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Results from MINERvA

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Neutrino Oscillations In One Slide

- Flavor eigenstates are not the same as mass eigenstates
- The existence of 3 generations of neutrinos means that there's a possibility of observing CP-violation in neutrino oscillations
- We also can use oscillations to tell us if the mass ordering of the neutrinos is like that of other fermions
- It's all done by measuring oscillation probabilities vs. Energy

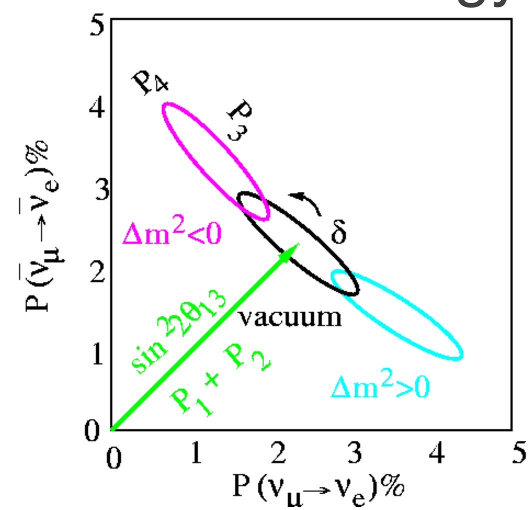
$$P_1 = \sin^2\theta_{23} \sin^2 2\theta_{13} \left(\frac{\Delta_{13}}{B_\pm}\right)^2 \sin^2\frac{B_\pm L}{2}$$

$$P_2 = \cos^2\theta_{23} \sin^2 2\theta_{12} \left(\frac{\Delta_{12}}{A}\right)^2 \sin^2\frac{AL}{2}$$

$$P_3 = J\cos\delta \left(\frac{\Delta_{12}}{A}\right)\left(\frac{\Delta_{13}}{B_\pm}\right) \cos\frac{\Delta_{13}L}{2} \sin\frac{AL}{2} \sin\frac{B_\pm L}{2}$$

$$P_4 = \mp J\sin\delta \left(\frac{\Delta_{12}}{A}\right)\left(\frac{\Delta_{13}}{B_\pm}\right) \sin\frac{\Delta_{13}L}{2} \sin\frac{AL}{2} \sin\frac{B_\pm L}{2}$$

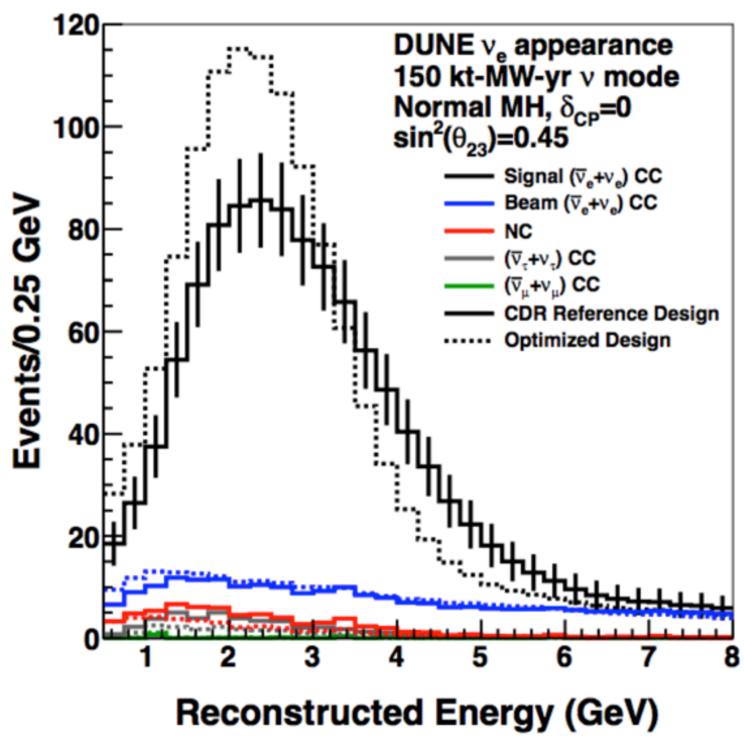
Δ_{ij} proportional to 1/E



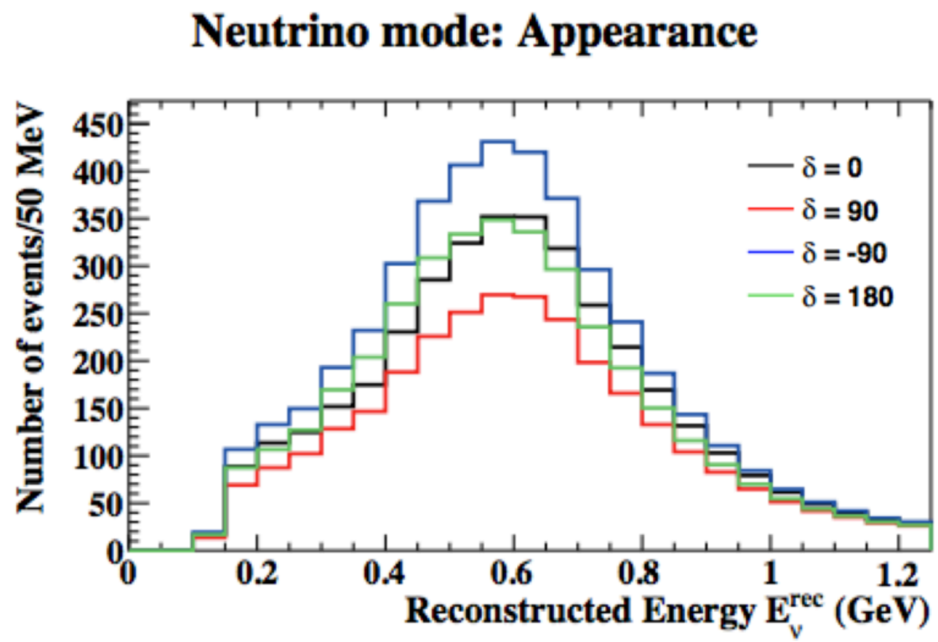
Minakata & Nunokawa JHEP 2001

Next Steps in Neutrino Oscillation Measurements

- Ambitious plans for new oscillation experiments: expect 1000's of events
  - Because of "large" mixing angles, will be looking for small differences in oscillation probabilities between neutrino and antineutrino mode
  - Neutrino Energy is a big part of extracting oscillation parameters



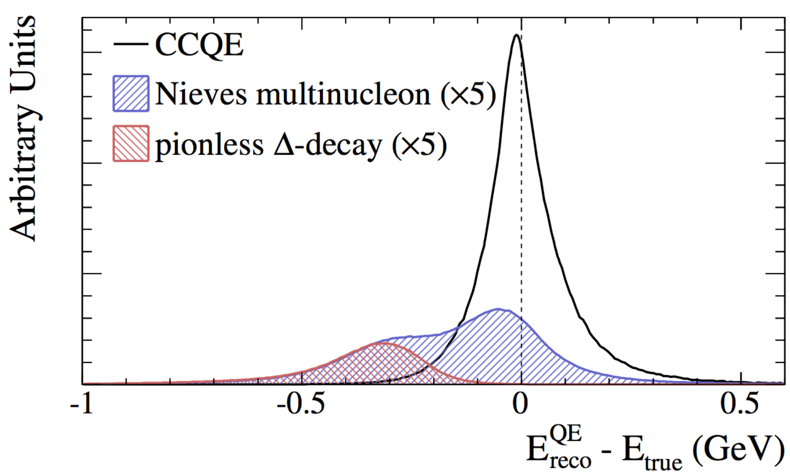
DUNE: arXiv:1512.06148



Hyper-K:arXiv:1412.4673

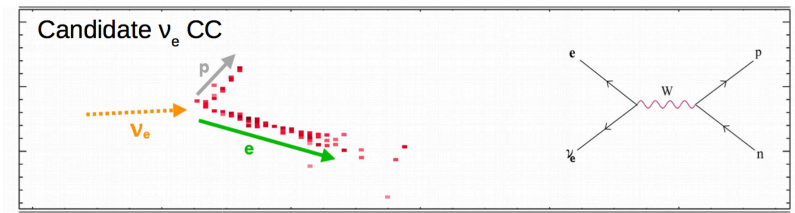
We are entering a world where systematics are important

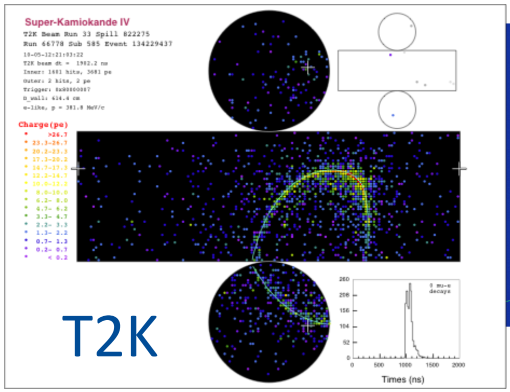
- "θ_{13} is large": need to understand signal process AND background process
- How a neutrino's energy shows up in a detector is an important effect: both for water-cerenkov and "fully active" detectors

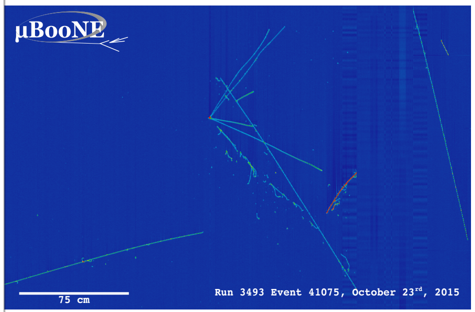


T2K, PRL 112 (2014) 181801

NOvA

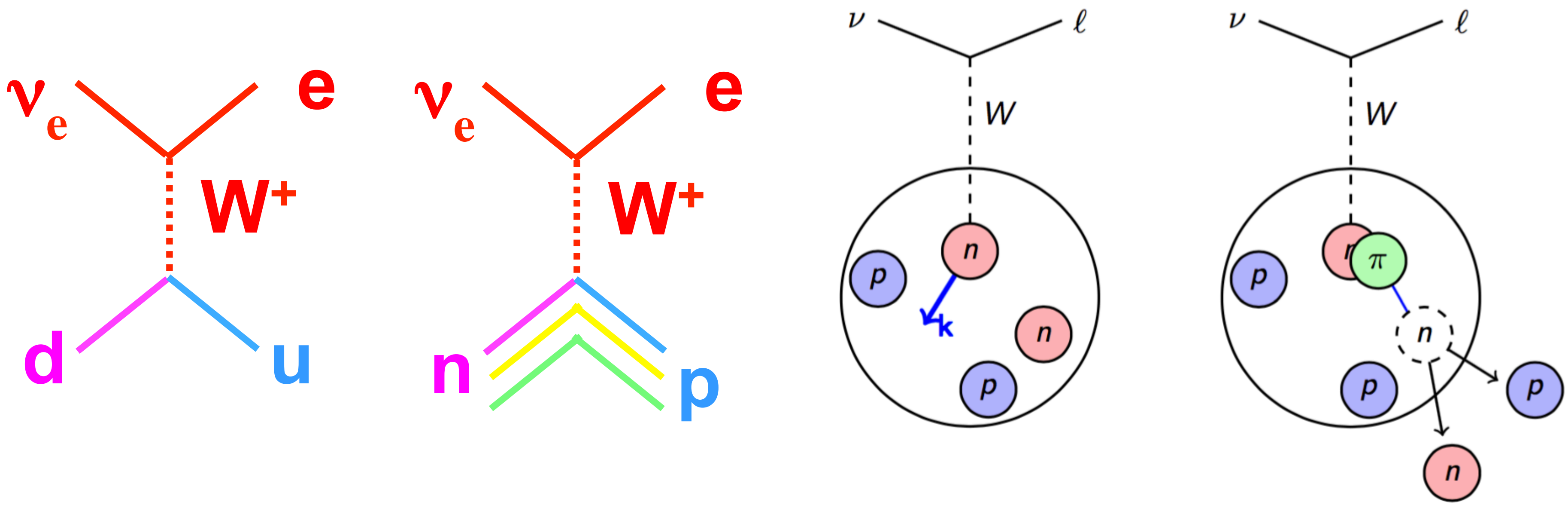






Why is reconstructing Neutrino Energy complicated?

- The nucleus is a complicated place…
- First you have to get the quarks inside the proton right
- Then you have to get the nucleons inside the nucleus right
- Then you have to get the effects on the nucleus on the outgoing particles right

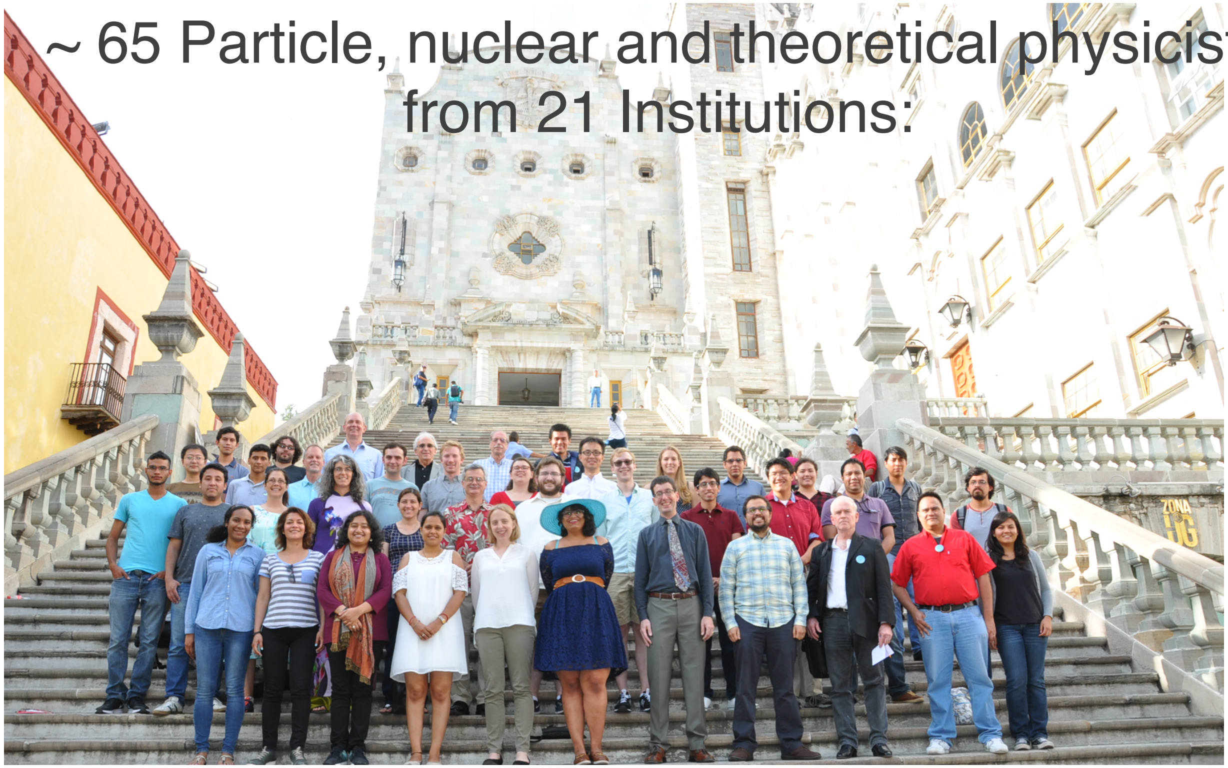


MINERvA's vital statistics

- Broad Range of Neutrino Energies
  - This gives a broad range of interaction channels
  - Able to measure ν_μ and ν_e both
- Capable detector
  - Low thresholds, good particle identification
- High intensity Neutrino Beam
  - Provides high statistics, but…
  - Need good flux constraints too
- Broad Range of Target Nuclei
  - To constrain both the nucleon-level processes and the role of the nucleus in what actually enters the detector

MINERvA Collaboration

~ 65 Particle, nuclear and theoretical physicists
from 21 Institutions:

