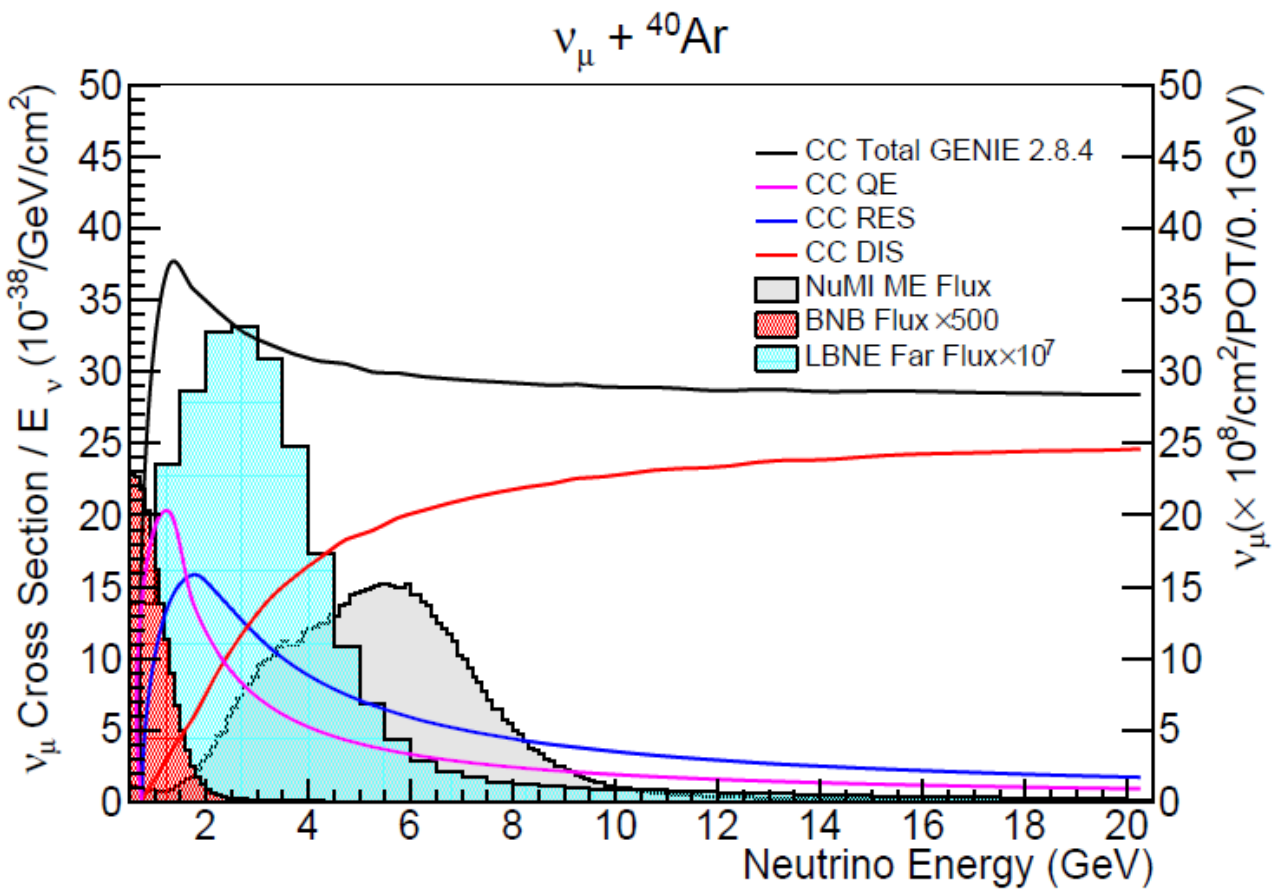


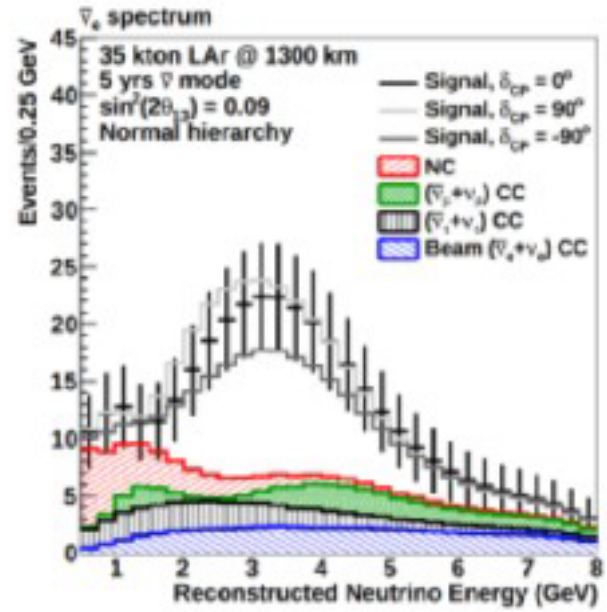
J. Paley, NuFact2013

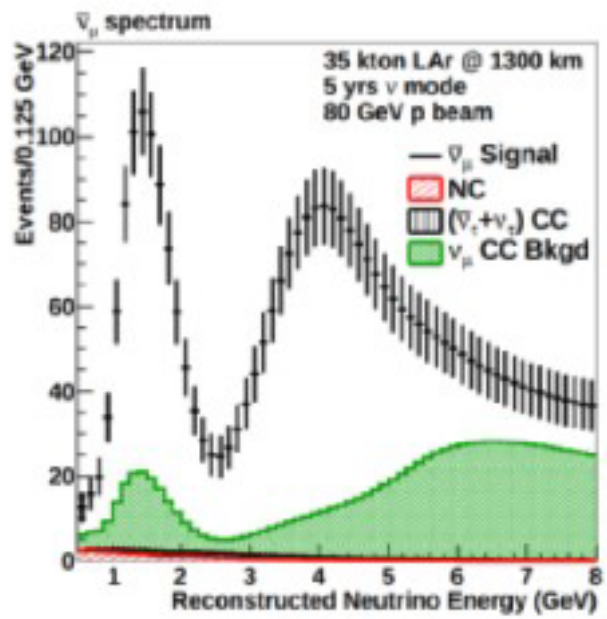
NOvA neutrino scattering program

- Program being defined in detail
- A very high statistics sample
  - > In the few months since ND completion have collected over 2M events
- Lots of interest within the collaboration
  - > QE, resonance production (charged & neutral pions), neutrino-electron scattering ++
- Narrow band beam above the T2K energies will allow detailed study of NC feed down
- Neutrinos now & future antineutrino running

