CHARGE CURRENT QUASI-ELASTIC SCATTERING OF NEUTRINOS AND ANTINEUTRINOS AT MINERVA

August 15,2013

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2013 DPF
UC SANTA CRUZ

Outline

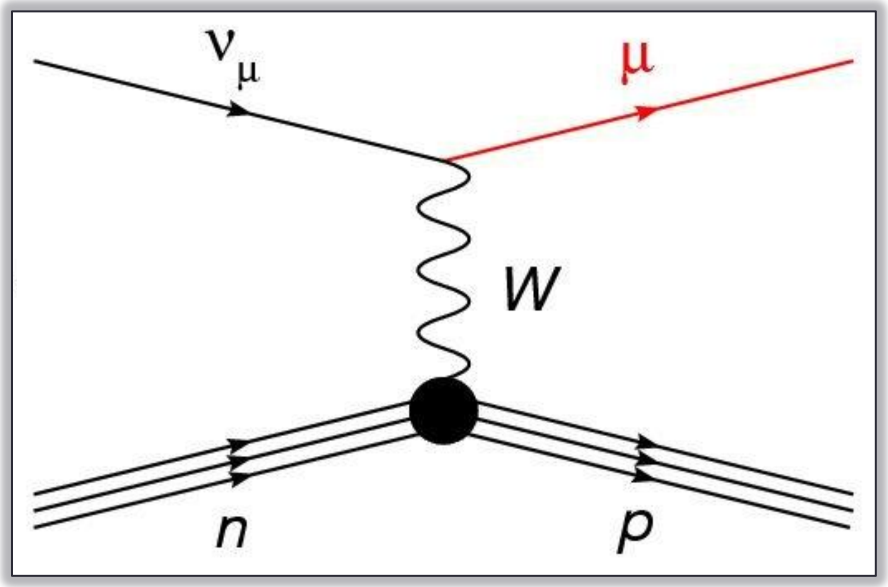
- Quasi-elastic scattering
- Relativistic Fermi Gas Model (RFG)
- MINERvA experiment
  - Isolating a QE sample
  - Systematic uncertainties
  - Interpretation of the results
- Future directions

Quasi-elastic scattering

- Neutrino or antineutrino scattering from a free or bound nucleon
- No observed pions in the final state
- Neutrino transformed to a charged lepton

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

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



Quasi-elastic scattering

E_ν and Q^2 are recontructed from muon kinematics assuming that the nucleon is at rest.

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

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

- M_n = neutron mass
- M_p = proton mass
- E_B = nucleon binding energy
- m_l = lepton mass
- E_l , q_l = lepton energy and angle

Relativistic Fermi Gas Model (RFG)

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

Llewellyn Smith, C.H., 1972, Phys. Rep. C3, 261.

- Free nucleon cross-section
- Nucleons behave as if they are independent in the mean field of the nucleus
- A,B and C are in function of 2 differents form-factors

$$F_1^V(Q^2) = \frac{G_E^V(Q^2) + \tau G_M^V(Q^2)}{1+\tau}$$

$$F_2^V(Q^2) = \frac{G_M^V(Q^2) - G_E^V(Q^2)}{1+\tau}$$

2 Vector Form Factors (F_1, F_2)

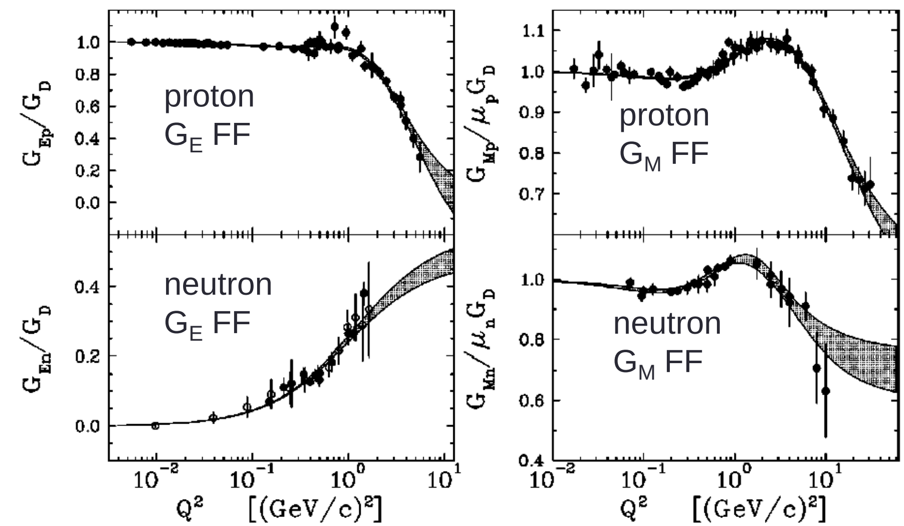
$$F_A(Q^2) = \frac{F_A(0)}{(1+Q^2/M_A^2)^2}$$

Axial-Vector Form Factor (F_A)

RFG model

- F_V (Vector Form Factors) measured from electron scattering.

Kelly, Phys. Rev. **C70**, 068202 (2004)



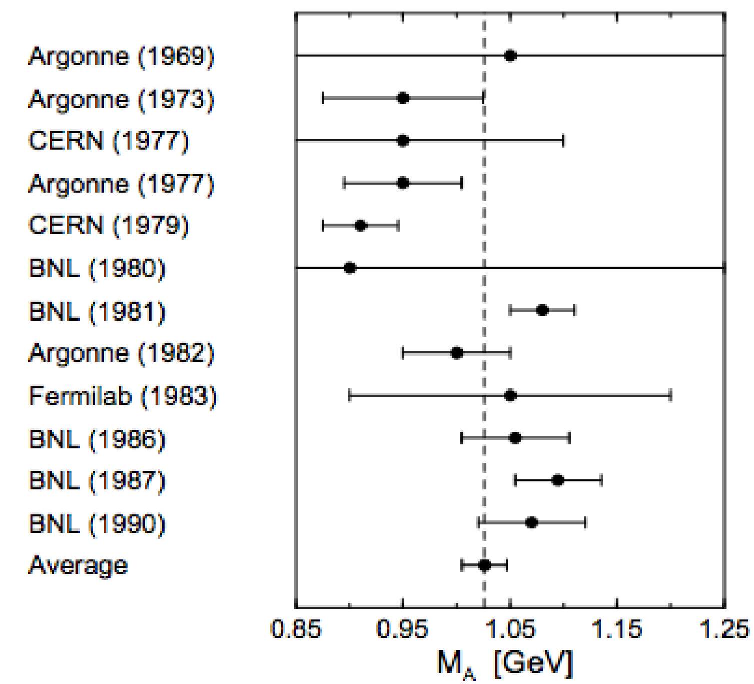
- Assume a dipole form for F_A (Axial-Vector Form Factor)

- use neutrino CCQE scattering data to determine the axial mass parameter

This is the value of Ma measured in Deuterium buble chamber

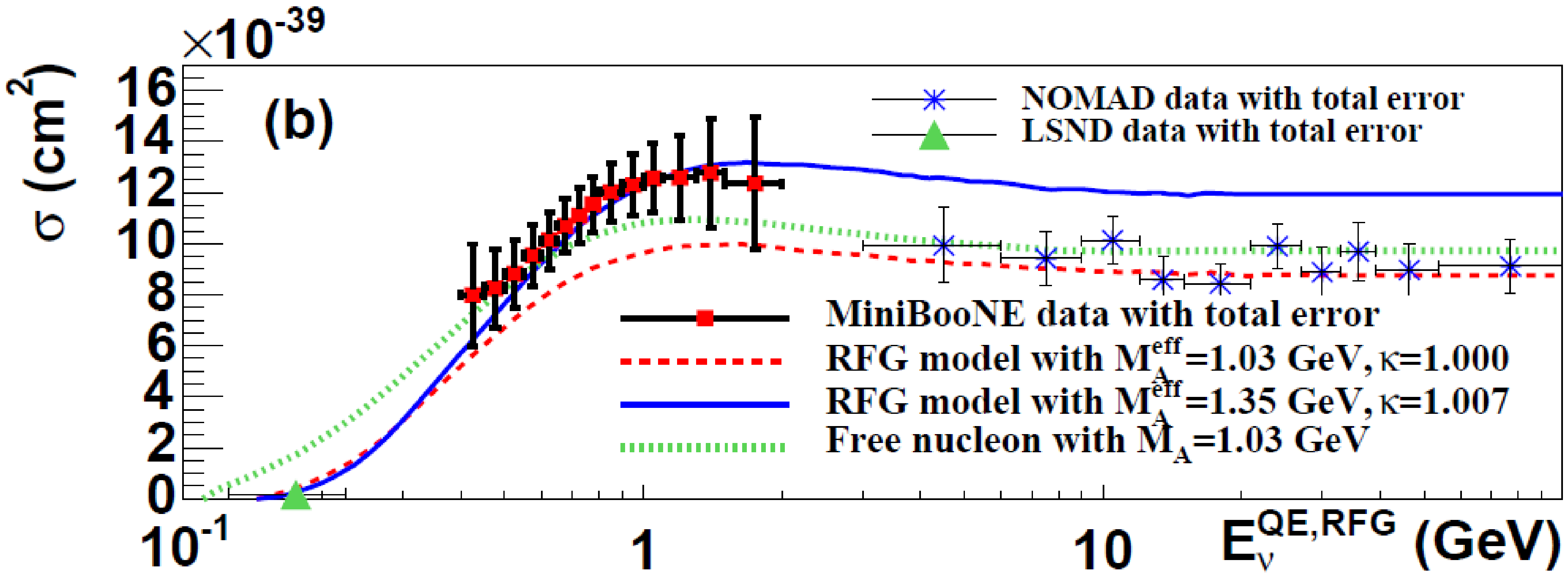
$$M_A \approx 1.0 \text{ GeV}/c^2$$

$$F_A(Q^2) = \frac{F_A(0)}{\left(1 + Q^2/M_A^2\right)^2}$$



Bernard et al. J.Phys.G28,R1(2002)

Nuclear Effect not included in the RFG



➢ Lower-energy experiments predict M_A=1.35 GeV, NOMAD predicts M_A=1.03 GeV when fitting to the same model.

