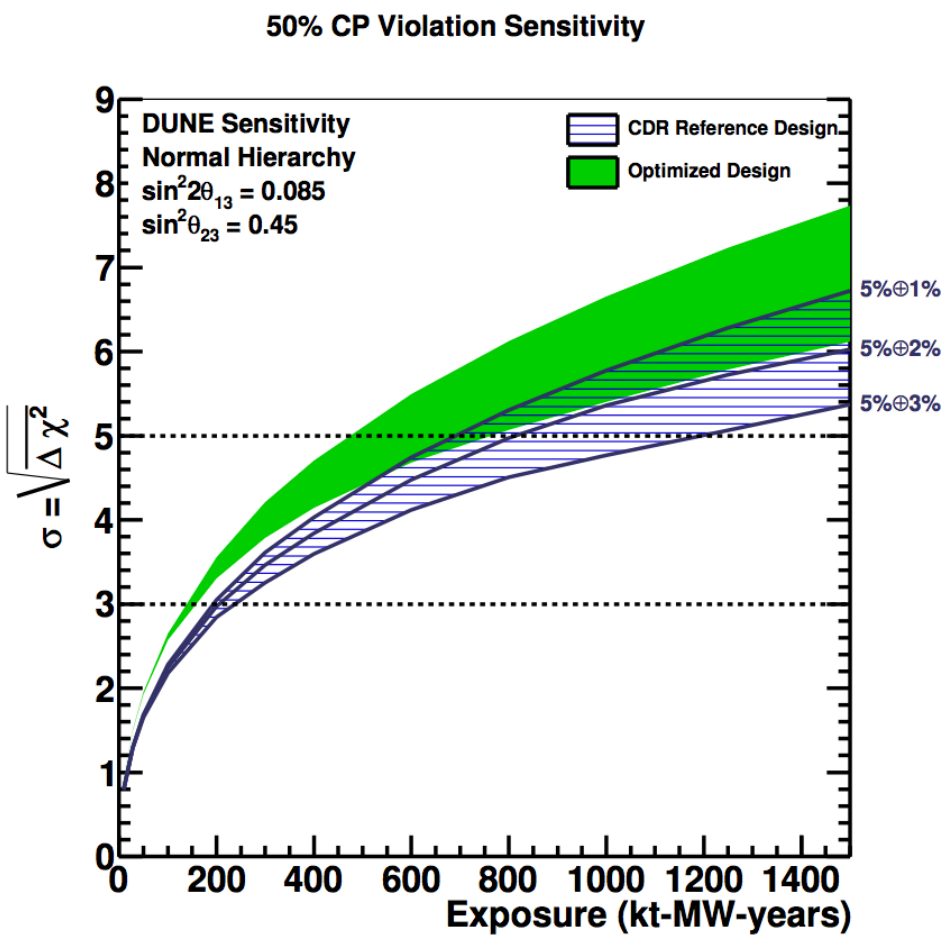
MINERvA Recent Results
On the Cross Section Road

Edgar Valencia-Rodriguez
On Behalf the MINERvA Experiment

September 25, 2017

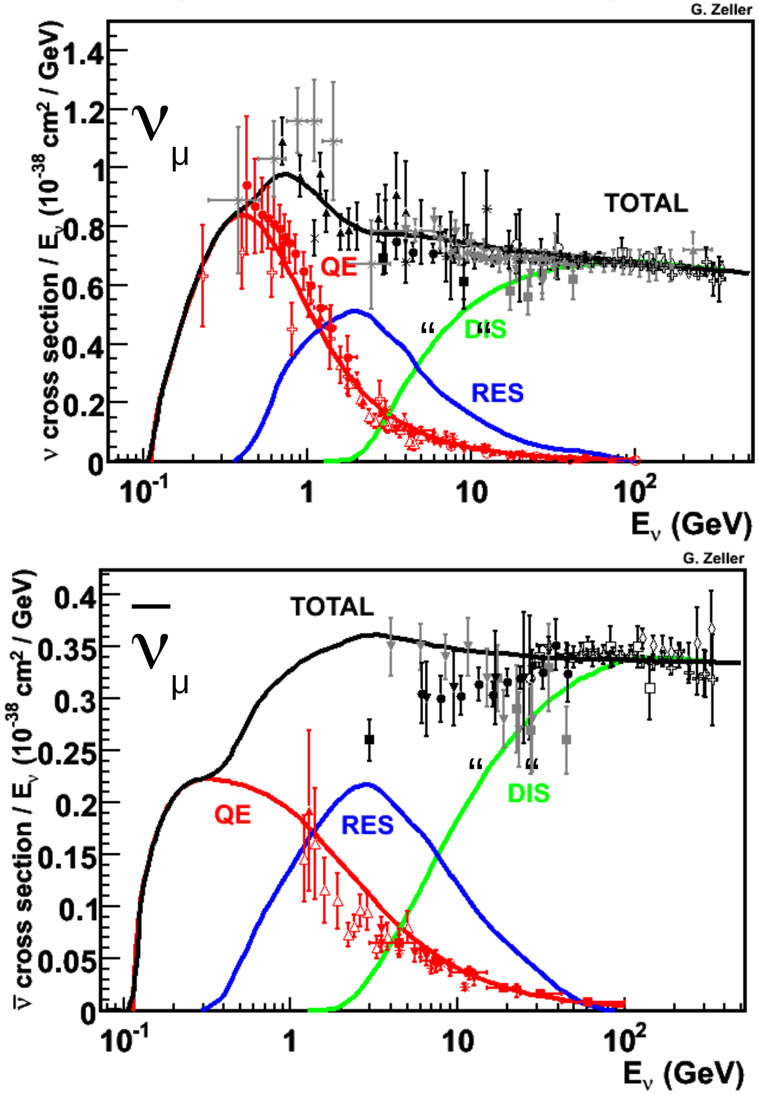
Introduction

DUNE CDR, arXiv:1512.06148

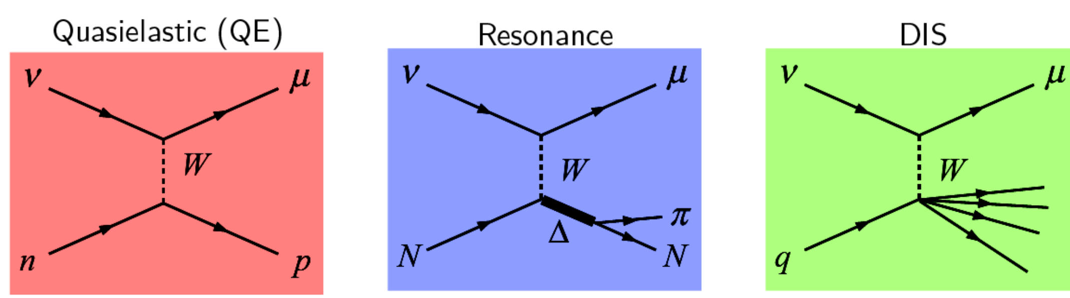


- **Systematic errors due to neutrino interaction cross sections are a large fraction of the error.**
- **Reaching low systematics goals requires control of all systematics, e.g. neutrino interaction cross sections.**
- **Accelerator-based oscillation experiments rely on neutrino-nucleus interaction models in neutrino event generators.**
- **Need high precision data to improve Models: MINERvA goals**

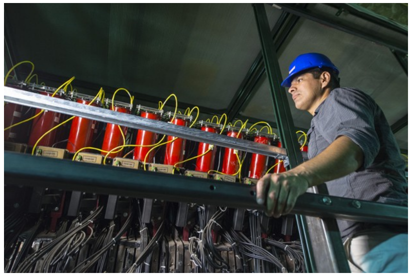
Rev. Mod. Phys. 84, 1307–1341 (2012)
(includes MiniBooNE results)

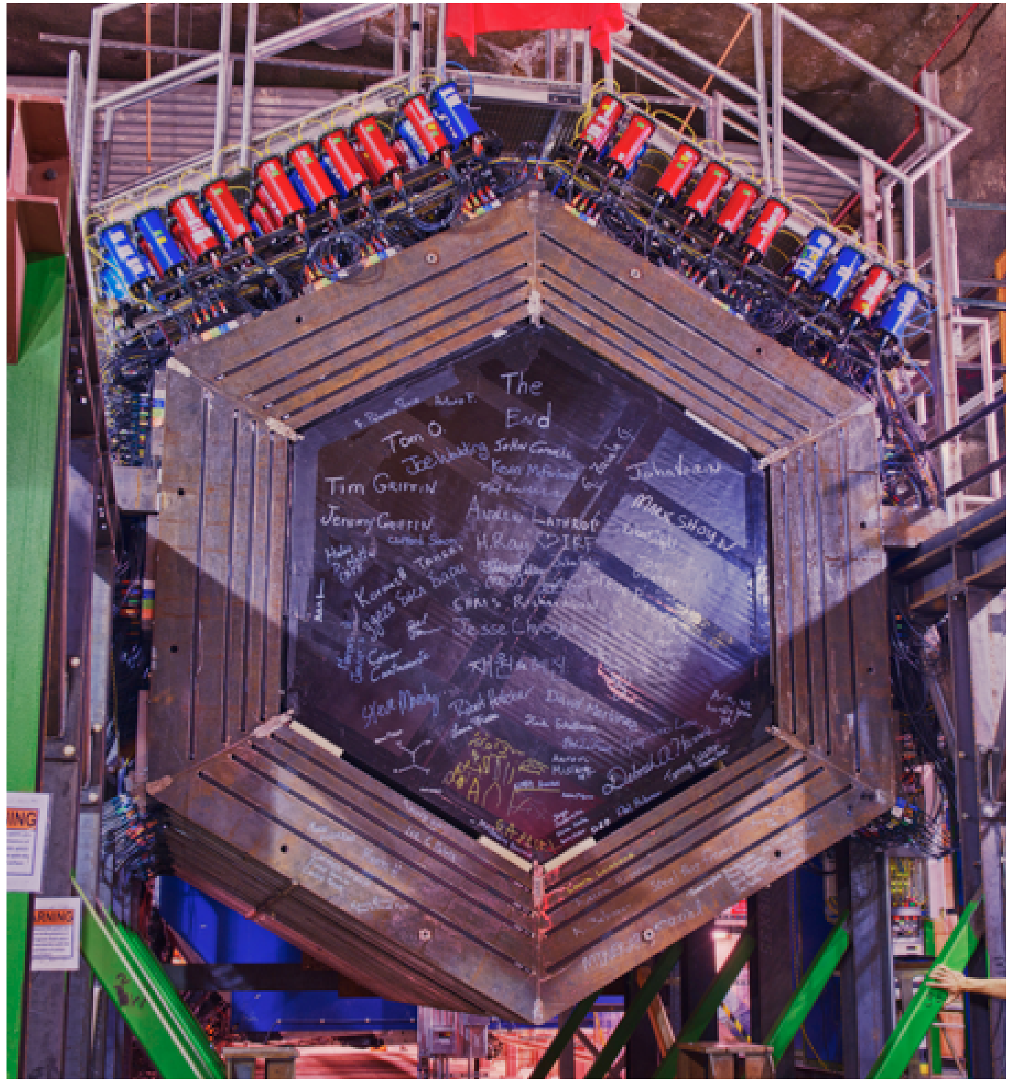


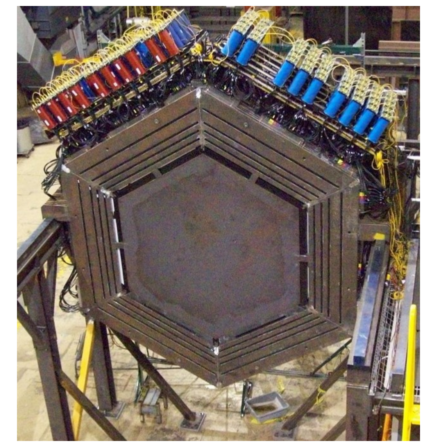
- Oscillation experiments (DUNE, NOvA, T2K, etc.) measure neutrino energy Eν in the 0.5-20 GeV region, where many interactions channels are open.
- This energy range is complicated.
- These interactions channels are signal and the majority of backgrounds in the oscillation experiment.

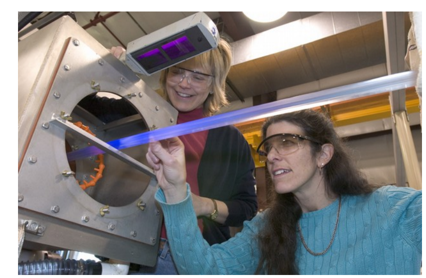


The MINERνA Experiment







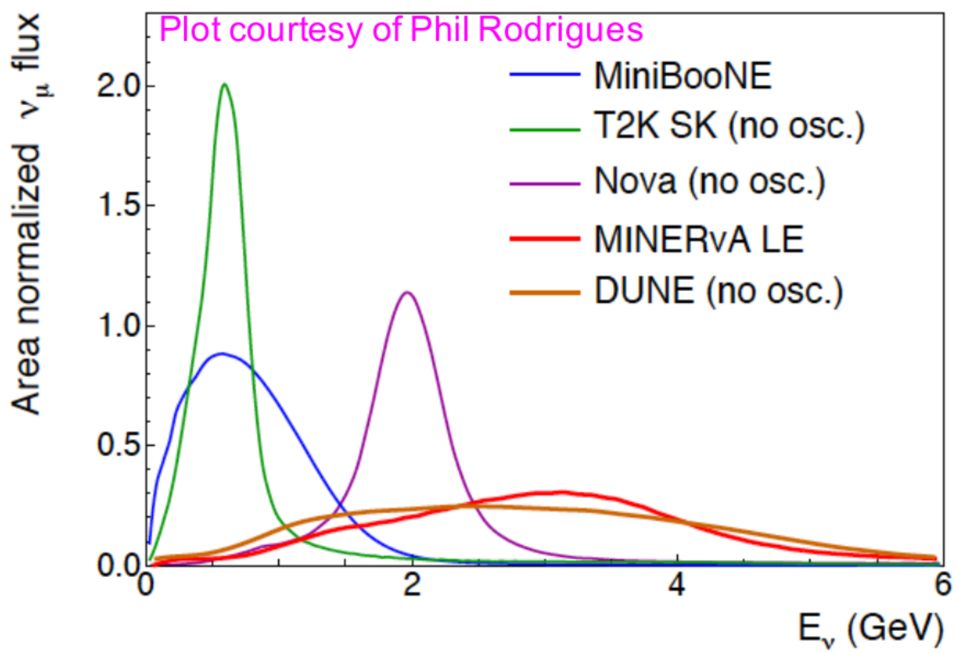


MINERvA Experiment

Overview

- **High precision measurement of neutrino interactions in Eν = 0.5 ~10 GeV**
- **Located ~100 m underground at Fermilab in the NuMI beamline.**
- **Exposed to neutrino/antineutrino beams in several different wide-band tunes**
- **Many different nuclei in the same beam (He, H20, C, Fe, Pb).**
- **Inclusive and exclusive final states**
- **Unique overlap to the DUNE Flux.**
- **Statistically independent of any oscillation measurement.**
- **MINERvA's results are very important to improve the modeling in generators.**

Dedicated neutrino-nucleus cross-section experiment.

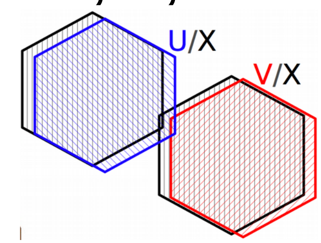


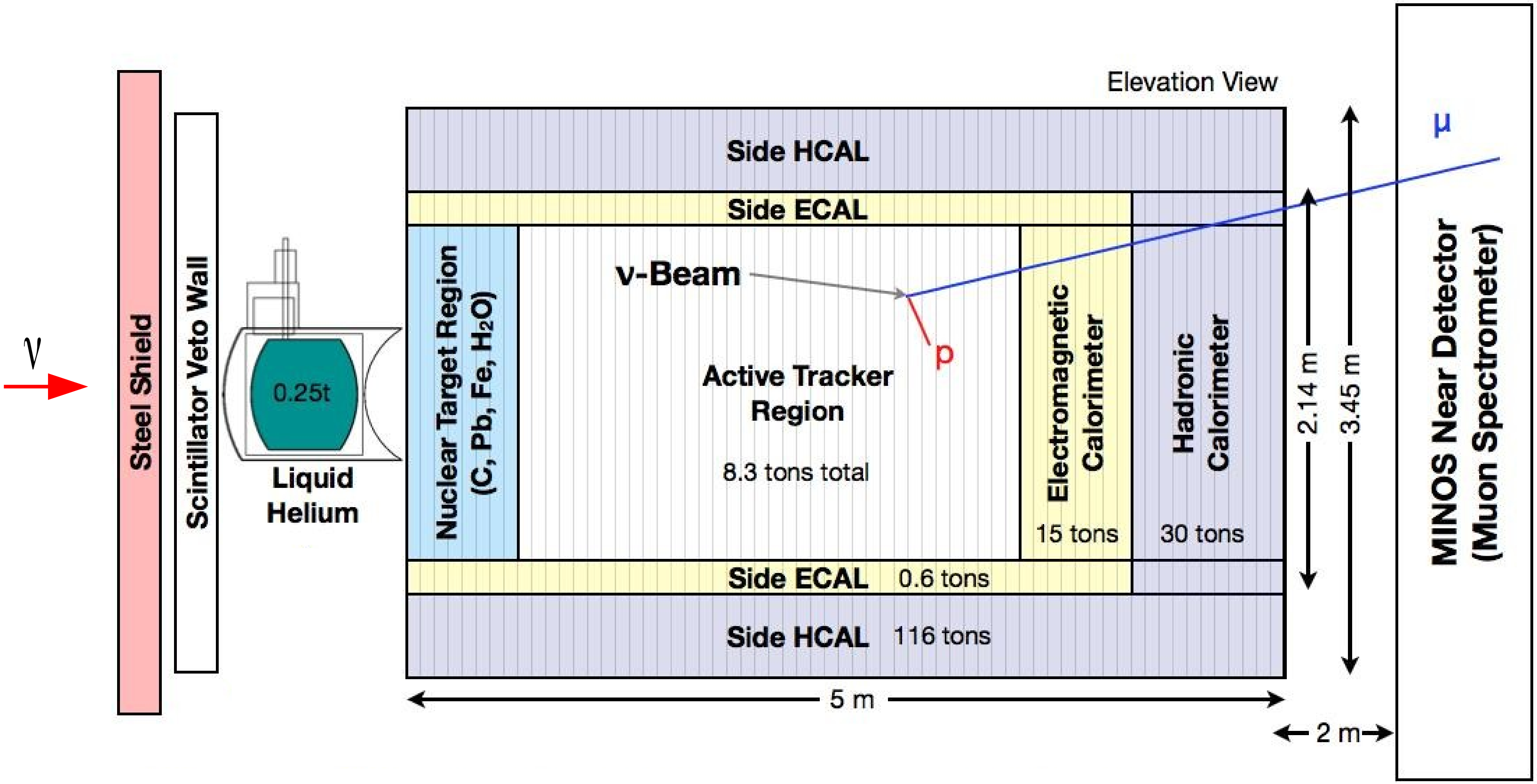
MINERvA
Main INjector ExperRiment for ν-A

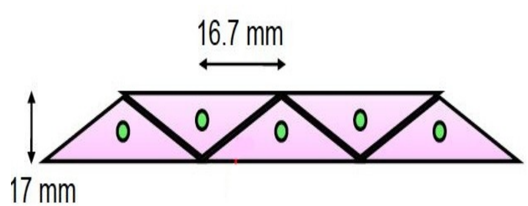
MINERvA Experiment
Detector

Active segmented polystyrene scintillator strips.
Passive nuclear targets of He, C, Water, Fe and Pb.

