MINERvA

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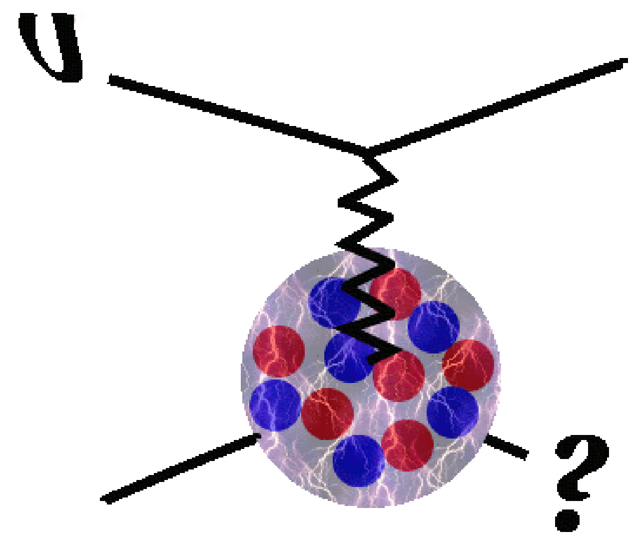
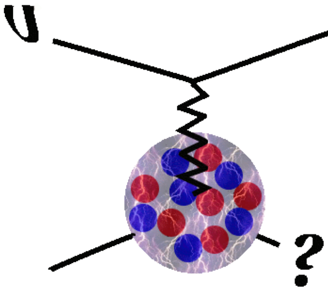
FNAL Intensity Frontier Seminar

1 May 2014

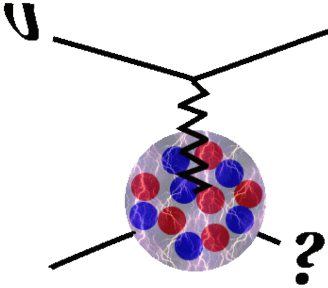


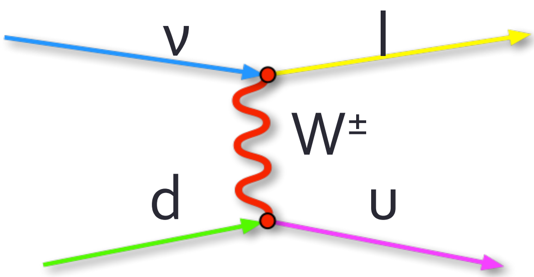
Outline



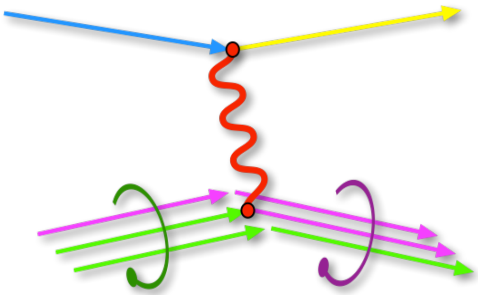
- Why study neutrino interactions?
- The MINERvA Experiment
- Results
  - Quasi-Elastic Scattering and Pion Production in a Nucleus
  - Ratios of Total Cross-Sections on Different Nuclei
  - “New” In Situ Flux Measurement Technique: Neutrino-Electron Scattering
- Conclusions and Prospects

Neutrino Interactions: Simple… until they aren't





Leptonic current is perfectly predicted in SM…
…as is the hadronic current for free quarks.

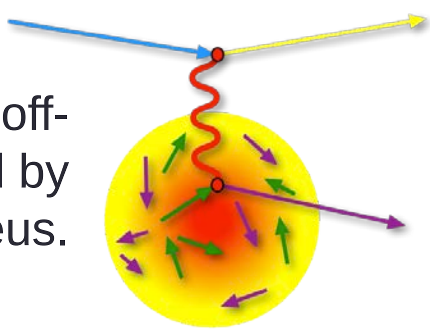


For inclusive scattering from a nucleon, add PDFs for a robust high energy limit prediction

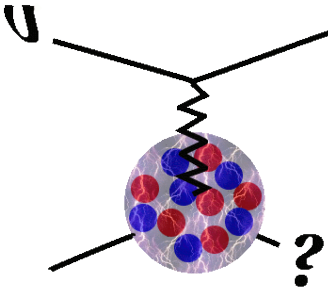
For exclusive, e.g., quasi-elastic scattering, hadron current requires empirical form factors.

(drawings courtesy G. Perdue)

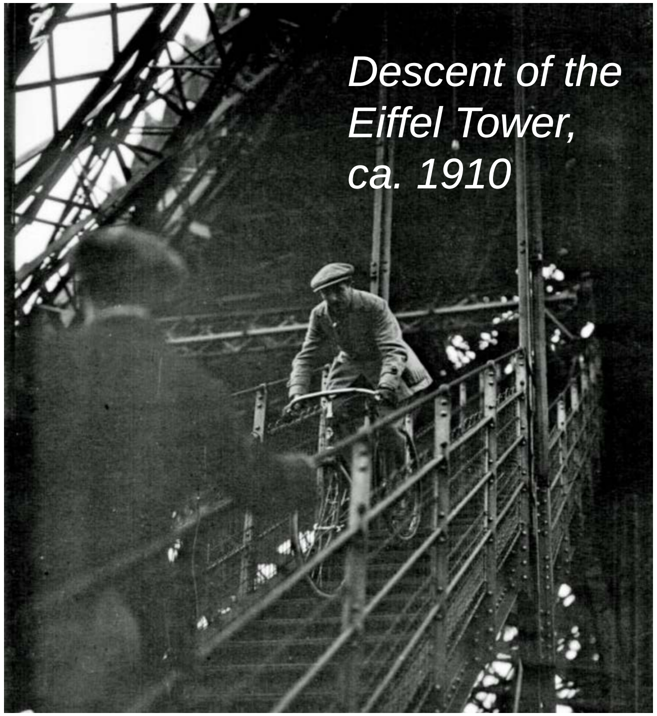
If the nucleon is part of a nucleus, it may be modified, off-shell, bound, etc. Also, exclusive states are affected by interactions of final state hadrons within the nucleus.

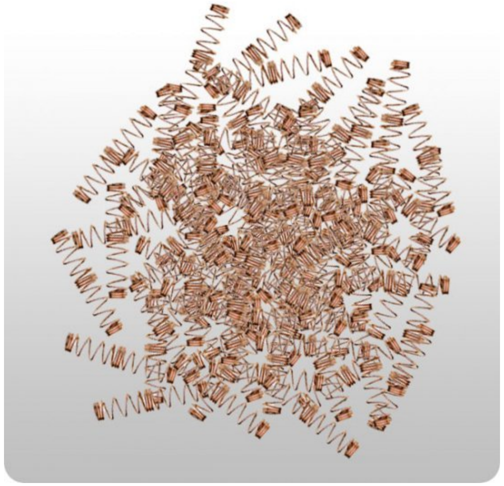


Wrong Tools for the Job?



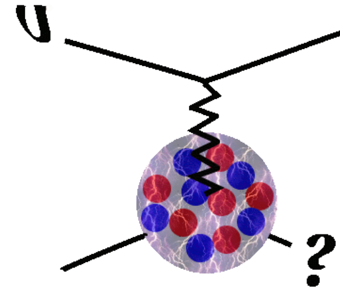
- Accelerator oscillation experiments require beam energies of 0.3-5 GeV
  - Nuclear response in this region makes the transition between inelastic and elastic processes.

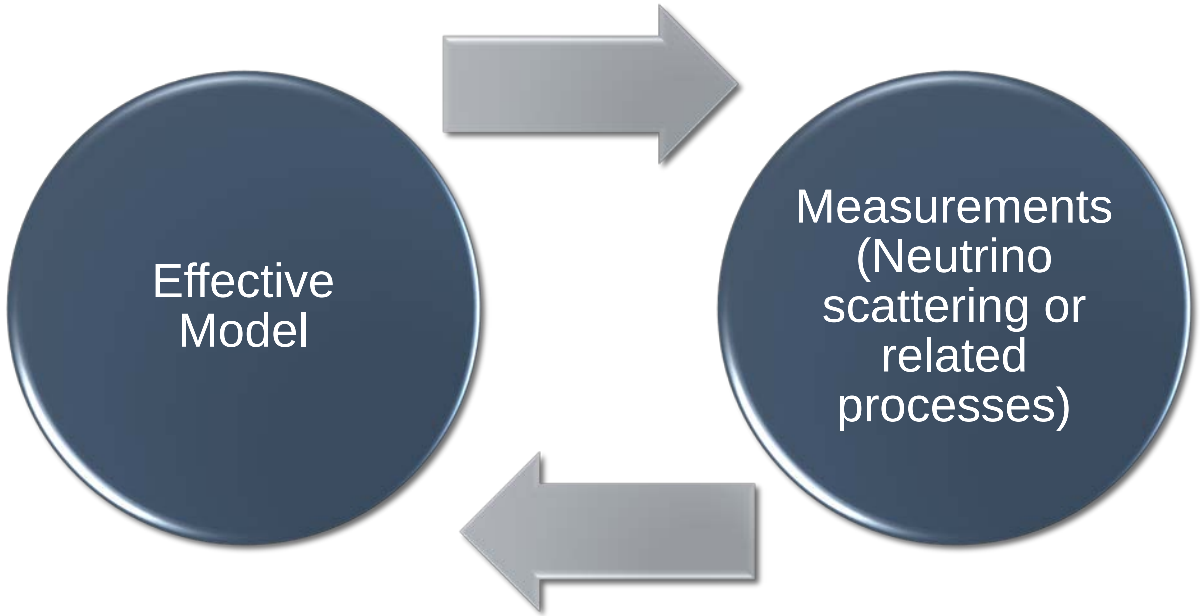




- First-principles calculations of the strongly bound target are impossible or unreliable.

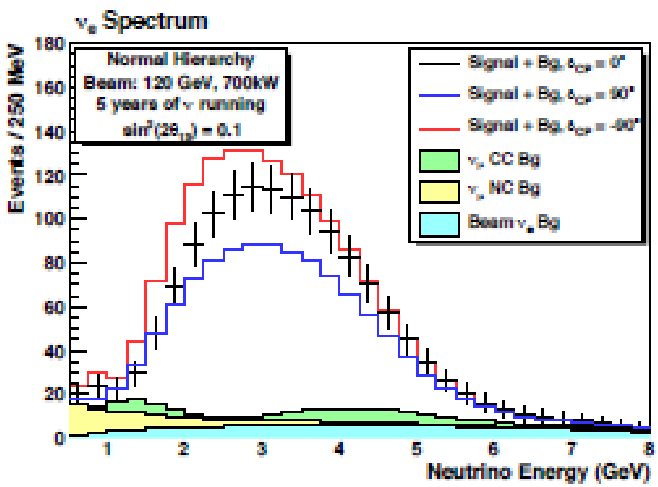
How do we Understand and Model Interactions?

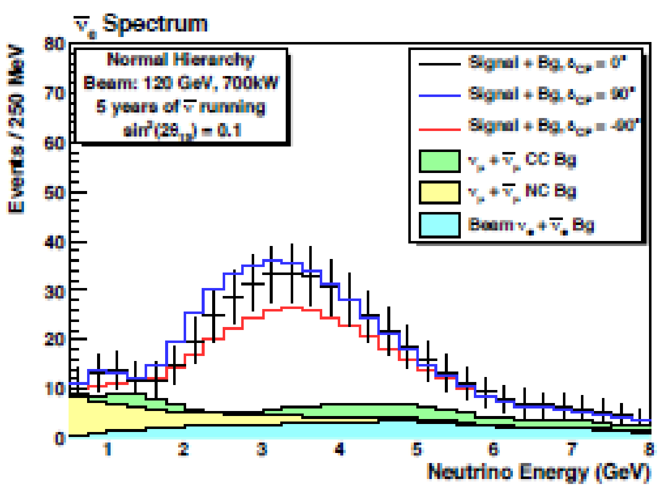




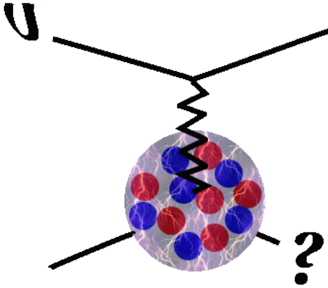
- Iterative process, using data to improve models
- Models are effective theories, ranging from pure parameterizations of data to microphysical models with simplifying assumptions.

Oscillations: Needs (LBNE)



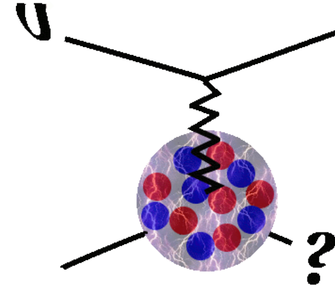


- Maximum CP effect is range of red-blue curve
- Backgrounds are significant, vary with energy and are different between neutrino and anti-neutrino beams
  - Pileup of backgrounds at lower energy makes 2nd maximum only marginally useful in optimized design
- Spectral information plays a role
  - Effect of non-zero δ may change rate, but it may also shift the energy spectrum of the oscillated neutrinos

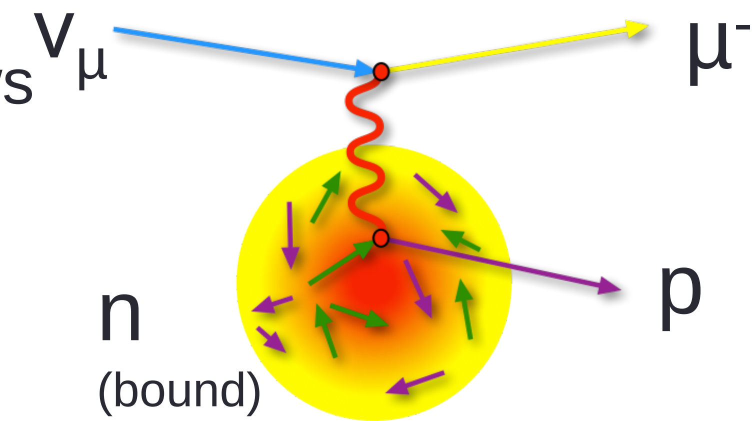


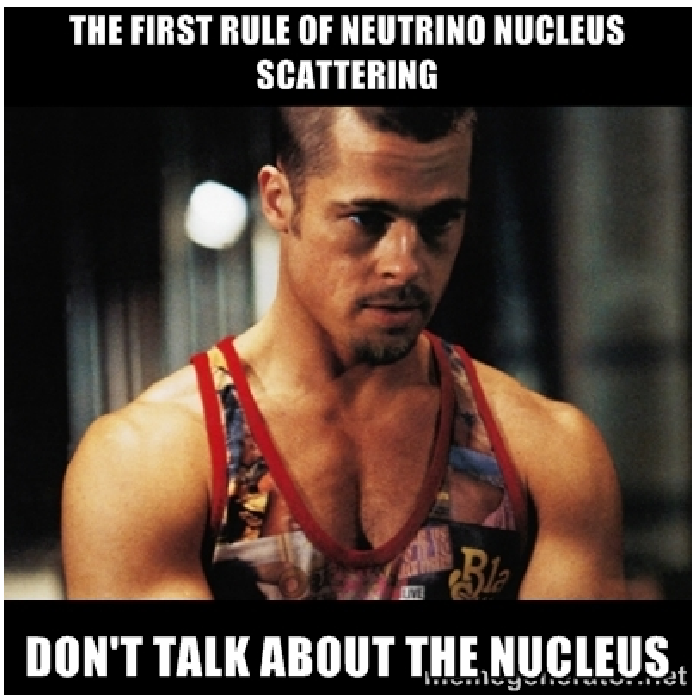
Example:
Quasi-Elastic Energy Reconstruction

Charged Current Quasi-Elastic Scattering



- Quasi-elastic reaction allows neutrino energy to be estimated from only the outgoing lepton:

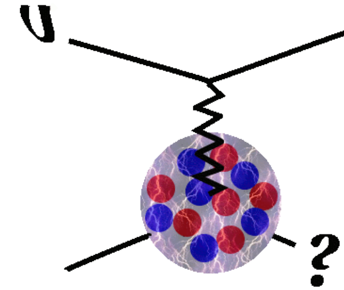




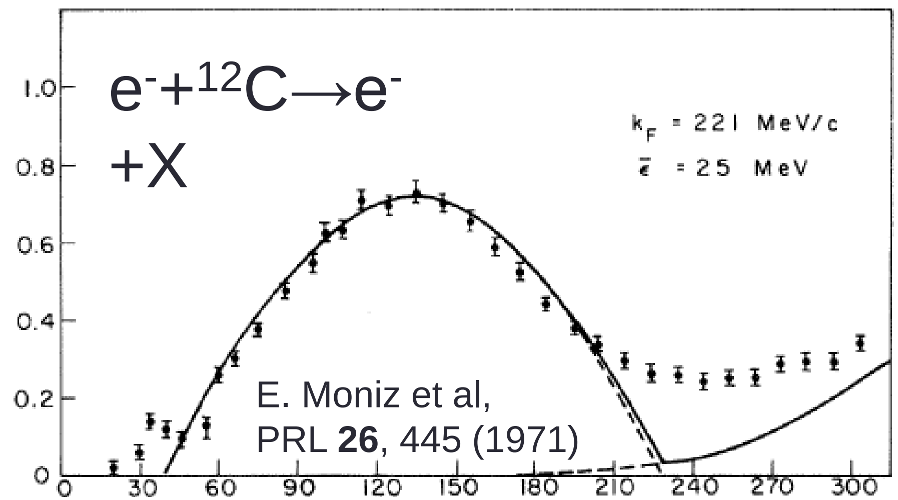
$$E_\nu^{\rm rec} = \frac{2(m_n - V)E_e + m_p^2 - (m_n - V)^2 - m_e^2}{2(m_n - V - E_e + p_e\cos\theta_e)};$$

- This assumes:
  - A single target nucleon, motionless in a potential well (the nucleus)
  - Smearing due to the nucleus is typically built into the cross-section model since it cannot be removed on an event-by-event basis

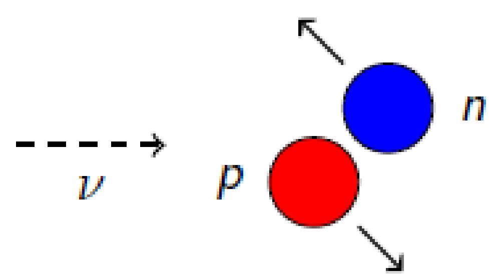
Simple Model of the Nucleon in a Nucleus



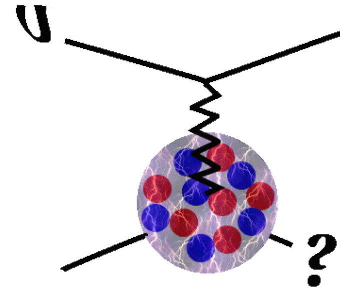
- Our models come from theory tuned to electron scattering
- Generators usually use Fermi Gas model, which takes into account effect of the mean field.
- Corrections to electron data from isospin effects in neutrino scattering.
- Hmmm… between elastic peak and pion production rise looks bad.



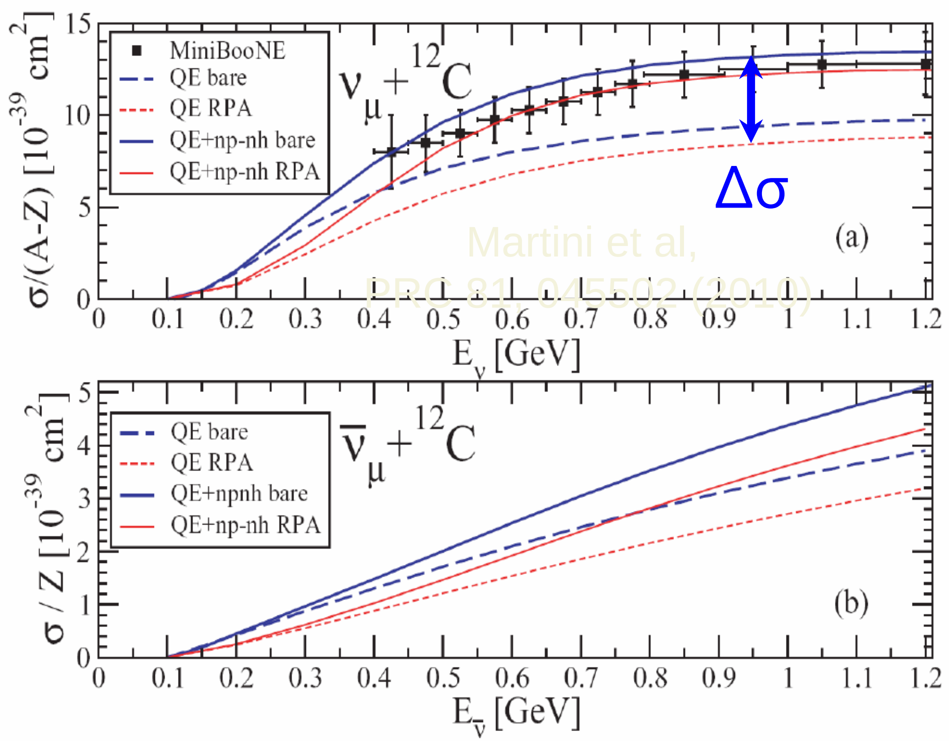
- This approach of quasi-free nucleons in a mean field neglects processes involving closely correlated nucleons



Solution to MiniBooNE CCQE "Puzzle"?



- From the ^{12}C experiment and calculations, expect a cross-section enhancement from correlated process: $\nu_\mu n \rightarrow \mu^- p \quad + \nu_\mu (np)_{corr.} \rightarrow \mu^- pp$

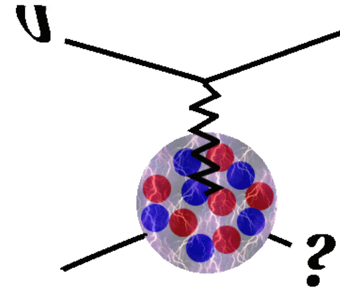


Recent work

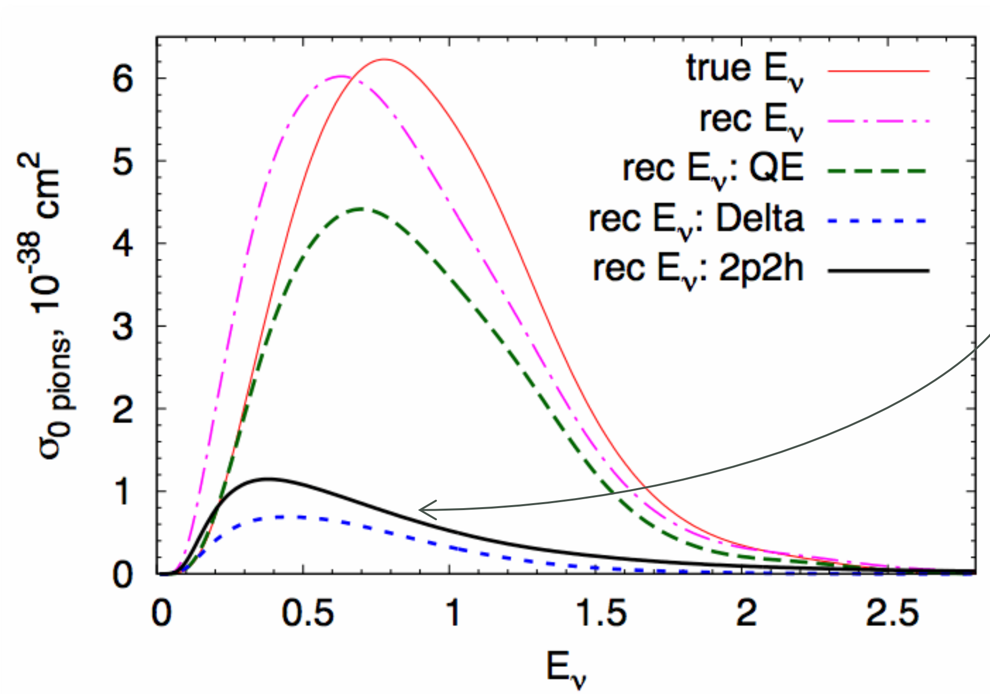
Nieves et al., arXiv:1106.5374 [hep-ph]
Bodek et al., arXiv:1106.0340 [hep-ph]
Amaro, et al., arXiv:1104.5446 [nucl-th]
Antonov, et al., arXiv:1104.0125
Benhar, et al., arXiv:1103.0987 [nucl-th]
Meucci, et al., Phys. Rev. **C83**, 064614 (2011)
Ankowski, et al., Phys. Rev. **C83**, 054616 (2011)
Nieves, et al., Phys. Rev. **C83**, 045501 (2011)
Amaro, et al., arXiv:1012.4265 [hep-ex]
Alvarez-Ruso, arXiv:1012.3871[nucl-th]
Benhar, arXiv:1012.2032 [nucl-th]
Martinez, et al., Phys. Lett **B697**, 477 (2011)
Amaro, et al., Phys. Lett **B696**, 151 (2011)
Martini, et al., Phys. Rev **C81**, 045502 (2010)

[compilation by G.P. Zeller]

Energy Reconstruction: Quasi-Elastic



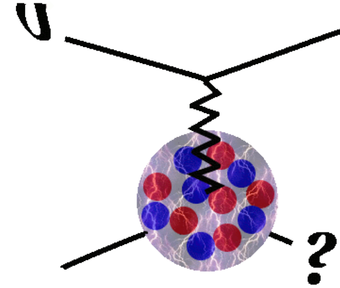
- Does it quantitatively matter if we model this effectively (e.g., alter nucleon form factors) or microphysically?
- Inferred neutrino energy changes if target is multinucleon.



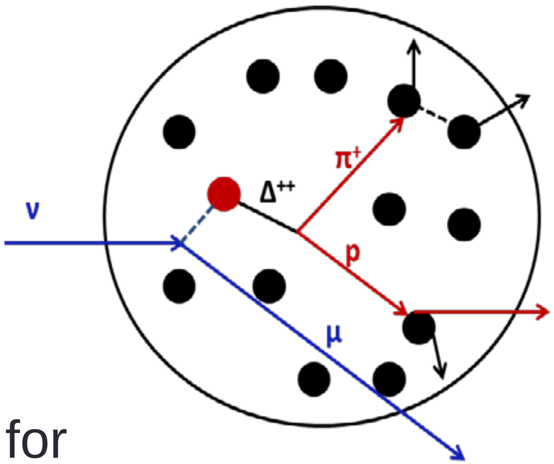
Effect at MiniBooNE calculated by Lalakulich, Gallmeister, Mosel,1203.2935

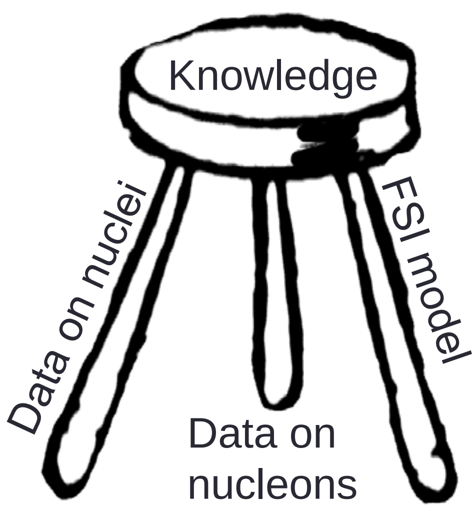
ex: Mosel/Lalakulich 1204.2269, Martini *et al*. 1202.4745, Lalakulich *et al.* 1203.2935, Leitner/Mosel PRC81, 064614 (2010)

Another Energy Reconstruction Problem

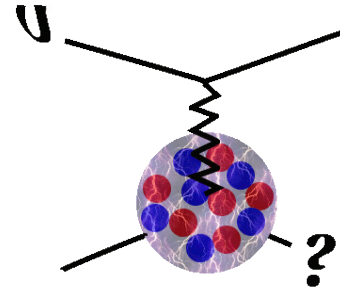


- In inelastic events the hadronic final state can in principle aid neutrino energy reconstruction
- But produced hadrons inside the nuclear targets interact as they exit
- This typically increases multiplicity of low energy nucleons
  - Detector response is unlikely to be uniform for charged and neutral pions, protons and neutrons
- Modeling this is non-trivial and verifying the knowledge is even more difficult
  - In part because we lack good data on free nucleons as a benchmark
  - Comparing different nuclei may be helpful





The MINERvA Experiment

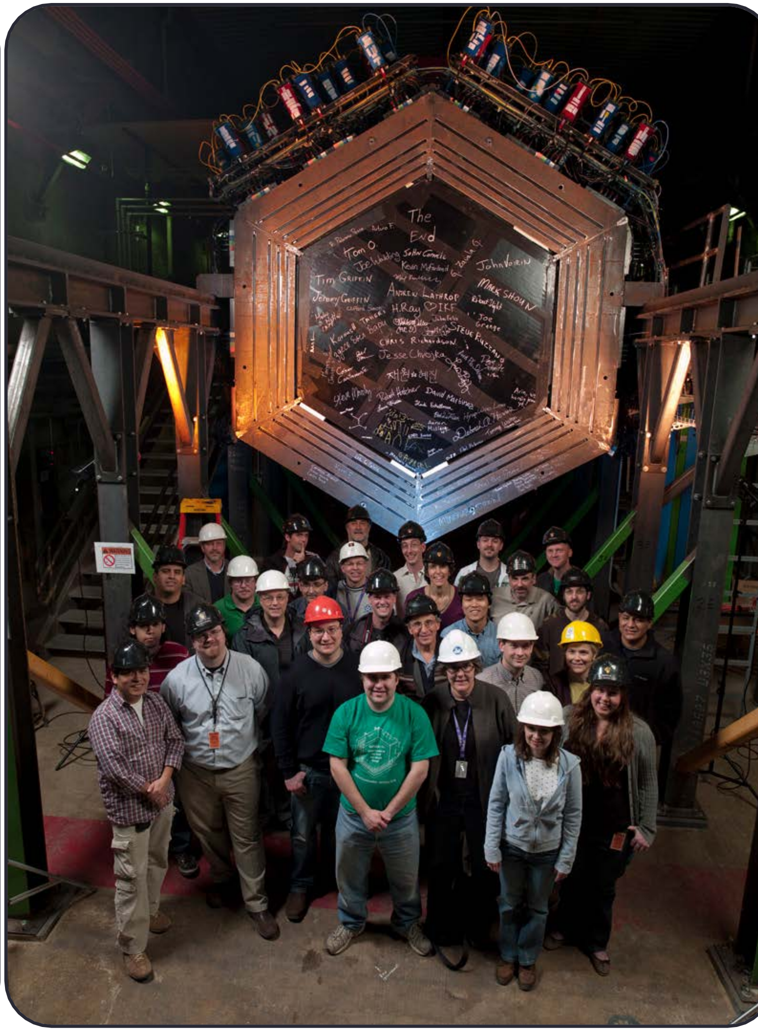


MINERvA Collaboration

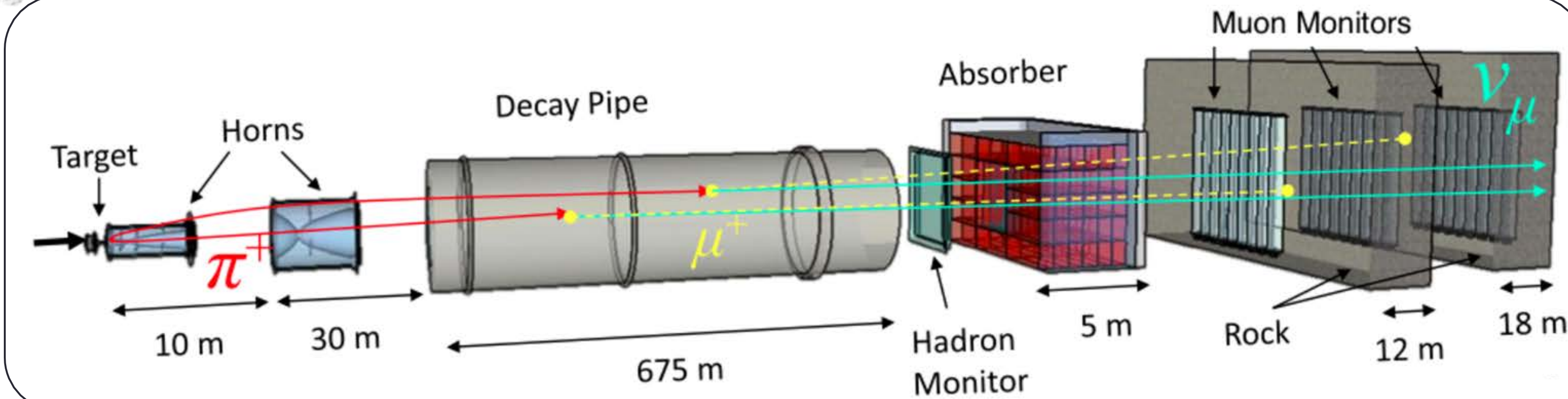
~80 collaborators from particle and nuclear physics

University of Athens
University of Texas at Austin
Centro Brasileiro de Pesquisas Físicas
Fermilab
University of Florida
Université de Genève
Universidad de Guanajuato
Hampton University
Inst. Nucl. Reas. Moscow
Mass. Col. Lib. Arts
Northwestern University
University of Chicago

Otterbein University
Pontificia Universidad Catolica del Peru
University of Pittsburgh
University of Rochester
Rutgers University
Tufts University
University of California at Irvine
University of Minnesota at Duluth
Universidad Nacional de Ingeniería
Universidad Técnica Federico Santa María
College of William and Mary

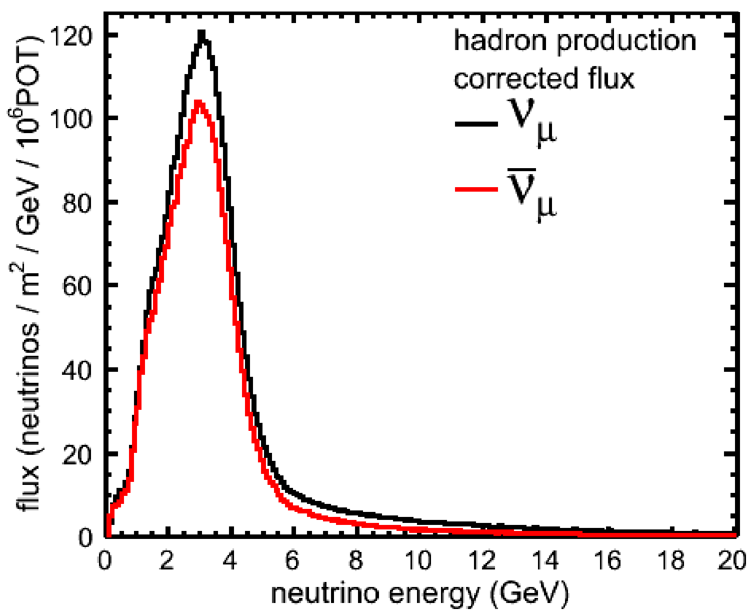


The NuMI Beam

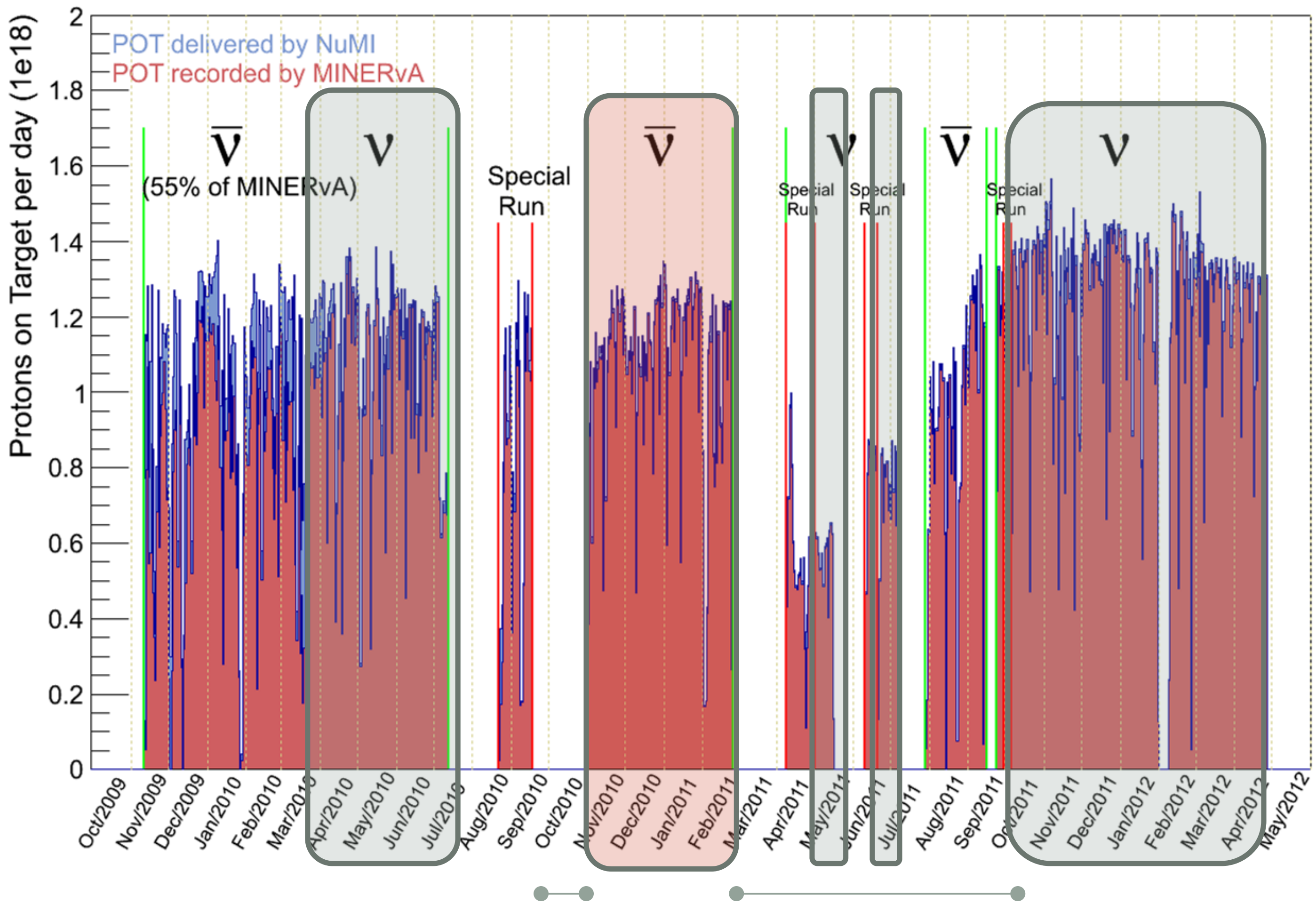


- NuMI is a "conventional" neutrino beam, with most neutrinos produced from focused pions
- Implies significant uncertainties in flux from hadron production and focusing
- Constrain, where possible, with hadron production data

NuMI Low Energy Beam Flux



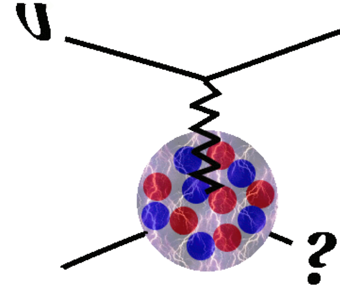
Datasets

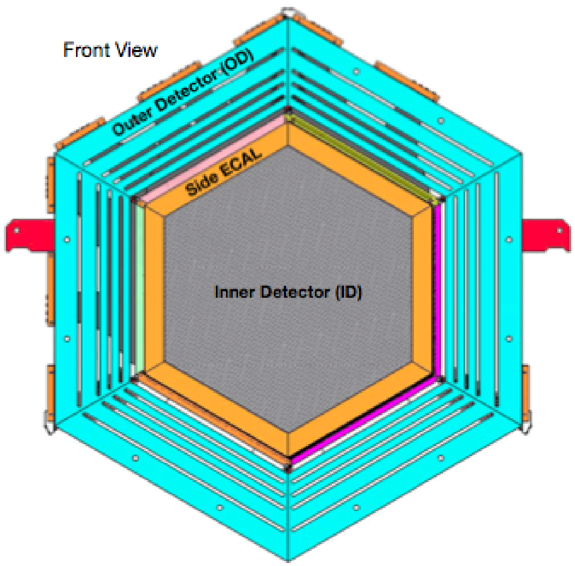


target troubles: running with damaged targets

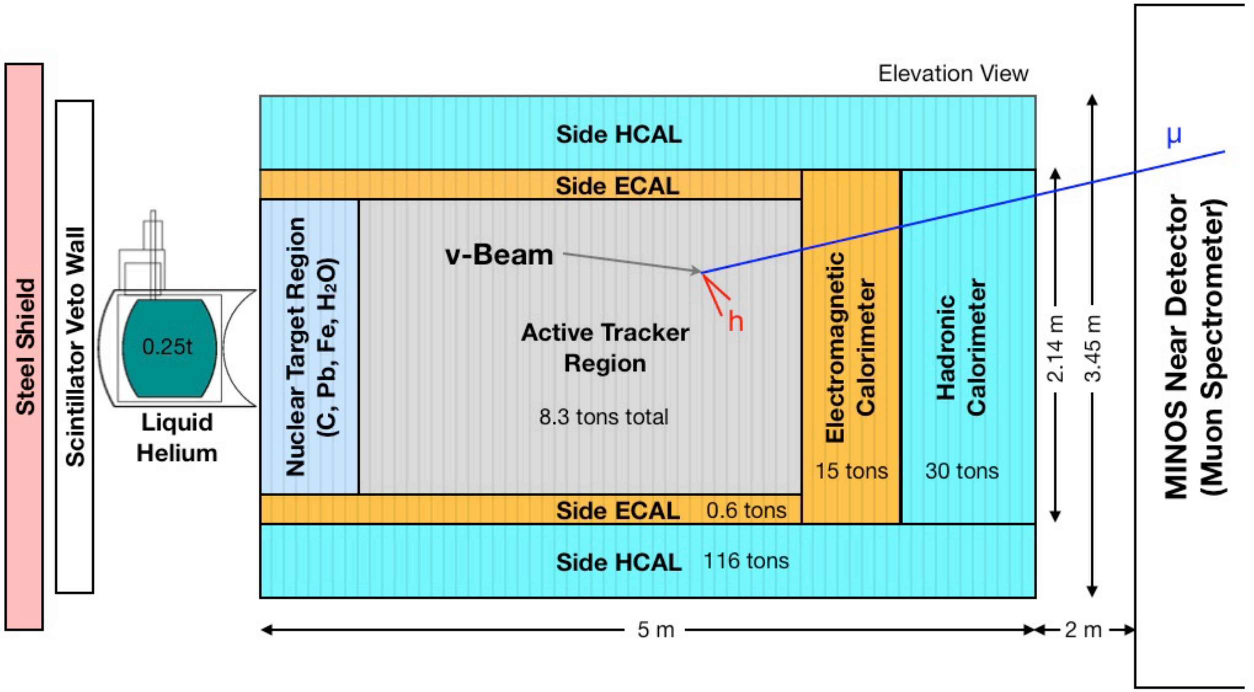
protons on target (POT) to MINERvA
neutrino (LE): 3.9E20 POT
anti-neutrino (LE): 1.0E20 POT

