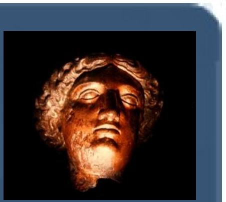
Recent MINERvA results and implications for neutrino energy reconstruction

NuFACT 2014
25-30 August 2014
University of Glasgow, Glasgow, Scotland



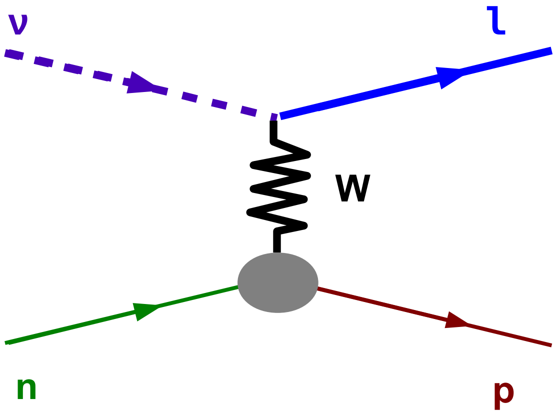
Jeremy Wolcott
University of Rochester
(on behalf of the MINERνA collaboration)

Outline

- Introduction: your E_ν distribution's dependence on models
- How MINERvA data reins models in:
  - CCQE scattering
  - Resonant charged pion production
  - Coherent pion production
- Summary and outlook

Ingredients for measuring $\{E_\nu\}$

1. Estimator = f(observables)



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

Fan favorite (and simplest case!): CC quasi-elastic

(let's consider as test case)

Ingredients for measuring $\{E_\nu\}$

2. Signal model

<u>CCQE formula only applies to CCQE events.</u>
What should CCQE look like in my detector,
with my neutrino flux?

Generator predictions

e.g.:

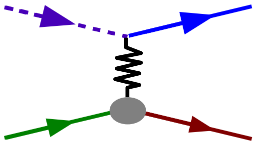
Free nucleon cross-section
[Llewellyn Smith, 1972]

+

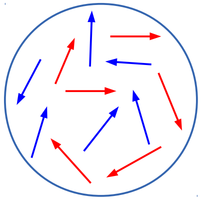
Relativistic Fermi Gas (RFG) of nucleons
[Smith & Moniz, 1972]

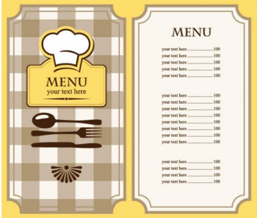
+

Choose your favorite nucleon correlation model(s)



(whose M_A?...)





Ingredients for measuring $\{E_\nu\}$

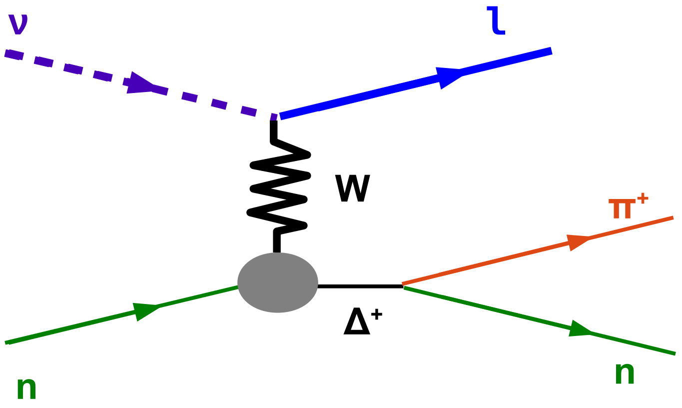
3. Background model

CCQE formula only applies to CCQE events.
What other kinds of events might I need to subtract off?

↓

Generator predictions

e.g.:



Resonant single pion production can look a lot like CCQE...

Ingredients for measuring $\{E_\nu\}$

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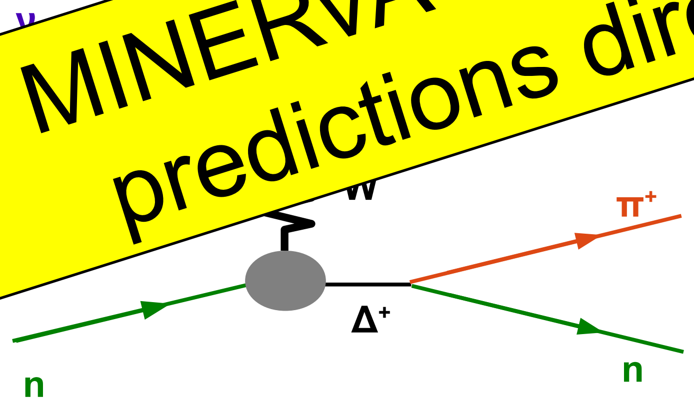
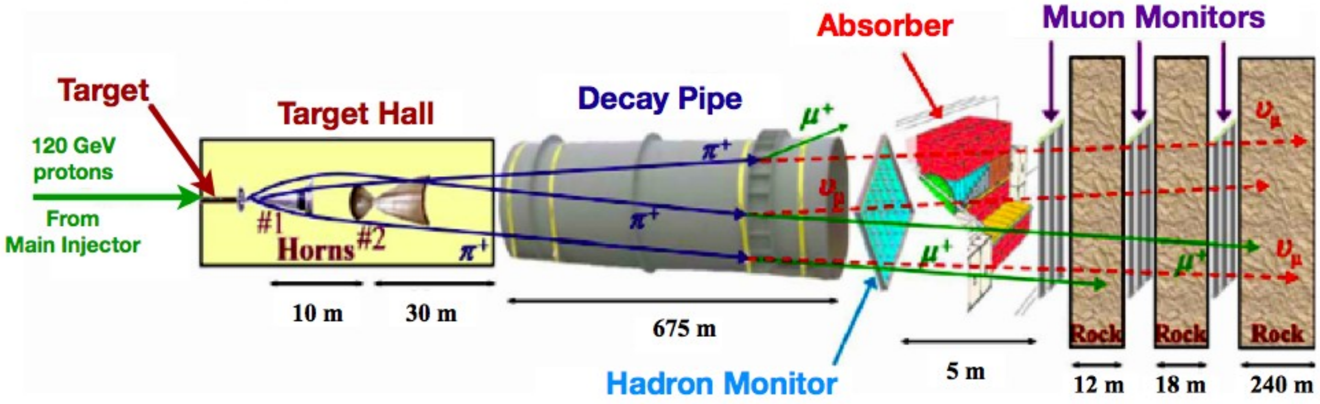
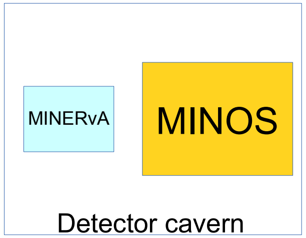


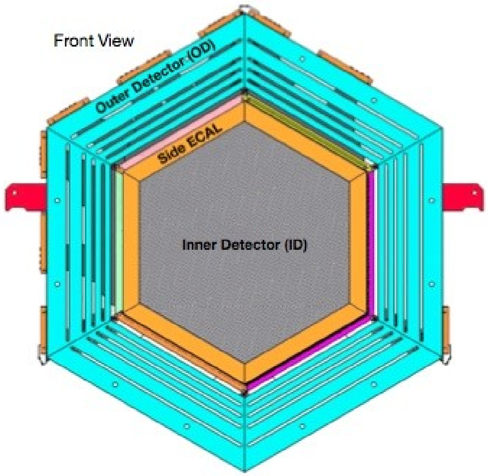
MINERvA tests these predictions directly

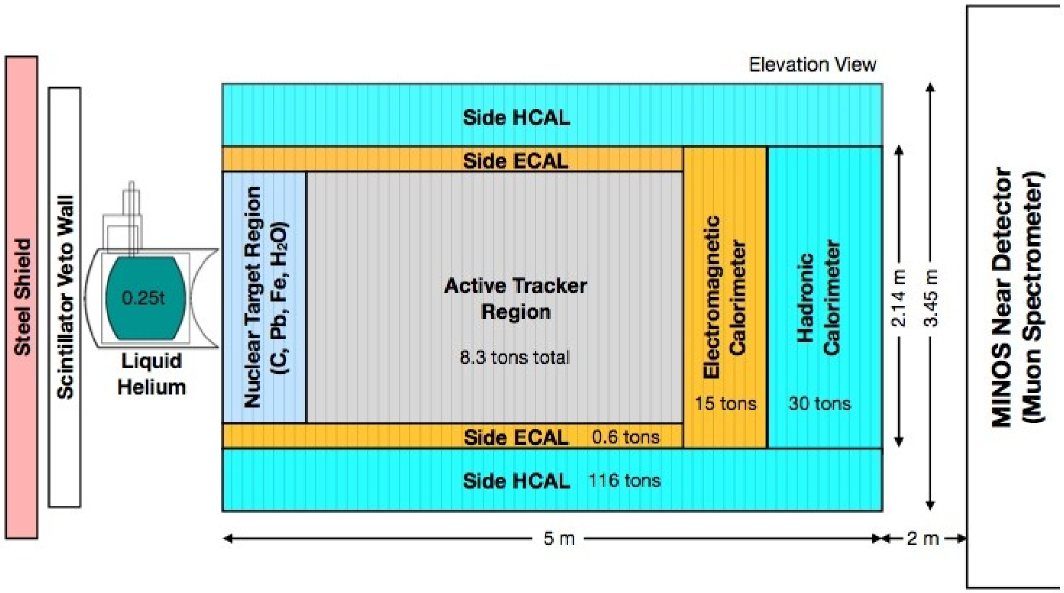
Resonant single pion production can look a lot like CCQE...

Enter: MINERνA

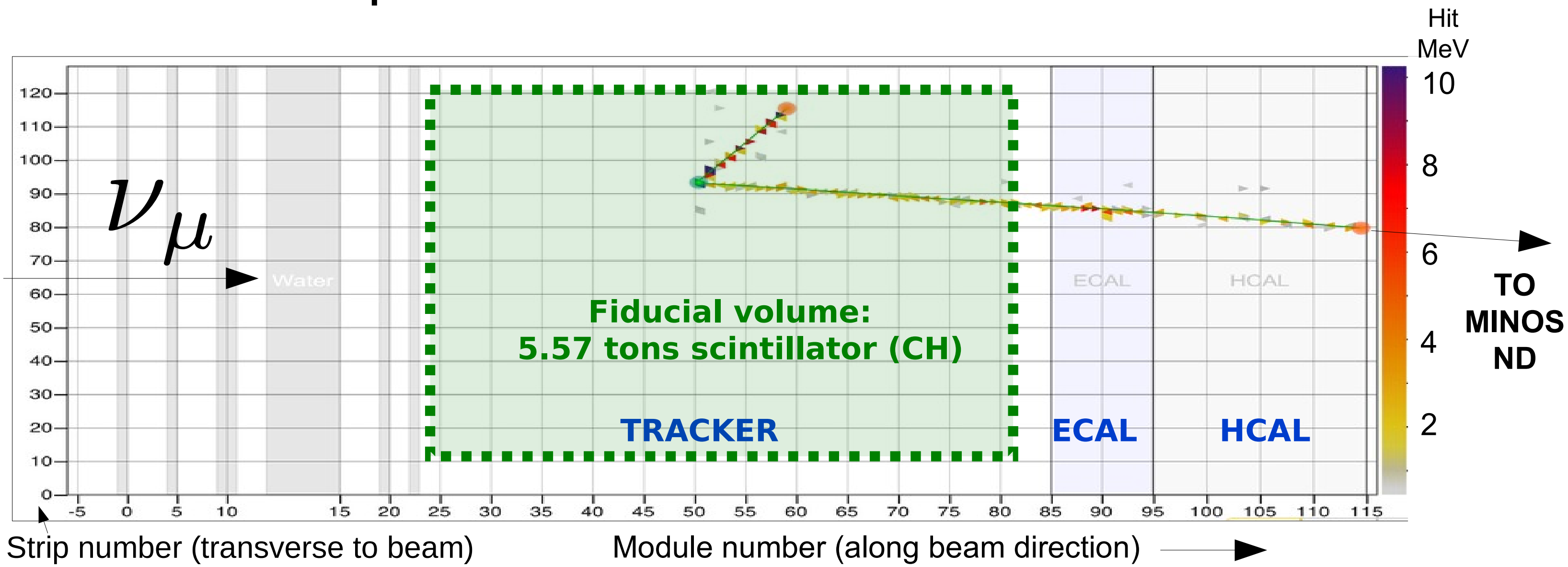






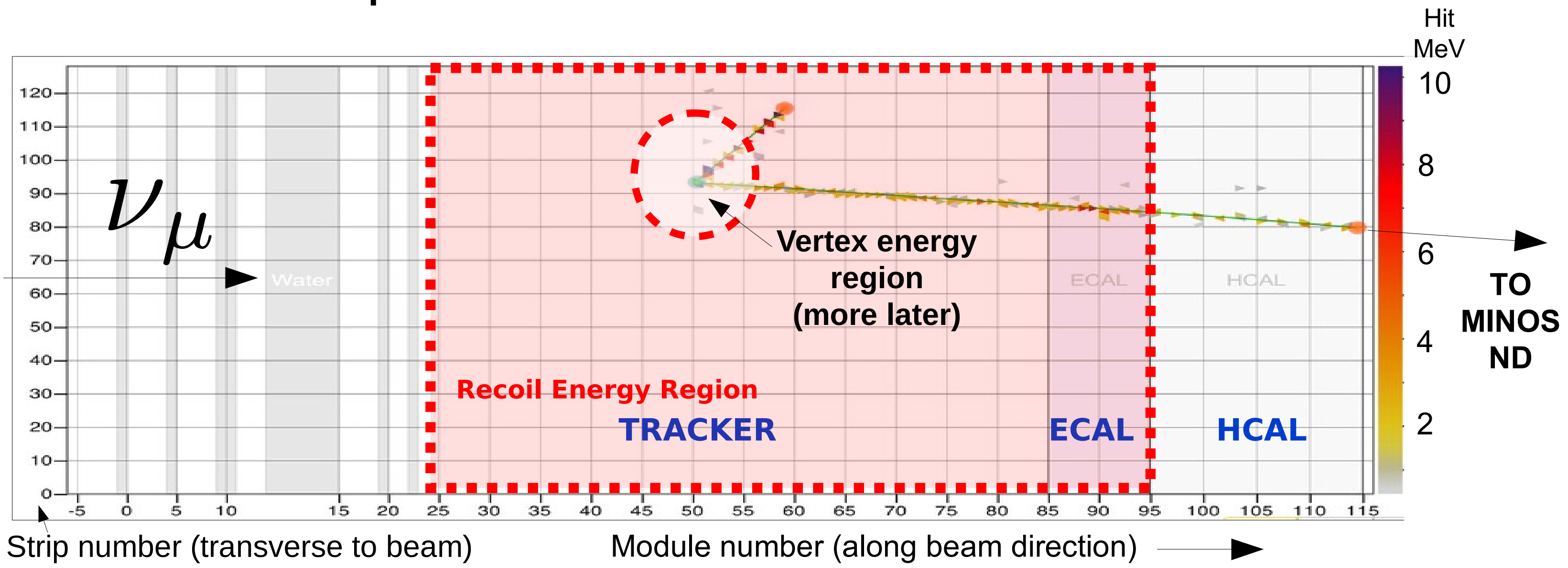


ν_μ CCQE in MINERvA



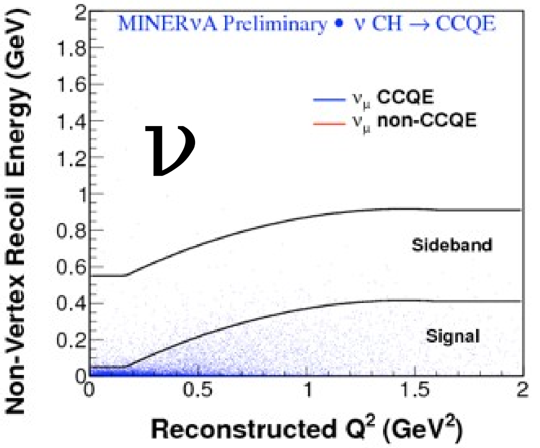
Find a MINOS-matched track...