3 strip orientations
-60°, 0°, +60°

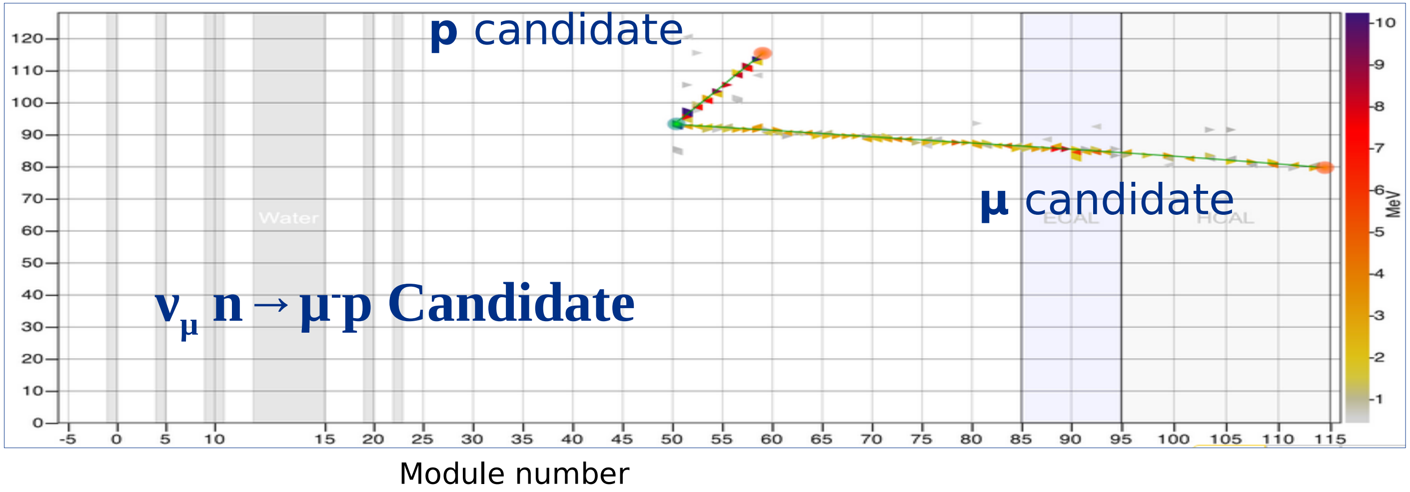


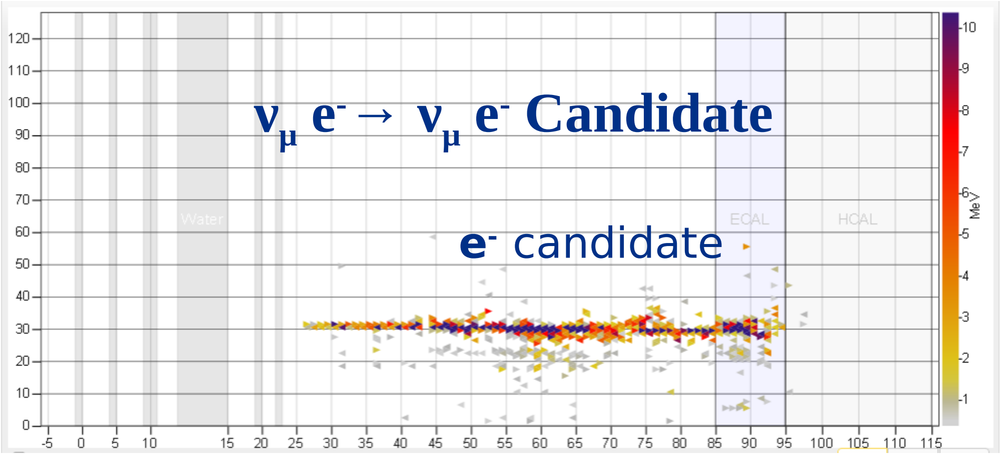


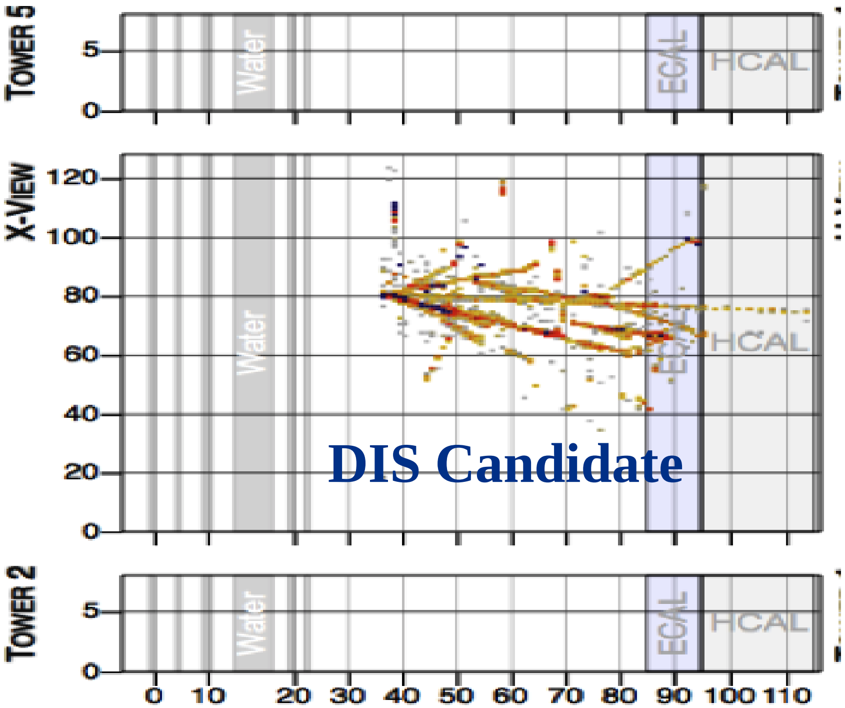


Single Plane Resolution: 2.65 mm.
Single Hit Timing resolution 4.20 ns.

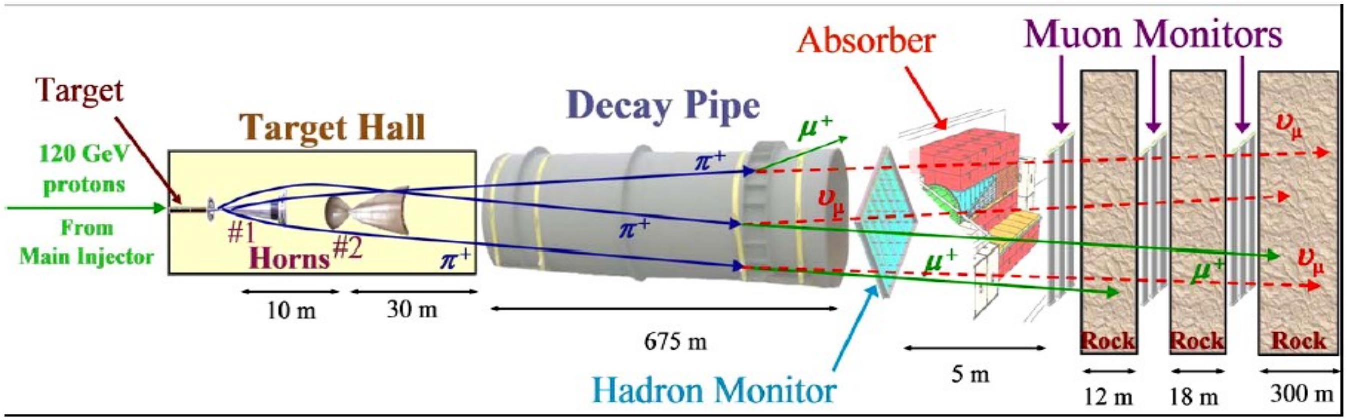
MINERvA Experiment
Event Display

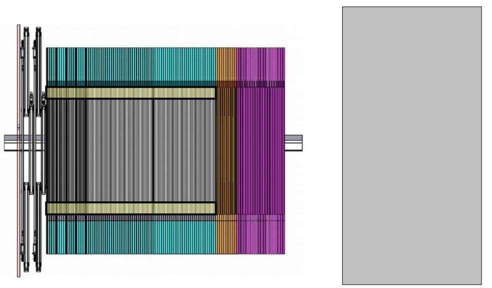


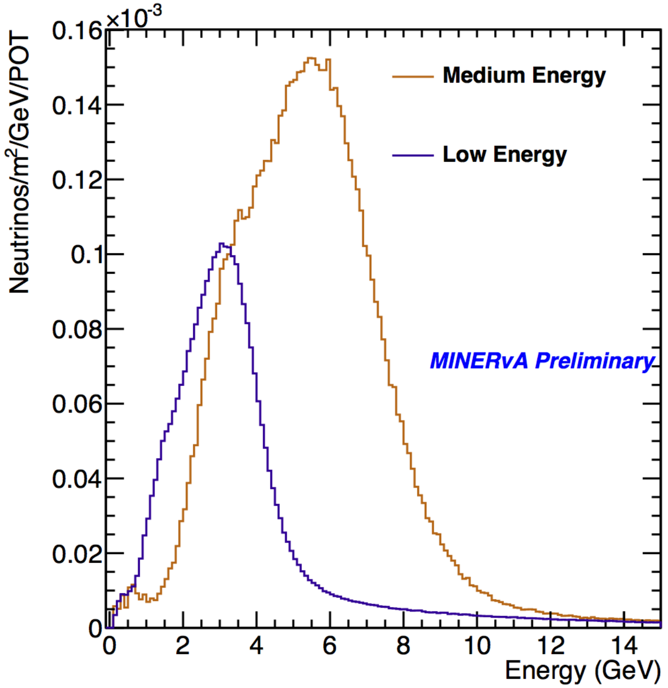




NuMI Beamline
Detector



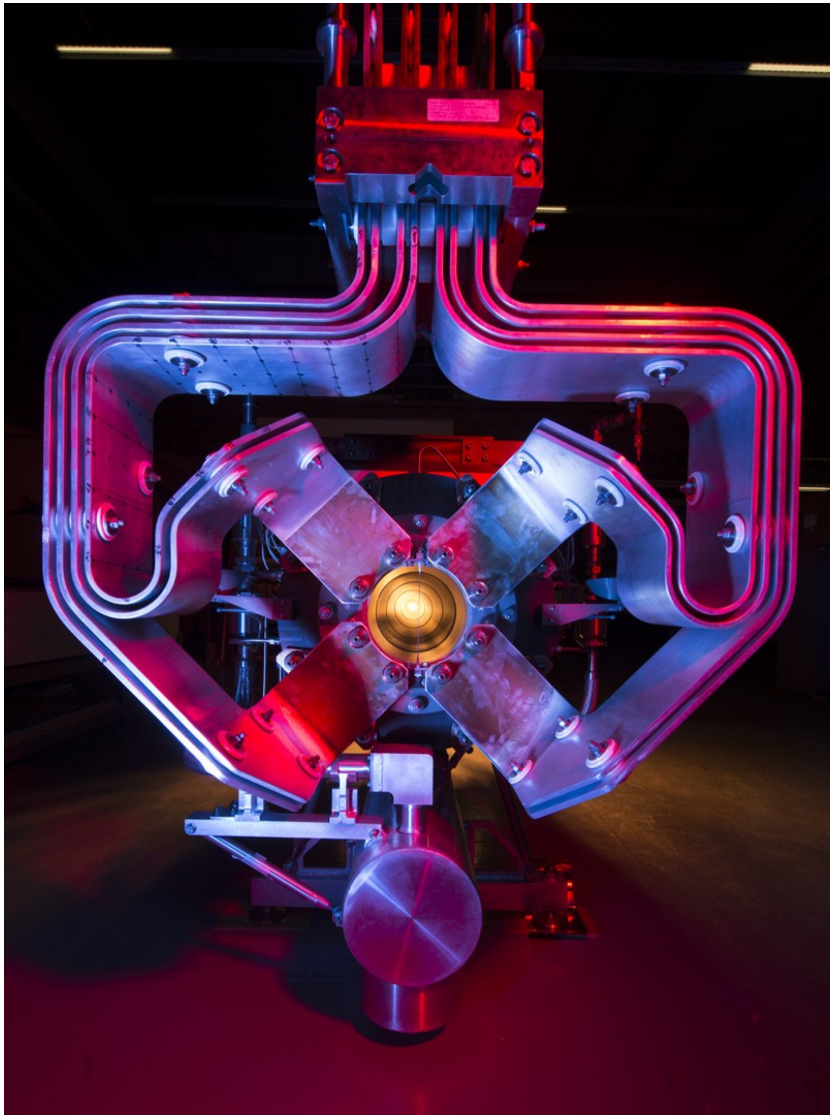


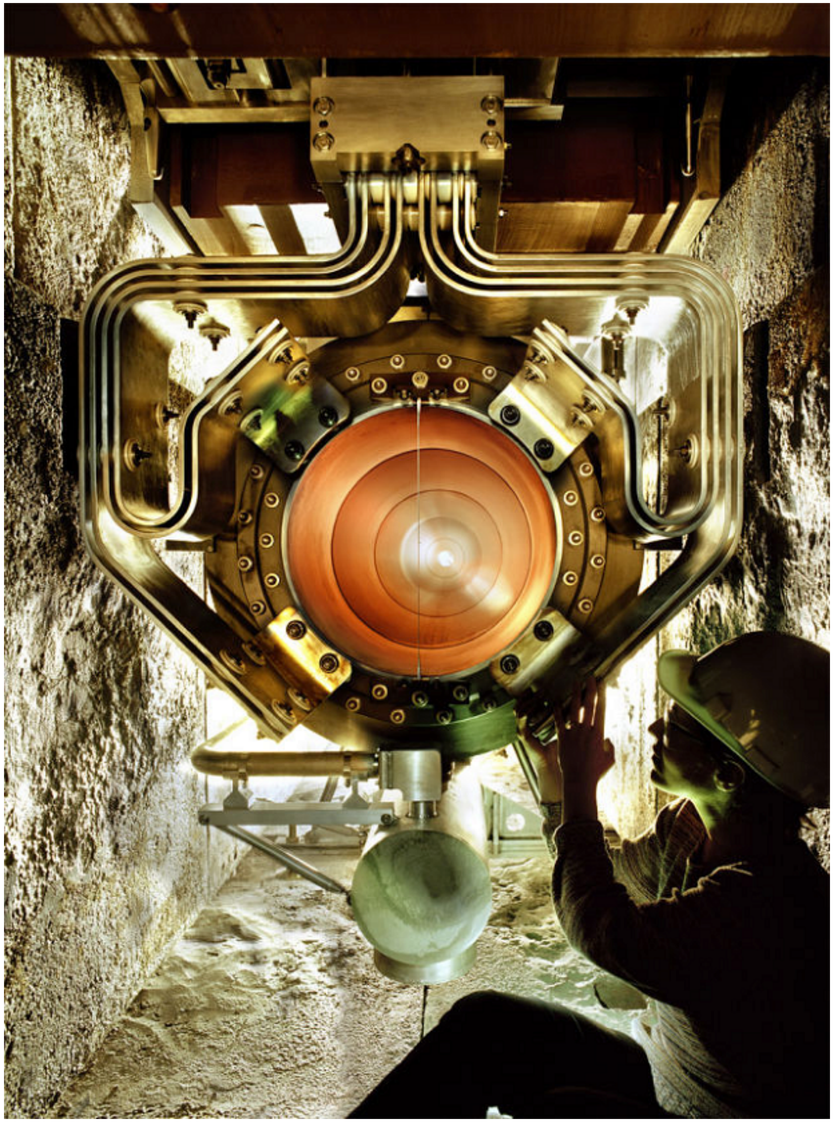


The NuMI beamline provides the most powerful neutrino flux in the world.

Range	Mode	Exposure (e20 POT)
Low Energy	Neutrino	3.43
Low Energy	Antineutrino	2.01
Medium Energy	Neutrino	9.45
Medium Energy	Antineutrino	Taking Data

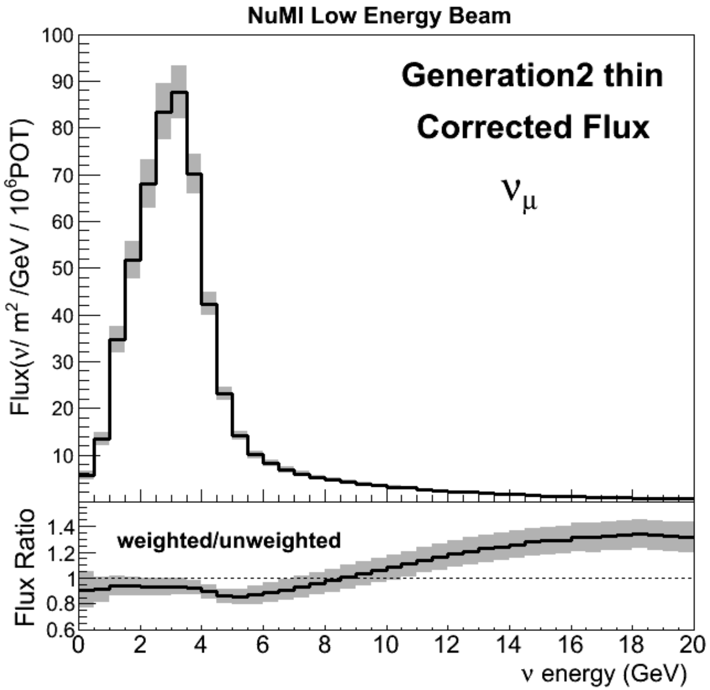
Determining the Neutrino Flux

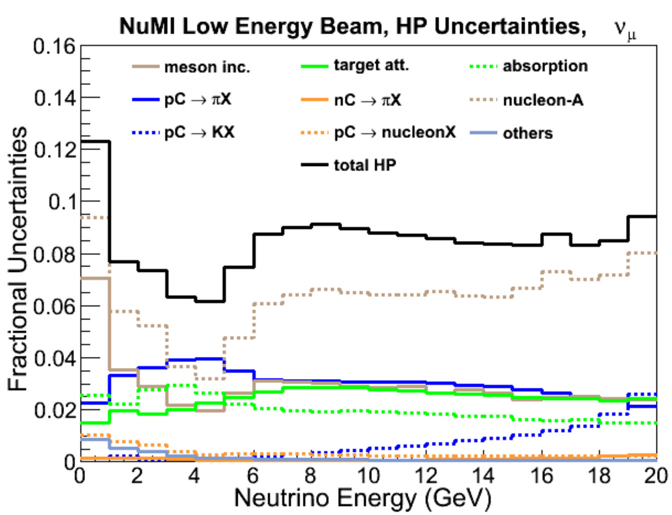




Flux Predictions Using External Data

Phys. Rev. D 94, 092005 (2016)