Detector





3 orientations
0°, +60°, −60°

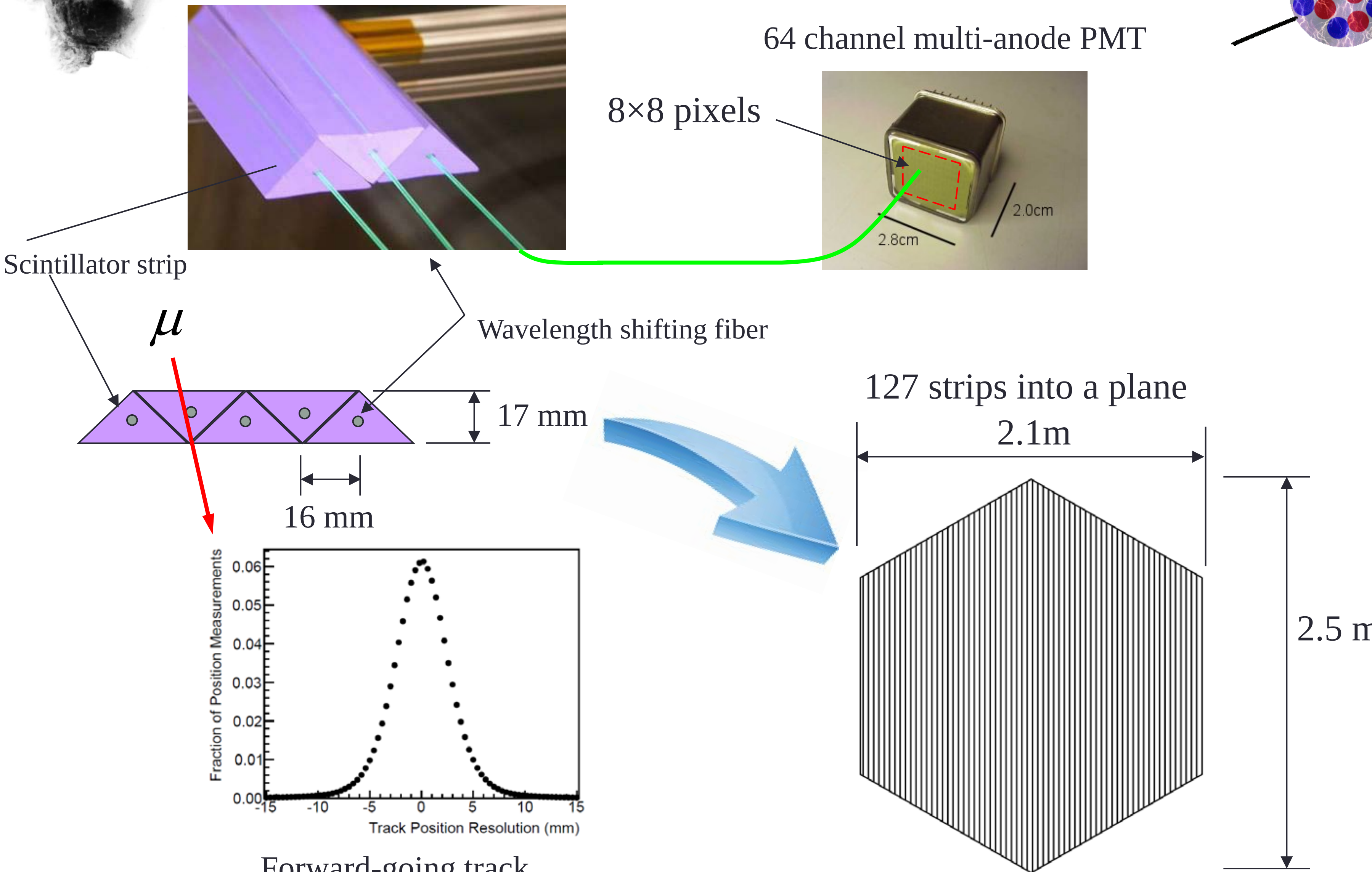


Detector comprised of **120 “modules”** stacked along the beam direction

Central region is **finely segmented scintillator tracker**

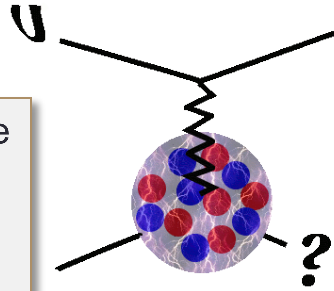
~32k plastic scintillator strip channels total

Detector Technology



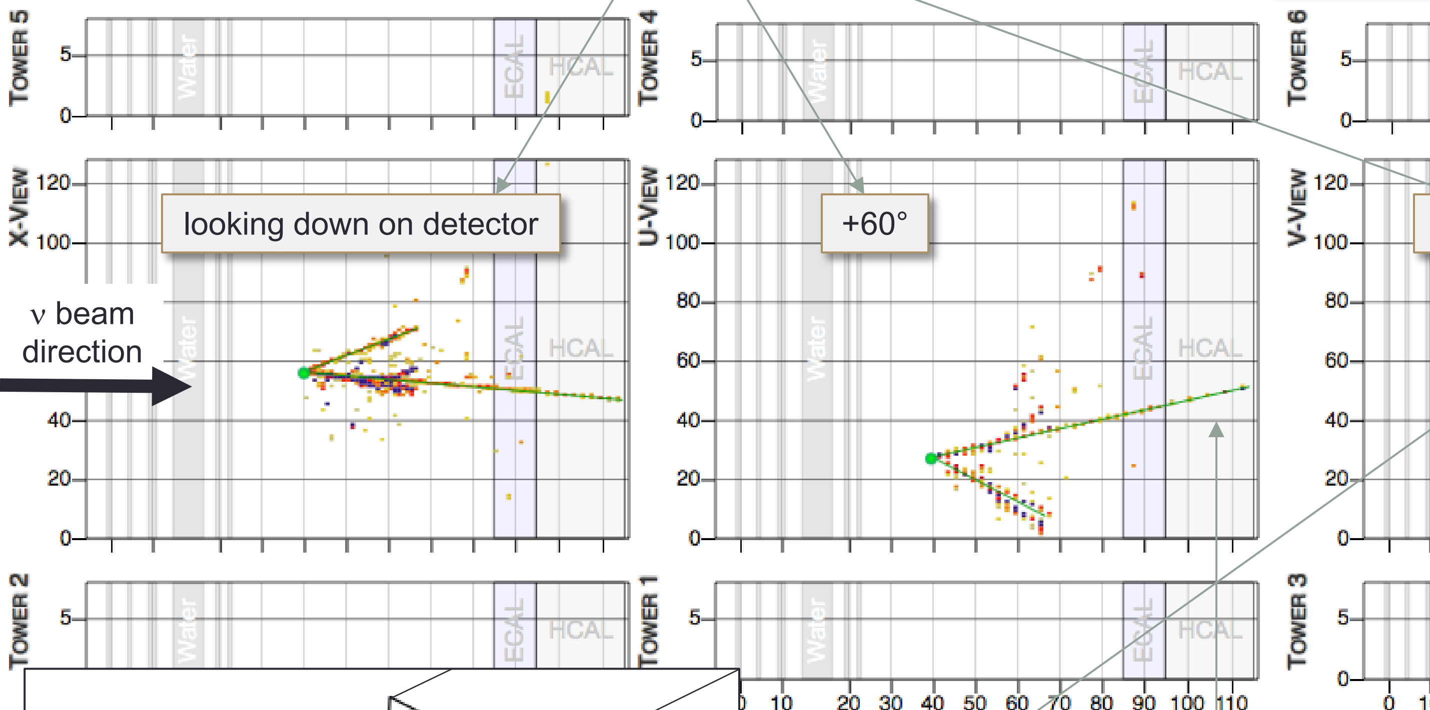
Forward-going track position resolution: ~3mm

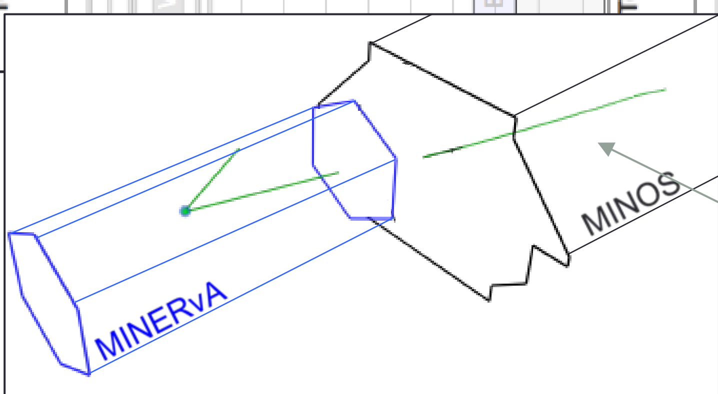
Events in MINERvA



3 stereo views, X—U —V , shown separately

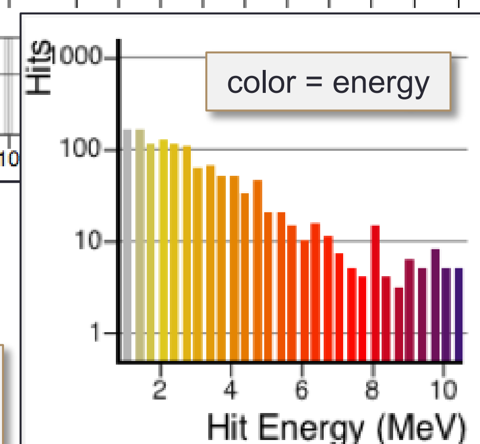
Particle leaves the inner detector, stops in outer iron calorimeter



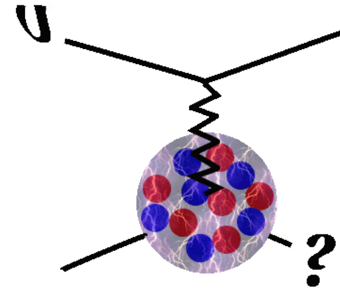


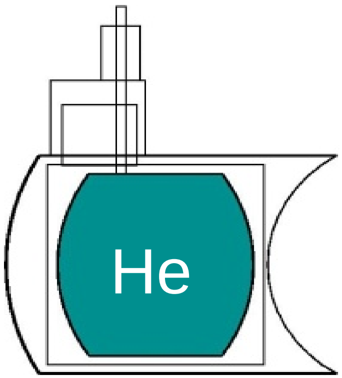
Stops in Scintillator, best hadron particle ID

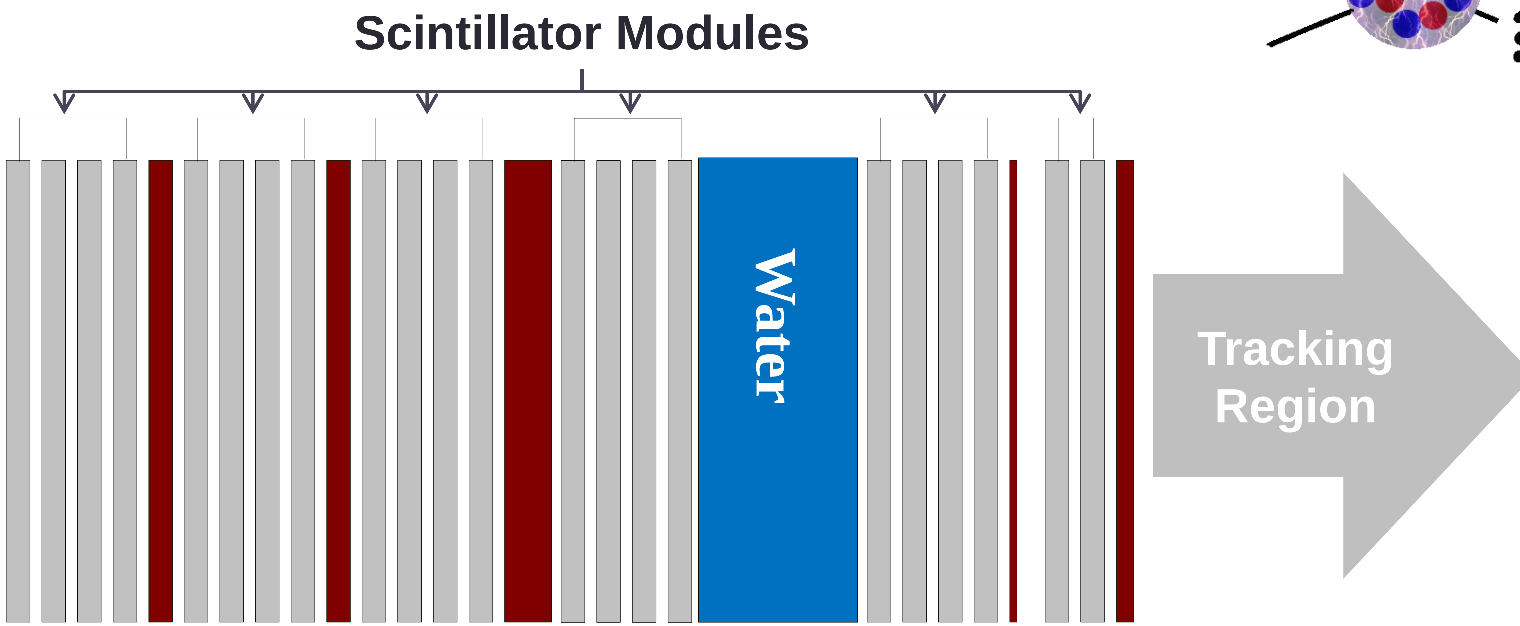
Muon leaves the back of the detector headed toward MINOS



Passive Nuclear Targets





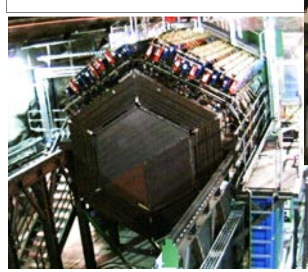


250 kg
Liquid He

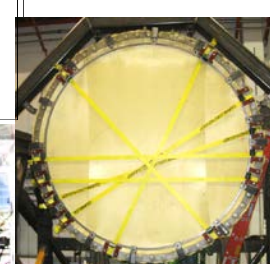
1" Fe / 1" Pb
323kg / 264kg

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

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



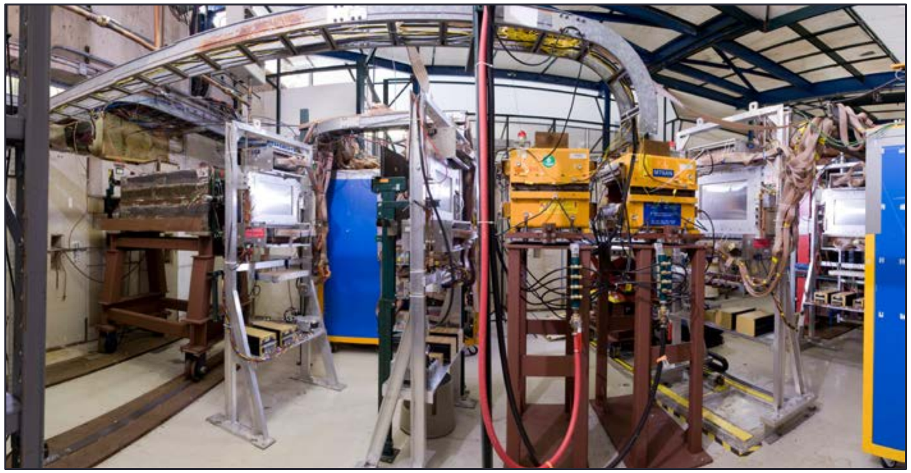
6" 500kg Water

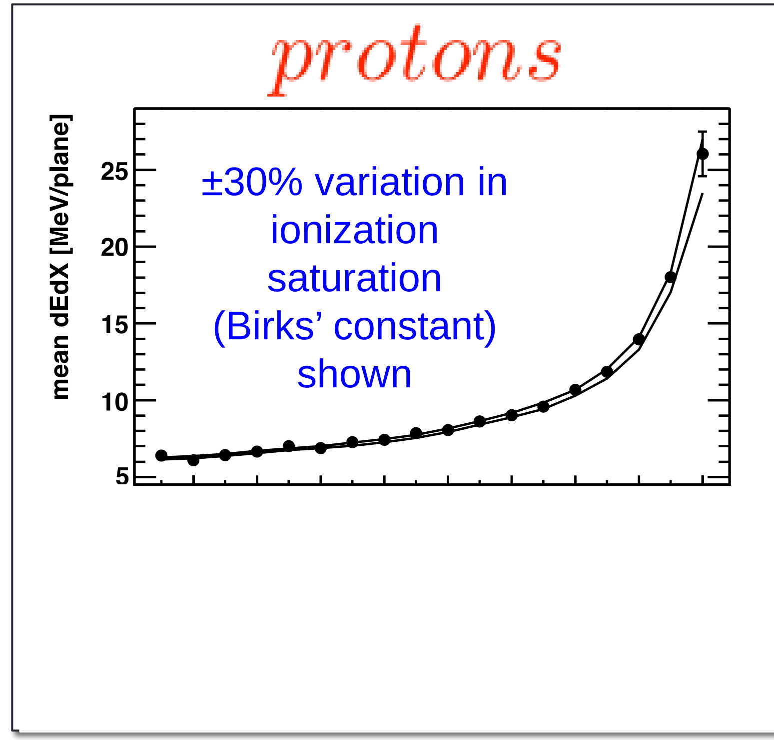


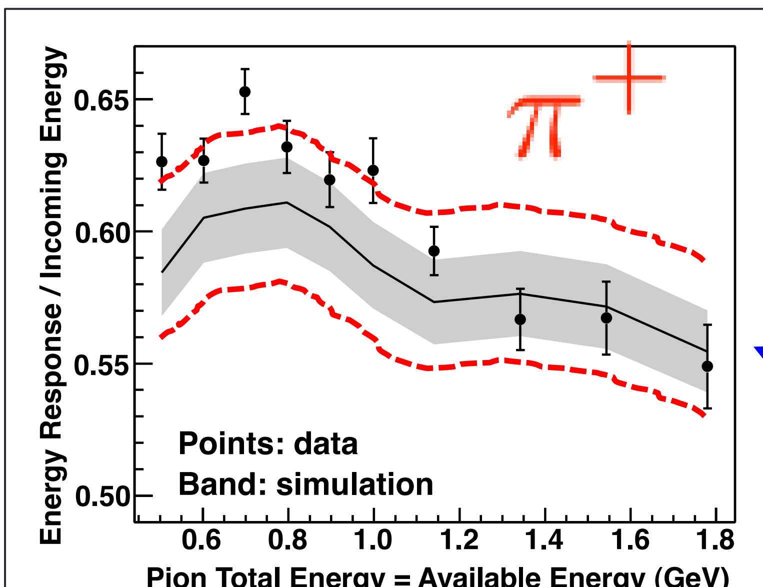
0.3" Pb
228kg

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

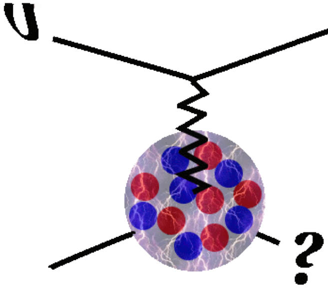
Hadron Testbeam





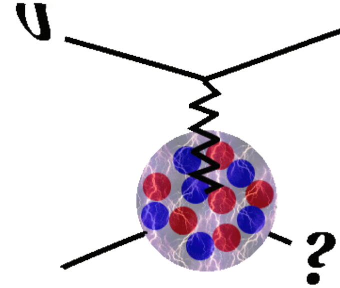


high-energy charged pion response uncertainty ≈ 5% (before tuning hadron interactions in detector)

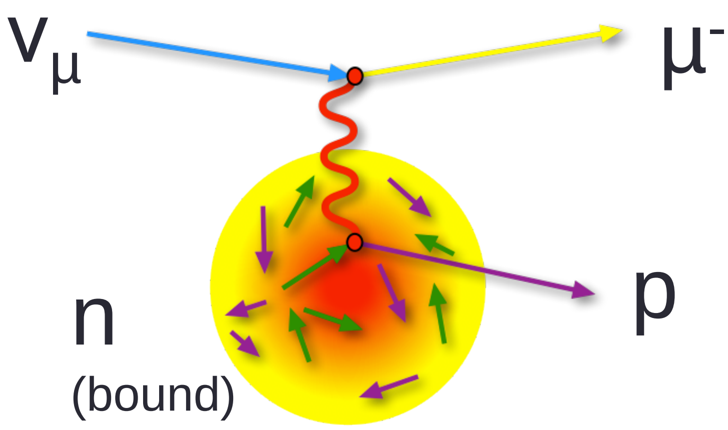


Quasi-Elastic Scattering

Identifying Quasi-Elastic Scattering



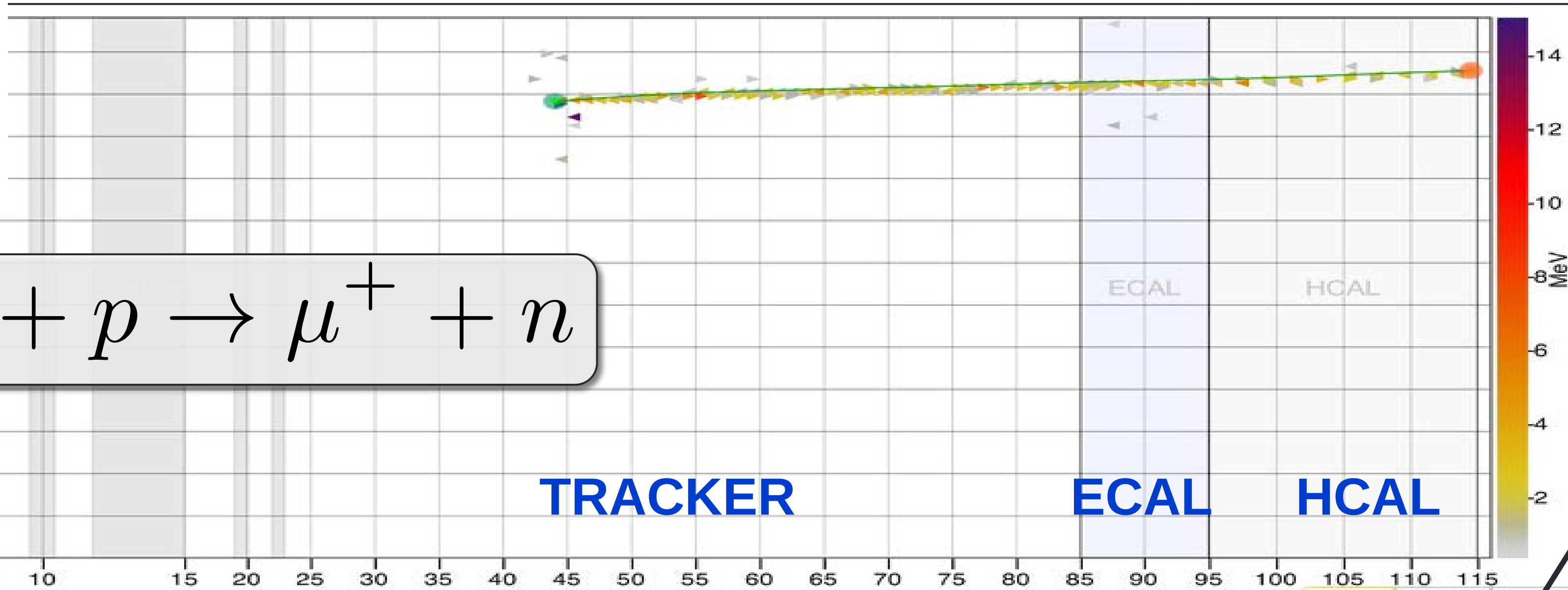
- Signature of quasi-elastic scattering is production of no mesons, photons or heavy baryons
- Breakup of nucleus or hadron reinteraction may produce additional protons and neutrinos in final state. Allow those as signal.



- Veto events with energy from pions (leading background)
- Today's "1-track" analysis identifies these calorimetrically as energy distant from vertex
- Other strategies (identification of recoil proton, adding a veto on Michel electrons from π^+) are also in progress

ν Beam

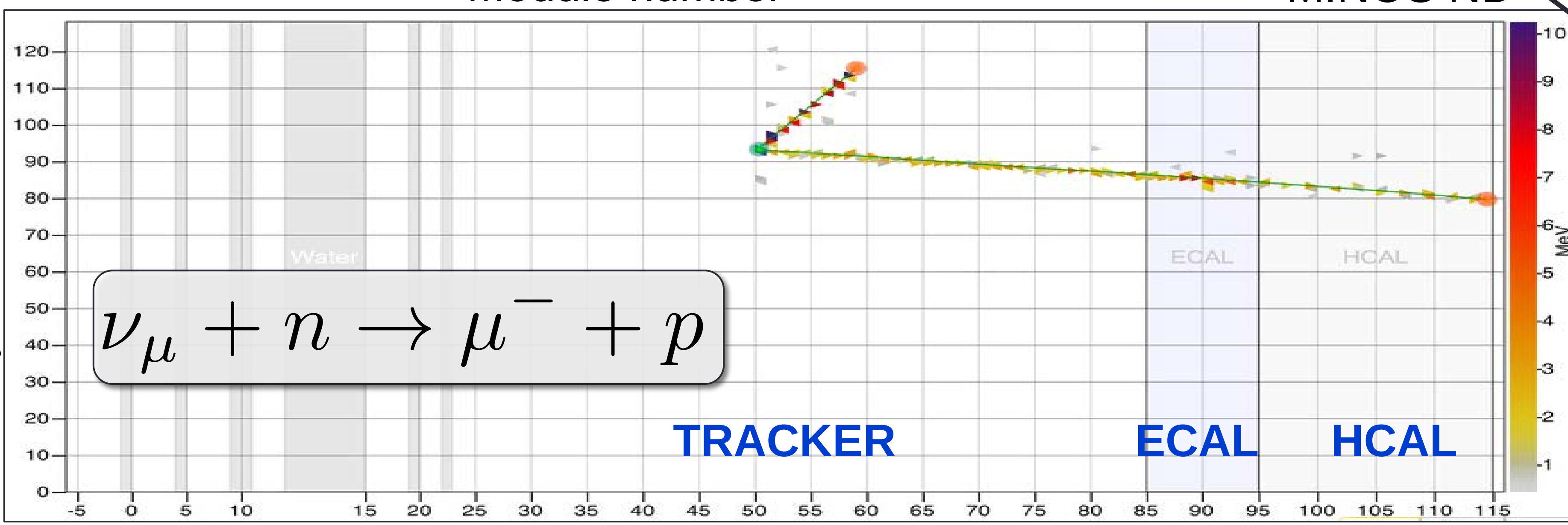
MeV



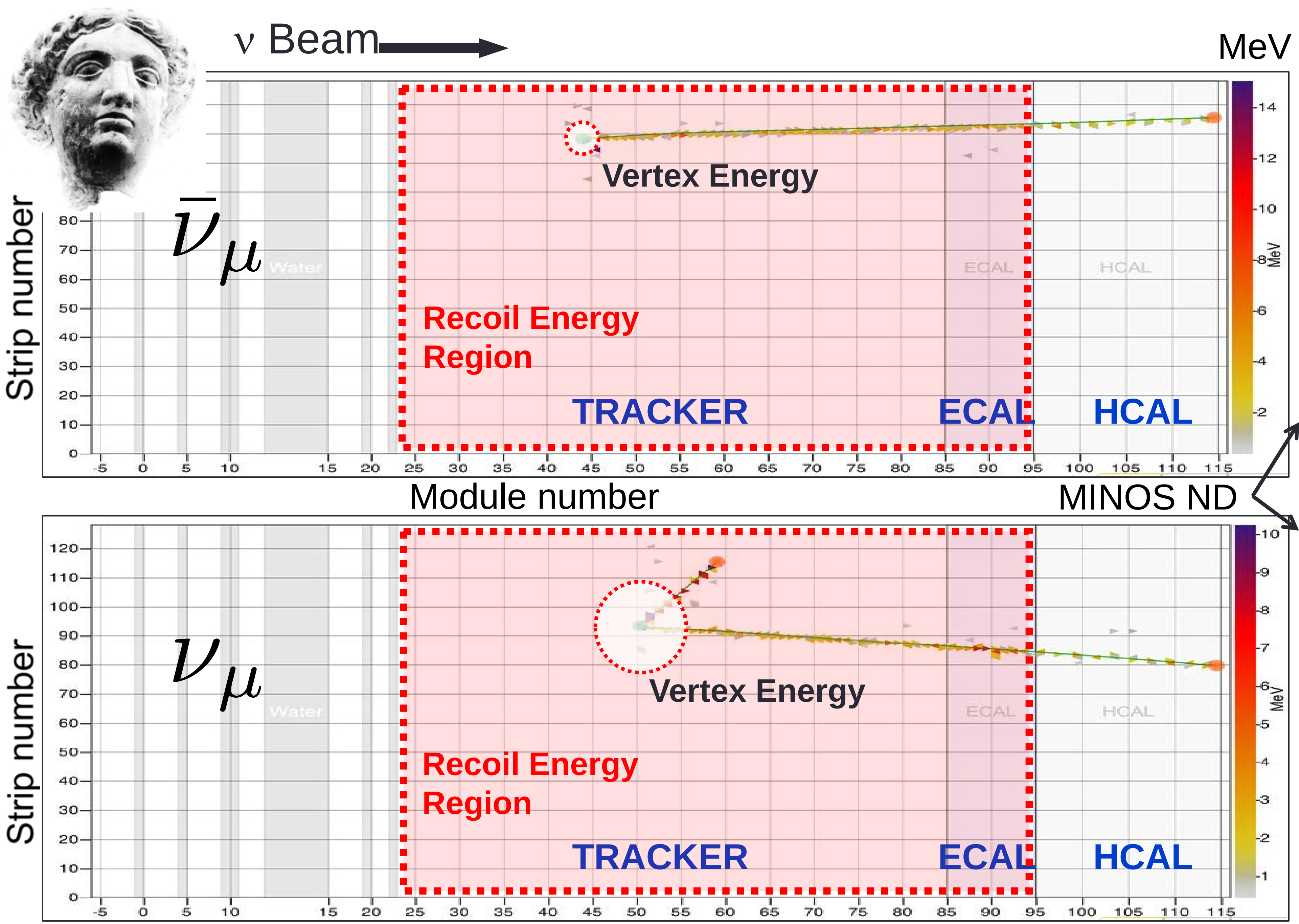
$$\bar{\nu}_\mu + p \rightarrow \mu^+ + n$$

Module number

MINOS ND

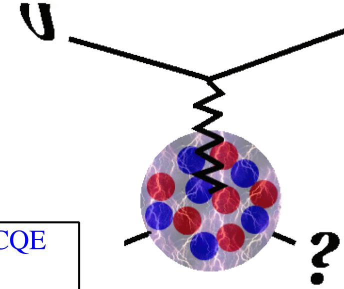


$$\nu_\mu + n \rightarrow \mu^- + p$$



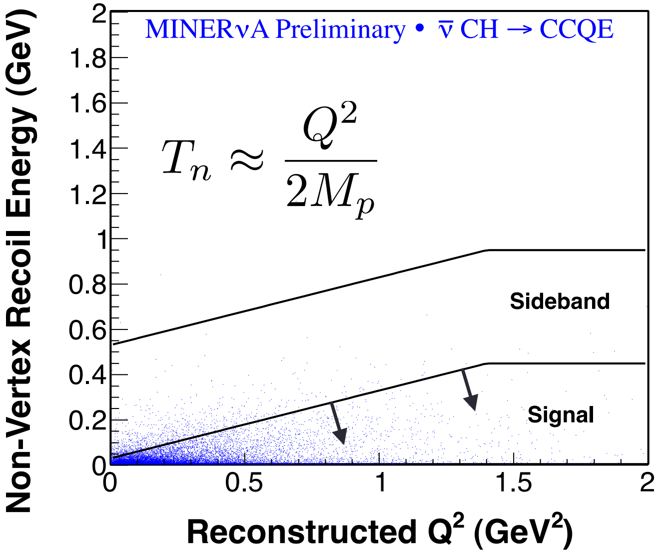
ν Beam
MeV
$\bar{\nu}_\mu$
Vertex Energy
Recoil Energy Region
TRACKER
ECAL
HCAL
Strip number
Module number
MINOS ND
ν_μ
Vertex Energy
Recoil Energy Region
TRACKER
ECAL
HCAL
Strip number

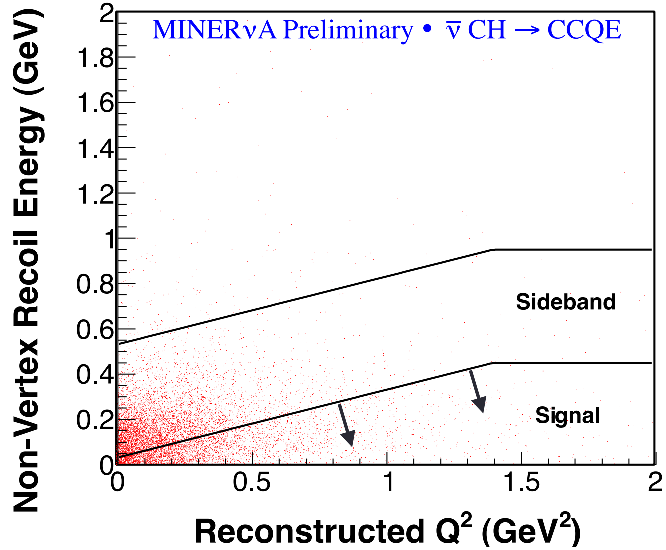
Recoil Energy Distributions



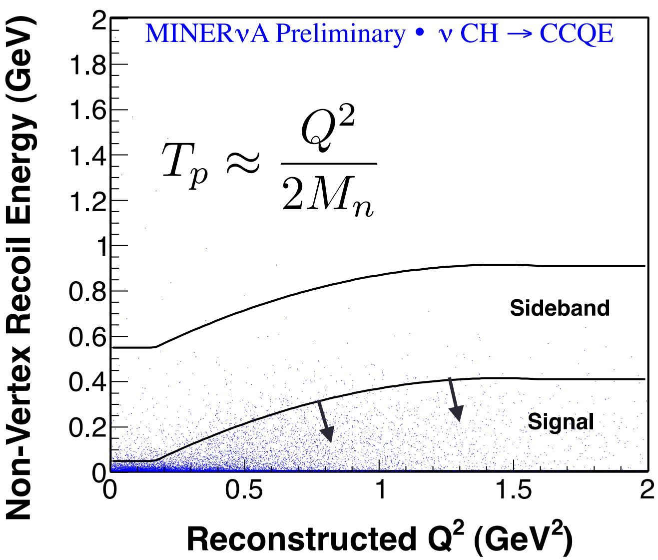
$\bar{\nu}_\mu$

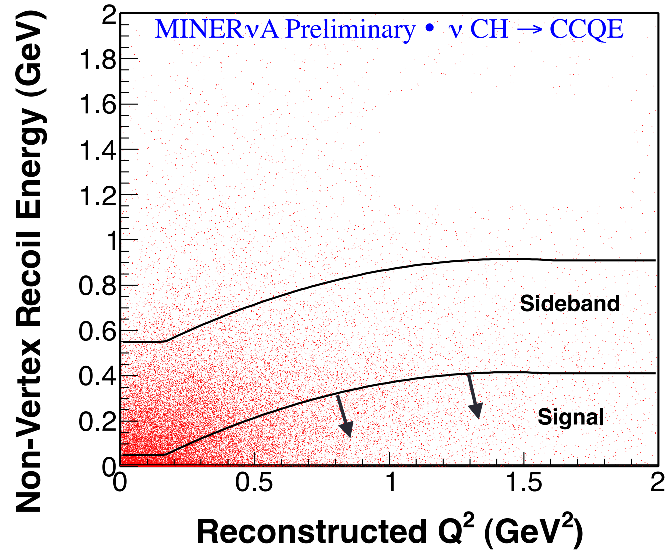
QE





ν_μ

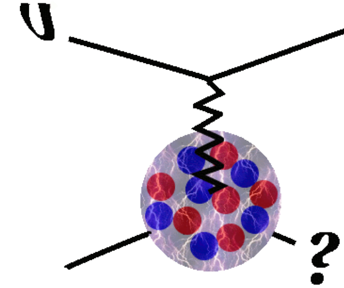




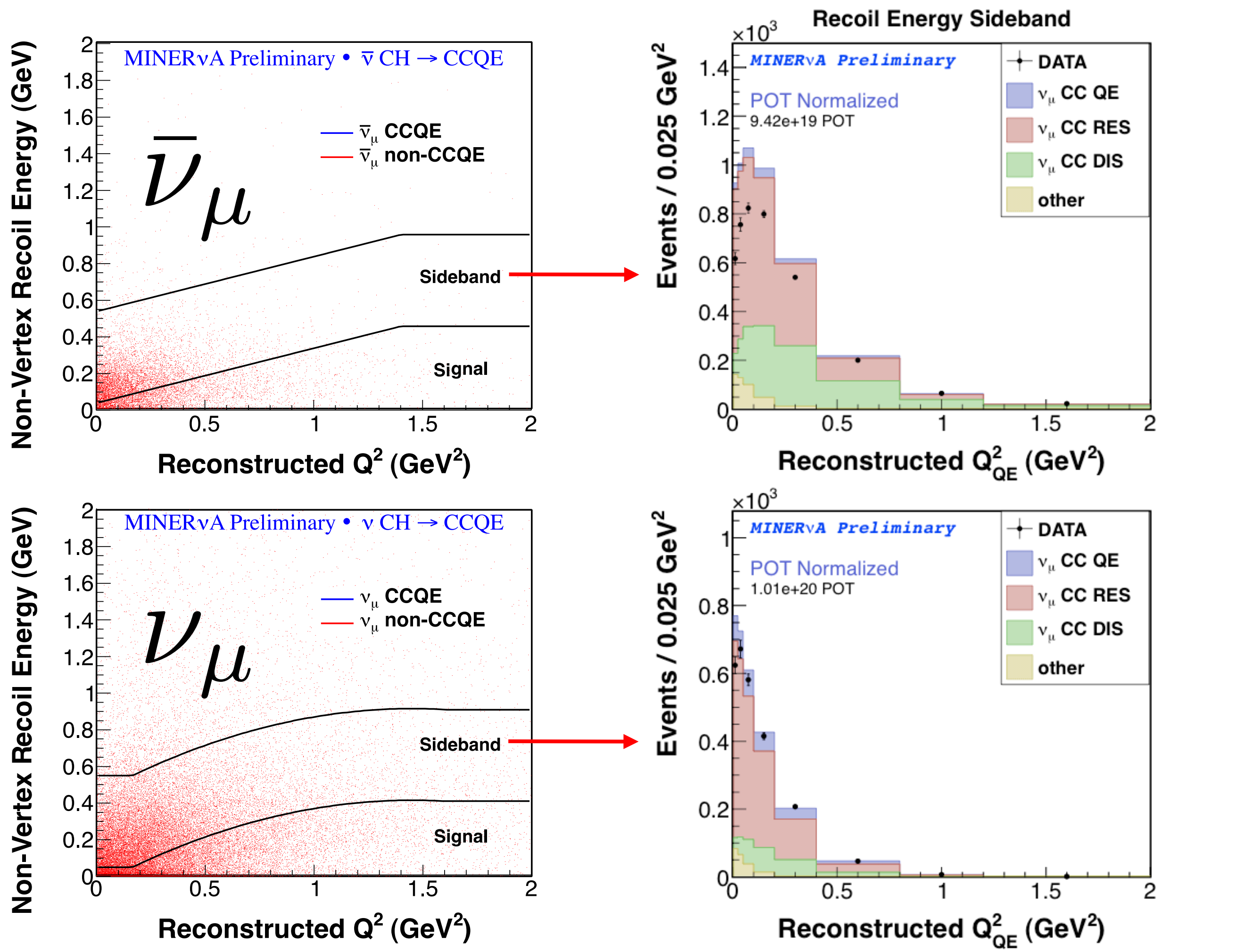
Estimate of 4-momentum transfered to nucleon

$$Q^2_{QE} = -m_\mu^2 + 2E_\nu^{QE}\left(E_\mu - \sqrt{E_\mu^2 - m_\mu^2}\cos\theta_\mu\right)$$