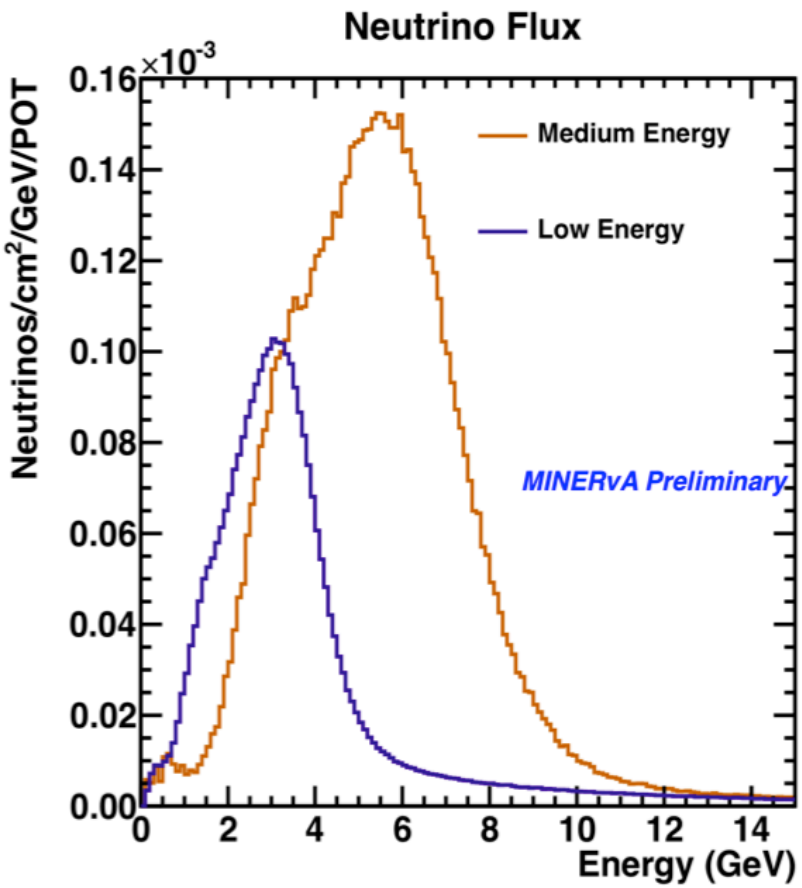
NuMI ME beam data (on and off axis) match first oscillations in LBNF







NuMI Medium Energy Neutrino Spectrum

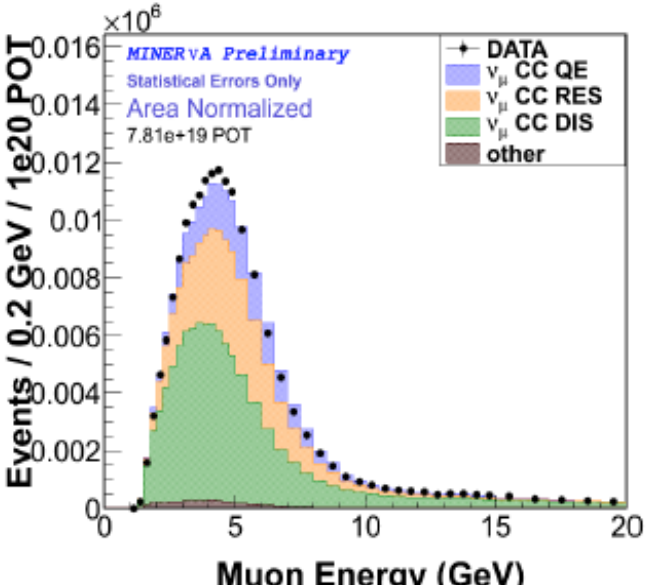


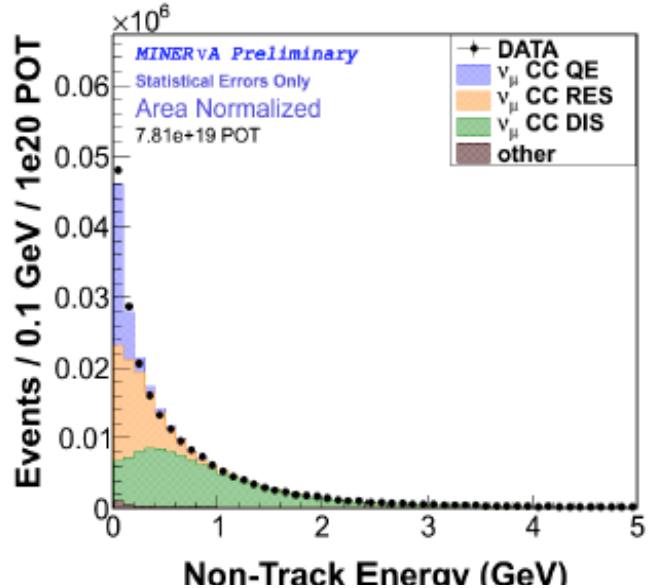
- MINERvA approved for 10e20 POT in ME neutrino running (40% in hand)
- 3.4 times more neutrino interactions per POT and a larger exposure
- MINERvA ME neutrino program represents a **ten-fold increase** in statistics

