NEUTRINO INTERACTIONS AT MINERvA

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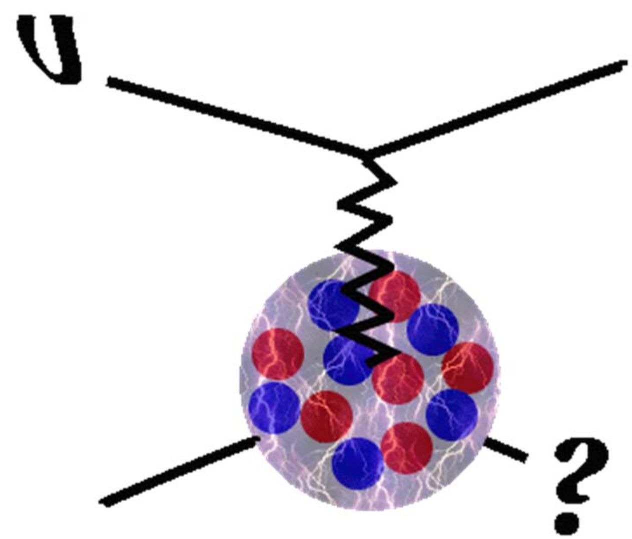
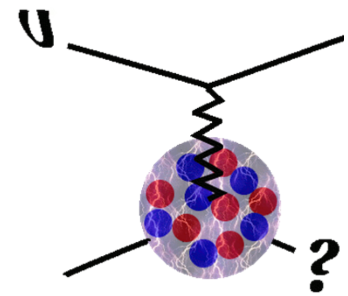
IPMU Seminar
9 February 2015

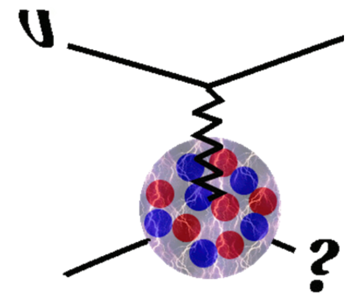


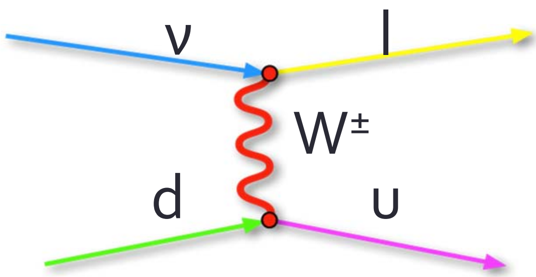
Outline



- Why we 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

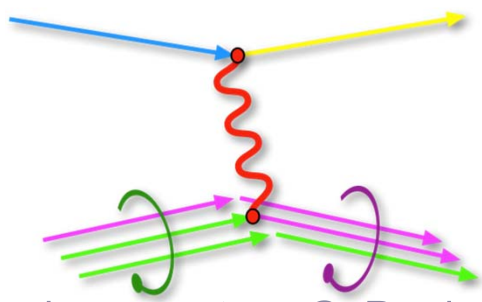
Neutrino Interactions: Simple… until they aren't





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

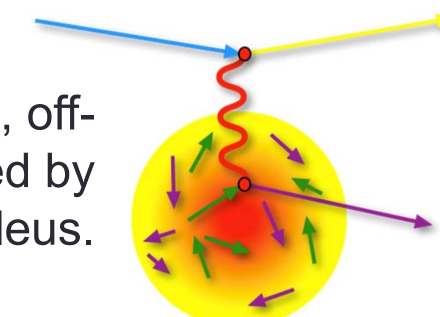
For inclusive scattering from a nucleon, add PDFs for a robust high energy limit prediction



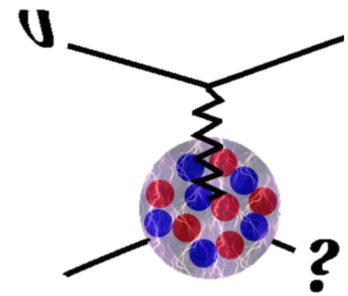
For exclusive, e.g., quasi-elastic scattering, hadron current requires empirical form factors.

(drawings courtesy G. Perdue)

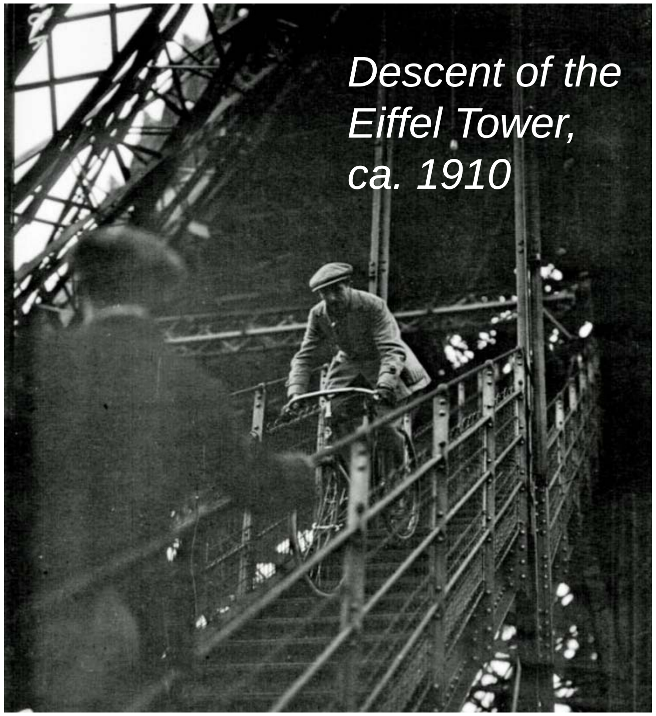
If the nucleon is part of a nucleus, it may be modified, off-shell, bound, etc. Also, exclusive states are affected by interactions of final state hadrons within the nucleus.

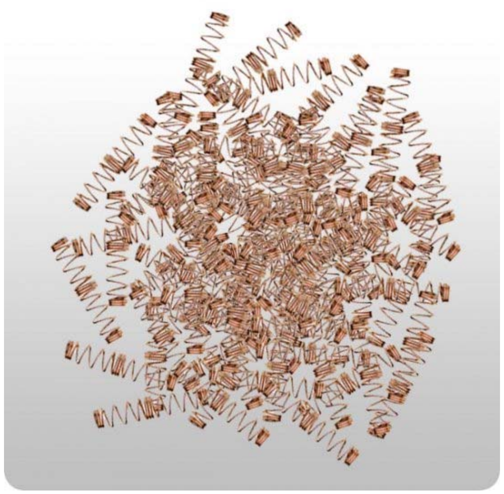


Wrong Tools for the Job?



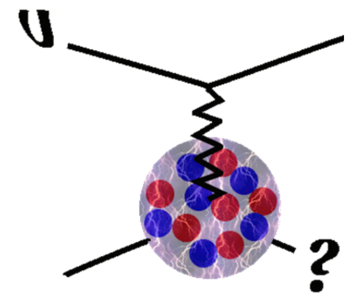
- Accelerator oscillation experiments require beam energies of 0.3-5 GeV
  - Nuclear response in this region makes the transition between inelastic and elastic processes.

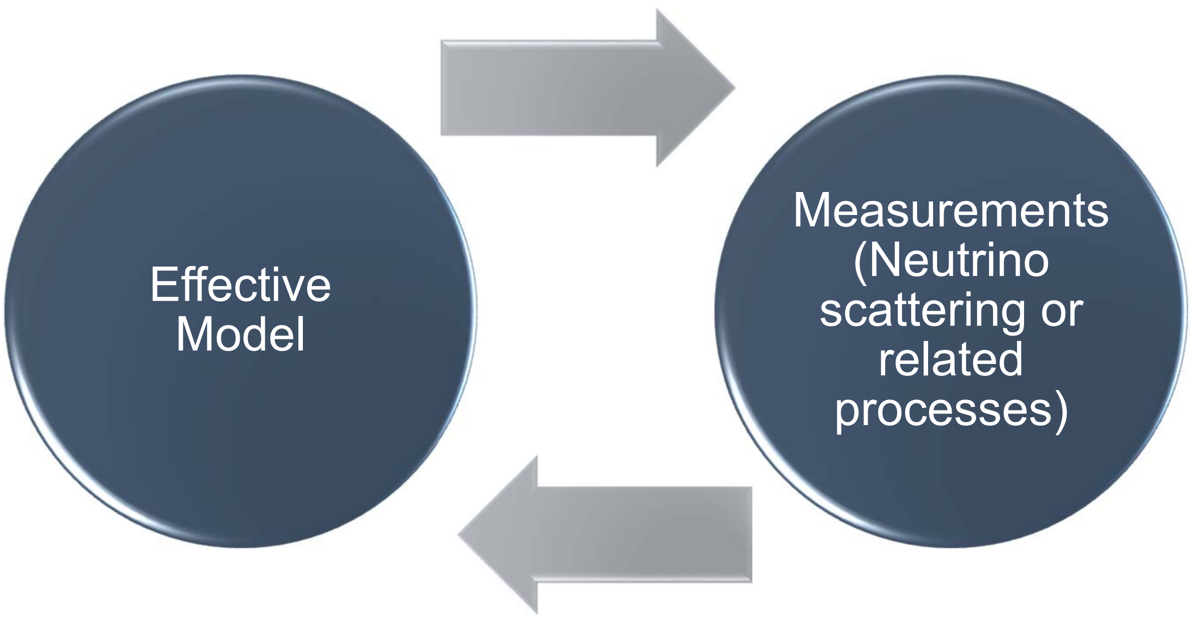

Descent of the Eiffel Tower, ca. 1910



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

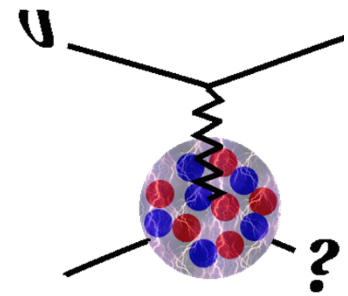
How do we Understand and Model Interactions?



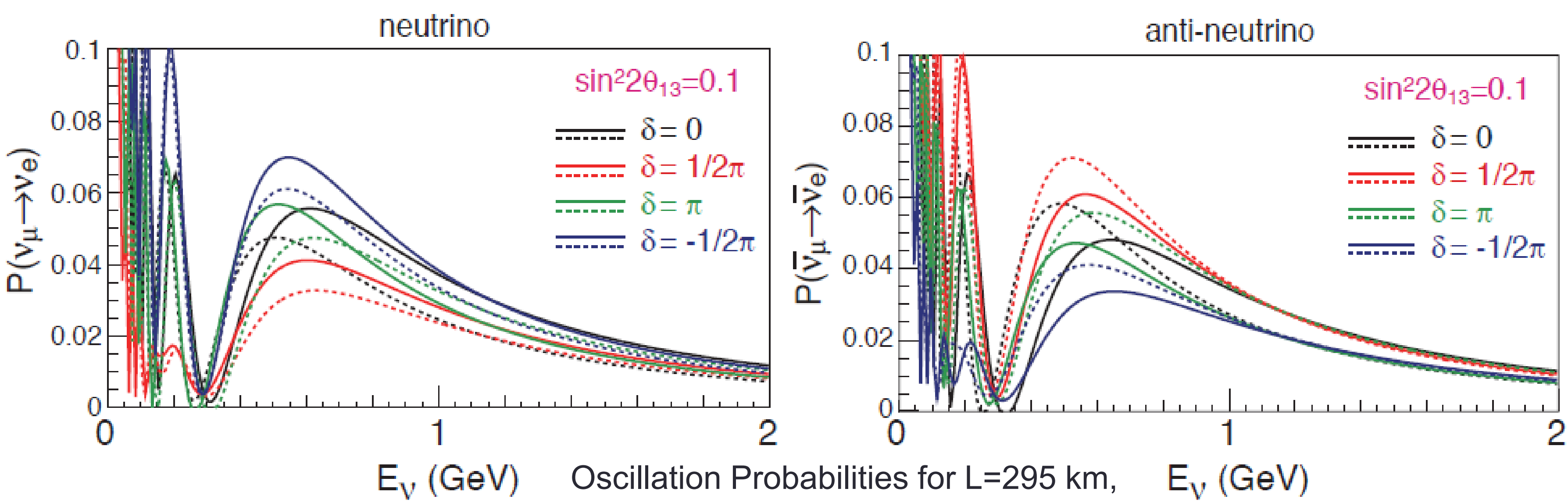


- Iterative process, using data to improve models
- Models are effective theories, ranging from pure parameterizations of data to microphysical models with simplifying assumptions.

Oscillations: Needs
(J-PARC to Hyper K)

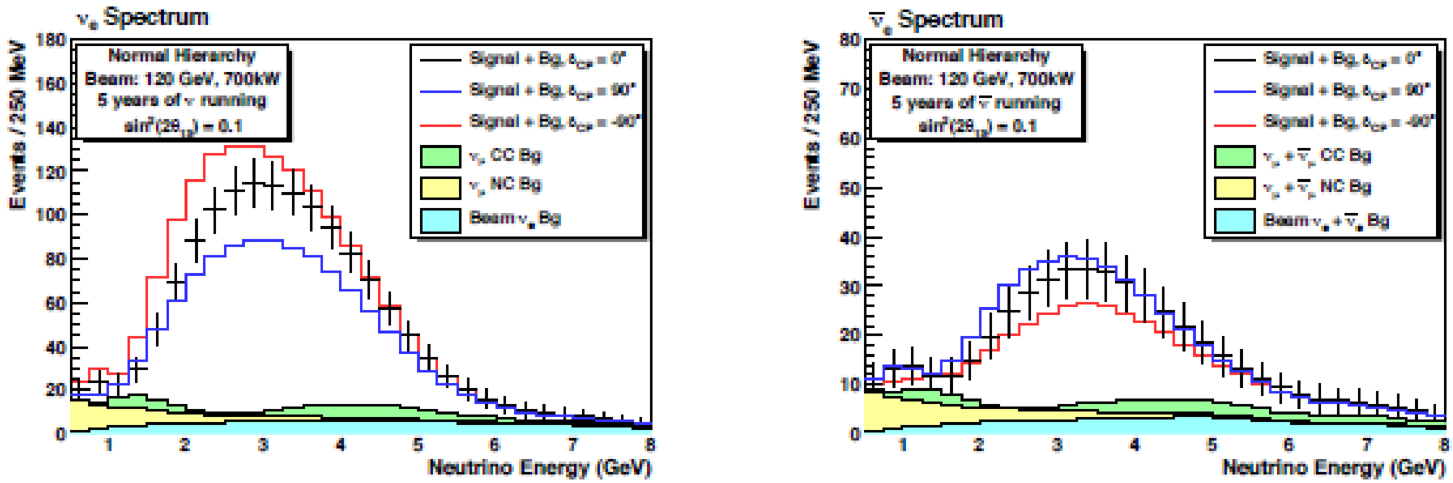


- Discovery of CP violation in neutrino oscillations requires seeing distortions of $P(\nu_\mu \rightarrow \nu_e)$ as a function of neutrino and anti-neutrino energy

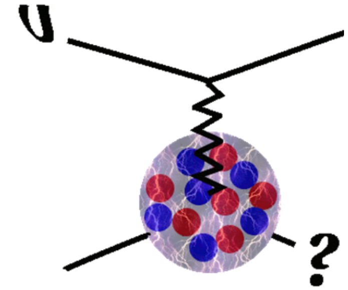


Oscillation Probabilities for L=295 km, Hyper-K LOI

Oscillations: Needs (LBNF)

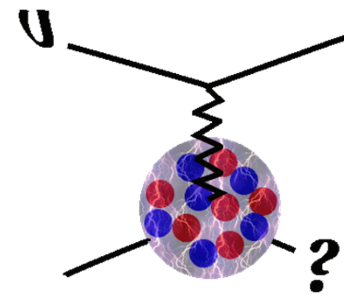


- Maximum CP effect is range of red-blue curve
- Backgrounds are significant, vary with energy and are different between neutrino and anti-neutrino beams
  - Pileup of backgrounds at lower energy makes 2^{nd} maximum only marginally useful in optimized design
- Spectral information plays a role
  - CP effect may show up primarily as a rate decrease in one beam and a spectral shift in the other

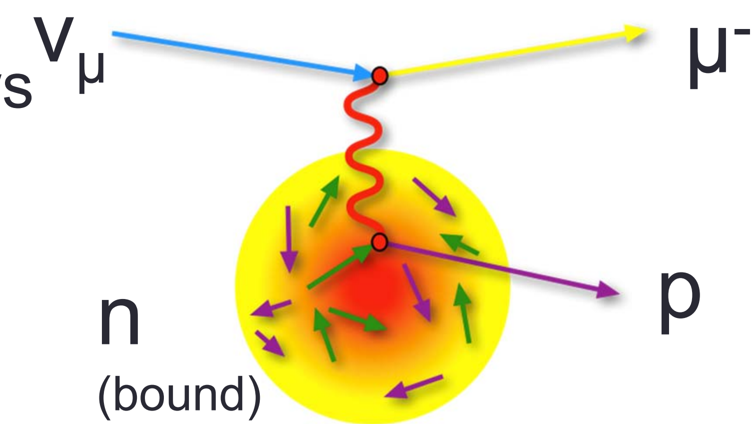


Example:
Quasi-Elastic Energy Reconstruction

Charged Current Quasi-Elastic Scattering



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

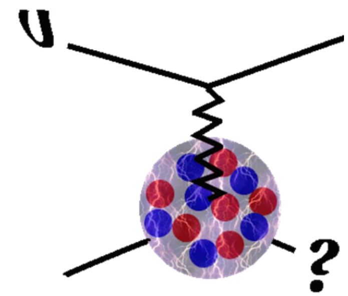


When things are too complicated, sometimes you give up trying!

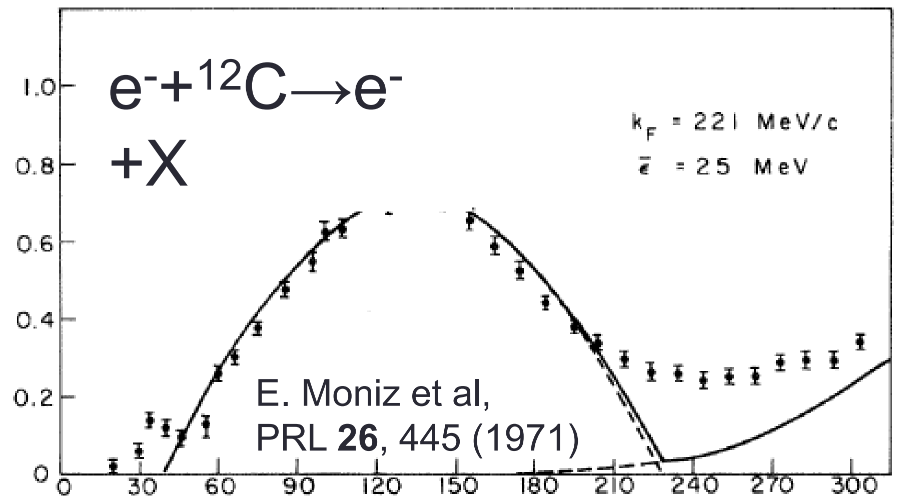
$$E_\nu^{\rm rec} = \frac{2(m_n - V)E_e + m_p^2 - (m_n - V)^2 - m_e^2}{2(m_n - V - E_e + p_e \cos\theta_e)};$$

- 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

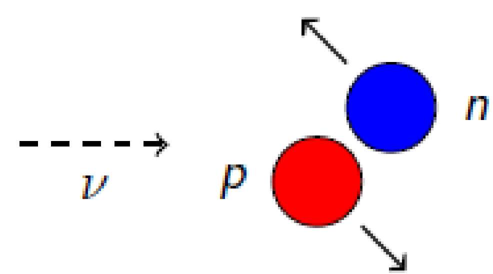
Simple Model of the Nucleon in a Nucleus



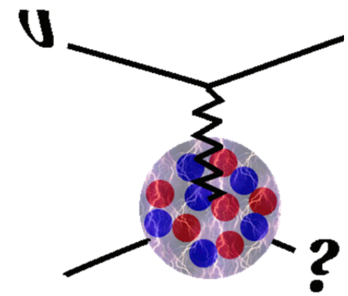
- Our models come from theory tuned to electron scattering
- Generators usually use Fermi Gas model, which takes into account effect of the mean field.
- Corrections to electron data from isospin effects in neutrino scattering.
- Hmmm… between elastic peak and pion production rise looks bad.



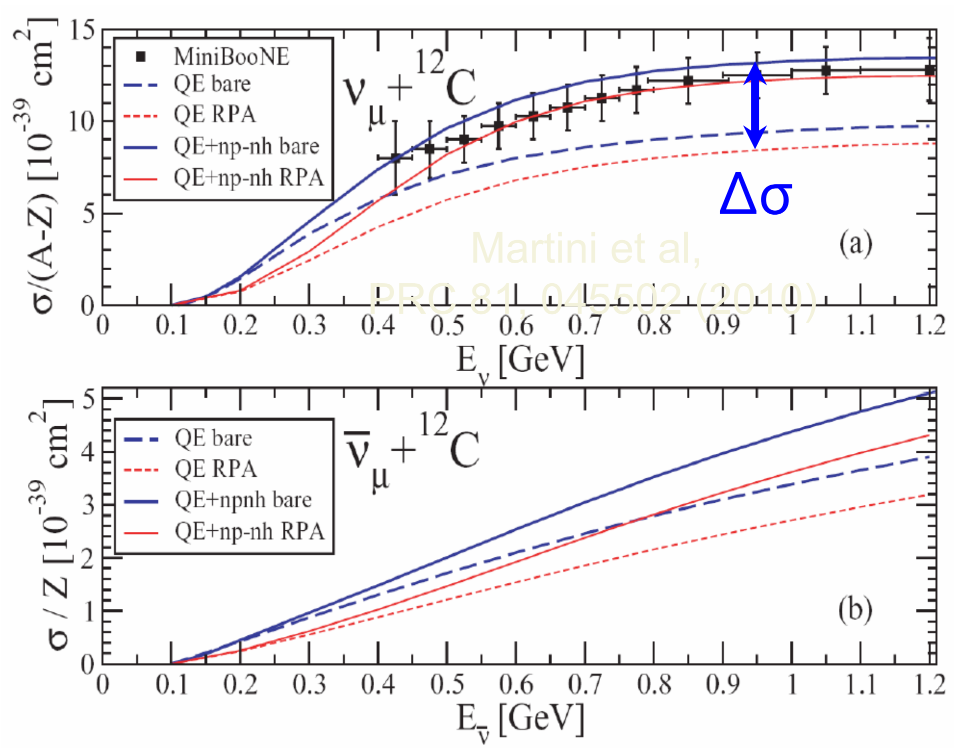
- This approach of quasi-free nucleons in a mean field neglects processes involving closely correlated nucleons



Solution to MiniBooNE CCQE "Puzzle"?



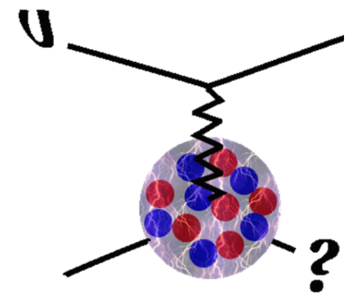
- From the ^{12}C experiment and calculations, expect a cross-section enhancement from correlated process: $\nu_\mu n \rightarrow \mu^- p \quad + \nu_\mu (np)_{corr.} \rightarrow \mu^- pp$



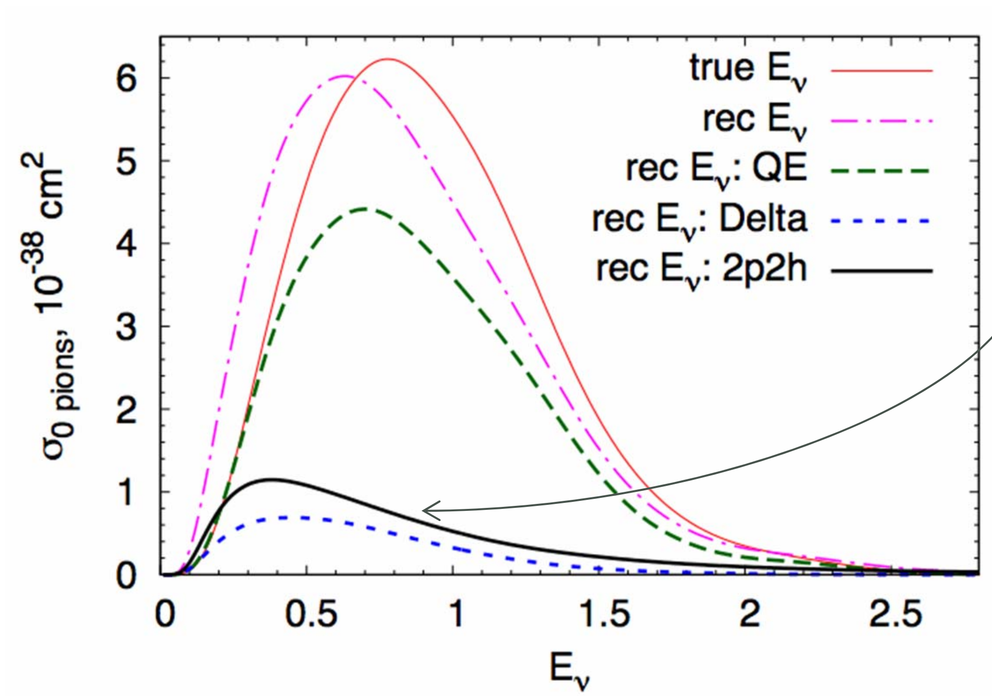
Recent work

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



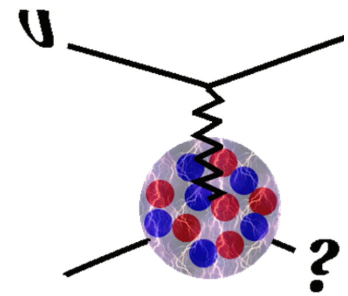
- Does it quantitatively matter if we model this effectively (e.g., alter nucleon form factors) or microphysically?
- Inferred neutrino energy changes if target is multinucleon.



