Neutrino-nucleus scattering results from MINERvA, part 1

Jeff Nelson
William & Mary

NuFact2016
8/22/16

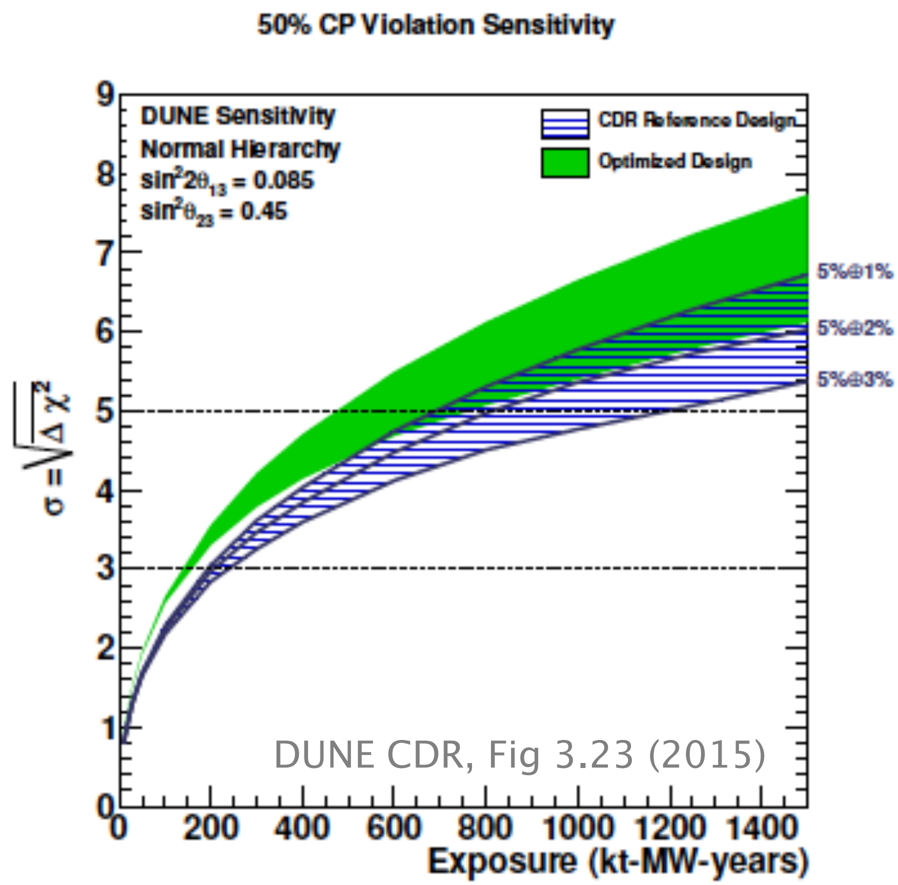
part 2 is Jorge's talk on Friday

Outline

- Goals of scattering for oscillations (i.e. why do I care?)
- Reminder of MINERvA
- Tools for precision cross sections
  - Benchmarking your detector
  - Benchmarking your flux
- MINERvA results (part 1 of 2)
  - Inclusive scattering
  - QE and QE-like scattering
  - Evidence for nuclear effects in low-recoil
  - Results on meson production and nuclear ratios will be covered in Jorge's talk in this WG on Friday
- Future plans
  - Prospects for the medium energy neutrino data set
  - Plans for additional antineutrino running

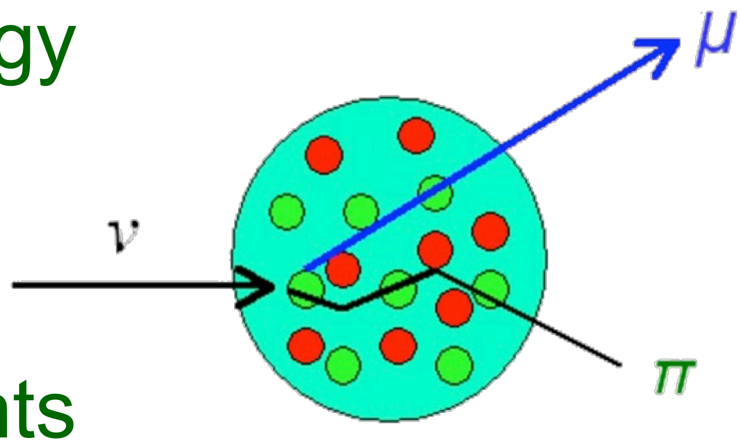
Goals of the long-baseline program

- 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



DUNE CDR, Fig 3.23 (2015)

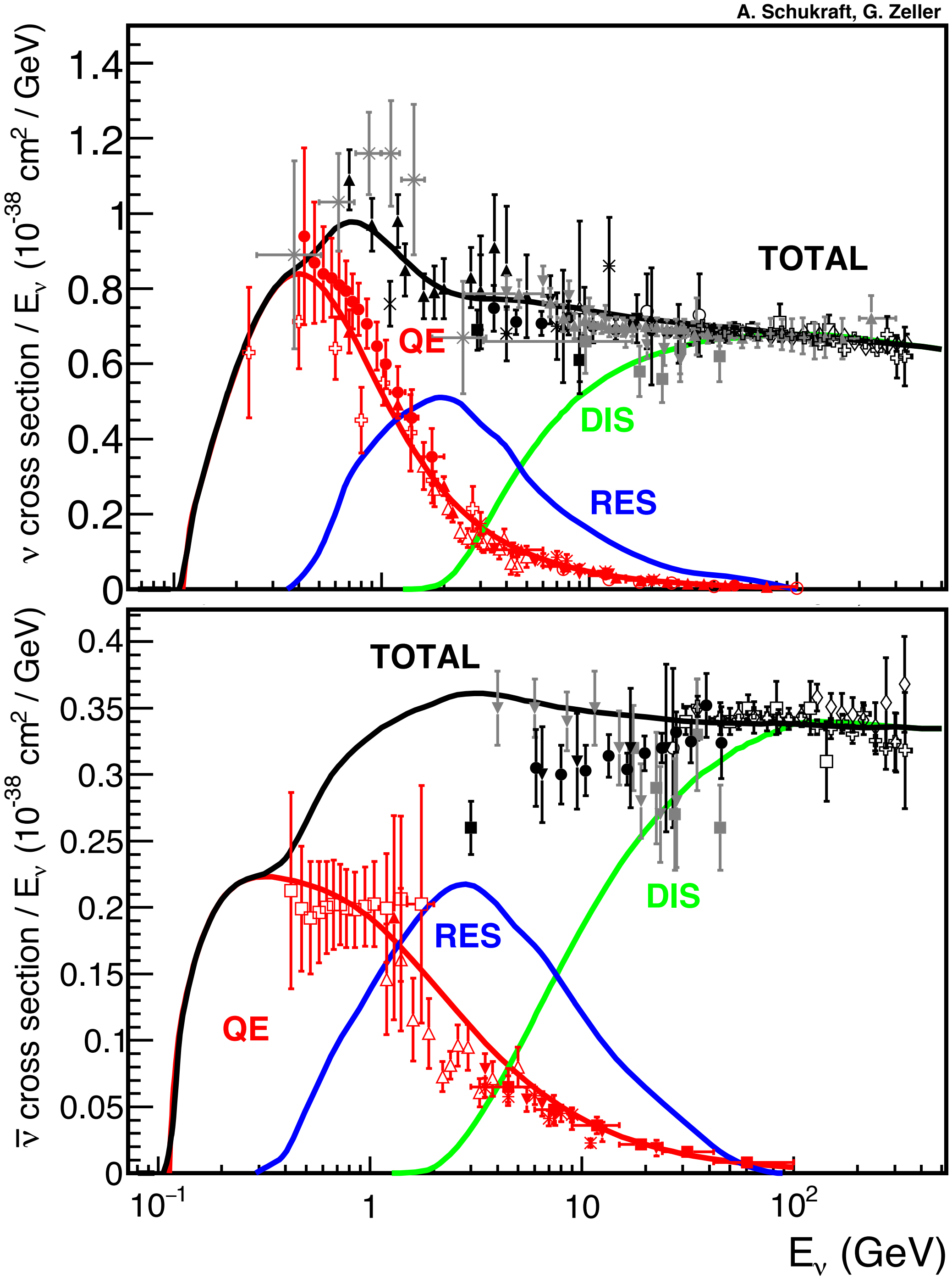
Neutrino interactions: why care?



- We need to estimate the energy of the incoming neutrino
  - > Different from the "visible" energy seen in the detector
- Neutrino oscillation experiments use nuclei as targets (e.g. O, C, Ar, Fe)
  - > This affects the visible energy …
  - > Motion of struck nucleon within nucleus
  - > Number of final state particles
    - We are not sensitive to their rest masses, binding energies
  - > Intra-nuclear absorption and scattering
  - > Nucleon itself is modified by the nucleus

State of scattering (ca. 2016)

- Final SPS and TeVatron results
  - > Tens GeV to hundreds of GeV
- Final results from MINOS
  - > Down into the many GeV region
- Final results from MiniBooNE, K2K, and SciBooNE
  - > All these are for E < ~1 GeV
  - > Dearth of antineutrino data starting to be addressed
- These days 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!!!



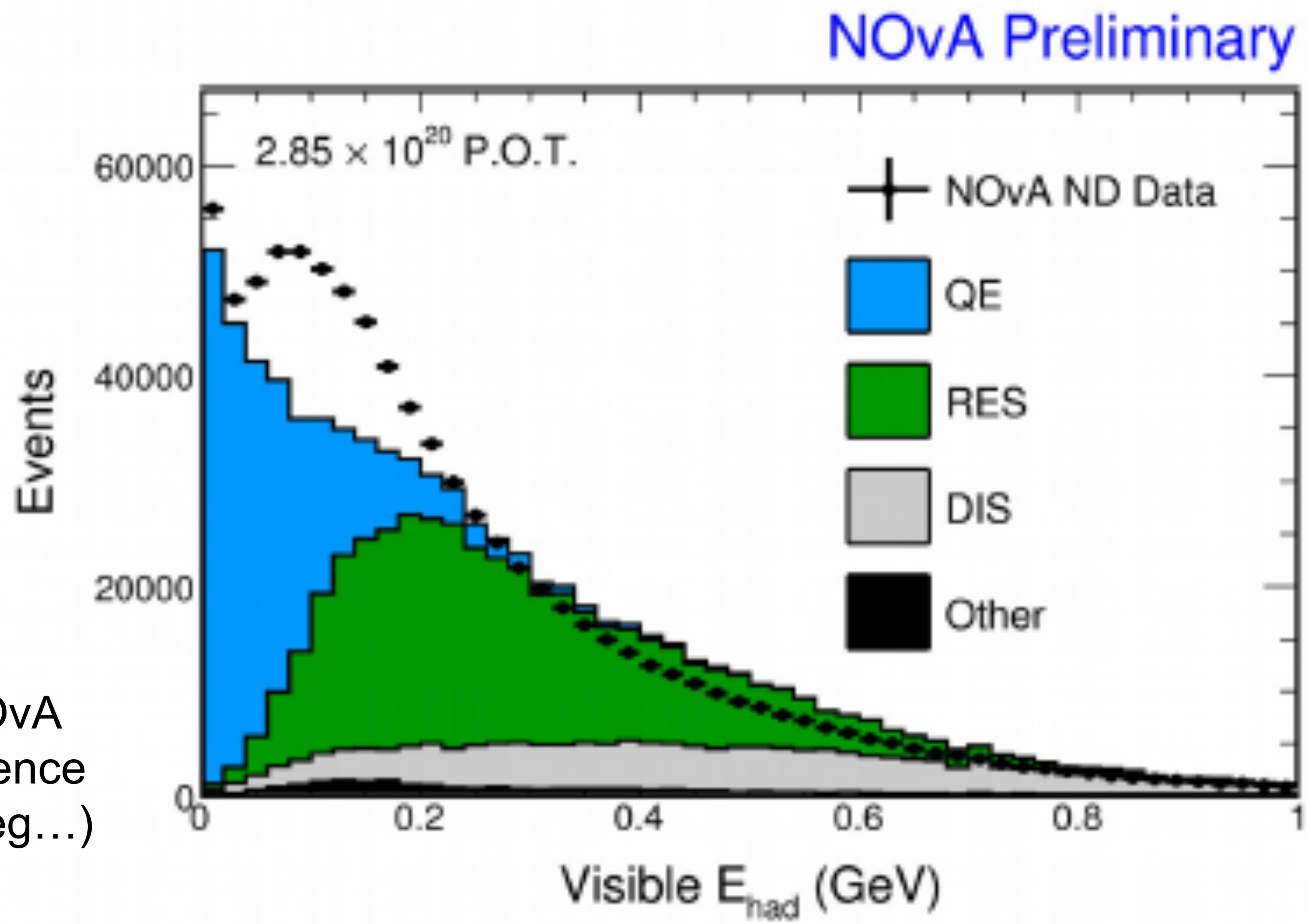
PDG2016 data summary

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 and models exist
  - > Some with fully specified final states
  - > Some only with computed physics distributions
- Central values for the generators are fits to scattering data

Examples of deficiencies: NOvA data and their data-driven modifications to GENIE



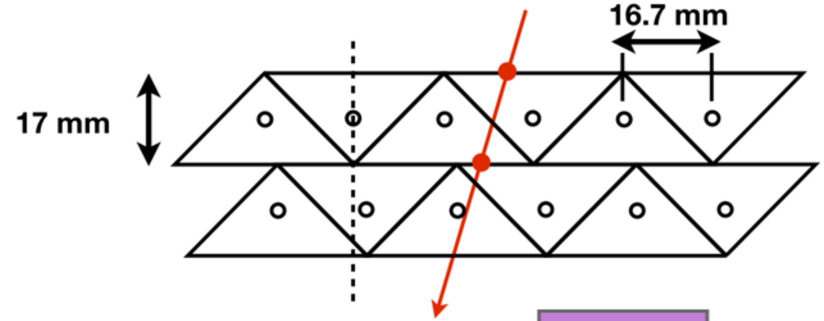
More from the NOvA talks at this conference (Chris, Jeremy, Greg…)

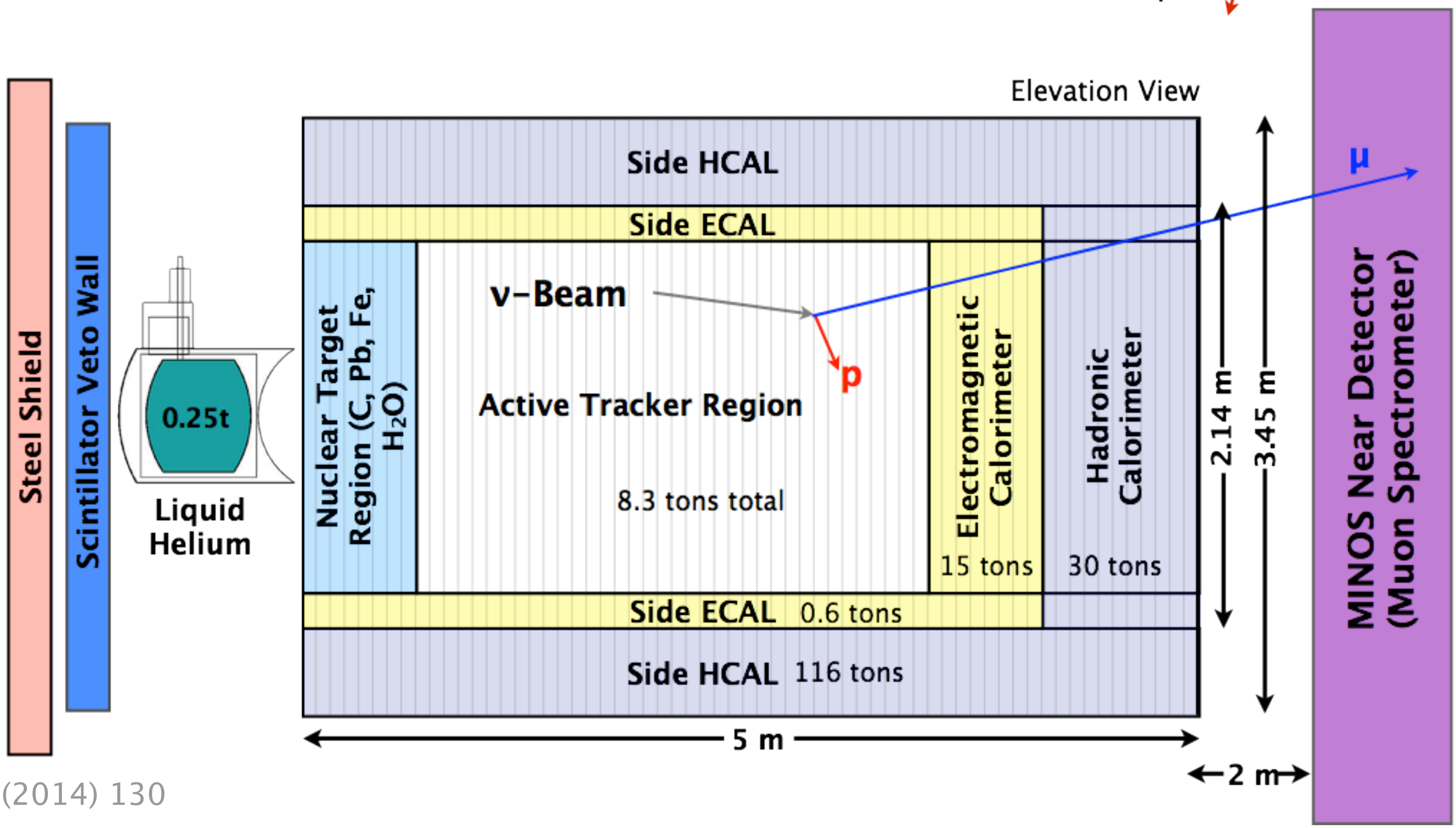
Debuted by P. L. Vahle at Neutrino2016

MINERvA and NuMI

MINERvA

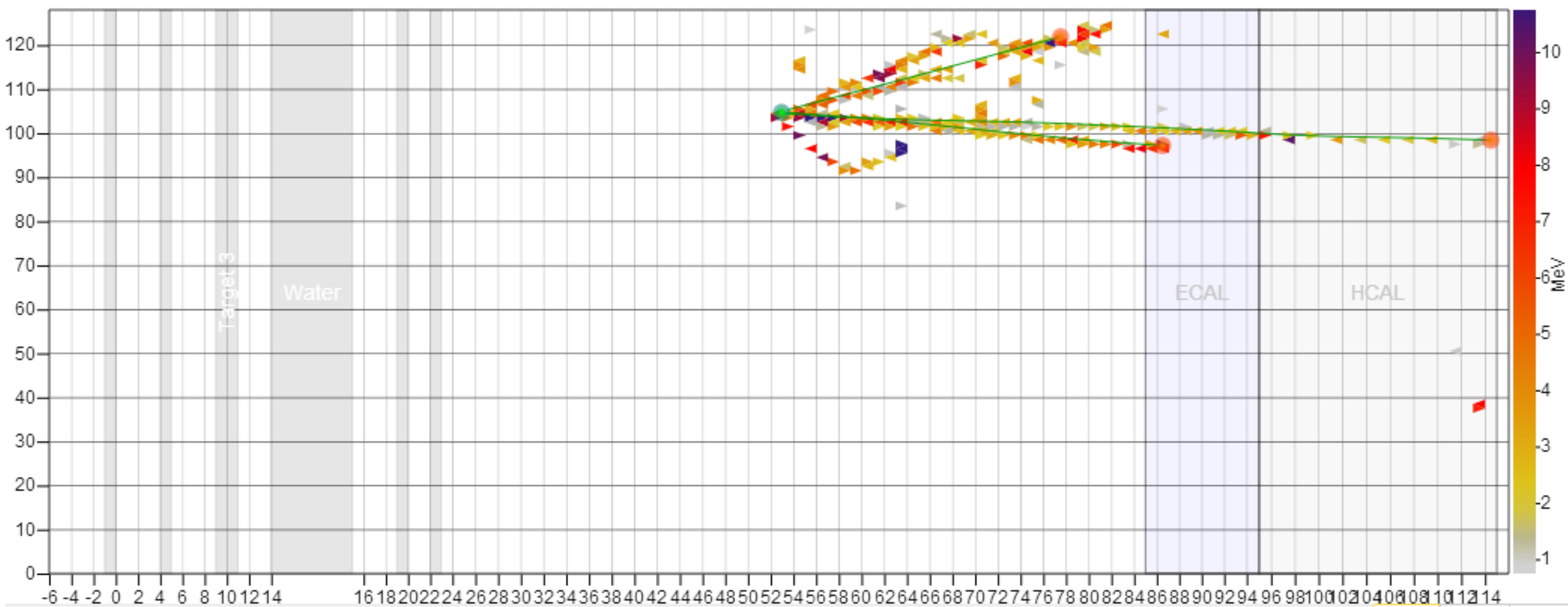
- Finely segmented solid scintillator (CH) detector on axis in NuMI
  - Active tracker is all scintillator
  - Calorimeters are scintillator w/ Fe or Pb
- MINOS detector for muon spectrometer