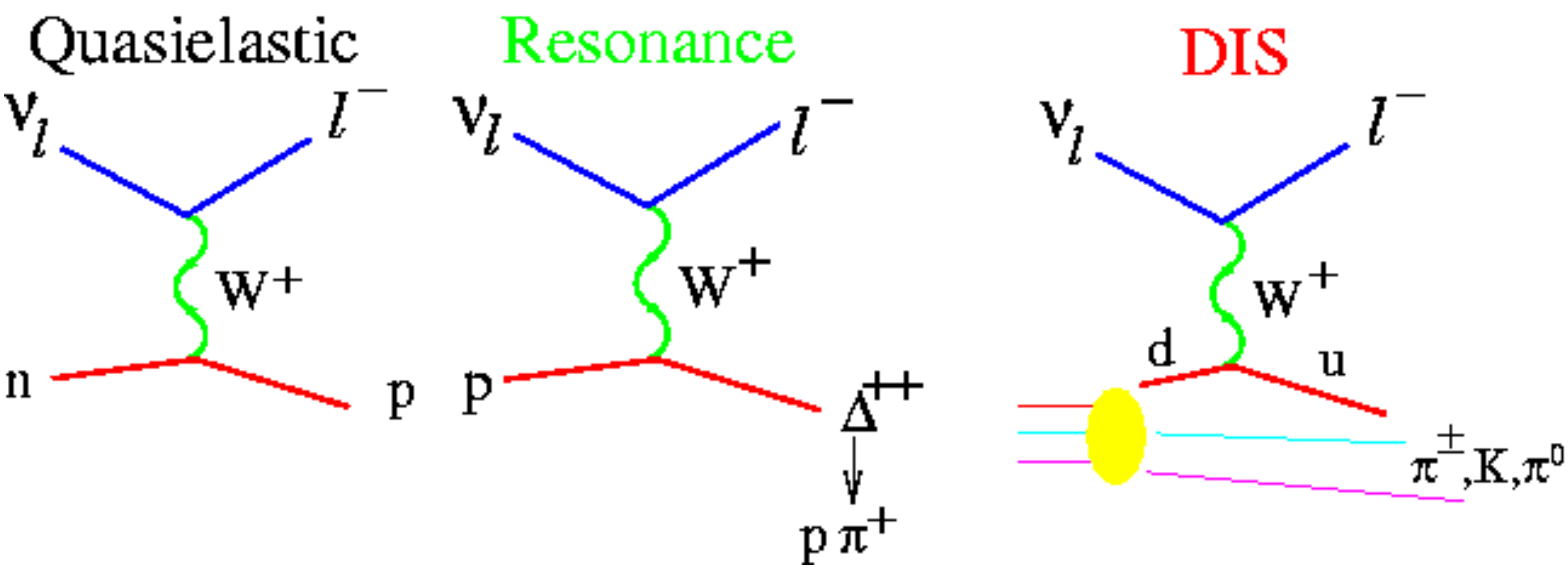


Aligarh Muslim University
Centro Brasileiro de Pesquisas Fisicas
Fermilab
University of Florida
Universite de Geneva
Universidad de Guanajuato
Hampton University
Massachusetts College of Liberal Arts
University of Minnesota at Duluth
University of Mississippi
Otterbein University

Universidad Nacional de Ingenieria
Potificia Universidad Catolica del Peru
University of Pennsylvania
University of Pittsburgh
University of Rochester
Rutgers, the State University of New Jersey
Universidad Tecnica Federico Santa Maria
Tufts University
College of William and Mary
University of Wroclaw

Interactions Studied by MINERvA

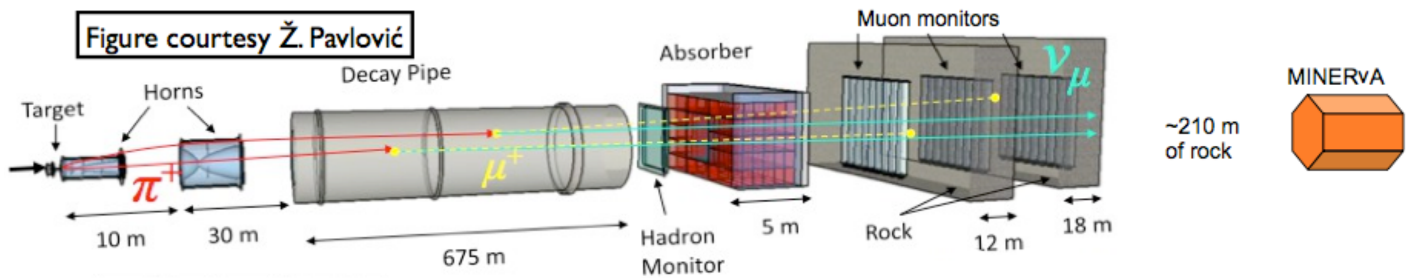
- Can go from low to high momentum transfer to the nucleus
  - Quasi-elastic: this is most of the events at T2K and MicroBooNE
  - Resonance: backgrounds in T2K, signal in NOvA and DUNE
  - DIS: part of the signal in the DUNE experiment, + ICECUBE

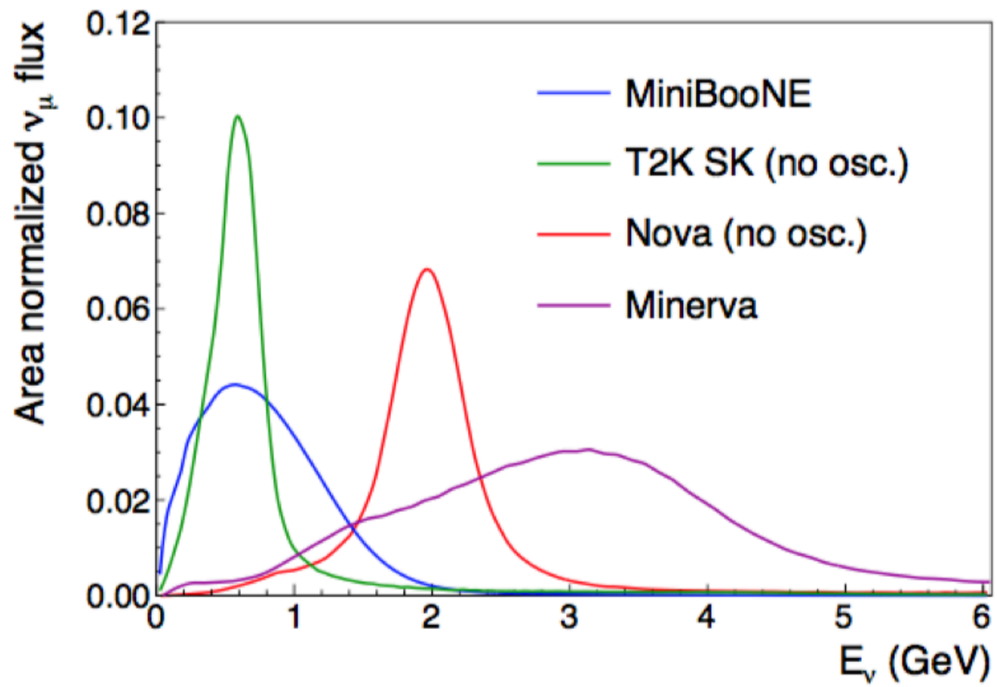


Momentum Transfer increasing

MINERvA's Flux in Oscillation Landscape

- NuMI Beamline
  - 120GeV protons
  - 2 focusing horns
  - 675m long decay region
  - MINERvA on axis at 1km
- MINERvA can see processes relevant for oscillation experiments from T2K to ICECUBE

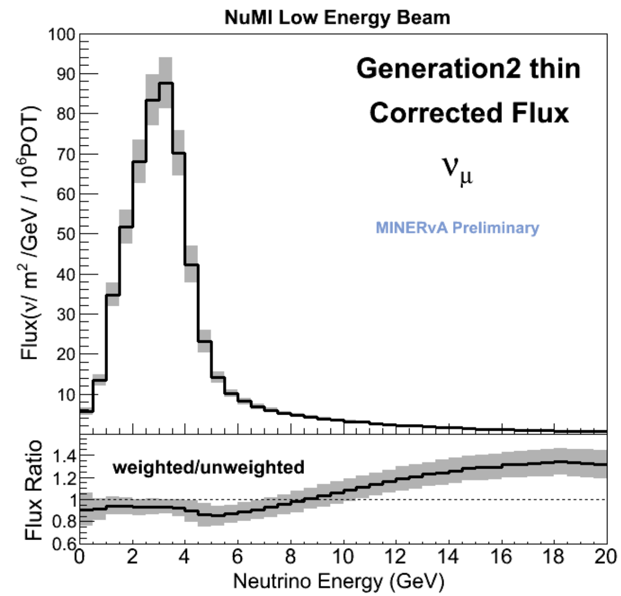


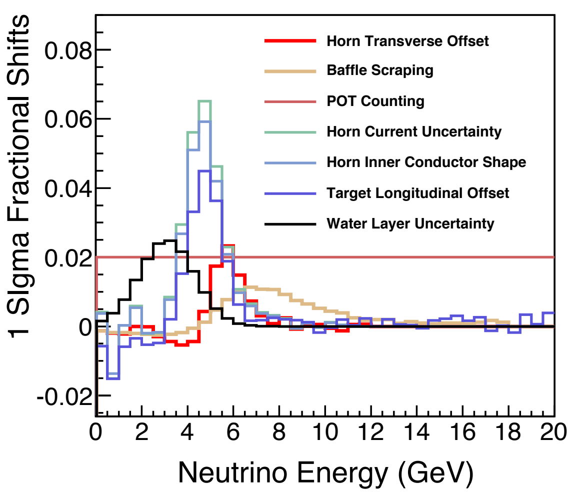


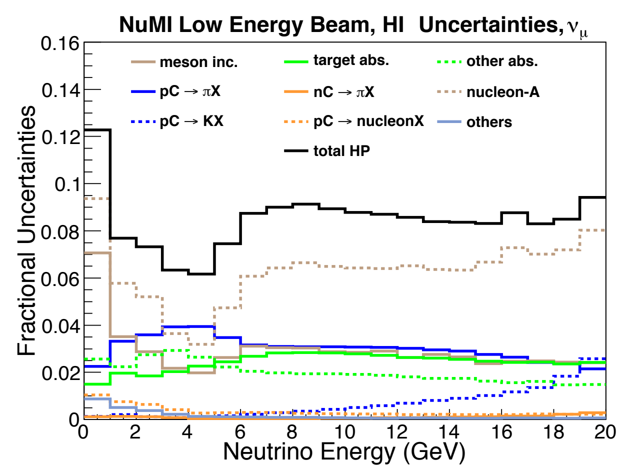
Plot courtesy P. Rodrigues

MINERvA: Low Energy Flux Uncertainties

- Use world's collection of hadron production data
- Compare with in situ flux shape measurement
- Constrain with neutrino-electron scattering events (standard candle)
- Low Energy Flux Uncertainty: ~8% at focusing peak, 10% integrated



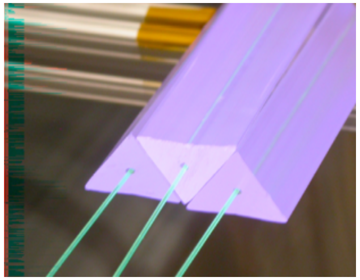


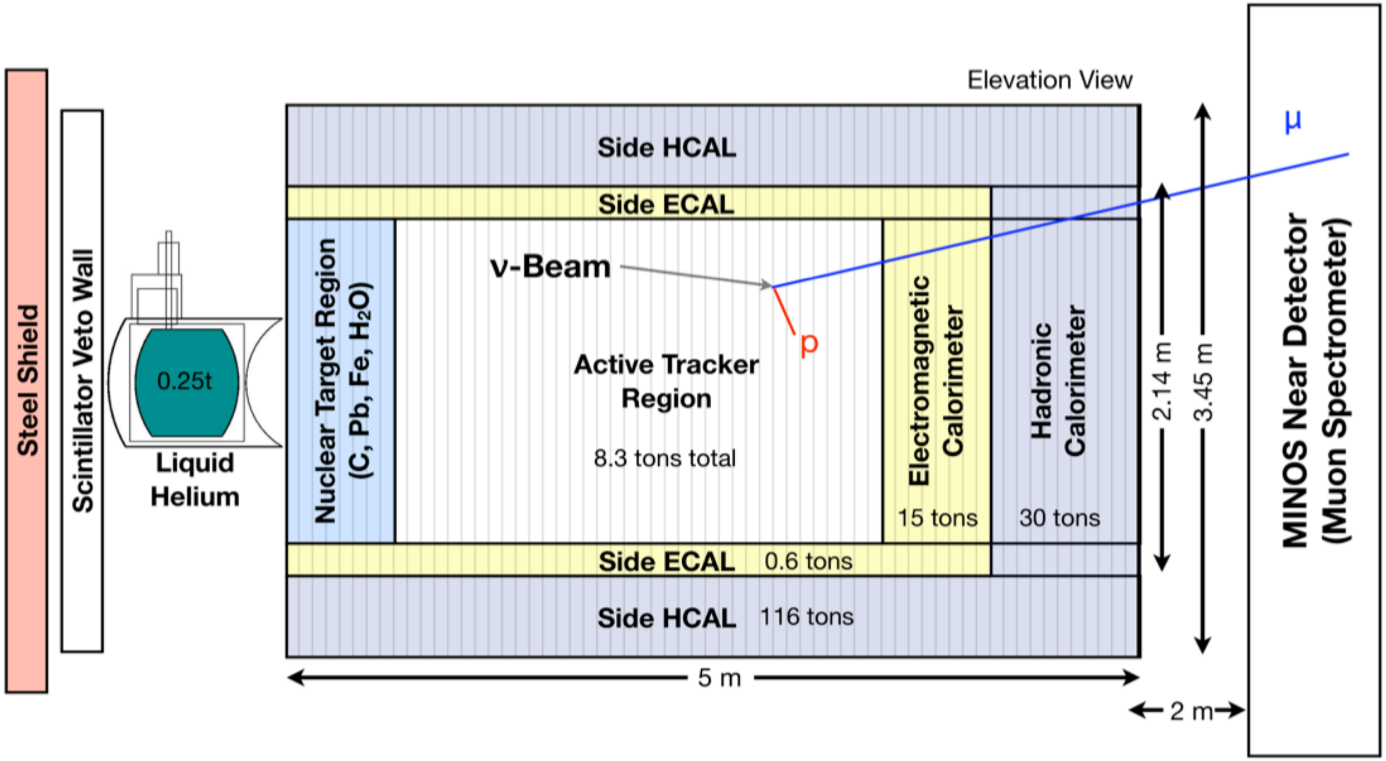


Ref: Aliaga et al, Phys. Rev. D94 2016

MINERvA Detector

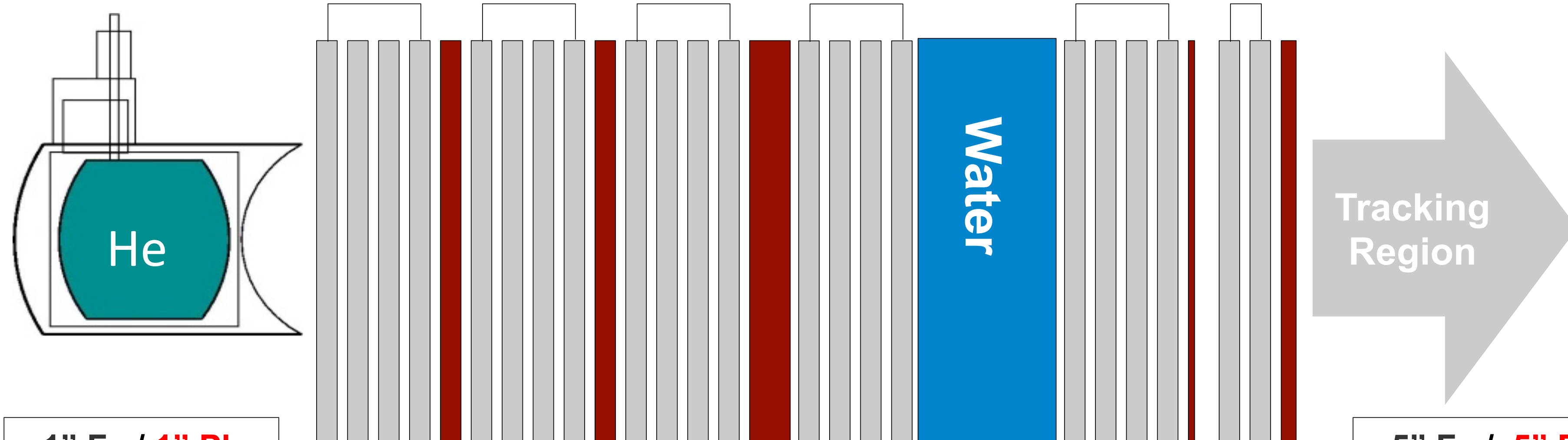
- Core of solid scintillator (CH) tracker
  - Tracking, particle ID, good energy reconstruction
  - Cell size: 1.7cm (transverse) x1.7cm (longitudinal)
- Surrounding electromagnetic and hadronic calorimetry
- MINOS Near Detector for μ charge and momentum



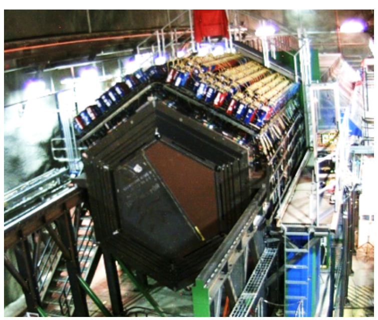


MINERvA's Nuclear Target Region

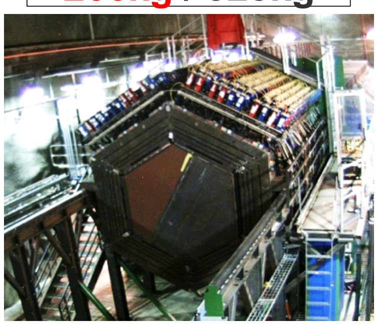
- Simultaneous targets in beam for robust test of models



