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Neutrino Cross Sections

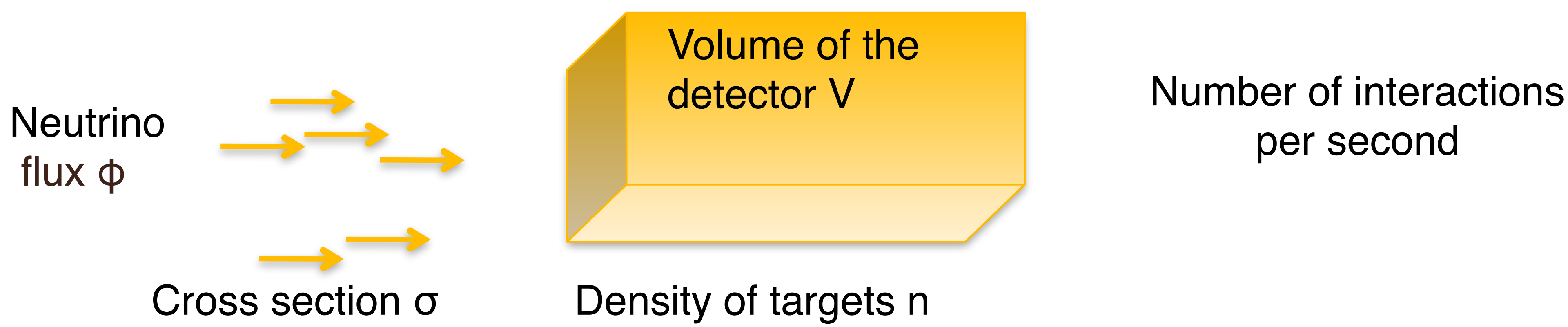
Minerba Betancourt

NPC Neutrino University

July 7 2016

Number of Interactions

- Number of neutrino events:



$$N = \Phi T \sigma$$

Number of interactions that occurred

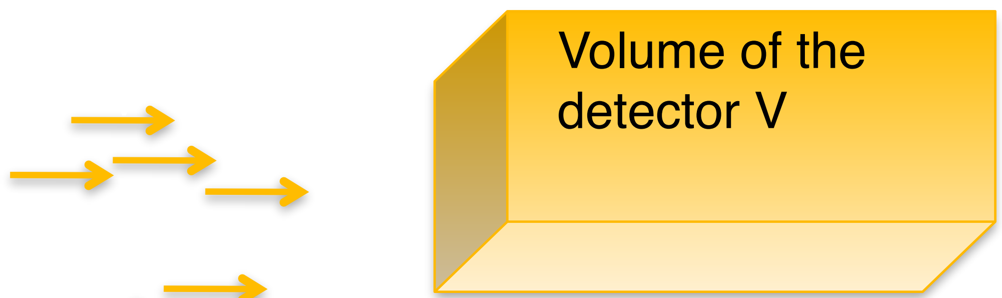
Total flux of incident neutrinos per unit area

Number of targets

Cross Section

Neutrino Cross Section

- What is the cross section?
  - A measure of the probability of an interaction occurring



Cross Section

$$\sigma = \frac{N}{\Phi T}$$

N: Number of interactions that occurred

Φ: Total flux of incident neutrinos per unit area

T: Number of targets

Neutrinos interact only by week force, at 1 GeV $\sigma(\nu N) \sim 10^{-38} cm^2 \longrightarrow$ tiny

compare with $\sigma(pp) \sim 10^{-26} cm^2$

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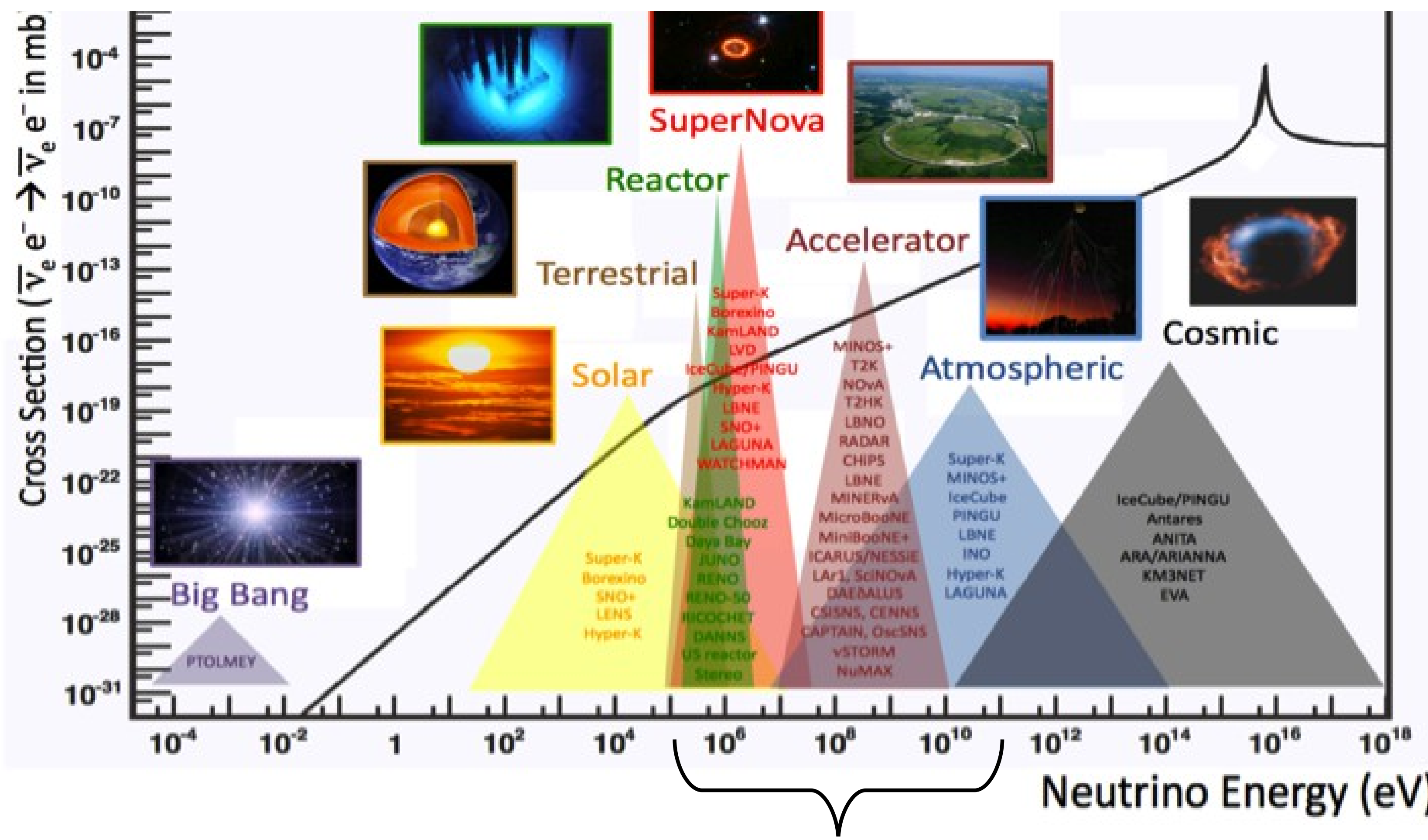
Different Neutrino Sources

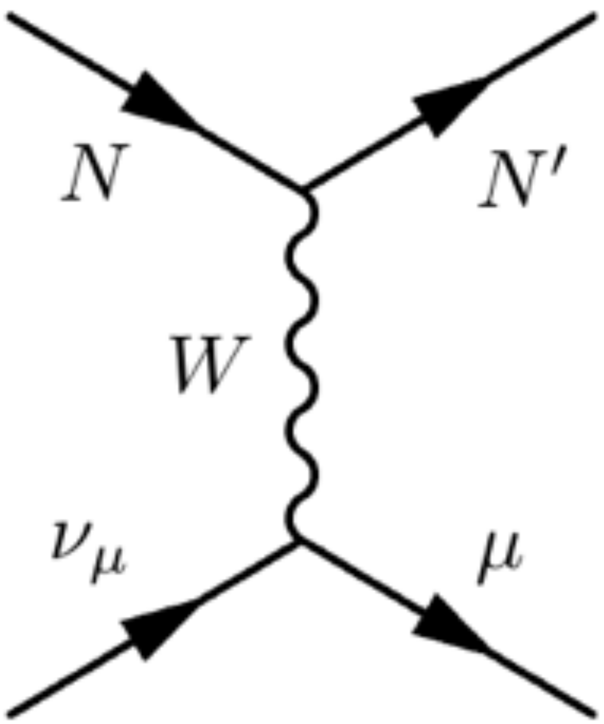
- Different neutrino sources determine the range of energies



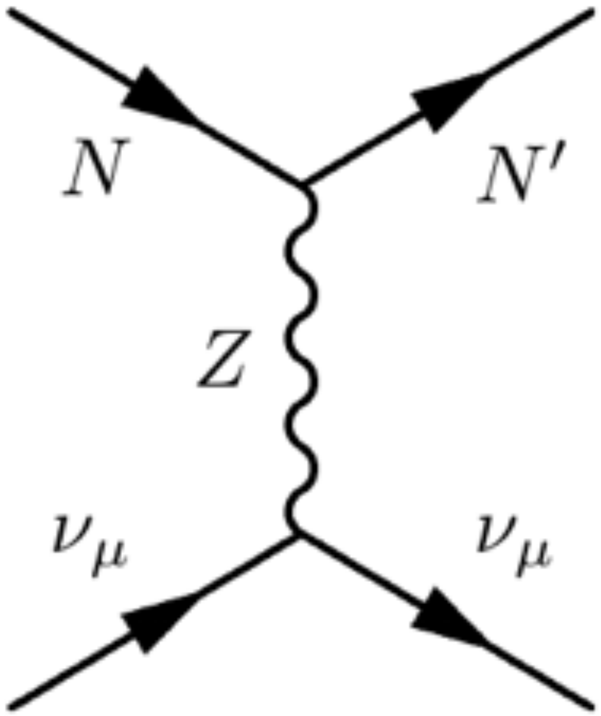
- Few GeV energy range neutrinos are very important for accelerator neutrino oscillations
- This talk reviews a few neutrino interactions relevant to neutrino oscillation at the few GeV region (Quasi-Elastic and Resonance)
- What happens when a few GeV neutrino interacts with a particle detector?

Neutrino Interactions

Charged Current (CC) interactions via a W-boson

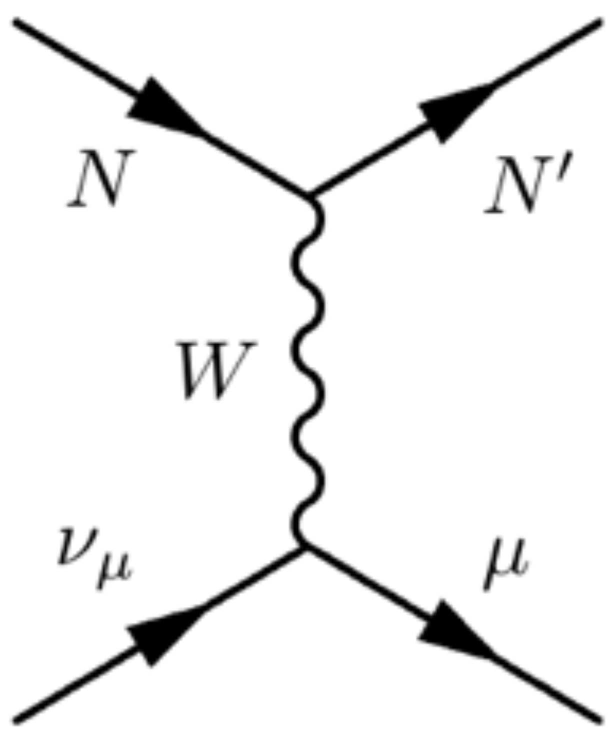


Neutral Current (NC) interactions via a Z-boson

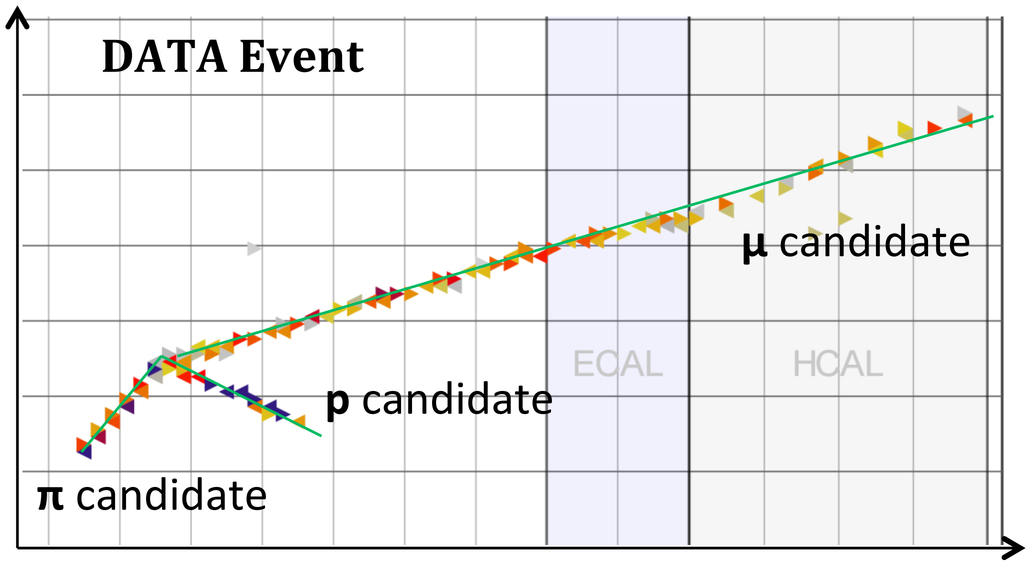


Neutrino Interactions

Charged Current (CC) interactions via a W-boson

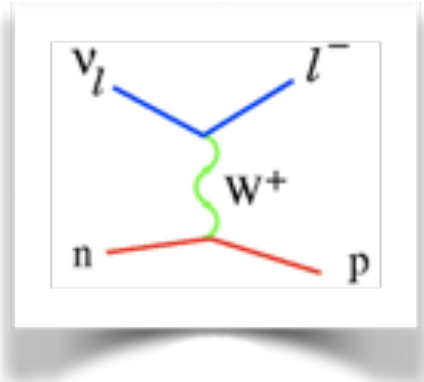


Example of charged Current Interaction

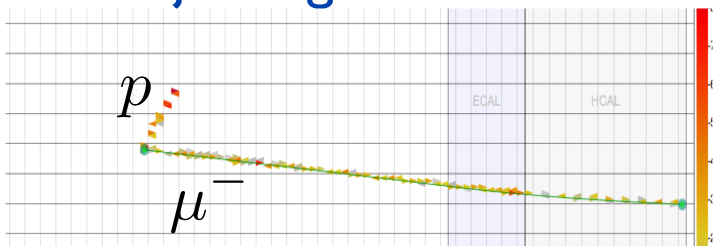


Charged Current Interactions

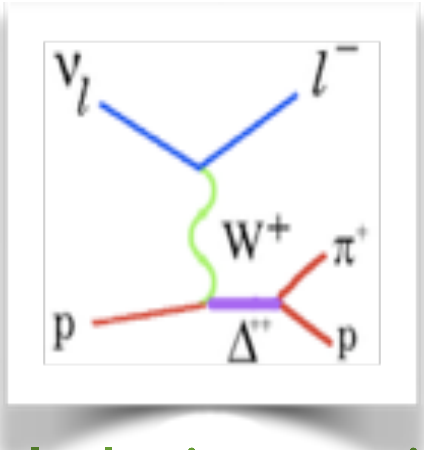
Quasi-elastic scattering (QE)



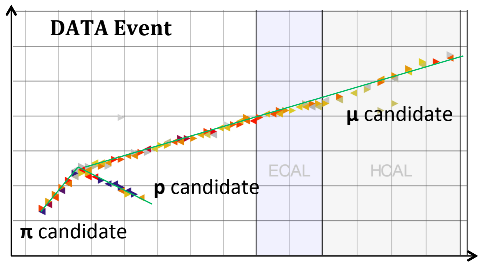
The neutrino scatters elastically off the nucleon ejecting a nucleon from the target



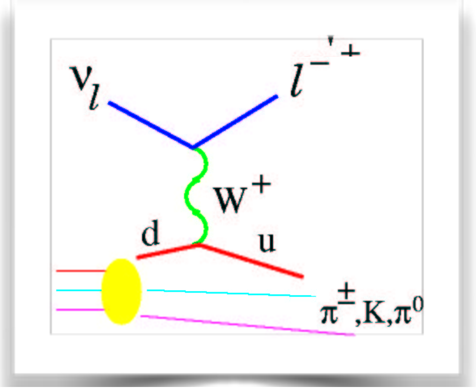
Resonance production (RES)



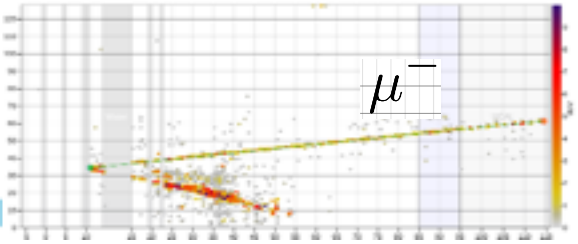
The neutrino can excite the target nucleon to a resonance state



Deep Inelastic scattering (DIS)

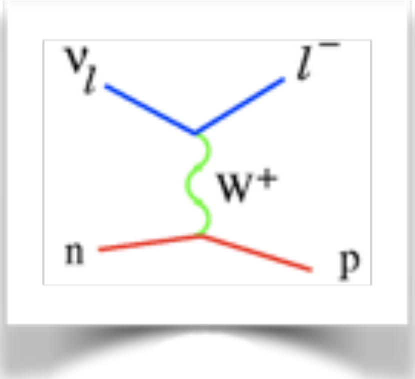


The neutrino scatters off a quark in the nucleon producing a hadronic system in the final state

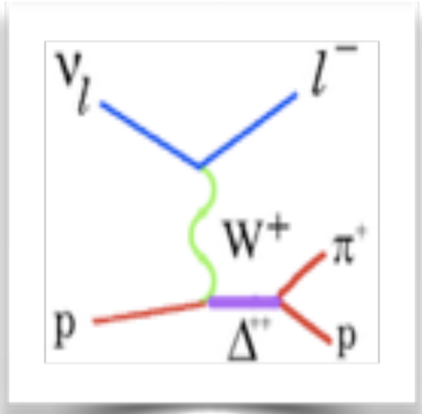


Charged Current Interactions

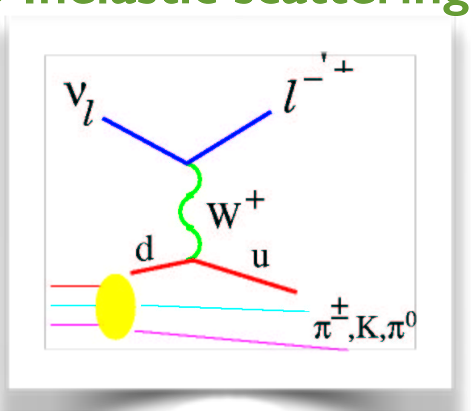
Quasi-elastic scattering (QE)

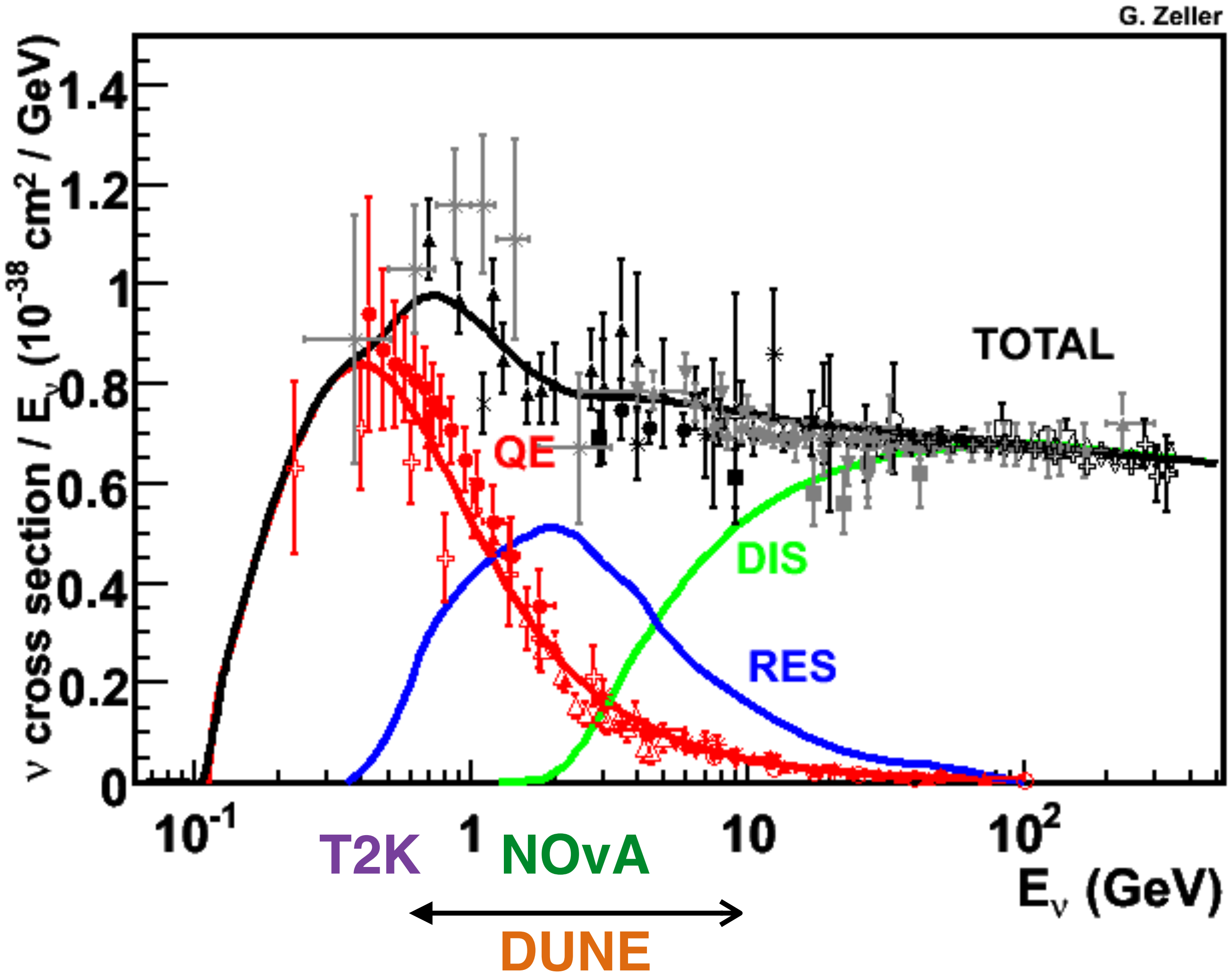


Resonance production (RES)



Deep Inelastic scattering (DIS)





J.A. Formaggio, G. Zeller, Reviews of Modern Physics, 84 (2012)

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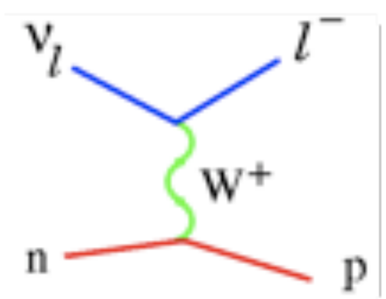
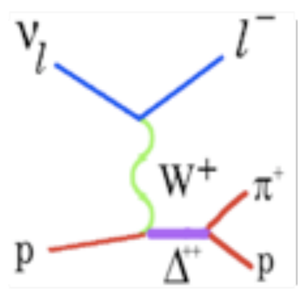
Why Do We Study Charged Current Interactions?