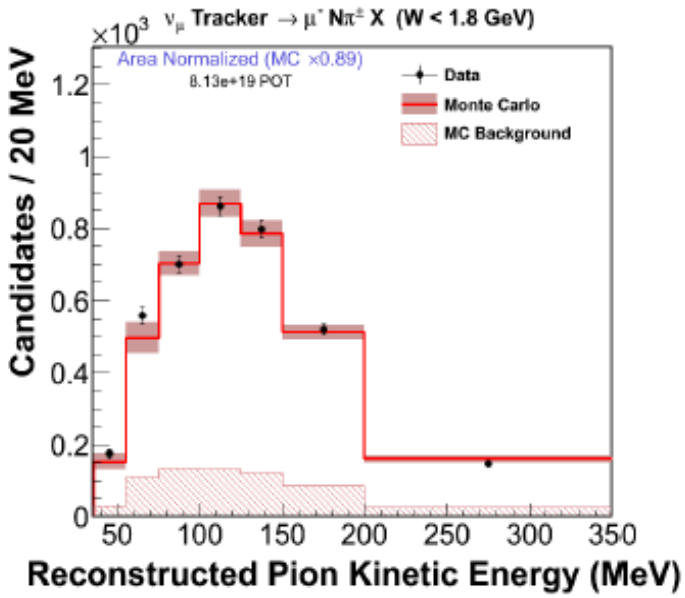
MINERvA in the Medium Energy Era:
Physics Program, Detector & Beamline Health

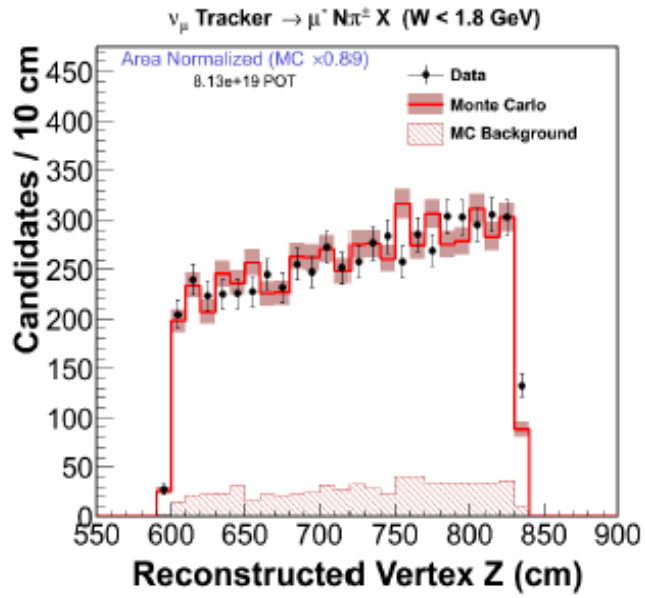
- Submitted to Fermilab PAC for the January 2015 meeting
- http://minerva-docdb.fnal.gov/cgi-bin/ShowDocument?docid=10568

ME data & MC : Demonstrating same level of reconstruction performance at these high intensities





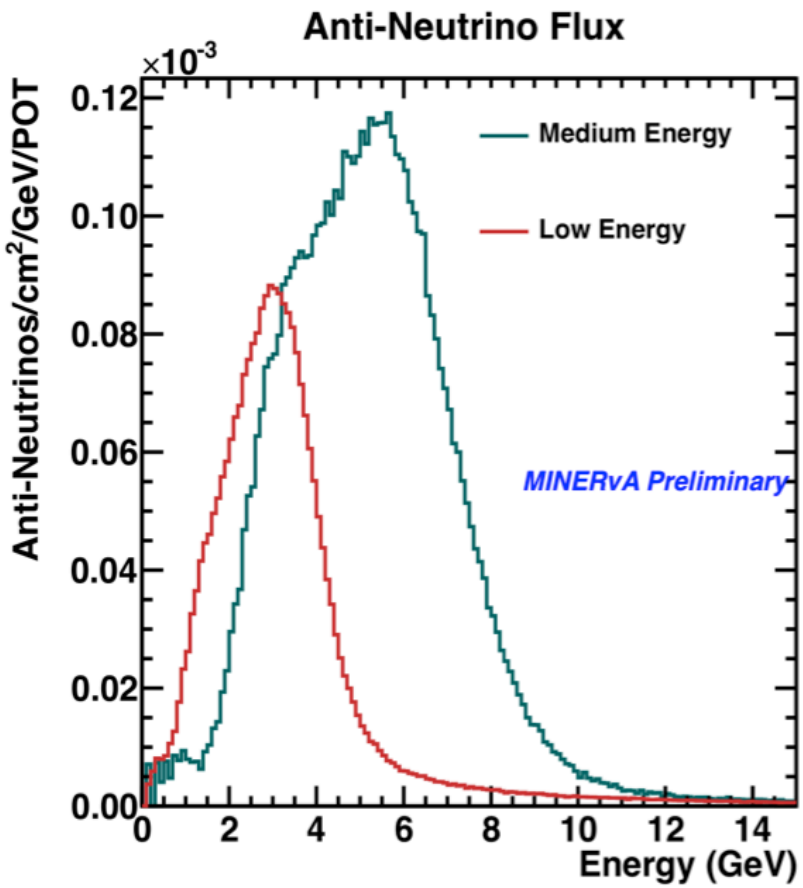




MINERvA Medium Energy Program

- The high statistics will allow detailed exclusive scattering studies in nuclear targets
  - Current MINERvA exclusives program largely focused on CH due to statistics
- Measurements on nuclei both lighter and heavier than those used to oscillation experiments can test the models of nuclear effects
  - Need detailed kinematics of the events because shape of the energy spectrum depends on the performance of your energy estimator, which ultimately depends on the mix states in your reconstructed channels
- Nuclear effects may be different between neutrinos & antineutrinos [slide]
  - Neutrinos and antineutrinos sample different quark flavors, a tool for measuring PDFs
  - Need to over-constrain the models to disentangle initial-state and final-state nuclear effects
  - Final-state interactions should nominally be identical between neutrinos and antineutrinos
  - Oscillation experiments will measure both probabilities to untangle CP violation and the mass hierarchy
- The MINERvA ME program also needs substantial antineutrino exposure