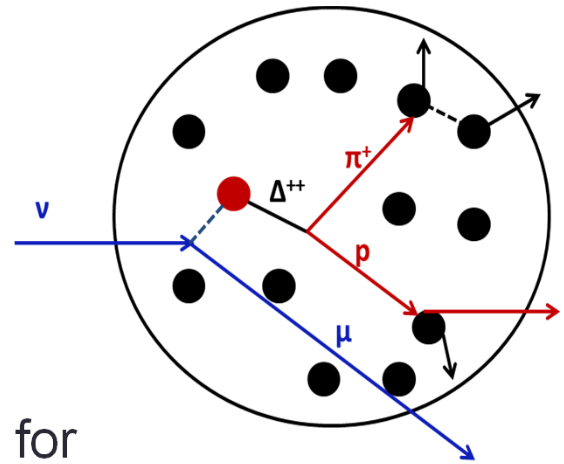
Effect at MiniBooNE calculated by Lalakulich, Gallmeister, Mosel,1203.2935

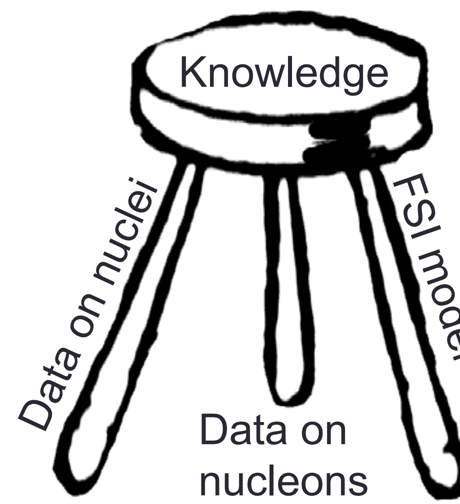
ex: Mosel/Lalakulich 1204.2269, Martini *et al*. 1202.4745, Lalakulich *et al.* 1203.2935, Leitner/Mosel PRC81, 064614 (2010)

Another Energy Reconstruction Problem



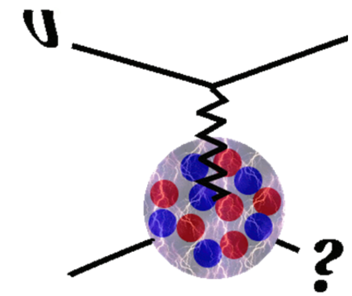
- In inelastic events the hadronic final state can in principle aid neutrino energy reconstruction
- But produced hadrons inside the nuclear targets interact as they exit
- This typically increases multiplicity of low energy nucleons
  - Detector response is unlikely to be uniform for charged and neutral 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





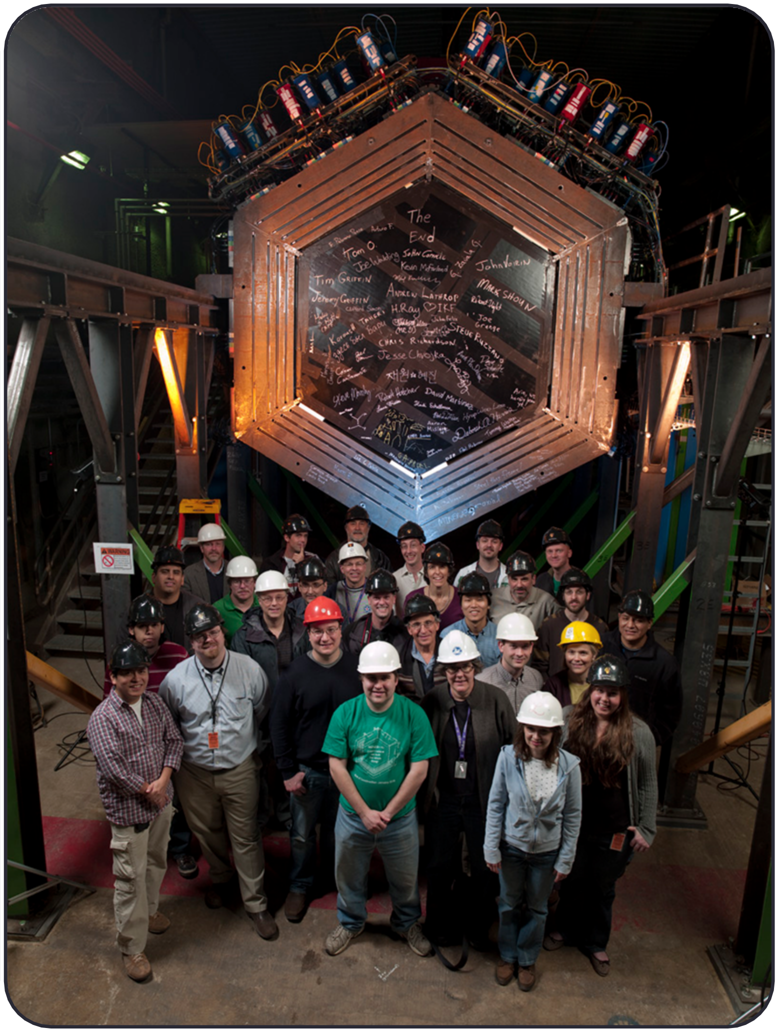
The MINERvA Experiment

MINERvA Collaboration

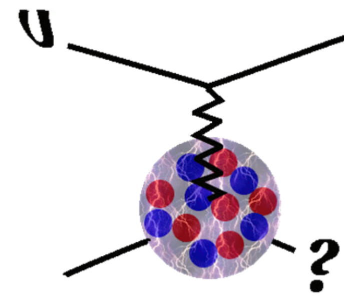


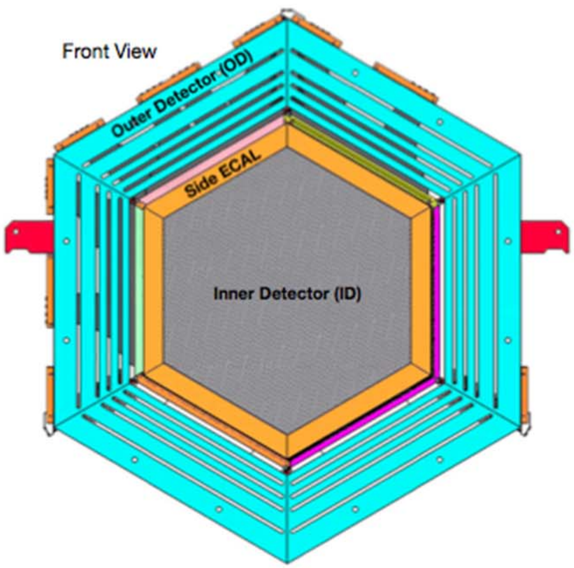
~70 collaborators from particle and nuclear physics

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 Minnesota at Duluth
Universidad Nacional de Ingeniería
Universidad Técnica Federico Santa María
College of William and Mary

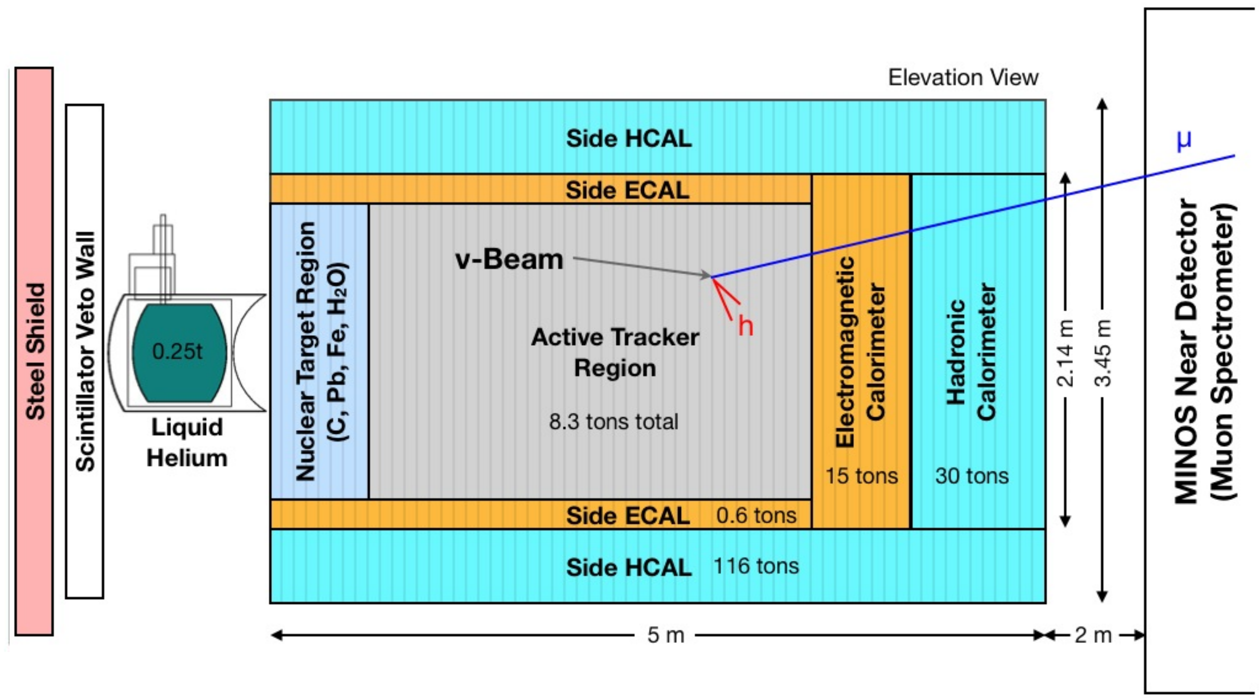


Detector





3 orientations
0°, +60°, −60°



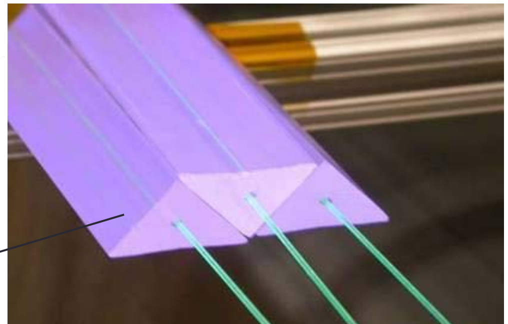
Detector comprised of **120 "modules"** stacked along the beam direction

Central region is **finely segmented scintillator tracker**

~32k plastic scintillator strip channels total

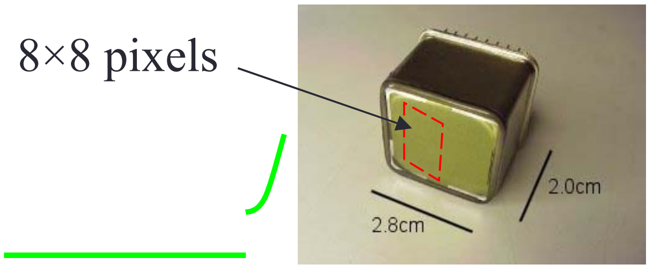
Detector Technology

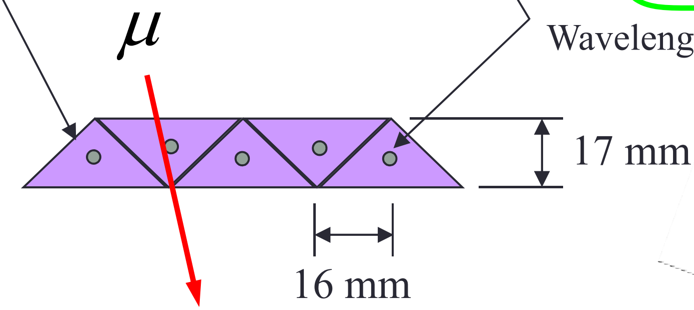
64 channel multi-anode PMT

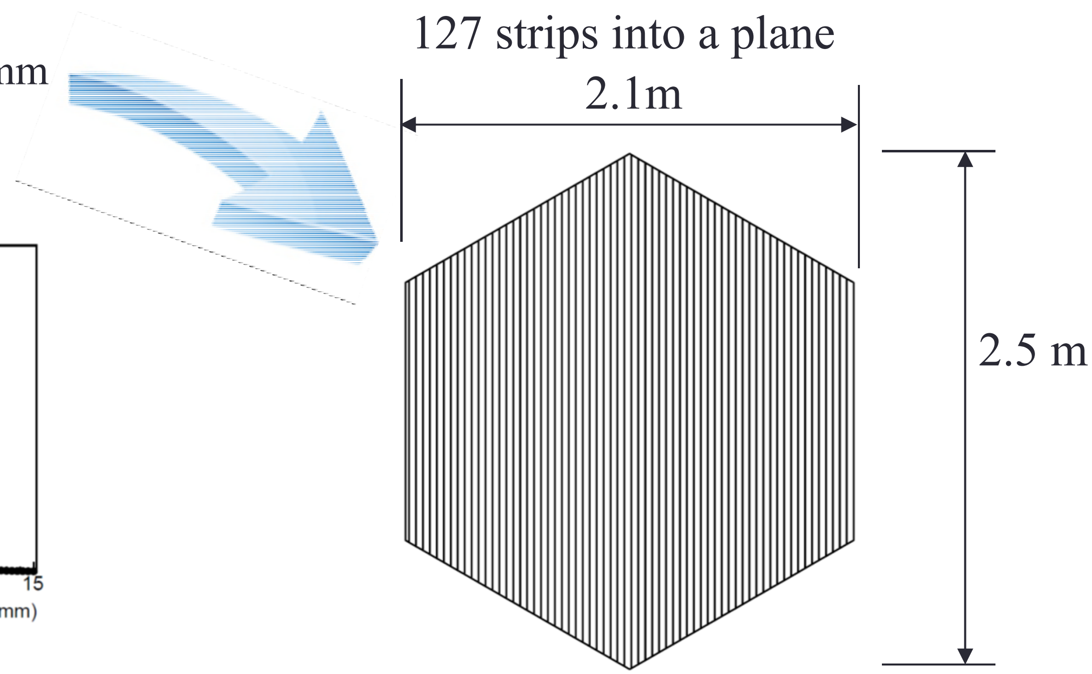


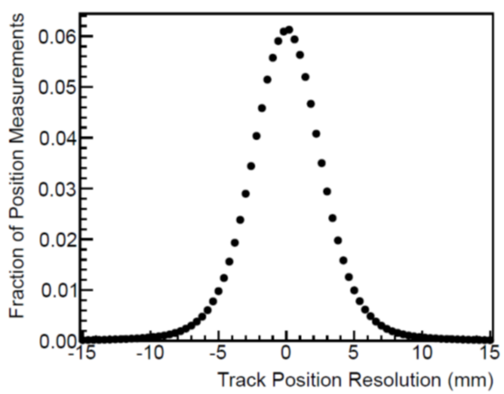
Scintillator strip

Wavelength shifting fiber







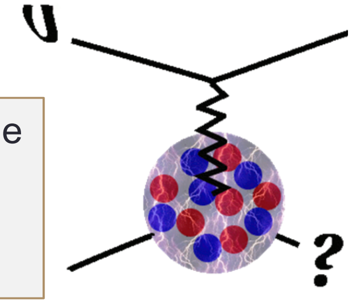


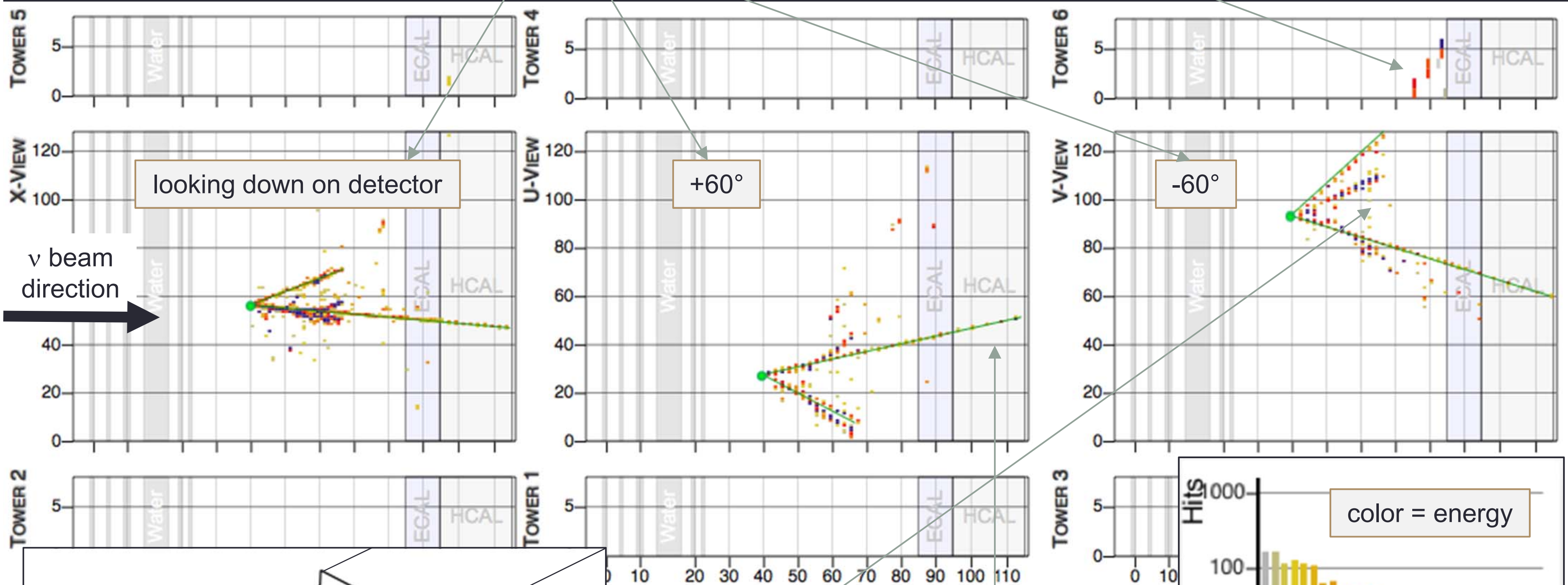
Forward-going track position resolution: ~3mm

Events in MINERvA

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

Particle leaves the inner detector, stops in outer iron calorimeter



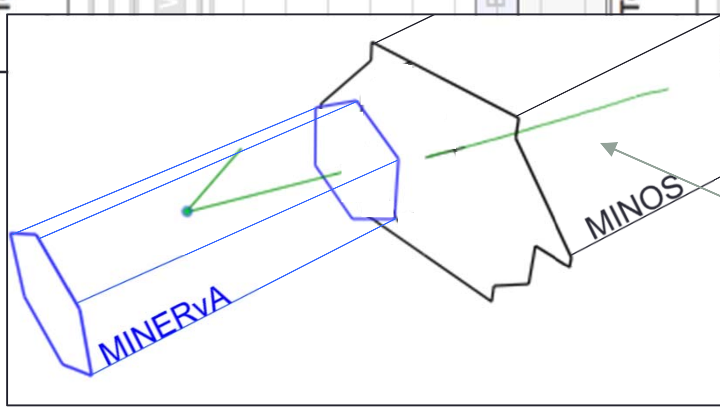


looking down on detector

+60°

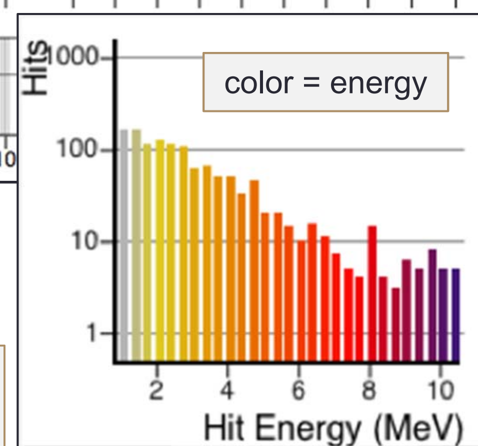
-60°

ν beam direction

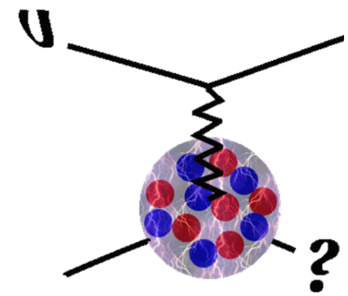


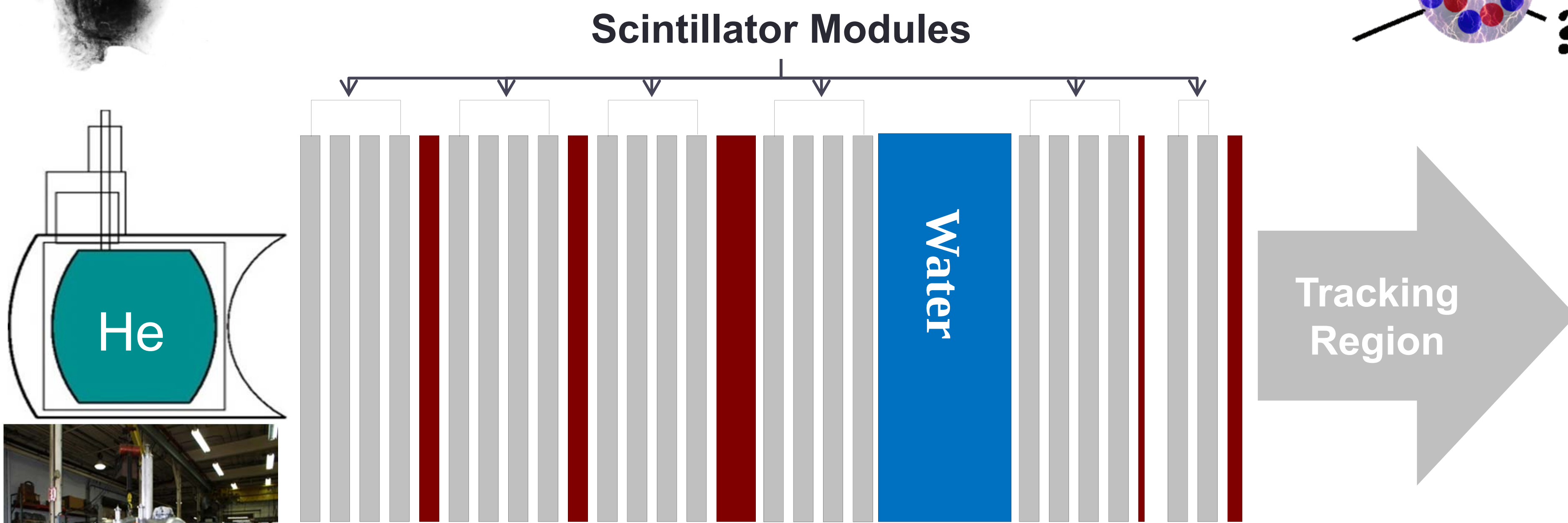
Stops in Scintillator, best hadron particle ID

Muon leaves the back of the detector headed toward MINOS



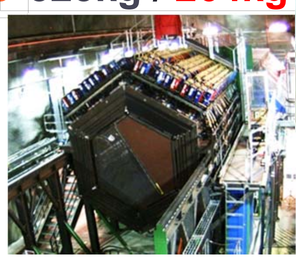
Passive Nuclear Targets





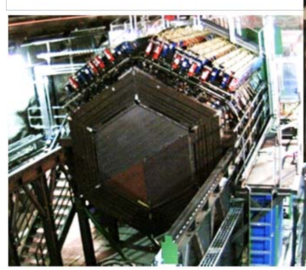
250 kg Liquid He

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

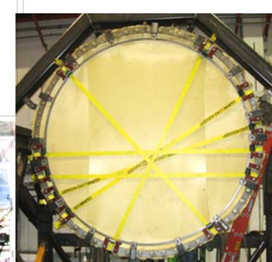


1" Pb / 1" Fe
266kg / 323kg

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



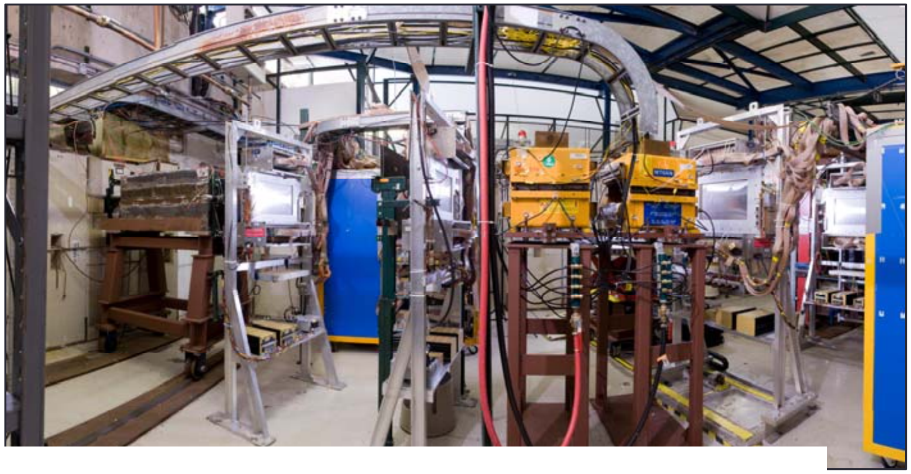
6" 500kg Water

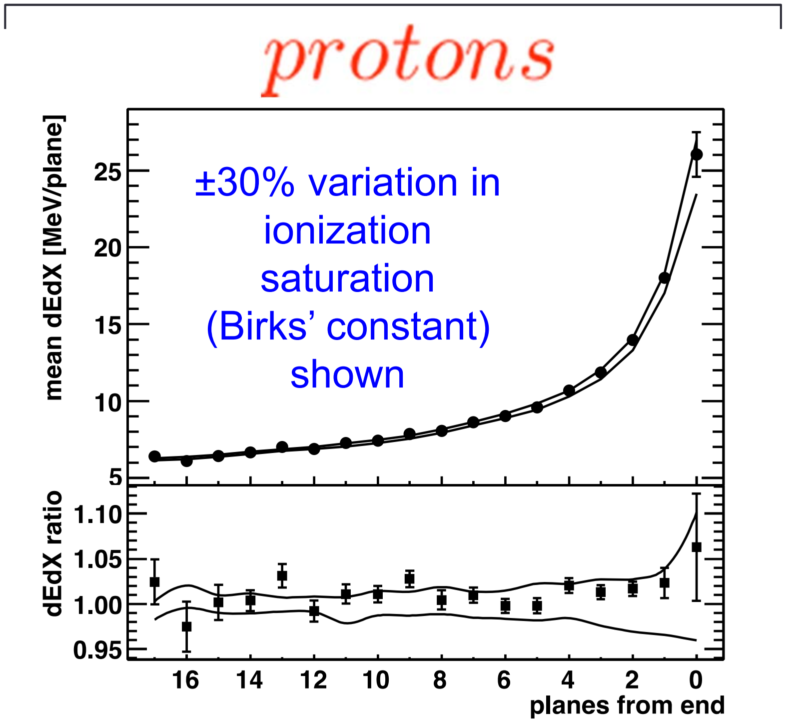


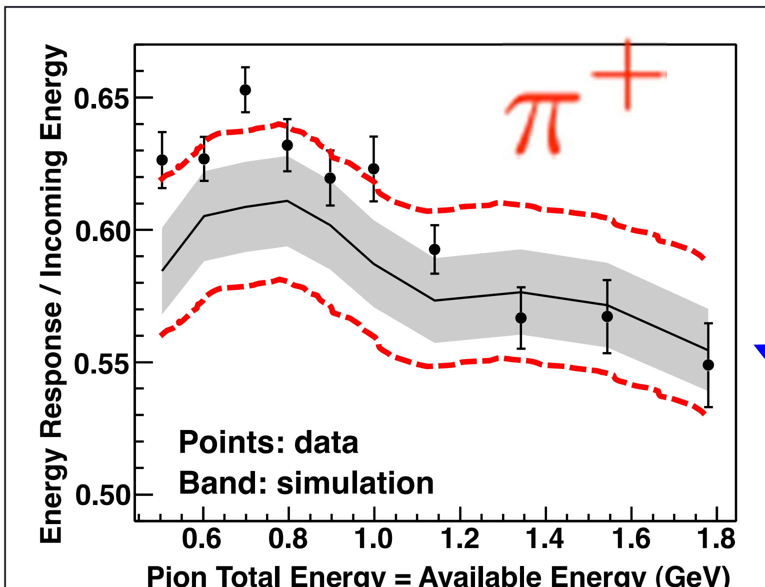
0.3" Pb
228kg

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

Hadron Testbeam

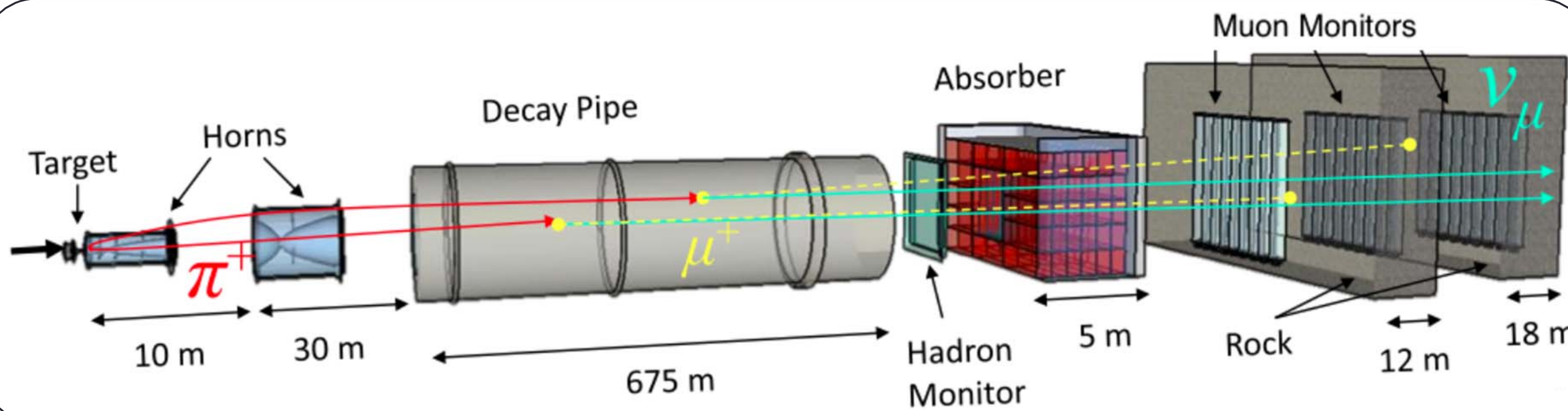






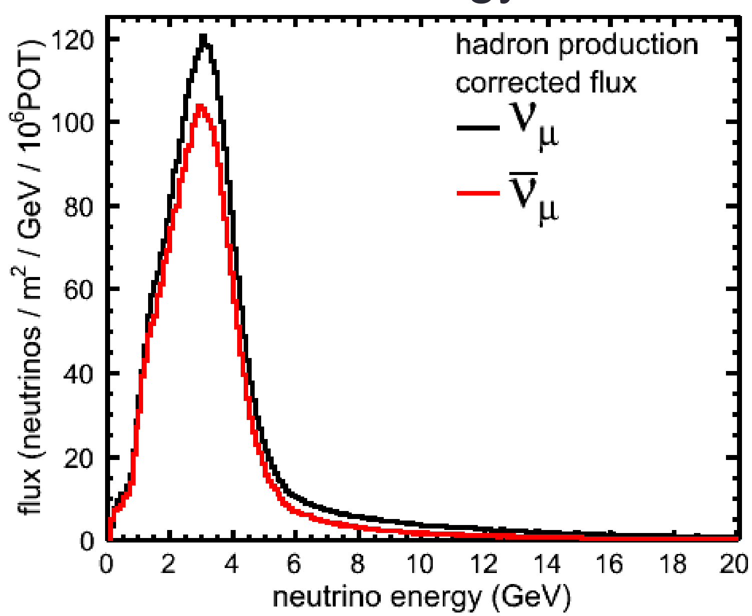
high-energy charged pion response uncertainty ≈ 5% (before tuning hadron interactions in detector)