➢ Best fits of MiniBooNE, SciBooNE and NOMAD cross-sections to the RFG model for carbon

Additional energy dependent nuclear effects behind the RFG model?

are there other nuclear effect?

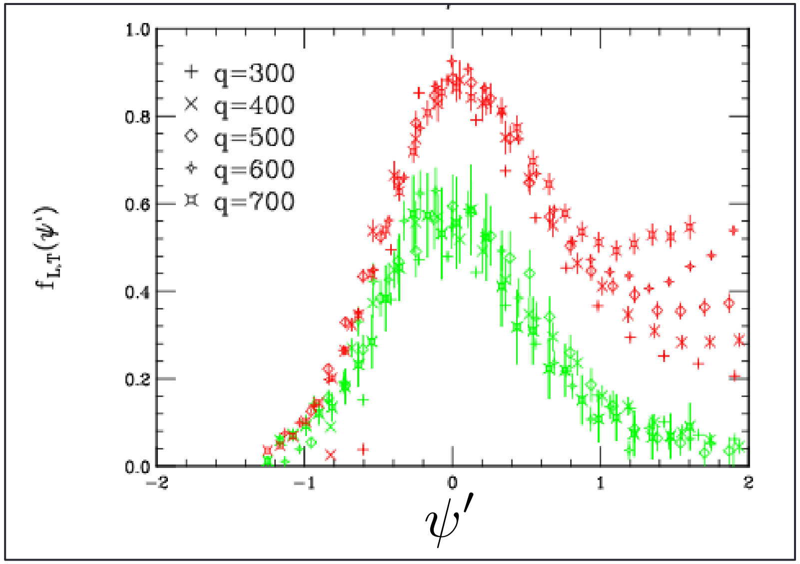
Multi-nucleon effects

- ***meson exchange currents (MEC)*** which may enhance part of the cross section significantly

- Low-momentum correlated pair can have high-momentum constituent nucleons

- Transverse enhancement is seen in electron-scattering cross-sections

Transverse vs. longitudinal cross-section in electron-N QE scattering on ^{4}He



J. Carlson et al, PRC 65, 024002 (2002)

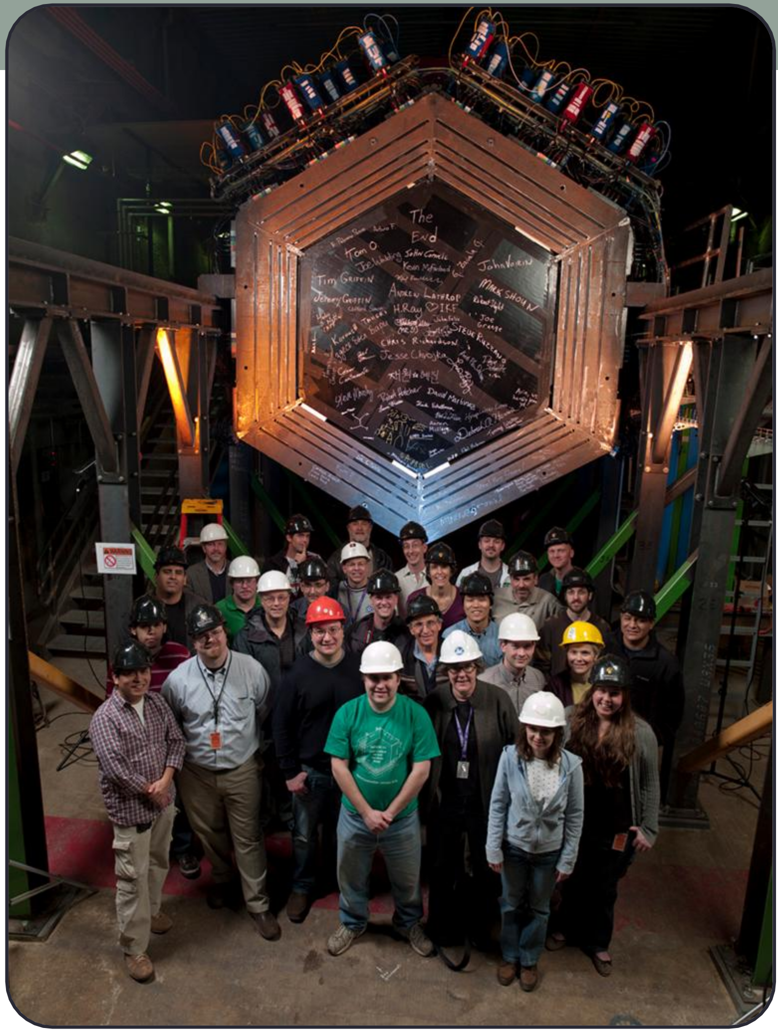
$$\psi' = \frac{\sqrt{\omega^2 + 2M\omega} - q}{k_F}$$

scaling parameter to show the transverse enhancement

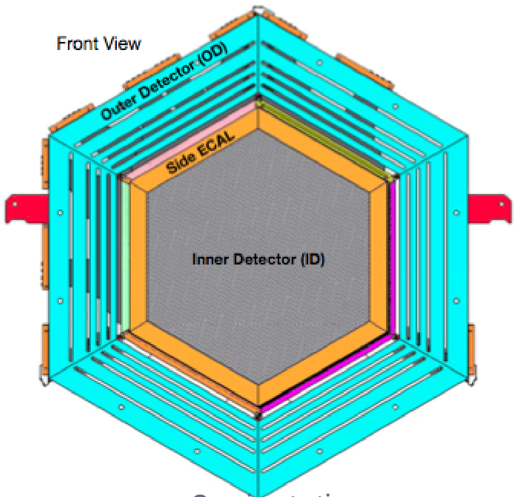
Minerva Experiment

~80 collaborators from particle and nuclear physics

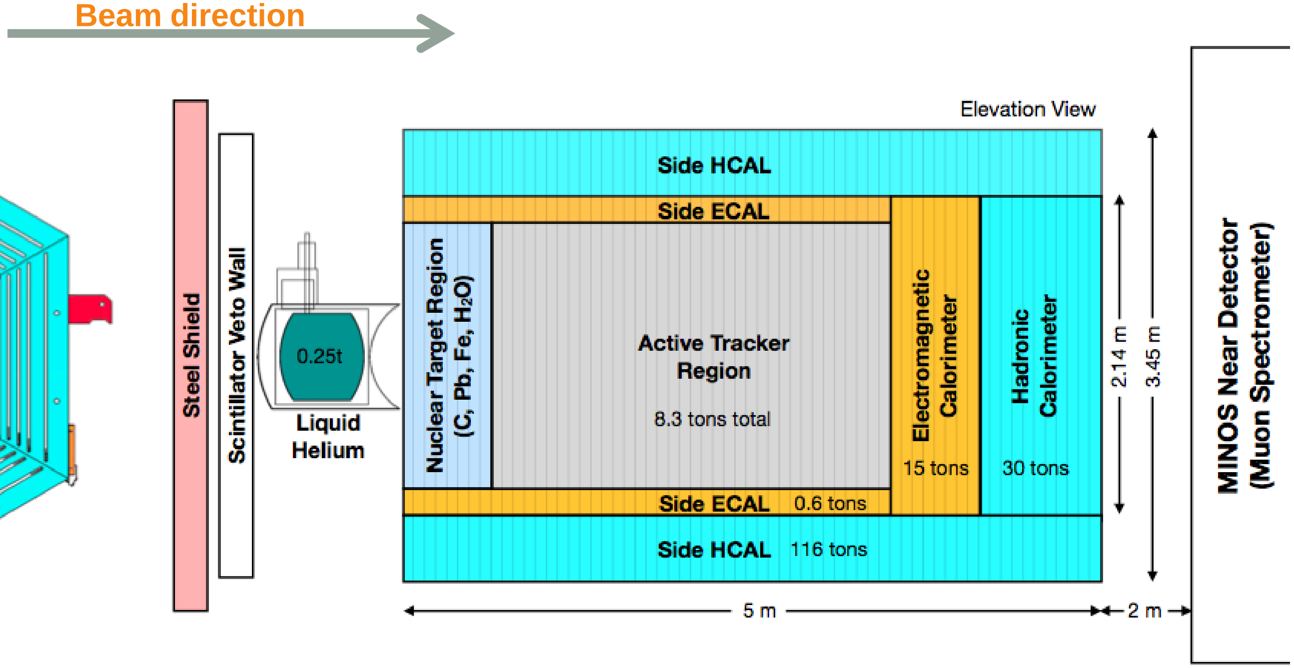
University of Athens
University of Texas at Austin
Centro Brasileiro de Pesquisas Físicas
Fermilab
University of Florida
Université de Genève
Universidad de Guanajuato
Hampton University
Inst. Nucl. Reas. Moscow
Mass. Col. Lib. Arts
Northwestern University
University of Chicago
Otterbein University
Pontificia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