ν_μ CCQE in MINERvA

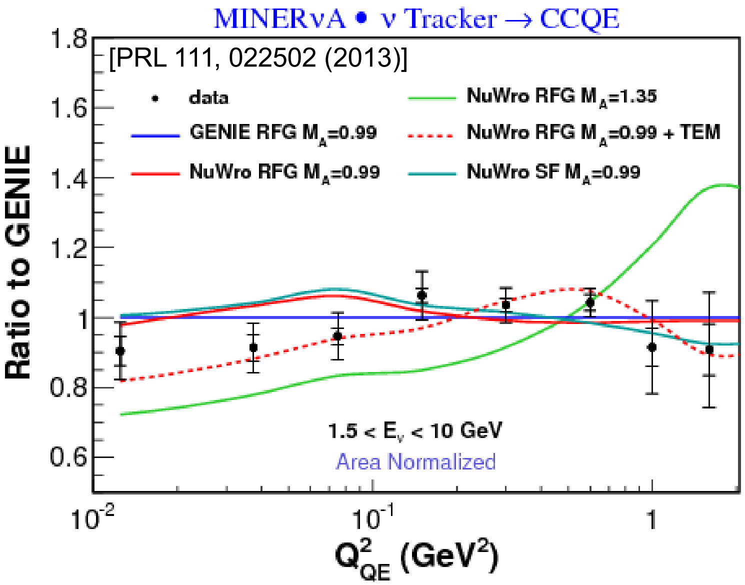


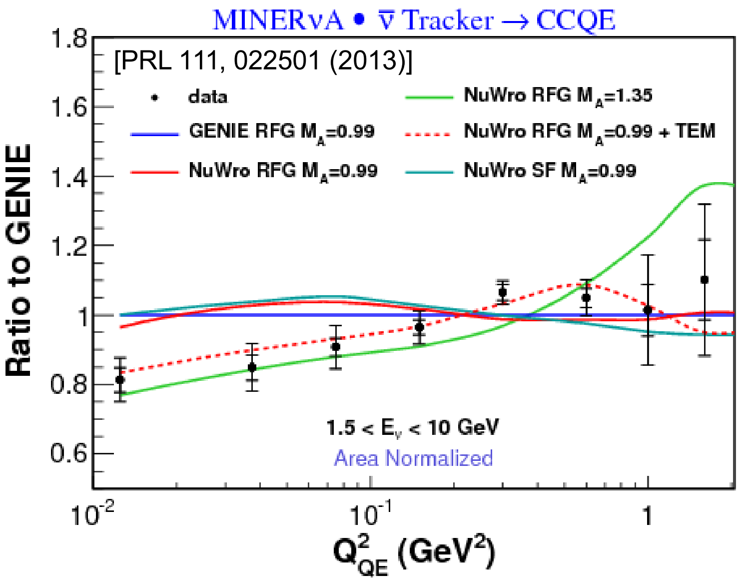
… in an event with little (non-vertex) recoil energy.

[We furthermore cut events with more than 2 (1) isolated shower(s) in (anti-)neutrino mode.]



ν_μ CCQE: model comparisons



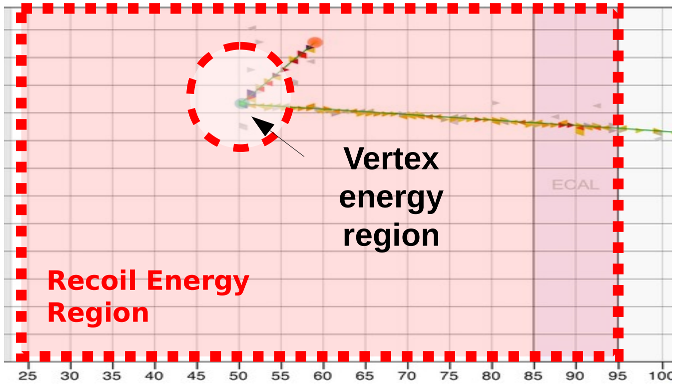


NuWro model	RFG M_A = 0.99	RFG + TEM M_A = 0.99	RFG M_A = 1.35	SF M_A = 0.99
ν shape χ^2/d.o.f.	4.1	1.7	2.1	3.8
$\bar{\nu}$ shape χ^2/d.o.f.	2.9	0.7	1.7	3.0

Model most preferred is **"vanilla" RFG**
+ empirical corrections for correlations (motivated by electron scattering)
(10-20% deviations from GENIE in some regions of phase space)

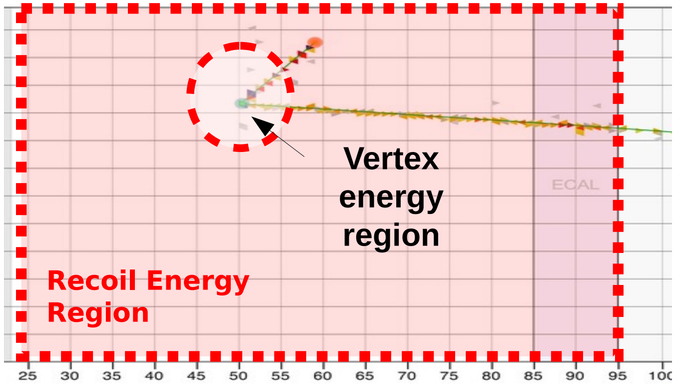
Corroboration: vertex activity

Remember the “blind spot” we left in the recoil region?
Nuclear activity from extra correlated nucleon should show up there...



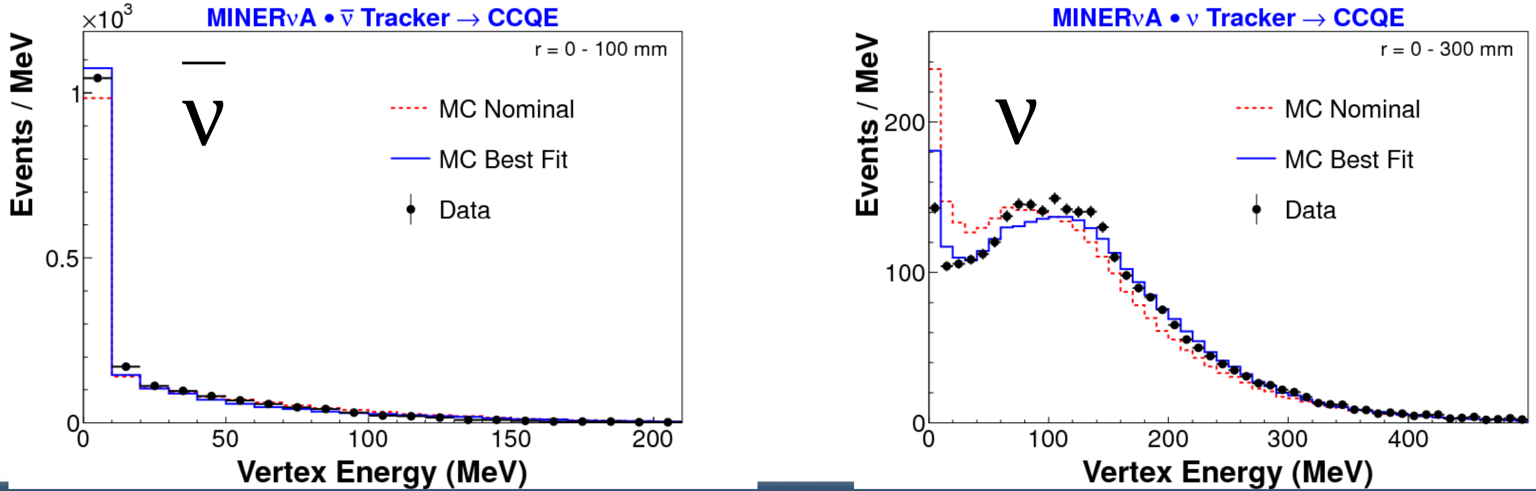
Corroboration: vertex activity

Remember the “blind spot” we left in the recoil region?
We fitted the distribution of energy in this region by adding a simulated proton to some events.



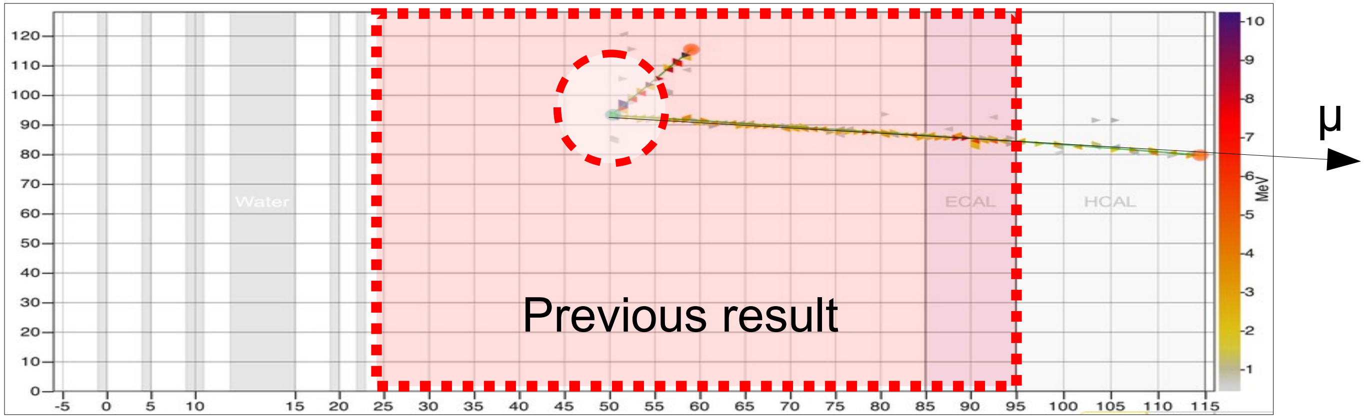
~(25±10)% of events in neutrino mode needed another proton to make the vertex energy distribution fit; contrast (-10±7)% in antineutrino mode

Since CCQE takes n → p for ν and p → n for $\bar{\nu}$
this suggests (unmodeled) initial-state np correlations

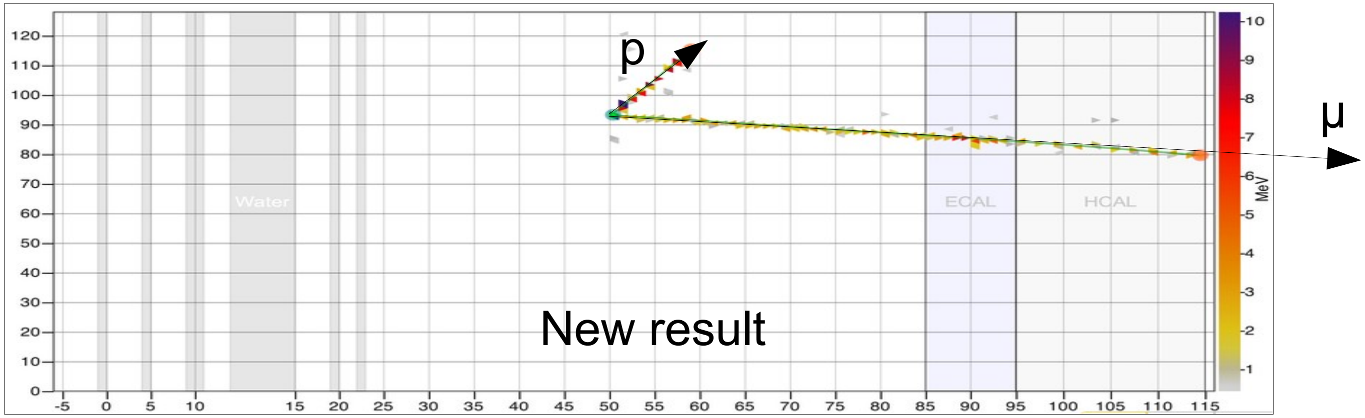


A different approach: CCQE with proton kinematics

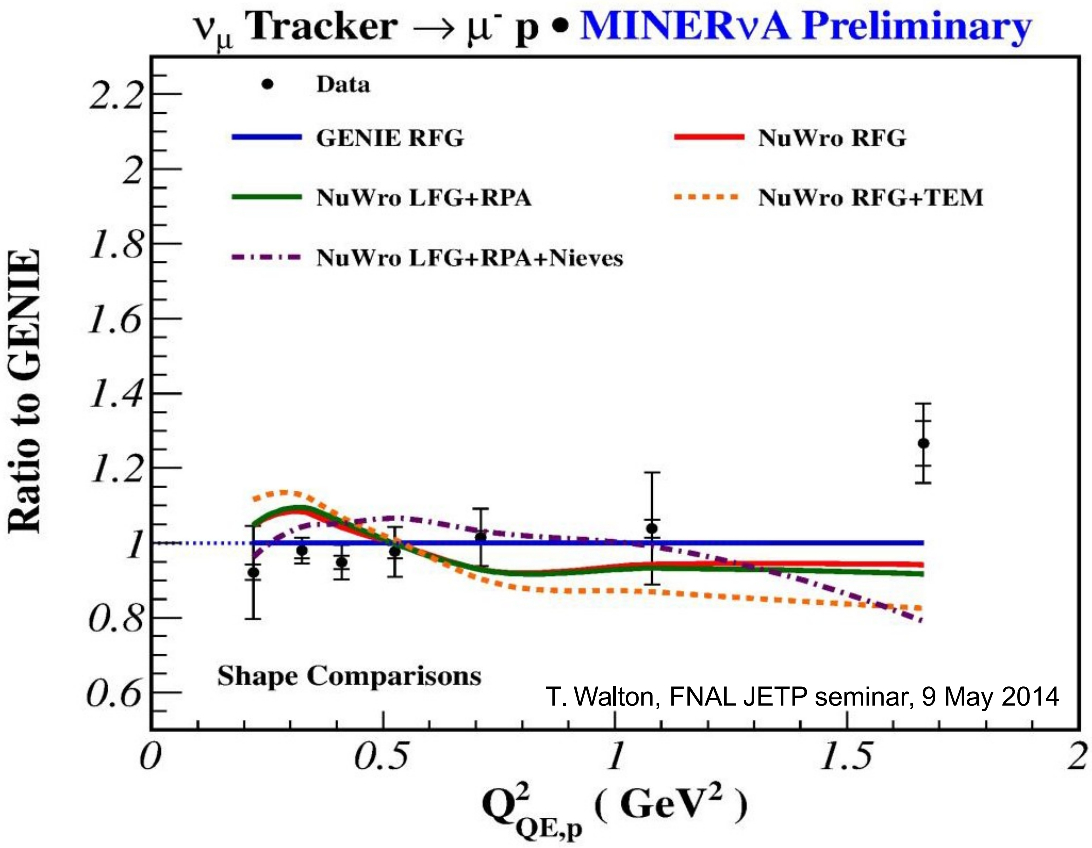
Use μ track, recoil for selection; use μ track for kinematics



Use μ and p tracks and recoil for selection; use p track for kinematics



A different approach: CCQE with proton kinematics



T. Walton, FNAL JETP seminar, 9 May 2014

The results agree with the "vanilla" GENIE model reasonably well (!)