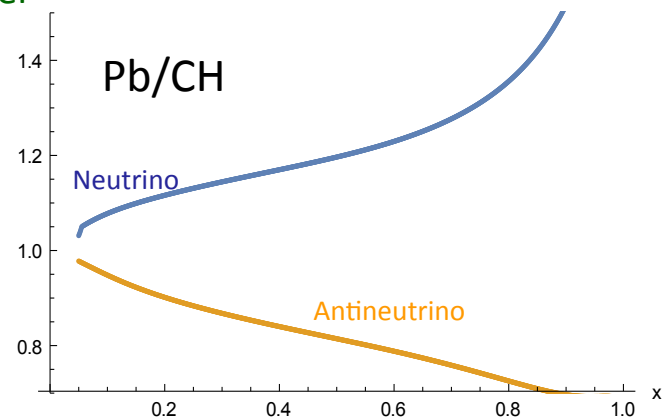
NuMI Medium Energy Antineutrino Spectrum



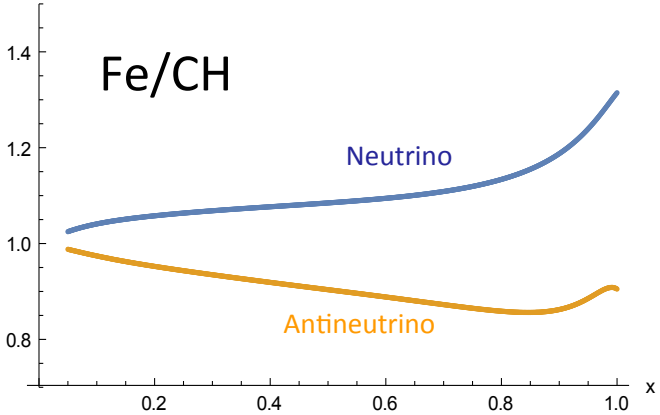
- MINERvA requests for 12e20 POT in ME antineutrino running
- 3.3 times more neutrino interactions per POT and a larger exposure
- The MINERvA ME program represents a **twenty-five times increase** in statistics
- The high statistics sample allow study of nuclear effects in antineutrinos

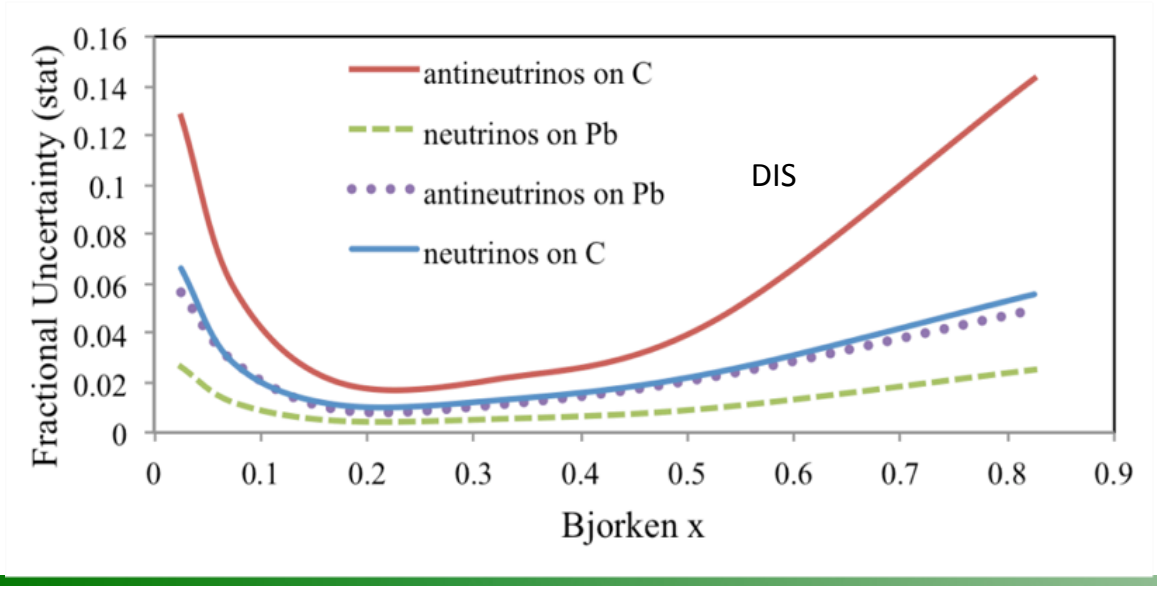
Flavor dependence and the EMC effect

- LE data has significant A-dependent surprises vs *x*
  - > Charged-leptons scattering data has informed our current models of nuclear effects
  - > Even in the precision charged-lepton world there is no universal model
- Studying both neutrino and antineutrino data offers a unique role in understanding this by probing the EMC effect in neutrinos
  - > 12E20POT in antineutrino mode allows MINERvA to map out the flavor dependence and test models
- MINERvA has shown DIS sample selection & good reconstruction of scaling variable x
  - > LE analysis shows we get to few percent systematic uncertainties in inclusive cross section ratios for neutrinos