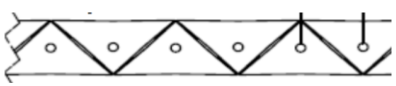


Minerva Detector



3 orientations
0°, +60°, −60°





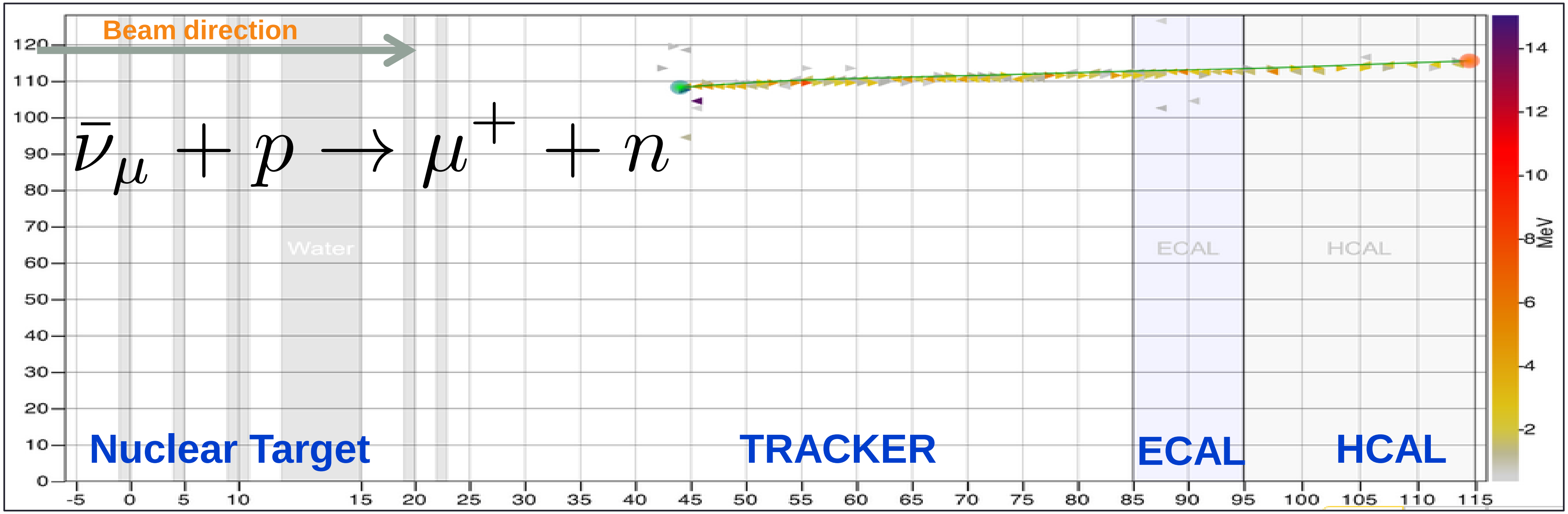
Charge-sharing triangular strips for ~3mm position resolution

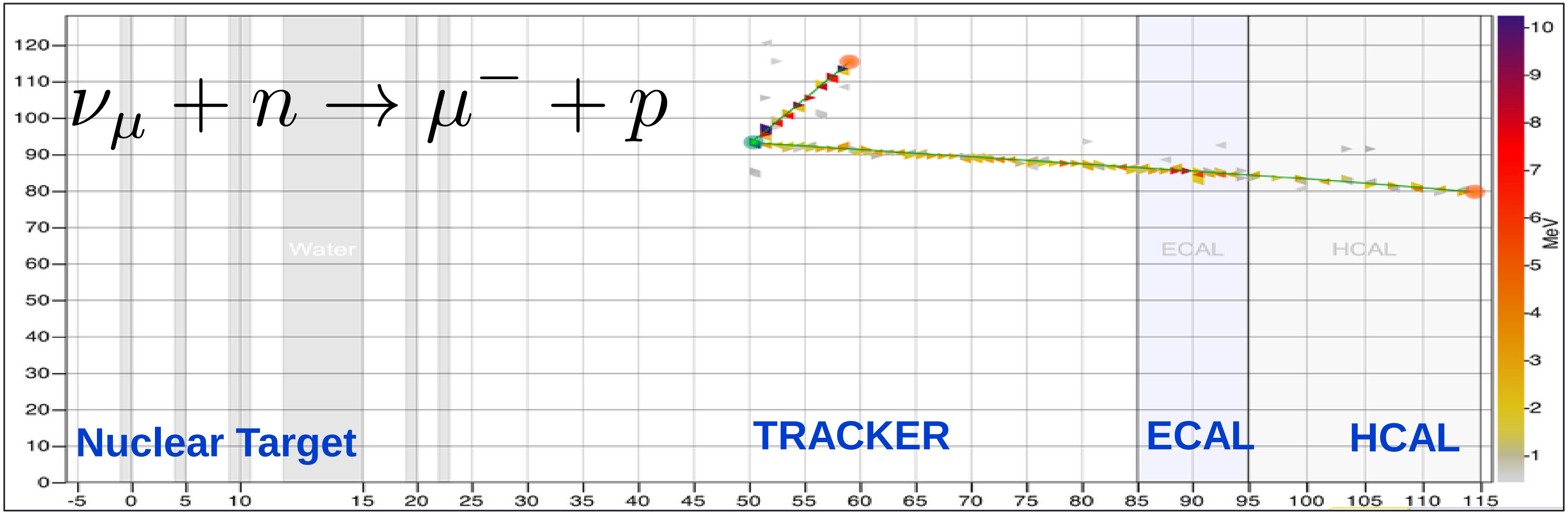
Detector comprised of **120 “modules”** stacked along the beam direction

Central region is **finely segmented scintillator tracker**

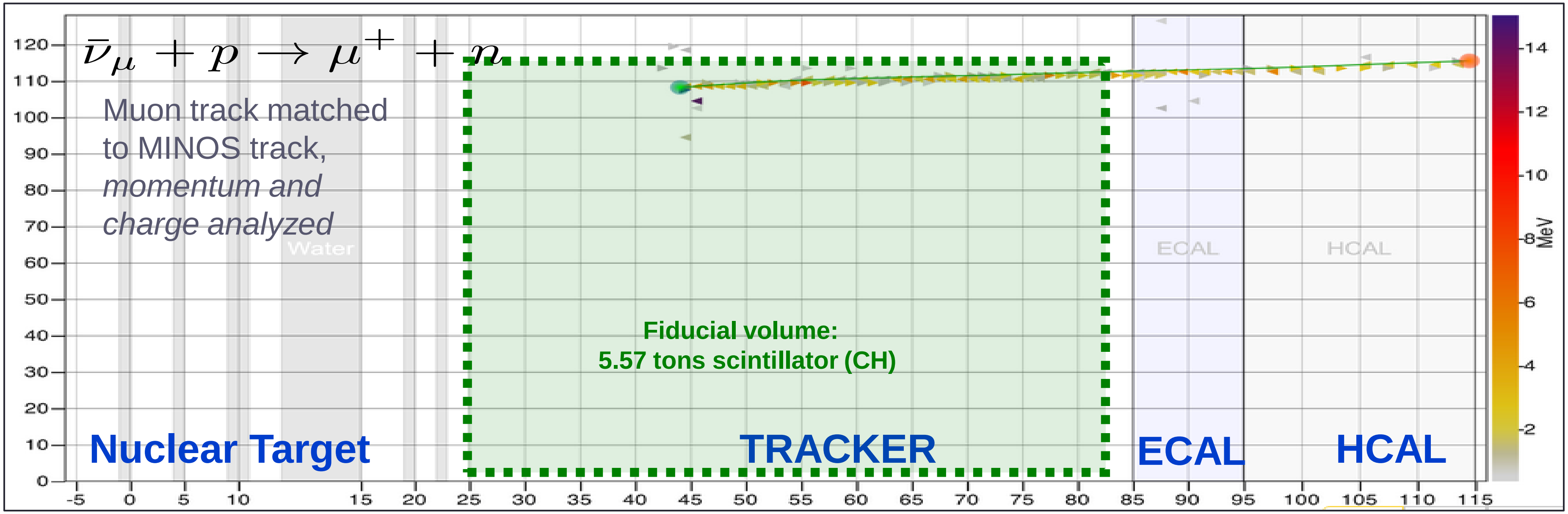
~32k plastic scintillator channels

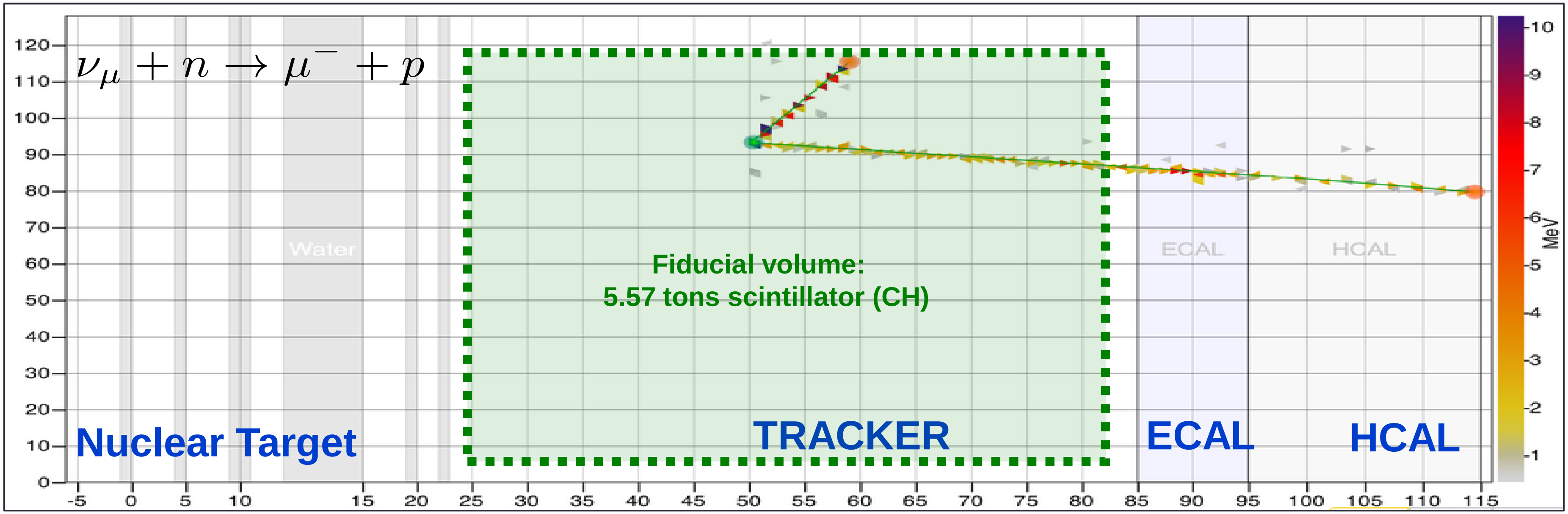
Quasi-Elastic candidate event.