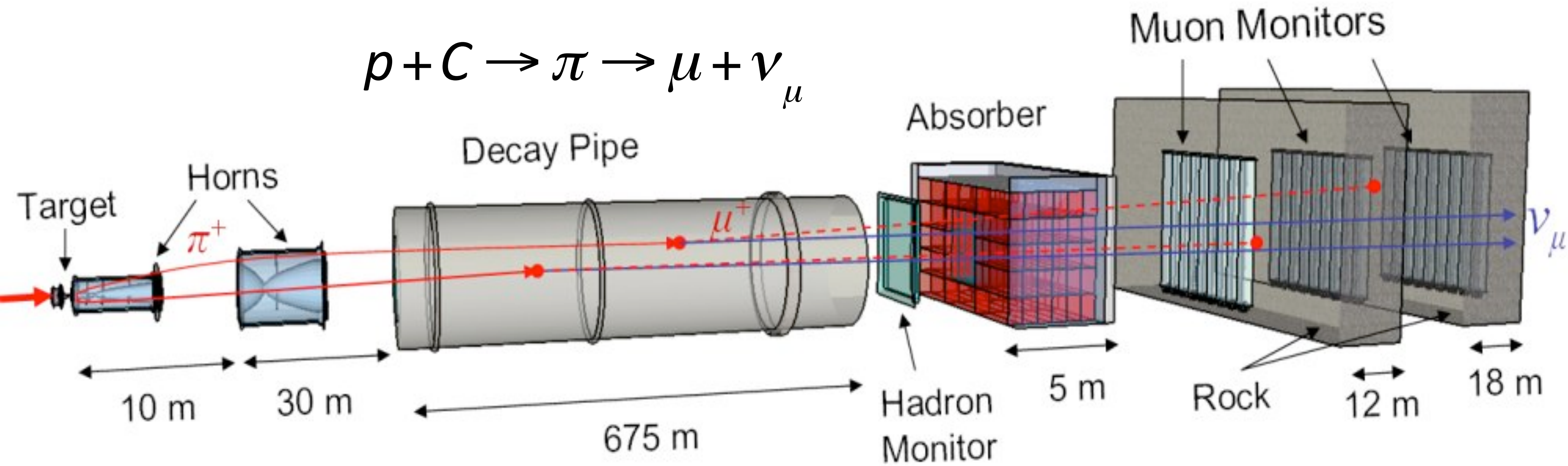


NIM A743 (2014) 130

A MINERvA data event



NuMI Neutrino Beam

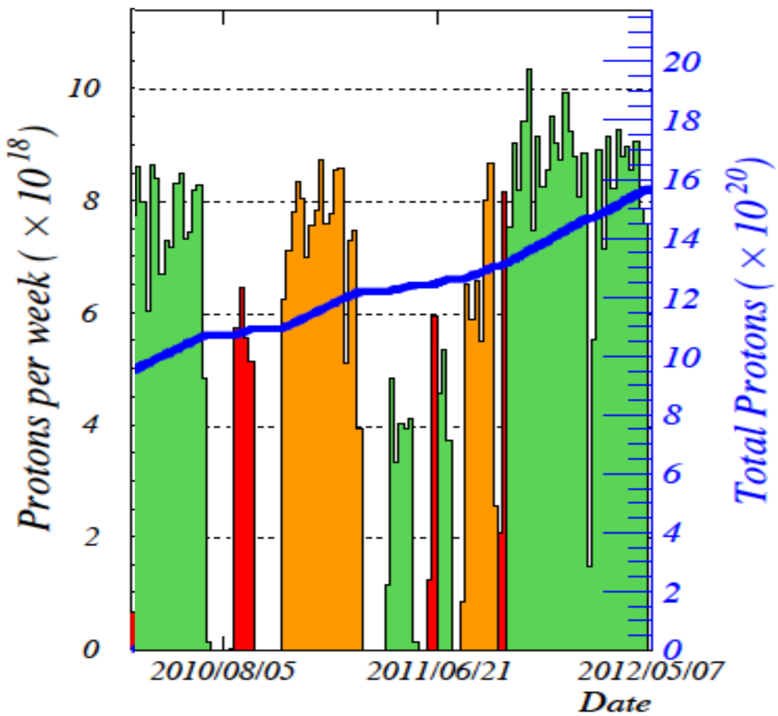


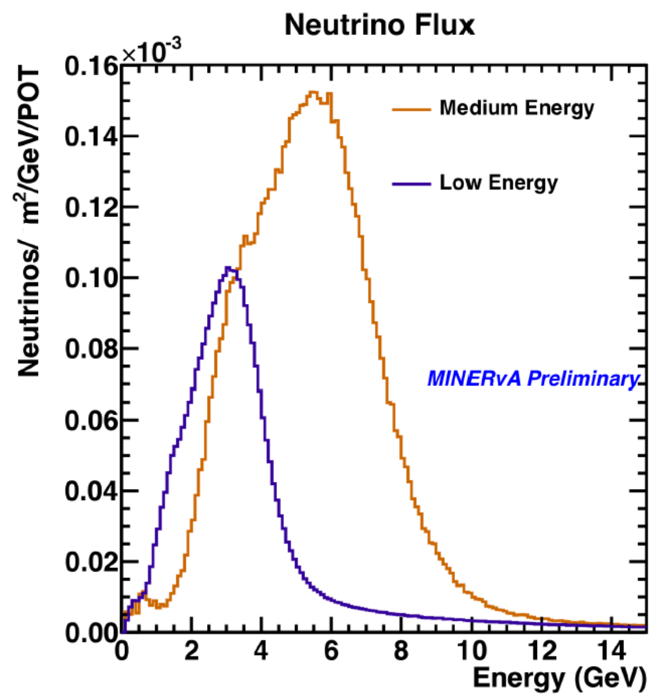
- 120 GeV protons impinge on a 2 interaction length graphite target
- Mesons are focused by 2 magnetic horns
- Beam composition selected by the polarity of the current in the horns
  - > Forward Horn Current (**FHC**) focuses π^+ creating a neutrino-enhanced beam
  - > Reverse Horn Current (**RHC**) 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

NIMA 806 (2016) 279

The data set

- NuMI low-energy tune (LE) data collected from 2010-2012
  - > **Antineutrinos** 1.09×10^{20} POT
  - > **Neutrinos** 3.18×10^{20} POT
  - > Main focus of this talk
- Since then we have been collecting data in NuMI's medium energy (ME) tune
  - > 1.1e21 POT in ME tunes
  - > More on this later



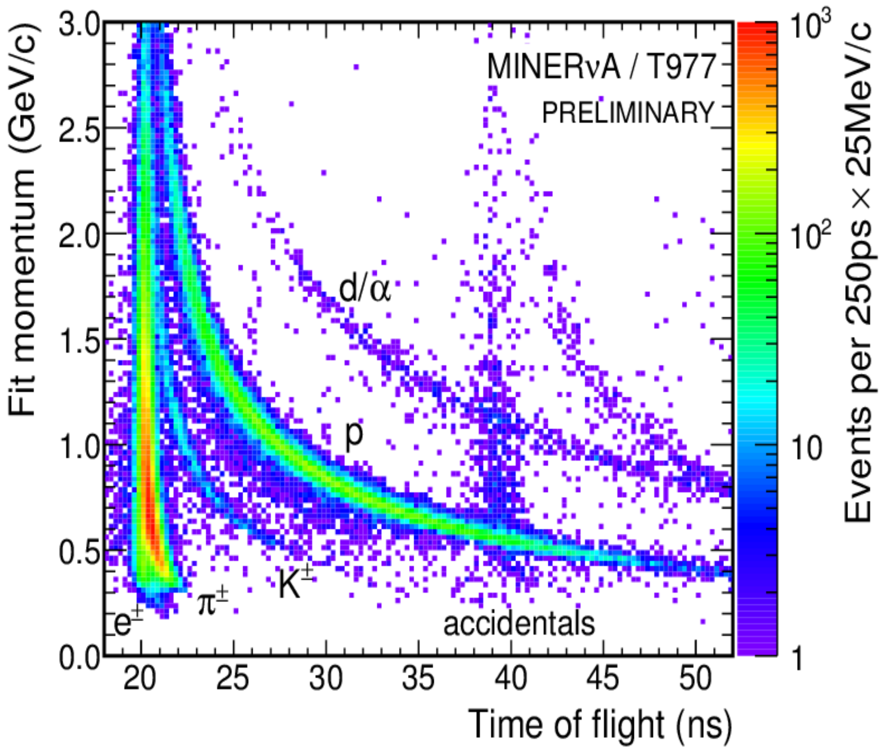


Benchmarking your detector

MINERvA test beam program

MINERvA test beam program

- Miniature version of the detector with configurable absorbers
- Tertiary beam for 350 MeV/c to 2 GeV/c (2010)
  - > Now in use (with upgrades) by LARIAT
- Secondary beam 2 GeV/s to 10 GeV/c (2015)
  - > Using the standard Fermilab test beam facility beam
- Magnetic analysis; Cherenkov and TOF systems for PID



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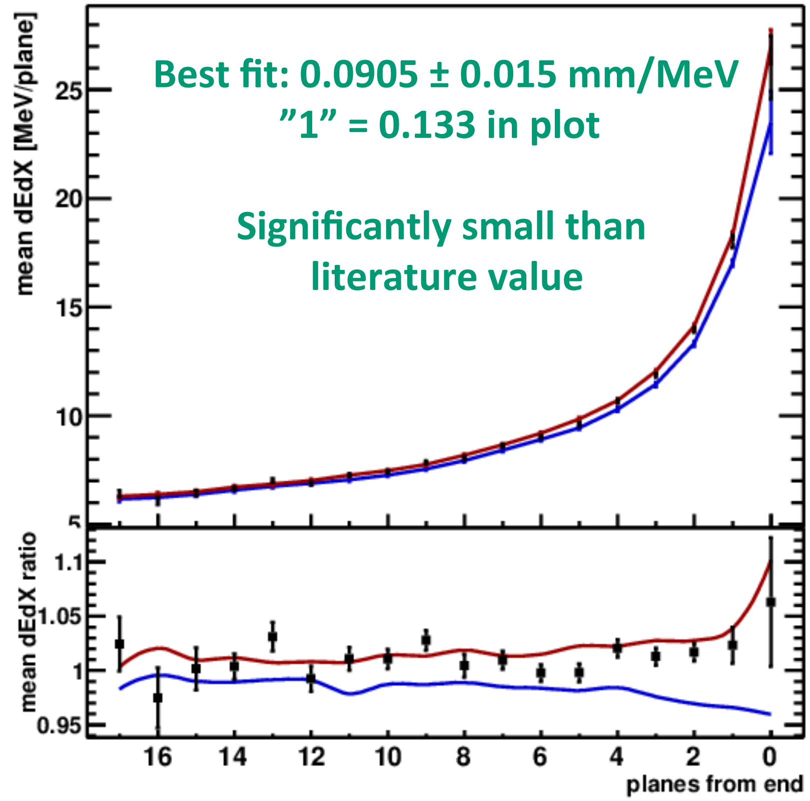
Key results from test beam program

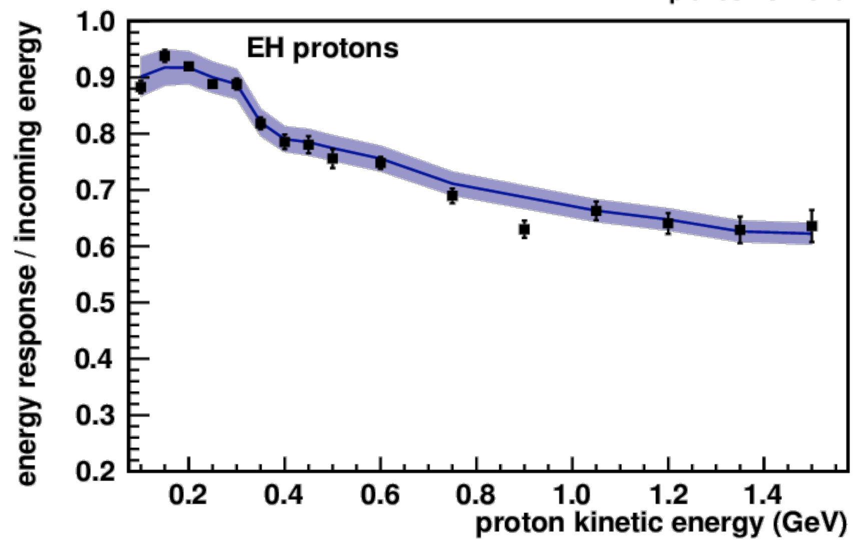
Test beam phase 1 (0.4 to 1.7 GeV/c)

- <2% systematics on beam momentum
- Optimization of the optical model
  - Esp. saturation calibration (Birk's constant)
- Proton energy scale and resolution modeled to the 3% level
- Pion energy scale and resolution modeled to the 4.5% level
- Electromagnetic energy scale modeled at the 3% level (also tested by neutral pion mass peak and Michel electrons)
- Tracking threshold modeled at the 1% level
- Mass model accurate to 2% level (via proton range)

Test beam phase 2 (2 to 10 GeV/c)

- In 2015 the collaboration collected more data at higher momenta
- Data calibration is underway along with preliminary analyzes





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Muon reconstruction

- Muon (for numu CC) are matched to a track in MINOS
  - > Imposes a 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
  - > 2% uncertainty on muon momentum from range due to mass model and dE/dx model in MINOS
  - > 0.6% uncertainty on muon momentum from curvature for momentum below 1.5GeV
    - Based on comparing magnetic field maps to magnetic induction measurements
    - Based on comparisons between range and curvature for tracks and deflection of stopping tracks in MINOS in data/MC
    - Added in quadrature to range uncertainty

NIM A743 (2014) 130

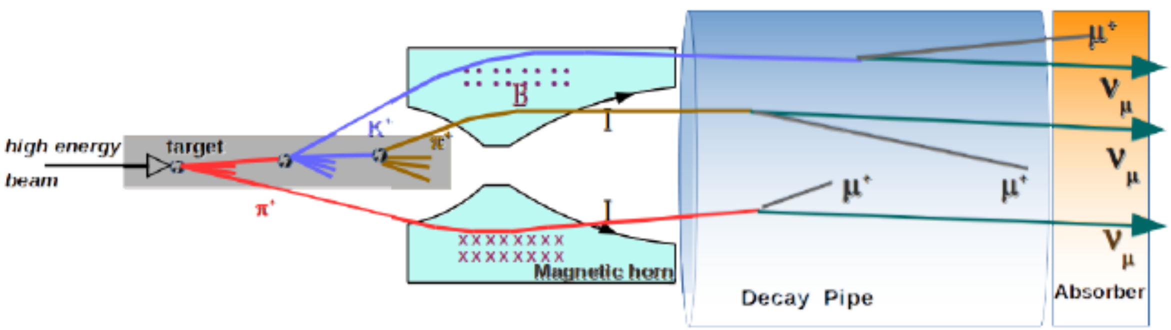
NuMI flux

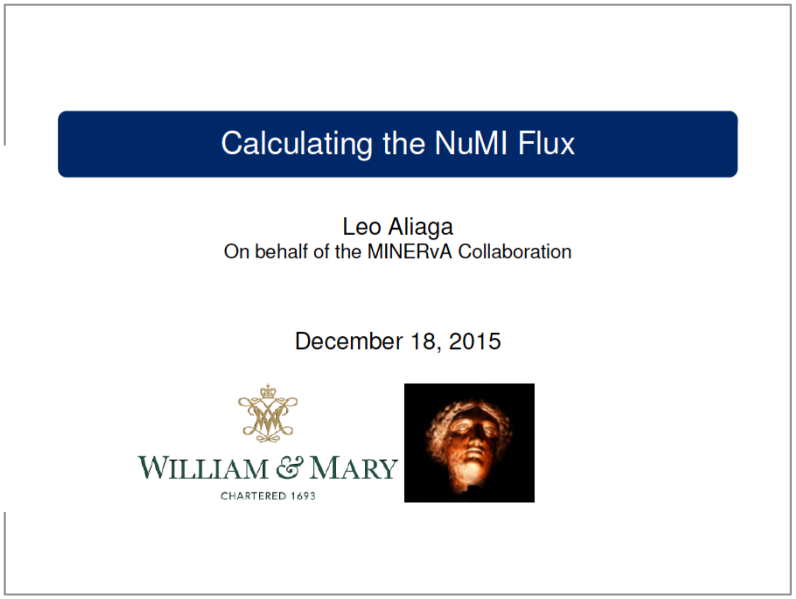
Flux tools: flux critical for any absolute measurement

- Hadron production data
  - >External thin target hadron production data legacy data from NA49, MIPP
  - >Future: US-NA61
- Can also use standard-candle cross sections
  - >Neutrino-electron scattering
  - >Low ν (low recoil) event rates