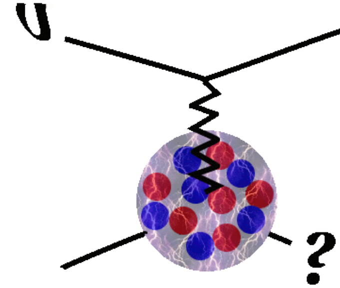
Constraint on Background

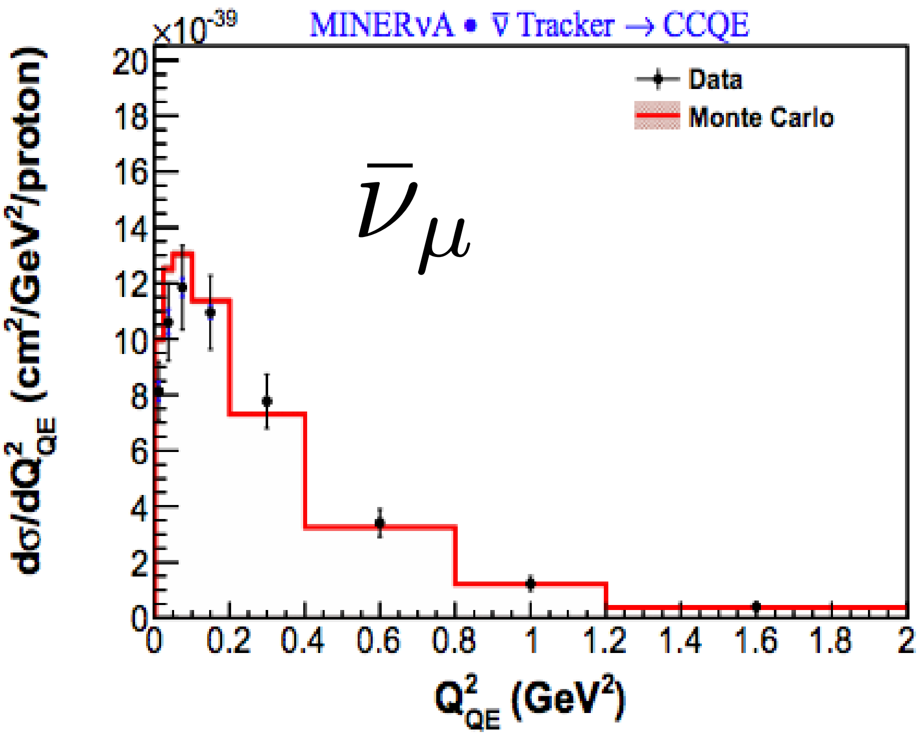


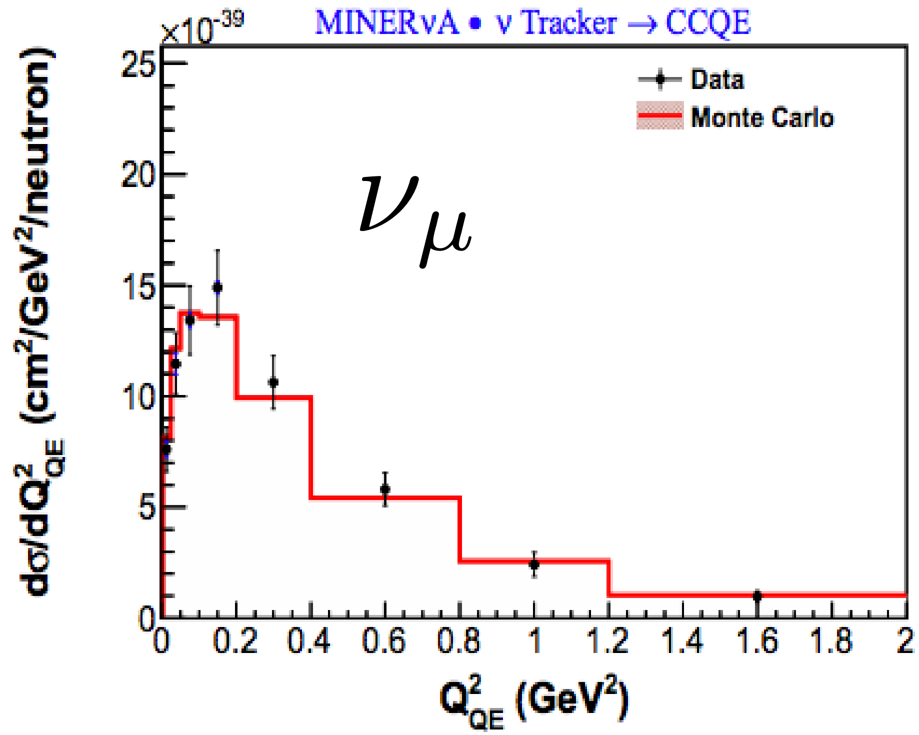
- Large uncertainties on background cross-section models
- Complicated by reinteraction inside nucleus "Final State Interactions" (FSI)
- Use high recoil events to study



Differential Cross-Sections

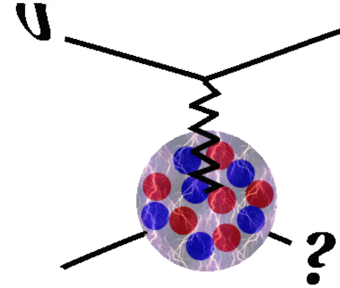




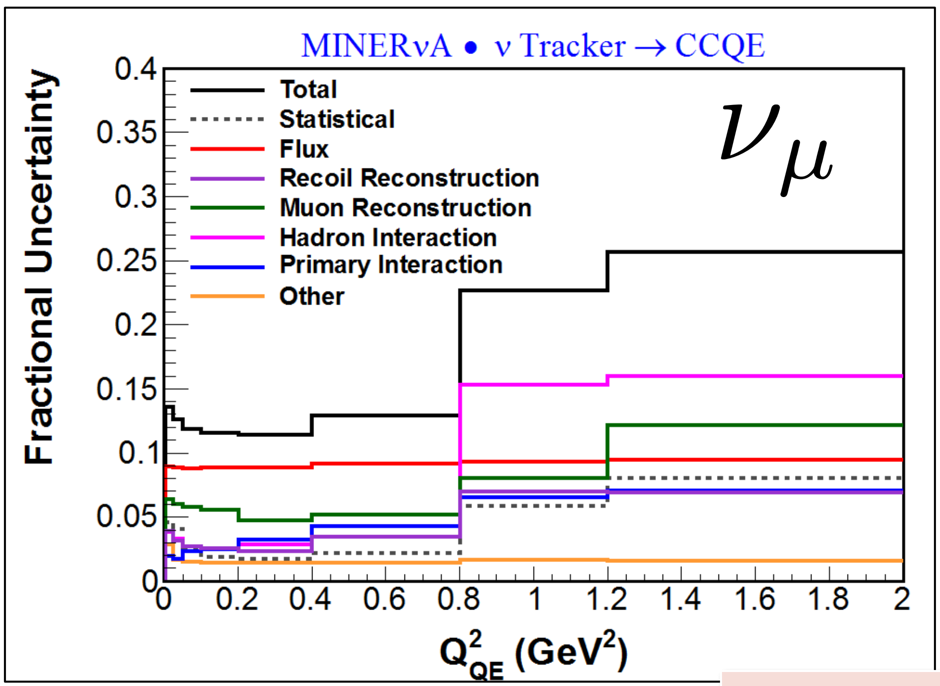


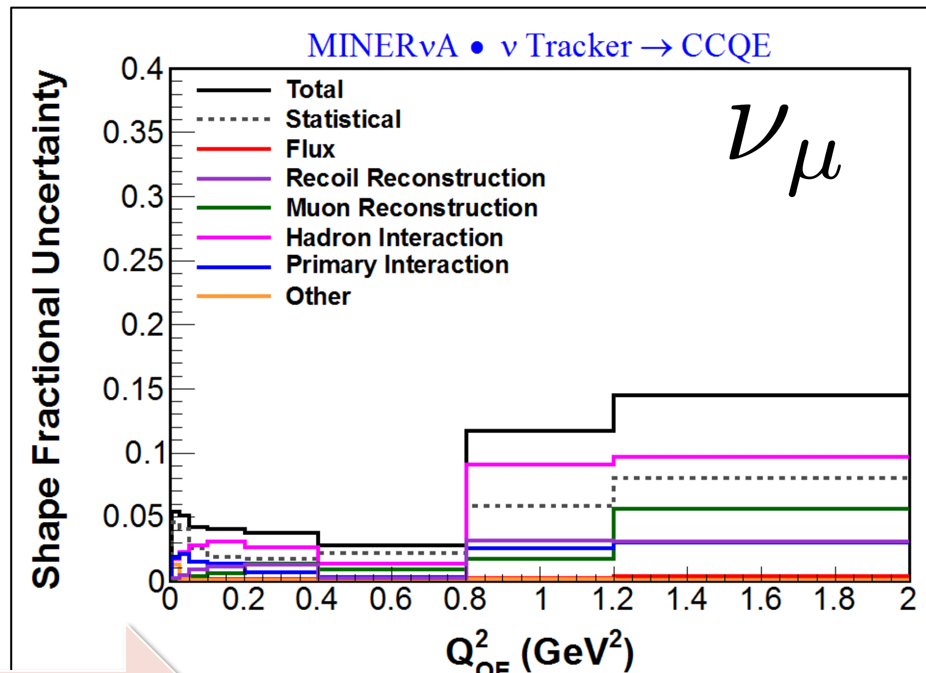
- MINERvA's best sensitivity to multi-nucleon effects:
  1. The shape of the $d\sigma/dQ^2$ differential cross-section
  2. The amount of energy near the vertex

dσ/dQ² Shape



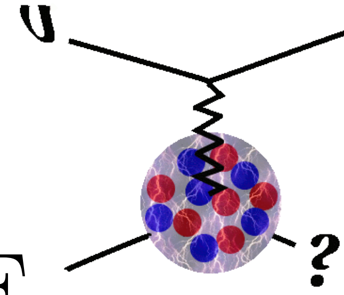
- Measuring the ***shape*** of the cross-section greatly reduces the impact of several mostly normalization errors, including knowledge of the neutrino fluxes



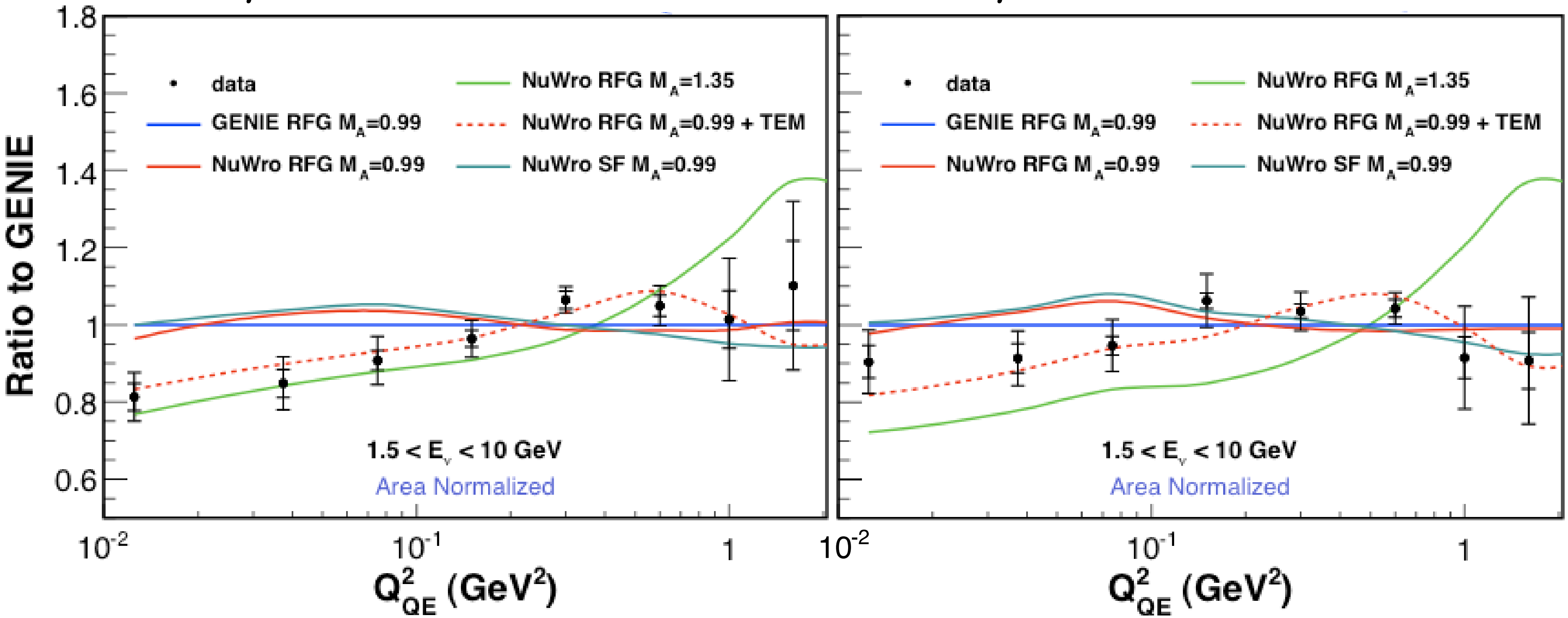


Shape only

dσ/dQ² Shape

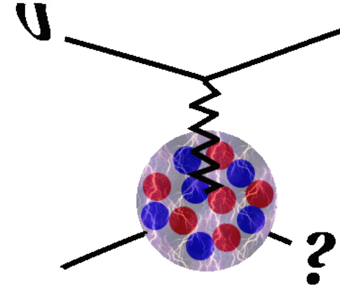


$\bar{\nu}_\mu$ CCQE $\qquad$ ν_μ CCQE



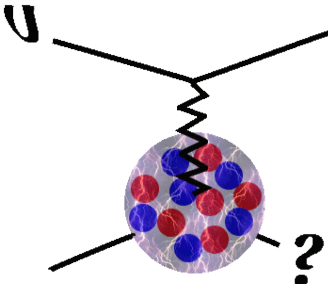
- Model used by MiniBooNE in oscillation analysis is the green line (enhance "effective" axial form factor at high Q^2)
- Best fit prefers data-drive multi-nucleon model

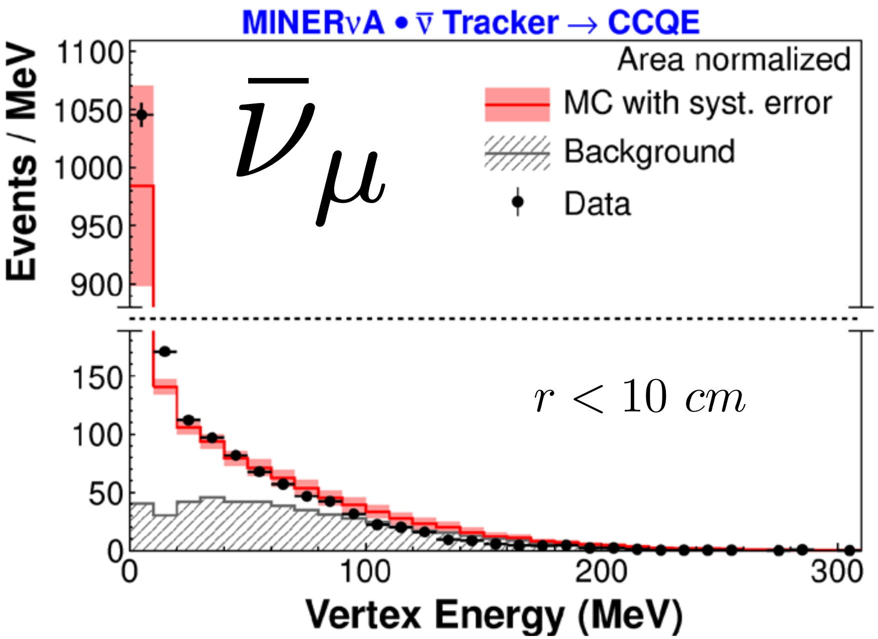
Vertex Energy

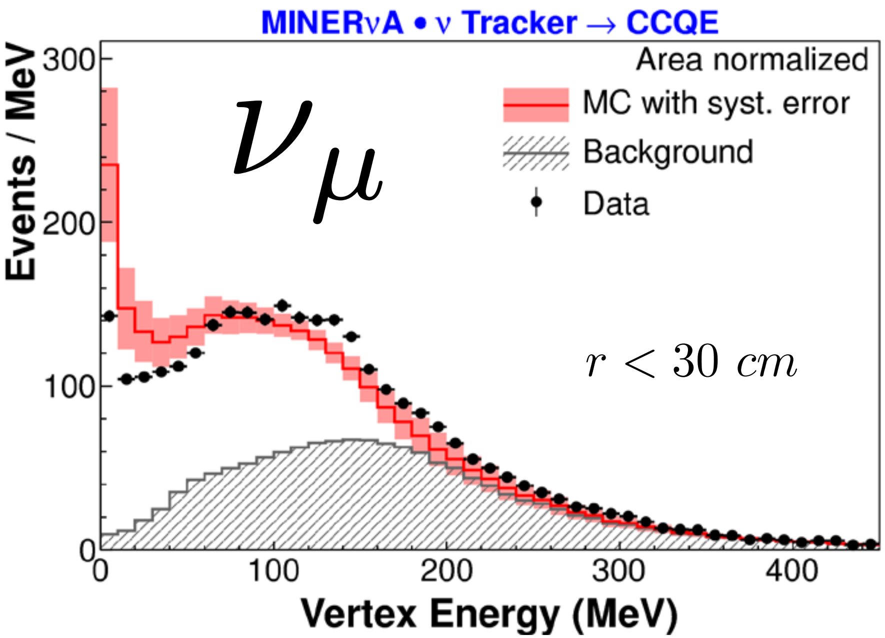


- Microscopic models of multi-nucleon (np-nh) contributions are not presently available in event generators at NuMI energies
- No prediction for the hadron kinematics in these classes of events
- In general, ***multi-nucleon emission is expected in interactions with correlated nucleons***, so this provides another possible signature
  - Additional nucleons beyond the expected leading neutron (antineutrino) or proton (neutrino) and nucleons knocked out from nuclear rescattering (FSI)
- So, we ***look very near the interaction vertex*** in neutrino and antineutrino events for ***excess energy*** coming from charged nucleons (protons)
  - Recall, we purposefully avoided this region when selecting QE candidates
    - Because we did not want our QE event selection biased by the MC not having these multi-nucleon events; now we look in the ignored region
  - Final State Interaction (FSI) uncertainties are very important in this analysis

Vertex Energy

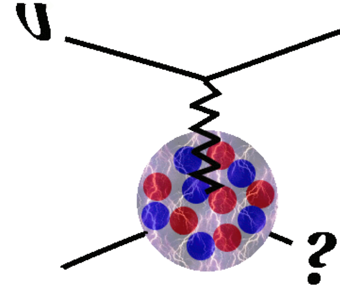




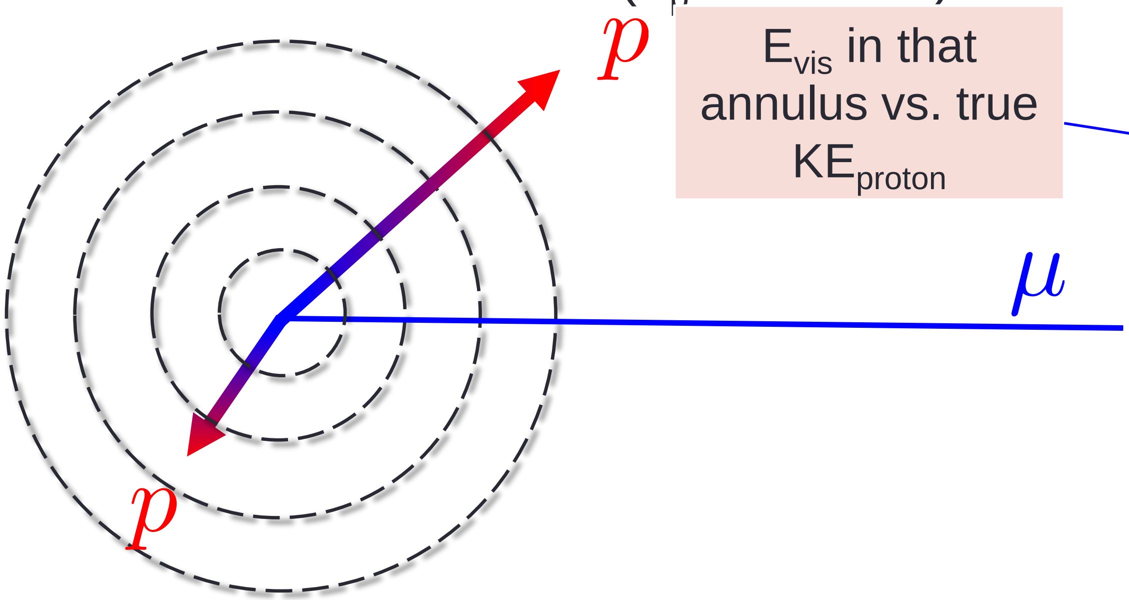


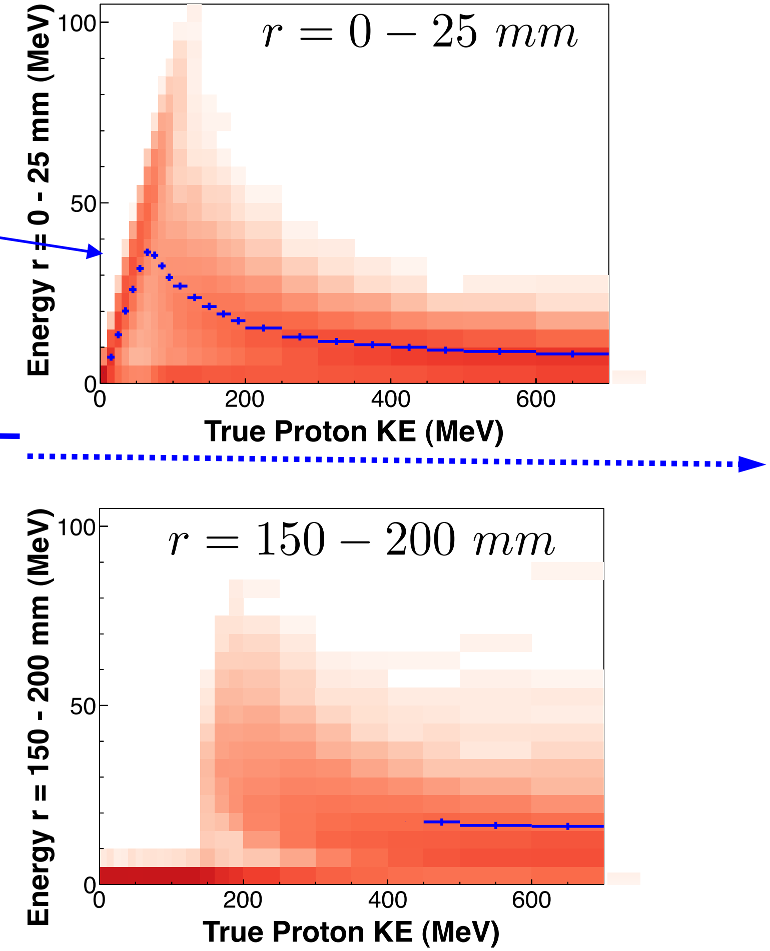
- A harder spectrum of vertex energy is observed in neutrinos
- All systematics considered, including energy scale errors on charged hadrons and FSI model uncertainties
- At this point, we make the ***working assumption*** that the additional vertex energy per event in data is ***due to protons***

Vertex Energy



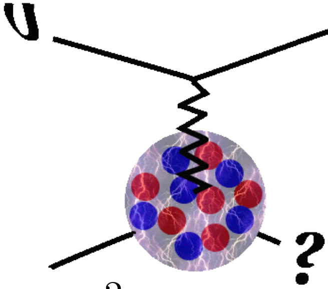
- Examine annular rings around the reconstructed vertex
  - To 10 cm for antineutrino (T_p~120 MeV)
  - To 30 cm for neutrino (T_p~225 MeV)

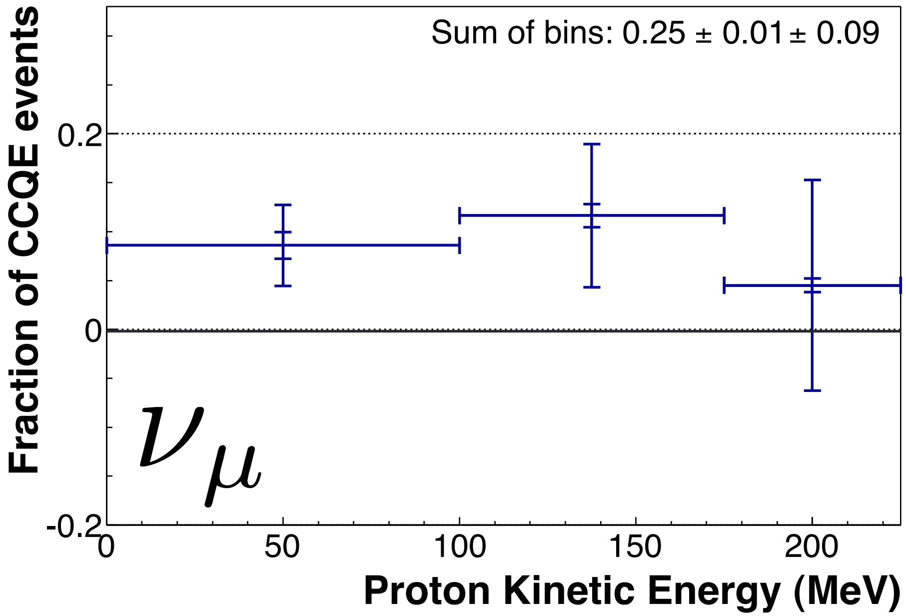


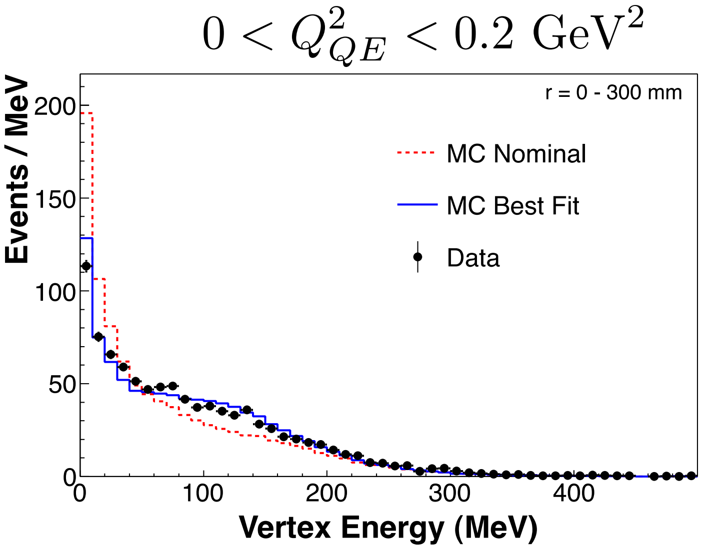


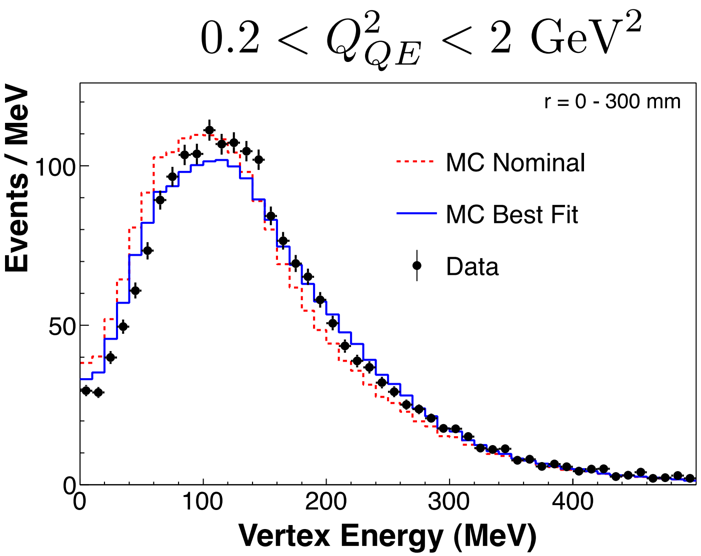
Note: to add visible energy to an inner annulus you must ***add a charged hadron***, not just increase energy of an existing one

Vertex Energy - Neutrinos



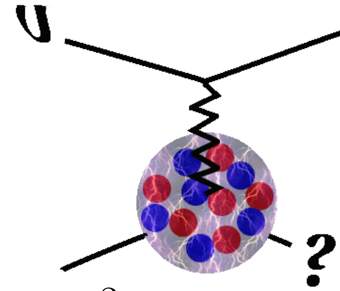


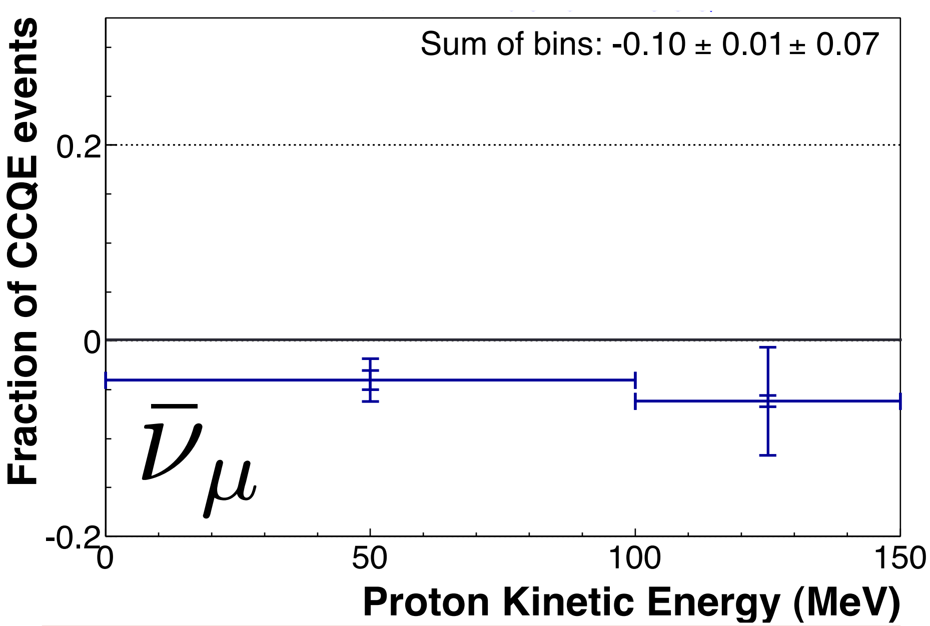




We find that adding an additional low-energy proton (KE < 225 MeV) to **(25 ± 9)% of QE events** improves agreements with data

Vertex Energy - Antineutrinos

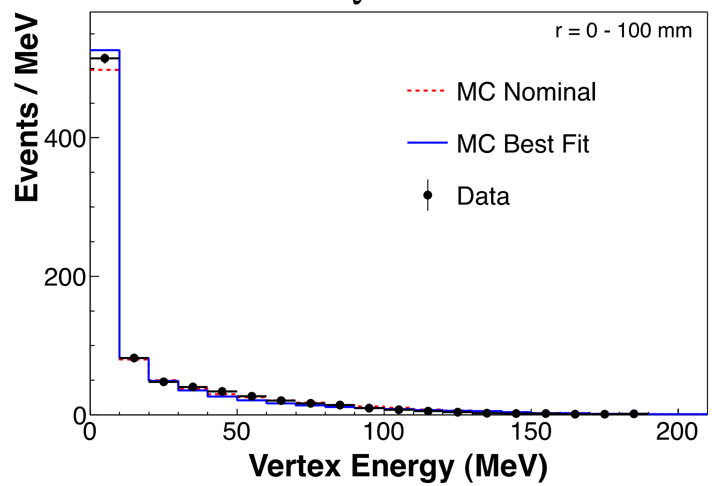




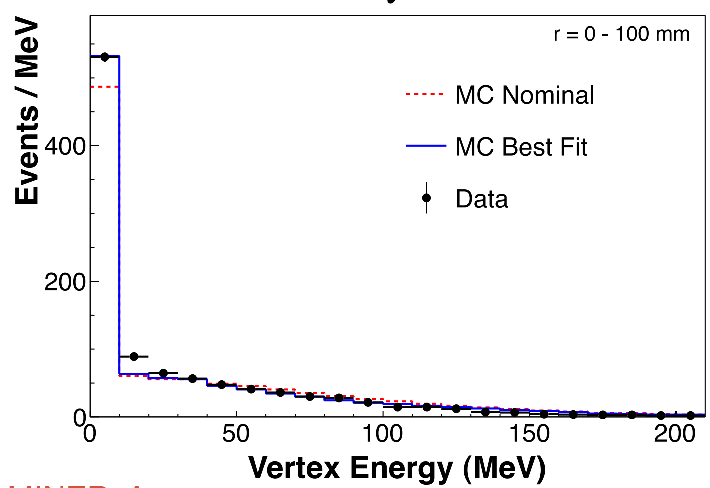
No such addition required for antineutrinos. Slight reduction if anything.

(-10 ± 7)% of QE events

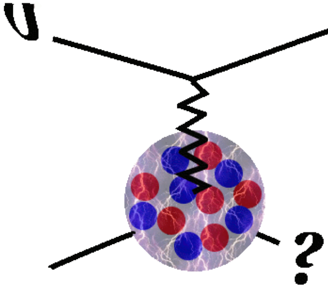
$0 < Q^2_{QE} < 0.2\ \mathrm{GeV}^2$



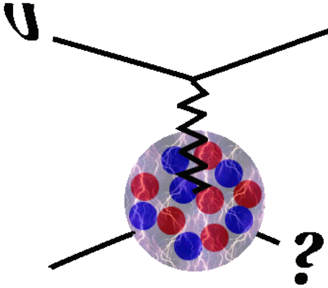
$0.2 < Q^2_{QE} < 2\ \mathrm{GeV}^2$



Quasi-Elastic: Discussion

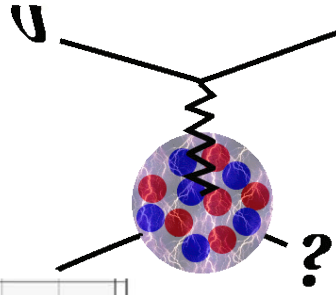


- Selected events that had muons and nucleons, but without pions
- Enhancement at moderate Q^2, consistent with other experiments, does not persist at high Q^2
  - Consistent with dynamical models of multi-nucleon processes
  - Not consistent with “standard” modification of nucleon form factors
- Also see presence of additional energy near vertex in neutrinos, but not anti-neutrinos
  - Consistent with interpretation of leading multi-nucleon correlations as an “np” state… so pp in neutrinos, but nn in anti-neutrinos
- Exclusive muon+proton measurements and other measurements from MINERvA to follow

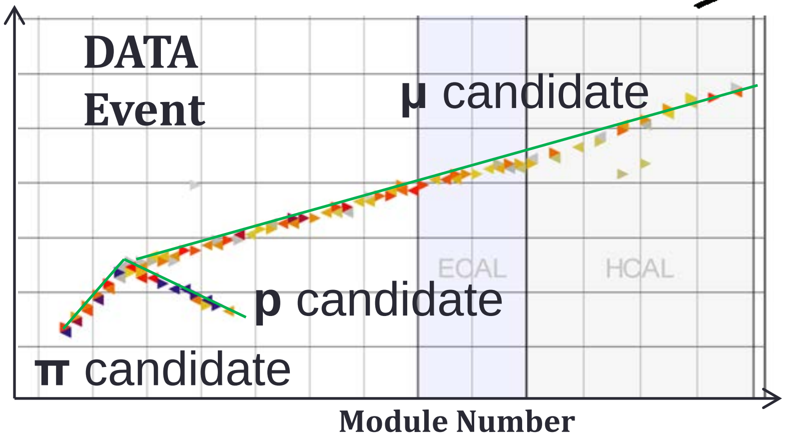


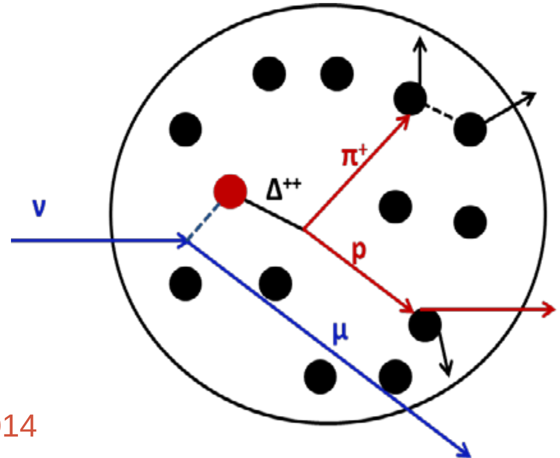
Pion Production

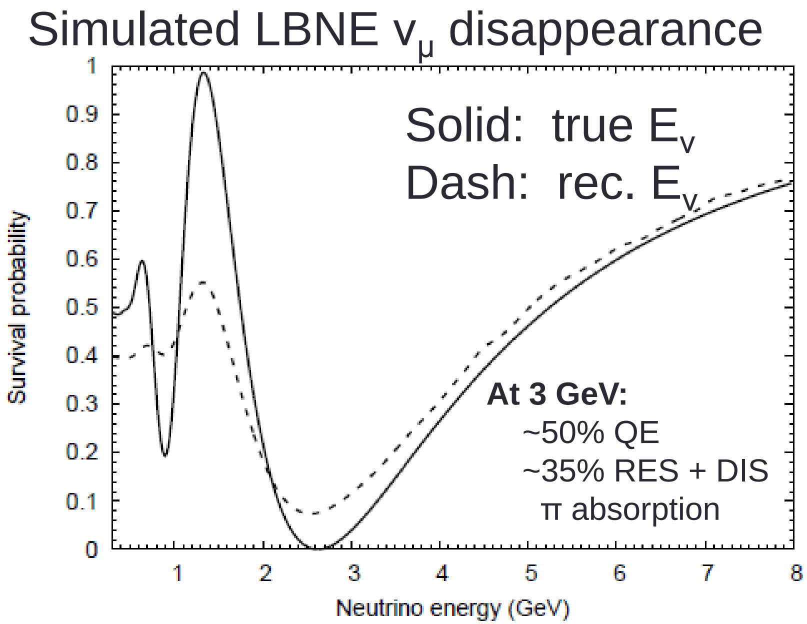
Charged Pion Production



- Most common inelastic interaction at low energies
- Oscillation experiments that don't identify the pion suffer an energy bias
- Produced pions strongly interact inside nucleus before emerging

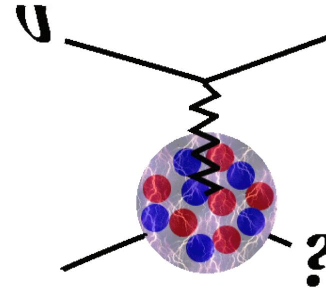




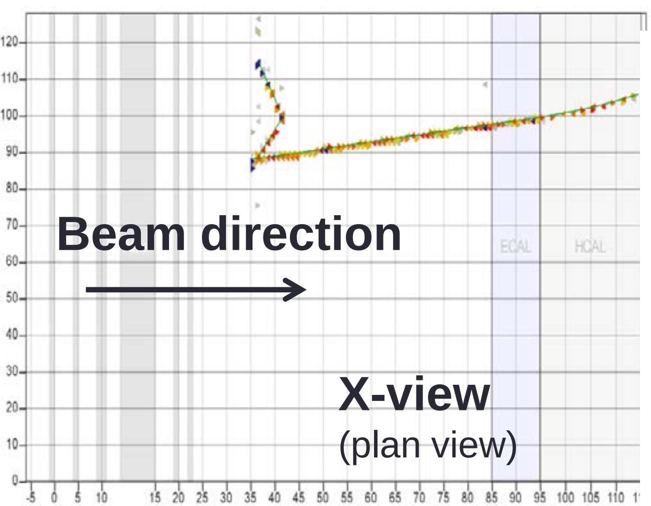


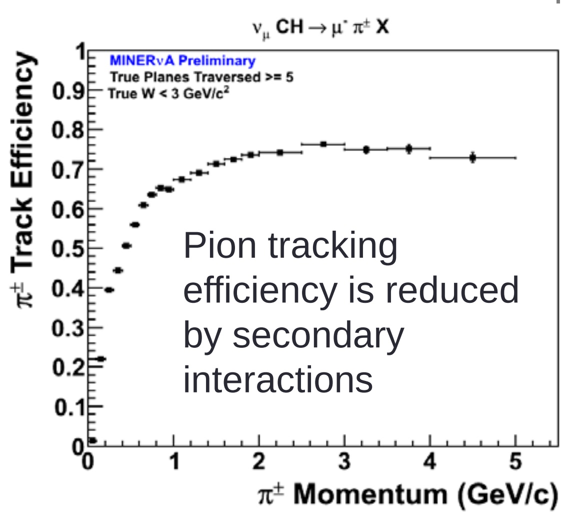
Mosel *et al*: arxiv 1311.7288

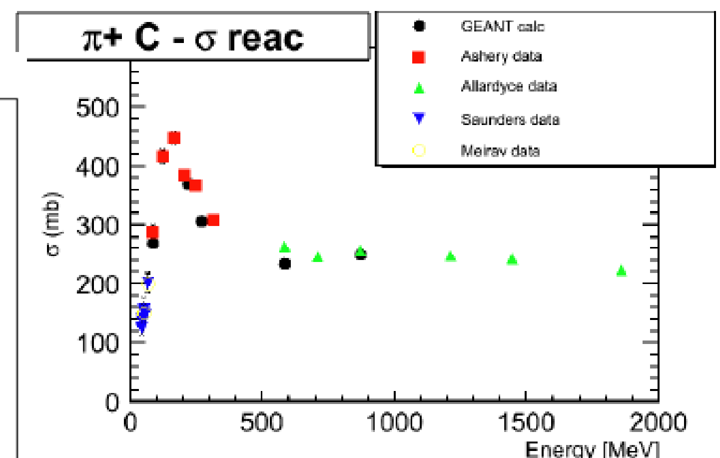
Pion Reconstruction



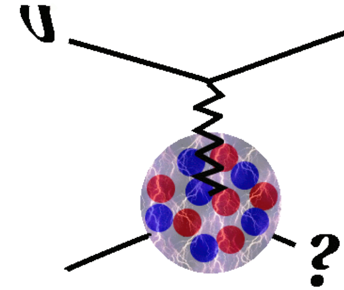
- Key is identification of a track as a pion by energy loss as a function of range from the vertex
- Confirmed by presence of Michel electron, $\pi \rightarrow \mu \rightarrow e$
- Elastic or inelastic scattering in scintillator is a significant complication of reconstruction
  - Study uncertainties by varying pion reactions, constrained by data