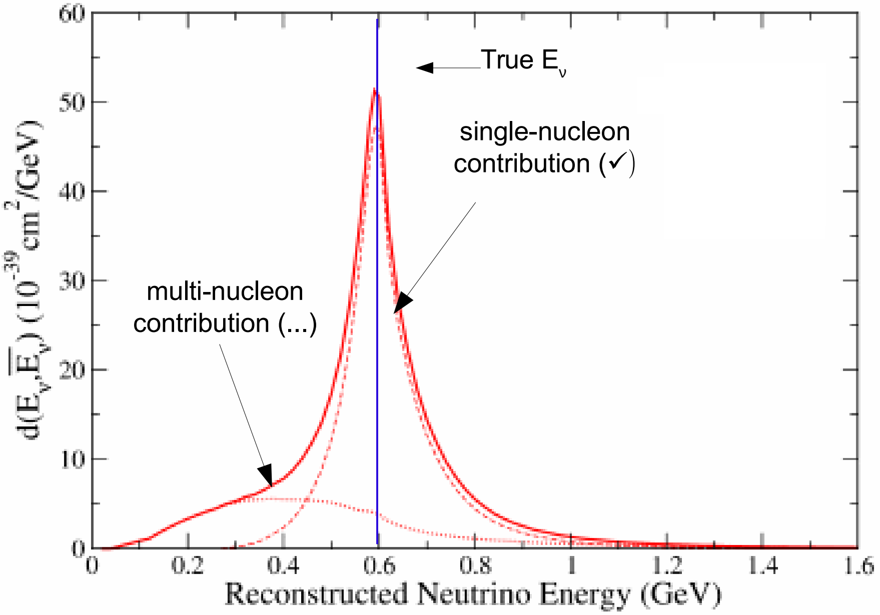
The (CCQE) lesson

How well you know the final-state particle content influences how well you can reconstruct the kinematics of an event

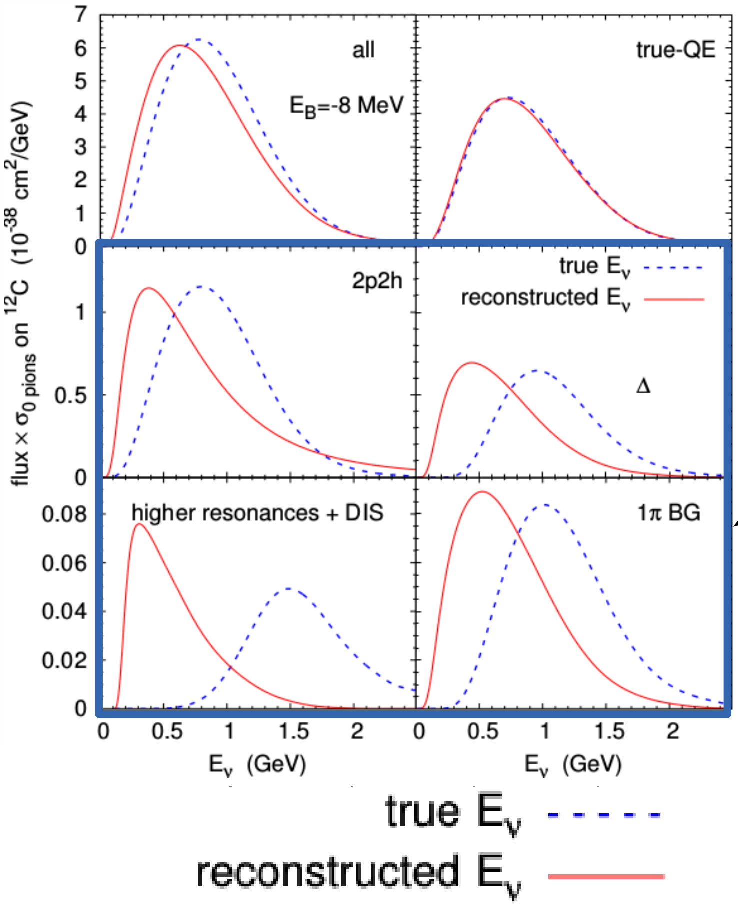
- RFG model struggles to get muon kinematics right for less restrictive "μ+little recoil"
- RFG model does ok at predicting proton kinematics in known "μ+p" events

Getting the kinematics wrong

[Adapted from Martini *et al.*, arXiv:1211.1523 by P. Rodrigues]



[Lalakulich *et al.*, arXiv:1208.3678]

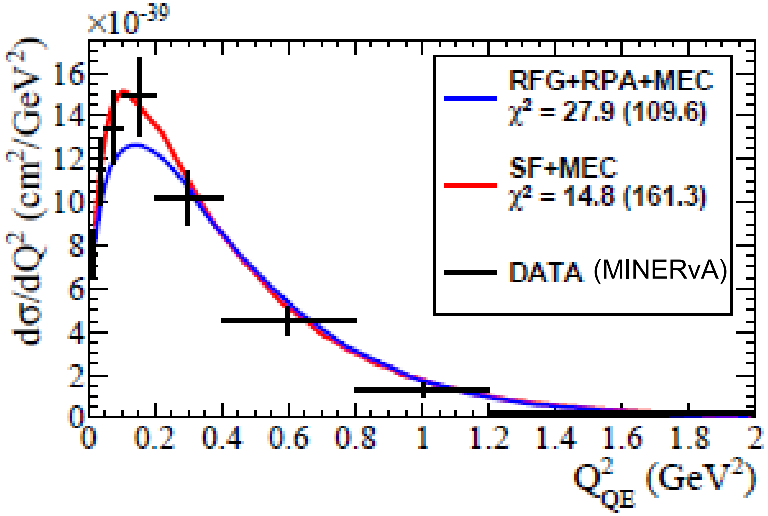


Not CCQE from quasi-free nucleon!

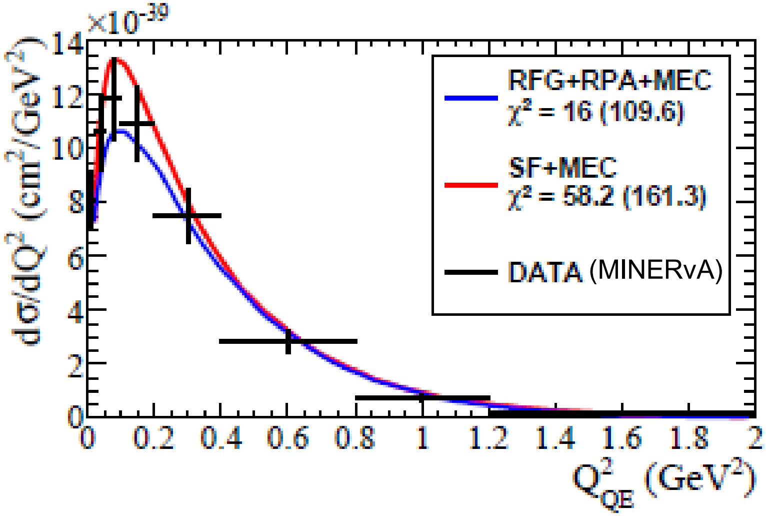
Worry that not accounting for the correlations could have significant consequences for E_ν reconstruction...

Not just a cautionary tale any more!

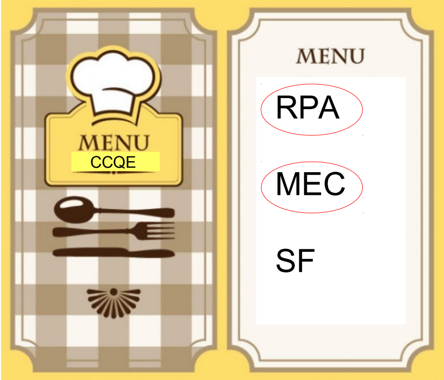
[C. Wilkinson, NuFACT 2014]



Neutrino



Antineutrino



There is work underway right now to use MINERvA data to constrain the models used in T2K's oscillation fits!

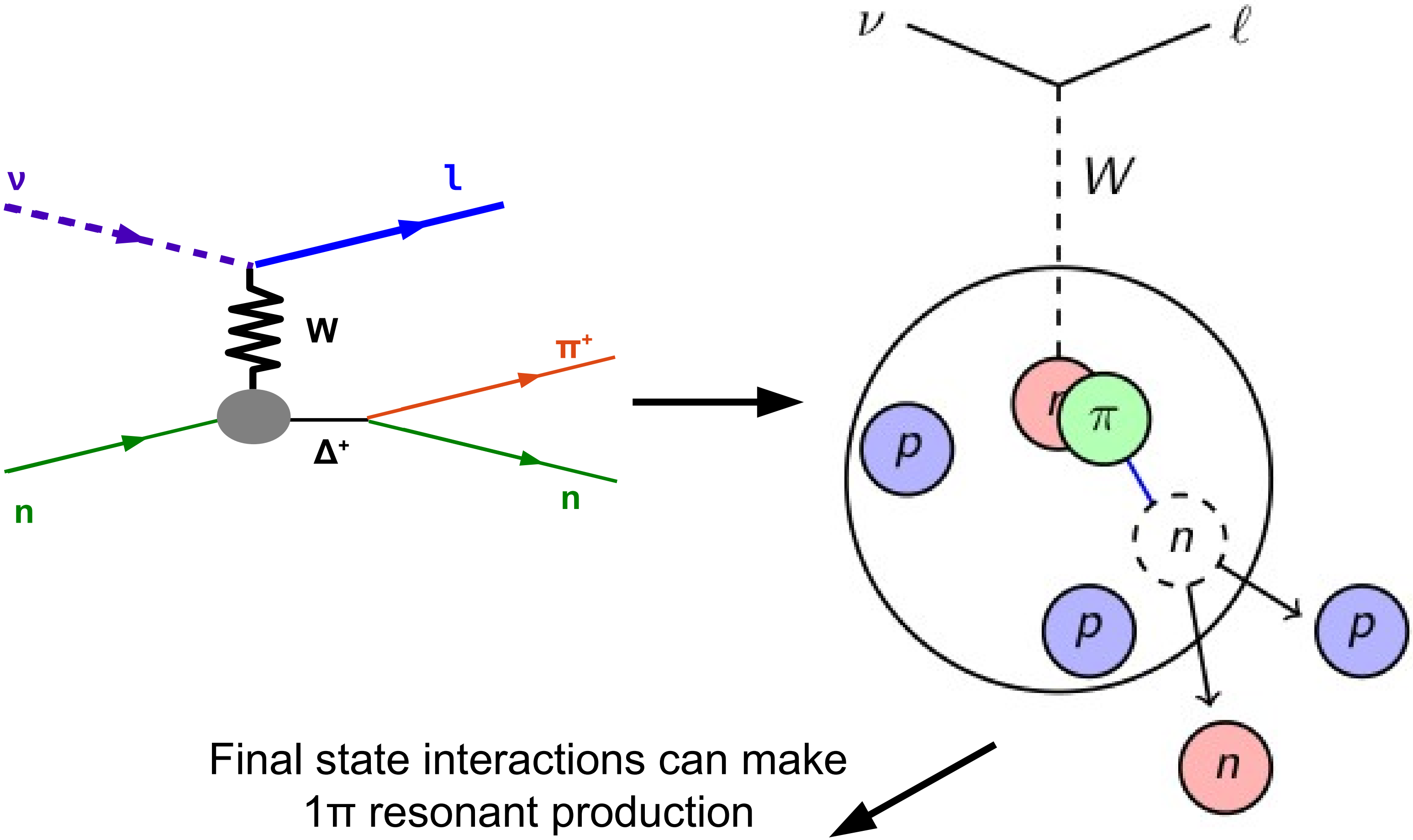
(See C. Wilkinson's talk in WG1 from Tuesday)

CCQE: what's still coming

Other MINERvA CCQE results coming soon will further exercise the models...

- Doubly differential XS in muon variables ($d^2\sigma/dp_z dp_t$) with Michel electron veto & exclusion of proton tracks from recoil (improves S/B)
- Electron neutrino CCQE (first ever!): see talk tomorrow by J.W.

Another energy estimator problem: FSI

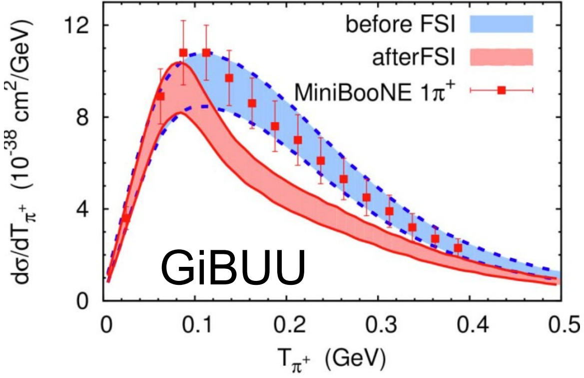


Final state interactions can make 1π resonant production indistinguishable from CCQE... *but CCQE formula doesn't apply*

Charged pion production

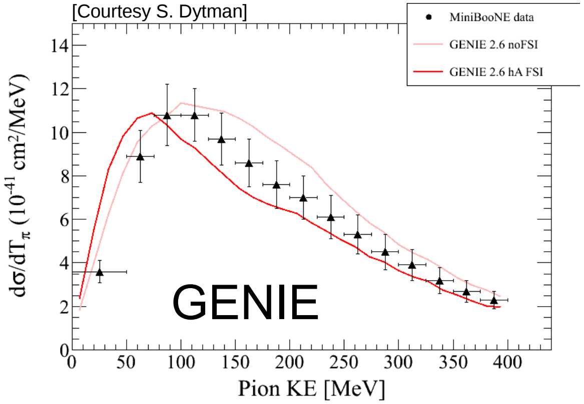
$\nu_\mu \mathrm{CH} \rightarrow \mu^- \pi^\pm X$

[O. Lalakulich et al, NuInt12 Proceedings]



Choice of FSI model impacts shape and normalization of cross-section (data from MiniBooNE exp't)

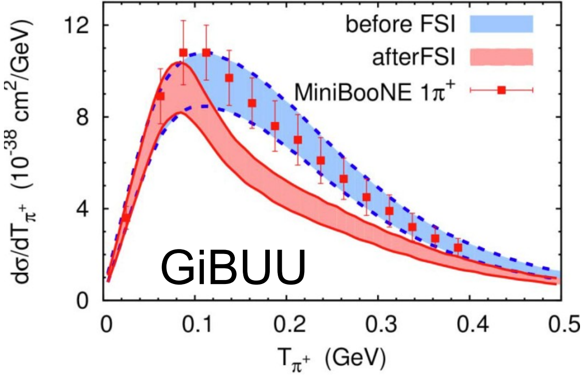
[Courtesy S. Dytman]



Charged pion production

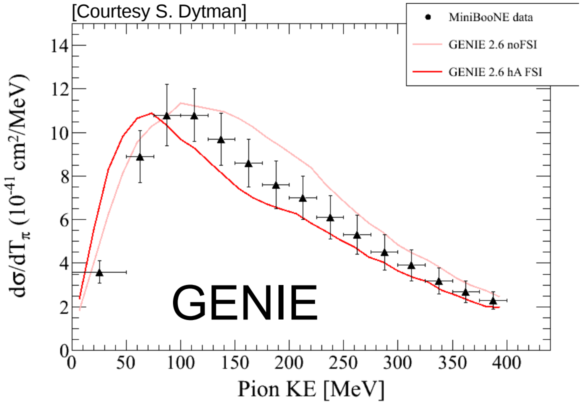
ν_μ CH → $\mu^- \pi^\pm$ X

[O. Lalakulich et al, NuInt12 Proceedings]

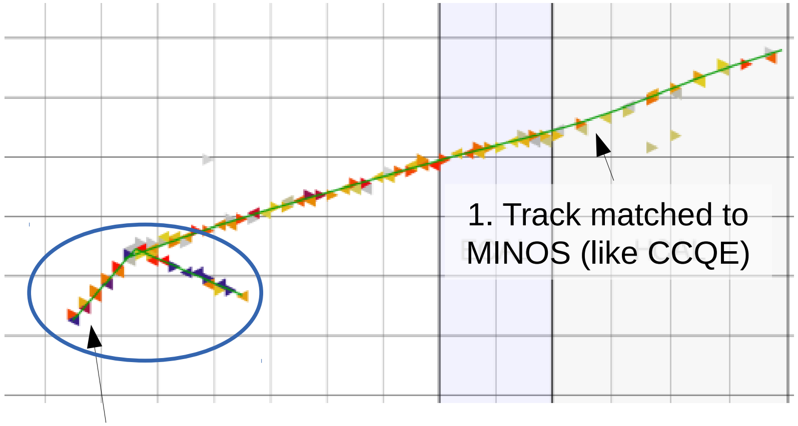


Choice of FSI model impacts shape and normalization of cross-section (data from MiniBooNE exp't)

[Courtesy S. Dytman]



in MINERvA:

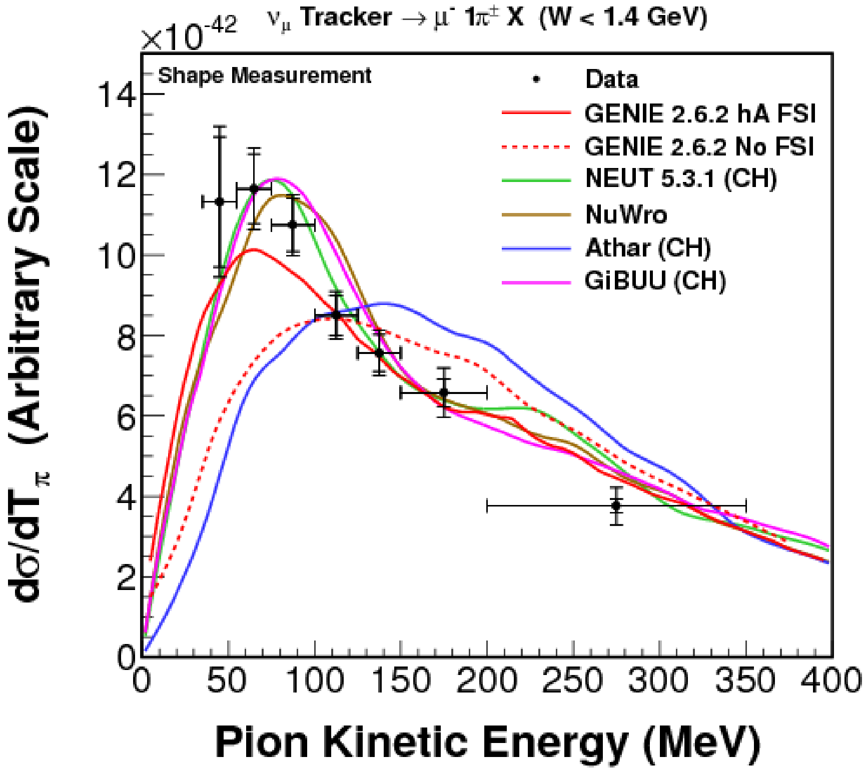


1. Track matched to MINOS (like CCQE)

2. One or two hadron track candidates, at least one of which is consistent with a pion by dE/dx and Michel e^-

Charged pion production in MINERvA

[arXiv:1406.6415]