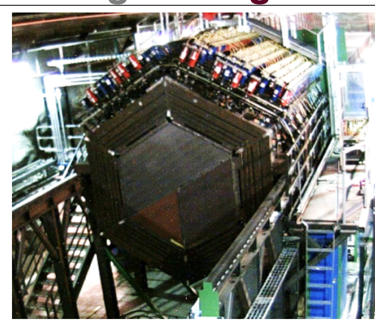
1" Fe / 1" Pb
323kg / 264kg



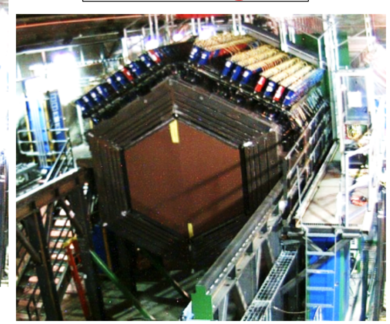
1" Pb / 1" Fe
266kg / 323kg



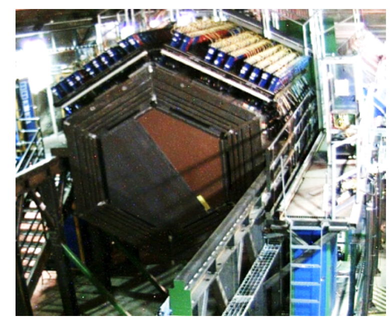
3" C / 1" Fe / 1" Pb
166kg / 169kg / 121kg



0.3" Pb
228kg



.5" Fe / .5" Pb
161kg/ 135kg



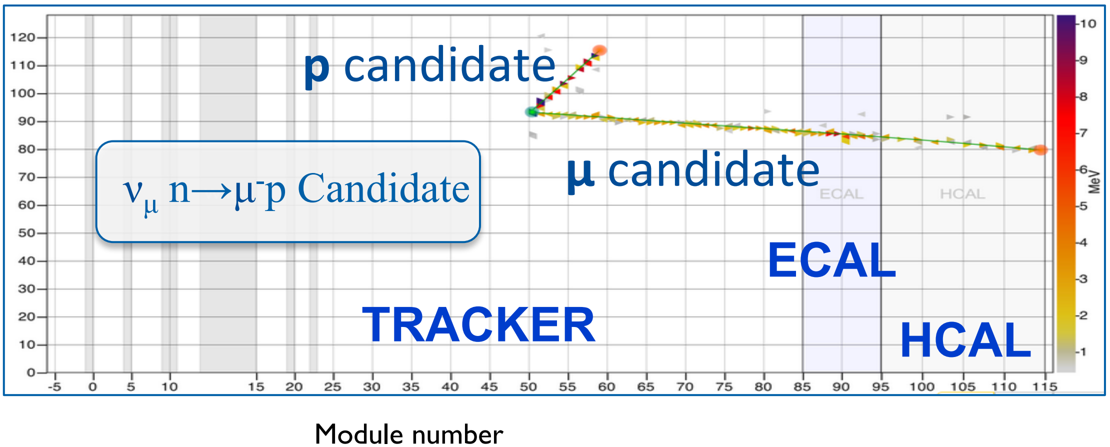
Recipie for Cross Section Measurements

$$\left(\frac{d\sigma}{dx}\right)_\alpha = \frac{\sum_j U_{j\alpha}(N_{data,j} - N^{bkgd}_{data,j})}{A_\alpha(\Phi T)(\Delta x)}$$

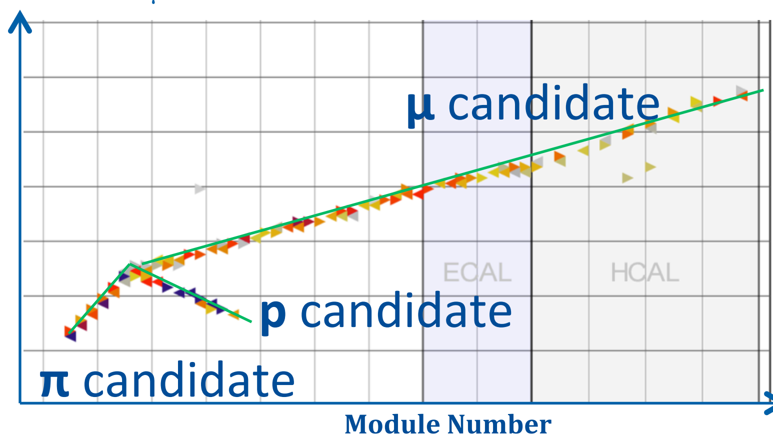
- Count events ($N_{data,j}$)
- Subtract backgrounds, predict using data ($N^{bkgd}_{data,j}$)
- Unsmear the data ($U_{j\alpha}$) to take out detector resolution
- Divide by acceptance x efficiency (A_α)
- Divide by flux and # of targets (ΦT)
- Δx: normalize by bin width
- j and α: reconstructed and true bin number

Events in MINERvA

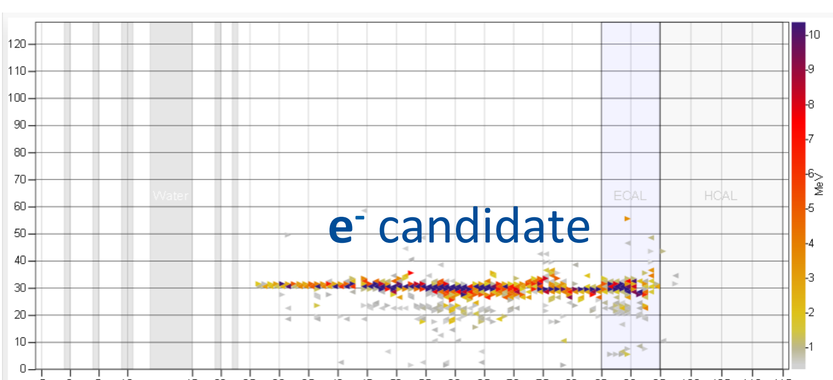
One out of three views shown, color = energy

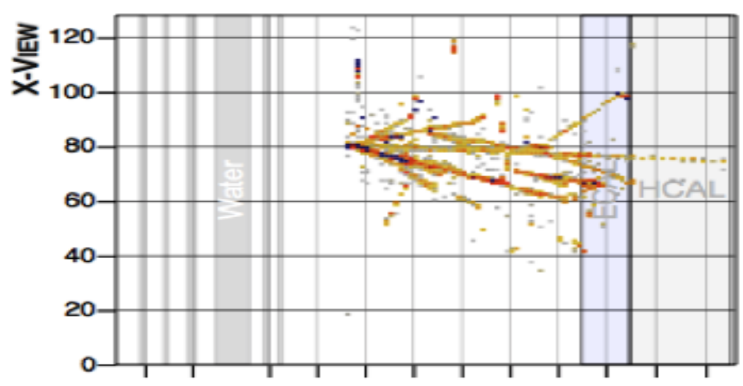


$\nu_\mu\, p \rightarrow \mu^- \Delta^{++}, \Delta^{++} \rightarrow p\pi^+$ Candidate

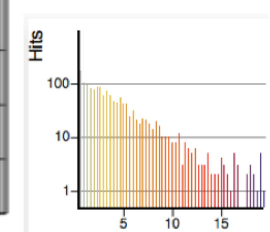


$\nu_\mu\, e^- \rightarrow \nu_\mu\, e^-$ Candidate





Deep Inelastic Scattering candidate



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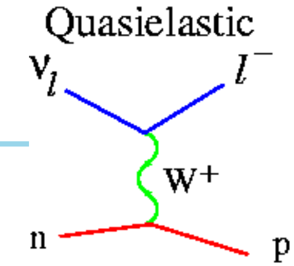
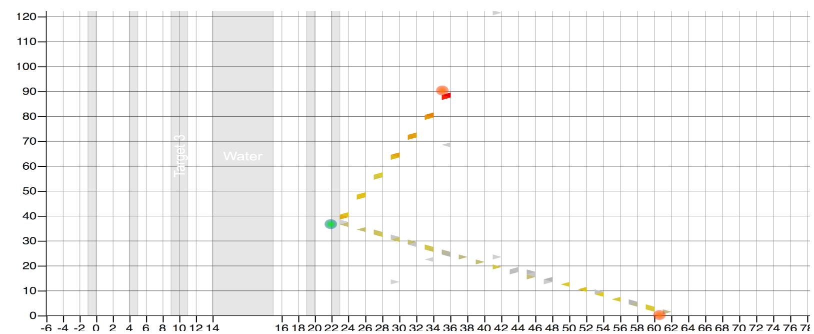
Quasi-Elastic Cross Section Ratios on Fe, Pb, C



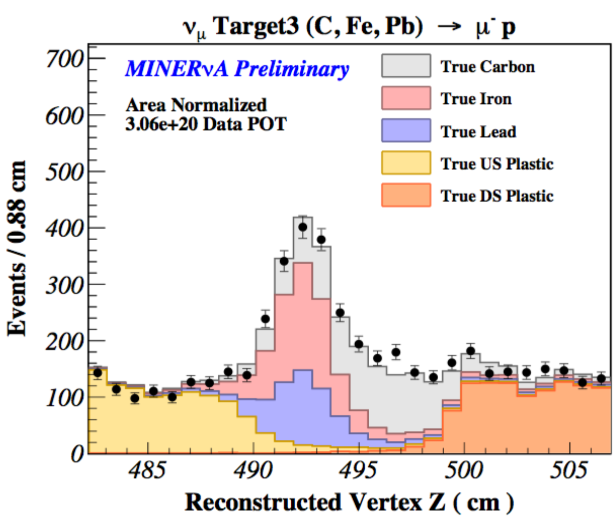
- Study of momentum transfer from the proton arm

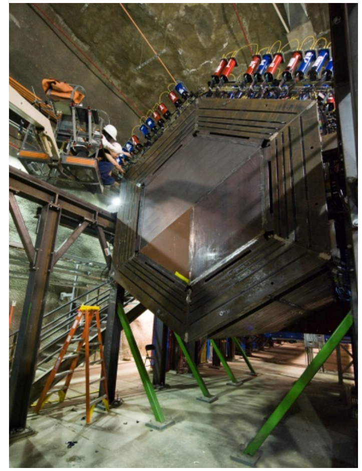
$$Q^2 = (M')^2 - M_p^2 + 2M'(T_p + M_p - M')$$

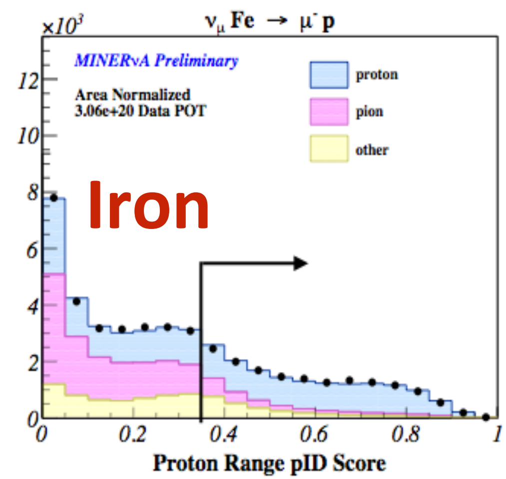
$M' = M_n - E_b$
E_b :binding energy
T_p : proton kinetic energy
M_n : neutron mass
M_p: proton mass



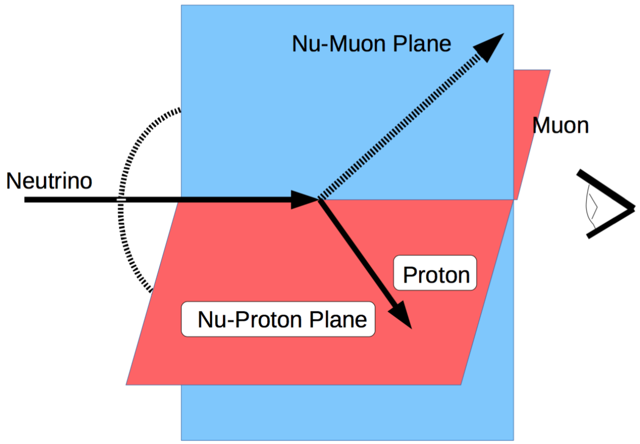
Ref: arXiv:1705:03791

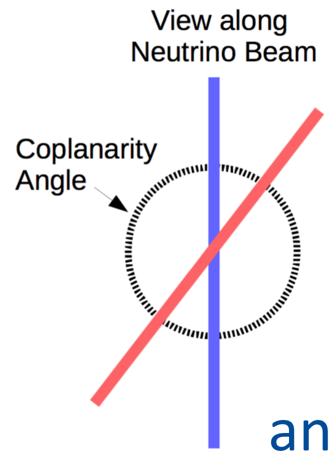






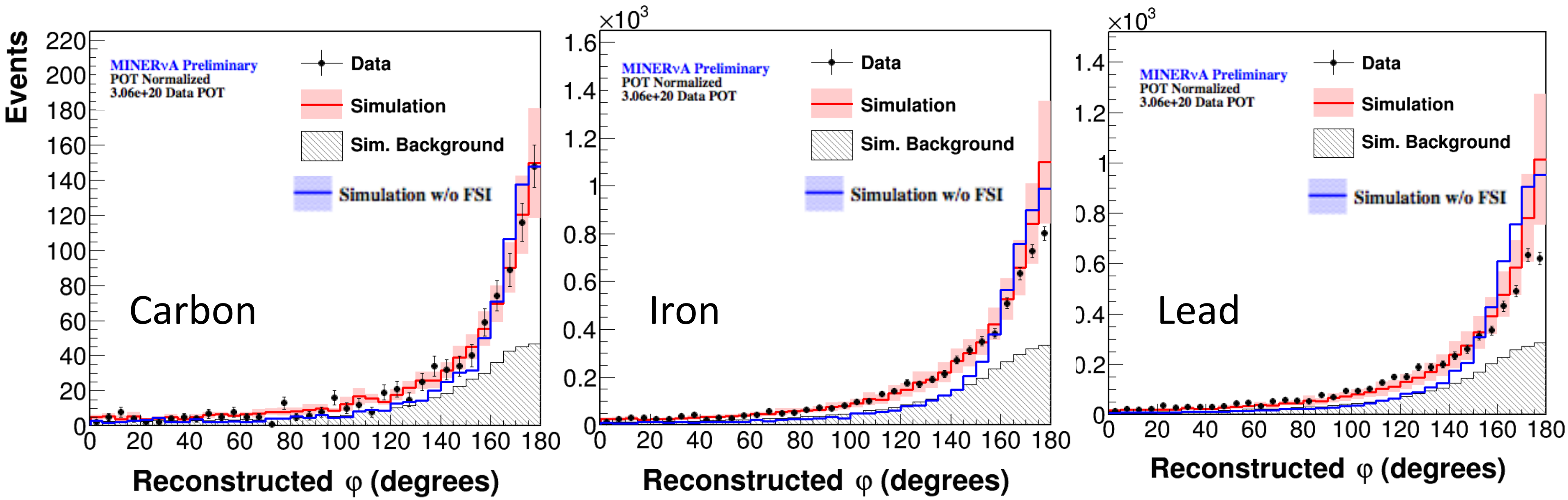
Quasi-Elastic Event Coplanarity on C, Fe, Pb





ϕ: Coplanarity

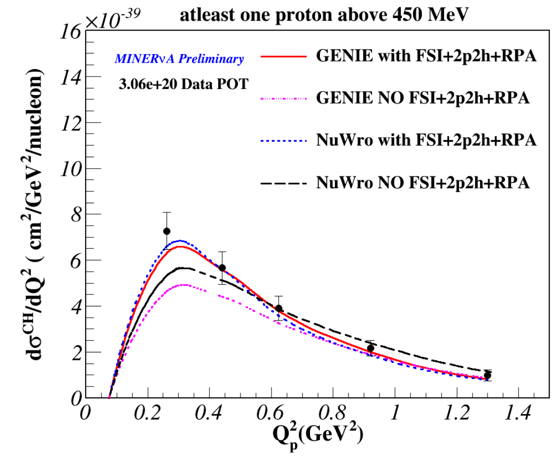
180° for proton at rest
and 2-body interaction
and no final state interactions

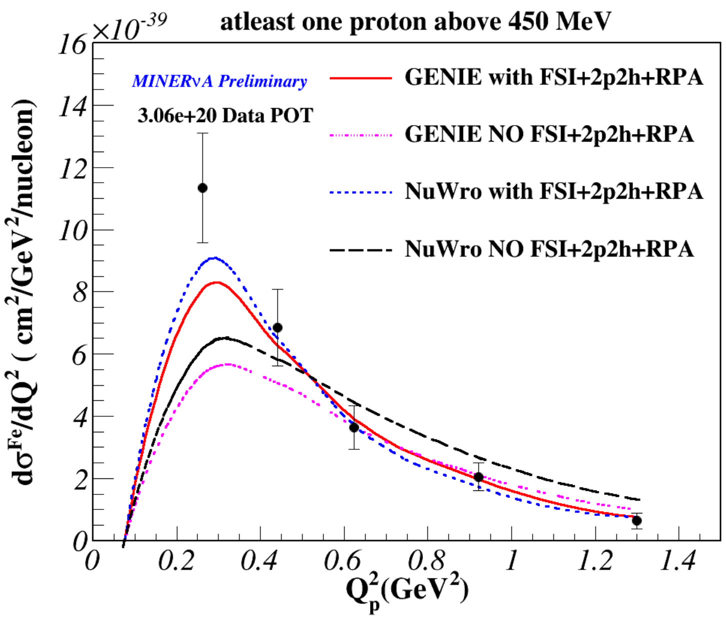


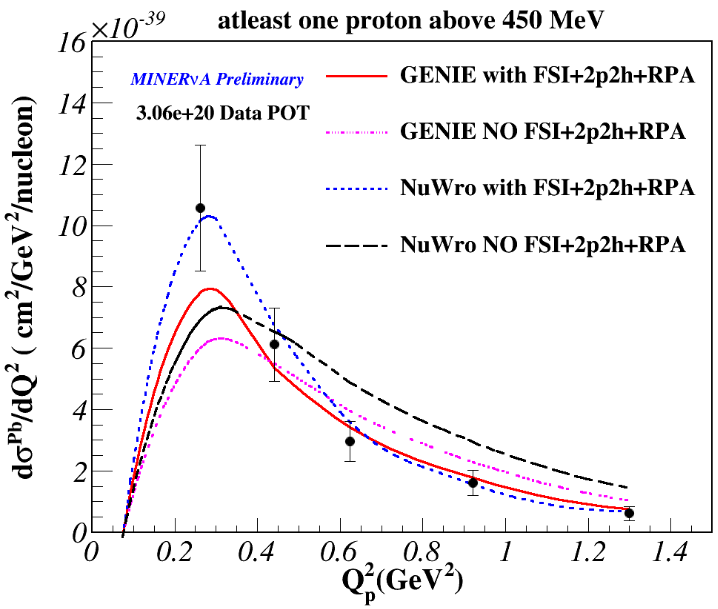
Ref: arXiv:1705:03791

Quasi-Elastic Cross Sections on C, Fe, Pb

- Just because a model gets C right does not mean it gets higher Z right
- Need to get nuclear effects of primary interaction AND Final state Interactions correct