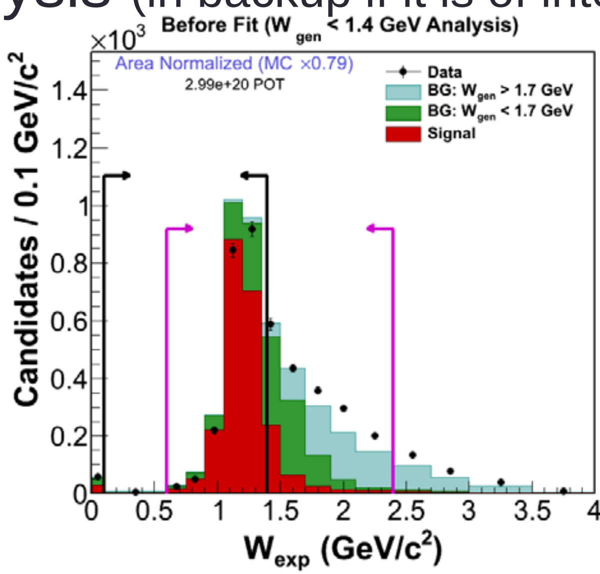


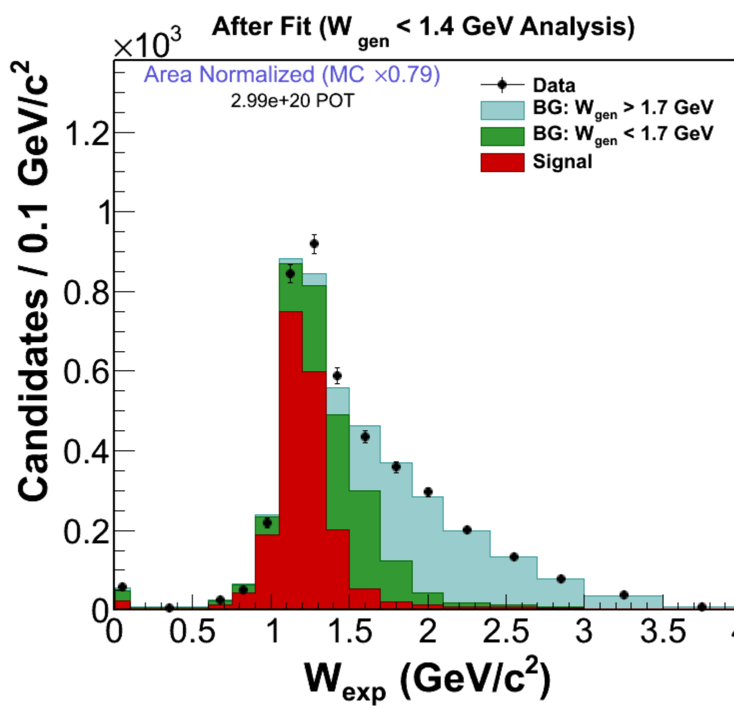


Event Selection



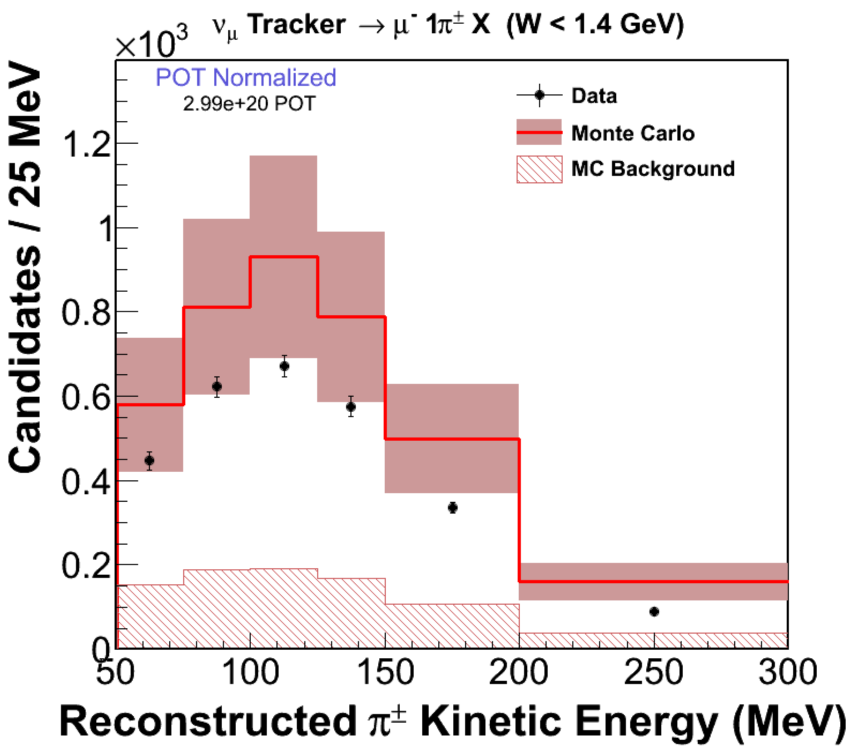
- Signal is restricted to low total recoil mass, W<1.4 GeV (events most likely to be backgrounds for T2K and NOvA)
  - W measured by lepton kinematics plus the total recoil energy
  - Coherent pion production is part of the signal in this measurement
- Background predictions are altered to match W_{exp} shape
- We have an alternate all W analysis (in backup if it is of interest)

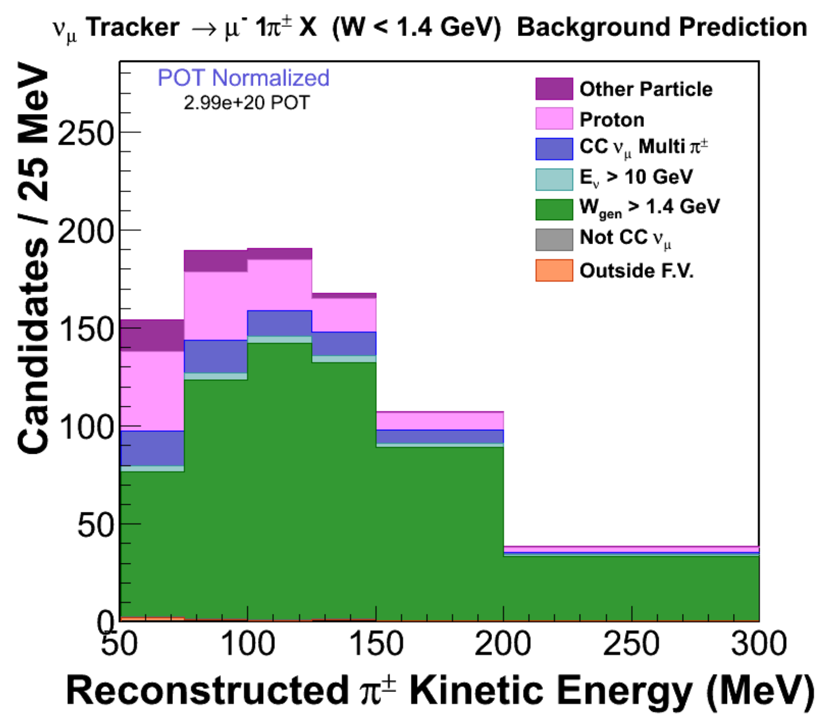




Signal and Background

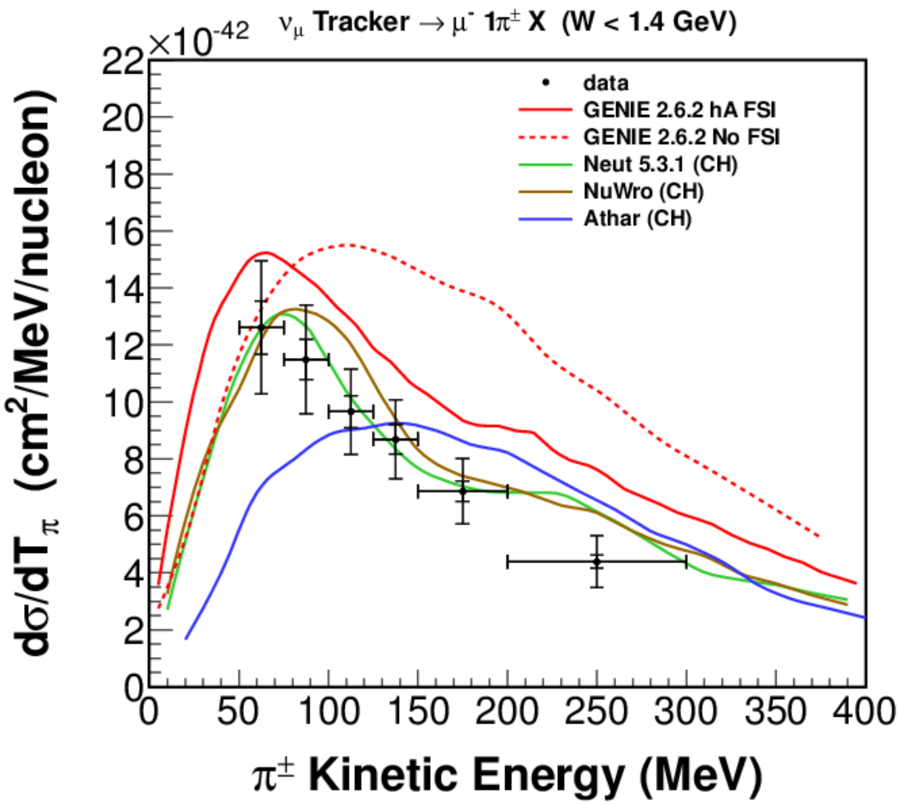
- Pion kinetic energy distributions with background prediction (untuned)
  - Green and blue are high W backgrounds
  - Pink (proton) and purple are non-pion events

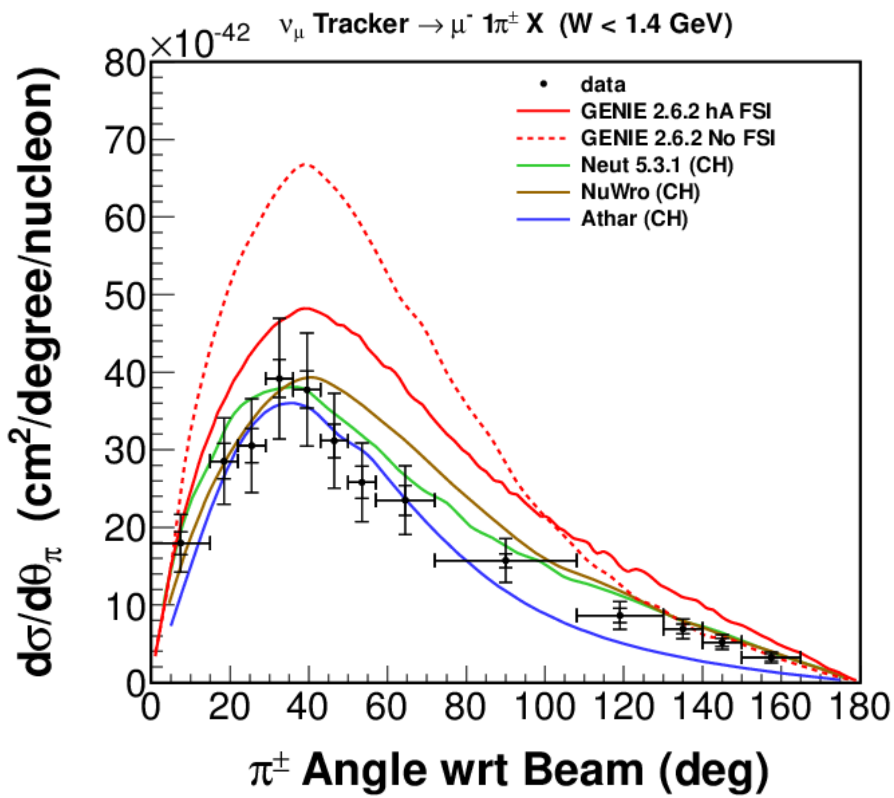




Pion Kinematics

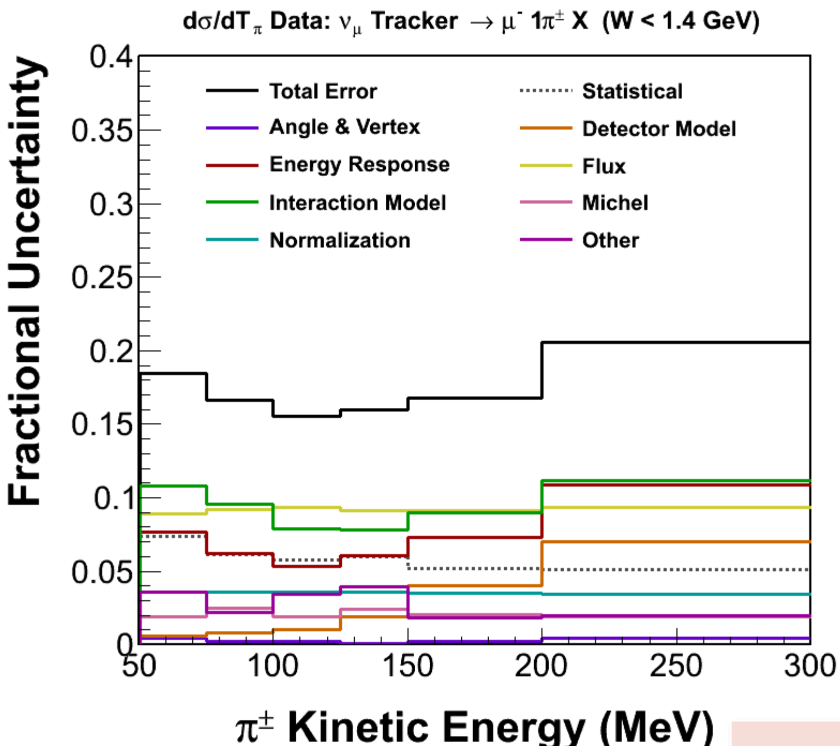
(Flux integrated)



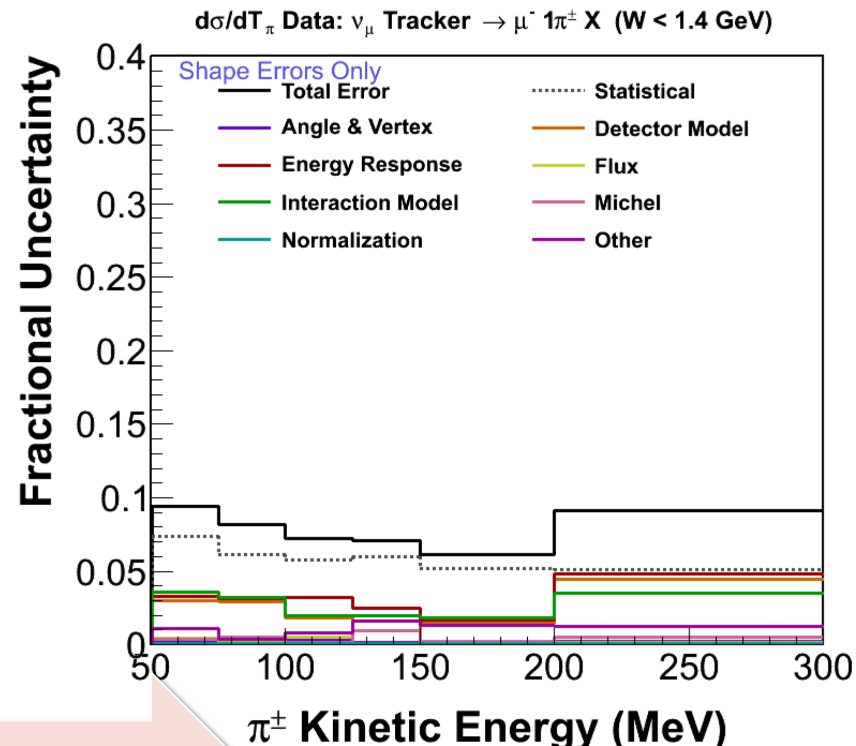


- Overall rate is very uncertain because knowledge from "free nucleon" targets (mostly weakly bound D_2) is poor

Uncertainties and “Shape”

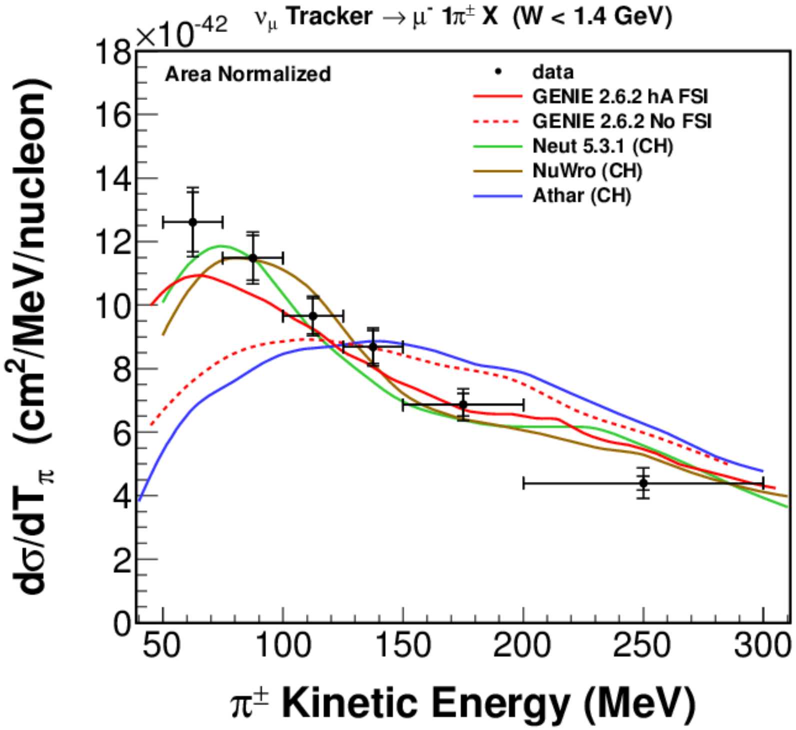


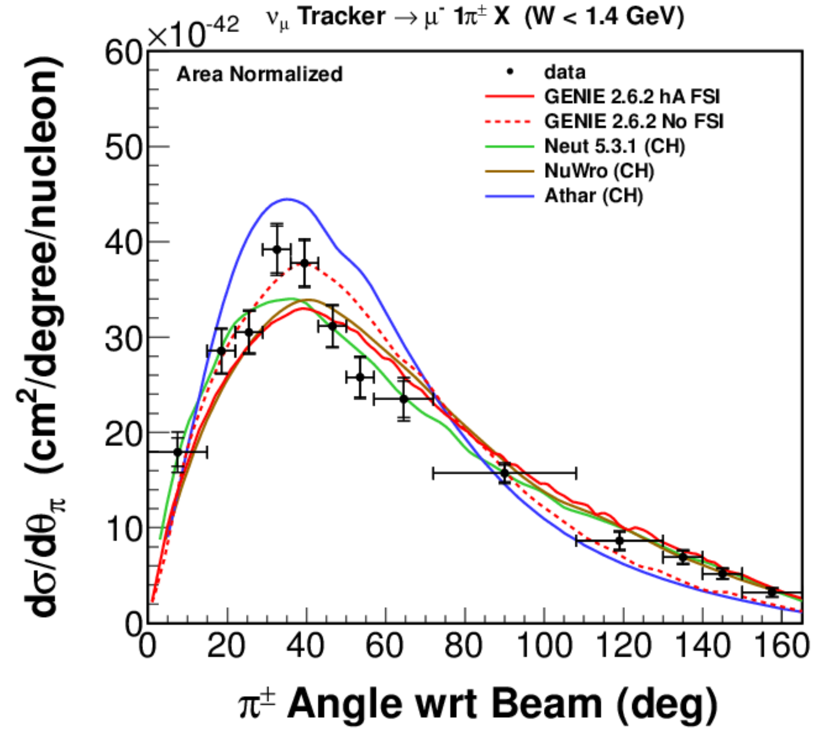
Shape only



- Flux uncertainties and (preliminary) uncertainty from extrapolation to high muon angle (high Q^2) both become insignificant in pion kinetic energy and angle shape distributions

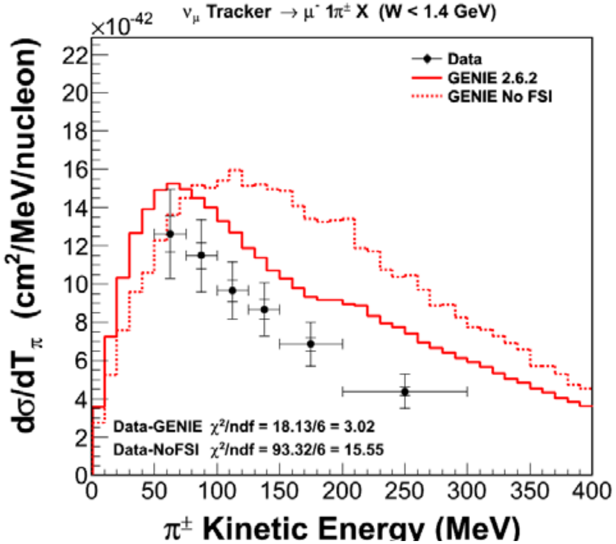
Shape and Final State Interactions

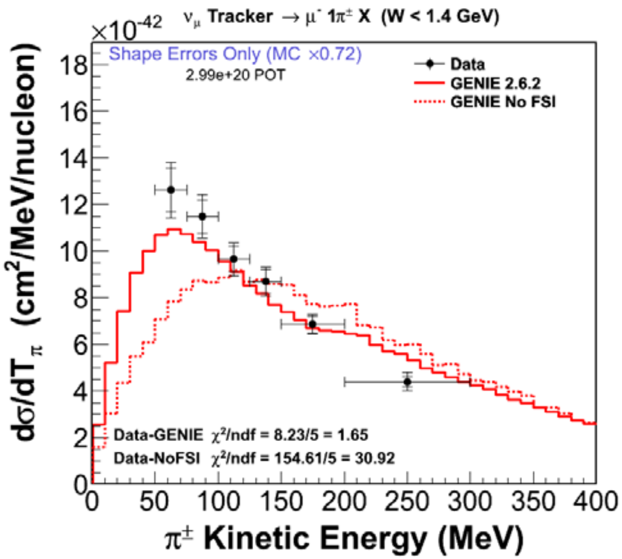


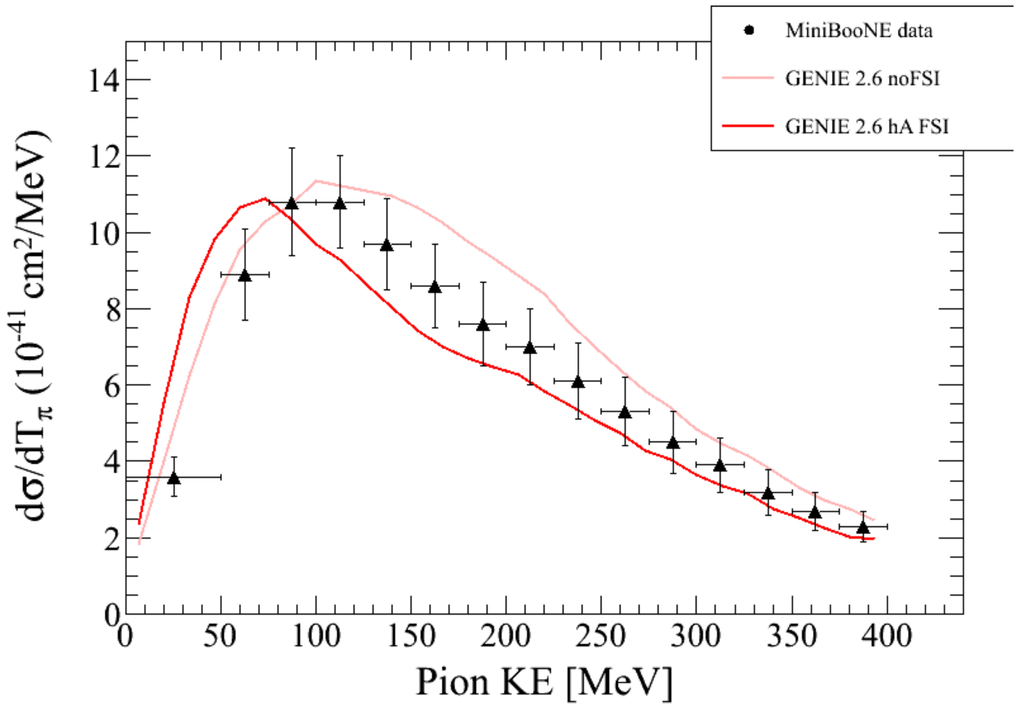


- **Conclusion:** NuWro, Neut, and GENIE all predict the data shape well
- **Conclusion:** Data insensitive to the differences in pion absorption shape between GENIE, NuWro, and Neut
- **Conclusion:** Athar, the sole theoretical calculation, does not agree with data. Likely due to an insufficient FSI model

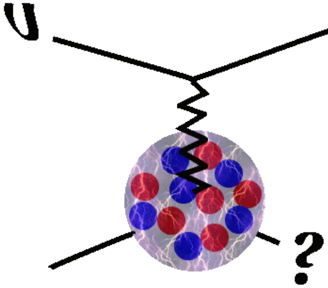
Comparison to MiniBooNE





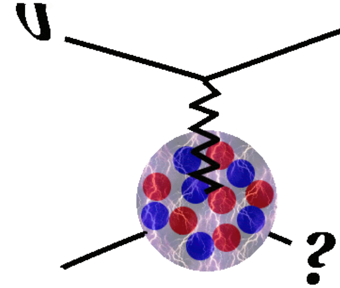


- Even with ~10% flux uncertainties from both experiments, there is ~2σ tension between MINERvA and MiniBooNE
- Some shape tension also



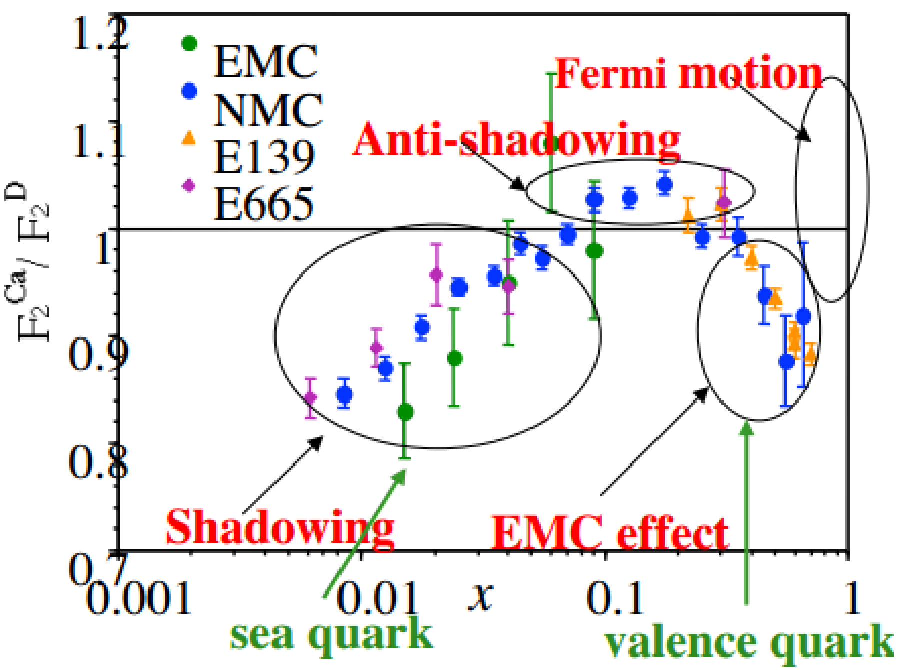
Nuclear Target Ratios

Charged Lepton Data



Charged lepton data show structure function F_2 effectively changes when nucleon bound in nucleus

μ/e – Ca Ratio



Physics Letters B123,
Issues 3–4, 31 March 1983, Pages 275–278

Abstract:
"Using the data on deep inelastic muon scattering on iron and deuterium the ratio of the nucleon structure functions $F_2(Fe)/F_2(D)$ is presented.
The observed x-dependence of this ratio is in disagreement with existing theoretical predictions. "

… and after much experimental and theoretical effort to explain this …

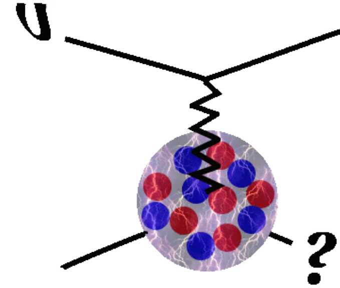
CERN COURIER

Apr 26, 2013

The EMC effect still puzzles after 30 years

Thirty years ago, high-energy muons at CERN revealed the first hints of an effect that puzzles experimentalists and theorists alike to this day.

Structure Functions



$$F_2(x,Q^2) = 2\sum_{q=u,d,\ldots}\left[xq(x,Q^2)+x\bar{q}(x,Q^2)\right]$$

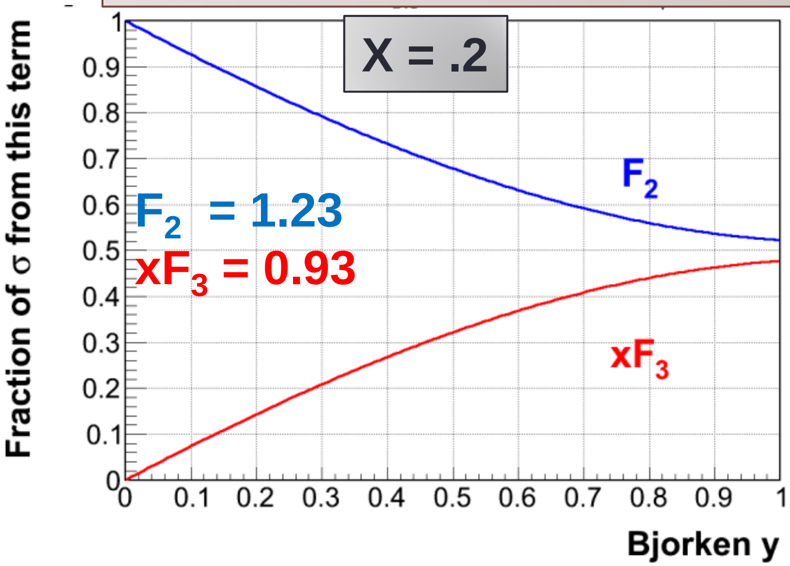
Sum of all quark and antiquark momentum

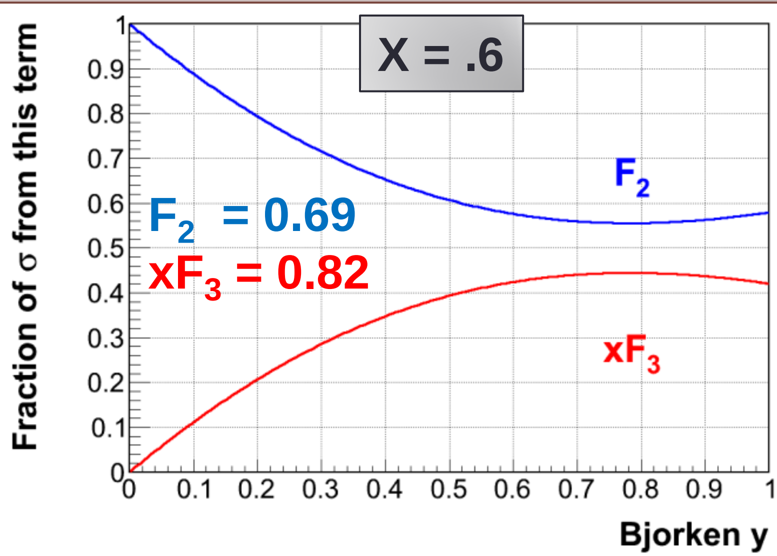
$$xF_3(x,Q^2) = 2\sum_{q=u,d,\ldots}\left[xq(x,Q^2)-x\bar{q}(x,Q^2)\right]$$

Sum of valence quark momentum

$$2xF_1(x,Q^2) = F_2(x,Q^2)\frac{1+4M^2x^2/Q^2}{1+R_L(x,Q^2)}$$

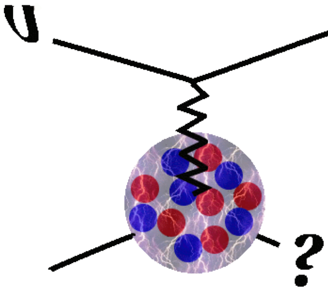
How much do they contribute to the neutrino DIS cross section?



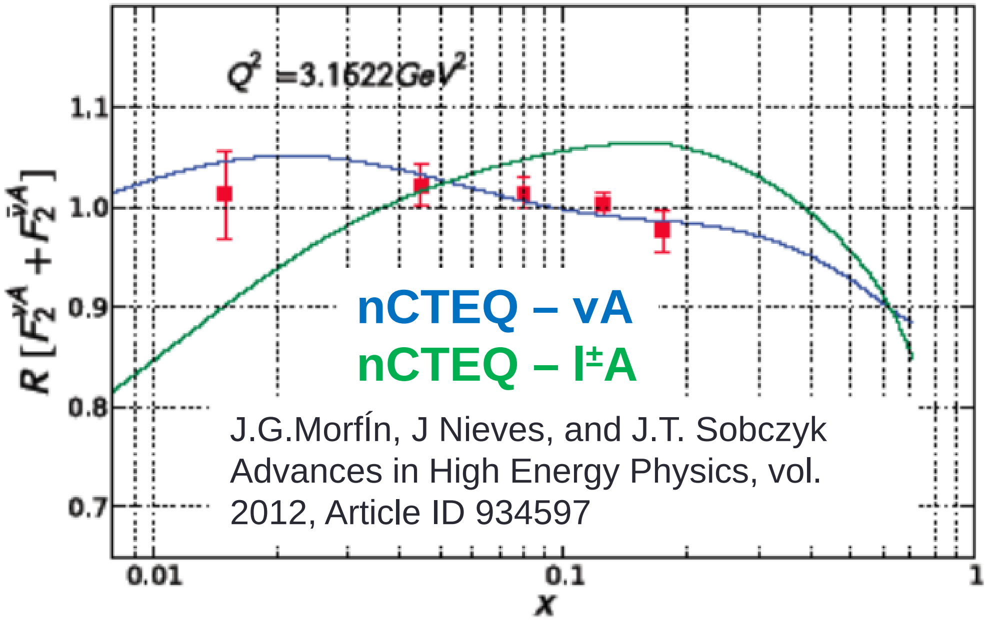


*Calculated for neutrino-neutron at Q^2 =1 GeV^2, E_ν = 4 GeV

No comparable neutrino data exists!



Compromise approach is to compare a theoretical calculation of free nucleon F_2 to, e.g., NuTeV (ν-Fe) data, and fit. Compared to fits to charged lepton data.

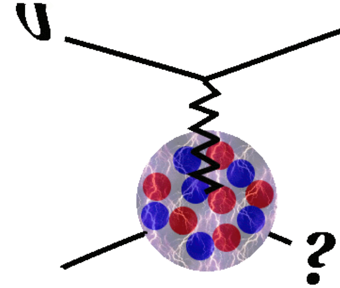


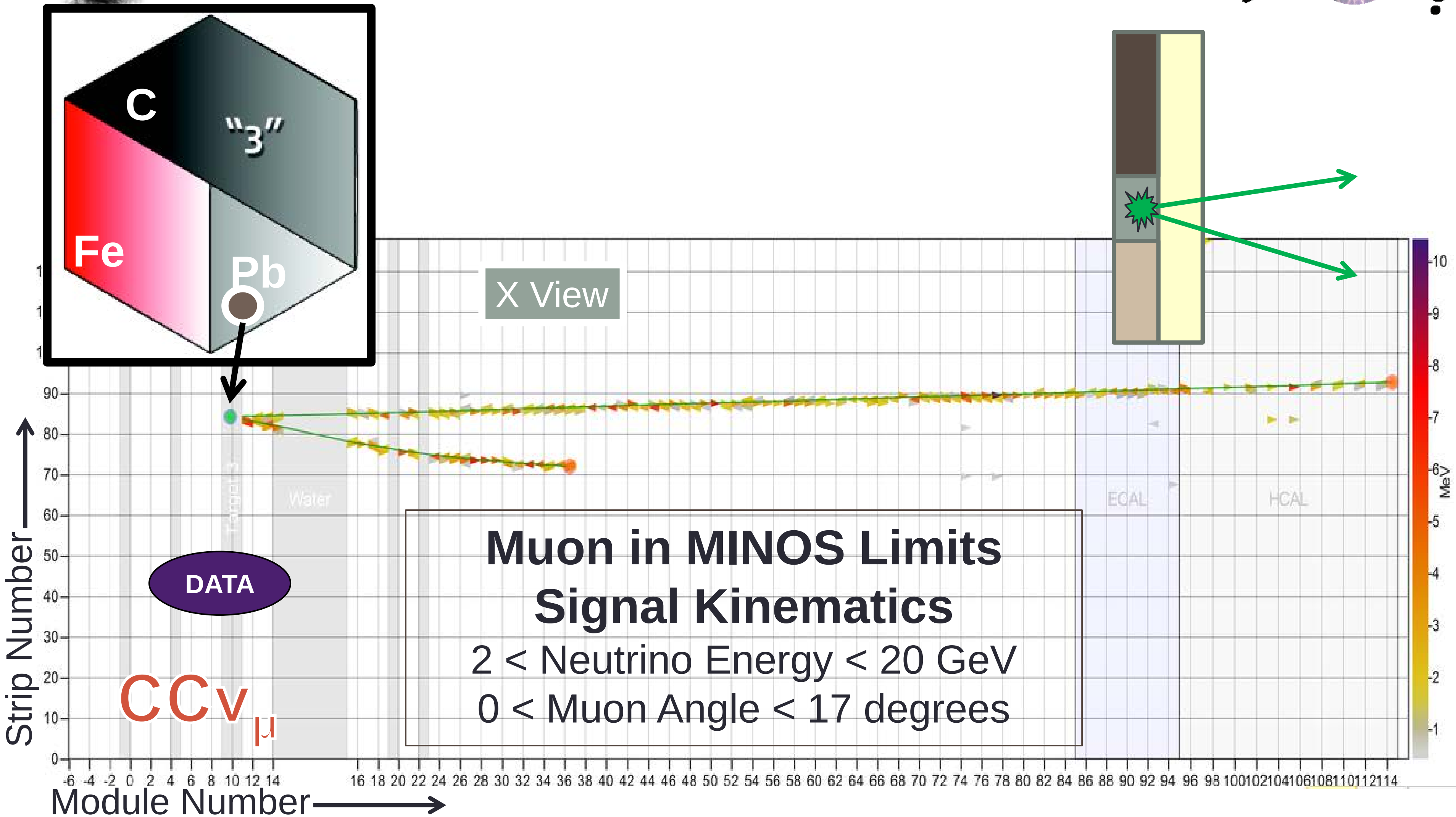
J.G.MorfÍn, J Nieves, and J.T. Sobczyk Advances in High Energy Physics, vol. 2012, Article ID 934597

Most dynamical explanations for "EMC effect" will give a different answer for neutrinos

- Neutrinos sensitive to structure function xF_3
  - (Charged leptons are not)
  - Gives neutrinos ability to separate valence and sea
- Neutrinos sensitive to axial piece of structure function F_2
  - (Charged leptons are not)
  - Axial effect larger at low x, low Q^2

MINERvA's Targets: Multi-track Pb Candidate

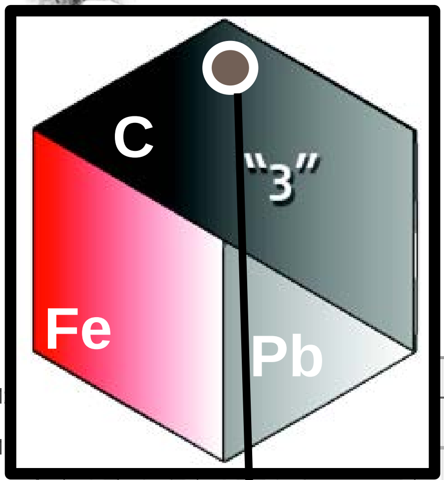




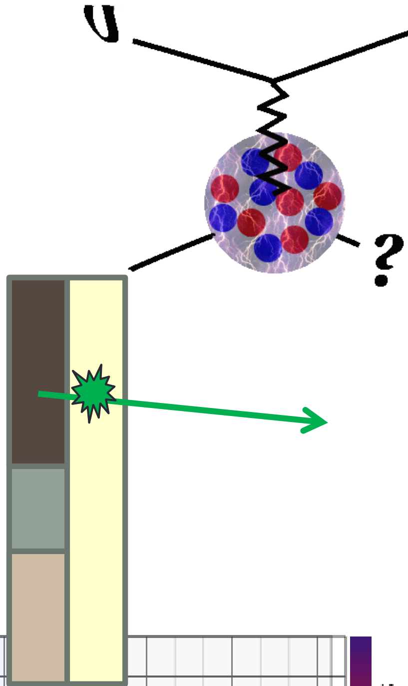
Muon in MINOS Limits
Signal Kinematics

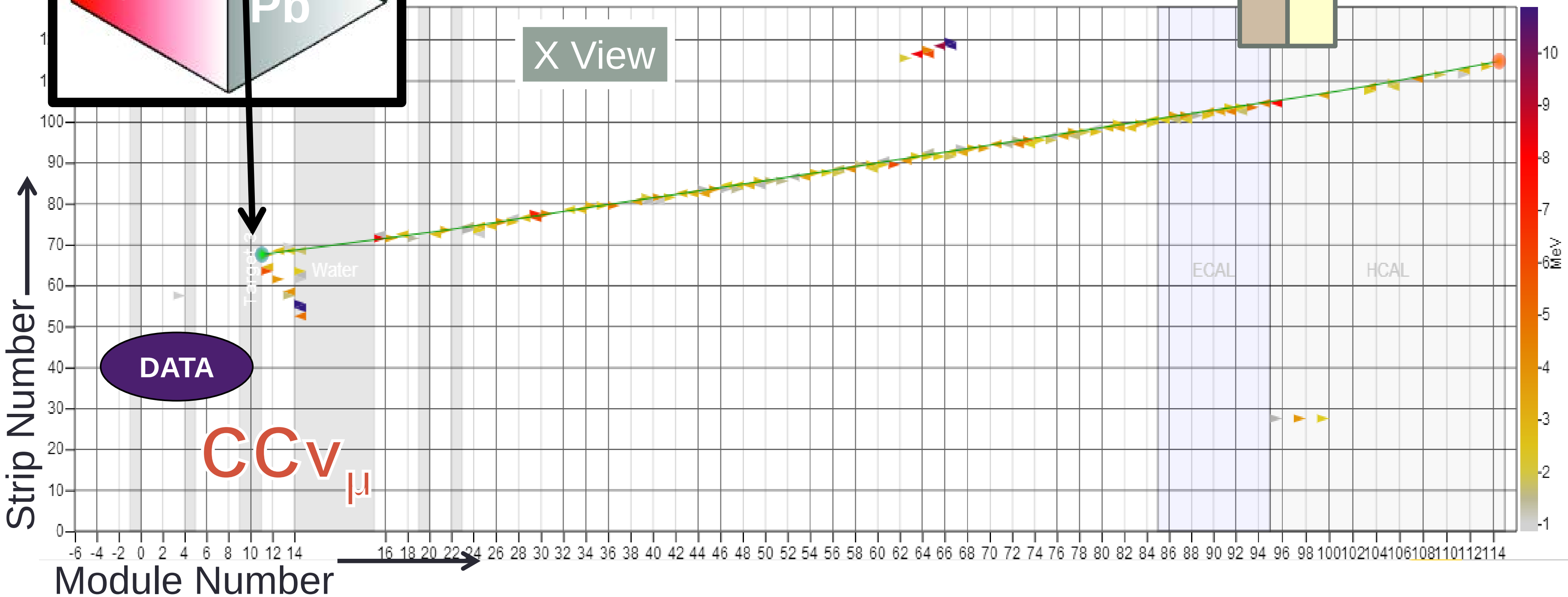
2 < Neutrino Energy < 20 GeV
0 < Muon Angle < 17 degrees