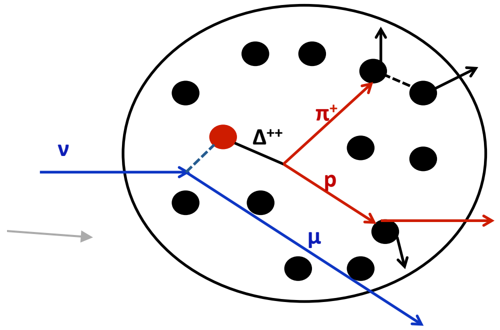
- Charged current processes are signal channels for oscillations experiments
- Due to nuclear effects combined with cross section, the signal channel and neutrino energy measured in detectors are not necessarily the same as the initial interaction

CC Quasi-Elastic



CC Resonance



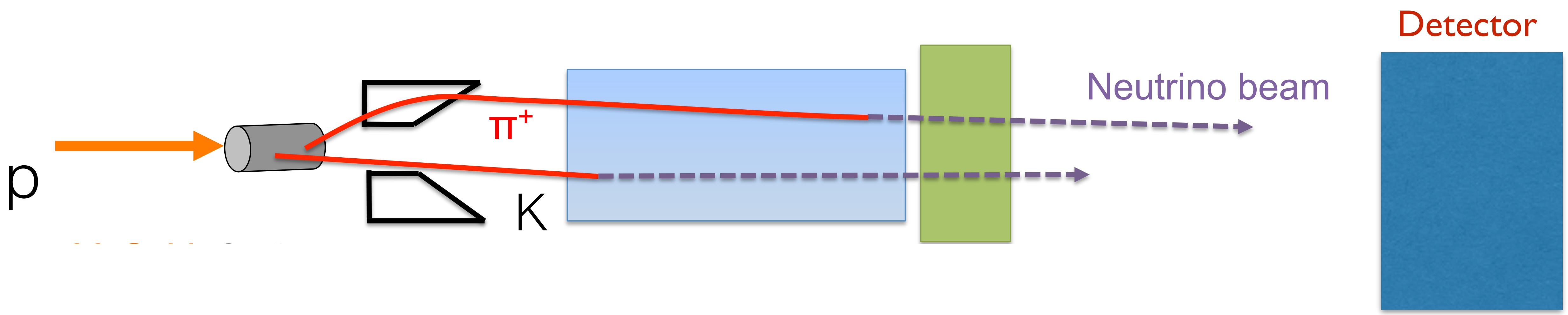


Pion Absorption: Due to final state interactions particles can interact with nucleons before exiting the nucleus

- A pattern of neutrino oscillation is analyzed based on distributions of detected particles and it is crucial to have a reliable Monte Carlo generator to read this pattern correctly
- Recent experimental data is not well described by current models
- Understanding the neutrino interactions with nuclei is vital for precision oscillation measurements

Neutrino Beam

- A proton beam interacts with a target and produces pions and kaons
- We use magnetic horns to focus the charged particles. These charged particles decay and produce the neutrino beam
- Long baseline experiments use near and far detectors to study neutrino oscillations



- To get sufficient statistics for oscillations we use powerful beams
- This powerful beam gives large statistics for near detector experiments to study neutrino scattering
- Different technologies are used to detector neutrinos

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Near and Far Detector

Events at the Near Detector $= \phi \times \sigma \times \epsilon$

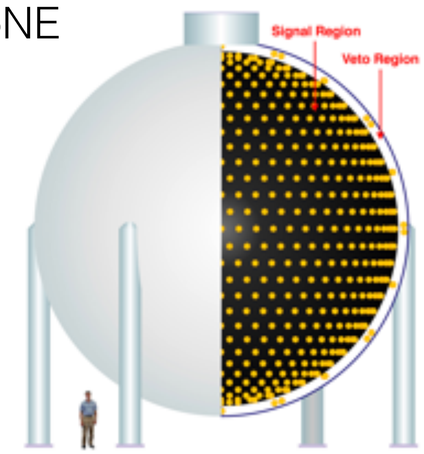
Events at the Far Detector $= \phi \times \sigma \times \epsilon \times P_{\nu_\mu \rightarrow \nu_e}$

- Flux is different in the near and far detector, so $\phi \times \sigma$ is too
- So while the two detectors help, one still needs to predict the ϕ and σ separately

Cross Section Experiments

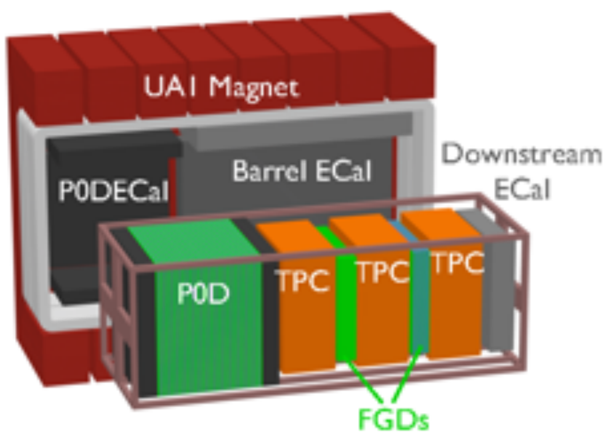
- Modern neutrino experiments using neutrino from accelerators
  - Different detector technologies and targets:
    - Oxygen, carbon, iron, liquid argon, helium, lead..
  - Different neutrino beams
- Common goal for all the experiments:
  - Study neutrino interactions

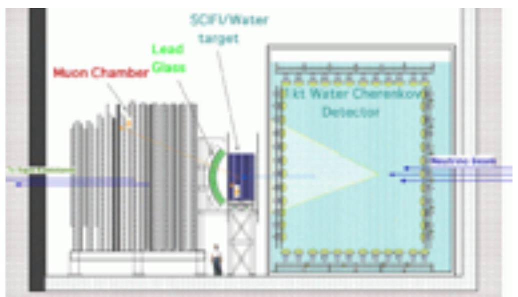
MiniBooNE



- For this talk, using examples from the MINERvA experiment

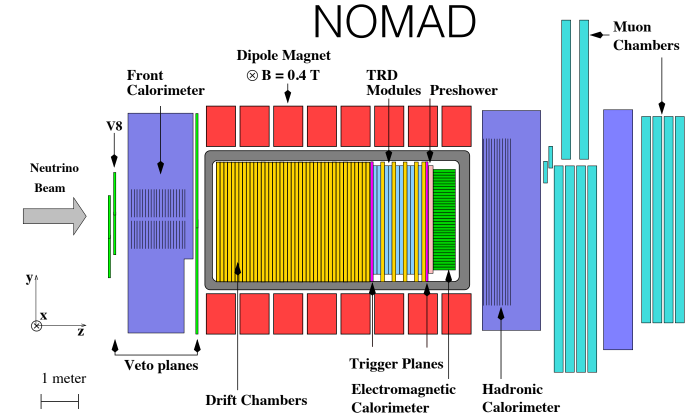
T2K





K2K

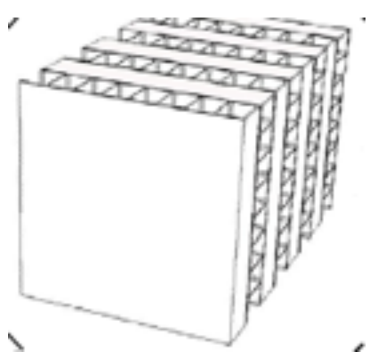
NOMAD



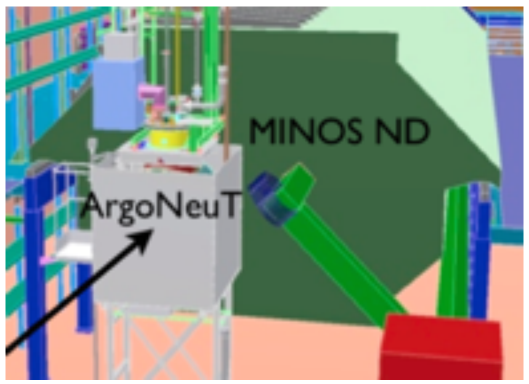
Argonut

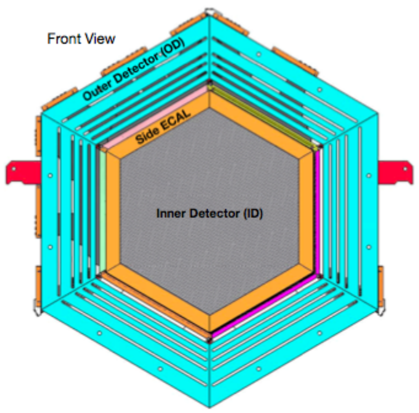
Minerva

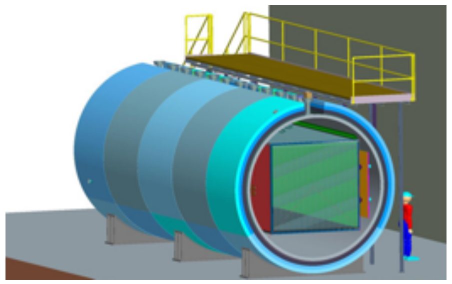
MicroBooNE



NOvA

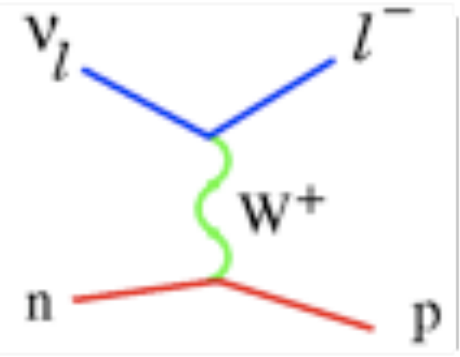


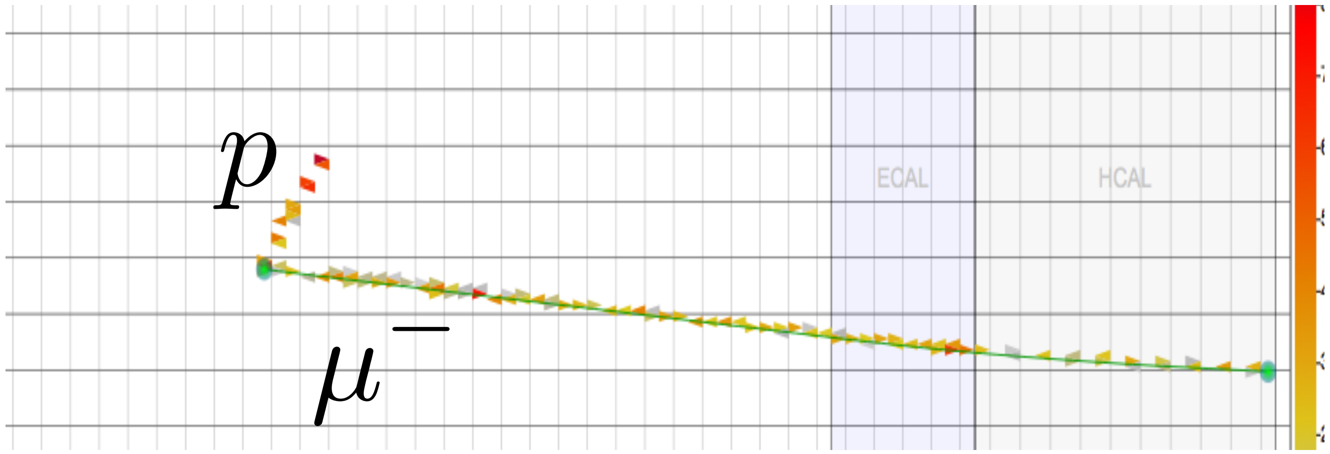




Review of Quasi-Elastic Scattering

- The Quasi-Elastic channel is one of the simplest channels in neutrino scattering





Quasi-Elastic Scattering (CCQE)

- We use the free nucleon CCQE formalism

$$\frac{d\sigma}{dQ^2_{QE}} = \frac{M^2 G_F^2 \cos^2\theta_C}{8\pi E_\nu^2}\{A(Q^2) \pm B(Q^2)\frac{s-u}{M^2} + C(Q^2)\frac{(s-u)^2}{M^4}\}$$

- Sign on B term is minus for neutrinos, plus for antineutrinos
- G_F is the Fermi constant, 1.17 x 10^{-5} GeV^2
- M is the average nucleon mass, 938.92 MeV
- θ_C is the Cabbibo angle $cos\theta_C = 0.9742$
- E is the neutrino energy
- s and u s are Mandelstam variables

Quasi-Elastic Scattering (CCQE)

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$$\frac{d\sigma}{dQ^2_{QE}} = \frac{M^2 G_F^2 \cos^2\theta_C}{8\pi E_\nu^2}\{A(Q^2) \pm B(Q^2)\frac{s-u}{M^2} + C(Q^2)\frac{(s-u)^2}{M^4}\}$$

- Where

$$\begin{aligned} A(Q^2) = \frac{m_\mu^2 + Q^2}{M^2}\Big\{&(1+\frac{Q^2}{4M^2})F_A^2 - (1-\frac{Q^2}{4M^2})F_1^2 + \frac{Q^2}{4M^2}(1-\frac{Q^2}{4M^2})(\xi F_2)^2 \\ &+\frac{Q^2}{M^2}Re(F_1^*\xi F_2) - \frac{Q^2}{M^2}(1+\frac{Q^2}{4M^2})(F_A^3)^2 \\ &-\frac{m_\mu^2}{4M^2}\left[|F_1+\xi F_2|^2 + |F_A + 2F_P|^2 - 4(1+\frac{Q^2}{4M^2})((F_V^3)^2 + F_P^2)\right]\Big\} \end{aligned}$$

$$B(Q^2) = \frac{Q^2}{M^2}Re\left[F_A^*(F_1+\xi F_2)\right] - \frac{m_\mu^2}{M^2}Re\left[(F_1 - \tau\xi F_2)F_V^{3*} - (F_A^* - \frac{Q^2}{2M^2}F_P)F_A^3)\right]$$

$$C(Q^2) = \frac{1}{4}\left\{F_A^2 + F_1^2 + \tau(\xi F_2)^2 + \frac{Q^2}{M^2}(F_A^3)^2\right\}$$

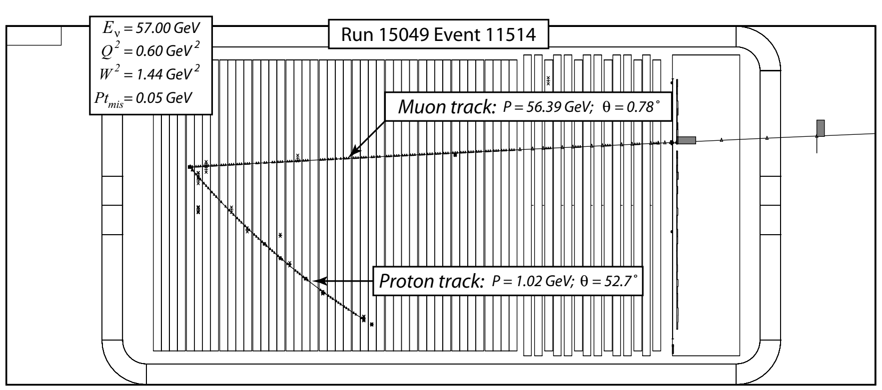
- Most of the form factors are known, except the axial form factor F_A. This is parameterized as a dipole

$$F_A(Q^2) = \frac{F_A(0)}{(1-\frac{q^2}{M_A^2})^2}$$

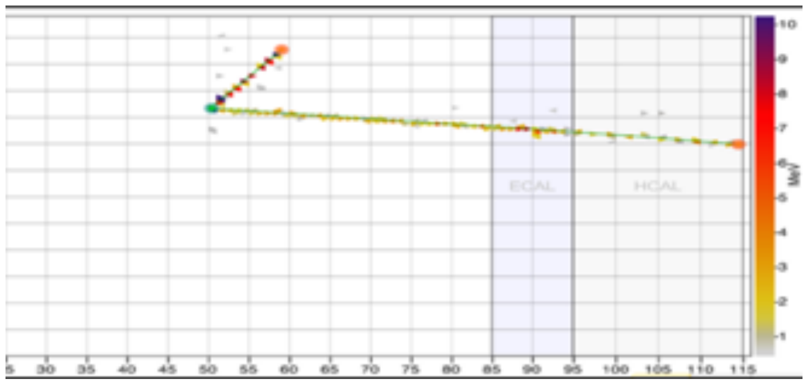
Quasi-Elastic Scattering (CCQE)

- The Quasi-elastic process gives the largest contribution for the signal in many oscillation experiments
- Early neutrino experiments used bubble chambers filled with D_2 with excellent purity 97-99%
- Modern experiments use different targets, such as carbon, iron, oxygen, liquid argon…etc
- We have more statistics, but with the heavy targets we have more nuclear effects which brings additional challenges
- In addition purities are much lower, below 80%
- The QE selection varies from experiment to experiment, some experiments use only the muon and others use the proton and muon