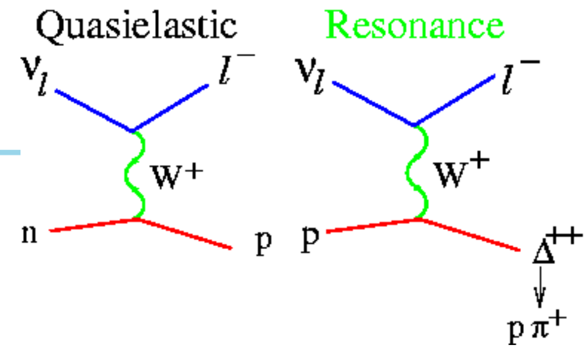




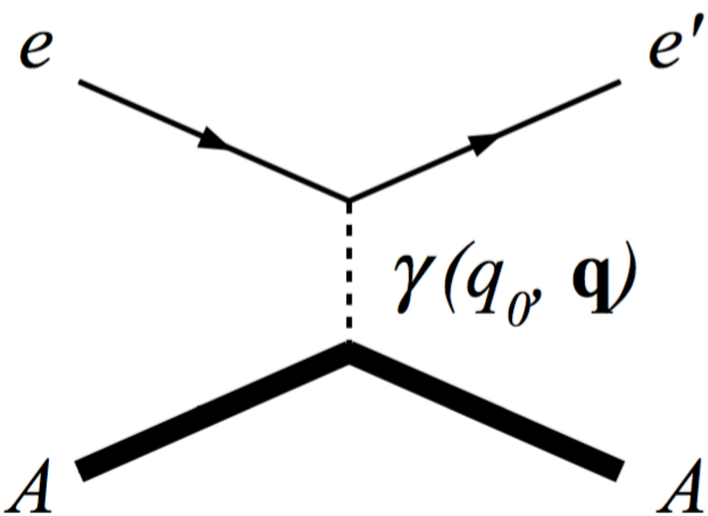


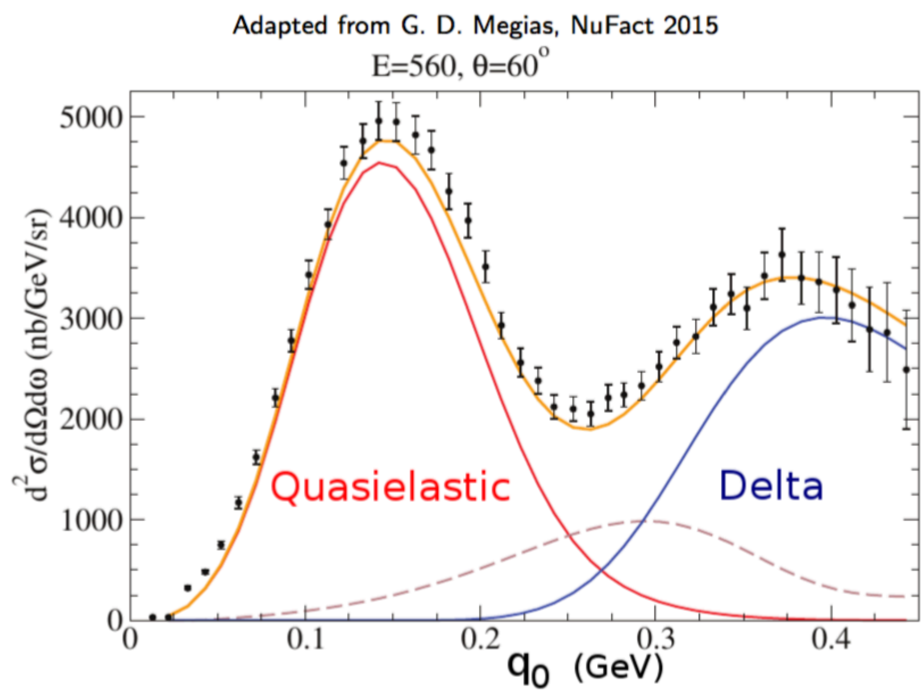
Ref : arXiv:1705:03791

Looking at more than just the proton…



- Electron Scattering measurements have seen surprises when looking near the Quasi-elastic peak

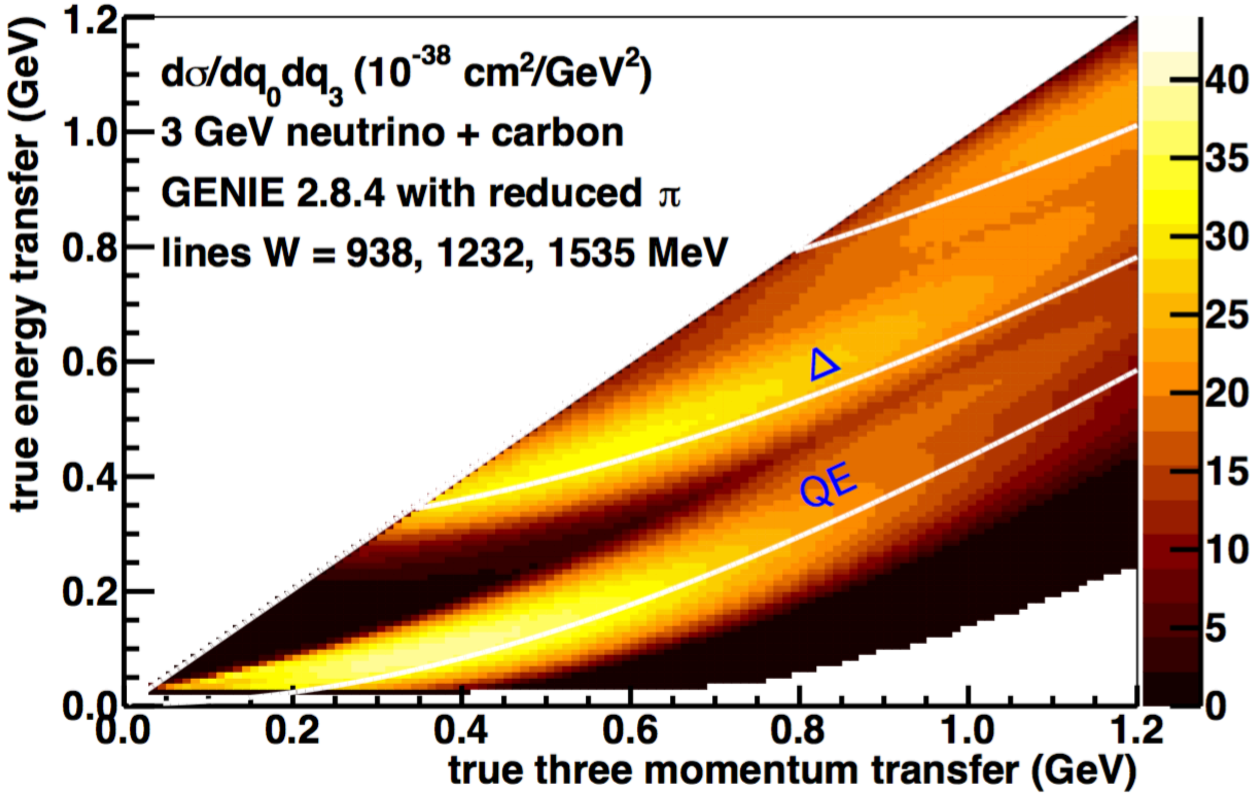




$$q_0 = E_e - E_{e'}$$

Try to get to the same kinematics in neutrino scattering

- Variables of interest: momentum transfer q
  - Total three-momentum transferred (q_0)
  - Total momentum along the beam direction (q_3)



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Now go to variables we can reconstruct well

- Problem with "q_0" is that it also depends on energy that goes into neutrons, which we don't see well
- Define new variable: "available energy" which is the energy that does go into our detector (KE of charged pions, photons, KE of protons, etc.)

Energy Transfer:

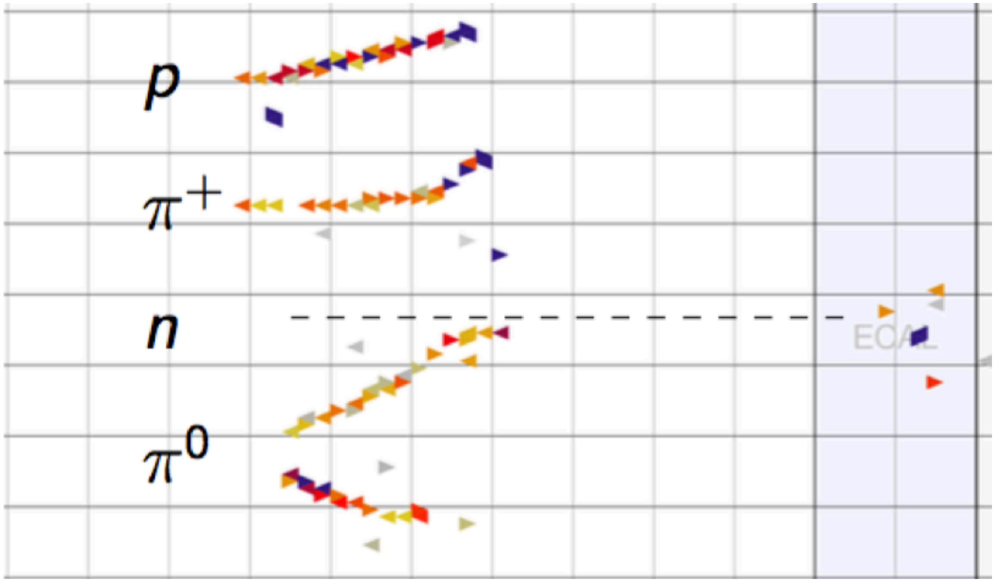
$$q_0 = \text{Calorimetric Hadronic Energy}$$

Neutrino Energy:

$$E_\nu = E_\mu + q_0$$

Momentum Transfer Squared:

$$Q^2 = 2E_\nu(E_\mu - p_\mu \cos\theta_m) - M^2_\mu$$



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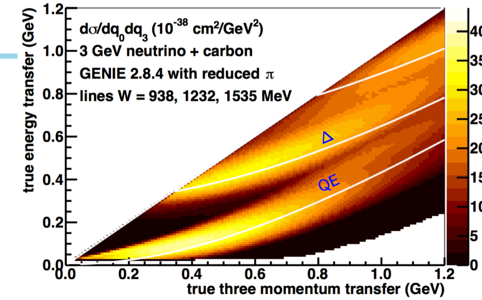
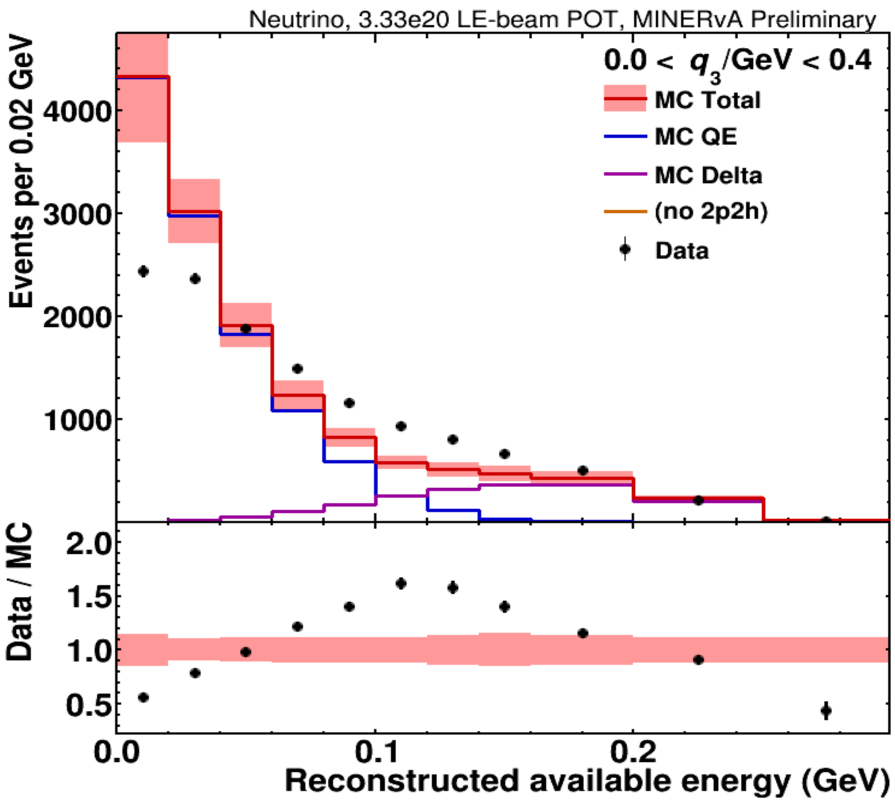
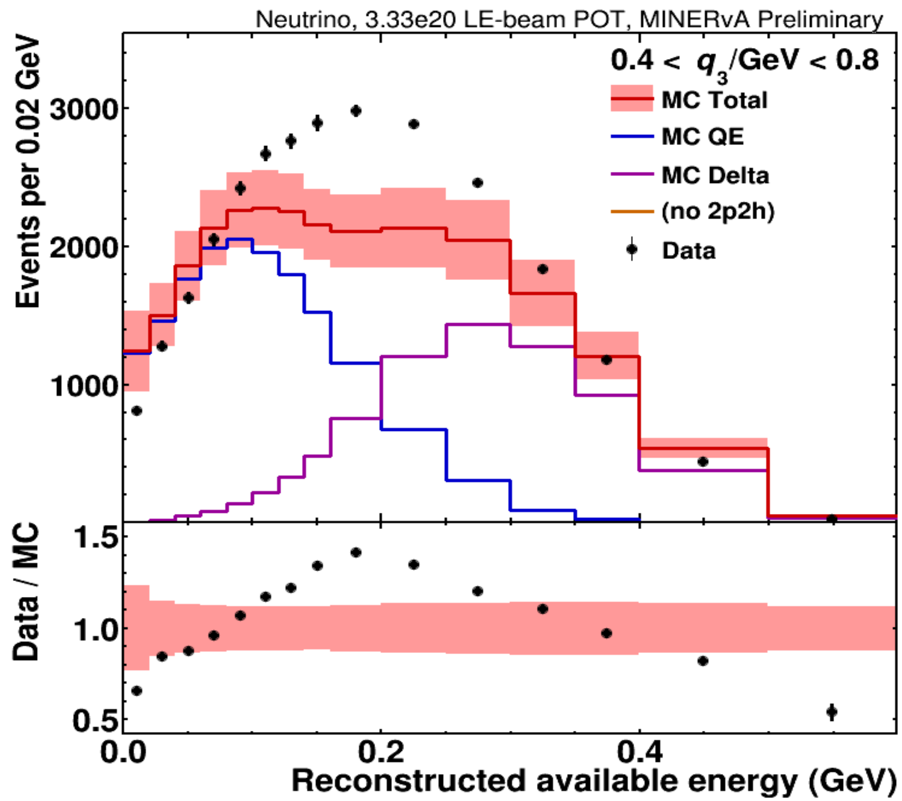
What do the data look like?