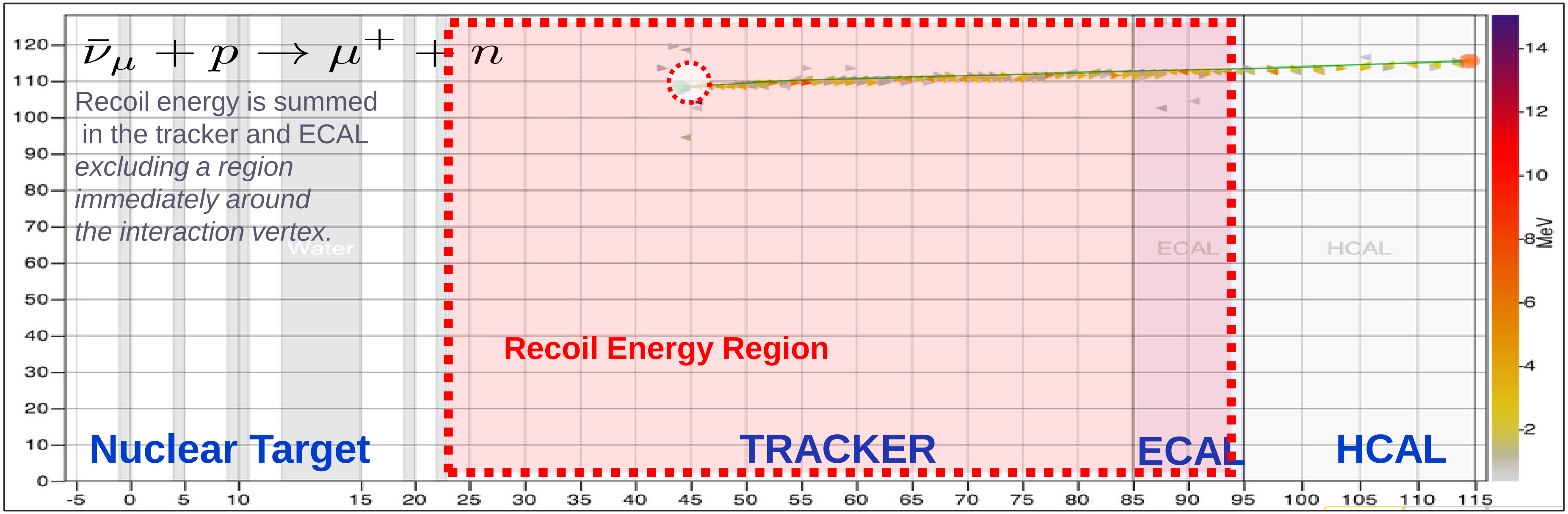


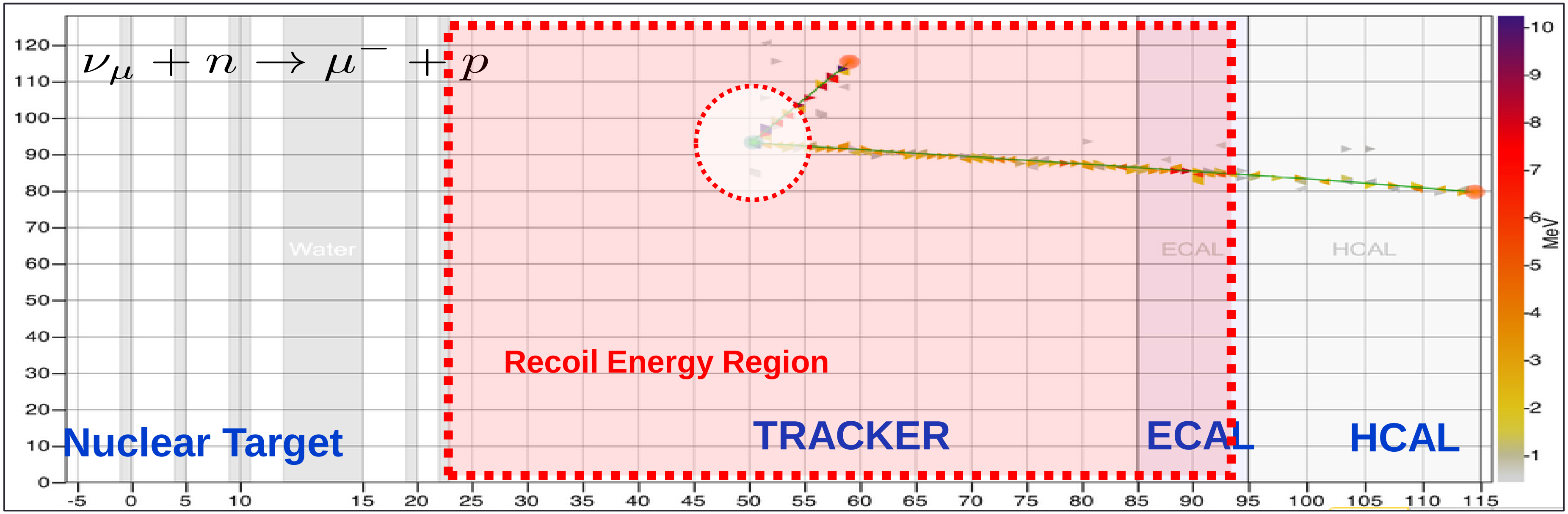
Quasi-Elastic event selection:Fiducial volume