MINERvA *a priori* flux estimation

- Central value is based on *ex situ* data
  - >Errors based on experimental data
- Additional errors due to the beam line geometry are evaluated using beam simulations and assumed survey/ geometry errors





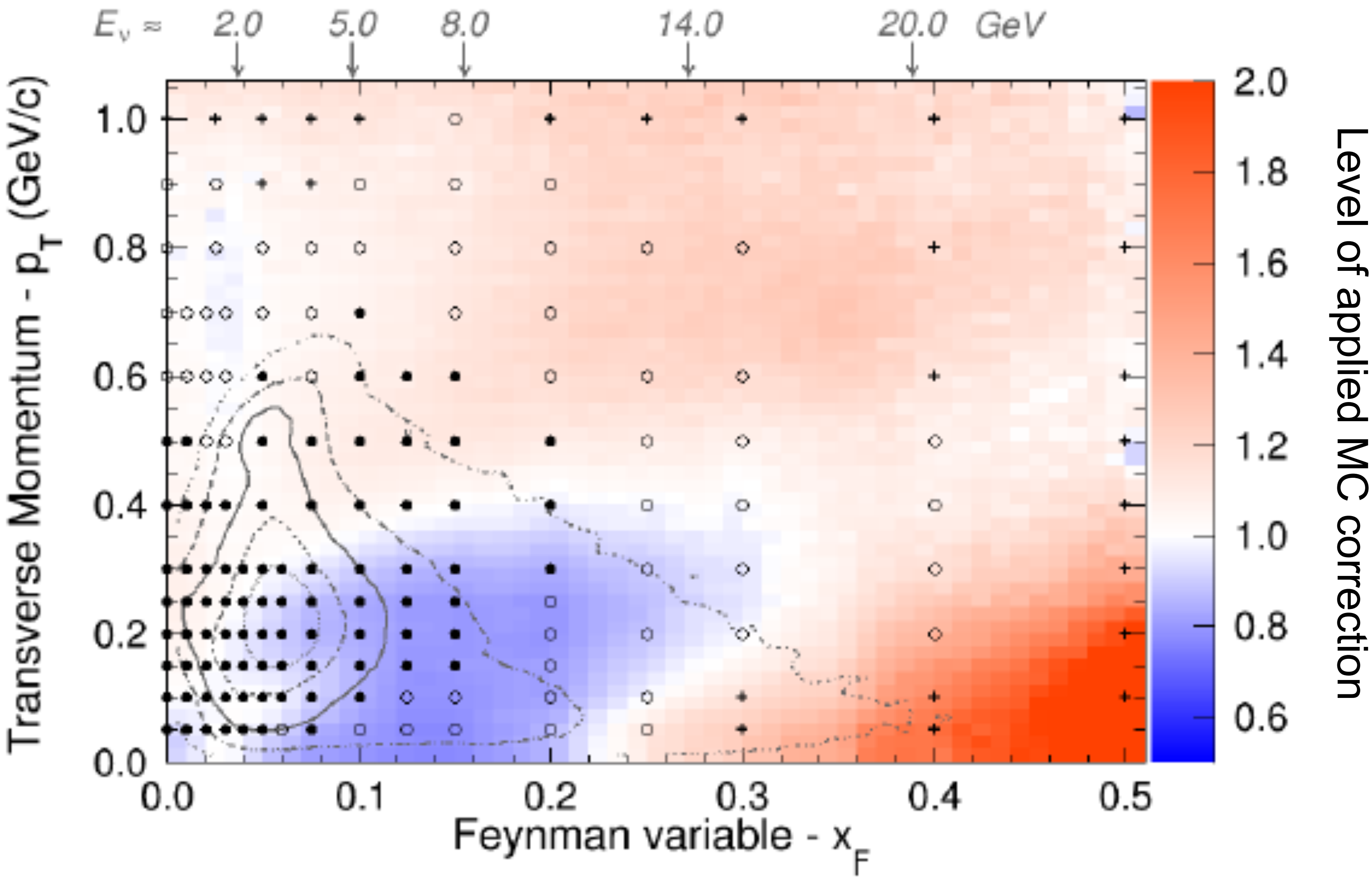
arXiv:1607.00704

The flux game plan

- Correct GEANT4 cross sections using NA49 pC data @158GeV
  - Then correct for particle attenuation in material due to changed interaction probability. This takes meticulous bookkeeping!
- Use FLUKA to scale to different incident energies (inc. reinteractions)
  - This scaling was checked by comparing with NA61 (pC)@31GeV
- Test the uncertainty associated with extending proton on carbon interaction to other materials
  - Extrapolate to data to hadronic cross section in different materials in similar kinematics (Barton, Skubic, Eichten).
- Extend to other incident particles
  - Pion production from neutron interactions using isospin arguments
  - K^0 production using quark counting arguments
- If no data available assume a 40% (!) systematic

arXiv:1607.00704

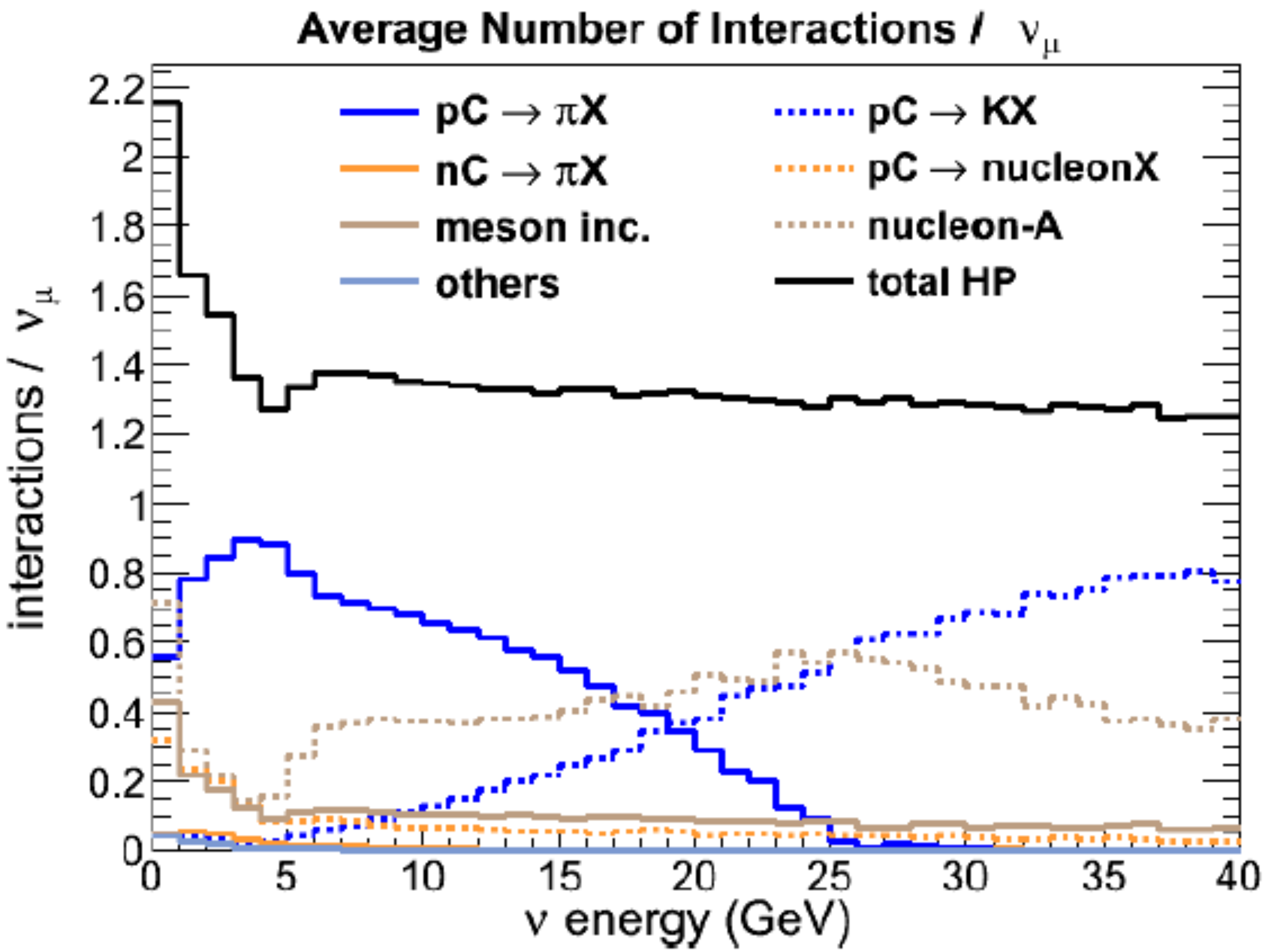
Coverage from NA49



Closed:	stat error < 2.5%
Open:	stat error 2.5 - 5.0%
Crosses:	stat error > 5%

arXiv:1607.00704

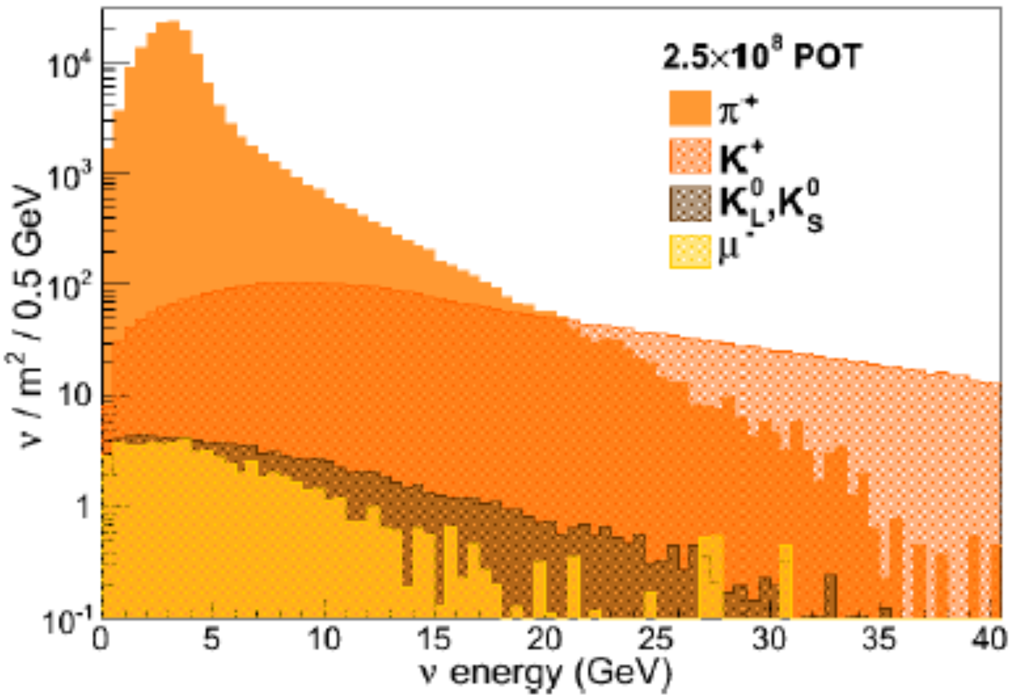
Rates for various interaction channels during neutrino production