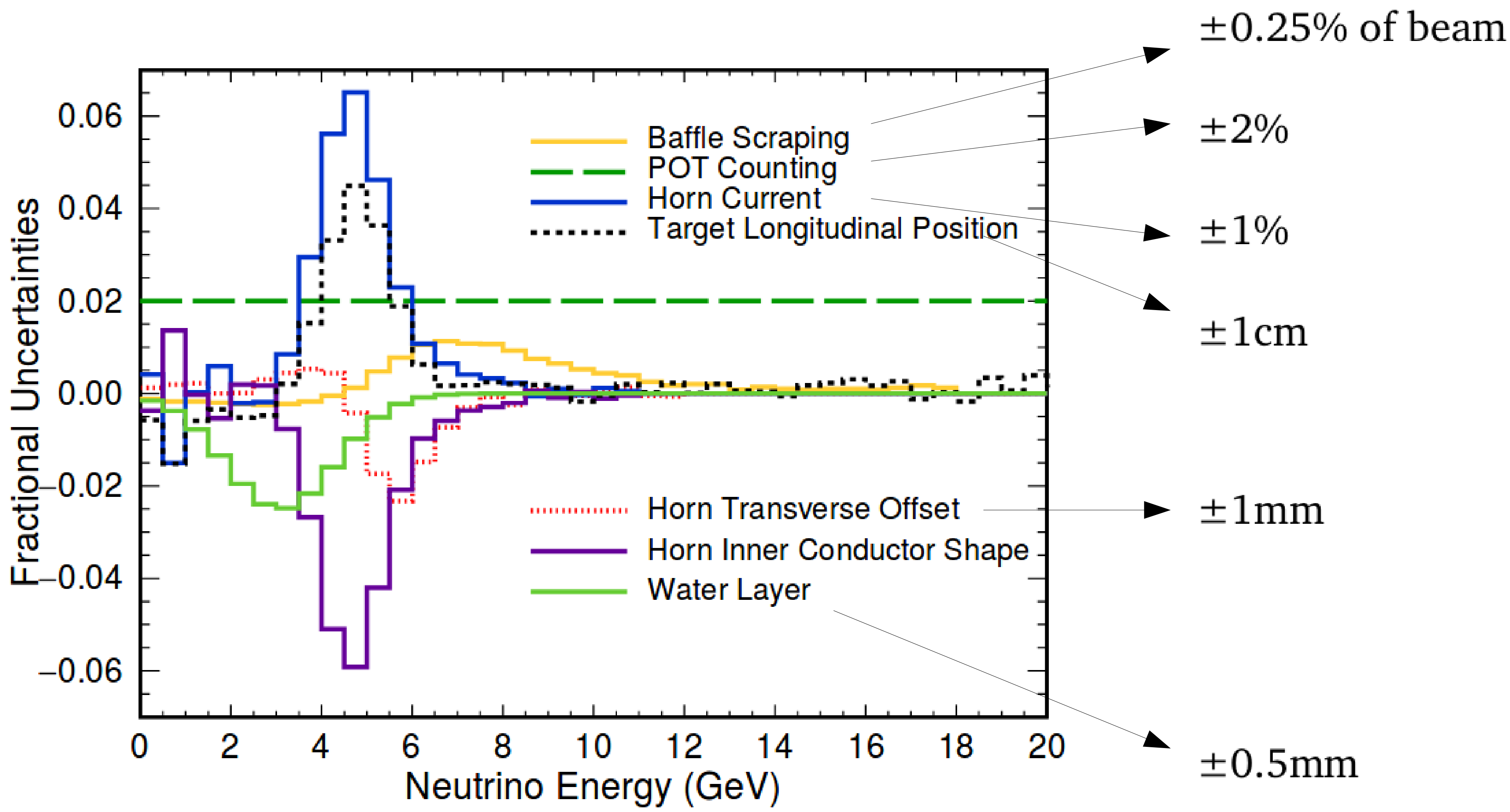




- The flux prediction is made via Gean4 simulation on NuMi beam line with external data from NA49 & NA61 experiments.
- The new flux predictions with it improvements, principal changes to beamline geometry and updates to the simulation called PPFX
- PPFX package available at Fermilab also predicts the DUNE flux.
- We expect ~5% errors for the ME with the addition of constraints from in situ measurements.
- Expect DUNE hadron production uncertainties to look similar, without further hadron production data.

Flux Predictions Using External Data

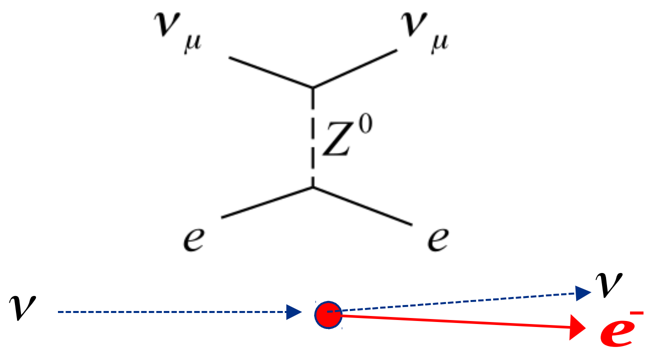
Beam Focusing Uncertainties



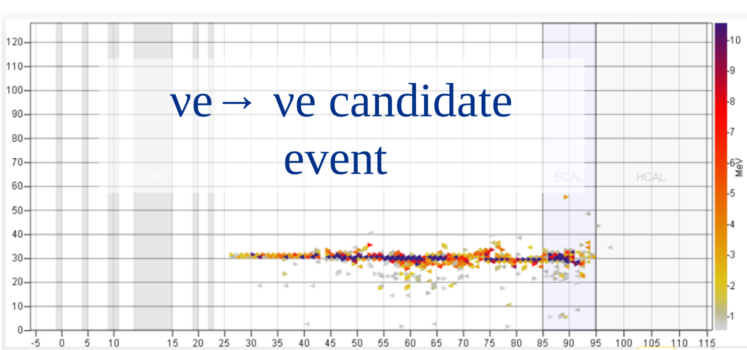
Flux Constraint from the Internal Data
Normalization form Neutrino Electron Scattering

Phys Rev. D 93, 112007 (2016)

Very forward single electron final state

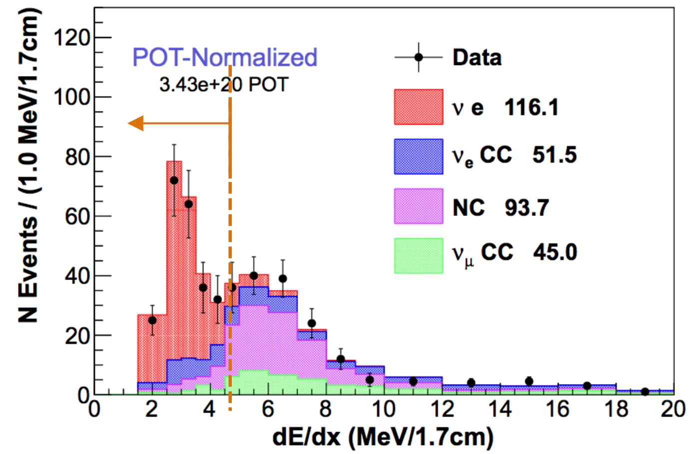


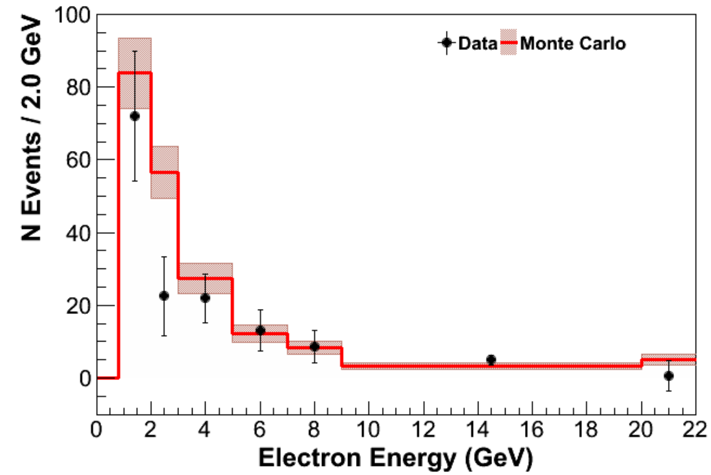
- **Well understood electroweak process**
- **Signal in MINERvA is a single electron moving in the beam direction**



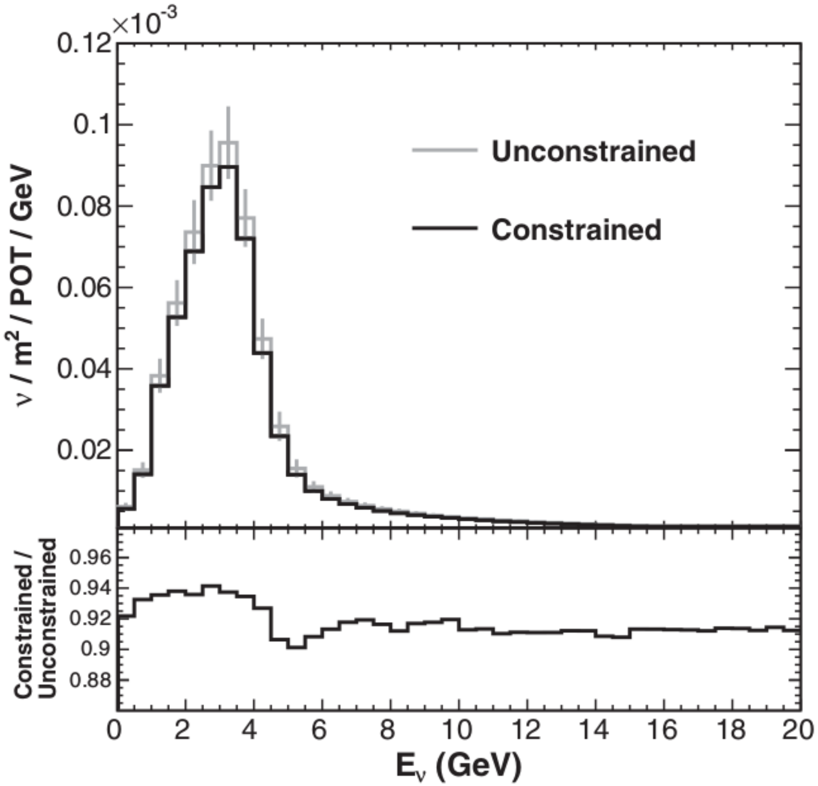
Module Number

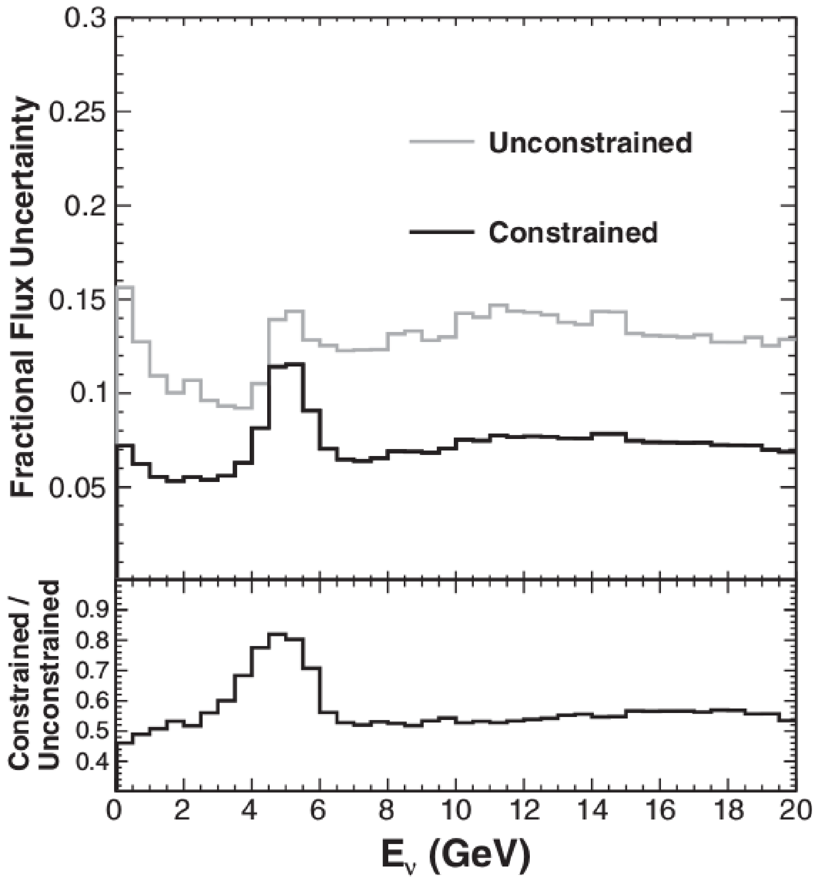
Use early ionization to reject photons and direction to reject interactions on nucleons





Flux Constraint from the Internal Data
Normalization form Neutrino Electron Scattering





- **This statistically limited result reduces MINER*v*A's flux uncertainties as a function of energy by 10-20% (of the a priori uncertainties).**
- **Systematics estimation shows what uncertainties DUNE will need to reduce to achieve 1-2% flux constraint with this method: mostly related to neutrino-nucleus interaction modeling.**

Flux Constraint from the Internal Data
Flux Shape from Low Nu Scattering

Phys. Rev. D 94, 112007 (2016)

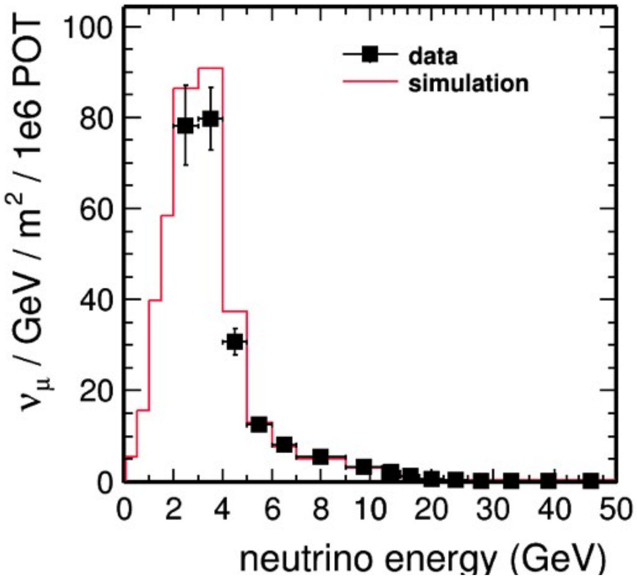
- **Charged-current scattering with low hadronic recoil energy ν is flat as a function of Eν**

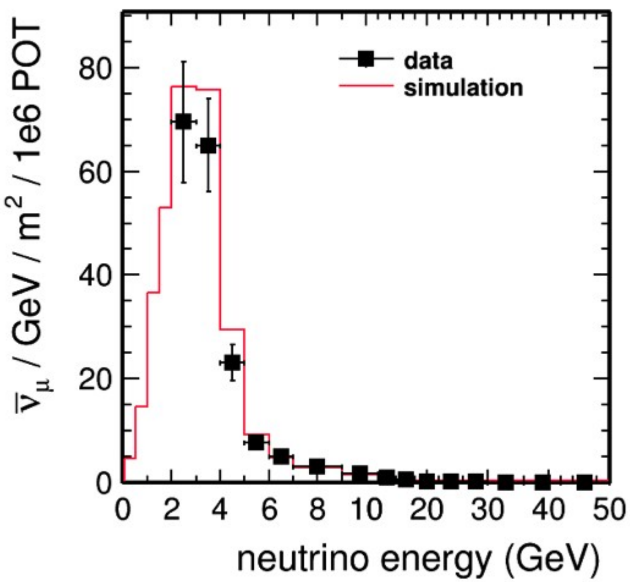
$$\frac{\mathrm{d}\sigma}{\mathrm{d}\nu} = A\left(1 + \frac{B}{A}\frac{\nu}{E_\nu} - \frac{C}{A}\frac{\nu^2}{2E_\nu^2}\right)$$

- **where A, B, and C depends on Integrals overs structure functions or form factors, in the low energy limit.**

- **Gives a measurement of the flux shape**

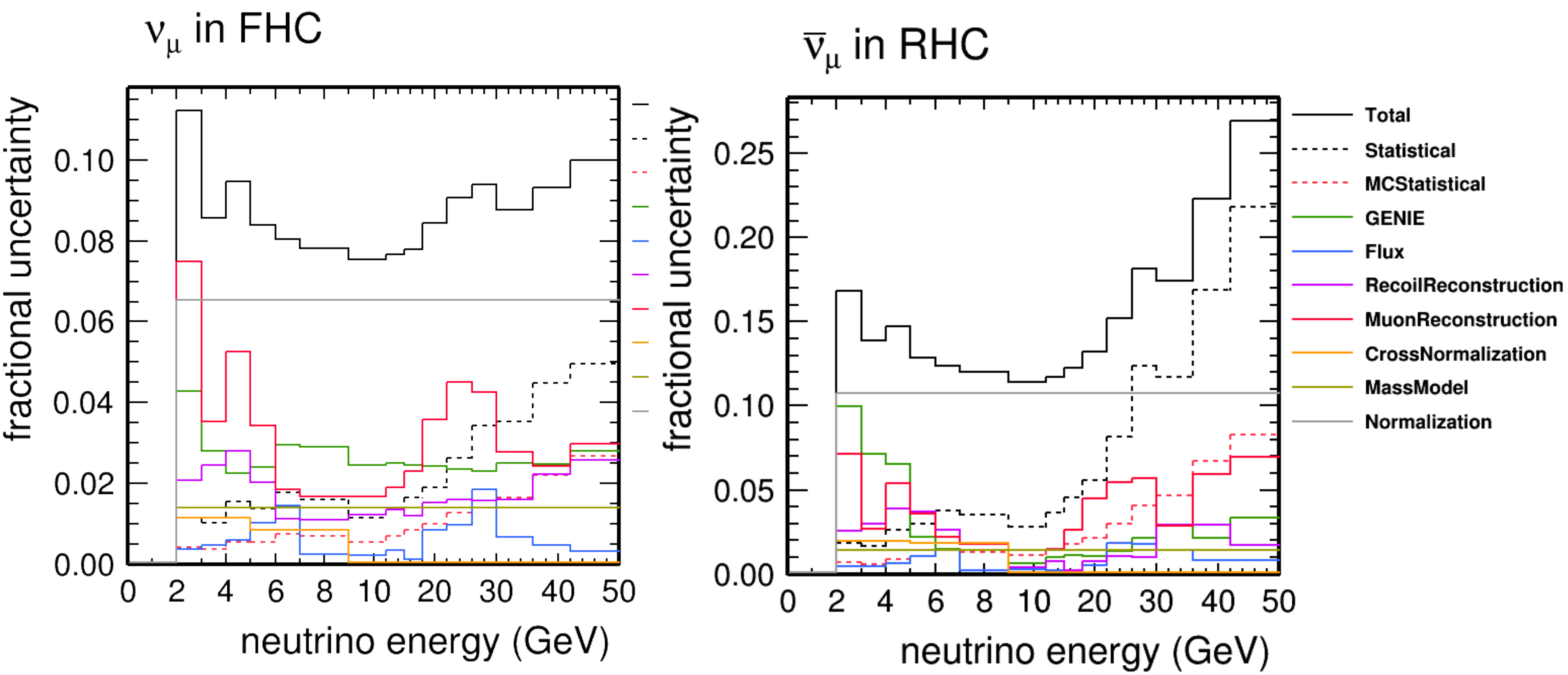
- **Low-ν method confirms the flux prediction made with external data: PRD 95, 072009(2017), PRD 93, 112007(2016).**