GENIE hA (generator): isospin symmetry + $A^{2/3}$ scaling extrapolation from π + Fe cross-section data

Neut (generator): stepping (semi-classical) cascade model tuned to π + C cross-section data

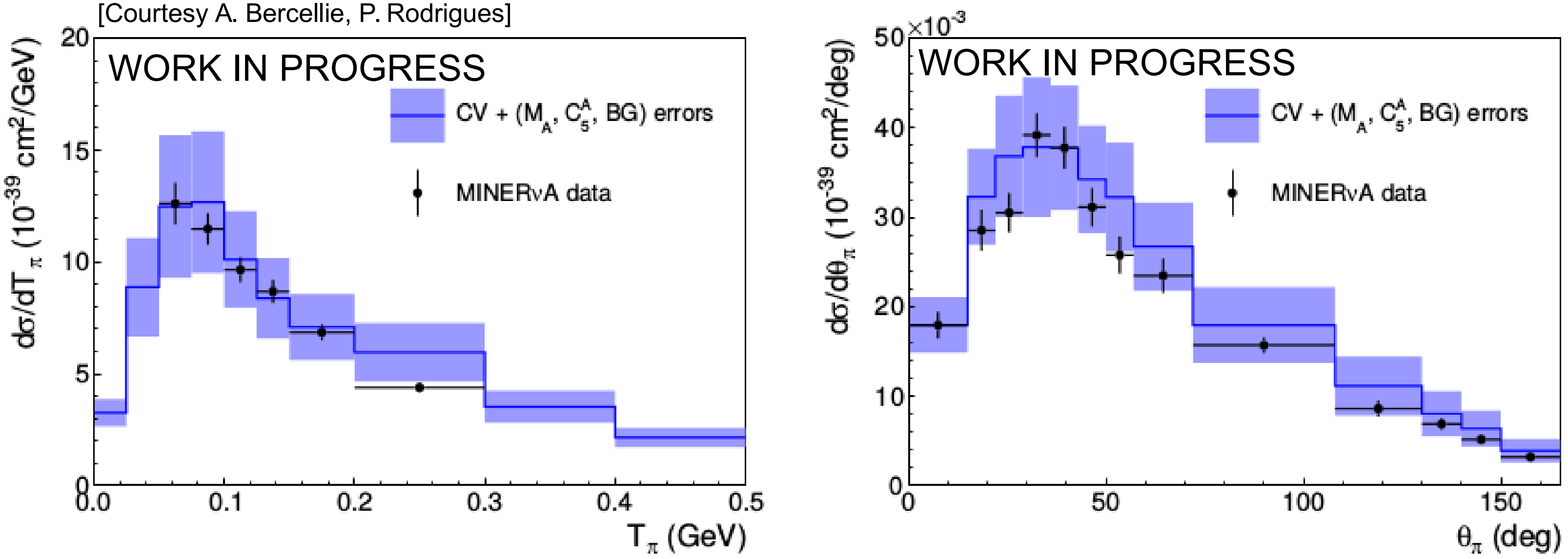
NuWro (generator): tuned similarly to Neut

Athar (theoretical calculation): theoretical model with *partial* FSI model (no pion re-scattering)

Models with full FSI treatment are preferred by shape of MINERvA data

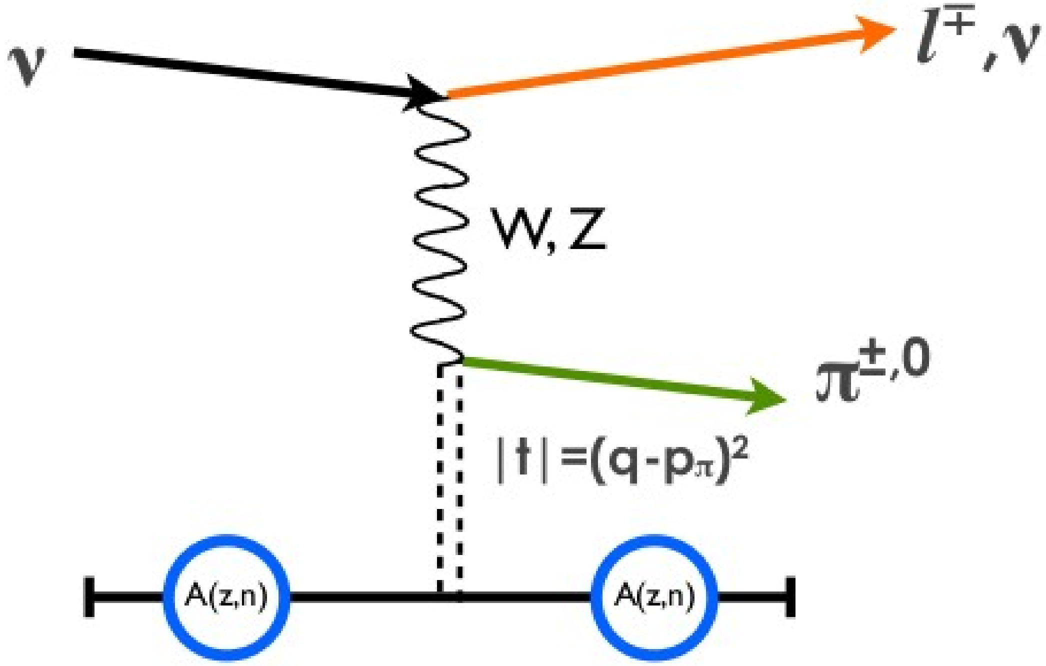
Using the result

[Courtesy A. Bercellie, P. Rodrigues]



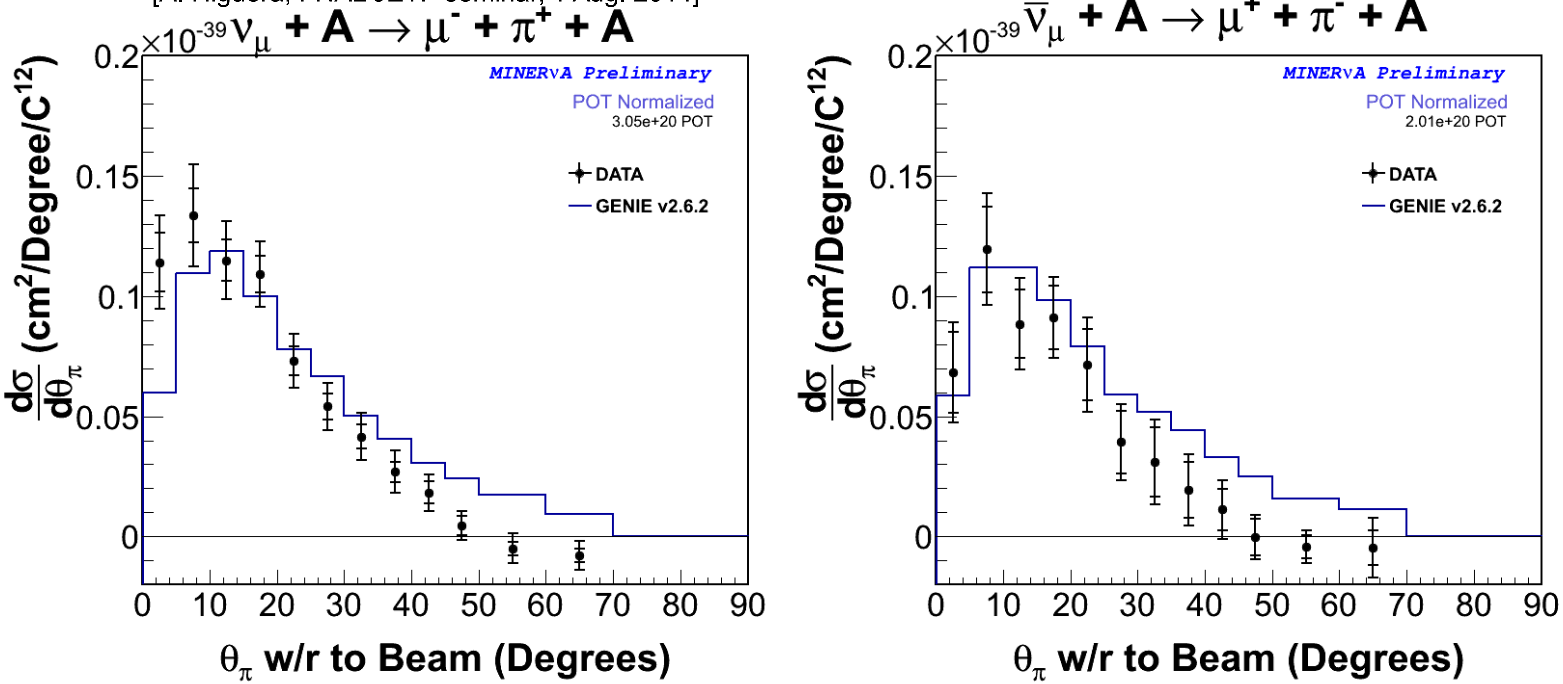
T2K collaborators have been applying MINERvA's data to tune the parameters used in NEUT's single pion production model

One last example: coherent π



Shares problem with resonant production
(can look like CCQE—particularly for NC coherent π^0, which can fake ν_e CCQE—but CCQE energy formula doesn't apply)

Coherent π



[A. Higuera, FNAL JETP seminar, 1 Aug. 2014]

MINERvA data indicates serious flaws in commonly-used model for coherent pion production (Rein-Sehgal).

See J. Morfín's talk tomorrow for many more details.

Summary

- MINERvA's cross-section measurements are already being put to work improving models needed for E_ν reconstruction
  - Comparison to CCQE models underscores the importance of understanding the role the initial state plays
  - Comparison to pion production models suggests that current generators' FSI model is reasonable and necessary to match the data
- Recent and forthcoming results promise to continue this tradition
  - Other CCQE: $d^2\sigma/dp_z dp_t$ for ν_μ; $d\sigma/dQ^2$, $d\sigma/d\theta$, $d\sigma/dE_e$ for ν_e
  - Coherent $\pi^\pm$

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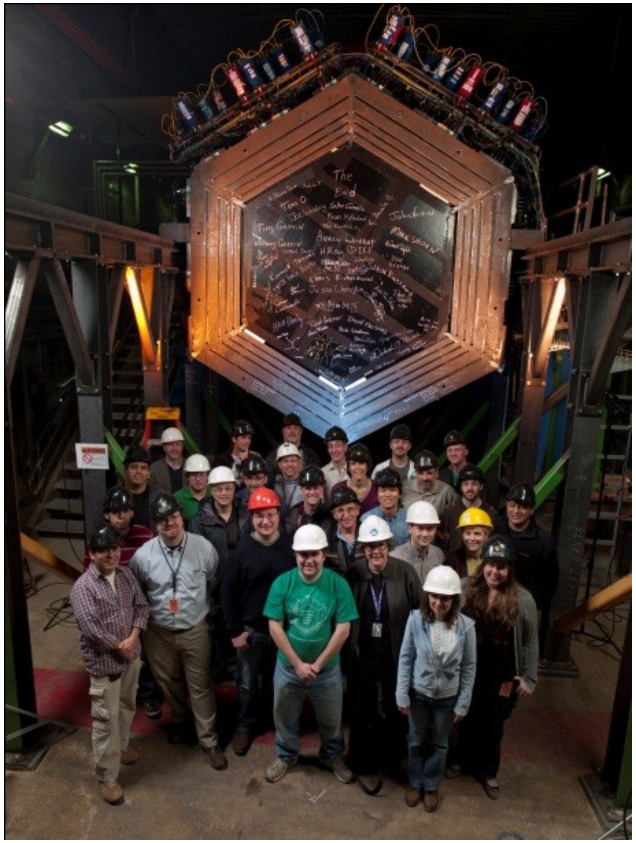
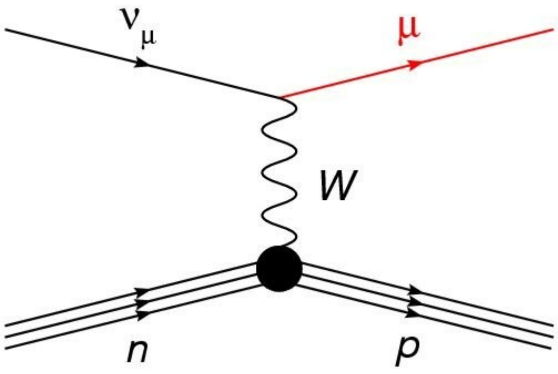


Thank you from MINERvA!

Backup slides follow

Models for ν_μ CCQE



CCQE = “standard candle?”
(simplest CC process)

Basic formalism for *free nucleon* cross-section well known...

(Llewellyn Smith, 1972)

$$\frac{d\sigma}{dQ^2} = \frac{M^2 G_F^2 cos^2\theta_C}{8\pi E_\nu^2} \times [A(Q^2) \mp \frac{(s-u)B(Q^2)}{M^2} + \frac{C(Q^2)(s-u)^2}{M^2}]$$

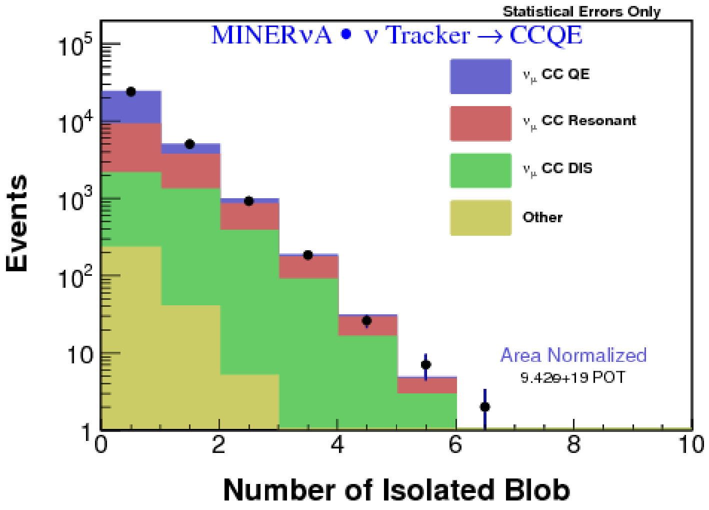
- Parameterized in terms of *nuclear form factors*
- One free parameter not constrained by electron scattering data: “axial mass” m_A
  - Fits to ν-D_2 and ν-C scattering data: $m_A = 0.99$ (ANL, BNL, NOMAD)
  - MiniBooNE fit to ν-CH_2 scattering data: $m_A = 1.35$

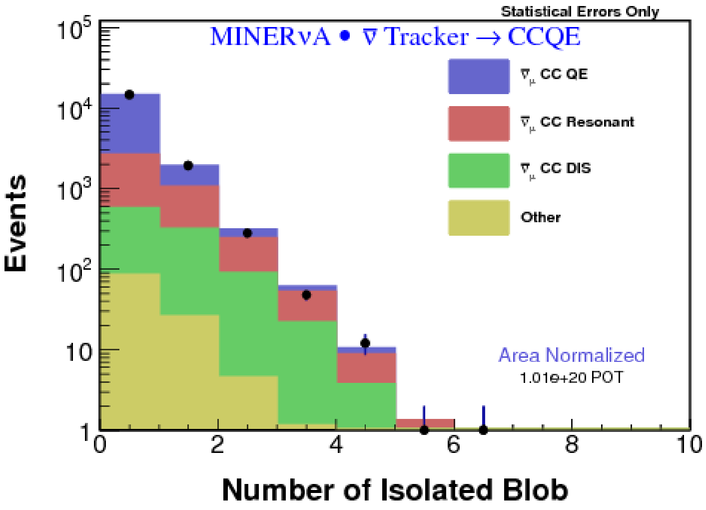
… but that *nucleus* ...

- Relativistic Fermi Gas (RFG): “vanilla” quasi-free nucleon model
- Spectral Function (SF): nucleon momentum spectrum including NN correlation effect (but ν still interacts with single nucleon)
  [Nucl. Phys. A579, 493 (1994)]
- Random Phase Approximation (RPA): models long-range correlations between nucleons (nuclear polarization) by altering electroweak coupling
  [Phys. Rev. C 70, 055503 (2004)]
- Meson Exchange Currents (MEC): models multi-nucleon ejection
  [Phys. Rev. C 49, 2650 (1994)]
- Transverse Enhancement Model (TEM): empirical model based on modification of cross-section observed in e+A scattering
  [Eur. Phys. J. C 71, 1726 (2011)]

Lots of models to mix and match!
(Where do they overlap?...)