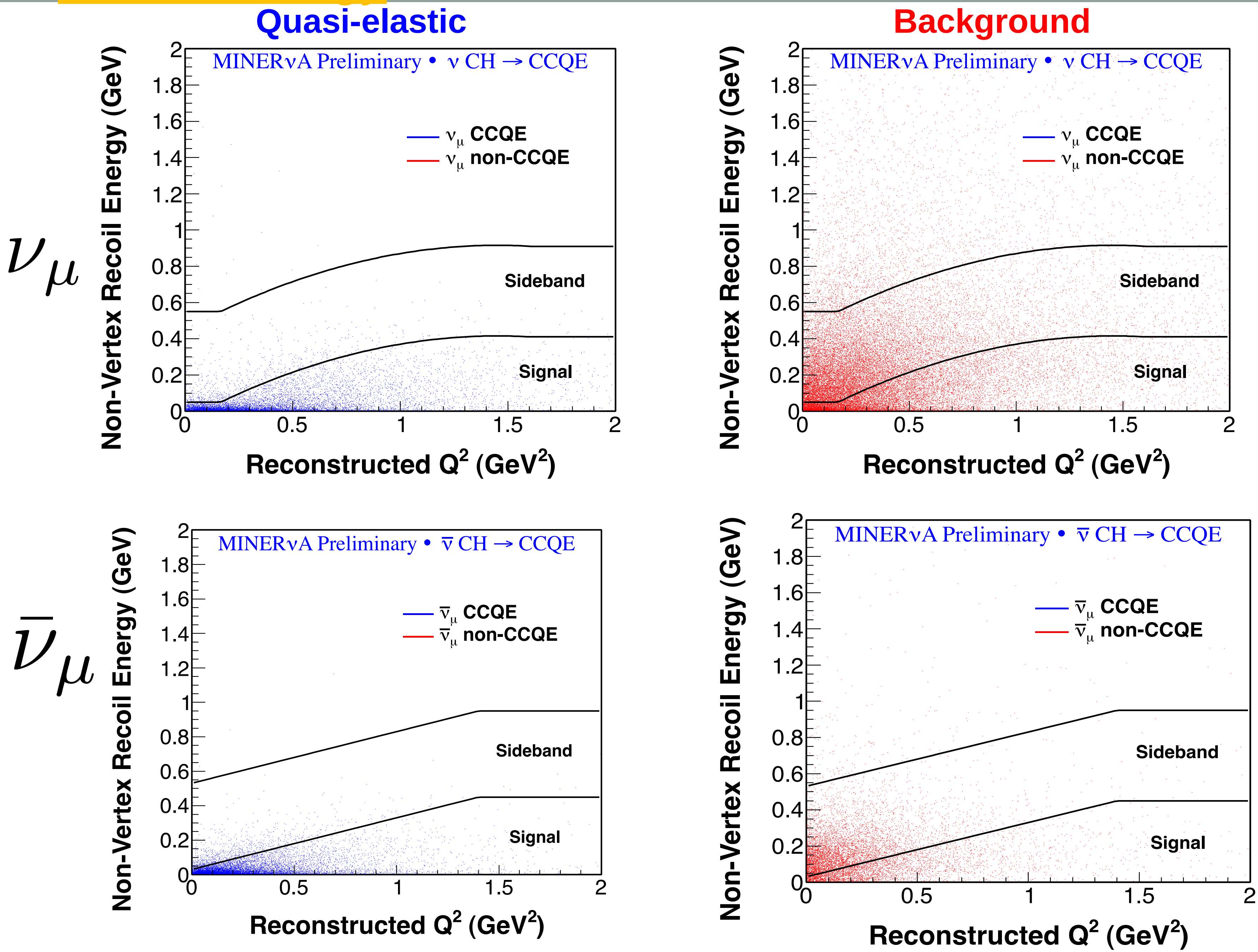


Quasi-Elastic:Recoil Energy cuts



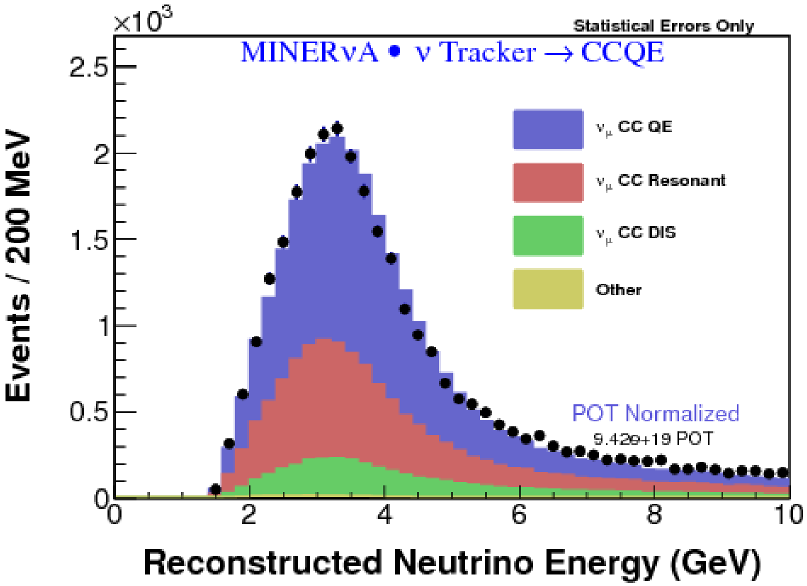


Recoil Energy

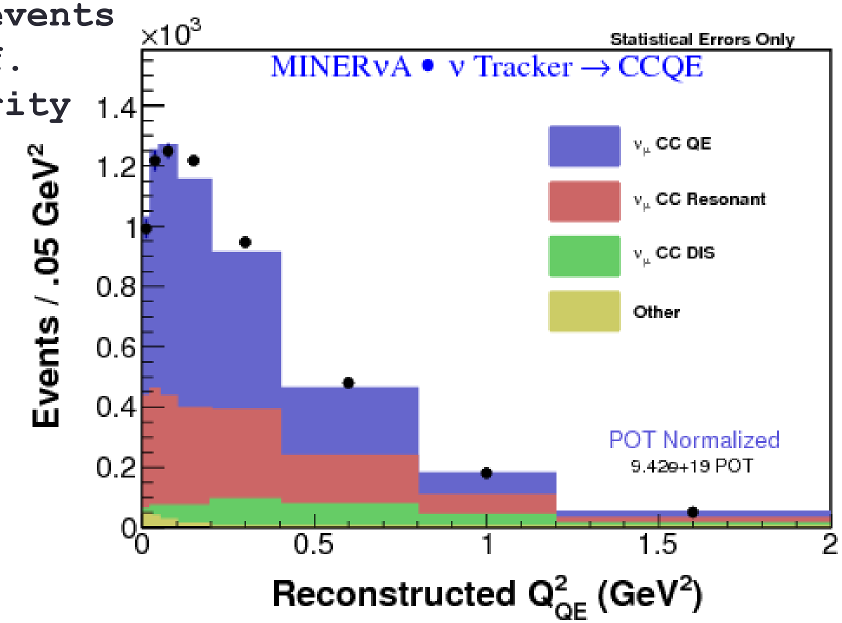


Quasi-Elastic Event Candidates: Kinematic distributions

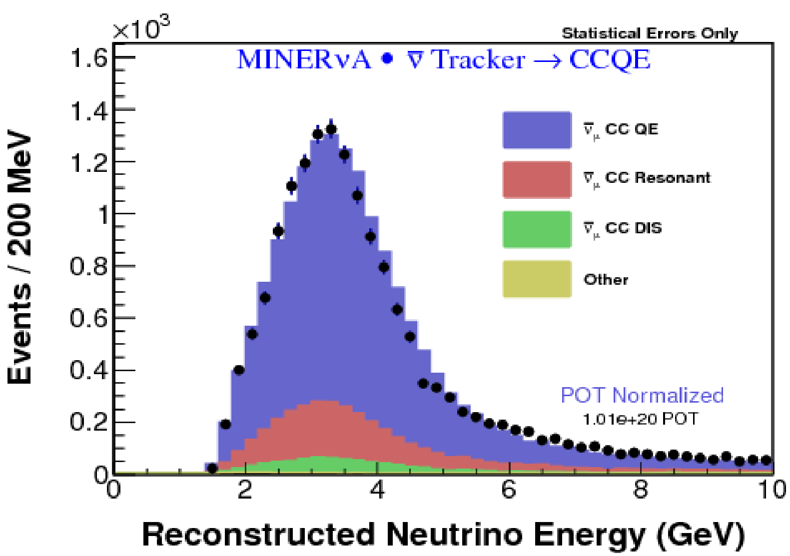
$$\nu_\mu + n \rightarrow \mu^- + p$$



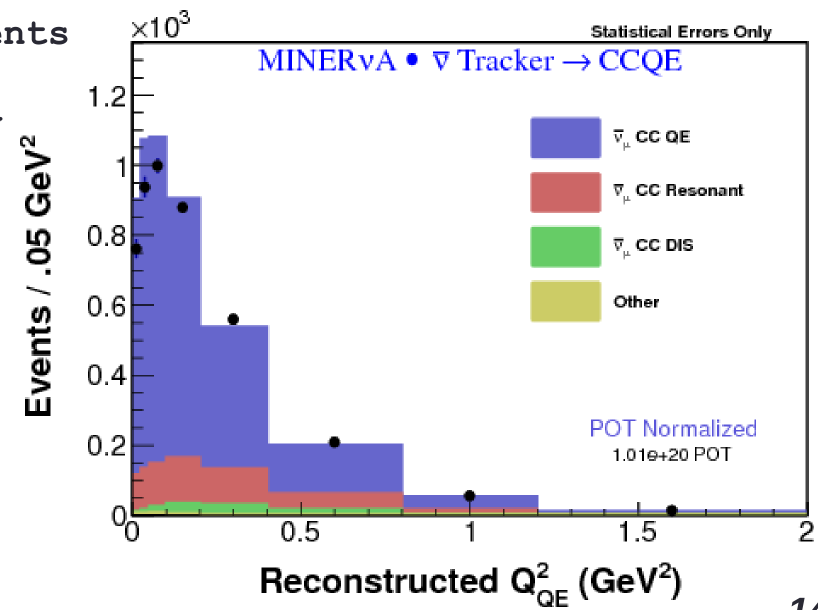
29,620 events
47% eff.
49% purity



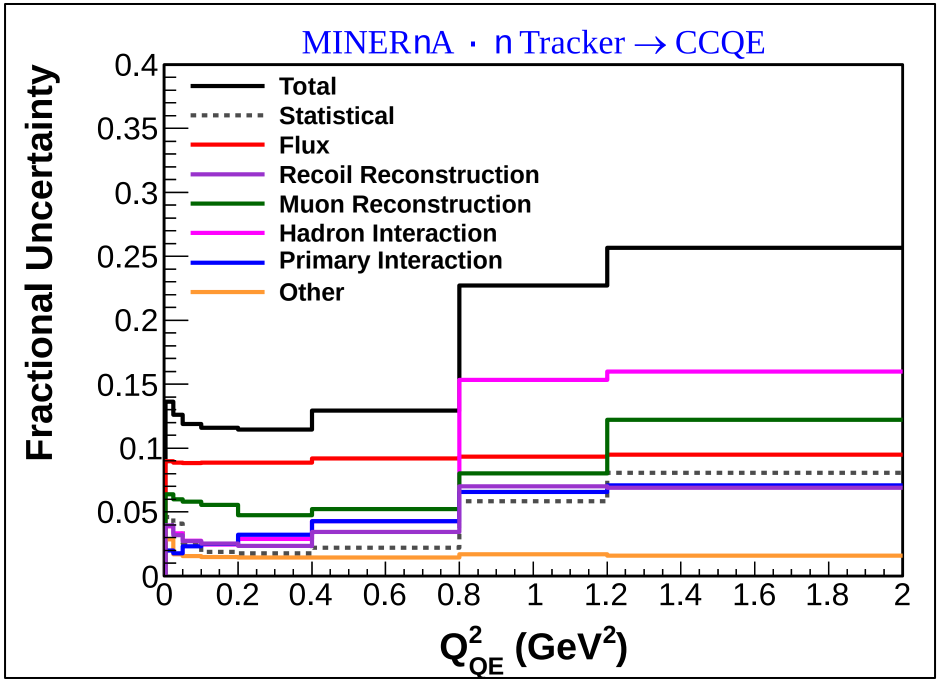
$$\bar{\nu}_\mu + p \rightarrow \mu^+ + n$$