DIS cross-section ratios vs x





I. C. Cloet, W. Bentz, A. W. Thomas, PRL 109, 182301
I. C. Cloet, private communication

Intermediate program: proposed

CAPTAIN-MINERvA

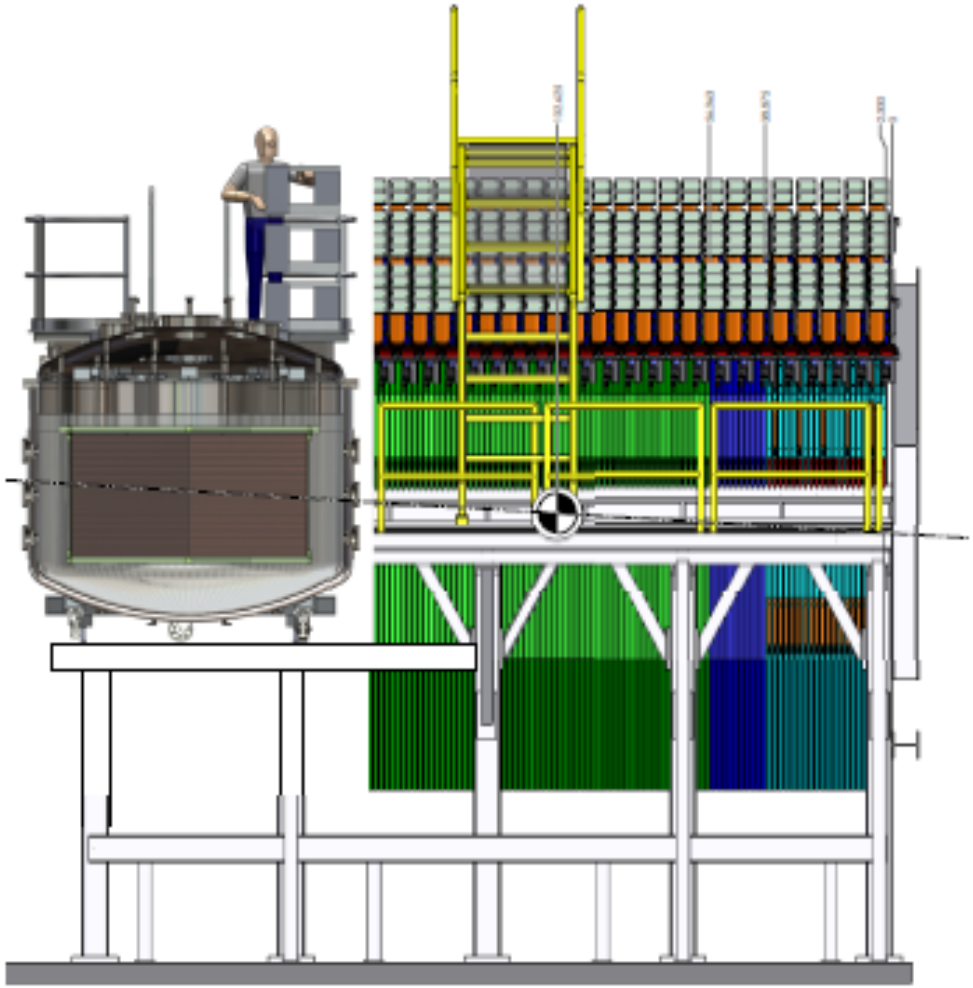
CAPTAIN-MINERvA: Neutrino-Argon Scattering in NuMI Medium-Energy Beam

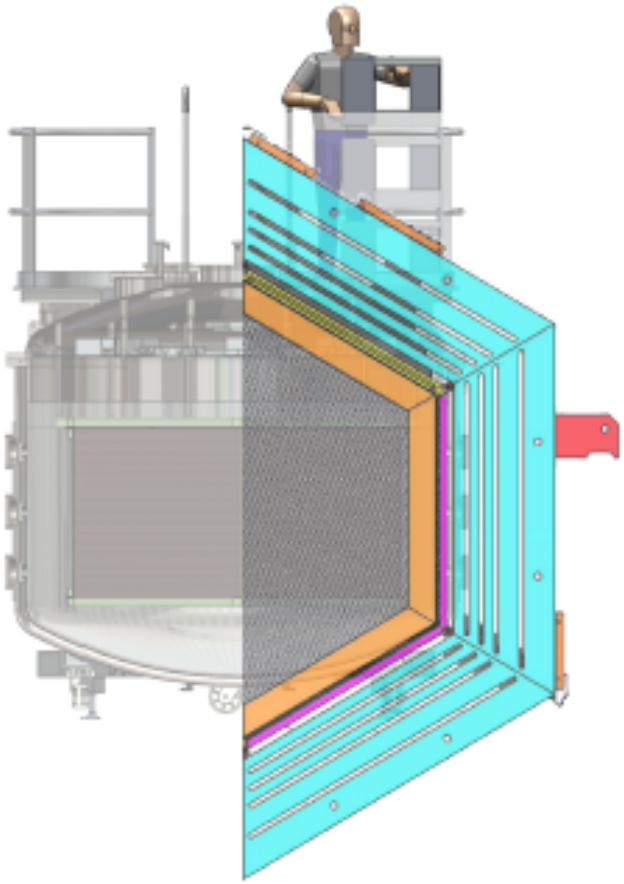
- LOI submitted to FNAL PAC for the January 2015 meeting
- MINERvA note 10576

  http://minerva-docdb.fnal.gov/cgi-bin/ShowDocument?docid=10576
- Presented by L. Whitehead on behalf of the CAPTAIN and MINERvA collaborations
- Allows simultaneous Ar and CH cross section measurement in same detector at few GeV
  - > Critical for modeling LBNE's FG ND to Ar FD

[c.f. C. Mauger]