MINERvA's Targets: One-track C Candidate

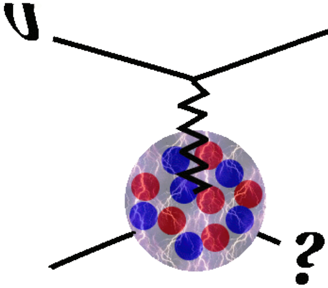


- One track candidates may originate from passive target or from downstream scintillator
- Source of background

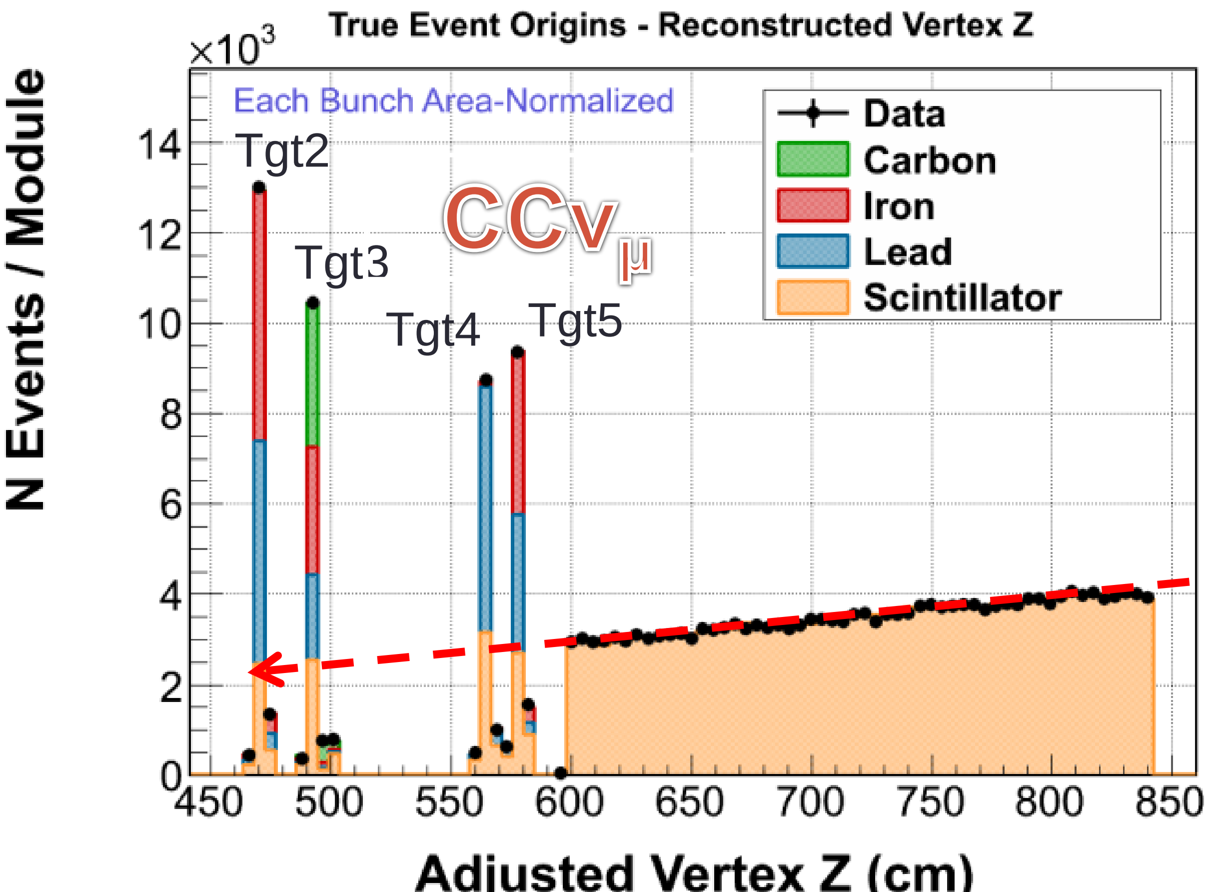


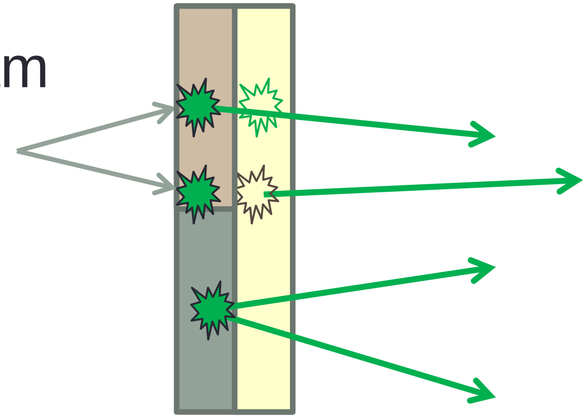


Scintillator Background

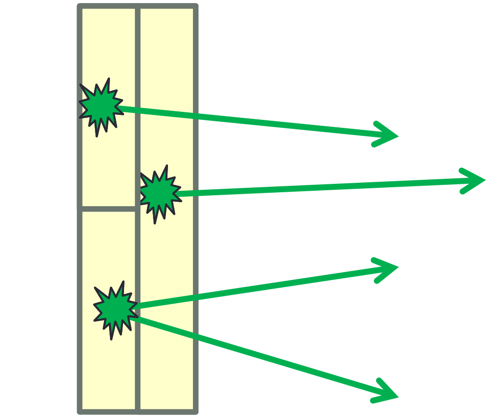


- Assume that single-track events downstream of passive target are from target

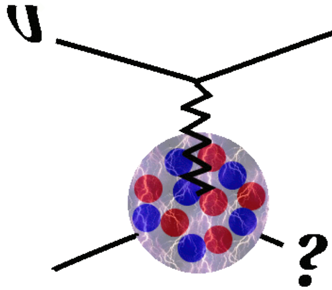


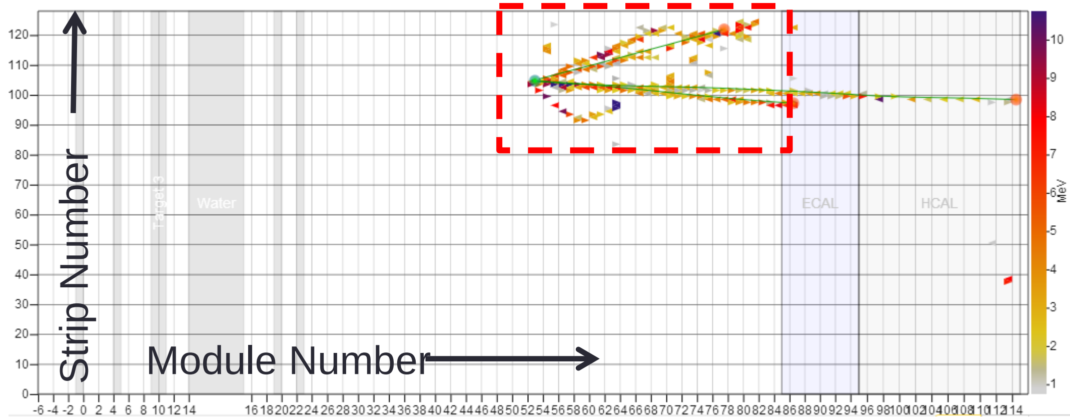


Use events in the tracker modules to predict and subtract the plastic background



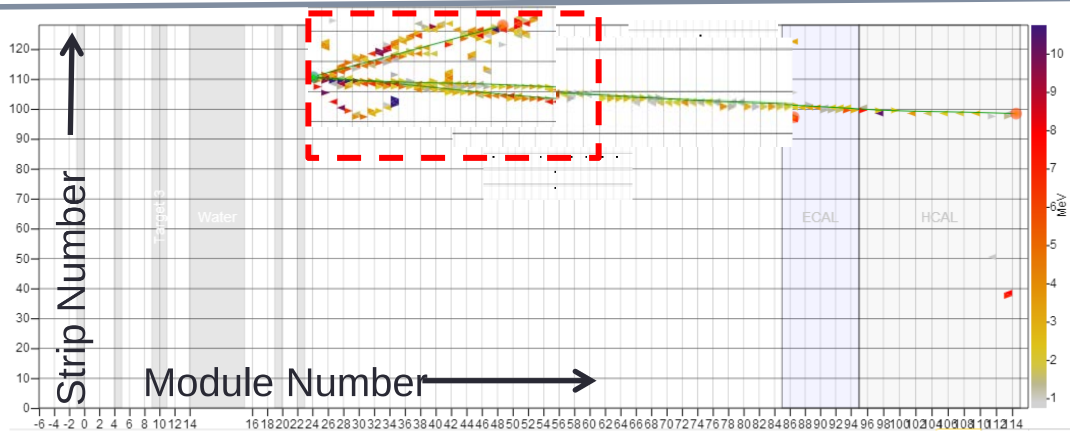
Predicting Scintillator Background



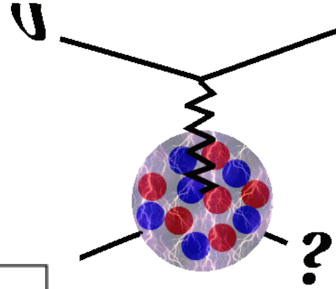


1. Find an event in scintillator of tracker
2. Move to a passive nuclear target

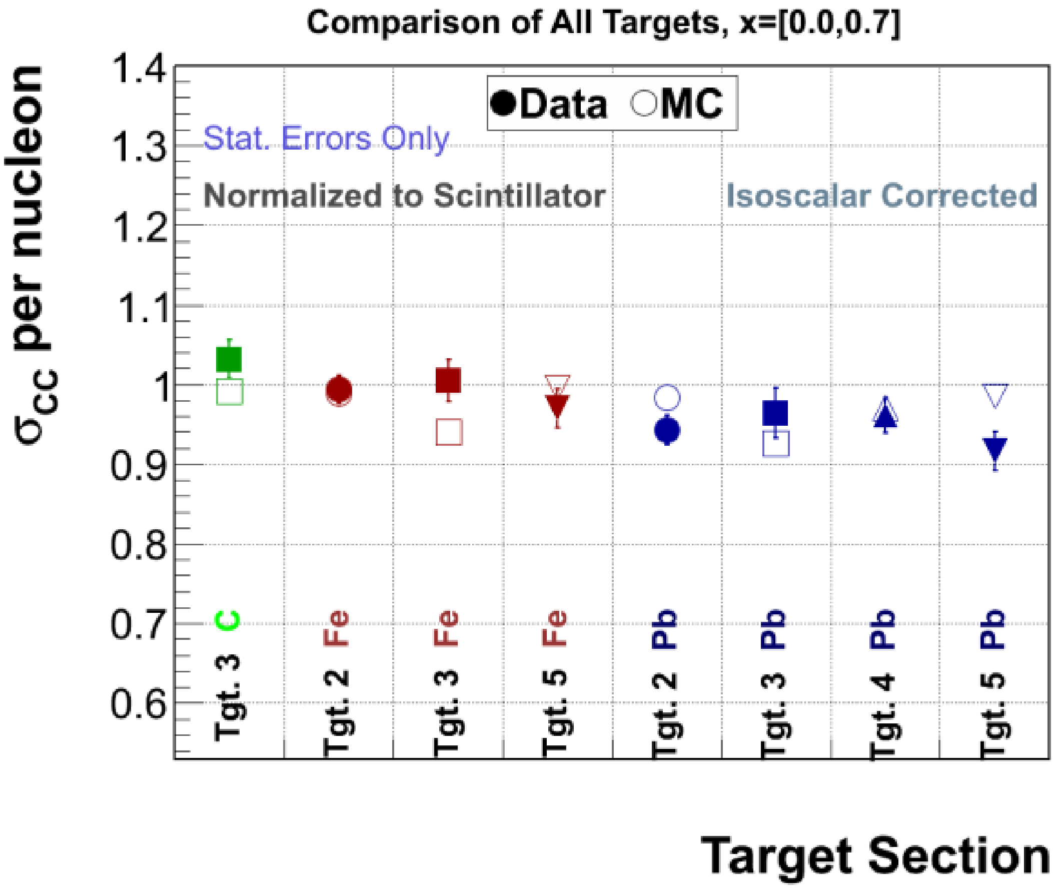
3. Use simulation to predict probability of track(s) being obscured by recoil shower
4. Evaluate uncertainties by comparing simulation procedure (and variants) against true event



Result of Subtraction



- Multiple iron and lead targets
- Can compare consistency among these
- Well within statistical uncertainties

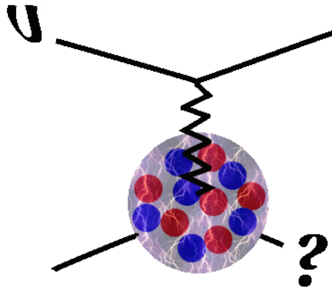


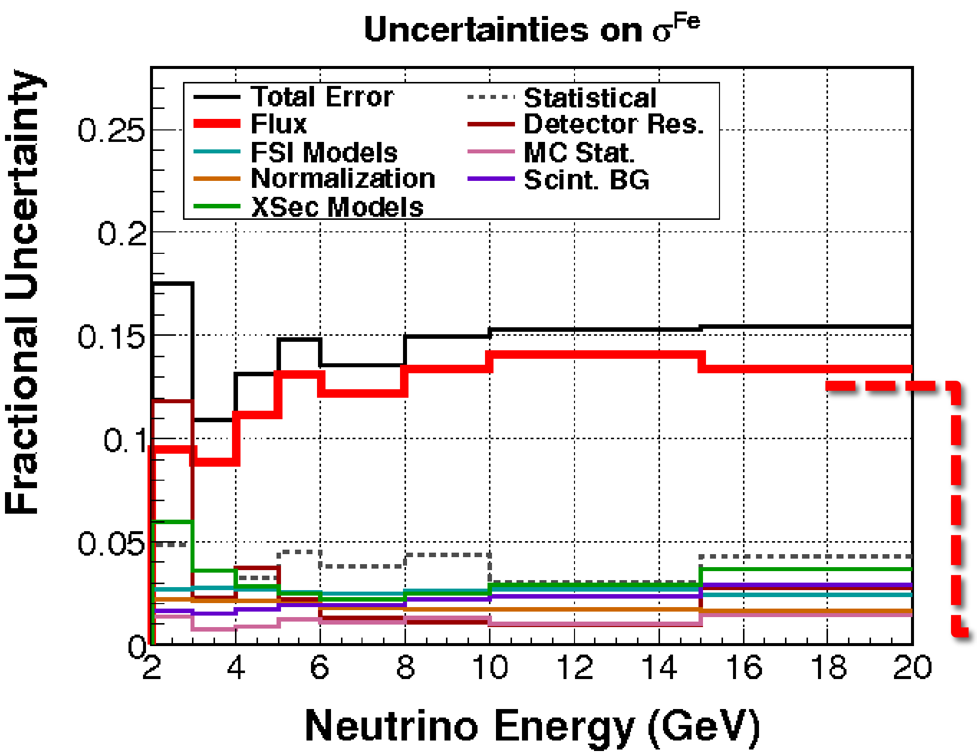
Isoscalar correction – remove effect of neutron excess.

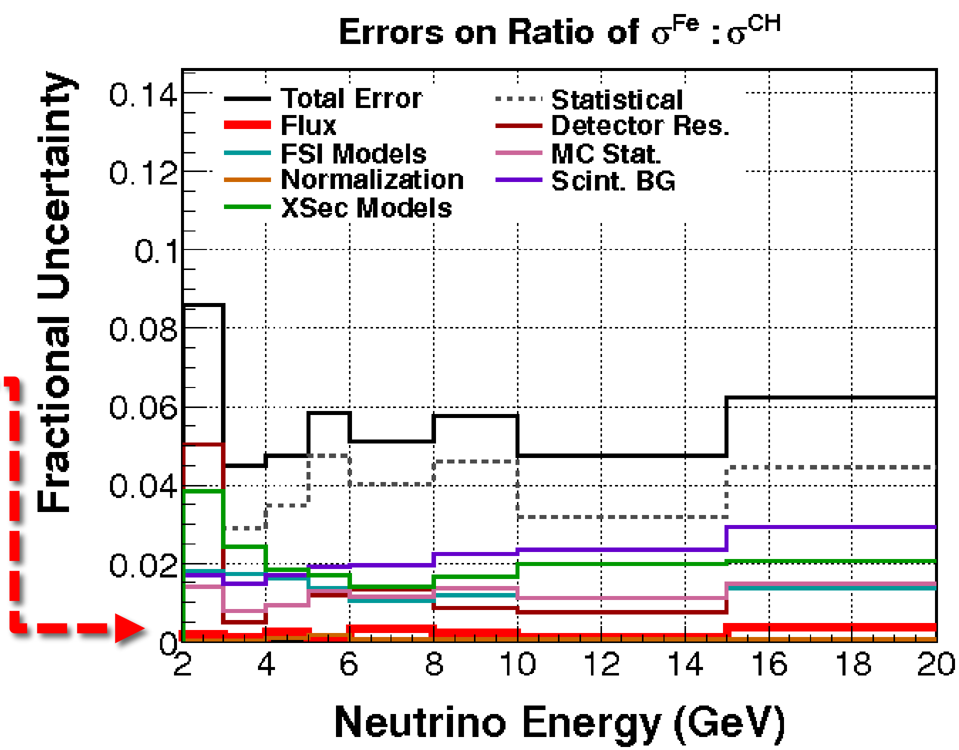
$$r(A) = \frac{Z\sigma_p + (A-Z)\sigma_n}{\sigma_p + \sigma_n}\frac{2}{A}$$

Calculated with GENIE 2.6.2

Target Ratio Technique: MINERvA's Advantage







Uncertainties on Absolute Cross Section

Uncertainties on Ratio of Cross Sections

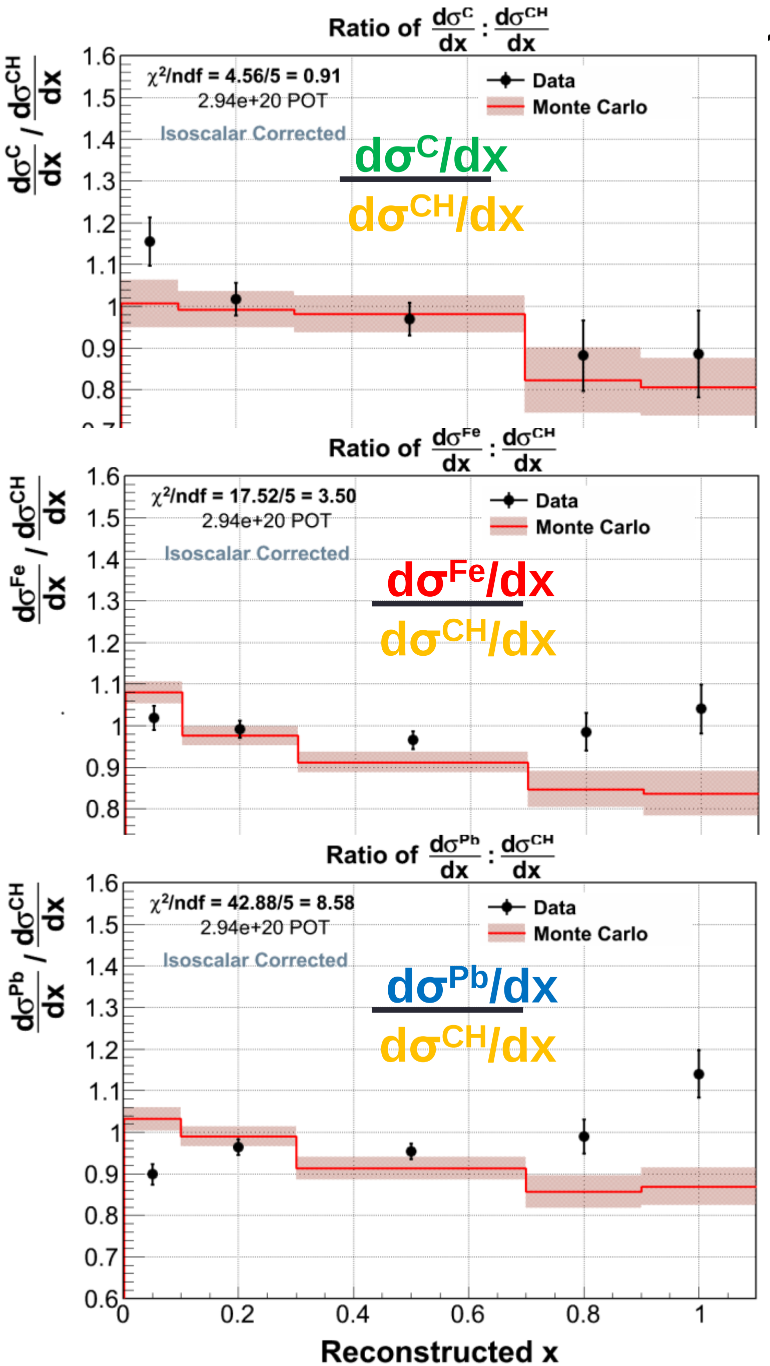
Low x Region

- At x=[0,0.1], we observe a **deficit** that increases with the size of the nucleus
- Data show effects not modeled in simulation

Expected Neutrino Differences

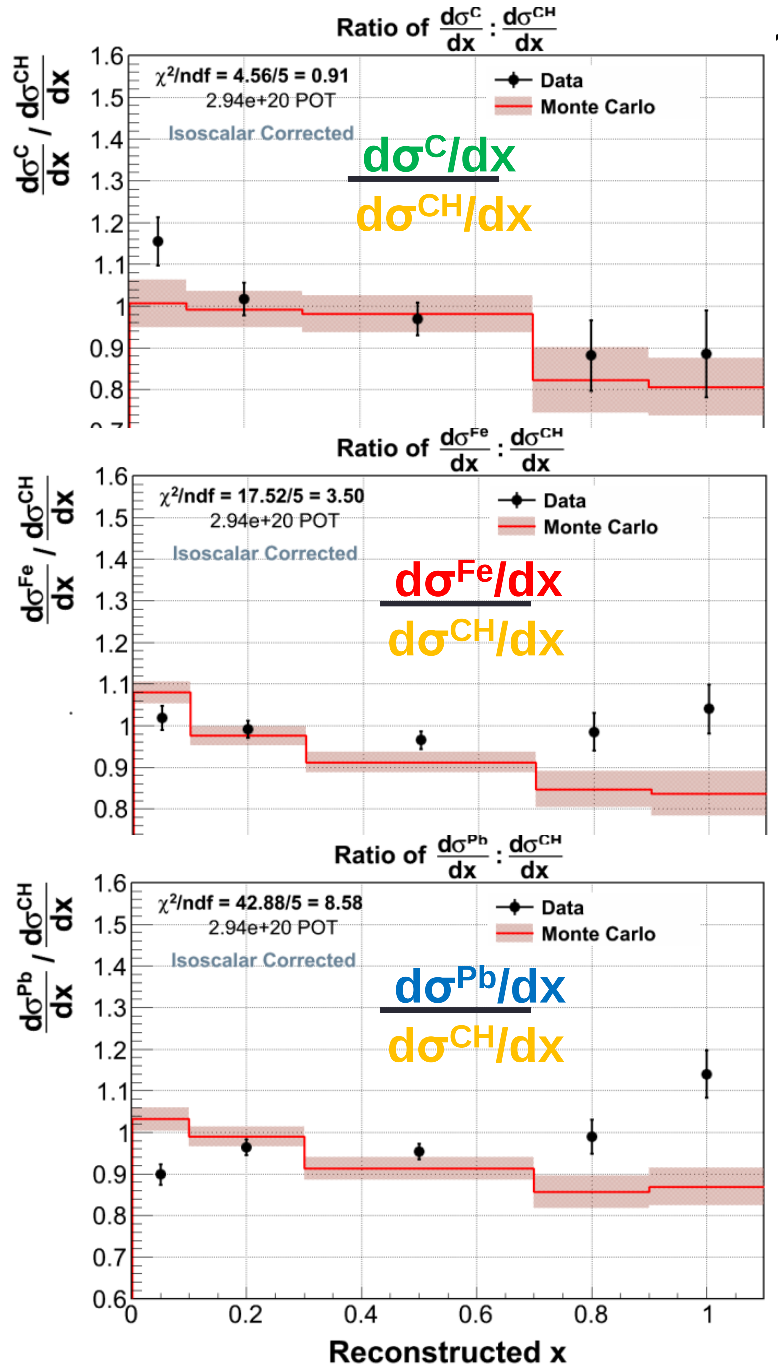
Neutrinos sensitive to structure function xF_3

Neutrinos sensitive to axial piece of structure function F_2

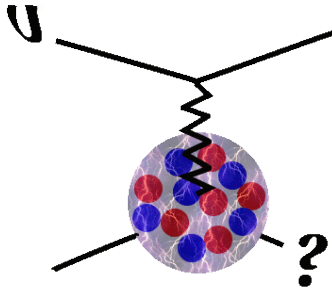


High x Region

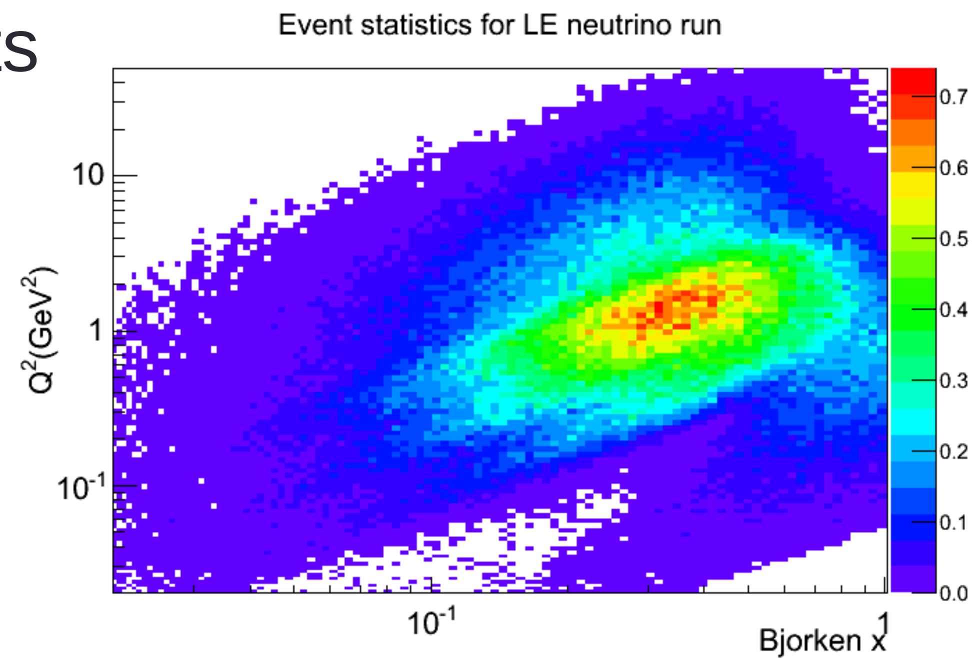
- At x=[0.7,1.1], we observe a **excess** that grows with the size of the nucleus
- This effect is also not observed in simulation
- But is due to not understanding physics of elastic processes, or that of inelastic processes?



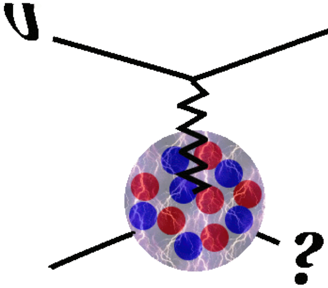
Nuclear Target Ratios



- MINERvA observes behavior not found in “standard” interaction generators
- There initial results are interesting, but also difficult to compare to physics of EMC effect because high x effects, at least, may be in elastic or nearly elastic events
- New running in NOvA beam tune will help kinematic reach and statistics and will add anti-neutrinos



Nuclear Target Ratios



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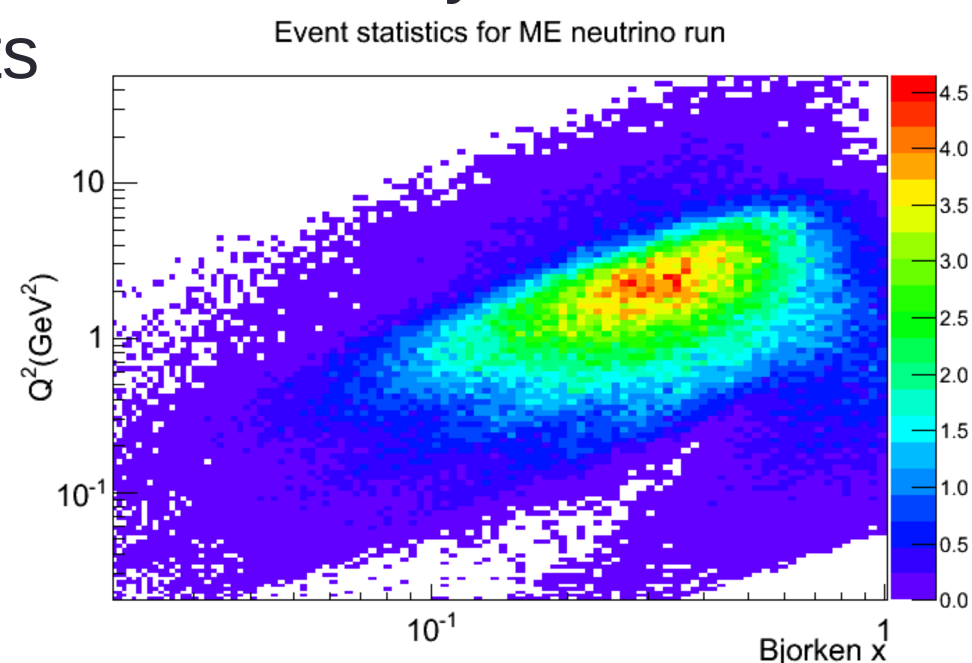
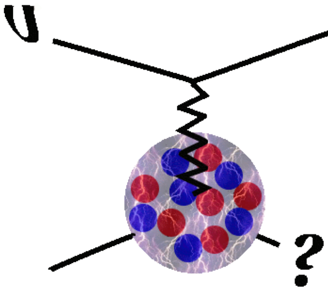
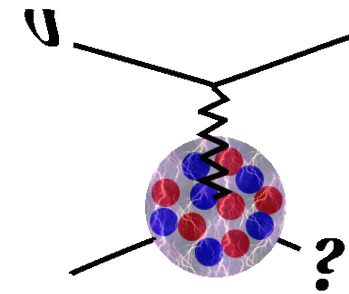




Neutrino-Electron Scattering

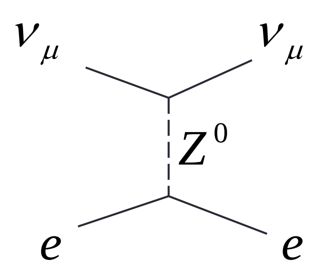
Neutrino-Electron Scattering?



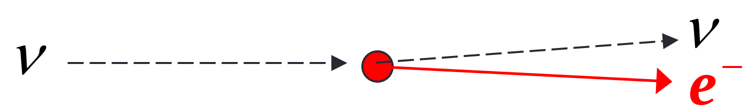
- Why on earth would we want to look at that?
  - Process is rare, roughly 1/2000 of neutrino-nucleon scattering
  - Statistics are bad, and will be swamped by background
  - Precision required to usefully probe electroweak standard model is a fraction of a percent (or a fraction per mil, if you don't take the NuTeV measurement of NC/CC seriously)

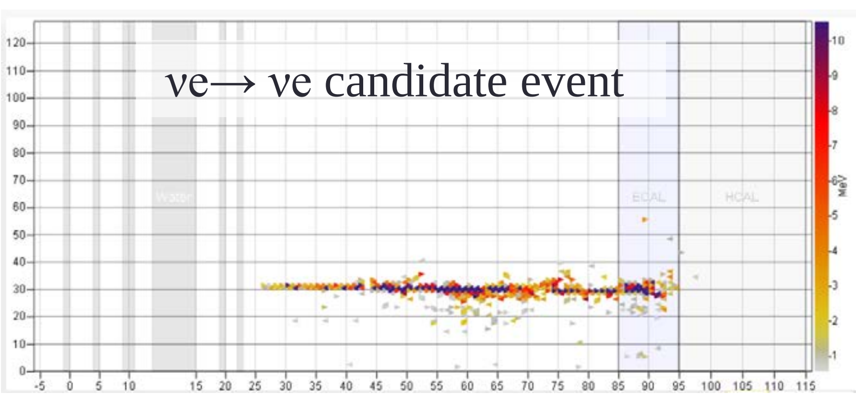
$$\nu_\mu + e^- \rightarrow \nu_\mu + e^-$$

$$\bar{\nu}_\mu + e^- \rightarrow \bar{\nu}_\mu + e^-$$



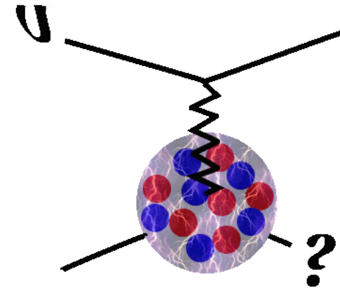
Very forward single electron final state





- But flux uncertainties are large. Is this our "standard candle"?
- If it works, could future experiments measure flux "cheaply"?

ν-e Scattering



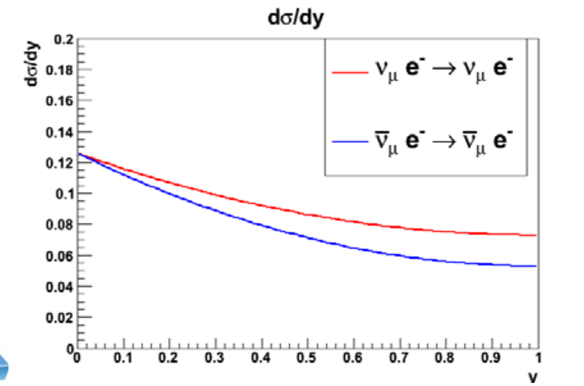
$$\text{here } y \equiv \frac{\text{(electron KE)}}{\text{(neutrino energy)}}$$

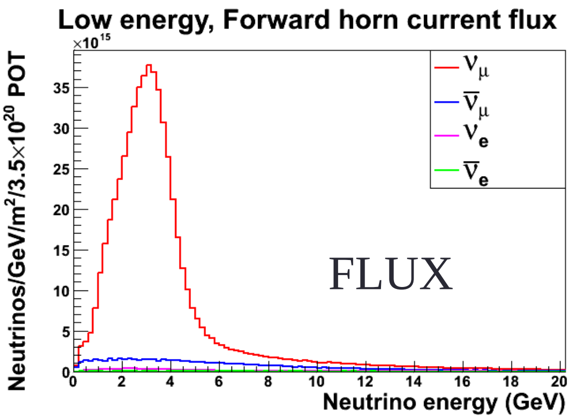
$$\frac{d\sigma(\nu_\mu e^- \to \nu_\mu e^-)}{dy} = \frac{G_F^{\,2} m_e E_\nu}{2\pi}\left[\left(\frac{1}{2} - \sin^2\theta_W\right)^2 + \sin^4\theta_W (1-y)^2\right]$$

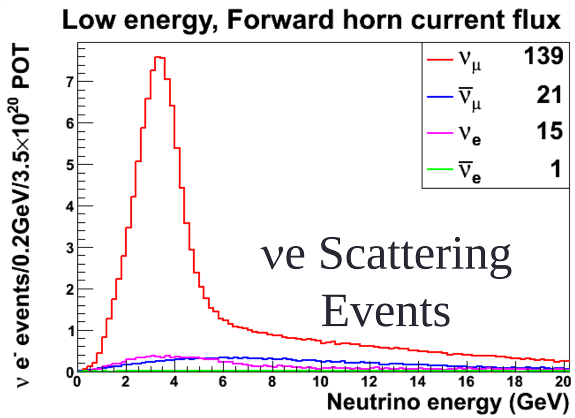
G_F and θ_W: well-known electroweak parameters

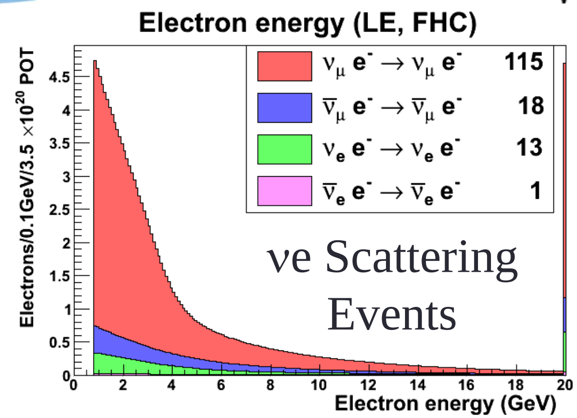
$$\sigma(\nu e) \propto E_\nu$$

$$\frac{d\sigma}{dy}$$



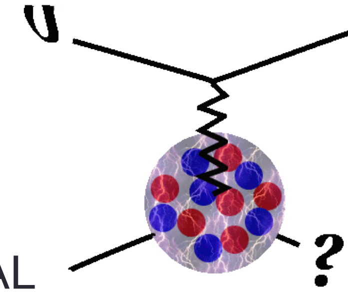


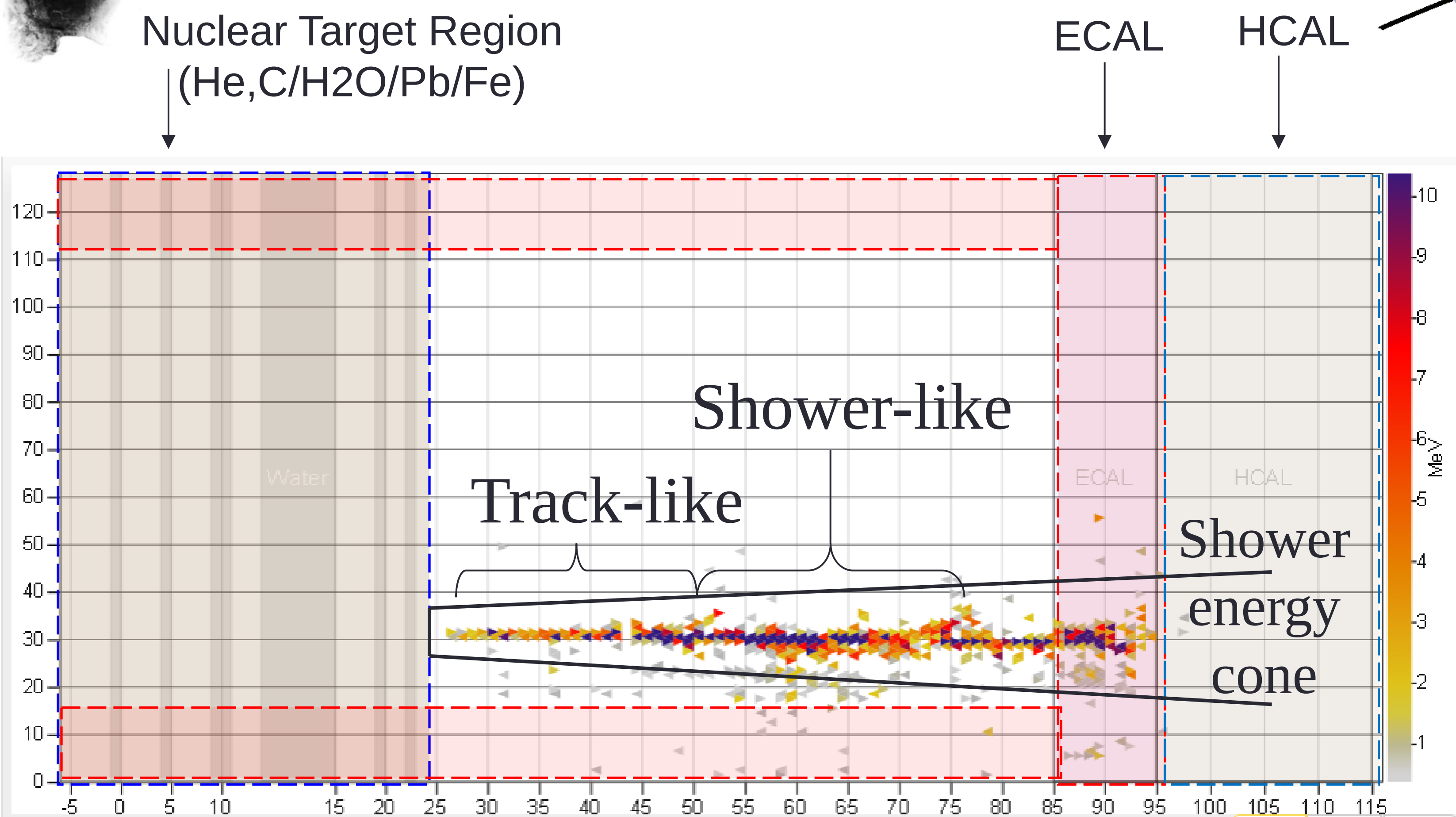




- Need a threshold (ours is E > 0.8 GeV) because reconstruction and backgrounds are difficult at low
- Predict 147 signal events for 3.43×10^{20} Protons On Target (POT)
  - ~100 events when you fold in (reconstruction + selection) efficiency of ~ 70%
- That's even useful for MINERvA if we can keep backgrounds low!