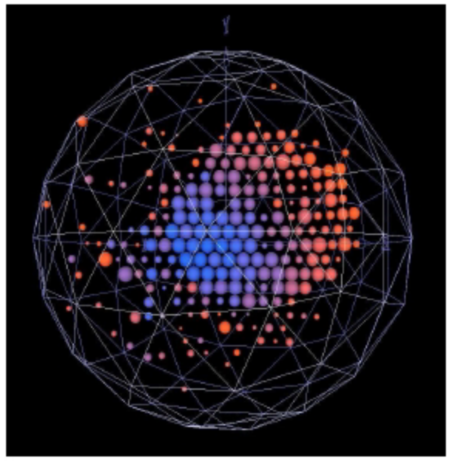
NOMAD



MINERvA



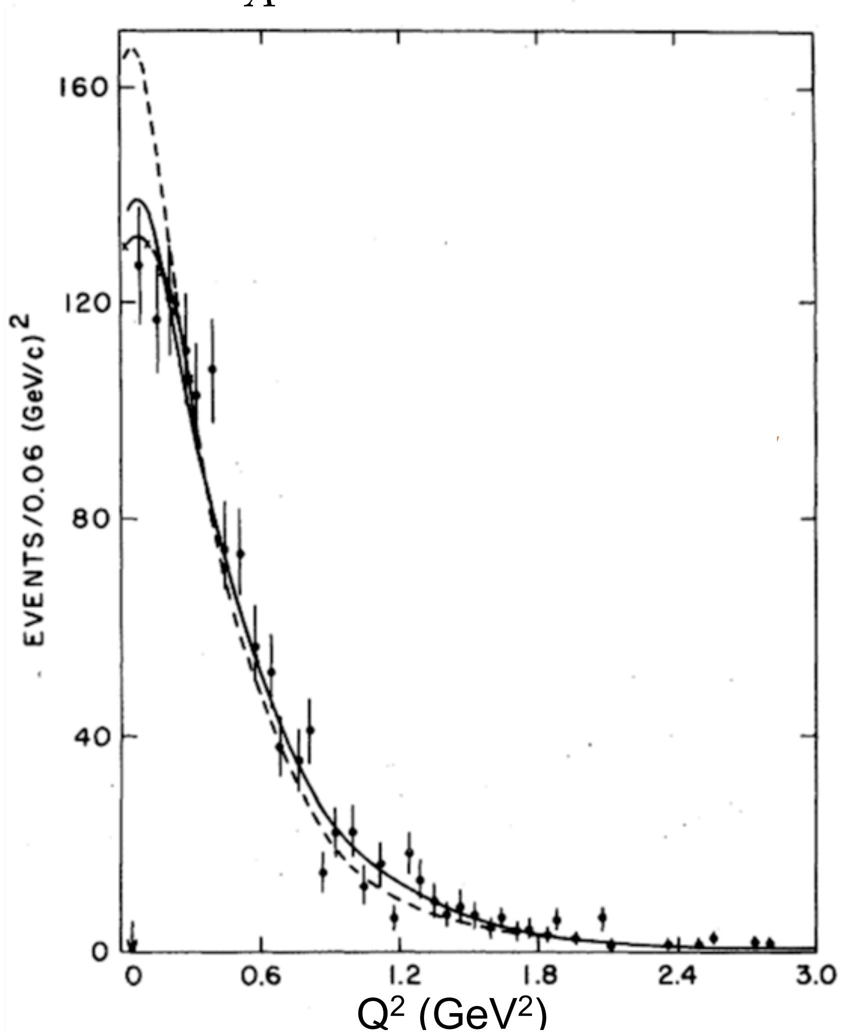
MiniBooNE



Quasi-Elastic Scattering (CCQE) Using D_2

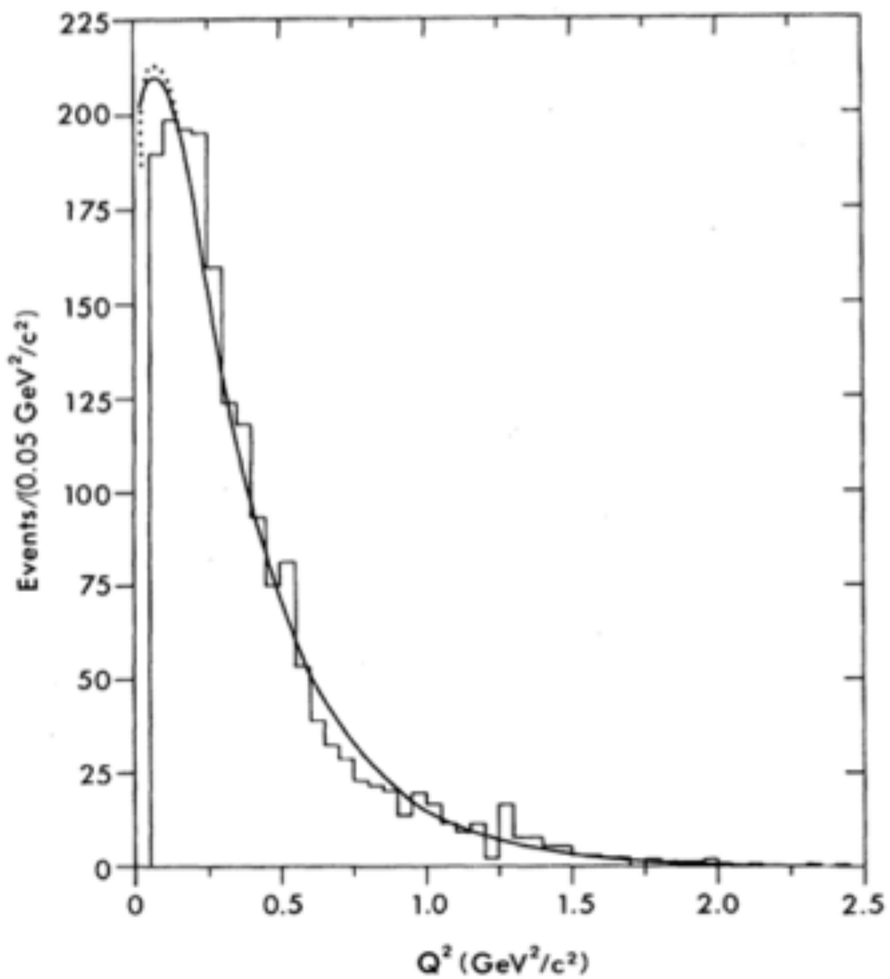
- These experiments measured the axial mass M_A, pretty good agreement between the experiments

$M_A = 1.07 \pm 0.06 GeV$



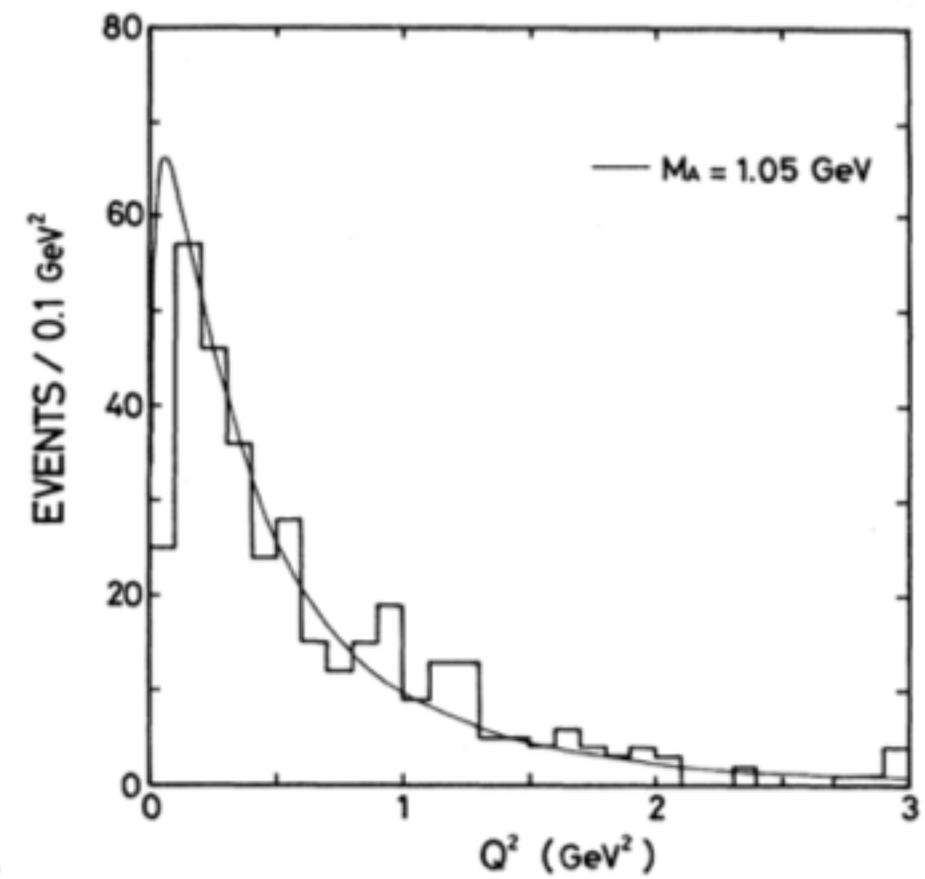
Baker, PRD 23, 2499 (1981)

$M_A = 1.00 \pm 0.05 GeV$



Miller, PRD 26, 537 (1982)

$M_A = 1.05 \pm 0.16 GeV$



Kitagaki, PRD 28, 436 (1983)

$$M_A = (1.026 \pm 0.021)\ GeV/c^2$$

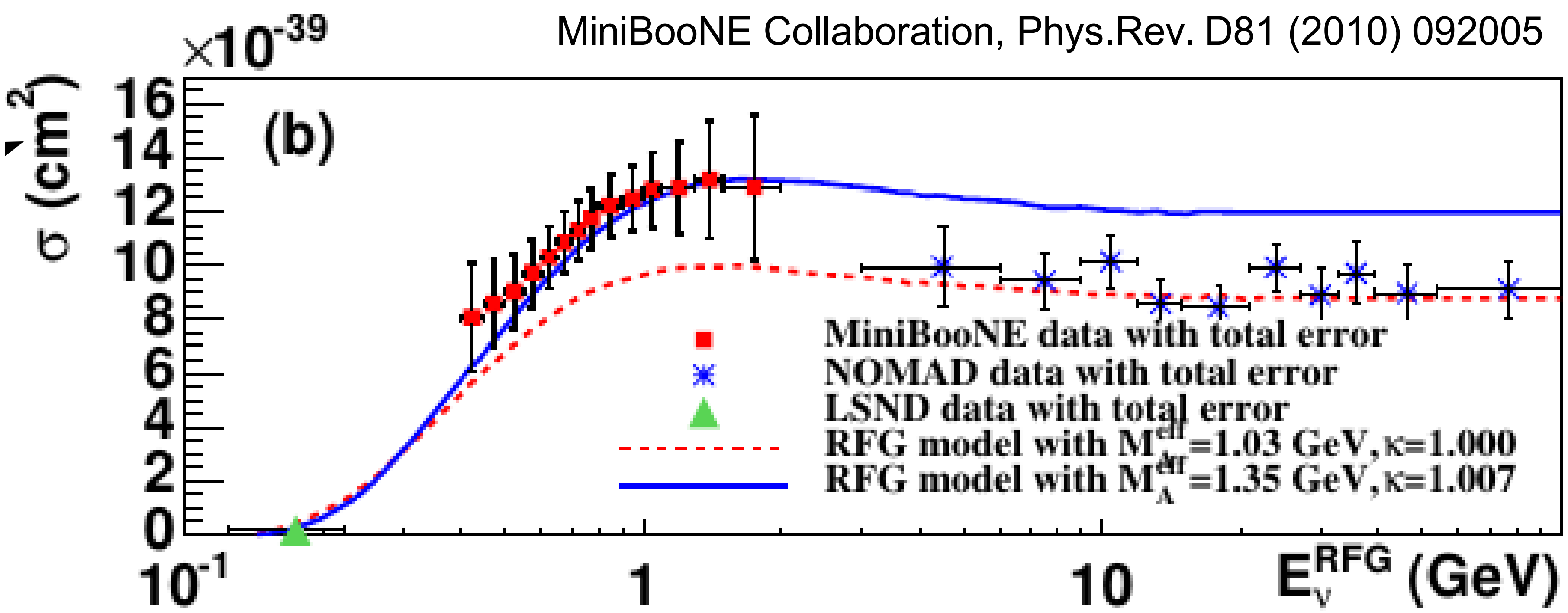
$$F_A(Q^2) = \frac{F_A(0)}{(1 - \frac{q^2}{M_A^2})^2}$$

Quasi-Elastic Scattering (CCQE)

- Some examples of modern experiments:
  - NOMAD experiment uses carbon as a target and a tracker detector with high energy experiment <E>=24GeV, both 1 and 2 track were measured (purity 50%). Signal definition: quasi-elastic events
  - MiniBooNE uses carbon as a target and a Cherenkov detector with low energy <E>=0.8GeV, analysis used ν_μ CC with no pions (purity 77%). Signal definition: events with no pions

Data is compared against a prediction based on Relativistic Fermi Gas Model

MiniBooNE Collaboration, Phys.Rev. D81 (2010) 092005

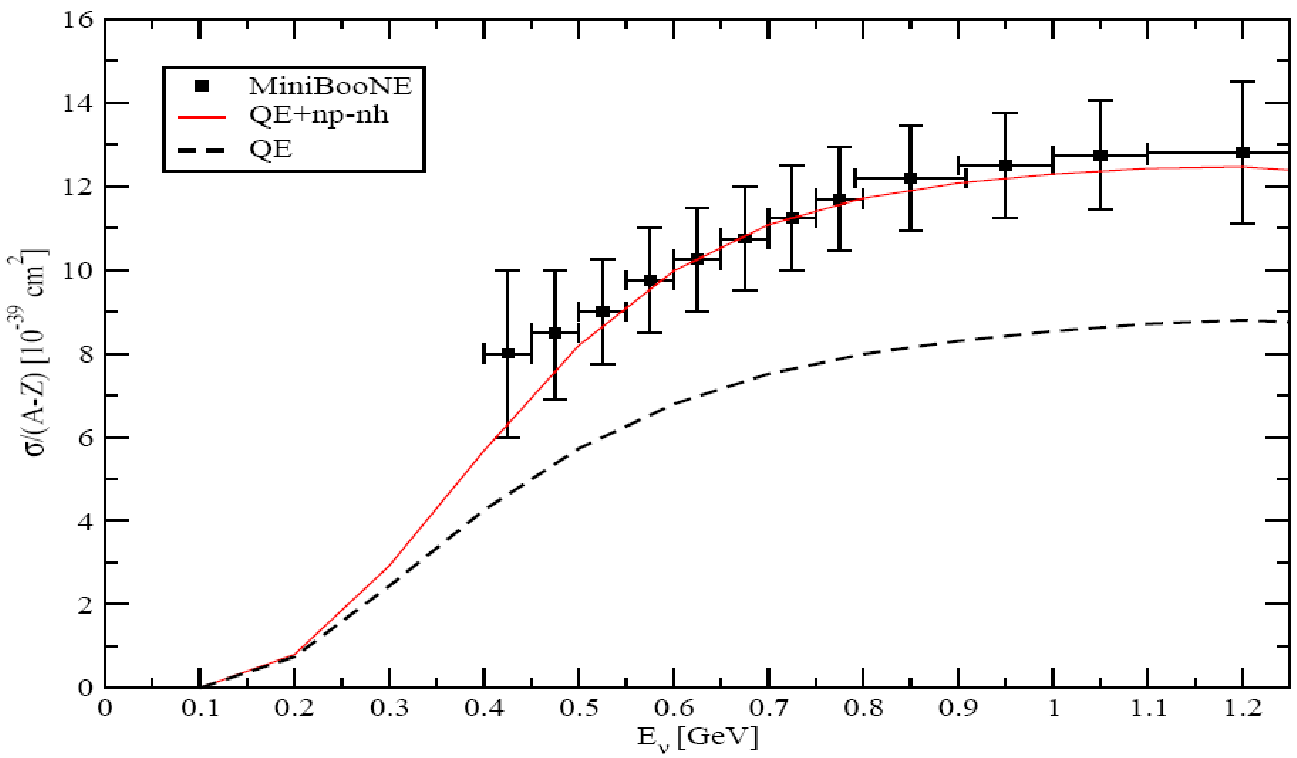


MiniBoonNE data fits better to an Axial Mass 1.35 GeV while NOMAD fits to an Axial Mass of 1 GeV

puzzle?

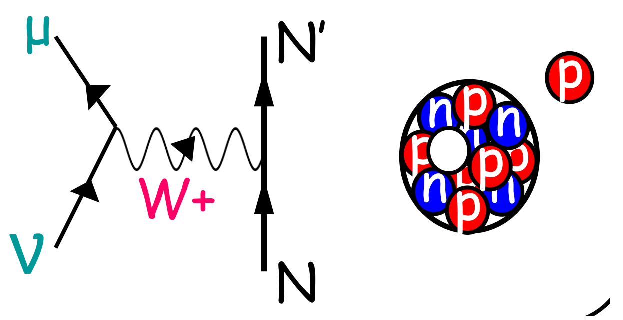
Quasi-Elastic Scattering (CCQE)

- Inclusion of the multi nucleon emission channel (np-nh) gives better agreement with data without increasing the axial mass

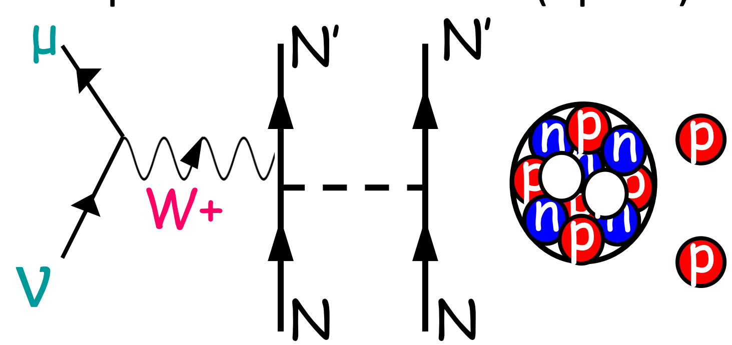


M. Martini, M. Ericson, G. Chanfray, J. Marteau Phys. Rev. C 80 065501 (2009)

Genuine CCQE



Two particles-two holes (2p-2h)

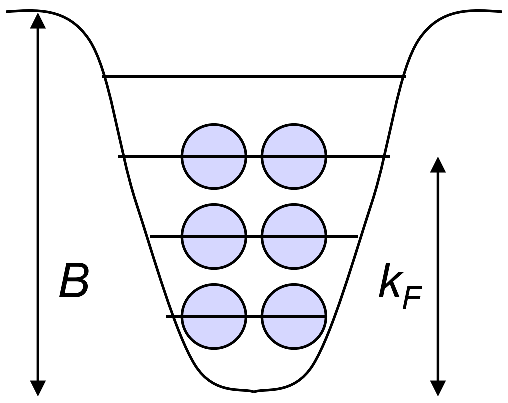


W+ absorbed by a pair of nucleons

- Theorists have made a lot of effort these past years to improve models

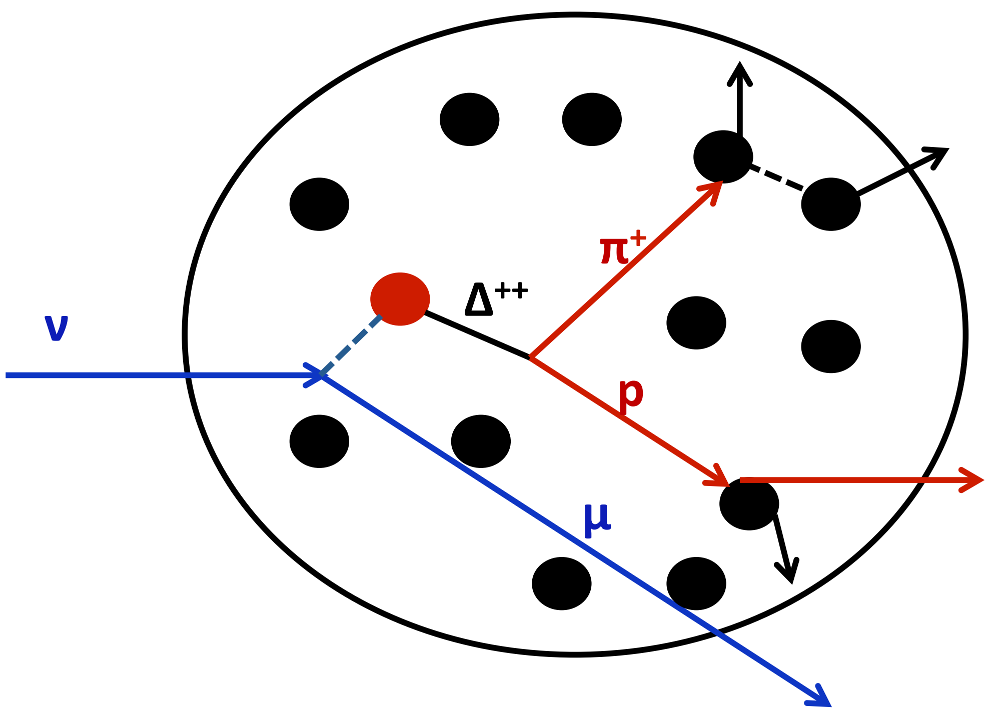
Nuclear Effects in Elastic Scattering

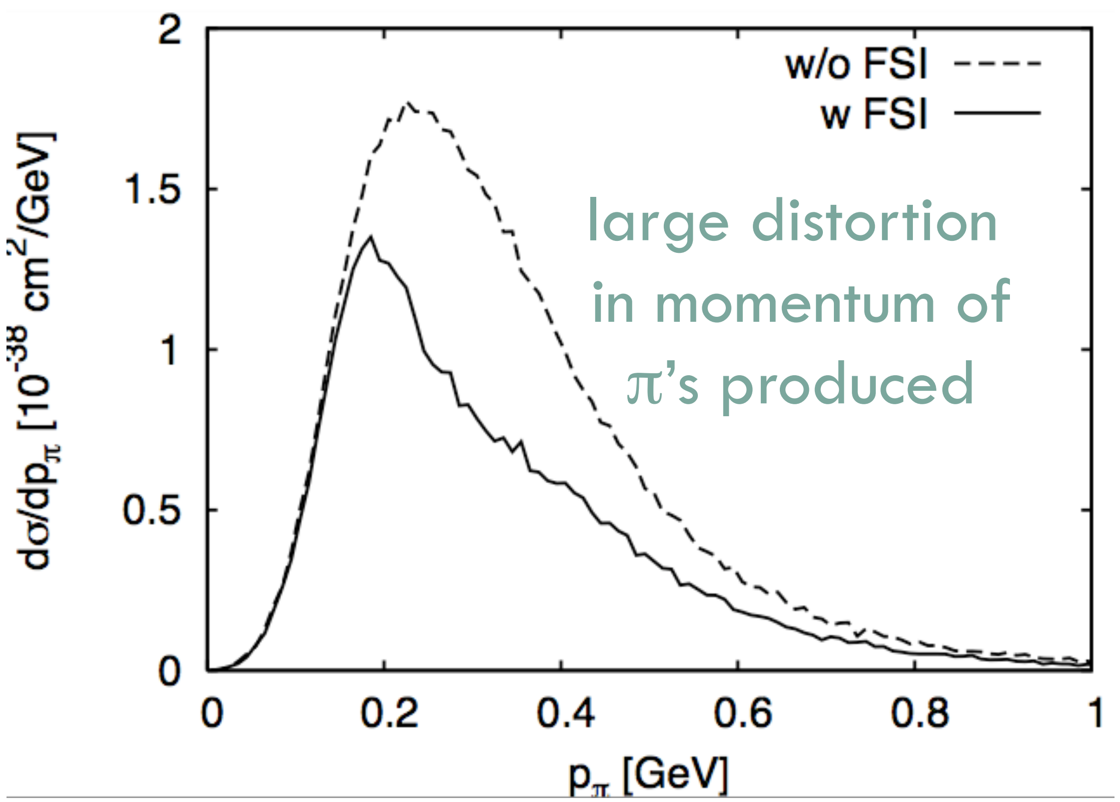
- Two effects
  - In a nucleus, the target nucleon has some initial momentum which modifies the observed scattering
    - Often handled in a "Fermi Gas" model of nucleons filling available states up to some initial state Fermi momentum, k_f
  - Outgoing nucleon can interact with the target
    - Usually treated as a simple binding energy
    - Also, Pauli blocking exists for nucleons not escaping nucleus, because states are already filled with identical nucleon