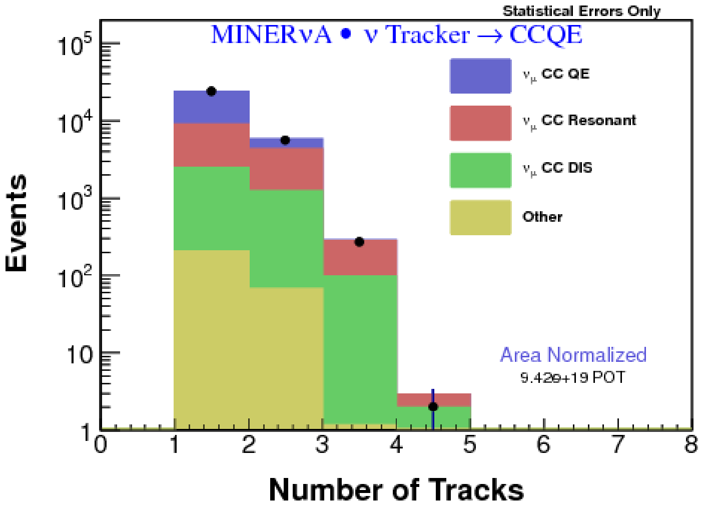
CCQE: isolated showers cut

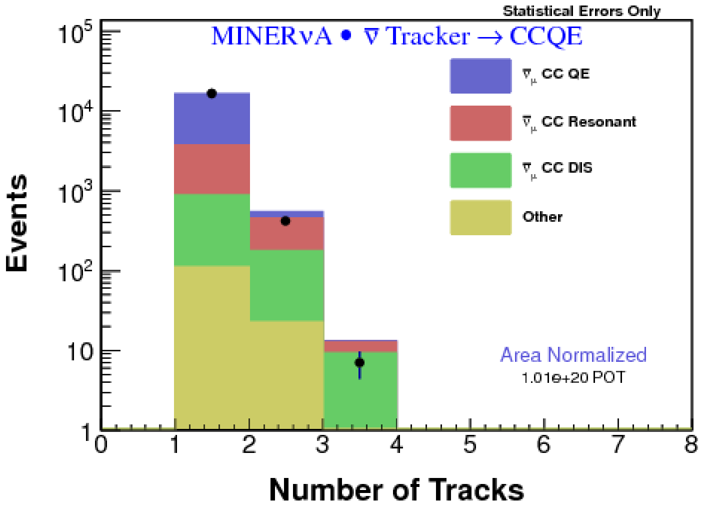




- <=2 for neutrino, <=1 for nubar

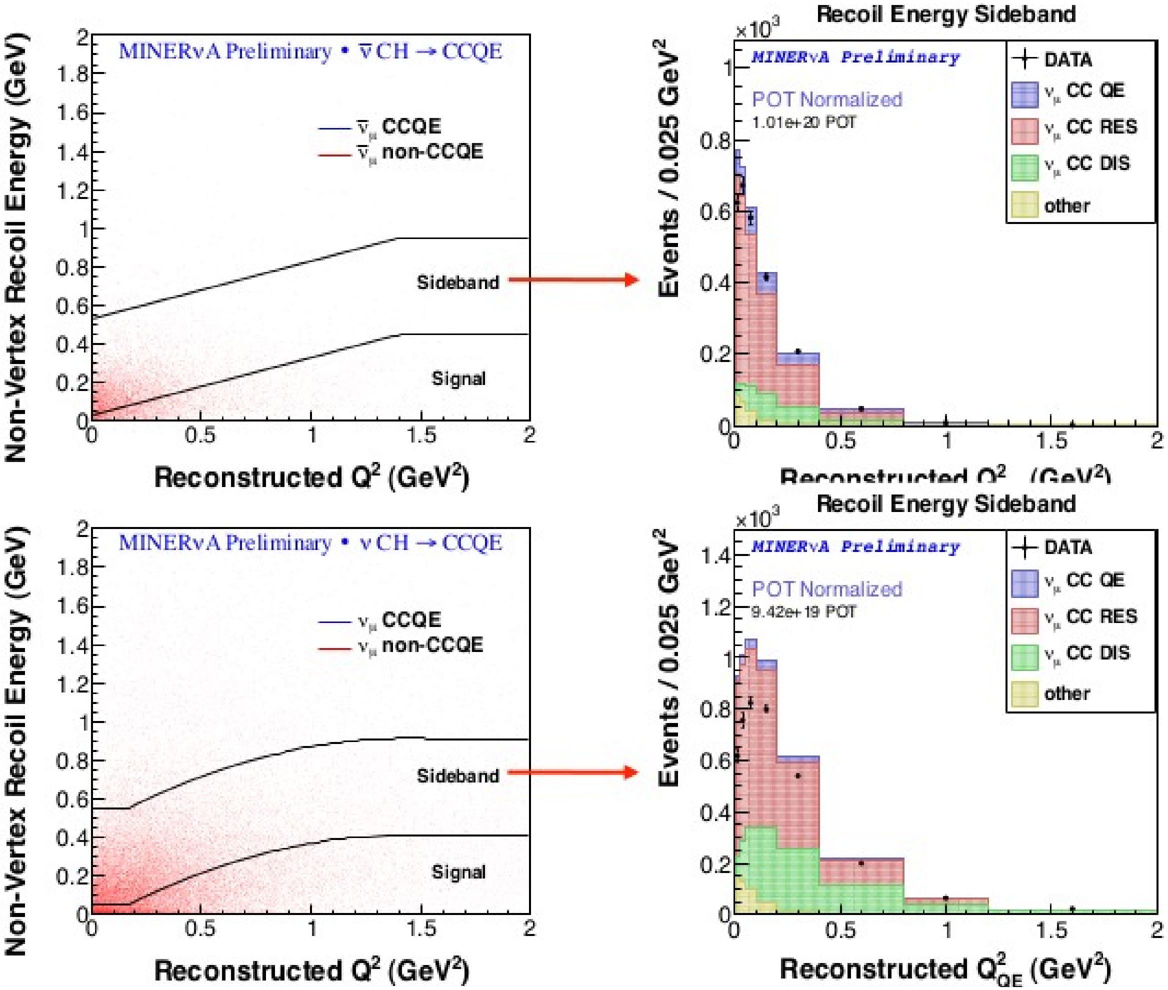
CCQE: number of tracks cut





- No more than 1 for nubar, no cut for neutrino

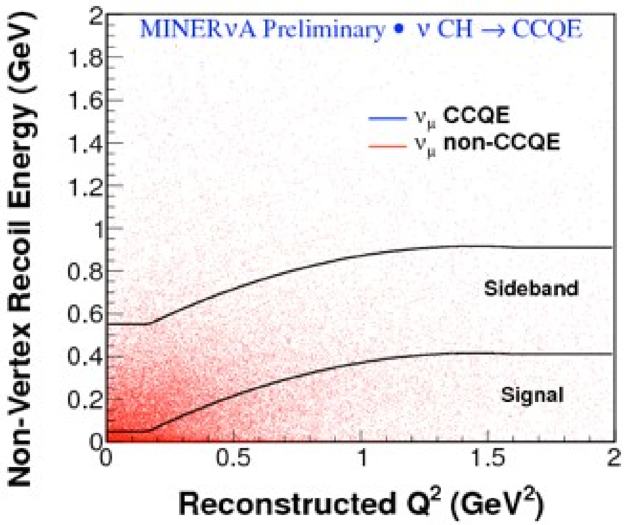
CCQE: sidebands



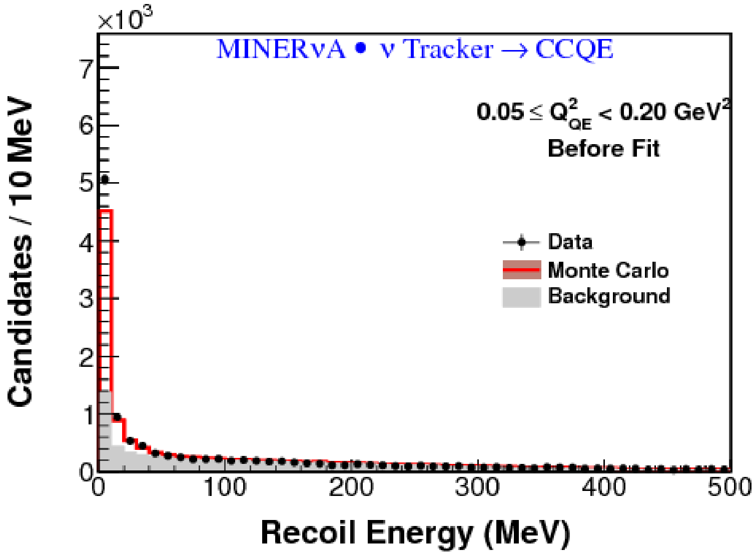
$\bar{\nu}_\mu$

ν_μ

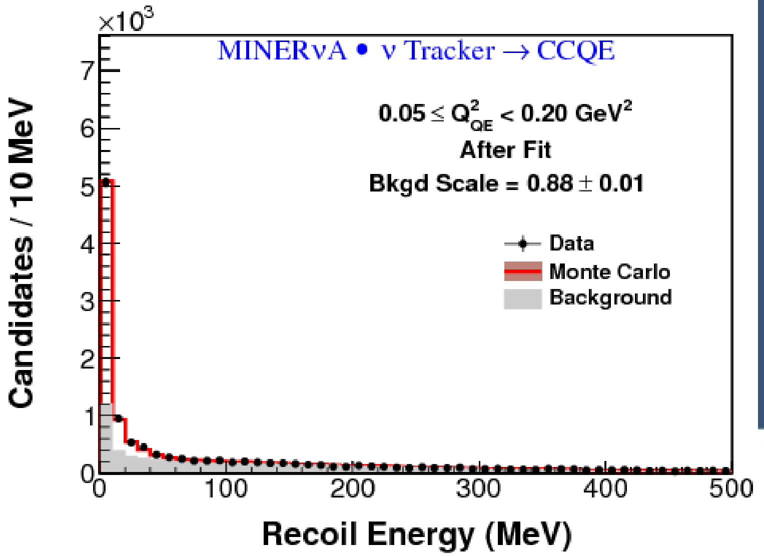
ν_μ CCQE: sideband constraint



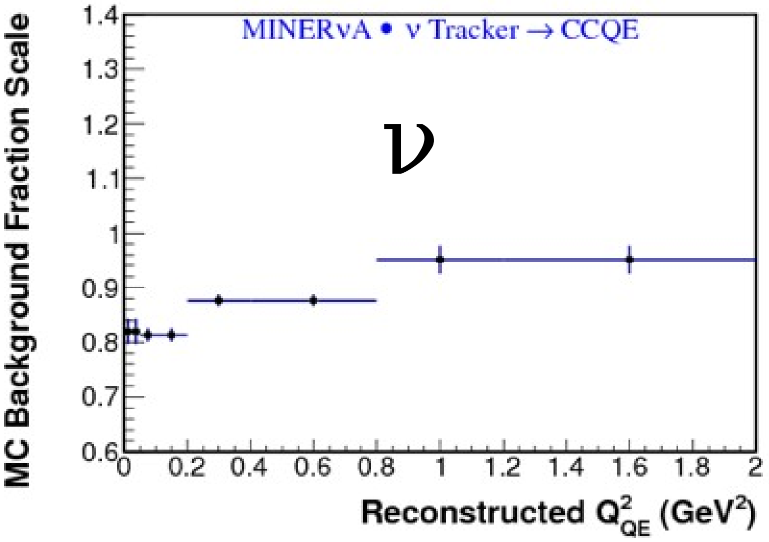
We use a sideband in the non-vertex recoil energy to constrain the background prediction in bins of Q^2.

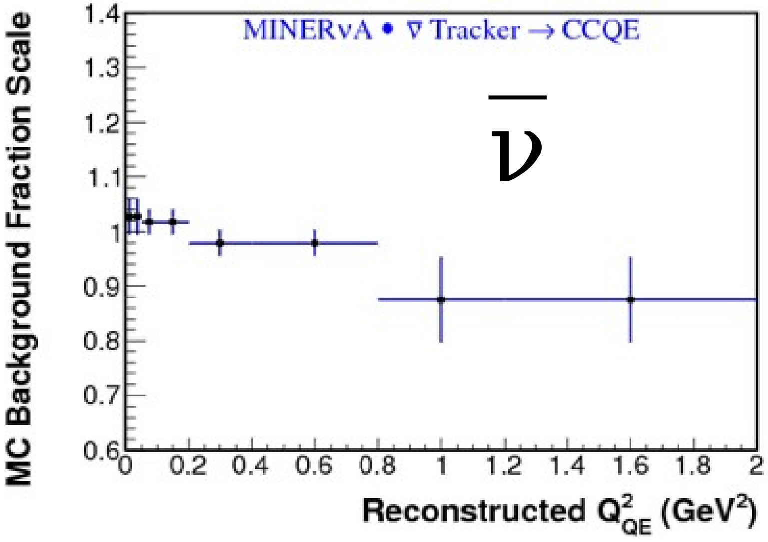


Sideband
fit



ν_μ CCQE: background scales



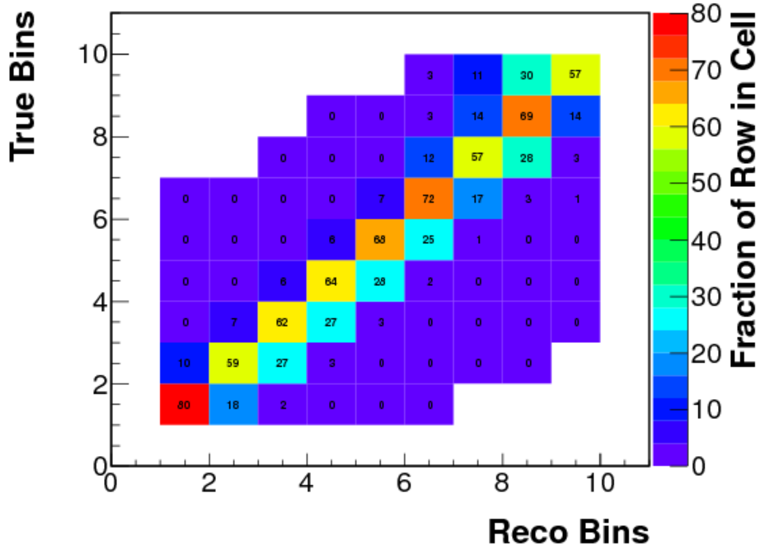


The corrections to background model
are not insignificant...

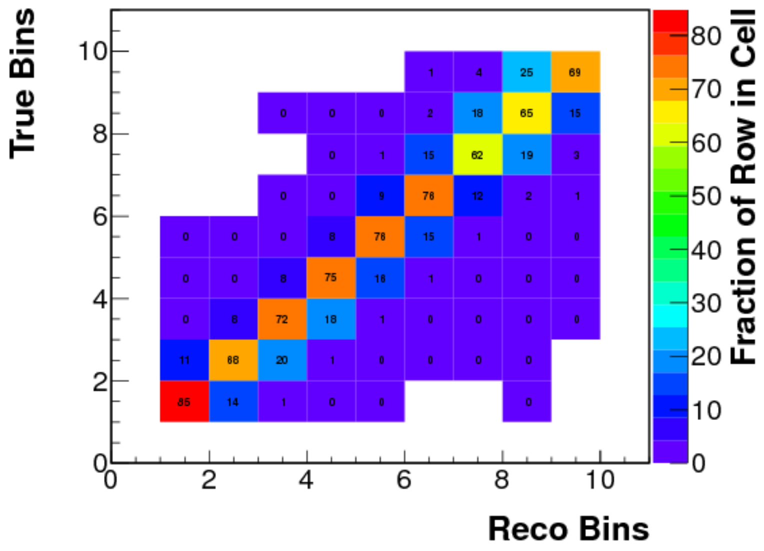
We then subtract the backgrounds, unfold to muon kinematic
variables, efficiency correct, and then...