Electron Reconstruction

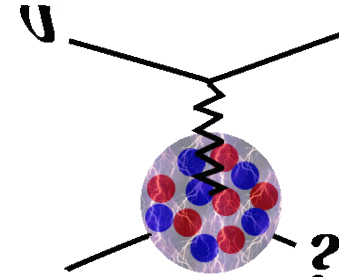


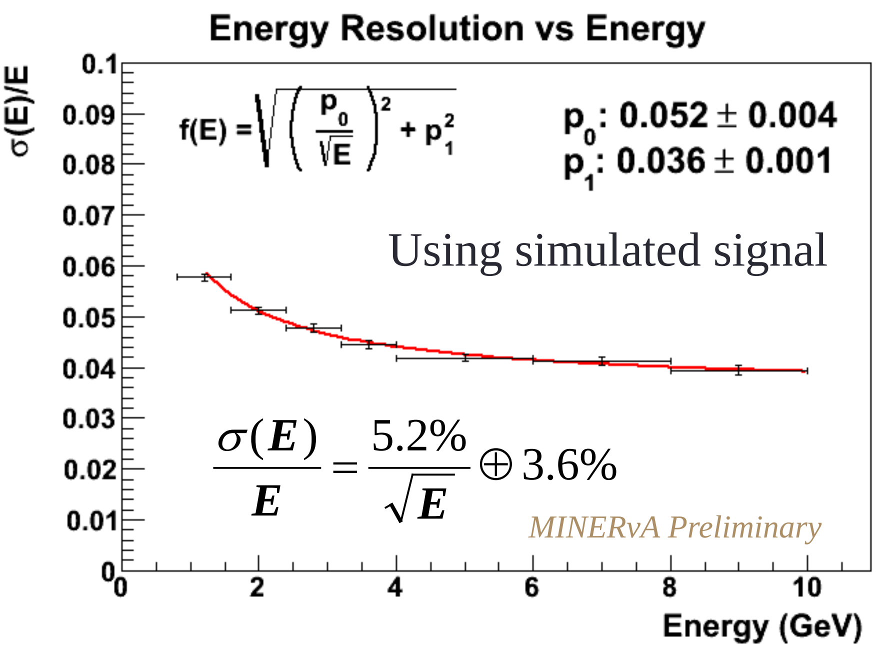


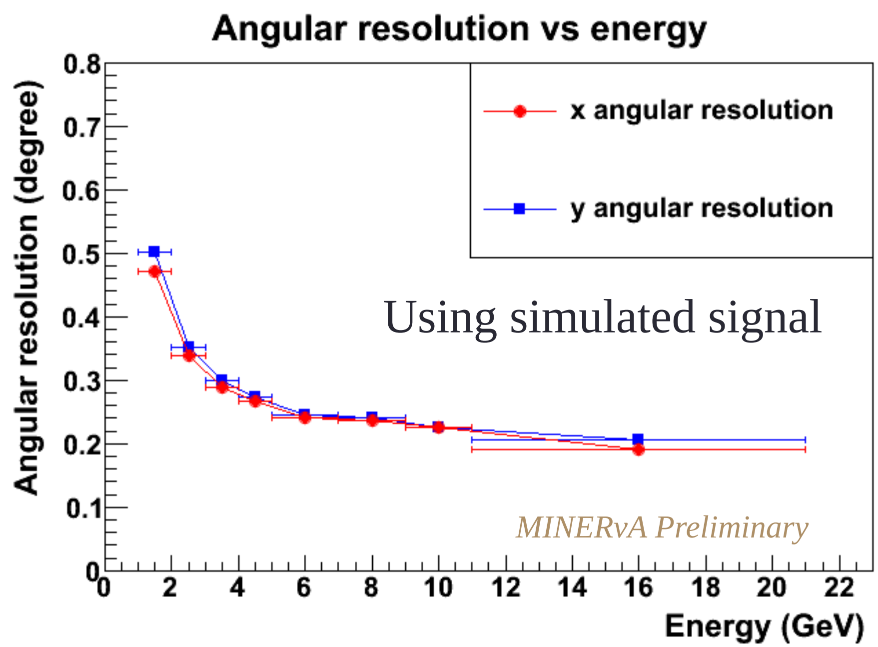
Track-like part (beginning of electron shower) gives good direction

Showery part identifies track as electron

Energy and Angle Reconstruction

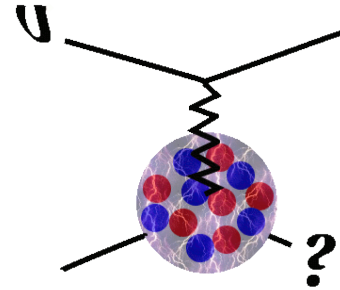




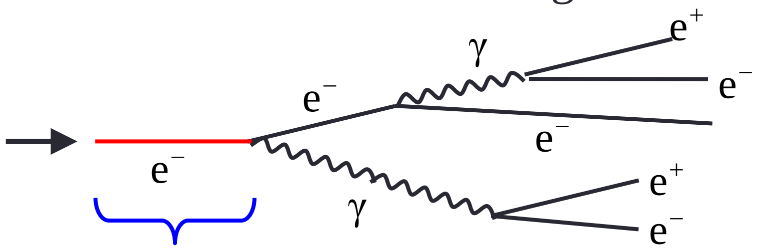


- Energy resolution ~ 5%. So that's very good.
- Projected angle resolution ~ 0.3 degree per view (2 sigma truncated RMS)
  - Typical angle for 1 GeV electron is ~0.4 degrees.
  - Not hopeless. (Precisely, signal has $E\theta^2 < 2m_e$)

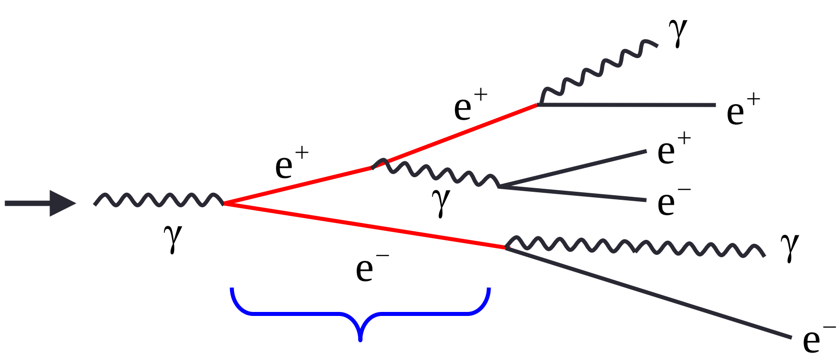
Electron Photon Discrimination using dE/dx

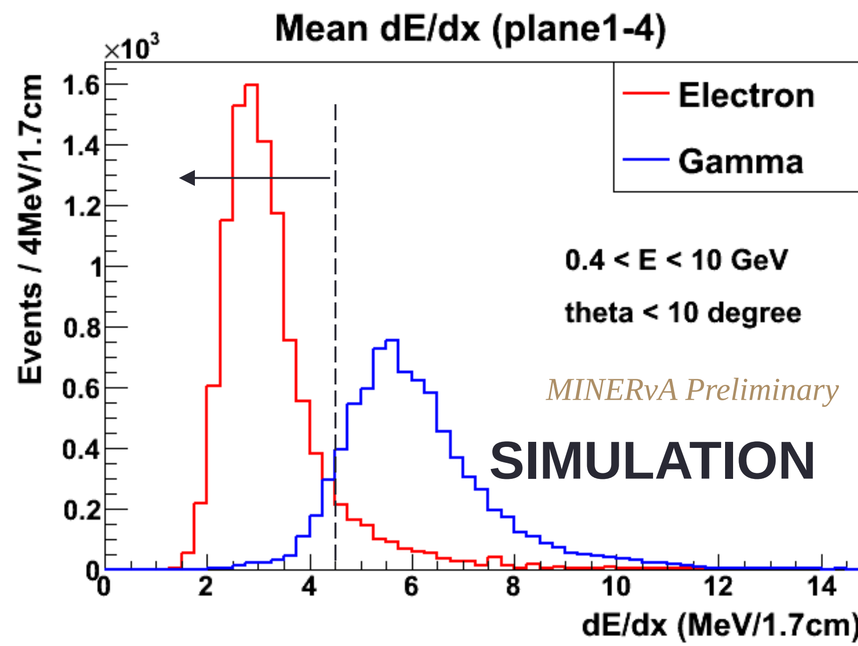


Electron-induced electromagnetic shower

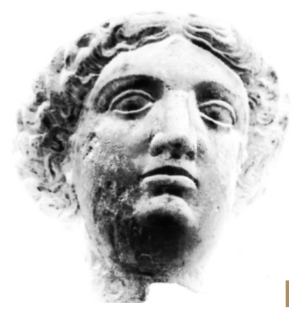


Photon -induced electromagnetic shower

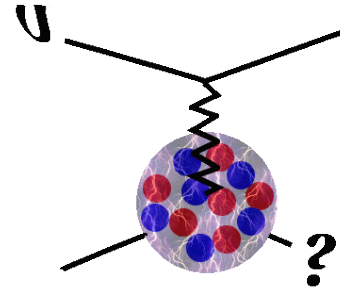


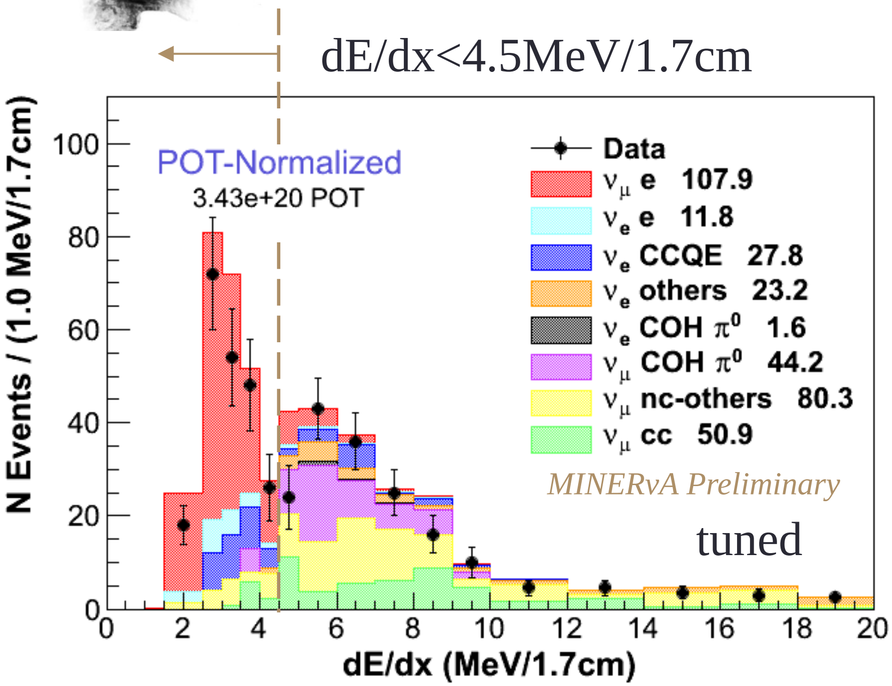


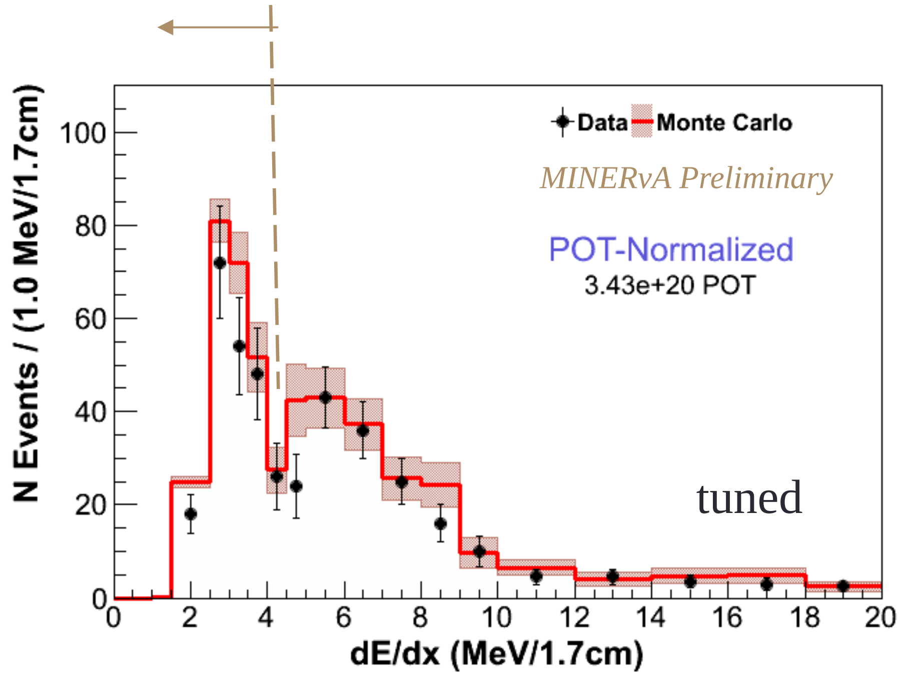
- Electromagnetic shower process is stochastic
  - Electron and photon showers look very similar
- Photon shower has twice energy loss per length (dE/dx) at the beginning of shower than electron shower
  - Photon shower starts with electron and positron



dE/dx Selection in Data

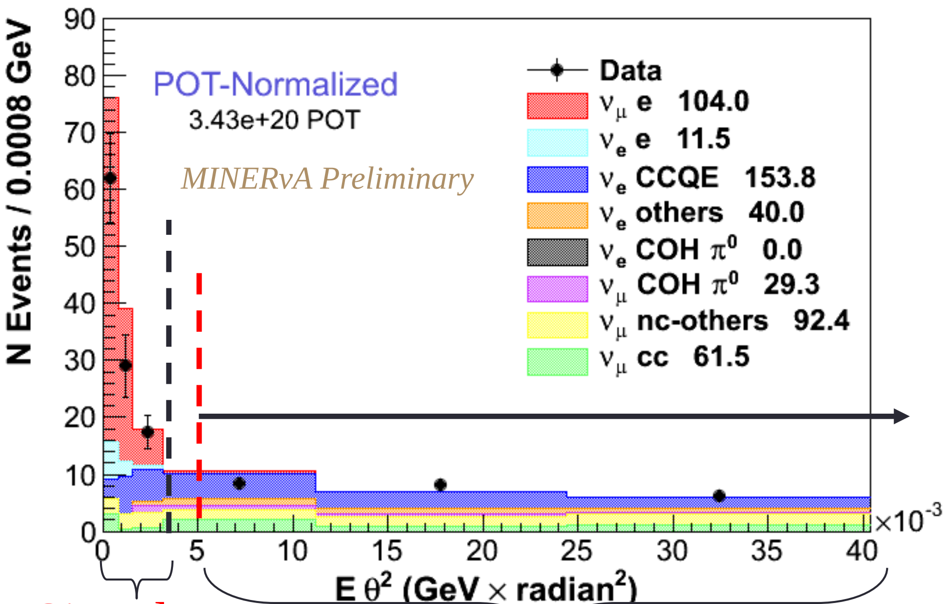






- All selections on data sample except dE/dx
- Note that for background, there is particle content other than single electron or photon (from π^0)
- This other activity affects dE/dx

Kinematic ($E\theta^2$) Selection and Electron Spectrum

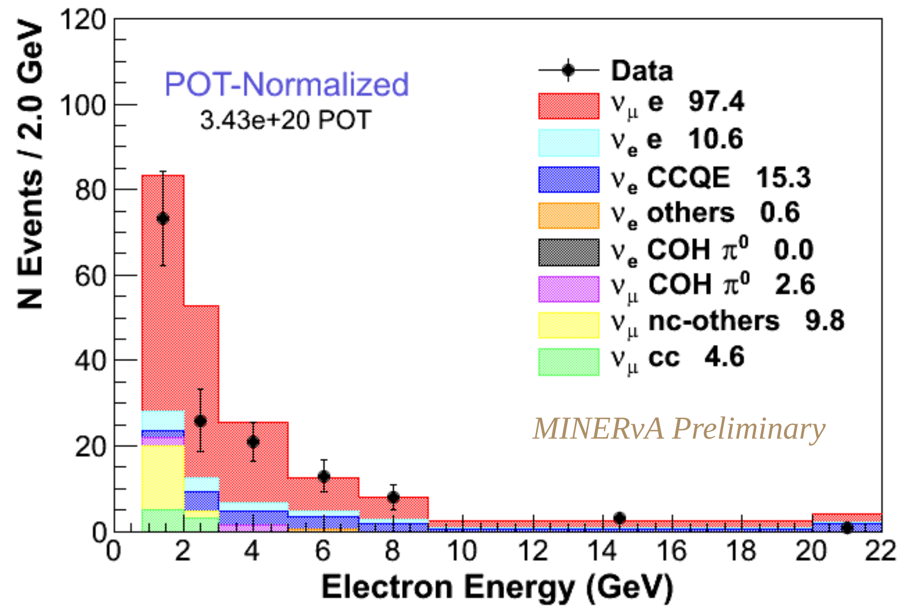


Signal

$E\theta^2 < 0.0032$

Sideband

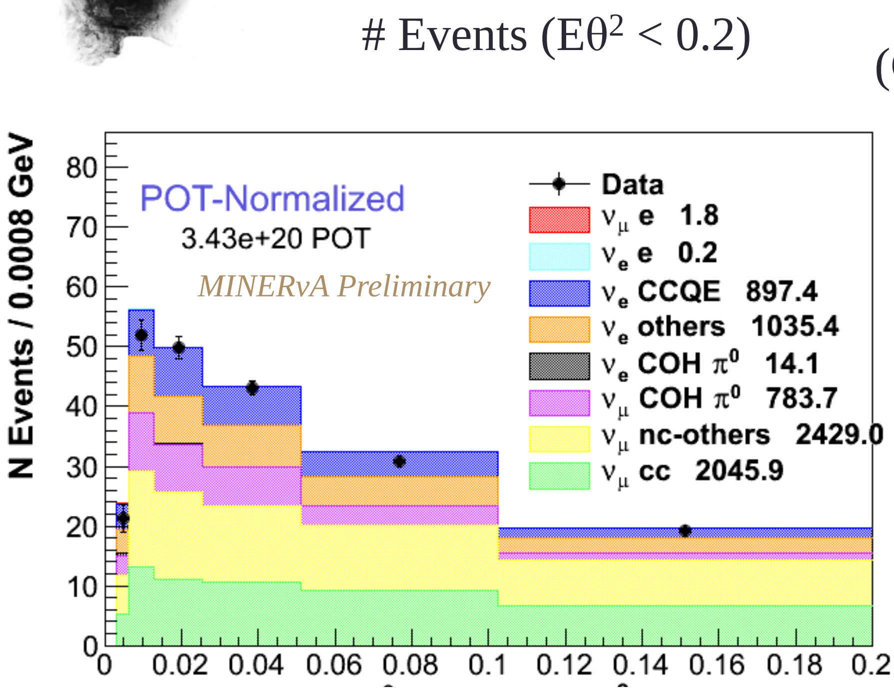
$E\theta^2 > 0.005\,\mathrm{GeV}\cdot\mathrm{rad}^2$

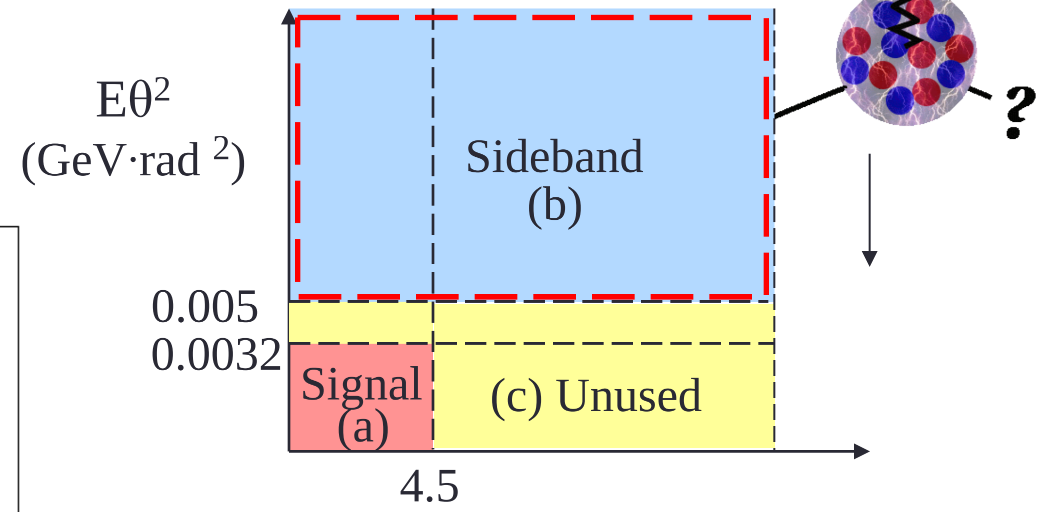


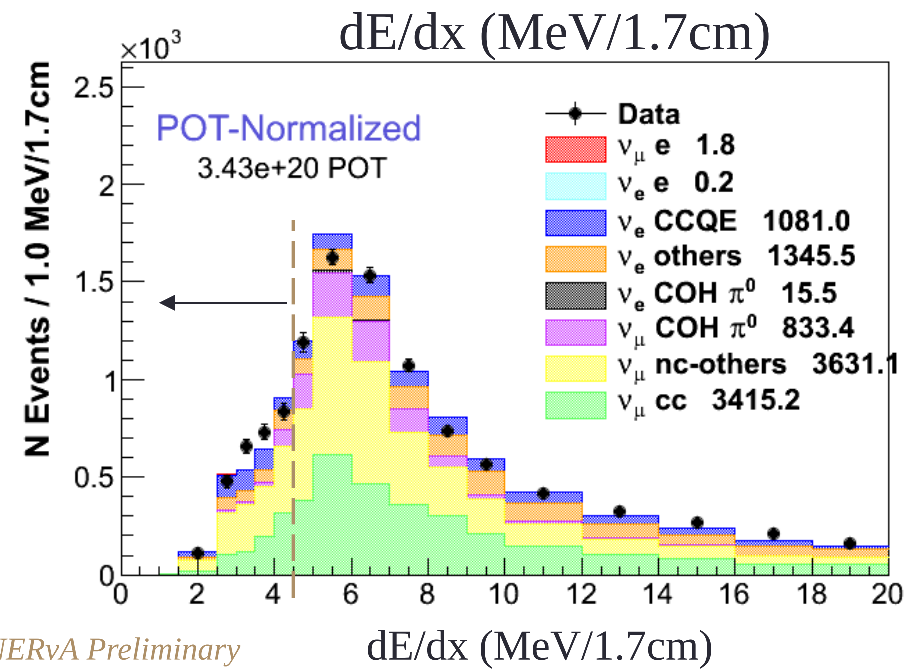
Need to know energy spectrum of background

- Background prediction is affected by the flux and physics model
  - Physics model is what MINERvA is trying to measure!
- Data-driven background prediction tuning is used to handle the uncertainty of predicted background

Sideband Kinematics after Tuning





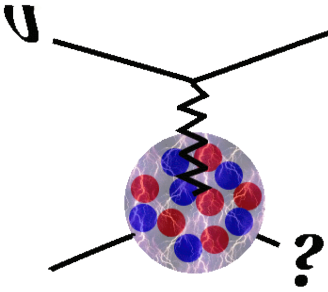


Parameter	Tuned value
ν_e	0.83 ± 0.04
ν_μ NC	0.81 ± 0.03
ν_μ CC	0.94 ± 0.01
COH π^0	0.90 ± 0.08

Systematic Uncertainties

Source	Uncertainty on Source	Systematic Uncertainty ν-e
Beam angle uncertainty	θ_x and θ_y : ± 1 mrad (measured with low recoil ν_μCC events	1.7%
Energy scale	4.2% (from Michel electrons)	1.9%
Absolute Electron Reconstruction Efficiency	<2% based on straight-through muon studies	2.8%
Simulation statistics (background)	Only a feature of the preliminary result.	6.0%
Flux (background)	Beam focusing, Beam tuning	1.3%
Reaction Models for Background processes (sideband extrapolation)	GENIE and CCQE Shape from MINERvA data (except to reduce x2 after retune)	6.3%

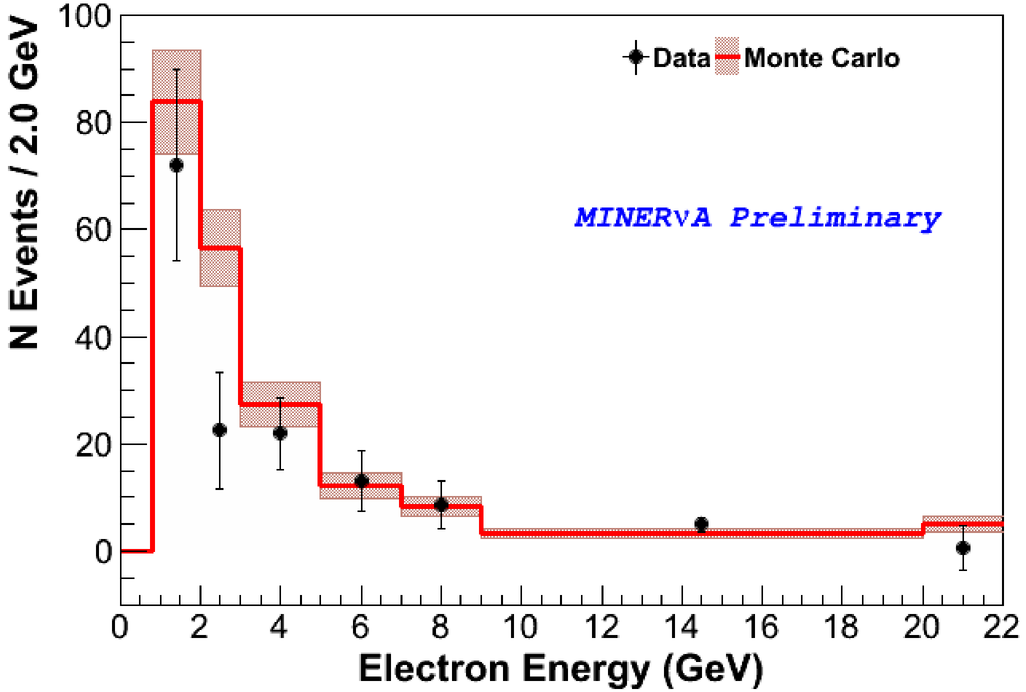
Result



- Found: 121 events before background subtraction
- ν-e scattering events after background subtraction and efficiency correction:

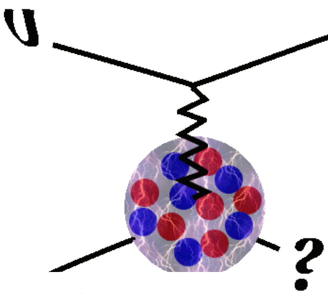
  123.8 ± 17.0 (stat) ± 9.1 (sys)

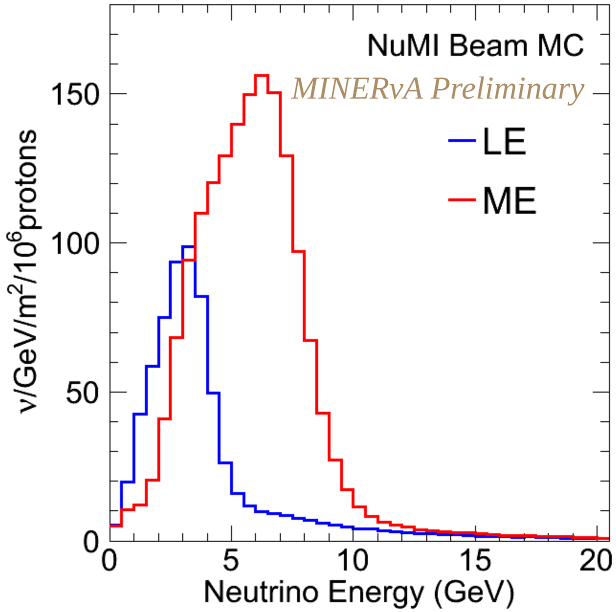
  total uncertainty: 15%
- Prediction from Simulation: 147.5 ± 22.9 (flux)
  - Flux uncertainty: 15.5%

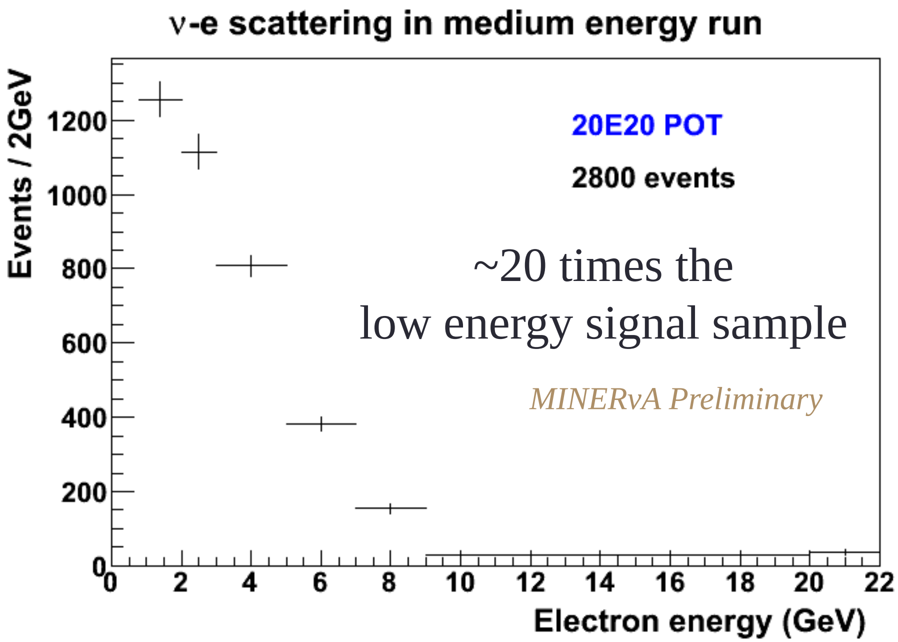


Observed ν-e scattering events give a constraint on flux with similar uncertainty as *a priori* flux uncertainty, consistent with that *a priori* flux

Future Flux at NuMI





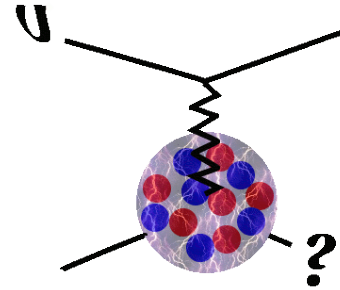


Medium Energy (NOvA) Run, as of September 2013

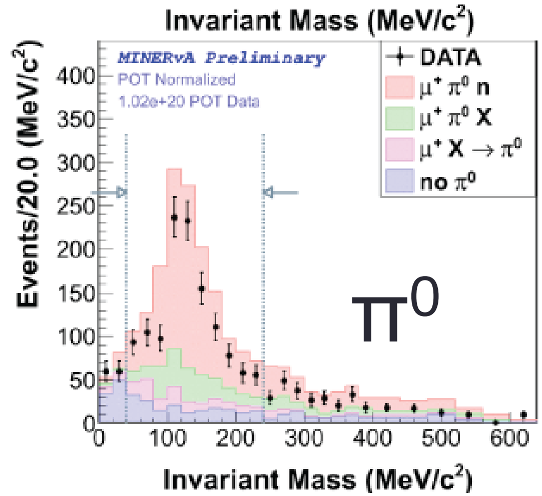
- Expect similar signal/background ratio as in Low Energy Run:
  - Can expect statistical uncertainty of ~2%
  - Systematic uncertainty on this measurement is now 7% → 5% "easily"
- As noted, this technique is, in principle, a "cheap" flux measurement for future oscillation experiments, at least for flux above ~1.5 GeV

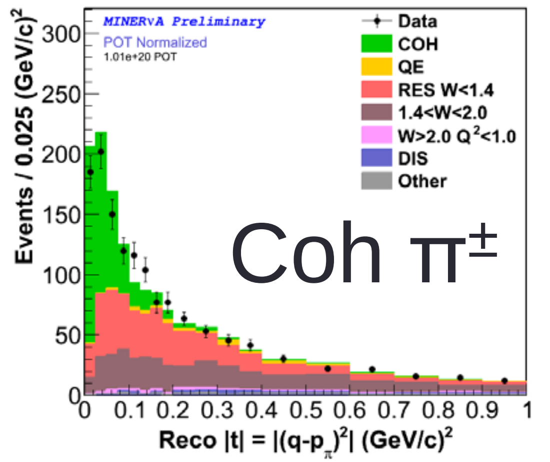
Conclusions and Outlook

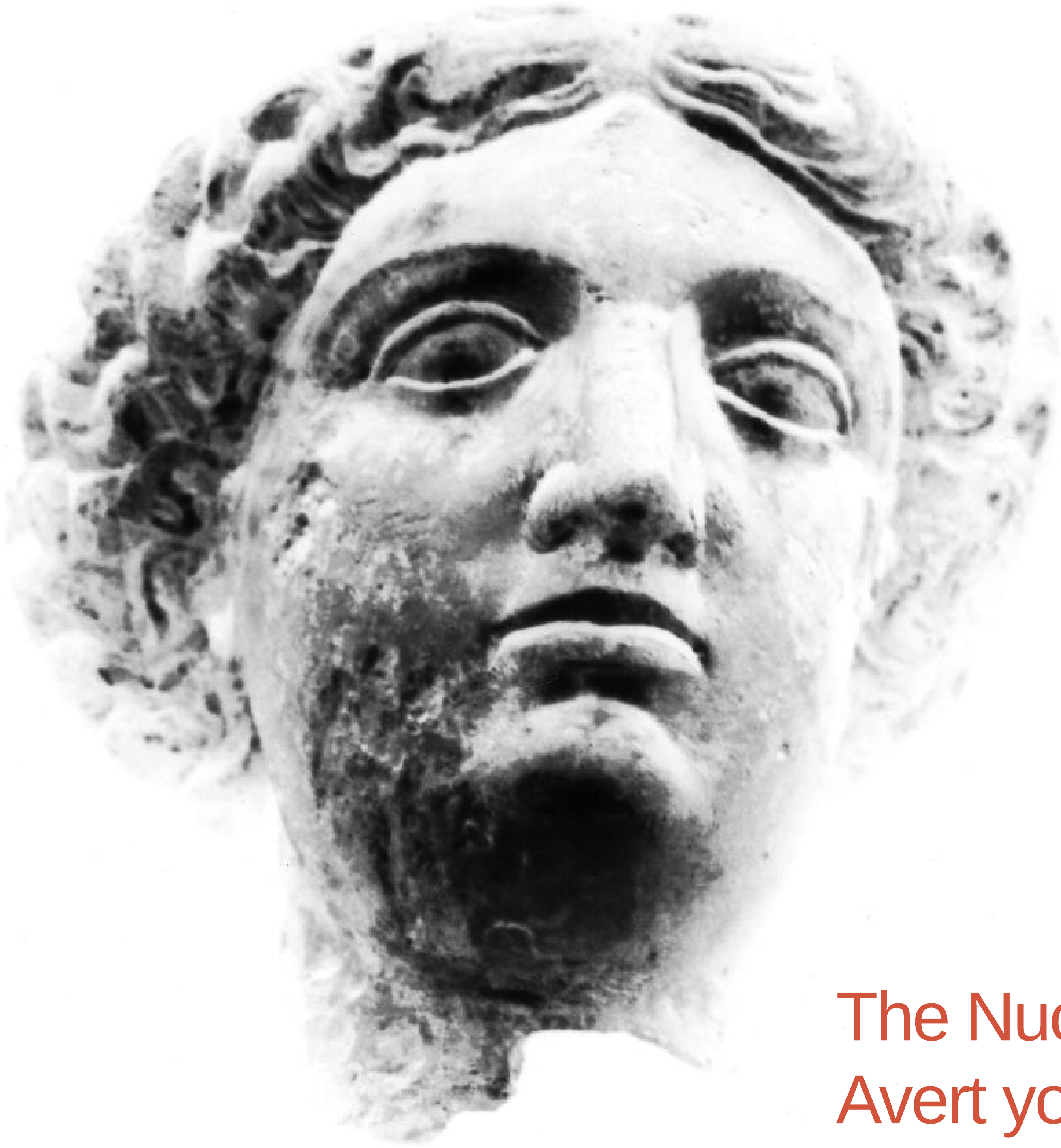
MINERvA Continues



- More news about quasi-elastic scattering in MINERvA's near future
  - Join us on May 8th for a Wine and Cheese seminar by Tammy Walton on exclusive μ+p
- At NuINT, at least one new pion result
  - Resonant π^0 companion to recent π^+
  - Coherent $\pi^\pm$ in neutrinos and anti-neutrinos
- In current (NOvA era) beam, we are collecting high statistics neutrinos and anti-neutrinos. Most beneficial for nuclear target ratios and DIS studies.
- Results should continue to improve model descriptions used by both theory and oscillation experiments



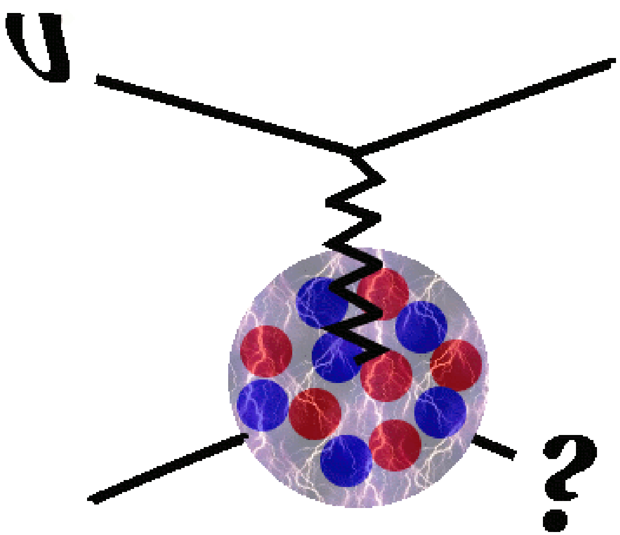


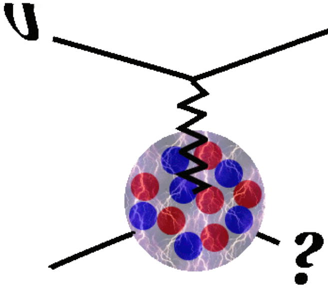


The Nucleus?
Avert your gaze!