Final State Interactions

- Final state interactions: Hadrons produced in a scattering interaction re-interact with other nucleons before they escape the nucleus
- Thus, particles that exit the nucleus might be different, both in type and in energy from those generated in the initial interaction
- Final states can contribute to apparent "quasi-elastic" scattering
- These effects are big





Example: Measuring Differential Cross Section

- Let's review a measurement from the MINERvA experiment as an example
- We already talk about flux, number of target and number of neutrino interactions, let's review the other components

Events Selected

Unfolding

Backgrounds

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

Bin-width

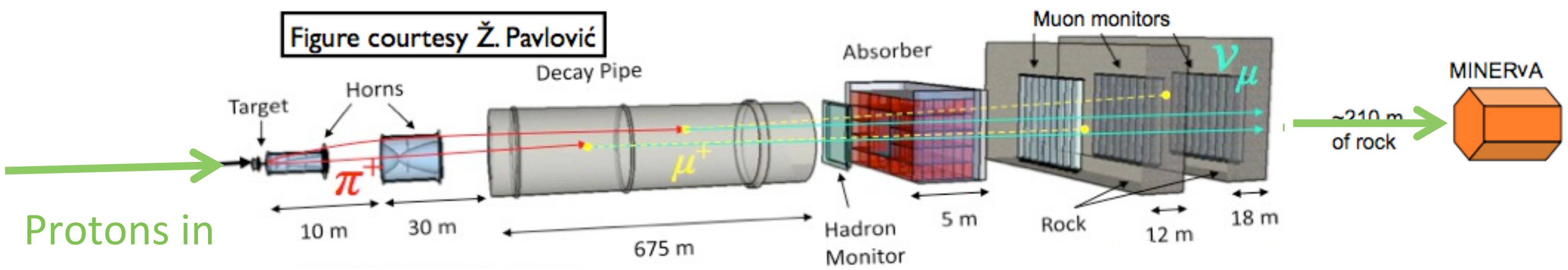
Acceptance

Flux

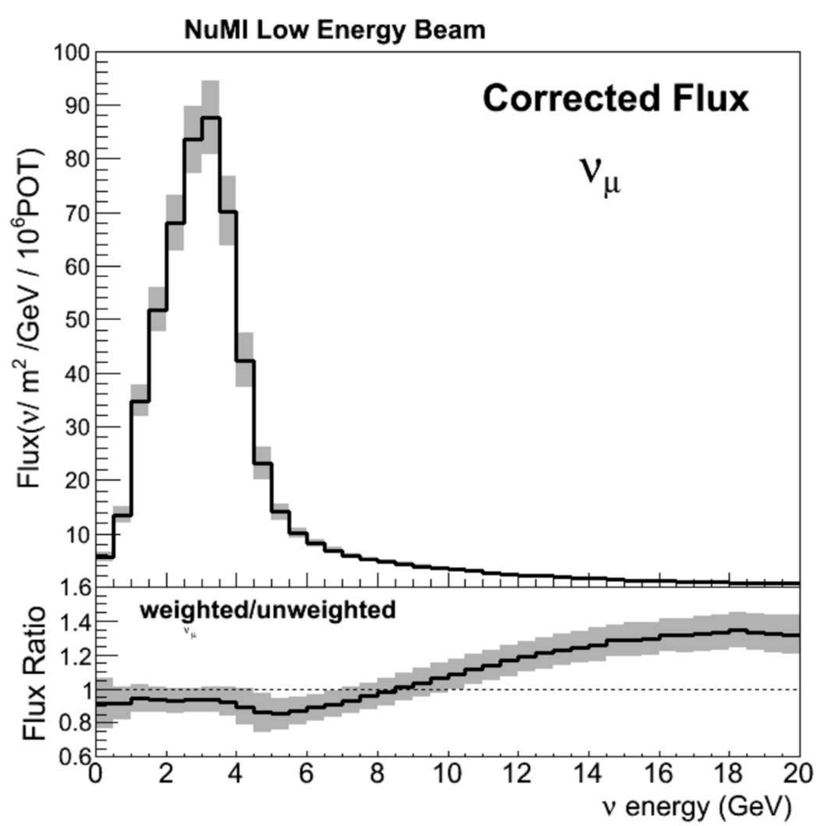
Targets

Flux

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



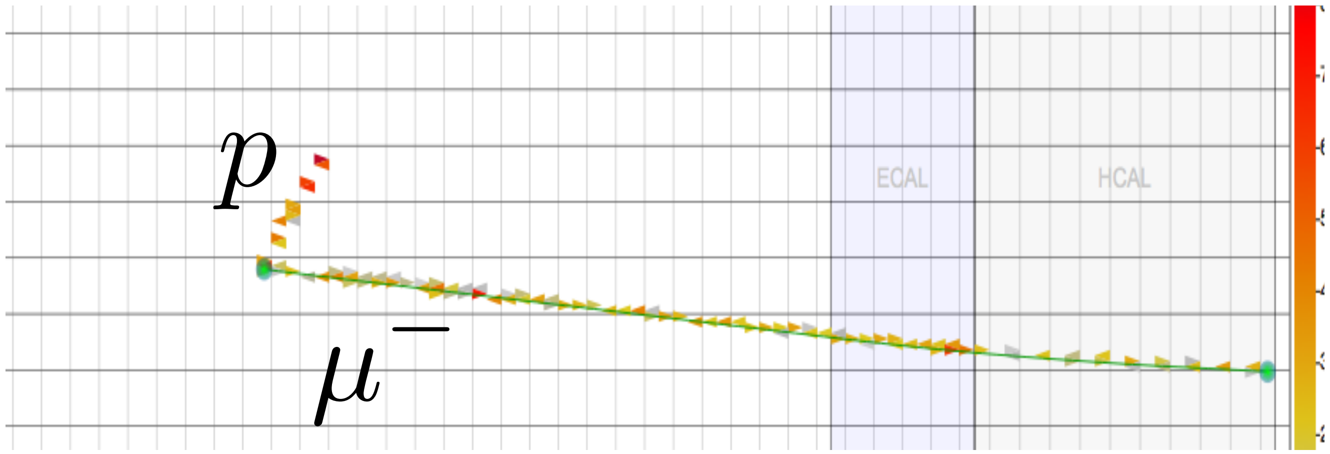
- The neutrino flux is hard to calculate and an important source of systematic uncertainty
- We have a prediction for the flux with uncertainties about ~8%



Selected Events

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

- We make a selection based on the topology of the event
- In the case of Quasi-Elastic scattering, what are we looking for in the detector?



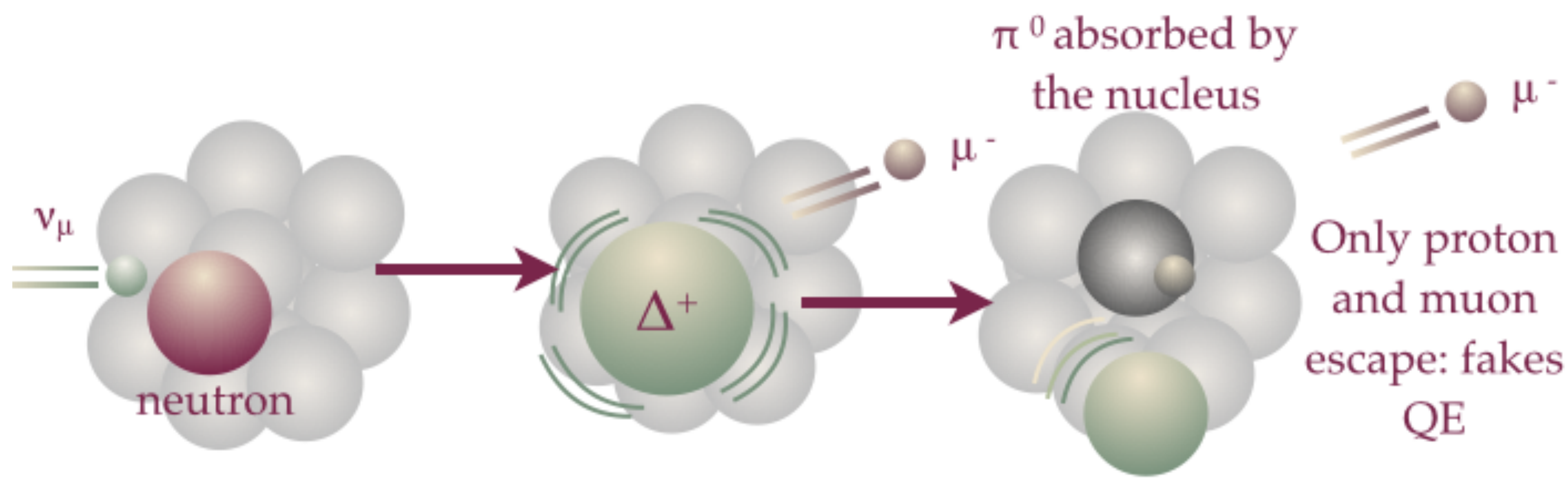
- But all we can measure is how energy is deposited in the detector
- We use our physics knowledge to infer what patterns of energy deposition correspond to our process, but it's not easy
  - Different processes can produce the same final state particles
  - Different initial interactions can produce the same final state particles
  - Some particles or configurations are difficult to detect (examples: neutral particles, two particles traveling right on top of one another)
- Even after our selection cuts, we have some background events that pass the cuts

Signal and Background

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

- Signal event: an event that matches what our analysis is looking for, regardless of whether we manage to identify the underlying process
- Background event: is an event that passes our analysis cuts, but which is not actually a true signal event. These events mimic our signal

Background event

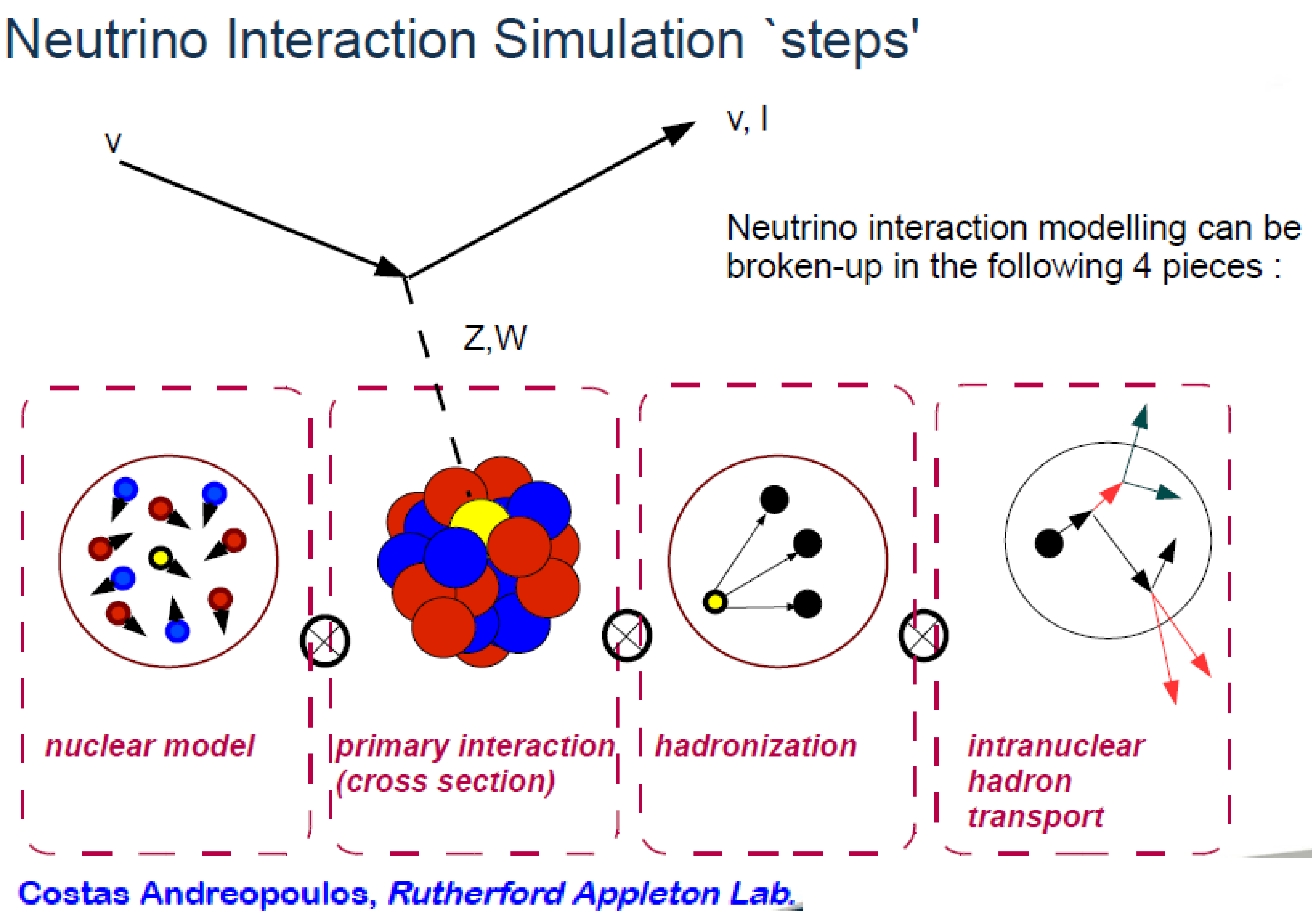


- Other processes like the resonance interactions produce pions, but these can be absorbed in the nucleus (final-state interactions), faking the signal

Simulations

- We use Monte Carlo simulations (GENIE) for the analysis

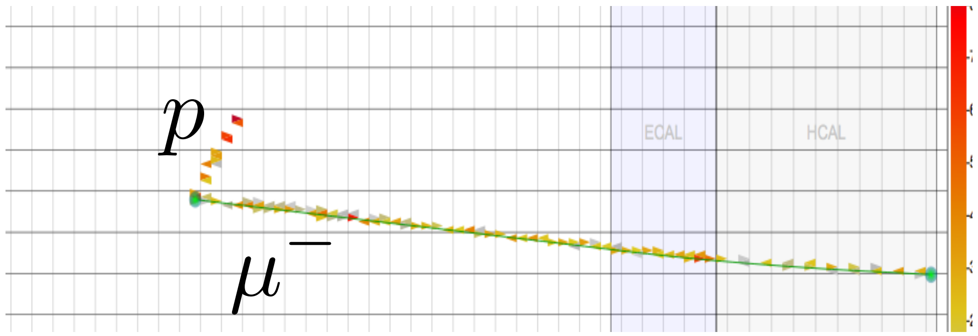
GENIE



Signal and Background

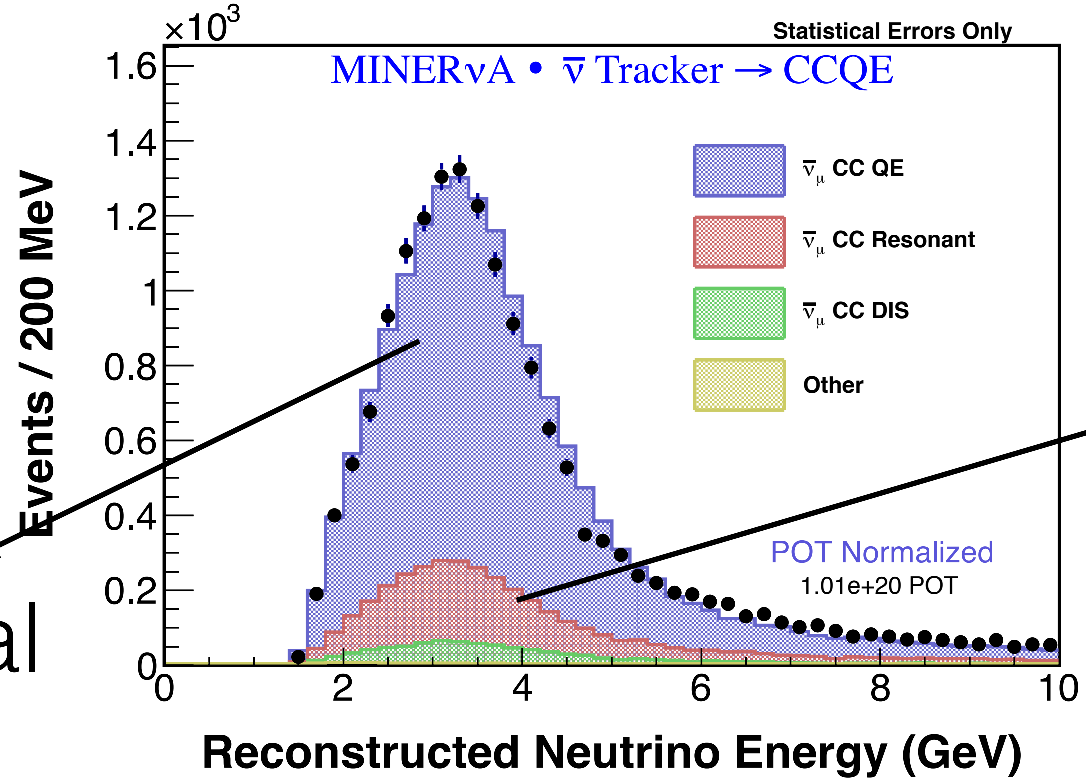
$$\left(\frac{d\sigma}{dx}\right)_\alpha = \frac{\sum_j U_{j\alpha}\left(N_{data,j} - N^{bkgd}_{data,j}\right)}{A_\alpha(\Phi T)(\Delta x)}$$

- We identify the particles
- Measure properties of those particles
  - Momentum, angle and energy



Neutrino Energy

$$E_{QE} = \frac{m_n^2 - (m_p - E_b)^2 - m_\mu^2 + 2(m_p - E_b)E_\mu}{2(m_p - E_b - E_\mu + p_\mu \cos\theta_\mu)}$$



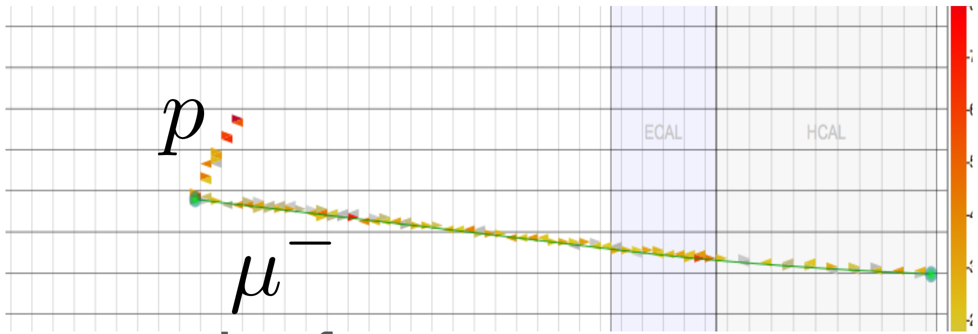
Signal

Background

We use Monte Carlo simulations (GENIE) to determine the background levels, but this is not enough, most of the time the models do not reproduce the real data