- Slice the 2-d space into two 1-d distributions



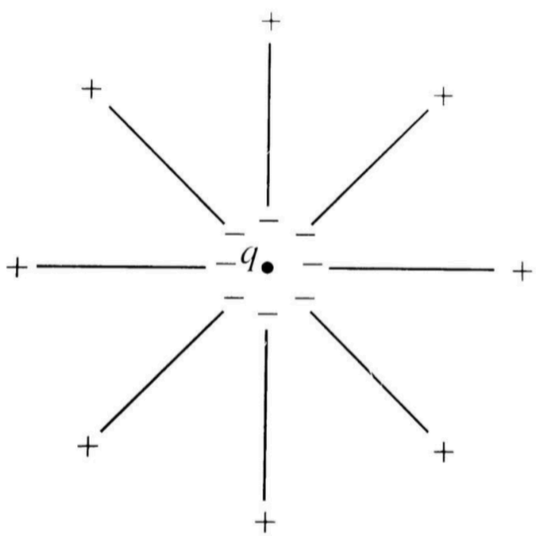


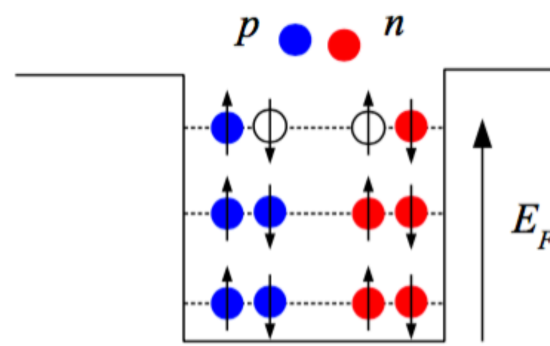


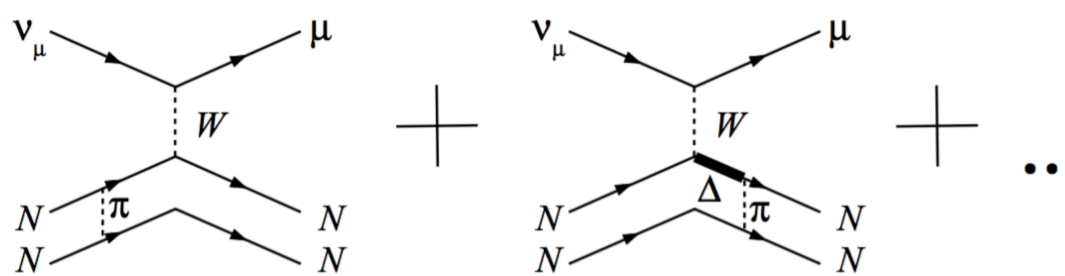
Phys. Rev. Lett. 116, 071802 (2016)

Missing ingredients

- Weak charge screening
- “2p2h” events to fill in the “dip” region between QE and resonance



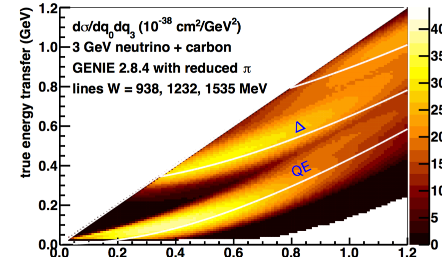


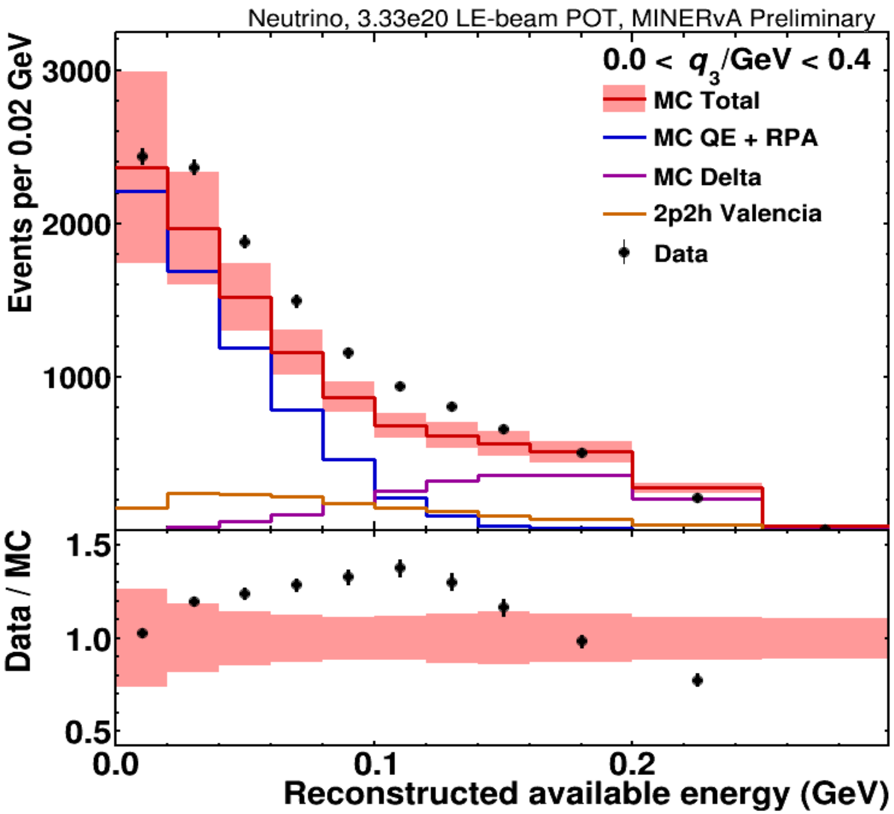


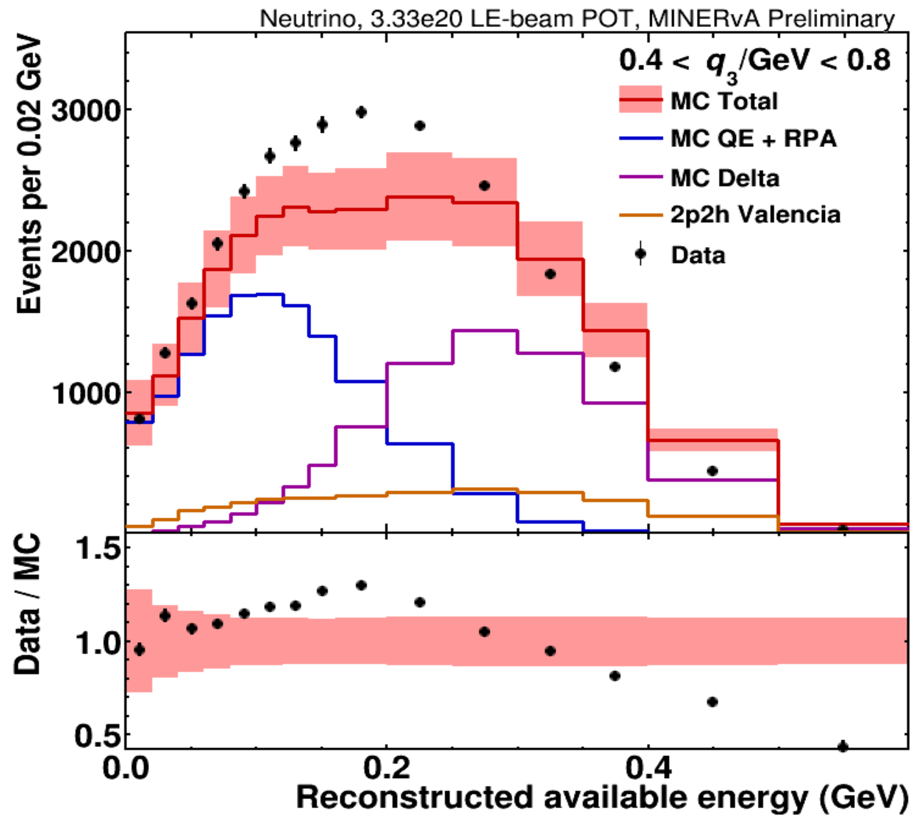
What happens when we add those two ingredients?

- The 2p2h contribution predicted by Nieves is not quite enough, but close!

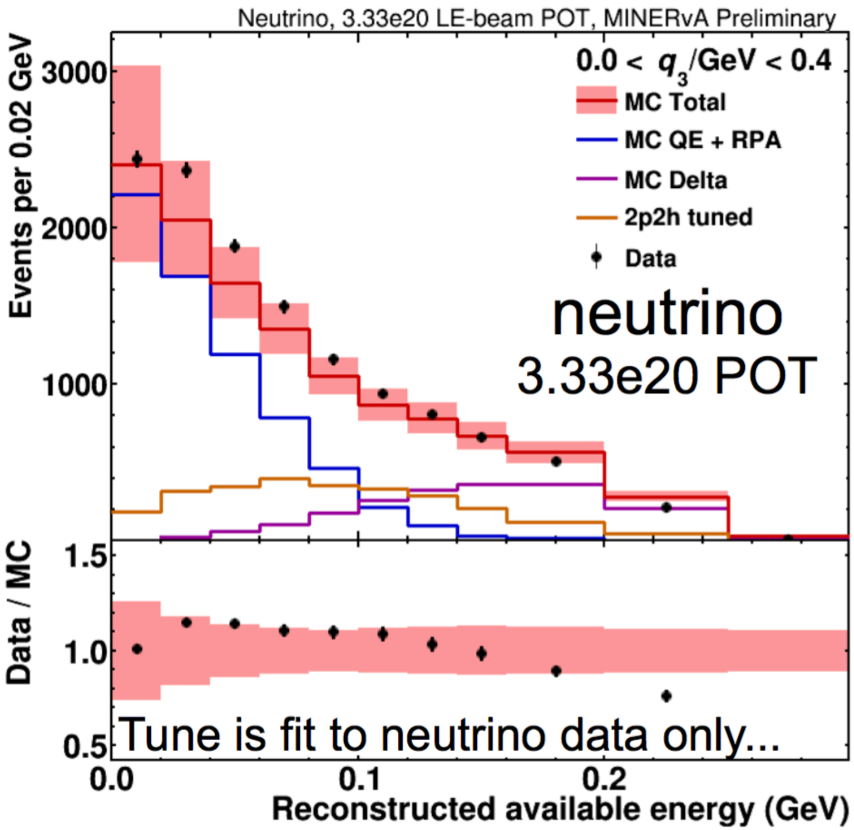
Phys. Rev. Lett. 116, 071802 (2016)

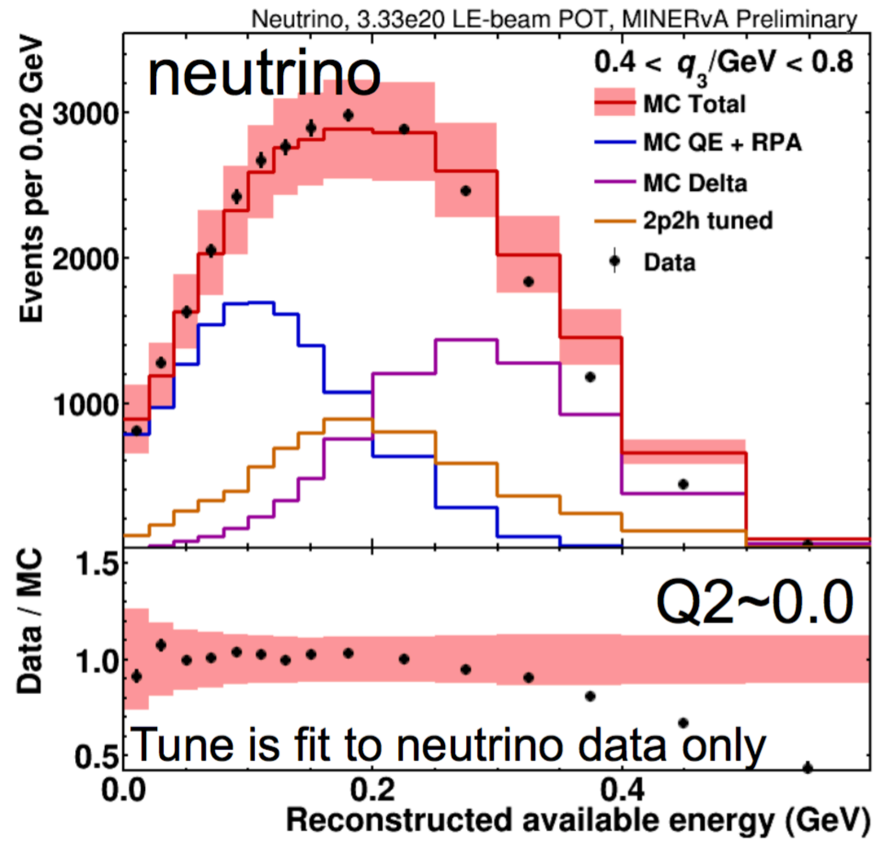






Fit to neutrino data, add extra strength to “dip” region

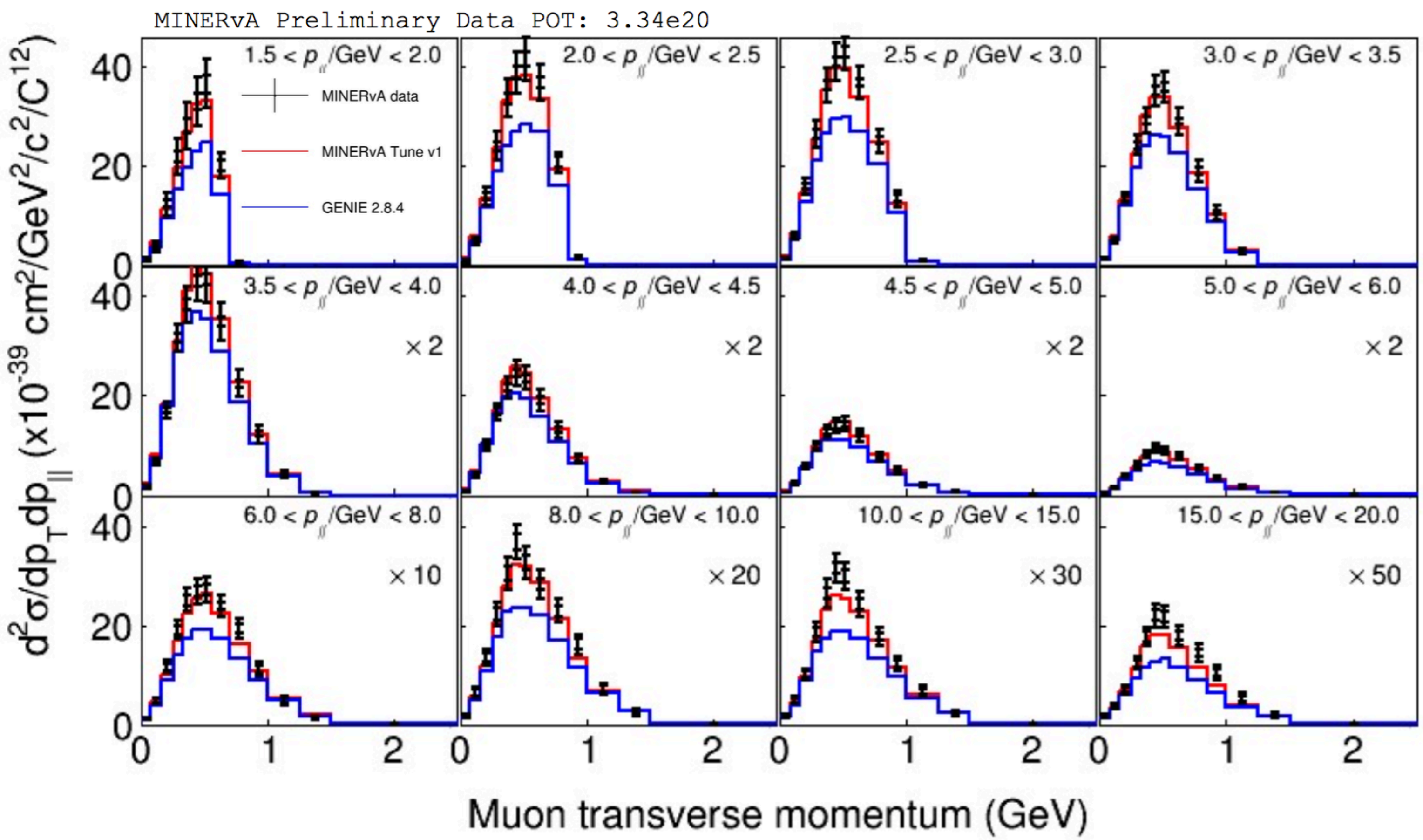




Fine, but does this new model have any predictive power?