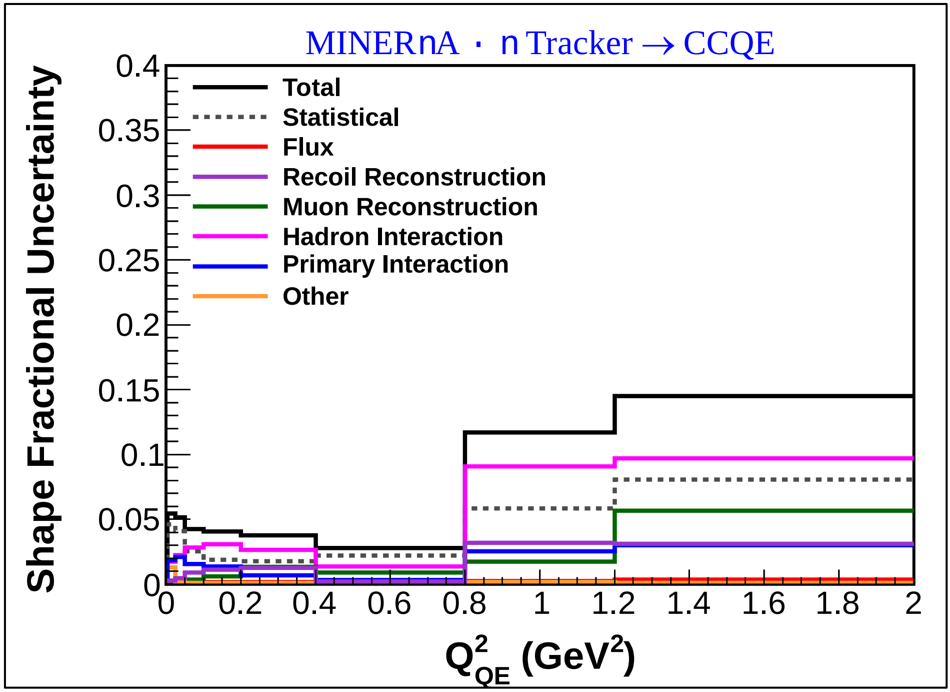


16,467 events
54% eff.
77% purity



Error Summary





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

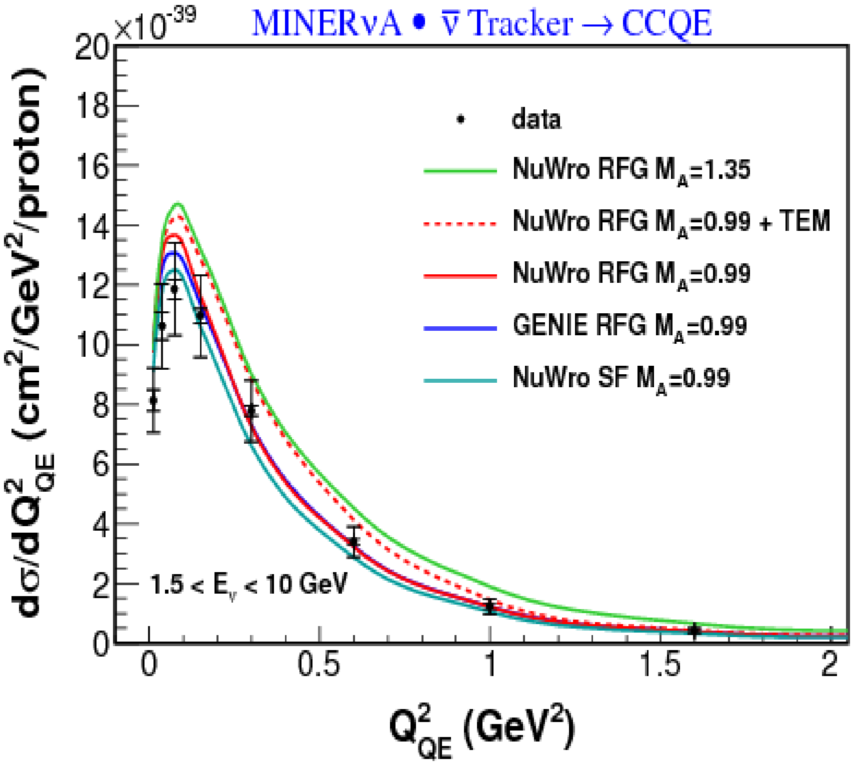
dσ/dQ^2 Shape

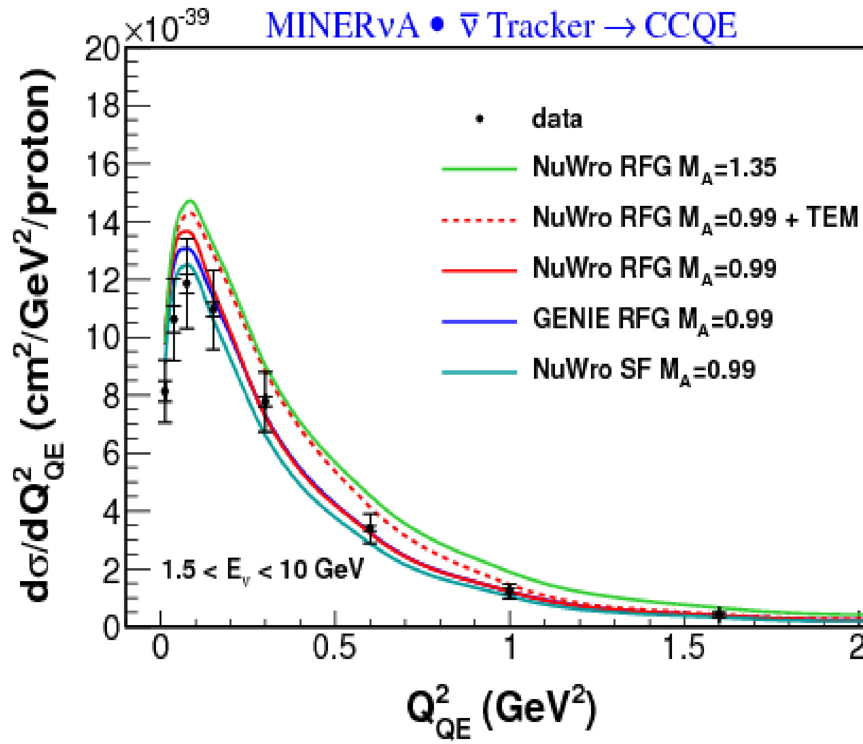
Restricting to the ***shape*** of the cross-section greatly reduces the impact of several mostly normalization errors, including knowledge of the neutrino fluxes

Absolute cross section

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

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





M_A = 1.35 — Best fit to MiniBooNE data

TEM — Empirical model based on electron scattering data

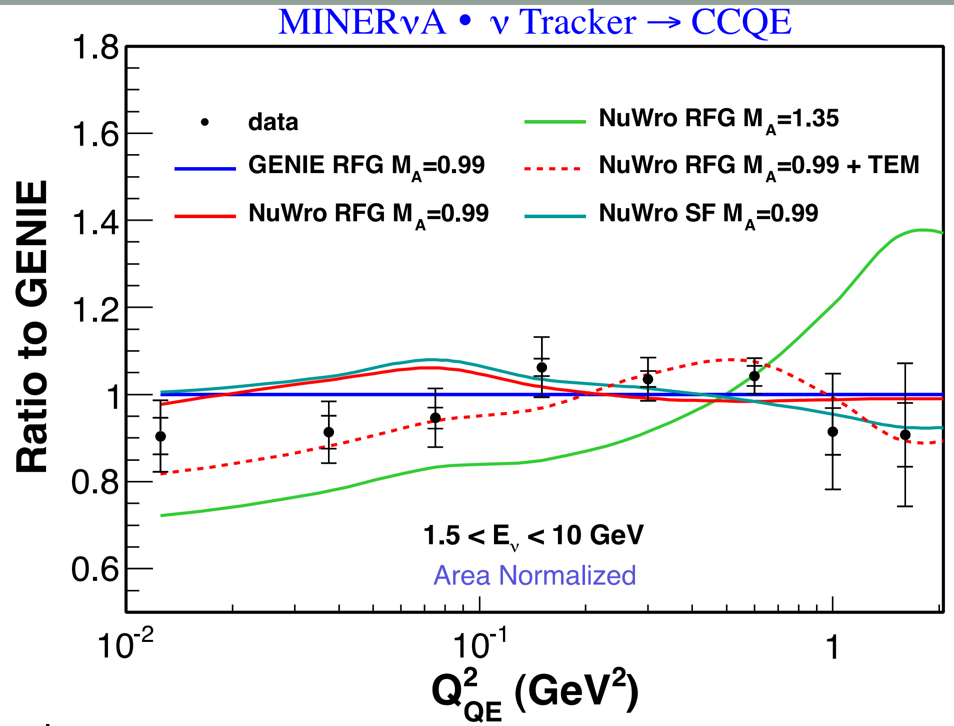
GENIE — Independent nucleons in mean field