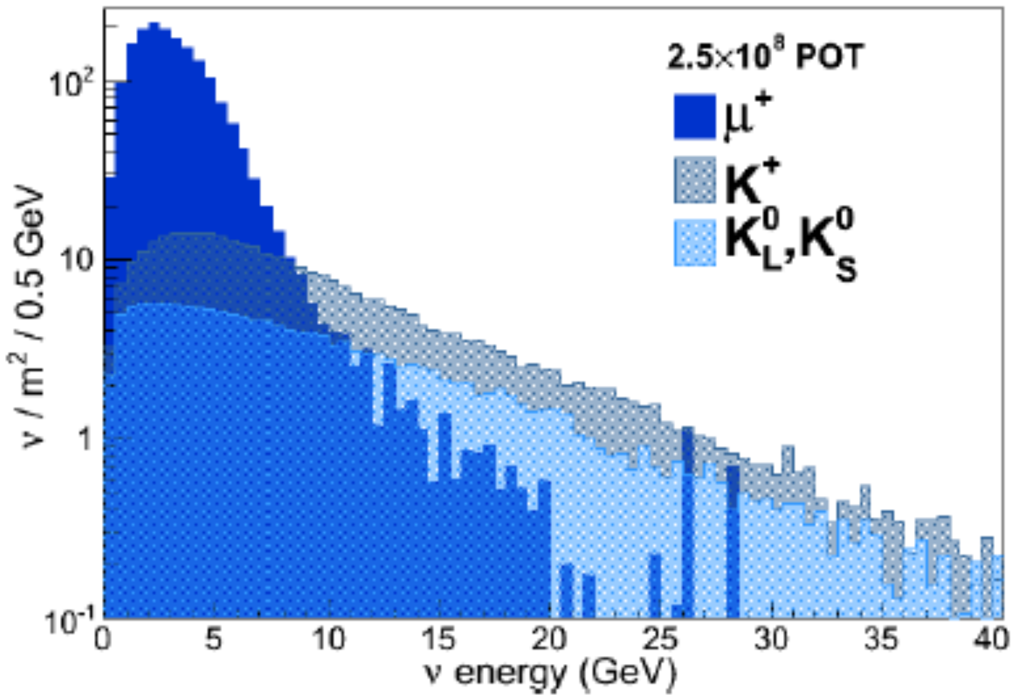
arXiv:1607.00704

Flux by parent particle

Muon neutrinos

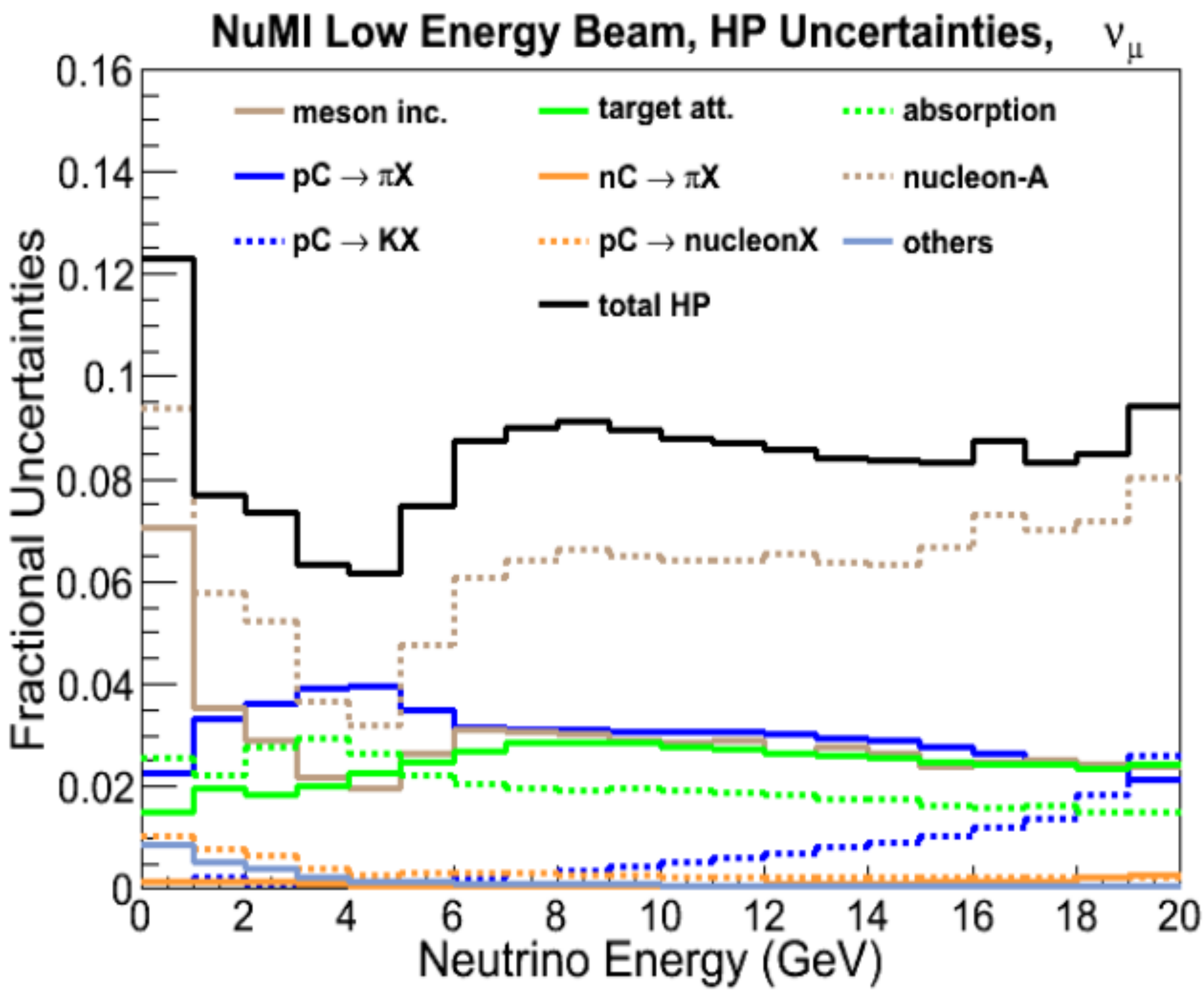


Electron Neutrinos



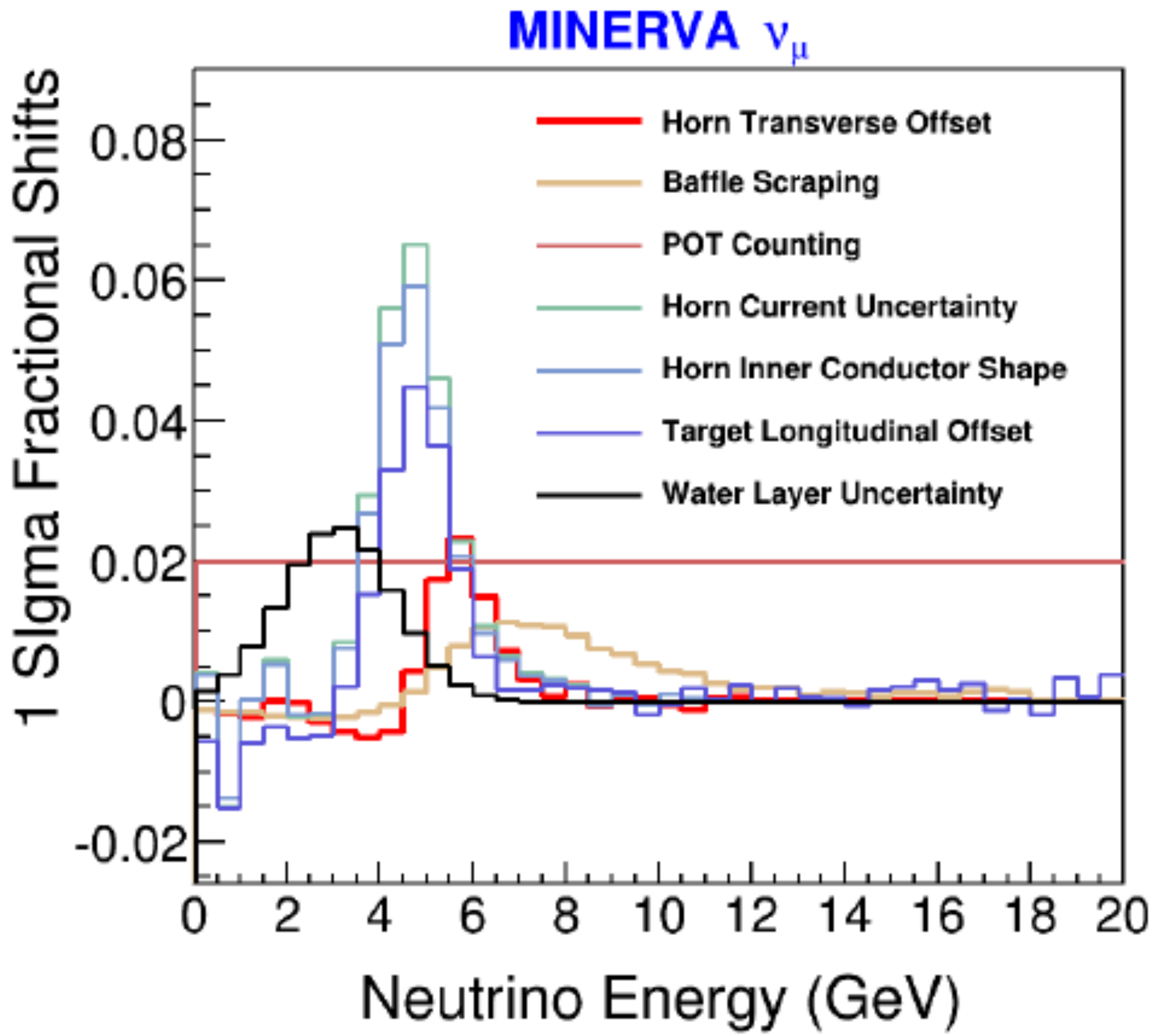
arXiv:1607.00704

Hadron production systematics



arXiv:1607.00704

Beam’s optical uncertainties



arXiv:1607.00704

Flux tools: flux critical for any absolute measurement

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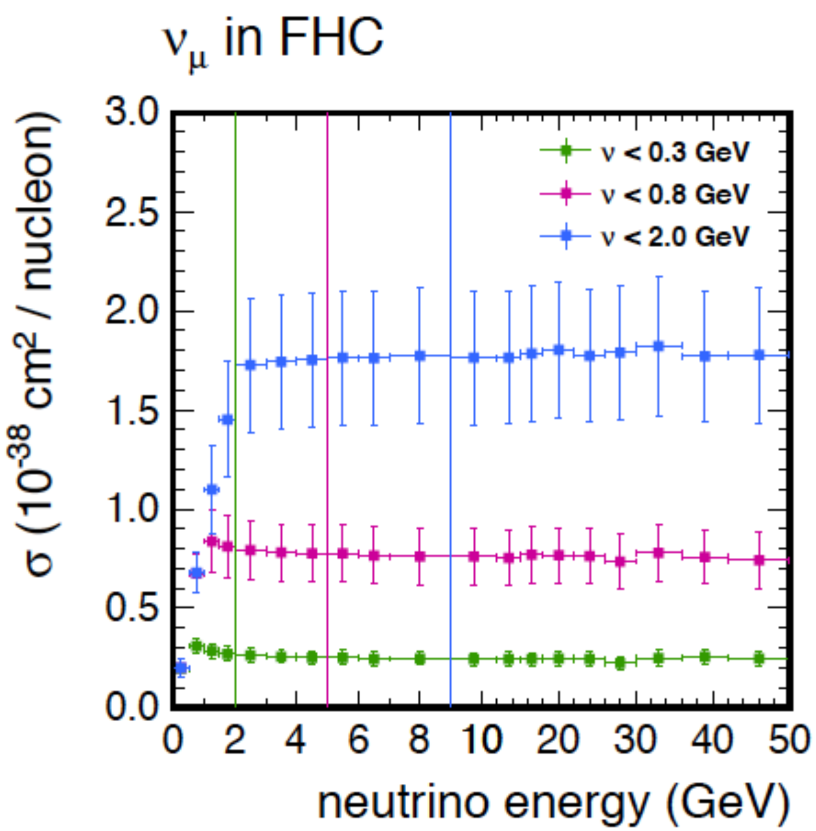
  - >Future: US-NA61
- Can also use standard-candle cross sections
  - >Neutrino-electron scattering
  - >Low ν (low recoil) event rates

Low ν flux method

- Charged-current scattering with low hadronic recoil energy (ν) is flat as a function of E_ν

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

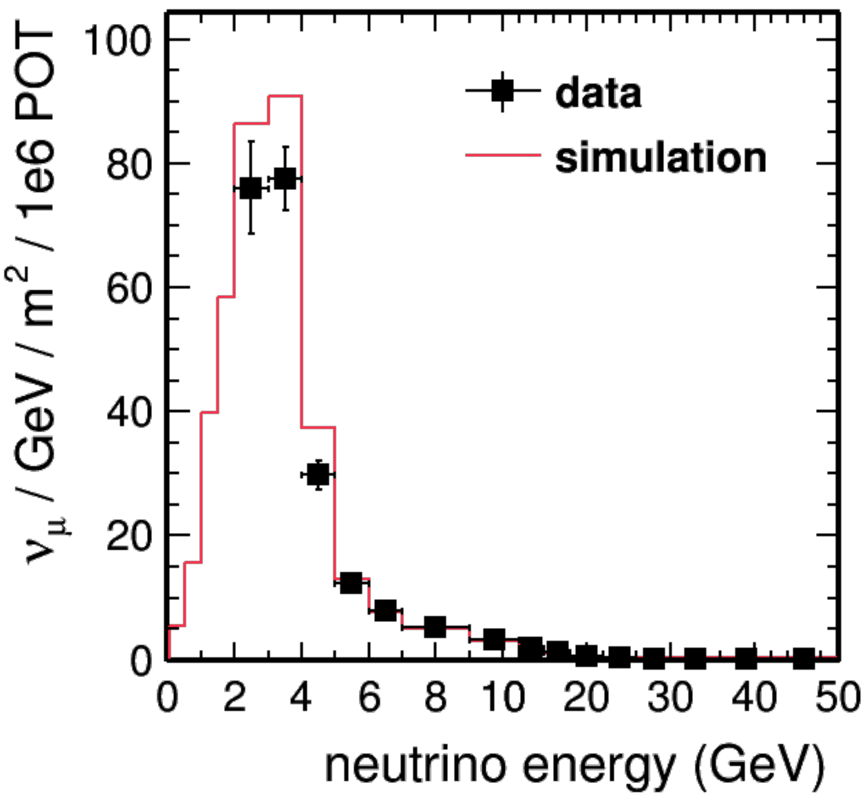
- Gives a measurement of the flux's shape
- This is a shape measurement:
  > Flux is normalized so that the extracted inclusive cross section matches an external value at high neutrino energy

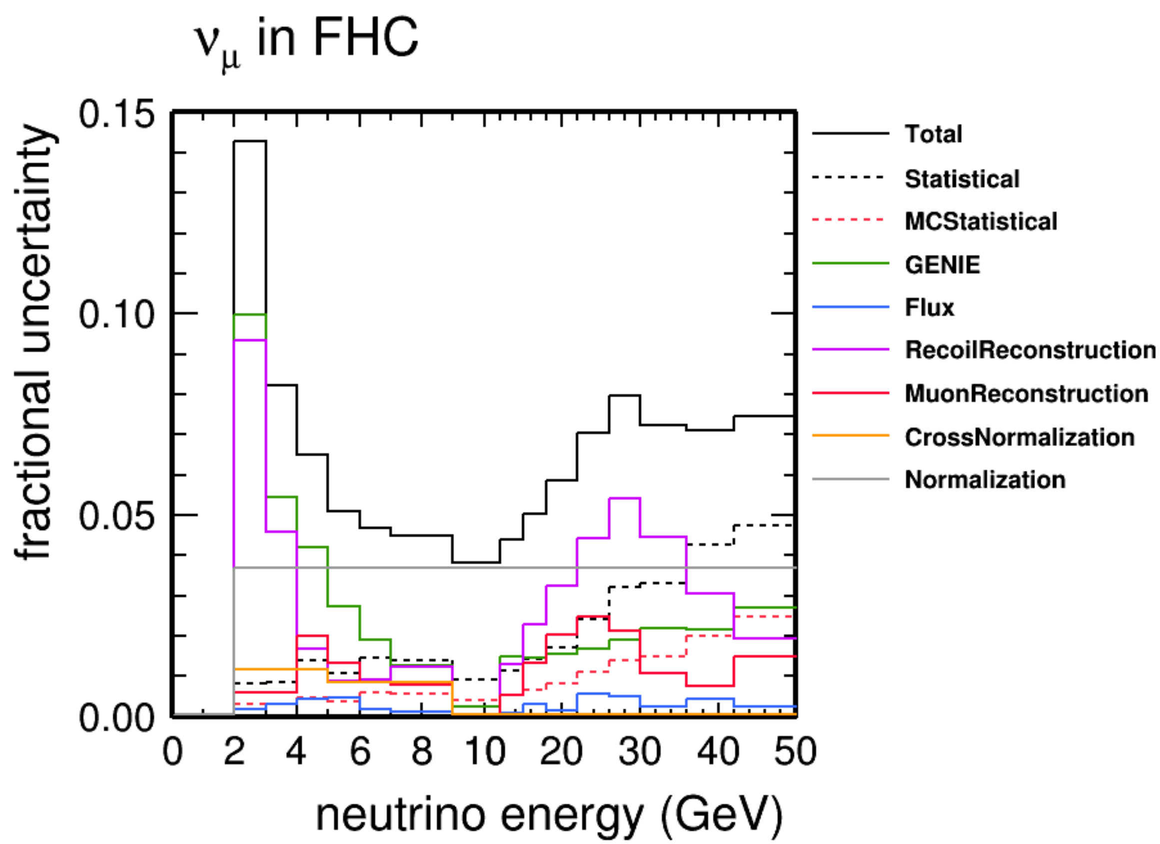


GENIE predictions

Unveiled at 8/1/16 FNAL wine & cheese

NuMI on-axis neutrino flux from the low-nu method





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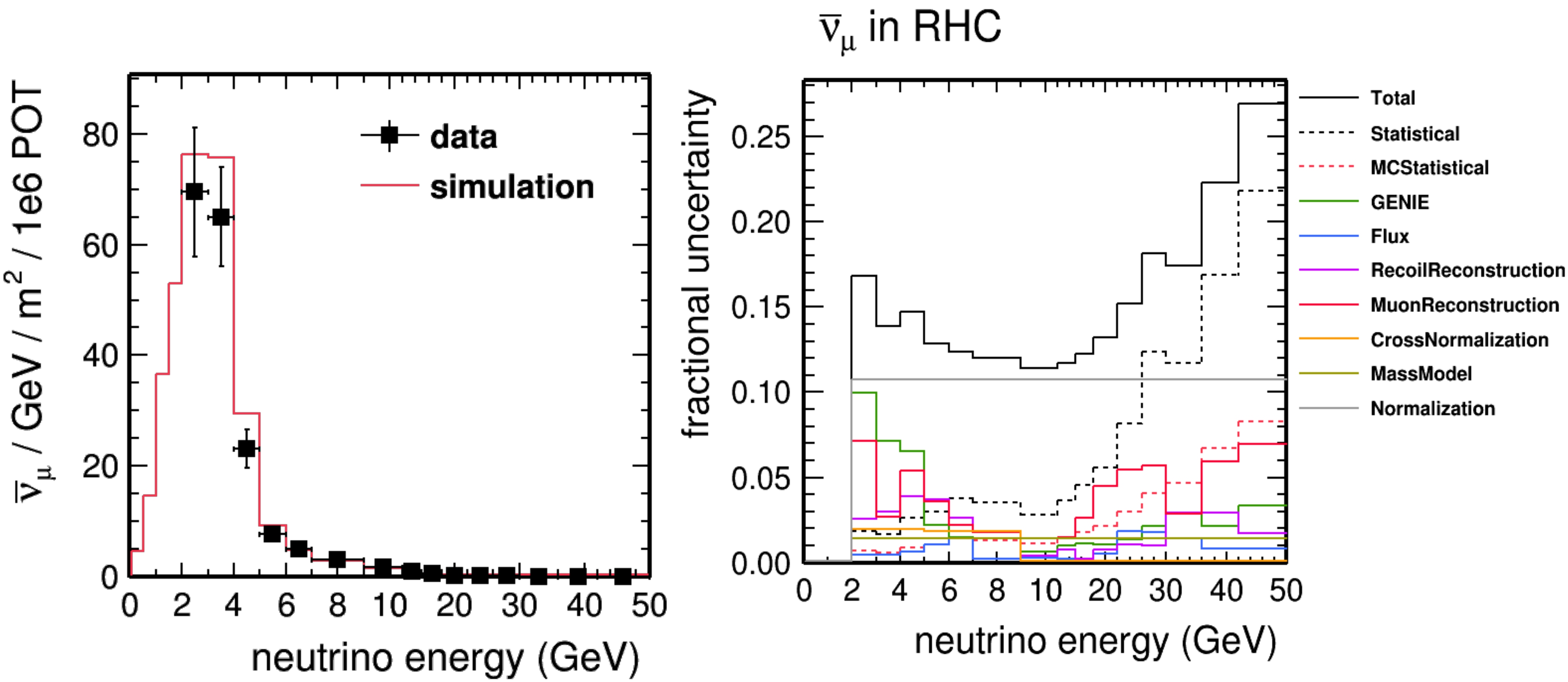
NuMI on-axis antineutrino flux from the low-nu method



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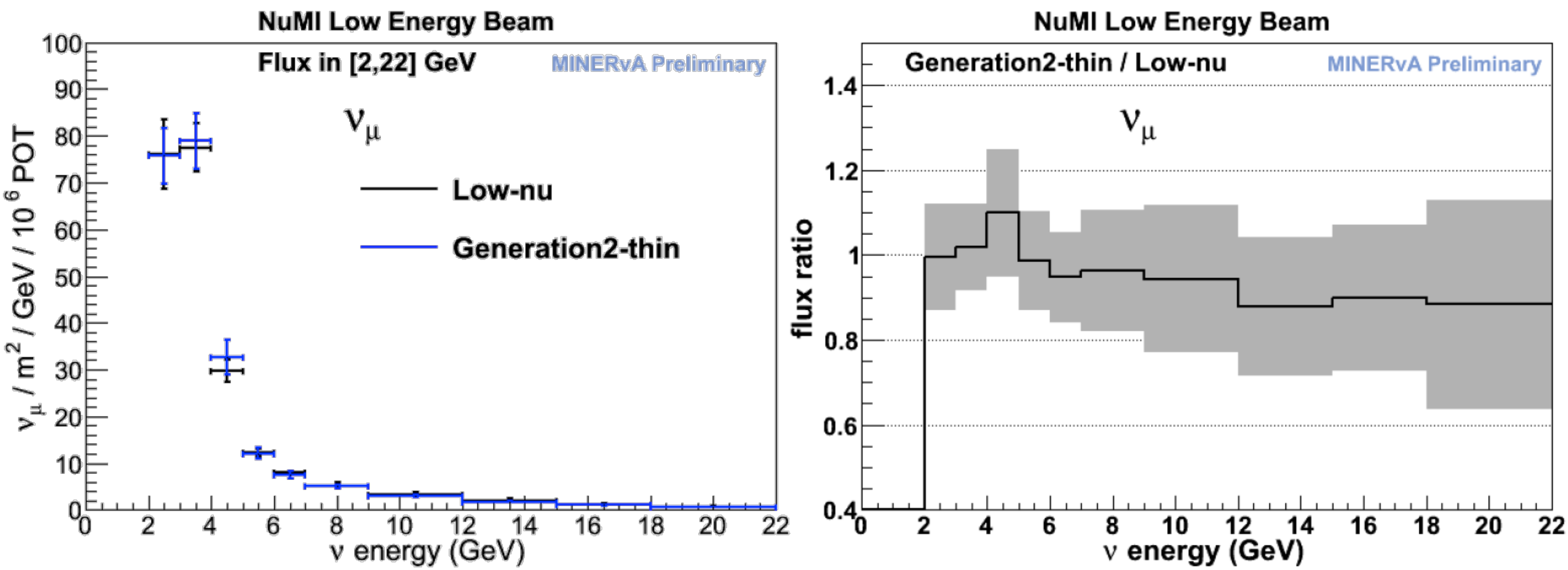
Comparisons between low-ν fluxes and other MINERvA flux constraints

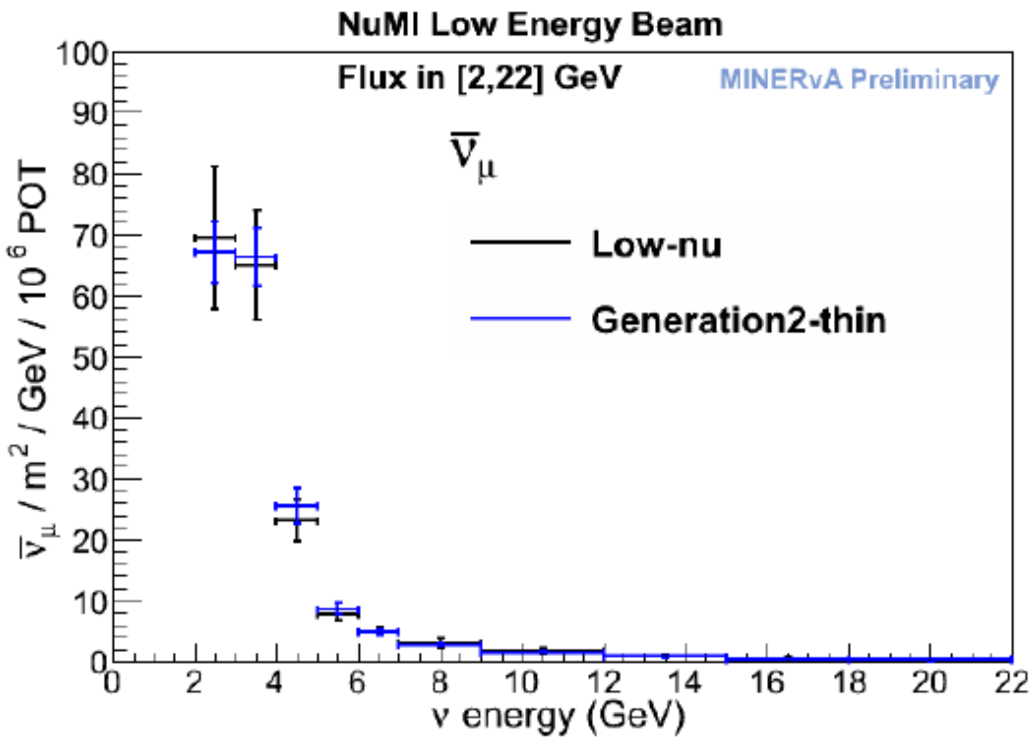
Low-ν flux and a priori thin-target neutrino comparison