Double Differential Neutrino CCQE Cross Sections

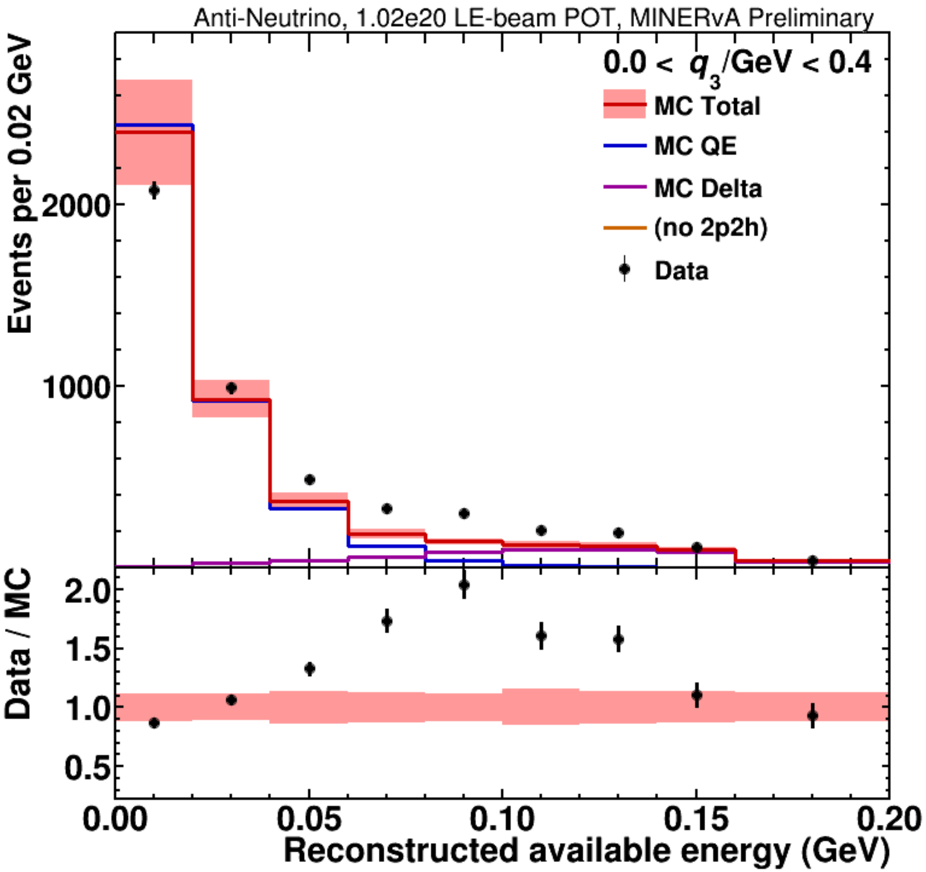
- Isolate only CCQE events: cut on extra energy outside the vertex, subtract backgrounds, extract cross sections

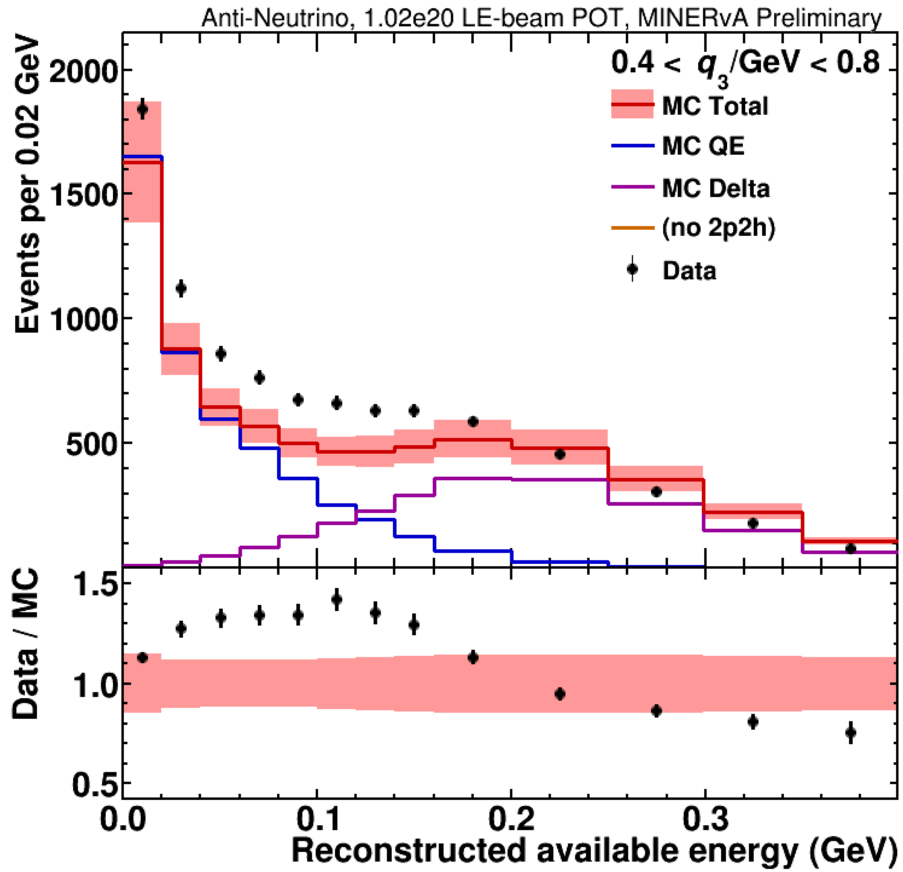


D. Ruterbories, FNAL Seminar, 3/2017

What about Antineutrinos?

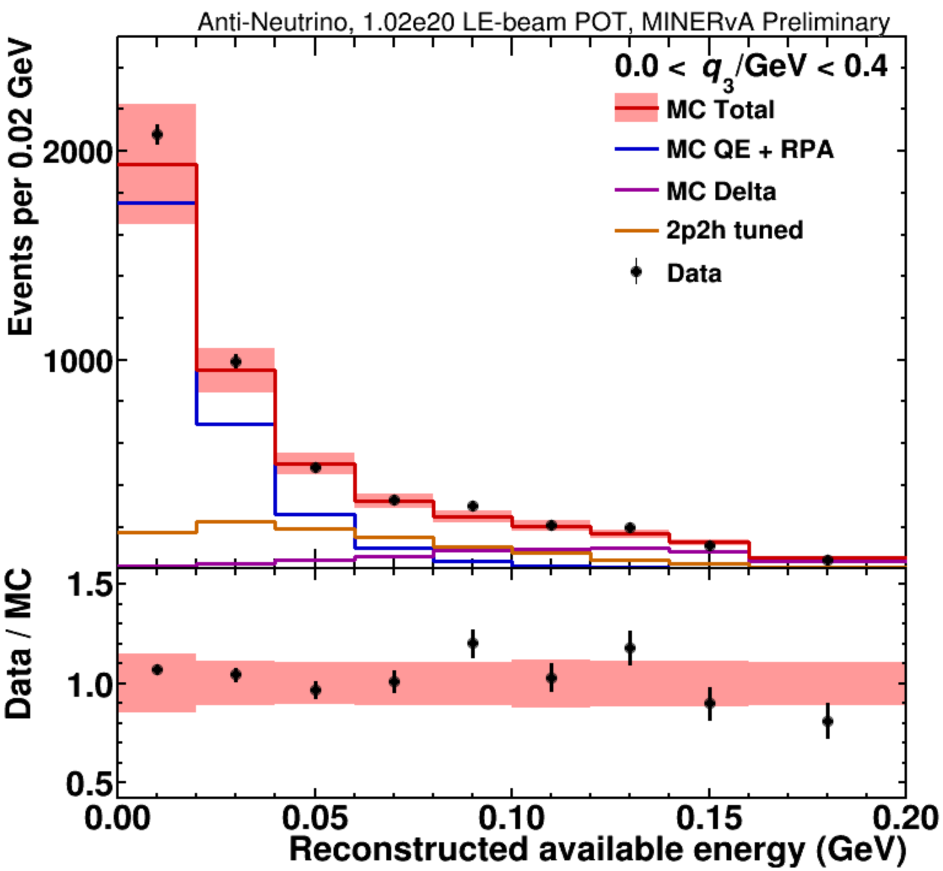
- Look in the same two kinematic regions: first with "out of the box" prediction Ref: R. Gran, NuINT'07

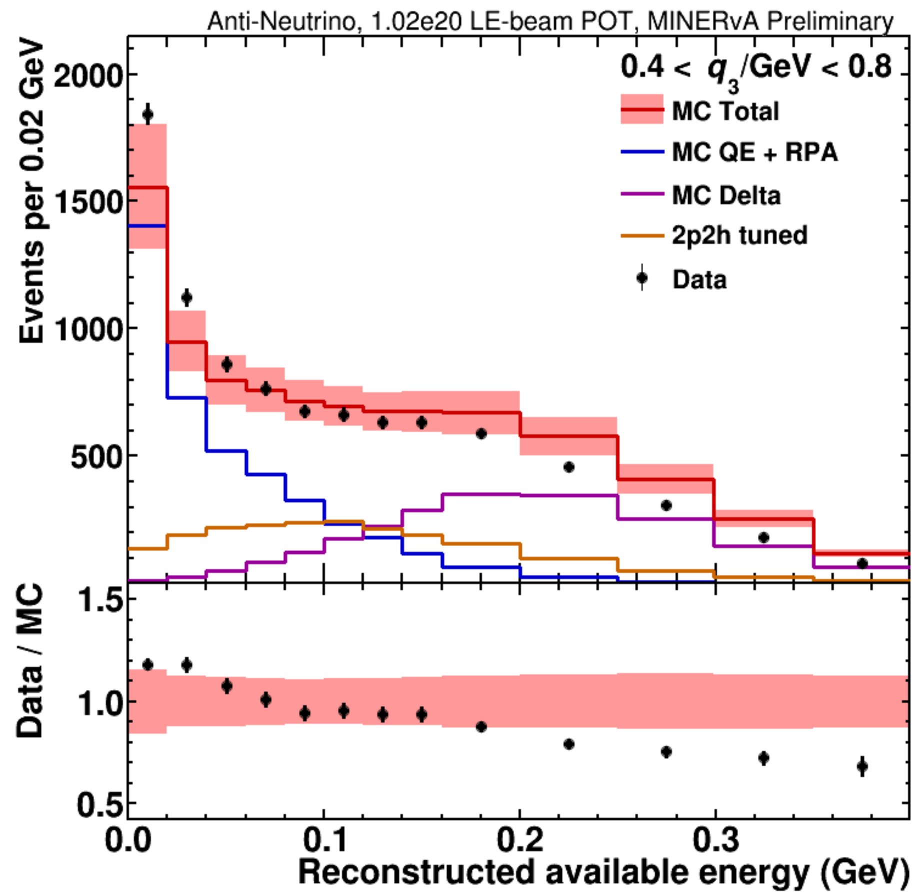




Antineutrino Inclusive Events at low recoil

- Add the fit from neutrino data to the antineutrino prediction…

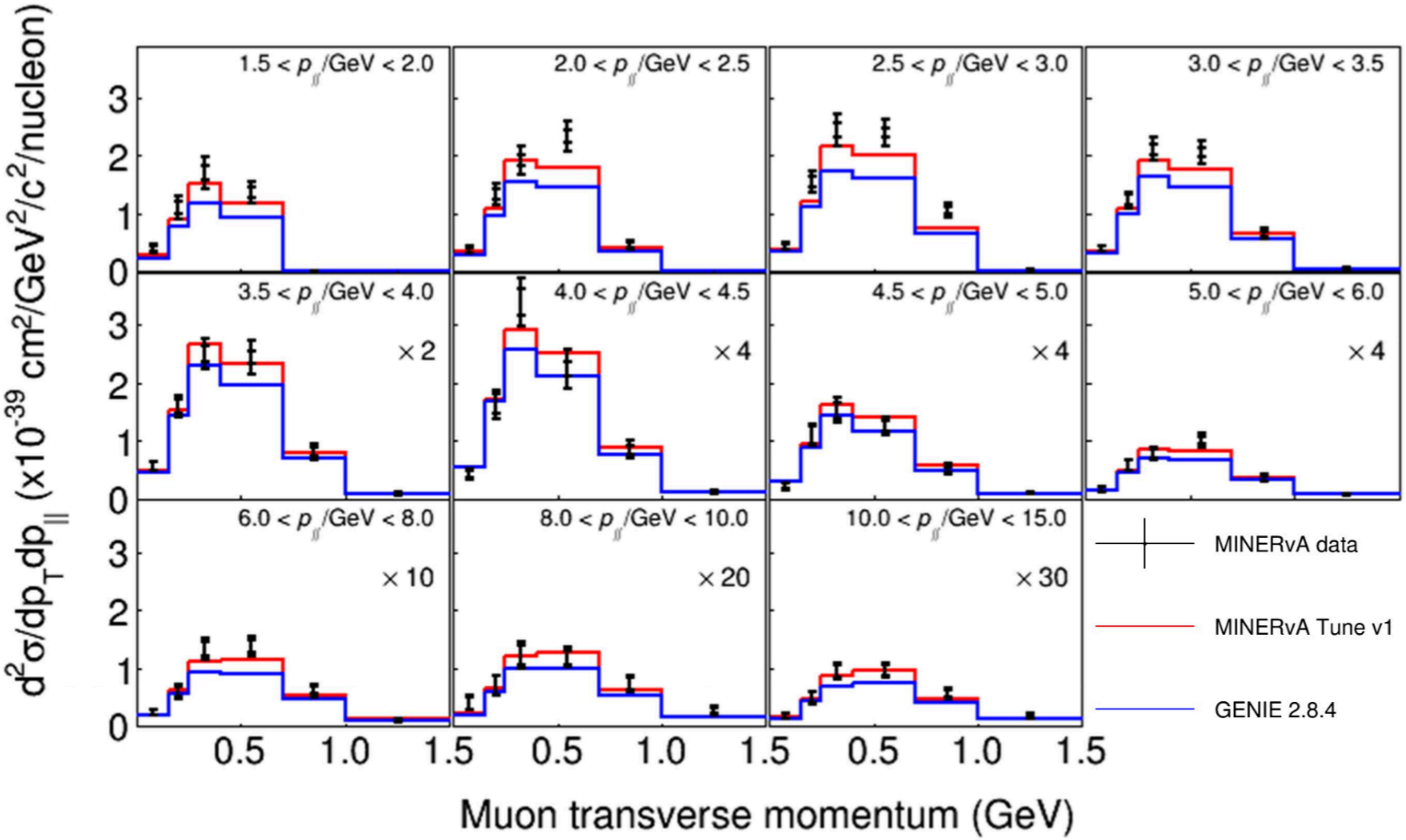




Ref: R. Gran, NuINT'17

Double Differential Antineutrino CCQE Cross Sections

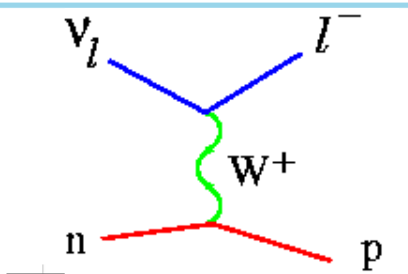
- Isolate only CCQE events: cut on extra energy outside the vertex, subtract backgrounds, extract cross sections

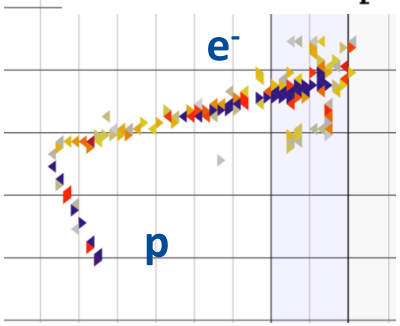


Extra strength coming at the right place in muon angle and momentum too

D. Ruterbories, FNAL Seminar, 3/2017

Electron Neutrino CCQE Cross Section



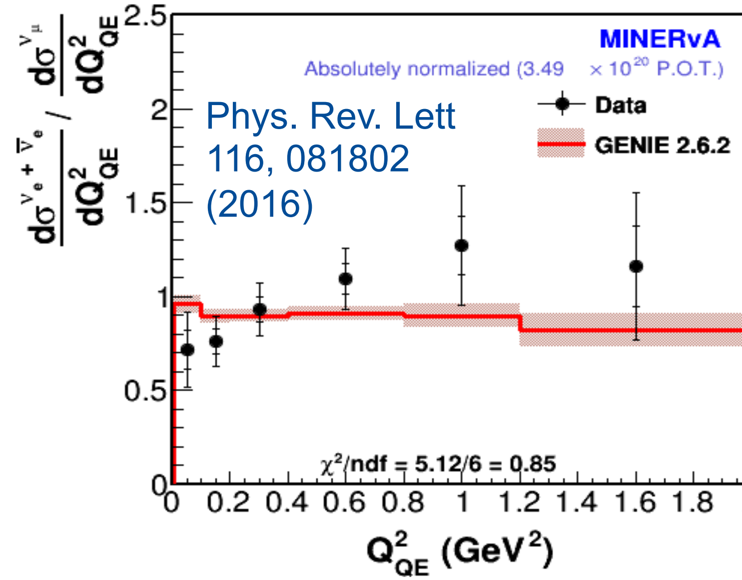


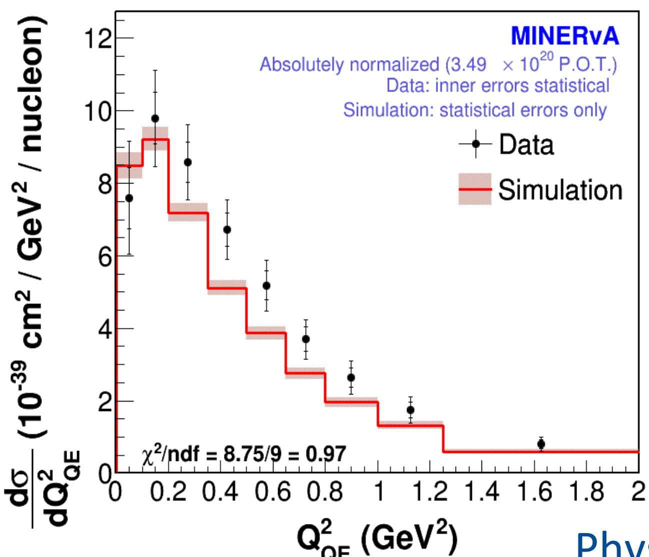
ν_e CCQE is oscillation signal, but almost no data.

We all assume fundamental coupling is universal, but know nuclear effects are not!