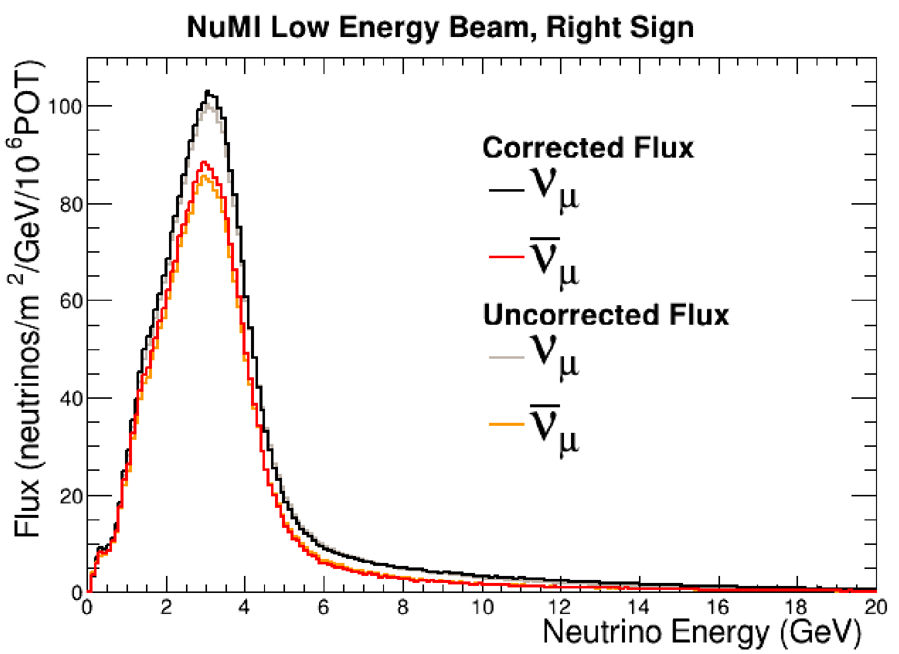
Flux Constraint from the Internal Data
Normalization from Low Nu Scattering

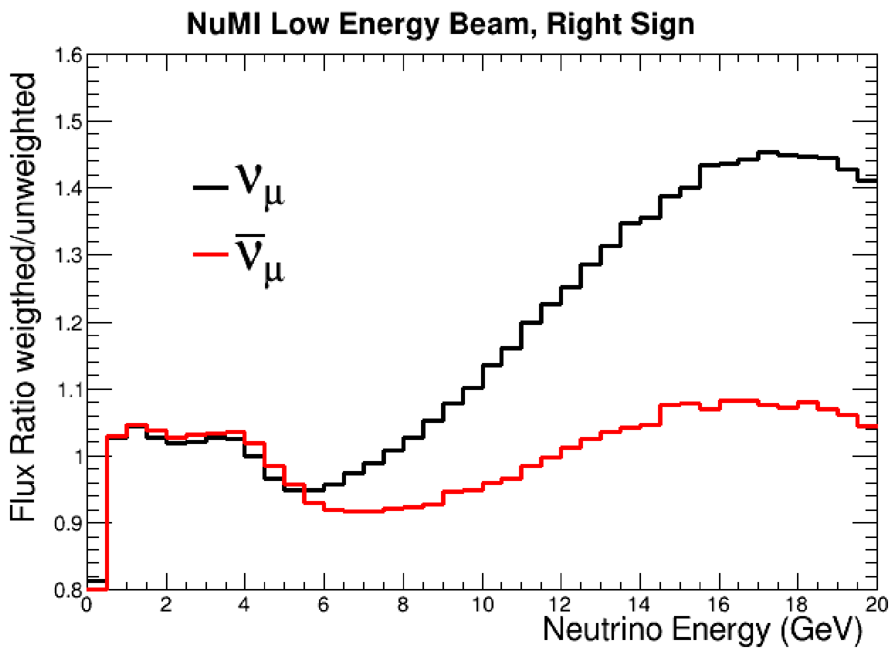
- **The external normalization uncertainty dominates over the shape-dependent uncertainties.**
- **Muon energy reconstruction contributes a significant uncertainty at lower neutrino energies.**



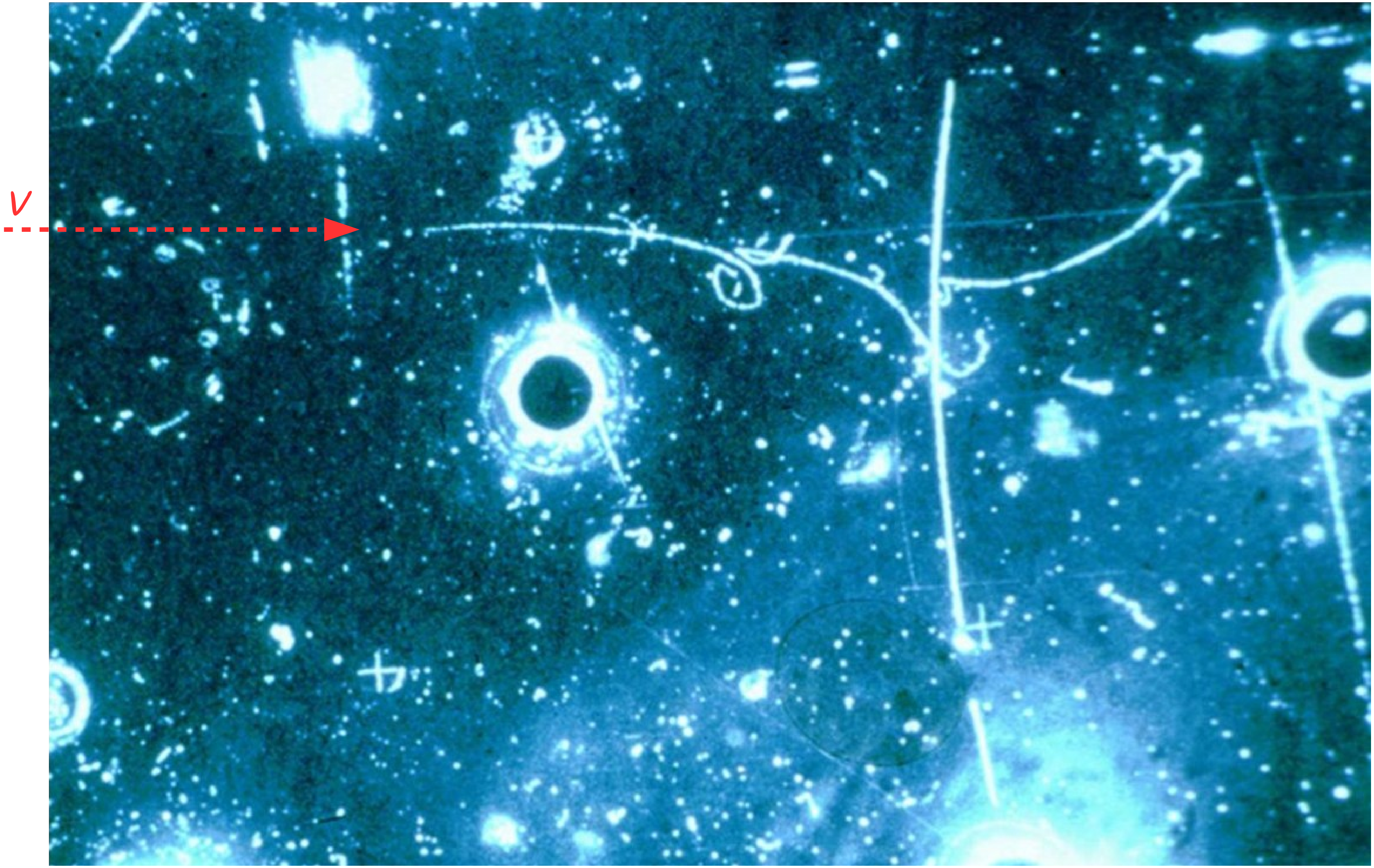
Flux Constraint from the Internal Data
Normalization form Low Nu Scattering

- A byproduct of this analysis is the ν_μ and $\bar{\nu}_\mu$ flux measurements, both for the forward and reverse horn polarities that have been used in the Low Energy NuMI beamline configuration.
- This is the first time a low-ν based technique has been used in the NuMI antineutrino-enhanced beam tune.
- This measurement is the lowest energy application of the low-ν-flux technique, and demonstrates that the technique is applicable to future neutrino beams operating at few-GeV energies



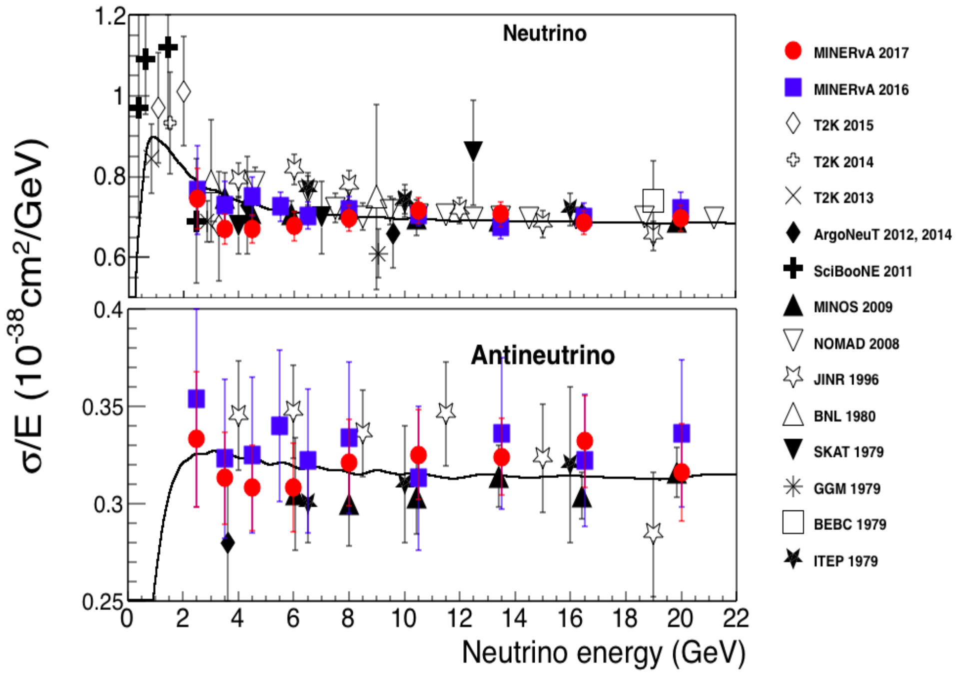


Cross Sections



Inclusive CC Scattering

Phys. Rev. D 95, 072009 (2017)

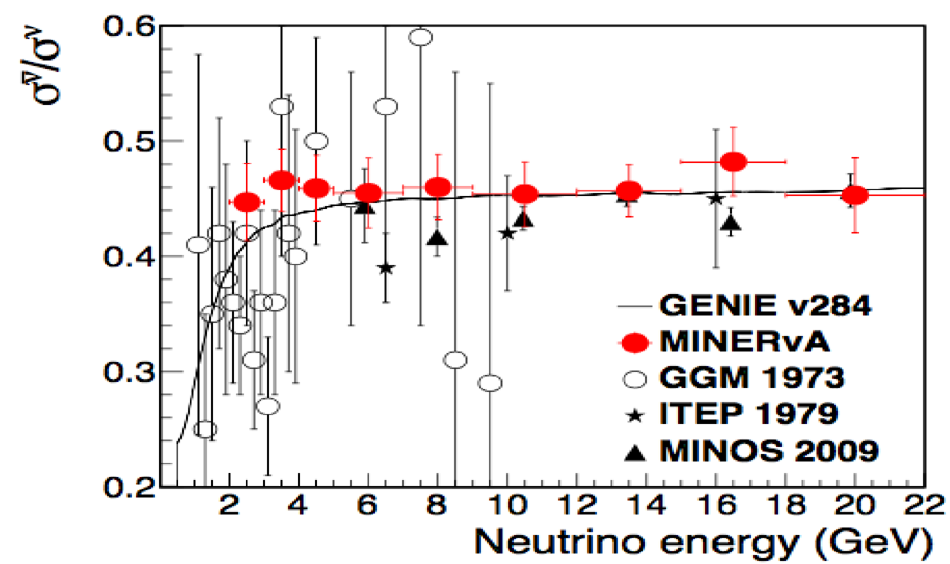


- **Antineutrino cross section result is the most precise to date below 6 GeV (errors dominated by statistical precision)**
- **Shows that the technique is applicable to future neutrino experiments operating at multi-GeV energies**

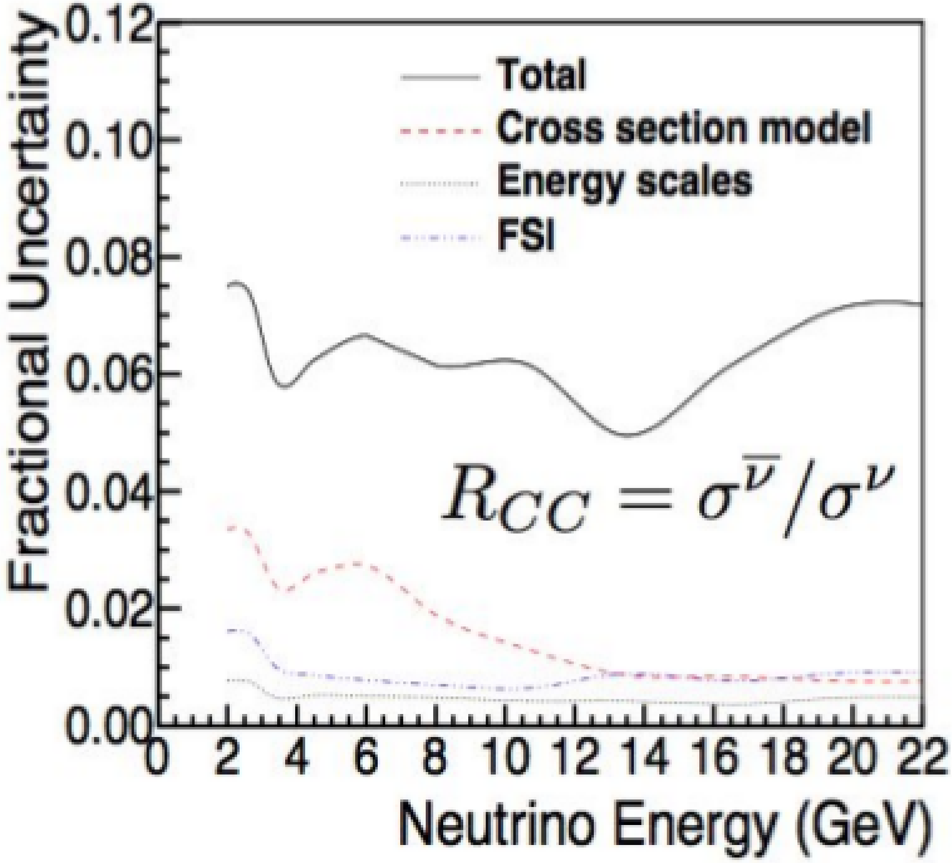
- **Long-Baseline oscillation experiments will measure a ratio of oscillation probabilities to constraint CP violation.**

$$\mathcal{A}_{CP} = \frac{P(\nu_\mu \rightarrow \nu_e) - P(\overline{\nu}_\mu \rightarrow \overline{\nu}_e)}{P(\nu_\mu \rightarrow \nu_e) + P(\overline{\nu}_\mu \rightarrow \overline{\nu}_e)}$$

- **New precise $\sigma_\nu/\sigma_{\bar{\nu}}$ ratio relevant to δ_{CP} measurement using the Low Nu Method.**

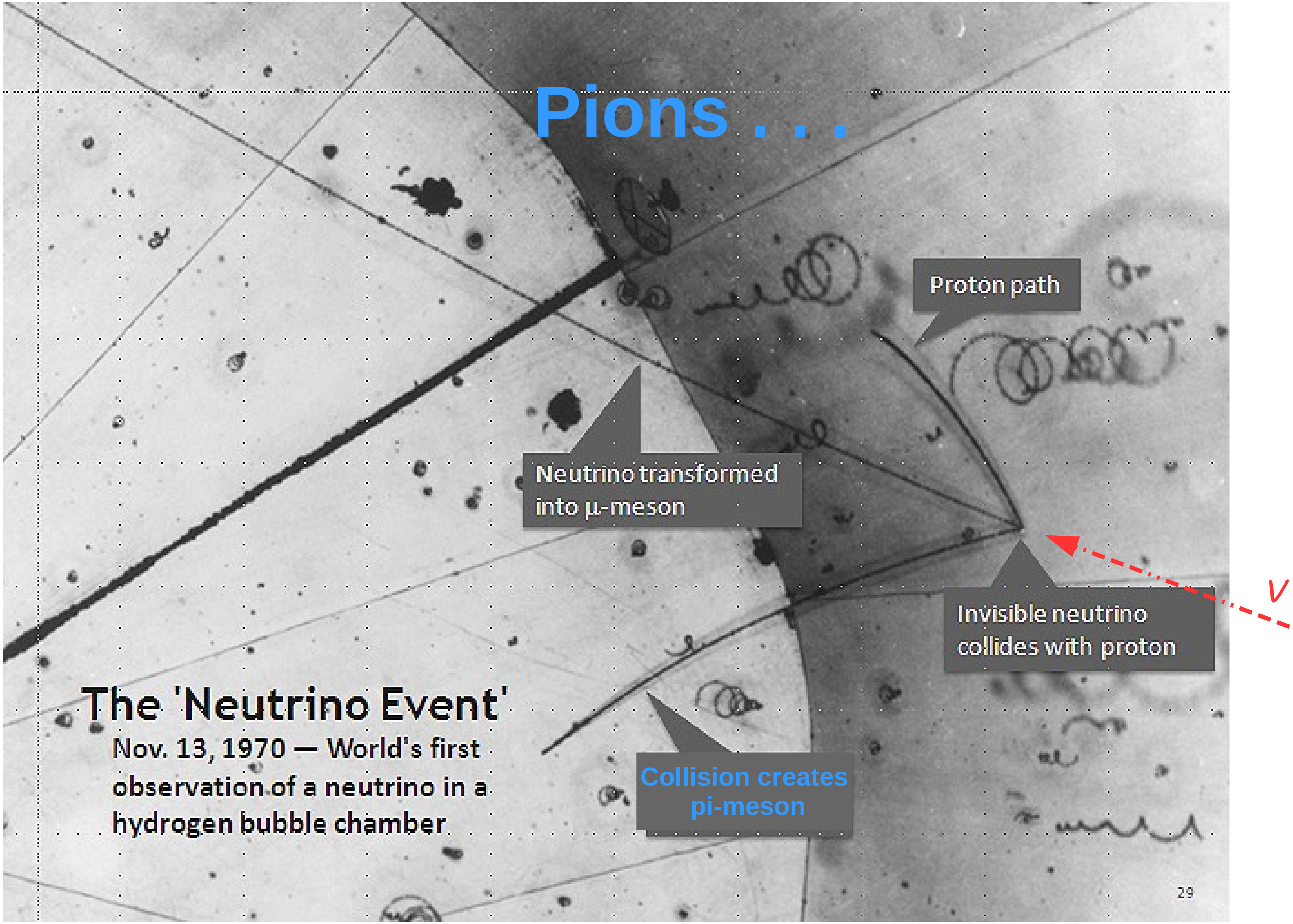


Inclusive CC Scattering
Systematics Uncertainties



- **Ratio**
  - **Common systematics of neutrino and antineutrino cross sections partially cancel in the ratio.**
  - **Statistical uncertainty dominates**

Pions . . .