CCQE unfolding matrices

neutrino

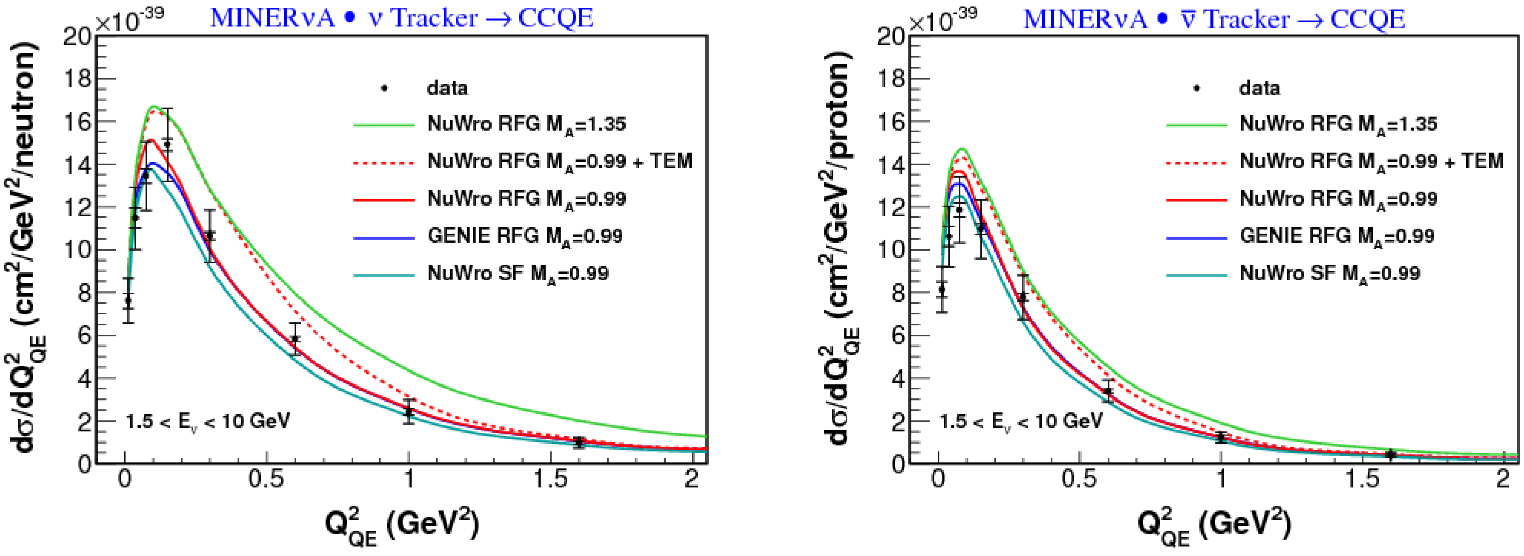


antineutrino



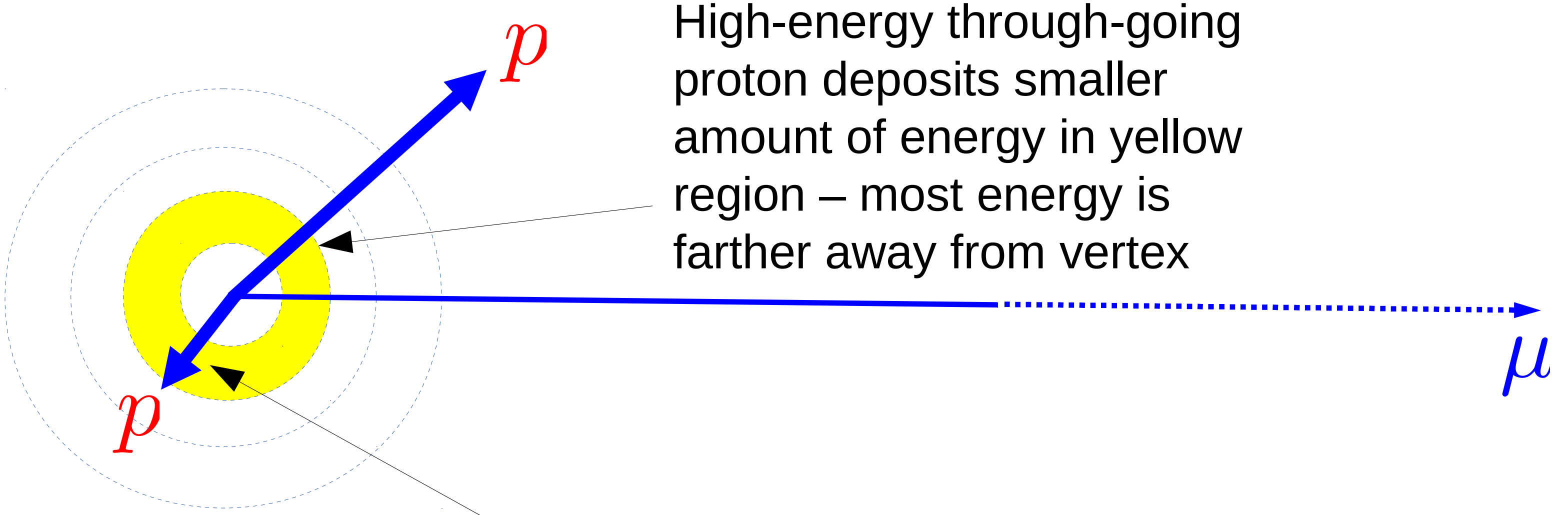
- Bins of Q^2_{QE}
- Unfolded using Bayesian method with 4 iterations

CCQE: absolute cross section



$M_A = 1.35$	—	best fit to MiniBooNE data
TEM	- - -	empirical model based on electron scattering data
GENIE	—	independent nucleons in mean field
SF	—	more realistic nucleon momentum-energy relation

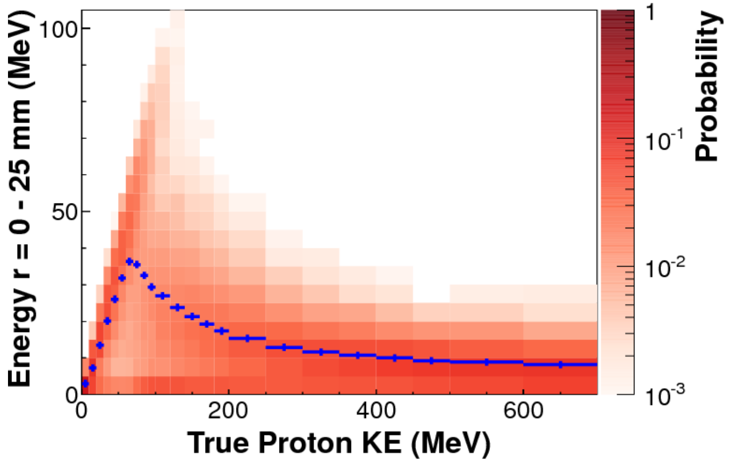
Vertex energy “annuli”

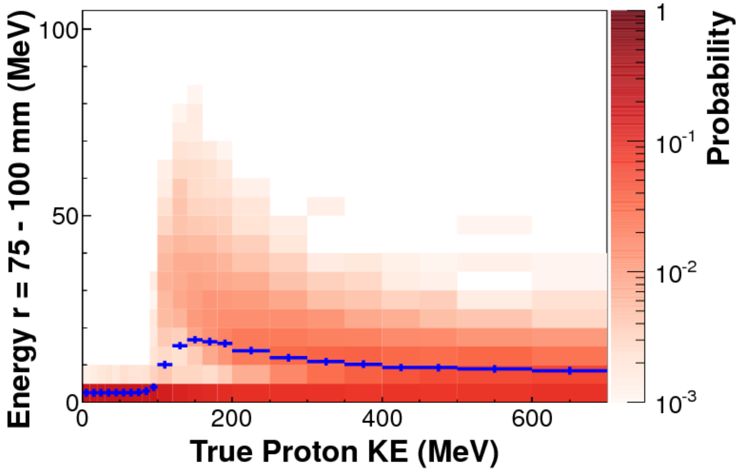


High-energy through-going proton deposits smaller amount of energy in yellow region – most energy is farther away from vertex

Low-energy proton Bragg peak is in yellow region – higher energy deposit

Vertex energy due to 1 proton



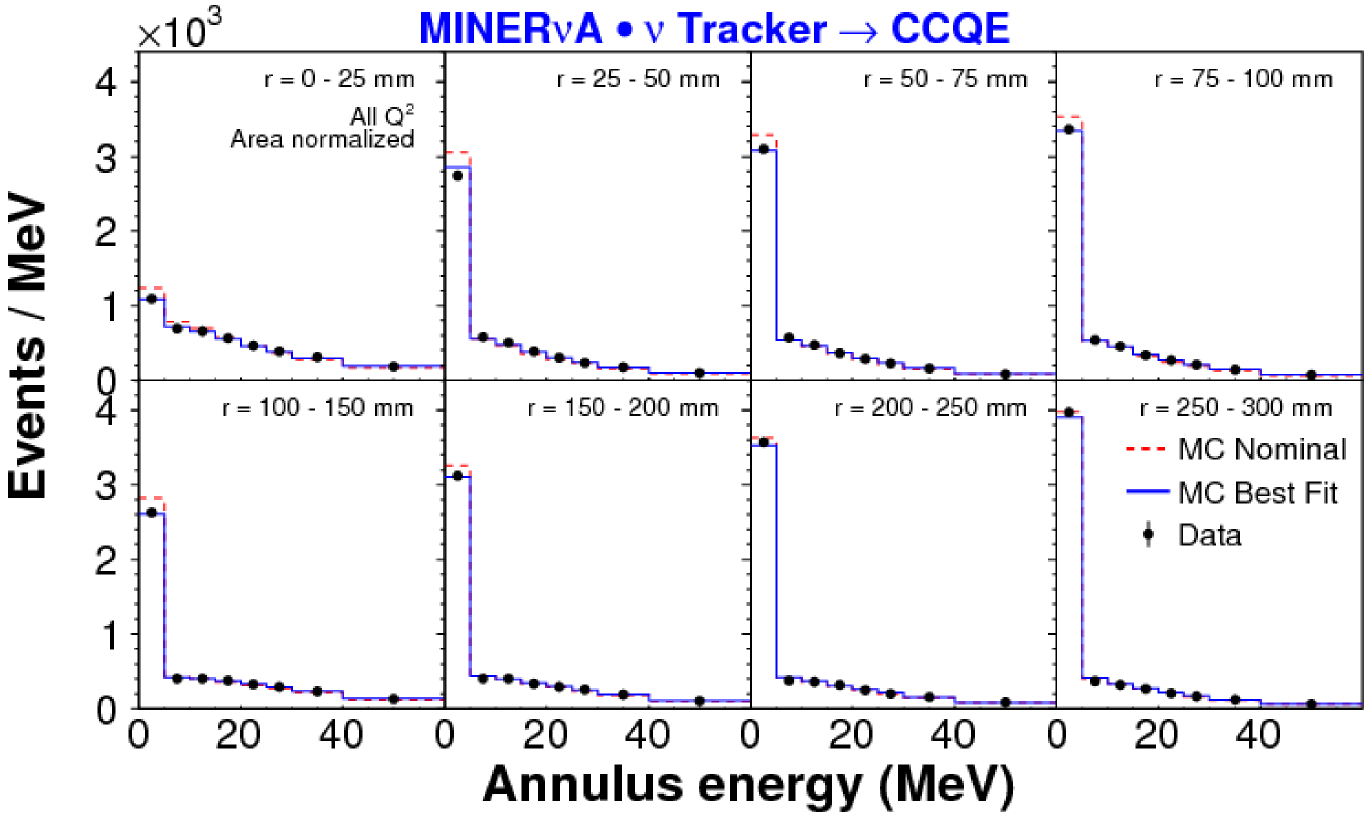


Simulated CC events with exactly 1 proton, no π/γ

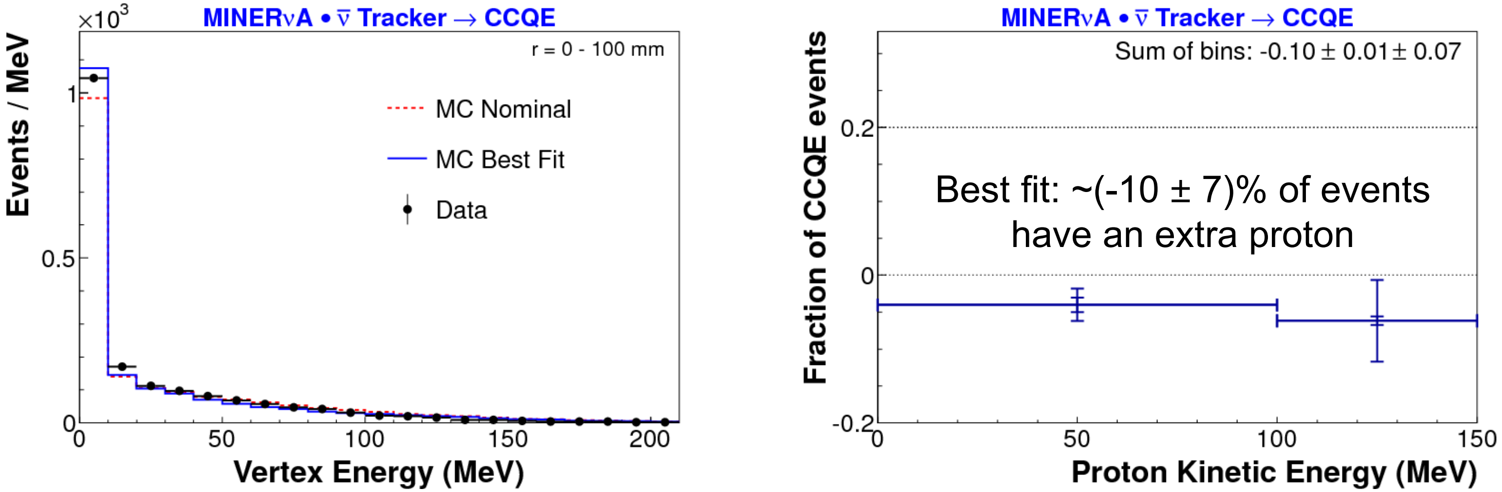
For proton of given KE, column represents probability distribution for energy deposit in given region

Fit by adding energy to some fraction of events based on these distributions

Vertex energy annulus fits



Vertex activity ($\bar{\nu}$ incident)



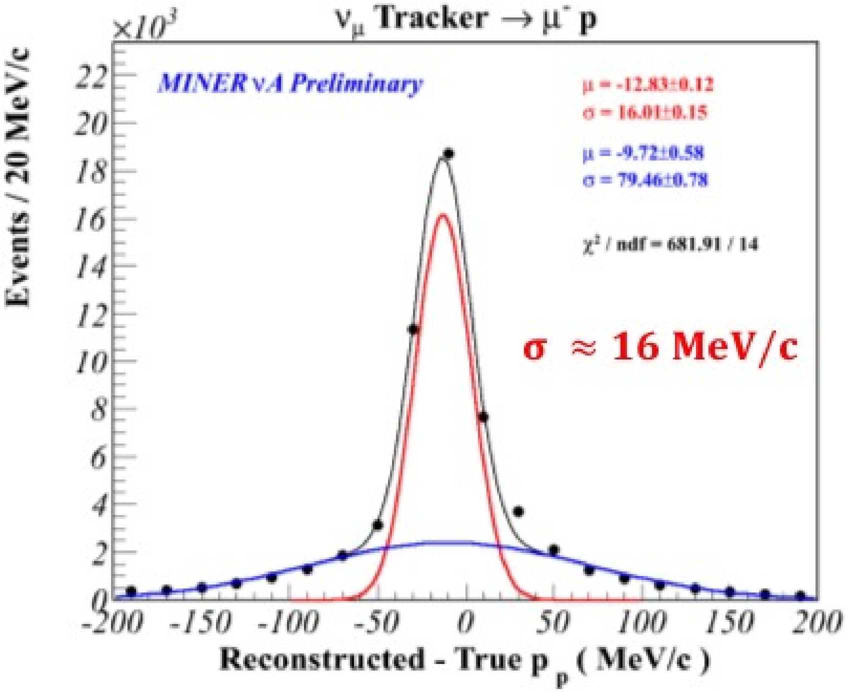
Best fit: ~(-10 ± 7)% of events have an extra proton

Fit suggests $\bar{\nu}$ events do not require any extra protons:

consistent with (n,p) correlated pair model (CCQE converts np → nn)

Q^2 from proton kinematics

- Reconstruct Q^2 using kinetic energy of the leading proton.
- Use the QE hypothesis.
- Assume scattering from a free nucleon at rest.
  - $\mathbf{Q^2_{QE,p} = (M')^2 - M_p^2 + 2M'(T_p + M_p - M')}$,
    - $M' = M_n - E_{bind}$
    - E_{bind} is the binding energy
    - T_p is the proton kinetic energy
    - M_n is the mass of the neutron
    - M_p is the mass of the proton