Measured cross sections and ν_e/ν_μ ratio consistent with GENIE model @ 1σ (~10-20% uncertainties)

Absolute level is high

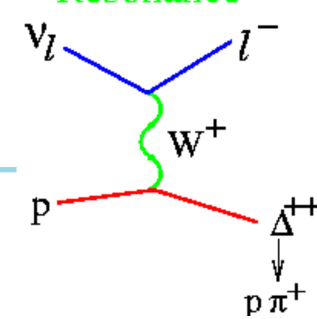




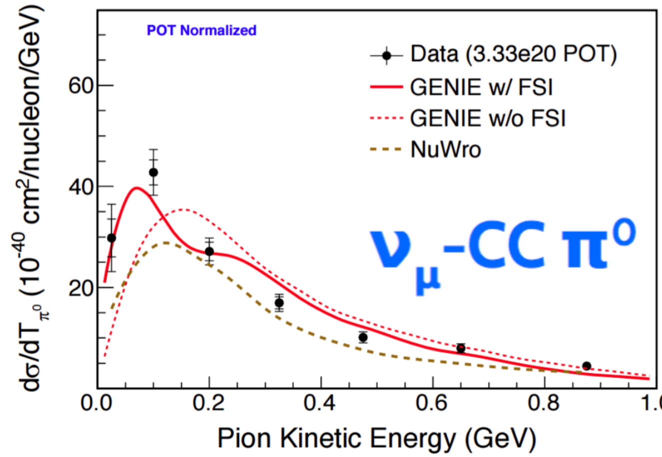
Also found an unsimulated background of photon like events, which we believe are due to diffractive production of π^0 from protons in scintillator.

Phys. Rev. Lett 116, 081802 (2016).

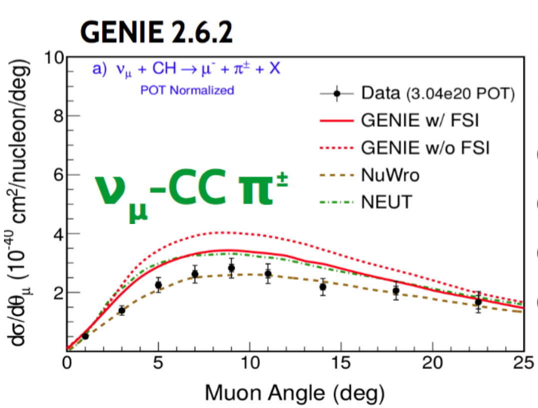
What about Pion Production?

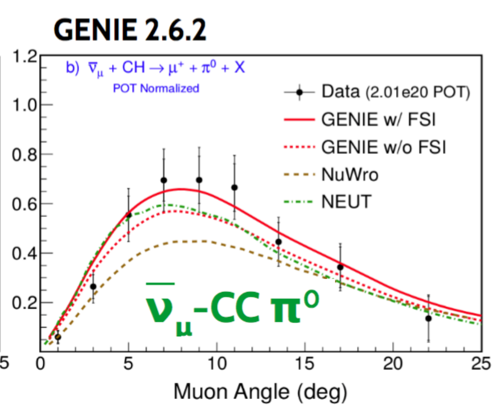


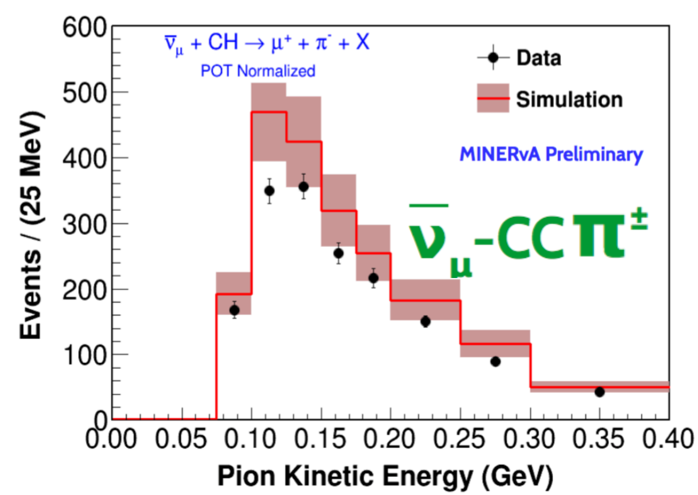
- After CCQE, pion production is the next most common channel for oscillation experiments
- Energy seen in detector depends on $\pi^{\pm}$ vs π^0 and how much energy pion loses leaving the nucleus
- MINERvA measuring all 4 modes, both π and μ kinematics



O. Altinok, JETP 7/17



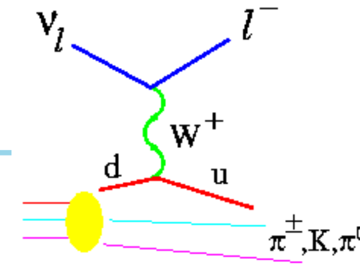




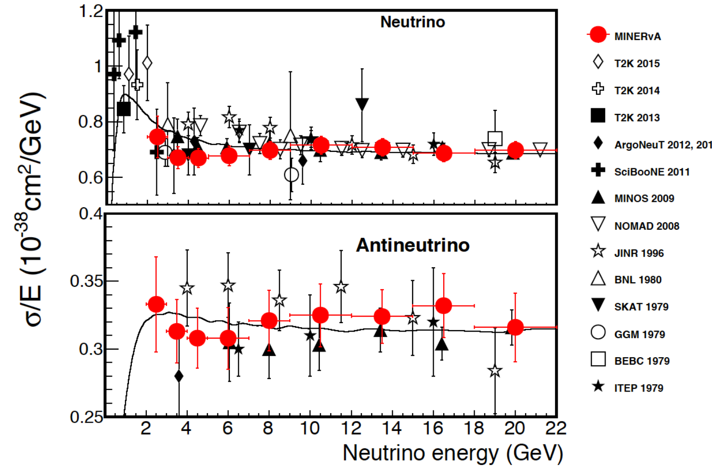
A. Ramirez, NuINT17

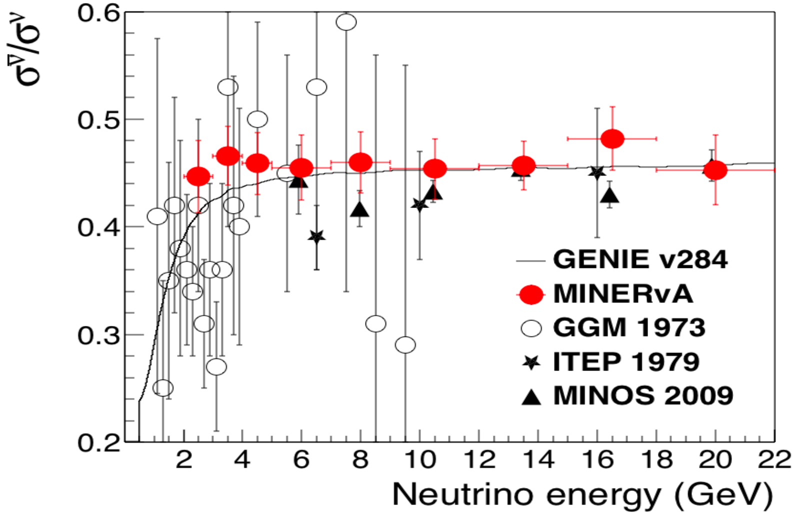
Phys.Rev. D94 (2016) no.5, 052005

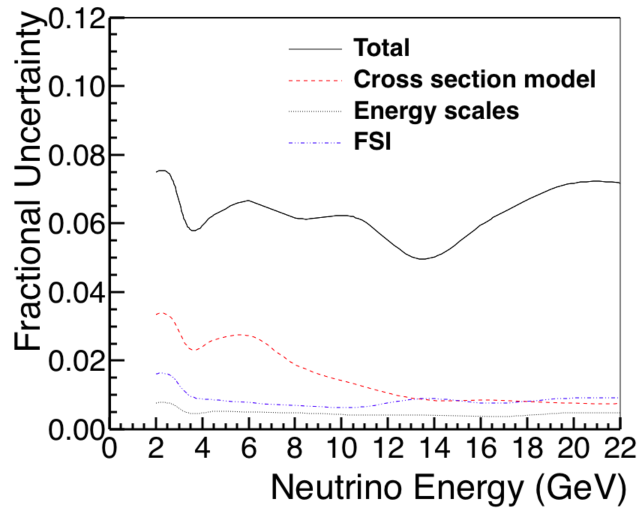
New precision on anti-ν/ν cross section ratio



- Take advantage of standard candle to determine the shape on anti-ν/ν shape as a function of energy
- Important for atmospheric ν experiment Mass Hierarchy measurements
- Systematics include known model deficiencies in multi-nucleon effects
- In anti-ν/ν ratio many systematics cancel

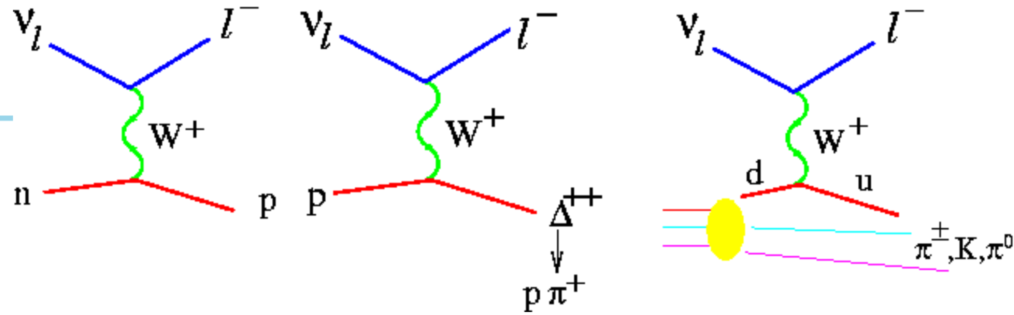






Phys. Rev. D 95, 072009 (2017)

Summary



- MINERvA looking at many processes in new ways
- Getting better understanding of role of nucleus
  - Beware of your simulation: "out of the box" event generator is not nature!
  - Putting together a new model, tuned on neutrino events that has predictive power on antineutrino events!
  - By looking at 4 modes of pion production we can probe final state interactions
  - Both affect the visible energy prediction for incoming ν energy
  - Better energy prediction means better oscillation measurements
- MINERvA taking ~6GeV antineutrino data now, working on our 6GeV neutrino statistics to extend these results

Summary of MINERvA's 21 publications

ν

NuMI Flux Determination (*a priori*, and from e^- scattering)

μ,e

Using Lepton variables only:
ν_μ and anti-ν_μ quasi-elastic
ν_e CCQE

W,Z

e,u,d,p,n,
C,Fe,Pb

Ratios comparing Pb,Fe,C to CH:
Total CC cross sections
Deep Inelastic Scattering
CCQE

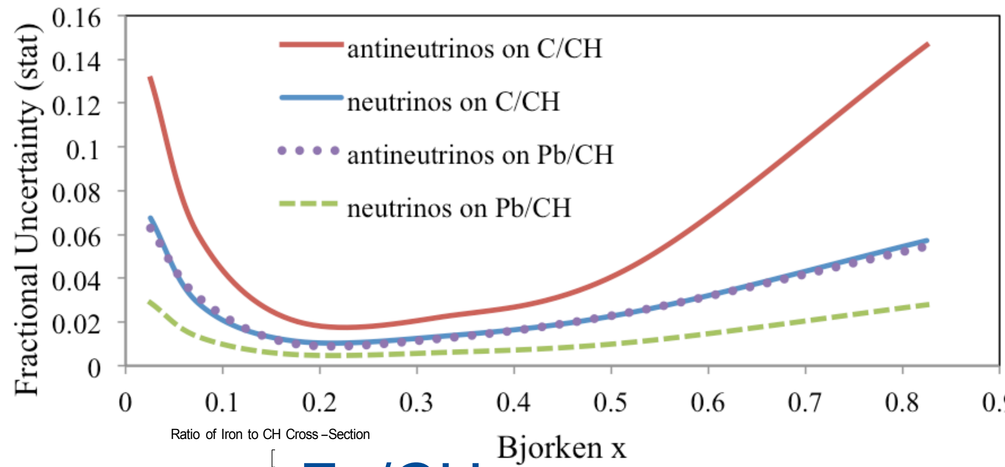
Inclusive "low recoil"
$\pi^\pm$ production by ν_μ
π^0 production by anti-ν_μ
$K^\pm$ production by ν_μ (NC,CC)
Coherent $\pi^\pm$, $K^\pm$ production
Inclusive anti-ν_μ/ν_μ ratios

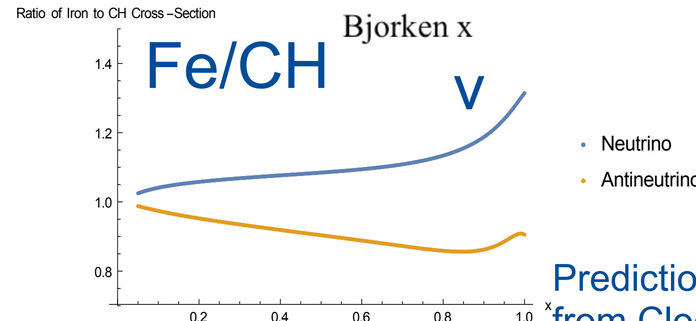
See http://minerva.fnal.gov

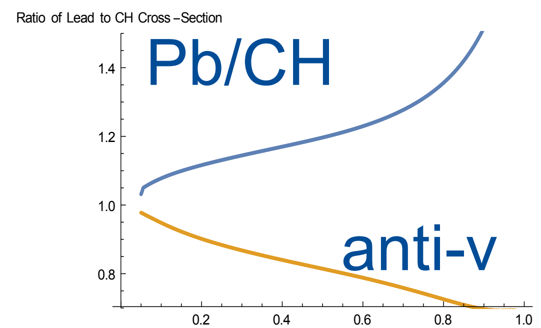
Backup

MINERvA's Current Physics Program

- Medium Energy results will feature 10x statistics
  - Higher flux and cross section, 3x more protons on target collected
  - Chance to look at nuclear effects in DIS at few % level!
    - Statistics above assume 12×10^{20} POT (2+ years) in antineutrino exposure
  - Exclusive channel ratio results for Fe, Pb, C, CH
  - Better Precision on ν_e scattering measurements





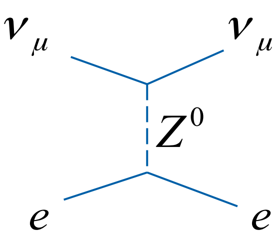


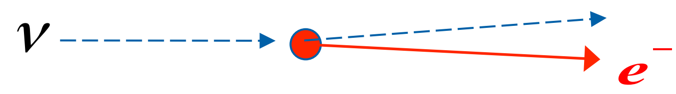
Prediction from Cloët model described in PRL 109, 182301

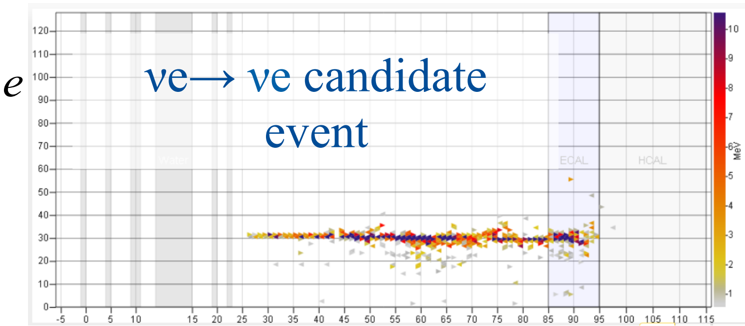
Fermilab

MINERvA: Neutrino-Electron Scattering to constrain Flux

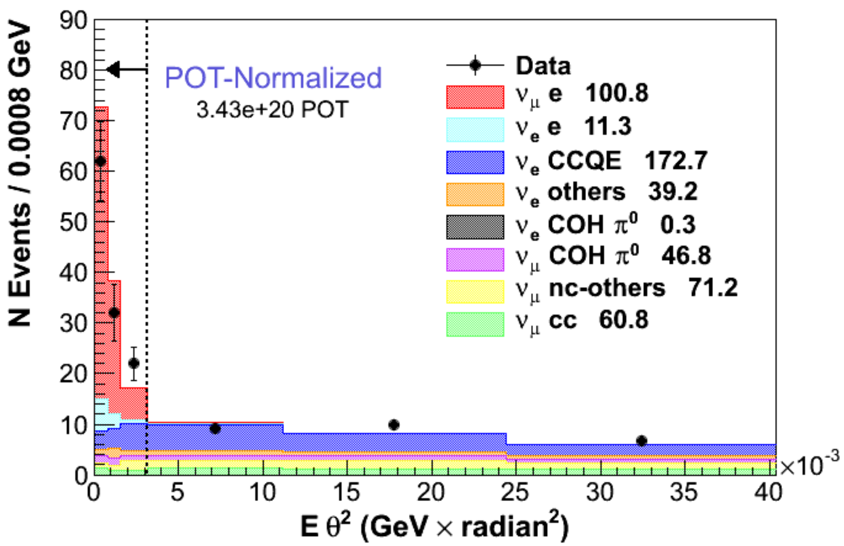
- Neutrinos scattering off electrons: pure electroweak process
- MINERvA used this channel in lower energy exposure to put 11% constraint on flux
- Medium Energy statistics expected to give 5% constraint on flux in neutrino mode