Proton path
Neutrino transformed into µ-meson
Invisible neutrino collides with proton
ν
Collision creates pi-meson
The 'Neutrino Event'
Nov. 13, 1970 — World's first observation of a neutrino in a hydrogen bubble chamber

Neutrino and Antineutrino Single Pions Production

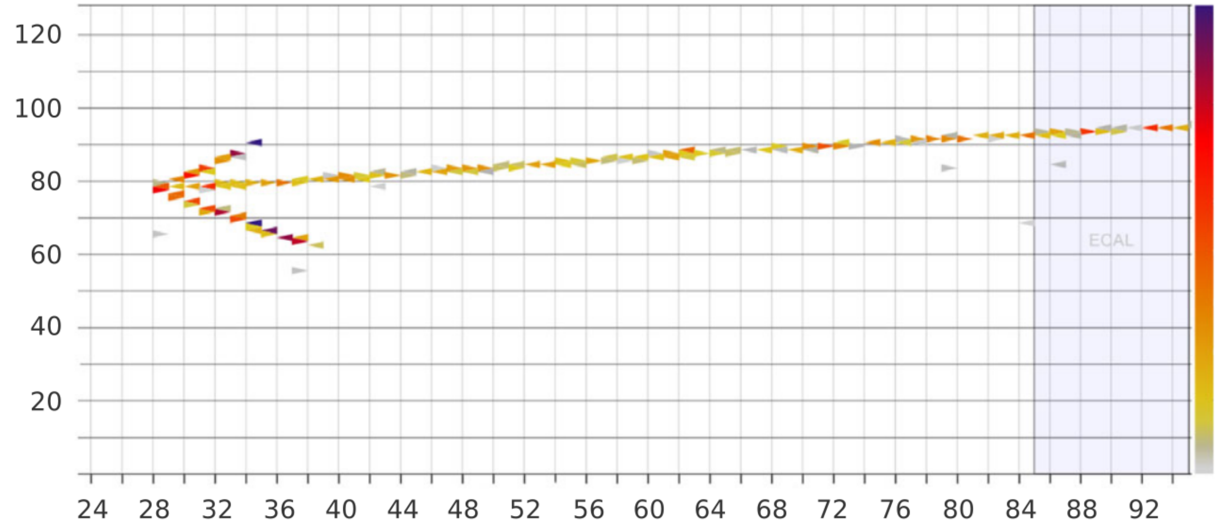
Phys. Rev. D 94, 052005 (2016)

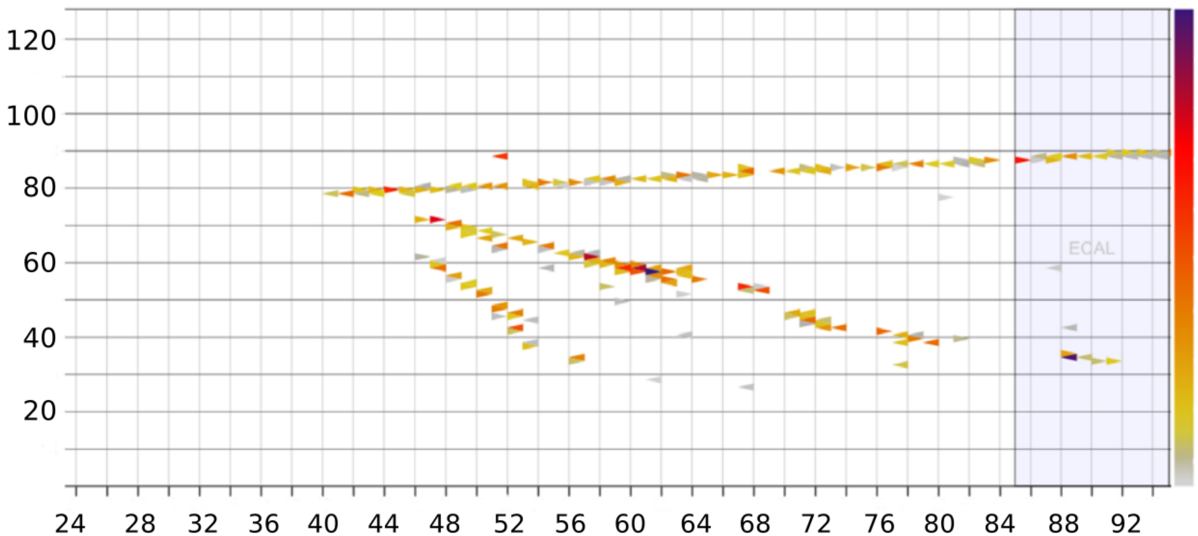
Neutrino

Single charged pion production

$$\nu_\mu + CH \to \mu^-(1\pi^\pm)X$$

X can contain any number of π^0s, no charged pions





Antineutrino

Single neutral pion production

$$\bar{\nu}_\mu + CH \to \mu^+(1\pi^0)X$$

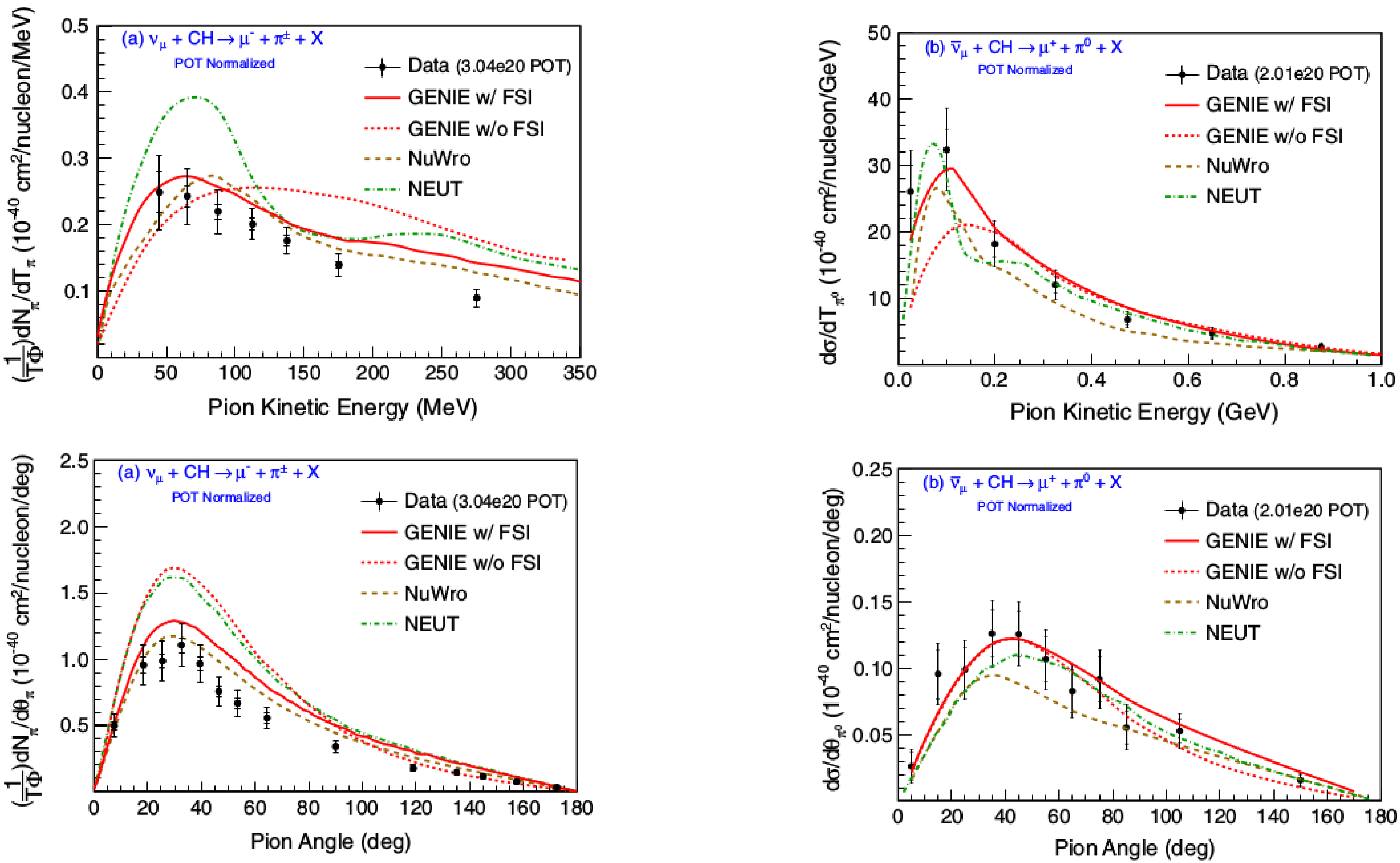
X contains no mesons

Neutrino and Antineutrino Cross Section from Pions

Generators Comparison

Phys. Rev. D 94, 052005 (2016)

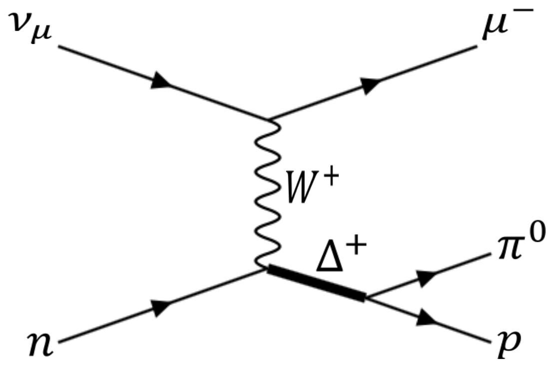
- **Shape of charged current pion production cross section versus pions kinematics is independent of FSI model.**



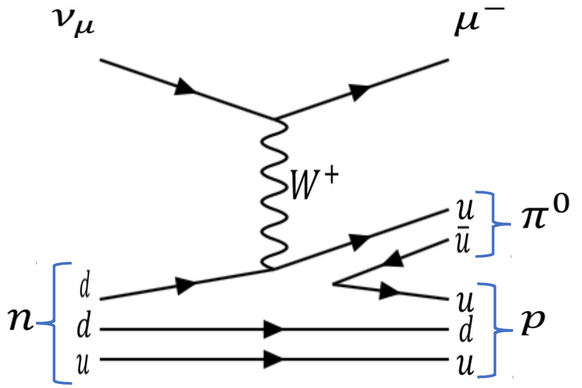
ν_μ CC Single π^0 Production

arXiv:1708.03723

Baryon Resonance Production
$\Delta^+(1232)$, higher-mass N*

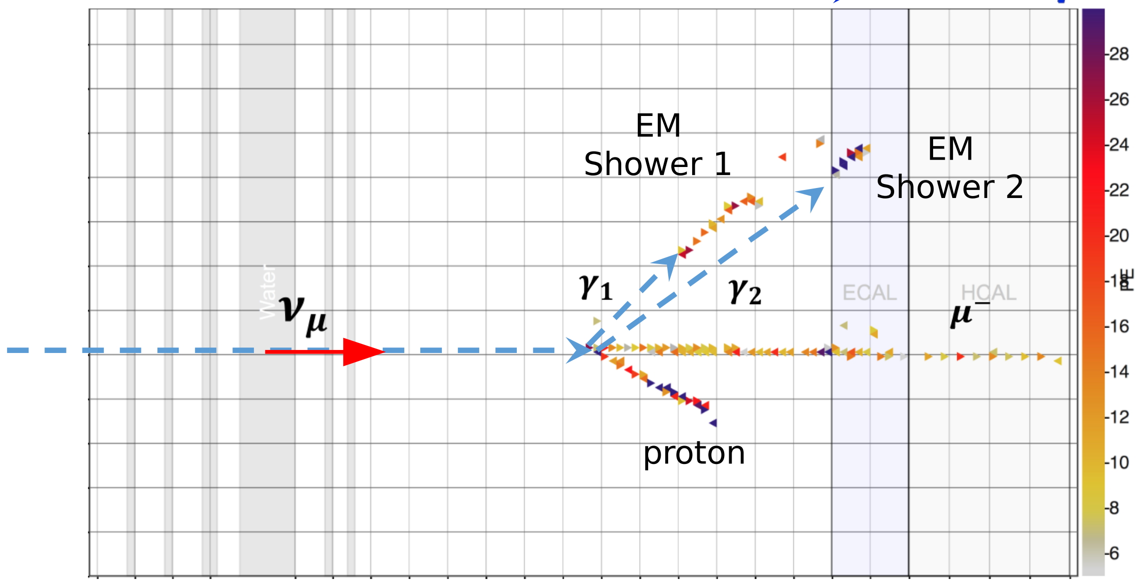


Non-Resonant Production
and Deep Inelastic Scattering



Example: $\nu_\mu + \{n\}_C \rightarrow \mu^- + \pi^0 + p$

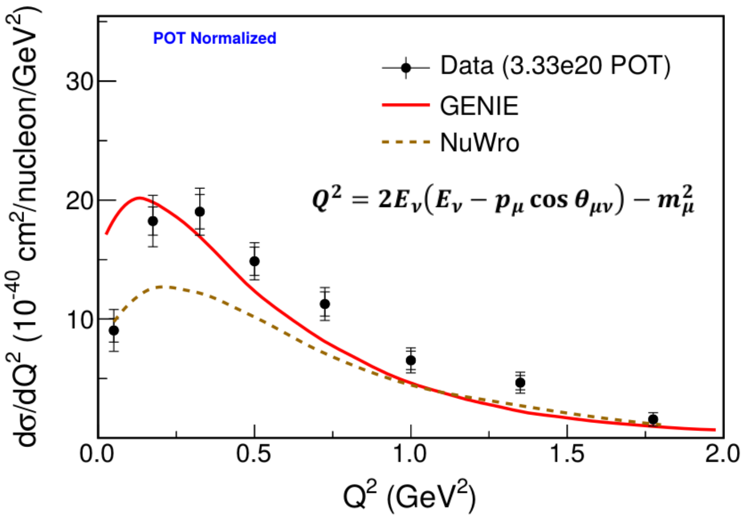
$\pi^0 \rightarrow 2\gamma$

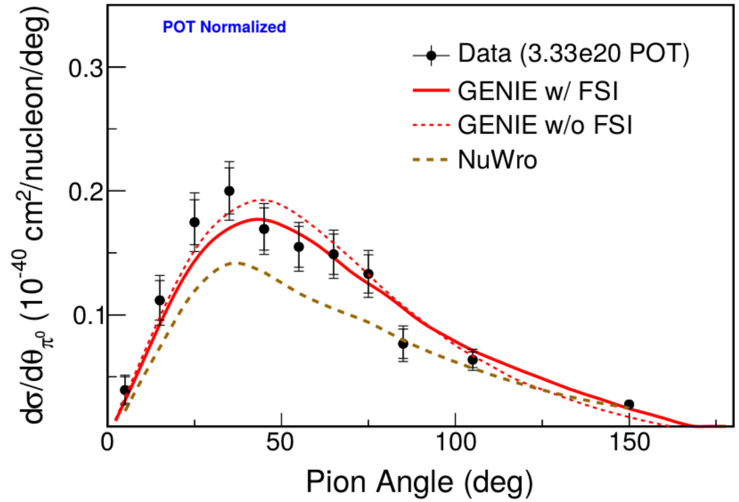


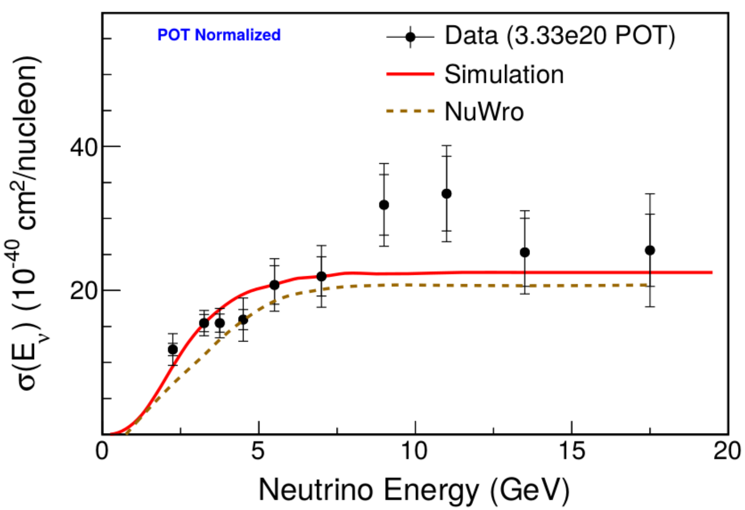
ν_μ CC Single π^0 Production

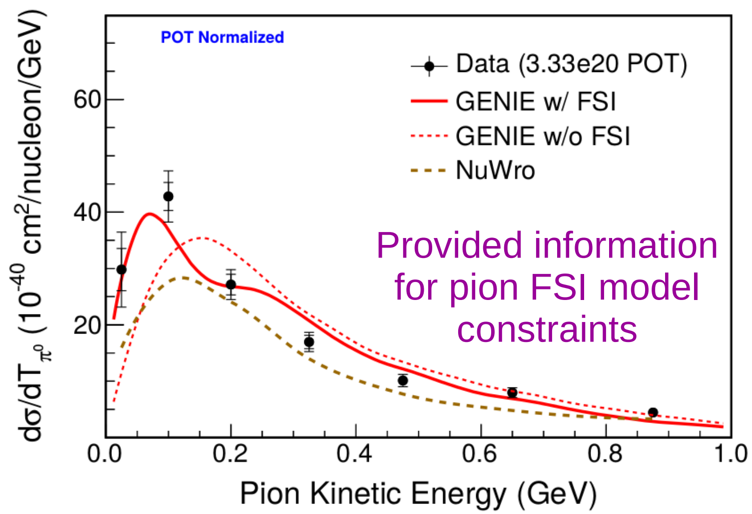
Kinematic Variables

- These new cross section measurements provide a detailed view of the signal channel.