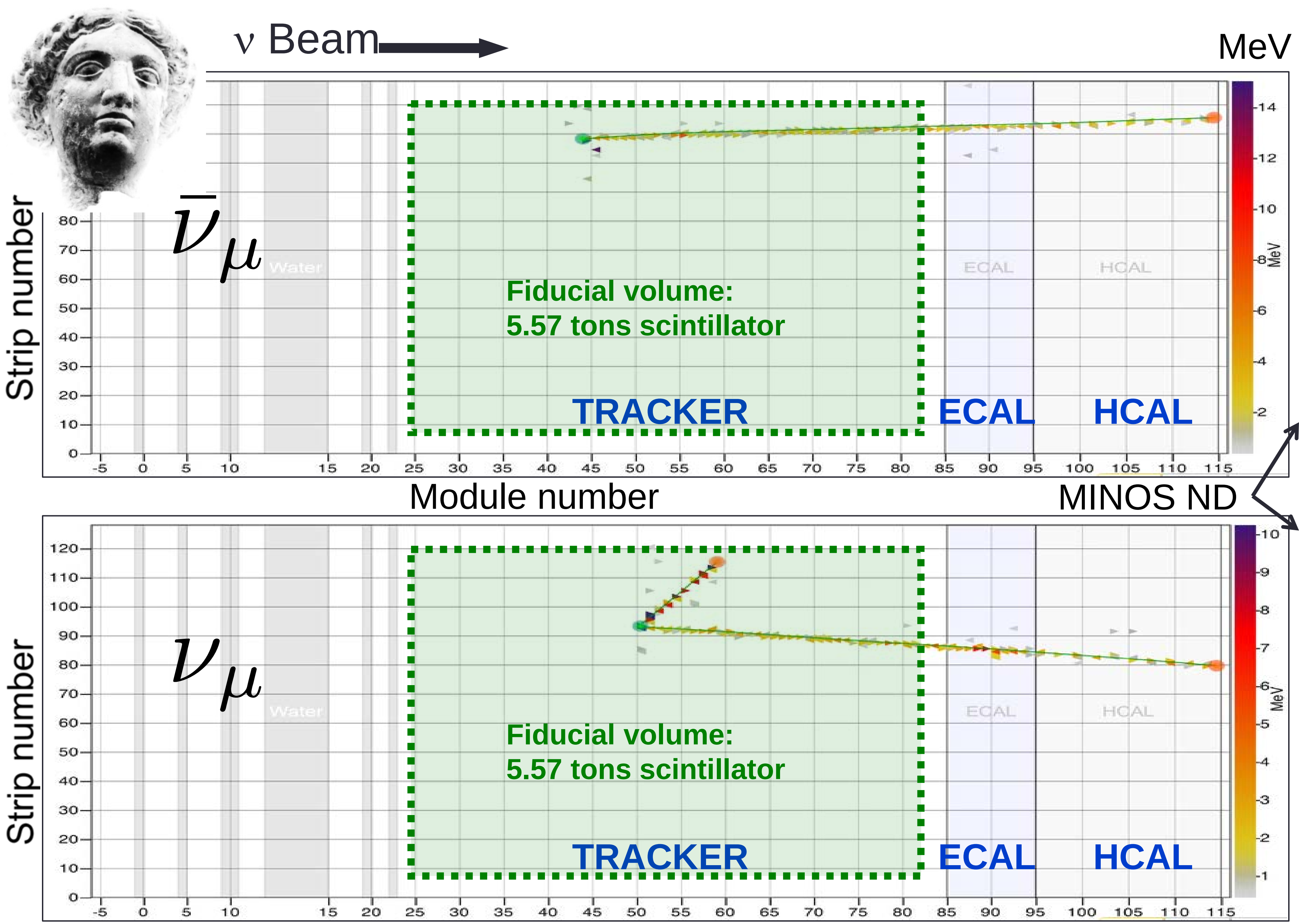
NEUTRINO INTERACTIONS AT MINERvA

Kevin McFarland
University of Rochester
FNAL Intensity Frontier Seminar
1 May 2014



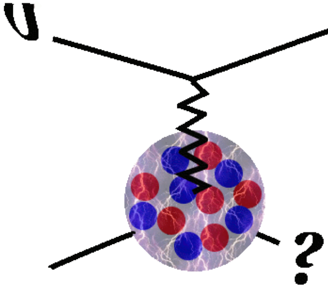


Extra CCQE Slides



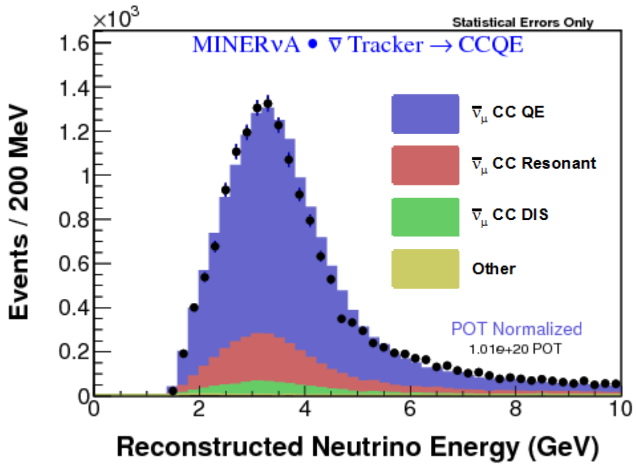
ν Beam
MeV
$\bar{\nu}_\mu$
Strip number
Water
Fiducial volume:
5.57 tons scintillator
TRACKER
ECAL
HCAL
Module number
MINOS ND
ν_μ
Strip number
Fiducial volume:
5.57 tons scintillator
TRACKER
ECAL
HCAL

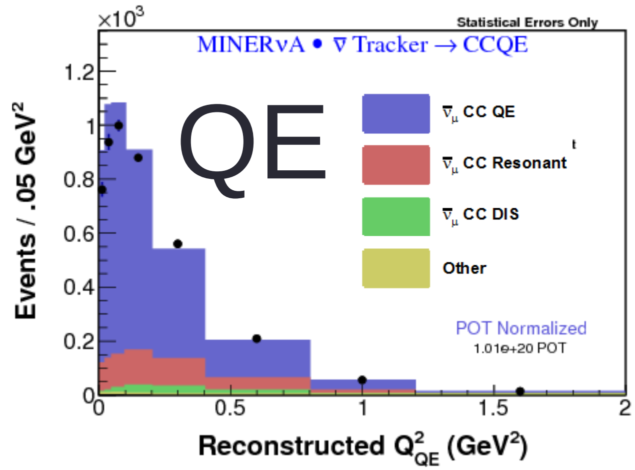
CCQE Event Candidates



$$E_\nu^{QE} = \frac{2\left(M_n - E_B\right)E_\mu - \left[\left(M_n - E_B\right)^2 + m_\mu^2 - M_p^2\right]}{2\left[\left(M_n - E_B\right) - E_\mu + \sqrt{E_\mu^2 - m_\mu^2}\cos\theta_\mu\right]}$$

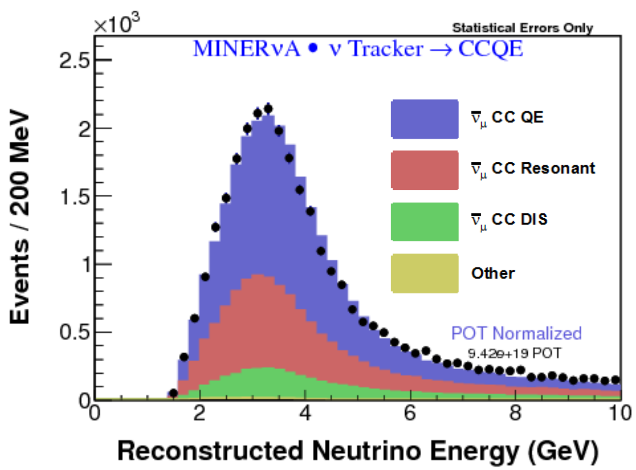
$$Q_{QE}^2 = -m_\mu^2 + 2E_\nu^{QE}\left(E_\mu - \sqrt{E_\mu^2 - m_\mu^2}\cos\theta_\mu\right)$$

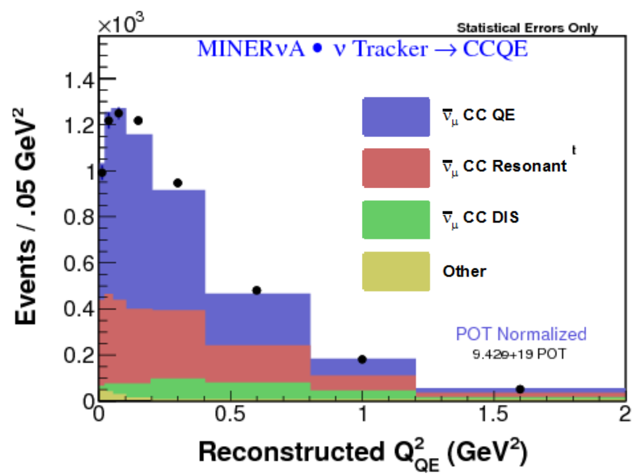




$\bar{\nu}_\mu$

16,467 events
54% eff.
77% purity

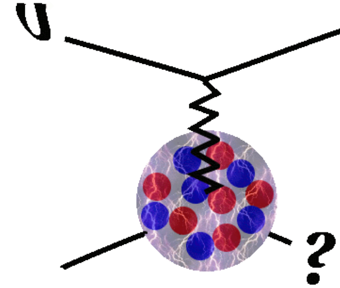




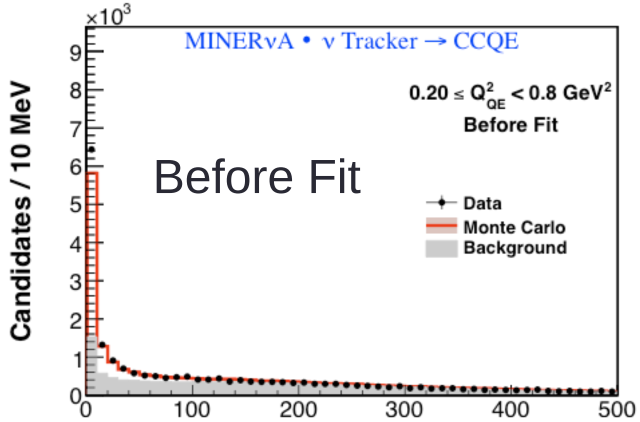
ν_μ

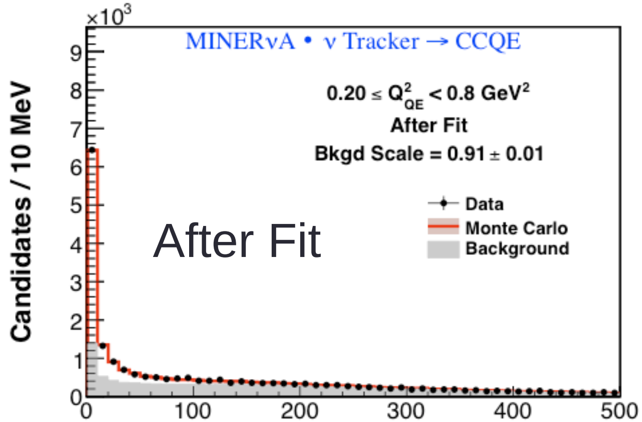
29,620 events
(uses first 1/3 of data)
47% eff.
49% purity

Constraint on Background



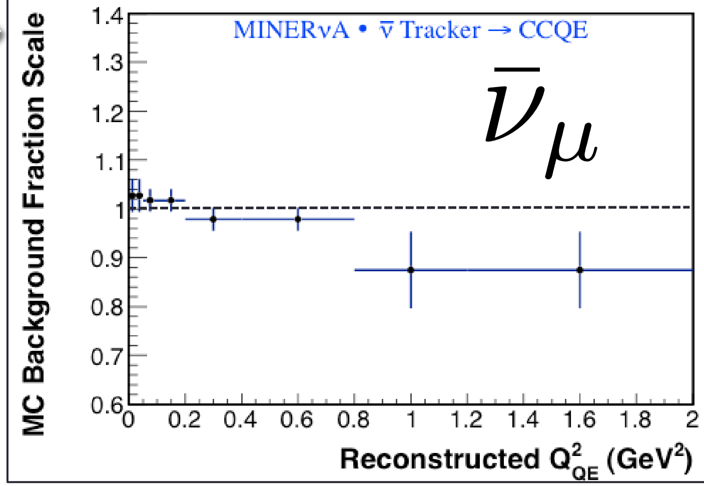
Sample Q^2_{QE} Bin

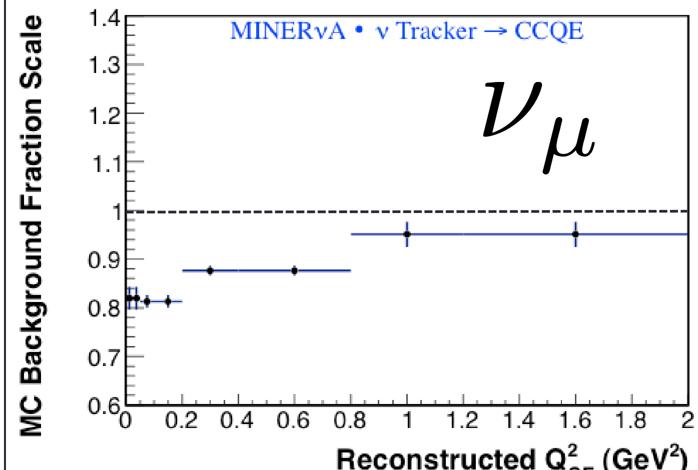




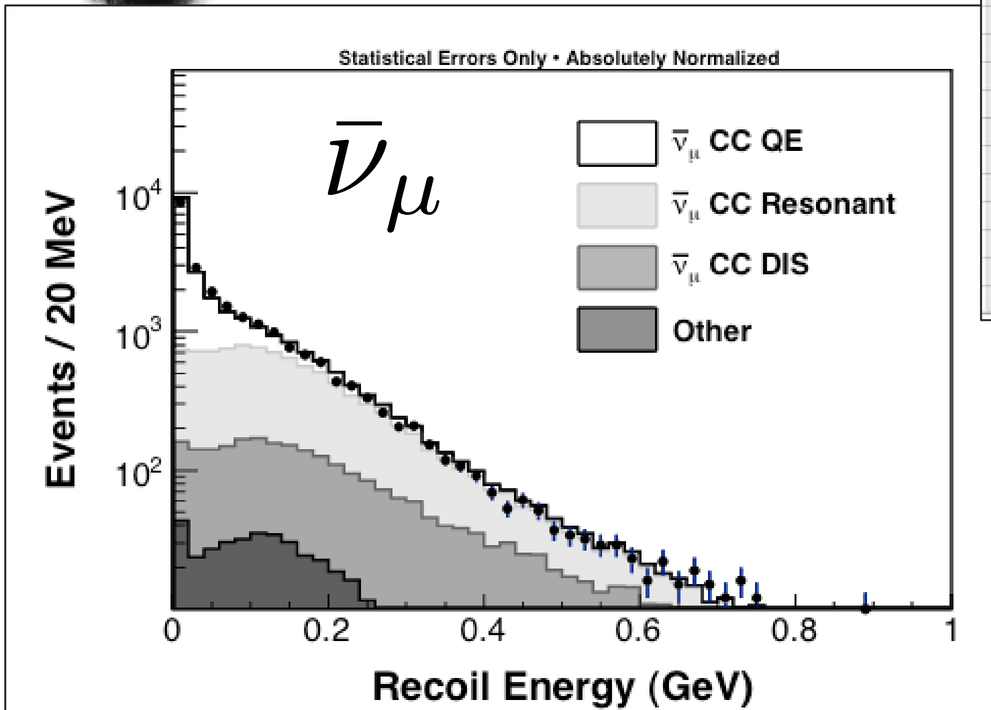
All Bins

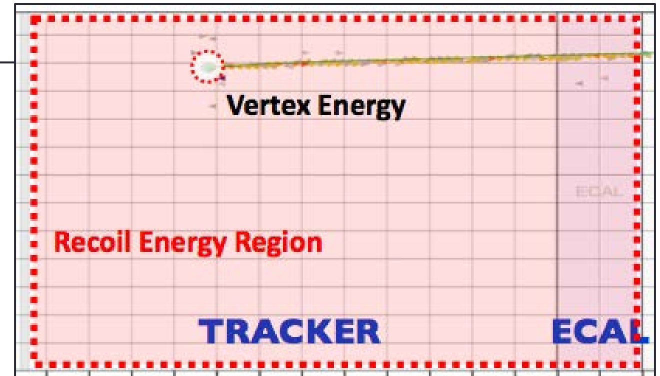
Modifies the predicted non-QE background rate by 5-15%

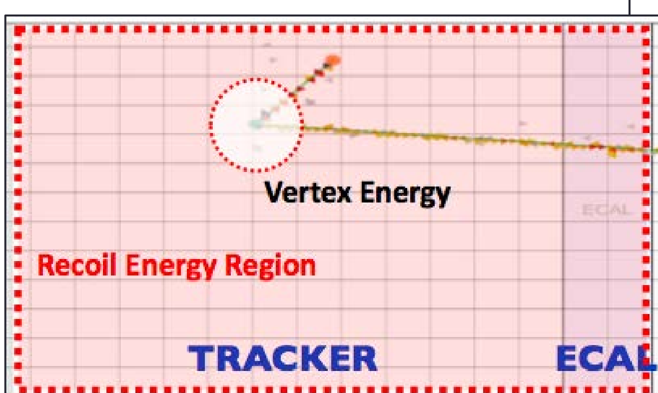


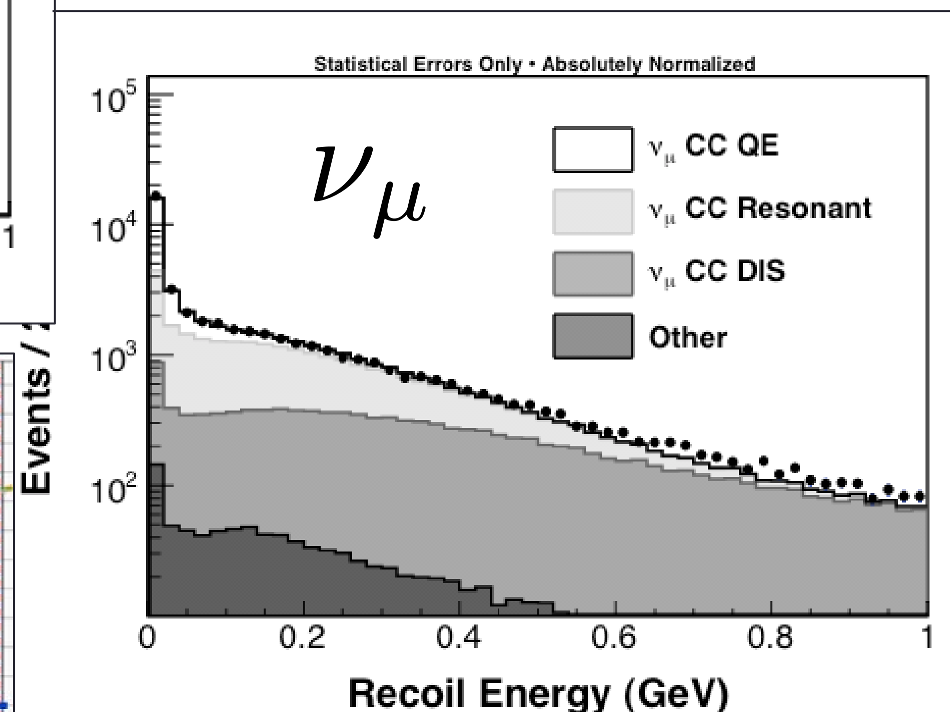


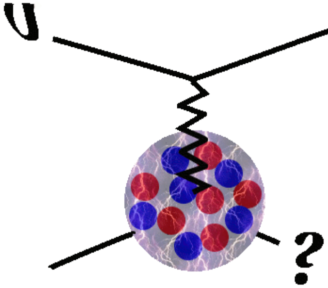
Post-fit Recoil Distributions





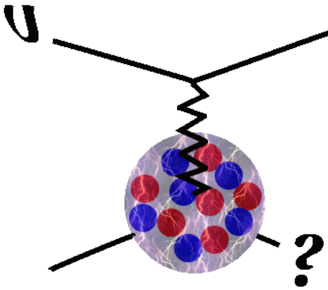






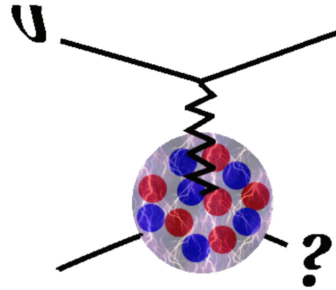
CCQE Models and χ^2

Models of $d\sigma/dQ^2$ Shape



- Models that introduce nuclear correlations of various kinds ***tend to modify the QE cross-section as a function of Q^2*** (for a given ν energy spectrum)
- The models:
  - Relativistic Fermi Gas (RFG), M_A = 0.99 GeV/c^2
    - The canonical model in modern event generators used by all neutrino experiments
  - Relativistic Fermi Gas (RFG), M_A = 1.35 GeV/c^2
    - Motivated by recent measurements where this change was fairly successful at reproducing data
  - Nuclear Spectral Function (SF), M_A = 0.99 GeV/c^2
    - More realistic model of the nucleon momentum – energy relationship than standard RFG
  - Random Phase Approximation (RPA), M_A = 0.99 GeV/c^2
    - Introduce an effective field induced by long-range correlations between nucleons
  - Transverse Enhancement Model (TEM), M_A = 0.99 GeV/c^2
    - Empirical model which modifies the magnetic form factors of bound nucleons to reproduce an enhancement in the transverse cross-section observed in ***electron-nucleus scattering*** attributed to the presence of meson exchange currents (MEC) in the nucleus

$d\sigma/dQ^2$ Shape



- The shape of the measured neutrino and antineutrino $d\sigma/dQ^2$ cross-sections ***disfavor a standard relativistic Fermi gas*** implementation for carbon with M_A = 0.99 GeV/c^2

$\bar{\nu}_\mu$

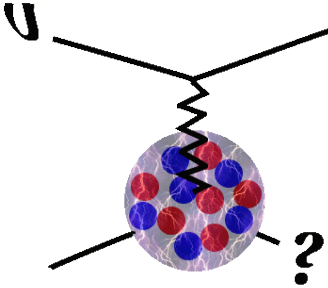
NuWro Model	RFG	RFG +TEM	RFG	SF	RPA
M_A (GeV)	0.99	0.99	1.35	0.99	0.99
Rate χ^2/d.o.f.	2.64	1.06	2.90	2.14	2.90
Shape χ^2/d.o.f.	2.90	0.66	1.73	2.99	3.70

ν_μ

NuWro Model	RFG	RFG +TEM	RFG	SF	RPA
M_A (GeV/c^2)	0.99	0.99	1.35	0.99	0.99
Rate χ^2/d.o.f.	3.5	2.4	3.7	2.8	7.75
Shape χ^2/d.o.f.	4.1	1.7	2.1	3.8	10.5

- Changing only the axial-mass M_A = 1.35 GeV/c^2 does marginally improve agreement with data

- The data most prefer an empirical model that attempts to transfer the observed ***enhancement*** in electron-nucleus scattering ***attributed to meson exchange current (MEC) contributions*** to neutrino-nucleus scattering

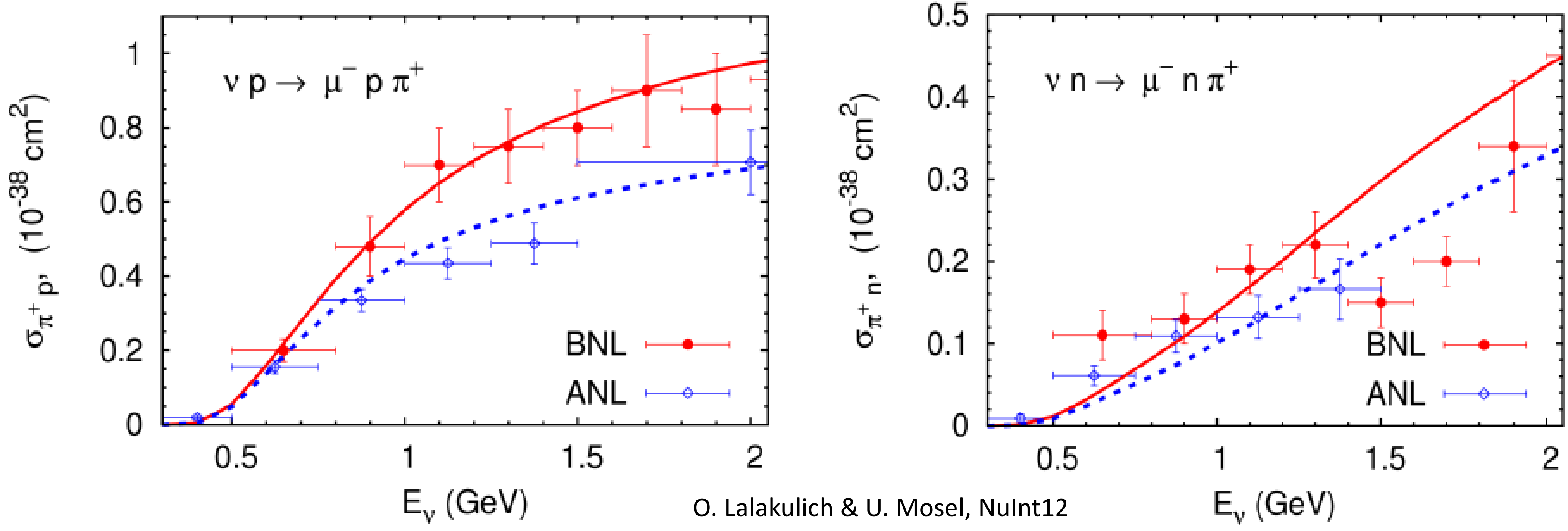


Extra Pion Slides

Resonance Pion Production: Deuterium

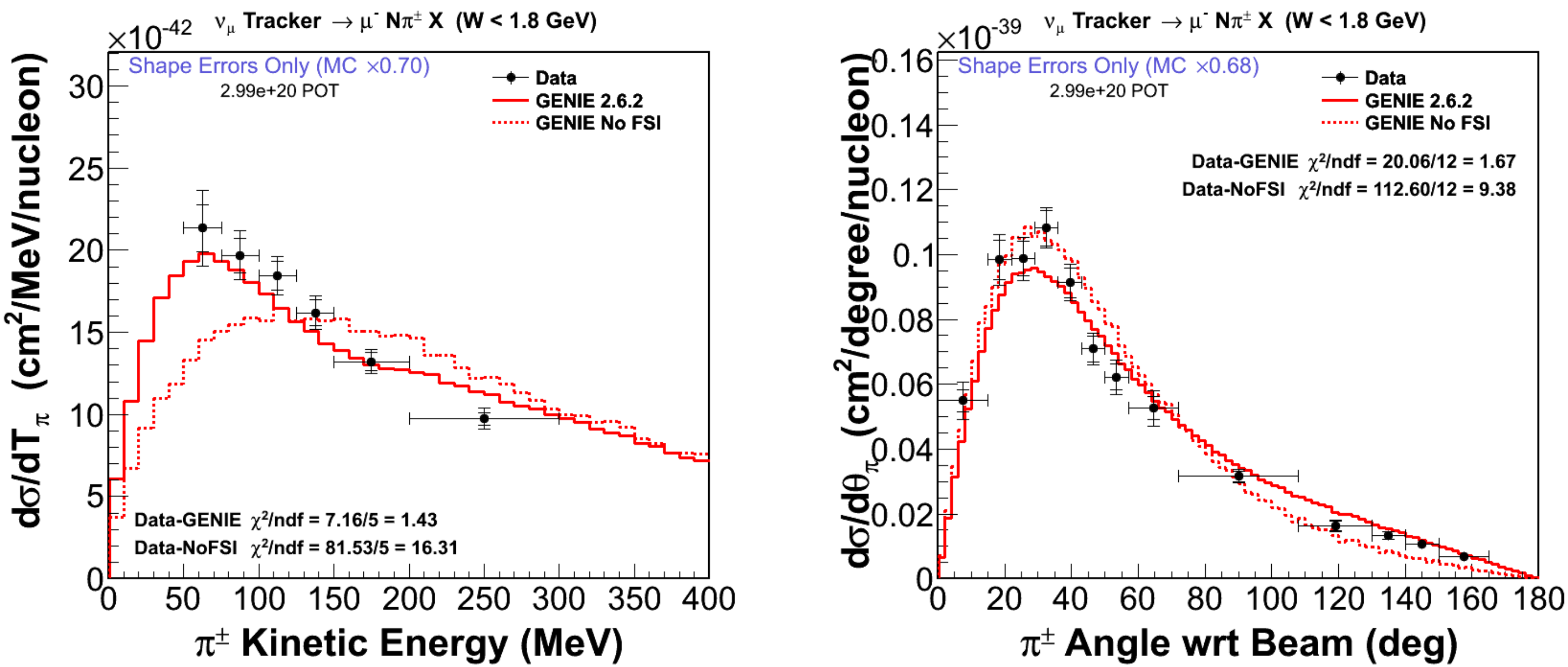
- Most experiments use the Rein-Sehgal model for νN resonance production
  - More recent models by M. Athar, Salamanca-Valencia, M. Pascos

- Experimentalist's dilemma: Whichever model you use, it will be poorly constrained by νN data



O. Lalakulich & U. Mosel, NuInt12

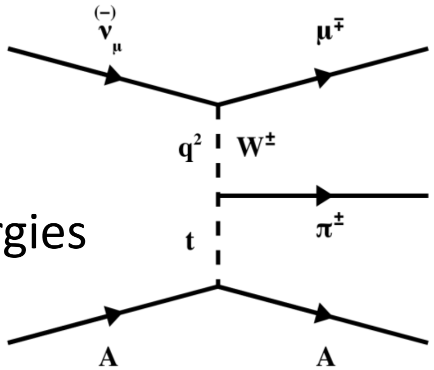
Shape Results, W < 1.8 GeV



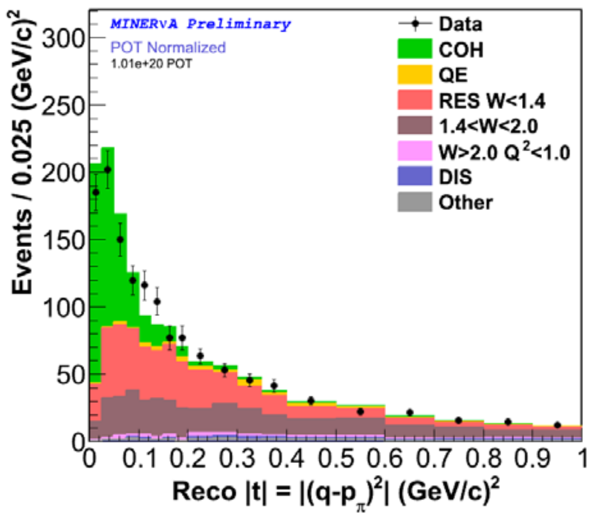
Another version of the analysis, allowing for multiple pions in the final state and higher order resonances: W < 1.8 GeV

An additional ~2000 pion candidates – shape is statistics limited

Future Pion Measurements in MINERvA

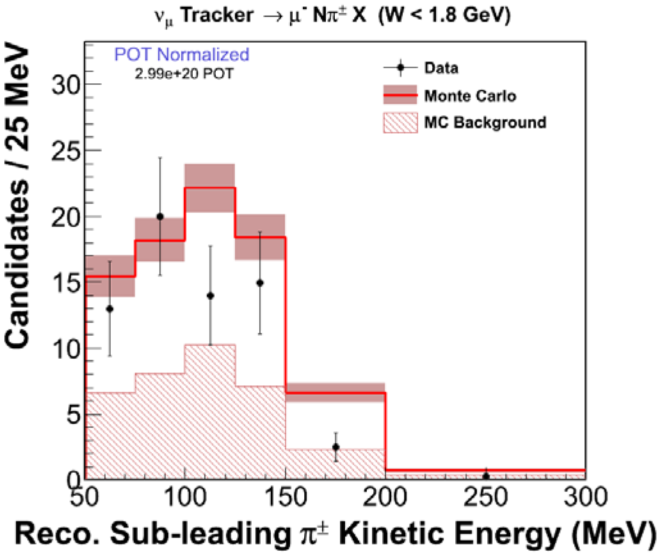


- Charged current coherent pion production
  - Has not been conclusively observed at ~few GeV energies



- Full suite of resonant pion 1D and 2D differential cross sections
  - Also for antineutrino and π^0

- Pion production (resonant and coherent) in the nuclear targets
  - A-dependence of cross sections, FSI

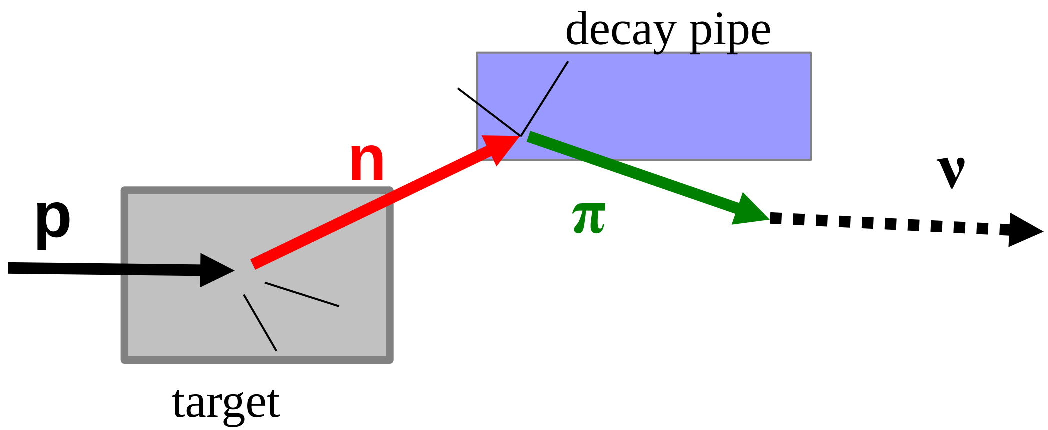


- Multi-pion events
  - Small sample, requires more statistics (ME beam) and/or better reconstruction (low energy pion reconstruction with Michels?)

Hadroproduction Constraints on Flux

Constraining flux with Hadron Production Data

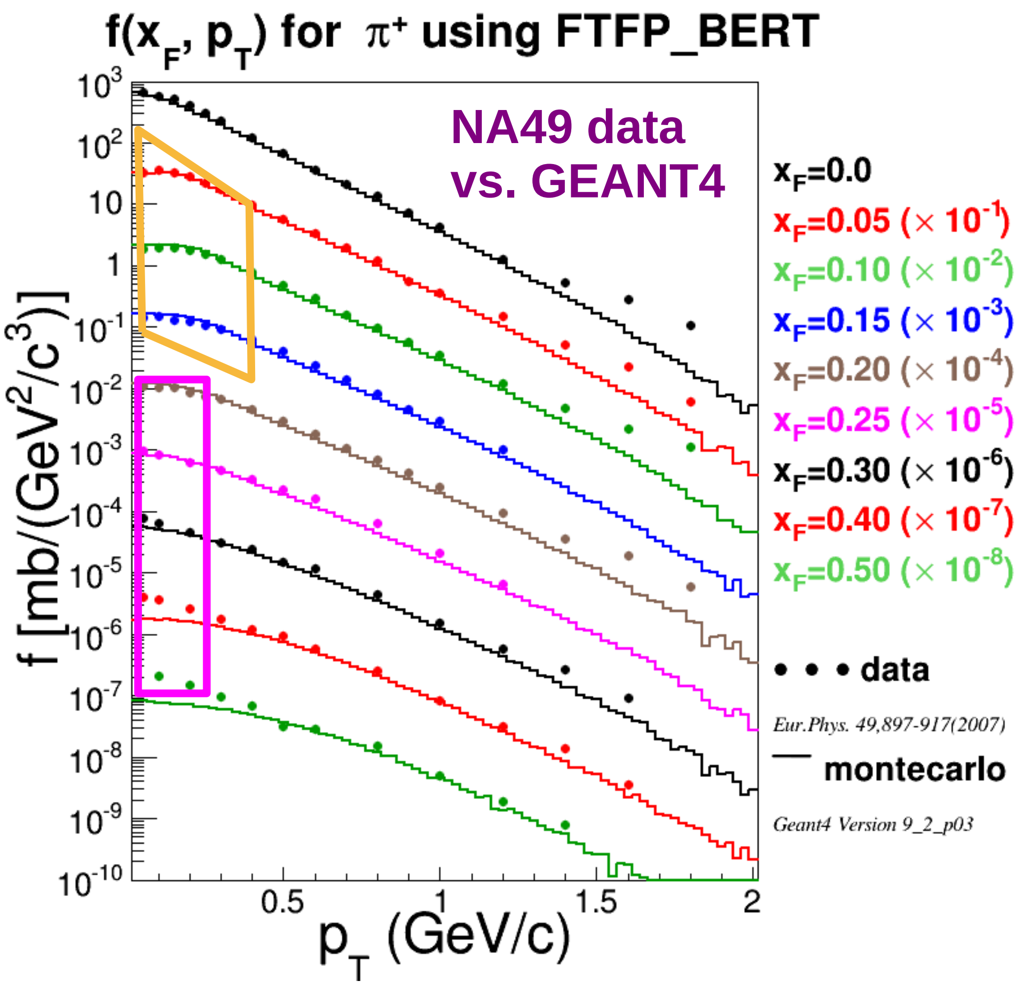
- Hadron production primarily function of x_F=pion/proton momentum ratio and $p_{transverse}$
  - Use NA49 measurements
  - Scale to 120 GeV using FLUKA (simulation)
  - Check by comparing to NA61 data at 31 GeV/c [Phys.Rev. C84 (2011)034604]
- Use MIPP (120GeV protons) for K/π ratio

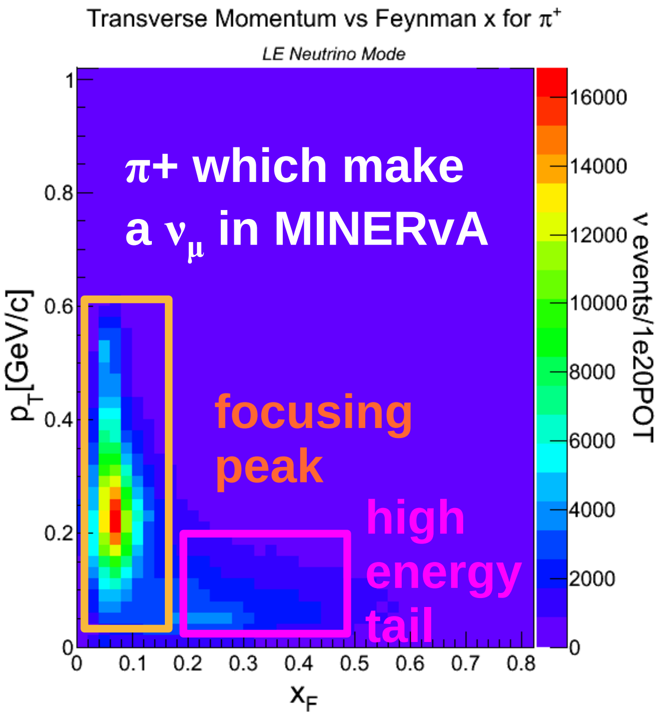


	Particle production	x_F	Reference
NA49 pC @158 GeV	$\pi^\pm$	<0.5	Eur.Phys.J. C49 (2007) 897
	$K^\pm$	<0.2	G. Tinti Ph.D. thesis
	p	<0.9	Eur.Phys.J. C73 (2013) 2364
MIPP pC @ 120 GeV	K/π ratio		A. Lebedev Ph.D. thesis

NA49: pC → π,K,p @ 158 GeV

$f(x_F,p_T) = E\, d^3\sigma/dp^3$ = invariant production cross-section

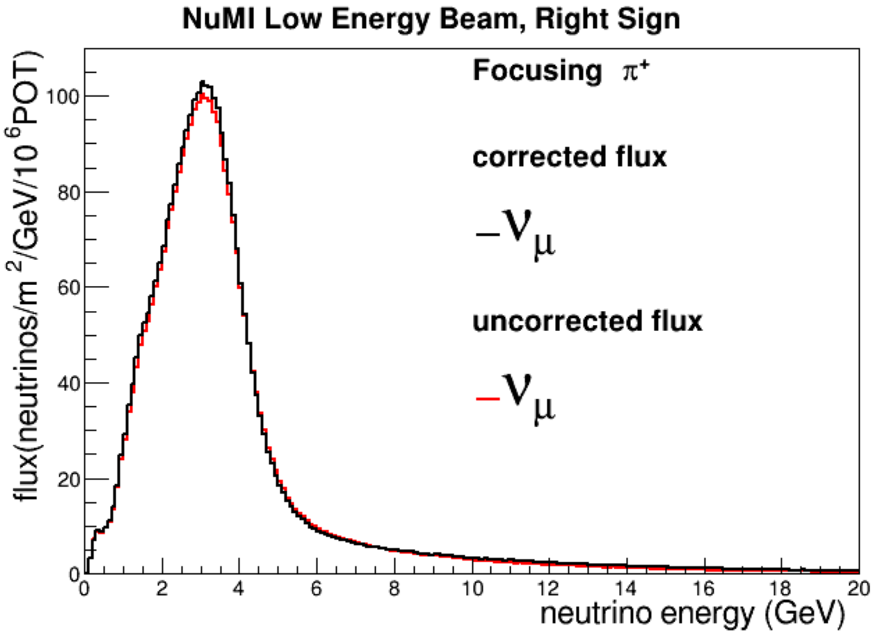




Uncertainties
7.5% systematic
2-10% statistical

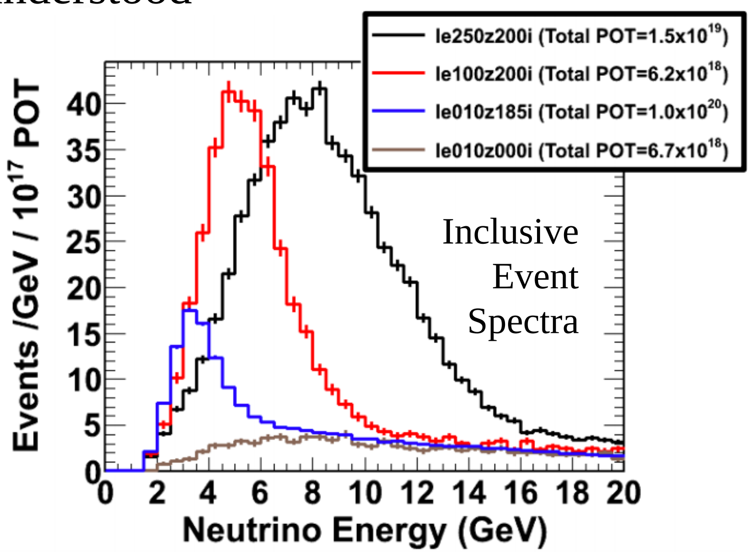
Need more than Hadron Production Measurements

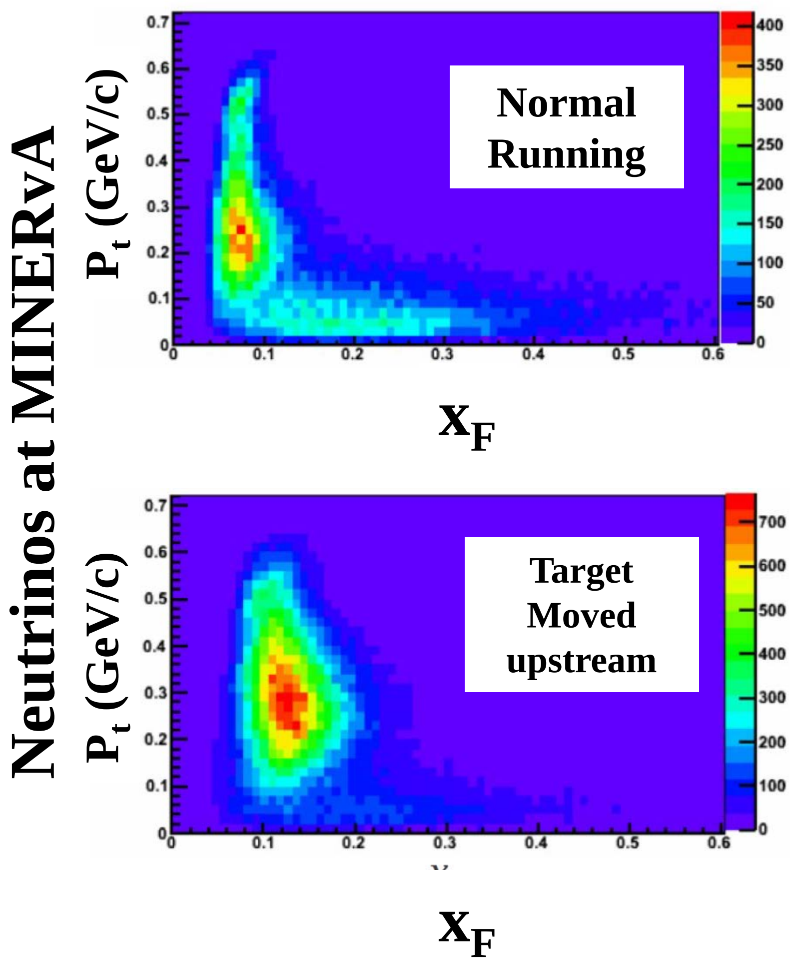
- Hadron Production measurements don't tell the whole story, only 70%
  - Some pion production is out of range of Hadron Production data
  - Tertiary production of neutrinos also important (n, η, $K_{L,S}$)
- Beamline geometry and focusing elements contribute uncertainties



Special Runs to Understand Flux

- MINERvA integrated 10% of our total neutrino beam exposure in alternate focusing geometries:
  - Changed horn current
  - Changed Target Position
- Purpose is to disentangle focusing uncertainties from hadron production uncertainties
  - Different geometry focuses different parts of xF p_T space, but same horn geometry and current
- MINERvA does this by using low hadron energy ν_μ charged current events, where energy dependence of cross section is very well understood