The NuMI Beam

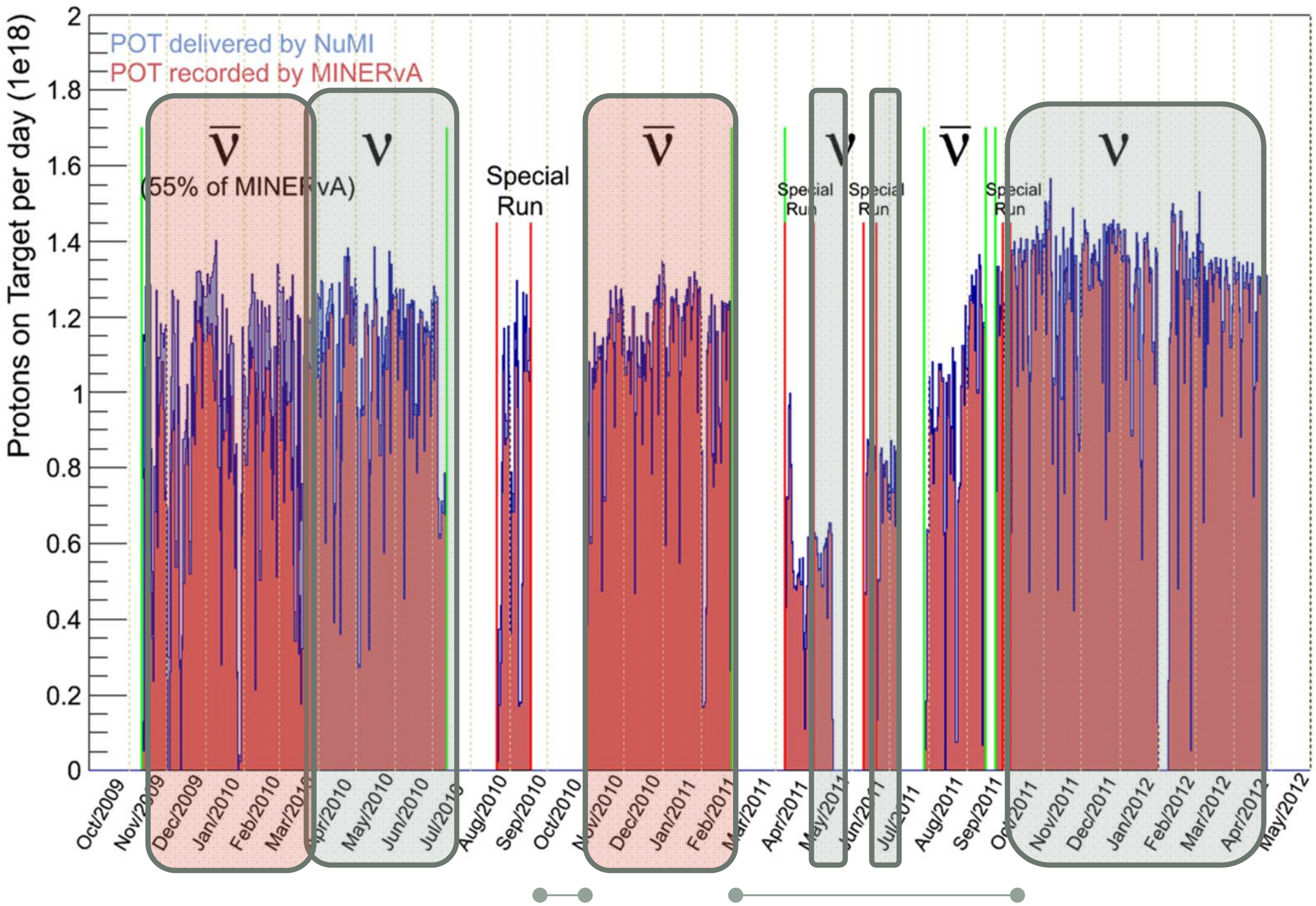


- NuMI is a “conventional” neutrino beam, with most neutrinos produced from focused pions
- Implies significant uncertainties in flux from hadron production and focusing
- Constrain, where possible, with hadron production data

NuMI Low Energy Beam Flux



Datasets

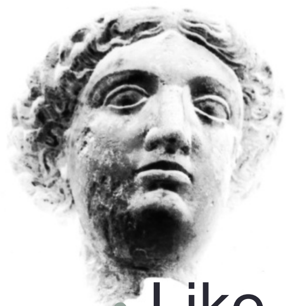


120 GeV protons on target (POT) to MINERvA

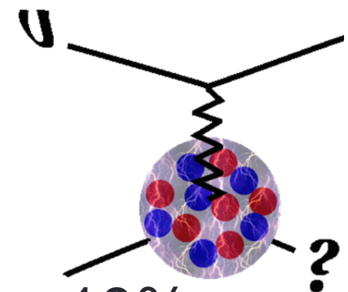
neutrino (LE): 3.9E20 POT

anti-neutrino (LE): 1.0E20 POT +0.9E20 POT with partial detector

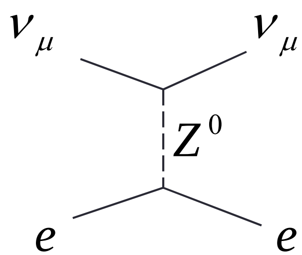
Neutrino beams are hard! NuMI target troubles: some running with damaged targets



Reducing Flux Uncertainty

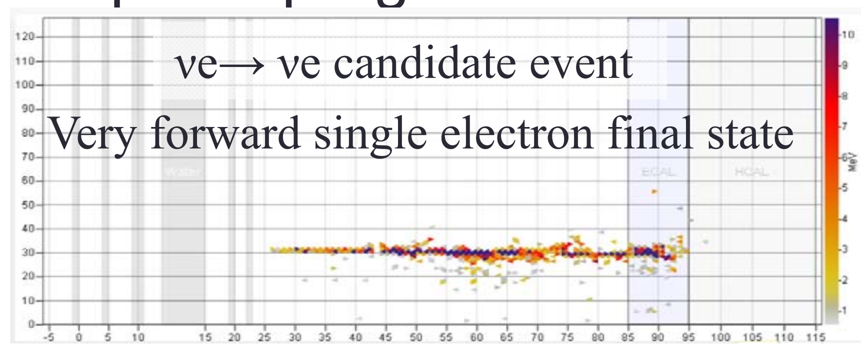


- Like almost all neutrino beams, flux is uncertain by ~10% because of hadron production and focusing uncertainties
- MINERvA also has a new technique in progress.

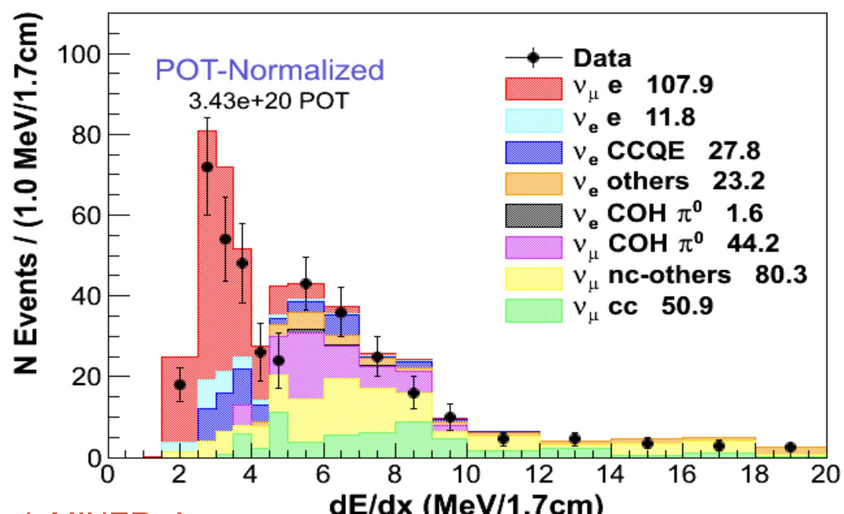


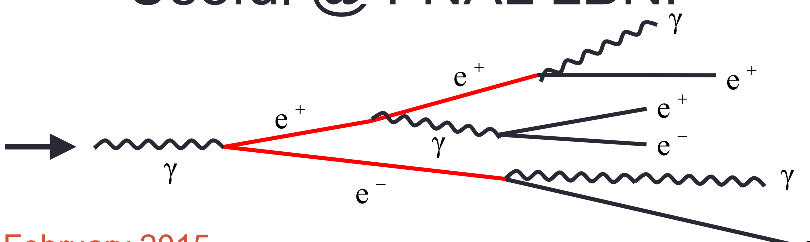
Precisely predicted (point-like fermions)

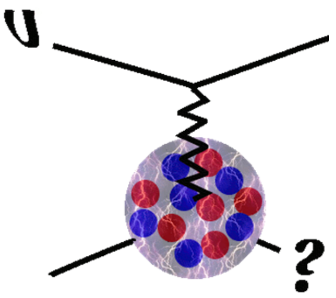
Process is very rare, 1/2000 of total cross-section. But we measure to ~10%, so know flux to same precision!



- Background is γ. Reject by dE/dx at start of "electron" track
- Useful @ FNAL LBNF

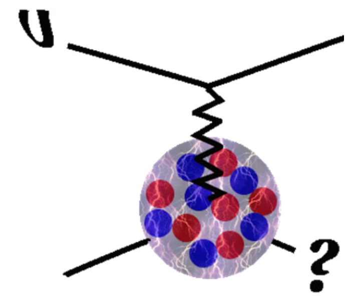




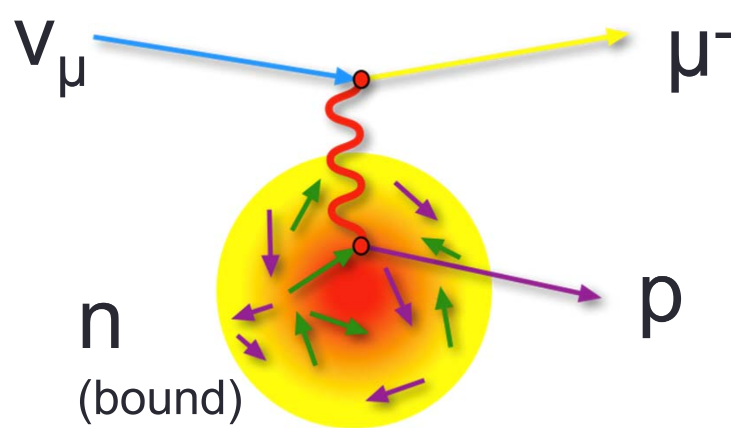


Quasi-Elastic Scattering

Identifying Quasi-Elastic Scattering

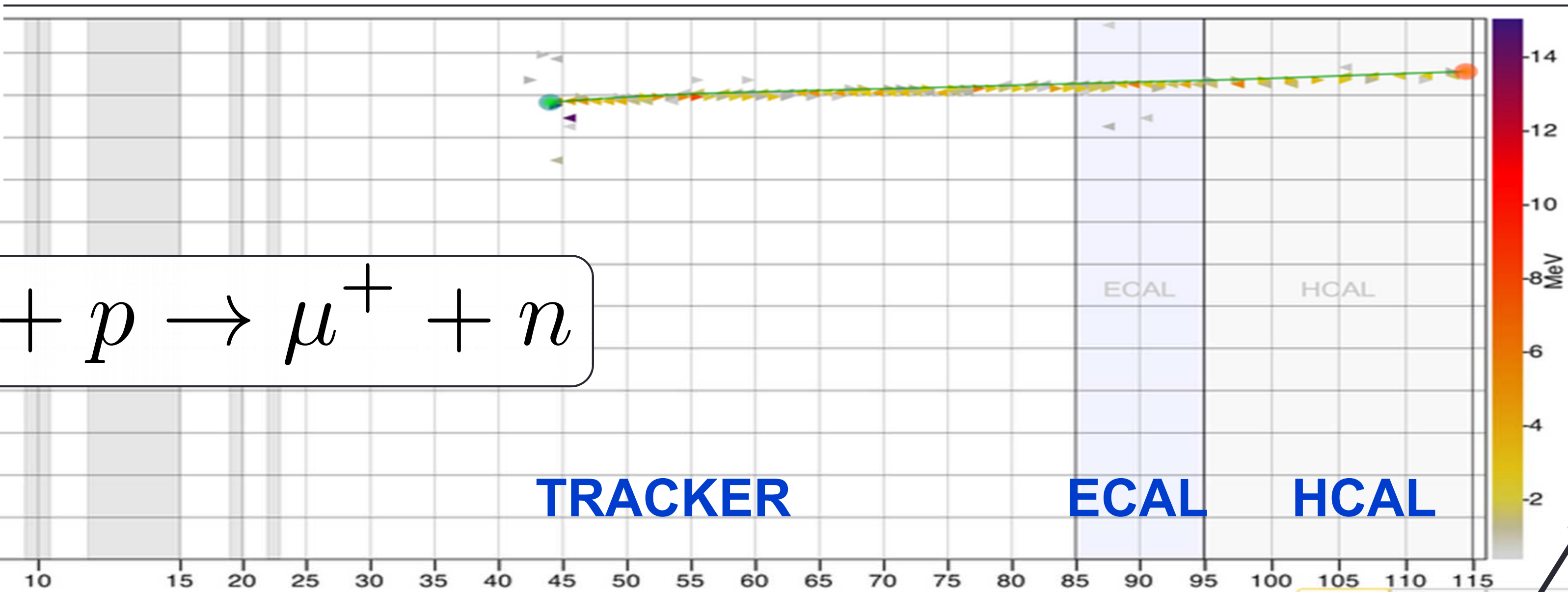


- Signature of quasi-elastic scattering is production of no mesons, photons or heavy baryons
- Breakup of nucleus or hadron reinteraction may produce additional protons and neutrinos in final state. Allow those as signal.



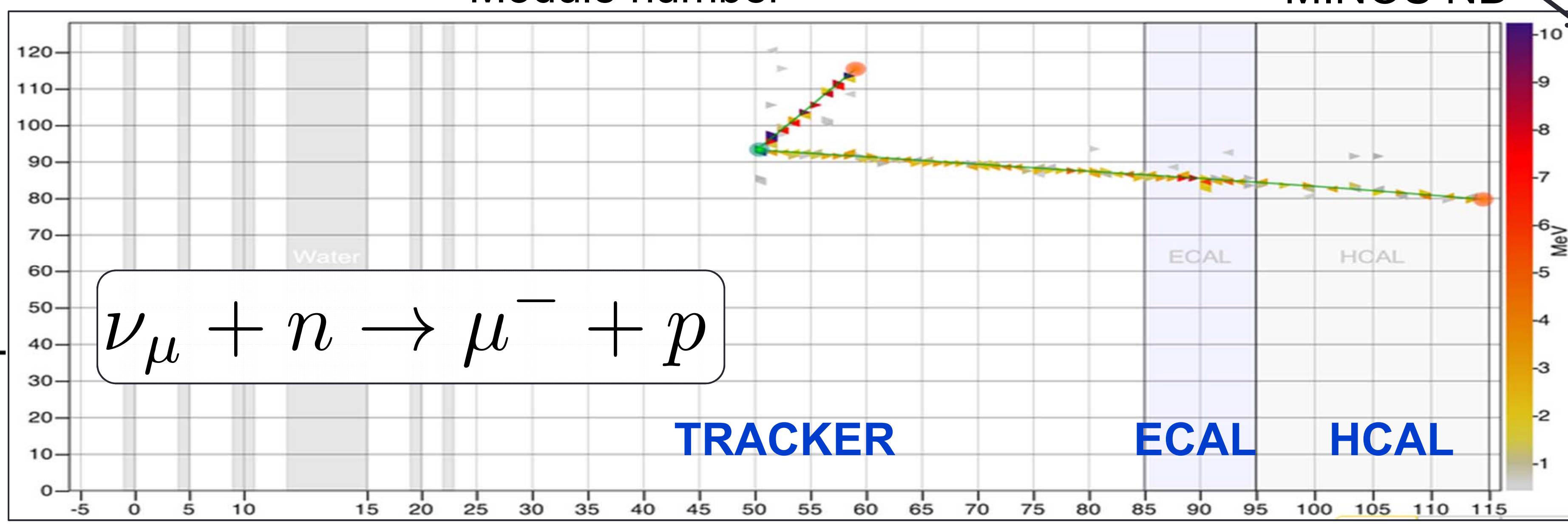
- Veto events with energy from pions (leading background)
- Strategies: (1) limit calorimetric recoil to be consistent with nucleons, (2) explicitly identify a leading proton or neutron, (3) veto on Michel electrons from π^+

ν Beam

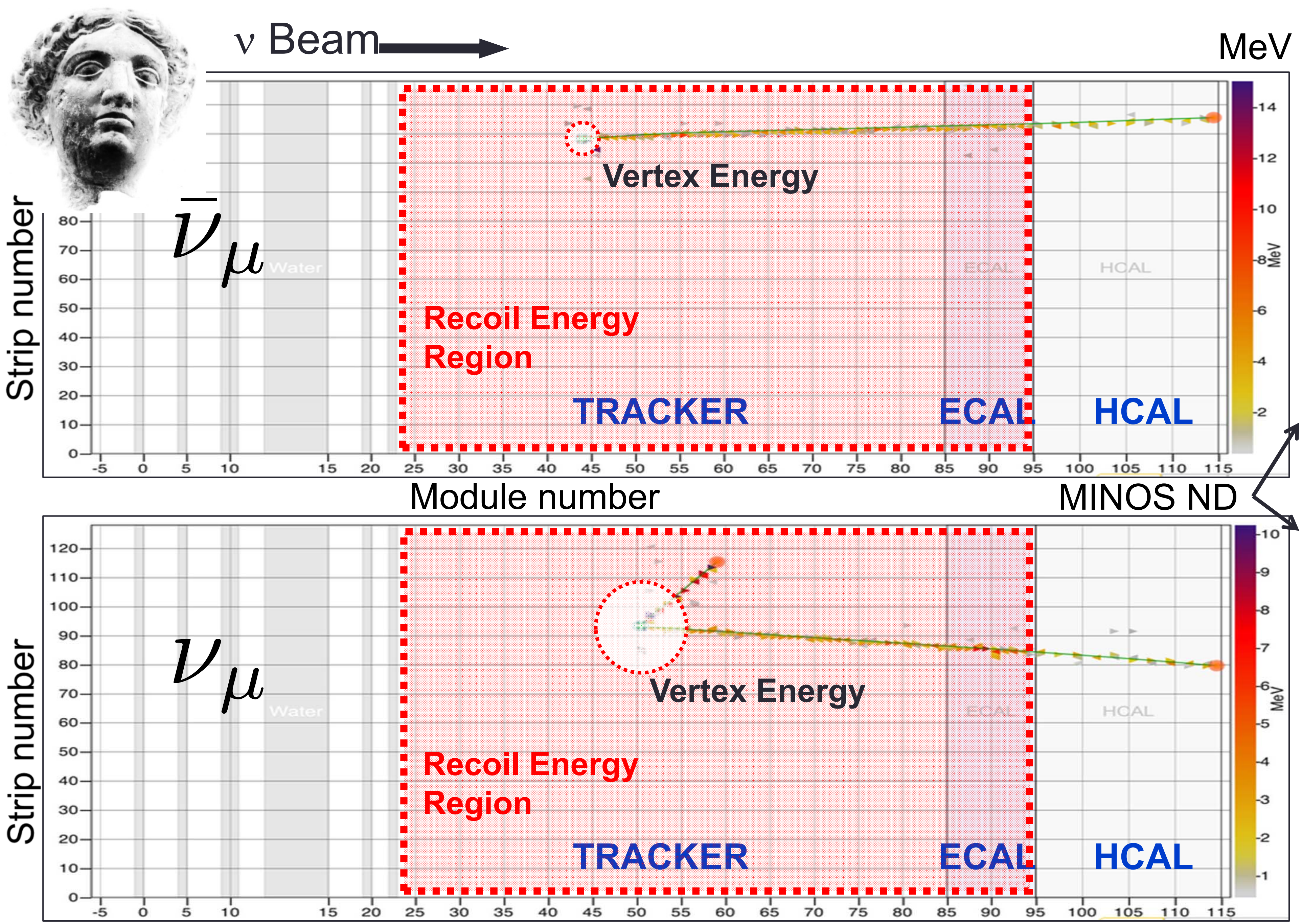


$$\bar{\nu}_\mu + p \rightarrow \mu^+ + n$$

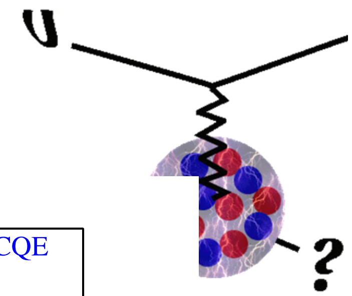
MINOS ND



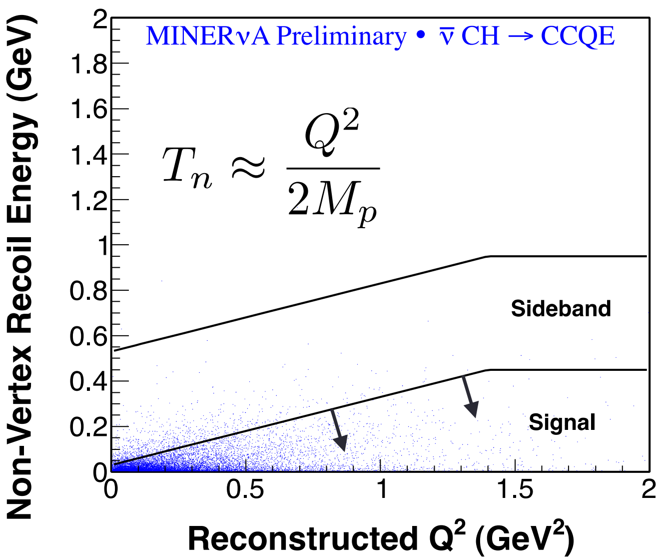
$$\nu_\mu + n \rightarrow \mu^- + p$$

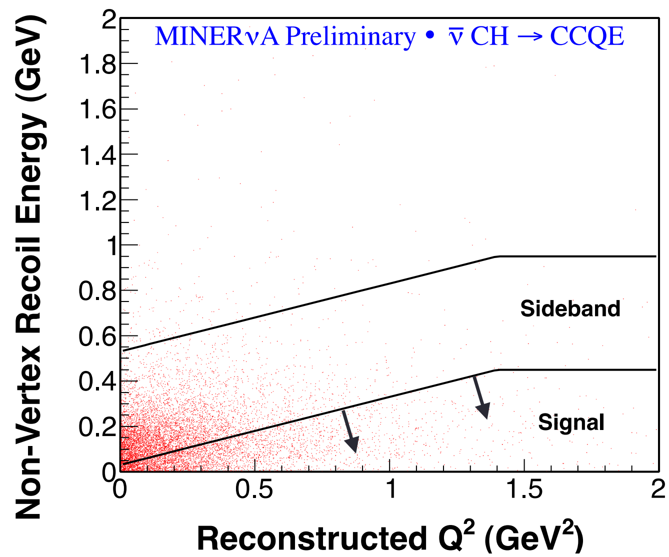

ν Beam
MeV
Vertex Energy
$\bar{\nu}_\mu$
Recoil Energy
Region
TRACKER
ECAL
HCAL
Strip number
Module number
MINOS ND
ν_μ
Vertex Energy
Recoil Energy
Region
TRACKER
ECAL
HCAL
Strip number