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

Signal and Background



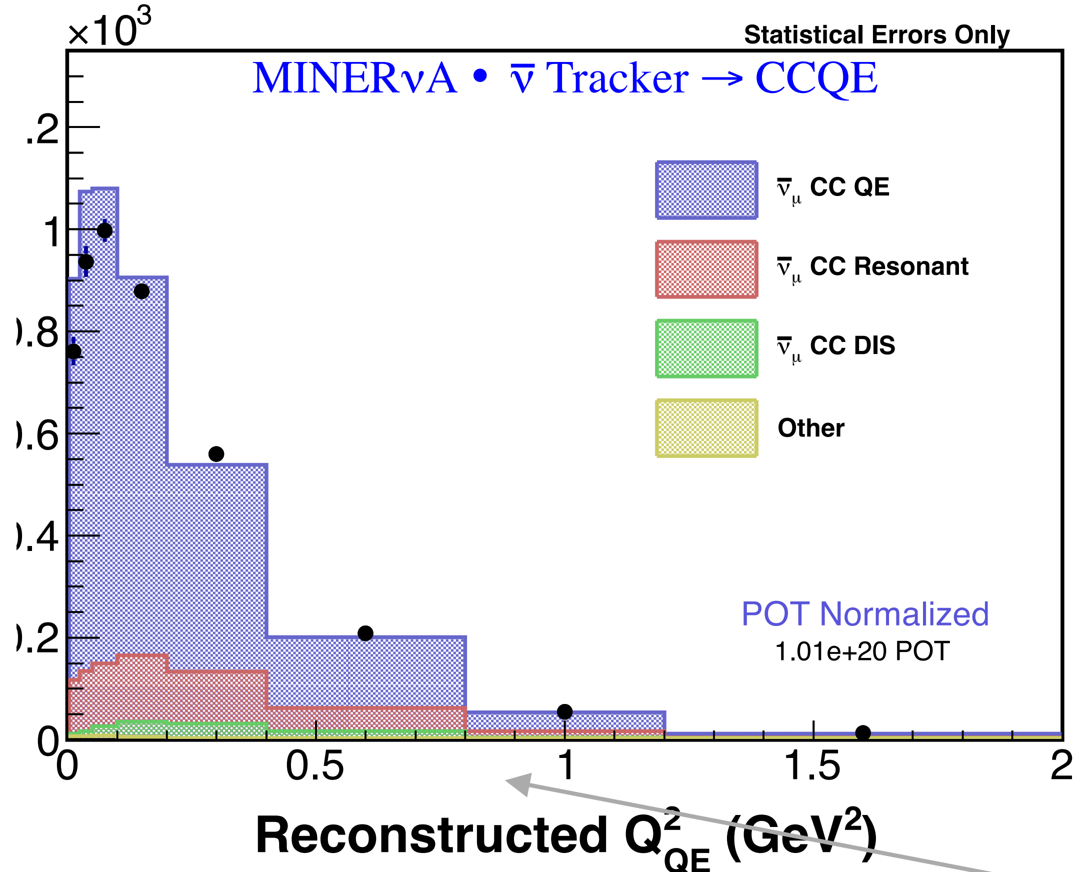
- We identifies the particles
- Measure properties of those particles
  - Momentum, angle and energy
  - Using the muon momentum and angle, we can compute the four momentum transfer

$$Q^2 = -m_\mu^2 + 2E_{QE}(E_\mu - p_\mu \cos\theta\mu)$$

$$E_{QE} = \frac{m_n^2 - (m_p - E_b)^2 - m_\mu^2 + 2(m_p - E_b)E_\mu}{2(m_p - E_b - E_\mu + p_\mu \cos\theta_\mu)}$$

  - Let's concentrate on describing how to measure the differential cross section as a function of Q^2

Selected events

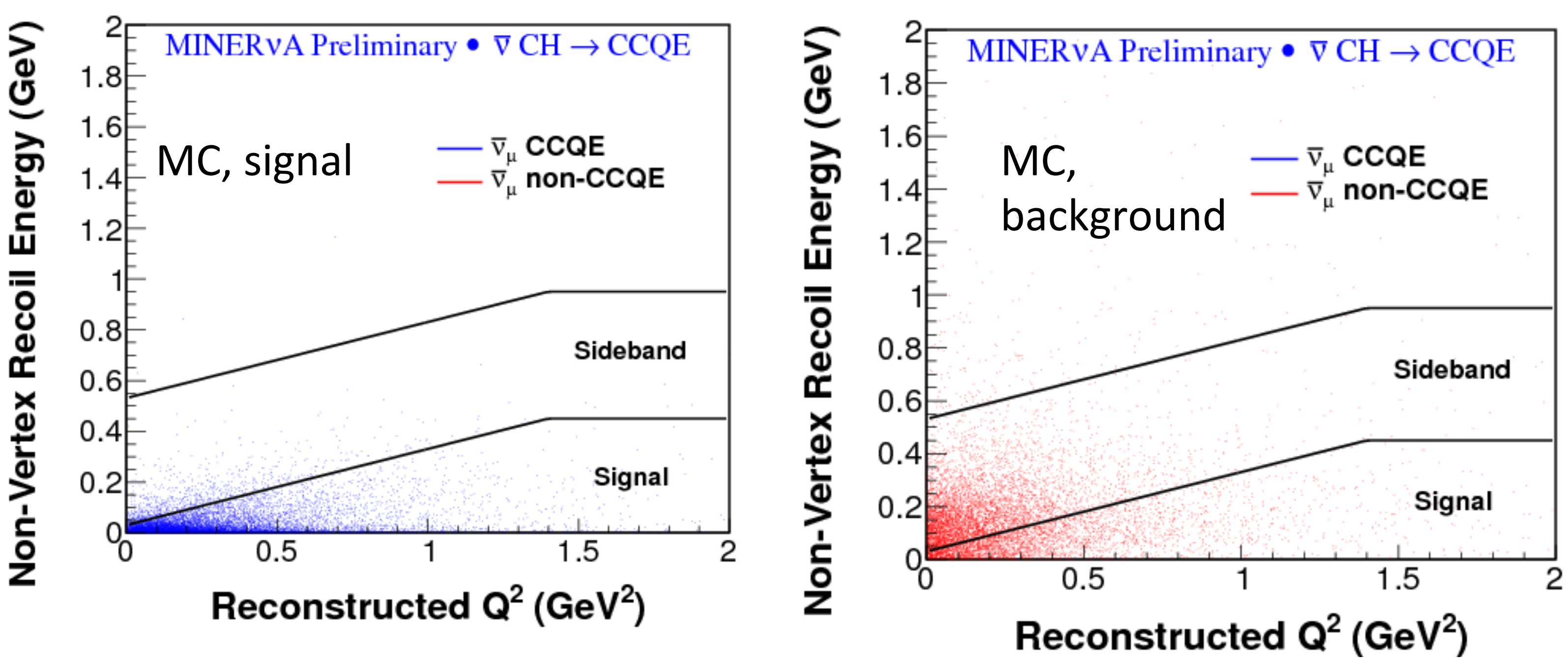


Main background from Resonant interactions

Background Prediction

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

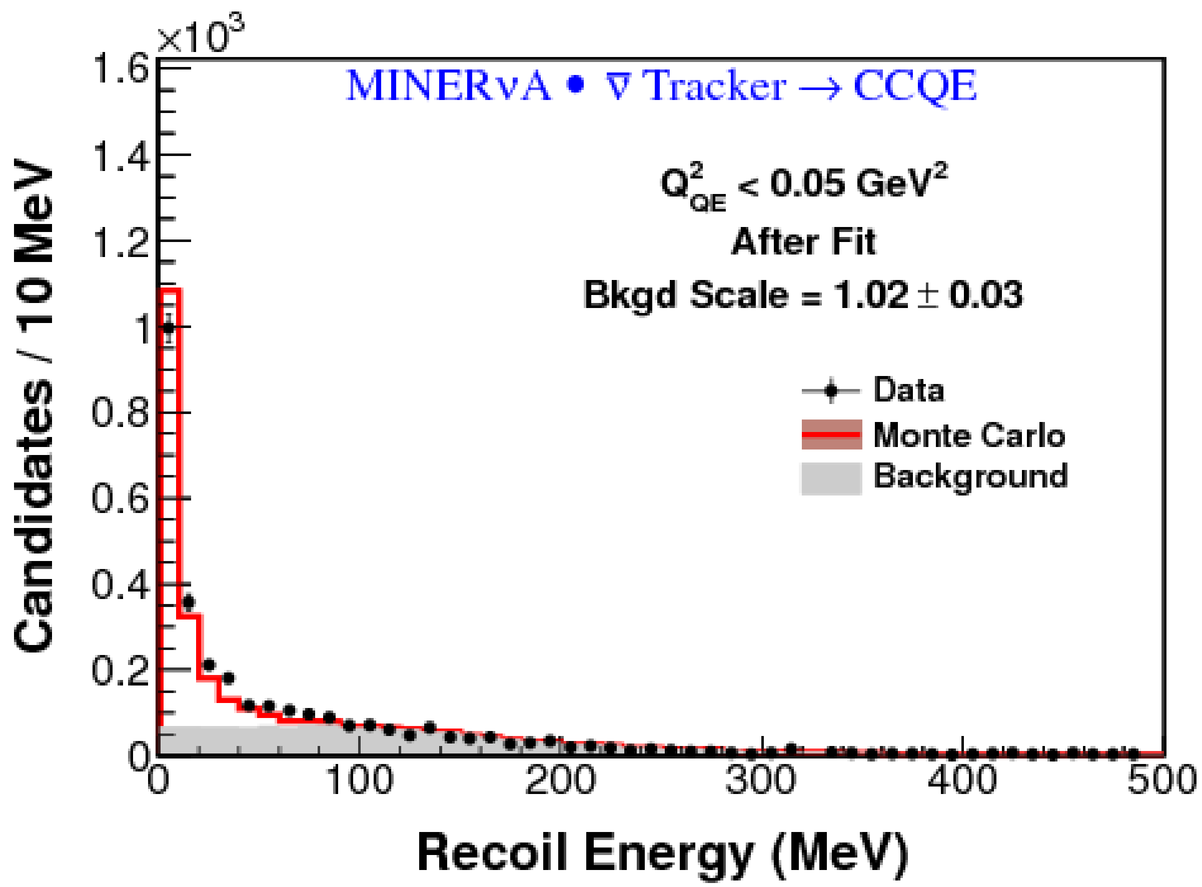
- We know the Monte Carlo models do not reproduce the real data
- Data is used to constrain the backgrounds
- Data driven background fit methods can reduce model-dependence
- An example from a MINERvA background constraint:
  - Taking the shape of the signal and background distributions in the Monte Carlo simulation
  - The relative weights of each of these distributions are varied until we get the combination that best matches the shape of the data
- Looking at the sideband region helps us to constrain the background in the signal region

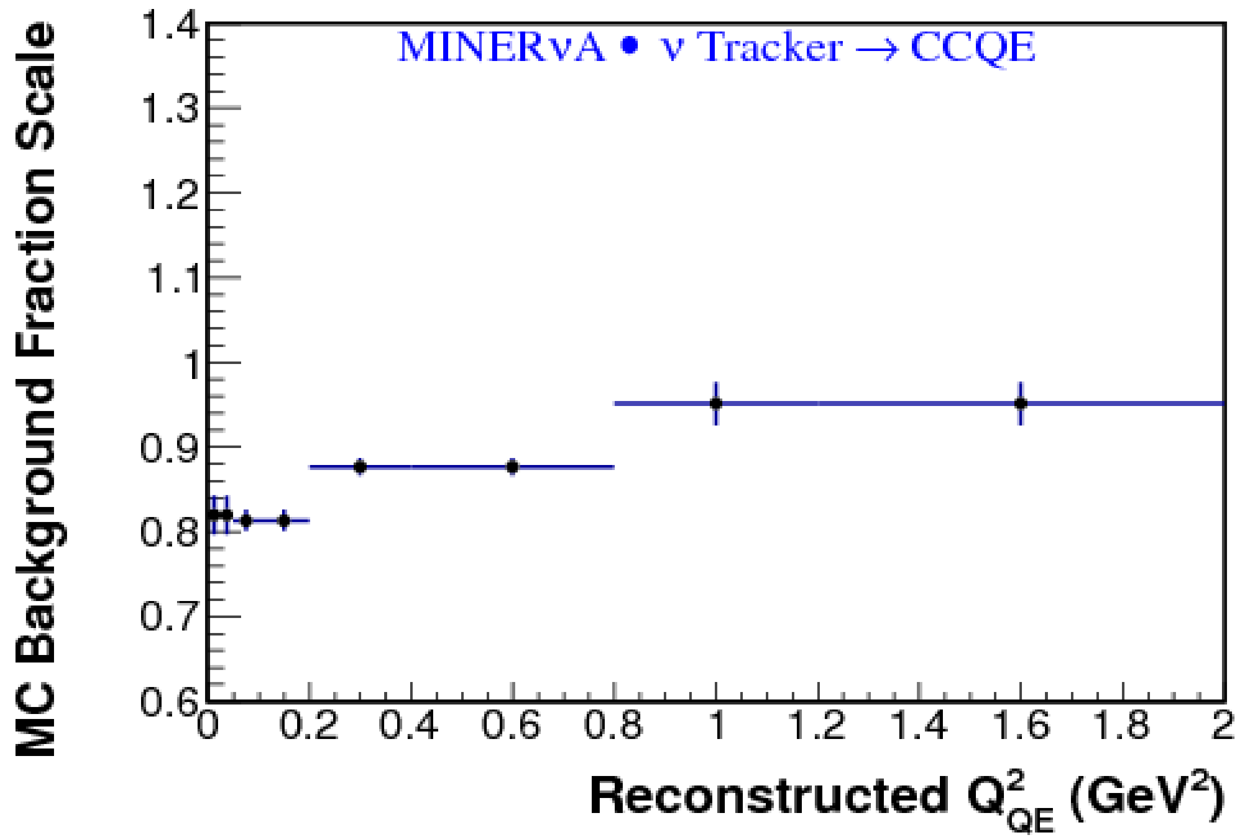


Example of Background Constraints

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

- Background levels are estimated by fitting recoils distributions
- We obtain weights for each bin of Q^2

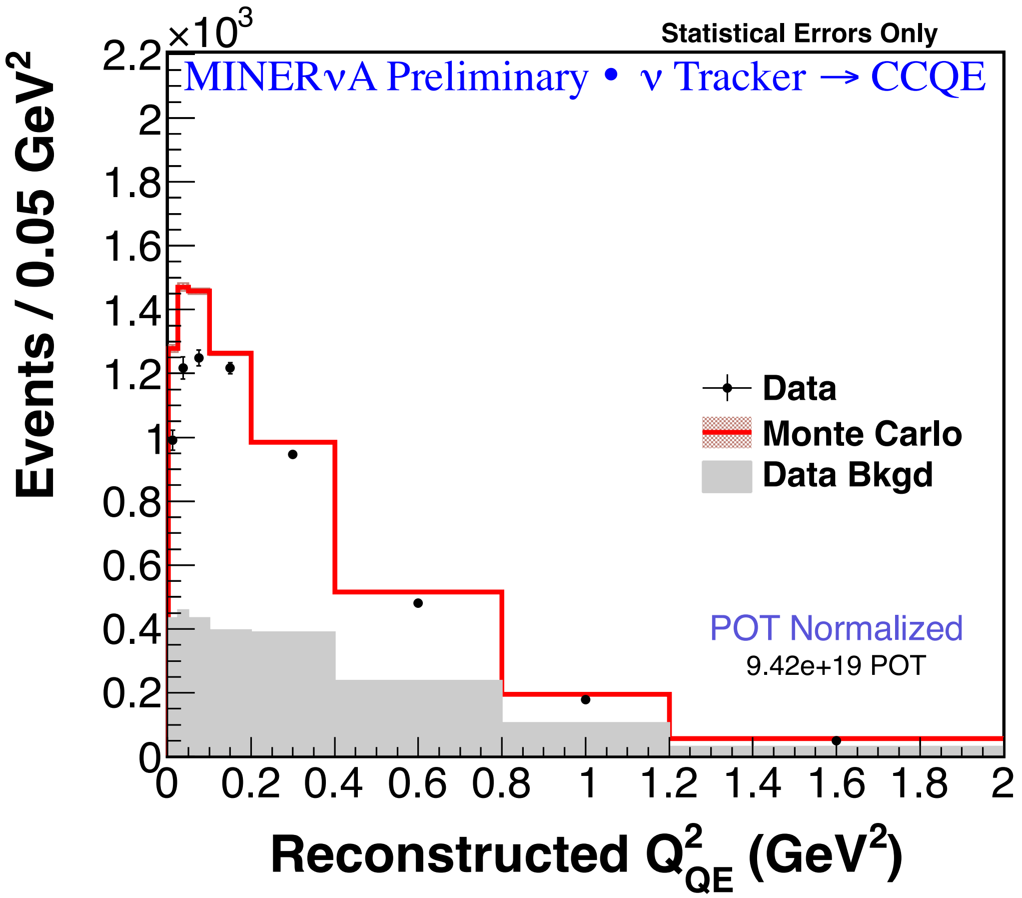


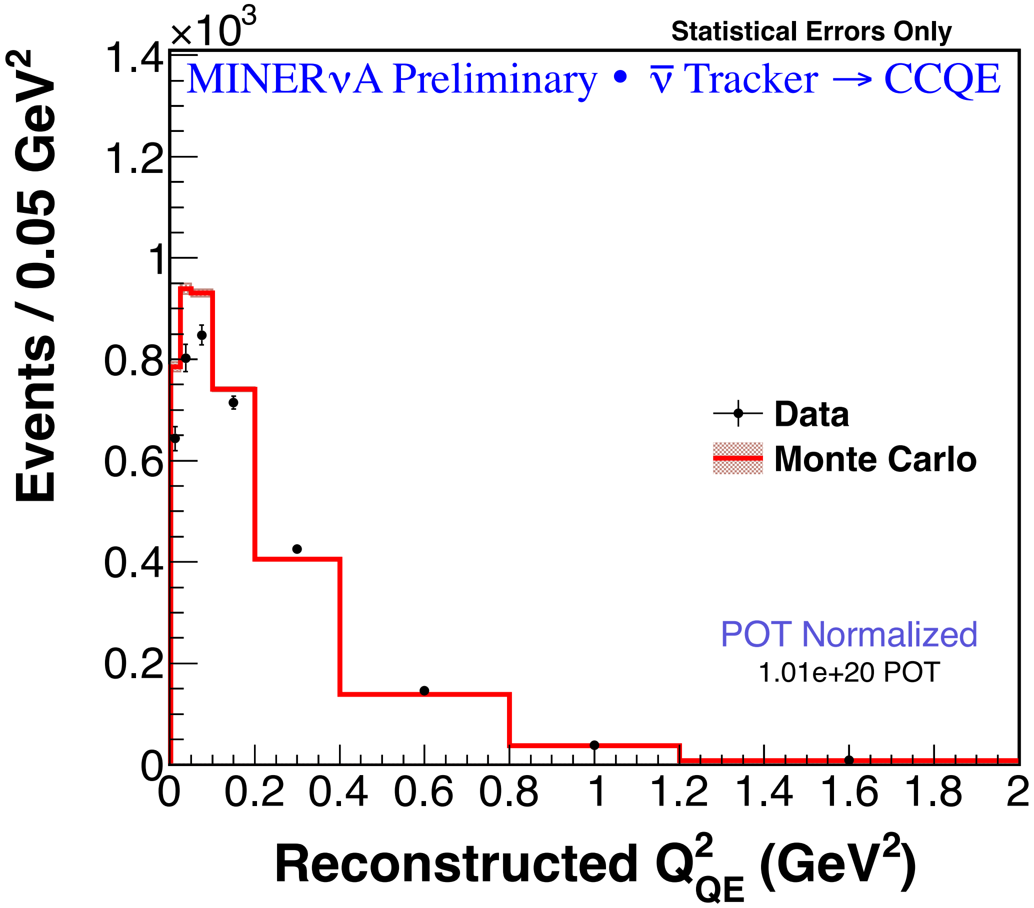


Background Subtraction

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

- After the background is constrained with data, we subtract the predicted background contribution from each bin of the desire quantity we want to measure

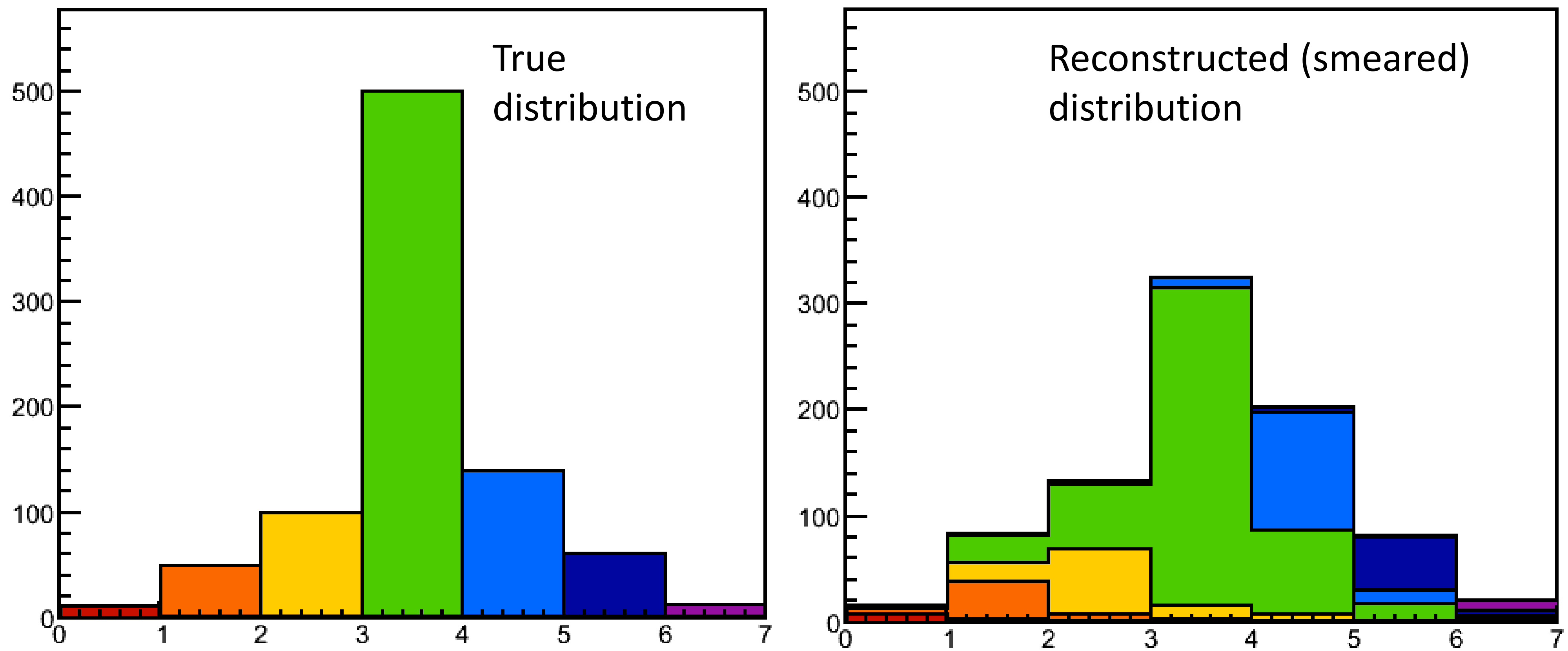




Unfolding

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

- We can't measure (or reconstruct) events with perfect precision, so we will always reconstruct some events into the wrong bin