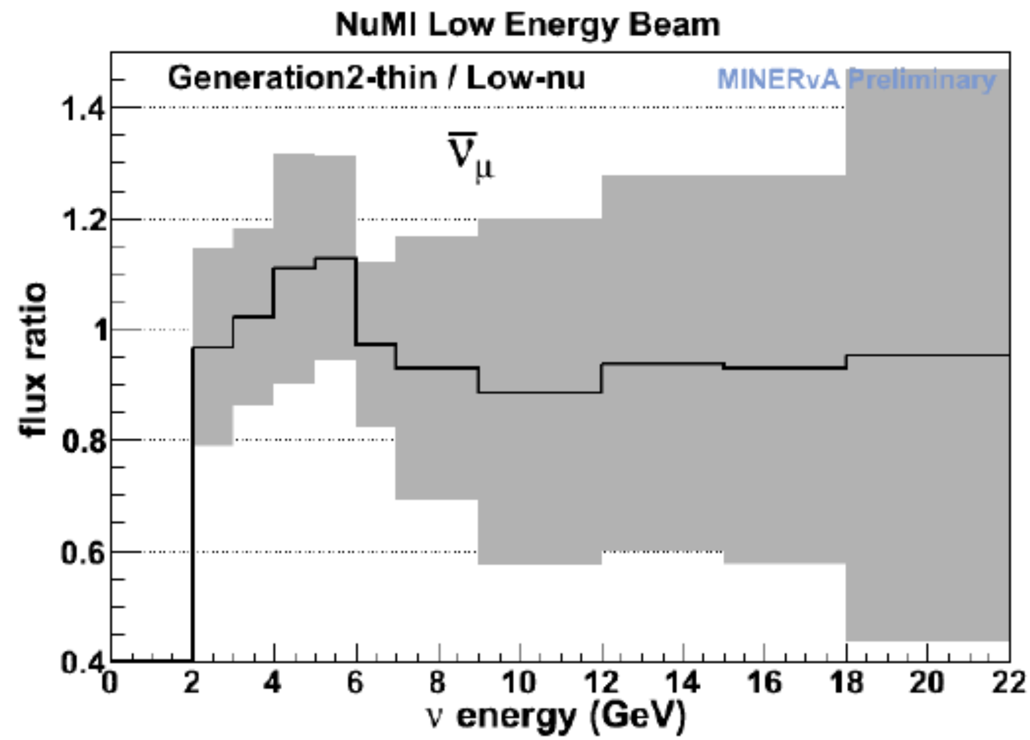


FHC neutrinos

arXiv:1607.00704

Low-ν flux and a priori thin-target antineutrino flux comparison

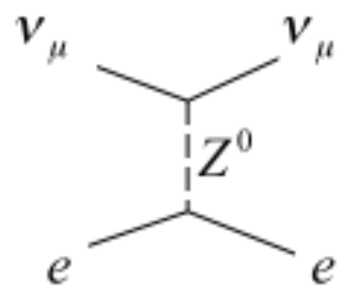




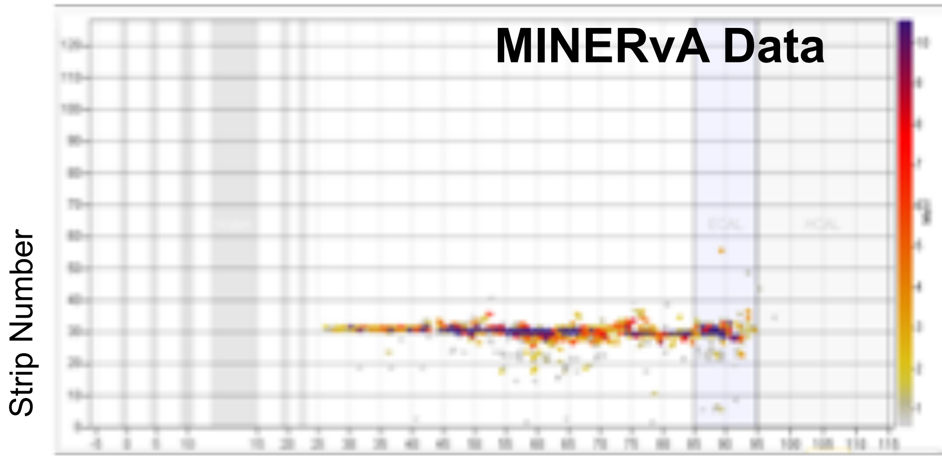
RHC antineutrinos

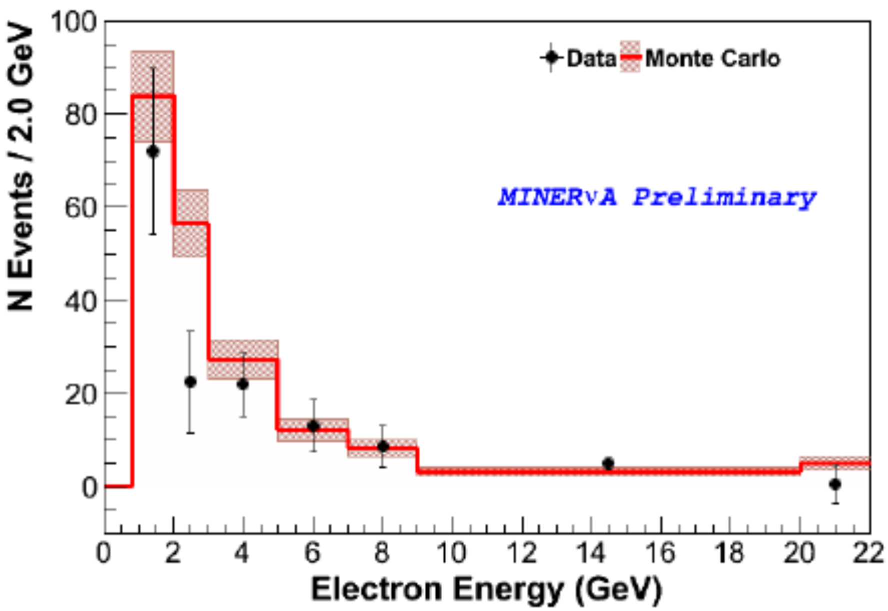
arXiv:1607.00704

Flux from ν on electron scattering



- 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* flux (~2%) and with the low ν flux
- Further confidence in flux!
  - > 3 independent methods yield consistent results





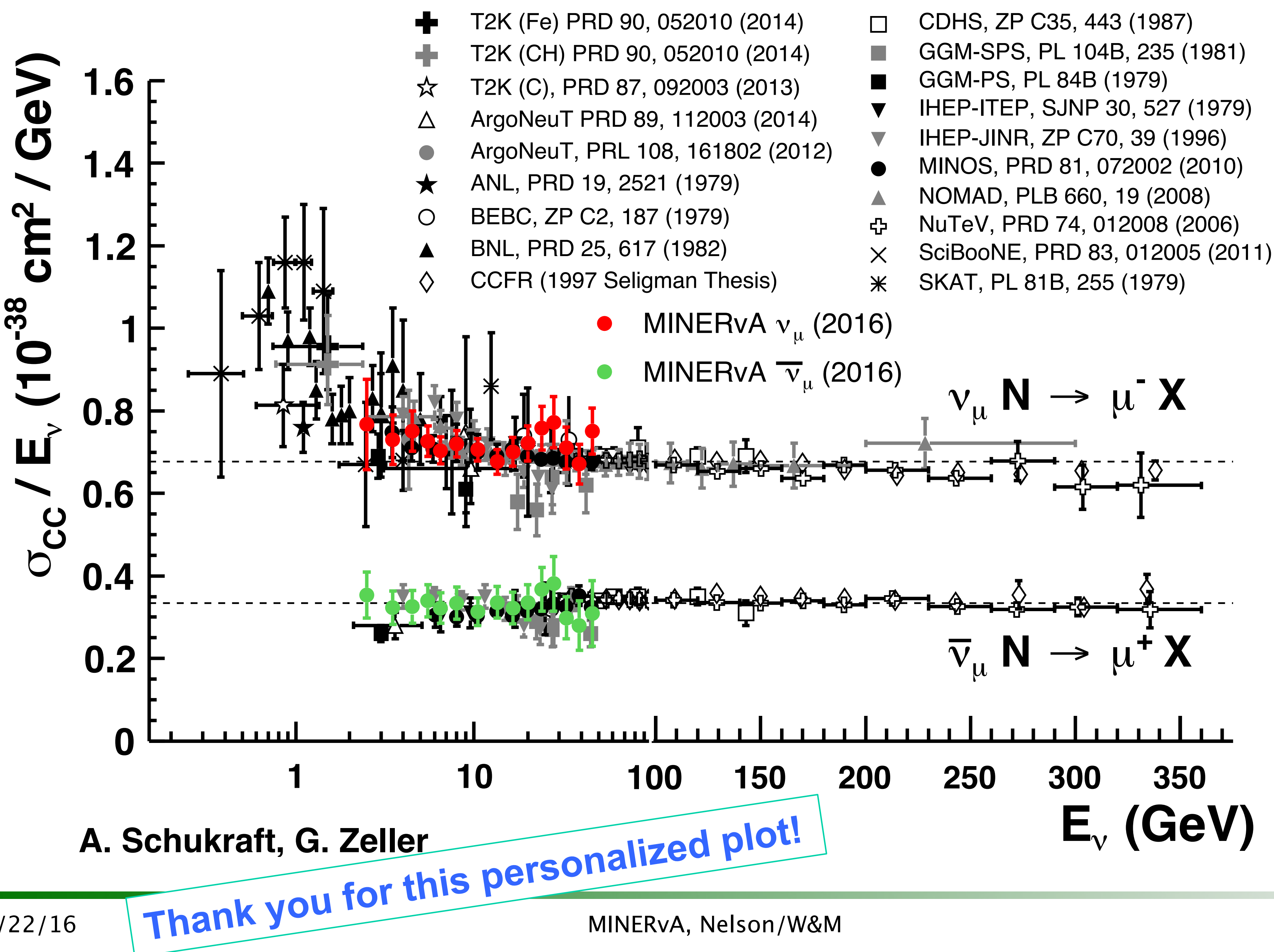
PRD 93, 112007 (2016)

Simplest thing…
inclusive charged current scattering

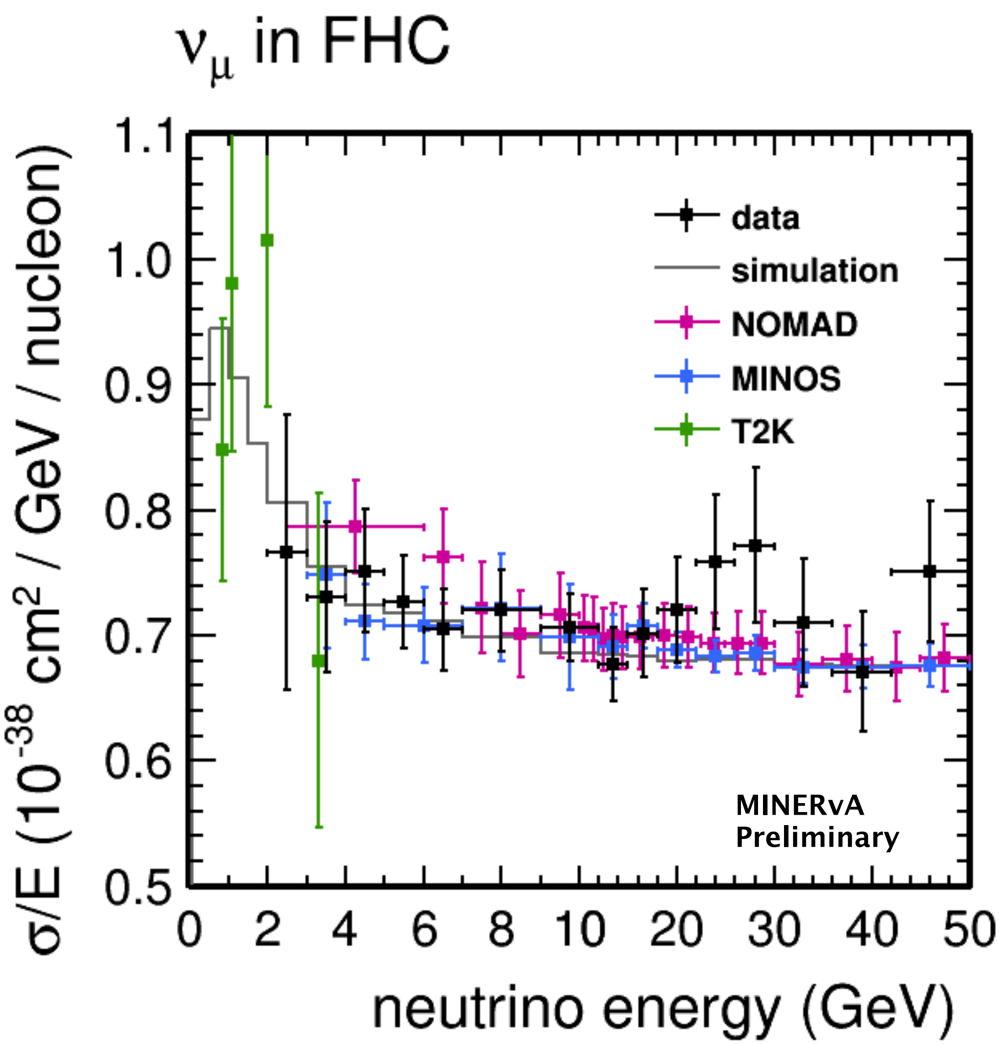
(these results use low-nu fluxes)

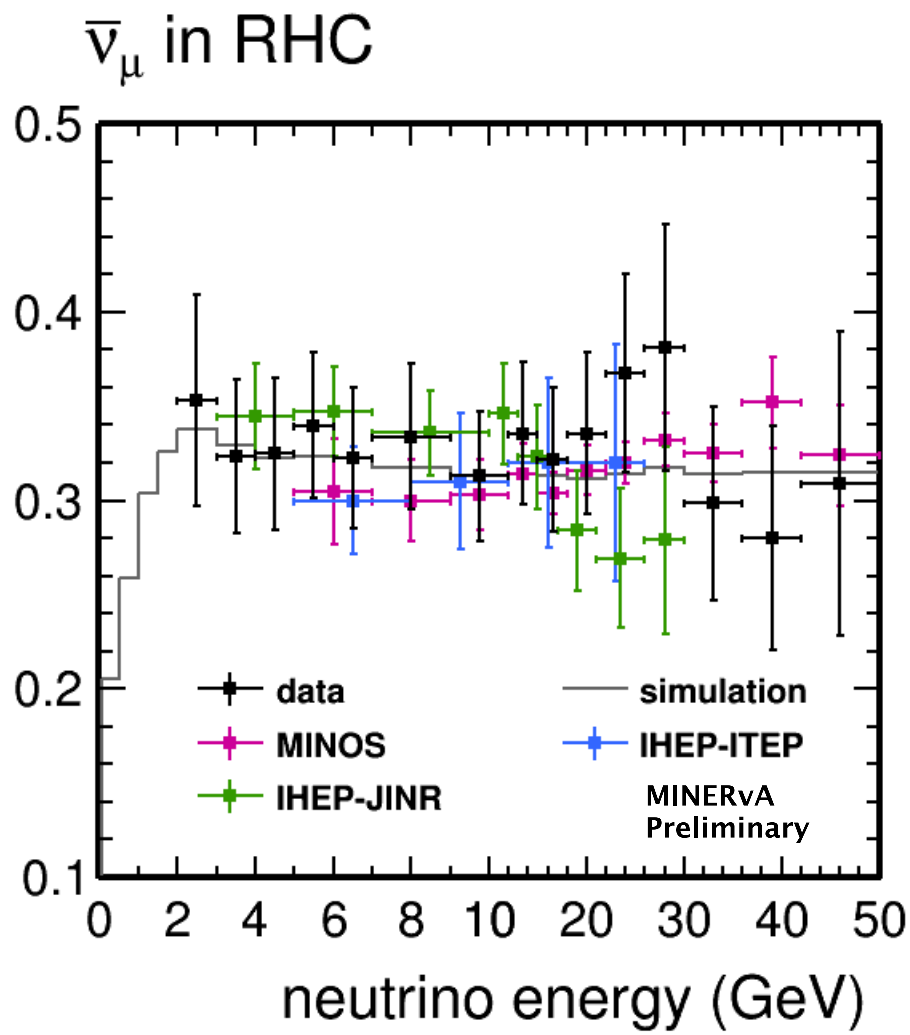
See J.K. Nelson, Fermilab Wine & Cheese (1/06)

Comparison to world data (the Big Picture)



MINERvA results from select low-energy world data





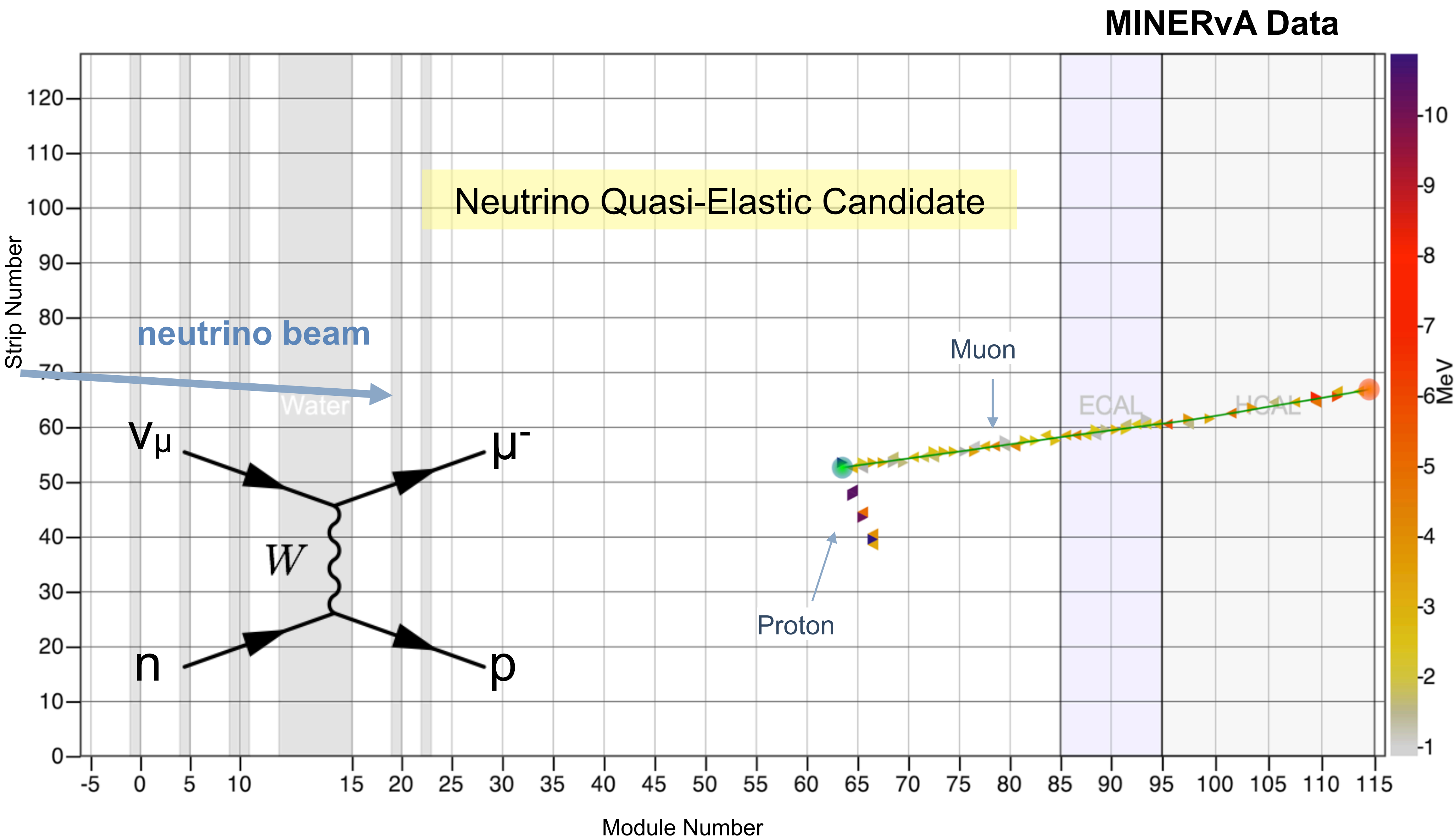
All points are isoscalar corrected

Simulation is GENIE

Next simplest thing… QE-like ?!?