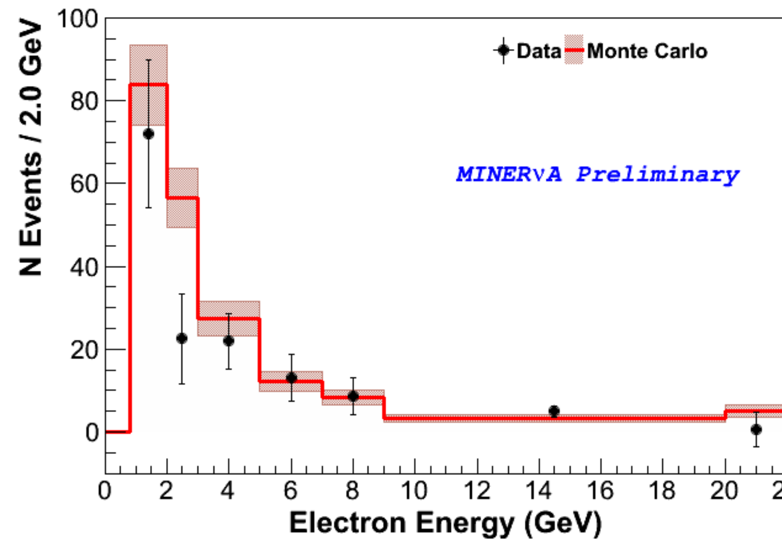






Ref: Phys. Rev. D 93, 112007

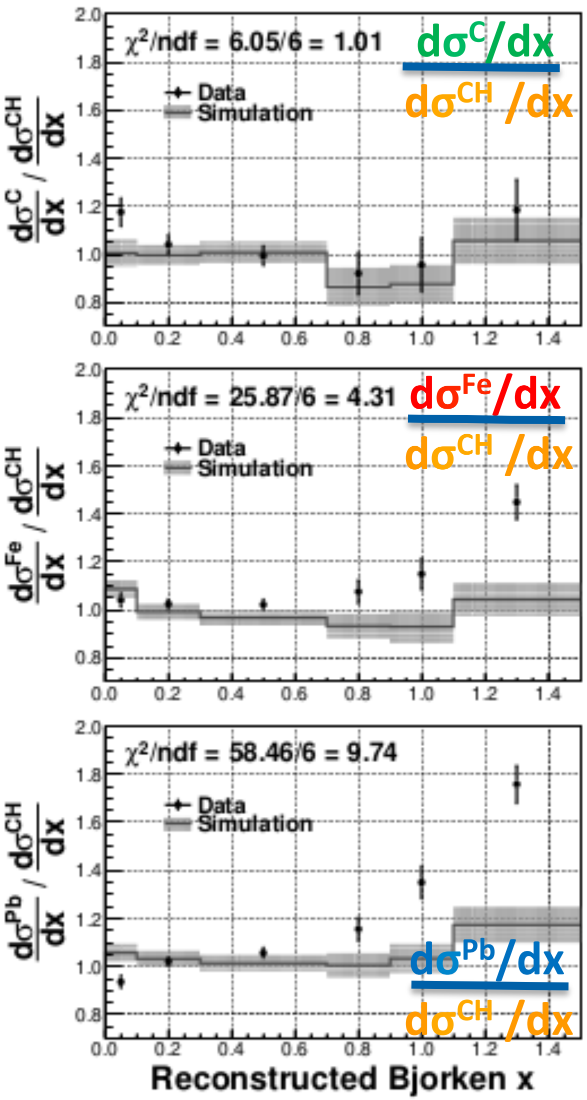


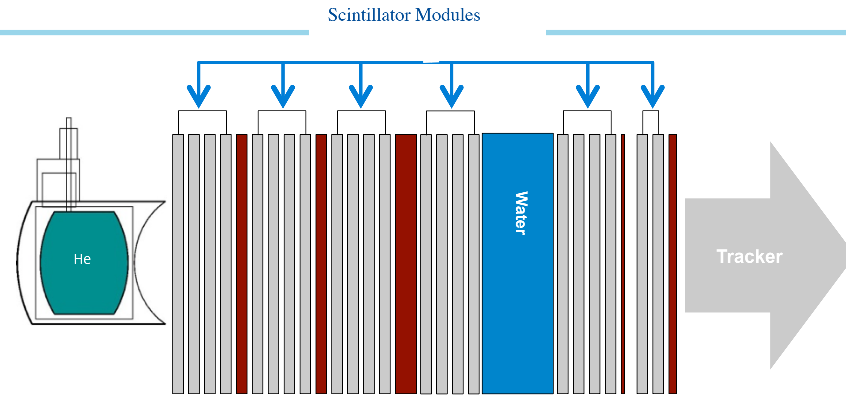


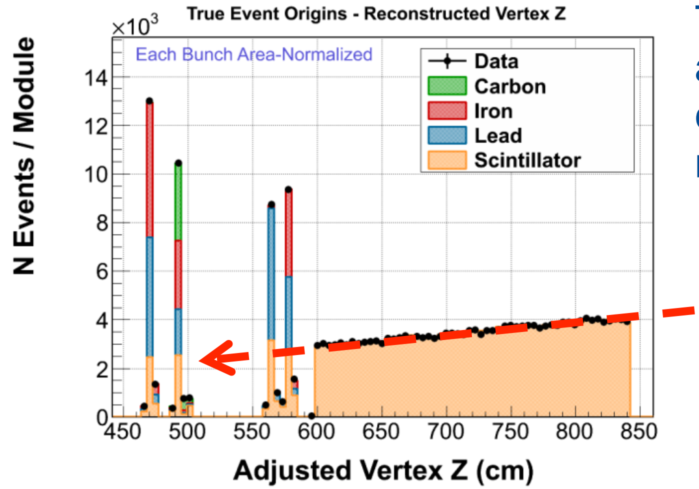
Fermilab

MINERvA: Ratios of Inclusive CC Reactions on Nuclei

Phys. Rev. Lett. 112, 231801 (2014)







Targets are passive and there is contamination from nearby scintillator.

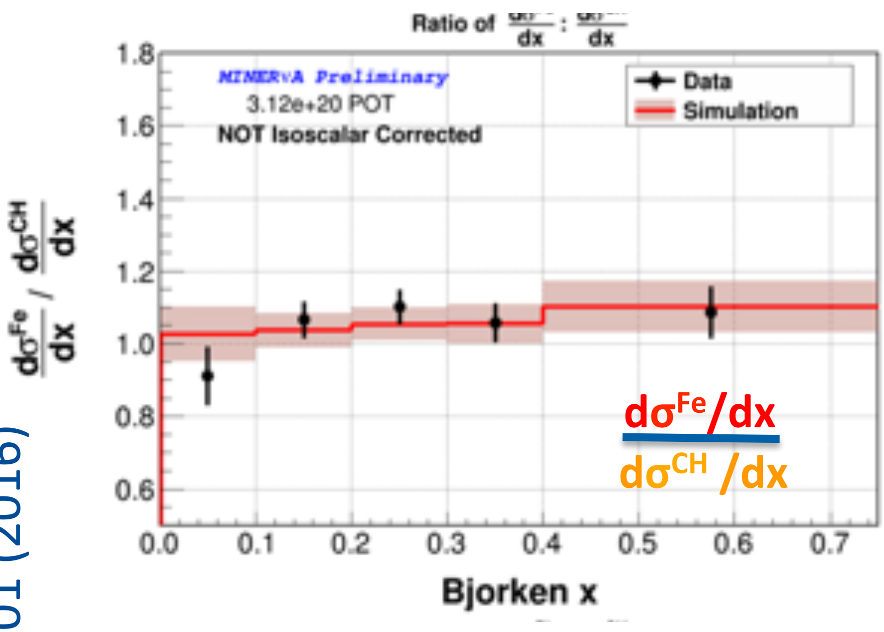
Use events in the tracker modules to estimate and subtract contamination from scintillator events.

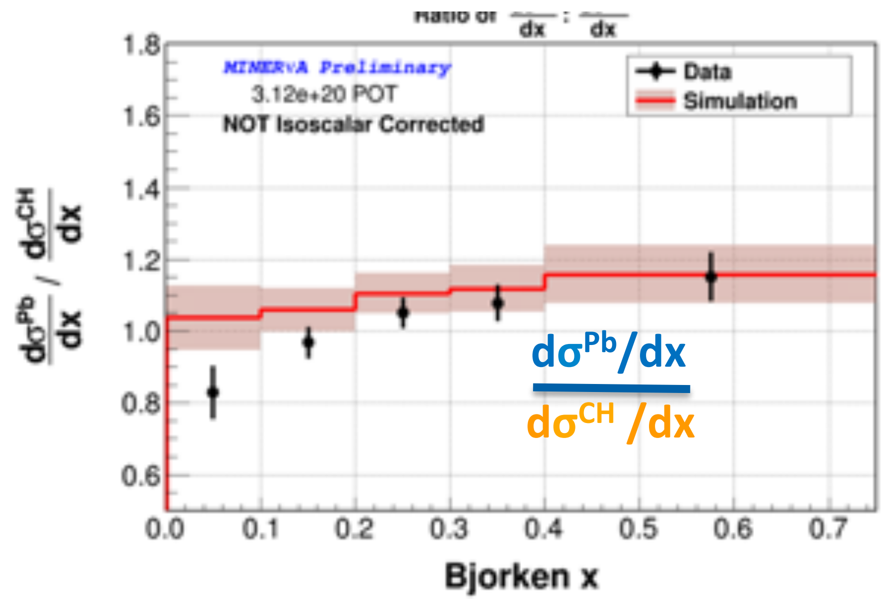
1. *At low x*, *deficit* that increases with A
2. *At high x*, *excess* that increases with A

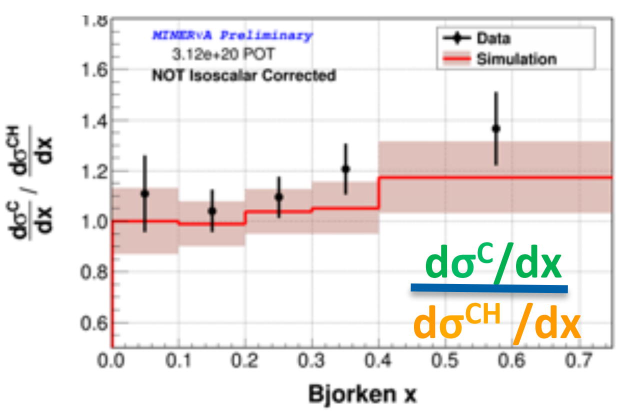
These effects are not reproduced by current neutrino interaction models.

MINERvA: DIS Cross Section Ratios, Fe and Pb to CH

Phys. Rev. D 93, 071101 (2016)







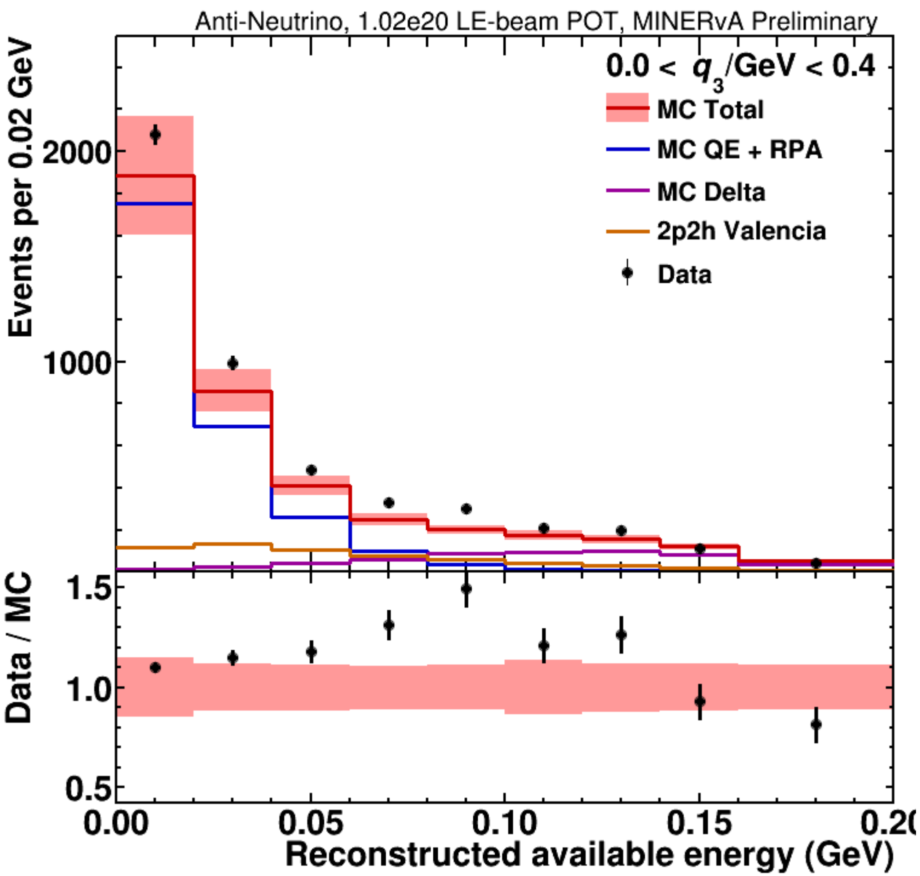
MINERvA is the first experiment to look for the "EMC Effect" in neutrino scattering

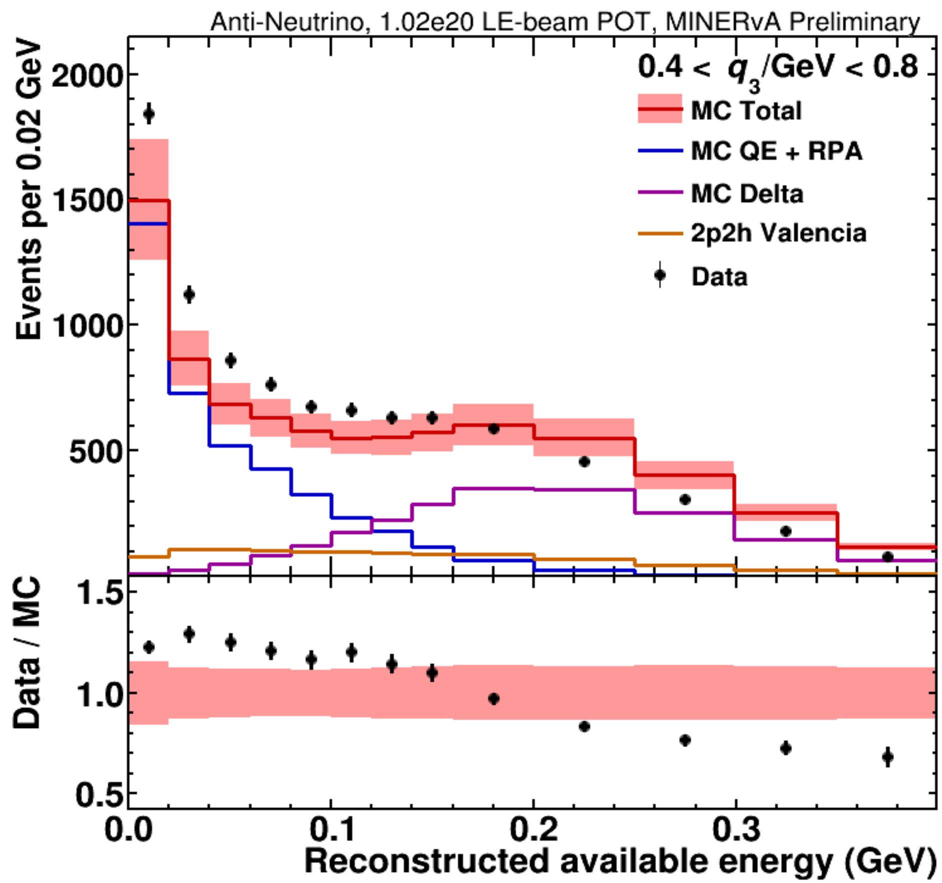
No evidence of discrepancy with model (which does not include EMC effect).

Low Energy measurement statistically limited.

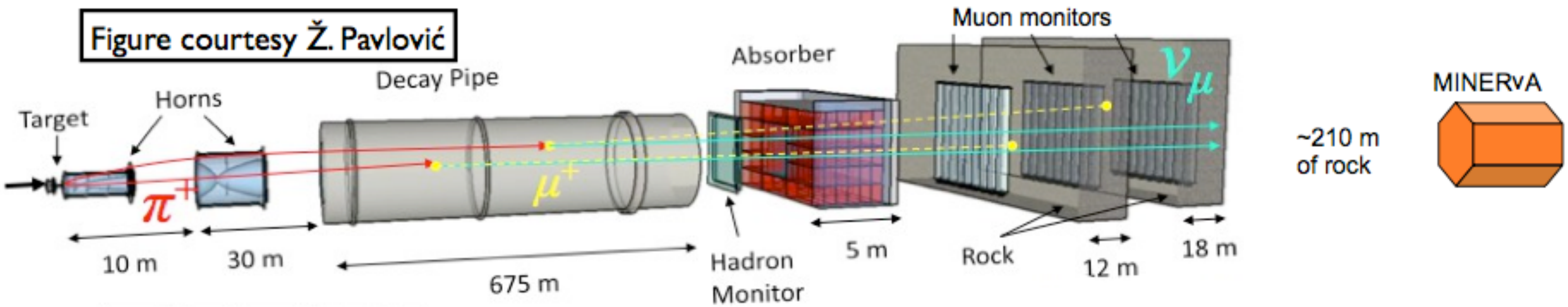
What about Antineutrinos?

- Look in the same two kinematic regions: jump to where we have added in two new effects: screening and 2p2h





NuMI Beamline



- 120GeV protons strike a C target
- 2 focusing horns
- 675m decay volume
- Near detector hall at 1km from target, home of MINERvA
- Off Axis trick used for NOvA in same beamline