- This has the effect of smearing out the features of our true distribution
- Correcting for the effects of detector smearing, which causes some events to be reconstructed into the wrong bin. The goal is, when presented with a smeared distribution, to recover out true distribution

Cheryl Patrick, MINERvA 101

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

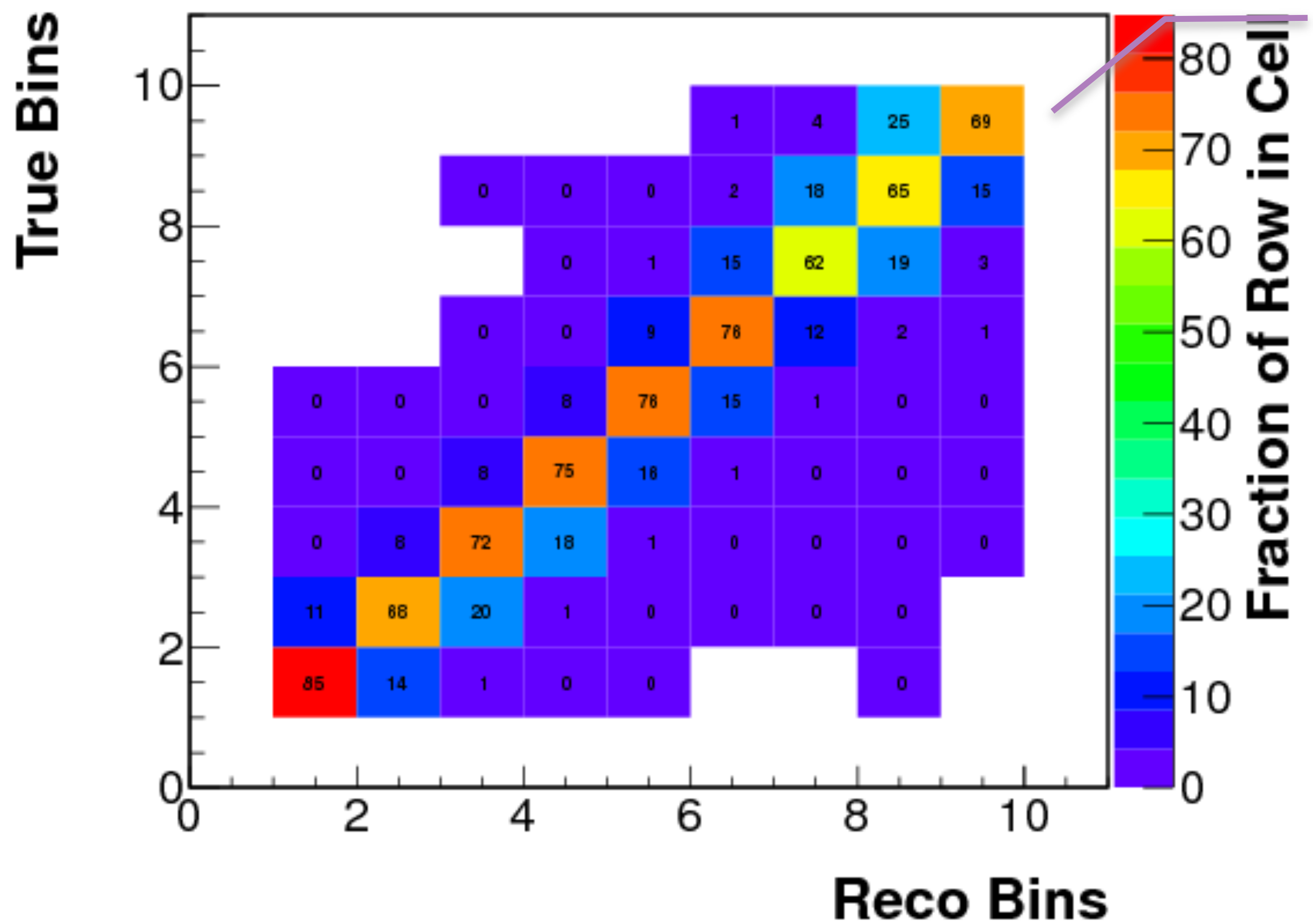
Unfolding

- We want to know, if an event is observed in bin j, what bin did it really happen in?
- In other words, what's the probability that an event observed in bin j actually occurred in bin α?
- We can use our Monte Carlo to inform a migration matrix indicating what fraction of events generated in each bin α were observed in each reconstructed bin j
- If we've done a good job with our initial reconstruction, the matrix should be close to diagonal
- In addition, if we chose bins that are too small compared to our resolution. This is also a problem because the matrix is not as diagonal

Unfolding

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

- Example from Quasi-Elastic scattering



Diagonal corresponds to events reconstructed in the right bin

- To get the unsmearing matrix U, we must invert the migration matrix

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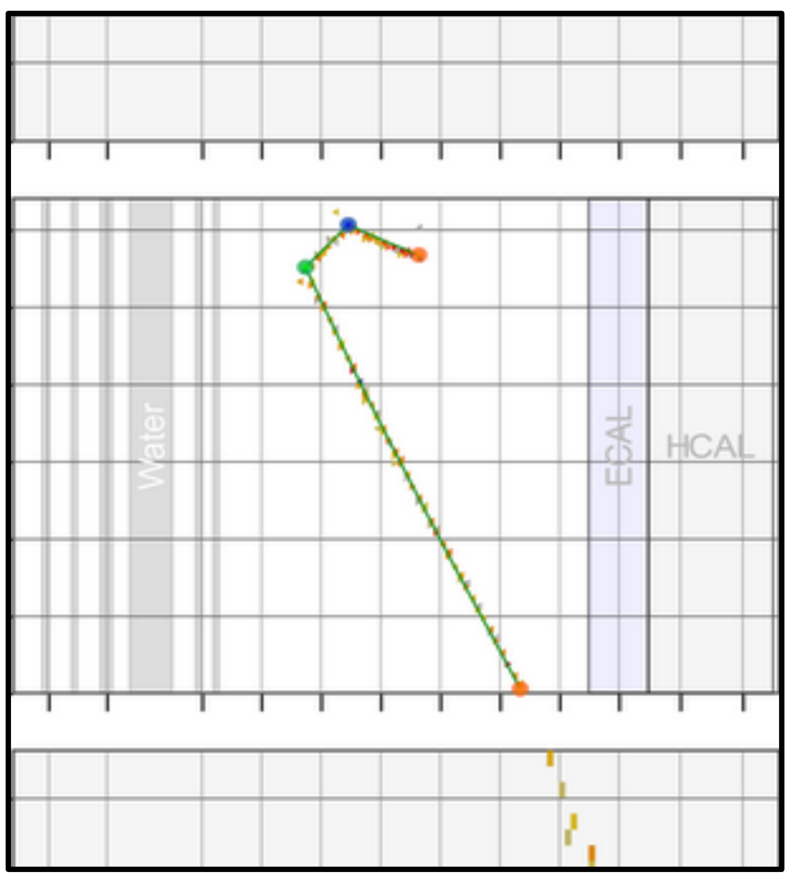
$$\left(\frac{d\sigma}{dx}\right)_\alpha = \frac{\sum_j U_{j\alpha}(N_{data,j} - N^{bkgd}_{data,j})}{A_\alpha(\Phi T)(\Delta x)}$$

Efficiency Correction

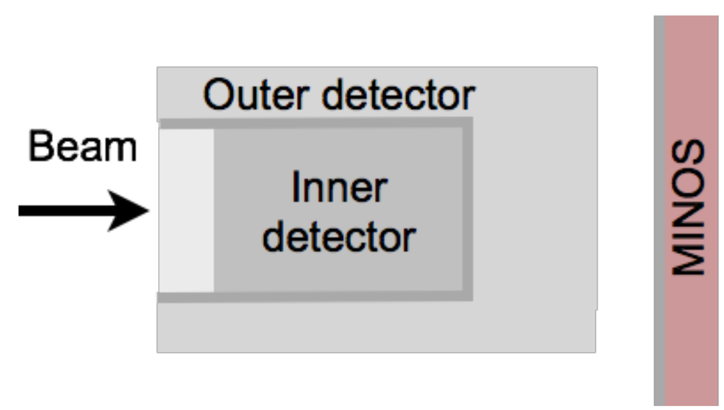
- A measure of how often we select signal events
- Inefficiency comes from reconstruction and detector geometry

$$\varepsilon = \frac{\text{number of signal events after event selection}}{\text{number of signal events in Monte Carlo}}$$

- An example from detector acceptance



Some analyses require muon track to be matched to a track in MINOS. Events where the muon exits the side of detector will be rejected



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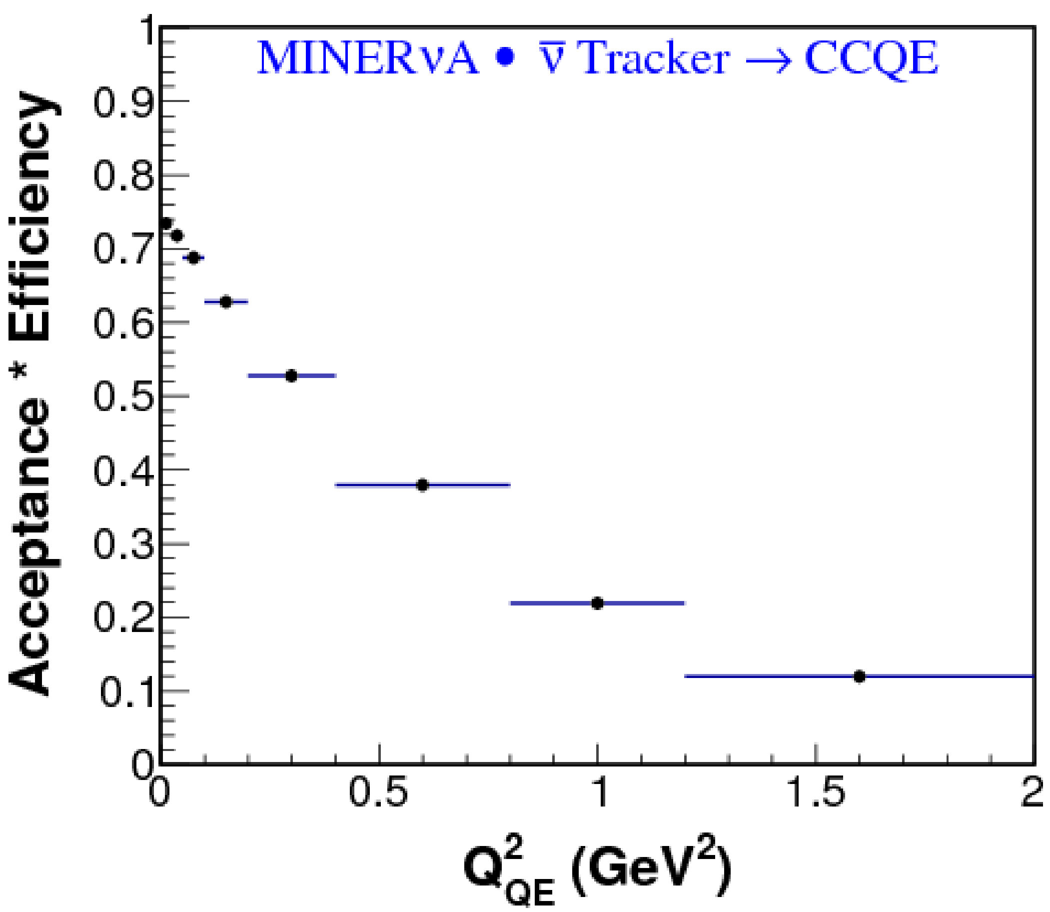
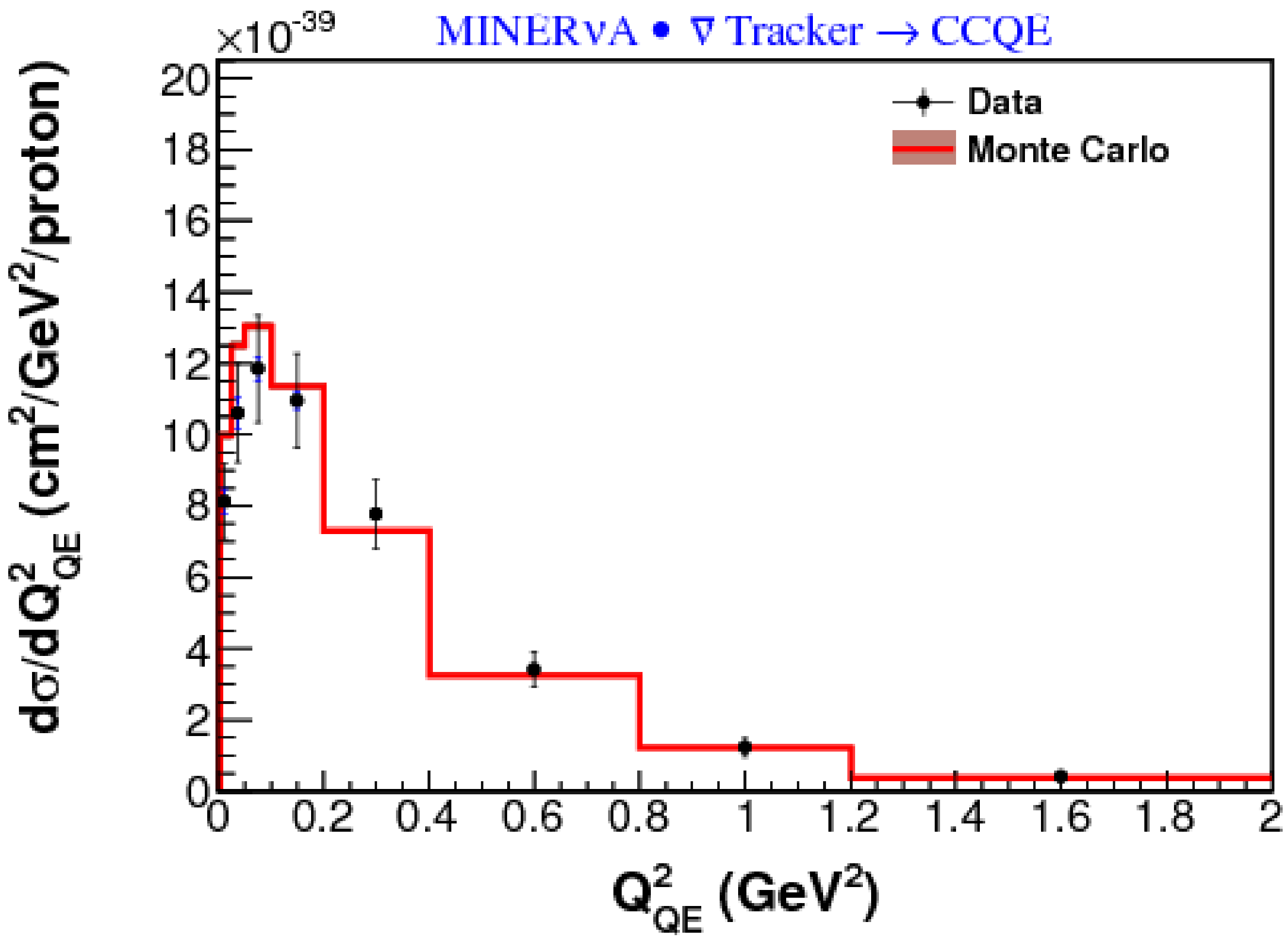
Efficiency Correction

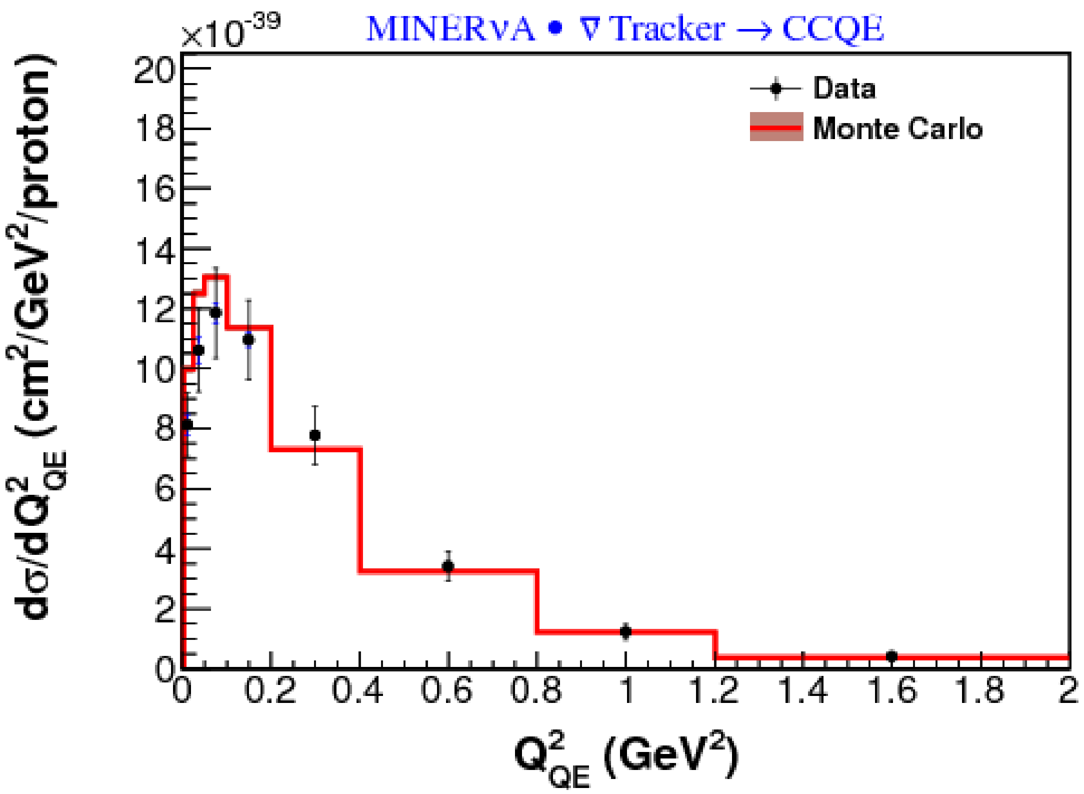
$$\left(\frac{d\sigma}{dx}\right)_\alpha = \frac{\sum_j U_{j\alpha}(N_{data,j} - N^{bkgd}_{data,j})}{A_\alpha(\Phi T)(\Delta x)}$$

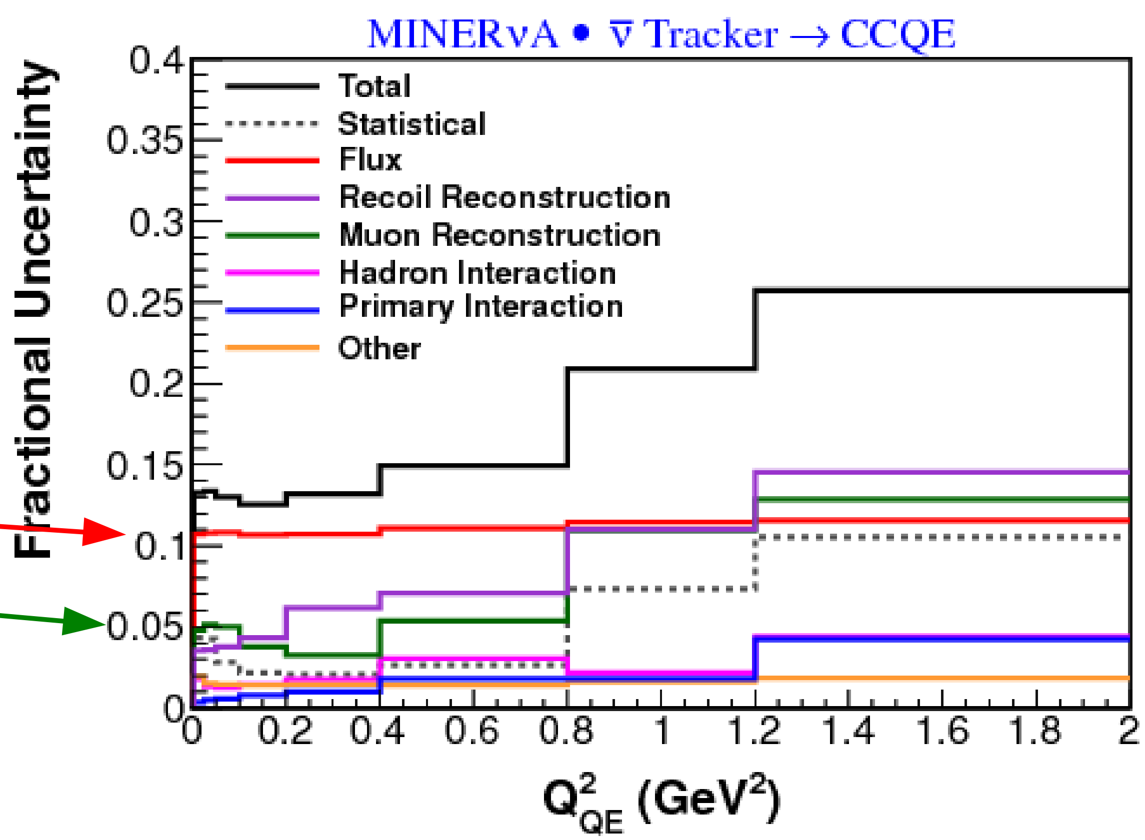
- Unfolded distributions are normalized by efficiency, flux and proton number to produce final cross section