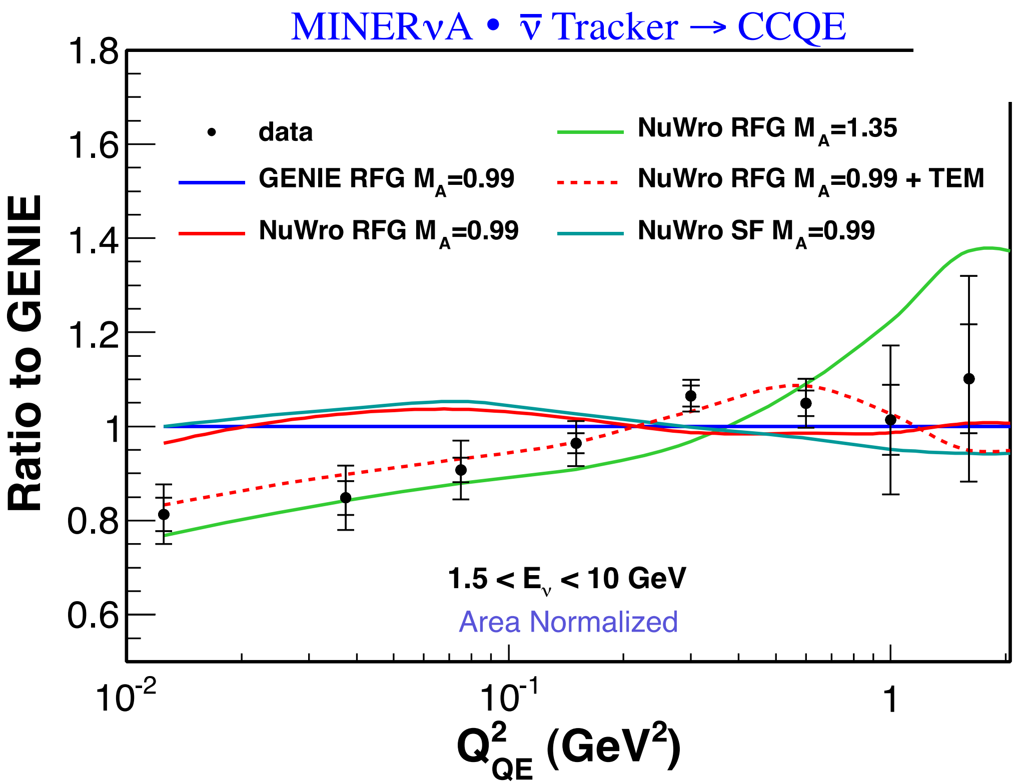
SF — More realistic nucleon momentum-energy relation

G. A. Fiorentini, D. W. Schmitz, P. A. Rodrigues et al. (MINERvA Collaboration), Measurement of Muon Neutrino Quasielastic Scattering on a Hydrocarbon Target at E~3.5GeV, , Phys. Rev. Lett. 111, 022502 (2013)
L. Fields, J. Chvojka et al. (MINERvA Collaboration), Measurement of Muon Antineutrino Quasielastic Scattering on a Hydrocarbon Target at E~3.5GeV, Phys. Rev. Lett. 111, 022501 (2013)

Shape only- Ratio

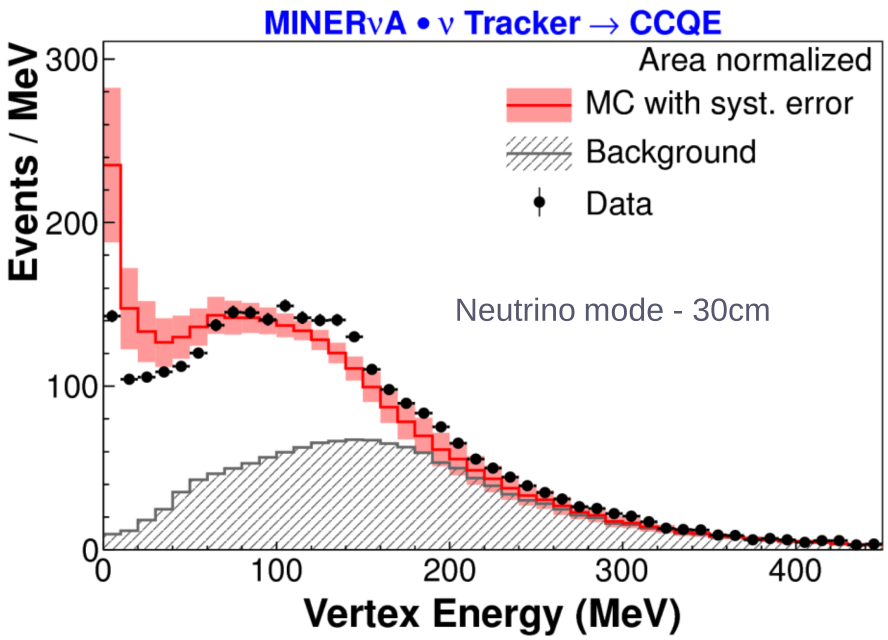
$$\nu_\mu + n \to \mu^- + p$$

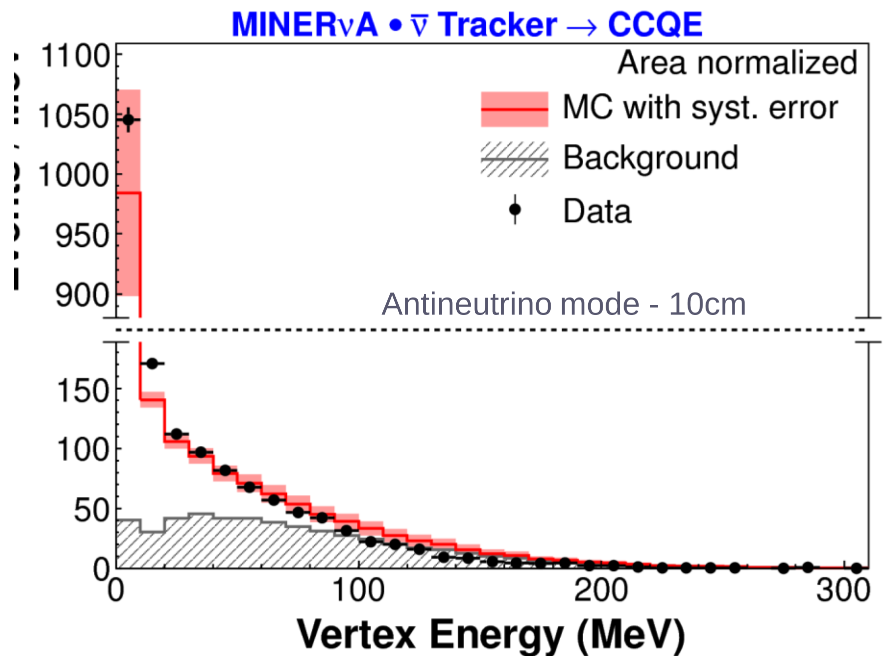




$$\bar{\nu}_\mu + p \to \mu^+ + n$$

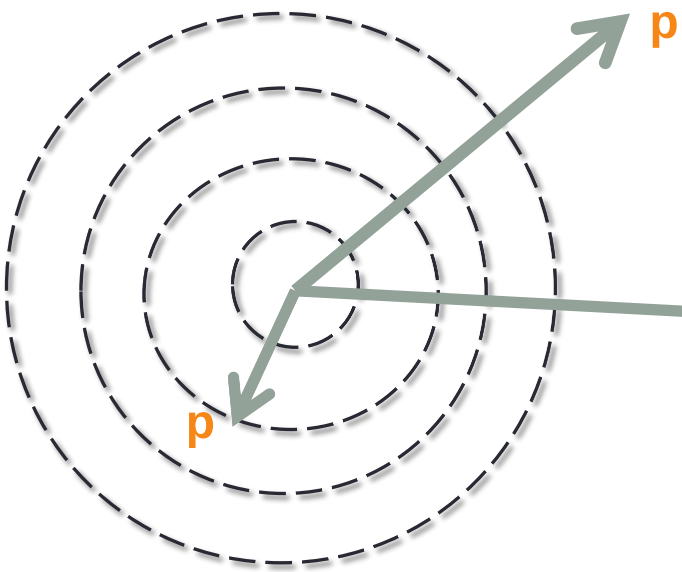
Vertex Energy distribution

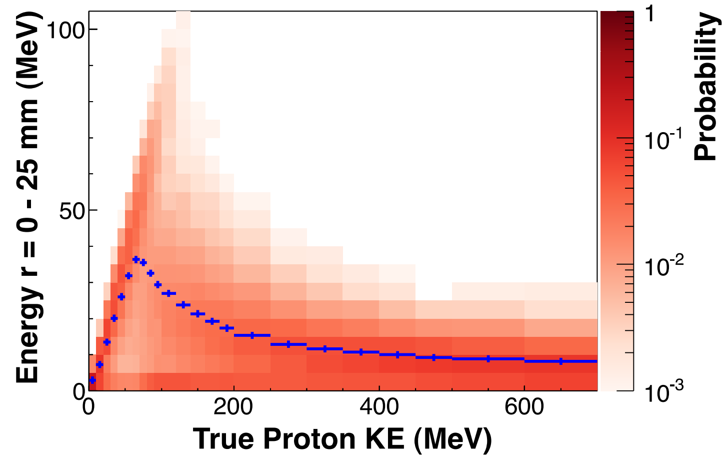




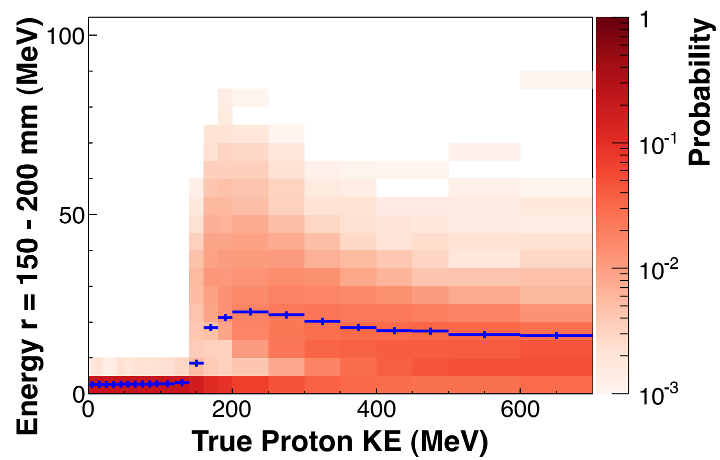
- A harder neutrino-mode energy spectrum is seen in data than MC
- It is not seen in antineutrino mode
- All systematics considered, including energy scale errors on charged hadrons and FSI model uncertainties

Vertex Energy





E_{vis} in that annulus vs. true KE_{pro}



Examine annular rings around the reconstructed vertex

- Out to 10 cm for antineutrino (~120 MeV proton)
- Out to 30 cm for neutrino (~225 MeV proton)

Conclusion

- Differential cross-section $d\sigma/dQ^2$ for neutrinos and antineutrinos on a hydrocarbon (CH) target has been measured.