Recoil Energy Distributions



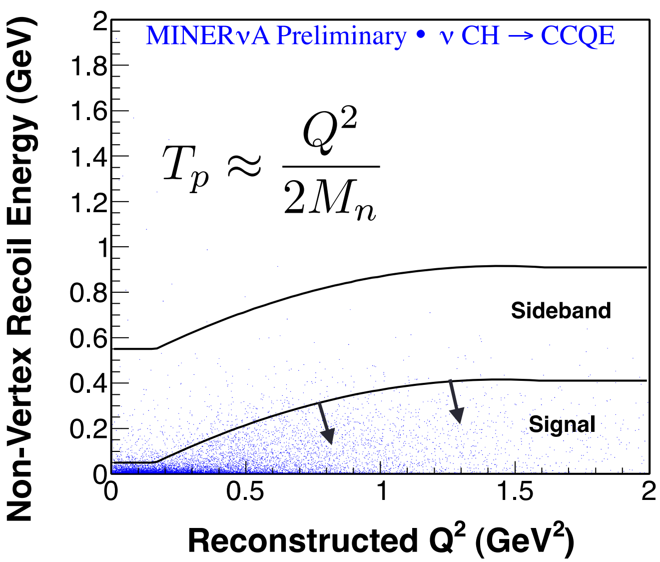
$\bar{\nu}_\mu$

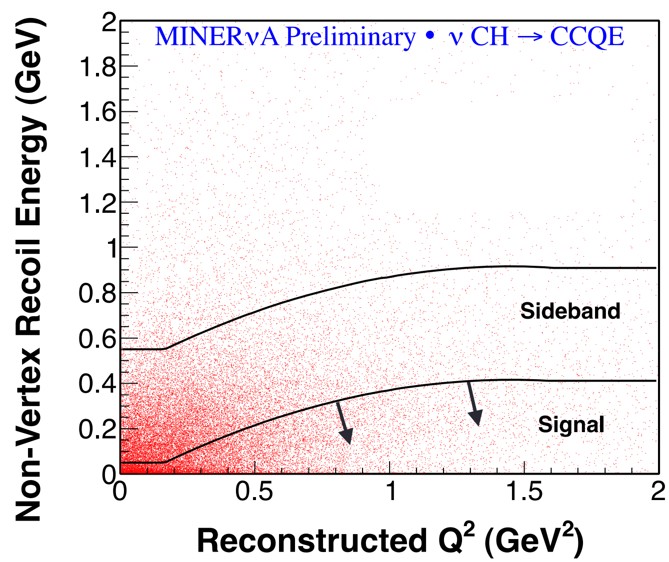




QE

ν_μ

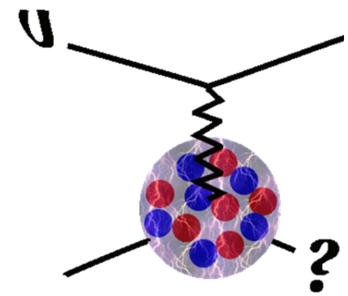




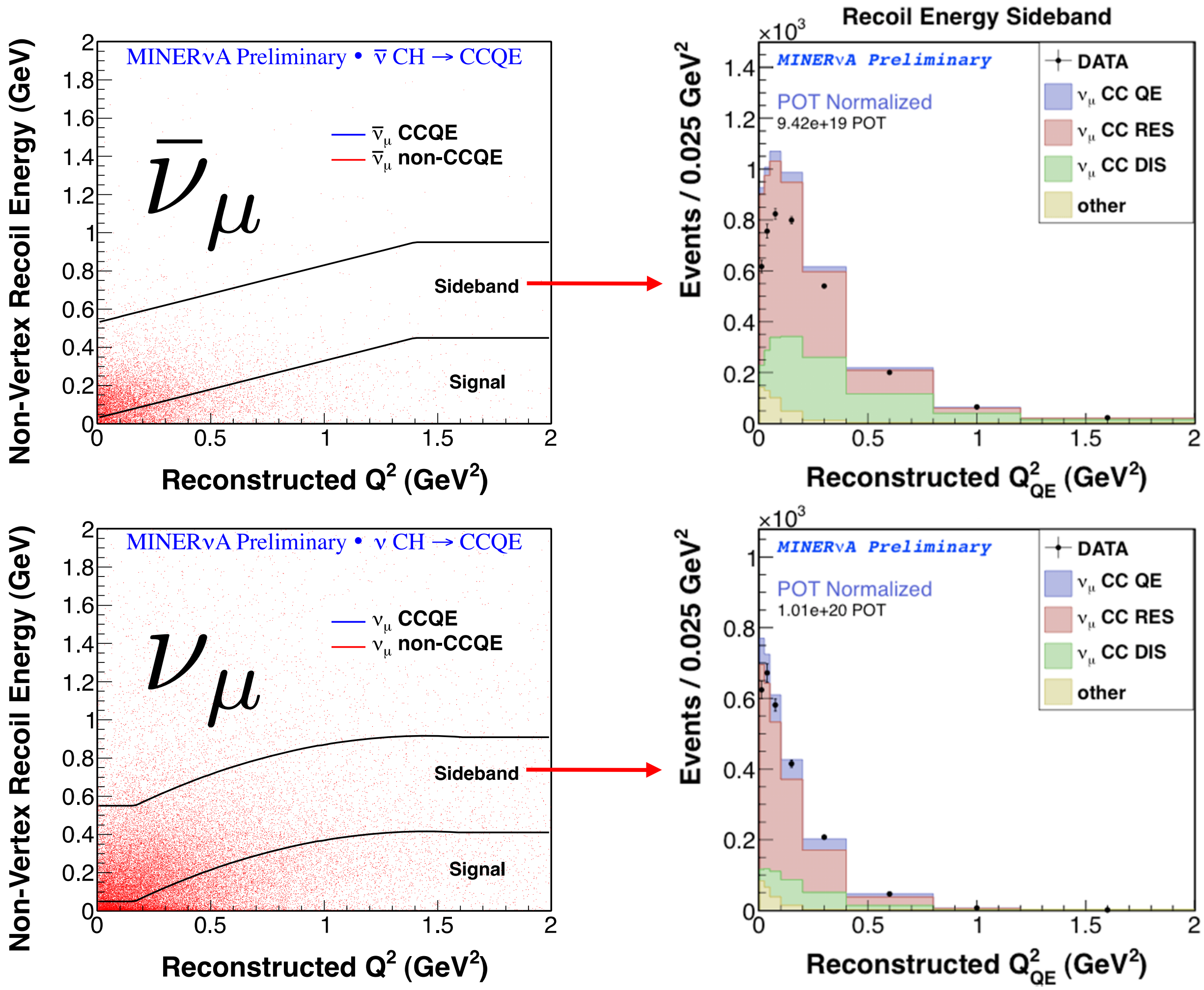
Estimate of 4-momentum transfered to nucleon

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

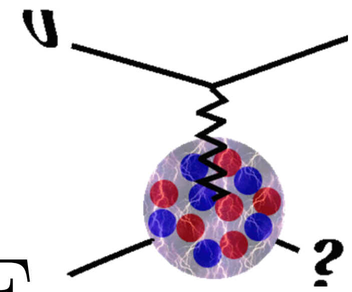
Constraint on Background



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

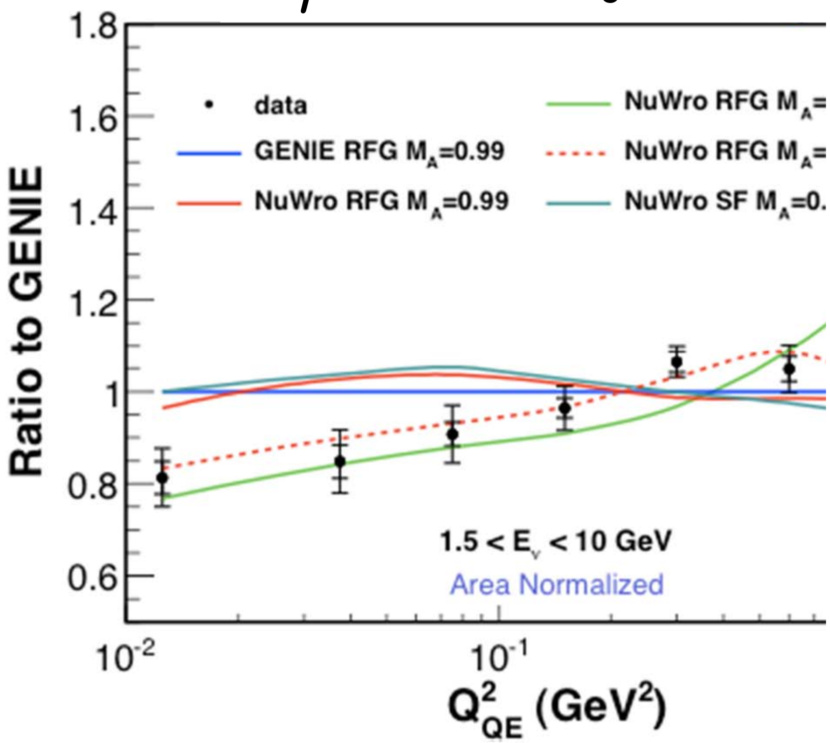


dσ/dQ^2 Shape



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

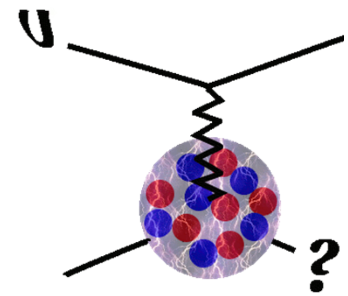
ν_μ CCQE



10^{-2}

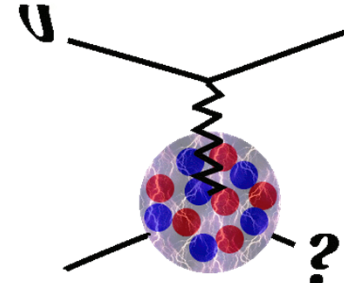
- Model used by MiniBooNE in oscillation analysis is the green line (enhance “effective” axial form factor at high Q^2)
- Best fit prefers data-drive multi-nucleon model

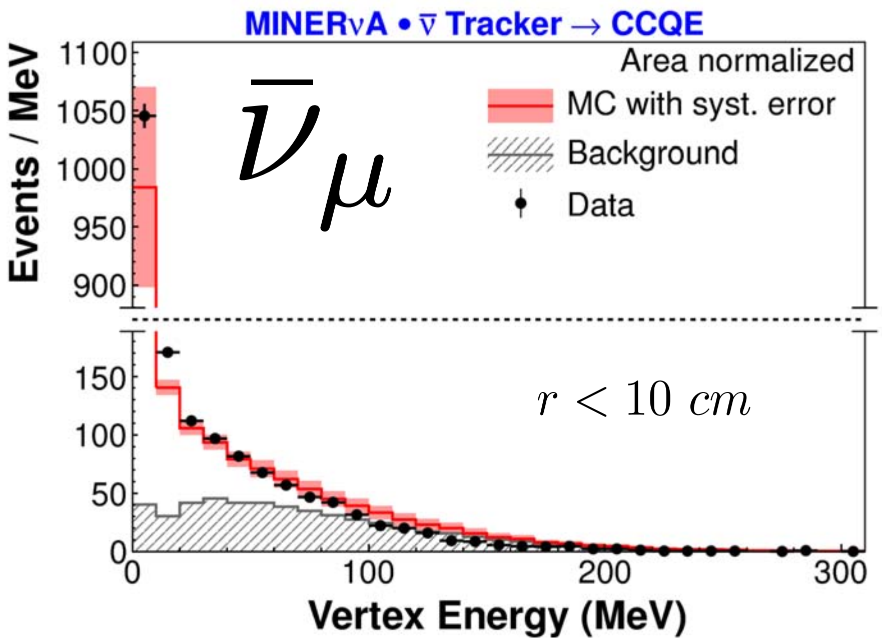
Vertex Energy

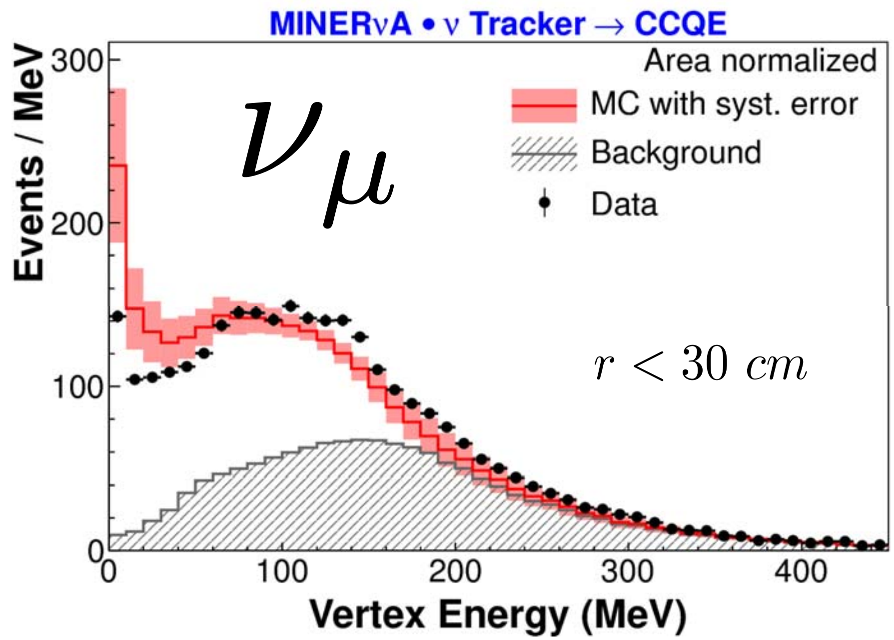


- Microscopic models of multi-nucleon (np-nh) contributions are not presently available in event generators at NuMI energies
- No prediction for the hadron kinematics in these classes of events
- In general, ***multi-nucleon emission is expected in interactions with correlated nucleons***, so this provides another possible signature
  - Additional nucleons <u>beyond</u> 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 <u>avoided</u> 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

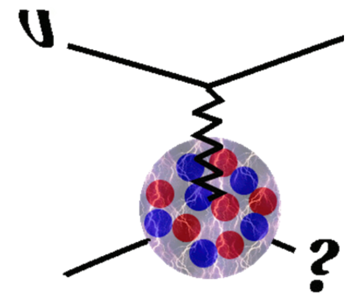




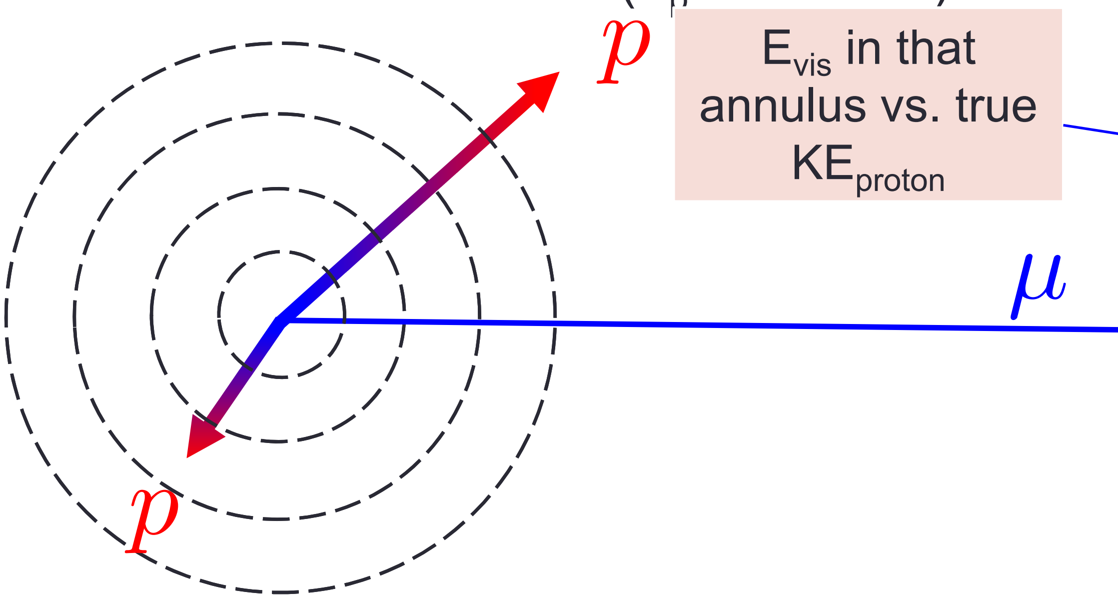


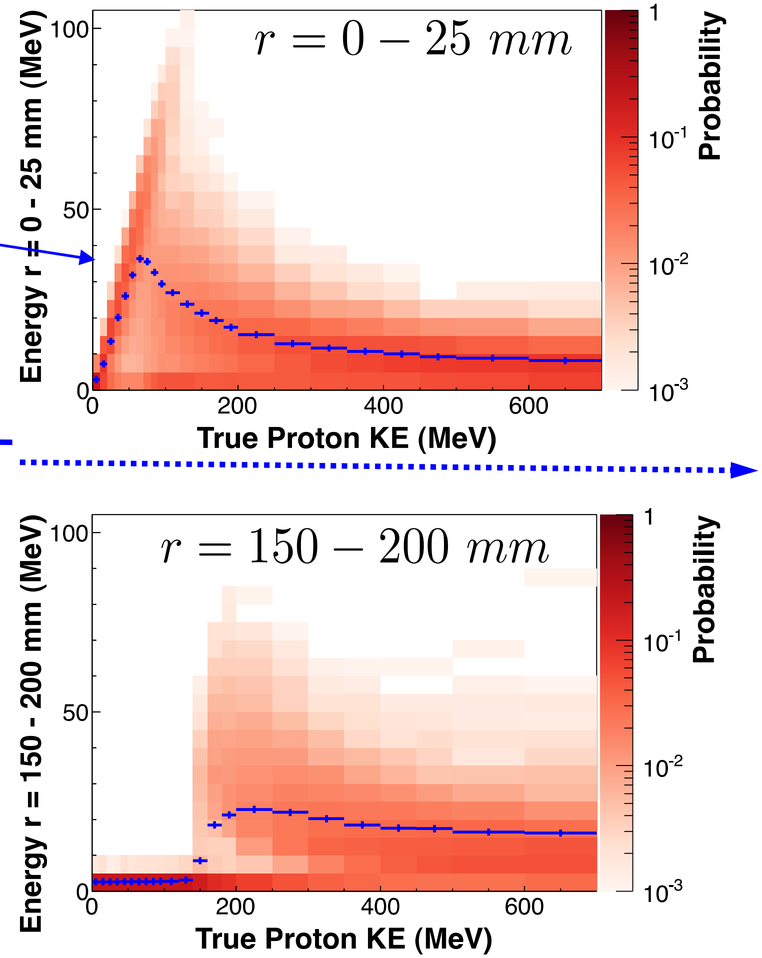
- A harder spectrum of vertex energy is observed in neutrinos
- All systematics considered, including energy scale errors on charged hadrons and FSI model uncertainties
- At this point, we make the ***working assumption*** that the additional vertex energy per event in data is ***due to protons***

Vertex Energy



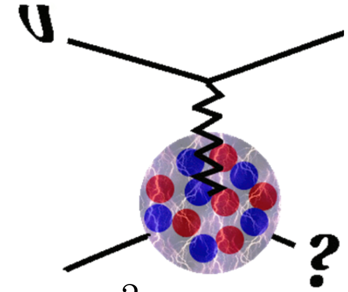
- Examine annular rings around the reconstructed vertex
  - To 10 cm for antineutrino (T_p~120 MeV)
  - To 30 cm for neutrino (T_p~225 MeV)

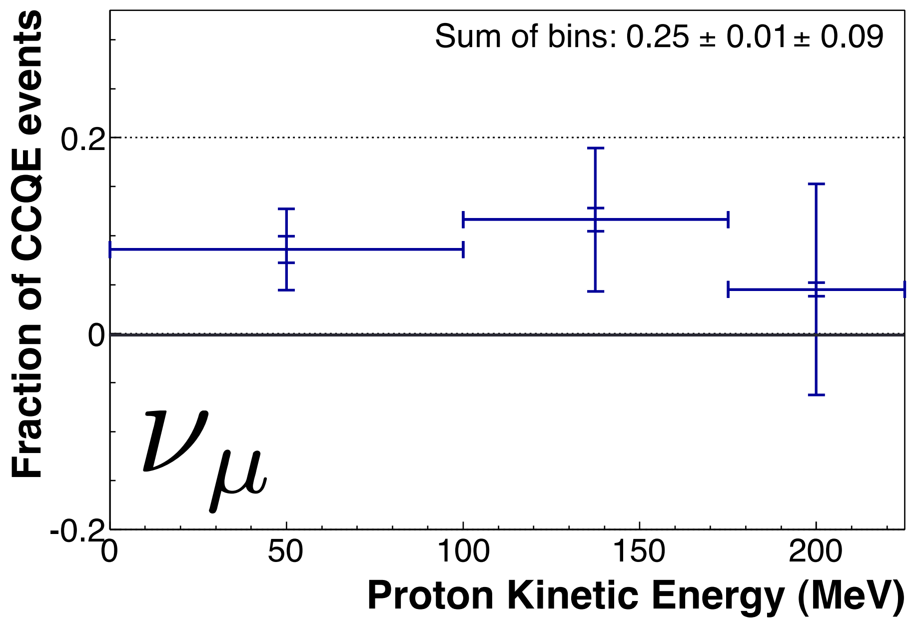


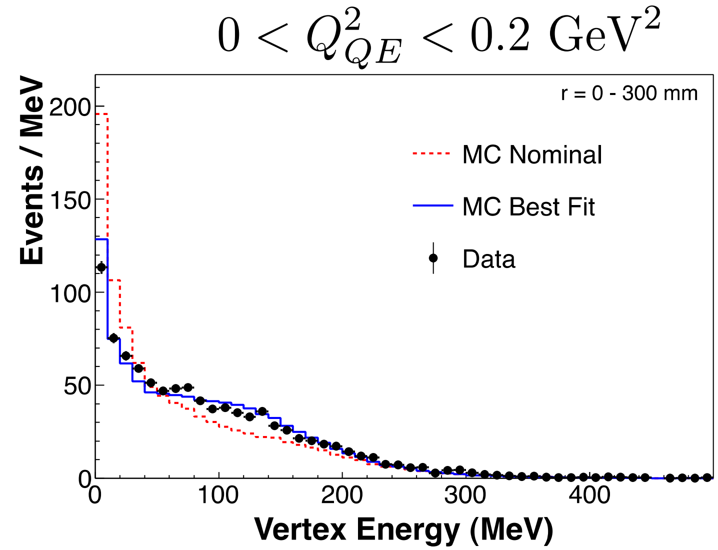


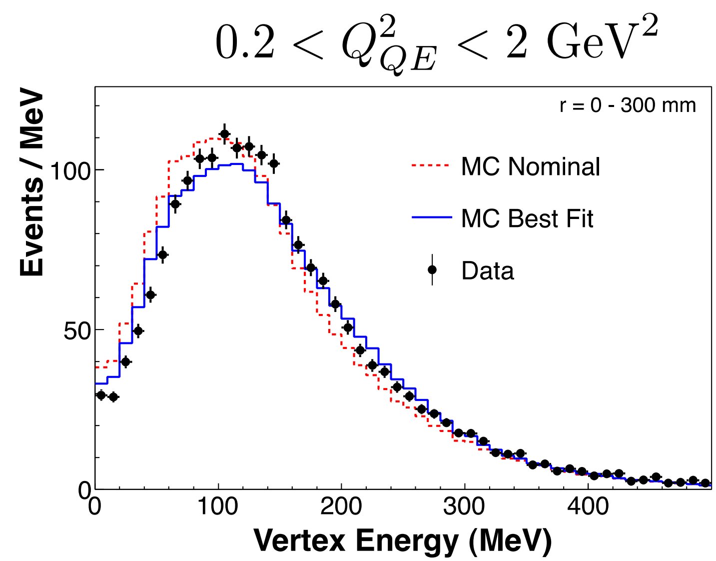
Note: to add visible energy to an inner annulus you must ***add a charged hadron***, not just increase energy of an existing one

Vertex Energy - Neutrinos



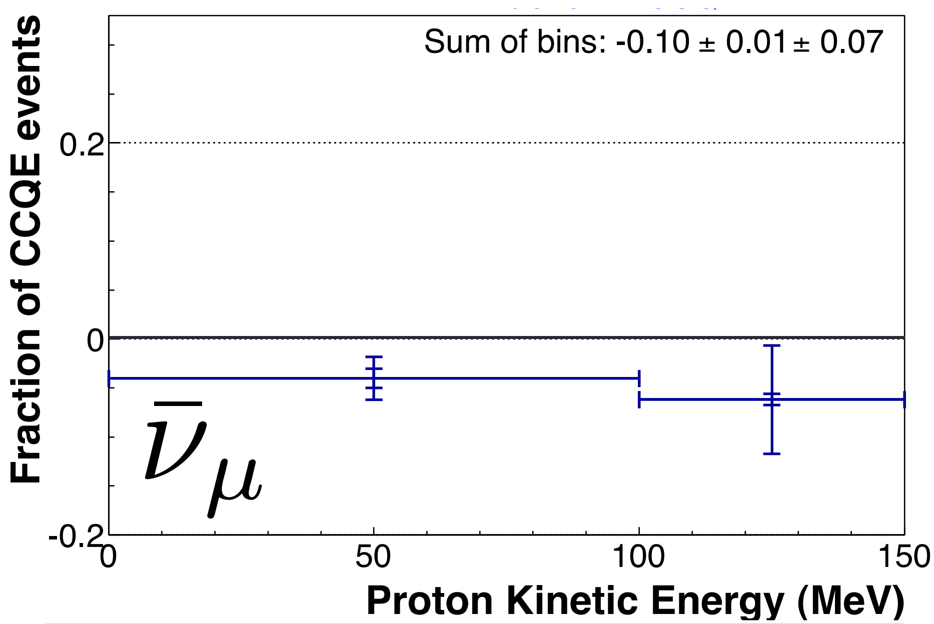






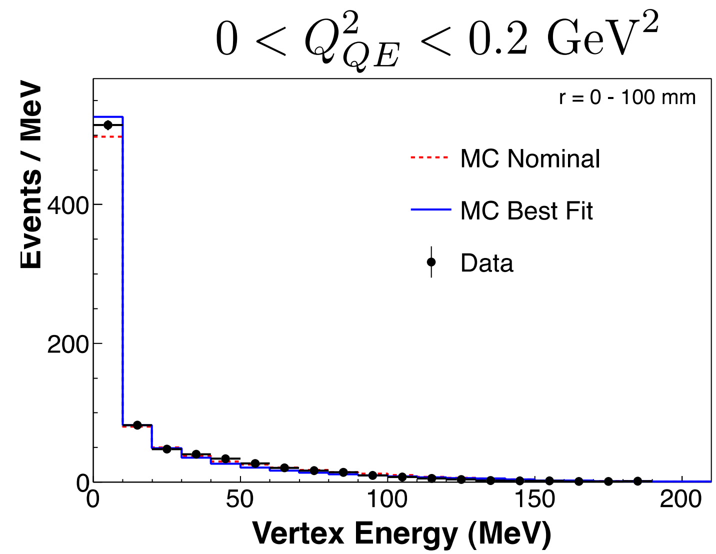
We find that adding an additional low-energy proton (KE < 225 MeV) to **(25 ± 9)% of QE events** improves agreements with data

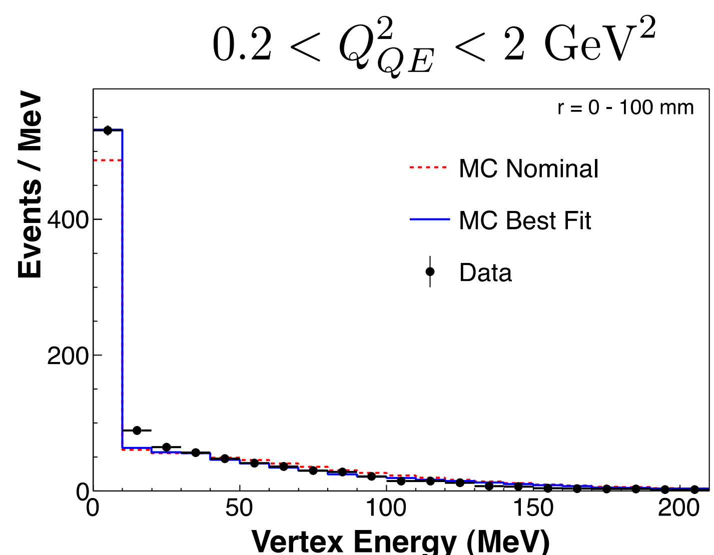
Vertex Energy - Antineutrinos



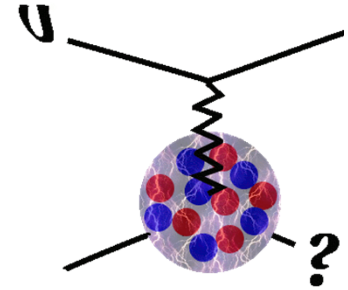
No such addition required for antineutrinos. Slight reduction if anything.