Systematic Uncertainties



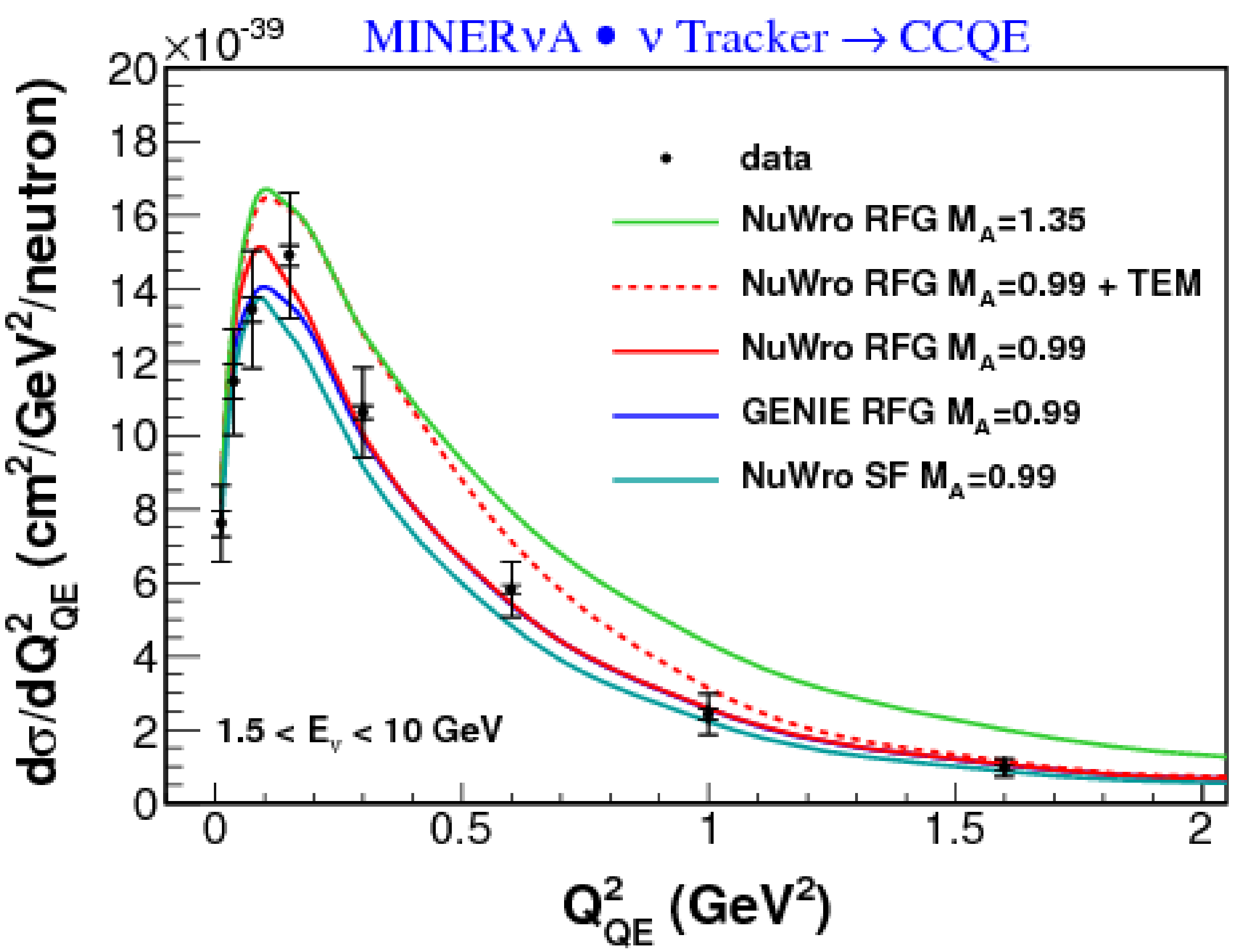


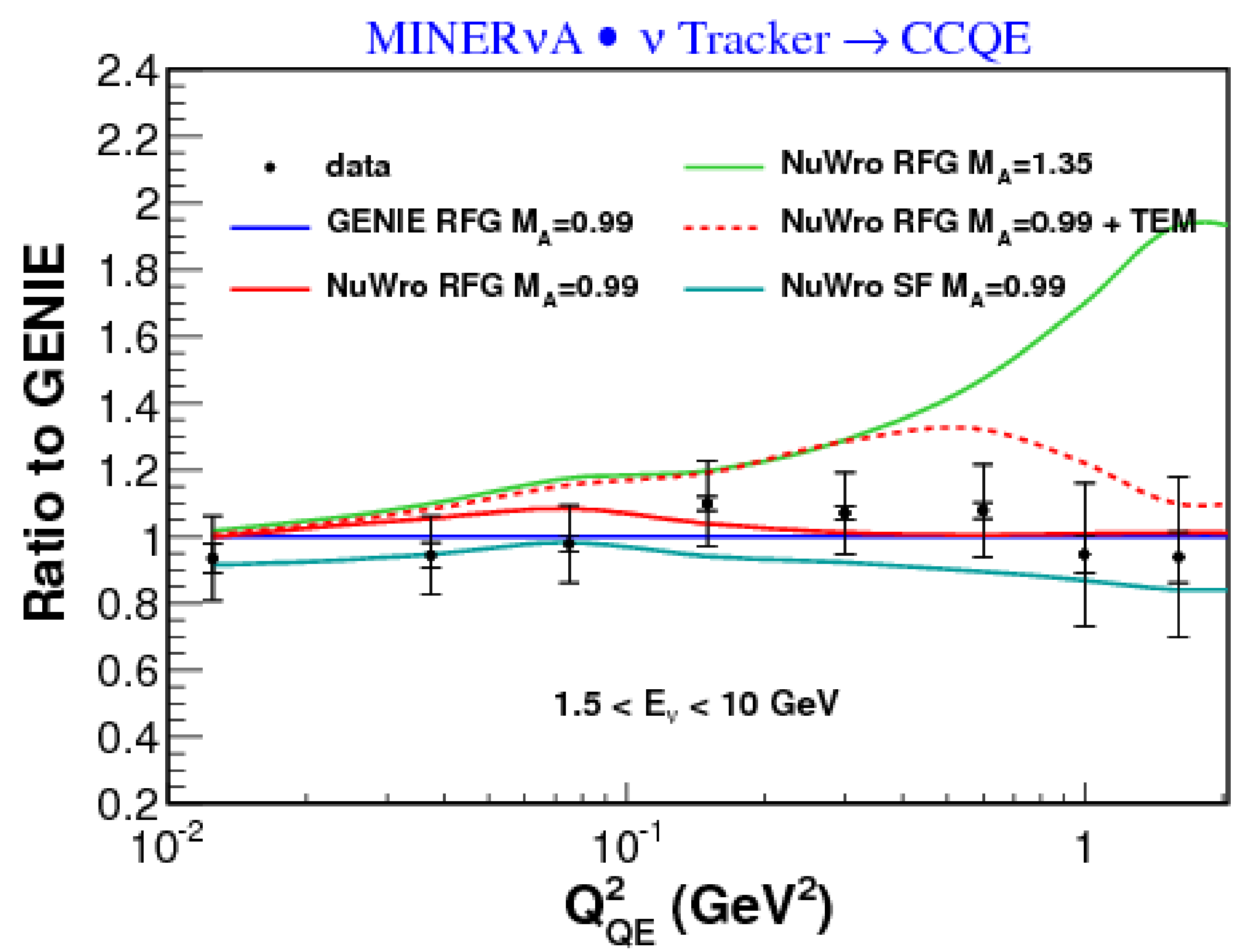
Flux uncertainties

Muon Reconstruction Uncertainty

Comparing with Models

- Data do not agree with some models





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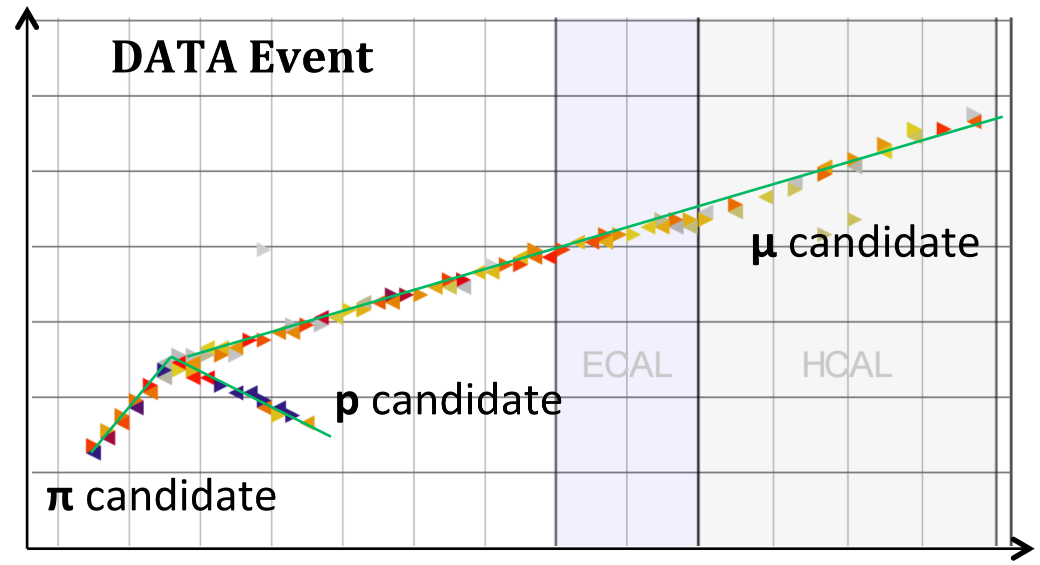
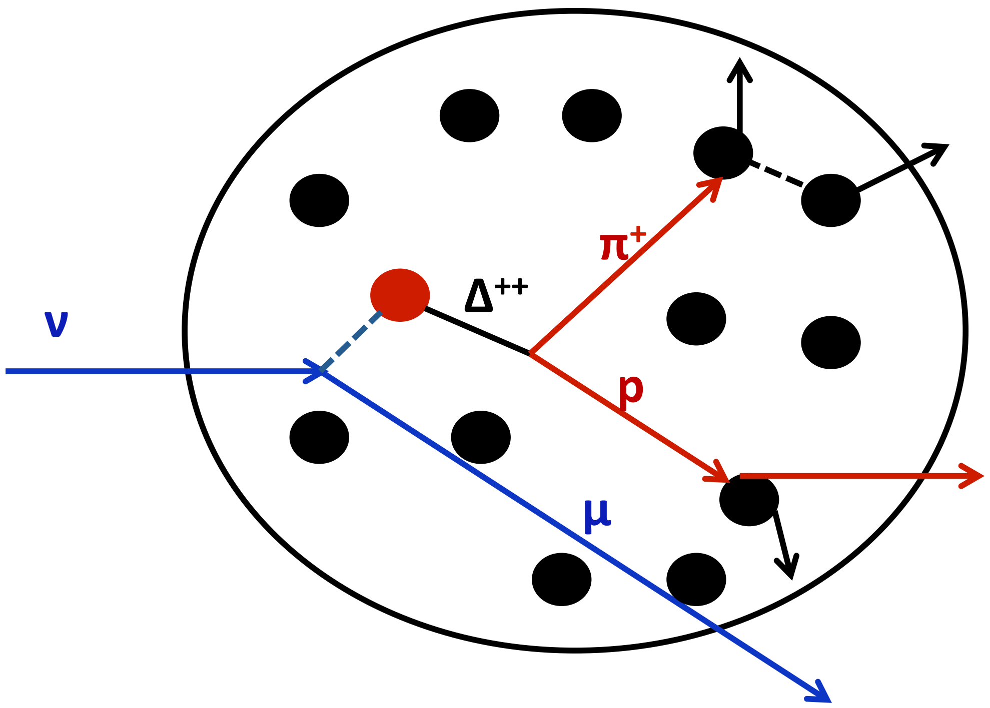
As an example of final state interaction effects, let's review a couple of examples from pion production

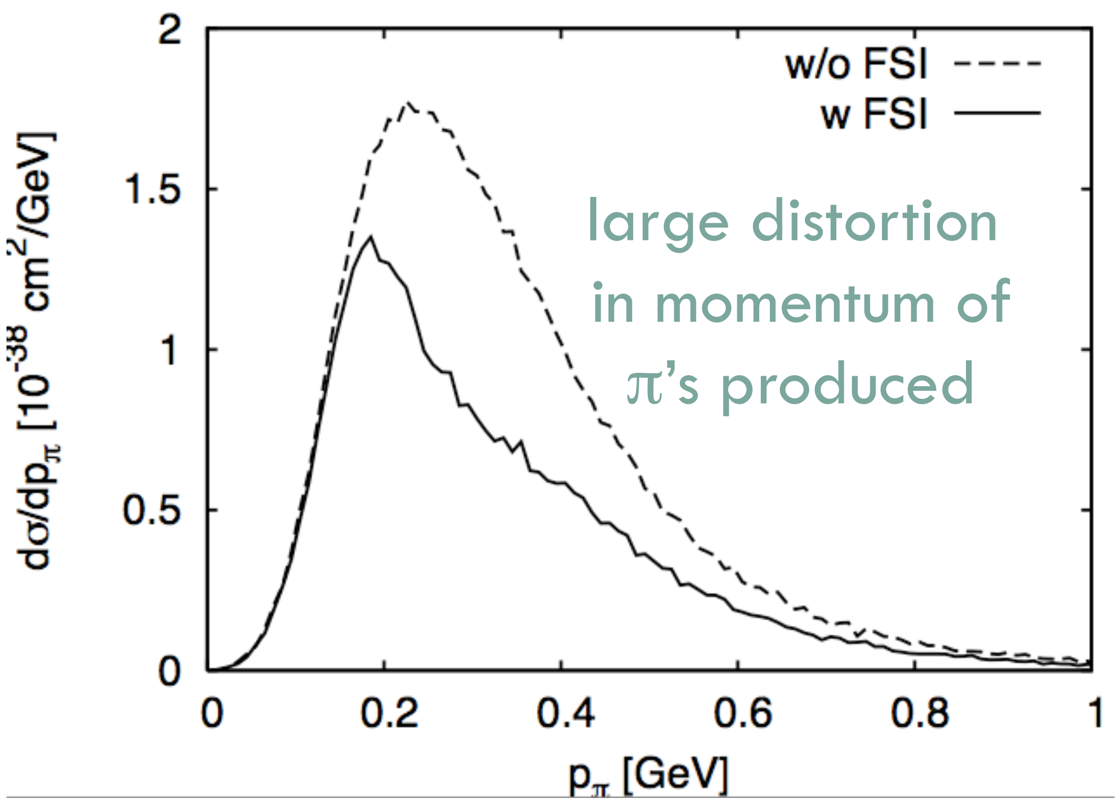


Let's concentrate on the pion candidate

Final State Interactions

- Final state interactions: Hadrons produced in a scattering interaction re-interact with other nucleons before they escape the nucleus
- Thus the particles that exit the nucleus my be different, both in type and in energy from those generated in the initial interaction
- Final states where pion is absorbed can contribute to apparent "quasi-elastic" scattering
- These effects are big

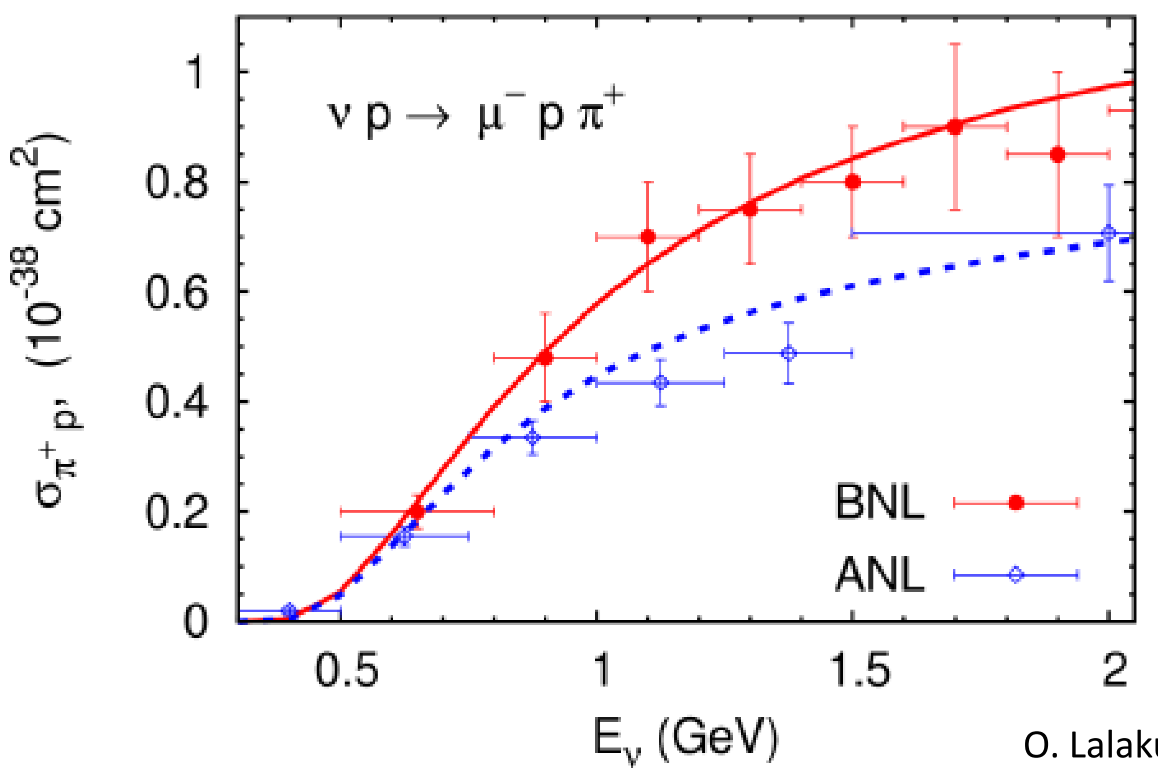




Charged Pion Production

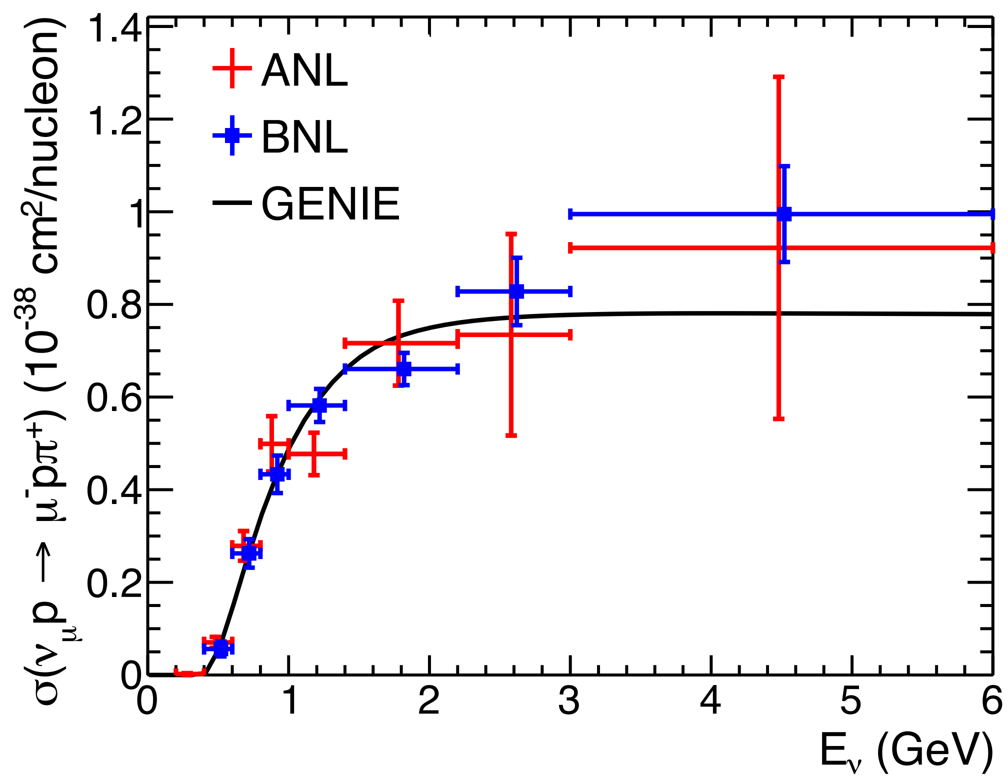
- Most experiments use the Rein-Sehgal model for nuN resonance production
  - More recent models by M. Athat, Salamanca-Valencia, M. Pascos
- Experimentalist’s dilemma: Whichever model you use, it will be poorly constrained by nuN data