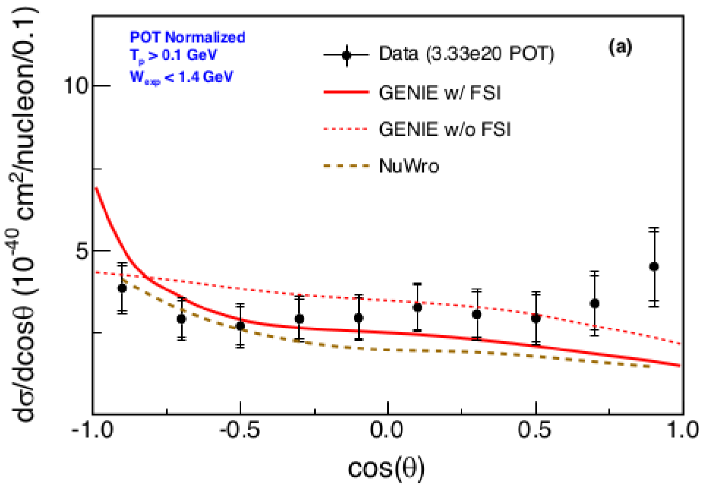


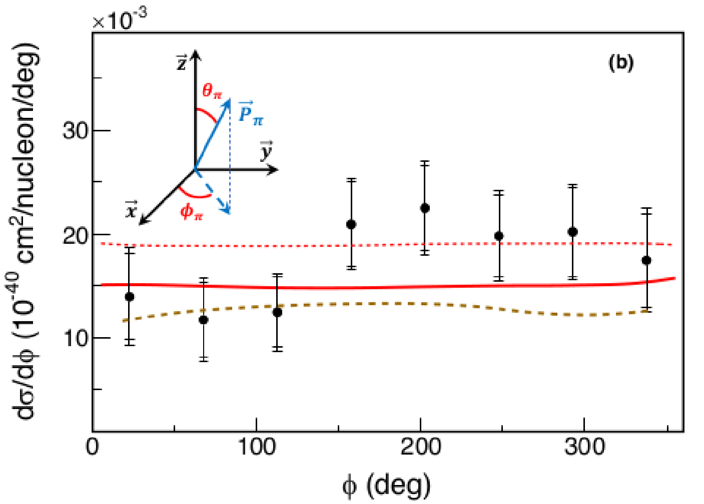


ν_μ CC Single π^0 Production

Hadronic System

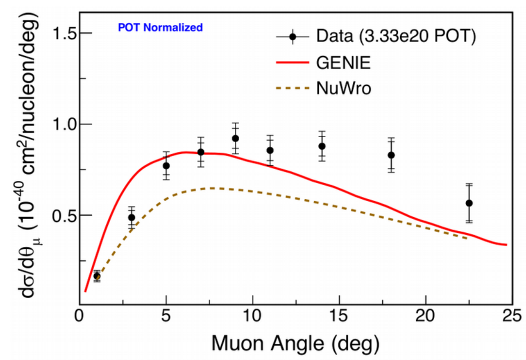
- **Δ^+ (1232) decay angles are measured for the first time!**



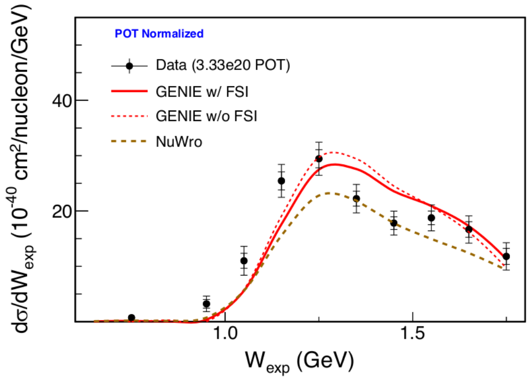


- **GENIE and NuWro assume isotropic Δ^+ (1232) decay**

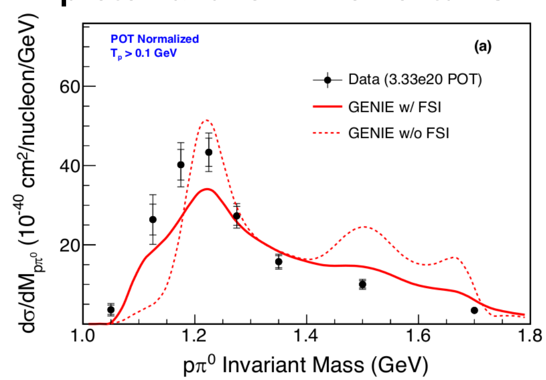
- **These disagreements identify areas in need of improvement.**



$$W_{exp} = \sqrt{m_n^2 + 2m_n(E_\nu - E_\mu) - Q^2}$$



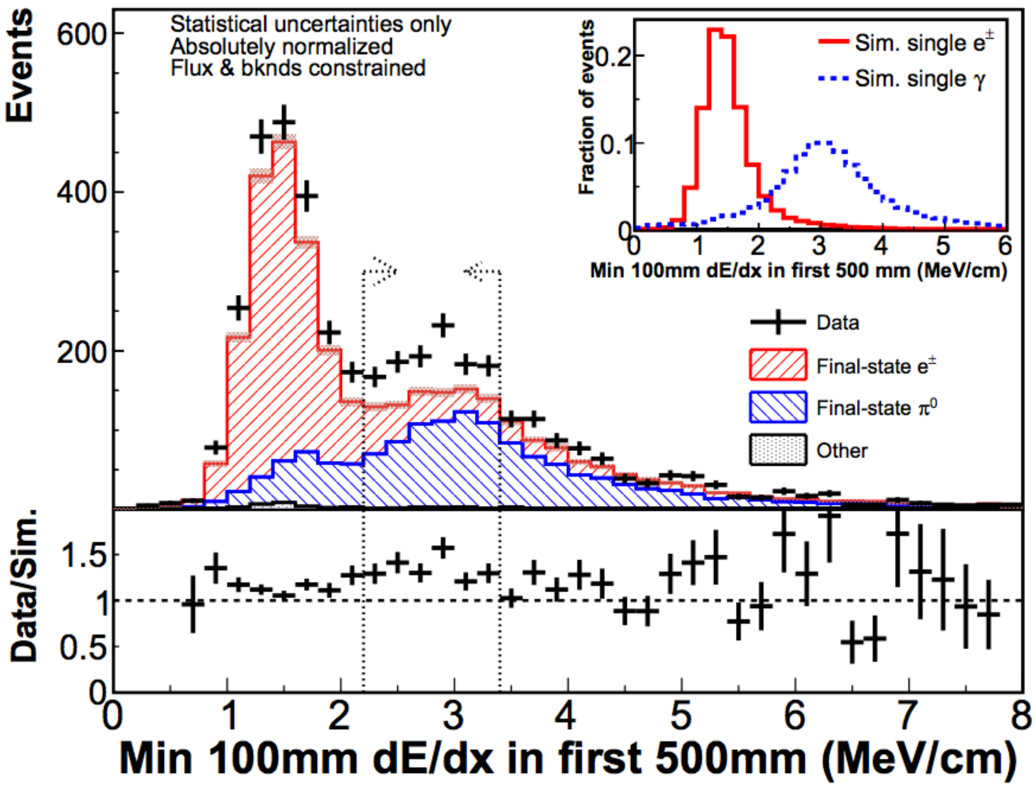
Invariant Mass calculated with proton and π^0 4-momentums



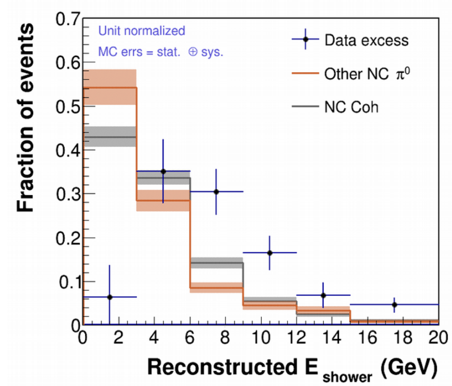
Diffractive Neutral Pion Production

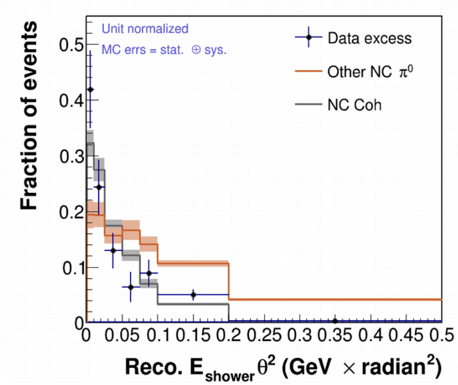
Phys. Rev. Lett. 117, 111801 (2016)

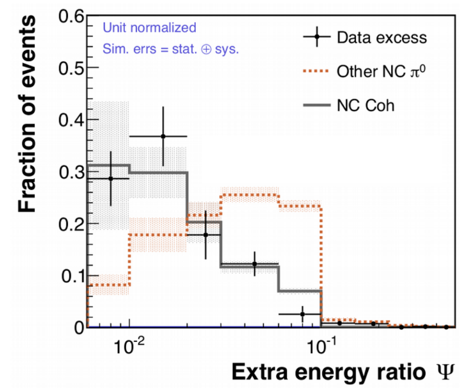
Observed as excess EM shower events in photon region of front dE/dx

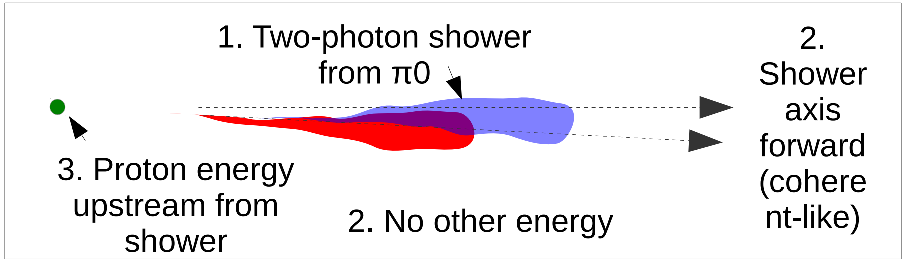


Observed energy behavior is very different from any other NC π^0 production models





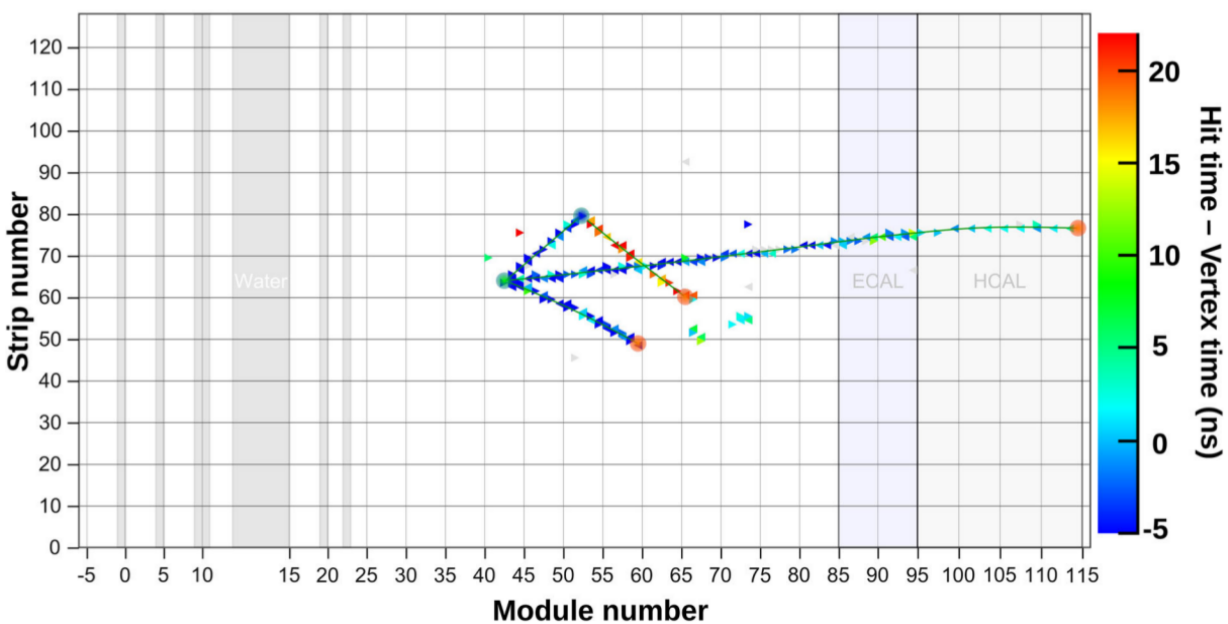


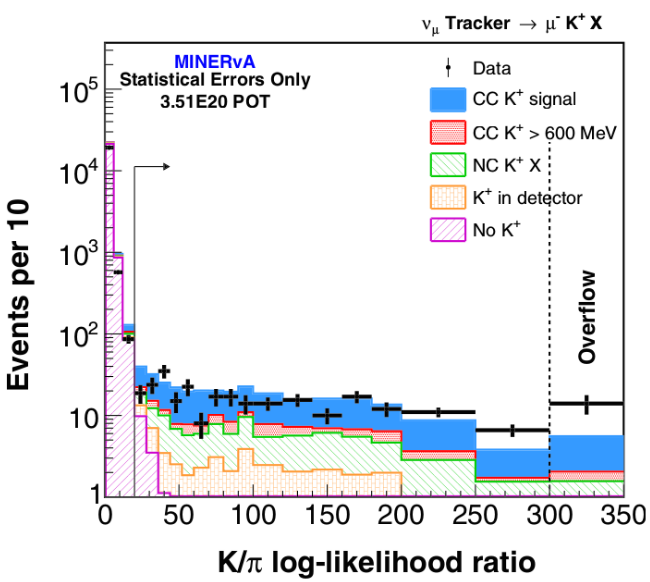


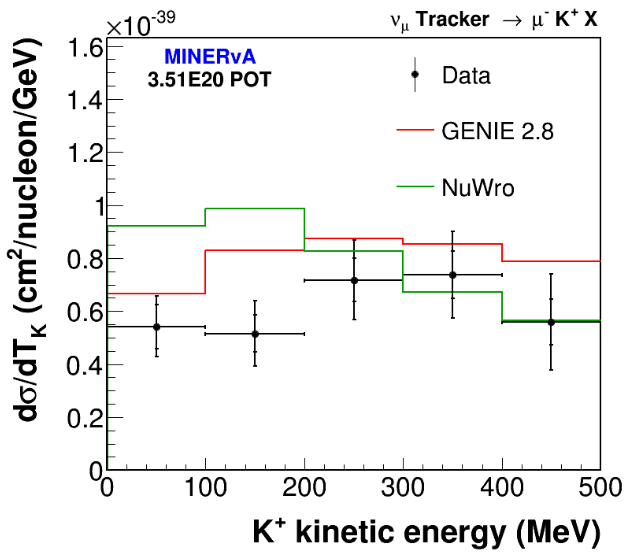
First direct experimental observation and characterization of this process!

Kaons . . .

Charge Current K$^+$ Production
Phys. Rev. D 94 012002 (2016)

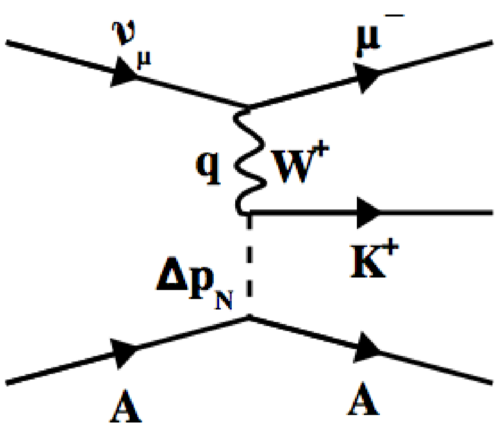




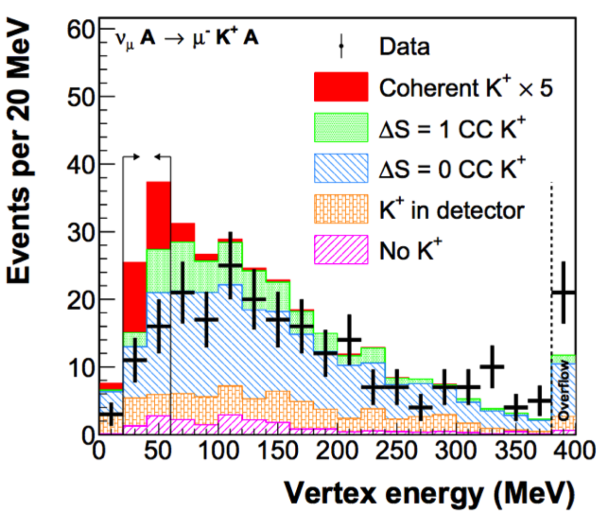


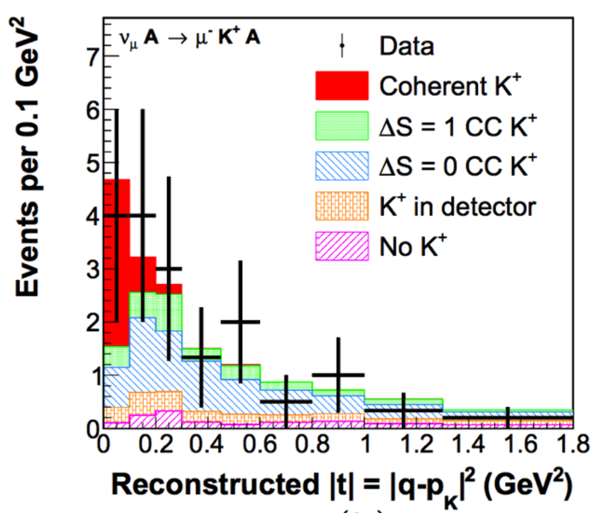
- Timing information used to isolate 885 CC candidate events.
- First high statistics measurement of the K$^+$ energy spectrum for kaon production in ν_μ CC interactions.
- Provides an additional constraint on K$^+$ FSI.
- The signal spectrum in $p \rightarrow K^+\nu$ due to kaon rescattering are well modeled in GENIE.
- NuWro disagreement tells the importance of an improved low-W DIS model for K$^+$ production.

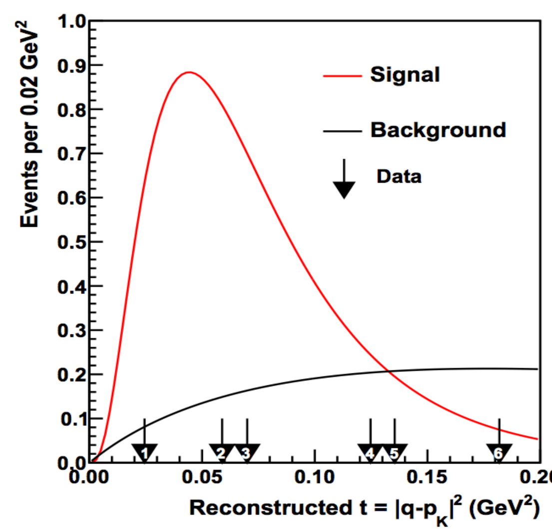
Coherent K^+ Production
Phys. Rev. Lett. 117, 061802 (2016)



- **Very rare inelastic electroweak process, brings K^+ on shell and leaves the target nucleus intact in its ground state.**
- **Kinematics of the FS used to reconstruct the small momentum transfer to the nucleus; model independent characteristic of coherent scattering.**
- **Identified via cuts on vertex energy and t, scans to remove π^0 contamination.**
- **6 events fund in signal region; fit estimates $3.77^{+2.64}_{-1.93}$ signal events at 3σ.**





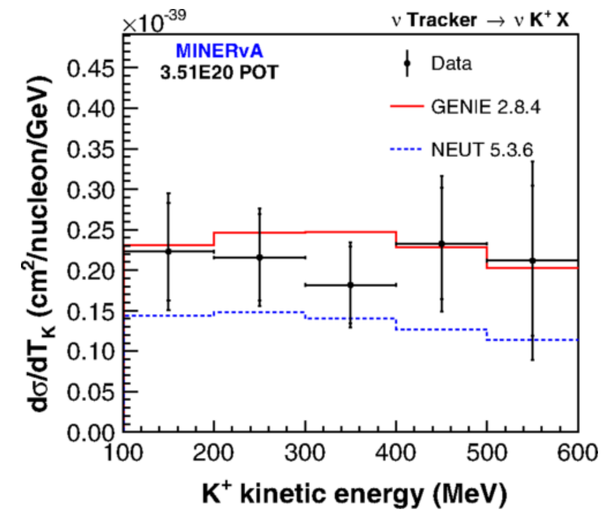


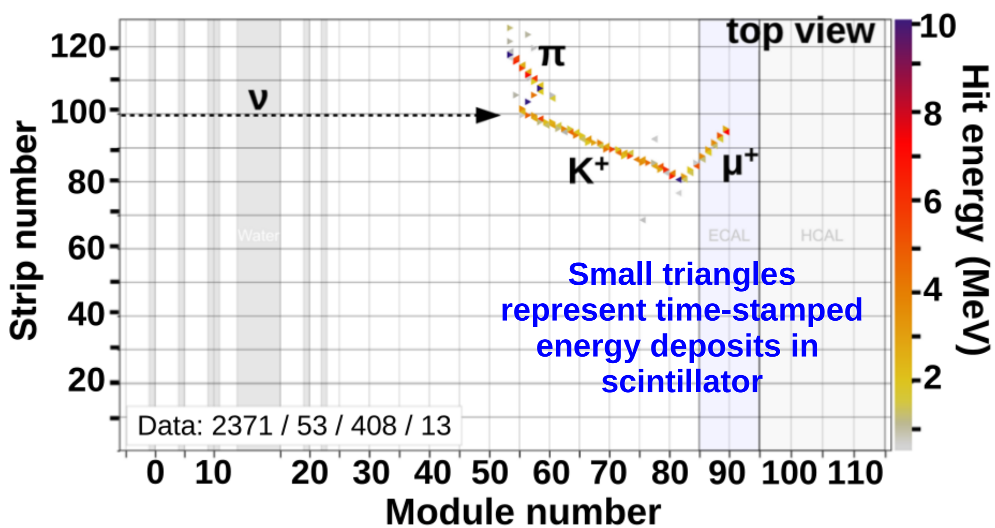
Neutral Current K^+ Production

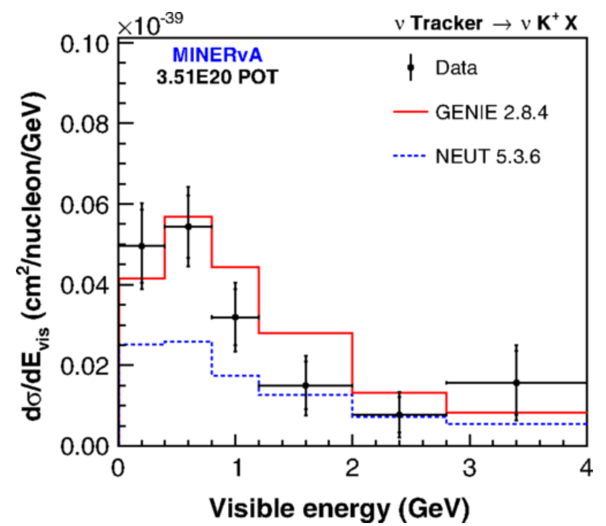
Phys. Rev. Lett. 199, 0011802 (2017)