(-10 ± 7)% of QE events

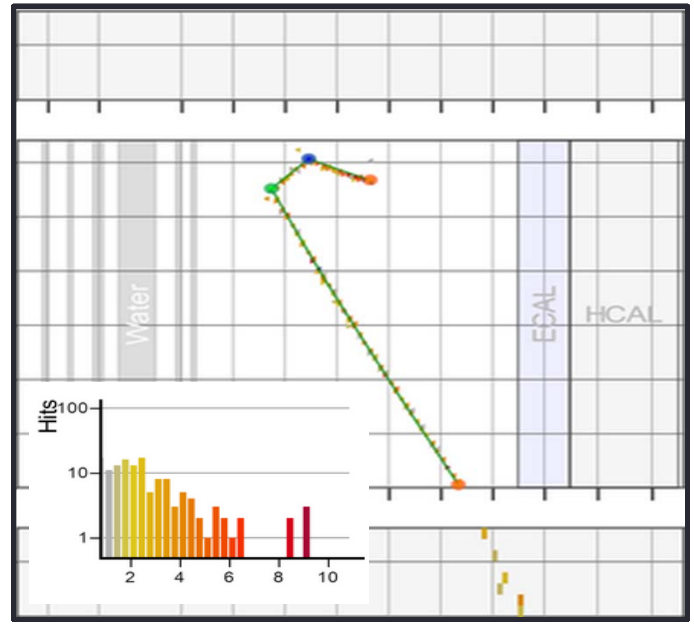


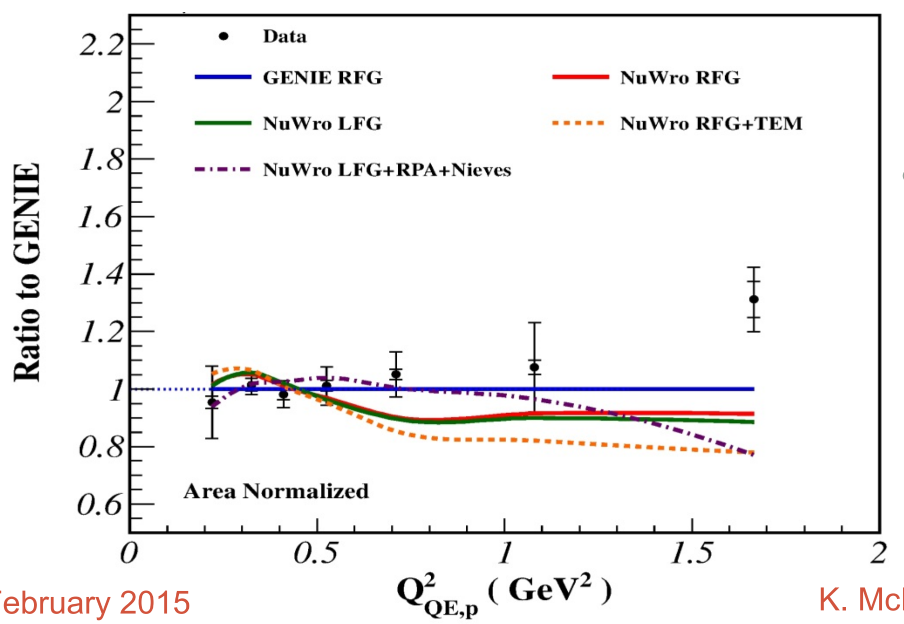


Exclusive Proton+Muon



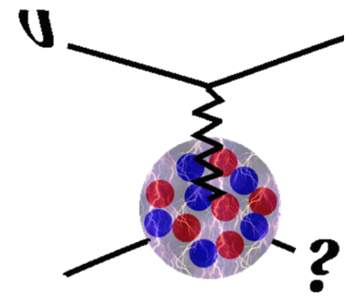
- Sample includes events where muon is fully contained and events where only muon angle is well measured
- Muon kinematics of sample are compatible with μ+X(0π) sample
- What about proton kinematics?



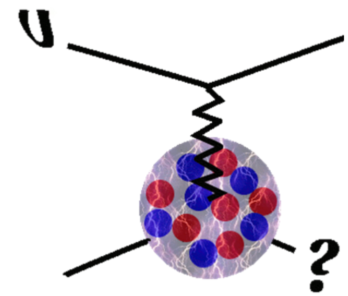


- Measure $Q^2_{QE,p}$ assuming quasi-elastic kinematics from the bound nucleon at rest
  - A model-independent quantity, $Q^2_{QE,p}(T_p,\theta_p)$, sensitive to final state interaction model

Quasi-Elastic: Discussion

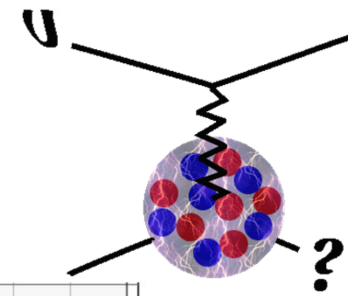


- Selected events that had muons and nucleons, but without pions
- Enhancement at moderate Q^2, consistent with other experiments, does not persist at high Q^2
  - Consistent with dynamical models of multi-nucleon processes
  - Not consistent with “standard” modification of nucleon form factors
- Also 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 suggest that final state hadrons are incorrectly modeled in GENIE & NuWro
- We can find no model that captures all these features

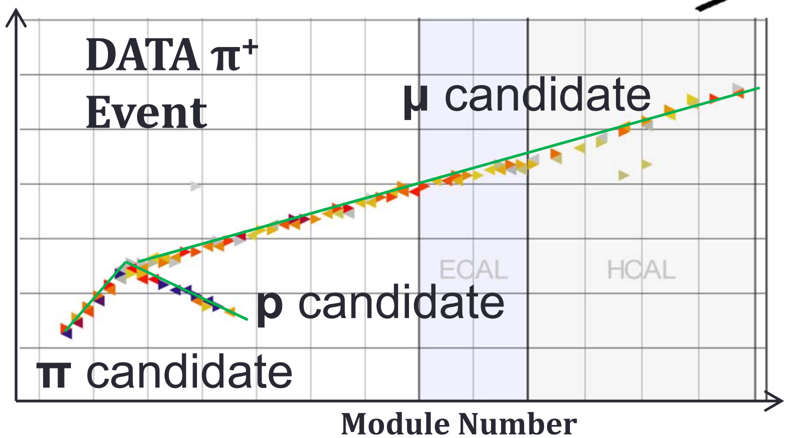


Pion Production

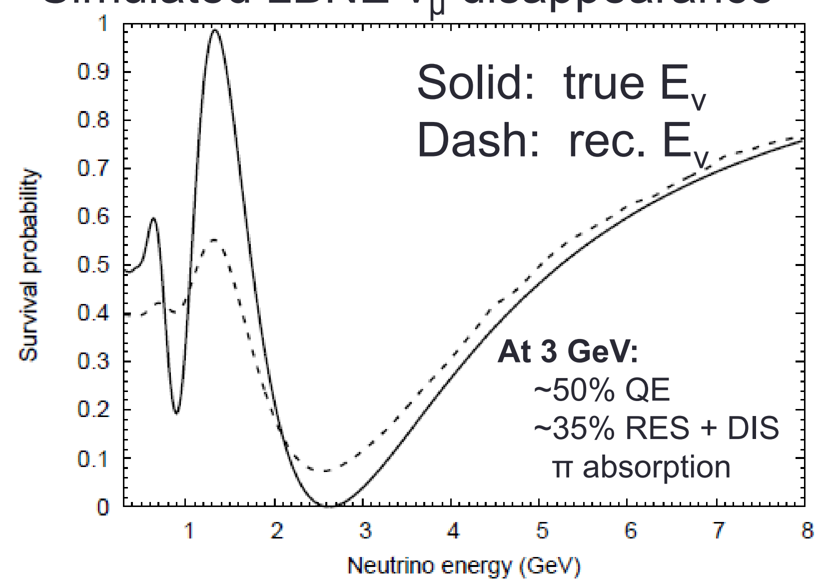
Pion Production



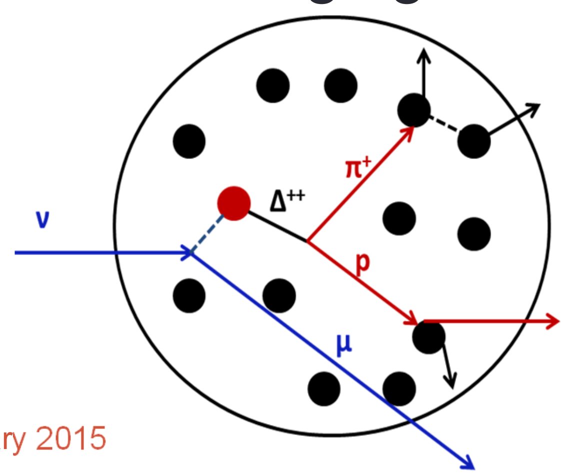
- Most common inelastic interaction at low energies
- Oscillation experiments that don’t identify the pion suffer an energy bias
- Produced pions strongly interact inside nucleus before emerging



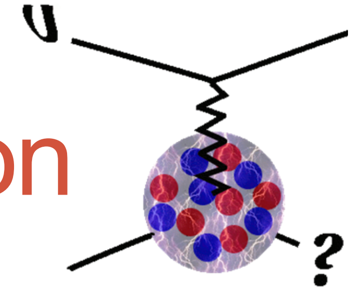
Simulated LBNE ν_μ disappearance



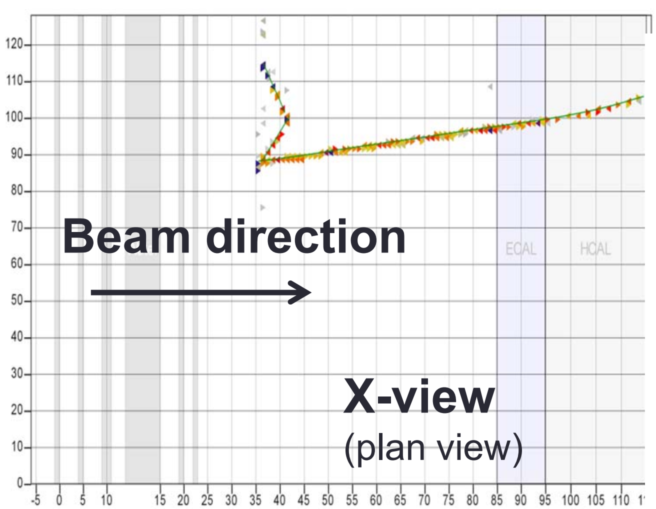
Mosel *et al*: arxiv 1311.7288

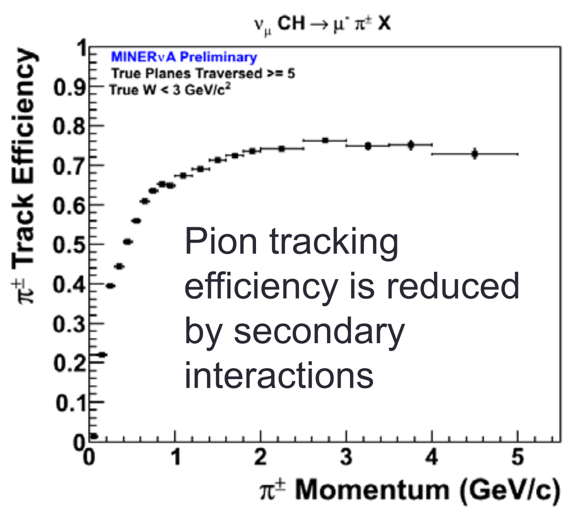


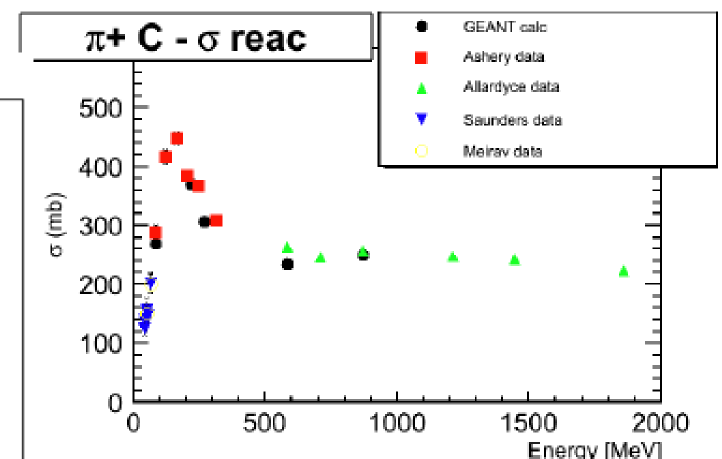
Charged Pion Reconstruction



- 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, π→μ→e
- Elastic or inelastic scattering in scintillator is a significant complication of reconstruction
  - Study uncertainties by varying pion reactions, constrained by data

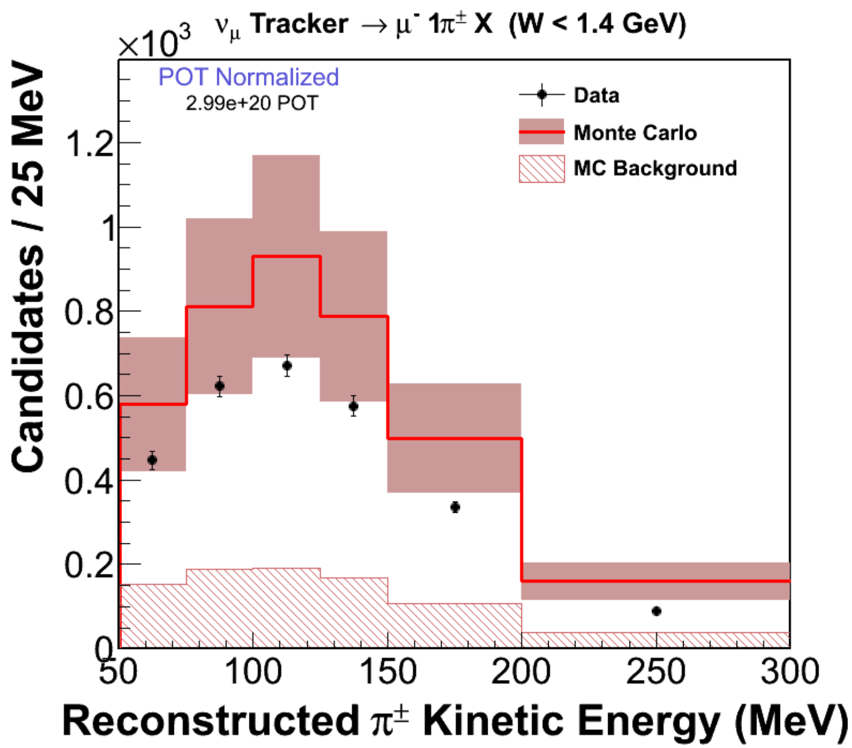


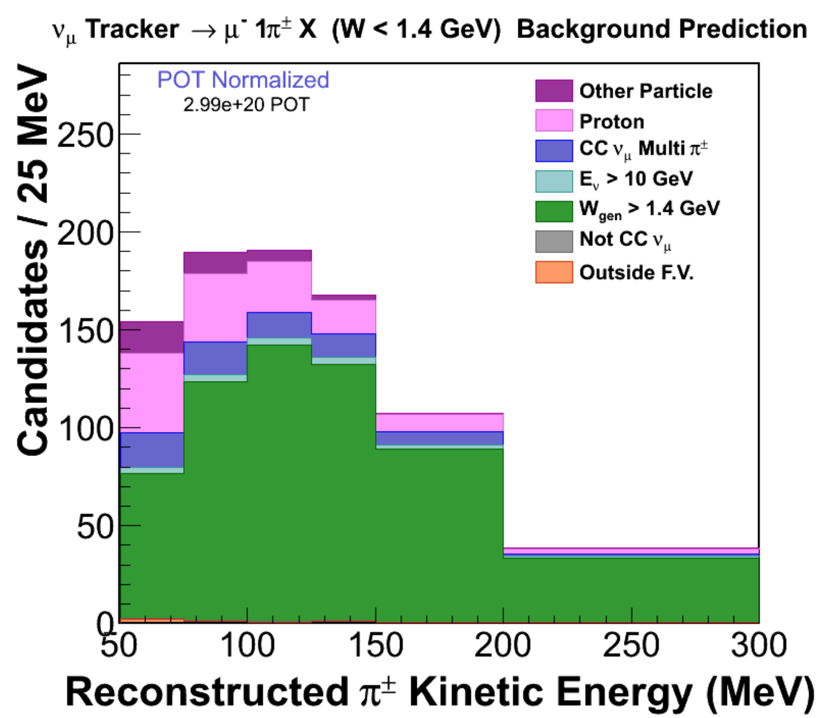




π^+ Signal and Background

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

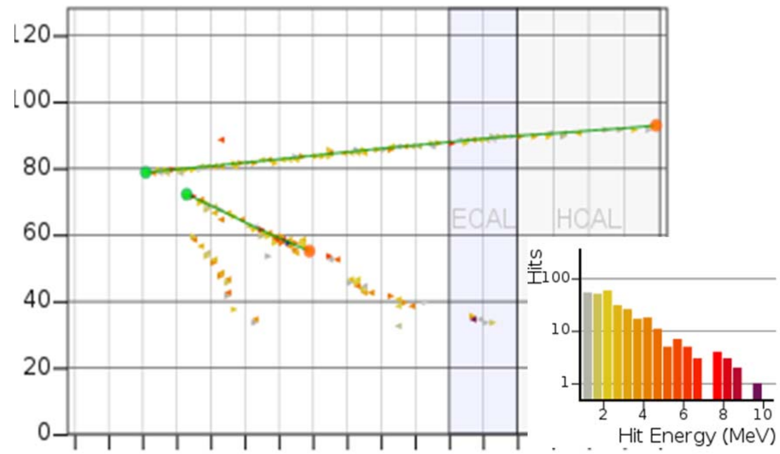


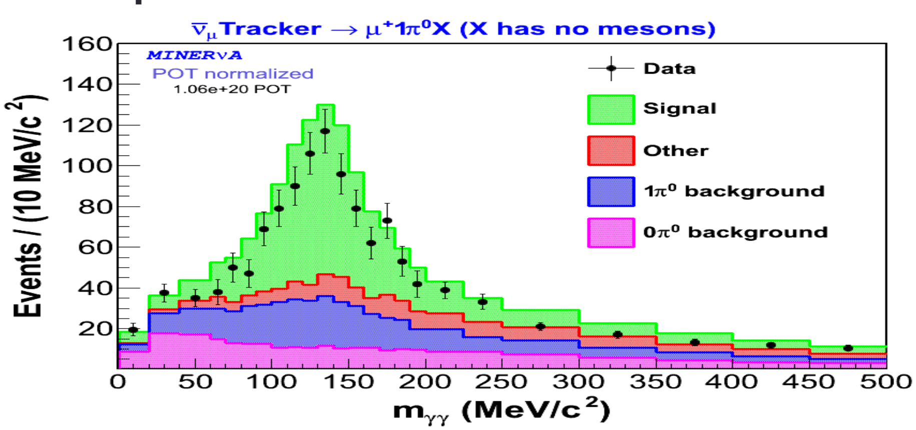


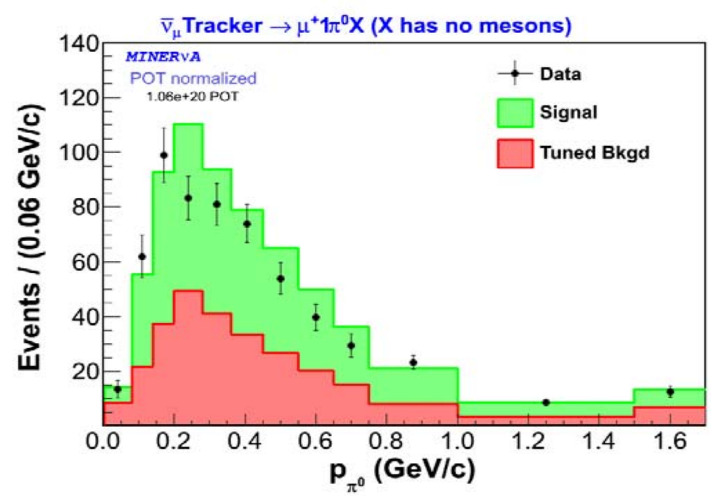
Neutral Pion Reconstruction

- Reaction is $\bar{\nu}_\mu + \mathrm{CH} \rightarrow \mu^+ \pi^0 X$
  $\qquad\qquad\qquad\qquad\quad \hookrightarrow \gamma\gamma$

- Reconstruction strategy is to find muon and "detached" vertices
  - Photons shower slowly in plastic, so they look like "fat tracks"
- Backgrounds can be constrained with pion mass

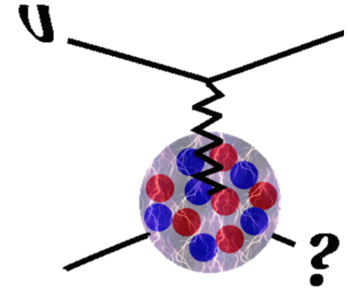


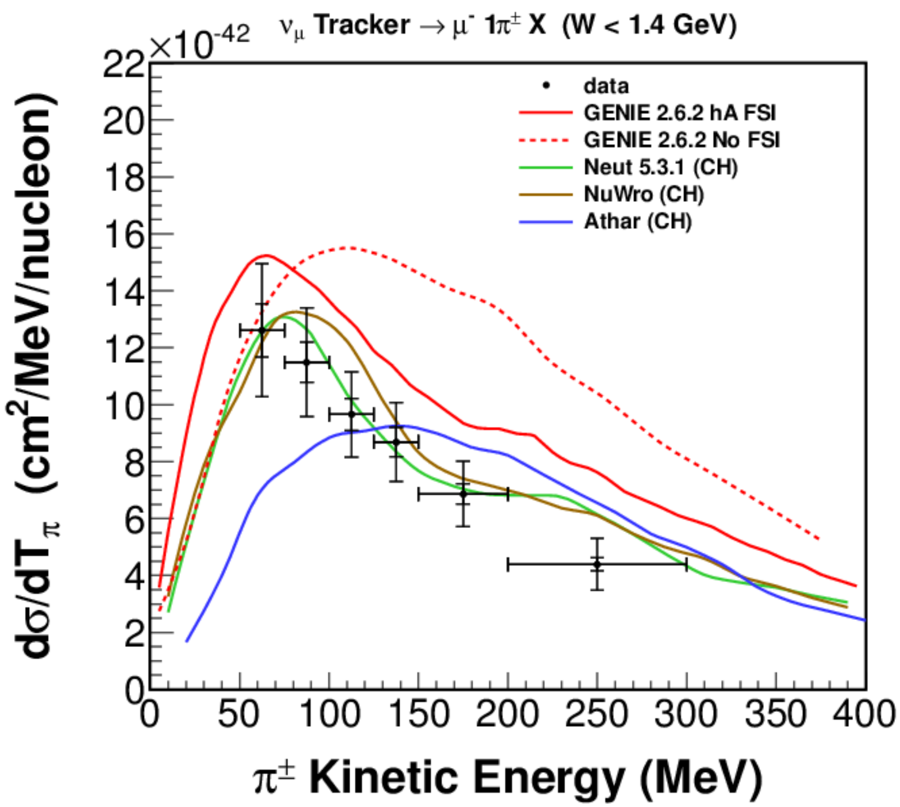


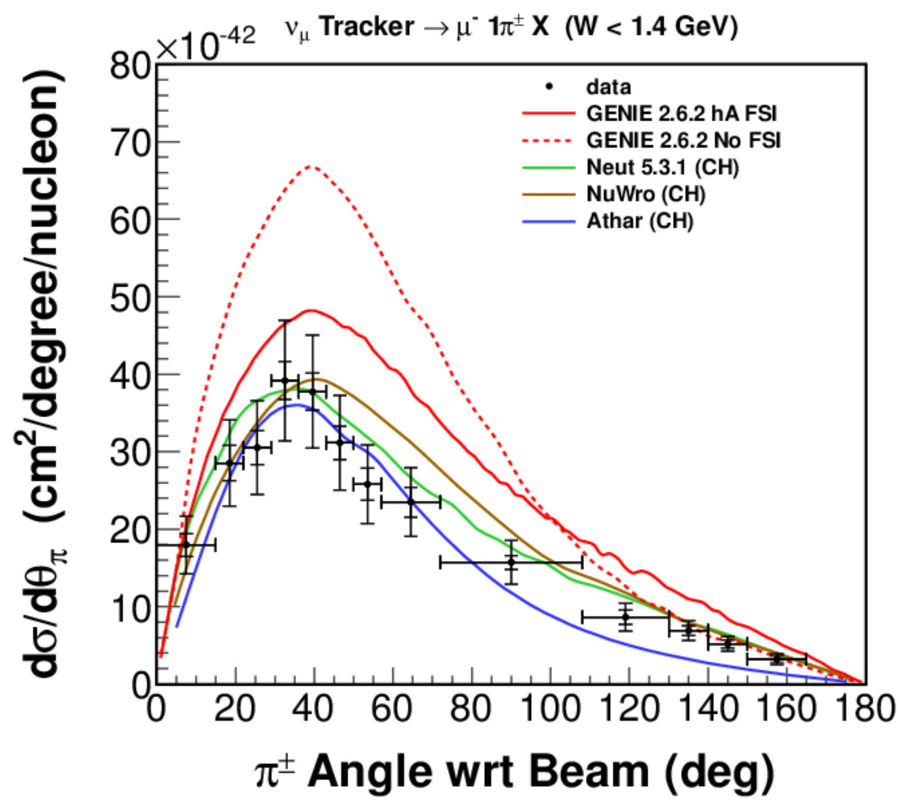


π^+ Kinematics

(Flux integrated)