Old bubble chamber deuterium data



O. Lalakulich

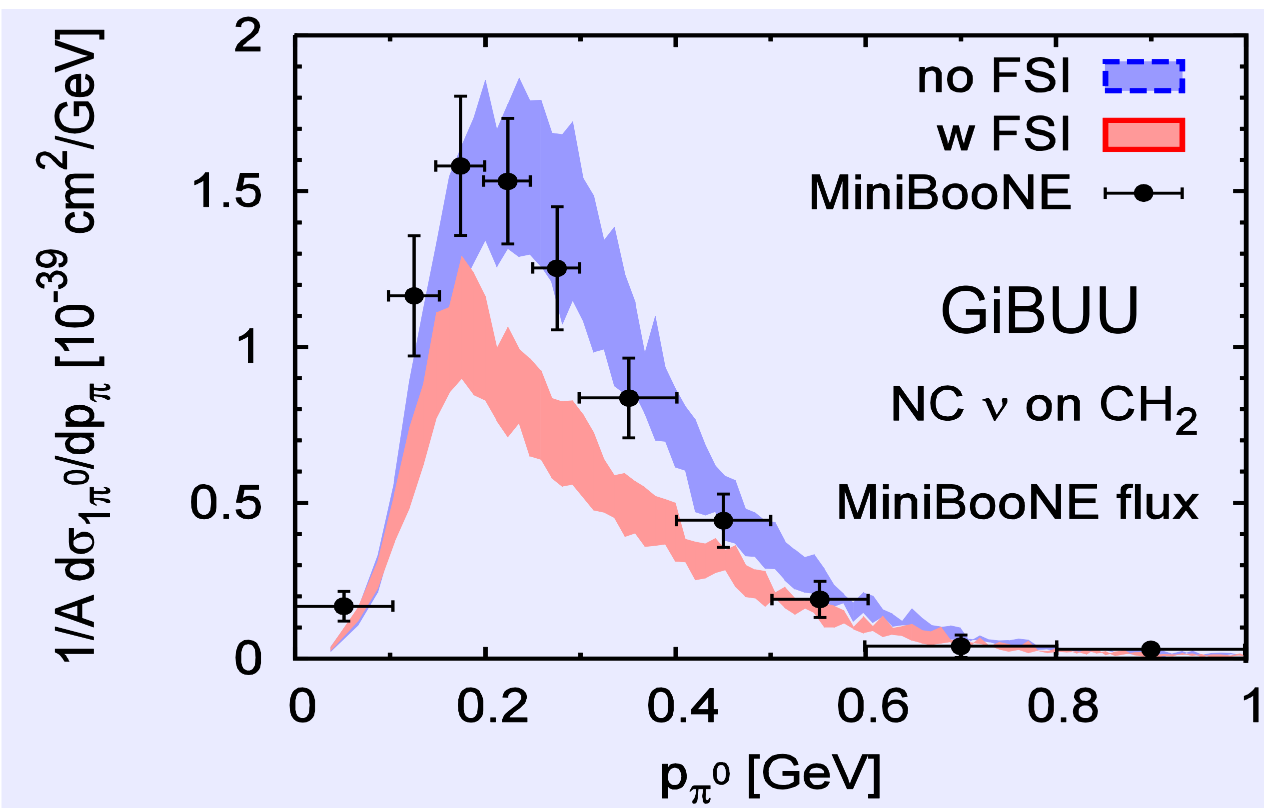
Recent reanalysis of deuterium data finds consistency between ANL and BNL

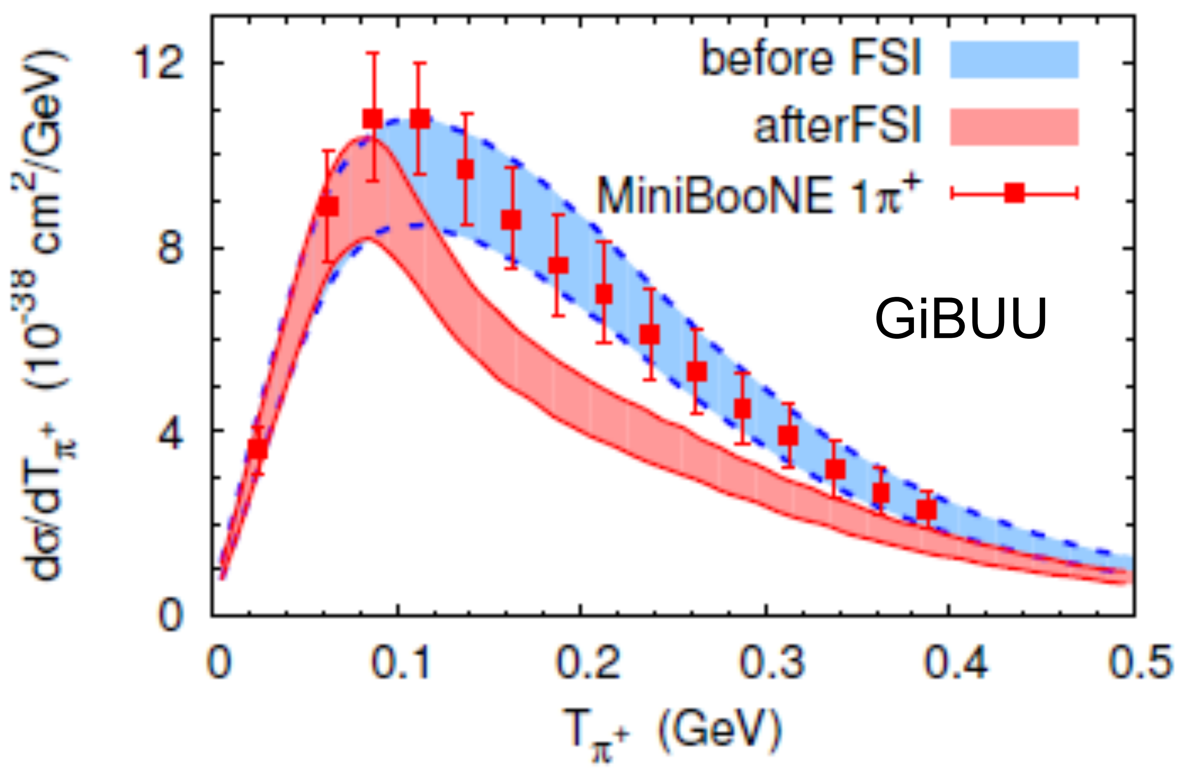


- All the generator are tuned to bubble chamber deuterium data

Comparisons of Models with Data from MiniBooNE

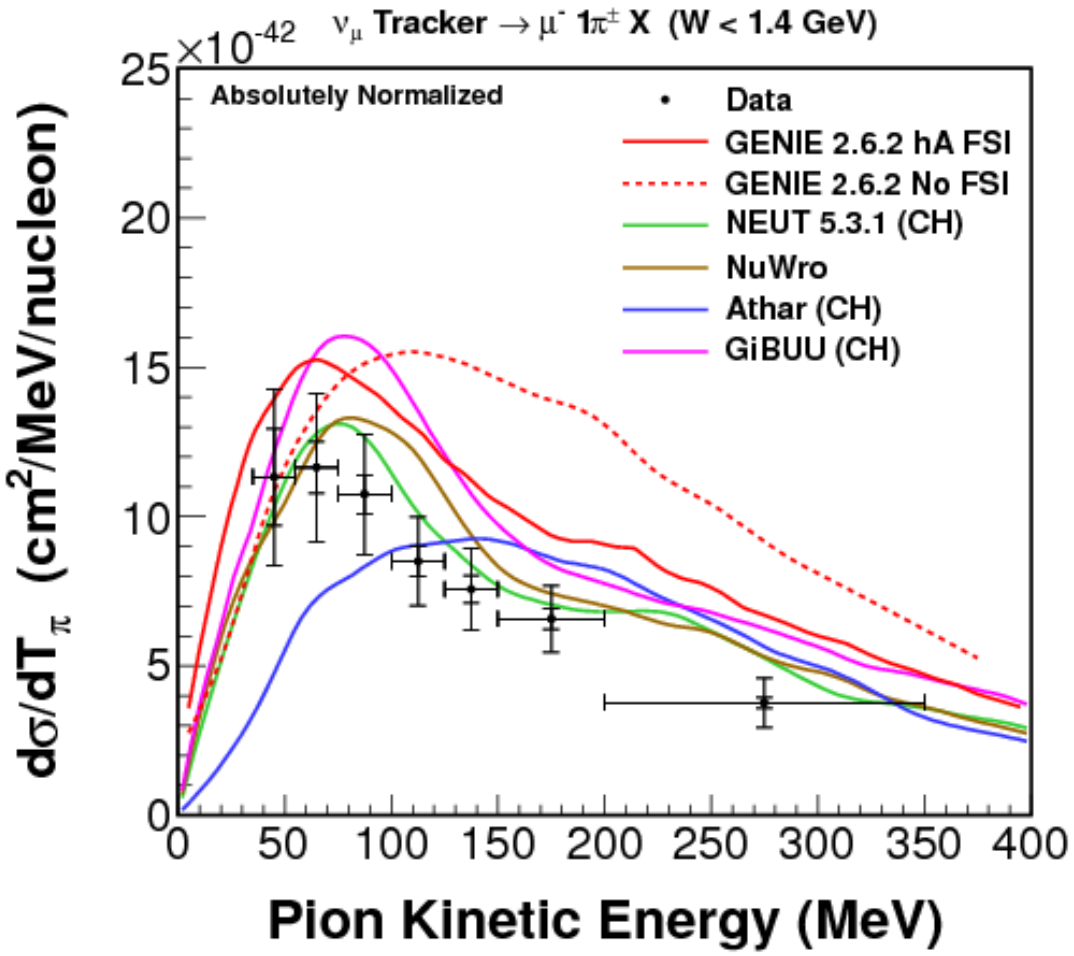
- Data is compared against a theoretical model (GIBUU)
- Data prefers GIBBU with no FSI for both π^0 and $\pi^\pm$

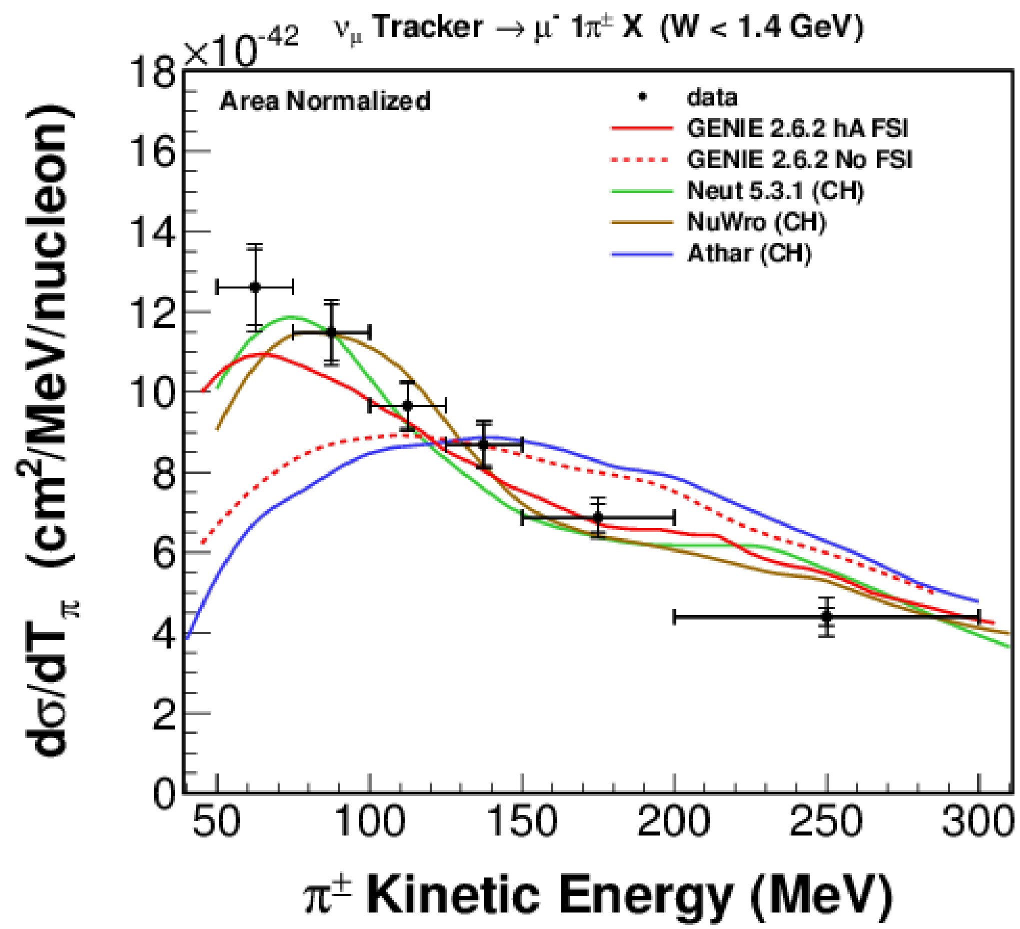




Comparison of Models with Data from MINERvA

- Differential cross section as a function of pion kinetic energy, left absolutely normalized and right area normalized





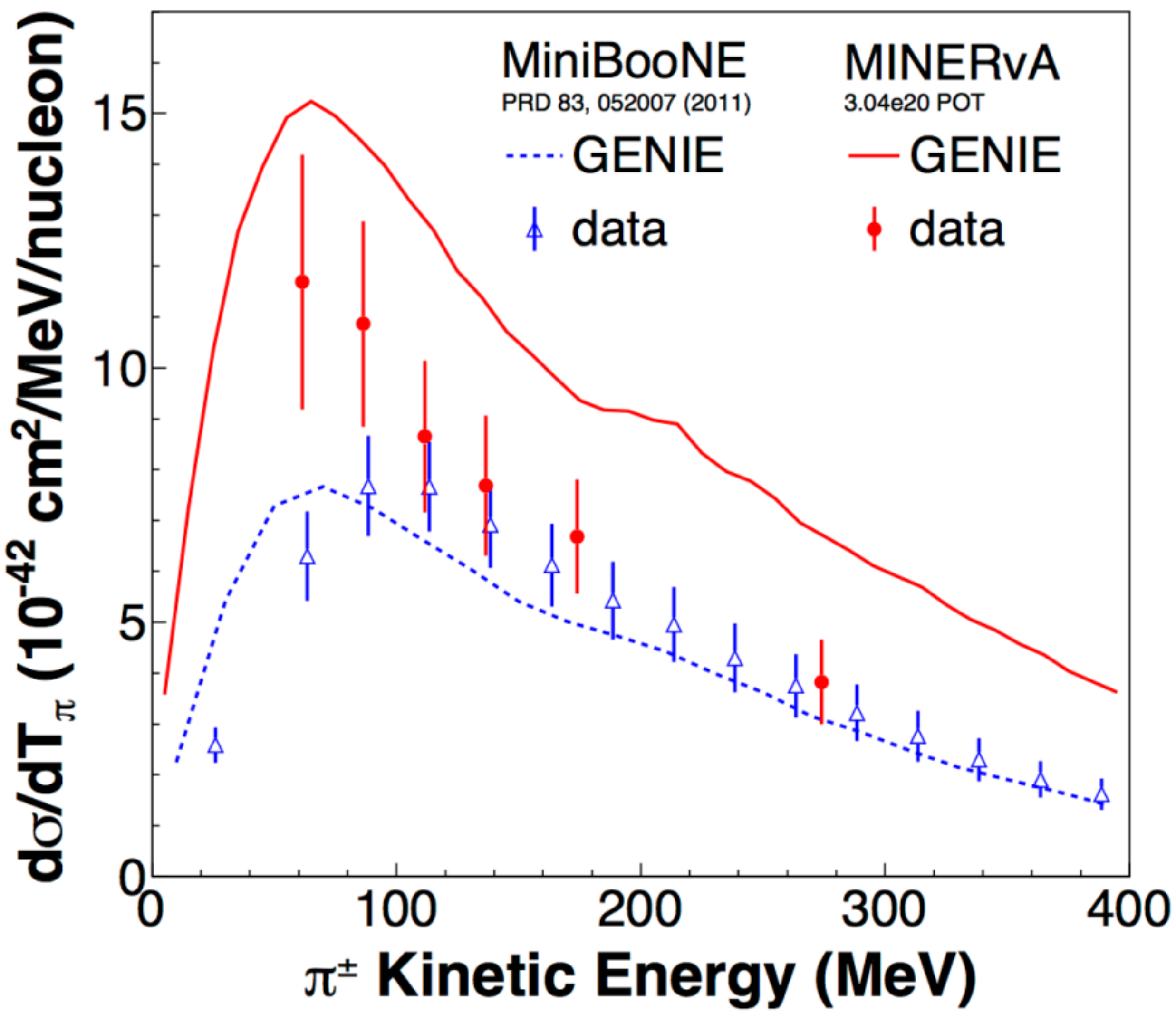
NEUT and NuWro normalization agree the best with data GIBBU, GENIE normalization disfavored

GENIE (with FSI), NEUT, and NuWro predict the shape well. Except for Attar, data is unable to distinguish different FSI model

Phys. Rev D92(2015)

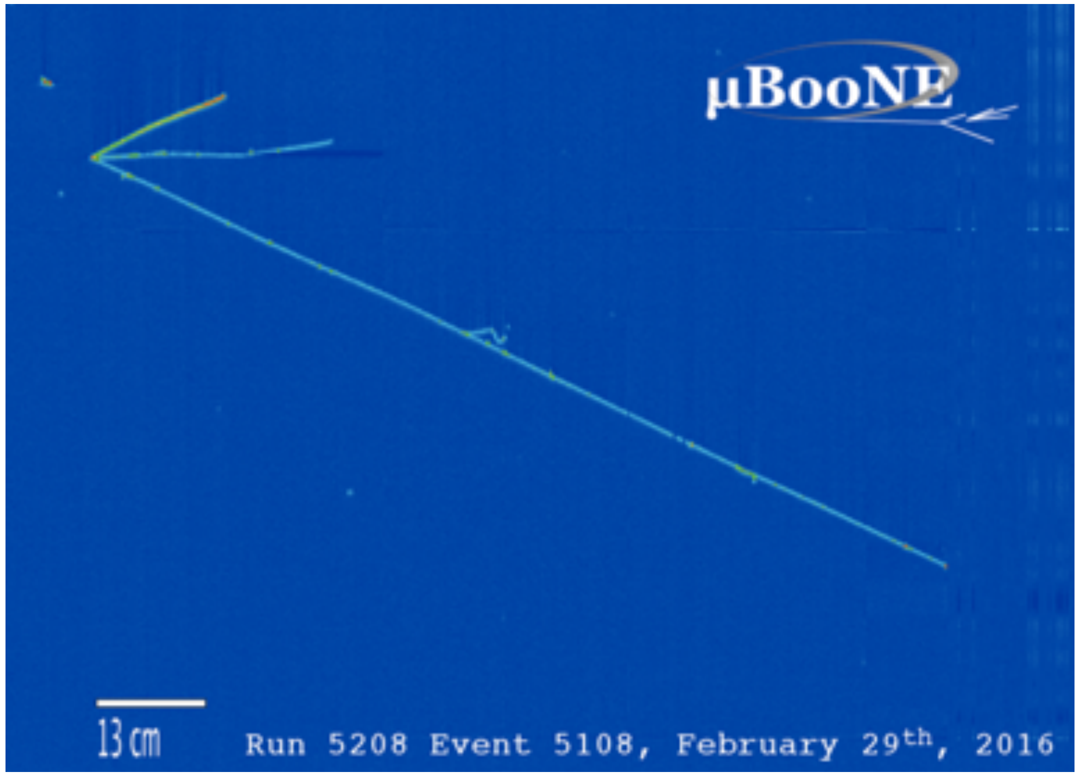
MINERvA and MiniBooNE Data

- No models describe all data sets well
  - MiniBooNE <E>~1 GeV: best theory models (GIBUU) strongly disagree in shape
  - MINERvA <E>=4 GeV: Event generator has shape but not magnitude



Present and Future

- We have several experiments studying different neutrino interactions and making precise cross section measurements
  - MINERvA, T2K, NOvA, MiniBooNE, ArgoNeut NOMAD and others..
- Future neutrino oscillation experiment (DUNE) will use new detector technology
  - New targets made of liquid argon
- Several experiments in the lab are leading the effort for the liquid argon (MicroBooNE, SBND and ICARUS)



Charged current candidate from MicrooBooNE

Summary

- Some cross section measurements are challenging because nuclear effects are not easy to disentangle
- We need to understand the interplay between nuclear effects and cross sections in neutrino nucleus interactions
- However, cross sections are very important, since they help us perfect the nuclear model we have in our event generator (GENIE)
- The nuclear model is esencial to transfer information from the near detector to the far detector in oscillation experiment
- Understanding the neutrino interactions with nuclei is vital for precision oscillation measurements