CAPTAIN-MINERvA





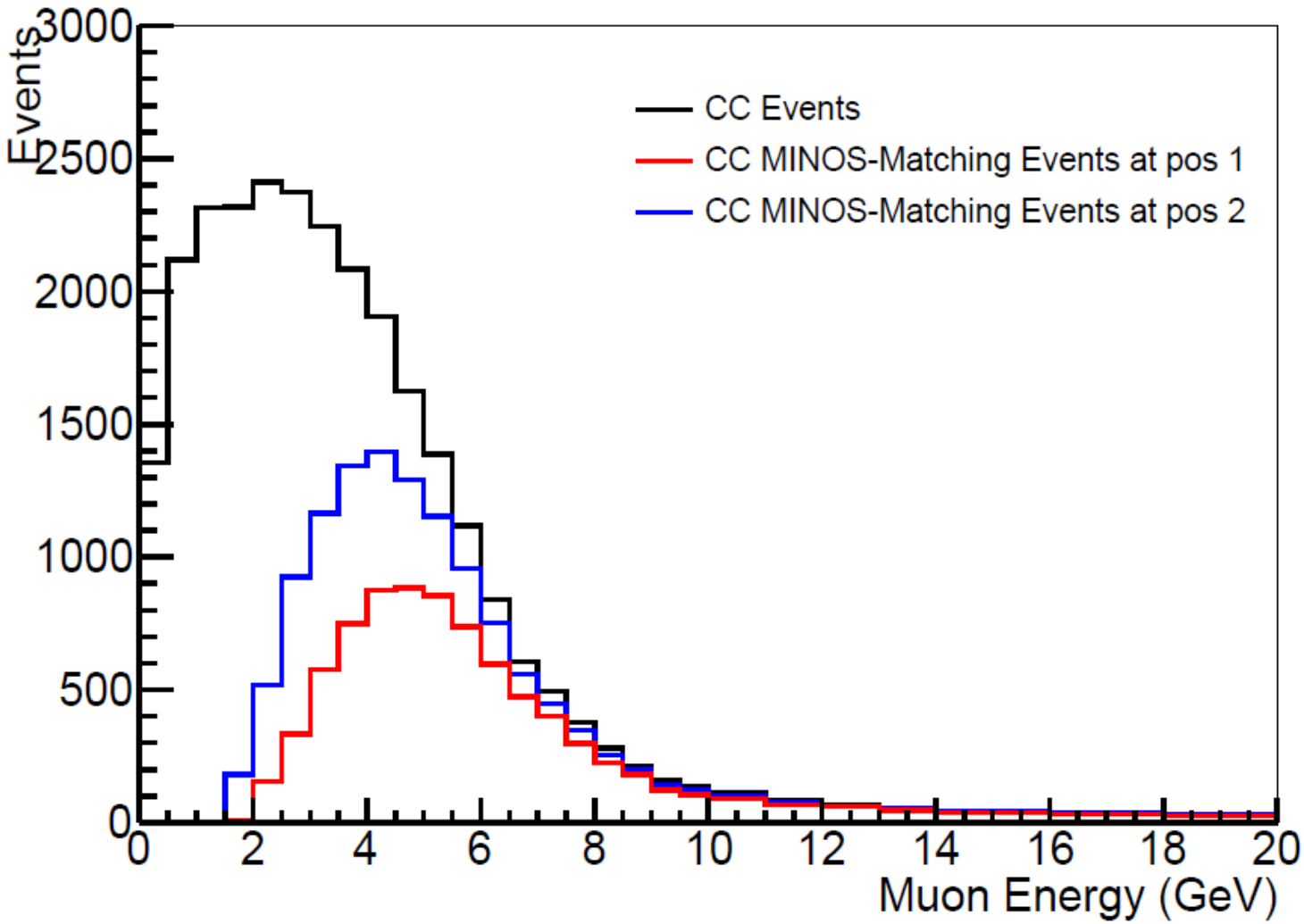
CAPTAIN-MINERvA
Event rates

Contained events (all outgoing particles except neutrons and leptons contained within CAPTAIN) efficiency is 25%

	Contained Events in CAPTAIN	Contained Events in CAPTAIN at pos 1 w/MINOS Match	Contained Events in CAPTAIN at pos 2 w/MINOS Match
CCQE-like	488,250	255,354	339,333
$CC1\pi^{\pm}$	191,250	59,478	88,930
$CC1\pi^{0}$	189,000	48,384	76,167

Table 1: Contained efficiency for CC events with a reconstructed muon using MINOS ND, assuming 6×10^{20} POT exposure.

CAPTAIN-MINERvA
Muon Acceptance in MINOS ND



From PAC presentation:

- The CAPTAIN and MINERvA collaborations share a core goal: to study neutrino interactions important for the future long-baseline program
- CAPTAIN-MINERvA is a joint proposal from both collaborations to study neutrino-argon interactions in the medium-energy NuMI beam
- Unique and complementary to existing LAr R&D
- The necessary preparations for the MINOS ND hall would need to begin soon to be ready for data-taking as early as 2016