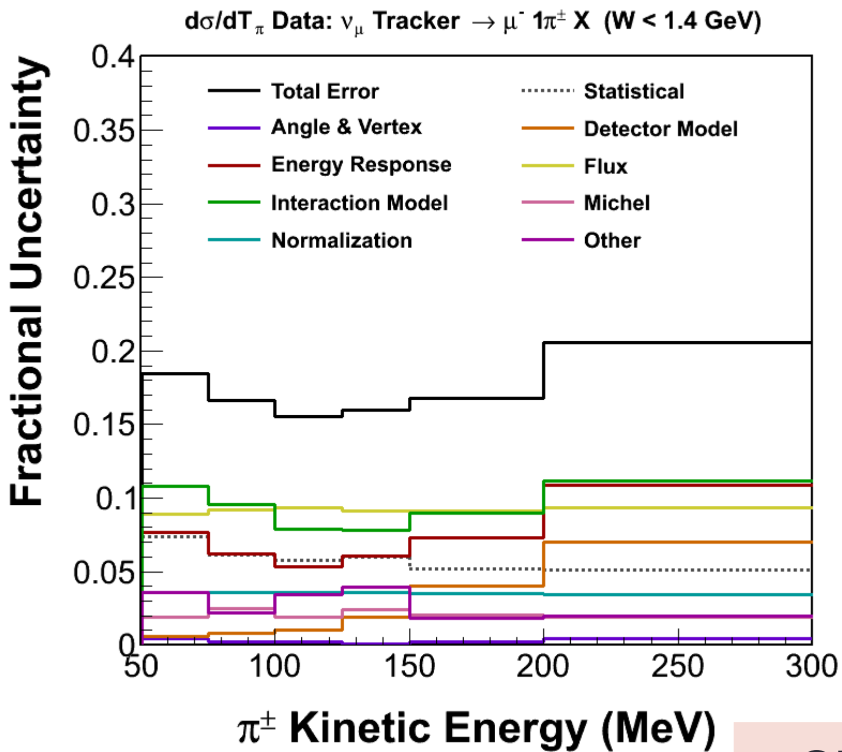




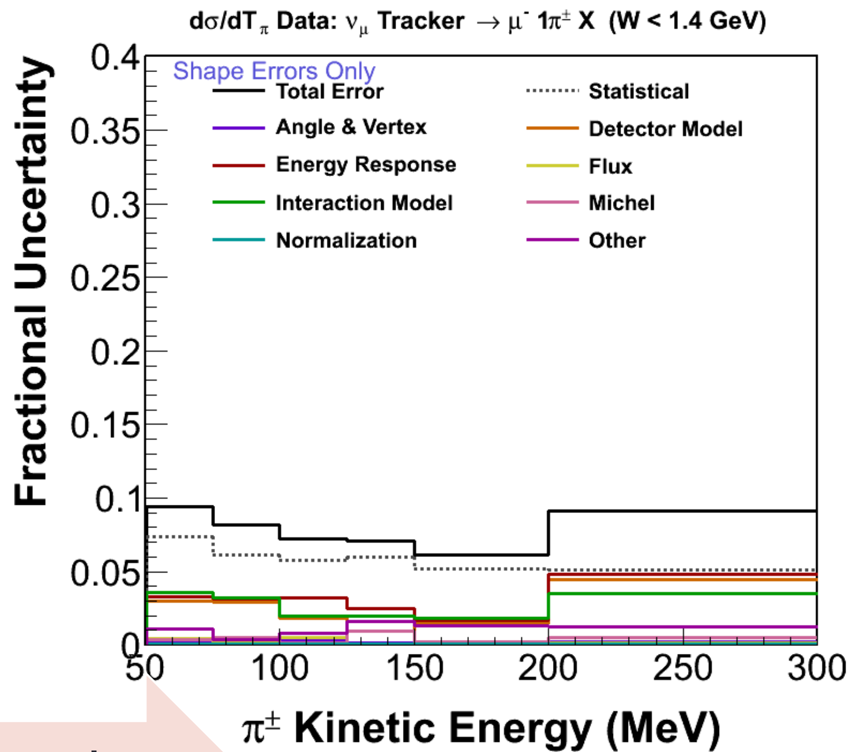


- Overall rate varies because knowledge from "free nucleon" targets (mostly weakly bound D_2) is unclear
- But see C. Wilkinson, P. Rodrigues *et al*,

Uncertainties and "Shape"

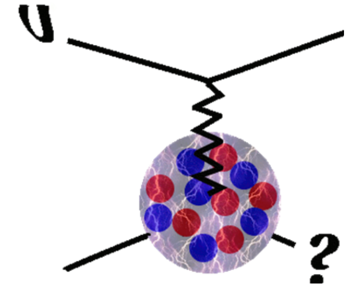


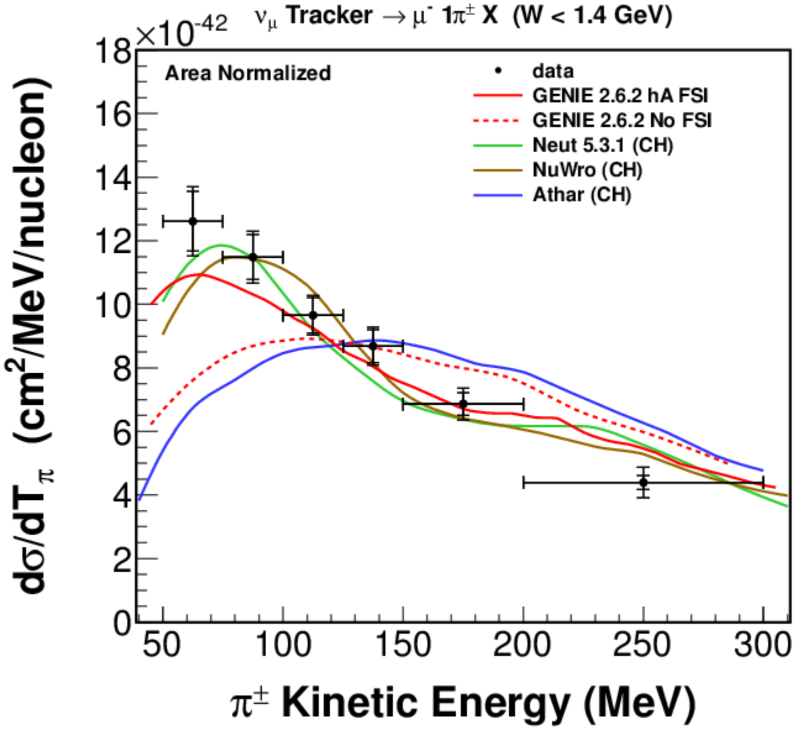
Shape only

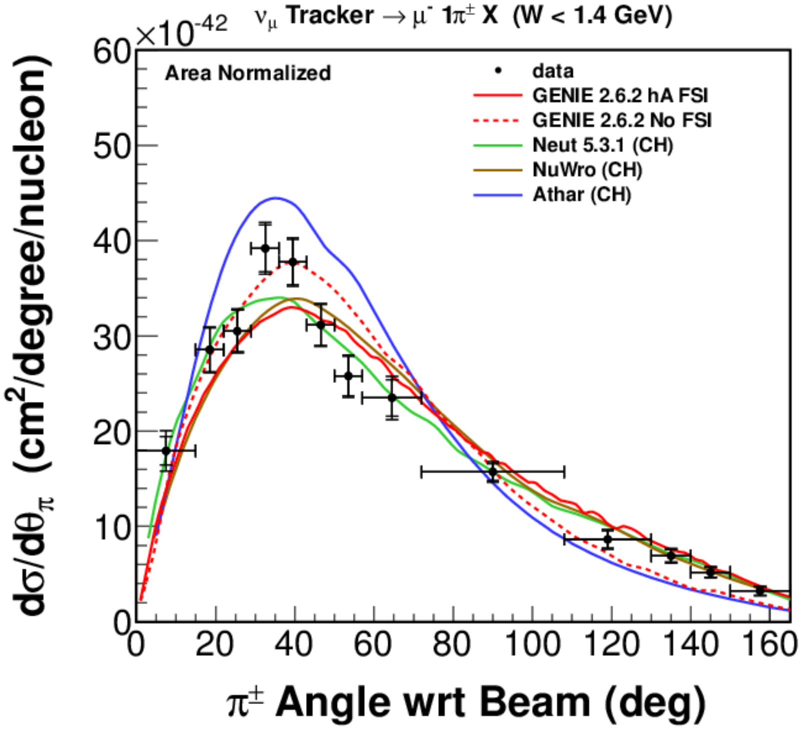


- Flux uncertainties and (preliminary) uncertainty from extrapolation to high muon angle (high Q^2) both become insignificant in pion kinetic energy and angle shape distributions

π^+ Shape and Final State Interactions

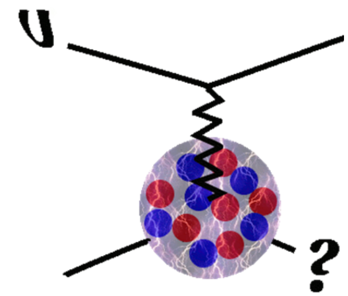




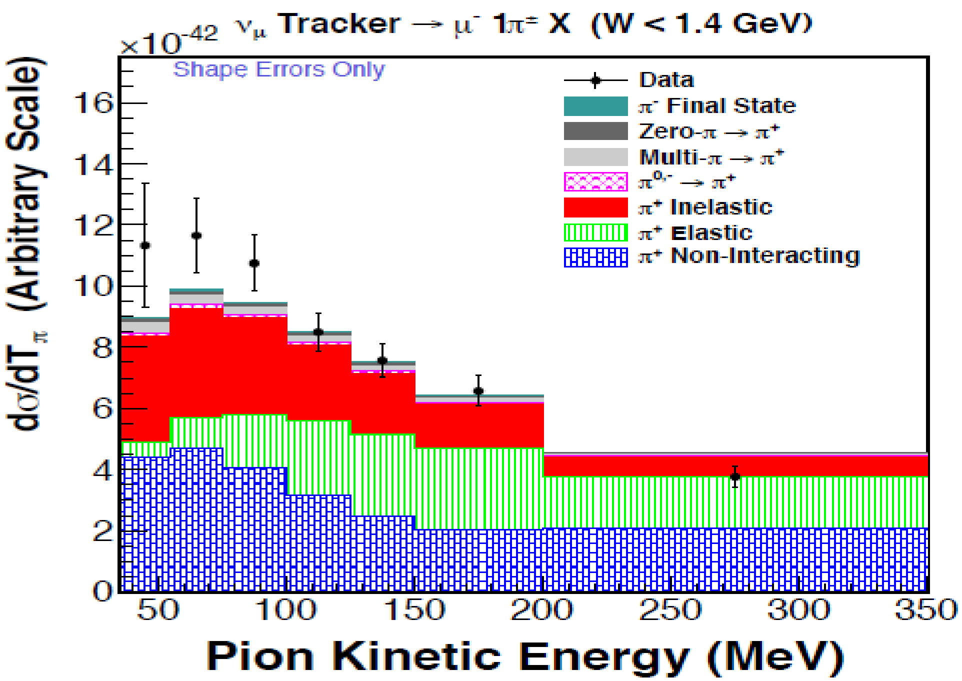


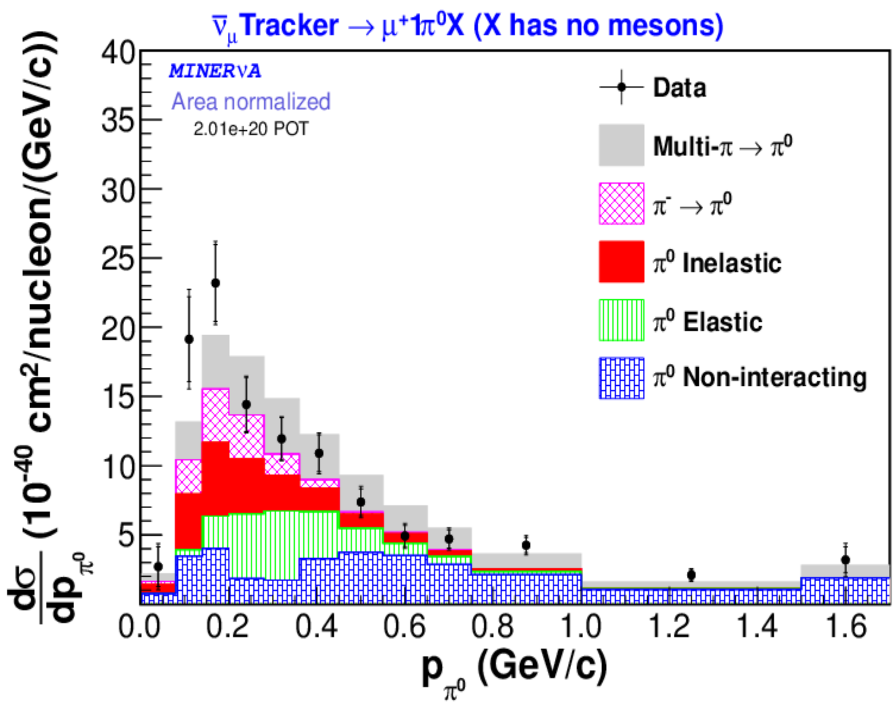
- **Conclusion:** NuWro, Neut, and GENIE all predict the data shape well
- **Conclusion:** Data insensitive to the differences in pion absorption shape between GENIE, NuWro, and Neut
- **Conclusion:** Athar, the sole theoretical calculation, does not agree with data. Likely due to an insufficient FSI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

Separating Final State Reactions

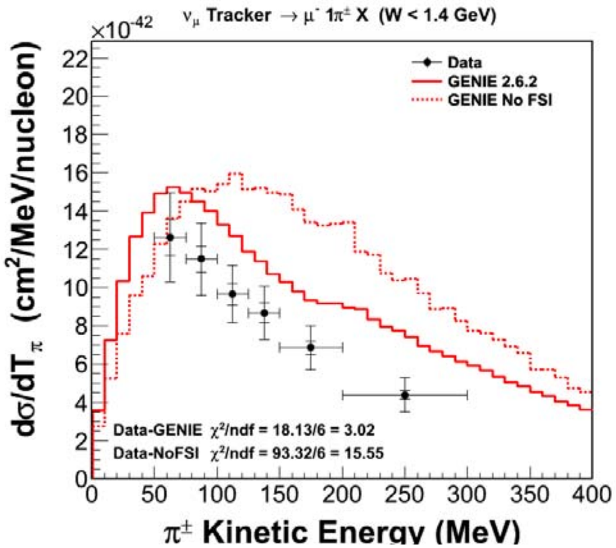


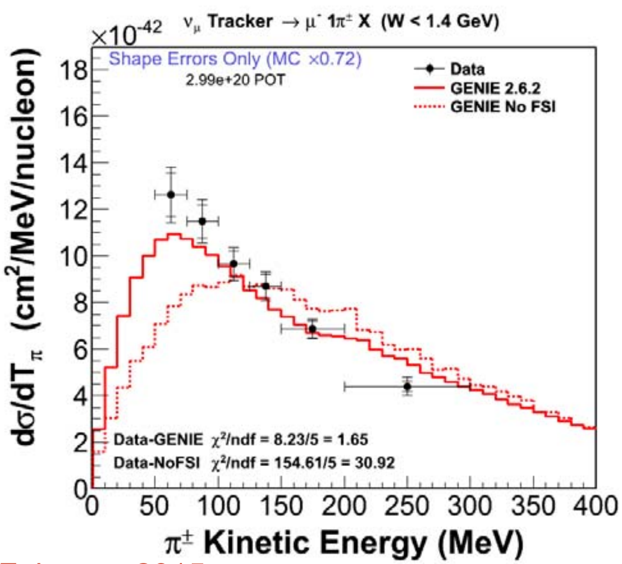
- Some ability of this data with different final states to probe different reactions of pions within the nucleus
- Both datsets would prefer a higher fraction of inelastic interactions of pions than current in GENIE generator

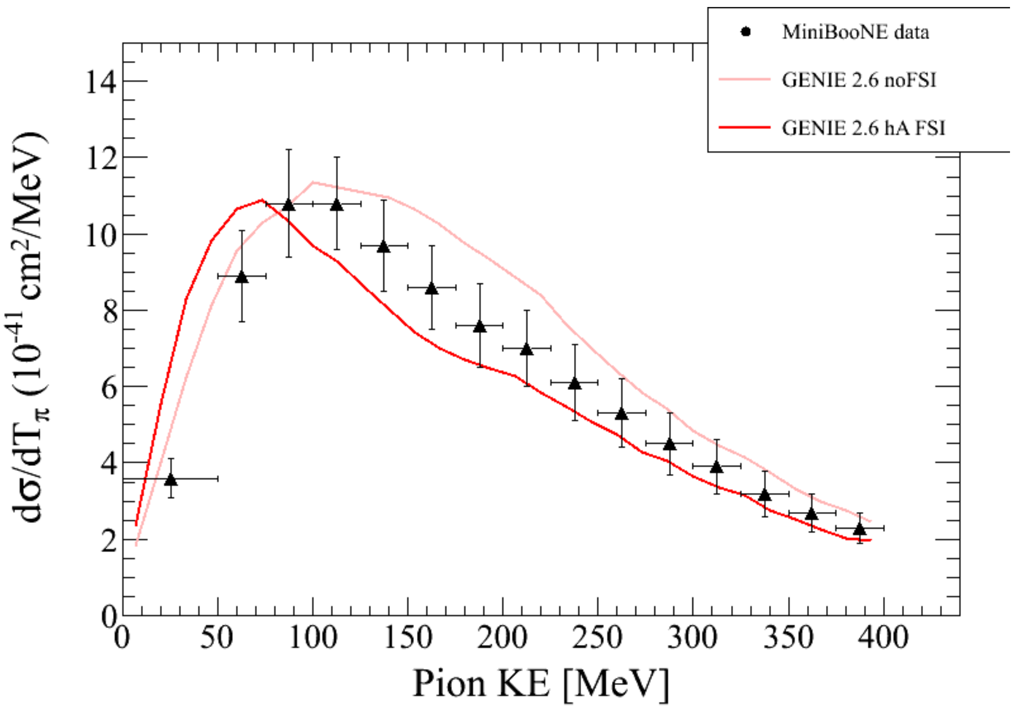




π^+ comparison to MiniBooNE

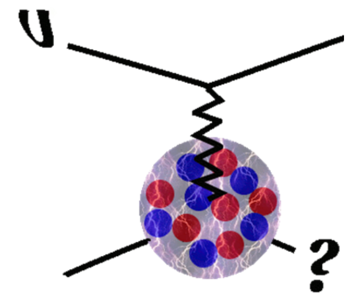




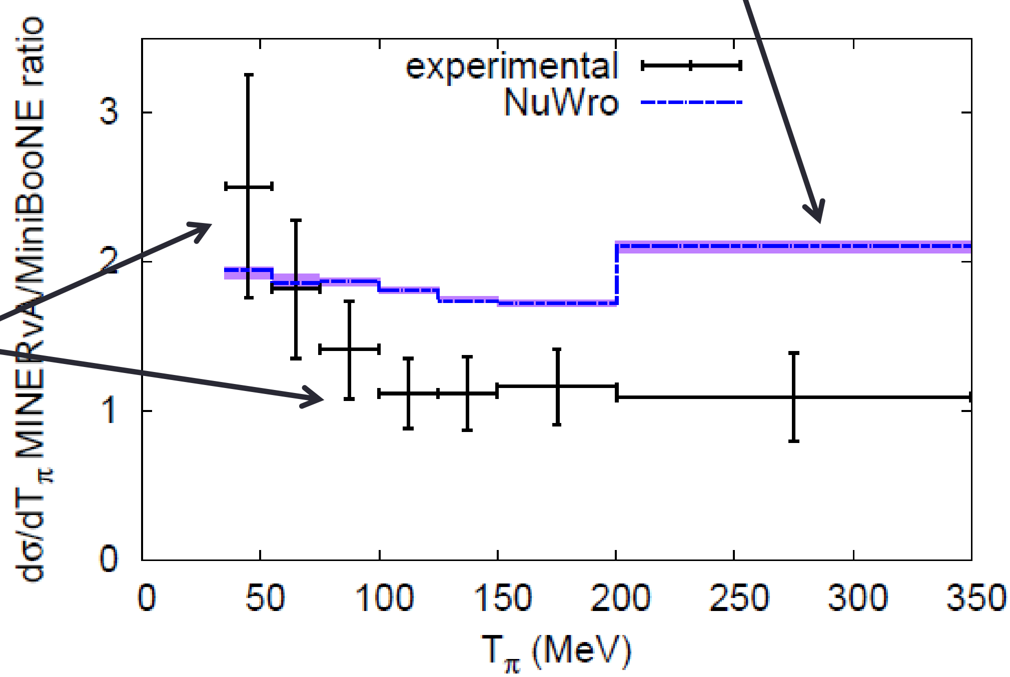


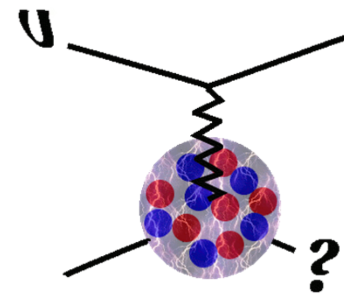
- Even with ~10% flux uncertainties from both experiments, there is ~2σ tension between MINERvA and MiniBooNE
- Shape tension also
- Note, MINERvA π^+ and π^0 are similar

Can Current Models Resolve this Tension?



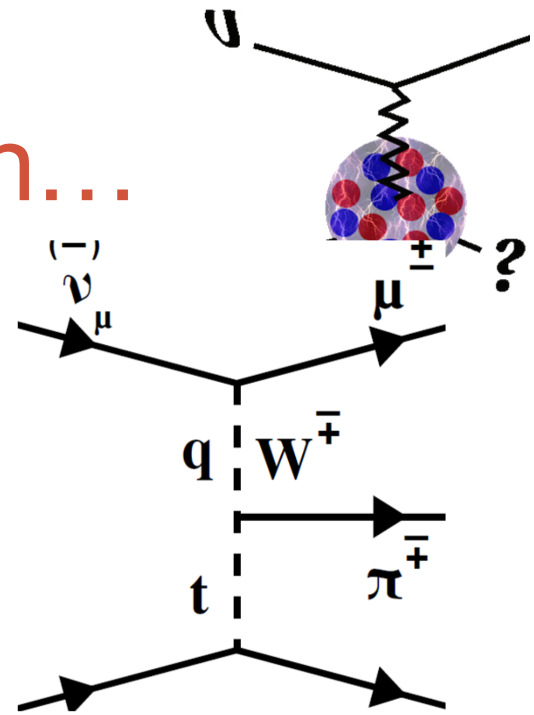
- Interesting study by Sobczyk and Zmuda (arXiV:1410.7788) asks if uncertainties in final state "cascade" models and pion production to explain MiniBooNE-MINERvA difference
- Their conclusion: it cannot. Theory uncertainties on the ratio are very small.
- Uncertainties in bins are highly correlated, so maybe explains high energy part?
- And maybe low energy is a statistical fluctuation?





Coherent (!) Pion Production

A Very Strange Reaction…

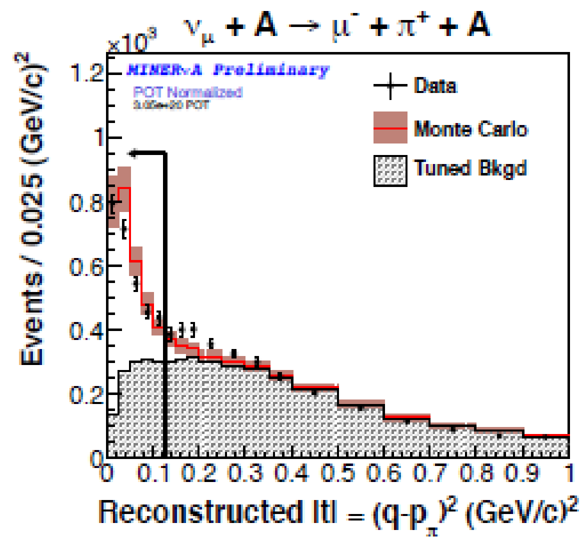


- Despite small binding energy of nucleus (few-10s MeV), a pion can be created from the off-shell W boson and leave the nucleus in its ground state
- Reaction has small 4-momentum transfer, t, to nucleus
- Can reconstruct |t| from final state
- Reconstruction of |t| gives a model-independent separation of coherent signal and background
  - Tune background at high |t|
  - Measure signal

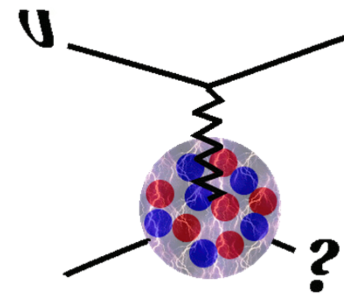
$$E_\nu = E_\mu + E_\pi$$

$$Q^2 = 2E_\nu(E_\mu - P_\mu cos\theta_\mu) - m_\mu^2$$

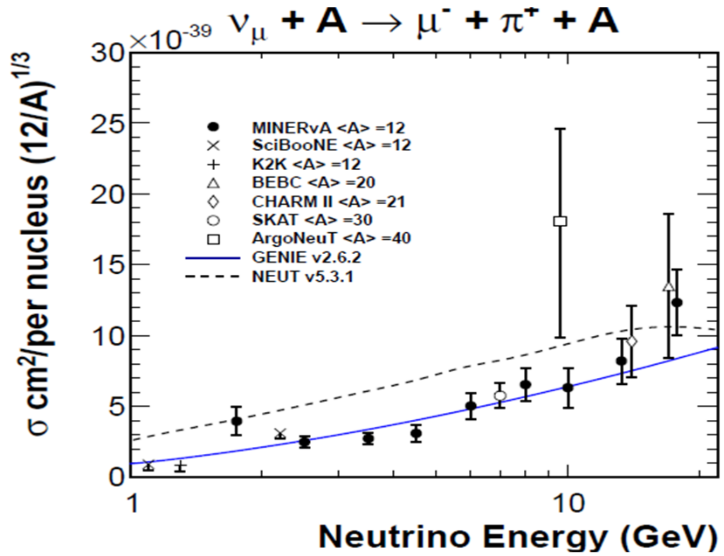
$$|t| = -Q^2 - 2(E_\pi^2 + E_\nu p_\pi cos\theta_\pi - p_\mu p_\pi cos\theta_{\mu\pi}) + m_\pi^2$$



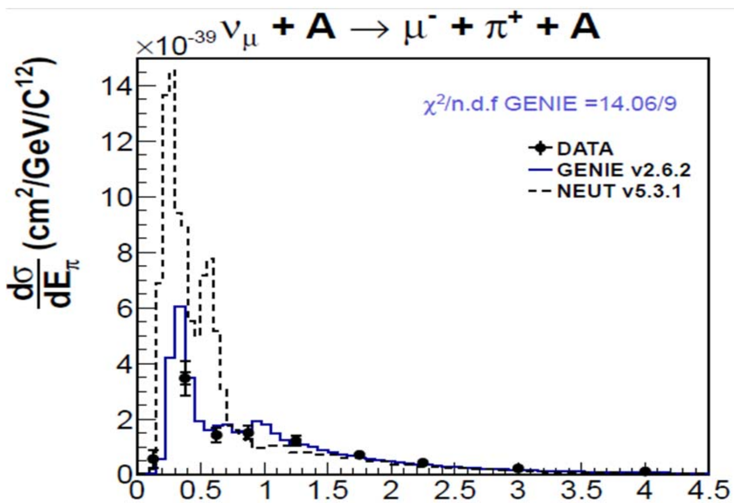
MINERvA Result

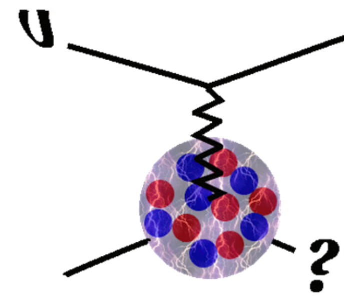


- Measure in both neutrinos and anti-neutrinos (signal cross-section should be the same)
- Models differ in treatment of one input (pion-nucleus elastic scattering cross-section) and in treatment of mass effects



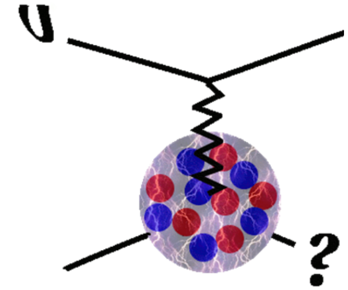
- Neither NEUT nor GENIE generators do well
- This is an important reaction for low energy oscillation experiments like T2K and H-K