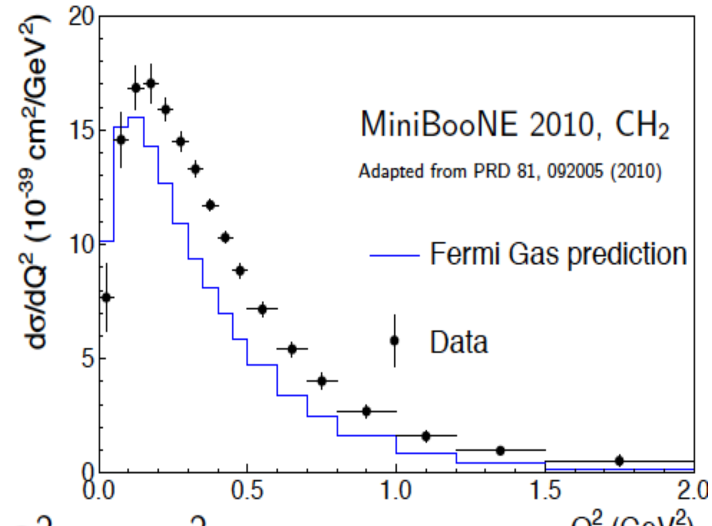
Results use new *a priori* flux

Quasi-elastic scattering

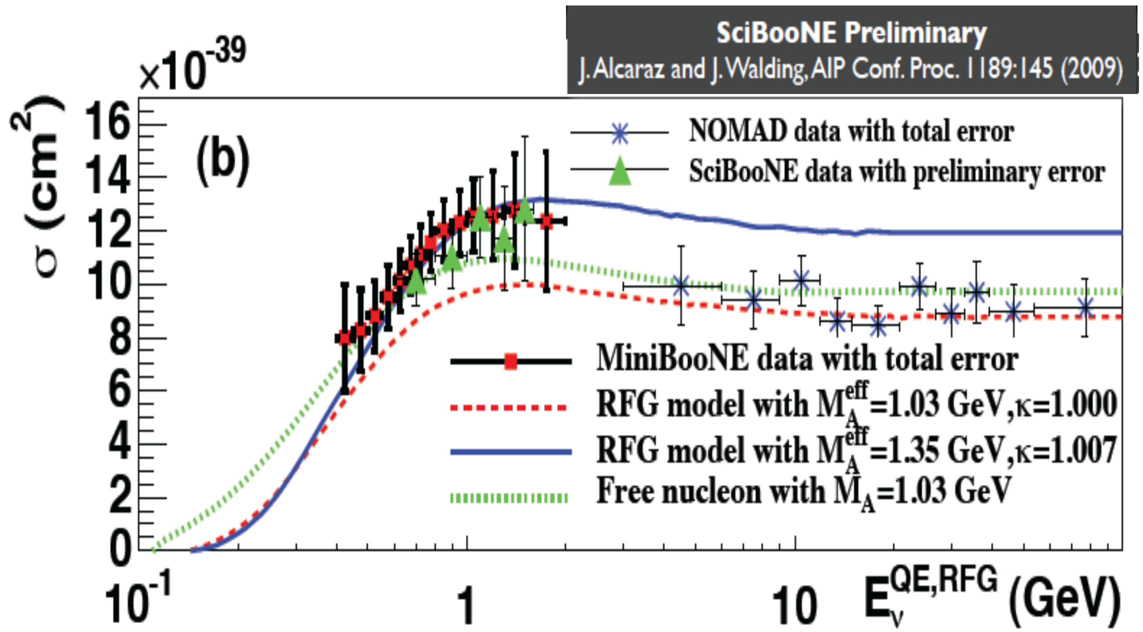


Long-standing problem in ν_μ CCQE

- NOMAD, bubble chambers
  - > Used two-track topology with low thresholds
  - > Consistent with RFG (like GENIE's model) with M_A=1 GeV but prefer a better nuclear model
- K2K, MiniBooNE, MINOS, SciBooNE
  - > Fine-grained scintillator so higher proton tracking threshold
  - > Look for a muon and low recoil; use muon kinematics for energy
  - > See a higher rate and different Q^2 distributions consistent with a higher M_A + low Q^2 suppression
- By 2010: becoming clear that this was probably due to an extra unmodeled process well known in electron scattering
  - > 2 particle, 2 hole (2p2h)
  - > Models include MEC & TE

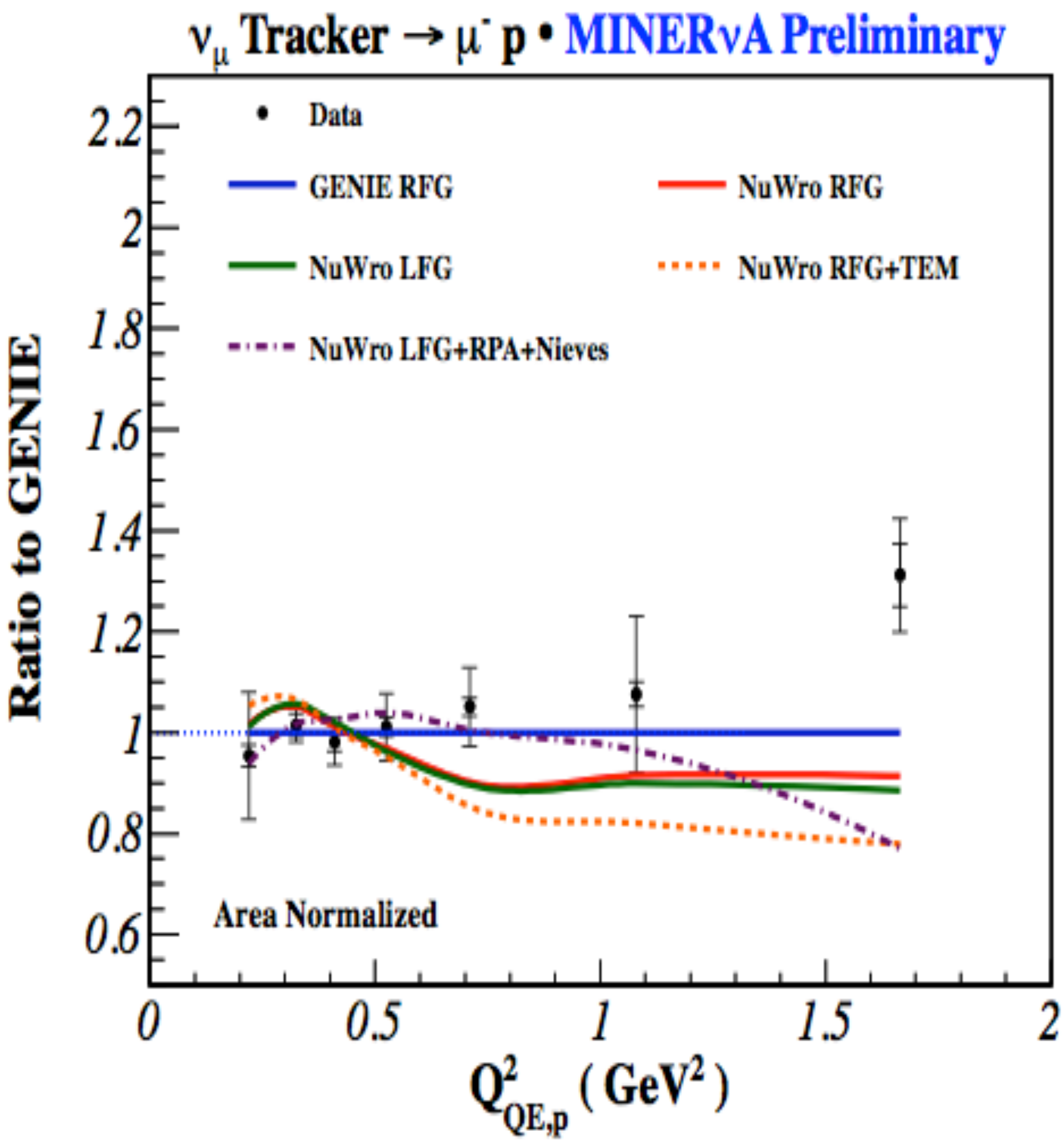


$$Q^2 = -q^2$$



NOMAD: EPJ C 63, 355 (2009)
MB: PRD 81, 092005 (2010)
K2K: PRD 74, 052002 (2006)
MINOS: PRD 91, 012005 (2015)
SB: J. Walding, IC thesis (2009)

2-track QE, proton-based reconstruction

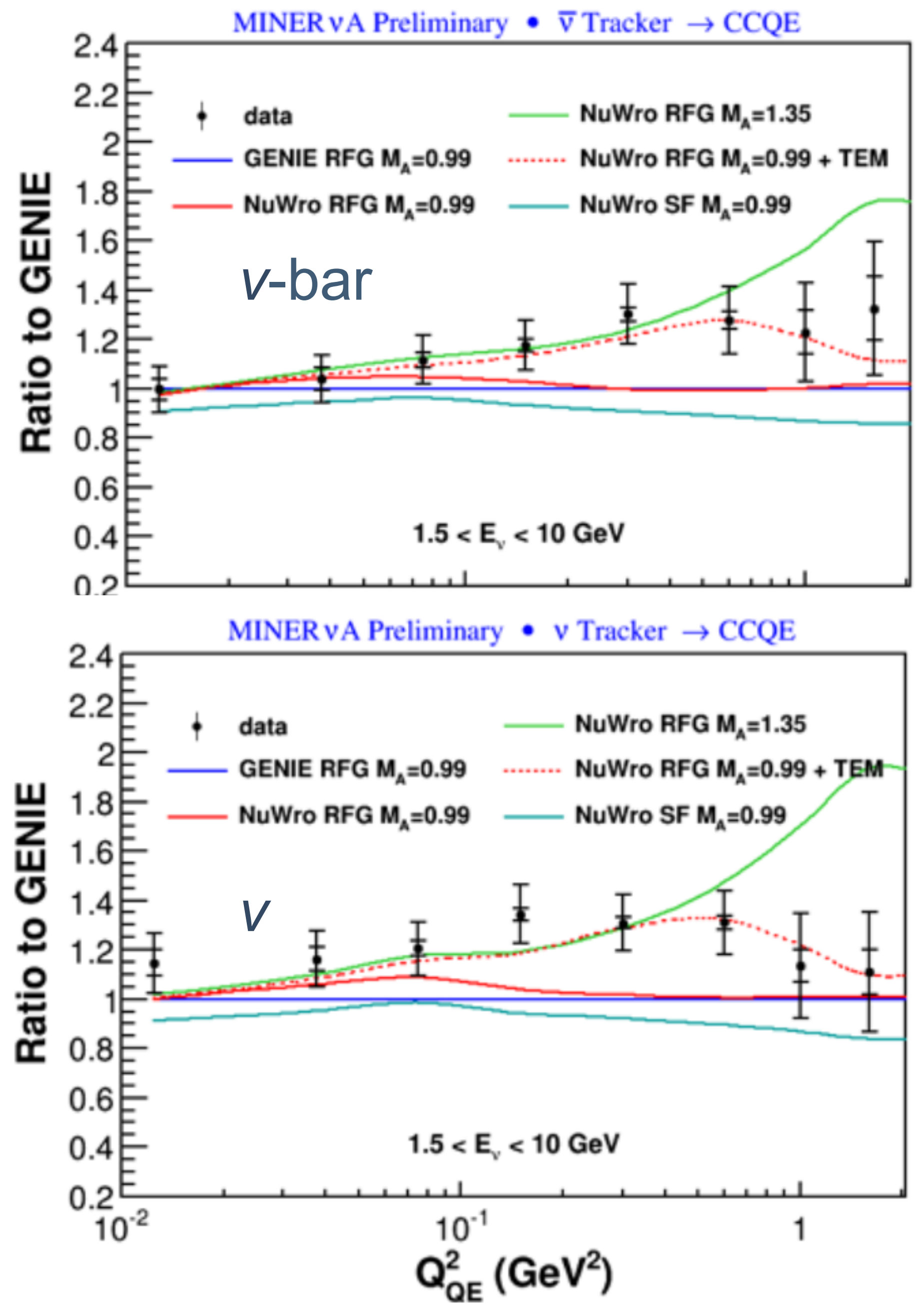


- Select events based on 1 PID'd stopping proton & 1 muon
- Reconstruct kinematics quantities using proton angle and energy
- Very sensitive to final state interactions
- Shape-only comparison
- In proton kinematic variables, see relatively good agreement with Relativistic Fermi Gas (RFA) model for QE scattering
- These 2-track QE make a pretty good standard candle

PRD 91 071301 (2015)

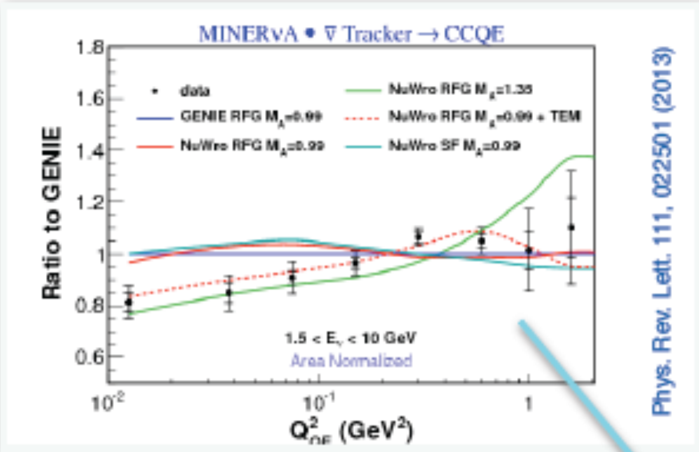
QE with lepton-based kinematics

- Reconstruct the muon
  - > Require not too much energy beyond a box around the vertex
  - > Relatively insensitive to final state interactions (only enter via the background estimate)
  - > POT normalized (new flux)
- Disagreement with Fermi Gas model seen in total cross section, shape of cross section
  - > Has model discriminating power
  - > Favors a 2p2h contribution
  - > TEM = Transverse Enhancement Model



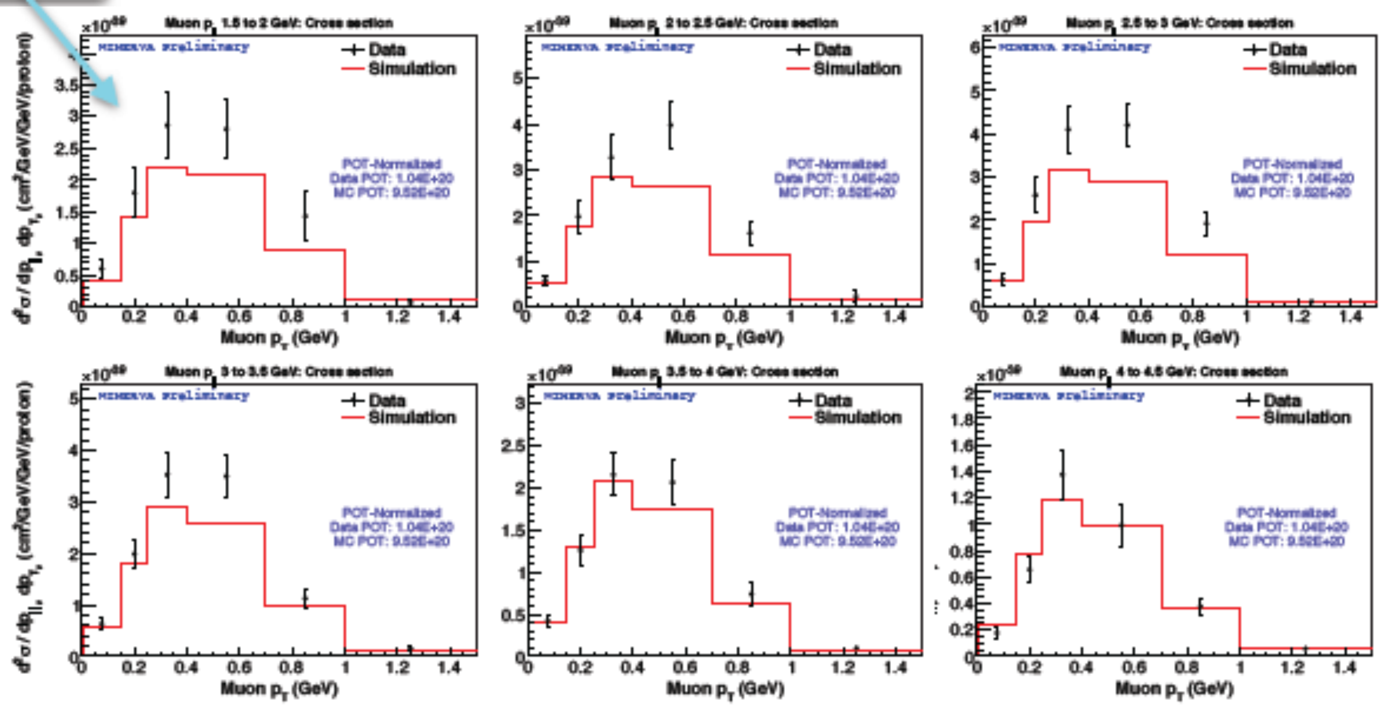
PRL 111, 022502 (2013), updated 1/16, web data release
PRL 111, 022501 (2013), updated 1/16, web data release