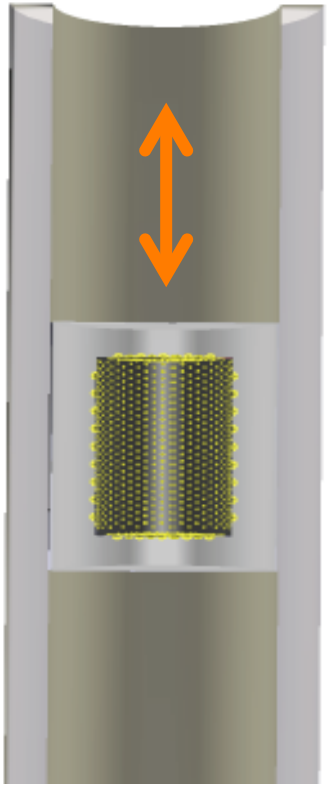
Beyond Intermediate

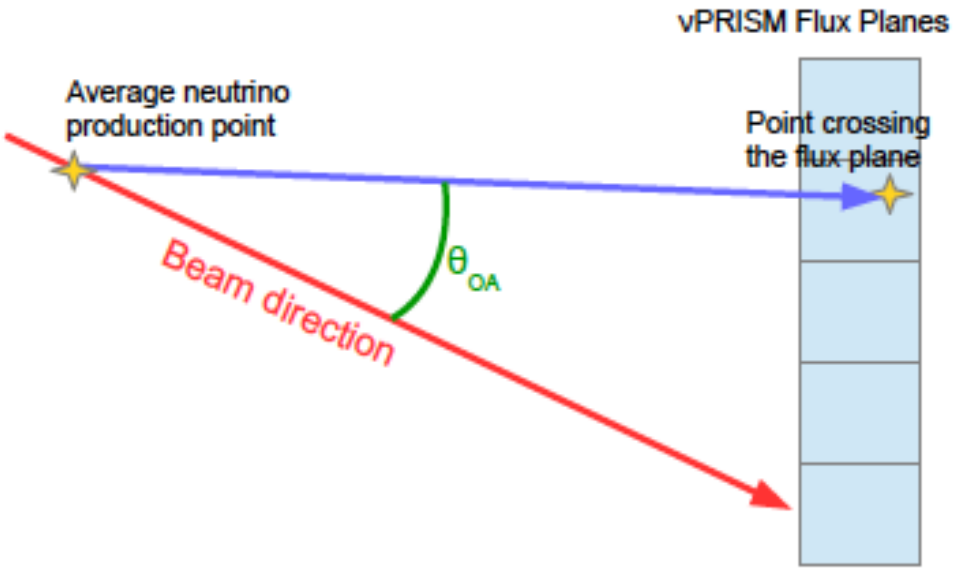
nuPRISM

LBNE ND

nuPRISM

- Concept:
  - > A movable near detector in a column (e.g. at JPARC to HK)
  - > A near-axis location
  - > Range of off-axis positions
  - > Subtract these spectra



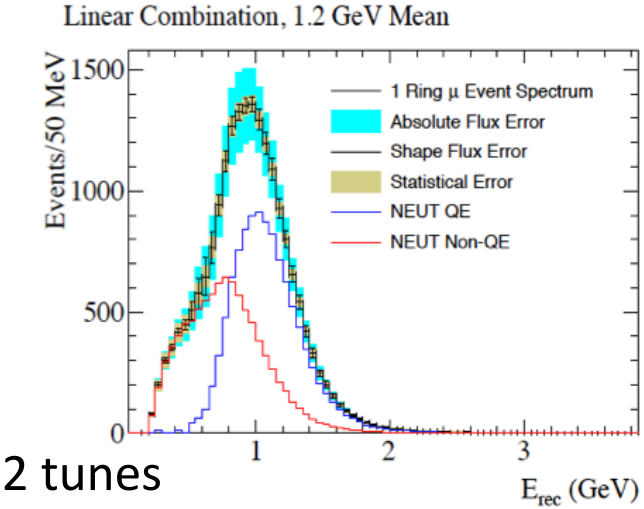


[c.f. M. Wilking today]

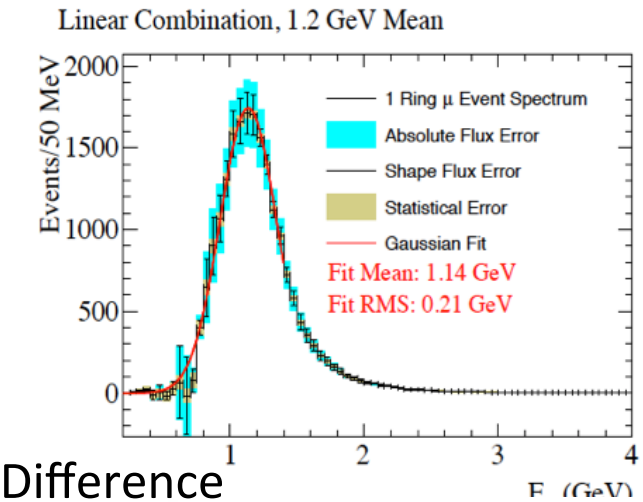
arXiv:1412.3086

nuPRISM

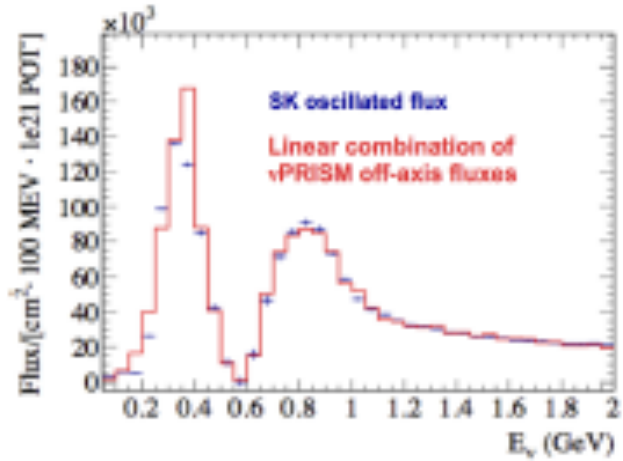
- Synthetic ultra-narrow-band beam
  - > Range of off-axis positions
  - > Subtract these spectra
  - > Can get better than 0.12% RMS in some locations
- Would enable systematic studies
  - > Energy dependencies
  - > Energy biases
    - Especially useful in SK-like detectors