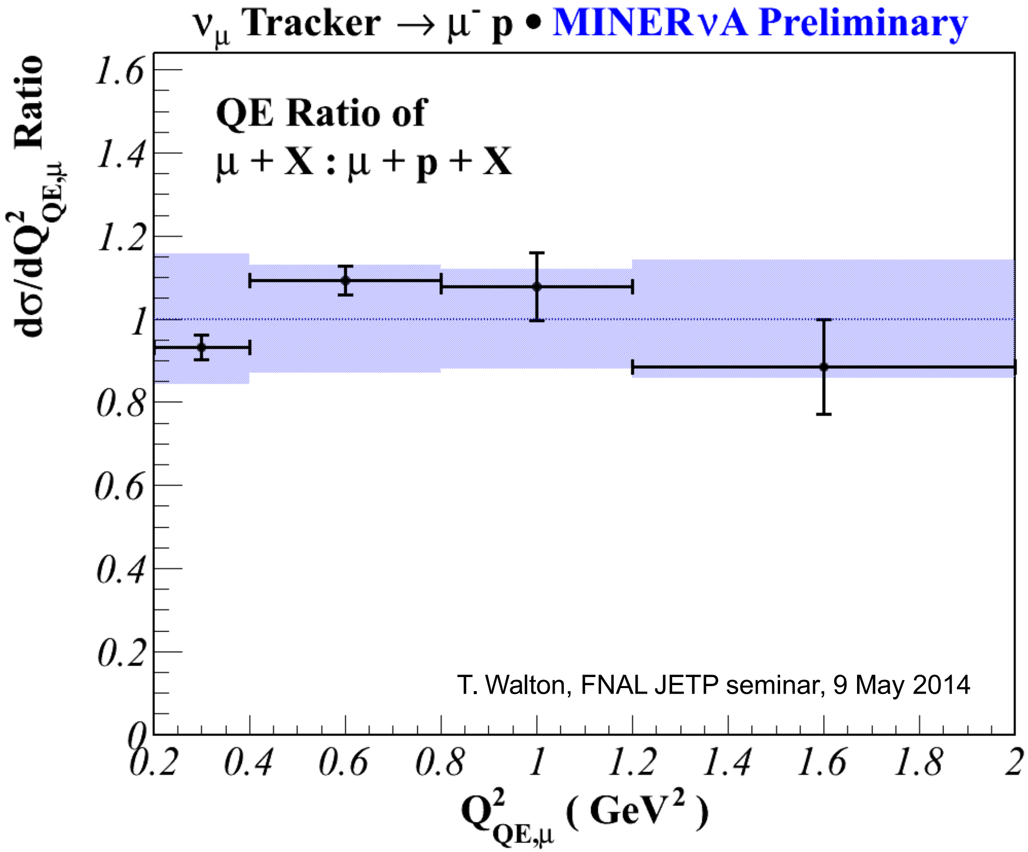


$\sigma \approx 16$ MeV/c

Compare Q^2 from muon kinematics:

$$Q^2_{QE} = 2E_\nu^{QE}(E_\mu - p_\mu \cos\theta_\mu) - m_\mu^2$$

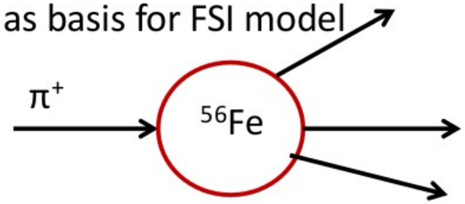
CCQE methods comparison



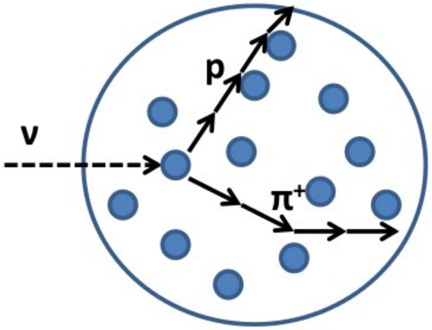
Results of "μ+little recoil" and "μ+p" techniques, when examined vs. muon variables, are consistent within systematics of "μ+p" (blue band)

Pion models & FSI

GENIE: Use p,π scattering on Fe data as basis for FSI model

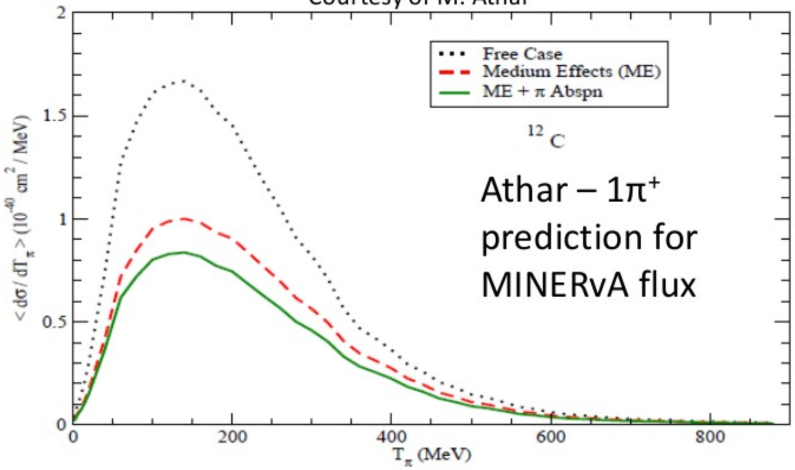


NuWro, Neut: Step interaction products through nucleus and use nucleon cross sections



Athar: Use an Eikonal approximation. Reduces observed pions, but does not significantly change T_π shape

Courtesy of M. Athar



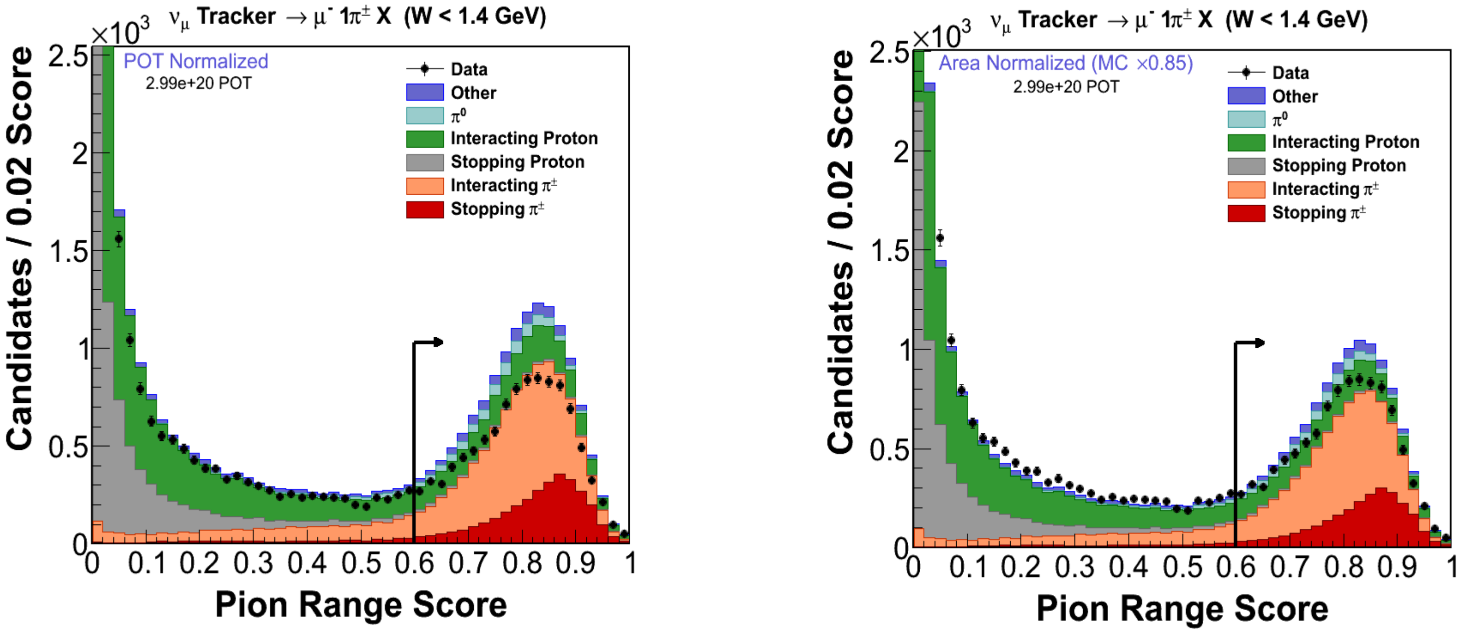
Athar – 1π^+ prediction for MINERvA flux

Pion ID

Select a pion (Particle ID):

- Use energy loss (dE/dx) profile of each hadron track to separate protons and pions

- Find the best fit momentum for a pion hypothesis: this is the ***reconstructed momentum***



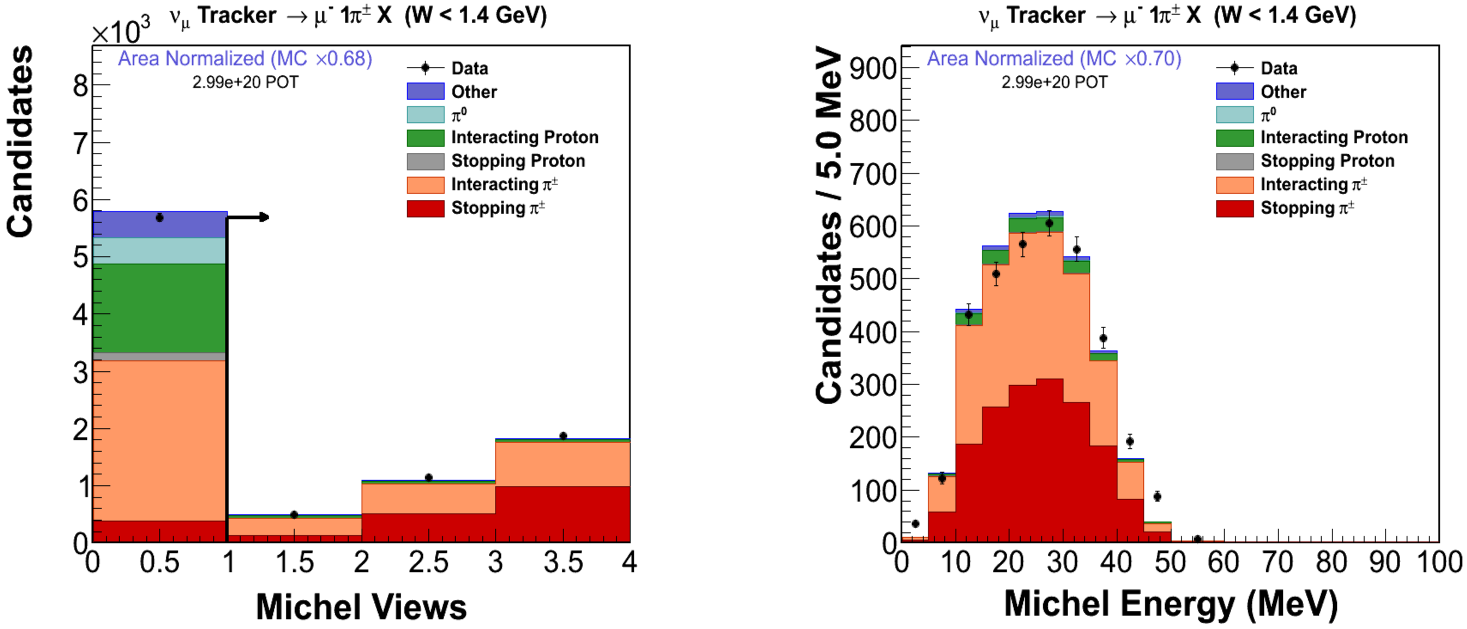
Pion ID

Select a pion (with good energy reconstruction):
Select pions that stop and decay in the detector by looking for a Michel electron at the end of the track

$$\pi^+ \rightarrow \mu^+ \nu_\mu$$

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

Shape Comparisons

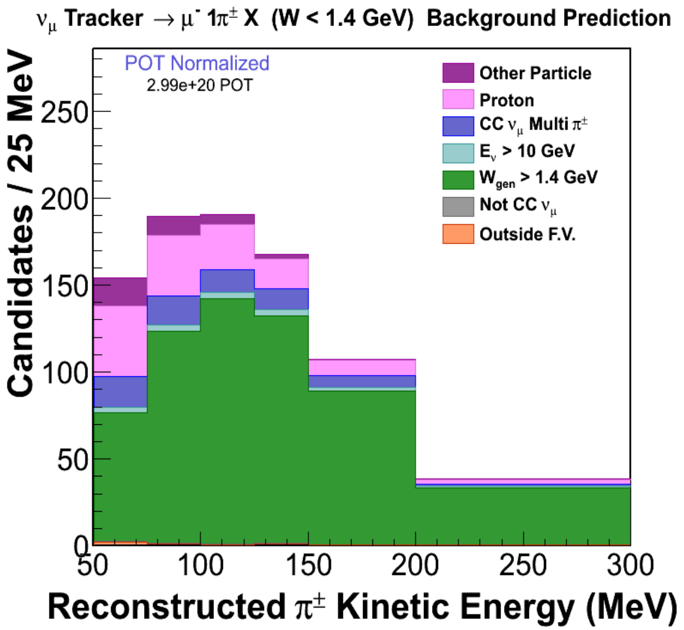


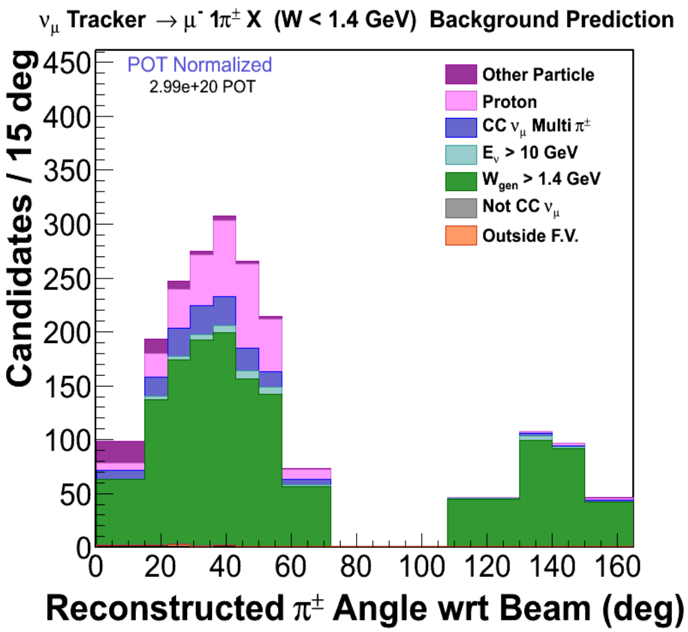
Pion Background Summaries

Largest background: W > 1.4 GeV **~17%** of sample

PID backgrounds: Protons and other particles mis-ID as pion **~ 4%** of sample

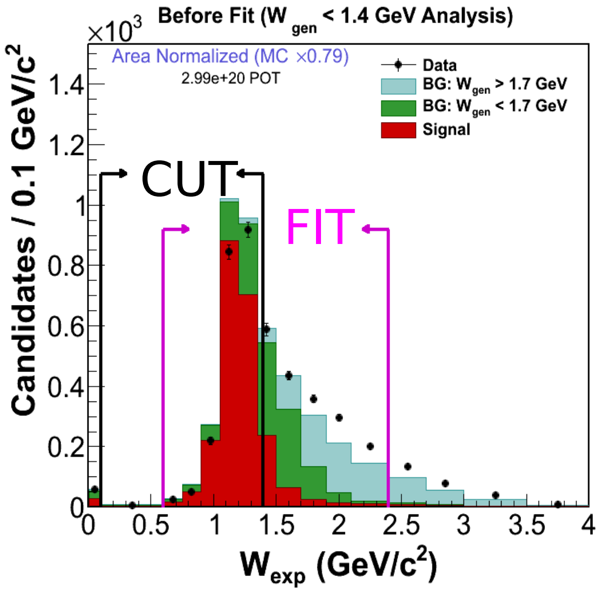
All other backgrounds combined: **~2%** of sample





Pion Background Subtraction

- Only significant background is feed down from large W. Concentrate on constraining this background with data