Double differential (muon kinematics) antineutrino QE analysis



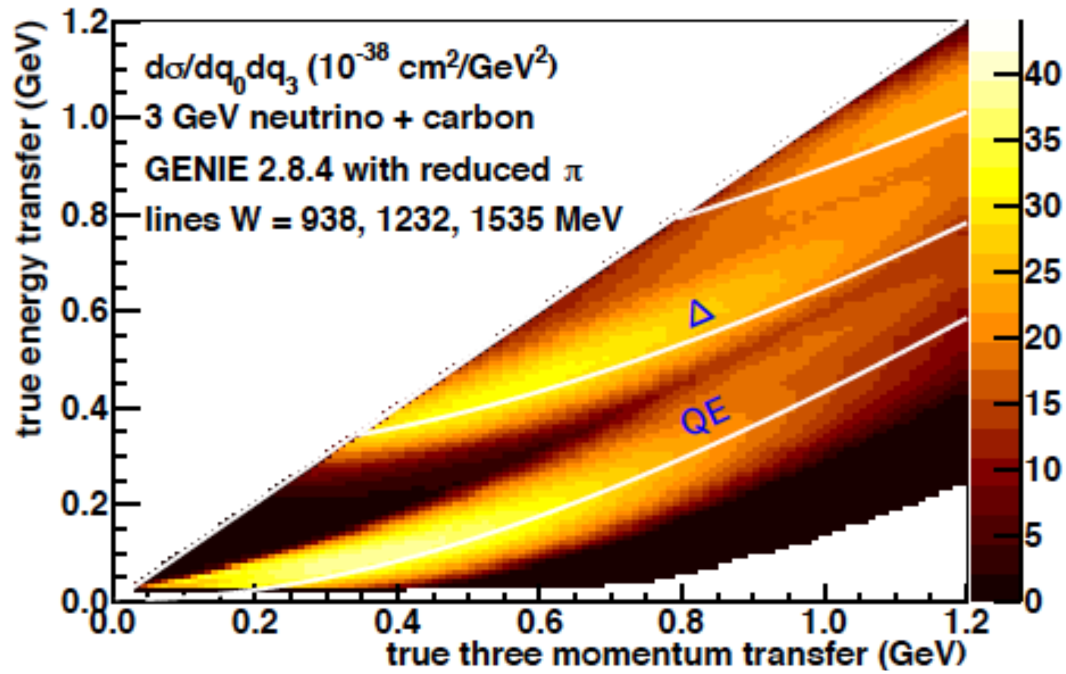
- Improved reconstruction and systematics WRT prior publications
- Double differential in muon transverse and longitudinal momentum
- Data indicates extra strength at moderate transverse momenta

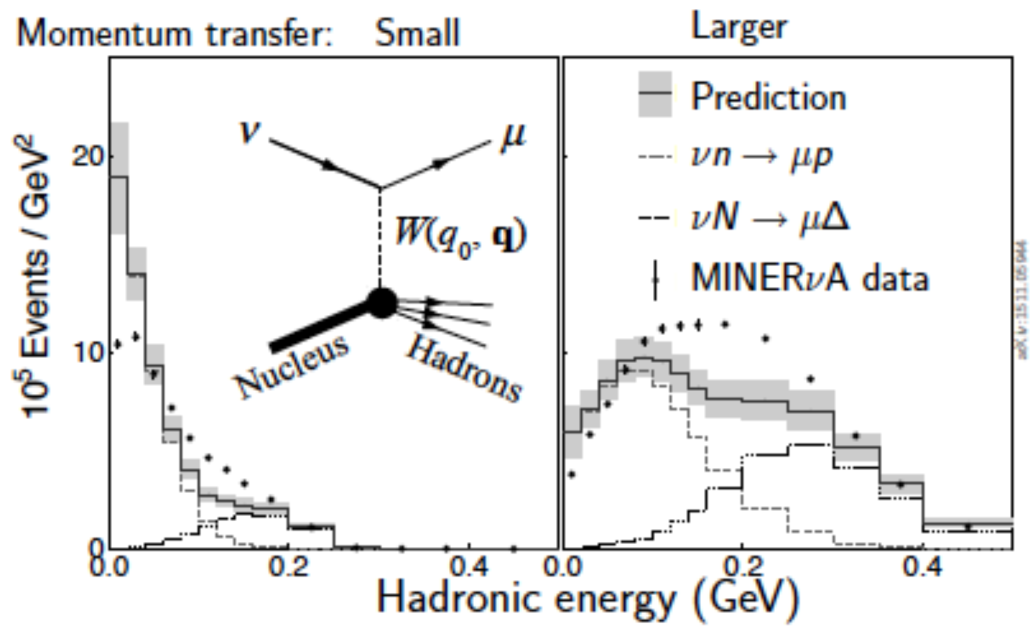
C. Patrick, FNAL seminar, 6/18/16



Muon Neutrino CC inclusive w/ low recoil

- Another tactic is not cut on the recoil, but rather to look at the low recoil in an inclusive sample
- Reconstruct energy both & momentum transfer (somewhat analogous to electron scattering techniques)
- Default GENIE model struggles to explain the data





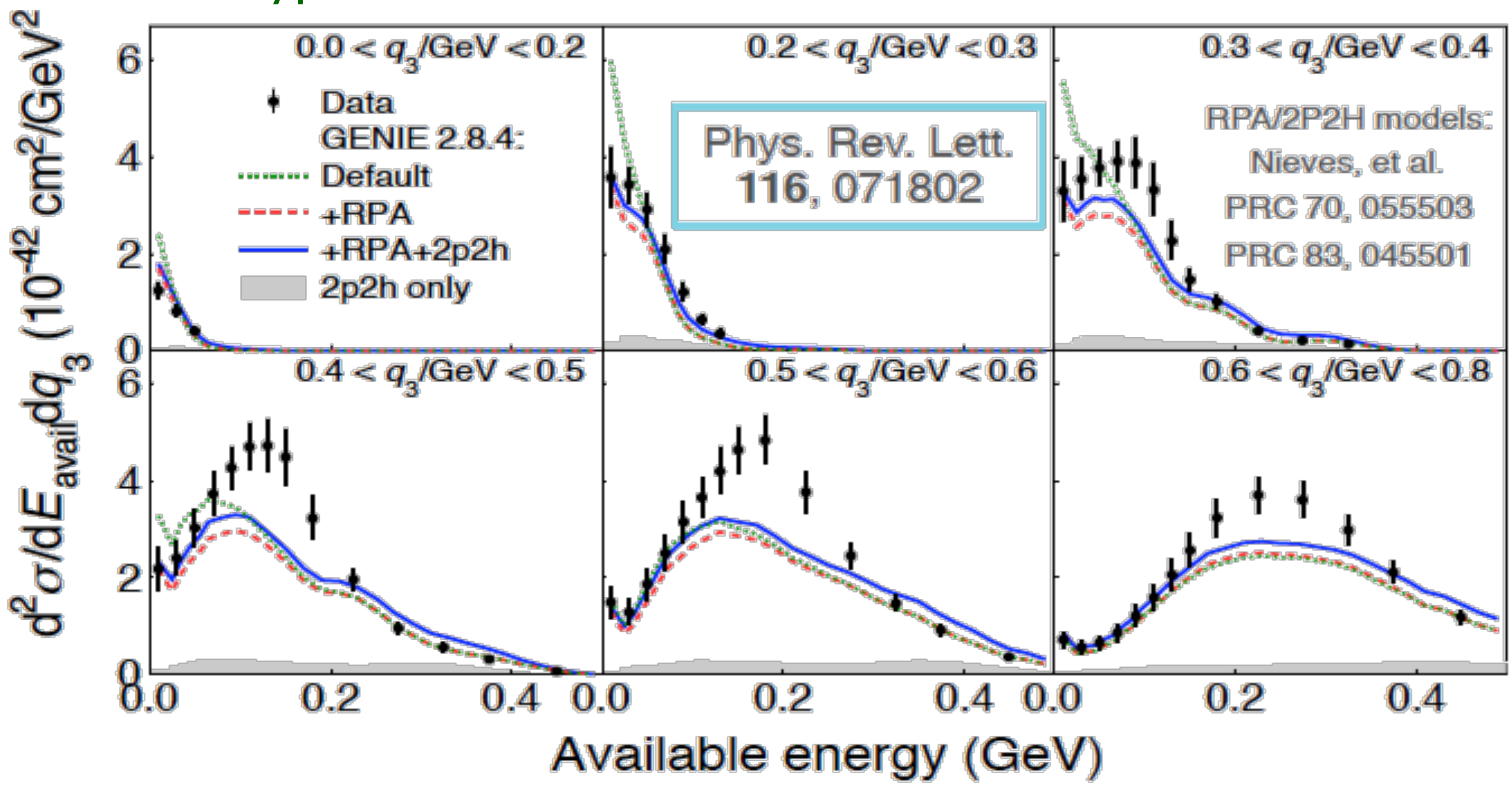
PRL 116, 071802 (2016)

Muon Neutrino CC inclusive w/ low recoil

- Compute the "available" energy

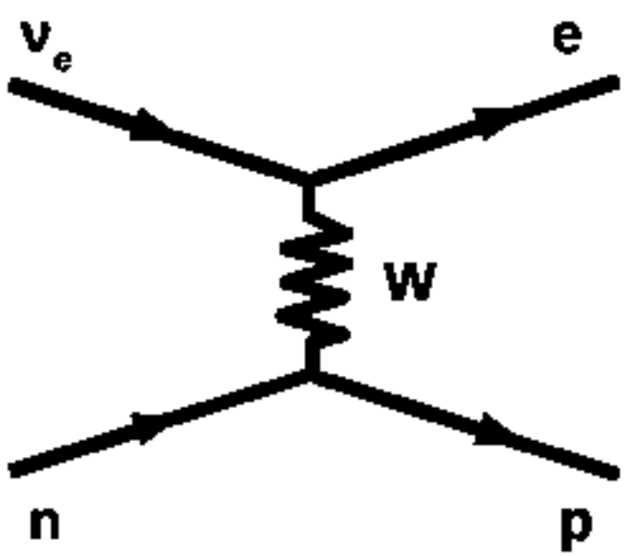
$$E_{\text{avail}} = \sum(\text{Proton and } \pi^{\pm} \text{ KE}) + (\text{Total } E \text{ of other particles except neutrons})$$

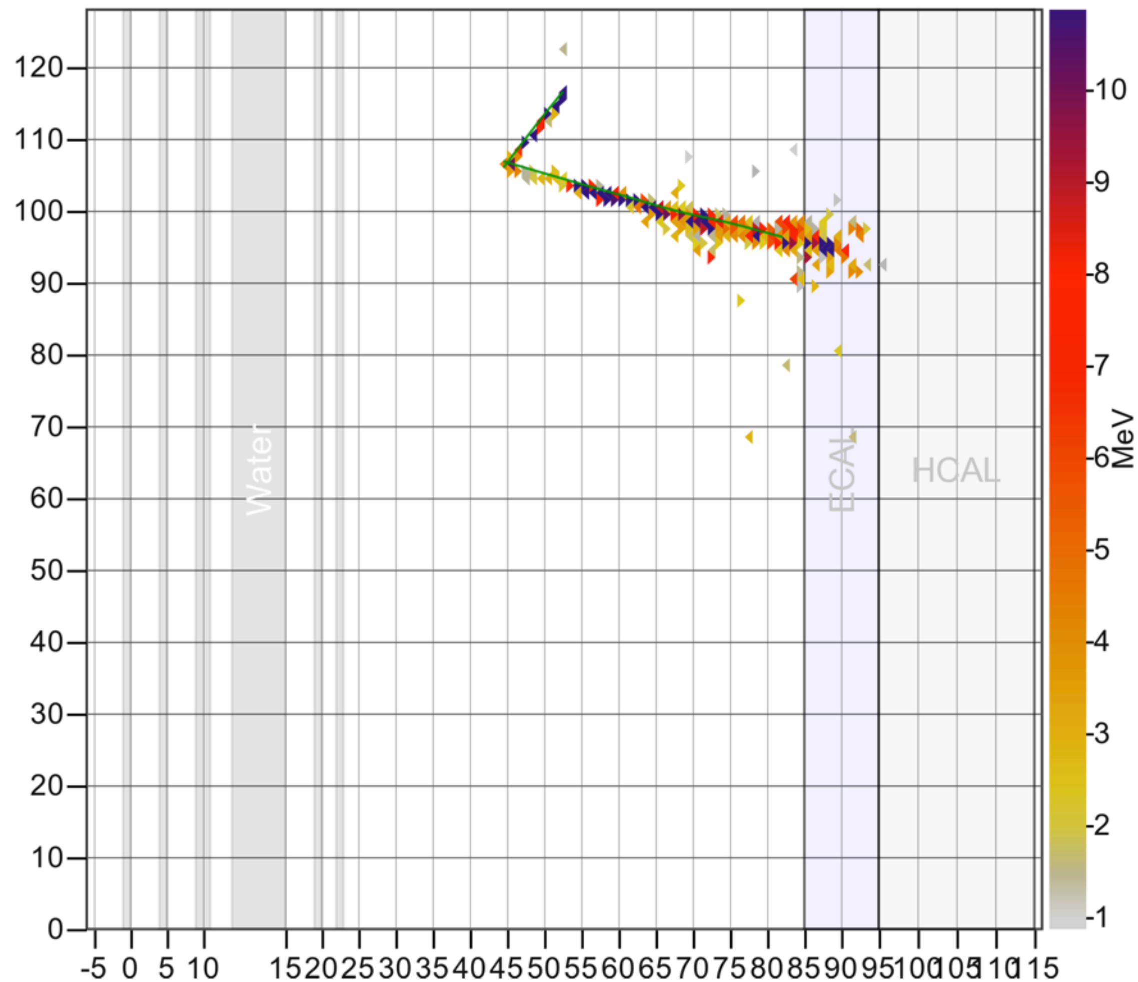
- Models adding RPA (charge screening nuclear) effect and a 2p2h process (in this case the Valencia model) improves agreement in some regions, but not strong enough to cover the observed rate
- A Bragg peak counting analysis is also compatible with multi-nucleon final states hypothesis



Electron neutrino QE scattering

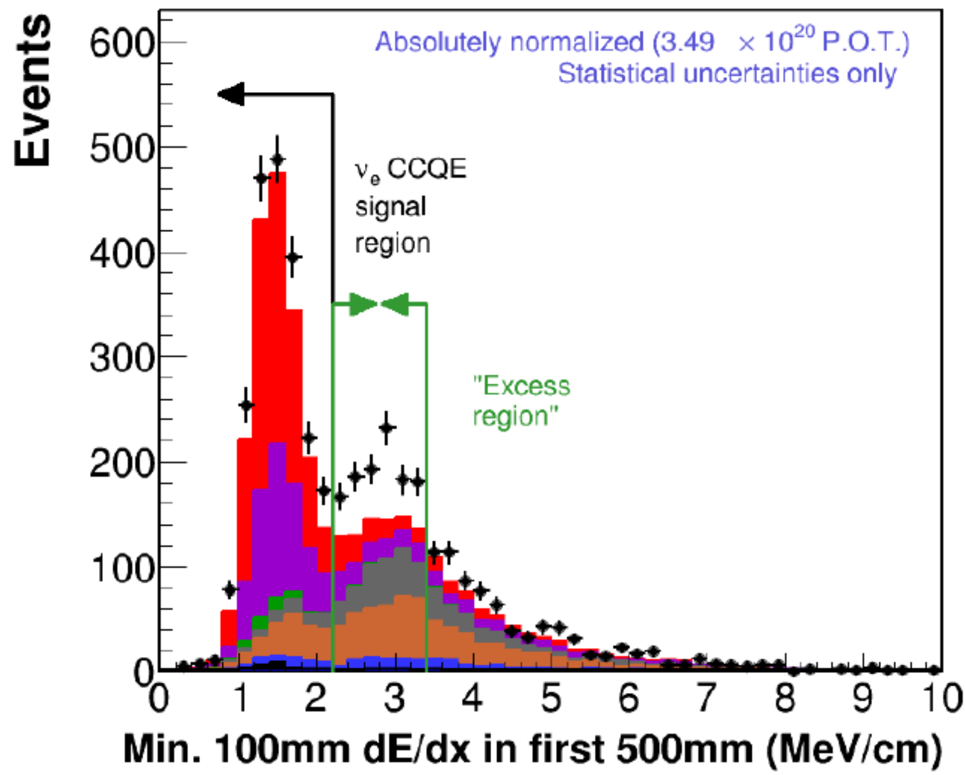
Electron neutrino CC QE:
Large signal for electron appearance





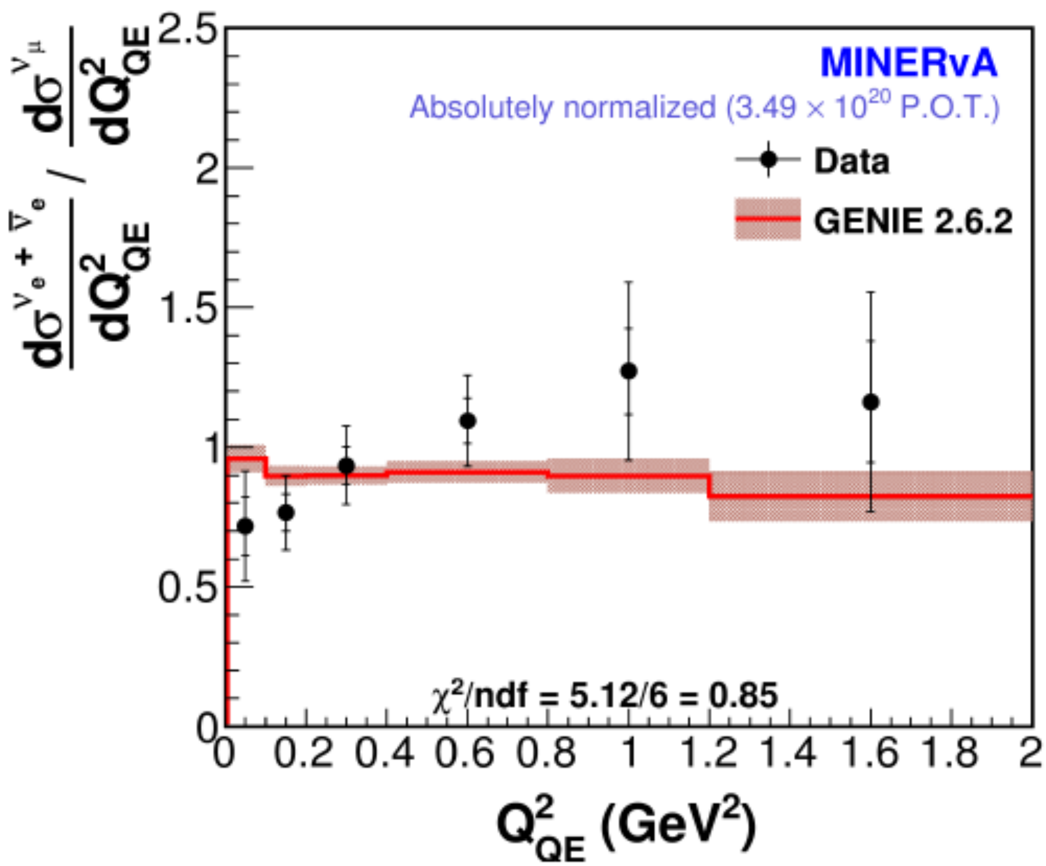
1^{st} time this channel has been measured