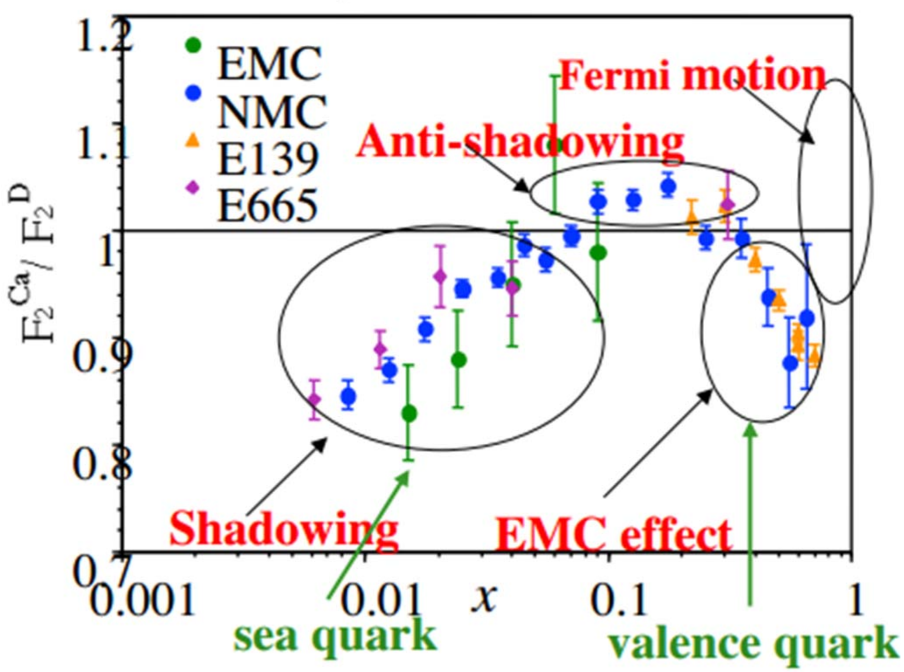
Nuclear Target Ratios

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 …

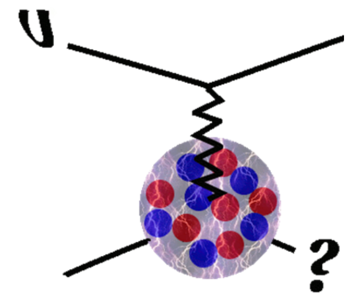
CERN COURIER

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



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

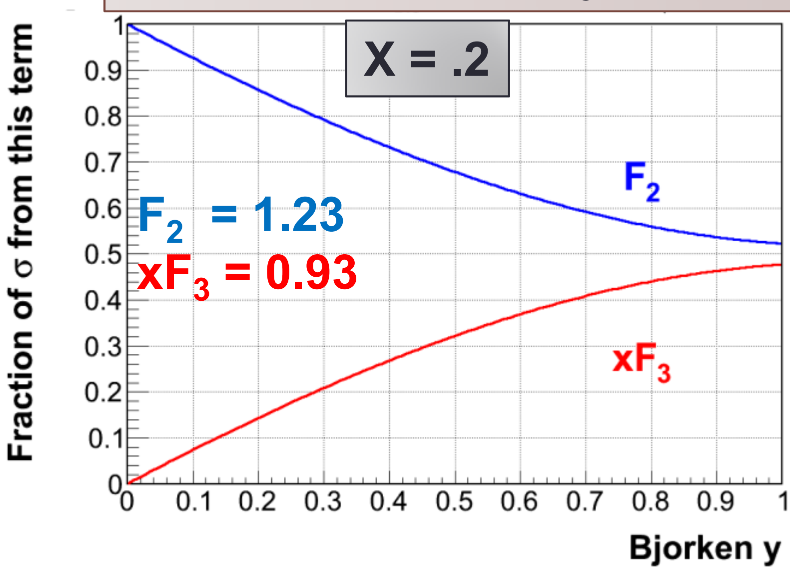
Sum of all quark and antiquark momentum

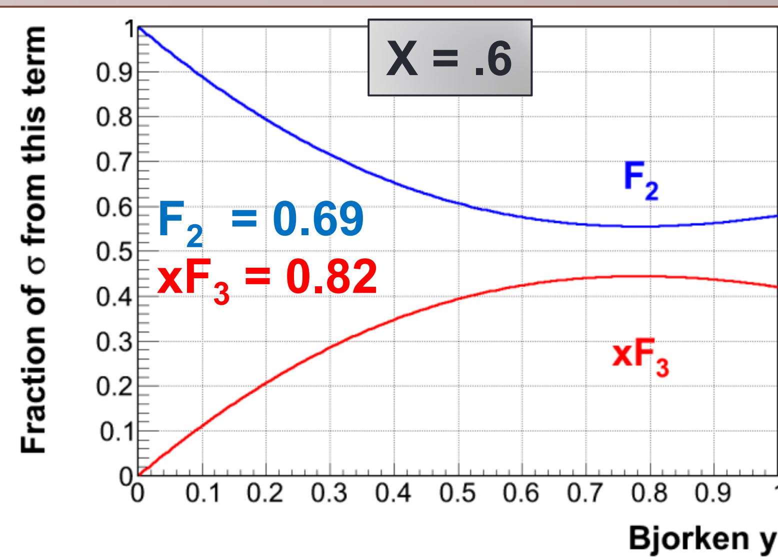
$$xF_3(x,Q^2) = 2\sum_{q=u,d,\ldots}\left[xq(x,Q^2) - x\bar{q}(x,Q^2)\right]$$

Sum of valence quark momentum

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

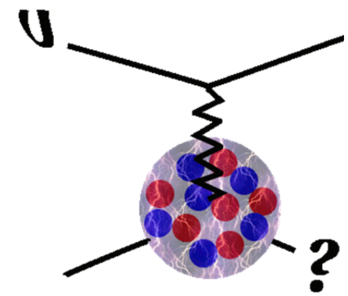
How much do they contribute to the neutrino DIS cross section?



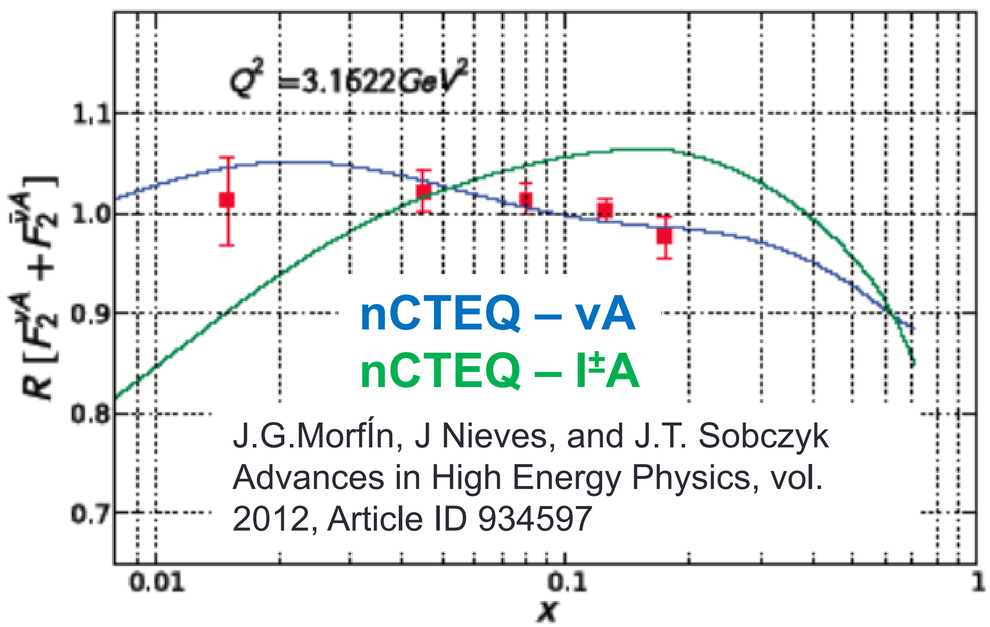


*Calculated for neutrino-neutron at Q^2 =1 GeV^2, E_ν = 4 GeV

No comparable neutrino data exists!



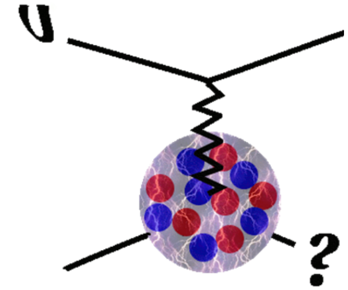
Compromise approach is to compare a theoretical calculation of free nucleon F_2 to, e.g., NuTeV (ν-Fe) data, and fit. Compared to fits to charged lepton data.

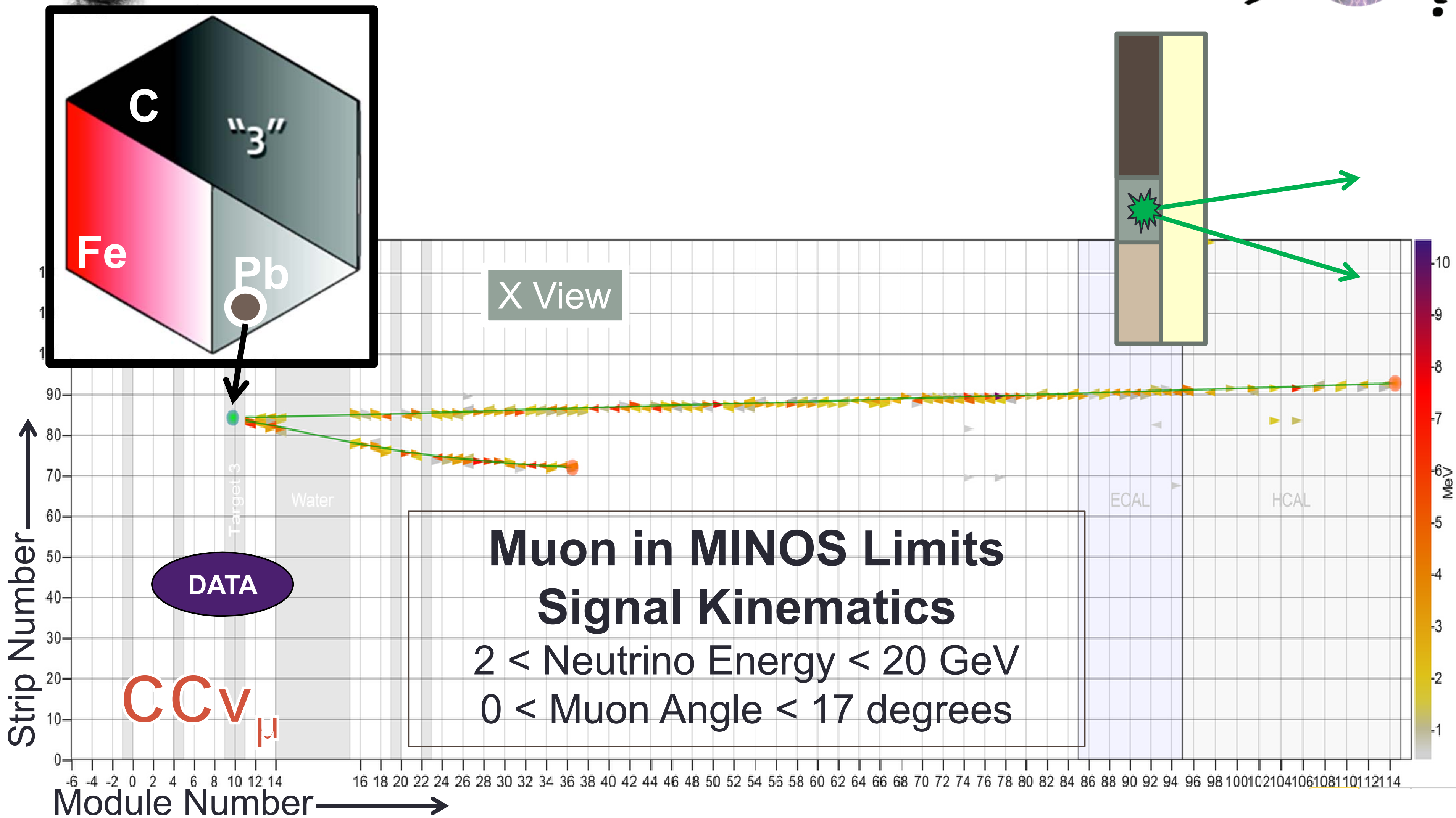


Most dynamical explanations for “EMC effect” will give a different answer for neutrinos

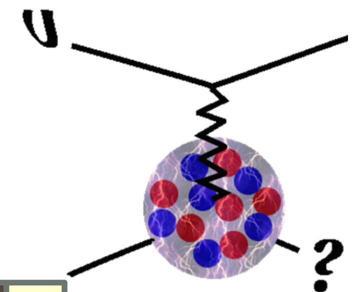
- Neutrinos sensitive to structure function xF_3
  - (Charged leptons are not)
  - Gives neutrinos ability to separate valence and sea
- Neutrinos sensitive to axial piece of structure function F_2
  - (Charged leptons are not)
  - Axial effect larger at low x, low Q^2

MINERvA's Targets: Multi-track Pb Candidate

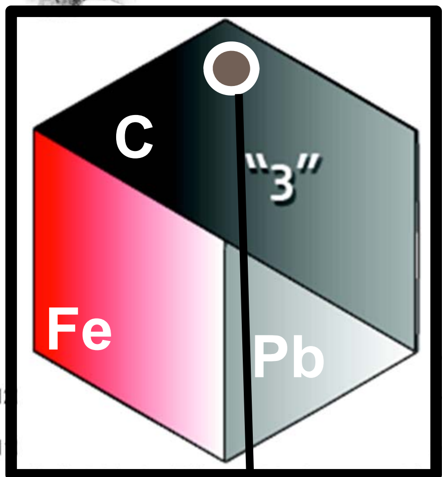


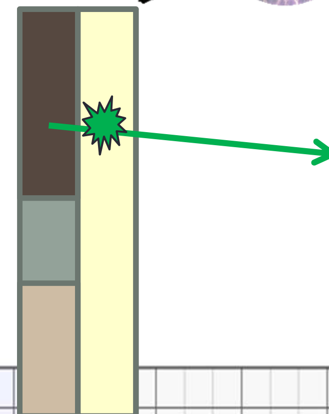


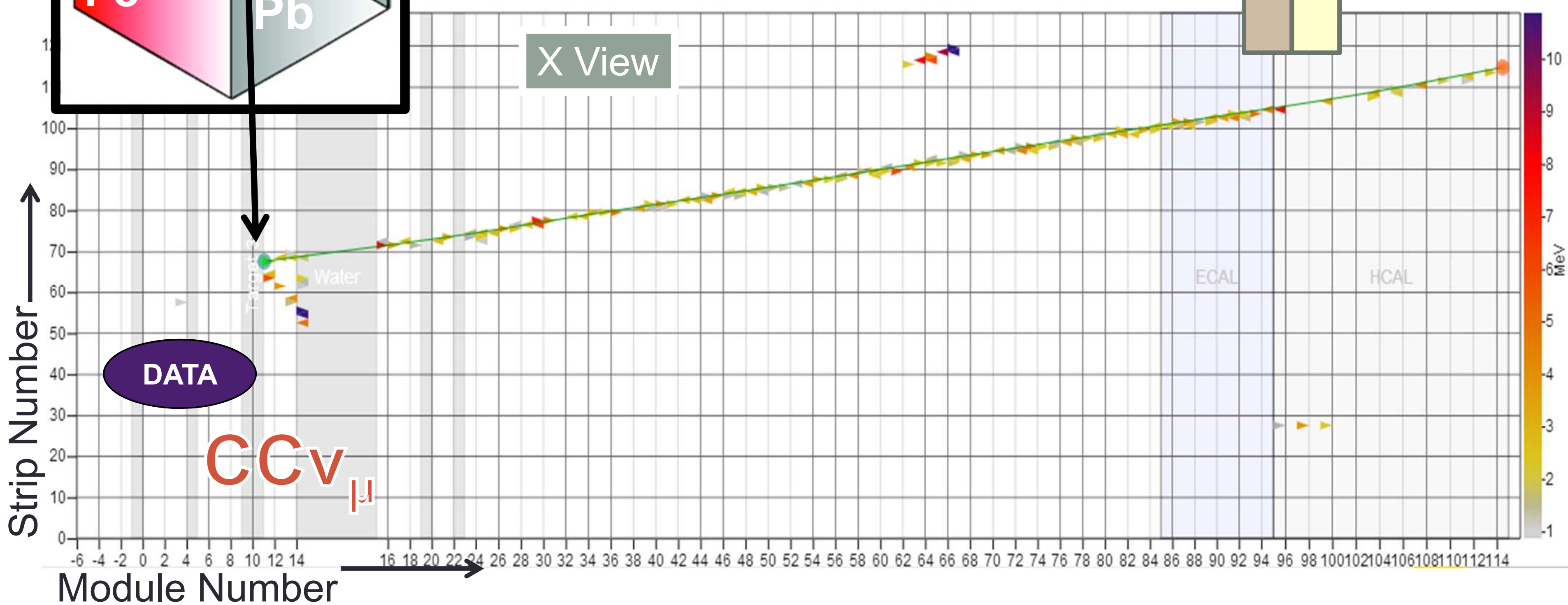
MINERvA's Targets: One-track C Candidate



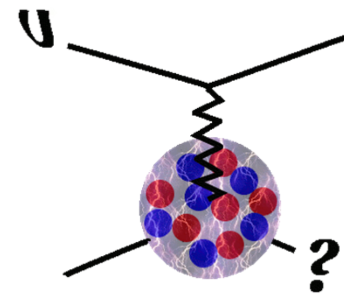
- One track candidates may originate from passive target or from downstream scintillator
- Source of background



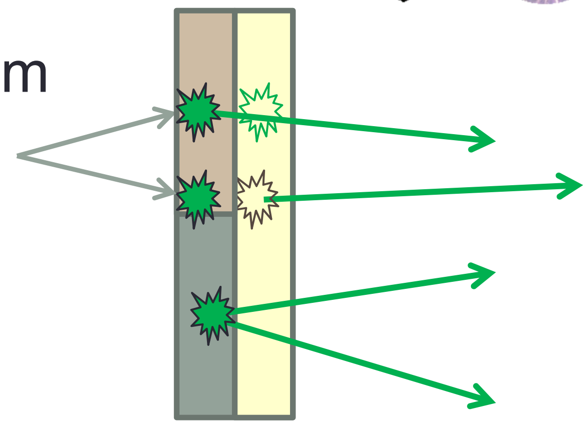


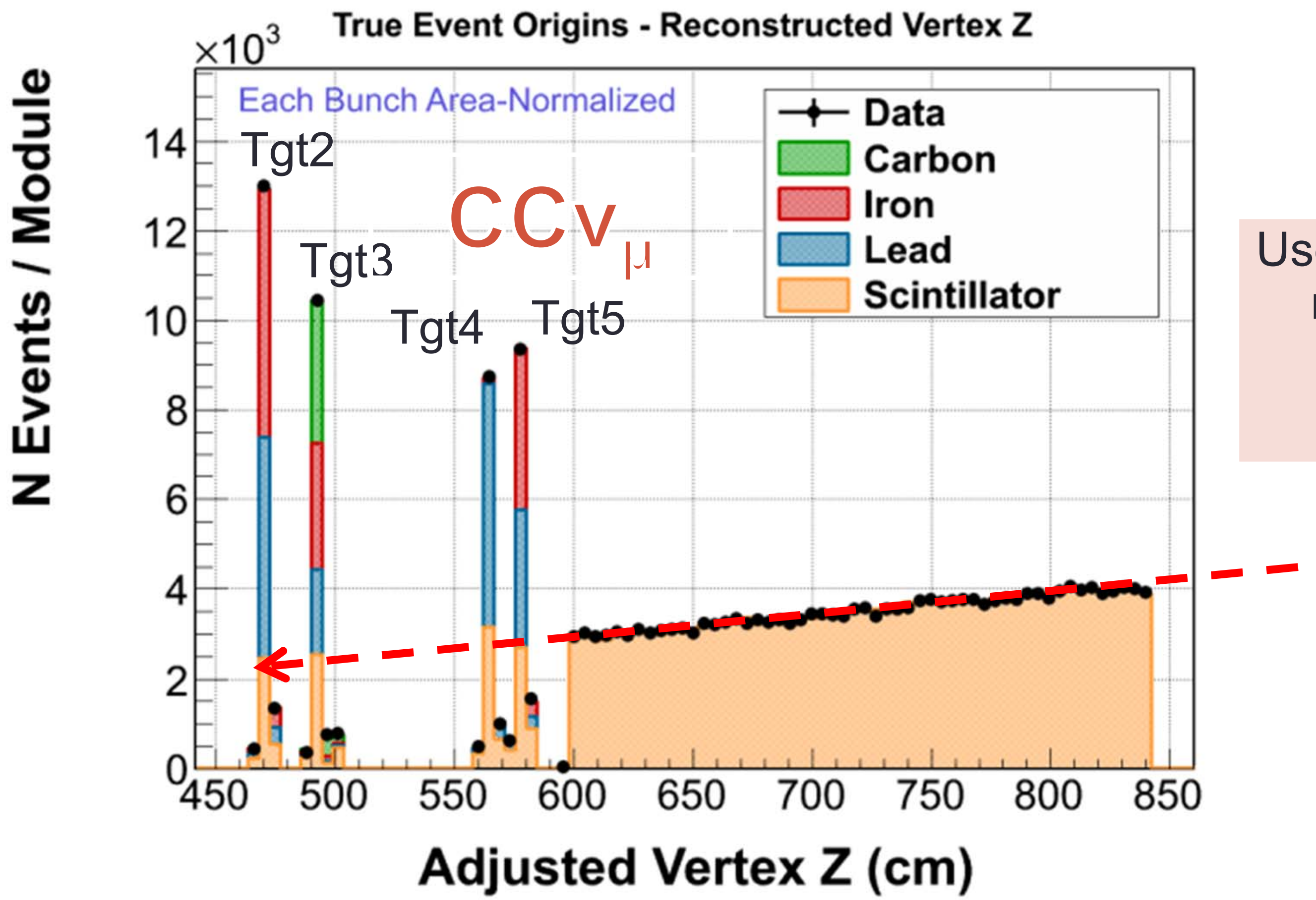


Scintillator Background

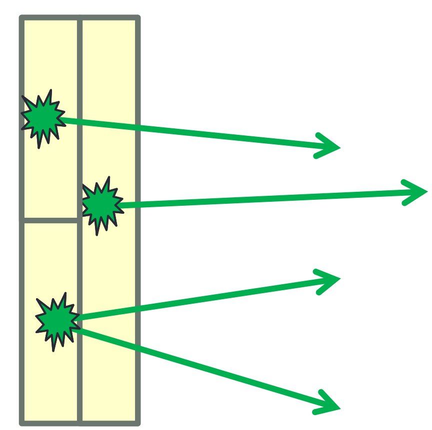


- Assume that single-track events downstream of passive target are from target

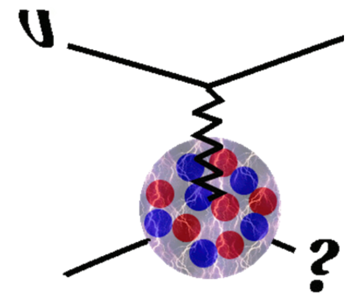


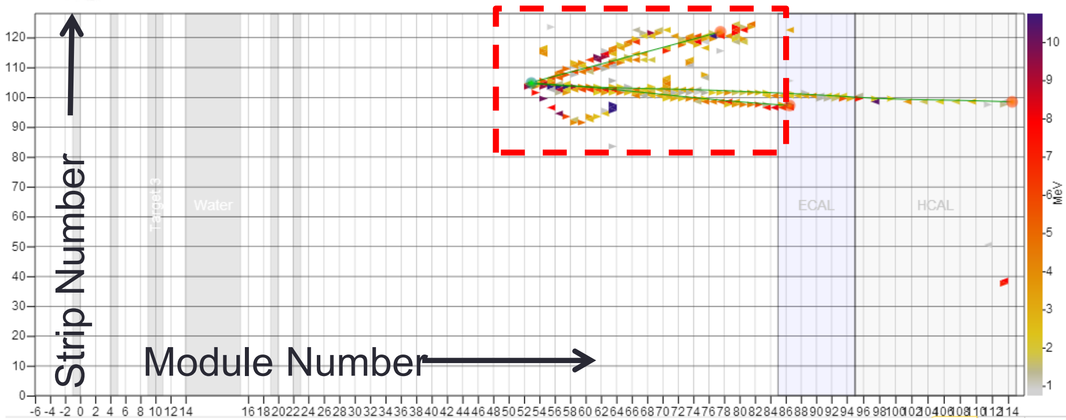


Use events in the tracker modules to predict and subtract the plastic background



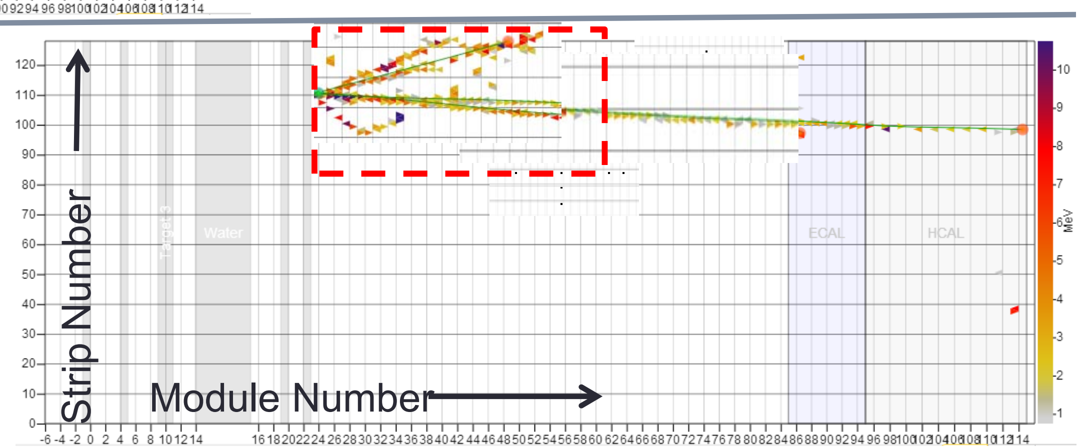
Predicting Scintillator Background



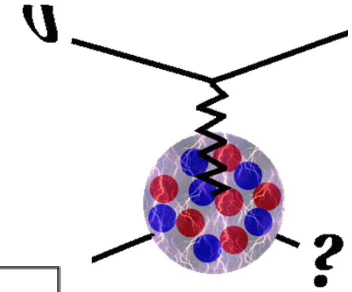


1. Find an event in scintillator of tracker
2. Move to a passive nuclear target

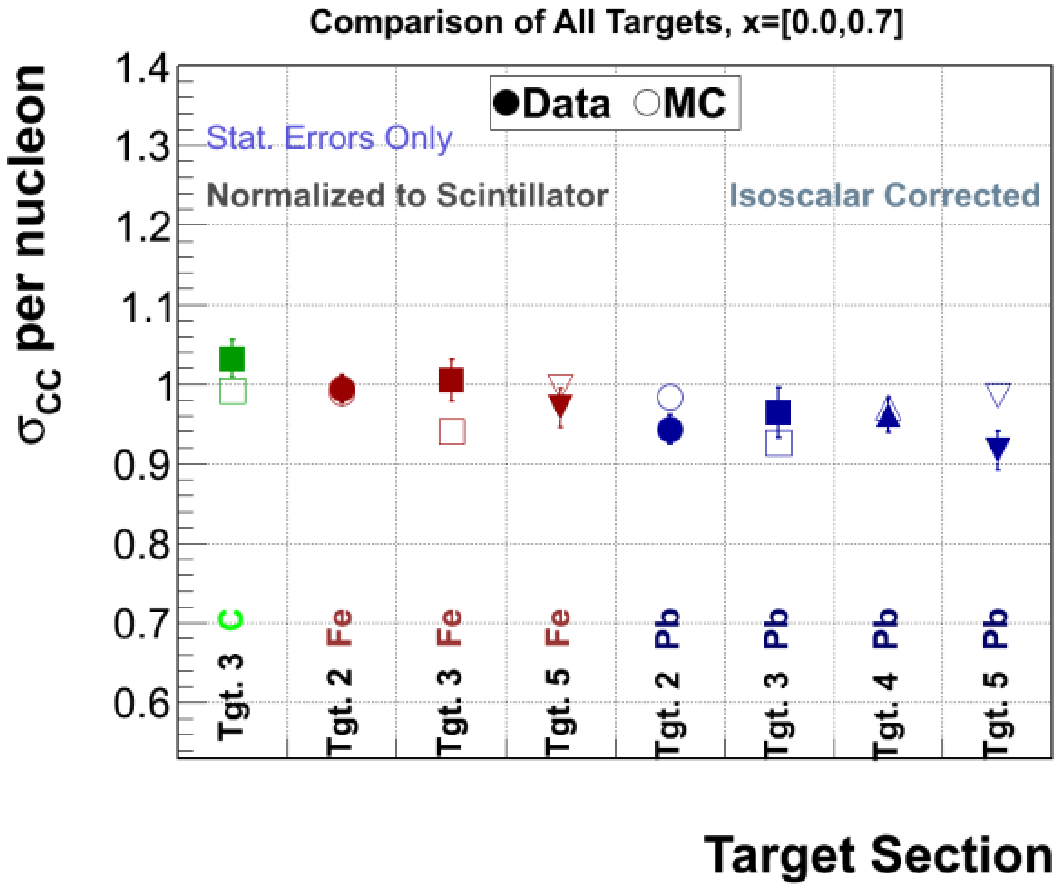
3. Use simulation to predict probability of track(s) being obscured by recoil shower
4. Evaluate uncertainties by comparing simulation procedure (and variants) against true event