  -> Integrated over the NuMI fluxes between 1.5 – 10 GeV

  -> CCQE dσ/dQ2 shape distributions prefer RFG+TEM model with M≈ 1 GeV for both neutrino and antineutrino

- Extra energy near vertex suggests additional protons in 25% of CCQE events in neutrino mode only, consistent with correlated nucleon pairs

Future Directions In CCQE @ MINERvA

- Reduce pions background with michel tag electron in neutrino sample

$$\pi^+ \rightarrow \mu^+ \rightarrow e^+$$

- μ+p reconstruction. Push on *low-energy tracking* threshold of protons to reconstruct final states like

$$\mu + p + p$$

- *Double-differential* cross sections in muon kinematics

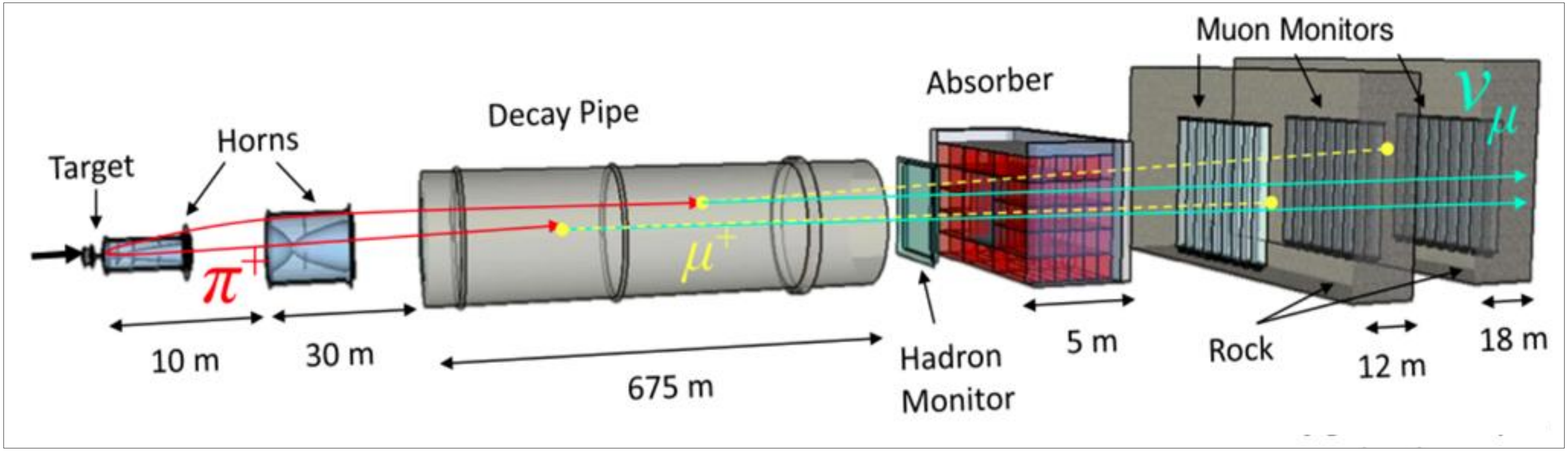
$$\frac{d^2\sigma}{dT_\mu d\theta_\mu}$$

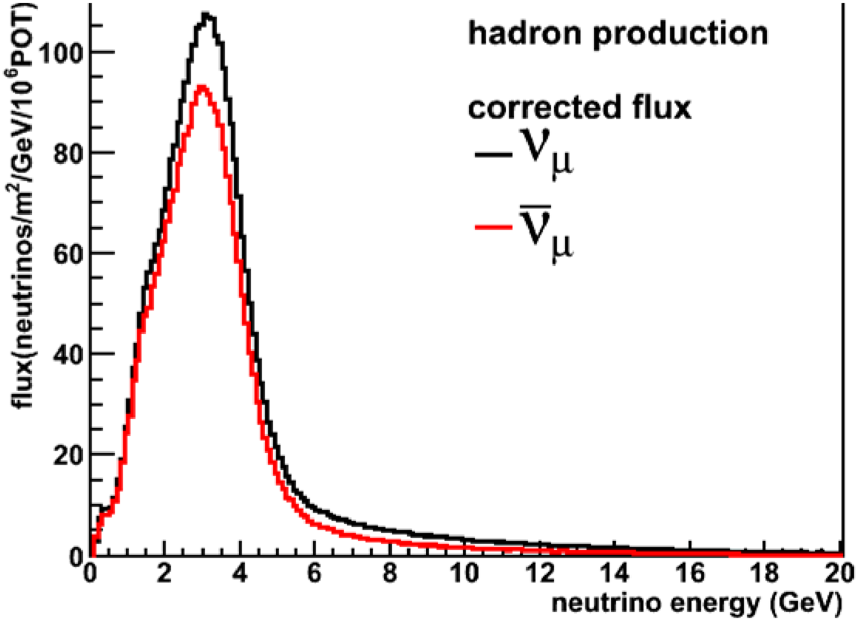
- CCQE in nuclear targets
- Two track Quasi-elastic.

THANK YOU

Back-up

NuMI beamline



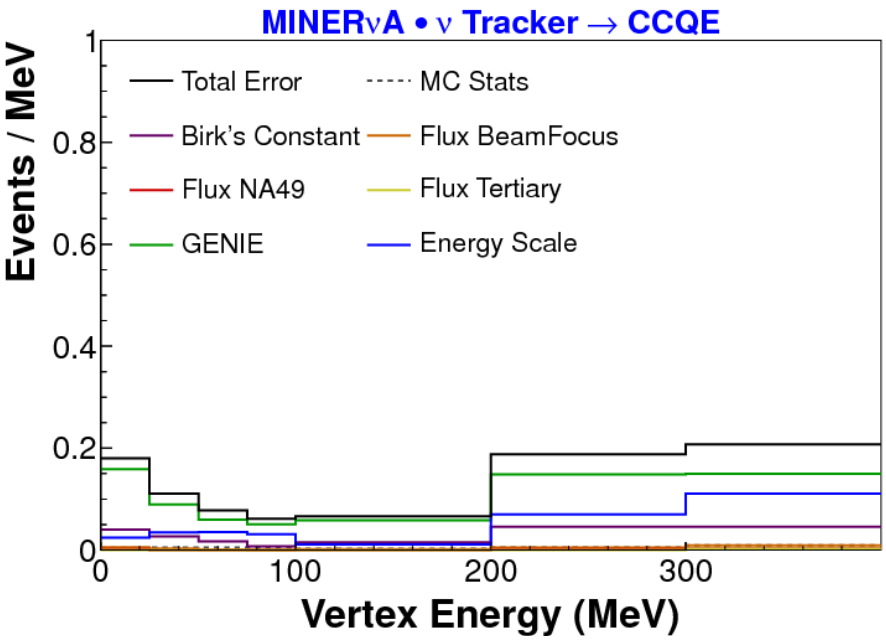


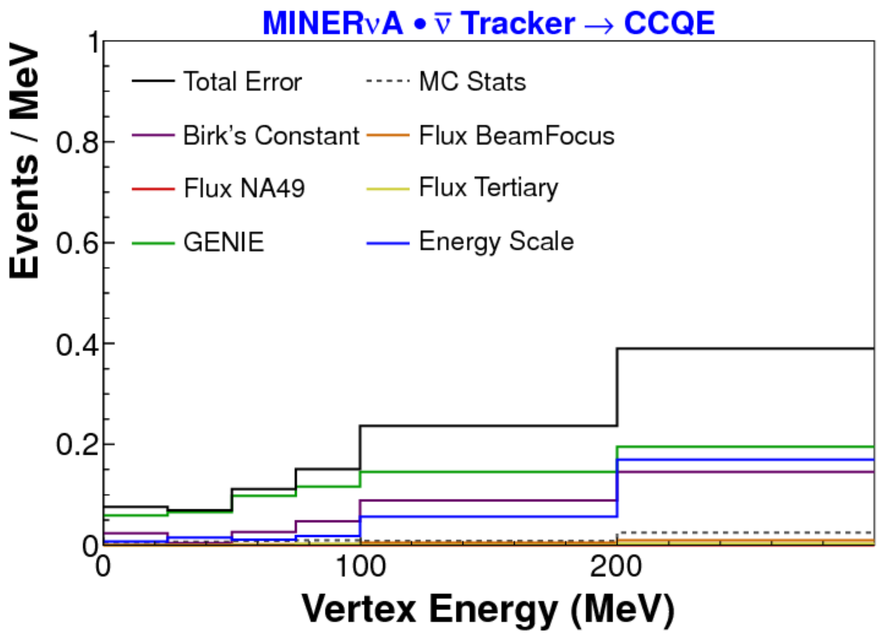
- 120 GeV protons from Main Injector incident on graphite target
- Pions focused by two horns, decay in 675-meter pipe
- 210 meters of rock before Minerva

Systematic uncertainties

- Flux
  - Simulated with GEANT4, reweighted by NA49 data
- Recoil energy reconstruction
  - Overall scale from muons, test beam for hadrons
- Muon energy reconstruction
  - Dominated by MINOS momentum errors
- Hadron interaction model
  - Affects FSI, hadron interactions inside detector
- Primary interaction (GENIE)
  - Impacts background subtraction
- Other
  - Detector mass, cross-talk, other detector effects

Vertex energy error summary





Dominated by modeling uncertainties (GENIE)