2 tunes



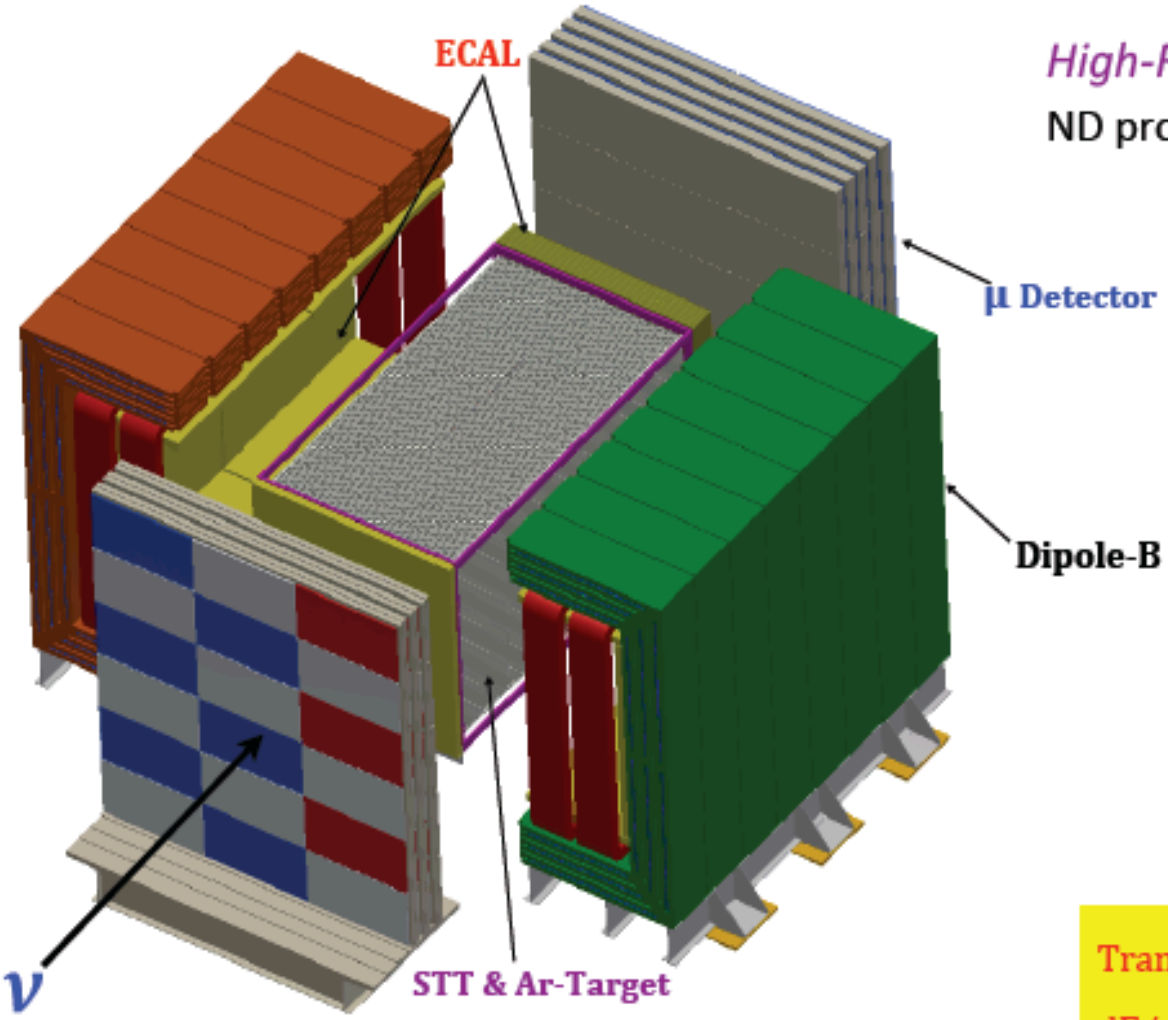
Difference



Synthetic oscillated spectrum

arXiv:1412.3086

LBNE fine-grain tracker ND concept



High-Resolution Fine Grain Tracker:
ND proposed by the *LBNE-India Group*

- ~3.5m x 3.5m x 7m STT ($\rho \simeq 0.1 gm/cm^3$)
- 4π-ECAL in a Dipole-B-Field (0.4T)
- 4π-μ-Detector (RPC) in Dipole and Downstream
- Pressurized Ar-target (≃x5 FD-Stat) ⇒ *LAr-FD*

Transition Radiation ⇒ $e^{+/-}$ ID ⇒ γ
dE/dx ⇒ Proton, $\pi^{+/-}$, $K^{+/-}$
Magnet/Muon Detector ⇒ $\mu^{+/-}$ $e^{+/-}$
(⇒ *Absolute Flux measurement*)

Current LBNE collaboration ND concept

- A fine-grained detector with excellent resolution in a very intense beam
  - > Low density
  - > Excellent particle ID
- Not based on an Argon target
  - > Need to extrapolation from lighter nuclei to Ar
  - > Makes the goals of Captain-MINERvA central to generator validation

Summary

- There is an intense stream of results coming from the current FGD scattering experiments
  - New initiatives coming online & current ones with more intense beams
  - Many more coming based on datasets in hand and those currently being collected
- Confronting both prior low-energy data and theoretical models with differential distributions, better detectors, and better understood beams
  - There are discrepancies with these models and prior data
  - Model errors lead to uncertain energy reconstruction and background systematics
  - Their nuclear dependencies must be understood to fully exploit our investments in the current and next-generation long-baseline experiments
- The results of combined FG and LAr scattering programs will be…
  - Better generators (models)
  - Lower systematics for current generation and next generation long-baseline experiments

Final thought

- Given the investment in the current experimental neutrino interaction program (esp. at FNAL), these collaborations should be supported so these data sets can be fully exploited
- Their conclusions will support the newly-initiated neutrino-scattering theory campaign and further the field's long term goals