- **K^+ production by atmospheric neutrinos (especially neutral current interactions) are backgrounds for SUSY-preferred proton decay $p \rightarrow K^+ \nu$**
- **Particularly problematic in Cherenkov detectors, where NC K^+ event with no particles above Cherenkov threshold will fake the signal process**
- **Mismodeled rates for K^+ nothing would also be a problem in liquid Argon detectors**

Kinematic distributions appear well modeled in GENIE, level in NEUT too low







. . . and More Results
From Low Energy Beam Configuration

- "Direct Measurement of Nuclear Dependence of Charged Current Quasielastic-like Neutrino Interactions using MINERvA" accepted by Phys. Rev. L
- "Measurement of neutral-current K+ production by neutrinos using MINERvA", Phys. Rev. Lett. 199, 0011802 (2017)
- "Measurement of the antineutrino to neutrino charged-current interaction cross section ratio on carbon" Phys. Rev. D 95, 072009 (2017)
- "Measurements of the Inclusive Neutrino and Antineutrino Charged Current Cross Sections in MINERvA Using the Low-ν Flux Method", Phys. Rev. D 94, 112007 (2016)
- "Neutrino Flux Predictions for the NuMI Beam", Phys. Rev. D 94, 092005 (2016)
- "First evidence of coherent K+ meson production in neutrino-nucleus scattering", Phys. Rev. Lett. 117, 061802 (2016)
- "Measurement of K+ production in charged-current νμ interactions", Phys. Rev. D 94 012002 (2016)
- "Cross sections for neutrino and antineutrino induced pion production on hydrocarbon in the few GeV region using MINERvA", Phys. Rev. D 94, 052005 (2016).
- "Evidence for diffractive neutral pion production from hydrogen in Neutrino Interactions on hydrocarbon", Phys. Rev. Lett. 117, 111801 (2016)
- "Measurement of Neutrino Flux using Neutrino-Electron Elastic Scattering", Phys. Rev. D 93, 112007 (2016)
- "Measurement of Partonic Nuclear Effects in Deep-Inelastic Neutrino Scattering using MINERvA", Phys. Rev. D 93, 071101 (2016).
- "Identification of nuclear effects in neutrino-carbon interactions at low three-momentum transfer", Phys. Rev. Lett. 116, 071802 (2016).
- "Measurement of electron neutrino quasielastic and quasielastic-like scattering on hydrocarbon at average Ev of 3.6 GeV", Phys.Rev. Lett. 116, 081802 (2016).
- "Single neutral pion production by charged-current anti-νμ interactions on hydrocarbon at average Ev of 3.6 GeV", Phys.Lett. B749 130-136 (2015).
- "Measurement of muon plus proton final states in νμ Interactions on Hydrocarbon at average Ev of 4.2 GeV" Phys. Rev. D91, 071301 (2015).
- "Measurement of Coherent Production of ?± in Neutrino and Anti-Neutrino Beams on Carbon from νμ of 1.5 to 20 GeV", Phys. Rev.Lett. 113, 261802 (2014).
- "Charged Pion Production in ν_μ Interactions on Hydrocarbon at average Ev of 4.0 GeV" , Phys.Rev. D92, 092008 (2015).
- "Measurement of ratios of ν_μ charged-current cross sections on C, Fe, and Pb to CH at neutrino energies 2-20 GeV", Phys. Rev. Lett. 112, 231801 (2014).
- "Measurement of Muon Neutrino Quasi-Elastic Scattering on a Hydrocarbon Target at Ev ~3.5 GeV", Phys. Rev. Lett. 111, 022502 (2013).
- "Measurement of Muon Antineutrino Quasi-Elastic Scattering on a Hydrocarbon Target at Ev ~3.5 GeV", Phys. Rev. Lett. 111, 022501 (2013).

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- “Measurement of the antineutrino to neutrino charged-current interaction cross section ratio on carbon” Phys. Rev. D 95, 072009 (2017)
- ”Measurements of the Inclusive Neutrino and Antineutrino Charged Current Cross Sections in MINERvA Using the Low-ν Fl... Method”, Phys. Rev. D 94, 112007 (2016)
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- “First ... roduction in neutrino-nucleus scattering”, Phys. Rev. Lett. 117, 061802 ...
- “Measure... -current νμ interactions”, Phys. Rev. D 94 012002 (2016)
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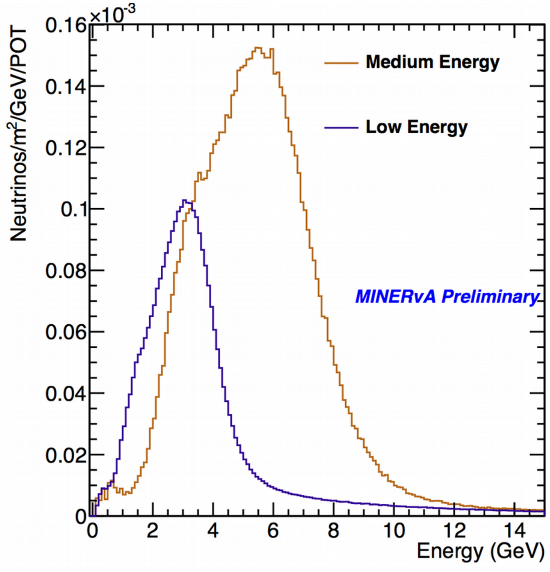
- “Measurement of ratios of ν_μ charged-current cross sections on C, Fe, and Pb to CH at neutrino energies 2–20 GeV”, Phys. Rev. Lett. 112, 231801 (2014).
- “Measurement of Muon Neutrino Quasi-Elastic Scattering on a Hydrocarbon Target at Eν ~3.5 GeV”, Phys. Rev. Lett. 111, 022502 (2013).
- “Measurement of Muon Antineutrino Quasi-Elastic Scattering on a Hydrocarbon Target at Eν ~3.5 GeV”, Phys. Rev. Lett. 111, 022501 (2013).

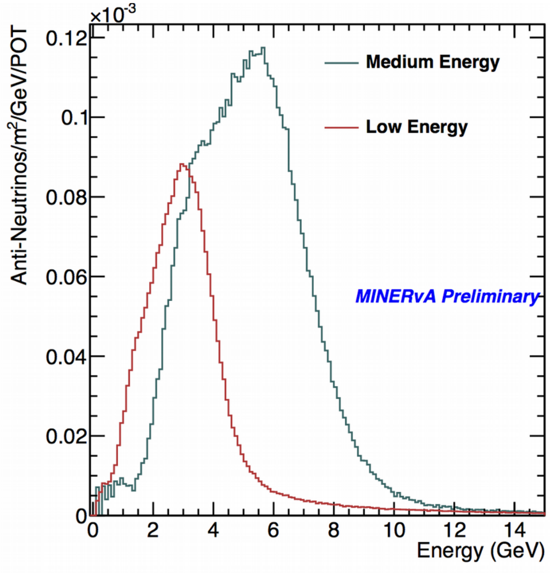
Sandro’s Talk
Tuesday 2:00 pm

Cheryl’s Talk
Friday 2:00 pm

MINERvA Status and Future Plans

- **MINERvA is now accumulating many more events in the Medium Energy beam configuration yielding high statistics**
- **We have over 10E 20 POT in the medium energy beam.**
- **Measurements of quasi-elastic, pion production, DIS and inclusive on iron, lead and carbon using the medium energy.**
- **Expect reduction in systematics, with a ~factor of 10 more statistics for the neutrino-electron scattering flux Constrain**
- **The higher energy beam tune gives us a much higher reach in four-momentum transfer squared (Q^2).**
- **Results in ME will increase the sensitivity to probe the nuclear effects.**





Conclusions

- **Neutrino cross section measurements are important for neutrino oscillation measurements and to understand the nature of neutrino-nucleus scattering.**
- **MINERvA has precisely studied neutrino interactions in the 1-20 GeV region, improving our knowledge (and models) of:**
  - **Flux Studies**
  - **ν-CC Interactions**
  - **Neutrino cross sections at low energy, low Q^2 .**
  - **A-Dependence in neutrino interactions (Targets He, C, Fe, Pb and H_2O)**
- **MINERvA is providing constraints from many channels: inclusive scattering, quasi-elastic scattering, pion production, kaon production, deep inelastic interactions**
- **Providing the first direct data constraint of backgrounds from atmospheric neutrinos to p->Kν proton decay**
- **These results will help resolve long standing discrepancies between experiments and will be important for minimizing systematic errors in oscillation experiments.**

From the MINERνA Collaboration
Thank You . . .

Back Up

From the MINERνA Collaboration
Thank You . . .

To obtain the incident beam flux, weemploy the "low-ν" method described previously.

The differential dependence of the cross section in terms of νis expanded in ν/E as

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

Where E is the incident neutrino energy. The coefficients A, Bν,¯ν, and Cν, ν̄ depend on integrals over structure functions (or form factors, in the low energy limit)

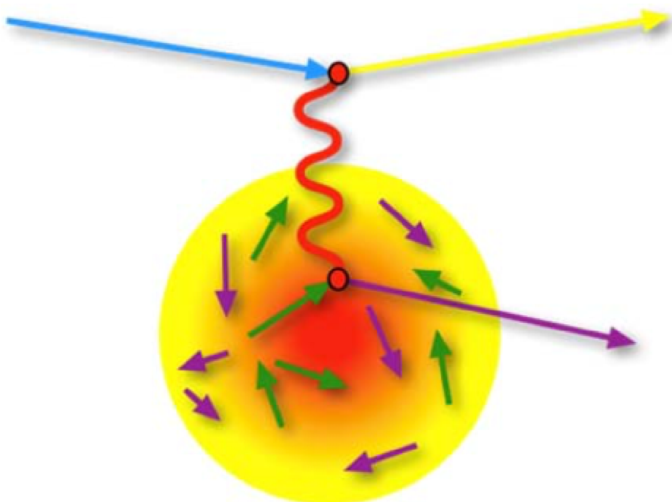
$$A = \frac{G_F^2 M}{\pi}\int F_2(x)dx,$$

$$B^{\nu,\bar{\nu}} = -\frac{G_F^2 M}{\pi}\int (F_2(x) \mp xF_3(x))dx,$$

$$C^{\nu,\bar{\nu}} = B^{\nu,\bar{\nu}} - \frac{G_F^2 M}{\pi}\int F_2(x)\left(\frac{1+\frac{2Mx}{\nu}}{1+R_L} - \frac{Mx}{\nu} - 1\right)dx.$$

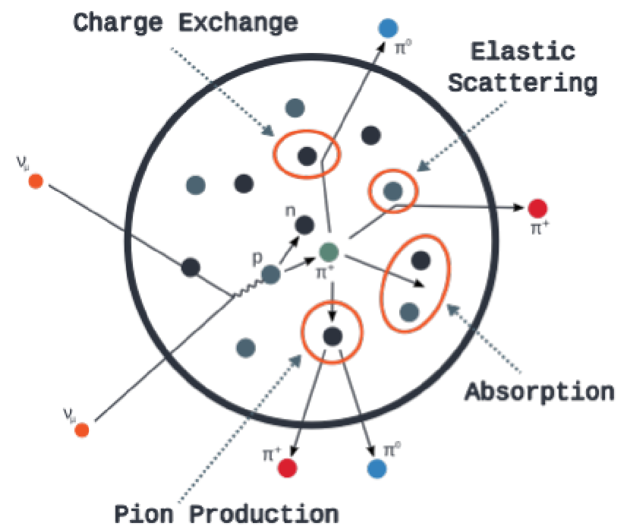
Nuclear Effects

Initial State Nuclear Effect



- Short, medium, and long range nucleon-nucleon correlations on the initial condition, e.g. "2p2h" effect , "RPA" effect

Final State Nuclear Effect



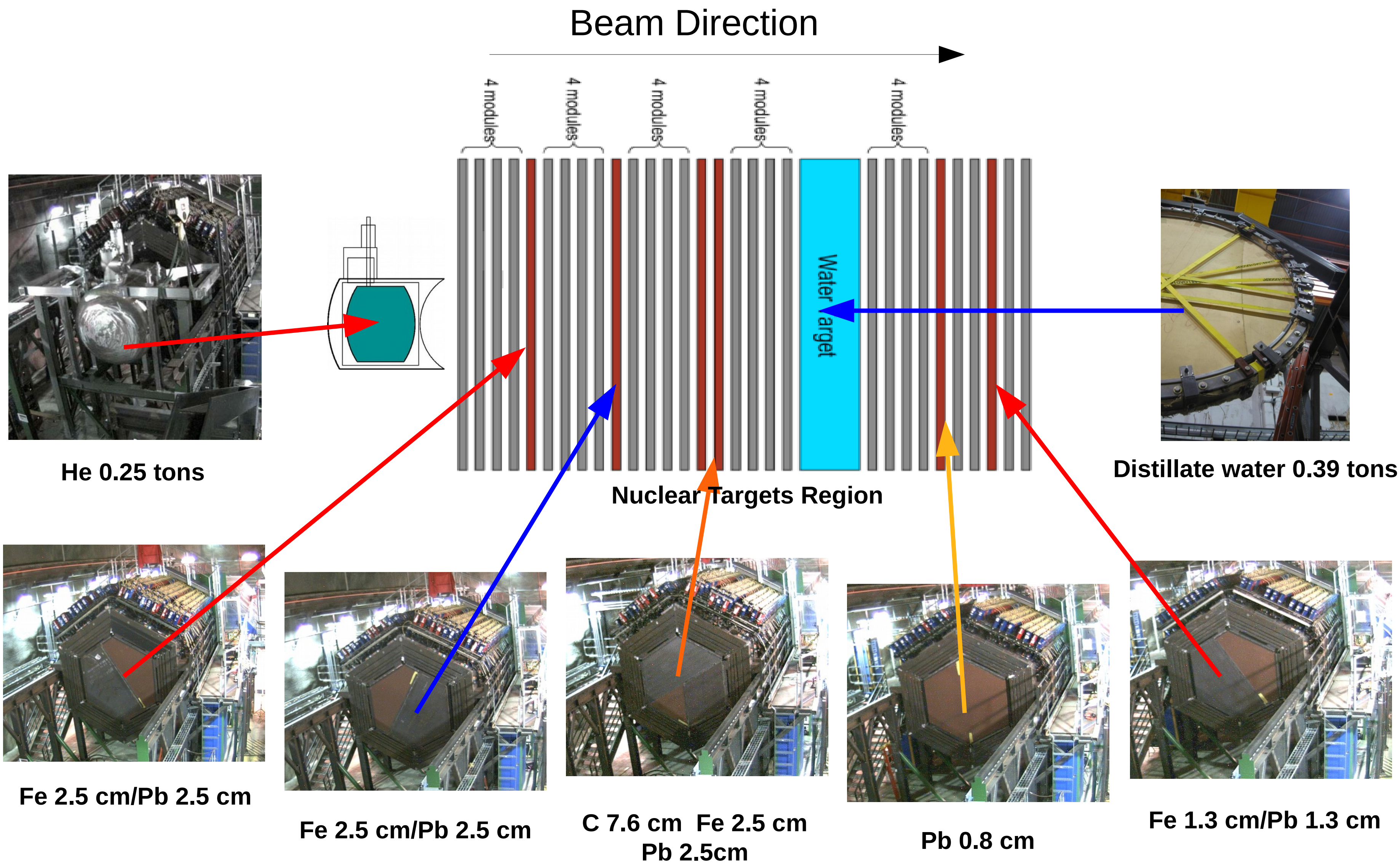
- Particles created have to work their way out of the nucleus, e.g. absorption

Signal ↔ Background Migration

MINERvA provides detailed description of final state particles and information on big source of uncertainties in the neutrino interaction!