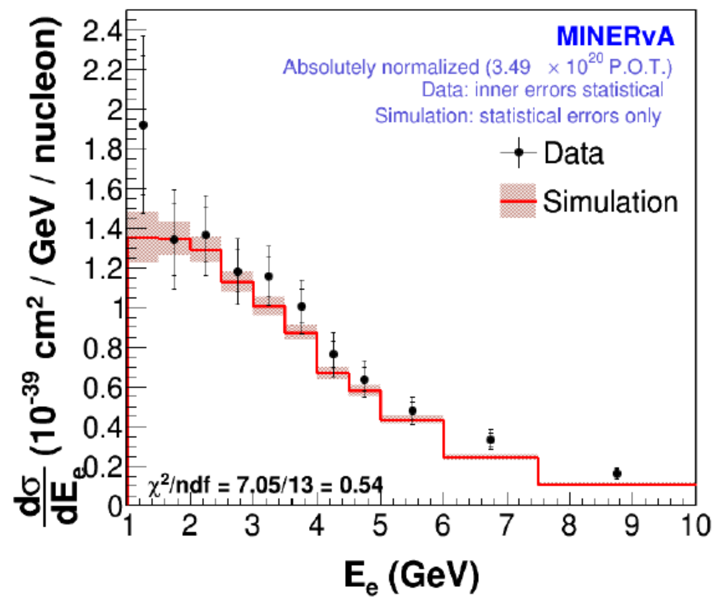
- Isolate the small electron neutrino sample (2% of beam)
- Rely on electrons having one prompt track while neutral pions start their shower with 2 tracks' ionization (e^+e^- pair)
- We also observe a previously unseen photon production process
  - > More from Jorge on Friday

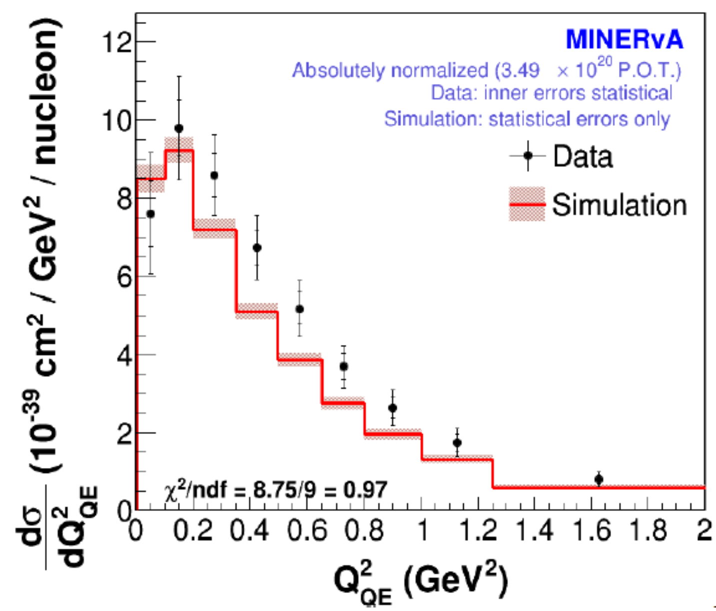


Electron neutrino CC QE is consistent with muon neutrino CC QE

Constrains differences the between nuclear effects to the 15% level

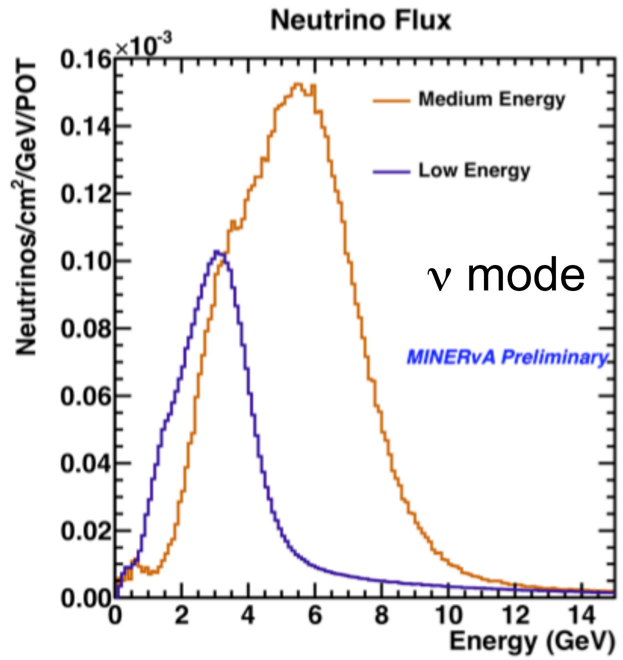


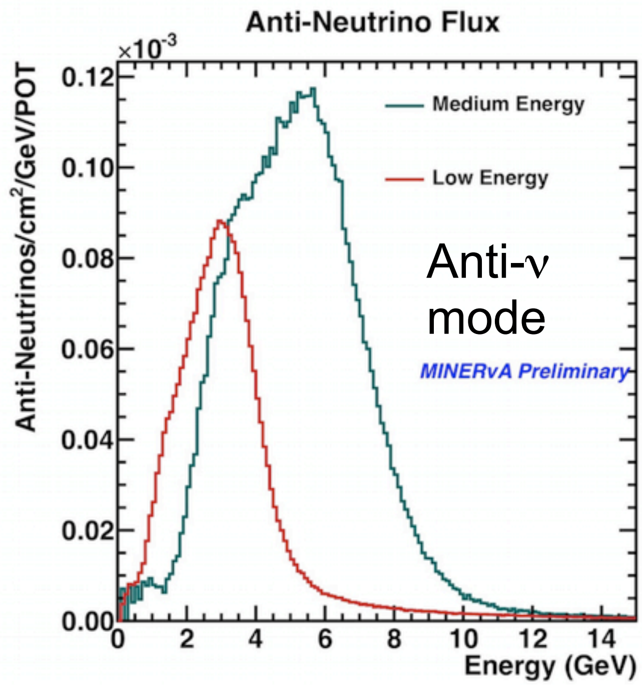


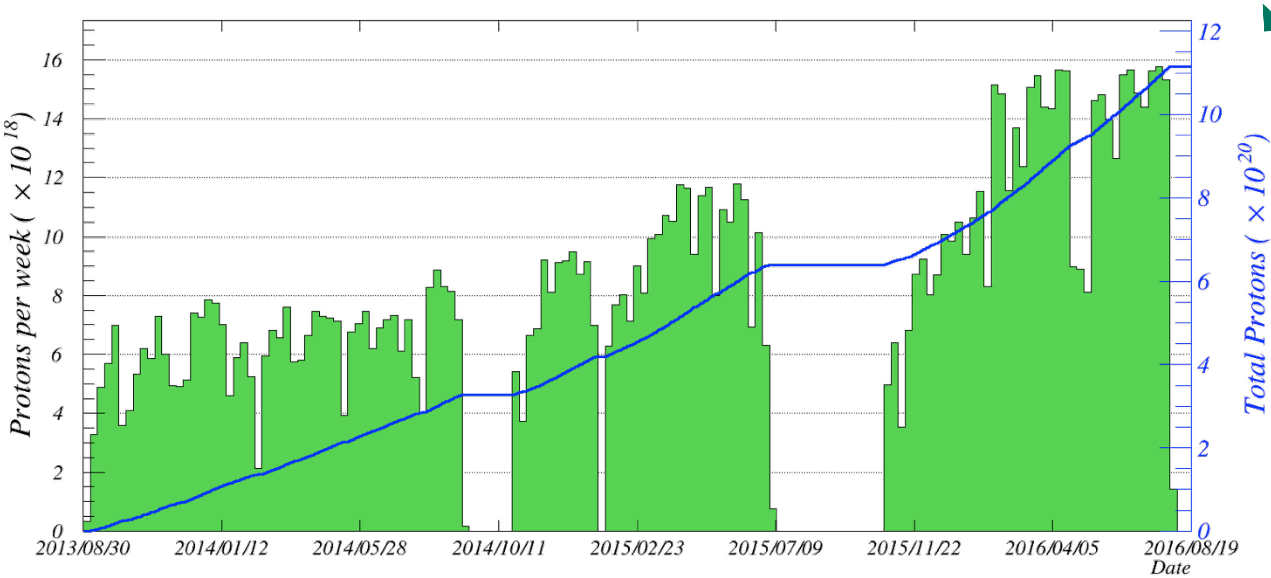


MINERvA ME Program

- More than 3X POT of LE sample
- 3.5 times more events/POT
- These statistics will allow study of nuclear effects in exclusive states
- Wider ranges of energies means wider range of kinematics to discriminate between models
- We plan to switch to ME antineutrino mode this winter after 12e20 POT

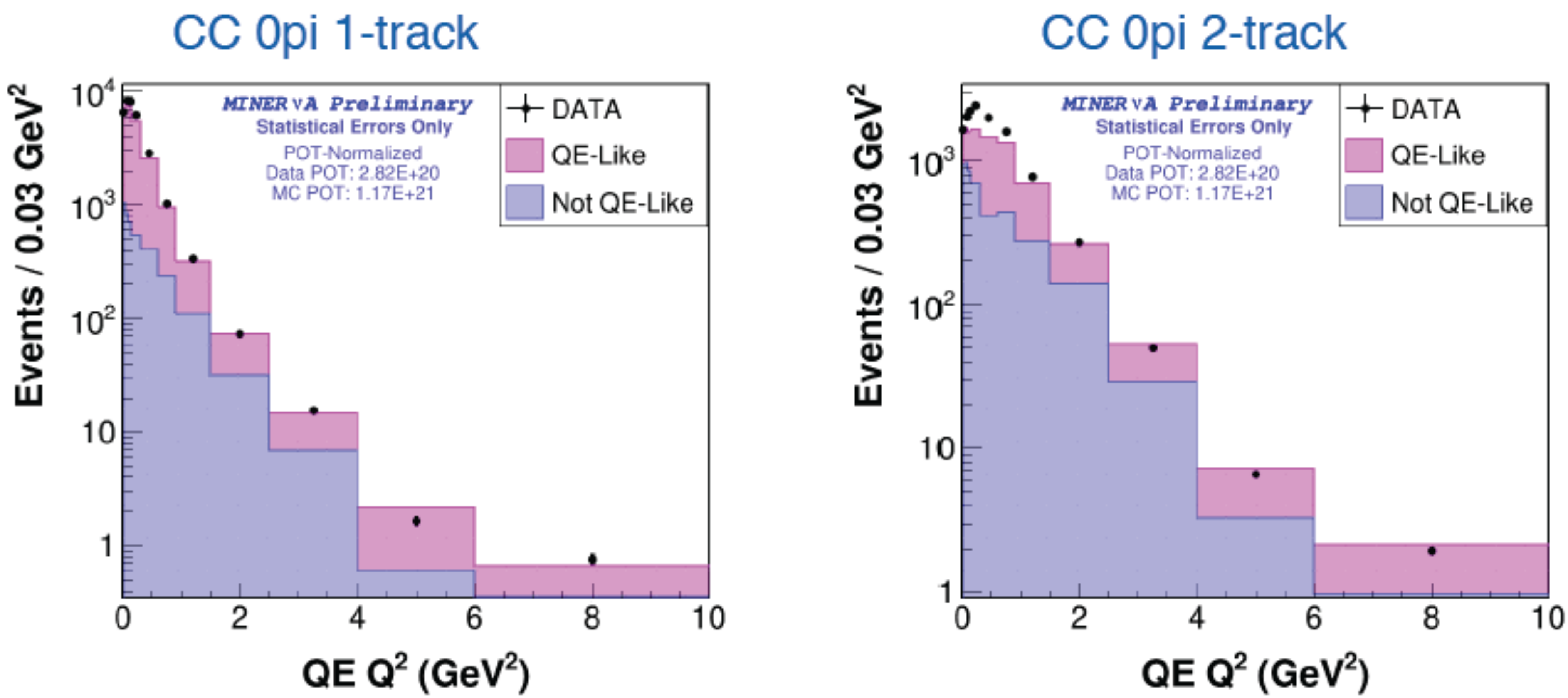




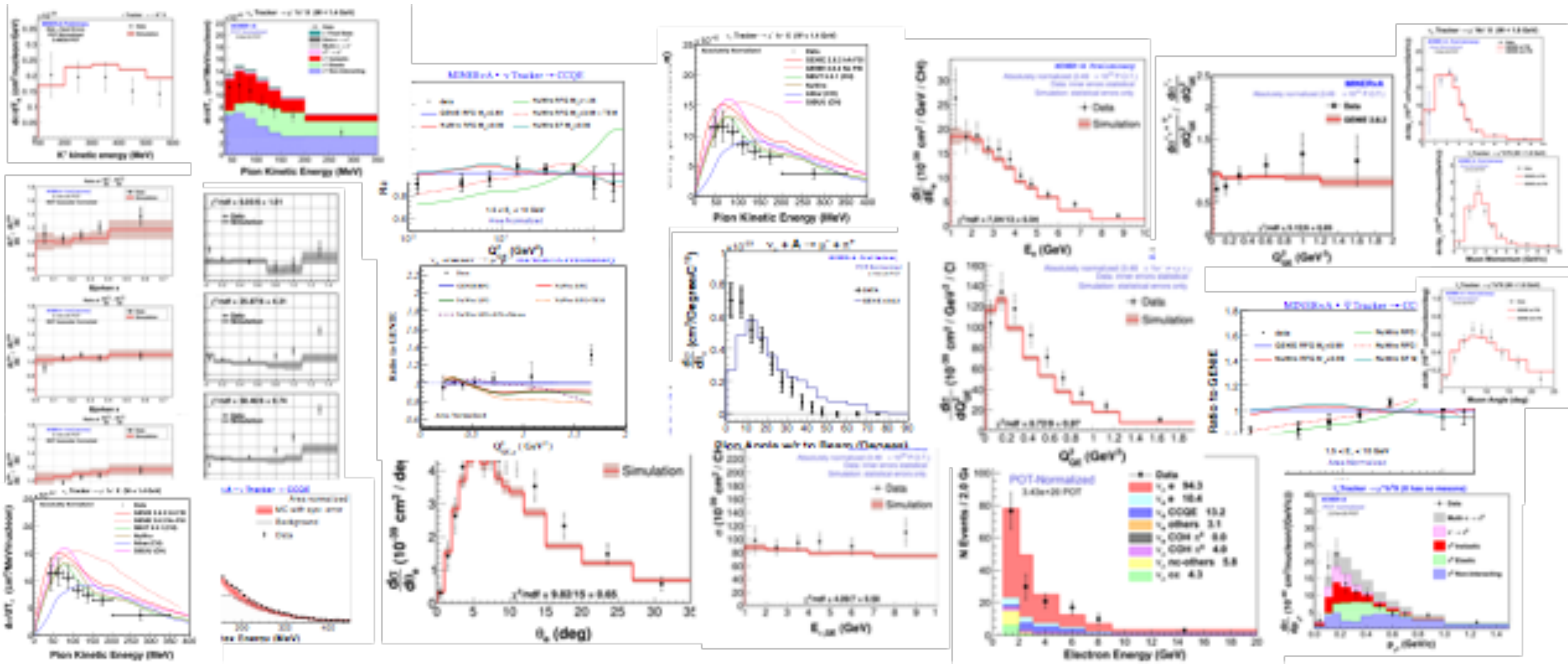


Example of increased kinematic coverage in ME data

- Less than 30% of collected data on these plots
- LE data only able to report out to $Q^2 \sim 2$ GeV^2



Recent MINERvA results… in plots



Recent MINERvA results... in citations

1. First evidence of coherent K^+ meson production in neutrino-nucleus scattering, PRL 117, 061802 (2016)
2. Measurement of Neutrino Flux using Neutrino-Electron Elastic Scattering, PRD 93, 112007 (2016)
3. Measurement of partonic nuclear effects in deep-inelastic neutrino scattering using MINERvA, PRD 93, 071101 (2016)
4. Identification of nuclear effects in neutrino-carbon interactions at low three-momentum transfer, PRL 116, 071802 (2016)
5. Measurement of electron neutrino quasielastic and quasielastic-like scattering on hydrocarbon at average E_ν of 3.6 GeV, PRL 116, 081802 (2016)
6. Single neutral pion production by charged-current anti-ν_μ interactions on hydrocarbon at average E_ν of 3.6 GeV, PLB 749 130 (2015)
7. Measurement of muon plus proton final states in ν_μ Interactions on Hydrocarbon at average E_ν of 4.2 GeV, PRD 91, 071301 (2015)
8. Measurement of coherent production of $\pi^\pm$ in neutrino and anti-neutrino beams on carbon from E_ν of 1.5 to 20 GeV, PRL. 113, 261802 (2014)
9. Charged pion production in ν_μ interactions on hydrocarbon at average E_ν of 4.0 GeV, PRD 92, 092008 (2015)
10. Measurement of ratios of ν_μ charged-current cross sections on C, Fe, and Pb to CH at neutrino energies 2-20 GeV, PRL 112, 231801 (2014)
11. Measurement of muon neutrino quasi-elastic scattering on a hydrocarbon target at E_ν~3.5 GeV, PRL 111, 022502 (2013)
12. Measurement of muon antineutrino quasi-elastic scattering on a hydrocarbon target at E_ν~3.5 GeV, PRL 111, 022501 (2013)

> Measurement of K^+ production in charged-current ν_μ interactions, arXiv:1604.01728
> Evidence for neutral-current diffractive neutral pion production from hydrogen in neutrino interactions on hydrocarbon, arXiv:1604.01728
> Cross sections for neutrino and antineutrino induced pion production on hydrocarbon in the few-GeV region using MINERvA, arXiv:1606.07127
> Neutrino flux predictions for the NuMI beam, arXiv:1607.00704

Several public results with in papers preparation

> Antineutrino quasielastic scattering
> Neutrino quasielastic scattering
> Charged current neutrino and antineutrino inclusive cross sections via the low-nu flux method

The MINERvA Collaboration (June '16)

More analysis topics than people… Consider joining us!

MINERvA Collaborating Institutions

- William & Mary (USA)
- Rochester (USA)
- Fermilab (USA)
- Rutgers (USA)
- MCLA (USA)
- Pittsburgh (USA)
- Florida (USA)
- Oregon State (USA)
- Hampton (USA)
- Minnesota-Duluth (USA)
- CBPF (Brazil)
- PUCP (Perú)
- UNI (Perú)
- Guanajuato (Mexico)
- USM (Chile)
- Geneva (Switzerland)
- Oxford (UK)