Result of Subtraction



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

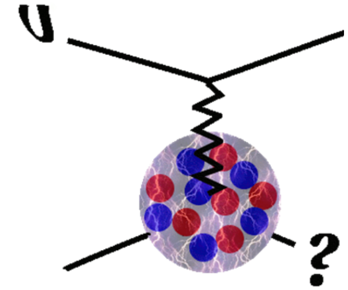


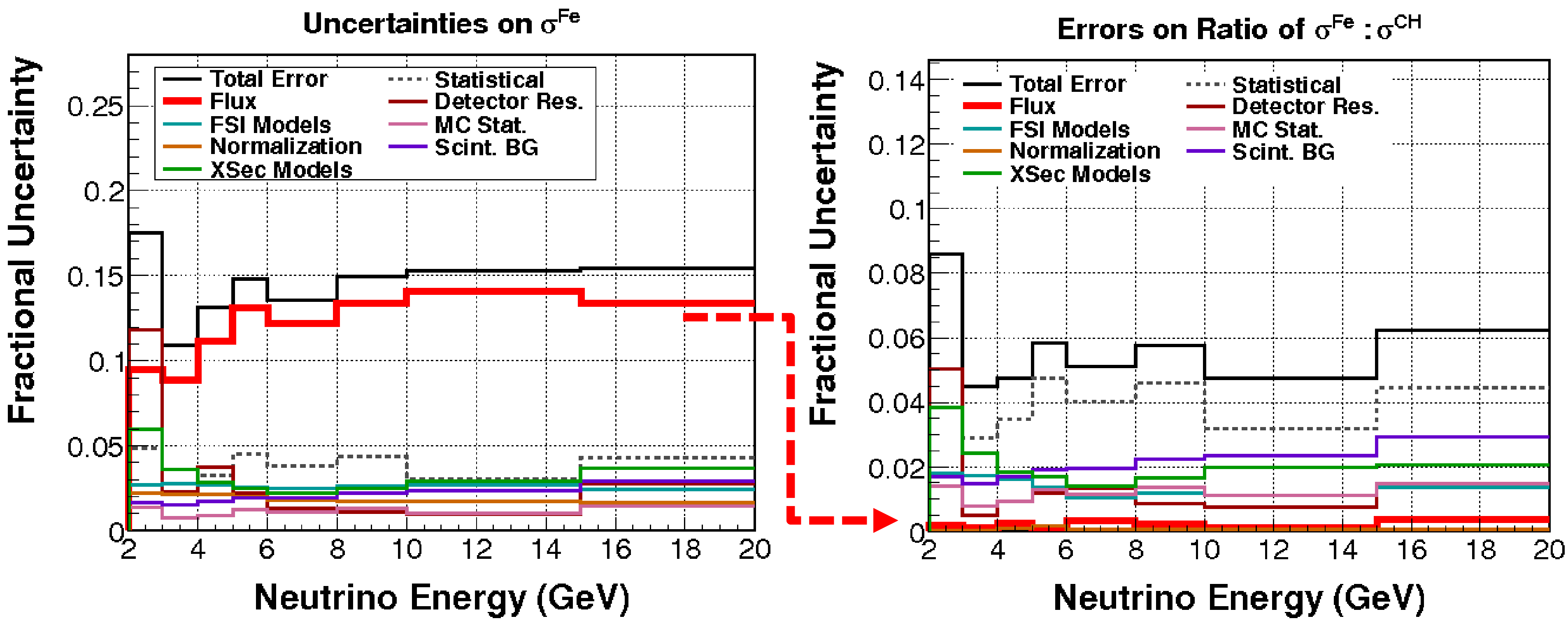
Isoscalar correction – remove effect of neutron excess.

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

Calculated with GENIE 2.6.2

Target Ratio Technique: MINERvA's Advantage





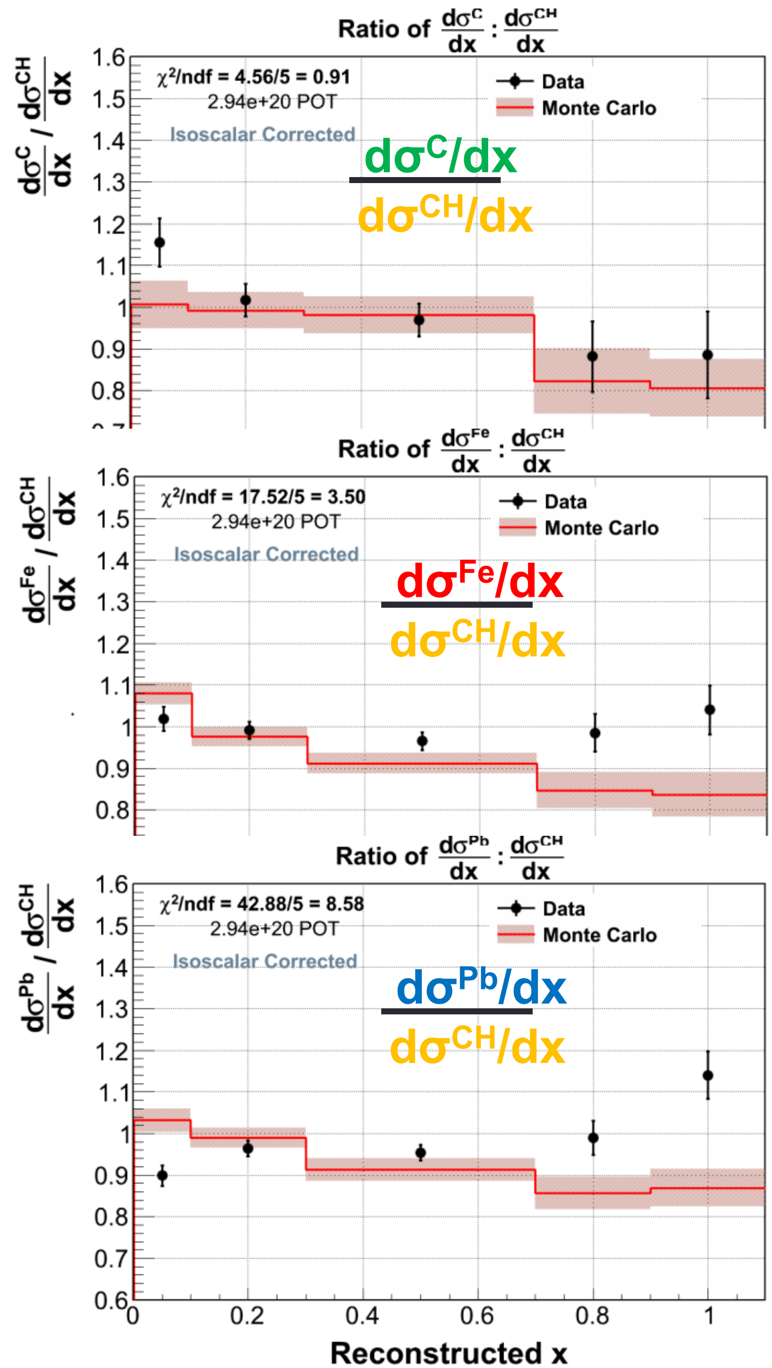
Uncertainties on Absolute Cross Section

Uncertainties on Ratio of Cross Sections

Low x Region

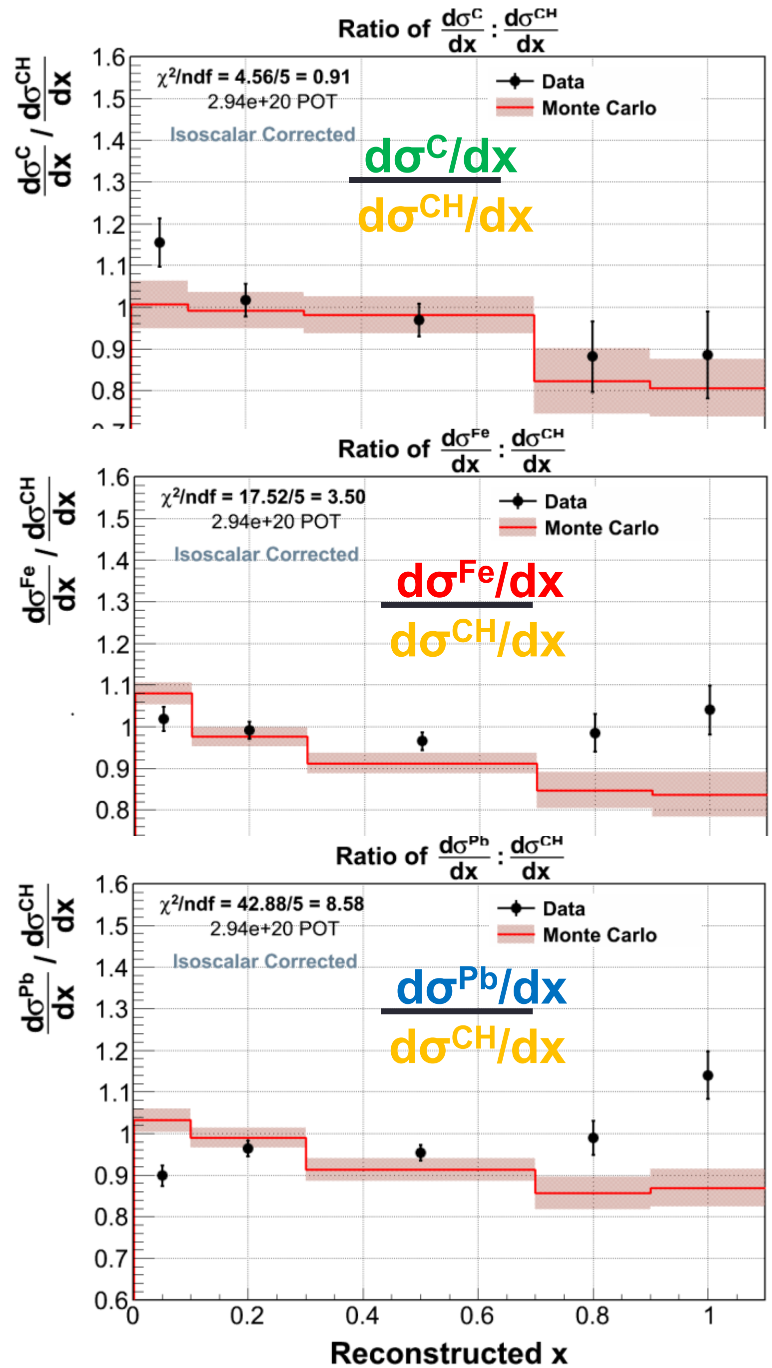
- At x=[0,0.1], we observe a **deficit** that increases with the size of the nucleus
- Data show effects not modeled in simulation

Expected Neutrino Differences
Neutrinos sensitive to structure function xF_3
Neutrinos sensitive to axial piece of structure function F_2

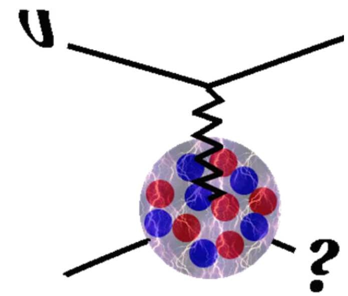


High x Region

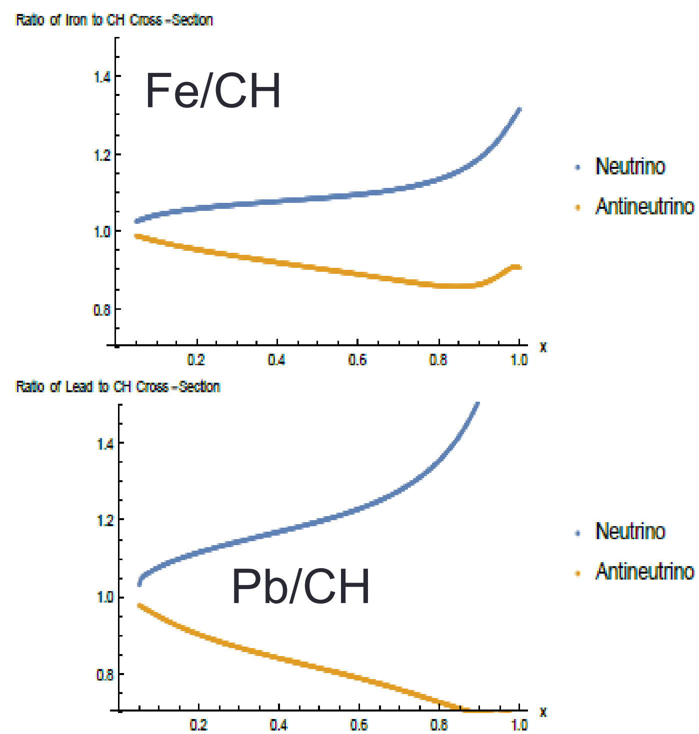
- At x=[0.7,1.1], we observe a **excess** that grows with the size of the nucleus
- This effect is also not observed in simulation
- But is due to not understanding physics of elastic processes, or that of inelastic processes?



Surprises in Nuclear Effects?

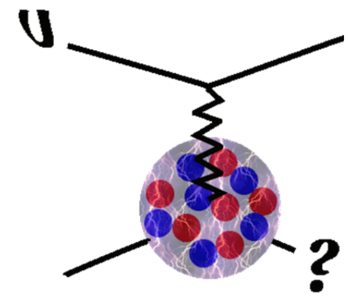


- Interesting recent idea is that EMC effect in heavy nuclei (suppression of cross-section on nuclei at moderate x) in electron scattering may also imply charge symmetry violating dynamics in non-isoscalar nuclei
  - Predicts a much stronger "EMC" effect in neutrinos
- Right now, one assumes same effect in neutrinos and electrons

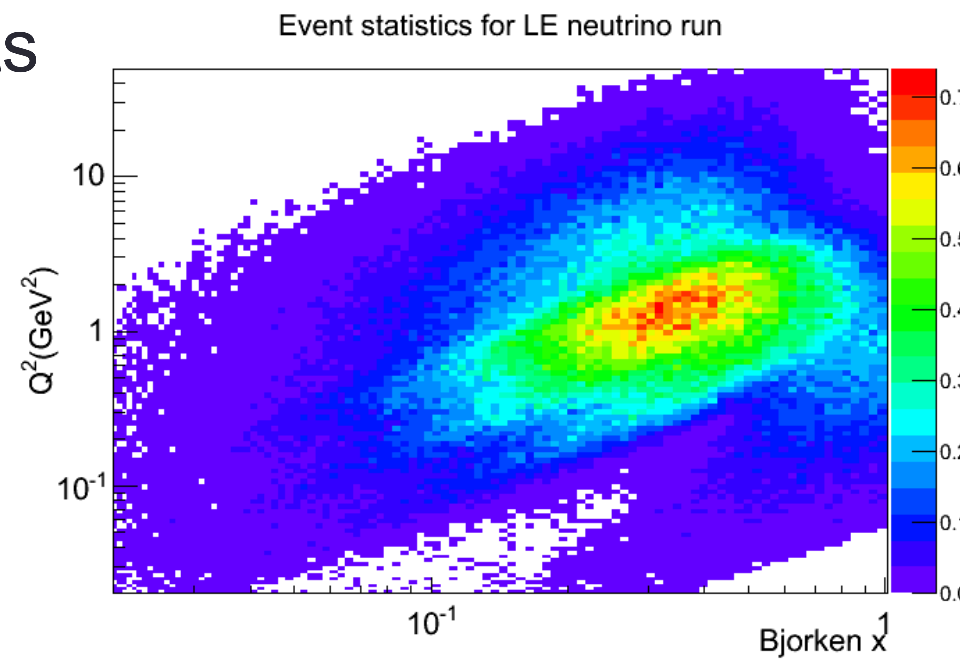


I. C. Cloet, W. Bentz and A. W. Thomas,
Phys. Rev. Lett. 109, 182301

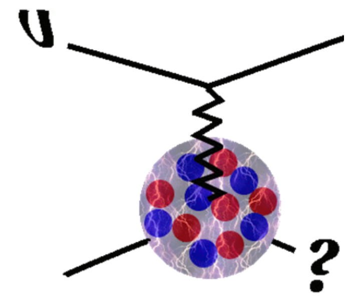
Nuclear Target Ratios



- 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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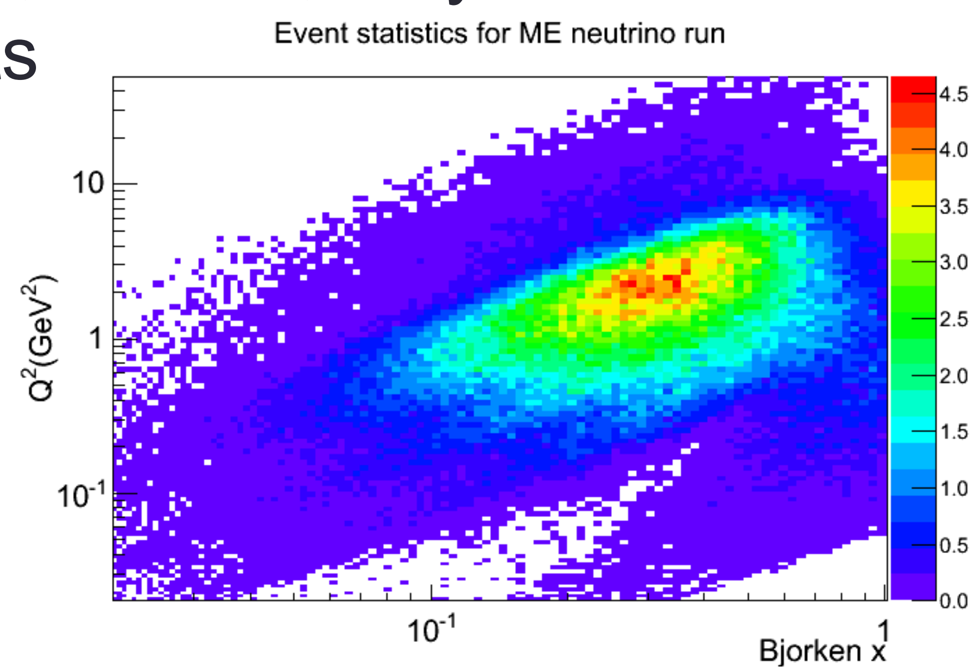
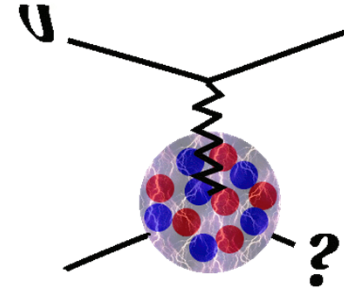
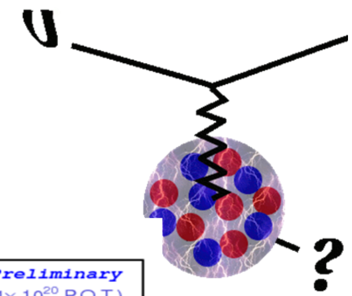


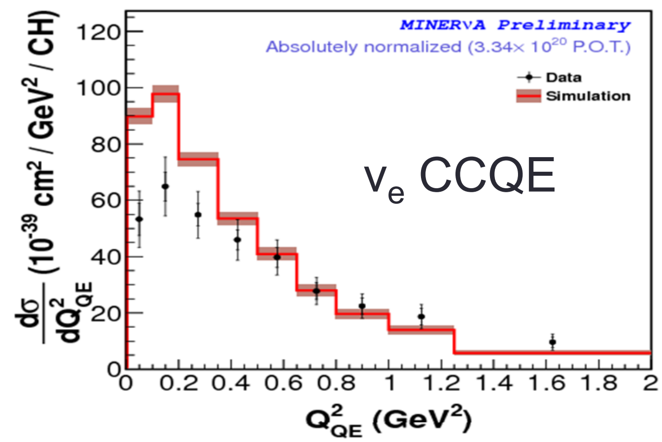


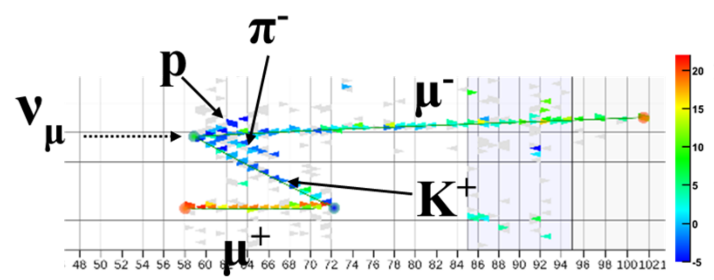
Conclusions and Outlook

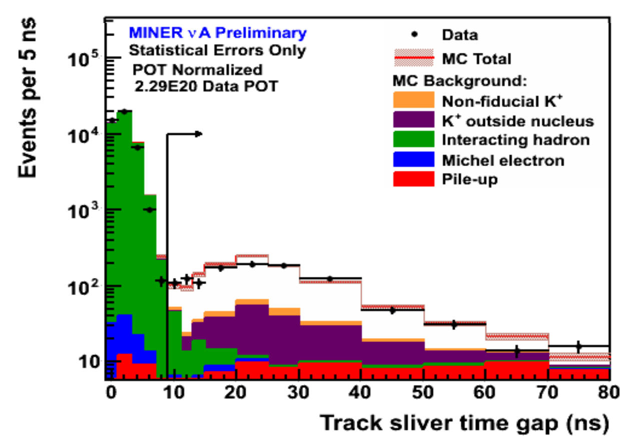
MINERvA Continues

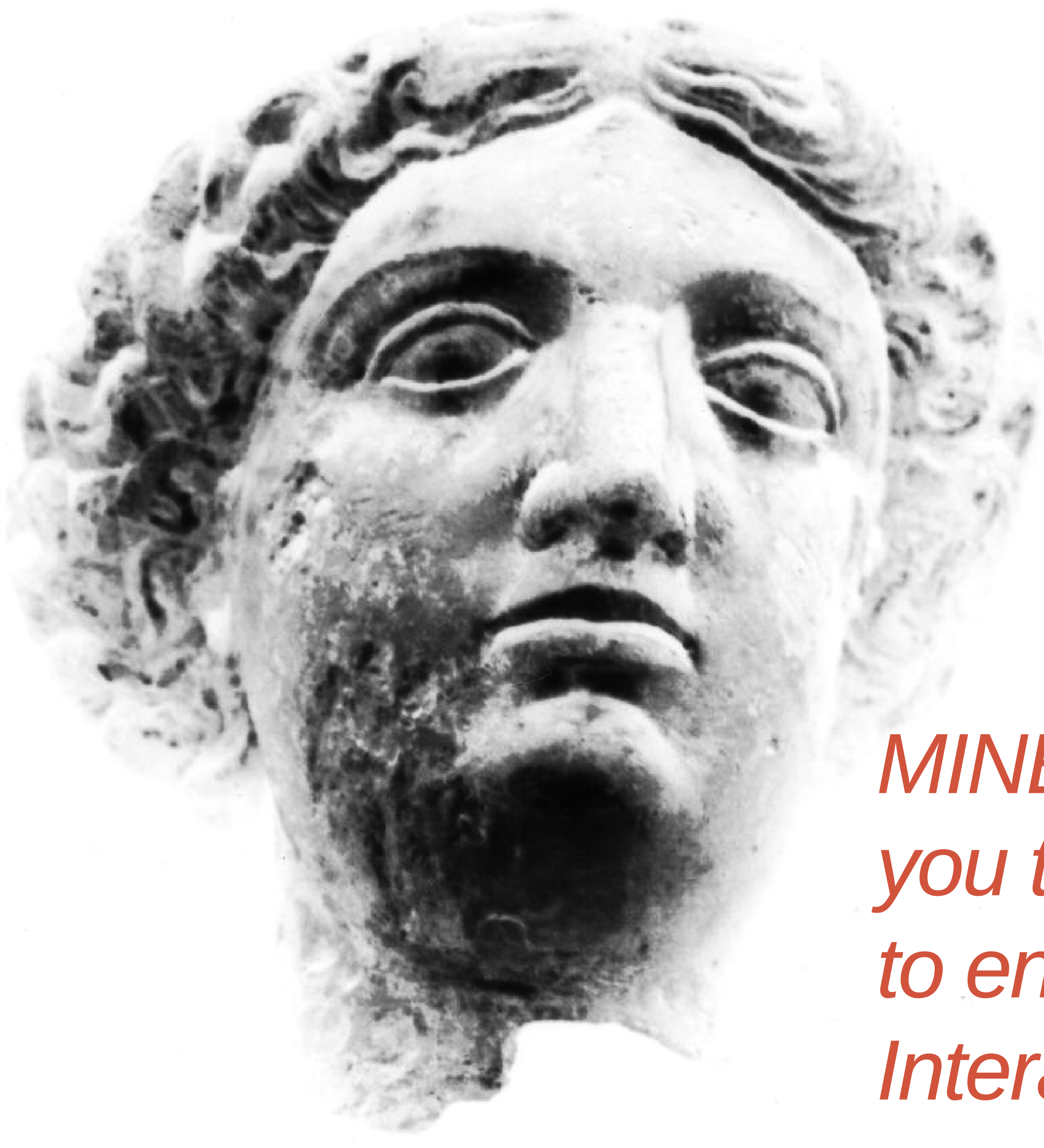


- By summer, we expect
  - ν_e/ν_μ ratio of CCQE
  - Kaon production results (one interest is atmospheric neutrino kaon production as a background to $p \to K^+\nu$)
  - Flux uncertainty → 6-7% (νe → νe)
- In current (NOvA era) beam, we are collecting high statistics neutrinos and anti-neutrinos. Most beneficial for nuclear target ratios and DIS studies.
- Results should continue to improve model descriptions used by both theory and oscillation experiments



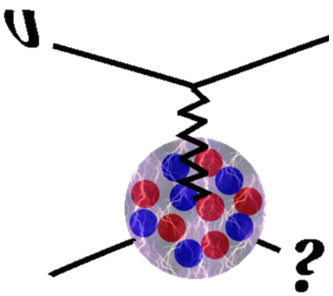






MINERvA invites you to continue to enjoy Neutrino Interactions!

MINERvA References



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