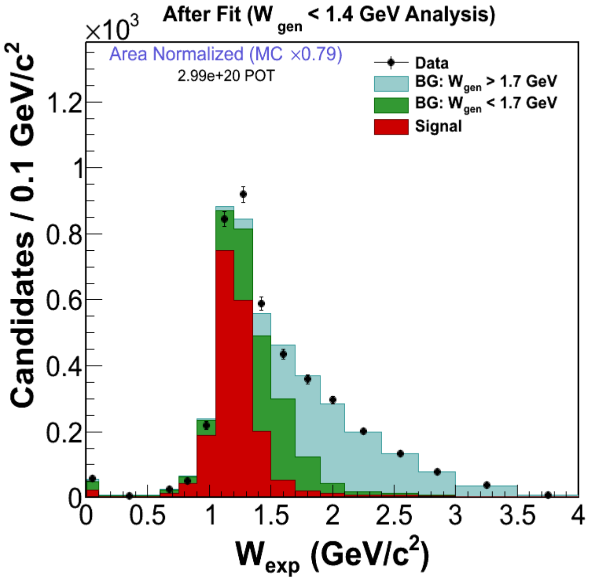


Procedure:

- Construct the W_{exp} distribution, applying all cuts except the W cut

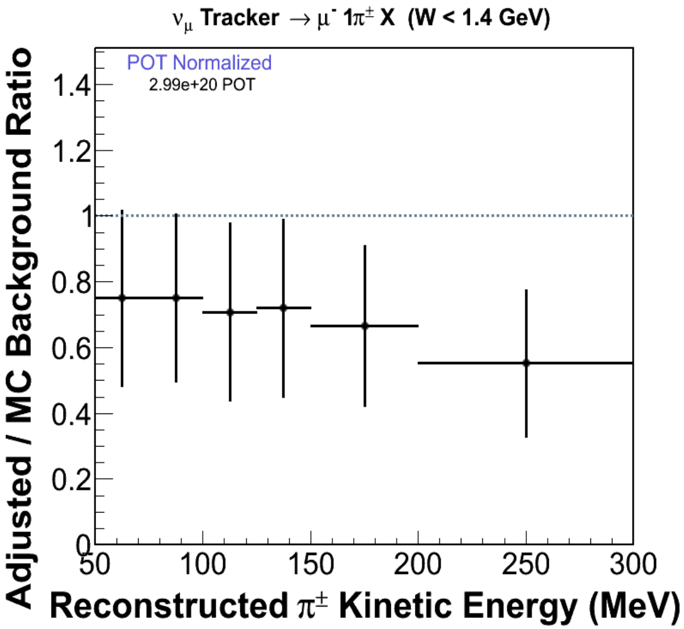
- Use the MC to create signal and background shape templates

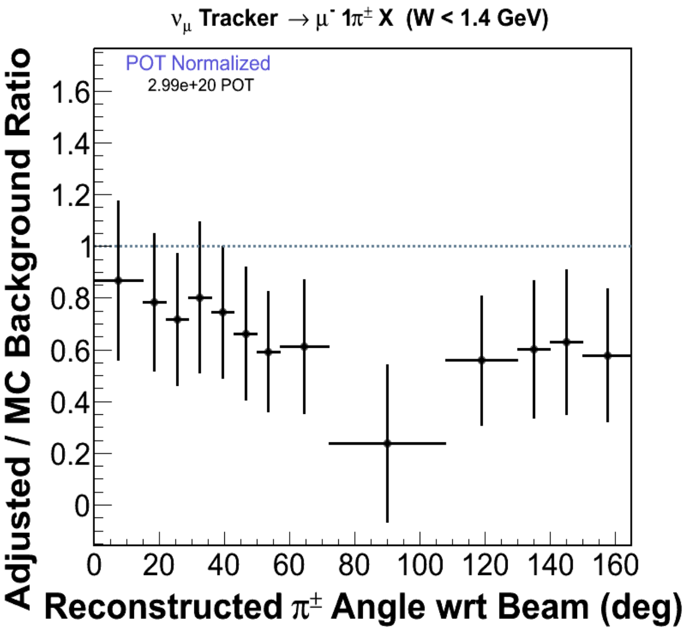
- Fit the data for the relative normalizations of the templates



Pion Background Scales

Ratio of adjusted to simulated background



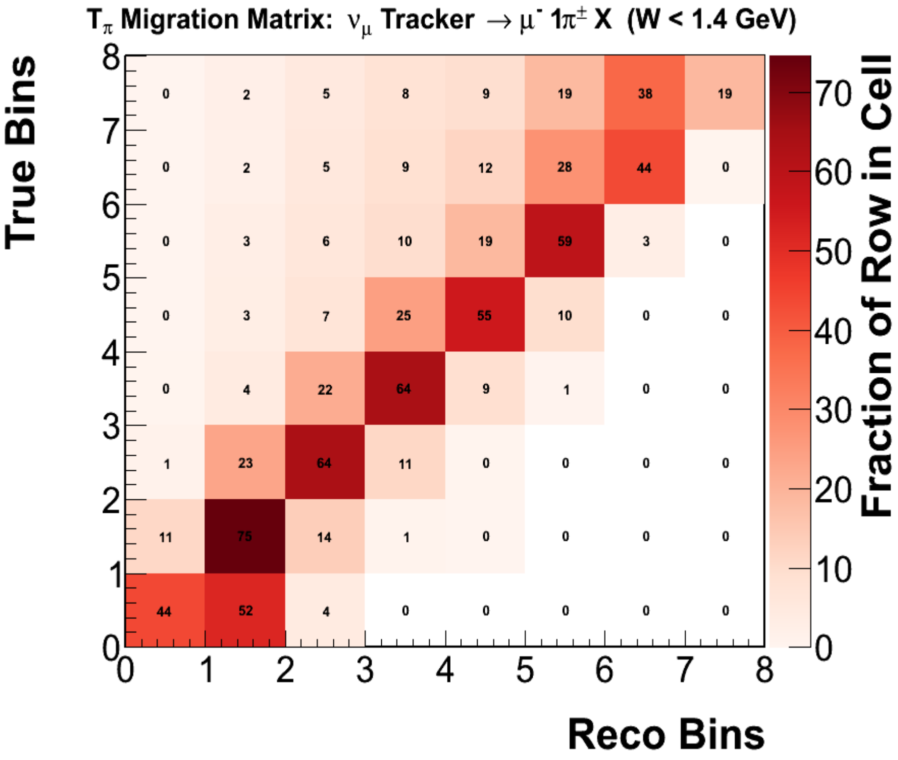


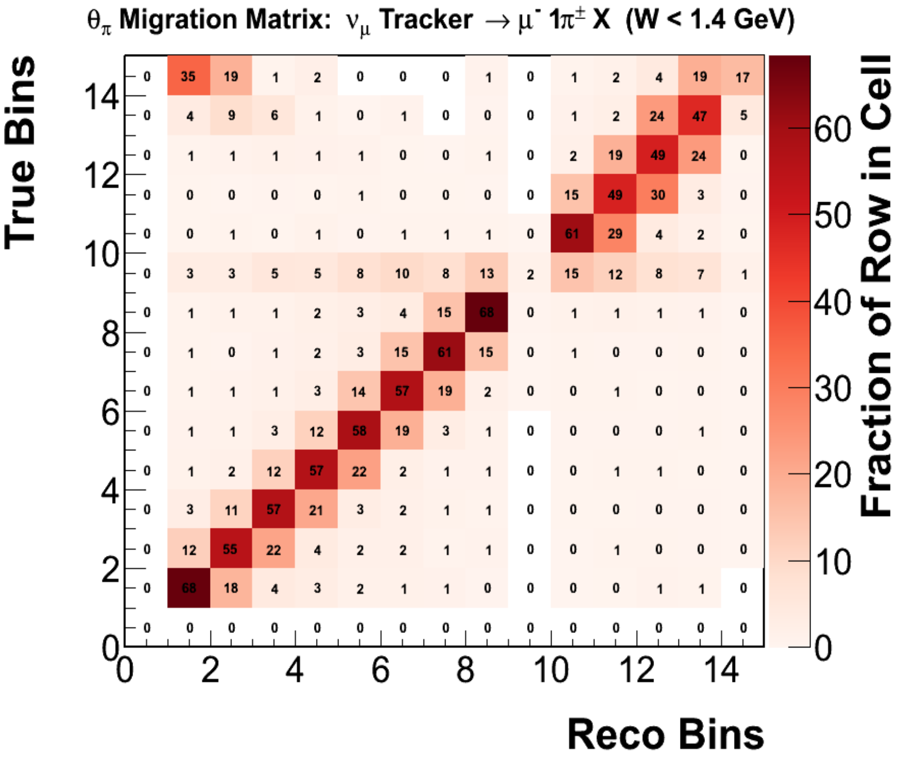
Dominant uncertainty on adjusted background is detector energy response

Pion Unfolding

- Unfolding removes detector resolution effects:
  - transform to "true" variables

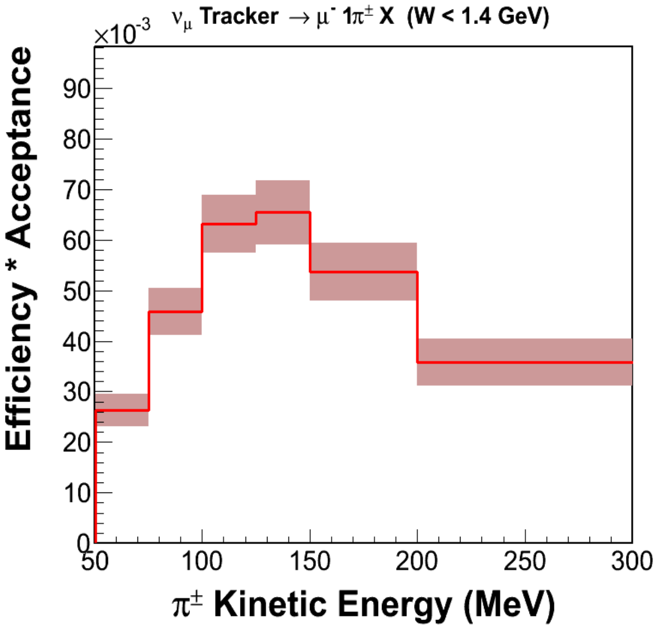
- Use an iterative Bayesian procedure: 4 iterations

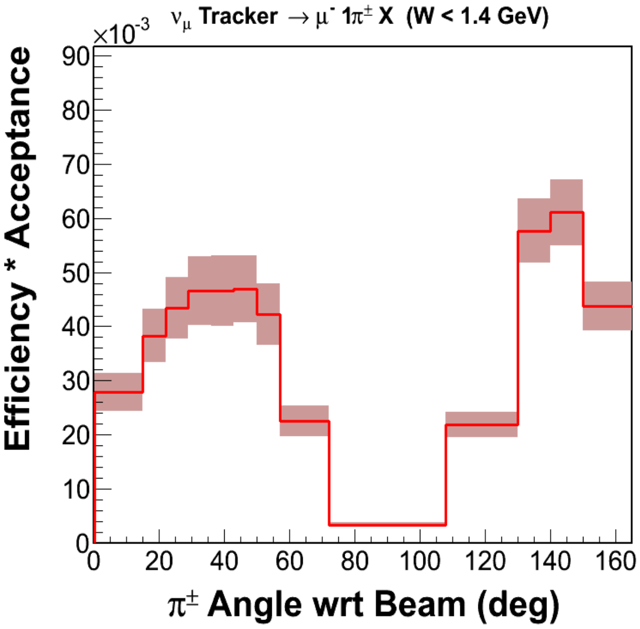




Pion Efficiency Correction

Correct to the full range of muon energies and angles





Pion Systematic Errors (1)

- Analysis uses GENIE 2.6.2 to simulate neutrino interactions in nuclei

- Cross section model uncertainties enter the analysis through the efficiency correction
    - ~10%, but negligible shape errors

- FSI uncertainties enter through background subtraction (change W)
    - ~3-4%, and < 2% shape errors

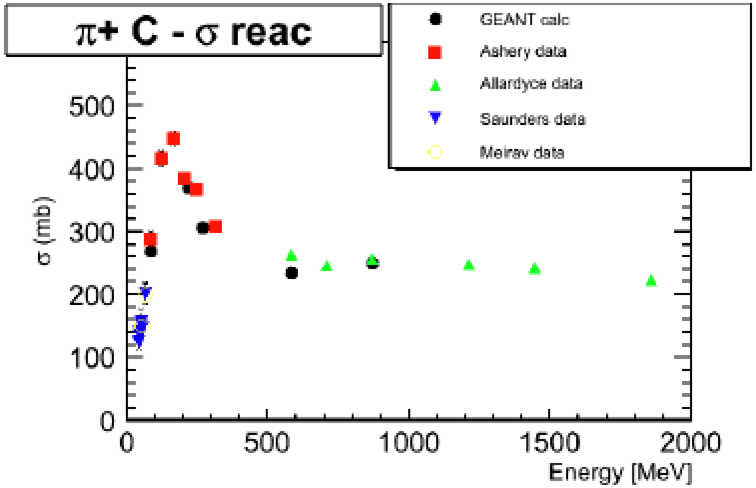
FSI model parameter	uncertainty
pion/nucleon mean path	±20%
pion/nucleon charge exchange	±50%
pion absorbtion	±30%
pion/nucleon inelastic cross-section	±40%
elastic cross sections	±10-30%

Pion Systematic Errors (2)

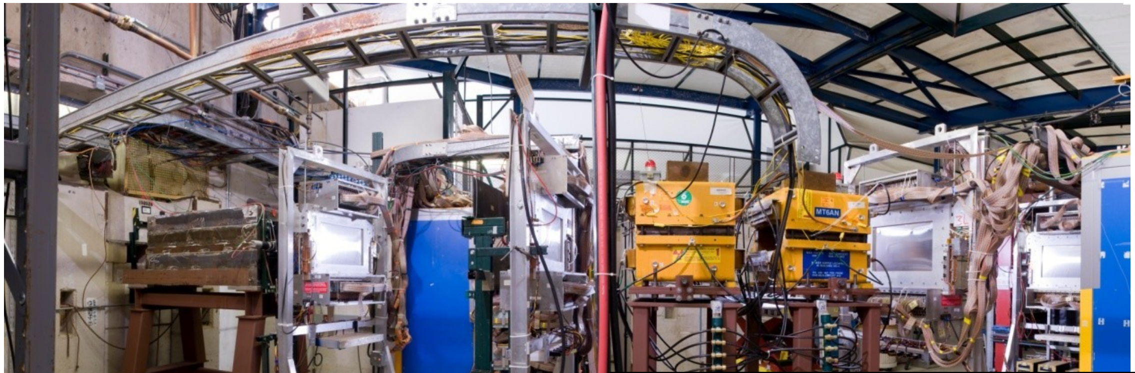
- Use Geant4 to simulate particle propagation in the detector

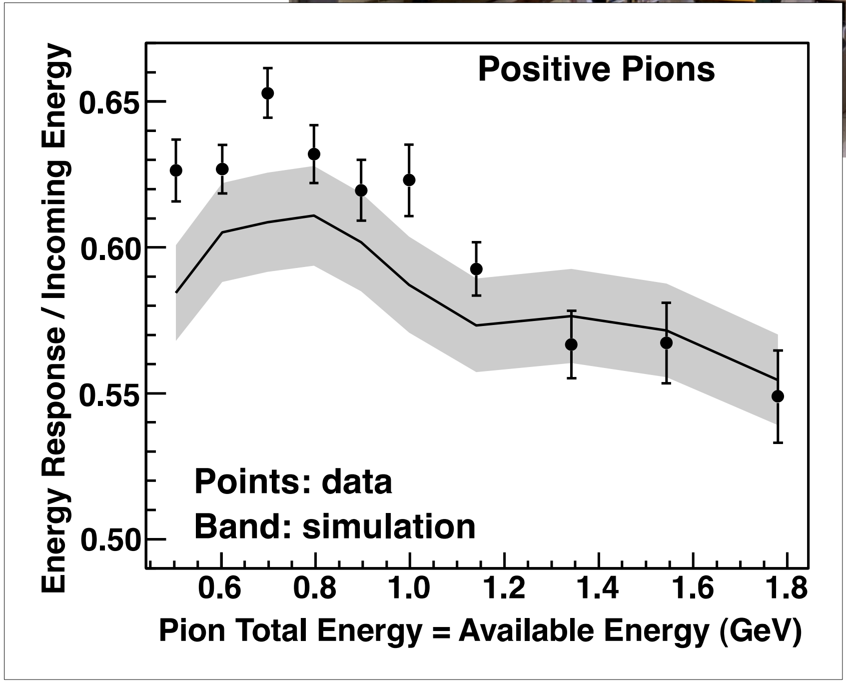
- Uncertainty on **inelastic pion** cross sections affects unfolding and efficiency correction. **Inelastic proton** cross section affects background estimate.

- Compare Geant4 predictions to external data to determine uncertainty on inelastic cross sections ~ 10%
  - Leads to up to 7% errors in analysis (greatest at large pion KE)



Pion systematic errors (3)





Points: data
Band: simulation