Pion Phase Space

Neutrino Flux and Cross-section Measurement

MINERvA

$$\sigma = \frac{N}{\varepsilon A \Phi}$$

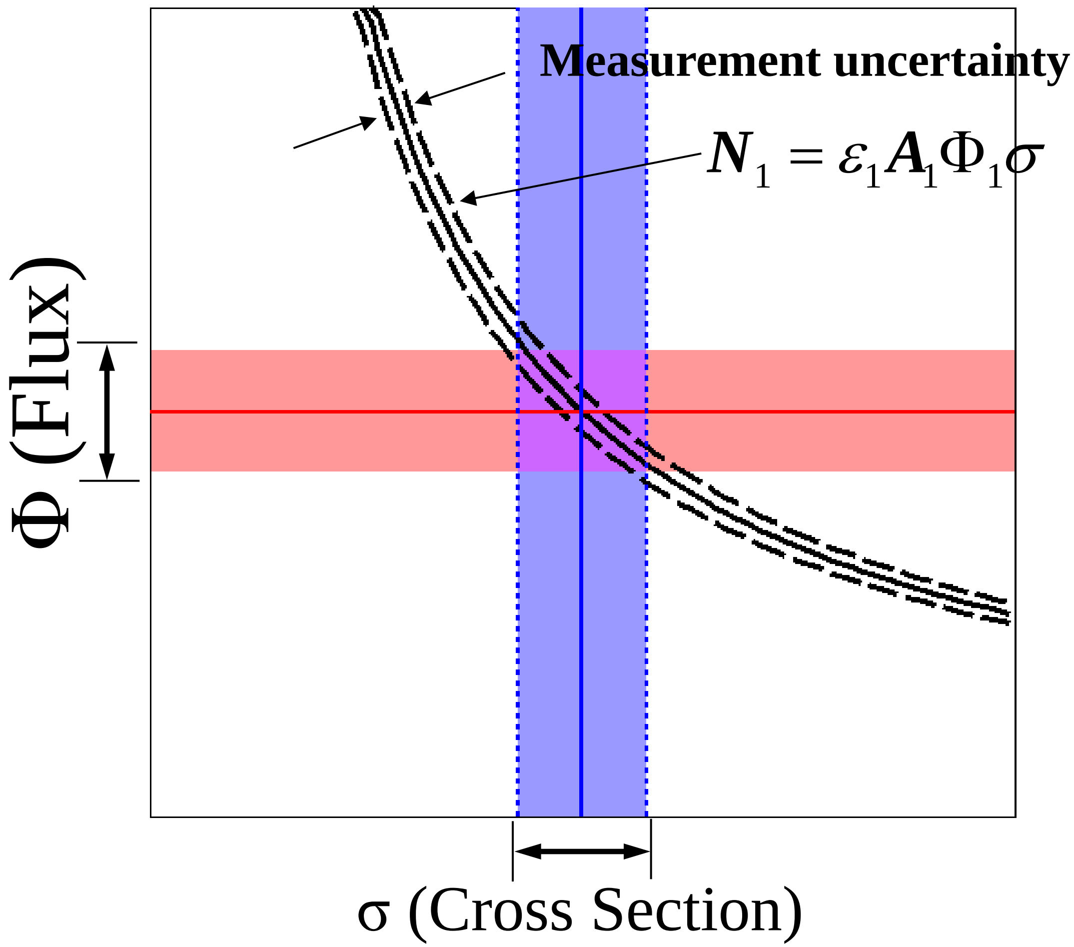
Flux uncertainty goes into cross-section uncertainty

Flux constraint using Near Detector

$$\Phi = \frac{N}{\varepsilon A \sigma}$$

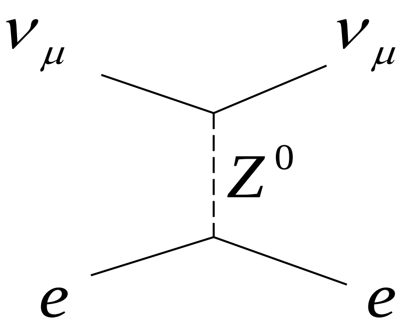
Cross-section uncertainty goes into flux uncertainty

N: Events
ε: Efficiency
A: Acceptance
σ: signal cross section



- Flux and cross-section are anti-correlated with given Near Detector constraint

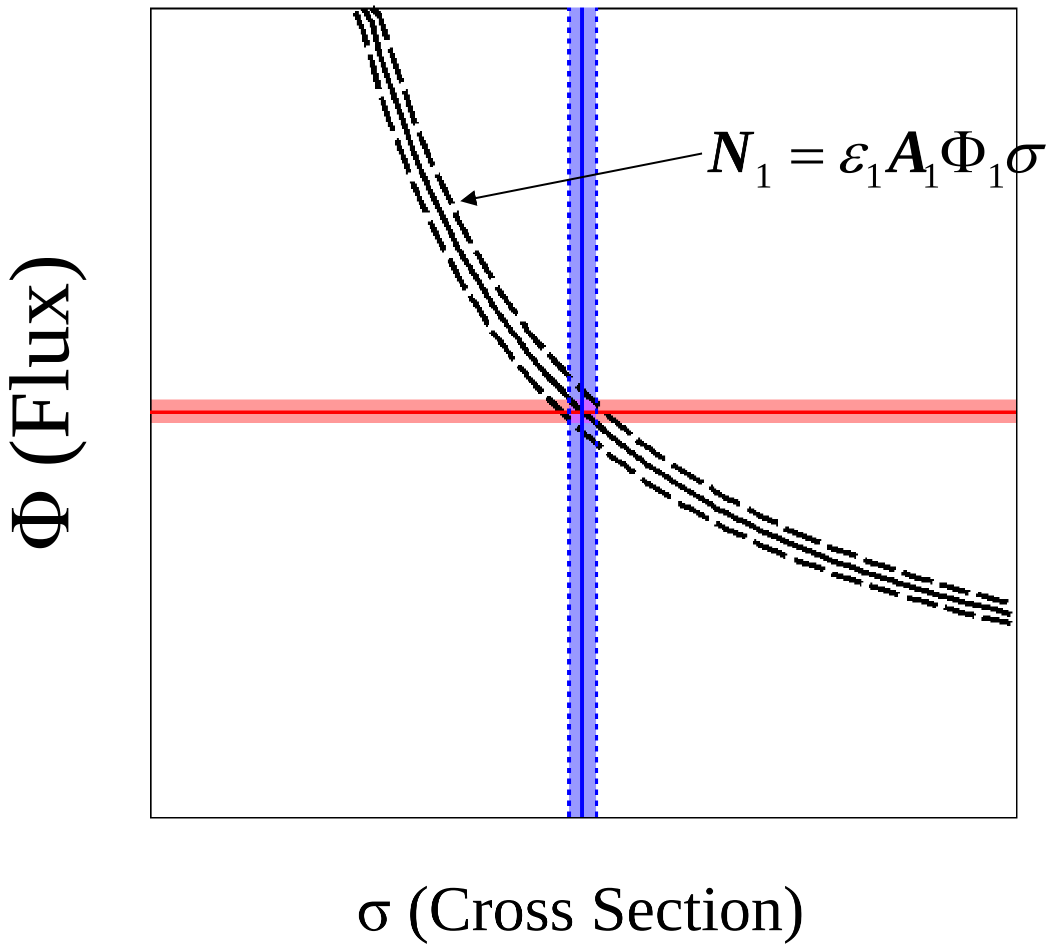
Known Interaction (Standard Candle)



Flux constraint using ND

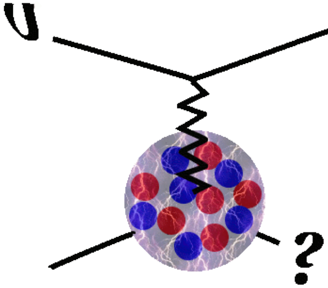
$$\Phi = \frac{N}{\varepsilon A \sigma}$$

Cross-section uncertainty goes into flux uncertainty



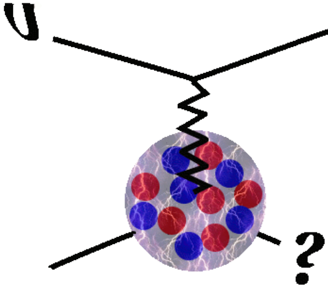
- ν-e scattering is well known interaction we can use to constrain the neutrino flux

ν-e Scattering

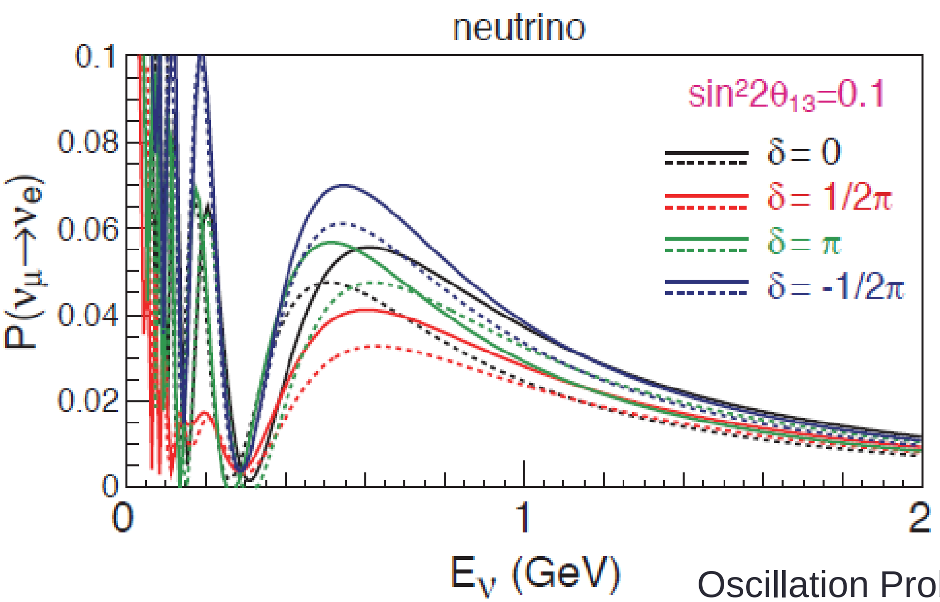


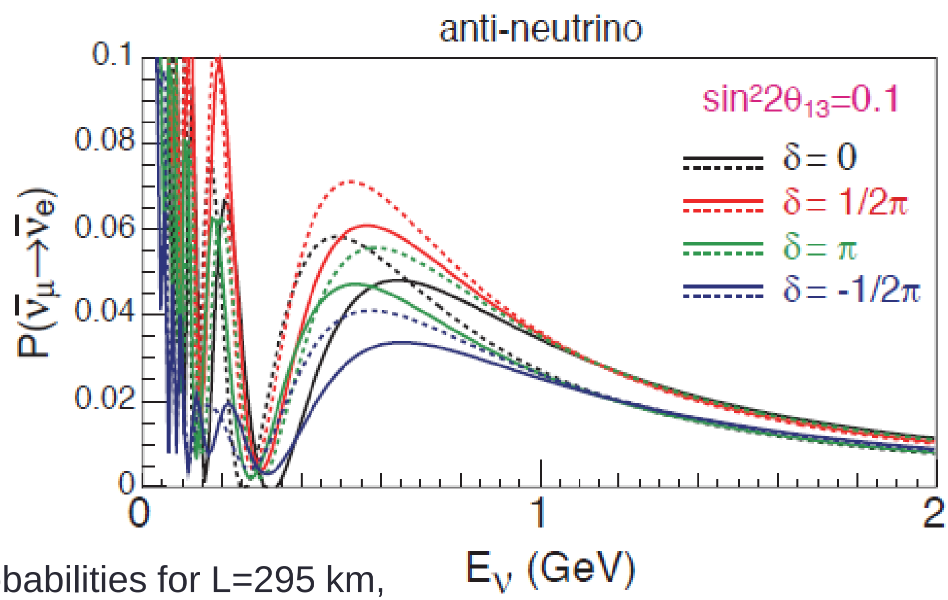
Oscillation Probabilities as a Function of Energy at Fixed Length

Oscillations: Needs



- Discovery of CP violation in neutrino oscillations requires seeing distortions of $P(\nu_\mu \rightarrow \nu_e)$ as a function of neutrino and anti-neutrino energy
- Note that δ can change rate, or spectrum, or both

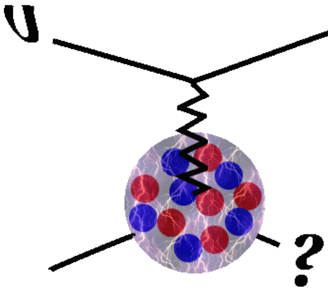




Oscillation Probabilities for L=295 km, Hyper-K LOI

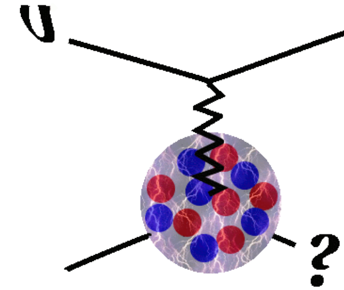
Oscillation Experiments and Near Detectors

Oscillations: Near Detectors

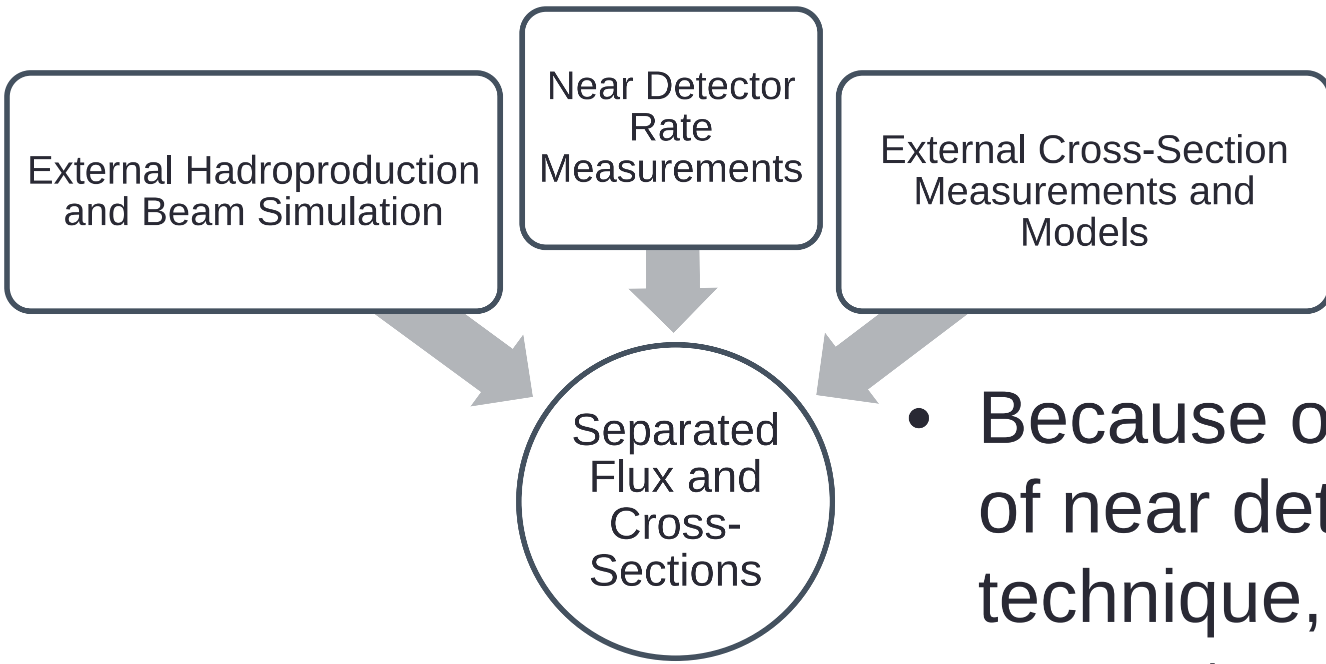


- Near detectors are a powerful tool for constraining uncertainties in flux and cross-sections
- Limitations of even "perfect" near detectors:
  1. Flux is never identical near and far, because of oscillations if for no other reason.
  2. Near detector has backgrounds to reactions of interest which may not be identical to far detector (see #1).
  3. Neutrino energy, on which the oscillation probability depends, may be smeared or biased.
  4. Near detectors measure (dominantly) interactions of muon neutrinos when signal is electron neutrinos.

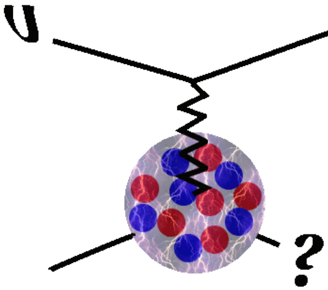
Oscillations: Breaking the Flux & σ Degeneracy



- Experiments have a, more or less, universal scheme for using the near detector data to get flux and cross-section

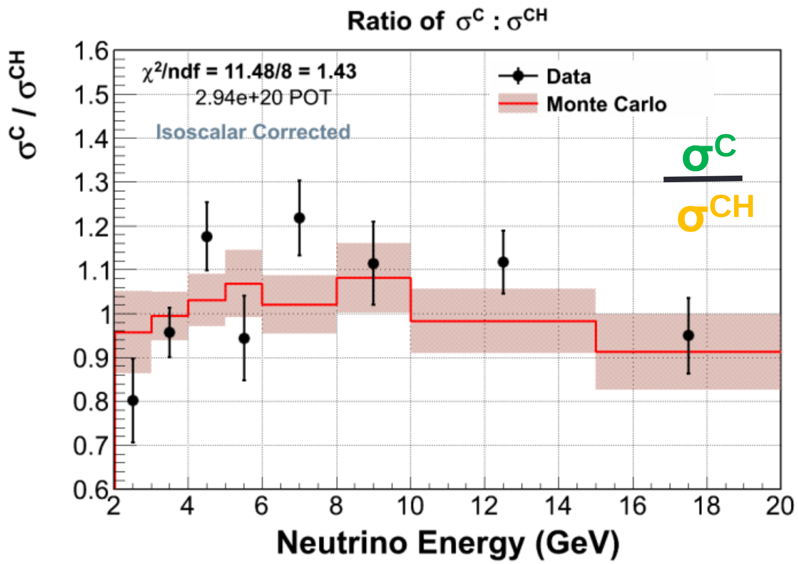


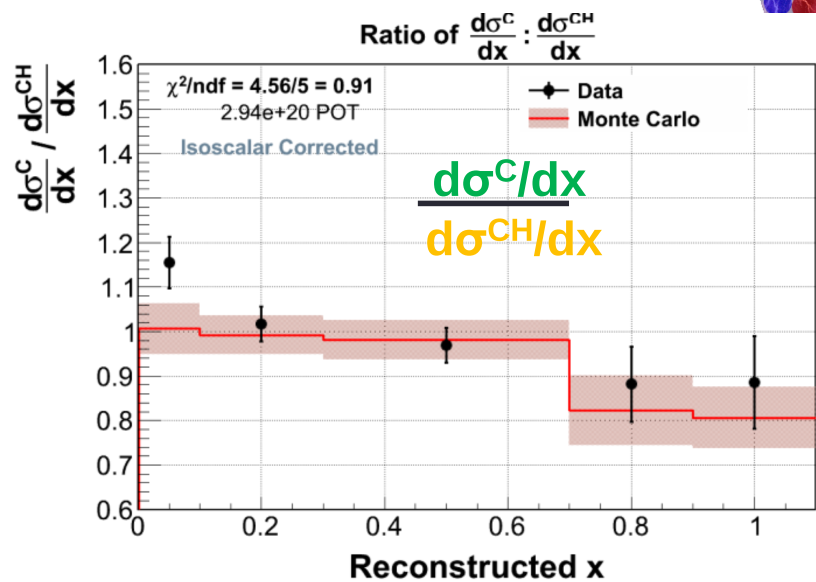
- Because of limitations of near detector technique, these rely on accurate models

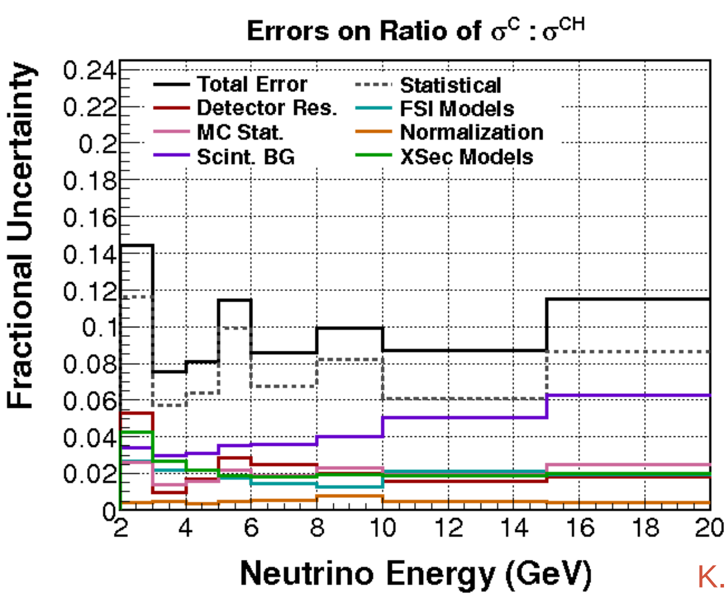


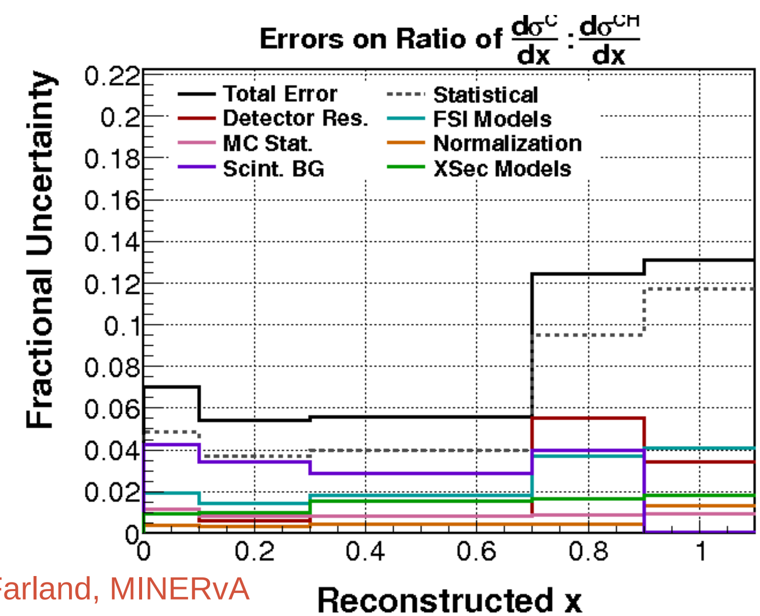
Full Target Ratios

Cross Section Ratios – Carbon

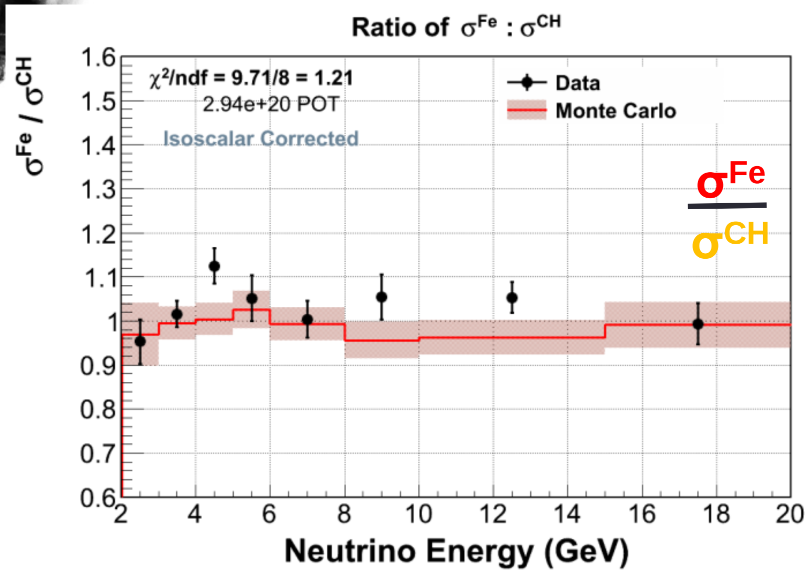


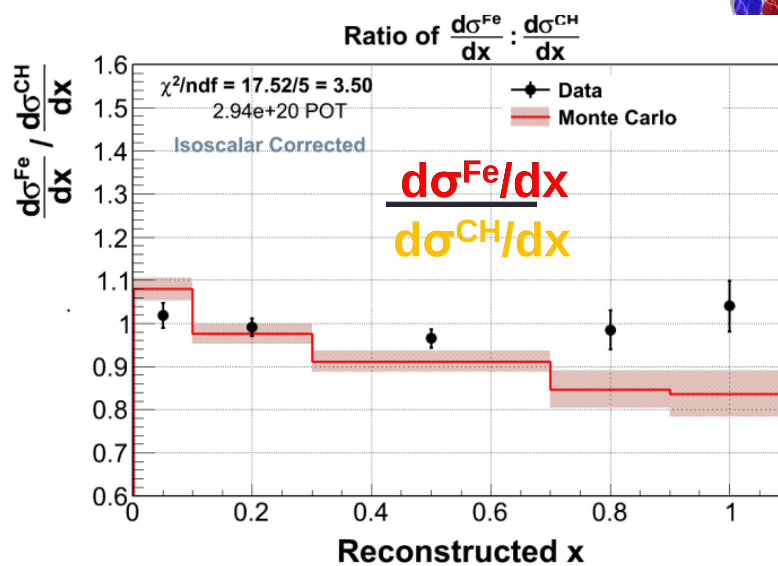


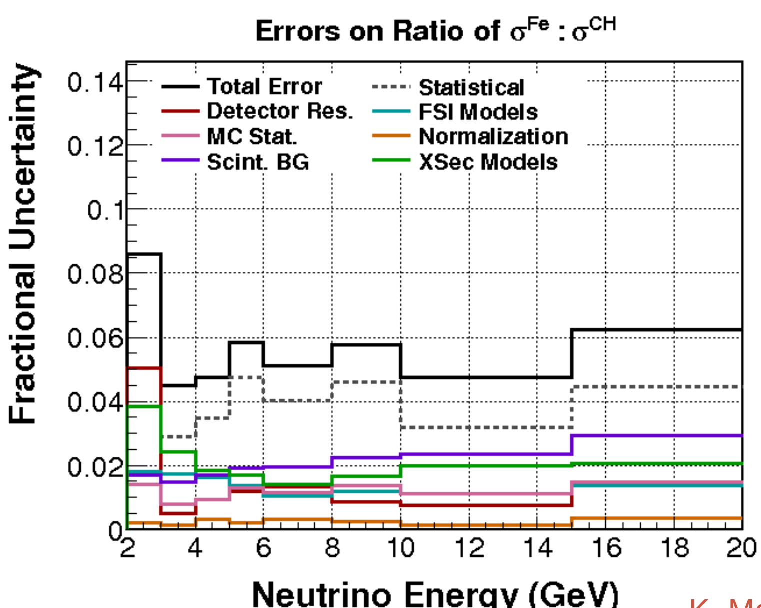


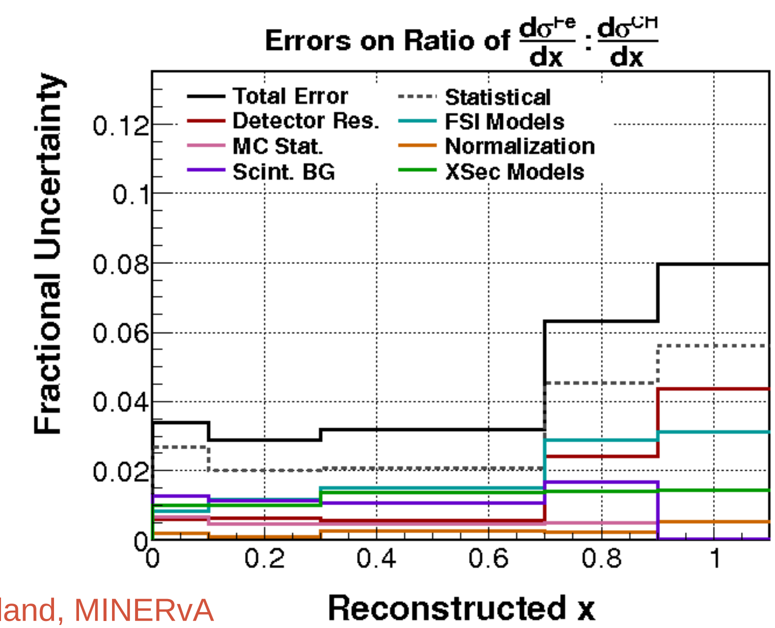


Cross Section Ratios – Iron

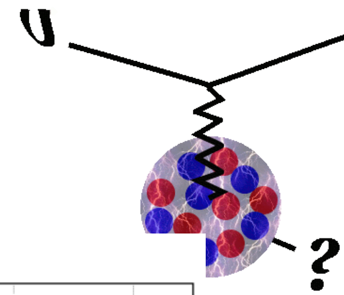


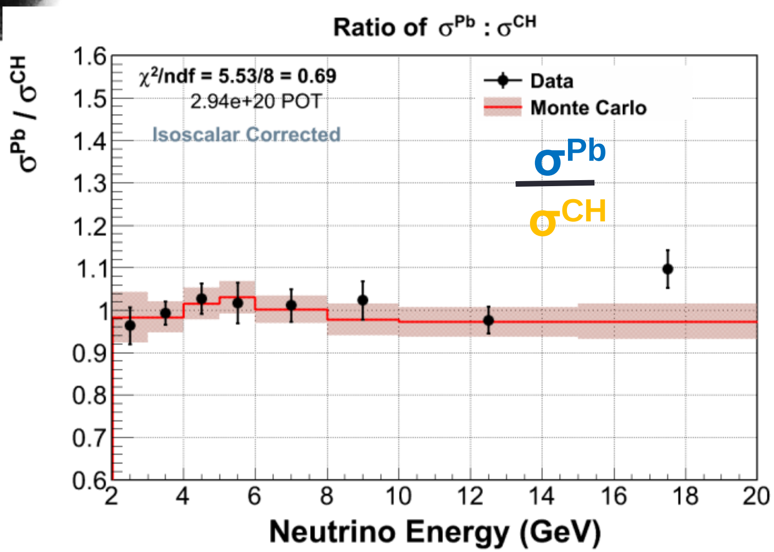


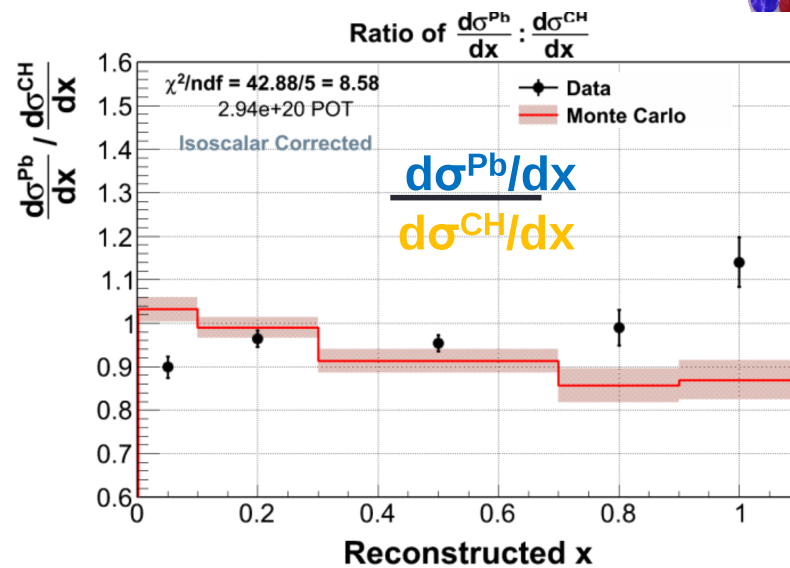


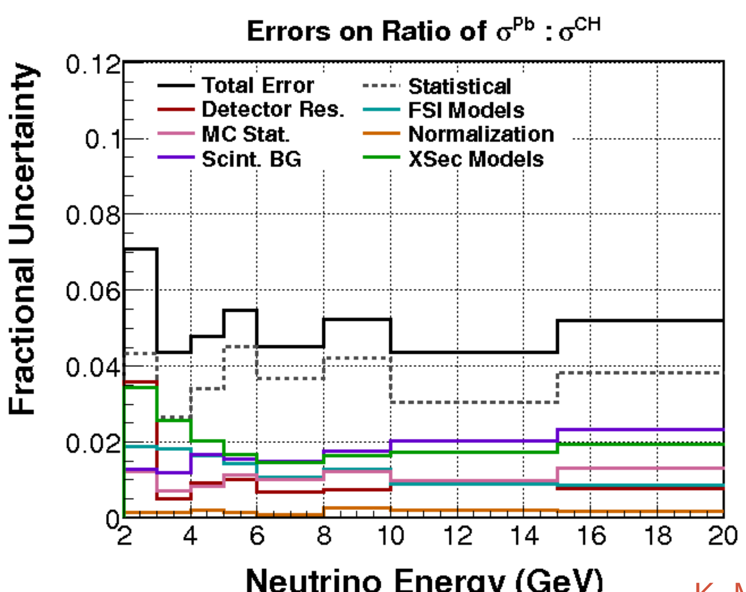


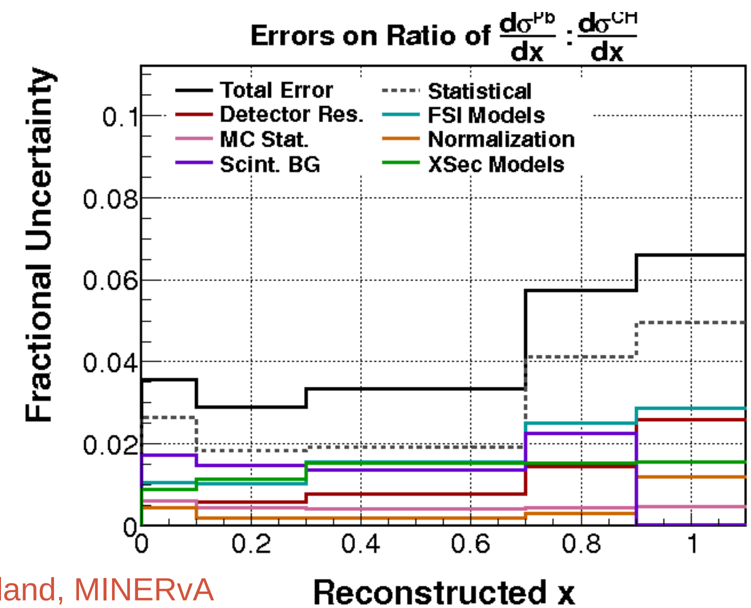
Cross Section Ratios – Lead



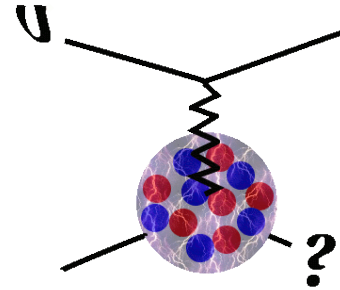








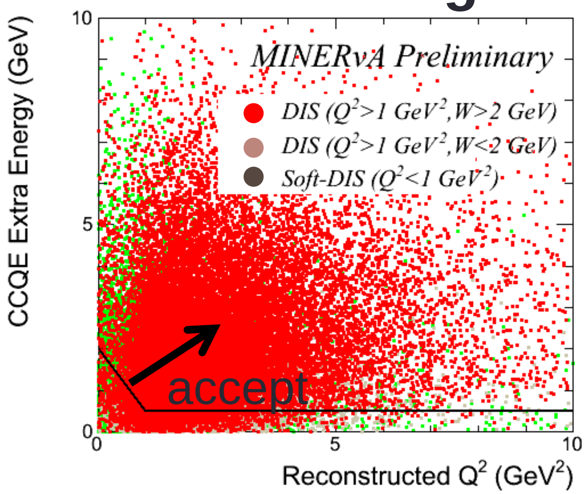
Removing Elastic-like Events?



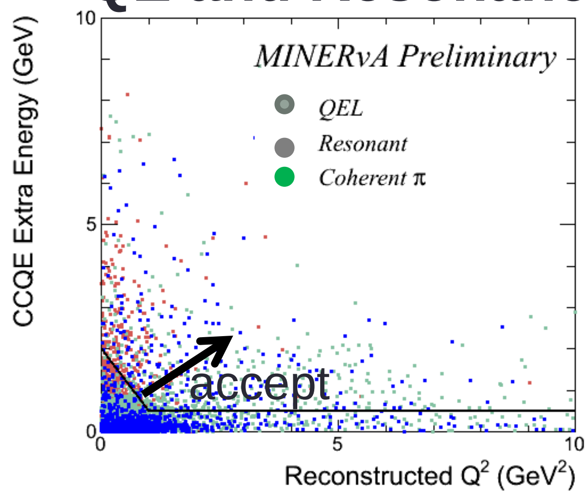
Select an **inelastic sample** (no quasi-elastic or baryon resonances)

Cut based on inverse of type of selection used in quasi-elastic analysis

Inelastic Signal



QE and Resonance



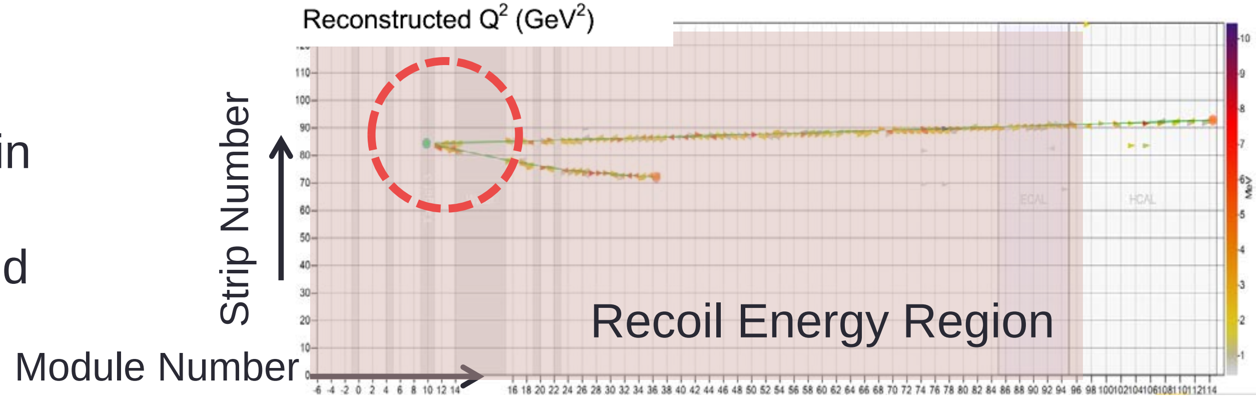
Purity – **inelastic** sample is 93% DIS (**inclusive** was 35%)

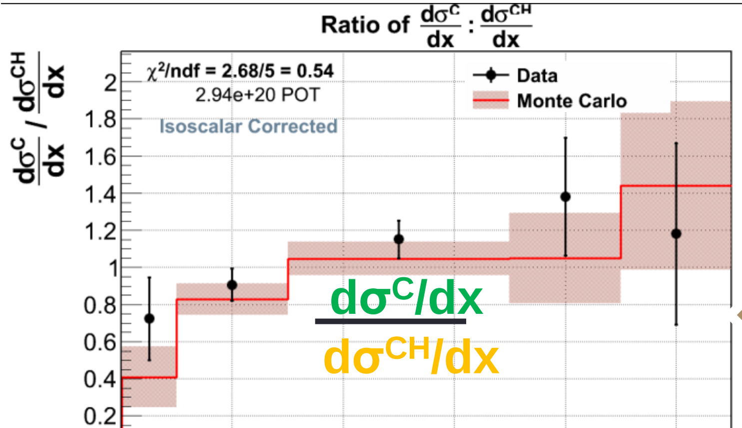
But **Inelastic** sample is 22% size of **inclusive**

CCQE Extra Energy

Non-muon hits that are not in hadronic calorimeter.

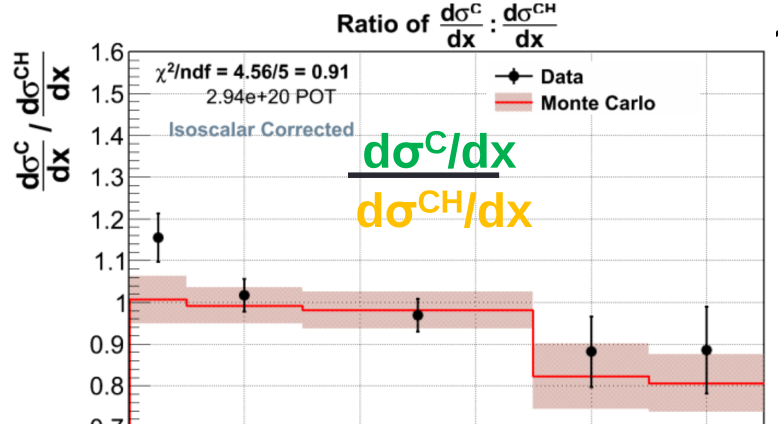
Exclude area 300mm around vertex.

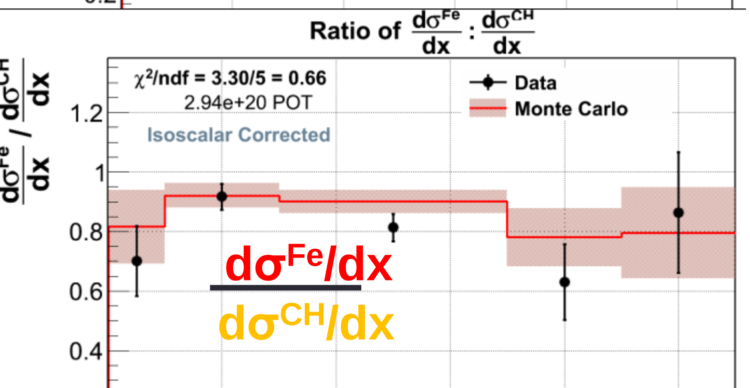




Inclusive

Inelastic





Too Statistically Limited to Draw Useful Conclusions