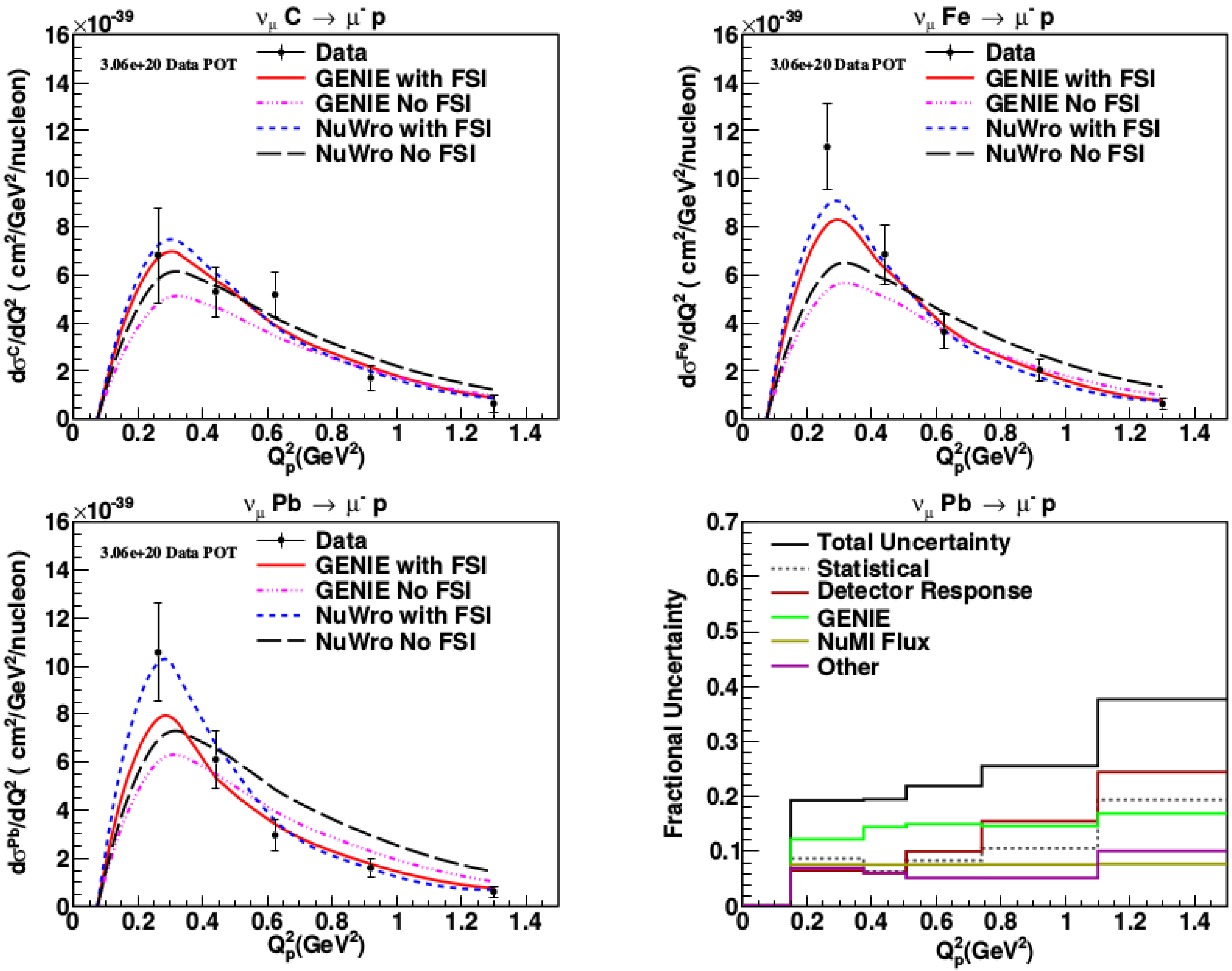
M. Wospakrik;
New Perspectives 2017

MINERvA Experiment
Detector



Nuclear Dependence of CC Quasielastic-like
Models Generators Comparison

The transfered four-momentum squared to the target nucleus, Q^2 , is reconstructed based on the kinematics of the leading proton,

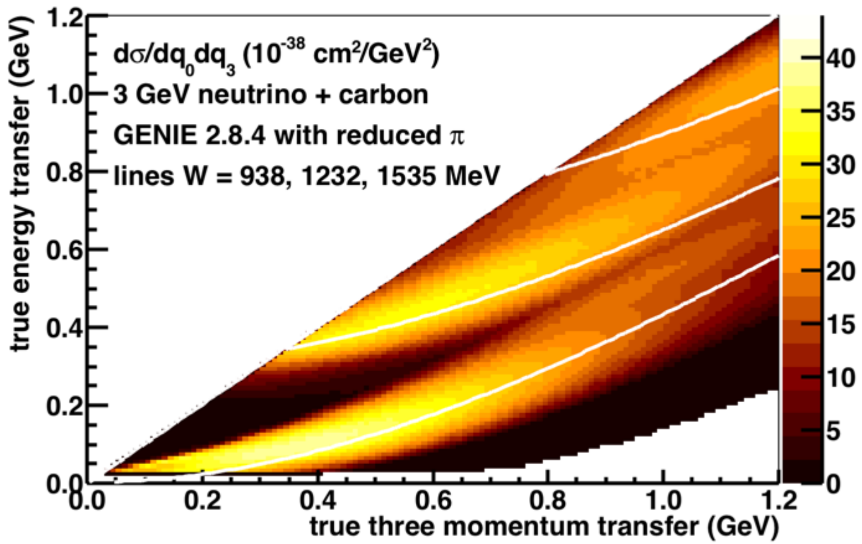


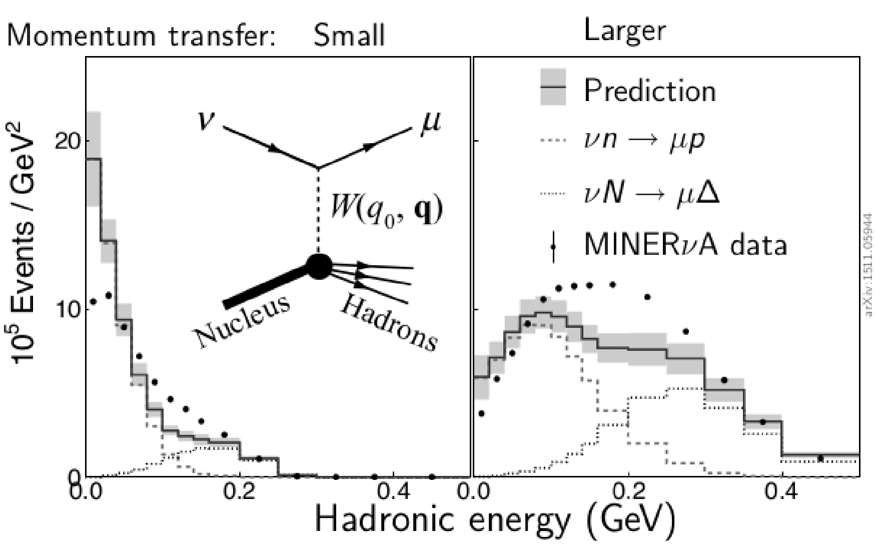
M. Betancourt FNAL
JETP Seminar
Oct 2016

Accepted by
Phys. Rev. L.

Nuclear Effects at Low Three-Momentum Transfer

Phys. Rev. Lett. 116, 071802 (2016)

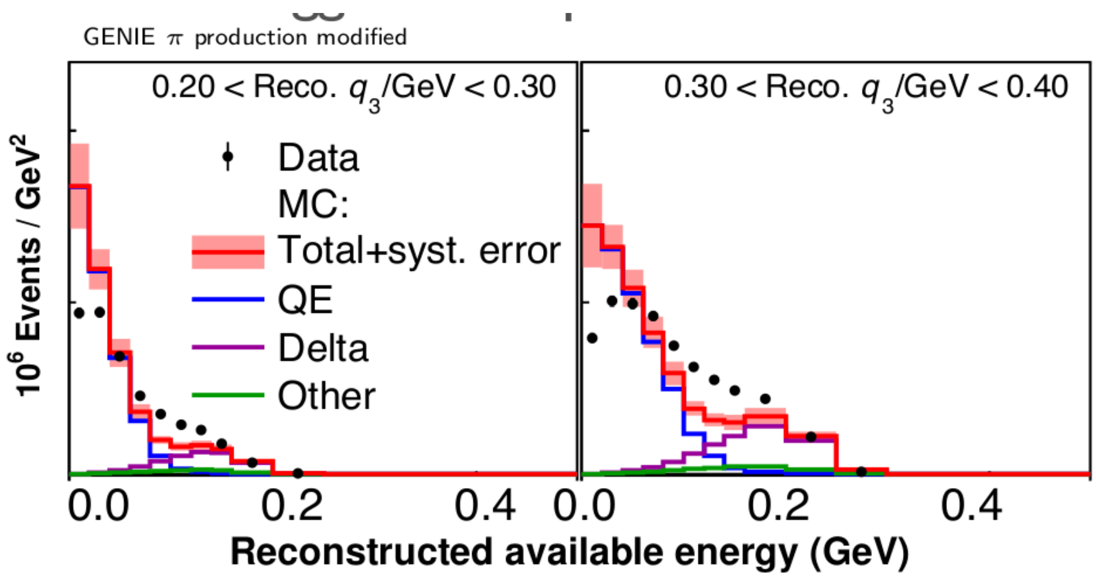




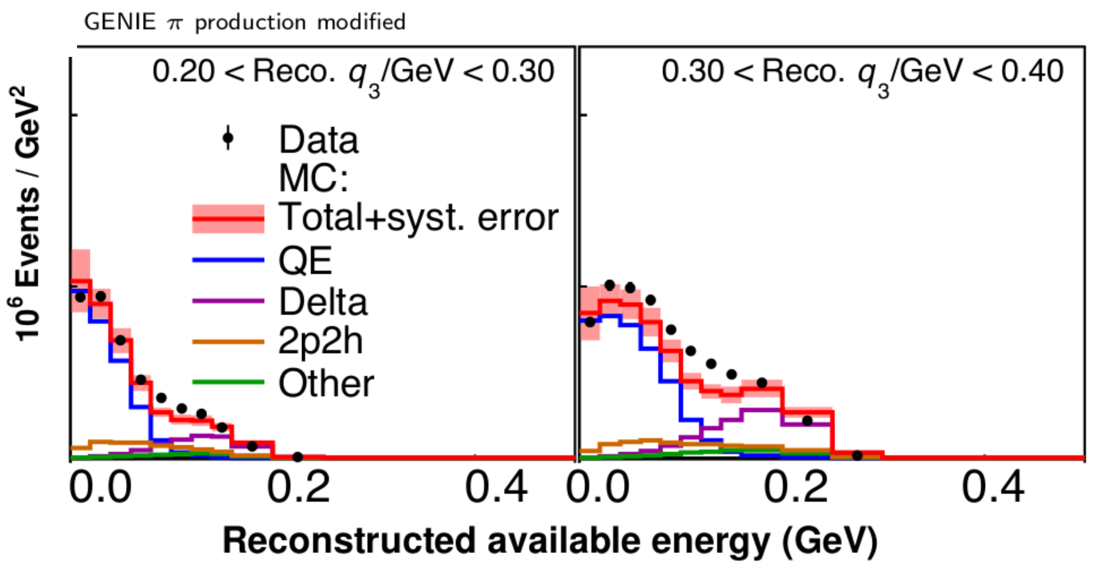
- **Look at inclusive scattering in 2 kinematic dimensions.**
- **Separate the four-momentu transfer squered; Q^2, into energy transfer q_0 and 3-momentum transfer q_3**
- **Reconstructing energy and momentum transfer allows us to isolate channels in a fashion (somewhat) analogous to electron scattering.**
- **We observe a small cross section at very low energy transfer that matches the expected screening effect of long-range nucleon correlations.**

Nuclear Effects at Low Three-Momentum Transfer

Phys. Rev. Lett. 116, 071802 (2016)



- **Default nuclear model struggles to explain data**

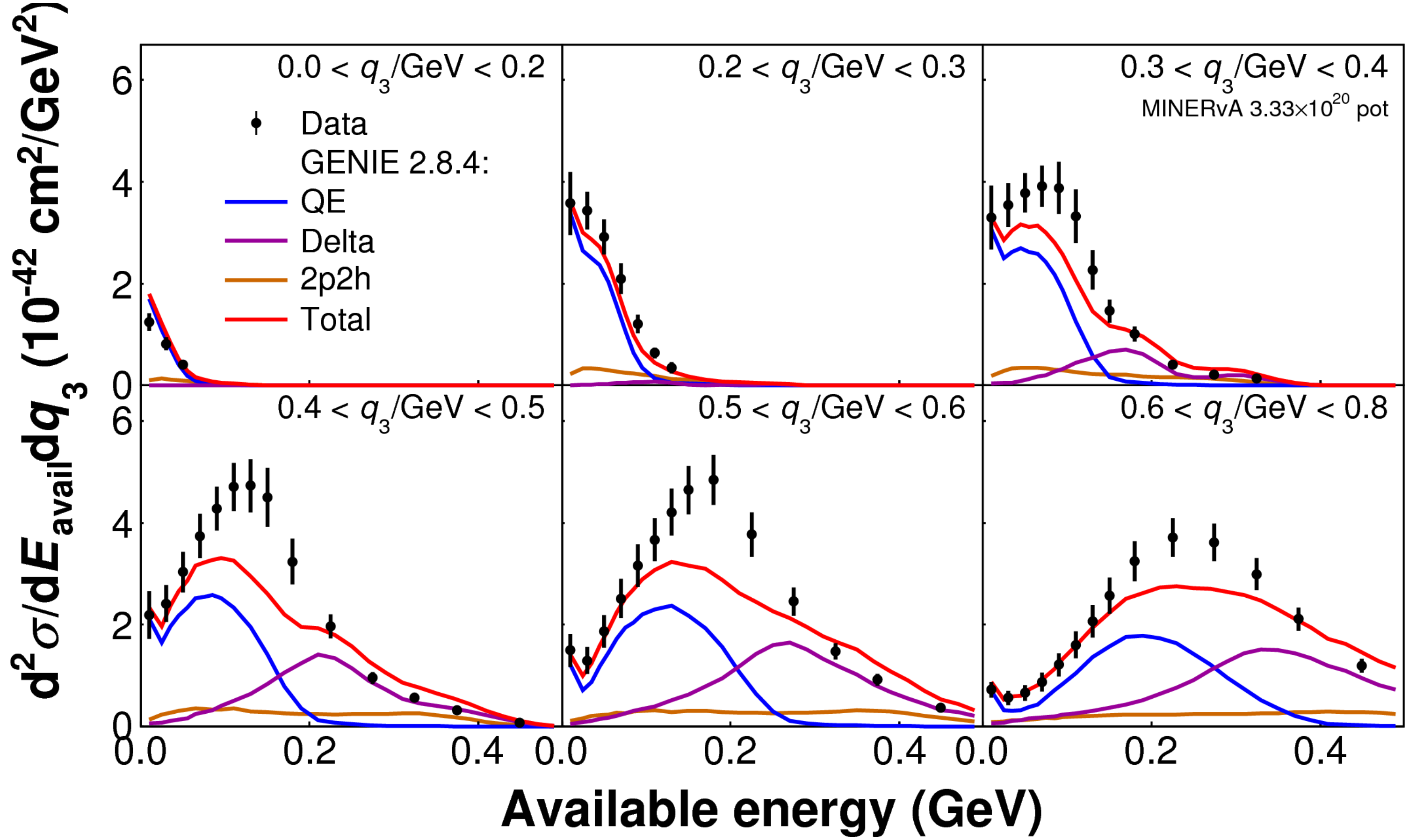


- **Including more sophisticated nuclear models (2p2h effects and RPA)**

Nuclear Effects at Low Three-Momentum Transfer

Phys. Rev. Lett. 116, 071802 (2016)

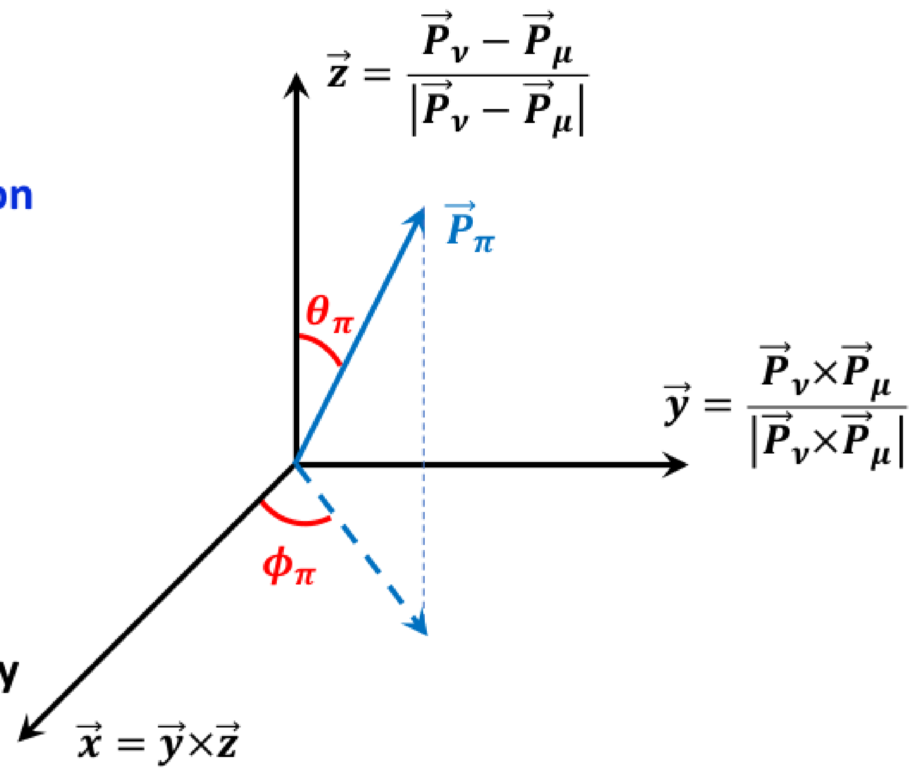
$$E_{\text{avail}} = \sum(\text{Proton and } \pi^{\pm} \text{ KE}) + (\text{Total } E \text{ of other particles except neutrons})$$



- **Adding in models of RPA (a charge screening effect) and 2p2h improves agreement in some regions, but not in others.**

$\Delta^+(1232)$ Polarization – Coordinate Axes

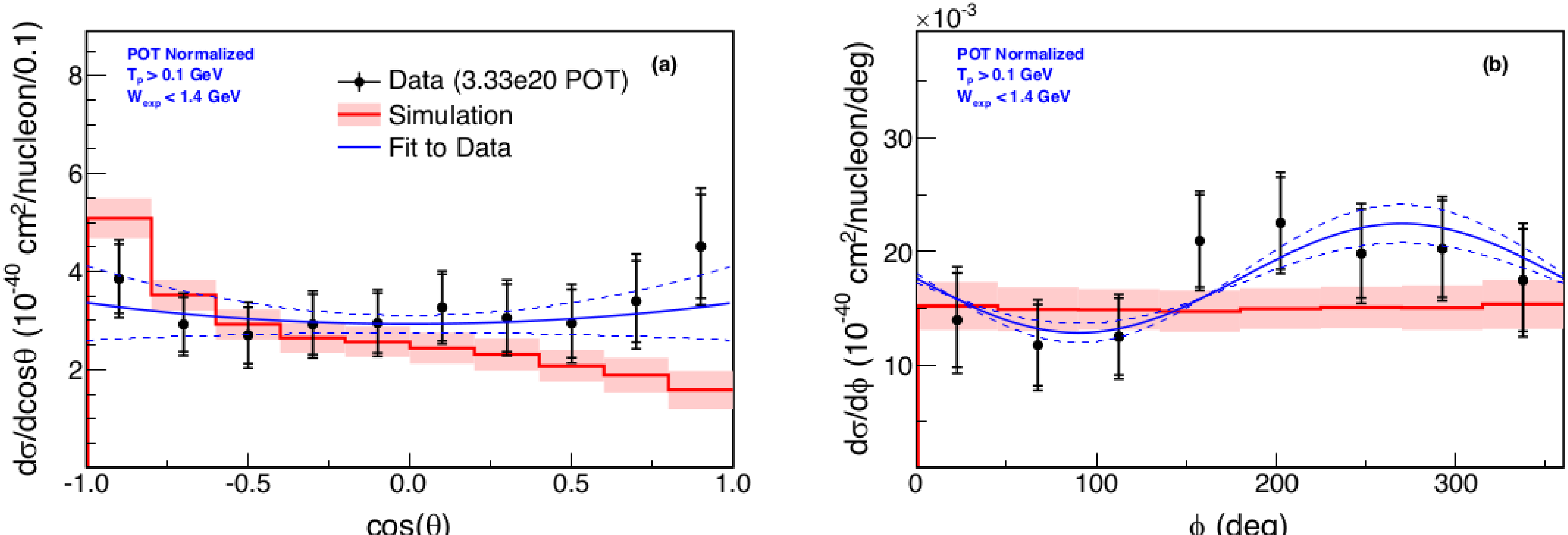
1. Boost all particles to Δ rest frame
2. Form z-axis along the momentum transfer direction
3. Form y-axis along the production plane normal
4. Form x-axis assuming the system is Right-Handed
5. Angle θ is between z-axis and $\vec{P}_\pi$
6. Angle ϕ is between x-axis and $\vec{P}_\pi$ projection on x-y plane



ν_μ CC Single π^0 Production

arXiv:1708.03723

$\Delta^+(1232)$ Polarization – cos(θ) and ϕ



$$y = \boldsymbol{A} + \boldsymbol{B}(\cos\theta)^2$$

$\boldsymbol{A} = 2.93 \pm 0.18, \boldsymbol{B} = 0.43 \pm 0.58$

$$\frac{\chi^2_{MC}}{dof} = \frac{20.1}{9} = 2.3 \qquad \frac{\chi^2_{fit}}{dof} = \frac{2.9}{8} = 0.4$$

$$y = \boldsymbol{A} + \boldsymbol{B}\sin\phi$$

$\boldsymbol{A} = 17.54 \pm 0.43, \boldsymbol{B} = -4.81 \pm 1.26$

$$\frac{\chi^2_{MC}}{dof} = \frac{10.3}{7} = 1.5 \qquad \frac{\chi^2_{fit}}{dof} = \frac{3.3}{6} = 0.6$$